

WEBVTT

1

00:00:00.000 --> 00:00:10.679

Eliot Quataert: request a 30 minute talk with 30 minutes for discussion so i'll kind of skip through certain parts fast, so that there's a bit more time for discussion, rather than just to talk.

2

00:00:11.880 --> 00:00:12.599

Eliot Quataert: This we're.

3

00:00:14.309 --> 00:00:26.100

Eliot Quataert: actually goes back a long way to work, I did with Todd Thompson starting 20 years ago and it's sort of been an ongoing an ongoing interest of mine, which has been.

4

00:00:26.730 --> 00:00:37.950

Eliot Quataert: rejuvenated in the past few years, and I should say, if you have questions as I go i'm not sure how you normally handle this but feel free to feel free to ask them I don't.

5

00:00:38.940 --> 00:00:49.020

Eliot Quataert: easily see the chat right now so maybe if there are questions you can either just ask or raise your hand and Morgan can call on you, so thanks.

6

00:00:50.220 --> 00:01:01.950

Eliot Quataert: Okay, also i'll stress the other person that a lot of the work that i've been doing is with is Philip kamsky who's a graduate student at uc Berkeley finishing this year.

7

00:01:04.170 --> 00:01:06.120

Eliot Quataert: So just to make sure we're all on the same page.

8

00:01:07.140 --> 00:01:20.820

Eliot Quataert: By cosmic rays, I mean a non thermal population of mostly relativistic particles that are basically everywhere in the universe, when we can look so in the solar system galaxies.

9

00:01:22.620 --> 00:01:31.620

Eliot Quataert: The entire cluster medium of galaxy clusters, presumably the serkan galactic media of galaxy halos the intergalactic medium, etc.

10

00:01:32.730 --> 00:01:40.320

Eliot Quataert: And why I find them particularly interesting is it's they sort of satisfy what you might call the Holy Trinity.

11

00:01:41.610 --> 00:01:48.840

Eliot Quataert: of research questions there's a lot of extremely interesting and subtle physics, in particular.

12

00:01:50.550 --> 00:01:57.780

Eliot Quataert: plasma physics and a lot of nuclear physics goes more into understanding the observational constraints in the Milky Way.

13

00:01:58.800 --> 00:02:05.970

Eliot Quataert: cosmic rays are measured in the interstellar medium of the Milky Way to be an energetically important component of the galaxy.

14

00:02:06.450 --> 00:02:10.380

Eliot Quataert: and energy density similar to that in turbulent motions for instance.

15

00:02:11.220 --> 00:02:22.650

Eliot Quataert: Likewise, probably not quite as large and energy density, but nonetheless significant and galaxy clusters and so they have a number of potential implications for understanding structure formation.

16

00:02:23.070 --> 00:02:41.130

Eliot Quataert: And then, lastly, their observable cosmic rays dominate the admission, we see from galaxies at a variety of wavelengths, in particular in the radio no unfamiliar mission synchrotron emission from electrons and in the gamma rays pion decay gamma Ray emission.

17

00:02:43.530 --> 00:02:59.670

Eliot Quataert: So just to orient you to kind of classic measurements that are made from institute detection of cosmic rays, or to measure the flux of cosmic rays hitting a detector that might be a balloon initially or on the space station or a satellite.

18

00:03:00.780 --> 00:03:10.050

Eliot Quataert: The Voyager has that has actually now measured cosmic rays outside the influence of the solar magnetic field, which is very important for understanding lower energy cosmic rays.

19

00:03:10.380 --> 00:03:21.360

Eliot Quataert: So it's really clarified the low energy spectrum of cosmic rays, the higher energy spectrum of cosmic rays is measured, because those particles penetrate into the.

20

00:03:22.080 --> 00:03:30.000

Eliot Quataert: solar system without being strongly affected by the solar magnetic field and there's some kind of in between energies where we still actually don't know super.

21

00:03:30.000 --> 00:03:31.590

Eliot Quataert: Well, a spectrum.

22

00:03:32.430 --> 00:03:45.810

Eliot Quataert: Because of the influence of the solar magnetic field, but if one integrates up the flux is functioning better do most of the energies in gv protons cosmic rays are detected sort of.

23

00:03:46.860 --> 00:03:55.980

Eliot Quataert: Many, many things in the periodic table a large fraction of periodic table shows up its cosmic rays, as well as things like positrons empty protons etc.

24

00:03:56.700 --> 00:04:08.400

Eliot Quataert: But for the purposes of the stuff that i'm going to talk about where we're interested in the dynamical effective cosmic rays that's mostly the gv protons didn't matter because that's most of the.

25

00:04:09.810 --> 00:04:19.230

Eliot Quataert: Those particles have a mean free path, which is a little bit bigger than the size of the sun, they have a cooler mean free path, which is a lot bigger than the size of the universe.

26

00:04:20.550 --> 00:04:36.150

Eliot Quataert: And so, how cosmic rays travel through the interstellar medium circle black with medium etc is governed entirely by the magnetic field, in particular by small scale fluctuations in the magnetic field which alter the propagation of possible.

27

00:04:38.400 --> 00:04:51.540

Eliot Quataert: So just to give you a feel for the possible energetic importance of cosmic Ray, this is a very crude estimate of the energy and cosmic rays in.

28

00:04:52.260 --> 00:05:02.010

Eliot Quataert: dark matter halos of different masses galaxy clusters Milky Way mass galaxies dwarf galaxies different masses dark matter halos.

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00:05:02.790 --> 00:05:16.170

Eliot Quataert: And the calculation here is based simple we basically assume that 10% of the energy of all supernovae goes into cosmic rays, and about 10^{-3} of the energy.

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00:05:16.770 --> 00:05:29.220

Eliot Quataert: Of the rest mass energy is for massive black holes also goes into cosmic rays via jets that tend to 10^{-3} number might actually be relatively conservative could be higher than.

31

00:05:30.180 --> 00:05:41.160

Eliot Quataert: And then what's plotted here is the ratio of the energy and cosmic rays in these different systems to the thermal energy of a very allies HALO.

32

00:05:41.670 --> 00:05:50.820

Eliot Quataert: So take the berry on fraction of the HALO at the various temperature of that HALO that is a thermal energy and compare the energy and cosmic rays.

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00:05:52.080 --> 00:05:59.670

Eliot Quataert: And so what you see is that, in particular, around Milky Way mass halos that energy and cosmic rays from supernovae is very significant.

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00:06:00.240 --> 00:06:11.370

Eliot Quataert: comparable to the variable energy of the V realized HALO it goes down at low masses and high masses and this just traces the stellar mass function of galaxy.

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00:06:12.360 --> 00:06:24.780

Eliot Quataert: Which is comparatively galaxy information is comparatively inefficient low and high masses and so, for those who are used to these plots This is basically like the Star and HALO relation just in different units.

36

00:06:26.190 --> 00:06:32.640

Eliot Quataert: For black holes you'll see that their effect is you know biggest and higher mass halos.

37

00:06:33.810 --> 00:06:48.120

Eliot Quataert: Primarily because that's where we have the best information on on the kind of black hole mass function, but the cosmic rays from black holes might well be more important and probably are more important than the cosmic rays from star formation and higher mass system.

