Gravitational waves and physics of compact objects

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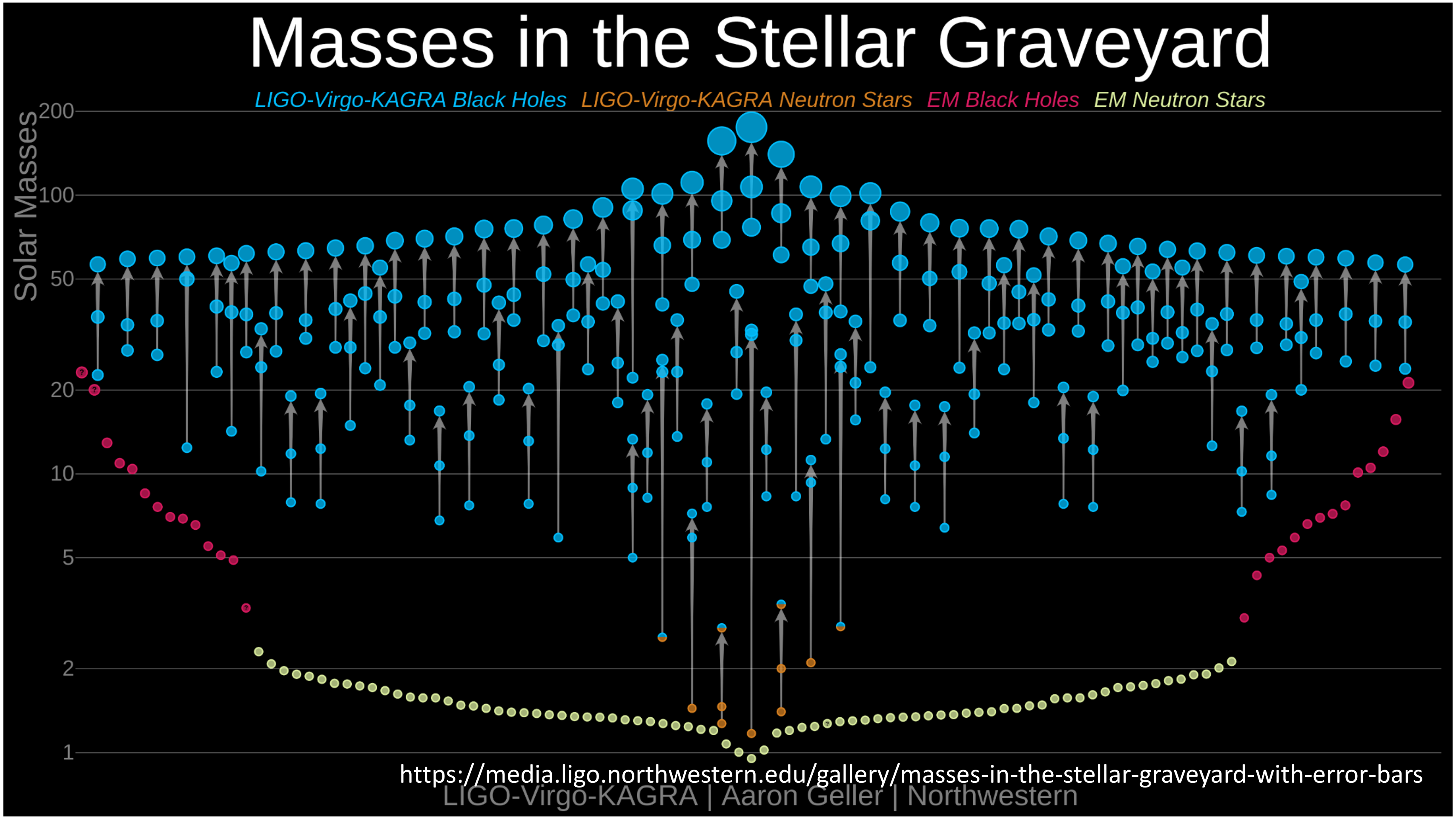
Plan of the talk

1. What we have learned: GW170817
2. What we will learn in the future
3. Summary

1. What we have learned: GW170817

Observed event by the end of O3

2 binary neutron star mergers appear to be confirmed



Neutron star

Remnant of massive stars

Mostly consists of neutrons

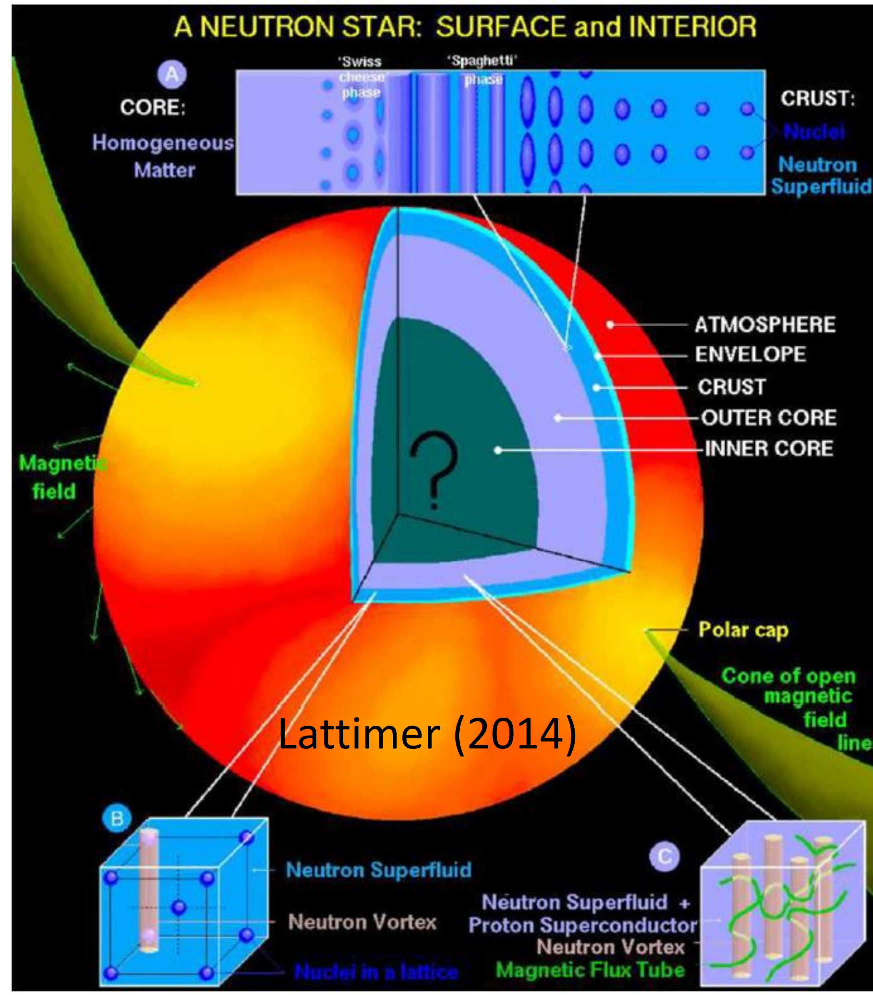
~1.4 solar mass, ~10km

-> density higher than

nuclear saturation density

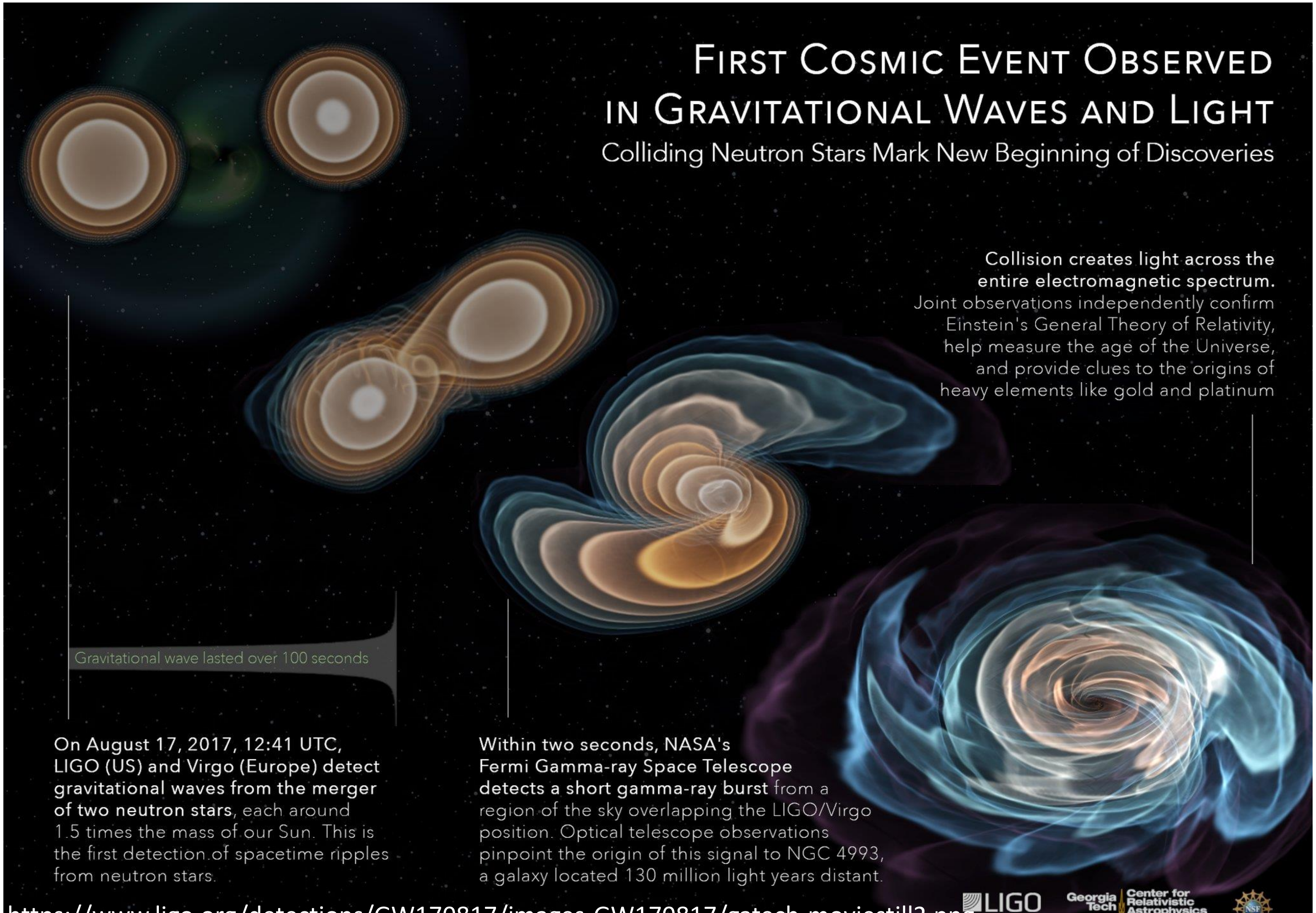
“a huge nucleus”

Natural arena for QCD and (extreme) nuclear physics



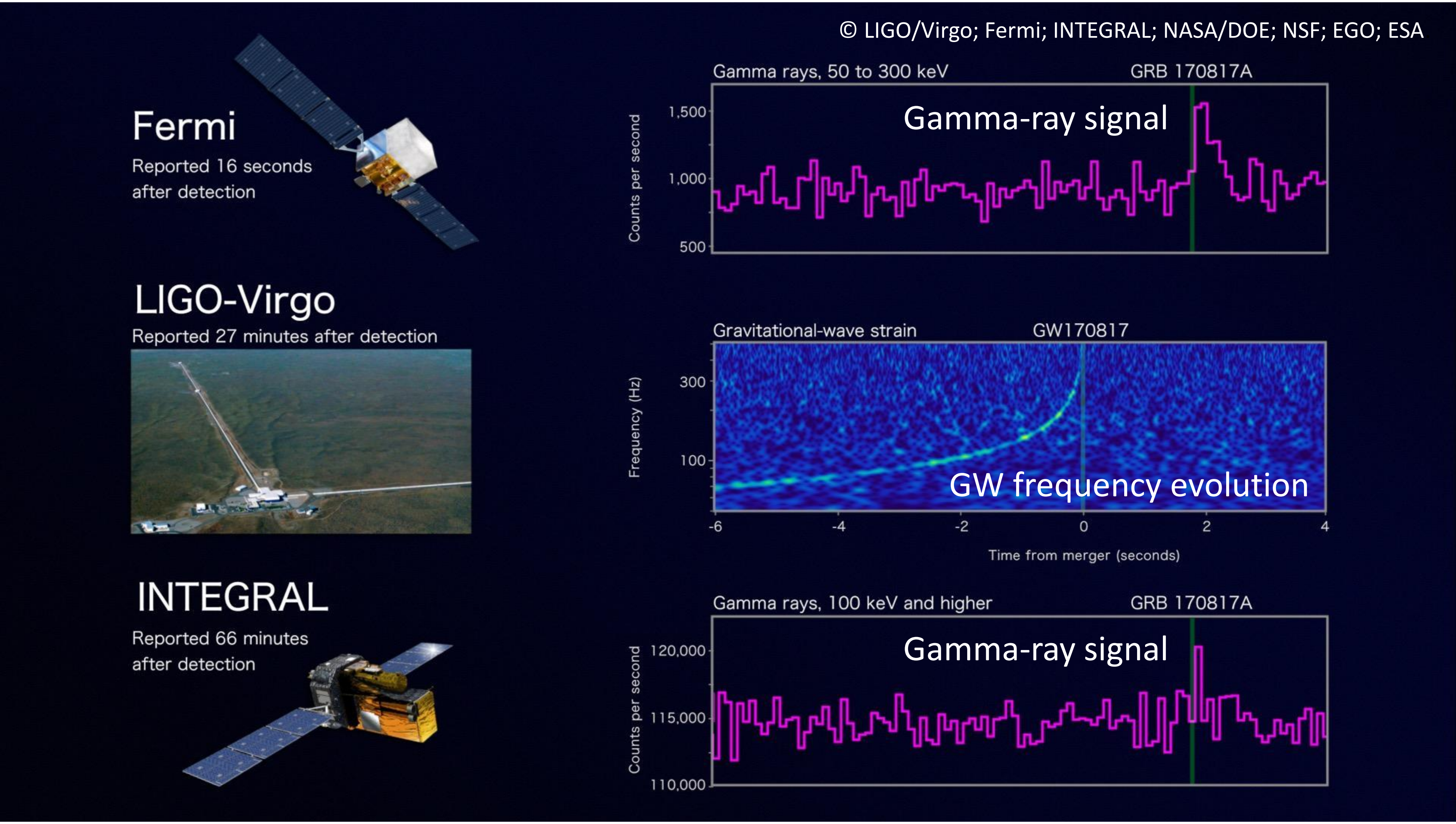
Lattimer (2014)

Multimessenger event: GW170817



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

GRB 170817A at 1.7s after merger



The difference of speeds in GW/EM

Timing difference $\Delta t = \left(D/v_{\mathrm{GW}}\right) - \left(D/v_{\mathrm{EM}}\right) = 1.7s$ renders the velocity difference $\Delta v \coloneqq v_{\mathrm{GW}} - v_{\mathrm{EM}}$

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\mathrm{EM}}} \leq 7 \times 10^{-16}$$

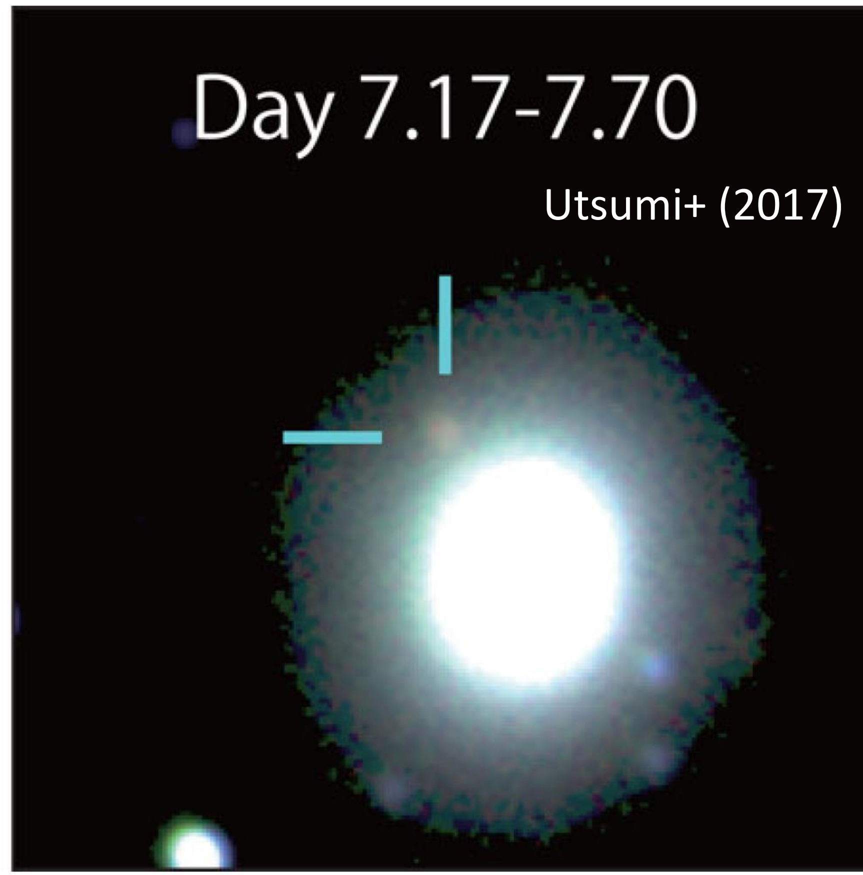
if the difference at the source is [0:10]s (model!)

