GW170817: STRINGENT CONSTRAINTS ON NEUTRON STAR RADII FROM MULTIMESSENGER OBSERVATIONS

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HANNOVER, GERMANY

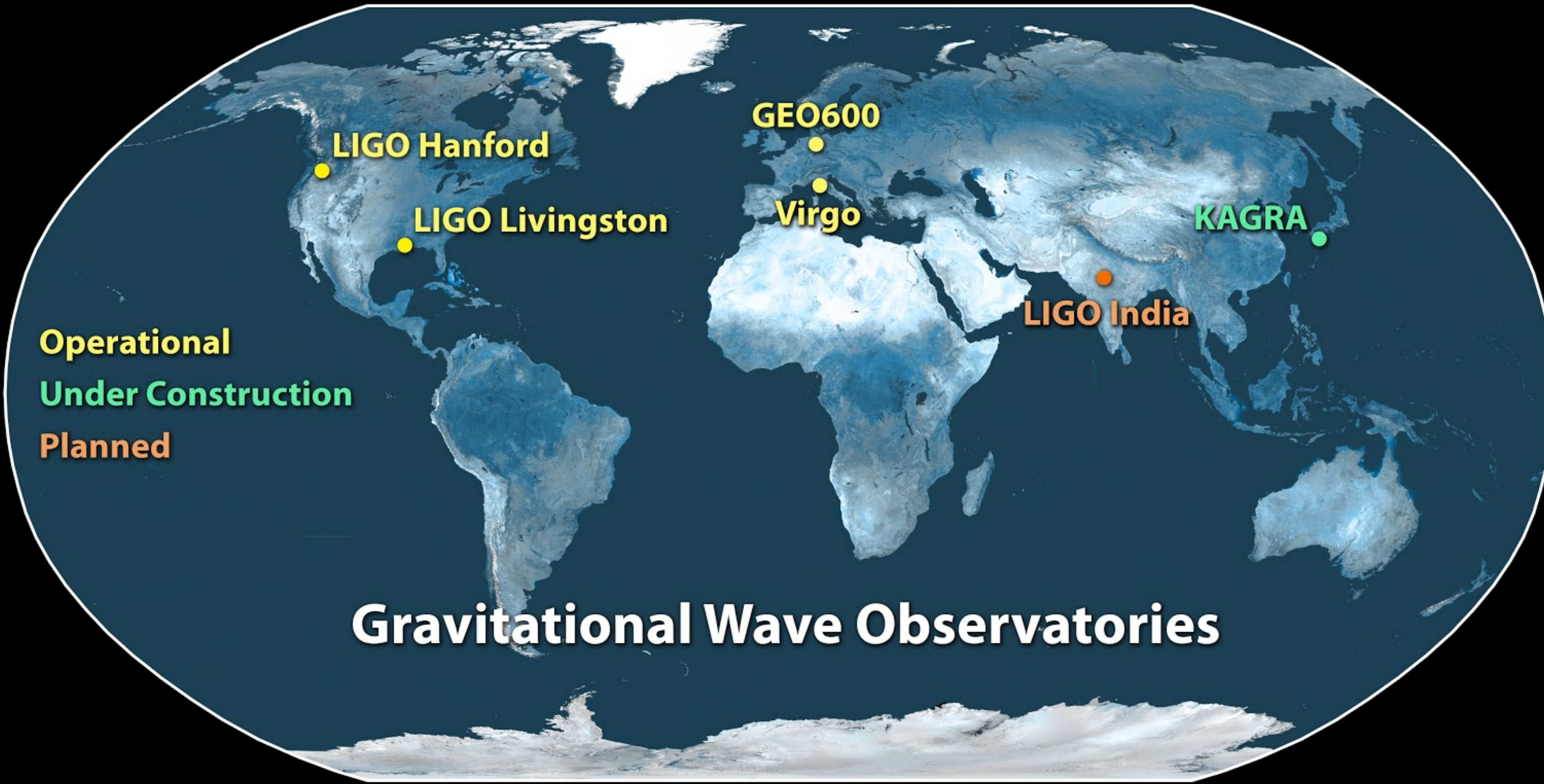
OUTLINE

I. OBSERVATION OF GW170817

II. CONSTRAINING THE EQUATION OF STATE FROM GW OBSERVATIONS

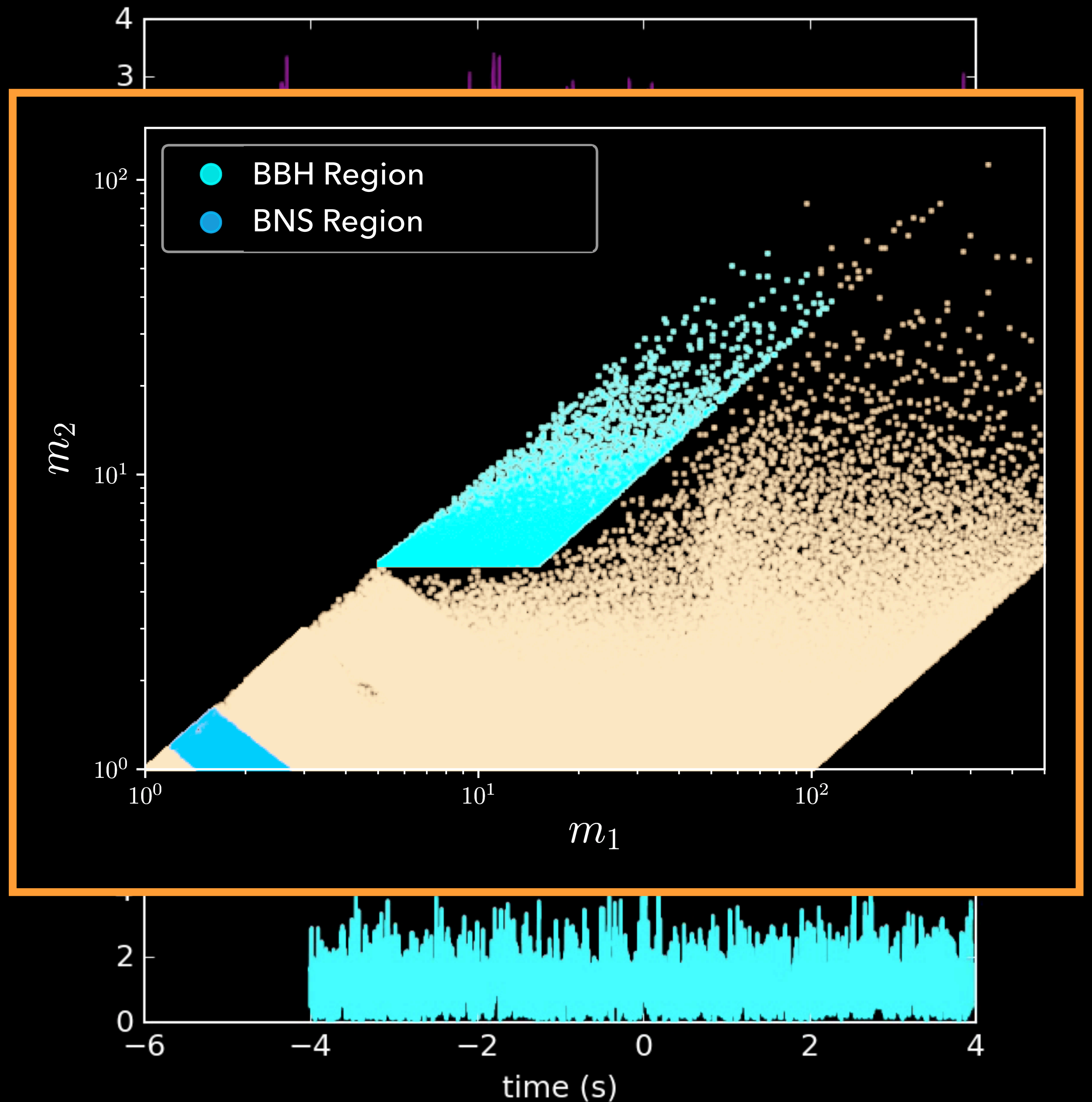
III. CONSTRAINING THE EOS WITH GW+EM+NUCLEAR THEORY

I. OBSERVATION



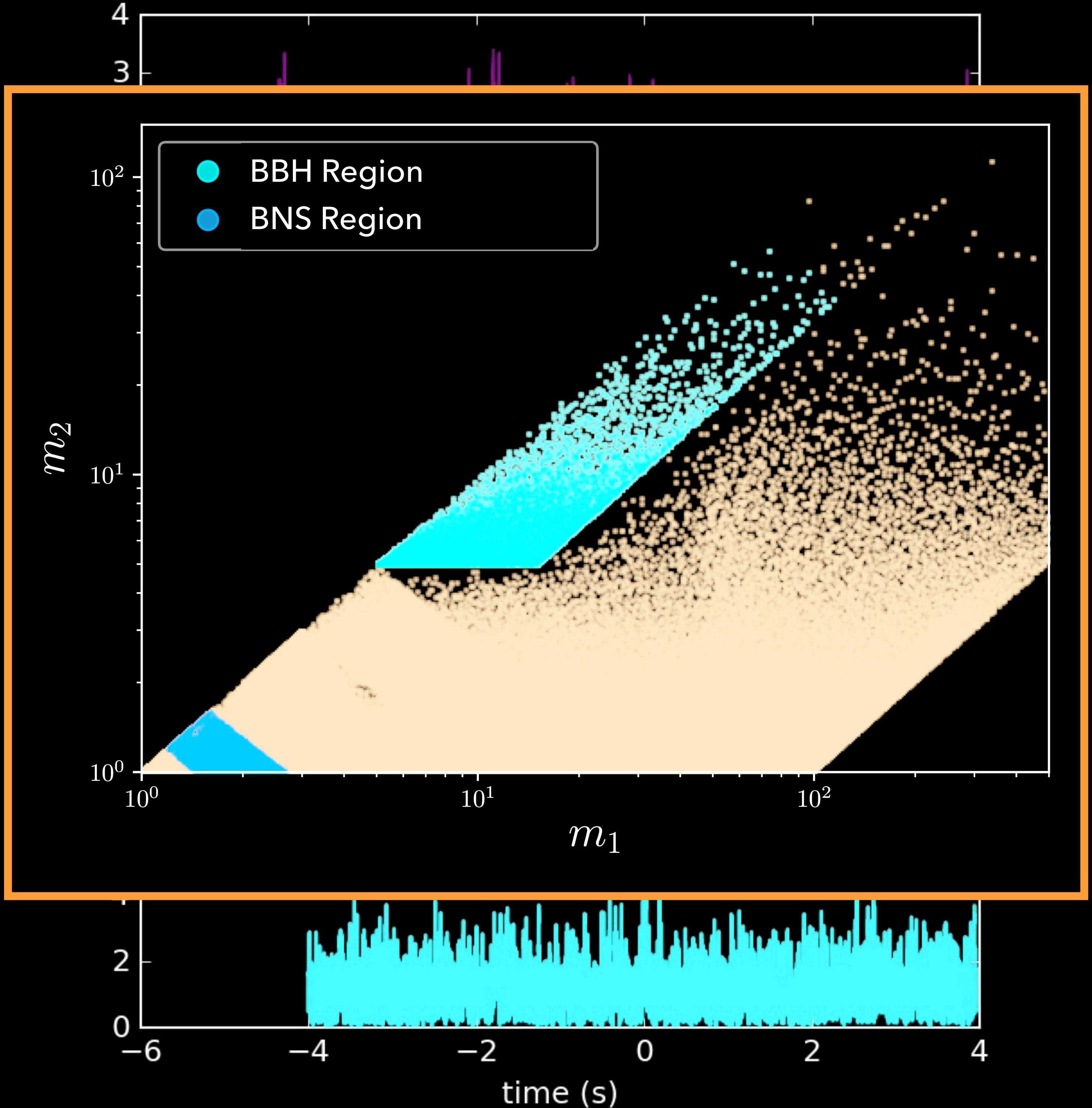
Caltech/MIT/LIGO Lab

GW CANDIDATE IDENTIFICATION



GW CANDIDATE IDENTIFICATION

- A bank of template waveforms is filtered through the data in each detector



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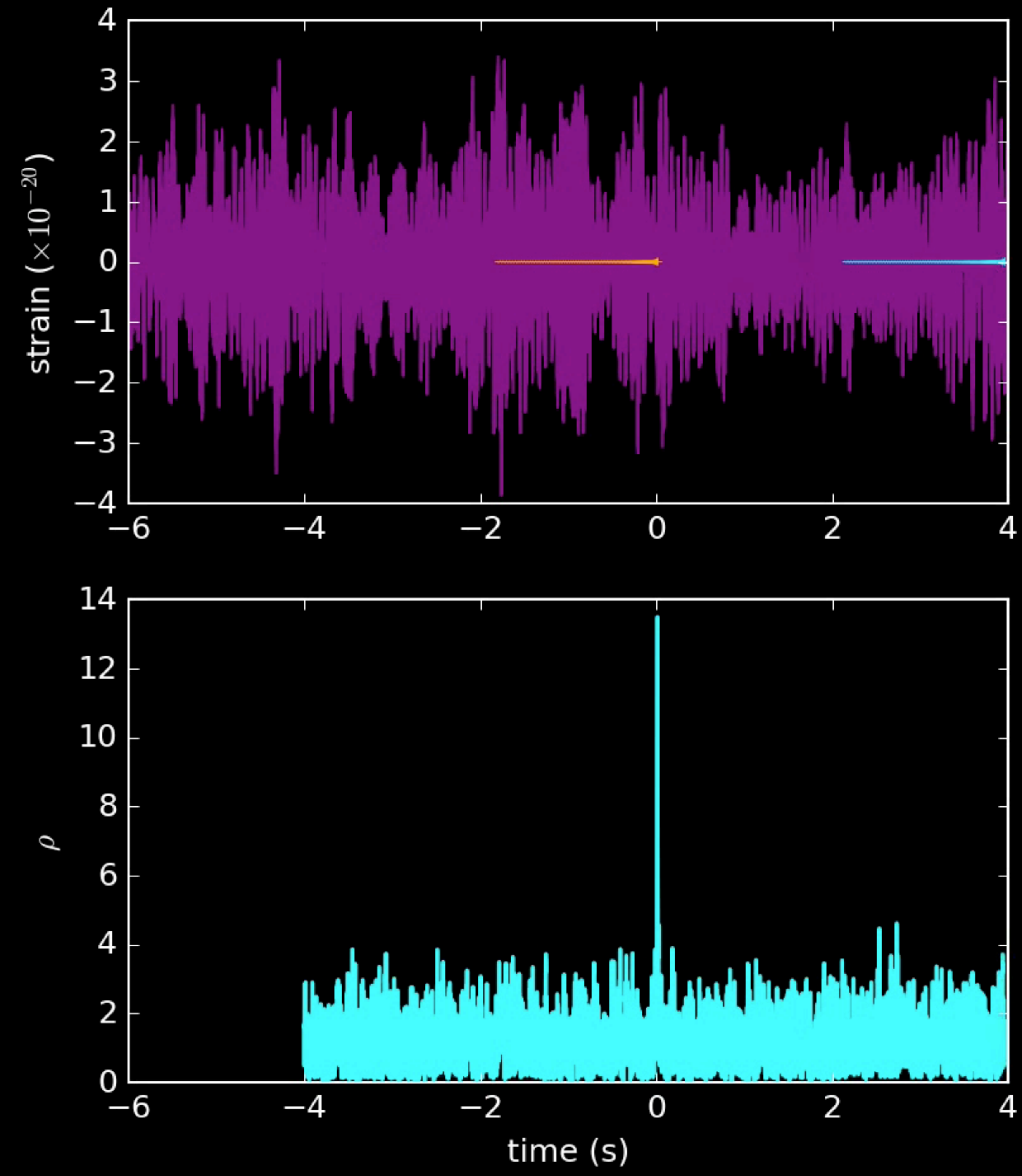

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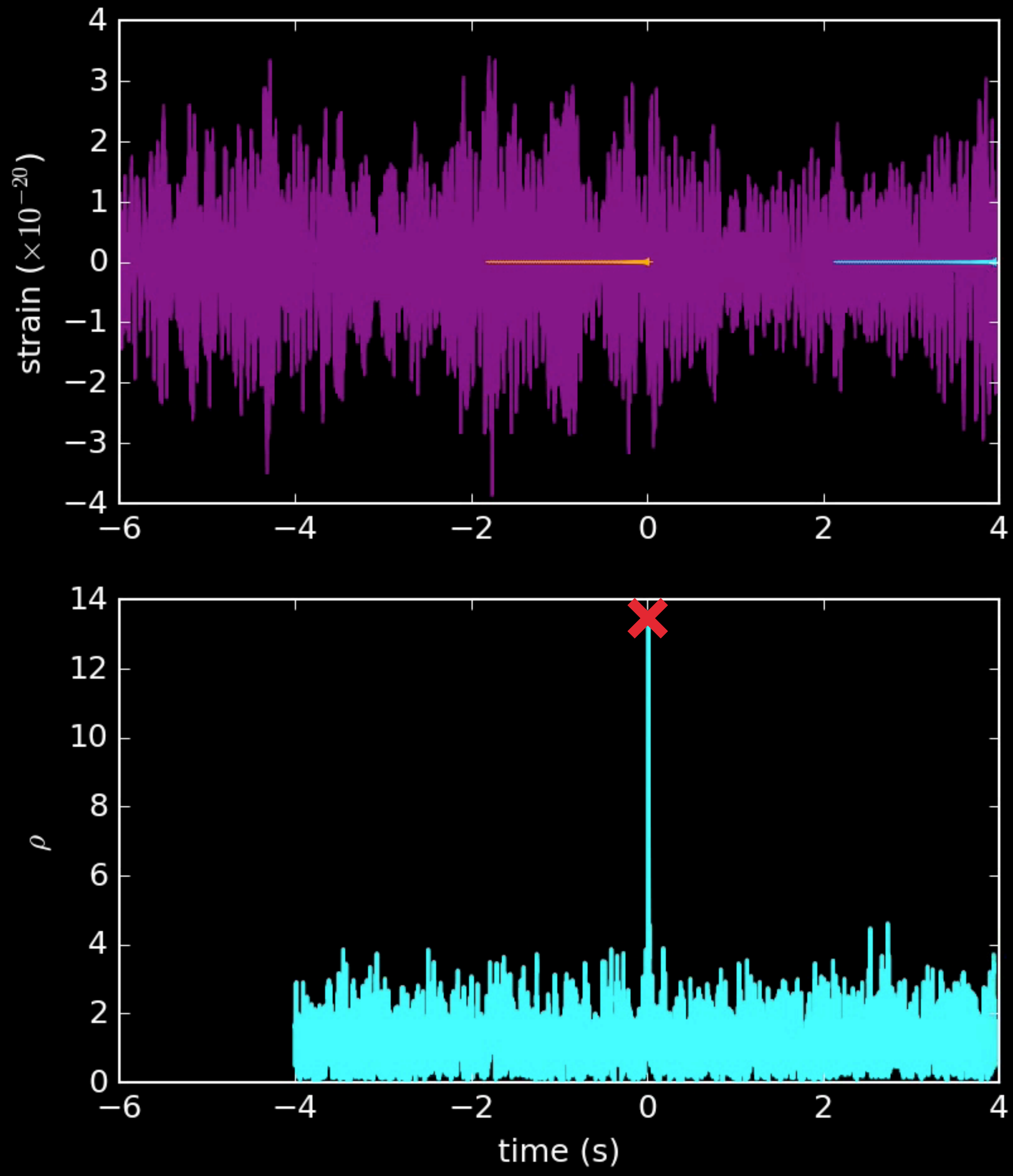
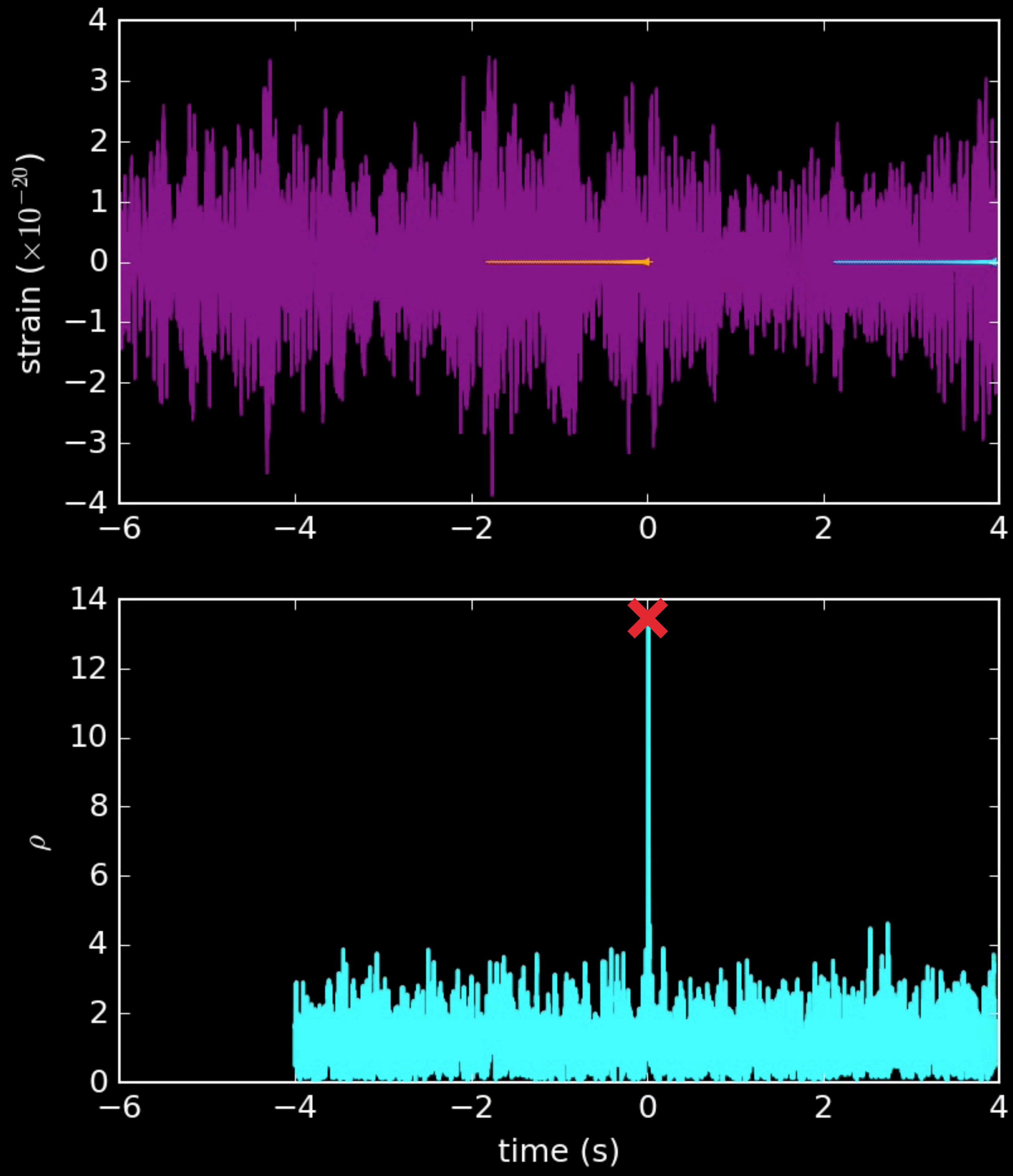
- Triggers are points where SNR is maximized



GW CANDIDATE IDENTIFICATION

- A bank of template waveforms is filtered through the data in each detector
- Triggers are points where SNR is maximized
- Look for coincidence between detectors
- Use relative time, phase, amplitude of triggers to estimate a sky location



17 AUGUST 2017

TIMELINE*

* constructed from Abbott et al., ApJL 848 L12 (2017)
& discussions with A. Nitz

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Basic Info

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

Coinc Tables

End Time (GPS)	1187008882.4457 s
Total Mass	2.7693 $M_\odot$
Chirp Mass	1.1977 $M_\odot$
SNR	14.4529
False Alarm Probability	5.089e-05
Log Likelihood Ratio	32.3969

Single Inspiral Tables

IFO	H1
Channel	GDS-CALIB_STRAIN
End Time (GPS)	1187008882.445709865 s
Template Duration	360.338000866 s
Effective Distance	85.493584 Mpc
COA Phase	-2.0127285 rad
Mass 1	1.5270051 $M_\odot$
Mass 2	1.2422962 $M_\odot$
η	0.24735758
F Final	1024.0 Hz
SNR	14.452881
χ^2	1.8652176
χ^2 DOF	1
spin1z	-0.015901944
spin2z	-0.035747342

Neighbors [-5,+5]

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

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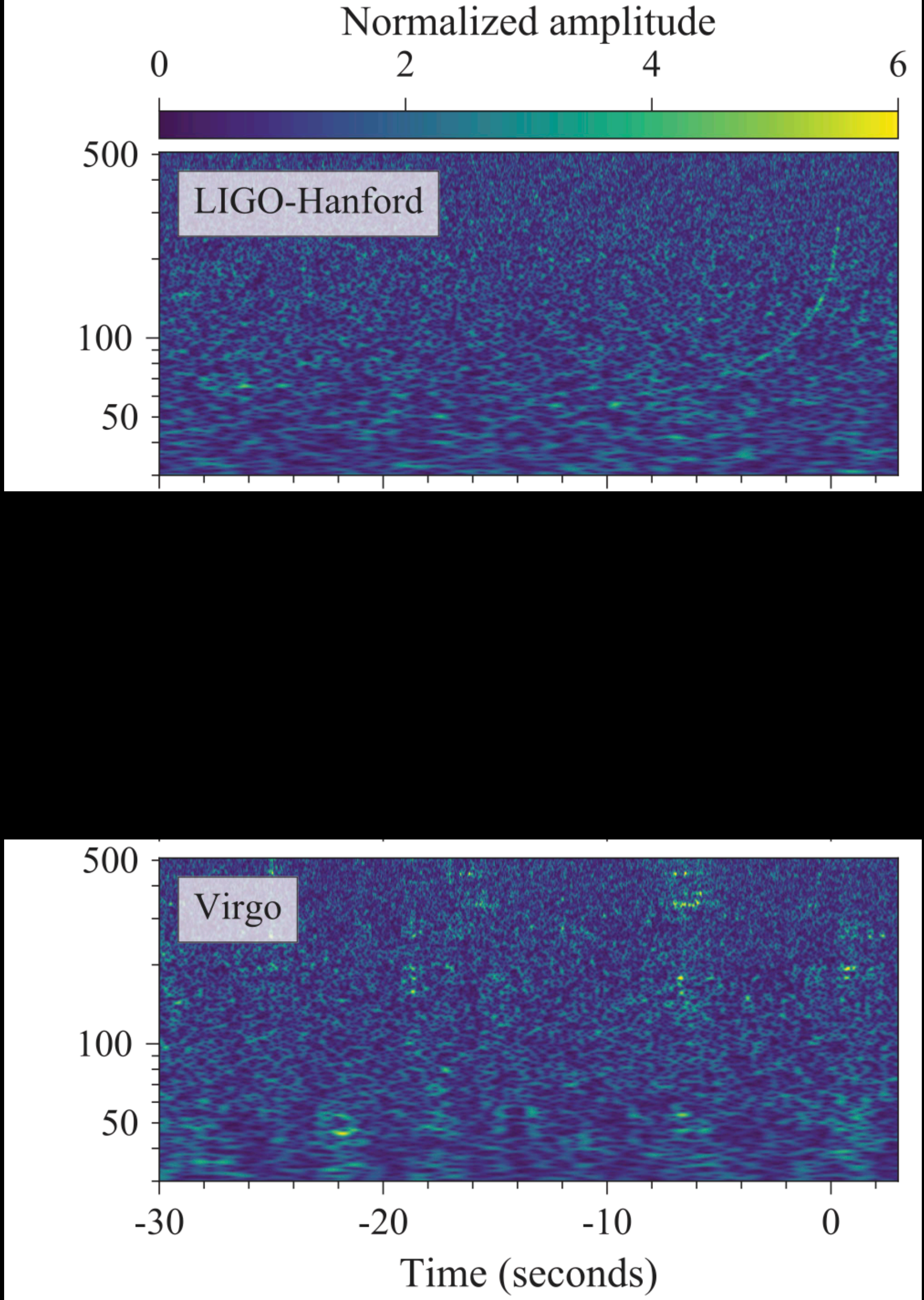

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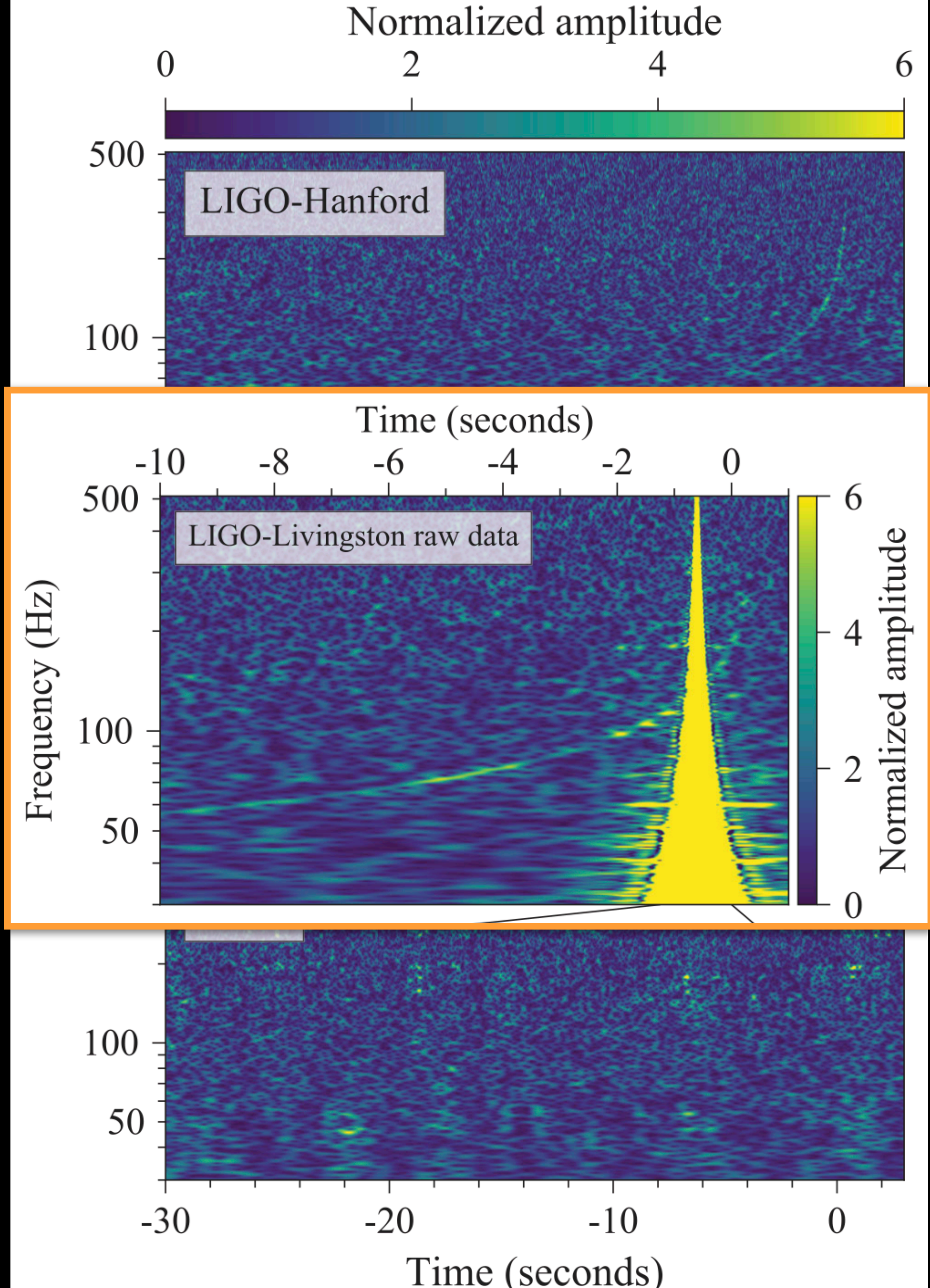

