Investigating ultra-high-density equations of state through gravitational waves from binary neutron stars mergers

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@ Compact Stars in the QCD phase diagram 2024

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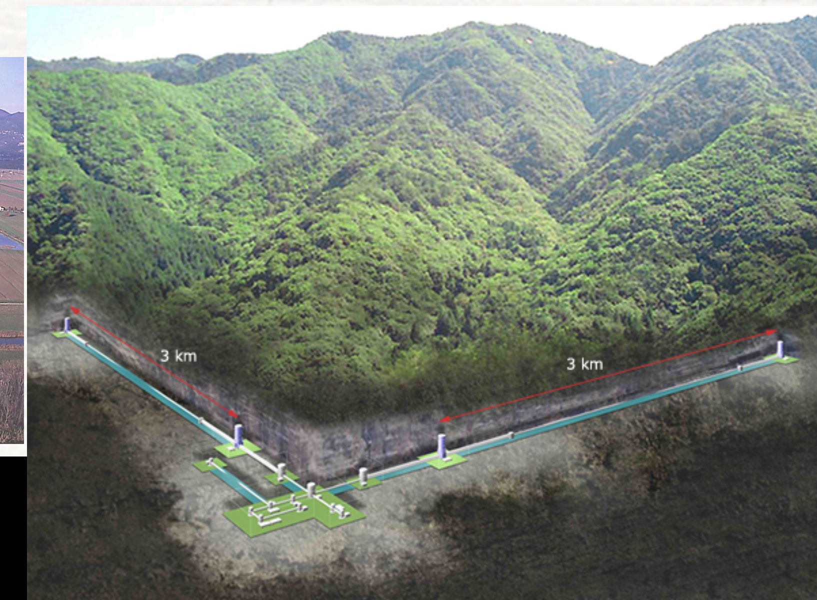
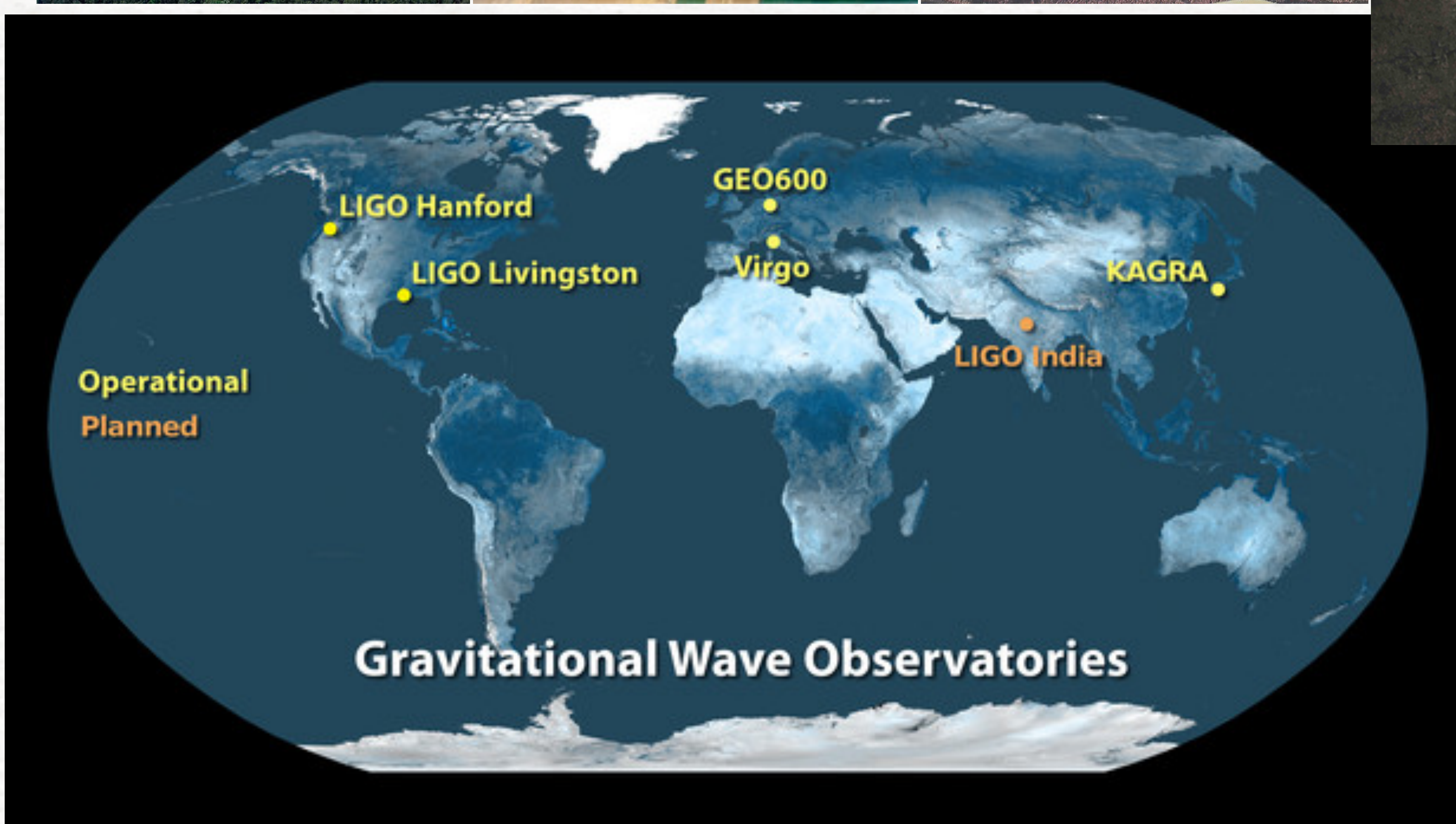
Plan of the talk

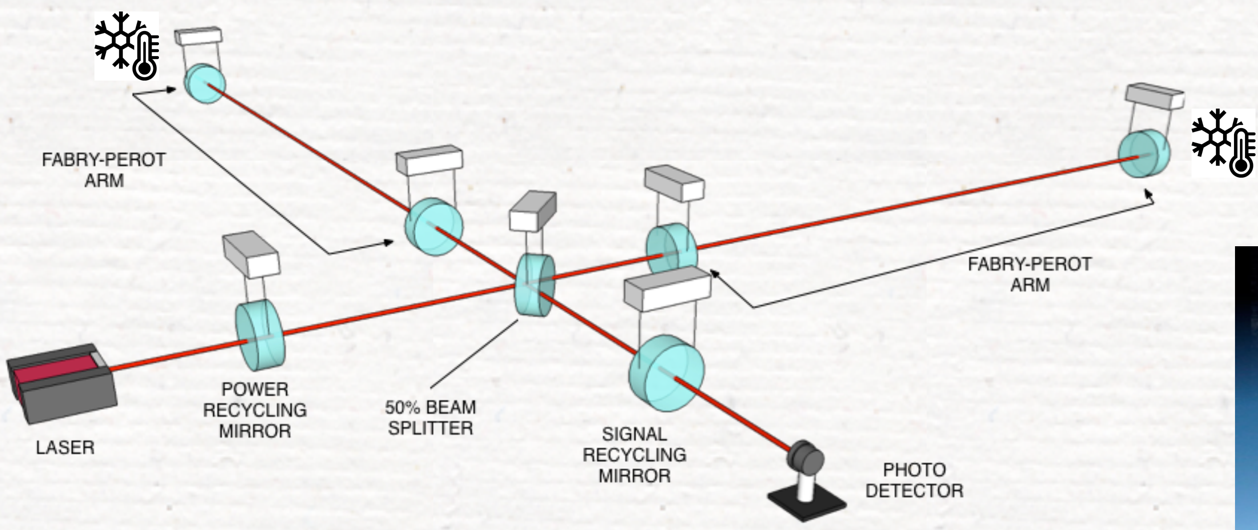
- Introduction to binary neutron star mergers
  - Importance of post-merger
  - Numerical relativity
  - Gravitational radiation from the post-merger
- Our EoSs:
  - first-order phase transition
  - quark-hadron crossover
- Results and interpretation
- Summary

Gravitational-wave interferometers



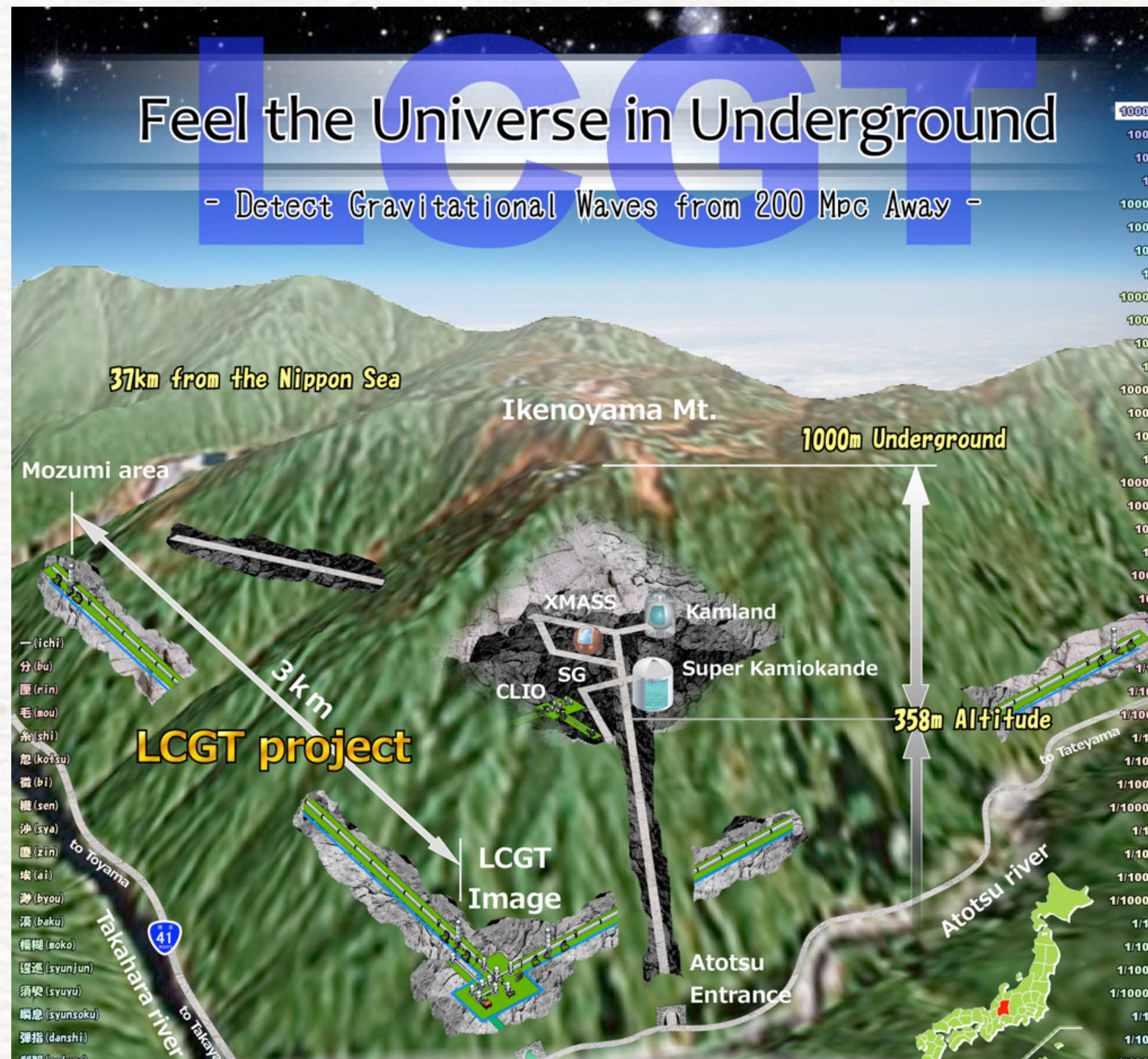


KAGRA



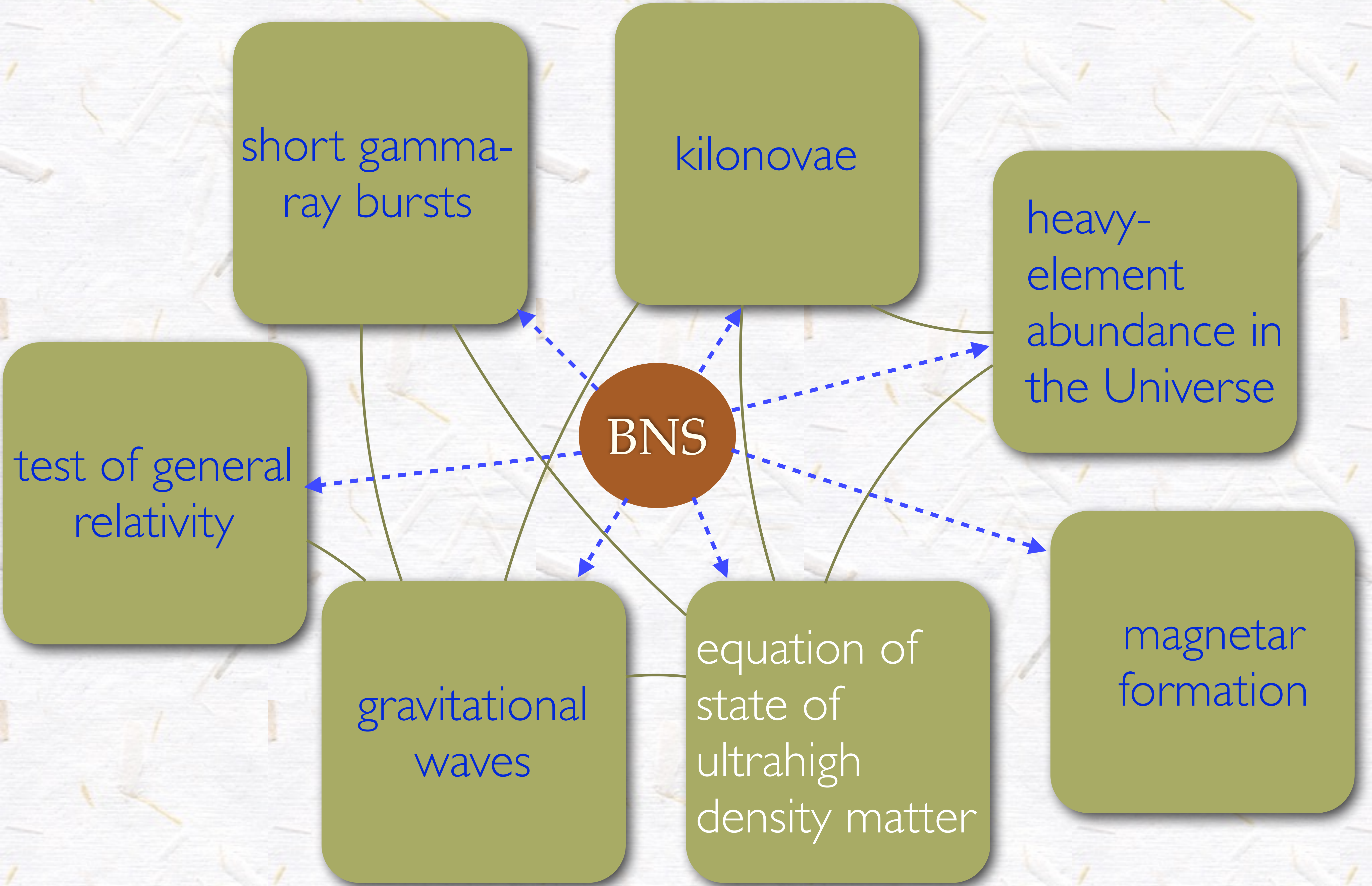
FABRY-PEROT ARM
FABRY-PEROT ARM
LASER
POWER RECYCLING MIRROR
50% BEAM SPLITTER
SIGNAL RECYCLING MIRROR
PHOTO DETECTOR