- Lower limit: gravitational delay 10s ->1.7s
- Upper limit: electromagnetic delay 0s -> 1.7s

Although the precise physics of GRB is not understood, multiple events will alleviate model dependence

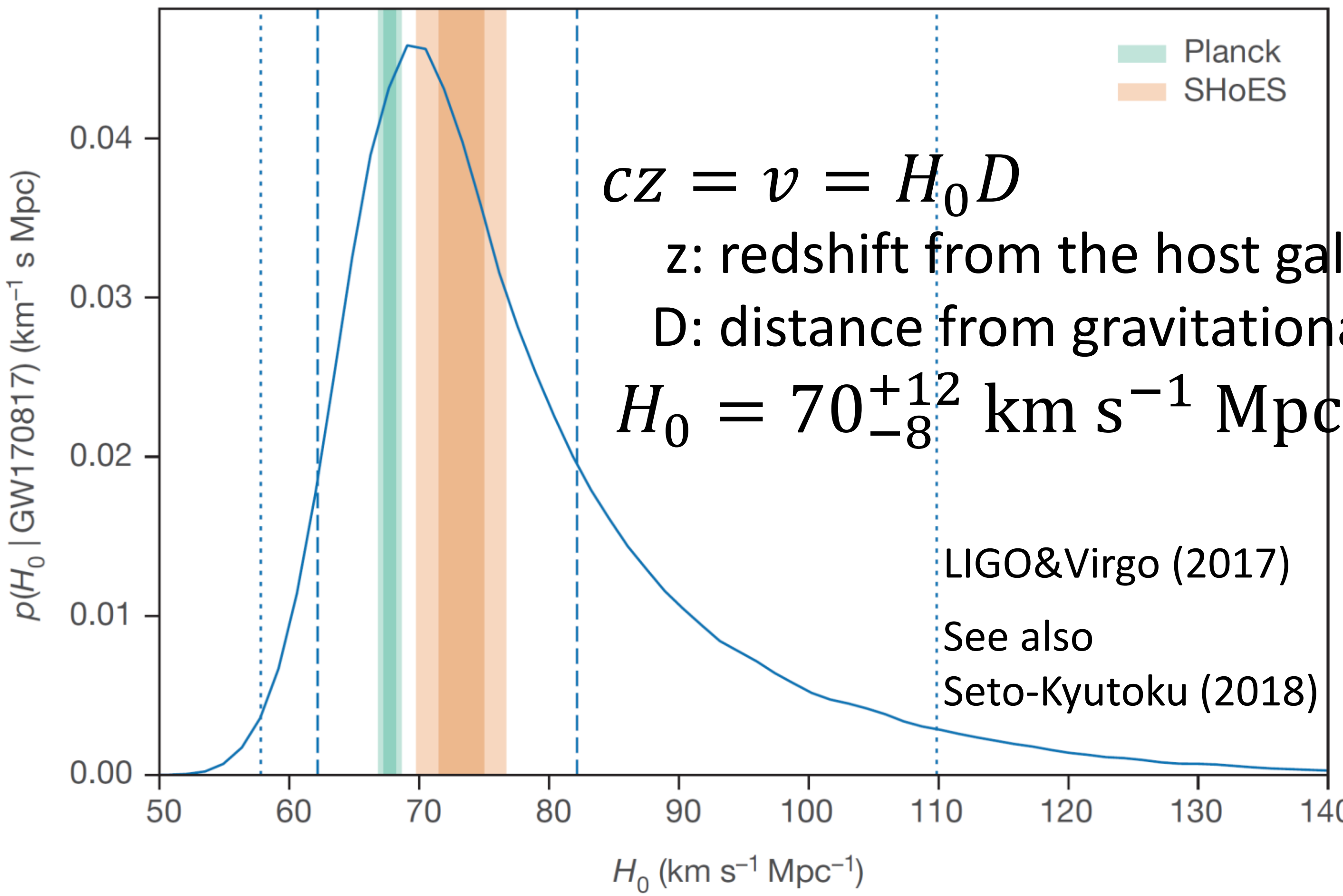
Kilonova and host galaxy

The host galaxy NGC 4993 with the redshift z~0.01



Gravitational-wave cosmology

More detections, more precise determination



CMB
Supernova

$$cz = v = H_0 D$$

z: redshift from the host galaxy

D: distance from gravitational waves

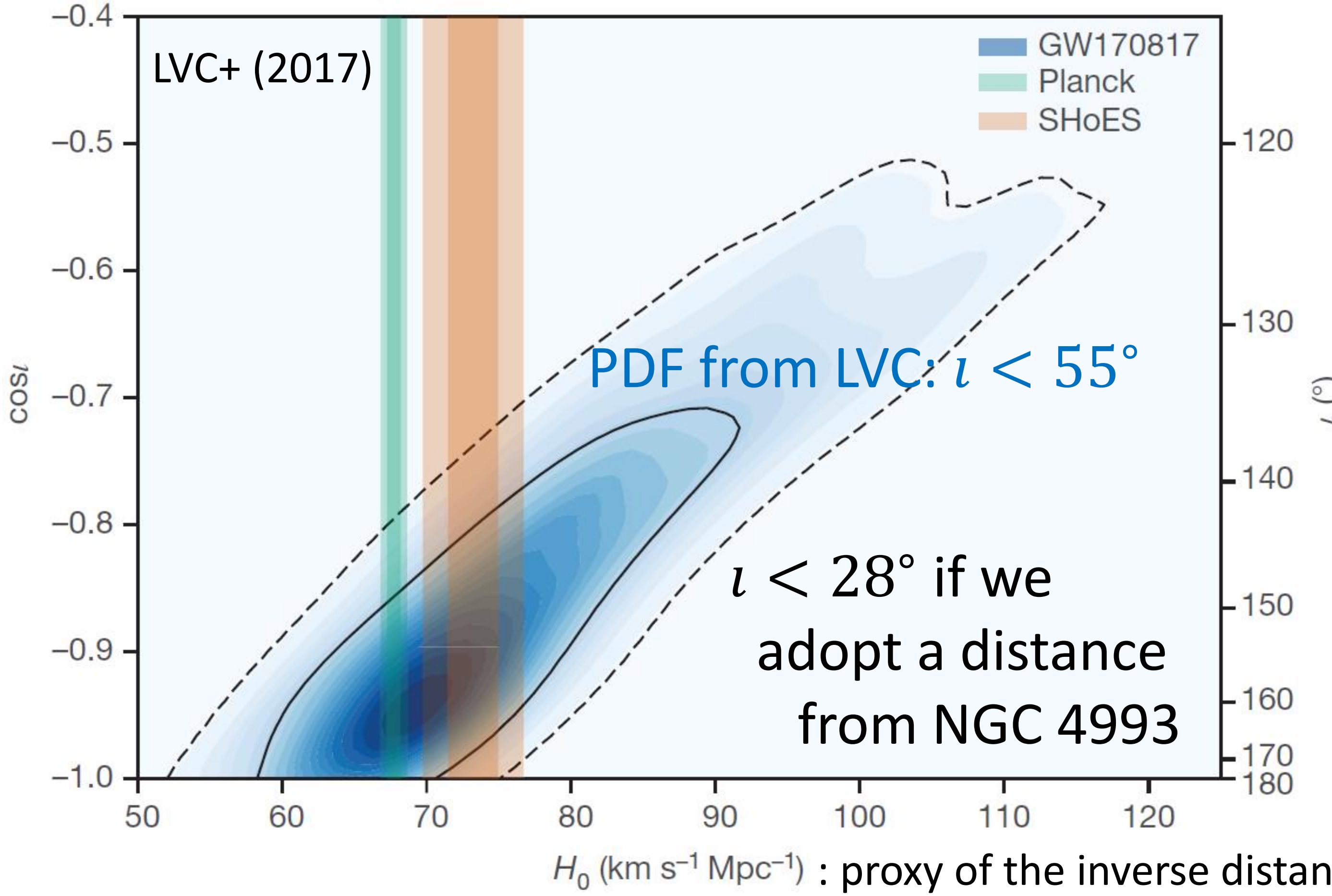
$$H_0 = 70^{+12}_{-8}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

LIGO&Virgo (2017)

See also
Seto-Kyutoku (2018)

Distance-inclination degeneracy

$\Delta\iota < 5^\circ$ is possible with Virgo or KAGRA [e.g., Arun+ 2014]

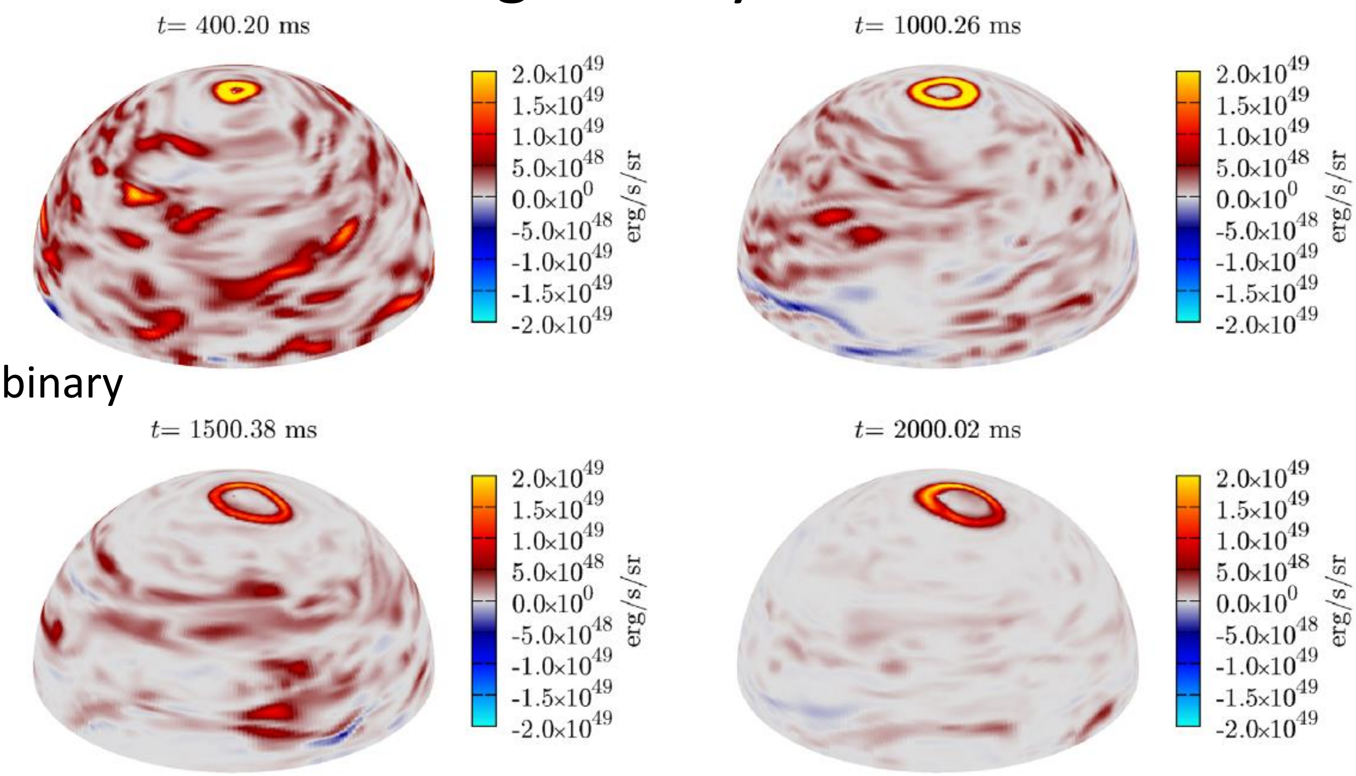


: proxy of the inverse distance here

Electromagnetic angle inference?

Statistical errors can be reduced at the cost of possibly introducing uncontrollable *systematic* errors

e.g., the jet and inclination angles may be different



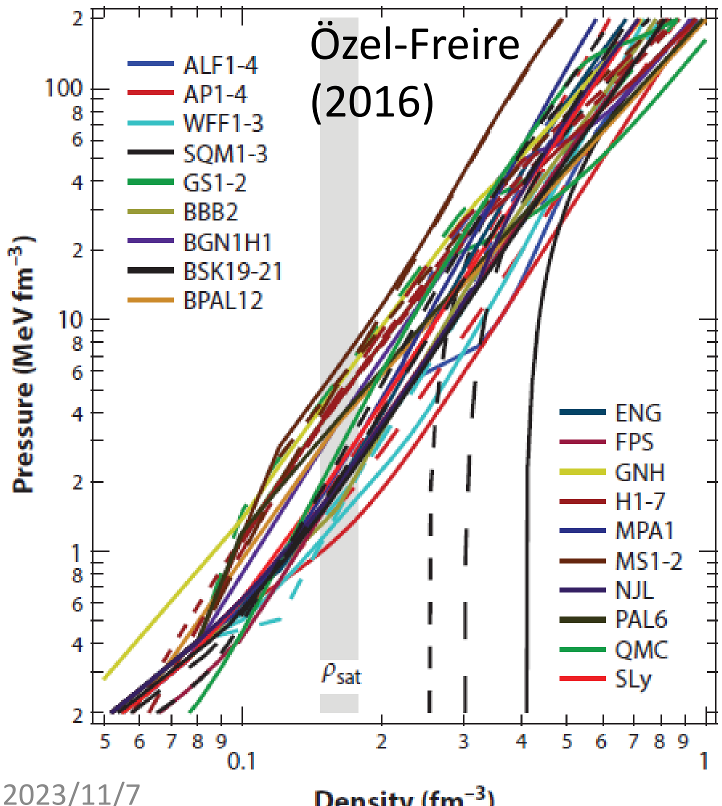
Hayashi+KK+ (2022)
Poynting luminosity for
a black hole-neutron star binary

Nuclear-matter equation of state

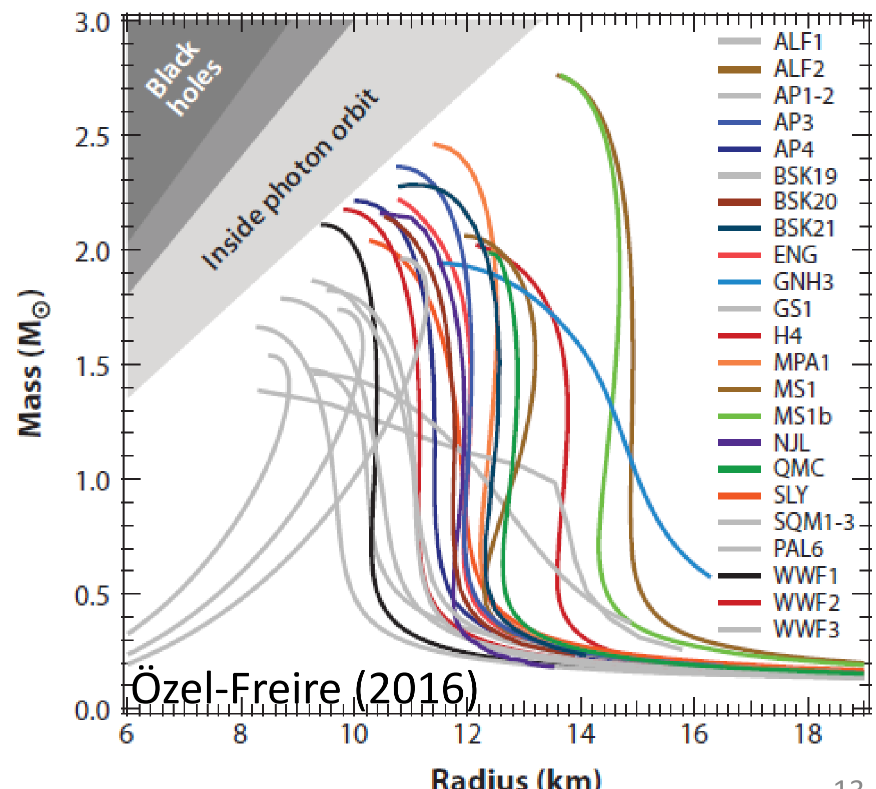
Note: not need to observe the radius, and other quantities may be fine

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

Equation of state: Nuclear physics



Mass-Radius relation: Astrophysics

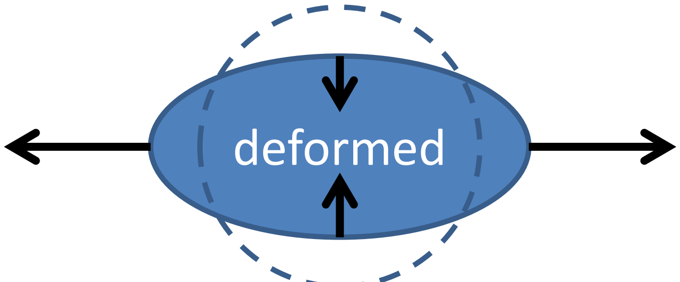


Quadrupolar tidal deformability

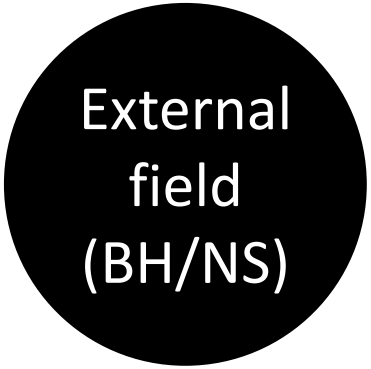
Leading-order finite-size effect on orbital evolution (strongly correlated with the neutron-star radius)

