PennState
Eberly College of Science

www.computational-relativity.org

Multimessenger Astrophysics with Neutron Star Mergers

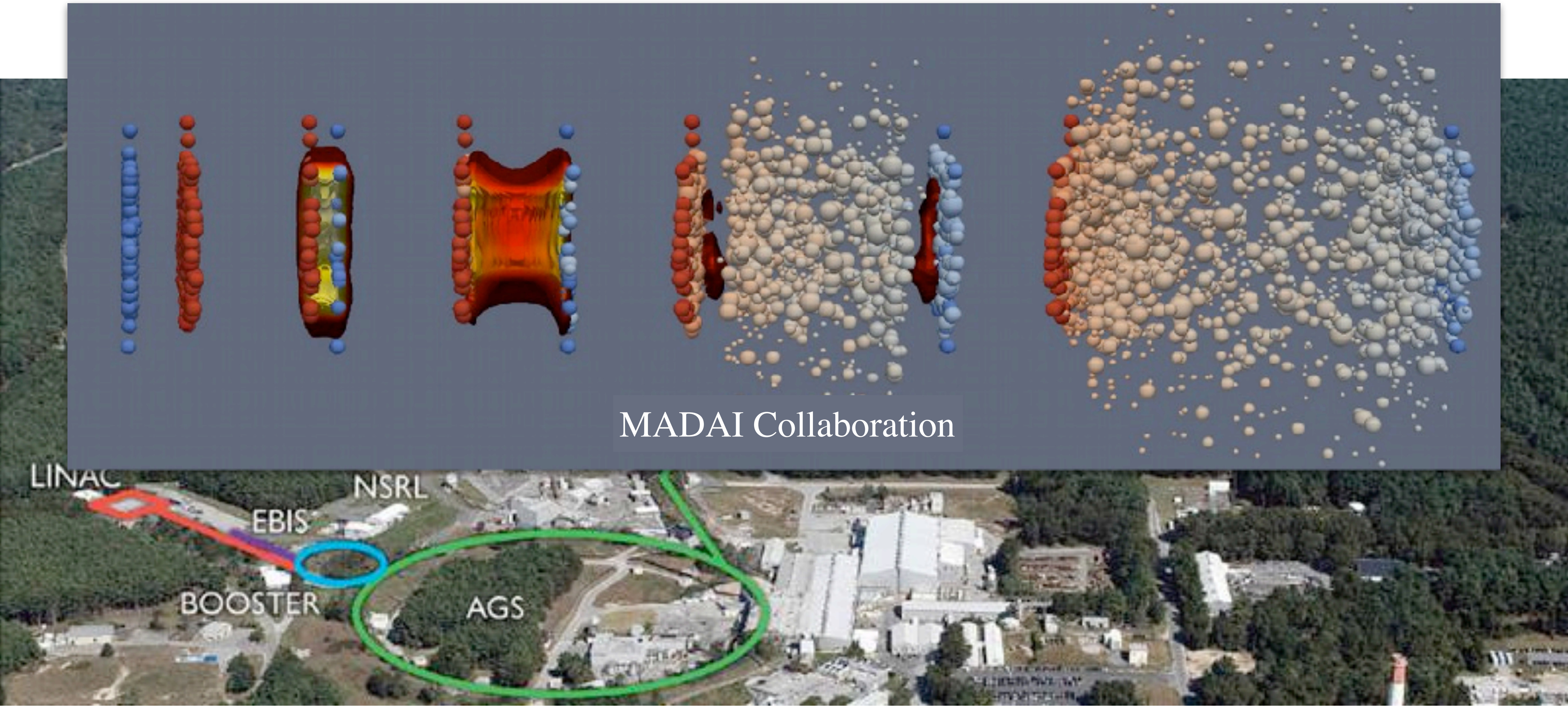
David Radice — Oct 26, 2021

https://sites.psu.edu/numrel

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

What happens to matter as it is compressed?

Relativistic heavy-ion collisions



RHIC at Brookhaven National Lab

QCD phase diagram

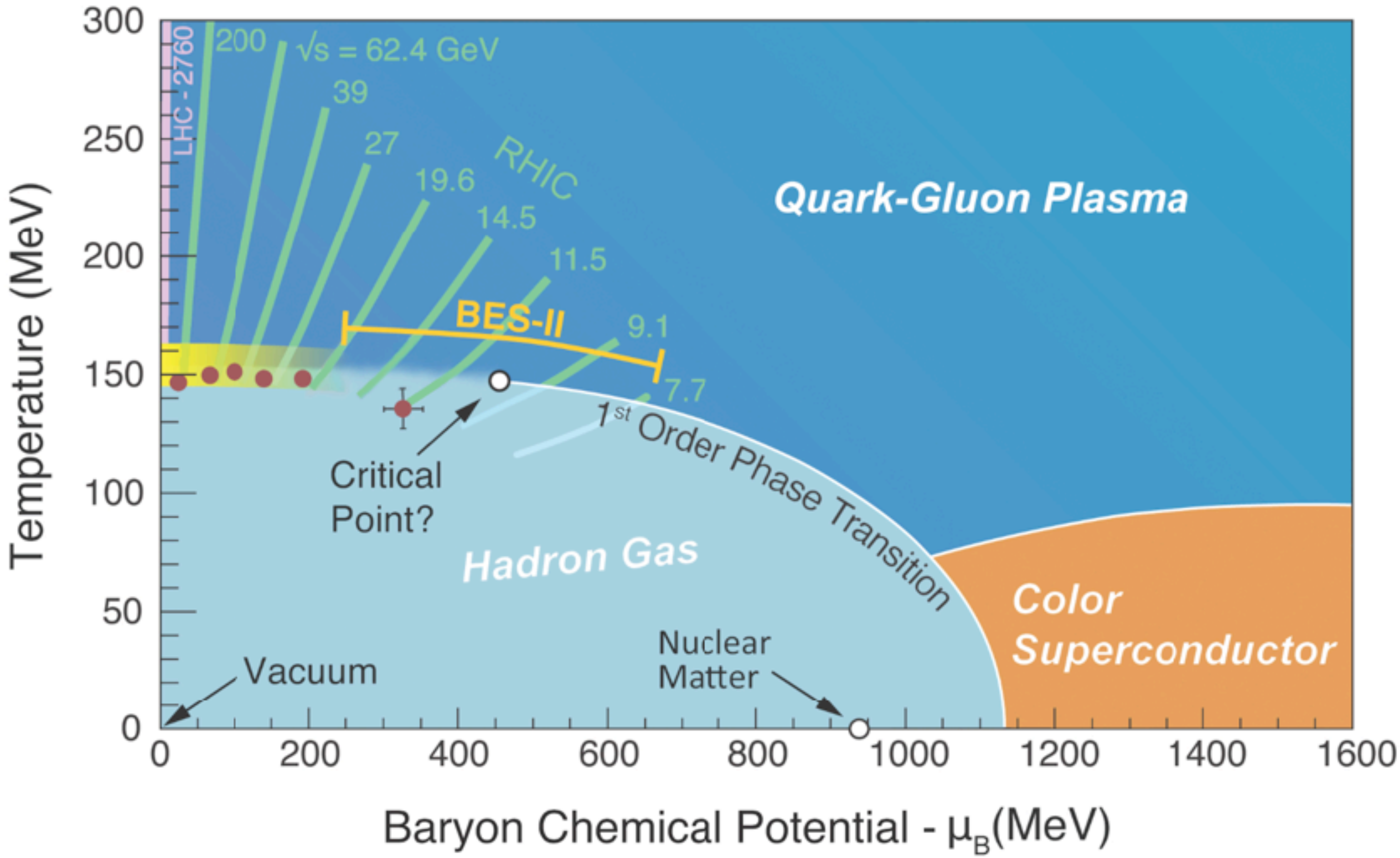
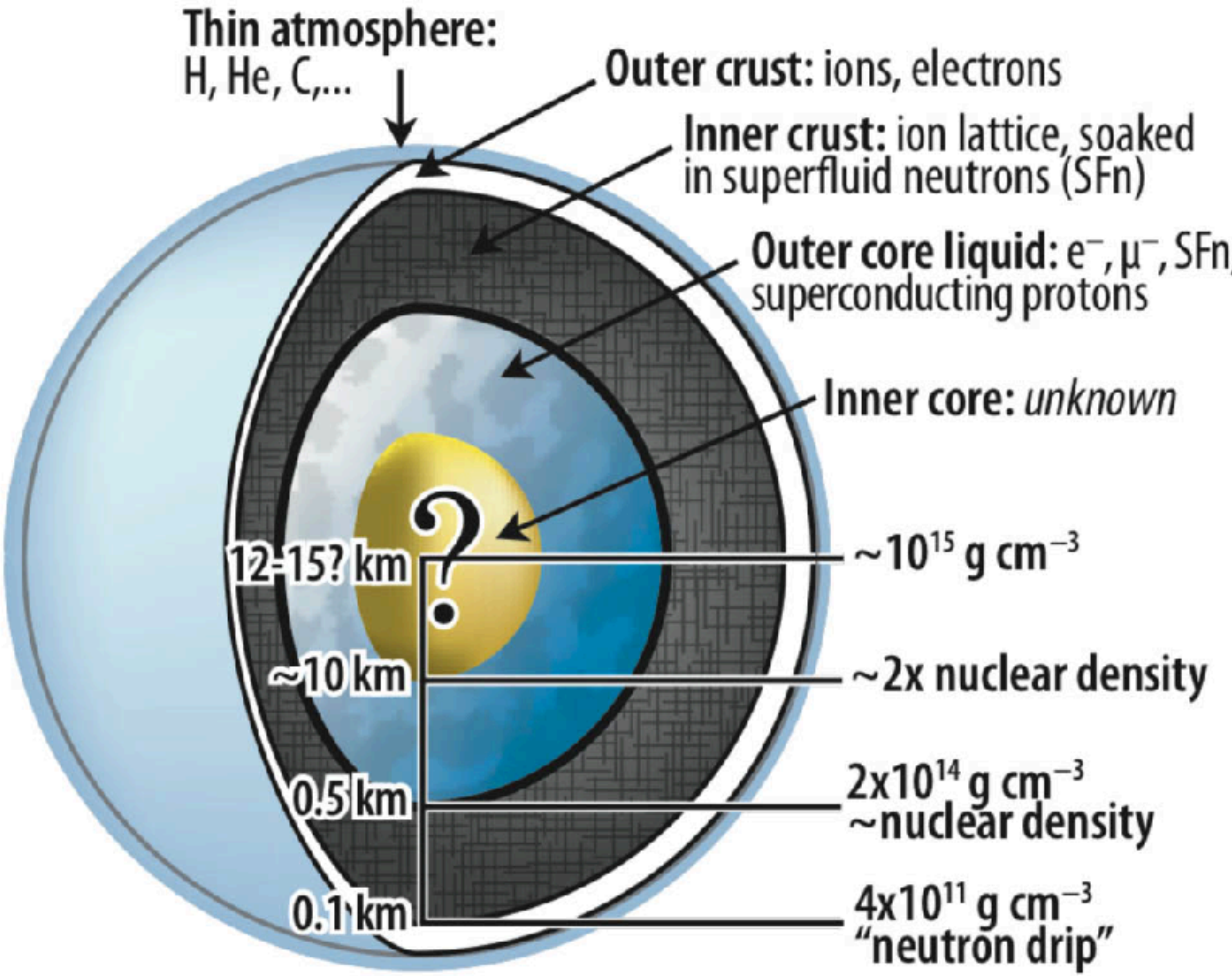


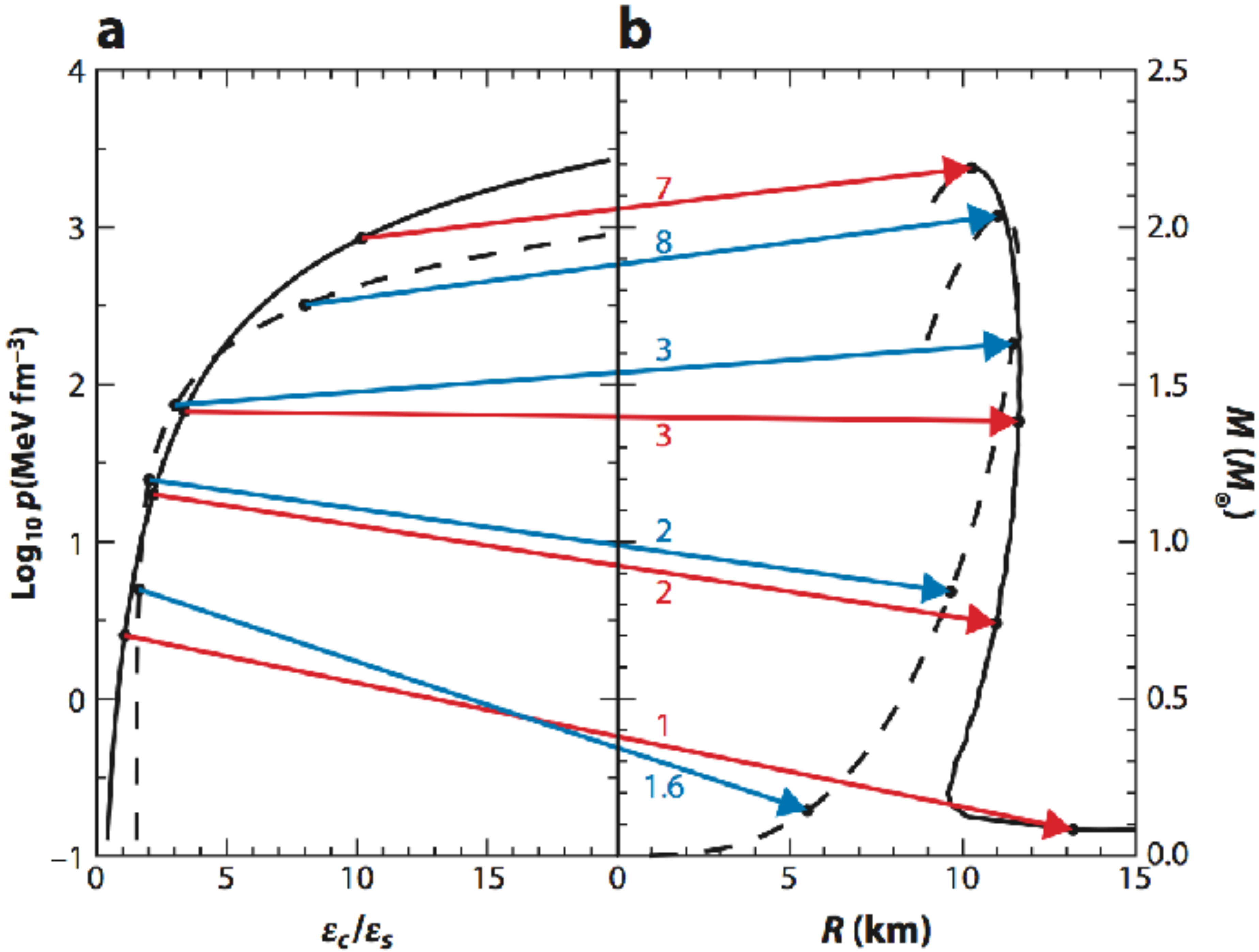
Illustration: Swagato Mukherjee, Brookhaven National Laboratory.