Credit: ICRR

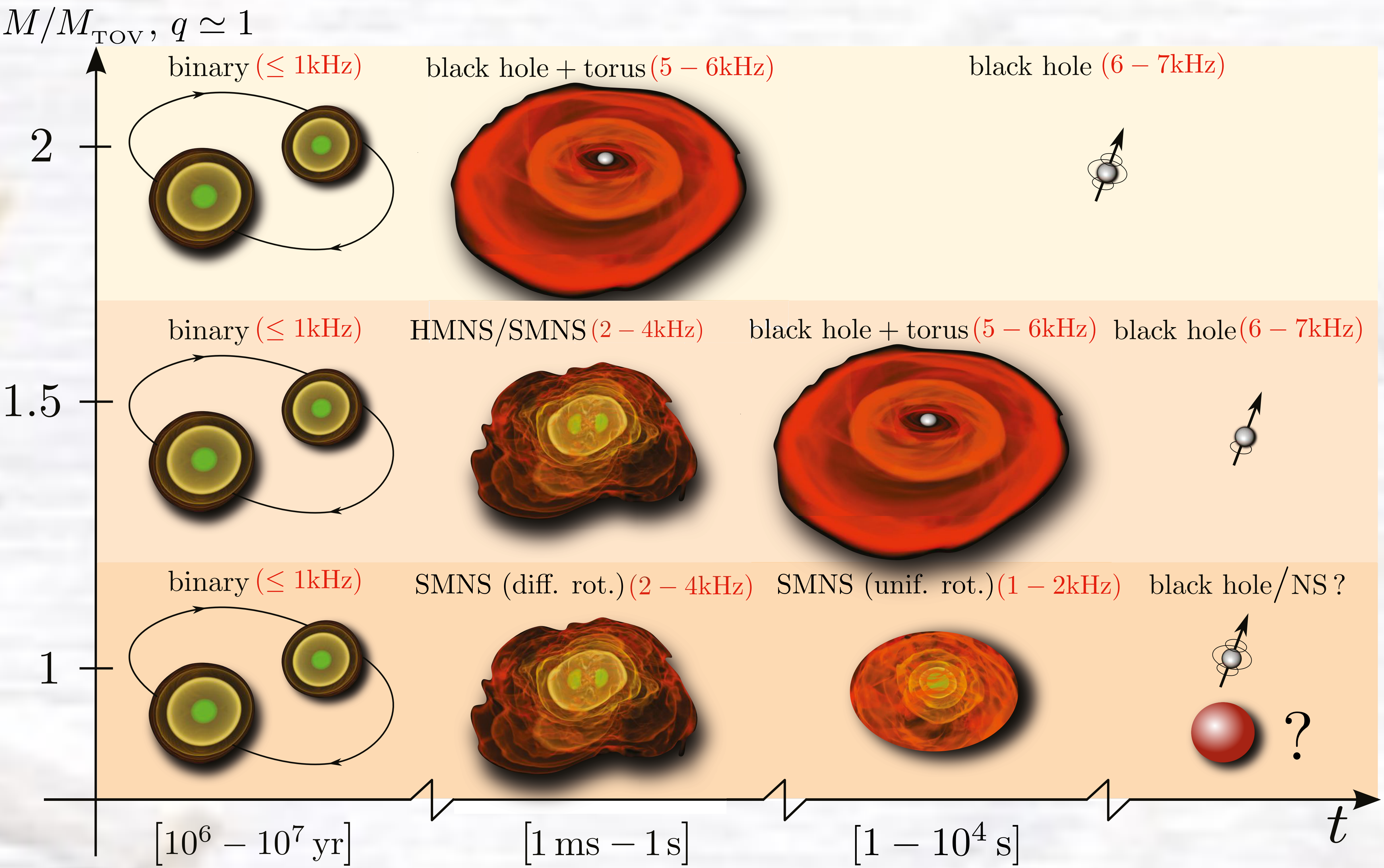


LCGT
Feel the Universe in Underground
- Detect Gravitational Waves from 200 Mpc Away -
37km from the Nippon Sea
Ikenoyama Mt.
1000m Underground
Mozumi area
XMASS
Kamland
Super Kamiokande
SG
CLIO
3km
358m Altitude
LCGT project
LCGT Image
Atotsu Entrance
Atotsu river
Takahara river
to Toyama
to Takayama
to Tateyama

Interest in binary neutron-star mergers



Dynamics of BNS



LB and Rezzolla, Reports on Progress of Physics 80, 2017

High-density EoS and BNS observations

Gravitational-wave and electromagnetic observations of BNS mergers can set constraints on the EoS by determining the

- Tidal deformability, from GWs from the (late) inspiral
- Maximum mass of a non-rotating compact star
- Amount of ejecta (kilonovae)
- **Post-merger frequencies**

Beyond equilibrium stars: BNS mergers

The post-merger phase can be used to probe higher densities and finite temperature.

- It is difficult to measure the maximum mass for a (non-rotating) NS
- Stars in equilibrium are not sensitive to the connection with pQCD
- Theoretical limits on the EOS depend somewhat on the implementation of pQCD constraints
- Studying the post-merger may be the only way to probe the connection to pQCD.

Post-merger phase

- Observations of the post-merger phase
  - Good point: Higher energy emission in GWs (in case of not prompt collapse).
  - Bad point: Emitted GW frequencies are higher, thus their signal-to-noise ratio in current and projected detectors is smaller than in the inspiral
    - Only marginally measurable by detectors like Advanced LIGO. Third-generation detectors are needed.
- Numerical simulations of the post-merger phase
  - Very difficult, because of turbulence, magnetic-fields instabilities, viscosity and other microphysical effects
  - Currently cannot reliably determine the phase of post-merger oscillations, but only the frequencies.

Simulations of binary neutron star mergers: Numerical relativity

Numerical relativity

Numerical relativity is the science of simulating (solving) general-relativistic dynamics on computers.

Problems with a straightforward discretization of the Einstein equations:

- formulation of the equations is not self-evident: e.g. time is not "simply" defined
- physical singularities may be present
- gauges play an important role (*e.g.*, to counteract grid stretching)
- numerical instabilities are present

The minimal set of equations to solve

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu} \qquad (\text{field eqs}: \; 6 + 6 + 3 + 1 \\ +1 + 3 + 1)$$

$$\nabla_\mu T^{\mu\nu} = 0 \, , \qquad (\text{cons. en./mom.}: \; 3 + 1)$$

$$\nabla_\mu (\rho u^\mu) = 0 \, , \qquad (\text{cons. of baryon no}: \; 1)$$

$$p = p(\rho, \epsilon, \ldots) \, . \qquad (\text{EoS}: \; 1 + \ldots)$$

A minimal set of equations to solve

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$$p = p(\rho, \epsilon, \ldots) \ . \qquad (\text{EoS}: \ 1 + \ldots)$$

$$\nabla^*_\nu F^{\mu\nu} = 0, \qquad (\text{Maxwell eqs.}: \ \text{induction}, \ \text{zero div.})$$

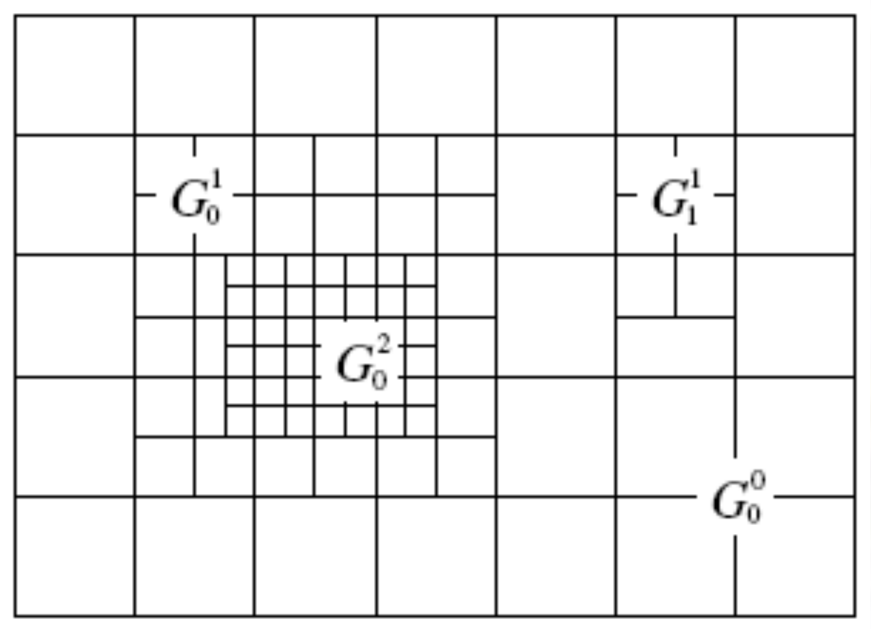
$$T_{\mu\nu} = T^{\text{fluid}}_{\mu\nu} + T^{\text{em}}_{\mu\nu} + \ldots$$

+ viscosity, radiation transport,...

The complete set of equations is solved numerically, with high-order finite differencing for the spacetime, and finite volume (high-resolution shock-capturing schemes) for matter or more advanced methods.

Carpet: a mesh-refinement driver

Schnetter et al. CQG 21, 1465 (2004); www.carpetcode.org



Carpet follows a (simplified) Berger-Oliger [J. Comput. Phys. 53, 484 (1984)] approach to mesh refinement, that is:

- refined subdomains consist of a set of cuboid (= rectangular parallelepiped) grids
- refined subdomains have boundaries aligned with the grid lines
- the refinement ratio between refinement levels is constant

No automatic move/creation of refined meshes, but they can be activated and deactivated during the evolution, obtaining moving-grid mesh refinement and progressive refinement.

WhiskyTHC: hydrodynamics code

Radice et al. MNRAS 437 http://personal.psu.edu/dur566/whiskythc.html

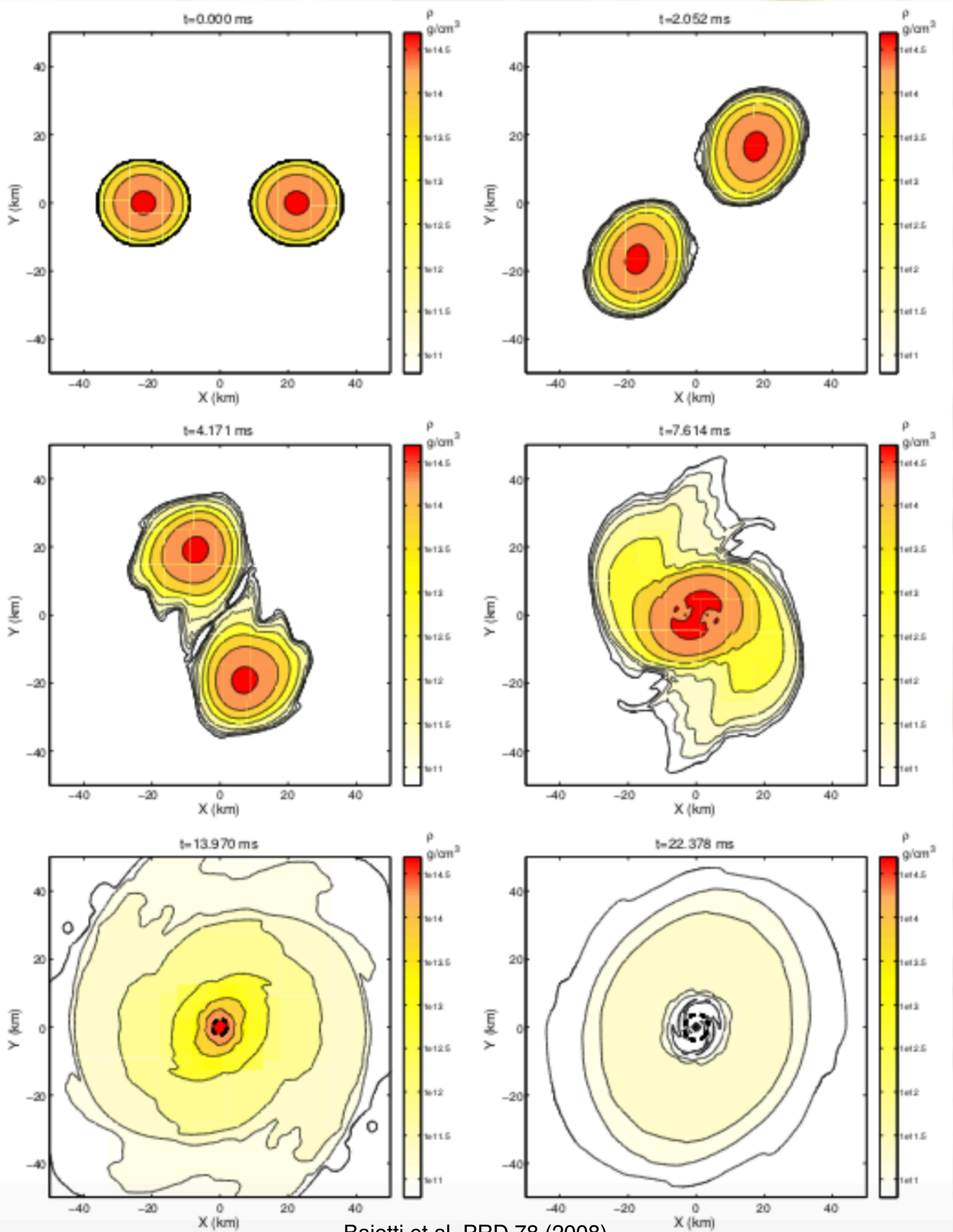
High-order flux-vector—splitting finite-differencing techniques (Radice Rezzolla A&A 547)

MP5 scheme (Suresh Huynh, Journal of Computational Physics 136) for reconstruction

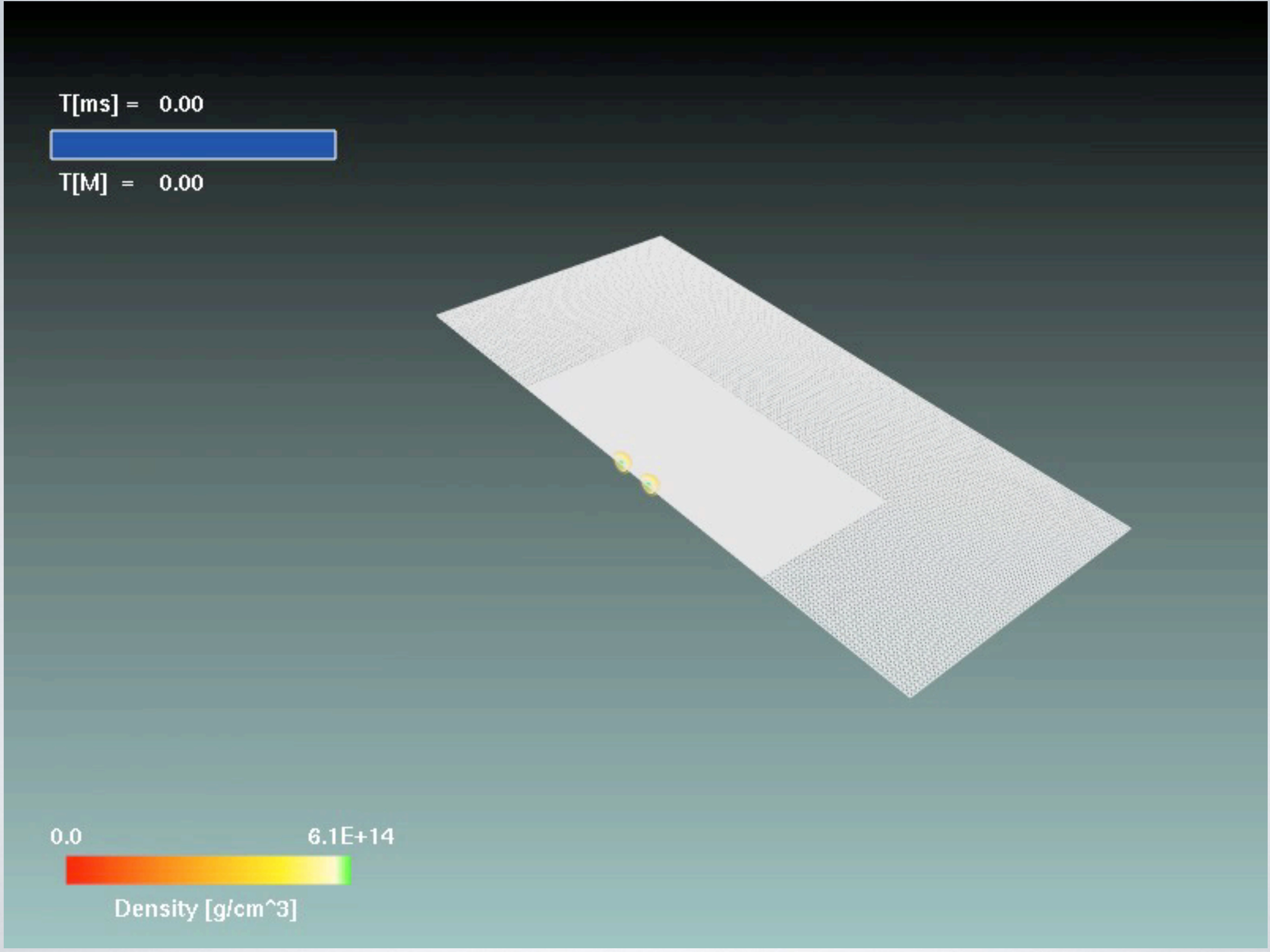
"Templated" refers to C++ *template metaprogramming*, in which part of the code is generated at compile time.

