Signature of hadron-quark crossover in binary-neutron-star mergers

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Plan of the talk

1. Inspiral: neutron-star equation of state
2. Postmerger: crossover vs. 1st-order phase transition
3. Summary

1. Inspiral: neutron-star equation of state

Neutron star binary coalescence

Gravitational waves

high-density matter signature: equation of state

test of the theory of gravitation in a non-vacuum

Formation of a hot massive remnant (star/disk)

central engine of short-hard gamma-ray bursts

Mass ejection of neutron-rich material

r-process nucleosynthesis

radioactively-driven kilonova

Candidate from O4

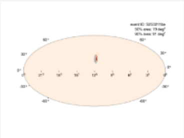
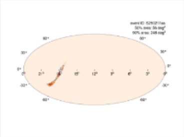
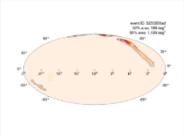
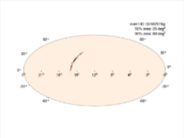
~200 binary black holes vs. **0 binary neutron stars**

(with a few black hole-neutron star merger candidates)

GraceDB Public Alerts Latest Search Documentation Login

https://gracedb.ligo.org/superevents/public/O4/#

Please log in to view full database contents.

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S250211be	BBH (99%), Terrestrial (1%)	Yes	Feb. 11, 2025 04:35:43 UTC	GCN Circular Query Notices | VOE		1 per 1.7778 years	
S250211aa	BBH (>99%)	Yes	Feb. 11, 2025 02:25:46 UTC	GCN Circular Query Notices | VOE		1 per 6.7779e+09 years	
S250208ad	BBH (>99%)	Yes	Feb. 8, 2025 03:51:06 UTC	GCN Circular Query Notices | VOE		1 per 84.502 years	
S250207bg	BBH (>99%)	Yes	Feb. 7, 2025 11:56:45 UTC	GCN Circular Query Notices | VOE		1 per 6.4428e+27 years	

Back-of-the-envelope estimation

Rate at the end of O3 [LIGO&Virgo&KAGRA 2023]

Now this might be lowered by ~3 (from #binary black holes)… 100?

Milky-way equivalent galaxy has the density of $\sim 0.01\ \mathrm{Mpc}^{-3}$

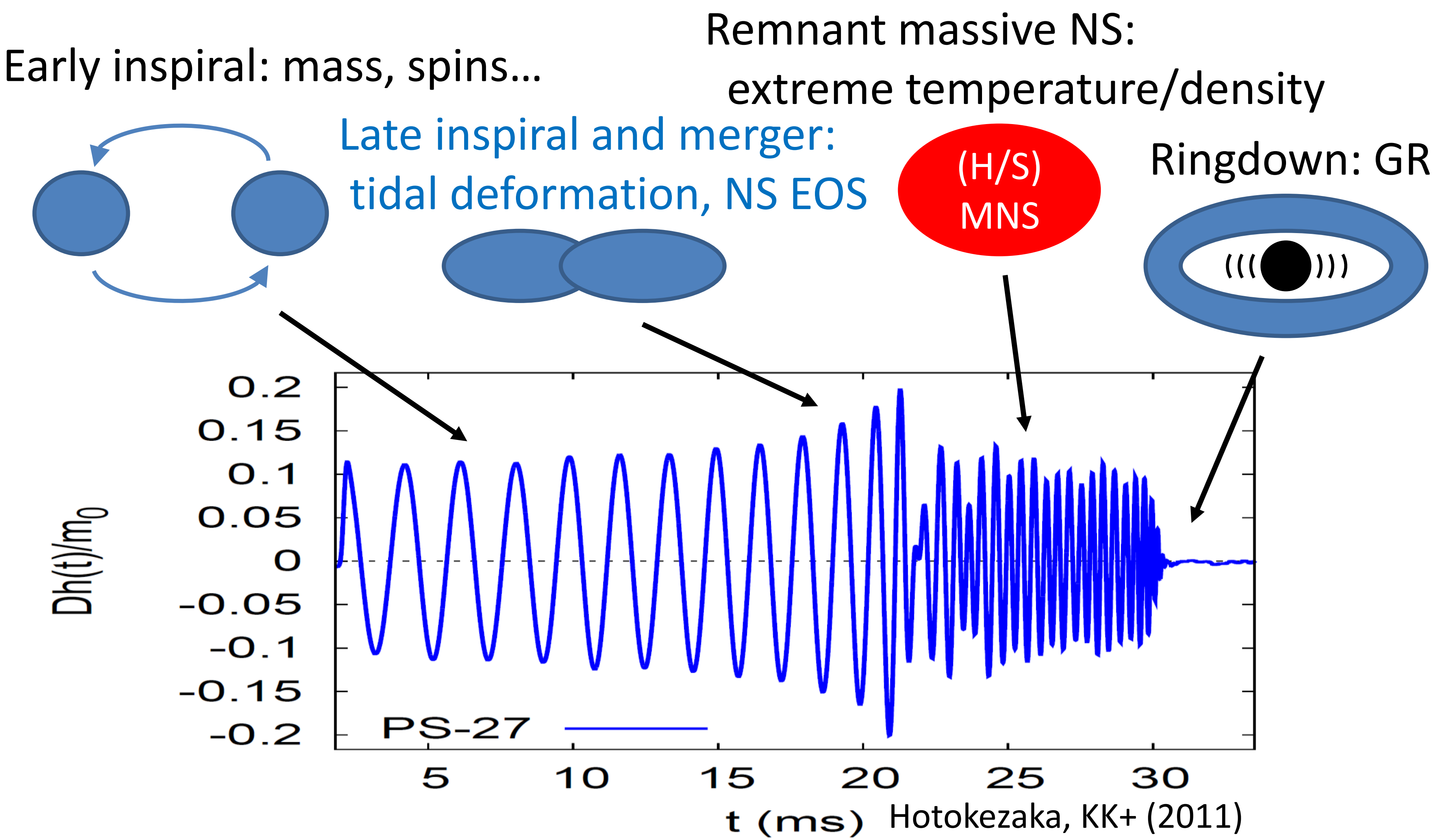
-> once in $\sim 10^5$ yr in our Galaxy?

Model	BNS $m_1 \in [1, 2.5]M_\odot$ $m_2 \in [1, 2.5]M_\odot$
PDB (pair)	170^{+270}_{-120}
PDB (ind)	44^{+96}_{-34}
MS	660^{+1040}_{-530}
BGP	$98.0^{+260.0}_{-85.0}$
MERGED	10–1700
	$\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Galactic r-process production rate $\sim 10^{-6} M_\odot\ \mathrm{yr}^{-1}$

One merger produces $\sim 0.1 M_\odot$ r-process element ???

Various phases of coalescence

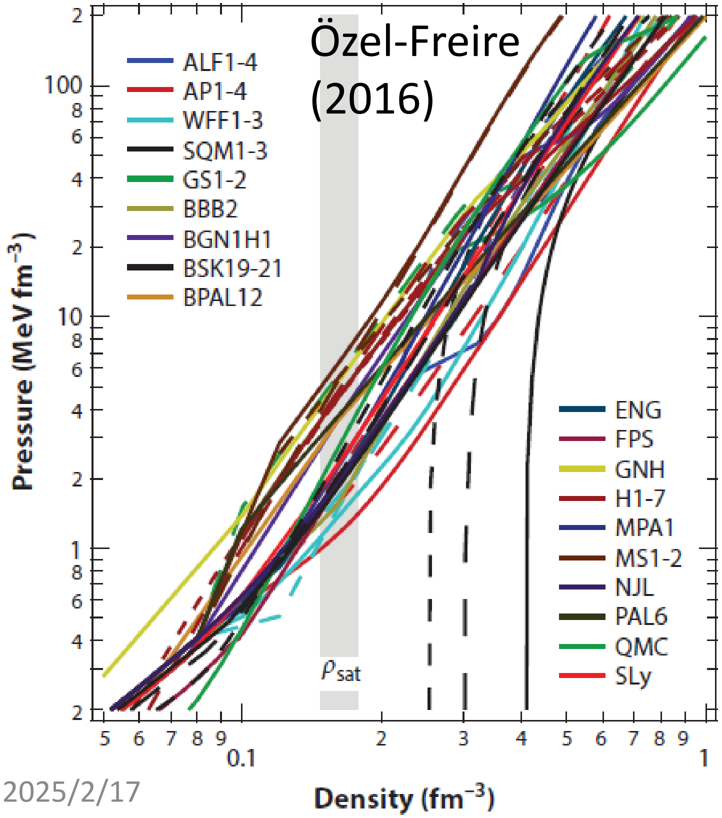


Hotokezaka, KK+ (2011)

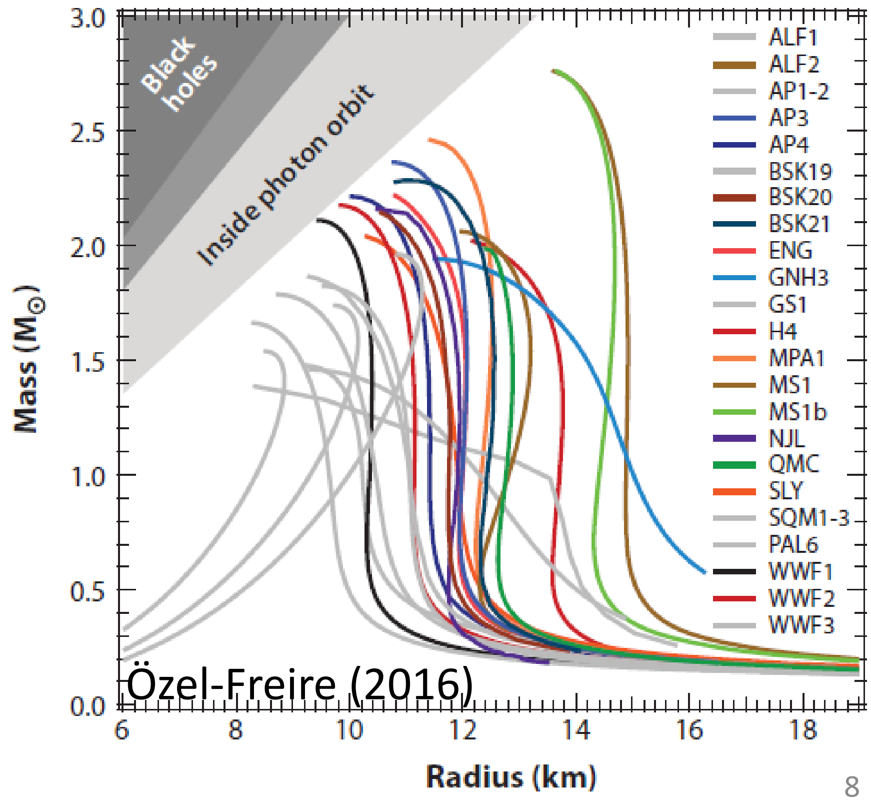
Neutron star equation of state

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

Equation of state: Nuclear physics



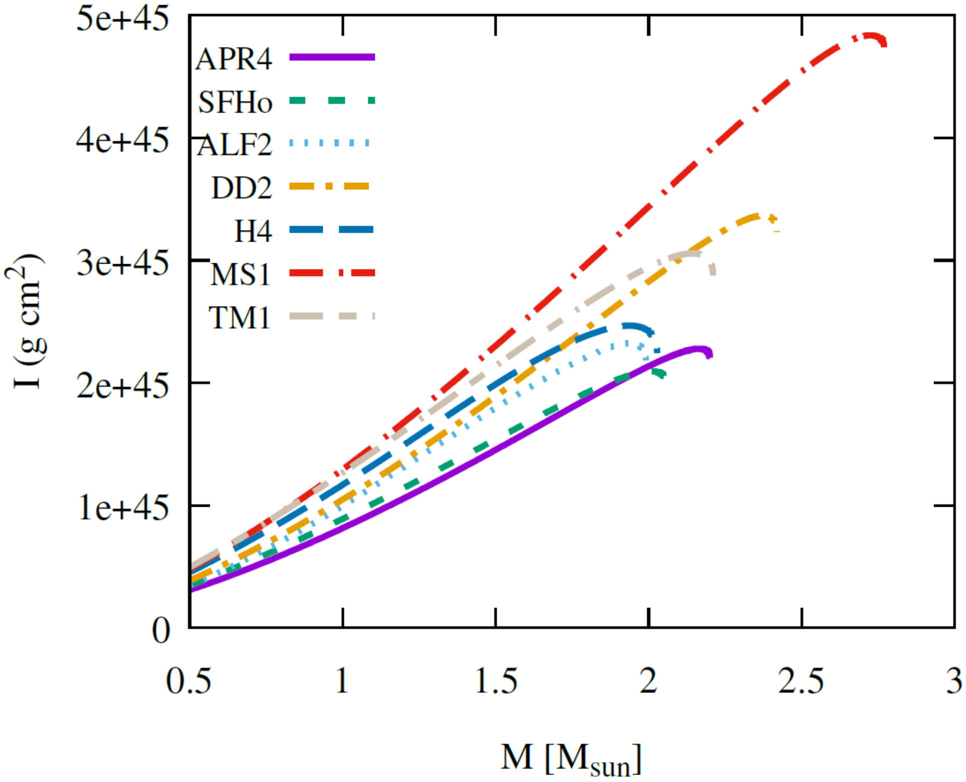
Mass-Radius relation: Astrophysics



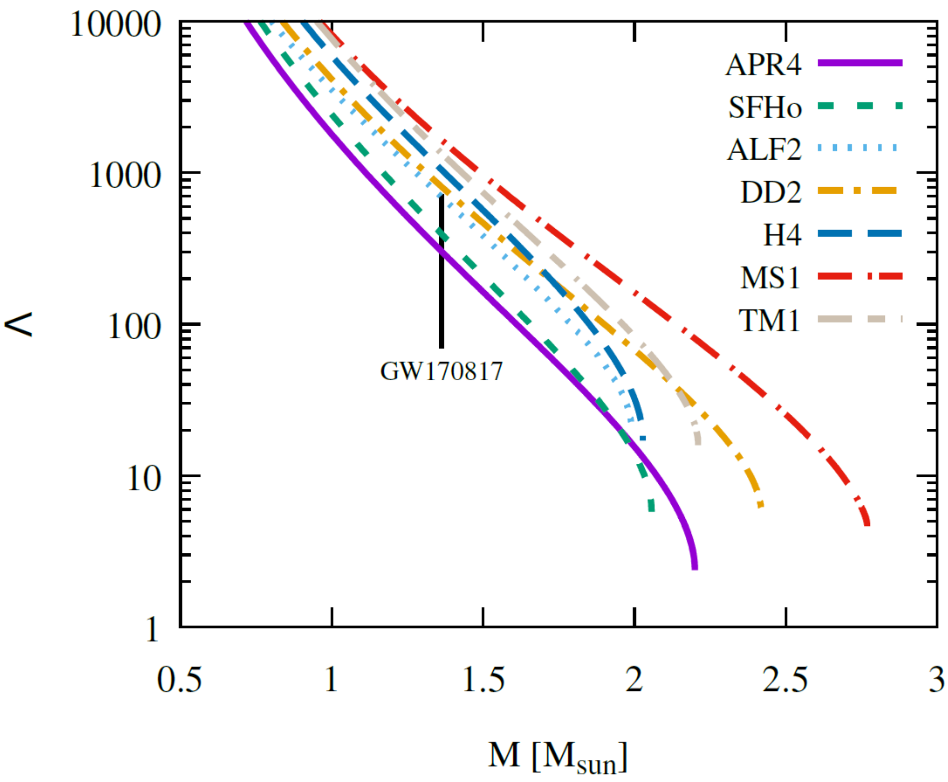
Other macroscopic observables

The binary dynamics, i.e., the orbital motion are affected more directly by other quantities such as

Moment of inertia



Tidal deformability

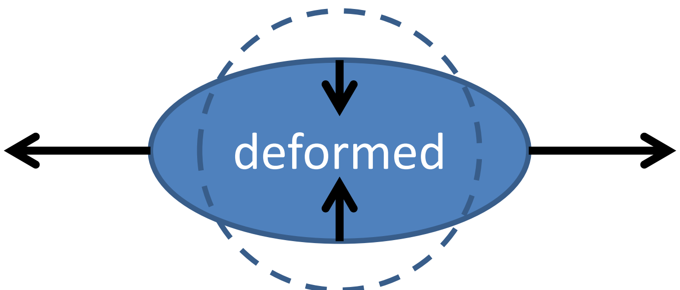


Quadrupolar tidal deformability

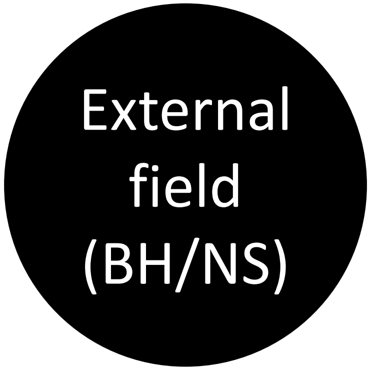
Leading-order finite-size effect on orbital evolution (strongly correlated with the neutron-star radius)

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

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



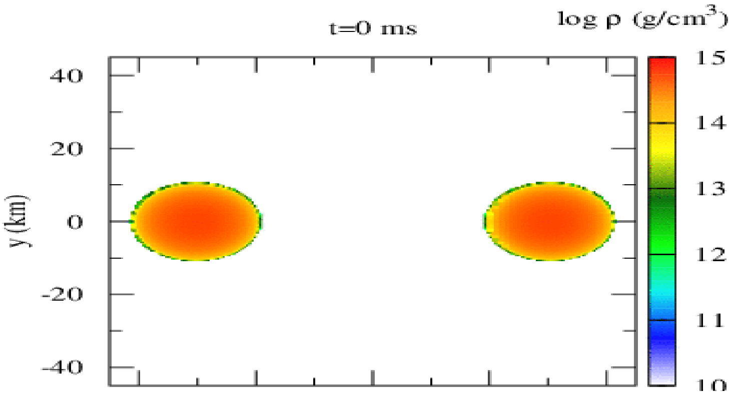
$$\mathcal{Q}_{ij} = -\lambda \mathcal{E}_{ij}$$



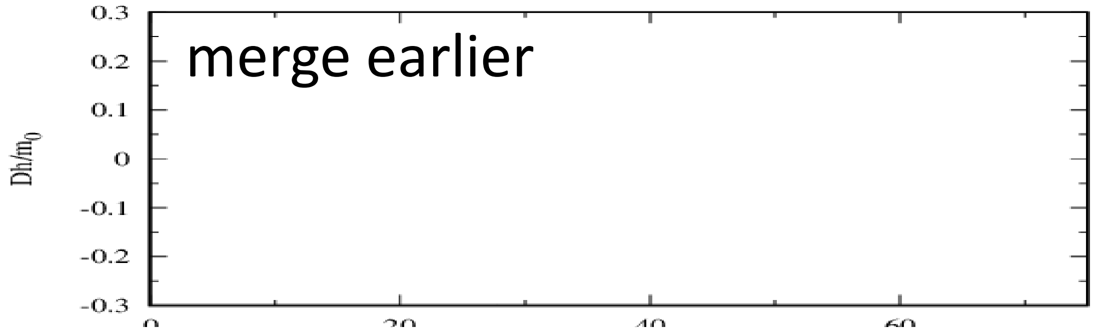
$$\mathcal{Q}_{ij} \equiv \int \rho \left(x_i x_j - \frac{1}{3} x^2 \delta_{ij} \right) d^3x$$

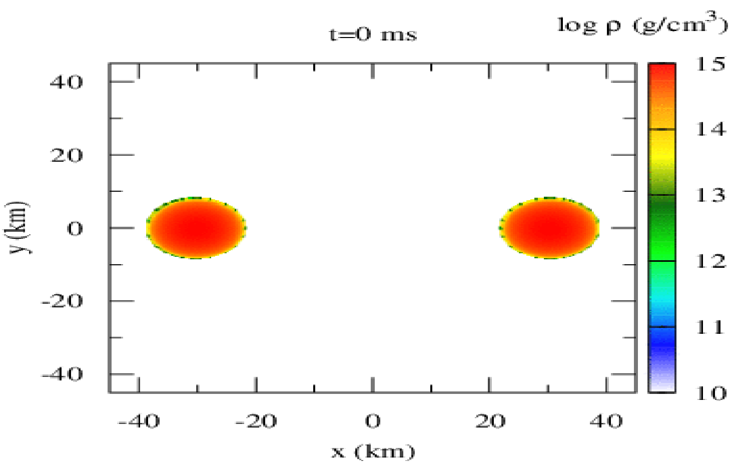
$$\mathcal{E}_{ij} \equiv \frac{\partial^2 \Phi_{\mathrm{ext}}}{\partial x^i \partial x^j}$$

Different orbital evolution

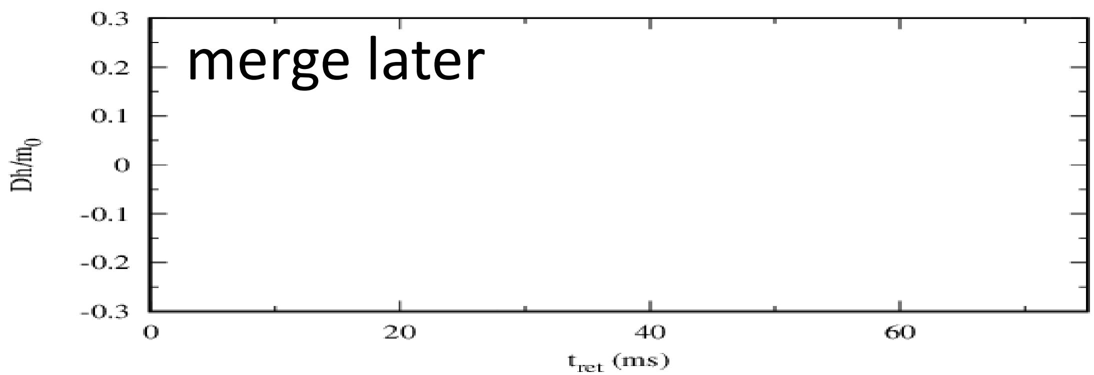


$R = 13.7\ \text{km}, \Lambda = 1211$





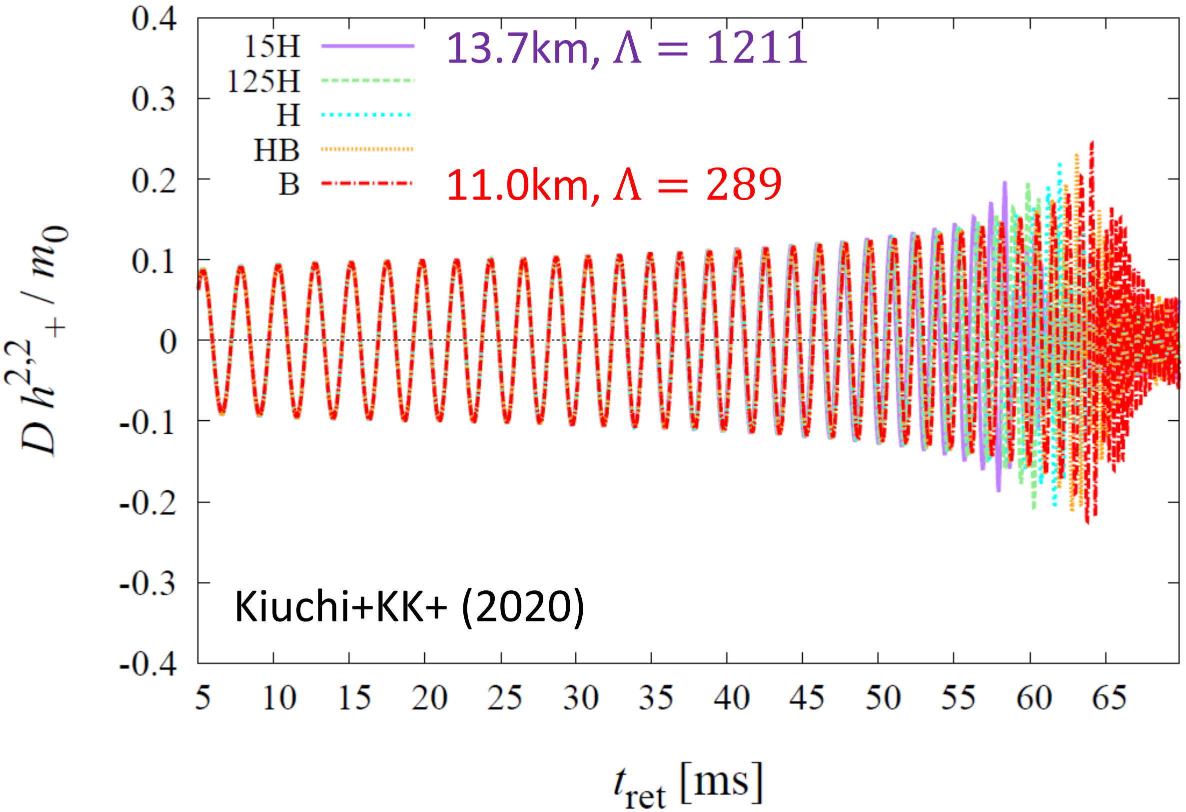
$R = 11.0\ \text{km}, \Lambda = 289$



Gravitational waveform

Binaries merge earlier for stiffer equations of state

This allows us to measure the tidal deformablity

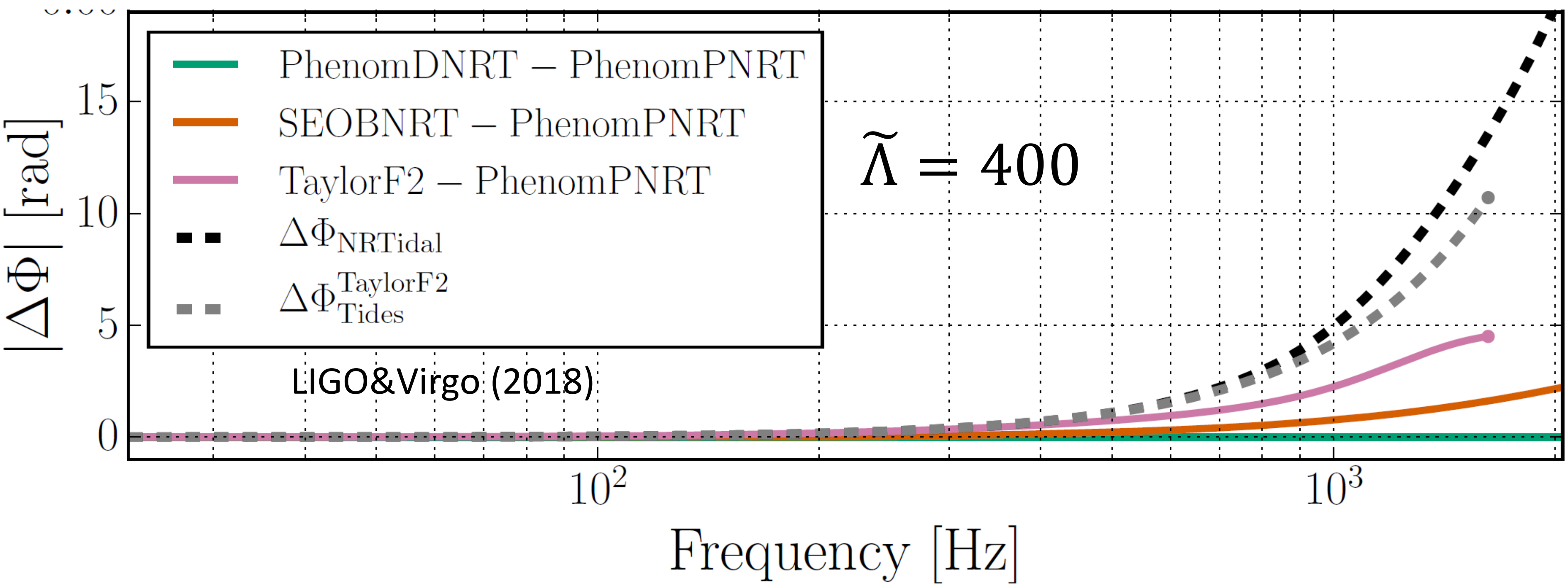


Uncertainty in the waveform model

1 radian difference usually makes differences

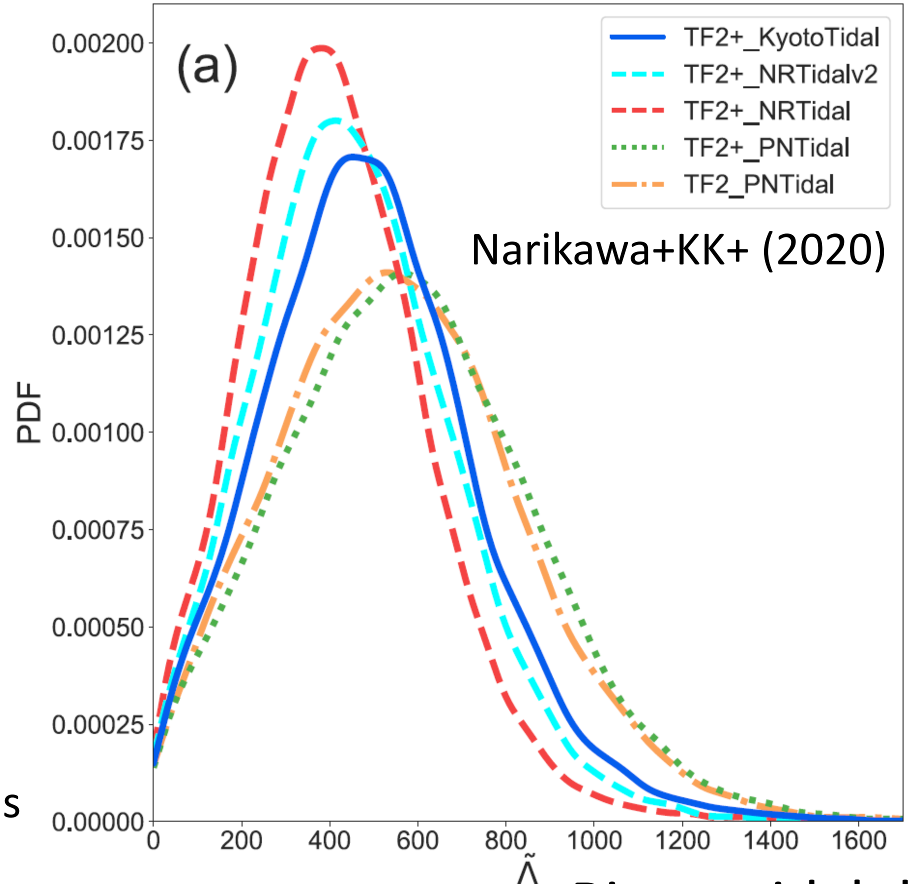
Current systematic errors are larger than 1 radian

