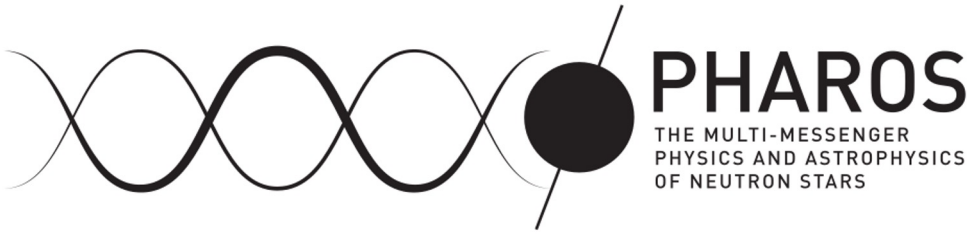
EoS at High-Baryon Density and Compact Stellar Objects

Veronica Dexheimer

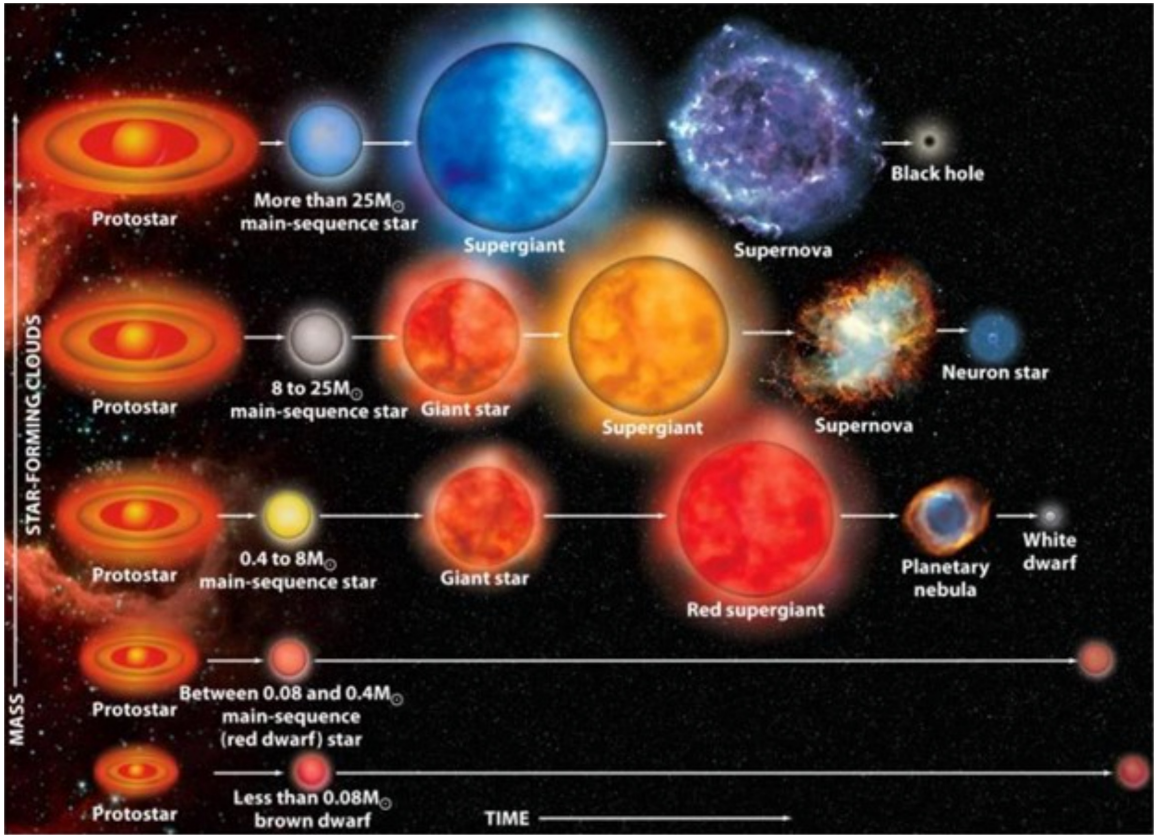


Summary

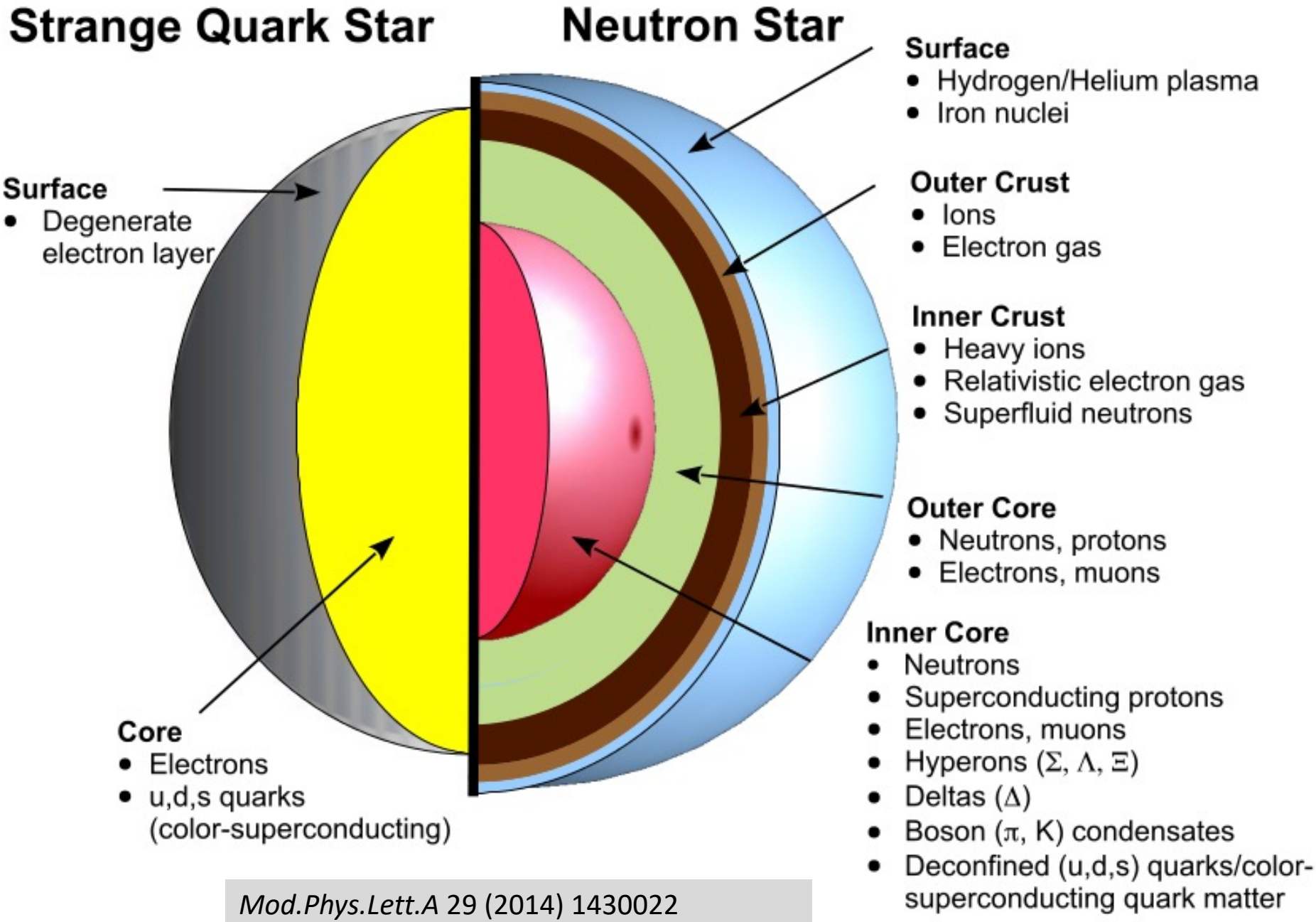
- Introduction to compact stars
- Neutron-star equation of state (EoS)
- Ingredients for the EoS
- Modern sources for EoS's
- EoS constraints
- Recent conclusions
- Deconfinement in supernova simulations
- Deconfinement in merger simulations
- Comparison of mergers and heavy-ion collisions
- Conclusions

