Gravitational waves from binary-neutron-star mergers and the equation of state

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Plan of the talk

1. Introduction
2. Inspiral: neutron-star equation of state
3. Postmerger: crossover vs. 1st phase transition
4. Discussion and summary

1. Introduction

Gravitational-wave detectors


Advanced LIGO
(Hanford/Livingston, USA)

https://www.advancedligo.mit.edu/graphics/summary01.jpg


http://gwcenter.icrr.u-tokyo.ac.jp/wp-content/themes/lcgt/images/img_abt_lcgt.jpg

KAGRA (Kamioka, Japan)

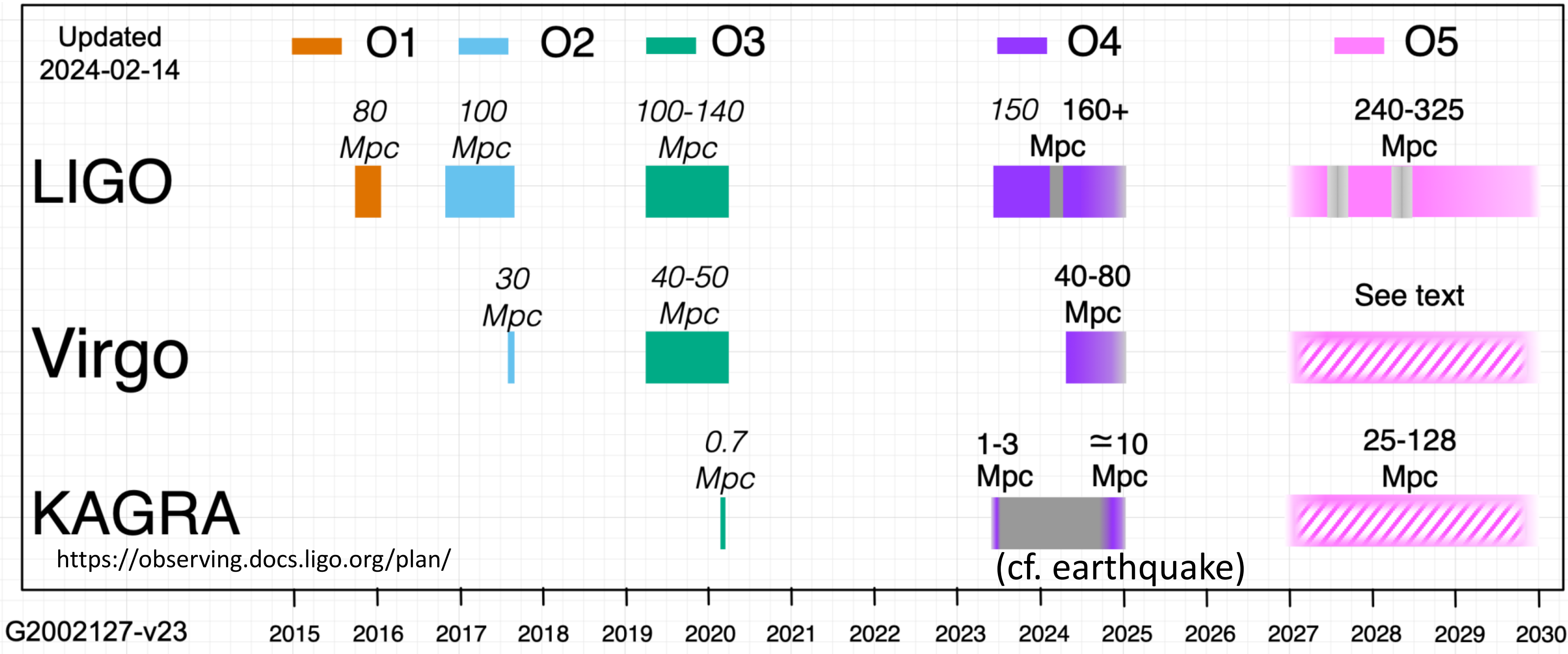

Advanced Virgo (Pisa, Italy)

http://virgopisa.df.unipi.it/sites/virgopisa.df.unipi.it.virgopisa/files/banner/virgo.jpg

Observation plan

O4 will continue throughout 2024 with improvement

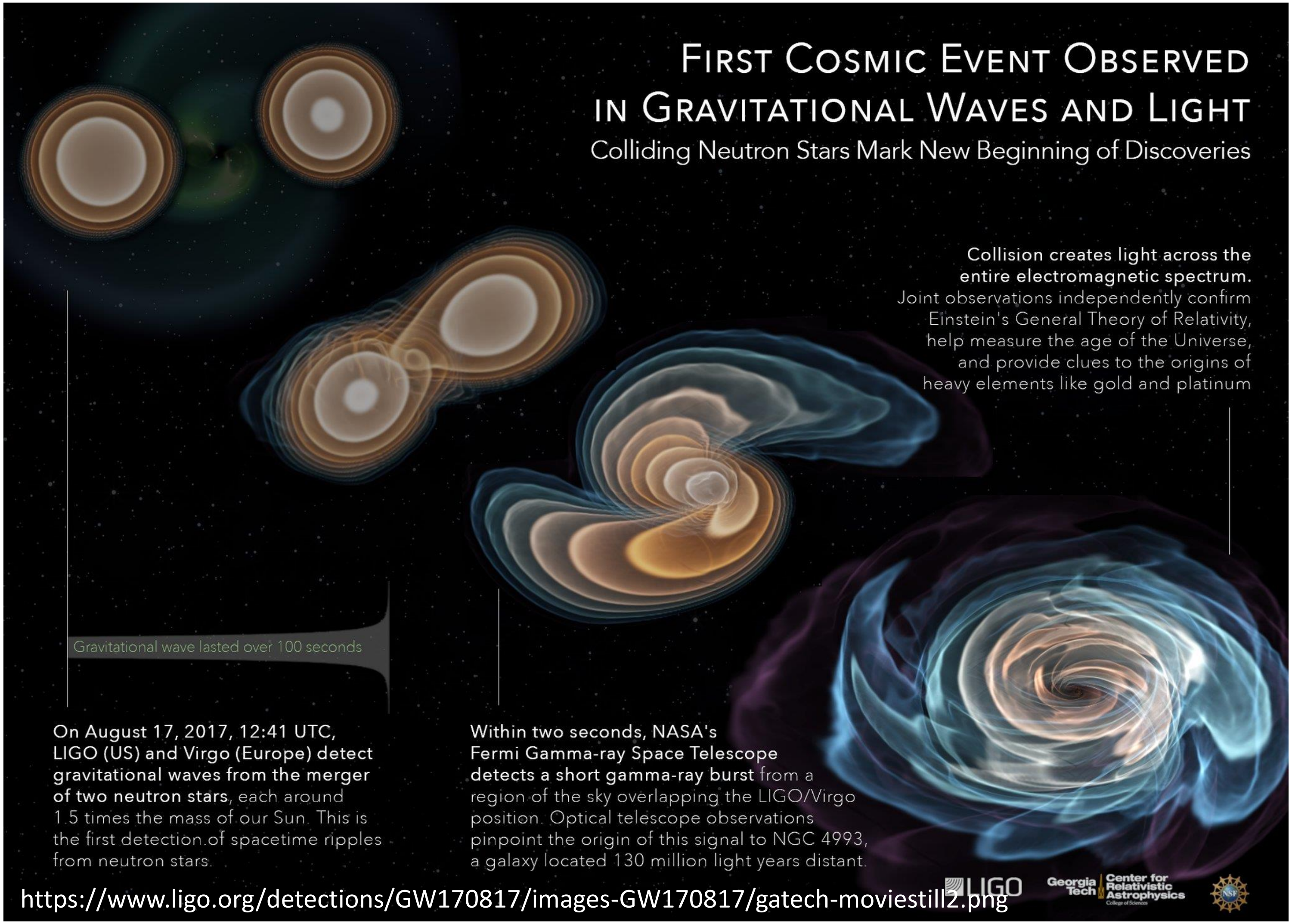
O5 is planned to start from the beginning of 2027



https://observing.docs.ligo.org/plan/

(cf. earthquake)

Gravitational waves: GW170817



FIRST COSMIC EVENT OBSERVED IN GRAVITATIONAL WAVES AND LIGHT

Colliding Neutron Stars Mark New Beginning of Discoveries

Collision creates light across the entire electromagnetic spectrum. Joint observations independently confirm Einstein's General Theory of Relativity, help measure the age of the Universe, and provide clues to the origins of heavy elements like gold and platinum

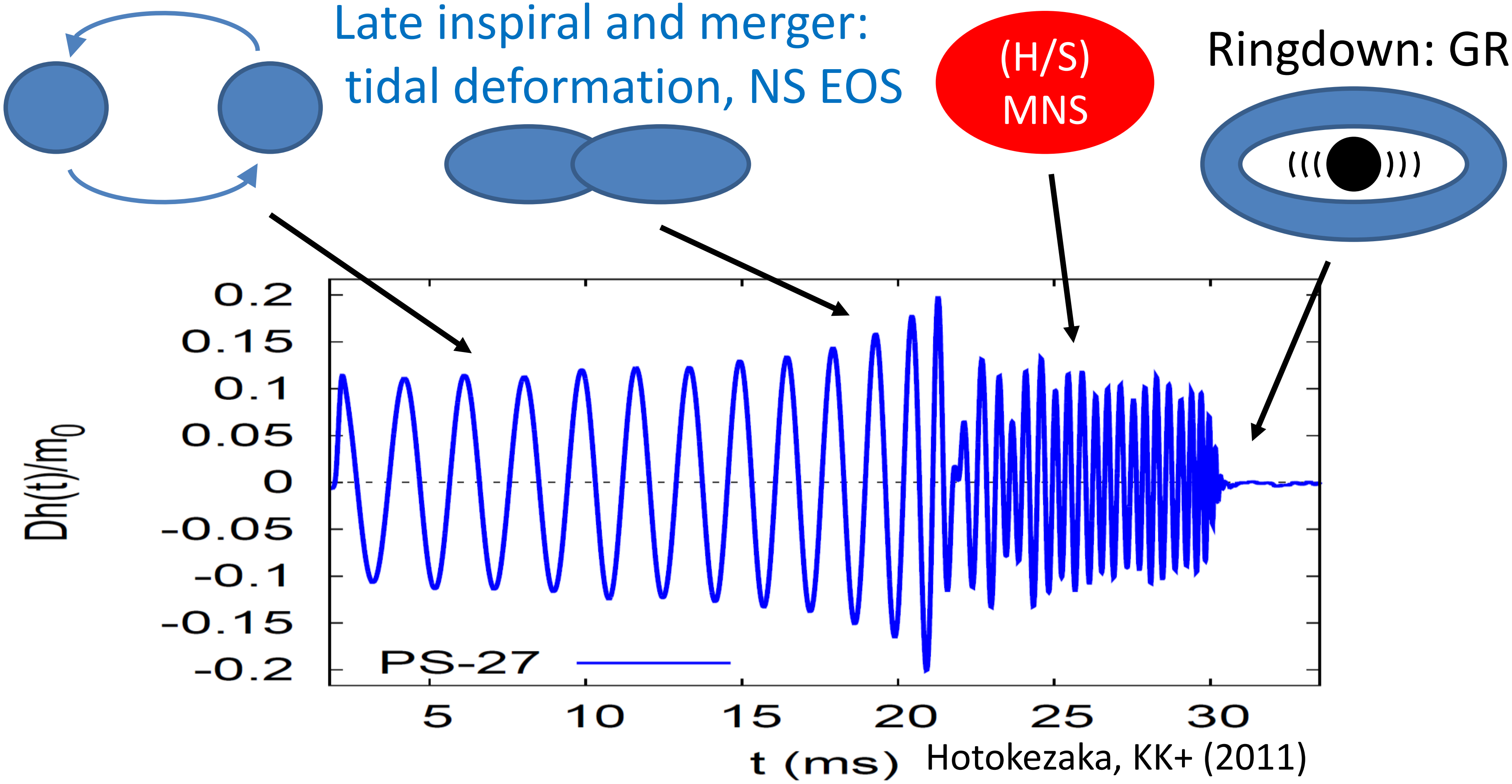
Gravitational wave lasted over 100 seconds

On August 17, 2017, 12:41 UTC, LIGO (US) and Virgo (Europe) detect gravitational waves from the merger of two neutron stars, each around 1.5 times the mass of our Sun. This is the first detection of spacetime ripples from neutron stars.

Within two seconds, NASA's Fermi Gamma-ray Space Telescope detects a short gamma-ray burst from a region of the sky overlapping the LIGO/Virgo position. Optical telescope observations pinpoint the origin of this signal to NGC 4993, a galaxy located 130 million light years distant.

https://www.ligo.org/detections/GW170817/images-GW170817/gatech-moviestill2.png

Various phases of coalescence



Early inspiral: mass, spins…

Late inspiral and merger:
tidal deformation, NS EOS

Remnant massive NS:
extreme temperature/density

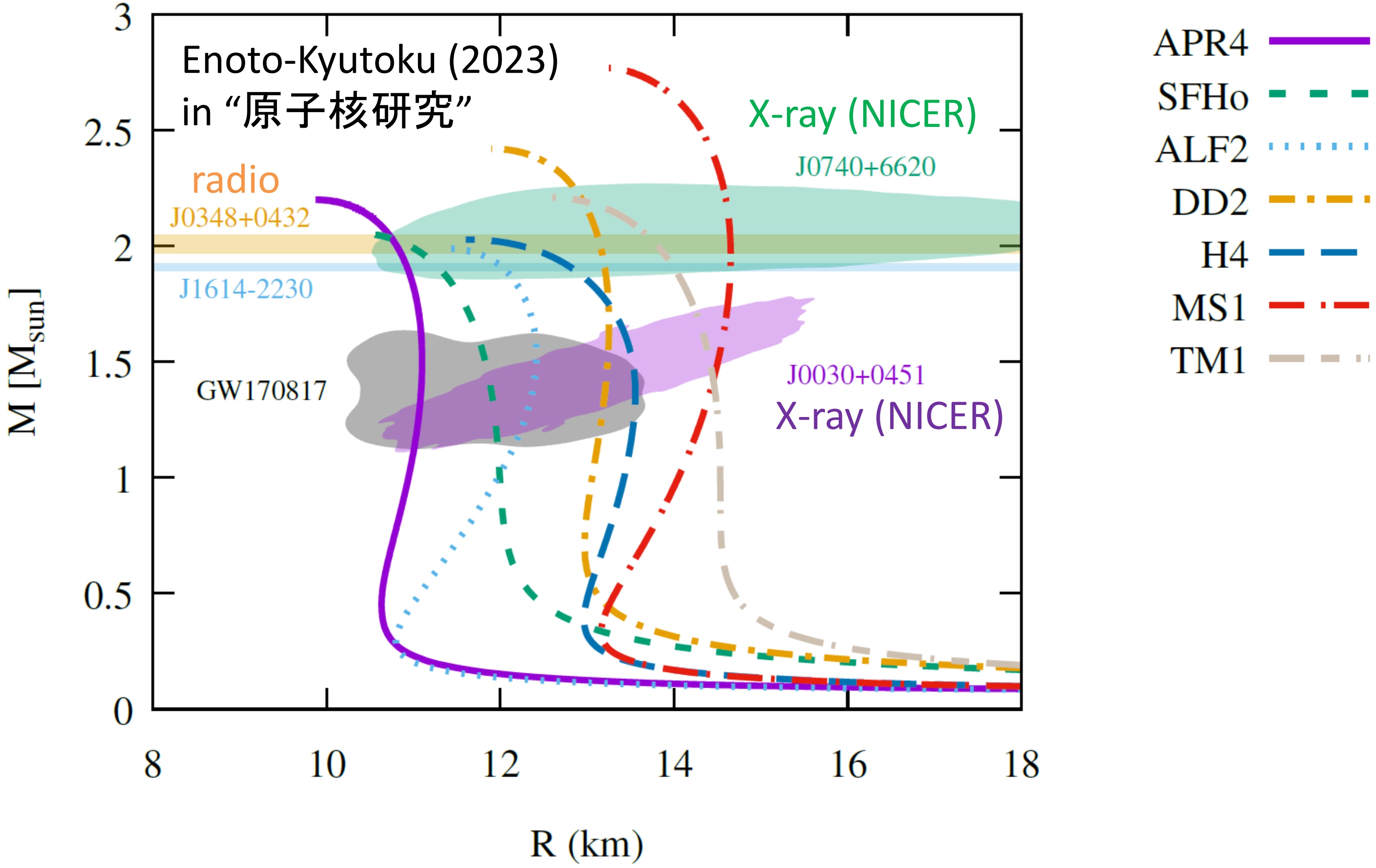
Ringdown: GR

Hotokezaka, KK+ (2011)

2. Inspiral: neutron-star equation of state

Current understanding

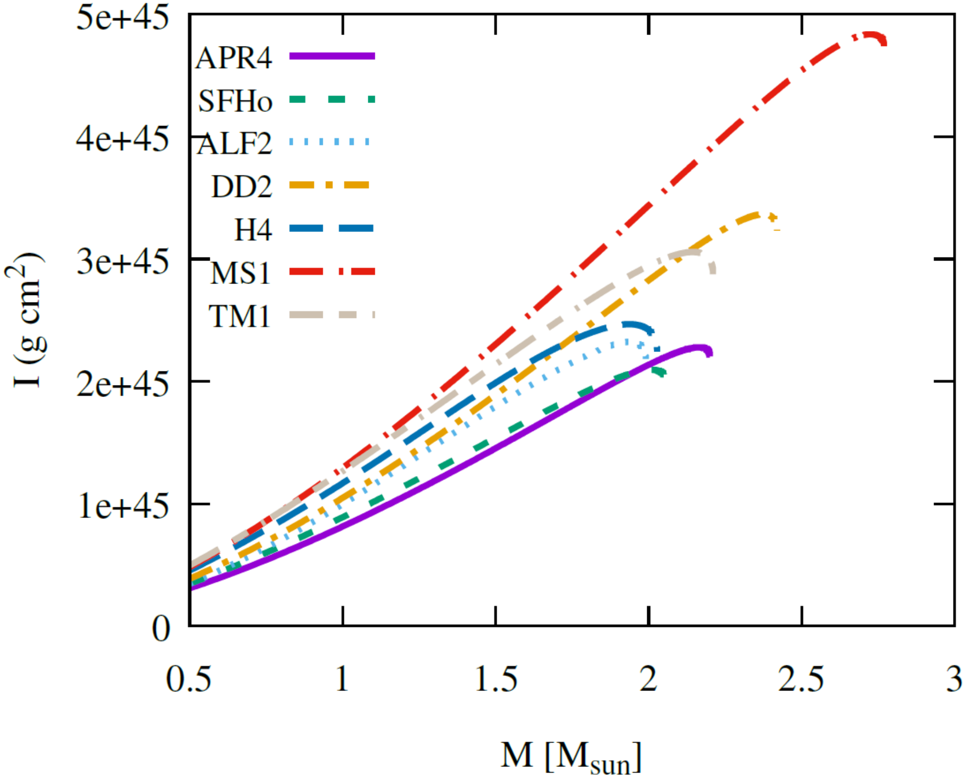
$\sim 11.5 - 13.5\mathrm{km}$ for typical-mass neutron stars?