We need accurate waveforms for better estimation



Constraint from GW170817

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



Narikawa+KK+ (2020)

Soft, small radius

Stiff, large radius

Binary tidal deformability

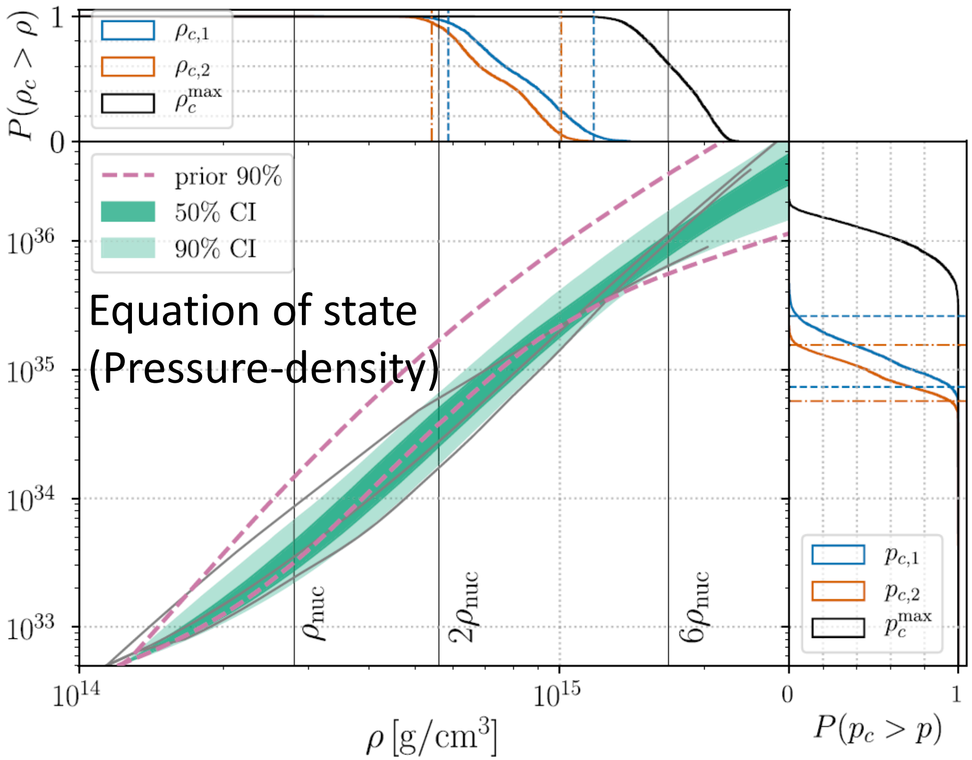
Kyoto: our NR-based model from Kawaguchi+KK+ (2018)

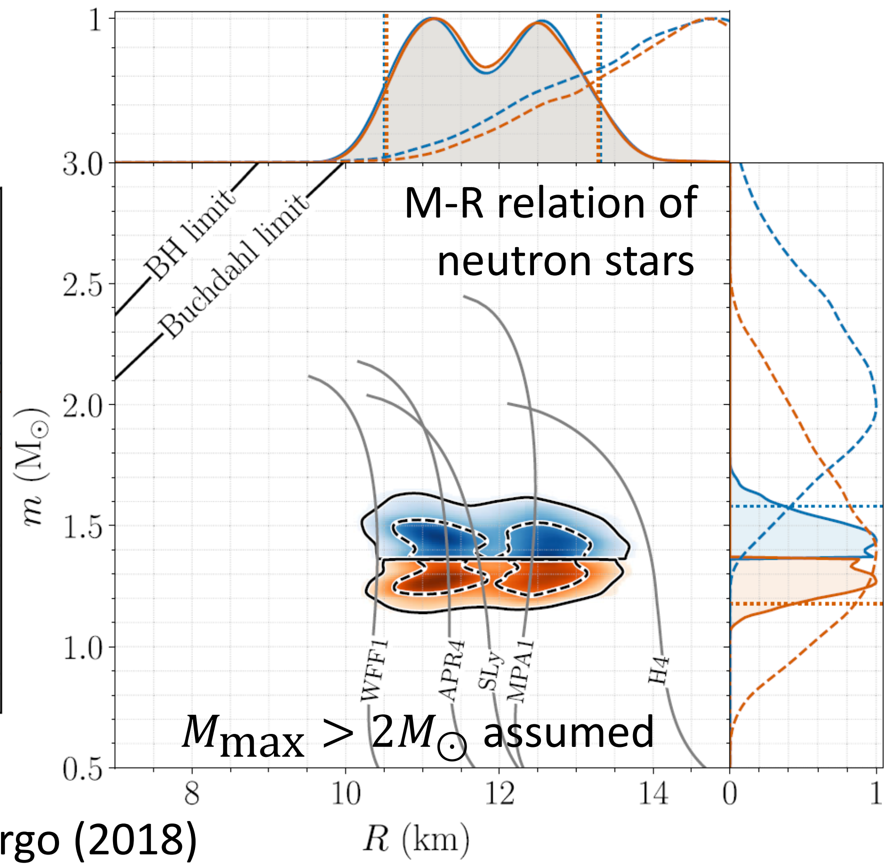
NRTidal: another NR-based model used in LVC analysis

PNtidal: post Newton

Current status of understanding

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



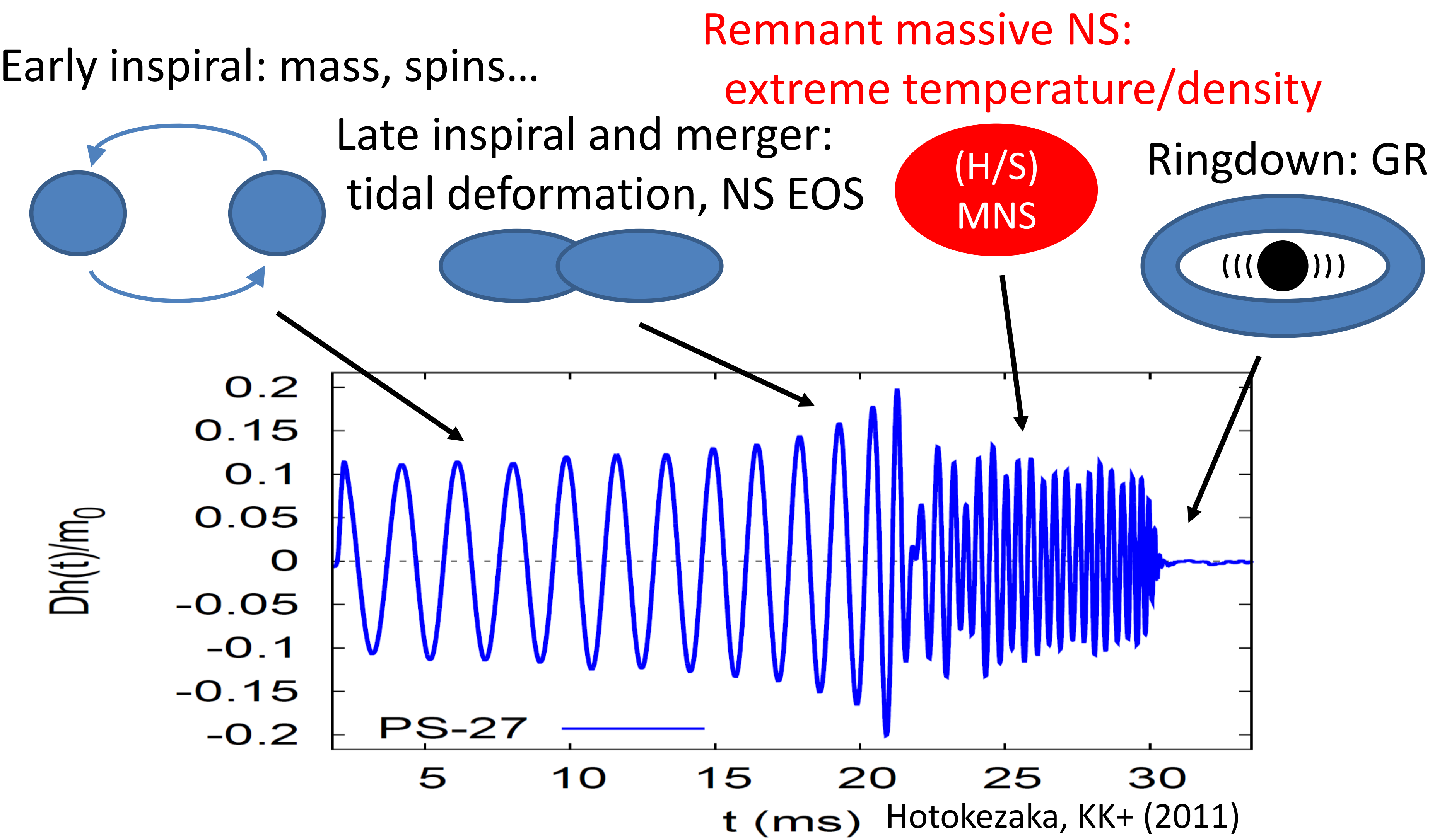


LIGO&Virgo (2018)

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

K. Cannon, K. Fukushima, R. Harada, K. Hotokezaka (U. Tokyo)
Y. Fujimoto (UCB/RIKEN)

Various phases of coalescence

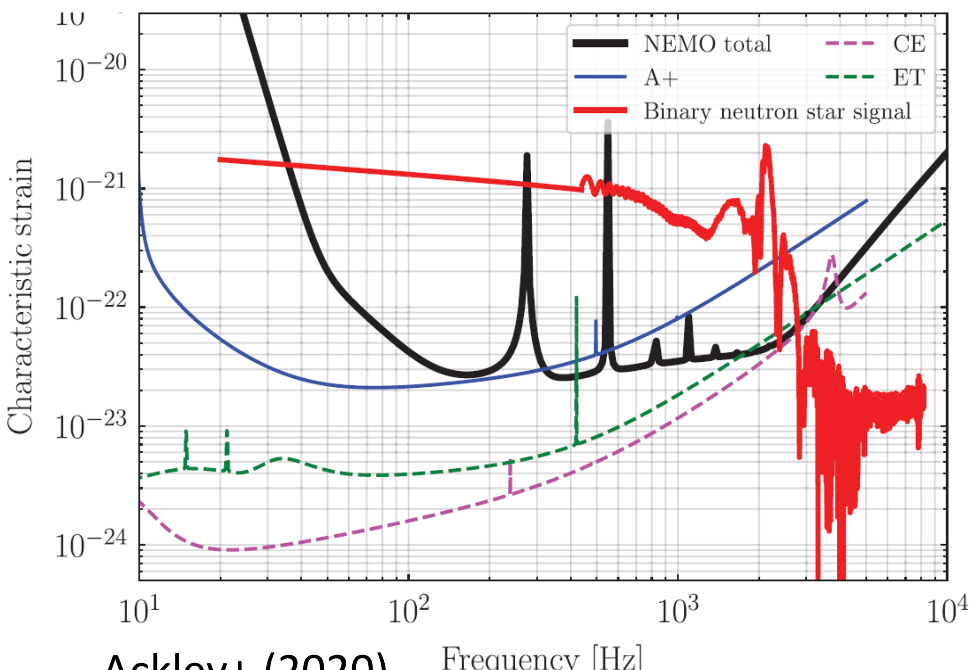


Future high-frequency observation

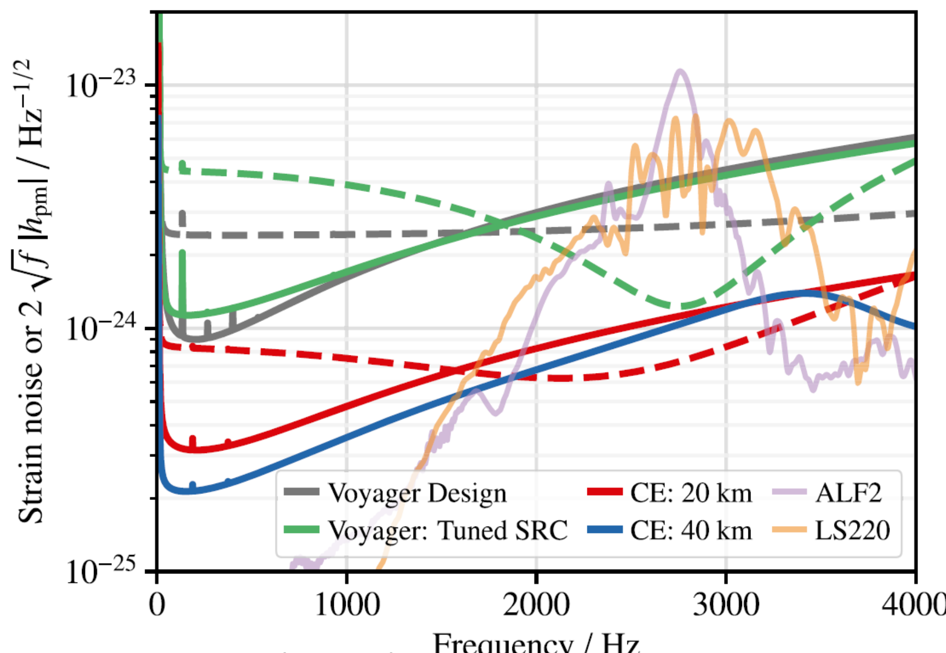
The high density requires high-frequency observations

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

Some proposals are made for postmerger signals



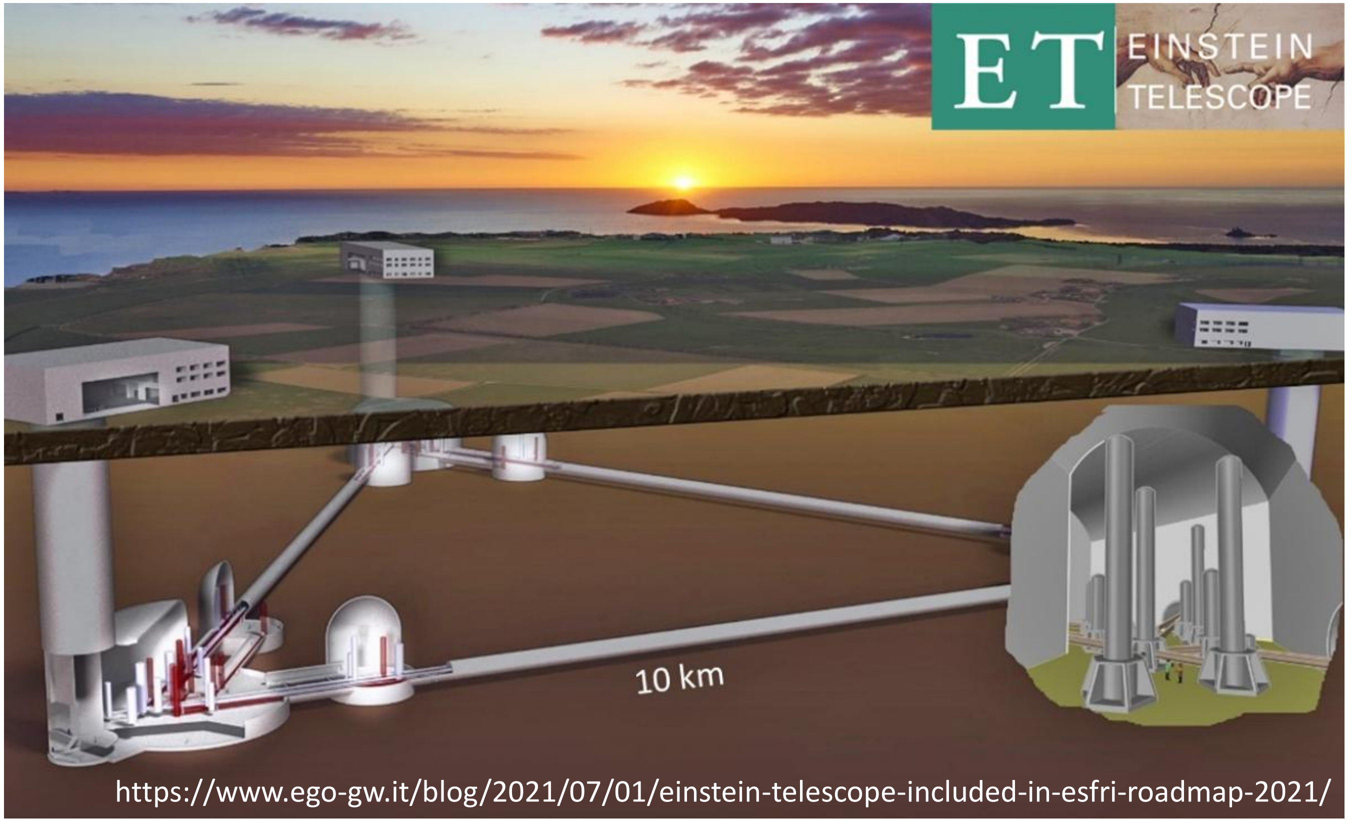
Ackley+ (2020)



Srivastava+ (2022)

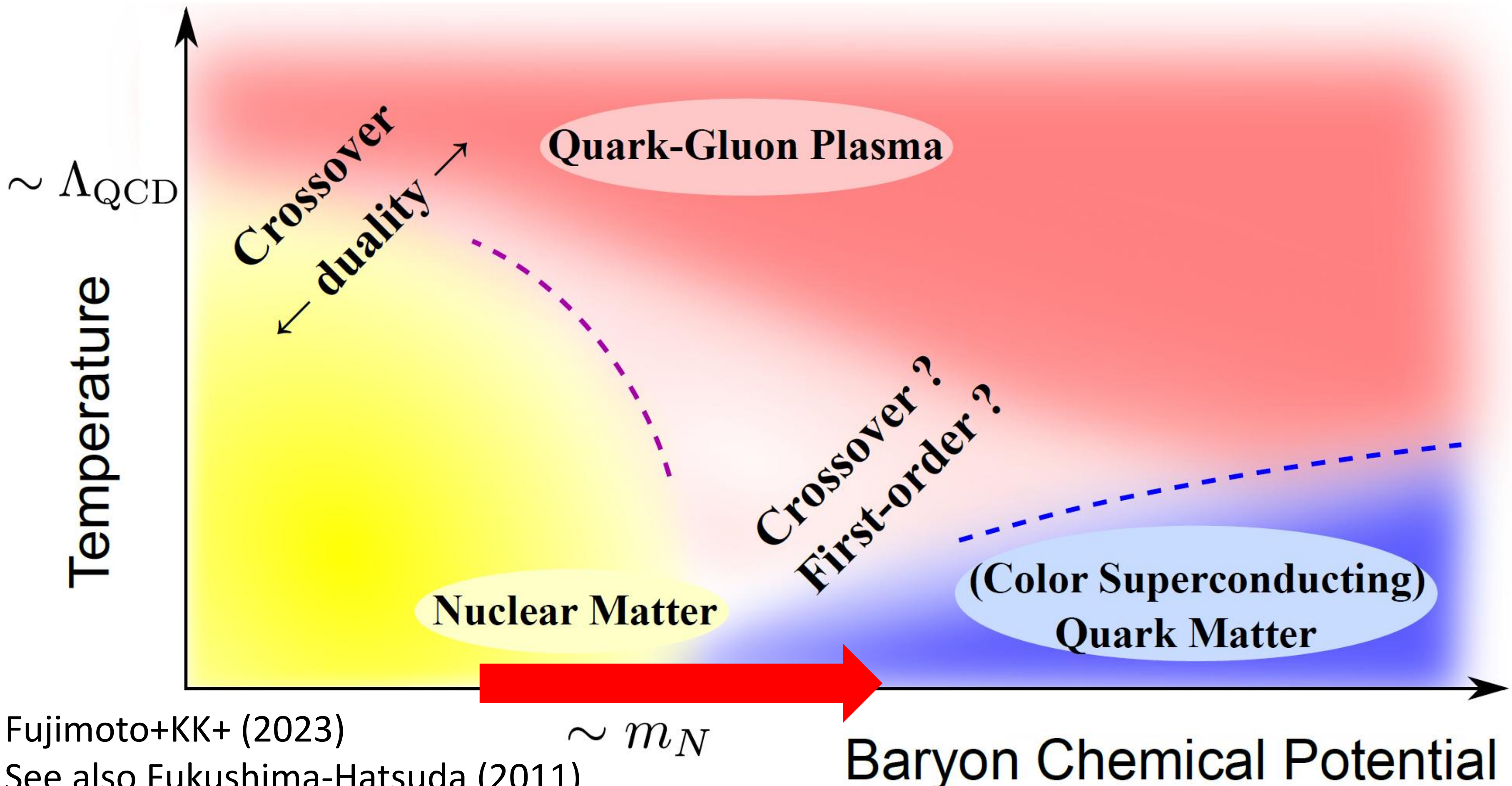
Third-generation detector

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



QCD phase diagram

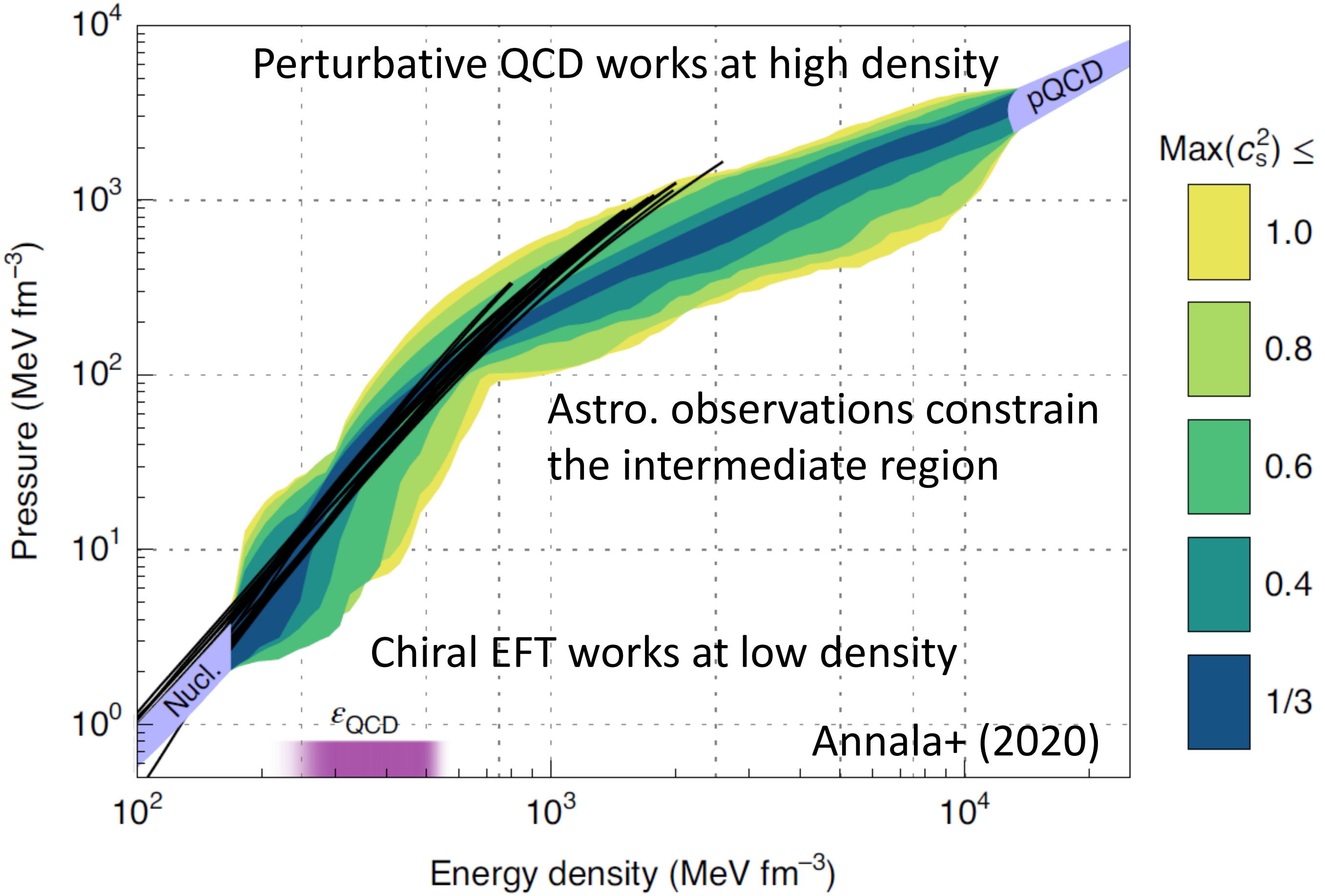
How hadronic matter transitions to quark matter?



