Gravitational waves from binary neutron stars and the equation of state

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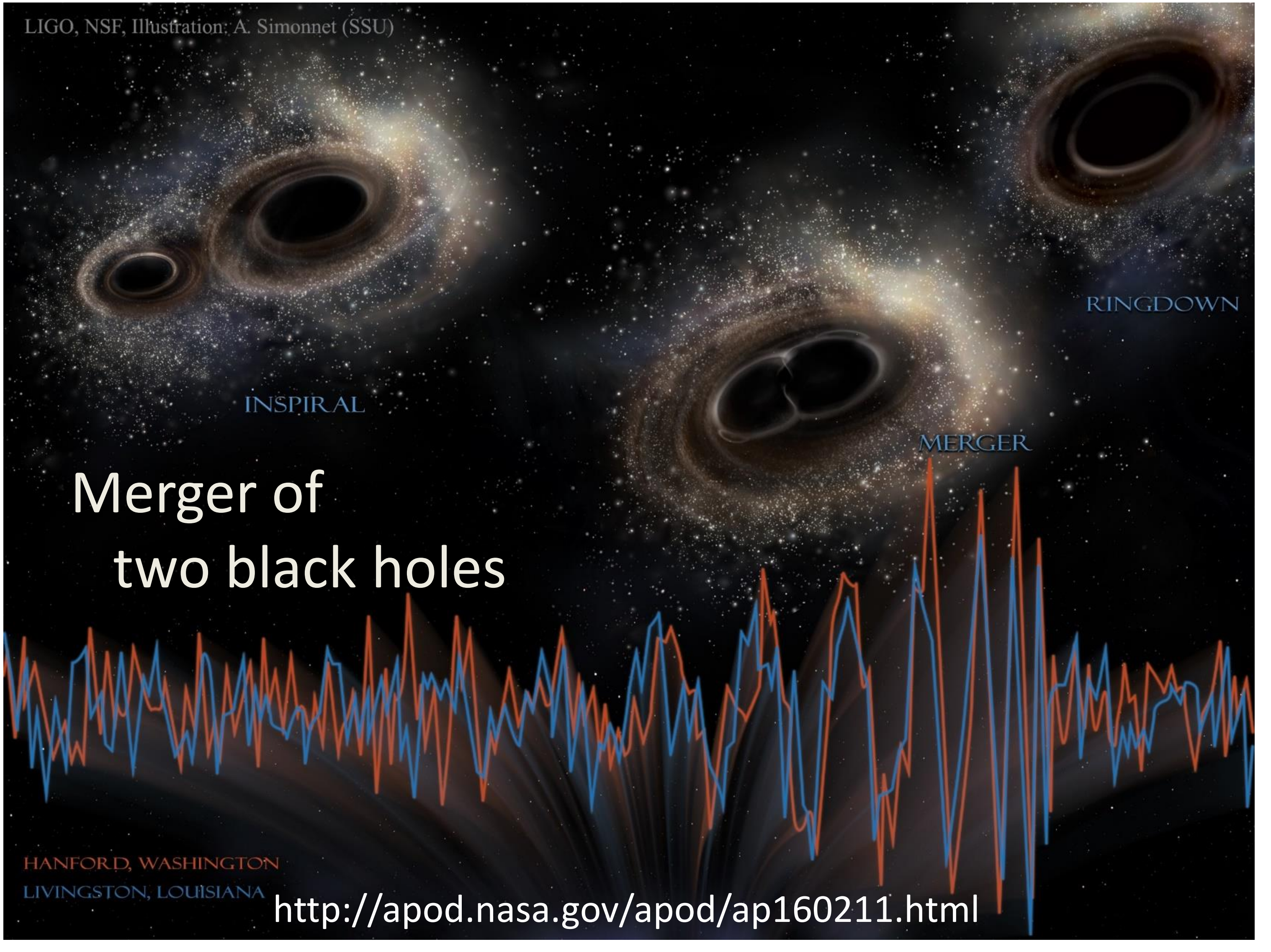
Plan of the talk

1. Introduction
2. Neutron star in astrophysics
3. Inspiral: neutron-star equation of state
4. Postmerger: crossover vs. 1st-order phase transition
5. Summary

1. Introduction

Gravitational-wave detectors

Binary black holes: GW150914



What we learned from GW150914

Masses of individual stars are measured

Many "massive" black holes have been found

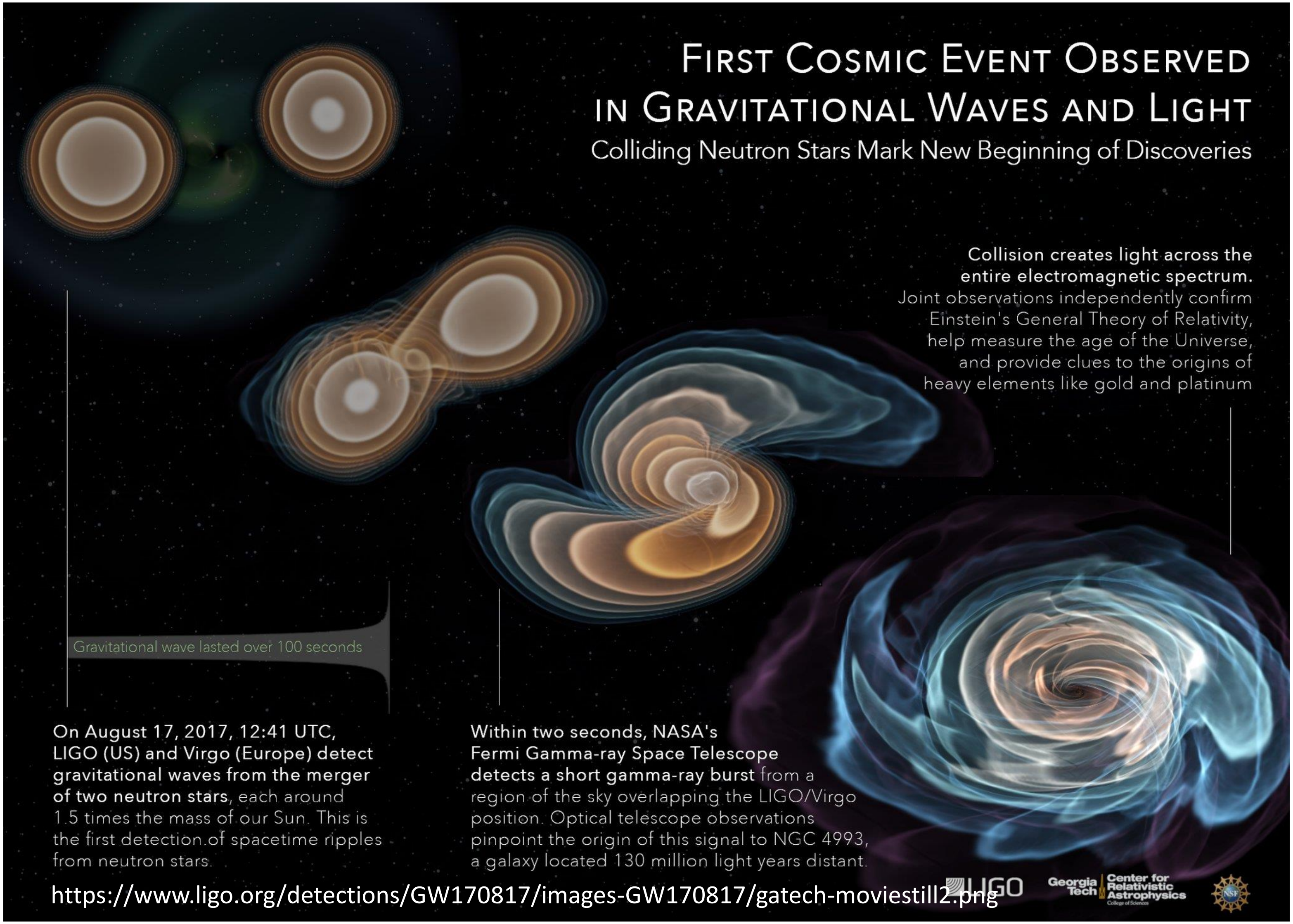
The luminosity distance is measured directly

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc

1Mpc ~ 3 million light years
~ 3 x 10^24 cm

LIGO&Virgo (2016)

Binary neutron stars: GW170817



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

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

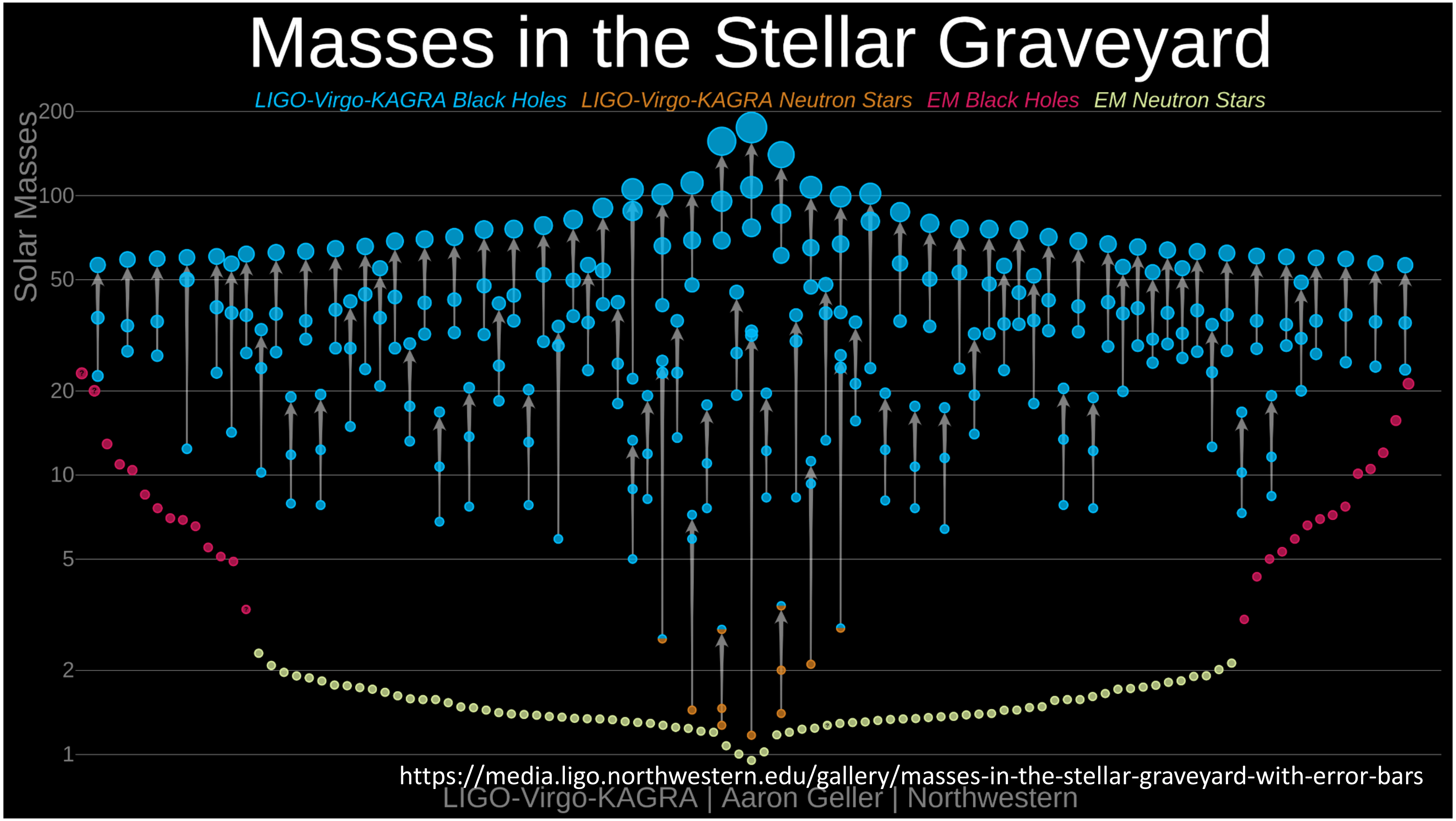
Mass ejection of neutron-rich material

r-process nucleosynthesis

radioactively-driven “kilonova/macronova”

Observed event by the end of O3

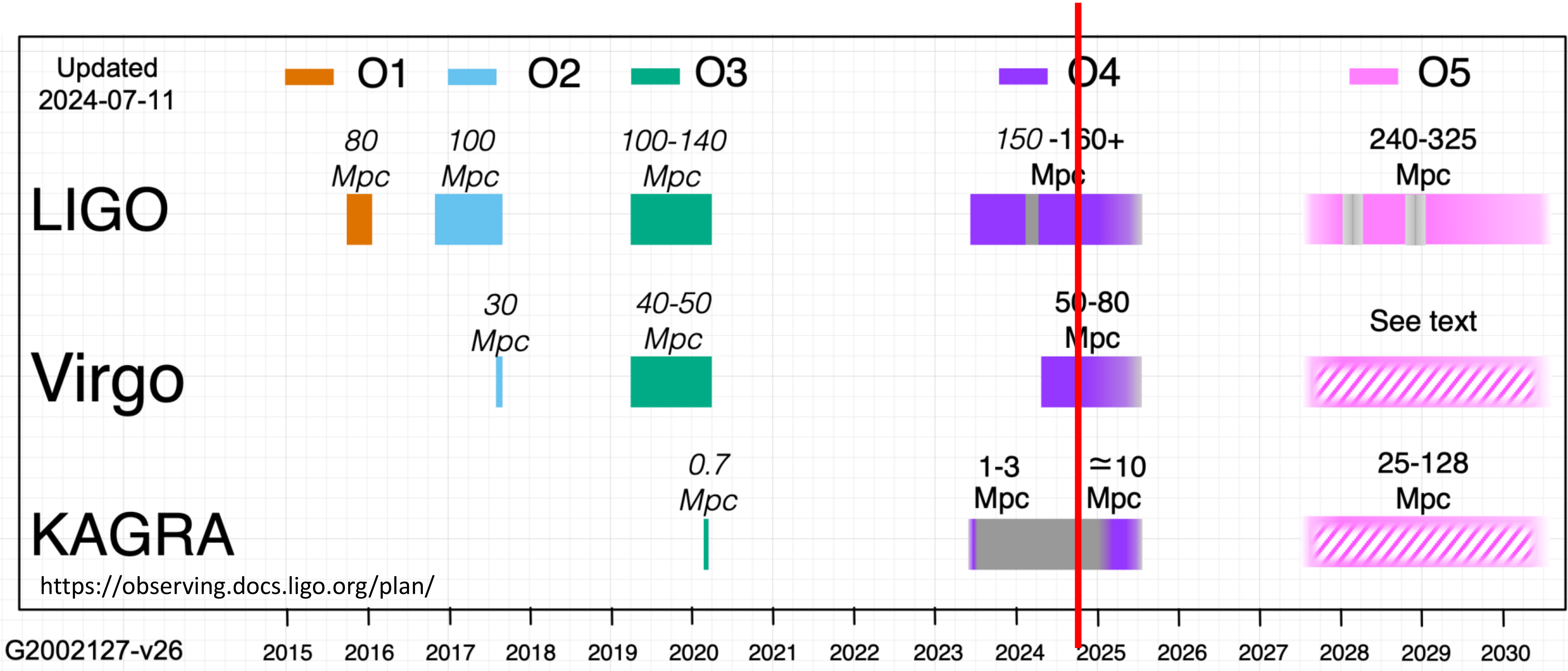
~90 binary black holes vs. 2 binary neutron stars



Observation plan and the status

O4b will continue until the middle of 2025

O5 will be 2027-2030, and then detectors are upgraded



Candidate from O4

~150 binary black holes vs. **0 binary neutron stars**

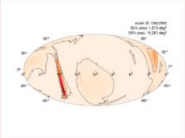
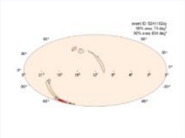
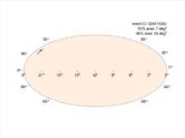
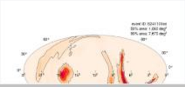
(a few black hole-neutron star merger candidates)

GraceDB Public Alerts Latest Search Documentation Login

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

Please log in to view full database contents.

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S241104a	Terrestrial (49%), NSBH (29%), BBH (22%)	Yes	Nov. 4, 2024 03:32:21 UTC	GCN Circular Query Notices | VOE		1.4349 per year	RETRACTED
S241102cy	BBH (>99%)	Yes	Nov. 2, 2024 14:47:29 UTC	GCN Circular Query Notices | VOE		1 per 2.0842 years	
S241102br	BBH (99%)	Yes	Nov. 2, 2024 12:40:58 UTC	GCN Circular Query Notices | VOE		1 per 2.7753e+33 years	
S241101ee	BBH (>99%)	Yes	Nov. 1, 2024	GCN Circular Query		1 per 2304.8 years	

Thought and concern

Binary-neutron-star mergers are

“less frequent than binary-black-hole mergers”

This is not particularly surprising at least for me

(and probably most gravitational-wave astronomers)

“in fact, two orders of magnitude less frequent”

Unexpected at least for me, unlikely to be a fluke

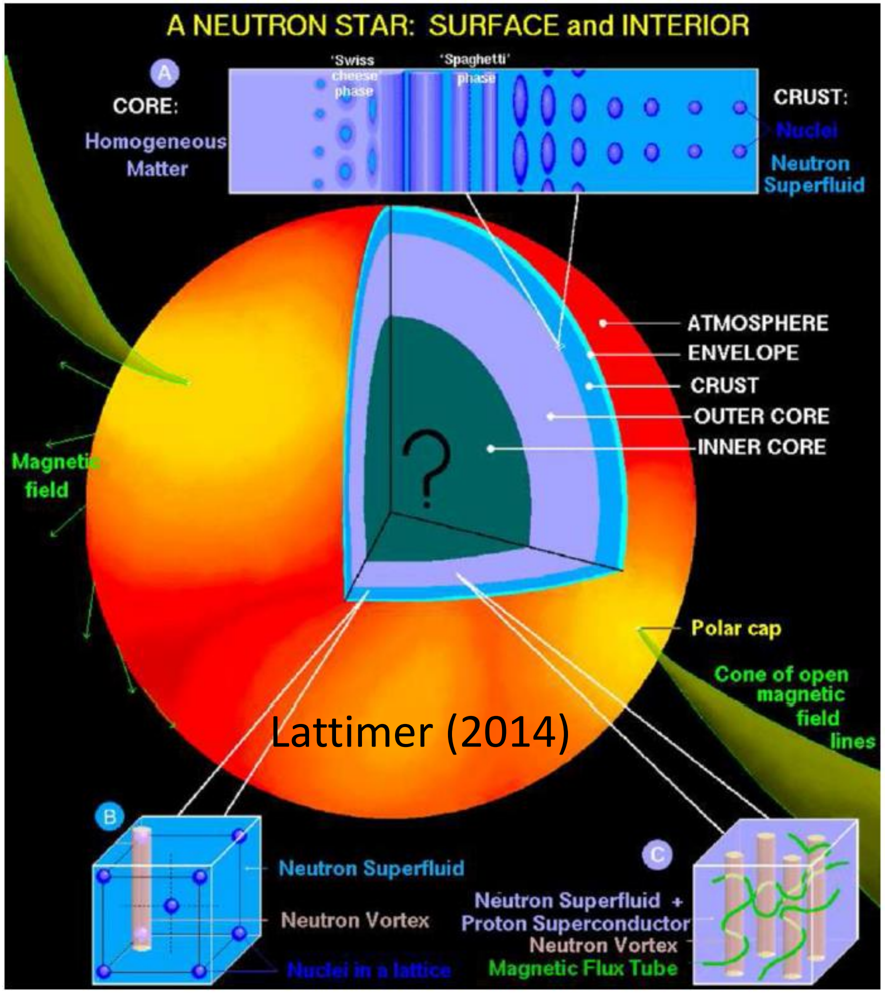
- consistent with short-hard gamma-ray bursts?
- consistent with r-process elements in the universe?

2. Neutron star in astrophysics

Neutron star

Remnant of massive stars
  (mass range is uncertain)

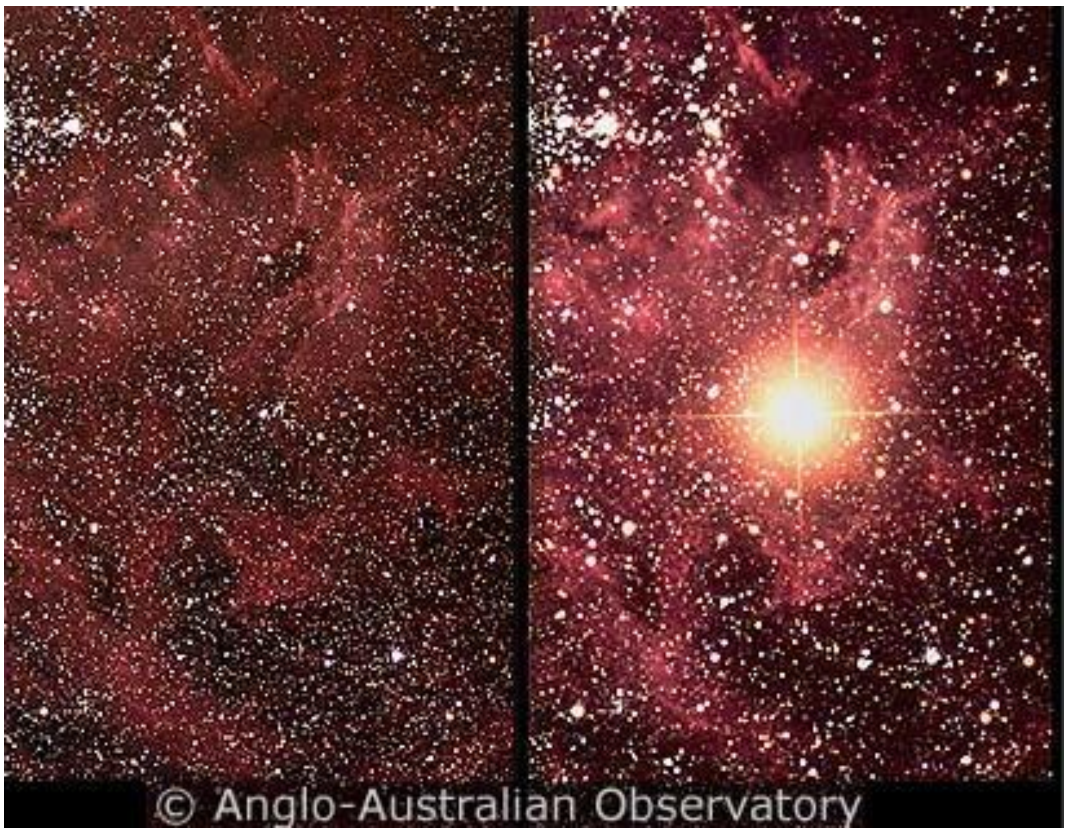
Mostly consists of neutrons
1.4 solar mass, ~10km
The density is higher than
  nuclear saturation values
    “a huge nucleus”
Arena for nuclear physics



Lattimer (2014)

Supernova: birth of a compact object

When the massive star dies, a supernova explosion could occur and leave a black hole or a neutron star

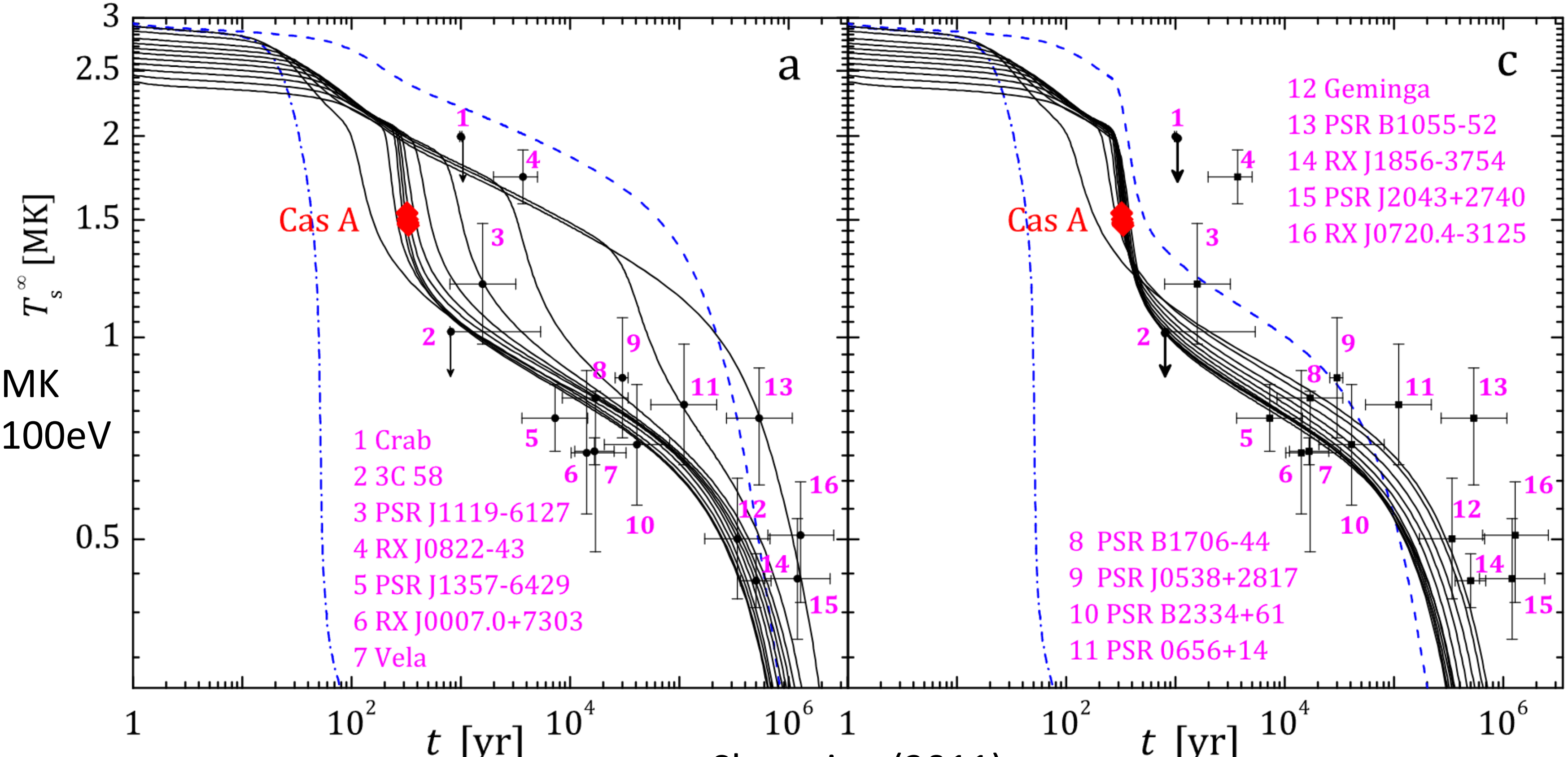


(Two outcomes may be distinguishable w/ neutrinos for nearby [Galactic] supernovae)

Neutron-star cooling

Rapid enough to realize $T \ll E_{\mathrm{F}}$ (Fermi energy >> MeV)

depend on mass, surface composition, superfluidity, etc.

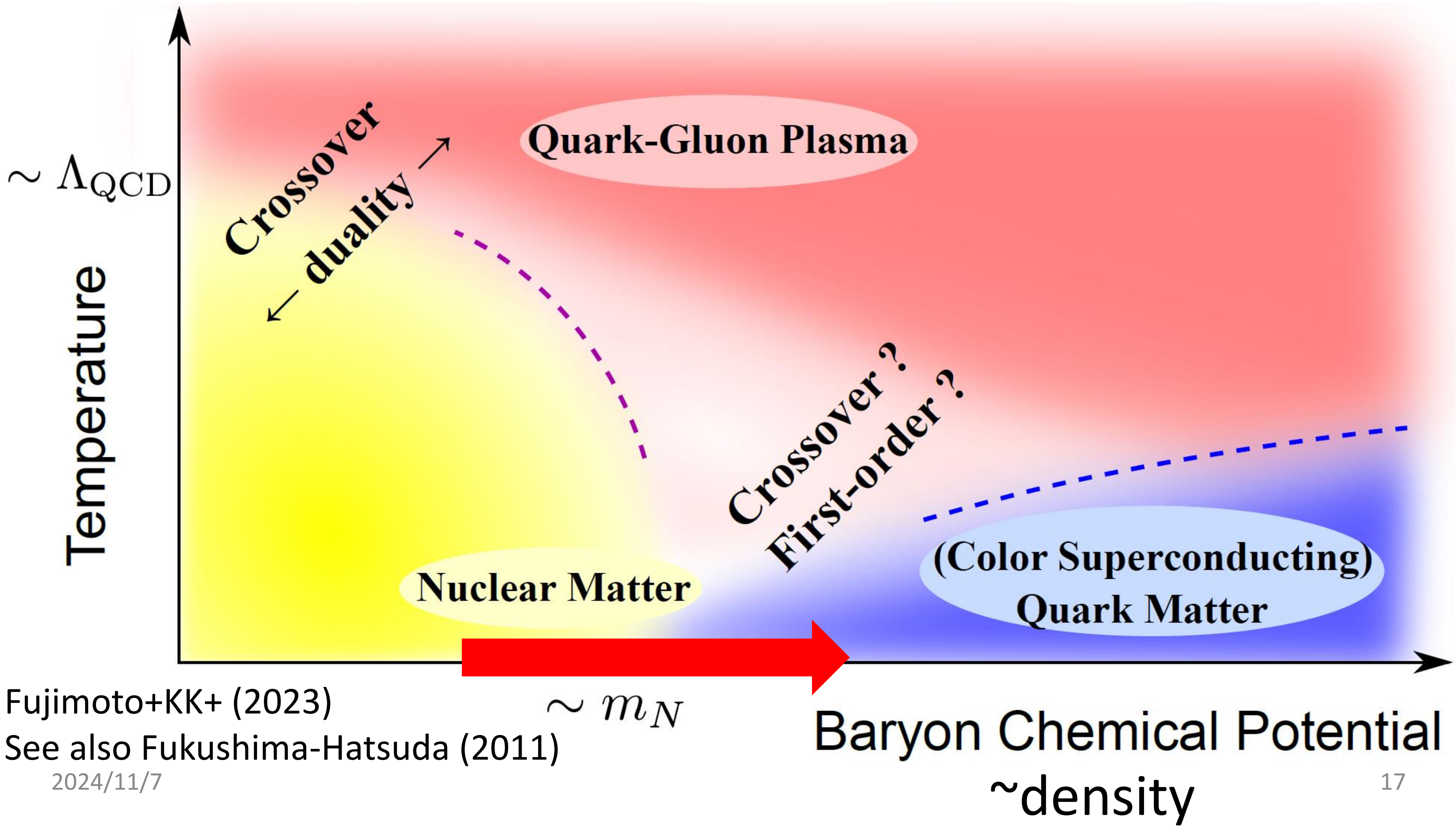


1MK
~100eV

Shternin+ (2011)

QCD phase diagram

Neutron stars are in the low-T, high-μ regime

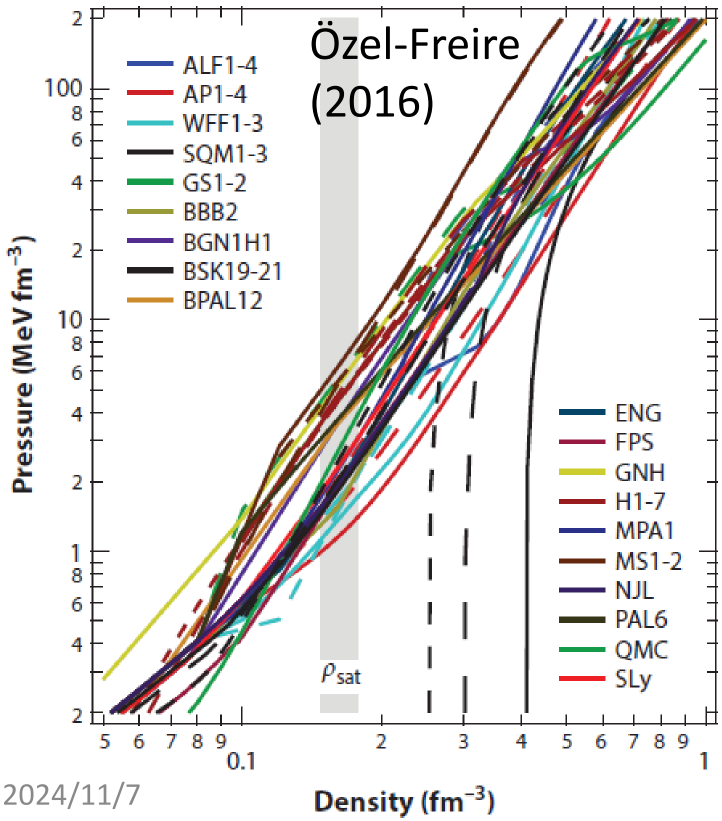


Fujimoto+KK+ (2023)
See also Fukushima-Hatsuda (2011)

