Gravitational waves from neutron star mergers

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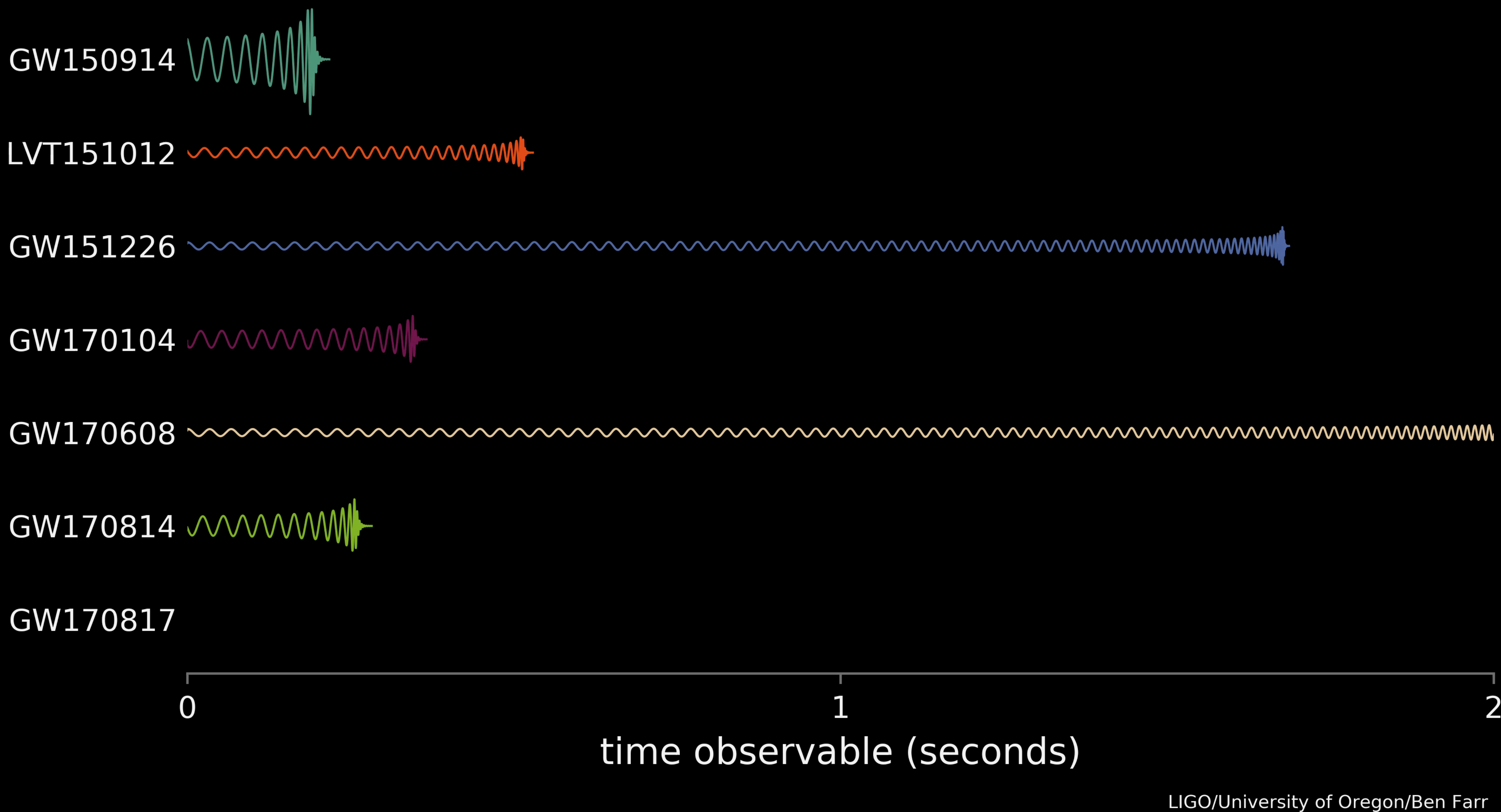
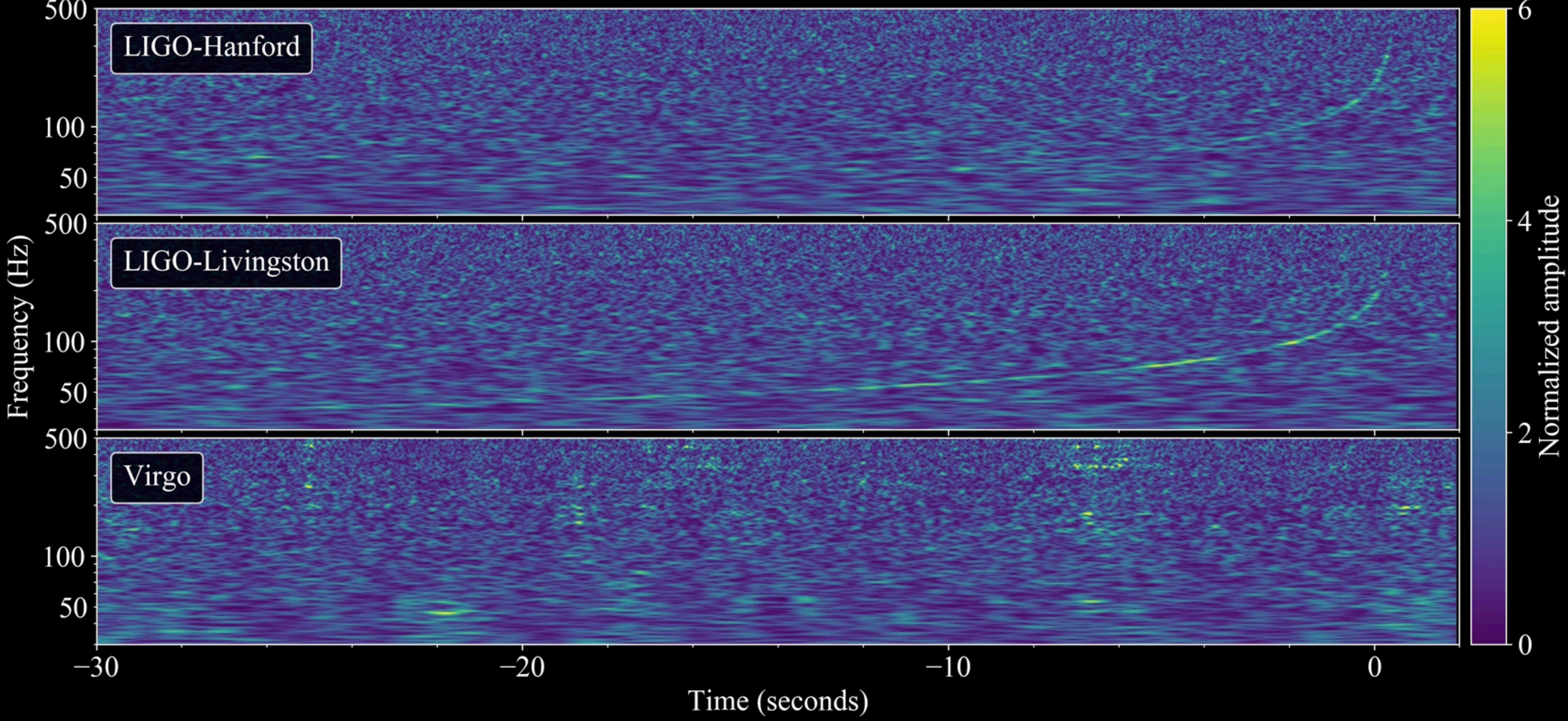
Flatiron Institute

3rd HEL.A.S. and DAAD School, October 10th


GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814
GW170817
0
1
2
time observable (seconds)
LIGO/University of Oregon/Ben Farr

August 17, 2017

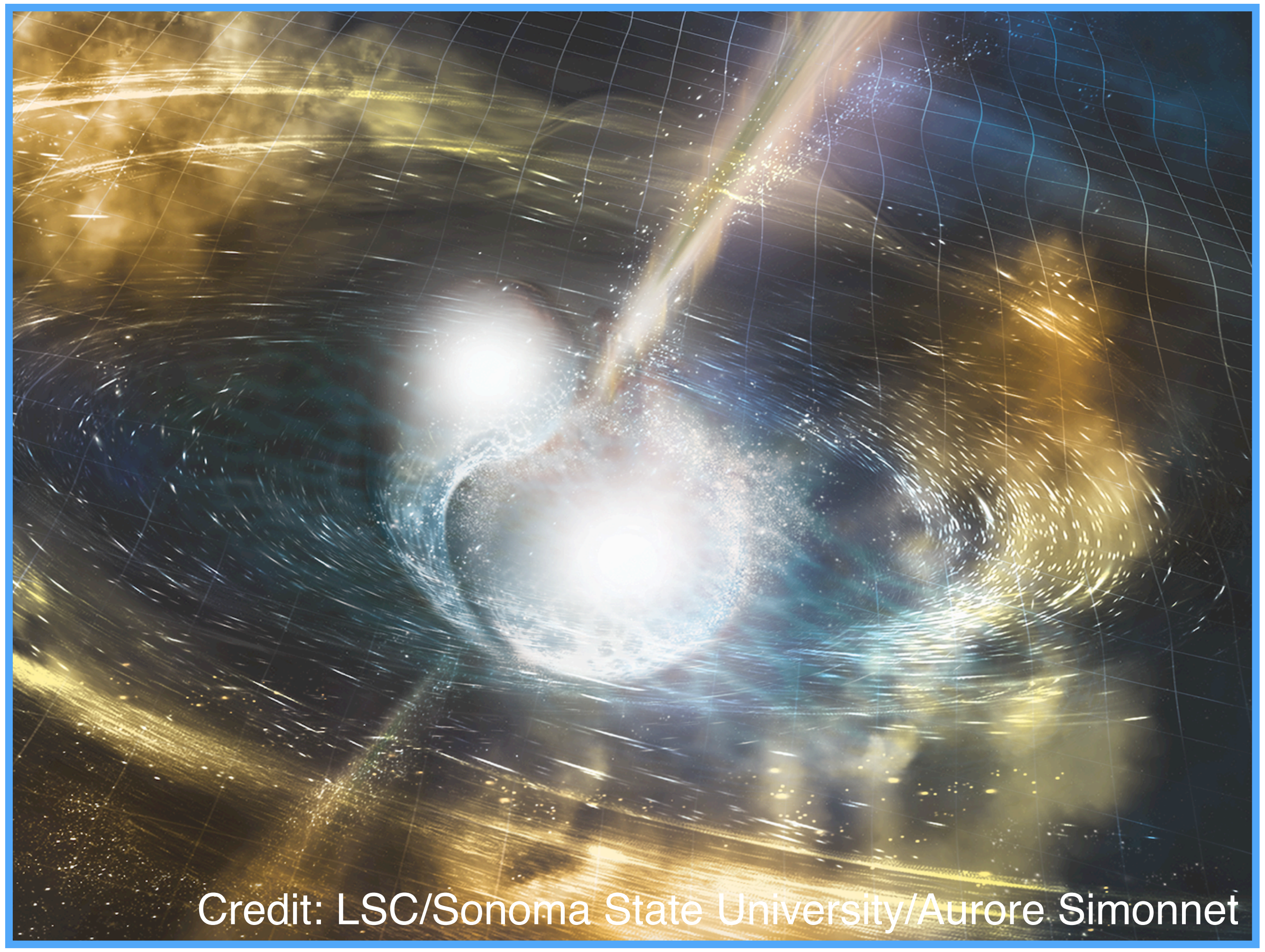


Credit: LIGO/Virgo/Lovelace, Brown, Macleod, McIver, Nitz

GW170817

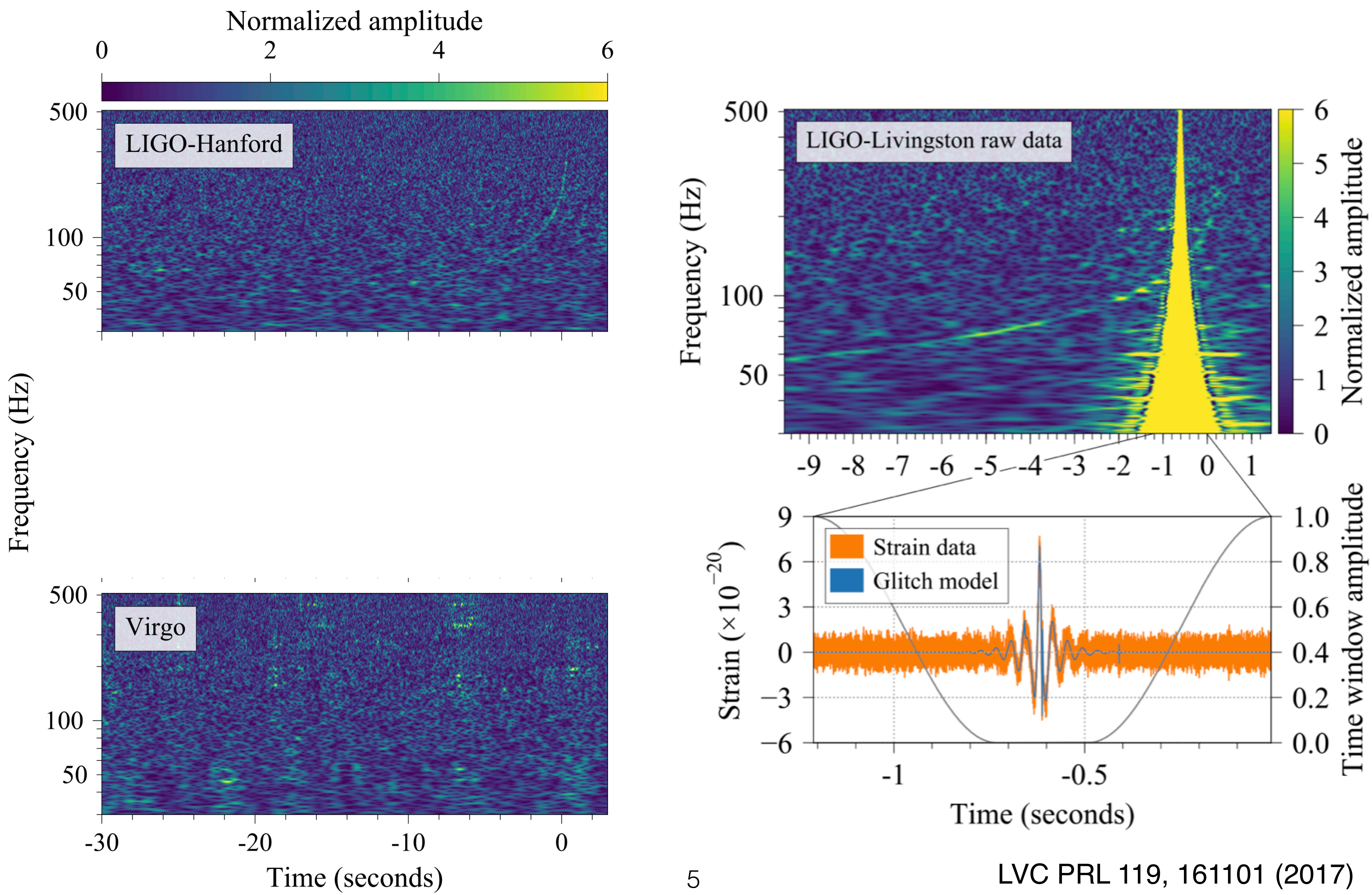
First detection of a binary neutron star coalescence

✓Gravitational wave
✓Short gamma ray burst
✓Optical/UV emission
✓X-ray (ongoing)
✓Radio (ongoing)



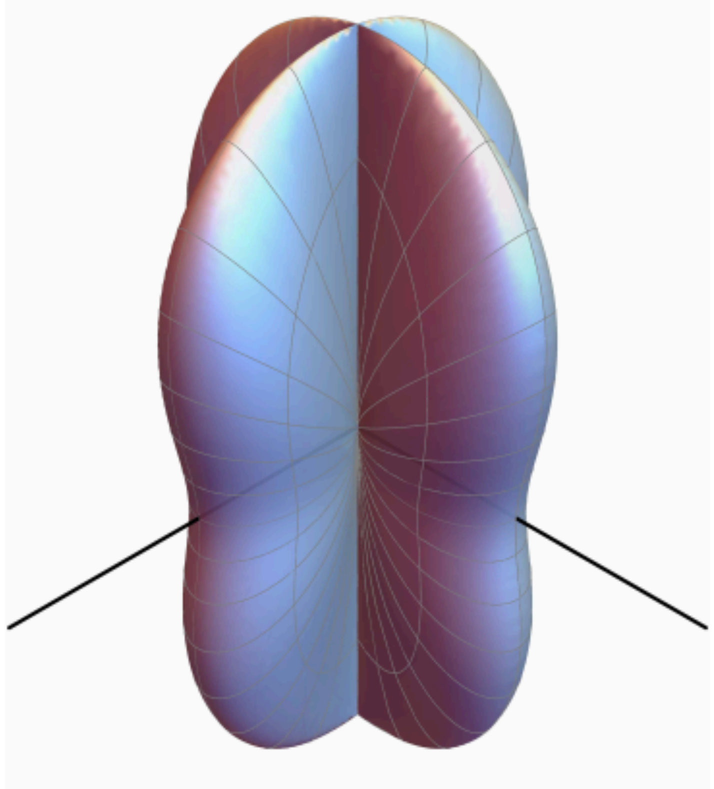
- Properties of supranuclear matter
- Astrophysical origin on sGRBs
- Origin of heavy elements
- Measurement of the Hubble constant
- Constraints on the speed of gravity