The post-merger phase
of binary neutron star mergers

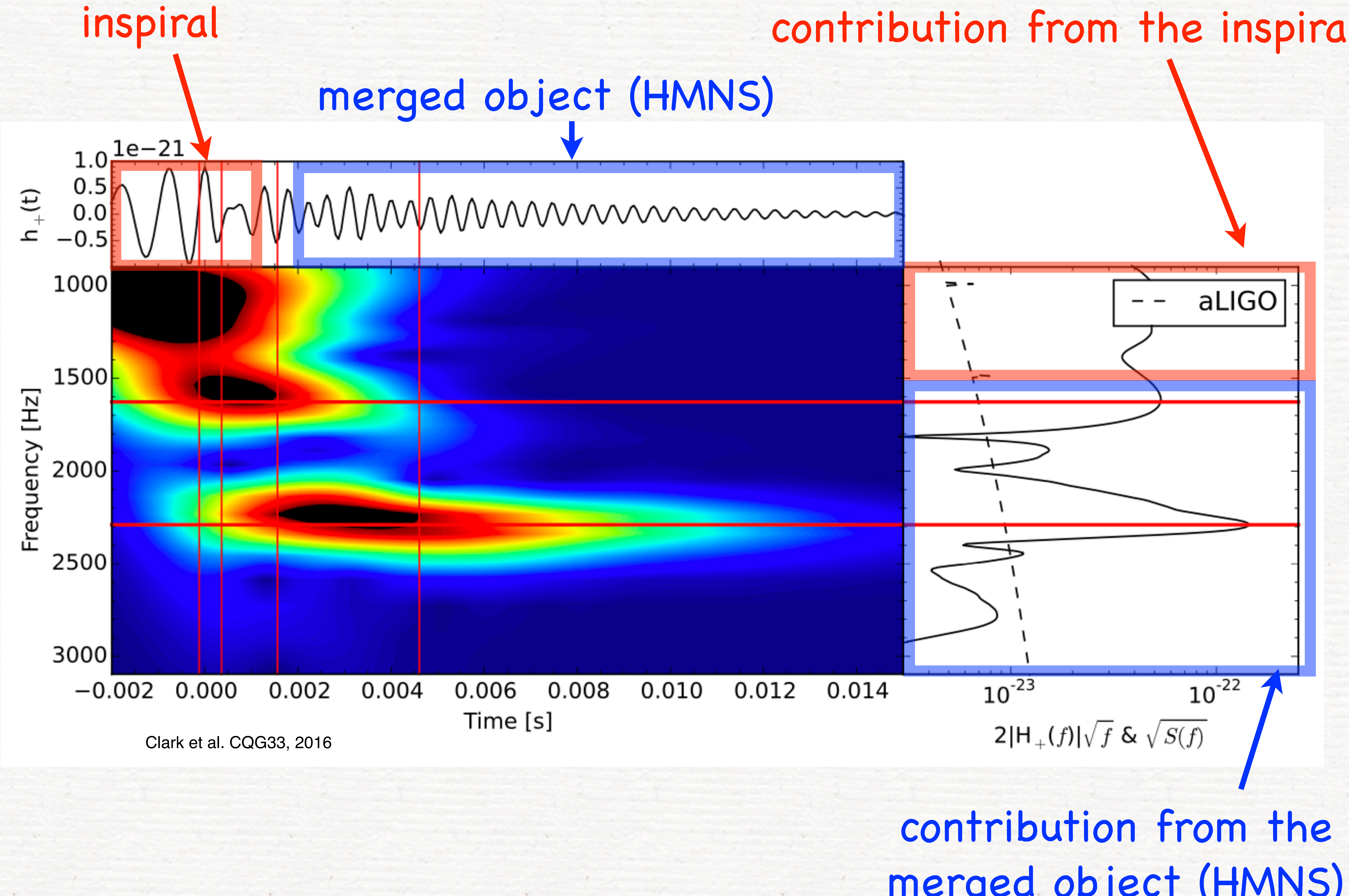
Dynamics of BNS



Baiotti et al. PRD 78 (2008)

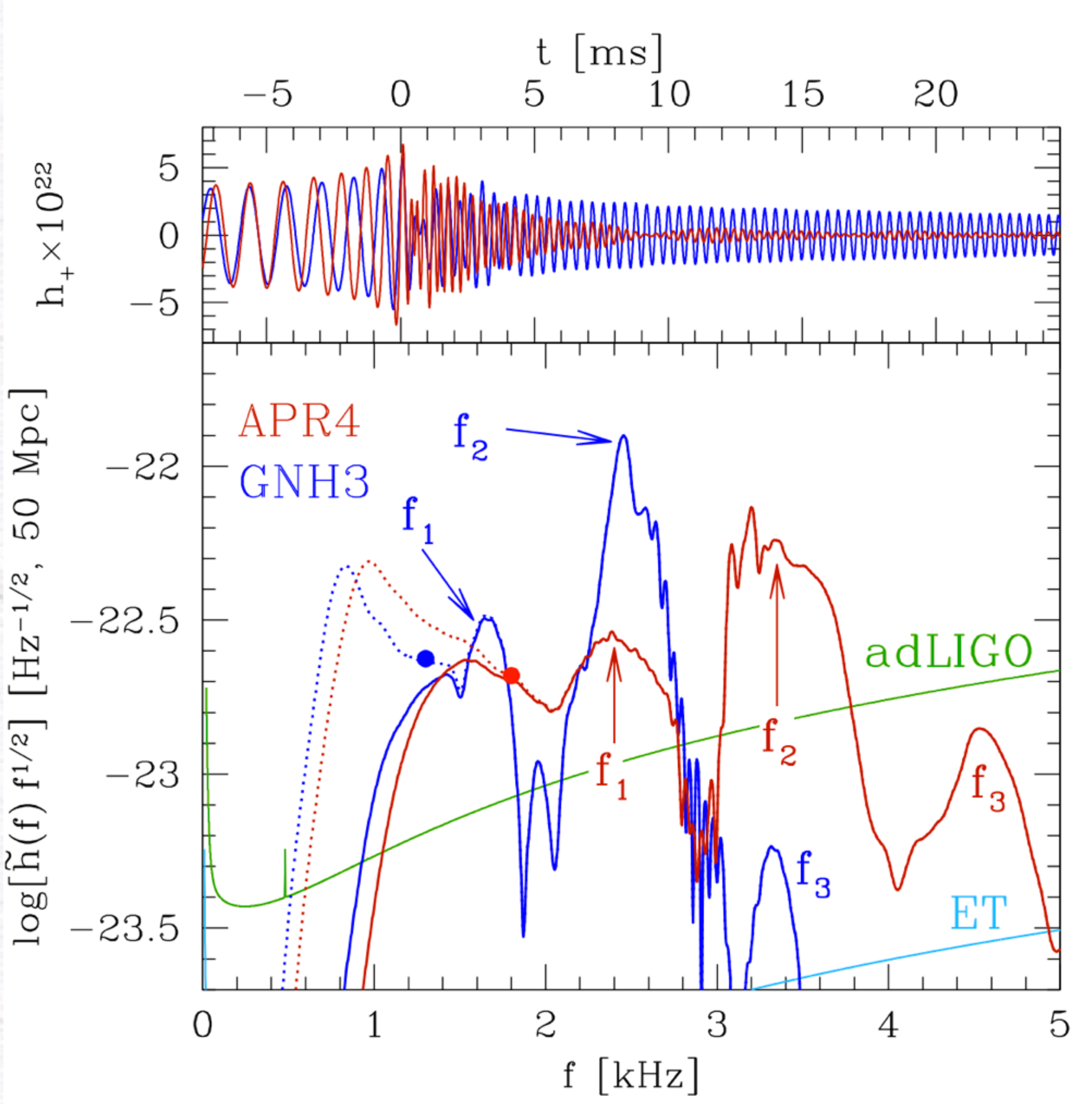

T[ms] = 0.00
T[M] = 0.00
0.0
6.1E+14
Density [g/cm^3]

Gravitational waves from binary neutron stars

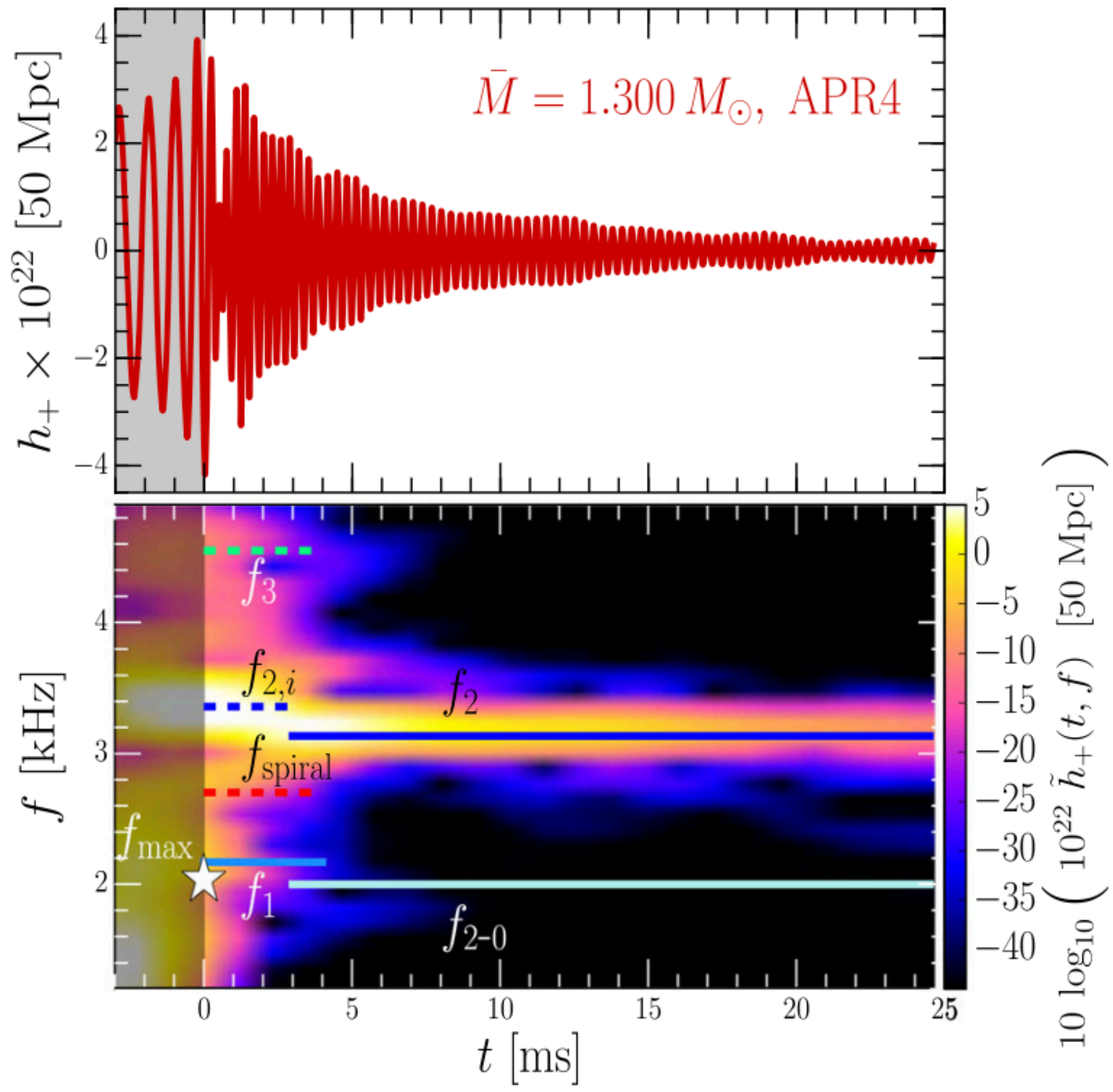


Peaks in the merger and post-merger spectra

- f_1 is related to the merger
- f_2 is related to the rotation and oscillations of the merged star
- f_3 has not been well interpreted yet