Thin atmosphere:
H, He, C,...
Outer crust: ions, electrons
Inner crust: ion lattice, soaked in superfluid neutrons (SFn)
Outer core liquid: e⁻, μ⁻, SFn, superconducting protons
Inner core: *unknown*
?
12-15? km
~10 km
0.5 km
0.1 km
~10^15 g cm^-3
~2x nuclear density
2x10^14 g cm^-3
~nuclear density
4x10^11 g cm^-3
"neutron drip"

Statement of the problem

The EOS of dense matter

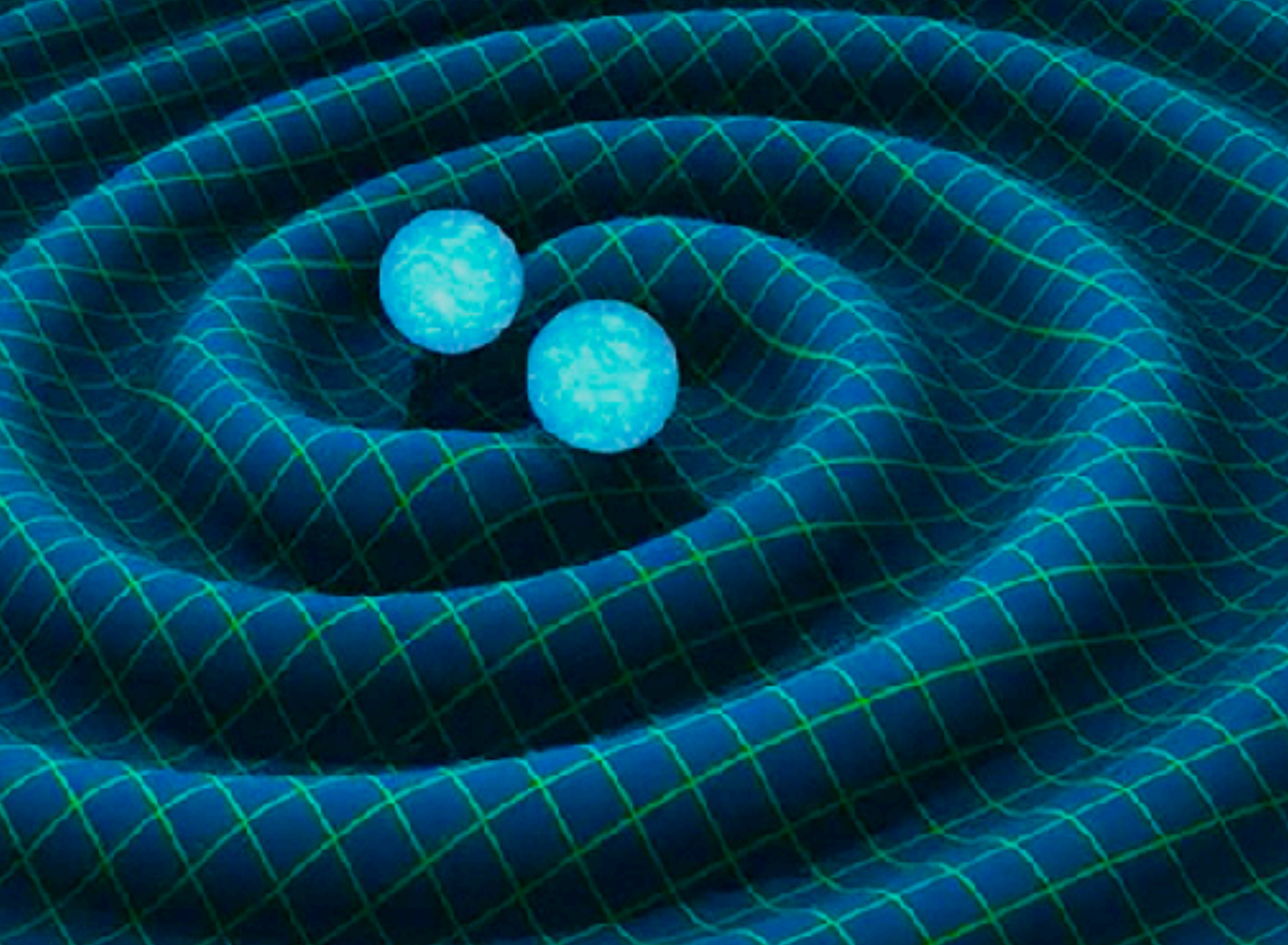


From Lattimer 2012

Binary neutron stars

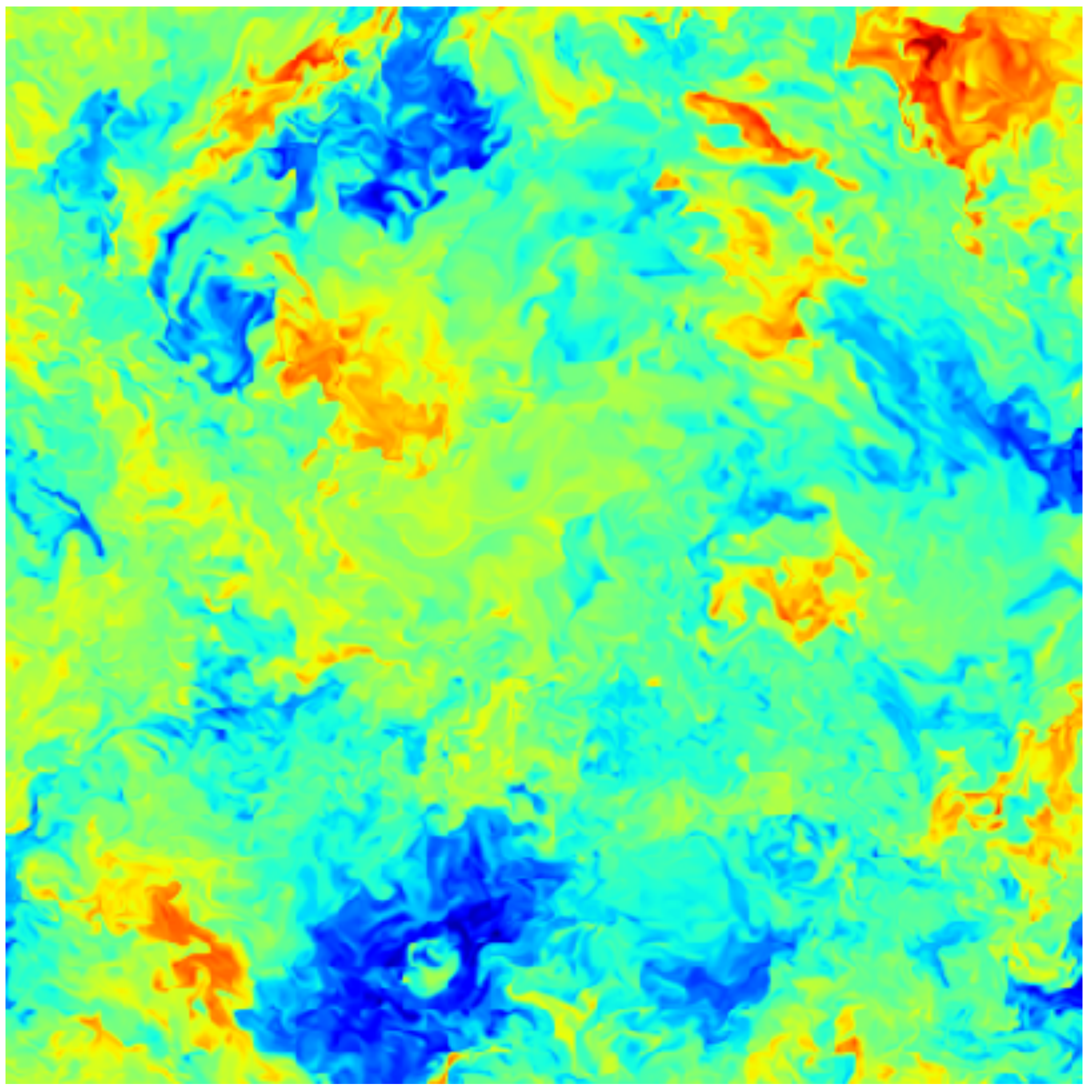
- Angular momentum radiated in gravitational waves
- Orbit shrinks
- Gravitational radiation increases
- …

?!?



WhiskyTHC

http://personal.psu.edu/~dur566/whiskythc.html

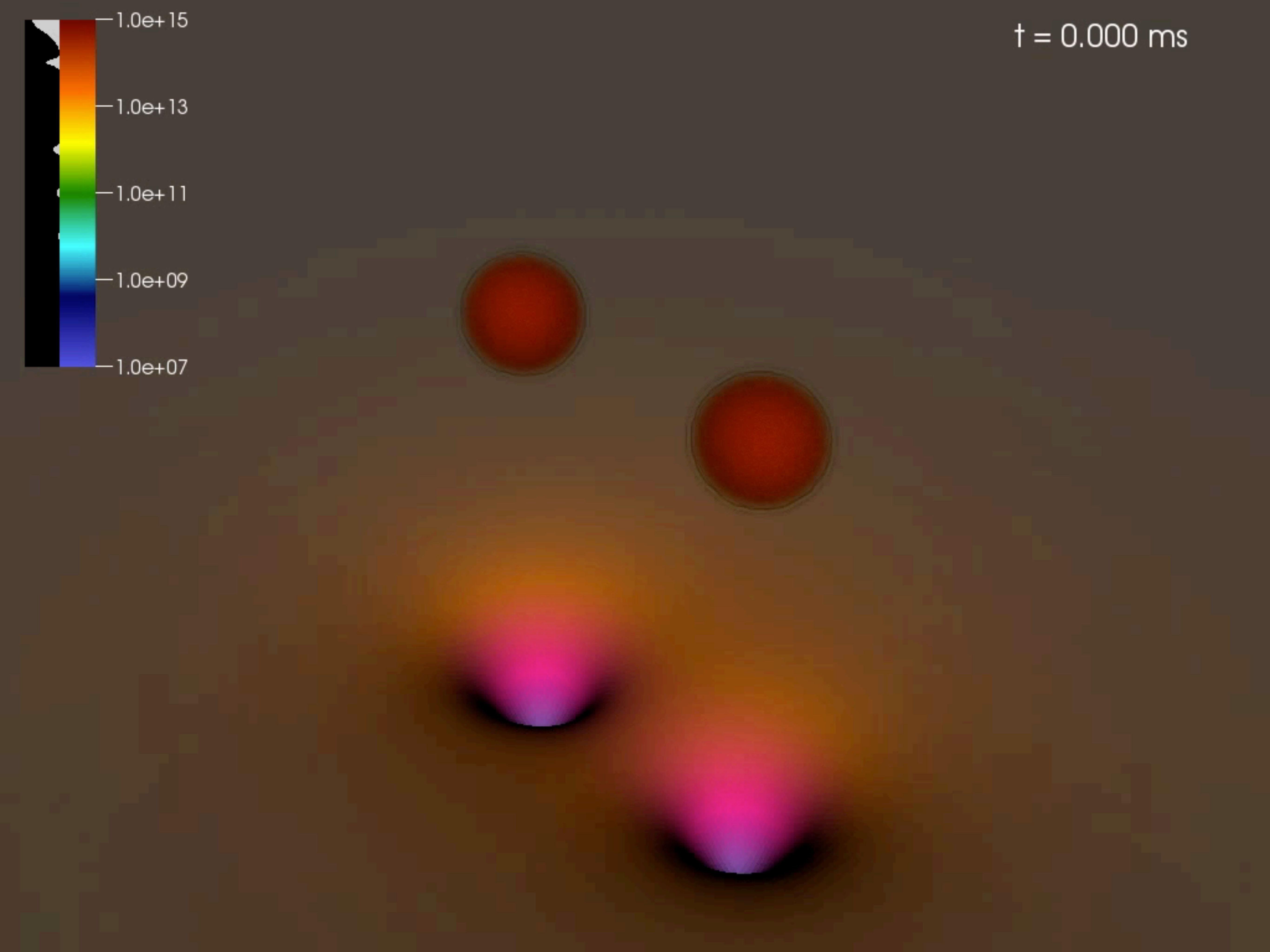


- Full-GR, dynamical spacetime*
- Nuclear EOS
- M0 & M1 neutrino treatment
- High-order hydrodynamics
- Open source!

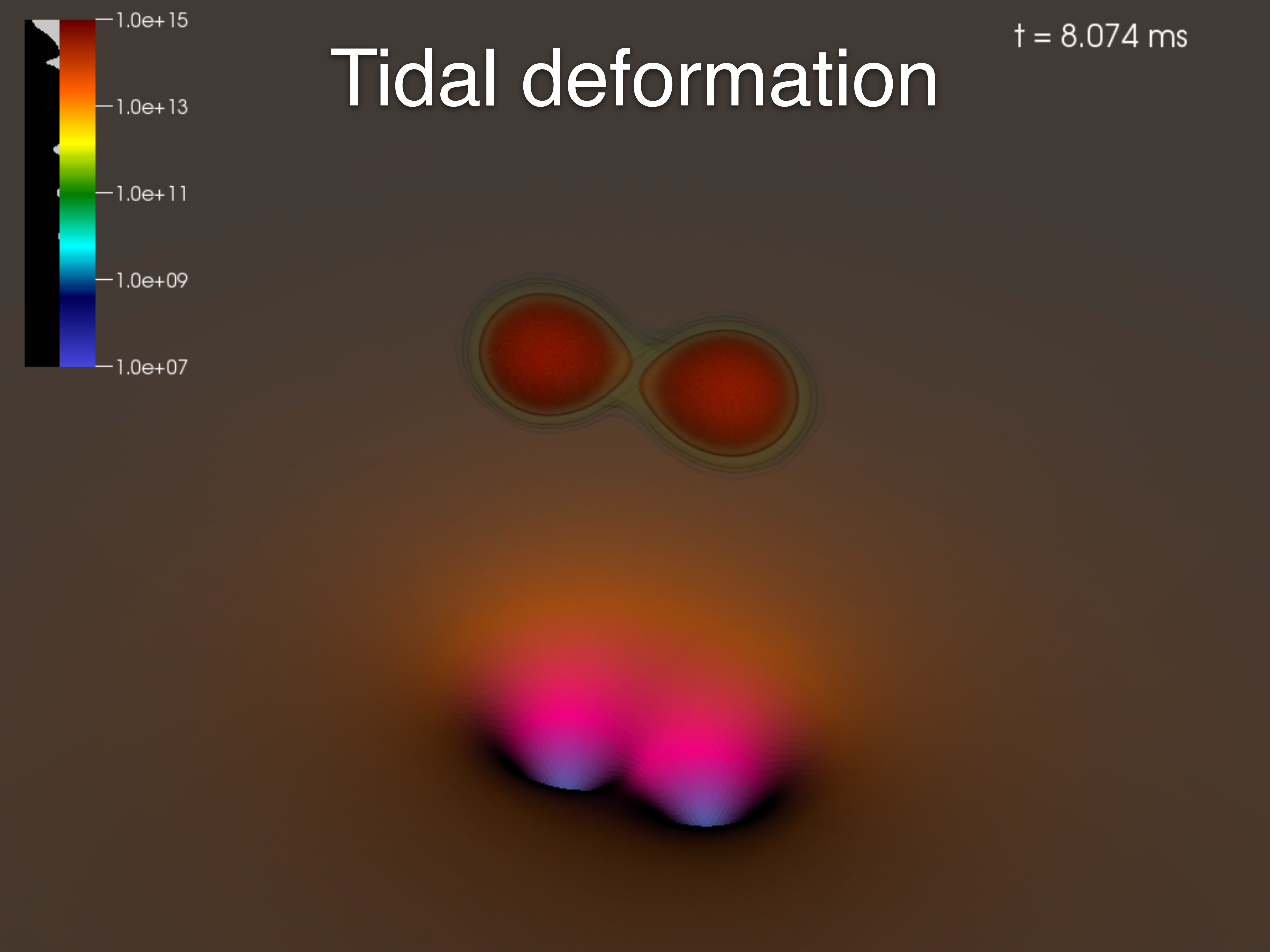
* using the Einstein Toolkit metric solvers