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

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



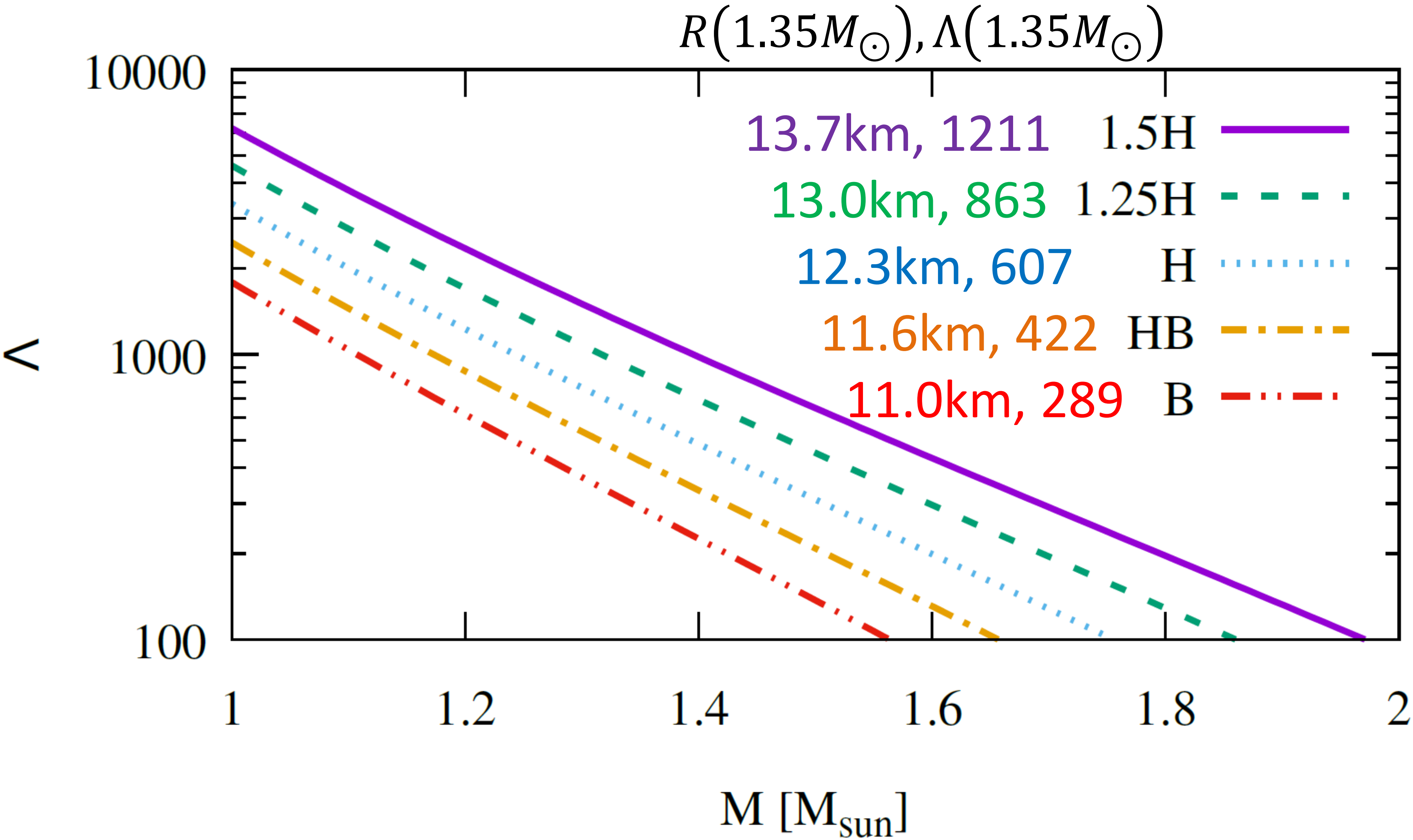
$$\mathcal{Q}_{ij} = -\lambda \mathcal{E}_{ij}$$



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

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

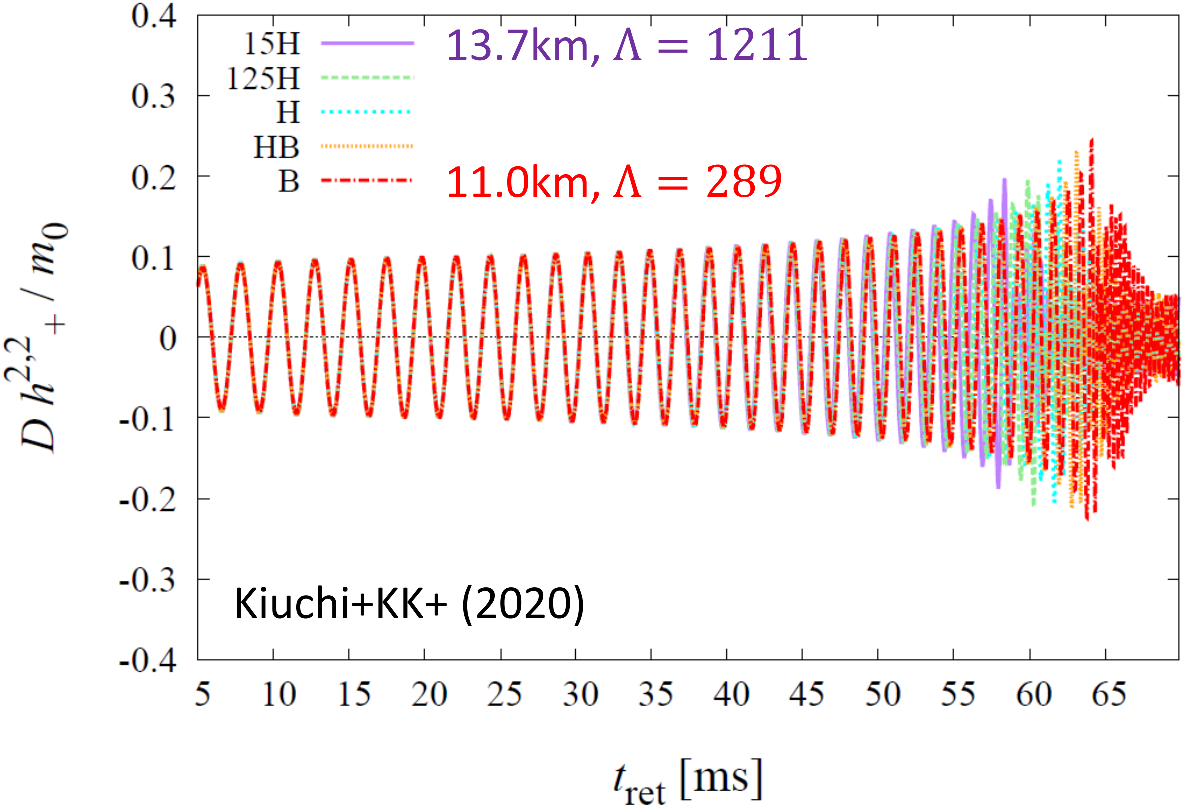
$M - \Lambda$ relation and equations of state



Numerical waveform

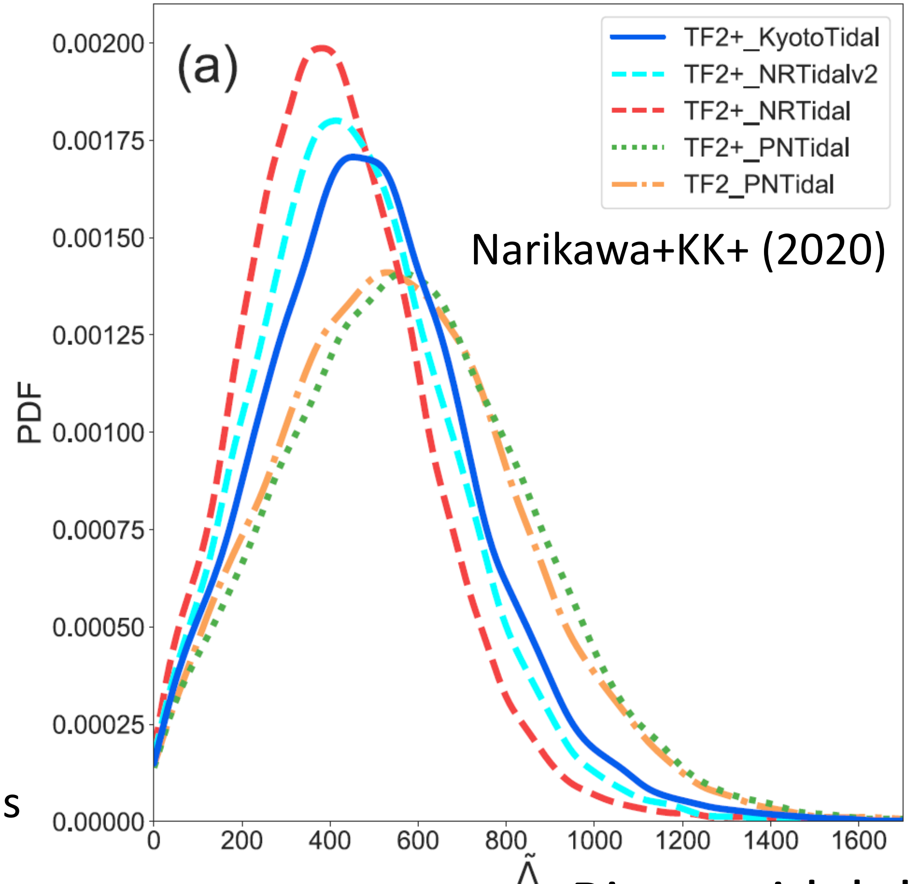
Binaries merge earlier for stiffer equations of state

This allows us to measure the tidal deformablity



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

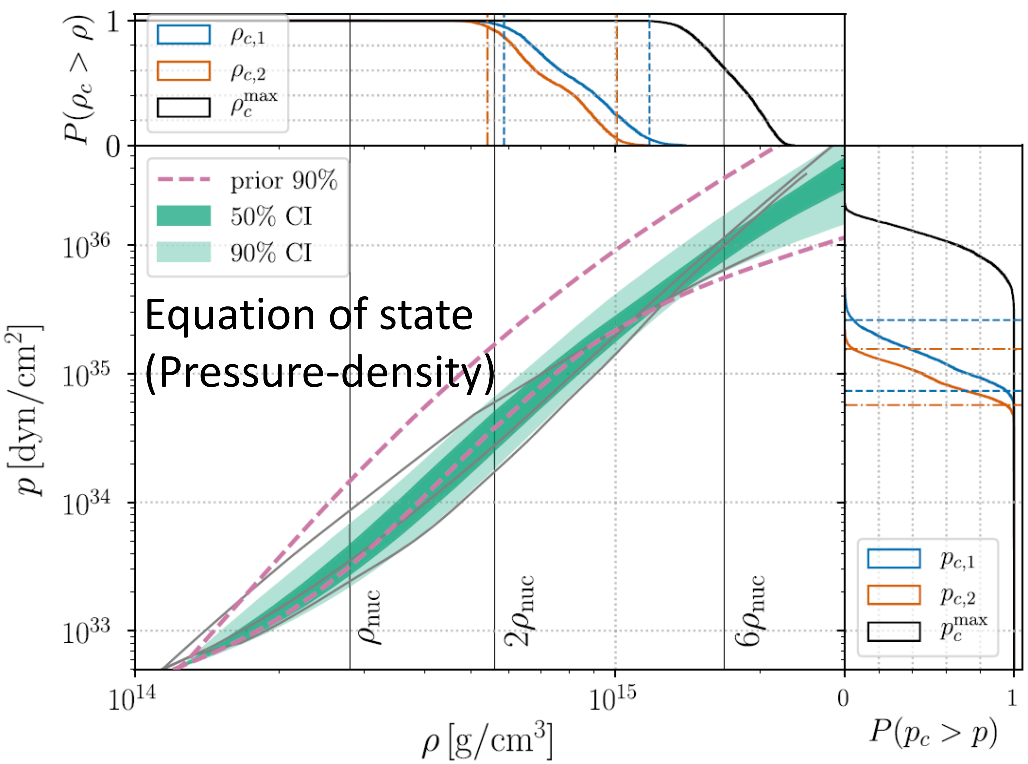
Soft, small radius

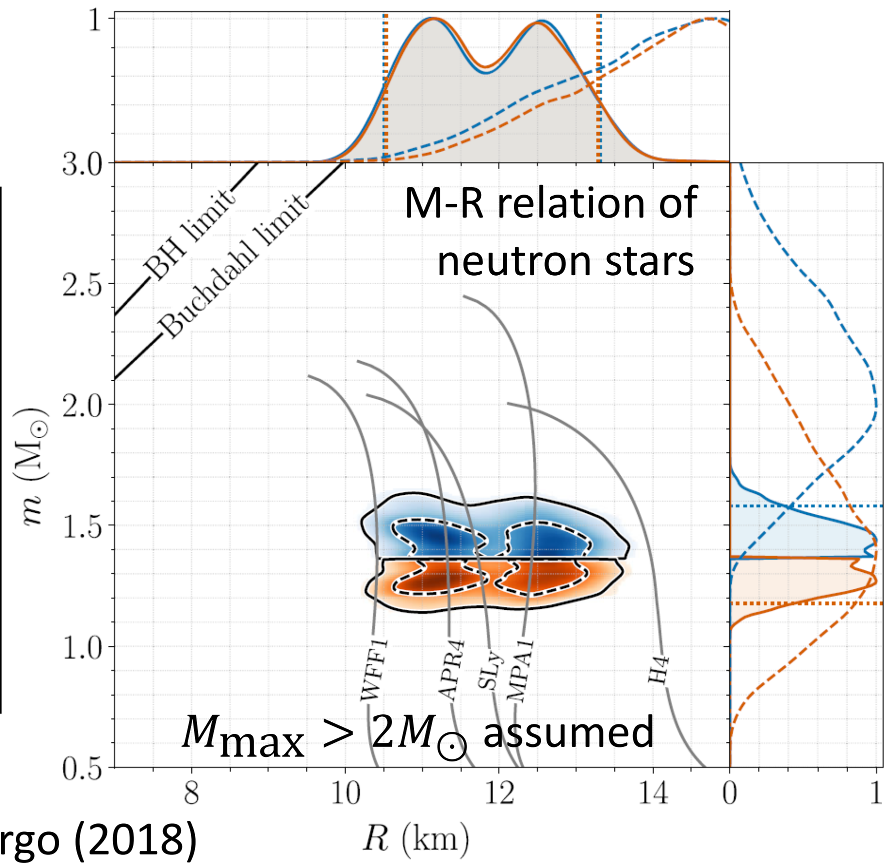
Stiff, large radius

Binary tidal deformability

Current understanding

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



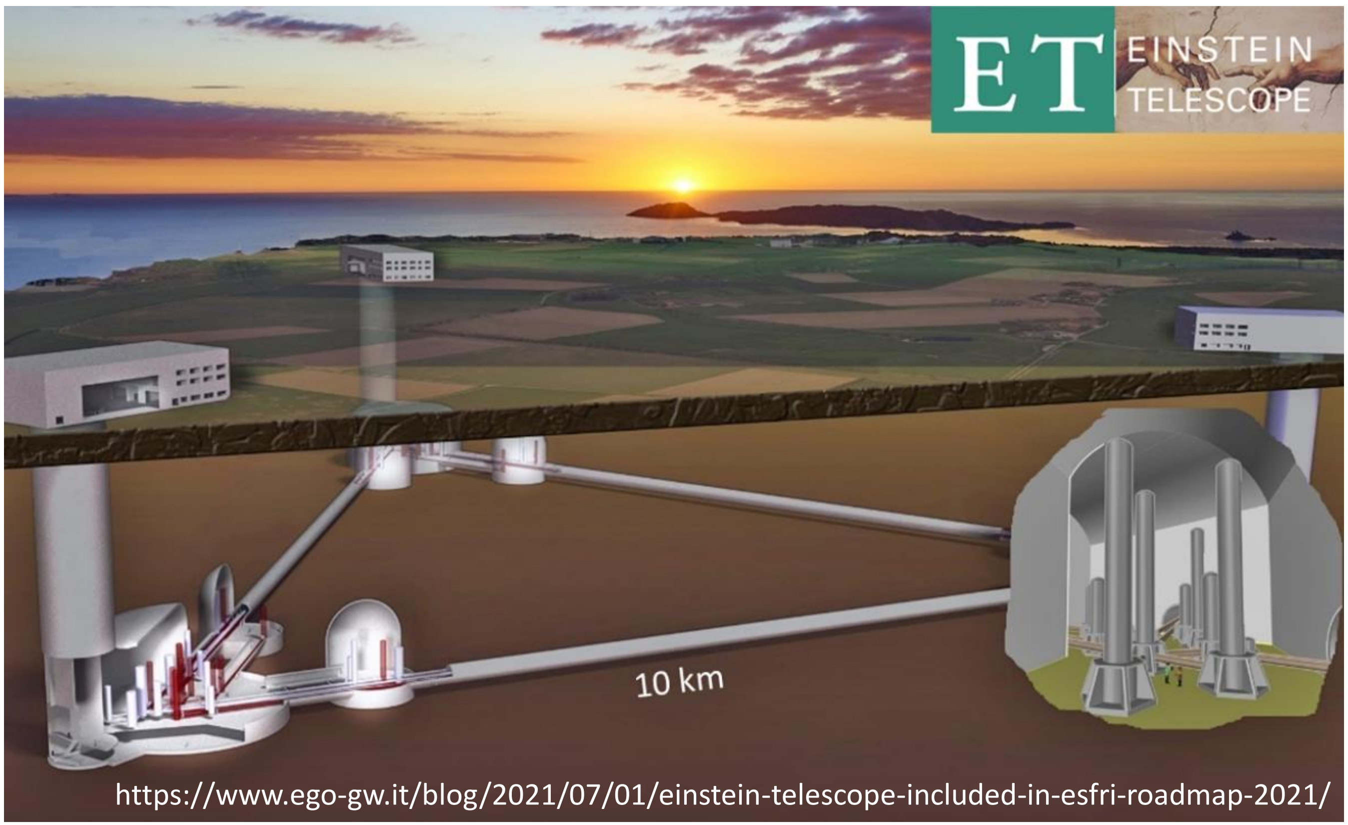


LIGO&Virgo (2018)

2. What we will learn in the future

Third-generation detector

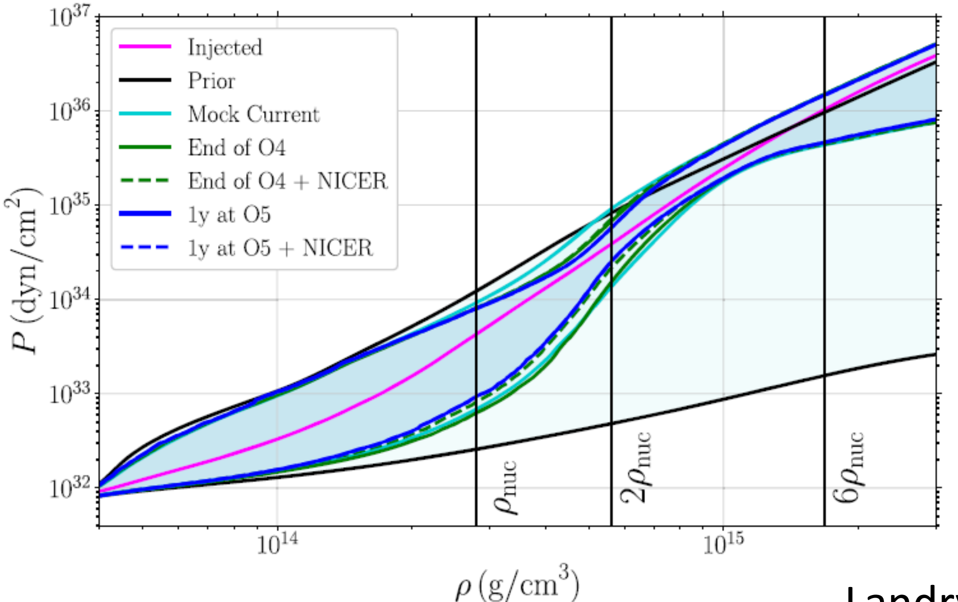
Einstein Telescope, Cosmic Explorer … aiming at more precise understanding of already-detected binaries

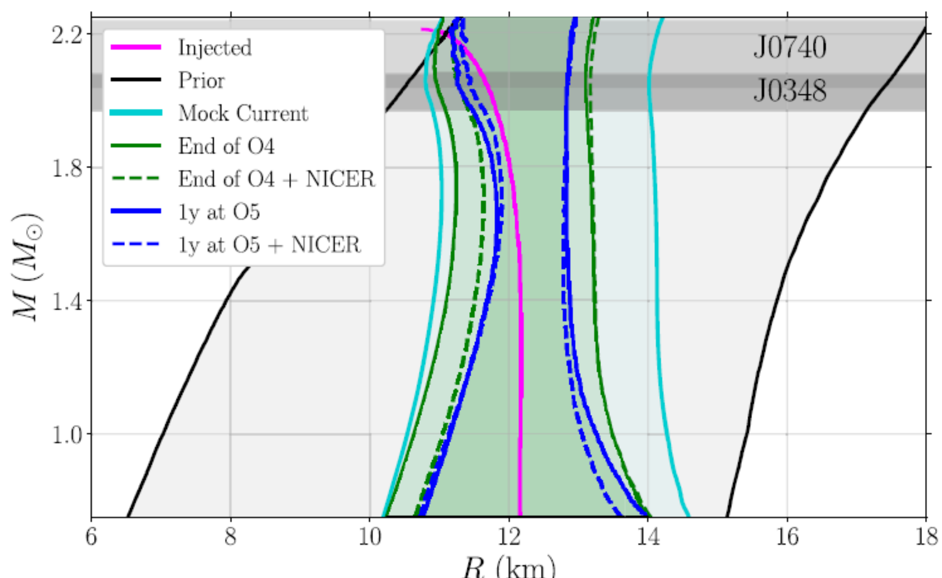


What should we understand then?