38

00:06:50.280 --> 00:07:04.200

Eliot Quataert: So, given this rough energetics there's basically, I would say three lines of arguments about the importance of cosmic rays, one is that in kind of Milky Way well now systems.

39

00:07:04.650 --> 00:07:19.290

Eliot Quataert: They may be an important source of galactic winds and higher mass systems cosmic rays may be an important way that feedback energy from supermassive black holes is coupled to the surrounding hot HALO.

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00:07:19.860 --> 00:07:30.900

Eliot Quataert: which can suppress star formation and keep massive halos quiescent basically elliptical galaxy formation and then I would say.

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00:07:31.440 --> 00:07:47.520

Eliot Quataert: One of the new insights that come out of the work that we've been doing is that actually the most dramatic effect of cosmic rays could be on the circ galactic medium of Milky Way mass halos in this sweet spot of this diagram around the 12 solar.

42

00:07:48.870 --> 00:07:50.160

Eliot Quataert: Know talk a little bit about.

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00:07:53.700 --> 00:07:54.210

Eliot Quataert: OK.

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00:07:56.610 --> 00:08:06.810

Eliot Quataert: So the big uncertainty and why I think this is such an interesting physics problem is that this plot here is a total energy.

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00:08:08.220 --> 00:08:12.990

Eliot Quataert: But to really understand the effects of cosmic rays, you need to know where that energy ends up.

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00:08:13.590 --> 00:08:21.480

Eliot Quataert: Right, you need to know whether all that energy and cosmic rays generated by supernovae ends up staying in the galaxy.

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00:08:21.960 --> 00:08:31.020

Eliot Quataert: In which case the energy density relative to the energy density in the galaxy would actually be quite a bit larger than implied by this plot.

48

00:08:31.590 --> 00:08:49.440

Eliot Quataert: Order, the cosmic rays just happily stream out of the variable radius of the HALO travel out into the intergalactic medium, in which case in this estimate we're overestimating the importance of cosmic rays, because in fact their energy is spread out over a larger volume.

49

00:08:50.430 --> 00:08:52.170

Eliot Quataert: So the big uncertainty.

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00:08:52.170 --> 00:09:00.900

Eliot Quataert: Then and understanding the effects of cosmic rays and galaxy formation is really the propagation of where did the cosmic grades actually and.

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00:09:03.780 --> 00:09:21.960

Eliot Quataert: So what do we know about that we know a decent amount about that empirically in the Milky Way the kind of classic measurements which go back decades, or that we can measure that some cosmic rays are produced primarily.

52

00:09:22.380 --> 00:09:23.130

Eliot Quataert: By.

53

00:09:23.190 --> 00:09:28.920

Eliot Quataert: What are called speculation reactions basically nuclear reactions a high energy proton hits a.

54

00:09:29.490 --> 00:09:43.710

Eliot Quataert: low energy proton in the interstellar medium and produces boron or beryllium that's the dominant production channel for blonde and brilliant in cosmic rays, and so you can measure we know the Cross section for that.

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00:09:43.710 --> 00:09:53.610

Eliot Quataert: reaction, you can measure the optical depth of that reaction by measuring the ratio of boron to other cosmic rays like carbon or oxygen.

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00:09:54.060 --> 00:10:03.630

Eliot Quataert: And so, since we know the Cross section and you measure the optical depth, you can measure the average column density of stuff that born in Berlin have moved through.

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00:10:04.530 --> 00:10:16.080

Eliot Quataert: And then, in one case in particular and radioactive really intense and you actually have an absolute lifetime measurement because you know the radioactive lifetime of the.

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00:10:16.770 --> 00:10:27.150

Eliot Quataert: really am 10 cosmic rays that are put in and the basic result that comes out of that is that cosmic rays leave galaxies or our galaxy.

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00:10:27.870 --> 00:10:35.040

Eliot Quataert: On a timescale of about 30 million years for gv cosmic Ray protons it's lower at higher energies.

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00:10:35.520 --> 00:10:39.810

Eliot Quataert: But for the gv protons that are energetically, the most important it's about 30 million years.

61

00:10:40.170 --> 00:10:53.220

Eliot Quataert: And that time scales of course really short compared to the hubble time or even the dynamical time of the galaxy but it's very long compared to the light crossing time the inequality here is backwards.

62

00:10:54.330 --> 00:11:01.470

Eliot Quataert: 20 million years as long compared to the light cross in time, the galaxy, and that means that cosmic rays don't leave directly.

63

00:11:02.040 --> 00:11:11.970

Eliot Quataert: And if we interpret what they're doing is undergoing a random walk diffuse of process the mean free path that's inferred as a few parsecs at a gv.

64

00:11:12.480 --> 00:11:25.200

Eliot Quataert: Just that time scale and a volume that's about the size of the radius of the galactic disk or a diffusion coefficient of about three times 10 to the 29th and a meter squared per second.

65

00:11:26.400 --> 00:11:31.920

Eliot Quataert: and on scales larger than that mean free path, just like basically we can treat.

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00:11:33.270 --> 00:11:42.000

Eliot Quataert: Gas in galaxies on scales larger than the mean free path is a fluid, we can do the same thing for cosmic or relativistic fluid with this diffusion.

67

00:11:44.130 --> 00:11:59.490

Eliot Quataert: The challenge theoretically and understanding that implicate the impact of cosmic rays and galaxy formation, is that we don't understand very well, where this 30 million year number comes from, and thus we don't understand very well how to extrapolate it to other Dallas.

68

00:12:01.500 --> 00:12:04.560

Eliot Quataert: So we think that the.

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00:12:05.820 --> 00:12:12.630

Eliot Quataert: scattering of cosmic rays, the main free path of cosmic rays is set by small scale fluctuations in magnetic field.

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00:12:13.110 --> 00:12:26.130

Eliot Quataert: fluctuations that are resonant with the cosmic rays, meaning that the the waves that scatter the particles are ways that have wavelengths comparable to the alarm or radius of.

71

00:12:26.730 --> 00:12:44.430

Eliot Quataert: Of the cosmic rays So these are waves that have wavelengths comparable to the size of the earth's orbit around the sun roughly 10s of solar radio hundreds of solar radio for gv particles and the amplitude of the fluctuations that matter or something like don't be ever be.

72

00:12:44.490 --> 00:12:45.540

Gus Beane: 10 minus three.

73

00:12:46.290 --> 00:12:47.760

Eliot Quataert: So to predict us from first.

74

00:12:47.760 --> 00:12:55.260

Eliot Quataert: principles is daunting that's certainly not possible in any computer simulations galaxy formation.

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00:12:55.800 --> 00:13:06.900

Eliot Quataert: Right, you want to know what is happening to the magnetic field on solar system spatial scale that's an extremely difficult thing to do, from first principles.

76

00:13:07.440 --> 00:13:13.500

Eliot Quataert: There are basically two theories for where those waves come from one is that they come from.

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00:13:13.920 --> 00:13:20.550

Eliot Quataert: The small scales of a turbo and cascading her stone meeting this turbulent the magnetic field is turbulent that cascades to small scales.

78

00:13:21.420 --> 00:13:33.540

Eliot Quataert: and eventually might week solar system scales or might not that's actually one of the questions that can produce scattering if that is inefficient if scattering by.

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00:13:33.990 --> 00:13:45.180

Eliot Quataert: The turbulent cascade of small scales is not affected then absent that scattering what would happen is the cosmic rays would happily try to leave at the speed of light.

