

WEBVTT

1

00:00:07.560 --> 00:00:21.840

Morgan Elowe MacLeod: Now let's get started. We are actually recording the full meeting today not starting a couple minutes in, like we normally managed to do. We're delighted today to have to cosmology focus talks so

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00:00:24.240 --> 00:00:26.400

Morgan Elowe MacLeod: But before we do that,

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00:00:28.680 --> 00:00:35.910

Morgan Elowe MacLeod: On a volunteer to say a couple words about something really exciting, which is happening today, which is the Gaia early data released three

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00:00:37.110 --> 00:00:49.620

Ana Bonaca: Yes, actually, when can you stop sharing. I heard, I wanted to do show something yeah bigger that it would be better if I

5

00:00:50.970 --> 00:01:05.130

Ana Bonaca: Instead of just talking about it show what actually happened. Um so yeah I guess if you're following galactic astronomy. You might have heard that the

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00:01:06.150 --> 00:01:17.760

Ana Bonaca: Early days literally Street from the Gaia mission as was released today and me so it's

7

00:01:20.340 --> 00:01:21.450

Ana Bonaca: Here at a conference.

8

00:01:30.120 --> 00:01:34.200

Ana Bonaca: As you see, like here you're going 1.6 million years, the future.

9

00:01:35.460 --> 00:01:39.360

Ana Bonaca: And the stars, which are stars are showing. Oh, no.

10

00:01:42.300 --> 00:01:51.660

Ana Bonaca: Because when we showed us moving. I think my favorite ones are like the CO moving pairs. Oh my gosh, it's like okay let's let's play it again.

11

00:02:03.480 --> 00:02:06.570

Ana Bonaca: See stars that become trails.

12

00:02:10.740 --> 00:02:13.050

Ana Bonaca: I will send the link and you will you can

13

00:02:13.080 --> 00:02:14.100

Morgan Elowe MacLeod: Look at it sounds great.

14

00:02:14.430 --> 00:02:15.030

Ana Bonaca: At here.

15

00:02:17.970 --> 00:02:23.730

Ana Bonaca: Is a bit lagging anyway, it's a it's a giant catalogue of 2 billion.

16

00:02:25.110 --> 00:02:39.780

Ana Bonaca: Stars and there are some cool results already published by the, the guy team on the structure of the anti center and also structures around the large and small Mitchell any clouds that you see over here one also really

17

00:02:40.320 --> 00:02:53.610

Ana Bonaca: Really cool resolve is that is from the emotions of like that the apparent motions are quasars. They managed to other Kathy managed to measure the gravitational acceleration of the sun.

18

00:02:54.690 --> 00:03:12.570

Ana Bonaca: In the galaxy which was like, pretty cool. And I think people expected this to be possible. And so with that, I'll just leave you with a instructions to go. Go ahead and check it out. And let's hear from

19

00:03:13.740 --> 00:03:16.290

Ana Bonaca: When upon what what happened in the past.

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00:03:19.680 --> 00:03:20.340

Morgan Elowe MacLeod: Well, thank you.

21

00:03:21.450 --> 00:03:36.120

Morgan Elowe MacLeod: Yes. So our first speaker today is when Rudy Glenn is an astronomer at Carnegie observatories before that you did your PhD at Caltech can get a bachelor's degree in New England at Dartmouth.

22

00:03:37.470 --> 00:03:43.500

Morgan Elowe MacLeod: And we're we're delighted to have you. Today, Glenn is an expert in spec talk

23

00:03:45.720 --> 00:03:45.990

Morgan Elowe MacLeod: About

24

00:03:47.700 --> 00:04:02.010

Morgan Elowe MacLeod: To say when you stumble over spectroscopy of quasars, but how we can use the spectrum to probe everything in between. And today we're gonna learn about the circle galactic so thank you so much.

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00:04:10.530 --> 00:04:12.630

Gwen Rudie (she/her/hers): I think you're seeing me now. Yes.

26

00:04:13.980 --> 00:04:18.390

Gwen Rudie (she/her/hers): I don't have control of my screen when or of zoom when I have my screen share

27

00:04:18.690 --> 00:04:22.290

Morgan Elowe MacLeod: Oh, no worries. And we'll give you like a five minute bill warning.

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00:04:22.980 --> 00:04:37.200

Gwen Rudie (she/her/hers): Okay, perfect. Well, thank you guys so much for having me. I'm delighted to be here, virtually to tell you about work I've been doing with a number of collaborators studying the Second Galactic medium of cosmic noon era galaxies around a redshift of two to three.

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00:04:39.000 --> 00:04:44.310

Gwen Rudie (she/her/hers): So I always like to start with a statement that I believe we can all sort of agree with

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00:04:45.000 --> 00:04:51.750

Gwen Rudie (she/her/hers): Which is that baryonic processes control sort of many of the observable properties of galaxies. So while dark matter may provide

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00:04:52.110 --> 00:04:59.100

Gwen Rudie (she/her/hers): The scaffolding onto which galaxies are formed. We understand that the way in which galaxies accrete gas from the intergalactic medium.

32

00:04:59.550 --> 00:05:11.430

Gwen Rudie (she/her/hers): Will be critical to the way in which galaxy formation proceeds. In addition to that, how the energetic processes that occur when stars form and when stars die. We understand drive

33

00:05:12.180 --> 00:05:21.660

Gwen Rudie (she/her/hers): Large scale galactic winds, which again impact the evolution of these galaxies and these processes are not actually particularly well understood.

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00:05:22.830 --> 00:05:33.630

Gwen Rudie (she/her/hers): We believe, however, that these gas flows actually may play a very dramatic role in shaping and regulating galaxies. So in particular, here I'm just showing

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00:05:34.200 --> 00:05:41.400

Gwen Rudie (she/her/hers): Given the time constraint at the top one example, which is the mass metallicity relation and galaxies and the local universe from Andreassen Martini.

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00:05:42.420 --> 00:05:49.260

Gwen Rudie (she/her/hers): And what we know is that as galaxies receive gas from the intergalactic medium. If it is lower metallicity then there is

37

00:05:50.220 --> 00:06:01.140

Gwen Rudie (she/her/hers): This will of course dilute the metal, a city of the next generation of stars that will be formed and similarly galactic winds in particular if they preferentially carry out

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00:06:01.770 --> 00:06:05.220

Gwen Rudie (she/her/hers): The metals that has been formed in the most recent epoch of star formation.

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00:06:05.940 --> 00:06:19.980

Gwen Rudie (she/her/hers): Is also going to significantly impact the chemistry of the stars that form and therefore the the full galaxy. And so understanding these sorts of processes is going to be very critical for understanding the evolution of galaxies.

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00:06:21.420 --> 00:06:32.340

Gwen Rudie (she/her/hers): Now, I would argue that if we're interested in studying these processes. One of the best times and the history of the universe to do so it would be around a redshift of two during sort of this cosmic peak of star formation.

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00:06:32.520 --> 00:06:48.960

Gwen Rudie (she/her/hers): When the star formation rate density of the Universe was highest there's some theoretical work that would also project that that epoch is also sort of the cosmic peak of these gas flows. So here I'm just showing to sort of beautiful images that come out of

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00:06:49.980 --> 00:07:01.530

Gwen Rudie (she/her/hers): Some simulation work over the last decade that sort of illustrate two main phenomenon that I'll talk about at some like today. And so the first on the left is feedback.

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00:07:01.950 --> 00:07:08.370

Gwen Rudie (she/her/hers): Galactic winds that blow out, as I've said, potentially metals, but certainly is an in general from these galaxies.

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00:07:09.120 --> 00:07:18.270

Gwen Rudie (she/her/hers): And we we observe in the spectra of of hi Richard galaxies very prominent features from winds. And so we know that these are occurring in the distant universe.

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00:07:19.170 --> 00:07:30.120

Gwen Rudie (she/her/hers): Very, very commonly on the right. I'm instead showing work that focuses instead on how galaxies accrete gas from the intergalactic medium and there's really been sort of a shift over the last

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00:07:30.450 --> 00:07:44.520

Gwen Rudie (she/her/hers): 15 years or so in the discussion of how galaxies received gas from the IGM with a particular emphasis on the idea that at early times like during these red shifts and previous to that that galaxies may in fact be able to accrete gas.

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00:07:45.720 --> 00:07:52.380

Gwen Rudie (she/her/hers): From the intergalactic medium in a relatively cold form and therefore, this may help to fuel star formation.

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00:07:53.400 --> 00:07:56.220

Gwen Rudie (she/her/hers): But regardless of exactly how these processes proceed.

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00:07:56.580 --> 00:08:01.200

Gwen Rudie (she/her/hers): One thing that I like to point out from beautiful images like this out of simulations.

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00:08:01.410 --> 00:08:09.960

Gwen Rudie (she/her/hers): Is that if we are interested in studying these processes, we would do well, not just to study the galaxies themselves but also to study the gas that surrounds them in detail.

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00:08:10.260 --> 00:08:20.550

Gwen Rudie (she/her/hers): In the Second Galactic medium. So if we look off the plane of these galaxies we might see direct evidence of the physical properties of gas and the CGM that might tie directly to these physical processes.

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00:08:22.050 --> 00:08:30.750

Gwen Rudie (she/her/hers): So that's exactly what I'll tell you about today work where we have taken very detailed spectra of distant quasars around a redshift of three we complement. This was very

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00:08:31.500 --> 00:08:36.960

Gwen Rudie (she/her/hers): Dense Galaxy Redshift surveys, focusing on galaxies in the foreground of these quasars.

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00:08:37.650 --> 00:08:47.430

Gwen Rudie (she/her/hers): Where if one of the galaxies lives very close to the line of sight. We can probe the gas distribution surrounding this galaxy and very high detail using these these coins are spectra.

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00:08:48.240 --> 00:08:57.030

Gwen Rudie (she/her/hers): So just to touch on the galaxy and Quasar survey that I've been talking about. This is the CAC baryonic structure survey. It covers 15 fields across the sky with

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00:08:57.390 --> 00:09:10.320

Gwen Rudie (she/her/hers): Some of the brightest high redshift quasars accessible to Northern Hemisphere telescopes, such as the galaxies that lie in the foreground of these probe this sort of cosmic peak and star formation just above a redshift have to

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00:09:11.340 --> 00:09:17.550

Gwen Rudie (she/her/hers): All of the spectrum, I'll tell you about today from of the quasars come from. Hi Rose and have really high signal to noise.

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00:09:18.540 --> 00:09:30.180

Gwen Rudie (she/her/hers): And high spectral resolution which allow us to measure very precisely the column densities, as well as wits of

individual absorption systems which tell us a lot about the physics of the gas in the CGM

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00:09:31.530 --> 00:09:41.010

Gwen Rudie (she/her/hers): I mentioned this is paired with a very large Galaxy Redshift Survey. But today, I'm not actually going to focus on most of that I'm going to focus instead on the galaxy is a very small sample.

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00:09:41.850 --> 00:09:48.750

Gwen Rudie (she/her/hers): That lie within the view the within 100 kilo parsecs of the line of sight to the quasar and so we actually probe.

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00:09:49.170 --> 00:10:00.810

Gwen Rudie (she/her/hers): Gas within the halo of these galaxies within the radius of these galaxies using the background Quasar sightline so just to touch on the sample a little bit more to give you some context for the types of galaxies. I'll be discussing today.

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00:10:01.890 --> 00:10:06.450

Gwen Rudie (she/her/hers): These galaxies are relatively luminous within about a factor of three of  $L_{\text{star}}$  these friendships.

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00:10:07.290 --> 00:10:15.270

Gwen Rudie (she/her/hers): They are relatively young, but with a wide range of ages anywhere from sort of a dynamical time scale up to effectively the age of the universe at these friendships.

64

00:10:15.780 --> 00:10:26.250

Gwen Rudie (she/her/hers): They have a wide range of star formation rates as well as stellar masses and a clustering analysis performed by Ryan trainer showed us these galaxies sit in typical dark matter halos have about 10 to 12 solar masses.

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00:10:26.610 --> 00:10:31.560

Gwen Rudie (she/her/hers): Corresponds to have your radius about 90 physical killer parsecs. So those are good numbers to keep in mind for scale.

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00:10:32.670 --> 00:10:41.760

Gwen Rudie (she/her/hers): Alright. So jumping right in the hierarchy of circle galactic medium. What does the CGM actually look like. Well, I'm a spectroscopy. So I will be showing you spectra.

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00:10:42.690 --> 00:10:52.230

Gwen Rudie (she/her/hers): during at least some portions of this talk. So what I'm, what I'm showing here in black is the continuum normalized spectrum of of this Quasar one of the quasars in our sample.

