Gravitational wave astronomy: *a new window into neutron star interiors*

Lecture 3

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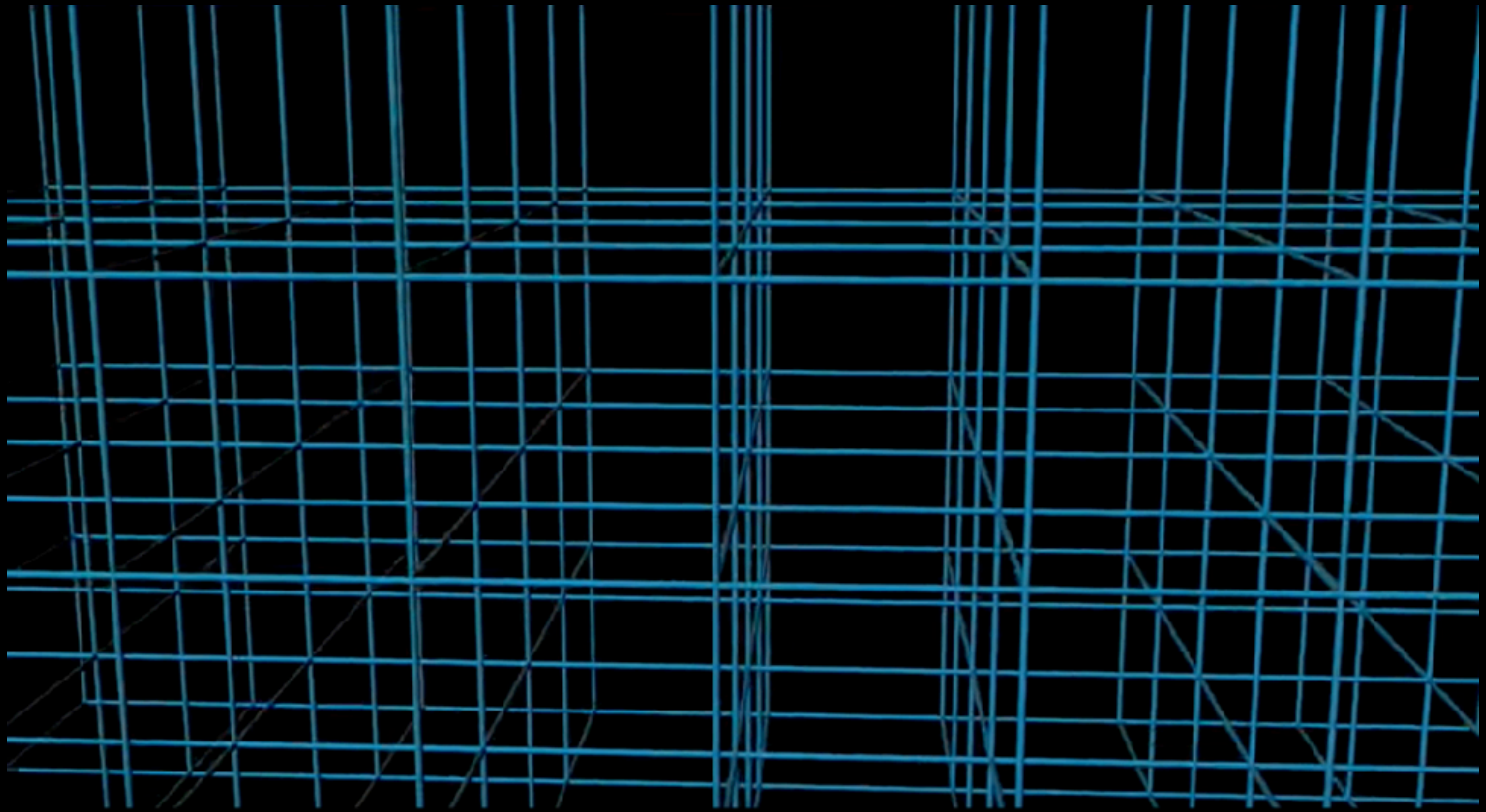
FLAD LUSO-AMERICAN DEVELOPMENT FOUNDATION

Outline:

1. Gravitational wave theory
2. Detectors
3. Constraints on the dense-matter EOS from current GW observations
4. What’s next in GW astronomy

“Matter tells space-time how to curve and space-time tells matter how to move.”

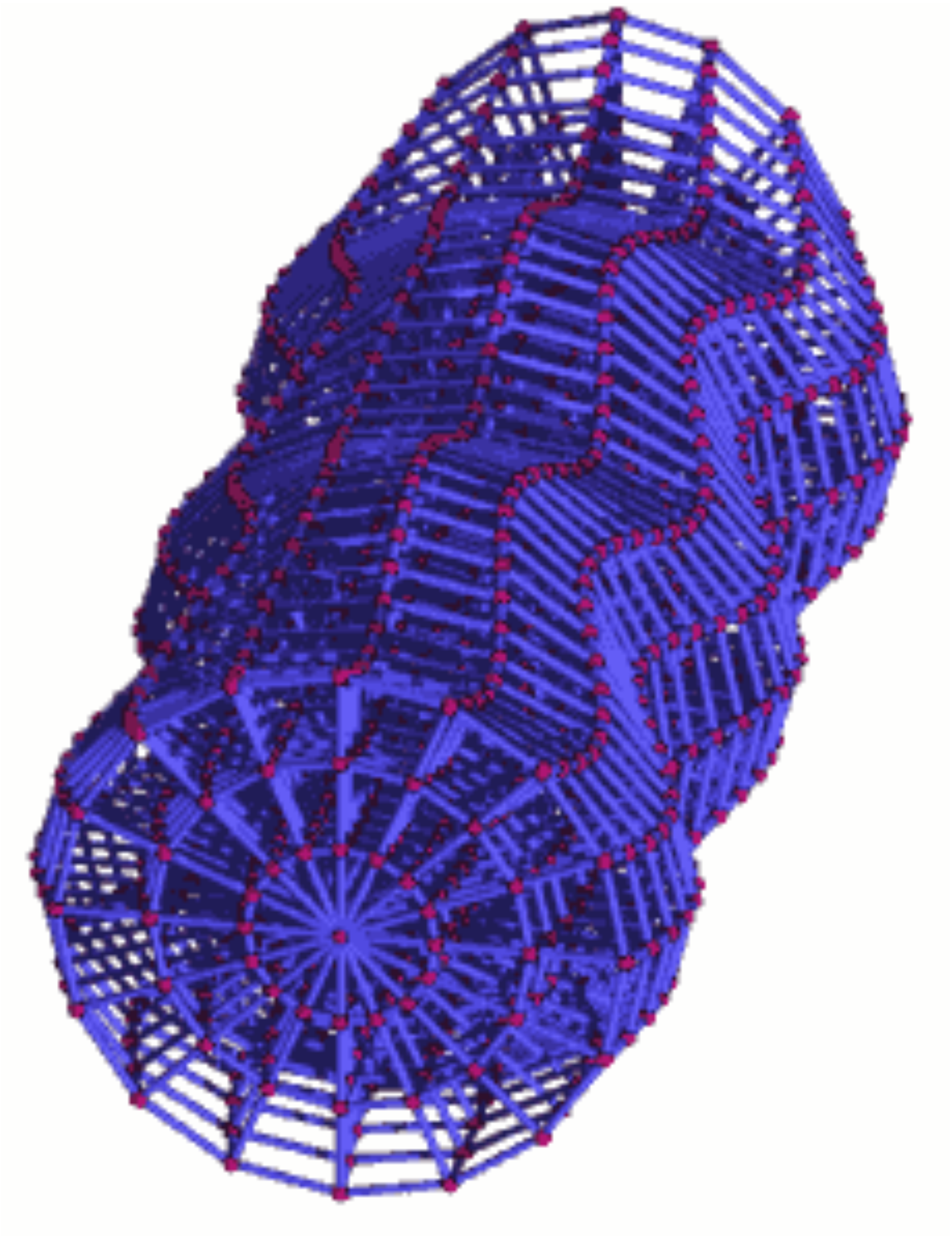
— John A. Wheeler



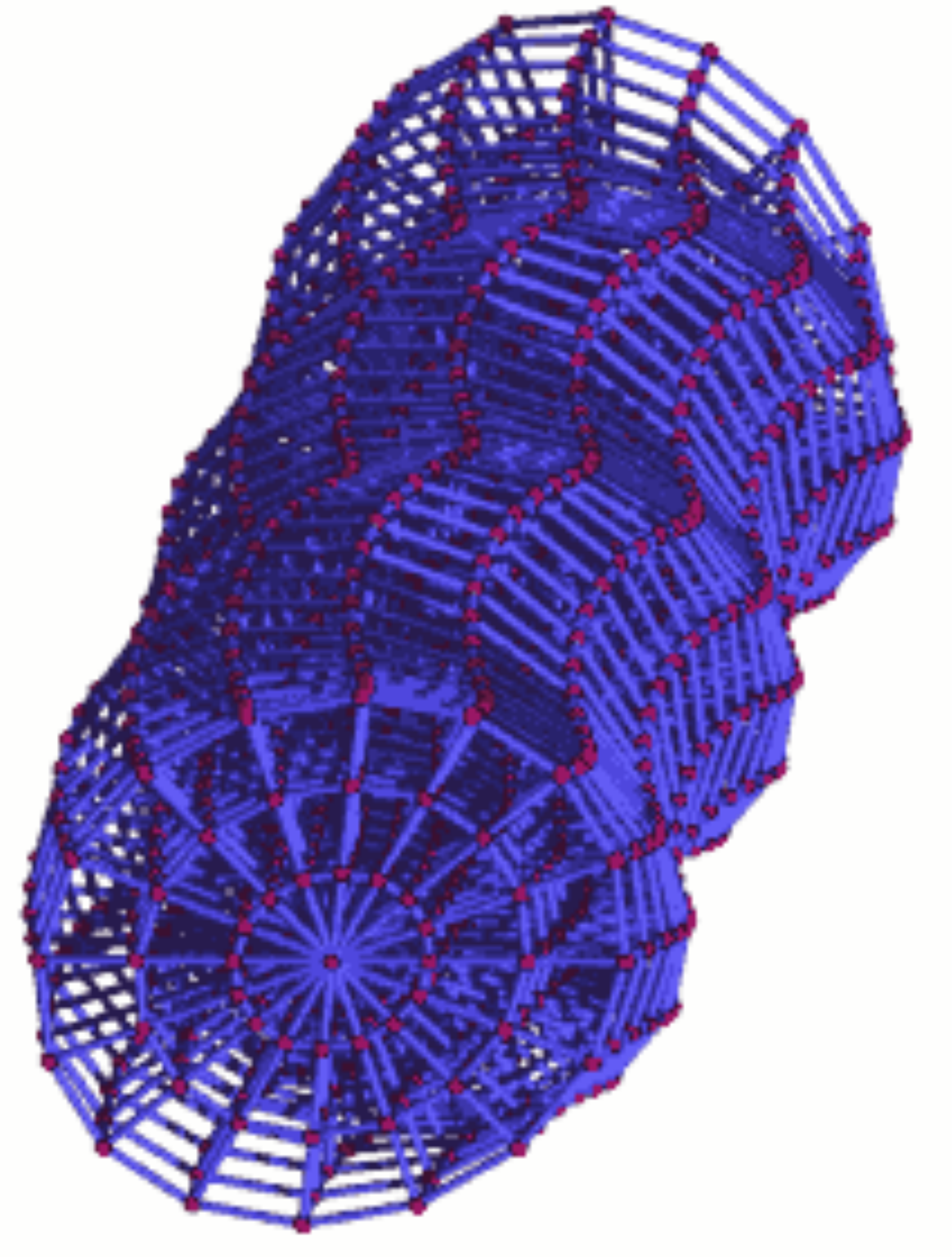
Video from American Museum of Natural History
“Gravity: Making Waves”
Slide credit: Jocelyn Read

Gravitational wave polarizations

Stretching / shrinking of distance between test particles (in red)
as a GW propagates through



Plus polarization



Cross polarization

Credit: https://www.einstein-online.info/en/spotlight/gw_waves/

The first binary pulsar: PSR B1913+16

- Discovered in 1974
- Nobel Prize in 1993 awarded to Hulse & Taylor for the *discovery* of the system

$M_1 = 1.438\ M_\odot$

$M_2 = 1.390\ M_\odot$

P_{orb} = 7.75 hours; $\dot{P} = -2.5 \times 10^{-12}$ s/s

$a = 1.95 \times 10^6$ km

Taylor & Weisberg 1983

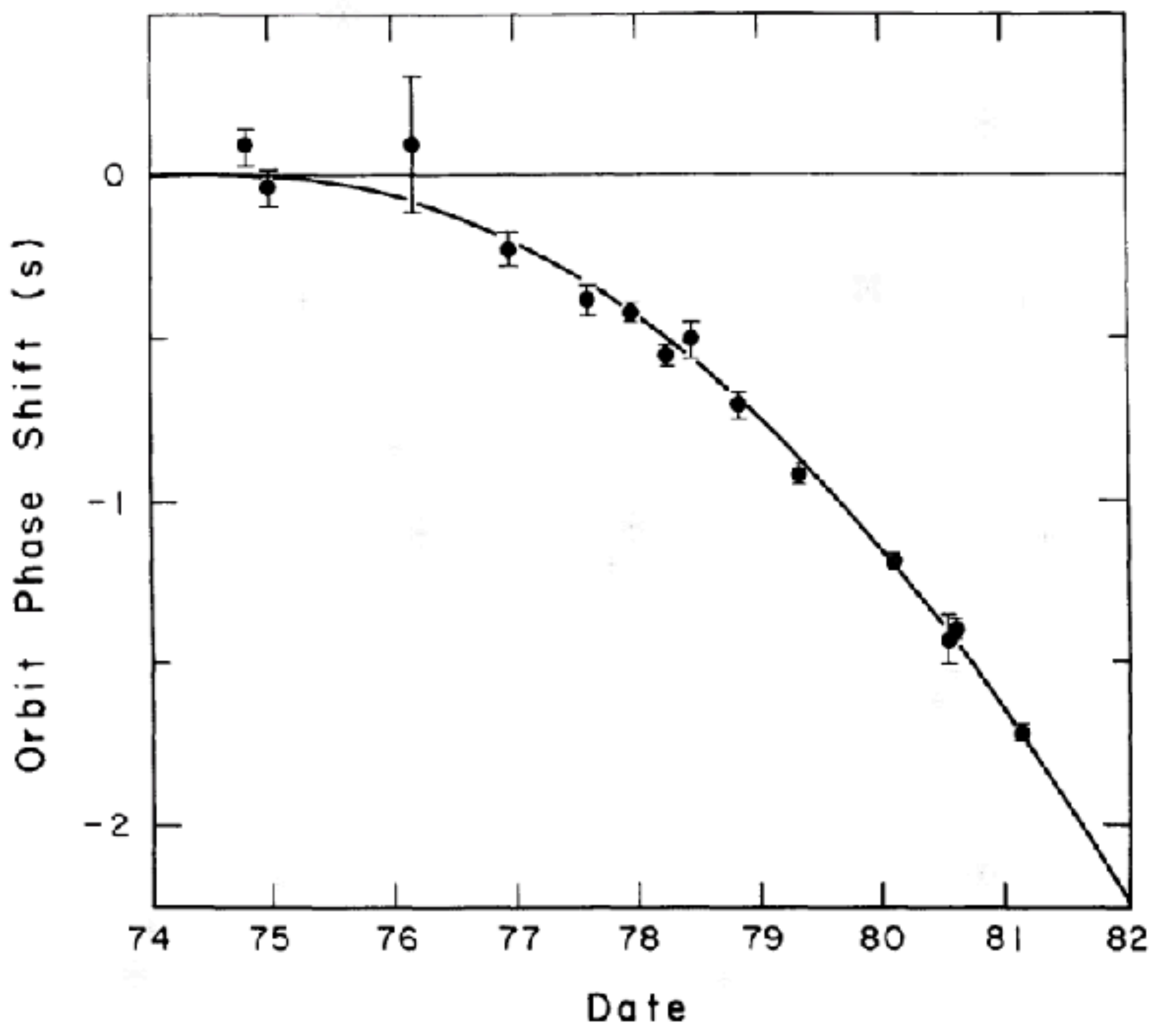


FIG. 6.—Orbital phase residuals, obtained from the data listed in Table 4. If the orbital period had remained constant, the points would be expected to lie on a straight line. The curvature of the parabola drawn through the points corresponds to the general relativistic prediction for loss of energy to gravitational radiation, or $\dot{P}_b = -2.40 \times 10^{-12}$.

Updated measurement of orbital decay

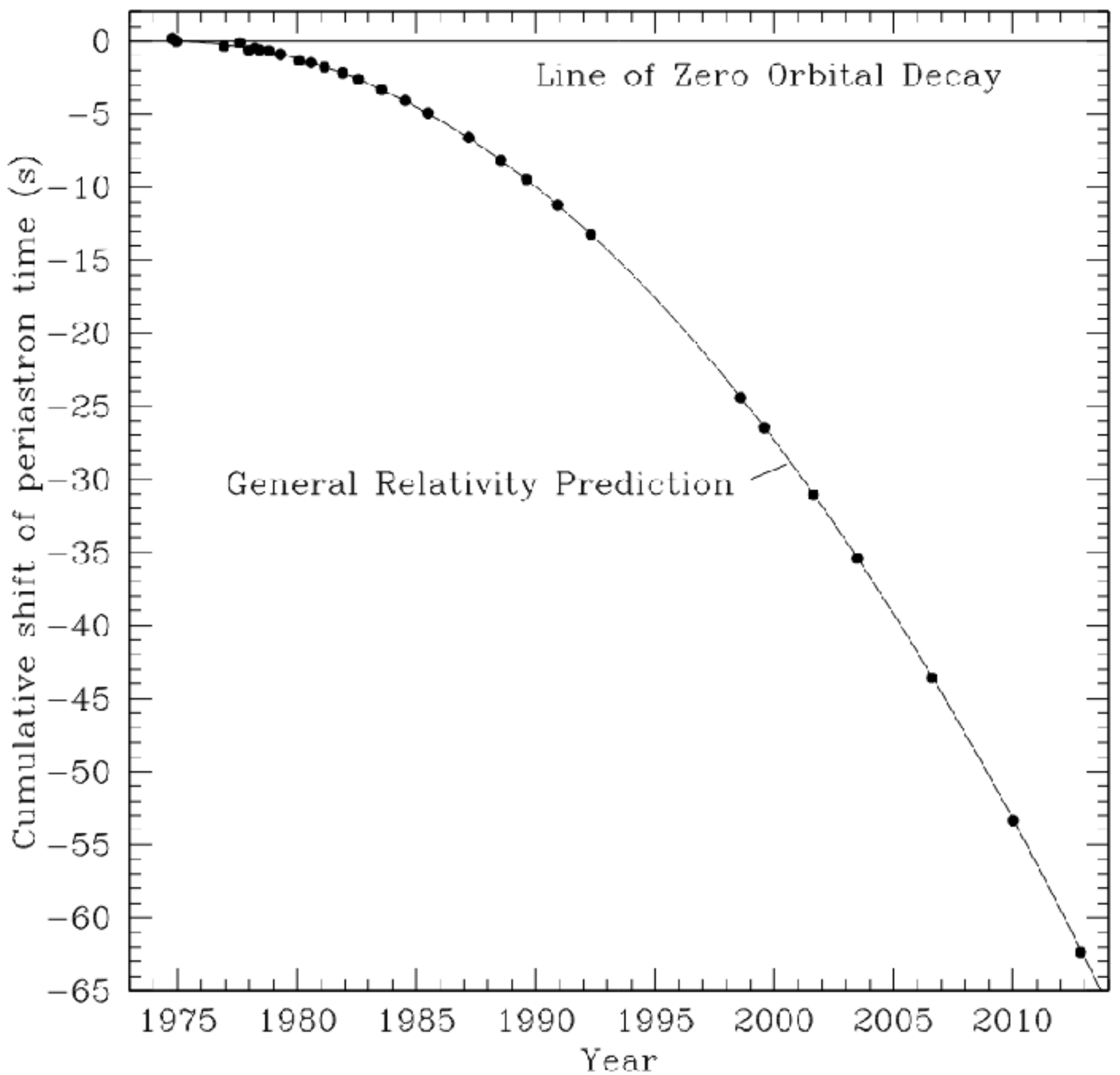
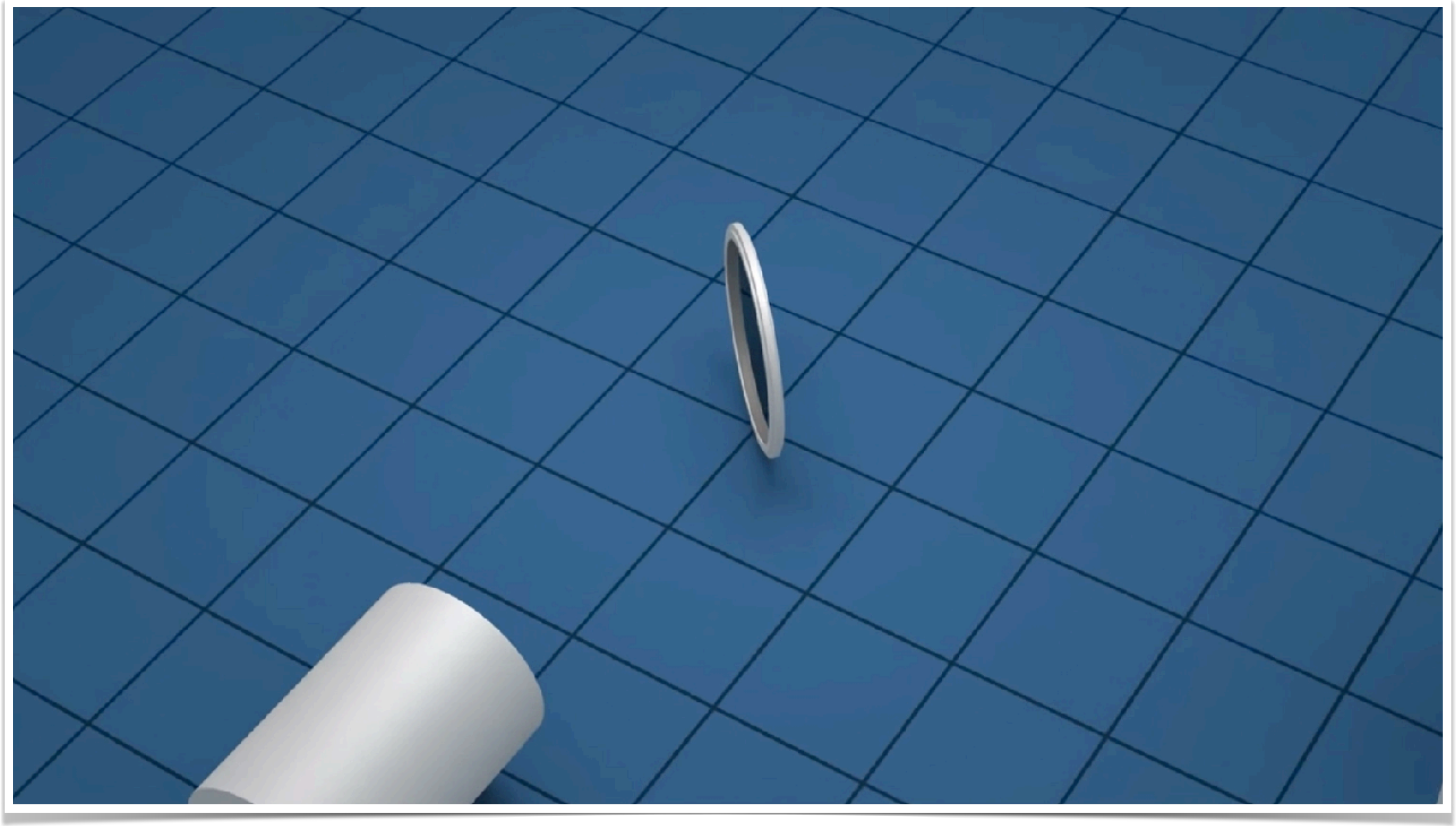


Figure 3. The orbital decay of PSR B1913+16 as a function of time. The curve represents the orbital phase shift expected from gravitational wave emission according to General Relativity. The points, with error bars too small to show, represent our measurements.

