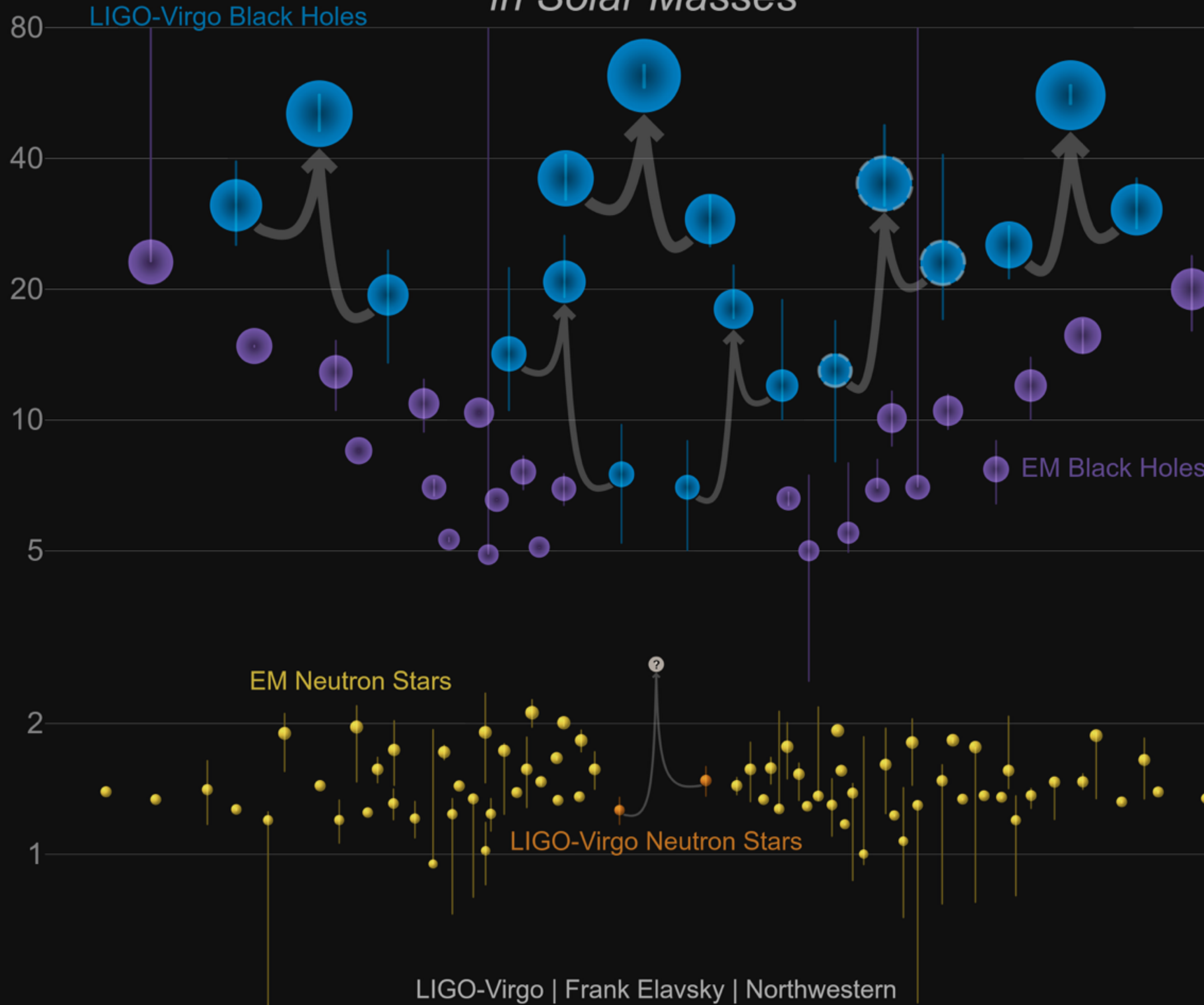


GW170817:
Discovery of a
Binary Neutron Star Merger

Duncan Brown
Syracuse University

Masses in the Stellar Graveyard

in Solar Masses



Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time	Event Time	FAR (Hz)	FAR (yr ⁻¹)	Links	UTC	Submitted
G298048	EM_COINC H1OK ADVOK L1OK V1OK	CBC	gstlal	O2VirgoTest	H1	X	1187008882.4457	3.478e-12	1 per 9111.7 years	Data	X	2017-08-17 12:47:18 UTC

Coinc Tables

End Time (GPS)	1187008882.4457 s
Total Mass	2.7693 M _⊙
Chirp Mass	
SNR	
False Alarm Probab	
Log Likelihood Ratio	32.3969

Single Inspiral Tables

IFO	H1
Channel	GPS_CALIB_STRAIN

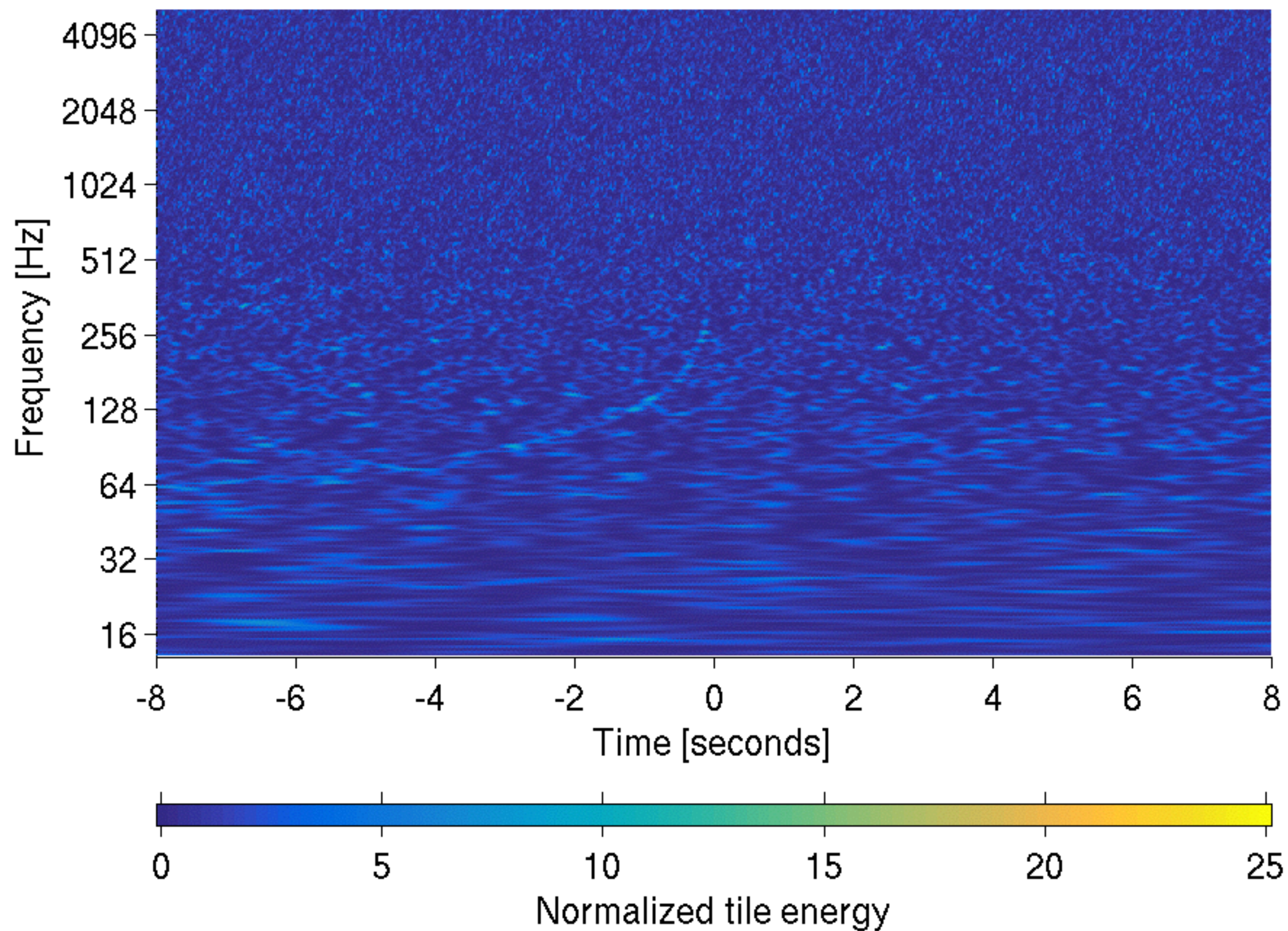
Low chirp mass
(1.00) ...
Fermi gamma-ray burst event
~ 2 second after merger!
neutron star...

But only seen at Hanford, even though Livingston and Virgo were operating...

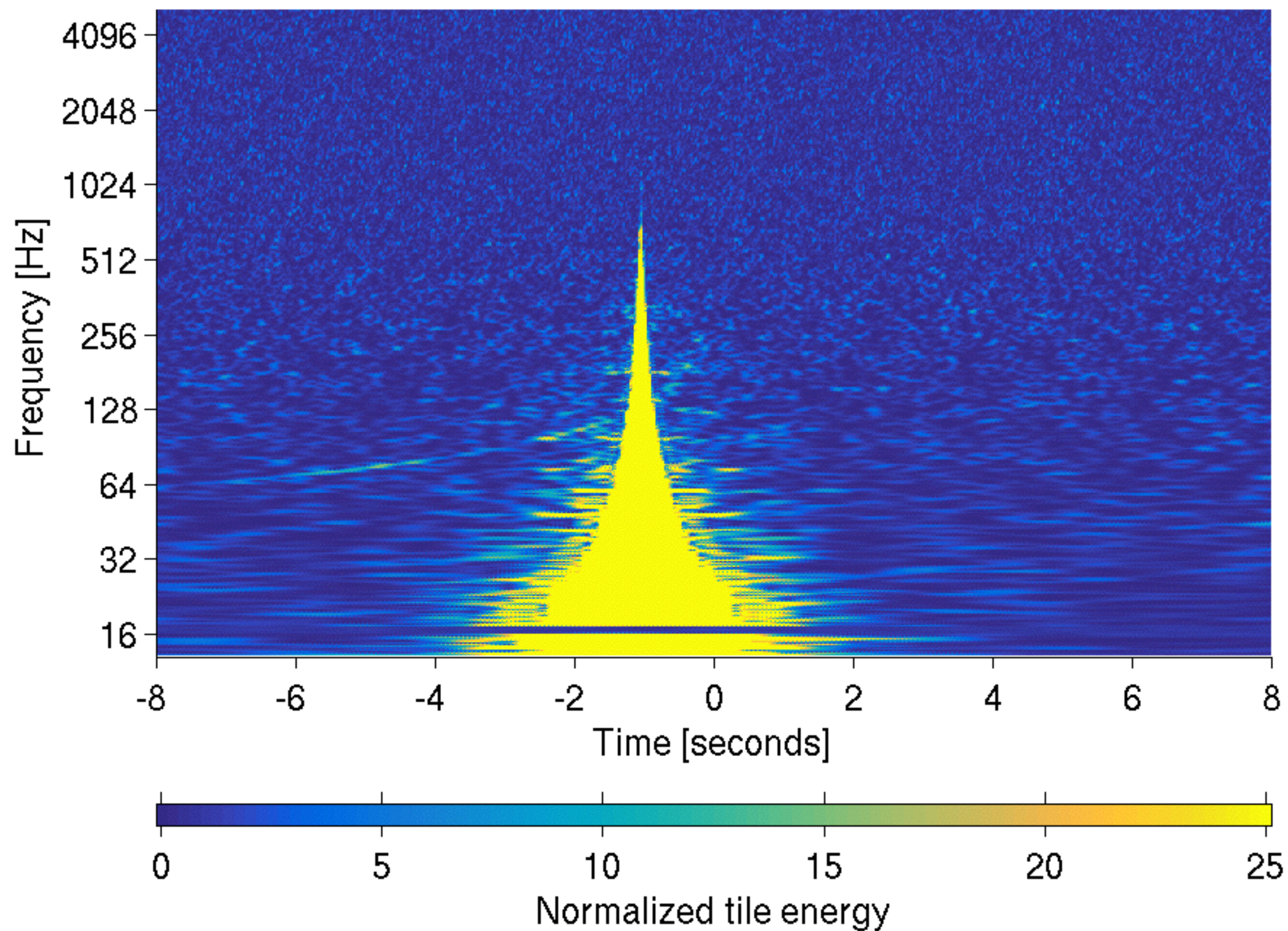
Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time	Event Time	Δgpstime	FAR (Hz)	Links	UTC	Submitted
E298046	EM_COINC	External	Fermi	GRB		X	1187008884.4700	2.024290		Data	X	2017-08-17 12:41:45 UTC

H1:GDS-CALIB_STRAIN at 1187008882.446 with Q of 104.4



L1:GDS-CALIB_STRAIN at 1187008882.446 with Q of 104.4



8/17/17, 09:07

GO!

check your email!