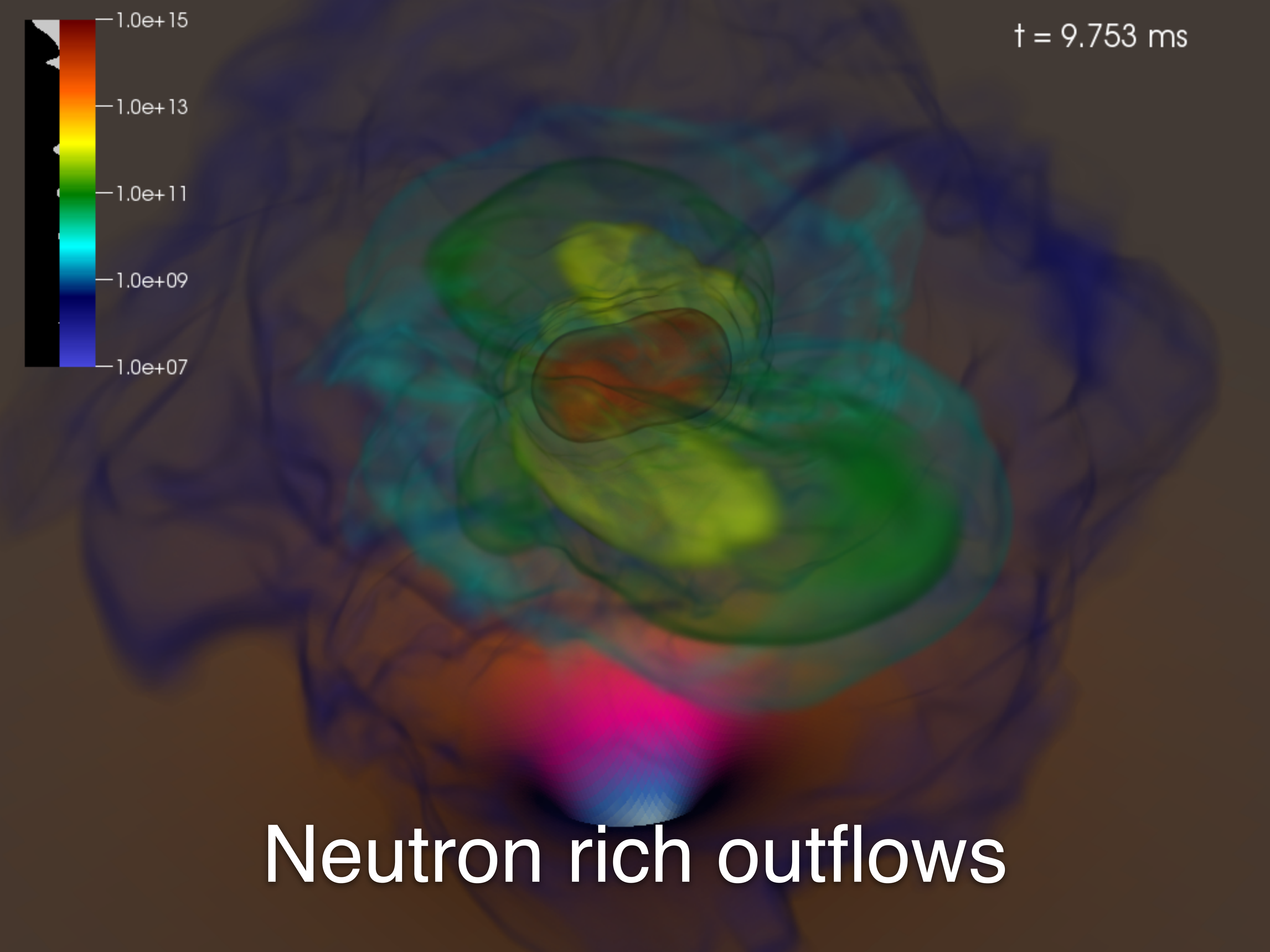
THC: Templated Hydrodynamics Code

Skip Ad ⏭

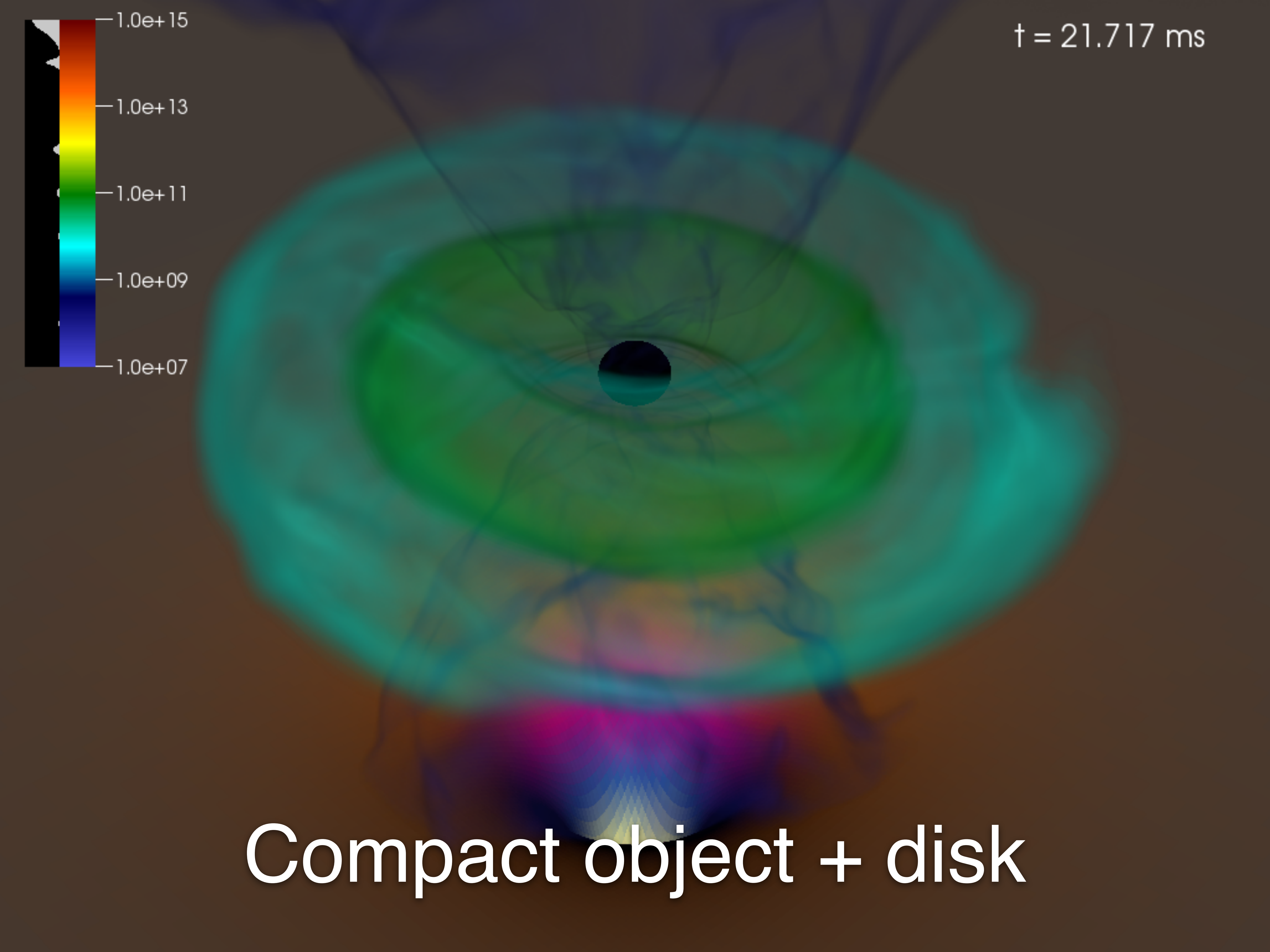

1.0e+15
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 0.000 ms

Tidal deformation



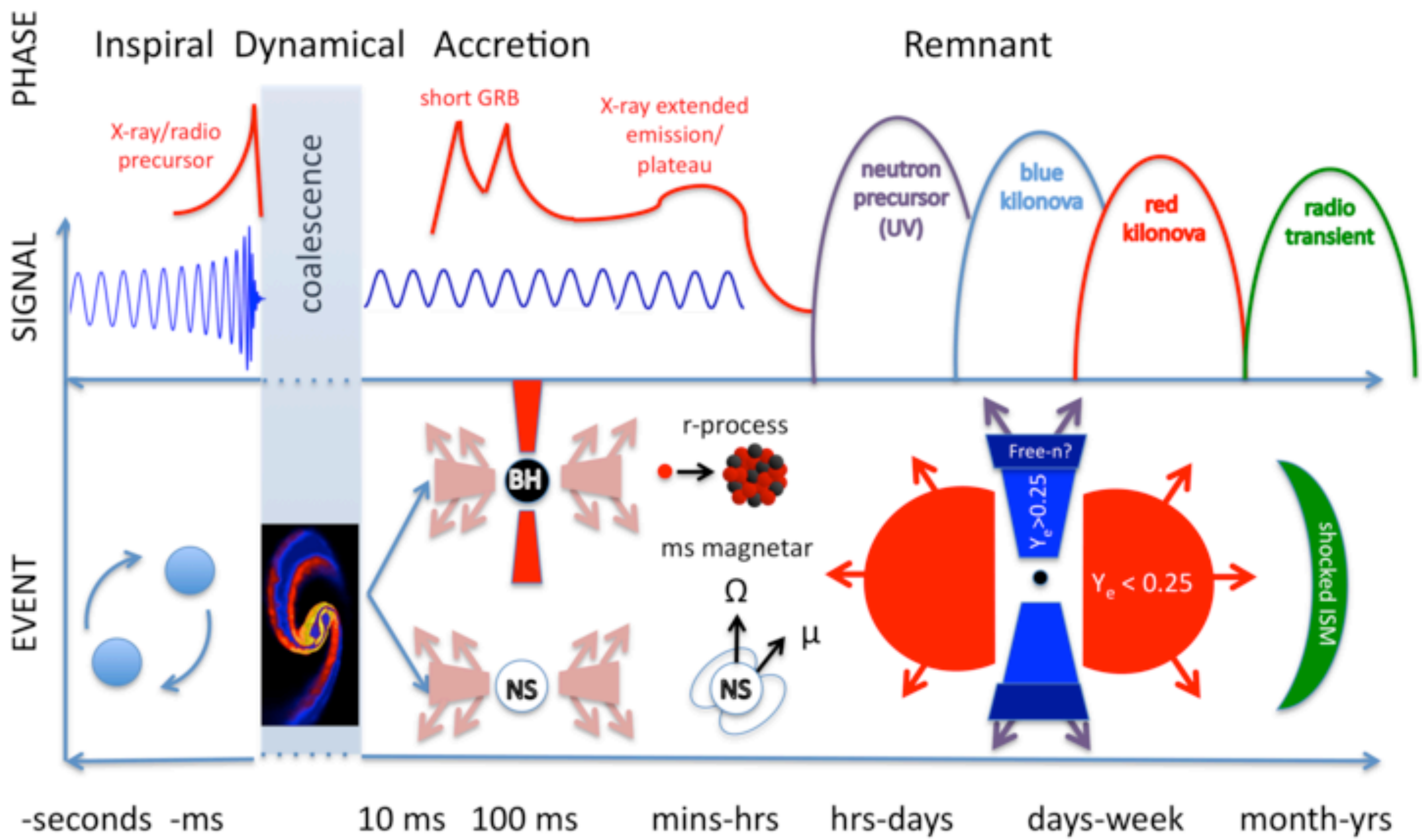


Neutron rich outflows

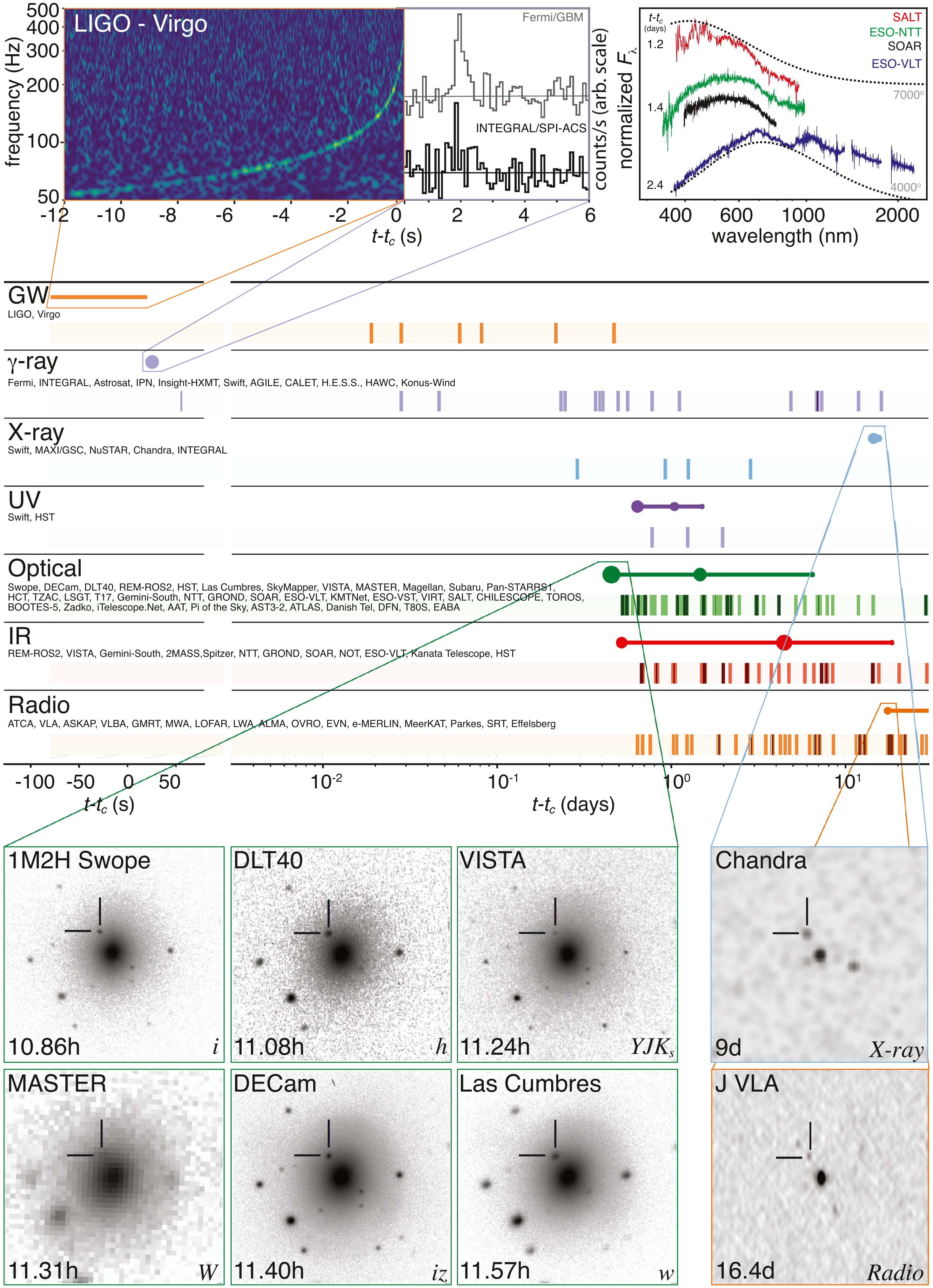

1.0e+15
1.0e+13
1.0e+11
1.0e+09
1.0e+07
t = 21.717 ms
Compact object + disk

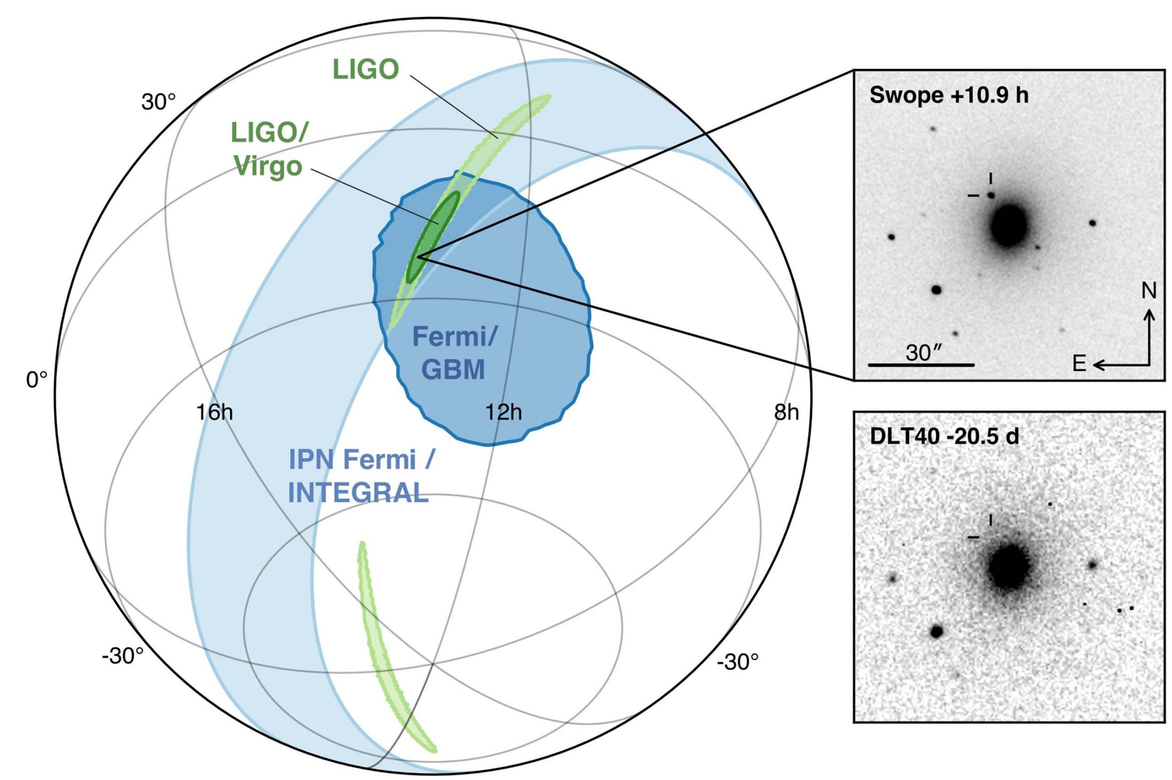
Multimessenger signals

The theorists' dreams



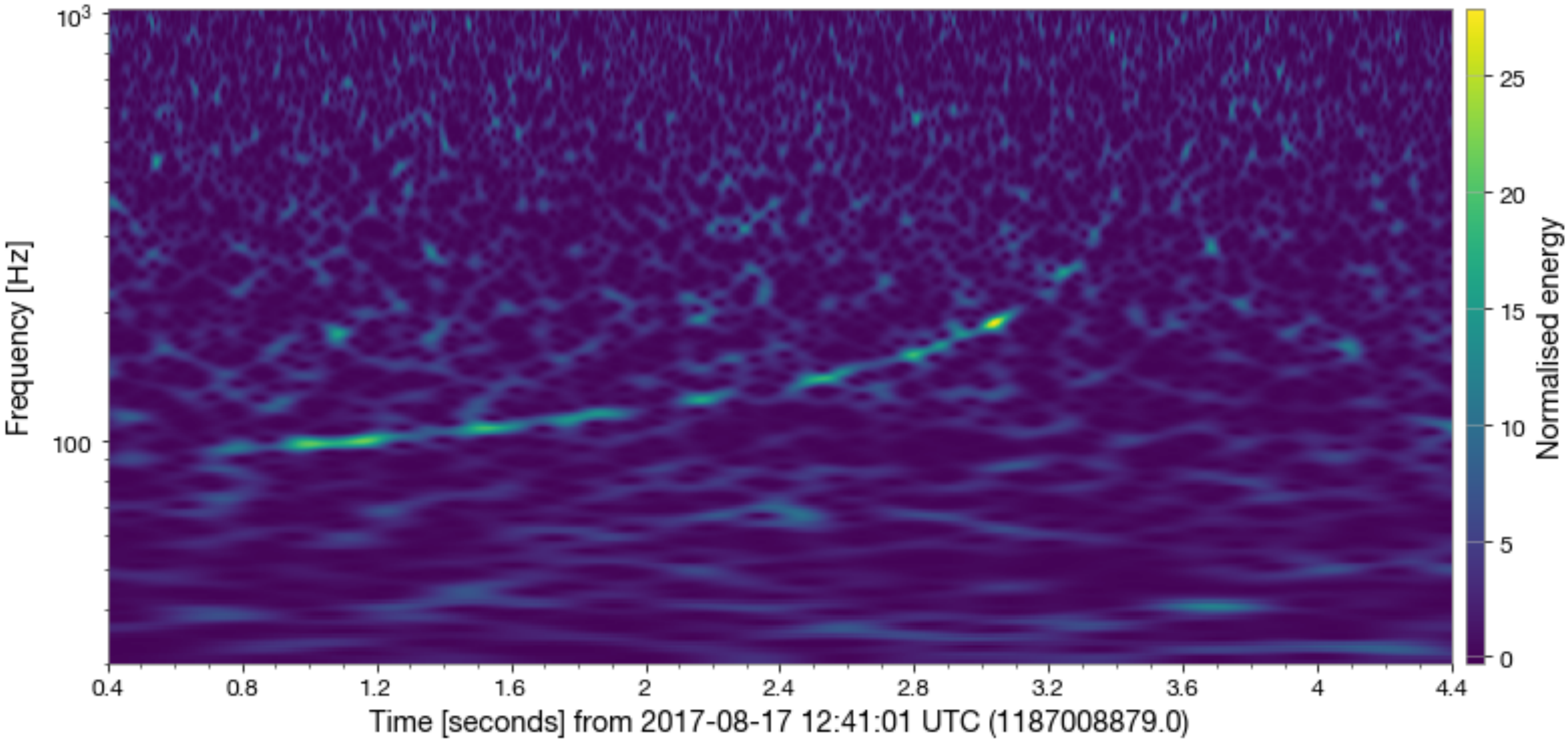
From Fernandez & Metzger 2016





From LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech- NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT ApJL 848:L12 (2017)