Introduction to compact stars

- White dwarfs: lattice of e.g. carbon, oxygen + degenerate electron gas
- Neutron stars: lattice of iron + degenerate gas of neutrons and electrons + core
- Black holes: ?



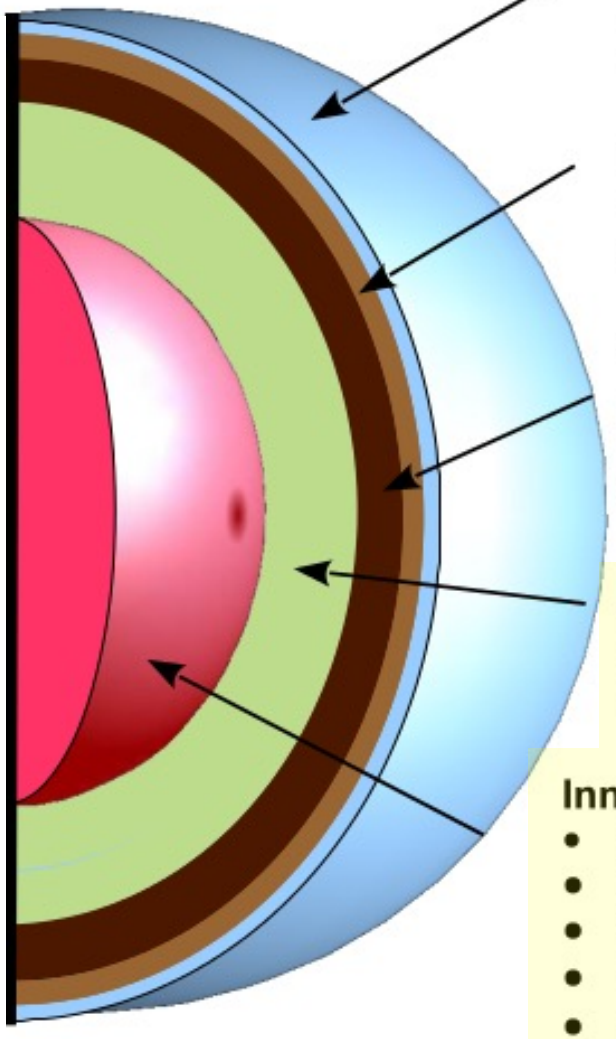
Universe, Tenth edition



Mod.Phys.Lett.A 29 (2014) 1430022
e-Print: 1408.0079

Strange Quark Star

Neutron Star



Surface
- Hydrogen/Helium plasma
- Iron nuclei

Outer Crust
- Ions
- Electron gas

Inner Crust
- Heavy ions
- Relativistic electron gas
- Superfluid neutrons

Outer Core
- Neutrons, protons
- Electrons, muons

Inner Core
- Neutrons
- Superconducting protons
- Electrons, muons
- Hyperons (Σ, Λ, Ξ)
- Deltas (Δ)
- Boson (π, K) condensates
- Deconfined (u,d,s) quarks/color-superconducting quark matter

Mod.Phys.Lett.A 29 (2014) 1430022
e-Print: 1408.0079

Neutron-star equation of state (EoS)

- Official meaning: a thermodynamic equation relating state variables (usually including the pressure)
- In astrophysics we (when available) also provide:
  - full thermodynamic list of variables
  - particle composition
  - microscopic information (pairing gaps, …)
  - stellar properties …
- 1D or 2D (usually for neutron stars or isospin symmetric)
- 3D (usually n_B, T, Y_Q) …

Ingredients for the EoS

- Crust EoS with nuclei (pasta?)
- Outer core EoS with interacting (pairing?) nucleons and leptons
- Inner core EoS with interacting (pairing?) nucleons, hyperons, Δ's , mesons, (transition to?) quarks (talk by Valentina Mantovani Sarti)
- Within description appropriate for high density and finite temperature (quantum relativistic description?)
- Reproduce chiral symmetry restoration (parity doubling?)
- Reproduce lattice QCD results at finite temperature?
- In agreement with heavy-ion collision physics at finite temperature?
- Reproduce perturbative QCD results in the relevant regime

Modern sources for EoS's

- CompOSE

  CompStar Online Supernovae Equations of State
  https://compose.obspm.fr
  (Stefan Typel, Micaela Oertel, Thomas Klaehn)

- Online service provides 1D, 2D, 3D EoS tables for astrophysical applications

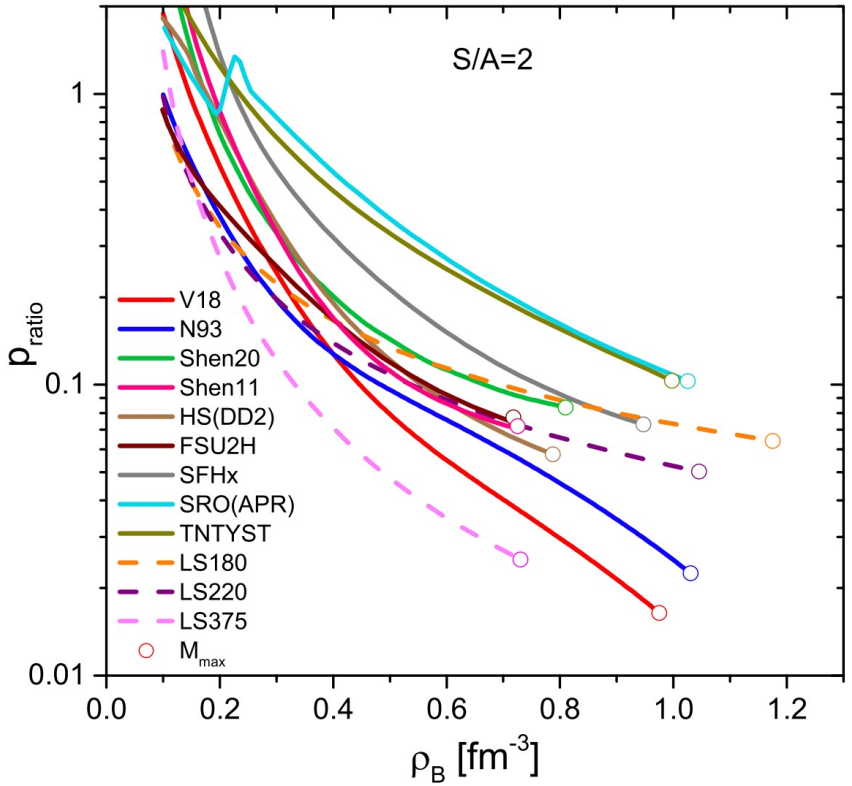
- Additional software to combine or interpolate data, calculate additional quantities, and graph EoS dependencies