<https://gcn.gsfc.nasa.gov/other/524666471.fermi>

Coincident BNS

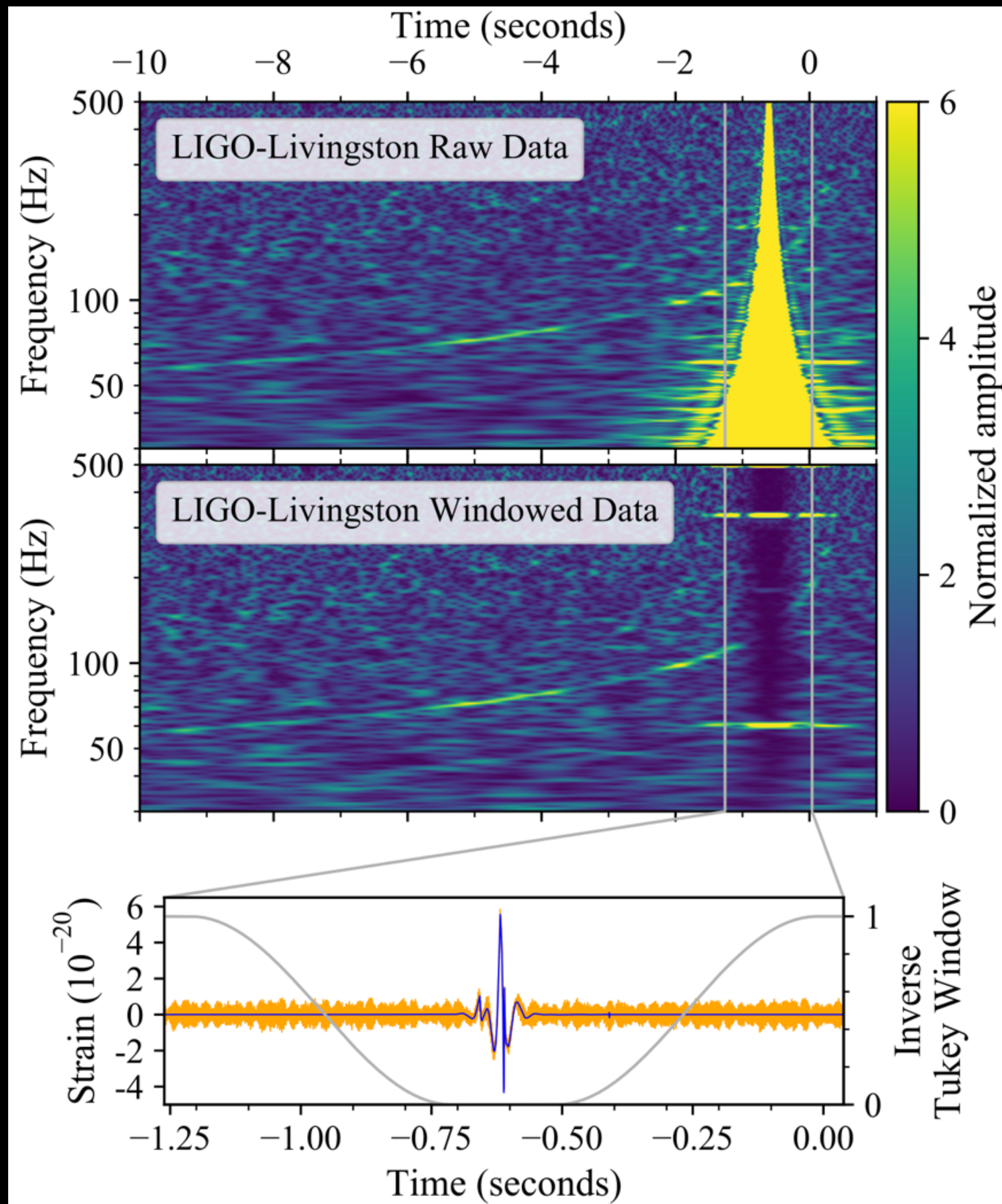
Can I call you later?

Sorry - stuck on a telecon

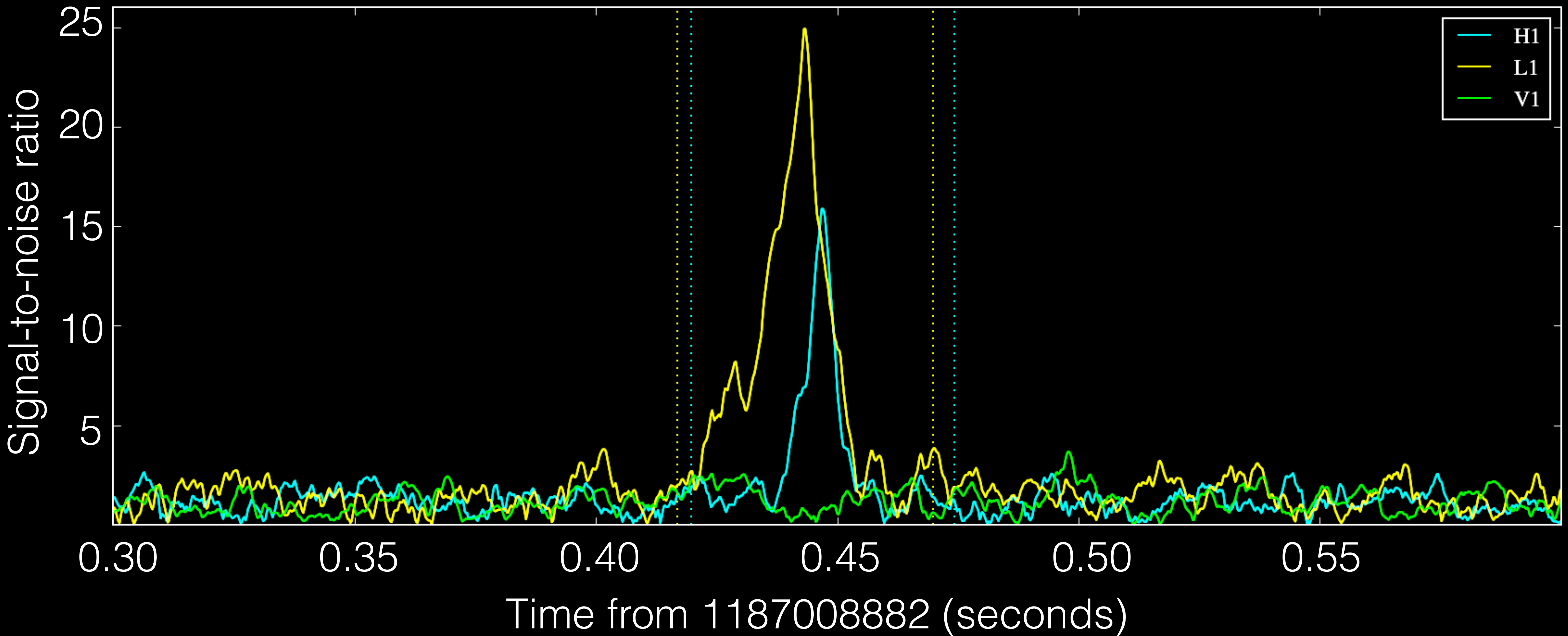
yes

hope it's a DECam telecon





Rapid offline re-analysis of Hanford, Livingston, and Virgo data



Usman,... DAB, et al. *Class.Quant.Grav.* **33** 215004 (2016)

Nitz, Dent, Del Canton, Fairhurst, DAB. *ApJ* **849** 118 (2017)



Laura Nuttall



Andy Lundgren



Tito Dal Canton



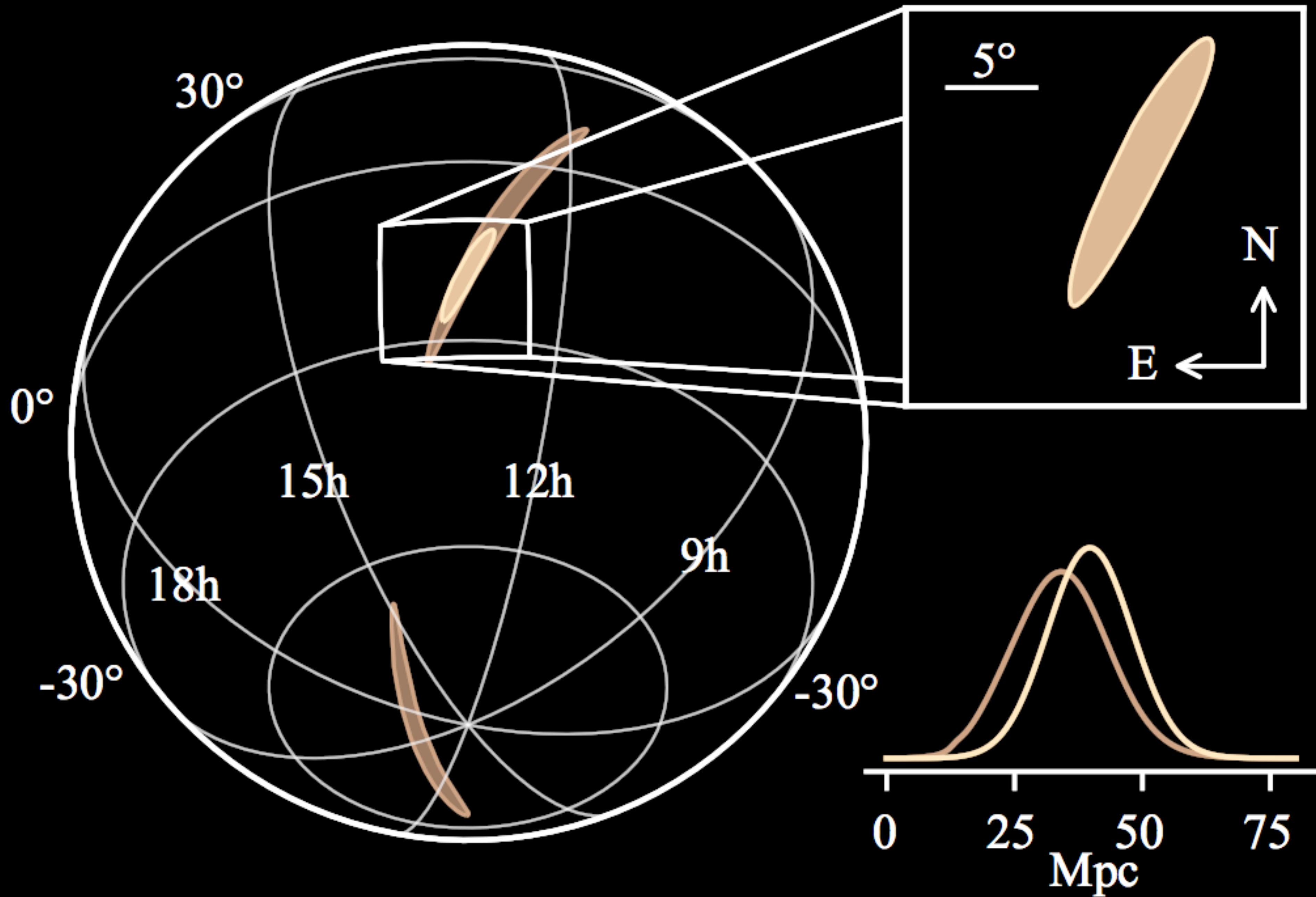
Ian Harry



Alex Nitz



TJ Massinger



8/17/17, 13:31

new sky map coming in a few mins

OK, you should have the HLV sky map from Bayestar

sucks for Virgo, it's in their dead spot!

but we get localization from the fact that they didn't see it...

This is an amazing localization!

Yep!

It's real close and real loud. The fact that Virgo didn't see anything really helps (ironically)

iMessage



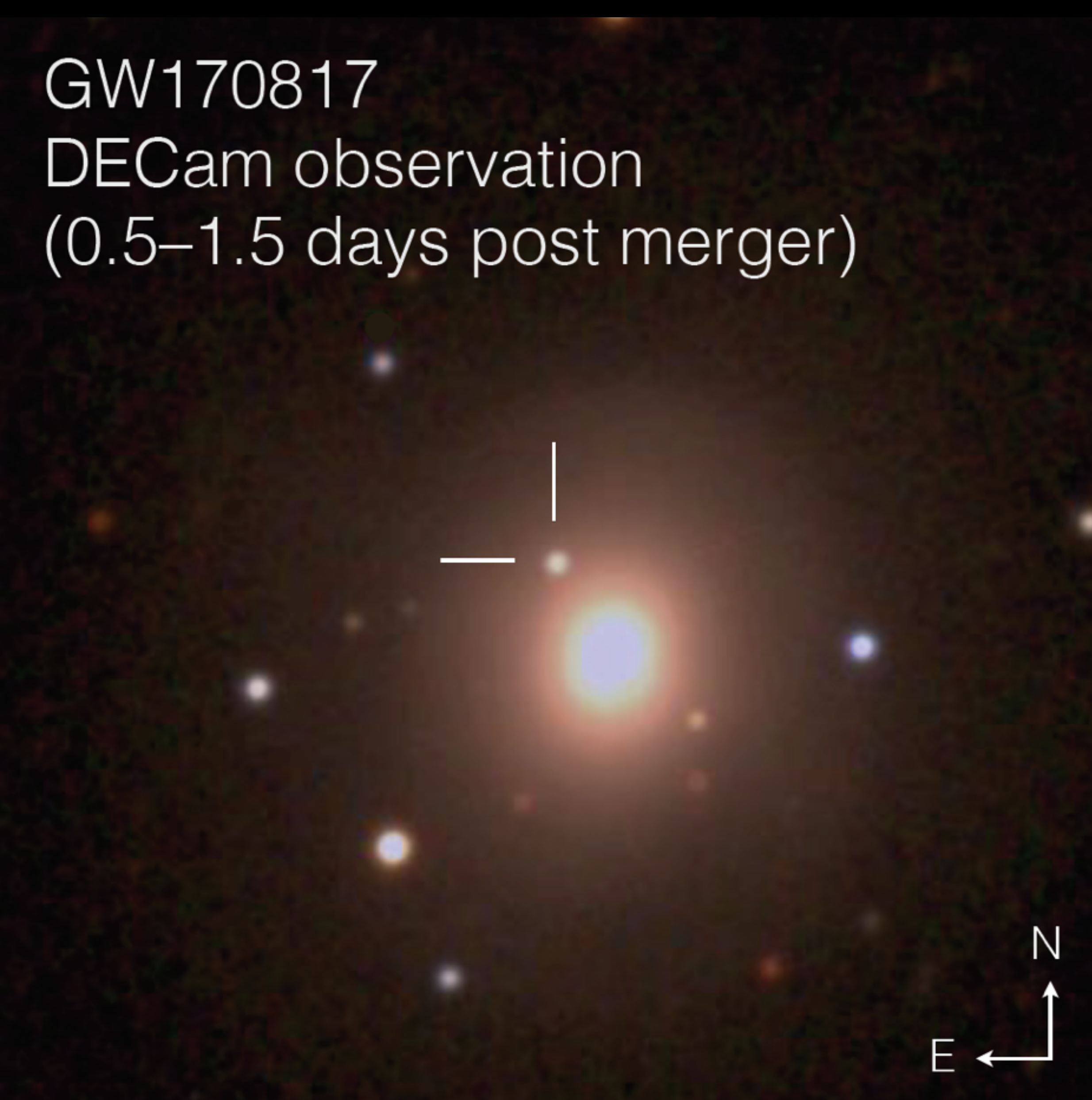
GCN 21513 at 1:54 pm EDT with localization...