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

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

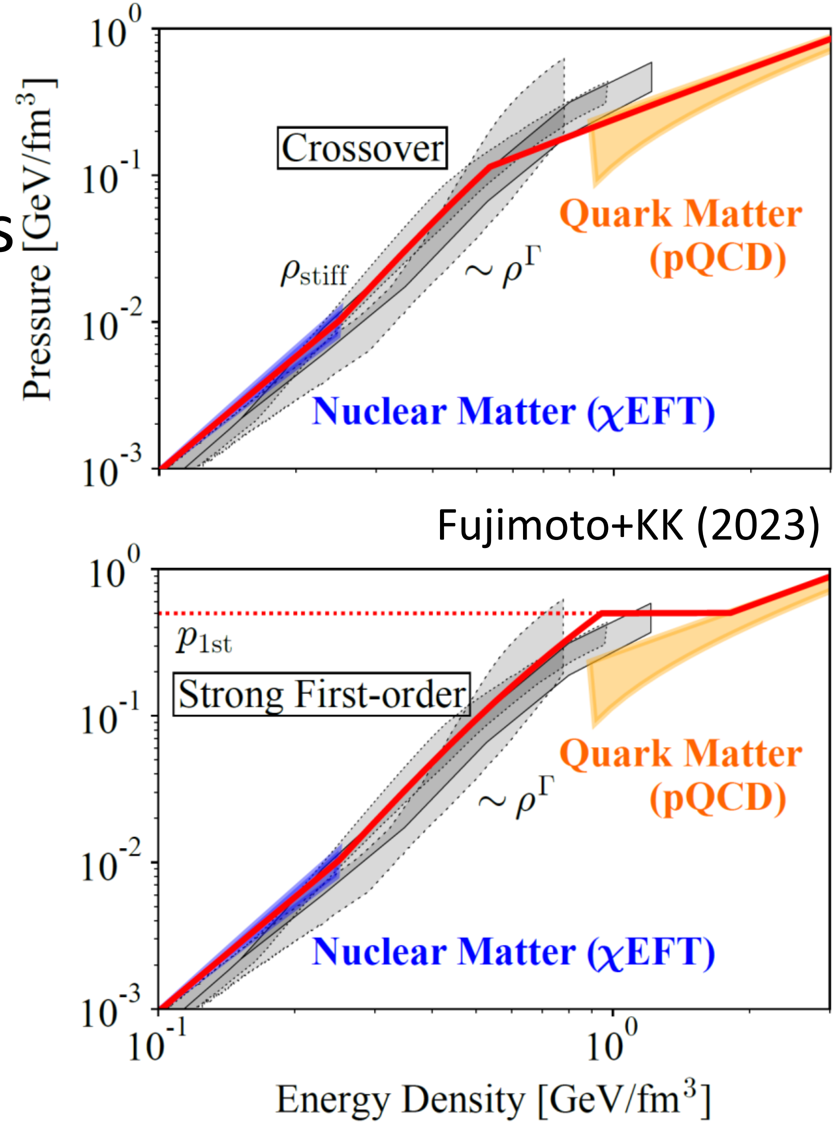
2 solar mass neutron stars

1st-order phase transition

Only very high density allows

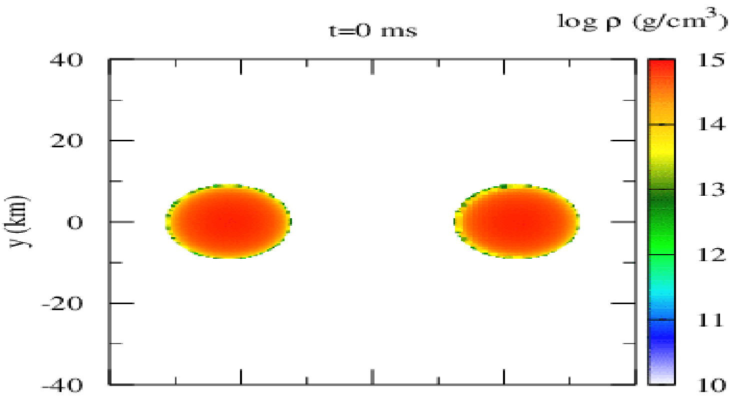
strong phase transition…

No effect on astrophysics?

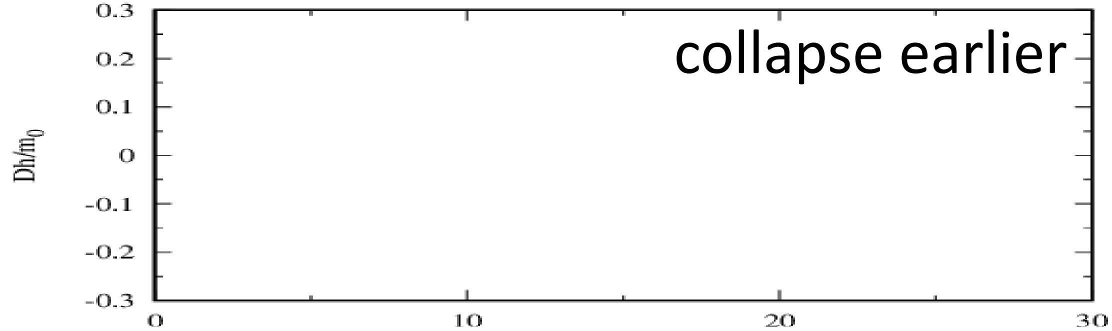


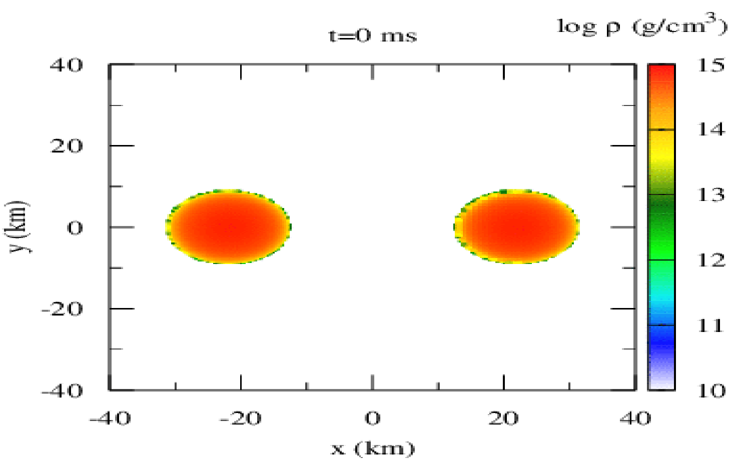
Fujimoto+KK (2023)

Merger and gravitational waves

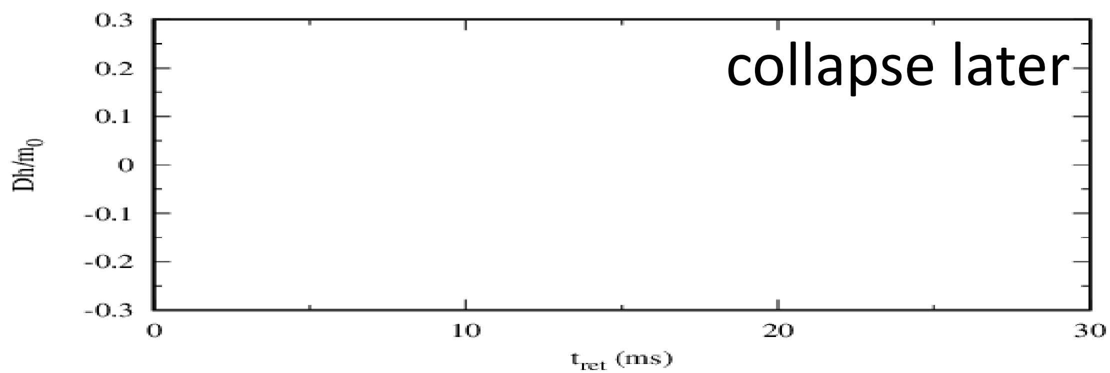


Crossover



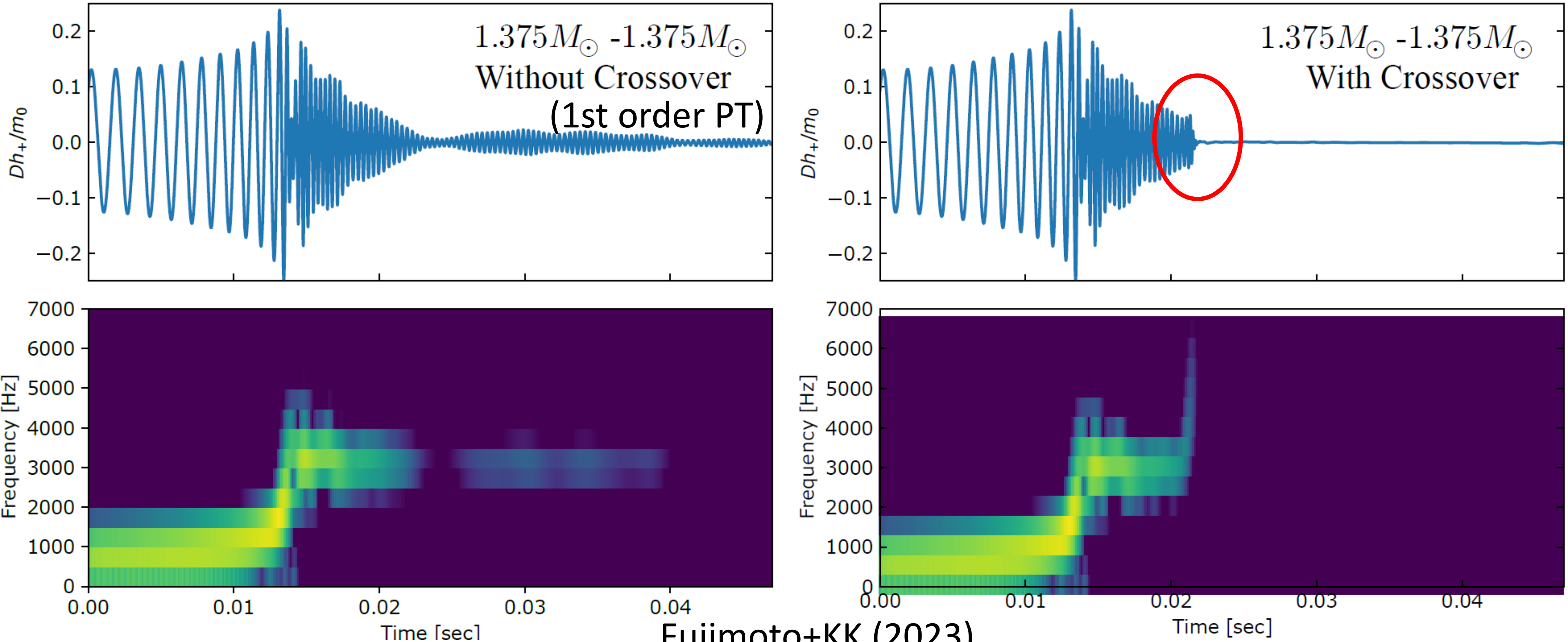


Strong first-order (~hadronic)



Black-hole formation as a key

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

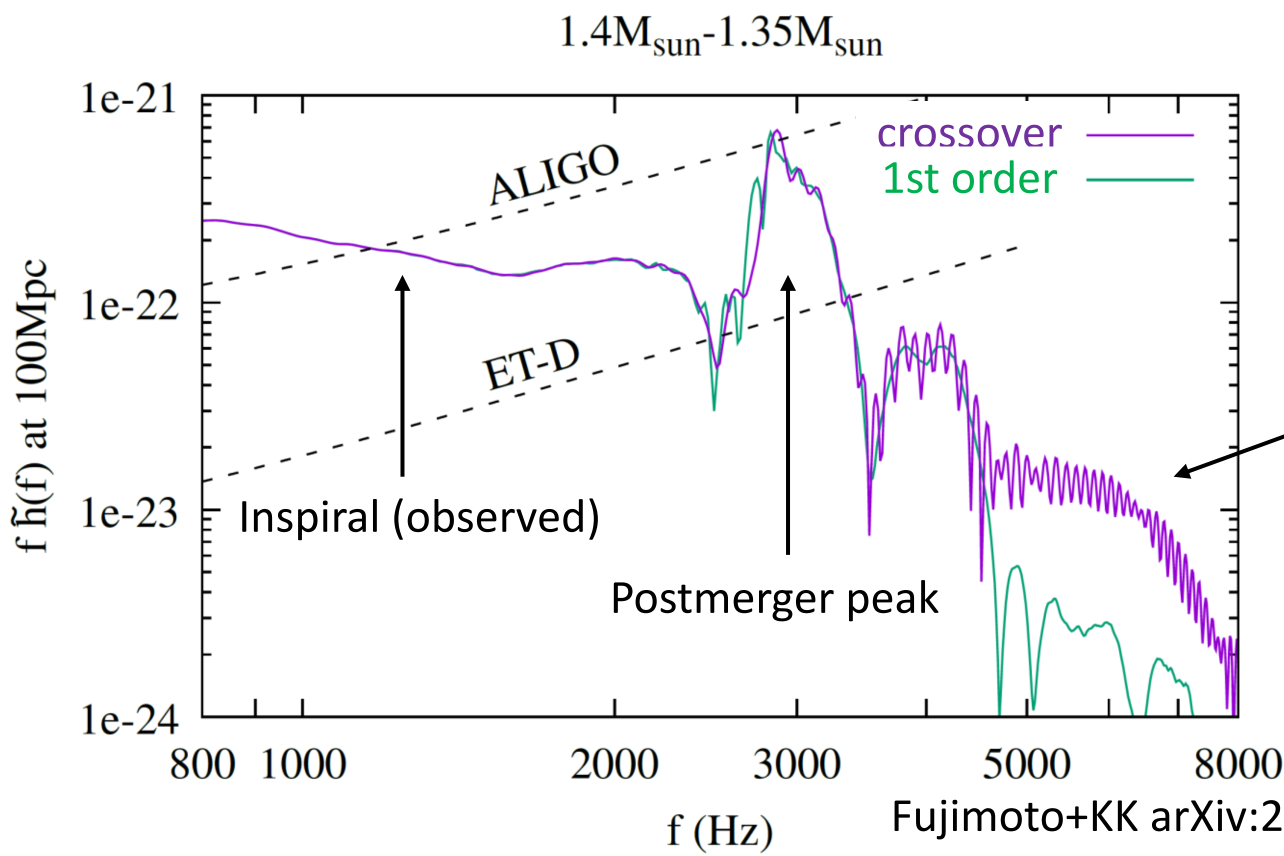


Fujimoto+KK (2023)

Gravitational-wave spectrum

The postmerger peaks do not differ appreciably

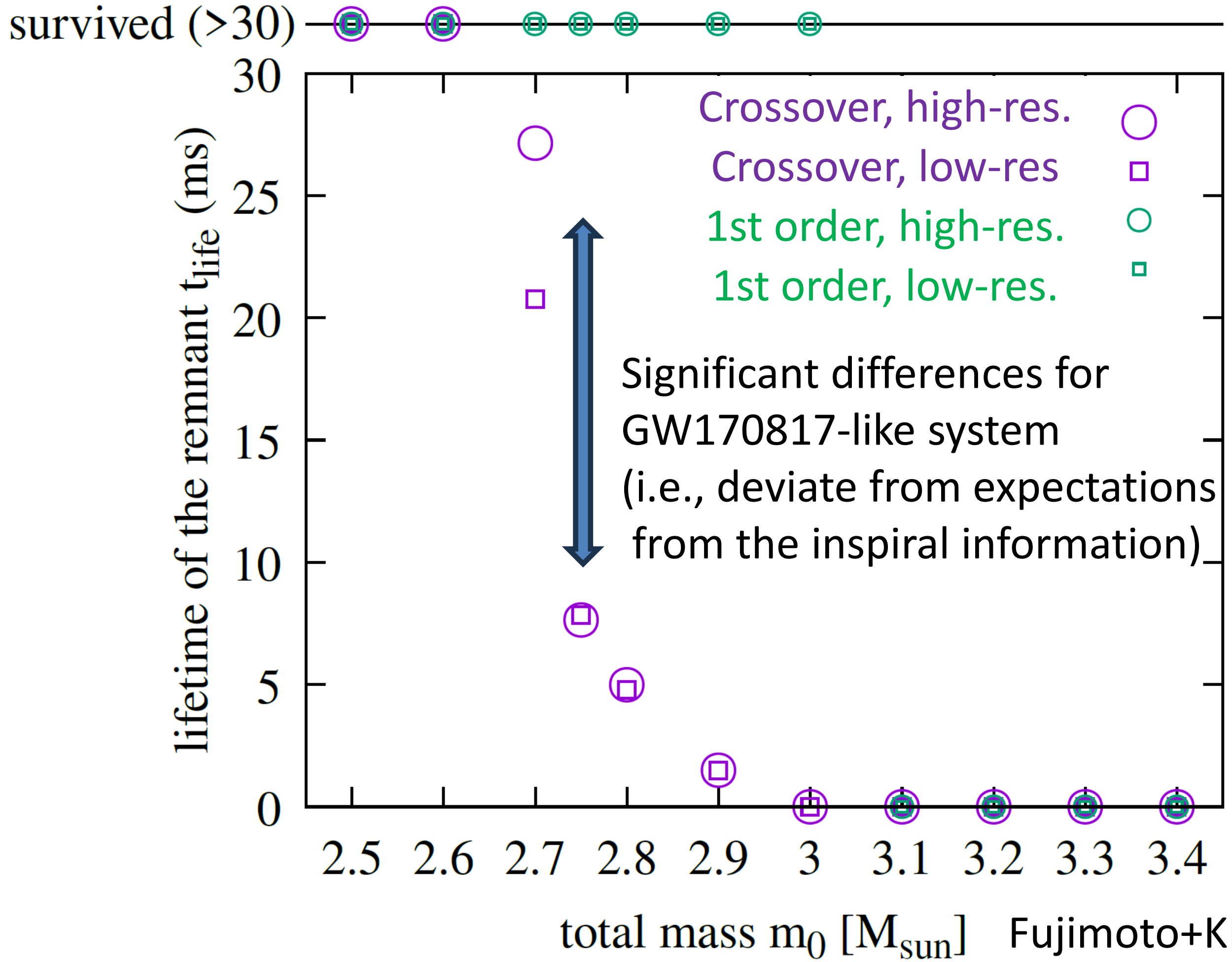
The quasinormal-mode cutoff could be distinguishing



Fujimoto+KK arXiv:2408.10298

Lifetime of the merger remnant

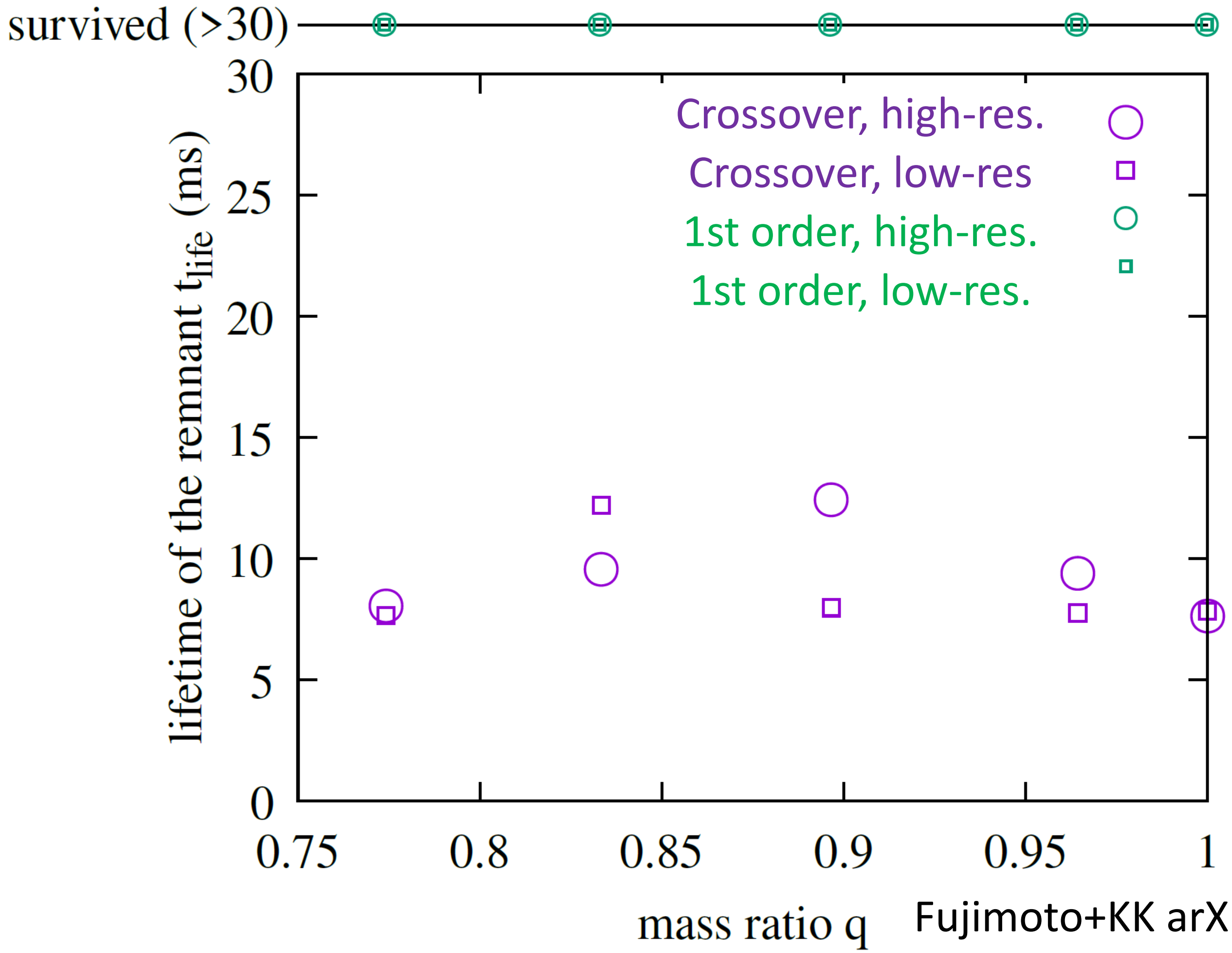
Determined primarily by the total mass of the binary



Fujimoto+KK arXiv:2408.10298

Weak dependence on mass ratio

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

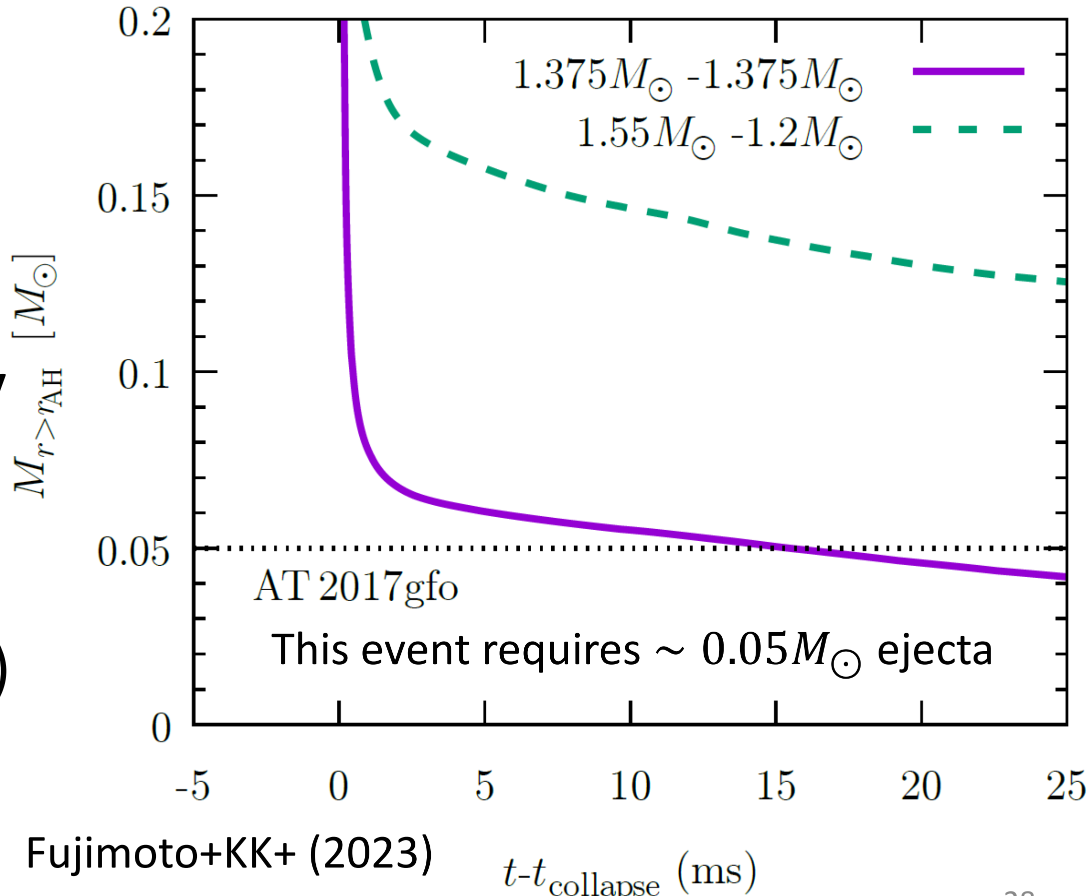


Fujimoto+KK arXiv:2408.10298

Multimessenger observation

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

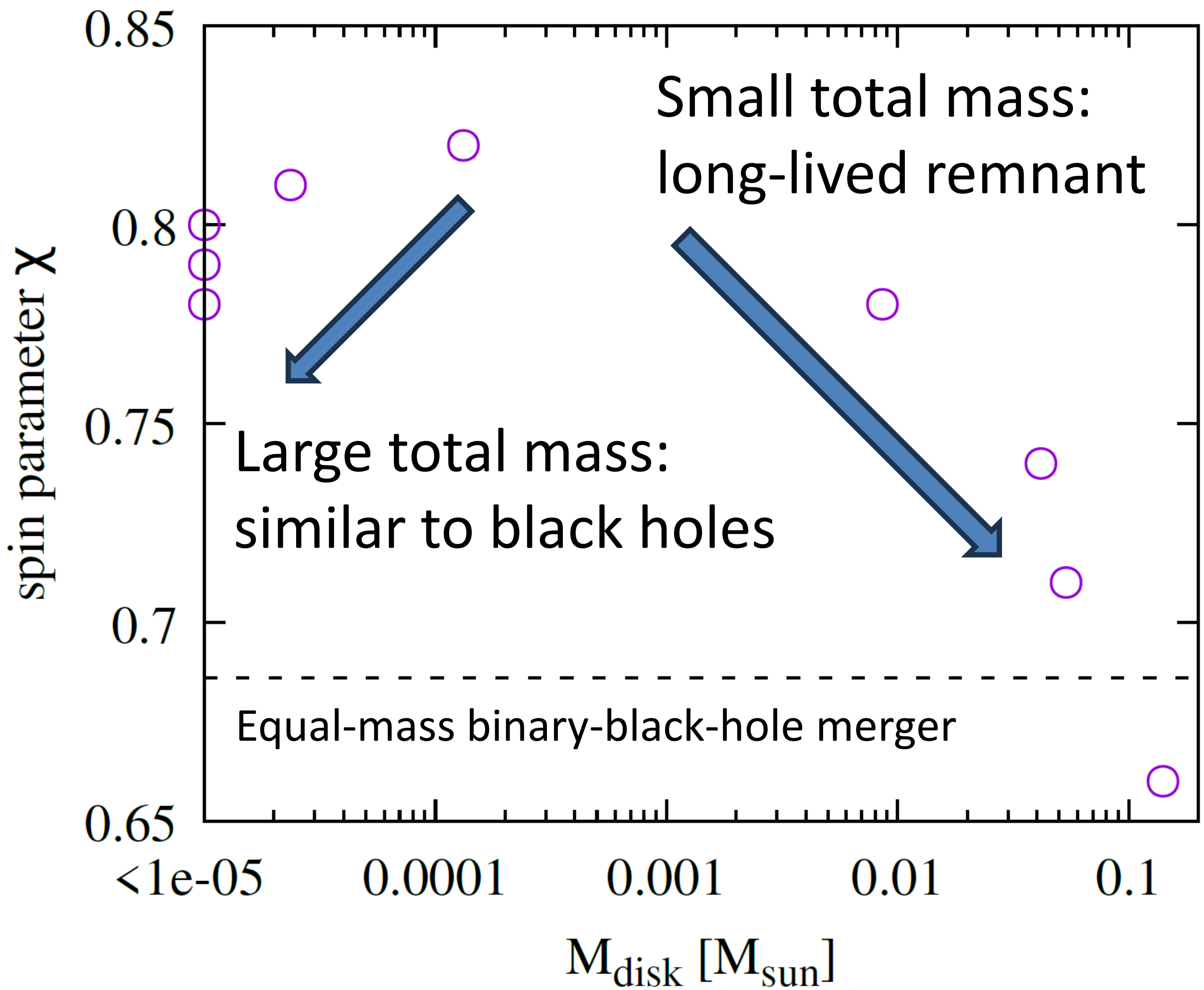
Our crossover model may be pass this test with mass asymmetry (1s-order PT trivially passes this test because no gravitational collapse)



Fujimoto+KK+ (2023)

Spin of the remnant black hole

Likely highest at the threshold of prompt collapse



Reason of the peak

A large amount of the angular momentum is retained

- For a small total mass, the remnant survives long to redistribute angular momentum to the envelope
- For a large total mass, the inspiral is effectively long to emit angular momentum via gravitational waves
- Mass asymmetry tends to enhance the angular momentum loss by tidal torque and mass ejection

Open question: what is the maximum possible spin?
which equation of state realizes it?