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00:10:52.830 --> 00:11:02.970

Gwen Rudie (she/her/hers): And I'm showing on this with respect to the redshift of one of the foreground galaxies that lies about 75 kilo parsecs or roughly three quarters of the variable radius from the line of sight to this Quasar

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00:11:04.230 --> 00:11:18.690

Gwen Rudie (she/her/hers): All of the colored curves show a full week profile decomposition of the absorption in a variety of ionized metal features from simply i&i silicon and carbon over here Tripoli ionized silicon and carbon and five times ionized oxygen here.

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00:11:20.160 --> 00:11:25.590

Gwen Rudie (she/her/hers): Now there's two main points that I want you to take away from looking at the spectrum. So the first is that

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00:11:25.860 --> 00:11:38.940

Gwen Rudie (she/her/hers): The gas in the circle electric medium is extremely cinematically complex. So you can see that this is fit with a very large number of subcomponent boy foot profiles that represent individual structures in the gas or density in much, ladies.

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00:11:40.680 --> 00:11:47.730

Gwen Rudie (she/her/hers): And they span a relatively wide range and velocity and you'll see later in the talk but they actually had a considerably wider range and what's shown here.

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00:11:49.110 --> 00:11:54.300

Gwen Rudie (she/her/hers): And but that overall, this is a relatively complex gashes structure.

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00:11:55.440 --> 00:12:06.510

Gwen Rudie (she/her/hers): The other point is that the gases in fact multi phase. So if we look at these lower ionization lines traced by the singly and Tripoli i&i species. These are actually fit with

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00:12:07.170 --> 00:12:22.980

Gwen Rudie (she/her/hers): A very similar overall components structure where the centroid and width of the lines are tied together, however, that structure doesn't at all is not at all represented in this oxygen six most ionized phase that we that we detect with these data.

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00:12:24.150 --> 00:12:28.560

Gwen Rudie (she/her/hers): However, there is still considerable oxygen six gas at the same velocity

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00:12:29.370 --> 00:12:35.850

Gwen Rudie (she/her/hers): But with very, very different structure. What that tells us is in fact the gas within the Second Galactic medium is multi-phase

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00:12:36.150 --> 00:12:44.790

Gwen Rudie (she/her/hers): And so we have evidence now that this the CGM in high redshift is both multi-phase and cinematically complex. What else can we learn from these data.

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00:12:45.300 --> 00:12:55.200

Gwen Rudie (she/her/hers): So one thing we can, we're lucky to be able to do is constrained the size scale of certain galactic medium gas clouds and that's normally very, very challenging because with a single pencil beam survey. All you have

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00:12:55.530 --> 00:13:04.650

Gwen Rudie (she/her/hers): Access to is is essentially these column densities, but we're fortunate that one of the galaxy. One of the quasars, one of our background quasars is in fact gravitationally lens.

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00:13:04.950 --> 00:13:17.370

Gwen Rudie (she/her/hers): And what that provides is two images of this background Quasar which at the redshift of this galaxy are separated by only 400 parsecs. And so we can actually trace the very small scale structure of these ionized metals.

82

00:13:18.750 --> 00:13:23.430

Gwen Rudie (she/her/hers): At this sort of three quarter distance three quarter view or radius distance from this galaxy.

83

00:13:24.210 --> 00:13:36.600

Gwen Rudie (she/her/hers): Alright, so what do we see when we look at that. All right. So what I'm going to do is replace the quasar spectrum that I've shown here with now the spectrum of the finger image of this Quasar which is again 400 parsecs away.

84

00:13:37.920 --> 00:13:46.290

Gwen Rudie (she/her/hers): And what do we see well overall, we see that the velocity scale of the absorption is roughly constant across these two lines of sight 400 parsecs apart.

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00:13:46.500 --> 00:13:52.170

Gwen Rudie (she/her/hers): So the overall structure that's causing this absorption appears to be larger and scale than 400 parsecs.

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00:13:52.710 --> 00:14:01.080

Gwen Rudie (she/her/hers): The oxygen six is completely consistent across the two lines of sight, suggesting that these oxygen six structures are in fact larger than 400 parsecs.

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00:14:01.440 --> 00:14:11.340

Gwen Rudie (she/her/hers): However, if we look at these individual little bumps and wiggles in these lower ionization state lines. What we see is, in fact, that the gas distribution, they are. It looks very, very different.

88

00:14:11.670 --> 00:14:22.140

Gwen Rudie (she/her/hers): So the individual structures that give rise to these individual sub components in the low ionization lower ionization gas have size scales, much smaller than 400 parsecs. On average,

89

00:14:25.110 --> 00:14:29.190

Gwen Rudie (she/her/hers): So overall this is consistent with the idea that these lower ionization

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00:14:29.670 --> 00:14:45.120

Gwen Rudie (she/her/hers): gas clouds may in fact be small clumps embedded in sort of a warmer volume filling medium that's traced in part by this oxygen six phase and overall that the structure that gives rise to all of this absorption appears to be larger than this 400% scale.

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00:14:46.440 --> 00:14:56.430

Gwen Rudie (she/her/hers): Now this the very small size of circle galactic media and metal absorbers. I think presents an enormous challenge for simulators, especially those interested in doing direct comparisons with observations.

92

00:14:56.970 --> 00:15:06.420

Gwen Rudie (she/her/hers): But I think that there's some novel approaches that have appeared in the literature that will be promising potentially for direct comparisons in the future. So here I'm just highlighting work from a handful of

93

00:15:07.110 --> 00:15:13.080

Gwen Rudie (she/her/hers): Simulating groups on the left. I'm showing where by Cameron humbles who has sort of pioneered work on

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00:15:13.980 --> 00:15:20.700

Gwen Rudie (she/her/hers): Sort of forcing high resolution all the way out to the rural radius of galaxies and these enhanced Halo resolution simulations.

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00:15:21.060 --> 00:15:26.820

Gwen Rudie (she/her/hers): Can get down to relatively high resolution even out at sort of the Bureau radius or half the radius.

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00:15:27.750 --> 00:15:32.730

Gwen Rudie (she/her/hers): These aren't quite converged, but I think that there's some hope here for for getting at these small scale structures.

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00:15:33.600 --> 00:15:44.760

Gwen Rudie (she/her/hers): On the right to panels. I'm showing work by Drummond Fielding and Evan Schneider that have worked on idealized when simulations and you can see that in the simulations, they impact do find extremely small structures.

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00:15:45.120 --> 00:15:51.570

Gwen Rudie (she/her/hers): Of cool gas in many cases precipitating out of a hot wind here in Edmond Snyder's work.

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00:15:52.560 --> 00:16:06.780

Gwen Rudie (she/her/hers): And that this might in fact be some of the types of metal servers that were actually observing here. And so I think that there's some promising work that can that can come out of, out of doing some direct comparisons out of sort of future simulations in this vein.

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00:16:08.190 --> 00:16:14.880

Gwen Rudie (she/her/hers): Alright, moving on. What are the physical conditions of gas within the circle galactic medium. And what does this tell us about accretion and outflows

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00:16:15.720 --> 00:16:27.840

Gwen Rudie (she/her/hers): So to study the physical conditions. What I'm going to rely on is the width of these individual absorption components which encodes information about the gas temperature and non thermal motions of the gas, which I'll call turbulence in this talk.

102

00:16:28.710 --> 00:16:41.400

Gwen Rudie (she/her/hers): So how does that work well for an ISO thermal gas cloud since the energy of different particles is effectively equivalent what we expect is that the velocity distribution of ions of higher mass

103

00:16:42.480 --> 00:16:49.860

Gwen Rudie (she/her/hers): Is overall narrower than that of things with lower mass, because the velocity should be inversely proportional to the square root of the mass of the ion.

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00:16:50.400 --> 00:16:59.250

Gwen Rudie (she/her/hers): And so we expect for instance the silicon profiles to be narrower than the carbon profiles of the same ionization state. So I'm showing on the right hand panel.

105

00:16:59.730 --> 00:17:06.960

Gwen Rudie (she/her/hers): Instances from the kiss data where believe you can see by I that we detect overall the thermo broadening of this gas.

106

00:17:07.710 --> 00:17:15.900

Gwen Rudie (she/her/hers): The right hand panel shows the opposite case where the bulk motions of the gas dominate here the velocity structure is constant across mass. And so you expect

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00:17:16.560 --> 00:17:21.870

Gwen Rudie (she/her/hers): Unlike mass elements to show very similar philosophy profiles, which is what's shown here on the right.

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00:17:22.380 --> 00:17:34.200

Gwen Rudie (she/her/hers): Now in practice we don't look through these data by I to measure temperatures we we fit them. And when we do that, this is the full temperature distribution that we pull out from the data where we were. It's possible to fits

109

00:17:34.650 --> 00:17:45.060

Gwen Rudie (she/her/hers): The temperatures of these absorption systems. Now this is not a this is this distribution is not without observational bias. I just want to add that copy up from the beginning.

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00:17:45.420 --> 00:17:55.320

Gwen Rudie (she/her/hers): In particular, we are not capable of tracing the majority of gas at high temperatures, because the UV absorbers that we're using are not sensitive to gas, a very high gas temperature

111

00:17:56.370 --> 00:18:05.670

Gwen Rudie (she/her/hers): So what's notable is not necessarily where there is an absence of absorption, but rather that there is a very large amount of absorbers that are detected at intermediate gas temperatures

112

00:18:06.780 --> 00:18:13.980

Gwen Rudie (she/her/hers): This is interesting for a variety of reasons. One is if you take sort of a very naive perspective of what gas in the CGM might look like.

113

00:18:14.280 --> 00:18:19.860

Gwen Rudie (she/her/hers): You might predict that you'd have gas at roughly the burial temperature which is at 10 to the six Calvin this orange line.

114

00:18:20.580 --> 00:18:26.970

Gwen Rudie (she/her/hers): For these galaxies or you might predict gas that's much closer to the typical intergalactic medium temperature which is around 10 of the four Calvin.

115

00:18:27.900 --> 00:18:33.690

Gwen Rudie (she/her/hers): We instead see most of the gas at this intermediate temperature fully half of the absorbers have these intermediate temperatures

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00:18:34.440 --> 00:18:44.850

Gwen Rudie (she/her/hers): The other reason this is interesting is that temperature gas at that temperature cools extremely rapidly it's at the peak of the cooling curve. And so in order for this gas to remain so prevalent.

117

00:18:45.300 --> 00:18:54.510

Gwen Rudie (she/her/hers): It requires either a constant reheating or replenishment of this gas which points to this idea that the high register from collective medium is dynamic and an excellent place to study.

118

00:18:54.870 --> 00:19:05.040

Gwen Rudie (she/her/hers): The types of of galactic physics. I was talking about at the beginning of the talk. Now, I think that these temperature distributions are broadly consistent with this idea of cold accretion.

119

00:19:06.060 --> 00:19:08.550

Gwen Rudie (she/her/hers): Combined with gas heating or accretion shocks.

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00:19:09.750 --> 00:19:14.610

Gwen Rudie (she/her/hers): But I think it will require more analysis to sort of get to the bottom of all of these things.

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00:19:14.970 --> 00:19:31.500

Gwen Rudie (she/her/hers): And now I told you, in addition to temperature. We can also measure turbulent velocity. So, this is showing. Now the turbo velocity distribution for absorbers in the kiss. Overall, the velocity scale of these internal motions within these clouds are relatively small. And if we cast that

122

00:19:32.070 --> 00:19:44.160

Gwen Rudie (she/her/hers): To try and put it in perspective, if we cast that is now the total thermal energy internal to these clouds compared to the total internal energy, we see that the vast majority of observers are in fact dominated by the thermal energy contribution.

123

00:19:44.820 --> 00:19:50.040

Gwen Rudie (she/her/hers): Was a little bit of algebra we can recast this as the Mach number of the internal velocities within these

124

00:19:50.040 --> 00:19:51.810

Gwen Rudie (she/her/hers): Clouds. And what we see is that

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00:19:52.170 --> 00:20:02.400

Gwen Rudie (she/her/hers): These internal motions are almost always sub sonic so 80% of absorbers that have Matt measured gas temperatures and turbulences show substantive motions.

126

00:20:02.820 --> 00:20:11.550

Gwen Rudie (she/her/hers): This is in contrast, potentially, to the overall motion of the cloud through the circle galactic medium which you'll see later in my talk can happen at quite high velocities

127

00:20:13.410 --> 00:20:24.330

Gwen Rudie (she/her/hers): So overall I think that this the physical state of the circle black gas is showing good evidence for these heating processes that we think might be very interesting to study.

128

00:20:25.530 --> 00:20:33.270

Gwen Rudie (she/her/hers): And is broadly consistent with the general theoretical paradigm. But I think there's actually a lot left on the table in terms of doing more direct comparisons with

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00:20:33.690 --> 00:20:38.610

Gwen Rudie (she/her/hers): With theoretical work that that would make predictions of the temperature distribution of gas and these halos.