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





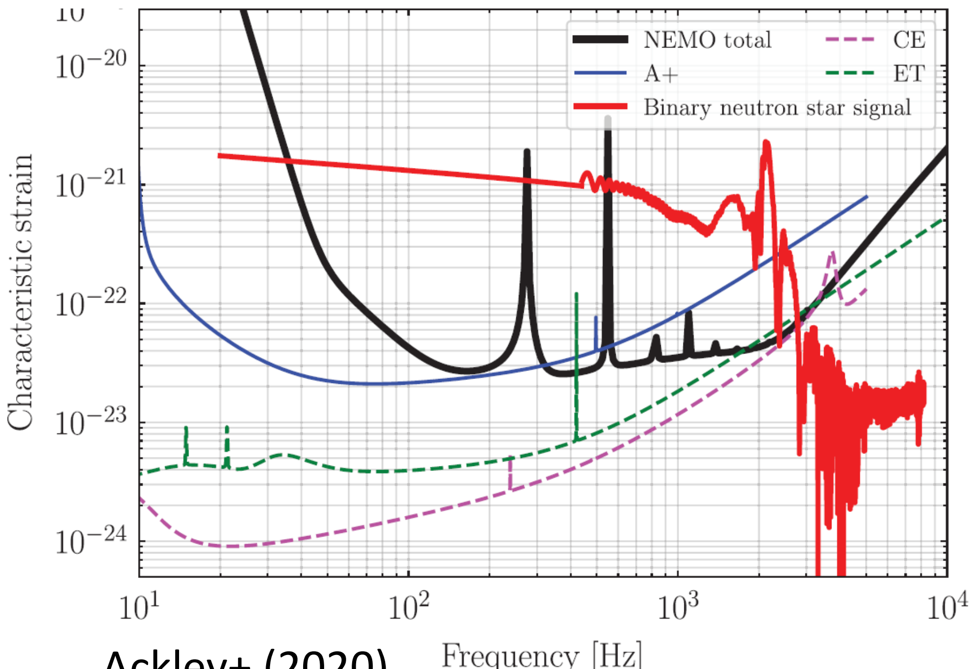
Landry+ (2020)

Future high-frequency observation

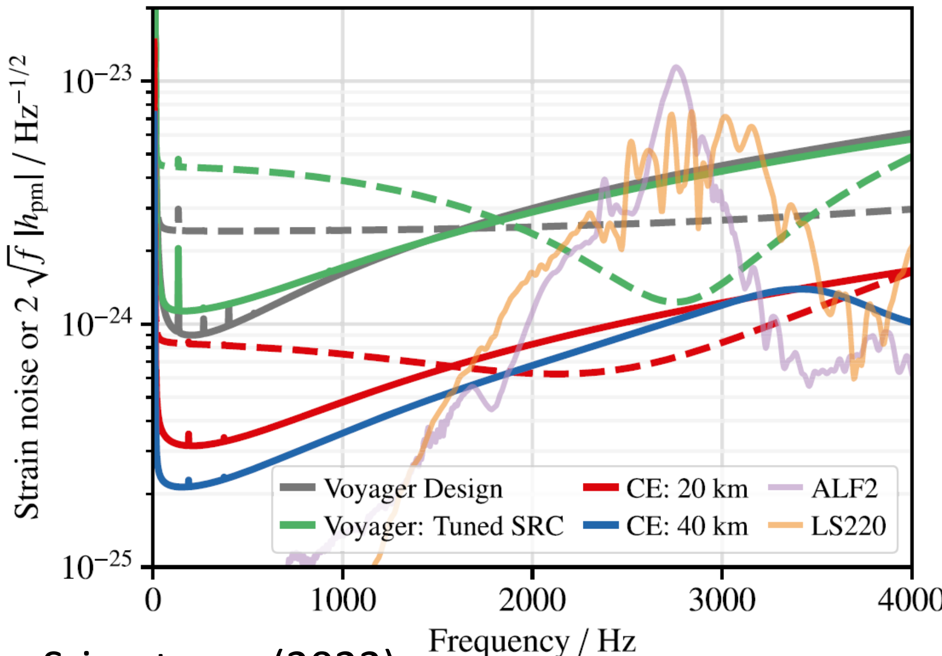
The high density requires high-frequency observations

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

Some proposals are made for postmerger signals



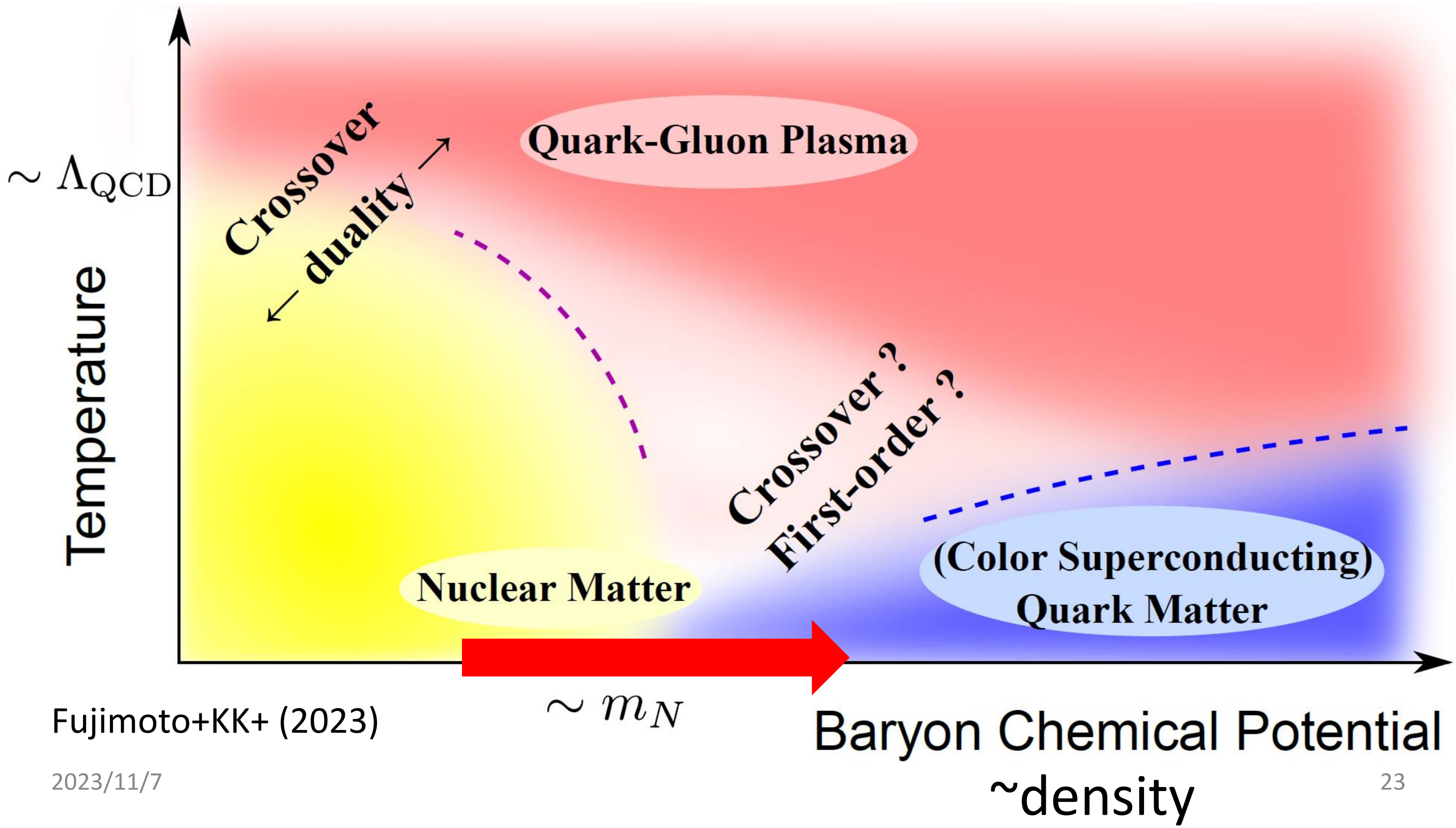
Ackley+ (2020)



Srivastava+ (2022)

QCD phase diagram

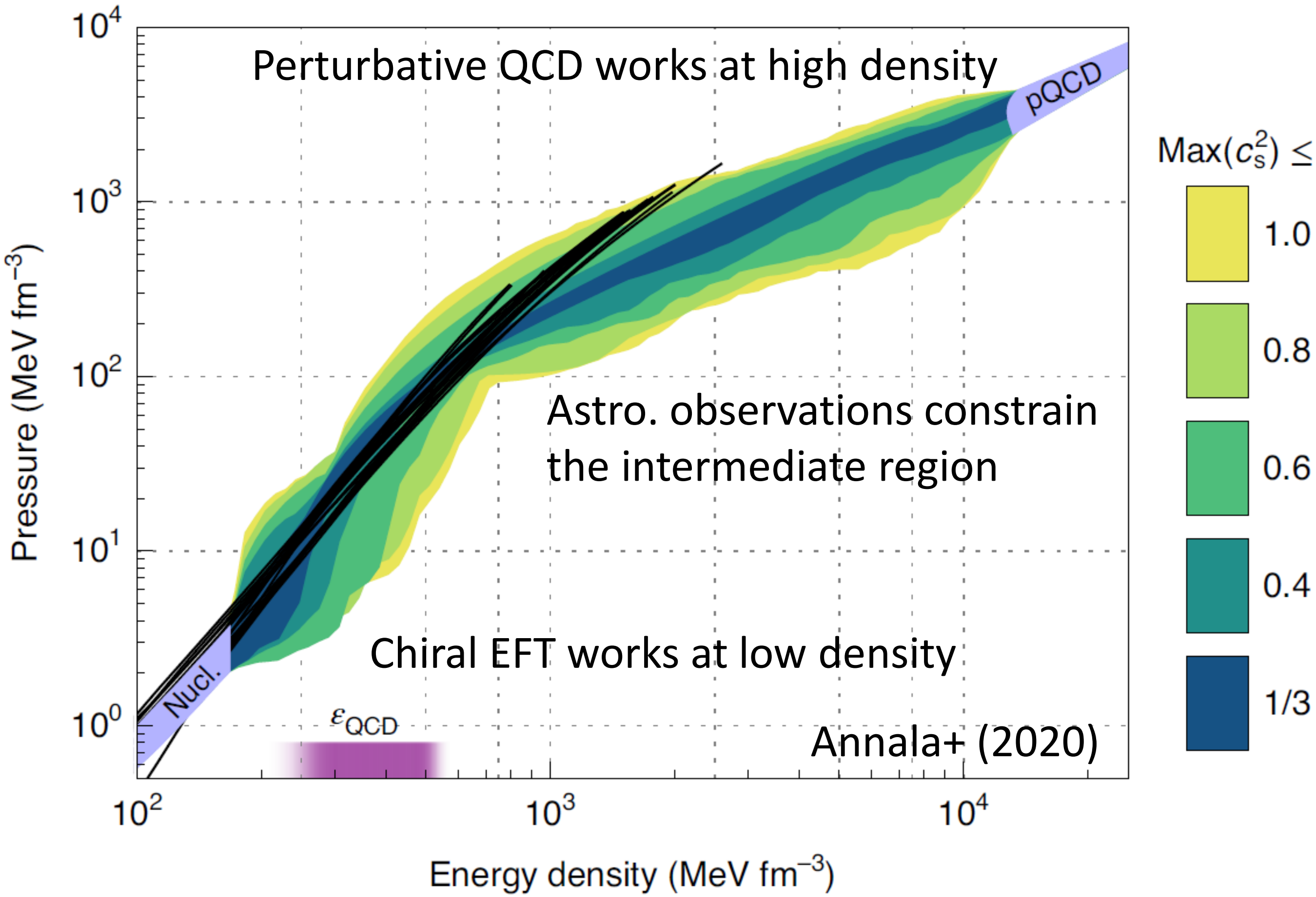
What kind of transition occurs from hadrons to quarks?



Fujimoto+KK+ (2023)

Current view of the transition

Smooth crossover transition might be realistic



Crossover vs. 1st order PT

Crossover

Smoothly connects two limits

Note: we need to explain

2 solar mass neutron stars

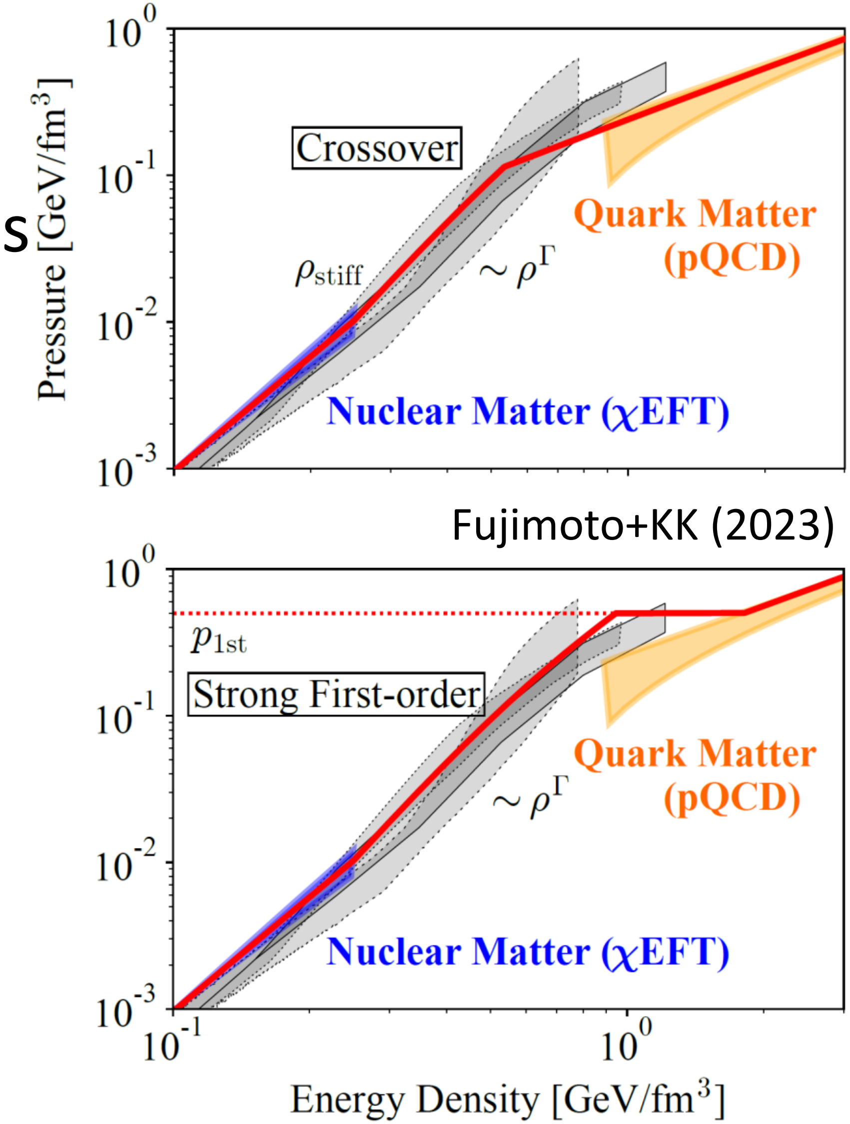
1st-order phase transition

Only very high density allow

strong phase transition…

No effect on astrophysics?

