Neutron stars and multimessenger physics

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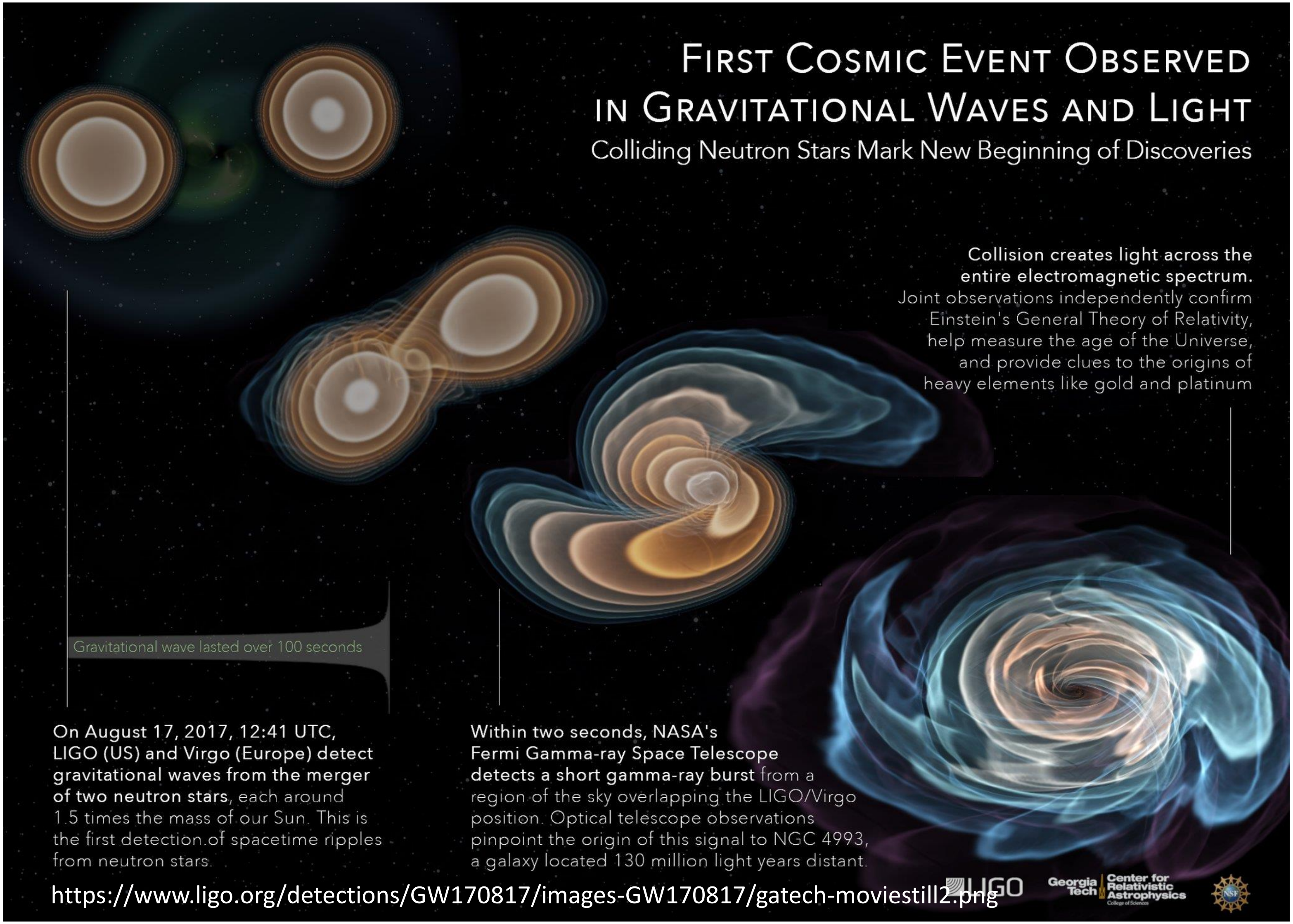
4. GW170817

Multimessenger event: GW170817



FIRST COSMIC EVENT OBSERVED IN GRAVITATIONAL WAVES AND LIGHT

Colliding Neutron Stars Mark New Beginning of Discoveries

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

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

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

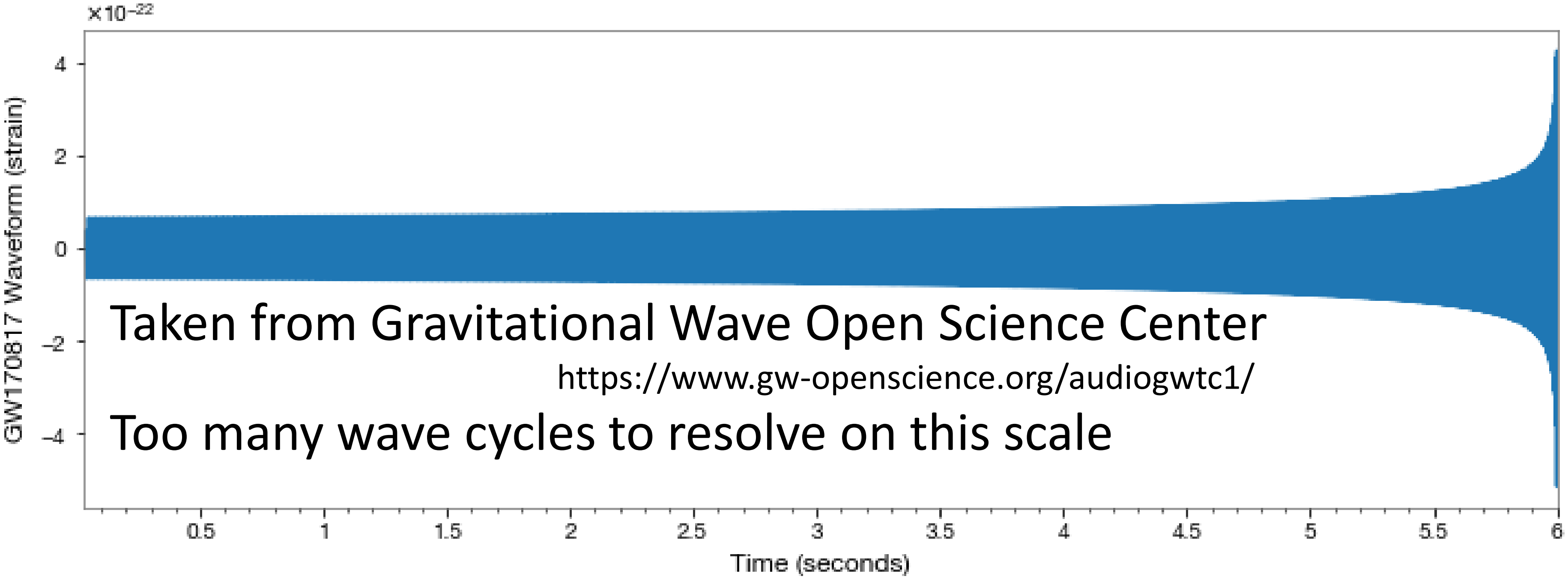
https://www.ligo.org/detections/GW170817/images-GW170817/gatech-moviestill2.png

GW170817

The longest signal ever (longer than 100 second)

Detected by LIGO Hanford/Livingston detectors

Virgo did not detect, but informative for localization

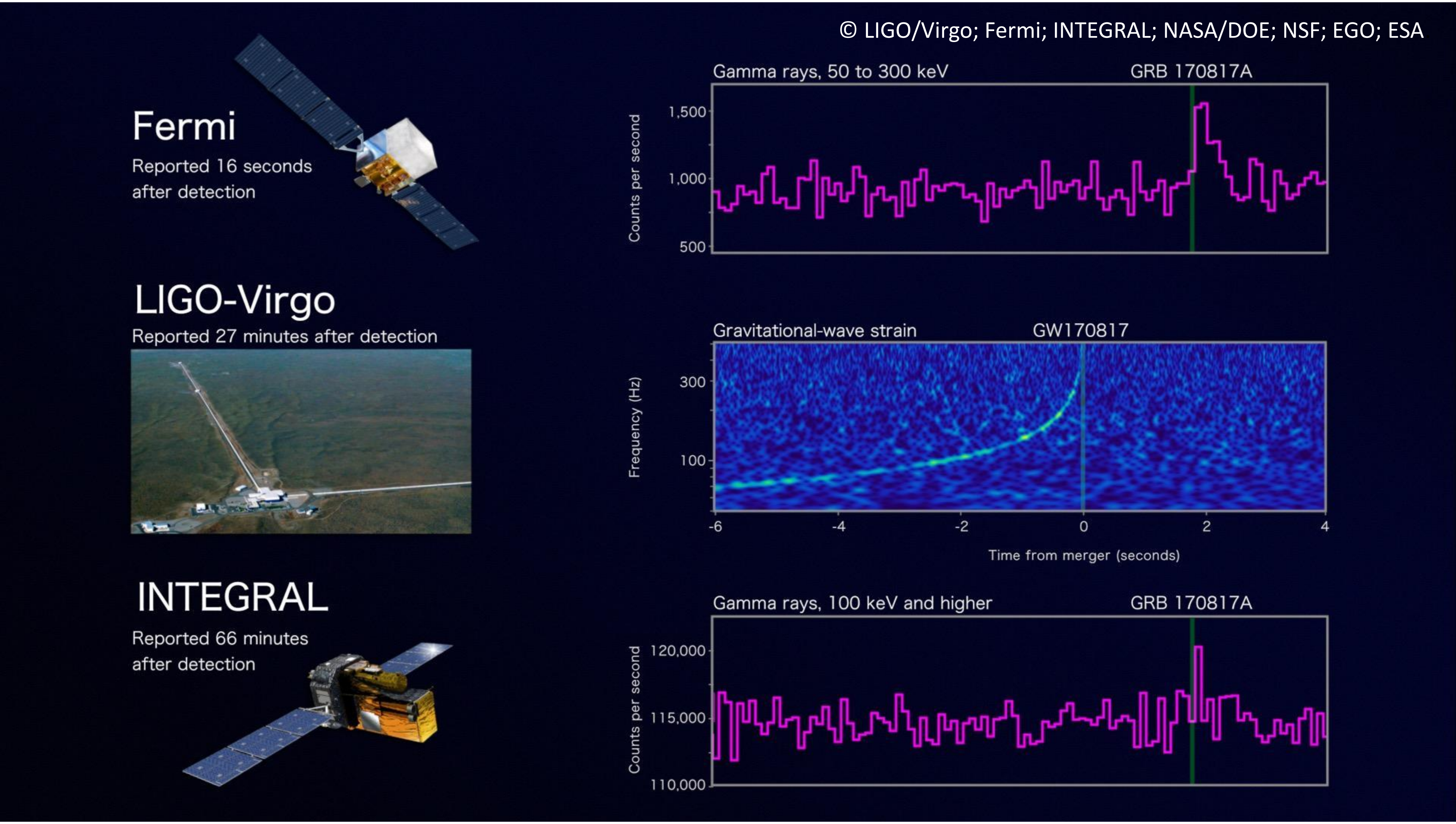


Taken from Gravitational Wave Open Science Center

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

Too many wave cycles to resolve on this scale

Gamma rays after 1.7s



© LIGO/Virgo; Fermi; INTEGRAL; NASA/DOE; NSF; EGO; ESA

Fermi

Reported 16 seconds after detection

LIGO-Virgo

Reported 27 minutes after detection

INTEGRAL

Reported 66 minutes after detection

Short gamma-ray burst

About 10^{51}erg/s explosions

- the sun is $\sim 4 \times 10^{33}$erg/s

Long-soft GRB: $\geq$ 2s

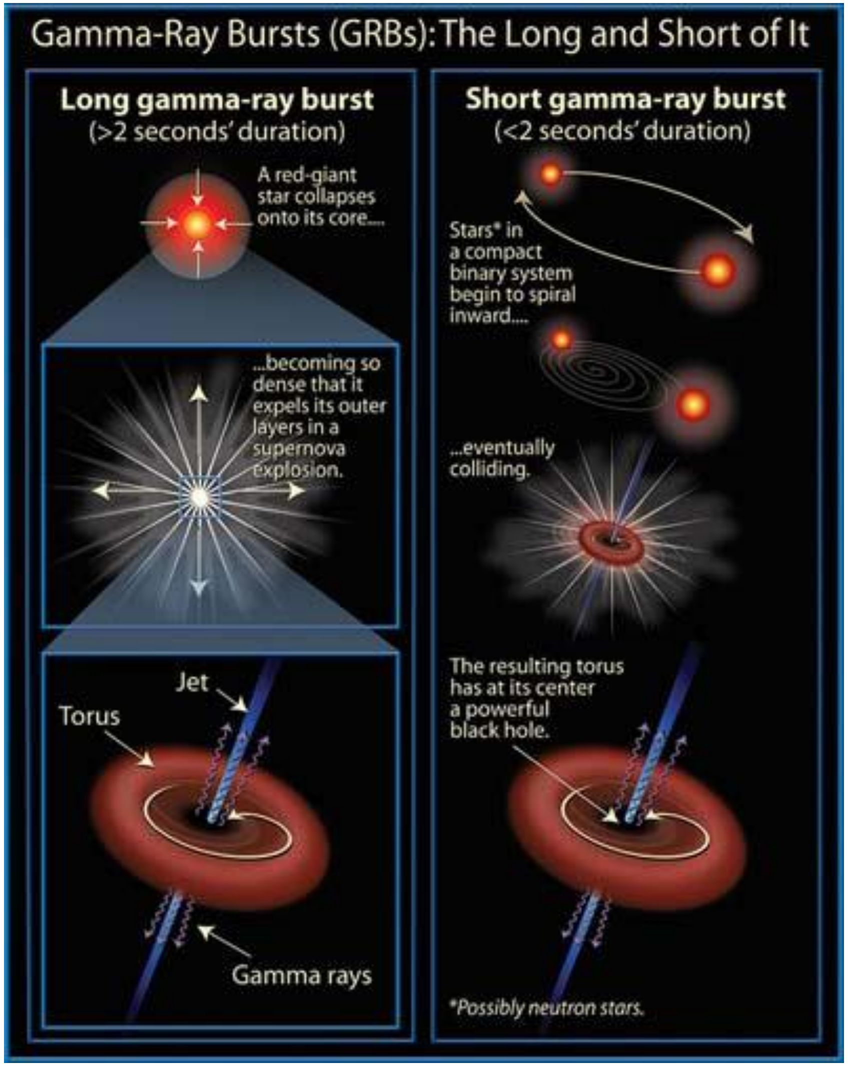
deaths of massive stars

Short-hard: $\leq$ 2s

neutron star binary merger?

rigorous confirmation needs

gravitational waves



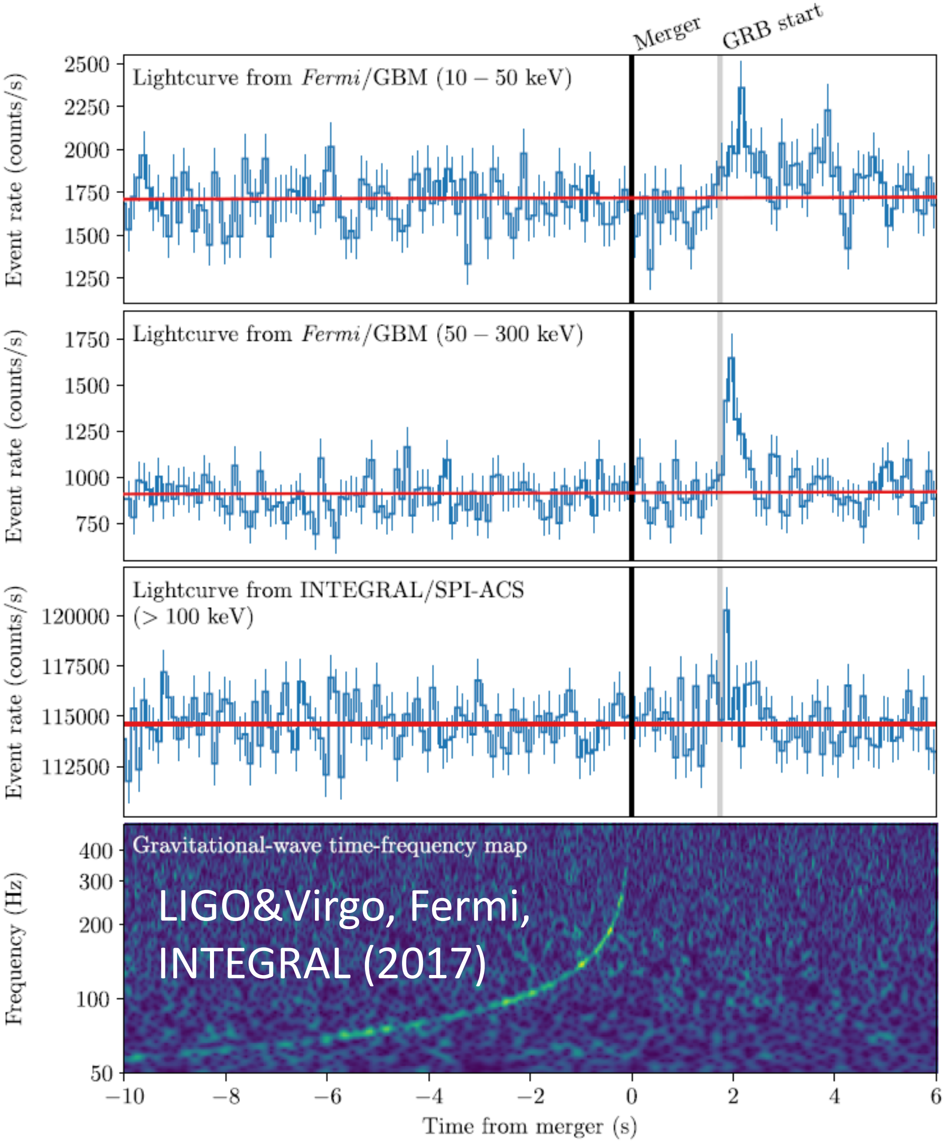
http://www.daviddarling.info/images/gamma-ray_bursts.jpg