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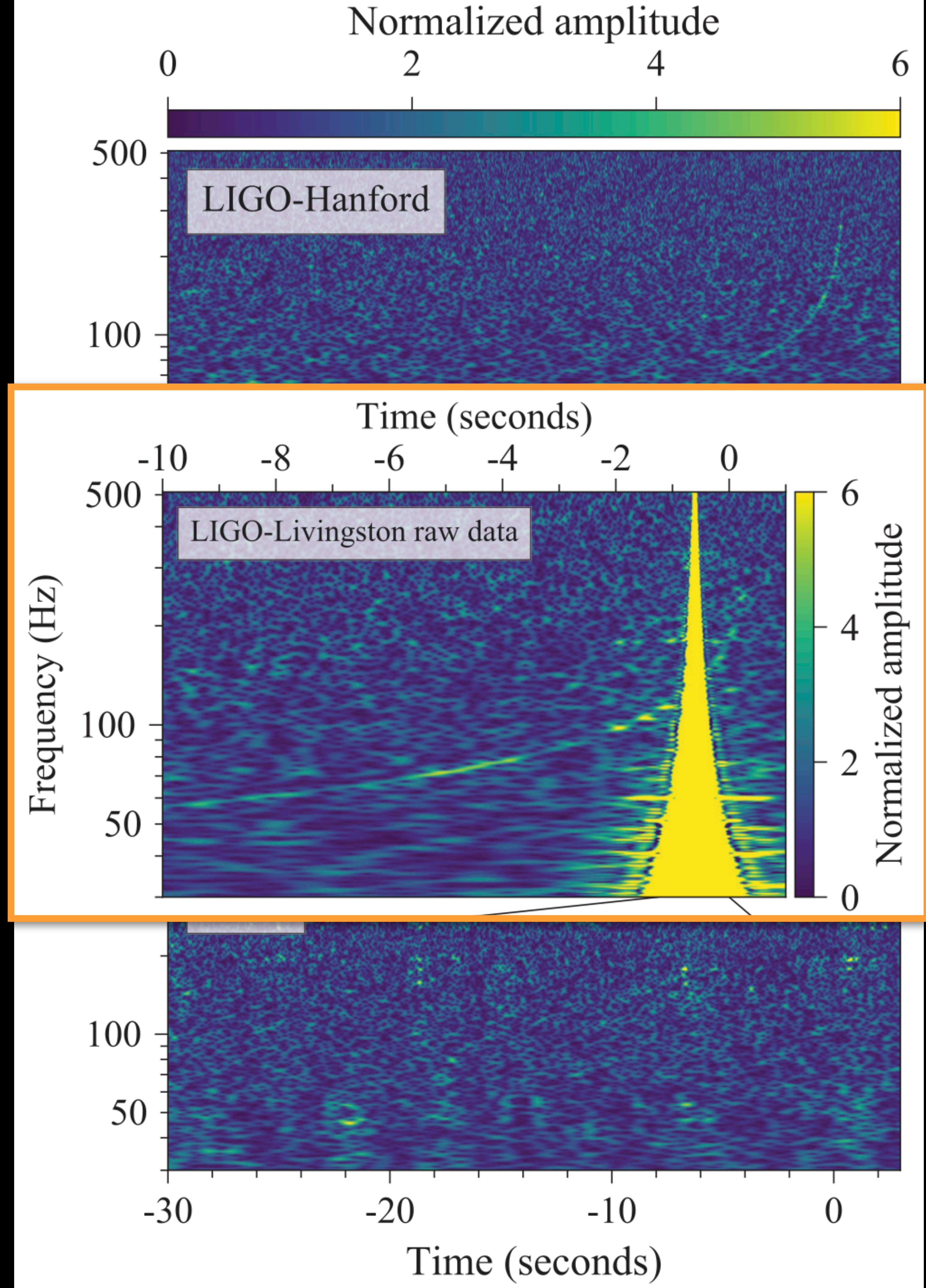

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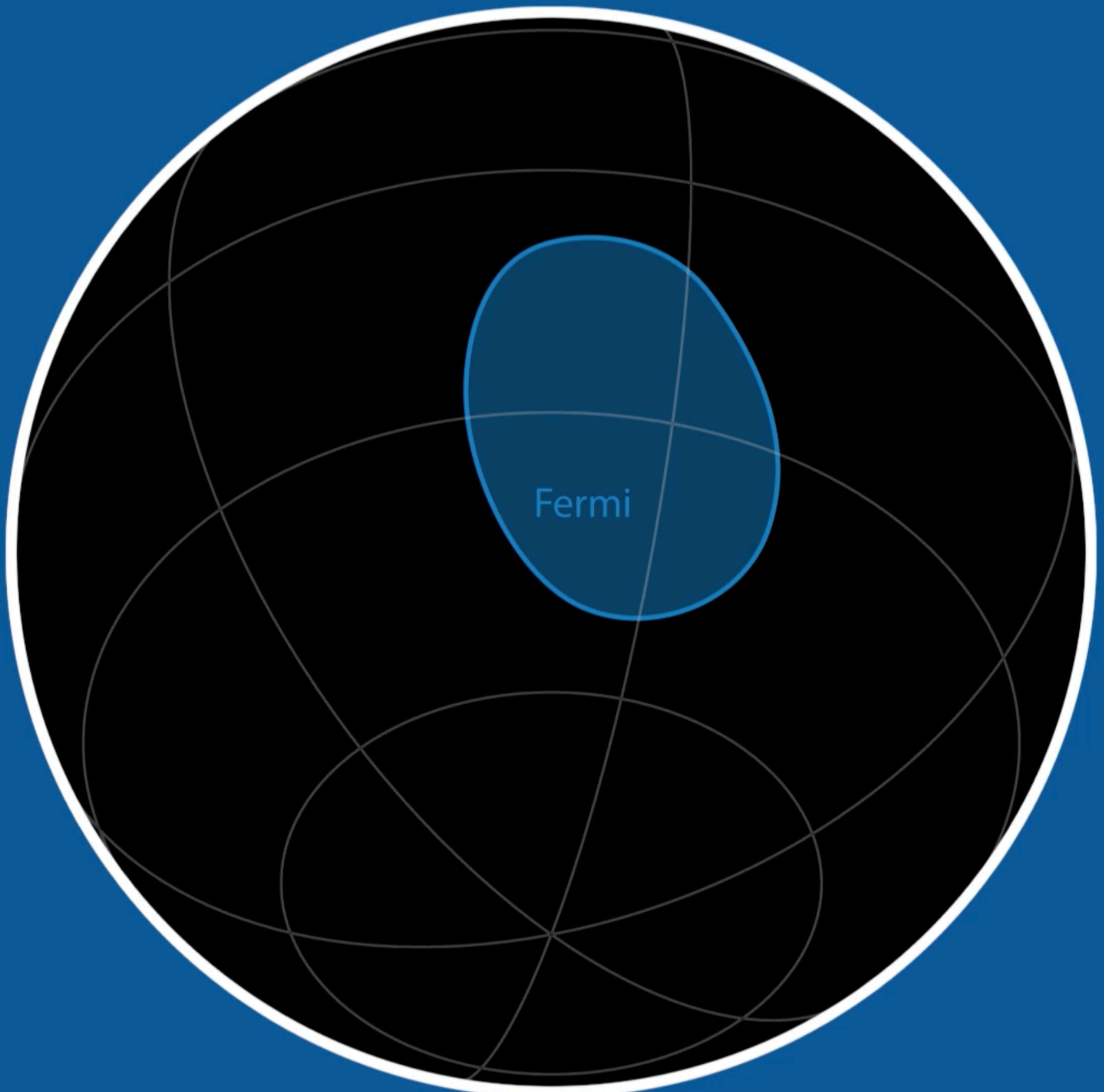

LIGO Collaboration, https://youtu.be/4X1j2b2atGM

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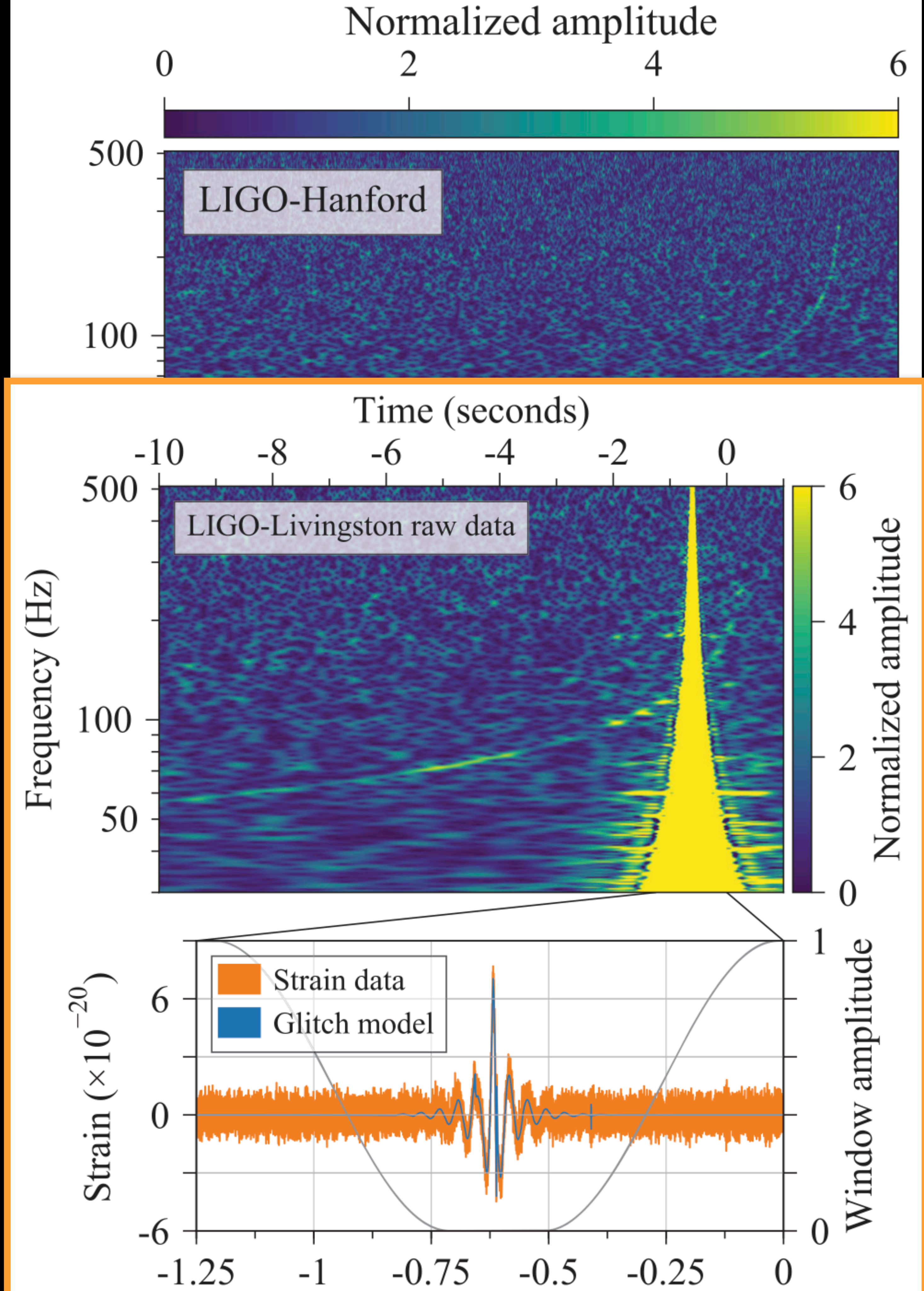

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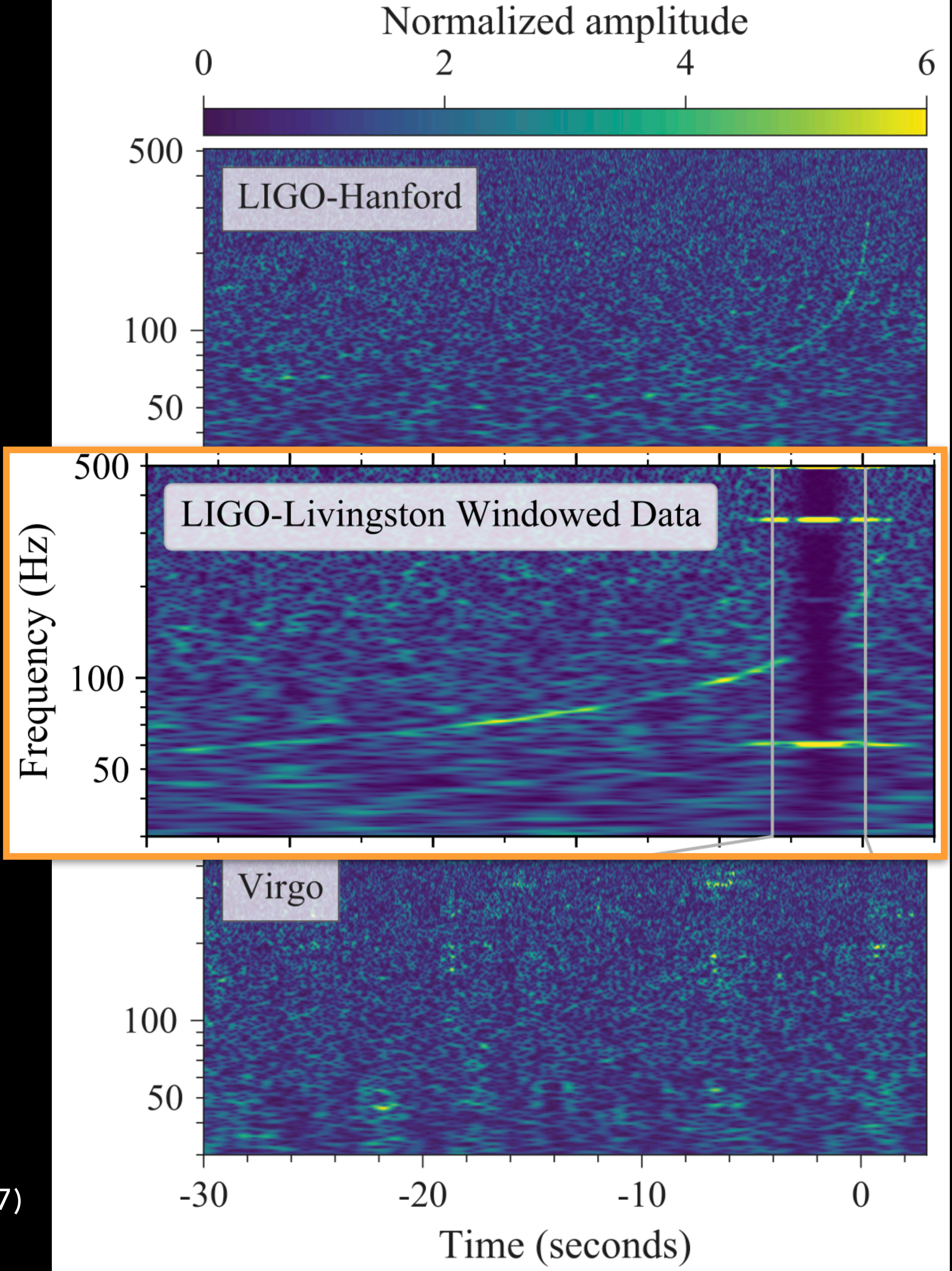

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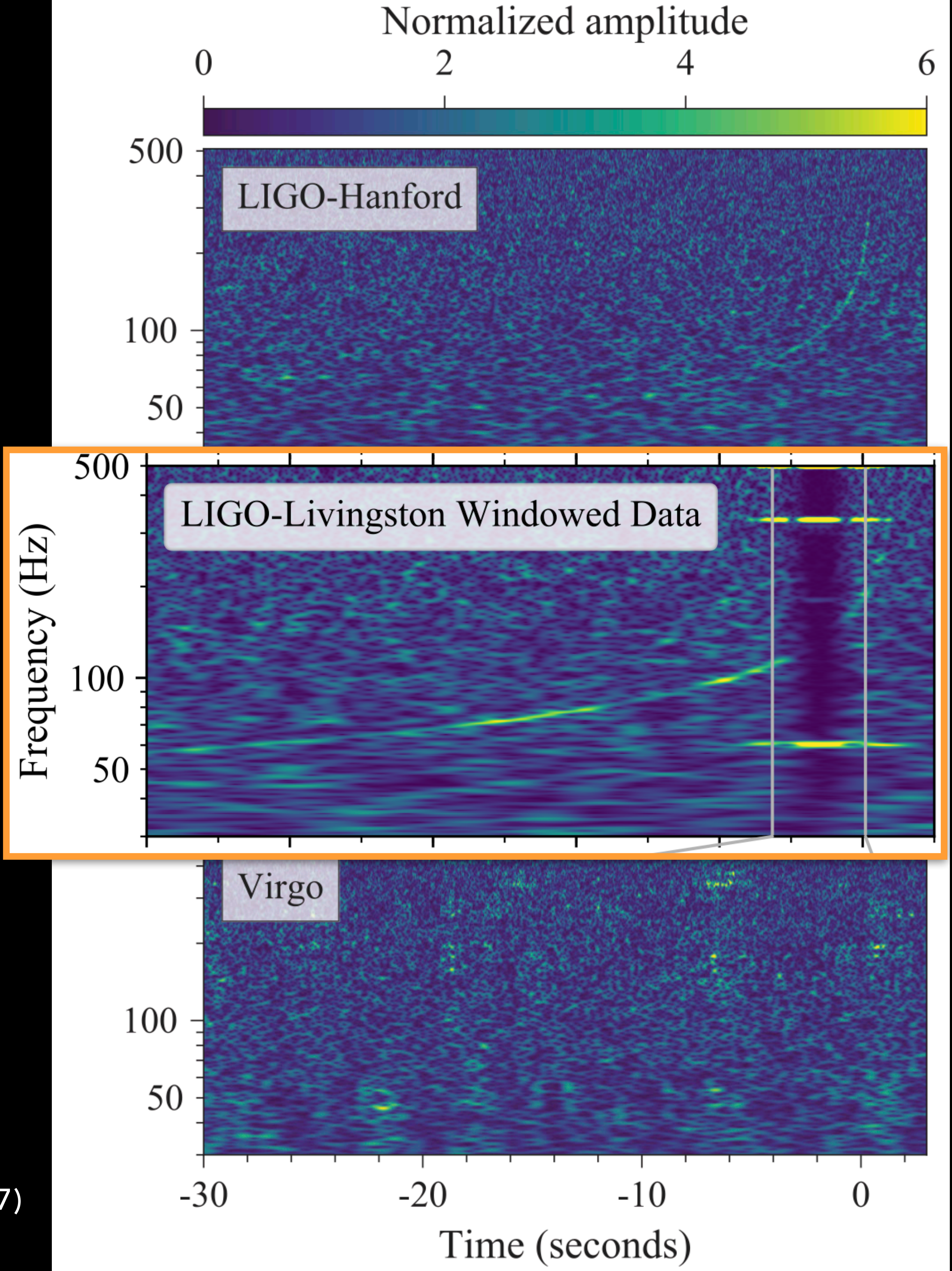

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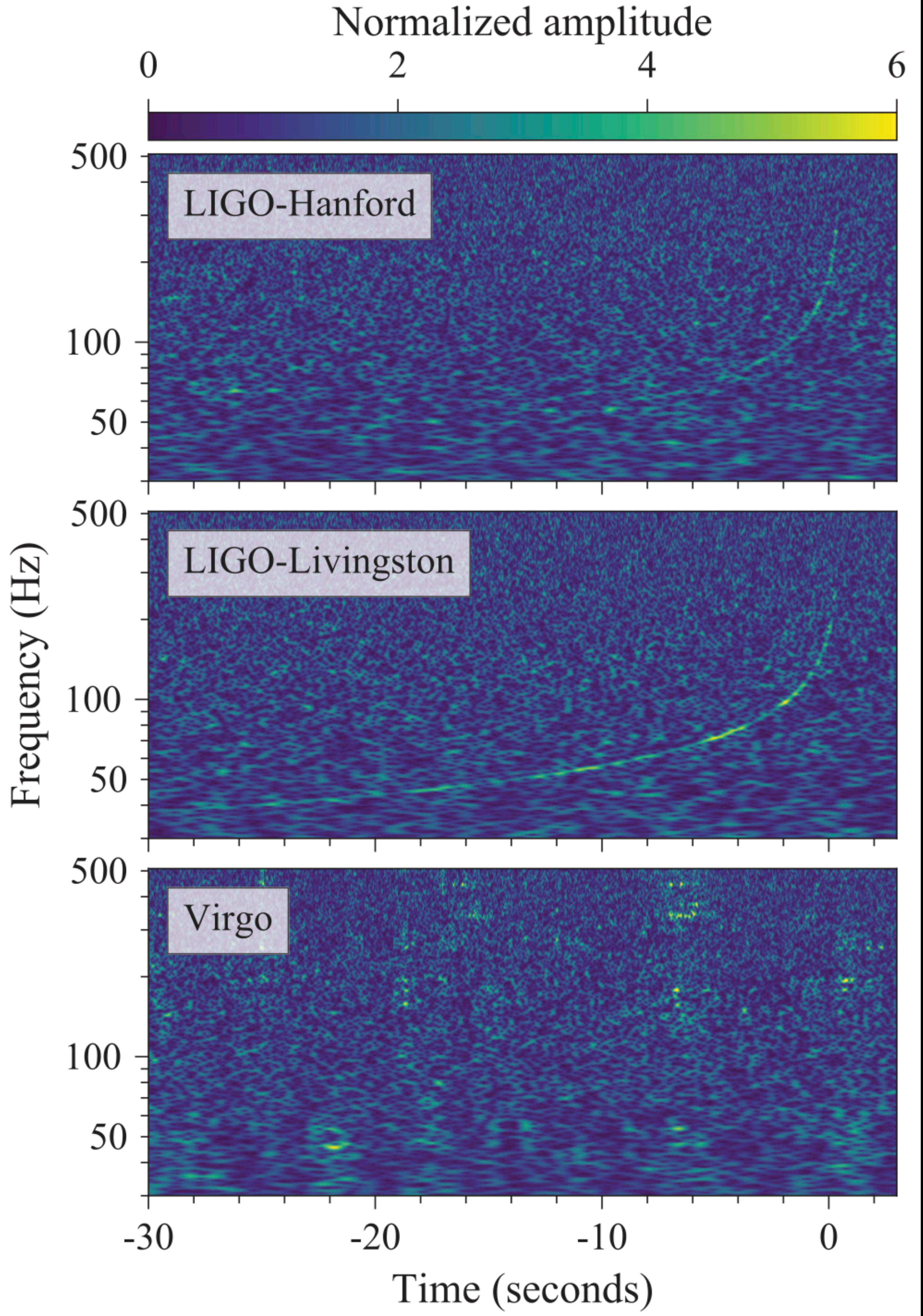

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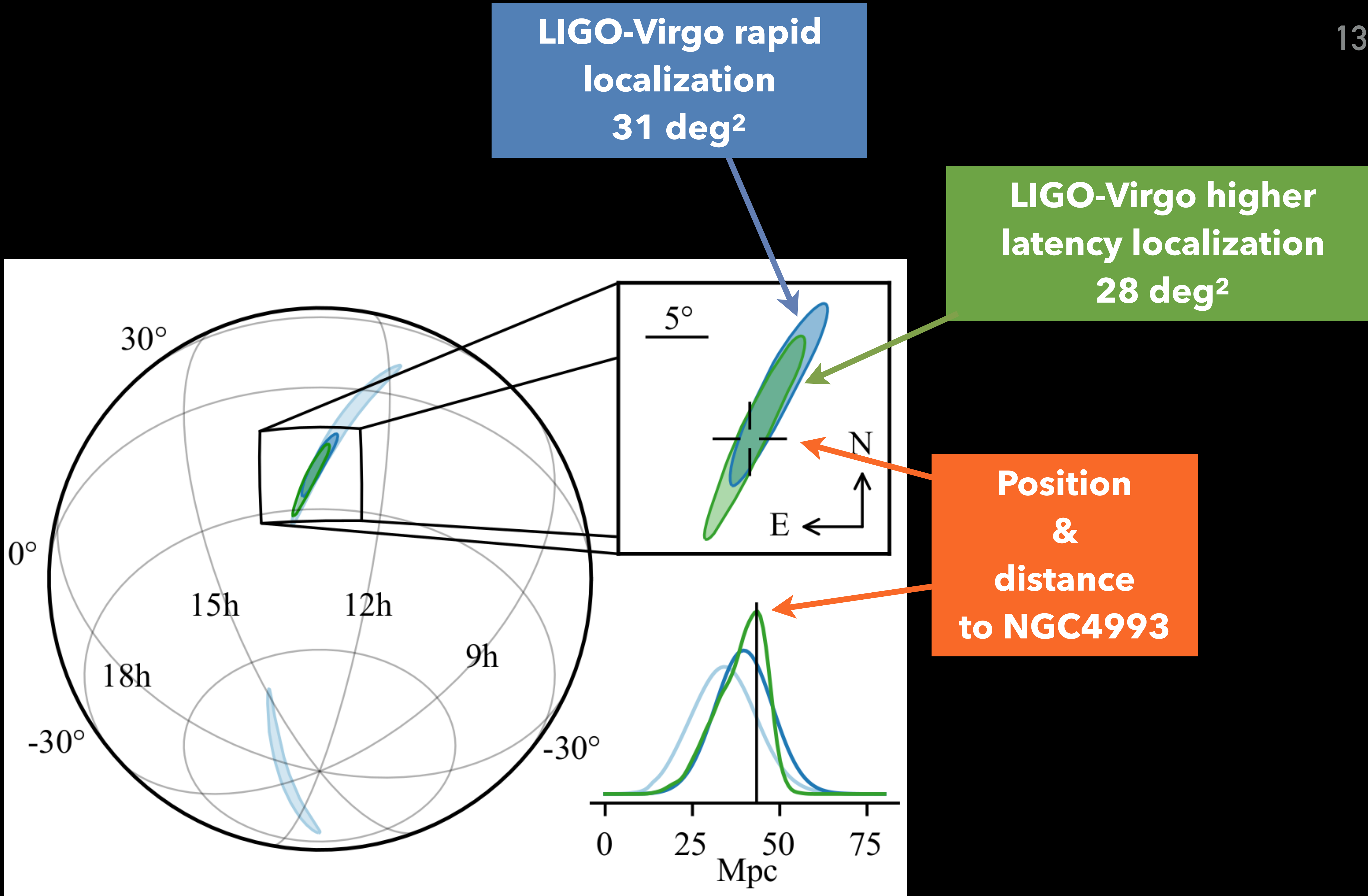
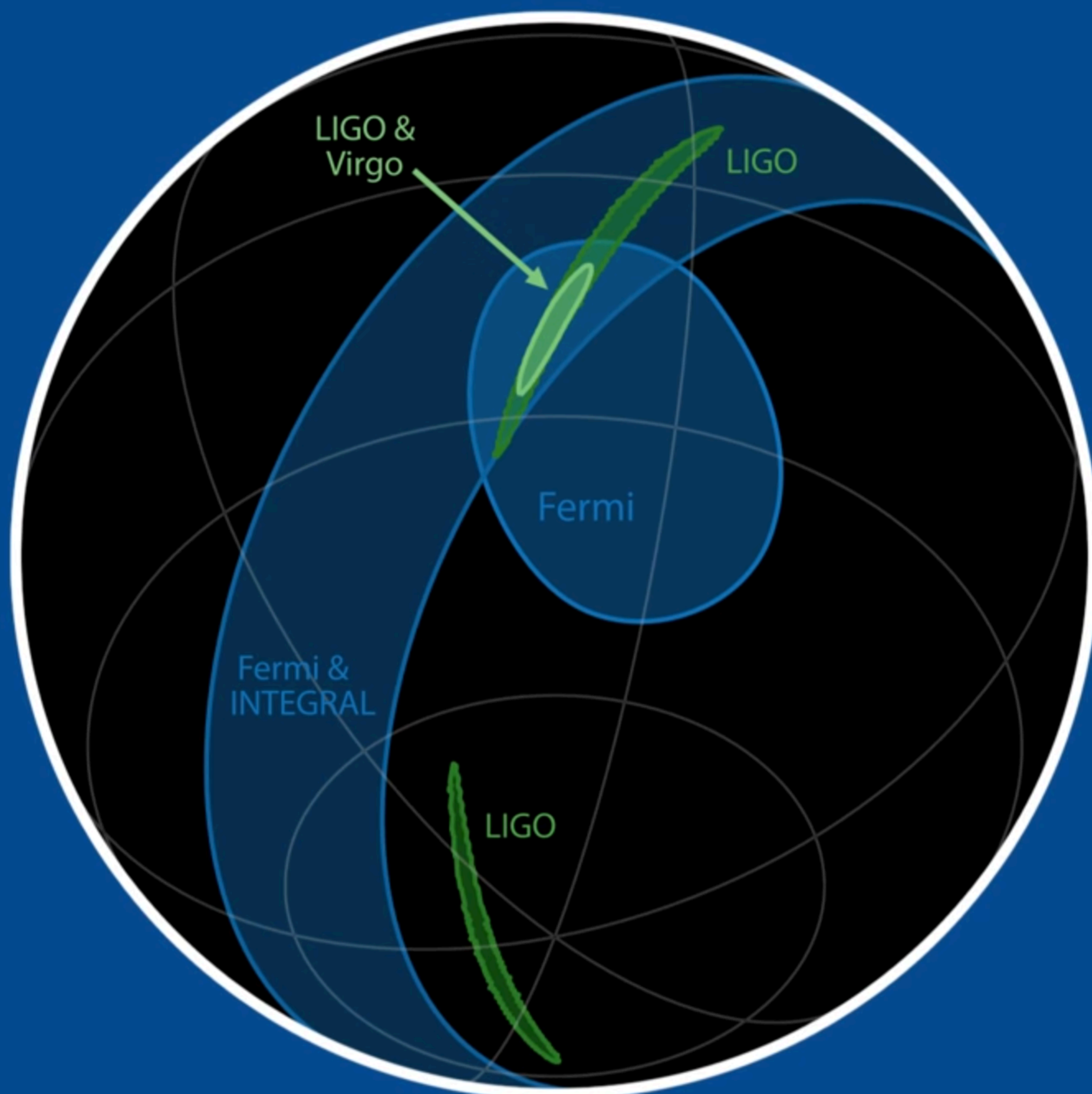


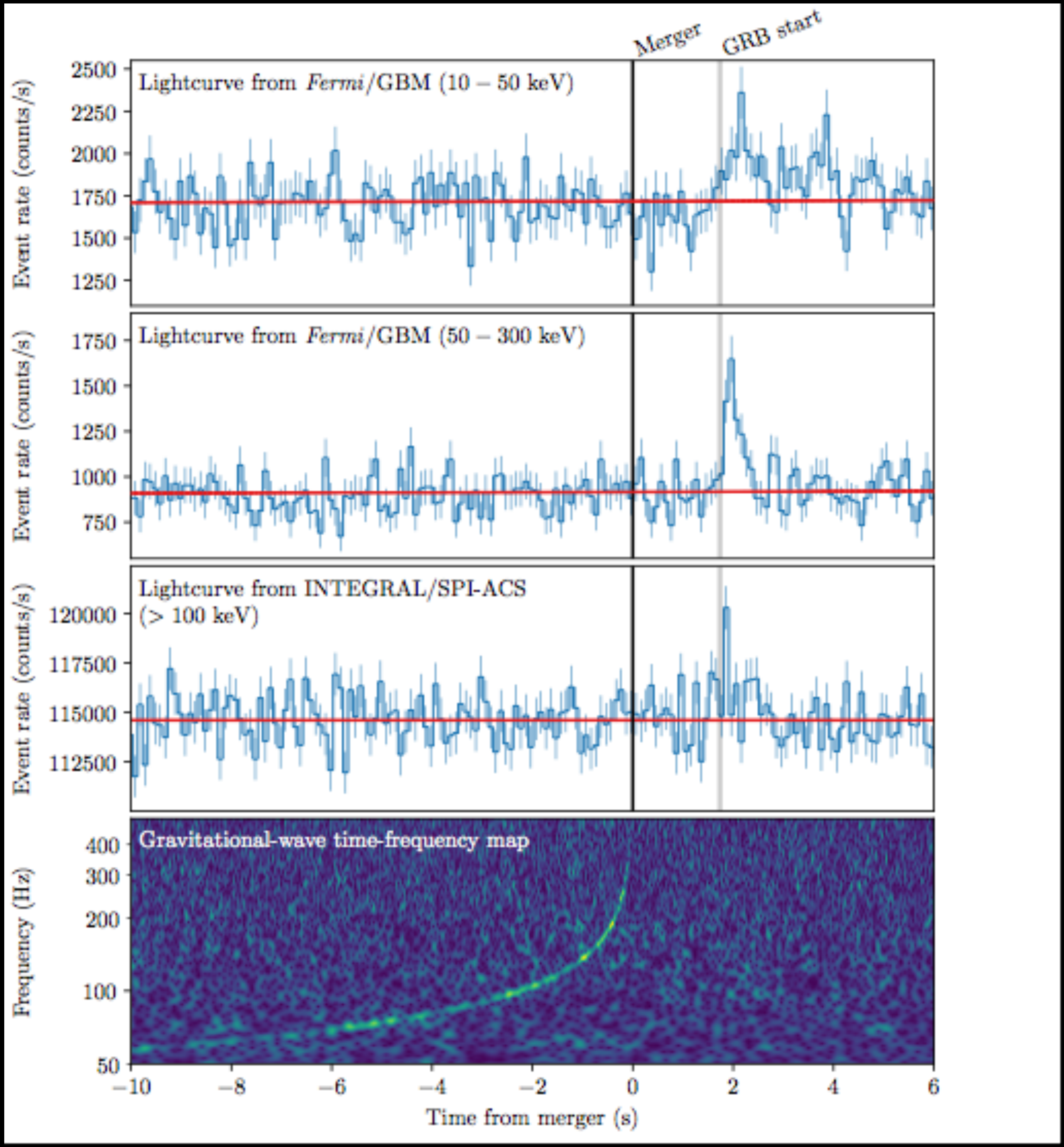
LSC+Virgo, PRL 119, 161101 (2017)