Takami et al. PRL113, 2014; PRD91, 2015



Rezzolla Takami PRD93, 2016

Phase transitions / crossover and gravitational waves

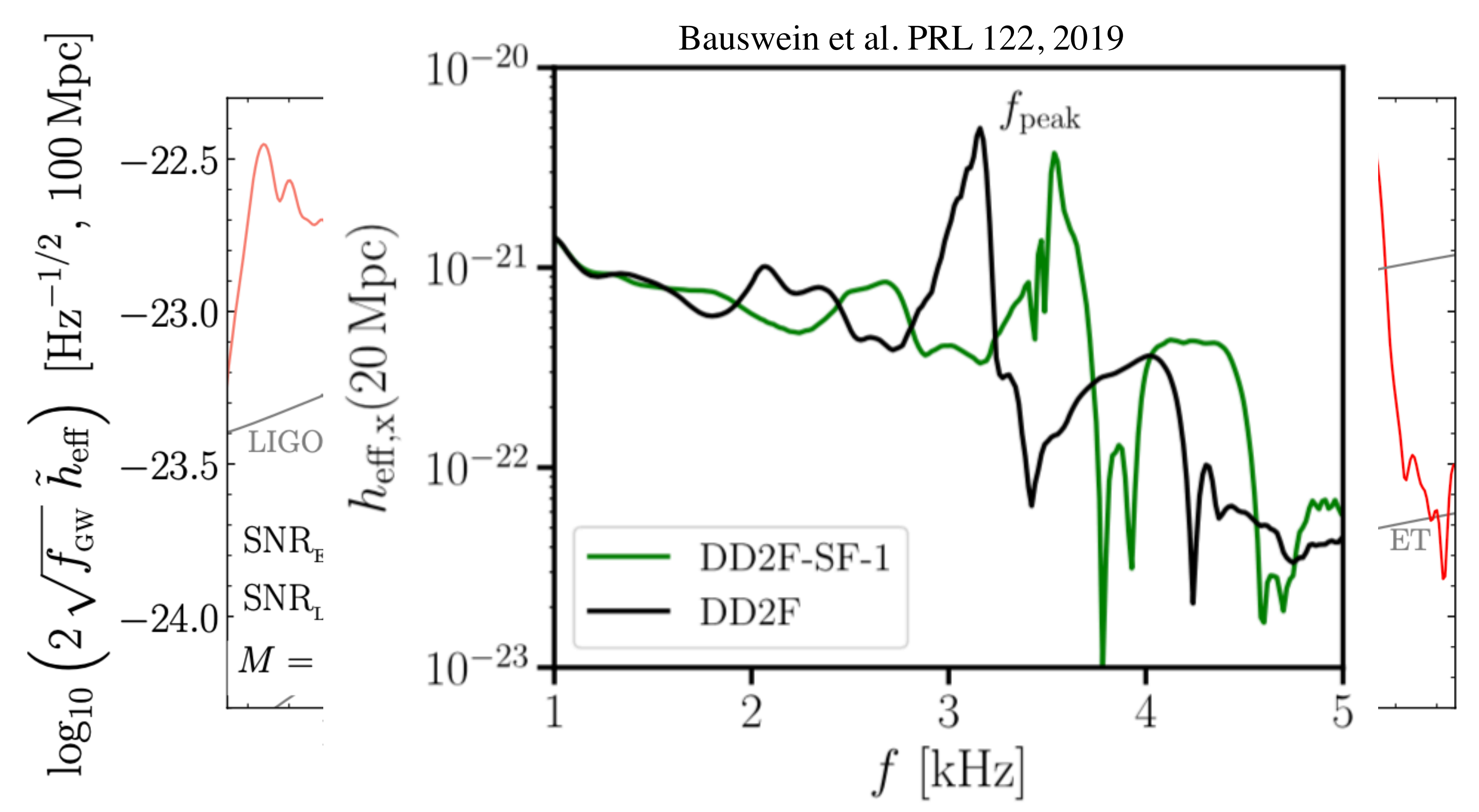
- **No phase transitions / crossovers → strong correlation** between

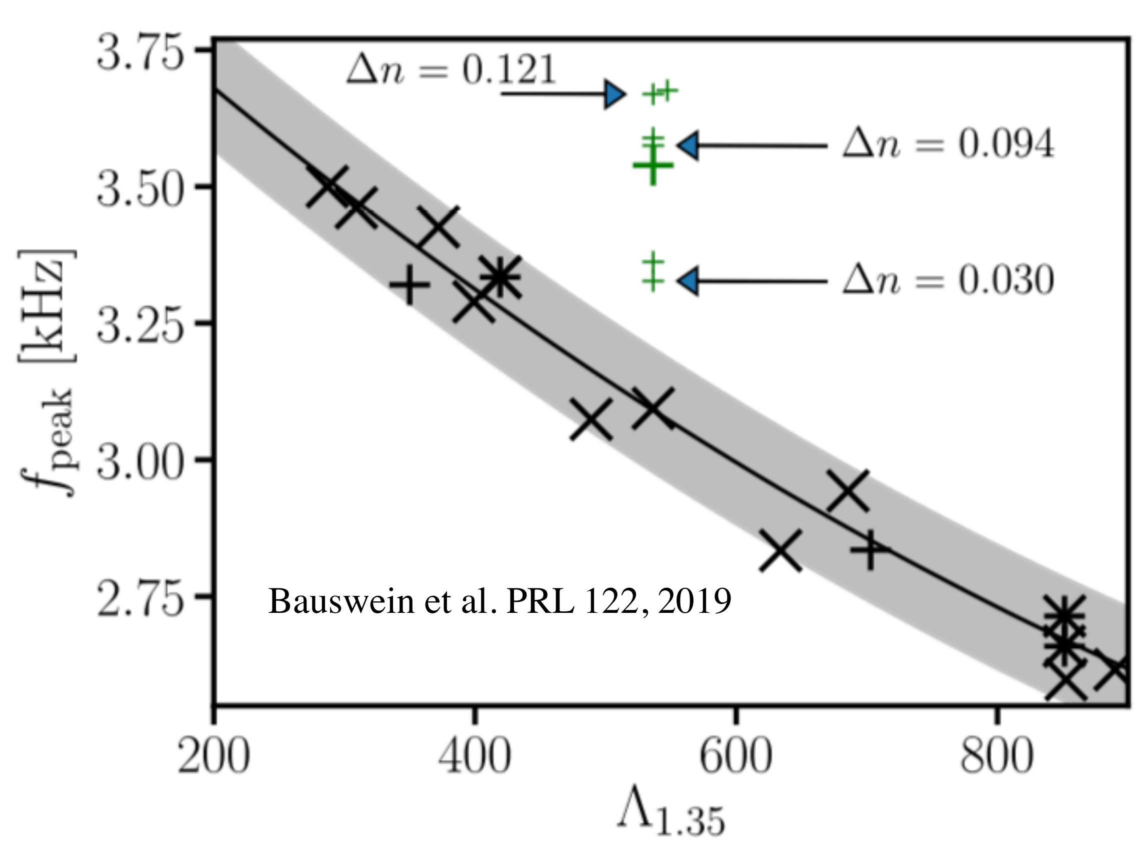
main peak frequencies of the post-merger spectrum	and	properties of a zero-temperature spherical equilibrium neutron star

See, e.g., Bauswein Janka, PRL 108, 2012; Bauswein et al. PRD 86, 2012; Takami et al. PRL 113, 2013; Bauswein et al. PRL 11, 2013; Bauswein et al. PRD 90, 2014; Takami et al. PRD 91, 2015; Rezzolla, K. Takami, PRD 93, 2016; Foucart et al. PRD 93, 2016; Lehner et al. CQG 33, 2016; De Pietri et al. PRD 93, 2016; Maione et al. PRD 96, 2017; Kiuchi et al. PRD 101, 2020; our review RPP 80, 2017

- If **phase transitions** affect GW emission → **no correlation**

See, e.g., Bauswein et al. PRL122, 2019; Most et al. PRL 122, 2019; Weih et al. PRL 124, 2020; Blacker et al. PRD102, 2020; Liebling et al. CQG 38, 2021.



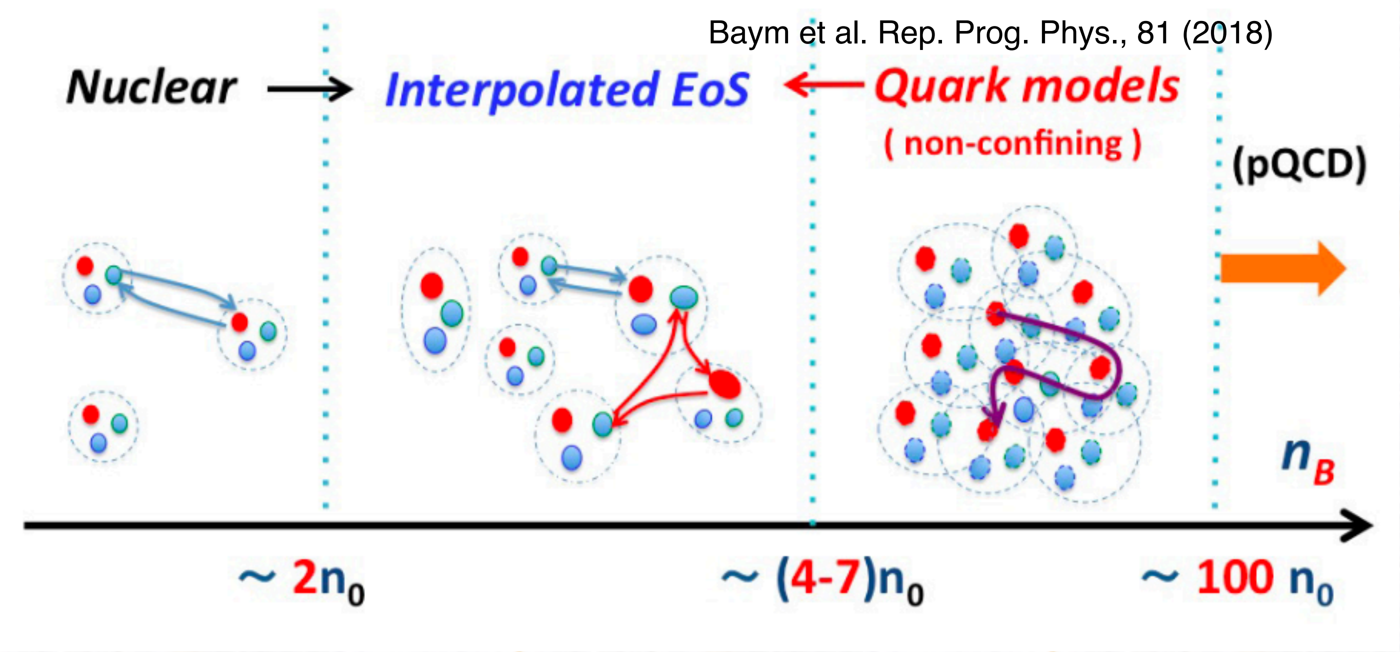


Simulations of
binary neutron star mergers
with a
quark-hadron crossover
or **first-order phase transition**
in the
equation of state

Huang et al. PRL 129, 2022; Hensh et al. arXiv:2407.09446

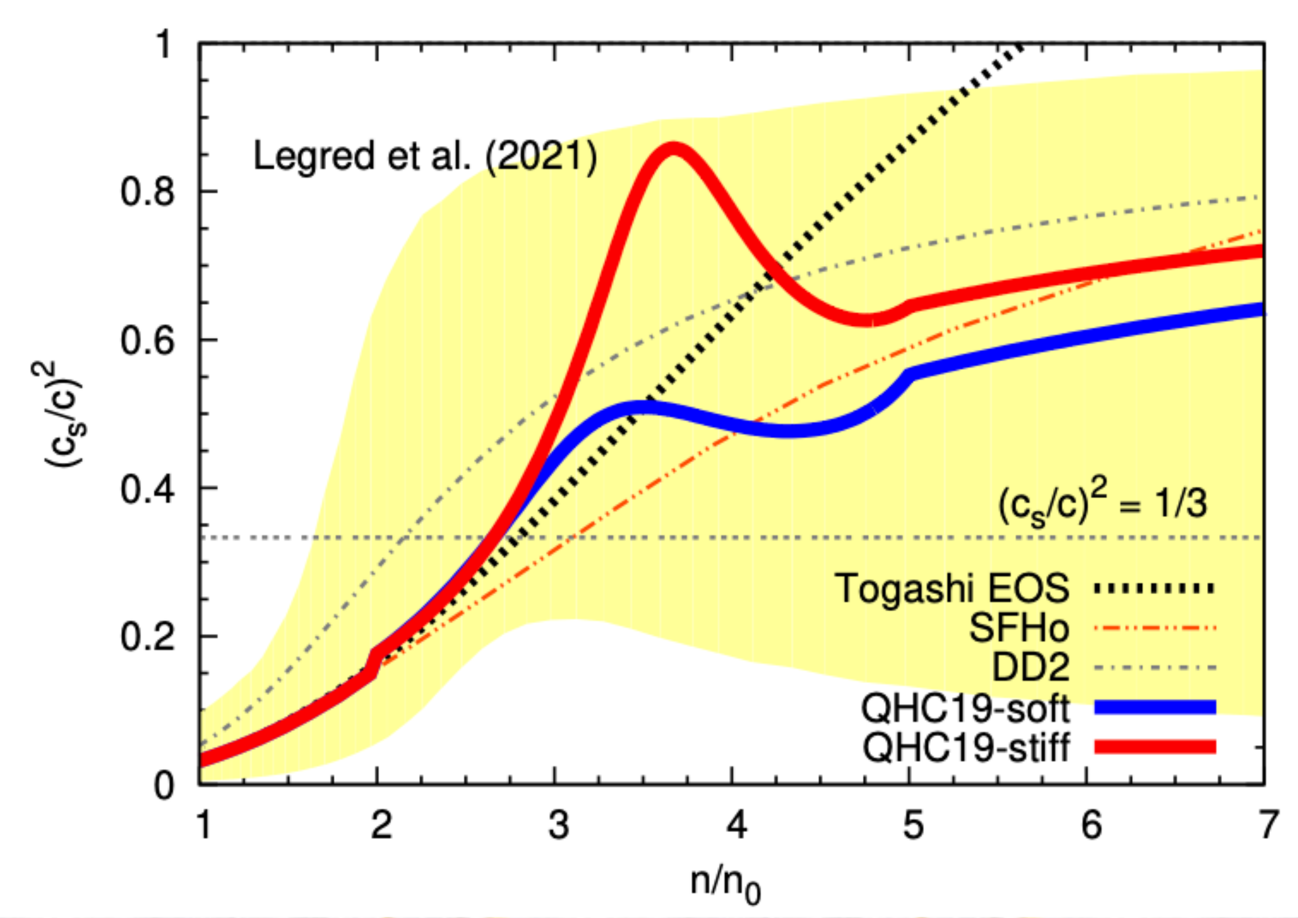
QHC19

- In our previous work (Huang et al. PRL 129, 2022), we used **QHC19 EoSs** (Baym et al. ApJ 885, 2019):
  - at low-end densities: the nucleonic-matter Togashi EoS (Togashi et al. Nuclear Physics A 961, 2017),
  - at high-end densities: the strongly interacting quark-matter EoS of the Nambu–JonaLasinio model (Nambu Jona-Lasinio Phys. Rev. 122, 1961),
  - and a thermodynamically consistent interpolation of pressure between the two regimes