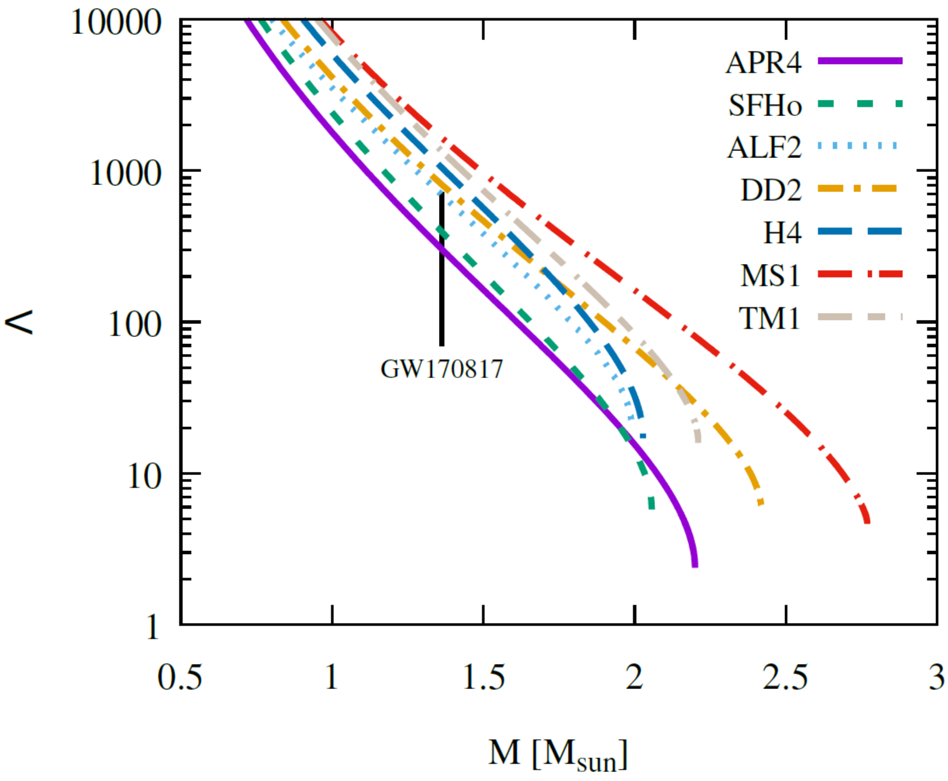
Other macroscopic observables

The binary dynamics are affected more directly by, e.g.,

Moment of inertia



Tidal deformability

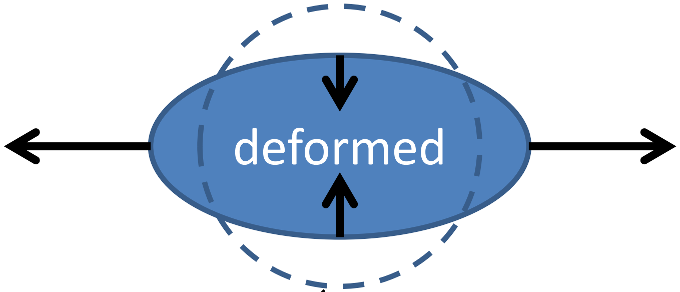


Quadrupolar tidal deformability

Leading-order finite-size effect on orbital evolution (strongly correlated with the neutron-star radius)

$$\Lambda = G\lambda\left(\frac{c^2}{GM}\right)^5 = \frac{2}{3}k\left(\frac{c^2R}{GM}\right)^5 \propto R^5$$

$k \sim 0.1$: (second/electric) tidal Love number



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

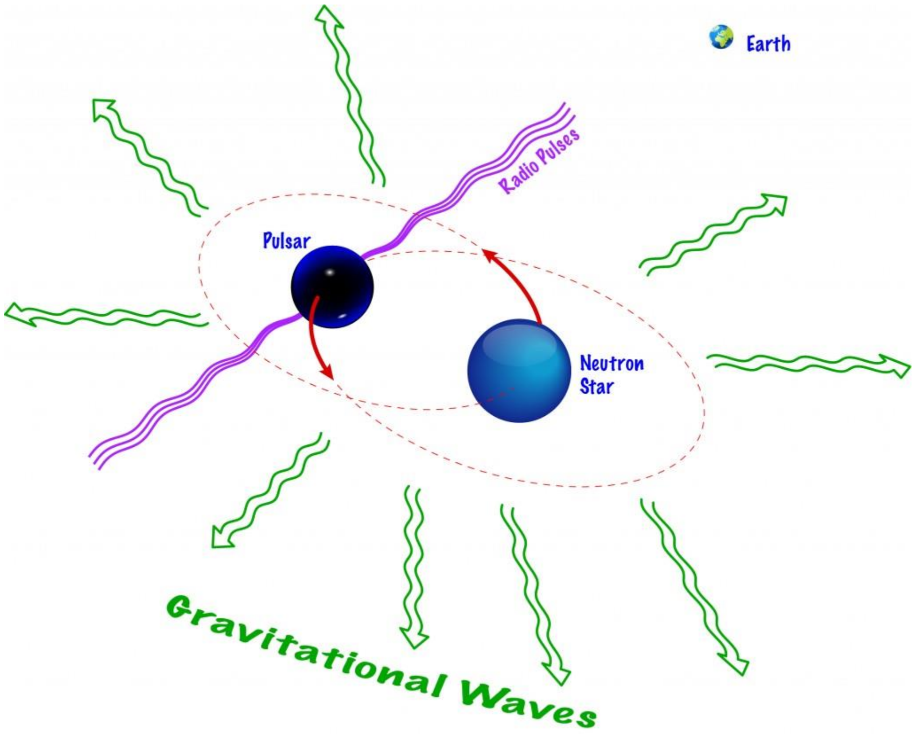
External field (BH/NS)

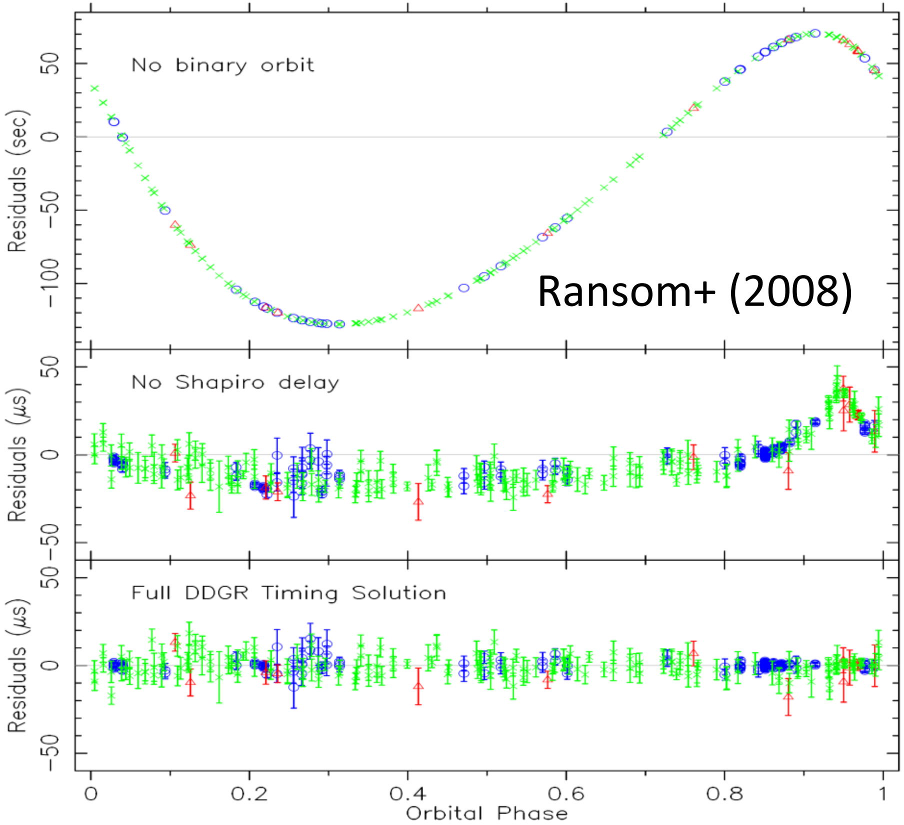
$$\mathcal{Q}_{ij} \equiv \int \rho\left(x_i x_j - \frac{1}{3}x^2\delta_{ij}\right)d^3x$$

$$\mathcal{E}_{ij} \equiv \frac{\partial^2\Phi_{\text{ext}}}{\partial x^i \partial x^j}$$

Binary as a two-body problem

Both gravitational-wave and radio observations basically analyze gravitational two-body problems

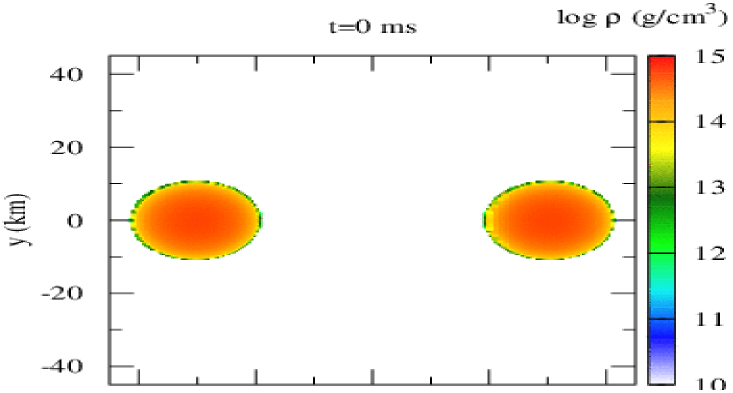




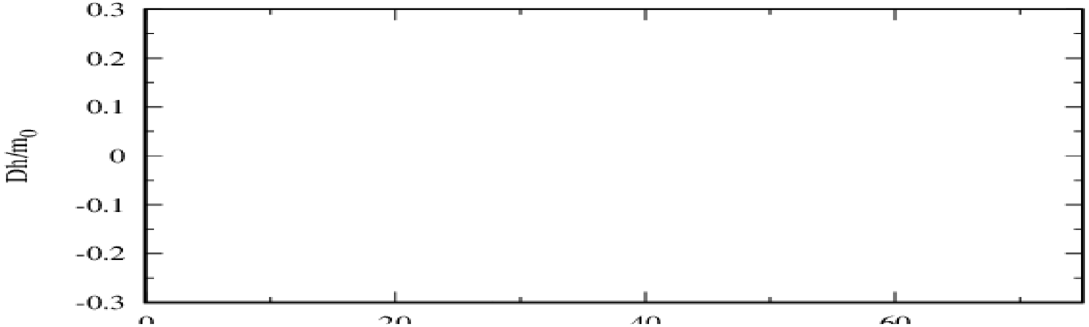
Ransom+ (2008)

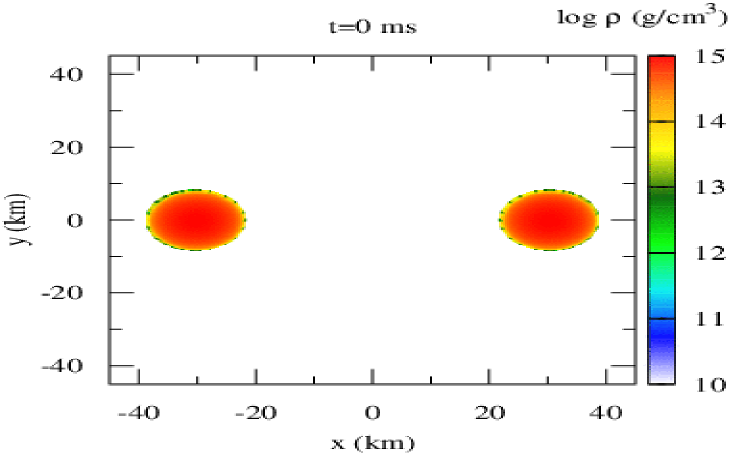
http://asd.gsfc.nasa.gov/blueshift/wp-content/uploads/2016/02/htbinarypulsar-1024x835.jpg

Different orbital evolution

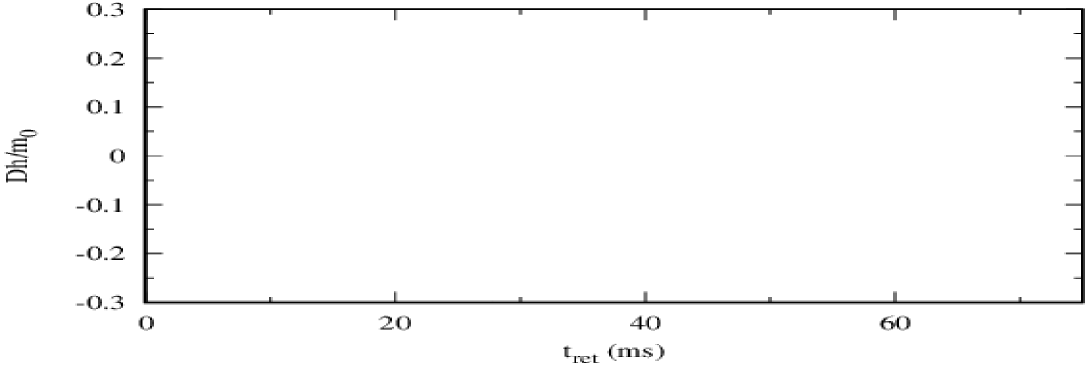


$R = 13.7\ \mathrm{km}, \Lambda = 1211$





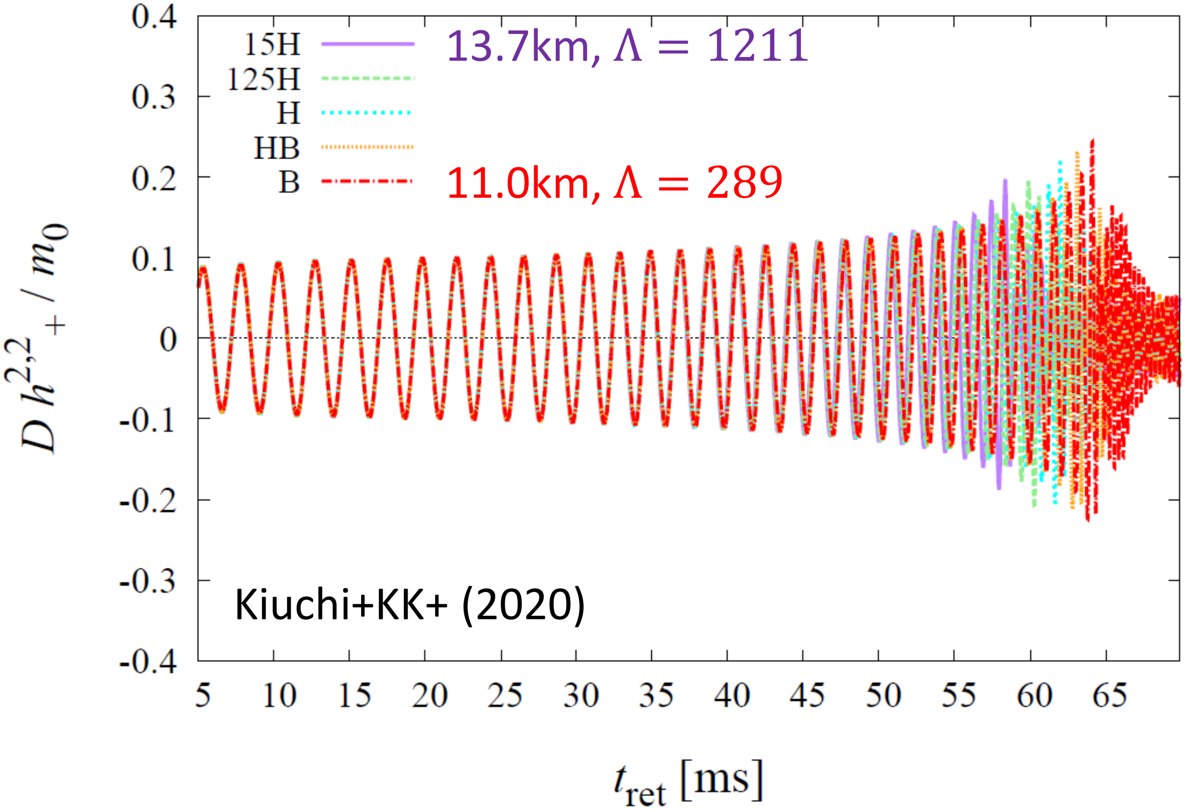
$R = 11.0\ \mathrm{km}, \Lambda = 289$



Numerical waveform

Binaries merge earlier for stiffer equations of state

This allows us to measure the tidal deformablity

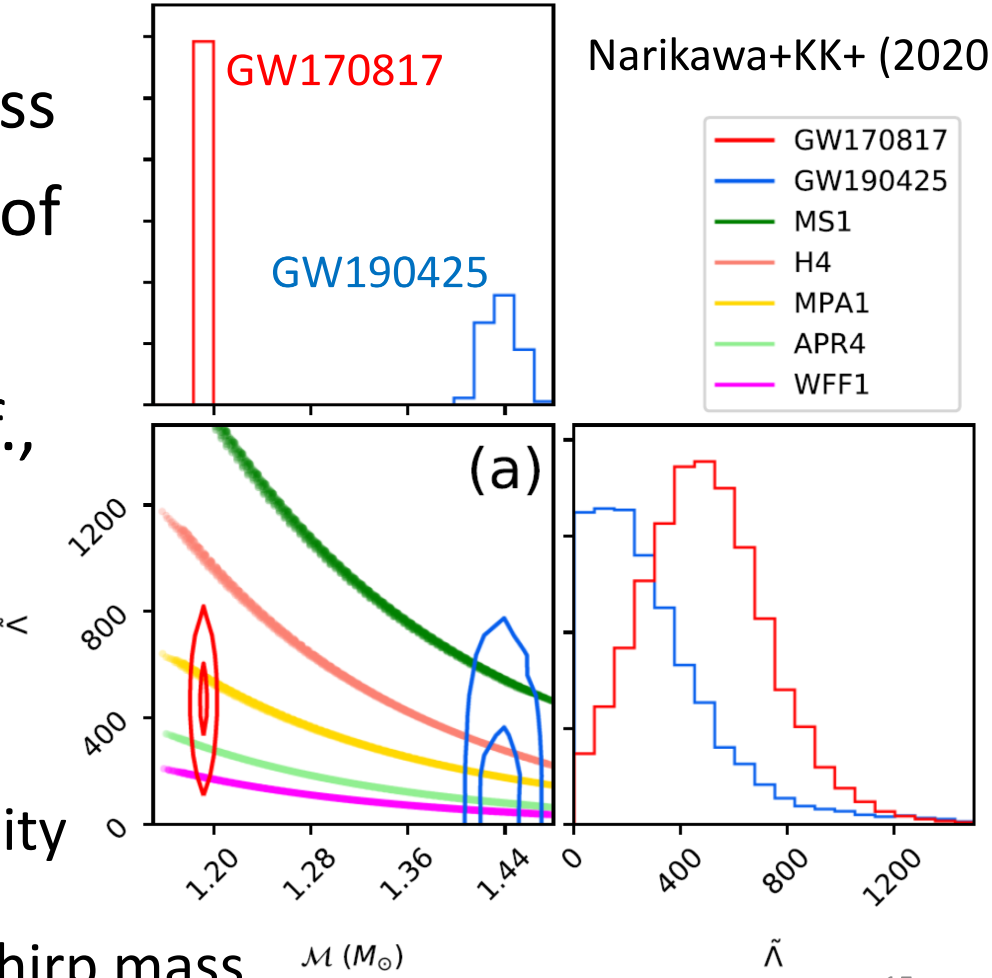


Parameter estimation

Essentially only the tidal deformability is measured now

The key behind this success may be the identification of this important quantity out of the functional d.o.f., i.e., the equation of state

[Flanagan-Hinderer 2008]



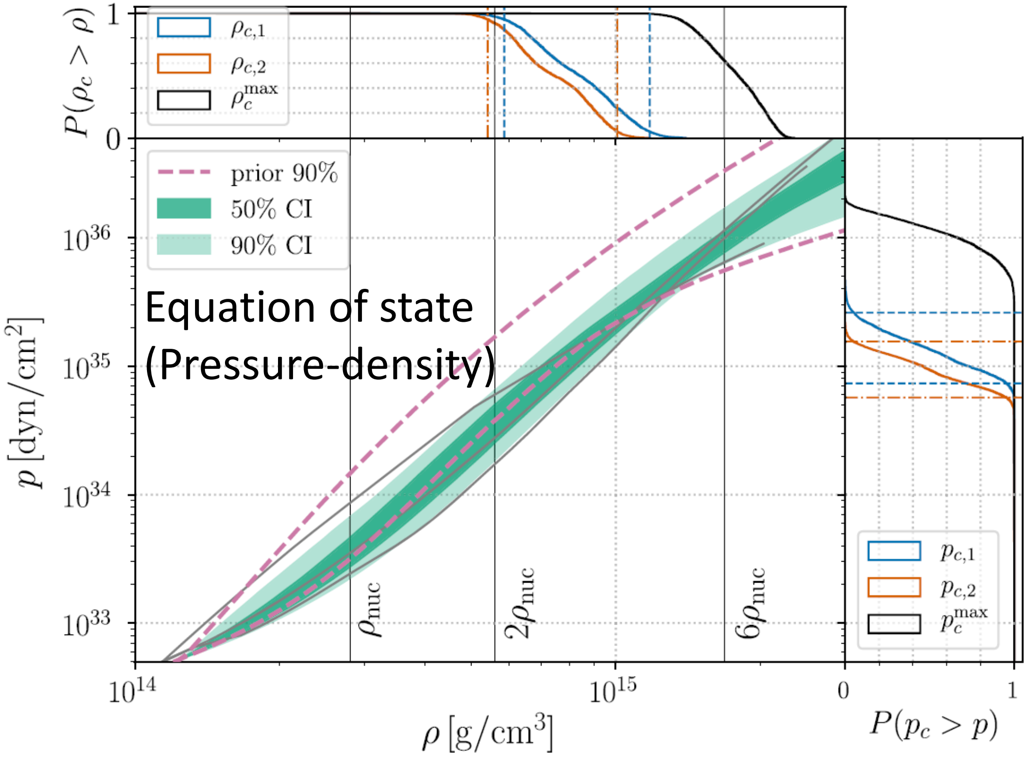
Narikawa+KK+ (2020)