GRB 170817A

Fermi and INTEGRAL agree each other though relatively weak

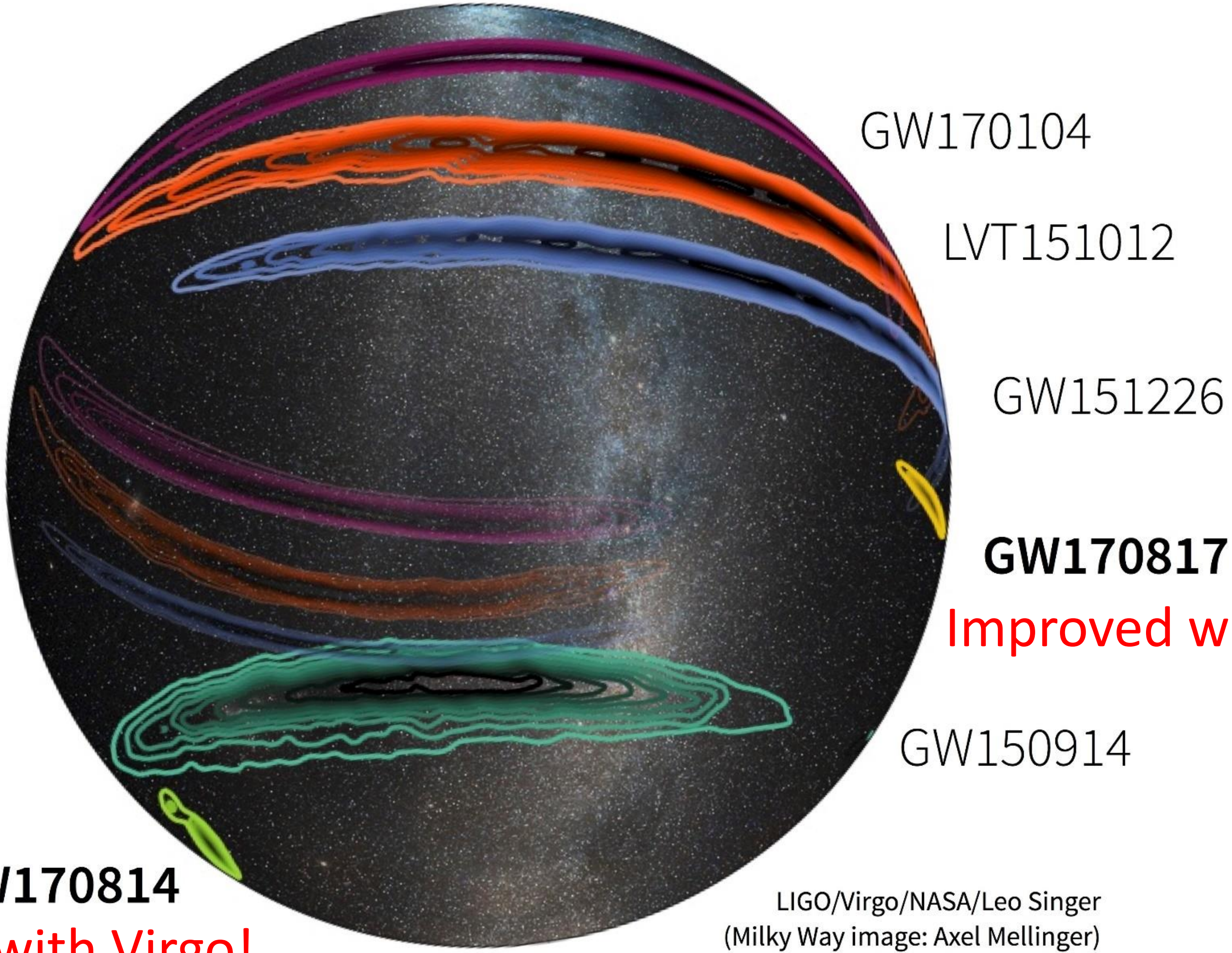
The 1.7s delay from GWs

- jet launch
- jet propagation in the ejected material
- onset of transparency



LIGO&Virgo, Fermi, INTEGRAL (2017)

Sky map and localization accuracy



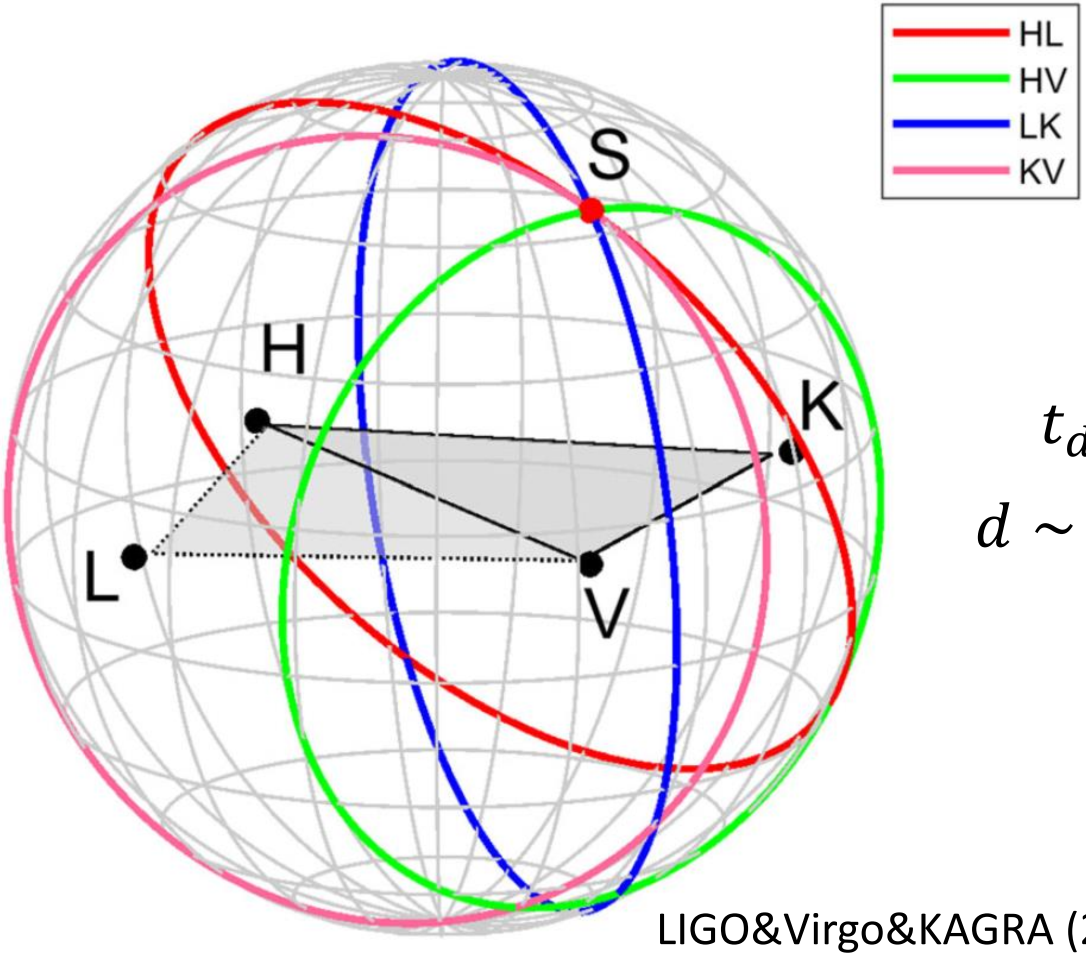
GW170817
Improved with Virgo!

GW170814
Improved with Virgo!

LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)
http://www.ligo.org/detections/GW170817/images-GW170817/O1-O2-skymaps-white.jpg

Triangulation by detectors

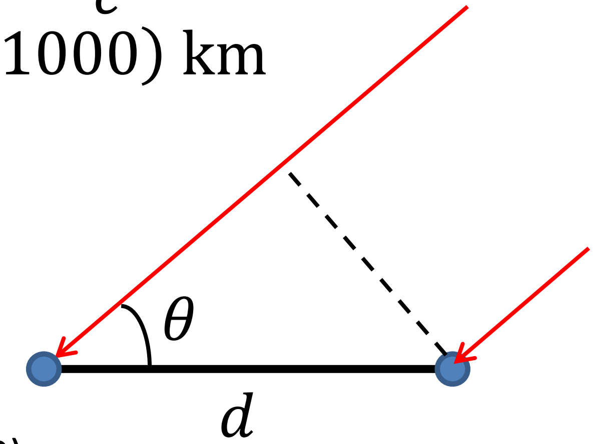
Sky position is determined via the timing difference



Multiple detectors
are indispensable

$$t_d = \frac{d \cos\theta}{c}$$

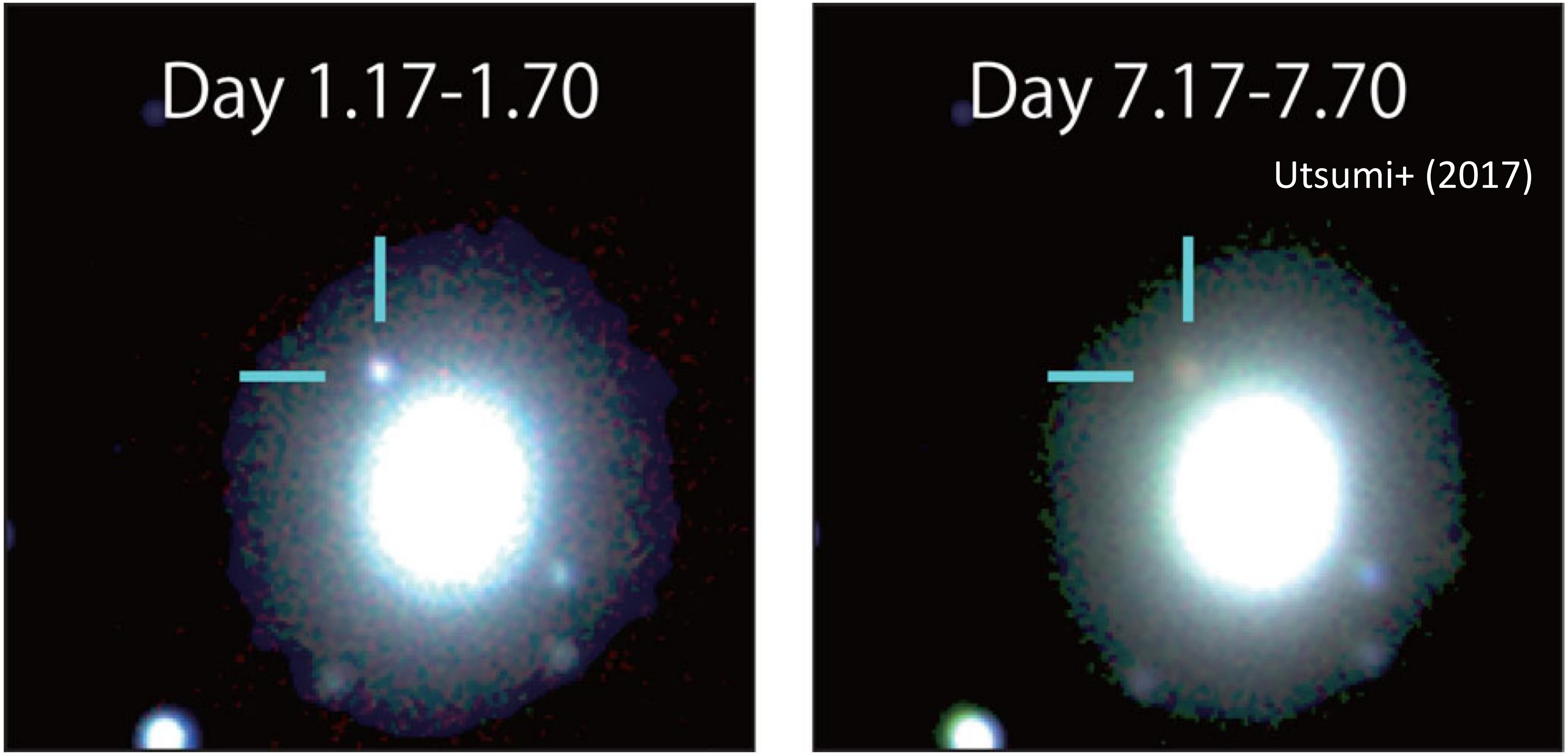
$$d \sim O(1000)\ \mathrm{km}$$



LIGO&Virgo&KAGRA (2020)

Transient and host galaxy

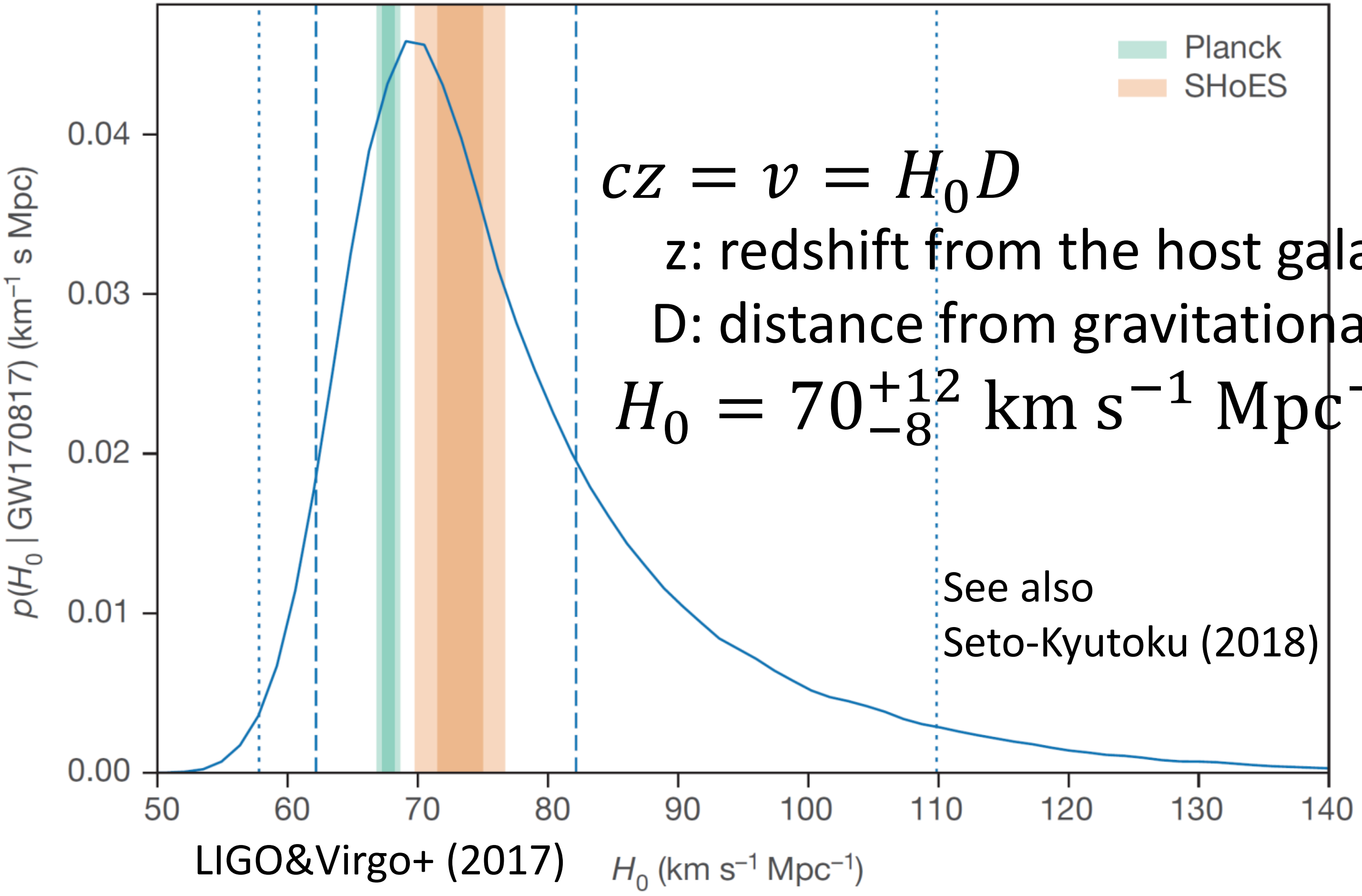
The event is pinpointed by optical telescopes



Utsumi+ (2017)

Gravitational-wave cosmology

Hubble's constant is determined in a novel manner



CMB

Supernova

$$cz = v = H_0 D$$

z: redshift from the host galaxy

D: distance from gravitational waves

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

See also

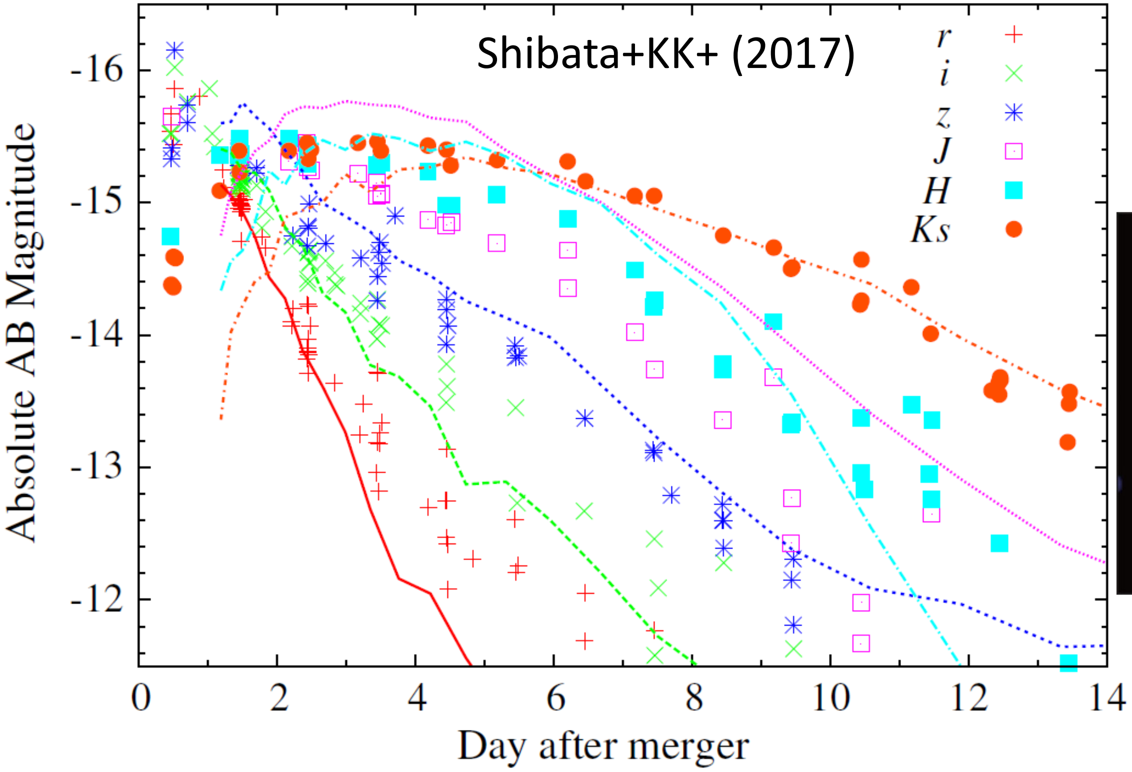
Seto-Kyutoku (2018)