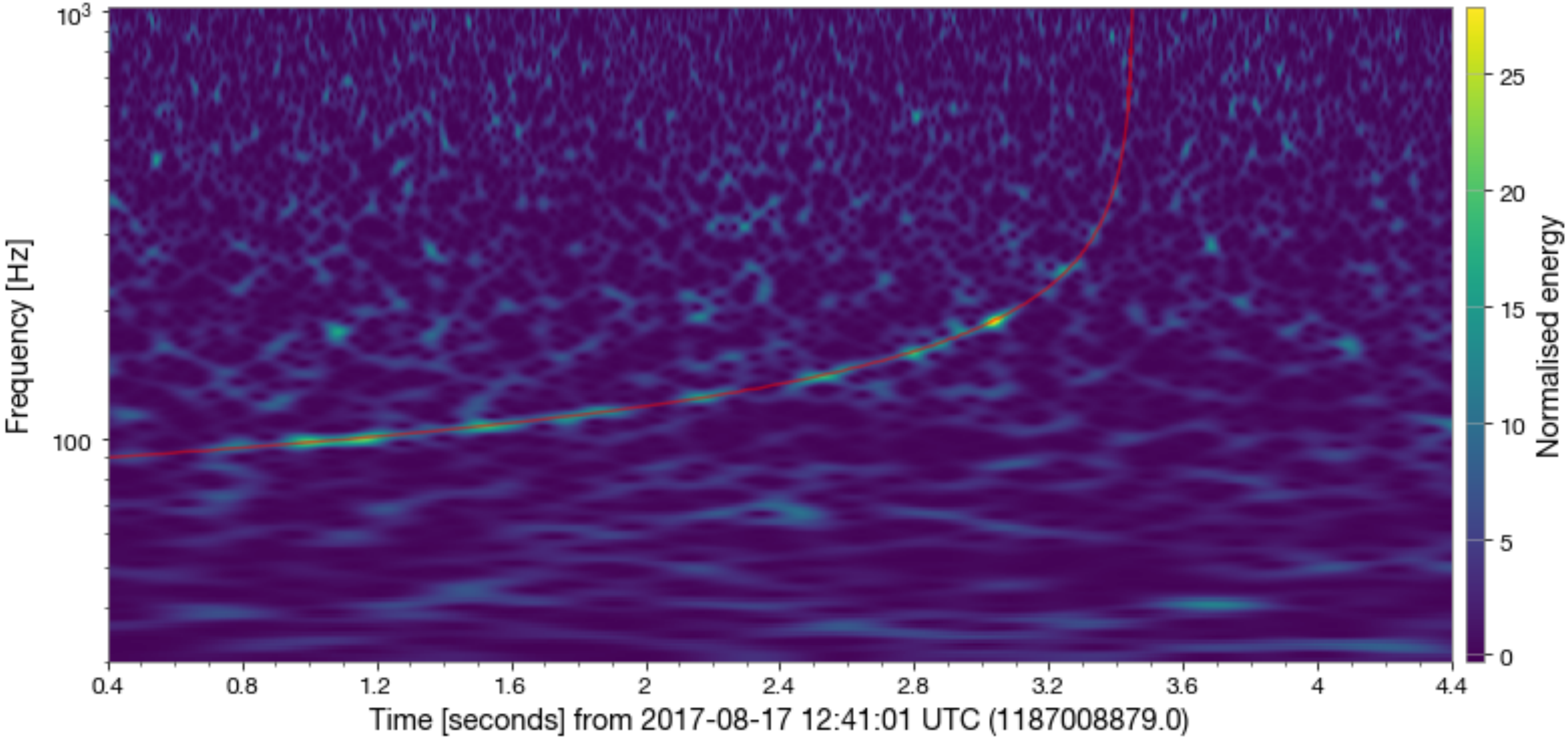
Gravitational waves



GW170817 — In the frequency domain vs theory prediction

https://teobresums.github.io/gwevents/

Gravitational waves

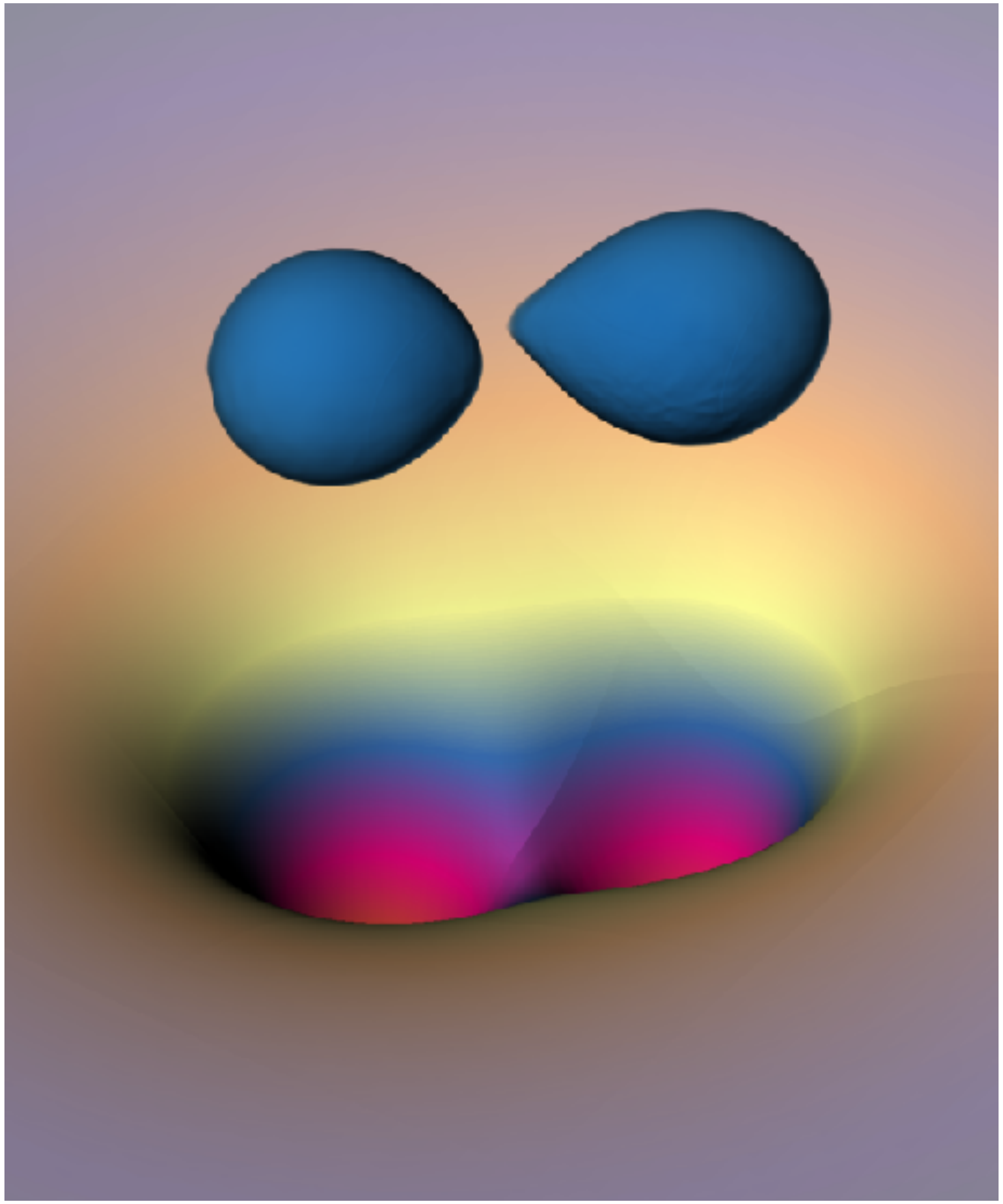


GW170817 — In the frequency domain vs theory prediction

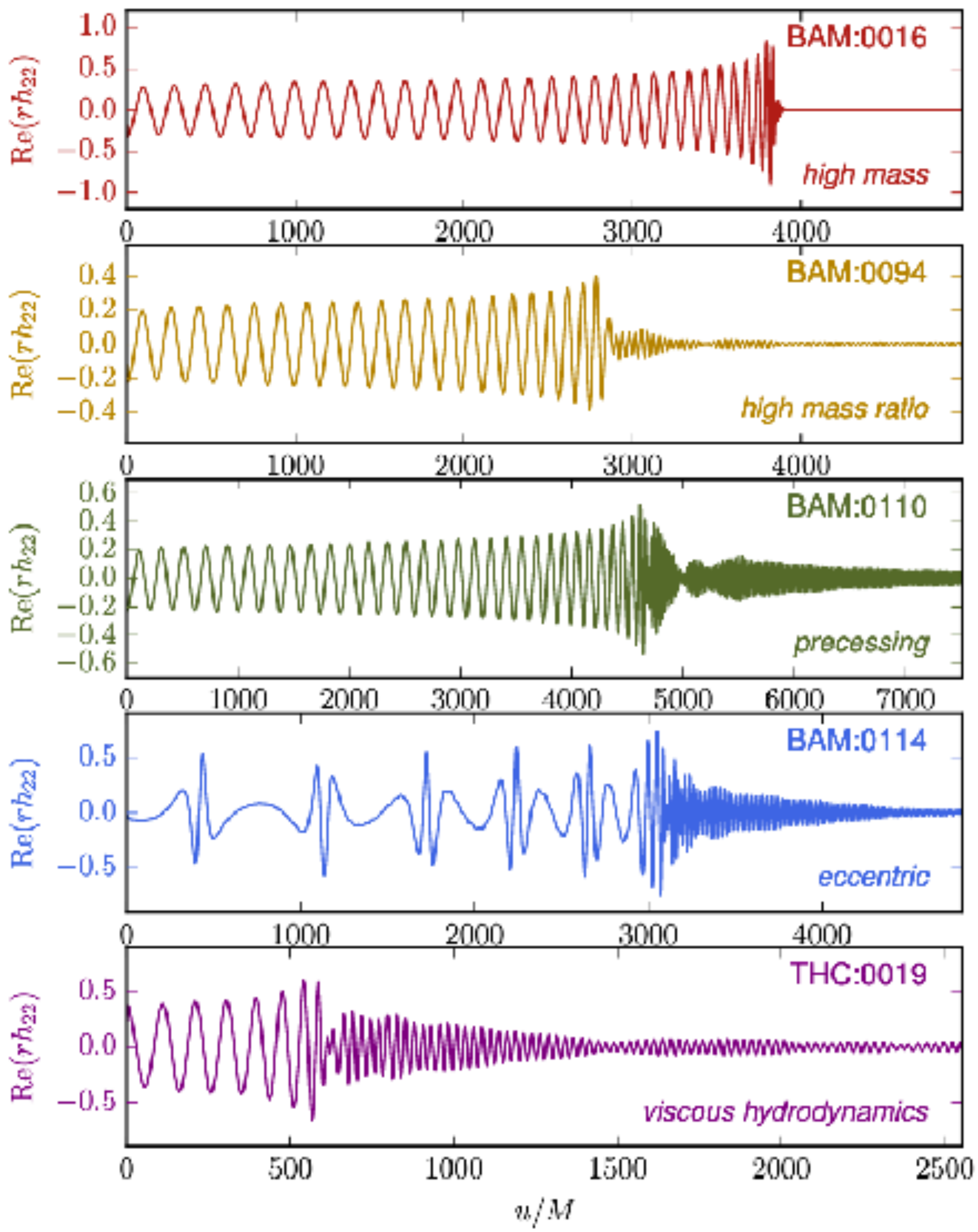
https://teobresums.github.io/gwevents/

Tidally interacting NSs

- The impact of tides
  1. The potential is modified and becomes more attractive:
     $$U^T \sim -\frac{\tilde{\Lambda}}{r^6}$$
  2. $\tilde{\Lambda} \sim (M/R)^{-6}$
  3. The tidal bulge contribute to the GW emission:
     $$L^T_{\rm GW} = \frac{G}{5c^5}\langle \dddot{Q}^T_{ij}\dddot{Q}^T_{ij}\rangle$$
- The inspiral is accelerated compared to that of two BHs with the same parameters as the BNS
- Read off tidal information from the dephasing of the wave



The CoRe catalog

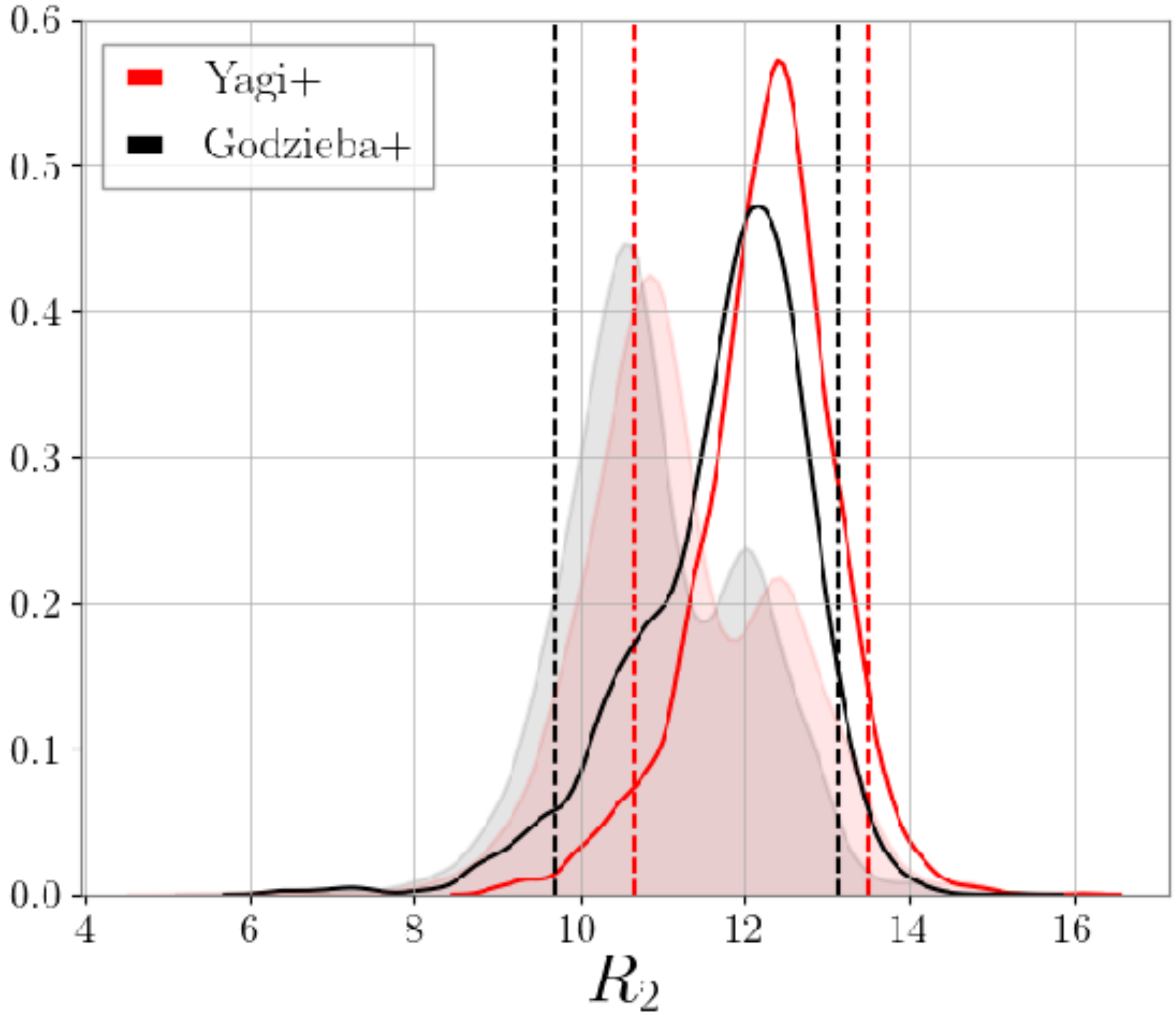


- Largest catalog of NR GW waveforms for BNS systems
- Two independent codes: cross validation
- Used for LVC TidalEOB, NRTides, waveform models calibration and validation
- EM light curves and r-process nucleosynthesis available
- Open source: simulation codes, initial data, EOS tables, parameter files, all available

www.computational-relativity.org

Dietrich, **DR**, Bernuzzi+ CQG 35:LT01 (2018)