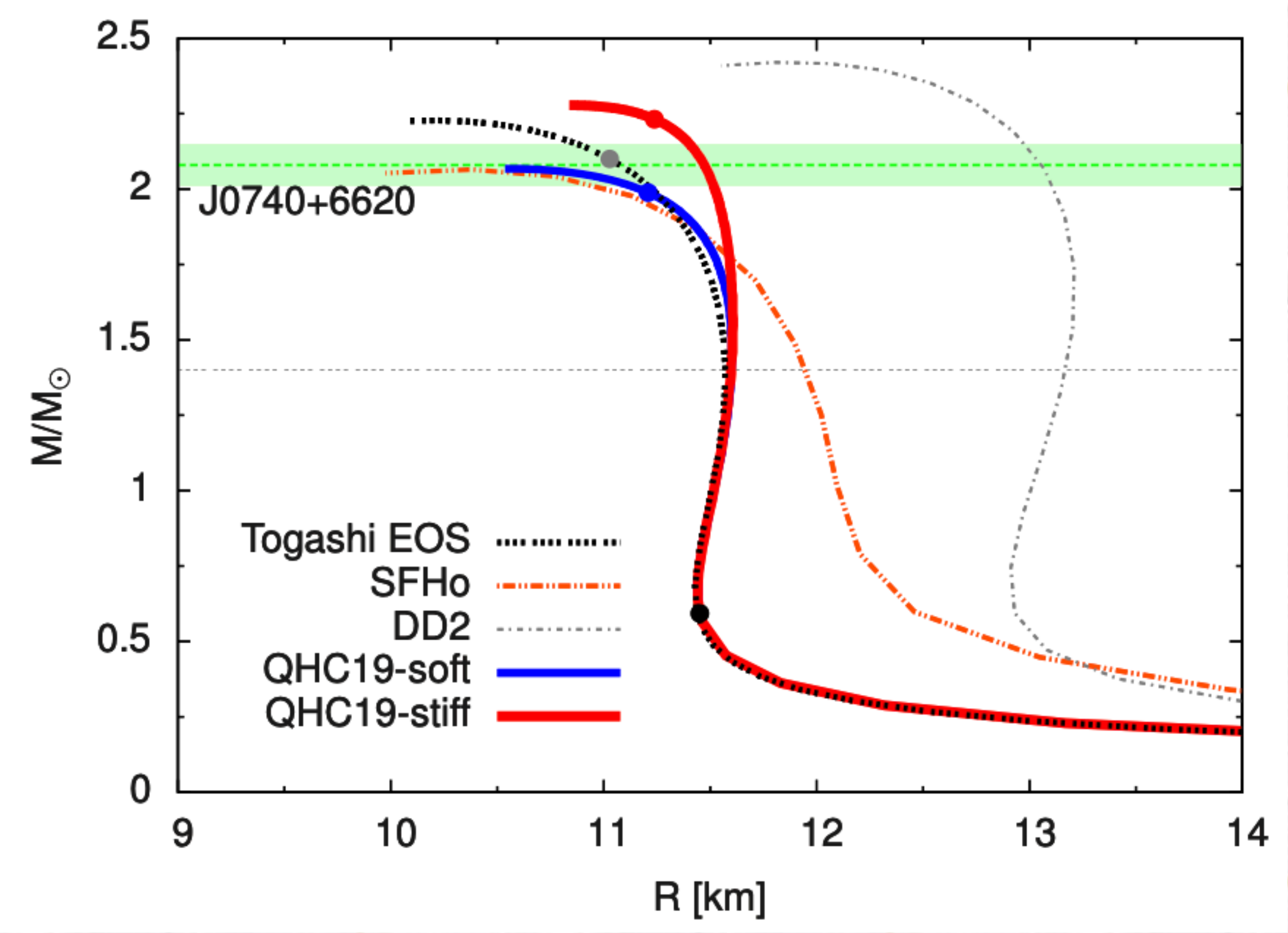


Properties of QHC19

Peak in the speed of sound



Mass-radius relation



Thermal part of the equation of state

- QHC19 is a *cold* EoS (zero temperature)
- Mimic thermal effects by adding to the pressure given by the cold EoS a component calculated by assuming an ideal-gas behaviour with a constant ideal-gas index Γ_{th}.

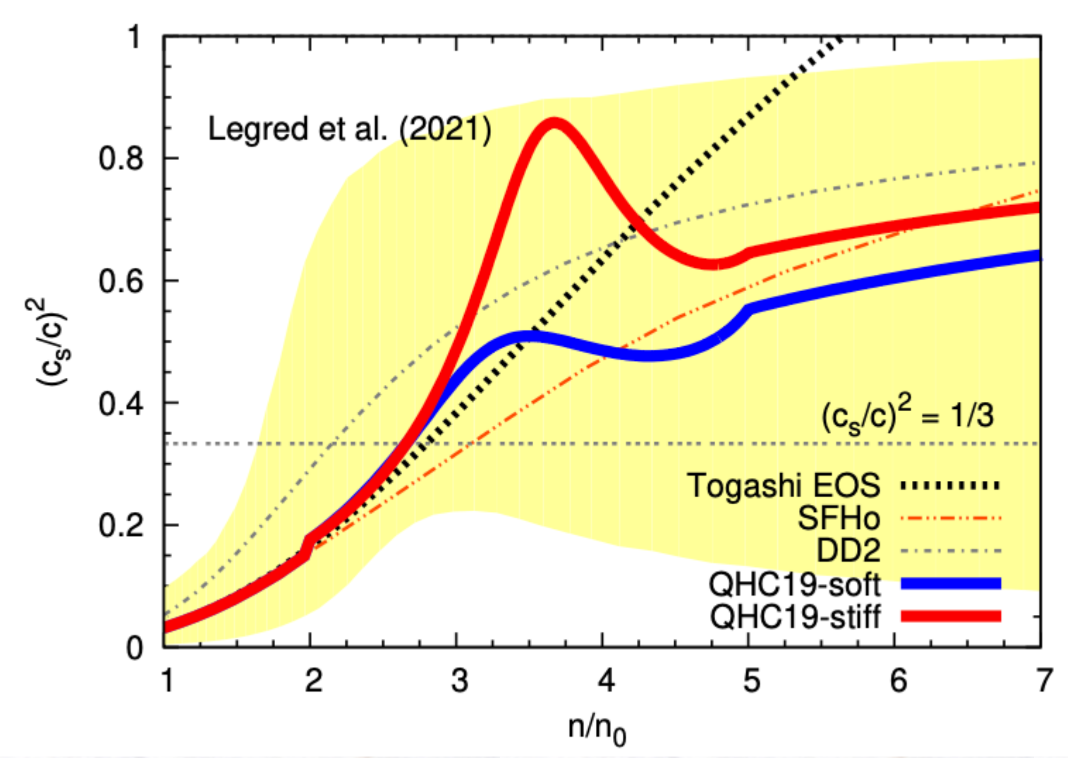
Codes for numerical simulations and initial configurations

- Fully general-relativistic hydrodynamics simulations (numerical relativity)
- WhiskyTHC code, Einstein Toolkit framework
- Adaptive-mesh refinement (Carpet code), with seven mesh-refinement levels
- Equal mass models
- Models with gravitational masses of each NS at infinite separation

  $M/M_\odot$ = 1.250, 1.300, 1.350, 1.375.

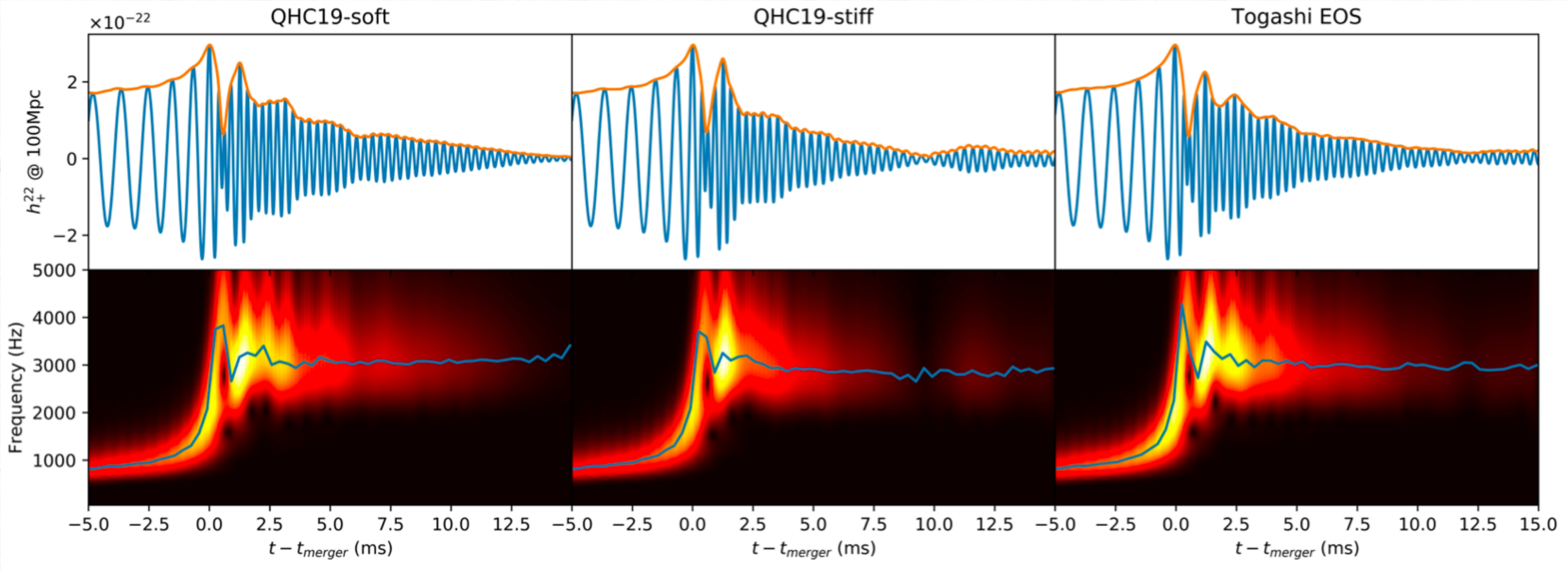
  (Names of models: M1.25, M1.30, M1.35, M1.375, respectively)
- Quasiequilibrium irrotational BNSs at a separation of 45 km
  - Last 5~7 orbits (depending on the model)

Gravitational waveforms and spectrograms



- No differences before the merger
- After the merger, QHC produces notable effects

Gravitational waveforms and spectra

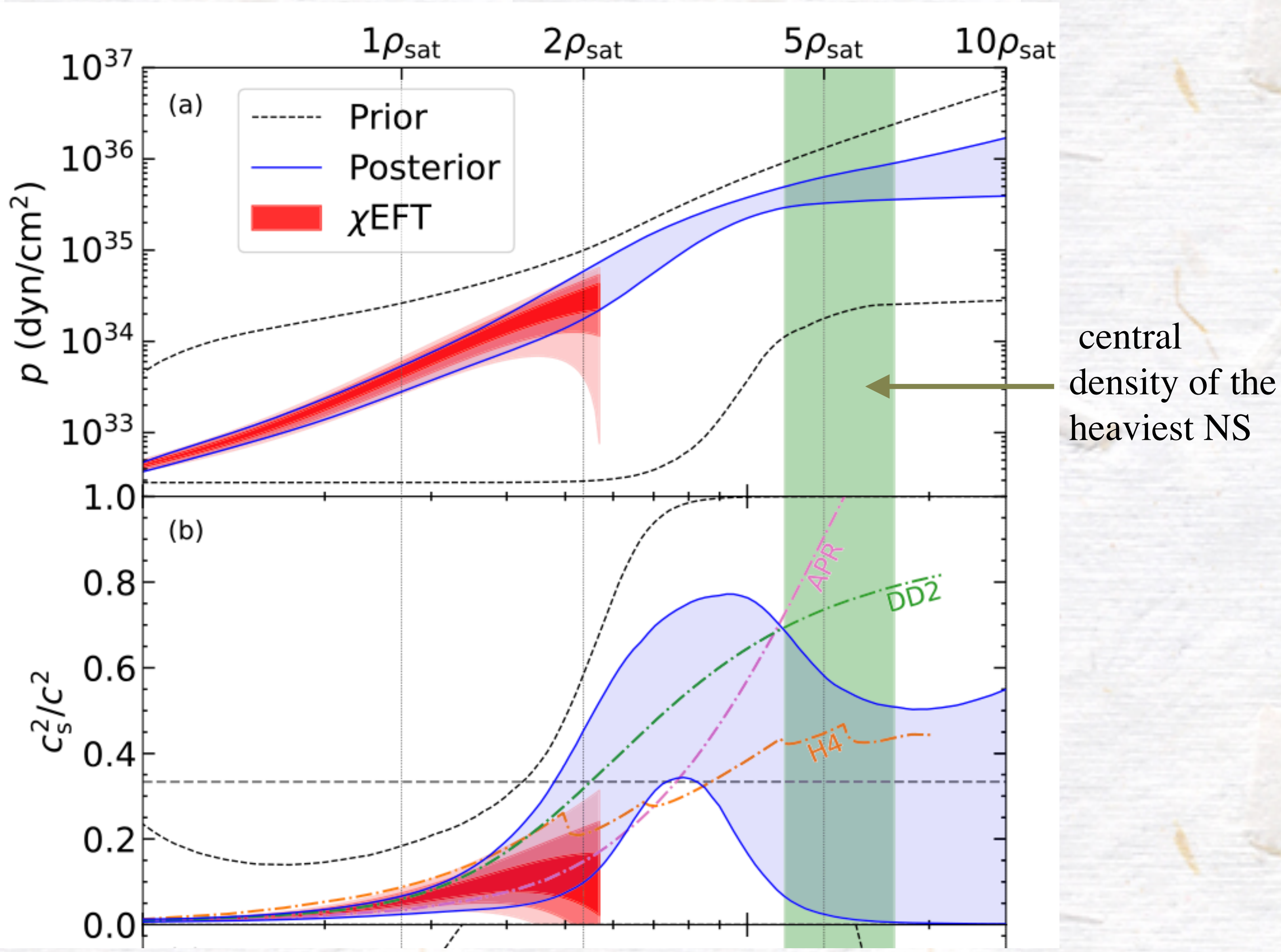


QHC21

Current observations:

- there is a very rapid growth of pressure with density in the range ~2–4 n_0
- substantial softening of matter (as per a strong first-order phase transition) between 2–3 n_0 and 4–5 n_0 is disfavored

Han, **Huang**, Tang, Fan, Science Bulletin 68, 2023



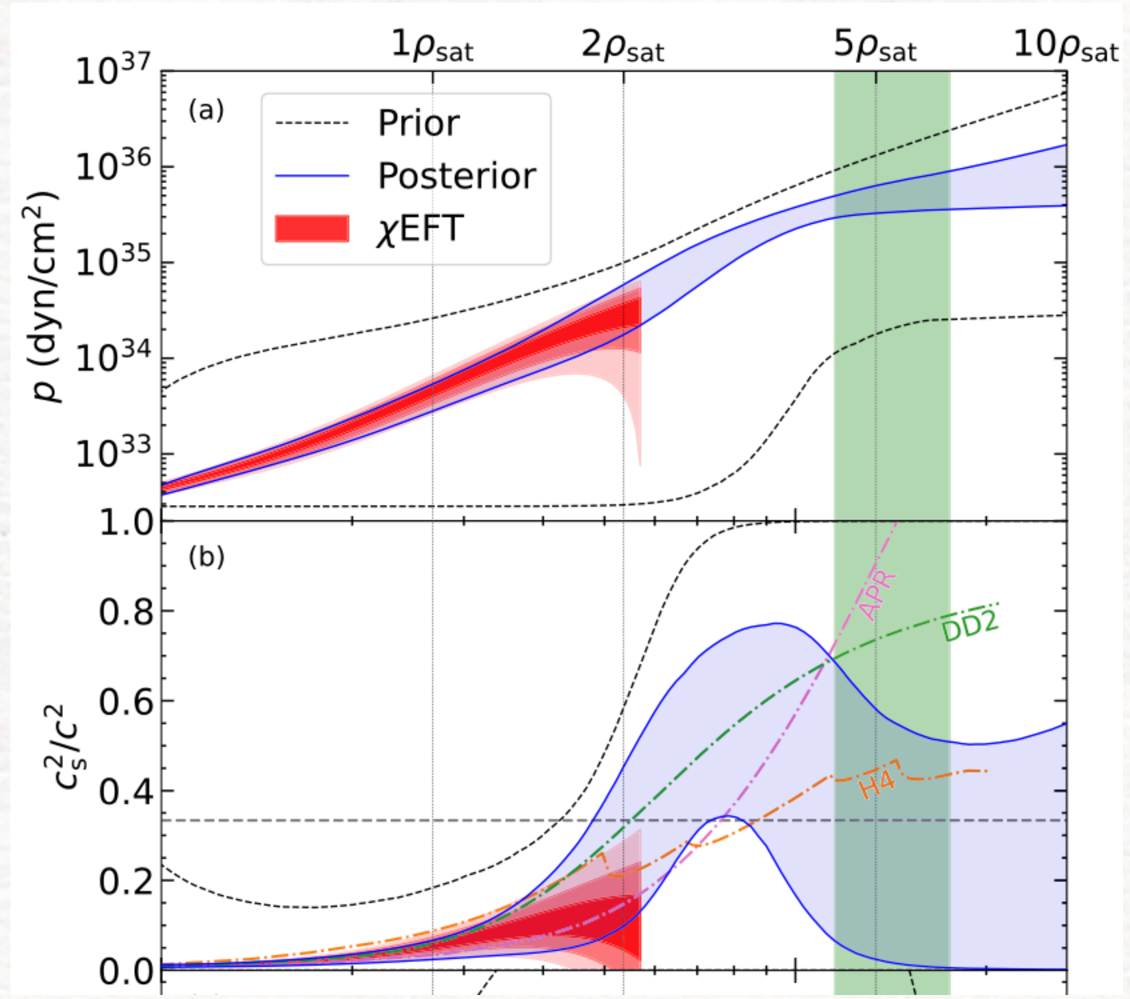
The red regions with different transparencies are credible intervals of the χEFT truncation errors.