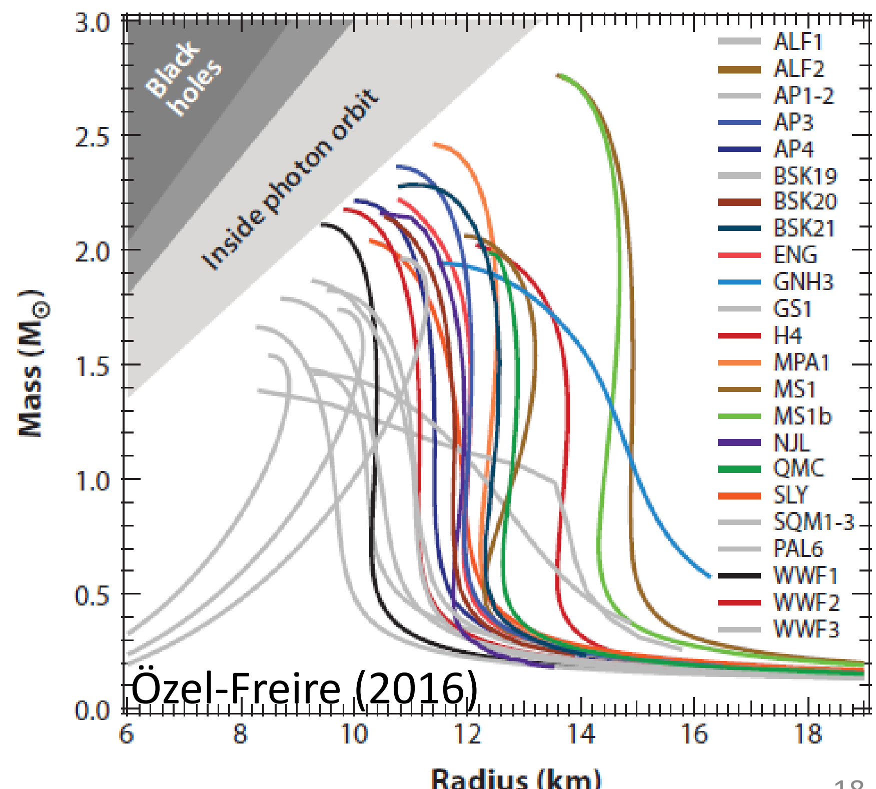
Neutron star equation of state

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

Equation of state: Nuclear physics



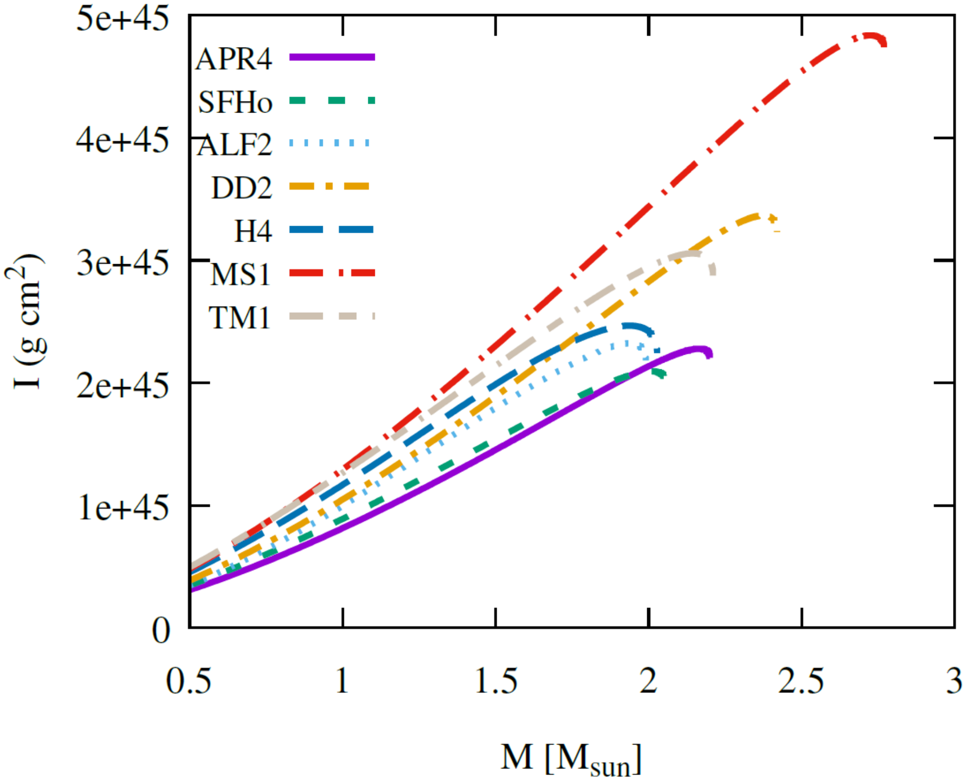
Mass-Radius relation: Astrophysics



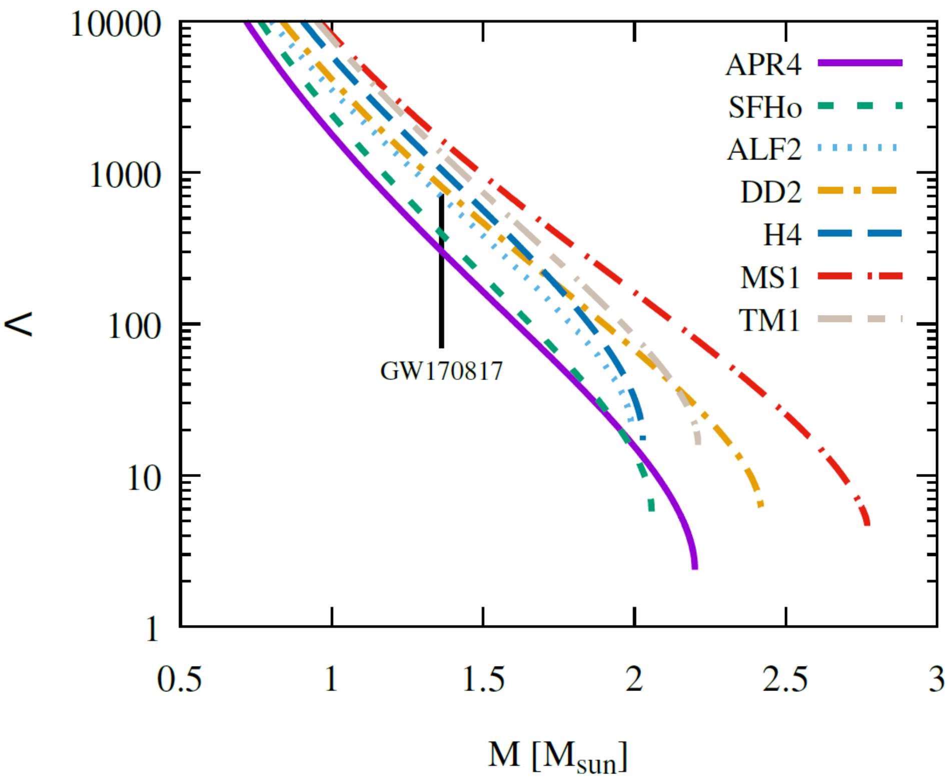
Other macroscopic observables

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

Moment of inertia



Tidal deformability



Astronomical observation

Maximum mass from radio pulsars

J1614-2230, J3048+0432, J0740+6620

Tidal deformability from gravitational waves

GW170817(, GW190425: not so informative)

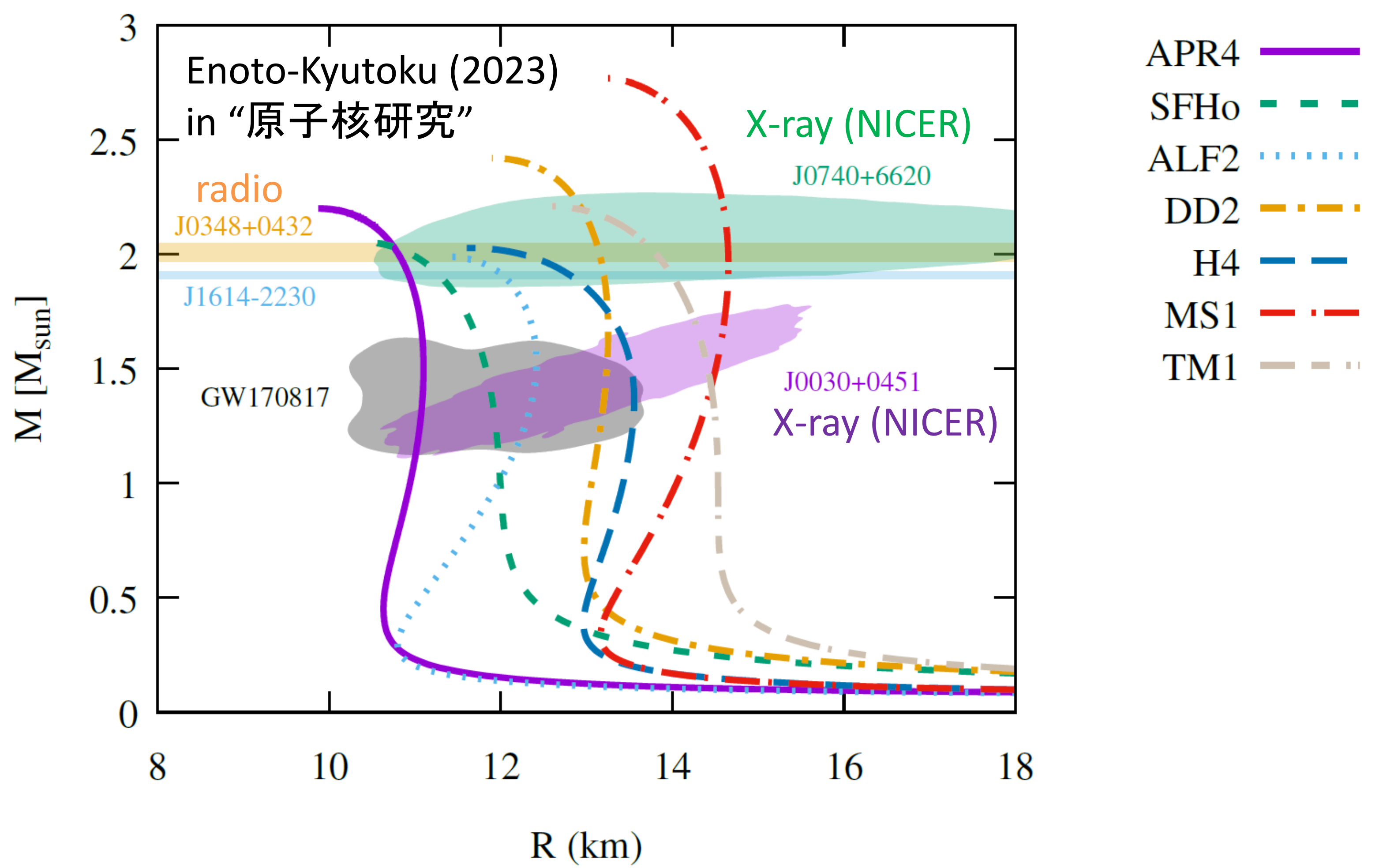
Compactness=mass/radius from X-ray pulsations

J0030+0451, J0740+6620

+ moment of inertia from radio pulsars in the future?

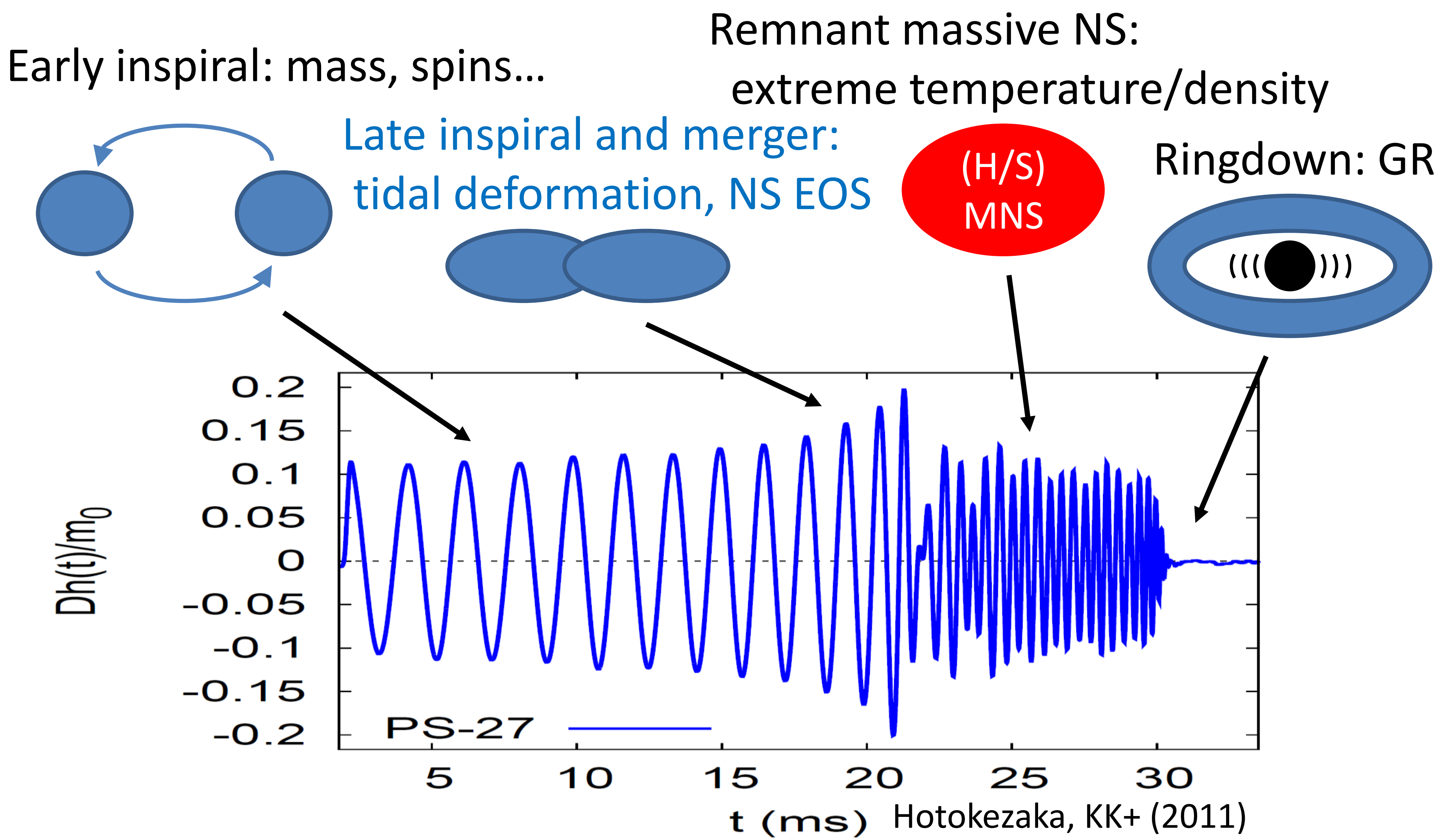
Current constraint

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



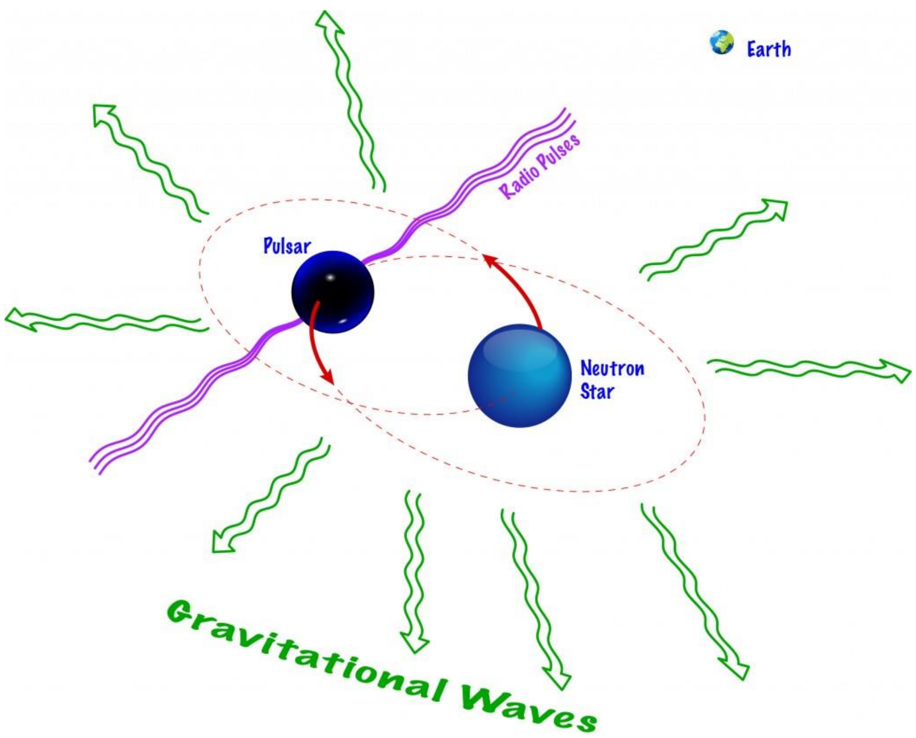
3. Inspiral: neutron-star equation of state

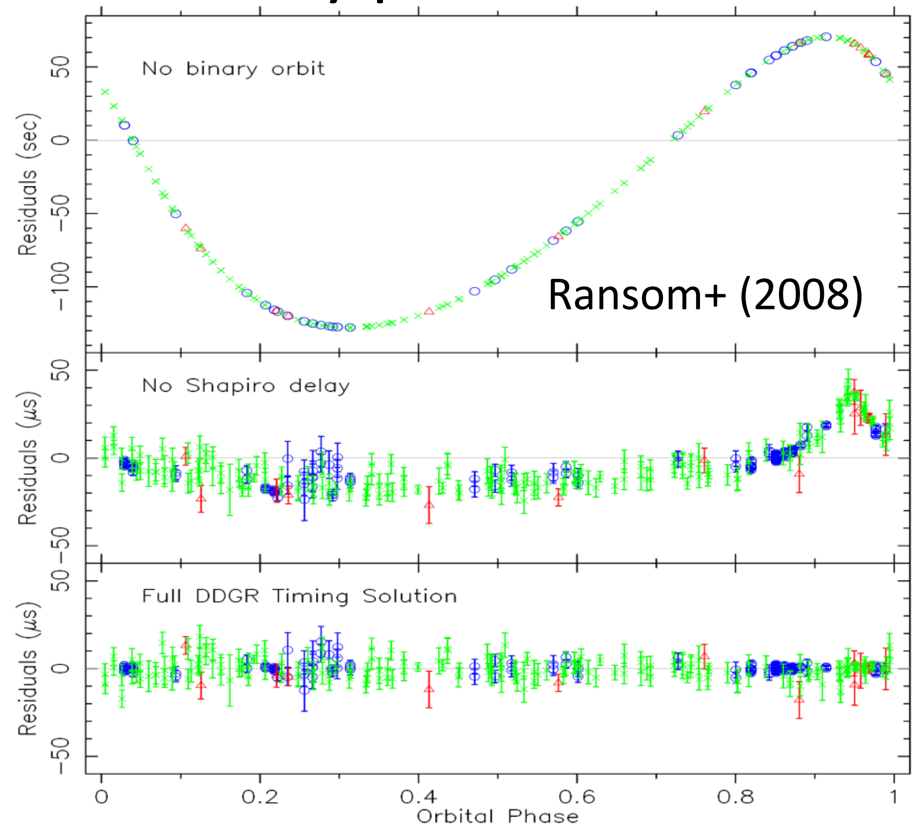
Various phases of coalescence



Binary as a two-body problem

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





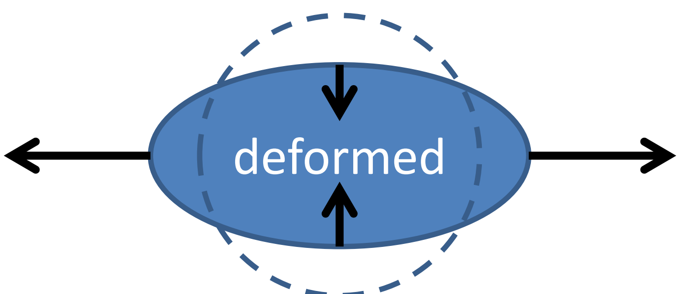
http://asd.gsfc.nasa.gov/blueshift/wp-content/uploads/2016/02/htbinarypulsar-1024x835.jpg

Quadrupolar tidal deformability

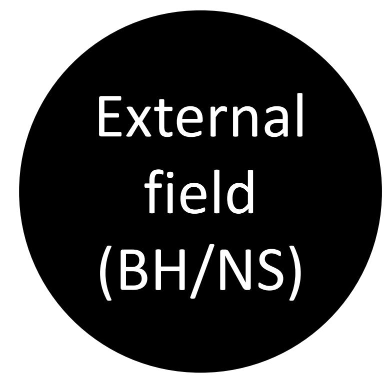
Leading-order finite-size effect on orbital evolution
(strongly correlated with the neutron-star radius)

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

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



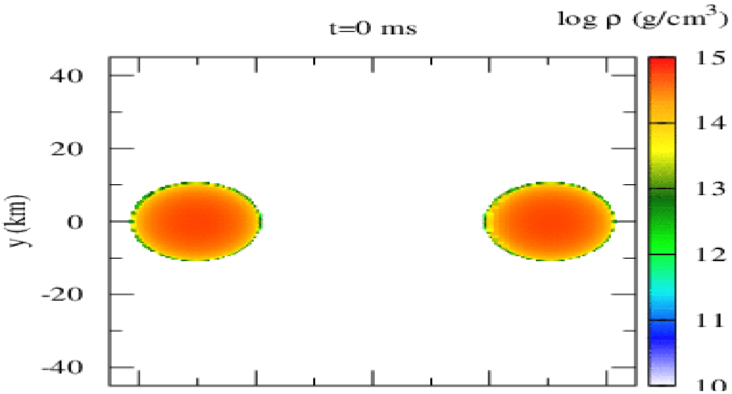
$$\mathcal{Q}_{ij} = -\lambda \mathcal{E}_{ij}$$



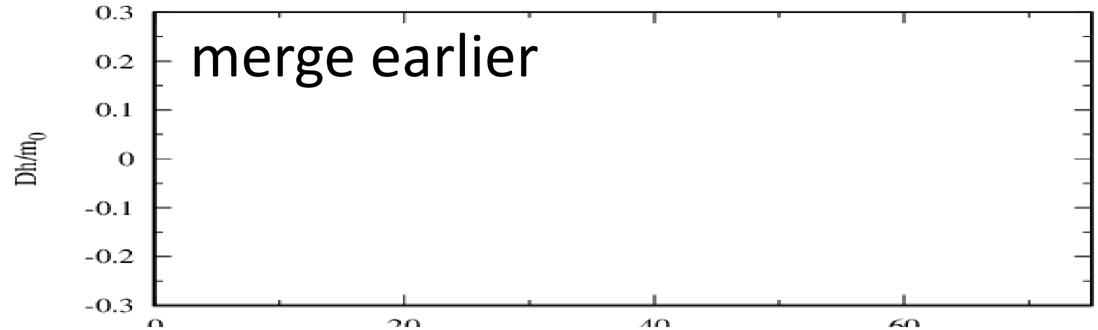
$$\mathcal{Q}_{ij} \equiv \int \rho \left(x_i x_j - \frac{1}{3} x^2 \delta_{ij} \right) d^3 x$$

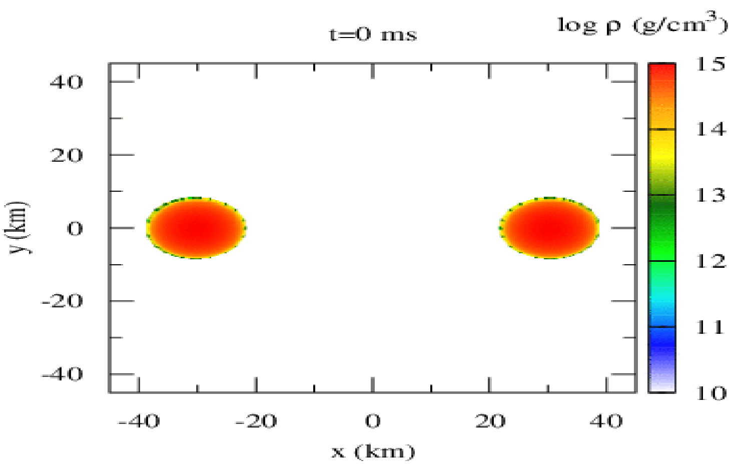
$$\mathcal{E}_{ij} \equiv \frac{\partial^2 \Phi_{\rm ext}}{\partial x^i \partial x^j}$$

Different orbital evolution

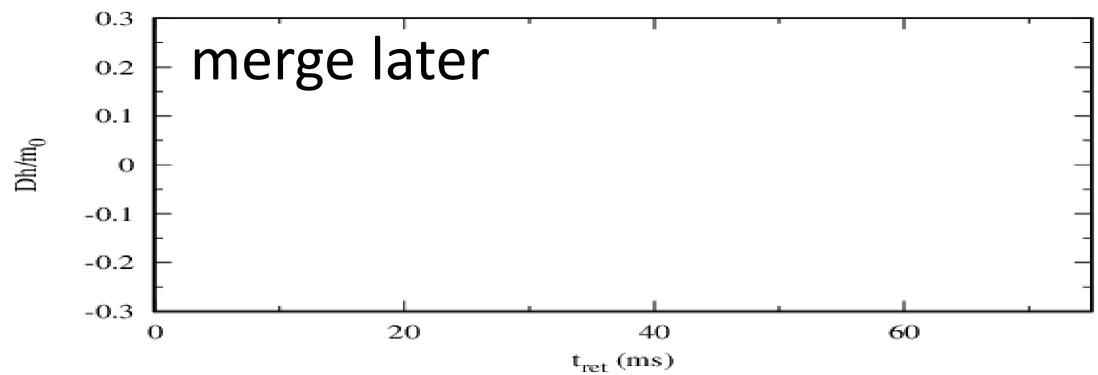


$R = 13.7\ \text{km}, \Lambda = 1211$





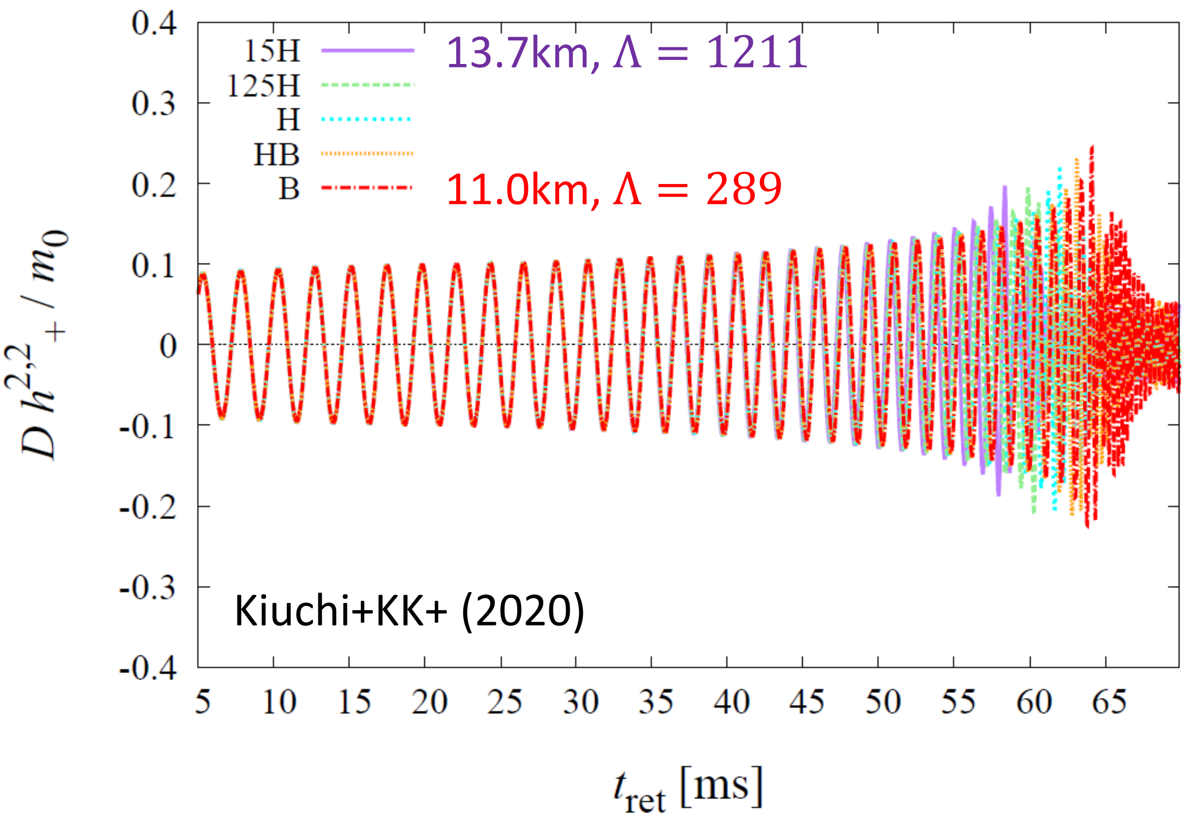
$R = 11.0\ \text{km}, \Lambda = 289$



Numerical waveform

Binaries merge earlier for stiffer equations of state

This allows us to measure the tidal deformablity

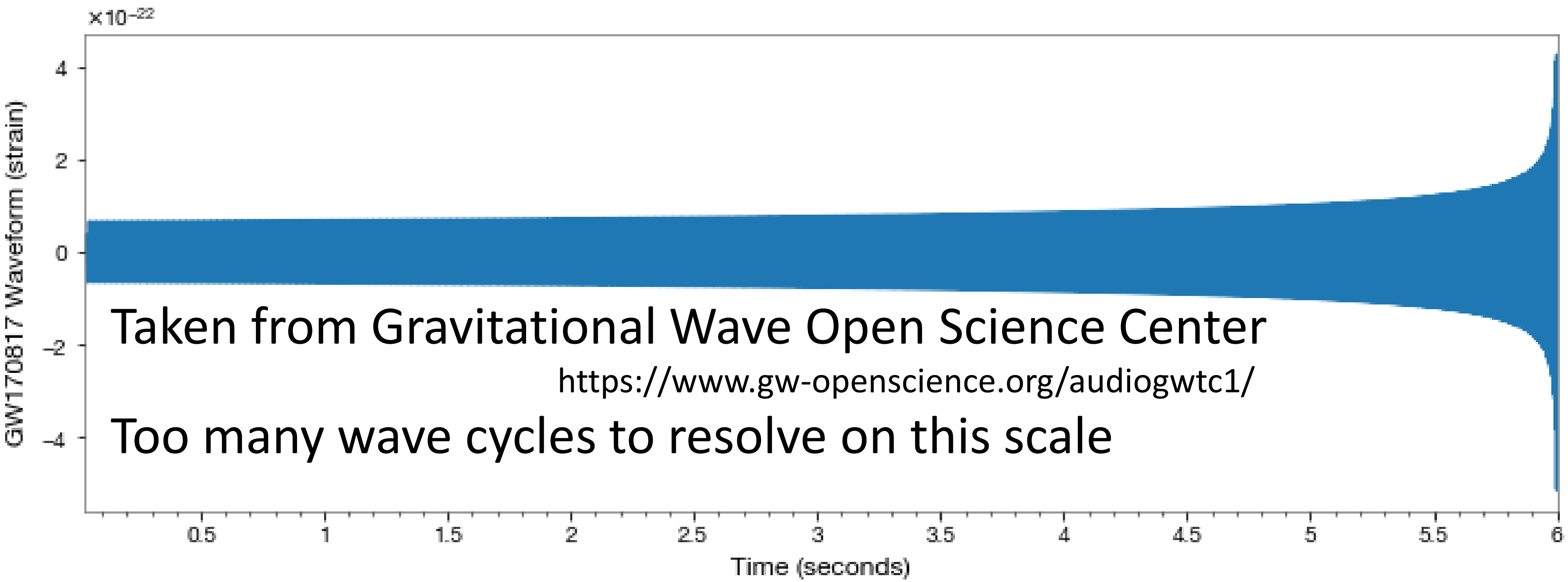


GW170817

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

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

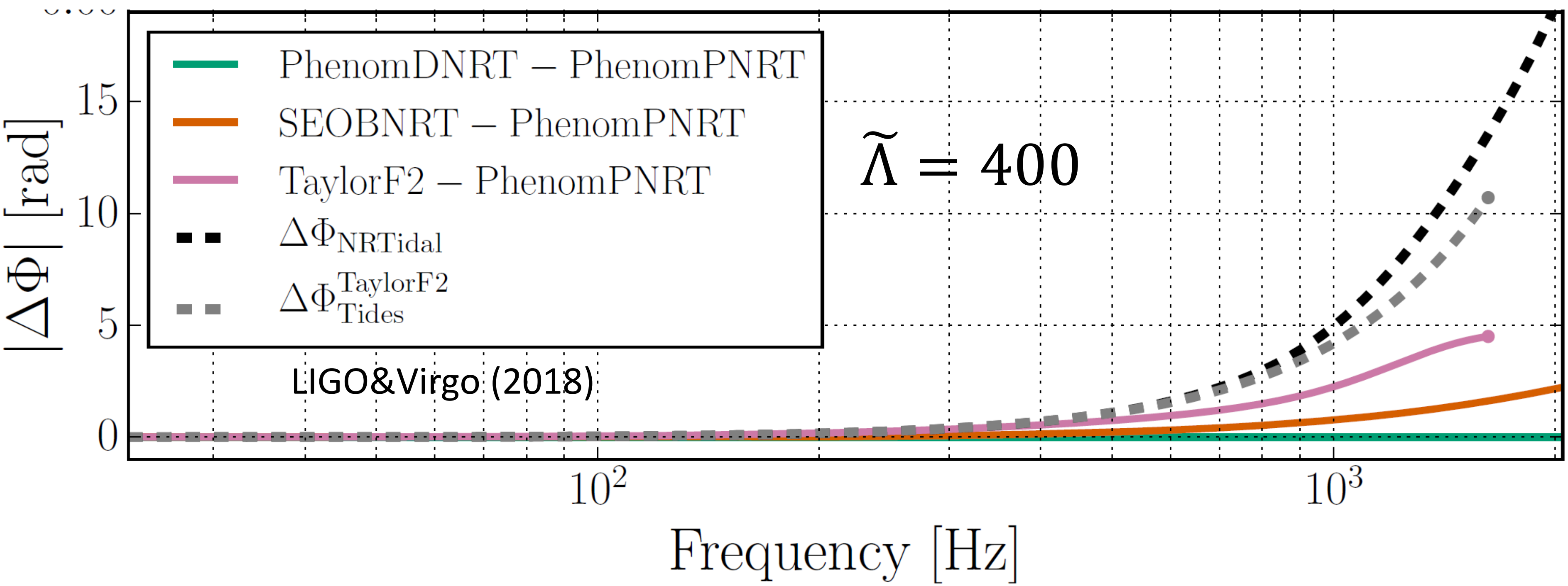
LIGO&Virgo (2019)