And a monstrous glitch

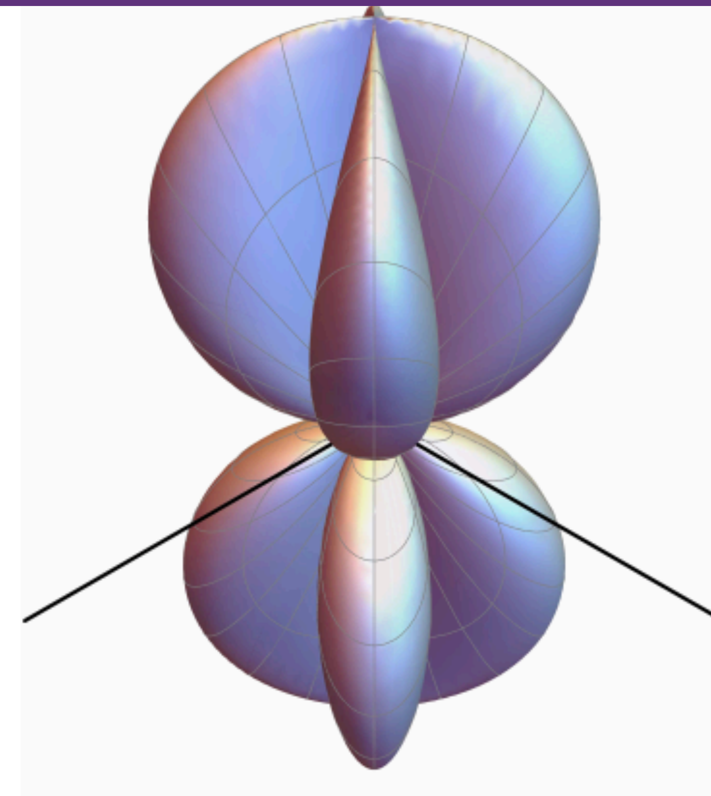


LVC PRL 119, 161101 (2017)

Detector sky response



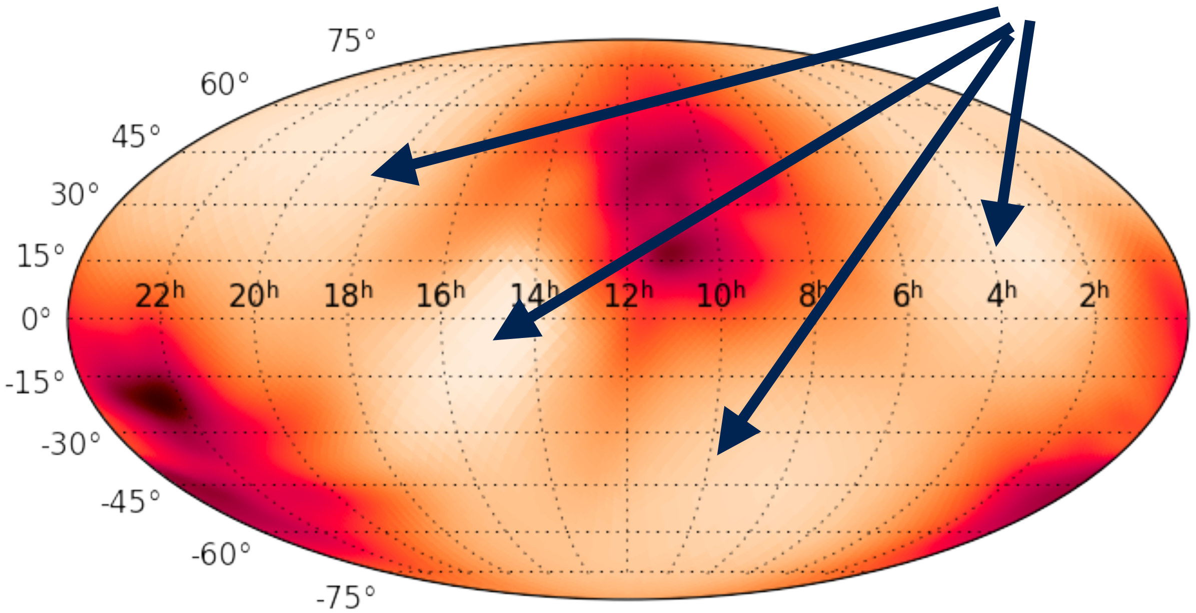
(a) Plus (+)



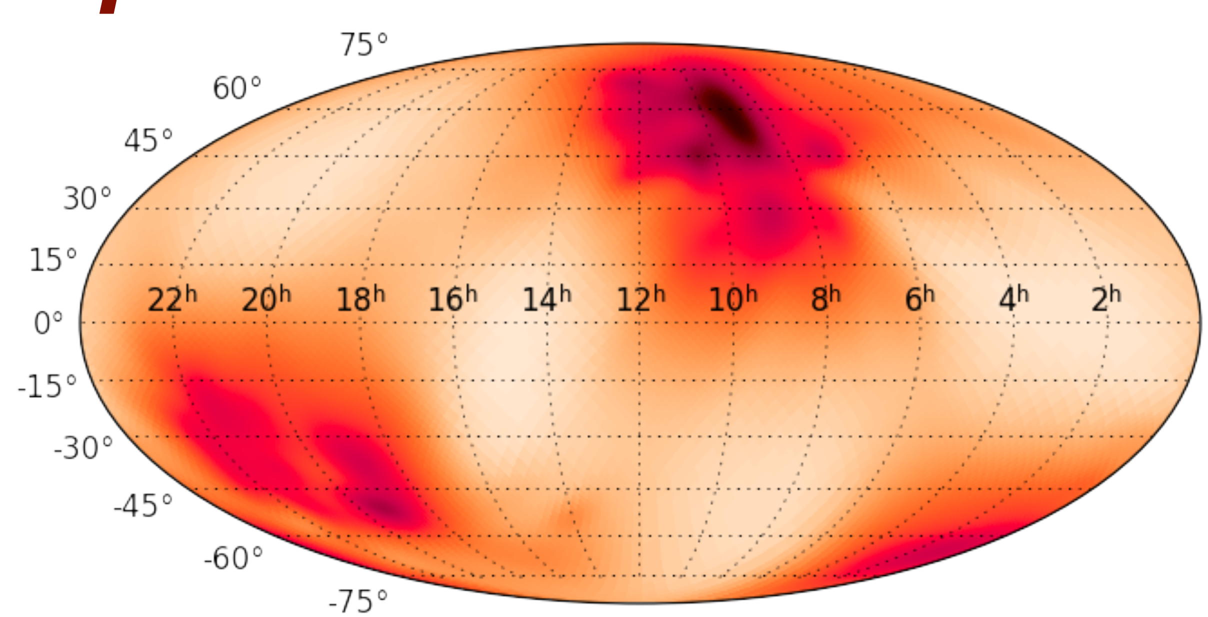
(b) Cross (×)

The detectors have “blind spots”

Livingston

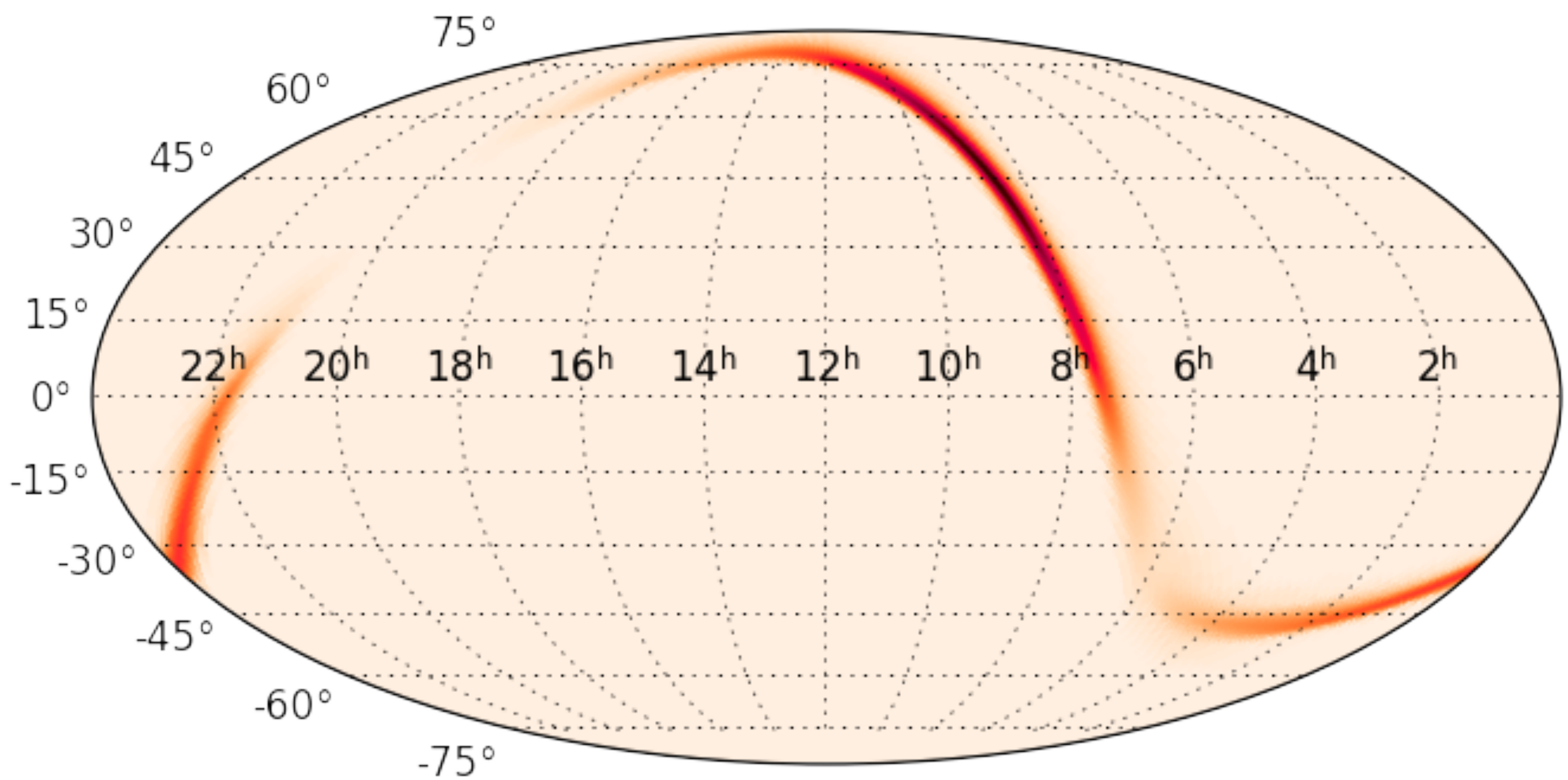


Hanford



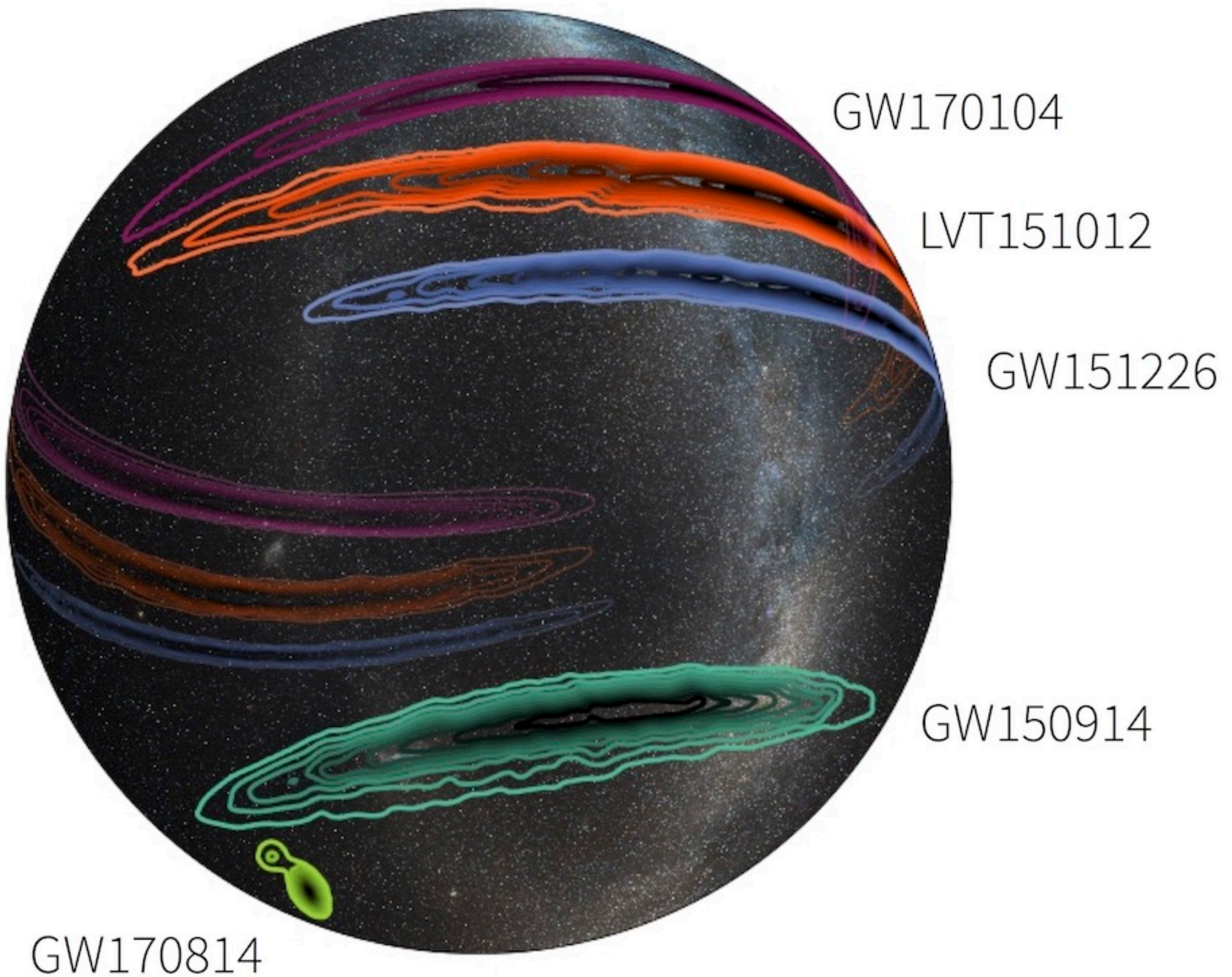
Triangulation

Using the time of arrival and relative amplitude and phase



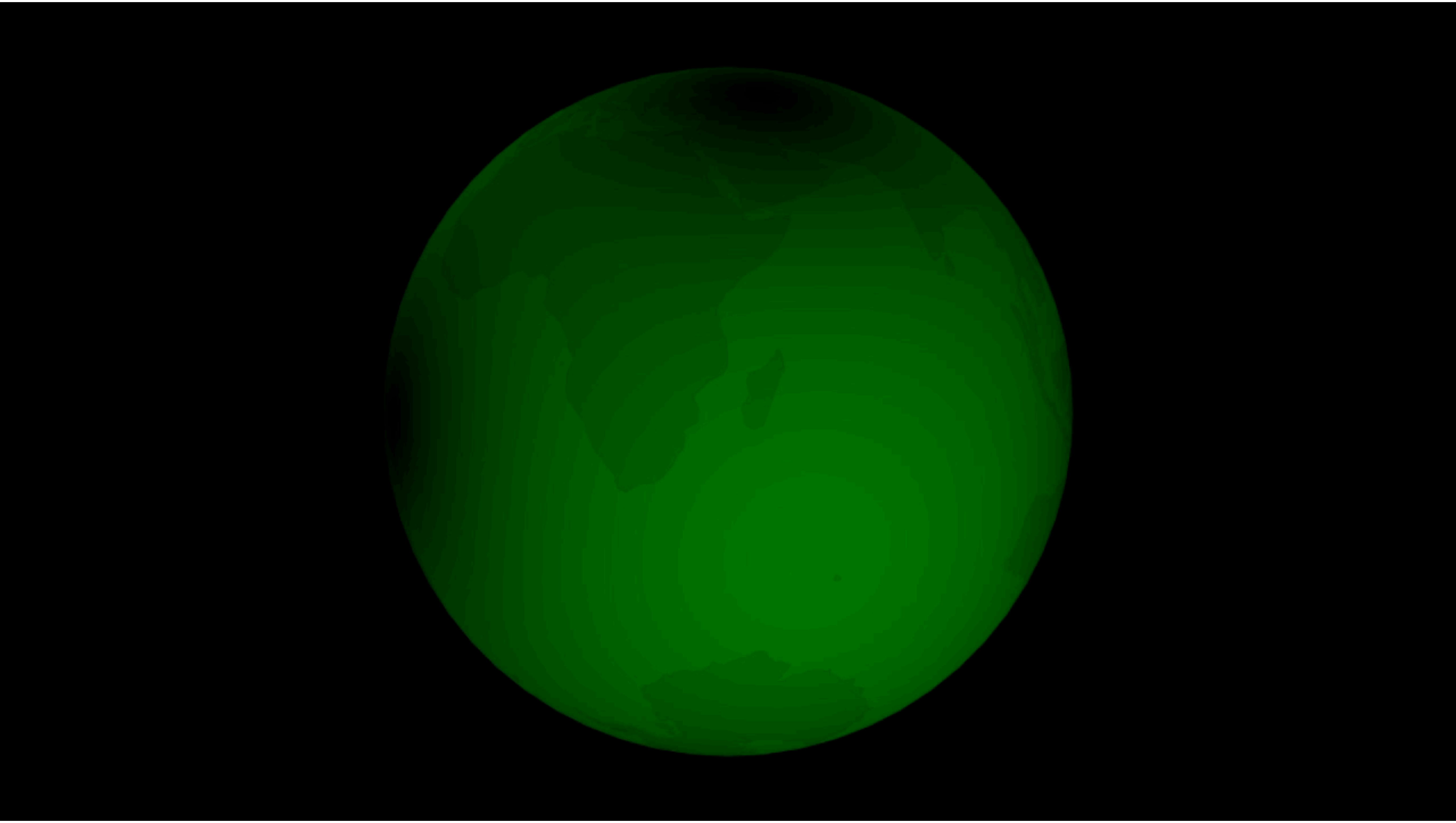
Question: Why is it not a full ring?