TITLE: GCN CIRCULAR
NUMBER: 21513
SUBJECT: LIGO/Virgo G298048: Further analysis of a binary neutron star candidate with updated sky localization
DATE: 17/08/17 17:54:51 GMT
FROM: Leo Singer at NASA/GSFC <leo.p.singer@nasa.gov>

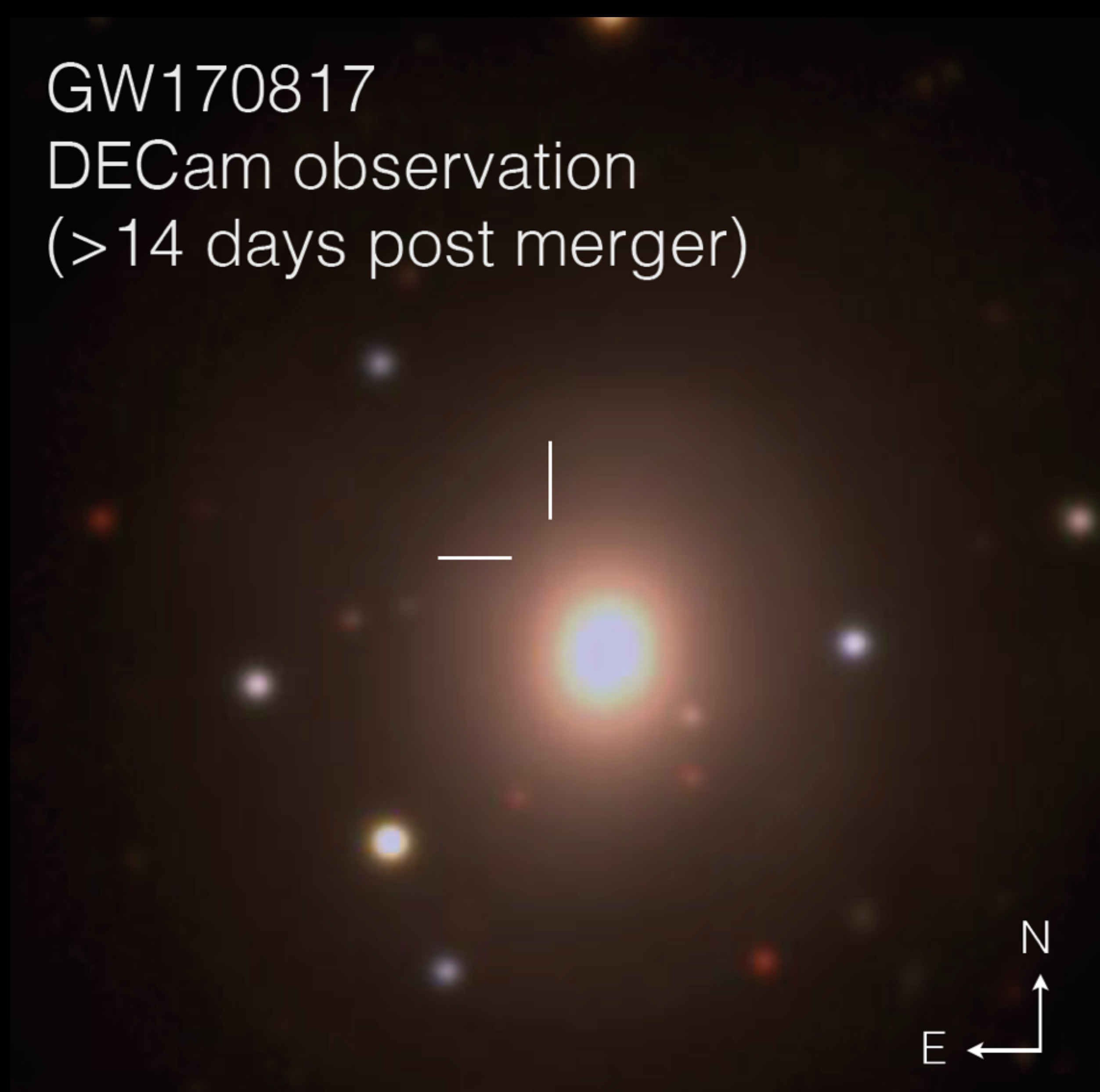
The LIGO Scientific Collaboration and the Virgo Collaboration report:

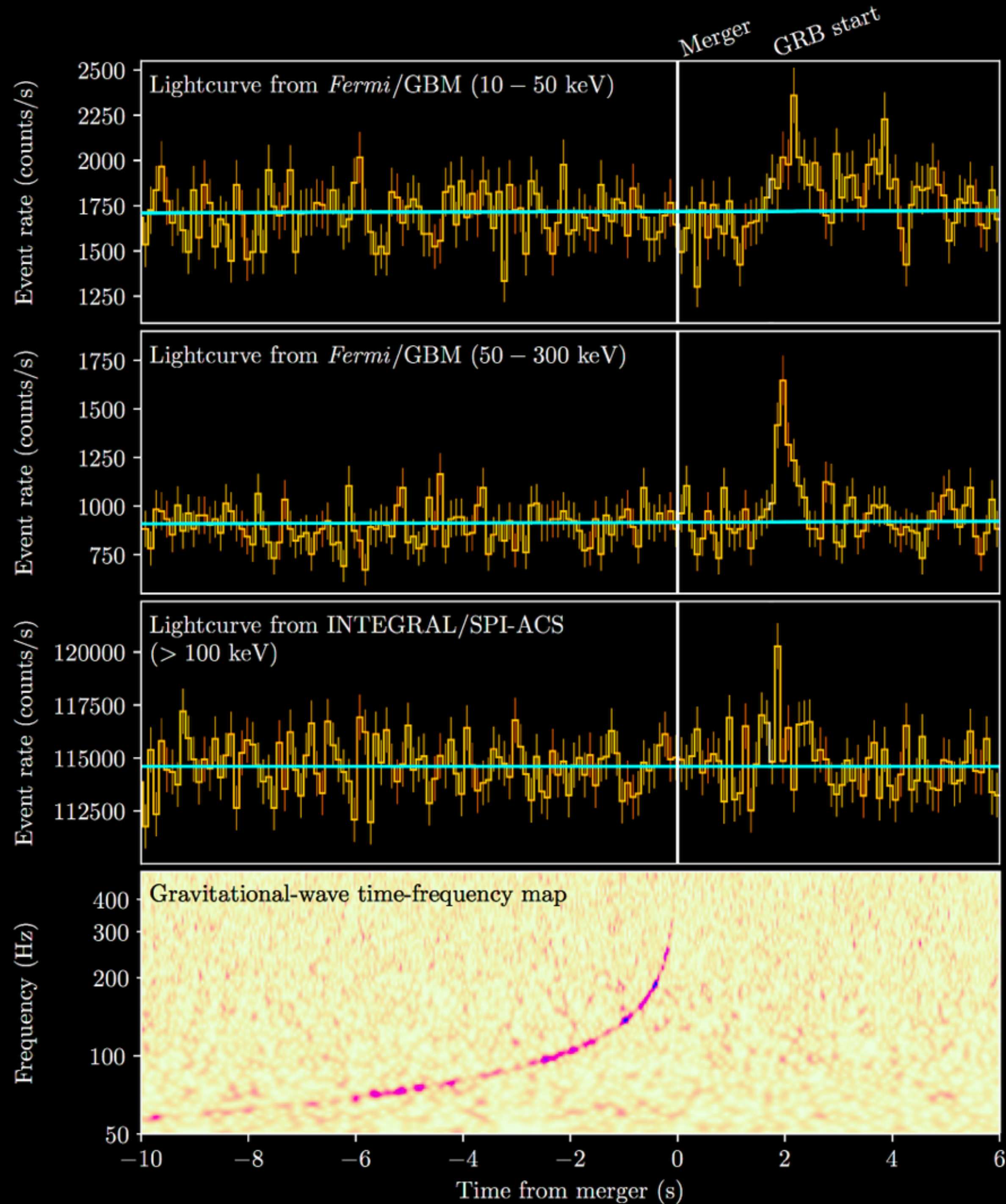
We performed a preliminary offline analysis using the PyCBC search (Nitz et al. arxiv:1705.01513, 2017) of the binary neutron star candidate G298048 (LSC and Virgo, GCN 21505, 21509, 21510) identified in low-latency by the gstlal online search (Messick et al. Phys. Rev. D 95, 042001, 2017).

GW170817
DECam observation
(0.5–1.5 days post merger)

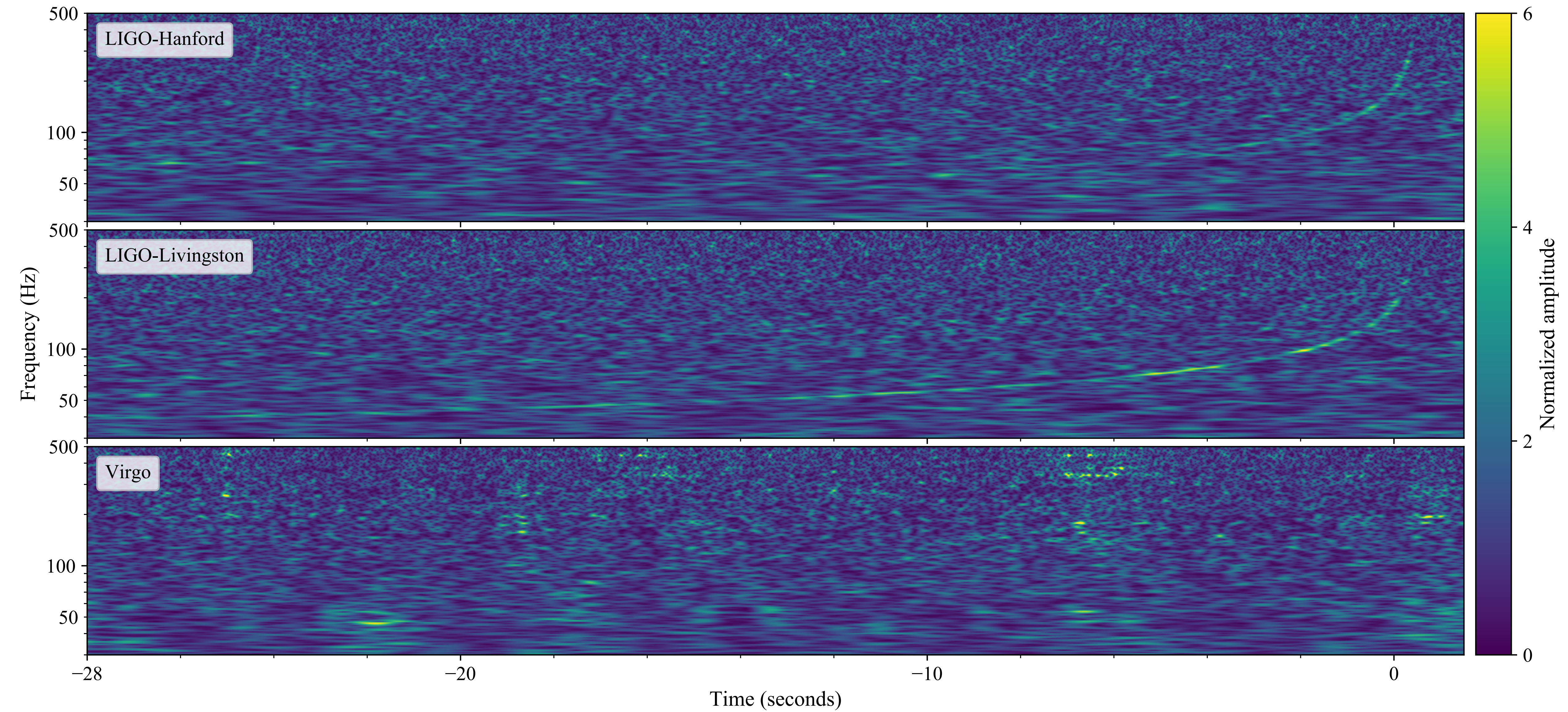


GW170817
DECam observation
(>14 days post merger)





- The probability of a chance temporal and spatial association of GW170817 and GRB170817A is 5.0×10^{-8}
- We can confirm binary neutron stars as the progenitors of short, hard gamma-ray bursts
- The time delay between the end of the gravitational-wave signal and the start of the gamma-ray burst is $1.74 (+/- 0.05) \text{ s}$



$$p(\vec{\theta} | \vec{d}(t), H) = \frac{p(\vec{\theta} | H) p(\vec{d}(t) | \vec{\theta}, H)}{p(\vec{d}(t) | H)}$$