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



Kyoto gravitational-wave model

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

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

+ correction terms associated w/ mass asymmetry

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

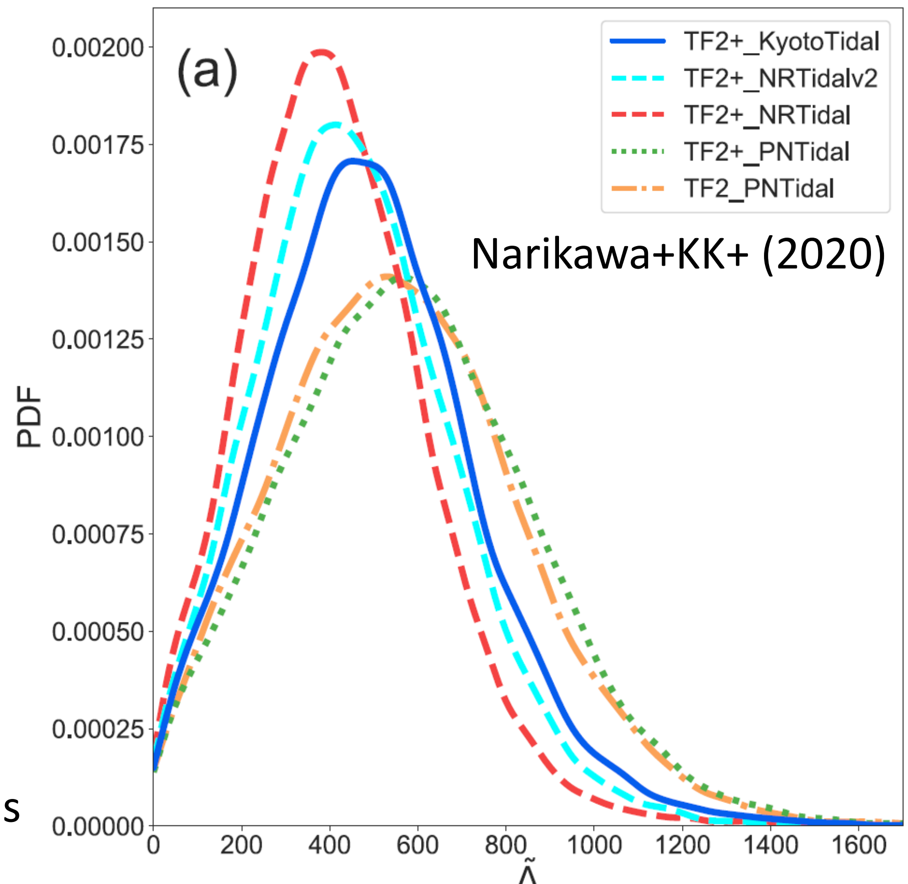
We introduce a nonlinear-in-$\tilde{\Lambda}$ term (empirically)

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

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

Constraint from GW170817

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



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

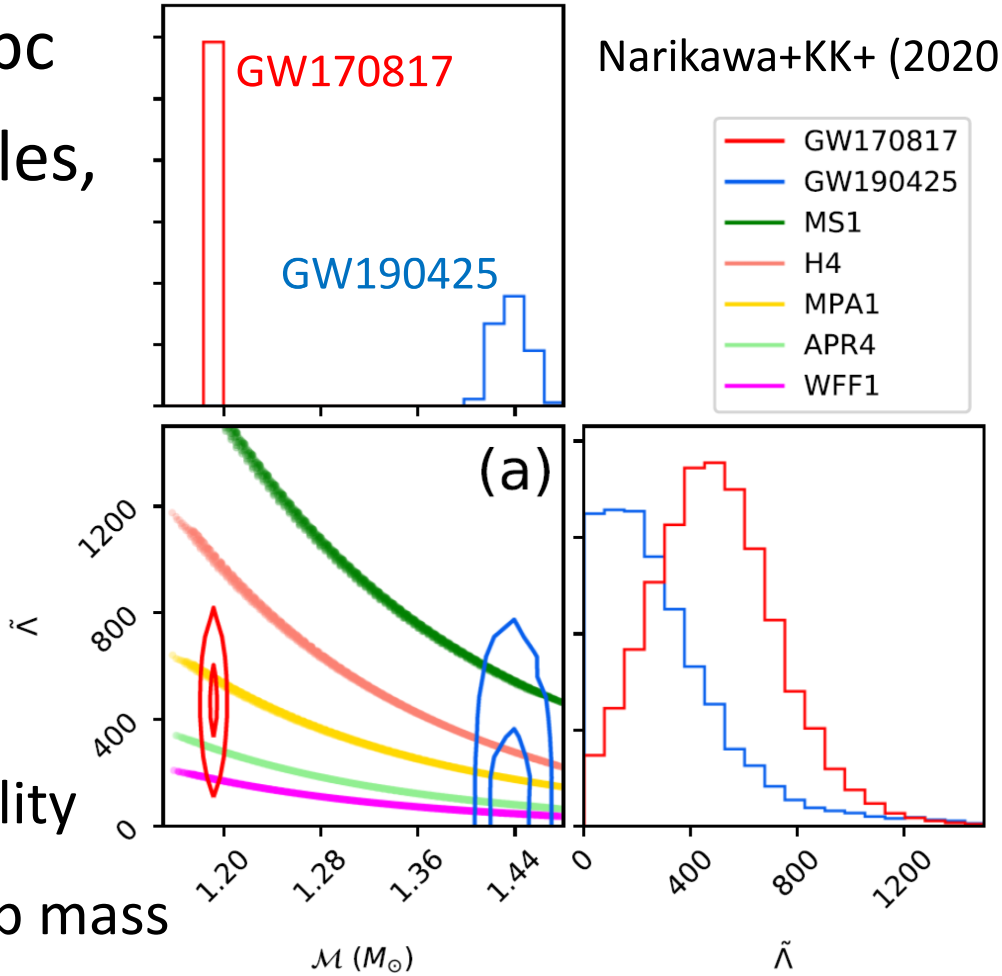
Case of GW190425

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

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

[see also Kyutoku+ (2020)]

Narikawa+KK+ (2020)



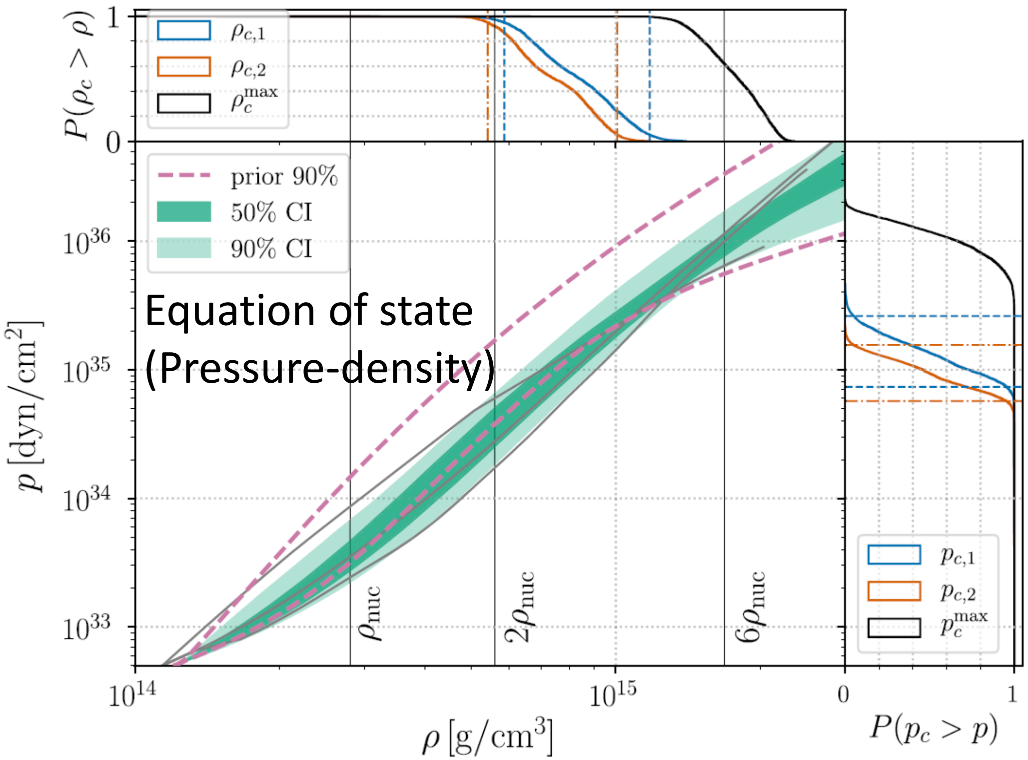
Simply GW170817 was extremely lucky

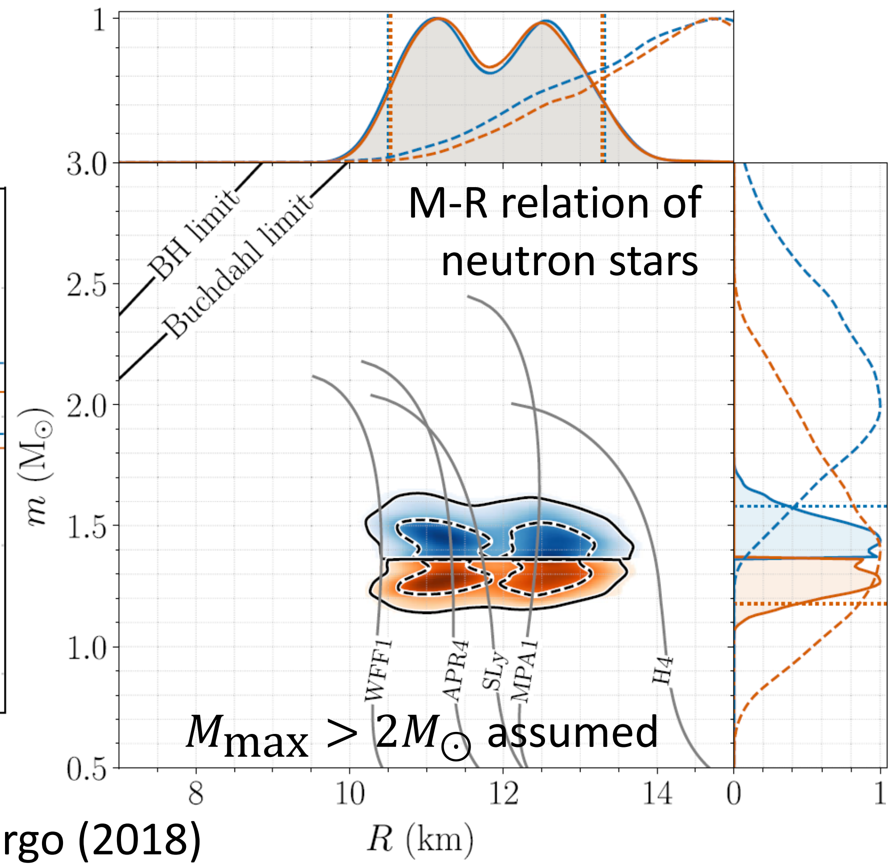
Binary tidal deformability

Chirp mass

Current status of understanding

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

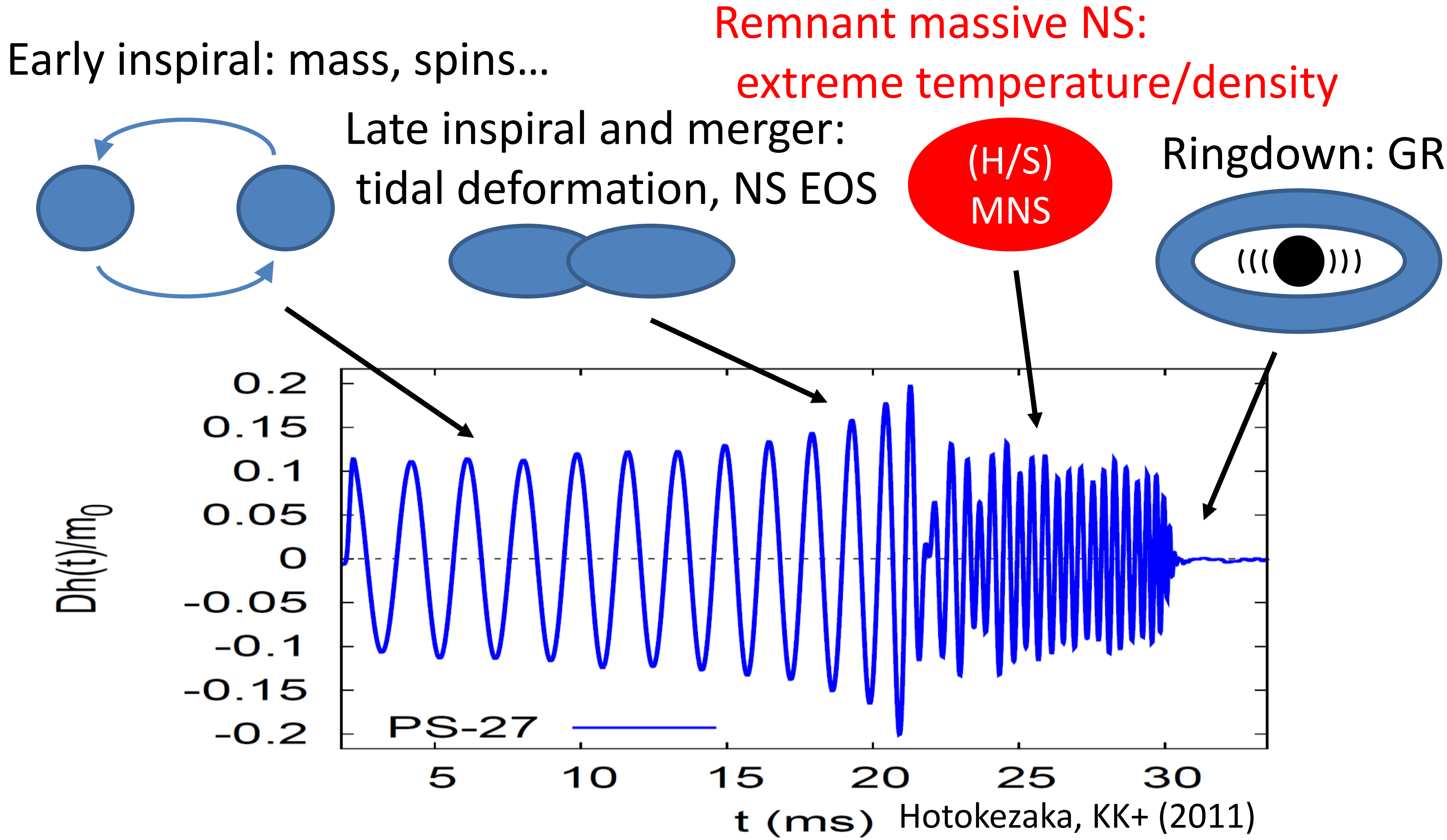




LIGO&Virgo (2018)

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

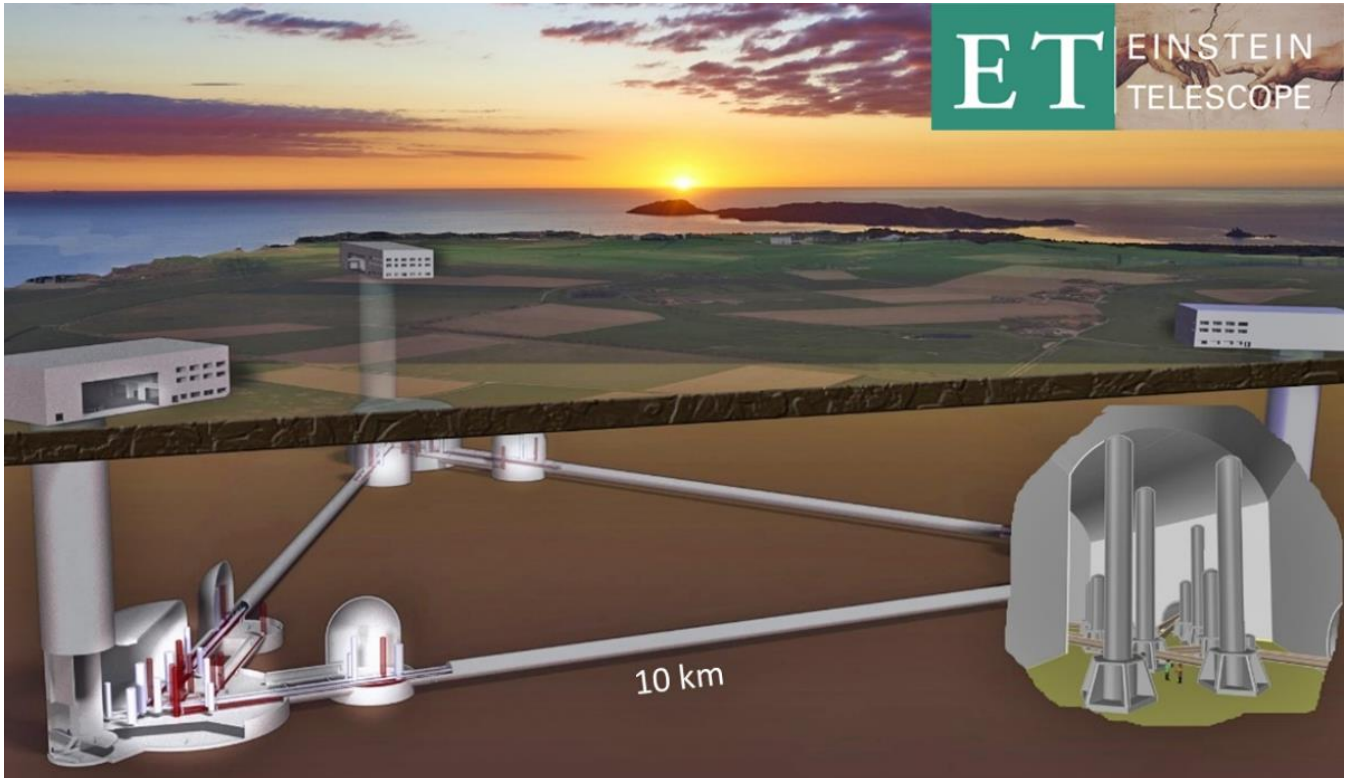
Various phases of coalescence



Hotokezaka, KK+ (2011)

Third-generation detector

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

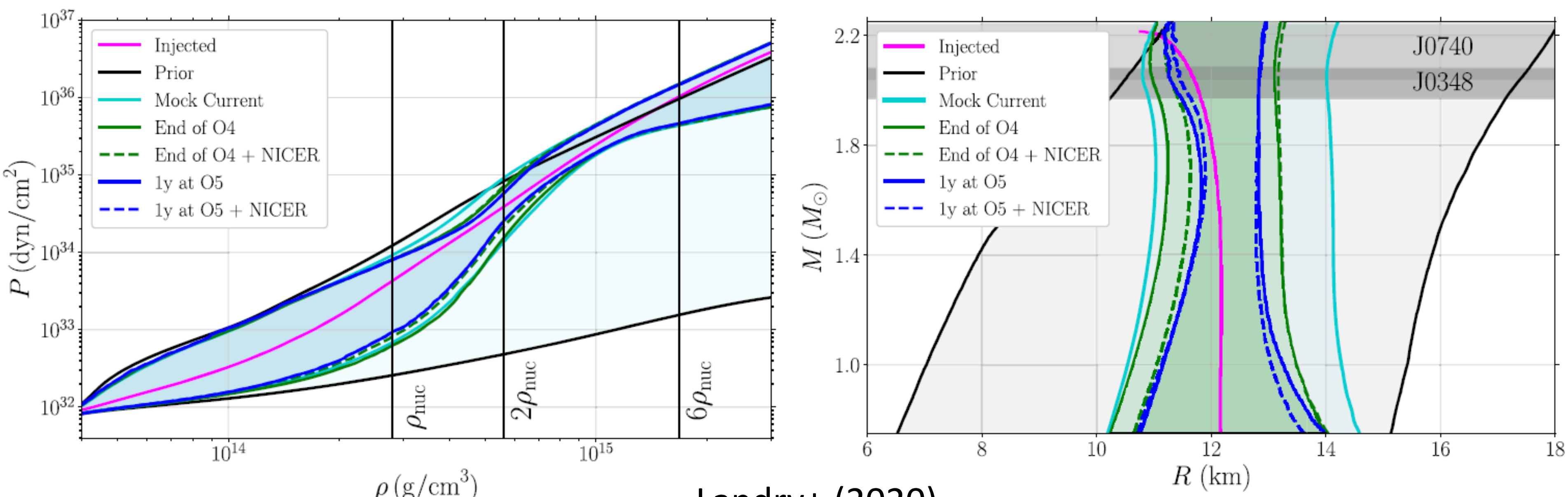


https://www.ego-gw.it/blog/2021/07/01/einstein-telescope-included-in-esfri-roadmap-2021/

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



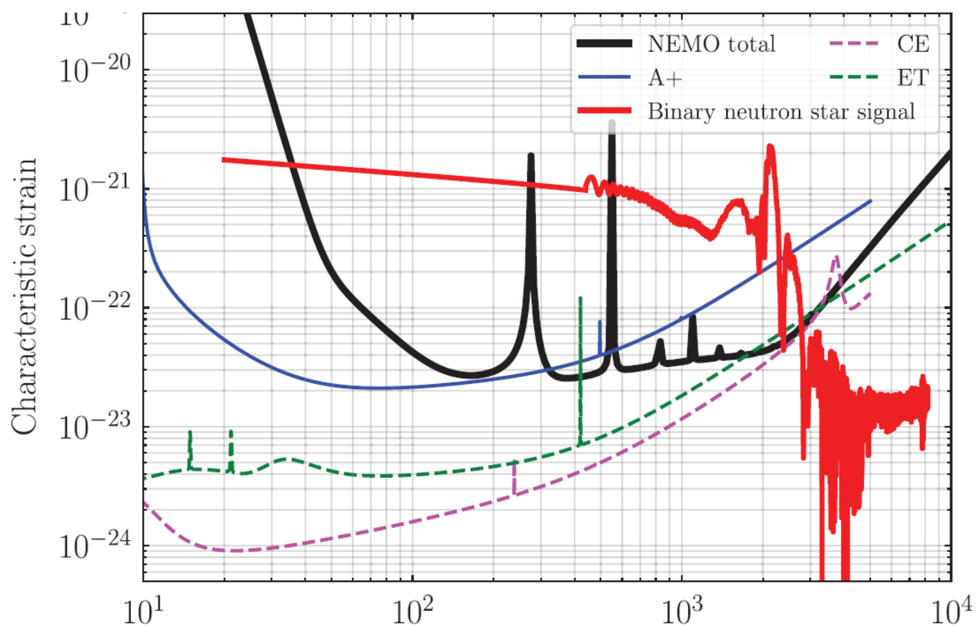
Landry+ (2020)

Future high-frequency observation

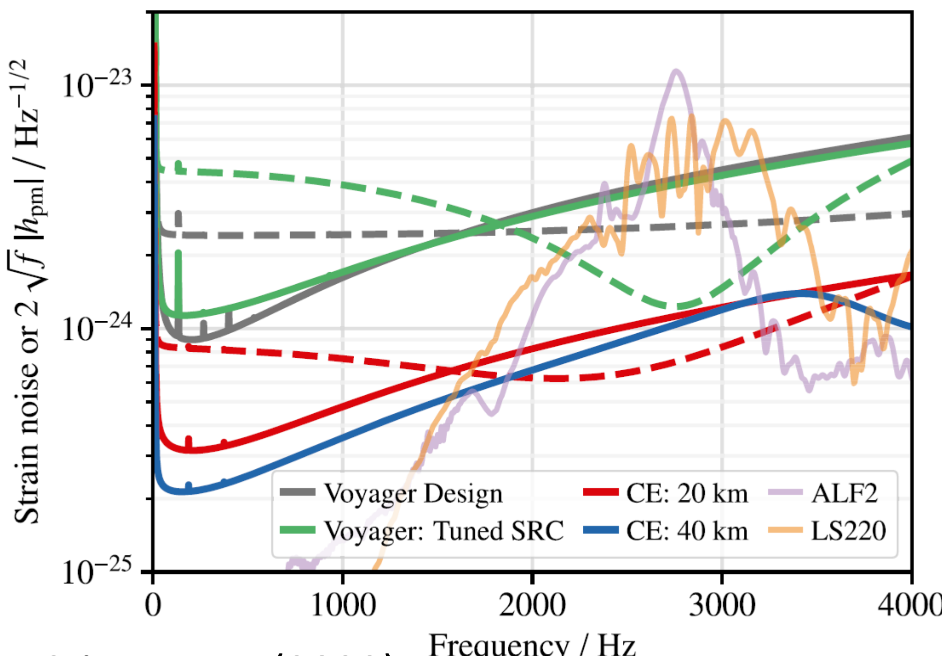
The high density requires high-frequency observations

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

Some proposals are made for postmerger signals



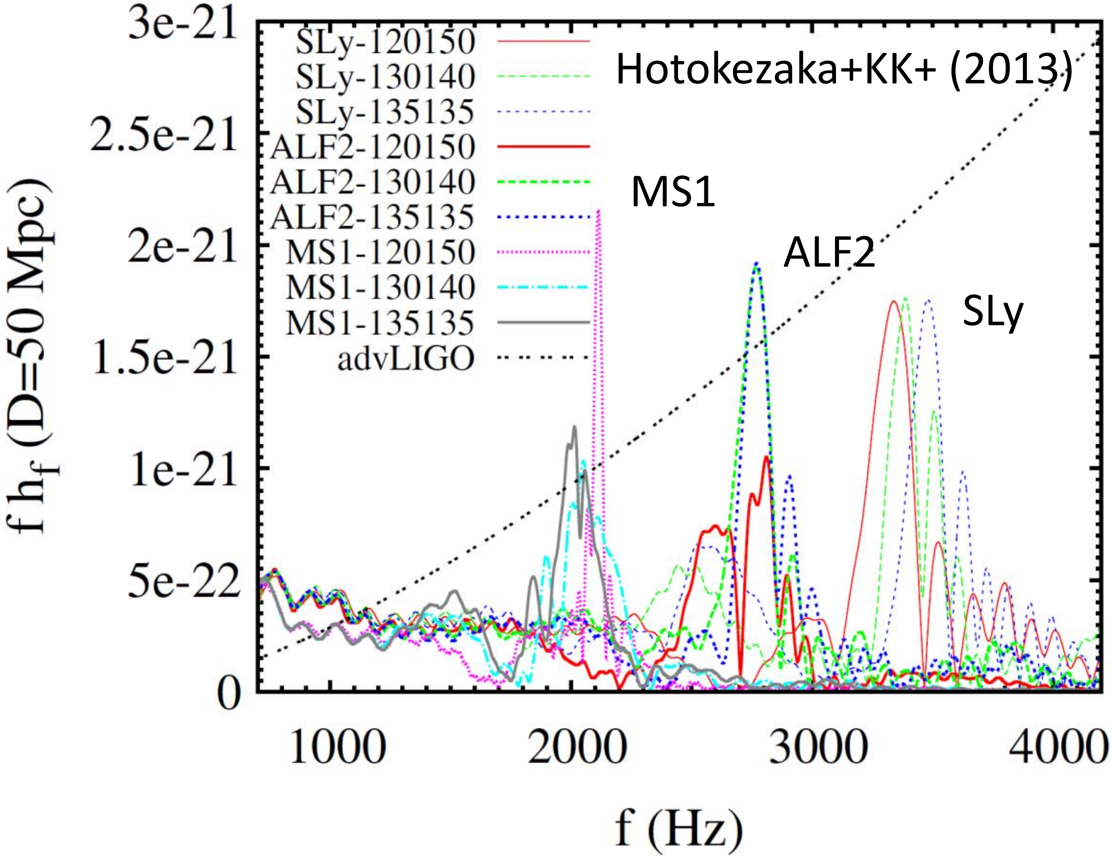
Ackley+ (2020)



Srivastava+ (2022)

Postmerger peak frequency

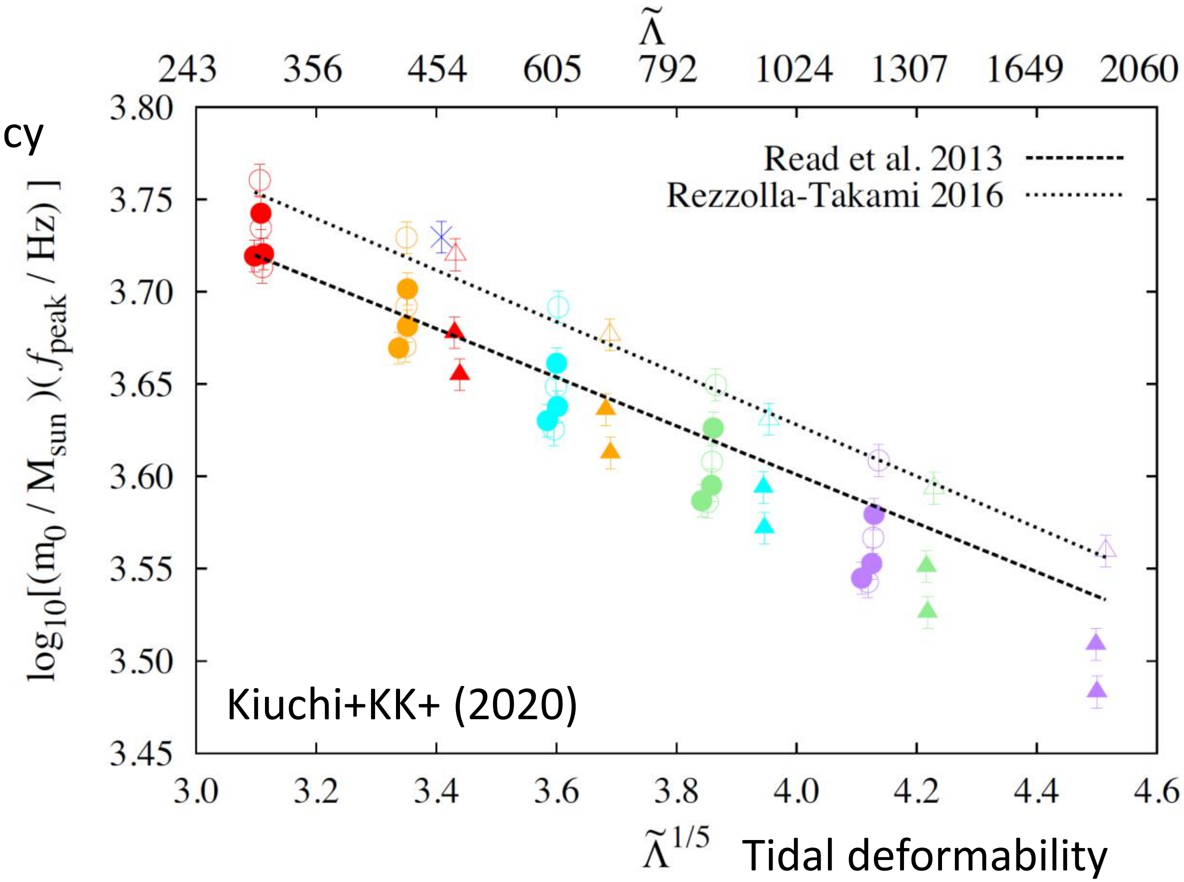
Depends on the equation of state and the total mass, also weakly on the mass ratio