Binary tidal deformability

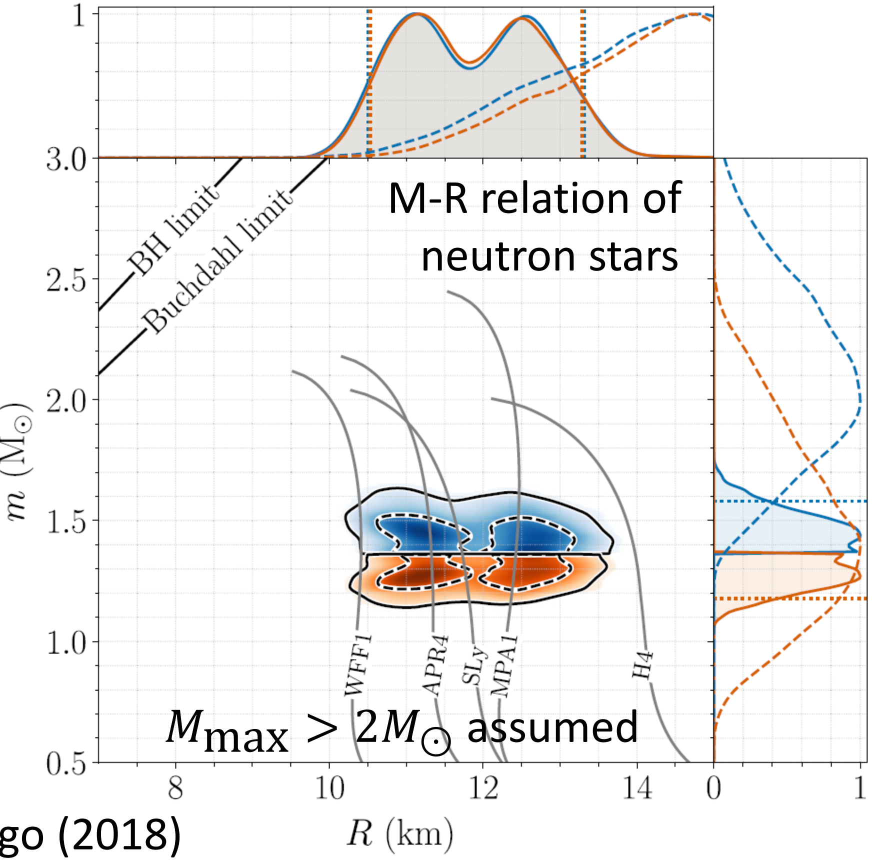
Chirp mass

Neutron-star equation of state

The equation of state has already been constrained and will be constrained more severely in the near future



Equation of state (Pressure-density)



M-R relation of neutron stars

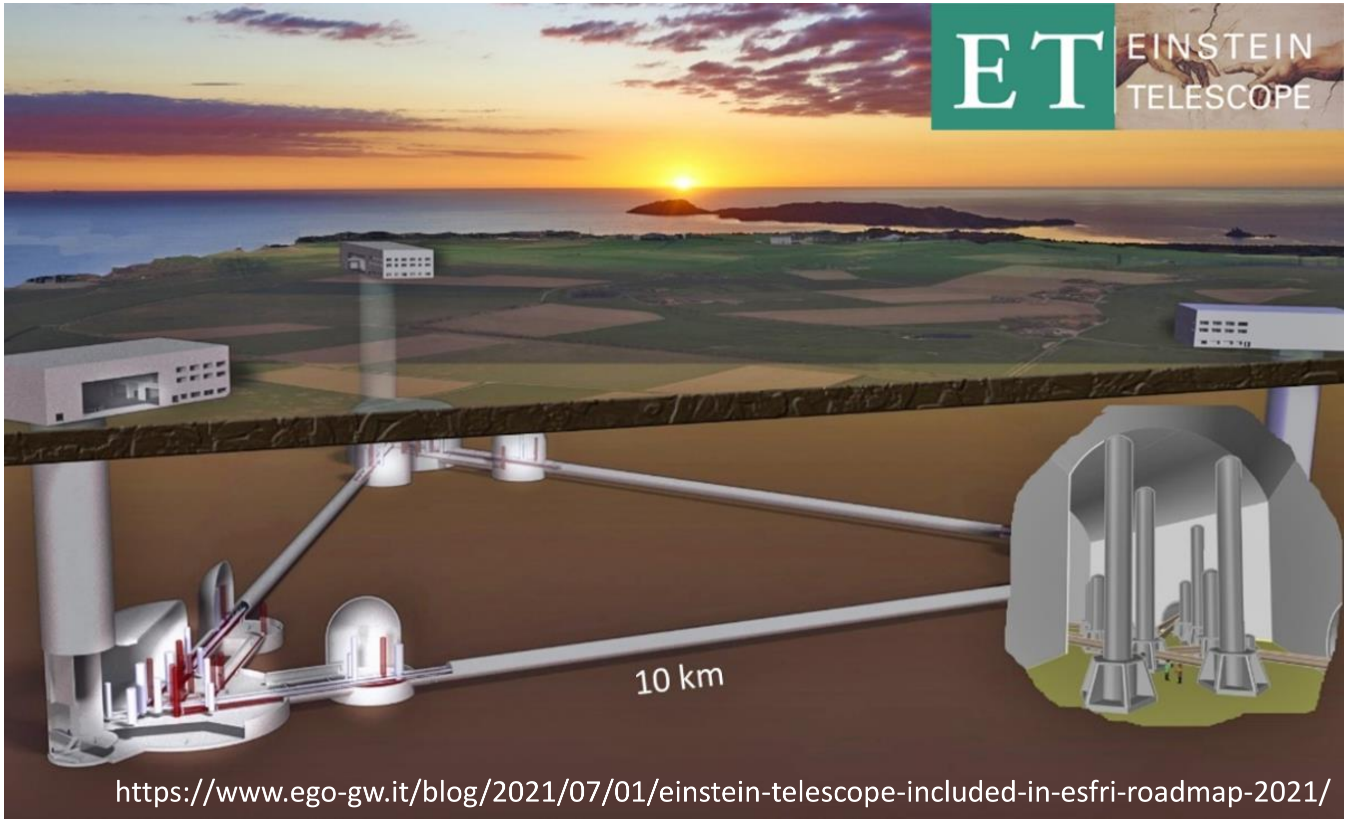
$M_{\max} > 2M_\odot$ assumed

LIGO&Virgo (2018)

3. Postmerger: crossover vs. 1st-order phase transition

Third-generation detector

Einstein Telescope, Cosmic Explorer … aiming at more precise understanding of already-detected binaries



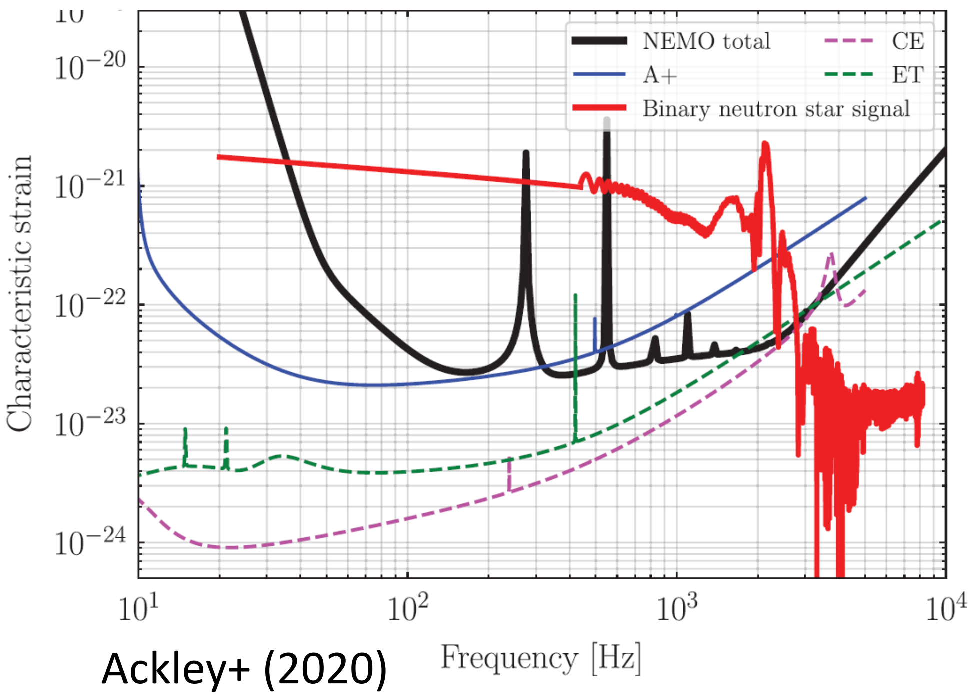
https://www.ego-gw.it/blog/2021/07/01/einstein-telescope-included-in-esfri-roadmap-2021/

Future high-frequency observation

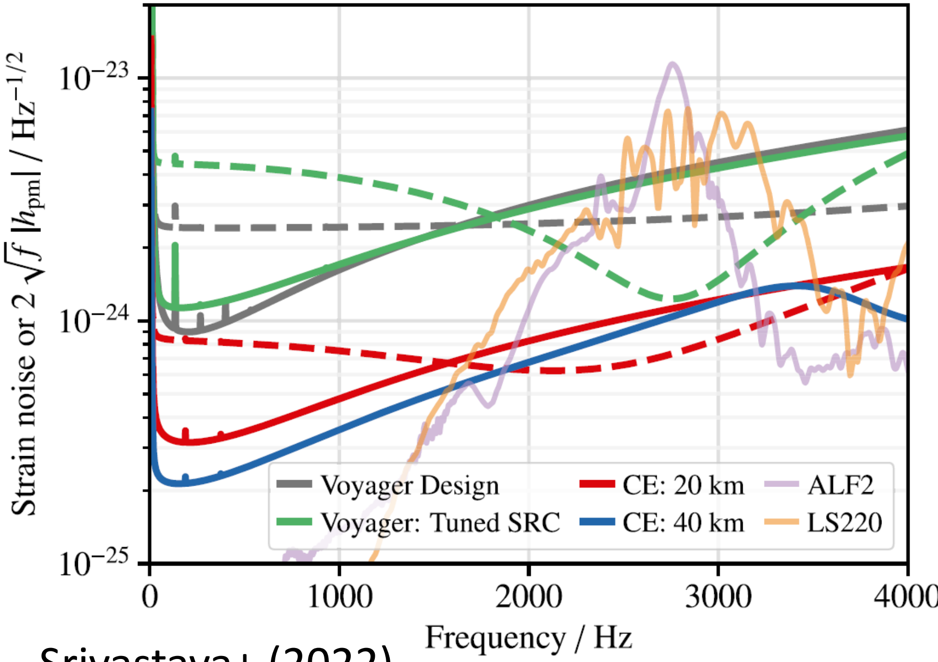
The high density requires high-frequency observations

$$f \sim \sqrt{G\rho}$$

Some proposals are made for postmerger signals



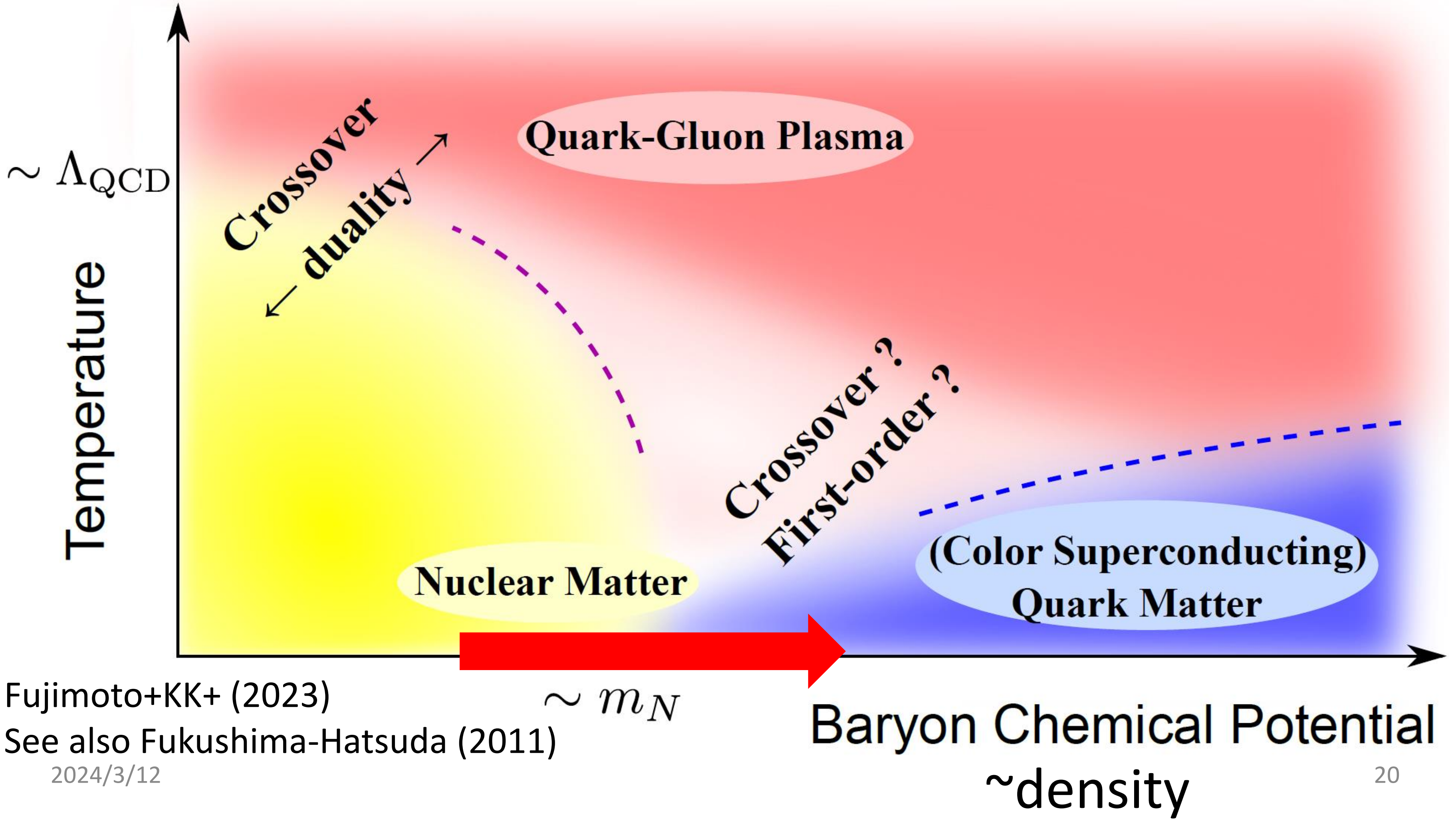
Ackley+ (2020)



Srivastava+ (2022)

QCD phase diagram

What kind of transition occurs from hadrons to quarks?

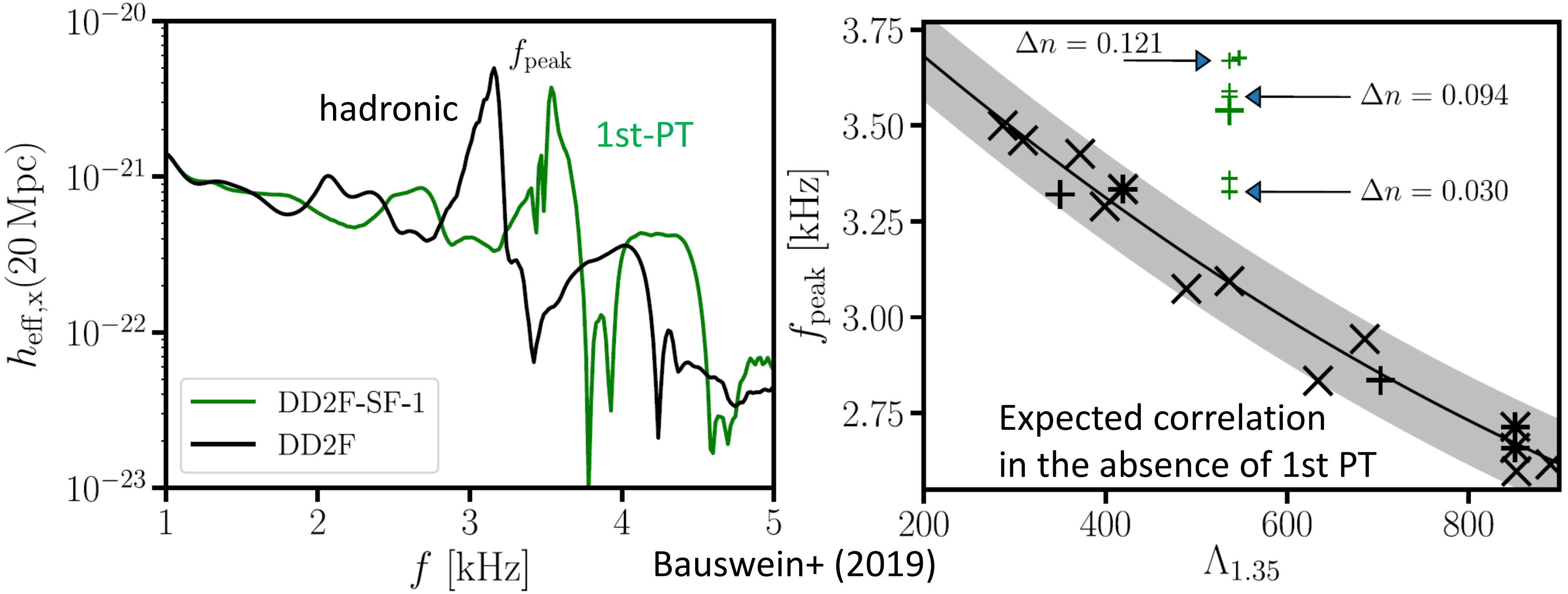


Fujimoto+KK+ (2023)
See also Fukushima-Hatsuda (2011)

1st-order phase transition

Postmerger neutron stars emit quasiperiodic signals

The shift in the peak frequency may reveal strong 1st-order phase transition at moderately high density

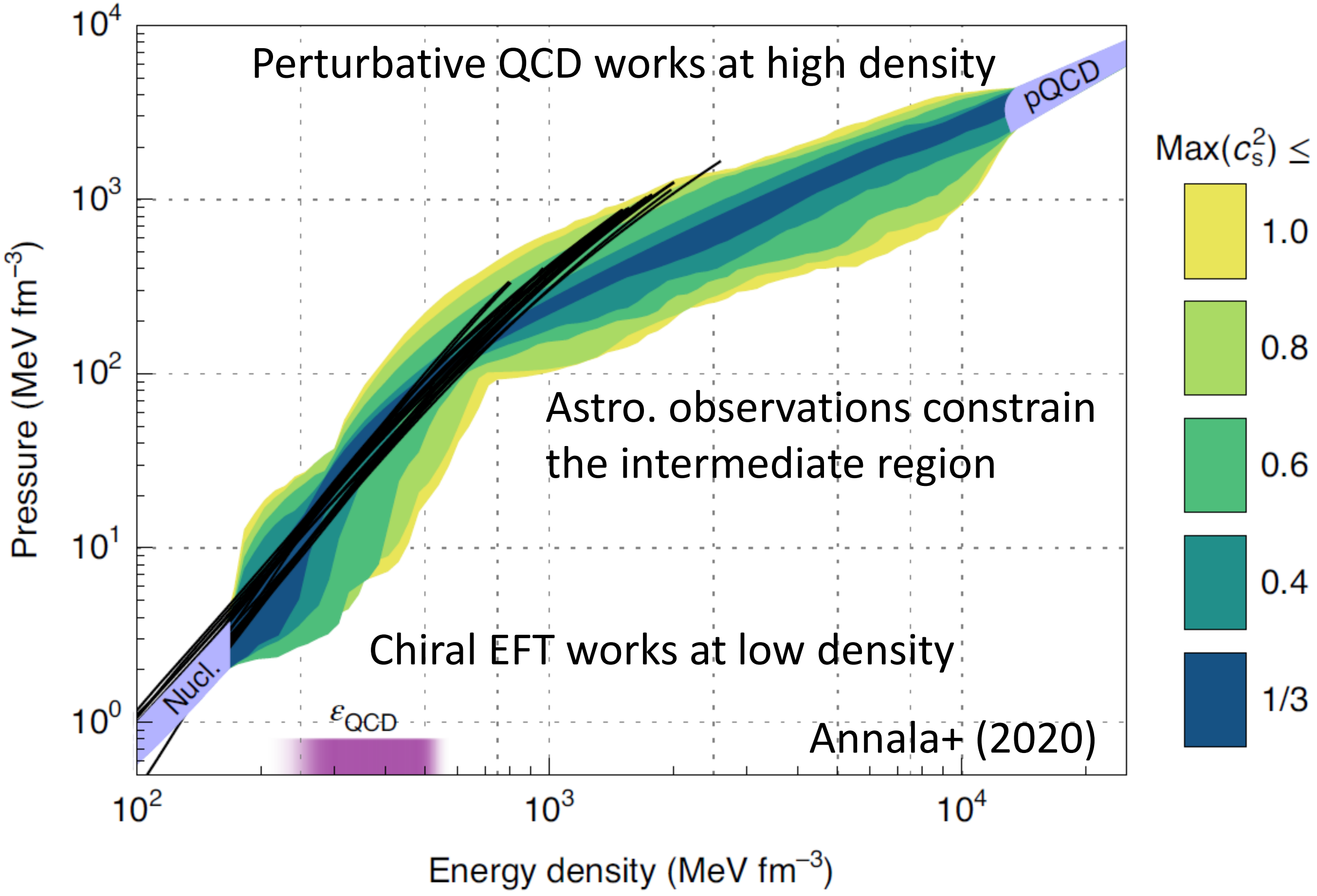


Expected correlation in the absence of 1st PT

Bauswein+ (2019)