More detectors



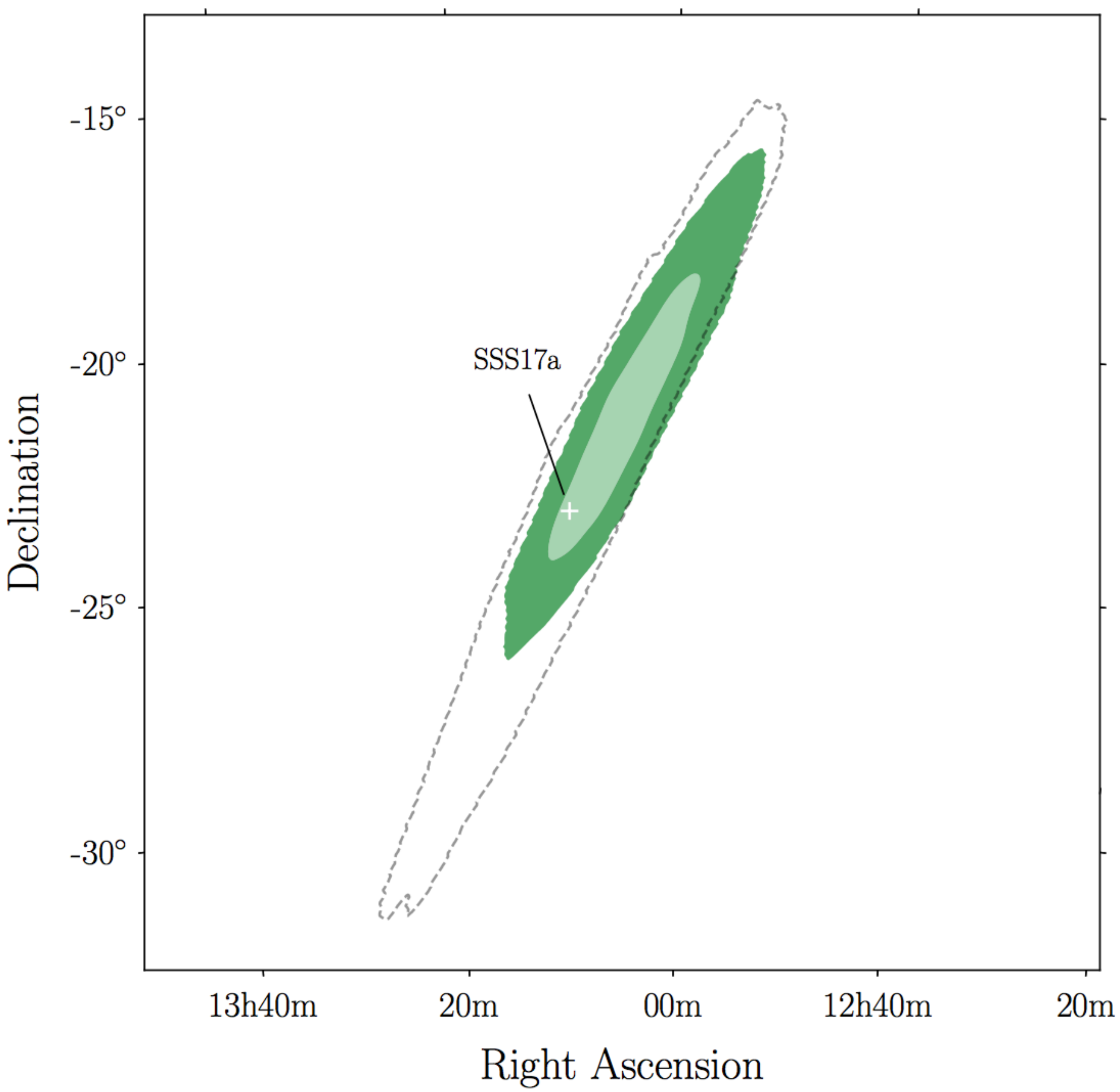
Credit: LIGO/Virgo/Singer

Localization

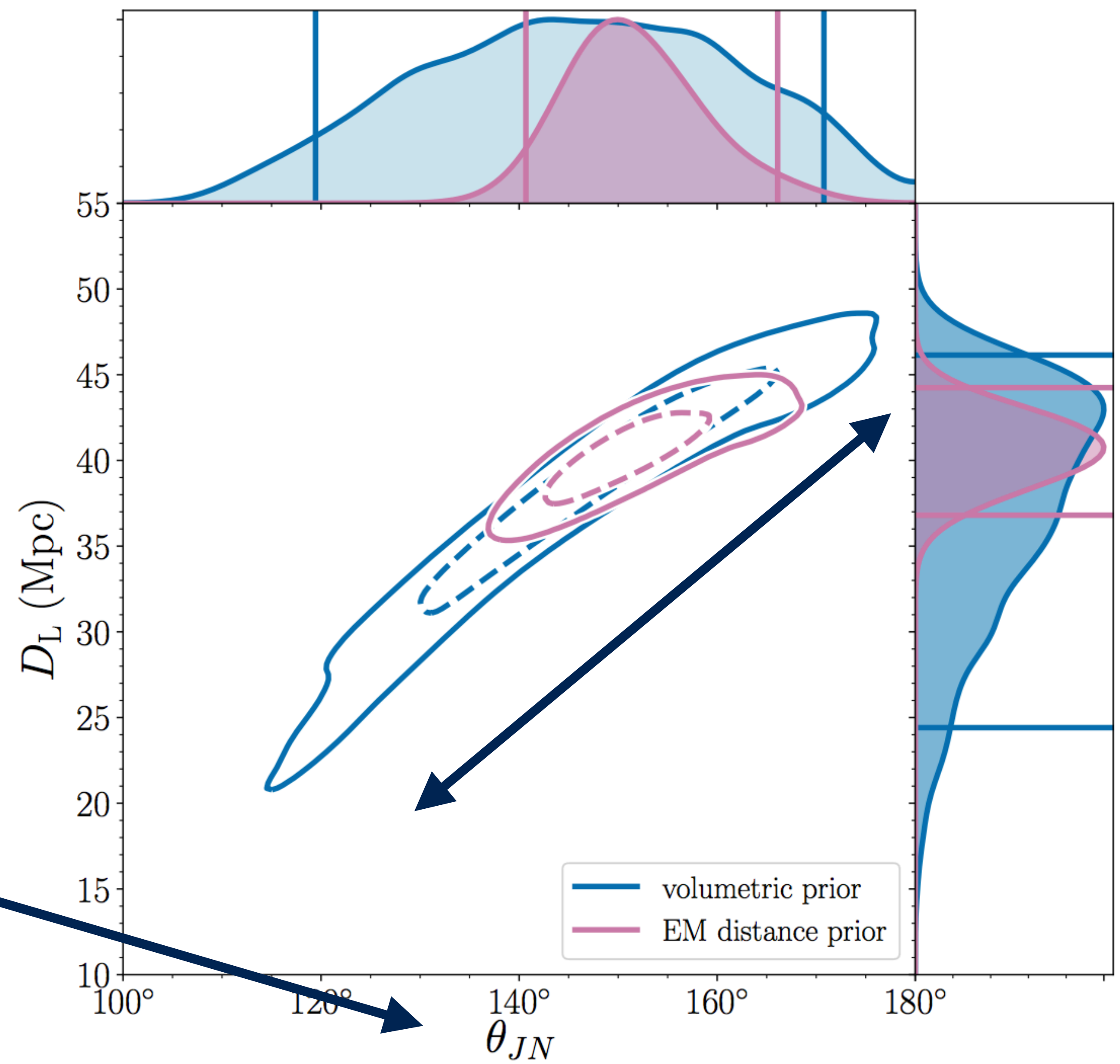


Credit: LIGO/Virgo/Singer

GW170817 extrinsic parameters



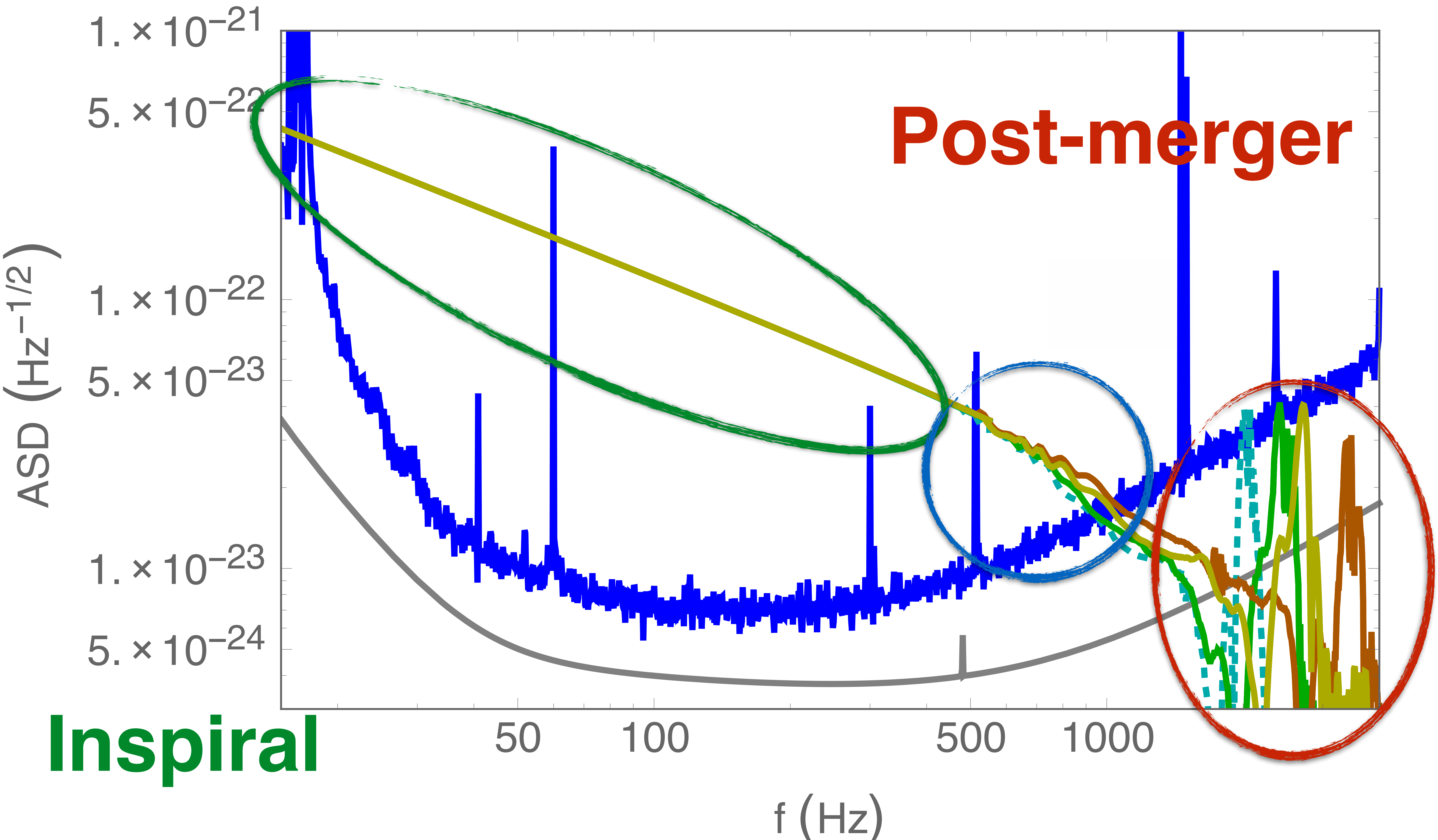
Initial localization to ~28 sq deg, updated localization to ~16 sq deg. Still consistent with NGC4993



Face off/away within ~20 deg

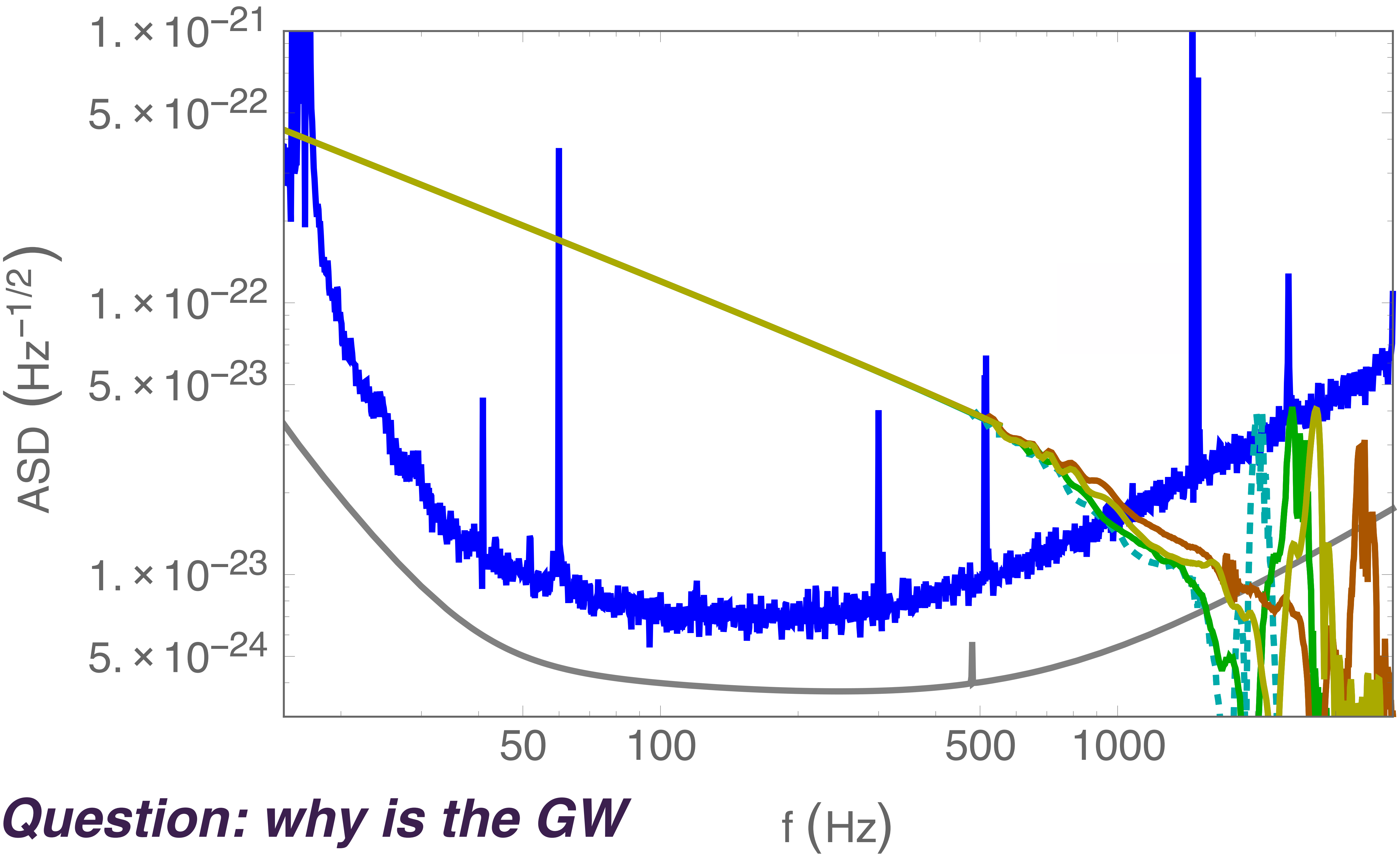
LVC (arxiv:1805.11579)

Anatomy of a BNS coalescence



Data Visualization by J. Read
Numerical data by Tim Dietrich (AEI/FSU/BAM Collaboration)
Phys. Rev. D95(12):124006 and Phys. Rev. D95(2):024029

Anatomy of a BNS coalescence



Question: why is the GW amplitude decreasing as the frequency increases?

Data Visualization by J. Read
Numerical data by Tim Dietrich (AEI/FSU/BAM Collaboration)
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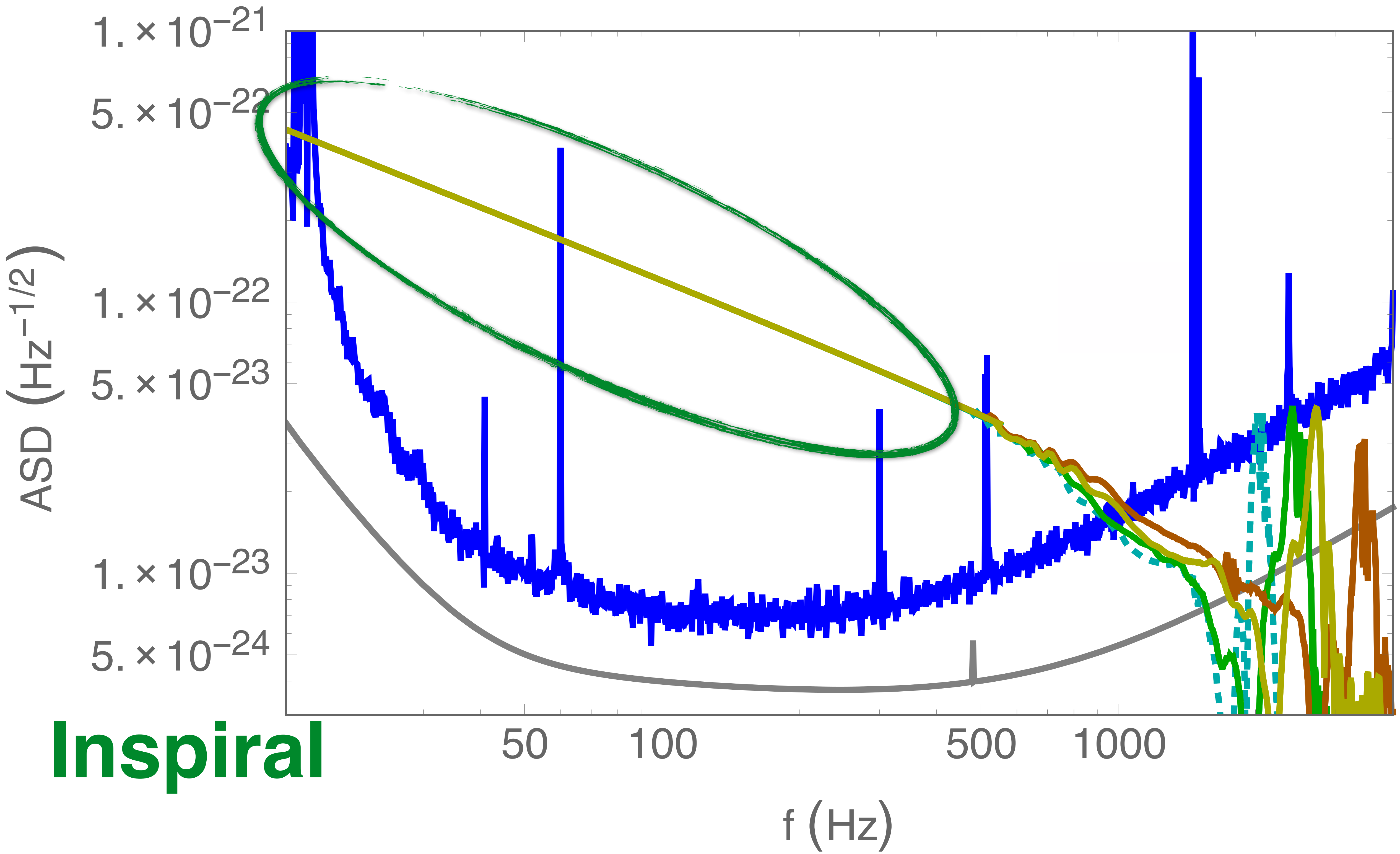
Anatomy of a BNS coalescence