QHC21

A new QHC EOS: QHC21 (Kojo et al., ApJ 943, 2022)

- Lower end (below ~1.5 n_0): two versions, covering the uncertainty range of microscopic nuclear calculations at lower densities.
  - Version 1: Chiral effective field theory (χEFT) EOS (Lonardoni et al. PRR 2, 2020; Drischler et al. Ann.Rev.Nucl.Part.Phys 71; PRC 103, 2021)
  - Version 2: Togashi EOS (Togashi et al. Nuclear Physics A 961, 2017)
- Upper end (from 3.5 n_0):
  - the Nambu–JonaLasinio (NJL) model (Nambu Jona-Lasinio Phys. Rev. 122, 1961)
- Transition region in between:
  - a smooth and highly constrained interpolation:
    - matching with the nuclear and quark matter EOSs at the boundaries of the crossover region (pressure and first and second derivatives of pressure with respect to the baryon chemical potential)
    - causality
    - thermodynamical stability

Our EoS with a phase transitions



Phase transitions seem disfavored by current observations, analyses, and statistical studies (see, *e.g.,* Han et al. Science Bulletin 68, 2023; Brandes et al. PRD108, 2023; Christian et al. PRD109, 2024).

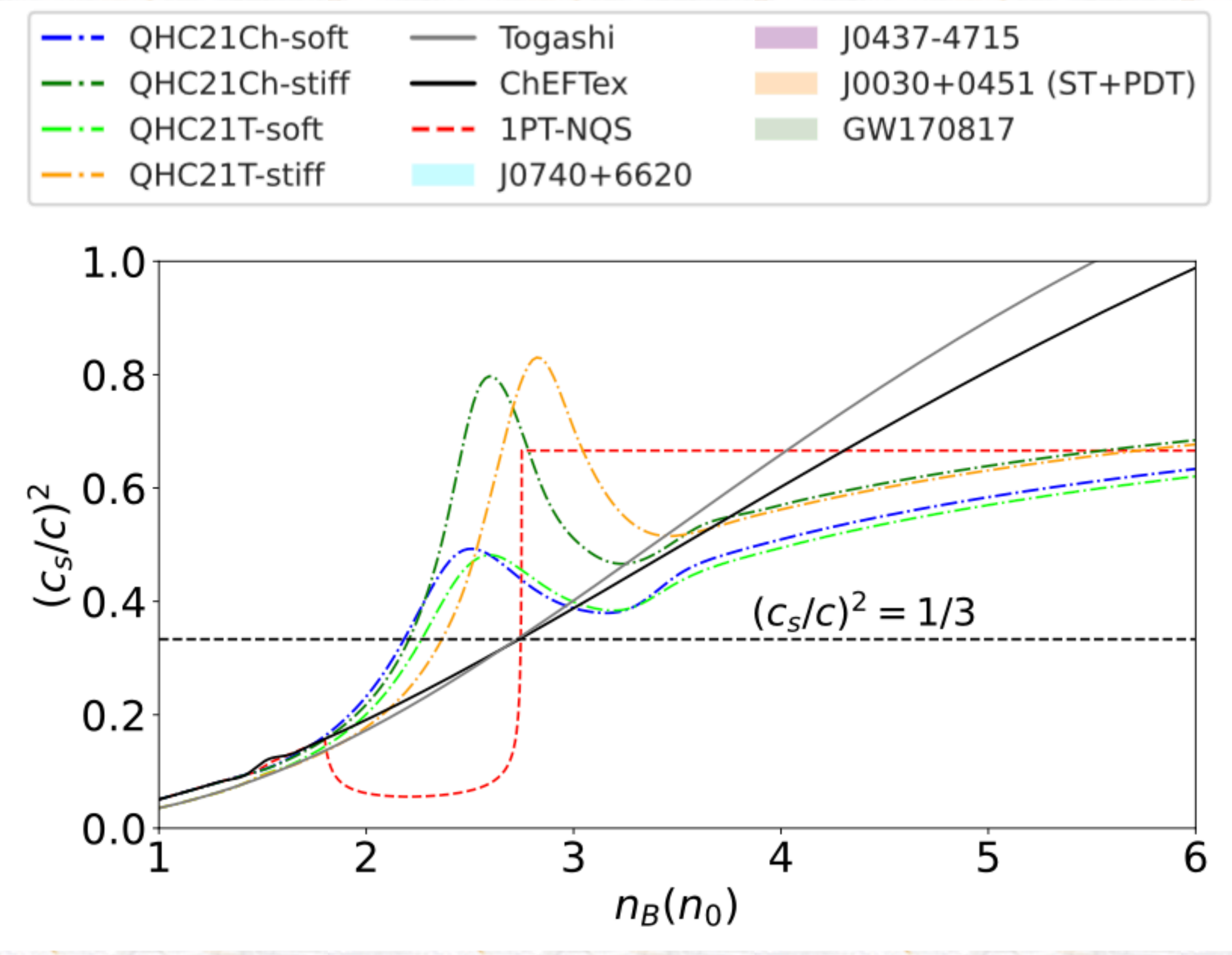
Still viable are:

- phase transitions occurring at higher density → Only very massive NSs would contain quark matter (these would undergo prompt collapse in a binary merger).
- phase transitions occurring at lower density → Quark matter is present in most neutron stars, even before the merger.

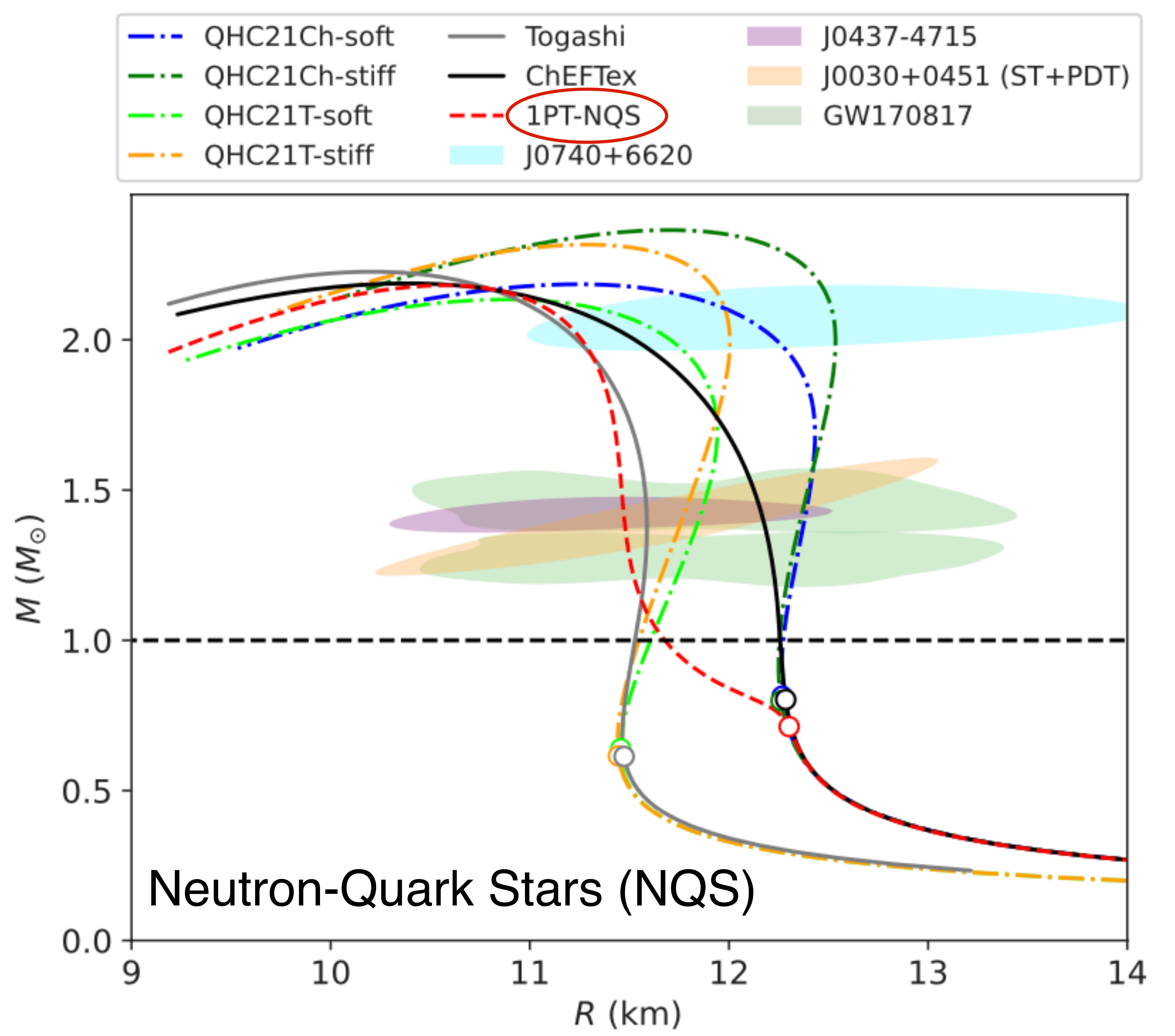
Our choice of EOS with first-order phase transition

- χEFT EOS up to $1.8n_0$
- The first-order phase transition starts at $\simeq 1.8n_0$ and ends at $\simeq 2.75n_0$.
- Constant-sound-speed parametrization: $(c_s)^2 = 2/3$ in the quark-matter part
- Note that the NSs already contain quark matter before the merger

- Since it is challenging to produce initial data that contain discontinuities, we smoothed out discontinuities in $(c_s)^2$
- To avoid any thermodynamic inconsistency, such smoothing was done at the level of $P(\mu_B)$
- Mimic thermal effects by adding an ideal-gas component to the pressure

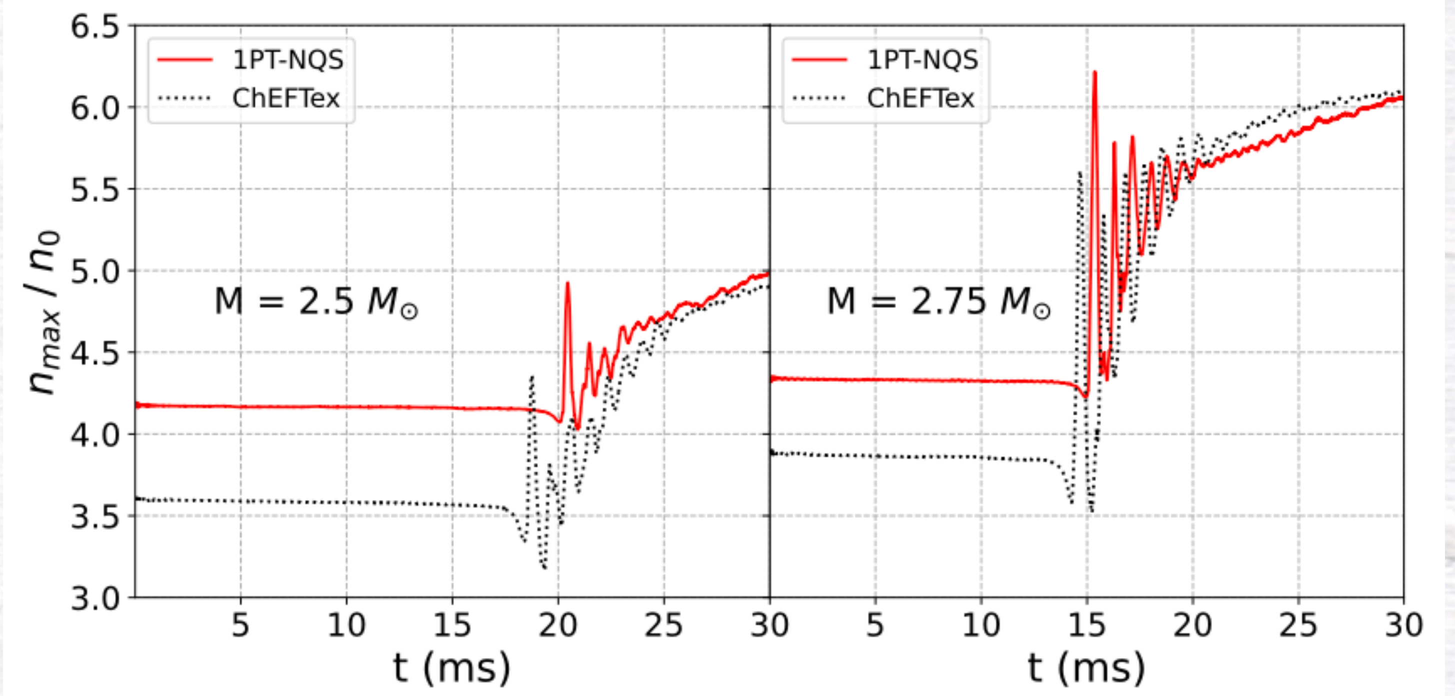


Mass-radius relations

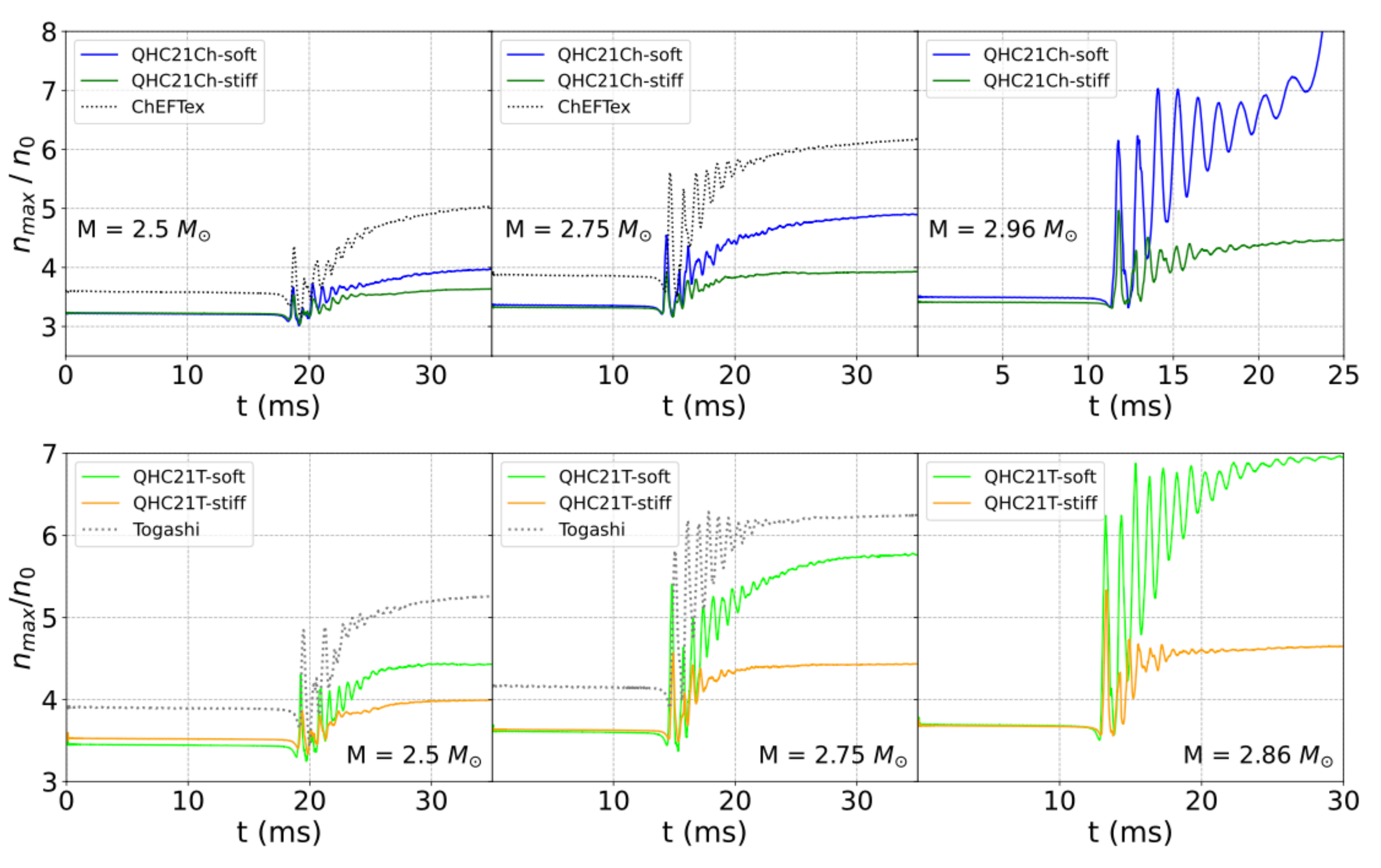


Open circles represent the theoretical NSs whose central density is $2n_0$.