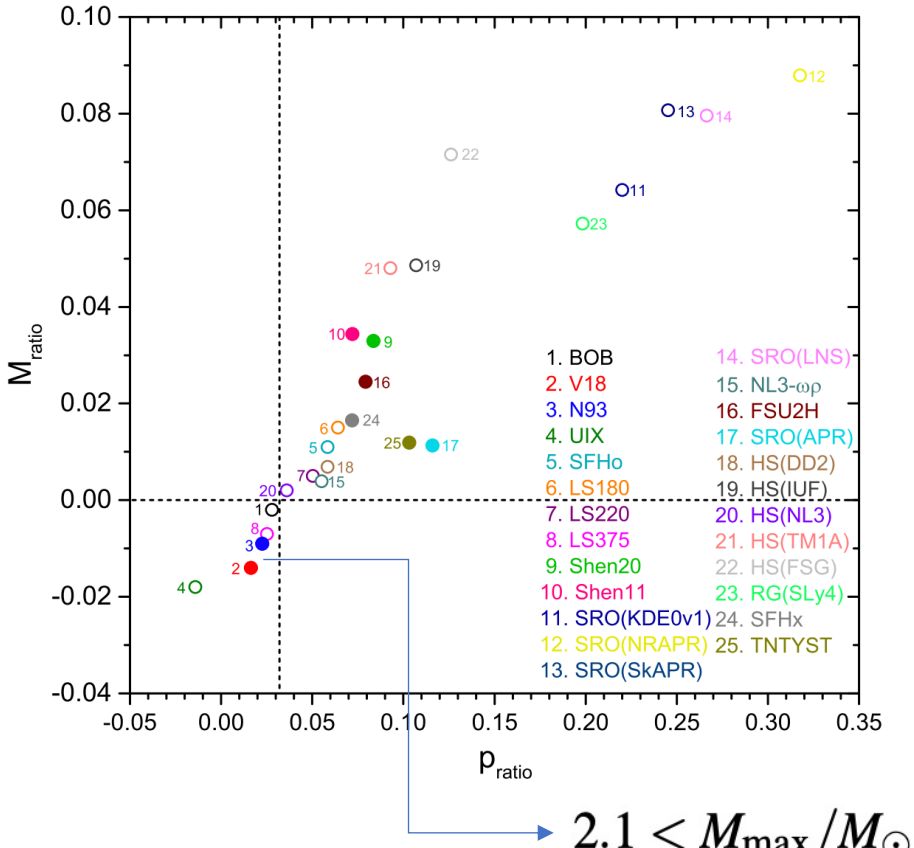
- Instruction manual e-Print: 2203.03209
  with summarized providers quick guide and users quick guide

CompOSE

- Example: young (hot) β-equilibrated stars

Phys.Rev.C 104 (2021) 6, 065806
e-Print: 2112.05323





$$2.1 < M_{\max}/M_{\odot} < 2.4$$

$$p_{\text{ratio}} \equiv \frac{p_{\text{th}}}{p_0}(\rho, T)$$

$$p_{\text{th}}(\rho, T) \equiv p(\rho, x_T, T) - p(\rho, x_0, 0)$$

$$M_{\text{ratio}} \equiv \frac{M_{\max}^{\text{hot}} - M_{\max}^{\text{cold}}}{M_{\max}^{\text{cold}}}$$

Modern sources for EoS's

- muses

  Modular Unified solver of the Equation of state
  https://muses.physics.illinois.edu/

- Modular: while at low μ_B the EoS is known from 1st principles, at high μ_B there will be different models for the user to choose
- Unified: different modules will be merged together to ensure maximal coverage of the phase diagram
- Developers: physicists + computer scientists will work together to develop the software that generates EoS's over large ranges of temperature and chemical potentials to cover the whole phase diagram
- Users: interested scientists from different communities, who provide input to the future open-source cyberinfrastructure

muses

PI and co-PIs

1. Nicolas Yunes; University of Illinois at Urbana-Champaign; **PI**
2. Jacquelyn Noronha-Hostler; University of Illinois at Urbana-Champaign; co-PI
3. Jorge Noronha; University of Illinois at Urbana-Champaign; co-PI
4. Claudia Ratti; University of Houston; co-PI and **spokesperson**
5. Veronica Dexheimer; Kent State University; co-PI

Senior investigators

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2. Roland Haas; National Center for Supercomputing Applications
3. Timothy Andrew Manning; National Center for Supercomputing Applications
4. Andrew Steiner; University of Tennessee, Knoxville
5. Jeremy Holt; Texas A&M University
6. Gordon Baym; University of Illinois at Urbana-Champaign
7. Mark Alford; Washington University in Saint Louis
8. Elias Most; Princeton University

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3. Katerina Chatziioannou; California Institute of Technology
4. Phillip Landry; California State University Fullerton
5. Reed Essick; Perimeter Institute
6. Rene Bellwied; University of Houston
7. David Curtin; University of Toronto
8. Michael Strickland; Kent State University
9. Matthew Luzum; University of Sao Paulo
10. Hajime Togashi; Kyushu University
11. Toru Kojo; Central China Normal University
12. Hannah Elfner; GSI/Goethe University Frankfurt