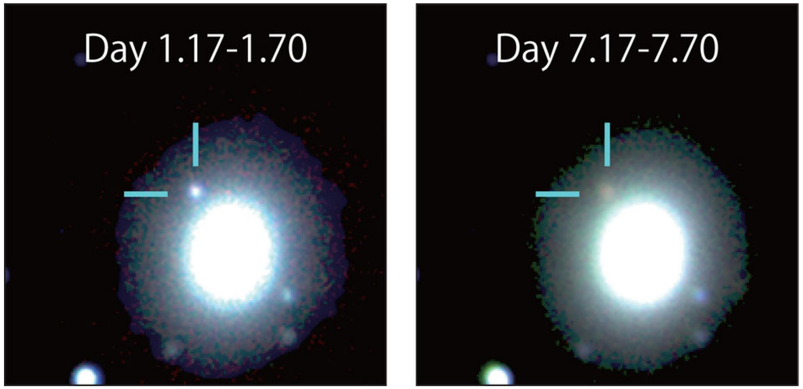
LIGO&Virgo+ (2017)

AT 2017gfo

Largely consistent w/ theoretical prediction

In particular, ~10day time scales in infrared bands: unique to kilonovae





Utsumi+ (2017)

Kilonova/macronova characteristics

For spherical ejecta (Li-Paczynski 1998, also Arnett 1982)

The peak luminosity: $L_{\text{peak}} \propto f\kappa^{-1/2}M^{1/2}v^{1/2}$

The peak time : $t_{\text{peak}} \propto \kappa^{1/2}M^{1/2}v^{-1/2}$

Heating efficiency f and opacity κ – microphysics

particularly, r-process elements have high opacity

Ejecta mass M and ejecta velocity v – macrophysics

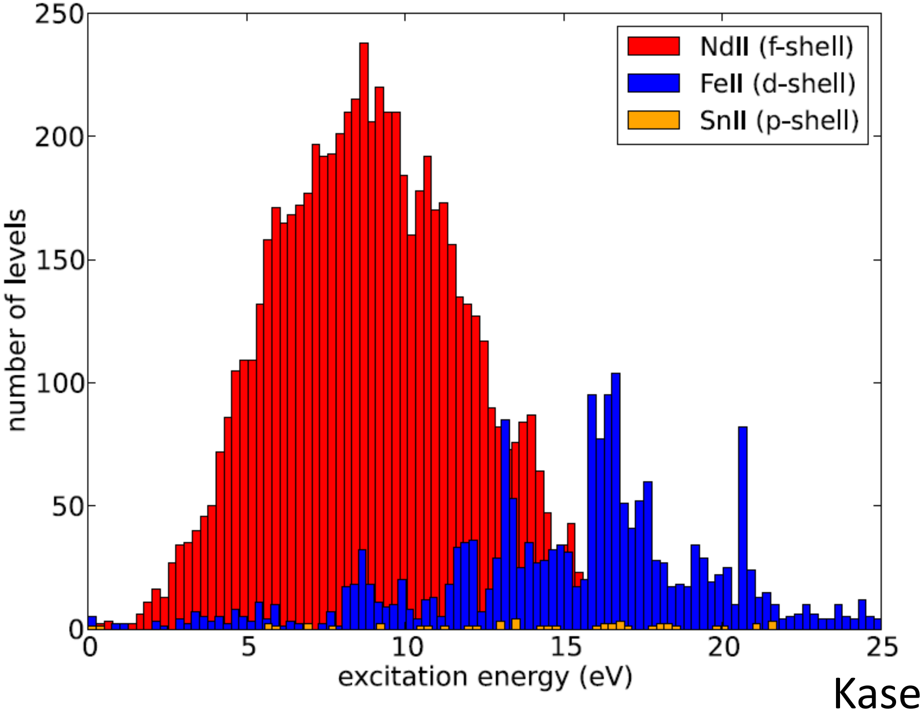
small mass and high velocity (vs supernovae)

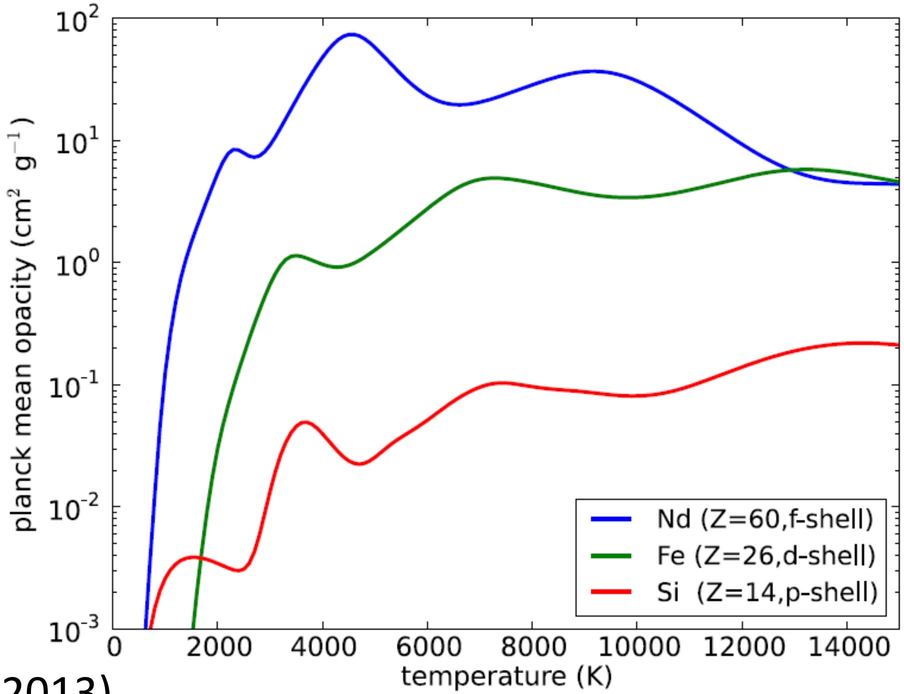
Too many lines of lanthanides

A bunch of energy levels -> complex line structures

-> very frequent interaction -> very high opacity

But modeling is incomplete (quantum many-body)



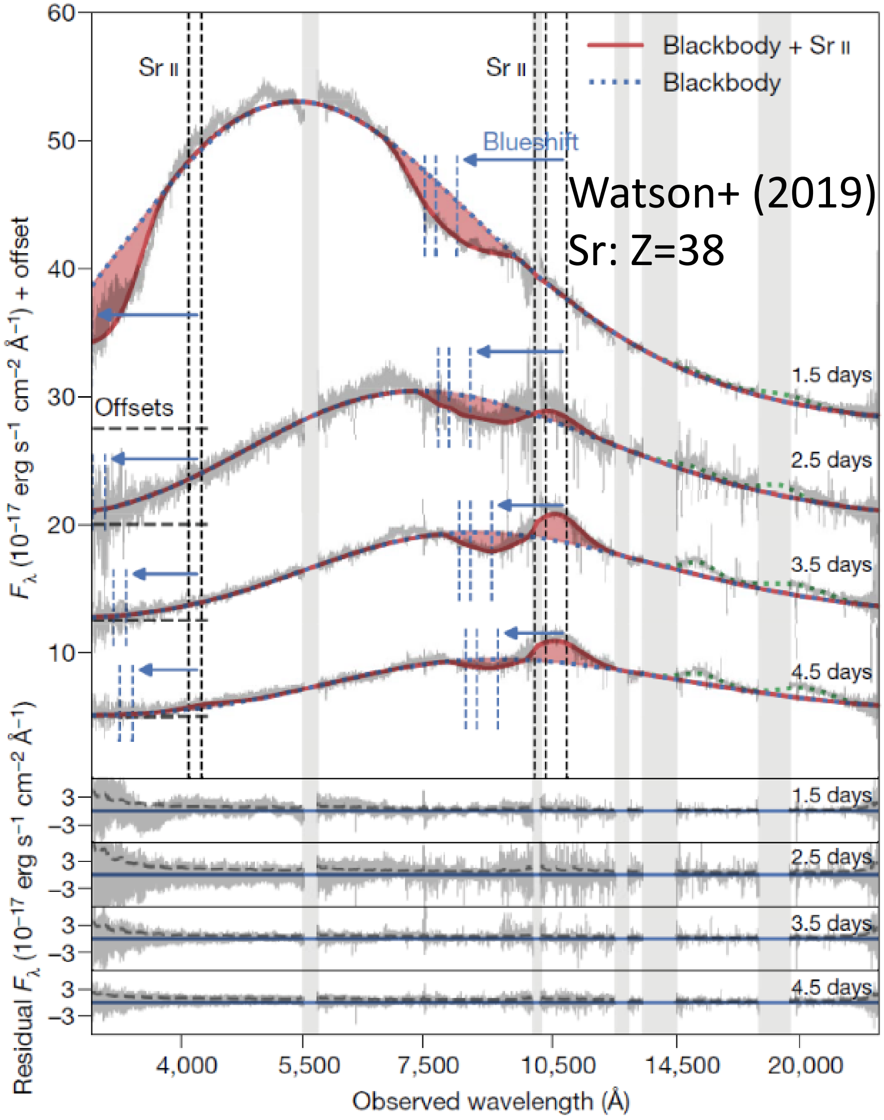


Kasen+ (2013)

Absorption line of strontium

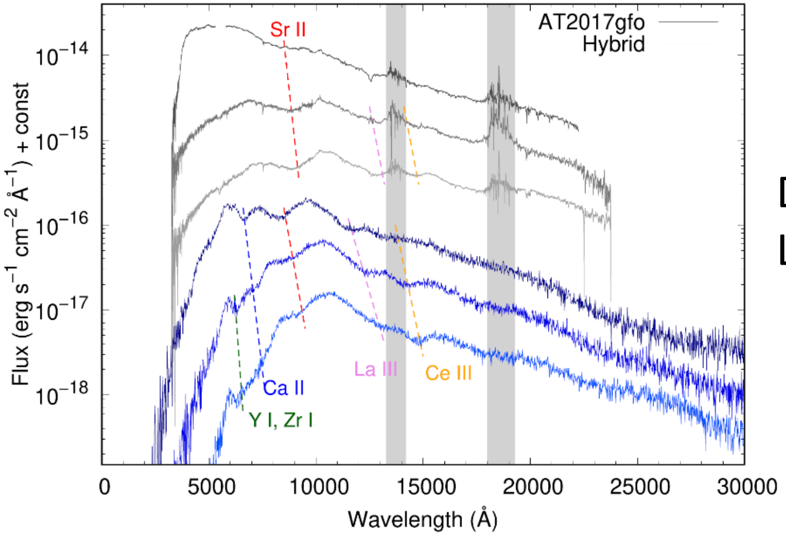
Identification of elements requires the spectrum and careful decomposition of absorption/emission lines

Although it is difficult for the kilonova because of fast motion/many elements, effort are ongoing



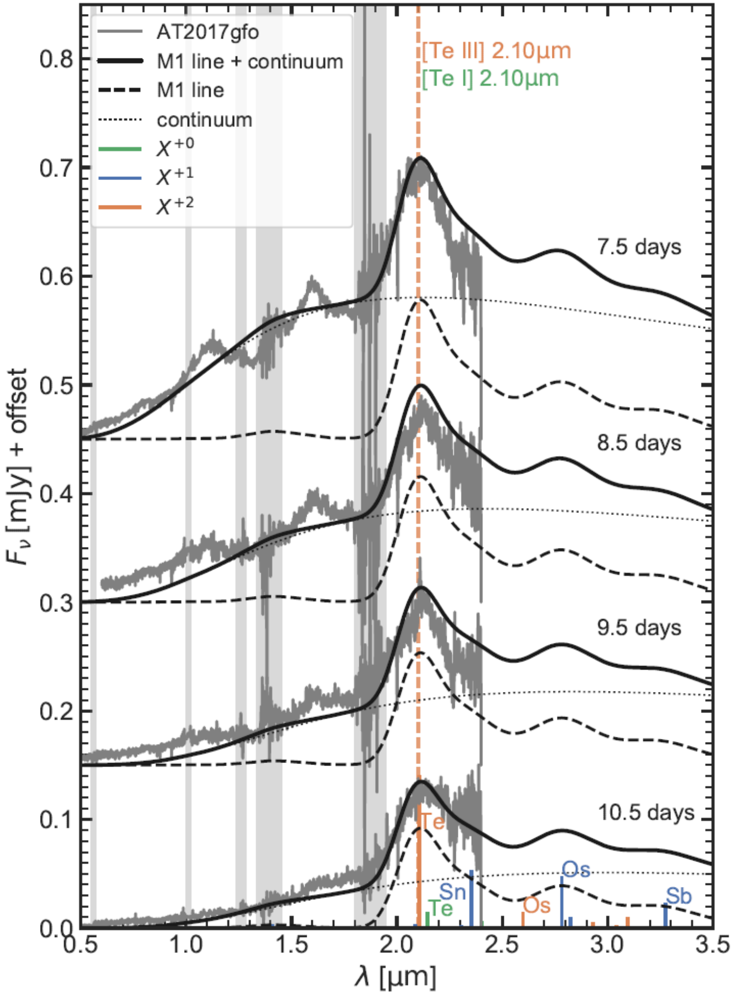
Watson+ (2019)
Sr: Z=38

And more heavy elements?

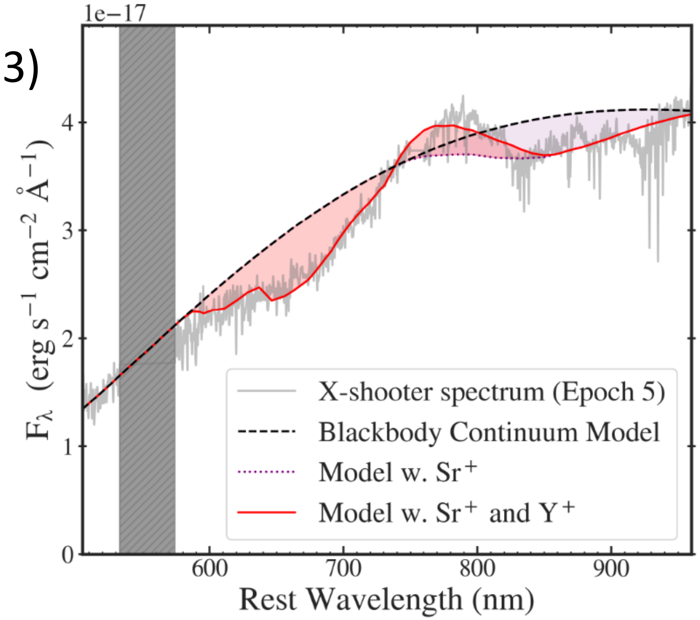


Domoto+ (2022)
La: Z=57, Ce: Z=58

Hotokezaka+ (2023), Te: Z=52



Sneppen-Watson (2023)
Sr: Z=38, Y: Z=39

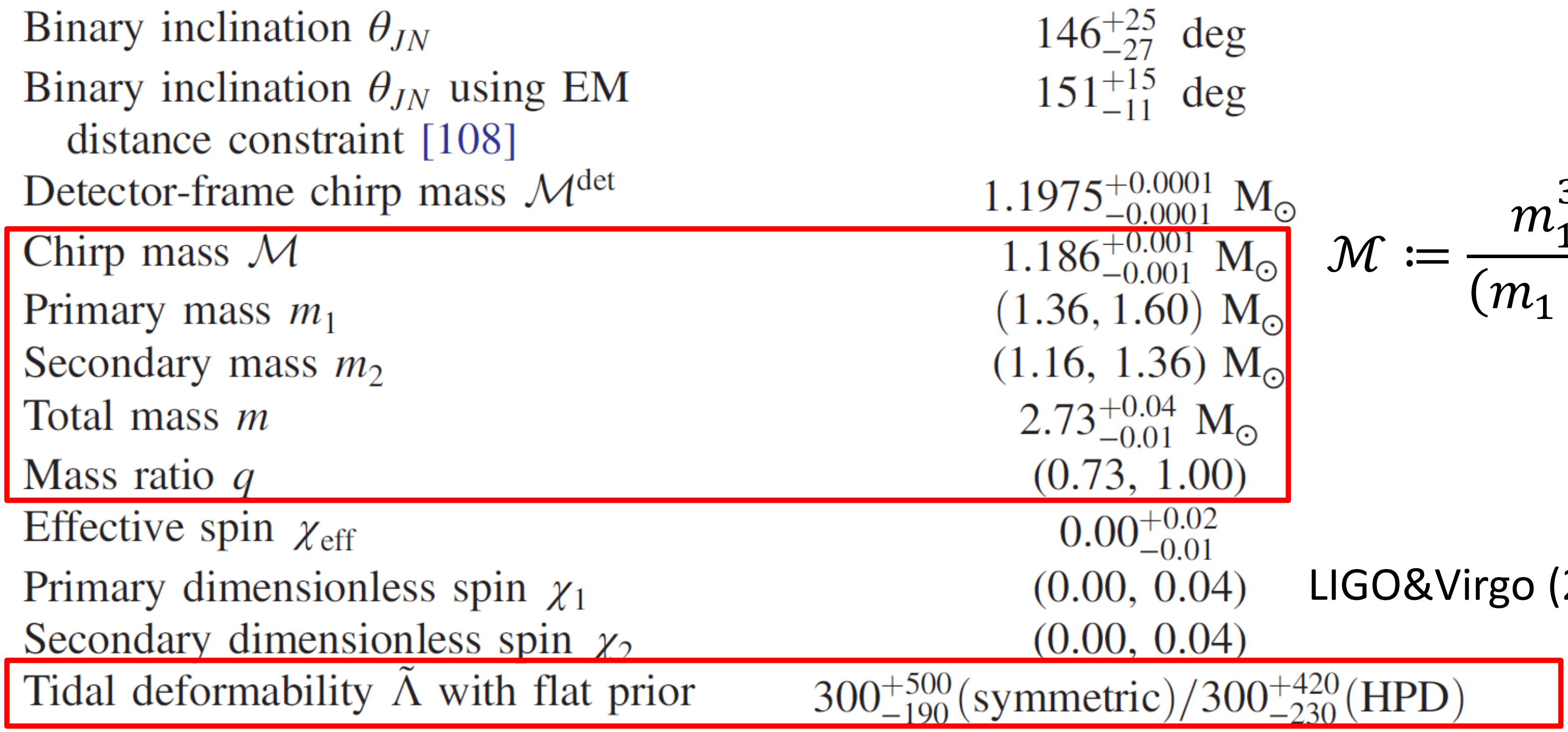


Parameters of GW170817

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 $\mathcal{M}^{\mathrm{det}}$	$1.1975^{+0.0001}_{-0.0001}$ $\mathrm{M}_{\odot}$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001}$ $\mathrm{M}_{\odot}$
Primary mass m_1	(1.36, 1.60) $\mathrm{M}_{\odot}$
Secondary mass m_2	(1.16, 1.36) $\mathrm{M}_{\odot}$
Total mass m	$2.73^{+0.04}_{-0.01}$ $\mathrm{M}_{\odot}$
Mass ratio q	(0.73, 1.00)
Effective spin χ_{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)