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00:20:39.210 --> 00:20:46.470

Gwen Rudie (she/her/hers): But if we want to sort of disentangle observational II absorbers that are heated by either outflow or accretion shocks, we would do well to study.

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00:20:46.950 --> 00:20:58.530

Gwen Rudie (she/her/hers): The kinematics as well as the chemical enrichment of that gas. So in the time that's remaining I'm going to tell you a little bit about those kinematics. What can we can we detect inflows and outflows in the CGM and

132

00:20:59.310 --> 00:21:06.390

Gwen Rudie (she/her/hers): What can the kinematics. Tell us about feedback. So, for starters, I'm going to rely on redshift space distortions. So this is now showing

133

00:21:06.840 --> 00:21:20.250

Gwen Rudie (she/her/hers): The Galaxy correlation function from the two degree field galaxy wretches survey, just to illustrate the idea. What we see here is the distribution of galaxies along the plan of the sky in the extraction and in the y direction. We see the velocity distribution.

134

00:21:21.480 --> 00:21:28.680

Gwen Rudie (she/her/hers): Trend transposed into a distance, and we see two main and I saw trapeze in this distribution which gives us

135

00:21:29.340 --> 00:21:42.750

Gwen Rudie (she/her/hers): clues about velocity and I saw a piece that exist in the Galaxy Redshift playing. So the first is this elongation on small scales. This is due to the radio velocity of individual galaxies and galaxy groups.

136

00:21:43.800 --> 00:21:45.120

Gwen Rudie (she/her/hers): That are sort of whipping about

137

00:21:47.100 --> 00:21:55.350

Gwen Rudie (she/her/hers): The opposite is seen on large scales we see an overall compression in the velocity scale. This is due to the coherence in fall of galaxies. Do the collapse of structure.

138

00:21:56.430 --> 00:22:04.440

Gwen Rudie (she/her/hers): Alright, so now I'm going to show you the same thing, but with gas and galaxies and I'm only going to show you a one core title of this distribution, just to have higher signal to noise.

139

00:22:05.430 --> 00:22:09.360

Gwen Rudie (she/her/hers): So this is now the distribution of gas with respect to galaxies in that same plane.

140

00:22:10.110 --> 00:22:14.070

Gwen Rudie (she/her/hers): Hydrogen is shown on the left panels on the right panel show for ionized metal species.

141

00:22:14.430 --> 00:22:19.080

Gwen Rudie (she/her/hers): And we see the same to distribution. So we see this finger of God, and I saw entropy

142

00:22:19.320 --> 00:22:25.650

Gwen Rudie (she/her/hers): Which is due to outflows from these galaxies, and we see compression on large scales in the H1 and metal distribution.

143

00:22:25.800 --> 00:22:33.870

Gwen Rudie (she/her/hers): which we believe is due to the overall in fall of this gas so we can detect inflows and outflows on large scales across the CGM and it appears to be common.

144

00:22:34.230 --> 00:22:41.700

Gwen Rudie (she/her/hers): Is there evidence that this is actually impacting the galaxies that are forming. So, in some cases we have evidence of spectacular examples.

145

00:22:42.480 --> 00:22:53.400

Gwen Rudie (she/her/hers): So this is an example of 1000 kilometers per second wind detected in absorption and a variety of metal species that has solar metallicity and also bears molecular gas.

146

00:22:54.450 --> 00:23:00.930

Gwen Rudie (she/her/hers): And I found the galaxy that we believe to be associated with this absorption system. It doesn't look that interesting in this

147

00:23:01.290 --> 00:23:10.440

Gwen Rudie (she/her/hers): infrared imaging where it was detected. But the spectrum shows us that's in fact a very broad line a GN that sits in Asia, and part of the PPT diagram.

148

00:23:11.220 --> 00:23:19.020

Gwen Rudie (she/her/hers): And when we looked at it star formation. Right. We saw that it was, in fact, I had a significantly lower star formation rate than what we would expect for sort of the typical star formation.

149

00:23:19.470 --> 00:23:27.510

Gwen Rudie (she/her/hers): For galaxies of its mass characterized here by the main sequence of star formation at the friendship at this galaxy. So this is one example where we believe

150

00:23:28.050 --> 00:23:36.570

Gwen Rudie (she/her/hers): A wind has driven off a very substantial amount of the ISS potentially bearing metals, excuse me, molecules as well. And this has impacted this galaxy.

151

00:23:36.870 --> 00:23:44.340

Gwen Rudie (she/her/hers): Now the question is, how common is this is this common across galaxies in the universe. And what we can say now is that yes, I think it is.

152

00:23:45.060 --> 00:23:53.550

Gwen Rudie (she/her/hers): So here I'm showing the velocity distribution of individual absorption structures around all of the kiss galaxies within this virile radius.

153

00:23:54.270 --> 00:24:00.600

Gwen Rudie (she/her/hers): So it's applauded now as a function of transverse distance on the sky and line of sight velocity in the y direction.

154

00:24:01.530 --> 00:24:04.080

Gwen Rudie (she/her/hers): And these are all of course the observed quantities with

155

00:24:04.590 --> 00:24:12.090

Gwen Rudie (she/her/hers): Without projection effects taken, taken into account. So they're all lower limits on the three space velocity of three space distance of these absorption systems galaxies.

156

00:24:12.540 --> 00:24:26.520

Gwen Rudie (she/her/hers): I'm comparing that now to the escape velocity profile for a dark matter Halo that would host one of these galaxies and what we can see definitively is that 70% of galaxies that have detected metal absorbers and the kiss have unbound metals.

157

00:24:27.720 --> 00:24:32.280

Gwen Rudie (she/her/hers): So that's pretty exciting. What would these unbound metals. What, what more can we learn about them.

158

00:24:32.610 --> 00:24:39.750

Gwen Rudie (she/her/hers): So here in plotting them as a function of their ionization state where the dark blue ones are the ones that are formally unbound I'll remind you that things that are

159

00:24:40.320 --> 00:24:48.900

Gwen Rudie (she/her/hers): Shaded just in this light blue may in fact also be unbound depending on how the gas is projected. But these are all formally unbound from the system.

160

00:24:49.650 --> 00:24:58.140

Gwen Rudie (she/her/hers): What we see is that these are most commonly detected and high end ionization that aligns and they are not particularly commonly detected in high neutral hydrogen column density systems.

161

00:24:58.440 --> 00:25:05.190

Gwen Rudie (she/her/hers): Now what that tells us is that it's likely that these absorption systems are either very highly ionized very metal enriched, or both.

162

00:25:05.640 --> 00:25:19.860

Gwen Rudie (she/her/hers): And so they're very much consistent with what we'd expect for an outflow from these galaxies, and it's not a particularly small quantity of metals, either for the five galaxies that have unbound carbon for fully 20% of their carbon for column density is unbound

163

00:25:20.910 --> 00:25:29.460

Gwen Rudie (she/her/hers): Now this gas is in fact due to an outflow from these galaxies. It represents metal and rich material that would be permanently removed from the system. And so I think this is pointing exactly to that.

164

00:25:30.240 --> 00:25:36.390

Gwen Rudie (she/her/hers): The point I made at the beginning of how the chemistry of galaxies and subsequent star formation can be broadly impacted by feedback.

165

00:25:37.740 --> 00:25:49.560

Gwen Rudie (she/her/hers): All right, so what can what more can we do, how can we learn more. I'm currently working on modeling the ionization conditions within these clouds in order to measure medalists cities and constrain masses for these individual absorption systems.

166

00:25:50.010 --> 00:25:59.100

Gwen Rudie (she/her/hers): I'm also very excited to connect to this work with lower redshift work that I'm leading along with show and chance on SHAWN JOHNSON in the cosmic ultraviolet Barry on survey or cubs.

167

00:25:59.550 --> 00:26:12.510

Gwen Rudie (she/her/hers): This is a survey, very much like the kiss 15 quasars now at a redshift of close to one observed with HST costs were here instead of tracing the cosmic Pico star formation. We're tracing the downturn of cosmic star formation.

168

00:26:13.770 --> 00:26:16.440

Gwen Rudie (she/her/hers): One other thing that I'm excited about that I think could really

169

00:26:16.860 --> 00:26:20.370

Gwen Rudie (she/her/hers): Add perspective, especially to the kinematics of gas in circle galactic medium.

170

00:26:20.580 --> 00:26:29.220

Gwen Rudie (she/her/hers): Would be new near infrared observations and I'm one of the project scientists for a new instrument concept called Miramar the Magellan infrared multi object spectrograph

171

00:26:29.400 --> 00:26:33.960

Gwen Rudie (she/her/hers): Which I wanted to tell you guys about since you all would have access to this instrument. If it makes it to Magellan

172

00:26:34.740 --> 00:26:51.390

Gwen Rudie (she/her/hers): The idea is full near infrared coverage simultaneously for a relatively wide field of view in multi object spectra spectroscopy, or to have an integral field unit with a relatively like quite a sizeable if you size for an infrared

173

00:26:52.560 --> 00:26:58.980

Gwen Rudie (she/her/hers): Contiguous field for an infrared moss and, in particular, that would be very exciting. I think for the CGM work.

174

00:26:59.790 --> 00:27:13.410

Gwen Rudie (she/her/hers): So here I'm just showing a schematic of what we might be able to do in terms of morphic kinematic analysis in optically thin certain galactic medium emission lines to be able to trace the kinematics of gas flowing in and out of these galaxies.

175

00:27:14.430 --> 00:27:24.990

Gwen Rudie (she/her/hers): Within the contiguous field of view of this exciting new spectrograph that we're hoping to fund for Magellan, and if we do so, relatively soon. We would hope would be on the telescope by 2025

176

00:27:26.070 --> 00:27:33.060

Gwen Rudie (she/her/hers): So that's all I have to tell you about today. I think I'm out of time, so I'm just going to leave my conclusions up but

177

00:27:34.110 --> 00:27:43.650

Gwen Rudie (she/her/hers): I did want to have one more note, which is that Carnegie is hiring staff scientists. So if you guys are interested in a role very similar to mine or have questions about it. I'd be delighted to answer them.

178

00:27:43.890 --> 00:27:52.770

Gwen Rudie (she/her/hers): The applications are due tomorrow, so you don't have a ton of time. But if you're interested in learning about that he delighted to tell you more about Carnegie and what these positions.

179

00:27:53.880 --> 00:27:58.050

Gwen Rudie (she/her/hers): Are all about. So I'll leave my conclusions up and thank you guys so much for your time and attention.

180

00:28:00.690 --> 00:28:01.170

Morgan Elowe MacLeod: Thank you.

181

00:28:04.260 --> 00:28:12.180

Morgan Elowe MacLeod: So this is really fascinating. And there are a lot of questions to ask. But I wondered if we could turn first

182

00:28:13.230 --> 00:28:15.240

Morgan Elowe MacLeod: To the molecular

183

00:28:16.290 --> 00:28:23.610

Morgan Elowe MacLeod: Signatures in the outflows you were seeing in those militia molecule rich wins and so

184

00:28:24.780 --> 00:28:43.470

Morgan Elowe MacLeod: Do you have insight into the temperatures of that molecular gas from those lines or is it all sort of kinematic broadening at those lower temperatures and and Could those be environments where you could sort of form stars in the outflows is a question of the is asking

185

00:28:44.280 --> 00:28:53.310

Gwen Rudie (she/her/hers): That's very interesting. So I'm not an expert actually in the the analysis of the molecular gas. This was actually the very first detection of

186

00:28:54.330 --> 00:29:04.770

Gwen Rudie (she/her/hers): Molecular carbon monoxide, etc. Was this exact absorption system and that was led by other authors and it was detected in the early, early 2000s. In fact,

187

00:29:05.610 --> 00:29:14.460

Gwen Rudie (she/her/hers): So I have not actually analyzed directly the the molecular gas in the system. I was interested in studying the second black imeem of sort of more evolved read galaxies.

188

00:29:14.610 --> 00:29:19.500

Gwen Rudie (she/her/hers): And happened upon the system. Now, in terms of what the conditions in this gas are

189

00:29:20.100 --> 00:29:34.080

Gwen Rudie (she/her/hers): The width of these lines does tell you something, the fact you can do actually detailed ionization analysis on the structure of the molecular species, the various molecular transitions that exist and learn something about the temperature, the temperature

190

00:29:34.350 --> 00:29:36.900

Morgan Elowe MacLeod: To be relative relative abundance of different

191

00:29:37.980 --> 00:29:39.480

Morgan Elowe MacLeod: Different transitions. He's okay.