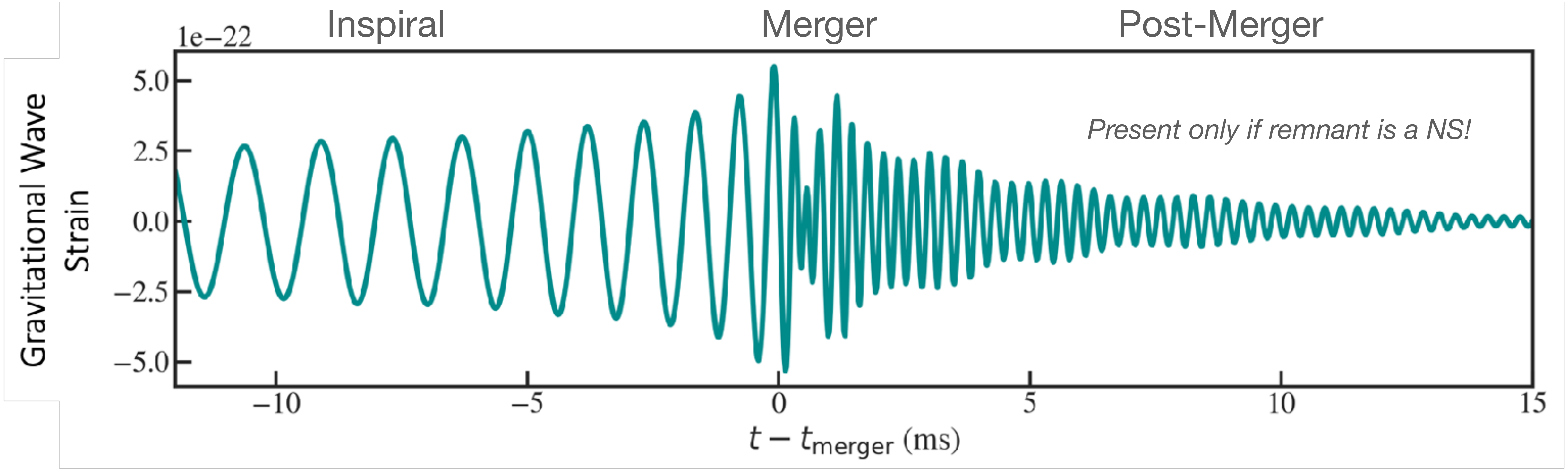
Weisberg & Huang 2016

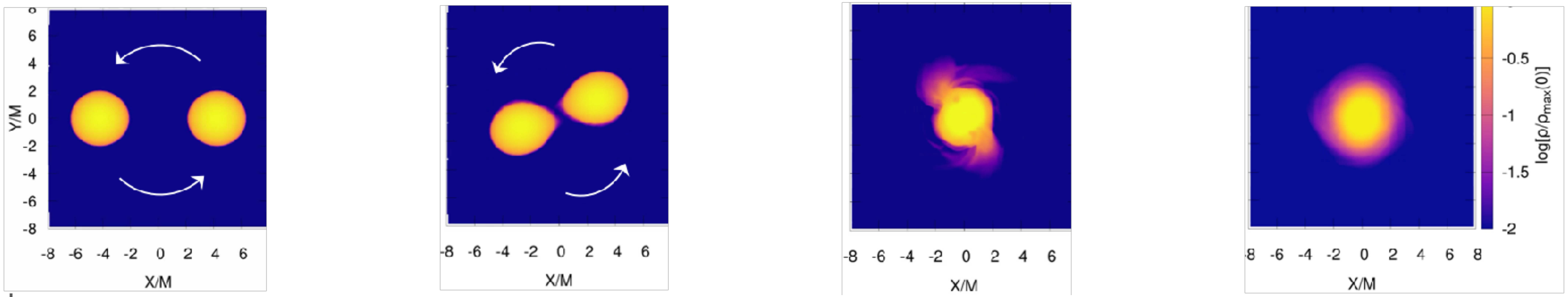
Schematic of a gravitational wave detector



Animation by T. Pyle, Caltech/MIT/LIGO Lab

Anatomy of a binary neutron star merger





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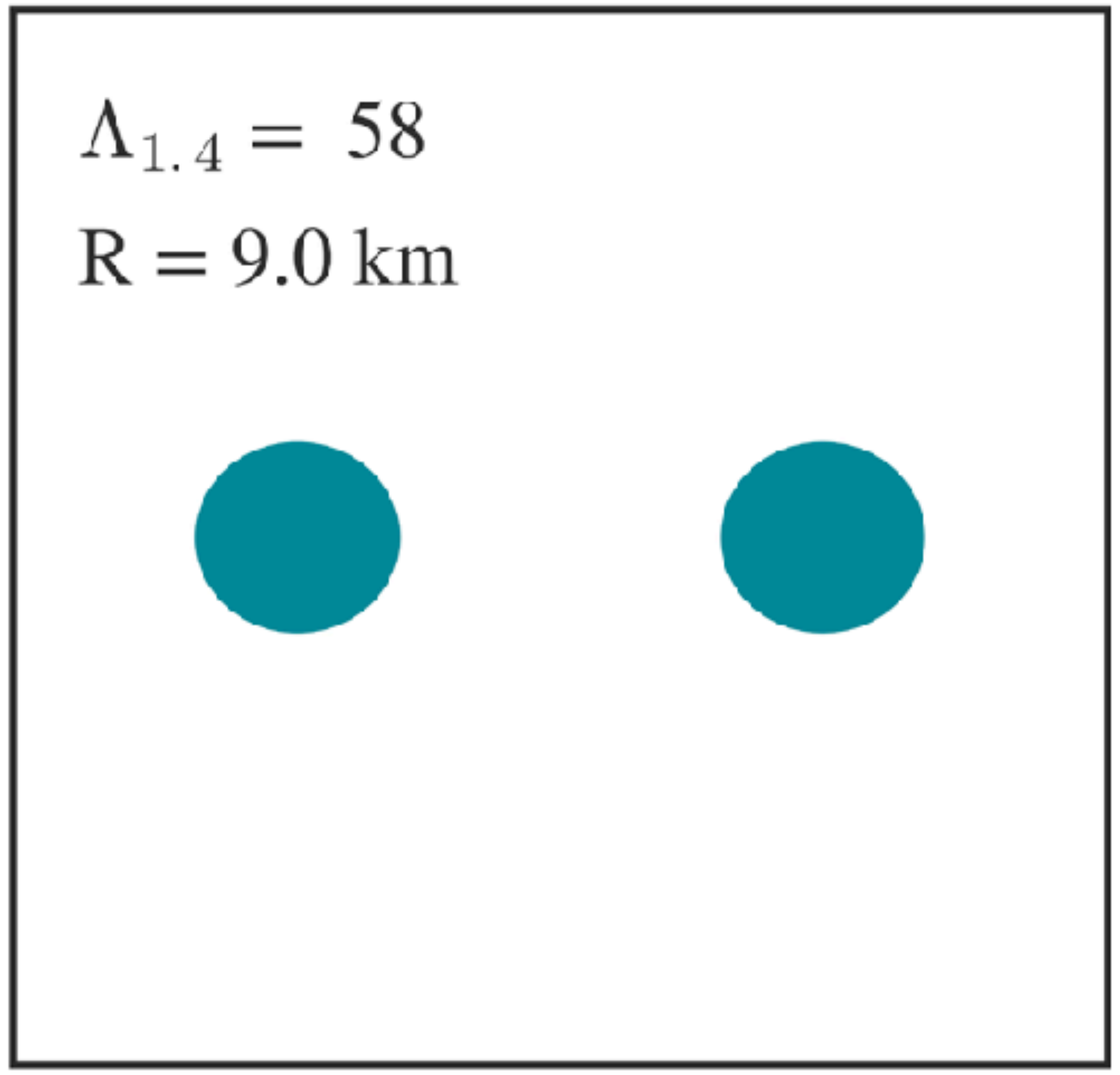
Tidal deformability

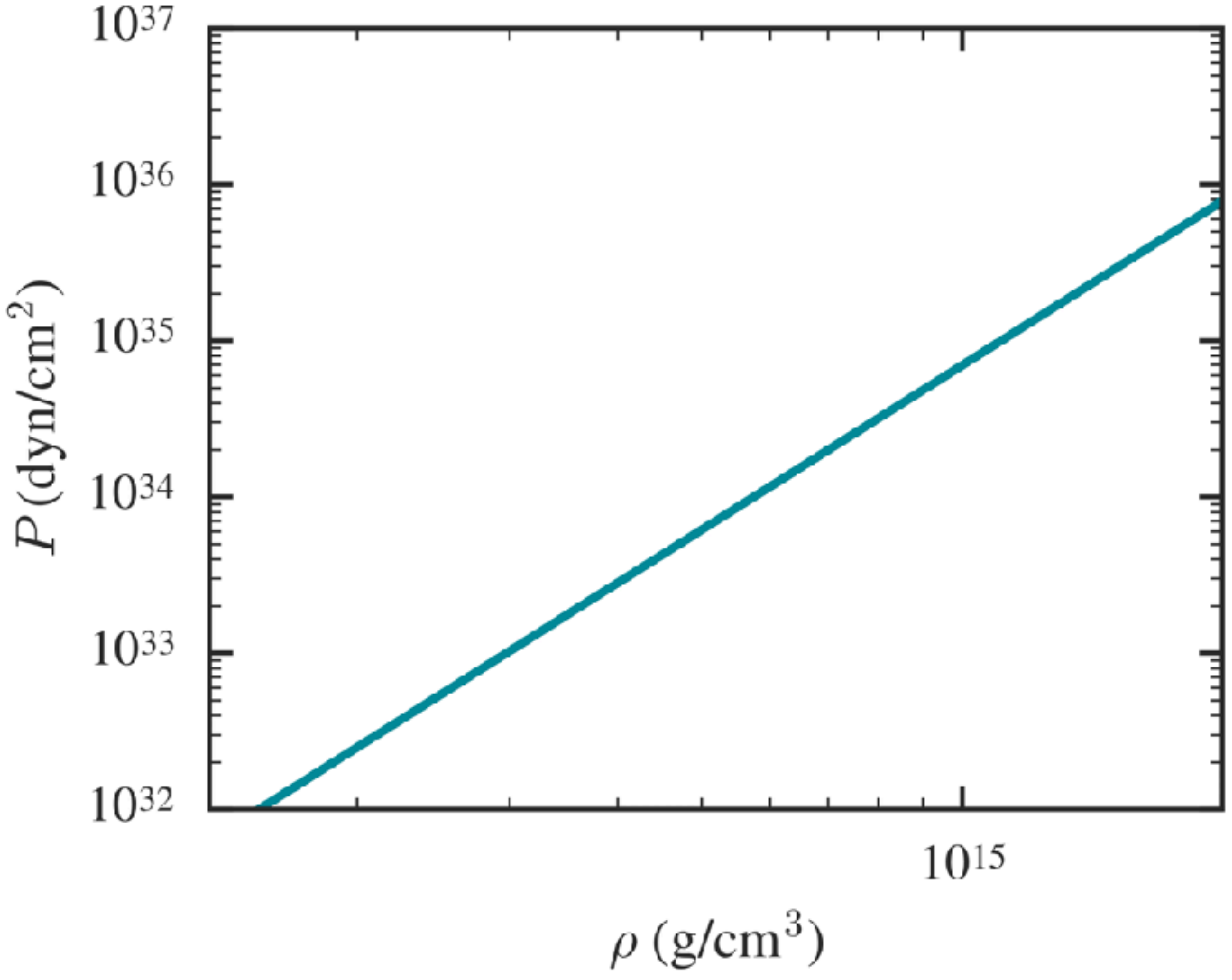
$$\Lambda = -\frac{Q_{ij}}{M^5 \varepsilon_{ij}} = \frac{2}{3} k_2 \left(\frac{M}{R}\right)^{-5}$$

depends on EOS

depends on EOS

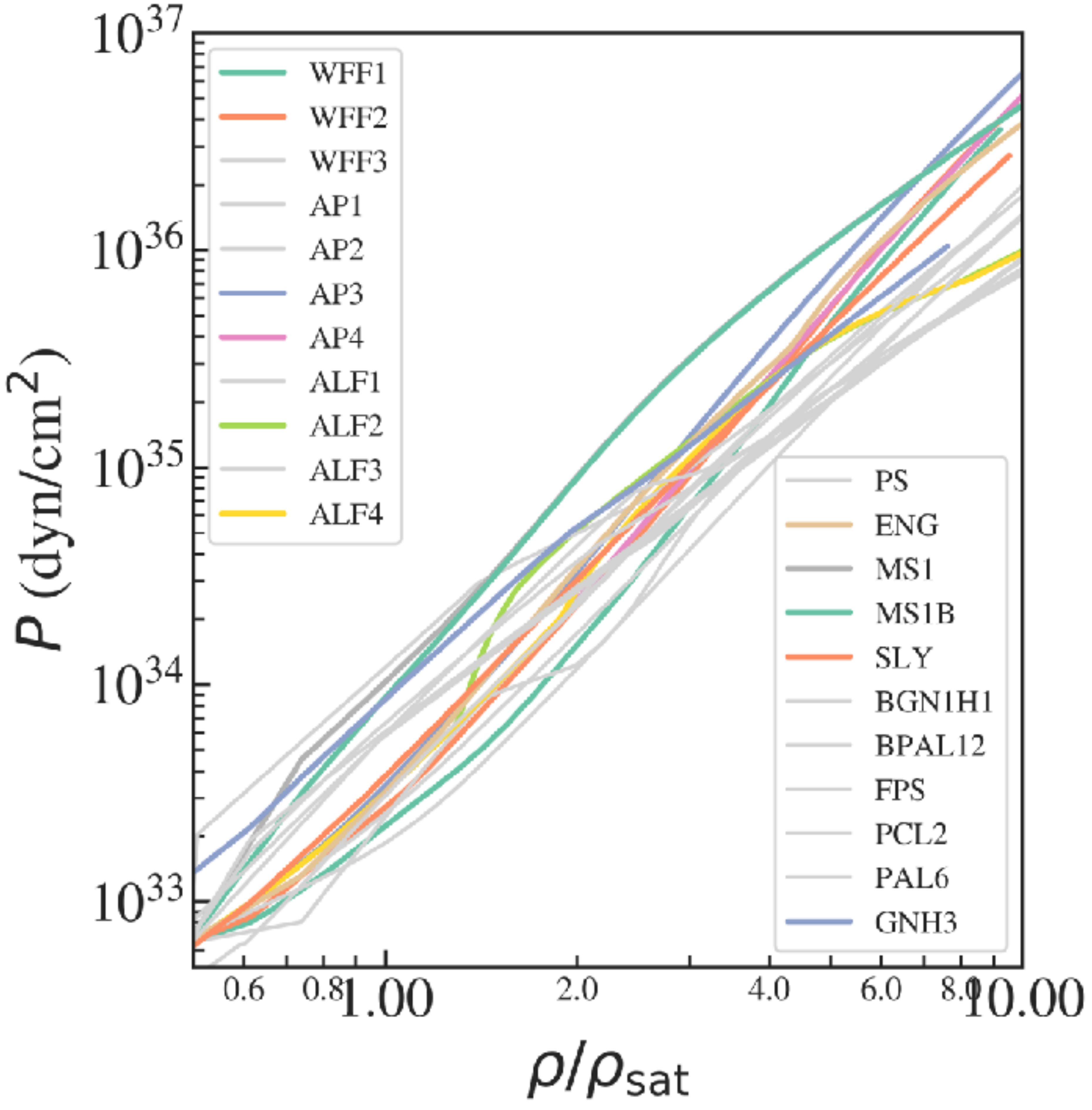
Quadrupolar response to the tidal potential of a binary companion