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

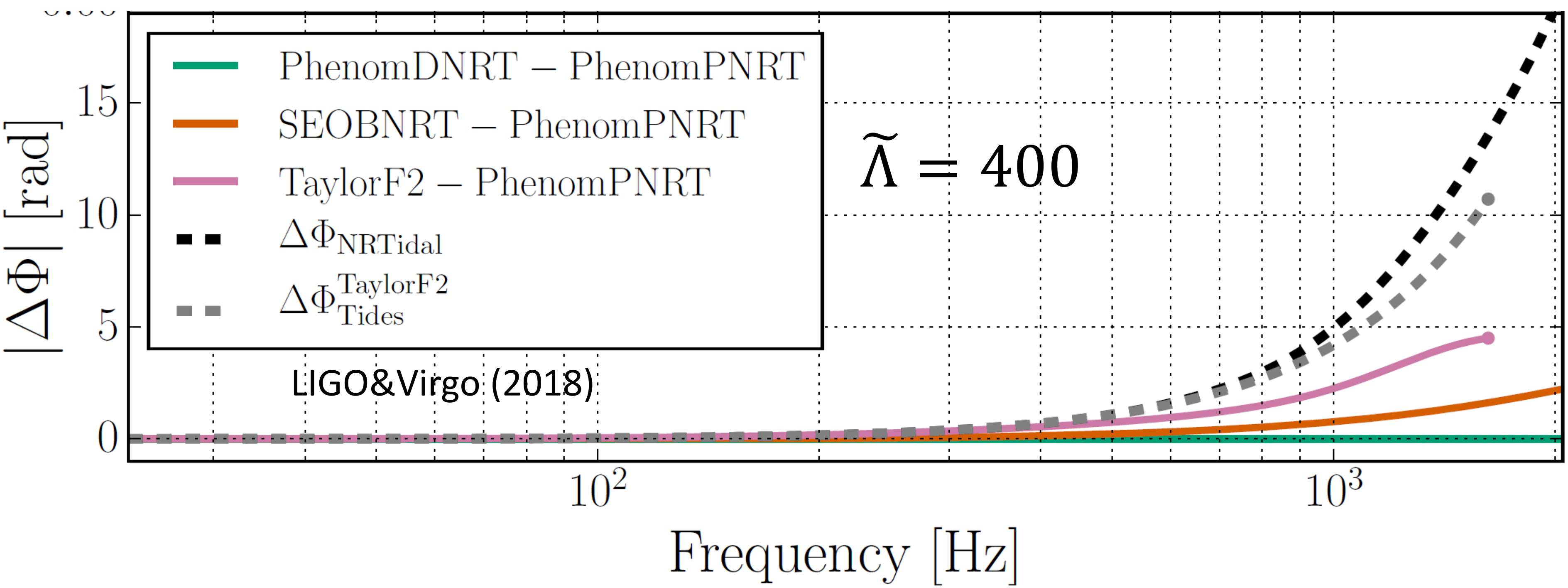
LIGO&Virgo (2019)

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



LIGO&Virgo (2018)

Kyoto gravitational-wave model

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

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

+ correction terms associated w/ mass asymmetry

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

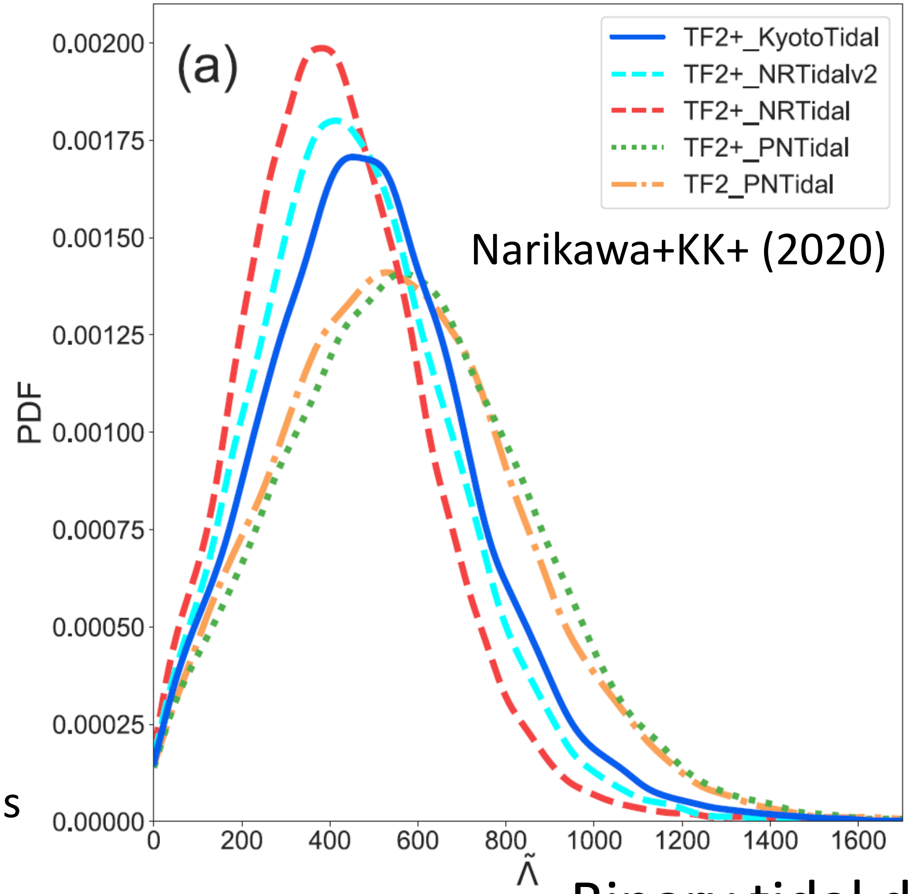
We introduce a nonlinear-in-$\tilde{\Lambda}$ term (empirically)

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

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



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

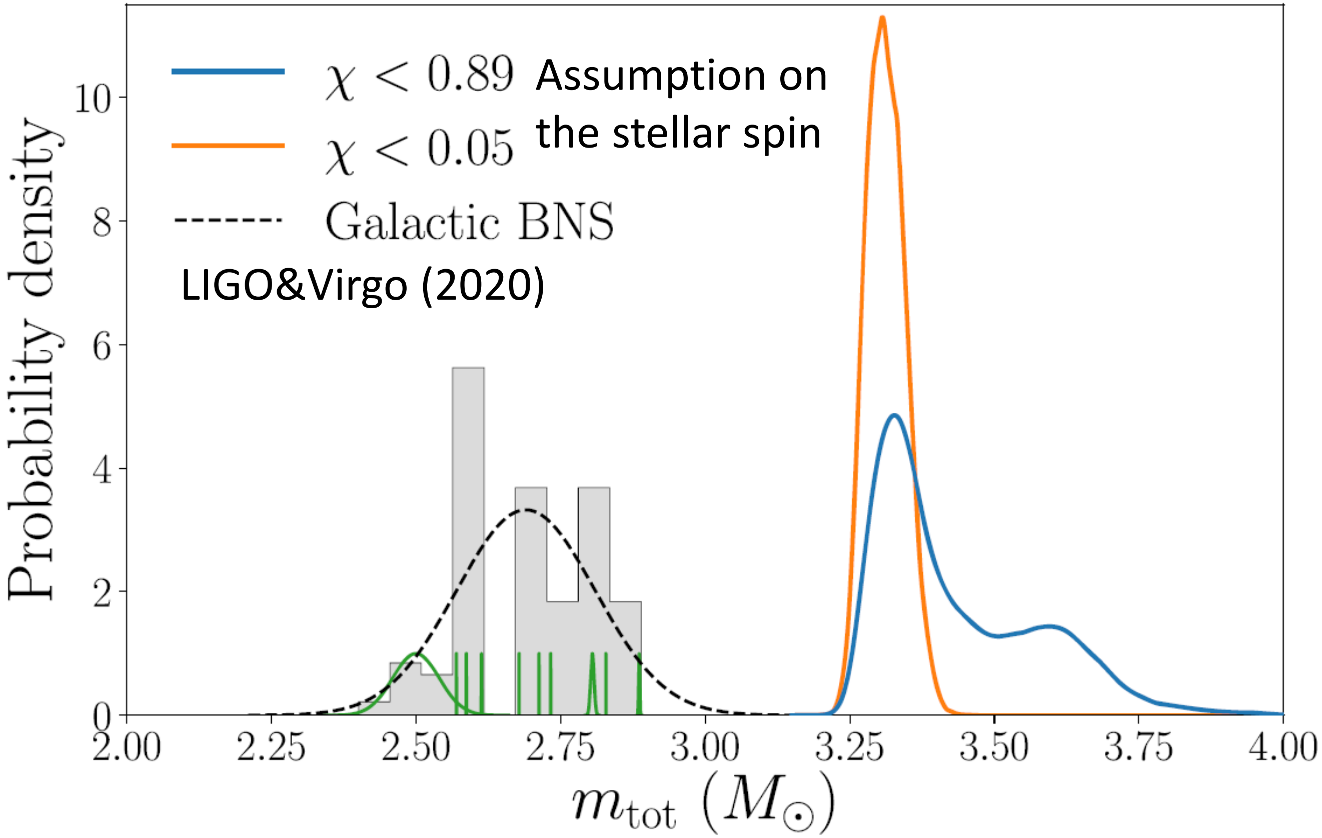
Stiff, large radius

Binary tidal deformability

GW190425

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

Heavier by >5sigma than Galactic binary neutron stars



Assumption on the stellar spin

LIGO&Virgo (2020)

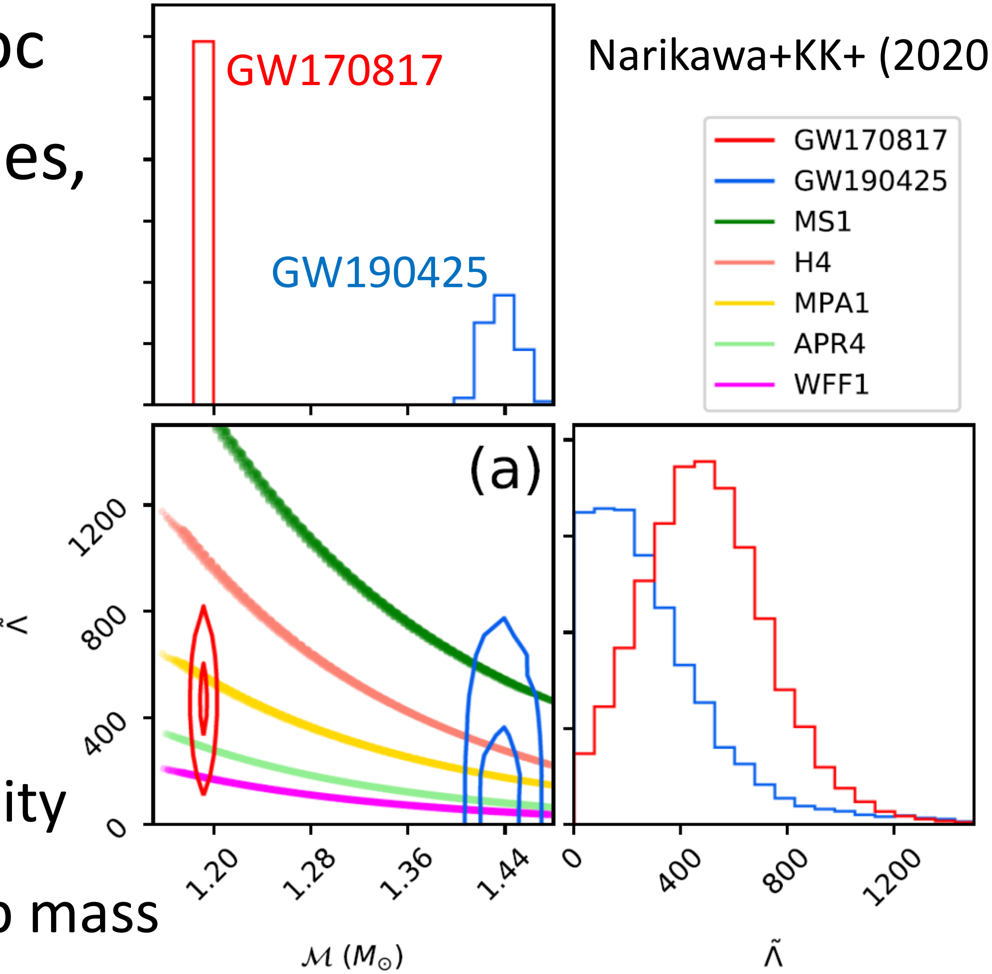
Case of GW190425

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



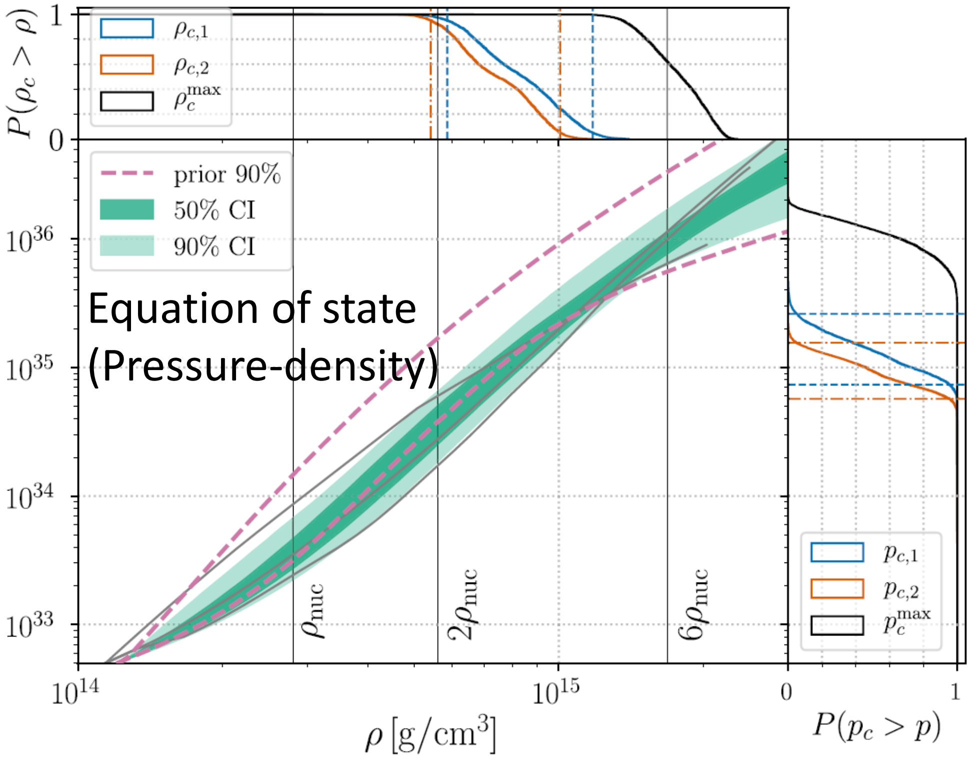
Narikawa+KK+ (2020)

Binary tidal deformability

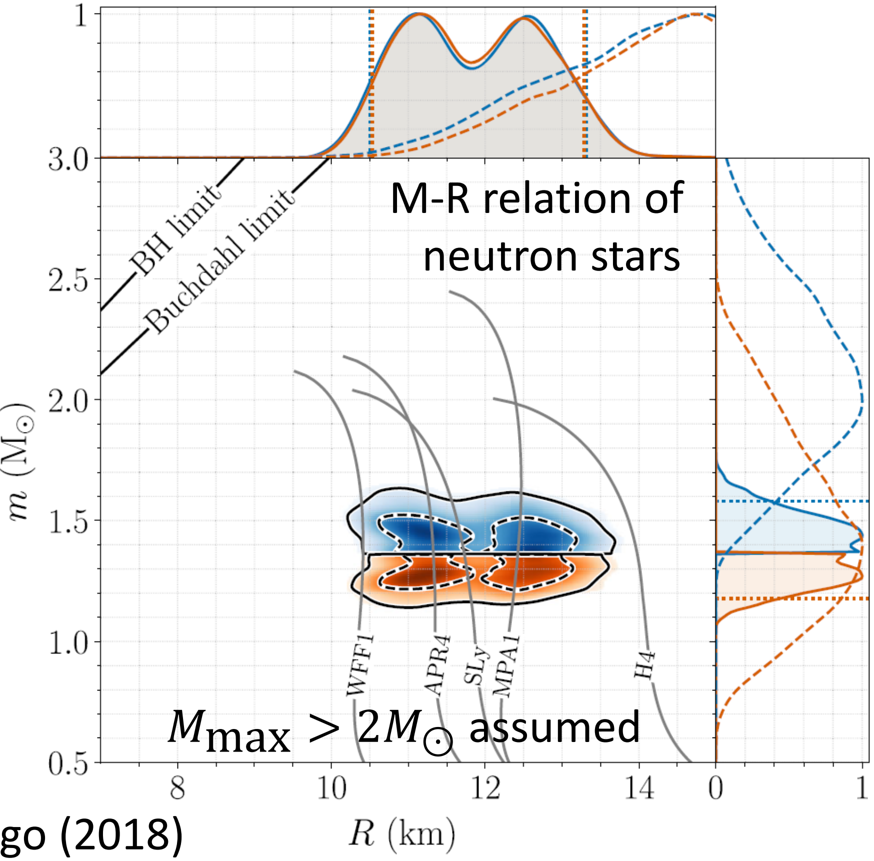
Chirp mass

Current status of understanding

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



Equation of state (Pressure-density)