192

00:29:39.660 --> 00:29:42.270

Gwen Rudie (she/her/hers): Yeah, it gives you, it gives you sort of a temperature sequence.

193

00:29:42.840 --> 00:29:43.170

Gwen Rudie (she/her/hers): I don't

194

00:29:43.320 --> 00:29:47.220

Gwen Rudie (she/her/hers): I don't know the full details of this, but that that is how it works.

195

00:29:48.570 --> 00:29:48.930

Gwen Rudie (she/her/hers): But

196

00:29:50.520 --> 00:29:54.900

Gwen Rudie (she/her/hers): It had did the gas does have to be relatively cold, otherwise this would disassociate

197

00:29:54.960 --> 00:30:00.690

Gwen Rudie (she/her/hers): So the the sort of intermediate temperature gas that we're talking about. That is likely things that would be traced

198

00:30:01.380 --> 00:30:06.300

Gwen Rudie (she/her/hers): Over here where we don't actually see. We can't detect molecular gas out at these sort of thousand convert for second.

199

00:30:06.540 --> 00:30:17.280

Gwen Rudie (she/her/hers): Locations, but here we're seeing very strong carbon for absorption, which is likely due to more ionized and also likely warmer gas and you can see it, it goes yeah there's there.

200

00:30:17.790 --> 00:30:27.360

Gwen Rudie (she/her/hers): The detections here metal species range over a very wide range of ionization state and and plausibly gas temperature. So I hope that addresses, at least some of the questions.

201

00:30:27.360 --> 00:30:29.790

Morgan Elowe MacLeod: Definitely. Um, and then

202

00:30:30.840 --> 00:30:45.780

Morgan Elowe MacLeod: I wondered if we could talk a little bit about sort of the pathway forward to compare to the simulation. So in this audience. There's a lot of people who run that sort of model or if not exactly that sort of model, then something related and

203

00:30:47.250 --> 00:30:48.300

Morgan Elowe MacLeod: I wondered

204

00:30:49.500 --> 00:31:04.830

Morgan Elowe MacLeod: If you could talk. I mean questions that spring immediately to mind is this idea that you were posing that there's like very volume filling components versus like this cold gas has got to be tiny volumes, but lots of mass and

205

00:31:06.000 --> 00:31:11.100

Morgan Elowe MacLeod: How, how do you like what do you imagine being the tracers that one could compare

206

00:31:12.870 --> 00:31:15.540

Morgan Elowe MacLeod: If, like what are, what are the

207

00:31:17.160 --> 00:31:20.880

Morgan Elowe MacLeod: Yeah. What are those, what are the quantities that one could get ahold of them.

208

00:31:22.050 --> 00:31:29.100

Gwen Rudie (she/her/hers): Sure. Um, so I think the way that I like to work on on this with with simulating groups is

209

00:31:30.090 --> 00:31:41.010

Gwen Rudie (she/her/hers): Is that I like to take the observations, a little bit past just the data itself to a little higher level of interpretation. So doing things like measuring these temperatures as opposed to just giving you guys raw line wants to work with.

210

00:31:42.060 --> 00:31:51.060

Gwen Rudie (she/her/hers): And and I also like to, you know, to the degree that it's possible provide things like column densities and so forth. And I think what that means is that it's actually not that hard to meet halfway in between.

211

00:31:51.090 --> 00:32:03.960

Gwen Rudie (she/her/hers): With simulators. So the challenges I can't detect all gas, whereas you guys have detections of all your gas obviously under simulations. You know where the gas that's that kind of the six and a half or 207 Kelvin exists.

212

00:32:04.620 --> 00:32:15.870

Gwen Rudie (she/her/hers): Is and the simulations. So I think doing something like asking for the gas that would be probed by, you know, sort of singly ionized carbon through

213

00:32:16.470 --> 00:32:23.490

Gwen Rudie (she/her/hers): Through three times i, and I as carbon. So asking for those structures and then making a temperature distribution of that gas would be very interesting.

214

00:32:24.060 --> 00:32:38.550

Gwen Rudie (she/her/hers): One challenge though, so I did like sort of a cheap comparison of this with one of the fire simulations PUBLISHED BY ZACH a fun. So he published the, the temperature distribution of gas in the halos of these fire. Fire galaxies.

215

00:32:40.080 --> 00:32:47.310

Gwen Rudie (she/her/hers): And one of the the challenges with this comparison, though, is the kiss, because I don't get have masses. I'm working on this ionization correction.

216

00:32:47.790 --> 00:32:55.320

Gwen Rudie (she/her/hers): The Kiss distributions that I showed you, temperature distributions are by number. So it's the number of absorbers. It's not a mass weighted quantity

217

00:32:56.220 --> 00:33:04.740

Gwen Rudie (she/her/hers): Whereas X work is is is mass waited, it makes more sense for the theoretical community to report such things. And so I'm working on on it from this direction, but I think

218

00:33:05.400 --> 00:33:16.020

Gwen Rudie (she/her/hers): I think with a little bit of sort of discussion with the theorists directly, we could actually probably come up with some pretty straightforward ways to look into.

219

00:33:16.560 --> 00:33:27.930

Gwen Rudie (she/her/hers): The temperature distribution and the simulations in a way that's actually quite analogous to how it is, how does analyze these data and I'm actually really excited about doing that kind of work, because I think we can learn quite a lot from each other. So

220

00:33:28.320 --> 00:33:28.950

Morgan Elowe MacLeod: Like it

221

00:33:29.670 --> 00:33:39.270

Morgan Elowe MacLeod: Yeah, that's really exciting. And when I see the richness of some of these spectral lines and this comes back to a question that I was asking, which is

222

00:33:41.070 --> 00:33:43.470

Morgan Elowe MacLeod: When we're seeing some structure there.

223

00:33:44.820 --> 00:33:50.520

Morgan Elowe MacLeod: There's, it seems like there's so much more information in those lines than just their equivalent with them. So do you think it's possible to

224

00:33:50.790 --> 00:34:02.610

Morgan Elowe MacLeod: Like separately detect clumps that are moving at like kinematic offsets, is that the substructure. We're seeing where is the difference actually lines, adding up to the sort of overall blended profile.

225

00:34:03.000 --> 00:34:09.930

Gwen Rudie (she/her/hers): Yeah, so it's, um, I think the way that I think about it, in particular, this, this first example that I showed

226

00:34:11.040 --> 00:34:24.630

Gwen Rudie (she/her/hers): So the sort of model that I have in my head that I don't think we have perfect evidence that it is a unique model, but it's the one that I think makes the most sense. Is that what we're actually doing is looking in this case through an outflow from one of these galaxies.

227

00:34:25.590 --> 00:34:27.750

Gwen Rudie (she/her/hers): The oxygen six is tracing sort of

228

00:34:29.730 --> 00:34:39.390

Gwen Rudie (she/her/hers): A warmer fluid that's likely more volume filling might be the majority of like this outflow. So if you imagine you know some like river of

229

00:34:40.350 --> 00:34:49.440

Gwen Rudie (she/her/hers): Relatively highly ionized gas coming out directly from the galaxy and then out of that is precipitating these small gas clouds and each one of these individual little

230

00:34:50.580 --> 00:35:04.770

Gwen Rudie (she/her/hers): clumps that you're seeing modeled as a single boy profile is now a significant different density contrast between this this sort of more volume filling wind and a smaller parcel of gas that's probably cooled out of this.

231

00:35:05.850 --> 00:35:15.810

Gwen Rudie (she/her/hers): Of this of this hotter media that's being thrown out of this galaxy. That's sort of what I carry around, but we know that not all CGM observers are that at these ratchets so

232

00:35:16.590 --> 00:35:25.650

Gwen Rudie (she/her/hers): I could show you examples. I don't have them in this slide deck, but there are instances where we see very large column densities of neutral hydrogen gas that have almost no associated battles with them.

233

00:35:26.100 --> 00:35:30.840

Gwen Rudie (she/her/hers): In terms of their kinematic alignment. Now those are cases where I think that's a very likely

234

00:35:31.410 --> 00:35:39.570

Gwen Rudie (she/her/hers): Absorption system that would represent one of these cold flows, because it's a very high H one column density with very, very few associated metals, because we can detect metals.

235

00:35:40.170 --> 00:35:46.680

Gwen Rudie (she/her/hers): Like pretty trace quantities of metals with with the spectra, just because of the high quality of the data and so

236

00:35:47.280 --> 00:35:59.130

Gwen Rudie (she/her/hers): So, you know, I've, I've shown here because I'm focused on the metal observers instances where I think that actually what you're likely looking at is outflows from these galaxies, but we know actually that the gas traces more than that in these halos.

237

00:36:00.270 --> 00:36:01.230

That's really amazing.

238

00:36:02.790 --> 00:36:20.670

Morgan Elowe MacLeod: Well, I think it's time for us to move on. But before we do, what's all thank Dr. Rudy. Again, this is amazing work and I feel like this slide is a wonderful place to pause because they're just such incredible richness of these data. And so there's so much to learn as you said so.

239

00:36:21.750 --> 00:36:30.120

Morgan Elowe MacLeod: Thank you for the really exciting summary. There's a few more questions coming in on the Slack channel as we talked. Then I had time to ask so

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00:36:31.020 --> 00:36:31.830

Gwen Rudie (she/her/hers): Thank you so much.

241

00:36:31.860 --> 00:36:33.900

Morgan Elowe MacLeod: Time in there at any point. Thank you.

242

00:36:36.540 --> 00:36:45.720

Morgan Elowe MacLeod: Our second speaker today is Priya natarajan Korea is a Professor of Physics and Astronomy at Yale University.

243

00:36:47.040 --> 00:36:47.820

Morgan Elowe MacLeod: And

244

00:36:49.080 --> 00:36:59.850

Morgan Elowe MacLeod: We. So I was thinking about how to introduce Priya without spending the entire 20 minutes of your talk and I thought that I could summarize some of your work.

245

00:37:00.990 --> 00:37:13.740

Morgan Elowe MacLeod: By the fact that you're an expert. I think you can kind of everything that you can't see in astrophysics right and you try to make the sort of traces of the unseen astrophysical constituents.

246

00:37:14.760 --> 00:37:19.020

Morgan Elowe MacLeod: Observable, so that's a hard thing to do. And without further ado,

247

00:37:20.250 --> 00:37:21.990

Morgan Elowe MacLeod: We're really grateful to have you here today.

248

00:37:23.100 --> 00:37:33.360

Priyamvada Natarajan: Thank you so much. Morgan and on a for inviting me. And I have to say that this is not ideal to I would have so much like to be there in person.

249

00:37:33.750 --> 00:37:45.690

Priyamvada Natarajan: But, you know, as given how the pandemic has gone for me in terms of the sense of isolation. I'm just so grateful and thrilled to be even on zoom. It's that bad, right, that some of us are

250

00:37:46.140 --> 00:37:54.360

Priyamvada Natarajan: Excited even to be on zoom. So, um, I, I must confess that I was under the impression to

251

00:37:54.900 --> 00:38:07.200

Priyamvada Natarajan: Yesterday, that this was a normal ITC colloquium length. So I had a long, you know, the usual introduction and sort of weave into what I wanted to talk about

252

00:38:07.650 --> 00:38:18.690

Priyamvada Natarajan: And so I have truncated it and to make sure that I share with you some really new, exciting results. So I'm going to focus really on a new result that

253

00:38:19.230 --> 00:38:37.890

Priyamvada Natarajan: We published a couple of months ago and sort of the lead up to it and explore the implications for this particular result. So I'm, what I'm really going to talk about is many of you know so first I want to say. I think that was an over kind introduction. Hate so. Thanks, Morgan for that.

254

00:38:39.300 --> 00:38:49.590

Priyamvada Natarajan: That I you know many of you know that I've been working for quite a while now trying to use clusters of galaxies as laboratories don't understand both

255

00:38:50.280 --> 00:38:56.610

Priyamvada Natarajan: What is powerful about them is that you can use them to study the properties of dark matter, as well as dark energy.

256

00:38:57.060 --> 00:39:04.920

Priyamvada Natarajan: And so they are really sort of interesting laboratories and gravitational lensing as a probe is particularly powerful as well because

257

00:39:05.340 --> 00:39:15.360

Priyamvada Natarajan: It's a chromatic it's independent of the dynamical state of the object which is relevant in this case because these are the most recently sort of actively assembling structures and the

258

00:39:15.690 --> 00:39:24.030

Priyamvada Natarajan: Universe very massive and also the most efficient lenses. So that's the reason why we really want to use clusters to study.

259

00:39:24.690 --> 00:39:27.600

Priyamvada Natarajan: So first I want to thank a lot of collaborators.

260

00:39:28.140 --> 00:39:40.050

Priyamvada Natarajan: Who over over the years in this, as I said, this particular quest that I've been on trying to stress test called dark matter models using substructure properties inside clusters.