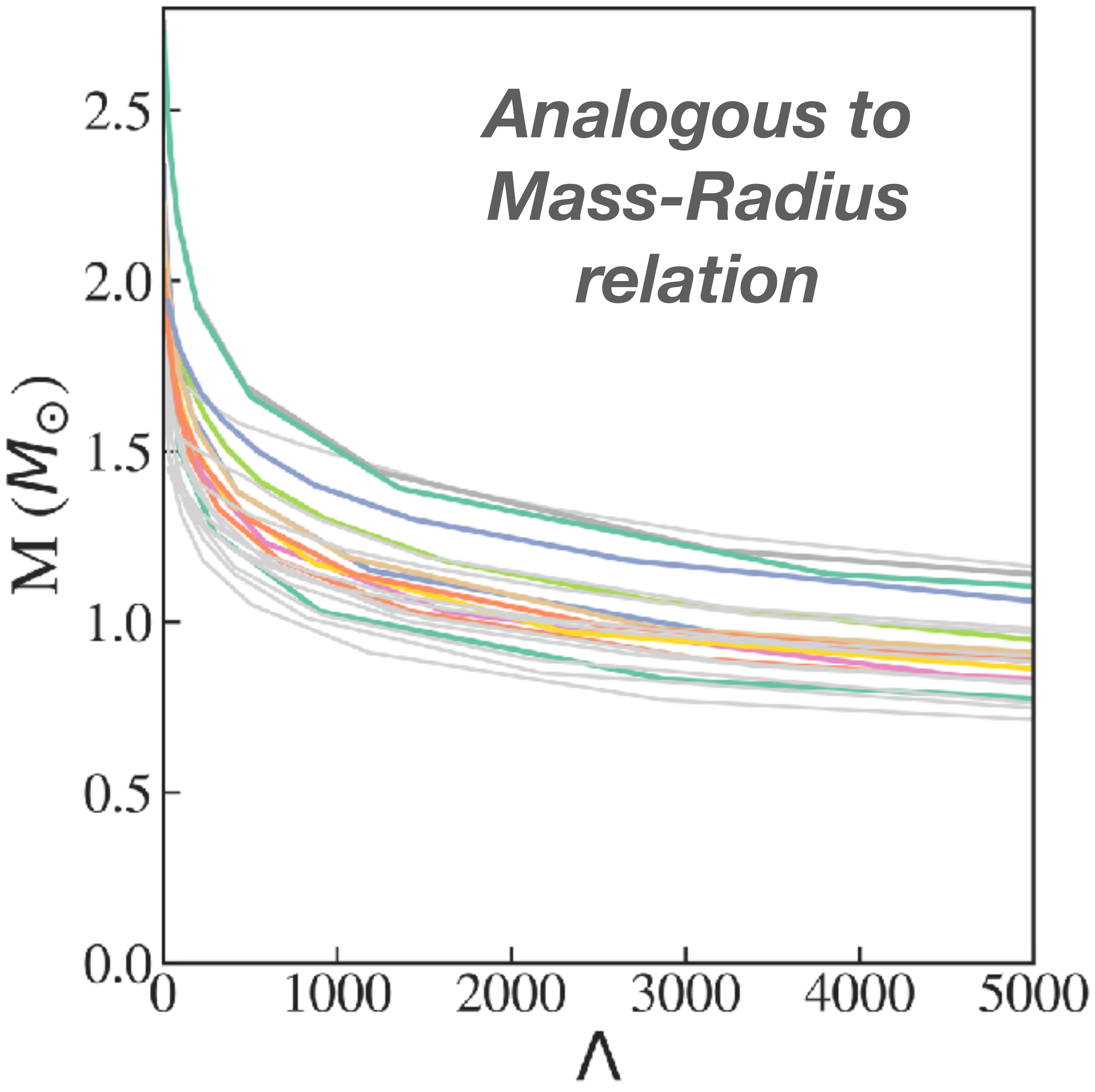




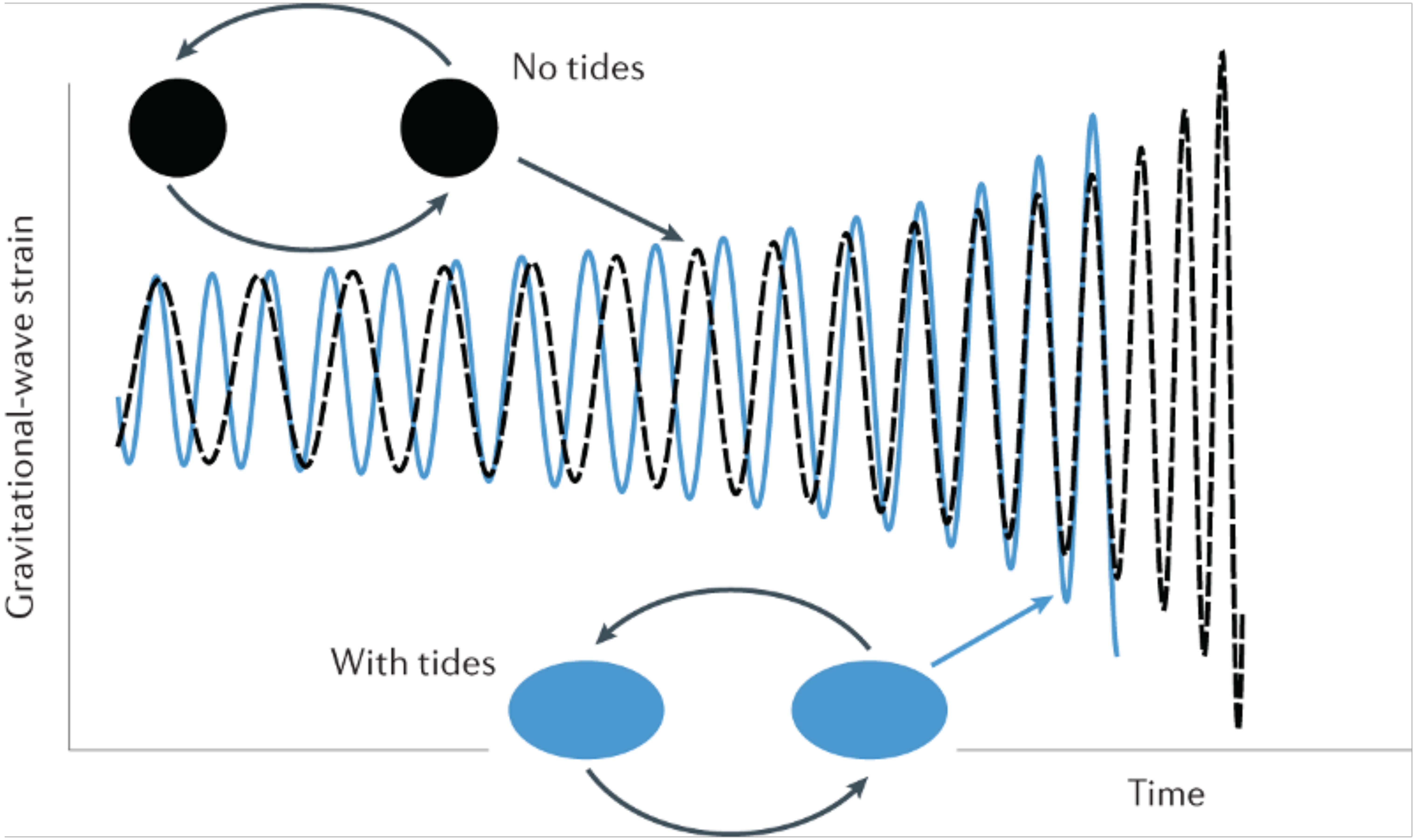
Simple picture for n=1 polytrope

Tidal deformability - theoretical predictions





Tidal deformability - impact on the waveform



Yunes et al. 2022 (adapted from Z. Carson)

Observations of gravitational waves

Current network of GW observatories

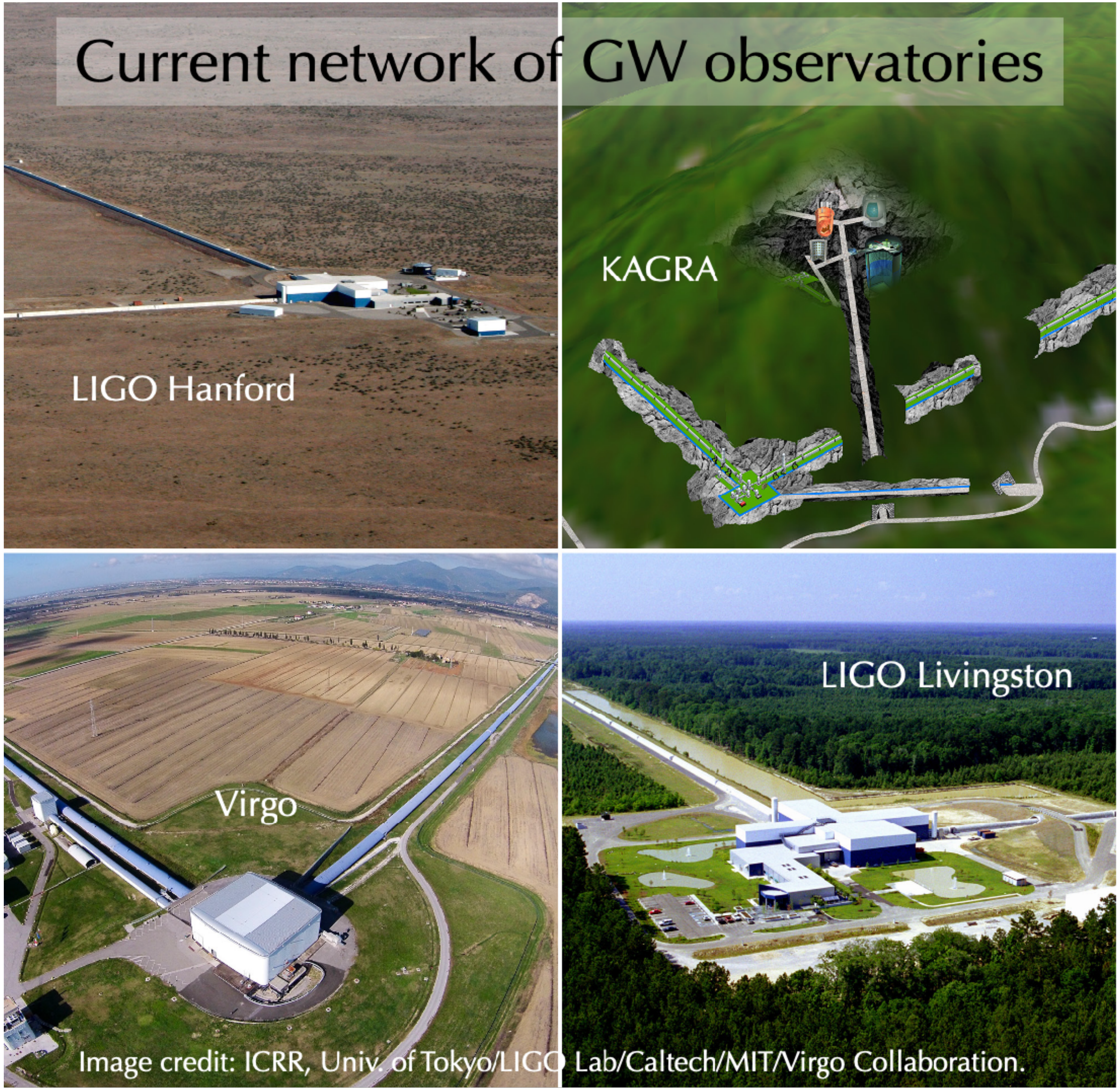
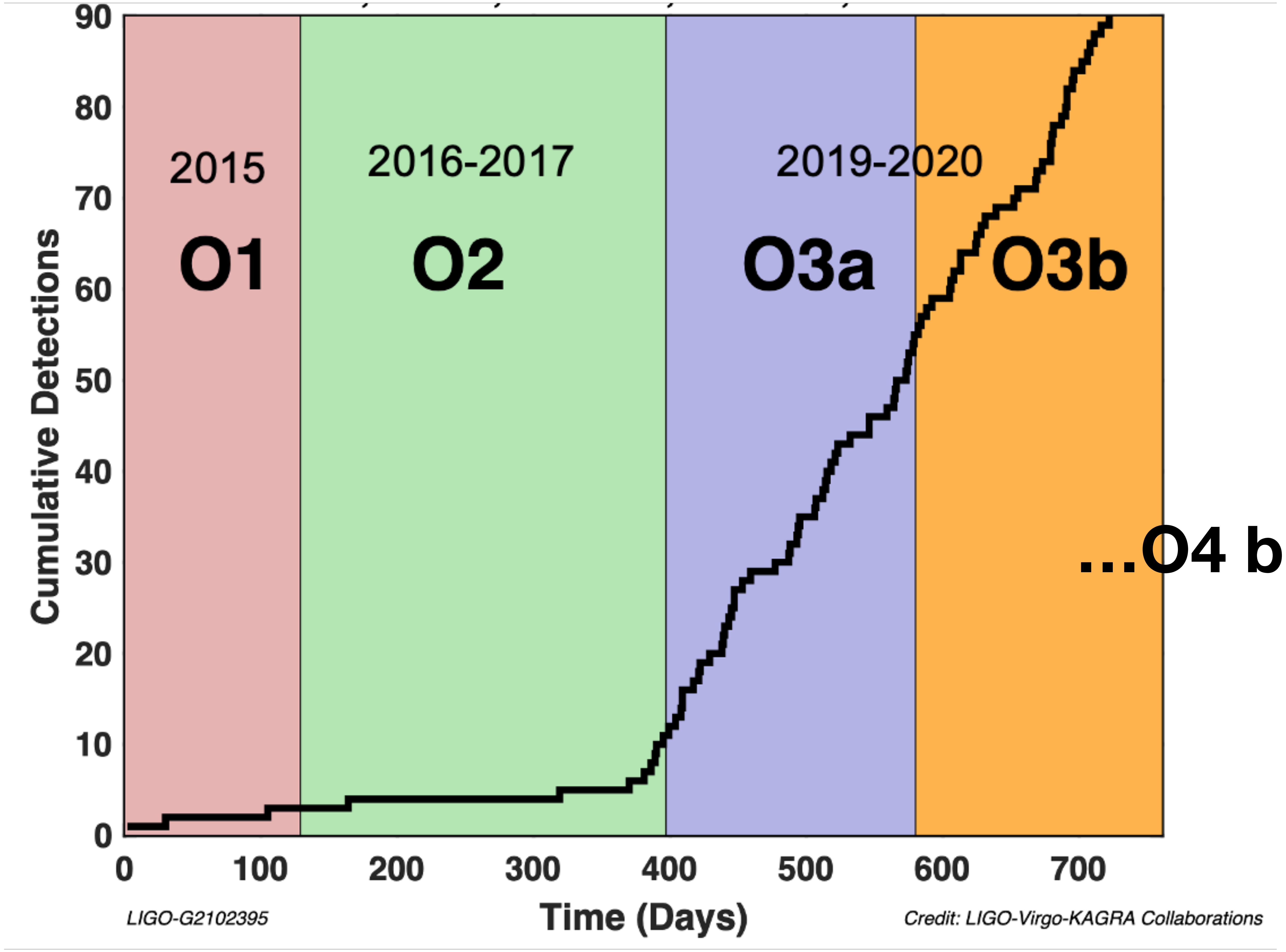


Image credit: ICRR, Univ. of Tokyo/LIGO Lab/Caltech/MIT/Virgo Collaboration.

90 (!) gravitational wave events have been detected so far

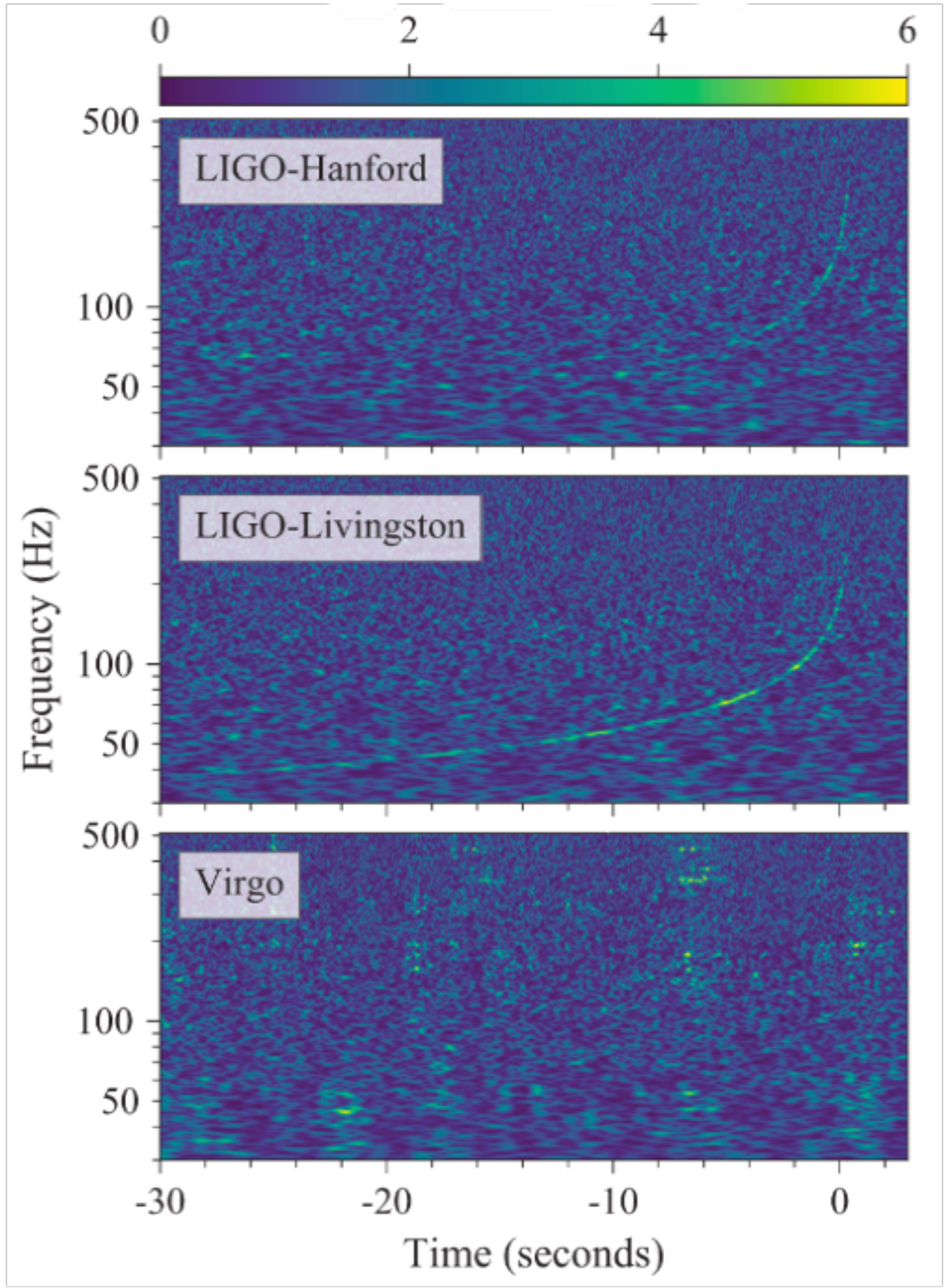


…O4 began in May!

“Stellar graveyard” of compact objects

Vast majority of GW events to date have been from black holes (*as expected!*)

GW170817: The first binary neutron star merger



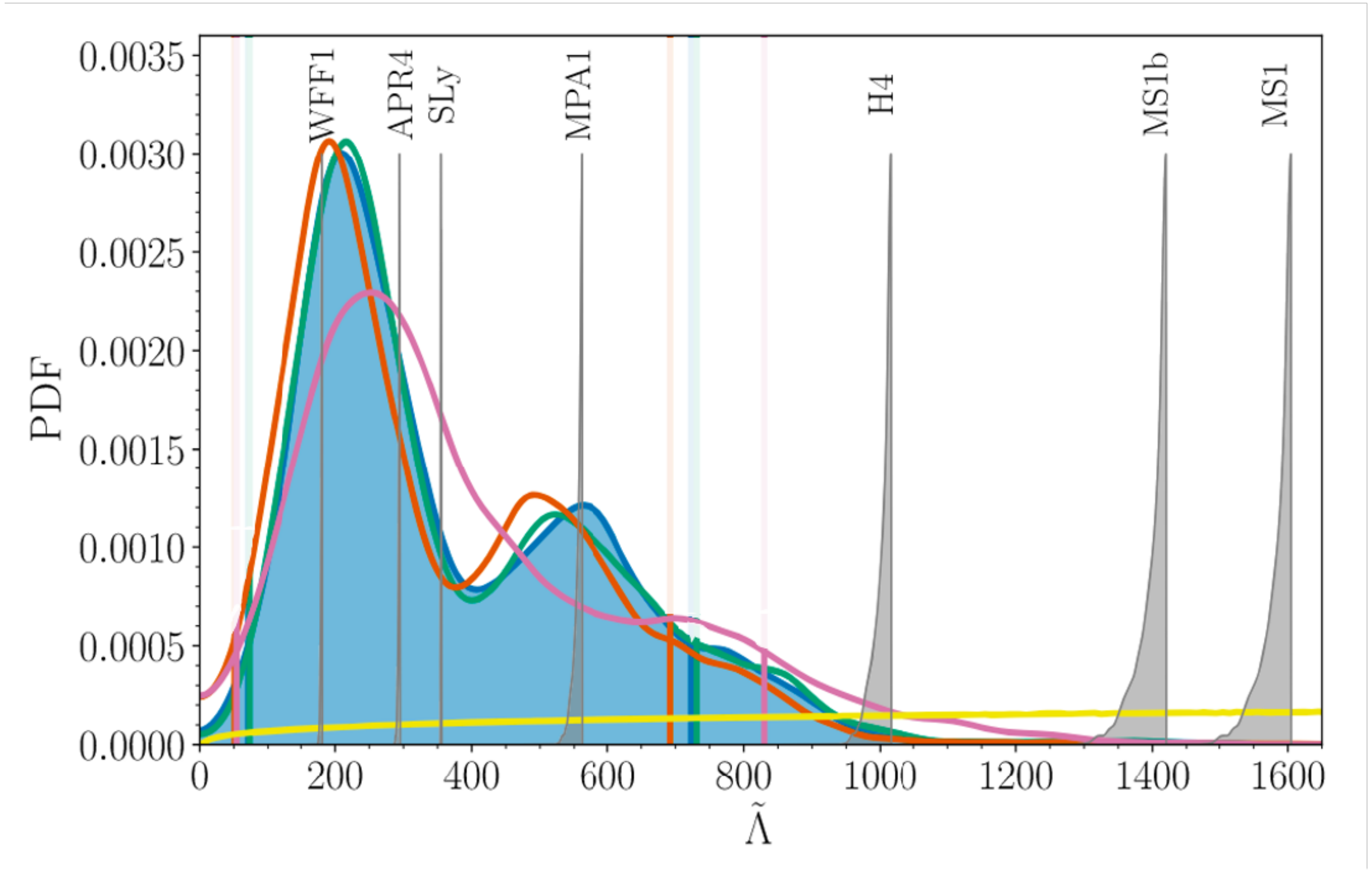
- Surprisingly nearby source (d=40 Mpc, SNR = 32.4)
- Individual component masses are correlated, but ***chirp mass*** is very well constrained

	Low-spin prior ($\chi \leq 0.05$)
Binary inclination θ_{JN}	146^{+25}_{-27} deg
Binary inclination θ_{JN} using EM distance constraint [108]	151^{+15}_{-11} deg
Detector-frame chirp mass $\mathcal{M}^{\rm det}$	$1.1975^{+0.0001}_{-0.0001}$ $M_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001}$ $M_\odot$
Primary mass m_1	(1.36, 1.60) $M_\odot$
Secondary mass m_2	(1.16, 1.36) $M_\odot$
Total mass m	$2.73^{+0.04}_{-0.01}$ $M_\odot$
Mass ratio q	(0.73, 1.00)
Effective spin $\chi_{\rm eff}$	$0.00^{+0.02}_{-0.01}$
Primary dimensionless spin χ_1	(0.00, 0.04)
Secondary dimensionless spin χ_2	(0.00, 0.04)
Tidal deformability $\tilde{\Lambda}$ with flat prior	300^{+500}_{-190} (symmetric)/300^{+420}_{-230} (HPD)

LVC 2017, 2019

GW170817: The first binary neutron star merger

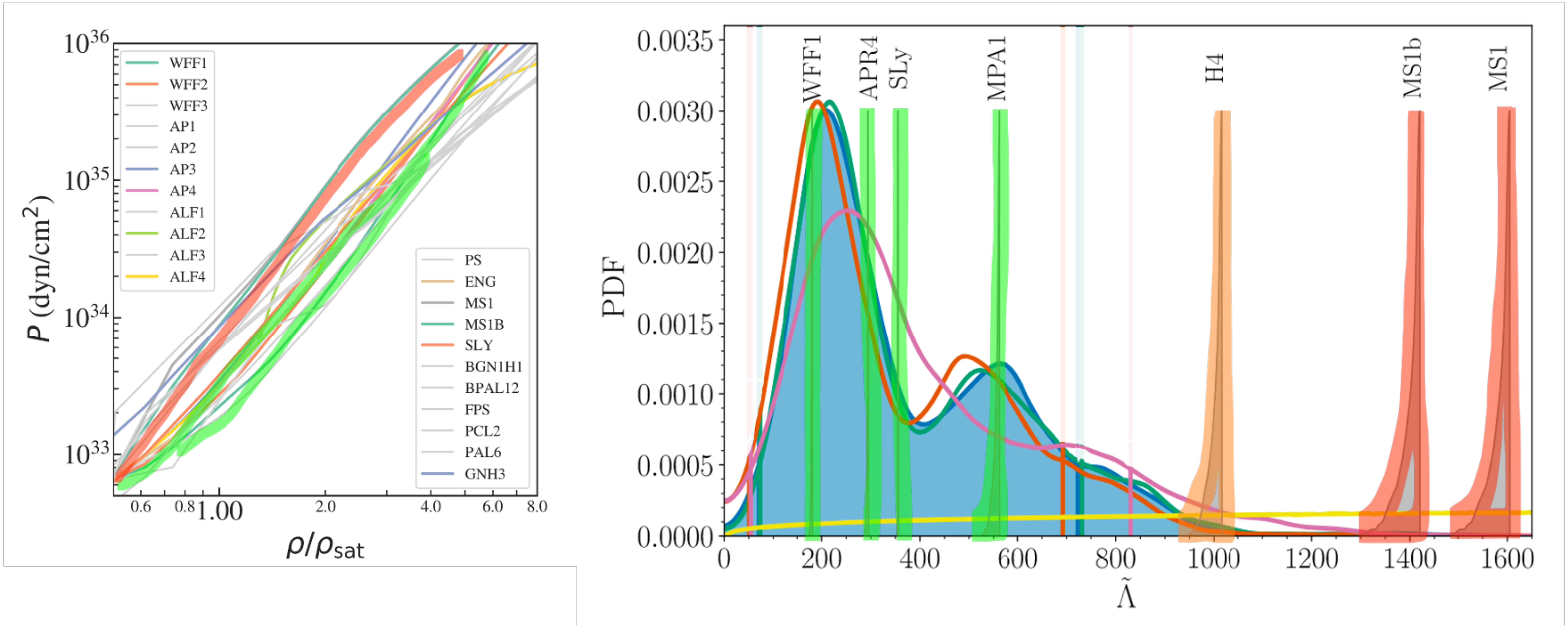
Inferred ***binary* tidal deformability**, after marginalizing over all other source properties (mass, inclination, etc.)