80

00:13:45.990 --> 00:13:55.890

Eliot Quataert: That turns out to be a horribly unstable situation and there's all kinds of instabilities that the cosmic rays trying to leave at the speed of light general.

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00:13:56.730 --> 00:14:07.590

Eliot Quataert: In particular, the most important of those is known as the streaming instability, which is that if the cosmic rays move through the interstellar medium faster than the local our feigned speed.

82

00:14:08.430 --> 00:14:17.790

Eliot Quataert: and by that I mean the average speed of the cosmic Ray distribution function is larger than the old things be there is an instability that's.

83

00:14:18.210 --> 00:14:35.040

Eliot Quataert: sets in which is basically an instability of this exact resonance that I was talking about here and that instability grows in amplitude fact we act on the cosmic rays and stops them from moving on average any faster than yellow things.

84

00:14:36.450 --> 00:14:48.780

Eliot Quataert: And what's interesting from the physics point of view is that in this picture of the streaming instability, the transport isn't really a random law.

85

00:14:49.290 --> 00:15:07.830

Eliot Quataert: In the standard diffuse of sense, rather the cosmic rays are just limited from moving no faster than the other things it's more like an infection or a streaming but at a speed relative to the gas about the things.

86

00:15:08.970 --> 00:15:15.000

Eliot Quataert: And this difference in physics is important actually for a lot of the implications cosmic rays for.

87

00:15:15.390 --> 00:15:25.620

Eliot Quataert: galaxy formation and we actually don't know which of these is the right theoretical picture to describe cosmic Ray transport that's still an outstanding question.

88

00:15:26.400 --> 00:15:32.880

Eliot Quataert: And it's one of the bigger most interesting theoretical questions it's one that i've been thinking about a lot.

89

00:15:33.660 --> 00:15:45.450

Eliot Quataert: And not making as much progress as I would like completely on it's just a very hard problem i'm happy to mostly i'm not going to talk about that work because it's a little more detail but i'm happy to talk about the question.

90

00:15:47.910 --> 00:15:48.390

Eliot Quataert: Okay.

91

00:15:49.800 --> 00:16:02.550

Eliot Quataert: I want to say a little bit first about the kind of impact of cosmic rays and lower mass galaxies Milky Way mass and lower where they might drive winds affect the cgm etc.

92

00:16:03.030 --> 00:16:16.080

Eliot Quataert: And to do that, I first want to tell you how a wee myself Todd Thompson other collaborators have tried to calibrate.

93

00:16:16.920 --> 00:16:27.330

Eliot Quataert: The uncertainties of cosmic Ray transport using observation so we've tried to say, although there's a lot of theoretical uncertainties and cosmic Ray transport.

94

00:16:27.660 --> 00:16:38.250

Eliot Quataert: We can get around some of that using the observations that we have to calibrate how cosmic rays leave other galaxies not just the Milky.

95

00:16:41.130 --> 00:16:49.950

Eliot Quataert: i'm going to skip over the radio stuff in the interest of time happy to answer questions about that i'll talk about the gamma Ray stuff because that's Actually, I think the most important constraint.

96

00:16:51.000 --> 00:17:01.890

Eliot Quataert: So I think the constraint that's been the most useful in constraining cosmic Ray transporting other galaxies is fair me gamma Ray observations of pion decay.

97

00:17:02.610 --> 00:17:23.280

Eliot Quataert: And the reason, this is so important is that we can directly observed the gv protons that have most of the energy and cosmic so pion decay directly constrains the energy density of the cosmic rays that matter, the most dynamically and gallons and those are the gv.

98

00:17:25.980 --> 00:17:37.590

Eliot Quataert: And in addition, it turns out that the pion decay, is the dominant gamma Ray emission channel for most star forming galaxy so the submission is also observable.

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00:17:39.090 --> 00:17:48.480

Eliot Quataert: So the basic reaction is the cosmic Ray proton hits a neutral hydrogen atom that produces a neutral pi on which decays into a.

100

00:17:48.510 --> 00:17:49.230

Lab Saha: gamma Ray.

101

00:17:49.590 --> 00:18:02.220

Eliot Quataert: It also produces charged ions which decay and to neutrinos and electron positron pairs those neutrinos might be detectable are the.

102

00:18:02.730 --> 00:18:14.430

Eliot Quataert: n le le Waxman it's nice work on this, but I really kicked myself for not having thought of giving it we had done the gamma Ray version of the the argument that they put forward.

103

00:18:15.180 --> 00:18:24.300

Eliot Quataert: The cross sections for these reactions are known, they turn out to actually be pretty independent of energy as long as you're above the rest mass energy the pie on.

104

00:18:24.810 --> 00:18:32.160

Eliot Quataert: And the Cross section turns into an a time scale for a cosmic Ray proton to lose the energy to pi on decay.

105

00:18:32.670 --> 00:18:38.160

Eliot Quataert: Which is about 50 million years if the density of the gas is about a particle per centimeter cube.

106

00:18:38.910 --> 00:18:55.860

Eliot Quataert: And that time scale you'll notice is interestingly, similar to the time scale for cosmic rays to with the Milky Way of 30 million years at a gv and so that means that pion decay sort of competes with escape in terms of last process.

107

00:18:57.060 --> 00:19:08.100

Eliot Quataert: So the prediction that Todd Thompson and ellie Waxman and I made well before family was launched actually was that fair me would be a great probe.

108

00:19:08.520 --> 00:19:35.010

Eliot Quataert: Of cosmic Ray transport and galaxies basically because if the pion decay timescale is less than the time for cosmic rays, to leave the galaxy by this random walk or streaming then most of the energy in cosmic Ray protons would go into pion.

109

00:19:36.180 --> 00:19:49.320

Eliot Quataert: And in that regime there should be a linear relationship that we predicted between the gv gamma Ray luminosity of galaxies and the star formation rate of gallons.

110

00:19:50.460 --> 00:19:58.740

Eliot Quataert: And that linear relationship is basically just set by how much energy.

111

00:20:00.570 --> 00:20:17.430

Eliot Quataert: Each gram of star formation puts into cosmic Ray protocol, and if it's about 10 to the 50 herbs of energy per supernovae which we think is about right, then it turns out the normalization of this linear gv.

112

00:20:19.380 --> 00:20:23.250

Eliot Quataert: star formation correlation is about three times 10 to the minds.

113

00:20:25.170 --> 00:20:33.330

Eliot Quataert: So fair me is now observed this in about a dozen or more galaxies it's a hard measurement to make.

114

00:20:33.930 --> 00:20:56.430

Eliot Quataert: Just because you know, compared to luminous agm star forming galaxies or rather faint in the gamma rays, and the data is shown with the black points and then a few red points up here, so these include systems, you know in love, like our own galaxy the Milky Way.

115

00:20:57.510 --> 00:21:07.560

Eliot Quataert: andromeda the magellanic clouds and maybe two and ngc 253 which has been particularly important, I would argue, are up to 20 ngc 1016.

116

00:21:09.360 --> 00:21:13.050

Eliot Quataert: The dashed line is this linear correlation that we predicted.

117

00:21:14.550 --> 00:21:21.360

Eliot Quataert: The dotted line is kind of a best fit to the observations and the basic takeaway.