EoS constraints

- Experimental nuclear physics data

  e-Print: 2203.03156

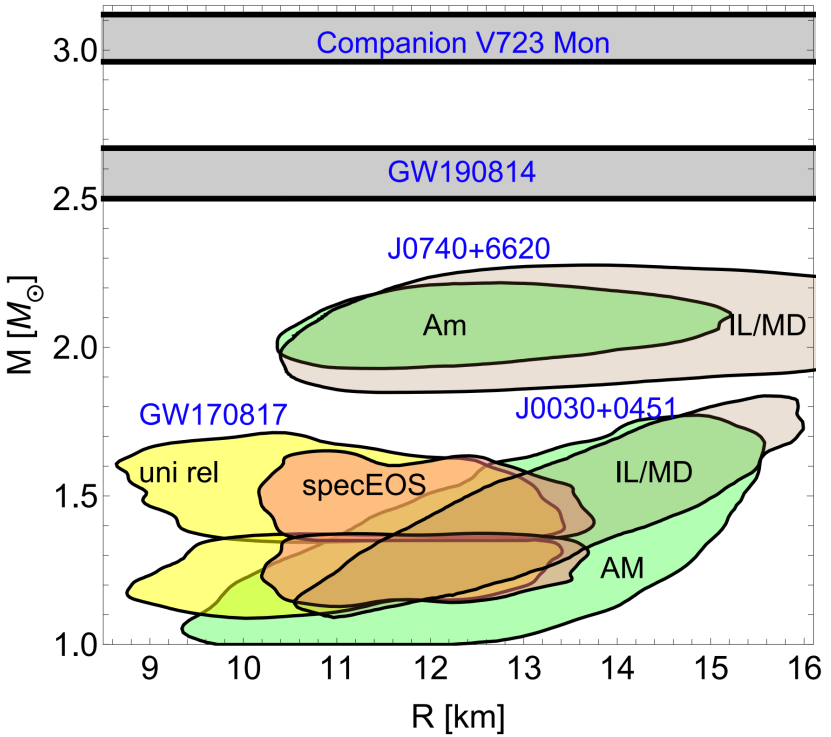
  - saturation properties: n_0, B/A, K, M_N^*/M_N, U_Λ, …
  - symmetry energy and derivative at saturation
  - LG critical point

- Observational data

  - stellar max. masses
  - stellar masses, some with corresponding radii
  - stellar mass with tidal deformability and radius

  e-Print: 2202.01820

  - possible very large masses
  - cooling data



Phys.Rev.D 105 (2022) 2, 023018
e-Print: 2106.03890

EoS constraints

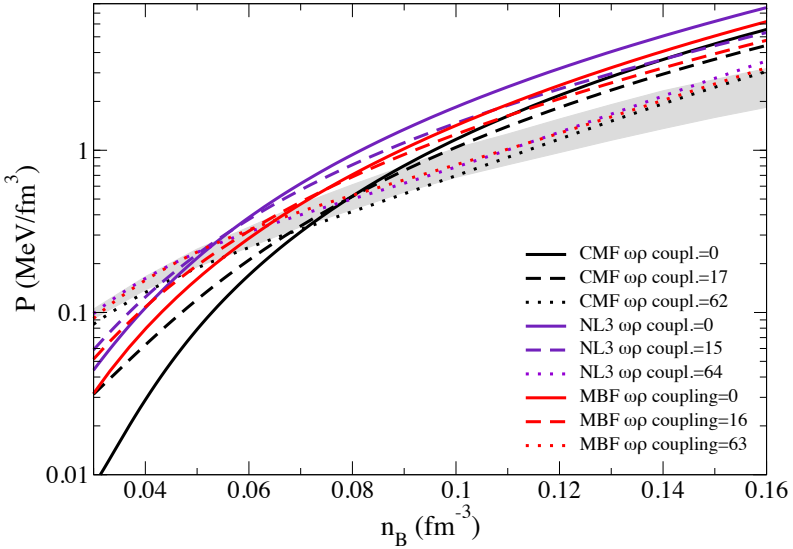
J.Phys.G 46 (2019) 3, 034002
e-Print: 1810.06109

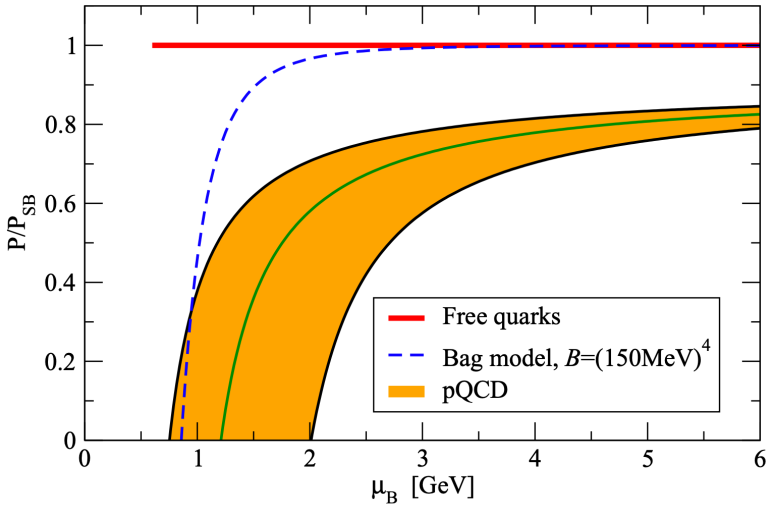
- 1st-principle theory

  - ChEFT: low T and n_B → guides the nuclear EoS

  - lattice QCD: EoS, susceptibilities, partial pressures, (smooth) phase transition line, critical point exclusion → allows calibration of EoS at large T

  - perturbative QCD: extremely large T and μ_B → guides quark matter EoS

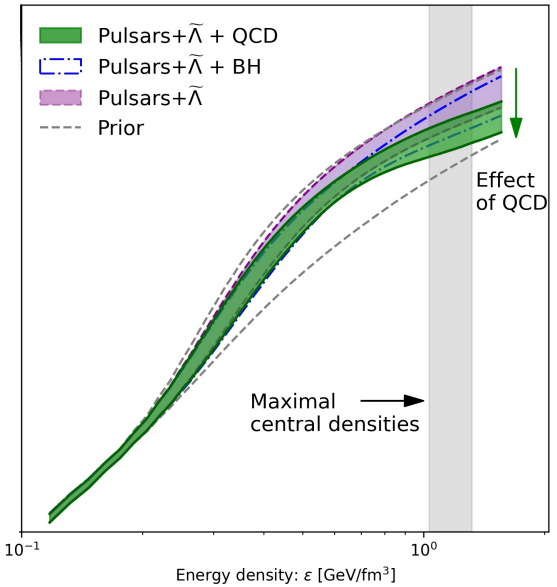




Astrophys.J.Lett. 781 (2014) 2, L25
e-Print: 1311.5154

Recent Conclusions

- Talk from Oleg Komoltsev



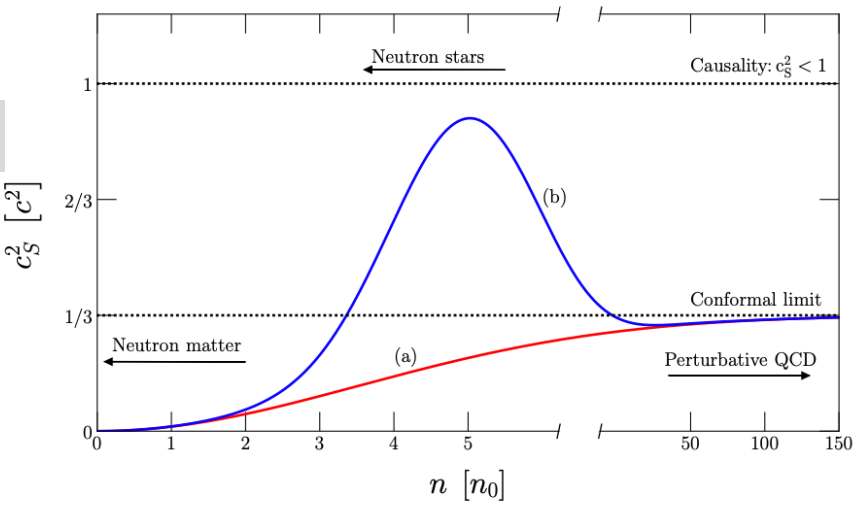
- "If the bound on the speed of sound is actually violated – as it is strongly suggested by our results– the speed of sound, as a function of the energy density, has a peculiar shape.