LVC 2019

GW170817: The first binary neutron star merger

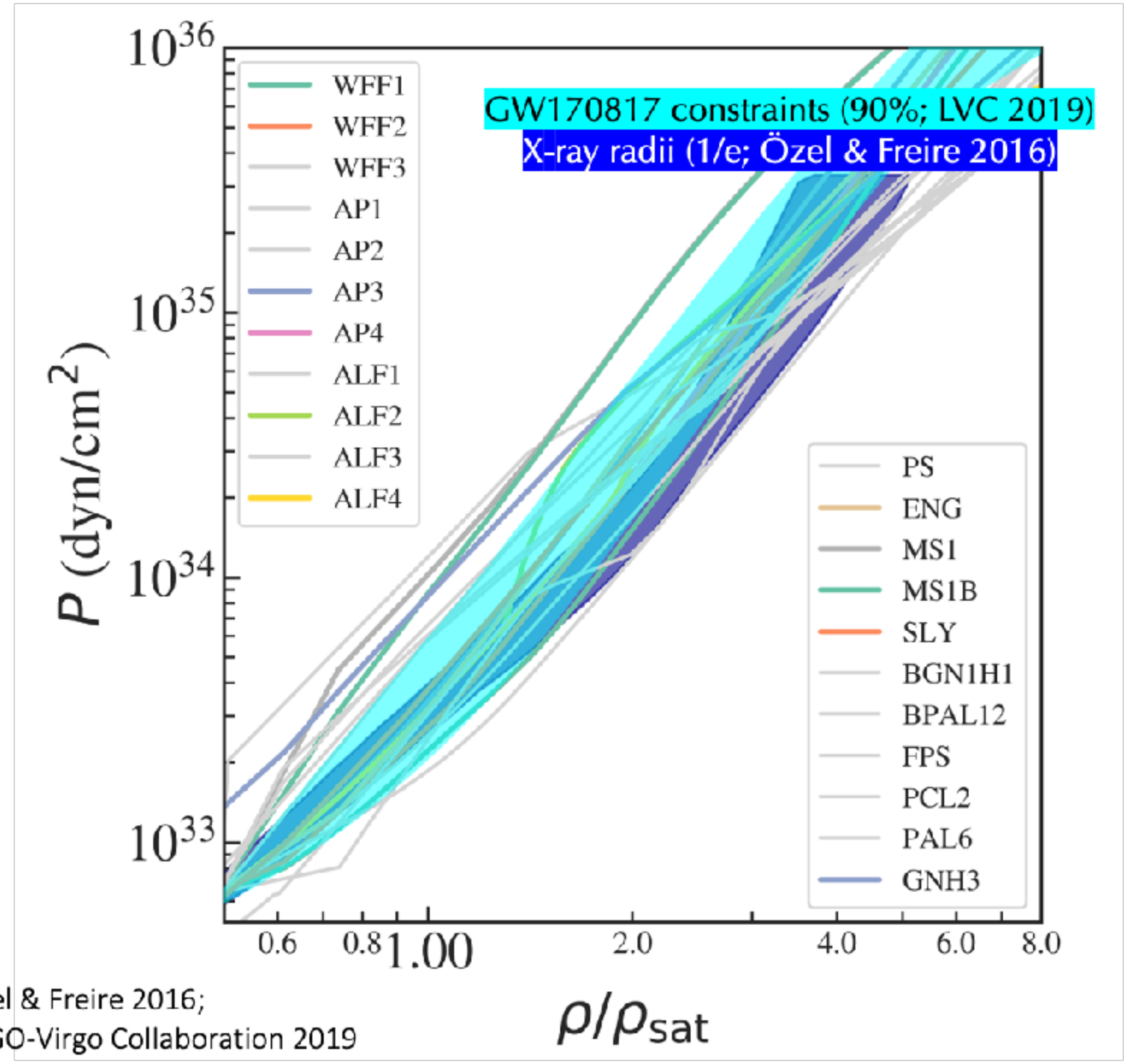
Vertical lines = predictions of different theoretical EOSs



LVC 2019

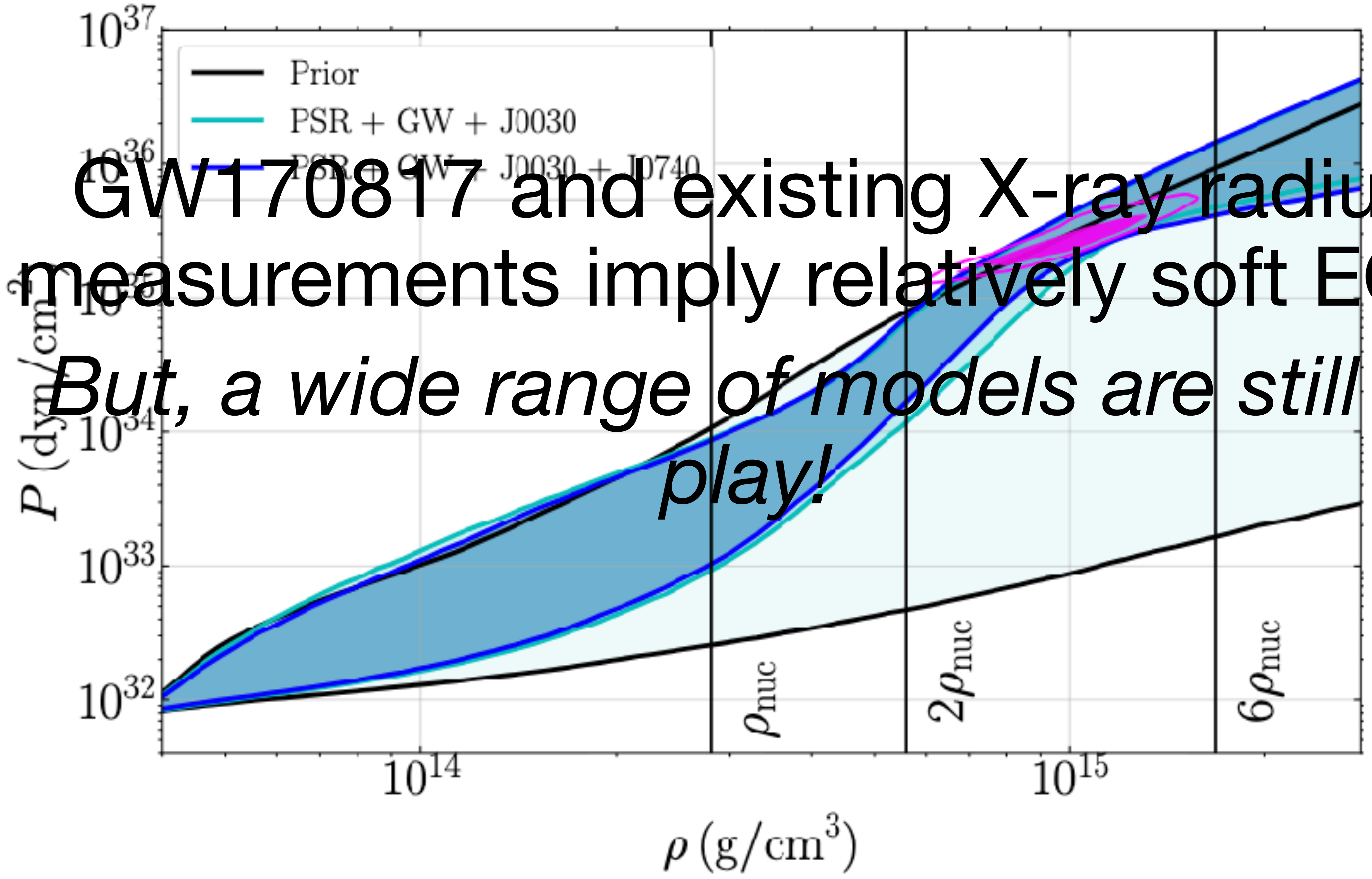
Tidal deformability constraints on the EOS

Comparing GW and spectroscopic radius measurements



Özel & Freire 2016;
LIGO-Virgo Collaboration 2019

Combining GW + NICER radius measurements

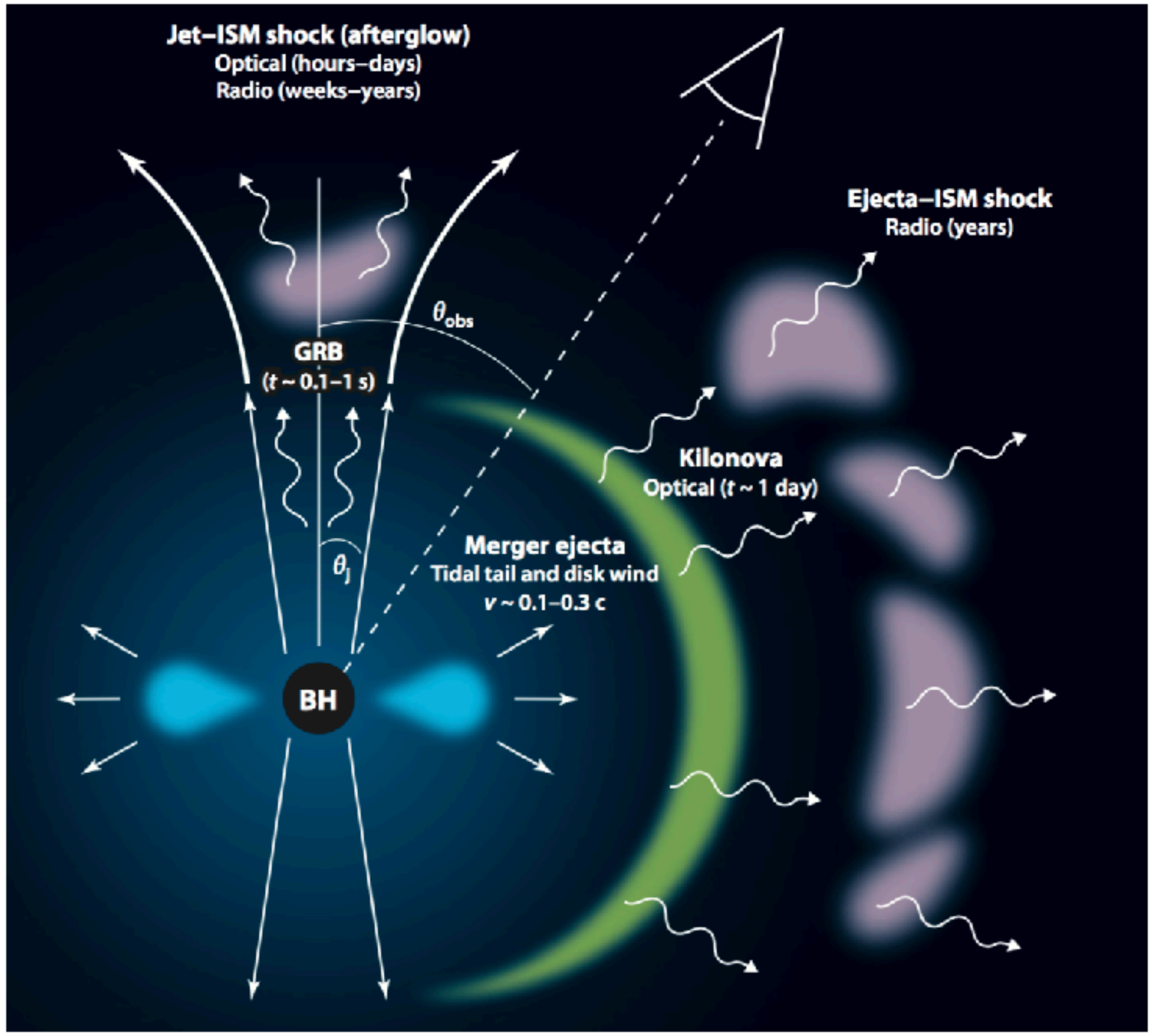


GW170817 and existing X-ray radius measurements imply relatively soft EOS

But, a wide range of models are still in play!