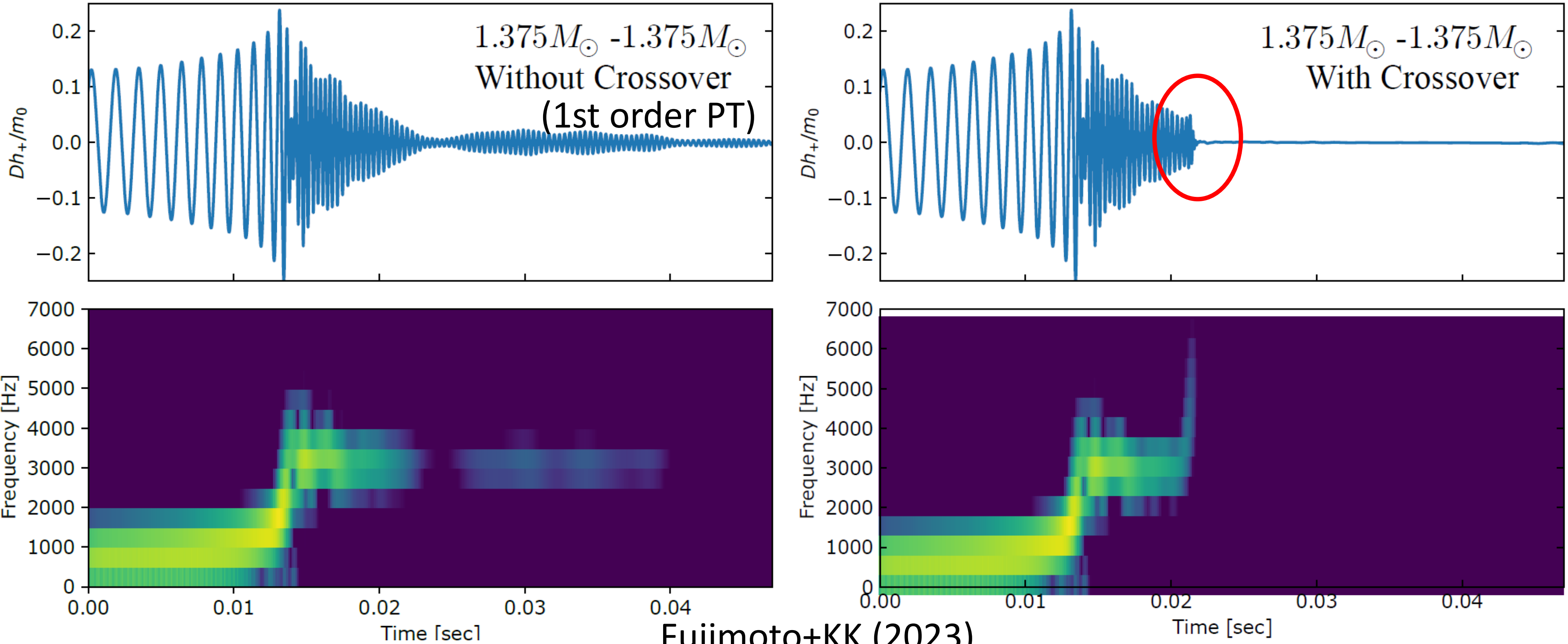
[see also Huang+ (2022), Kedia+ (2022)]



Fujimoto+KK (2023)

Black-hole formation as a key

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



Fujimoto+KK (2023)

Did GW170817 form a black hole?

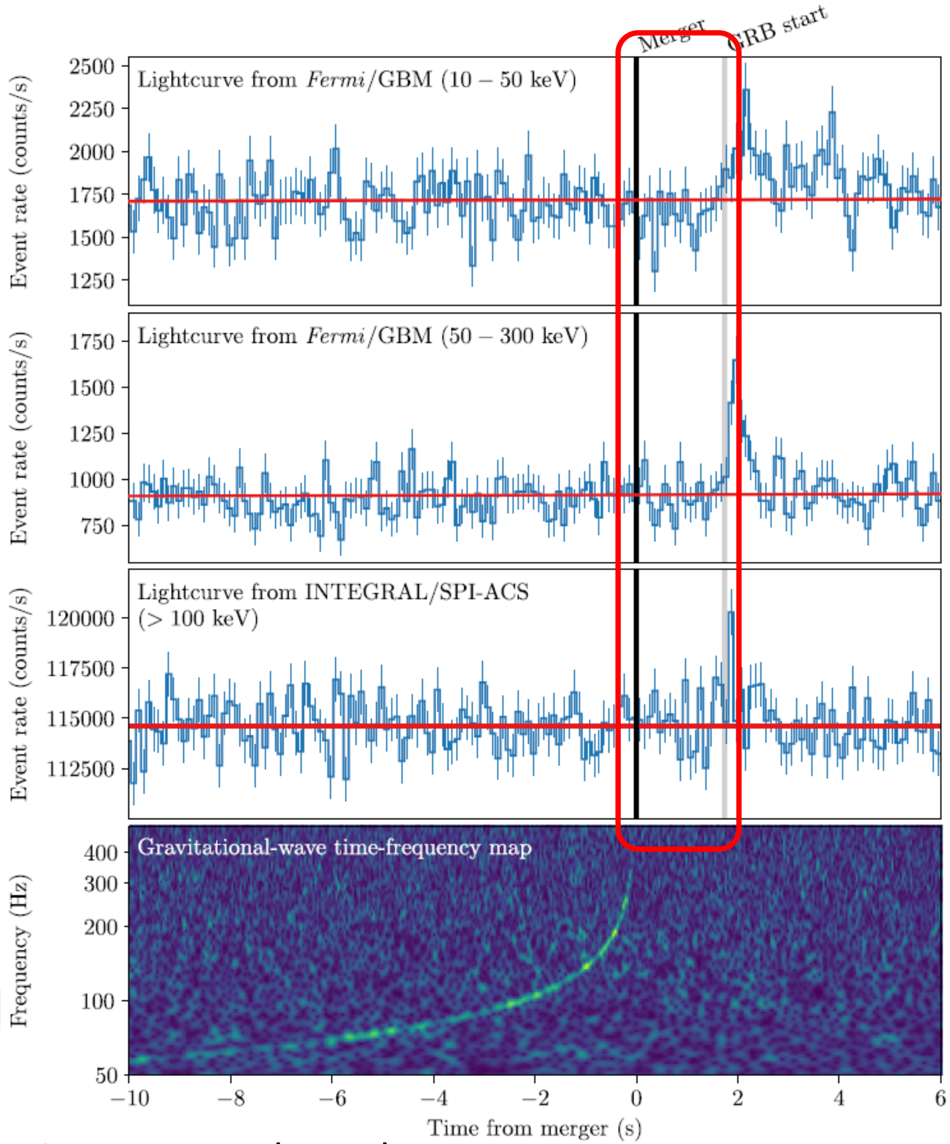
Nobody knows the answer

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]

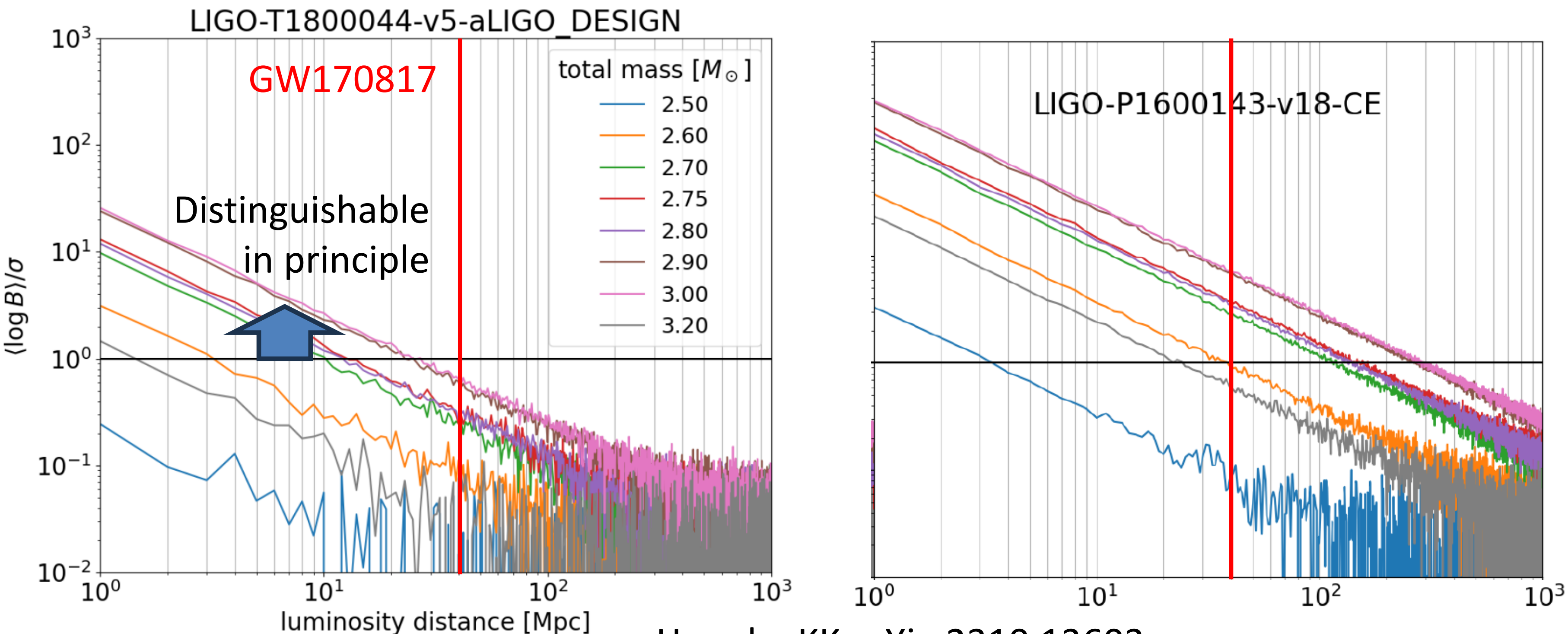


LIGO&Virgo&Fermi&INTEGRAL (2017)

Distinguishability in data analysis

AdLIGO is insufficient even at design sensitivity (left)

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



Harada+KK arXiv:2310.13603

3. Summary

Summary

- Multimessenger observations of binary-neutron-star mergers have delivered important information about theory of gravity and cosmology.
- The neutron-star equation of state is constrained by measuring tidal deformability from inspiral gravitational waveforms.
- In the future, postmerger gravitational waveforms may enable us to study the QCD phase diagram via the gravitational collapse of merger remnants.

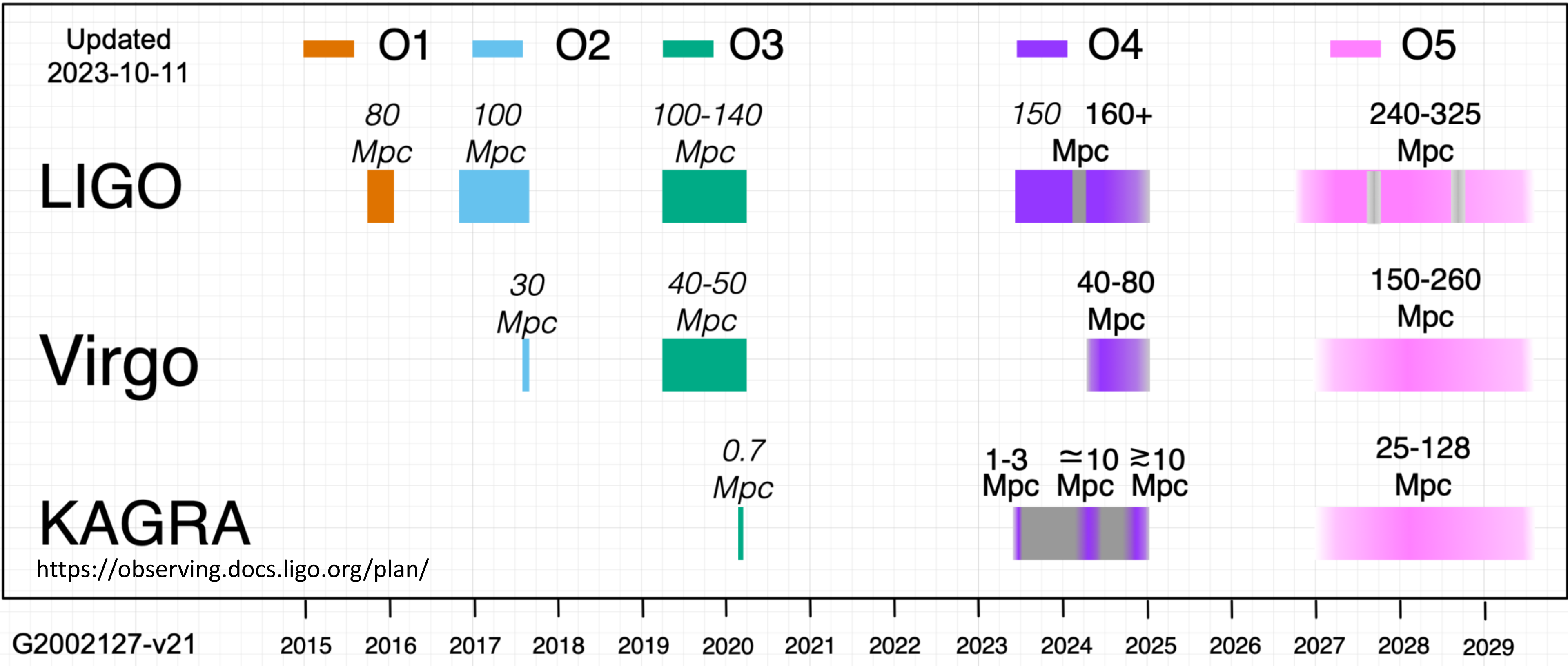
Appendix

Gravitational-wave detectors

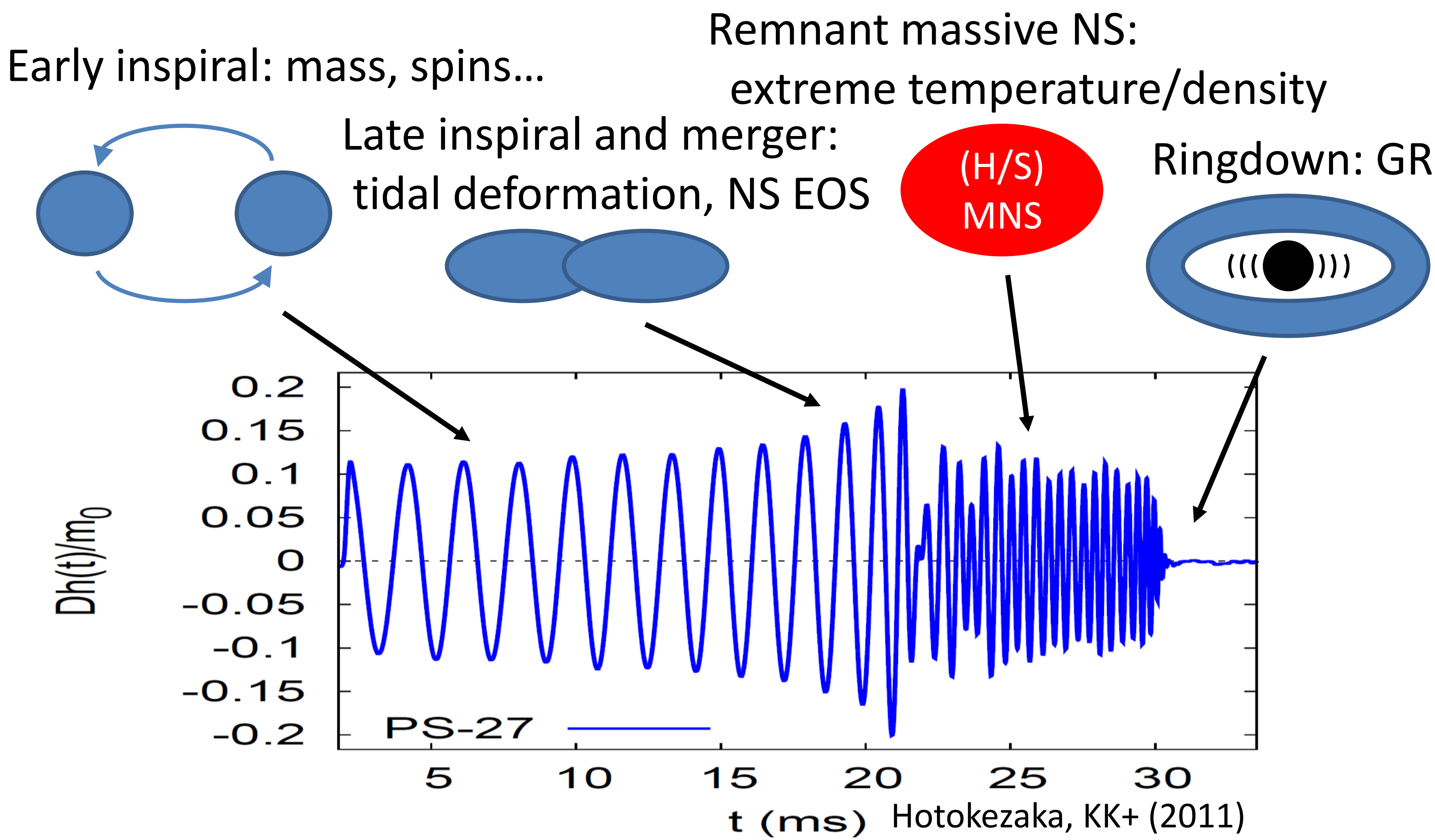
Observation plan

O4 will continue throughout 2024 with improvement

O5 is planned to start from the beginning of 2027



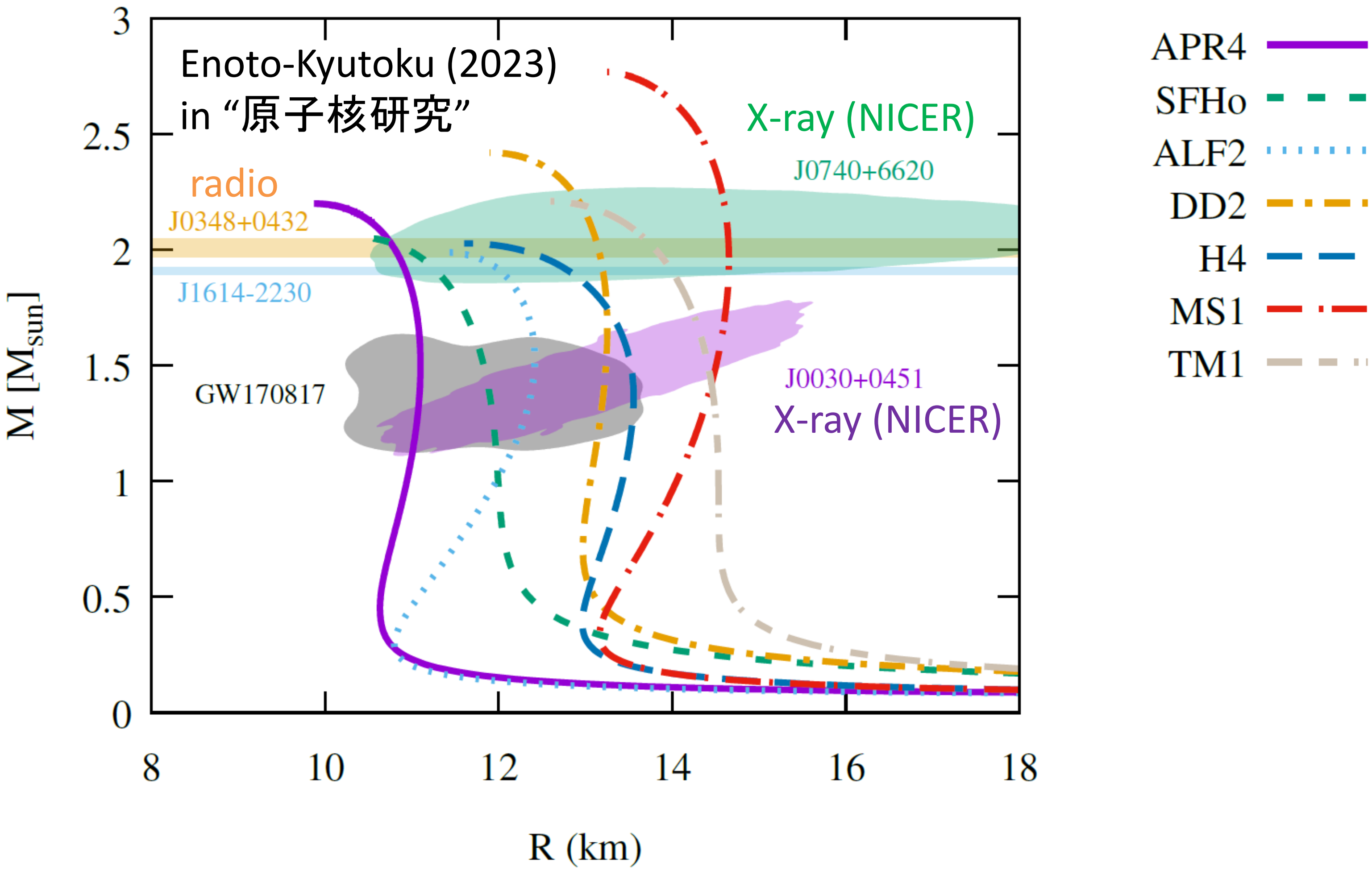
Various phases of coalescence



Hotokezaka, KK+ (2011)