Did GW170817 form a black hole?

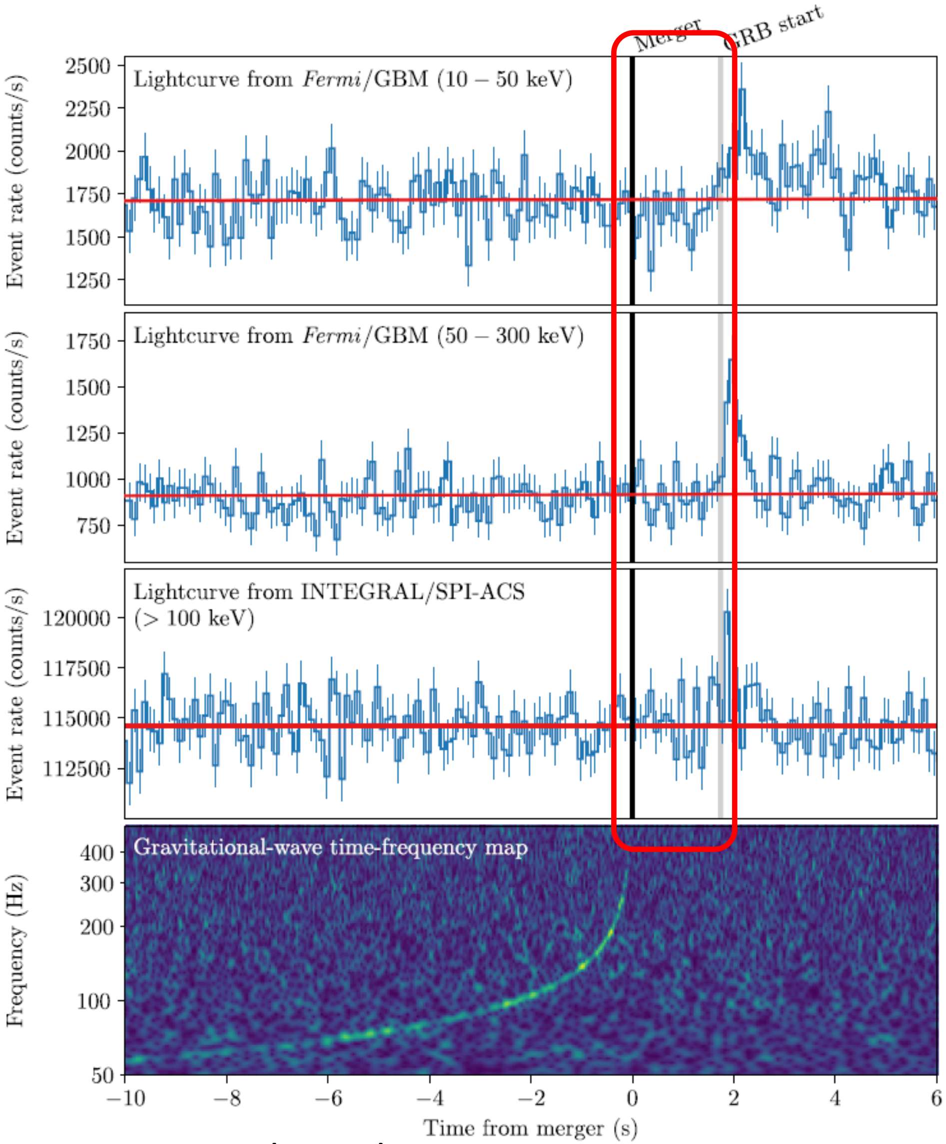
Nobody knows the answer

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)

Distinguishable in reality?

Bayesian hypothesis testing with simulated real signals

$$B = \frac{Z_{\mathrm{co}}}{Z_{\mathrm{pt}}} \sim \frac{L(\mathrm{data}|\mathrm{crossover})}{L(\mathrm{data}|\mathrm{phase\ transition})}$$

Compare the consistency of the residual with the noise

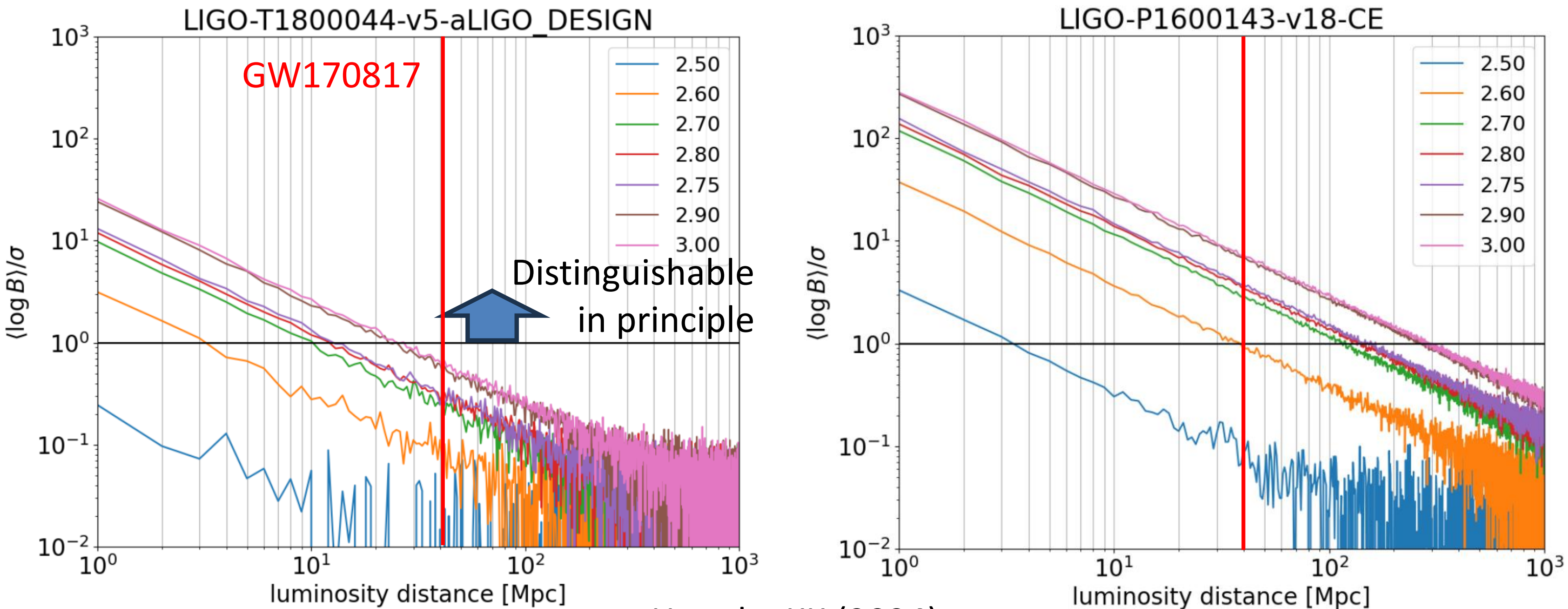
$$L \propto \exp\left(-\frac{1}{2}|\mathrm{data} - \mathrm{waveform\ model}|^2\right)$$

Transition scenarios should easily be distinguishable with sensitive detectors and/or nearby events

Distinguishability in data analysis

AdLIGO is insufficient even at design sensitivity (left)

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



Harada+KK (2024)

3. Summary

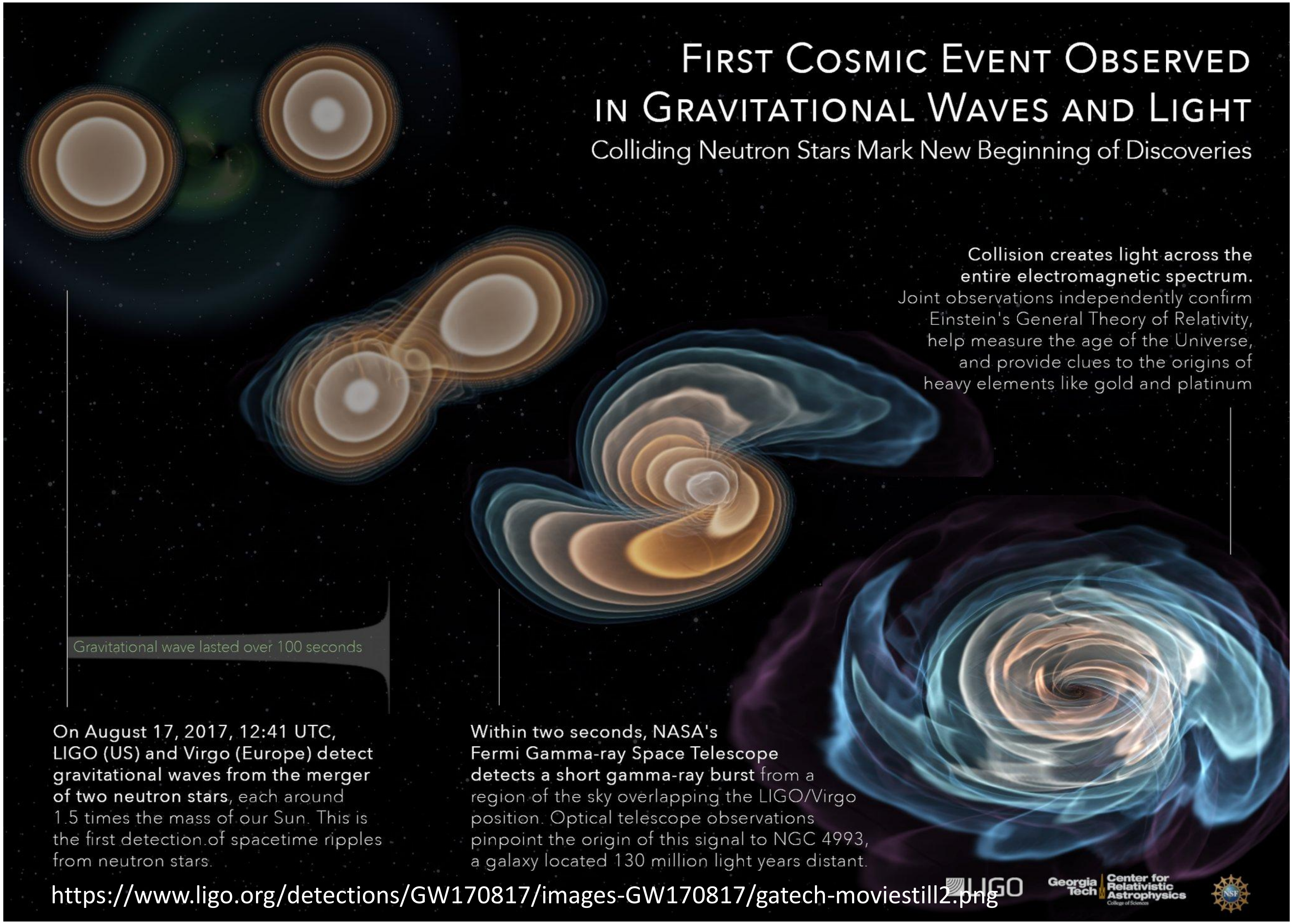
Summary

- 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.

Appendix

Gravitational-wave detectors

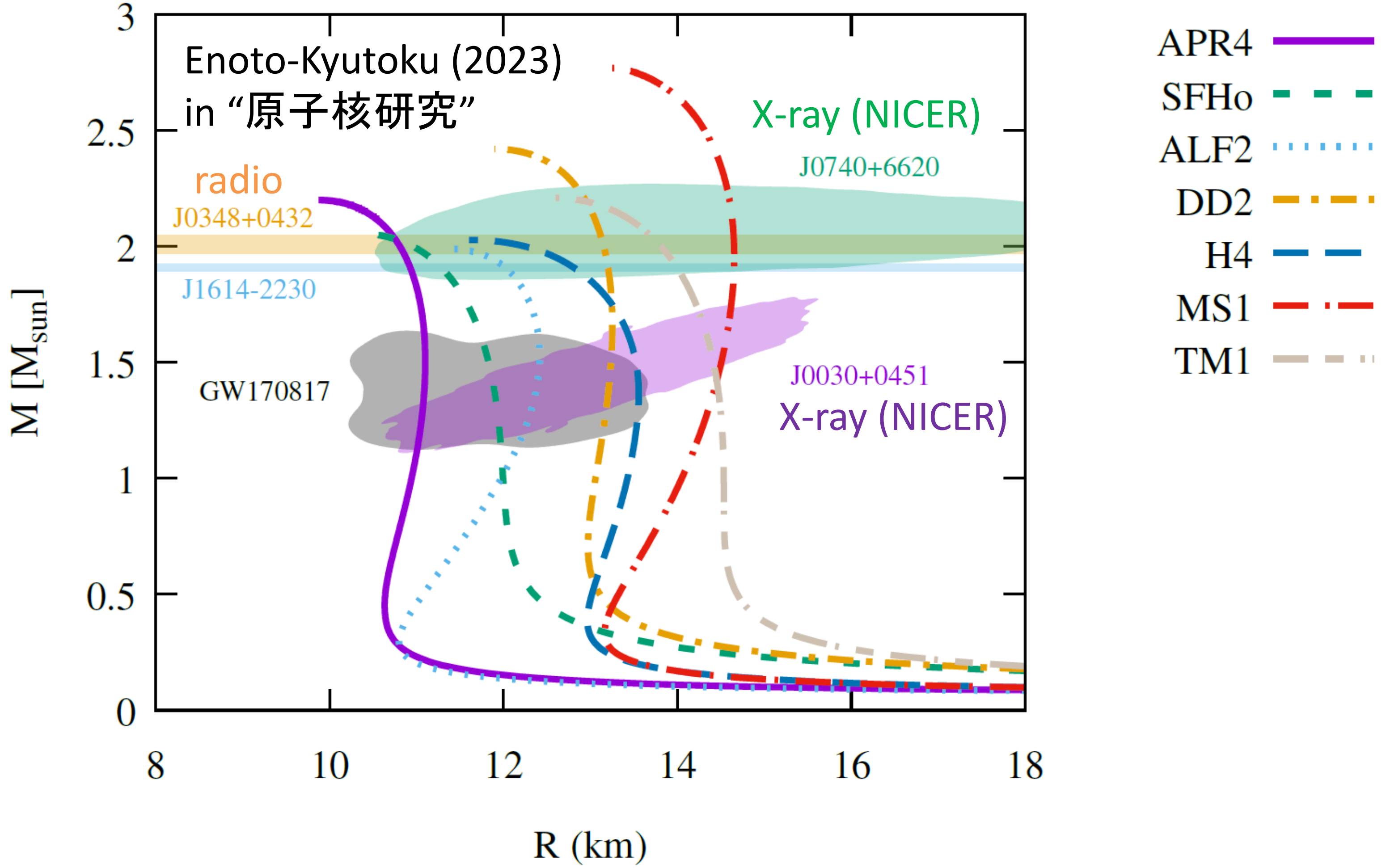
Binary neutron stars: GW170817



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

Current constraint

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



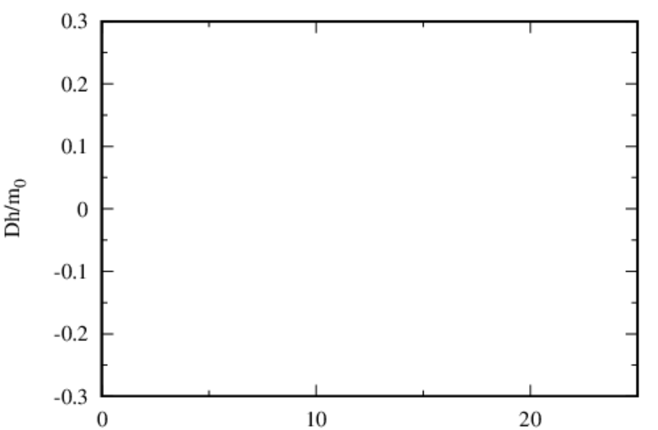
Binary-neutron-star coalescence

A remnant massive neutron star will be formed

Collapse into a black hole radiating angular momentum

Spacetime curvature, log(rescaled absolute value)

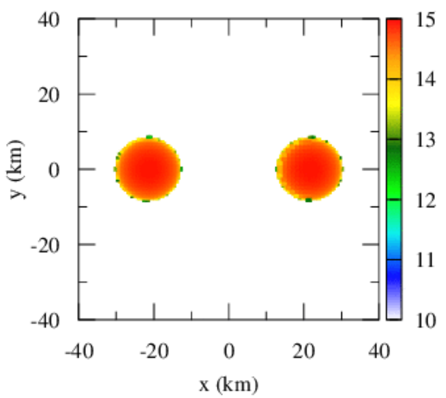
Gravitational waveform



time (ms)

2000km one side

Rest-mass density (g/cc)



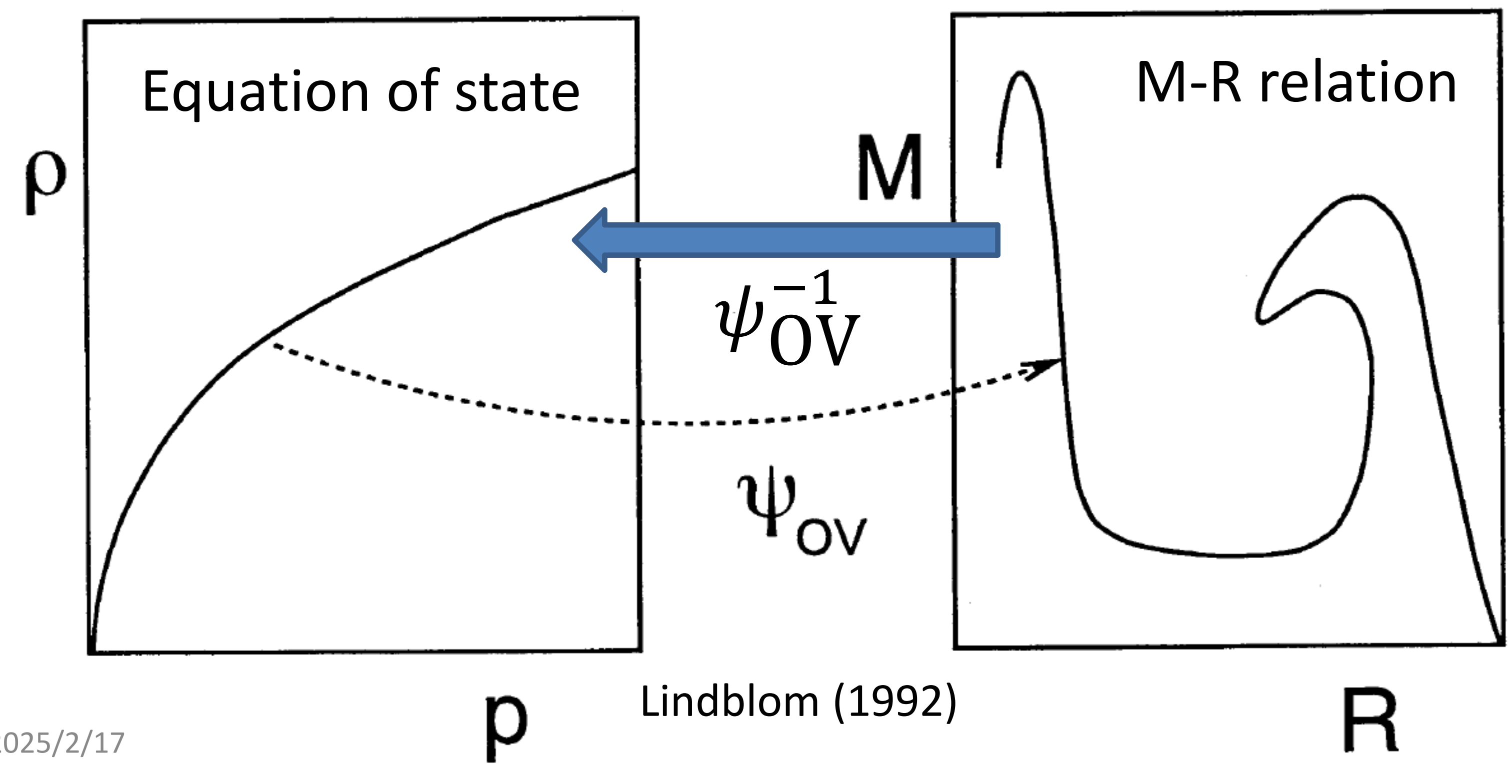
40km one side

One-to-one correspondence

Via Tolman-Oppenheimer-Volkoff equation of GR

$$\frac{dP}{dr} = -\frac{(e+P)\left(m+4\pi P r^3\right)}{r(r-2m)} \quad \left(\to -\frac{\rho m}{r^2}\right)$$

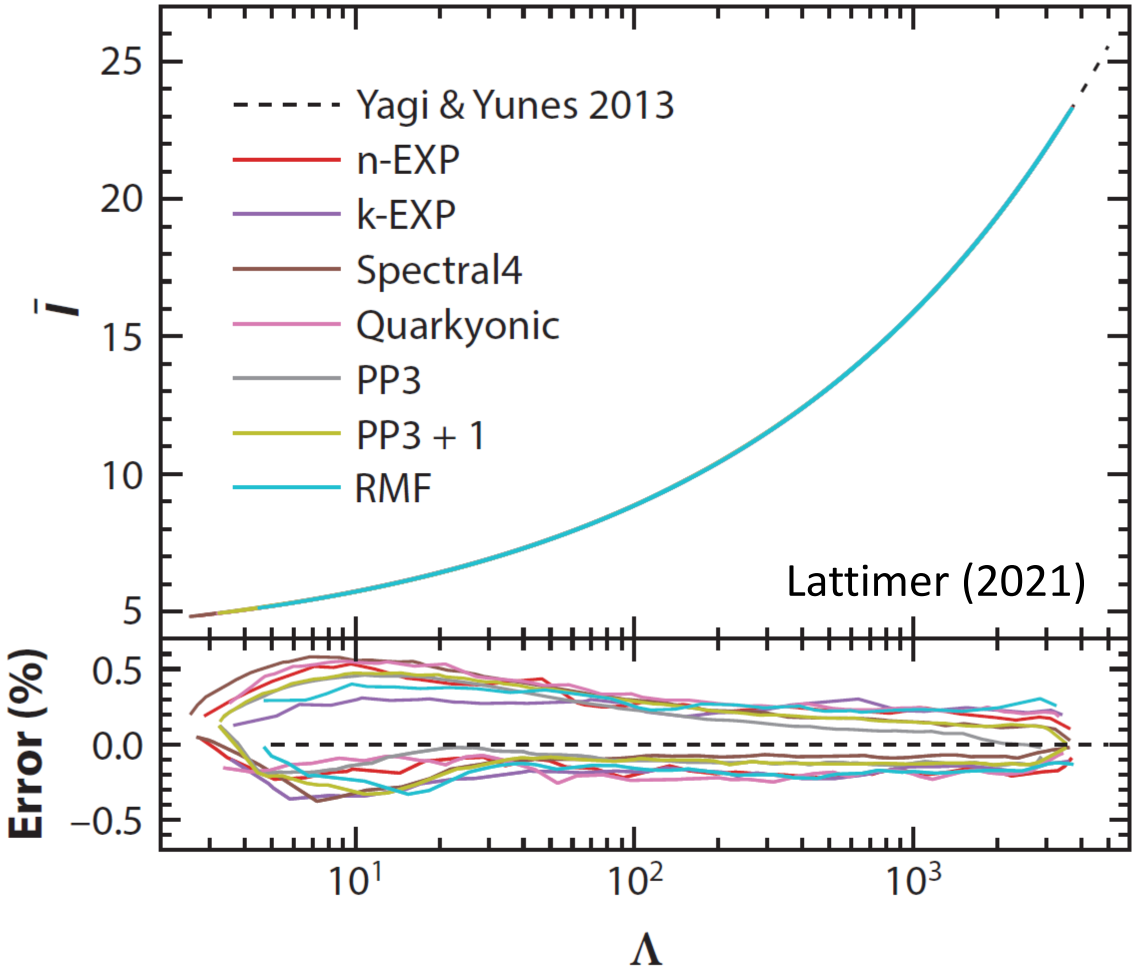
$(G = c = 1)$



Lindblom (1992)

Tight correlation

Not necessarily independent information is encoded



Astronomical observation

Maximum mass from radio pulsars

J1614-2230, J3048+0432, J0740+6620

Tidal deformability from gravitational waves

GW170817(, GW190425: not so informative)

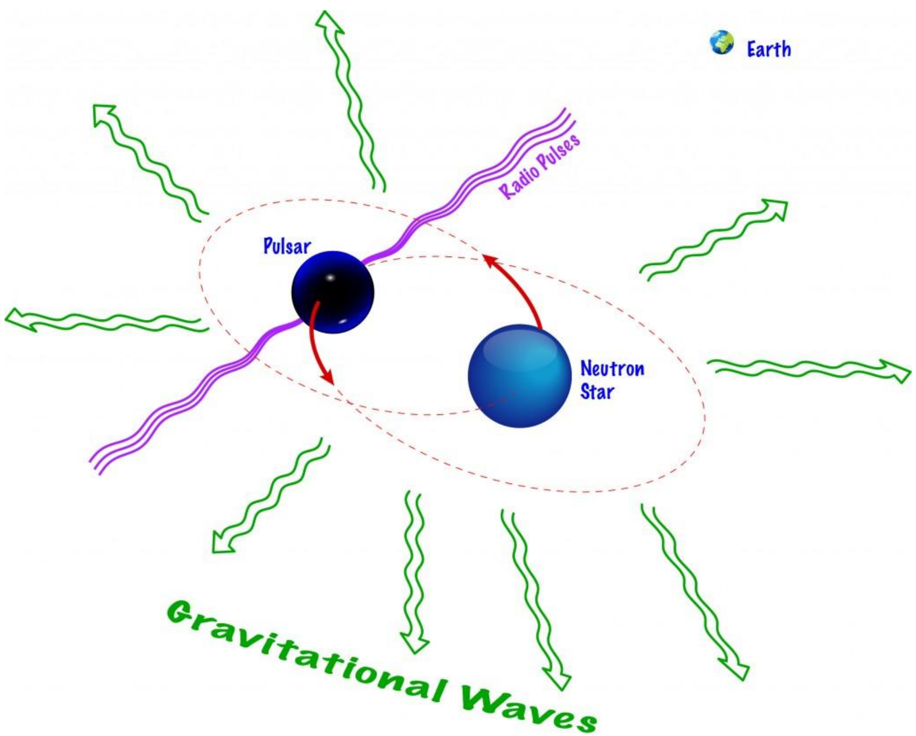
Compactness=mass/radius from X-ray pulsations

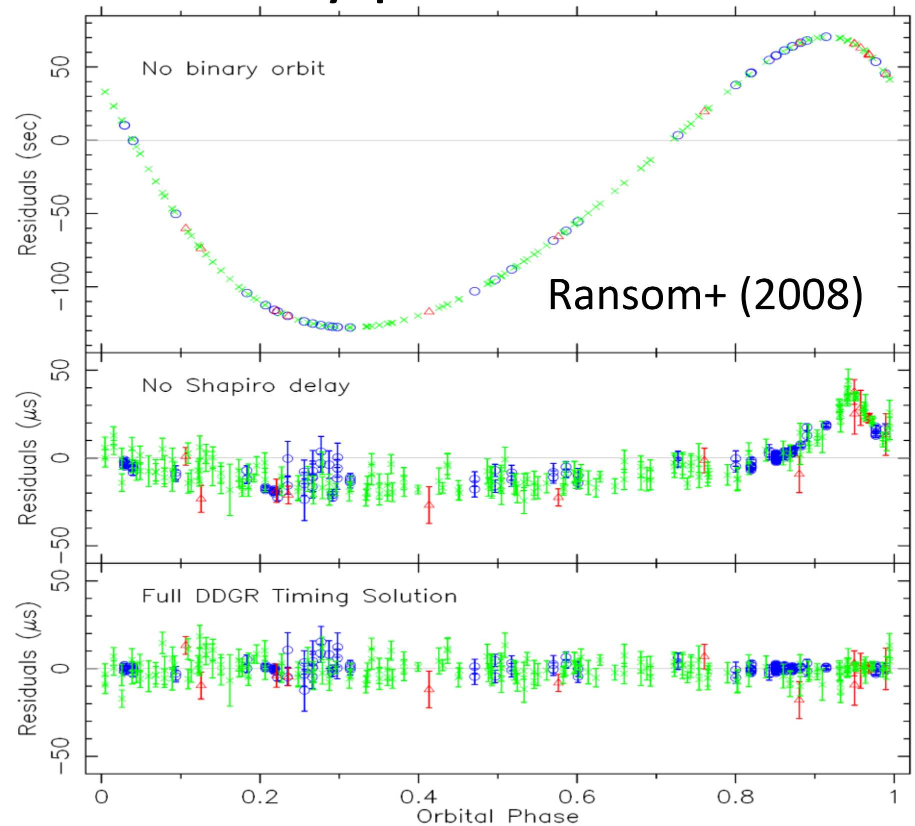
J0030+0451, J0740+6620

+ moment of inertia from radio pulsars in the future?