LIGO Collaboration, https://youtu.be/4X1j2b2atGM

GRB170817A

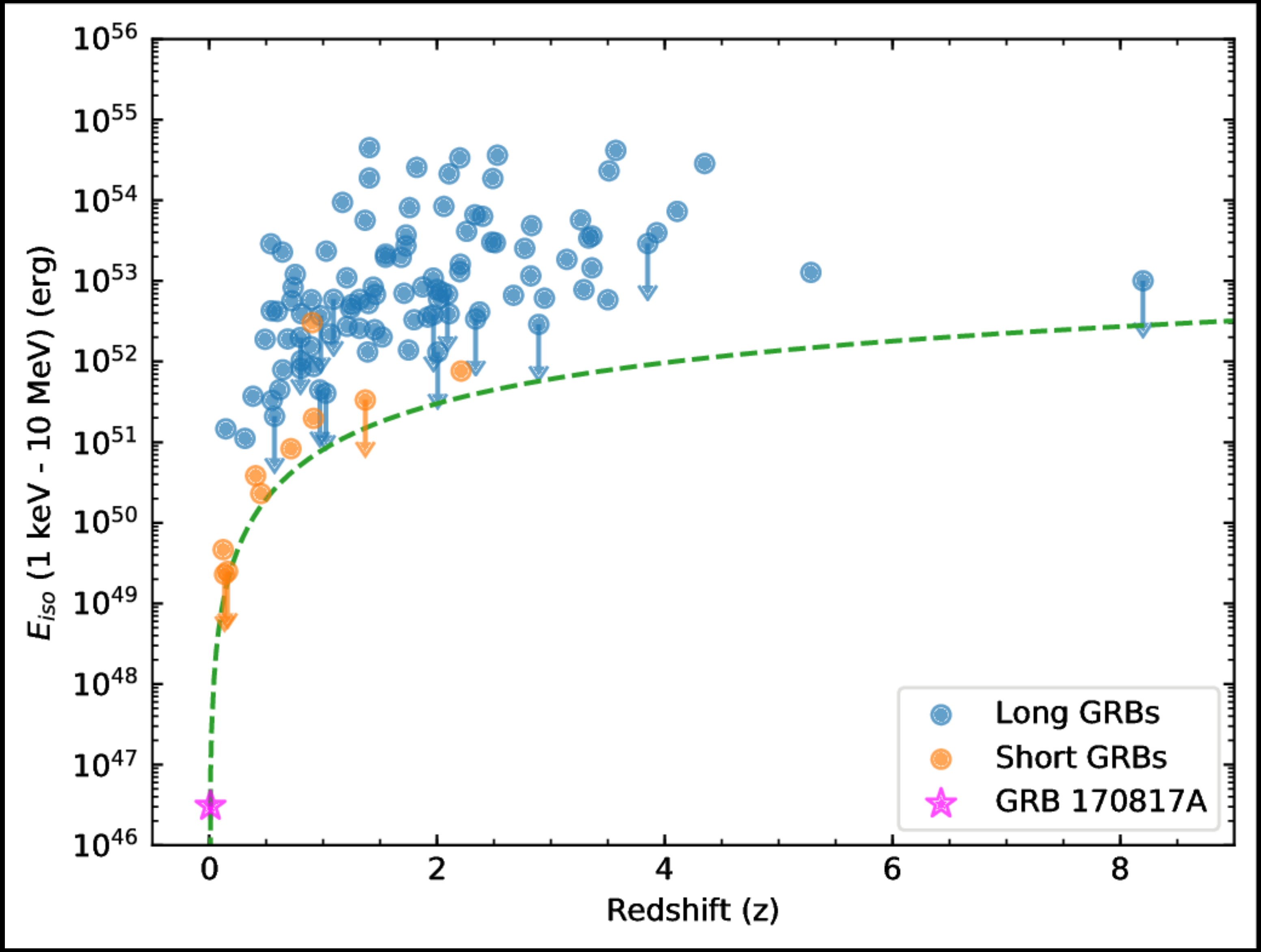
- Occurred (1.74 ± 0.05) seconds after GW170817
- Probability that GW170817 and GRB170817A occurred this close in time and with location agreement by chance is 5.0x10-8 (Gaussian equivalent significance of 5.3σ)



LSC+Virgo, Fermi GBM, & INTEGRAL, ApJL 848, L13 (2017)

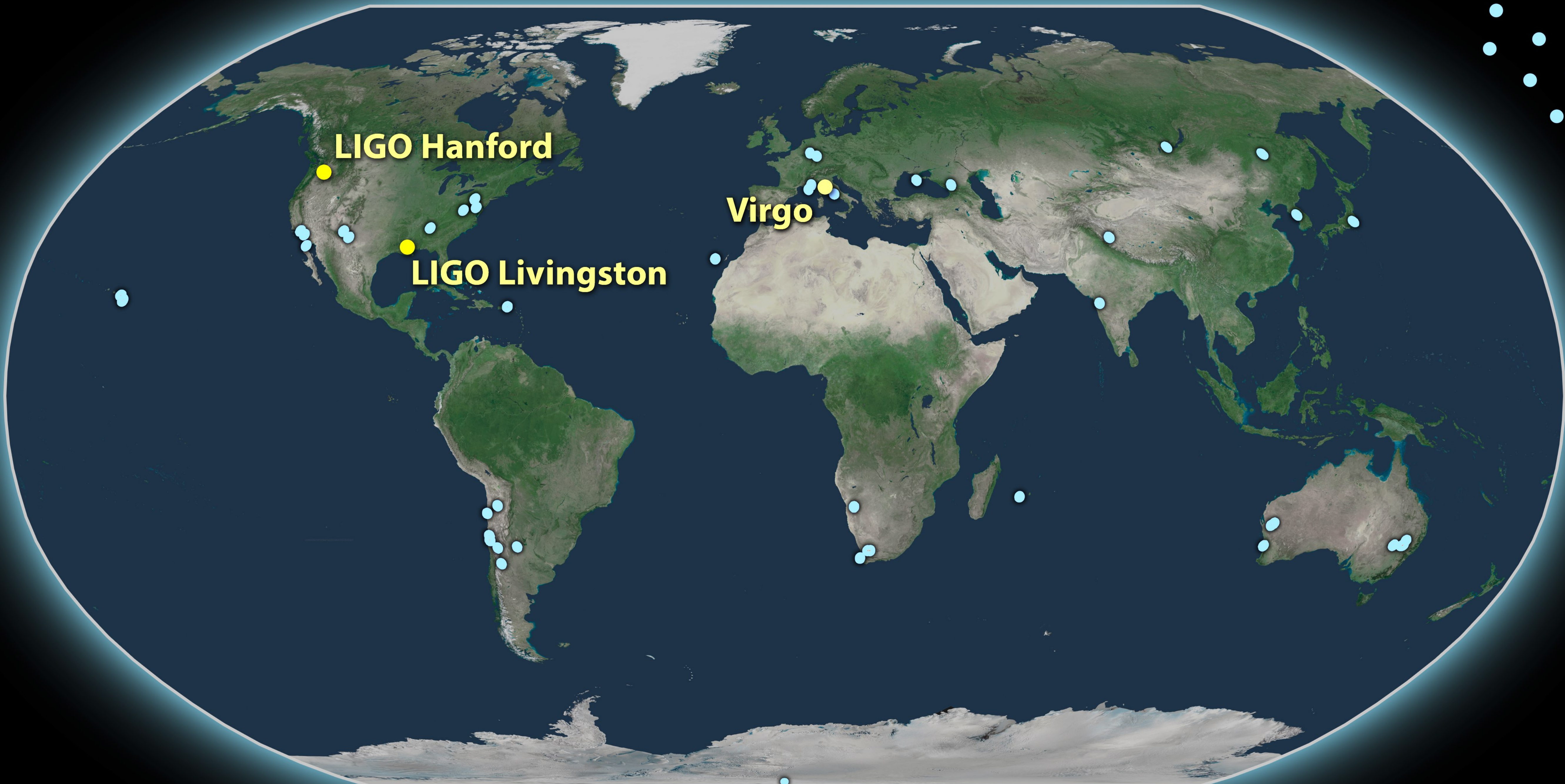
GRB170817A

- Closest GRB ever found with known redshift
- Unusually dim
- Suggests that viewing angle is off axis



LSC+Virgo, Fermi GBM, & INTEGRAL, ApJL 848, L13 (2017)

credit: LIGO Collaboration



credit: LIGO Collaboration

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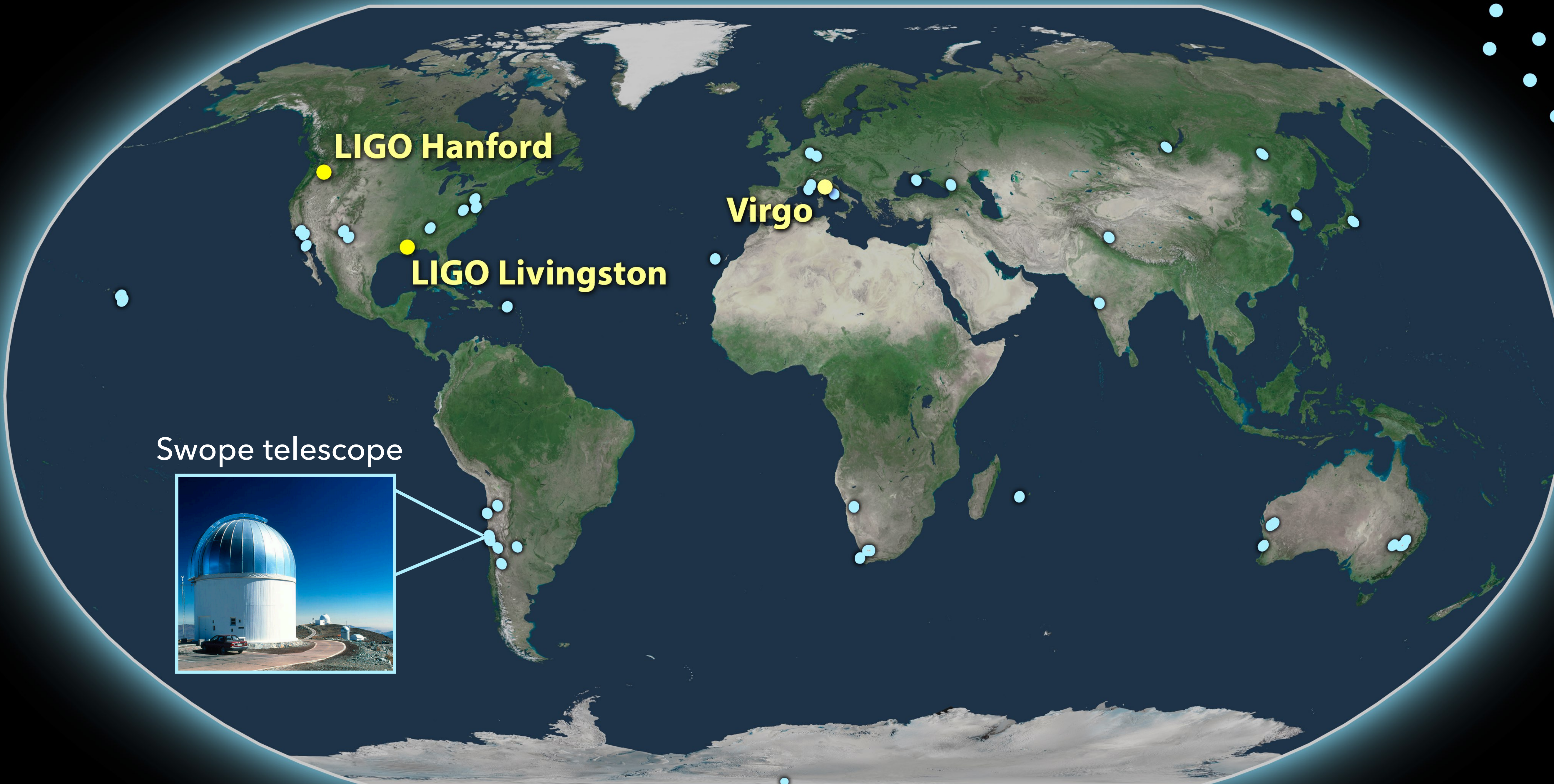
Optical transient may have been observed ~5 hours earlier if not for the glitch in L1

credit: LIGO Collaboration



+10.9h (23:33 UTC) Swope observes optical transient

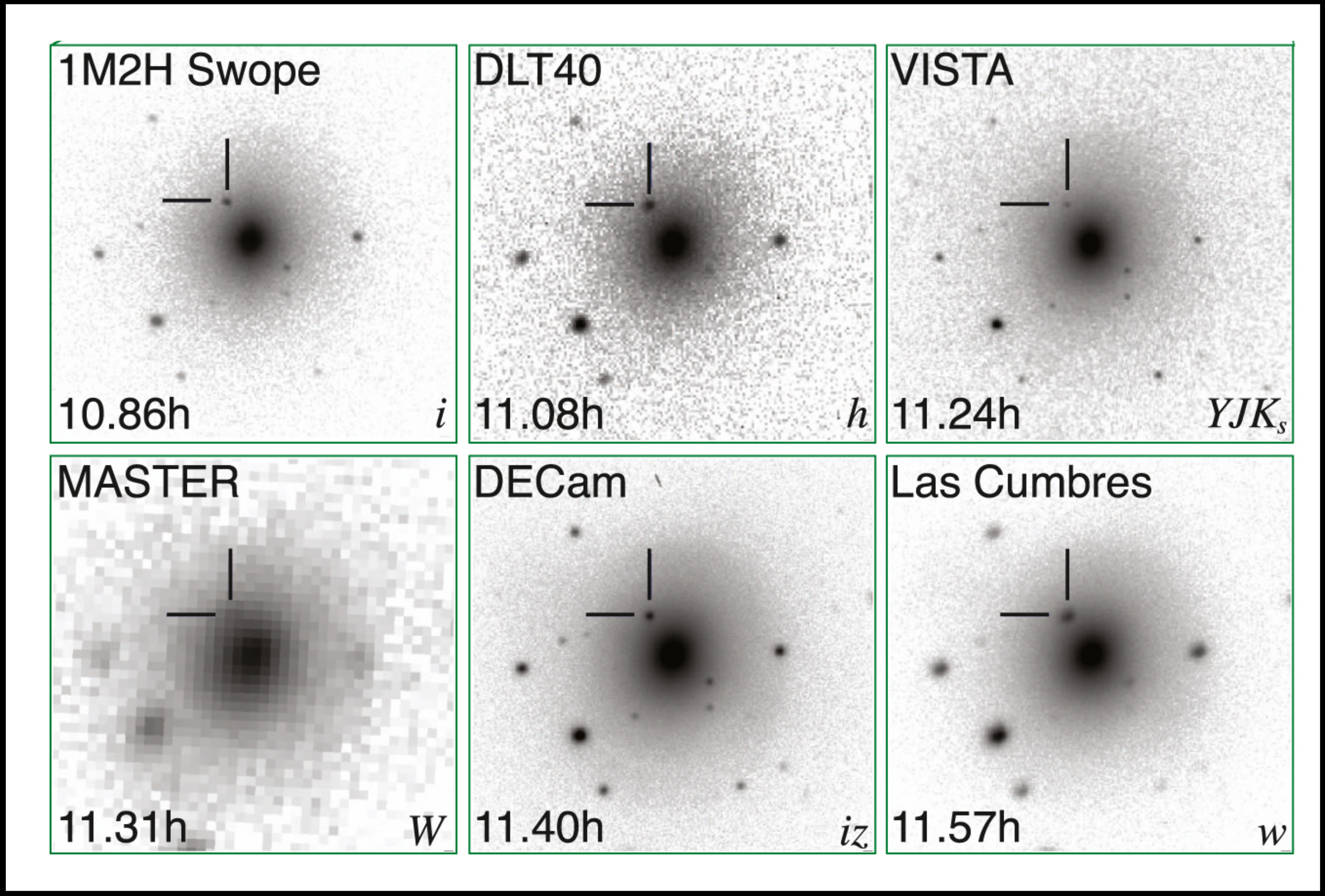
+12.5h (1:05 UTC) 1M2H team issues GCN

SSS17a (AT 2107gfo)

Credit: 1M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

LIGO G

SSS17a (AT 2107gfo)



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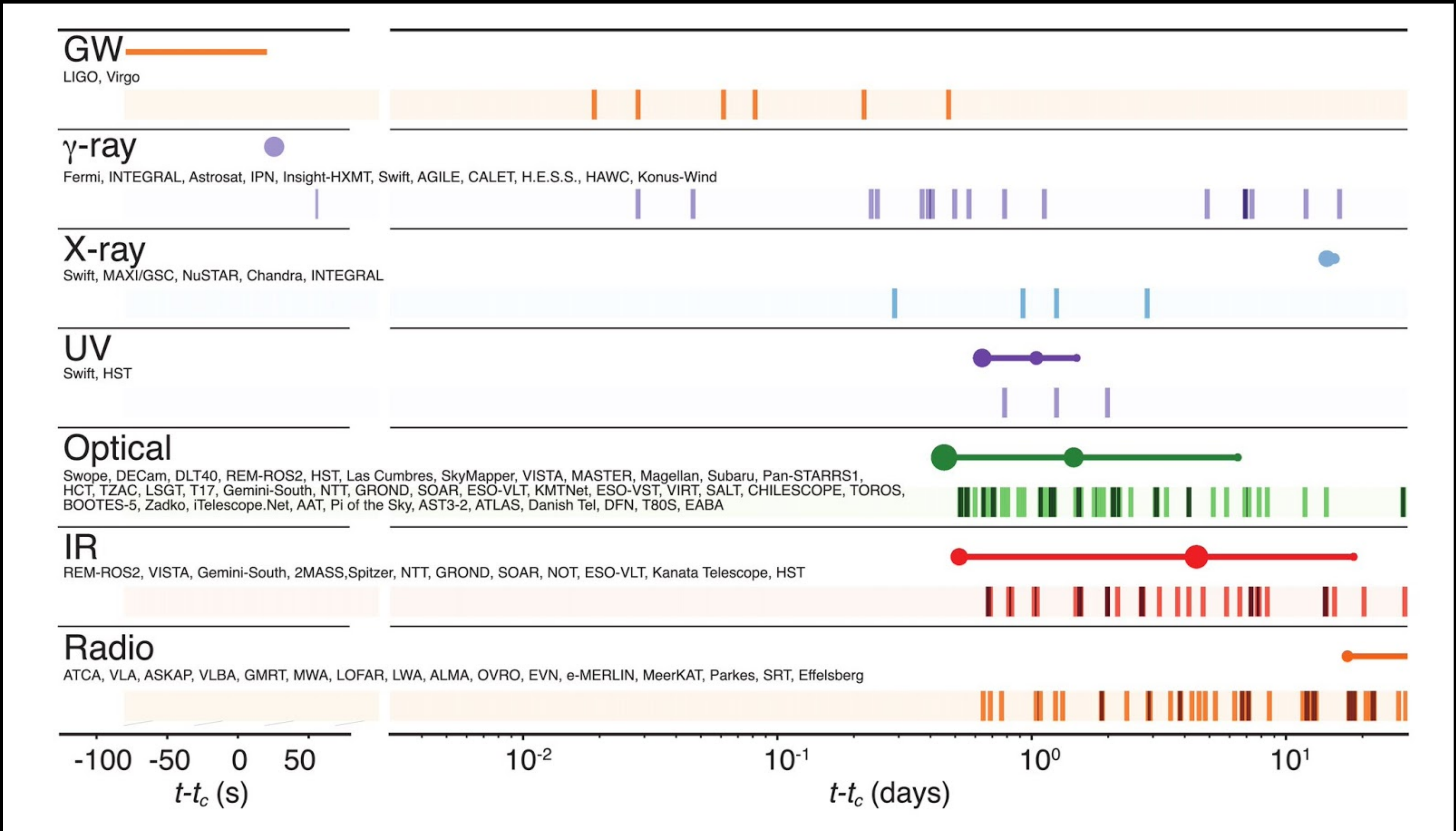
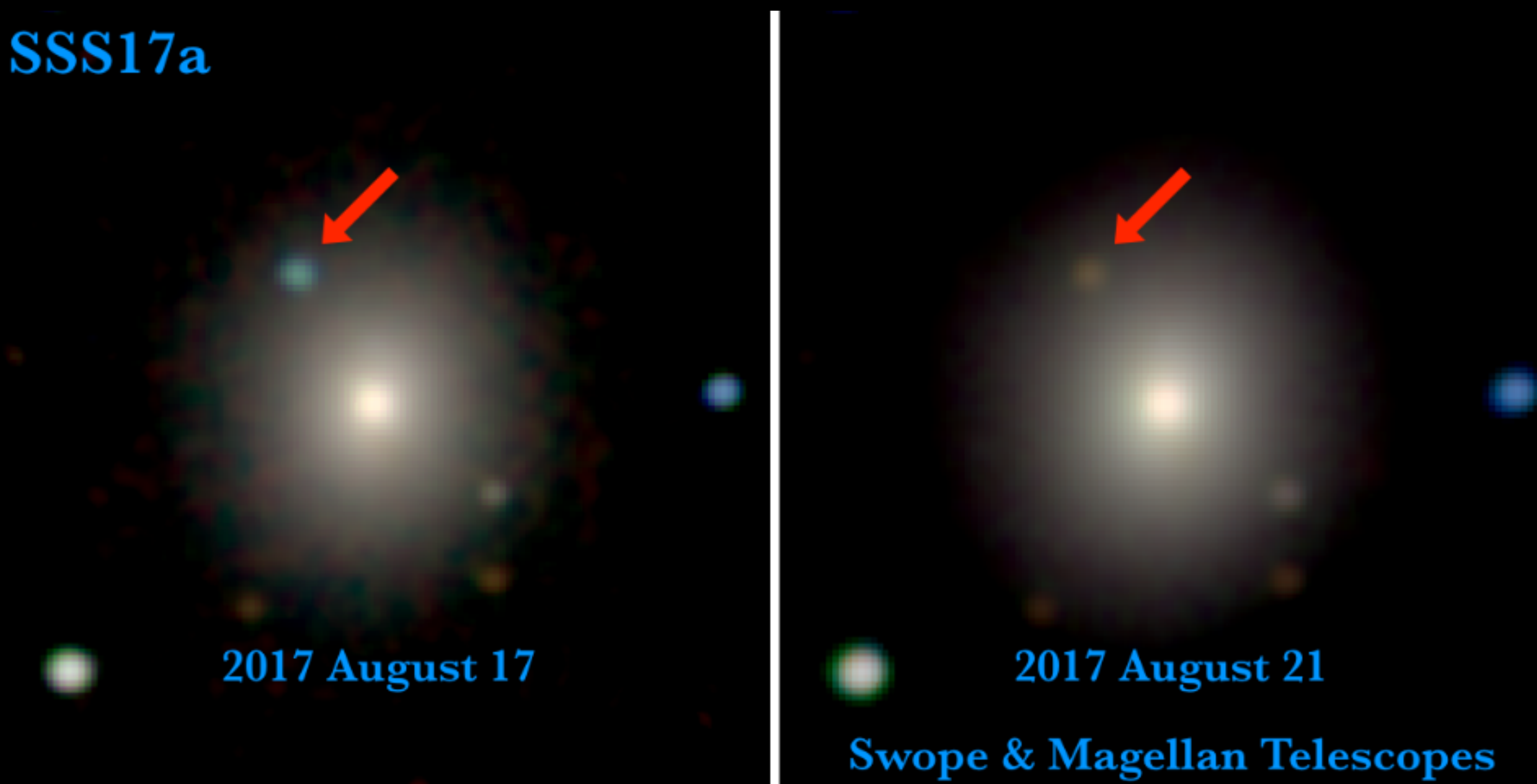


Abbott et al., ApJL 848 L12 (2017)

OPTICAL



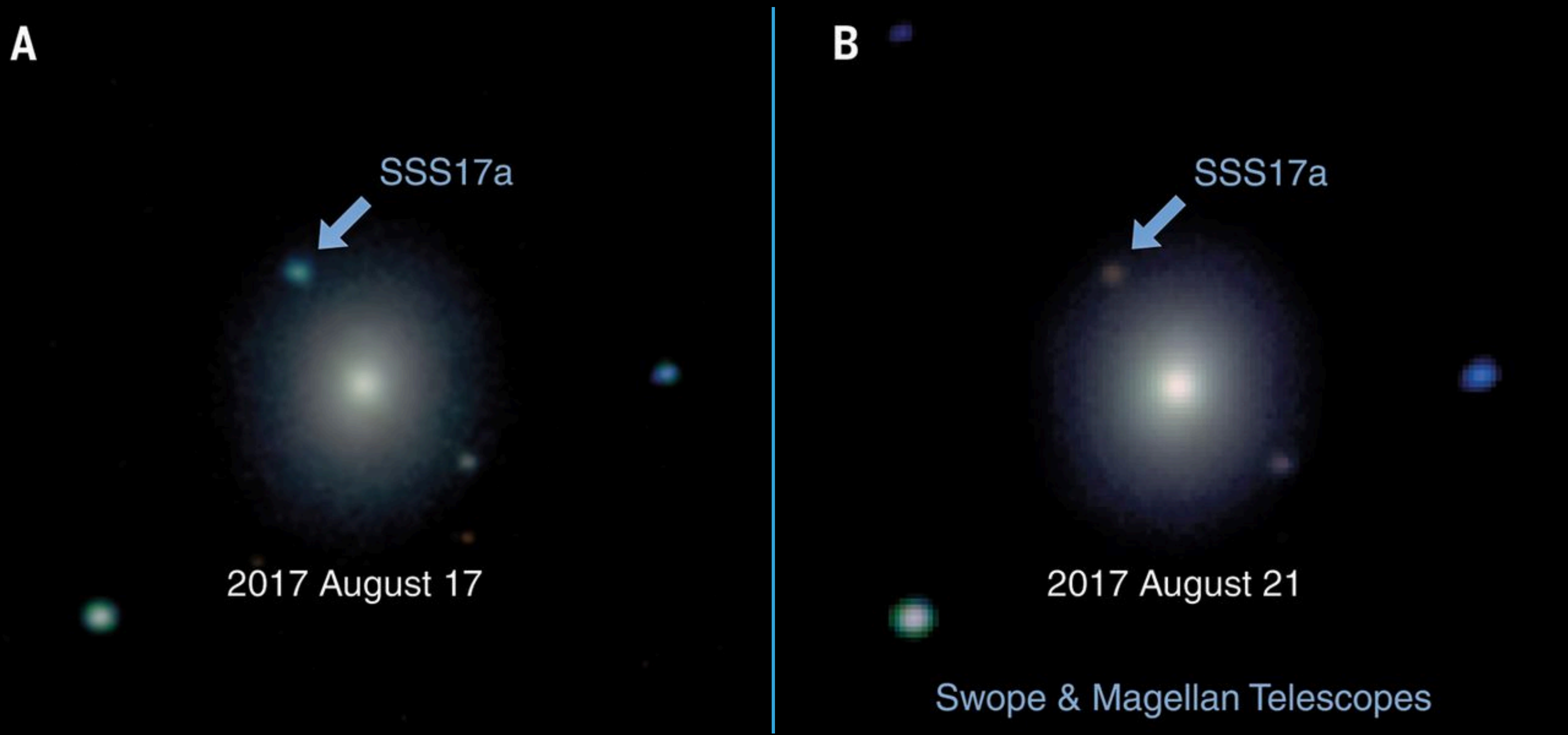
Credit: 1M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

LIGO G1702110

- Faded and reddened within days

INFRARED

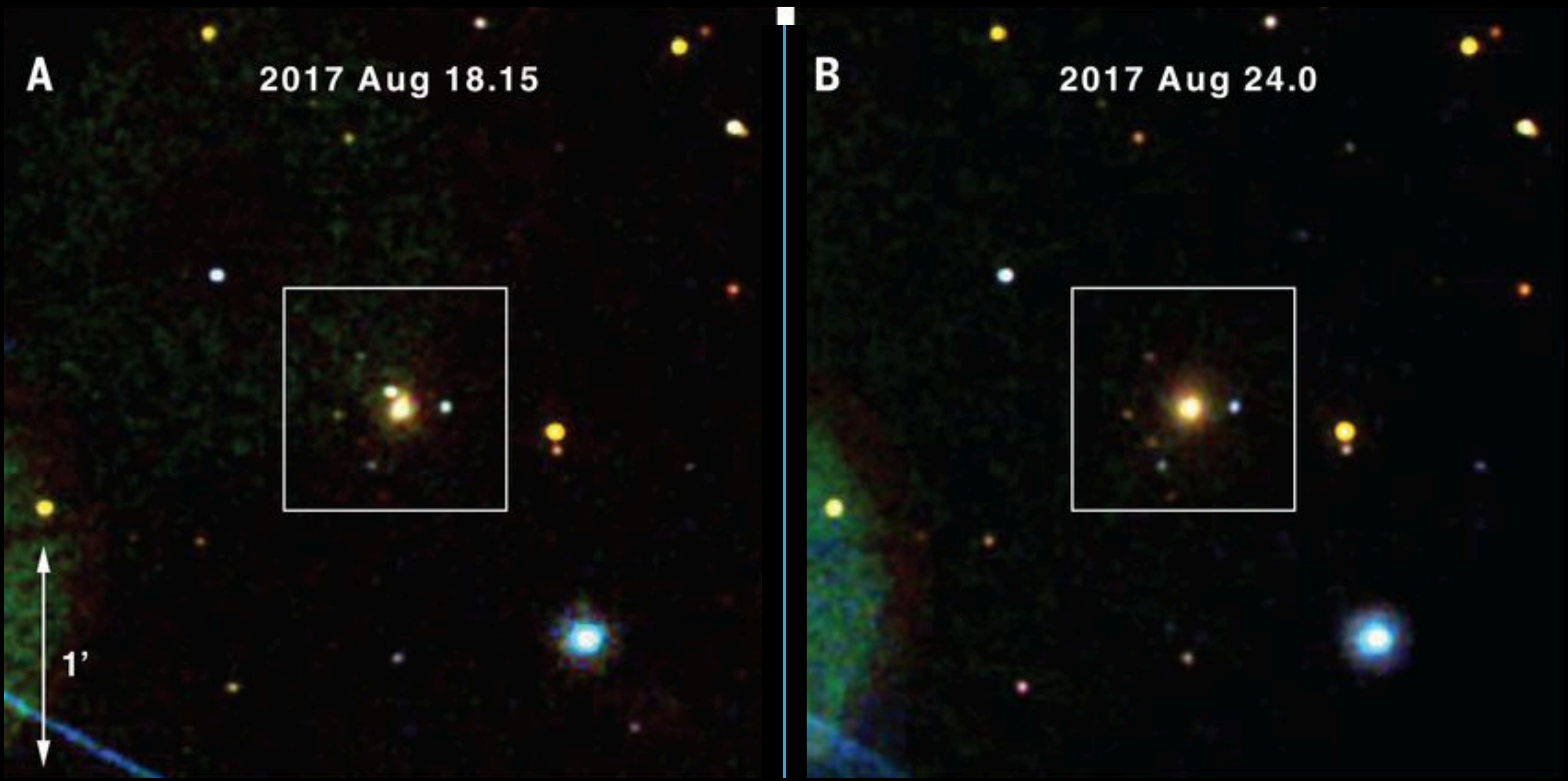
Drout et al., Science 358, 6370 (2017)



- Found 11.5 hours after merger
- Faded more slowly than optical

ULTRAVIOLET

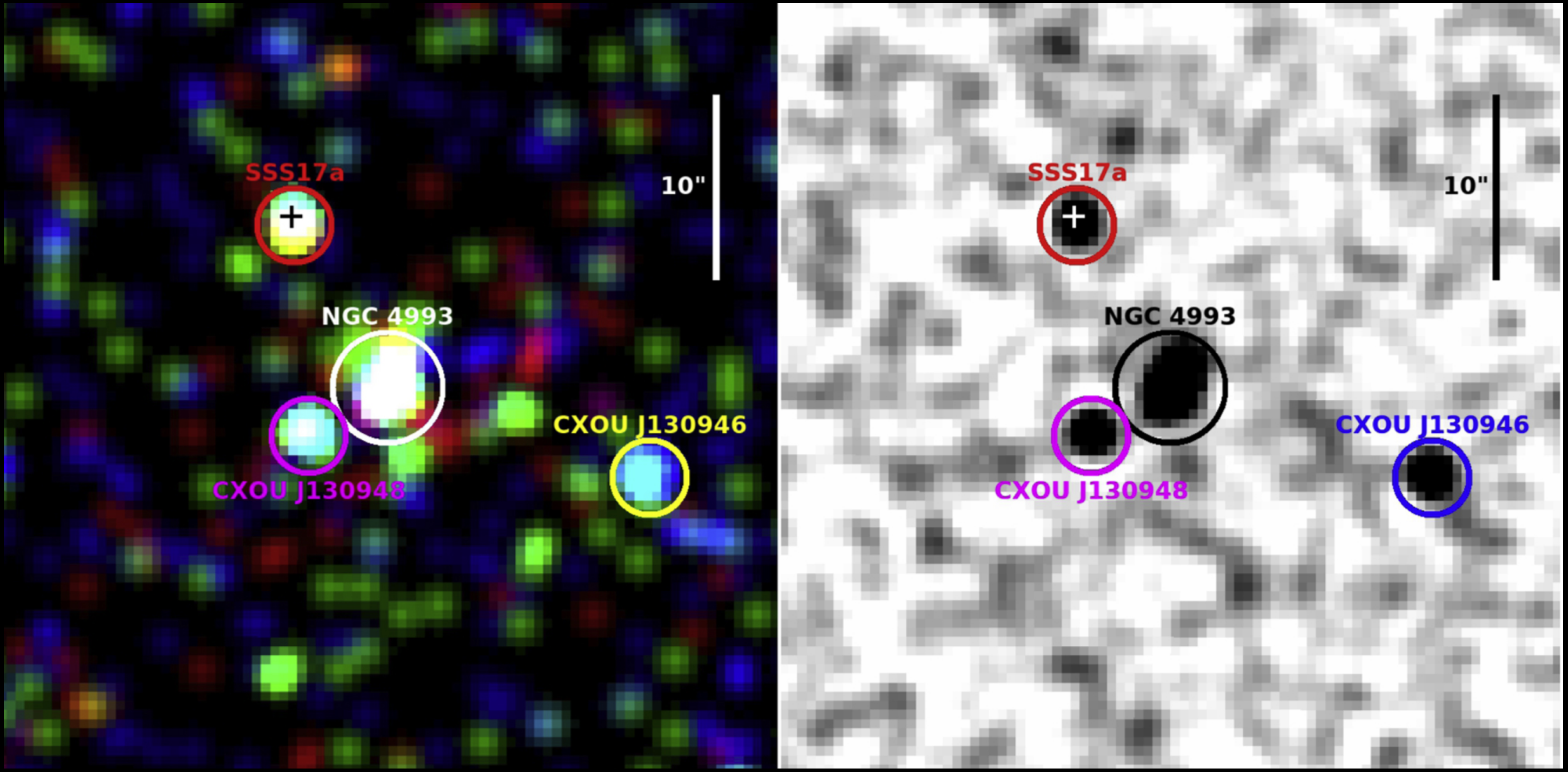
Evans et al., Science 358, 6370 (2017)