GW170817



From Godzieba+ Phys. Rev. D 103, 063036 (2021)

- Robust upper limits $\tilde{\Lambda} < 800$
- Very stiff EOS are ruled out at high confidence
- Lower limits: dependency on details of the analysis, waveform model, etc.
- Probing the EOS on the soft side more challenging: we need multimessenger observations

See also: LVC 2017, De+ 2018, LVC 2018, Radice+2018, Capano+ 2019, Gamba+ 2020, …

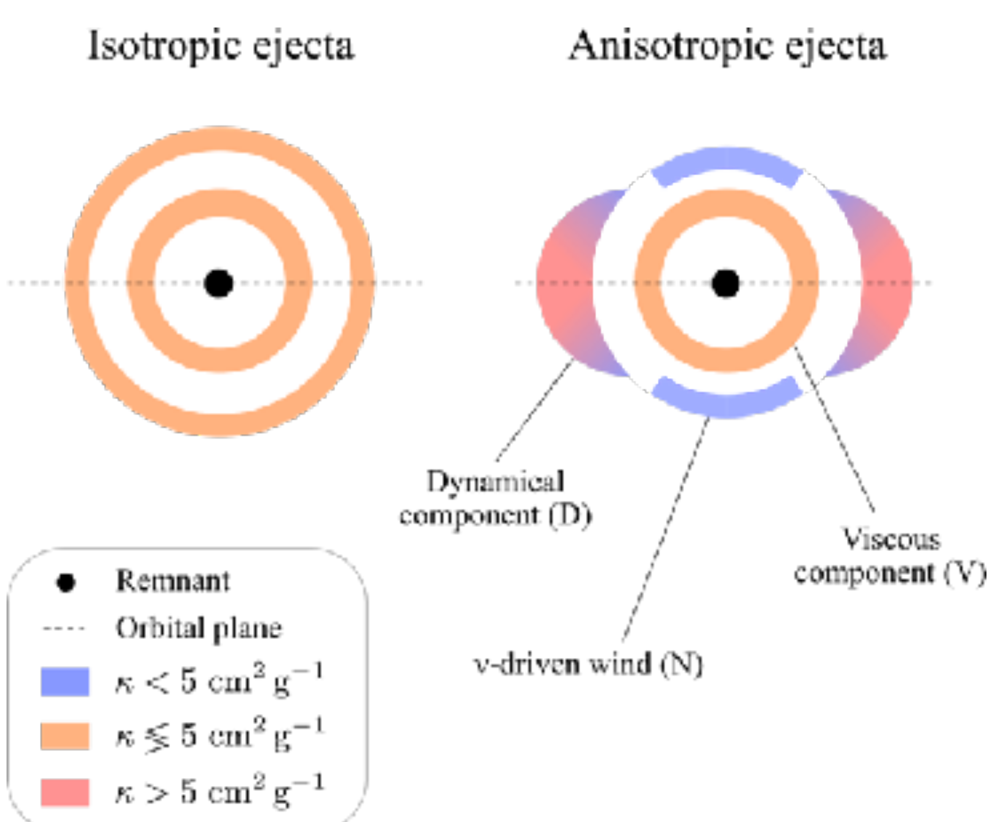
Multimessenger PE

$$P[\theta|d]$$

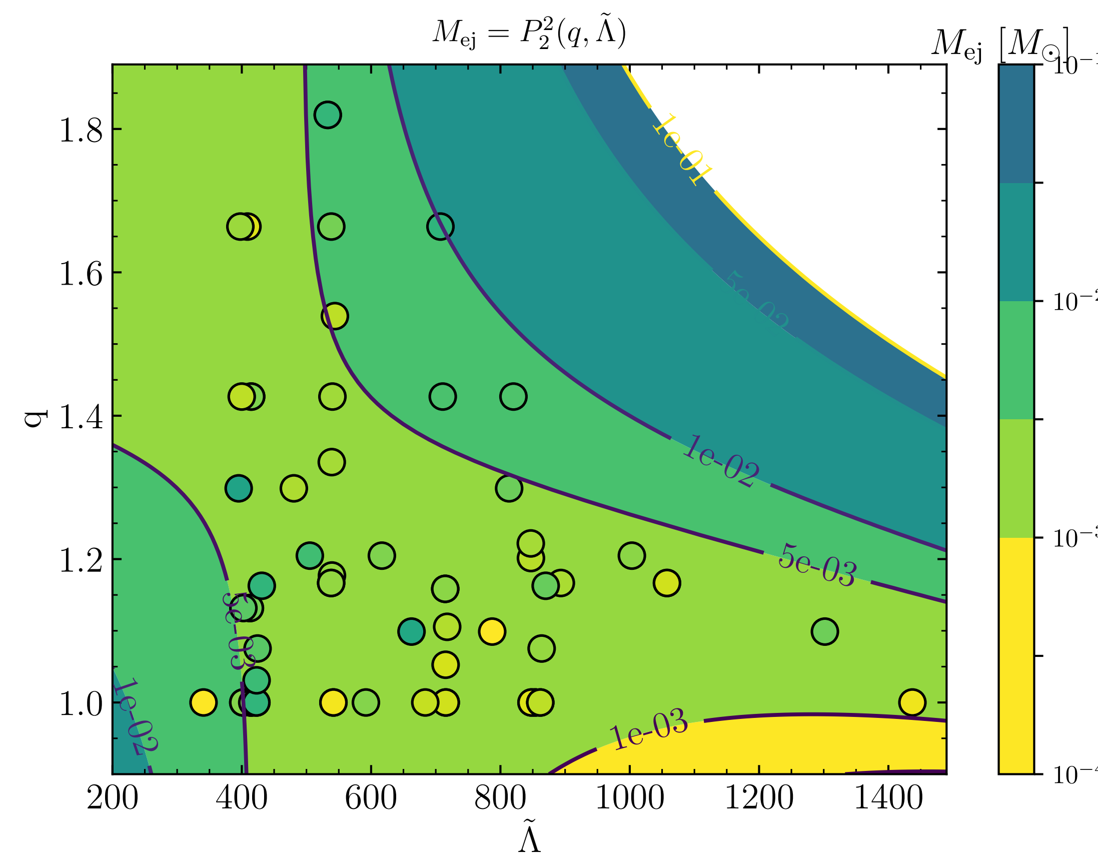
GW modeling and data analysis

kilonova modeling

NR simulations

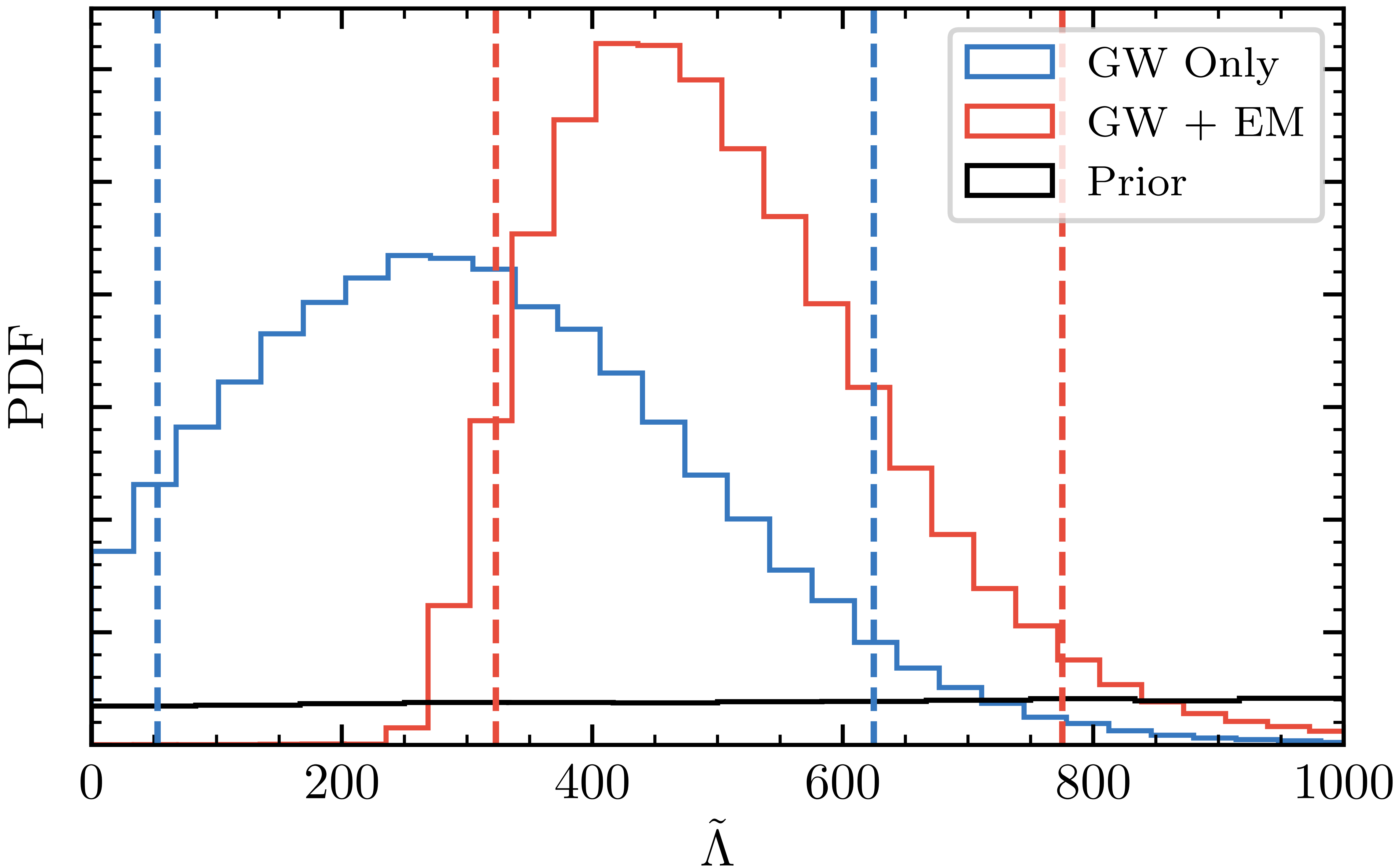


Breschi+ 2021, MNRAS 505:1661 (2021)



Nedora+ 2020, 2011.11110

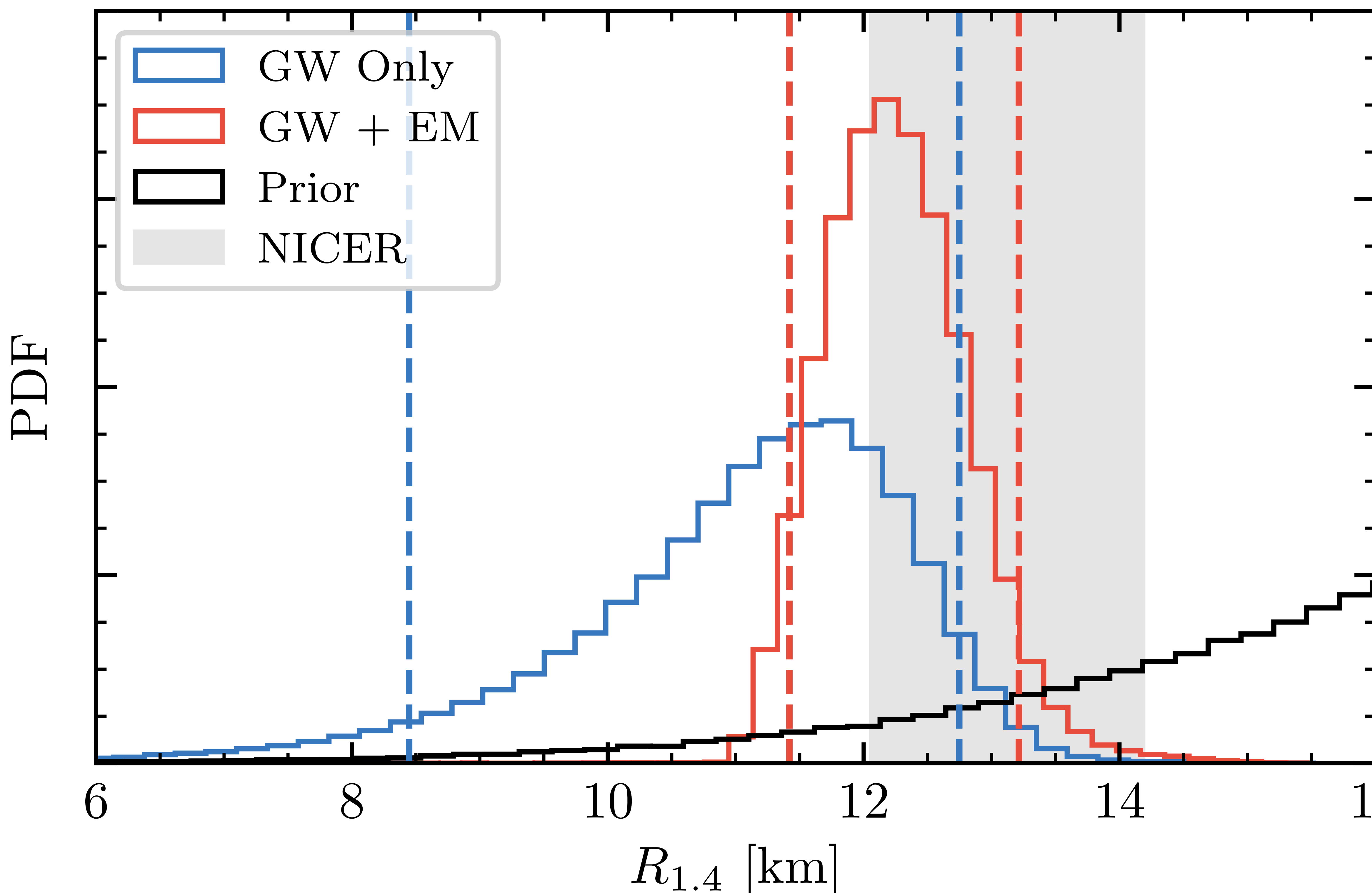
Equation of state constraints



See also Coughlin+ 2018; Capanno+ 2019; Dietrich+ 2020; Gamba+ 2020; …

DR, Perego+ ApJL 852:L29 (2018);
DR & Dai, Eur. Phys. J. A 55: 50 (2019)

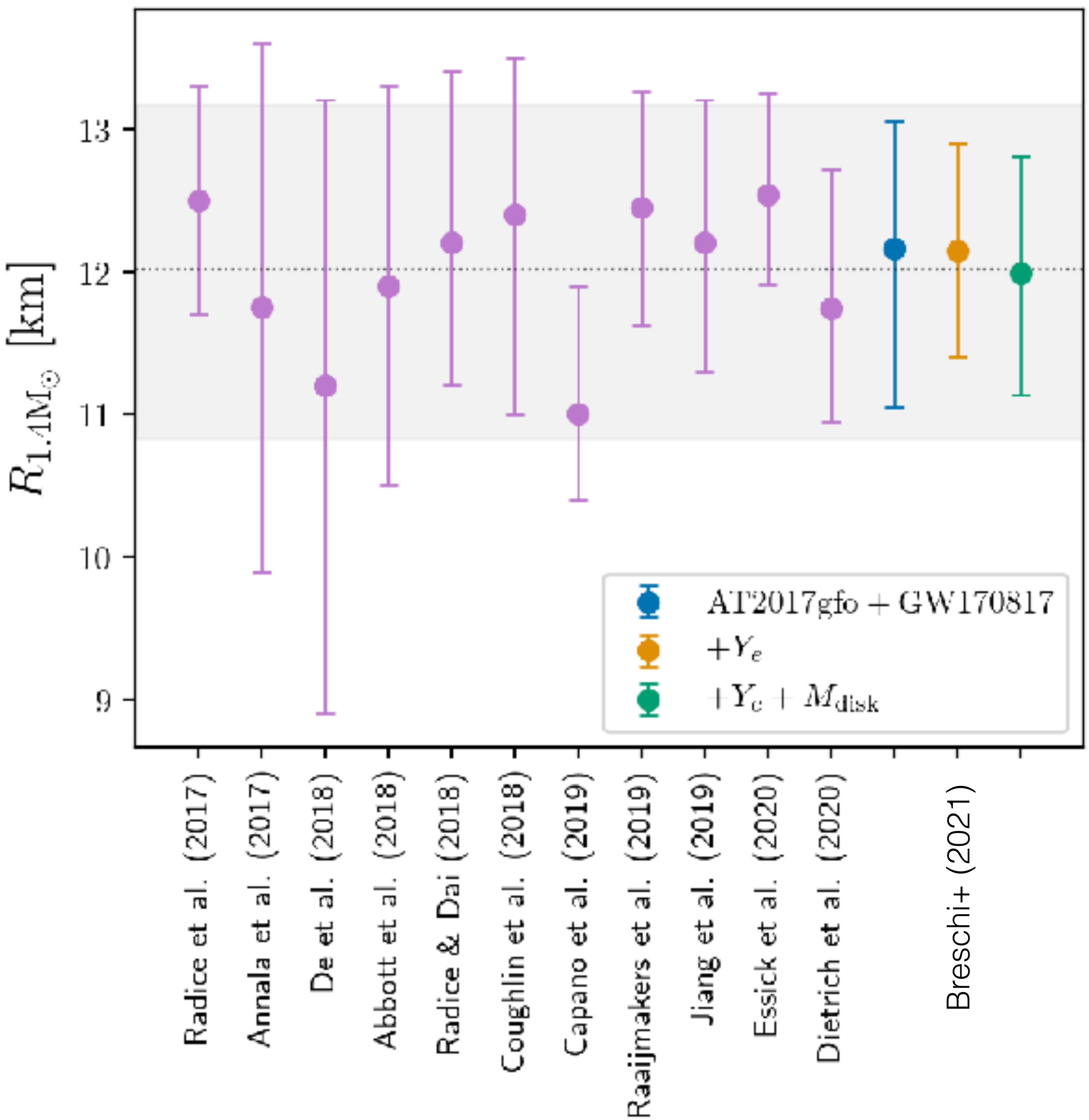
Equation of state constraints



See also Gamba+ 2020

DR, Perego+ ApJL 852:L29 (2018);
DR & Dai, Eur. Phys. J. A 55: 50 (2019)