Current constraint

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

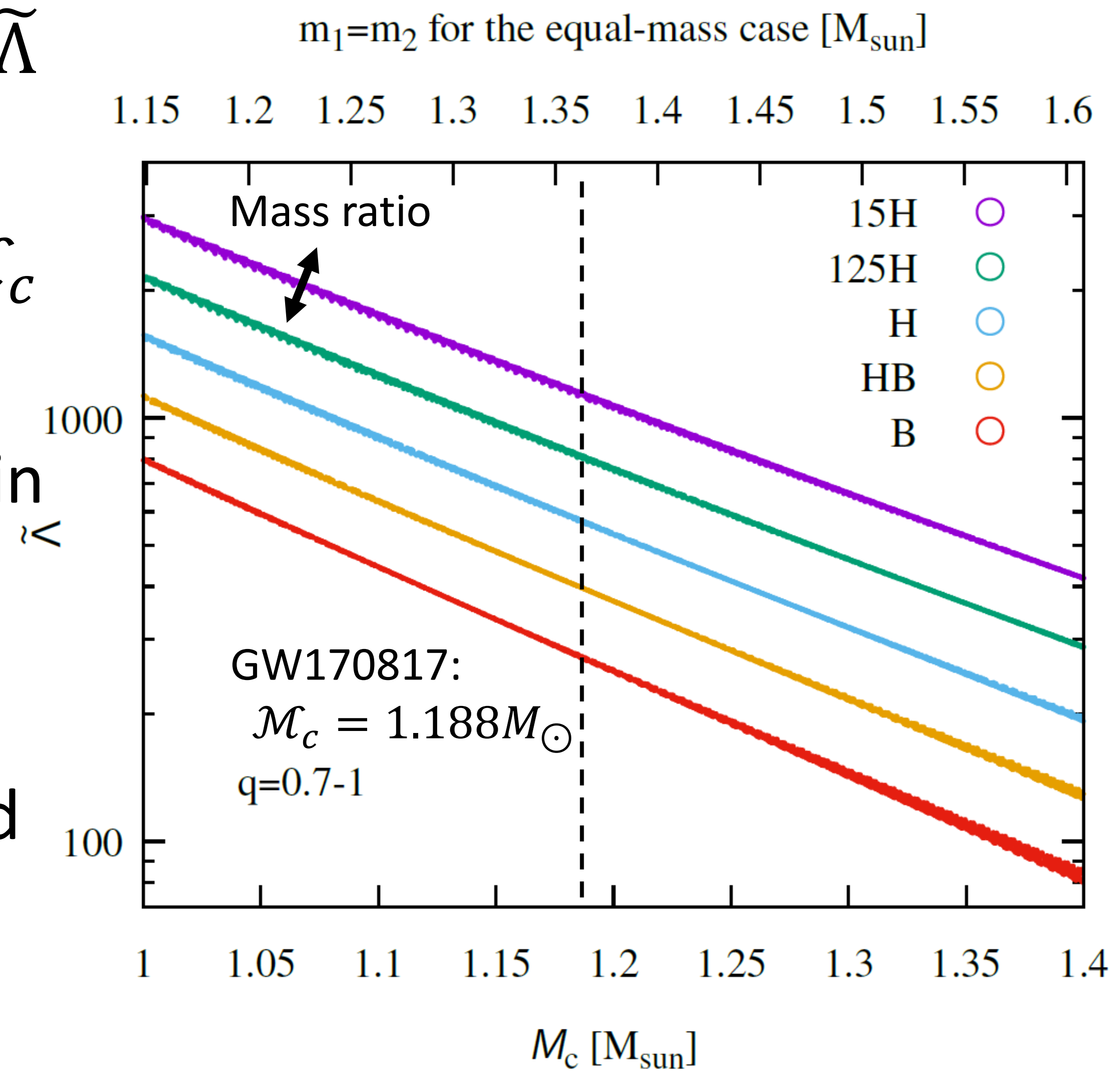


Strong correlation of $\tilde{\Lambda} - \mathcal{M}_c$

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

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

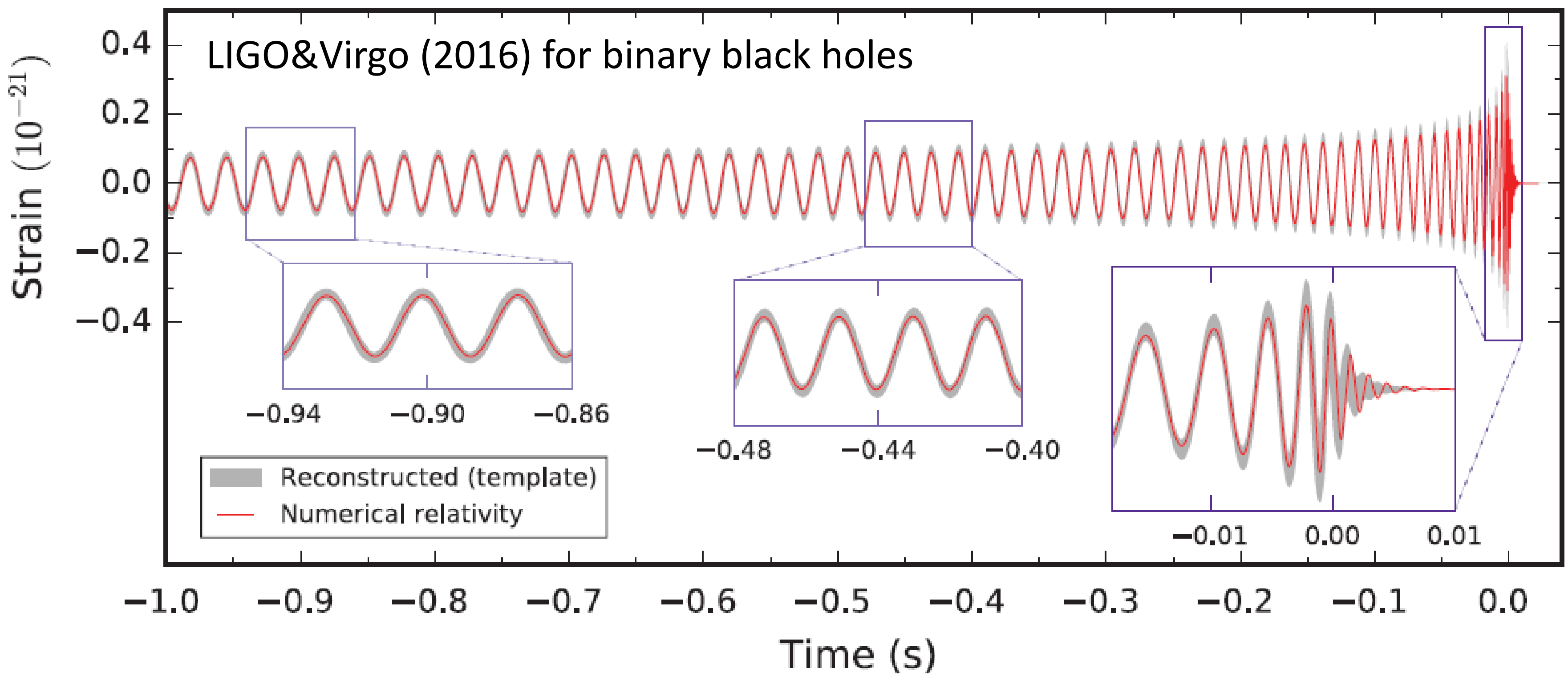
>13-14km is disfavored



Role of theoretical templates

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

Accurate theoretical models are indispensable

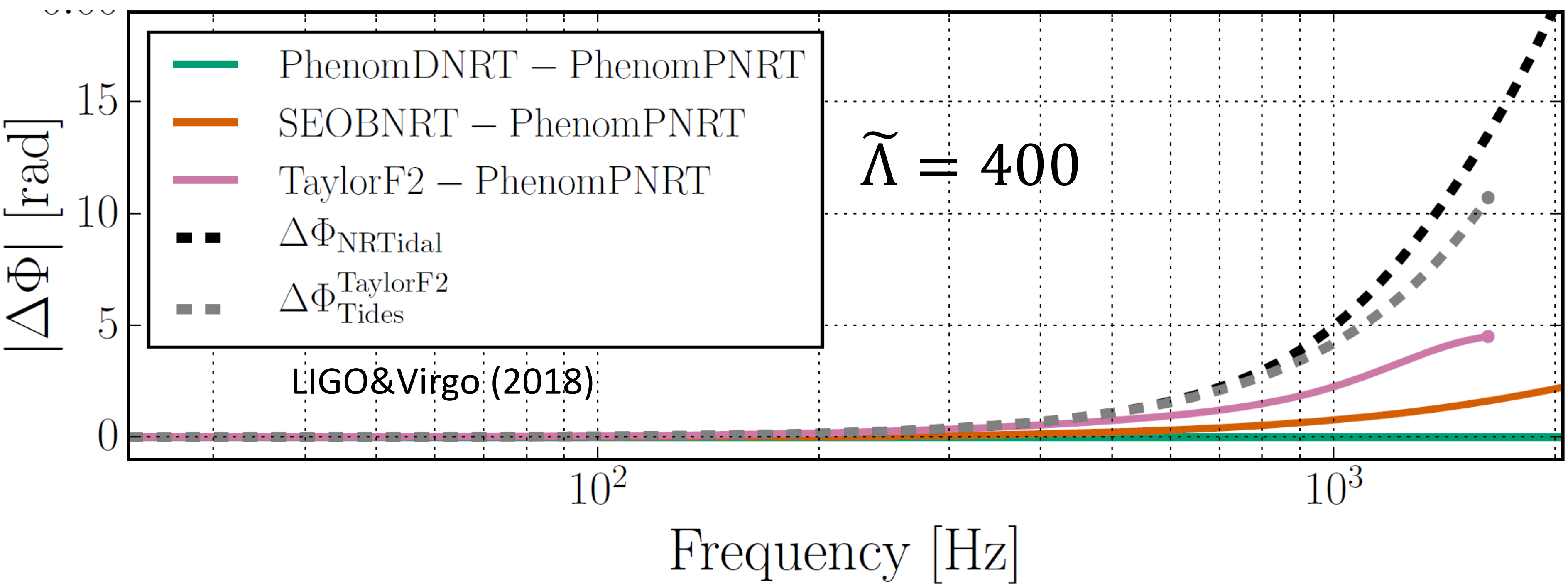


Uncertainty in the waveform model

1 radian difference usually makes differences

Current systematic errors are larger than 1 radian

We need accurate waveforms for better estimation



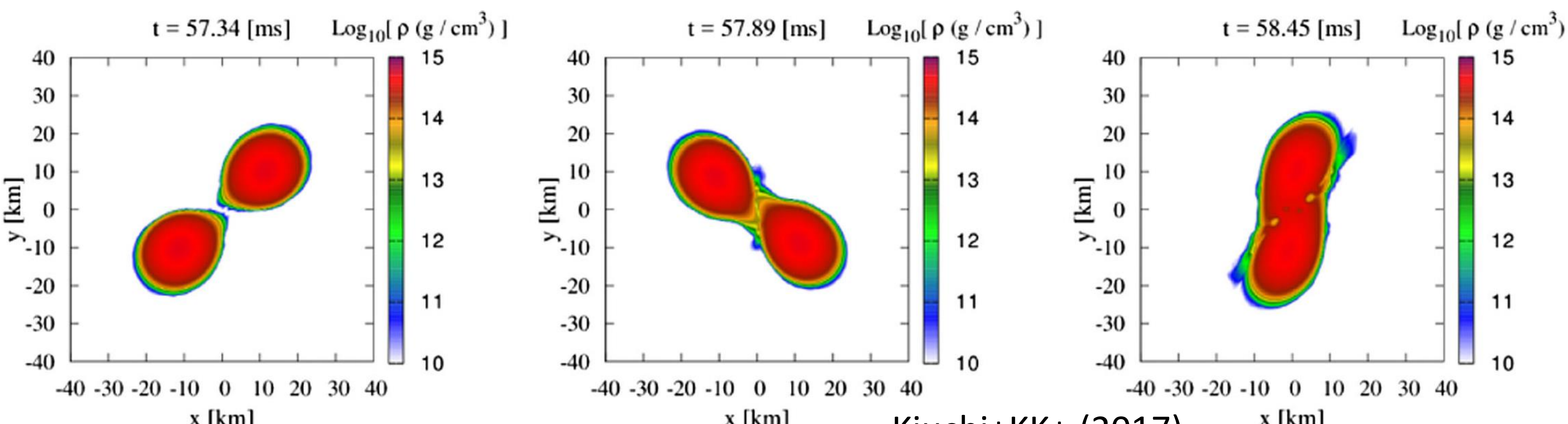
LIGO&Virgo (2018)

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

Kyoto gravitational-wave model

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

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

+ correction terms associated w/ mass asymmetry

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

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

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

Case of GW190425

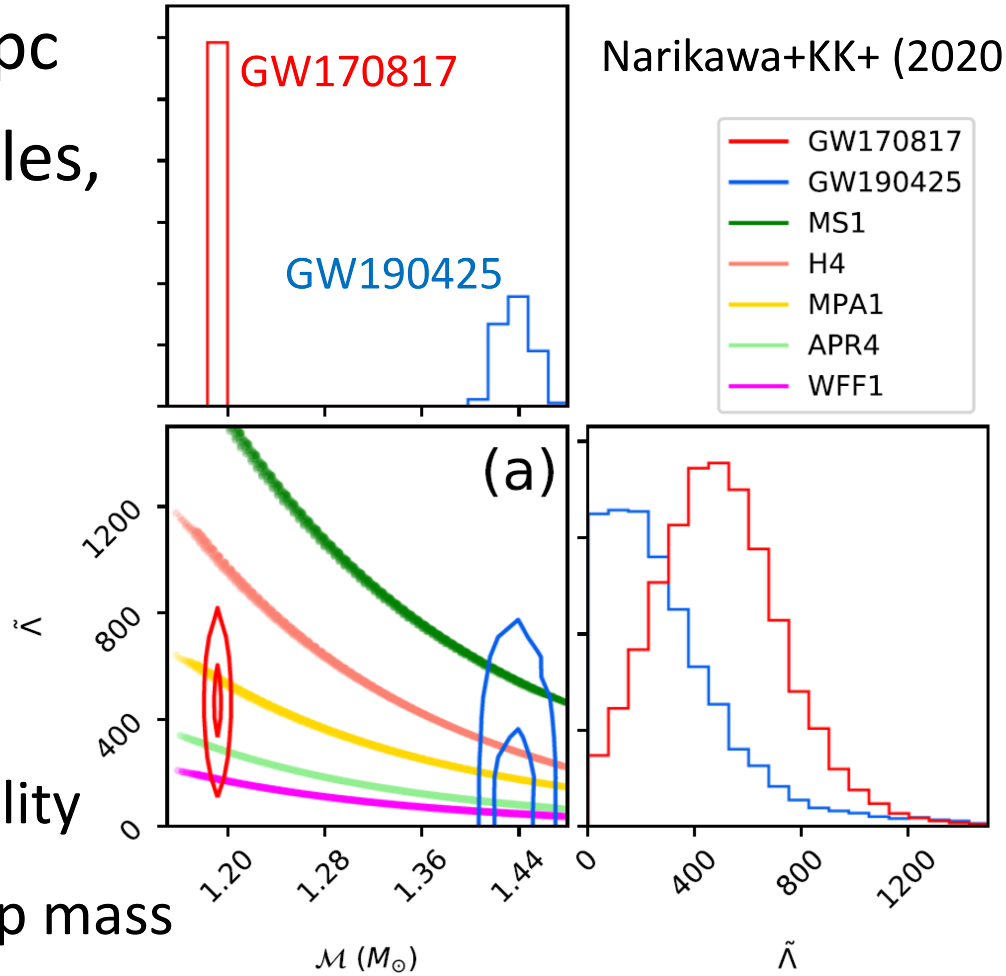
Weak constraint due to the high mass $3.4M_{\odot}$ and the large distance 150-250Mpc