118

00:21:21.870 --> 00:21:30.330

Eliot Quataert: Is that, with the possible exception of the most luminous star forming galaxies which have the densest interstellar mediums systems like.

119

00:21:30.810 --> 00:21:50.310

Eliot Quataert: You learn like our to 20 in most star forming galaxies most of the cosmic Ray proton energy is not lost apply on decay, because we don't see it in the gamma Ray instead the cosmic rays have to leave the galaxy and go out into the HALO out into the circle galactic.

120

00:21:53.280 --> 00:21:59.460

Eliot Quataert: that's sort of the takeaway I would we would love of course for the data to be better to be able to.

121

00:21:59.910 --> 00:22:14.220

Eliot Quataert: been galaxies by medalist city and surface density, not just star formation rate, but we can't do that with the presence sample and so we're sort of restricted to this correlation between gamma Ray luminosity in star.

122

00:22:16.440 --> 00:22:25.170

Eliot Quataert: One can turn this relatively easily into a constraint on the cosmic Ray diffusion coefficient and other galaxies.

123

00:22:25.650 --> 00:22:34.410

Eliot Quataert: To order magnitude estimate that you can check after the talk or actually while I go through this slide it's just a few lines of algebra.

124

00:22:34.950 --> 00:22:42.480

Eliot Quataert: That the ratio of the time for cosmic rays to random walk out of the galaxy to the pie on decay time scale.

125

00:22:42.810 --> 00:22:50.580

Eliot Quataert: Basically, just depends on the size of the region that cosmic rays are scattering in which is about the size of the galactic disk.

126

00:22:51.120 --> 00:23:01.020

Eliot Quataert: To the surface density of gas, and then the cosmic and then the cosmic Ray diffusion coefficient is a pi on is just basically constants like the Cross section for Python.

127

00:23:02.520 --> 00:23:13.860

Eliot Quataert: and, interestingly, if you take the observations to invert the observations to try to constrain the cosmic Ray diffusion coefficient and other galaxies.

128

00:23:14.280 --> 00:23:21.510

Eliot Quataert: What we find is a cosmic Ray diffusion coefficient that is surprisingly similar across other galaxies.

129

00:23:22.020 --> 00:23:35.010

Eliot Quataert: A few times 10 to 2029 10 years where per second in the magellanic clouds the Milky Way and maybe two weeks, and that might actually be a quite interesting constraint on cosmic Ray property.

130

00:23:36.330 --> 00:23:43.320

Eliot Quataert: But for now, what I want to do is use that to constrain the properties of galactic winds didn't driven by cosmic.

131

00:23:44.640 --> 00:23:50.250

Eliot Quataert: And the argument How did this constraint works is basically as fallen.

132

00:23:51.570 --> 00:24:02.460

Eliot Quataert: there's a maximum possible mass loss rate that cosmic rays could drive from galaxy that set by energy conservation.

133

00:24:03.480 --> 00:24:19.770

Eliot Quataert: And the maximum mass loss rate is actually quite big it's given by the following argument imagine there's a total rate at which cosmic rays are being dumped into the interstellar medium by supernovae at cosmic Ray.

134

00:24:20.880 --> 00:24:38.100

Eliot Quataert: The most mass you can drive out of the galaxy by cosmic rays is then given by using all of that energy to escape the gravitational potential the galaxy with no energy left at infinity.

135

00:24:38.910 --> 00:24:50.160

Eliot Quataert: So basically the terminal speed of the wind is zero so the energy dump in goes into unblinding mass from the gravitational potential.

136

00:24:51.300 --> 00:25:01.710

Eliot Quataert: that's the maximum mass loss rate and that's a big number for a galaxy a dwarf galaxy within escape speed of 100 kilometers a second for the typical.

137

00:25:01.740 --> 00:25:03.840

Eliot Quataert: 10 of the 50 year olds and cosmic rays.

138

00:25:03.870 --> 00:25:08.760

Eliot Quataert: per supernovae you get a mass loss rate which might be 10 times the star from it.

139

00:25:11.100 --> 00:25:15.390

Eliot Quataert: that's a big number that would be interesting from the point of view of understand the galaxy.

140

00:25:16.680 --> 00:25:25.860

Eliot Quataert: The problem is, in this limit, this is a limit in which the cosmic rays leave the galaxy very slow.

141

00:25:26.700 --> 00:25:48.360

Eliot Quataert: So that infinity you have no energy you're just slowly lifting the cosmic the gas out of the galaxy and the cosmic rays, along with the gas and in that process, the speed of the cosmic rays, is that every point in space flash time much less than the local escape speed of the galaxy.

142

00:25:49.710 --> 00:26:06.510

Eliot Quataert: But if you leave the galaxy slowly, you have plenty of time to produce gamma rays by pion decay and it turns out, you vastly over predict the gamma Ray luminosity of galaxies like the Milky Way and that's one clouds and 31 maybe.

143

00:26:08.190 --> 00:26:13.710

Eliot Quataert: And so we can use our constraint on the cosmic Ray diffusion coefficient.

144

00:26:15.150 --> 00:26:24.180

Eliot Quataert: to constrain the mass loss rates of galaxies and we've developed theoretical models for outflows driven by cosmic rays.

145

00:26:24.990 --> 00:26:36.930

Eliot Quataert: That depends on the diffusion coefficient depends on the size of the galactic disk the sound speed of gas and the galaxy that sort of gets the sound speed initially gets the outflow going.

146

00:26:39.030 --> 00:26:47.880

Eliot Quataert: But that observational calibration is a very low mass out for way compared to this maximum possible down.

147

00:26:49.050 --> 00:26:54.540

Eliot Quataert: it's a map it's a mass outflow rate that's a fraction at most of the star.

148

00:26:56.310 --> 00:26:57.090

Eliot Quataert: And so.

149

00:26:59.100 --> 00:27:10.980

Eliot Quataert: The basic punch line from this observational calibration is that, given that the gamma Ray data tells us that cosmic rays leave galaxies relatively quickly.

150

00:27:11.850 --> 00:27:21.840

Eliot Quataert: Because they don't lose most of their energy to pion decay a corollary of that, given what we know about how pions are produced.

151

00:27:22.800 --> 00:27:42.300

Eliot Quataert: And what we know about the theory of galactic winds different driven by cosmic rays, which we've developed both analytically and using numerical simulations I think the conclusion is that actually outflows from galaxies directly driven by cosmic rays are relatively minor.

152

00:27:45.720 --> 00:28:02.100

Eliot Quataert: So where did the cosmic rays end up they end up in the circle galactic meeting because that's sort of the point of this argument actually is that cosmic rays escape galaxies rather than losing their energy to pion production or other costs.

153

00:28:03.750 --> 00:28:04.380

Eliot Quataert: So.

154

00:28:05.970 --> 00:28:14.670

Eliot Quataert: What we've done then is we've included cosmic rays as a second fluid in numerical simulations of galaxies.

155

00:28:16.530 --> 00:28:24.660

Eliot Quataert: These are a relativistic fluid we've used this observational calibration of the diffusion coefficient.

156

00:28:27.930 --> 00:28:38.670

Eliot Quataert: To blindly Askew, which is undoubtedly incorrect, but is sorta not quite but sort of the best that we can do right now.