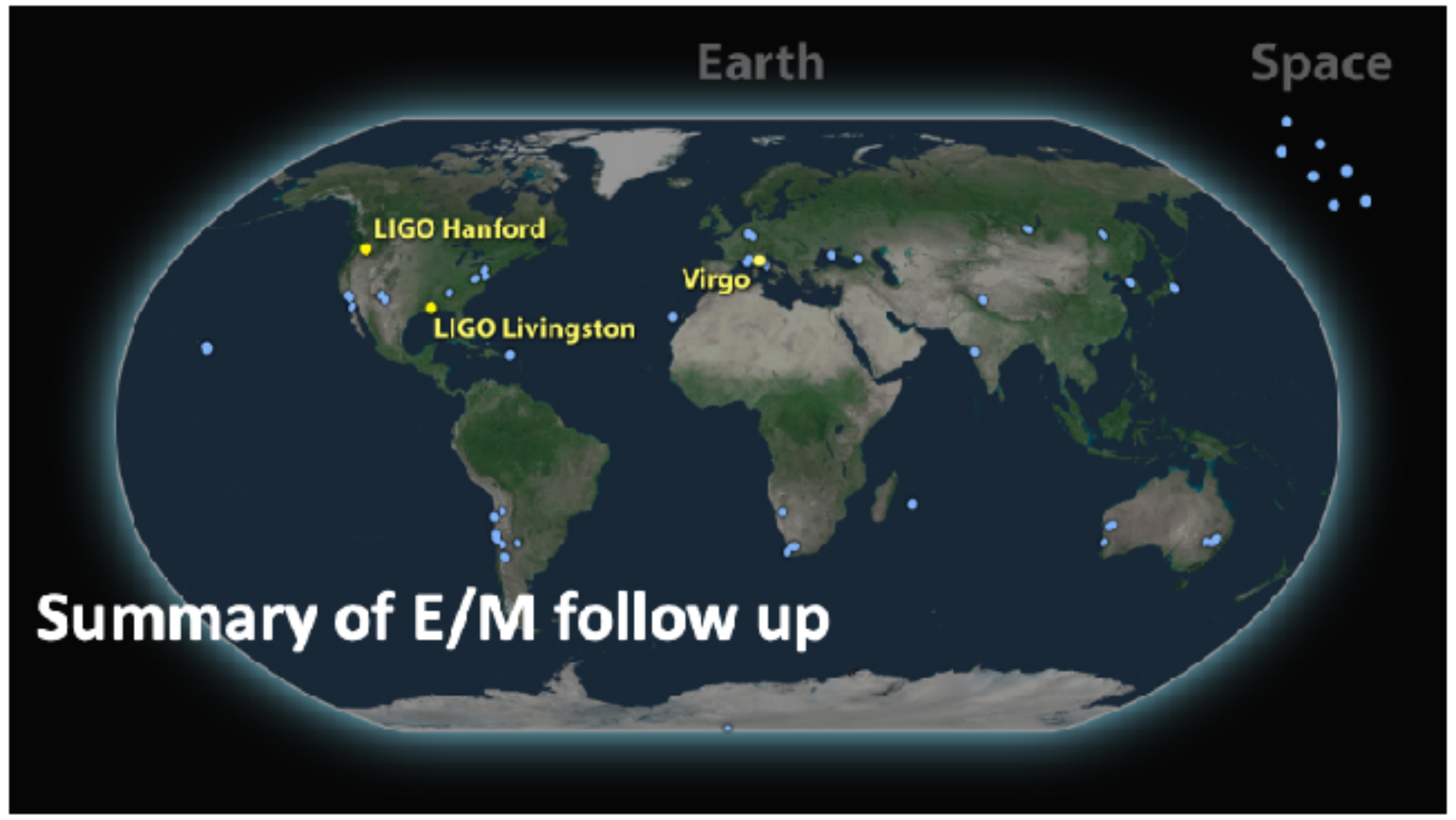
Legred et al. 2021

E/M counterparts to binary NS mergers

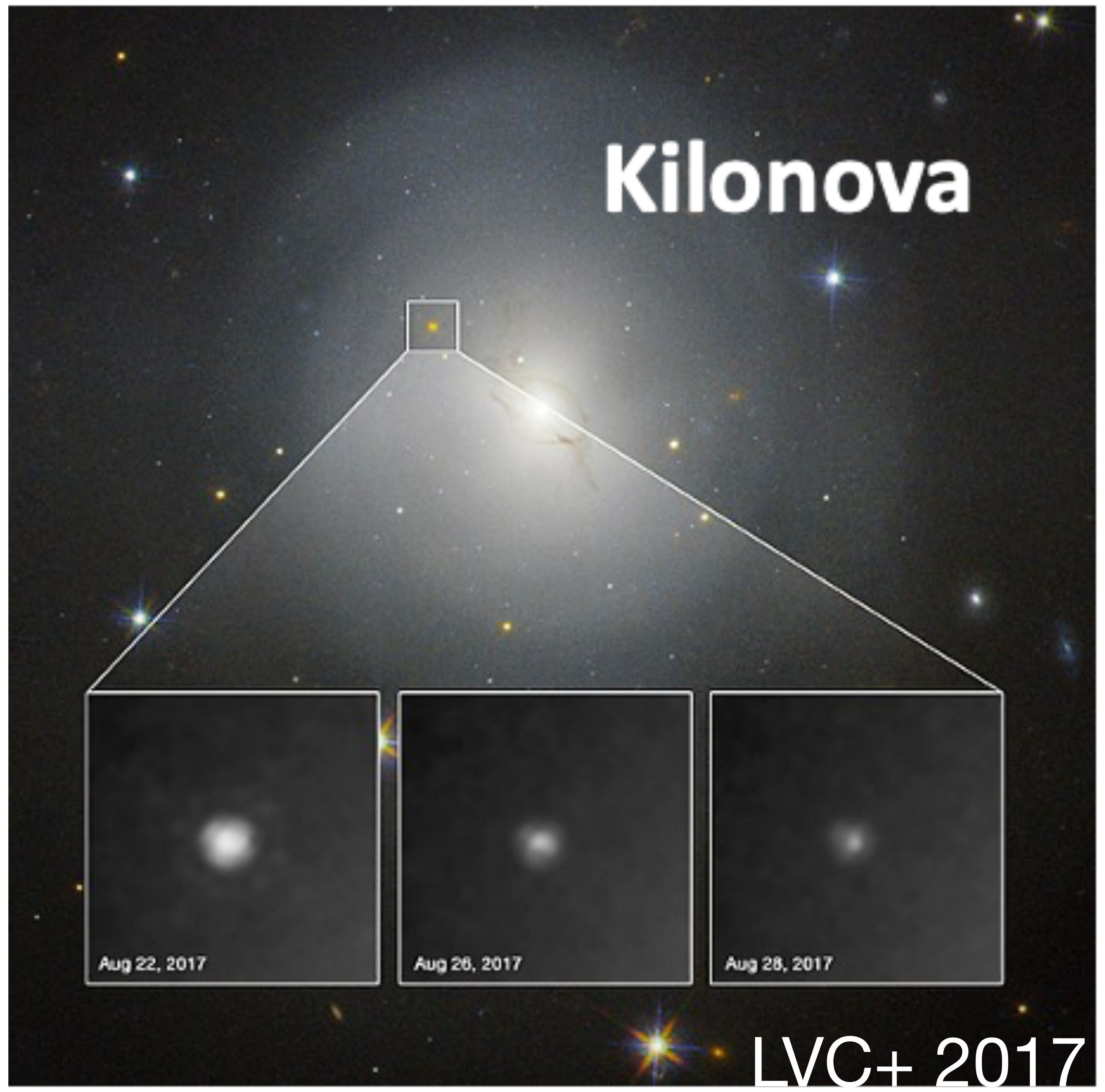


Metzger 2020
Modified from Metzger & Berger 2012

E/M counterparts to GW170817

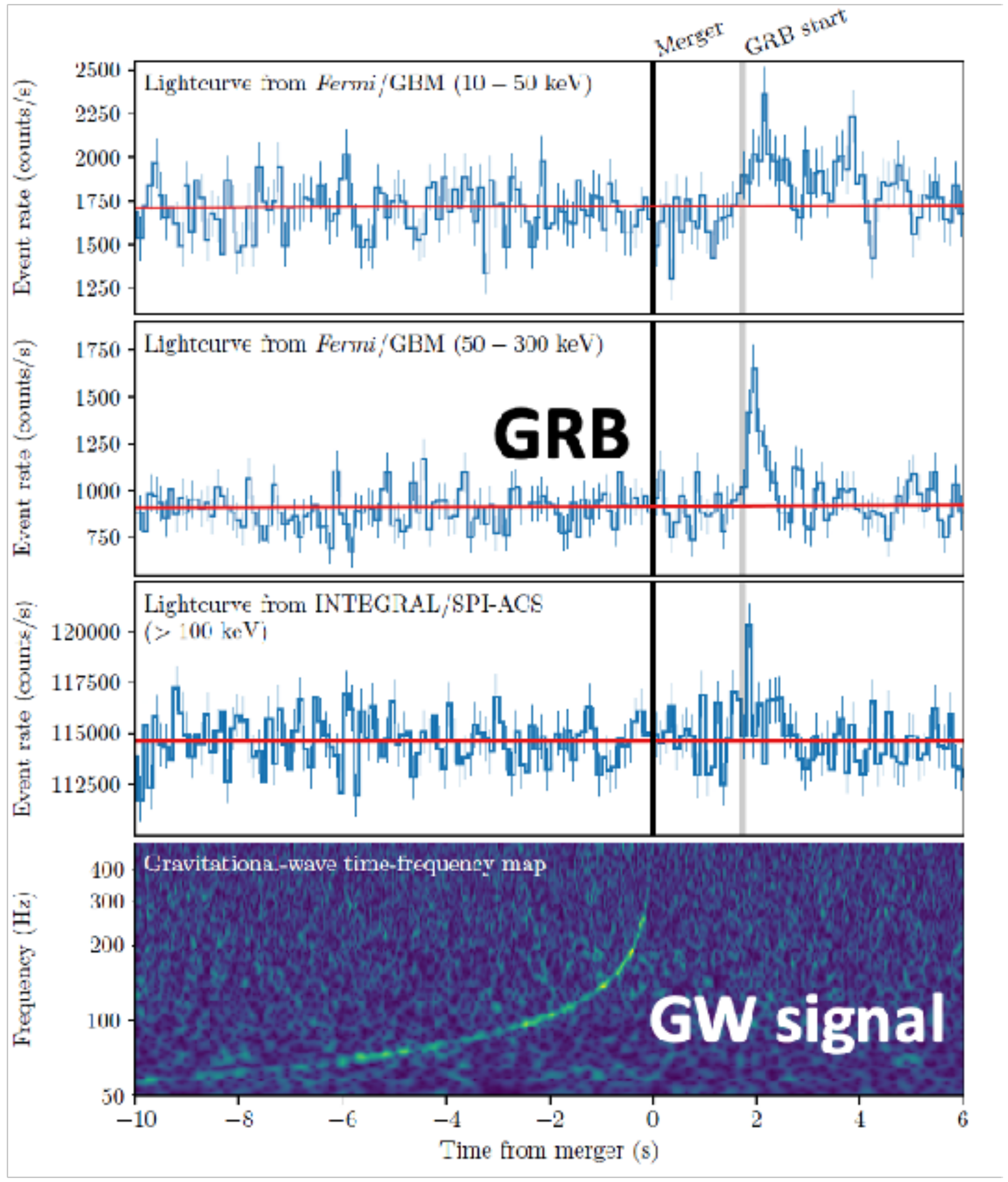


Event was followed by across the E/M spectrum, by 70 different observatories on every continent and from space



First observed kilonova

powered by the radioactive decay of heavy, neutron-rich elements synthesized in the expanding ejecta

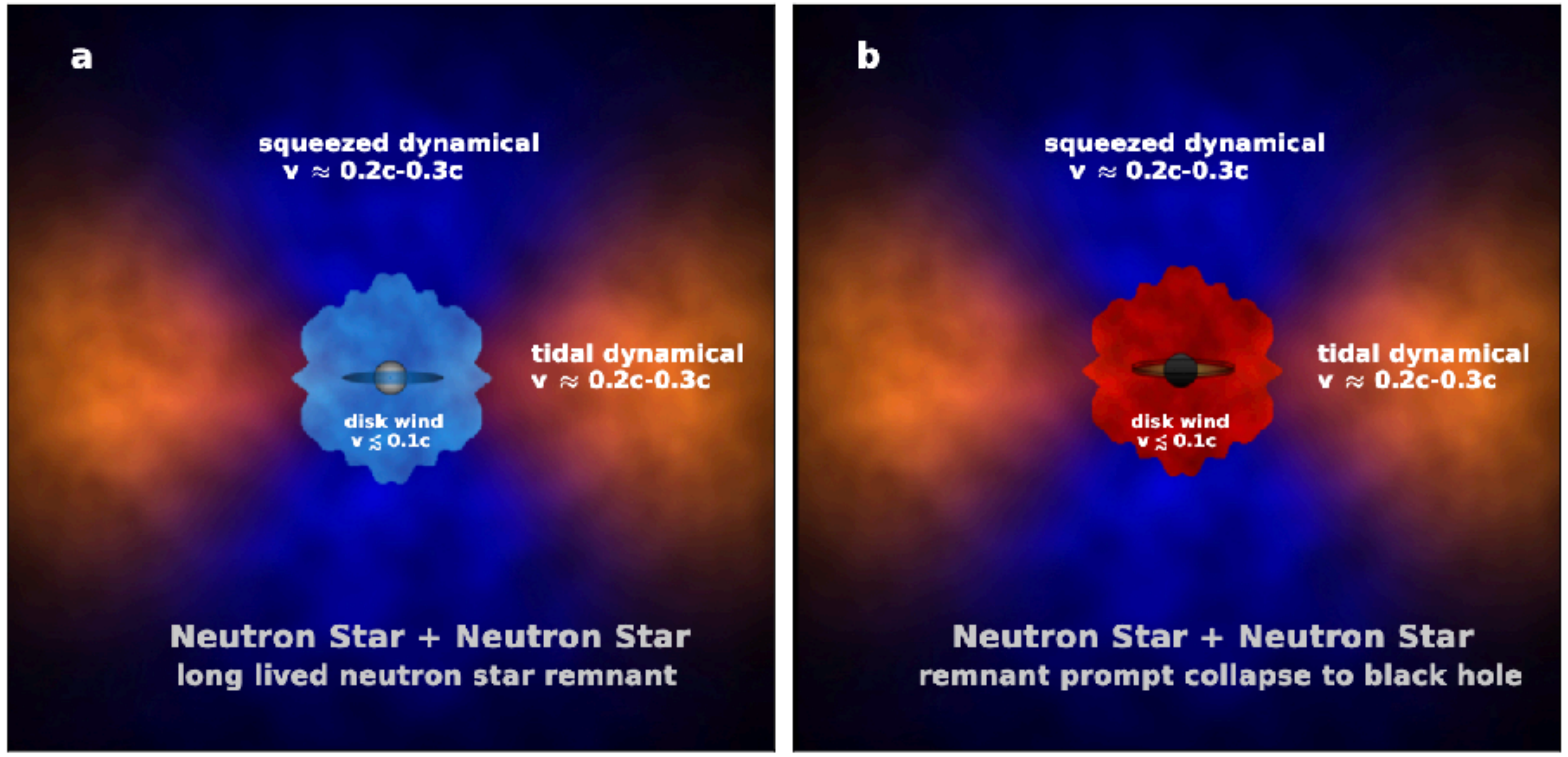


First confirmed association of a short-GRB with a BNS merger

Kilonova AT2017gfo

Kasen et al. 2017

- heavy r-process elements
- light r-process elements

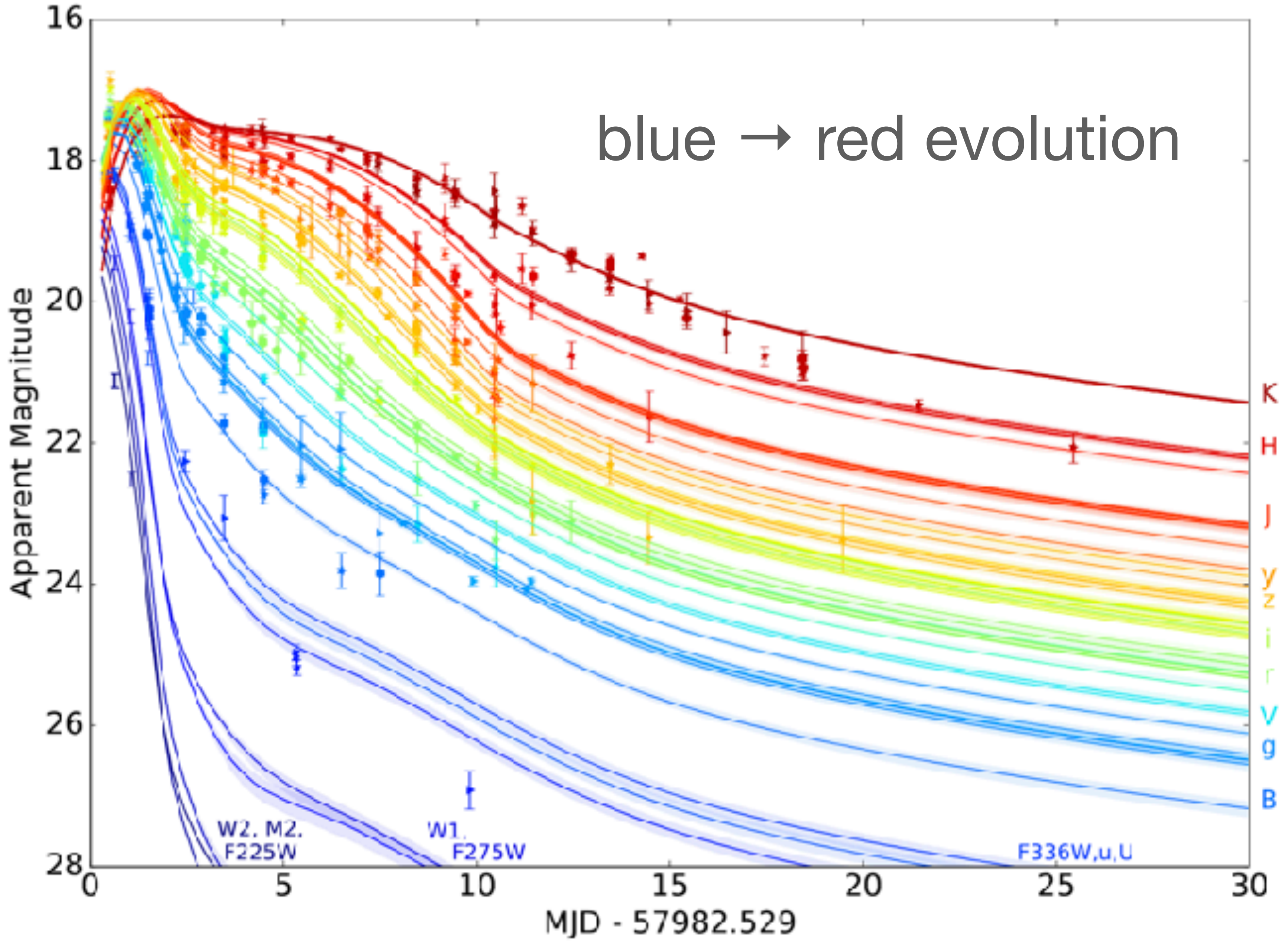


The presence of a remnant NS has a strong effect on the ejecta composition because it is a significant source of electron neutrinos, which convert neutrons to protons

$$\nu_e + n \rightarrow p + e^-$$

Lanthanide production (which leads to red kilonova) requires $Y_e \lesssim 0.25$

Combined UVOIR light curves

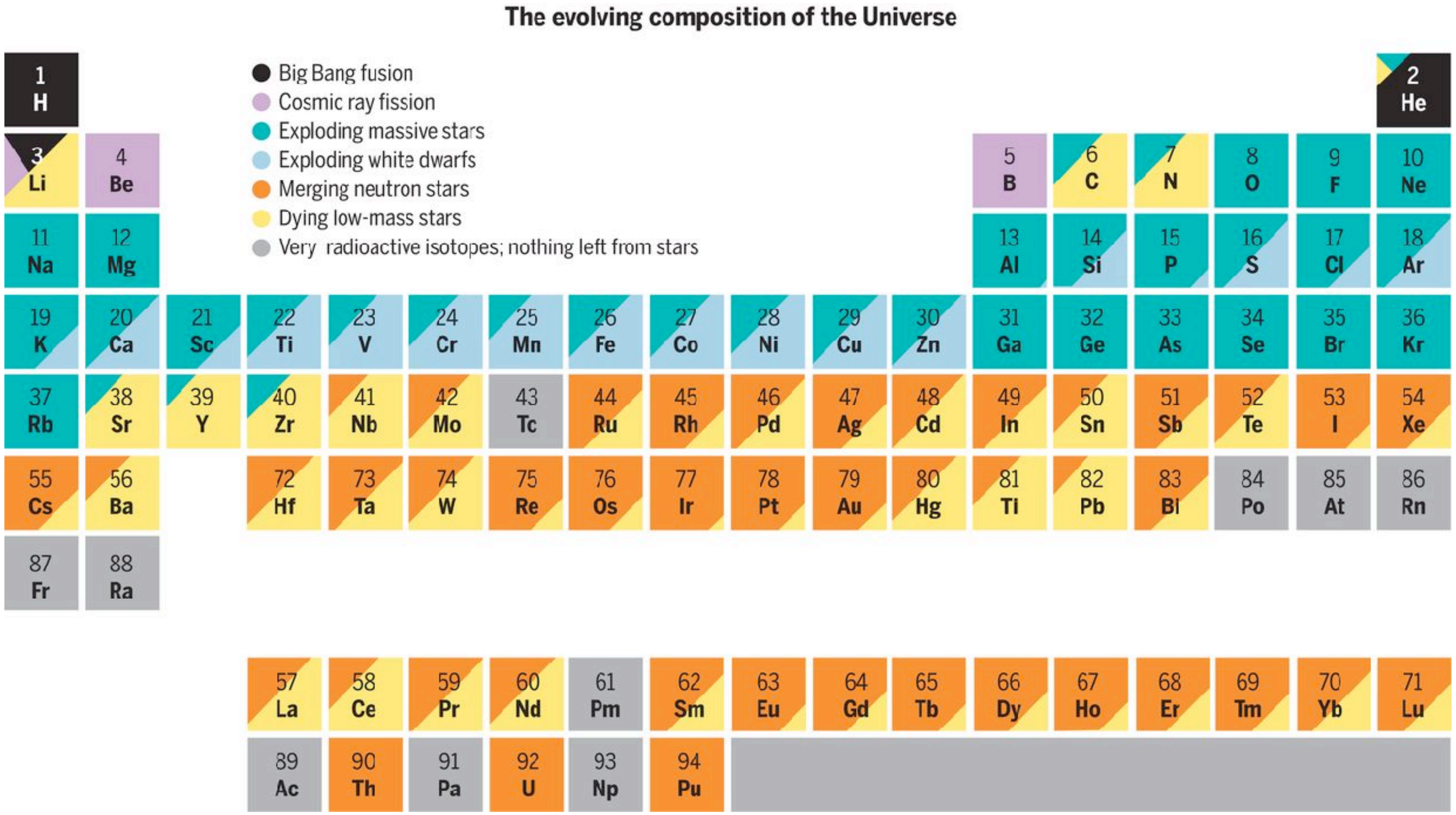


Time since event (in days)

Villar et al. 2017

Data compiled from Andreoni et al. 2017; Arcavi et al. 2017; Coulter et al. 2017; Cowperthwaite et al. 2017; Díaz et al. 2017; Drout et al. 2017; Evans et al. 2017; Hu et al. 2017; Kasliwal et al. 2017; Lipunov et al. 2017; Pian et al. 2017; Pozanenko et al. 2017; Shappee et al. 2017; Smartt et al. 2017; Tanvir et al. 2017; Troja et al. 2017; Utsumi et al. 2017; Valenti et al. 2017

NS mergers are a significant production site of heavy elements



Graphic from Jennifer Johnson

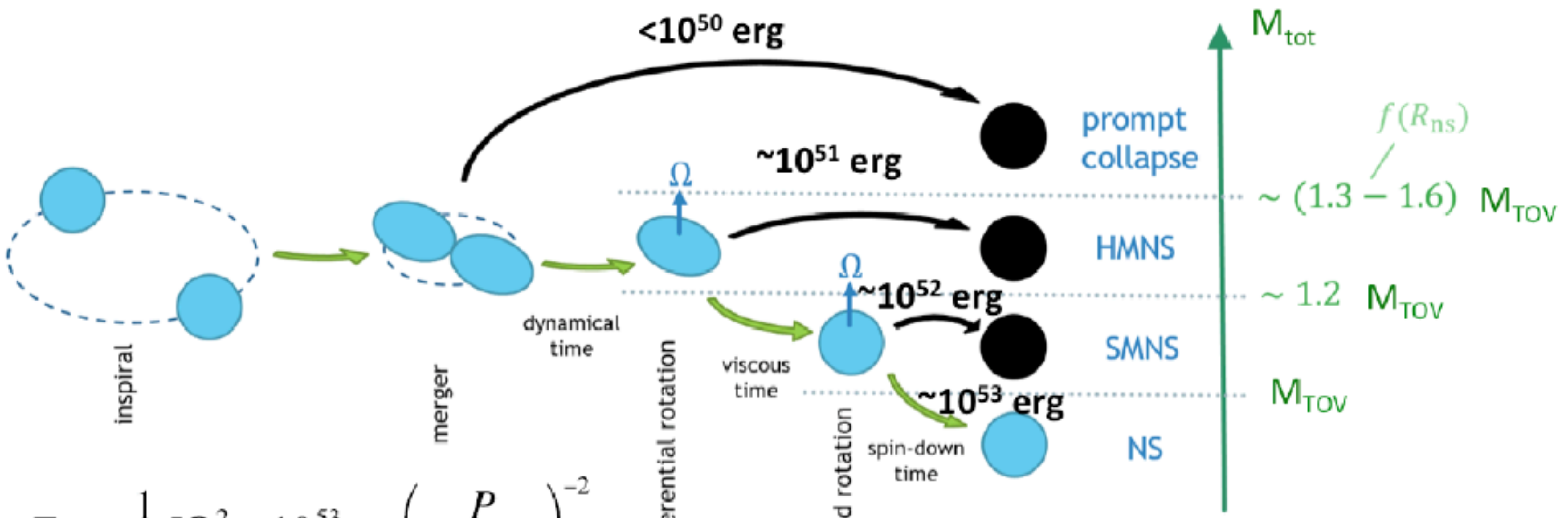
A new *upper limit* on the maximum mass

- Remnant survived temporarily (~0.1-1s) as a NS before collapsing to a BH
- By combining total mass ($M = 2.73\ M_\odot$, *from GWs*) with energetics of kilonova or relations between rotating and TOV M_{max} (*from simulations*), can infer ***upper limit on M_{max}***

Presence of lanthanide-rich ejecta (red kilonova)

Presence of GRB

Kinetic energy of kilonova and GRB



$$E_{rot} = \frac{1}{2} I \Omega^2 = 10^{53} \mathrm{erg} \left(\frac{P}{0.8\ \mathrm{ms}} \right)^{-2}$$

Implies ***upper limit*** on maximum mass: $M_{\max} \lesssim 2.3\ M_\odot$

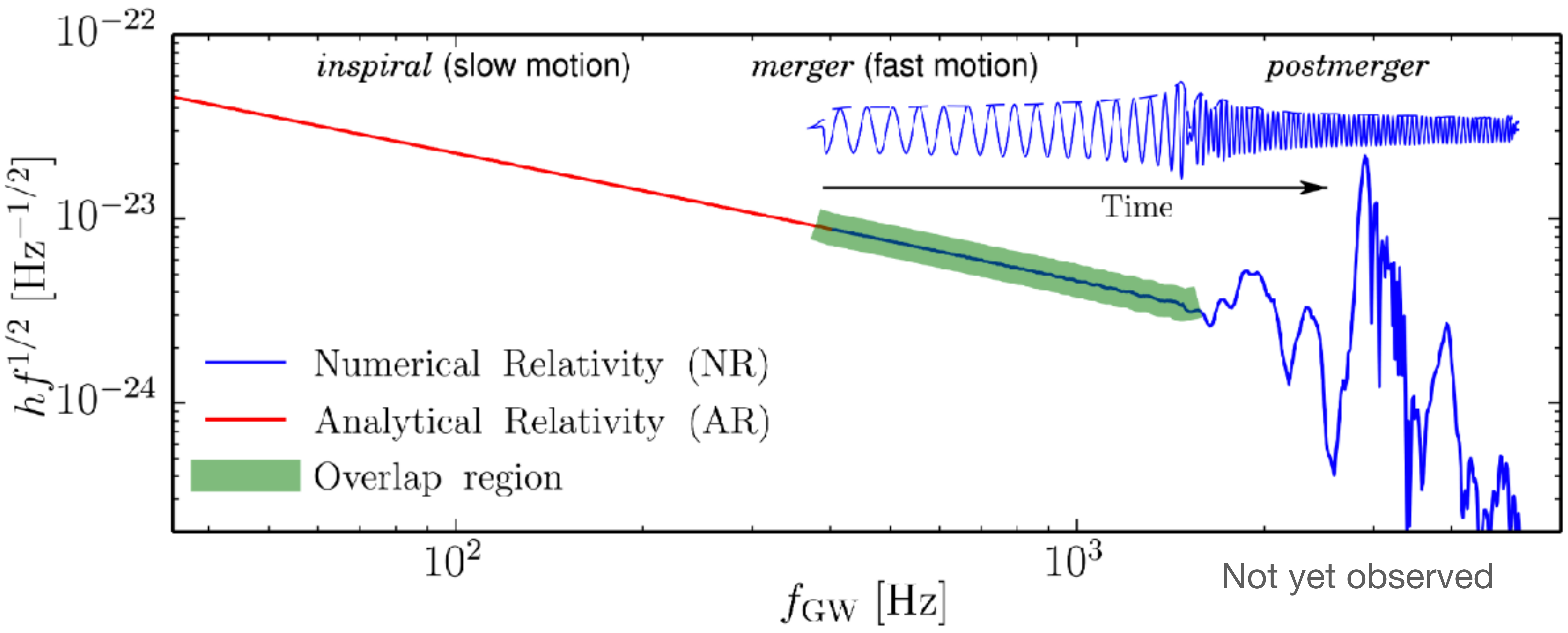
Review: Metzger 2019, figure from Ben Margalit