Current view of the transition

Smooth crossover transition might be realistic



Perturbative QCD works at high density

Astro. observations constrain the intermediate region

Chiral EFT works at low density

Annala+ (2020)

Crossover vs. 1st-order PT

Crossover

Smoothly connects two limits

Note: we need to explain

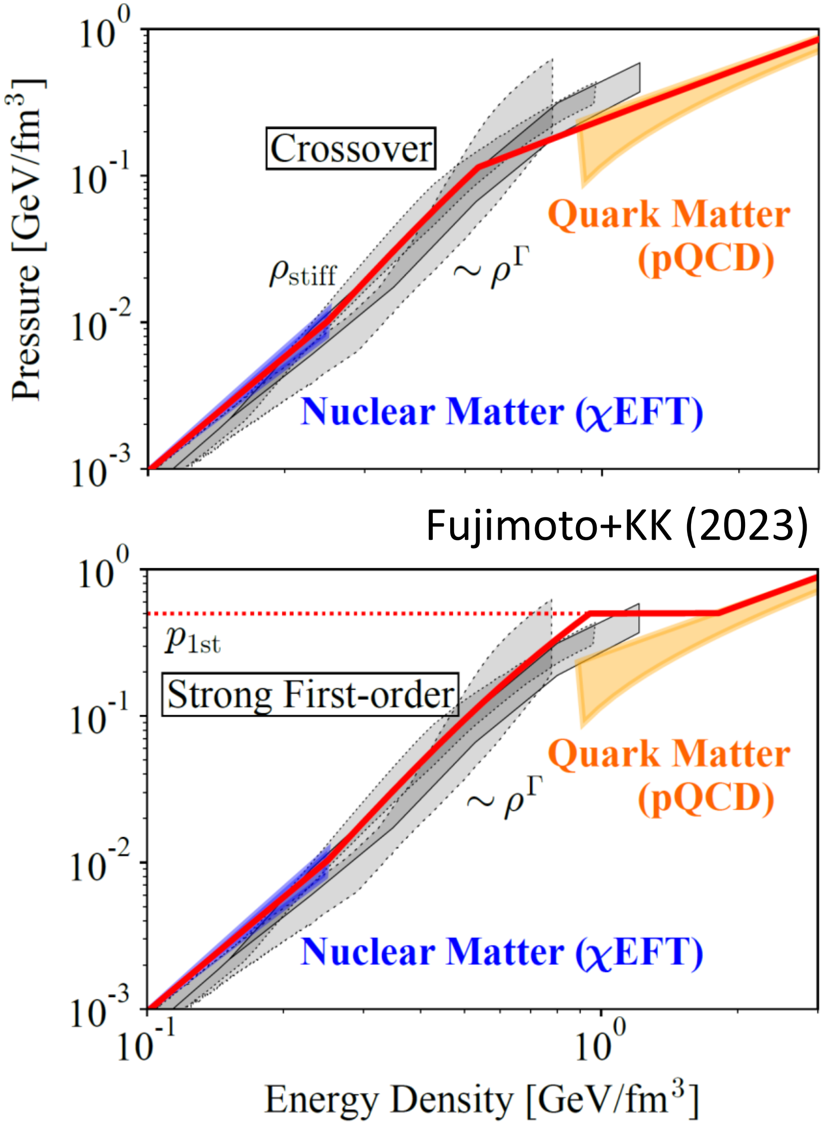
2 solar mass neutron stars

1st-order phase transition

Only very high density likely

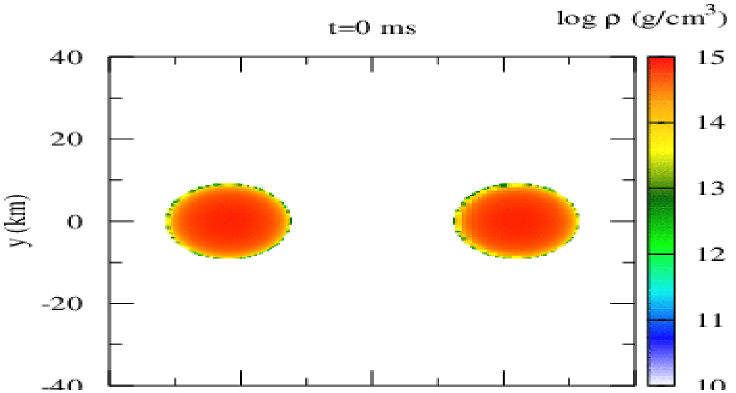
allows strong density jumps…

Invisible in astrophysics?

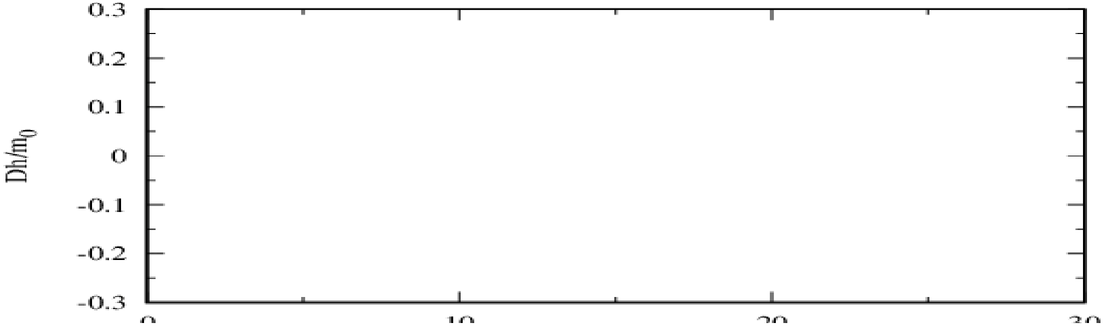


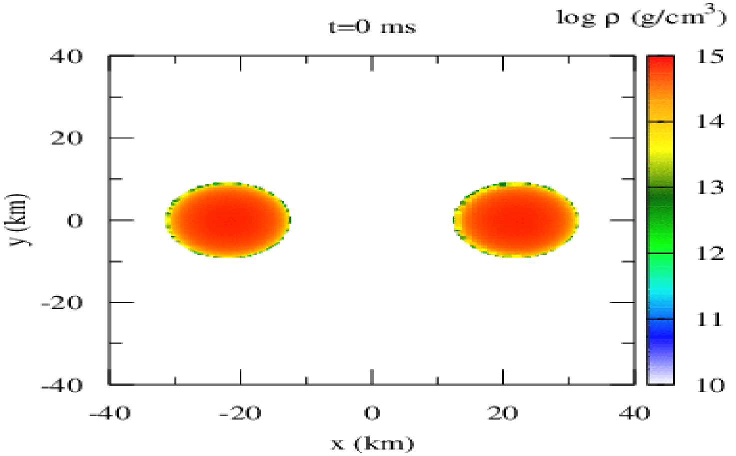
Fujimoto+KK (2023)

Different postmerger evolution

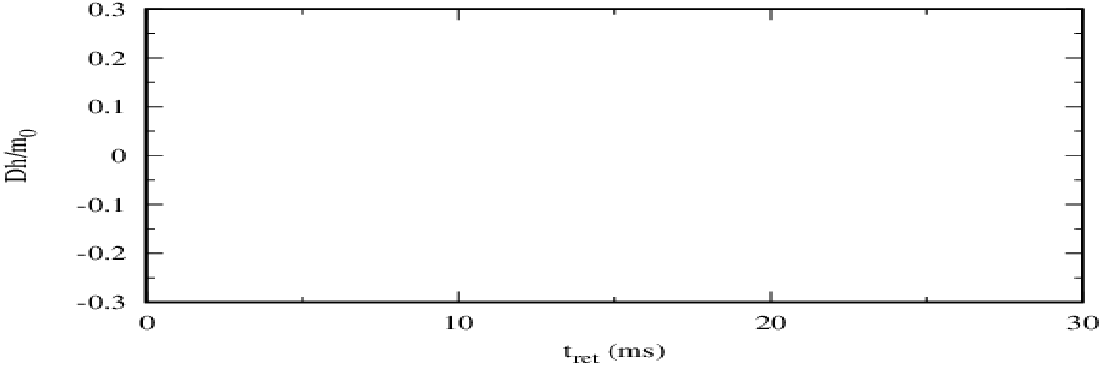


Crossover



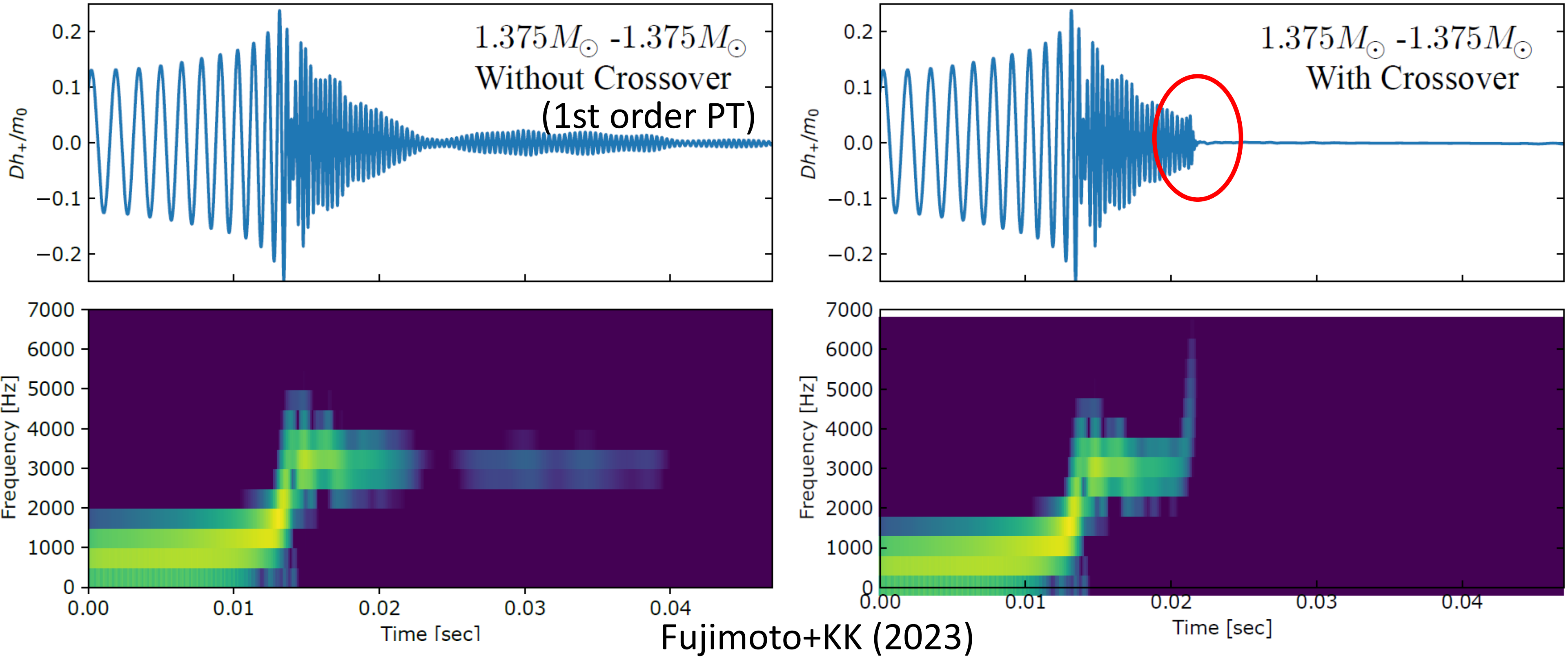


Strong first-order PT



Black-hole formation as a key

Gravitational emission suddenly ends for crossover because of the gravitational collapse of the remnant



Fujimoto+KK (2023)

Gravitational-wave spectrum

The postmerger peaks do not differ appreciably

The quasinormal-mode cutoff could be distinguishing

preliminary

Lifetime of the merger remnant

Determined primarily by the total mass of the binary

preliminary

Weak dependence on mass ratio

May be good news, as the mass ratio is hard to infer

preliminary

Possible source of uncertainties

Finite-temperature effect? (modeled by "Γ_{th}")

We vary systematically the strength of thermal pressure

Neutrino effect? (neglected)

Its time scale is ~1s, much longer than our target

Magnetic-field effect? (neglected)

Its time scale is ~0.1s, again longer than our target

Grid resolution? (finite, of course)

Checked that dependence is weak, but not clean

Did GW170817 form a black hole?

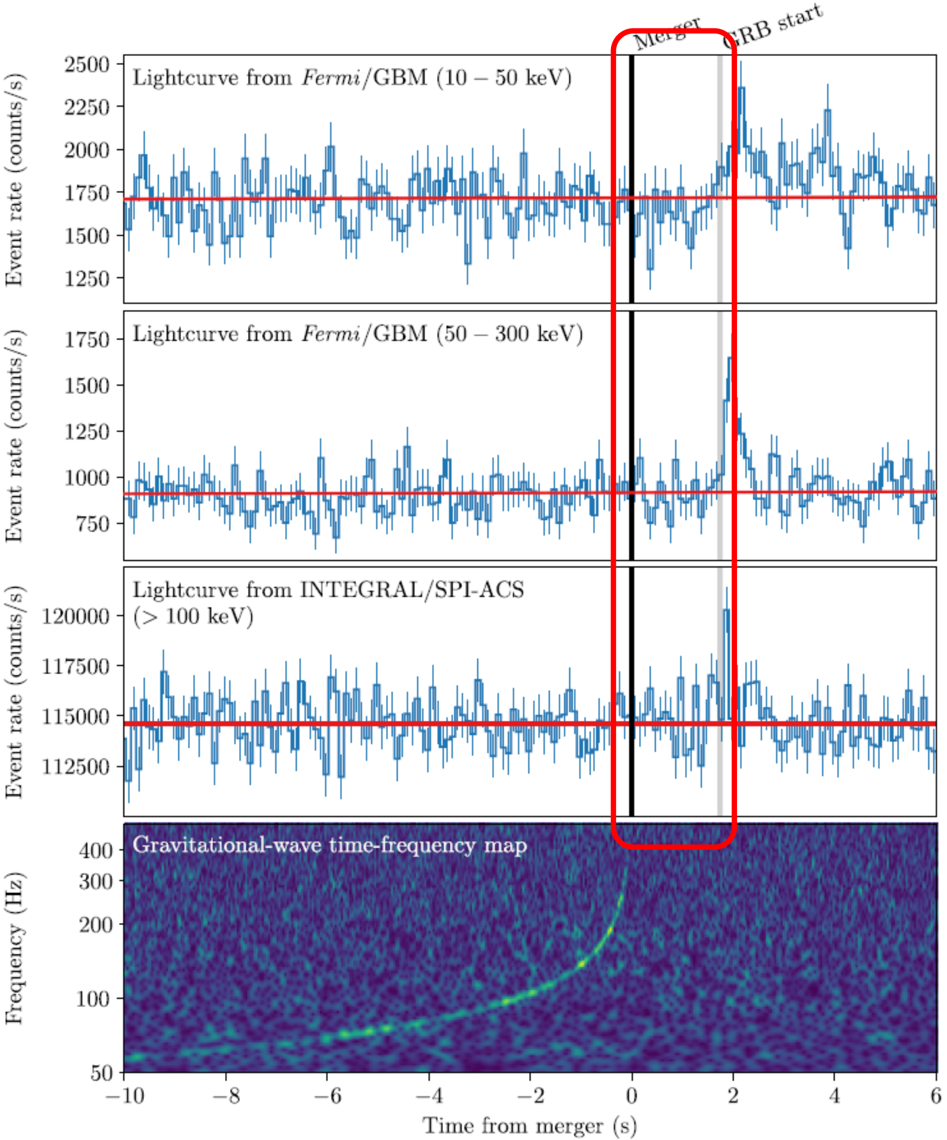
Nobody knows the answer

Important for

- QCD phase structure
- gamma-ray burst
- r-process and kilonova

Gravitational waves are emitted for 10-100ms at ~kHz and will be the key

[neutrinos? Kyutoku-Kashiyama 2018]

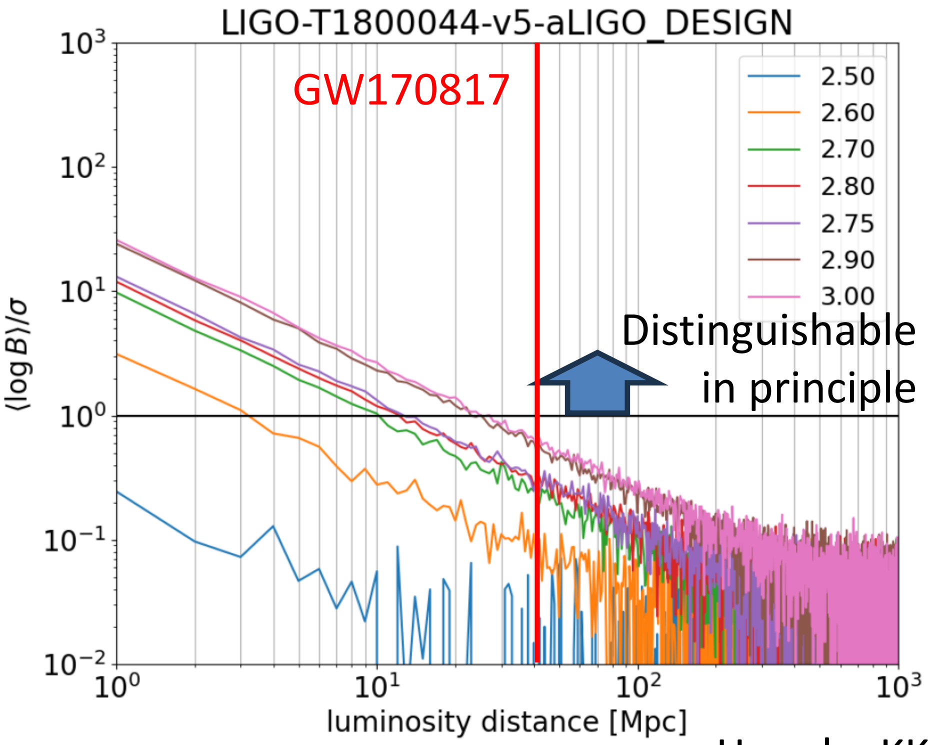


LIGO&Virgo&Fermi&INTEGRAL (2017)

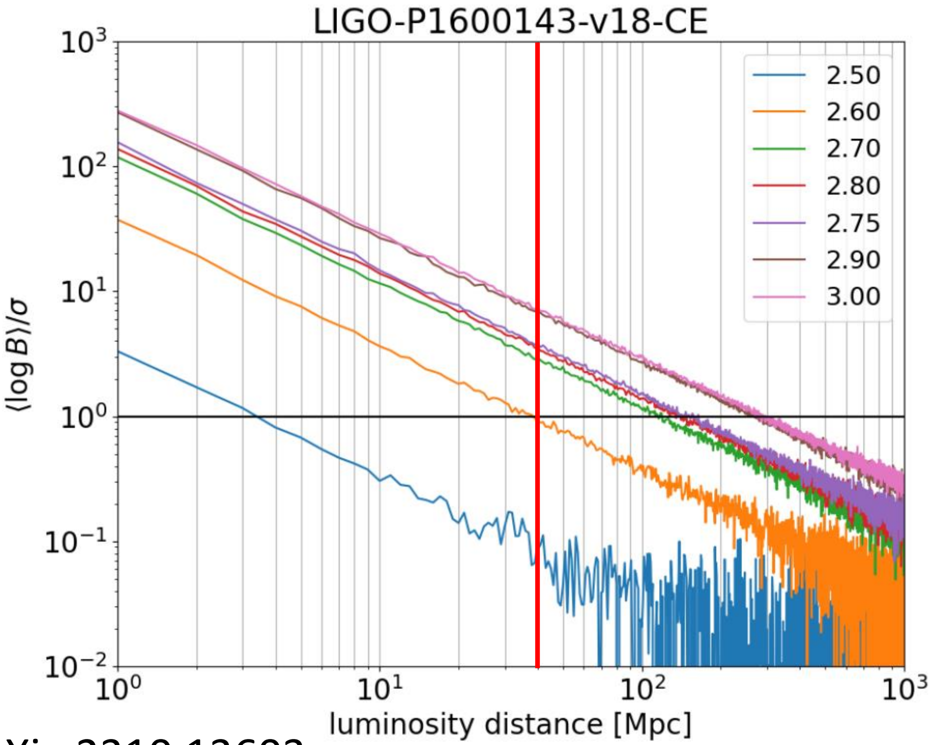
Distinguishability in data analysis

AdLIGO is insufficient even at design sensitivity (left)

Third-generation detectors may do at >100Mpc (right)



Distinguishable in principle



Harada+KK arXiv:2310.13603

Which density range we can see?

The collapse is likely to set in when the central density reaches the maximum density of spherical stars

Not likely to dig into the unstable branch [cf. Ujevic+ 2024]

Various total masses

Various mass ratios

preliminary

preliminary

4. Discussion and summary

Future direction and discussion

We have considered only two representative scenarios
need systematic surveys or physics considerations

How tiny 1st-order phase transition should be find?
- theoretically motivated strength of the transition?
- simply “as tiny as astro. observations can do?”