157

00:28:39.270 --> 00:28:50.940

Eliot Quataert: That cosmic rays, have a time and space independent diffusion coefficient of a few times 10 to 29 centimeter square per second and then we've included cosmic rays.

158

00:28:51.690 --> 00:28:56.550

Eliot Quataert: sourced by Cork lab supernovae and type one a supernovae in simulations of galaxy.

159

00:28:57.390 --> 00:29:06.900

Eliot Quataert: So the we has now changed it's not tied Thompson and yon page and fill kempinski it's now phil Hopkins and the fire collaboration.

160

00:29:07.770 --> 00:29:14.190

Eliot Quataert: Where we've included done a bunch of calculations now, including cosmic rays, and this is a movie by Cameron humbles.

161

00:29:14.640 --> 00:29:27.270

Eliot Quataert: showing you the energy density and cosmic rays as a function of time in the simulations of galaxy formation with cosmic rays time and redshift are shown in the lower left.

162

00:29:28.500 --> 00:29:47.250

Eliot Quataert: You can see as time goes on, the cosmic rays are filling up the circle galactic medium of lower mass galaxies and then they're ultimately filling up the so called galactic medium and, in fact, a decent amount of the energy even leaves the burial radius of the HALO of the galaxy.

163

00:29:49.500 --> 00:29:54.540

Eliot Quataert: So the the dashed line here is the Bureau radius, and this is a simulation of the Milky Way and mass gallons.

164

00:29:58.140 --> 00:30:06.720

Eliot Quataert: It turns out that in these calculations, the impact of cosmic rays is actually the strongest in Milky Way mass gallons.

165

00:30:08.280 --> 00:30:26.760

Eliot Quataert: And that's basically because Milky Way mass galaxies sit at this point where they sit at the maximum of the stellar mass to him a mouse relation and nuts, they sit at the maximum of the available cosmic Ray energy relative to other energies and galaxies.

166

00:30:30.060 --> 00:30:39.570

Eliot Quataert: And I would say, one of the particularly interesting and not previously fully anticipated results that came out of this work.

167

00:30:40.800 --> 00:31:02.820

Eliot Quataert: Is that cosmic rays can actually in principle dramatically change the structure of the circular galactic medium of Milky Way mass scale and so just to remind you, those who are not thinking about galaxy formation on a day to day basis the circular galactic medium, is where the HALO of gas.

168

00:31:03.990 --> 00:31:24.900

Eliot Quataert: surrounding a galactic disk, that is, the reservoir the fuel reservoir for ongoing star formation and galaxies gas creeps from CG and galaxy fuels ongoing star formation outflows drive mass out back out into the cgm driving both cosmic rays, and also have the elements out into this.

169

00:31:26.460 --> 00:31:31.530

Eliot Quataert: So the i'm showing you plots here in the simulations of.

170

00:31:32.520 --> 00:31:49.410

Eliot Quataert: Milky Way mass galaxies from the fire collaboration without cosmic rays with cosmic rays without cosmic rays with cosmic rays, these are the same simulation showing basically the same information, one is a visual representation of the thermodynamic state of the gas.

171

00:31:50.490 --> 00:32:06.420

Eliot Quataert: Wear red is sort of the hot cgm Green is intermediate temperature cgm and why is lower temperature gas so think of the hot the red is sort of V realized gas the normal V realized HALO.

172

00:32:06.840 --> 00:32:24.330

Eliot Quataert: Green is gas that's more ionization equilibrium with ambient radiation field and white is cool gas that has cool to 10 before TV blow that might ultimately be fuel first start from.

173

00:32:27.900 --> 00:32:33.450

Eliot Quataert: And so what you see in the images and then in these phase diagrams these are plots of temperature versus density.

174

00:32:35.040 --> 00:32:42.660

Eliot Quataert: Is that the face structure of the cgm is extremely different and simulations with cosmic rays versus simulations without cosmic rays.

175

00:32:43.770 --> 00:32:52.350

Eliot Quataert: Without cosmic rays, you have a very allies galactic medium, most of the gas and cgm is relatively hot round the various temperature.

176

00:32:52.770 --> 00:33:01.500

Eliot Quataert: With cosmic rays, most of the gas is substantially cooler in photo ionization equilibrium and actually most of the pressure.

177

00:33:02.190 --> 00:33:21.270

Eliot Quataert: In the cgm is actually in the form of cosmic rays, these are cosmic rays dominated hailer rather than being well they're dark matter dominated halos the baryons or cosmic great dominated rather than being gas dominated in terms of pressure and energy density.

178

00:33:22.890 --> 00:33:37.320

Eliot Quataert: And this has a number of observational implications for instance the oxygen six column density, so one of the probes of the feminine amec state of the cgm of galaxies.

179

00:33:37.740 --> 00:33:48.630

Eliot Quataert: is to use lines of sight at different impact parameters relative to the size of the HALO that's on the X axis impact parameter well to the size, the HALO.

180

00:33:49.620 --> 00:34:00.780

Eliot Quataert: And to look at the column density of different ions as a function of impact parameter, this has been done extremely productively with the cost spectrograph on HST.

181

00:34:01.110 --> 00:34:13.770

Eliot Quataert: And also, at higher redshift by ground based observations, where the lines are red shifted into the rest frame optical by chuck stay down now there's for lyman break galaxies and systems like that these are.

182

00:34:15.090 --> 00:34:25.950

Eliot Quataert: What shown here in the blue is the sample of star forming local galaxies absorbed by costs and then the red is a sample of elliptical galaxies or by costs.

183

00:34:27.120 --> 00:34:33.000

Eliot Quataert: And the sort of Orange ish reddish band with the median shown the line here.

184

00:34:34.380 --> 00:34:47.370

Eliot Quataert: And the bluish and medium shown by the blue line are the simulations of Milky Way mass halos with cosmic rays, and without for one particular Ion oxygen so.

185

00:34:48.780 --> 00:35:03.870

Eliot Quataert: In that case, the fact that there's more gas at a temperature of the few times 10 to the five kelvin in the simulations with cosmic rays means you produce higher oxygen six column densities more consistent with observation.

186

00:35:05.610 --> 00:35:15.510

Eliot Quataert: On the other hand, just to be completely transparent, there are other observations were having this cooler cgm.

187

00:35:16.110 --> 00:35:27.810

Eliot Quataert: seems to be intention with so, for example in the Milky Way there's work by Joel bregman and colleagues using X Ray lines to constrain.

188

00:35:28.260 --> 00:35:38.940

Eliot Quataert: The hotter phase of the circle galactic medium of the Milky Way and that seems to suggest that there's actually a substantial amount of hot gas.

189

00:35:39.360 --> 00:35:52.920

Eliot Quataert: And the simulations with cosmic rays, as I described to you here under produced by a bit, the amount of hot gas, because a lot of the gas is in the lower temperature phase and the CG.

190

00:35:54.060 --> 00:36:04.980

Eliot Quataert: So I think the importance of this work is not that it definitively shows that the cgm of Mickey Mouse Mickey Mouse halos are cosmic Ray dominated.

191

00:36:05.430 --> 00:36:12.360

Eliot Quataert: I don't think it shows that definitively because this still depends on uncertainties and cosmic Ray trans.