Pre-postmerger correlation

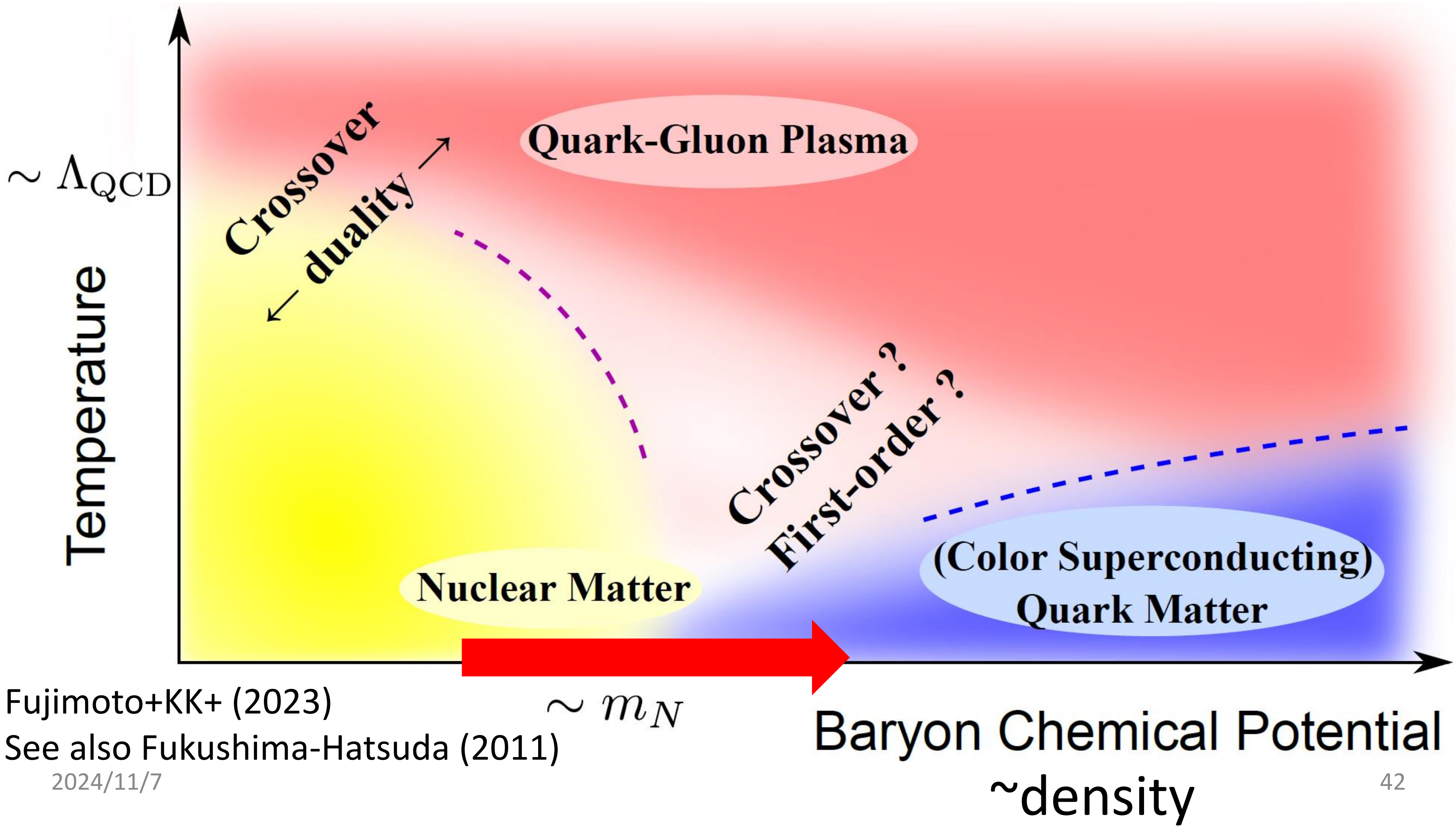
Frequency at the amplitude peak is correlated strongly with the property of premerger neutron stars

Peak frequency (rescaled)



QCD phase diagram

What kind of transition occurs from hadrons to quarks

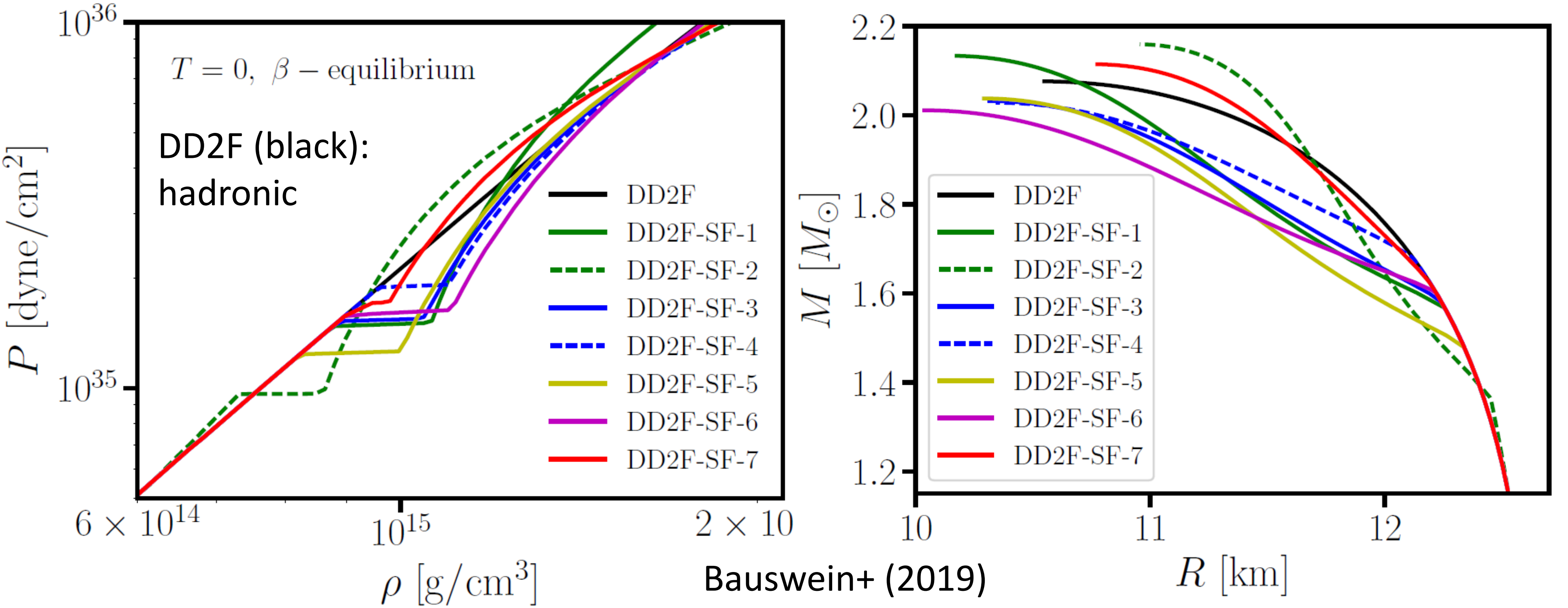


Fujimoto+KK+ (2023)
See also Fukushima-Hatsuda (2011)

Strong 1st-order phase transition

The mass-radius relation breaks suddenly

An extreme case results in the so-called "twin star"

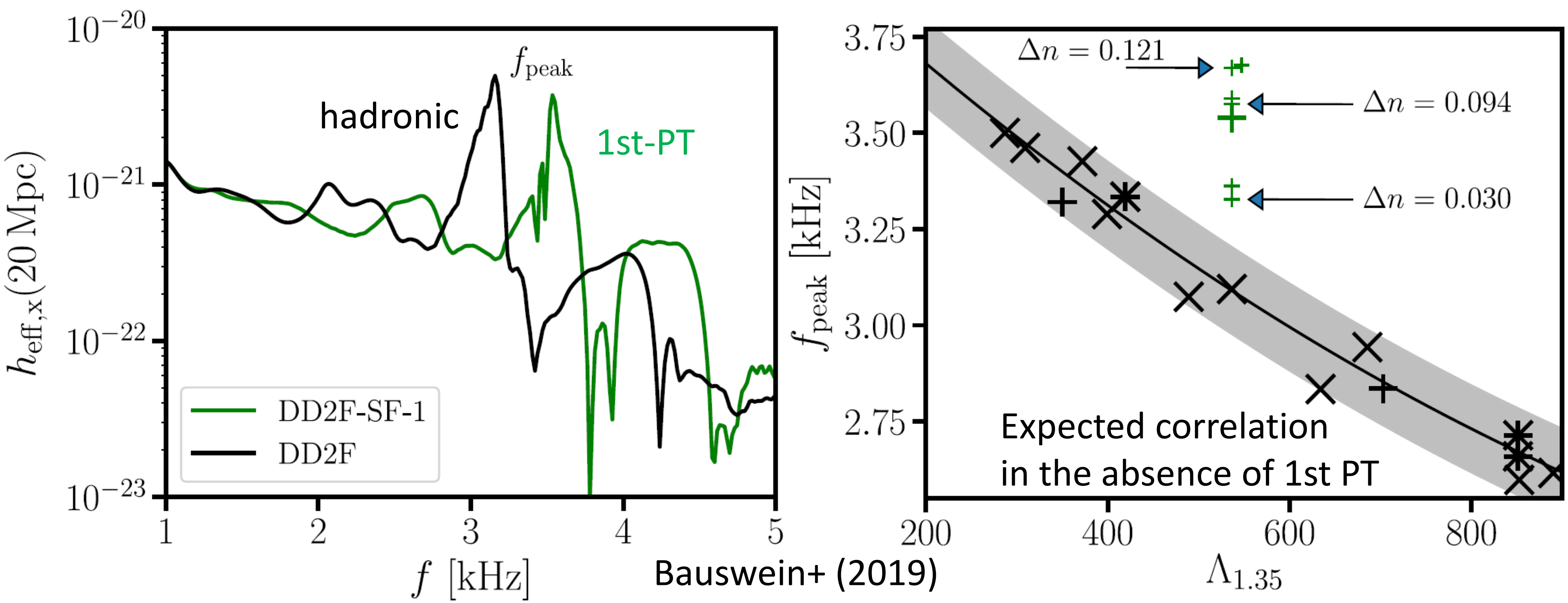


Bauswein+ (2019)

Effect on the postmerger peak

Significant deviation from hadronic expectations

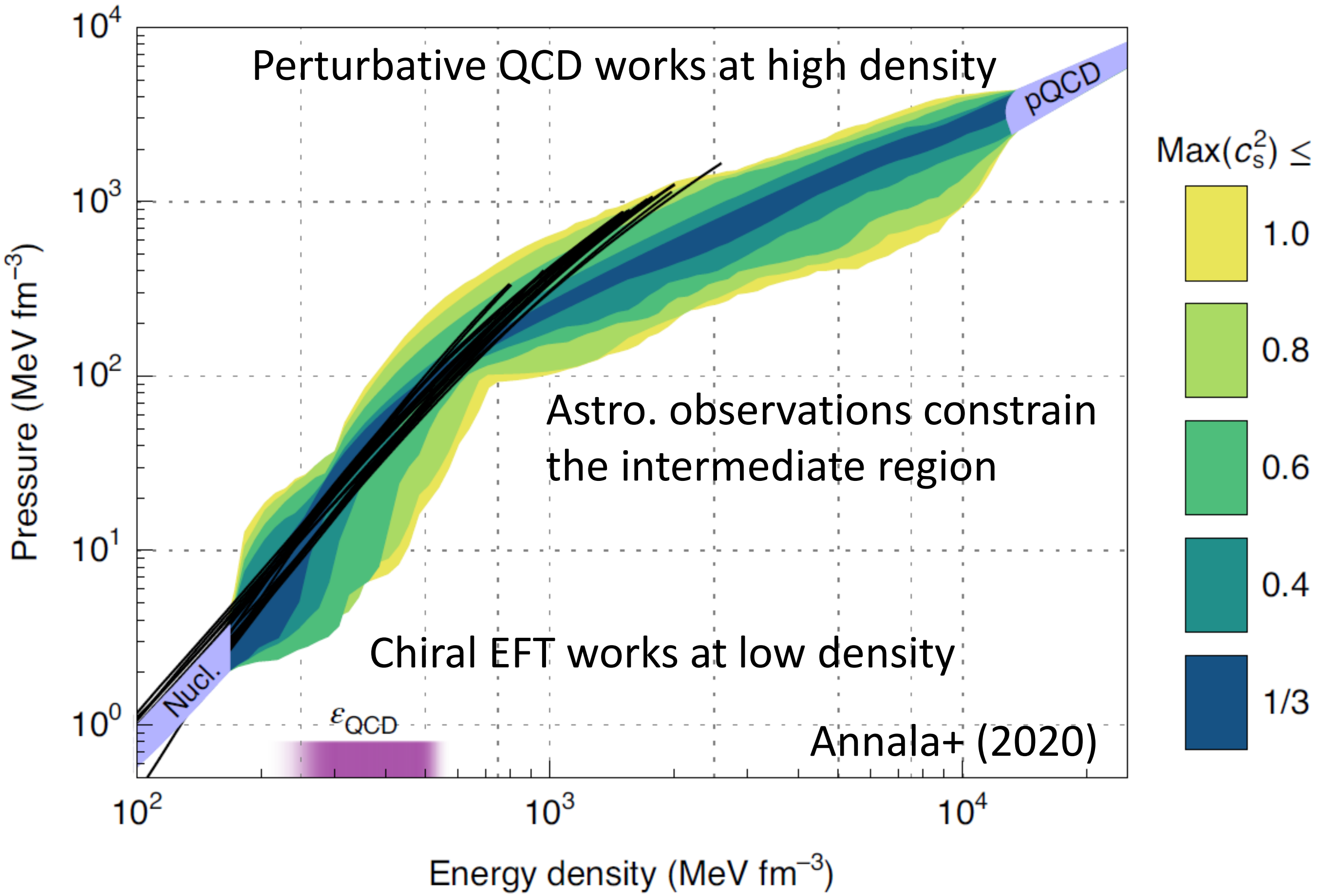
The shift in the peak frequency may reveal strong 1st-order phase transition at moderately high density



Bauswein+ (2019)

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

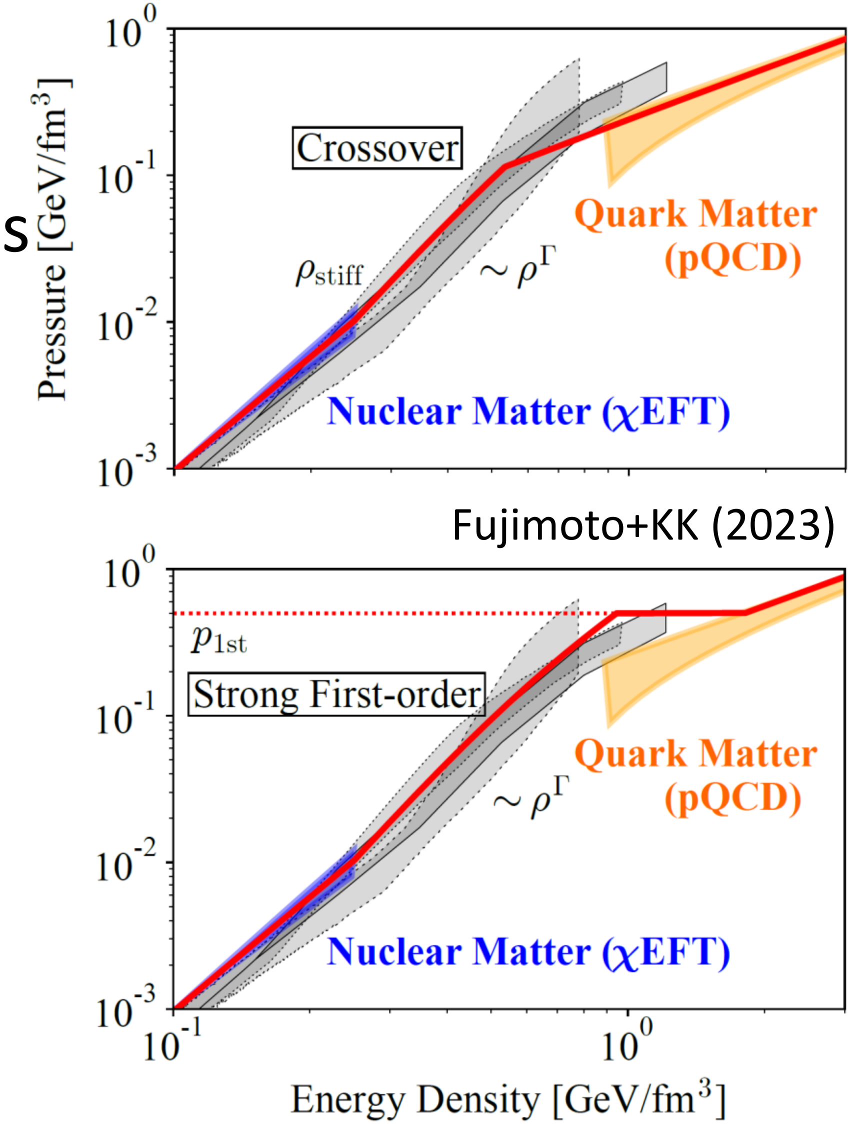
2 solar mass neutron stars

1st-order phase transition

Only very high density allow

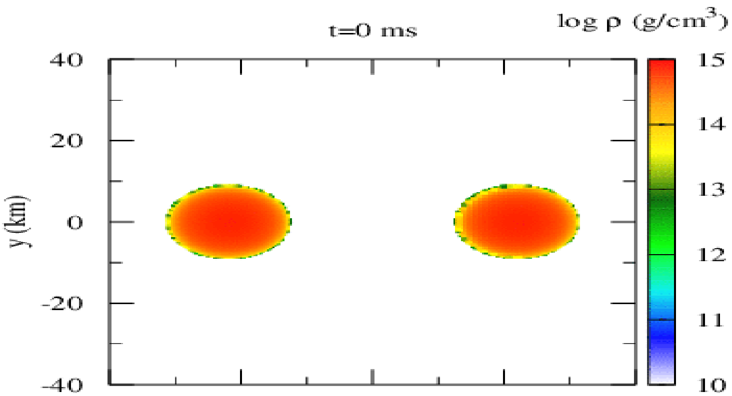
strong phase transition…

No effect on astrophysics?

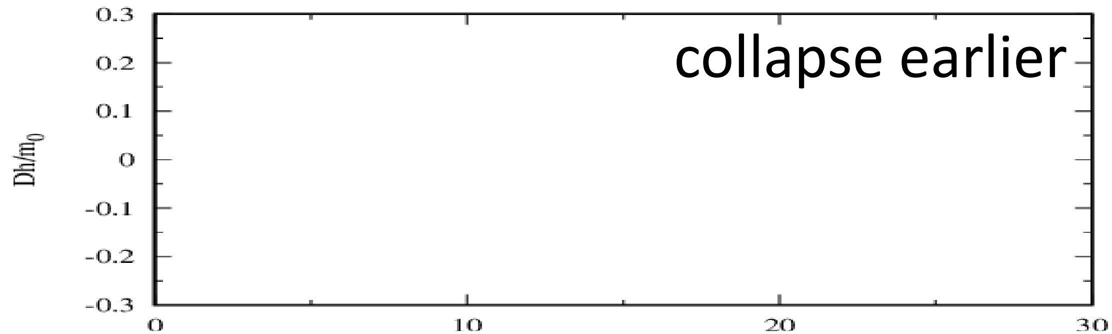


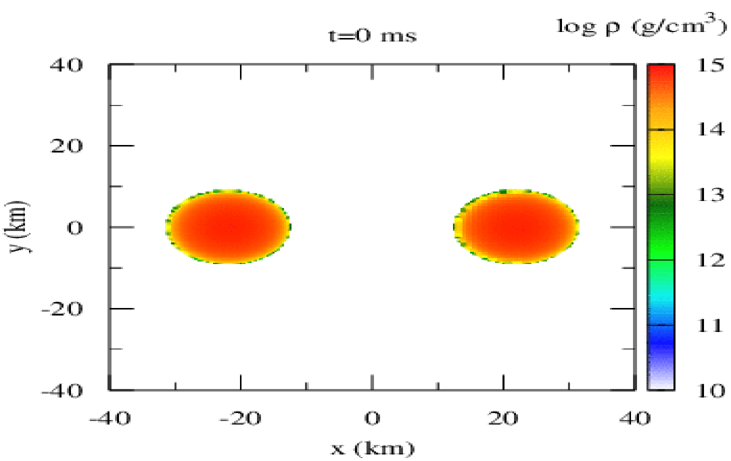
Fujimoto+KK (2023)

Merger and gravitational waves

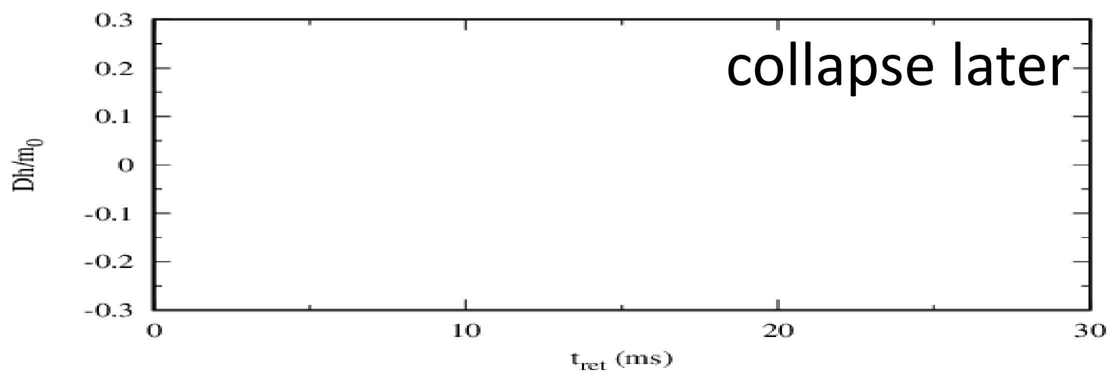


Crossover



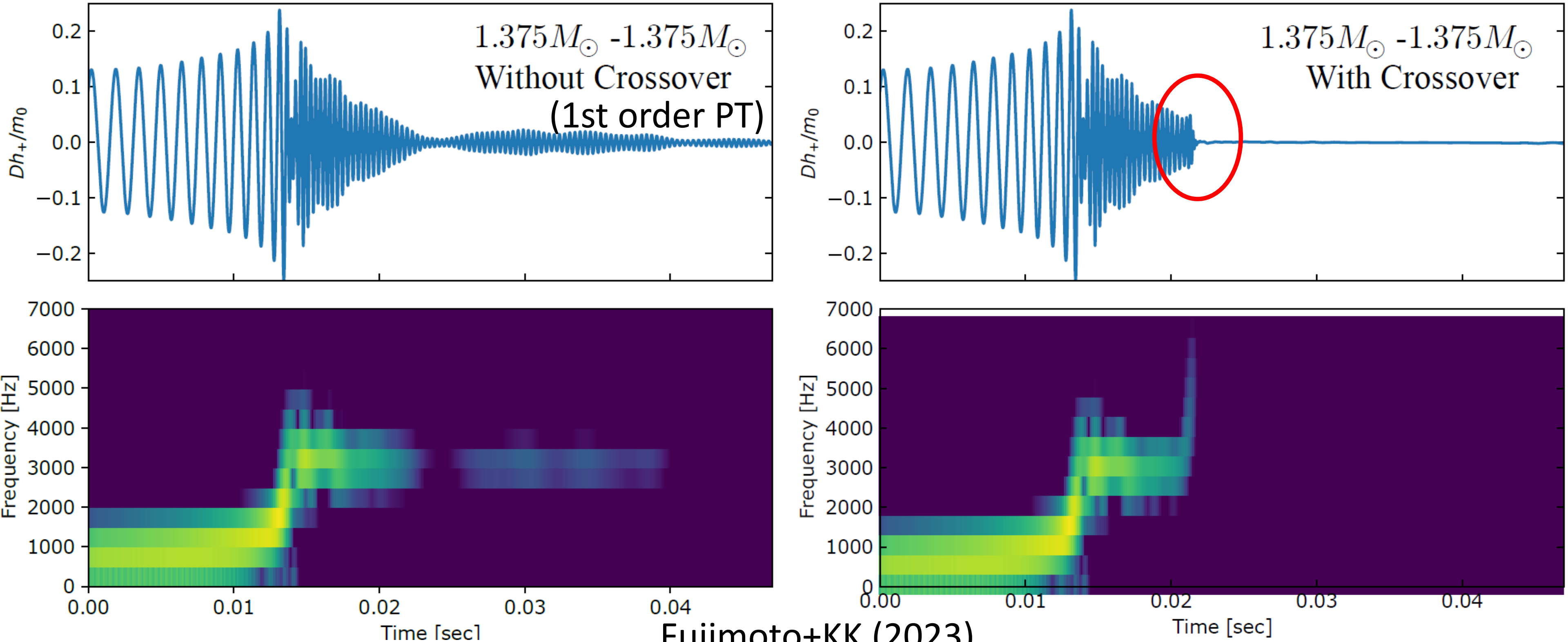


Strong first-order (~hadronic)



Black-hole formation as a key

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

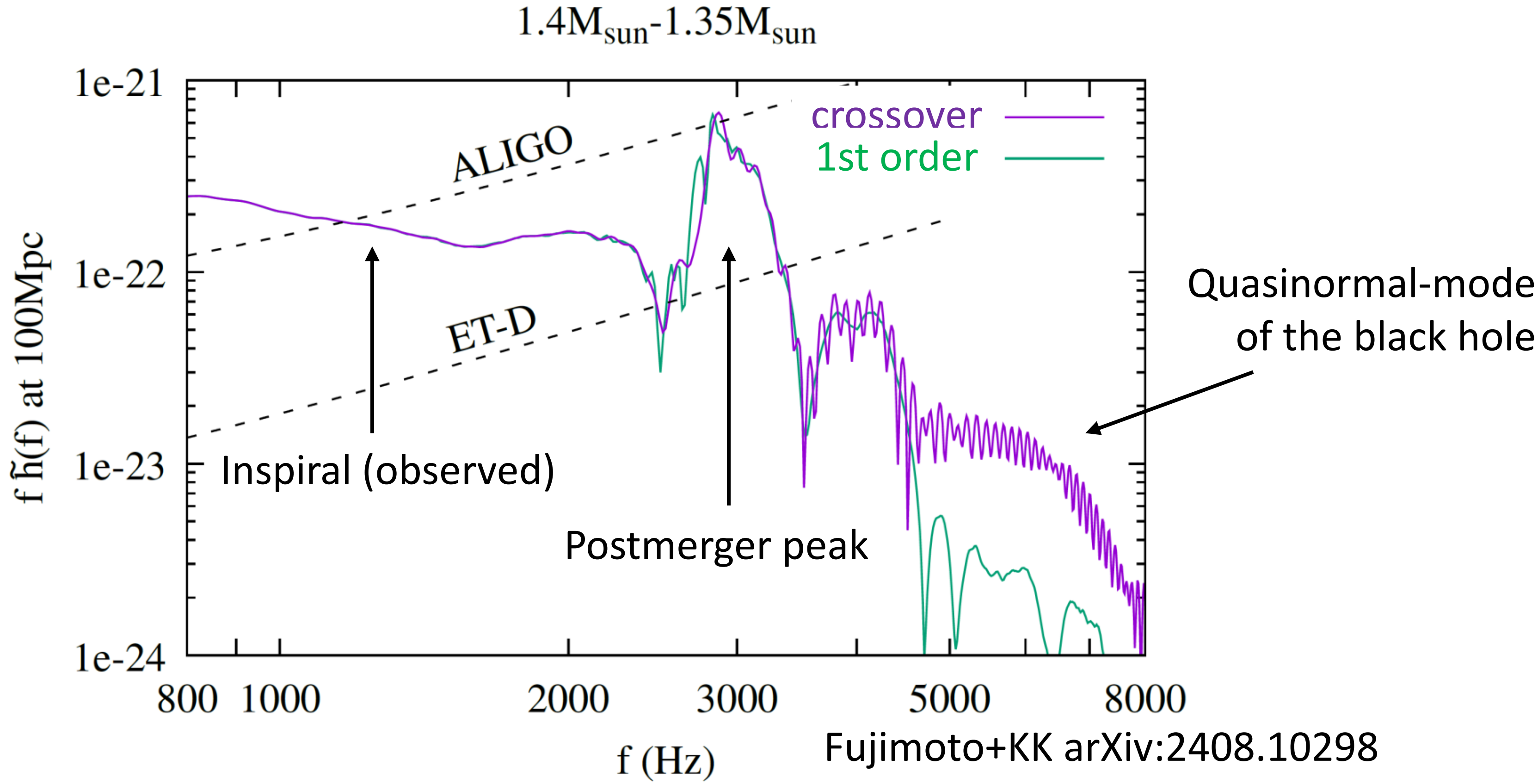


Fujimoto+KK (2023)

Gravitational-wave spectrum

The postmerger peaks do not differ appreciably

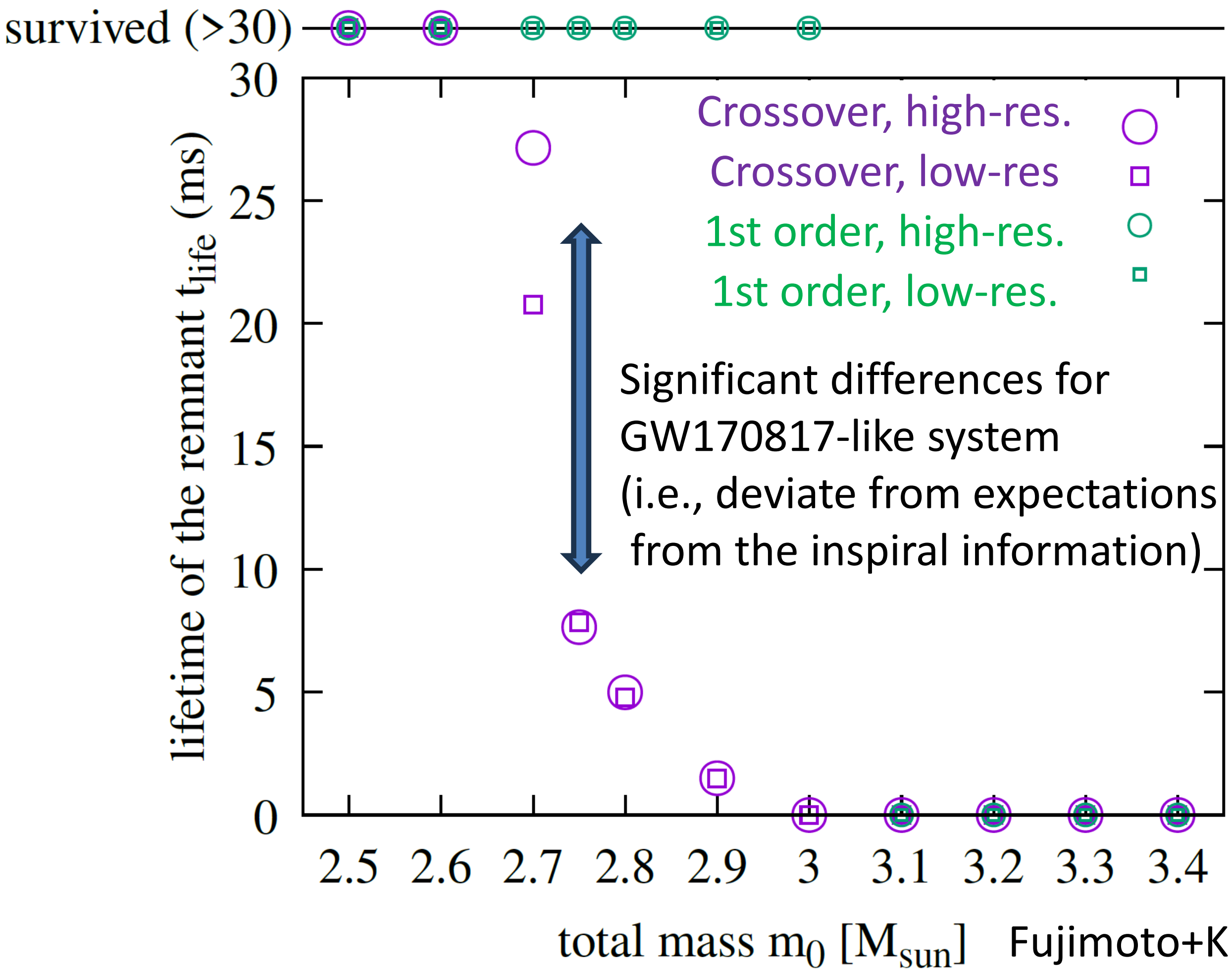
The quasinormal-mode cutoff could be distinguishing



Fujimoto+KK arXiv:2408.10298

Lifetime of the merger remnant

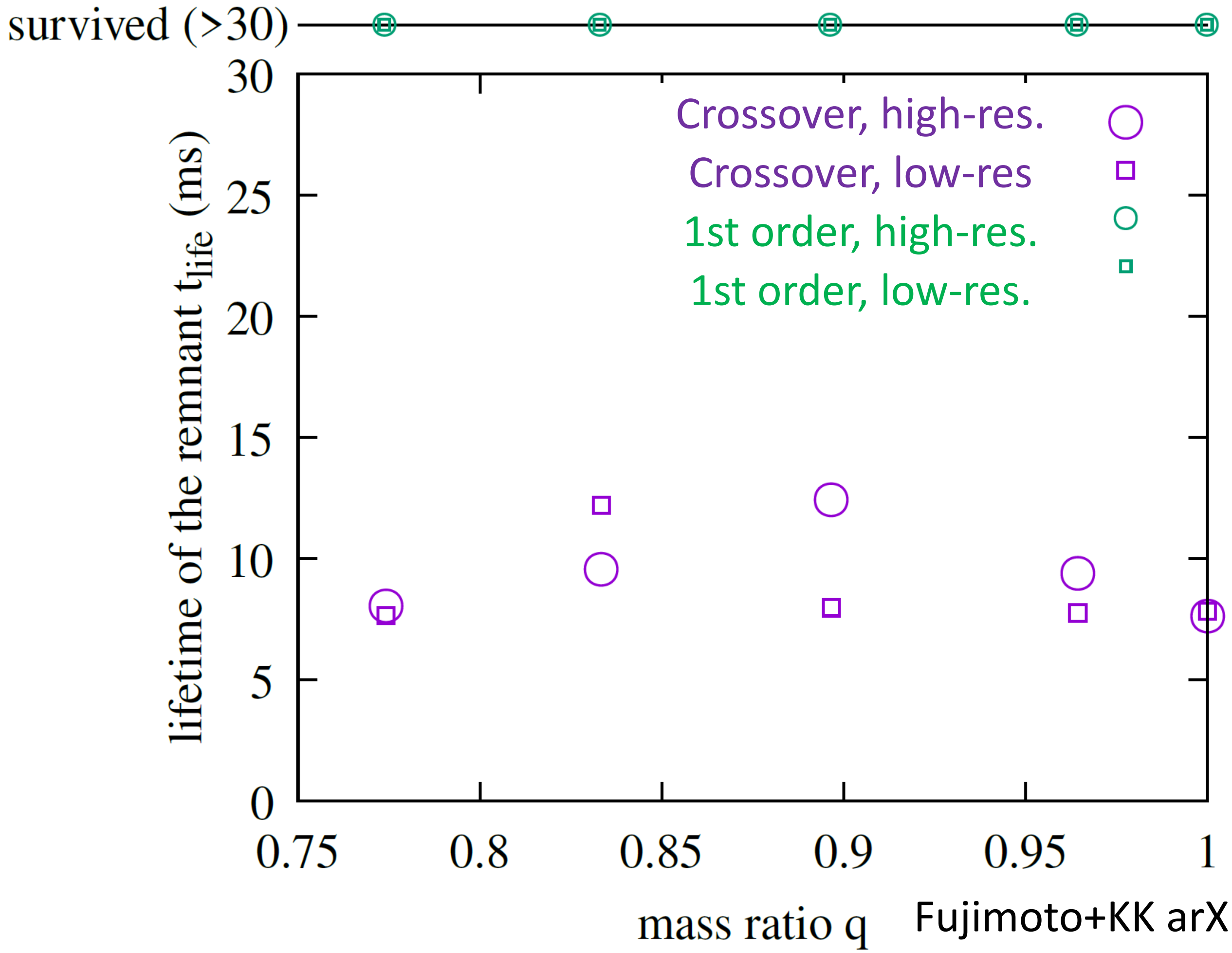
Determined primarily by the total mass of the binary



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

Did GW170817 form a black hole?