Can we identify representative quantity (in general)?
- hard to infer $P(n, T, Y_e), \mu(n, T, Y_e), \zeta(n, T, Y_e)$ …
- $f_{\mathrm{peak}}(m_1, m_2)$ is not very independent from $\Lambda(m)$

Summary

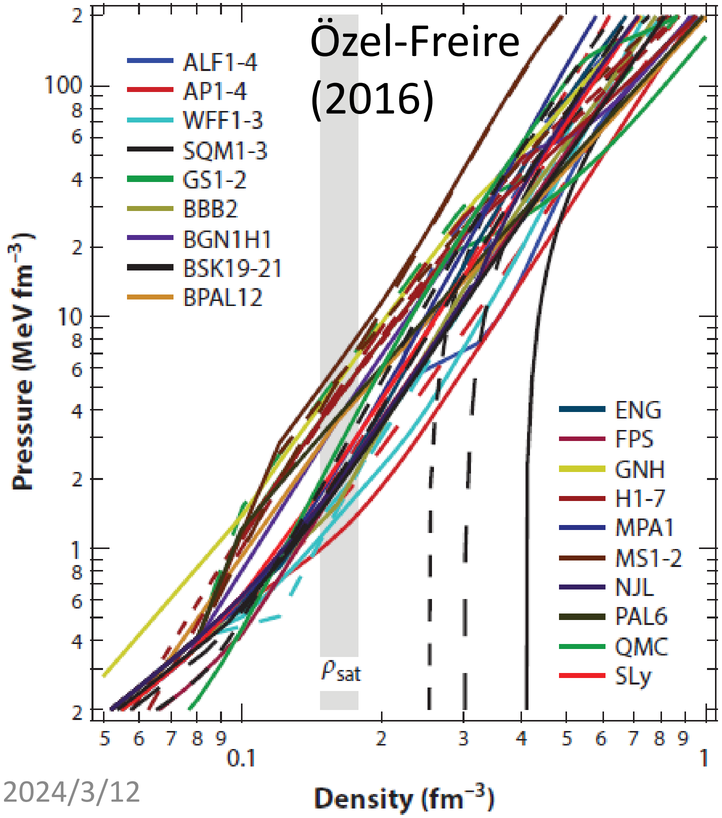
- The neutron-star equation of state is constrained by measuring tidal deformability from inspiral gravitational waveforms, particularly GW170817.
- In the future, postmerger gravitational waveforms may enable us to study the QCD phase structure via the gravitational collapse of merger remnants.
- The key toward these goals is the sensitivity at high frequency, specifically (1) ~3kHz for postmerger peaks, and (2) ~7kHz for quasinormal modes excited at the black-hole formation.

Neutron star equation of state

Note: not need to observe the radius, and other quantities may be fine

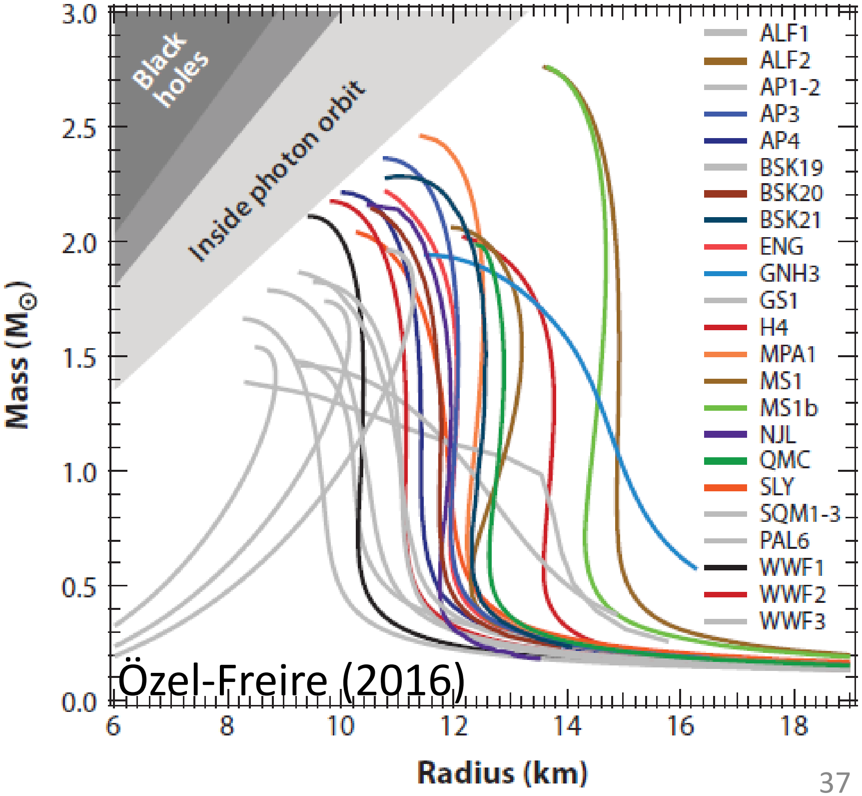
We want to know the realistic equation of state, that uniquely determines the mass-radius relation

Equation of state: Nuclear physics



Özel-Freire (2016)

Mass-Radius relation: Astrophysics



Özel-Freire (2016)

Astronomical observation

Maximum mass from radio pulsars

J1614-2230, J3048+0432, J0740+6620

Tidal deformability from gravitational waves

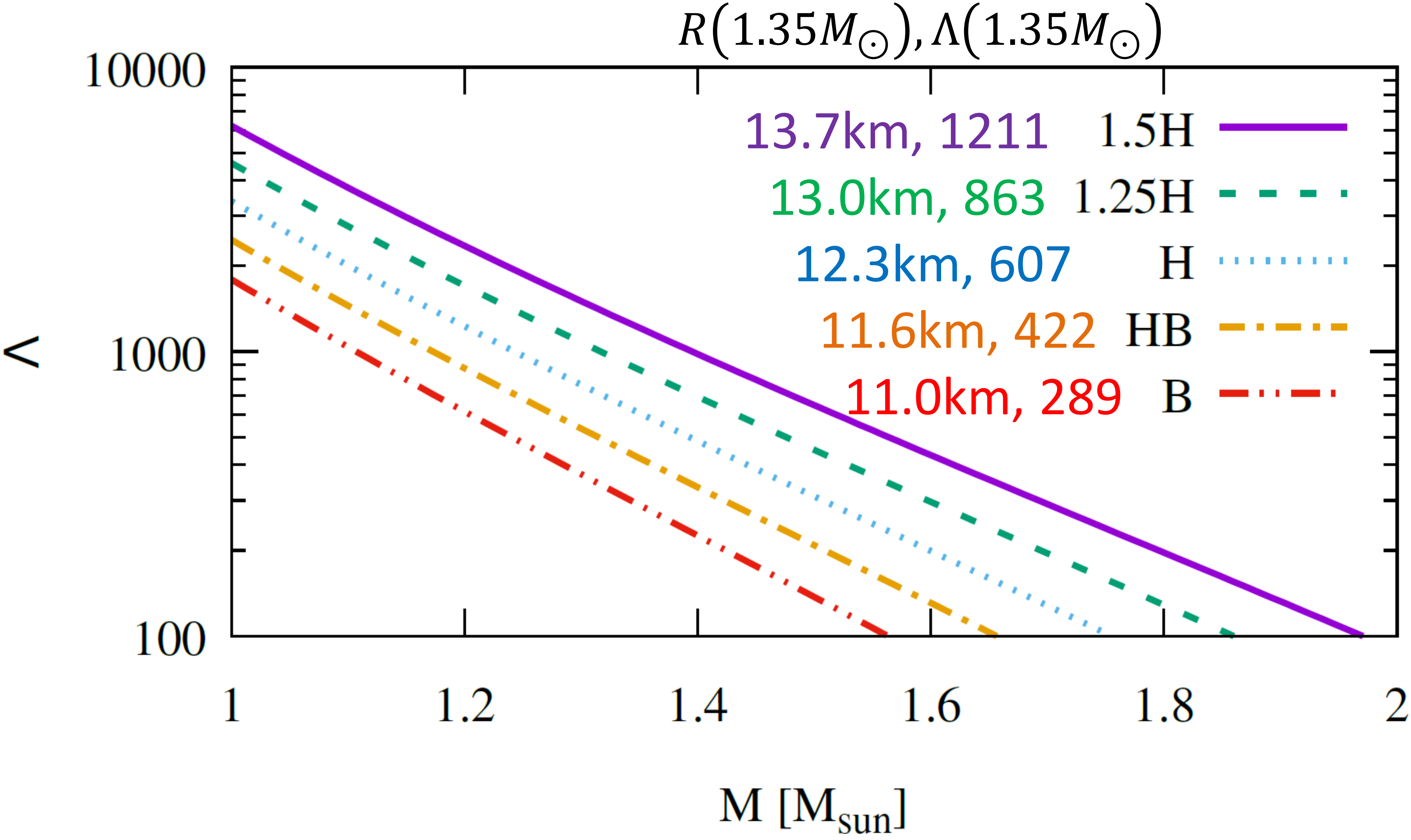
GW170817(, GW190425: not so informative)

Compactness=mass/radius from X-ray pulsations

J0030+0451, J0740+6620

+ moment of inertia from radio pulsars in the future?

$M - \Lambda$ relation and equations of state

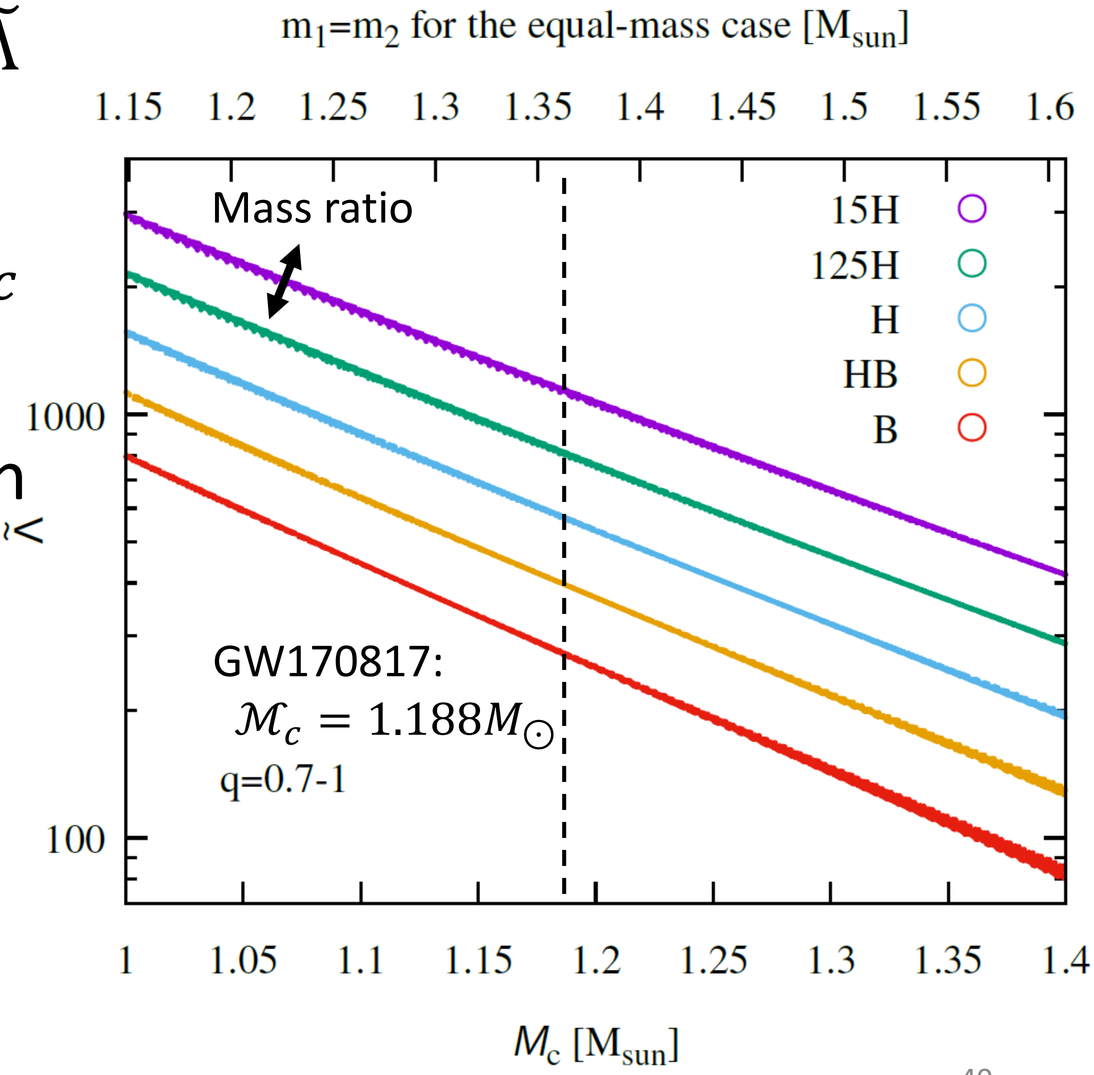


Strong correlation of $\tilde{\Lambda} - \mathcal{M}_c$

The most measurable $\tilde{\Lambda}$
Is correlated strongly
with the chirp mass $\mathcal{M}_c$

We effectively constrain
$\Lambda\left(M = 2^{1/5}\mathcal{M}_c\right)$

>13-14km is disfavored

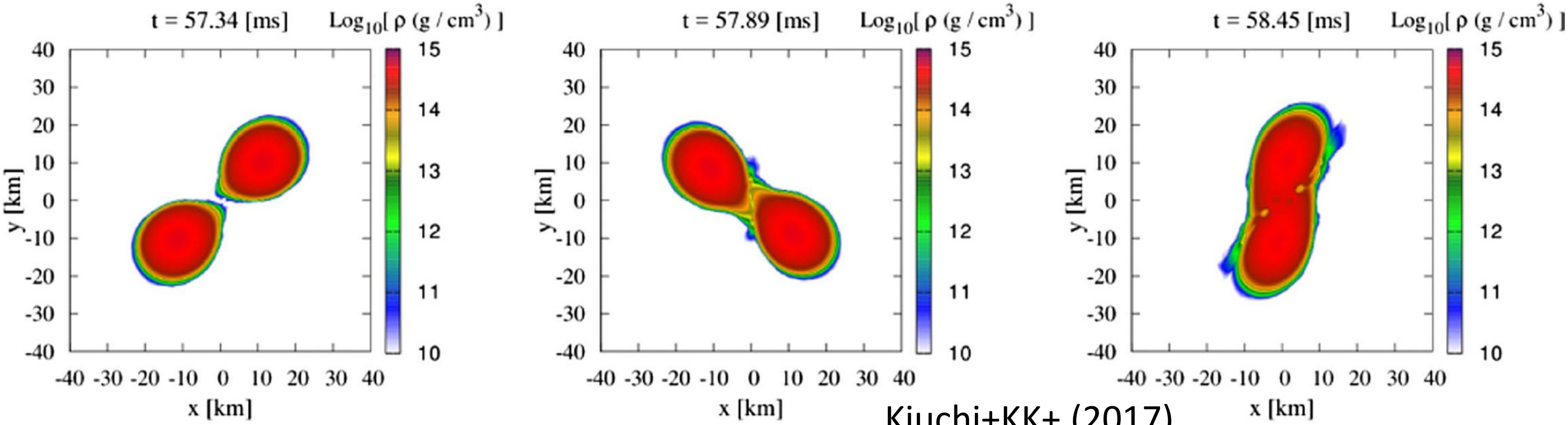


Necessity of numerical simulations

The amplitude maximum comes after the contact

- Gravity (post-Newtonian correction) is nonlinear
- Hydrodynamics (tidal effect) is also nonlinear

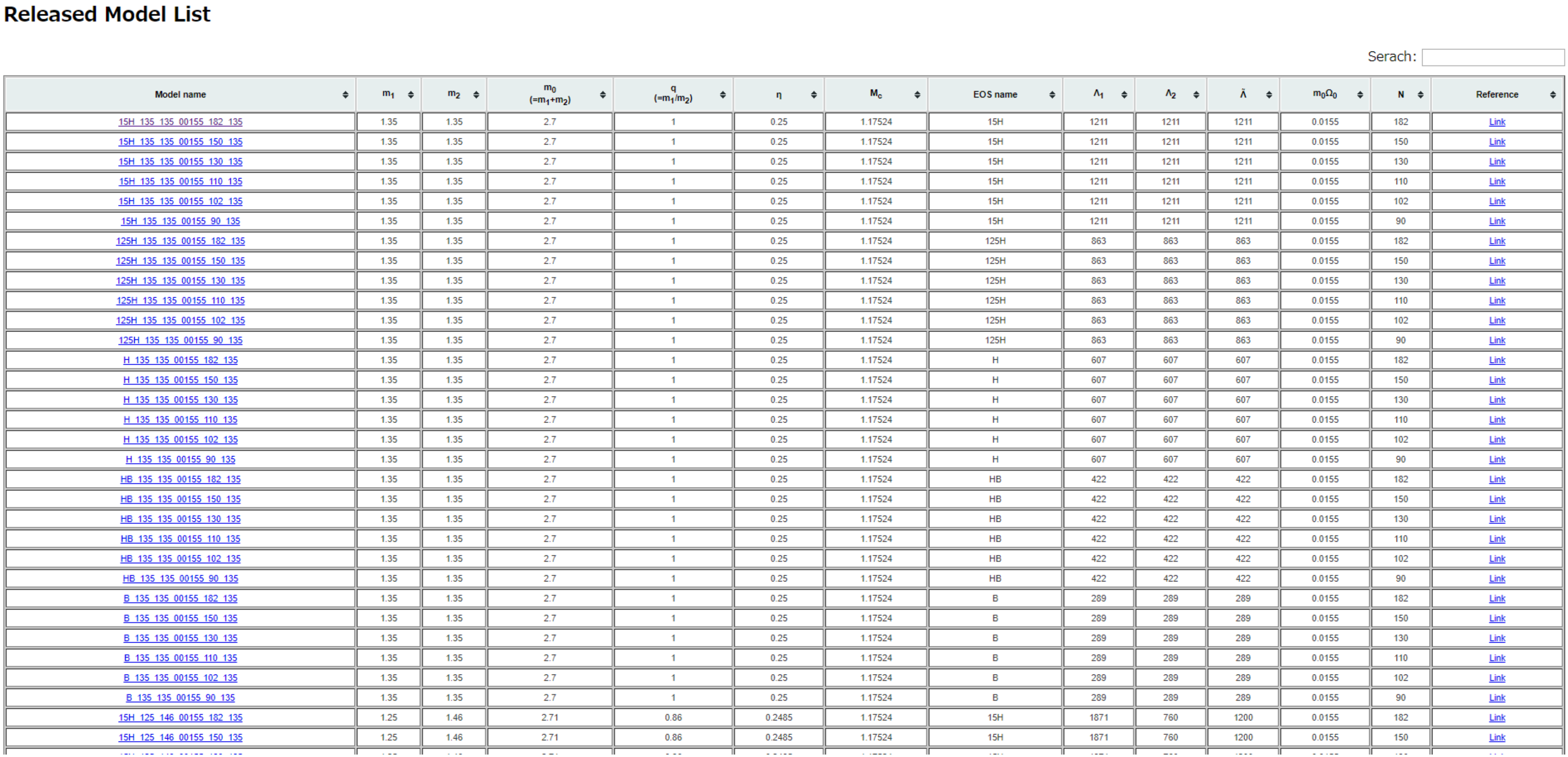
Analytic computations cannot be fully accurate



Kiuchi+KK+ (2017)