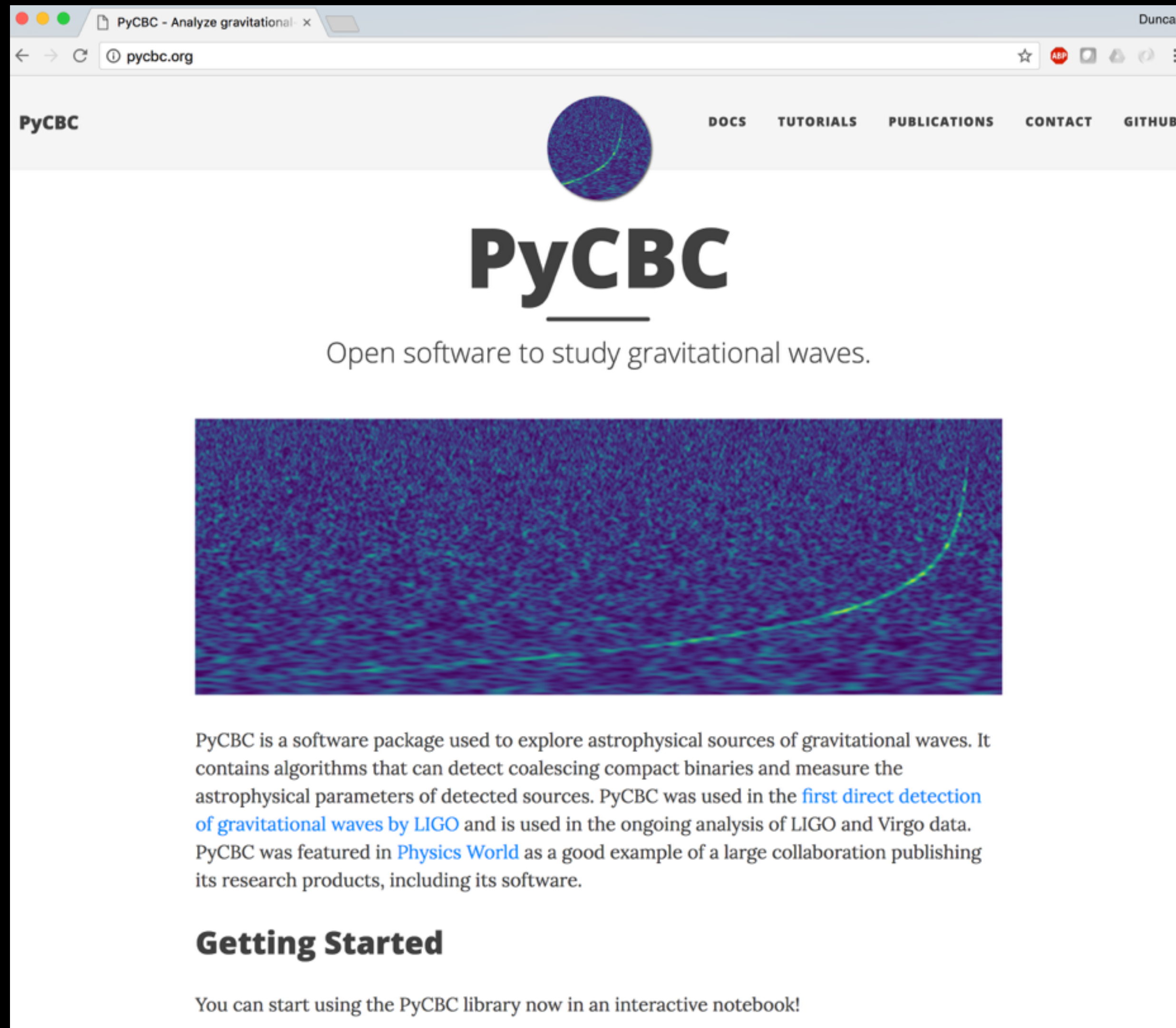
Need the data, $\vec{d}(t)$

Need a model, $H \equiv h(t; \alpha, \delta, m_1, m_2, \vec{s}_1, \vec{s}_2, \lambda_1, \lambda_2, \dots)$

Need a likelihood, $p(\vec{d}(t) | \vec{\theta}, H)$

Need priors, marginalization, and visualizing software

- PyCBC (primarily developed by Syracuse, Albert Einstein Institute)

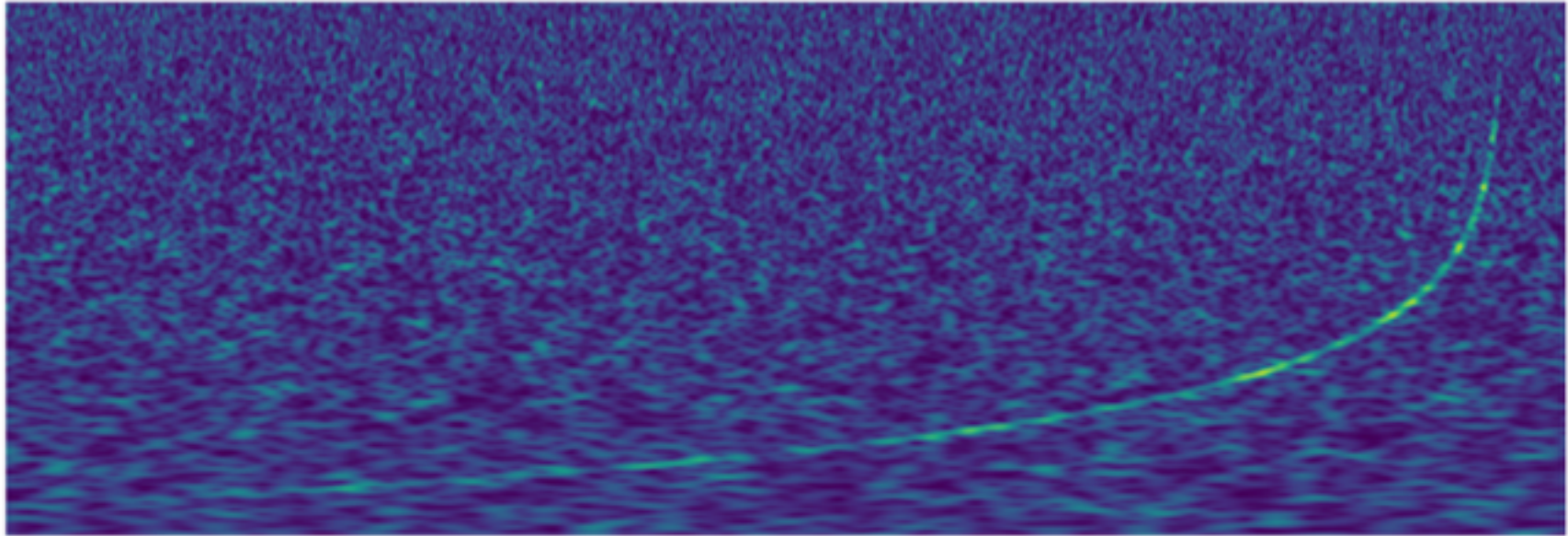


PyCBC

DOCS TUTORIALS PUBLICATIONS CONTACT GITHUB

PyCBC

Open software to study gravitational waves.



PyCBC is a software package used to explore astrophysical sources of gravitational waves. It contains algorithms that can detect coalescing compact binaries and measure the astrophysical parameters of detected sources. PyCBC was used in the [first direct detection of gravitational waves by LIGO](#) and is used in the ongoing analysis of LIGO and Virgo data. PyCBC was featured in [Physics World](#) as a good example of a large collaboration publishing its research products, including its software.

Getting Started

You can start using the PyCBC library now in an interactive notebook!

- Establishing the confidence of GW150914, GW151226, LVT150914, GW170814
- Discovering GW170104, GW170608
- Sky location of GW170817
- Newly developed Bayesian parameter estimation code
- pycbc.org



Chris Biwer

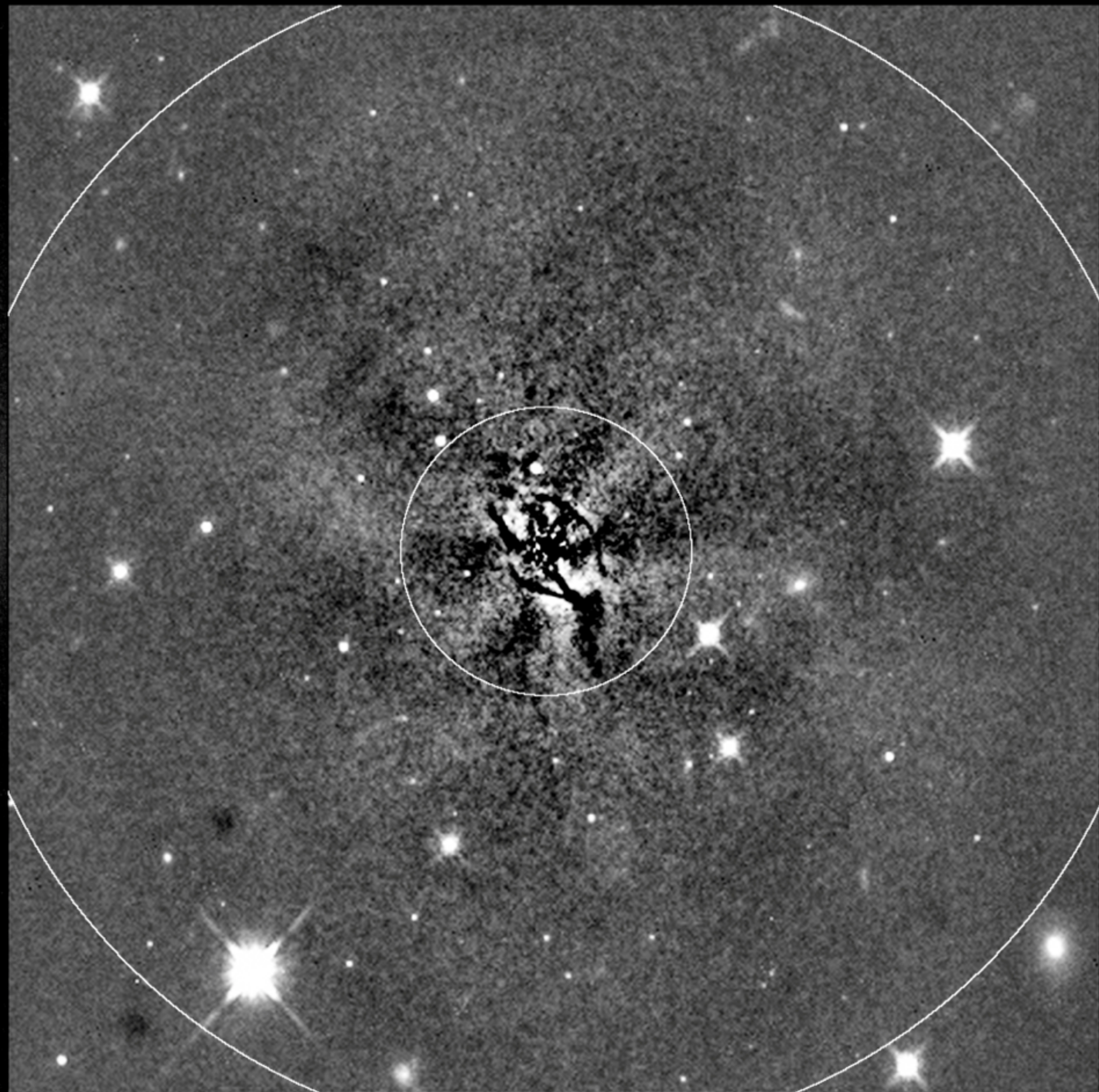
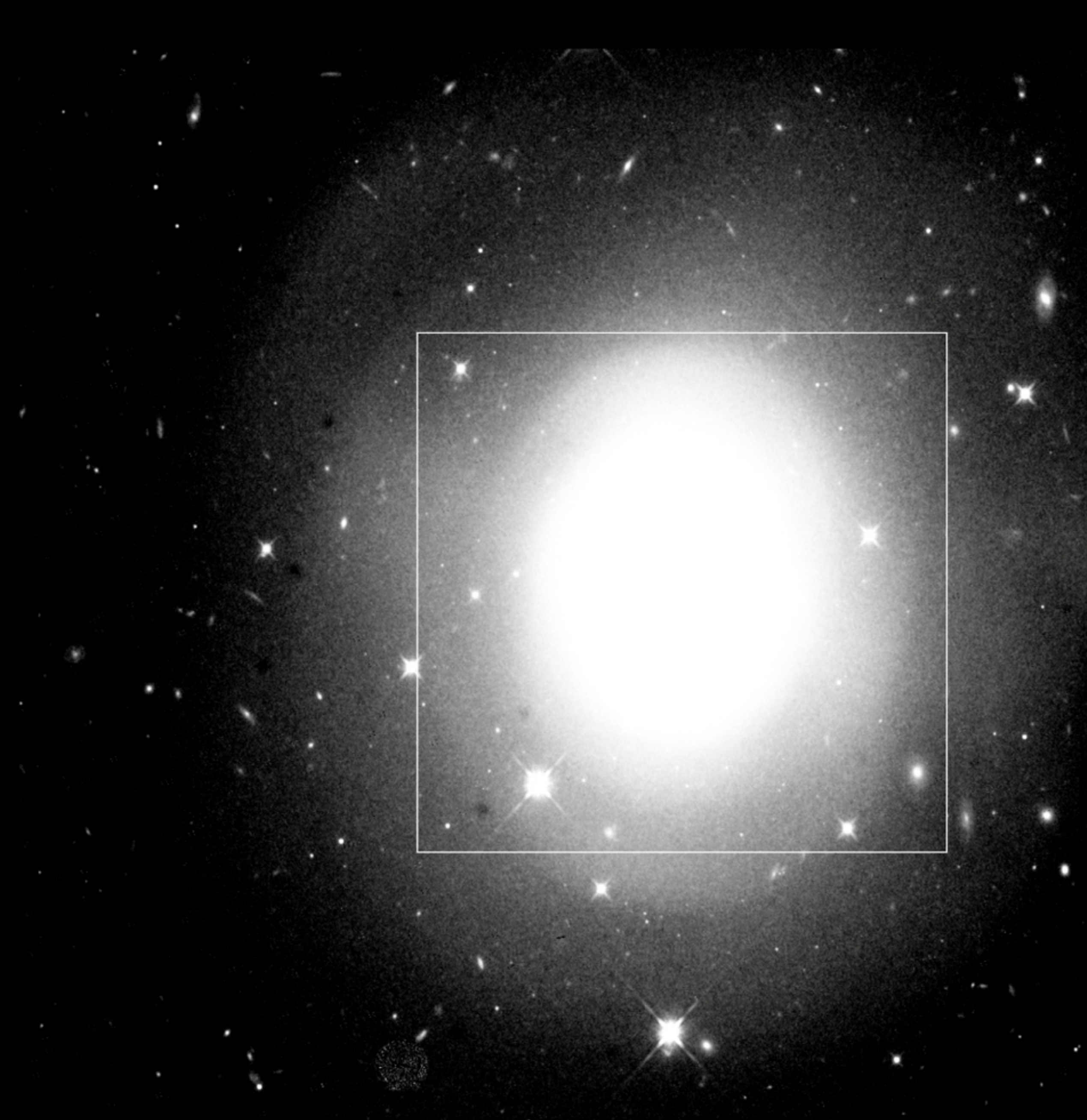


Collin Capano



Alex Nitz

Measuring the inclination angle
of GW170817



- Precise sky location measurement from Soares-Santos, et al.
- Prior on distance from Cantiello, et al. $d_L = 40.7 \pm 2.36$ Mpc
- LIGO and Virgo data from LOSC
- PyCBC parameter estimation from Biwer, et al.
- emcee Markov Chain Monte Carlo sampler from Forman, et al.