M-R relation of neutron stars

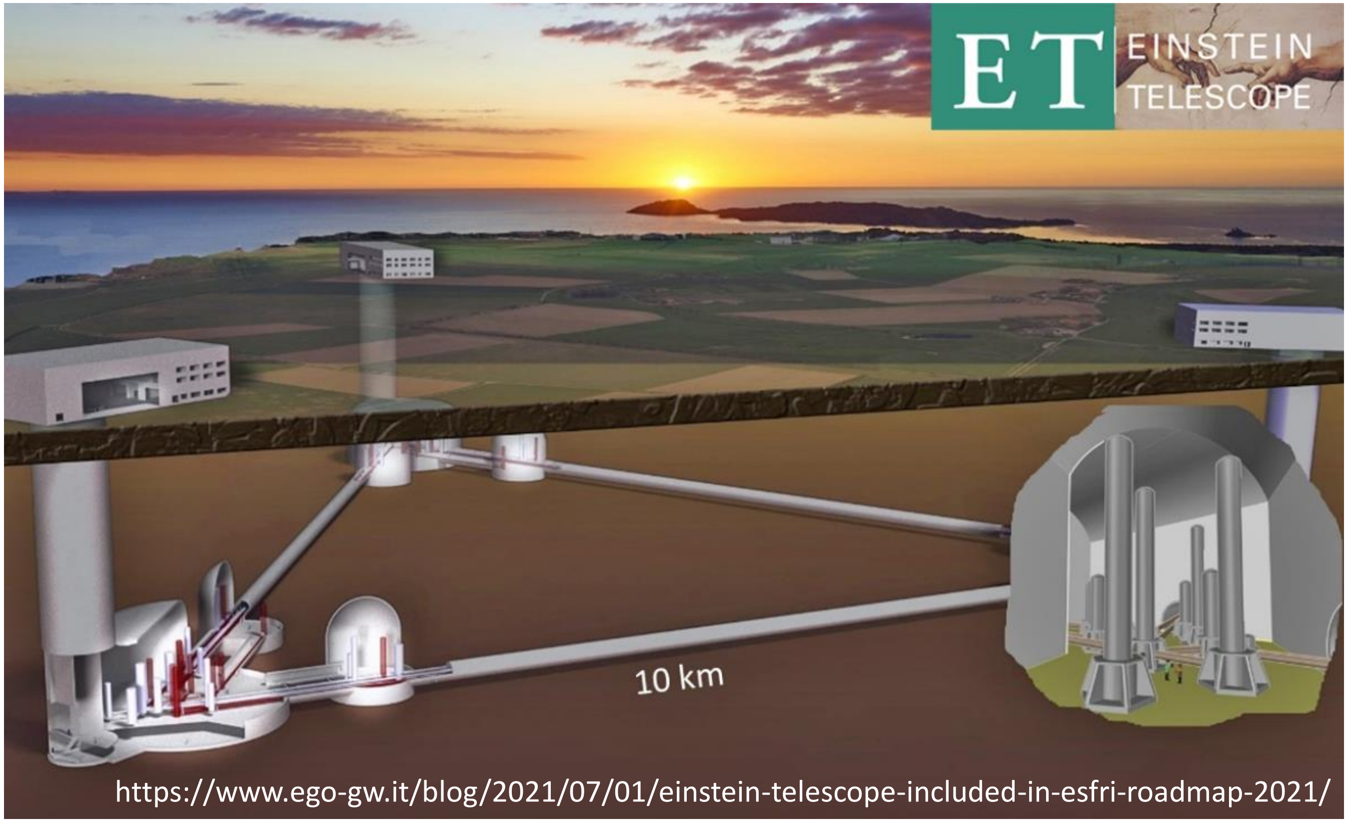
$M_{\max} > 2M_\odot$ assumed

LIGO&Virgo (2018)

5. Future direction

Third-generation detector

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

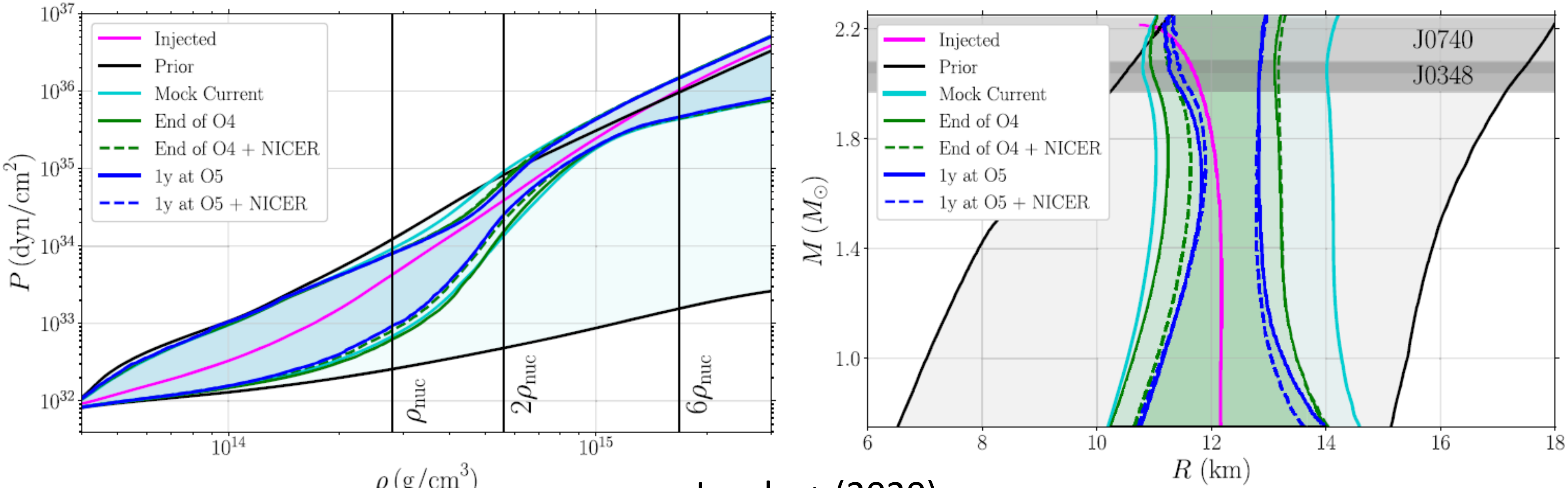


https://www.ego-gw.it/blog/2021/07/01/einstein-telescope-included-in-esfri-roadmap-2021/

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



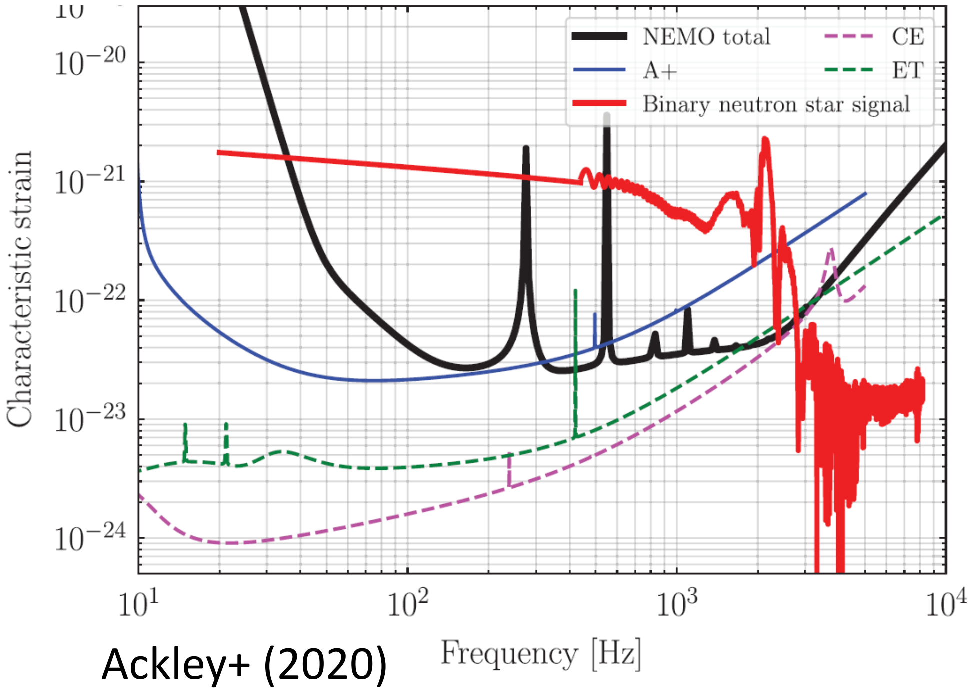
Landry+ (2020)

Future high-frequency observation

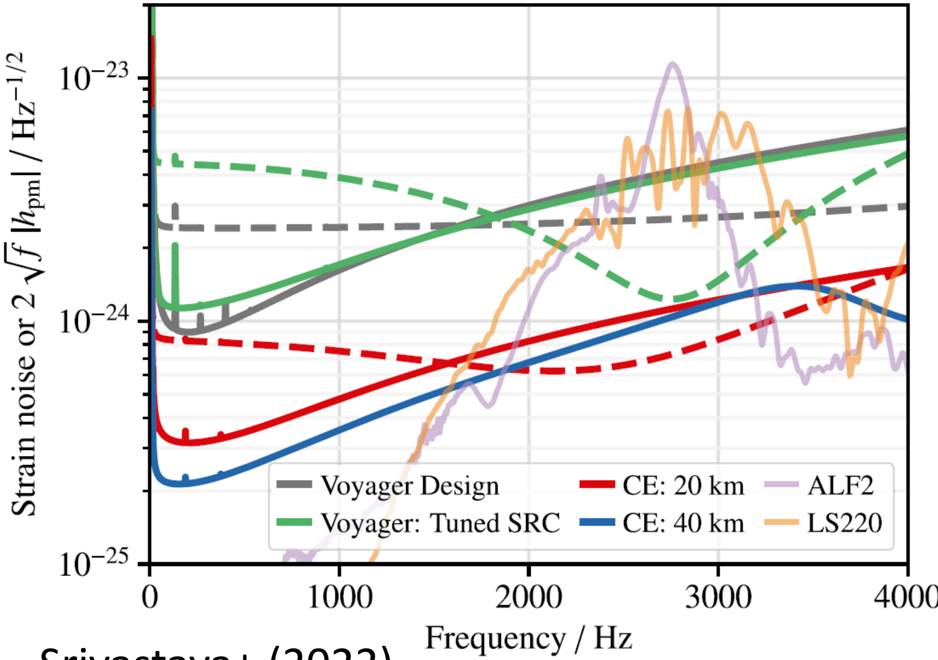
The high density requires high-frequency observations

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

Some proposals are made for postmerger signals



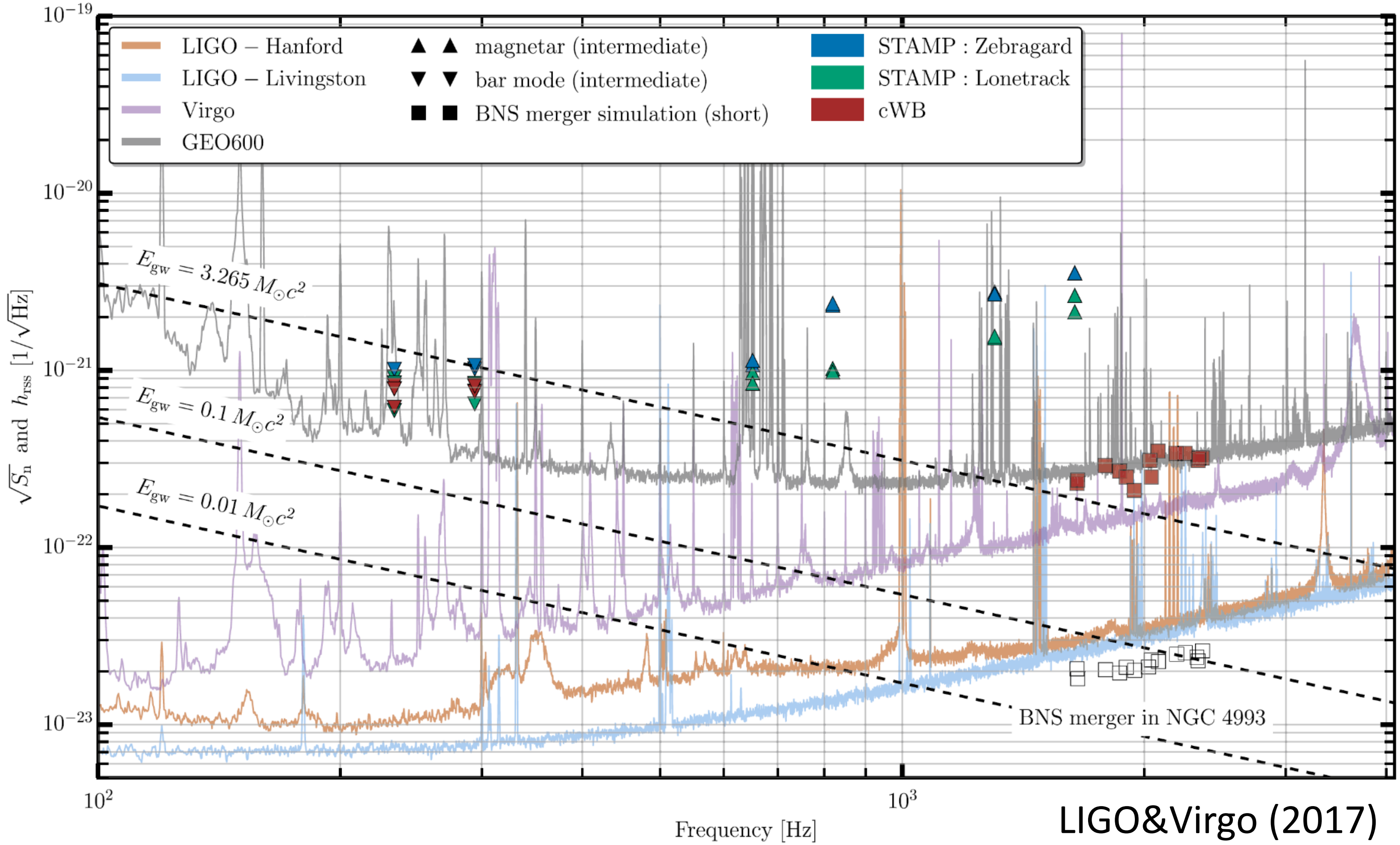
Ackley+ (2020)



Srivastava+ (2022)

Nondetection for GW170817

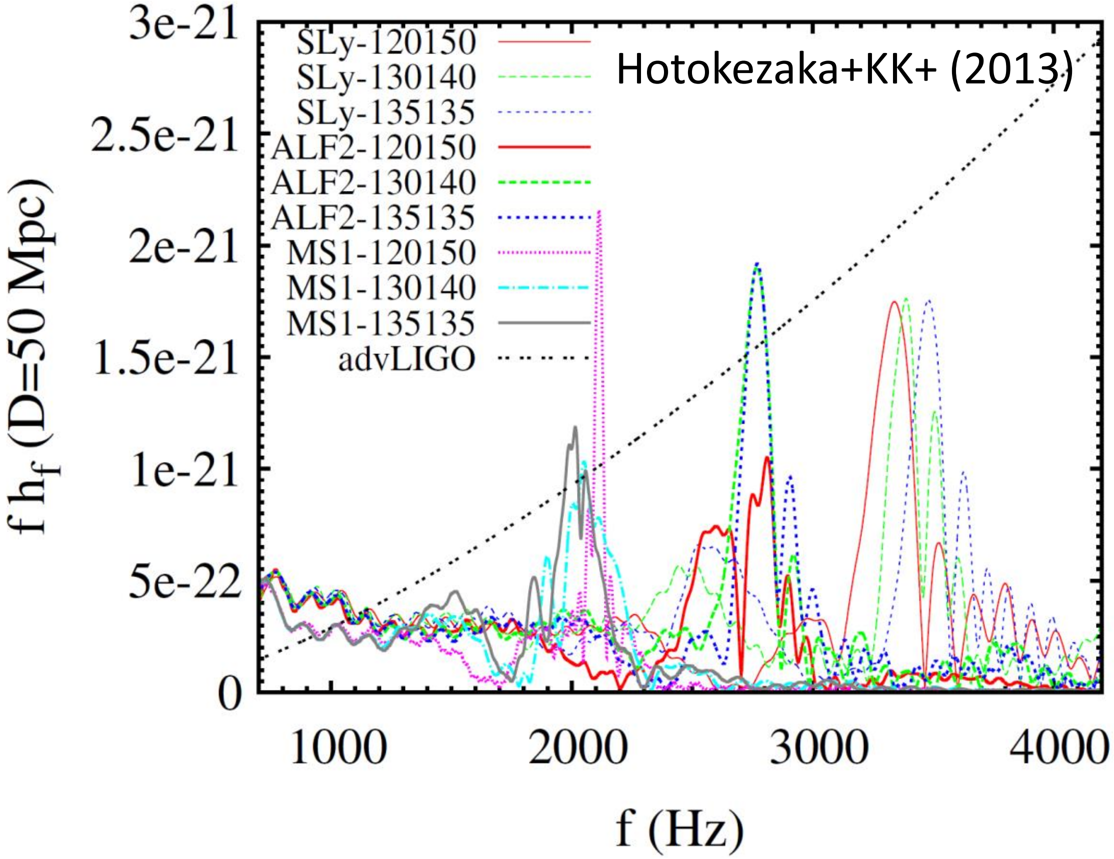
Simply, sensitivity at high frequency is insufficient