Waveform library

https://www2.yukawa.kyoto-u.ac.jp/~nr_kyoto/SACRA_PUB/catalog.html



Released Model List

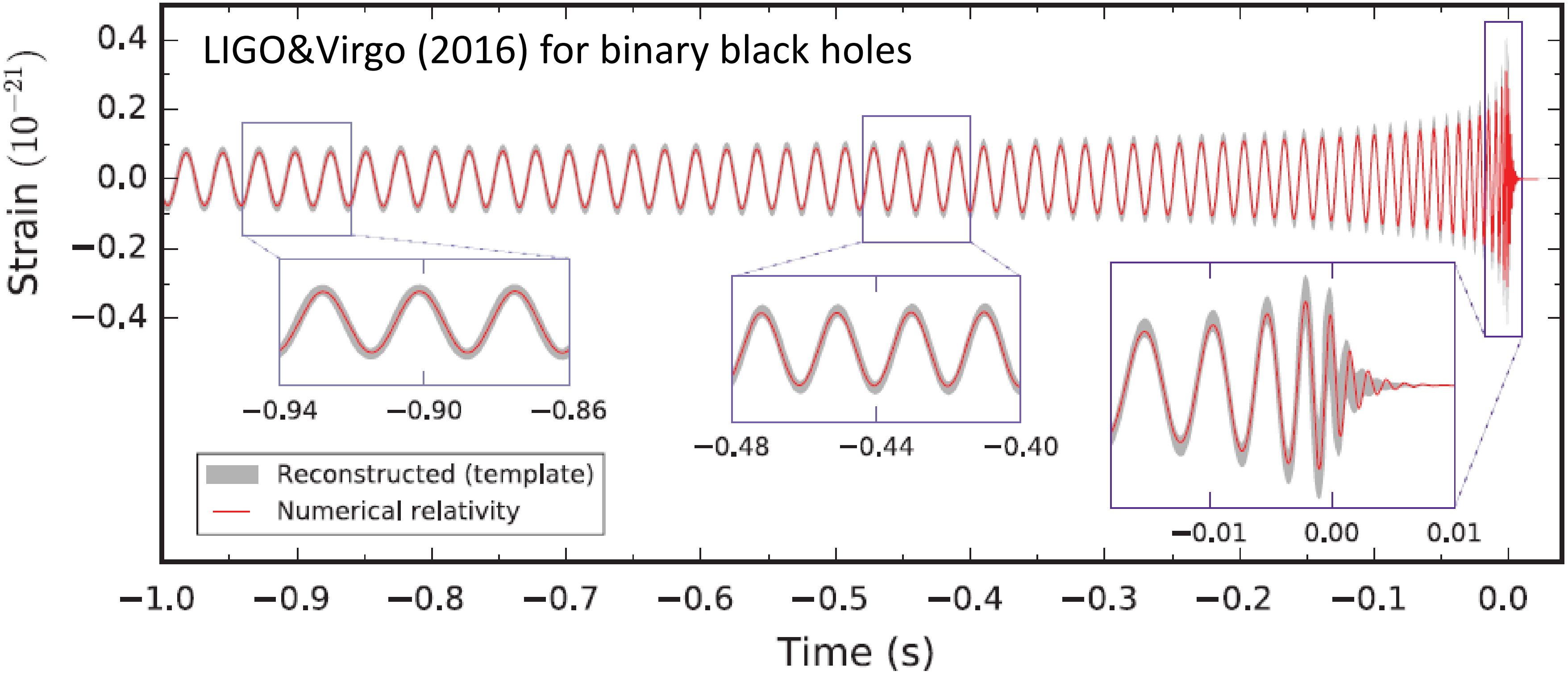
Serach:

Model name	m_1	m_2	m_0 (=m_1+m_2)	q (=m_1/m_2)	η	M_c	EOS name	Λ_1	Λ_2	$\tilde{\Lambda}$	$m_0\Omega_0$	N	Reference
15H_135_135_00155_182_135	1.35	1.35	2.7	1	0.25	1.17524	15H	1211	1211	1211	0.0155	182	Link
15H_135_135_00155_150_135	1.35	1.35	2.7	1	0.25	1.17524	15H	1211	1211	1211	0.0155	150	Link
15H_135_135_00155_130_135	1.35	1.35	2.7	1	0.25	1.17524	15H	1211	1211	1211	0.0155	130	Link
15H_135_135_00155_110_135	1.35	1.35	2.7	1	0.25	1.17524	15H	1211	1211	1211	0.0155	110	Link
15H_135_135_00155_102_135	1.35	1.35	2.7	1	0.25	1.17524	15H	1211	1211	1211	0.0155	102	Link
15H_135_135_00155_90_135	1.35	1.35	2.7	1	0.25	1.17524	15H	1211	1211	1211	0.0155	90	Link
125H_135_135_00155_182_135	1.35	1.35	2.7	1	0.25	1.17524	125H	863	863	863	0.0155	182	Link
125H_135_135_00155_150_135	1.35	1.35	2.7	1	0.25	1.17524	125H	863	863	863	0.0155	150	Link
125H_135_135_00155_130_135	1.35	1.35	2.7	1	0.25	1.17524	125H	863	863	863	0.0155	130	Link
125H_135_135_00155_110_135	1.35	1.35	2.7	1	0.25	1.17524	125H	863	863	863	0.0155	110	Link
125H_135_135_00155_102_135	1.35	1.35	2.7	1	0.25	1.17524	125H	863	863	863	0.0155	102	Link
125H_135_135_00155_90_135	1.35	1.35	2.7	1	0.25	1.17524	125H	863	863	863	0.0155	90	Link
H_135_135_00155_182_135	1.35	1.35	2.7	1	0.25	1.17524	H	607	607	607	0.0155	182	Link
H_135_135_00155_150_135	1.35	1.35	2.7	1	0.25	1.17524	H	607	607	607	0.0155	150	Link
H_135_135_00155_130_135	1.35	1.35	2.7	1	0.25	1.17524	H	607	607	607	0.0155	130	Link
H_135_135_00155_110_135	1.35	1.35	2.7	1	0.25	1.17524	H	607	607	607	0.0155	110	Link
H_135_135_00155_102_135	1.35	1.35	2.7	1	0.25	1.17524	H	607	607	607	0.0155	102	Link
H_135_135_00155_90_135	1.35	1.35	2.7	1	0.25	1.17524	H	607	607	607	0.0155	90	Link
HB_135_135_00155_182_135	1.35	1.35	2.7	1	0.25	1.17524	HB	422	422	422	0.0155	182	Link
HB_135_135_00155_150_135	1.35	1.35	2.7	1	0.25	1.17524	HB	422	422	422	0.0155	150	Link
HB_135_135_00155_130_135	1.35	1.35	2.7	1	0.25	1.17524	HB	422	422	422	0.0155	130	Link
HB_135_135_00155_110_135	1.35	1.35	2.7	1	0.25	1.17524	HB	422	422	422	0.0155	110	Link
HB_135_135_00155_102_135	1.35	1.35	2.7	1	0.25	1.17524	HB	422	422	422	0.0155	102	Link
HB_135_135_00155_90_135	1.35	1.35	2.7	1	0.25	1.17524	HB	422	422	422	0.0155	90	Link
B_135_135_00155_182_135	1.35	1.35	2.7	1	0.25	1.17524	B	289	289	289	0.0155	182	Link
B_135_135_00155_150_135	1.35	1.35	2.7	1	0.25	1.17524	B	289	289	289	0.0155	150	Link
B_135_135_00155_130_135	1.35	1.35	2.7	1	0.25	1.17524	B	289	289	289	0.0155	130	Link
B_135_135_00155_110_135	1.35	1.35	2.7	1	0.25	1.17524	B	289	289	289	0.0155	110	Link
B_135_135_00155_102_135	1.35	1.35	2.7	1	0.25	1.17524	B	289	289	289	0.0155	102	Link
B_135_135_00155_90_135	1.35	1.35	2.7	1	0.25	1.17524	B	289	289	289	0.0155	90	Link
15H_125_146_00155_182_135	1.25	1.46	2.71	0.86	0.2485	1.17524	15H	1871	760	1200	0.0155	182	Link
15H_125_146_00155_150_135	1.25	1.46	2.71	0.86	0.2485	1.17524	15H	1871	760	1200	0.0155	150	Link

Role of theoretical templates

Parameters of binaries are estimated by measuring the match between data and theoretical waveforms

Accurate theoretical models are indispensable

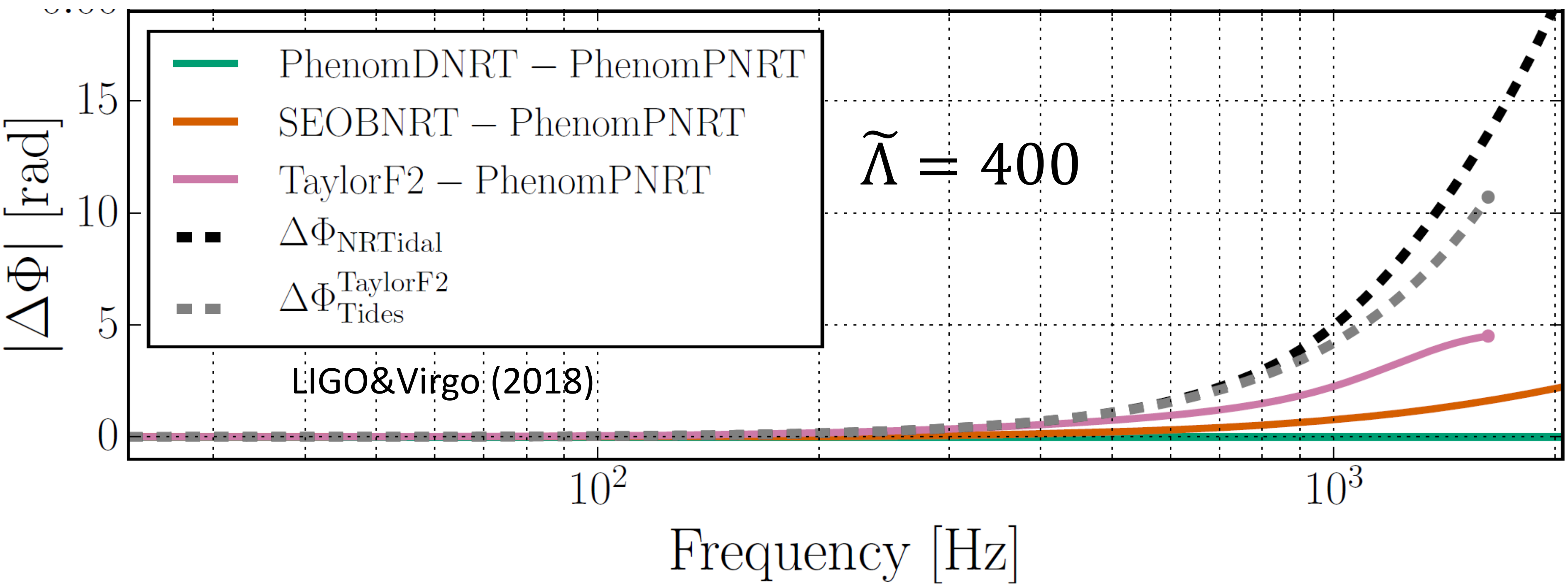

LIGO&Virgo (2016) for binary black holes

Uncertainty in the waveform model

1 radian difference usually makes differences

Current systematic errors are larger than 1 radian

We need accurate waveforms for better estimation



LIGO&Virgo (2018)

Kyoto gravitational-wave model

TaylorF2: analytic, Post-Newton phase $\left(x \propto f^{2/3}\right)$

$$\Psi_{\rm tidal}^{\rm 2.5PN} = \frac{3}{128\eta}\left(\boxed{-\frac{39}{2}\tilde{\Lambda}}\right)x^{5/2}\left[1+\frac{3115}{1248}x-\pi x^{3/2}+\frac{28024205}{3302208}x^2-\frac{4283}{1092}\pi x^{5/2}\right]$$

\+ correction terms associated w/ mass asymmetry

($\widetilde{\Lambda}$: binary tidal deformability, i.e., weighted average)

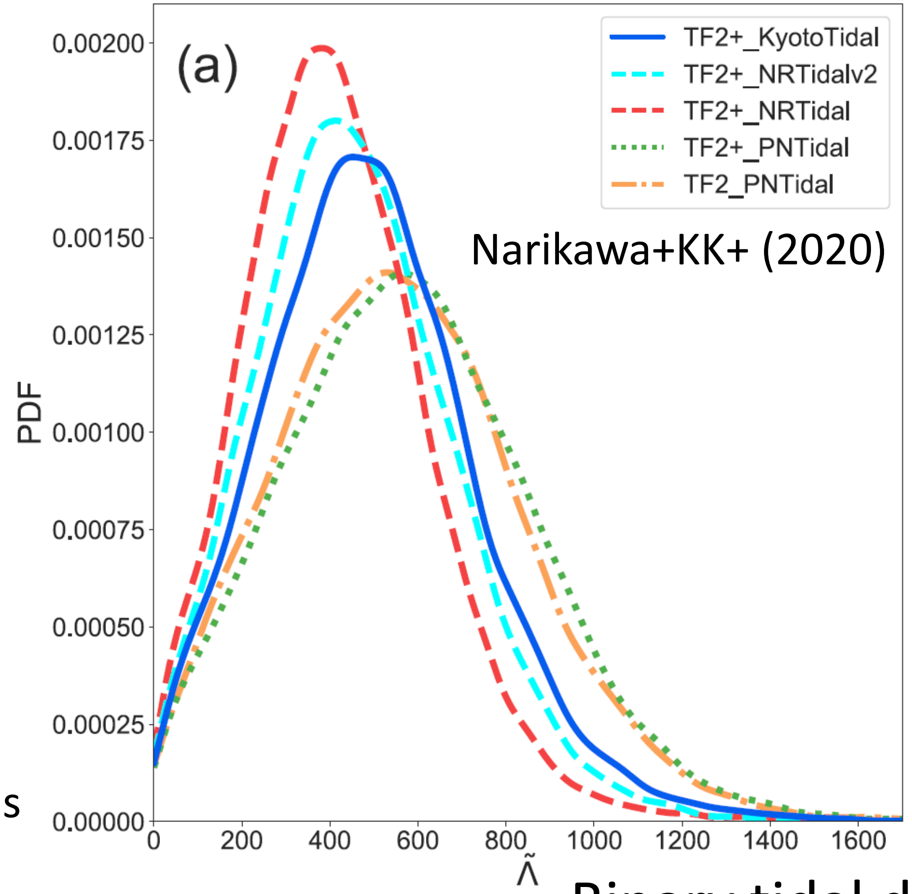
We introduce a nonlinear-in-$\widetilde{\Lambda}$ term (empirically)

$$-\frac{39}{2}\tilde{\Lambda}(1+12.55\tilde{\Lambda}^{2/3}x^{4.240})$$

This $\widetilde{\Lambda}^{2/3}$ term well reproduces numerical relativity

Constraint from GW170817

Systematic bias is only ~100 and currently negligible but may become problematic in the foreseeable future



Narikawa+KK+ (2020)

Kyoto: our NR-based model from Kawaguchi+KK+ (2018)

NRTidal:
another NR-based model
used in LVC analysis

PNtidal: post Newton

Soft, small radius

Stiff, large radius

Binary tidal deformability

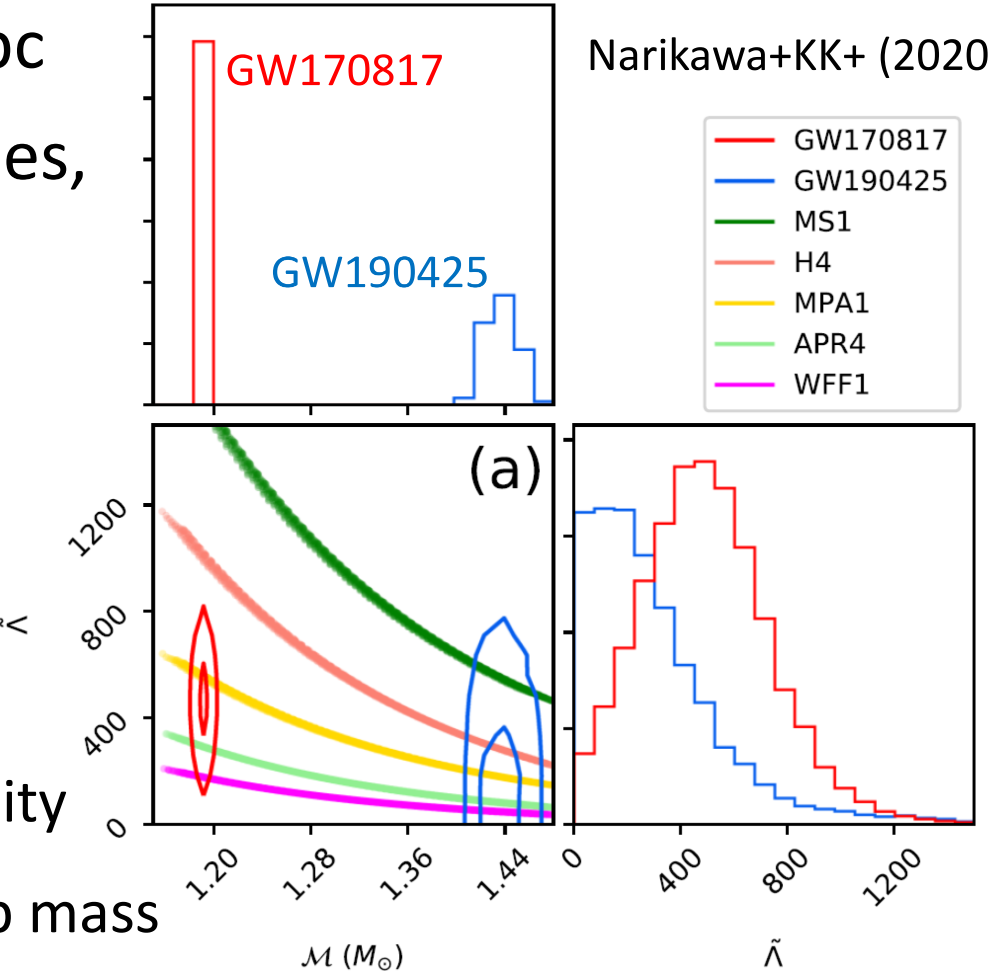
Case of GW190425

Weak constraint due to the high mass $3.4M_\odot$ and the large distance 150-250Mpc

Even $\tilde{\Lambda} = 0$, i.e., black holes, may not be disfavored

[see also Kyutoku+ (2020)]

Simply GW170817 was extremely lucky



Narikawa+KK+ (2020)

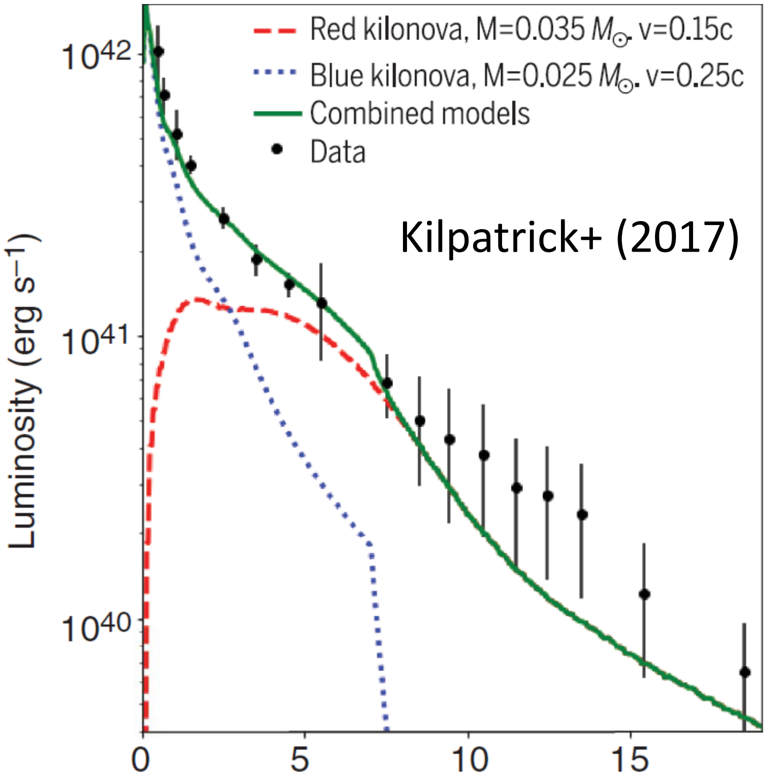
Binary tidal deformability

Chirp mass

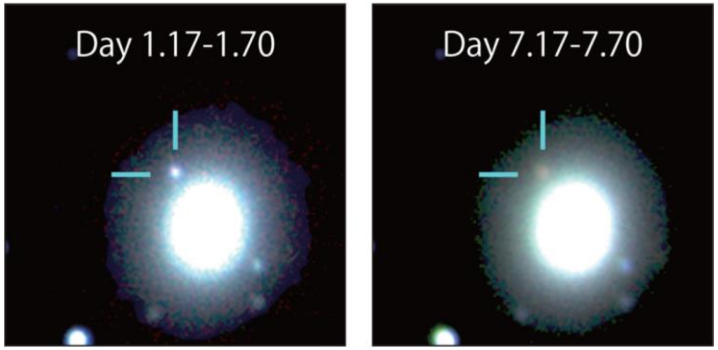
Kilonova: AT 2017gfo

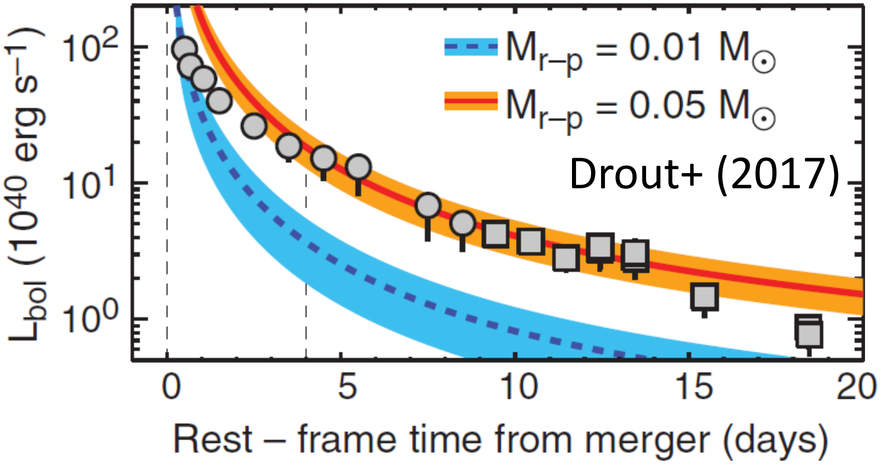
Indication of the large ejecta mass of $\sim 0.05 M_{\odot}$

It has been claimed that “this requires $\tilde{\Lambda} > 400$”