- Detected 15 hours after merger
- Faded much more quickly than optical & infrared

X-RAY

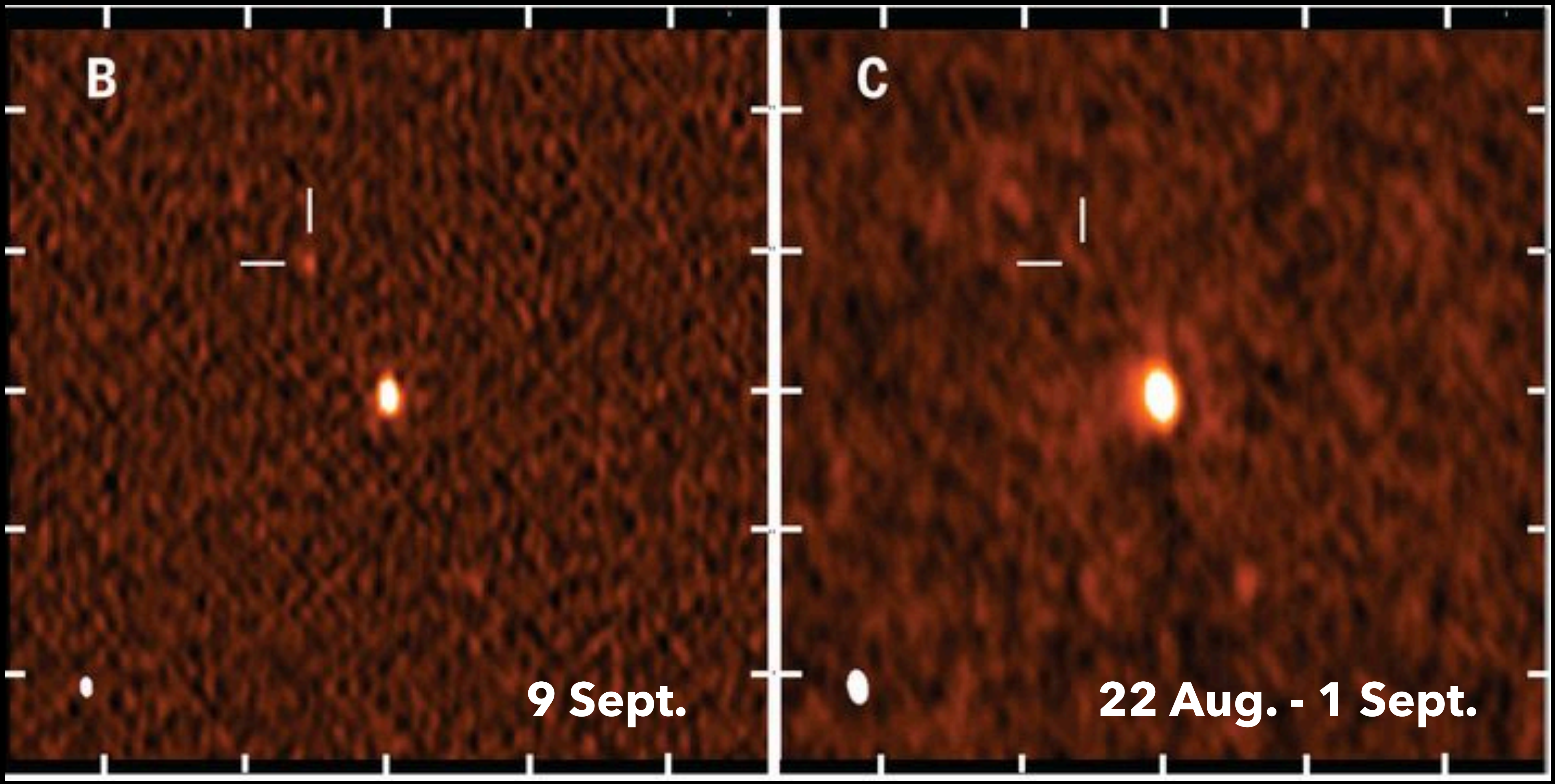
D. Haggard et al., ApJL 848 2 (2017)



- Detected 9 days later

RADIO

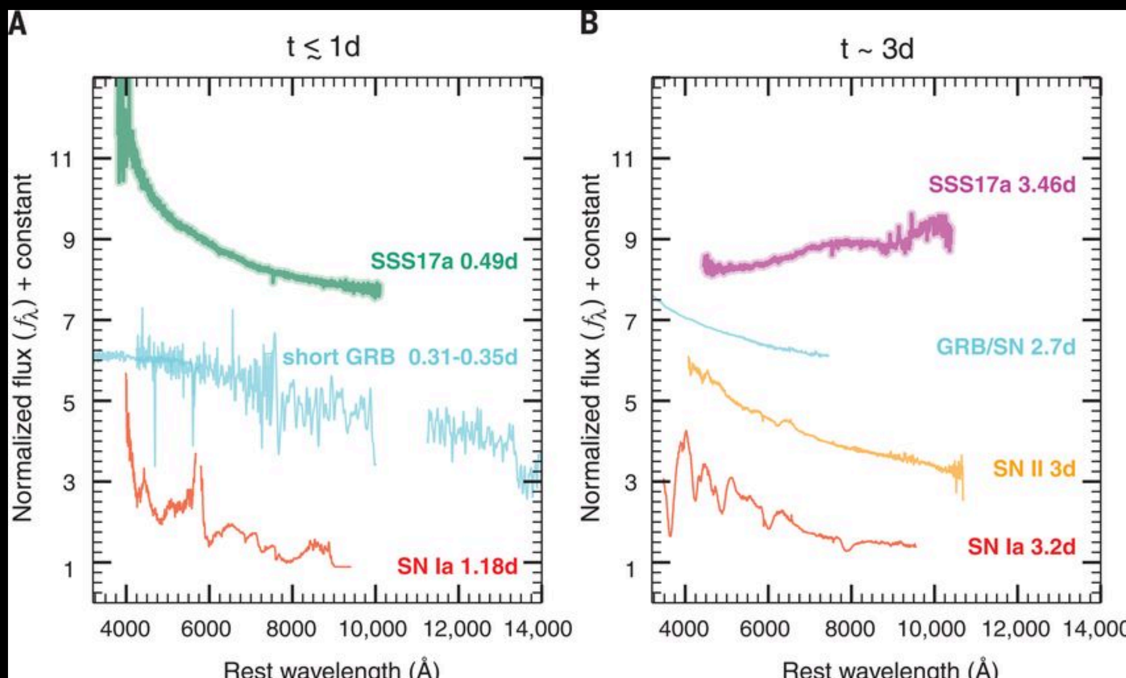
Hallinan et al., Science 358, 6370 (2017)



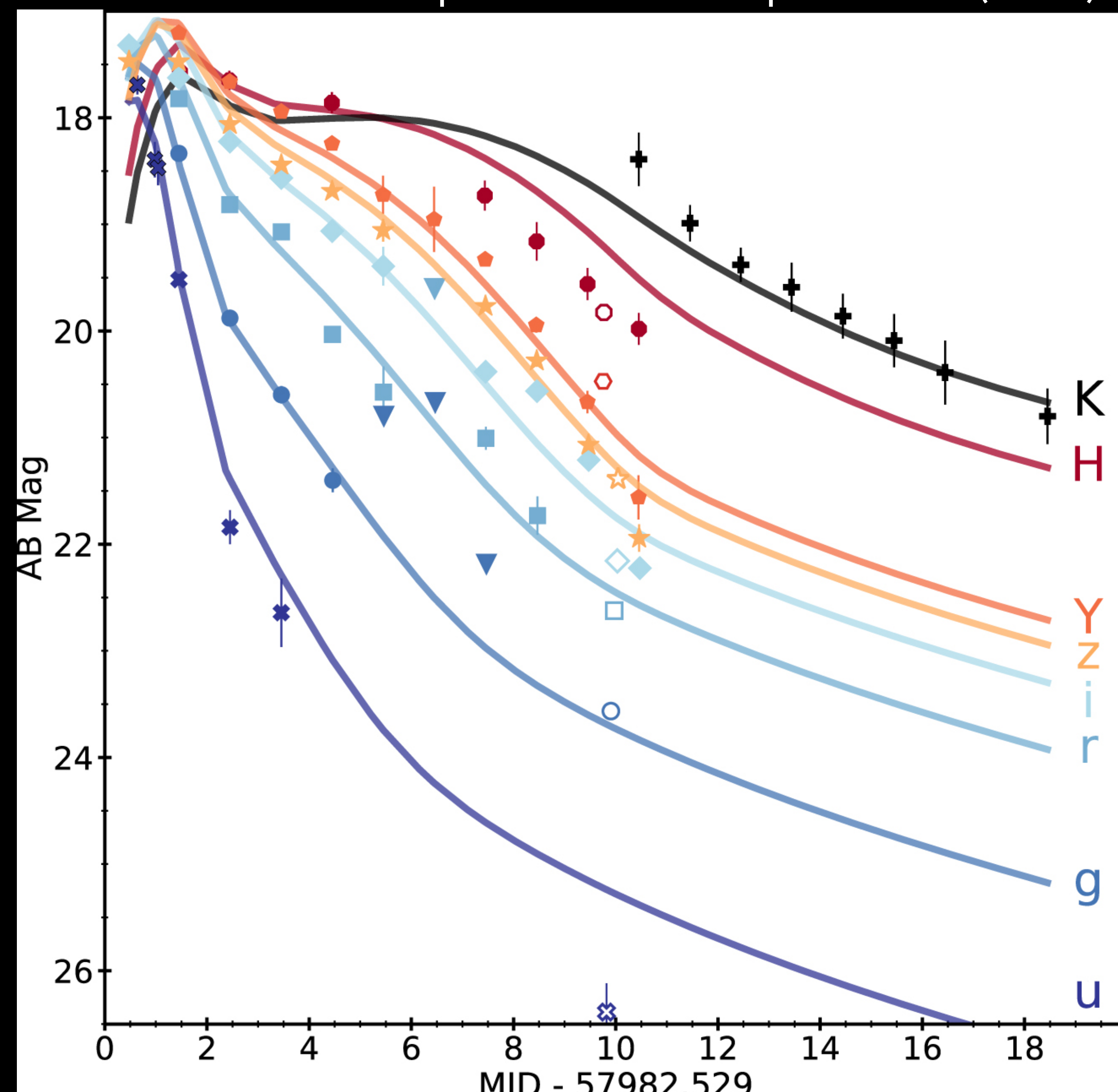
- Detected 16 days later

EARLY SPECTRA

Cowperthwaite et al. ApJ 848 L17 (2017)

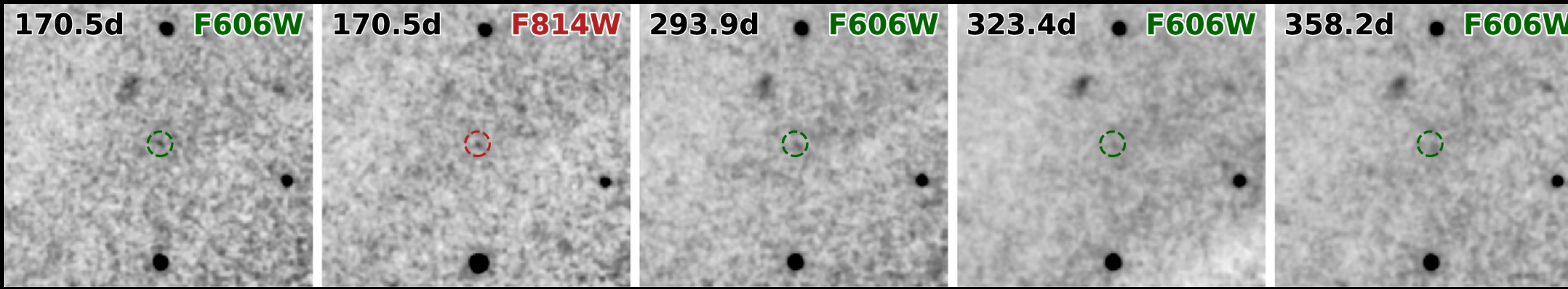


Shappee et al., Science 358, 6370 (2017)

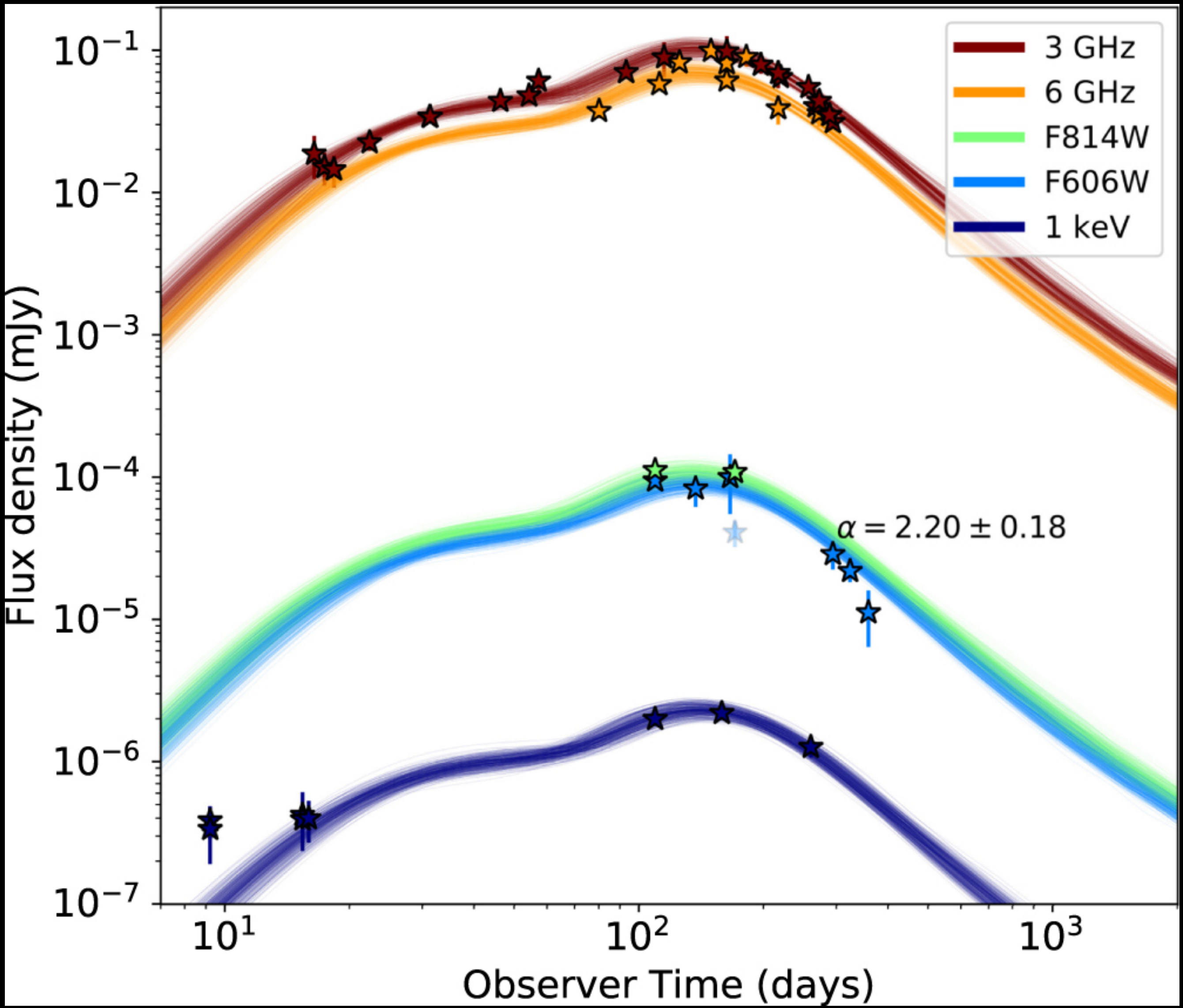


- Spectra and spectral evolution rule out supernova
- No x-ray, radio emissions at early time suggest viewing off-axis
- Consistent with 2-component kilonova: lanthanide-poor (blue) & lanthanide rich (red) ejecta

AFTERGLOW

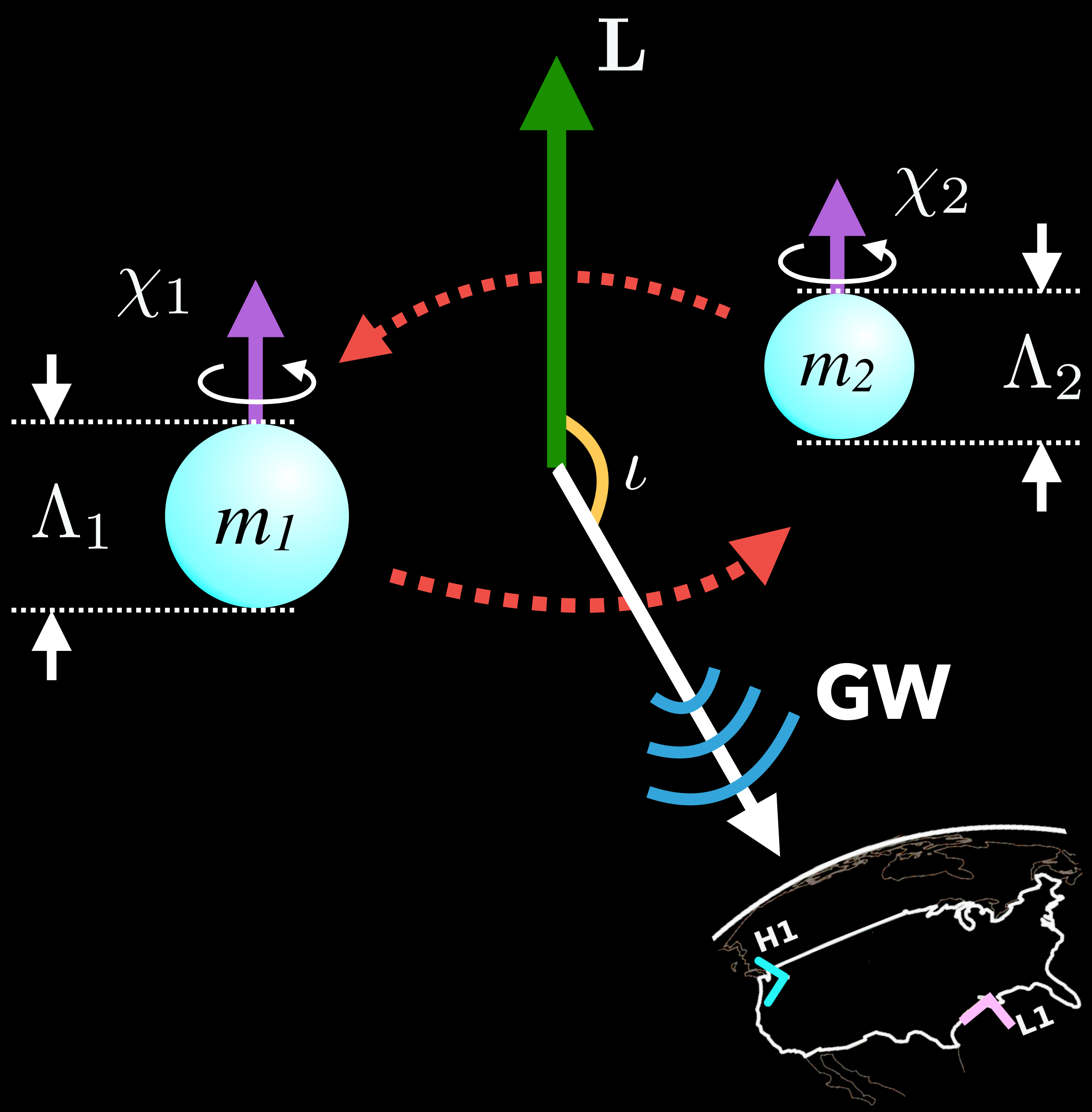


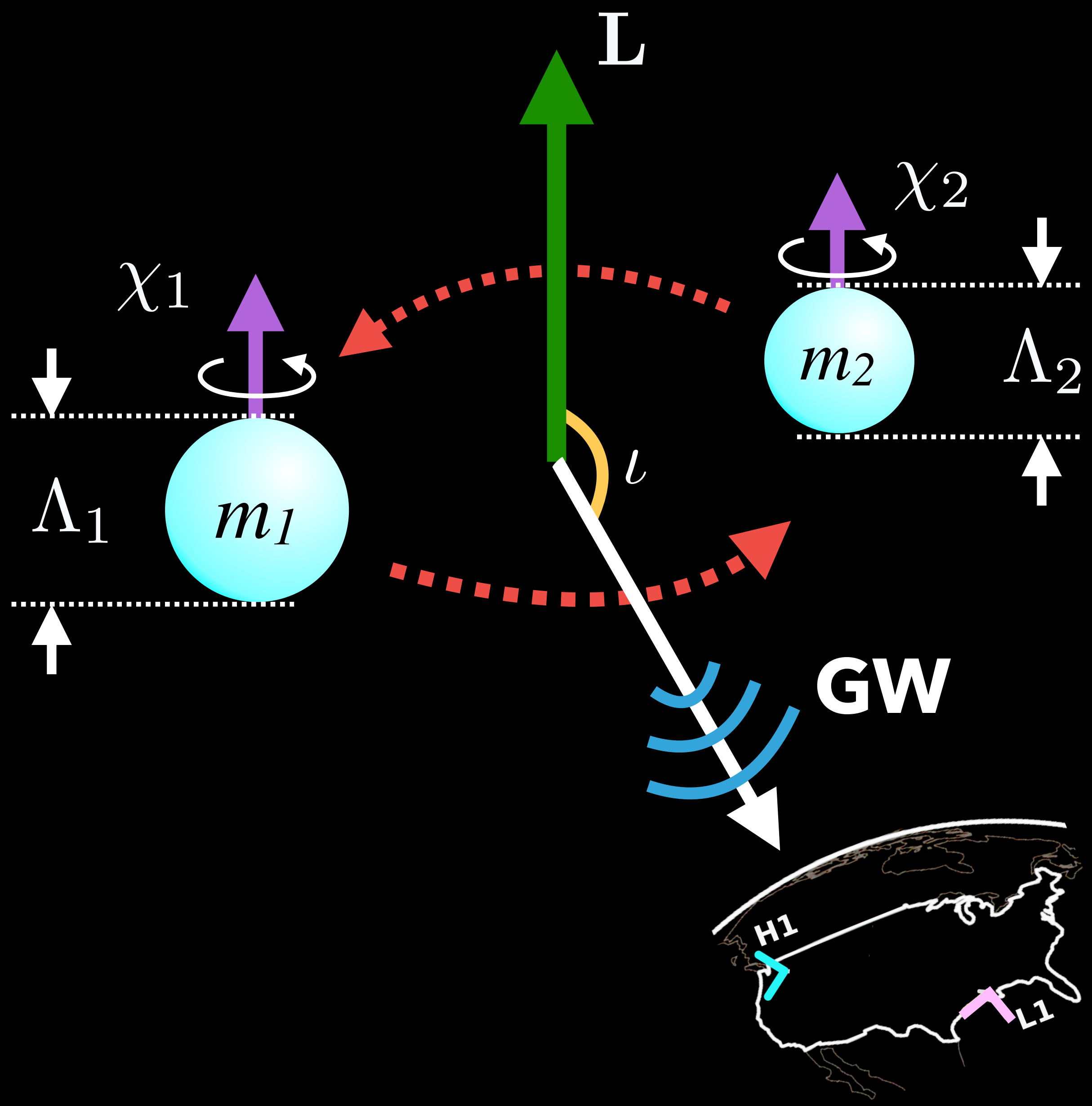
- X-ray, radio peaked ~100 days after
- Afterglow caused by jet hitting interstellar medium
- Important for understanding jet structure



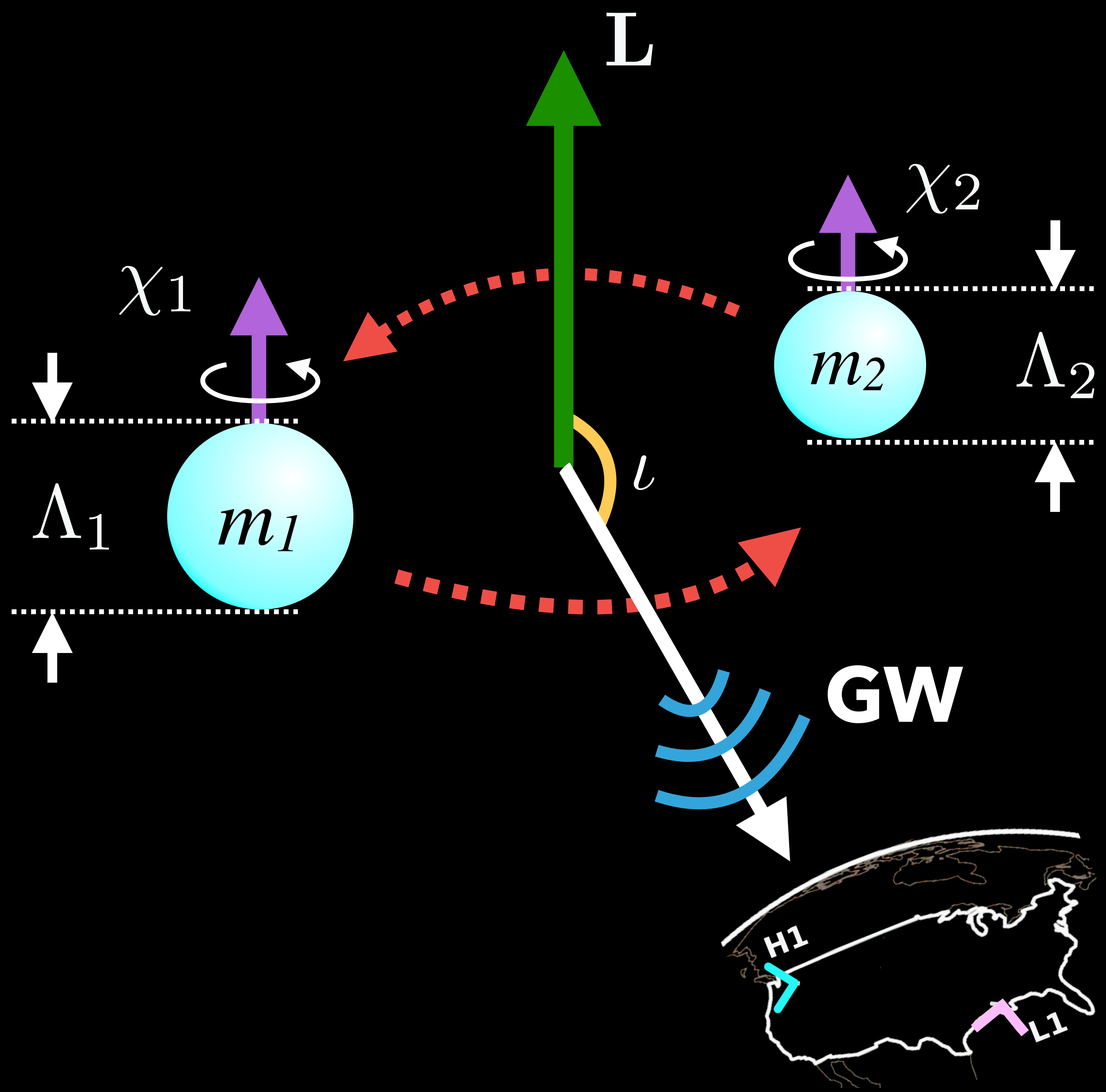
HST; Lamb et al., ApJ. 870 (2019) no.2, L15

CONSTRAINING THE EOS FROM GW OBSERVATIONS


L
χ_2
χ_1
m_2
Λ_2
Λ_1
m_1
ι
GW
H1
L1



- Tidal forces cause neutron stars to deform



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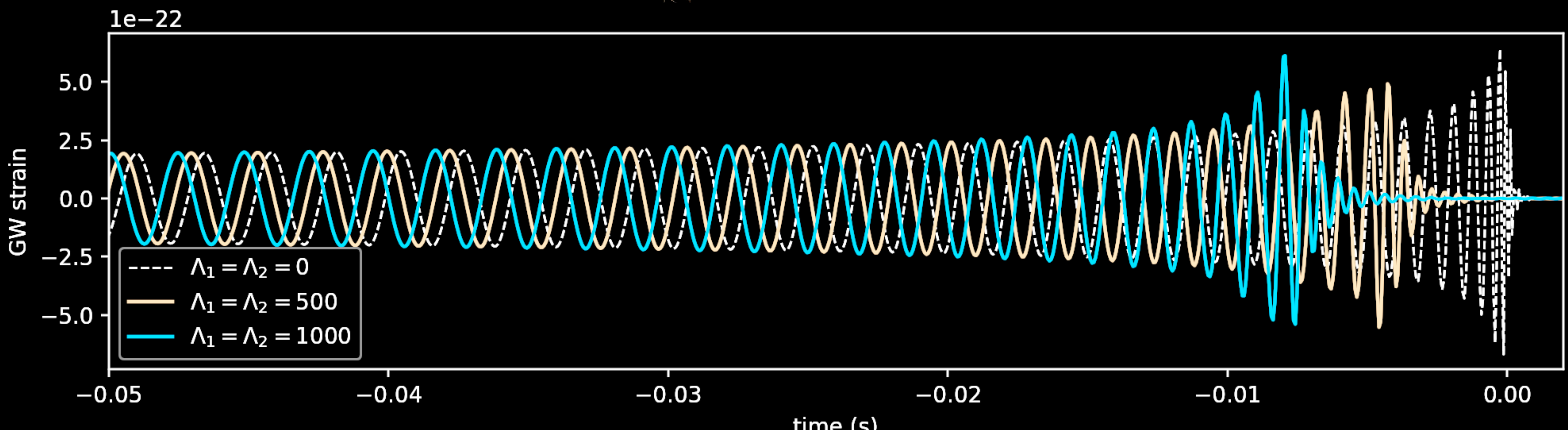
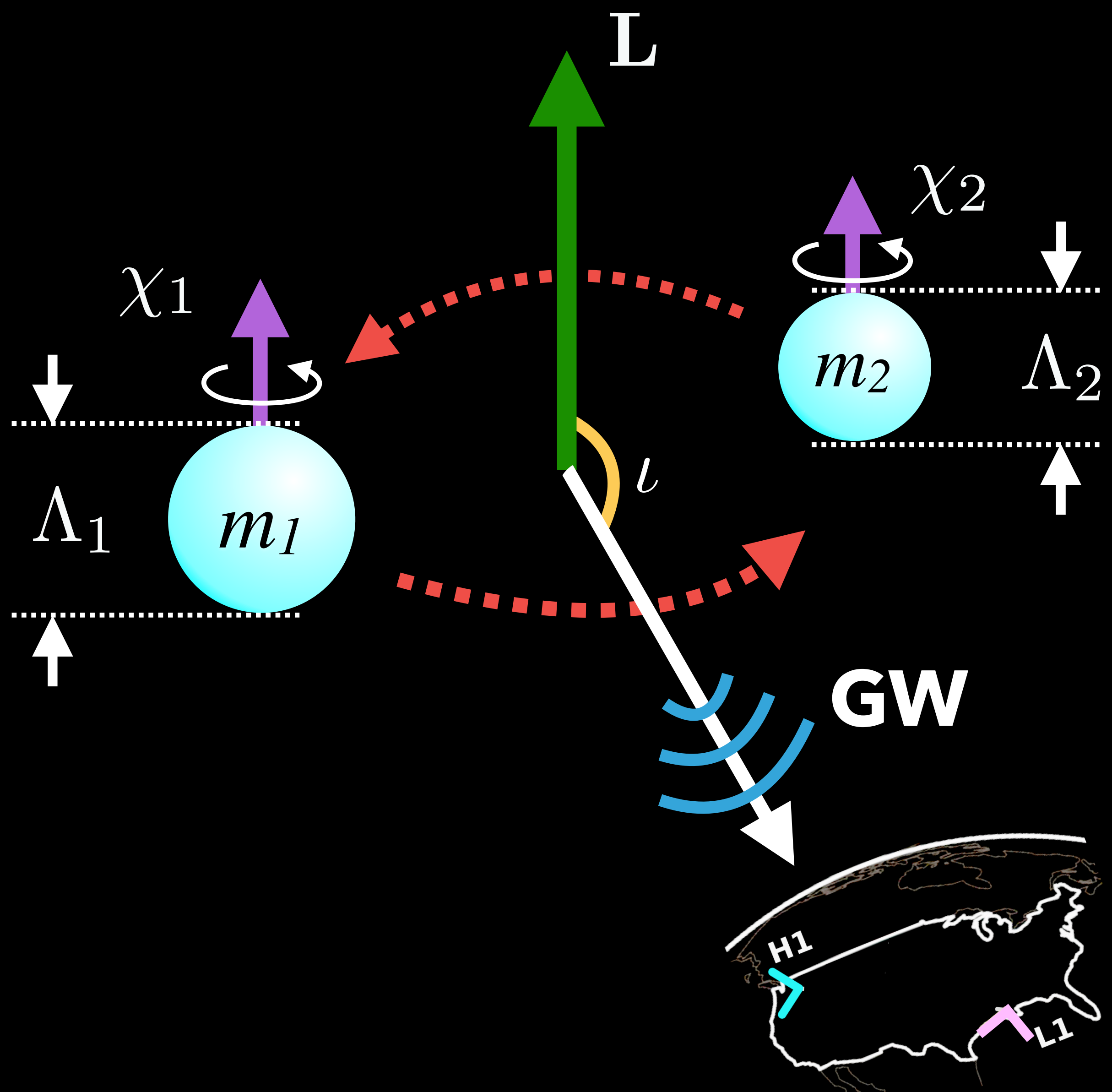
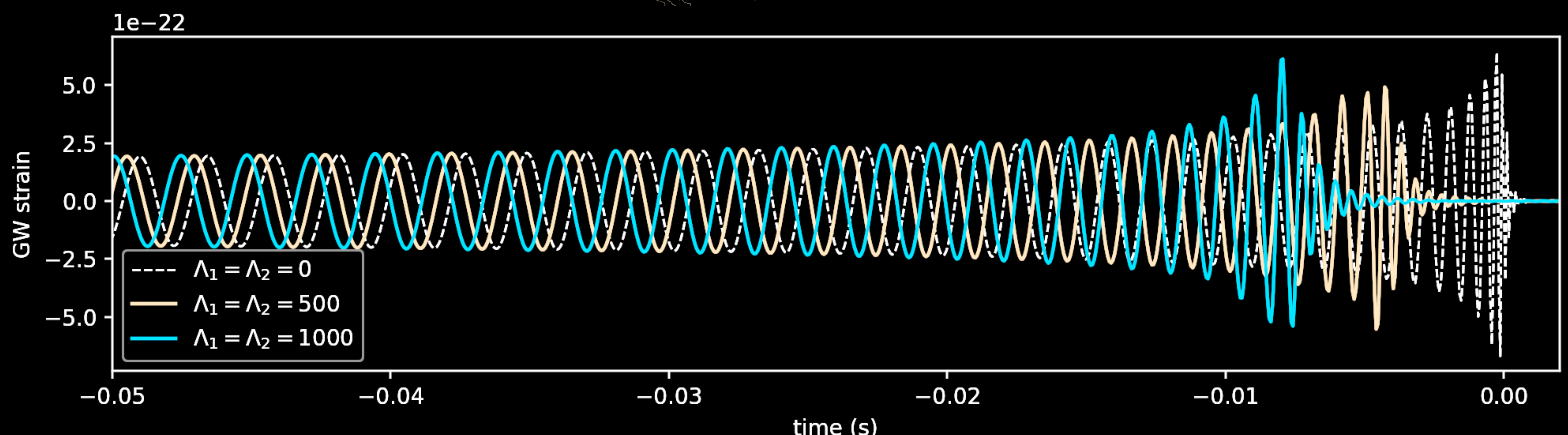