Phys.Rev.Lett. 114 (2015) 3, 031103 e-Print: 1408.5116

Astrophys.J. 860 (2018) 2, 149 e ePrint: 1801.01923

Astrophys.J. 885 (2019) 4 e-Print: 1903.08963

Nucl.Phys.A 843 (2010) 37-58 e-Print: 0912.3800



Recent Conclusions

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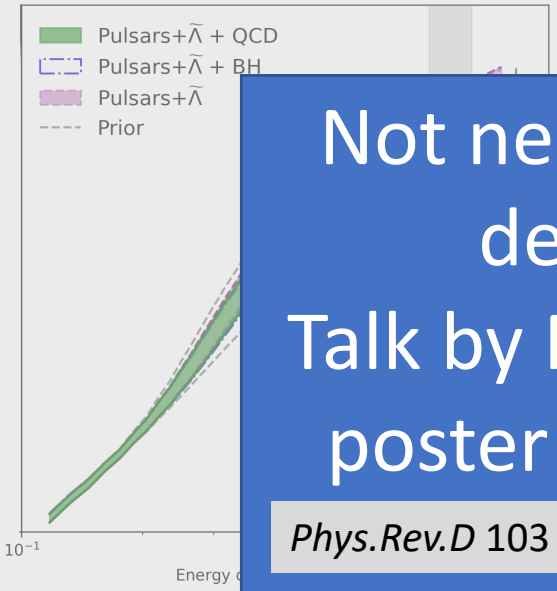


- "If the bound on the speed of sound is actually violated – as gested by our ed of sound, the energy eculiar shape.

Not necessarily related to deconfinement?
Talk by Michael Marczenko, poster by Jorge Noronha,

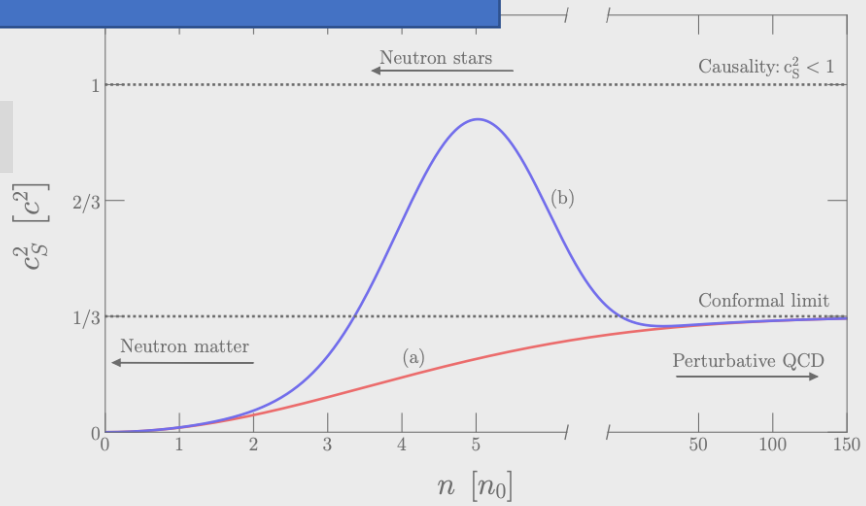
Phys.Rev.D 103 (2021) 7, L071504 e-Print: 2101.05813

31103 e-Print: 1408.5116

Astrophys.J. 860 (2018) 2, 149 e ePrint: 1801.01923

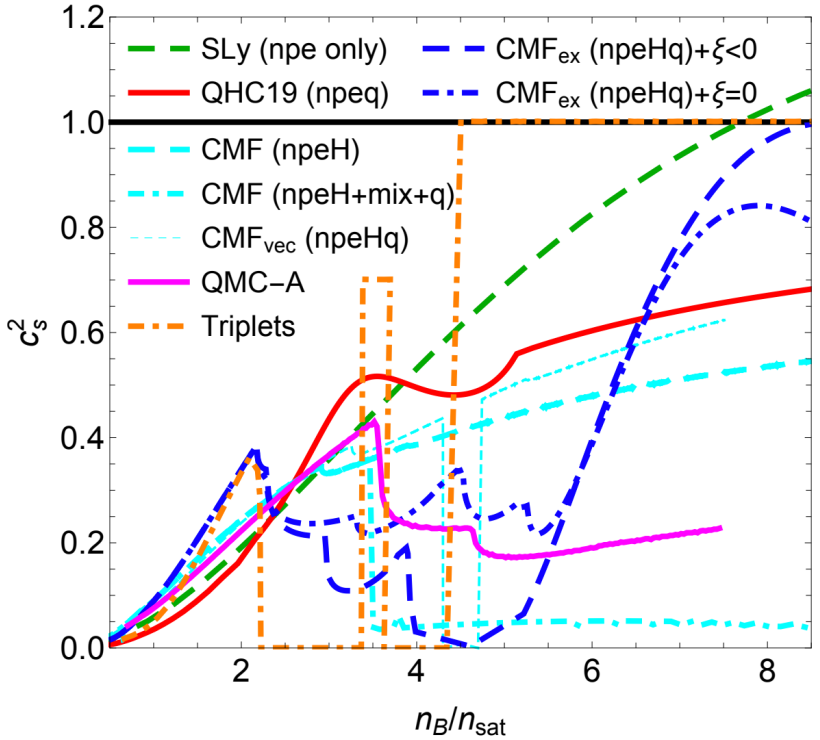
Astrophys.J. 885 (2019) 4 e-Print: 1903.08963