Kilpatrick+ (2017)

Utsumi+ (2017)



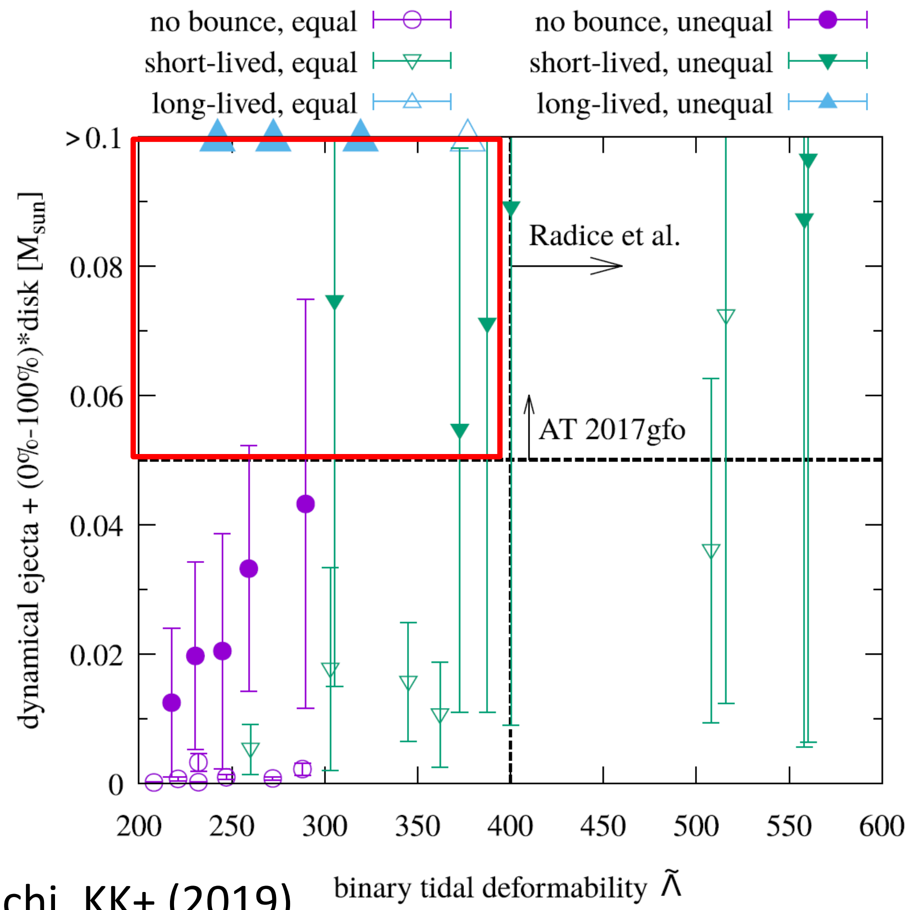

Drout+ (2017)

A lot of counterexamples

Our conclusion:

Lower limits on $\tilde{\Lambda}$ can be derived only under restrictive assumptions

(vertical bars denote
mass ejection efficiency
from the disk, not errors)

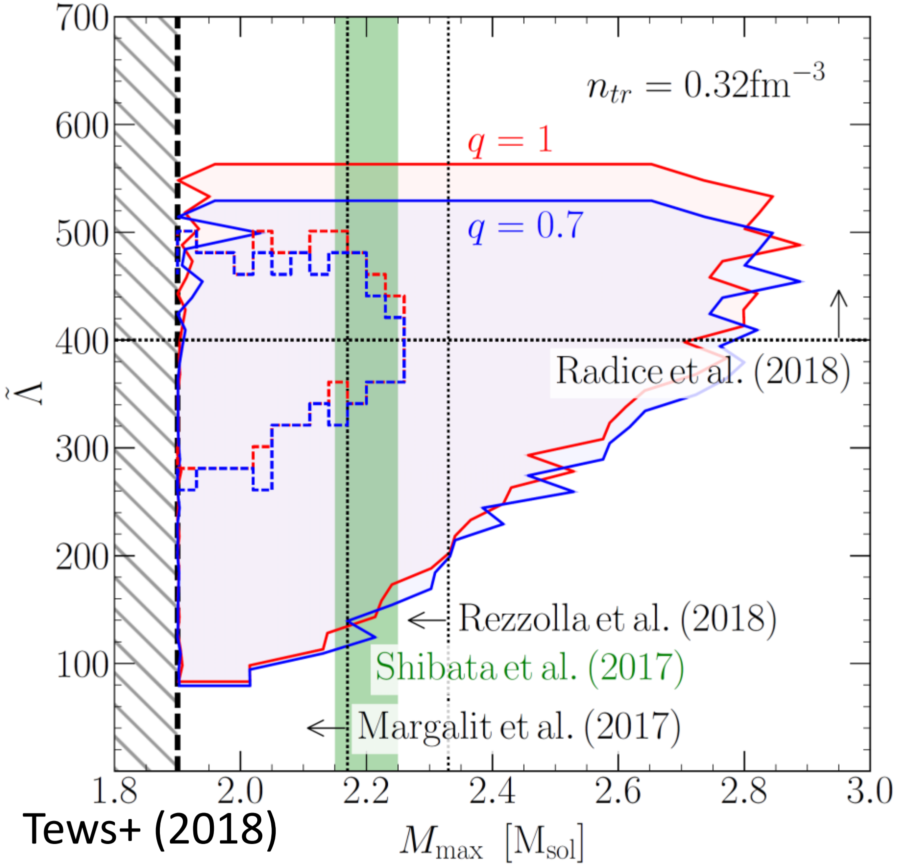


Kiuchi, KK+ (2019)

Reason?

$M_{\max}$ may not be strongly correlated with $\tilde{\Lambda} \propto R^{\sim 6}$ of typical-mass neutron stars

If the remnant survived moderately long due to the large value of $M_{\max}$, there should be no reason that mass ejection is weak

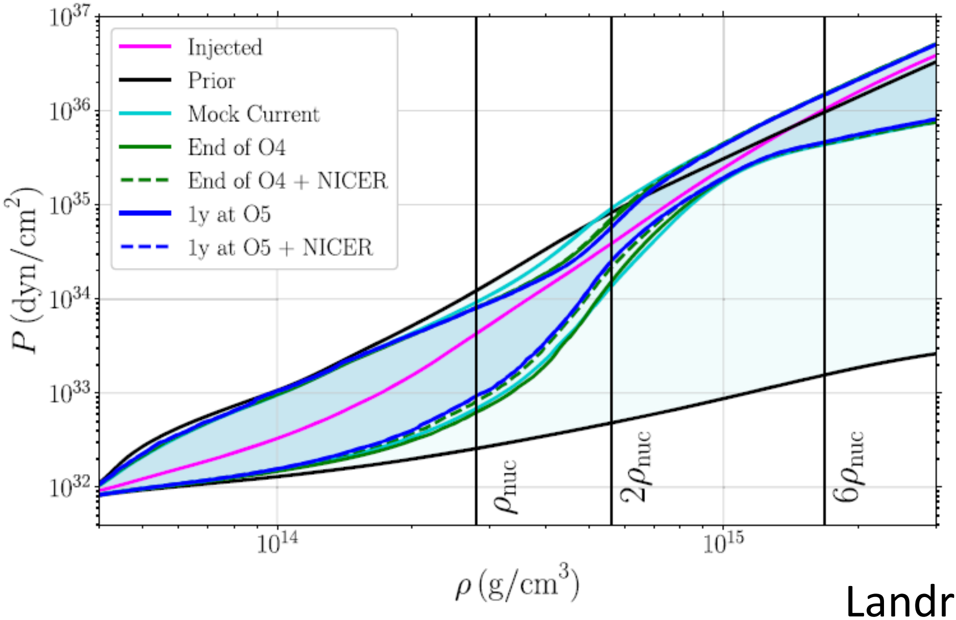


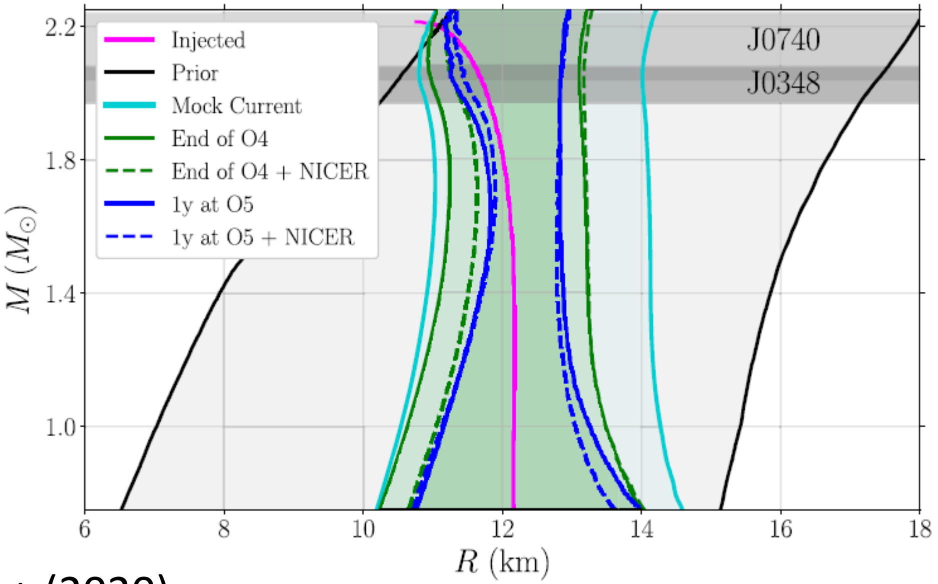
Tews+ (2018)

What should we understand then?

Moderate-density (around twice the saturation density) will be understood precisely by a lot of observations

On the basis of this idea, we would like to understand properties of ultrahigh-density matter

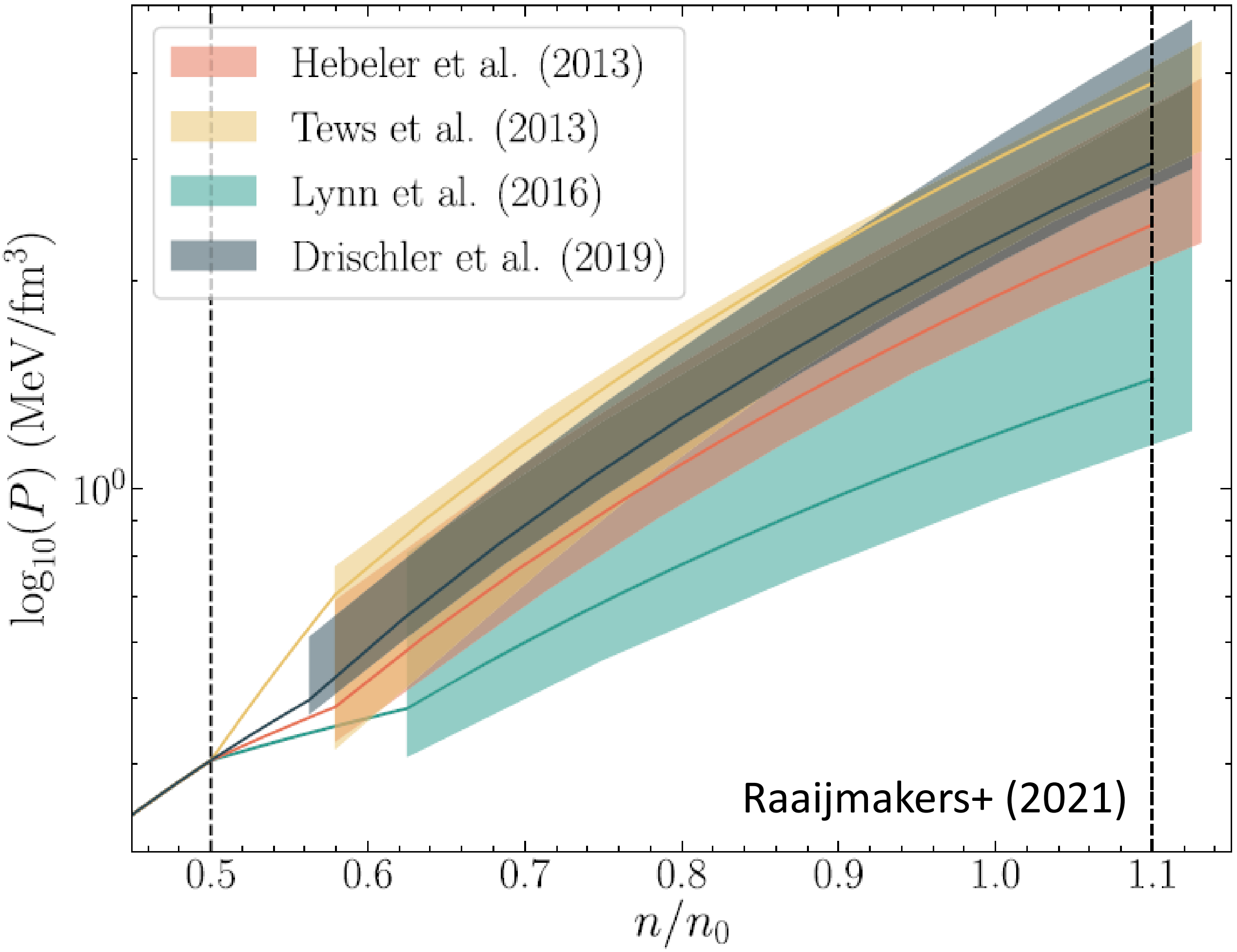




Landry+ (2020)

Uncertainty in chiral EFT

The validity range is crucial for strength of constraints

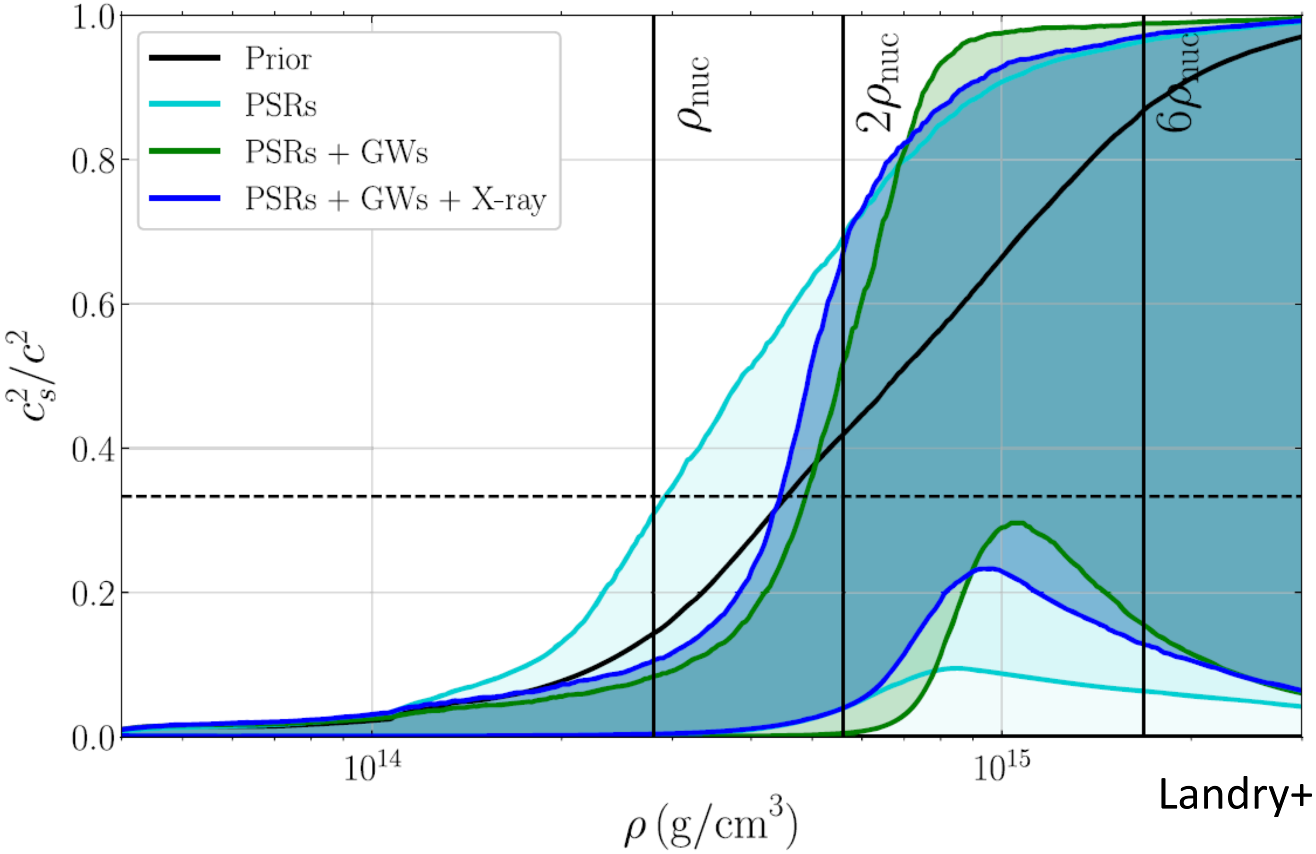


Raaijmakers+ (2021)

Current view on the sound speed

Not stiff at low density, but $2M_\odot$ must be supported.

Conformal limit ($c_s^2/c^2 = 1/3$) is likely to be exceeded

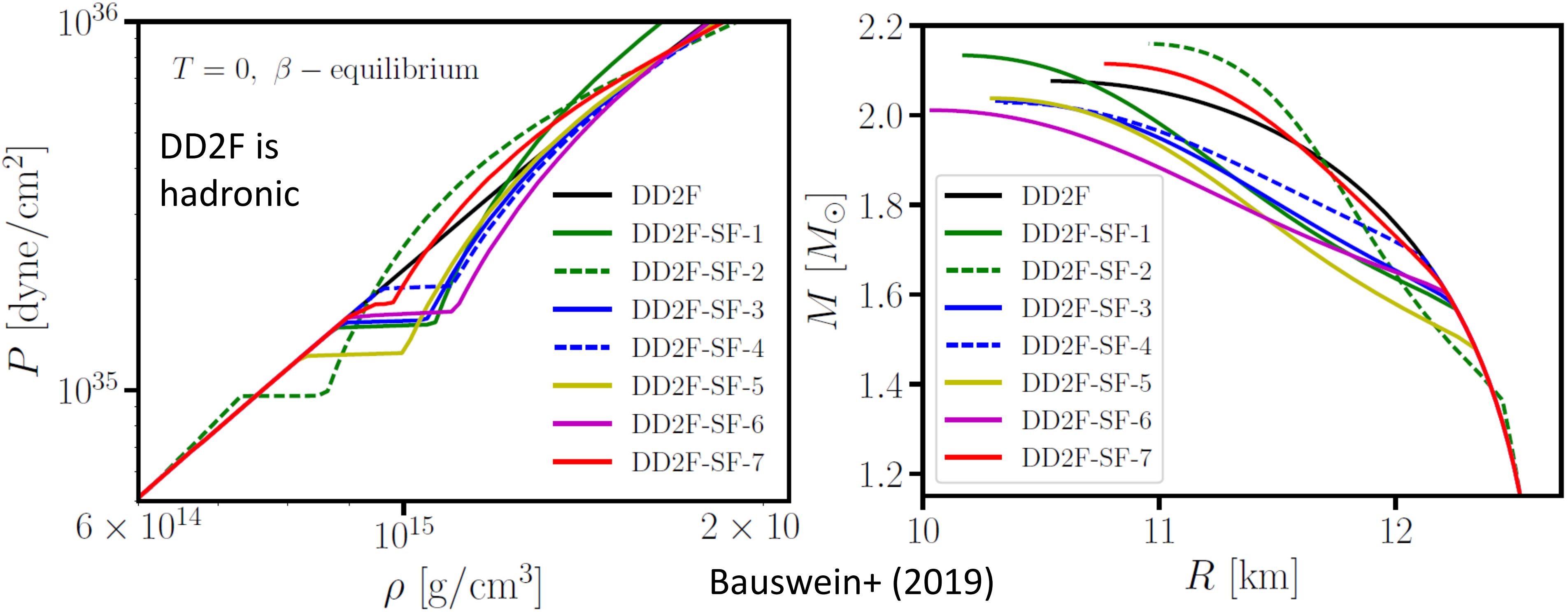


Landry+ (2020)

First-order phase transition

The mass-radius relation breaks suddenly

An extreme case results in the so-called “twin star”