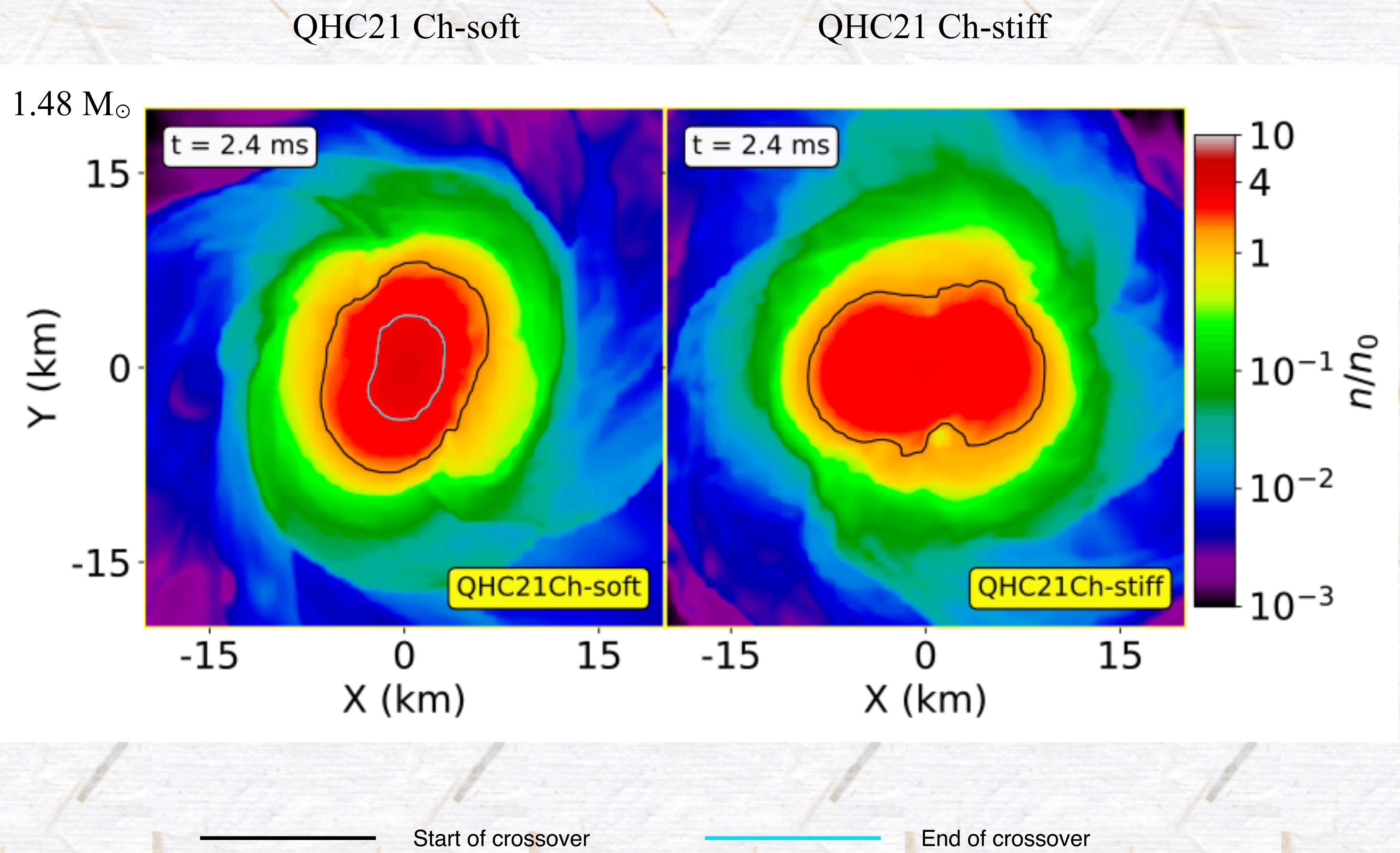
Time evolution of the maximum of the rest-mass density (number density)



Equal mass models with gravitational masses of each NS at infinite separation $M/M_\odot$ = 1.250, 1.375, 1.430~1.480.

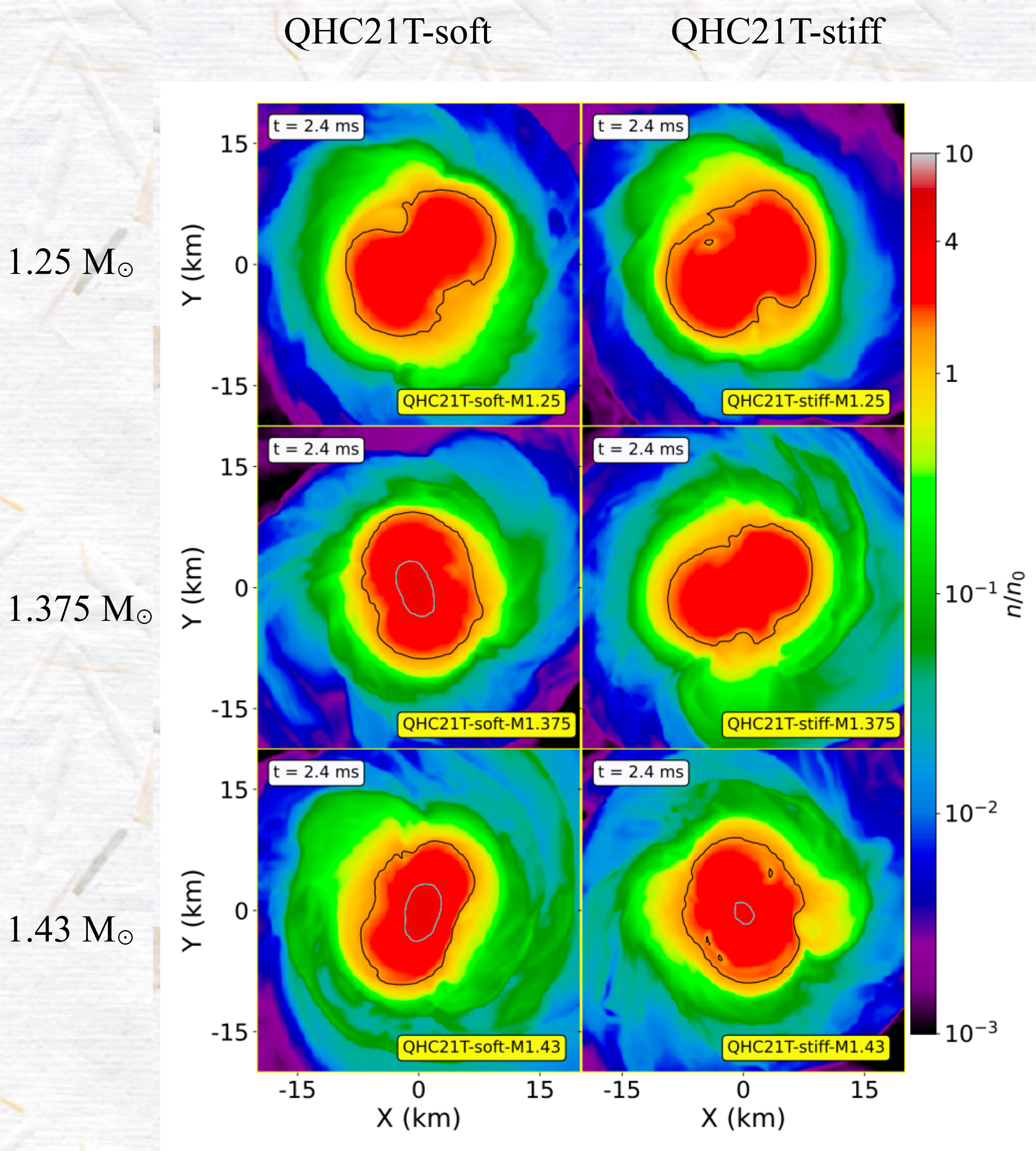


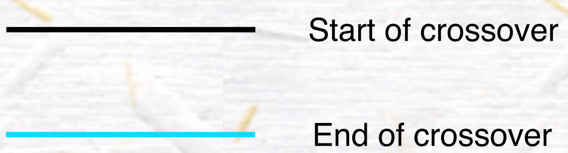
2D rest-mass density snapshots: QHC EOSs