Binary as a two-body problem

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





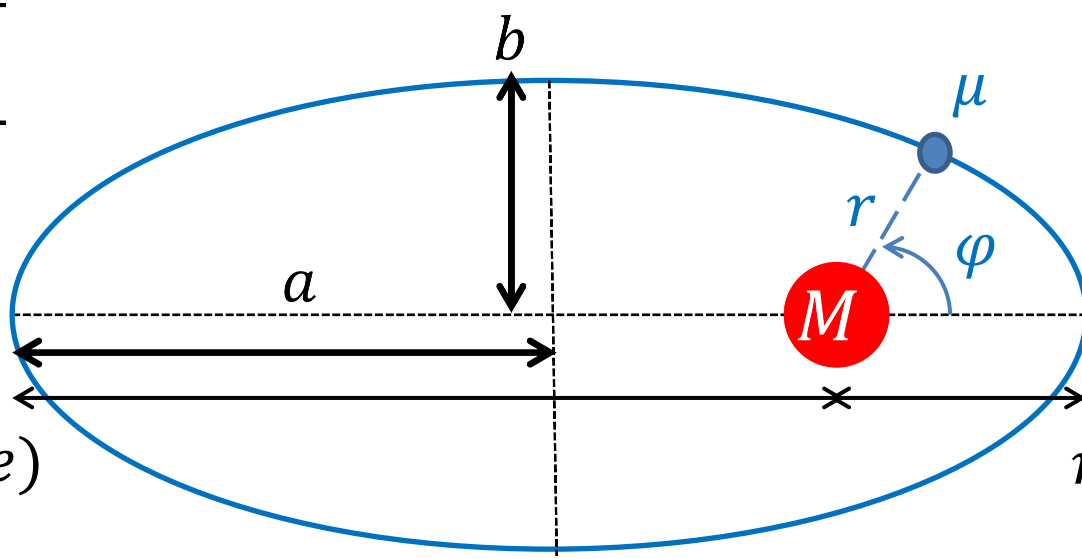
http://asd.gsfc.nasa.gov/blueshift/wp-content/uploads/2016/02/htbinarypulsar-1024x835.jpg

Newton two-body problem

Kepler motion: elliptic orbit characterized by (a, e)

Physically, the energy and the angular momentum

$$e = \sqrt{1 - \frac{b^2}{a^2}}$$



$$r_a = a(1 + e)$$

$$r_p = a(1 - e)$$

Note: actual location of M is more outward

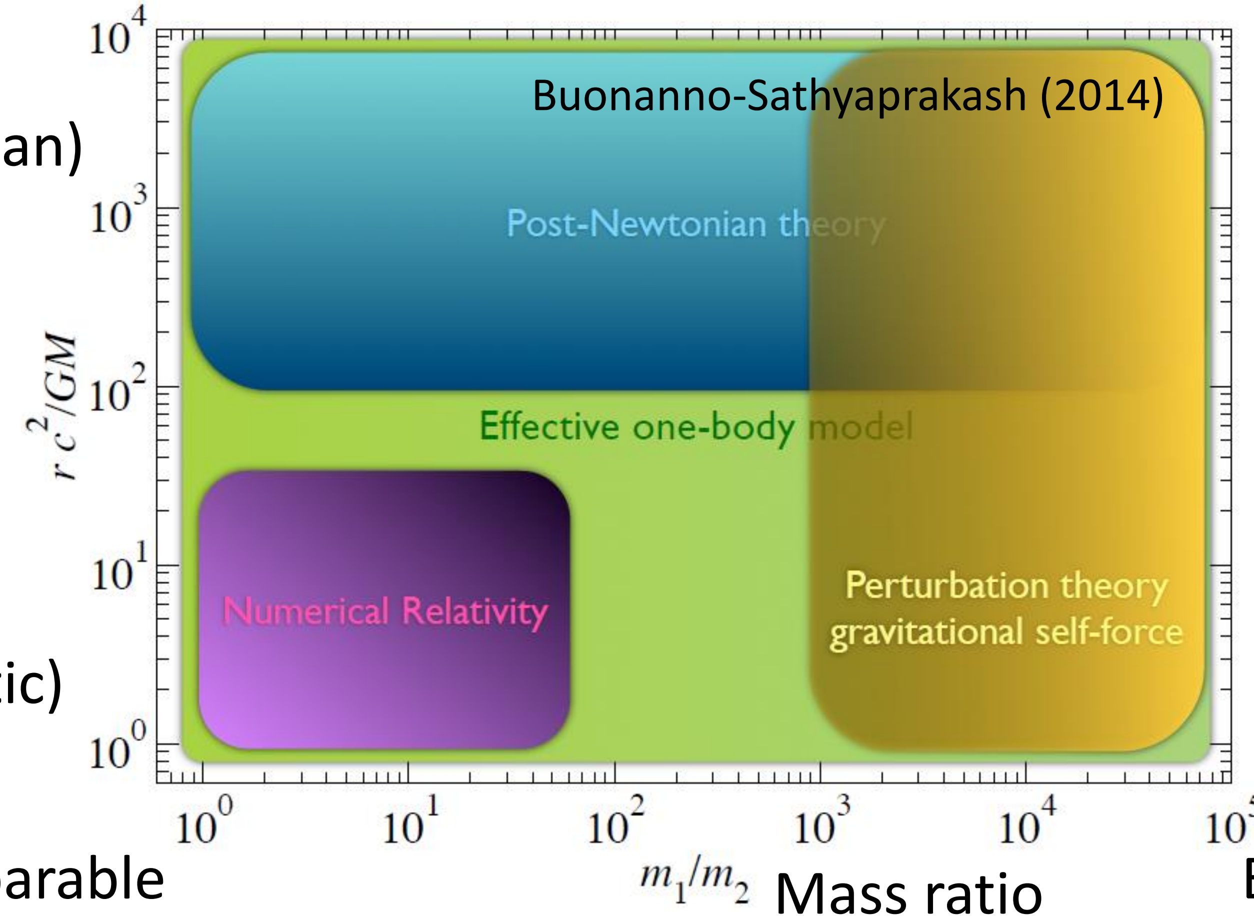
Relativistic two-body problem

Neglecting spins, eccentricity, finite-size effects...

Distant (Newtonian)

Orbital separation

Close (relativistic)



Comparable

Mass ratio

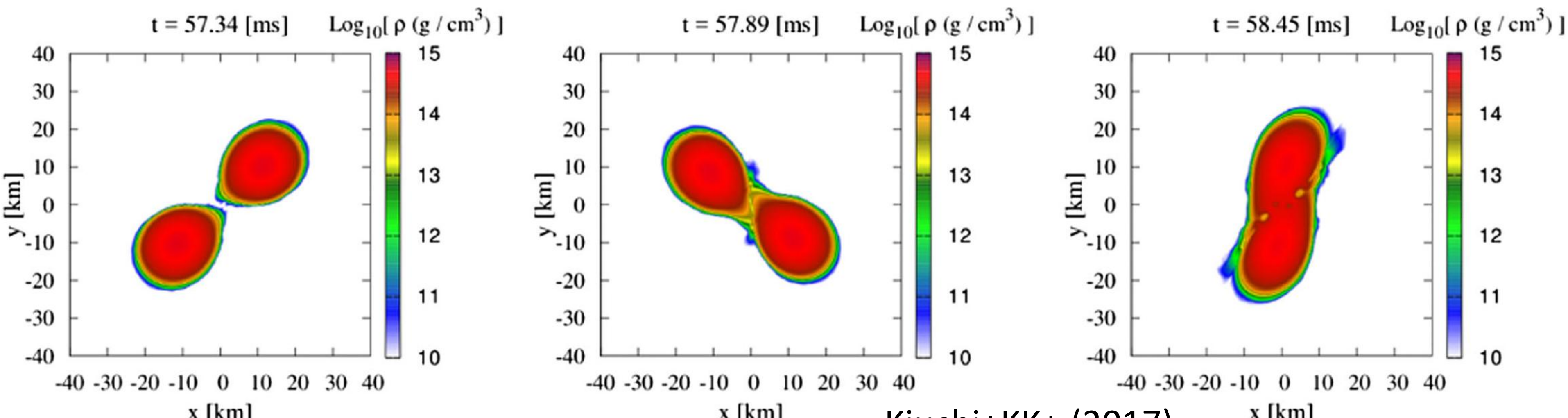
Extreme

Necessity of numerical simulations

The amplitude maximum comes after the contact

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

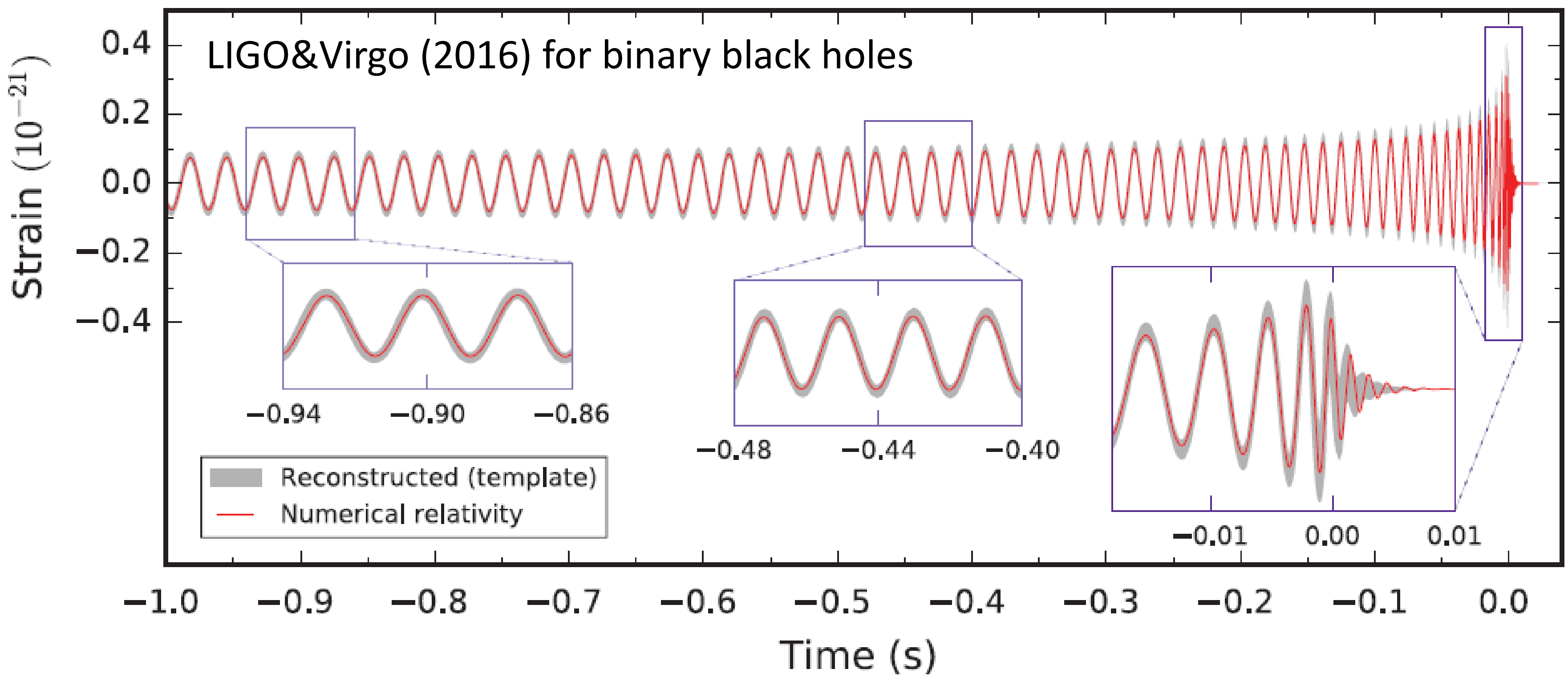
Analytic computations cannot be fully accurate



Kiuchi+KK+ (2017)

Role of theoretical templates

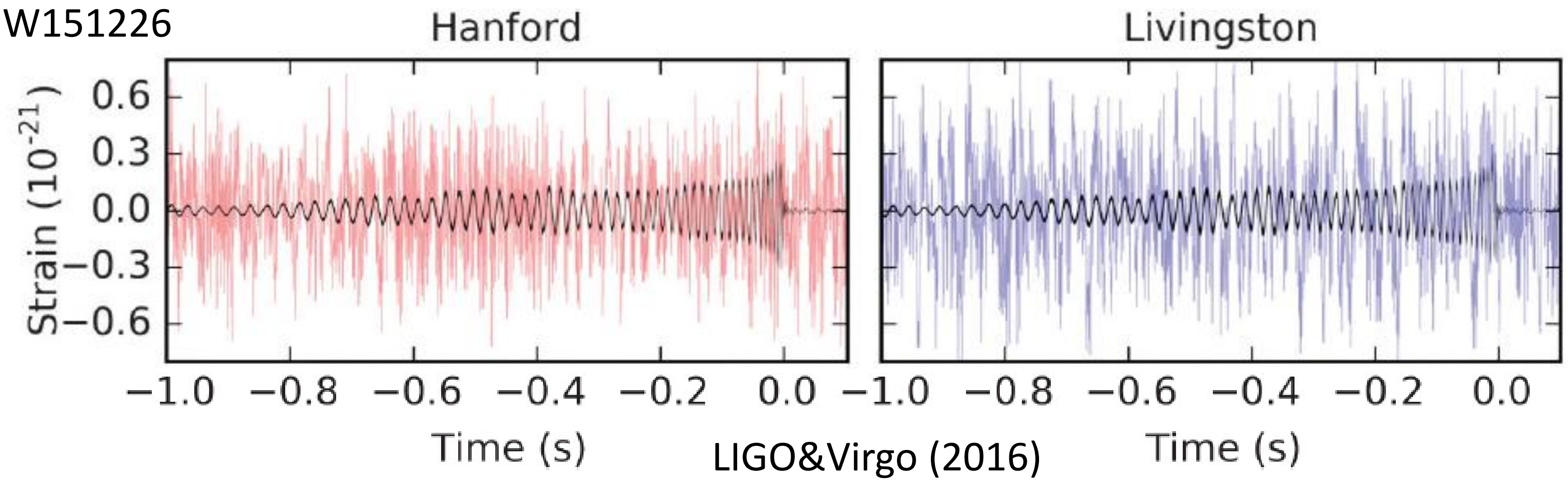
Parameters of binaries are estimated by measuring the match between data and theoretical waveforms
Accurate theoretical models are indispensable



Theoretical waveform and the noise

Signals are usually weaker than the detector noise

GW151226

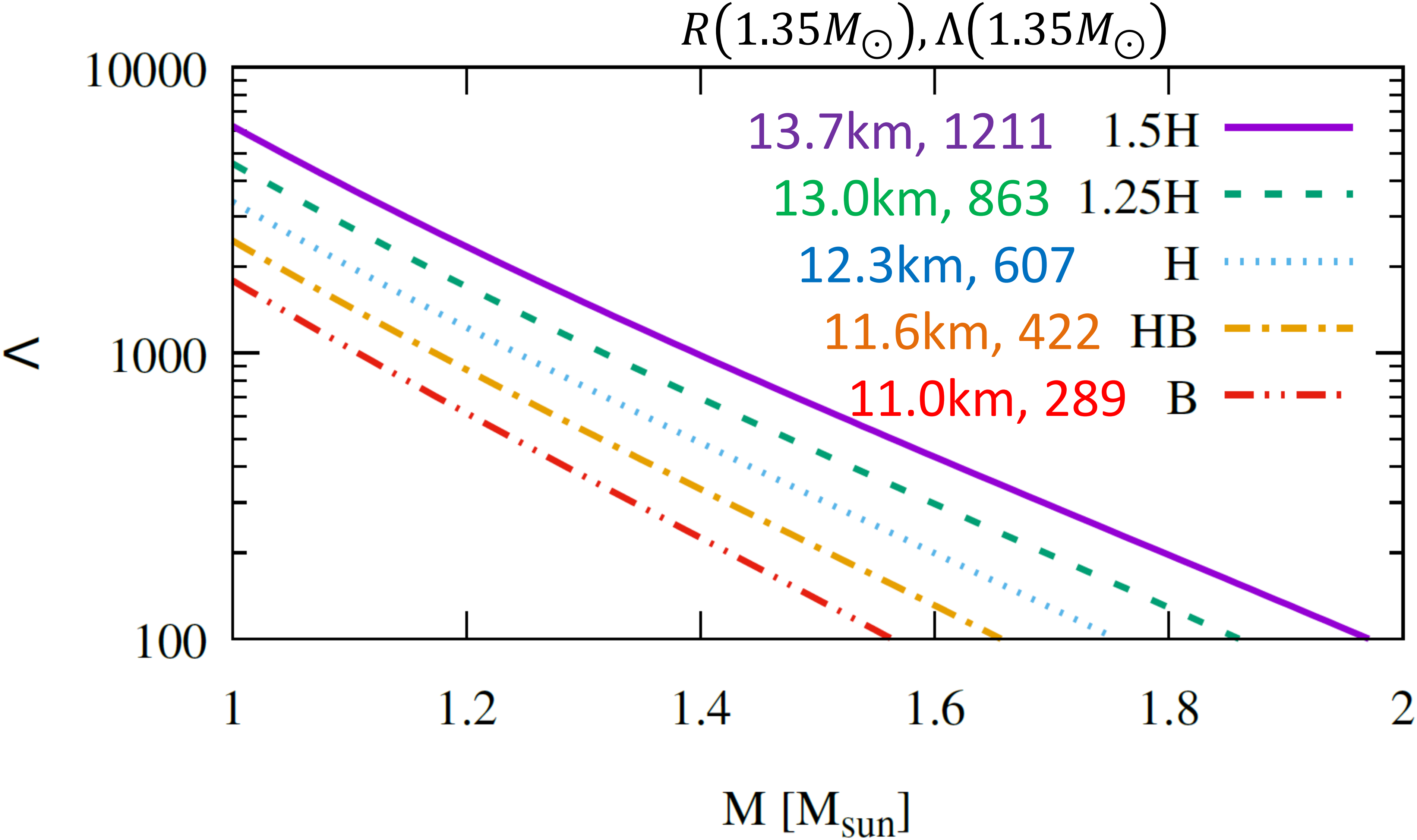


LIGO&Virgo (2016)

Taking the correlation with theoretical waveform

Accurate theoretical calculations are very important

$M - \Lambda$ relation and equations of state

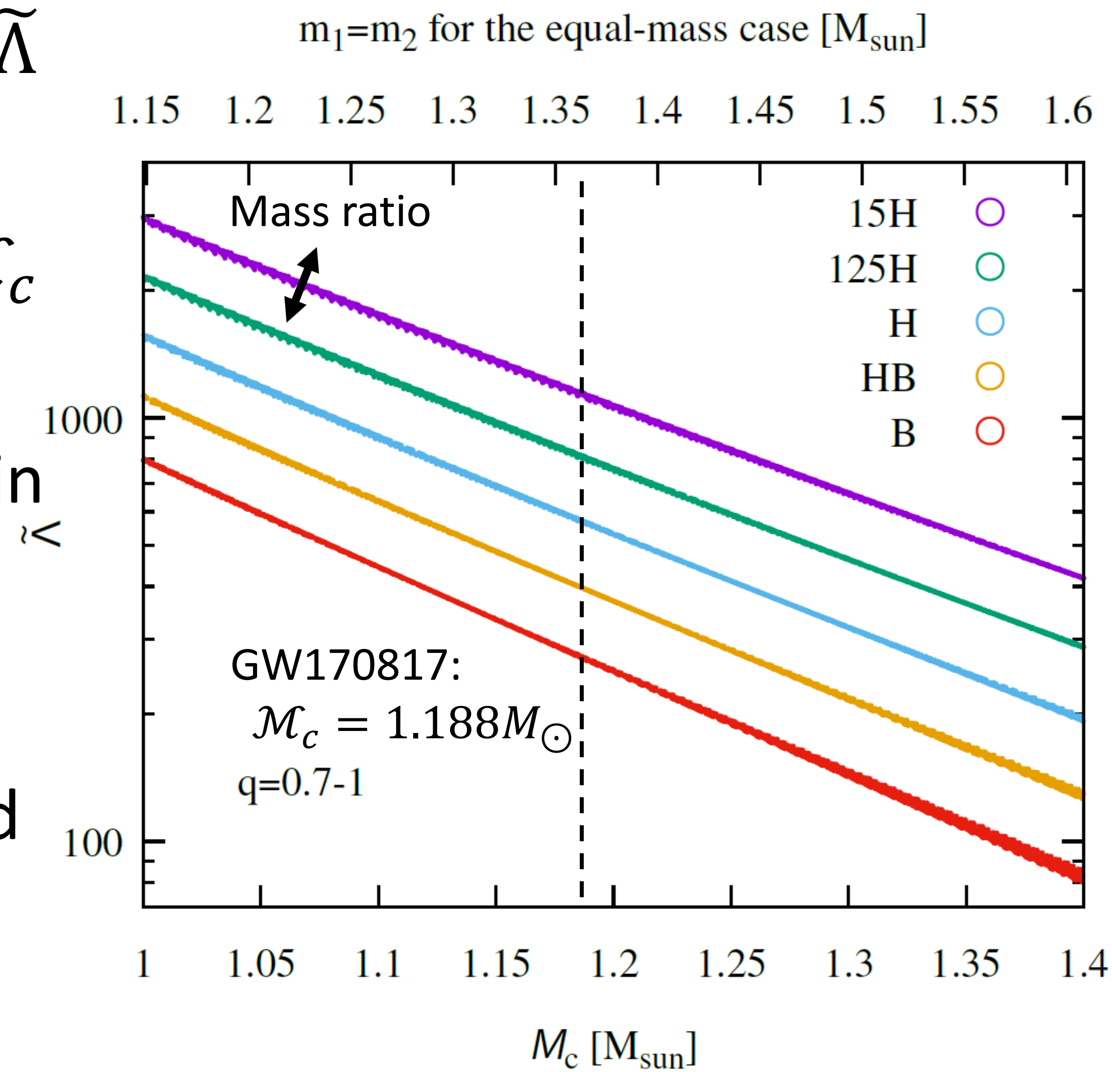


Strong correlation of $\tilde{\Lambda} - \mathcal{M}_c$

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



Waveform library

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

Released Model List

Serach:

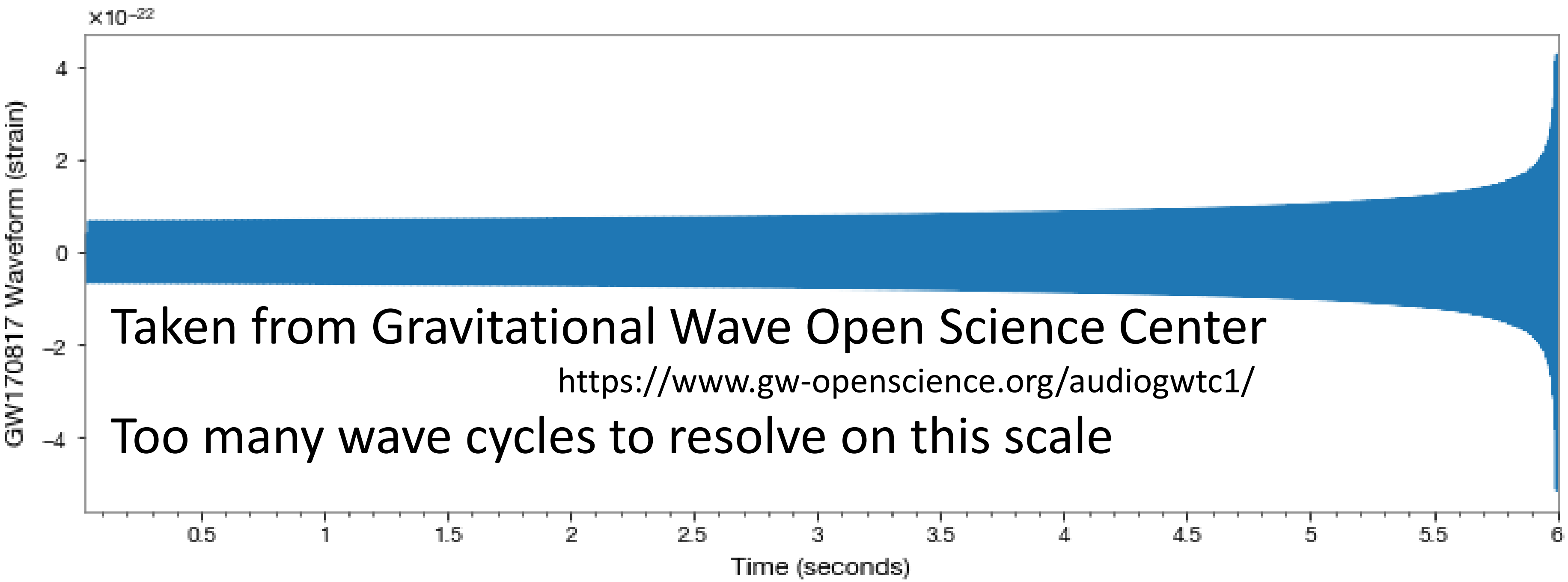
Model name	m_1	m_2	m_0 ($=m_1+m_2$)	q ($=m_1/m_2$)	η	M_c	EOS name	Λ_1	Λ_2	$\tilde{\Lambda}$	$m_0\Omega_0$	N	Reference
15H_135_135_00155_182_135	1.35	1.35	2.7	1	0.25	1.17524	15H	1211	1211	1211	0.0155	182	Link
15H_135_135_00155_150_135	1.35	1.35	2.7	1	0.25	1.17524	15H	1211	1211	1211	0.0155	150	Link
15H_135_135_00155_130_135	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

GW170817

The longest signal ever (longer than 100 second)

Detected by LIGO Hanford/Livingston detectors

Virgo did not detect, but informative for localization



Taken from Gravitational Wave Open Science Center

https://www.gw-openscience.org/audiogwtc1/

Too many wave cycles to resolve on this scale

Parameters of GW170817

The chirp mass is determined to $10^{-3} M_{\odot}$ precision

The masses suggest that both are neutron stars

Tidal deformability was measured for the first time

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 $\mathcal{M}^{\det}$	$1.1975^{+0.0001}_{-0.0001}$ $M_{\odot}$
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)

$$\mathcal{M} := \frac{m_1^{3/5} m_2^{3/5}}{(m_1+m_2)^{1/5}}$$

LIGO&Virgo (2019)