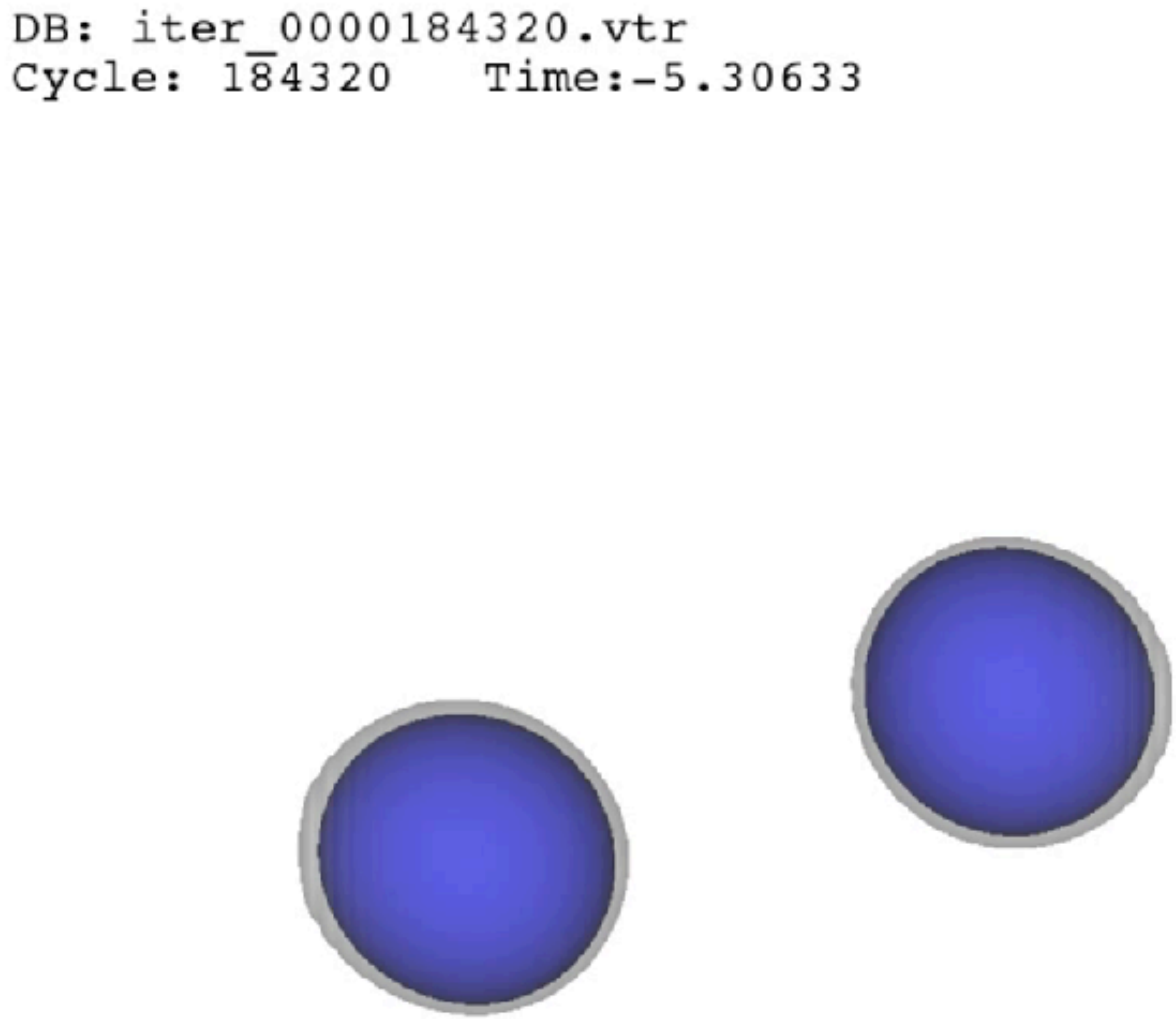
Multimessenger constraints



- Potential to constrain the EOS and/or q: the basic physics is understood and included in the simulations
- Modeling uncertainties appear to be under control
- Systematic errors still dominant
- Need to explore the parameter space: EOS, mass ratios, etc.
- Need long term 3D GRMHD simulations

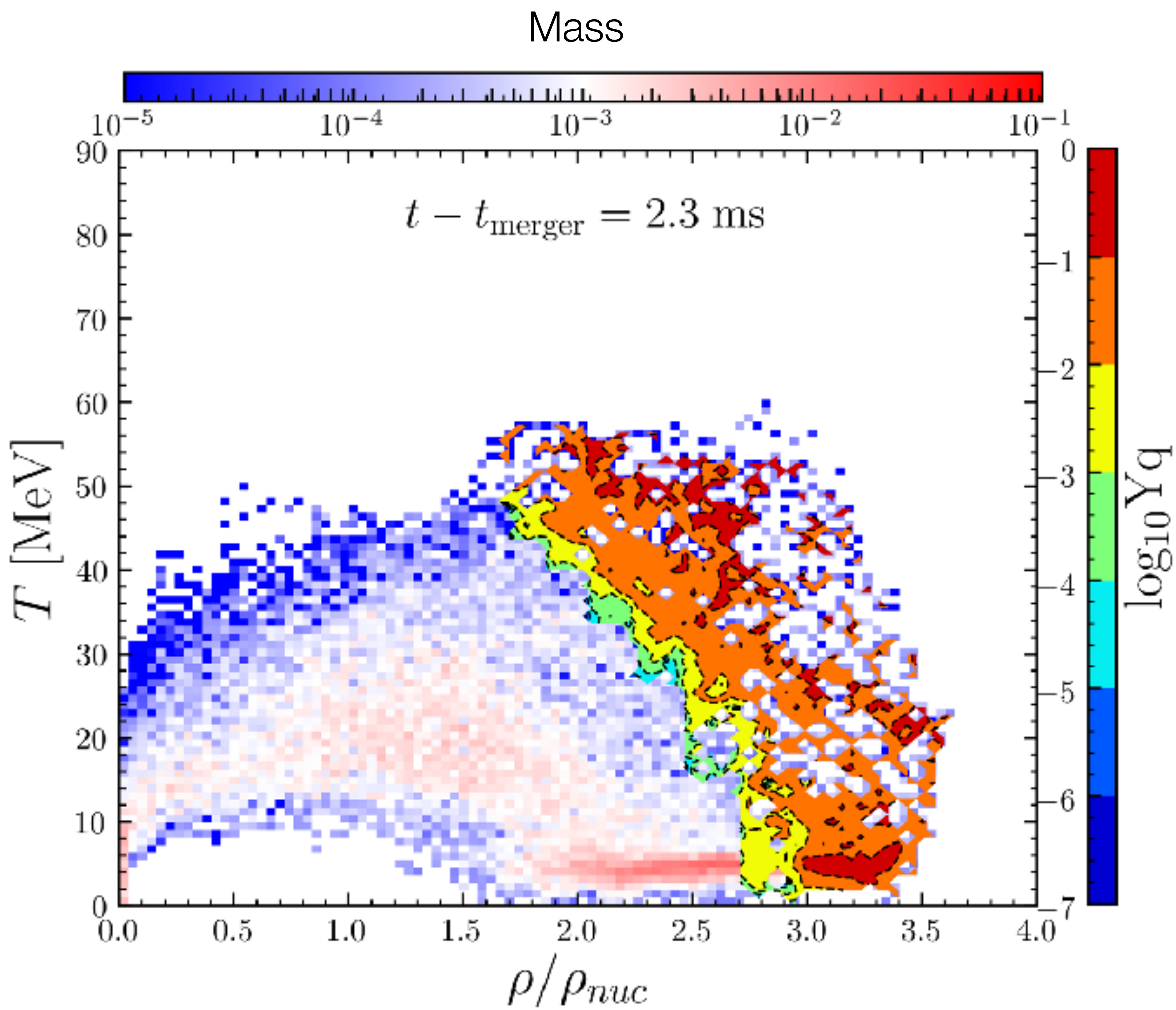
Breschi+ 2021, MNRAS 505:1661 (2021)

Probing the QCD phase diagram



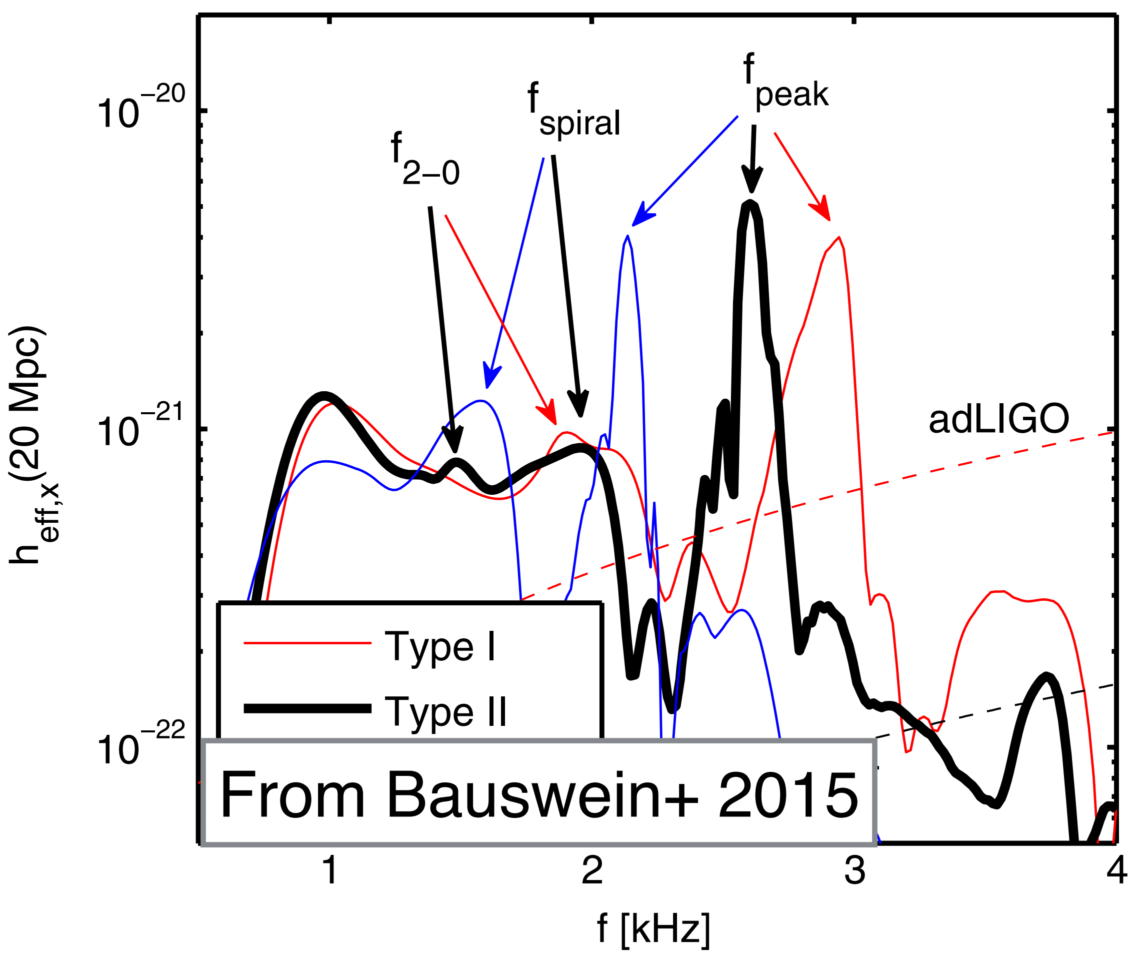
Prakash, **DR**+, PRD in press, 2106.07885