Nucl.Phys.A 843 (2010) 37-58 e-Print: 0912.3800



Recent Conclusions

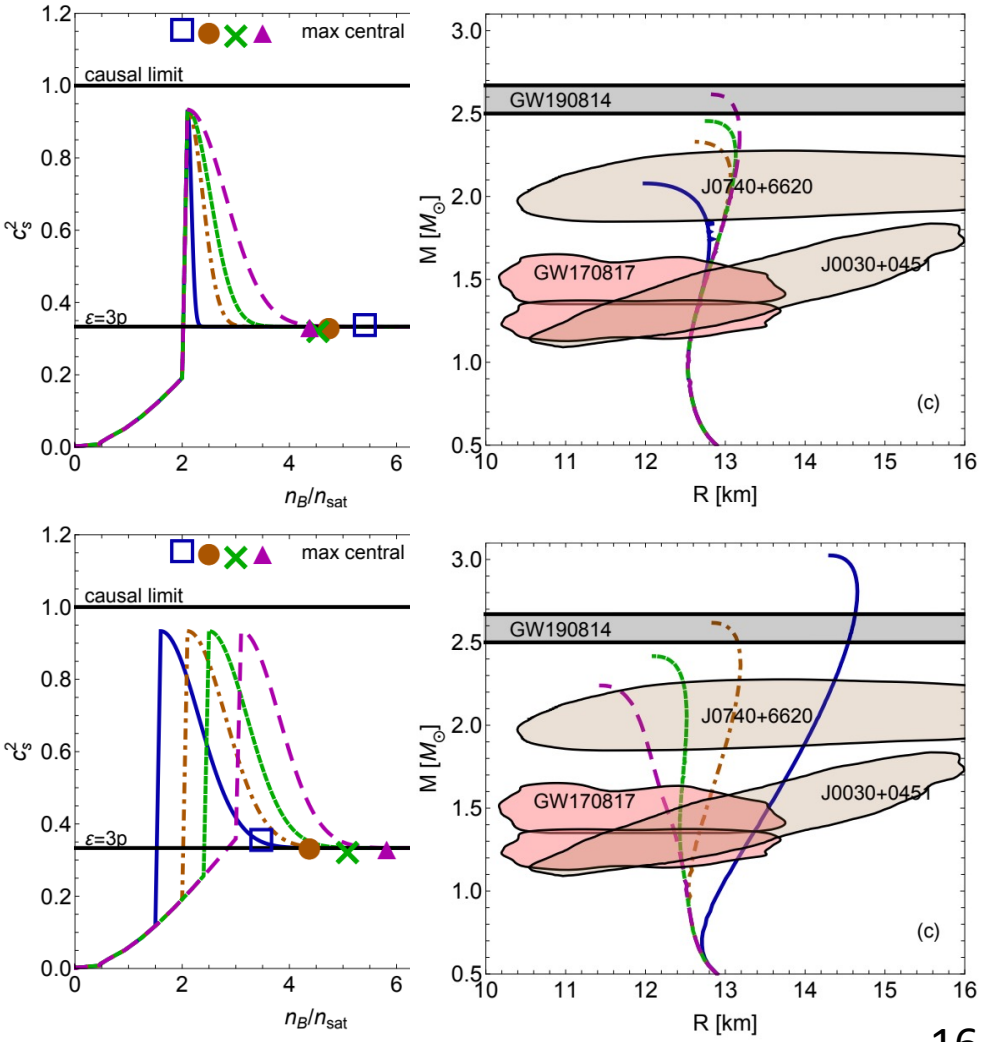
- "Bumps" in effective models



- Stellar masses and radii: information about "bump"

Phys.Rev.D 105 (2022) 2, 023018 e-Print: 2106.03890

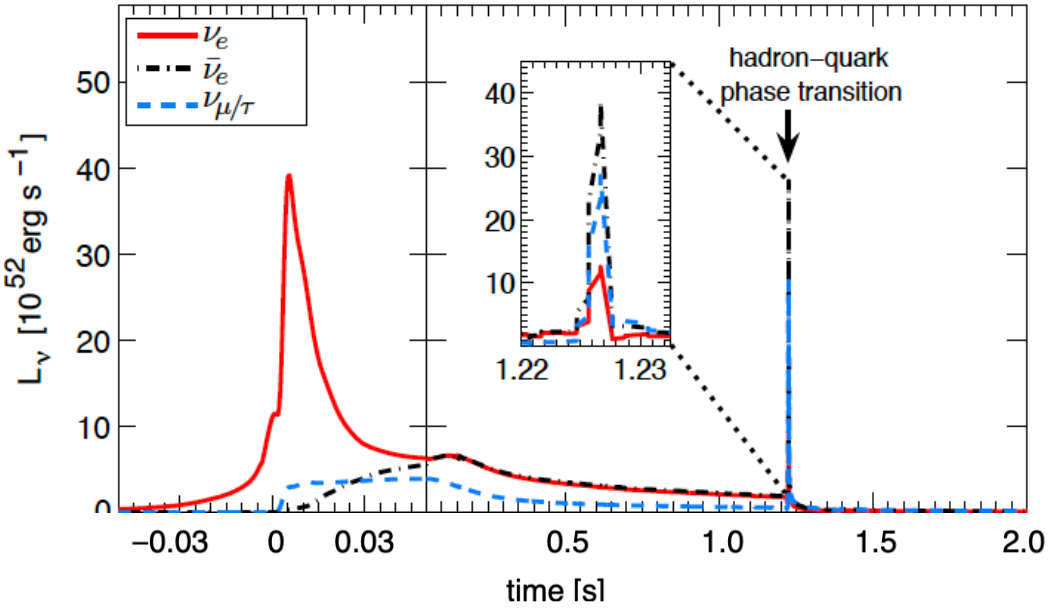
… and in parametric models

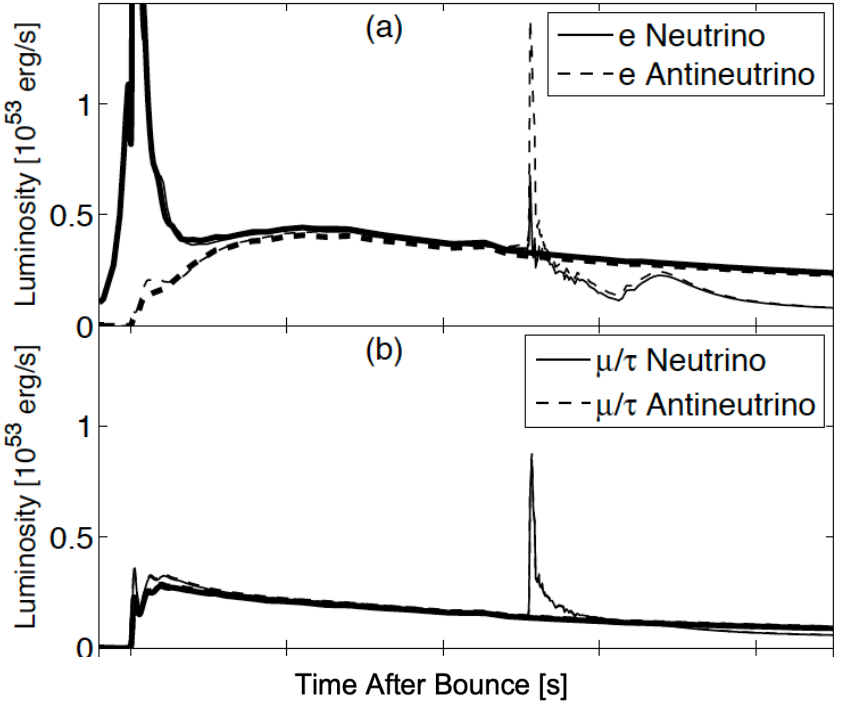


Deconfinement in supernova simulations

- Second burst of neutrinos after bounce when 3D hybrid EoS Shen-MIT bag model with mixed phase (thin lines) is used