LIGO&Virgo (2017)

Postmerger peak frequency

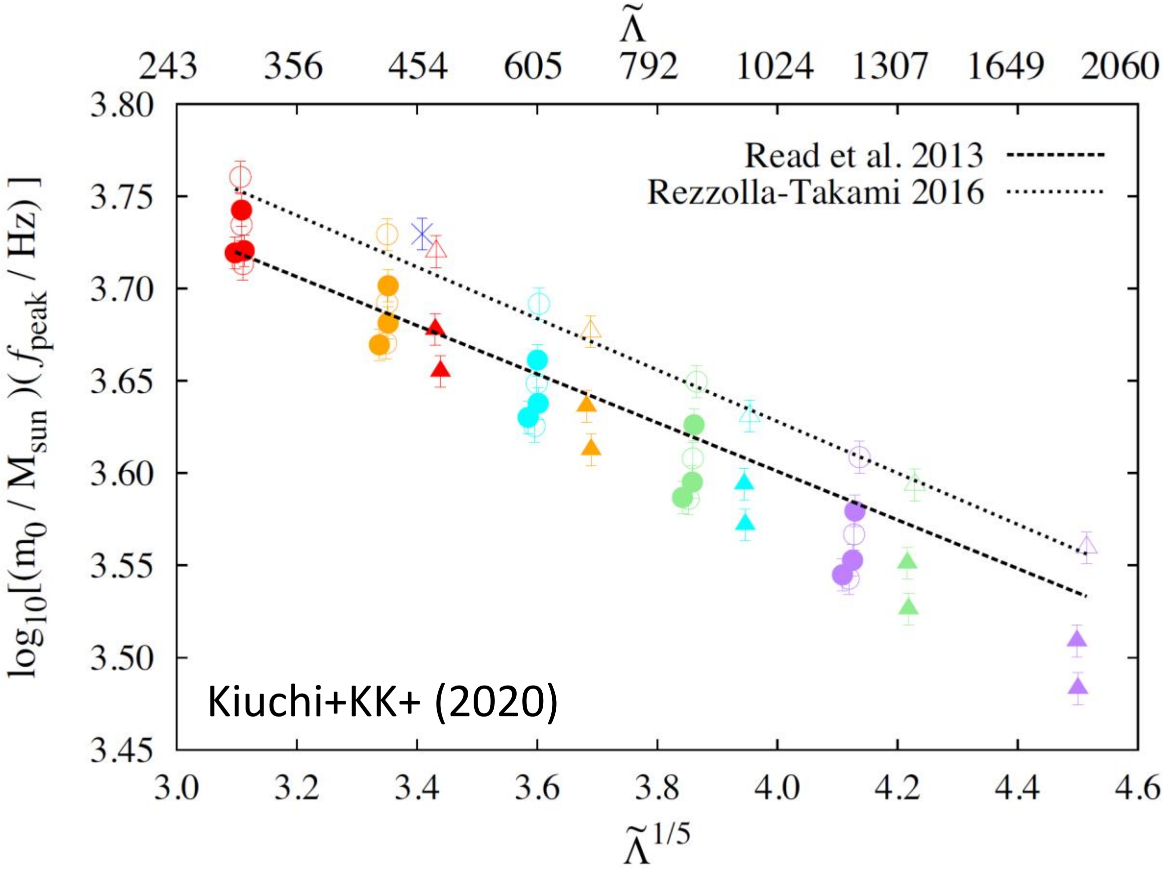
Depends on the equation of state and the total mass, also weakly on the mass ratio



Hotokezaka+KK+ (2013)

Pre-postmerger correlation

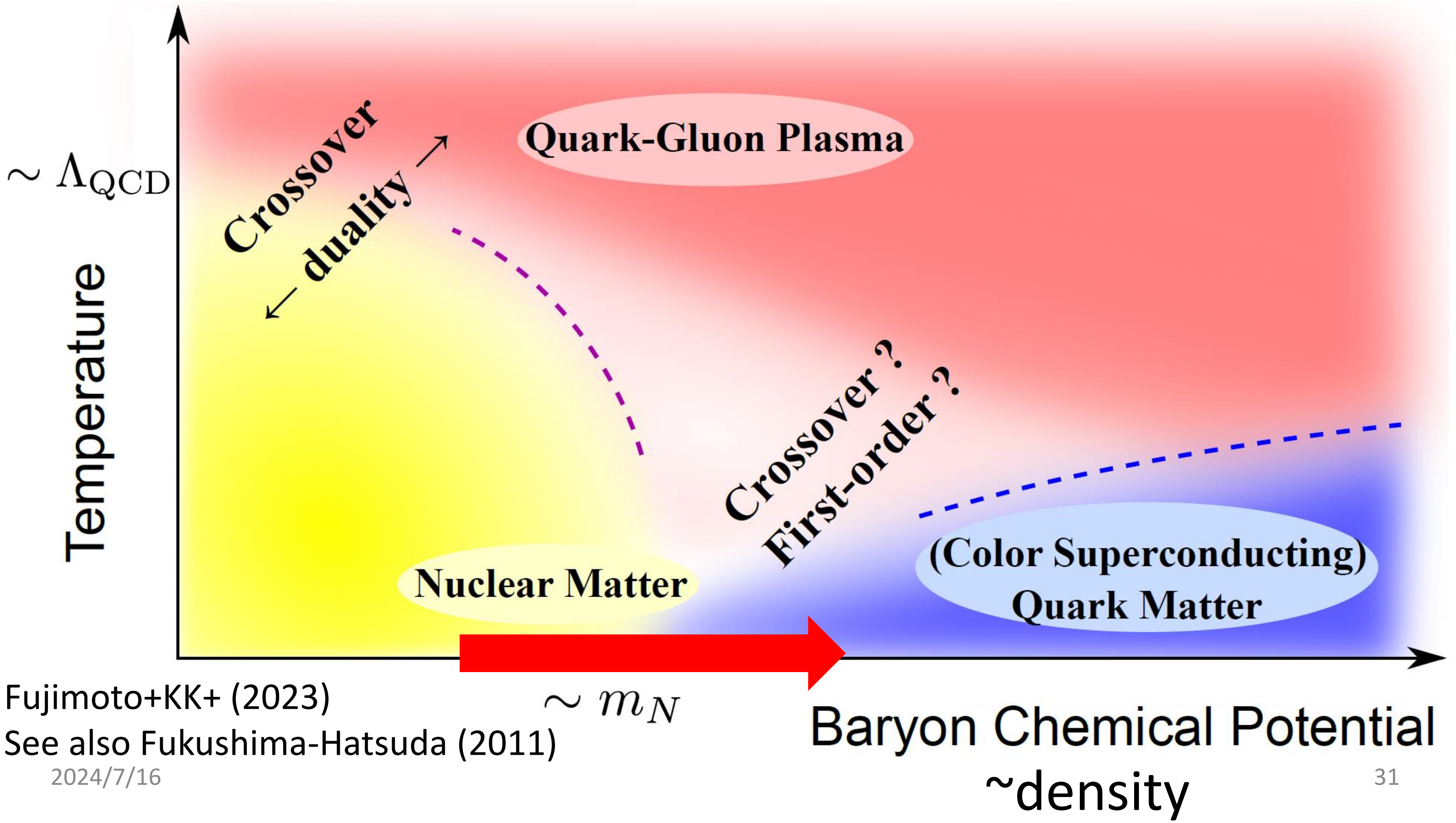
Frequency at the amplitude peak is correlated strongly with the property of premerger neutron stars



Kiuchi+KK+ (2020)

QCD phase diagram

What kind of transition occurs from hadrons to quarks

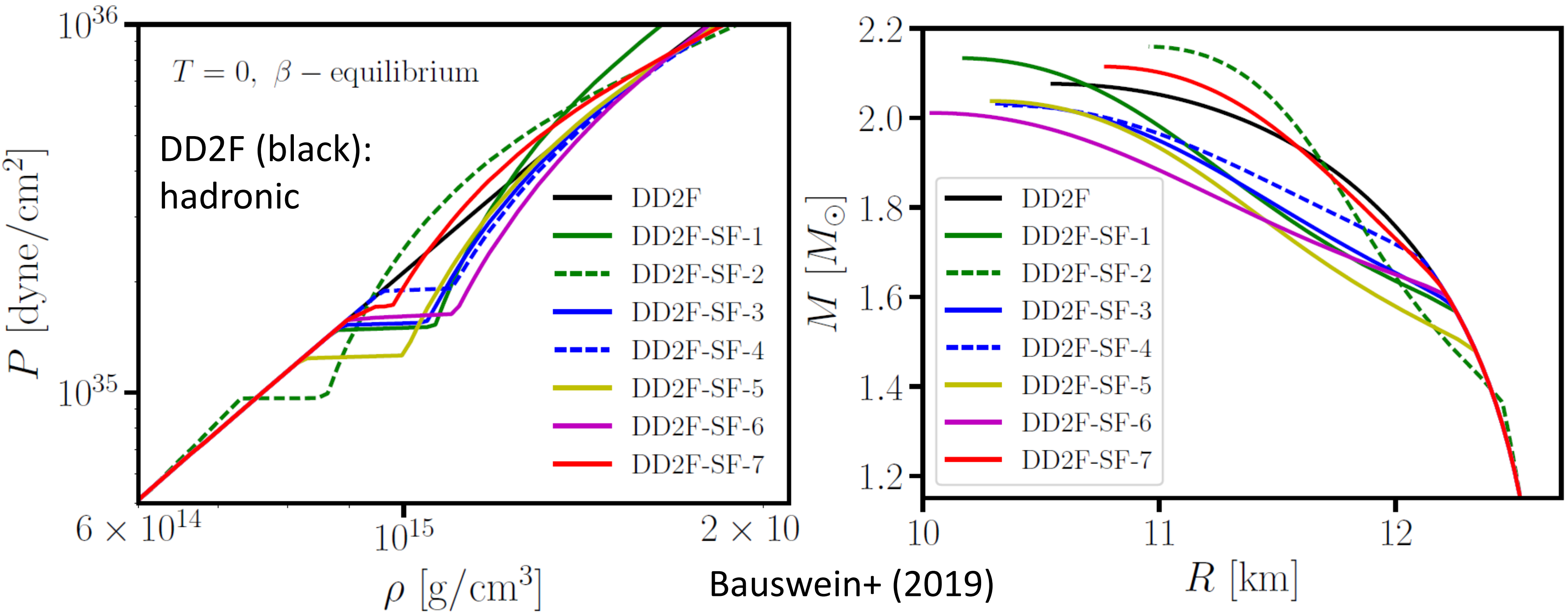


Fujimoto+KK+ (2023)
See also Fukushima-Hatsuda (2011)

Strong 1st-order phase transition

The mass-radius relation breaks suddenly

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



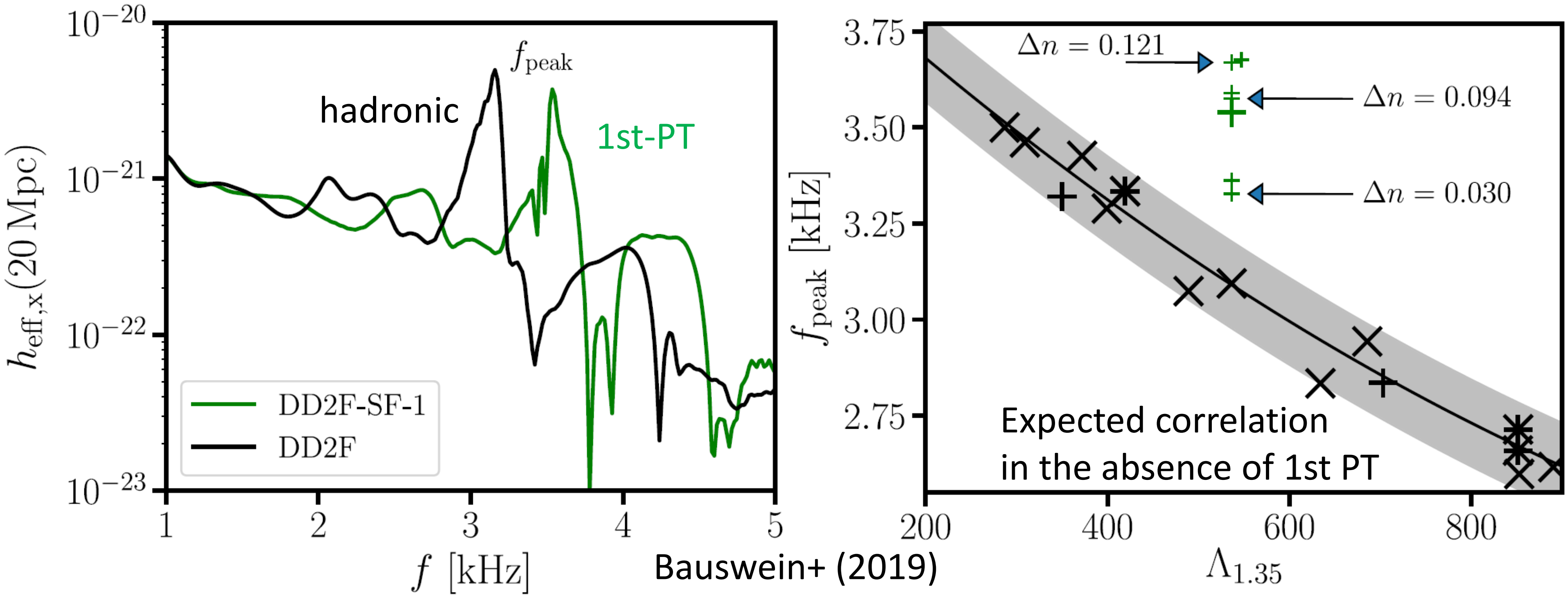
DD2F (black): hadronic

Bauswein+ (2019)

Effect on the postmerger peak

Significant deviation from hadronic expectations

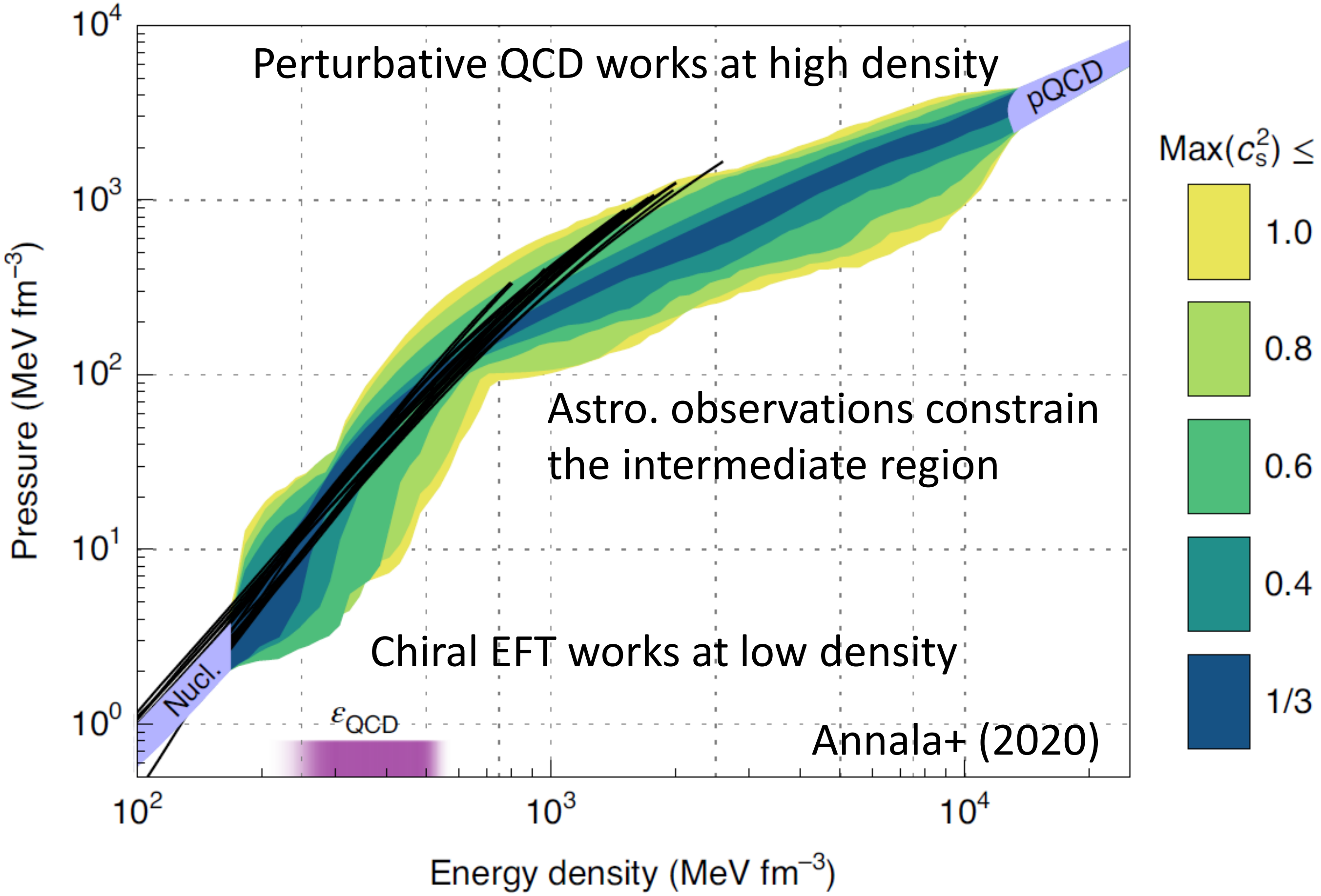
The shift in the peak frequency may reveal strong 1st-order phase transition at moderately high density



Bauswein+ (2019)