Margalit & Metzger 2017, Shibata et al. 2017, Rezzolla et al. 2018, Ruiz et al. 2018

Post-merger gravitational waves

Predicting the EOS signature during/after the merger requires numerical relativity simulations

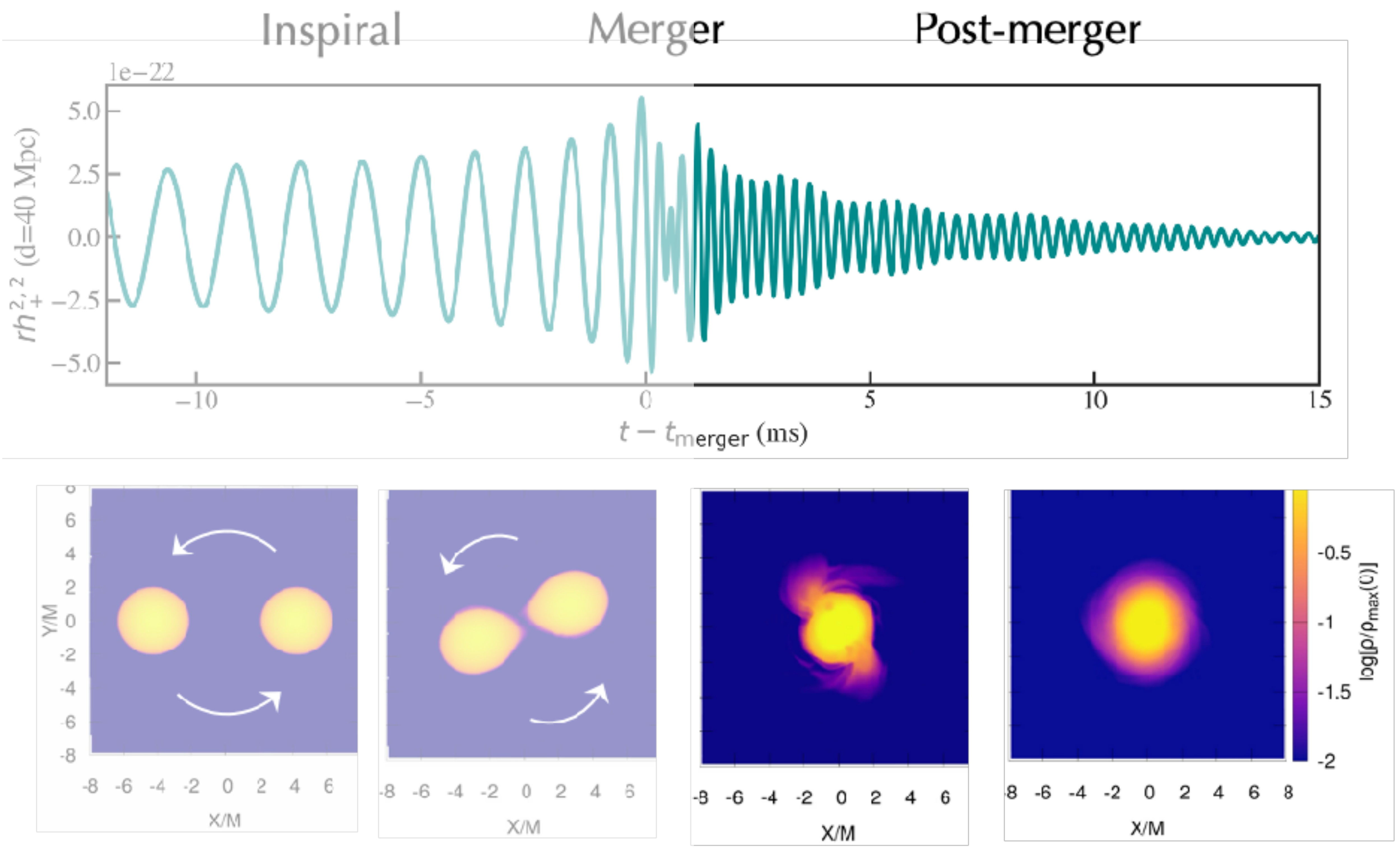
to simultaneously solve Einstein equations and equations of (ideal) relativistic magnetohydrodynamics*



Not yet observed

Radice, Bernuzzi, & Perego 2020

Asteroseismology of the NS remnant with post-merger GWs



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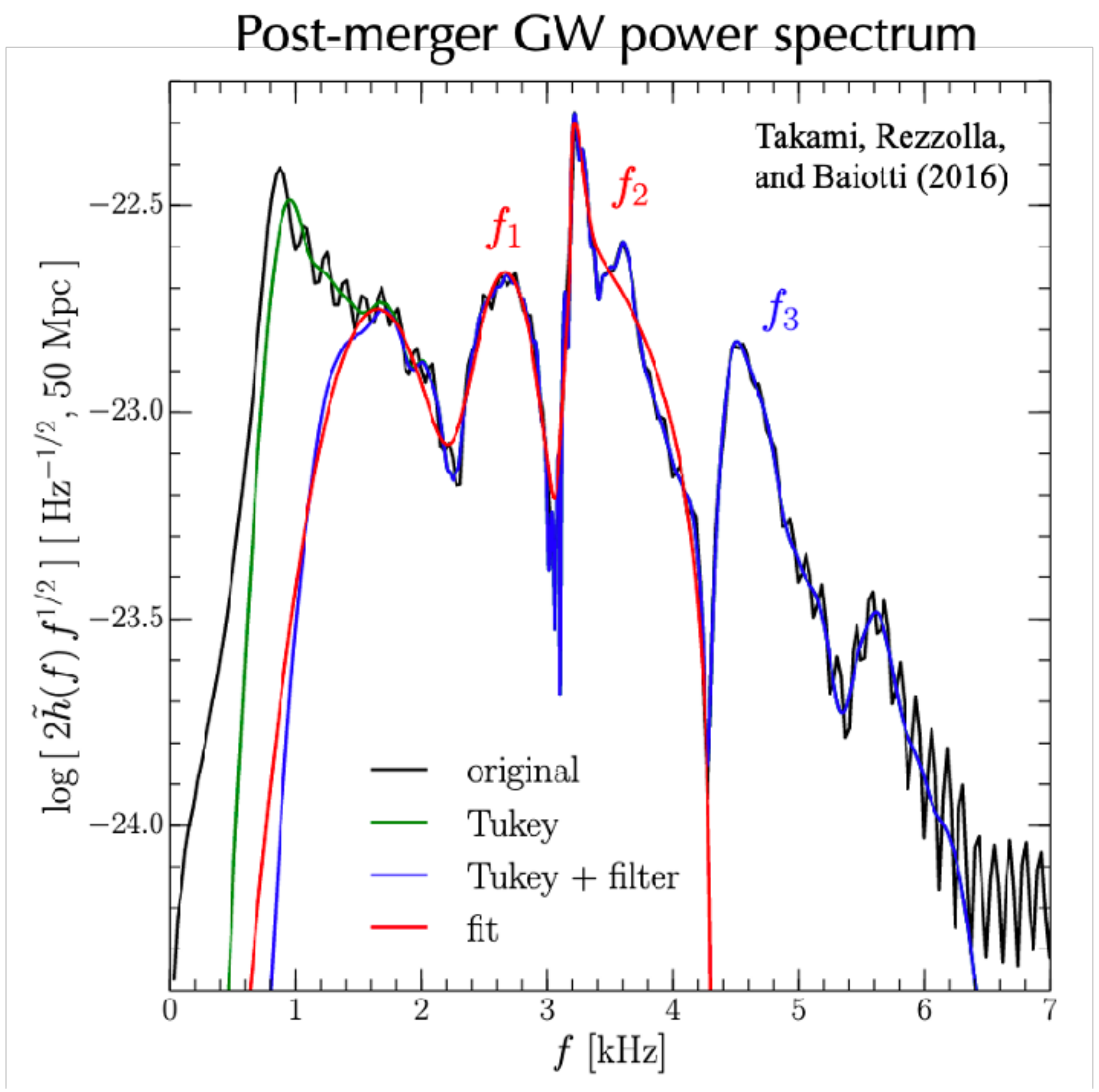
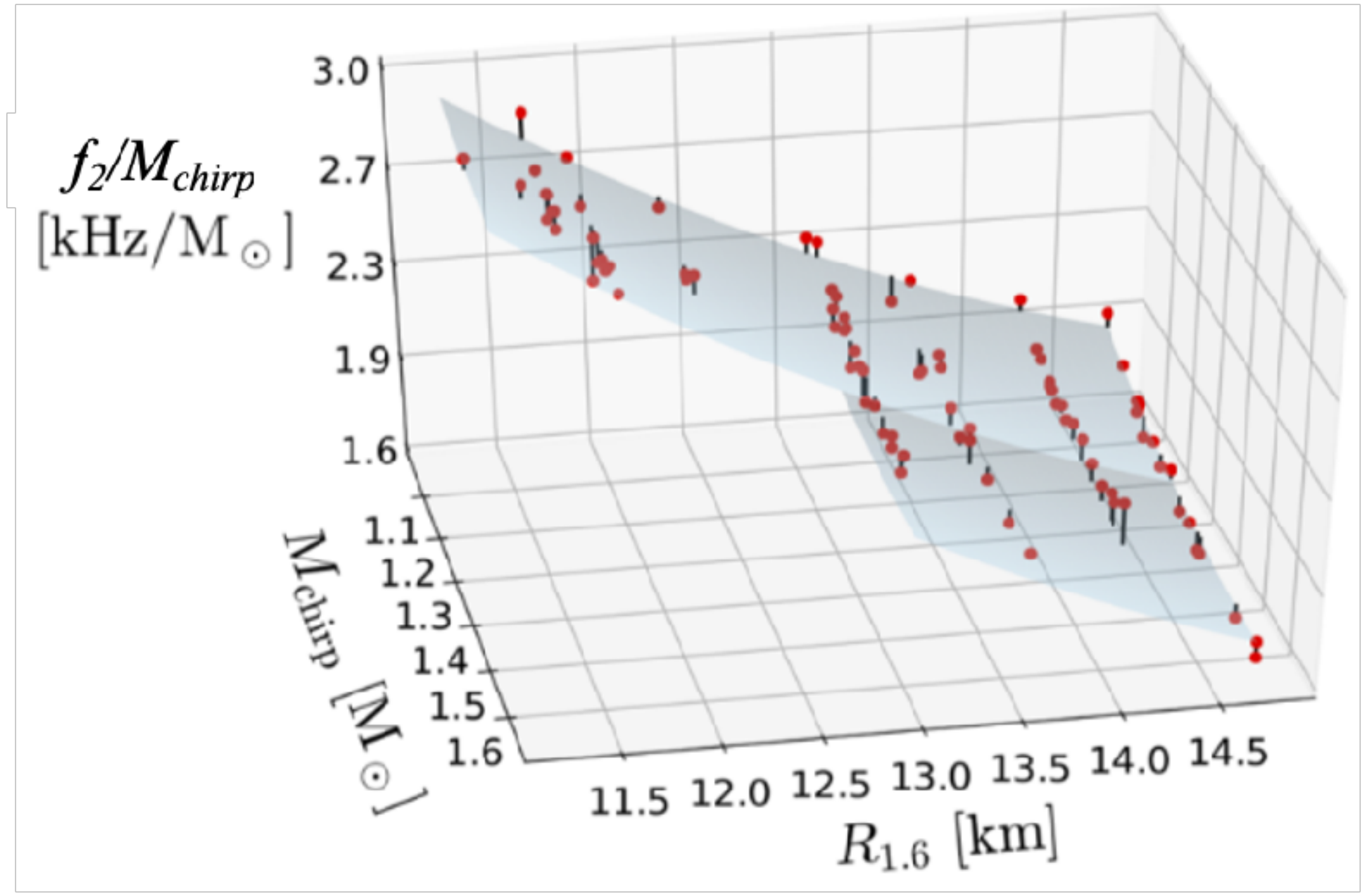


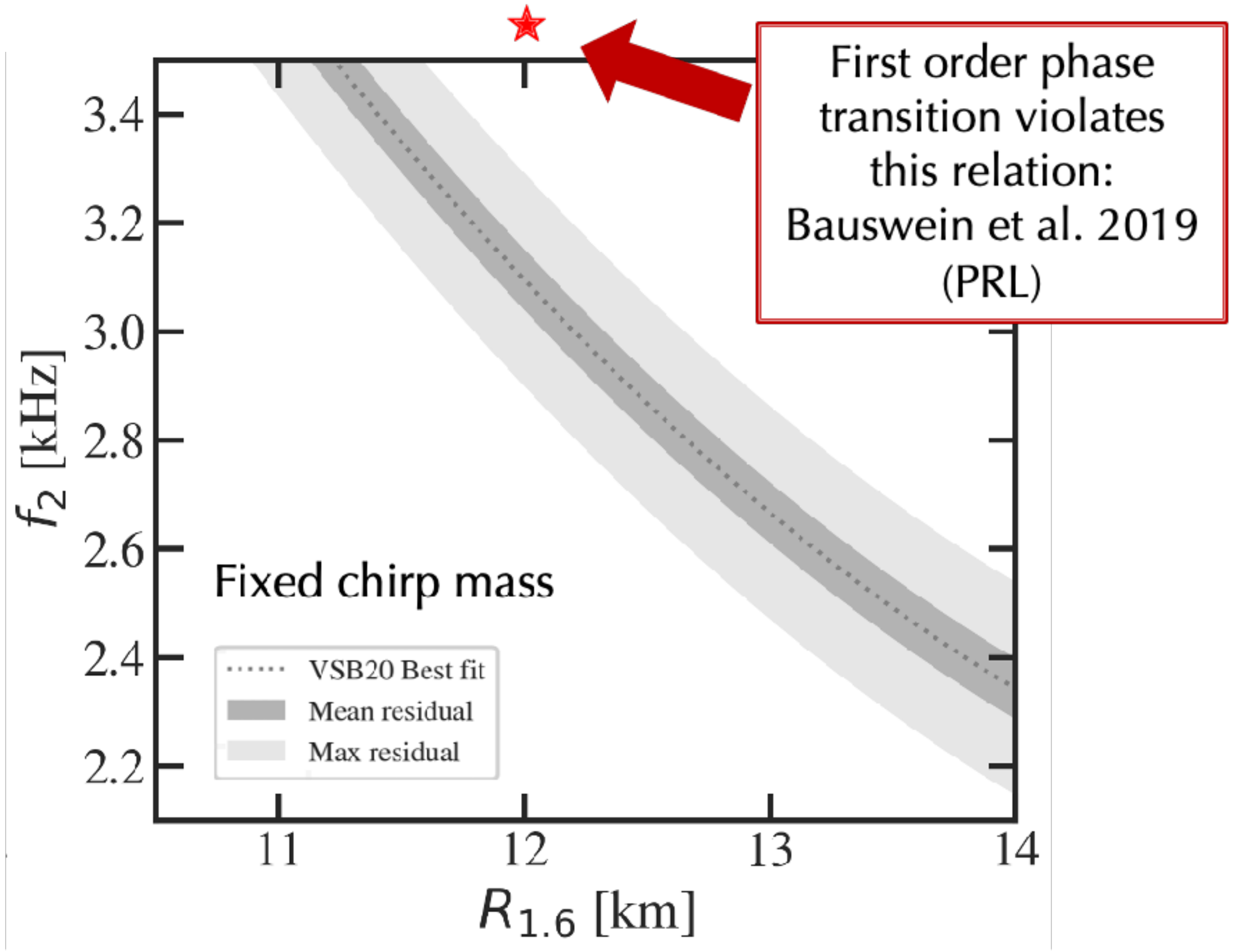
“Quasi-universal” relations between GW peak frequencies and properties of the EOS

- Each point = 1 EoS + 1 set of binary parameters



Vretinaris, Stergioulas, and Bauswein (2020)

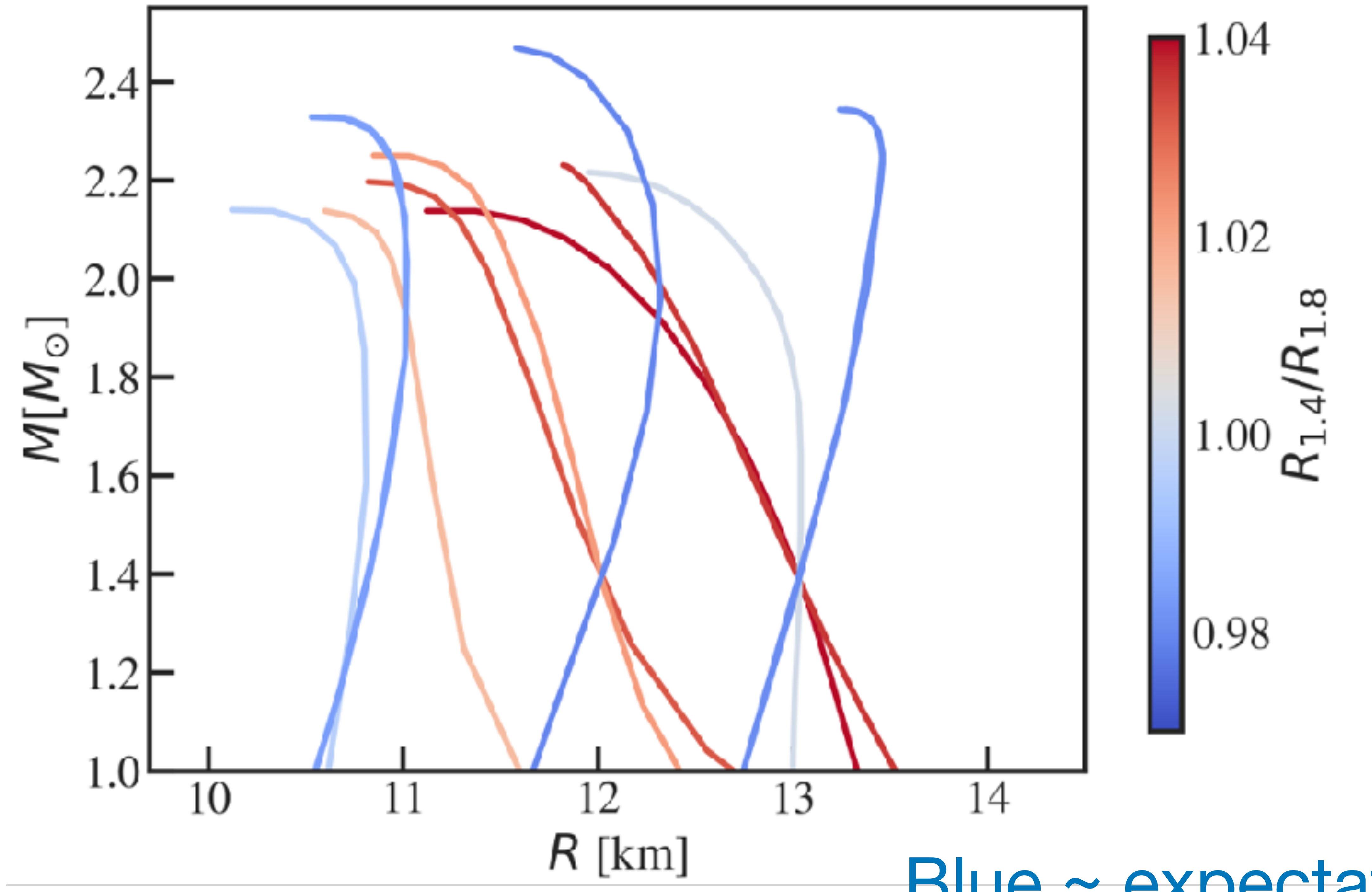
[For reviews, e.g.: Baiotti & Rezzolla 2017; Paschalidis & Stergioulas 2017; Bauswein & Stergioulas 2019; Bernuzzi 2020]