Phys.Rev.Lett. 102 (2009) 081101
e-Print: 0809.4225





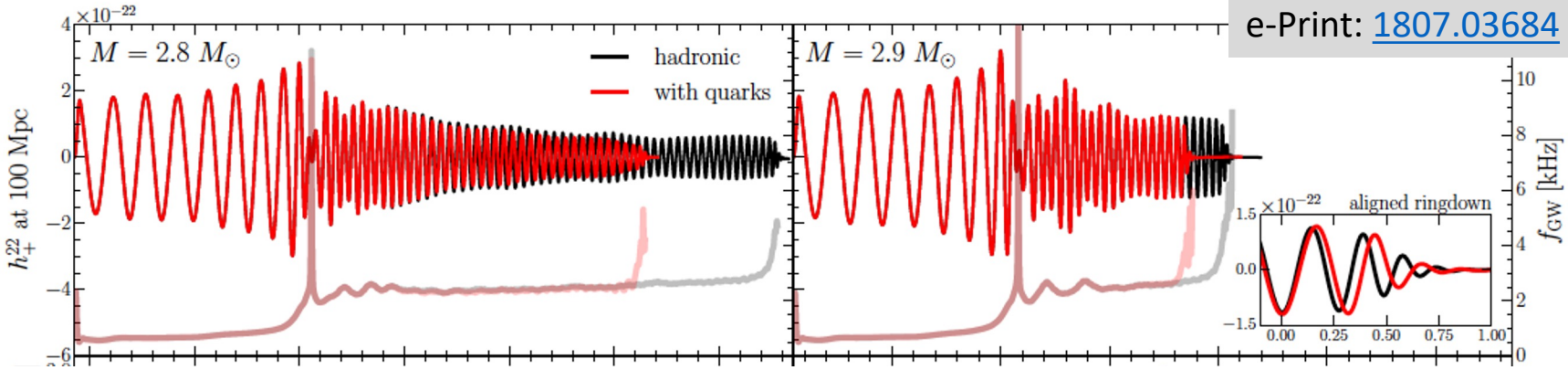
- Results reproduced with 3D hybrid EoS 2-flavor SF (RDF) quark model

Nature Astron. 2 (2018) 12, 980-986
e-Print: 1712.08788

Deconfinement in merger simulations

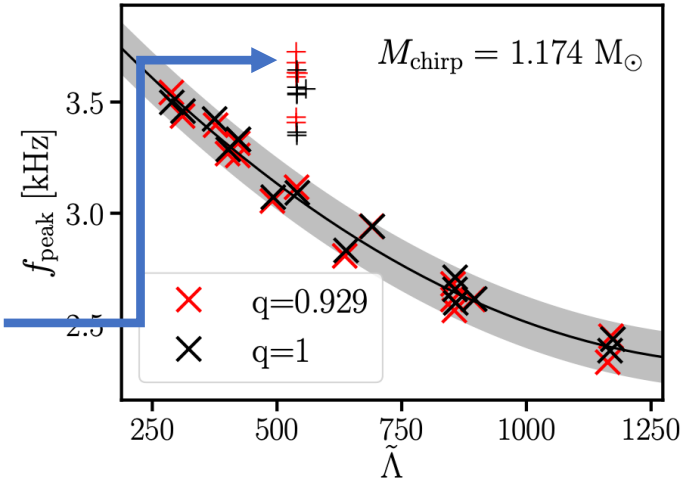
- 3D CMF EoS with/without quarks into hydrodynamics system using full GR Frankfurt/Illinois GRMHD code: effects from quarks (h, f, phase) only after the merger

PRL 122 (2019) 6, 061101
e-Print: 1807.03684



- 3D DD2-SF (RDF) hybrid EoS with mixed phase (+ hadronic ones) into GR SPH code: different postmerger dominant frequencies for hybrid EoS

Phys.Rev.D 102 (2020) 12, 123023
e-Print: 2006.03789



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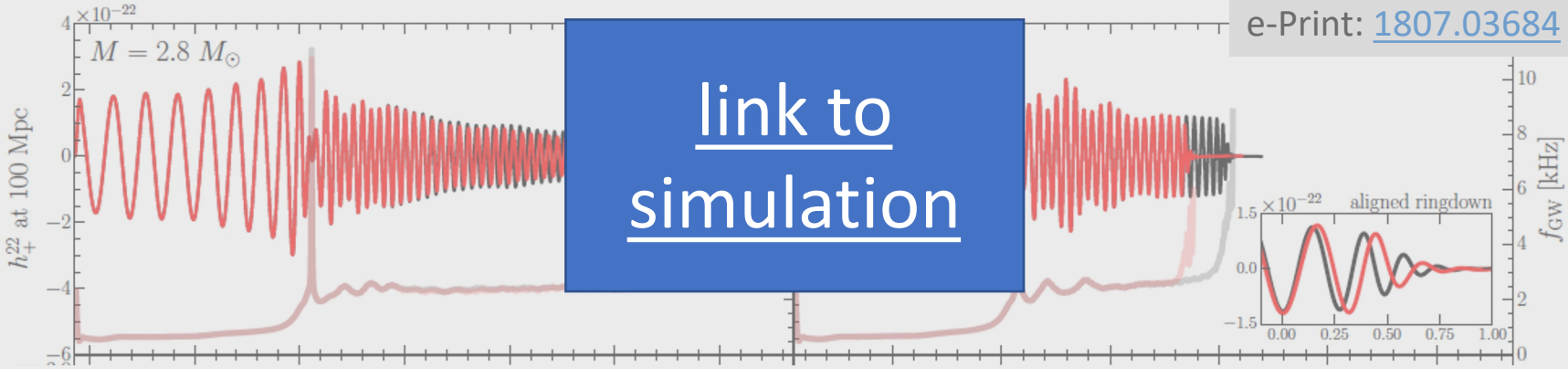
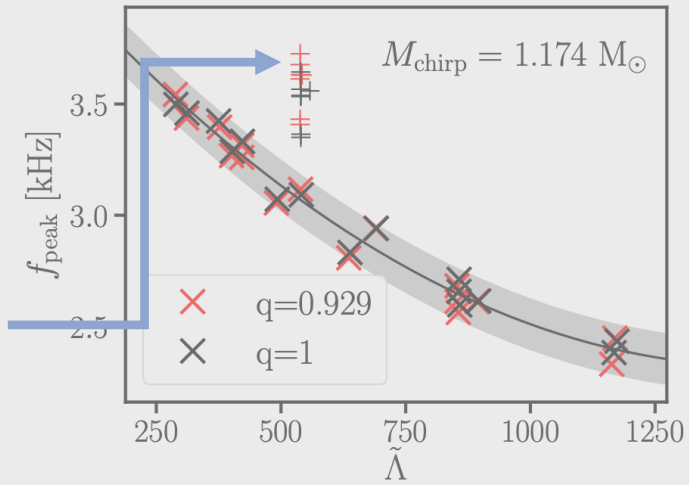
PRL 122 (2019) 6, 061101
e-Print: 1807.03684



link to simulation

- 3D DD2-SF (RDF) hybrid EoS with mixed phase (+ hadronic ones) into GR SPH code: different postmerger dominant frequencies for hybrid EoS