Kyoto gravitational-wave model

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

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

+ correction terms associated w/ mass asymmetry

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

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

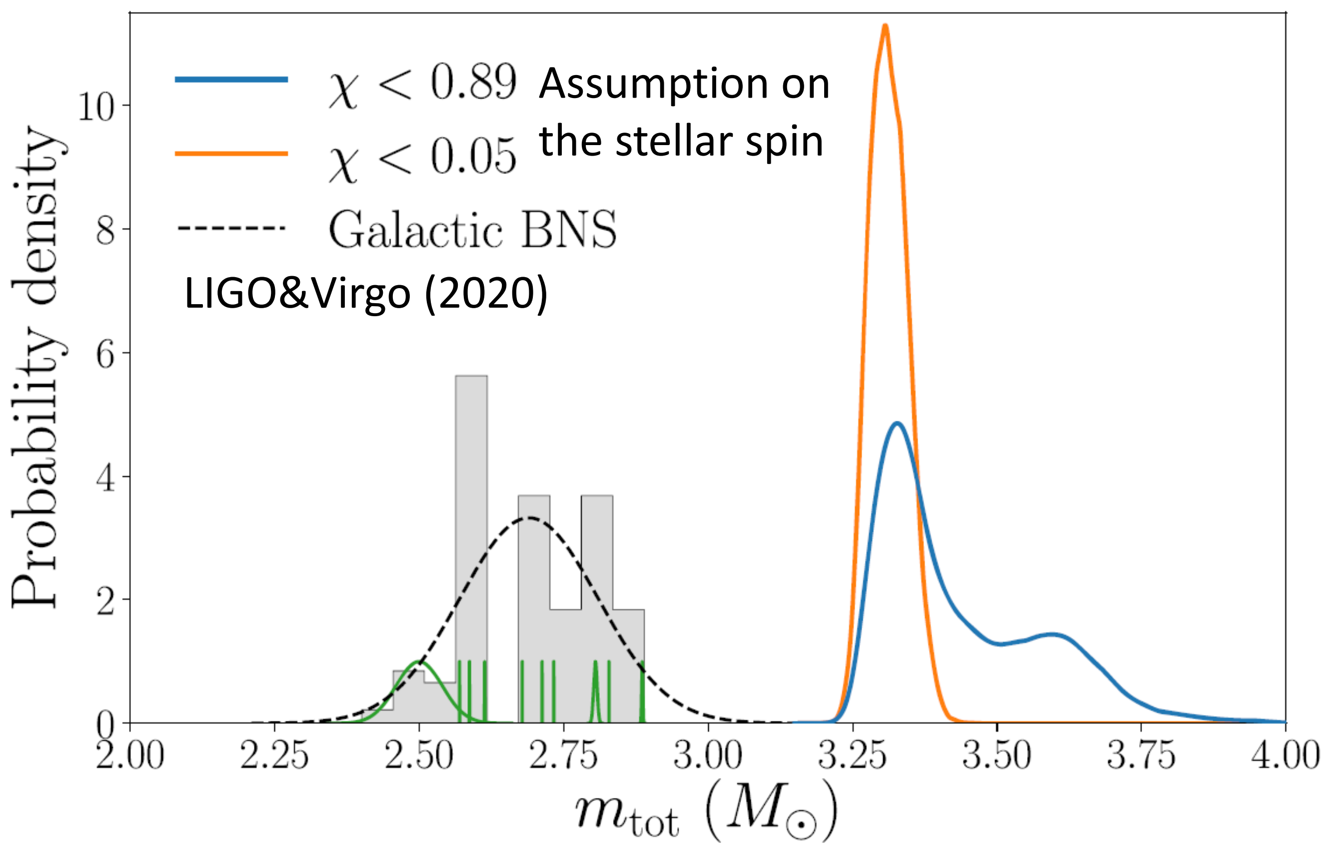
$$-\frac{39}{2}\tilde{\Lambda}(1 + 12.55\tilde{\Lambda}^{2/3}x^{4.240})$$

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

GW190425

Total mass $m_{\text{tot}} = 3.4^{+0.3}_{-0.1} M_{\odot}$, no EM counterpart

Heavier by >5sigma than Galactic binary neutron stars



Case of GW190425

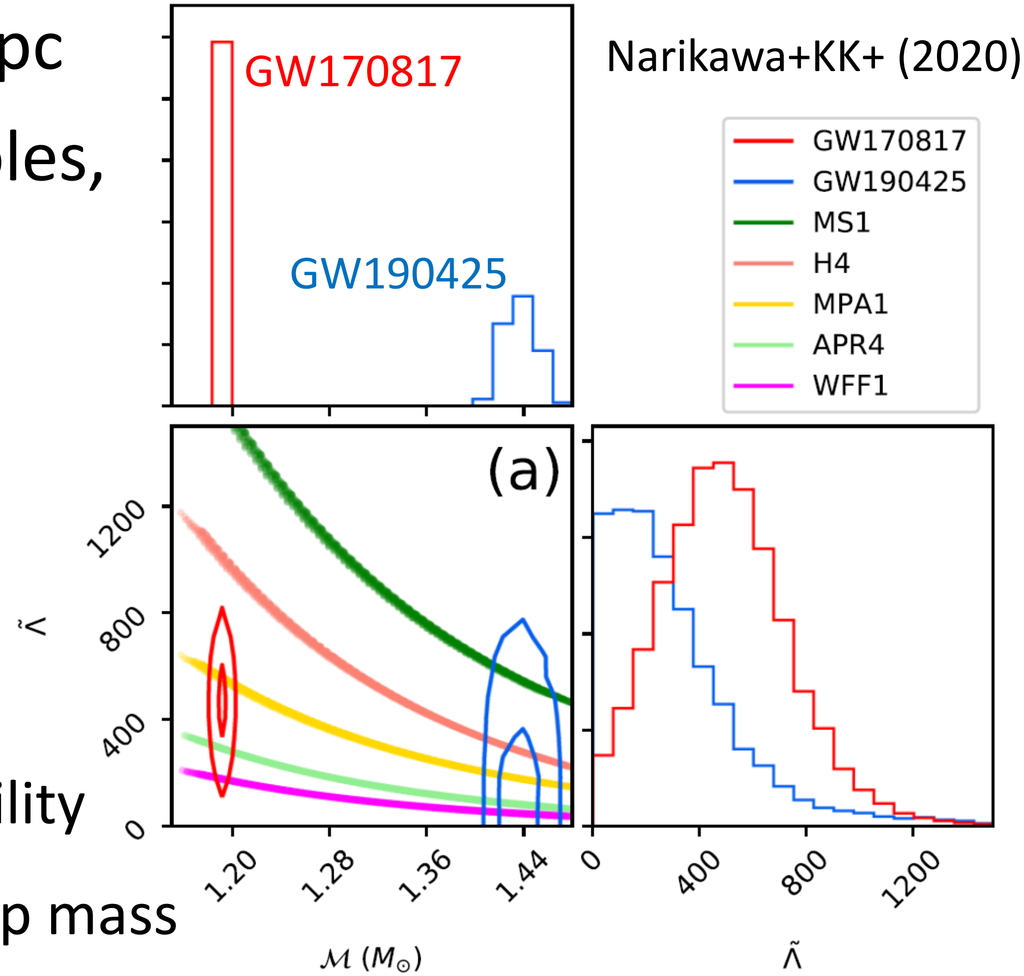
Weak constraint due to the high mass $3.4M_\odot$ and the large distance 150-250Mpc

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

[see also Kyutoku+ (2020)]

Simply GW170817 was extremely lucky

Narikawa+KK+ (2020)



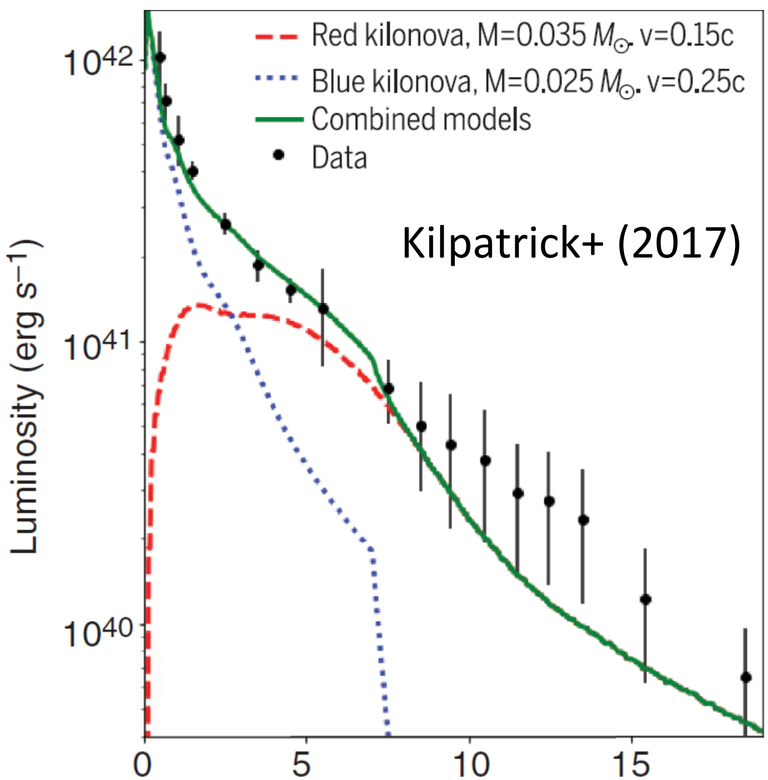
Binary tidal deformability

Chirp mass

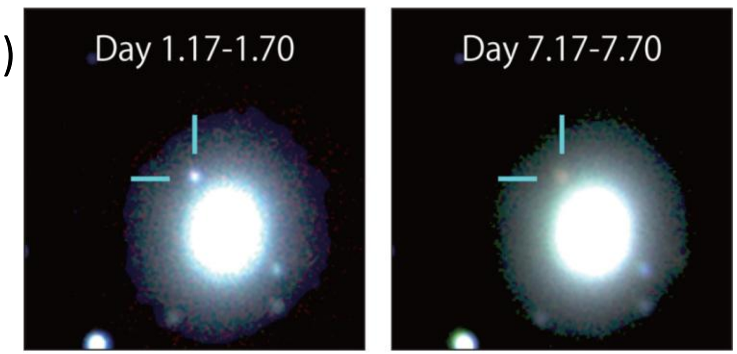
Constraint from the kilonova?

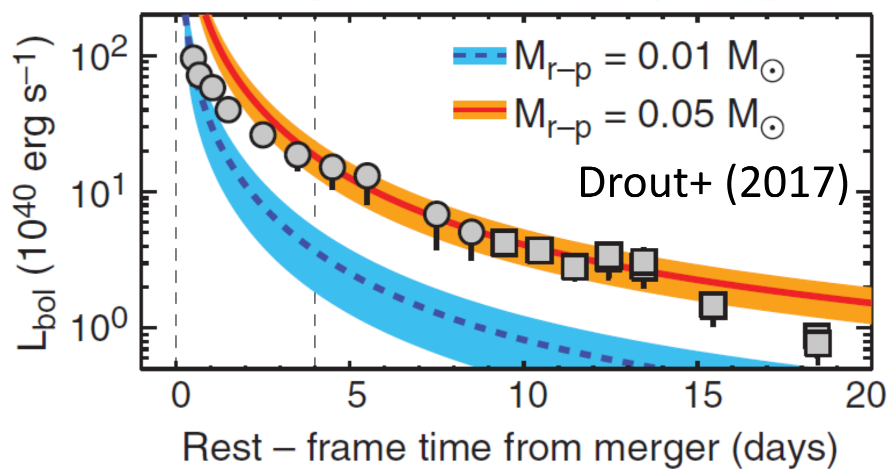
Indication of the large ejecta mass of $\sim 0.05 M_{\odot}$

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



Utsumi+ (2017)



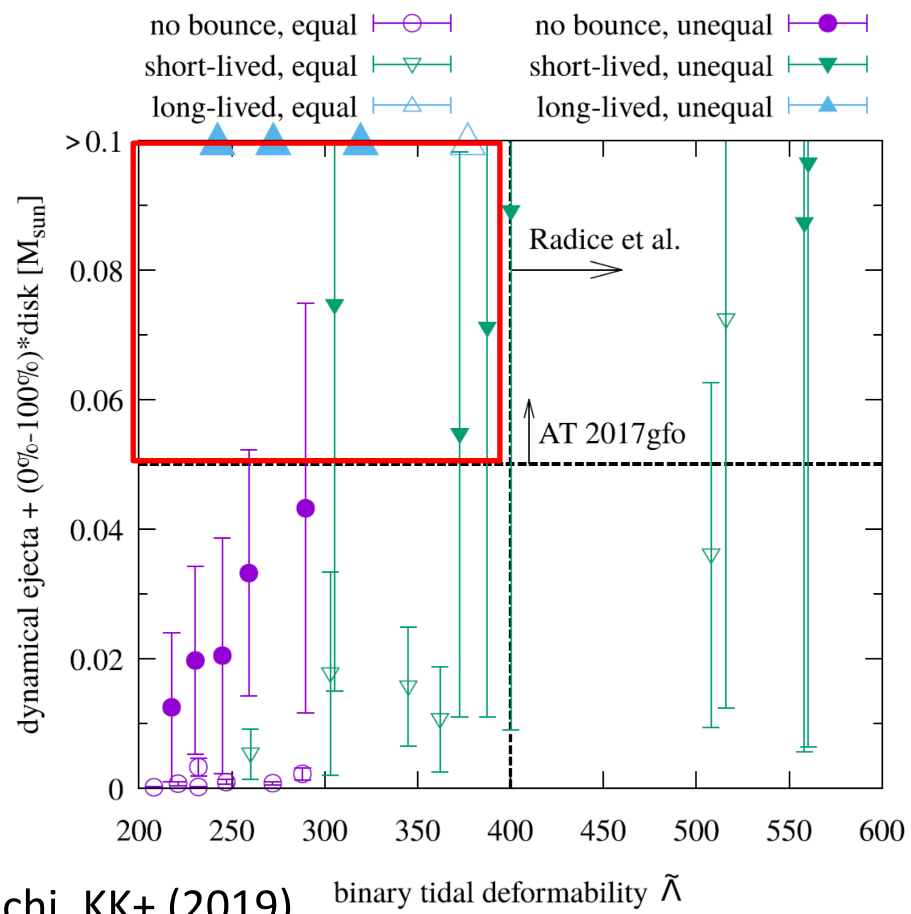


A lot of counterexamples

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)

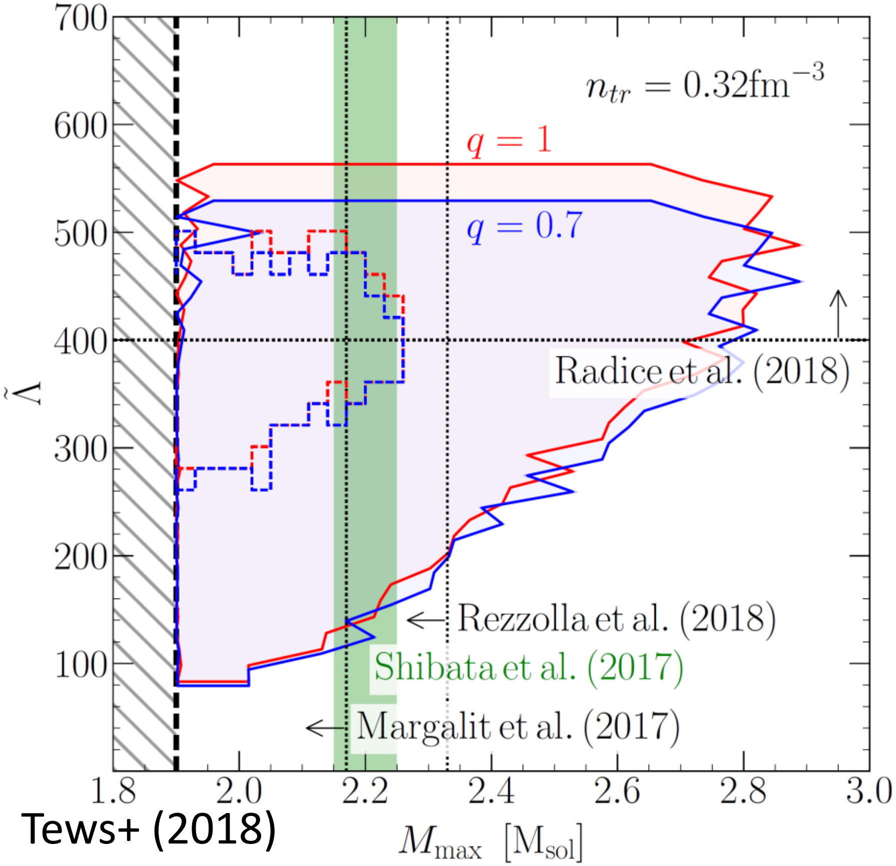


Kiuchi, KK+ (2019)

Reason?

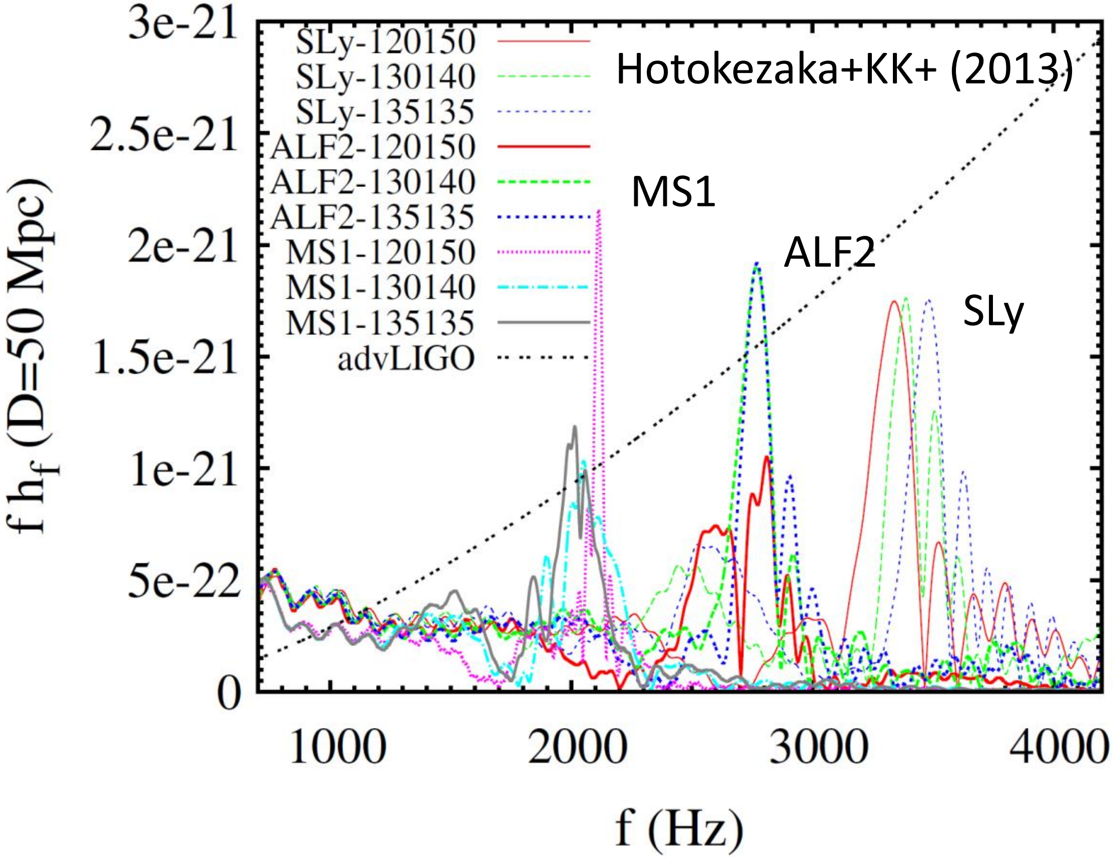
$M_{\max}$ may not be strongly correlated with $\tilde{\Lambda} \propto R^{\sim 6}$ of typical-mass neutron stars

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



Postmerger peak frequency

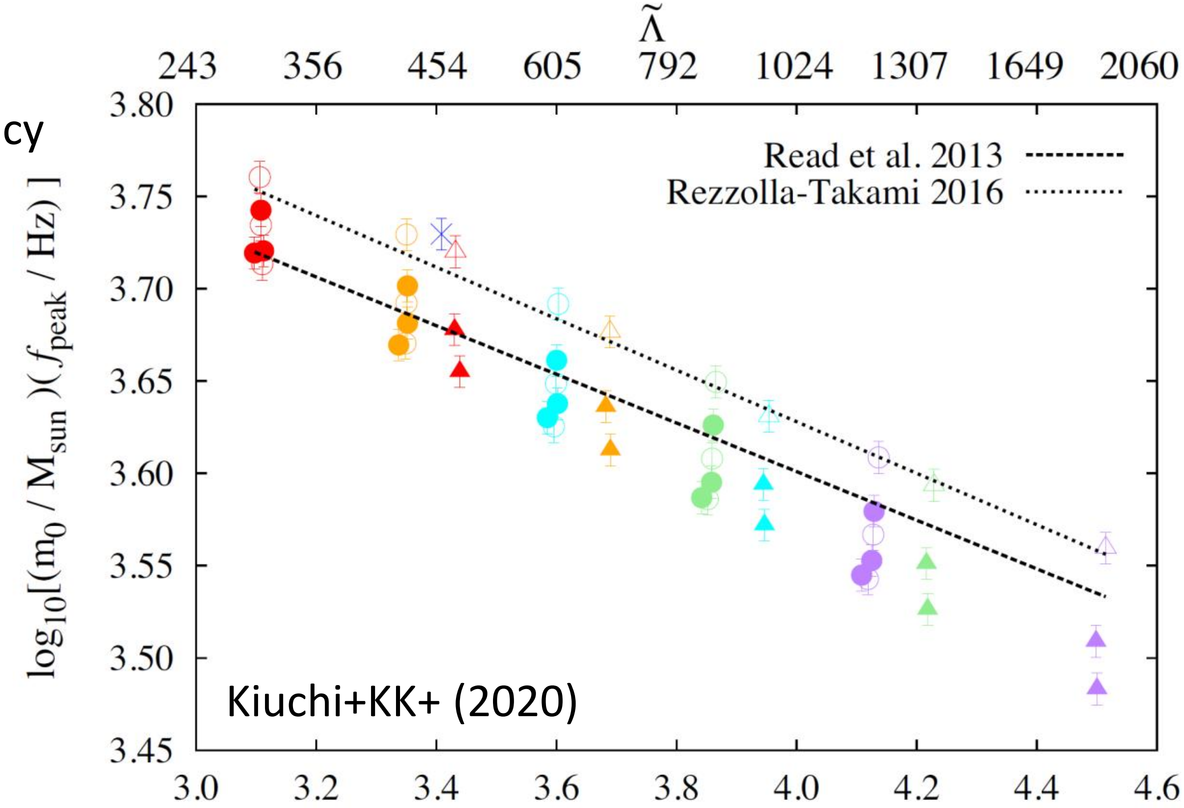
Depends on the equation of state and the total mass (also weakly on the mass ratio)



Pre-postmerger correlation

Frequency at the amplitude peak is correlated strongly with the property of premerger neutron stars

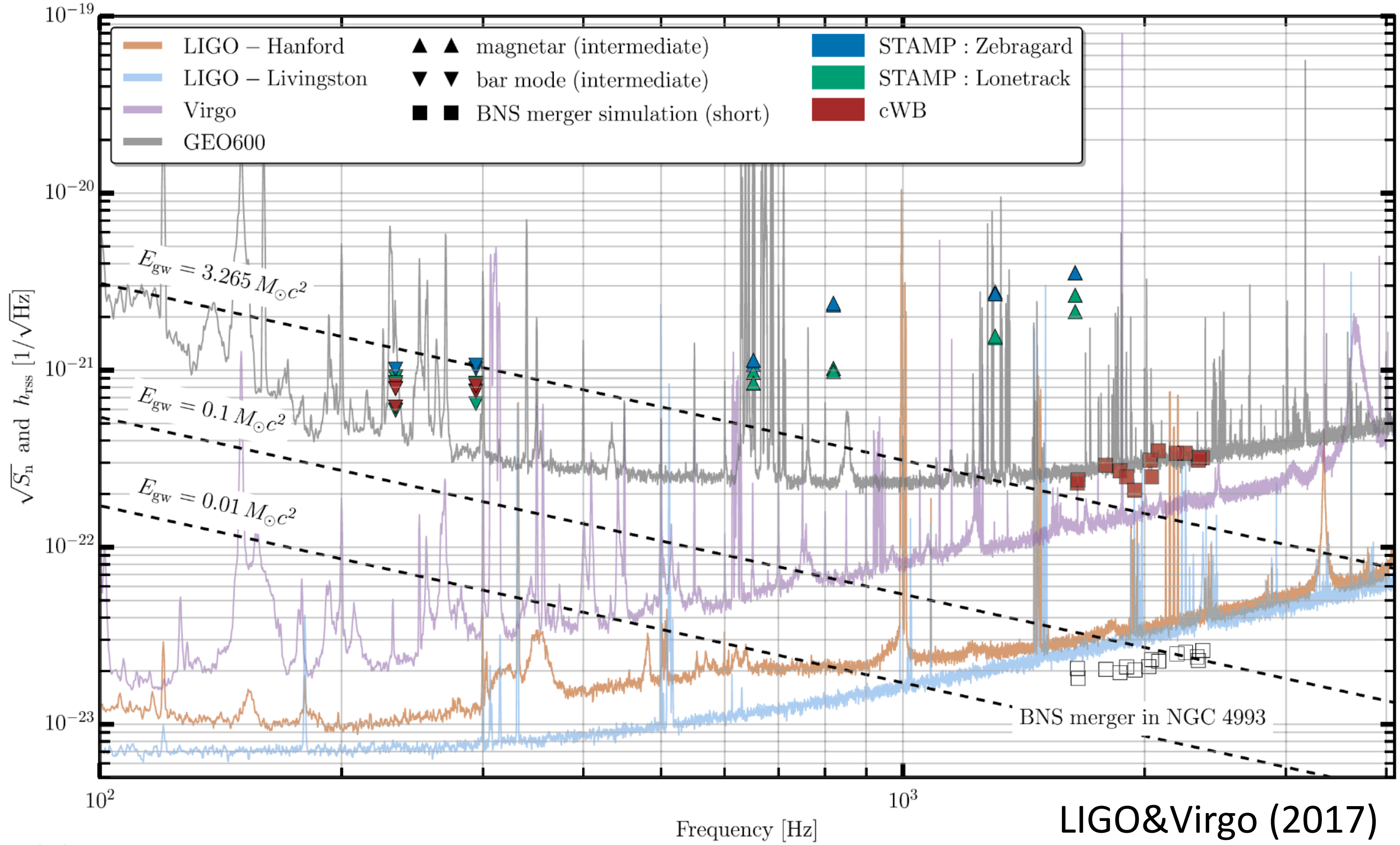
Peak frequency (rescaled)



Tidal deformability

Nondetection for GW170817

Simply, sensitivity at high frequency is insufficient

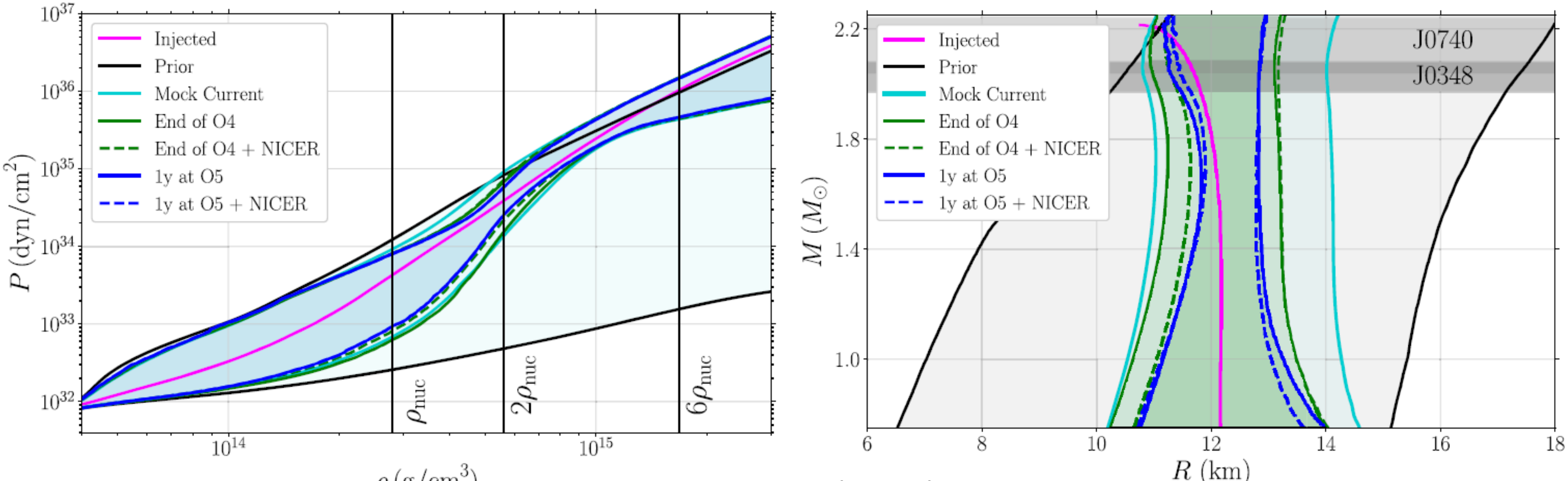


LIGO&Virgo (2017)

What should we understand then?