$\mathcal{M}^{det} = 1.1975^{+0.0001}_{-0.0001}$
 $1.1975^{+0.0001}_{-0.0001}$
 $1.1975^{+0.0001}_{-0.0001}$

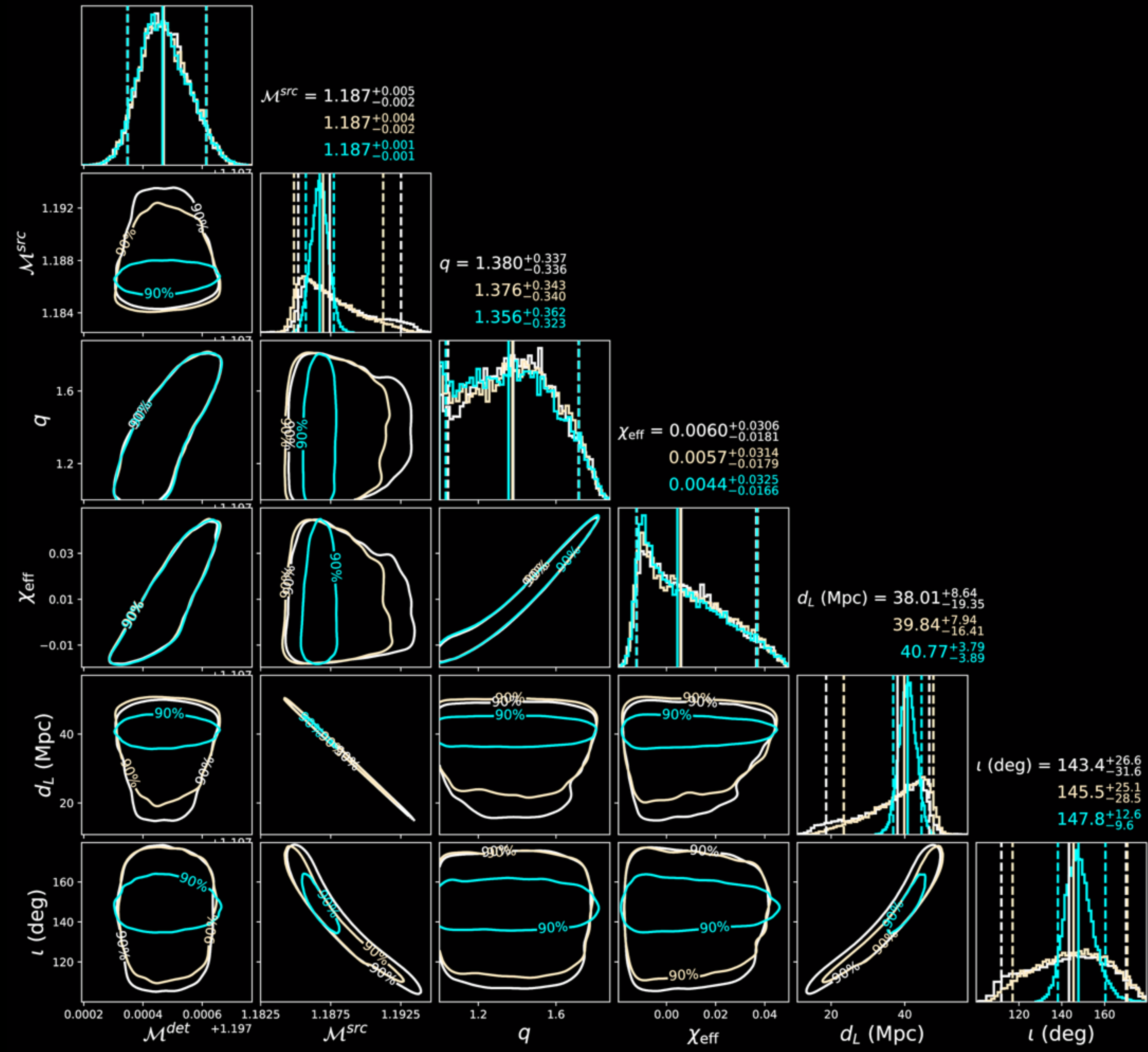
$\mathcal{M}^{src} = 1.187^{+0.005}_{-0.002}$
 $1.187^{+0.004}_{-0.002}$
 $1.187^{+0.001}_{-0.001}$

$q = 1.380^{+0.337}_{-0.336}$
 $1.376^{+0.343}_{-0.340}$
 $1.356^{+0.362}_{-0.323}$

$\chi_{eff} = 0.0060^{+0.0306}_{-0.0181}$
 $0.0057^{+0.0314}_{-0.0179}$
 $0.0044^{+0.0325}_{-0.0166}$

d_L (Mpc) = $38.01^{+8.64}_{-19.35}$
 $39.84^{+7.94}_{-16.41}$
 $40.77^{+3.79}_{-3.89}$

ι (deg) = $143.4^{+26.6}_{-31.6}$
 $145.5^{+25.1}_{-28.5}$
 $147.8^{+12.6}_{-9.6}$