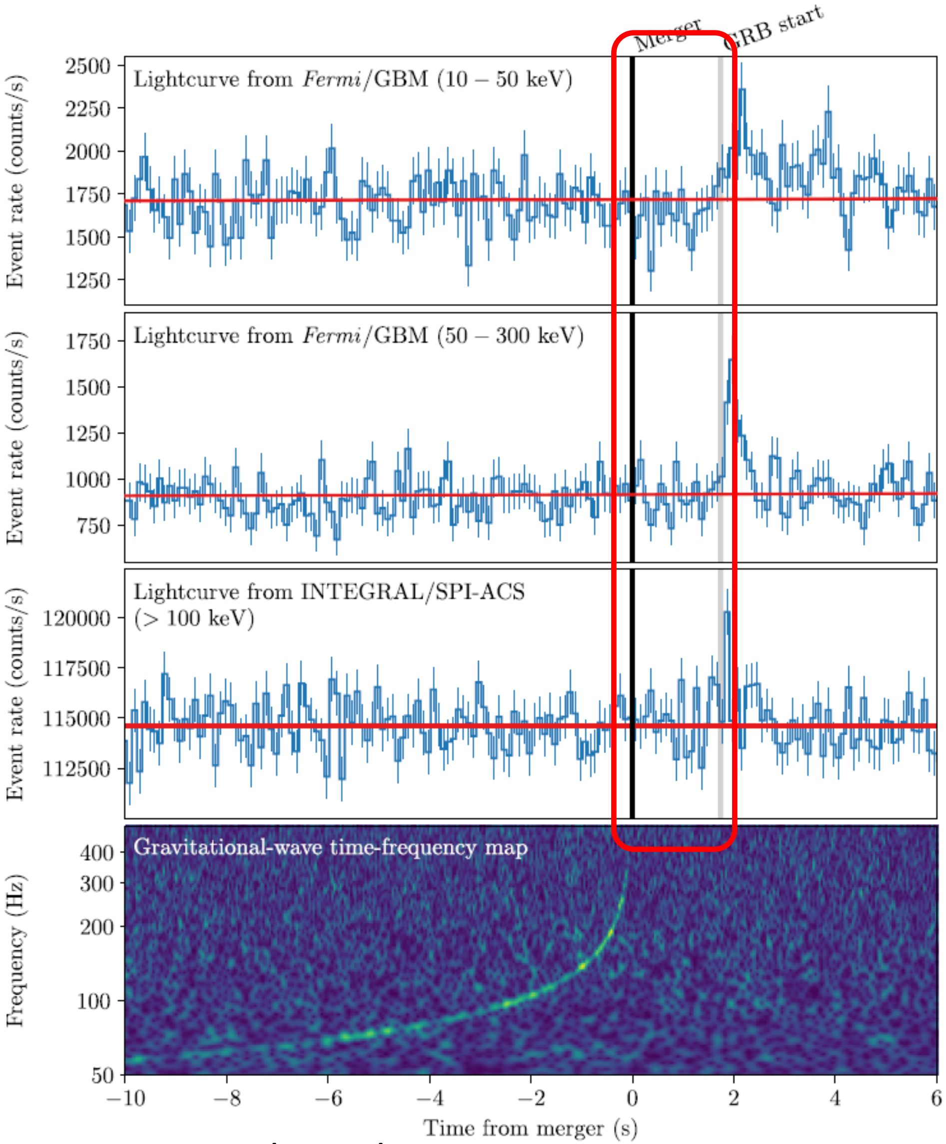
Nobody knows the answer

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

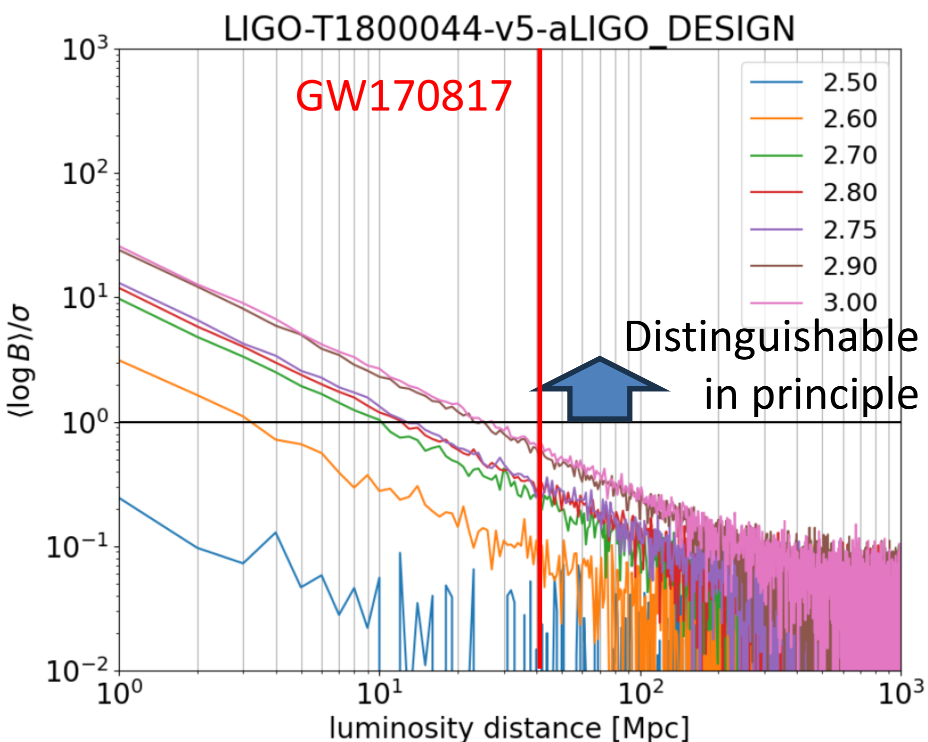
$$L \propto \exp\left(-\frac{1}{2}|\mathrm{data} - \mathrm{waveform\ model}|^2\right)$$

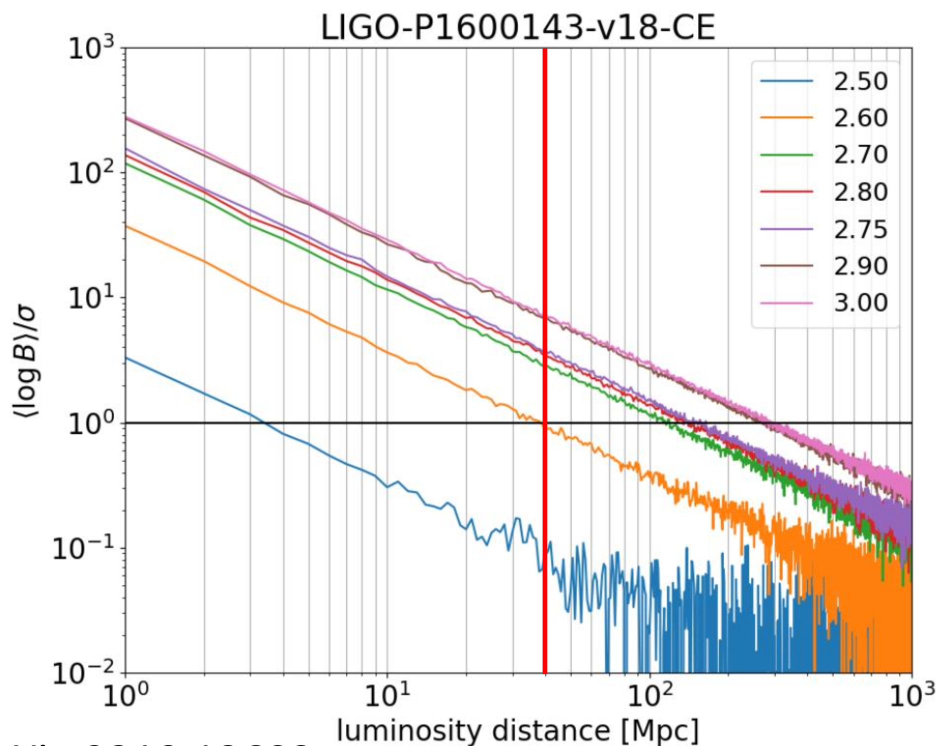
Transition scenarios should easily be distinguishable with sensitive detectors and/or nearby events

Distinguishability in data analysis

AdLIGO is insufficient even at design sensitivity (left)

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





Harada+KK arXiv:2310.13603

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

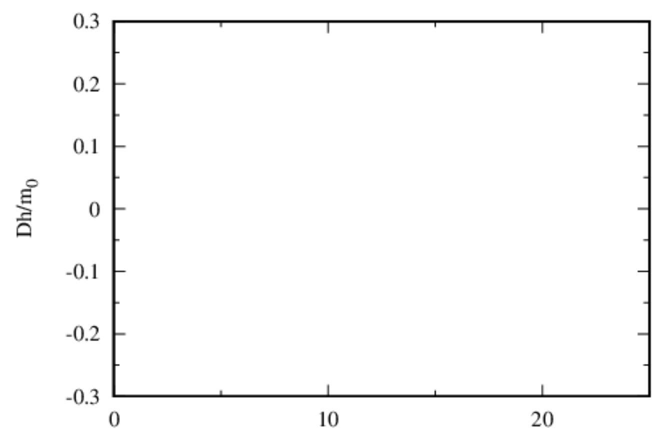
Binary-neutron-star coalescence

A remnant massive neutron star will be formed

Collapse into a black hole radiating angular momentum

Spacetime curvature, log(rescaled absolute value)

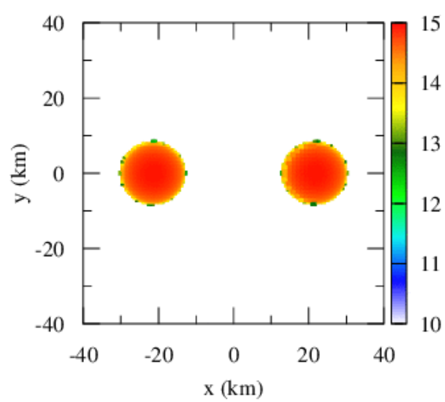
Gravitational waveform



time (ms)

2000km one side

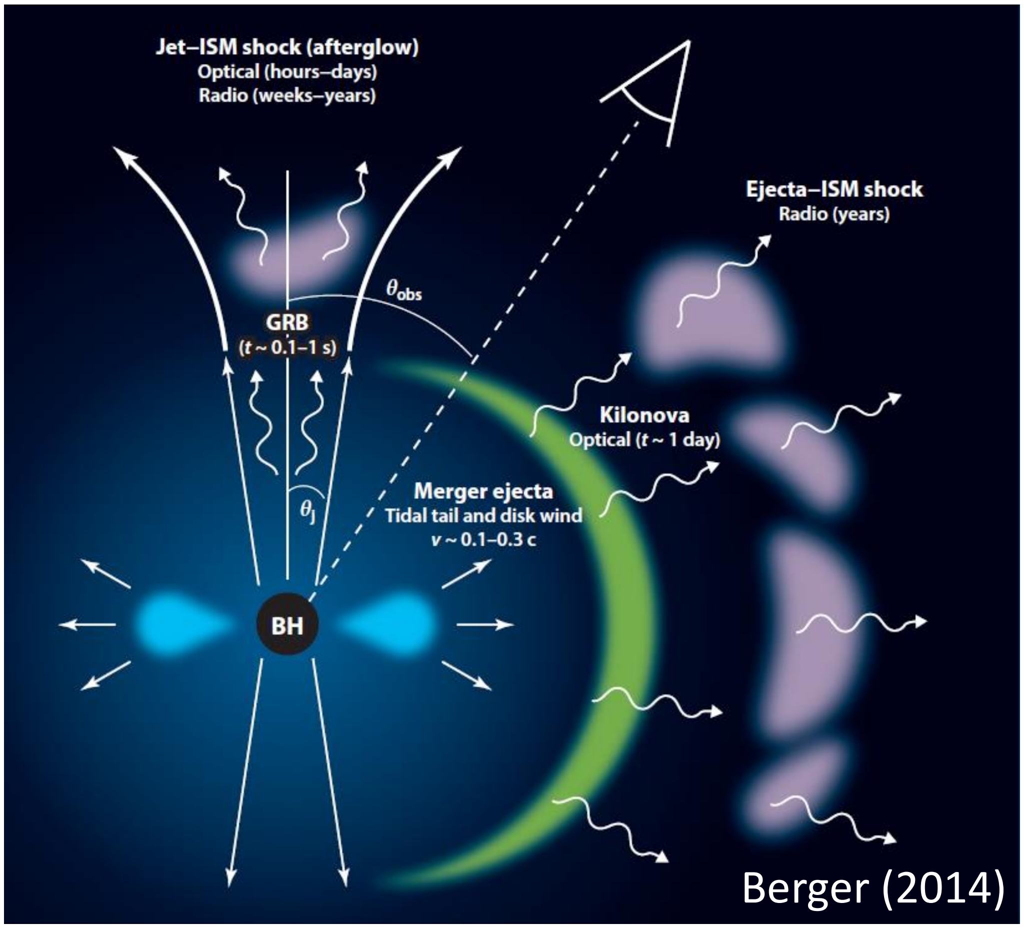
Rest-mass density (g/cc)



40km one side

Electromagnetic counterpart

EM radiation will accompany neutron star mergers



localization

host identification

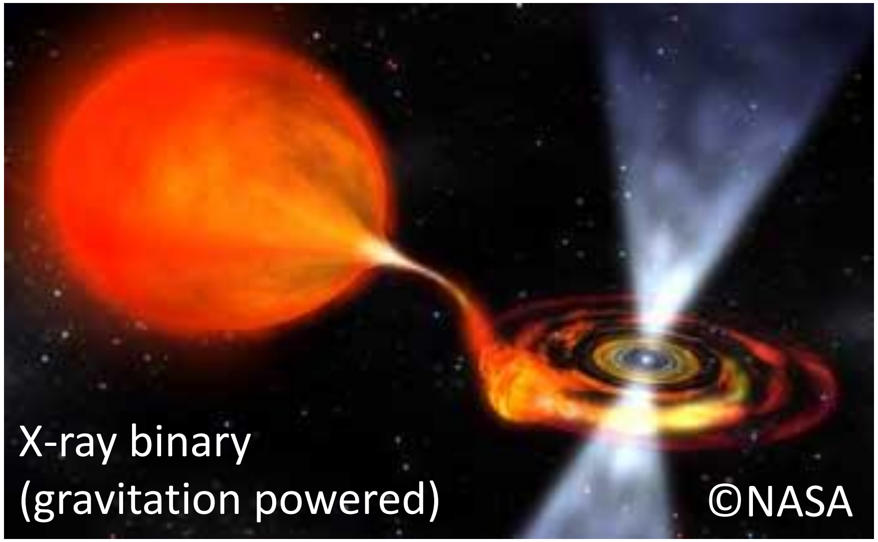
cosmological redshift

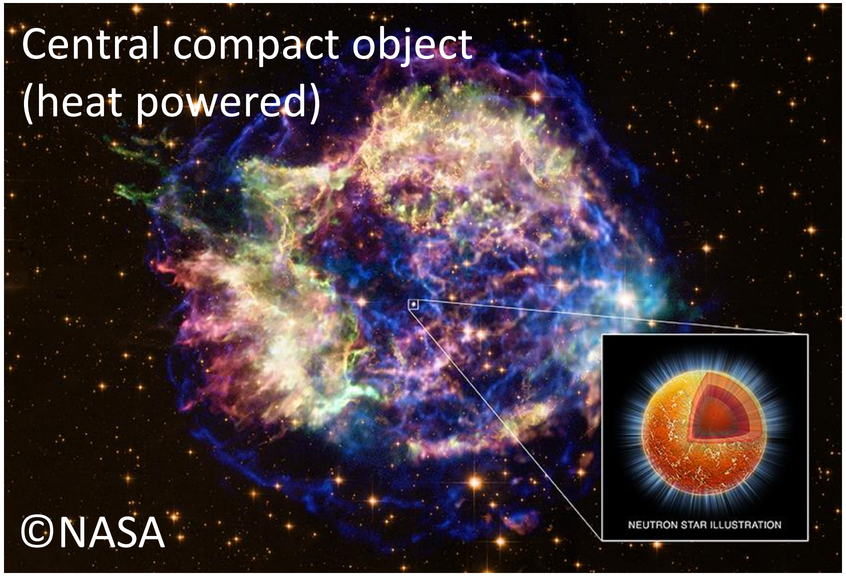
ejecta properties

ejection mechanism

r-process element

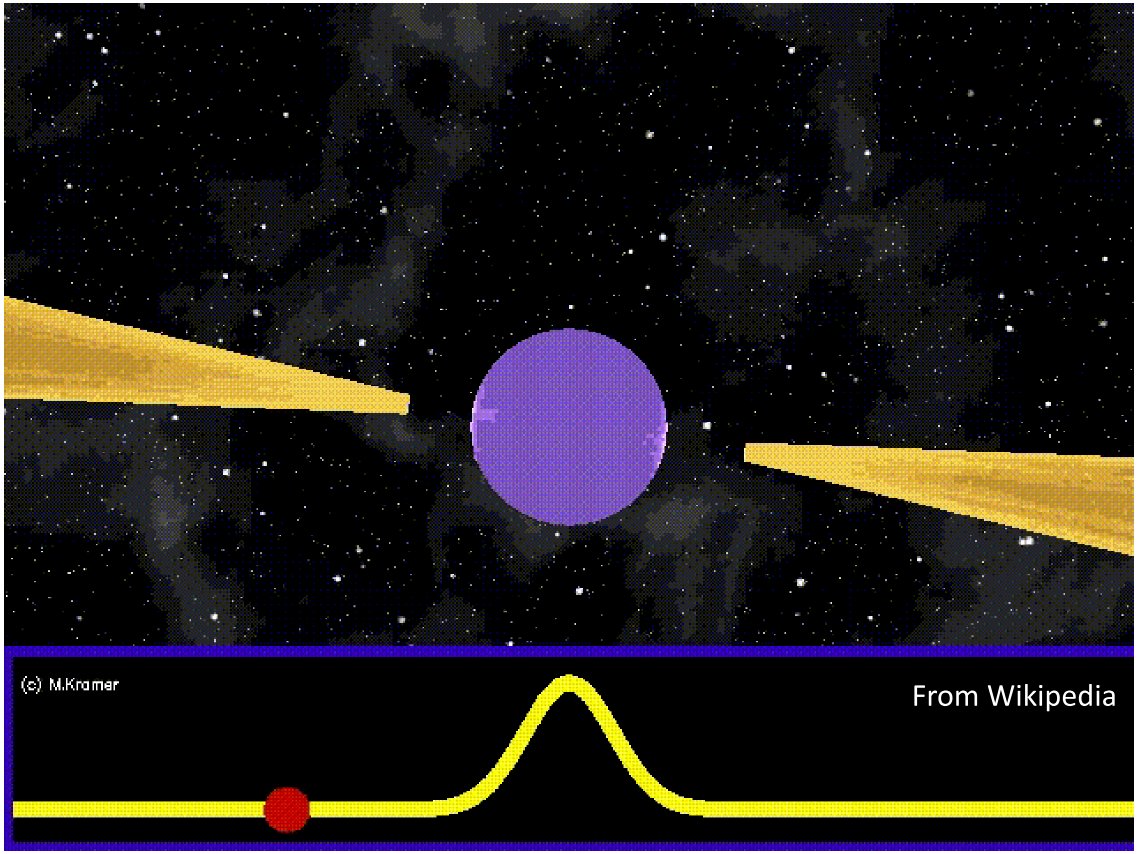
Diversity of neutron stars



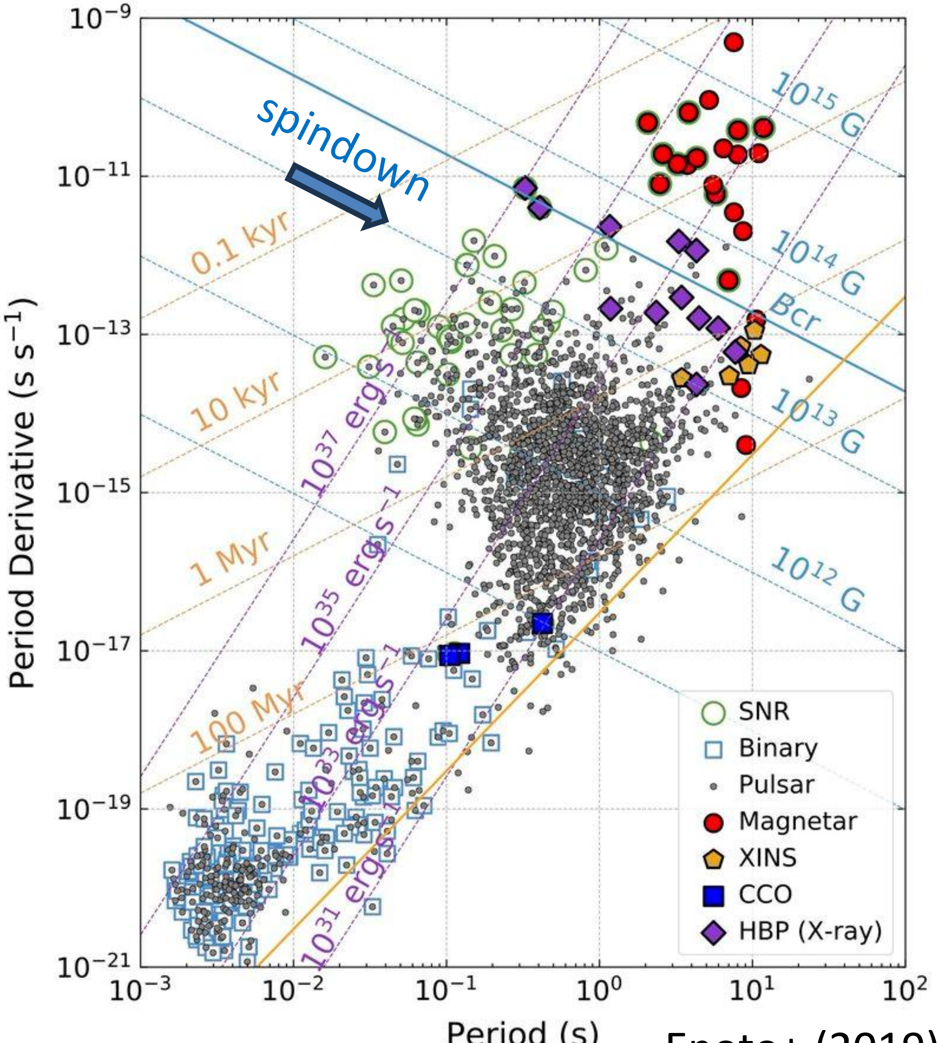


Dipole radiation and spindown

The rotational energy is radiated via magnetic fields and the spin is decelerated, i.e., the period increases



P-Pdot diagram



Enoto+ (2019)

(surface) magnetic field:

$$B \sim 3 \times 10^{19}\ \mathrm{G}\ \left(\frac{P\dot{P}}{\mathrm{s}}\right)^{1/2}$$

above $B_{\mathrm{cr}} \sim 4 \times 10^{13}\mathrm{G}$, QED becomes important

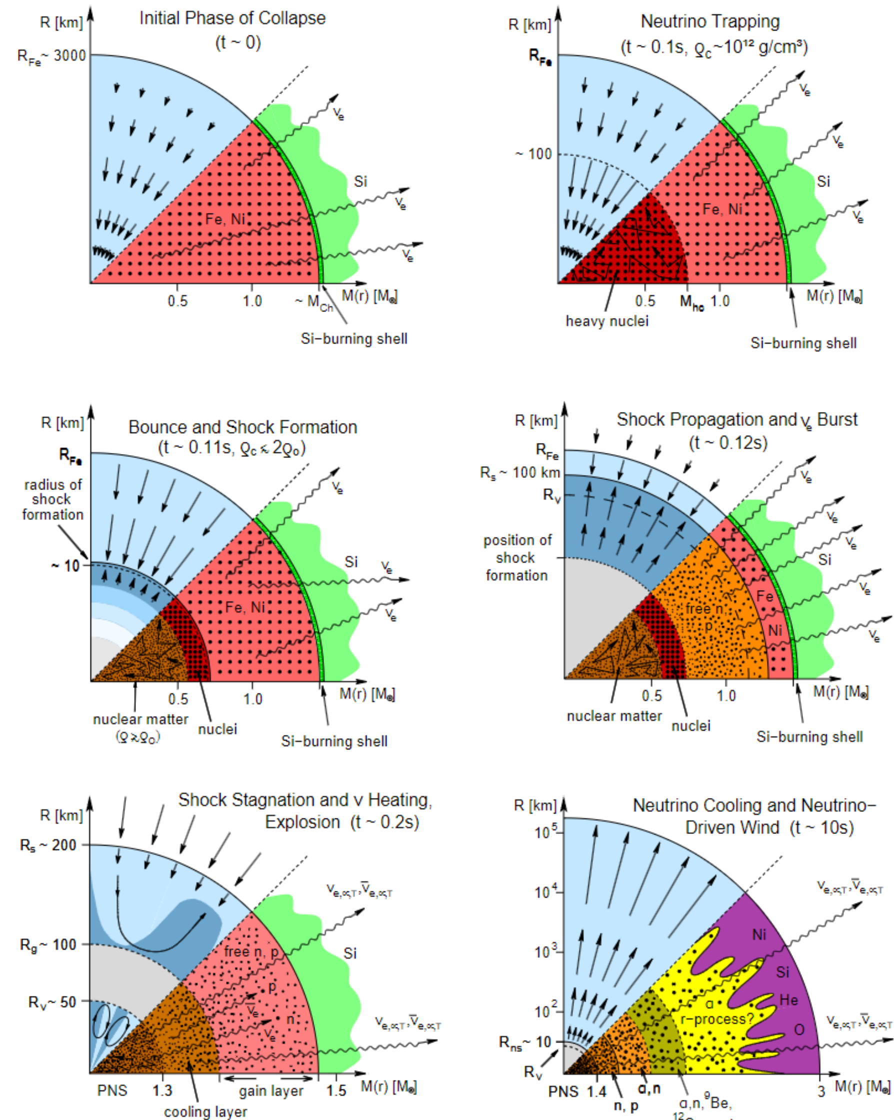
low-B, rapid neutron stars are produced by accretion

Supernova explosion mechanism

The iron core has exhausted all the nuclear fuel

The collapse sets in due to photodissociation of irons

One the density approaches the nuclear saturation value, the core bounce triggers shock waves … supernova



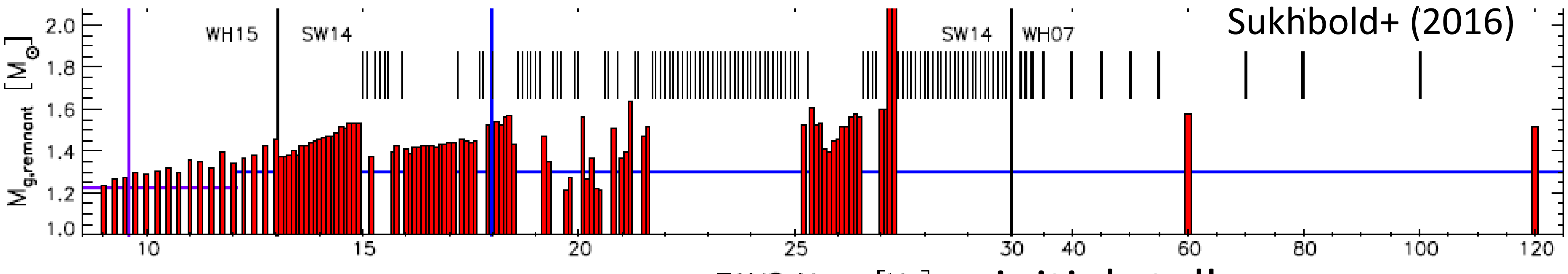
Janka+ (2007)

The remnant is not monotonic

There is no single threshold of the initial mass separating neutron-star and black-hole formation

…stellar evolution is a highly complicated process

(and calculations/simulations are not mature enough)



= initial stellar mass

Red bar: explode -> a neutron star is formed

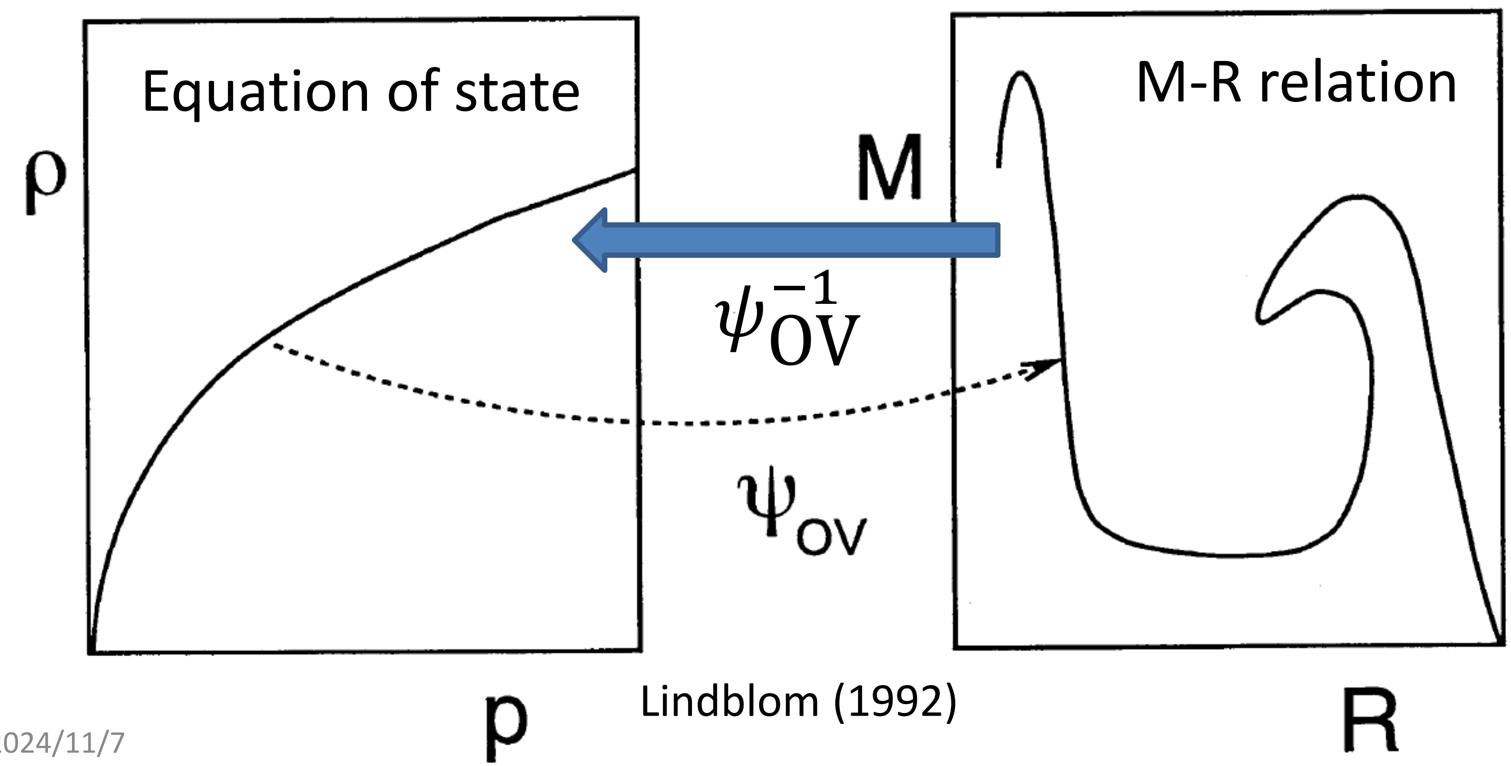
Black line: not explode -> a black hole is formed