192

00:36:13.140 --> 00:36:25.470

Eliot Quataert: If we change the cosmic Ray diffusion coefficient fire lot or if the cause and create diffusion coefficient is different in the circle galactic media, and it is an interstellar medium that could change these predictions.

193

00:36:26.220 --> 00:36:49.410

Eliot Quataert: What I think this shows is that we really need to understand cosmic Ray transport better to understand their impact on galaxy formation and, in particular, that the dominant impact of cosmic rays might actually be on the thermal structure of the cgm of Milky Way Moscow.

194

00:36:50.550 --> 00:36:59.190

Eliot Quataert: And I think there's a lot more theoretical work and observational work sort of testing this this type of model that's needed to understand this.

195

00:37:02.010 --> 00:37:08.640

Eliot Quataert: Okay, so that's what I wanted to say about Milky Way mass galaxies.

196

00:37:11.010 --> 00:37:24.900

Eliot Quataert: i'll just very briefly mentioned some work that we've done on higher mass systems galaxy clusters and then all, and so we have time for a little bit more discussion and.

197

00:37:26.820 --> 00:37:46.050

Eliot Quataert: So basically just to remind you, there is a paradigm that's developed over the last decade or so, which is that relativistic jets from supermassive black holes are the energy source that suppresses the cooling of hot gas in massive dark matter.

198

00:37:47.310 --> 00:37:51.840

Eliot Quataert: galaxy groups galaxy clusters potentially even.

199

00:37:52.980 --> 00:37:56.790

Eliot Quataert: Isolated elliptical galaxies and relatively massive darkness.

200

00:37:58.200 --> 00:38:01.110

Eliot Quataert: And a lot of the argument for that.

201

00:38:02.250 --> 00:38:09.750

Eliot Quataert: relies basically on two things one is that it doesn't seem like there's quite enough feedback energy from star formation.

202

00:38:10.110 --> 00:38:19.950

Eliot Quataert: To offset radiative cooling of gas in high mass halos the cooling rates are too strong relative to the available energy from stellar feedback.

203

00:38:20.400 --> 00:38:37.050

Eliot Quataert: And also, it comes from beautiful observational work combining, for instance Chandra and the vla observations of galaxy groups and clusters, where there's clear evidence for radio jets interacting with the hot.

204

00:38:38.130 --> 00:38:54.960

Eliot Quataert: intro group and enter cluster medium the radio emitting plasma, which is synchrotron the mission from Rome electrons seems to displace the hot X Ray emitting gash on here in kind of a grayscale surface brightness map.

205

00:38:56.310 --> 00:39:06.000

Eliot Quataert: And so it looks like the jets are displacing the hot gas pushing it around and dumping, the feedback energy from the black hole into the intro cluster.

206

00:39:08.220 --> 00:39:21.810

Eliot Quataert: There is enough energy, at least at the order of magnitude level coming out in relativistic jets to substantially impact the thermal structure of the hot gas in groups and clusters.

207

00:39:22.530 --> 00:39:43.140

Eliot Quataert: But what we don't understand well and I would say, this is still a big question of how exactly does the black hole energy get transmitted relatively spiritually out into the surrounding in triggering for intra cluster.

208

00:39:44.220 --> 00:39:56.070

Eliot Quataert: Because it's not enough to just heat gas along the JET right you want to stop the gas over here in the group when cluster from cooling as well, you don't just want to stop the gas.

209

00:39:57.810 --> 00:40:06.750

Eliot Quataert: So there's a need to redistribute the JET energy relatively spirally and relatively uniformly in top.

210

00:40:08.070 --> 00:40:15.960

Eliot Quataert: And there's a variety of different ways that people have thought of to do this one is way that.

211

00:40:16.680 --> 00:40:36.270

Eliot Quataert: Time variable jets can drive waves and turbulence into the entire cluster medium and that can keep the surrounding plasma and that's actually what i'm showing you in this simulation that we did where a time dependent jet is driving sort of large amplitude sound waves or.

212

00:40:37.290 --> 00:40:55.950

Eliot Quataert: We shocks relatively more spirally than the JET itself into the medium and the other ideas actually that most of the energy in jets after all was in relativistic particles that's what a jet is it's a theme of relativistic particles recent glanford.

213

00:40:57.180 --> 00:41:11.490

Eliot Quataert: And so it's basically cosmic rays, and so, if those cosmic rays can transmit their energy to the surrounding medium maybe they're the vector by which the feedback energy gets transmitted to the surrounding medium stifling.

214

00:41:13.290 --> 00:41:36.990

Eliot Quataert: And what we've shown in work that I particularly like over the last couple of years, and this is work led by Philip Kamsky and when I say lead is really his ideas, as well as his calculations what he's shown actually is, I think, an amazing result it's that in galaxy cluster plasma.

215

00:41:38.340 --> 00:41:50.550

Eliot Quataert: Both sound waves and internal gravity waves are two of the three basic linear waves and the problem, the other being the Alpha waves.

216

00:41:52.110 --> 00:42:02.490

Eliot Quataert: Both sound waves and internal gravity waves are linearly unstable due to the presence of cosmic rays in the cluster in trouble.

217

00:42:03.750 --> 00:42:11.190

Eliot Quataert: And what allows the instability to operate it turns out, is that the Alpha thing way.

218

00:42:12.210 --> 00:42:23.130

Eliot Quataert: which affects how cosmic rays moves through the plasma depends on the mean free path of the hot in truck cluster Plasma.

219

00:42:25.110 --> 00:42:35.040

Eliot Quataert: This is basically viscosity changes the alpha and speed in cluster medium conditions.

220

00:42:35.430 --> 00:42:45.420

Eliot Quataert: And that drives sound waves and internal gravity waves when you're the stable the sound waves Philip has calculated growing amplitude until they steep him.

221

00:42:45.780 --> 00:42:56.070

Eliot Quataert: into week shocks shown in this numerical simulation that he's done again treating the cosmic rays as well mystic fluid the week shocks in.

222

00:42:56.820 --> 00:43:14.490

Eliot Quataert: that are produced in Philip simulations actually bear a lot of resemblance to the week shocks that have been seen by carefully looking for surface brightness fluctuations in the perseus cluster this is work that Andy Fabian is famous for its you're seeing.

223

00:43:15.720 --> 00:43:22.710

Eliot Quataert: Hundreds of killer parsecs image of perseus subtracting off the means surface brightness profile and just looking at.

224

00:43:23.190 --> 00:43:40.140

Eliot Quataert: The fluctuations due to what are either waves or week shocks if some calm, so the speculation that we're proposing and trying to study in more detail is that cosmic rays generated in jets.

225

00:43:42.450 --> 00:43:52.920

Eliot Quataert: In bubbles in particular you create these cosmic Ray dominated plasmas that are very unstable to the instabilities that Philip has discovered.

226

00:43:53.460 --> 00:44:01.320

Eliot Quataert: Those instability SAP a lot of the cosmic green energy in the form of waves, which can travel spiritually out into the entire cluster medium.

227

00:44:01.740 --> 00:44:10.830

Eliot Quataert: depositing their energy over relatively long distances and strongly affected affecting the thermal evolution of the cluster.

228

00:44:11.760 --> 00:44:24.570

Eliot Quataert: And so we're kind of have understood that when you're instabilities and their saturation and are trying to work out now how this actually operates in sort of a global interest cluster media and content.