approximately 2.4 ms after the merger

2D rest-mass density snapshots: QHC EOSs



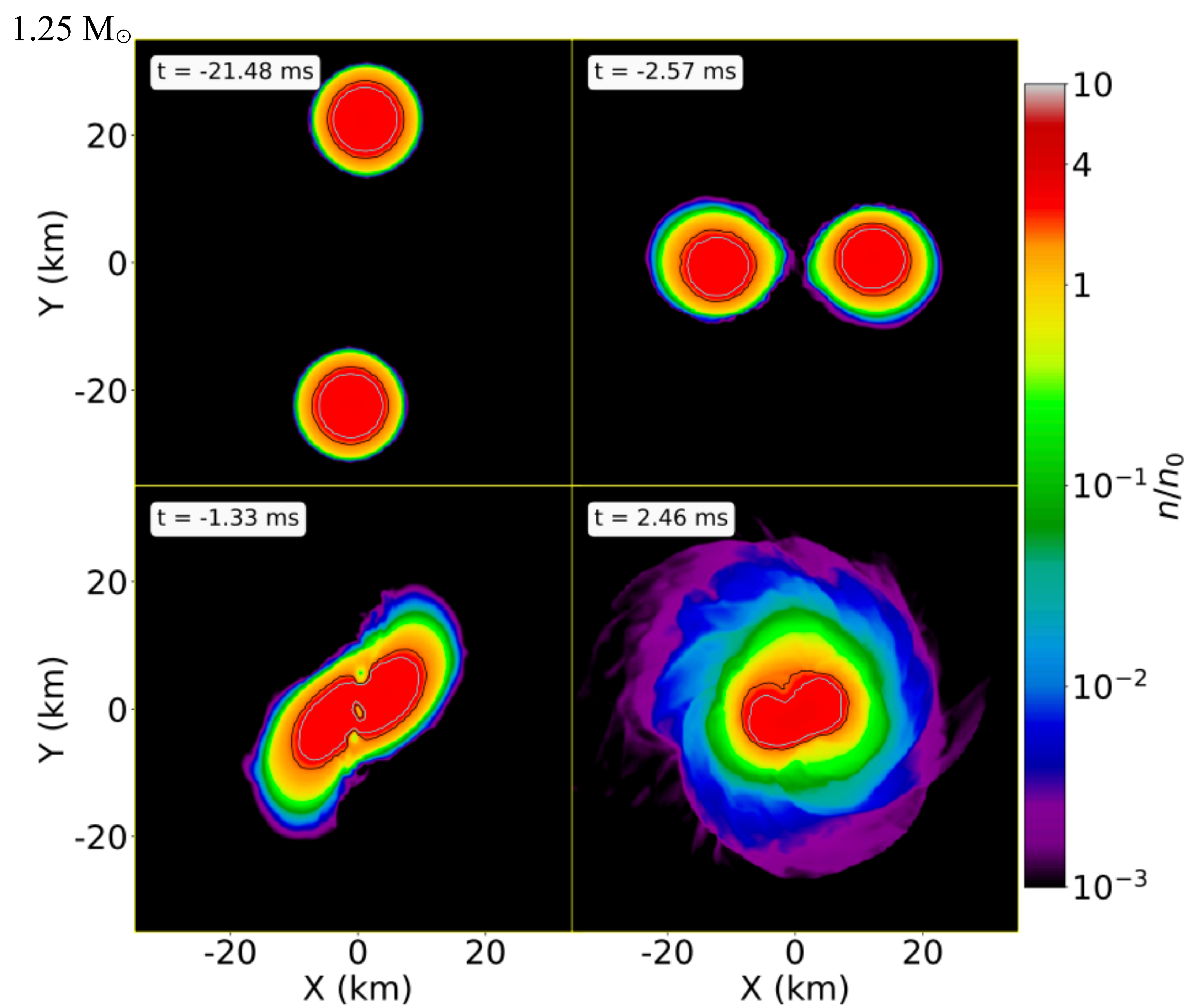


approximately 2.4 ms after the merger

2D rest-mass density snapshots: 1PT EOS

Start of 1PT

End of 1PT



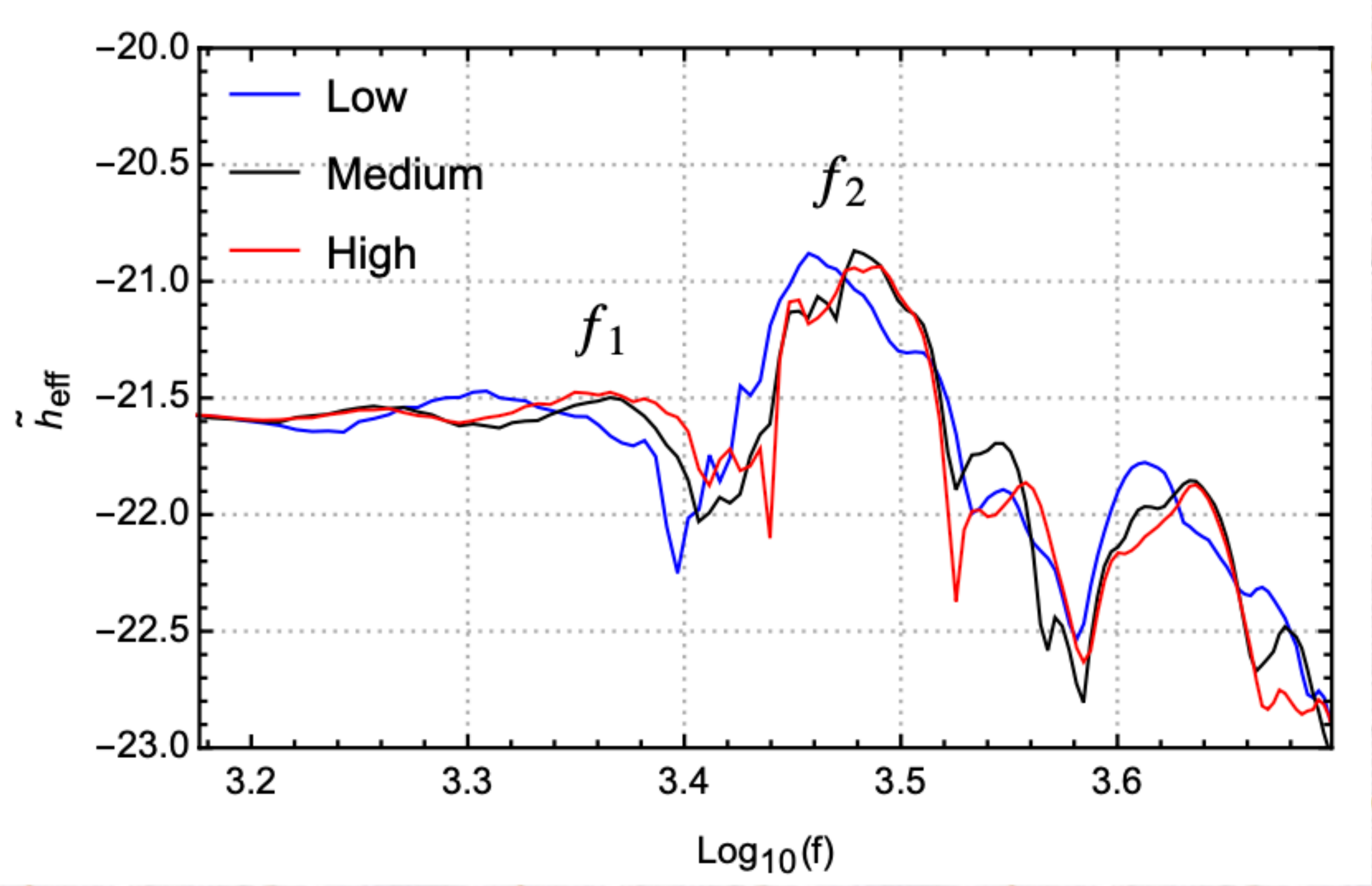
t=0 is the time of the merger

Gravitational wave spectra: Fitting of the gravitational-wave spectra to find f_2

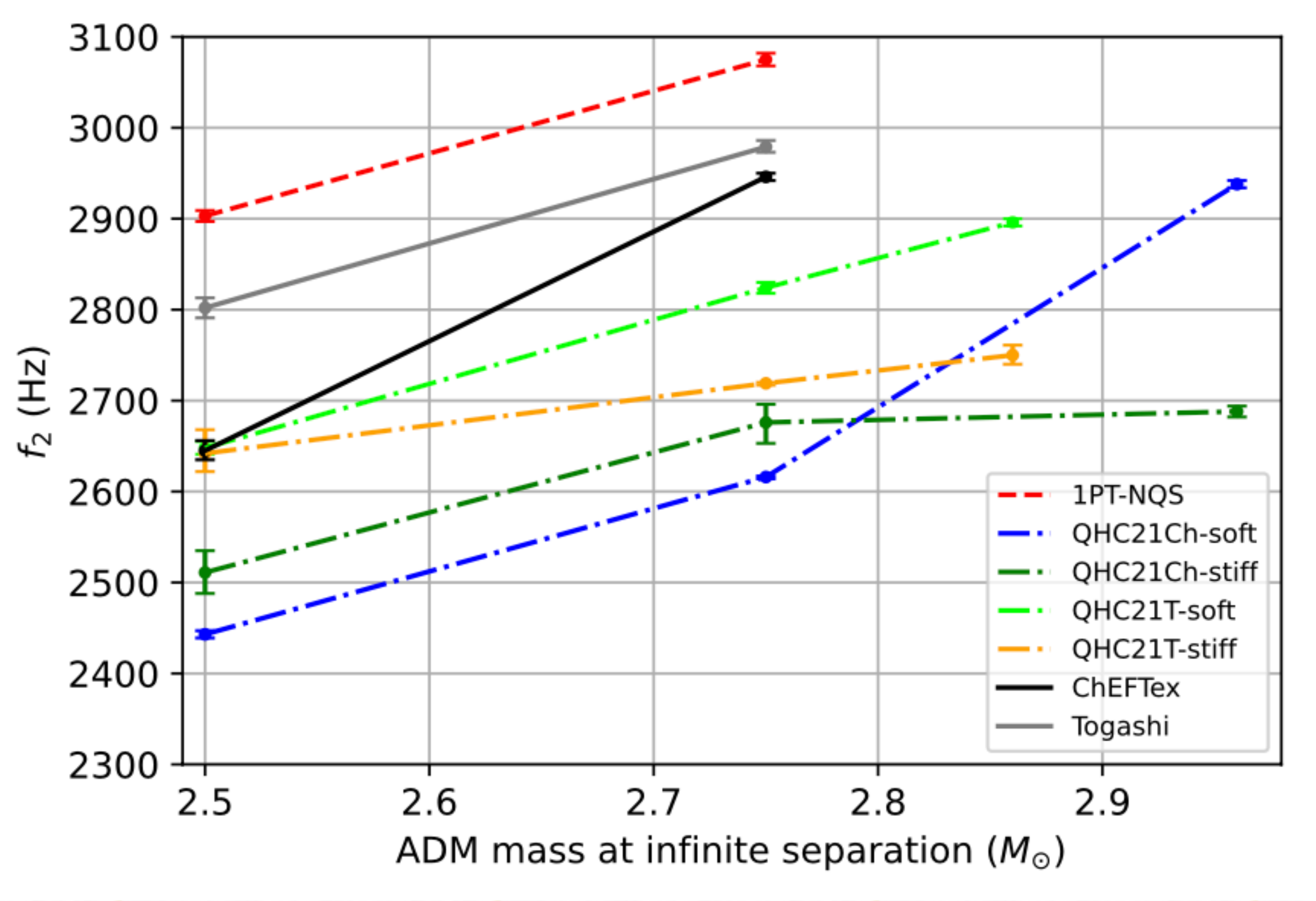
- Markov Chain Monte Carlo fitting method based on Bayesian inference (*emcee* code)
- We fit the f_1 peak with a Gaussian model and the f_2 peak with a model that considers skewness:

$$S(f) = A_1 e^{-\frac{(f-F_1)^2}{2W_1^2}} + S_2$$

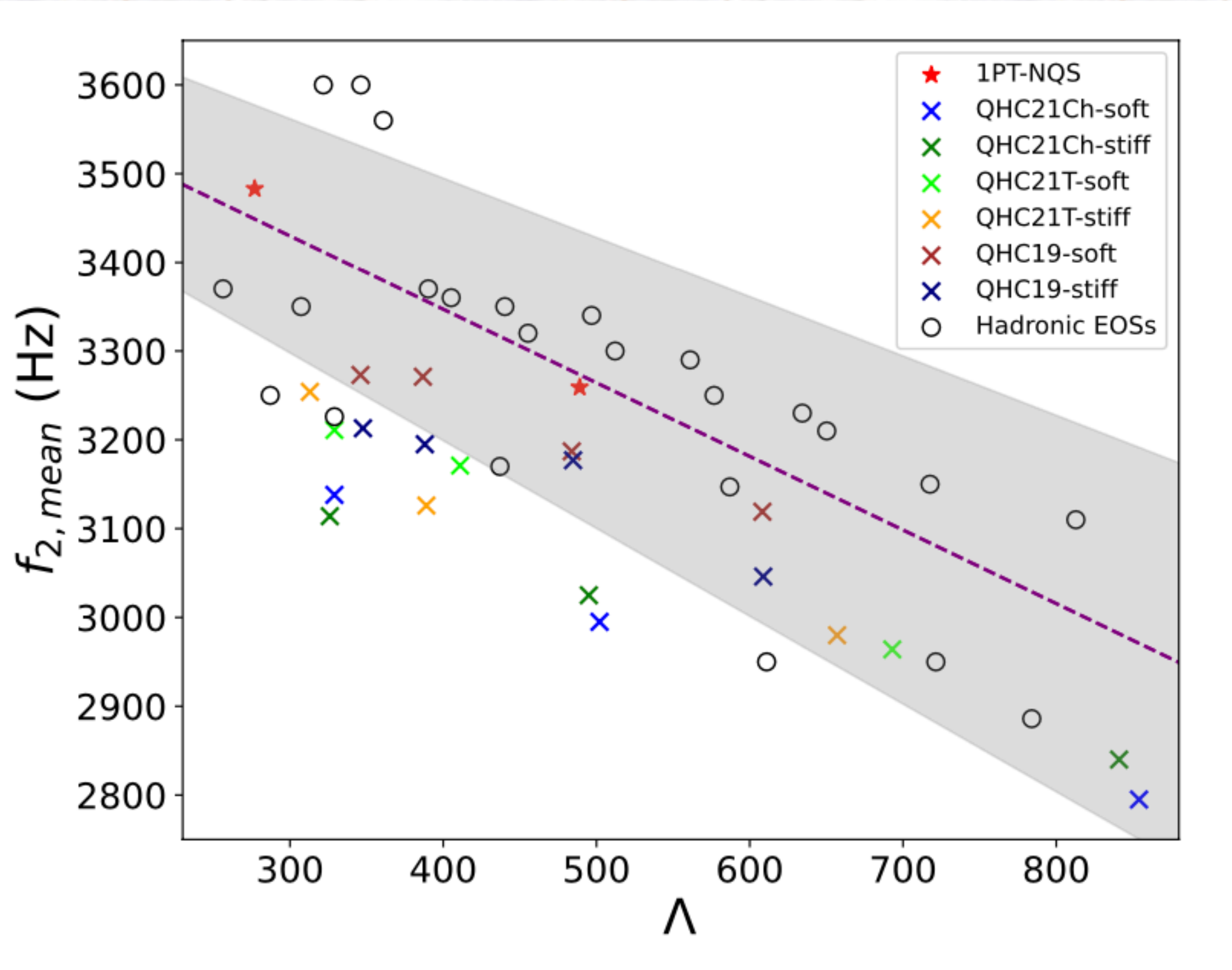
$$S_2 = A_2 e^{-\frac{(f-F_2)^2}{2W_2^2}} \int_{-\infty}^{\alpha_2 \frac{(f-F_2)}{W_2}} e^{-\frac{t^2}{2}} dt$$

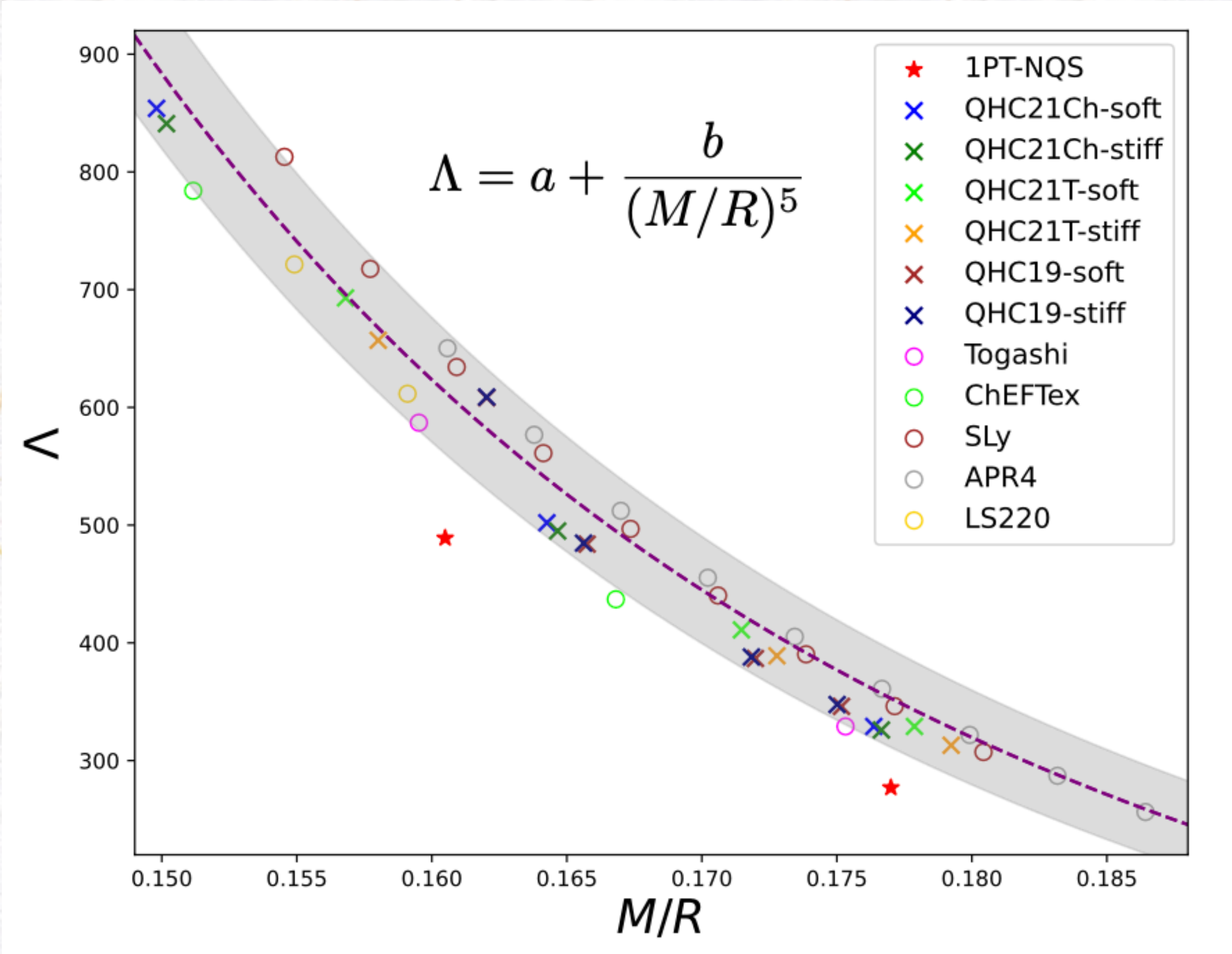


Post-merger GW frequency f2 vs. binary mass: baseline EoSs and EoSs with quarks.



Relations between f_2, compactness, tidal deformability





QHC EOSs stand out

1PT-NQS EOS stands out

A measured Λ that corresponds to a radius (measured, *e.g.*, by NICER) larger than that expected from the Λ–compactness hadronic relation would be in support of the 1PT-NQS scenario.

Conclusions

- Fully general-relativistic simulations of BNS mergers with an EoS based on quark-hadron crossover (QHC) and with quark matter in inspiralling NSs (1PT-NQS)
- A QHC EoS, with a pronounced peak in sound speed, leaves a measurable signature in the post-merger main frequency f_2.
- In our 1PT-NQS simulations, we do not see a detectable signature in the Λ-f_2 relation, because quark matter is already in the inspiralling stars.
- However the 1PT-NQS EoS stands out from the Λ - M/R relation.
- This is likely the only type of 1PT EoS that may produce a post-merger signal.
- The results of this work will become relevant to observations when gravitational waves in the kHz band are surveyed with higher sensitivity by upgraded and third-generation observatories (Einstein Telescope, Cosmic Explorer, NEMO)