One-to-one correspondence

Via Tolman-Oppenheimer-Volkoff equation of GR

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

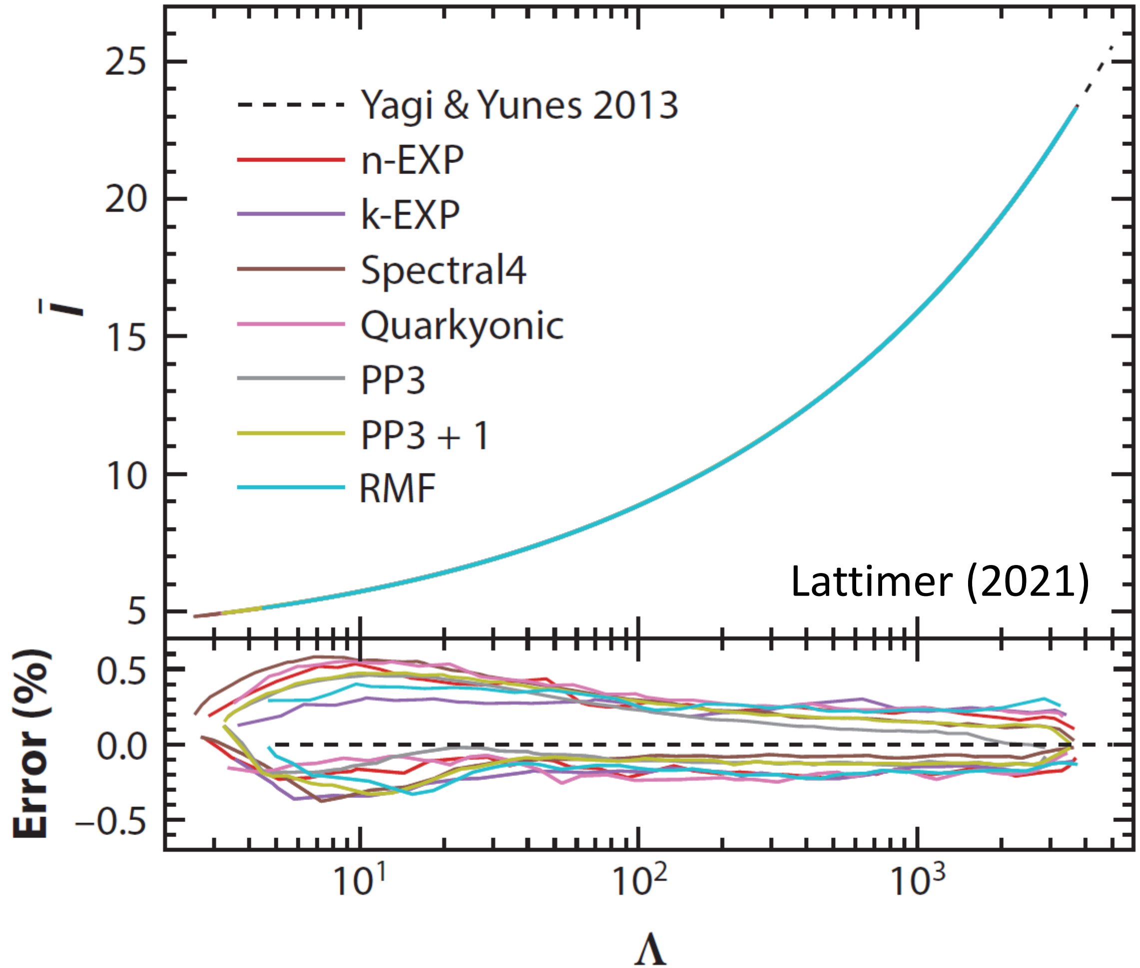
$(G = c = 1)$



Lindblom (1992)

Tight correlation

Not necessarily independent information is encoded



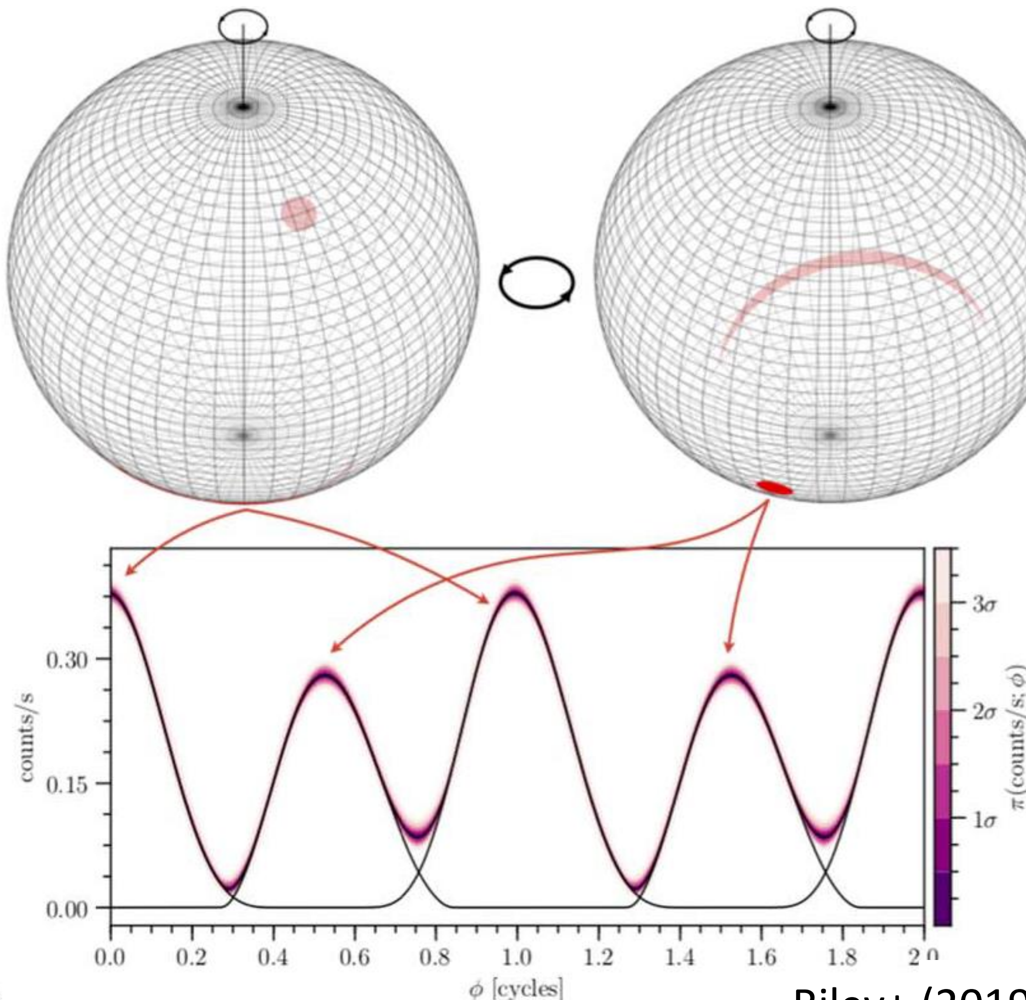
NICER X-ray pulse observation

Hot spots behind can be seen thanks to light bending in general relativity

The compactness

$C \sim M/R$

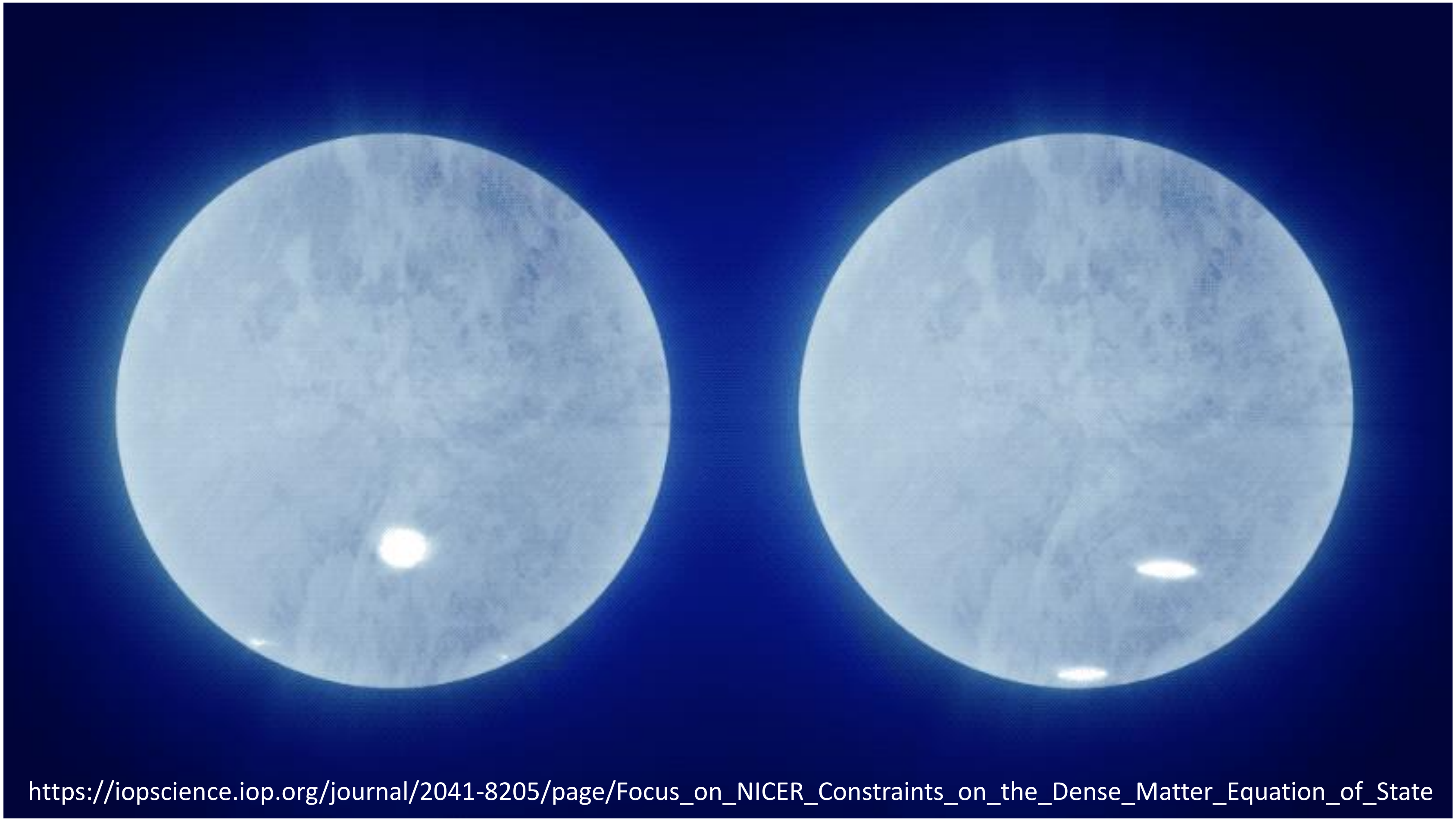
is constrained well because it is essentially the grav. potential



Riley+ (2019)

How reliable?

In principle OK, but the shape of the hot spots are...?

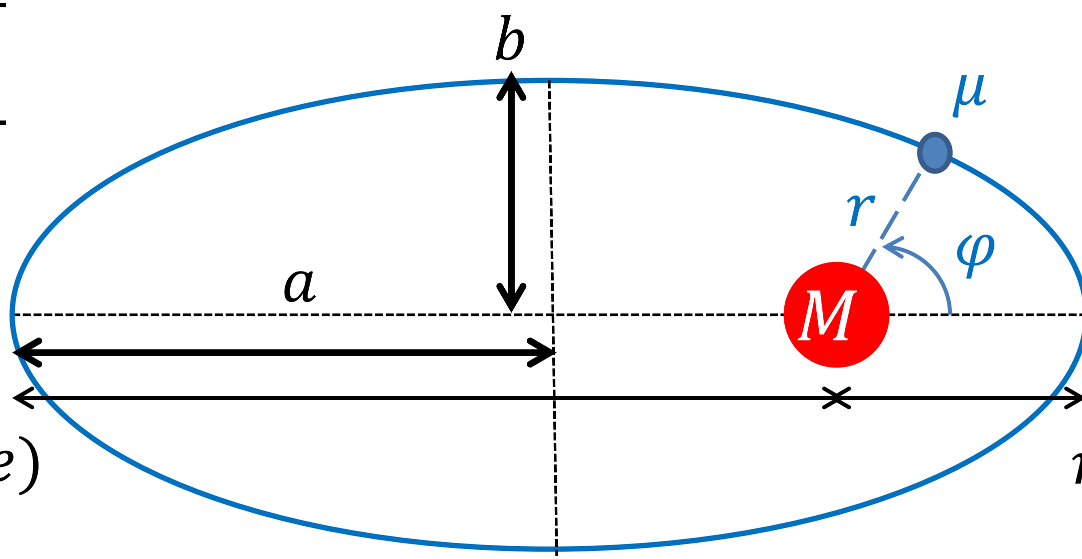


Newton two-body problem

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

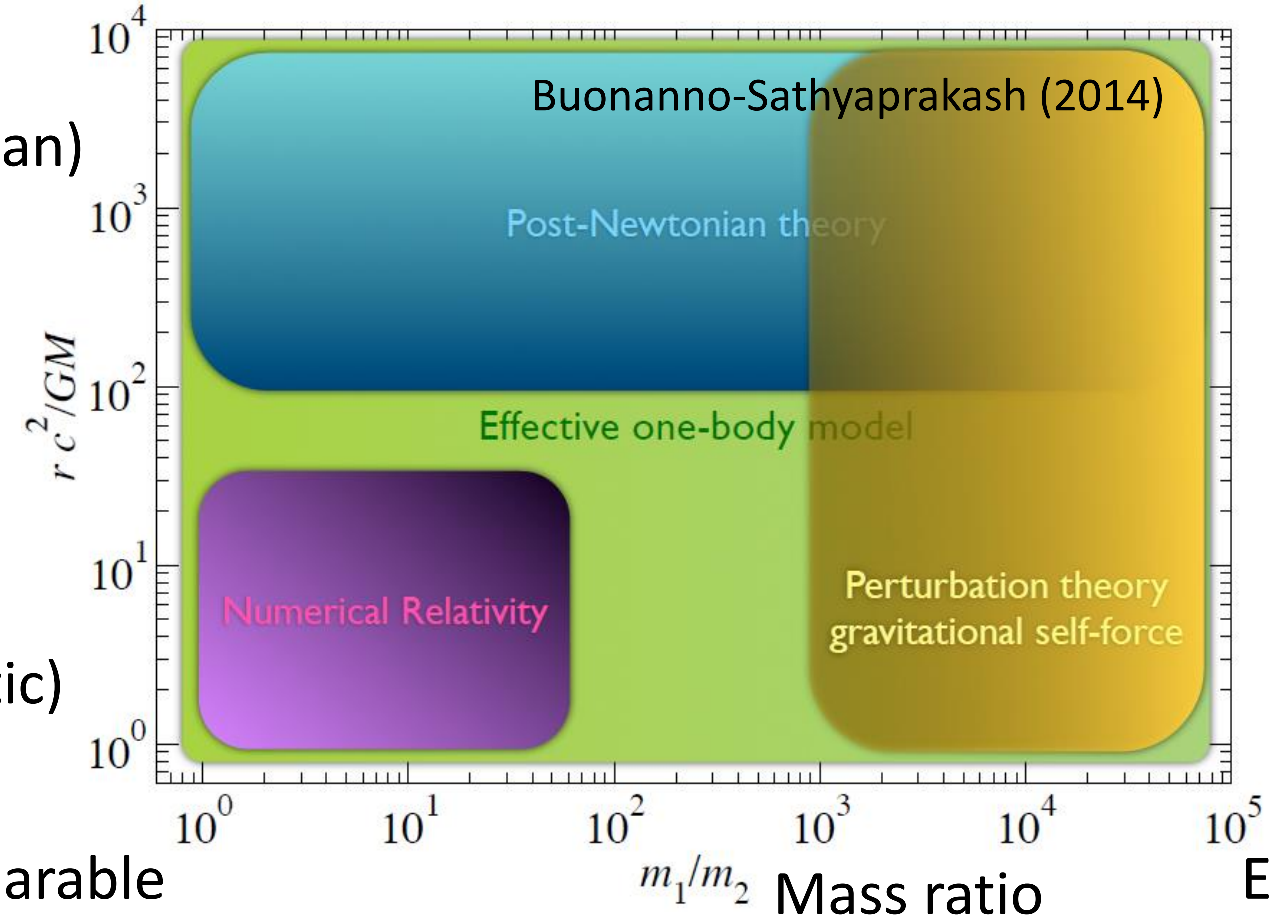
Relativistic two-body problem

Neglecting spins, eccentricity, finite-size effects…

Distant (Newtonian)

Orbital separation

Close (relativistic)



Comparable

Mass ratio

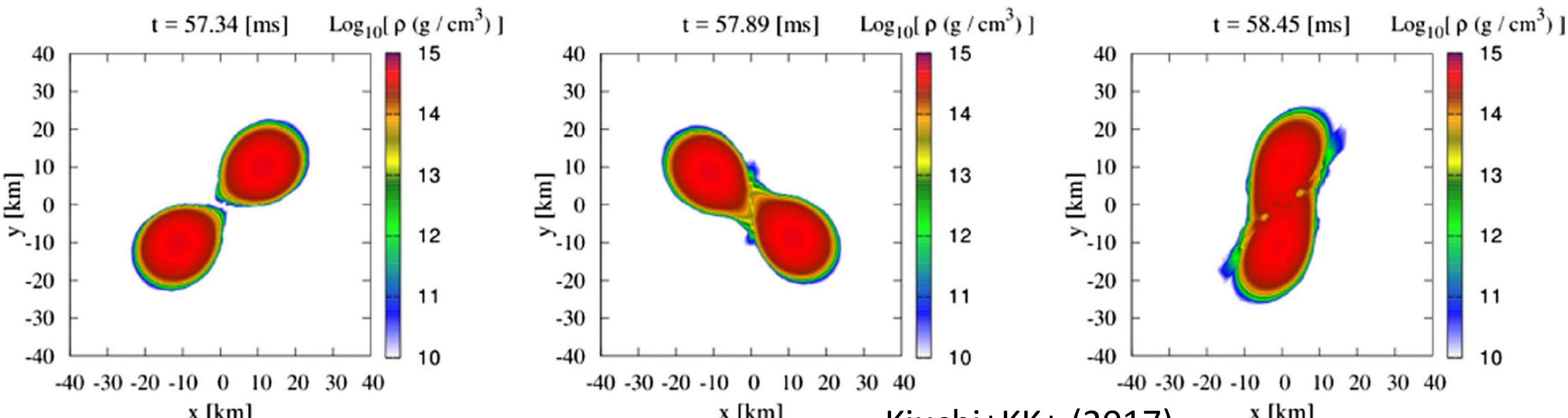
Extreme

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

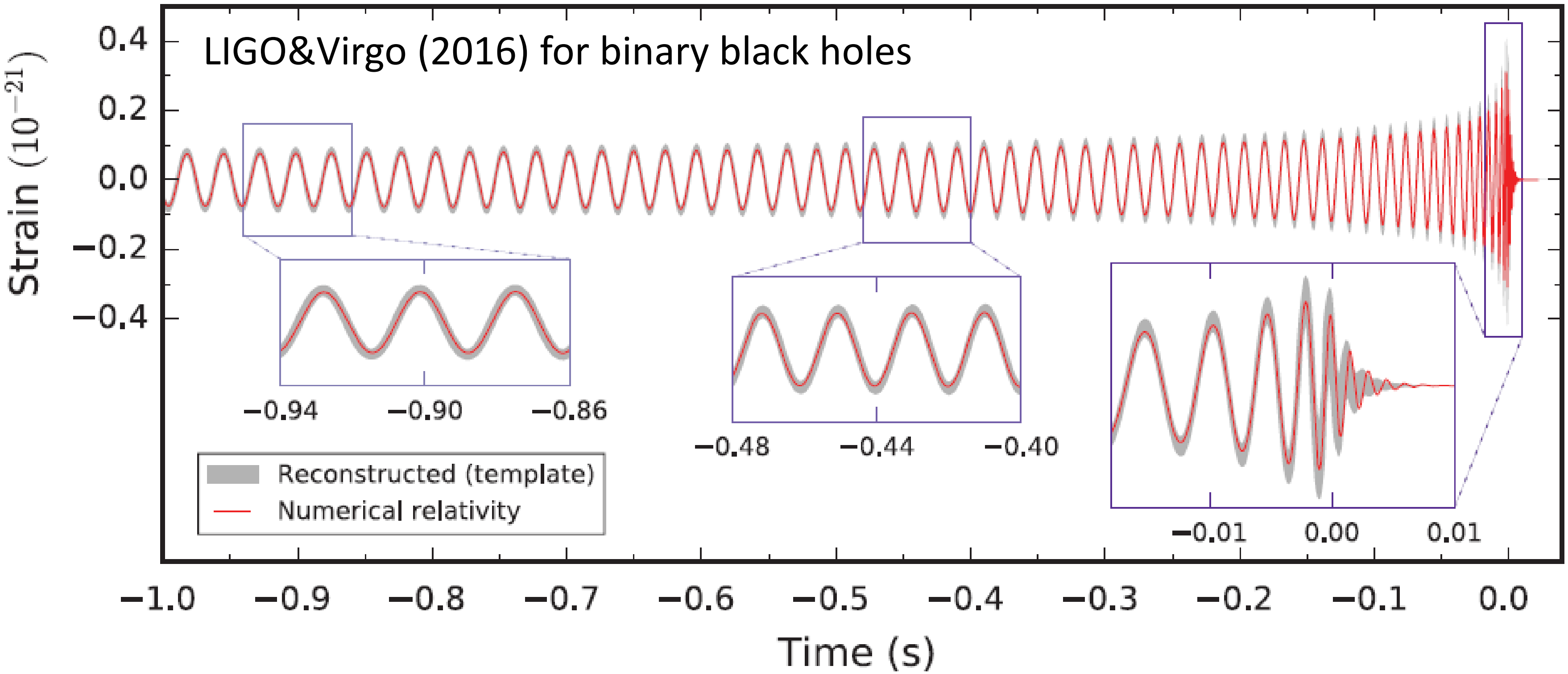


Kiuchi+KK+ (2017)

Role of theoretical templates

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

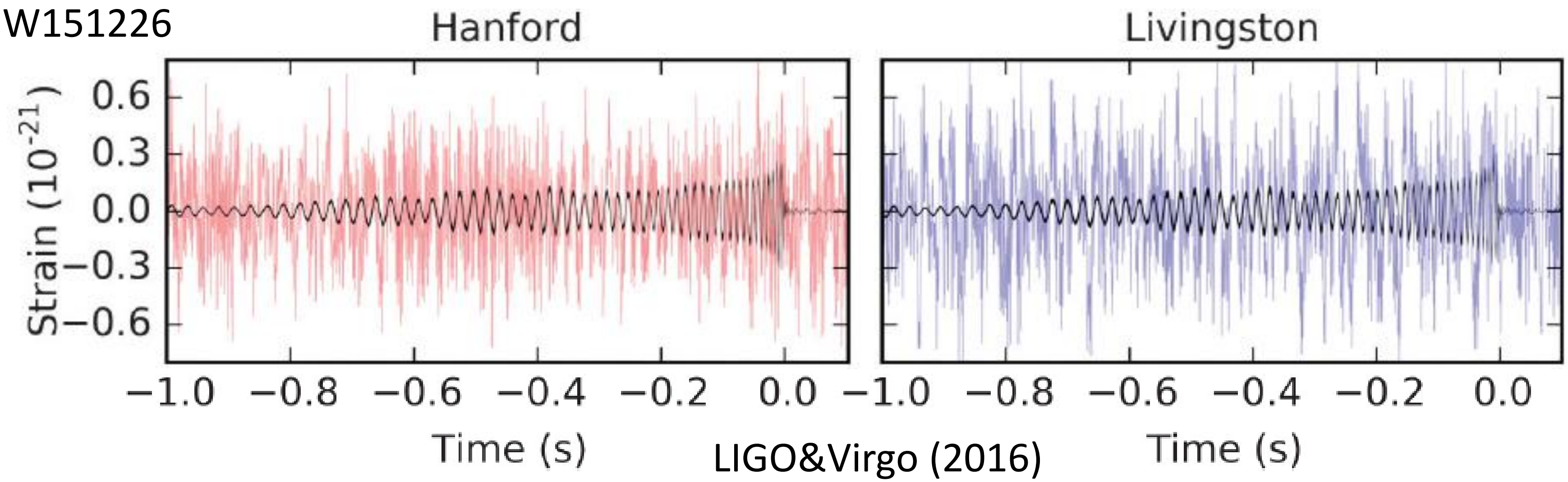
Accurate theoretical models are indispensable



Theoretical waveform and the noise

Signals are usually weaker than the detector noise

GW151226

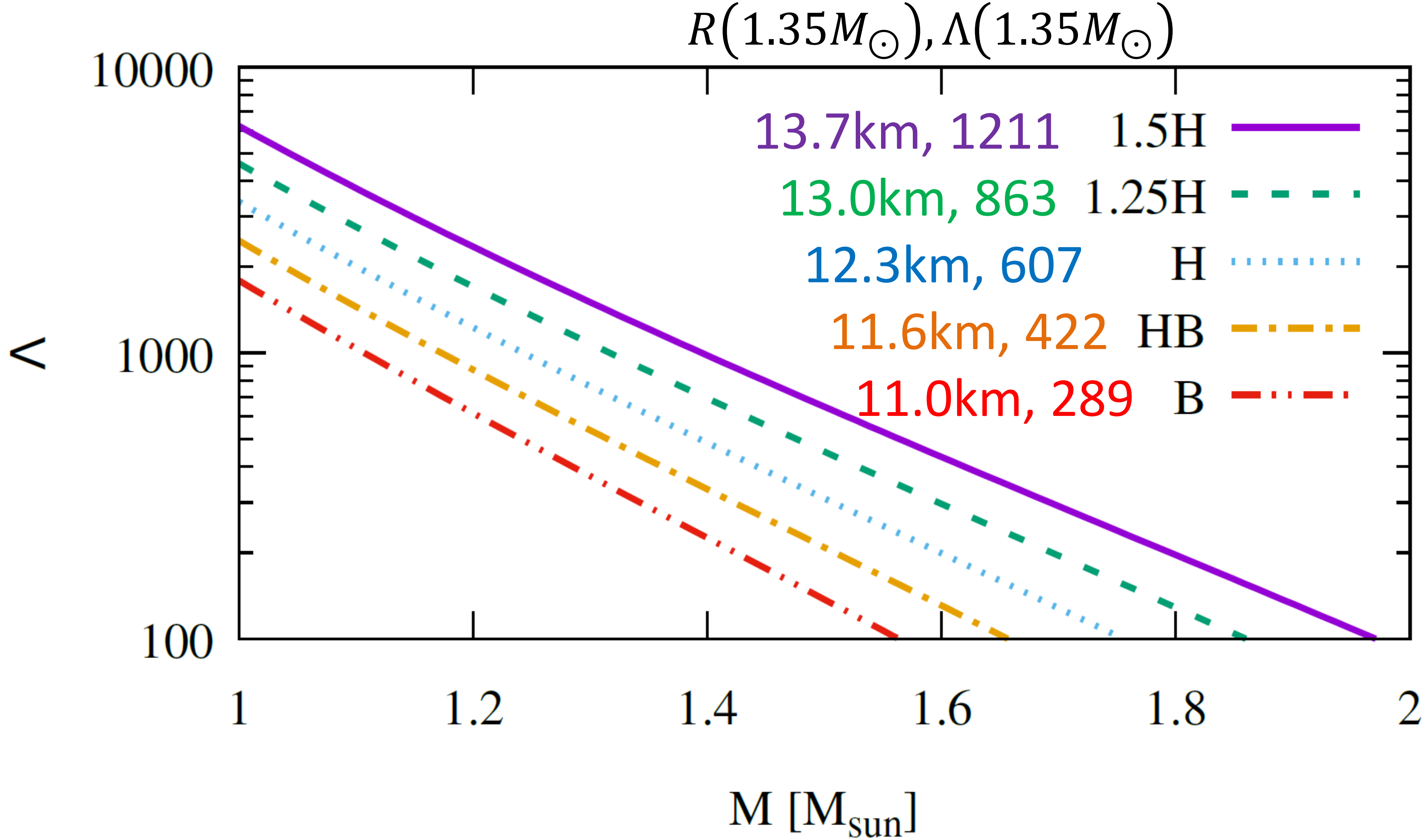


LIGO&Virgo (2016)