- Tidal forces cause neutron stars to deform
- Deformation is encoded in gravitational wave
- Amount of deformation depends on EOS

$$\Lambda_i \equiv \frac{2}{3} k_2 \left(\frac{G m_i}{R_i c^2} \right)^{-5}$$



BAYESIAN INFERENCE

- GW's source parameters are estimated using Bayesian inference.
- Assume a signal h exists in data d.
- Probability that the signal has parameters $\vartheta = \{m_1, m_2, \ldots\}$ is:

$$p(\vec{\vartheta}|d, h) = \frac{p(d|\vec{\vartheta}, h)\, p(\vec{\vartheta}|h)}{p(d|h)}$$

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- Marginal distribution:

$$p(\vartheta_n|d,h) \propto \int p(d|\vec{\vartheta},h)p(\vec{\vartheta}|h)\mathrm{d}\vartheta_1 \cdots \mathrm{d}\vartheta_{n-1}$$

BAYESIAN INFERENCE

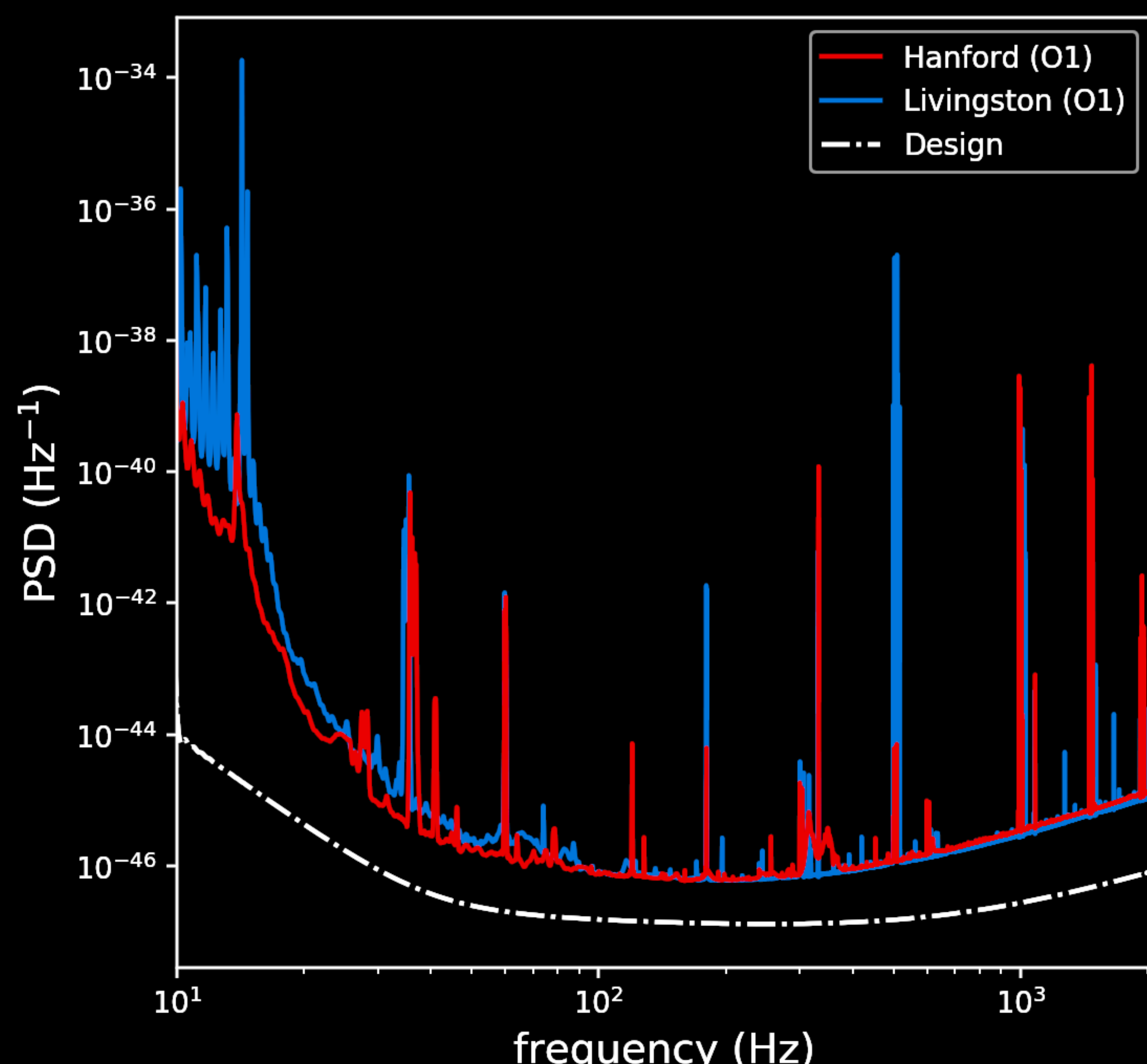
- In N_d detectors with wide-sense stationary Gaussian noise, likelihood is:

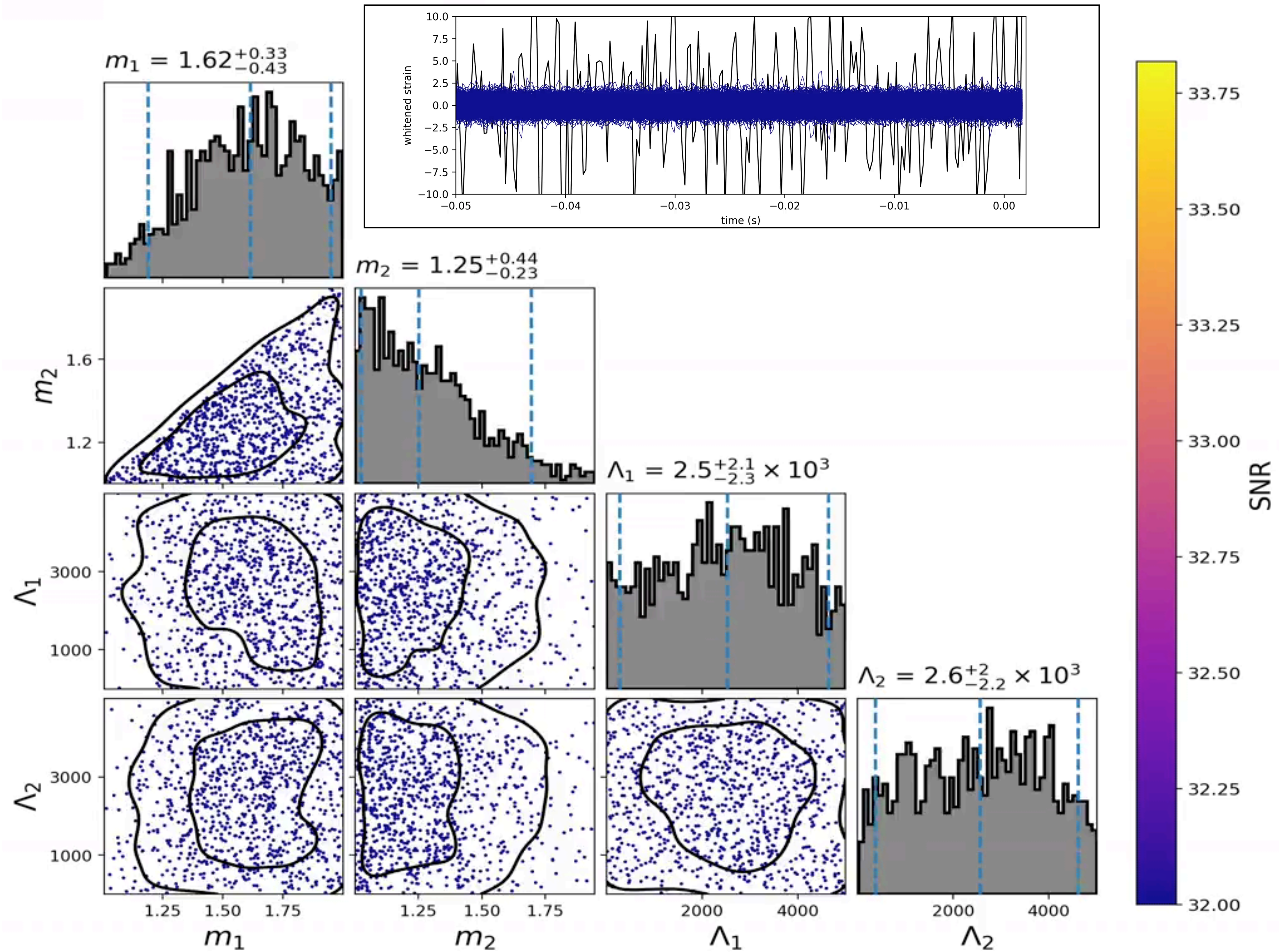
$$\log p(d|\vec{\vartheta}, h) \propto -\frac{1}{2}\sum_{i=1}^{N_d}\left\langle d_i - h_i(\vec{\vartheta}),\, d_i - h_i(\vec{\vartheta})\right\rangle$$

where:

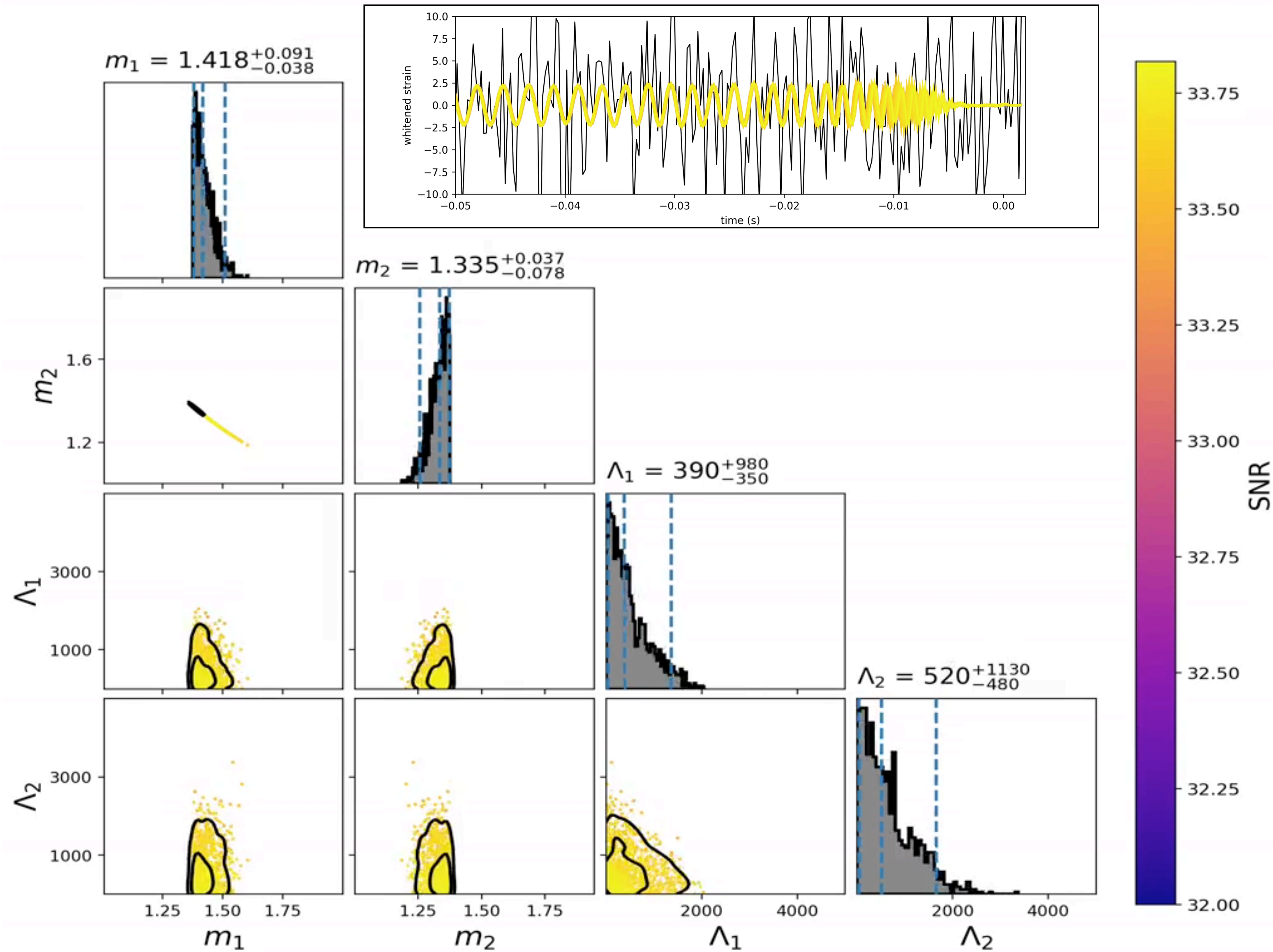
$$\langle a,\, b\rangle = 4\Re\int_0^\infty \frac{\tilde{a}^*(f)\tilde{b}(f)}{S_n(f)}\mathrm{d}f$$

Power Spectral Density (PSD)





$m_1 = 1.62^{+0.33}_{-0.43}$
$m_2 = 1.25^{+0.44}_{-0.23}$
$\Lambda_1 = 2.5^{+2.1}_{-2.3} \times 10^3$
$\Lambda_2 = 2.6^{+2}_{-2.2} \times 10^3$
whitened strain
time (s)
SNR
m_1
m_2
Λ_1
Λ_2



whitened strain
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
−0.05
−0.04
−0.03
−0.02
−0.01
0.00
time (s)
$m_1 = 1.418^{+0.091}_{-0.038}$
$m_2 = 1.335^{+0.037}_{-0.078}$
$\Lambda_1 = 390^{+980}_{-350}$
$\Lambda_2 = 520^{+1130}_{-480}$
m_2
1.6
1.2
Λ_1
3000
1000
Λ_2
3000
1000
1.25
1.50
1.75
m_1
1.25
1.50
1.75
m_2
2000
4000
Λ_1
2000
4000
Λ_2
SNR
33.75
33.50
33.25
33.00
32.75
32.50
32.25
32.00

INITIAL ANALYSIS

- Initial result: tidal deformation of each component allowed to vary independently
- Equivalent to allowing each NS to have a different EOS
- Enforcing both NS to have the same EOS requires sampling over EOS is some way

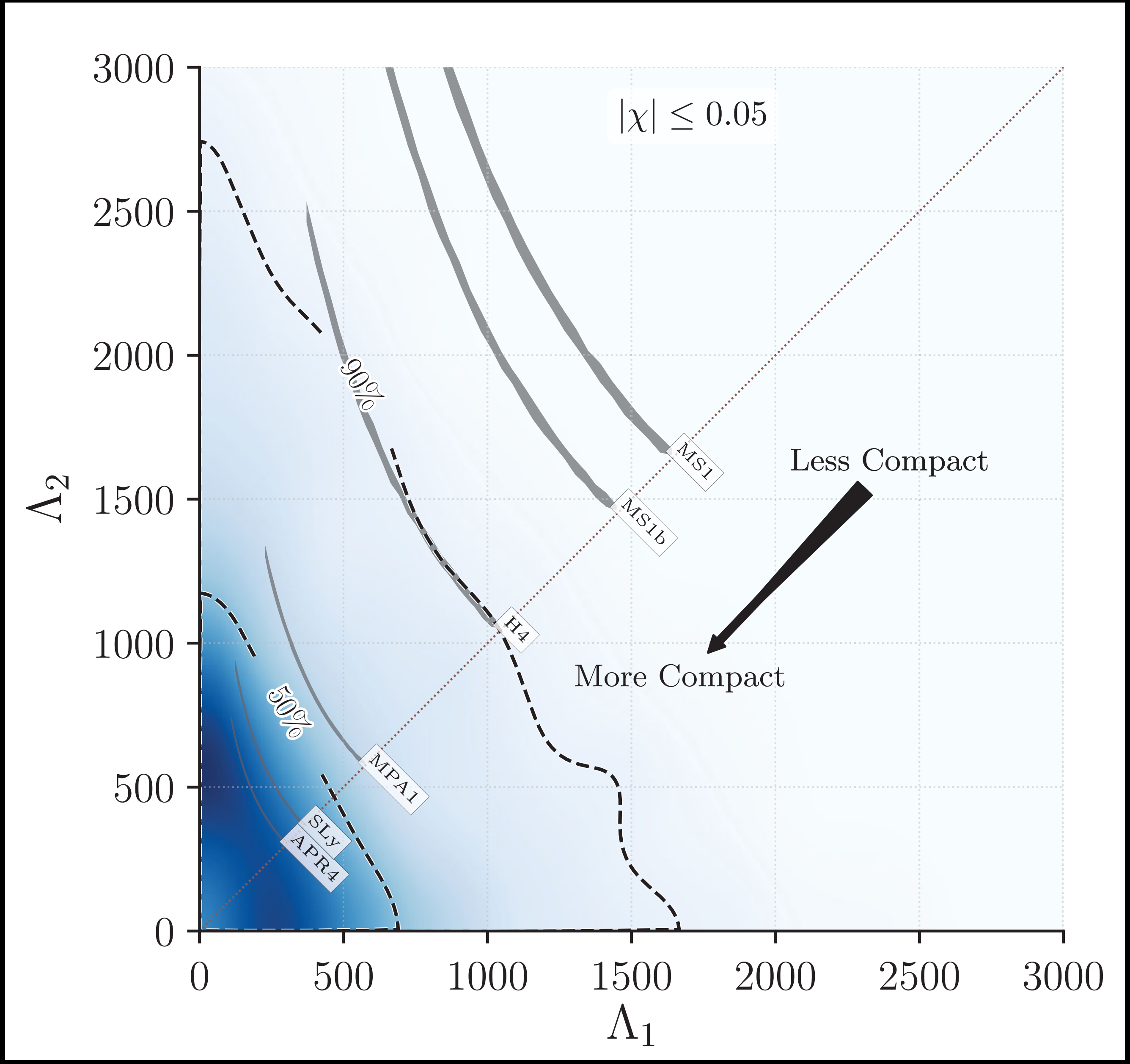
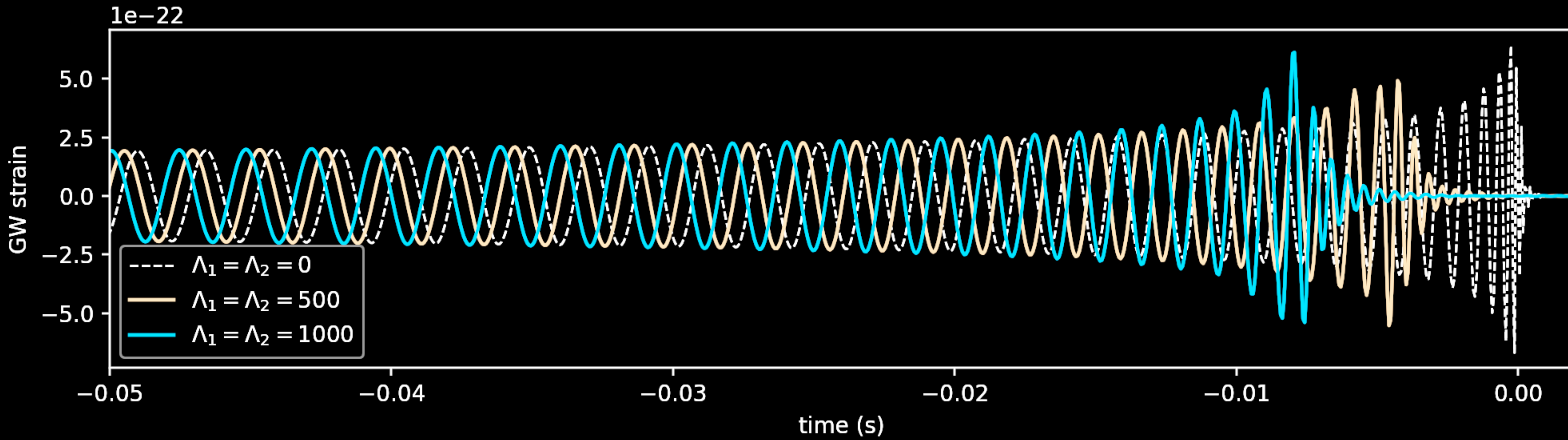
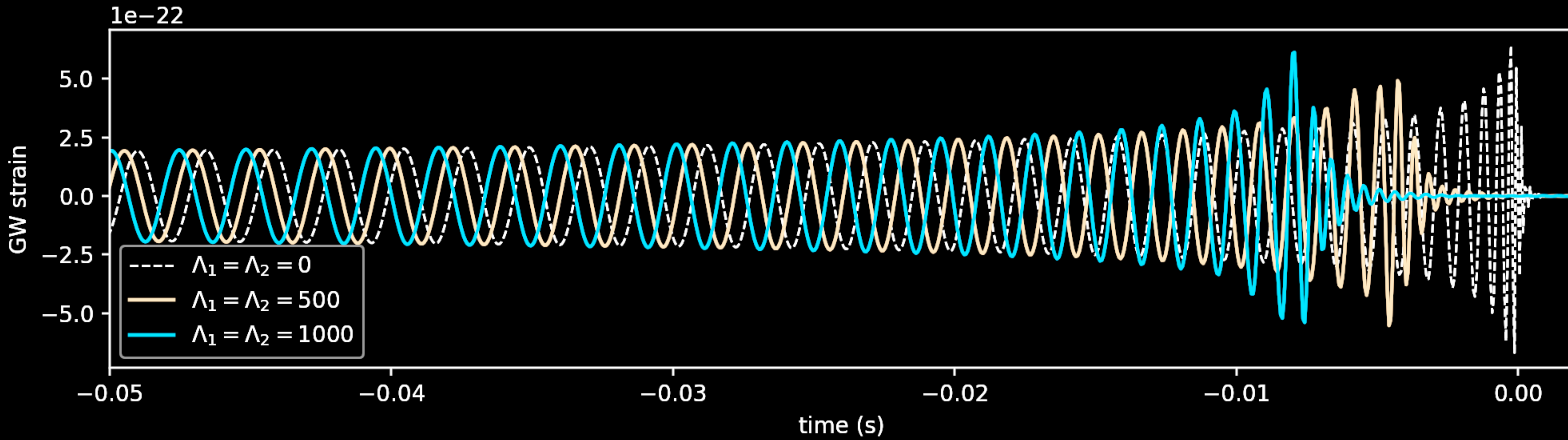


Fig. 5 from LSC+Virgo PRL 119 161101 (2017)



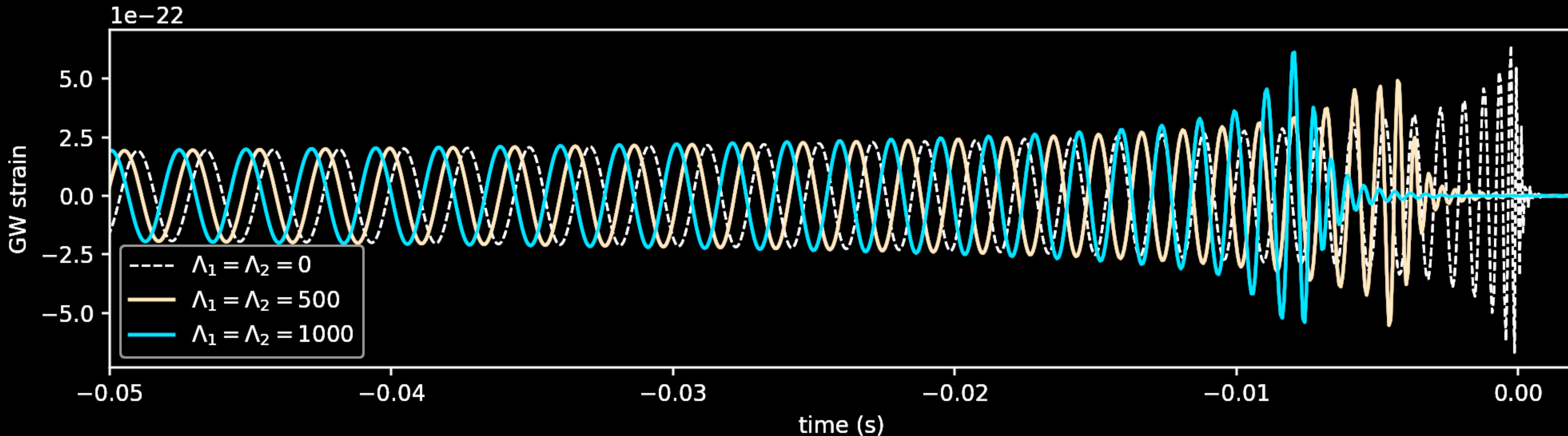
1e−22
5.0
2.5
0.0
−2.5
−5.0
GW strain
$\Lambda_1 = \Lambda_2 = 0$
$\Lambda_1 = \Lambda_2 = 500$
$\Lambda_1 = \Lambda_2 = 1000$
−0.05
−0.04
−0.03
−0.02
−0.01
0.00
time (s)



$$\Phi_{\mathrm{GW}}(t) \sim \varphi_0(\mathcal{M};t)\left[1+\varphi_1(\eta;t)\left(\frac{v}{c}\right)^2+\ldots+\varphi_5(\tilde{\Lambda};t)\left(\frac{v}{c}\right)^{10}\right]$$

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

Flanagan & Hinderer, PRD 77 021502 (2008)



$$\Phi_{\rm GW}(t) \sim \varphi_0(\mathcal{M};t)\left[1+\varphi_1(\eta;t)\left(\frac{v}{c}\right)^2+\ldots+\varphi_5(\tilde{\Lambda};t)\left(\frac{v}{c}\right)^{10}\right]$$

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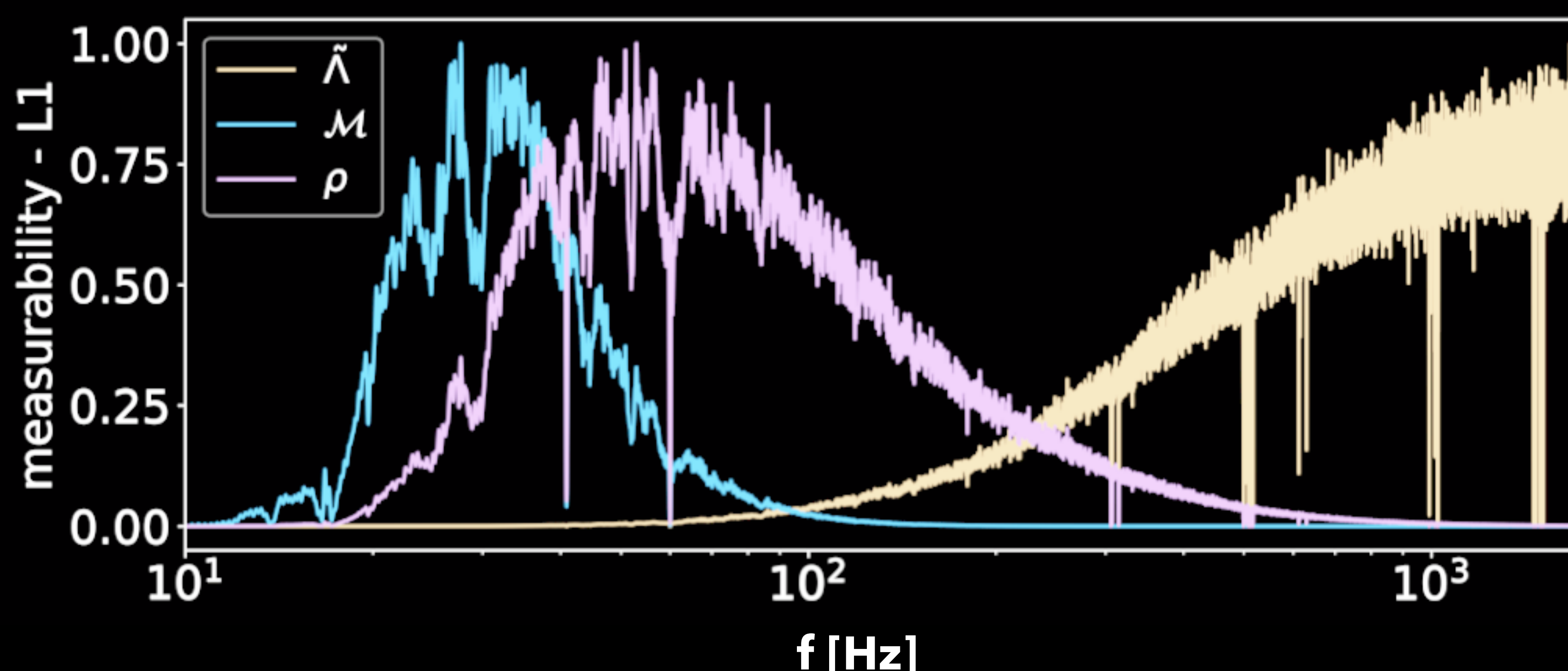
Flanagan & Hinderer, PRD 77 021502 (2008)



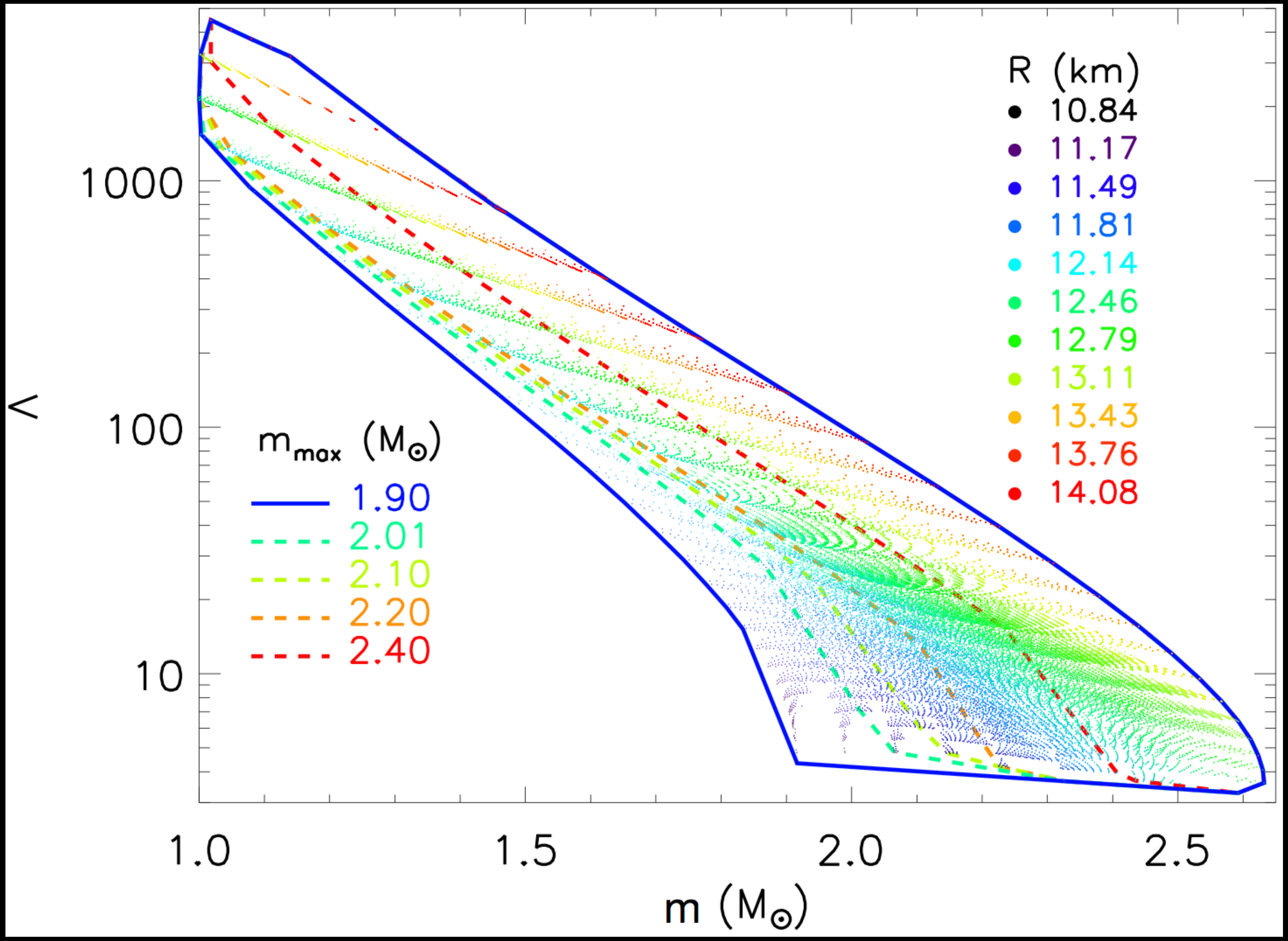
COMMON EOS CONSTRAINT

De et al., PRL 121, 091102 (2018)