261

00:39:40.440 --> 00:39:49.320

Priyamvada Natarajan: It has a long history there have been lots of people who've. There are many were skeptical at the start that this could even be done, but they were many more very supportive and who collaborated

262

00:39:49.830 --> 00:40:05.700

Priyamvada Natarajan: Right now I want to give a shout out to a couple of people. One is Massimo many Getty, with whom I've been working closely for several years, who has provided the expertise on simulations Matilda issue, Zach, who is

263

00:40:06.840 --> 00:40:17.310

Priyamvada Natarajan: at Durham and she has really helped in honing the lens mass modeling techniques and methods and the models that I'll be short sharing with you today.

264

00:40:18.000 --> 00:40:27.750

Priyamvada Natarajan: I, of course, want to thank laws. A lot of the early work in pushing through happened with comparisons with Illustrator. So on a pillar page and Lars were really helpful.

265

00:40:28.170 --> 00:40:42.270

Priyamvada Natarajan: And I want to give a shout out to my former project student Mila Charlie Murray, who's people from a few years ago actually was where we saw the first hint of something very interesting. That was really worth following up

266

00:40:43.320 --> 00:40:51.600

Priyamvada Natarajan: In terms of mismatches between predictions theoretical predictions and observational data. So just a quick summary.

267

00:40:52.500 --> 00:41:03.900

Priyamvada Natarajan: To tell you why clusters are so interesting and important for the particular purpose of testing the nature of dark matter as all of you know one of the

268

00:41:04.590 --> 00:41:11.790

Priyamvada Natarajan: limitations and challenges of using astrophysical observations to nail down the particle nature of dark matter.

269

00:41:12.300 --> 00:41:21.900

Priyamvada Natarajan: Is the question of scales. Right. So there's a real kind of what is accessible to us, both in terms of observations and simulations right so simulations are have

270

00:41:22.350 --> 00:41:37.170

Priyamvada Natarajan: Grown in sophistication greatly, but we are still not at the level we are not actually modeling an individual quite a particle, we are modeling aggregates of particles, but clusters. There are unique properties of clusters is observational

271

00:41:38.520 --> 00:41:46.980

Priyamvada Natarajan: Sites in the universe, because they the mass of the overall baryonic mass in clusters is of the order of 10 to 12% at most.

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00:41:47.280 --> 00:41:54.570

Priyamvada Natarajan: But 1% is in all the stars and the galaxies and 10% is in the x ray meeting hot gas and the rest is all dark matter.

273

00:41:54.960 --> 00:42:00.750

Priyamvada Natarajan: And the reason this is interesting is because then the measure deflections lensing deflections

274

00:42:01.200 --> 00:42:13.680

Priyamvada Natarajan: Are really going to be reflecting the detailed distribution of dark matter with greater fidelity than in most other objects, where this ratio might be tilted differently. For example, galaxies.

275

00:42:14.370 --> 00:42:22.440

Priyamvada Natarajan: And so the big questions that people have looked at for clusters is, you know, what is the total mass. And as you all may know and we have heard the lower

276

00:42:22.770 --> 00:42:28.440

Priyamvada Natarajan: clusters are also the objects that first provided the observational evidence for dark matter.

277

00:42:29.100 --> 00:42:38.310

Priyamvada Natarajan: So then there are deeper questions that you can ask about the connection between light and mass in particular, does how well light traces mass

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00:42:38.730 --> 00:42:43.140

Priyamvada Natarajan: And again clusters are very interesting place to probe this relationship.

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00:42:43.590 --> 00:42:55.110

Priyamvada Natarajan: And of course, as I said, though we can't nail down the particle, we can really say quite a lot, as I will show you today about the nature of dark matter just from the spatial mapping the spatial distribution of dark matter.

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00:42:55.590 --> 00:43:07.410

Priyamvada Natarajan: And not only are we able to now give you estimate of the total mass integrated massive objects. What we are now I show you that we are able to

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00:43:08.670 --> 00:43:18.480

Priyamvada Natarajan: Derive the granularity of dark matter at a level where there's real convergence between the sophistication of what simulations offer today and observational data.

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00:43:18.750 --> 00:43:25.800

Priyamvada Natarajan: So it's a very, very interesting powerful moment when they are sort of better aligned, as I said, I've been trying to do this for

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00:43:26.340 --> 00:43:37.140

Priyamvada Natarajan: More than a decade. And initially, the data was not good enough for what I wanted to do but then the simulations were not as good. Once the data got better. So there was a lack of alignment for a long time, but

284

00:43:37.470 --> 00:43:51.210

Priyamvada Natarajan: Finally, now in the last three, four years, the, you know, both the kinds of simulations and the variety of simulations and simulators independent groups that are simulating clusters and providing

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00:43:51.660 --> 00:44:02.250

Priyamvada Natarajan: Predictions for substructure on small scales within clusters has grown and the data has enormously improved because of the depth of HST data that's now available.

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00:44:02.940 --> 00:44:10.740

Priyamvada Natarajan: So just as I said I'm going to skip a lot of preliminary. So if there are students who want to learn more. I'm happy to hang around and chat on Slack or

287

00:44:11.130 --> 00:44:19.290

Priyamvada Natarajan: Well, you know, I'm you know in in the in our universe when things get better. I am on sabbatical. And I was hoping to hang around, you know,

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00:44:20.580 --> 00:44:27.840

Priyamvada Natarajan: CFA and be a chai. So, you know, you can catch me hopefully in person right in a few months. We have to be optimistic.

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00:44:28.530 --> 00:44:38.010

Priyamvada Natarajan: So the interesting thing is that if this is just a cute little schematic to drive home two points about gravitational lensing. As you all know, it's the deflection of light.

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00:44:38.790 --> 00:44:50.640

Priyamvada Natarajan: Distant sources. In this particular case, they're actually going to be galaxies deflected by foreground mass distributions. Here I have a cartoon of a galaxy as a lens intervening lens.

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00:44:51.150 --> 00:44:58.740

Priyamvada Natarajan: But the case that I'm going to talk about is obviously clusters of galaxies. So you have a source here in between us and distant galaxies.

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00:44:59.070 --> 00:45:07.440

Priyamvada Natarajan: And the total mass integrated mass within the cylinder, all the way from us to the source is what matters the surface mass density and closed and

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00:45:08.430 --> 00:45:16.110

Priyamvada Natarajan: There's a deflection angle and this deflection angle that gives you an observable effect that we will see in a minute, that's measurable.

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00:45:16.500 --> 00:45:29.130

Priyamvada Natarajan: Is proportional to the total integrated mass in the cylinder, the projected mass in the cylinder and the lines of sites two clusters which are really where objects are pretty much dominated by that individual cluster.

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00:45:29.790 --> 00:45:37.260

Priyamvada Natarajan: And it's also proportional the strength of lensing. The efficiency is proportional to the ratio of angular diameter distances.

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00:45:37.740 --> 00:45:46.500

Priyamvada Natarajan: Between the US, the lens and the source and so interestingly the underlying world model so cosmological parameters dark energy, etc, etc.

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00:45:46.860 --> 00:45:56.190

Priyamvada Natarajan: Come feed in in this ratio of angular diameter distance. So obviously, you can see that if the deflections are measurable directly from observations.

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00:45:56.490 --> 00:46:04.470

Priyamvada Natarajan: Then you can map the mass distribution, knowing the underlying cosmology as a prior or you can do vice versa. You can do one or the other.

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00:46:04.770 --> 00:46:09.540

Priyamvada Natarajan: And if the data is good enough. We now have enough statistical techniques to actually try to do

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00:46:09.960 --> 00:46:20.670

Priyamvada Natarajan: Both simultaneously right so constrained, for example, dark matter and dark energy. But in what I'm going to talk to you about today we are going to take the underlying cosmological model as a prior so

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00:46:20.940 --> 00:46:30.330

Priyamvada Natarajan: Omega lambda etc are going to be put in by hand and the Hubble constant and we're going to be really fiddling around with the mass distribution and what we can derive

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00:46:30.600 --> 00:46:40.620

Priyamvada Natarajan: What detail properties we can derive that will enable comparison direct comparison with cosmological simulations in this particular case of the lambda CDN body.

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00:46:41.640 --> 00:46:53.700

Priyamvada Natarajan: So this is just to give you another sort of a quick view of what we are really trying to do when you get the observational data. So what you really see the way lensing manifests. So you see the first image.

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00:46:54.210 --> 00:47:00.090

Priyamvada Natarajan: Able 370 where you see this blue arc, you can see in the top left hand corner.

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00:47:00.960 --> 00:47:12.150

Priyamvada Natarajan: And so that's a highly distorted image of a distant background galaxy that lies behind this foreground cluster. You can see on the cluster members in those little fuzzy yellow dots as the cluster galaxies.

306

00:47:12.720 --> 00:47:24.030

Priyamvada Natarajan: And so in the schematic. You can see now I'm giving you a more sort of realistic cartoon where I'm showing you that there could be blobs of dark matter. So sub halos that are associated, as we'll see in a minute.

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00:47:24.630 --> 00:47:29.670

Priyamvada Natarajan: We will make that association or with the light with cluster locations of cluster galaxies.

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00:47:30.150 --> 00:47:39.870

Priyamvada Natarajan: And so what lensing really allows you to do is to map from the observed image playing sort of these distorted shapes superpowers distorted shapes on the

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00:47:40.500 --> 00:47:46.050

Priyamvada Natarajan: On the lens, which is cluster galaxies and the overall BCG and so on in the lens.

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00:47:46.470 --> 00:47:56.910

Priyamvada Natarajan: And that is, there are these multiple regimes in terms of a mapping, if you think of it as a mapping from the image plane to the source plane. It's not as simple mapping. It's a nonlinear mapping

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00:47:57.570 --> 00:48:04.470

Priyamvada Natarajan: Because there's a region strong lensing region where an individual background source lining up just behind

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00:48:05.880 --> 00:48:16.830

Priyamvada Natarajan: The mass distribution could get multiple image magnified and multiply image. So that's a highly nonlinear regime. Then as you go out as you mean as you

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00:48:17.550 --> 00:48:30.390

Priyamvada Natarajan: Move to less exquisite alignment, you have weak systematic distortion in shape. So that's sort of a linear regime and a lot of the mass modeling building that we do combines the data, the observations.

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00:48:30.750 --> 00:48:34.740

Priyamvada Natarajan: From these. And of course, there's an in between measles scale regime where you have

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00:48:35.430 --> 00:48:44.670

Priyamvada Natarajan: Both a little bit of magnification and stretching and distortion of shape. So these are all now part and parcel of the information we extract from the observations.

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00:48:44.940 --> 00:48:47.640

Priyamvada Natarajan: And include in the creation of this lens model.

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00:48:47.940 --> 00:48:57.420

Priyamvada Natarajan: And so there are codes that we use standard codes and the one that I will be showing you that we have used to construct the lens models is a very old one that I was part of developing way back when.

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00:48:57.720 --> 00:49:07.020

Priyamvada Natarajan: It's of course extremely sort of evolved since then. And it's called lens tool it's publicly available software. So once again, and in the little

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00:49:07.440 --> 00:49:15.210

Priyamvada Natarajan: Sort of animation that I'm showing you it's just to show you the range of observed geometries for strong lensing that you are likely to get

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00:49:15.570 --> 00:49:25.530

Priyamvada Natarajan: And give you a feel. So what you see there and fuzzy pink sort of to shaded pink regions or two large scale clumps of dark matter and the systematic lensing effect.

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00:49:25.800 --> 00:49:30.180

Priyamvada Natarajan: On a set of sources circular sources, all of them are circular

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00:49:30.570 --> 00:49:37.200

Priyamvada Natarajan: And what you are seeing in the distortions are the lensing effects in the two regions, there's multiple imaging strong regime.

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00:49:37.470 --> 00:49:50.400

Priyamvada Natarajan: The Misal regime and the week regime at the outskirts of this image. So these are the observed features that you include in the model. And all you need to remember for the purposes of this talk.

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00:49:51.960 --> 00:49:59.610

Priyamvada Natarajan: Are that these two regimes are characterized by very different observational manifestations and we now know how to delete.

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00:49:59.970 --> 00:50:05.850

Priyamvada Natarajan: Them because we have data we can confirm spectroscopic Lee all these multiple images.

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00:50:06.360 --> 00:50:21.990

Priyamvada Natarajan: Multiple image sources and many multiple families have multiple image sources as well. These are very important tight constraints in the modeling. So let me show you now give you a feel for what it is that

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00:50:23.460 --> 00:50:31.200

Priyamvada Natarajan: The mapping permits you to do. So as I said, you have this image plane where you see these observed highly distorted multiply embed sources.