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 $\tilde{\Lambda}$

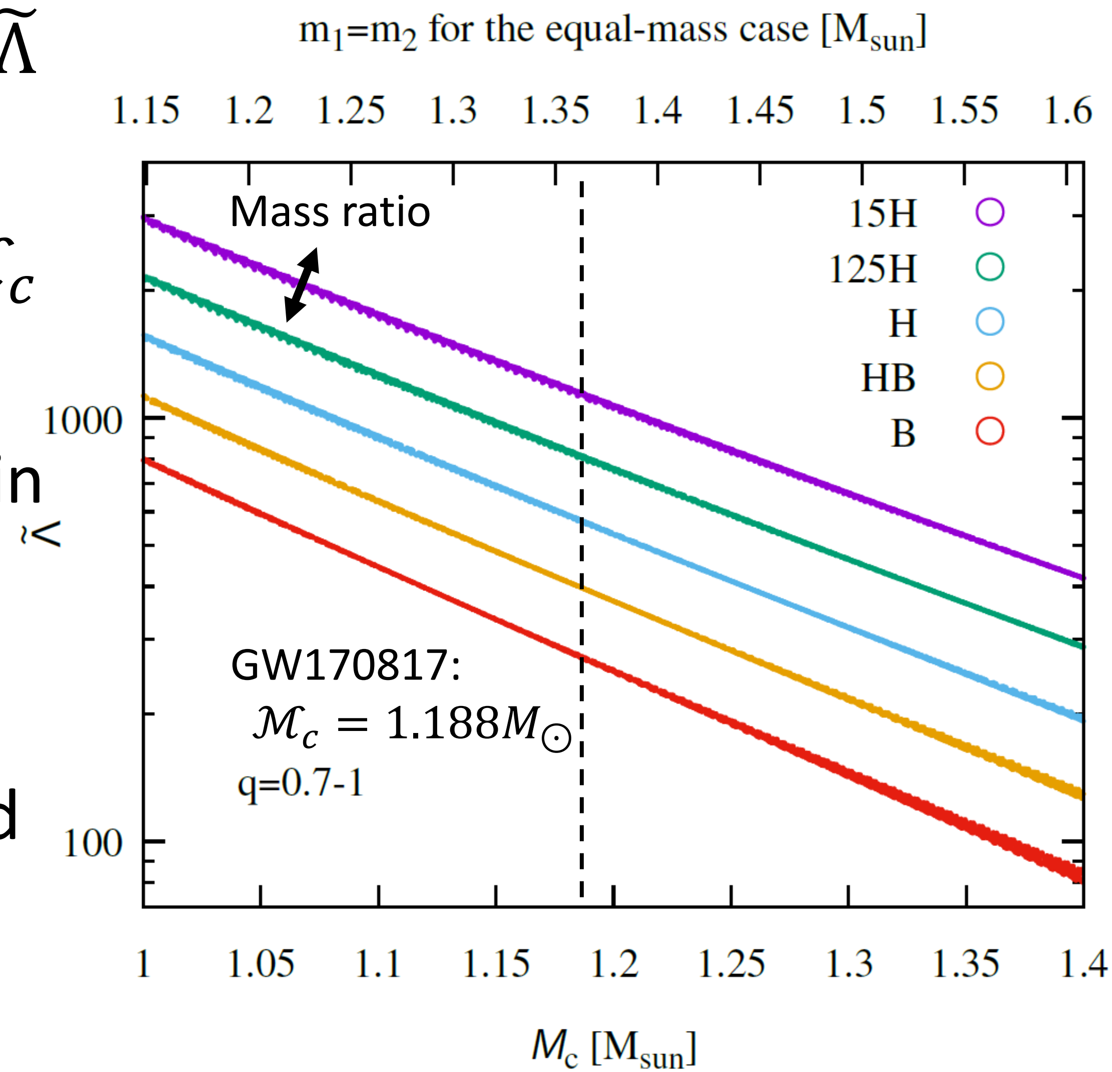
Is correlated strongly

with the chirp mass $\mathcal{M}_c$

We effectively constrain

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

>13-14km is disfavored



Waveform library

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

Released Model List

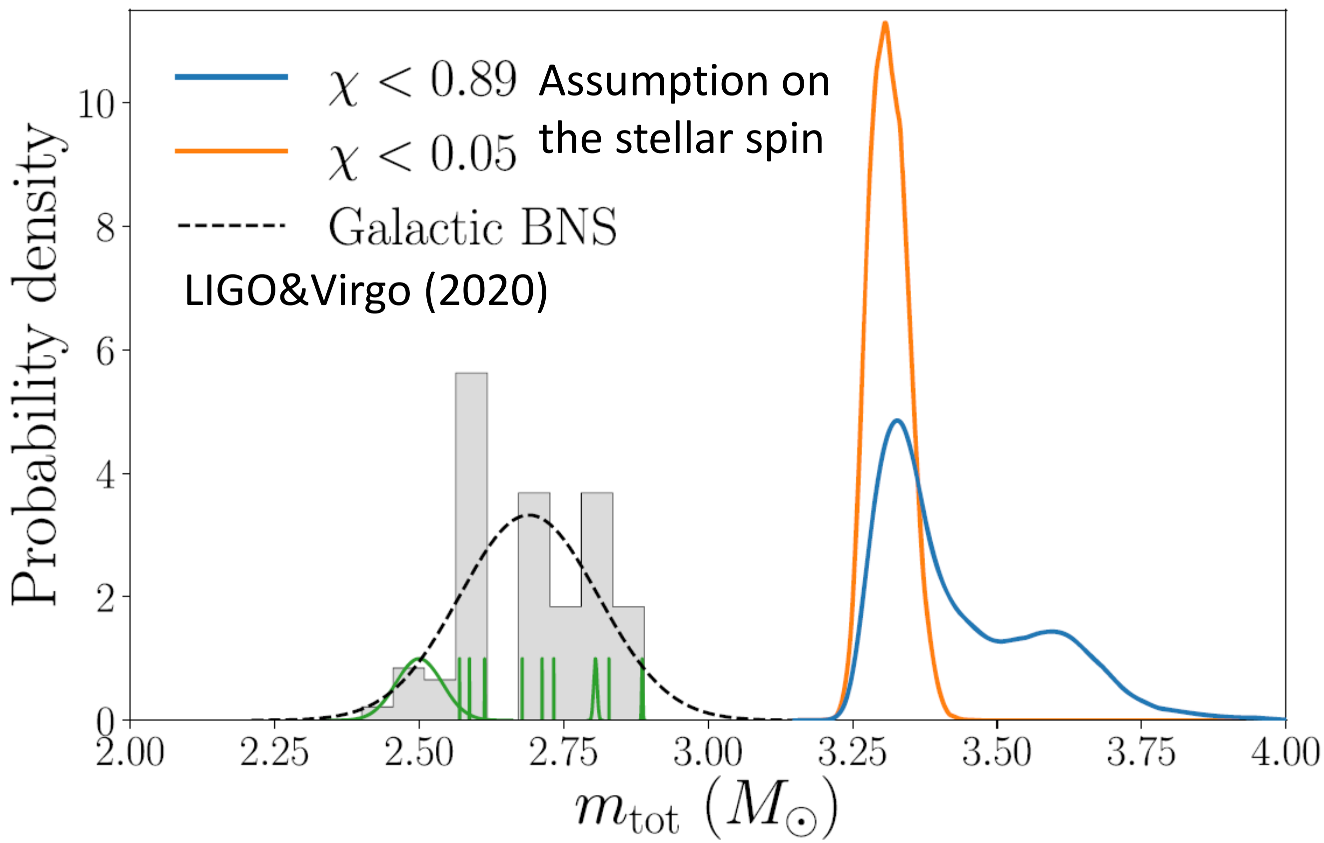
Serach:

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

GW190425

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

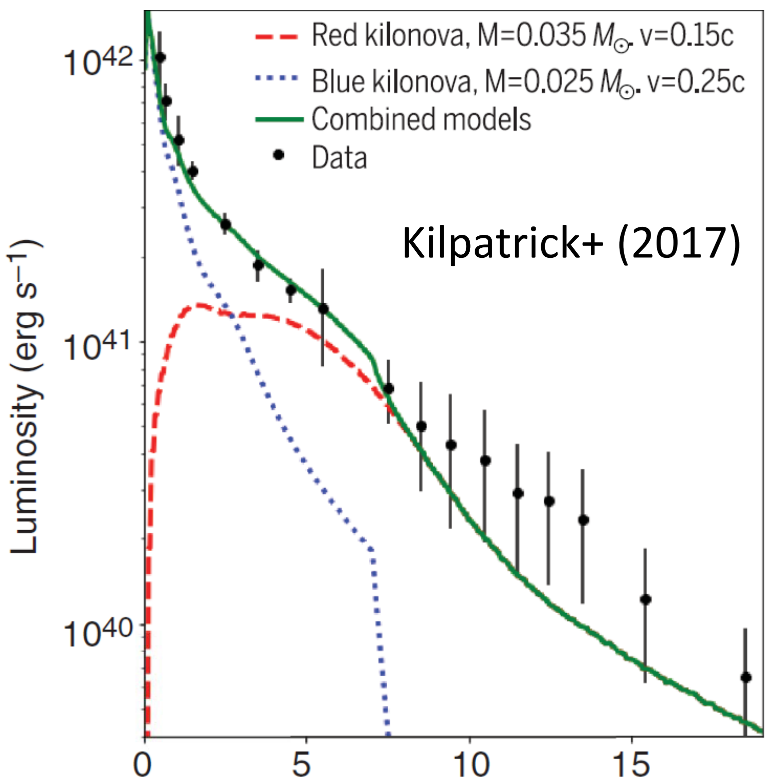
Heavier by >5sigma than Galactic binary neutron stars



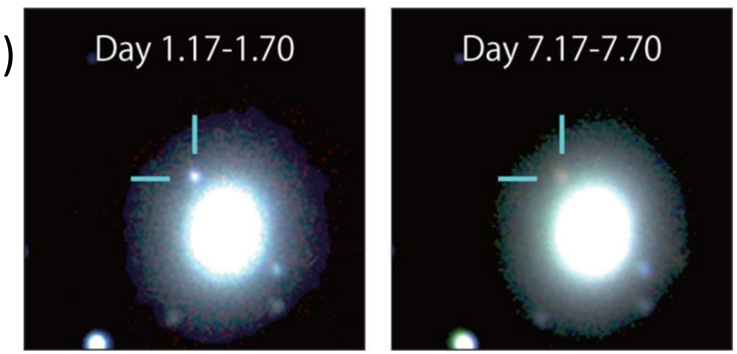
Constraint from the kilonova?

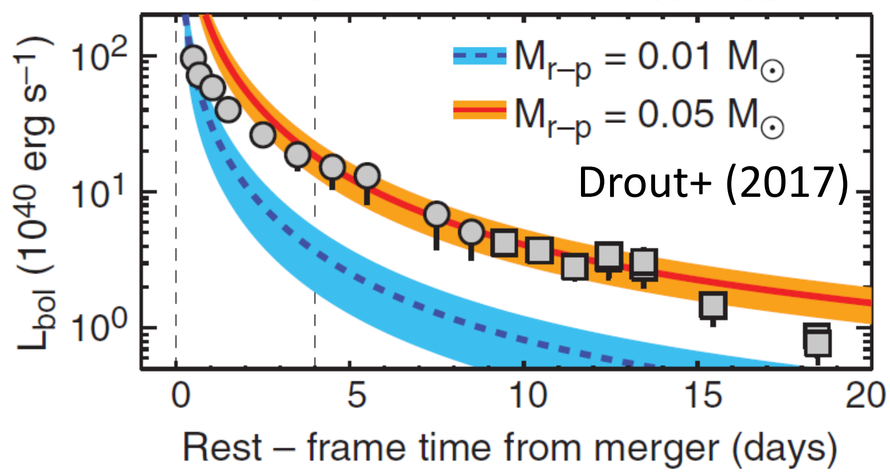
Indication of the large ejecta mass of $\sim 0.05 M_{\odot}$

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



Utsumi+ (2017)



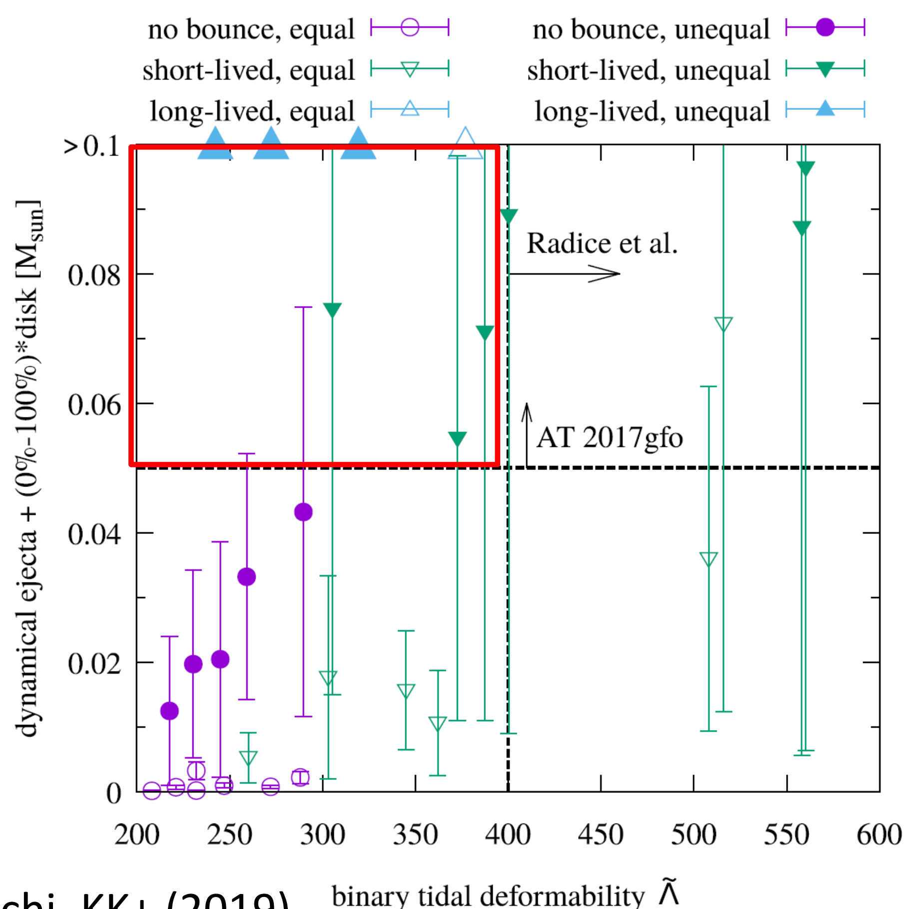


A lot of counterexamples

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)

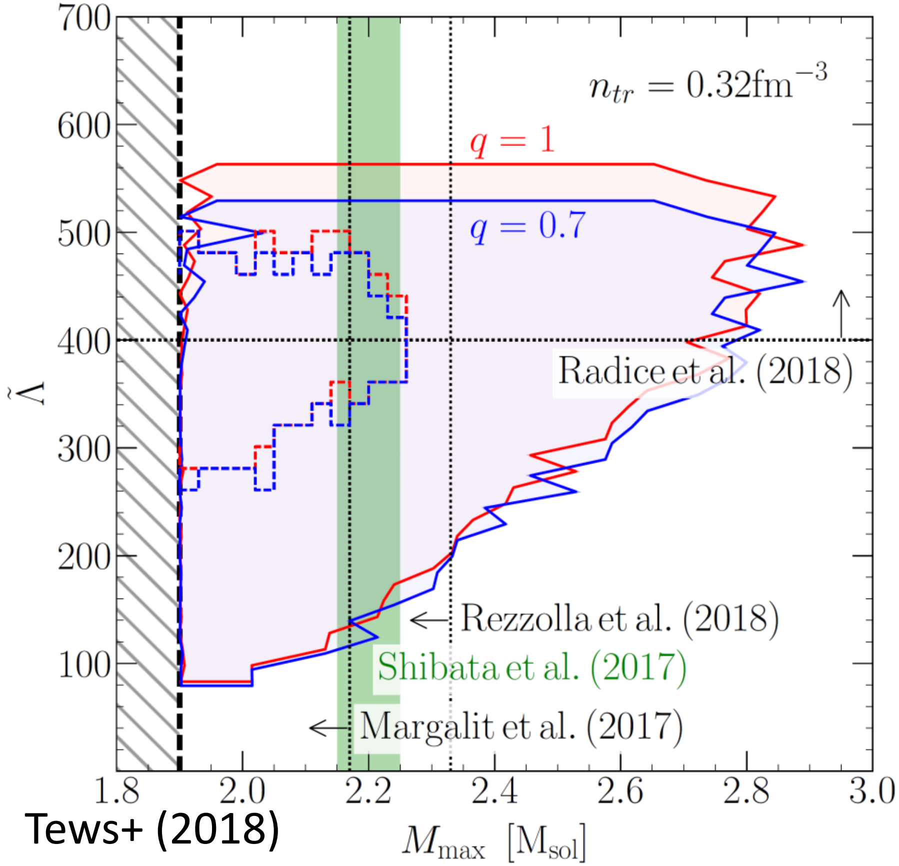


Kiuchi, KK+ (2019)

Reason?

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

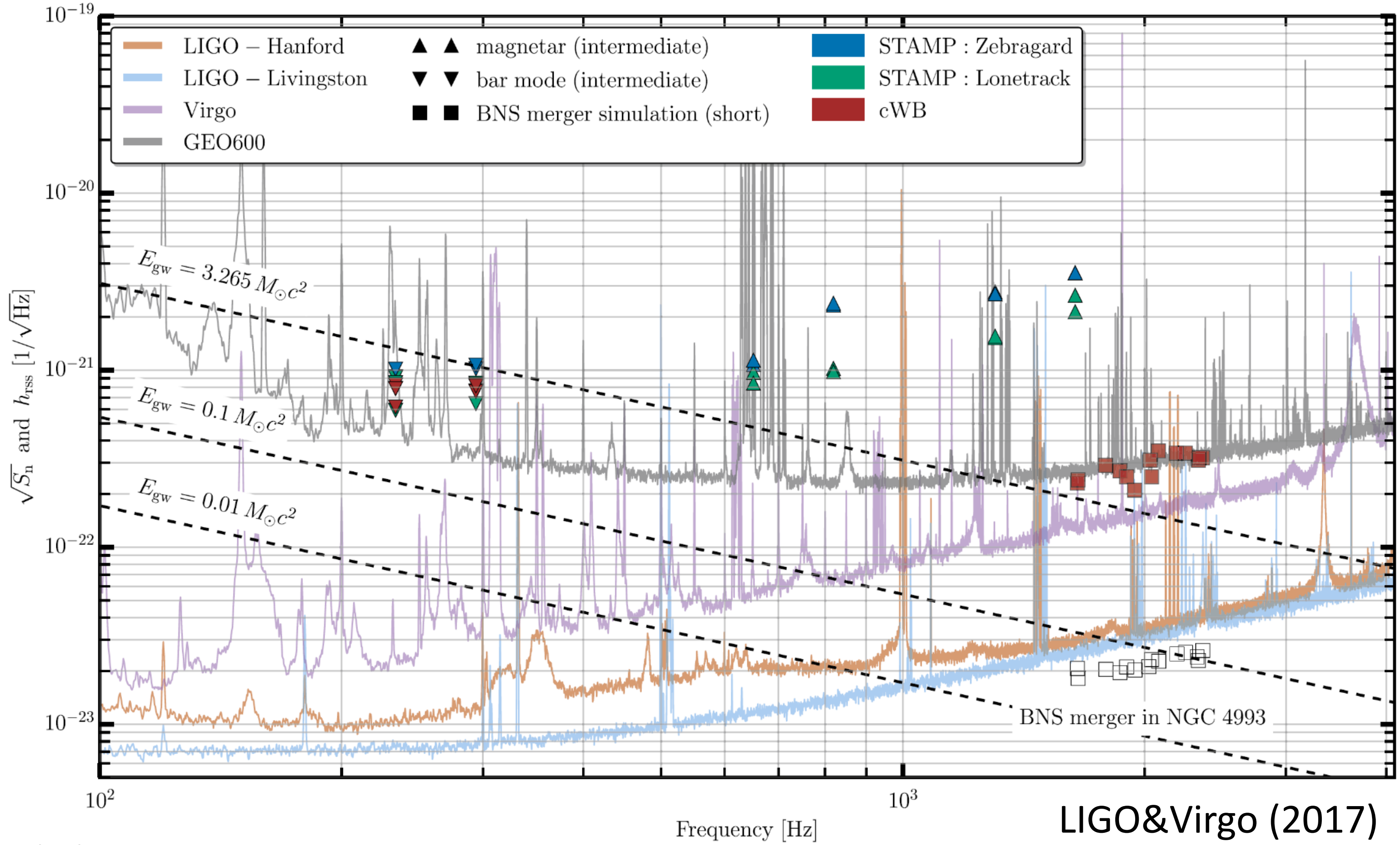
If the remnant survived moderately long due to the large value of M_{max}, there should be no reason that mass ejection is weak



Tews+ (2018)

Nondetection for GW170817

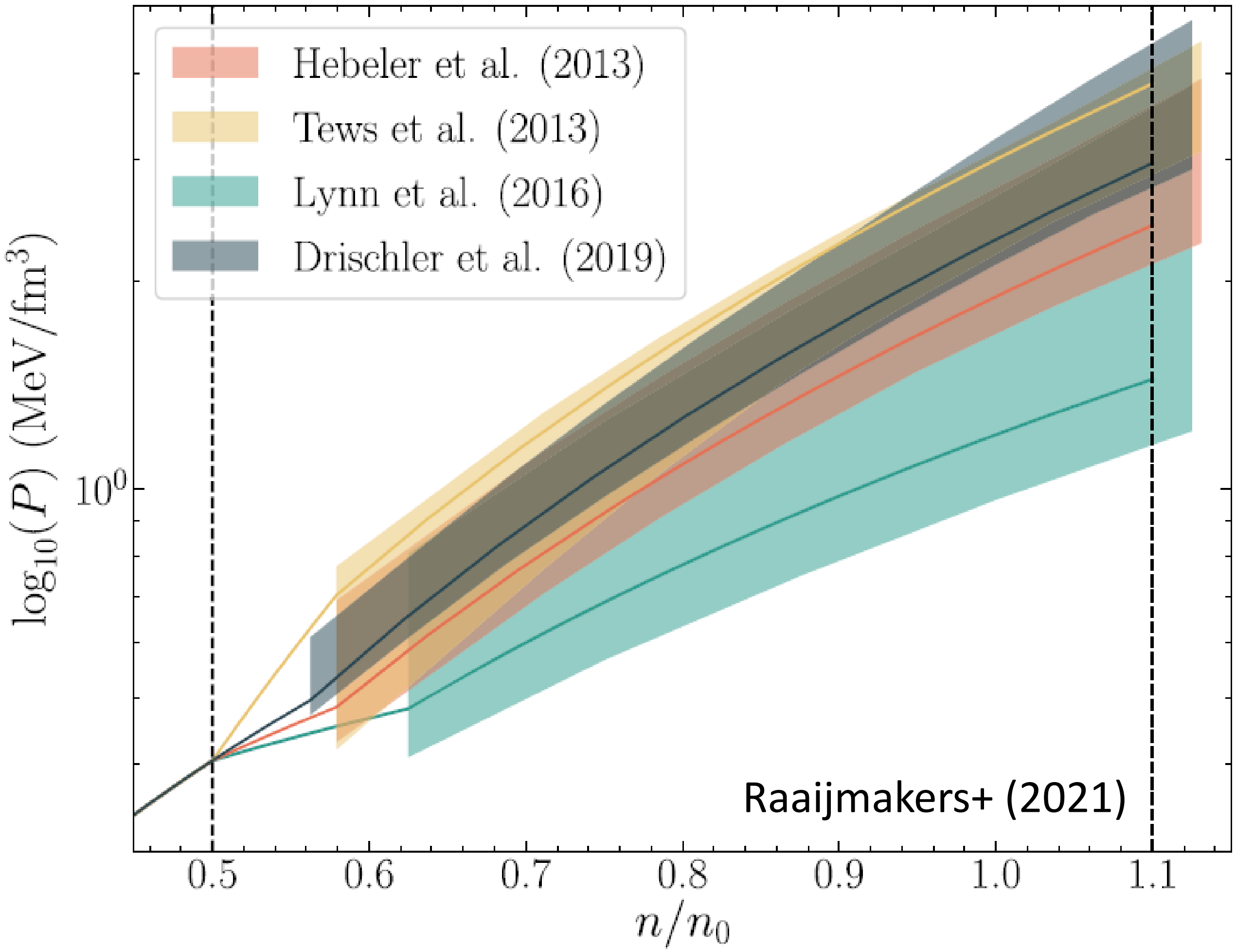
Simply, sensitivity at high frequency is insufficient



LIGO&Virgo (2017)

Uncertainty in chiral EFT

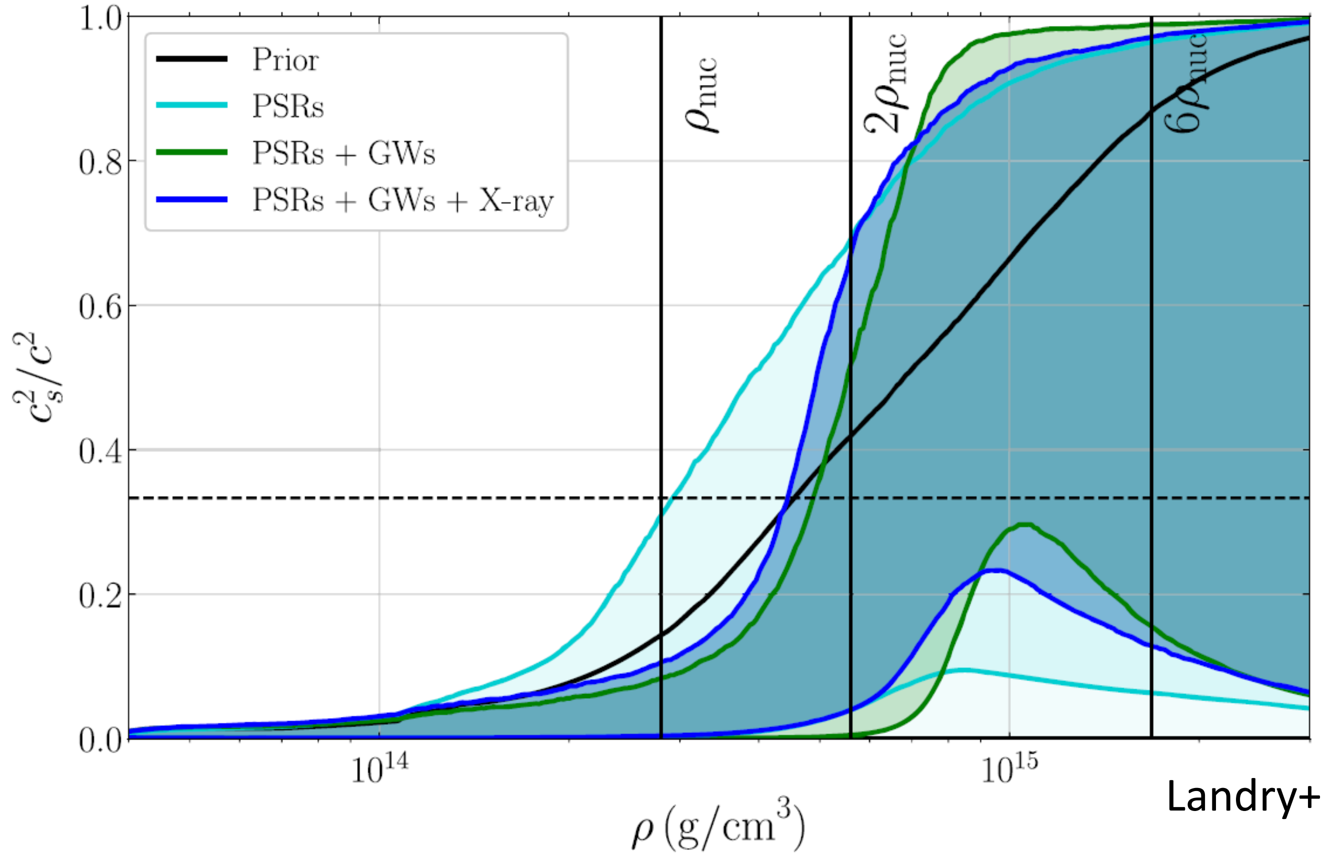
The validity range is crucial for strength of constraints



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



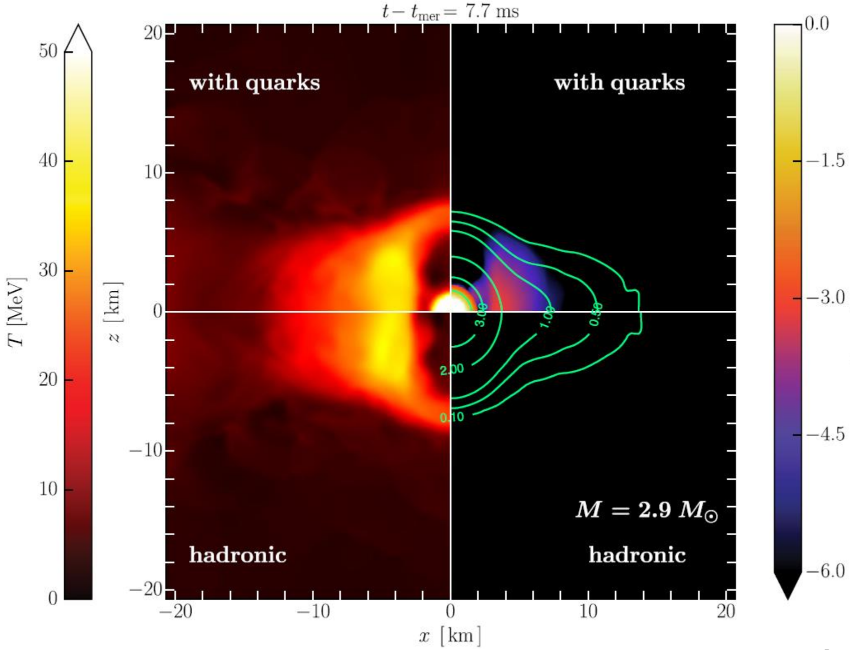
Landry+ (2020)

Structure of the merger remnant

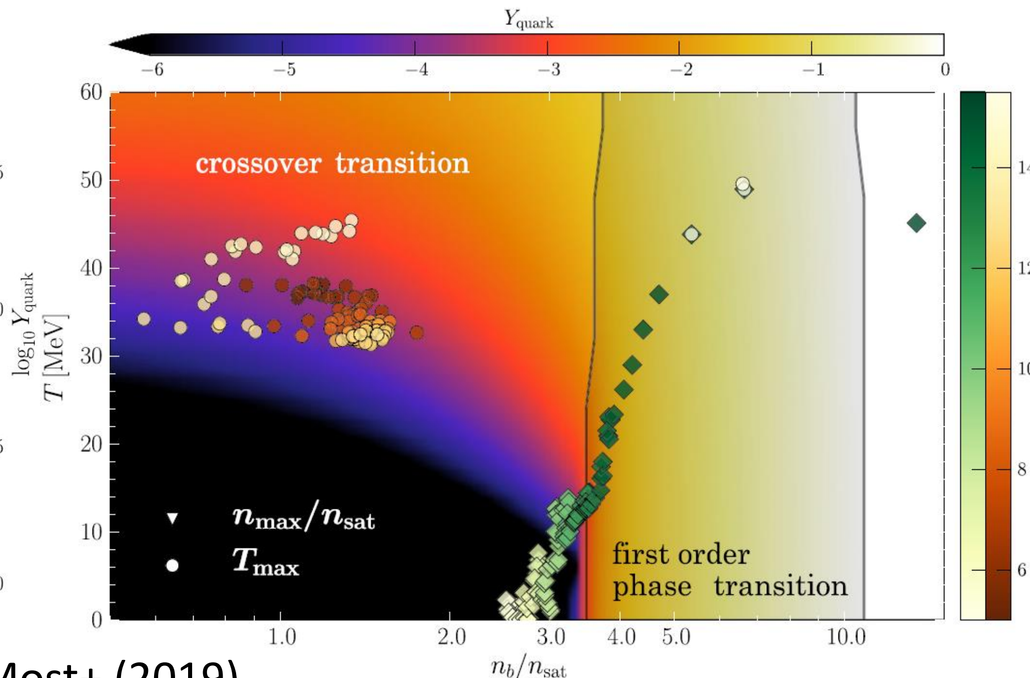
Density/temperature structures are not very different

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

Top: w/ quark, bottom: hadron only



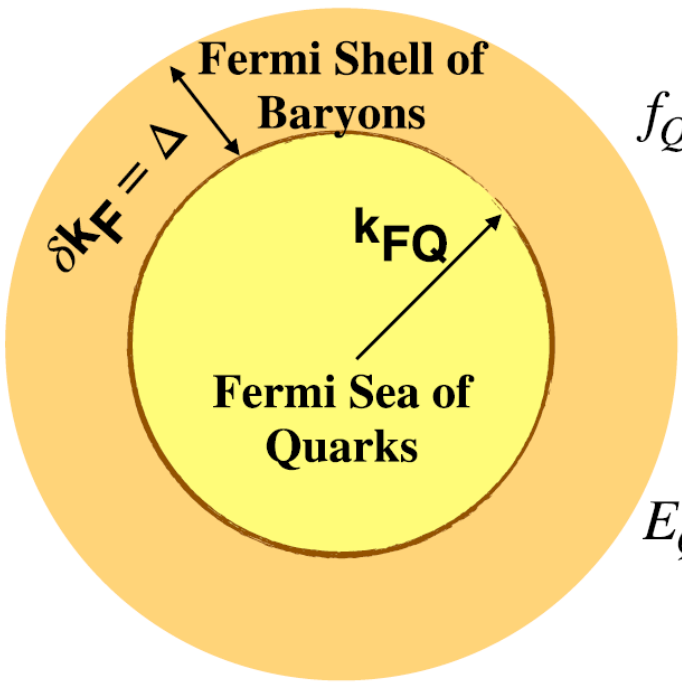
Time evolution of maximum n and T



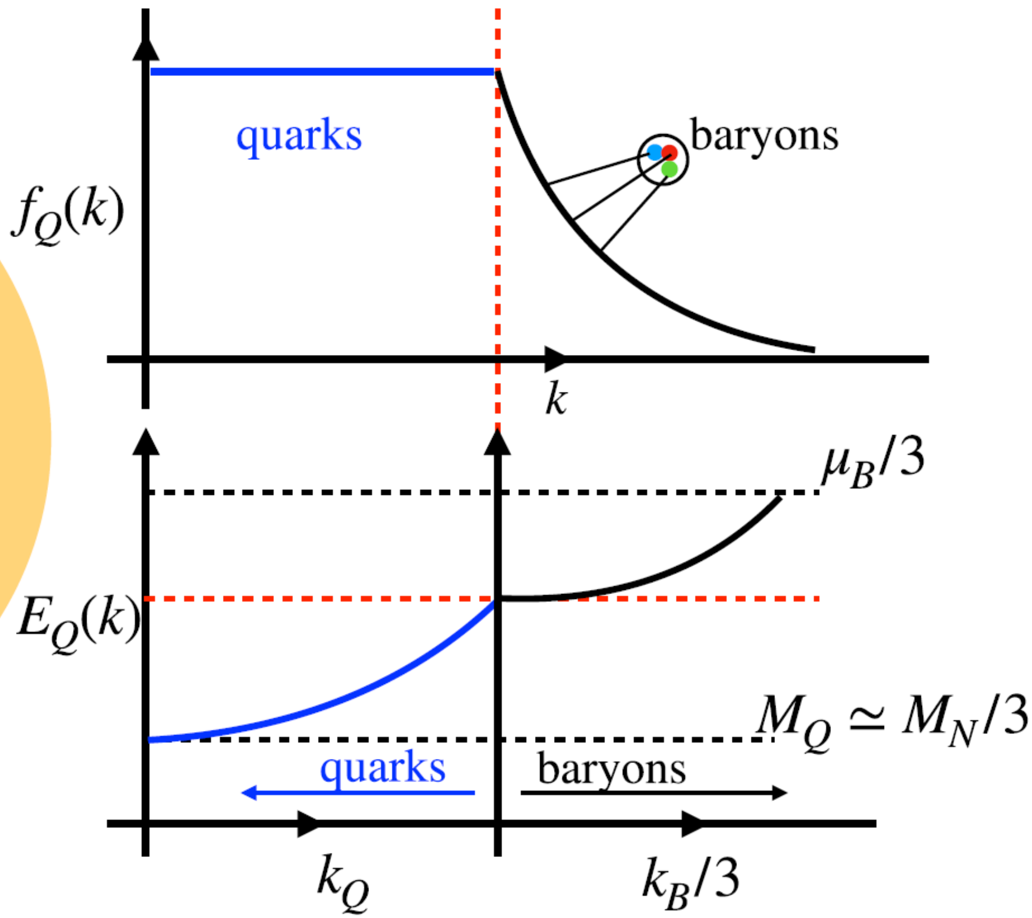
Most+ (2019)