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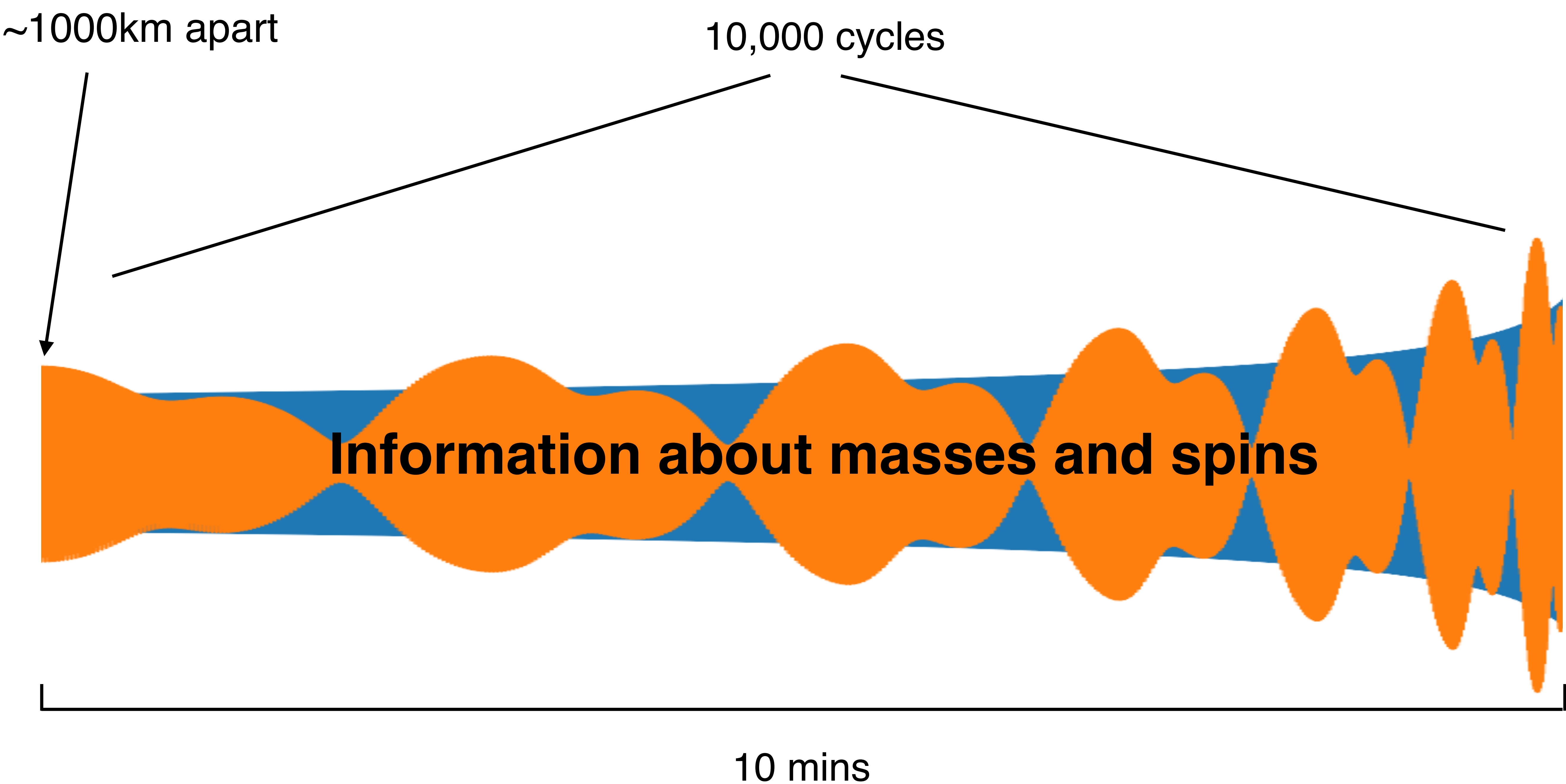
Inspiral



~1000km apart
10,000 cycles
Information about masses and spins
10 mins

Inspiral phase calculation

The bodies are moving slowly (compared to c),
so we expand in small velocities

The binding energy of the system is $$E = -\frac{1}{2}\mu v^2$$

GWs carry away energy $$L = -\frac{dE}{dt} = \frac{32}{5}\frac{\mu^2}{M^2}v^{10} \sim \dddot{Q}$$

So the phase is $$\frac{d^2\Psi}{dt^2} = \frac{d\omega}{dt} = \frac{d\omega}{dE}\frac{dE}{dt} = \frac{\dot{E}}{dE/d\omega}$$

Homework

1. Compute the leading order phase term and derive the “chirp mass” (remember $f_{orb} = f_{GW}/2$).

2. Compute the number of GW cycles for GW170817 between 20Hz and merger (let’s say 1000Hz).

Hint: $$\Psi = \int \frac{d\Psi}{dt} dt = \int \omega dt = \int \omega \frac{dt}{df} df = \int \omega \frac{dt}{dE} \frac{dE}{df} df$$

and use appropriate limits of integration

3. How much time did we observe GW170817 for?

Hint: $$T = \int dt = \int \frac{dt}{df} df = \ldots$$

Waveform phase

Putting decades of work to compute the binding energy and the flux to a high post-Newtonian order together

measure less well

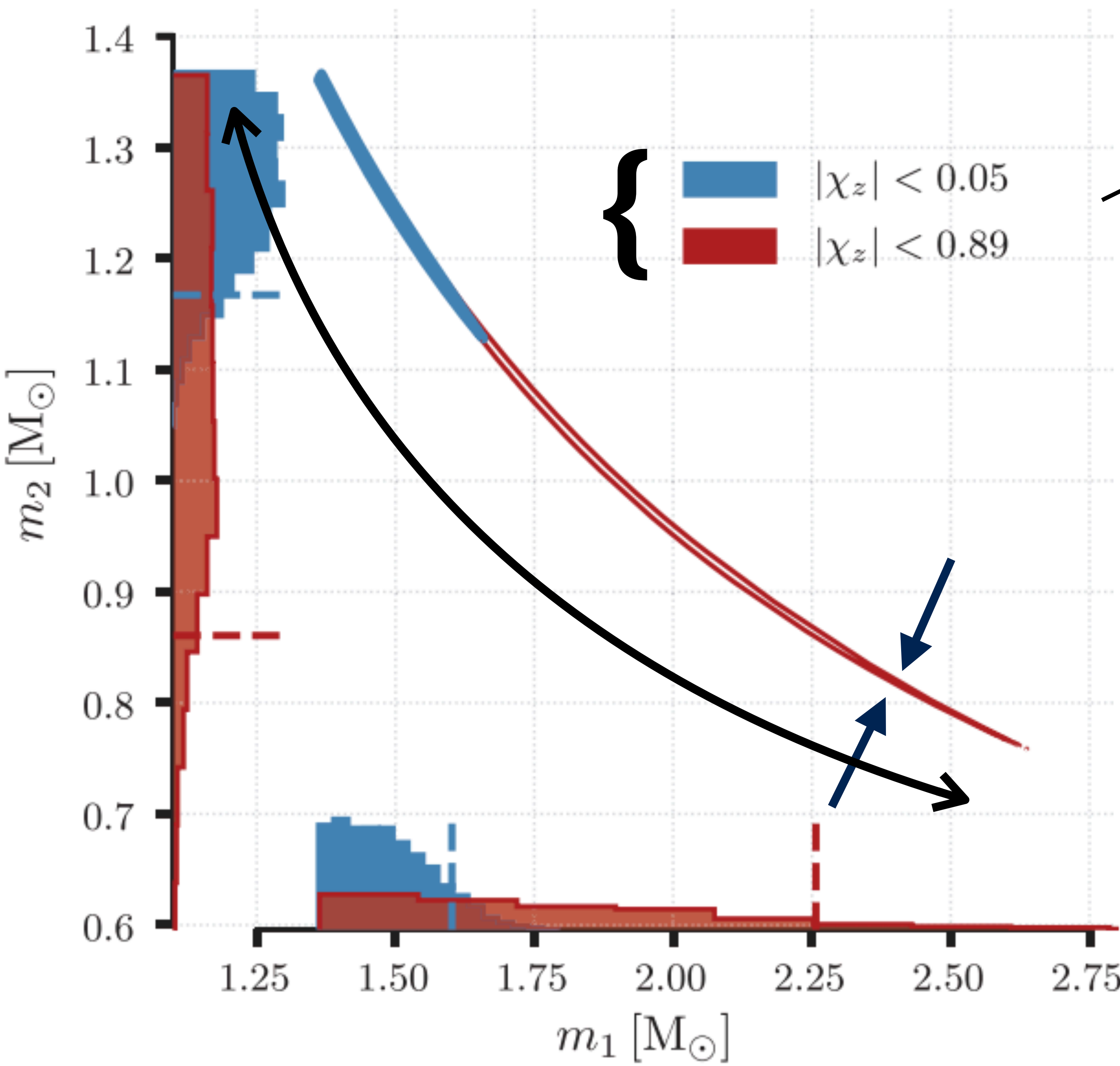
mass and spin enter together

$$\Psi(u) \sim a_0(\mathcal{M})u^{-5}\left[1 + a_2(\eta)u^2 + a_3(\eta, \vec{S}_i)u^3 \right.$$

measure VERY well

$$\left. + \qquad \cdots \right]$$

GW170817 masses



$$\chi \sim 0.4 \frac{1\mathrm{ms}}{T}$$

The chirp mass is measured very well

The mass ratio is measured less well

The mass ratio is correlated with the spin

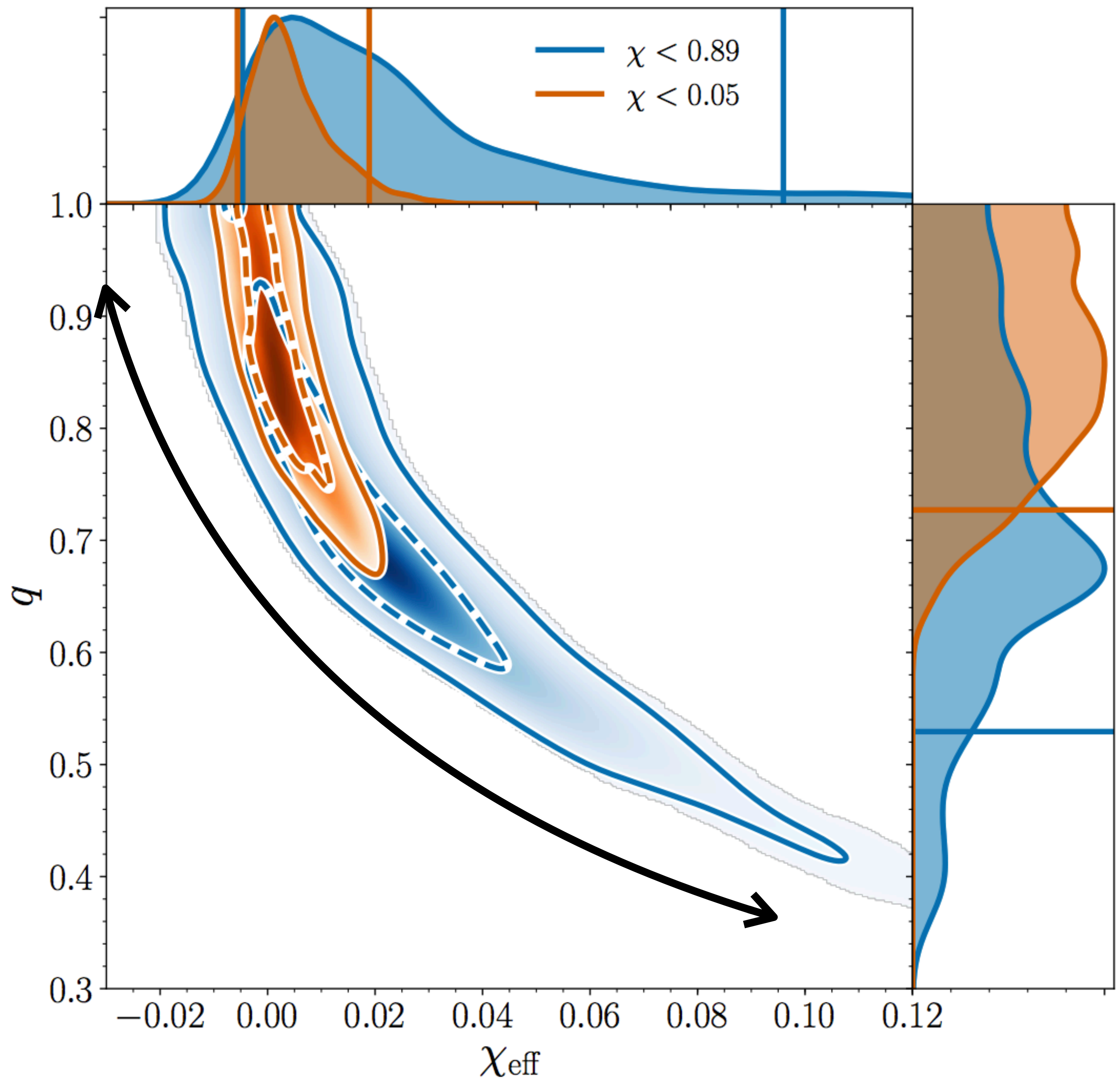
LVC PRL 119, 161101 (2017)

GW170817 spins

Effective spin:
a conserved spin
combination that is
“well” constrained

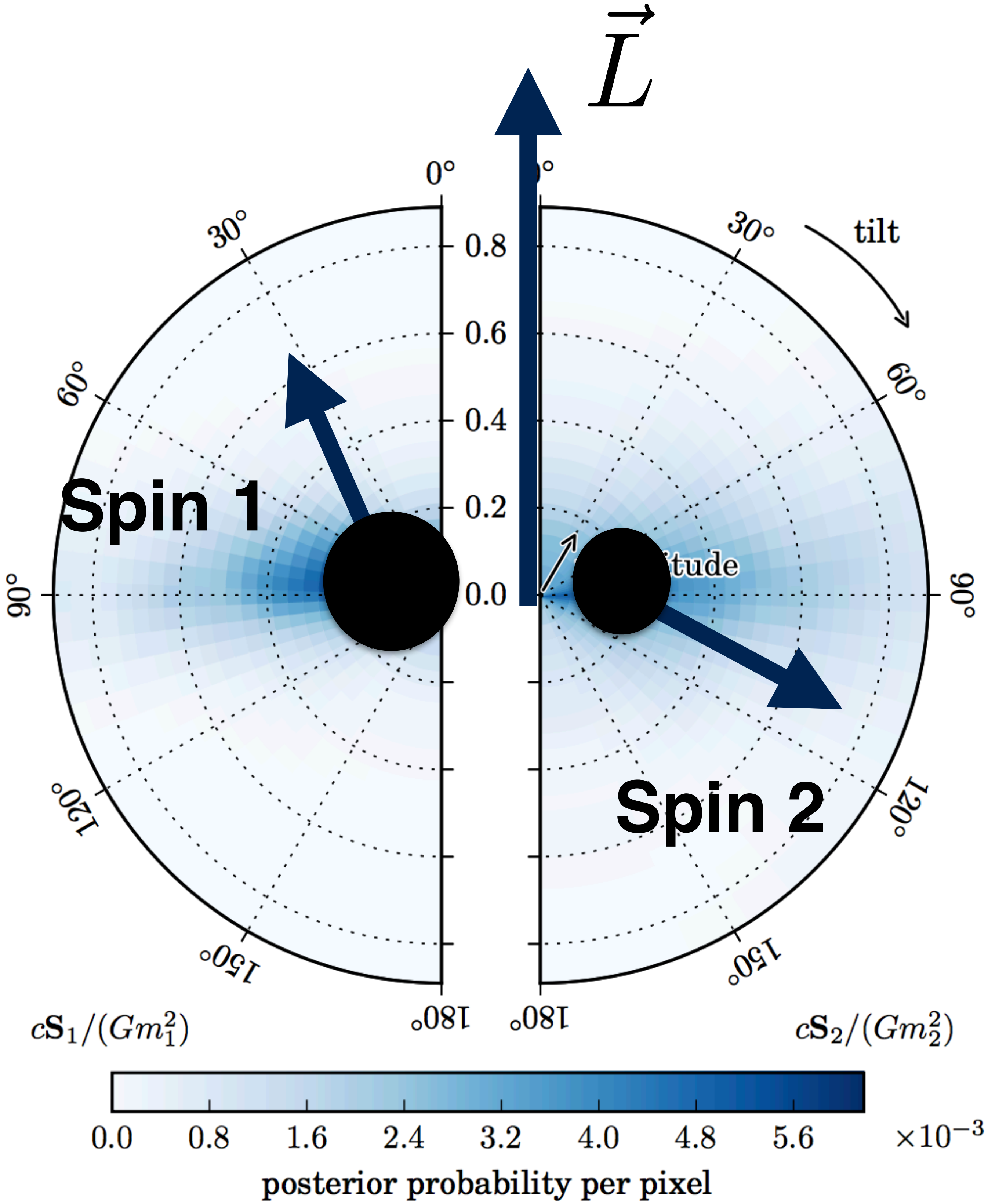
$$\chi_{\rm eff} = \frac{m_1(\chi_1 \cdot \vec{L}) + m_2(\chi_2 \cdot \vec{L})}{m_1 + m_2}$$