DD2F is hadronic

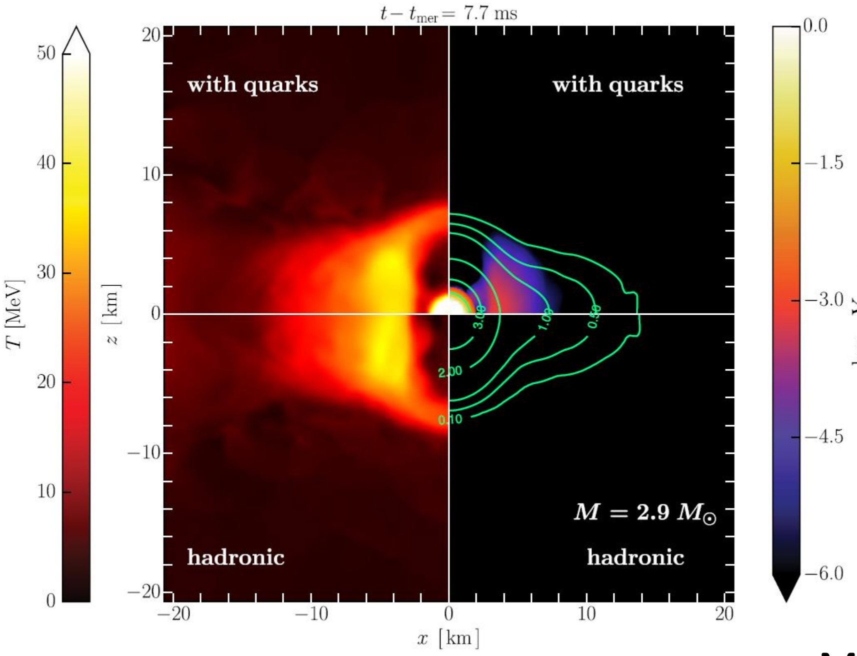
Bauswein+ (2019)

Structure of the merger remnant

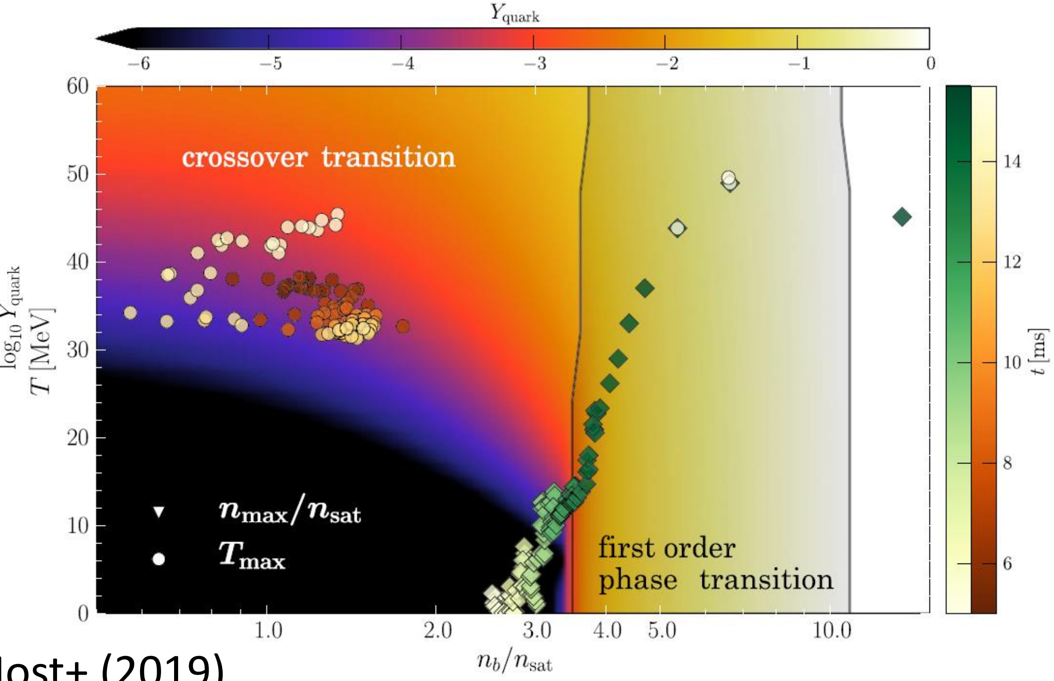
Density/temperature structures are not very different

Quarks appear at the high-n core and high-T envelope

Top: w/ quark, bottom: hadron only



Time evolution of maximum n and T

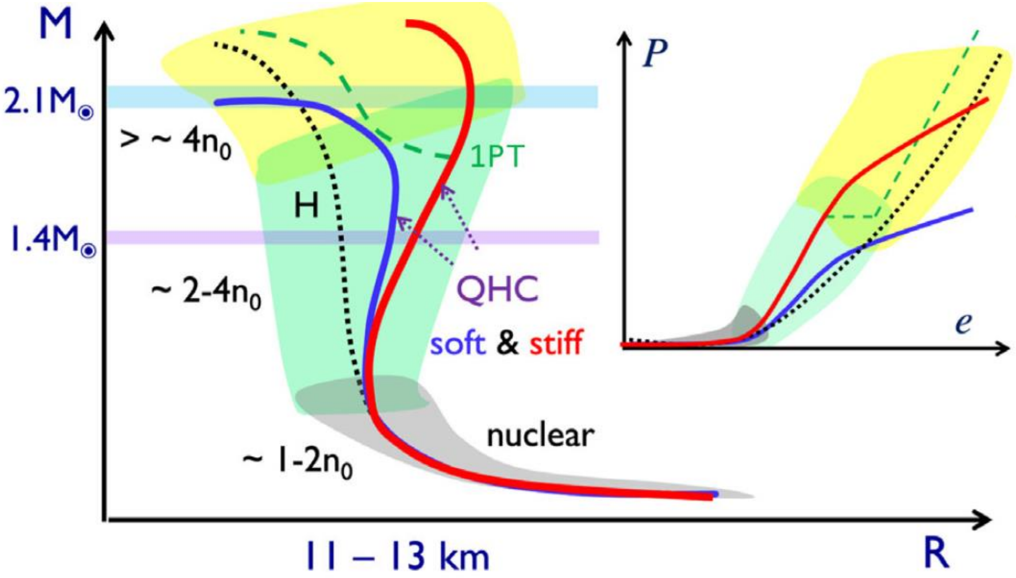


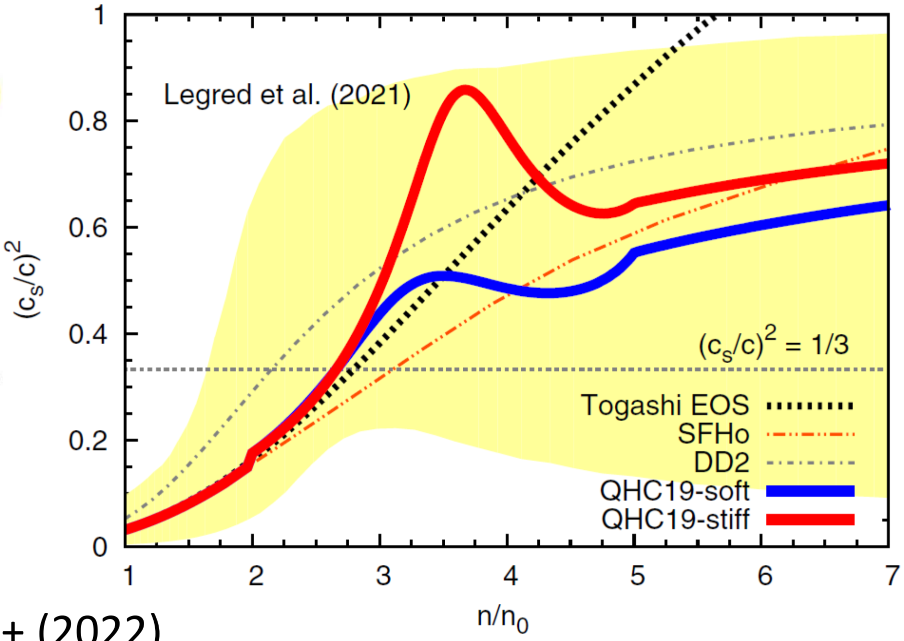
Most+ (2019)

Relation to independent studies

There exists other studies, e.g., those based on QHC

We require explicitly that the perturbative QCD regime is realized after the crossover from hadronic matter

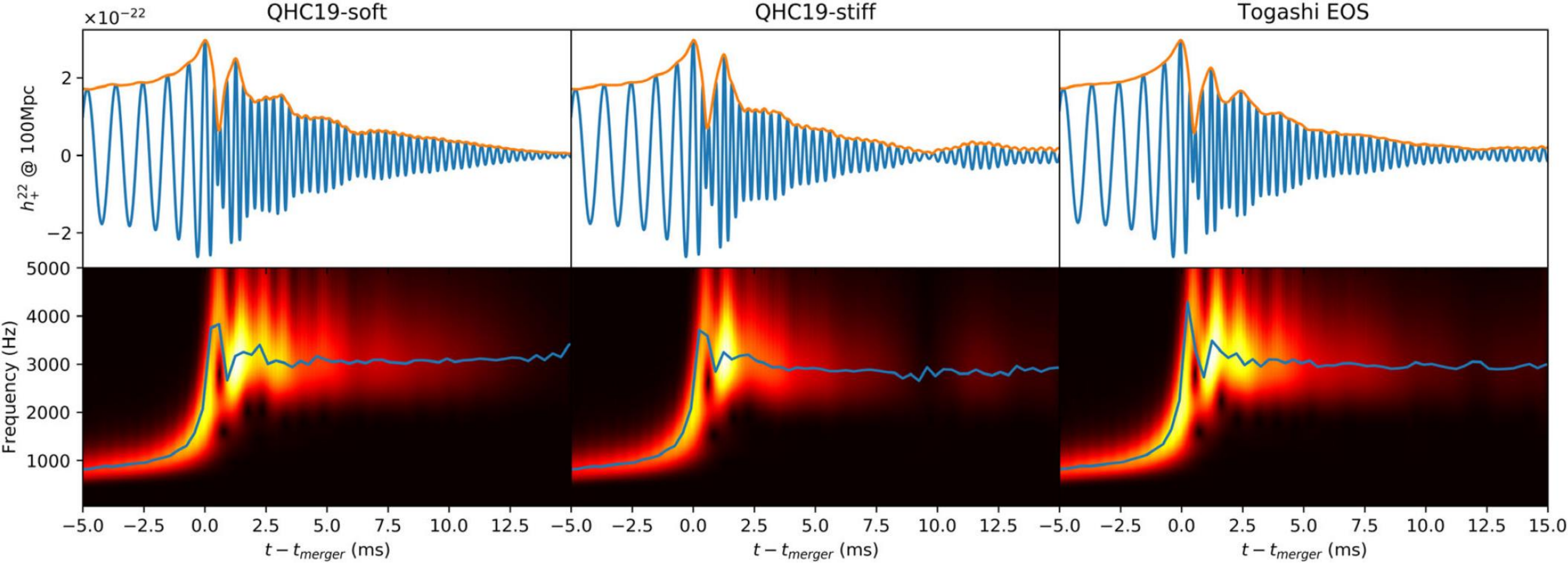




Huang+ (2022)

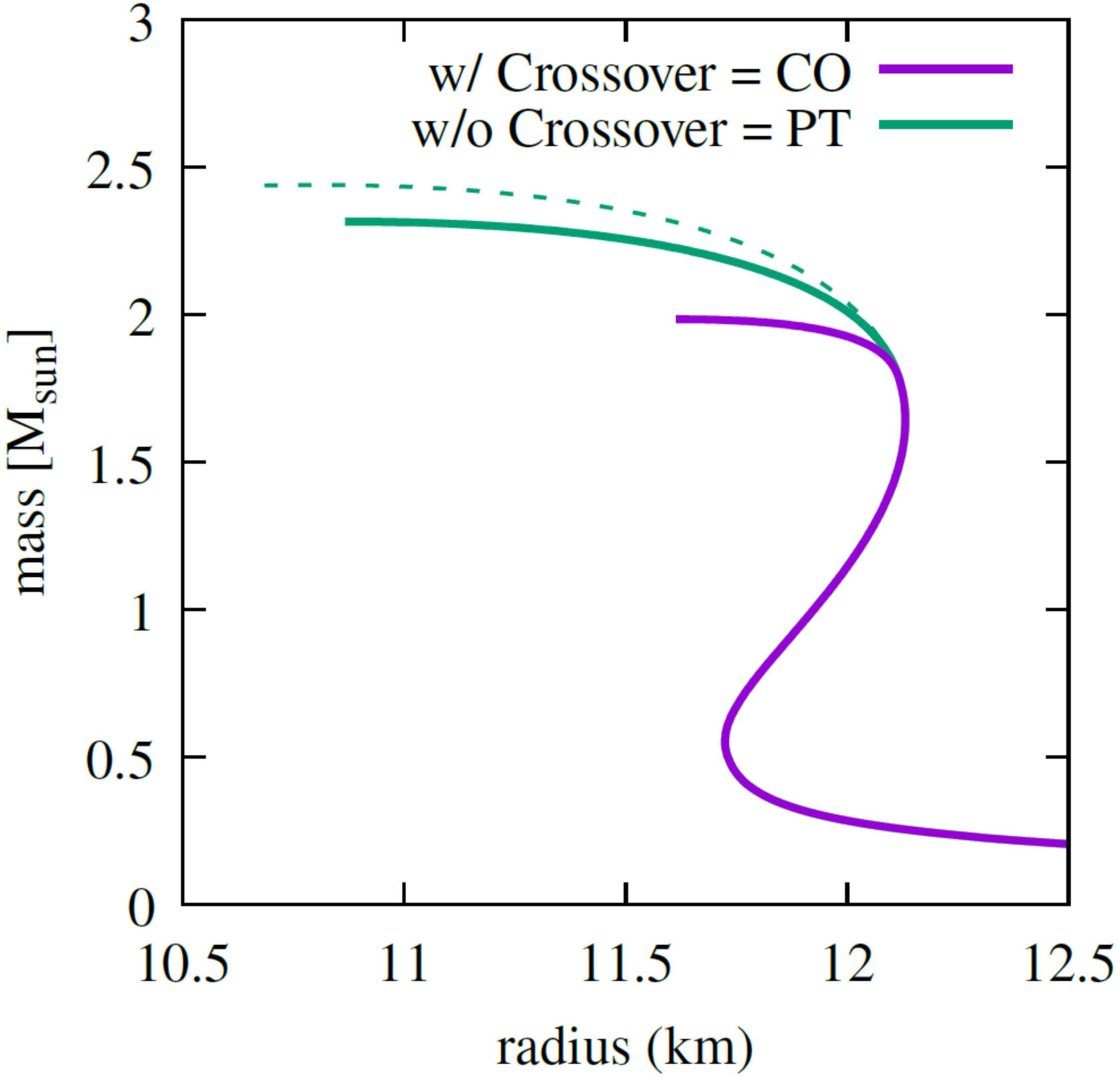
Results derived with QHC

Soft equations of state at high density derive high postmerger frequency: also consistent with our results



Huang+ (2022)

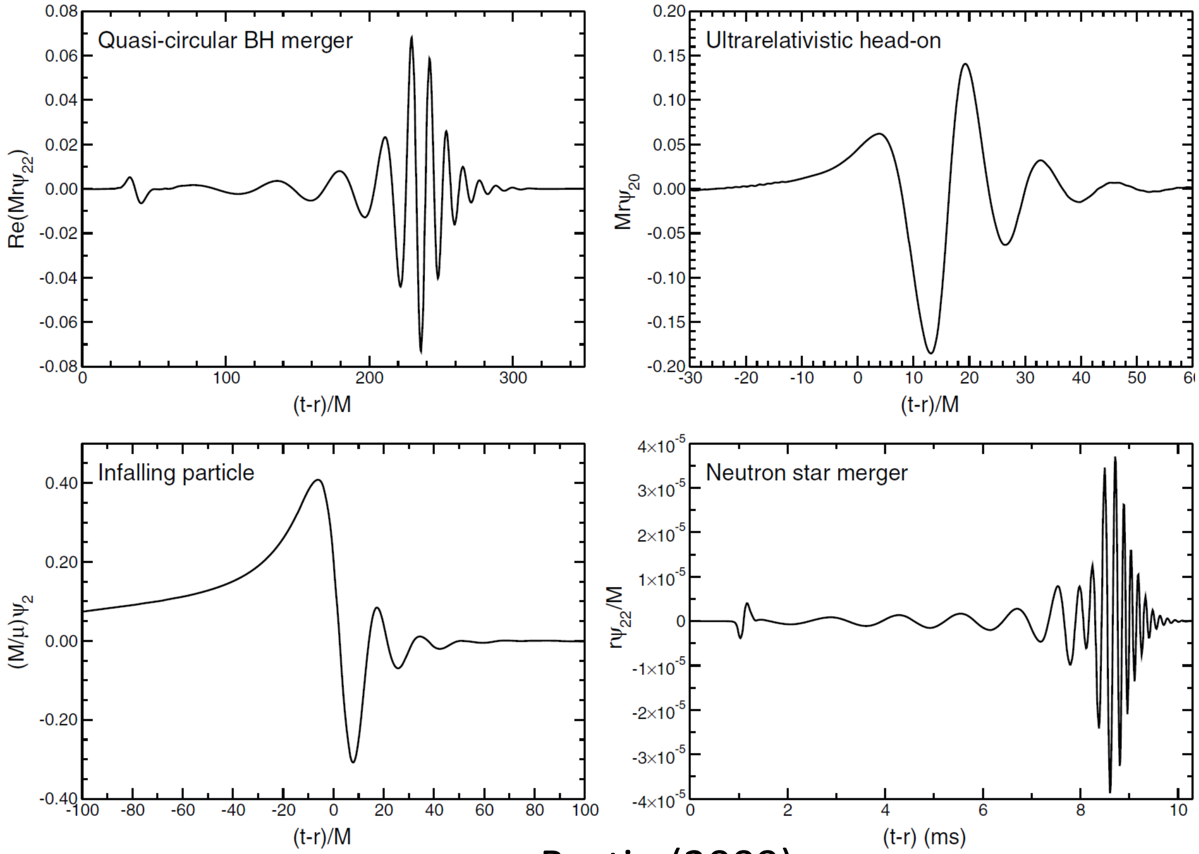
Mass-radius relation



Quasinormal modes of black holes

Damped oscillations governed by the mass and spin

Excited when they are formed in gravitational collapse



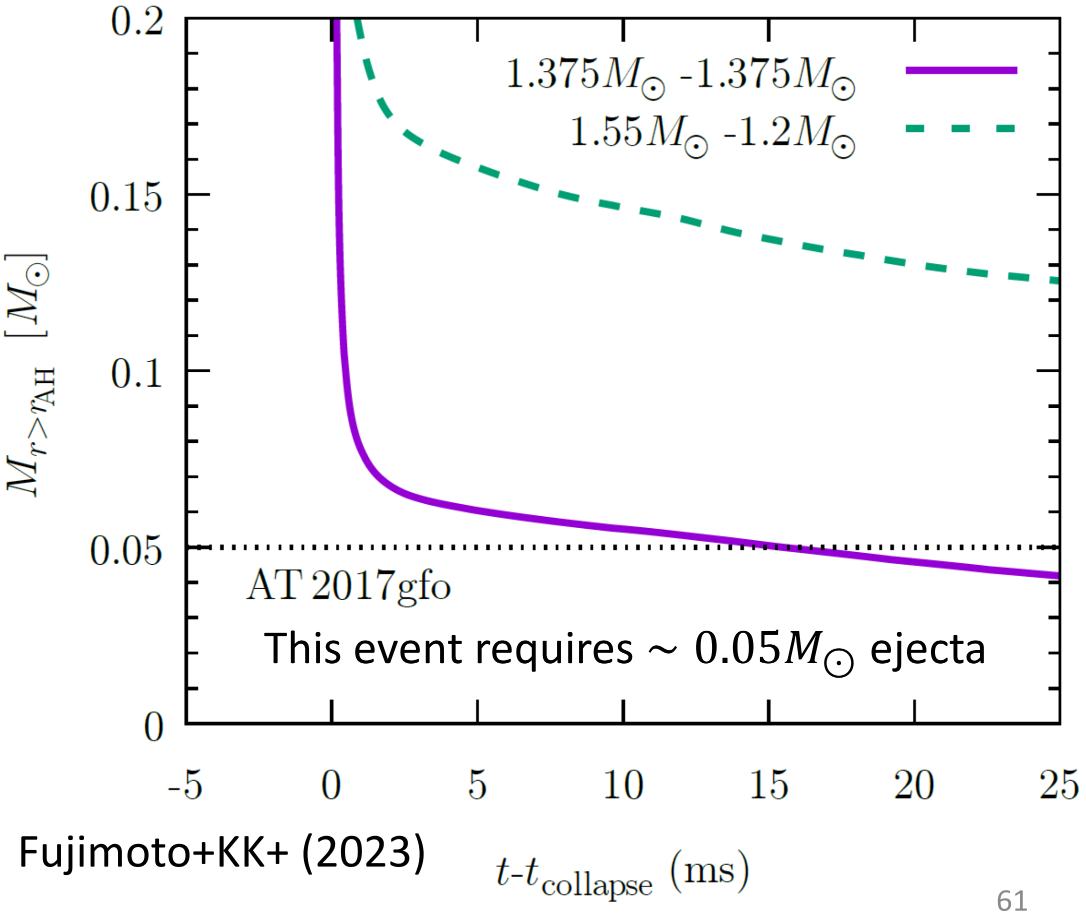
Berti+ (2009)

Multimessenger observation

If the collapse is too early, no material is left outside and the kilonova cannot be as bright as AT 2017gfo

Our crossover model may be pass this test with mass asymmetry

(1s-order PT trivially passes this test because no gravitational collapse)



This event requires $\sim 0.05M_\odot$ ejecta

Fujimoto+KK+ (2023)