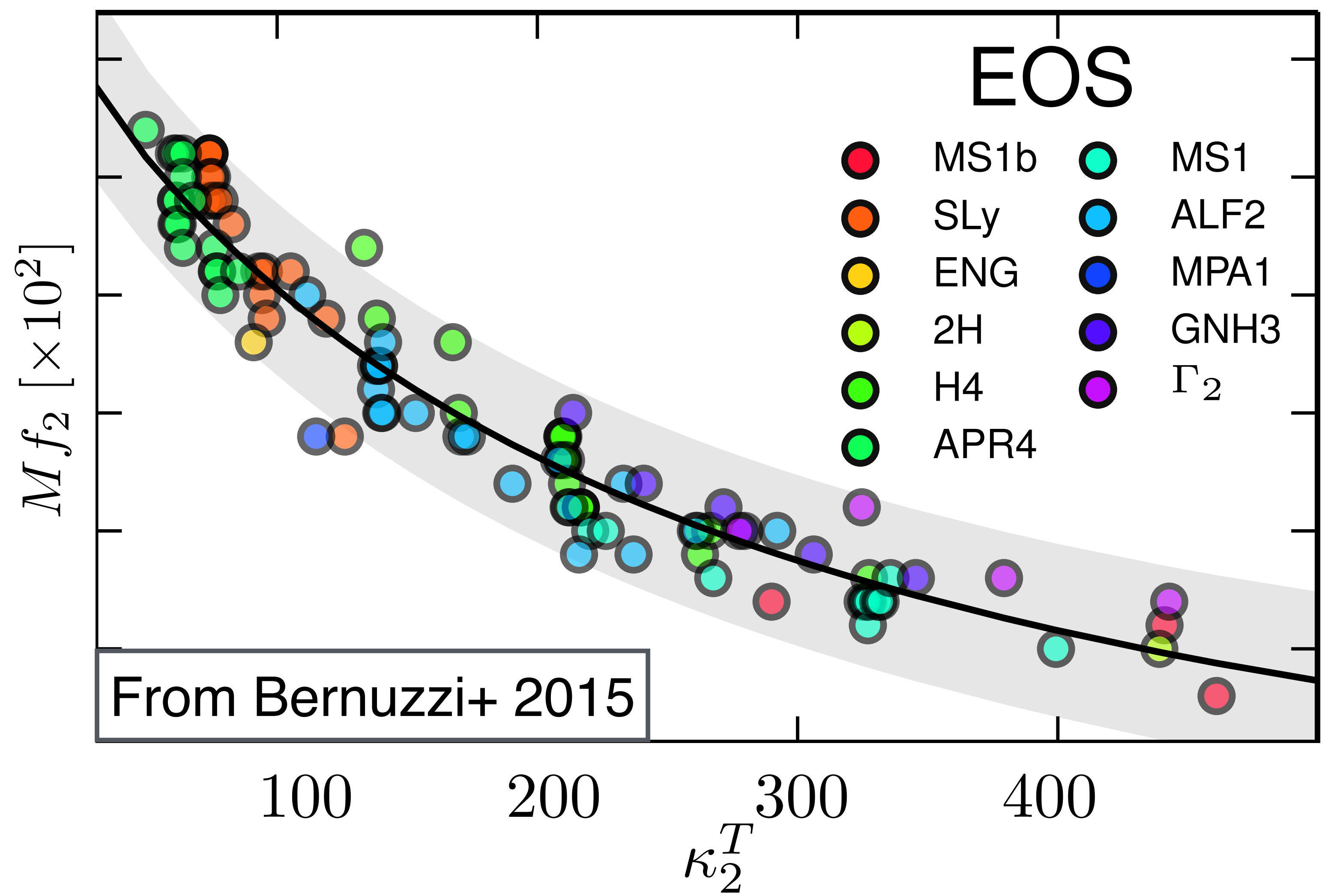
Postmerger physics



Prakash, **DR**+, PRD in press, 2106.07885

Postmerger peak frequency

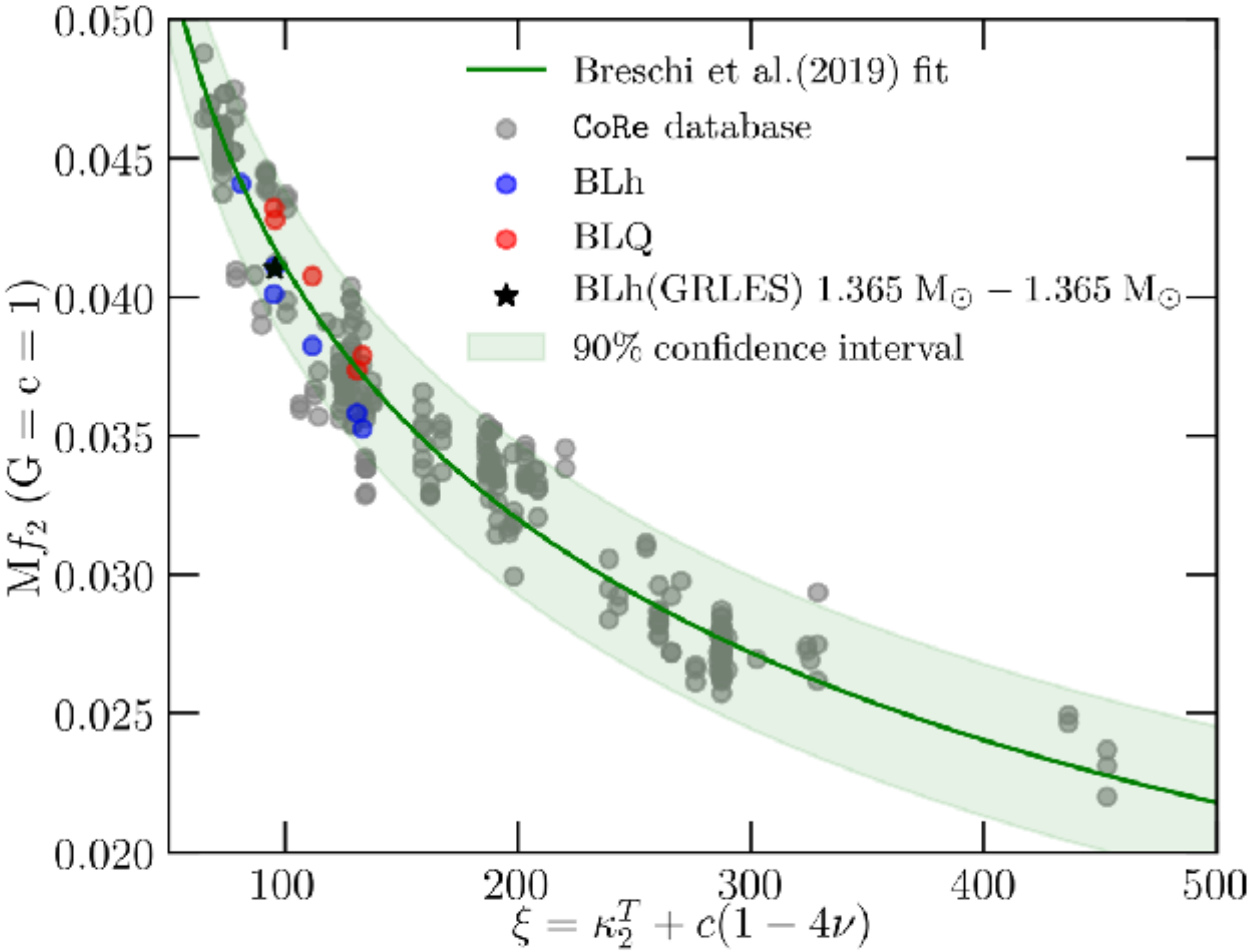




- Post-merger signal has a characteristic peak frequency
- f_{peak} correlates with the NS radius and tidal deformability
- Systematics not fully understood (e.g., turbulence [Radice+ 2017], bulk viscosity [Alford+ 2018], pions [Fore+ 2019]); very high SNR needed

See also Takami+ 2014; Rezzolla & Takami 2016; Dietrich+ 2016; Bauswein+ 2019; …

QCD phase transitions

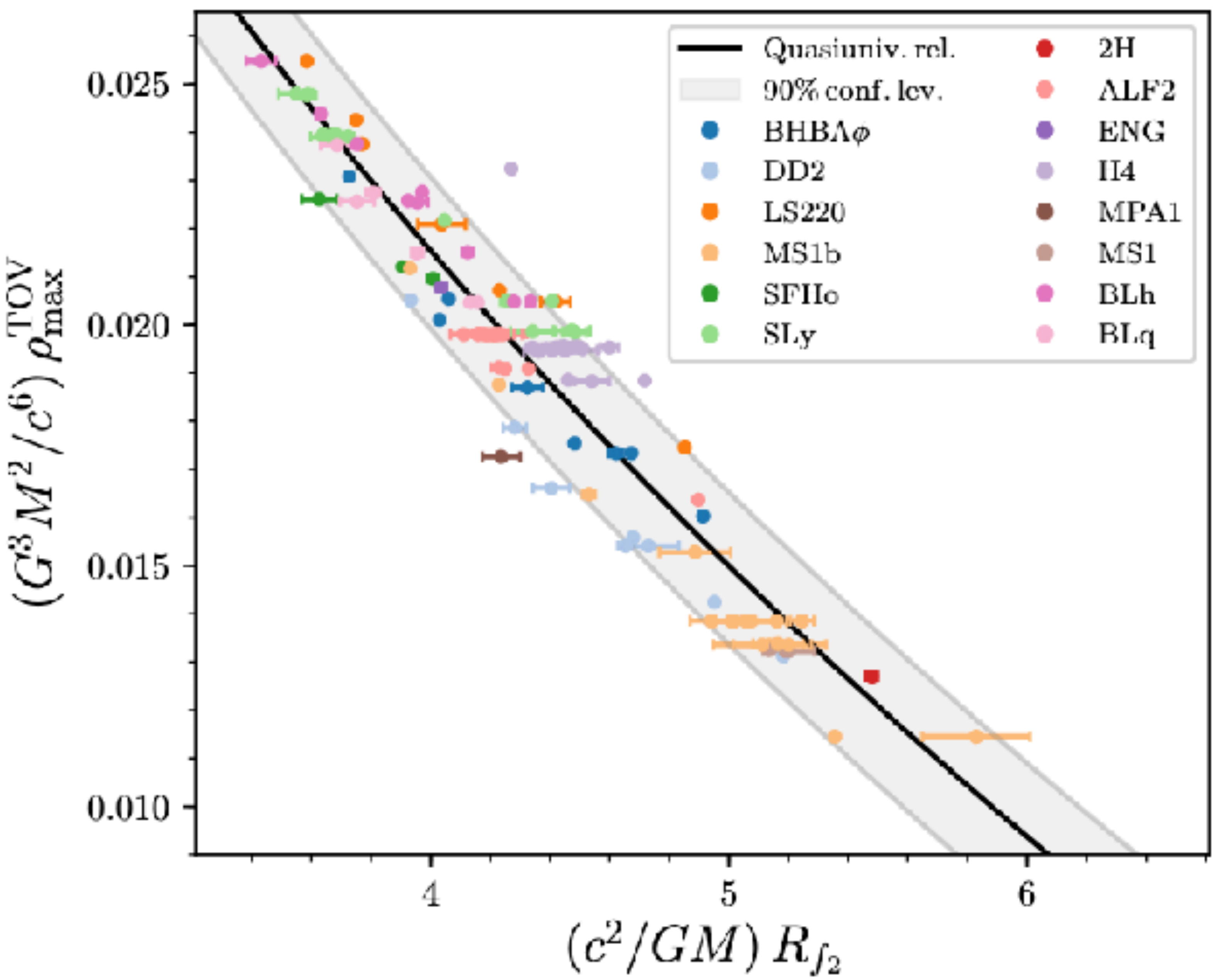


- QCD transition can lead to early collapse
- Increase GW luminosity
- First order phase transitions can lead to shifts in f_{peak}
- The effect can be subtle, degenerate with other physics… more work is needed

See also Most+ 2018; Bauswein+ 2018; Weih+ 2019; Blacker+ 2020

Prakash, **DR**+, PRD in press, 2106.07885

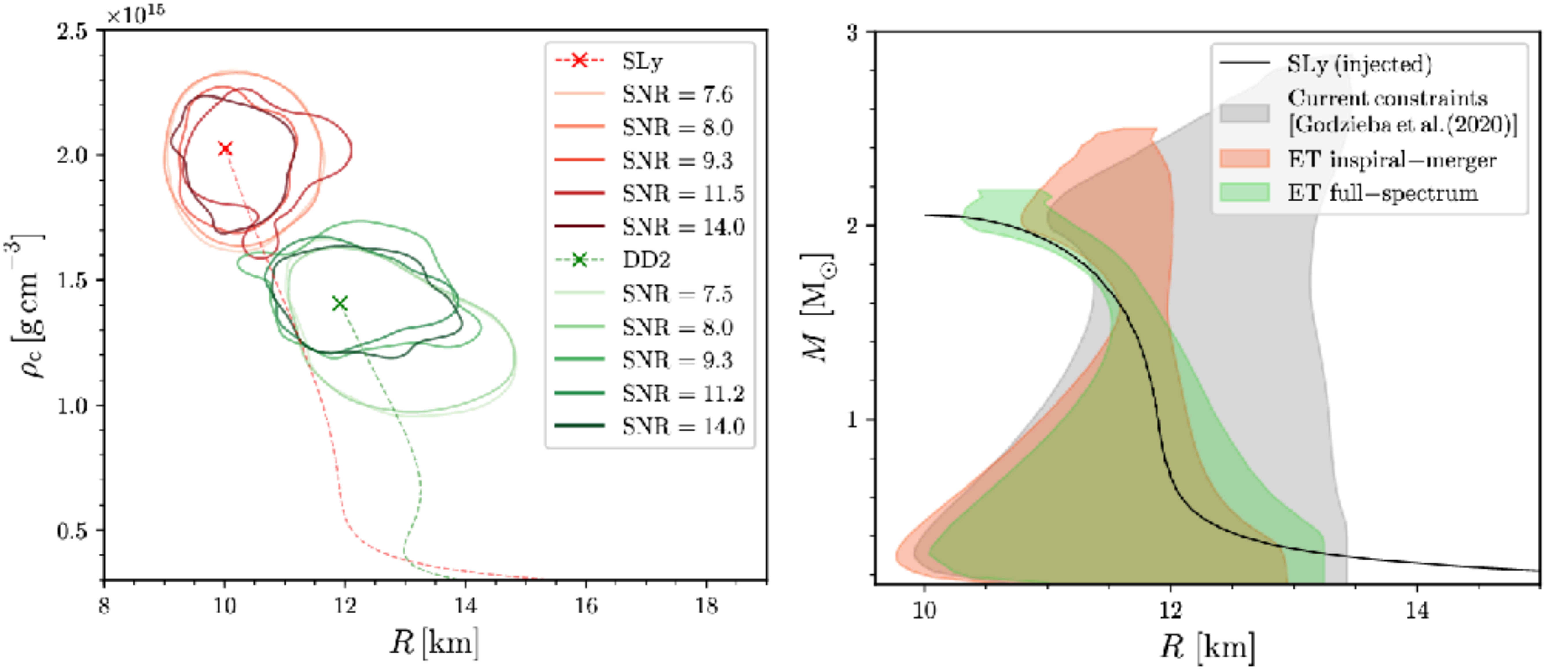
NS maximum mass (I)



EOS insensitive relation between the remnant Kepler radius and $\rho_{\max}^{\rm TOV}$

Breschi+ 2110.06957

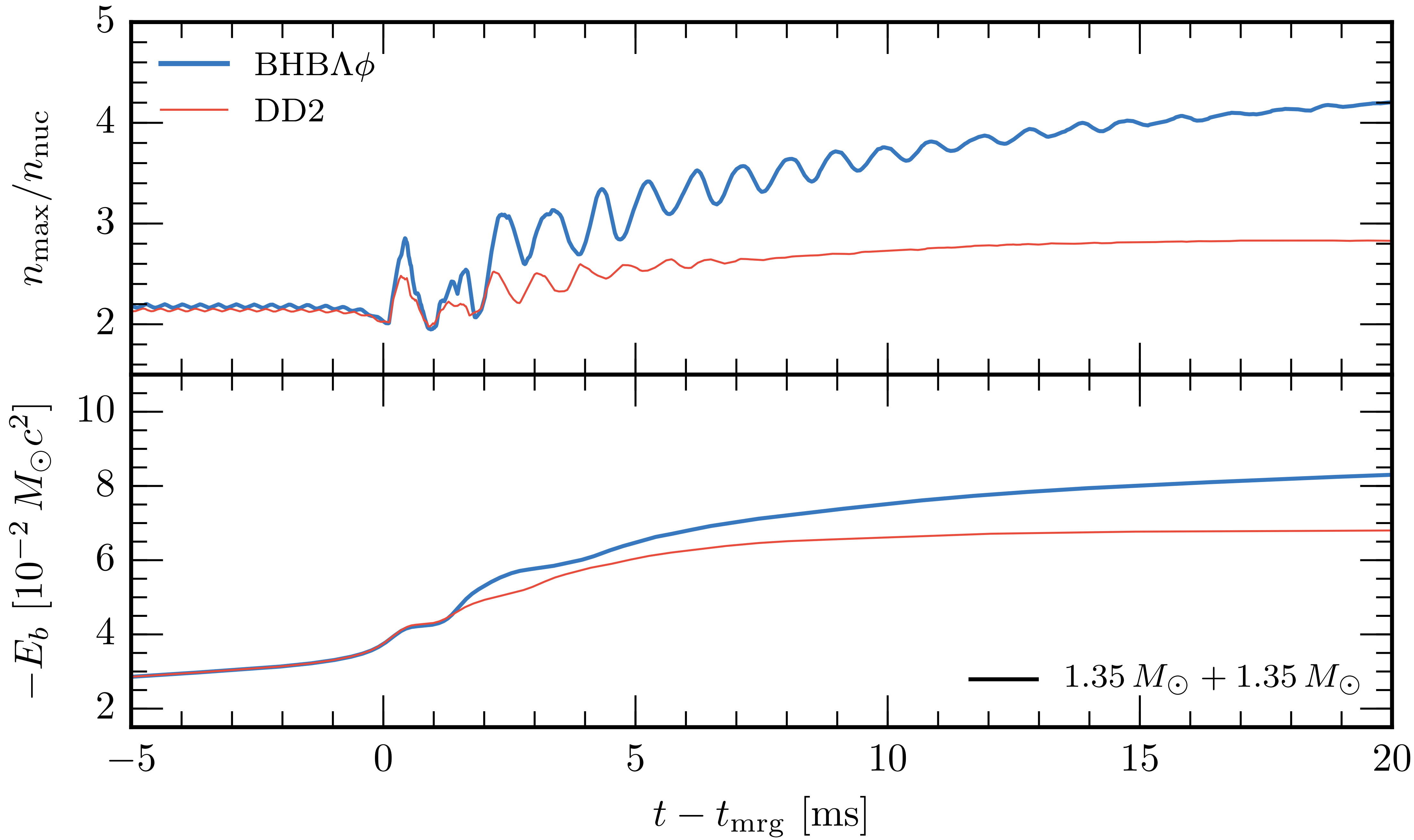
NS maximum mass (II)



Tight constraints on $M_{\max}$ even after a single detection at threshold SNR

Breschi+ 2110.06957

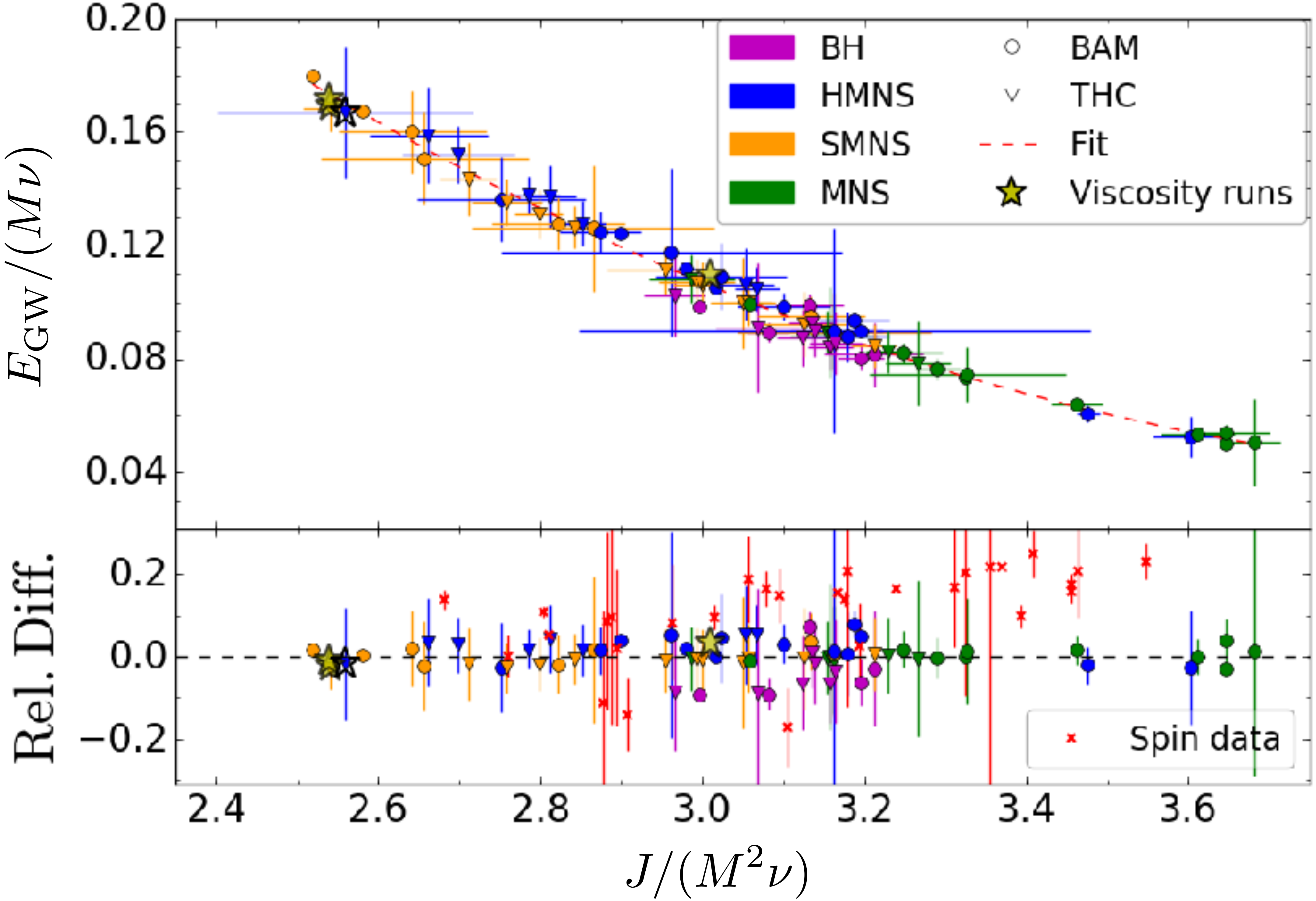
Postmerger amplitude



High-density EOS encoded in the binding energy

DR, Bernuzzi, Del Pozzo+, ApJL 842:L10 (2017)