The mass ratio is correlated with the spin



LVC (arxiv:1805.11579)

GW170817 spins

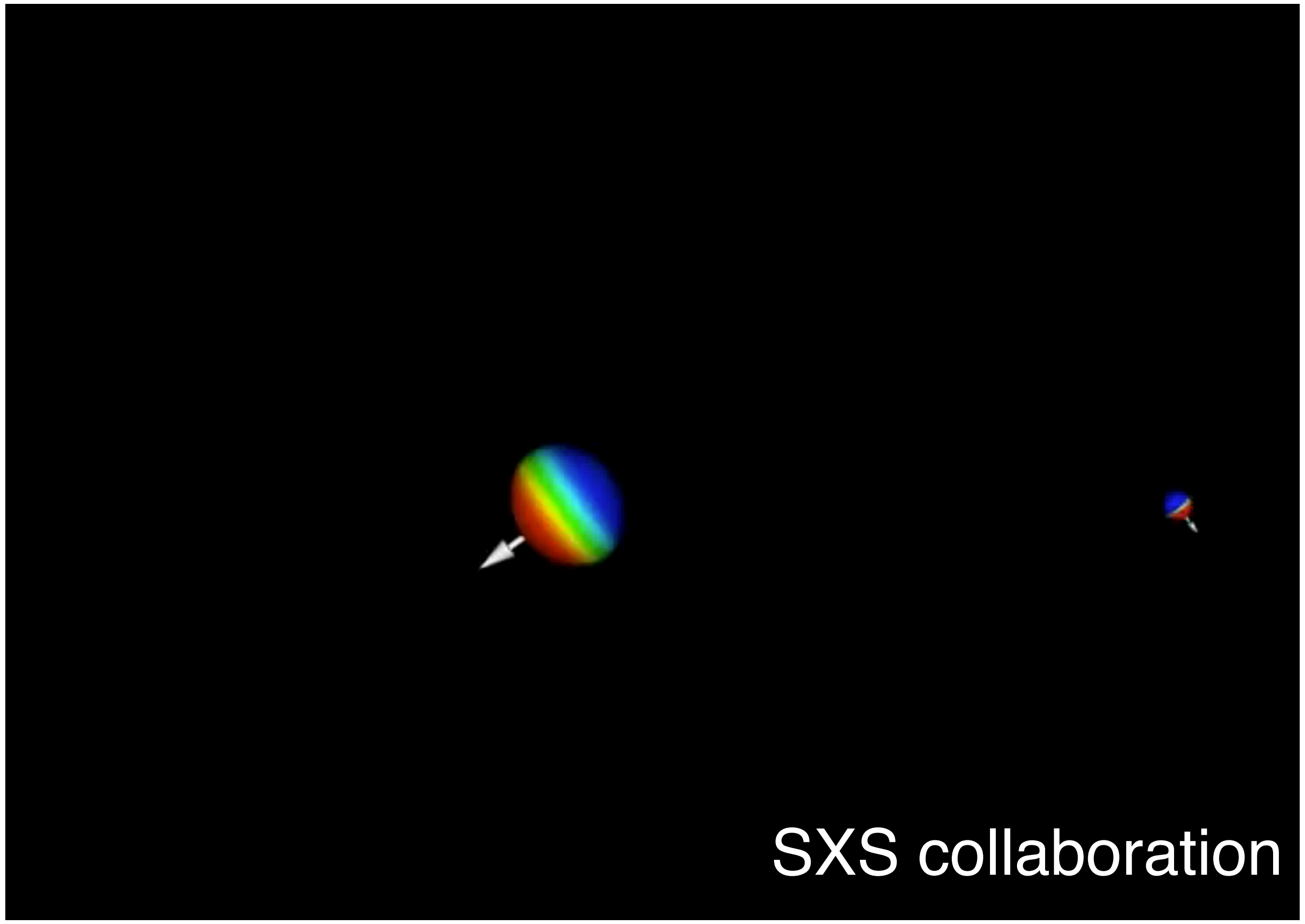


Individual spin components and directions are very hard to measure due to high PN order and parameter correlations

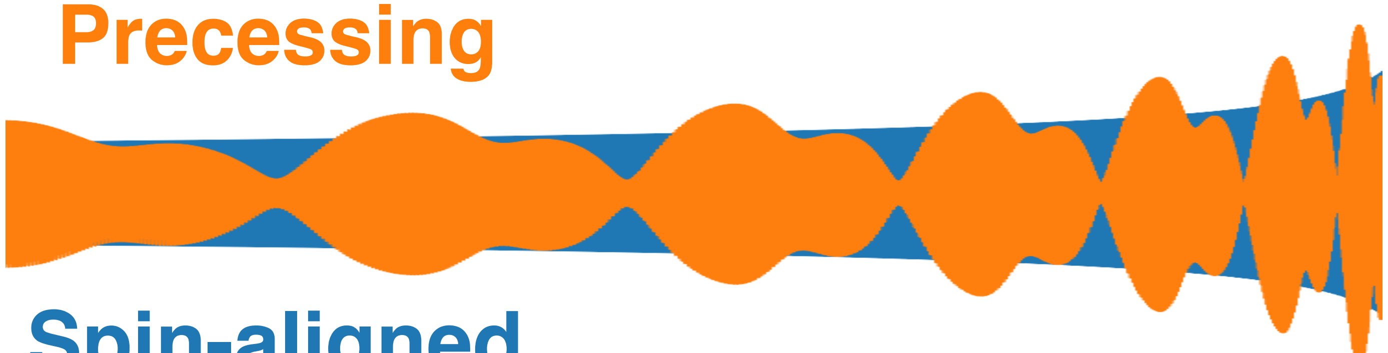
This has been true for the BBH detections too so far. But why do we care about directions?

LVC (arxiv:1805.11579)

GW170817 precession

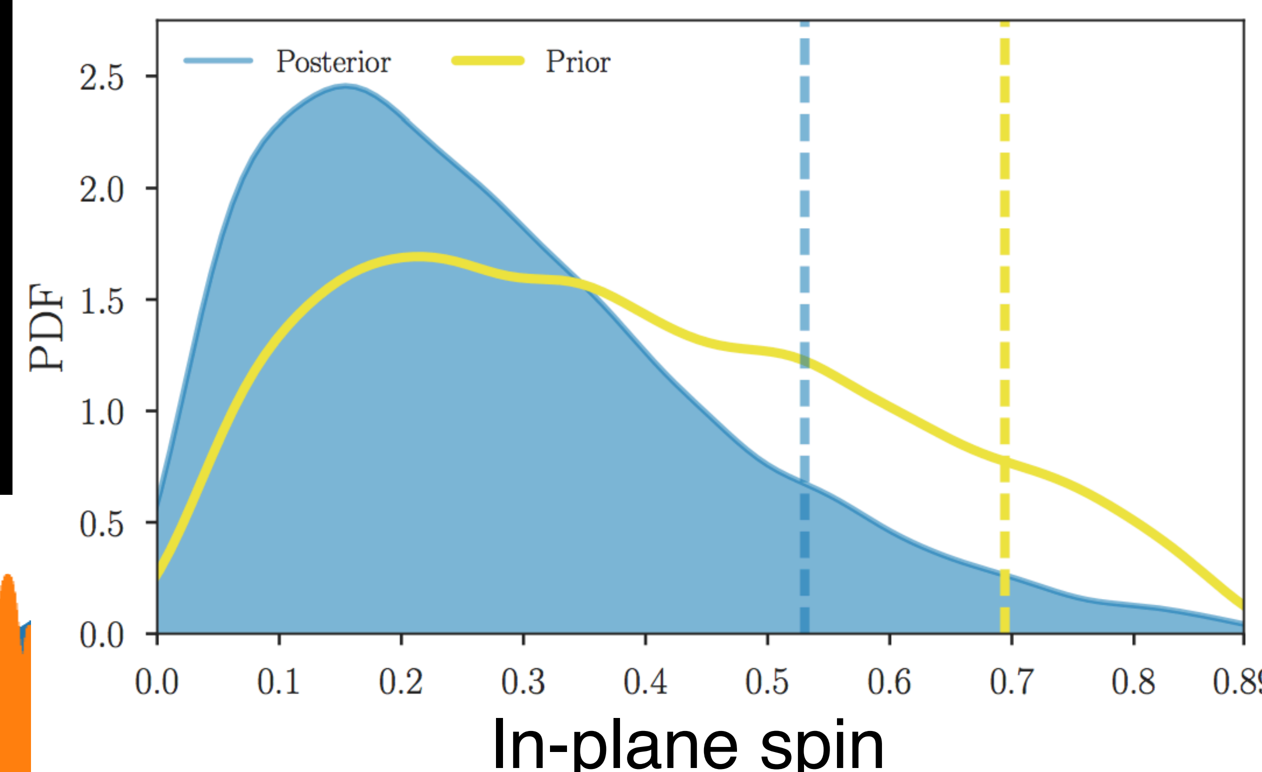


Precessing



Spin-aligned

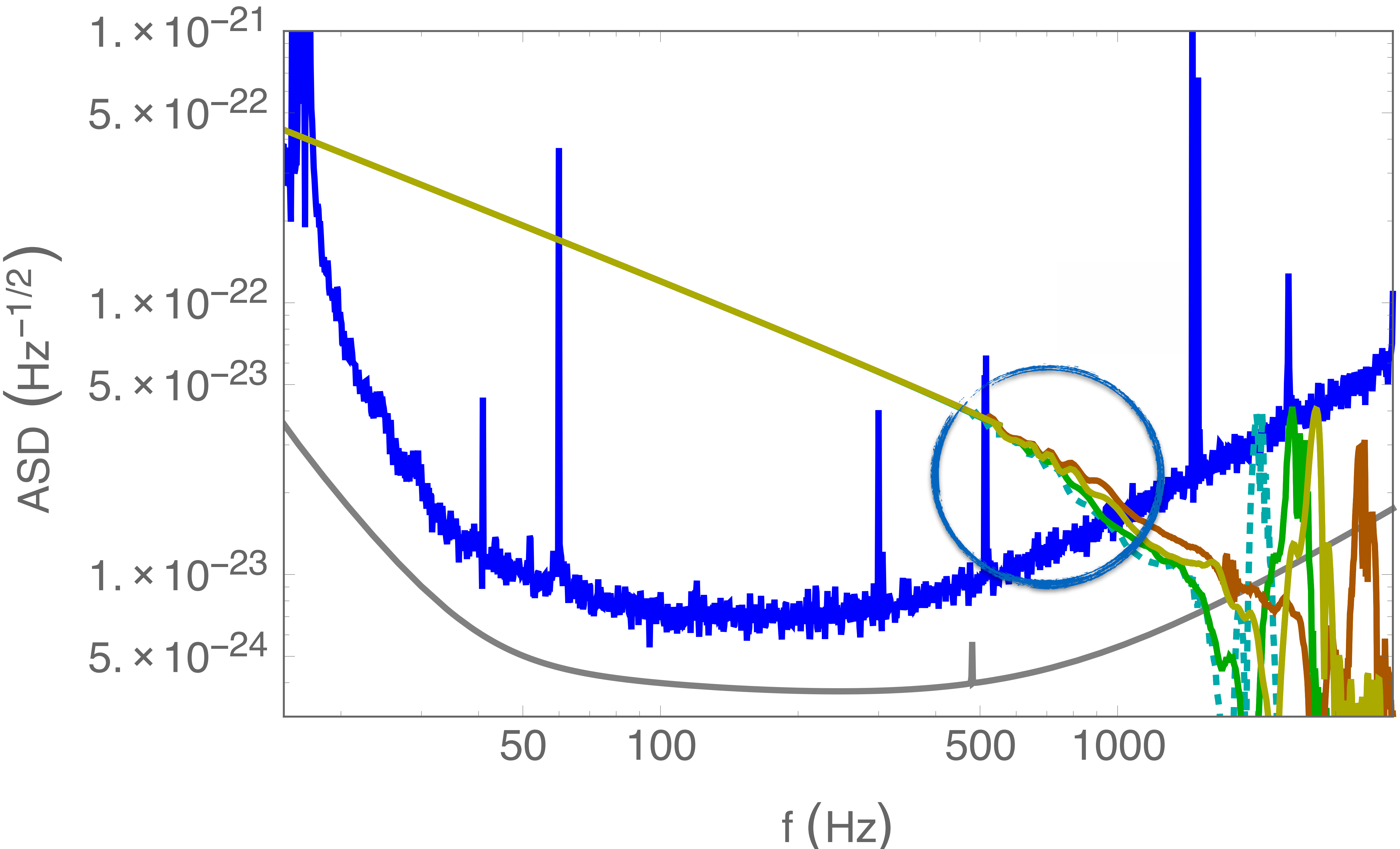
No constraints on precession



LVC (arxiv:1805.11579)

Unclear so far whether spins are aligned or small. This can have important implication for *how* the binaries formed.

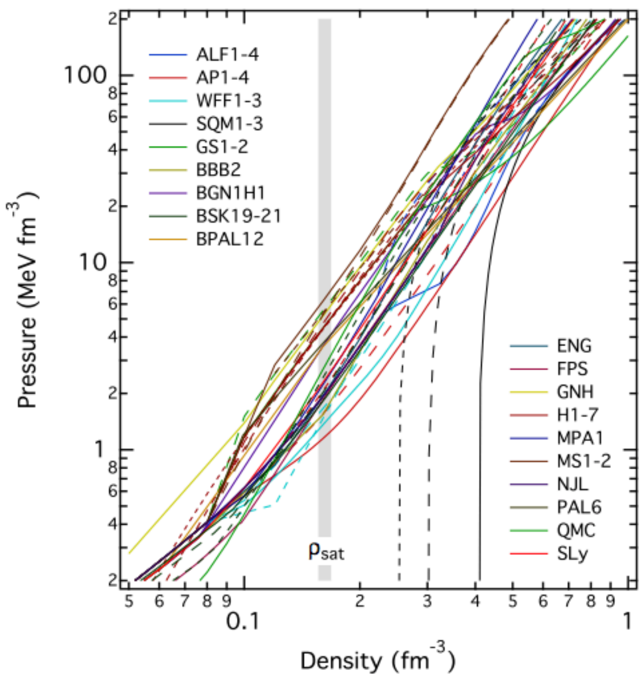
Anatomy of a BNS coalescence

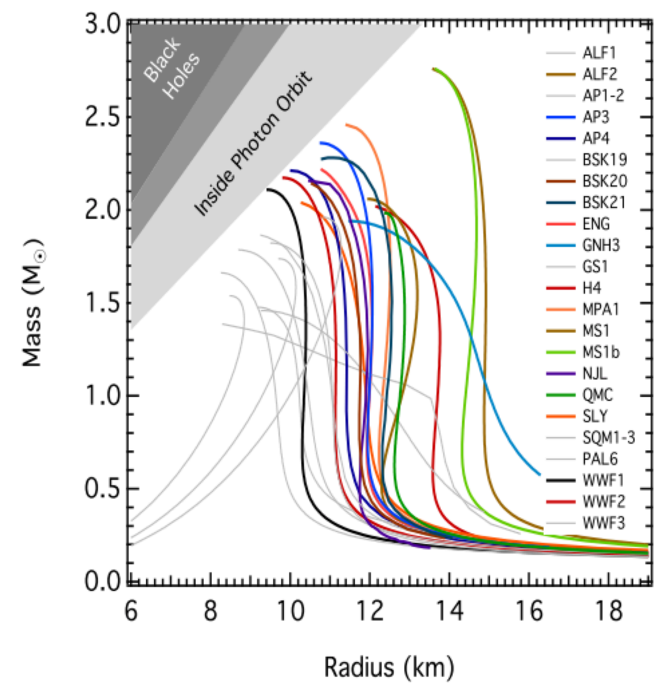


Late inspiral

Data Visualization by J. Read
Numerical data by Tim Dietrich (AEI/FSU/BAM Collaboration)
Phys. Rev. D95(12):124006 and Phys. Rev. D95(2):024029