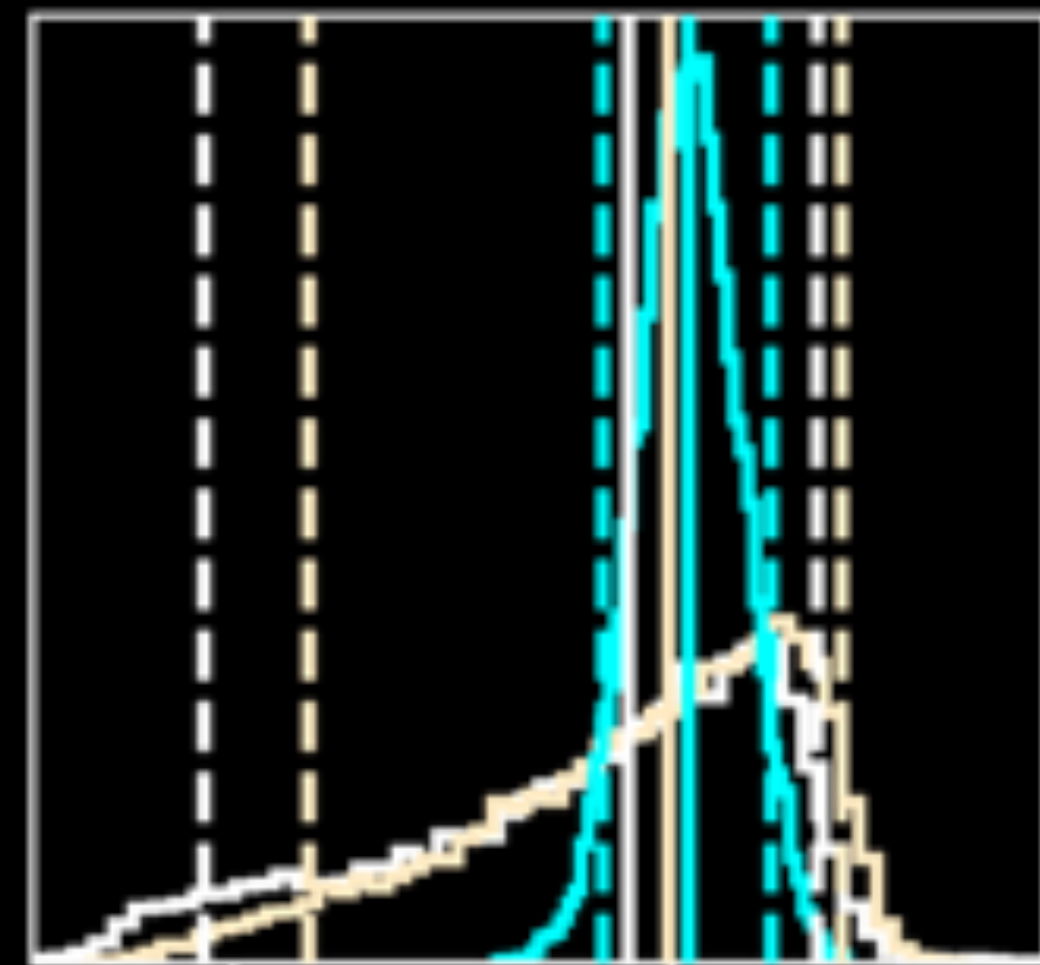


Daniel Finstad

$$d_L \text{ (Mpc)} = 38.01^{+8.64}_{-19.35}$$

$$39.84^{+7.94}_{-16.41}$$

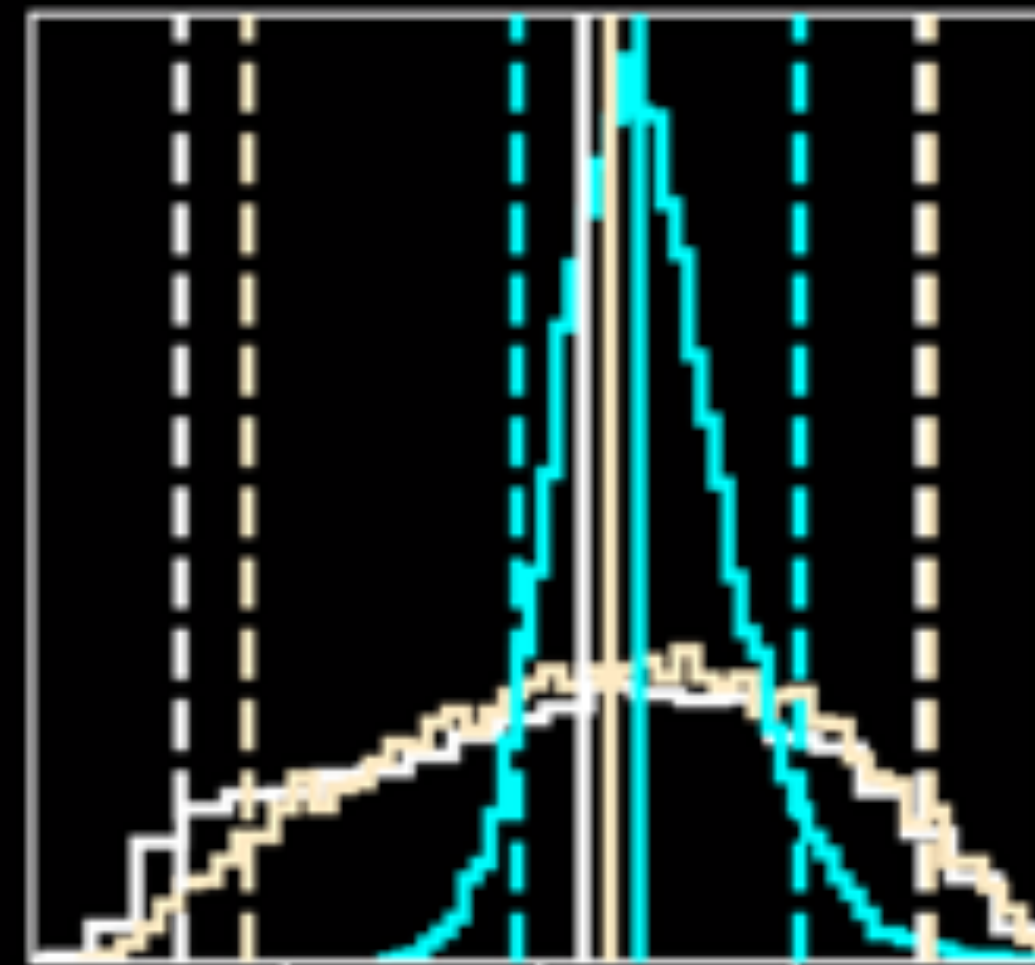
$$40.77^{+3.79}_{-3.89}$$



$$l \text{ (deg)} = 143.4^{+26.6}_{-31.6}$$

$$145.5^{+25.1}_{-28.5}$$

$$147.8^{+12.6}_{-9.6}$$

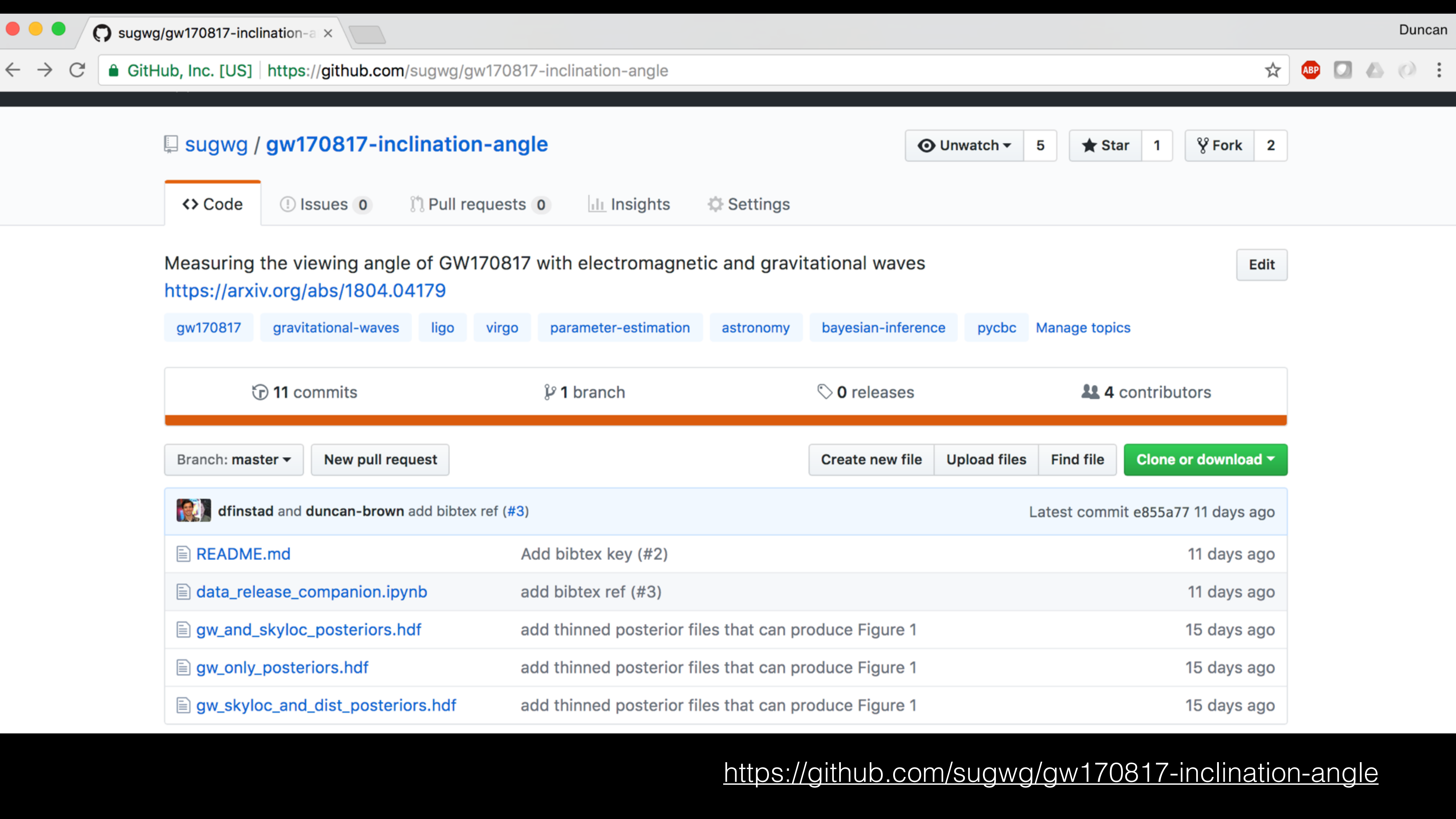


20 40 d_L (Mpc)

120 140 160 l (deg)

Viewing angle is $32^{+10}_{-13} \pm 1.7$ deg

Lower limit of ≥ 13 deg
robust to choice of prior



sugwg / gw170817-inclination-angle

Unwatch 5

Star 1

Fork 2

Code

Issues 0

Pull requests 0

Insights

Settings

Measuring the viewing angle of GW170817 with electromagnetic and gravitational waves

Edit

<https://arxiv.org/abs/1804.04179>

gw170817

gravitational-waves

ligo

virgo

parameter-estimation

astronomy

bayesian-inference

pycbc

Manage topics

11 commits

1 branch

0 releases

4 contributors

Branch: master

New pull request

Create new file

Upload files

Find file

Clone or download



dfinstad and duncan-brown add bibtex ref (#3)

Latest commit e855a77 11 days ago



README.md

Add bibtex key (#2)

11 days ago



data_release_companion.ipynb

add bibtex ref (#3)

11 days ago



gw_and_skyloc_posteriors.hdf

add thinned posterior files that can produce Figure 1

15 days ago



gw_only_posteriors.hdf

add thinned posterior files that can produce Figure 1

15 days ago



gw_skyloc_and_dist_posteriors.hdf

add thinned posterior files that can produce Figure 1

15 days ago

Using the posterior probability data

The posterior data is stored as flattened arrays in the `samples` group of the hdf files in this repository. The parameter names for each of the arrays that exist in a file can be accessed through a `variable_args` attribute of the file:

```
In [2]: fp = h5py.File("gw_only_posteriors.hdf", "r")
print fp.attrs['variable_args']
fp.close()
```

```
['tc' 'ra' 'dec' 'mass1' 'mass2' 'coa_phase' 'inclination' 'polarization'
 'distance' 'spin1z' 'spin2z']
```

Each of these parameter names can then be used to access that parameter's data in the `samples` group of the file. For example, the inclination angle posterior samples (in radians) from our run using the GW signal as well as EM sky location and Gaussian distance prior can be accessed this way:

```
In [3]: fp = h5py.File("gw_skyloc_and_dist_posteriors.hdf", "r")
inc_samples = fp['samples/inclination'][:]
fp.close()
print inc_samples
```

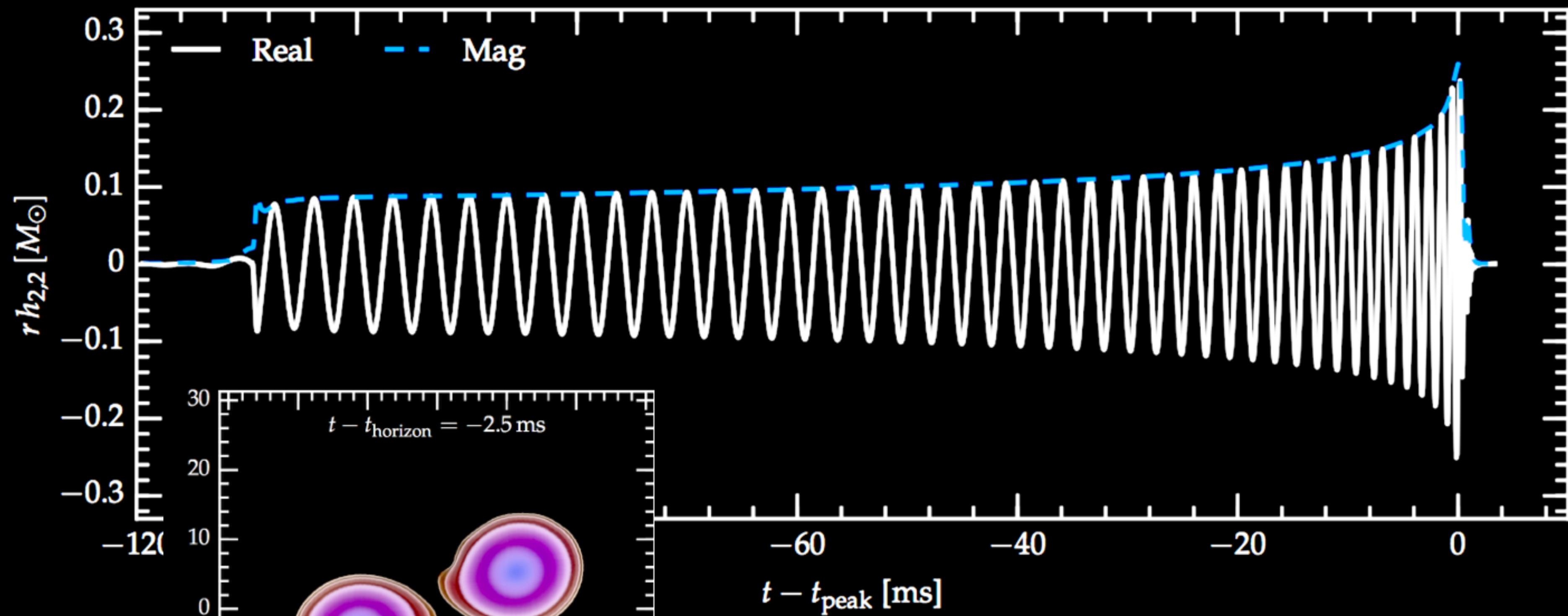
```
[2.74223087 2.58393159 2.49176962 ... 2.53901635 2.61125559 2.45446383]
```

By default, the PyCBC software used to create these files stores the mass parameters only as `mass1` and `mass2`, but other mass parameters like chirp mass and mass ratio can be derived from these. For example, using the PyCBC toolkit:

```
In [4]: from pycbc import conversions

fp = h5py.File("gw_and_skyloc_posteriors.hdf", "r")
mass1 = fp['samples/mass1'][:]
mass2 = fp['samples/mass2'][:]
fp.close()
```

Constraining the nuclear
equation of state with GW170817



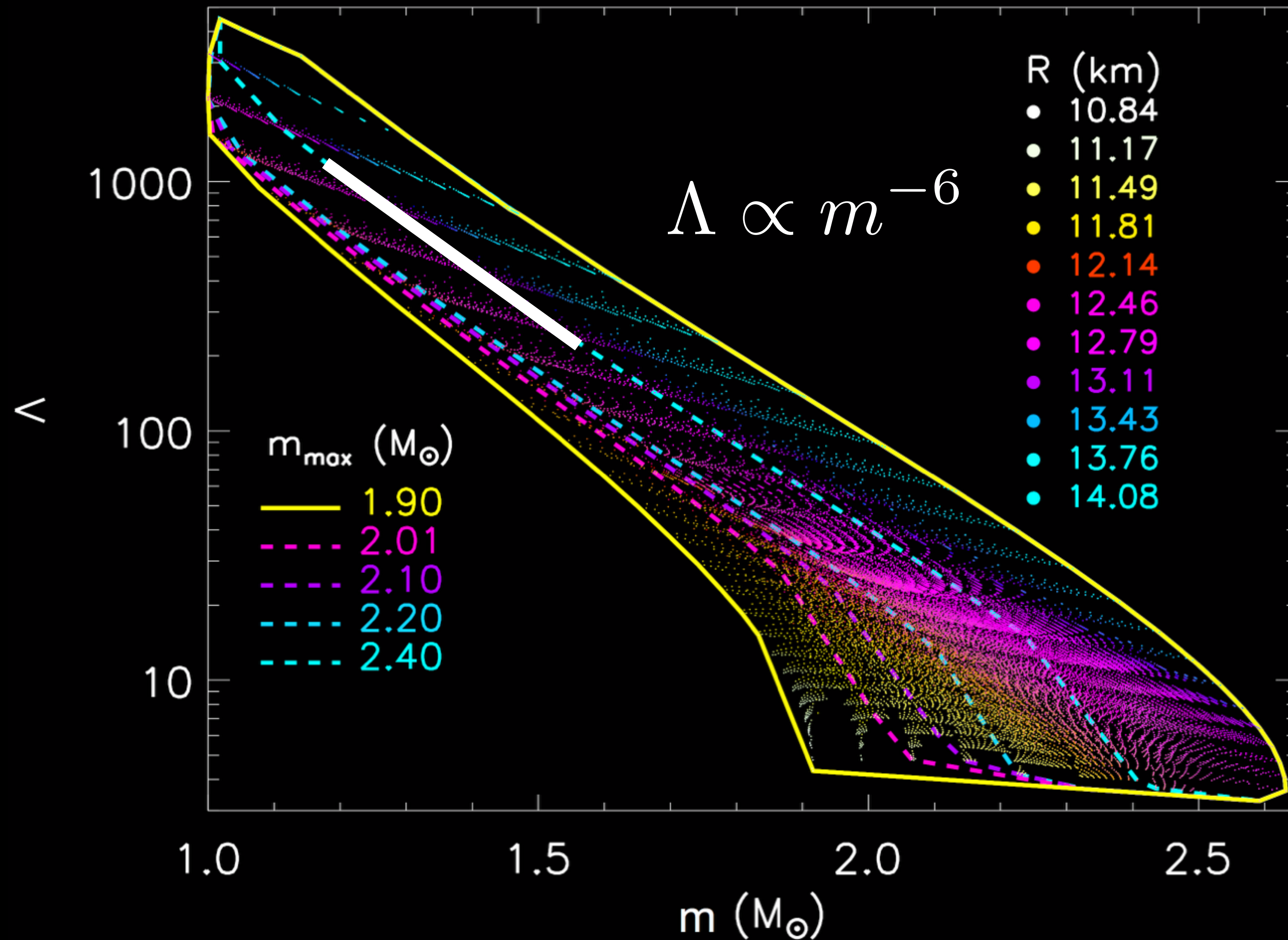
$$Q_{ij} = -\Lambda(\text{EOS}, m) m^5 \mathcal{E}_{ij}$$

Tidal effects enter the post-Newtonian gravitational-wave phase as

$$\tilde{\Lambda} = \frac{16}{13} \frac{(12q + 1)\Lambda_1 + (12 + q)q^4\Lambda_2}{(1 + q)^5}$$

$$\Lambda_{1,2} = \frac{2}{3} k_2 \left(\frac{R_{1,2} c^2}{G m_{1,2}} \right)^5$$

$$q = m_2/m_1 \leq 1$$



Results of TOV
 integrations for
 physically realistic
 polytopes

$$\Lambda = \alpha \left(\frac{Gm}{Rc^2} \right)^{-6}$$

- For nearly every specific EOS in the mass range relevant to GW170816 [1.1, 1.6] solar masses, range of radii is very small