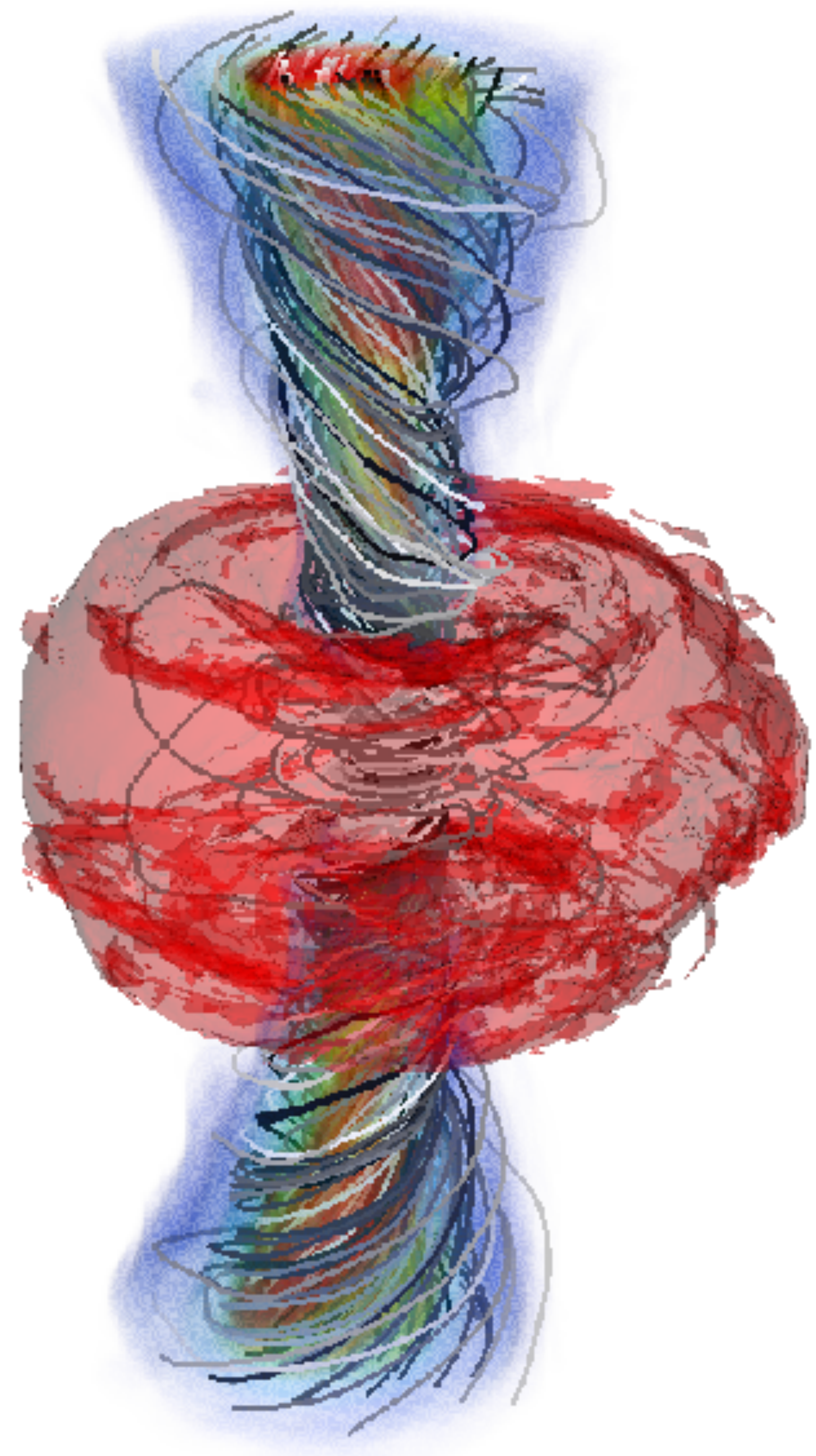
Remnant angular momentum



Zappa, Bernuzzi, **DR**+, Phys. Rev. Lett. 120, 111101 (2018)

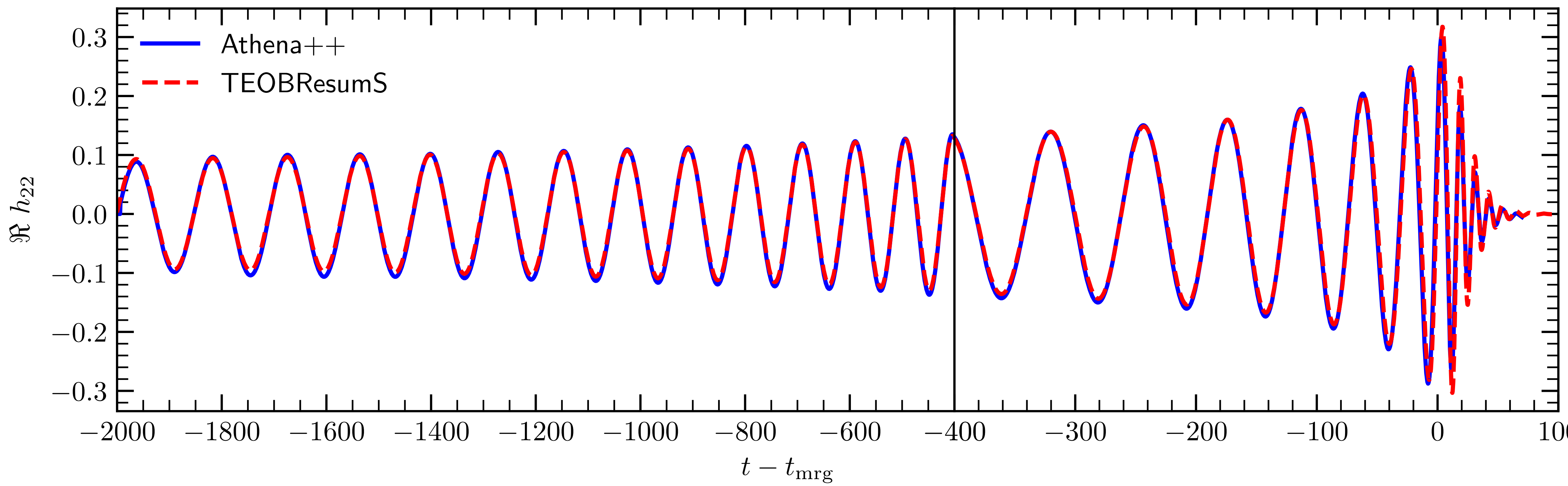
Challenges

- Current simulations O(1) month of computer time on O(1000) CPUs for for O(10 ms) of evolution
- Accurate prediction of EM counterparts and outflows require simulation spanning O(a few) seconds
- More sophisticated neutrino transport and MHD are also needed
- Working on the next generation NR code: GR-Athena++



Mösta, **DR**+ 2020

GRAthena++



GRAthena++

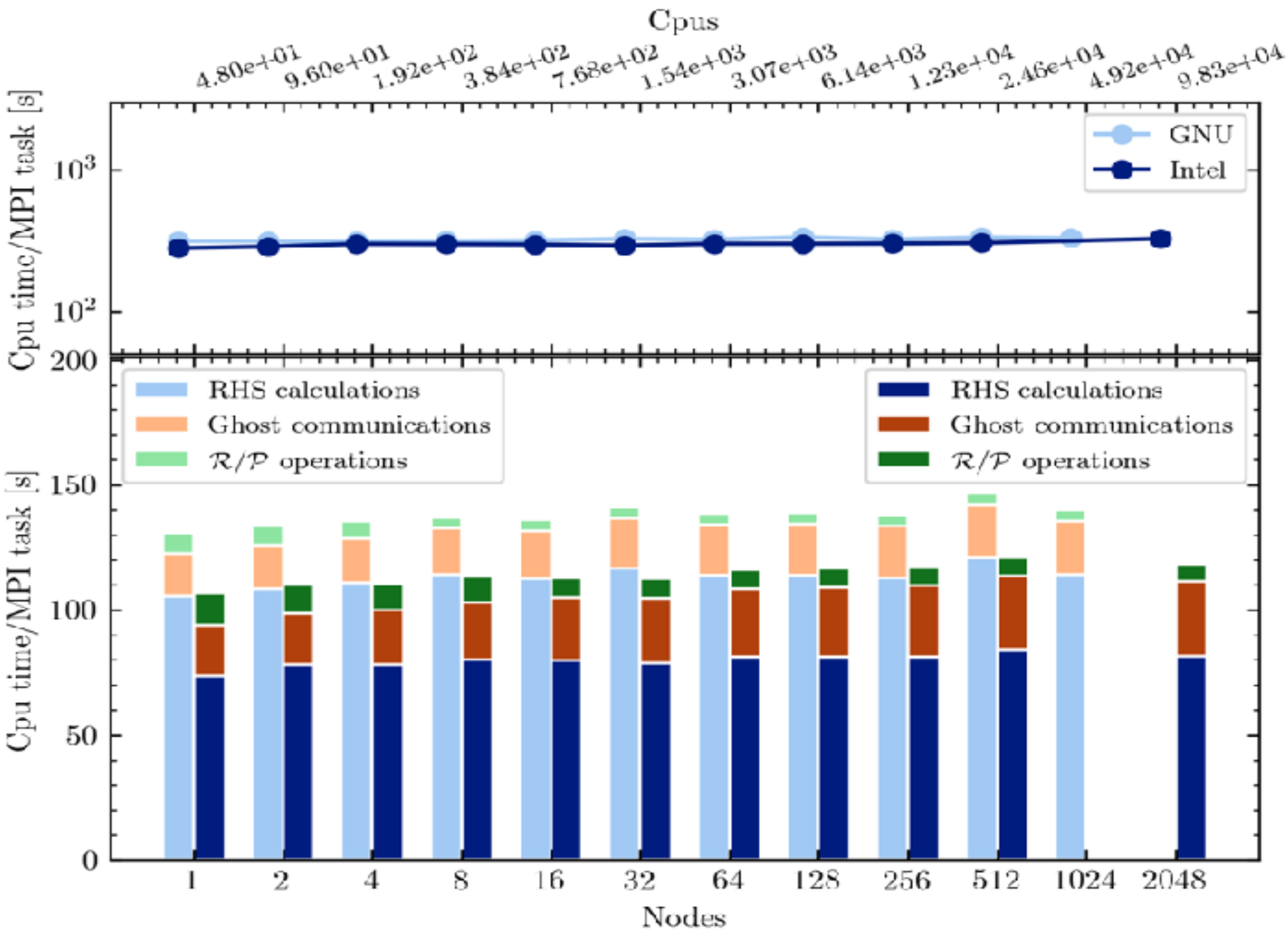
- Vertex centered octree AMR
- High order FD and low-storage Runge-Kutta time integration
- Hybrid MPI/OpenMP, SIMD vectorized

Coming soon

- GRMHD (already working, but needs testing)
- GPU acceleration (with Kokkos)
- Spectral-like compact FD

Daszuta+ 2021, 2101.08289

GRAthena++



Daszuta+ 2021, 2101.08289

Conclusions

- We can already do multimessenger astrophysics!
- Postmerger GWs can reveal the physics of matter at extreme densities
- The physics becomes increasingly complex on longer timescales in the postmerger. Higher resolution, longer, and more sophisticated simulations are needed

Gravitational waves (II)

Inclination, sky position, etc.

$$\tilde{h}(f) = \frac{Q}{D}\mathcal{M}^{5/6} f^{-7/6} \exp[i\Psi(f)]$$

Distance

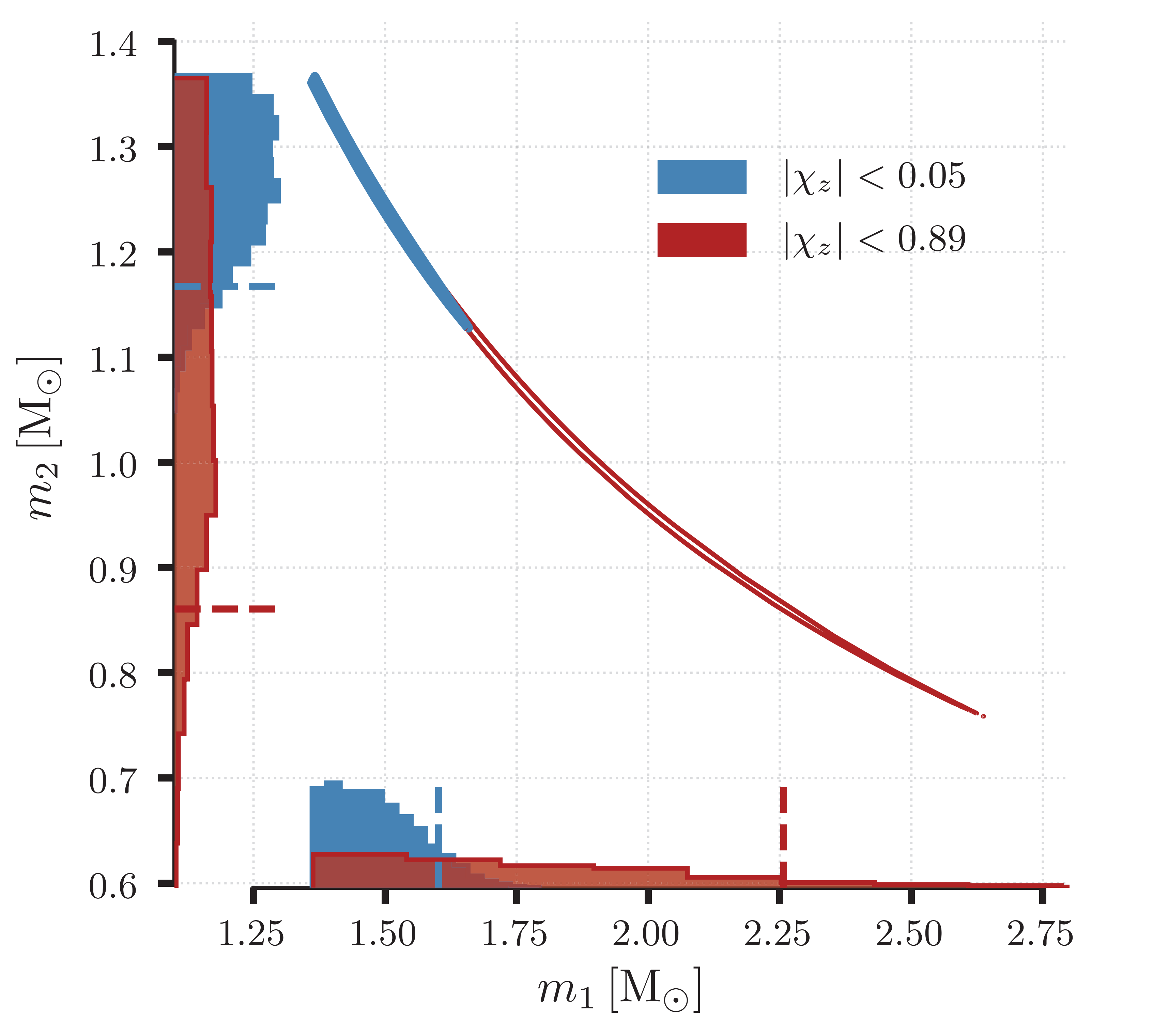
Chirp mass

Phase

$$\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M1 + M_2)^{1/5}}$$

Gravitational waves (III)

$$\Psi(f) = 2$$



$$\Psi_j f^{\frac{2j}{3}} \Big]$$

Time and p

, spins,
cts, etc.

From LIGO/Virgo collaboration, PRL 119:161101 (2017)