229

00:44:26.550 --> 00:44:40.350

Eliot Quataert: Okay, so all i'll stop there, I hope, i've given you a bit of a feel for some of the interesting physics and astrophysics of cosmic rays and galaxy formation what some of the impacts might be.

230

00:44:40.890 --> 00:44:55.140

Eliot Quataert: Why, that is not pin down yet theoretically or observational Lee and what some of the interesting avenues for continued research so thanks a lot for for your time.

231

00:44:55.860 --> 00:44:56.610

Morgan Elowe MacLeod: Thank you.

232

00:44:58.110 --> 00:45:02.610

Morgan Elowe MacLeod: um I have a couple questions coming in and just a reminder to folks.

233

00:45:04.140 --> 00:45:10.440

Morgan Elowe MacLeod: If you want to message me the just sort of basic topic of your question i'll call on you, so.

234

00:45:11.580 --> 00:45:14.370

Morgan Elowe MacLeod: First, we had a question from Avi would you like to go ahead.

235

00:45:15.240 --> 00:45:20.400

Abraham Loeb: Sure nice nice to see you Gordon excellent talk and.

236

00:45:21.480 --> 00:45:26.220

Abraham Loeb: it's too bad that you cannot visit us in person, given that you are much closer than in the past.

237

00:45:27.540 --> 00:45:38.190

Abraham Loeb: So, in the context of the mass carried by the wind, driven by cosmic rays, I had the following question massive stars have wins very powerful wins and.

238

00:45:39.840 --> 00:45:45.570

Abraham Loeb: The optical depth to the radiation within the wind is a folder unity and what people find is that.

239

00:45:46.200 --> 00:45:56.070

Abraham Loeb: The mass loss rate of the wind is roughly given by momentum conservation, in other words, if you take the luminosity of the star divide by the speed of light that's the momentum, bringing the time.

240

00:45:57.270 --> 00:46:09.450

Abraham Loeb: The positive in the wind and that's roughly \dot{m} times the escape from the star so a very good fit to the mass loss rating massive stars is that is given by this balance of momentum not energy.

241

00:46:10.110 --> 00:46:18.930

Abraham Loeb: And the difference from the energy equation that you mentioned, which gives the maximum mass loss rate is a factor of the over the escape of receipt.

242

00:46:19.530 --> 00:46:35.790

Abraham Loeb: Now the question is whether that gives him a closer fit to the line that you showed us, or is it still off and I guess it could be off because perhaps the optical depth is not for the unity for that so, can you elaborate.

243

00:46:36.480 --> 00:46:49.560

Eliot Quataert: yeah so that's a great question and you're absolutely right there's a lot of analogies between galactic winds driven by cosmic rays, especially in the diffusion approximation and.

244

00:46:50.550 --> 00:46:59.340

Eliot Quataert: winds from massive stars, driven by radiation when things are optically thick driven by diffuse of radiation.

245

00:47:00.330 --> 00:47:22.980

Eliot Quataert: So the the analogy is a bit more to what are called continuum driven radiation wins rather than line driven wins but that's exactly right there's a very close analogy, so the momentum conservation argument definitely is closer to the result that one gets.

246

00:47:24.090 --> 00:47:37.680

Eliot Quataert: calibrating to the sort of empirically constrained diffusion coefficient it's not exactly the same, but it is definitely much closer So if you made an on zotto that the.

247

00:47:40.140 --> 00:47:48.420

Eliot Quataert: that the momentum terminal momentum flux in the wind is related to how much momentum is being dumped into the surrounding medium.

248

00:47:49.080 --> 00:48:02.550

Eliot Quataert: That is is definitely closer to what one gets from the more detailed when calculations calibrated empirically in the way that I described it's not exactly the same, but it's close yeah good question.

249

00:48:06.360 --> 00:48:14.430

Morgan Elowe MacLeod: We have a few questions about how the cgm is affected by cosmic Ray so ramesh why don't you lead the way.

250

00:48:16.860 --> 00:48:27.930

ramesh: So Elliot great talk, but I missed one small point, you must have mentioned it, but I don't I must have blinked up, you say that the cgm becomes cooler.

251

00:48:28.770 --> 00:48:38.730

ramesh: When you include the cosmic Ray contribution it kind of goes against my intuition why Why exactly does it get cooler if you add this extra pressure.

252

00:48:40.260 --> 00:48:43.230

Eliot Quataert: Yes, so no that's a great question.

253

00:48:44.460 --> 00:48:46.170

Eliot Quataert: And we definitely.

254

00:48:47.310 --> 00:48:56.220

Eliot Quataert: You know, looked into that mechanistic Lee because I agree it's not entirely you know it's a bit it's a bit counterintuitive.

255

00:48:57.690 --> 00:48:58.290

Eliot Quataert: You know.

256

00:48:59.400 --> 00:49:00.120

Eliot Quataert: In.

257

00:49:02.850 --> 00:49:25.140

Eliot Quataert: I think the basic thing that's going on is that in the case without cosmic rains a lot of the gas that's actually driven out of the galaxy is driven out and the hot phase, you get a strong aerial shot coming into the galaxies you have hot gas coming from both direction.

258

00:49:26.190 --> 00:49:33.030

Eliot Quataert: Two things happen with the cosmic rays, one is that you actually suppress the variable Shaw.

259

00:49:33.930 --> 00:49:49.080

Eliot Quataert: The cosmic rays get driven actually sufficiently far out into the cgm if they go out into the intergalactic media and they suppress the normal variable shock that heats gas up and creates this serialized HALO.

260

00:49:50.100 --> 00:49:59.190

Eliot Quataert: And the other thing is that actually a lot of the gas driven out of the galaxy into the sort from galactic medium is initially driven out and clear phases, and the first.

261

00:50:00.360 --> 00:50:14.310

Eliot Quataert: So I think it's a combination of both of those things, one is that you're actually accreting cooler gas because you're suppressing the importance of the variable shock and you're driving cooler gas out into those cgm in the first.

262

00:50:16.560 --> 00:50:16.920

Thank you.

263

00:50:19.770 --> 00:50:20.910

Morgan Elowe MacLeod: auntie want to.

264

00:50:21.300 --> 00:50:22.560

Morgan Elowe MacLeod: continue along this.

265

00:50:24.060 --> 00:50:38.430

Anna L Rosen: yeah hey Elliot you had a couple questions on well The first was regarding what you spoke about about a lot of the cosmic rays leading Laura Lopez had a paper on the SEC, a couple years ago, looking at the Fermi.

266

00:50:40.320 --> 00:50:47.220

Anna L Rosen: gamma Ray emission observations and then also comparing it with the polarization previous polarization she found that.

267

00:50:48.000 --> 00:51:02.730

Anna L Rosen: Basically, look at the polarization you do see the cosmic rays 10 per week or gamma Ray emission along the magnetic field lines, so I don't know if you guys have looked at that, with the escape fractions and your simulations to see how it follows the magnetic fields lines.

268

00:51:03.000 --> 00:51:10.740

Eliot Quataert: yeah we have not, we have not done that in detail, yet, and there are various yeah we have not done that.

269

00:51:11.280 --> 00:51:11.640

yeah.

270

00:51:12.720 --> 00:51:14.850

Anna L Rosen: is crazy, because I know you just.