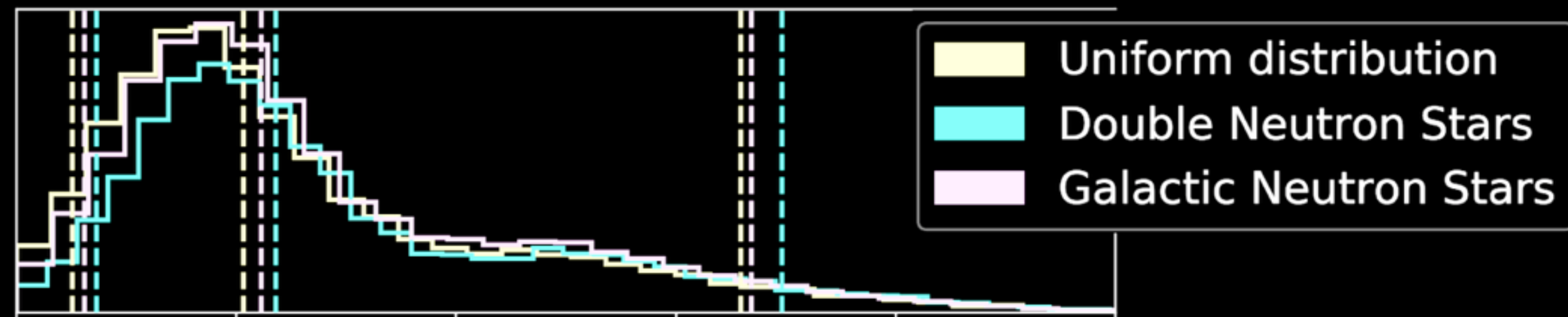
$$\langle \Delta R \rangle \equiv \langle R_{1.6} - R_{1.1} \rangle = -0.070 \text{ km}$$

$$\sqrt{\langle \Delta R \rangle^2} = 0.11 \text{ km}$$

- Common EOS constraint $\hat{R} \equiv R_1 \approx R_2$ $\Lambda_1 = q^6 \Lambda_2$

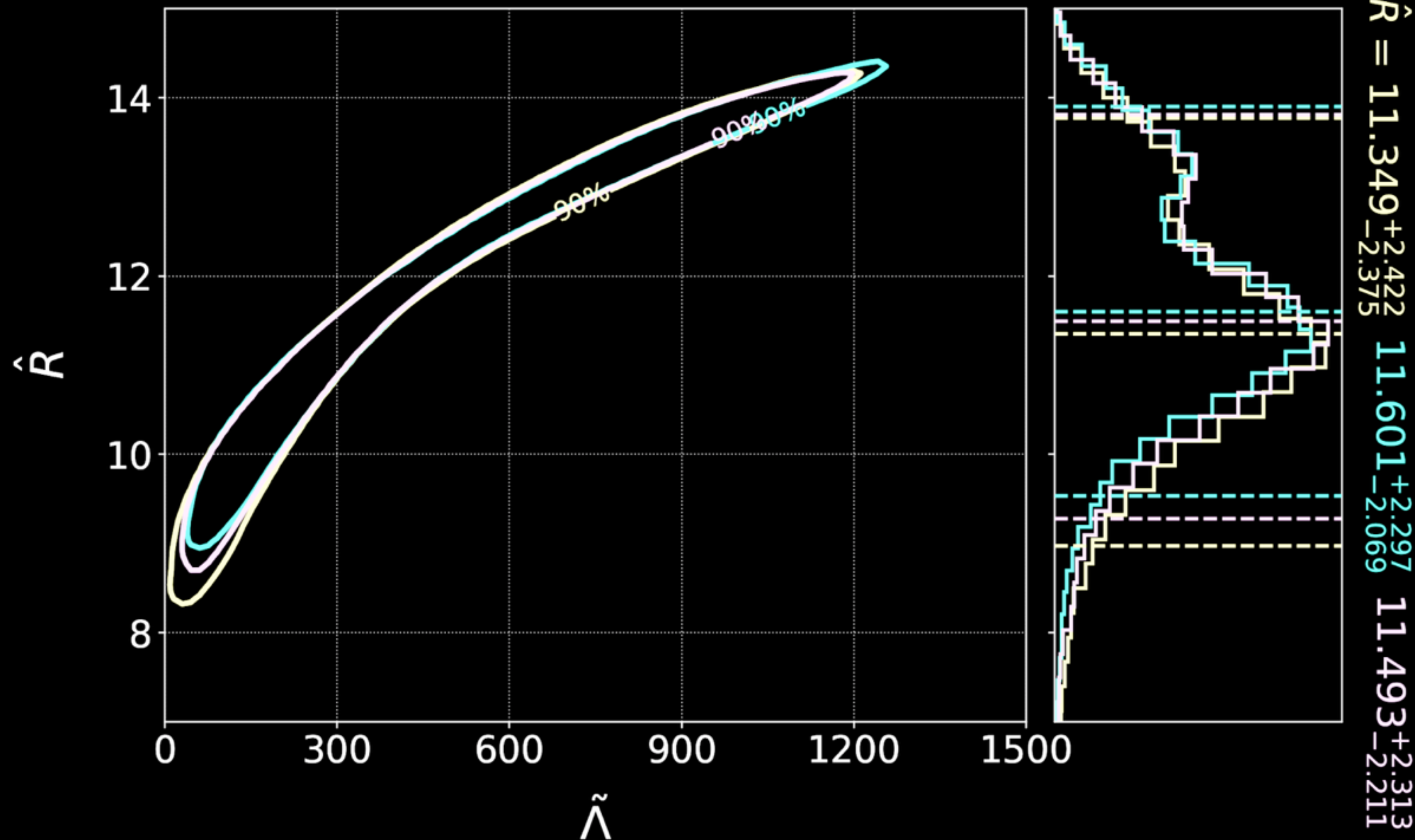
- Explore three different mass priors:
 - Uniform [1,2] solar masses
 - Double neutron star masses from radio observations
 - All neutron star masses from radio observations
- Calculate constrained EOS and unconstrained evidences
- For all three cases, Bayesian model selection strongly favors the common EOS constraint

$$\tilde{\Lambda} = 309.89_{-234.10}^{+678.93} \quad 353.53_{-244.76}^{+691.16} \quad 334.19_{-241.39}^{+669.28}$$

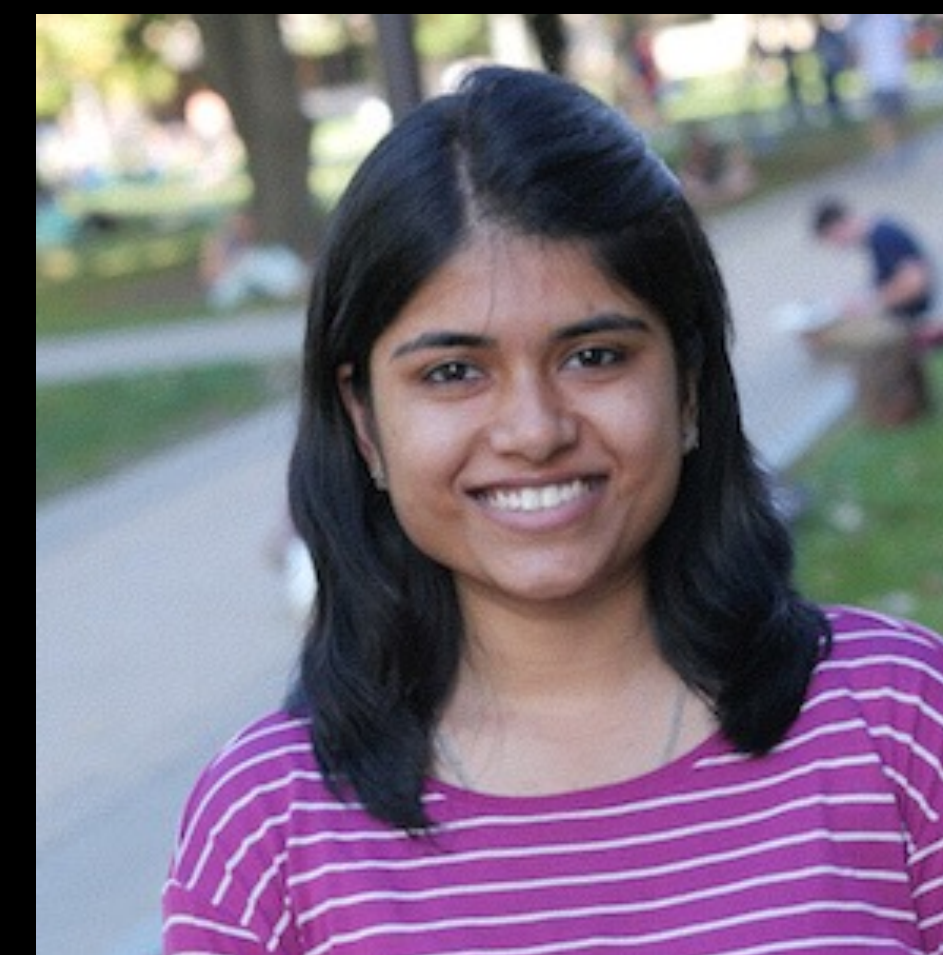


Compare to Abbott, et al.

$$\tilde{\Lambda}_{90\%} \leq 800$$



$$\tilde{\Lambda}_{90\%} \leq 825, 852, 888$$



Soumi De

$\mathcal{M}^{src} = 1.1868^{+0.0002}_{-0.0001}$
 $1.1868^{+0.0002}_{-0.0001}$
 $1.1868^{+0.0002}_{-0.0001}$

■ Uniform distribution
■ Double Neutron Stars
■ Galactic Neutron Stars

$q = 0.83961^{+0.14498}_{-0.21189}$
 $0.94126^{+0.05304}_{-0.10129}$
 $0.87937^{+0.10817}_{-0.17128}$

$\langle \hat{R} \rangle = 11.5 \text{ km}, \hat{R} < 14.1 \text{ km}, \hat{R} > 8.8 \text{ km}$

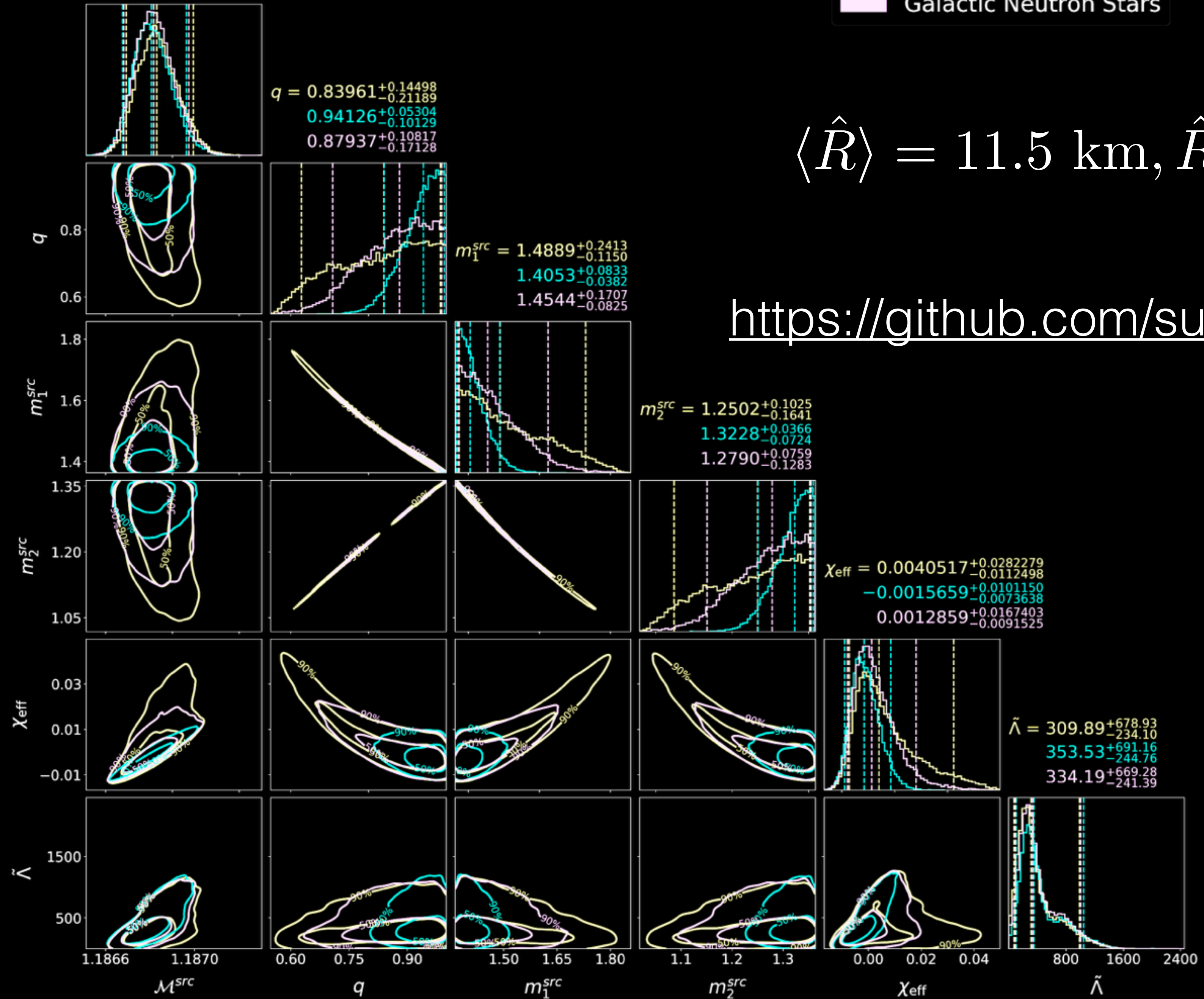
<https://github.com/sugwg/gw170817-common-eos>

$m_1^{src} = 1.4889^{+0.2413}_{-0.1150}$
 $1.4053^{+0.0833}_{-0.0382}$
 $1.4544^{+0.1707}_{-0.0825}$

$m_2^{src} = 1.2502^{+0.1025}_{-0.1641}$
 $1.3228^{+0.0366}_{-0.0724}$
 $1.2790^{+0.0759}_{-0.1283}$