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

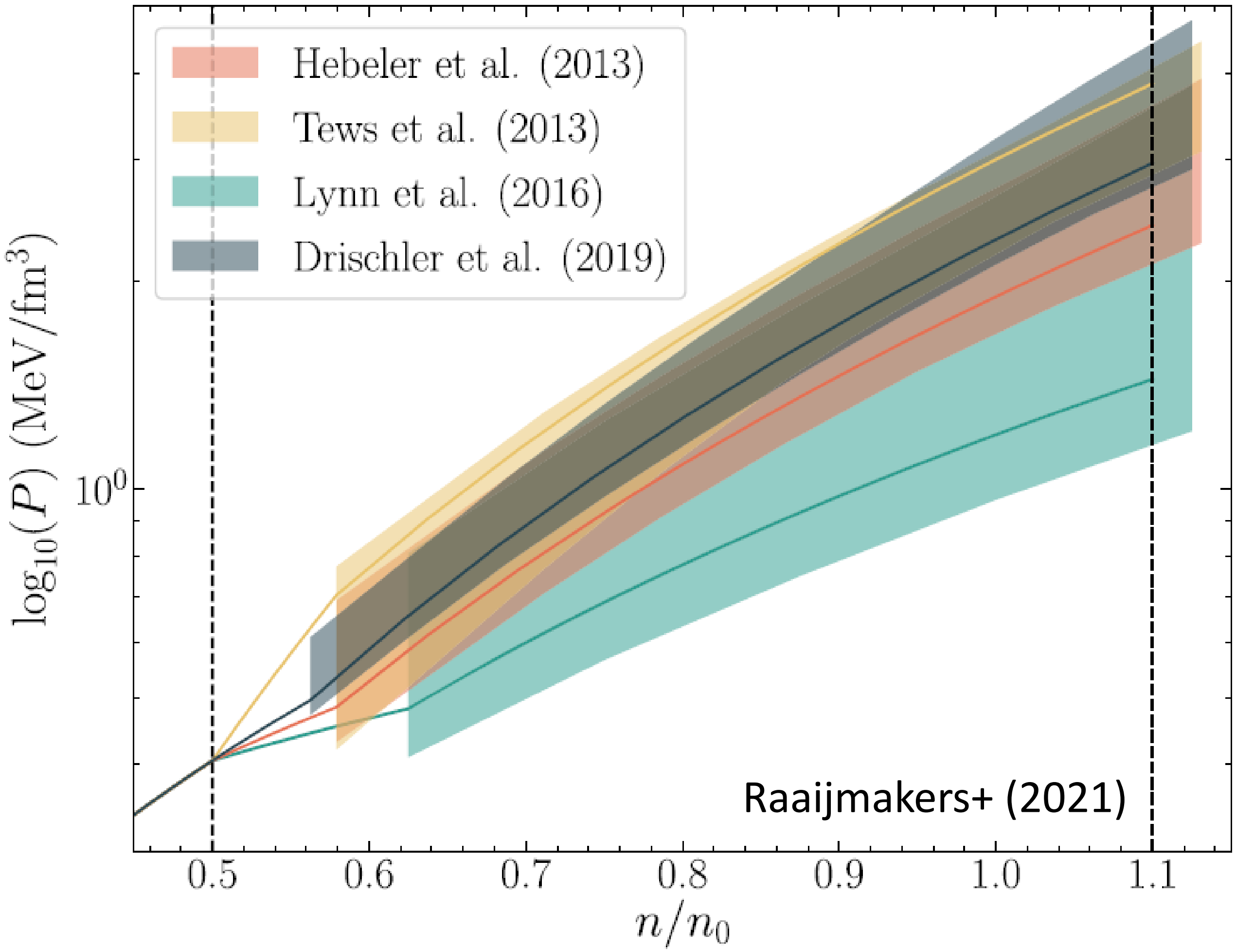
On the basis of this idea, we would like to understand properties of ultrahigh-density matter



Landry+ (2020)

Uncertainty in chiral EFT

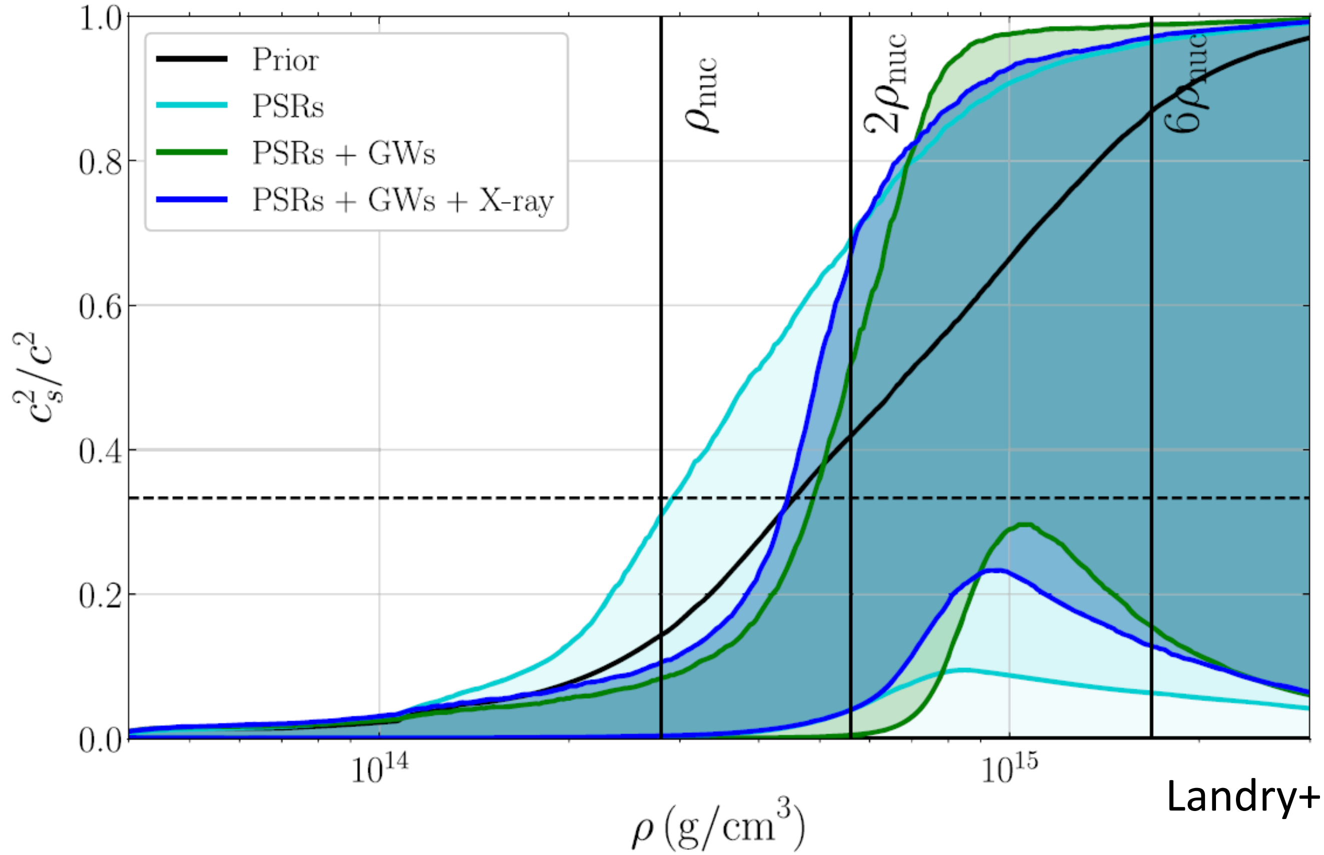
The validity range is crucial for strength of constraints



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

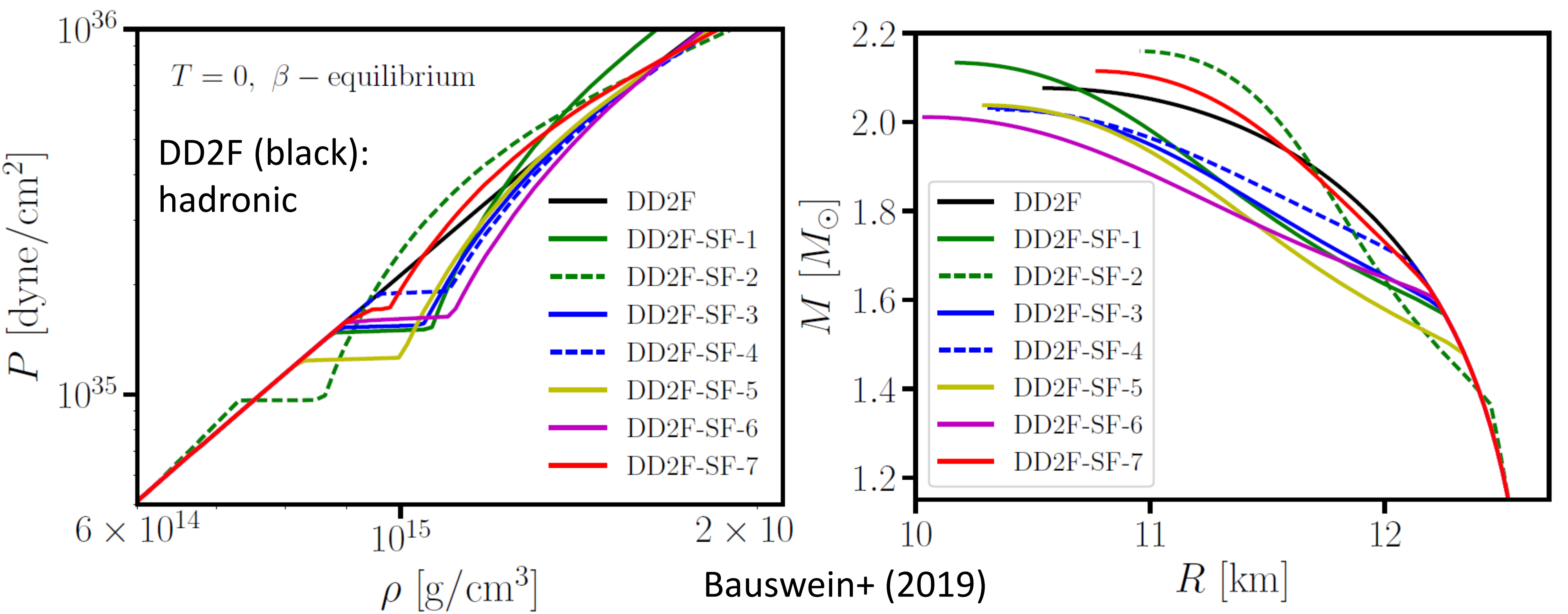


Landry+ (2020)

Strong 1st-order phase transition

The mass-radius relation breaks suddenly

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

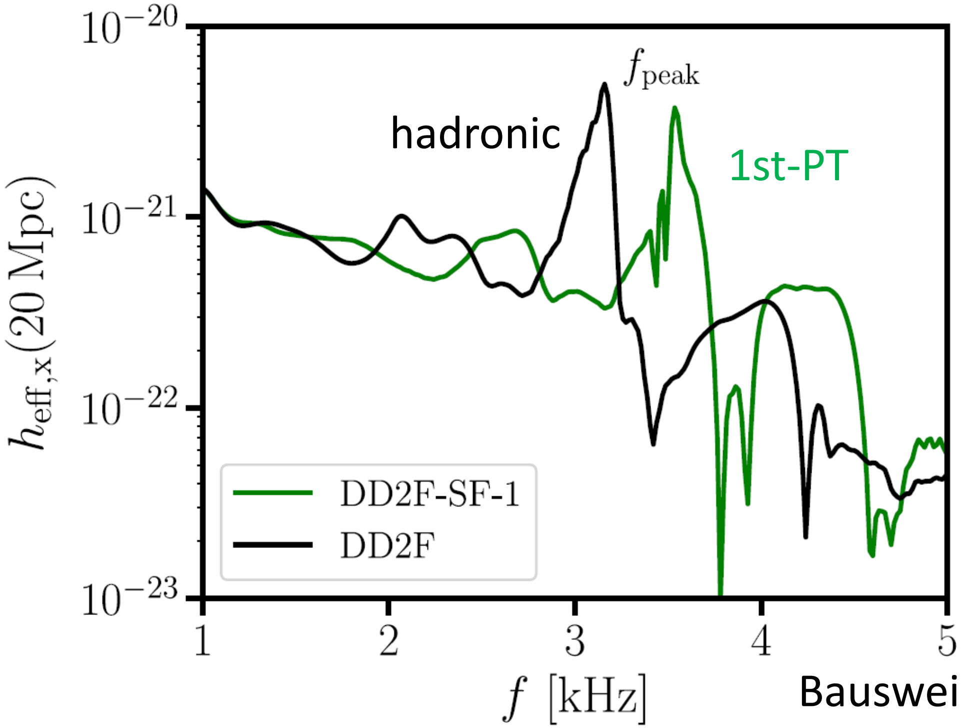


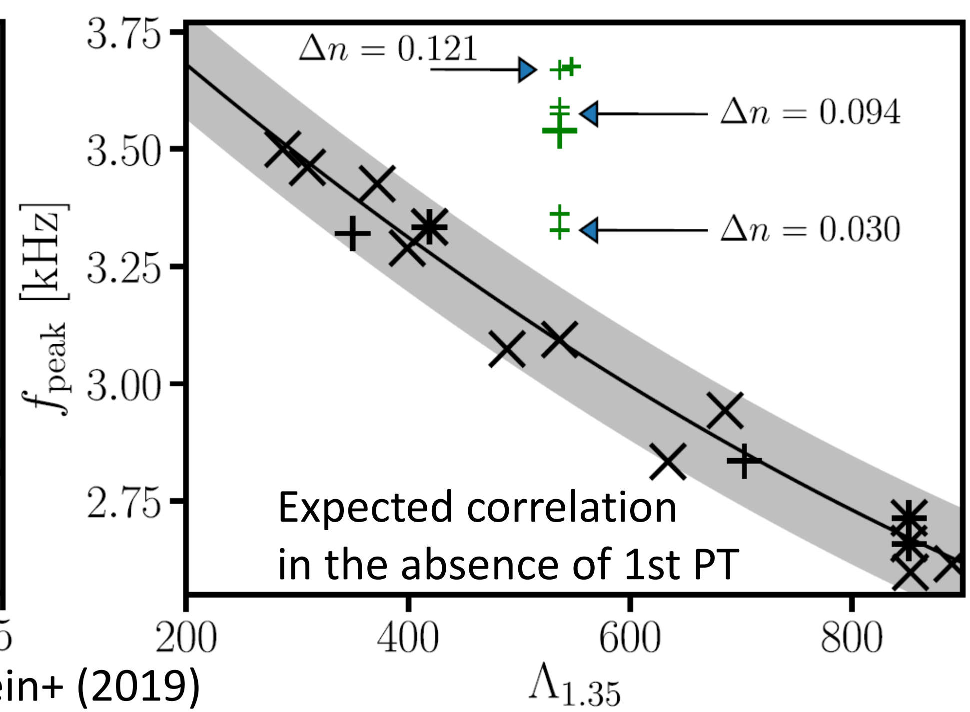
Bauswein+ (2019)

Effect on the postmerger peak

Significant deviation from expectation for hadrons

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





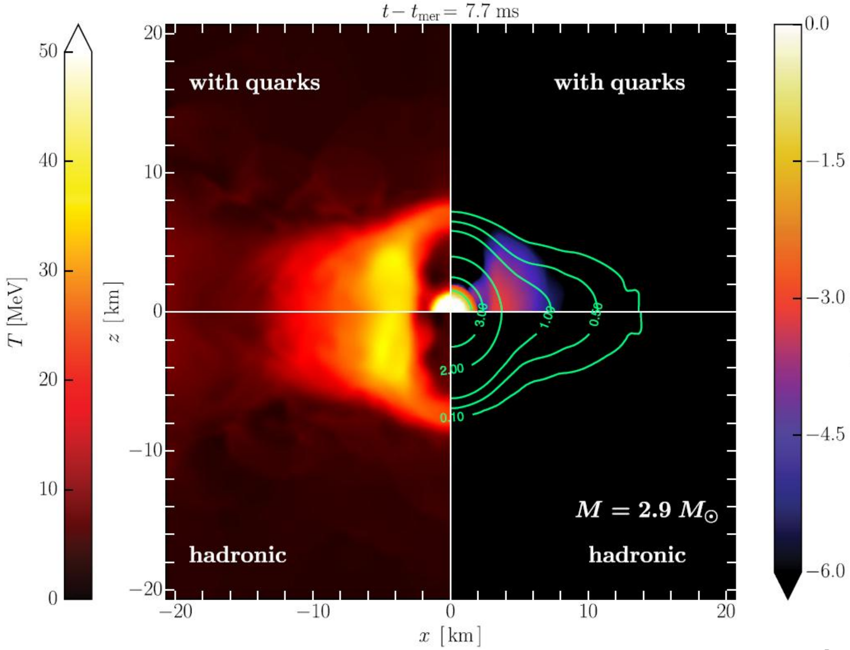
Bauswein+ (2019)

Structure of the merger remnant

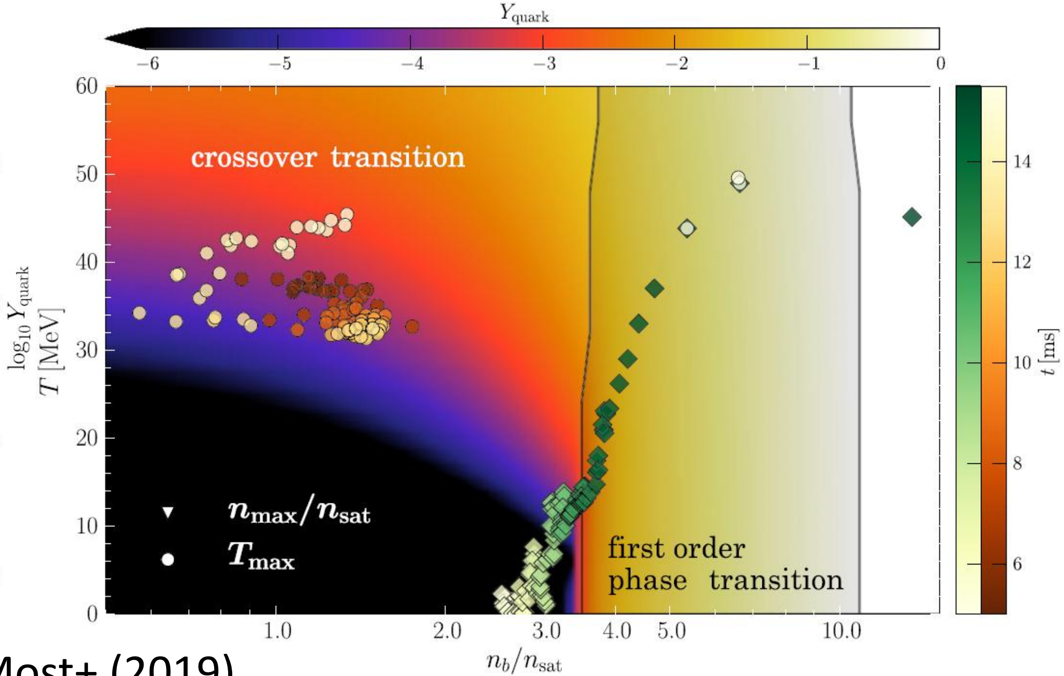
Density/temperature structures are not very different

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

Top: w/ quark, bottom: hadron only



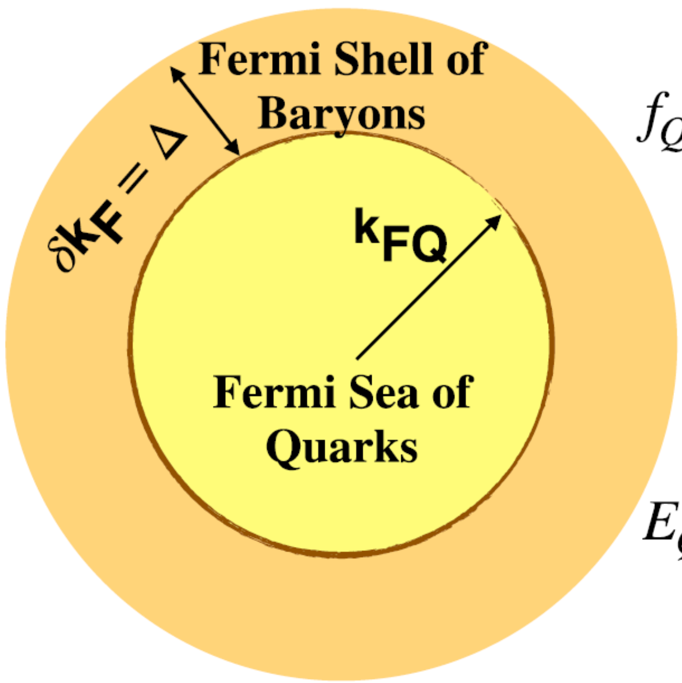
Time evolution of maximum n and T



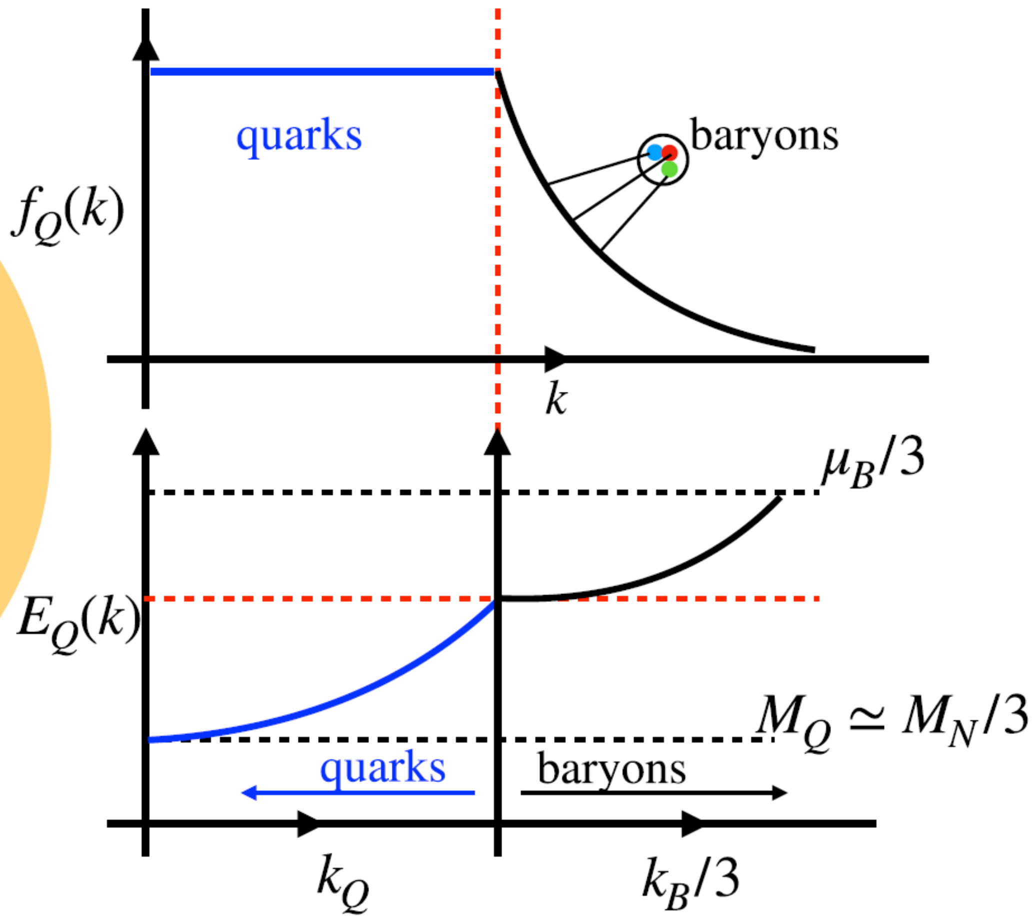
Most+ (2019)

Quarkyonic matter

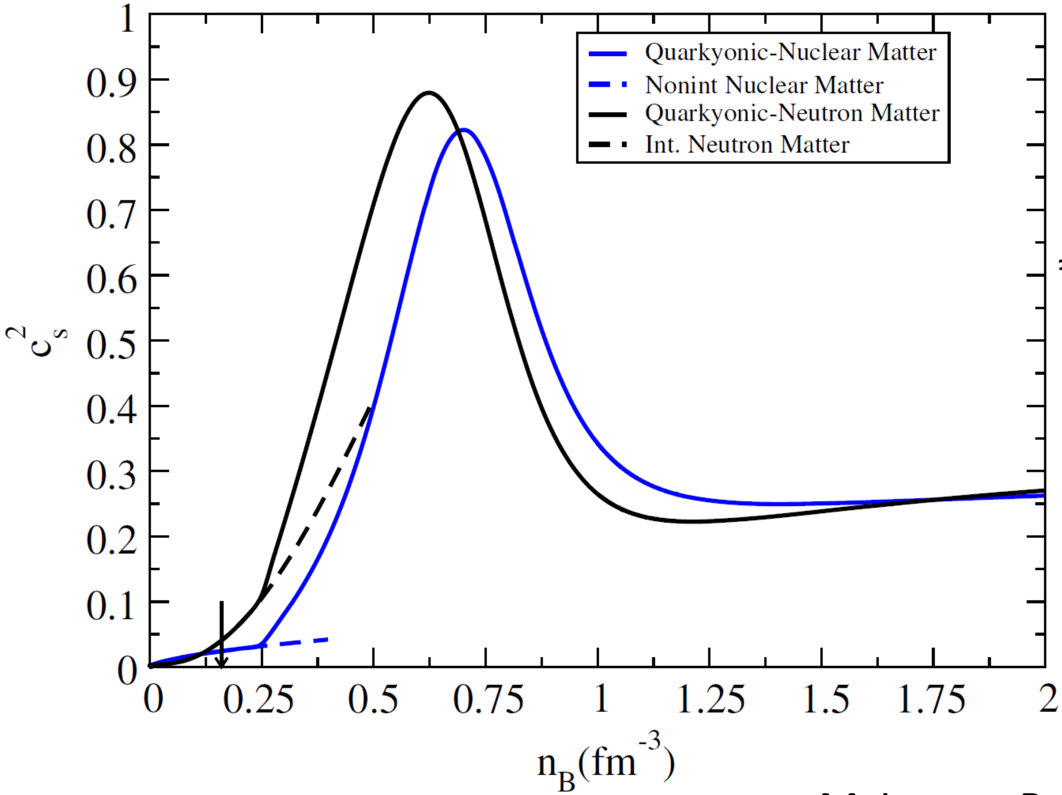
Baryons emerges near the Fermi surface of quarks