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00:50:31.650 --> 00:50:42.060

Priyamvada Natarajan: And you have a mass distribution of gravitational potential and you see on the when you map it back to the source plane, what you see is this diamond shape.

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00:50:42.450 --> 00:50:49.350

Priyamvada Natarajan: Region is the caustic, this is the region, behind which, as I said, you have this exquisite alignment of a source.

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00:50:49.650 --> 00:50:59.880

Priyamvada Natarajan: As shown now as a circular saws in red, blue, and it's inside that region. This caustic marks the region where the magnification, or the amplification of a background source.

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00:51:00.210 --> 00:51:04.590

Priyamvada Natarajan: diverges, it, it goes to infinity. In reality, just becomes very, very large.

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00:51:04.950 --> 00:51:15.450

Priyamvada Natarajan: And so once you cross, you know that you cross this call a caustic when the image geometries change dramatically. So the red corresponds to the red multiple images that you see and so on so forth.

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00:51:16.140 --> 00:51:23.550

Priyamvada Natarajan: So this area of the caustic right this region and closed within the construct is a measure

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00:51:23.910 --> 00:51:35.370

Priyamvada Natarajan: Of the ability of a gravitational potential to strongly lens a background. So, so I wanted to make a note of that because we're going to come back to that property. A little later on.

335

00:51:36.090 --> 00:51:43.620

Priyamvada Natarajan: So let's move now to lambda CDN. So, you know, there have been many tests of lambda CDMA as you all know, it's a spectacularly successful model.

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00:51:43.980 --> 00:51:50.520

Priyamvada Natarajan: But Chris it's precisely because it's so spectacularly successful that we need to really do precision tests and stress tested.

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00:51:50.970 --> 00:52:01.290

Priyamvada Natarajan: And so this one very interesting robust prediction. Of course, there are many, including density profiles, etc. I'm going to focus on one today and that is the

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00:52:02.250 --> 00:52:16.140

Priyamvada Natarajan: Properties of the sub halos collapse sub halos that inhabit larger scale halos. In this particular case cluster scale halos and the substructure inside cluster scale Halo. So about 10 to 15 solar mass cluster scale halos.

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00:52:16.650 --> 00:52:29.160

Priyamvada Natarajan: And substructure down to about 10 to the nine solar masses. As we'll see, and so the prediction, the robust prediction from CDN is that this slope of this mass functions of Halo mass function is

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00:52:30.000 --> 00:52:41.250

Priyamvada Natarajan: Minus 1.8 and I want to visually also show you that this is a very clear cut prediction in CDN and it's fundamentally different. If you change the nature of the dark metal particles. So,

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00:52:41.490 --> 00:52:56.970

Priyamvada Natarajan: On the right hand side of this panel, you'll see a warm dark matter simulation of the same cluster. At the same time, the same initial conditions, except for one dark matter. And you see that the substructure has been smoothed out in warm dark matter compared to cold.

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00:52:57.000 --> 00:52:57.540

Ana Bonaca: Dark matter.

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00:52:57.780 --> 00:53:00.930

Priyamvada Natarajan: So it's very tantalizing as I said right astrophysics why

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00:53:00.930 --> 00:53:01.200

Ana Bonaca: Is the

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00:53:01.680 --> 00:53:02.130

Priyamvada Natarajan: Challenge.

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00:53:02.310 --> 00:53:03.600

Priyamvada Natarajan: That we cannot get down.

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00:53:03.630 --> 00:53:05.610

Priyamvada Natarajan: To the nature of the dark matter particle

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00:53:06.090 --> 00:53:06.480

But

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00:53:08.310 --> 00:53:19.560

Priyamvada Natarajan: So here you can see there's a real sharp difference. And so if I can tabulate and add up all the substructure. If I can map the substructure somehow and count it up.

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00:53:19.950 --> 00:53:30.360

Priyamvada Natarajan: Then I can really test whether there is agreement with cold dark matter models are not so quickly to just show you conceptually. To do this, precisely conceptually

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00:53:31.320 --> 00:53:39.690

Priyamvada Natarajan: During my PhD years I realized that there. We need to build a model that is particularly attuned to comparison.

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00:53:40.080 --> 00:53:46.920

Priyamvada Natarajan: Of observational data with the simulations with what cosmological simulations are doing right what providing in terms of data.

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00:53:47.610 --> 00:53:52.860

Priyamvada Natarajan: And to find analogs to literally to do mock observations of the simulation and to do detailed comparisons.

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00:53:53.190 --> 00:54:04.230

Priyamvada Natarajan: So the premise here is that you think of the complicated complex gravitational potential of a cluster partitioned into two scales to largely speaking to large scales.

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00:54:04.500 --> 00:54:08.190

Priyamvada Natarajan: So one is a large scale smooth the distribution of dark matter.

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00:54:08.580 --> 00:54:17.970

Priyamvada Natarajan: It's a sum of potentials that are smoother and as some operators and these servers, we associate them small scale perturb us with the locations of individual cluster galaxies.

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00:54:18.390 --> 00:54:22.680

Priyamvada Natarajan: So, you know, this game has been done. I've been doing this and many other workers, people who have been

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00:54:23.220 --> 00:54:30.510

Priyamvada Natarajan: groups around the world who have adopted this framework, but have independent implementations. We know these lens bottles are quite robust

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00:54:30.810 --> 00:54:35.520

Priyamvada Natarajan: We are able to characterize the errors, the degeneracy. So this is like a well trodden path.

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00:54:35.820 --> 00:54:43.230

Priyamvada Natarajan: So, and roughly what we are doing is we are constructing these models that I show you here for April 2218 and we produce maps of the sub

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00:54:43.590 --> 00:54:58.350

Priyamvada Natarajan: sub structure distribution. So the granular dark matter distribution, show us peaks and valleys straight. So we are able to do that. And to do that, I told you that we have to make one assumption of how to relate the location of the sub halos with

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00:54:59.460 --> 00:55:05.490

Priyamvada Natarajan: Light sources of light in the cluster that is cluster galaxies so frequently we have adopted.

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00:55:06.030 --> 00:55:17.040

Priyamvada Natarajan: You know, self similar parametric models to model the sub halos and you'll be of use various models and FW a pseudo ISO thermal elliptical mass distributions ISO Thomas fears, etc, etc.

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00:55:17.400 --> 00:55:29.490

Priyamvada Natarajan: The only key thing to remember is that a that the parametric models. It's very well supported that these kind of work and I can talk about it later how we know that these work and so on.

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00:55:30.600 --> 00:55:41.040

Priyamvada Natarajan: The key thing here is that we exploit that. What this allows you to do this particular way of attaching light to mass allows you to use empirically observed relations.

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00:55:41.280 --> 00:55:44.280

Priyamvada Natarajan: For cluster galaxy. So the favor Jackson law, for example.

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00:55:44.610 --> 00:55:55.950

Priyamvada Natarajan: Helps you relate the mass to the light in individual cluster galaxy. So we adopt that framework in the work that I'm going to show you we are actually the data is good enough that we can leave that index free

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00:55:56.220 --> 00:56:07.380

Priyamvada Natarajan: We do not have to assume that the central velocity dispersion of a model sub Halo is scales as one fourth to the luminosity scaled in terms of health star.

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00:56:08.130 --> 00:56:19.110

Priyamvada Natarajan: Okay, so let me quickly now tell you about other small scale problems. So, you know, obviously, you probably realize there is a small scale problem that I'm going to talk about. So that's the big reveal here, right.

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00:56:19.410 --> 00:56:28.320

Priyamvada Natarajan: So there have been other problems that have been pointed out in CDN. One of them was the customer problem. So that's the internal structure of of halos.

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00:56:28.710 --> 00:56:33.690

Priyamvada Natarajan: And here we are talking about the shape of the density profile inside one k PC or so.

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00:56:34.200 --> 00:56:45.300

Priyamvada Natarajan: And so it's predicted you know CDN predicts that you know the slope should be a power loss slope, the density profile and what is found, especially with low mass worth galaxies and so on, that the

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00:56:45.810 --> 00:56:48.990

Priyamvada Natarajan: There is evidence for a turnover and therefore a core

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00:56:49.380 --> 00:57:00.480

Priyamvada Natarajan: So this problem was claimed as a huge crisis for CDN, but it was resolved so I'm not gonna spend much time on it because I really want to get to the new problem that is I want you to remember here. This is a problem on

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00:57:00.870 --> 00:57:09.960

Priyamvada Natarajan: kilo per sec scales, where you can imagine that you know refinements in the resolution of simulations could go to

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00:57:11.250 --> 00:57:20.790

Priyamvada Natarajan: And resolve this. And indeed, you know, feedback and improving ingredients that go into the simulations and being able to find feta fainter

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00:57:22.530 --> 00:57:31.950

Priyamvada Natarajan: dwarfs, where you can make those measurements resolve the issue right then there's another small scale problem, this is not this is now we are talking not on

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00:57:32.400 --> 00:57:43.320

Priyamvada Natarajan: Individual galaxy scales. What's rather sort of group of scales, which is the missing satellites problem. And this, you know, again, you've all heard a ton about and we know that there was a paucity of there is

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00:57:43.830 --> 00:57:49.470

Priyamvada Natarajan: A paucity of detected. So the observation of the real universe does not

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00:57:50.190 --> 00:57:58.800

Priyamvada Natarajan: Give you as many satellites a CDN predicts. Right. So again, this is sort of been resolved. This is not something that is a nail in the coffin of CDs. Okay.

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00:57:59.400 --> 00:58:08.580

Priyamvada Natarajan: So let me know. Come back to tell you about this new problem that has revealed, which I think is much more serious therefore interesting and intriguing.

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00:58:09.090 --> 00:58:18.360

Priyamvada Natarajan: So first of all, quickly to show you this lens mapping technique allows you to map sub halos and the sub Halo mass function inside cluster. So in red. You see,

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00:58:18.780 --> 00:58:24.780

Priyamvada Natarajan: This is what previous work that we did with the Millennium simulation. So the black histogram is the Millennium simulation.

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00:58:25.140 --> 00:58:37.560

Priyamvada Natarajan: And the red histogram is derived from lending data. So you can see, by and large, the x axis right it's quite remarkable completely independent techniques. The number abundance of sub halos. We don't have a problem on cluster scales.

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00:58:38.040 --> 00:58:43.860

Priyamvada Natarajan: We don't have the analog of a missing satellite from. We actually have the right number of civilians, right.

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00:58:44.370 --> 00:58:48.930

Priyamvada Natarajan: And so now, with an improved simulations. This is what that was done in 2017

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00:58:49.380 --> 00:59:04.080

Priyamvada Natarajan: And with illustrious and with a brand new data set with deepest images of clusters April 2744 that was part of the Hubble frontiers fields. Once again, we find that you know the abundance is not an issue. So we don't have a problem like the

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00:59:05.310 --> 00:59:13.200

Priyamvada Natarajan: The missing satellites problem on this scale in CDN, but we actually found another issue. I think

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00:59:13.950 --> 00:59:20.880

Priyamvada Natarajan: I missed that slide, which is now because the models were good enough. We could actually plot the radial distribution of substructure.

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00:59:21.240 --> 00:59:28.260

Priyamvada Natarajan: And that did not match. So that was the first clue that there was even though we can match the abundance, it's very obvious.

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00:59:28.950 --> 00:59:34.170

Priyamvada Natarajan: That somehow the internal structure of sub halos does not match. Okay.

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00:59:34.620 --> 00:59:41.550

Priyamvada Natarajan: And so you can see the mismatch in the radio distribution of some halos the rent histogram, once again, is able 2744

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00:59:41.760 --> 00:59:50.670

Priyamvada Natarajan: I mean, I mean, these are obviously you know cases, these are special cases, these are extreme lenses and so on. As you will see, I will enlarge the sample and do the analysis and show you what we find.

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00:59:51.120 --> 01:00:03.300

Priyamvada Natarajan: So what we did. Now, is that okay, we've got to look more deeply with better model. So we use 20 you know clusters chosen from the clash program, which is a Shallow. SHALLOW look program and the deep graph Frontier Fields.

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01:00:03.810 --> 01:00:15.480

Priyamvada Natarajan: And then we followed up with data from us. So we have spectroscopic redshift for almost all the multiply imaged families that we can recognize and and associated with each other.

396

01:00:16.080 --> 01:00:25.950

Priyamvada Natarajan: As you saw in those geometries that would be that I know familiar and cluster membership. So you know we did as good a job as we possibly can. So we built a best possible mass models.

397

01:00:26.400 --> 01:00:36.720

Priyamvada Natarajan: Including kinematic data measured velocity central velocity dispositions for cluster galaxies. They were we first tested our models. And then we realized we could the models were very robust

398

01:00:37.020 --> 01:00:45.840

Priyamvada Natarajan: And now we actually incorporate them as priors. Okay, so then what is a new diagnostic now that you have such a great mass model. What can you do, how can you push it further.