Quarkyonic matter

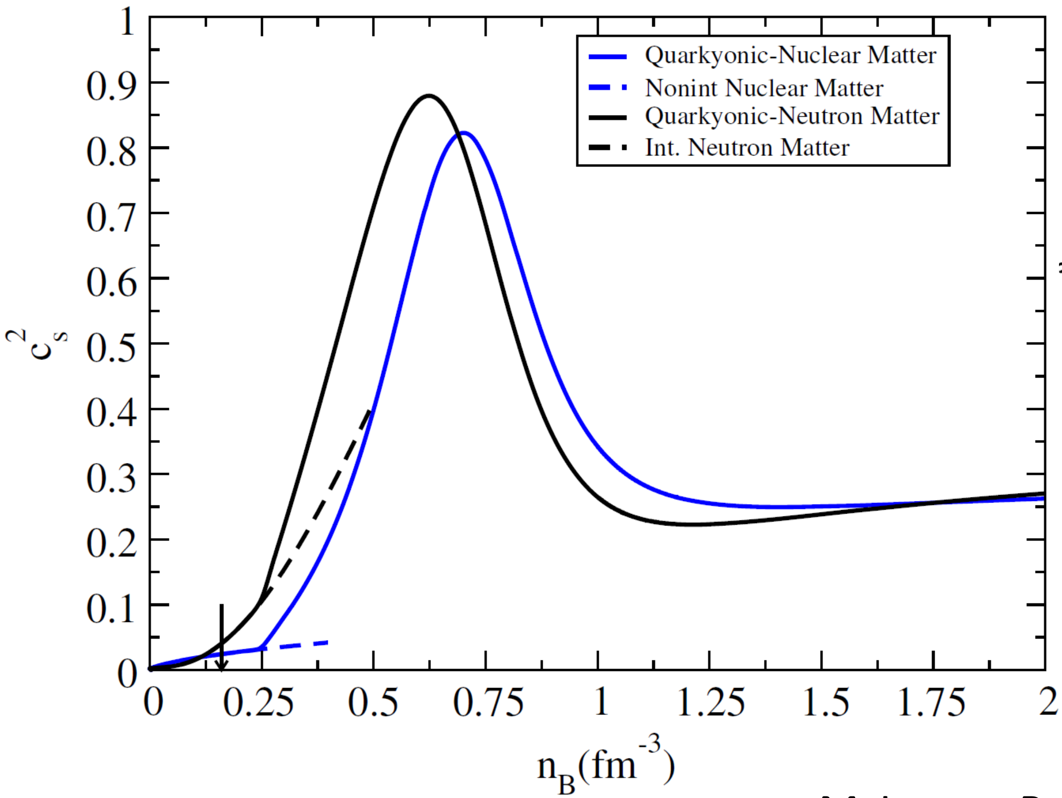
Baryons emerges near the Fermi surface of quarks

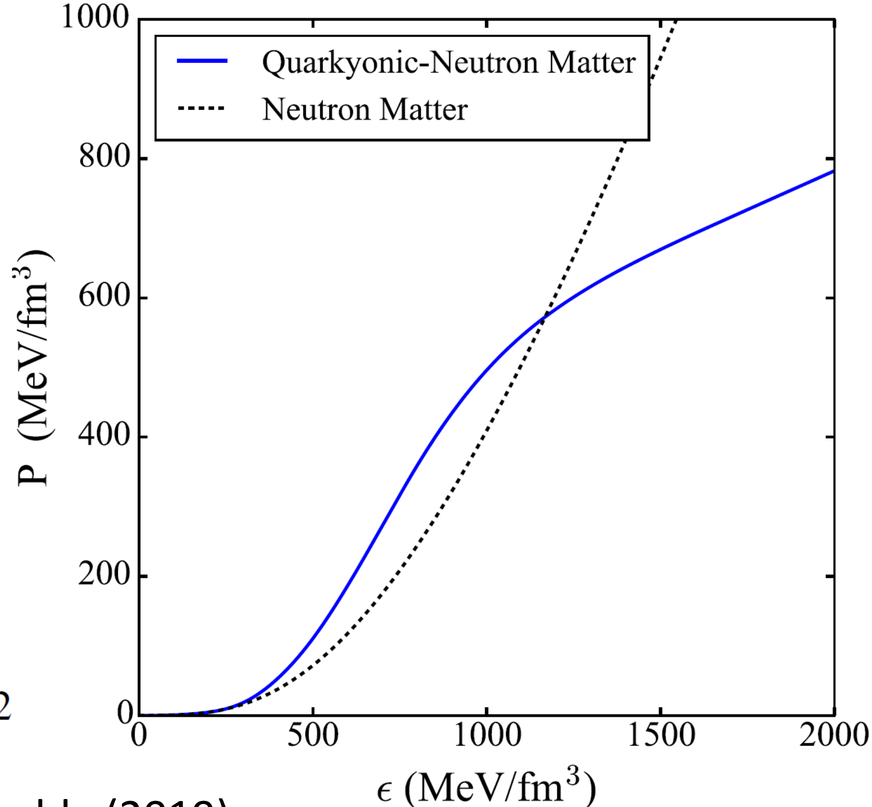


McLerran-Reddy (2019)



Sound speed of quarkyonic matter



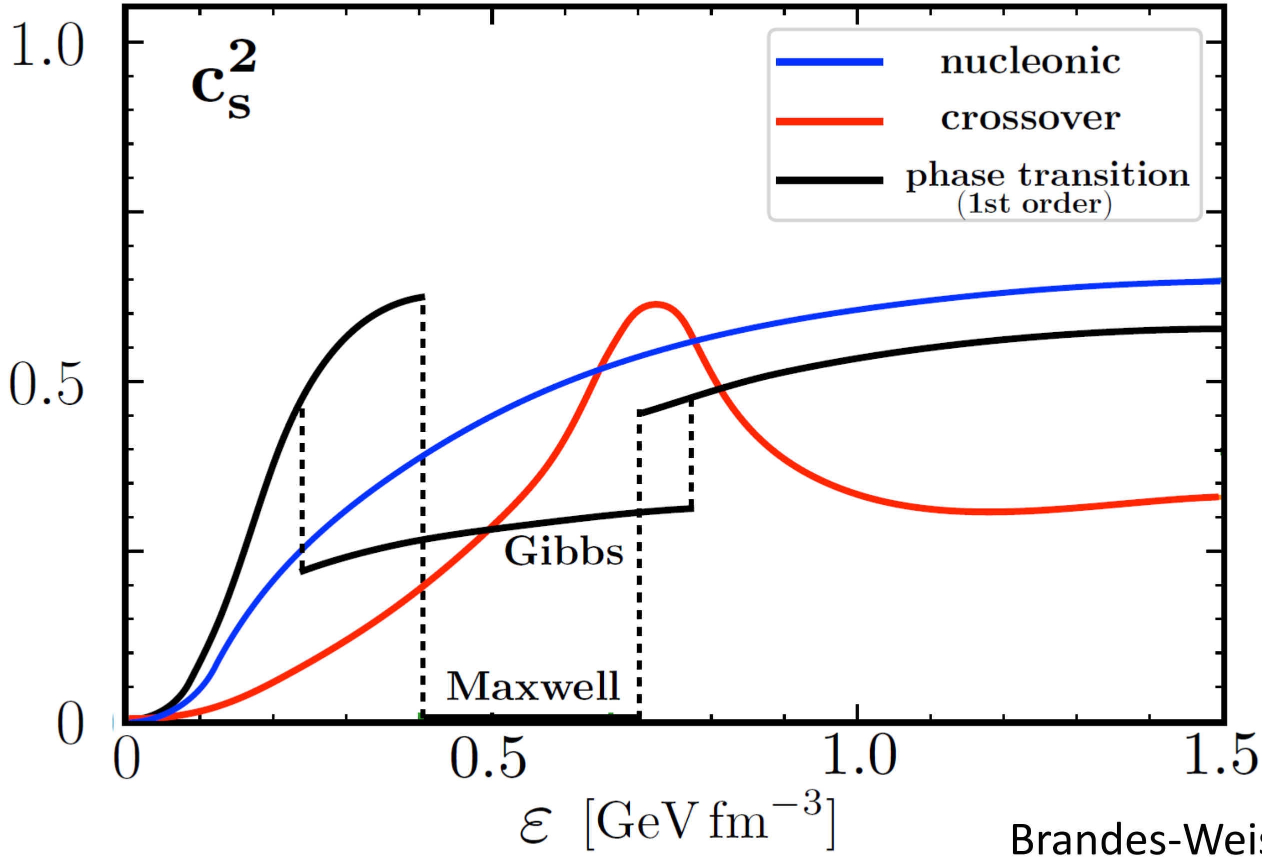


McLerran-Reddy (2019)

Sound speed in the crossover

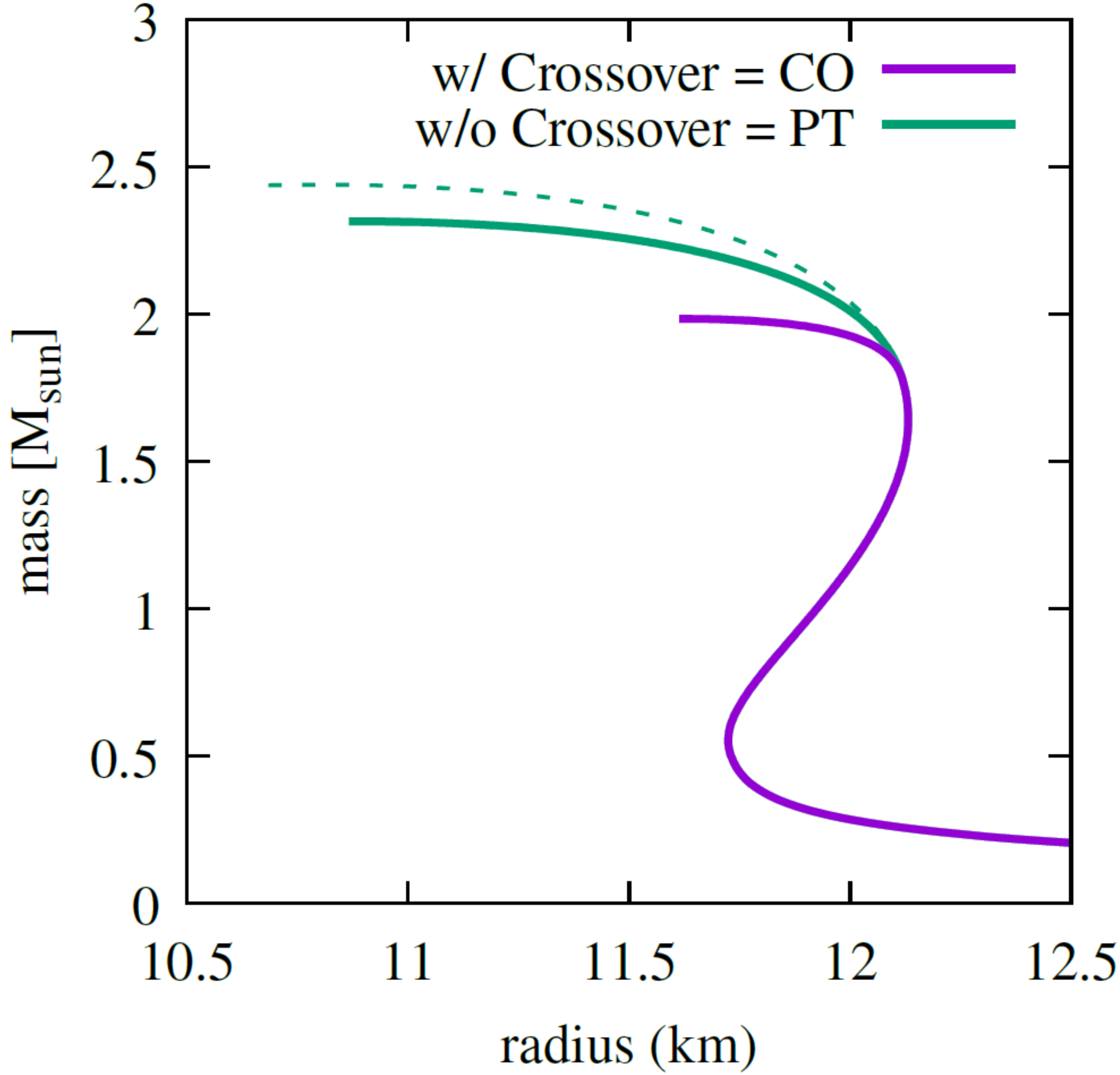
Crossover may induce a peak in the sound speed

Phase transition makes the sound speed very low



Brandes-Weise (2024)

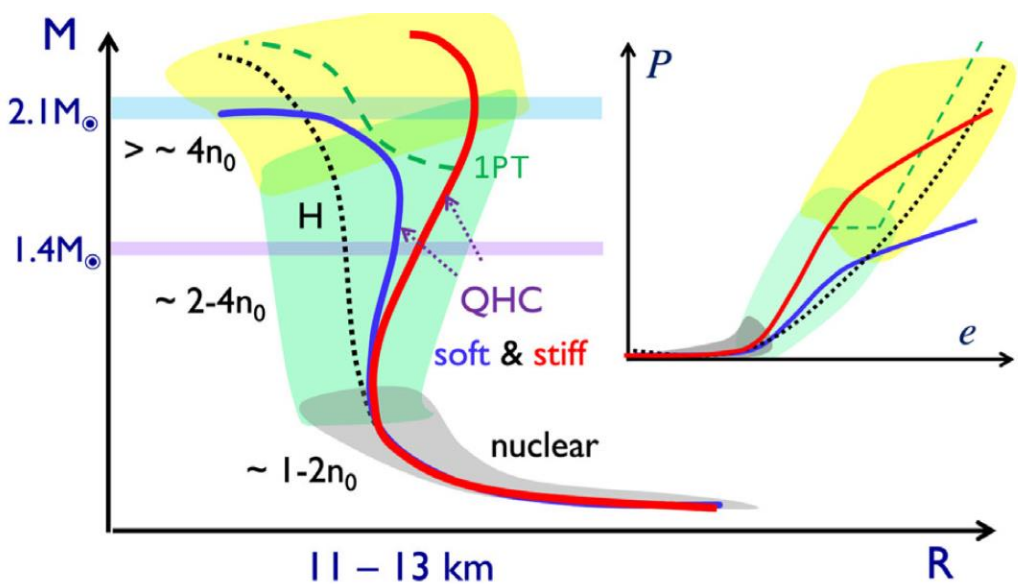
Mass-radius relation

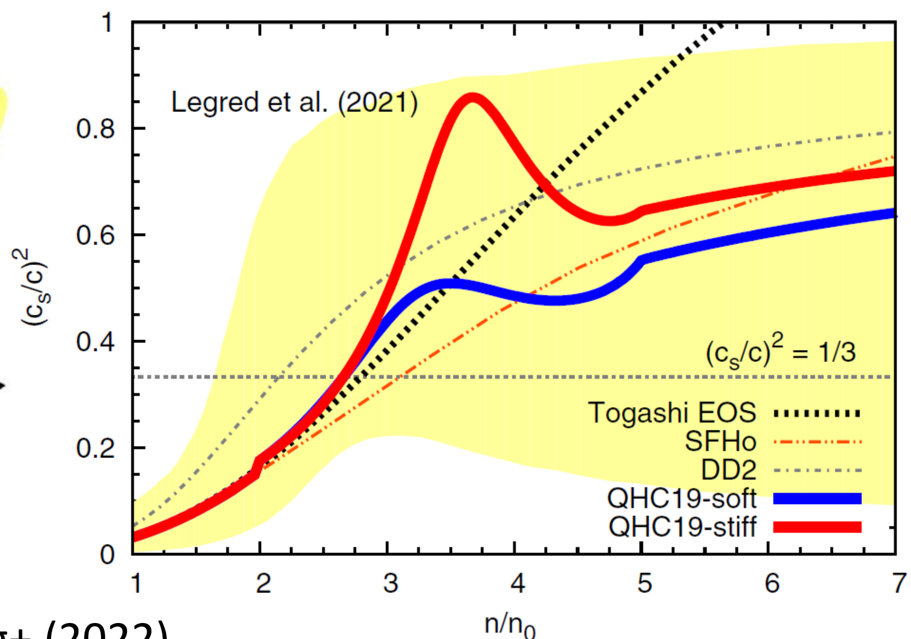


Relation to independent studies

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

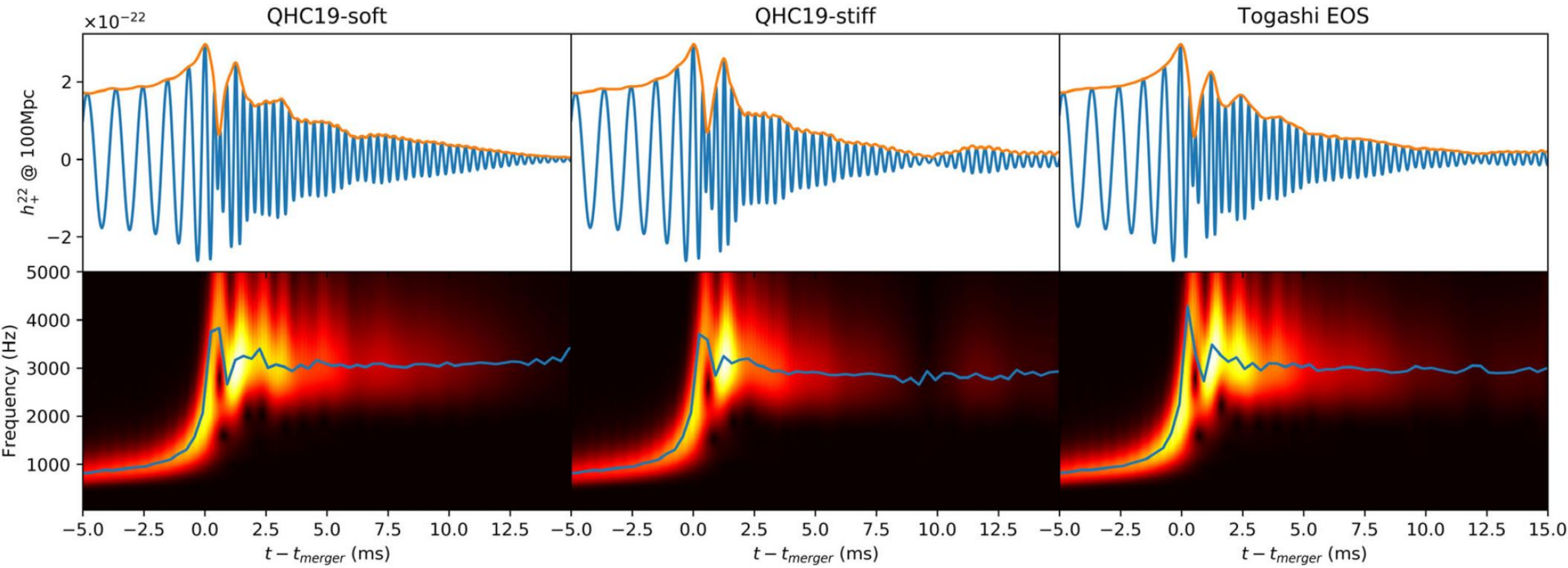




Huang+ (2022)

Results with QHC

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

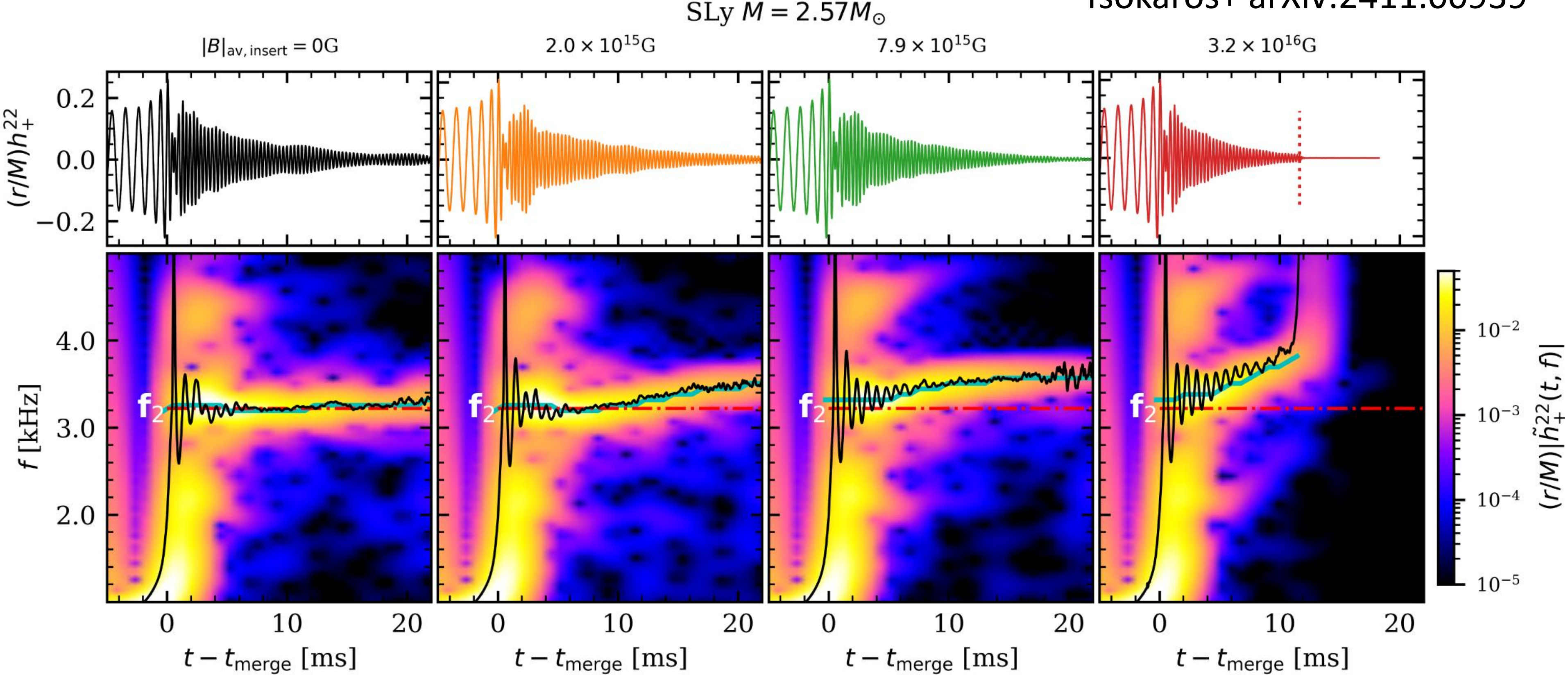


Huang+ (2022)

Magnetic-field and the peak

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

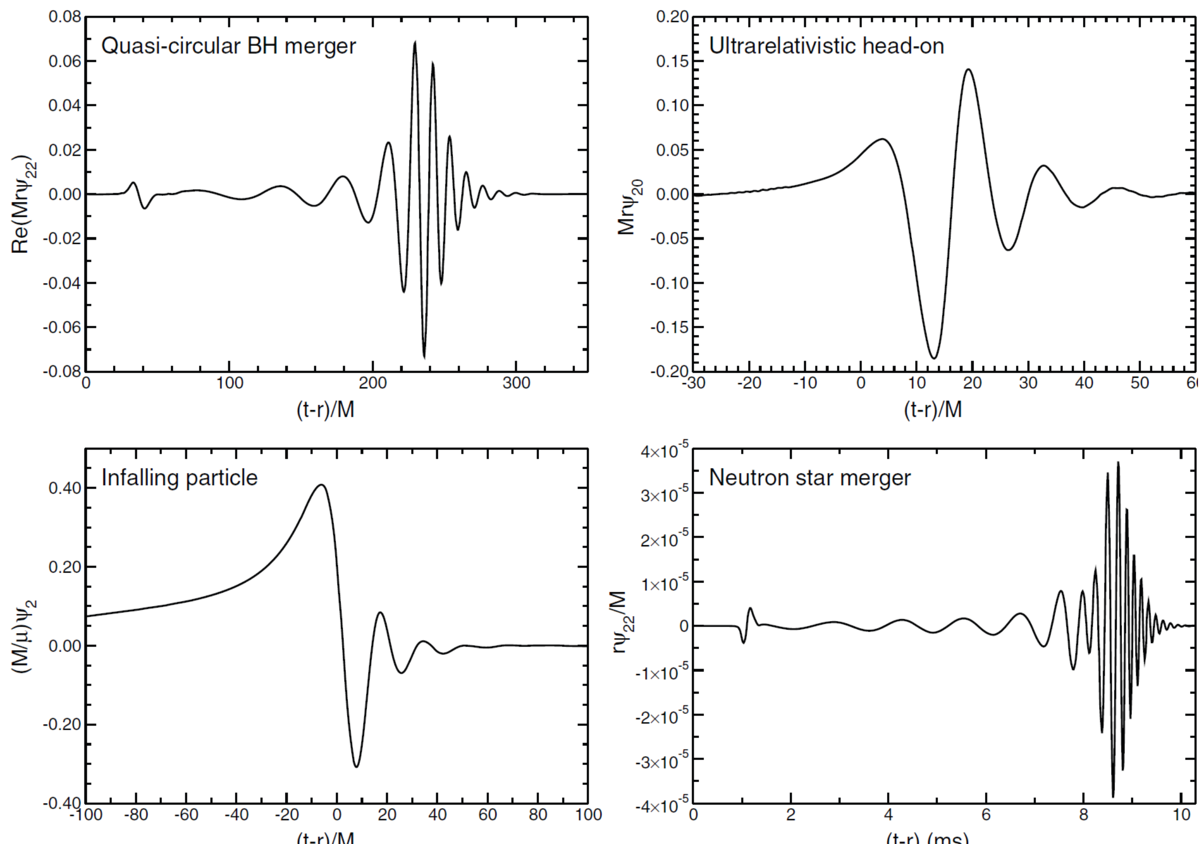
Tsokaros+ arXiv:2411.00939



Quasinormal modes of black holes

Damped oscillations governed by the mass and spin

Excited when they are formed in gravitational collapse



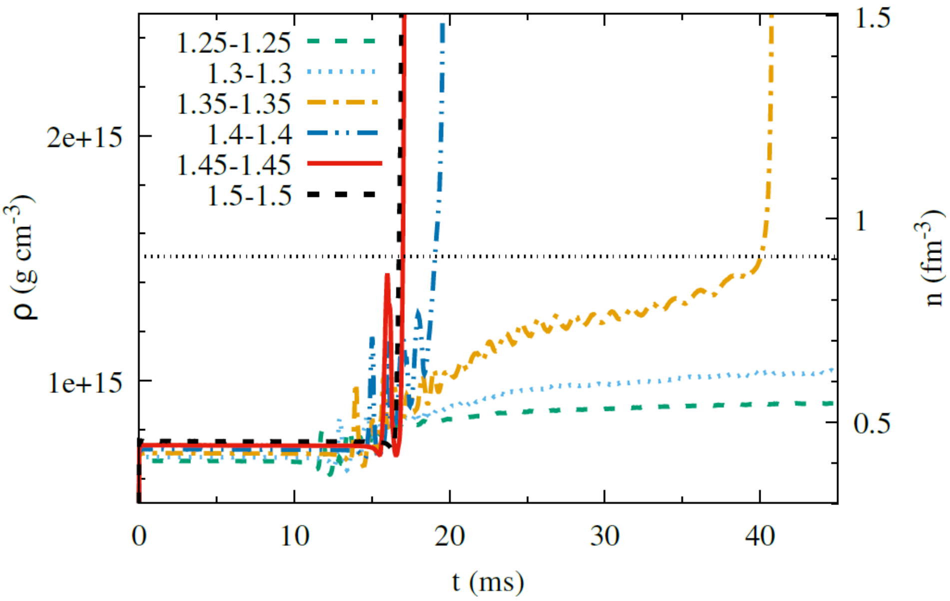
Berti+ (2009)

Which density range we can see?

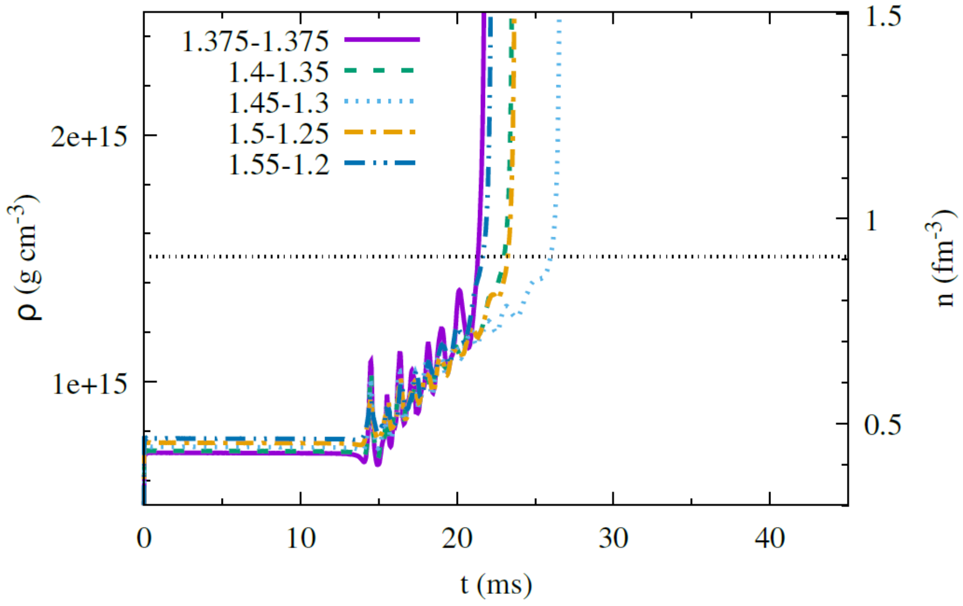
The collapse is likely to set in when the central density reaches the maximum density of spherical stars

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

Various total masses



Various mass ratios

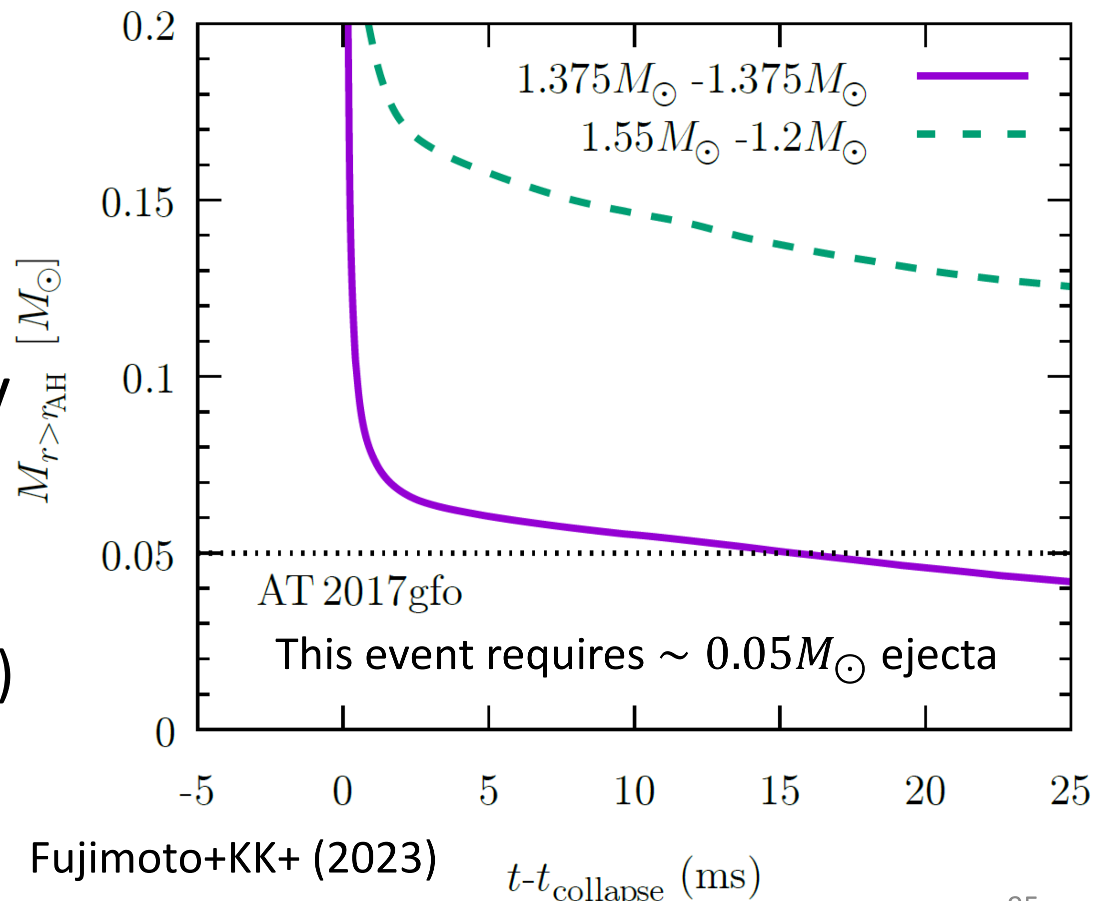


Multimessenger observation

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)

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