Current view of the transition

Smooth crossover transition might be realistic



Perturbative QCD works at high density

Astro. observations constrain the intermediate region

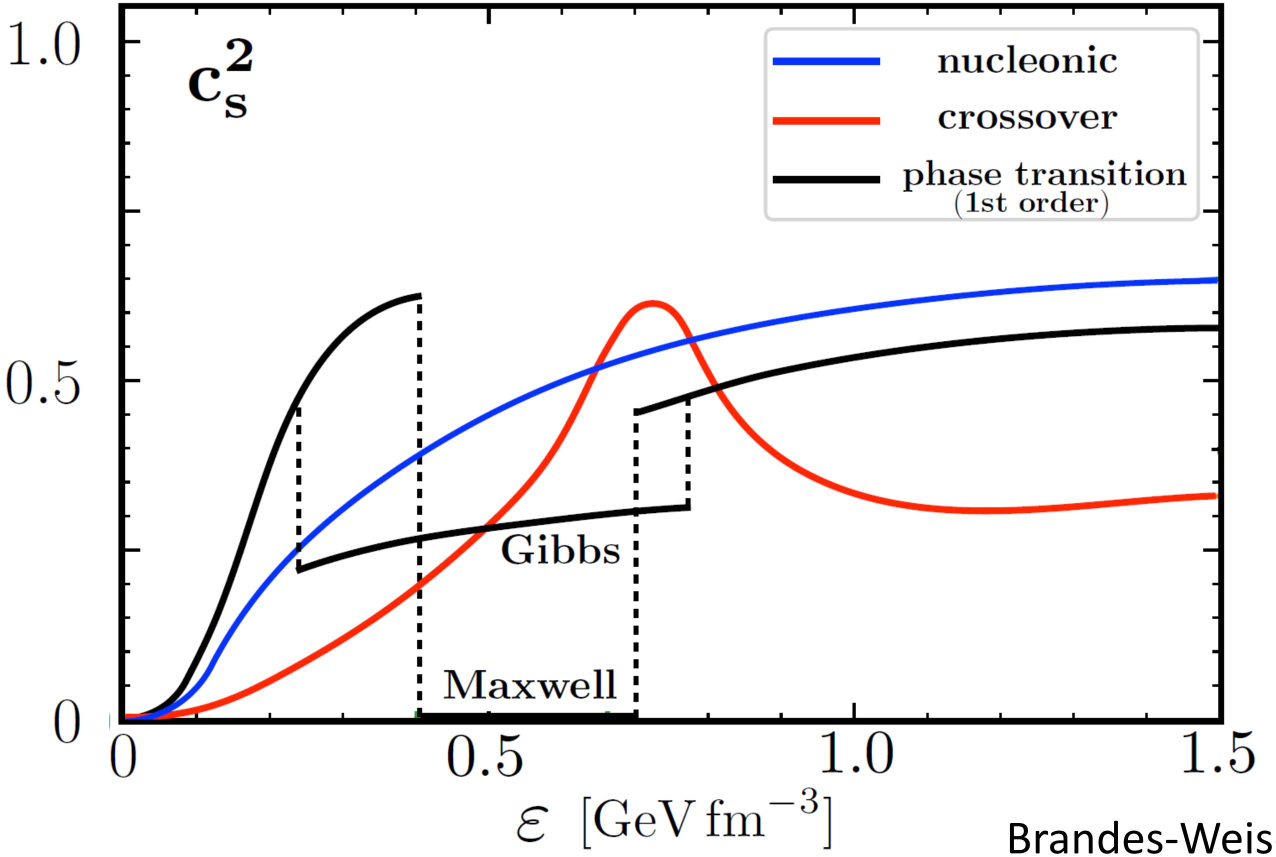
Chiral EFT works at low density

Annala+ (2020)

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)

Crossover vs. 1st order PT

Crossover

Smoothly connects two limits

Note: we need to explain

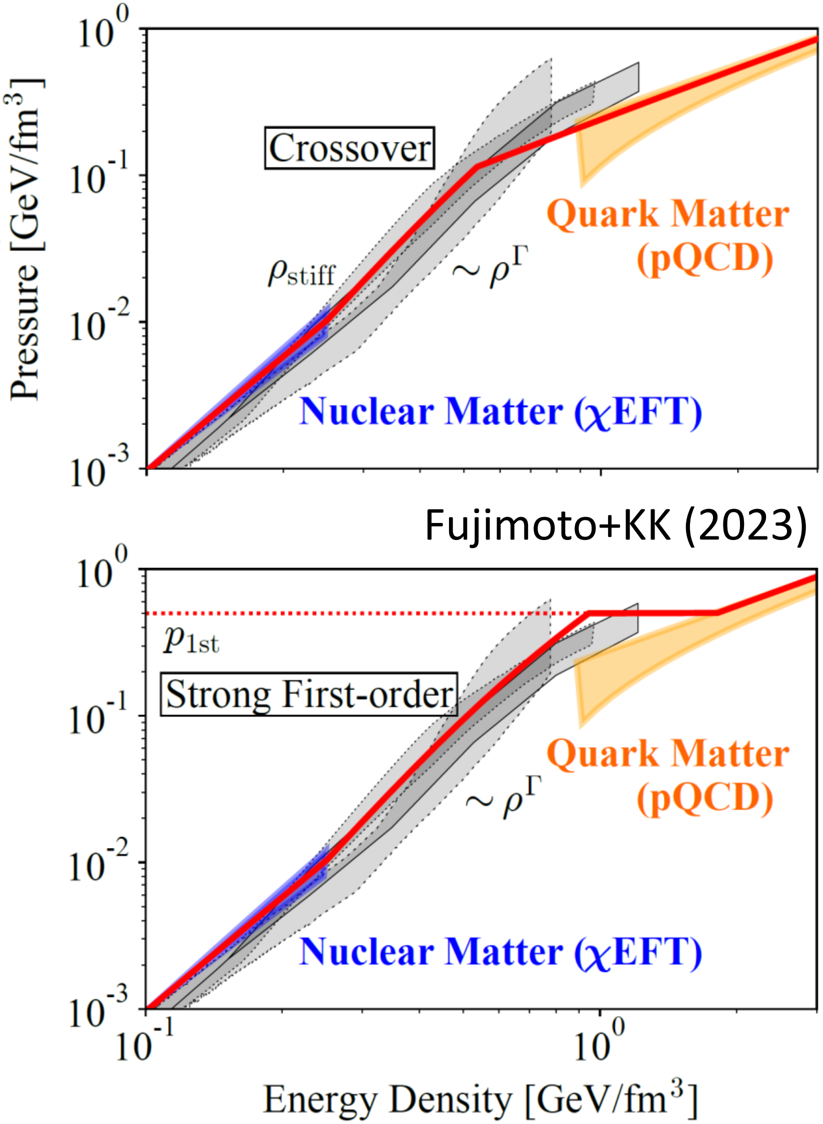
2 solar mass neutron stars

1st-order phase transition

Only very high density allow

strong phase transition…

No effect on astrophysics?

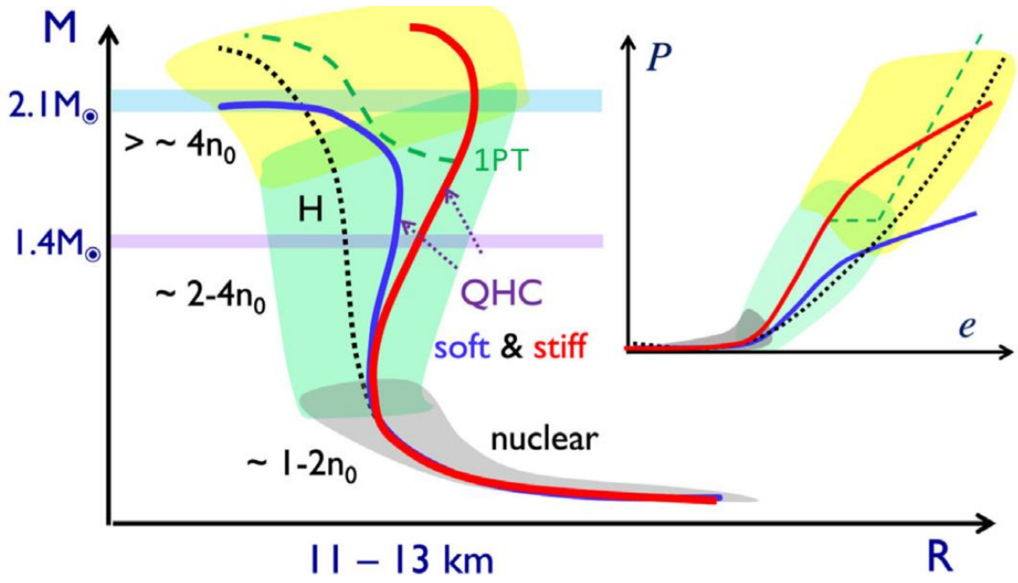


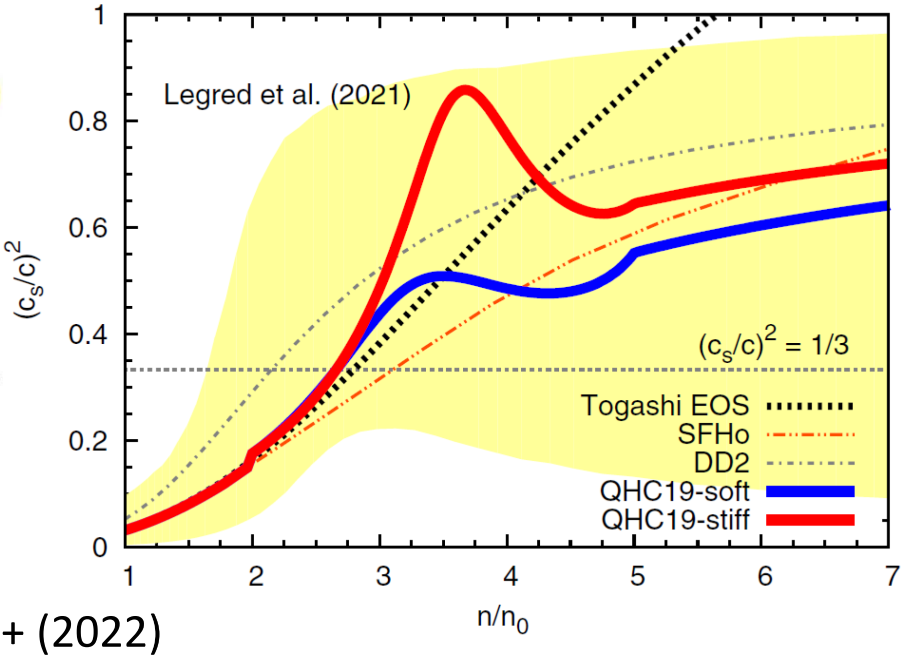
Fujimoto+KK (2023)

Relation to independent studies

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

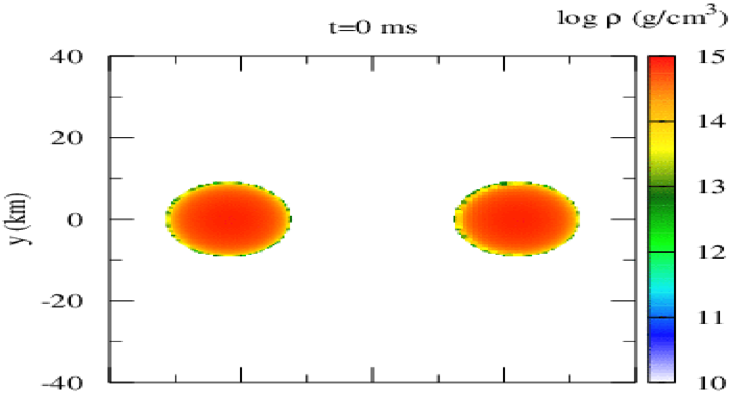
We require explicitly that the perturbative QCD regime is realized after the crossover from hadronic matter



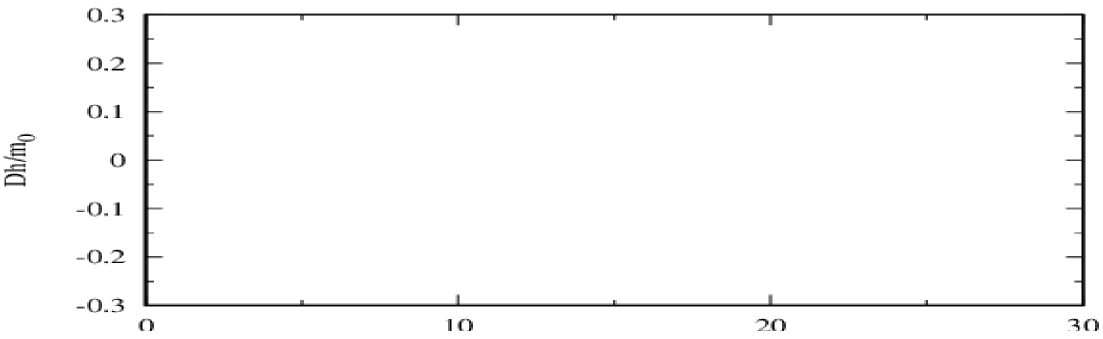


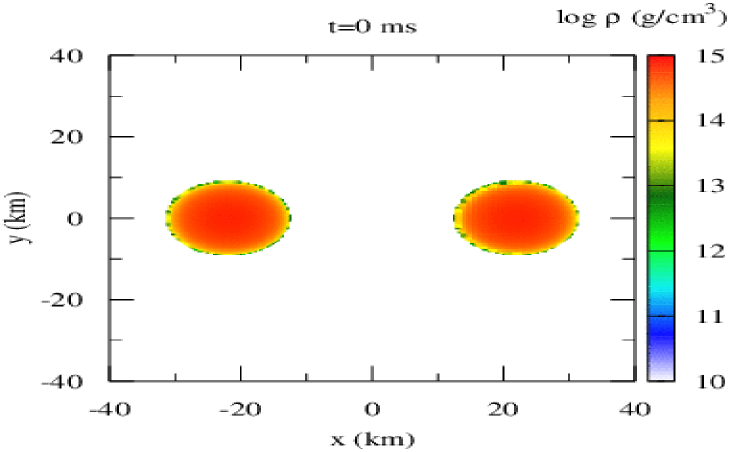
Huang+ (2022)

Merger and gravitational waves

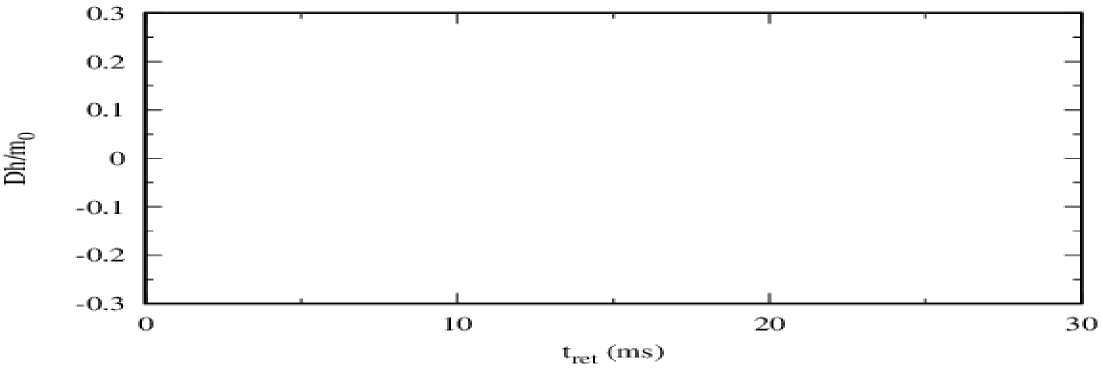


Crossover



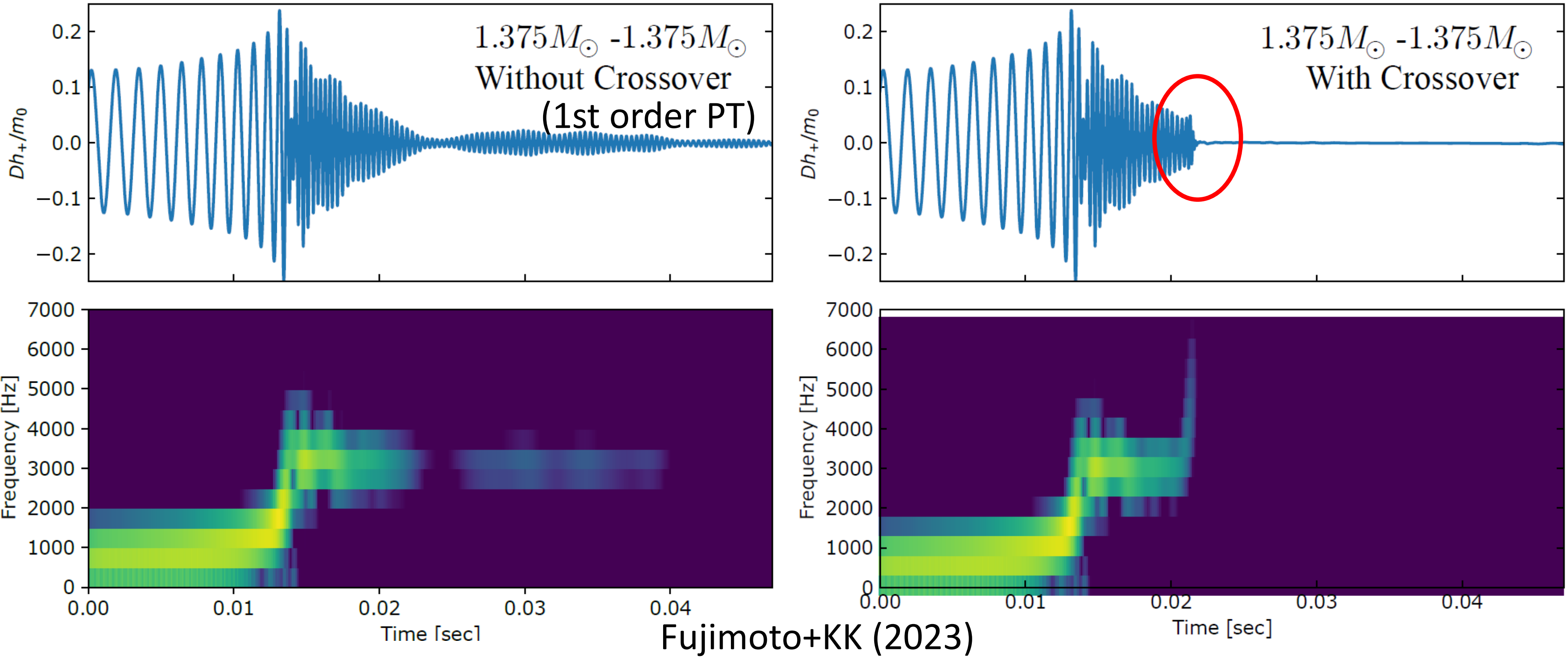


Strong first-order



Black-hole formation as a key

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



Fujimoto+KK (2023)