399

01:00:46.170 --> 01:01:01.620

Priyamvada Natarajan: As we saw earlier, those critical curves. What we can do is we can look at a lens mass model and sort of an observed lens and look at a mass matched analog in a simulation and map the area of these

400

01:01:02.760 --> 01:01:10.290

Priyamvada Natarajan: Core Stix provided by small scale structure and the small scale structure. I'm talking about here, right in this context is not sub kilo per sec

401

01:01:10.620 --> 01:01:14.580

Priyamvada Natarajan: We're talking about five K PC five to 10 K PC scale because

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01:01:14.910 --> 01:01:24.720

Priyamvada Natarajan: That's the scale on which we are actually sensitive to picking up strong lensing by individual cluster galaxies on top of the overall cluster. Okay.

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01:01:24.930 --> 01:01:35.820

Priyamvada Natarajan: So this new metric is the galaxy galaxy strong lensing probability. It is just a sum of all the little cost X that you have that are produced by all the little clumps of sub halos.

404

01:01:36.300 --> 01:01:46.350

Priyamvada Natarajan: And that is scaled by the overall area of the smooth components caustic and this of course depends. As you can imagine, on the

405

01:01:46.890 --> 01:01:49.710

Priyamvada Natarajan: Source of action depends on the redshift of the source.

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01:01:50.010 --> 01:01:58.140

Priyamvada Natarajan: So here is from one of the best mass models that we have for a cluster here is the probability GSR probability for this cluster.

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01:01:58.320 --> 01:02:04.920

Priyamvada Natarajan: And this is giving you a feel of all the uncertainties in the models and the things that we can tweak in the models. And you can see it nicely tank so

408

01:02:05.490 --> 01:02:15.720

Priyamvada Natarajan: Okay, this is great. So how does this compare with CDN simulations. So what we get from CDN simulations is the orange curve. So there's an order of magnitude discrepancy

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01:02:16.650 --> 01:02:20.340

Priyamvada Natarajan: And so we can think of many possible ways in which you might be able to resolve.

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01:02:20.790 --> 01:02:27.660

Priyamvada Natarajan: This maybe, you know, the clusters are not as representative of all clusters, you know, clusters that we are finding as lenses are extreme and so on.

411

01:02:28.290 --> 01:02:34.680

Priyamvada Natarajan: And it turns out that you know after enormous investigation of all possibilities. This persists.

412

01:02:35.220 --> 01:02:45.030

Priyamvada Natarajan: What this is telling you is that the inner regions of cluster galaxies are significantly more concentrated in the real universe than see me simulation suggest

413

01:02:45.870 --> 01:02:54.750

Priyamvada Natarajan: A couple of other diagnostic so there's one interesting clue that we see that we can see that were simulations are probably

414

01:02:55.200 --> 01:03:05.580

Priyamvada Natarajan: Falling shorter I wanting is, as I said in this internal structure of the some halos and that you can see immediately when you look at the circular velocity of substructure.

415

01:03:05.850 --> 01:03:14.010

Priyamvada Natarajan: Inside simulated clusters. Those are all the dots and the black is what we get from the lending model. So that's the gap that we see and

416

01:03:15.570 --> 01:03:28.050

Priyamvada Natarajan: So I'll quickly move to the conclusions. So you know I so we just had a science paper out in September, and we had like

52 pages of supplementary material where we looked at each one of these possibilities. So

417

01:03:28.410 --> 01:03:37.500

Priyamvada Natarajan: I'm not going to spend time just going to tell you that all the obvious things we have looked at and we have arrived at. So you just now have two possibilities. Right.

418

01:03:37.980 --> 01:03:47.940

Priyamvada Natarajan: And they're both in in incredibly interesting intriguing and important. And so first is that either there is some missing.

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01:03:48.480 --> 01:03:54.720

Priyamvada Natarajan: Piece in terms of the interplay between dark matter and barriers in cluster regions in particularly in this high density regions.

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01:03:55.230 --> 01:04:05.070

Priyamvada Natarajan: And I'm saying that because I already showed you that this is not related. In fact, it goes in the opposite direction to all the other crises and mismatches of small scale in CDN.

421

01:04:06.150 --> 01:04:13.620

Priyamvada Natarajan: And the other possibility, of course, you know, and we have to be open minded is that there could be deeper problems with the zoom nature of dark matter itself so

422

01:04:13.740 --> 01:04:24.300

Priyamvada Natarajan: I mean, and you know, I don't want to speculate too much. We did. We're very cautious, that it's one or the other. And, you know, and I tend to think that the problem is likely that we are missing a component in the simulations.

423

01:04:25.620 --> 01:04:35.460

Priyamvada Natarajan: Partly because as I showed you that we can see that, plus the properties of cluster galaxies are not quite as a reproduced as well as we would like. So anyway, I end up just

424

01:04:36.600 --> 01:04:39.300

Priyamvada Natarajan: Stop here and open up for questions.

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01:04:42.630 --> 01:04:43.620

Priyamvada Natarajan: Thank you so much.

426

01:04:46.560 --> 01:04:54.120

Morgan Elowe MacLeod: So if you had a question which related to one of the two points. You just put up. So maybe you want to go ahead and ask yourself.

427

01:04:55.920 --> 01:04:58.830

loeb: Well, first of all I wanted to say happy birthday.

428

01:04:59.100 --> 01:05:01.320

Priyamvada Natarajan: Thank you. Thank you so much. Yeah.

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01:05:04.380 --> 01:05:11.520

loeb: Obviously, I mean the one Achilles heel of any influence about the nature. I mean this could mean something about the nature of dark matter, but

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01:05:11.970 --> 01:05:27.240

loeb: But the question is whether the barriers make a difference and especially in the course of galaxies, where we know there are other issues and so do. Do you think that the simulations are sufficiently reliable in terms of the bionic physics.

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01:05:28.410 --> 01:05:30.690

loeb: For us to consider this is

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01:05:31.710 --> 01:05:34.740

loeb: Any indication about the nature of the Dartmouth. Yeah.

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01:05:35.220 --> 01:05:43.770

Priyamvada Natarajan: Now, that's a great question. And thanks, Avi for the birthday wishes. So as I said, right. So, what we are finding

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01:05:44.280 --> 01:05:54.600

Priyamvada Natarajan: This statistic is sensitive to the mass and closed within a few seconds. So around a few seconds. So the Einstein radio individual some halos.

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01:05:54.990 --> 01:06:05.460

Priyamvada Natarajan: So that corresponds to about five to 10 K PC and so that is the mass that implicates the mass well outside the light. So this is the integrated mass within that region.

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01:06:05.970 --> 01:06:12.990

Priyamvada Natarajan: So you know we are a lot less sensitive in detail to the baryonic processes, except

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01:06:13.470 --> 01:06:25.200

Priyamvada Natarajan: One of the things that we did try is we looked at simulations and which we artificially turned off Ag and feedback which is tuned to be quite strong in clusters and which is

438

01:06:25.710 --> 01:06:32.520

Priyamvada Natarajan: Which causes the arrangement of mass on very large scales inside cluster galaxies.

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01:06:33.120 --> 01:06:43.380

Priyamvada Natarajan: And we found that, yes, then this gap does shrink a little bit. You can't, you know, no one process or set of processes could bridge this order of magnitude gap.

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01:06:43.800 --> 01:06:50.940

Priyamvada Natarajan: So, but, you know, but you do need feedback for many other have to match. Many other observable and clusters like the overall

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01:06:51.570 --> 01:07:04.500

Priyamvada Natarajan: You know census of baryons and so on. You need feedback. So I think what is intriguing about this particular discrepancy. The, the scale. I mean it is small scale, but it's not as small scale as

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01:07:05.820 --> 01:07:14.670

Priyamvada Natarajan: The other problems. And this is also a small scale but issues, we believe, of resolution and the interplay with baryons

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01:07:15.540 --> 01:07:24.840

Priyamvada Natarajan: Are not going to be the only part of the solution because we believe that they can't be only because of the scale. So because you know if you actually look at

444

01:07:25.470 --> 01:07:38.340

Priyamvada Natarajan: Five to 10 K PC of around the cluster galaxy to well outside the light. So this aperture size, I think is kind of intriguing. So one of the things that we are doing right so in terms of simulations.

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01:07:38.850 --> 01:07:45.450

Priyamvada Natarajan: It's clear that in simulate. There's a lot of dynamical processing and transformation. When galaxies fall into clusters.

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01:07:45.840 --> 01:07:52.410

Priyamvada Natarajan: And there been many questions raised about whether you know our prescriptions for title stripping and dynamical friction, whether they really are.

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01:07:53.160 --> 01:08:03.300

Priyamvada Natarajan: Accurate accurately implemented and, you know, there's this issue of numerical artifact of over over stripping of titles dropping

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01:08:03.810 --> 01:08:16.830

Priyamvada Natarajan: And but we found that that cannot account again for an order of magnitude. But I think in future work. What we want to do is to see, you know, another way to separate out whether its overall large scale dynamics in the cluster.

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01:08:17.220 --> 01:08:25.260

Priyamvada Natarajan: Is that we are going to extend these lens models. They were just on the core. So there is HST data in a project that I'm involved in called buffalo, which will map.

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01:08:25.710 --> 01:08:35.700

Priyamvada Natarajan: Allow us to map the data out to the middle radius, then we can really been even if it's just two radial bins. We can look at the contribution to this cross section.

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01:08:36.000 --> 01:08:45.930

Priyamvada Natarajan: From to radial bins and look at regions where, you know, the inner regions are where you expect expect a lot of processing to have happened for these clusters of galaxies.

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01:08:46.260 --> 01:08:56.700

Priyamvada Natarajan: And in the outer regions because of the crossing time, those are not guys that could have made many, many passages and being affected as much. So we think we should be able to sift out a lot of these

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01:08:57.510 --> 01:09:14.700

Priyamvada Natarajan: These issues and also you know my NSF proposal recently was to also look across various kinds of simulations, which, as you pointed out that implement the subject physics and fundamentally different ways to see if that, you know, could be a possible source.

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01:09:15.990 --> 01:09:18.810

Priyamvada Natarajan: Yeah, no, I'm not. I'm, you know, I am not want to

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01:09:19.590 --> 01:09:31.950

Priyamvada Natarajan: Want to jump to an alternative dark matter model. But, you know, in the interest of the preservation intellectual preservation. It's just that, you know, just opens up, you know, more work.

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01:09:32.400 --> 01:09:41.370

Priyamvada Natarajan: We're not going to run out of things to imagine speculate and have fun with. So I think one thing that one avenue that we are exploring there.

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01:09:41.670 --> 01:09:50.610

Priyamvada Natarajan: That I'm particularly interested in is that you know all the self interacting no self interacting dark matter does not go in the right way, as it is proposed it would have to be tweaked

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01:09:51.150 --> 01:09:58.710

Priyamvada Natarajan: In order to explain this. So as I said, none of the solutions that were proposed to explain the other small scale problems.

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01:09:59.040 --> 01:10:08.400

Priyamvada Natarajan: Are going to they're actually going to make it worse for this problem. So nothing that is currently available works like out of the package. There's a little bit of room to play. So one room to play.

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01:10:08.730 --> 01:10:22.980

Priyamvada Natarajan: Our potential document models where their self interaction cross section does not depend on velocity, but depends directly on the density that is different. And I think that's one thing that we are trying to play with, to see if it can give us something.

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01:10:24.270 --> 01:10:25.290

It's really fascinating.

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01:10:26.340 --> 01:10:30.810

Morgan Elowe MacLeod: Along those lines, Julian. I'm gonna have a question. Do you want to just pick up and ask yourself.

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01:10:32.100 --> 01:10:44.700

Julian Munoz: Yeah, sure. It's about this last tension you showed us, which is very interesting. Do we really can we confirm that the sub Halo or denser rather than there are more than we expect, can we distinguish two hypotheses.

464

01:10:45.990 --> 01:10:55.200

Priyamvada Natarajan: Yeah we because I told you that the numbers match, right. So the overall numbers. So we don't have a problem. We don't have accounting problem.

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01:10:55.680 --> 01:11:07.590

Priyamvada Natarajan: What we really so we can reproduce the numbers and but what we are not able to reproduce is the internal structure because this metric is designed exactly for that.

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01:11:08.040 --> 01:11:25.950

Priyamvada Natarajan: And, you know, so we have a paper that will come out very soon, which has been submitted in which we are doing, you know, using another metric. And I think that also very clearly shows that what is really off is the internal structure of the sub Halo.