$\chi_{eff} = 0.0040517^{+0.0282279}_{-0.0112498}$
 $-0.0015659^{+0.0101150}_{-0.0073638}$
 $0.0012859^{+0.0167403}_{-0.0091525}$

$\tilde{\Lambda} = 309.89^{+678.93}_{-234.10}$
 $353.53^{+691.16}_{-244.76}$
 $334.19^{+669.28}_{-241.39}$



28 commits 1 branch 0 releases 3 contributors

Branch: master ▾ New pull request Create new file Upload files Find file Clone or download ▾

soumide1102	Update bibtex key	Latest commit e02bf60 3 days ago
.gitattributes	add large hdf files	4 days ago
README.md	Update bibtex key	3 days ago
data_release_common_eos_companion...	Update bibtex key	3 days ago
dns_mass_prior_common_eos_posterio...	Add DNS common EOS posteriors file	5 days ago
dns_mass_prior_common_eos_posterio...	add large hdf files	4 days ago
dns_mass_prior_independent_lambdas...	add large hdf files	4 days ago
galactic_ns_mass_prior_common_eos...	Add galactic NSs common EOS posteriors file	5 days ago
galactic_ns_mass_prior_common_eos...	add large hdf files	4 days ago
galactic_ns_mass_prior_independent_l...	add large hdf files	4 days ago
independent_lambda_uniform_mass_p...	Add independent lambda unifrom mass posteriors file	5 days ago
uniform_mass_prior_common_eos_pos...	Add uniform mass common EOS posteriors file	5 days ago
uniform_mass_prior_common_eos_pos...	add large hdf files	4 days ago
uniform_mass_prior_independent_lam...	add large hdf files	4 days ago
uniform_mass_prior_lambda_s_lesstha...	add large hdf files	4 days ago

- New constraints in the inclination angle of GW170817

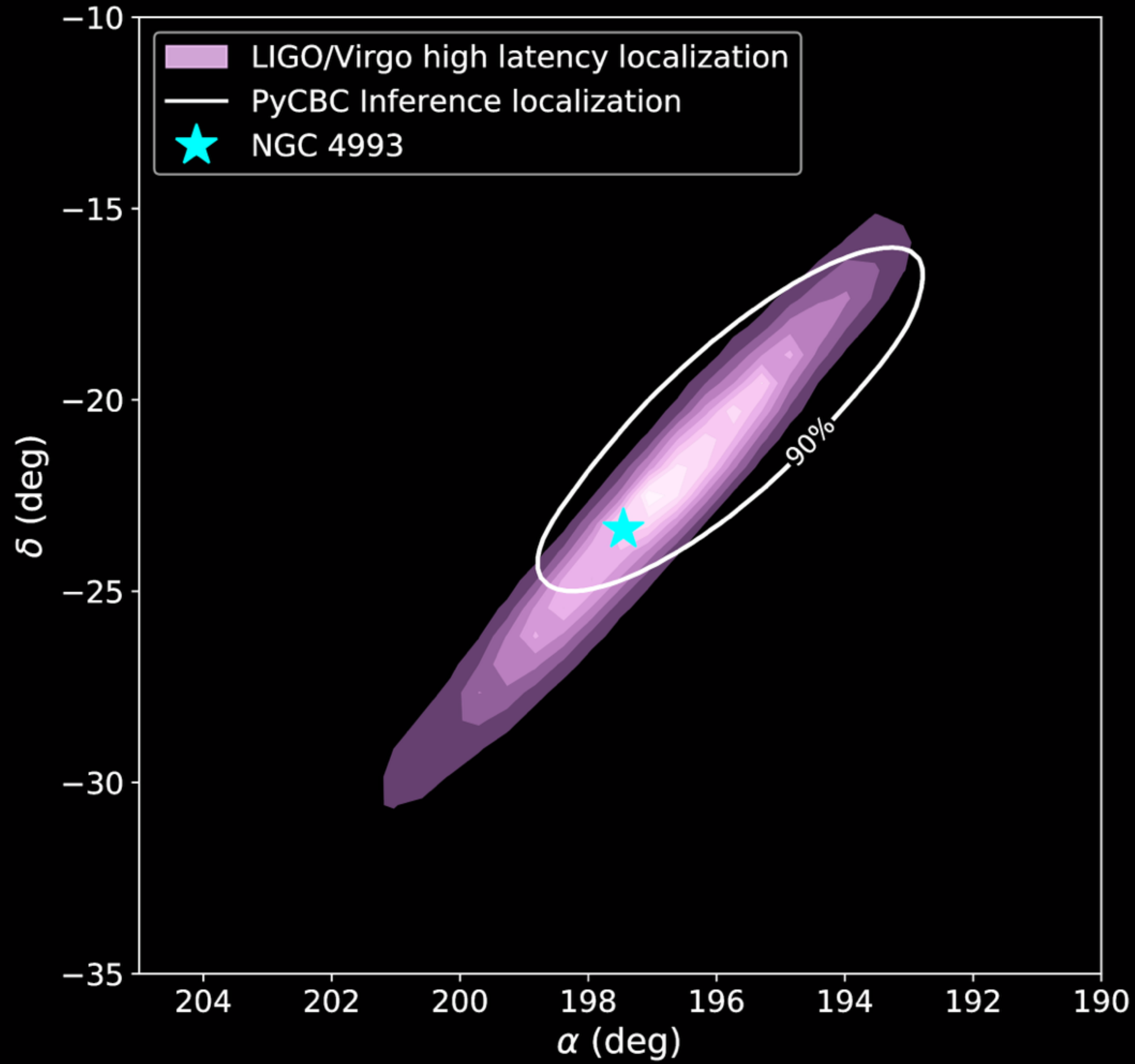
$$\text{Viewing angle} = 32_{-13}^{+10} \pm 1.7 \text{ deg}$$

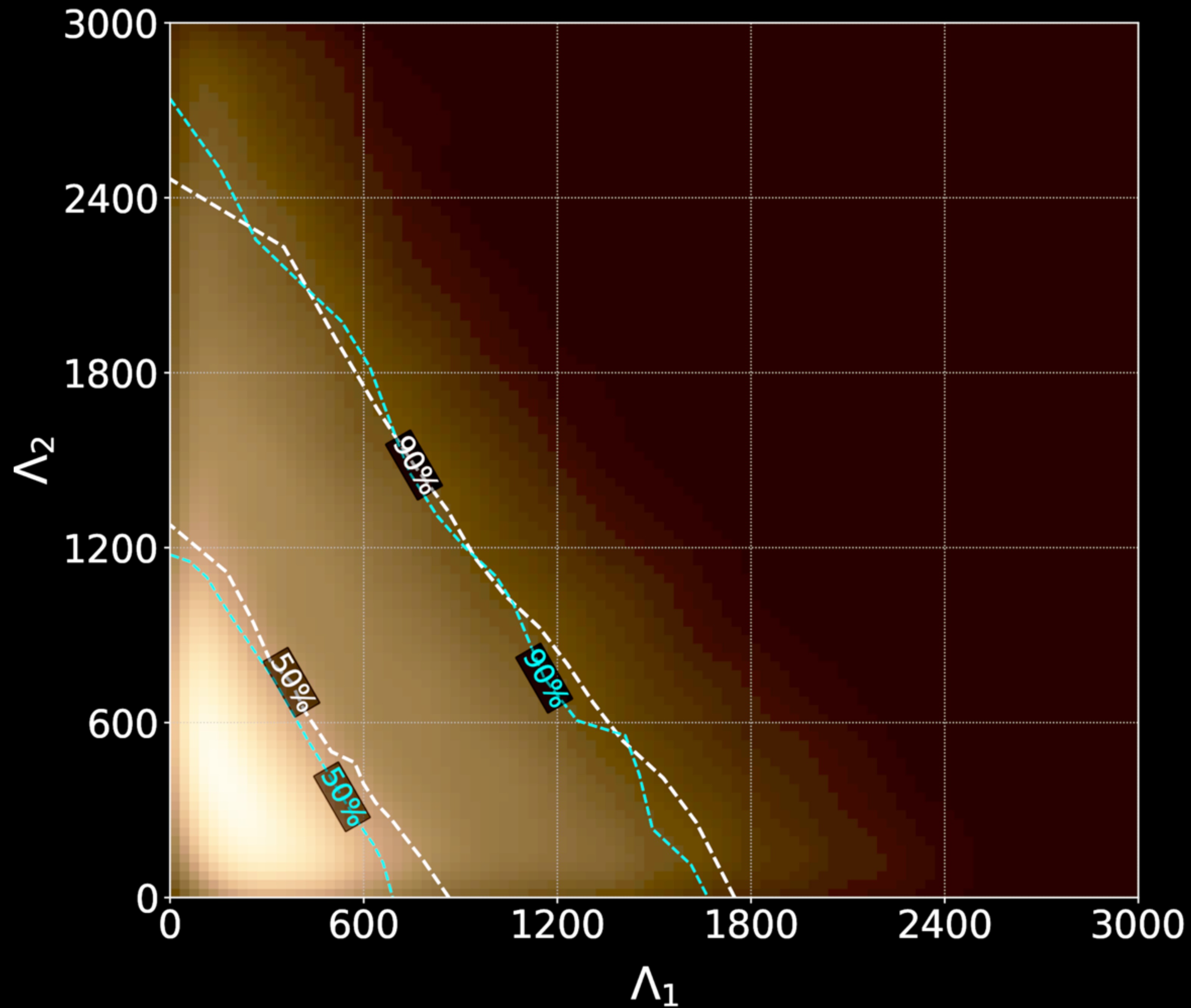
- New constraints on the neutron star radius using the common EOS constraint

$$\langle \hat{R} \rangle = 11.5 \text{ km}, \hat{R} < 14.1 \text{ km}, \hat{R} > 8.8 \text{ km}$$

- Open data, open code, and open analysis allow new, reproducible science
- The community should push for more openness in gravitational-wave astronomy to get the best science for everyone and for the long-term health of the field

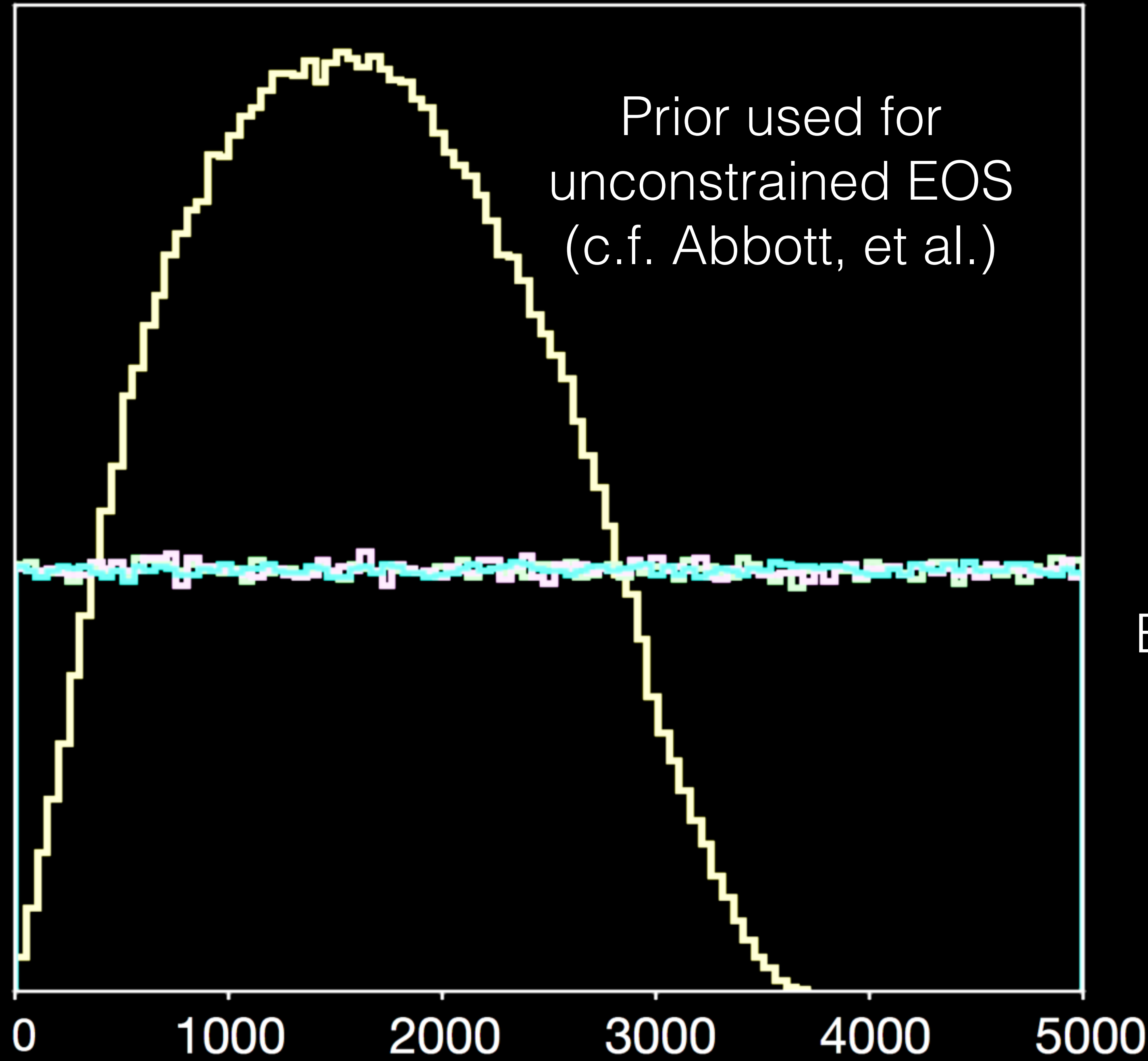
Extra Slides





Compare to
Abbott, et al. (2017)

Probability density function



Prior used for
unconstrained EOS
(c.f. Abbott, et al.)

Priors from
common
EOS constraint

0 1000 2000 3000 4000 5000

$\tilde{\Lambda}$