271

00:51:15.930 --> 00:51:22.530

Anna L Rosen: You your plot showed up to that llc so i'm curious to see how that works, down to the SMC and other things.

272

00:51:23.700 --> 00:51:30.210

Anna L Rosen: Including for the diffusion coefficient and then another question, I had was so project that i've been working on on.

273

00:51:30.900 --> 00:51:37.560

Anna L Rosen: is to try to understand the galaxy and mission it's and galaxy clusters and it's a lot weaker than you would expect, and so.

274

00:51:37.950 --> 00:51:51.090

Anna L Rosen: We developed this model to kind of we have different sources of gamma rays so like glue most supermassive black hole at the Center for the you know BCG and then included like another couple of.

275

00:51:52.110 --> 00:52:02.040

Anna L Rosen: Mechanisms but with that you know we can constrain either the efficiency, like how much of whatever energy goes into accelerating accelerating cosmic rays.

276

00:52:02.790 --> 00:52:22.200

Anna L Rosen: Or we can also look at the the diffusion coefficient so either based on that so i'm just curious so like with with our model, we find that you'd expect the most energy injection would likely be due to the suit the cgm supermassive black hole sorry.

277

00:52:24.150 --> 00:52:25.620

Anna L Rosen: BCG and.

278

00:52:26.790 --> 00:52:30.630

Anna L Rosen: supermassive black hole because that's the most passive but.

279

00:52:31.740 --> 00:52:39.810

Anna L Rosen: Now i'm curious but, but then we have to have a much lower diffusion coefficient is a crapshoot to be high to account for the.

280

00:52:41.520 --> 00:52:58.380

Anna L Rosen: For the low gamma emission or we need a very low efficiency or now I you know with what you talked about the fact that you're transferring energy to try these often radio waves, so how much of that energy would you say is is doing that.

281

00:52:58.950 --> 00:53:04.680

Eliot Quataert: Right, so I so just maybe to step back for everybody else, and then i'll answer.

282

00:53:06.660 --> 00:53:07.740

Eliot Quataert: A great set of questions so.

283

00:53:08.070 --> 00:53:22.740

Eliot Quataert: I could have talked about trying to observation, we calibrate cosmic Ray transport as ana's nice questions alluded to, I could have talked about that in the context of galaxy clusters, just as well as galaxies.

284

00:53:22.980 --> 00:53:31.770

Eliot Quataert: yeah the differences that in galaxy clusters, we have not yet detected be gamma emission from Python decay, this was a big hope with Fermi actually is that it would.

285

00:53:32.130 --> 00:53:35.010

Eliot Quataert: Well, maybe, and maybe in.

286

00:53:35.400 --> 00:53:36.360

Eliot Quataert: The Middle.

287

00:53:36.690 --> 00:53:39.390

Eliot Quataert: yeah it's not it's not as well.

288

00:53:39.450 --> 00:53:42.390

Eliot Quataert: characterized, even though the star formation.

289

00:53:42.780 --> 00:53:50.460

Eliot Quataert: star forming galaxies are only you know moderately well characterized it's yet less well characterized in in galaxy clusters and so.

290

00:53:50.880 --> 00:54:07.770

Eliot Quataert: As as Anna said, this is a constraint on some combination of diffusion coefficient and efficiency of injecting cosmic Ray energy, you know I think the direct empirical constraint is that the energy density and cosmic rays is not equal to the thermal energy density of.

291

00:54:07.800 --> 00:54:08.340

galaxies.

292

00:54:09.360 --> 00:54:21.960

Eliot Quataert: Like it is roughly in the Milky Way instead it's 10% of that or 3% of that are probably depends exactly where you are in the cluster and whose bottle you take those are the typical number so.

293

00:54:23.670 --> 00:54:34.440

Eliot Quataert: I think that that is so that's interesting for two reasons, I mean one is it it really constrains the direct heating.

294

00:54:35.100 --> 00:54:47.070

Eliot Quataert: Of cosmic rays sorry direct heating of the thermal gas by streaming cosmic rays just one mechanism that people then vote to heat the entire cluster medium.

295

00:54:47.970 --> 00:54:55.950

Eliot Quataert: and actually the specific reason that when I talked about the instabilities generating waves and then traveling out.

296

00:54:56.400 --> 00:55:03.780

Eliot Quataert: I sort of intentionally said that maybe the waves are excited near the bubbles, and then they travel out.

297

00:55:04.230 --> 00:55:22.020

Eliot Quataert: And the reason I sprained it that way is precisely because I think the cosmic Ray energy density it sort of has to be high near the bubbles because they're strictly dominated plasmas but for just the observational reasons you gave it seems to be low elsewhere.

298

00:55:22.290 --> 00:55:22.560

Anna L Rosen: yeah.

299

00:55:22.590 --> 00:55:40.200

Eliot Quataert: I think the region that is the most efficient at generating the way, is in fact the plasma sort of at the boundary between the bubbles, and the rest of the intro cluster media because that's where the cosmic Ray energy densities, are the highest.

300

00:55:40.650 --> 00:55:41.880

Anna L Rosen: yeah okay.

301

00:55:41.970 --> 00:55:51.180

Eliot Quataert: And I think the question that we're trying to answer now, which is still a bit challenging is how far the waves get.

302

00:55:52.050 --> 00:56:00.780

Eliot Quataert: and propagate to transport their energy well that depends on the wavelengths of the waves that are excited and how quickly they steep in.

303

00:56:01.170 --> 00:56:17.340

Eliot Quataert: And so that depends, you know, not just on the linear instability, but on how it saturates non linearly and so that's the part of the problem that that we're still trying to understand, but I think, for the reasons that you gave.

304

00:56:18.450 --> 00:56:37.890

Eliot Quataert: I think either direct heating of the cluster medium by cosmic rays or cosmic rays exciting in situ waves, you know 100 K PC away from the JET I think that's probably unlikely.

305

00:56:38.910 --> 00:56:44.520

Eliot Quataert: Because the cosmic Ray energy density seem to be pretty low as constrained by the gamma Ray.

306

00:56:46.200 --> 00:56:55.920

Eliot Quataert: that's that's My guess, but this is something that we're also you know, trying to to think through and make sure we understand exactly what the observation constraints are etc.

307

00:56:56.940 --> 00:57:07.890

Anna L Rosen: yeah i'm sorry I haven't looked at this project and what else i've been finishing up and doing lots of other things, but something I you know i've been meaning to get back to working on and finishing um but yeah i'll send you an email i'll talk to you more about it.

308

00:57:08.850 --> 00:57:09.600

Eliot Quataert: that's great Thank you.

309

00:57:09.720 --> 00:57:10.620

Anna L Rosen: yeah thanks.

310

00:57:12.300 --> 00:57:22.800

Morgan Elowe MacLeod: So much I think we're reaching our 12 o'clock threshold there so maybe we can join me in thanking Elliot one more time.

311

00:57:24.060 --> 00:57:29.580

Morgan Elowe MacLeod: There are a few questions left I don't know if you can stay for five more minutes Elliot.

312

00:57:29.820 --> 00:57:30.660

Eliot Quataert: i'm happy.

313

00:57:30.750 --> 00:57:38.970

Morgan Elowe MacLeod: But you know people who need to leave go ahead, but if you had an outstanding question feel free to stay, if you if you're able to.