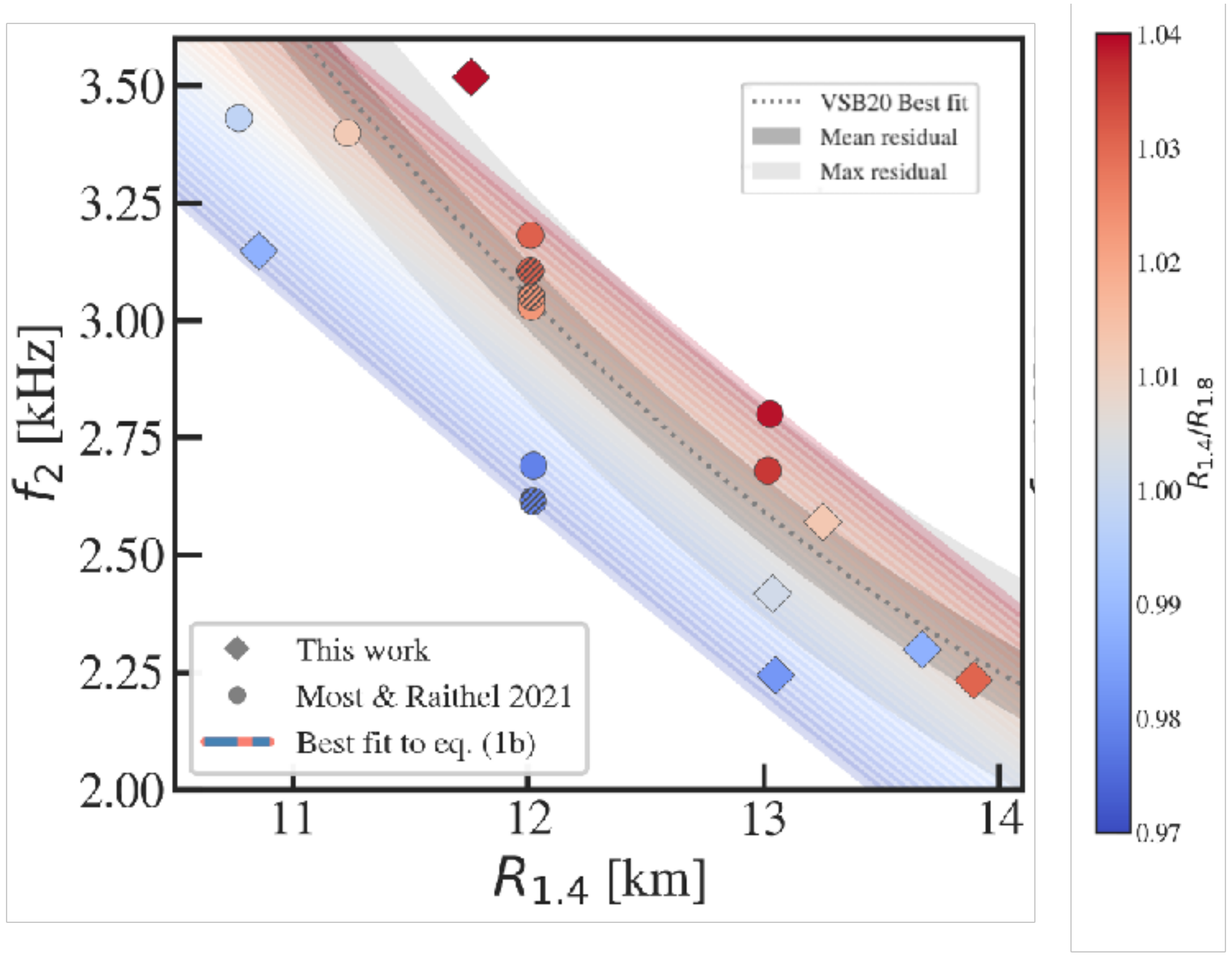


Broadening of quasi-universal relations for different types of phase transitions

Red ~ expectation for **crossover PT**

Phenomenological EOS models

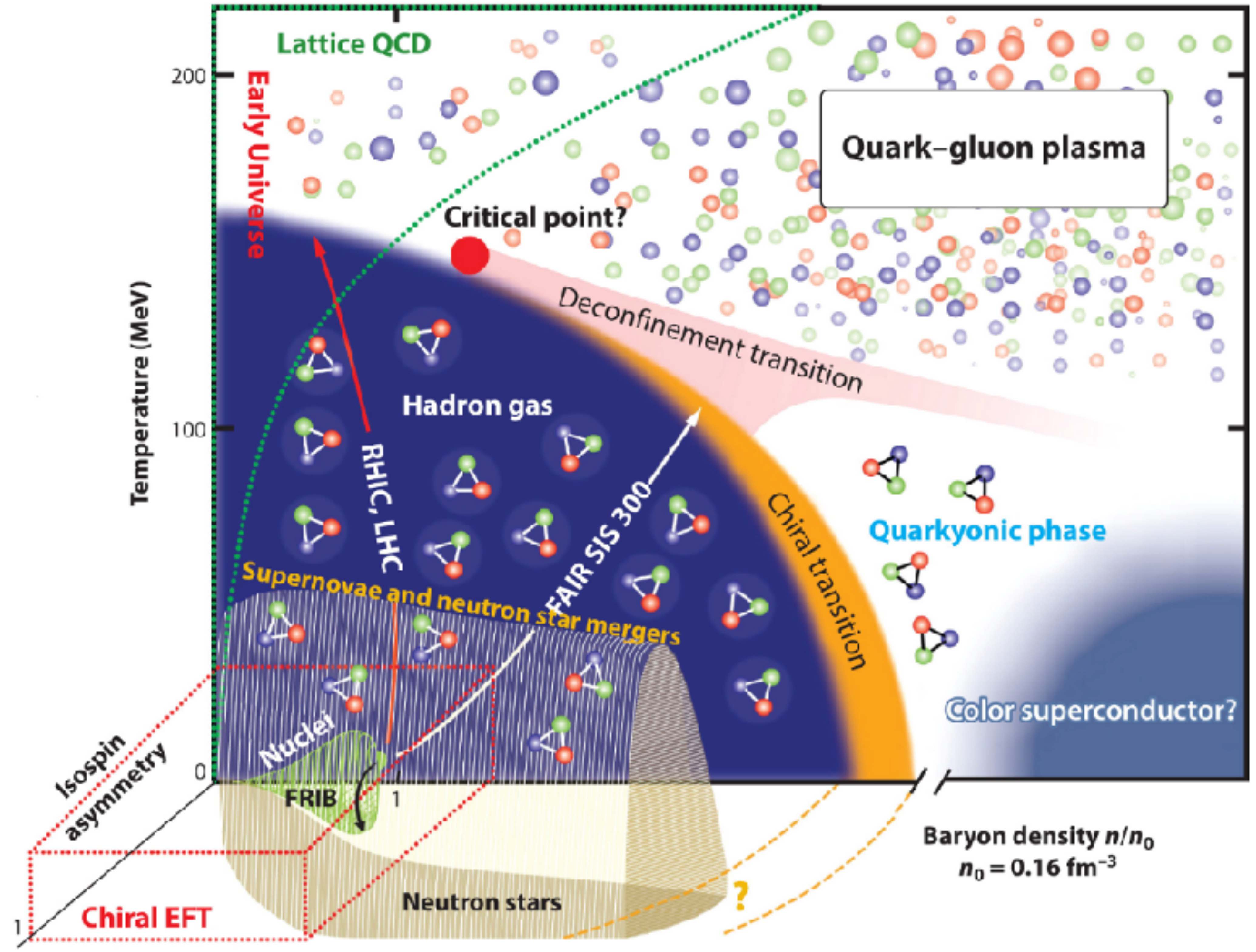




Blue ~ expectation for **quarkyonic matter**

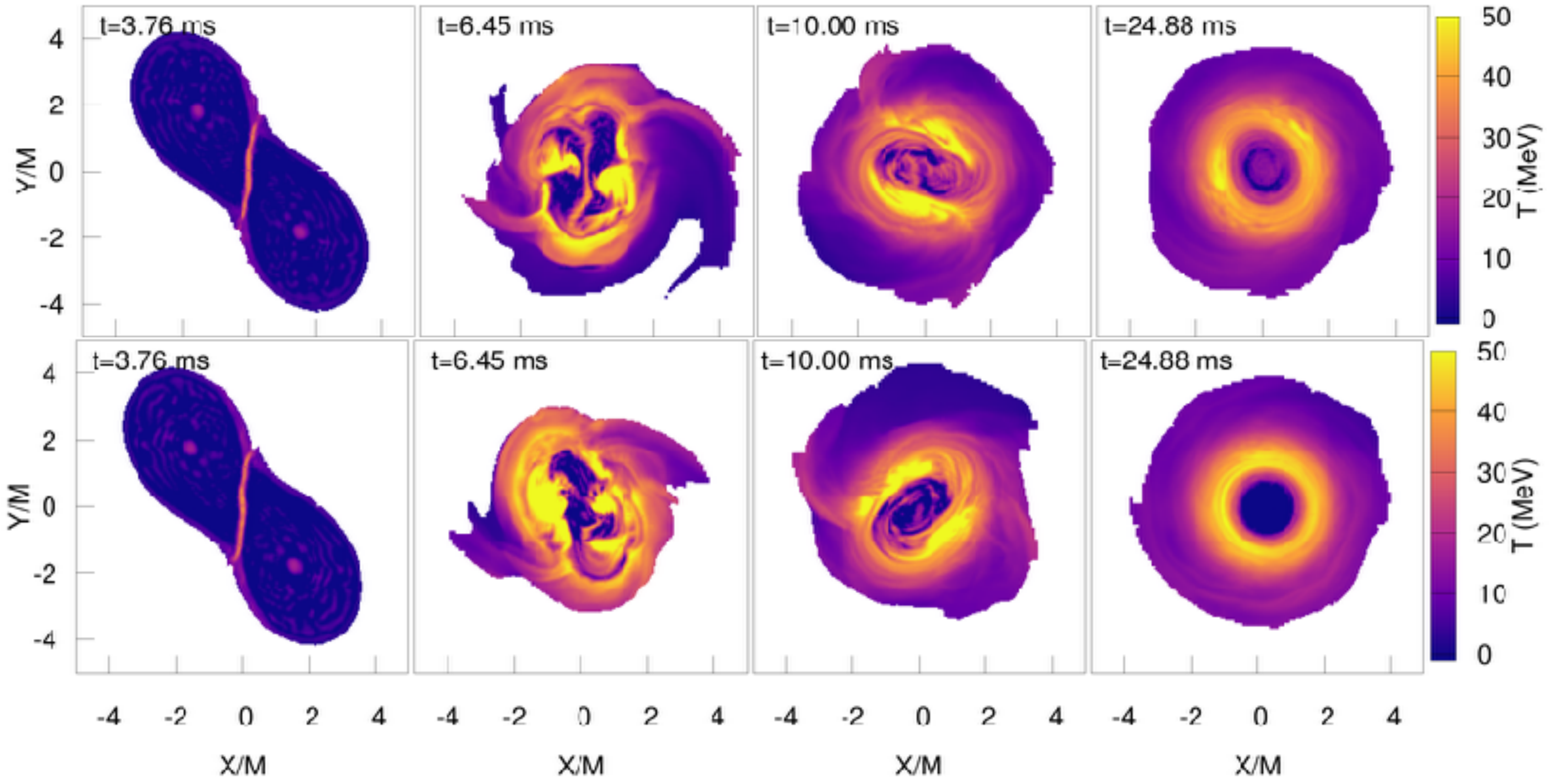
Raithel & Most (2022, ApJL); Most & Raithel (2021 PRD)

Probing hot, dense, and non-equilibrium matter in the post-merger phase



Drischler et al. 2021

Heating of neutron stars from numerical merger simulation



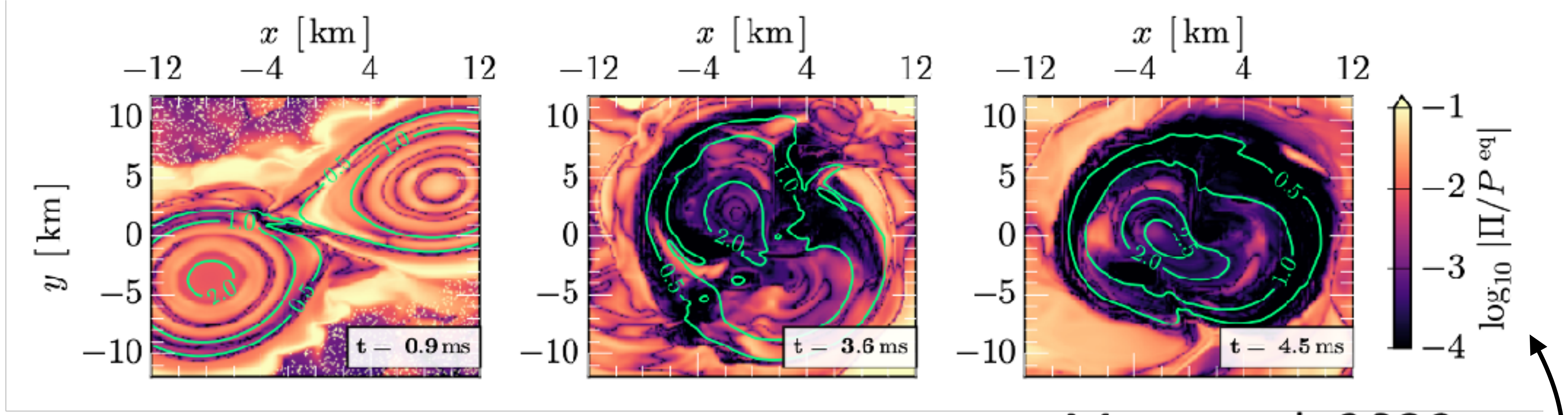
Different degrees of heating, depending on microphysics of the thermal prescription

↳ ***leaves imprint on the post-merger GWs*** *(≲ 190 Hz)*

Raithel et al. 2021, 2023

Probing non-equilibrium physics

Out-of-equilibrium effects (e.g., **bulk viscosity**) may be important in the remnant NS

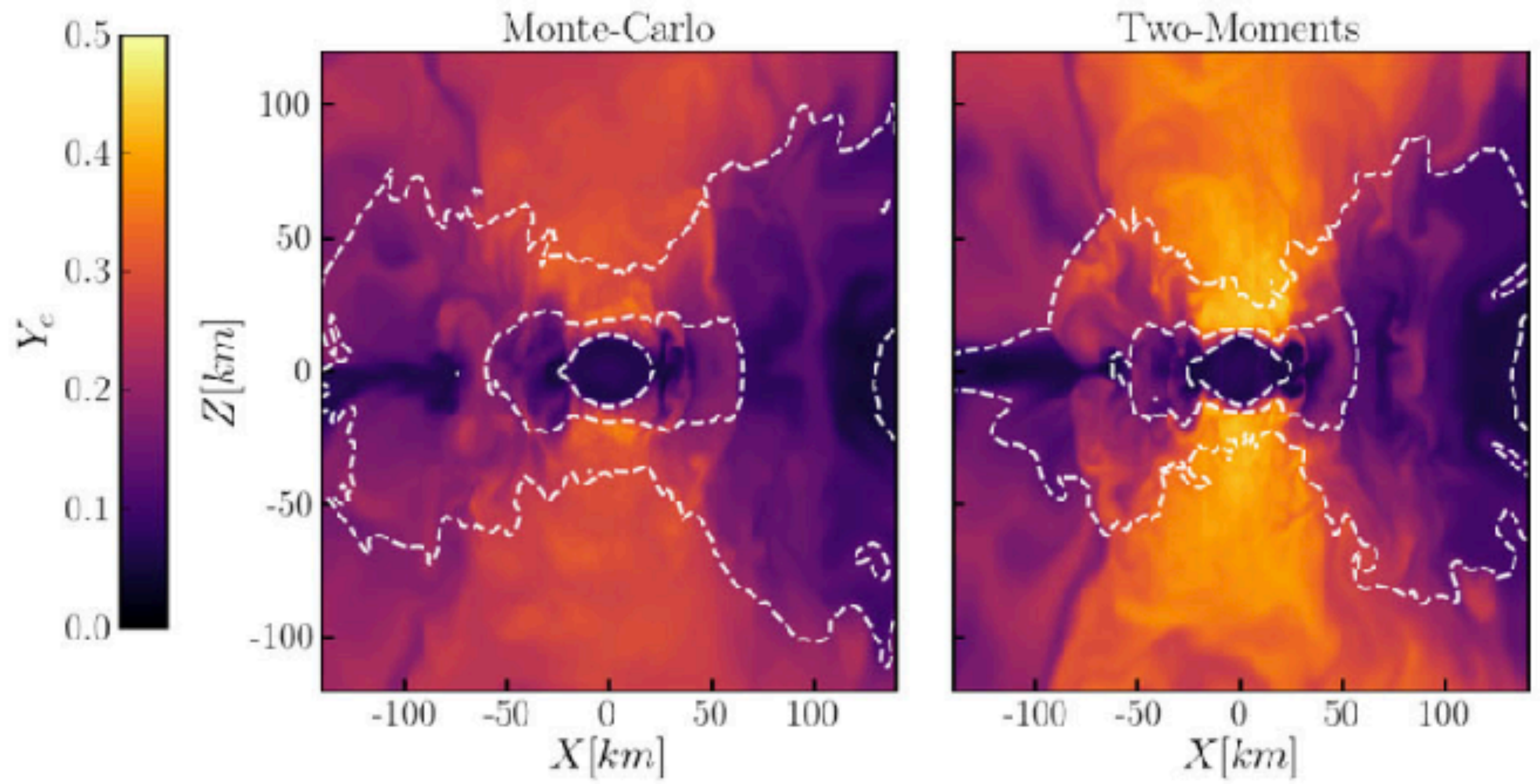


Most et al. 2022

Out-of-equilibrium contribution to the pressure, relative to the equilibrium pressure

Most et al. 2022, Hammond et al. 2022;
but see Radice et al. 2022, Zappa et al. 2023

Neutrino transport is important for capturing the composition in outflows from simulations



Foucart et al. 2020
Review: Foucart 2022;
see also Zappa et al. 2023

What’s next in GW astronomy?

Prospects for upcoming observations

- Detectors are now back online (since May 2023) for O4 observing run
- Expectation: ~8 binary NS inspirals in O4 and up to ~40 (!) in O5
    - *Large uncertainties in predicted rates*