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

[see also Kyutoku+ (2020)]

Simply GW170817 was extremely lucky

Narikawa+KK+ (2020)

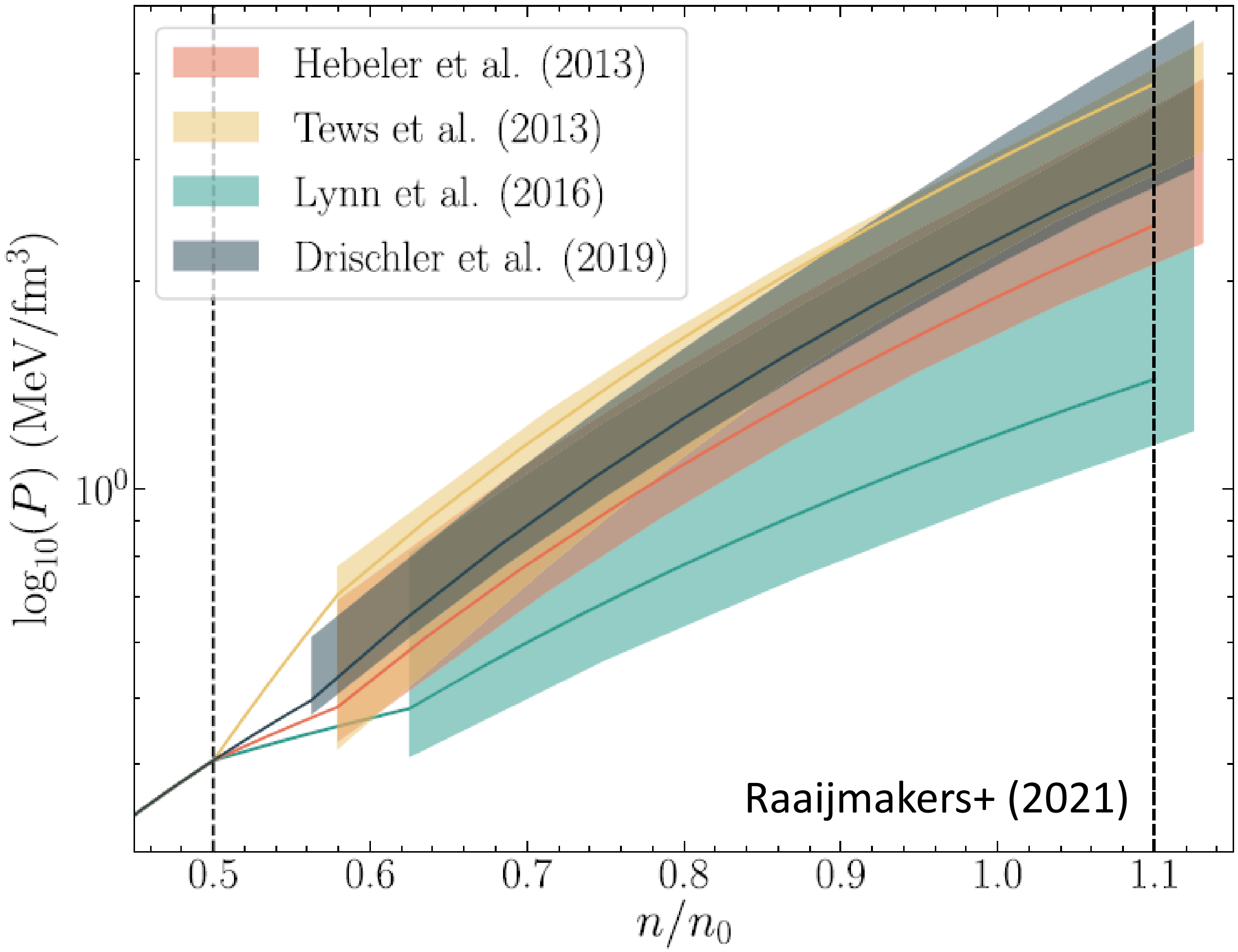


Binary tidal deformability

Chirp mass

Uncertainty in chiral EFT

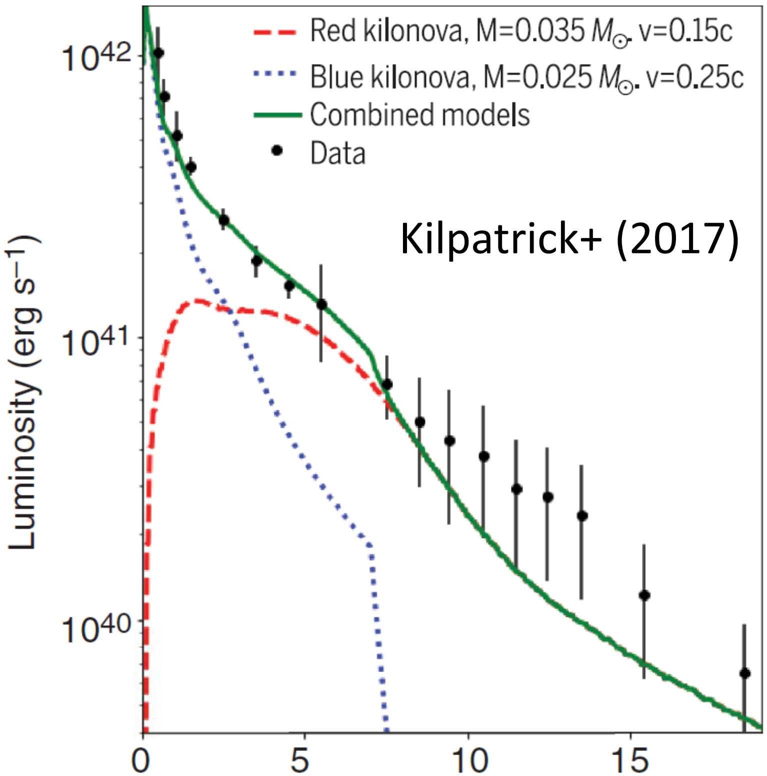
The validity range is crucial for strength of constraints



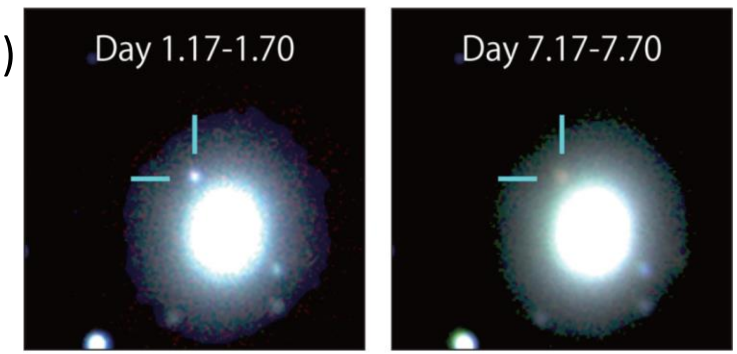
Kilonova: AT 2017gfo

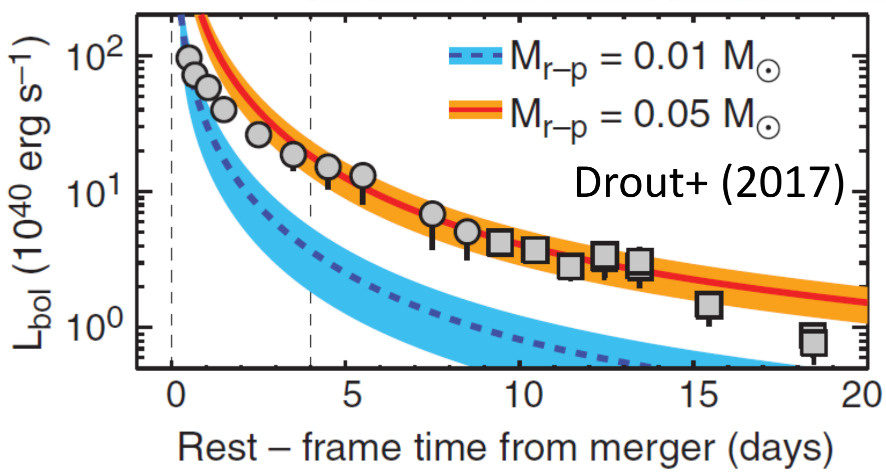
Indication of the large ejecta mass of $\sim 0.05 M_{\odot}$

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



Utsumi+ (2017)



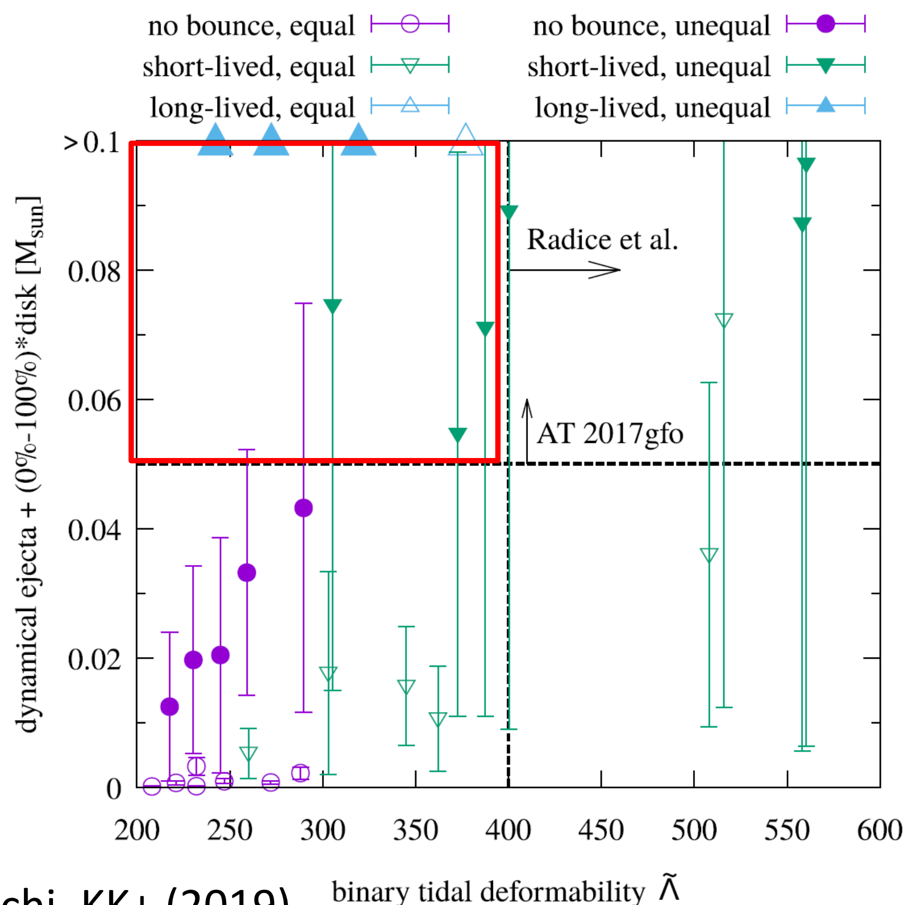


A lot of counterexamples

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)

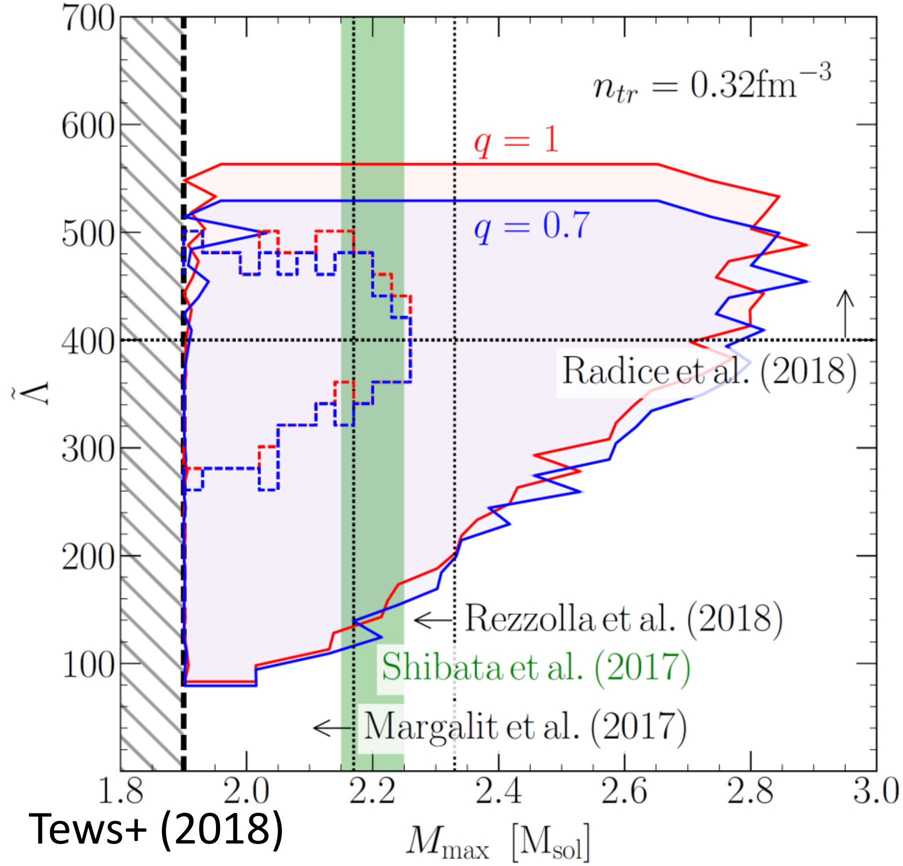


Kiuchi, KK+ (2019)

Reason?

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

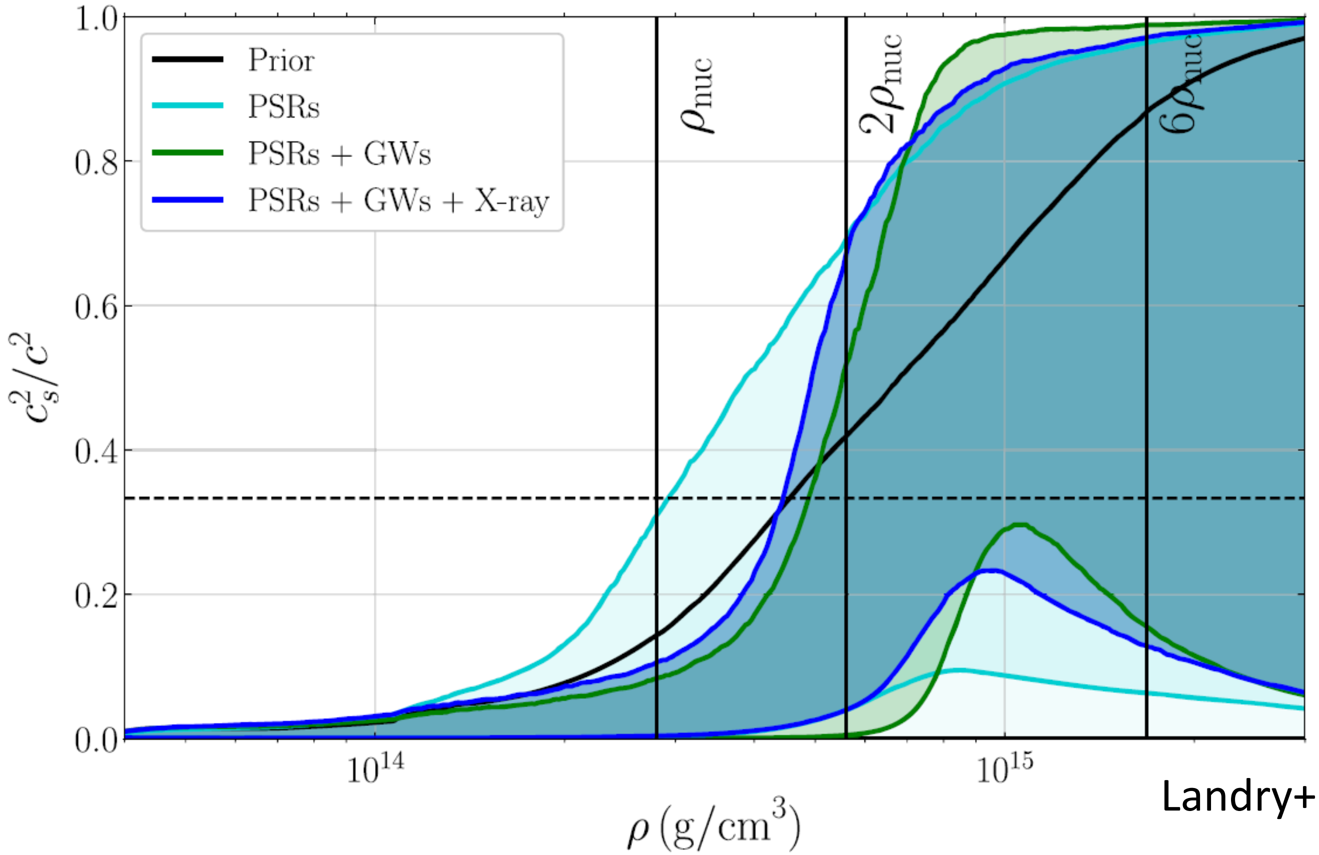
If the remnant survived moderately long due to the large value of M_{max}, there should be no reason that mass ejection is weak