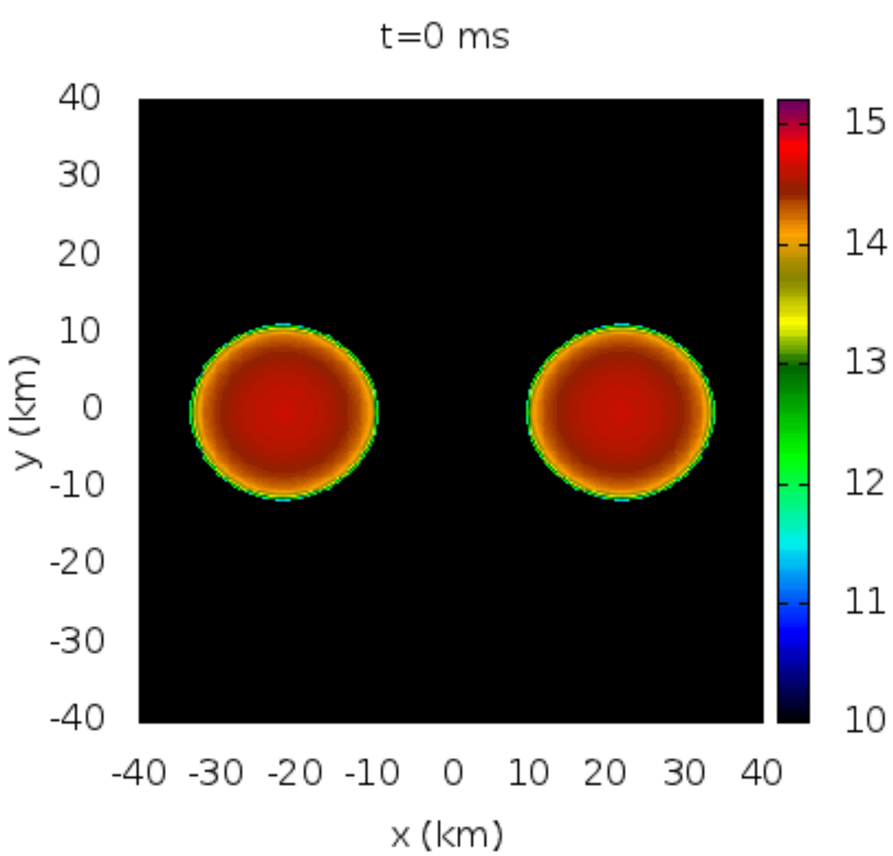
Effect of internal composition

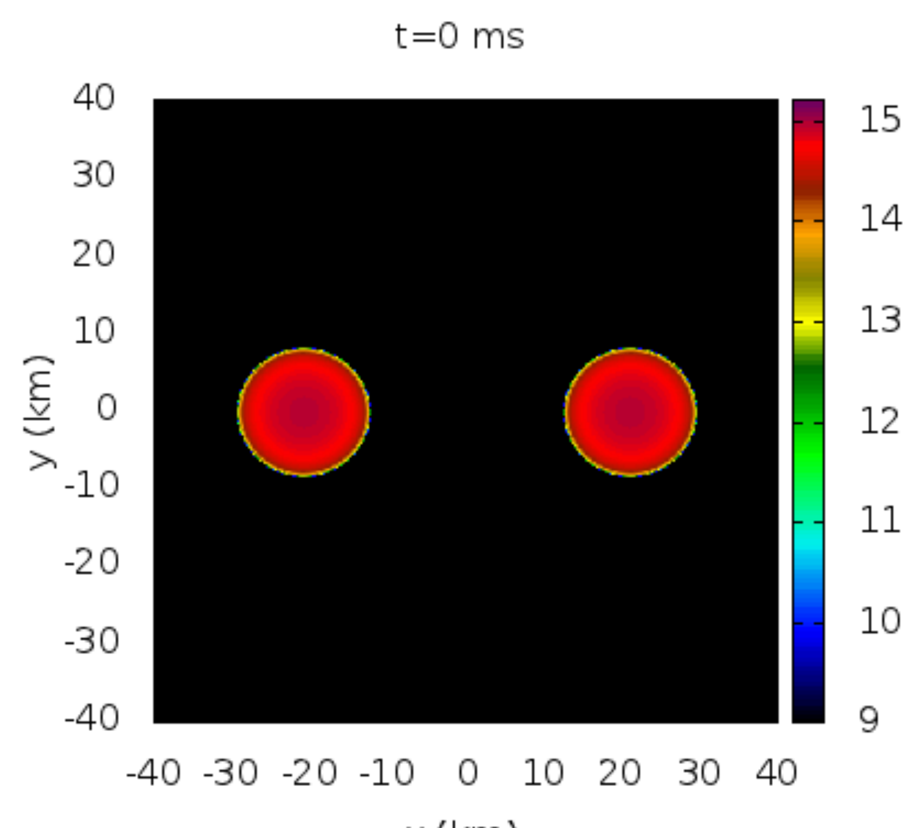




Ozel, Freire (AnnuRev. of Astronomy and Astrophysics 54,401-440)

Neutron stars are extended bodies with structure



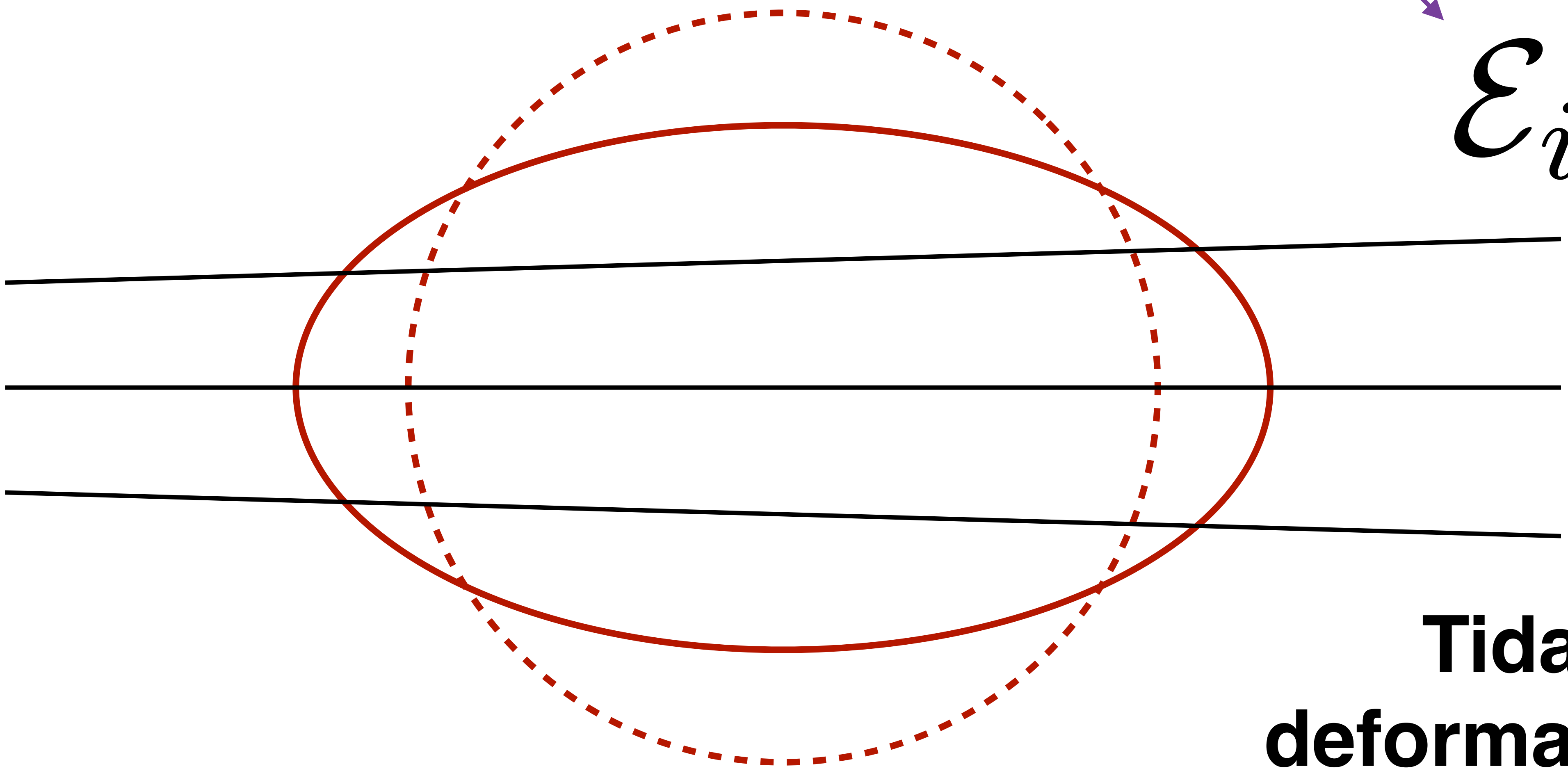


Simulation by Kenta Hotokezaka

Late inspiral

Caused by the companion

$$\mathcal{E}_{ij}$$



Tidal deformability

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

Tidally induced quadrupole

Spacetime metric

The metric far from the source (multipolar expansion) is

External

$$-\frac{1+g_{tt}}{2} = -\frac{m}{r} - \frac{3Q_{ij}}{2r^3}n^i n^j + \ldots + \frac{\mathcal{E}_{ij}}{2}r^2 n^i n^j + \ldots$$

Monopole

Quadrupole

Flanagan+ (arxiv:0709.1915)

Hinderer+ (arxiv:0911.3535)

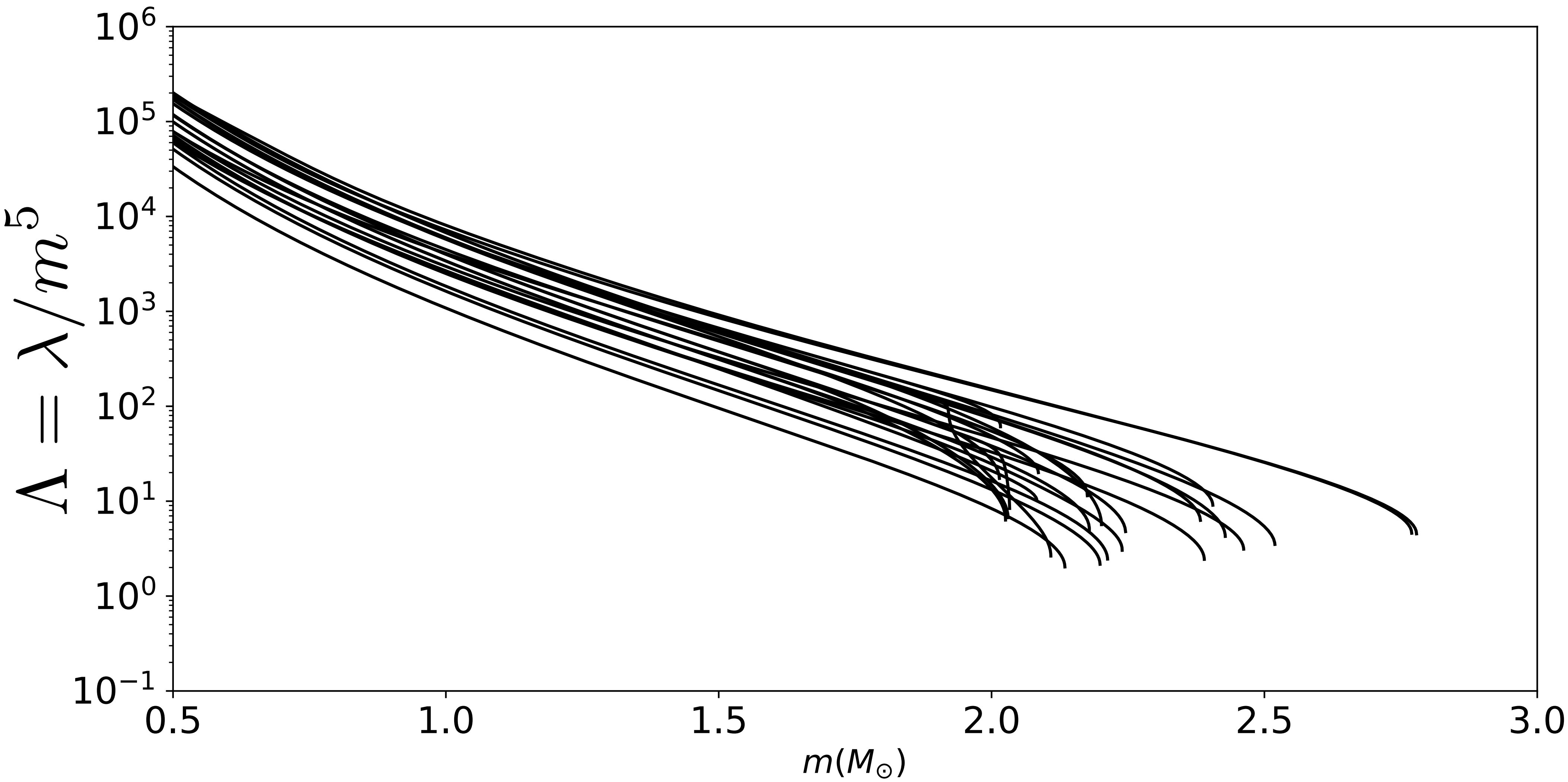
In Newtonian Theory

$$\mathcal{Q}_{ij} = \int d^3x\rho(\vec{x})\left(x_i x_j - \frac{1}{3}r^2\delta_{ij}\right) \qquad \mathcal{E}_{ij} = \frac{\partial^2\Phi_{ext}}{\partial x^i \partial x^j}$$

In full GR you have to solve for the metric perturbation (Andreas Bauswein's talk)

Information about EoS

The tidal deformability depends (quite sensitively) on the EoS



More compact stars are harder to deform and have a smaller tidal deformability

Late inspiral phase

$$\frac{d^2\Psi}{dt^2} = \frac{d\omega}{dt} = \frac{d\omega}{dE}\frac{dE}{dt} = \frac{\dot{E}}{dE/d\omega}$$

The quadrupole moment of the system changes $Q \sim \mu r^2 + \frac{Q_5(\lambda)}{r^3}$

And that affects both the binding energy
and the energy emitted

$$\dot{E} \sim \dddot{Q}$$

The tidal deformation accelerates the inspiral (***Question: why?***)

Flanagan+ (arxiv:0709.1915)

Vines+ (arxiv:1101.1673)

Waveform phase

measure
less well

mass and spin
enter together

$$\Psi(u) \sim a_0(\mathcal{M})u^{-5}\Big[1 + a_2(\eta)u^2 + a_3(\eta, \vec{S}_i)u^3$$

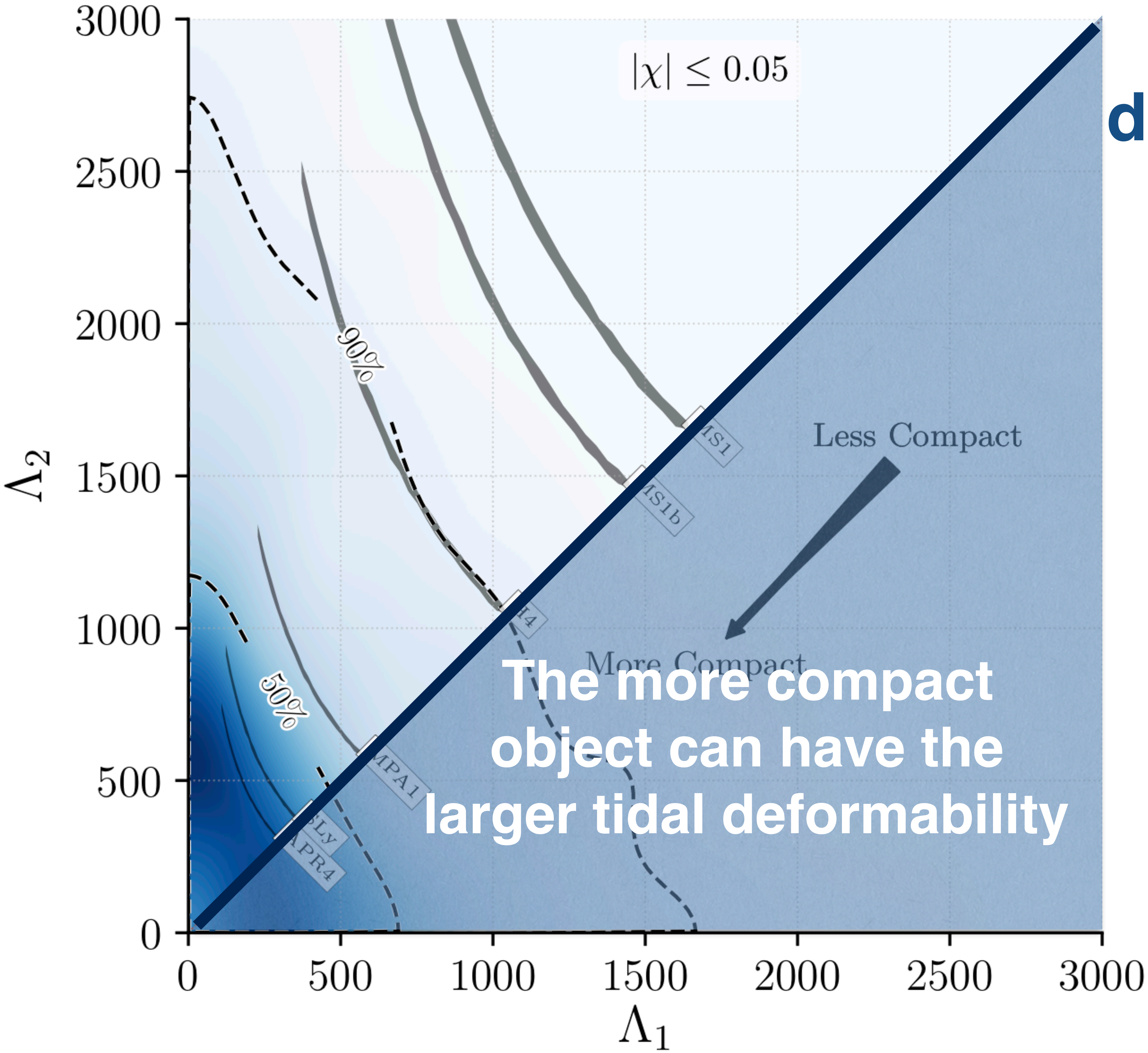
$$+a_4(\eta, S_i^2, Q_i)u^4 + ... + a_{10}(\Lambda)u^{10} + ...\Big]$$

measure
VERY well

information
about the EoS

GW170817 deformability

Bodies of the same mass are allowed to have different tidal parameters



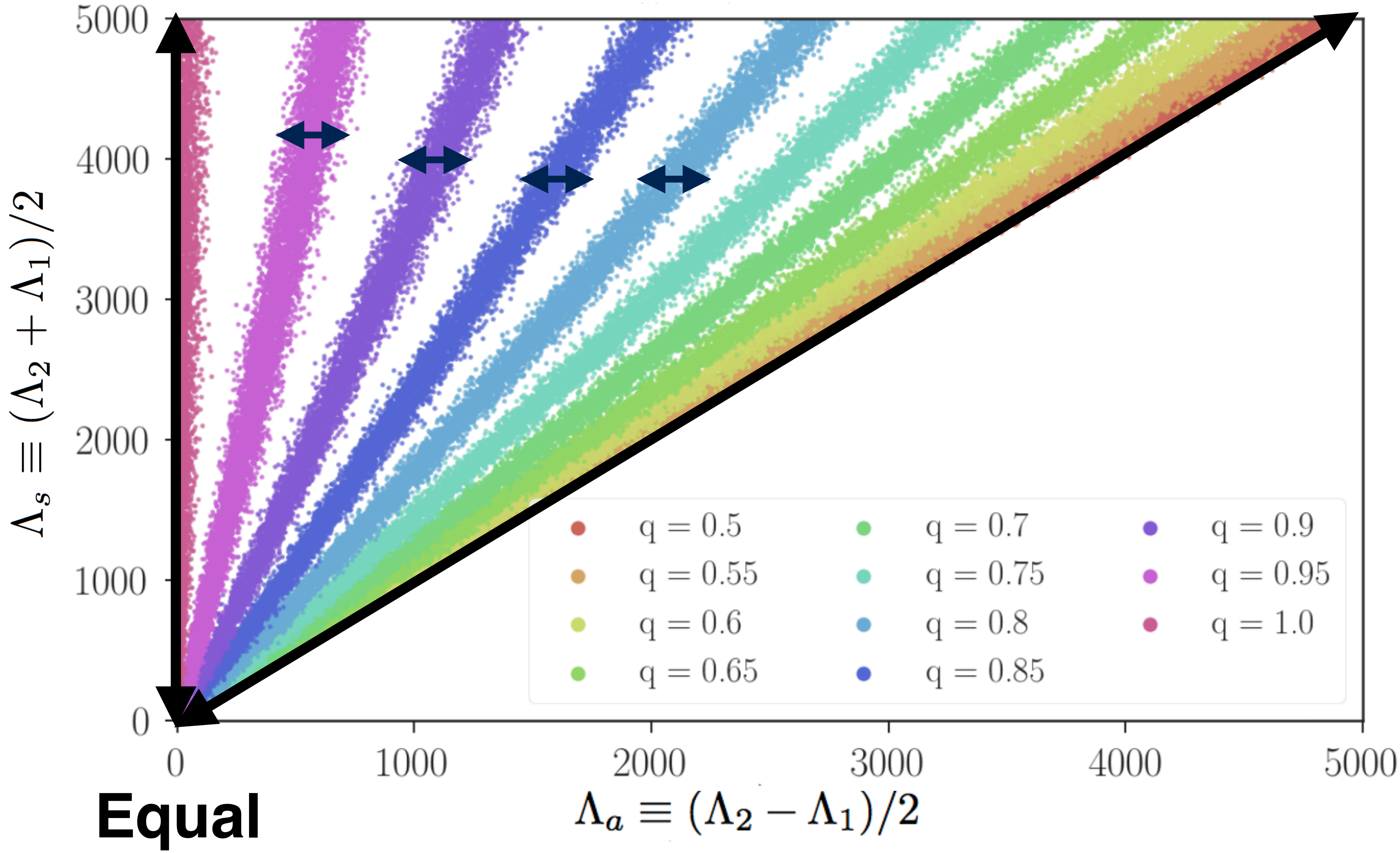
No assumptions on the nature of the bodies