Gravitational-wave spectrum

The postmerger peaks do not differ appreciably

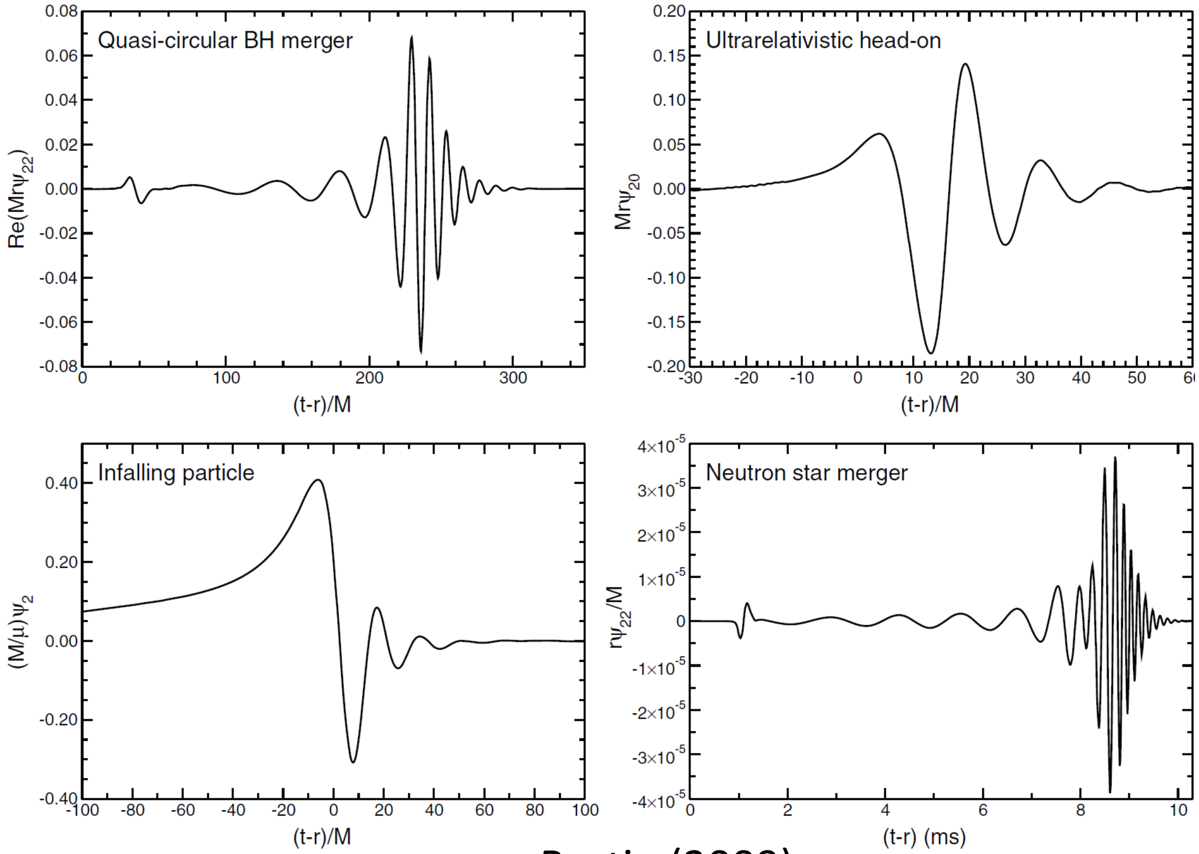
The quasinormal-mode cutoff could be distinguishing

preliminary

Quasinormal modes of black holes

Damped oscillations governed by the mass and spin

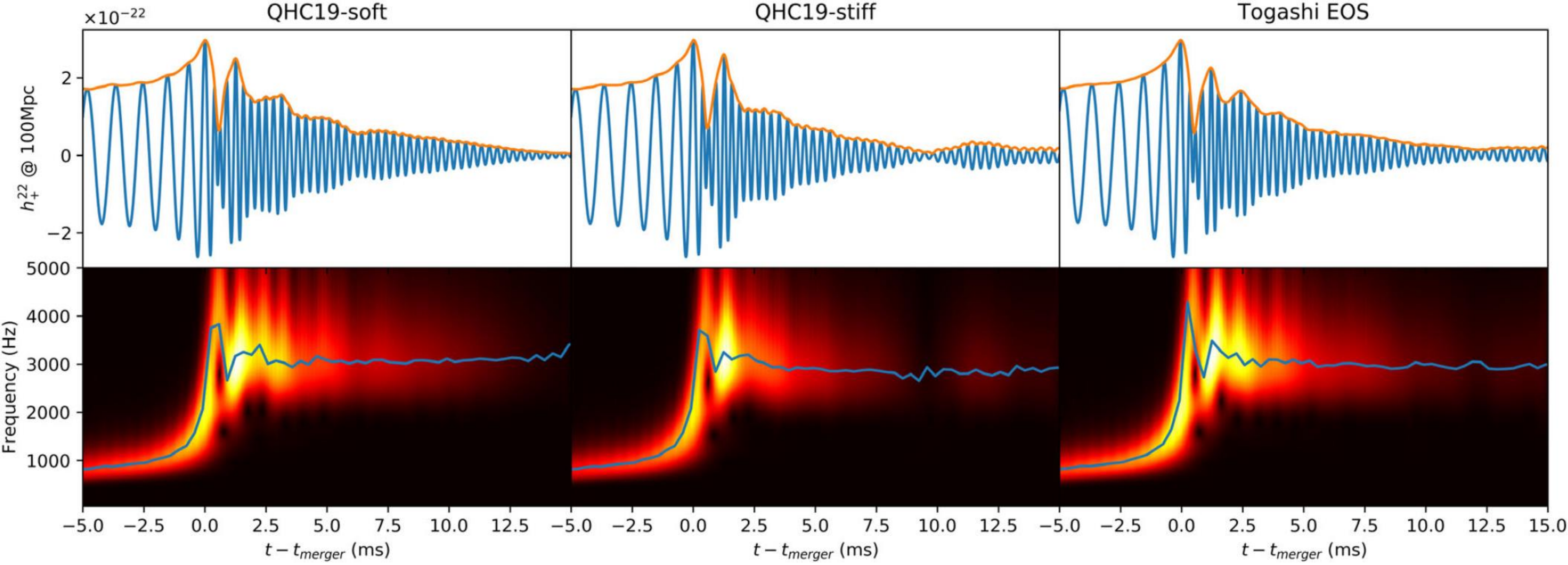
Excited when they are formed in gravitational collapse



Berti+ (2009)

Cf: results with QHC (other study)

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



Huang+ (2022)

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

preliminary

Various mass ratios

preliminary

Lifetime of the merger remnant

Determined primarily by the total mass of the binary

preliminary

Weak dependence on mass ratio

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

preliminary

Possible source of uncertainties

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

We vary systematically the strength of thermal pressure

Neutrino effect? (neglected)

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

Magnetic-field effect? (neglected)

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

Grid resolution? (finite, of course)

Checked that dependence is weak, but not clean

Did GW170817 form a black hole?

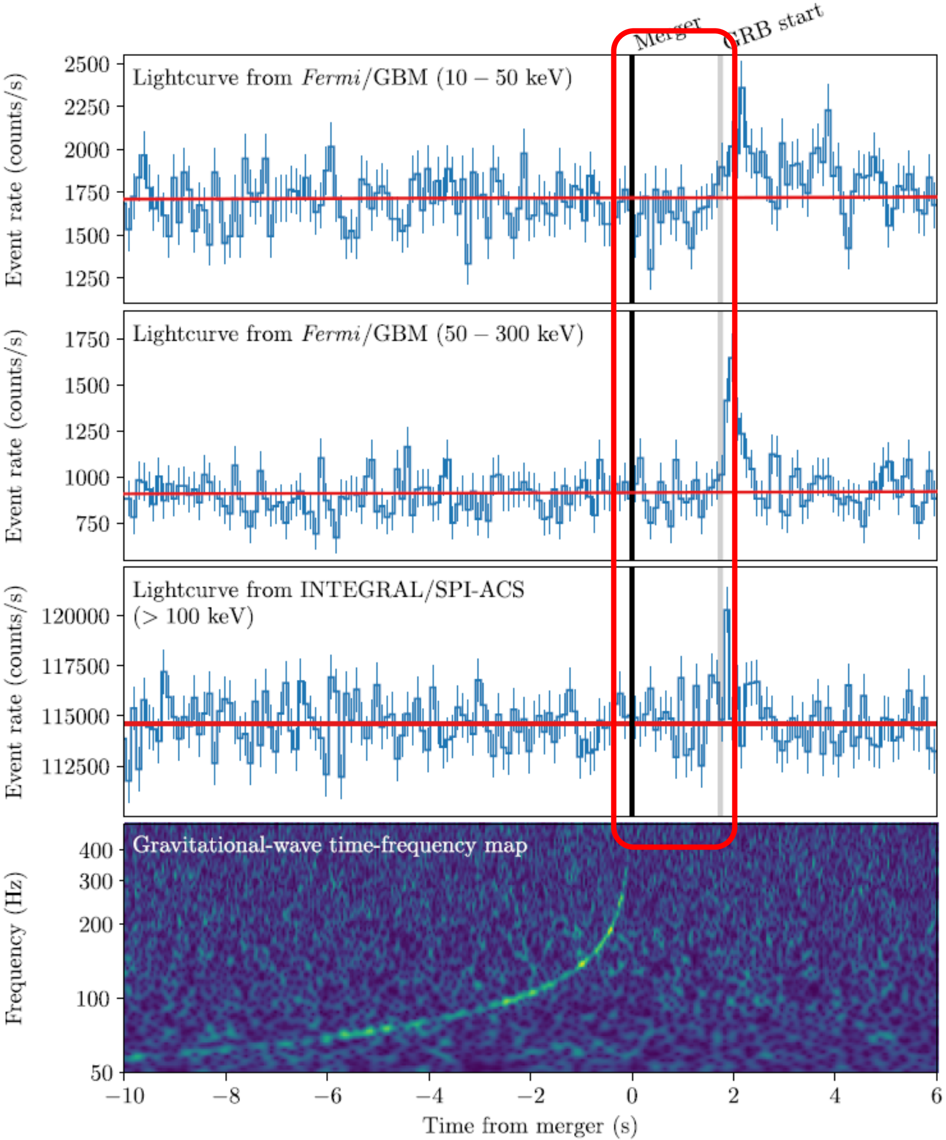
Nobody knows the answer

Important for

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

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

[neutrinos? Kyutoku-Kashiyama 2018]



LIGO&Virgo&Fermi&INTEGRAL (2017)

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

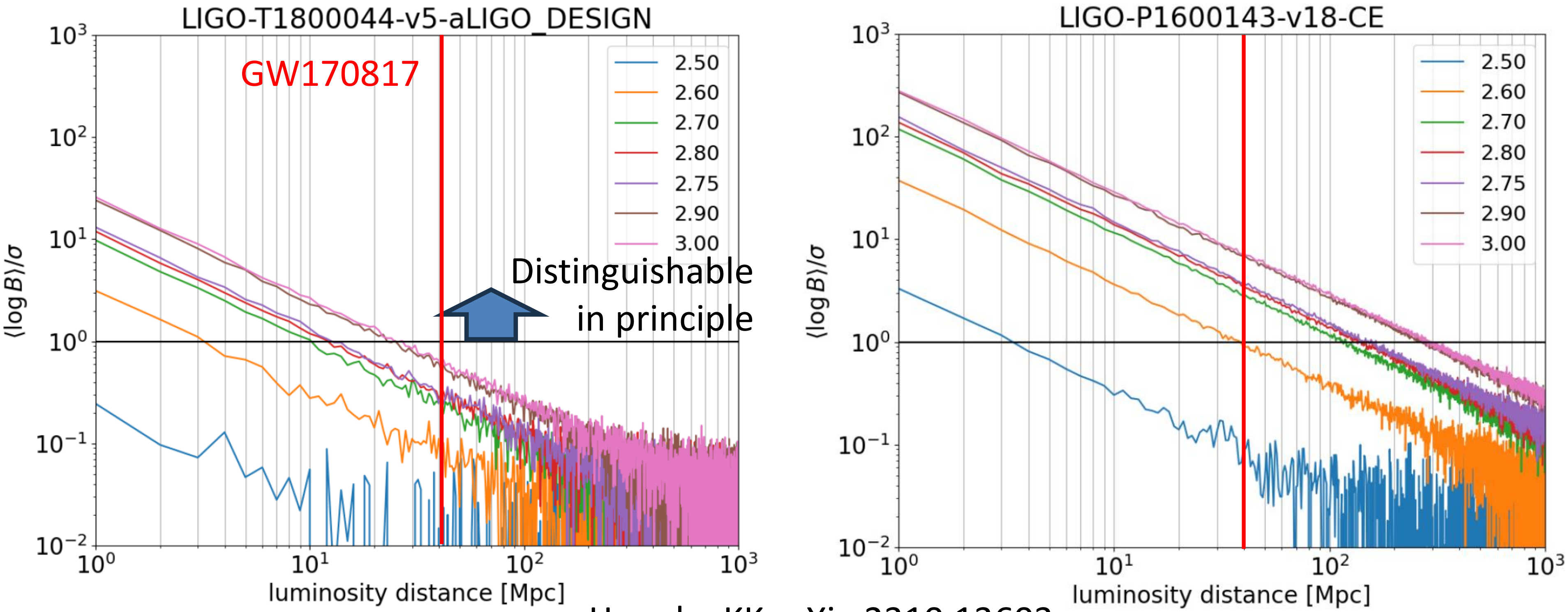
$$L \propto \exp\left(-\frac{1}{2}|\mathrm{data} - \mathrm{waveform\ model}|^2\right)$$

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)



Distinguishable in principle

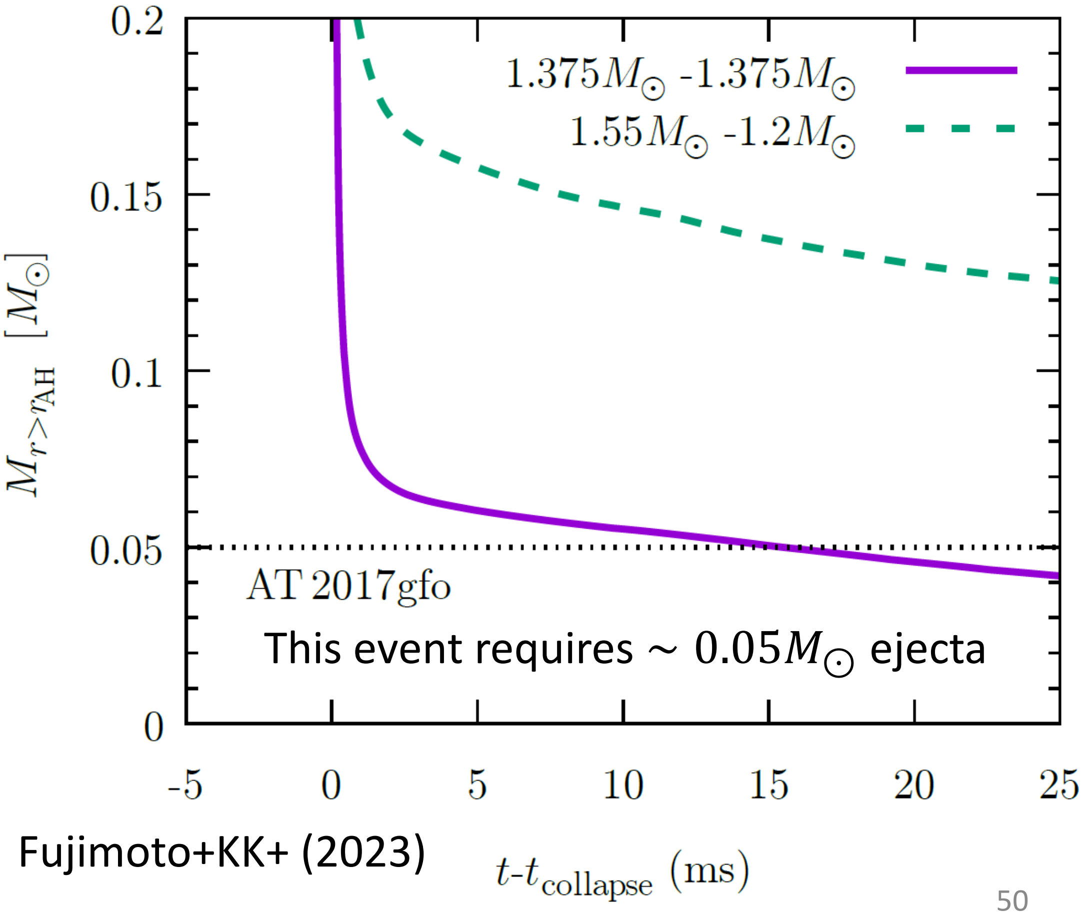
Harada+KK arXiv:2310.13603

Multimessenger observation

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

Our crossover model may be pass this test with mass asymmetry

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



This event requires ~ $0.05M_\odot$ ejecta

Fujimoto+KK+ (2023)

Summary

Summary

- Neutron stars are fascinating objects for both astrophysics and nuclear physics.
- To investigate the low-T high-μ regimes of QCD, finite-size properties such as the radius and tidal deformability play an important role.
- Current multimessenger observations tell us that typical-mass neutron stars likely have 11.5-13.5km.
- In the future, the gravitational collapse may clarify whether the hadron-quark transition at high density is crossover or 1st-order phase transition.