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01:11:27.000 --> 01:11:38.400

Priyamvada Natarajan: When that is, you know, doing sort of a power spectrum analysis and looking which you know as a function of scale, then you can say something about the compare simulations and the observational maps.

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01:11:39.810 --> 01:11:50.220

Priyamvada Natarajan: Yeah, so I think it's, it's very clear that that's what is happening and and I think the reason we want to keep the room open for

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01:11:51.300 --> 01:11:58.500

Priyamvada Natarajan: You know the dynamical processing is that, you know, we know that you know the masses of sub halos.

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01:11:59.400 --> 01:12:06.390

Priyamvada Natarajan: Do change dramatically after title stopping you can lose quite a lot of mass and principal a dark matter in the cluster environment.

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01:12:06.630 --> 01:12:15.720

Priyamvada Natarajan: Yeah, you lose stars you spell out a few stars and you spell out gas and so on. But you primarily you lose a lot of the dark matter content of the sub Halo.

472

01:12:16.200 --> 01:12:23.790

Priyamvada Natarajan: So that's why you know the it's probably something to do with the dynamics. I mean, I don't know. There, you know, there are many other kinds of

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01:12:25.020 --> 01:12:34.980

Priyamvada Natarajan: crazy things that happen, right. So, for example, I'm not, I'm not pushing this idea. Okay, by any means, but just because the, your question is so interesting.

474

01:12:35.400 --> 01:12:39.690

Priyamvada Natarajan: That you know if you would run the simulation forward in time.

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01:12:40.440 --> 01:12:48.810

Priyamvada Natarajan: Then you'll find something very interesting. So if you, you know, so right now I'm comparing like with like, so I've compared a cluster lensing cluster at redshift point three.

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01:12:49.170 --> 01:12:58.680

Priyamvada Natarajan: With simulated analogs at Richard's point three, but if I actually because you're talking about the internal structure and internal density structure of sub halos.

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01:12:59.100 --> 01:13:14.400

Priyamvada Natarajan: If I then try to compare with a cluster of the same mass matched at either an earlier raper or a later episode that I'm seeing something quite interesting, which is why I think you know we are missing something in the internal structure and what the dynamical processing.

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01:13:15.930 --> 01:13:19.590

Julian Munoz: Great, thank you for the answer. I look forward to seeing this year. Yeah. Well, thanks.

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01:13:19.620 --> 01:13:30.720

Morgan Elowe MacLeod: Julian, Sabrina. Do you think that there's like an observational counterpart to that. Like, could one make a map this detailed have a higher redshift cluster and ask if

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01:13:31.920 --> 01:13:37.710

Morgan Elowe MacLeod: Like is it feasible to repeat this experiment, essentially, with different lenses now.

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01:13:37.770 --> 01:13:41.580

Priyamvada Natarajan: The whole problem. I think that the problem with

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01:13:42.600 --> 01:13:54.660

Priyamvada Natarajan: The lending, as I said, why the lending itself is independent of the dynamical state of the cluster the actual dynamics is actually quite complex. Right, so

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01:13:54.690 --> 01:14:04.830

Priyamvada Natarajan: Yeah, I'd hire redshift, even if I find a mass analog, it will not be the right dynamical analog to something at a different redshift.

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01:14:05.490 --> 01:14:15.930

Priyamvada Natarajan: So, you know, so to be consistent. You really do have to run the clock, you know, down to the same time except that, you know, you see, because the

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01:14:16.590 --> 01:14:26.550

Priyamvada Natarajan: Problem is that the sub halos in the real universe are more concentrated and they're more efficient strong lenses, then

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01:14:27.090 --> 01:14:37.800

Priyamvada Natarajan: The question is, you know, the we know when structure assembles how the you know the internal density structure actually changes right so

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01:14:38.100 --> 01:14:45.270

Priyamvada Natarajan: One can try playing with the clock in the simulation, but you can't really do it in the real universe, but it will tell you something.

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01:14:45.750 --> 01:14:59.640

Priyamvada Natarajan: Again, I think the point is that you know if simulations are suspect we really want to see whether, as are we asked whether it's the feedback or whether I mean as Julian much whether it's the dynamics. You want to separate out what in the simulations we are getting wrong.

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01:15:00.690 --> 01:15:10.980

Priyamvada Natarajan: What we could be getting when we all know that probably Dido striping and you know dynamical friction. We know we're not getting wrong. We're not getting. Right. Right. I mean, we know that from another problem.

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01:15:11.490 --> 01:15:16.710

Priyamvada Natarajan: That a lot of us many, many people on this call also work on which you know murders of black holes and so on.

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01:15:17.220 --> 01:15:23.190

Priyamvada Natarajan: When we look at the last part of that problem. This than the other. When we look at, you know, there's something kind of missing in our picture.

492

01:15:23.910 --> 01:15:38.850

Priyamvada Natarajan: Because you know black holes should merge much more easily. And we think that's why you know gases implicated and so on so forth. But it's it's key that our simulations are really not quite there in terms of modeling. Many of these important processes.

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01:15:41.490 --> 01:15:52.830

Morgan Elowe MacLeod: Um, can I ask you to take maybe one or two minutes and reflect on I think something that came through really clearly in your lecture was

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01:15:53.370 --> 01:16:03.300

Morgan Elowe MacLeod: That all of this work has kind of defined a methodology and you're thinking about new tracers and and and so, you know, I imagine it taking, you know, this

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01:16:03.810 --> 01:16:17.730

Morgan Elowe MacLeod: So many years to do this for this one cluster, but really you're kind of like setting up a way to do this. So what happens if we repeat this and you made a good argument for why clusters are a favorable place to do this. But what if we do this on a smaller scale.

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01:16:17.970 --> 01:16:25.410

Morgan Elowe MacLeod: You know, like can when I've heard some conversation about like lensing of stars by

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01:16:26.070 --> 01:16:42.690

Morgan Elowe MacLeod: Like galaxies Halo. So could we like go further down that mass distribution. What do you do you think there's something to be learned there by looking for some structure on like galactic halo level and what do you how do you think one would proceed.

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01:16:42.990 --> 01:16:47.820

Priyamvada Natarajan: Yeah, no, that's a great question. In terms of like the future directions that I wanted to show this.

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01:16:48.720 --> 01:17:07.560

Priyamvada Natarajan: Lot. So notice the x axis here. I've been showing you some Halo mass. Right. So one clear prediction of CDN is that this ratio of substructure to parent Halo mass right so I could make the same plot for the Milky Way. And I could

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01:17:08.670 --> 01:17:24.810

Priyamvada Natarajan: That is what that we are doing right now, which is to try. The only problem is that you know the mass measurements, how you measure the mass and what that mass is for the substructure. In the case of lower mass halos is not as well defined. So

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01:17:25.710 --> 01:17:37.980

Priyamvada Natarajan: It's a trickier comparison to make, but CPM is very clear, right, because if what we have found is a problem that is endemic in CDN, then it should show up in

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01:17:38.340 --> 01:17:50.100

Priyamvada Natarajan: In smaller scales. So, I mean, I recently saw that, you know, Jenny, green and collaborators have tried to do this. I think Karsten is the name of the first author of that paper, and he was a student at Princeton.

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01:17:50.670 --> 01:17:58.500

Priyamvada Natarajan: And they tried to do a very similar analysis, you know, and they found that the radial distribution of substructure.

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01:17:58.980 --> 01:18:04.110

Priyamvada Natarajan: For Milky Way scale halos exactly the same problem. You know that they tried to do

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01:18:04.560 --> 01:18:07.770

Priyamvada Natarajan: And what they are able to what they can claim. I mean, you know,

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01:18:08.070 --> 01:18:17.160

Priyamvada Natarajan: The problem is when you have one object. Right. Oh, by the way, the results that I showed you here are for an ensemble of 11 clusters. So it's not one tweaked by one peculiar object. Right.

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01:18:17.550 --> 01:18:25.980

Priyamvada Natarajan: So, I mean, the problem with having like you know one object in which you are able to make observation of measurements and then extrapolate from that that

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01:18:26.580 --> 01:18:30.180

Priyamvada Natarajan: is tricky because. And what they find is that if you populate

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01:18:30.600 --> 01:18:42.630

Priyamvada Natarajan: Back the radial positions of the so called orphan halos right and you the ones that get artificially totally stripped if you put them back in. Then you can match the radial distribution.

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01:18:43.320 --> 01:18:52.320

Priyamvada Natarajan: Better. So I told you that in the case of clusters, right, that, you know, we do not have because of the scales involved.

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01:18:52.710 --> 01:19:05.850

Priyamvada Natarajan: There are no halos that are completely disrupted that we have access to. So you may remember that we have access to. I mean, this technique with the best deepest HST data can take us down.

512

01:19:06.480 --> 01:19:19.890

Priyamvada Natarajan: To about 10 to the nine pushing even one order of magnitude down in the sub Halo mass is extremely difficult and you know it's the neck. You know, we can do this maybe statistically, we won't be able to do it this kind of individual

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01:19:20.610 --> 01:19:28.410

Priyamvada Natarajan: Modeling like we've been able to do here in the future with Roman and all the and GW there there are sort of

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01:19:28.830 --> 01:19:40.710

Priyamvada Natarajan: Possibilities of doing things more statistically, and maybe extending this lower mass cut off. But if you look at tend to the 15 is the mass of the overall cluster. And this is tend to the nine right so

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01:19:41.340 --> 01:19:52.800

Priyamvada Natarajan: It'd be analog that you would want to do in this plot. So that's 10 to the minus six. So that remember if you go for the Milky Way type Halo. Right. That is a tent to the six solar mass clump.

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01:19:53.340 --> 01:20:05.370

Priyamvada Natarajan: That is that is still not quite with all the nice stuff that you know ANA and others are doing looking at streams and other signatures. We're not quite there to get a full census.

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01:20:05.610 --> 01:20:10.950

Priyamvada Natarajan: You may be able to say, Oh, there's one sub Halo there that punch through and we are seeing the signature.

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01:20:11.310 --> 01:20:16.650

Priyamvada Natarajan: But the kind of work that we're doing with this population of that mass we still don't have that.

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01:20:16.890 --> 01:20:25.410

Priyamvada Natarajan: And from the modeling of individual galaxy lenses. People like see Mona. We Getty and others have been showing. And I think God working is also doing work along those lines now.

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01:20:25.770 --> 01:20:35.400

Priyamvada Natarajan: Which is trying your they are once again able to say that looking at these multiple images on galaxy scales. They said, well, I think maybe there is a 10 to the six or 10 to the seven solar mass Halo.

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01:20:35.850 --> 01:20:46.830

Priyamvada Natarajan: One of them that should be placed roughly at that location to reproduce the images better. So I think we don't yet have, you know, the sort of the kind of census, you would like

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01:20:47.640 --> 01:20:53.850

Priyamvada Natarajan: That we have on cluster scale yet, but I think that is, you know, that's a very interesting and promising direction.

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01:20:54.450 --> 01:21:07.200

Priyamvada Natarajan: To go forward and especially I think there are surveys upcoming surveys, where you know the saga survey and so on where you will have many Milky Way level mass. Sorry.

524

01:21:07.920 --> 01:21:24.150

Priyamvada Natarajan: Galaxies for which you may have, you know, substructure mapping possible satellite mapping. So we might be able to say something, then. But I think at the moment, it's worth exploring whether there is a replication of this kind of problem on other skills.

525

01:21:27.810 --> 01:21:32.220

Morgan Elowe MacLeod: Well, I think that we should stop there for the moment.

526

01:21:33.300 --> 01:21:38.730

Morgan Elowe MacLeod: And and thank both of our speakers. I know that Glenn had to log out. But thank you again.

527

01:21:39.660 --> 01:21:45.270

Priyamvada Natarajan: Thank you very much. Yeah. Thanks everyone.  
Everyone say Steve when have a safe holiday season.

528

01:21:45.600 --> 01:21:53.820

Morgan Elowe MacLeod: That's right. And so I think we will resume this  
particular forum in about a month. And in the meantime, everyone. Stay  
safe, as I said,

529

01:21:54.870 --> 01:21:55.170

Priyamvada Natarajan: I

530

01:21:56.070 --> 01:21:57.090

Morgan Elowe MacLeod: Hi, thank you so much.

531

01:21:58.290 --> 01:21:59.040

Julian Munoz: For putting this together.

532

01:22:02.370 --> 01:22:03.030

Thank you.

533

01:22:07.710 --> 01:22:08.220

Wonderful.

534

01:22:16.620 --> 01:22:18.330

Ana Bonaca: Quite a number of people around.

535

01:22:19.620 --> 01:22:20.460

Us. Pretty cool.

536

01:22:23.910 --> 01:22:24.750

Morgan Elowe MacLeod: Yeah, I didn't