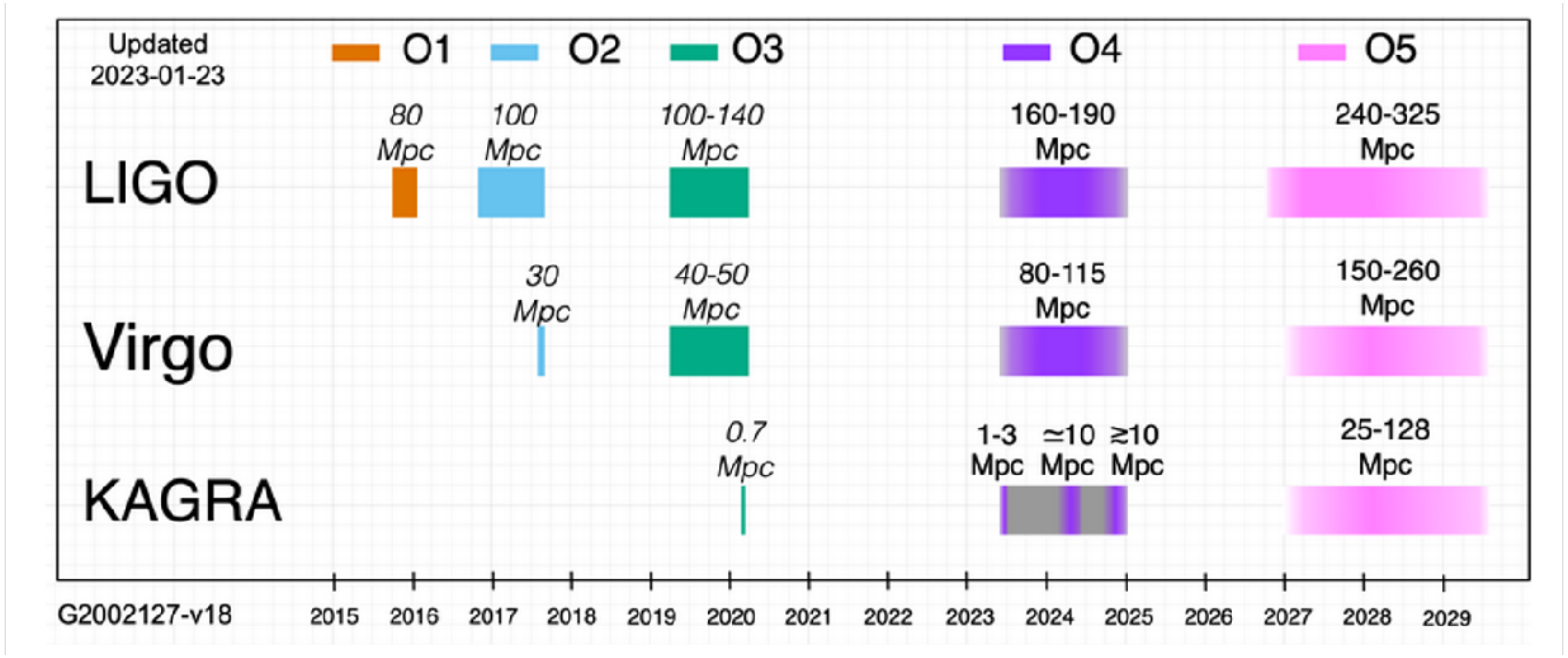
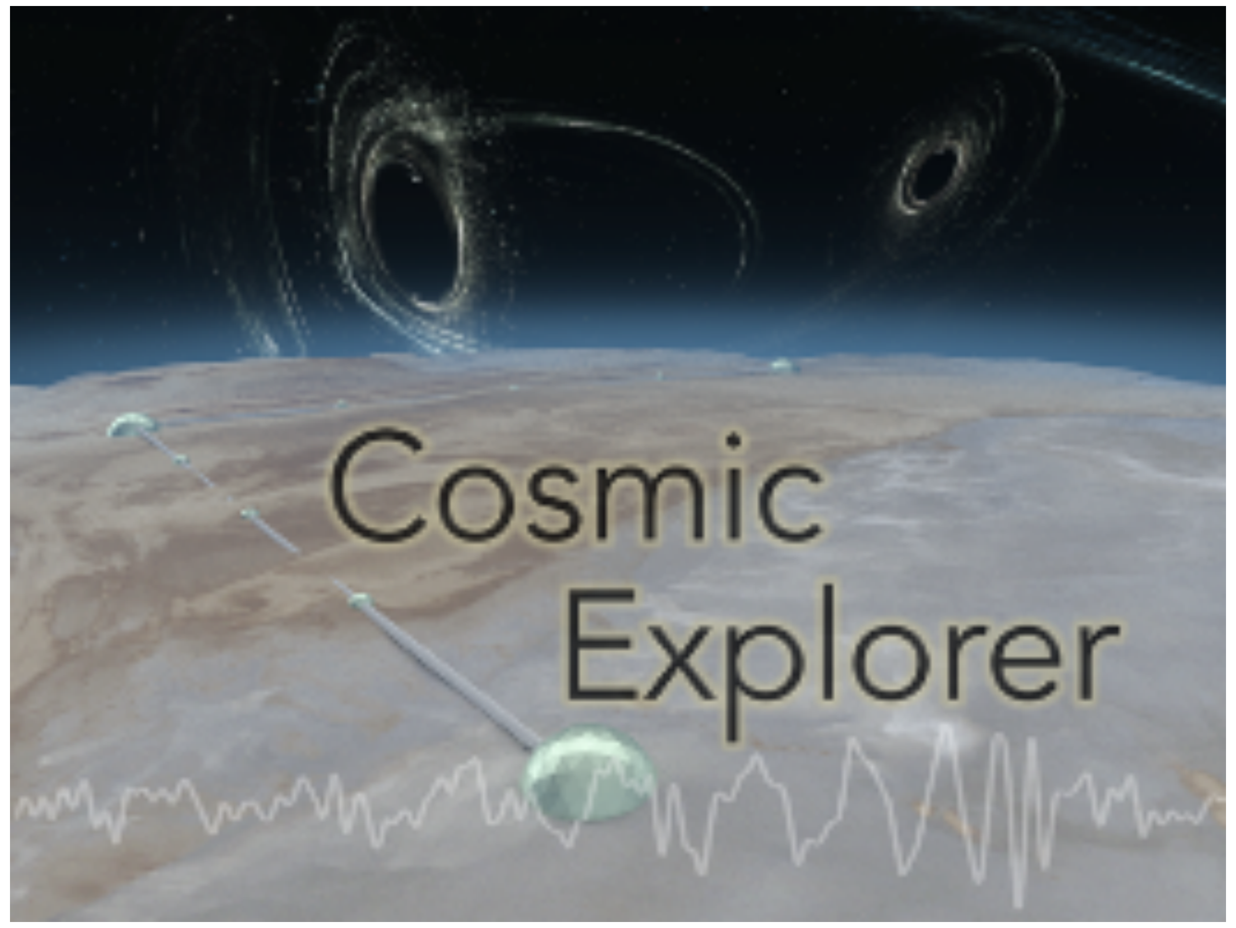
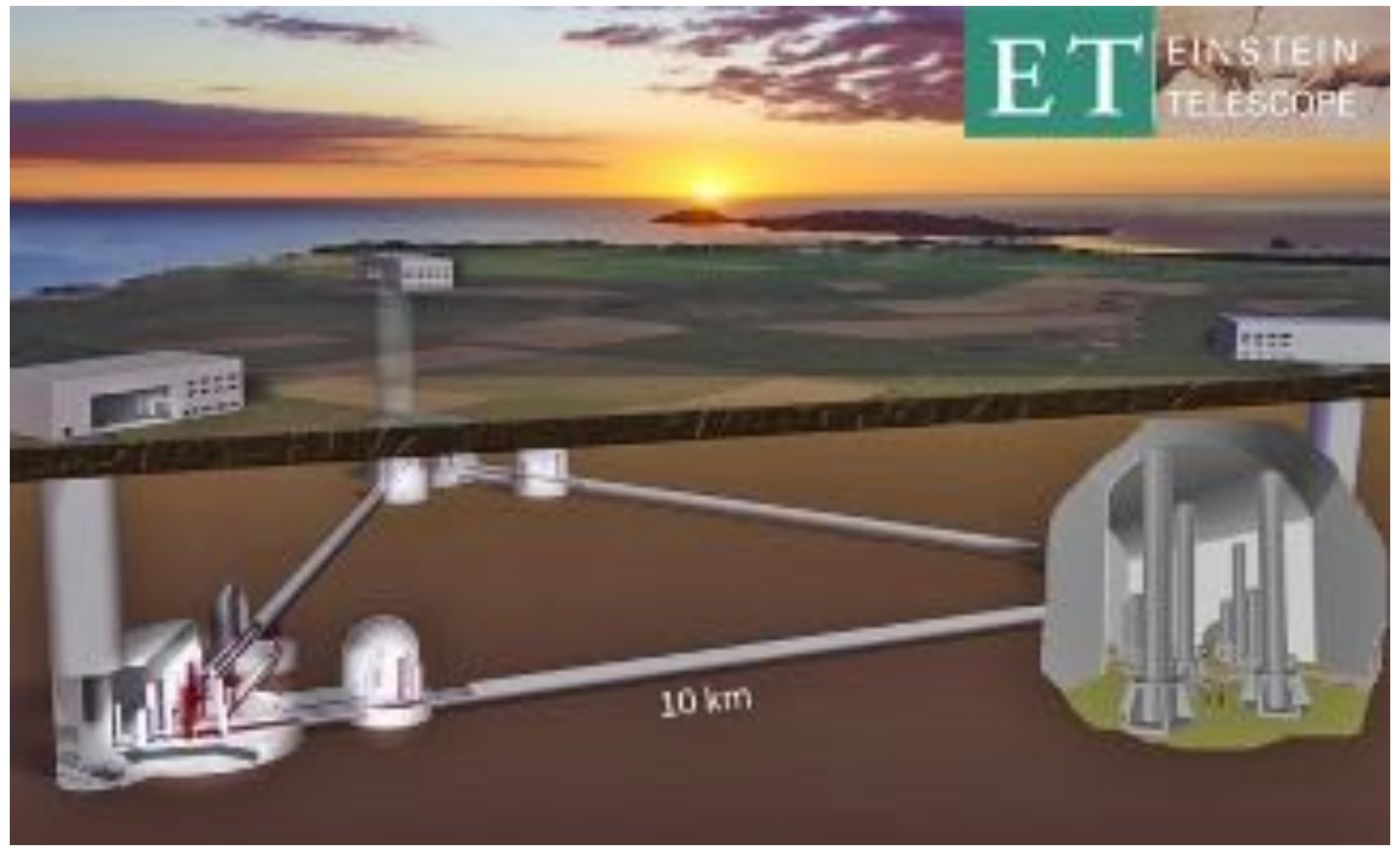
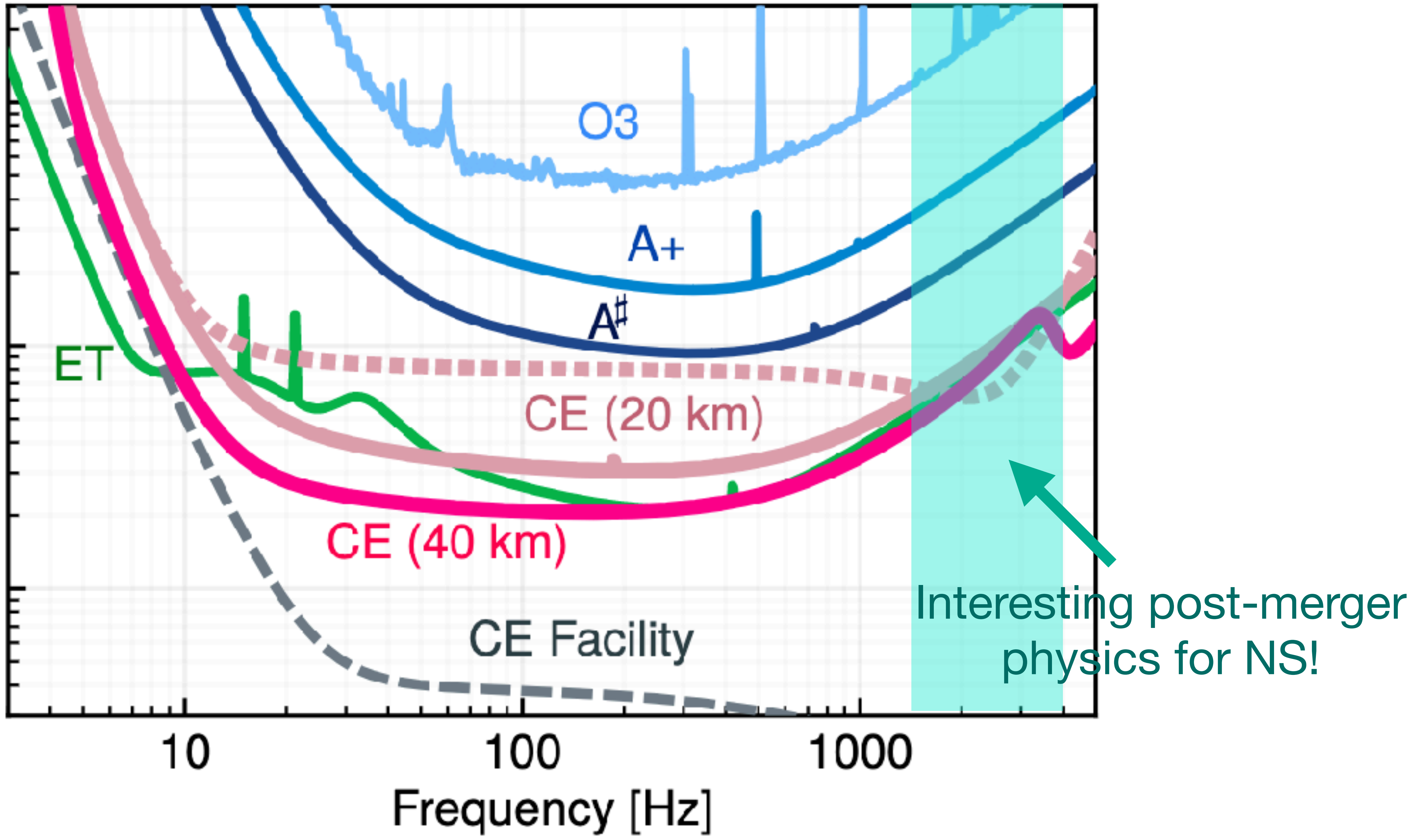


Image credit: LIGO

Next-generation detectors will be ~10x more sensitive

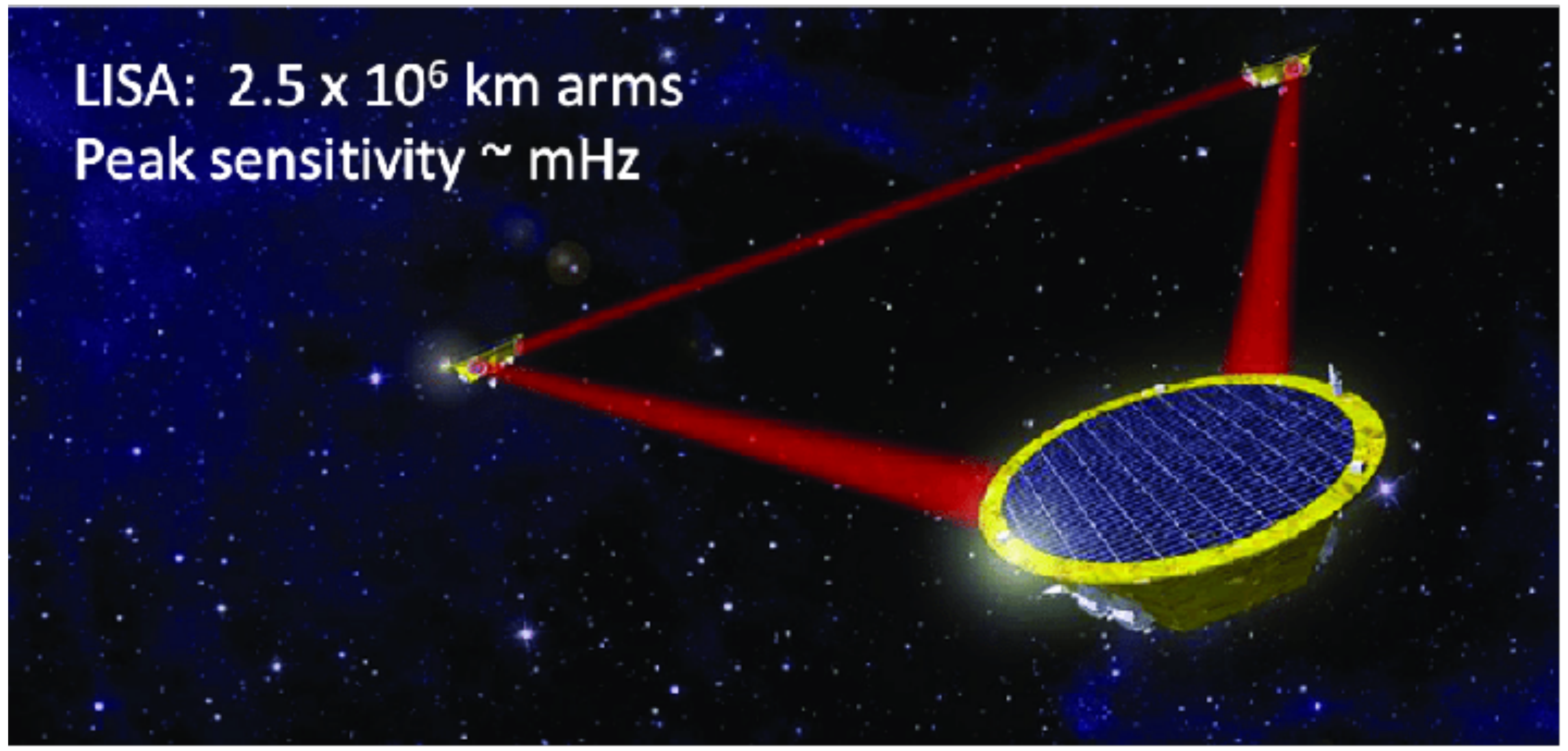


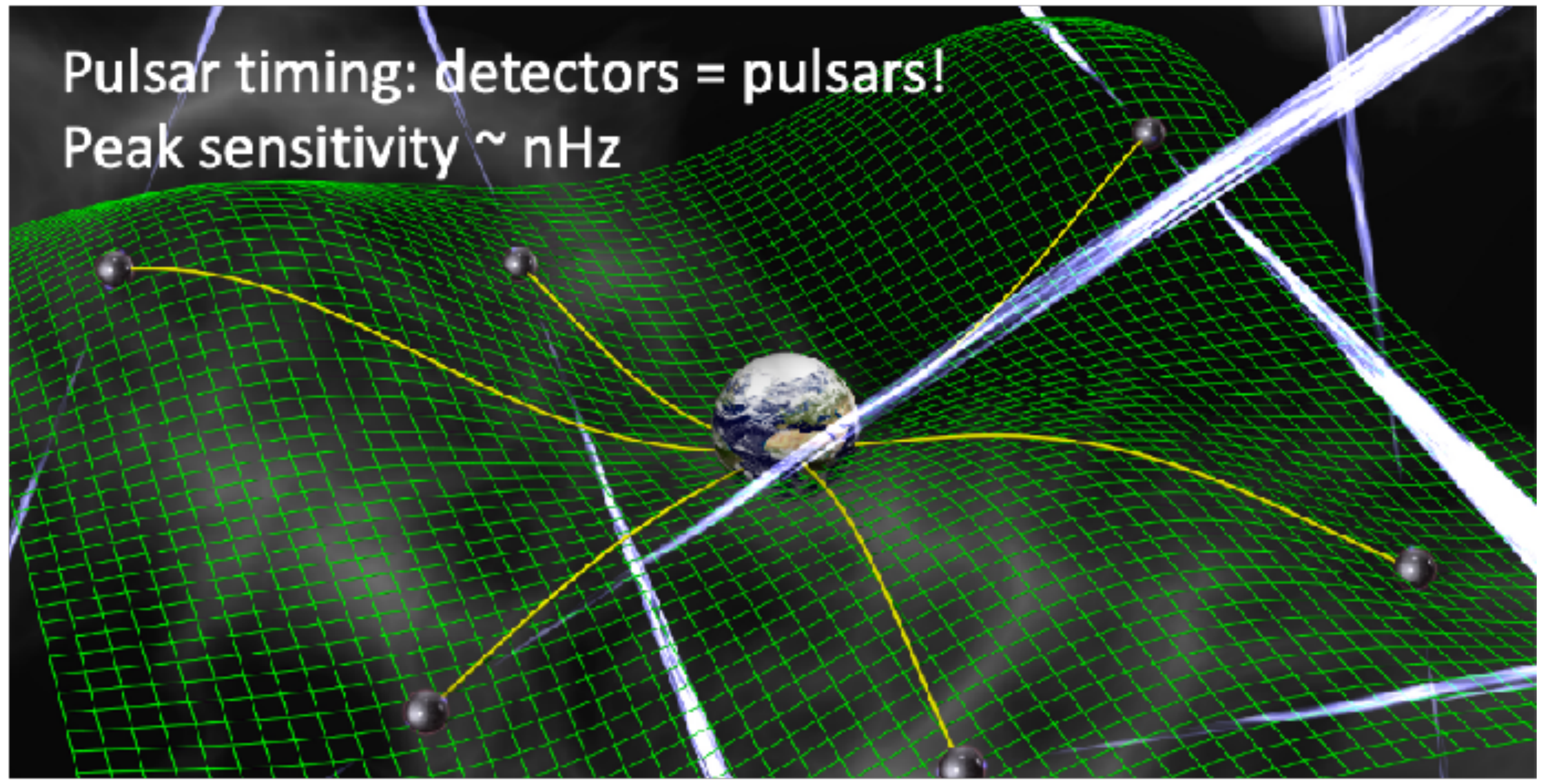


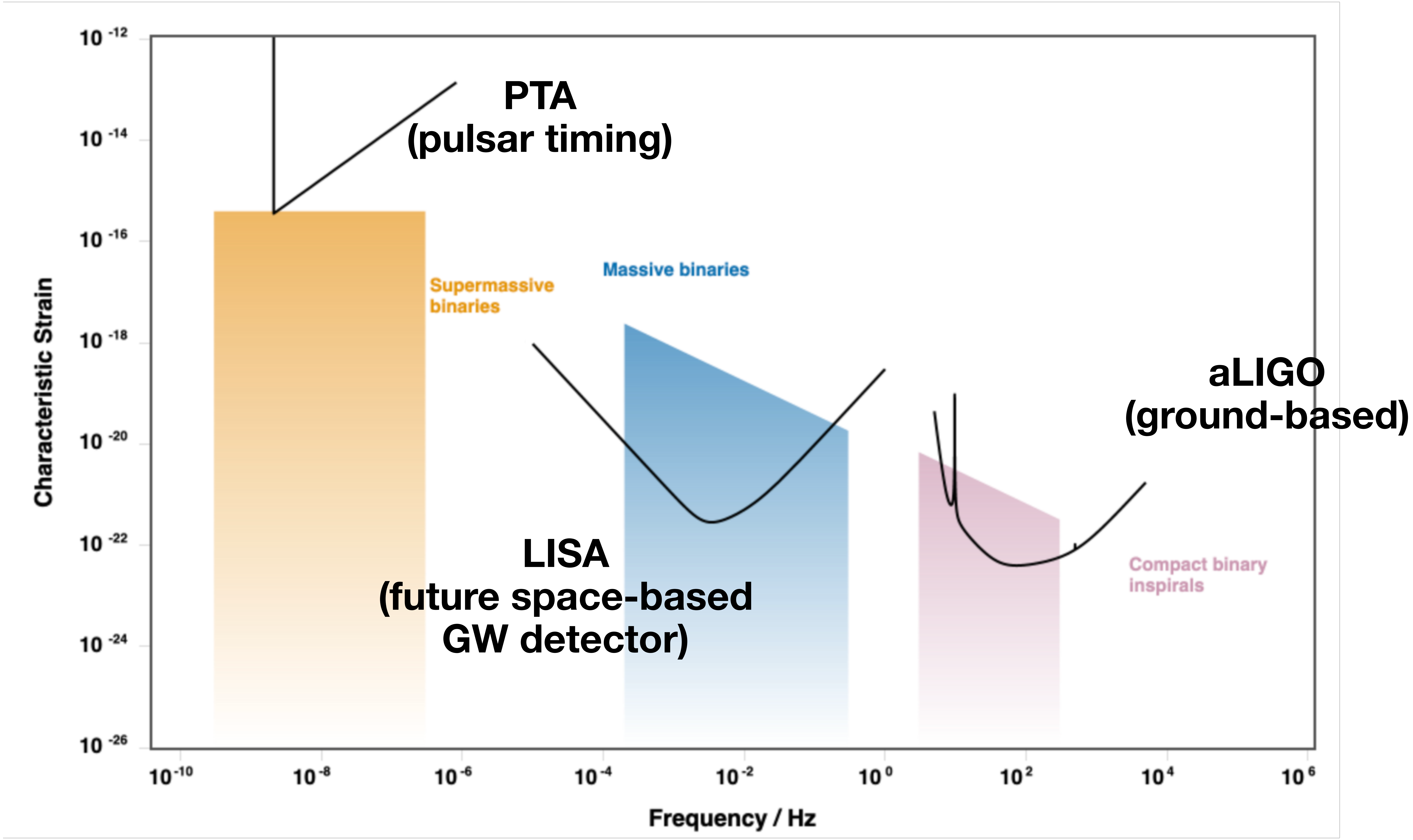


Cosmic Explorer White Paper
Evans et al. 2023

Going beyond ground-based GW detectors







PTA
(pulsar timing)
Supermassive binaries
Massive binaries
aLIGO
(ground-based)
LISA
(future space-based GW detector)
Compact binary inspirals
Characteristic Strain
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Frequency / Hz

Further reading:

Merger dynamics / reviews:

- Andersson, "Gravitational-Wave Astronomy: Exploring the Dark Side of the Universe" (2019, *Oxford University Press*)
- Bernuzzi, "Neutron star merger remnants" (2020, GR *and Gravitation*)
- Radice et al., "The Dynamics of Binary Neutron Star Mergers and of GW170817" (2020 *Annual Rev. of Astr. & Astroph.*)

Reviews of dense-matter constraints from GW170817:

- Baiotti, "Gravitational waves from neutron star mergers and their relation to the nuclear equation of state" (2019, *Prog. in Particle and Nuclear Physics*)
- Raithel, "Constraints on the neutron star equation of state from GW170817", (2019, *EPJA*)
- Chatziioannou, "Neutron-star tidal deformability and equation-of-state constraints", (2020, *GR and Gravitation*)

E/M counterparts:

- Abbott et al.,"Multi-Messenger Observations of a Binary Neutron Star Merger" (2017, *APJL*)
- Metzger, "Kilonovae" (2020, *Living Rev. of Relativity*)