Results of TOV integrations for physically realistic polytropes:

- $$\Lambda \approx \alpha \left(\frac{Gm}{Rc^2}\right)^{-6}$$
- $$\langle \Delta R \rangle \equiv \langle R_{1.6} - R_{1.1} \rangle = -0.070\text{km}$$

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



COMMON EOS CONSTRAINT

De et al., PRL 121, 091102 (2018)

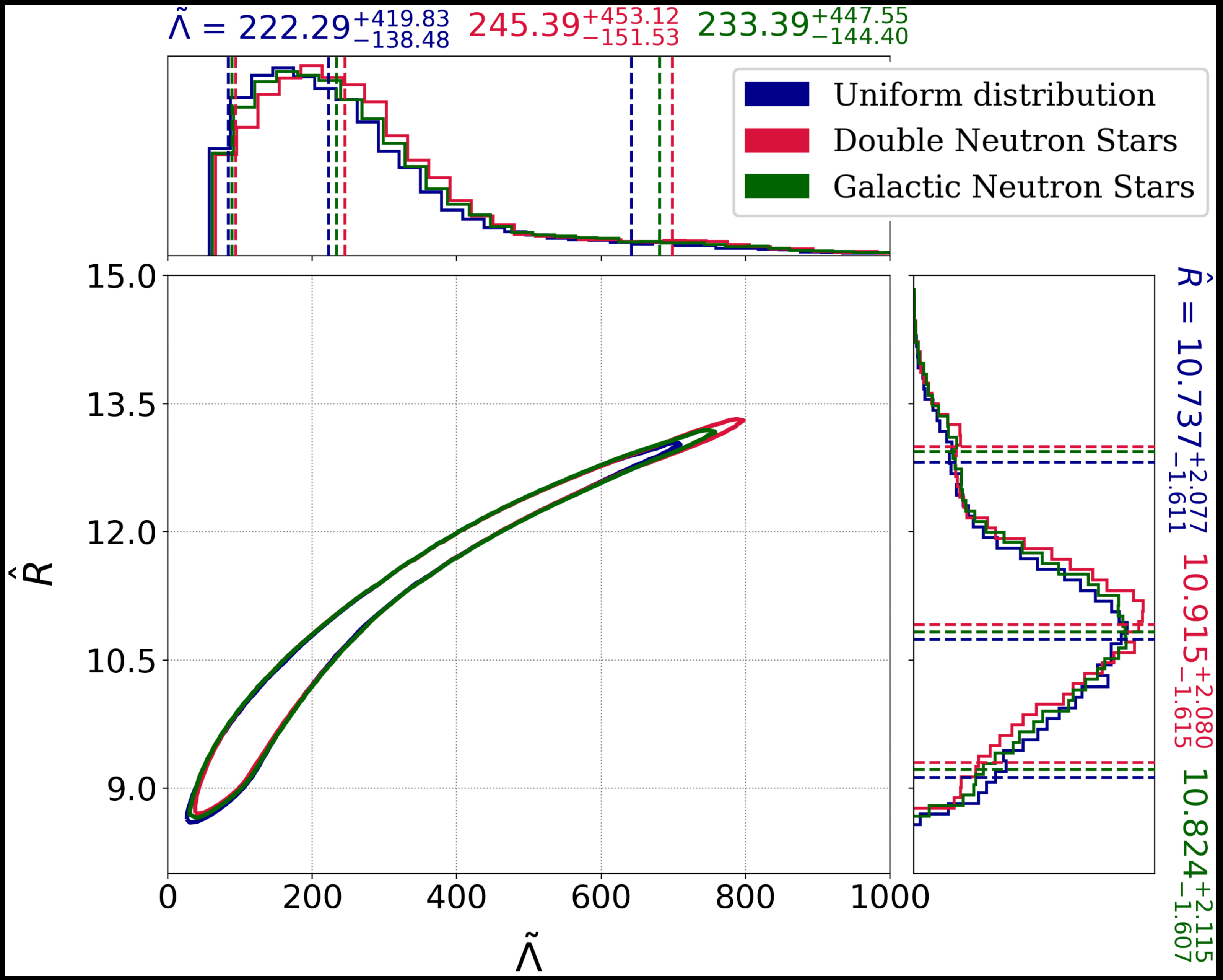
Adopt a common EOS constraint:

$$\hat{R} \equiv R_1 \approx R_2$$

$$\Lambda_1 = q^6 \Lambda_2$$

Get:

$$\hat{R} = 10.74^{+2.08}_{-1.61}\ \mathrm{km}$$



COMMON EOS (LVC)

LSC+Virgo, PRL 121, 161101 (2018)

LVC used two methods to enforce a common EOS

1. "EOS insensitive relations"
   - Use (anti-)symmetric tidal parameters:

$$\Lambda_{s/a} \equiv \frac{1}{2}(\Lambda_1 \pm \Lambda_2)$$

   - And a universal fit* over EOS to relate the two:

$$\Lambda_a = F(\Lambda_s, q; \vec{b})$$

   - Then sample in $\boldsymbol{\Lambda}_s$, with uniform prior in [0, 5000)

*Yagi & Yunes, CQG 33, 13LT01 (2016)

COMMON EOS (LVC)

LSC+Virgo, PRL 121, 161101 (2018)

LVC used two methods to enforce a common EOS

2. "Parameterized EOS"

- Use spectral expansion* of EOS adiabatic index Γ:

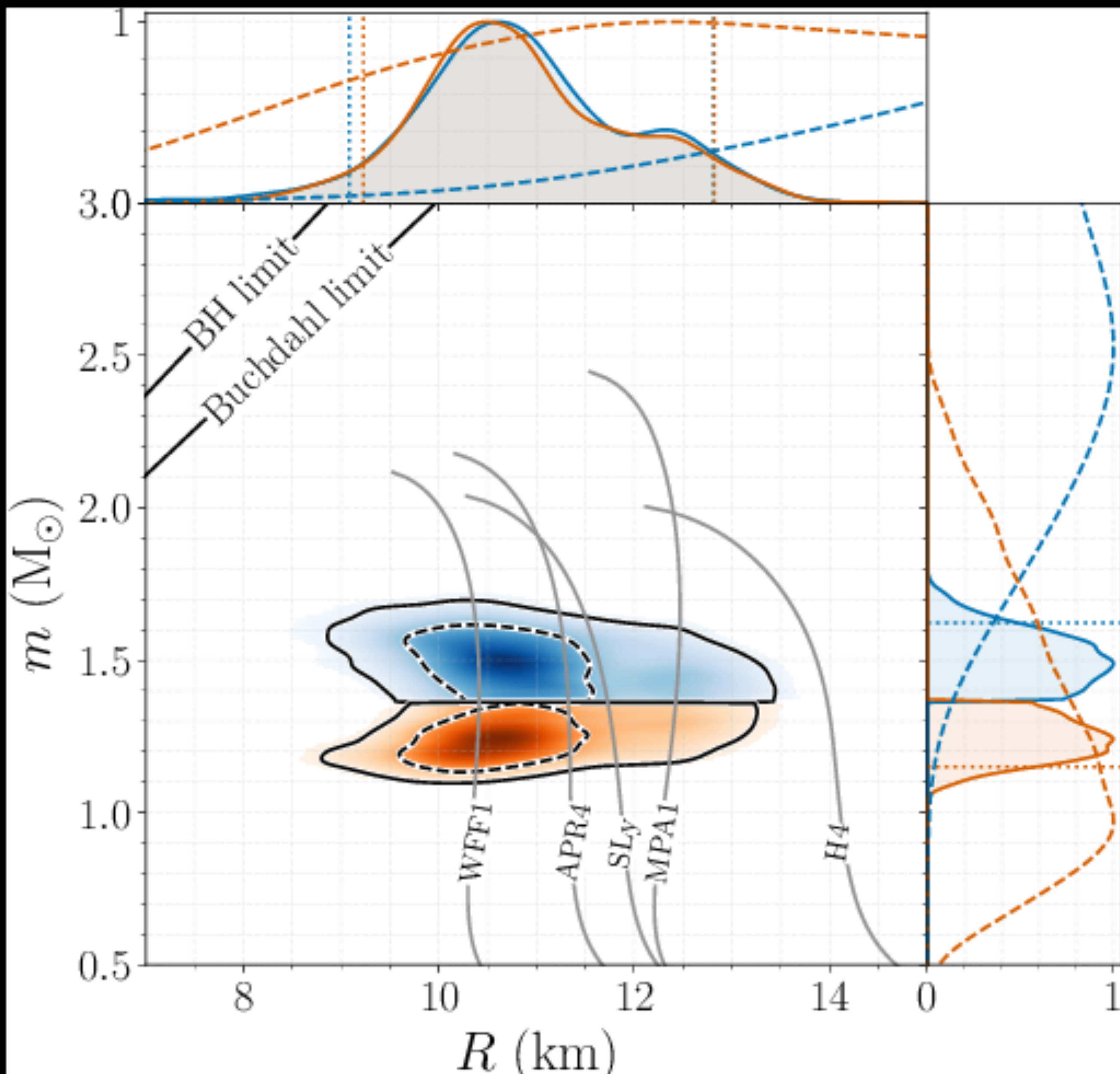
$$\Gamma(p) \equiv \frac{\epsilon + p}{p} \frac{\mathrm{d}p}{\mathrm{d}\epsilon} \approx \exp\left[\sum_{k=0}^{3} \gamma_k \log(p/p_0)\right]$$

- Sample directly in the four γ_k
- For each set of $\{\gamma_k\}$, integrate TOV equations to get $\Lambda_{1,2}$
- Include constraint that EOS must support $M_{NS} > 1.97 M_\odot$

*Lindblom, PRD 82, 103011 (2010)

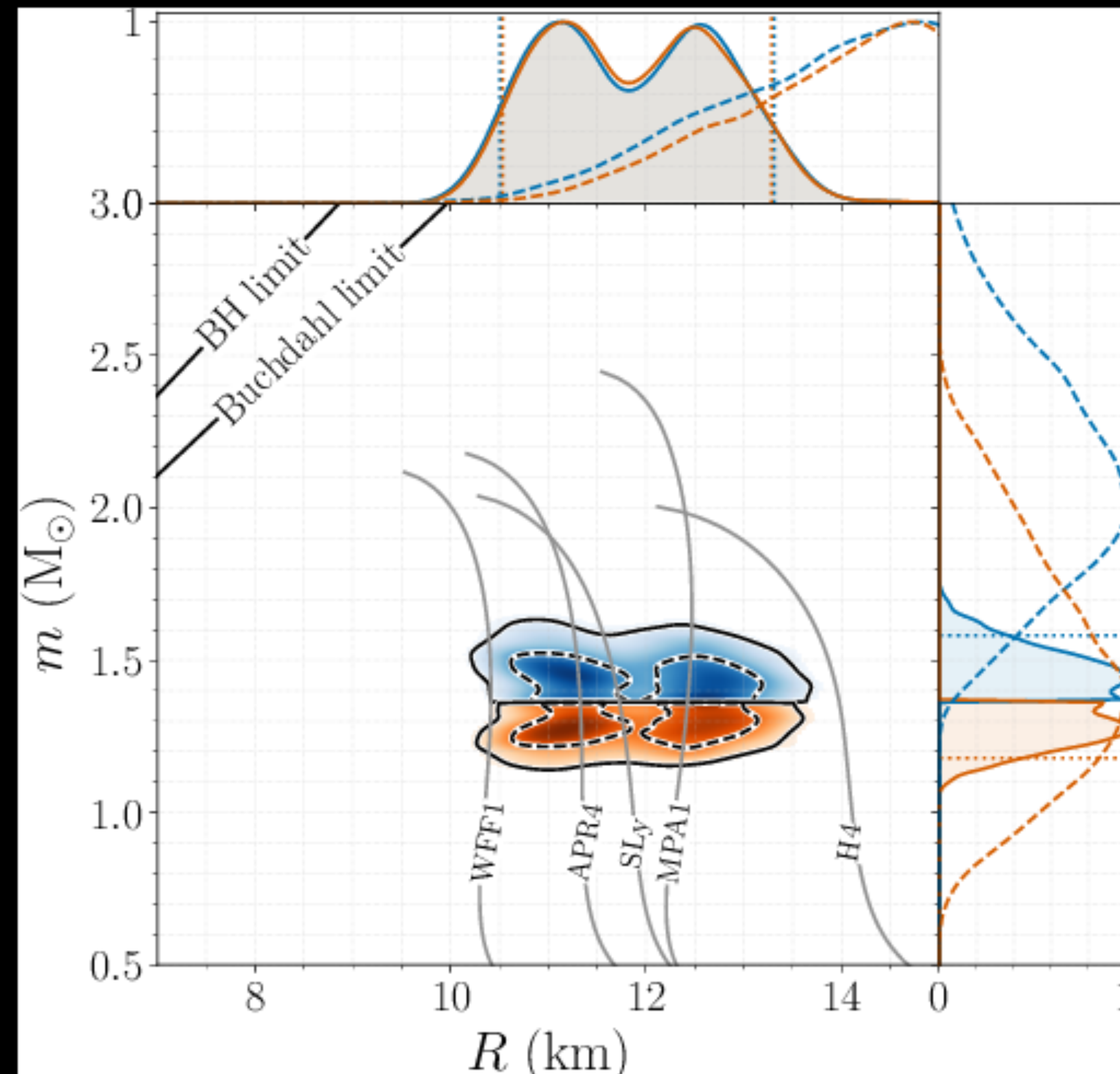
COMMON EOS (LVC)

EOS Insensitive



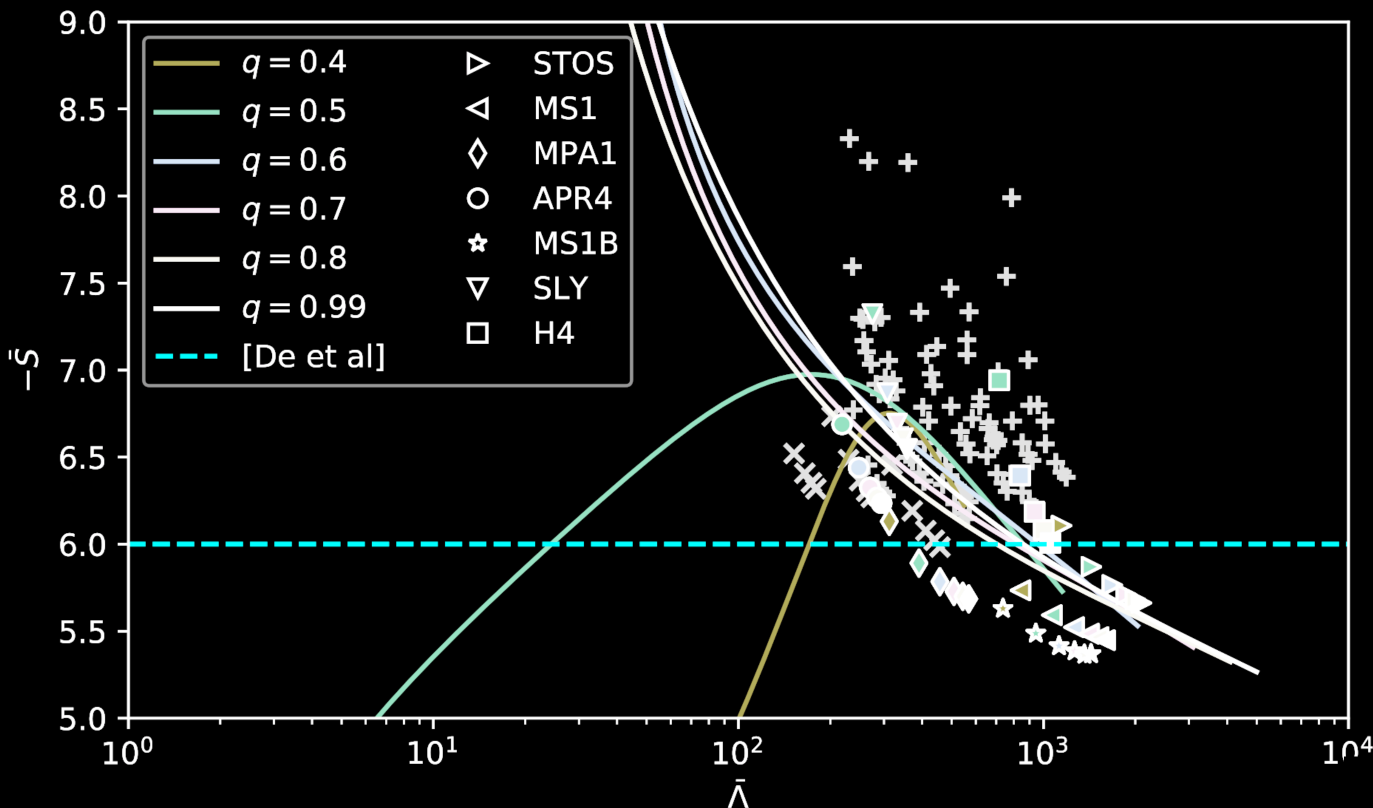
$$R_1 = 10.8^{+2.0}_{-1.7}\,\mathrm{km},\ \mathrm{R}_2 = 10.7^{+2.1}_{-1.5}\,\mathrm{km}$$

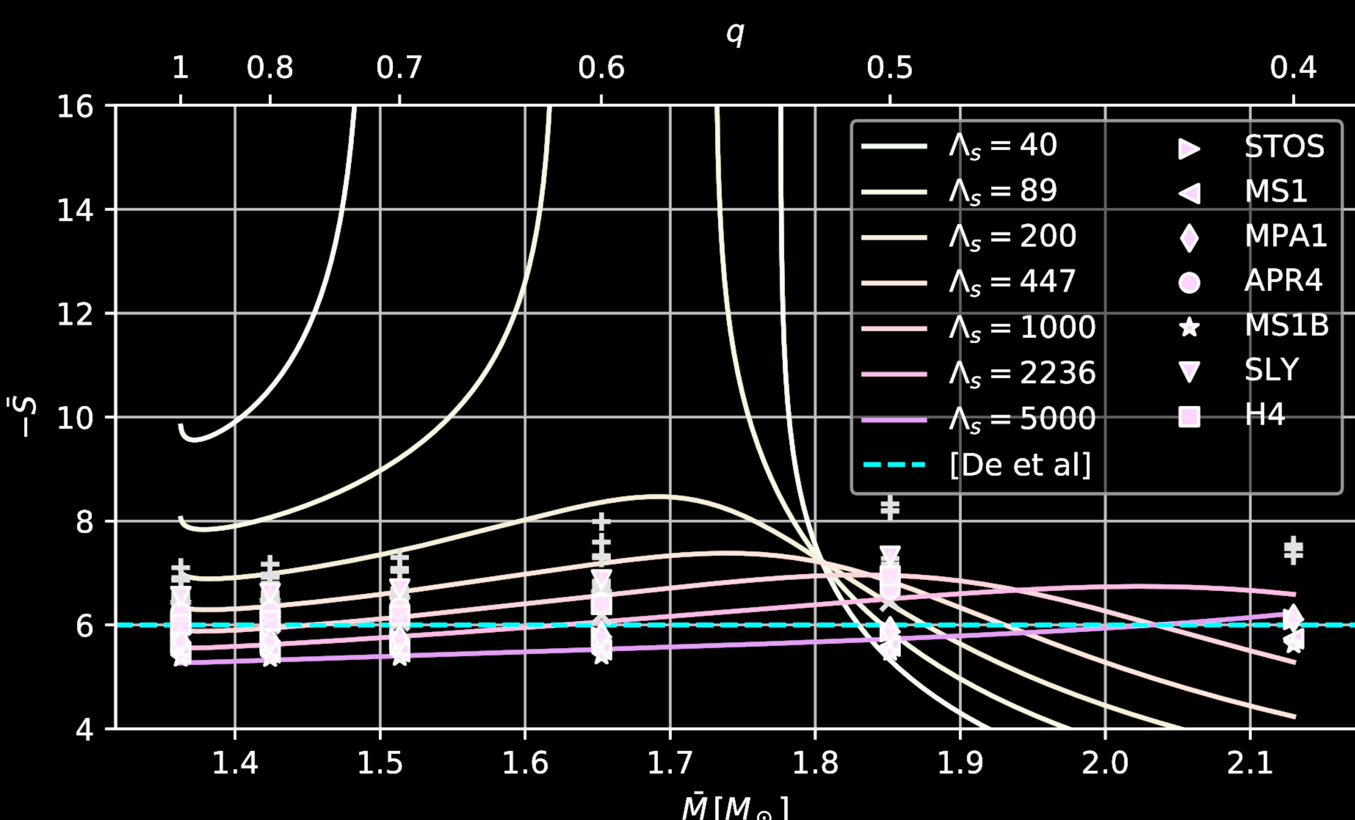
Parameterized EOS



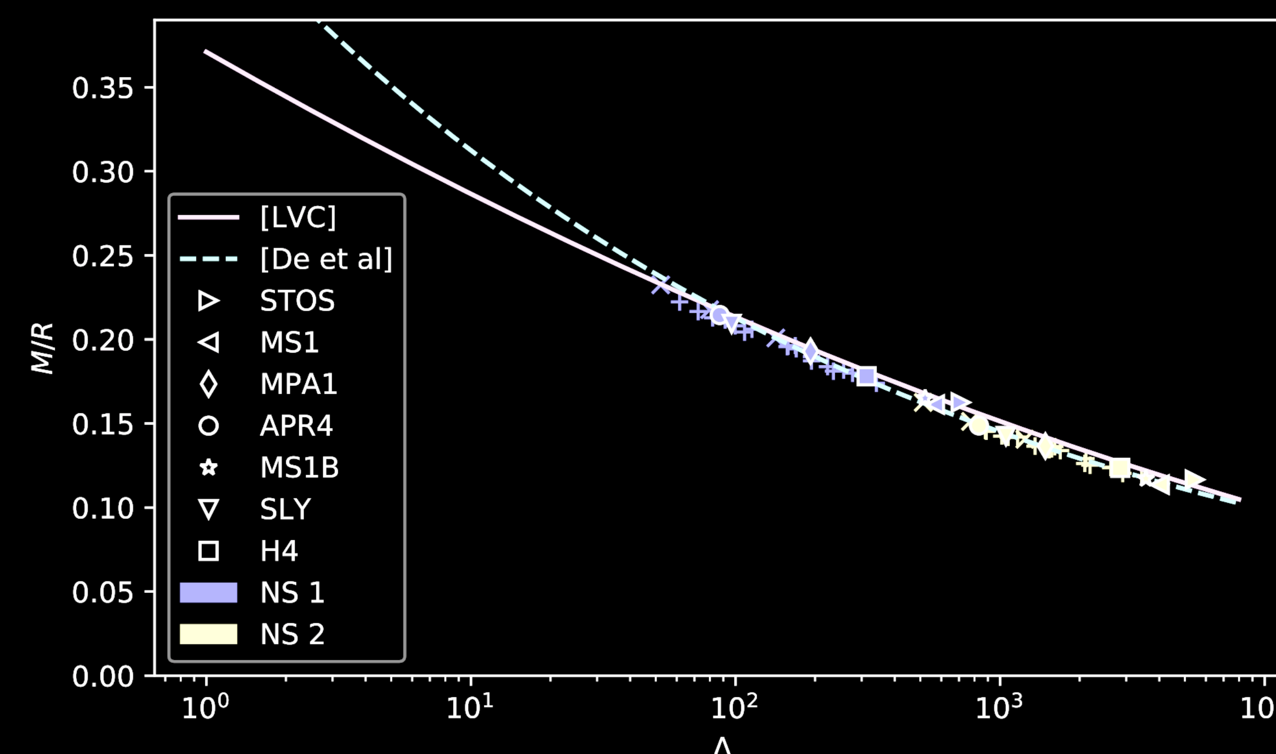
$$R_{1,2} = 11.9^{+1.4}_{-1.4}\,\mathrm{km}$$

LOWER BOUND ISSUES

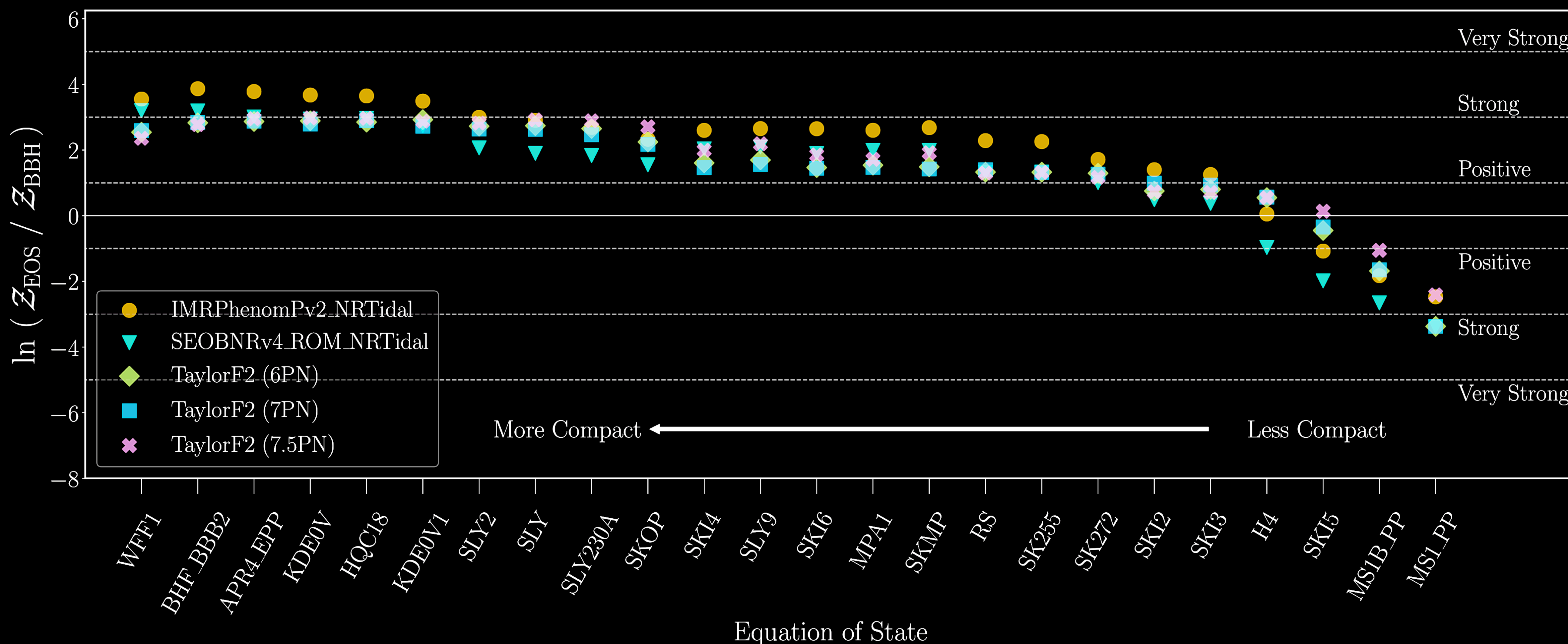




- Kastaun & Ohme* pointed out that the quoted lower bounds on the Λ's and radii are somewhat meaningless

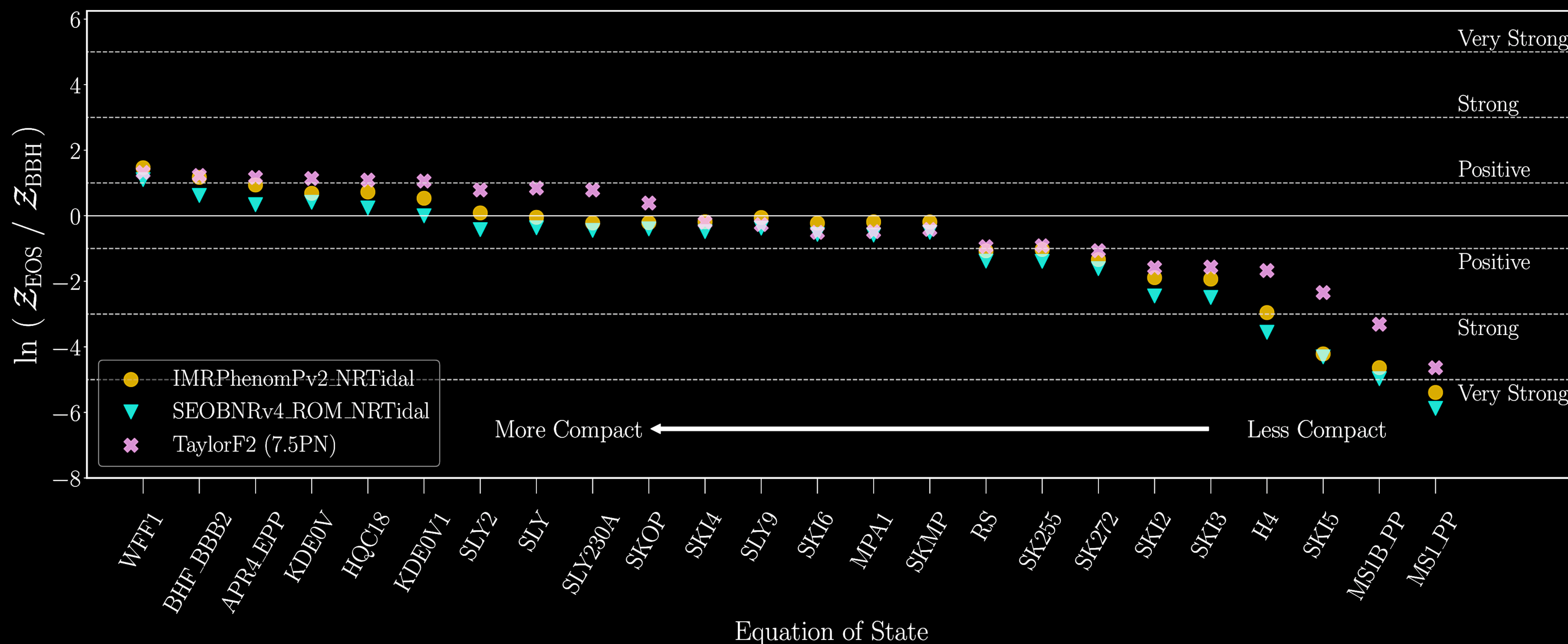


*Kastaun & Ohme, arXiv:1909.12718 (2019)



$$m_{1,2}/\mathrm{M}_\odot \sim \mathcal{N}(1.33, 0.09)$$
$$|\chi_{1,2}| \sim U(0, 0.05)$$

LSC+Virgo, arXiv:1908.01012 (2019)
[see also De et al., PRL 121, 091102 (2018)]

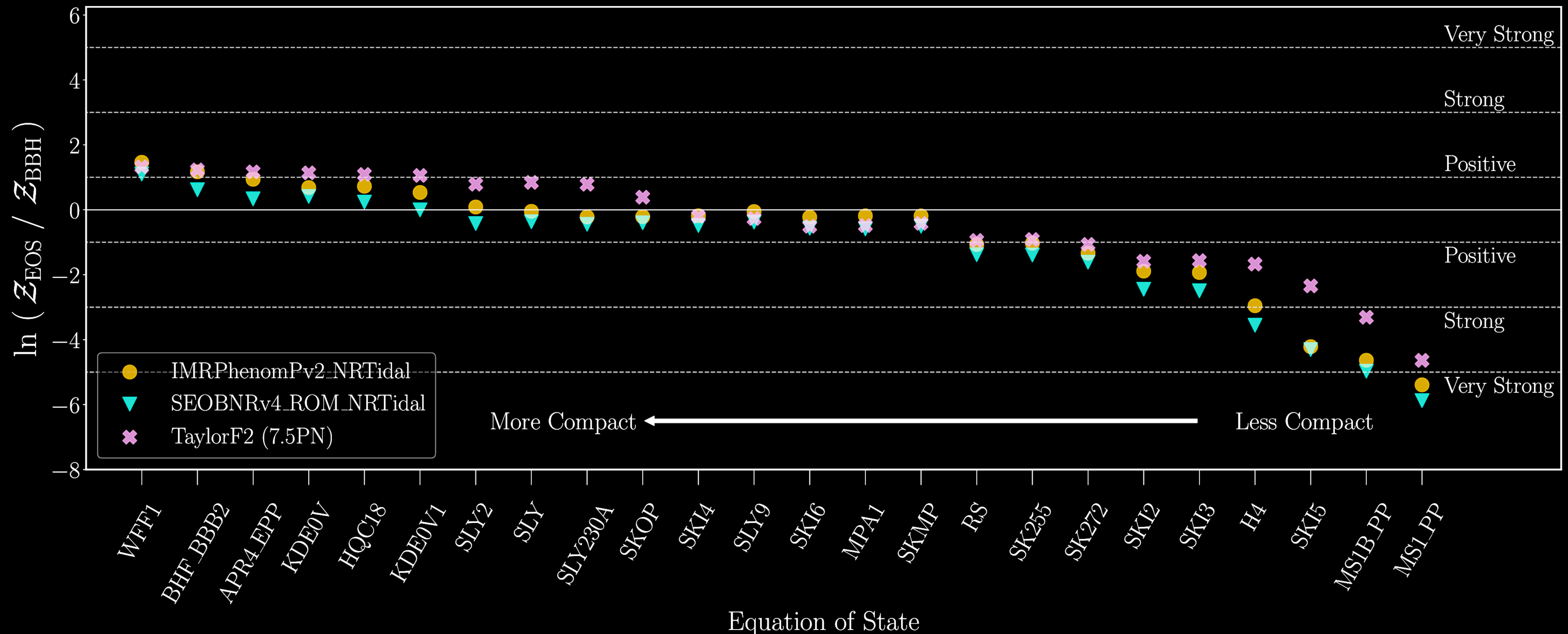


$$m_{1,2}/\mathrm{M}_\odot \sim U(0.7, 3)$$
$$|\chi_{1,2}| \sim U(0, 0.7)$$

LSC+Virgo, arXiv:1908.01012 (2019)