LVC PRL 119, 161101 (2017)

EoS-insensitive relation

$$\Lambda_a(\Lambda_s, q; \vec{b}) = F_n(q)\Lambda_s \frac{1 + \sum_{i=1}^{3}\sum_{j=1}^{2} b_{ij} q^j \Lambda_s^{-i/5}}{1 + \sum_{i=1}^{3}\sum_{j=1}^{2} c_{ij} q^j \Lambda_s^{-i/5}}$$

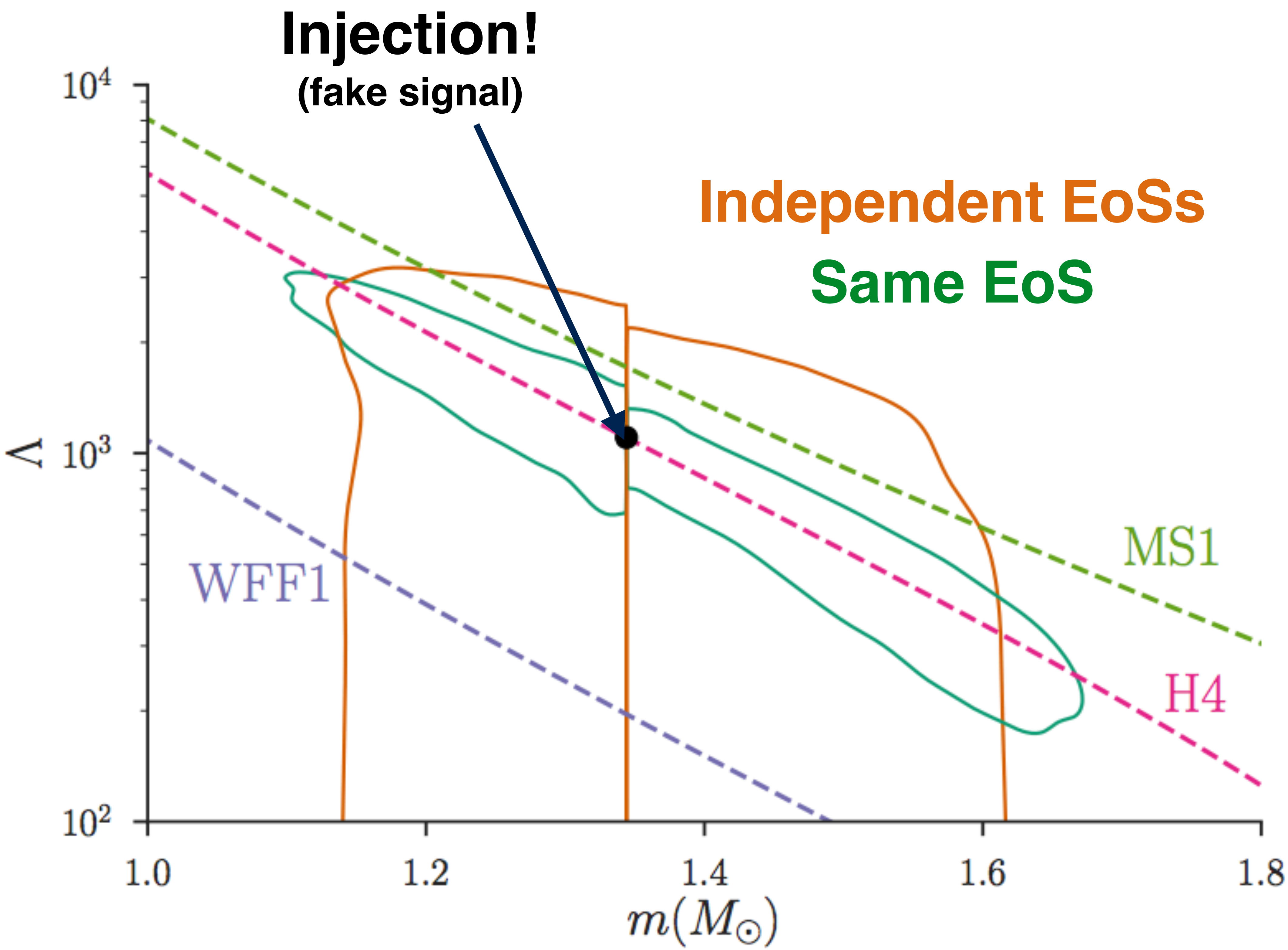
Large mass ratios



Equal masses

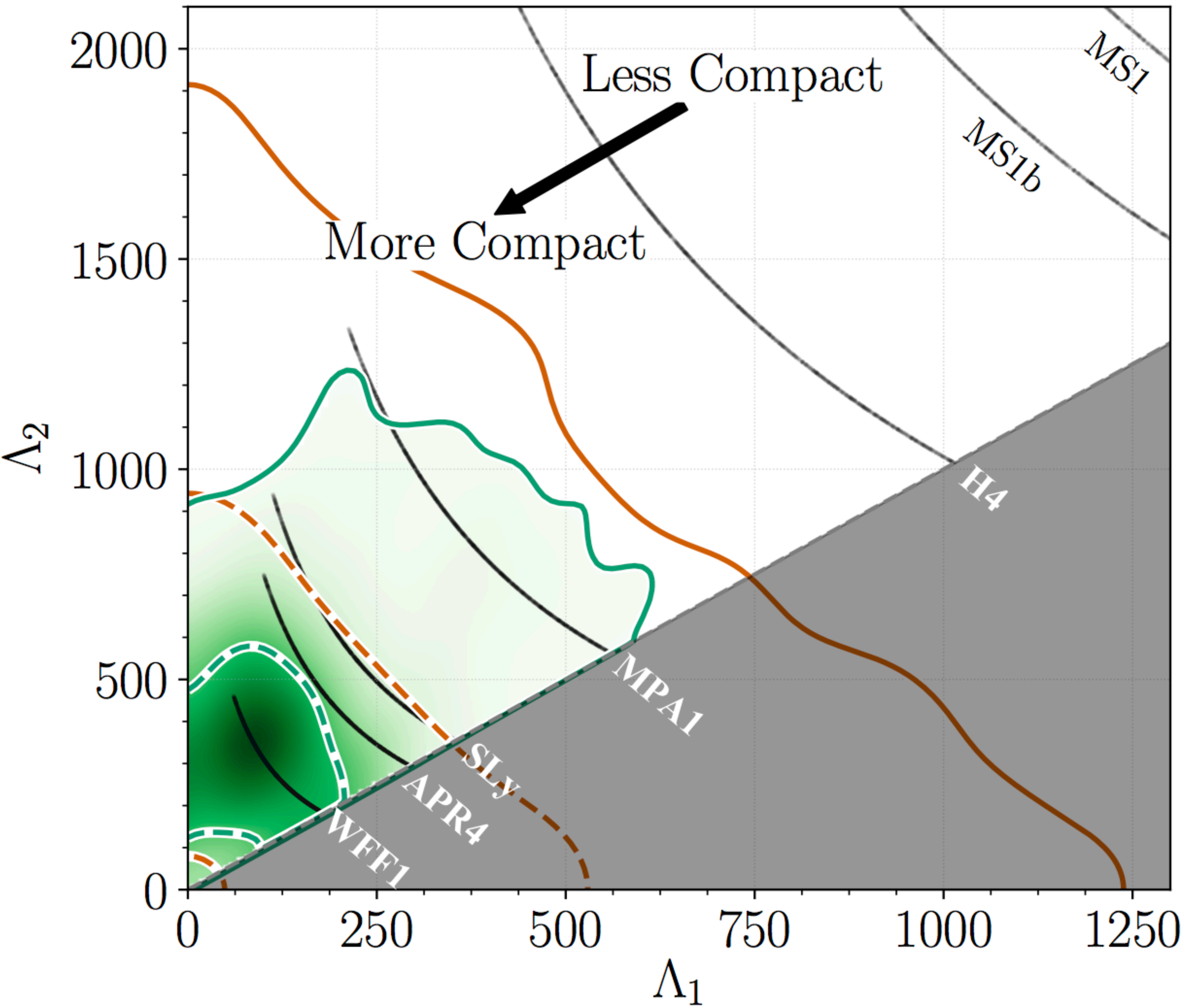
Yagi, Yunes (CGQ 33 13)
Chatziioannou+ (PRD 97, 104036)

NSs have the same EoS



Chatziioannou+ (PRD 97, 104036)

GW170817 tides



LVC (arxiv:1805.11581)

Independent EoSs (no assumptions)

Same EoS (assume BNS)

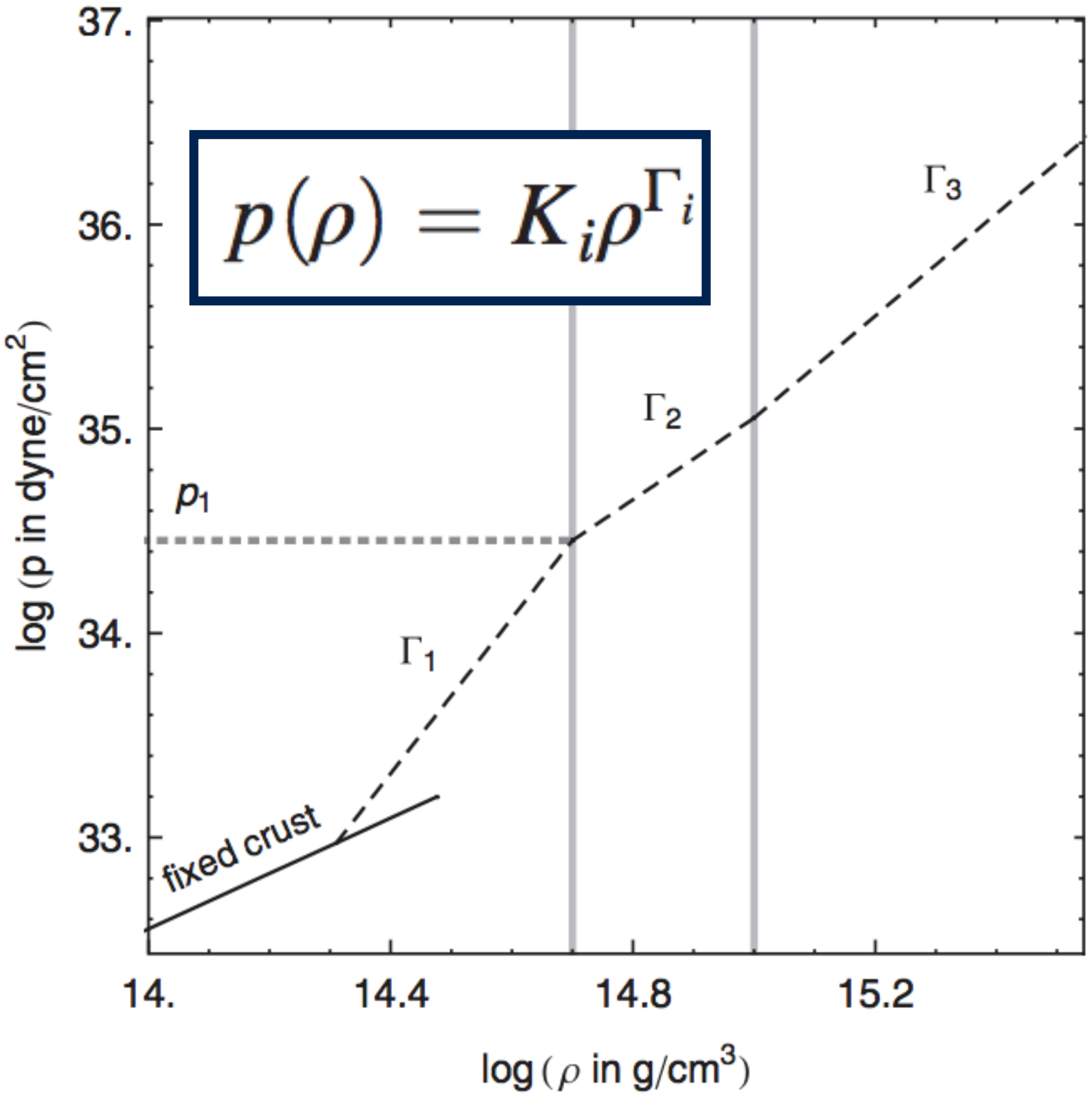
GW data point to small(ish) tidal parameters

Question: have we proved the bodies are NSs?

EoS parametrization

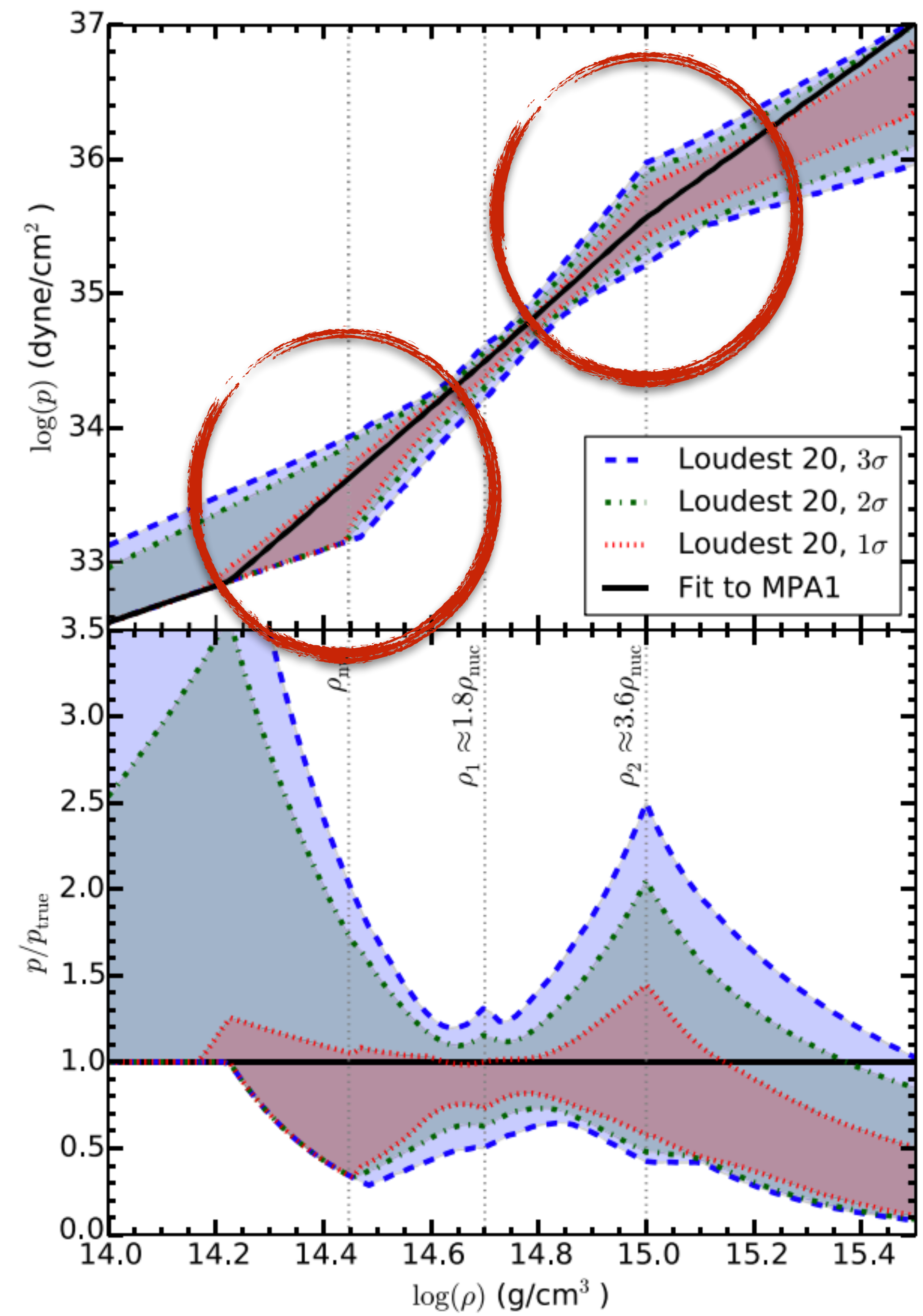
Piecewise polytropes

$$p(\rho) = K_i \rho^{\Gamma_i}$$



Read+ (PRD 79 124032)