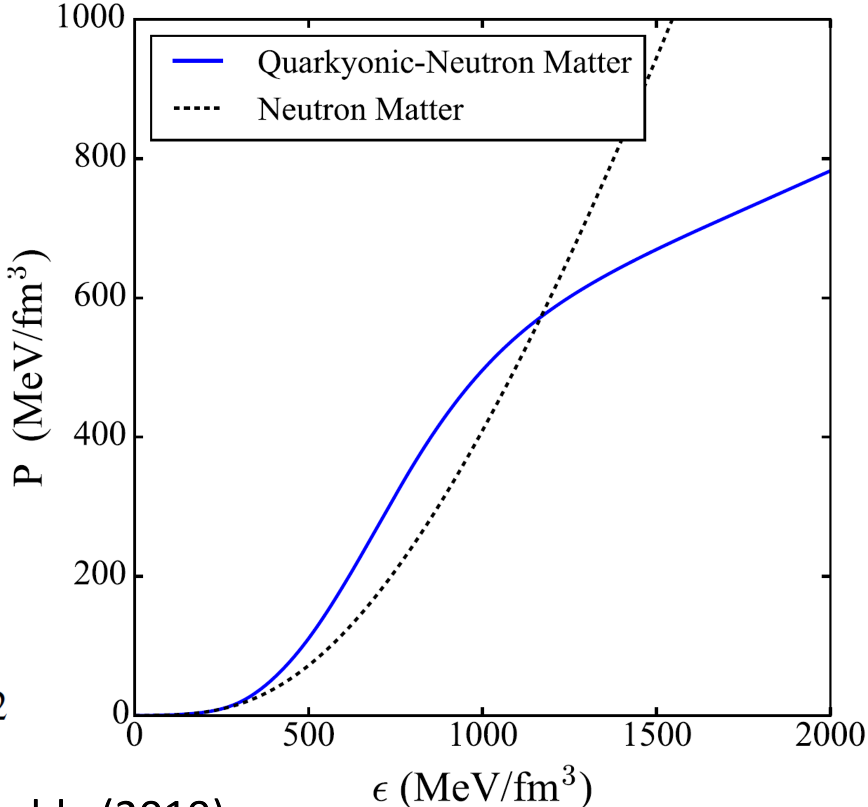


McLerran-Reddy (2019)



Sound speed of quarkyonic matter



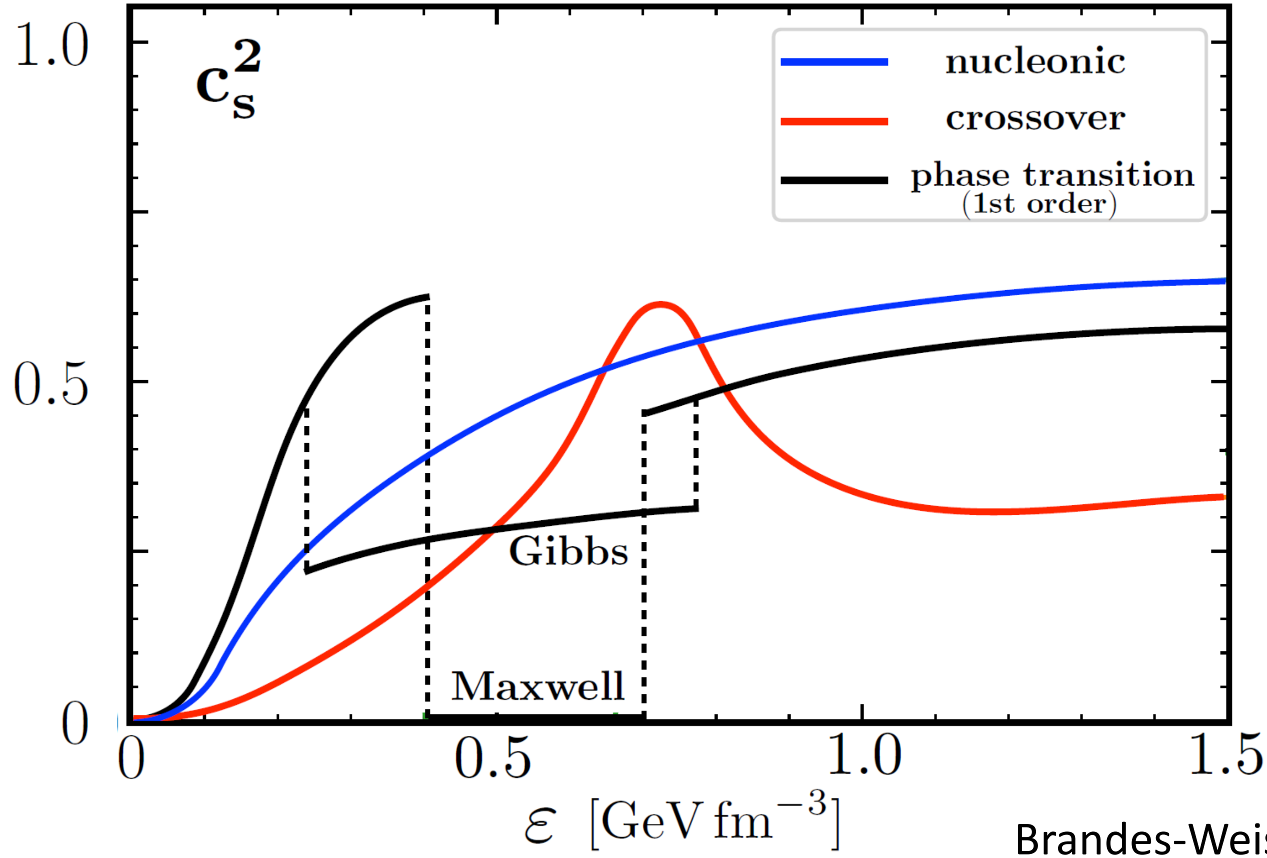


McLerran-Reddy (2019)

Sound speed in the crossover

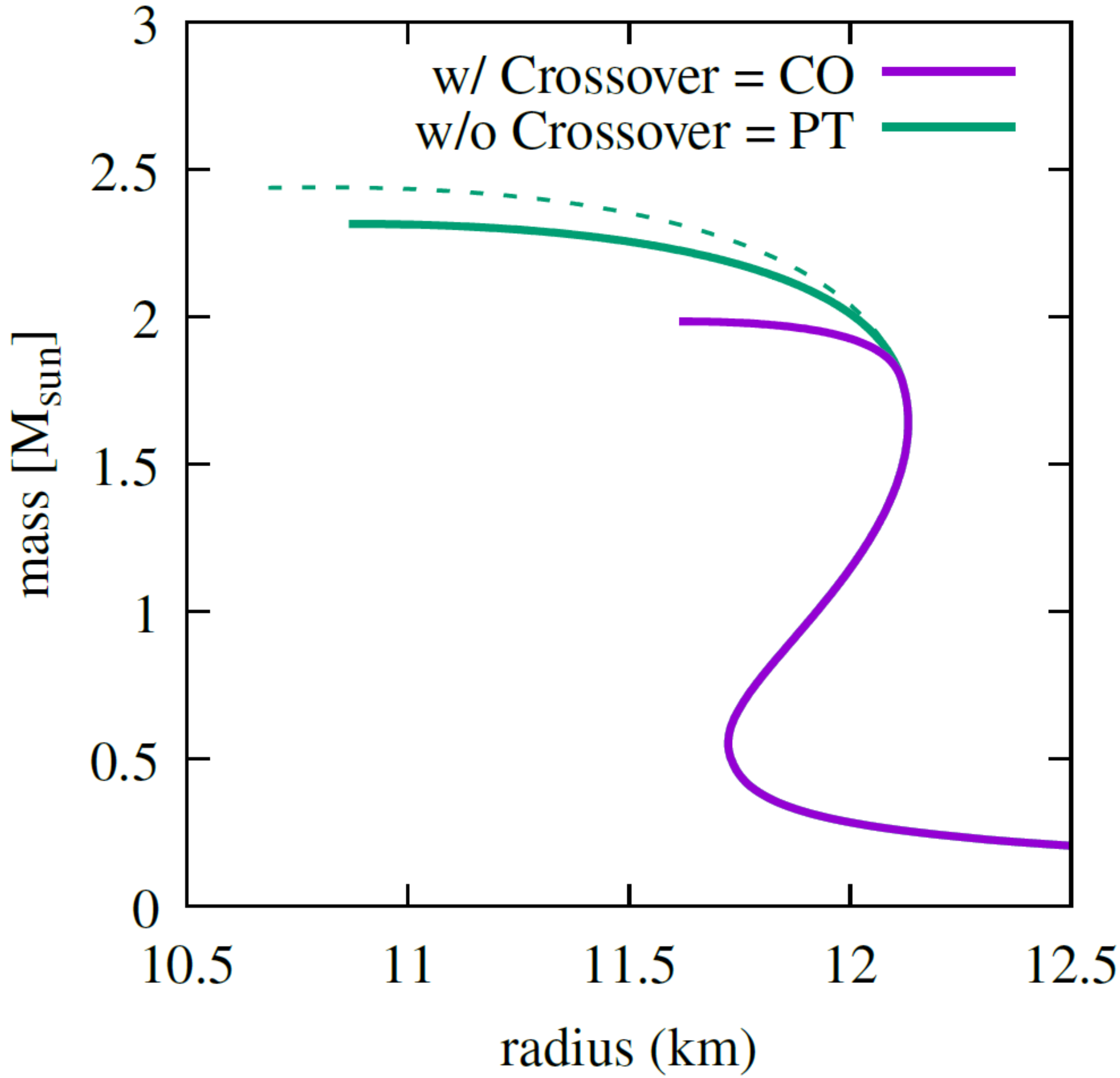
Crossover may induce a peak in the sound speed

Phase transition makes the sound speed very low



Brandes-Weise (2024)

Mass-radius relation



Difference from our previous work

The conformal limit, $P \propto \rho^{\Gamma}$ with $\Gamma \sim 4/3$, is realized at high density relevant to postmerger remnants

(we also assume 1st-order phase transition achieves this at superhigh density beyond astronomical reach)

We have not investigated such a soft high-density case

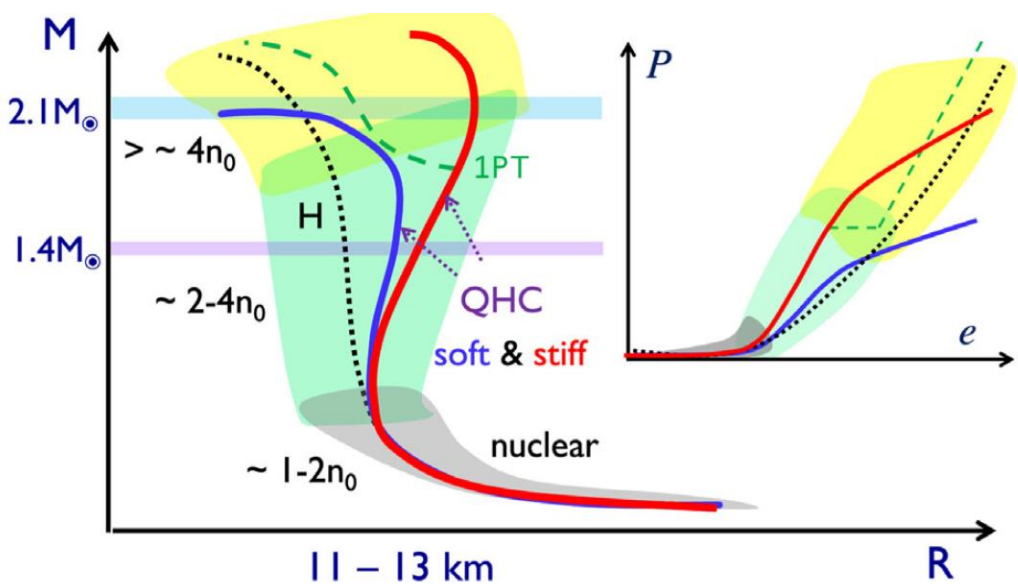
EOS	$\log P_1$(dyne/cm^2))	Γ_1	Γ_2	Γ_3	$M_{\max}(M_\odot)$	$R_{1.4}$(km)	Approach	Composition
APR4	34.269	2.830	3.445	3.348	2.213	11.428	Variational method	np
SLy	34.348	3.005	2.988	2.851	2.049	11.736	Effective-one-body potential	np
H3	34.646	2.787	1.951	1.901	1.788	13.840	Relativistic mean field	npH
H4	34.669	2.909	2.246	2.144	2.032	13.759	Relativistic mean field	npH
ALF2	34.055	4.070	2.411	1.890	2.086	13.188	APR + Quark matter	npQ
PS	34.671	2.216	1.640	2.365	1.755	15.472	Pion condensation	nπ^0

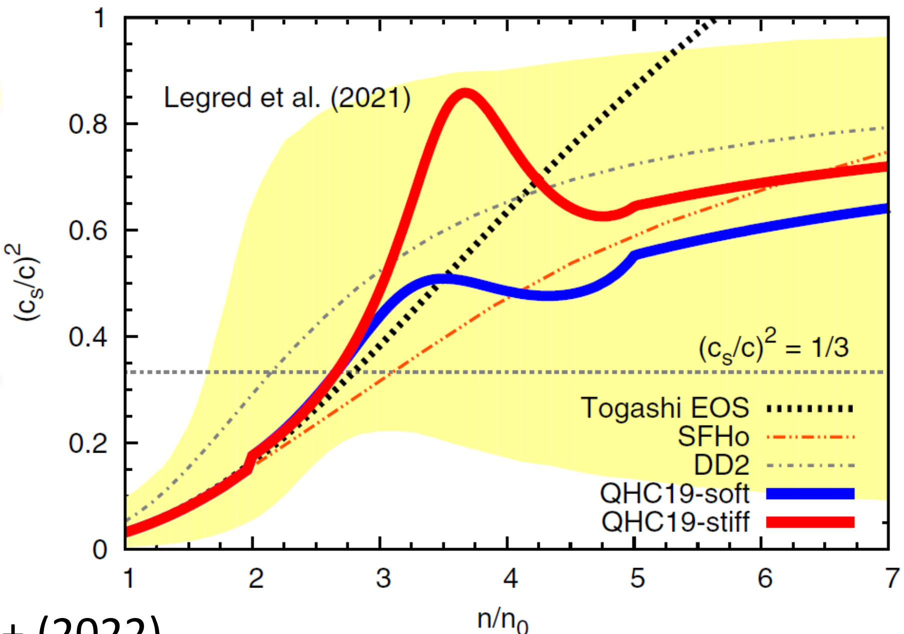
Hotokezaka, KK+ (2011)

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

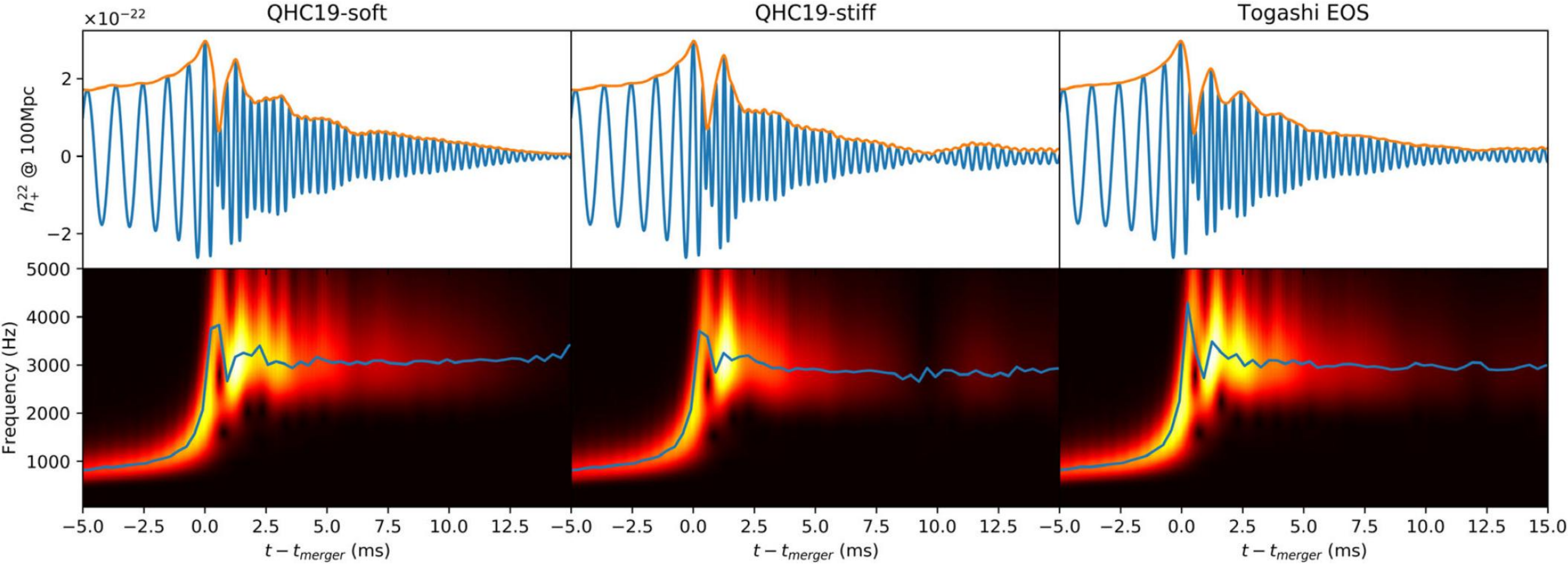




Huang+ (2022)

Results with QHC

Stiffening associated with the sound-velocity peak modifies the peak frequency to some extent

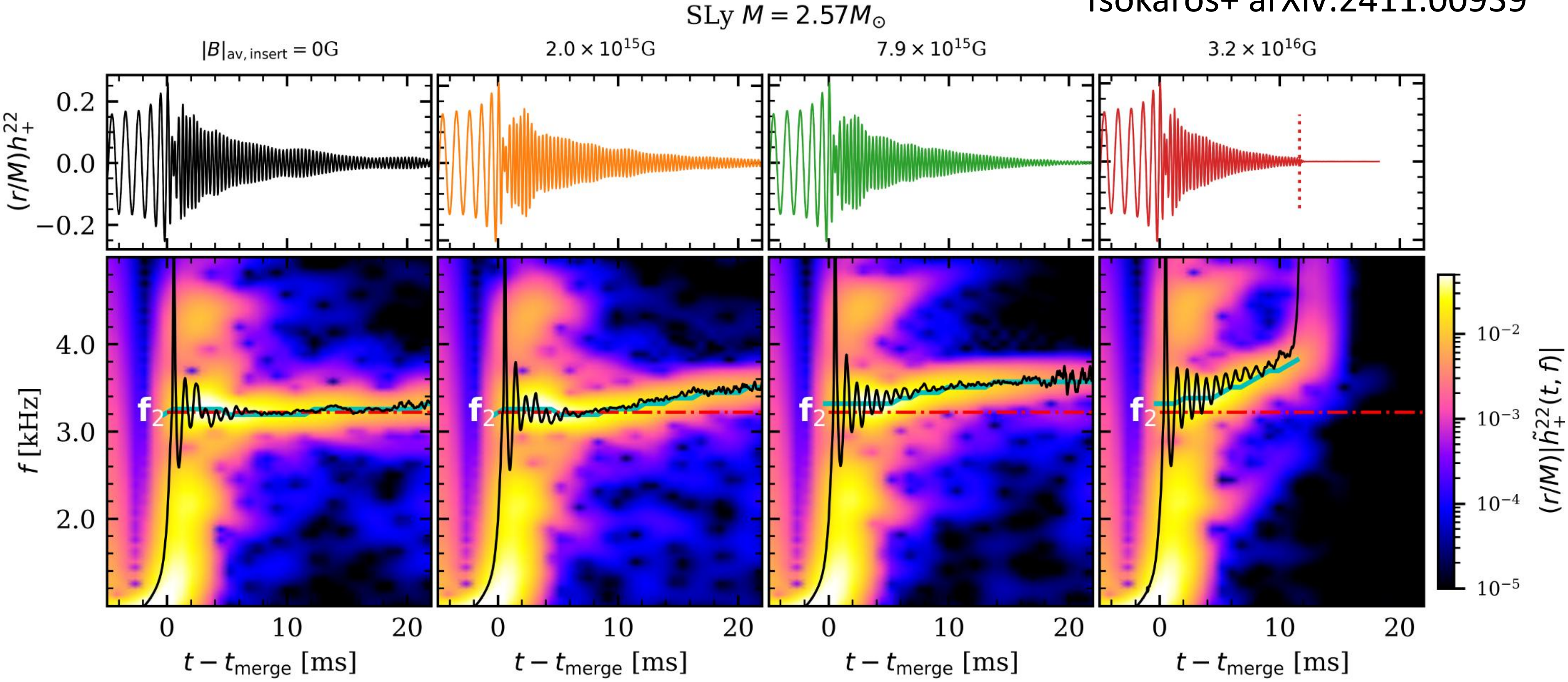


Huang+ (2022)

Magnetic-field and the peak

Magnetar-level premerger magnetic fields could also affect the peak frequency

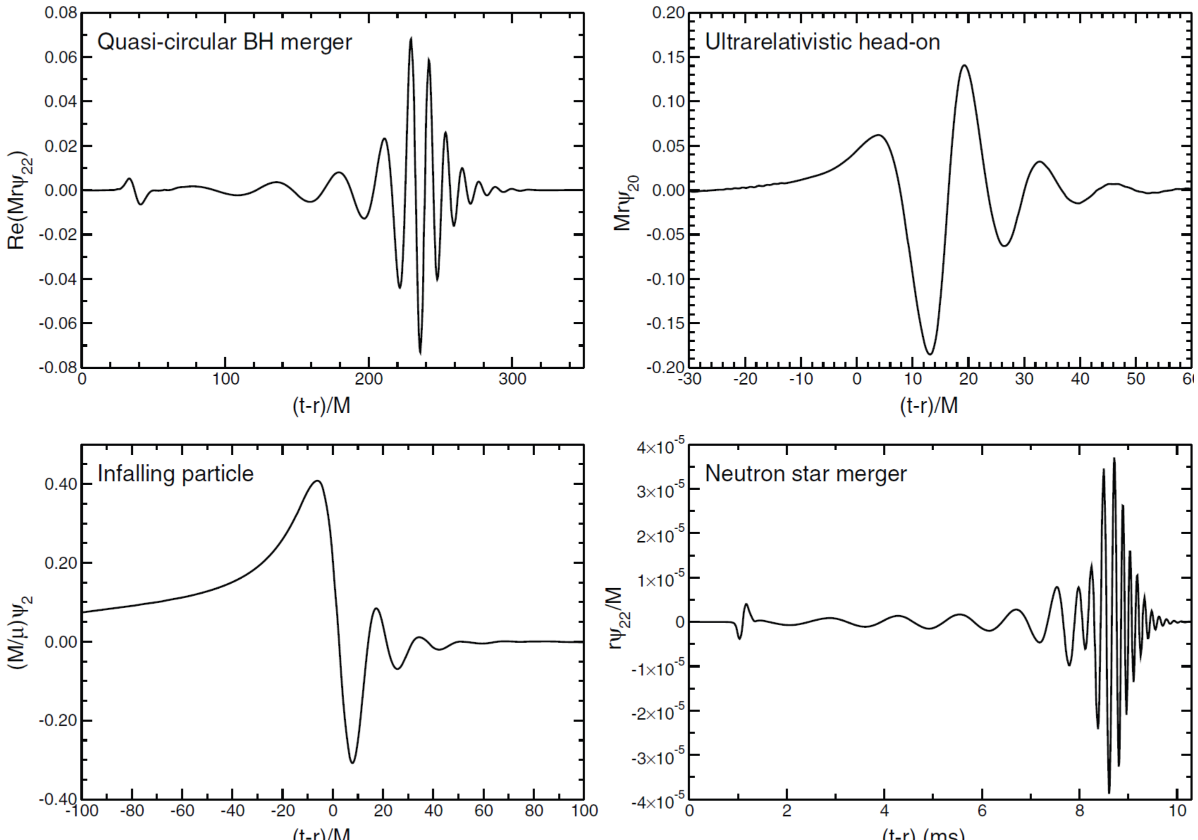
Tsokaros+ arXiv:2411.00939



Quasinormal modes of black holes

Damped oscillations governed by the mass and spin

Excited when they are formed in gravitational collapse



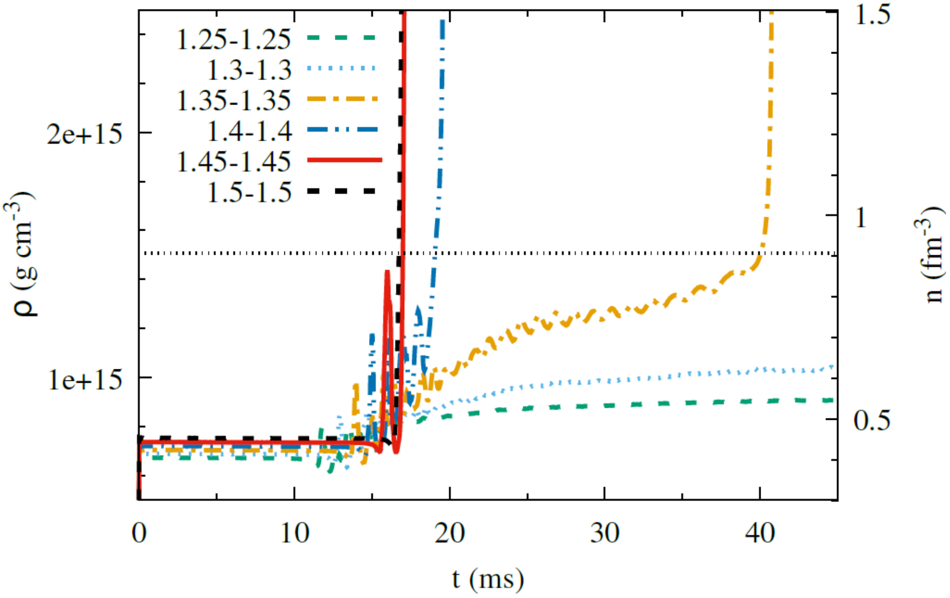
Berti+ (2009)

Which density range we can see?

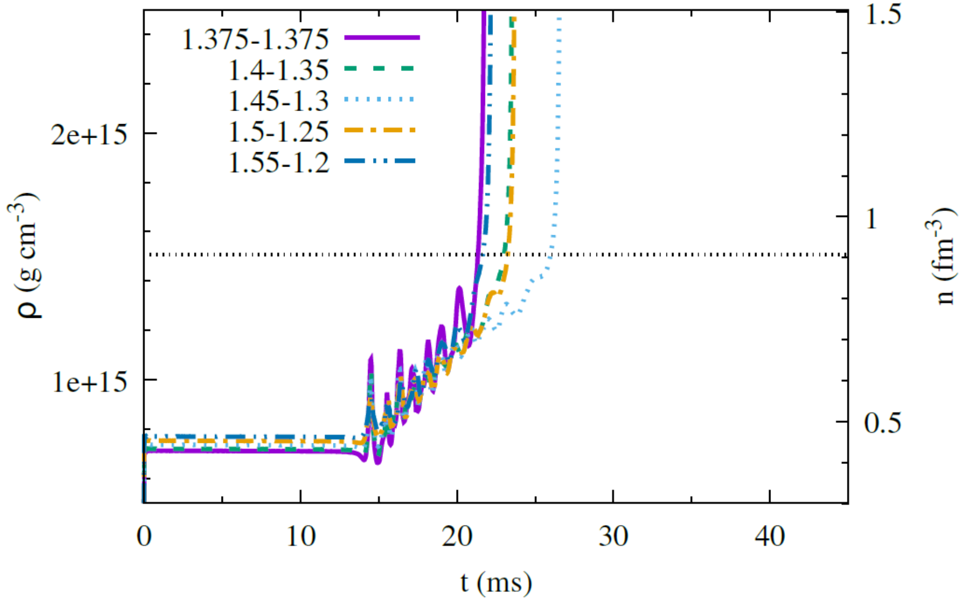
The collapse is likely to set in when the central density reaches the maximum density of spherical stars

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

Various total masses



Various mass ratios



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