[see also De et al., PRL 121, 091102 (2018)]

GW data alone cannot distinguish BH from NS



$$m_{1,2}/\mathrm{M}_\odot \sim U(0.7, 3)$$
$$|\chi_{1,2}| \sim U(0, 0.7)$$

LSC+Virgo, arXiv:1908.01012 (2019)
[see also De et al., PRL 121, 091102 (2018)]

COMBINING NUCLEAR THEORY WITH GW AND EM OBSERVATIONS

Capano et al., arXiv:1908.10352 (2019)

COLLABORATORS

- Ingo Tews, Los Alamos National Lab
- Stephanie Brown, AEI Hannover
- Ben Margalit, UC Berkeley
- Soumi De, Syracuse University
- Sumit Kumar, AEI Hannover
- Duncan Brown, Syracuse University
- Badri Krishnan, AEI Hannover
- Sanjay Reddy, University of Washington

OUR STUDY

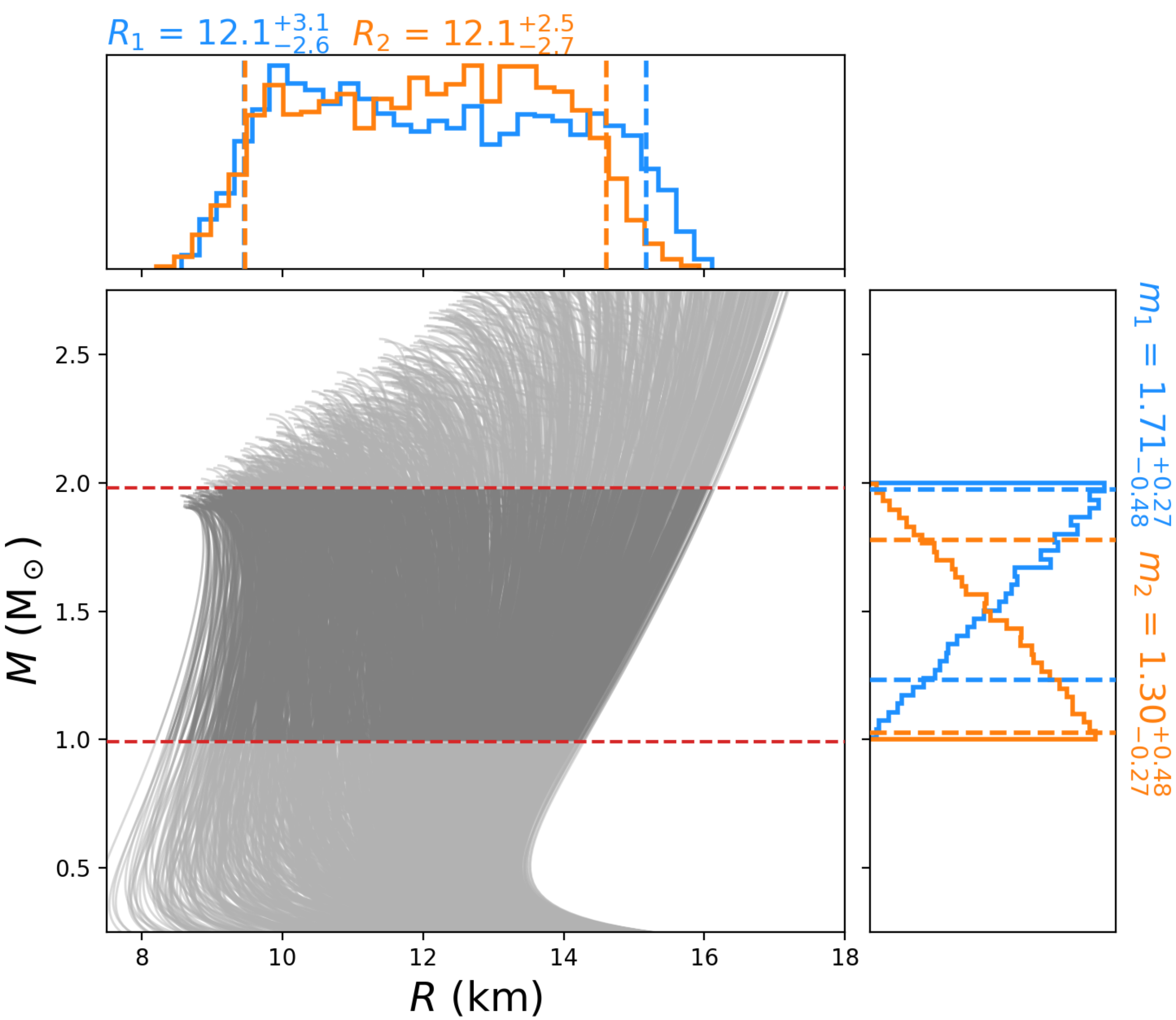
- Use chiral effective field theory (EFT) to produce a collection of physically-plausible equations of state
- Two collections of equations of state considered
- Enforce EFT constraints up to:
  - nuclear saturation density (n_{sat})
  - twice nuclear saturation density ($2n_{sat}$)
- At higher densities, enforce causality & EOS supports NS masses $\geq 2M_{\odot}$

OUR STUDY

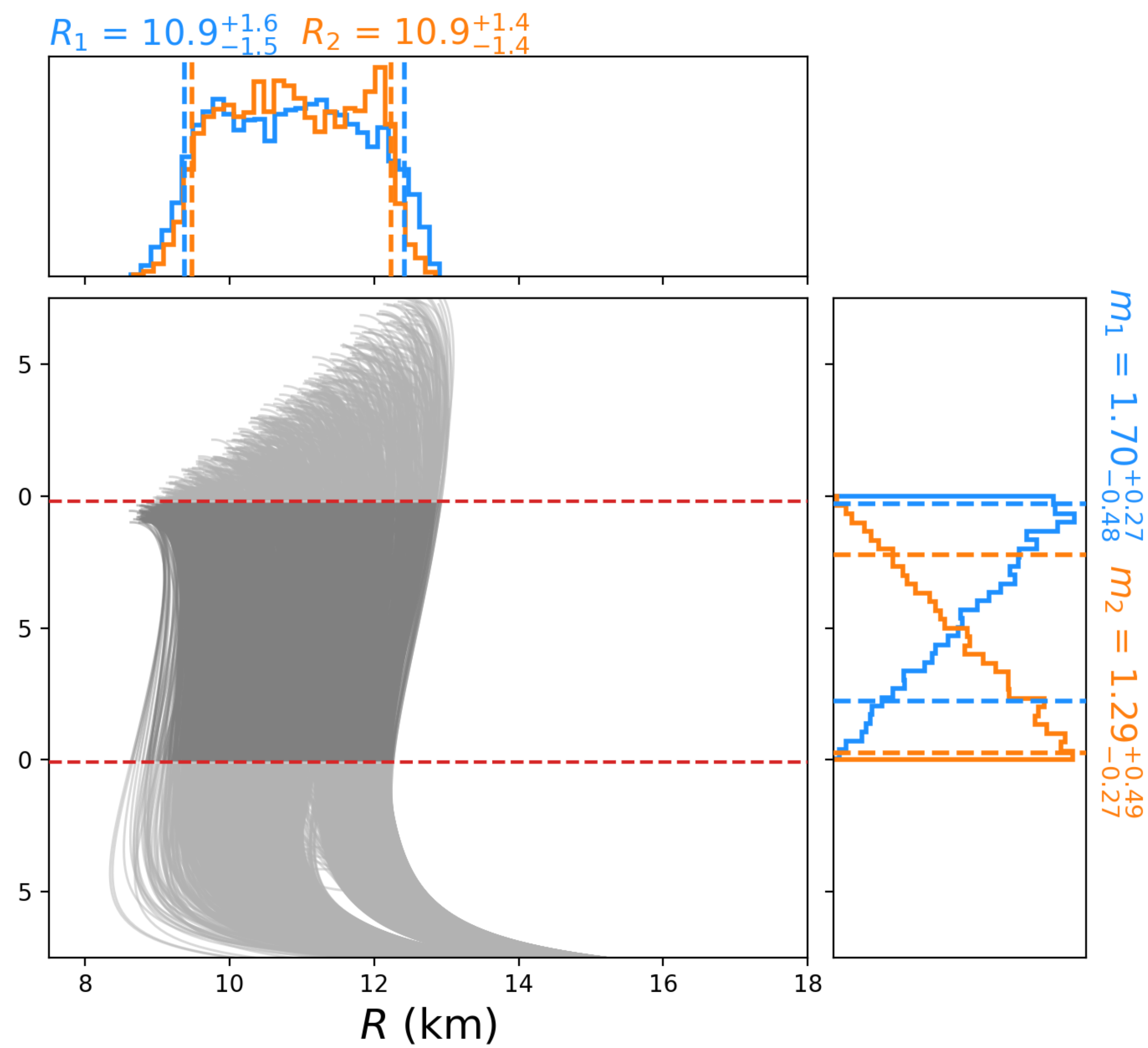
- EOS are constructed such that the prior on $R_{1.4}$ ~ uniform
- Order EOS by $R_{1.4}$
- Sample directly over discrete equations of state

PRIOR

n_{sat}

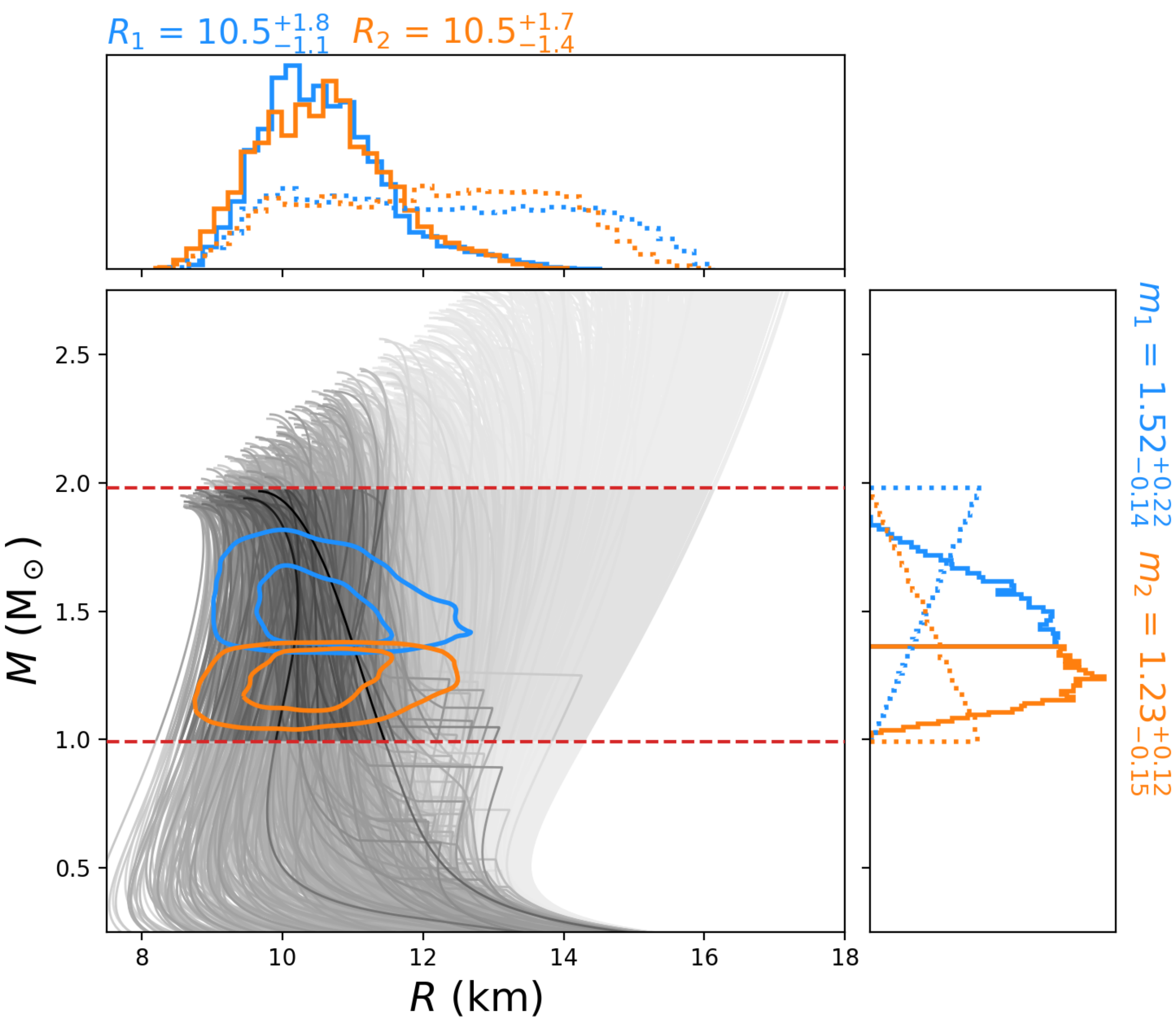


$2n_{sat}$

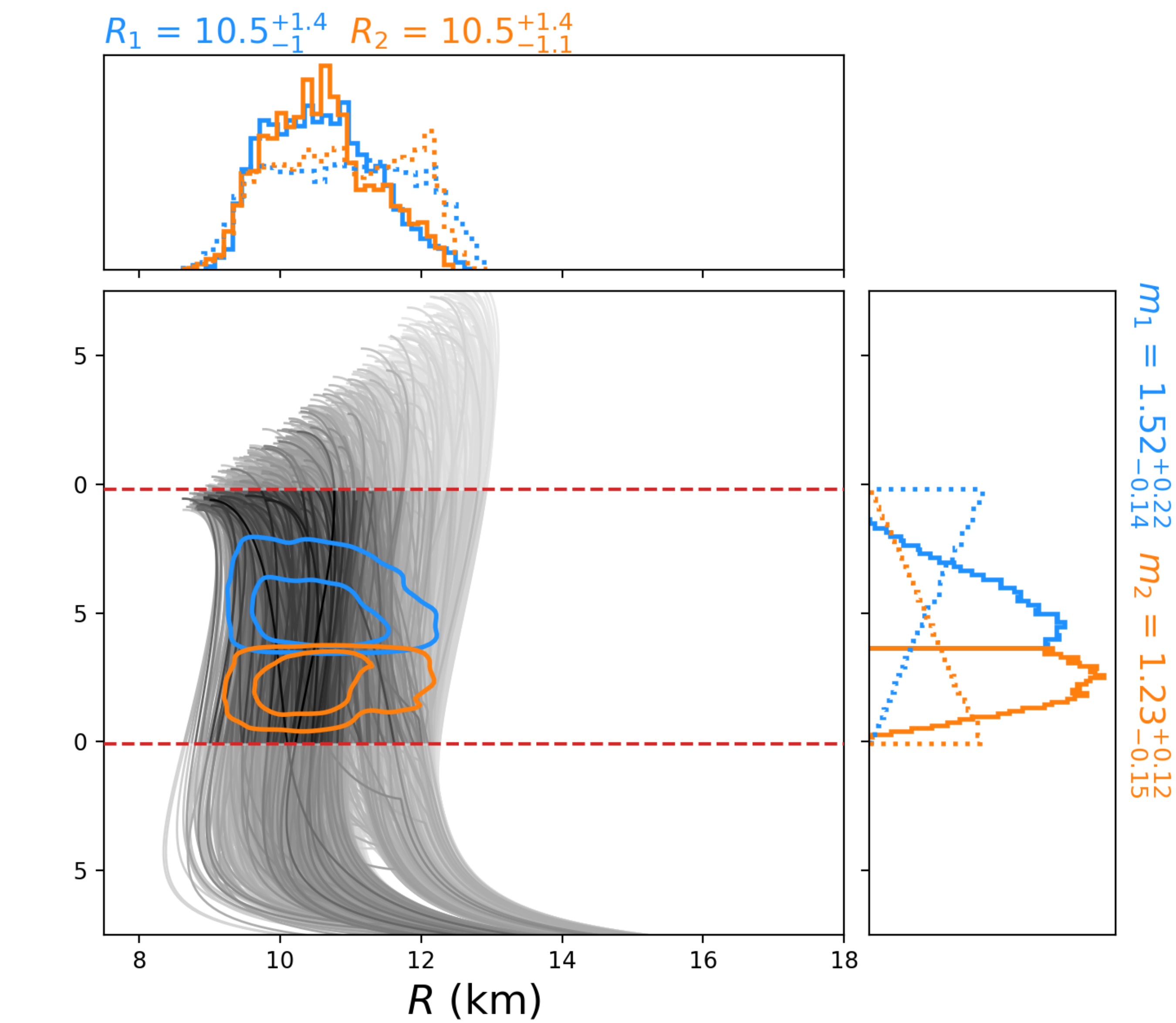


GW POSTERIOR

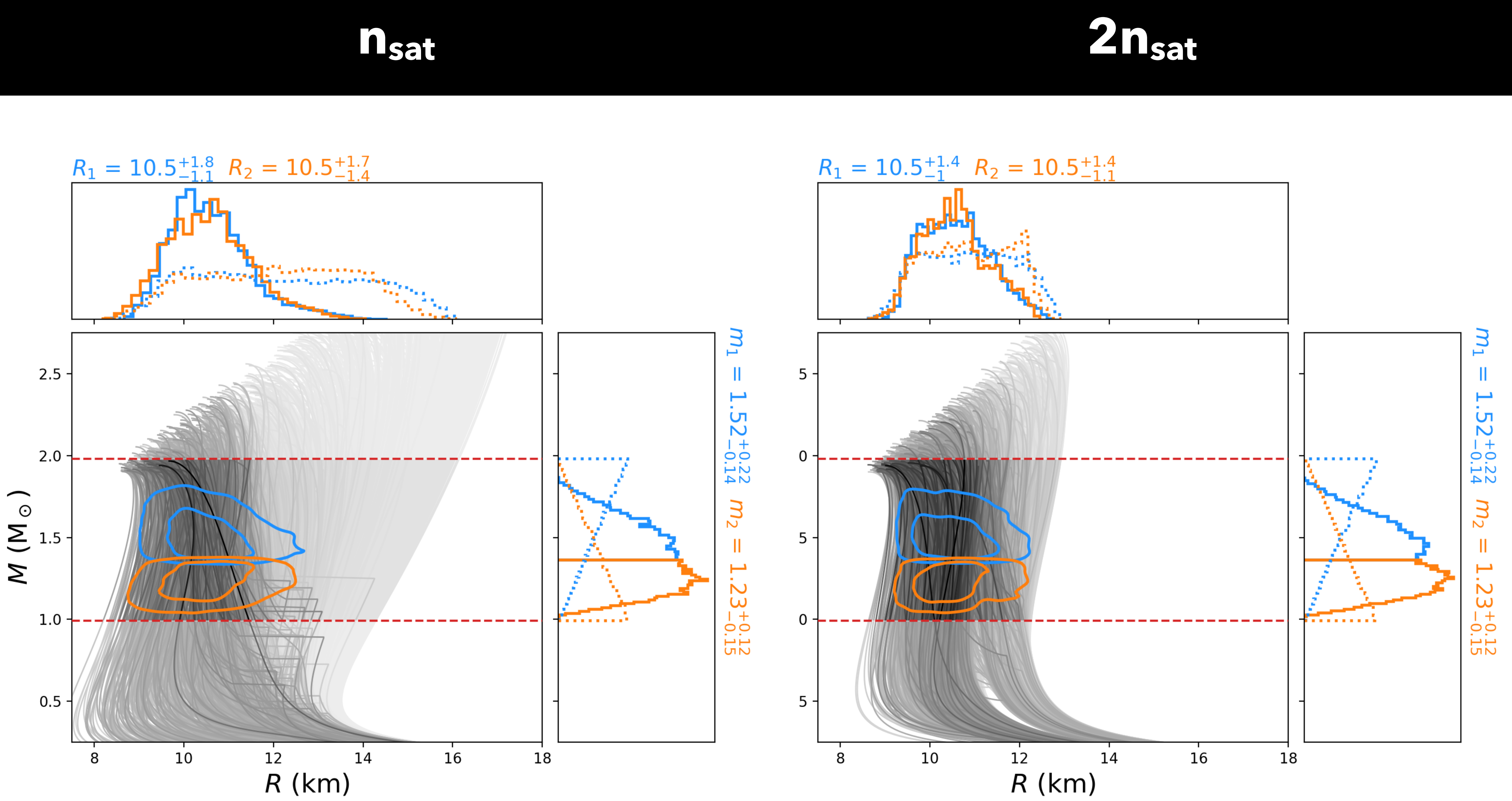
n_{sat}



$2n_{sat}$

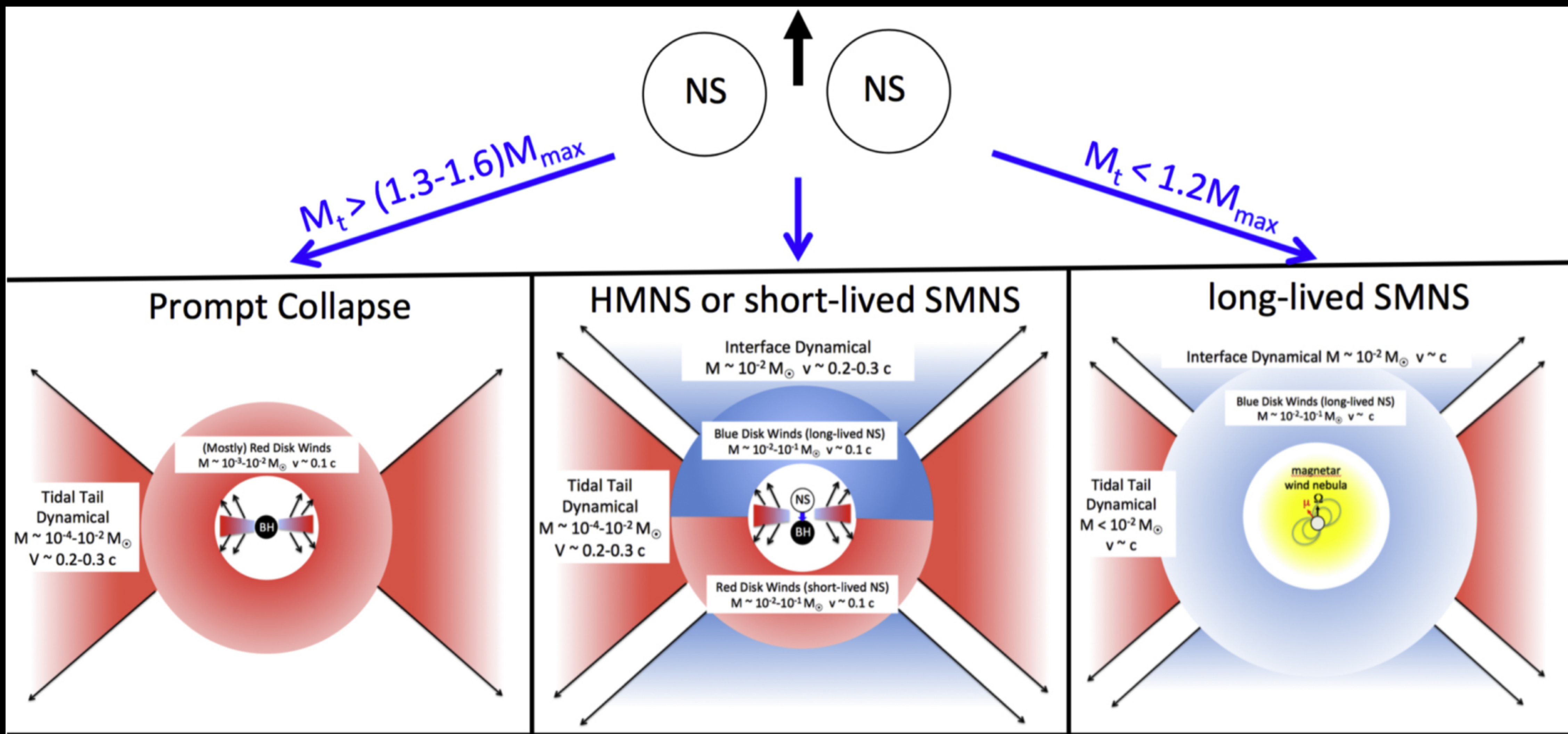


GW POSTERIOR



Suggests the chiral EFT approach can be applied up to twice nuclear saturation density

EM CONSTRAINTS

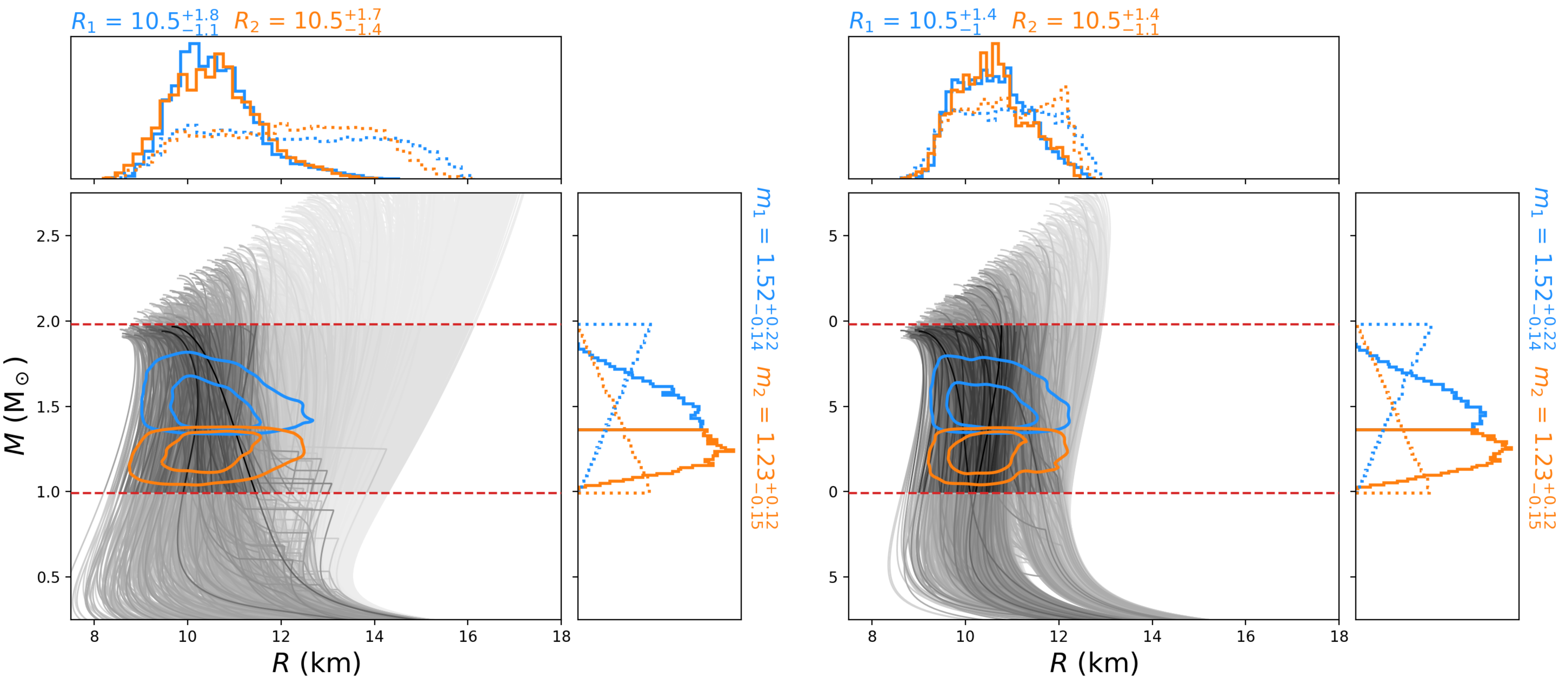


Margalit & Metzger, ApJ 850 (2017) no.2, L19

- Use fit from Bauswein et al. to estimate threshold mass for prompt collapse; exclude any points with total mass larger than threshold
- Also exclude any points with maximum NS mass > $2.3M_\odot$