Impose thermodynamic stability, causality, and observational constraints

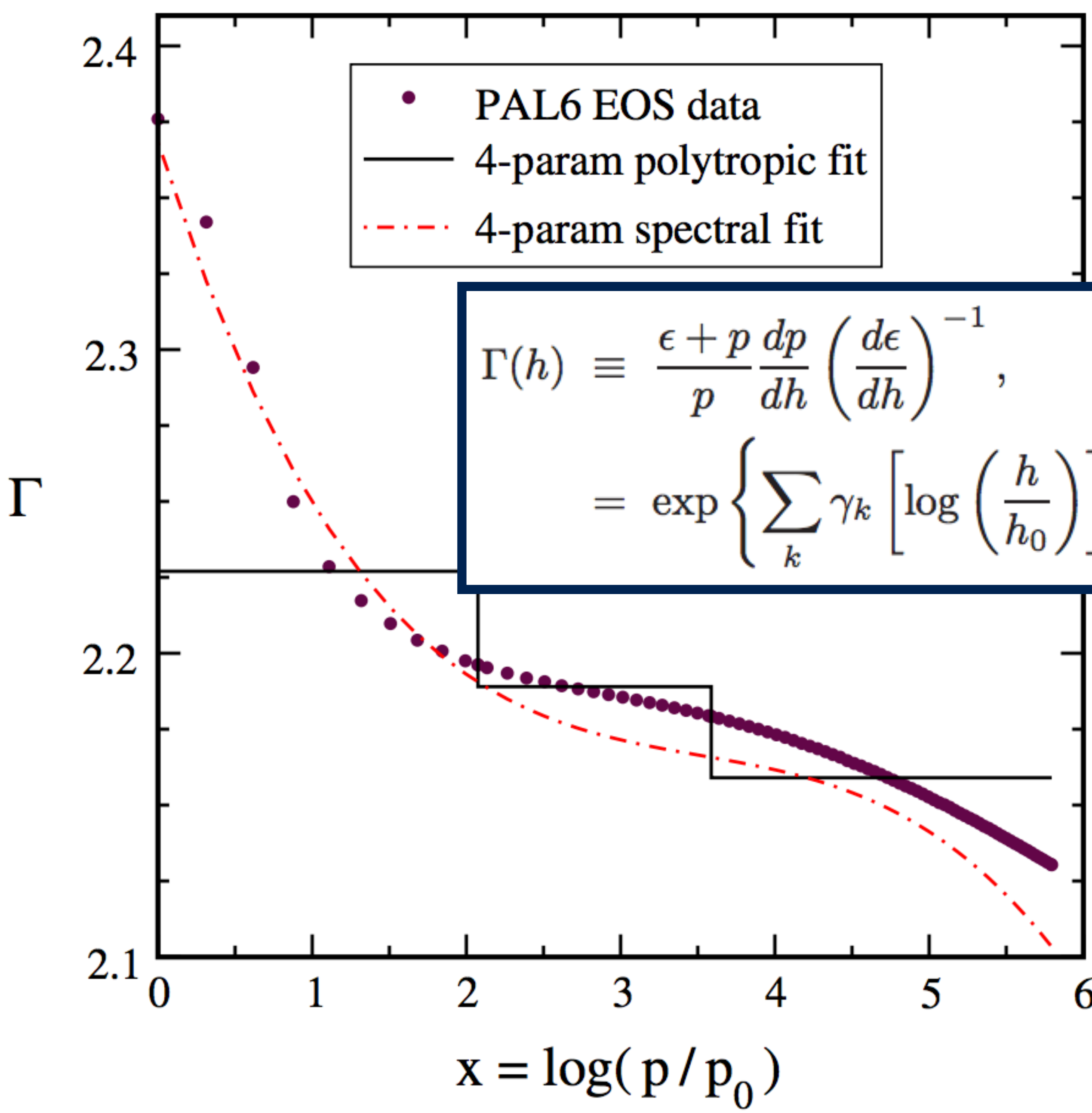


Lackey and Wade (PRD 91 043002)

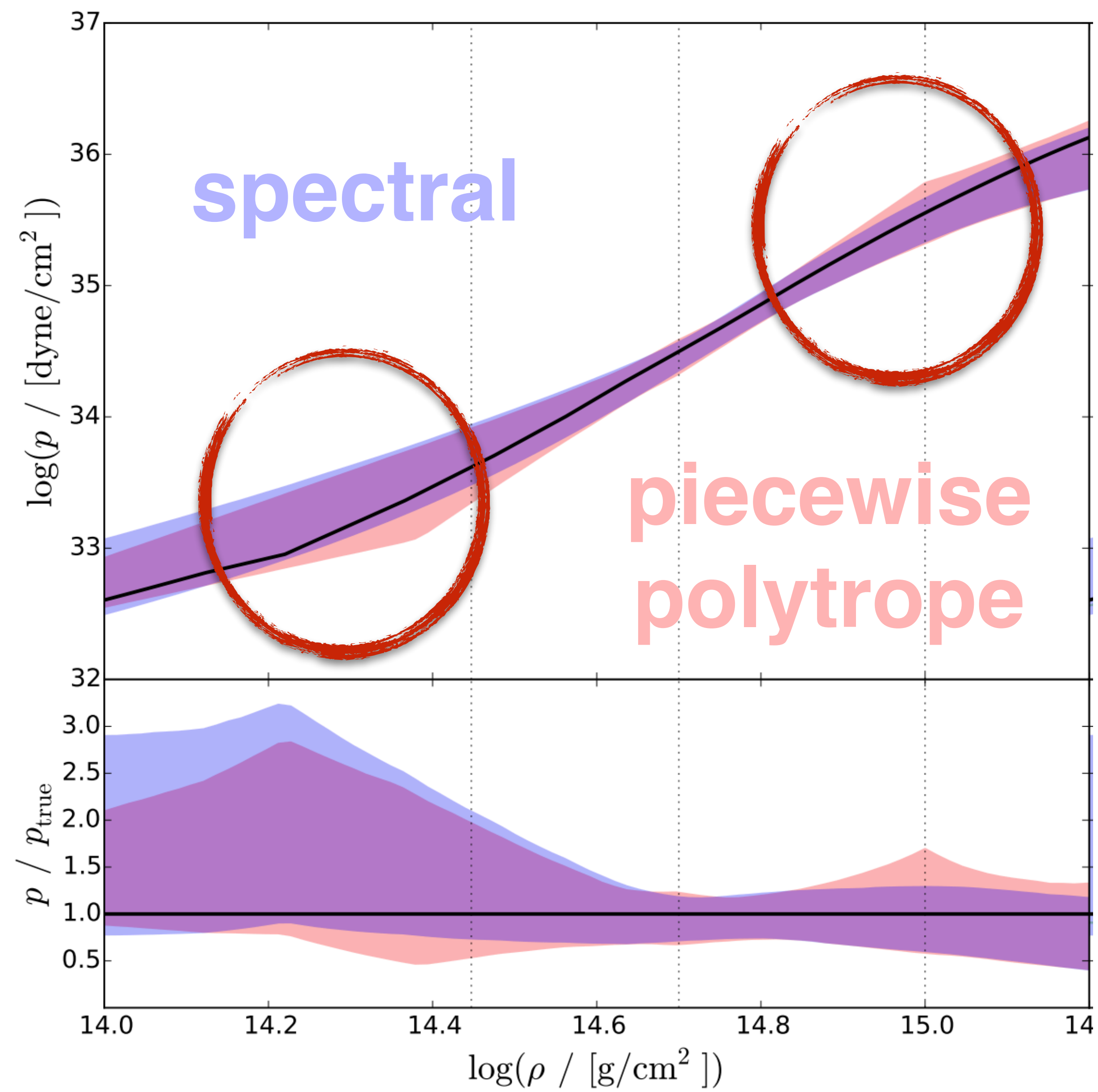
EoS parametrization

Spectral decomposition

Impose thermodynamic stability, causality, and observational constraints



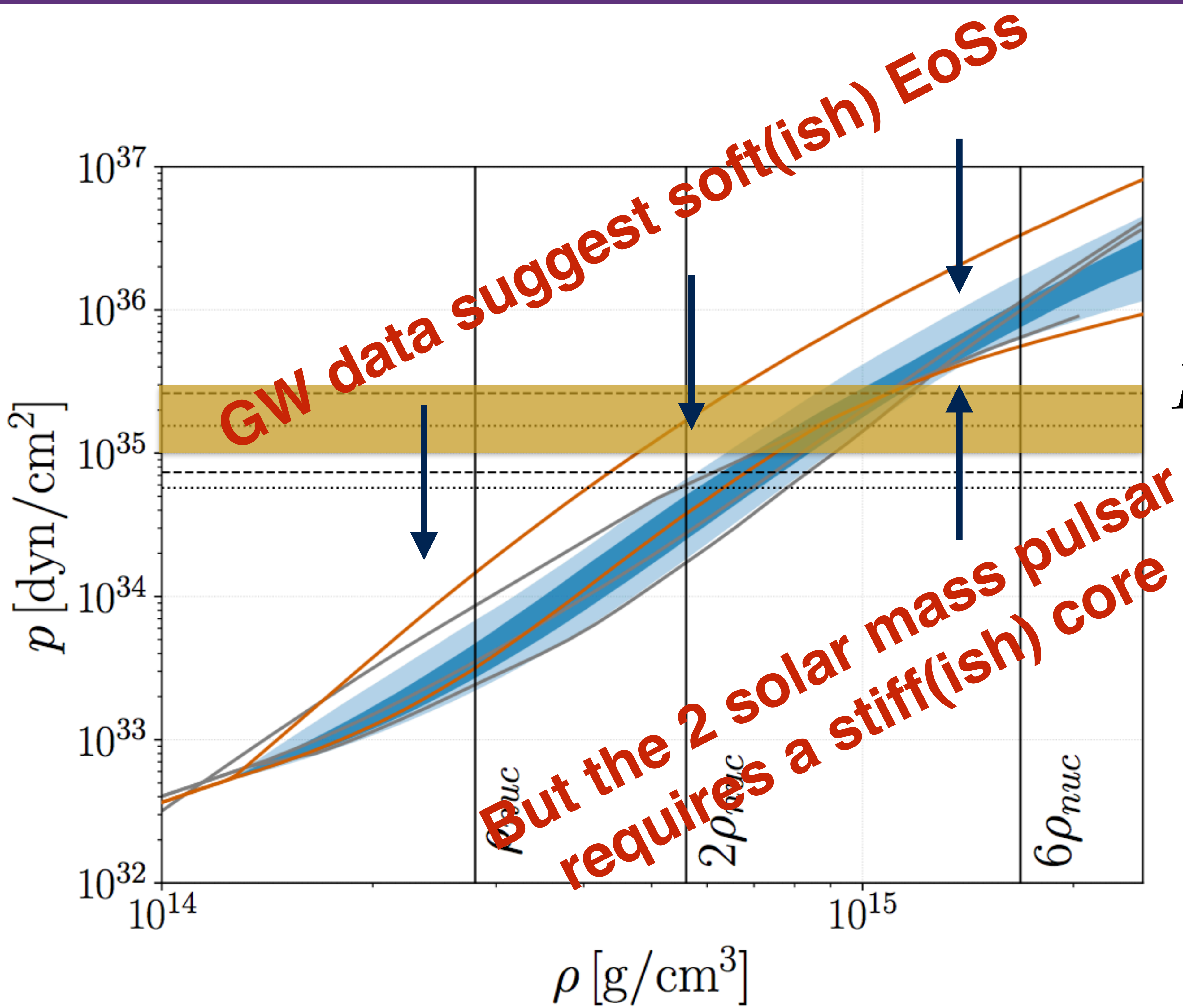
$$\Gamma(h) \equiv \frac{\epsilon + p}{p}\frac{dp}{dh}\left(\frac{d\epsilon}{dh}\right)^{-1},$$
$$= \exp\left\{\sum_k \gamma_k \left[\log\left(\frac{h}{h_0}\right)\right]^k\right\}$$



Lindblom (PRD 82 103011)

Carney+ (arxiv:1805.11217)

GW170817 EoS



Overall

$$R \in [10.5, 13.3]\mathrm{km}$$

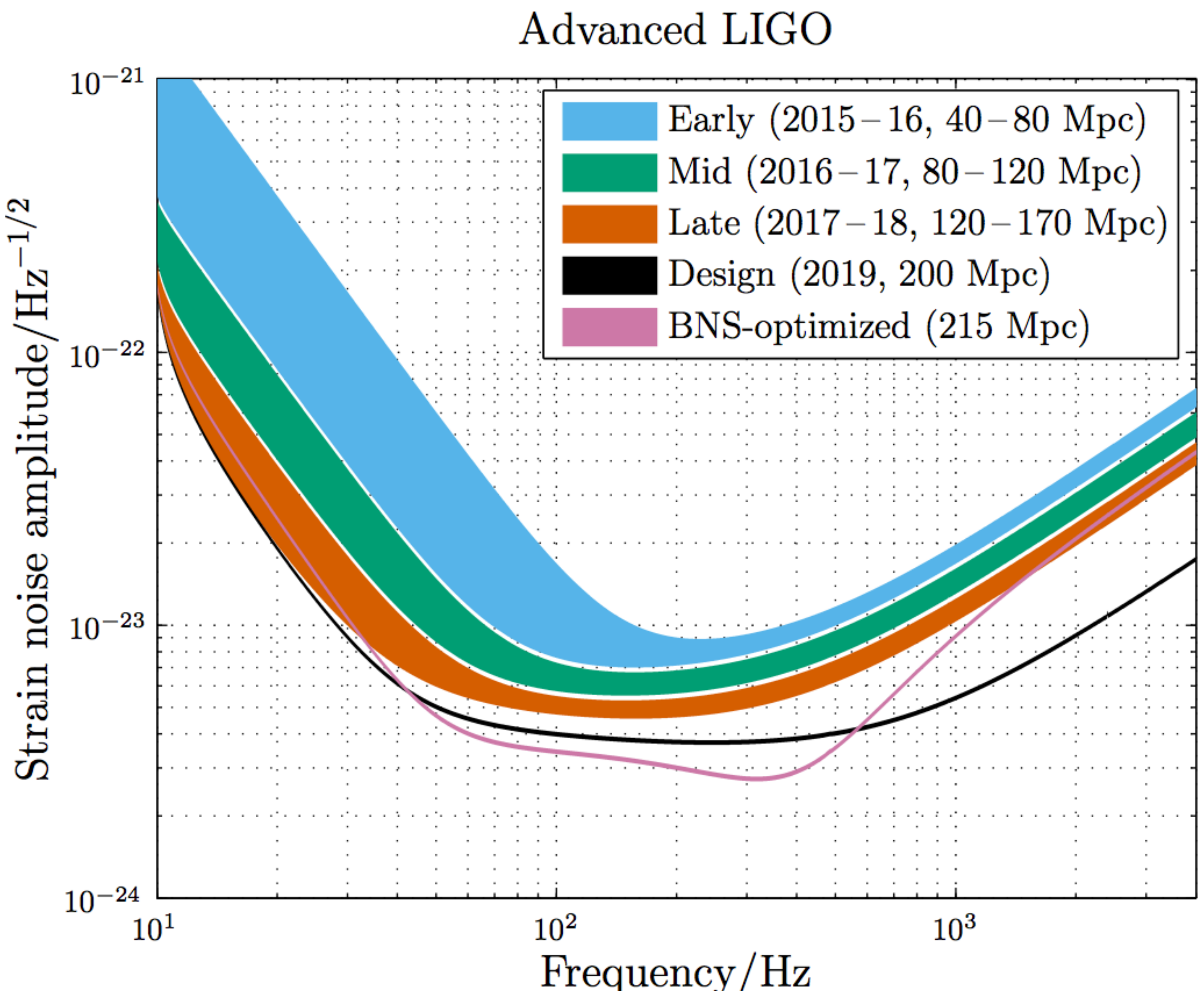
LVC (arxiv:1805.11581)

Missing stuff

- Missing PN terms (point particle is fully known to 3.5PN and partially to 4PN, spin-orbit to 4PN, spin-spin to 2PN)
- Octupole deformation $Q_{ijk} \sim \lambda_3 \mathcal{E}_{ijk}$
- Dynamical tides
- Nonlinear response $\mathcal{O}(\lambda^2)$
- Spins/tidal couplings $J_{ij} \sim \mu_2 \mathcal{B}_{ij}$

Homework?

Looking ahead



LVC LRR 19 (2016) 1

At design sensitivity

BNS: 0.4-400/year
NSBH: 0.2-300/year
BBH: 0.4-1000/year

LVC ApJL 832, 2 (2016)
LVC CQG 27, 173001 (2010)

Epoch		2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration		4 months	9 months	12 months	(per year)	(per year)
Achieved BNS range/Mpc	LIGO	60 – 80	60 – 100	—	—	—
	Virgo	—	25 – 30	—	—	—
	KAGRA	—	—	—	—	—
Estimated BNS detections		0.05 – 1	0.2 – 4.5	1 – 50	4 – 80	11 – 180
Actual BNS detections		0	1	—	—	—

Bibliography

1. Blanchet (LRR 17 2) ***Gravitational Radiation from Post-Newtonian Sources and Inspiralling Compact Binaries***

   Comprehensive review of post-Newtonian theory

2. Poison and Will ***Gravity: Newtonian, Post-Newtonian, Relativistic***

   Everything! Also discussion of tidal interactions both Newtonian and Relativistic

1. Flanagan+ (arxiv:0709.1915): derivation of the tidal deformability term in the GW phase and nice physical intuition of the phenomenon
2. Read+ (PRD 79 124032): piecewise polytropes and EoS parametrization
3. Lindblom+ (PRD 86 084003): spectral EoS parametrization
4. LVC (arxiv:1805.11579, arxiv:1805.11579): current understanding of the properties of GW170817
5. LVC (LRR 19 1): “Observing scenarios paper”