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

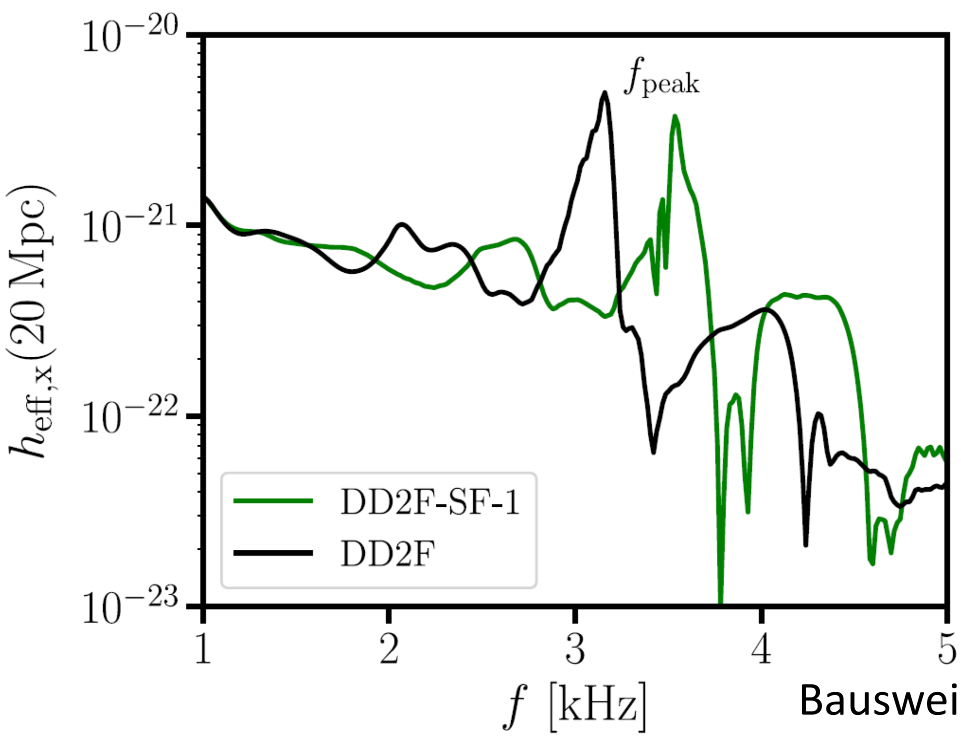


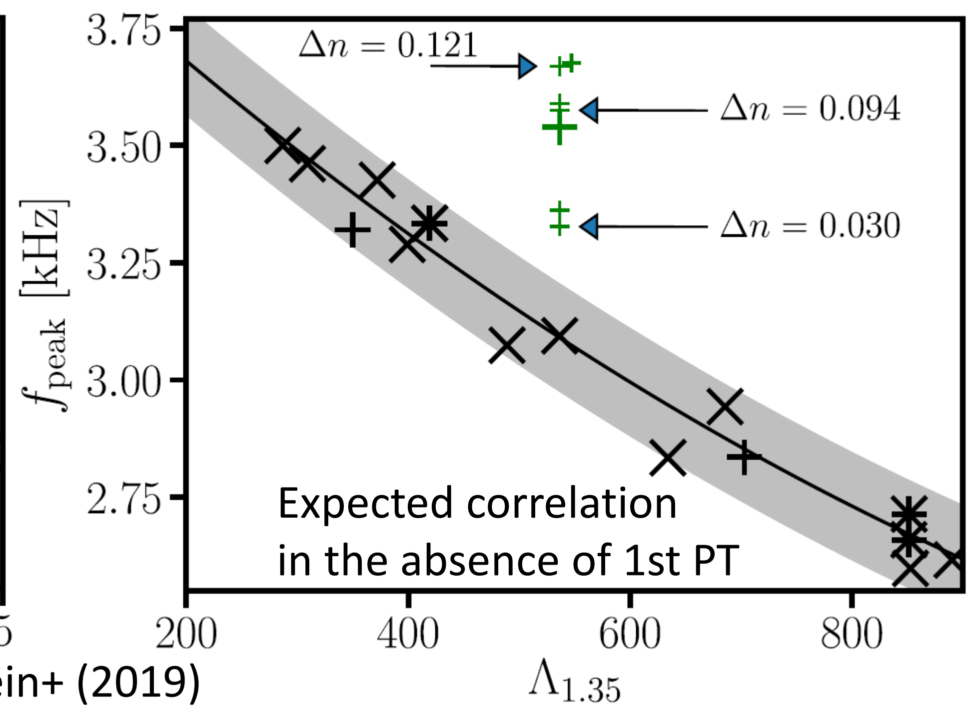
Landry+ (2020)

1st-order phase transition

Postmerger neutron stars emit quasiperiodic signals

Strong first-order phase transition at very high density may be identified via the shift of the peak frequency





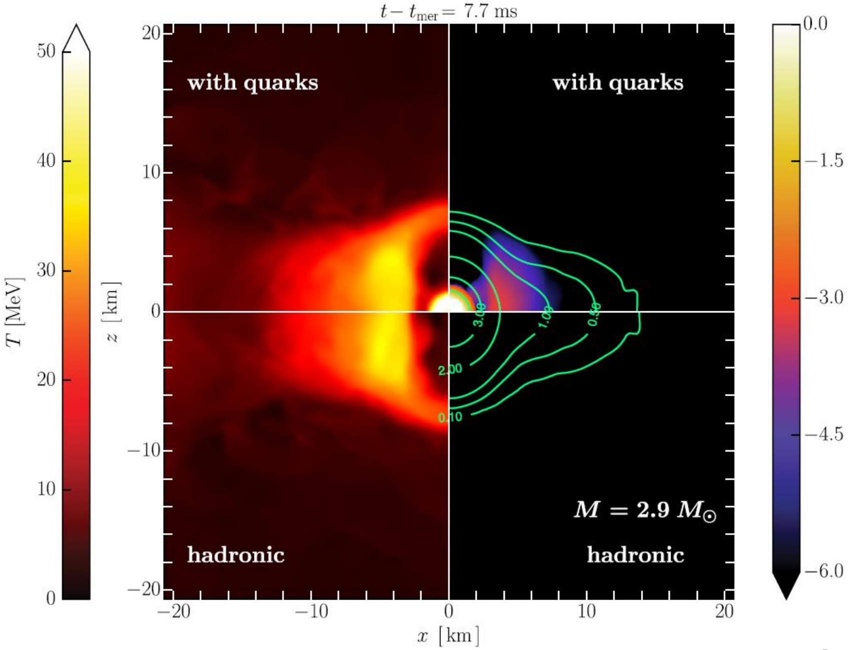
Bauswein+ (2019)

Structure of the merger remnant

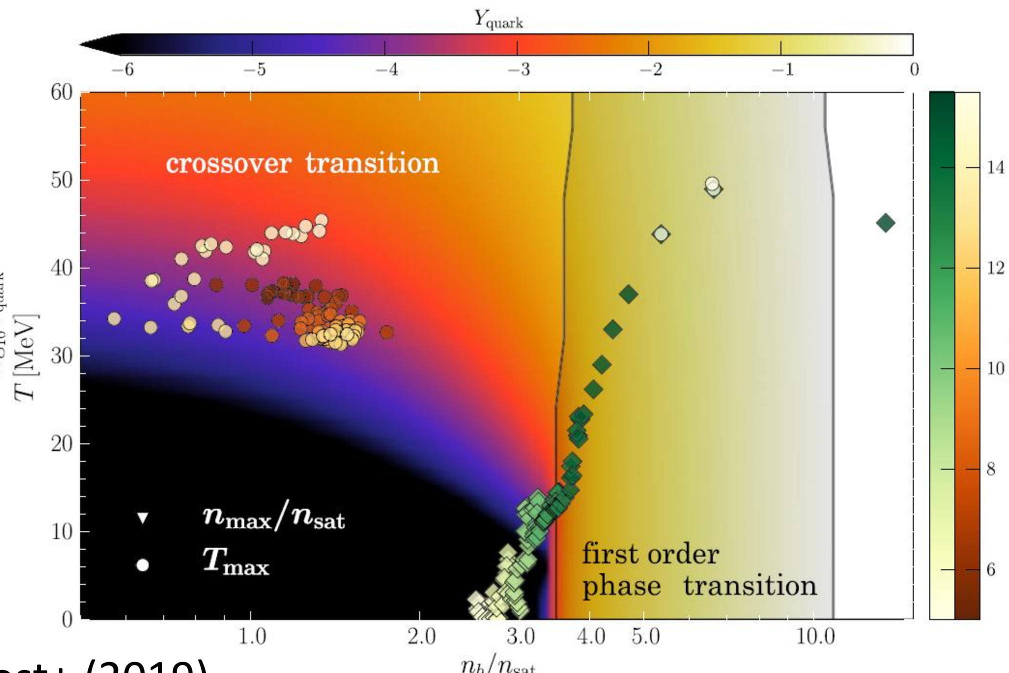
Density/temperature structures are not very different

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

Top: w/ quark, bottom: hadron only



Time evolution of maximum n and T

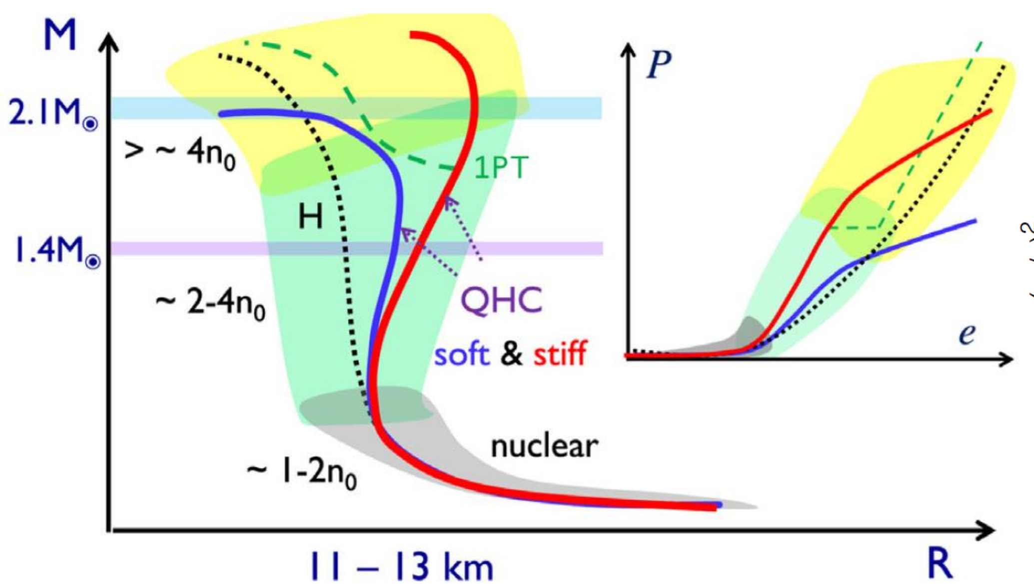


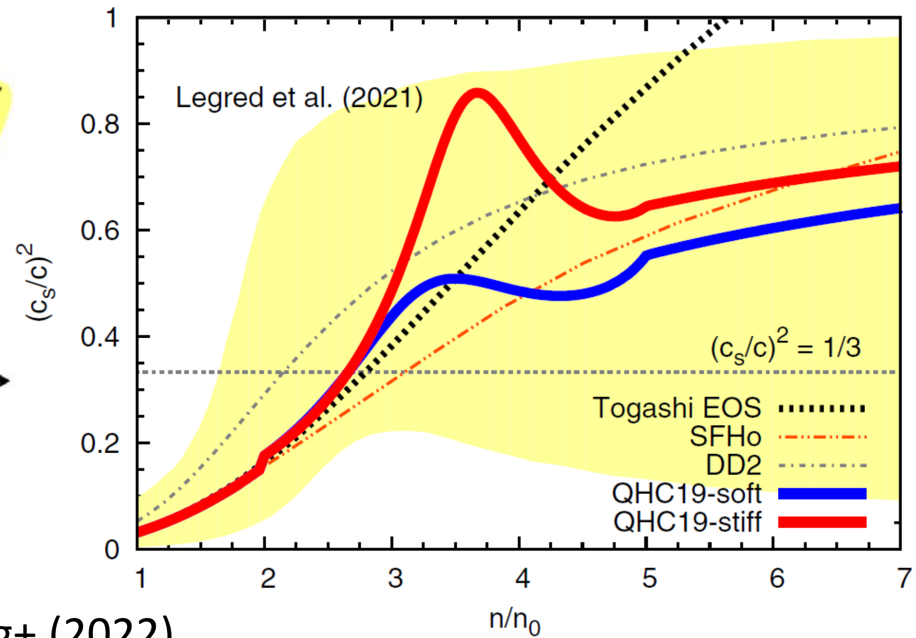
Most+ (2019)

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

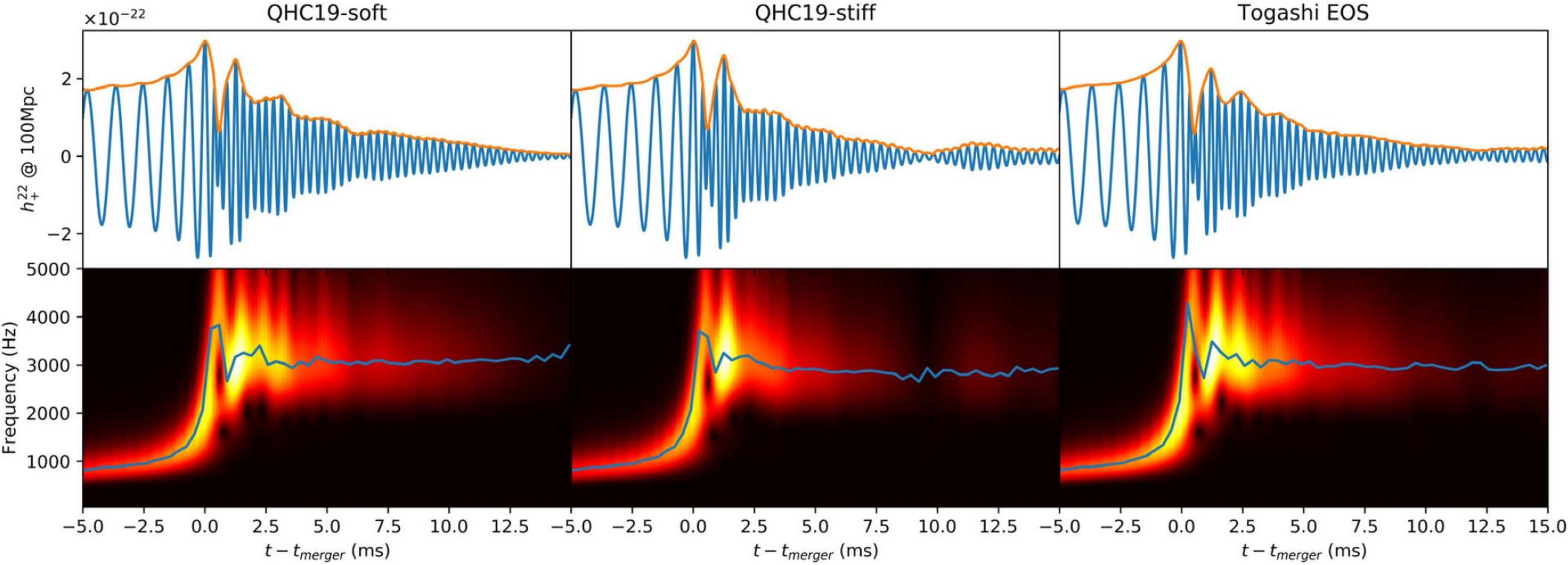




Huang+ (2022)

Cf: results with QHC (other study)

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



Huang+ (2022)

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

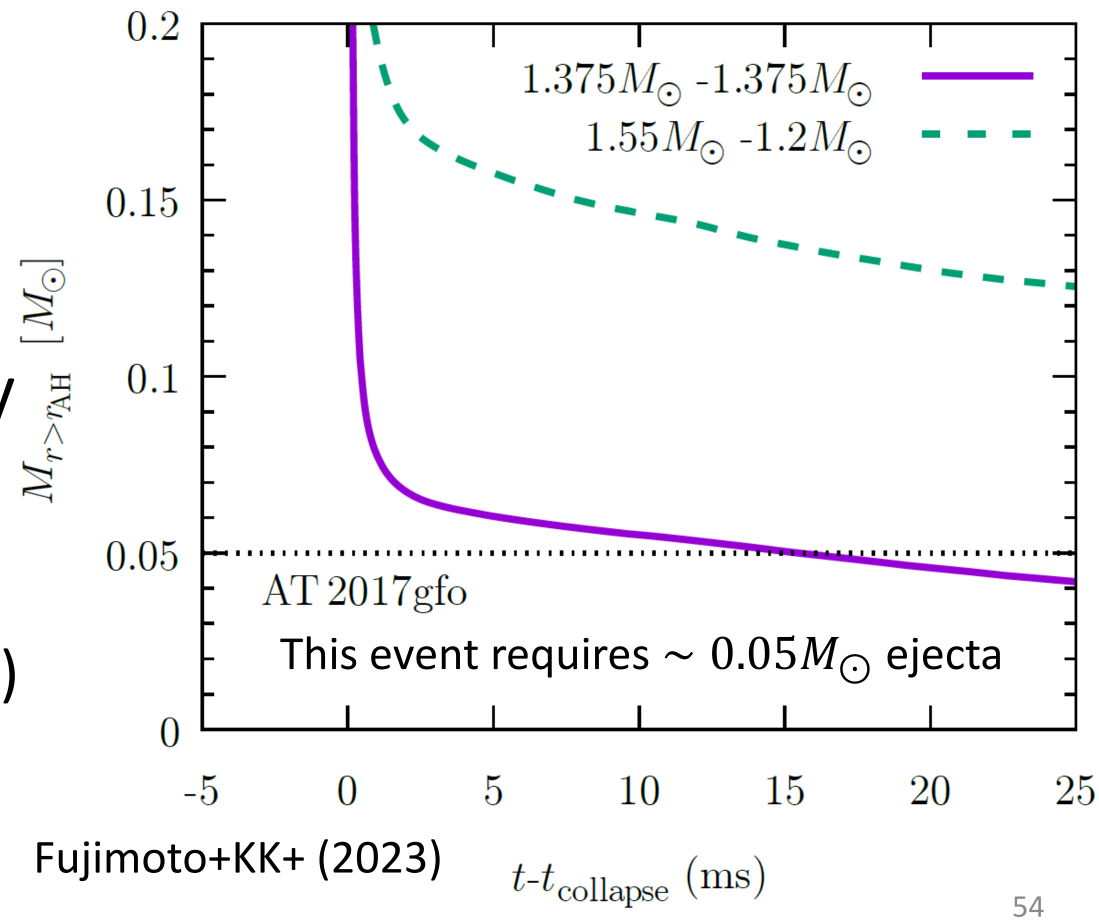
Grid resolution? (finite, of course)

Checked weak dependence but always a touch topic

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)



Fujimoto+KK+ (2023)