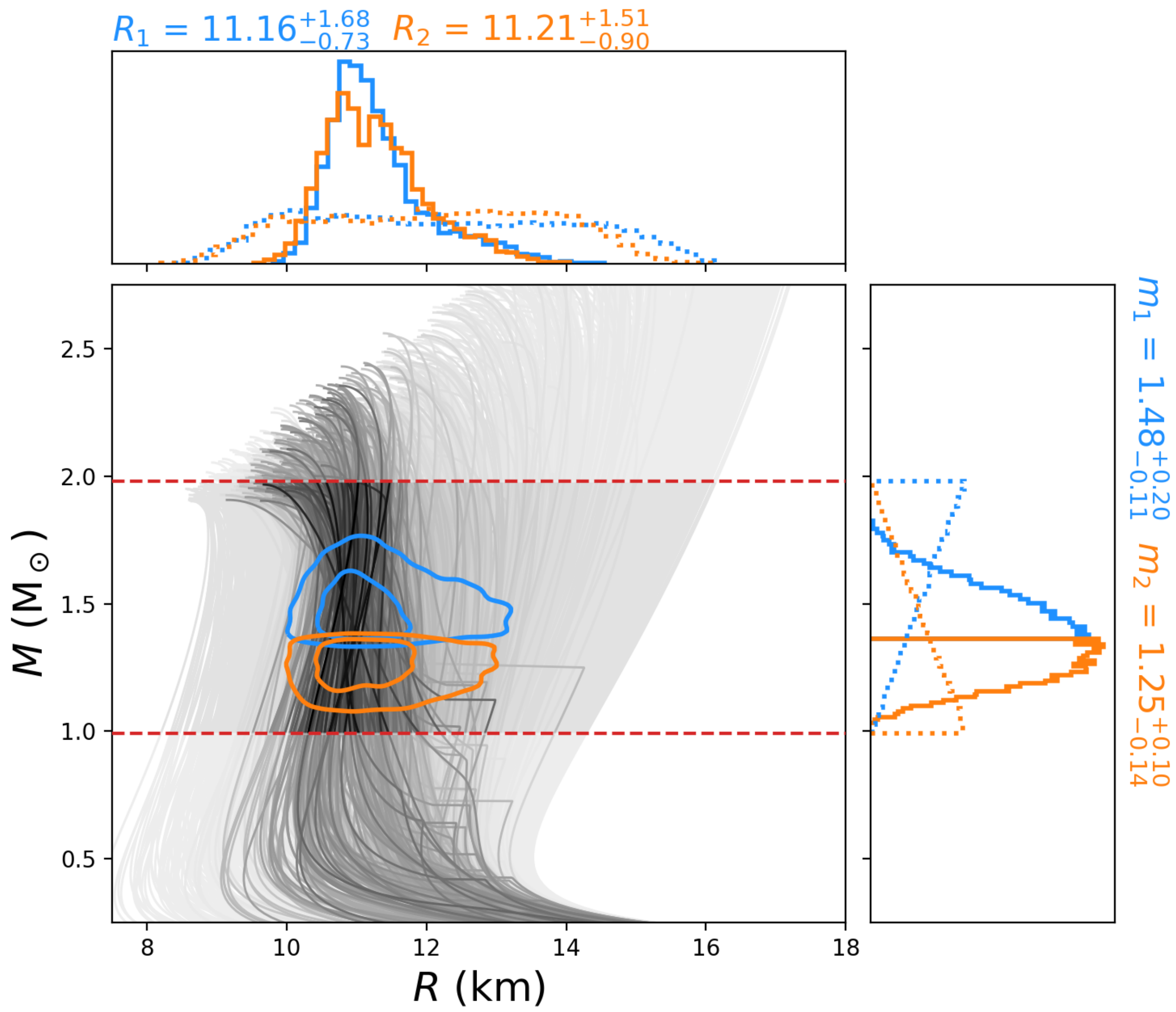
GW

n_{sat} $2n_{sat}$

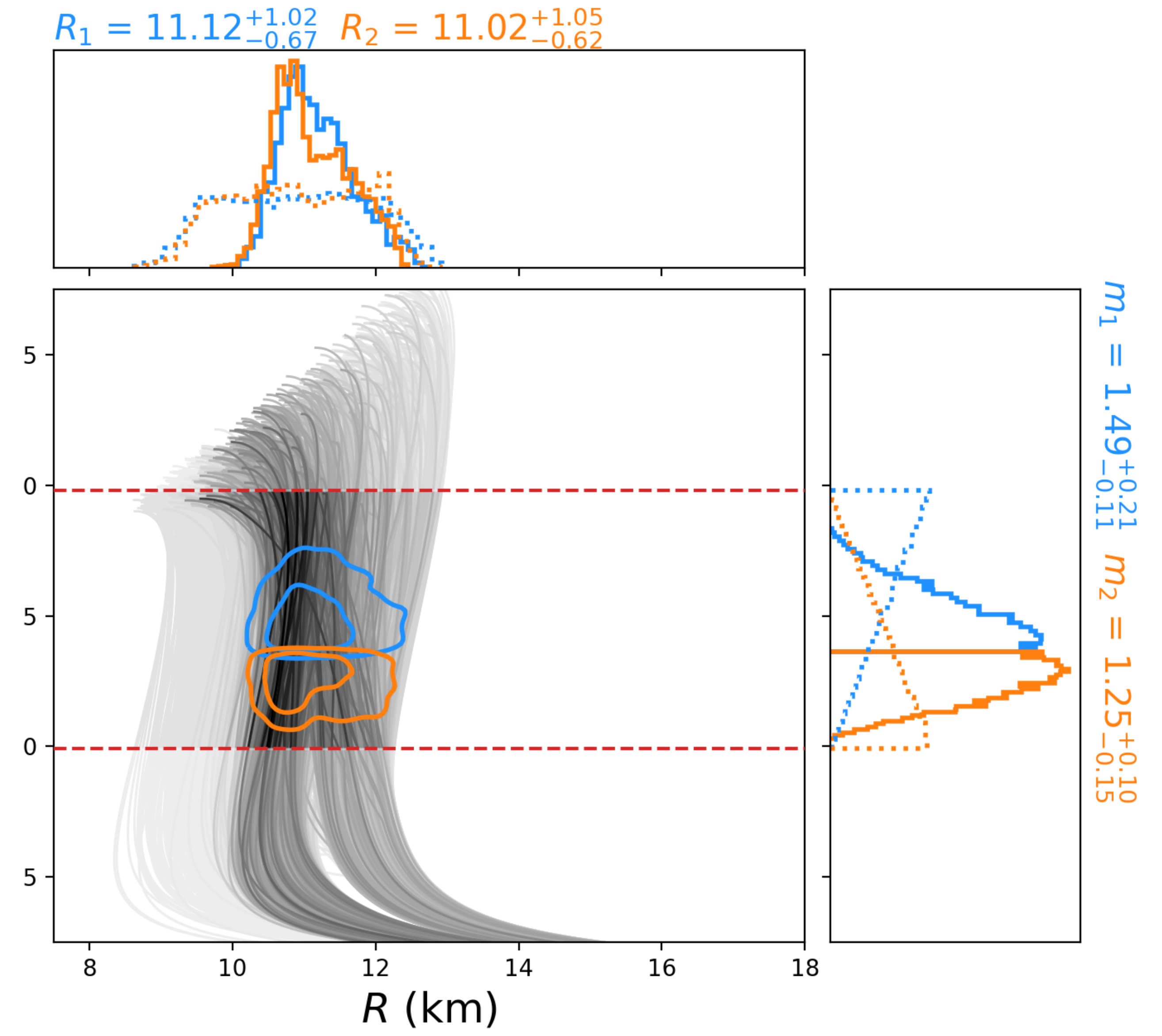


GW + $M_{TOTAL} \leq M_{THRESH}$

n_{sat}

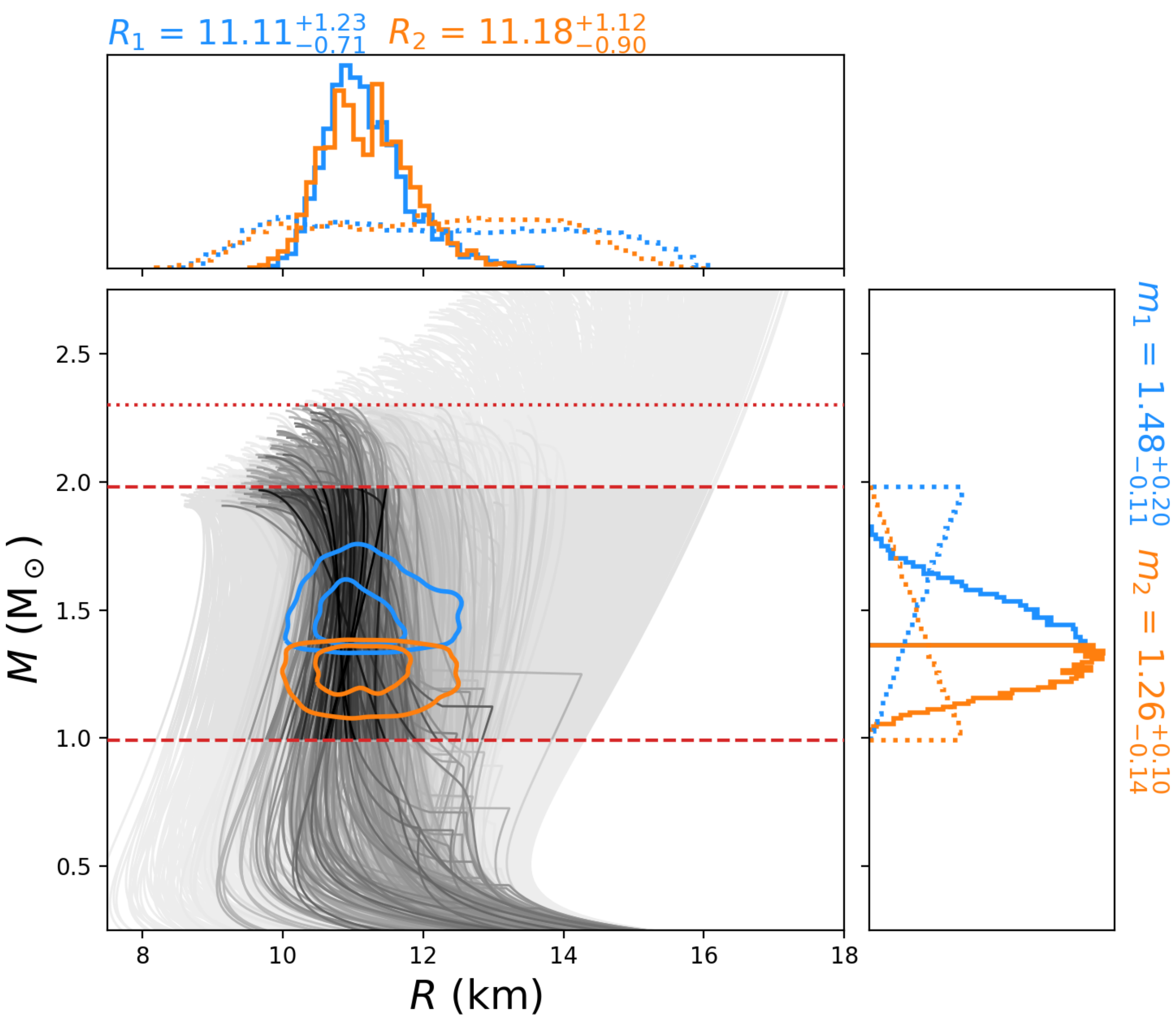


$2n_{sat}$

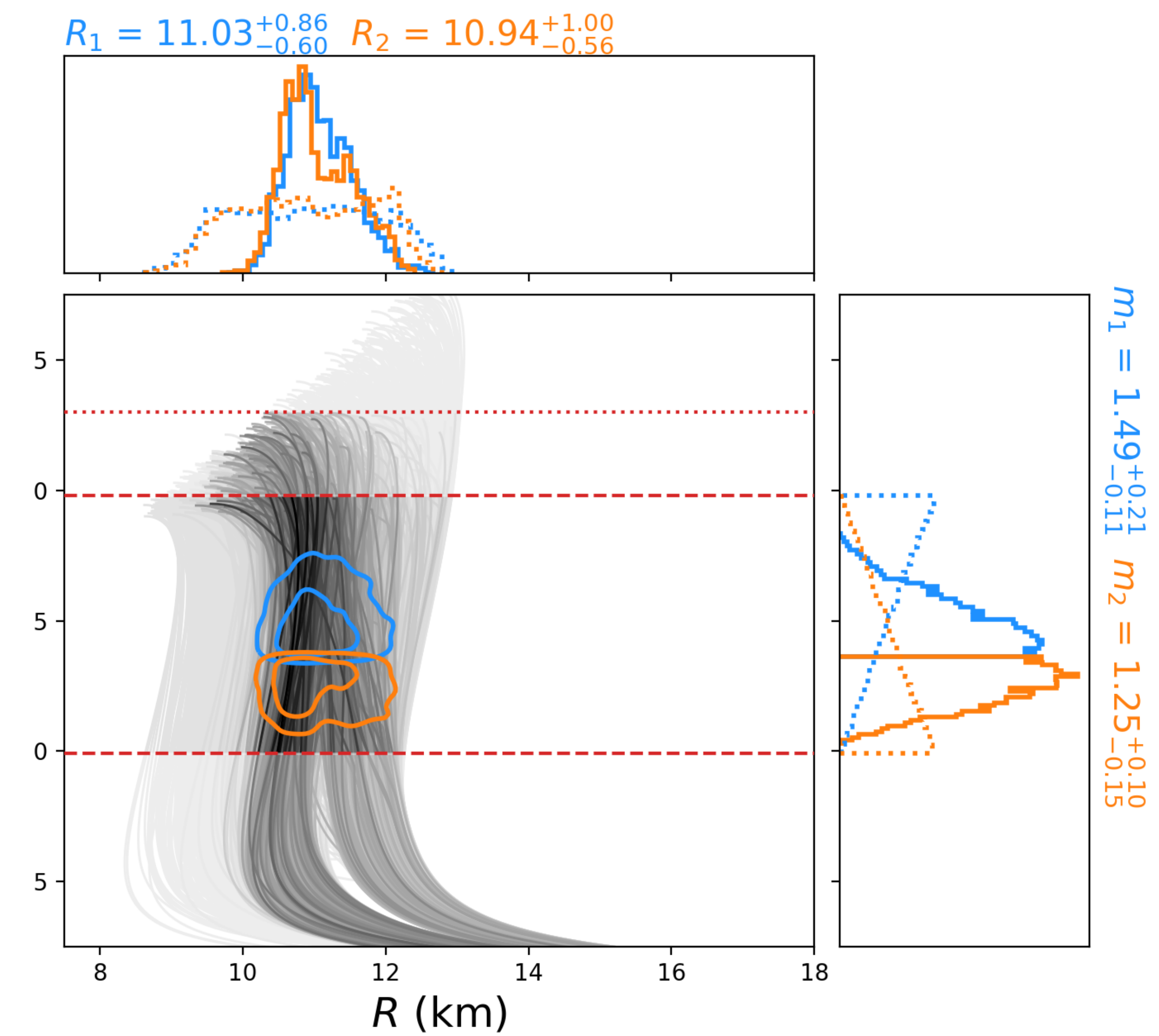


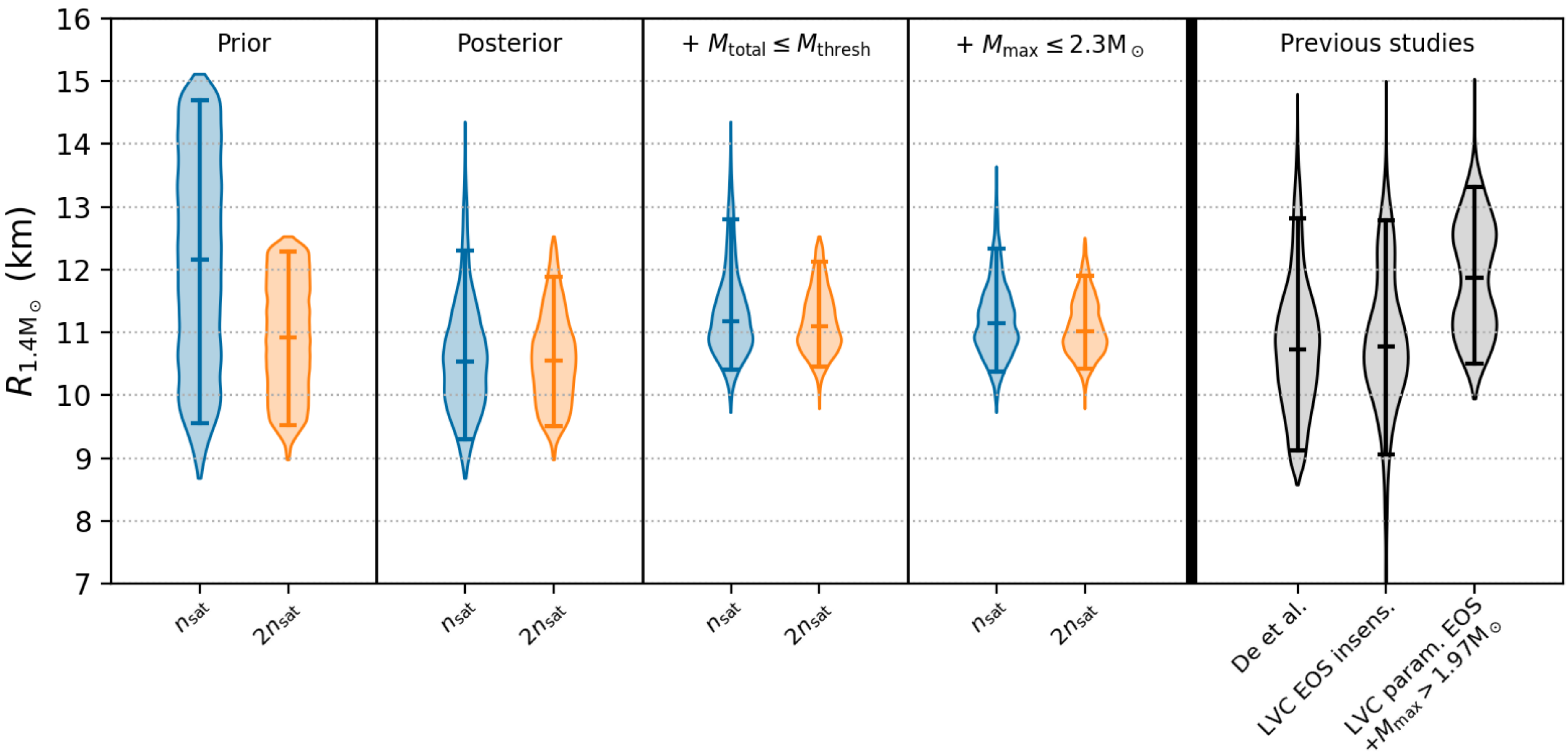
GW + $M_{TOTAL} \leq M_{THRESH}$ + $M_{MAX} < 2.3\ M_\odot$

n_{sat}



$2n_{sat}$

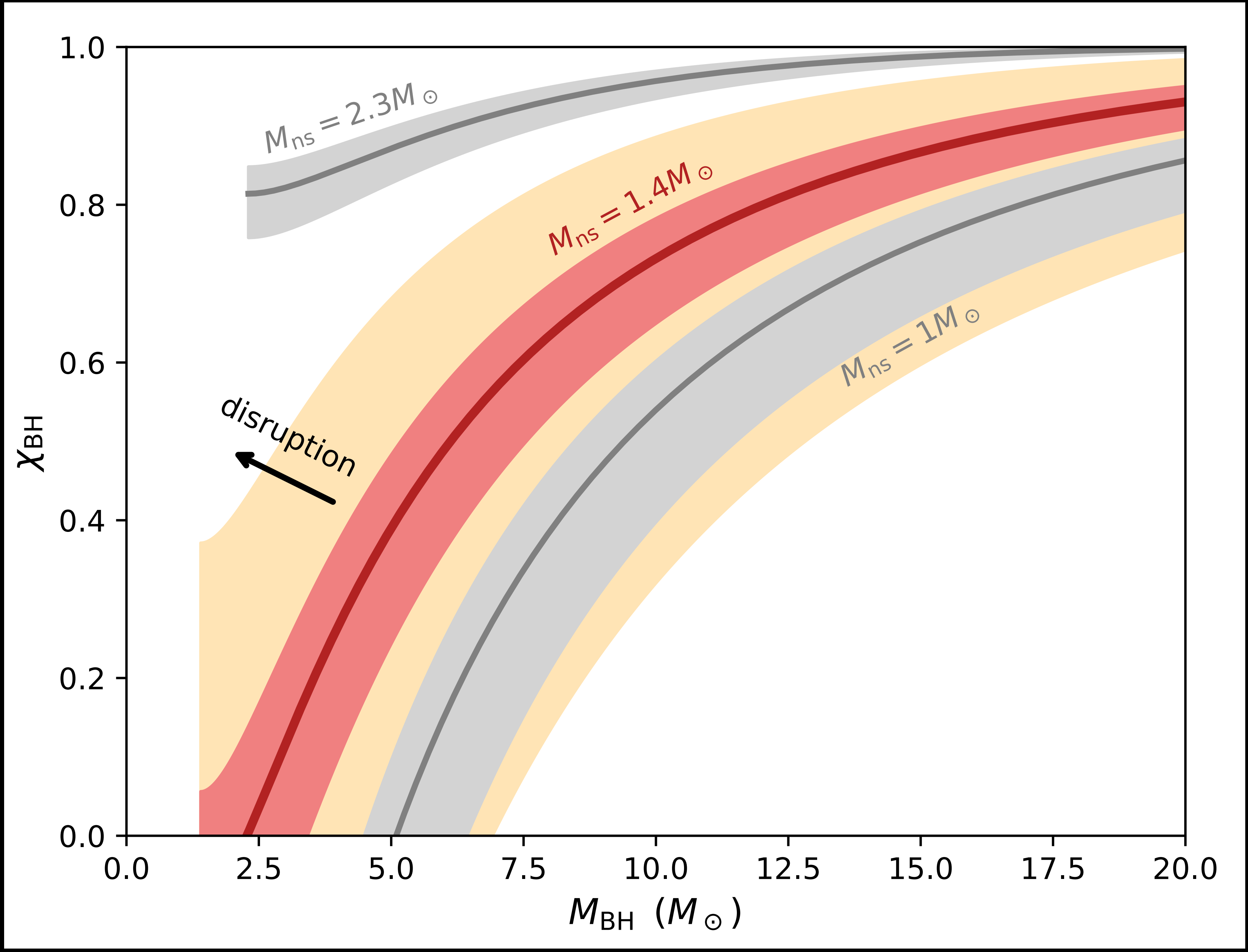




Prior
Posterior
+ $M_{total} \leq M_{thresh}$
+ $M_{max} \leq 2.3M_\odot$
Previous studies
$R_{1.4M_\odot}$ (km)
16
15
14
13
12
11
10
9
8
7
n_{sat}
$2n_{sat}$
De et al.
LVC EOS insens.
LVC param. EOS
$+M_{max} > 1.97M_\odot$

NSBH IMPLICATIONS

- Only expect EM counterpart from NSBH if NS is disrupted
- Our constraints imply we need a highly-spinning, or unusually low mass, BH to get a counterpart



Created using fit from Foucart et al., PRD 98, 081501(R) (2018)

S190814BV

GraceDB — Gravitational-Wave Candidate Event Database

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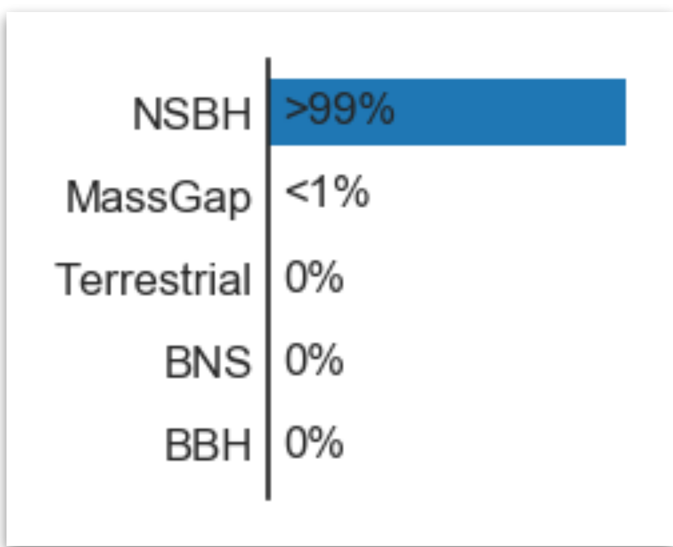
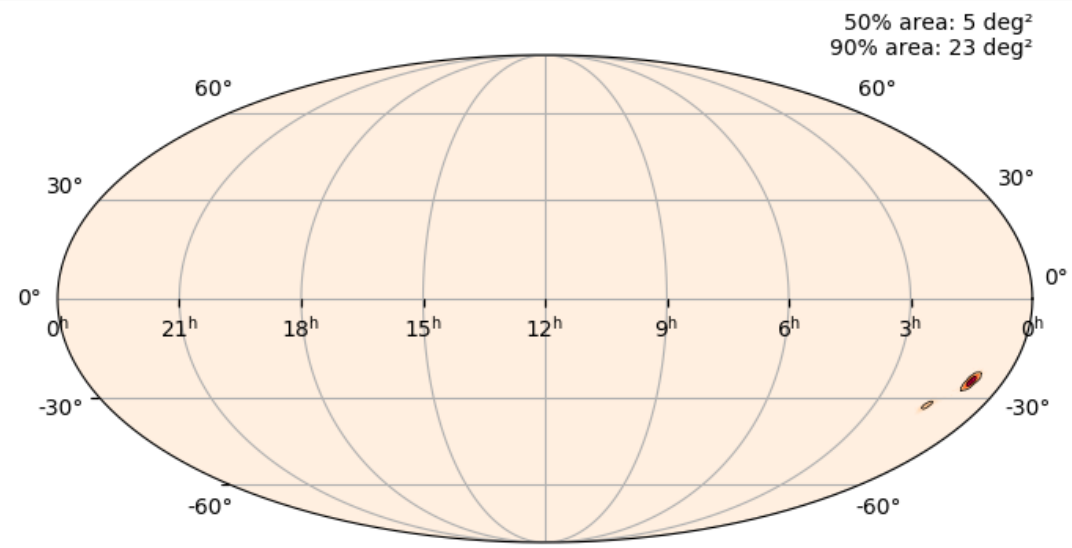
Superevent Info

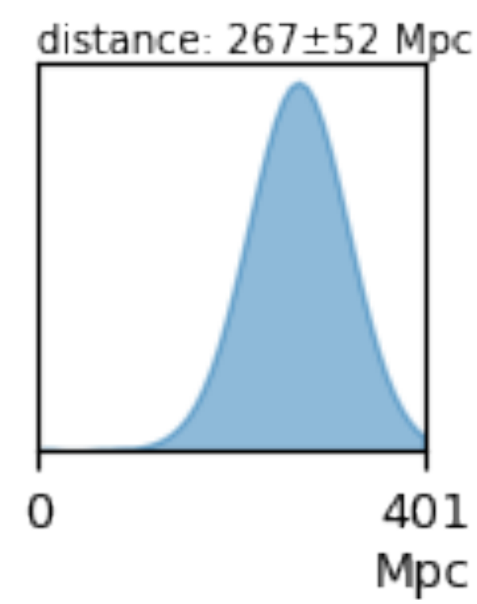
Superevent ID	Category	Labels	FAR (Hz)	FAR (yr^{-1})	t_start	t_0	t_end	UTC Submission time	Links
S190814bv	Production	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	2.033e-33	1 per 1.559e+25 years	1249852255.996787	1249852257.012957	1249852258.021731	2019-08-14 21:11:18 UTC	Data

Preferred Event Info

Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
CBC	gstlal	AllSky	H1,L1,V1	1249852257.0130	2019-08-14 22:35:49 UTC

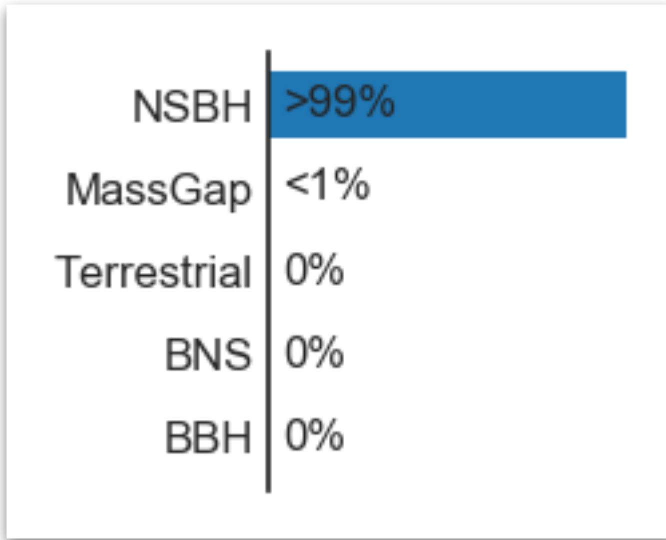


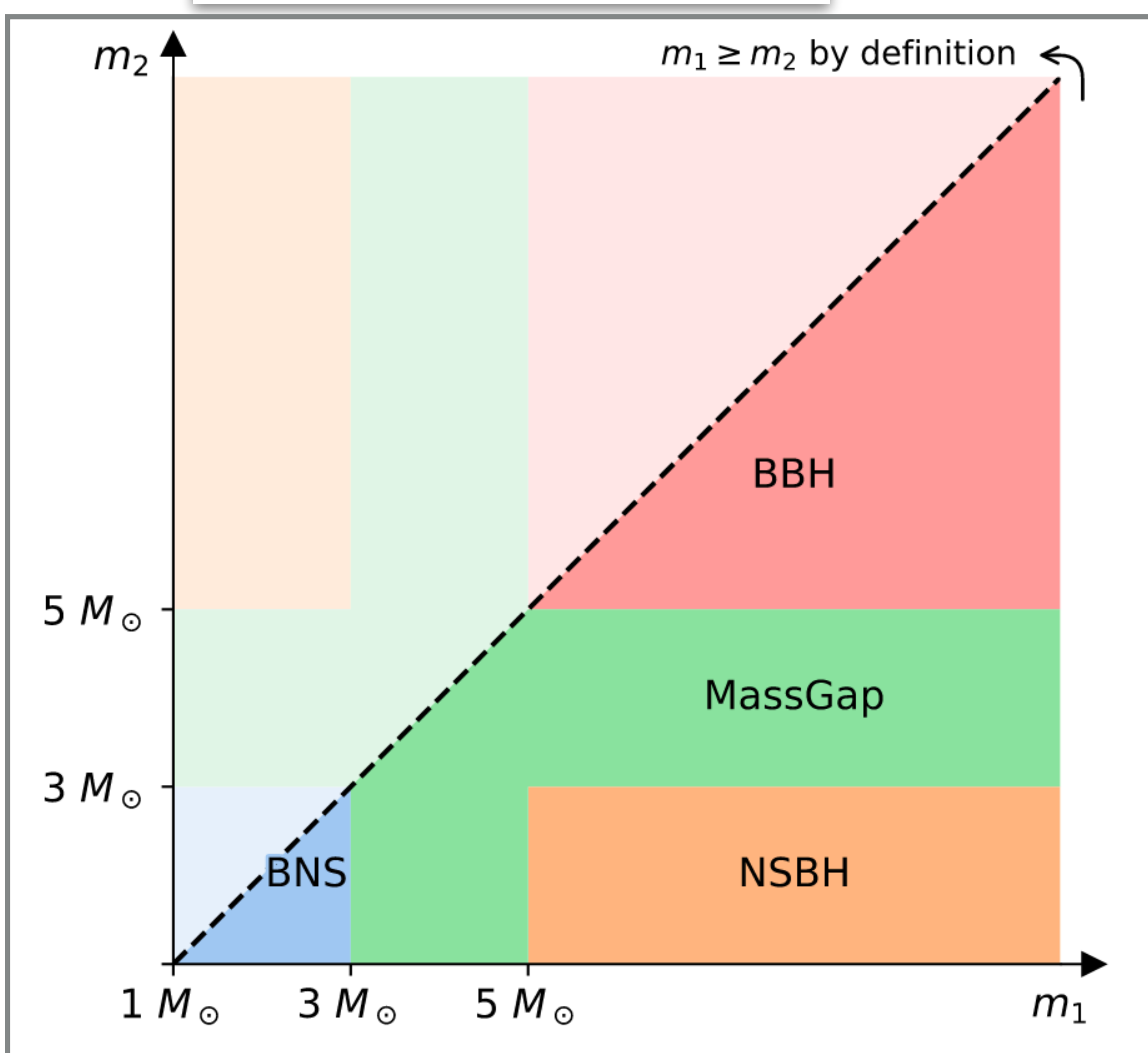




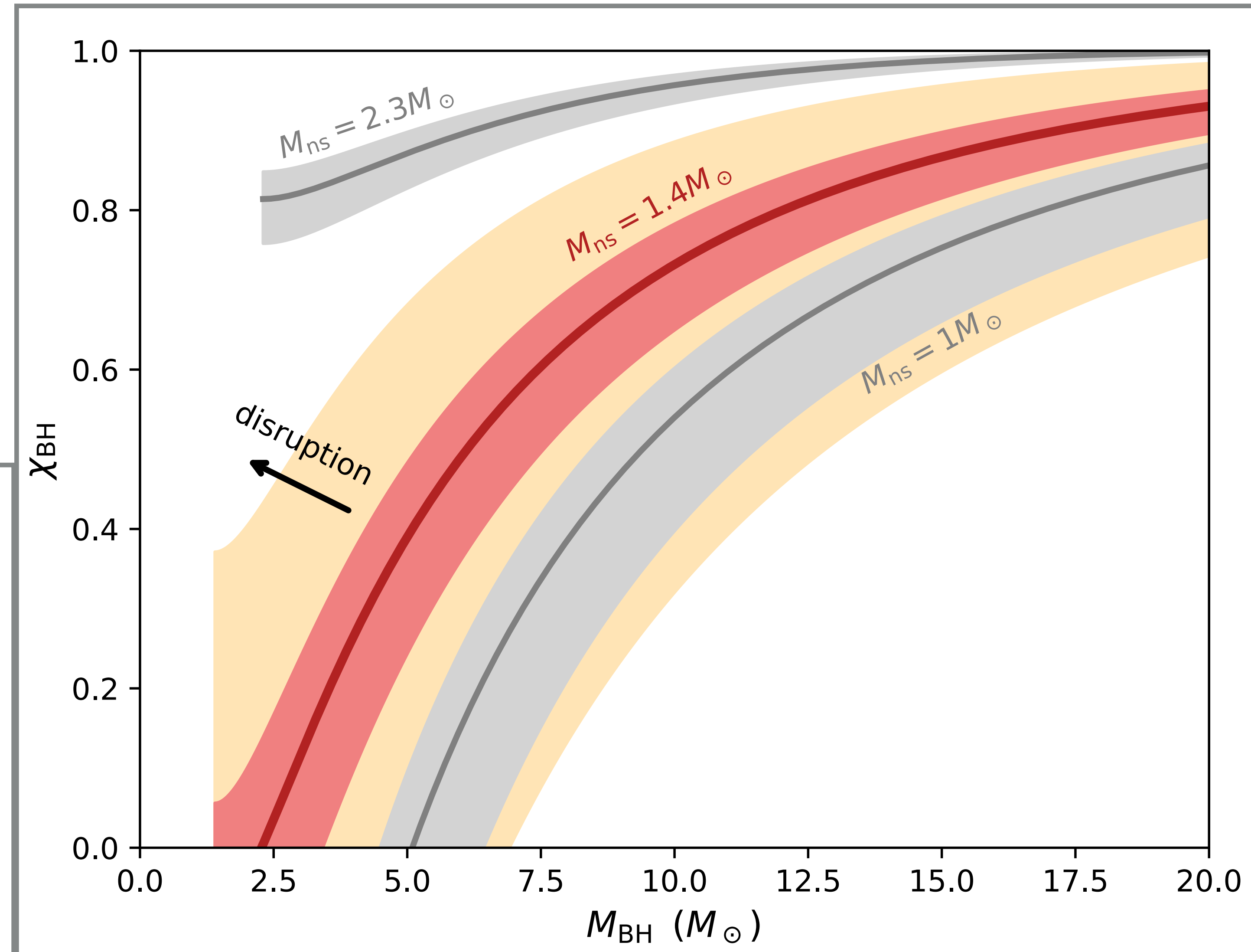
No EM counterpart detected

S190814BV





https://emfollow.docs.ligo.org/userguide/



- Lack of EM counterpart (assuming it wasn't missed) suggests BH spin >~0.5
- PE on this event will offer nice consistency test

LOOKING FORWARD

- Without EM counterpart, will need to rely on GW to distinguish NSBH from BBH
- We simulated a $m_{bh} = 10M_{\odot}$, $m_{ns} = 1.4M_{\odot}$ NSBH at 40 Mpc
  - Used softest EOS in our 90% credible interval ($\Lambda = 370$)
  - Assumed exact knowledge of EOS
  - Advanced LIGO design sensitivity (SNR = 190)
- Bayes factor between NSBH and BBH model still ~1
- May be difficult to distinguish high-mass NS from mass-gap BH until next generation (A+, Voyager, or 3G) detectors built

LOOKING FORWARD

- Straightforward to combine results from future events
- Use posterior on EOS as prior for next event, etc.
- Will be able to further constrain EOS from GW data, even if no EM counterpart available

SUMMARY

- GW170817 has offered a wealth of information
- GW data disfavor stiff EOS, but cannot rule out BBH
- EM observations suggest no prompt collapse, no long-lived NS
- Combining EM & GW observations with nuclear theory, we obtained tighter constraints on NS radius
- NSBH EM counterparts will require unusually low-mass or high-spin BH
- Results can be combined with future events to further constrain EOS

THANK YOU!