Phys.Rev.D 102 (2020) 12, 123023
e-Print: 2006.03789

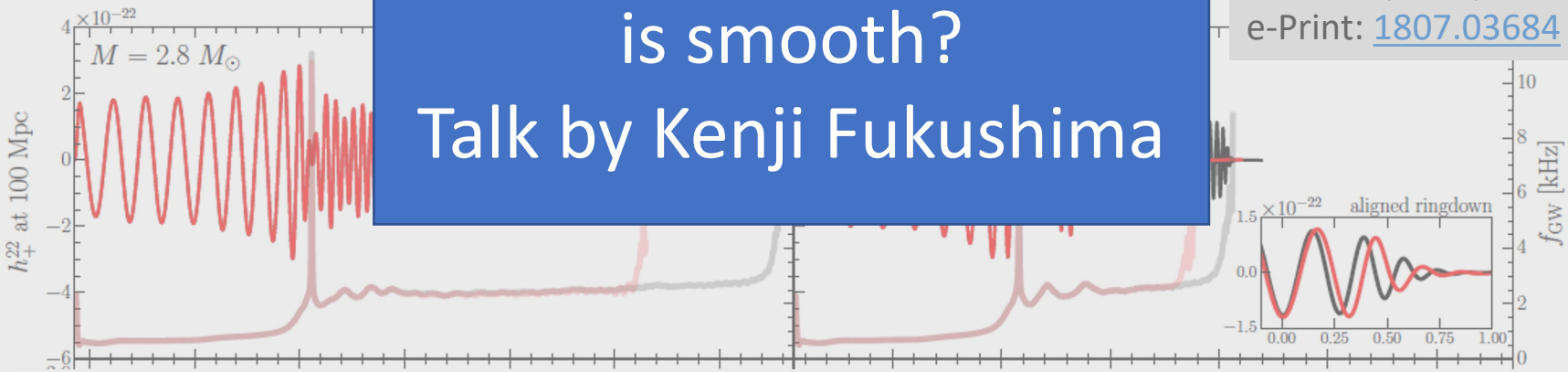


Deconfinement in merger simulations

- 3D CMF EoS with/without quarks into hydrodynamics system using full GR F[illegible]: effects from quarks (h, f, p[illegible]

What if the transition is smooth?
Talk by Kenji Fukushima

PRL 122 (2019) 6, 061101
e-Print: 1807.03684



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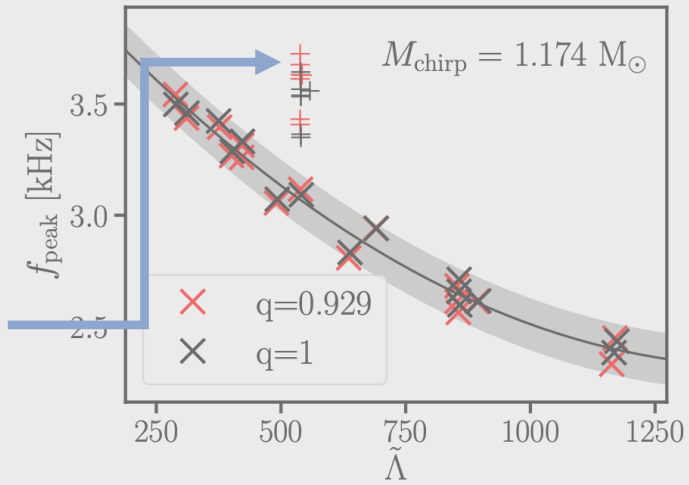
Phys.Rev.D 102 (2020) 12, 123023
e-Print: 2006.03789



Comparisons with heavy-ion collisions

- CMF with excluded volume that reproduces crossover

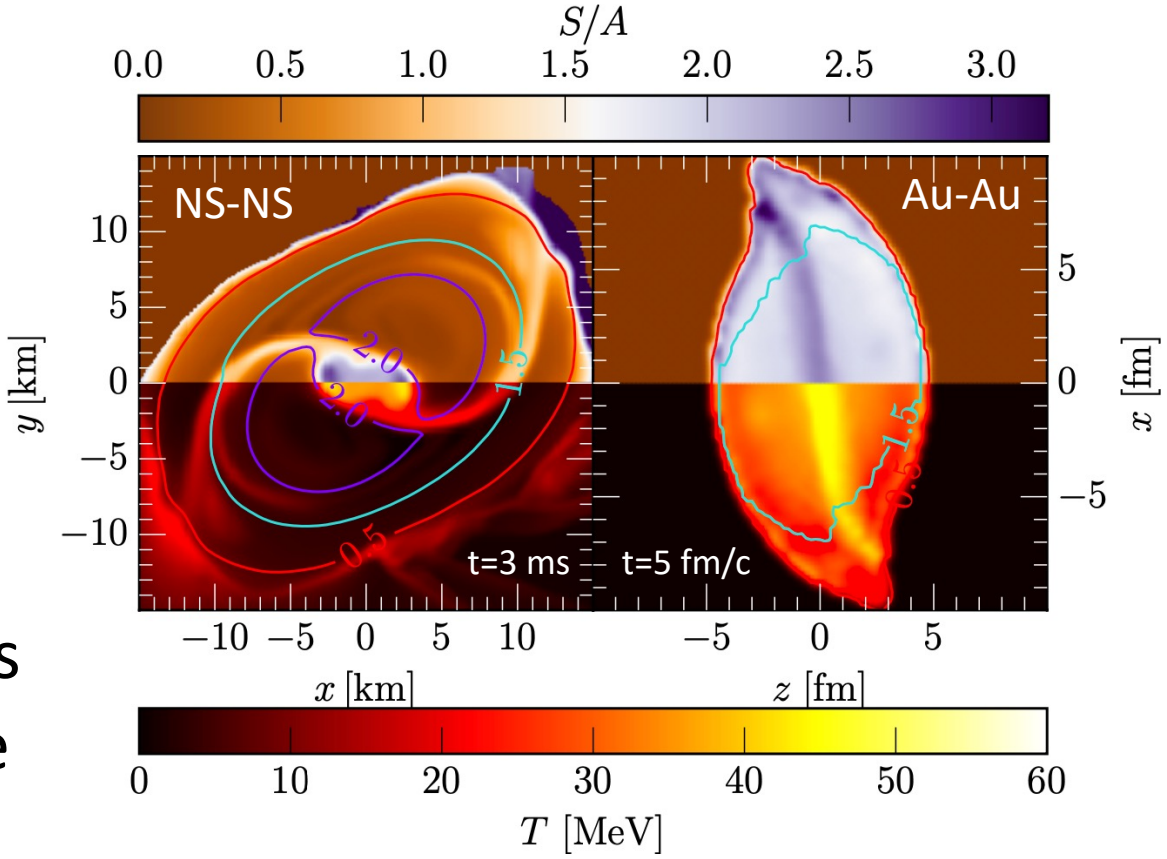
Astron.Astrophys. 608 (2017) A110 e-Print: 1706.09191

PRC 101 (2020) 3, 034904 e-Print: 1905.00866

- Relativistic hydrodynamics simulations using: full GR Frankfurt/Illinois GRMHD code and Frankfurt SHASTA code
- Final merger mass of 2.9 M_{Sun} and low-energy collision with E_{lab} = 450 MeV

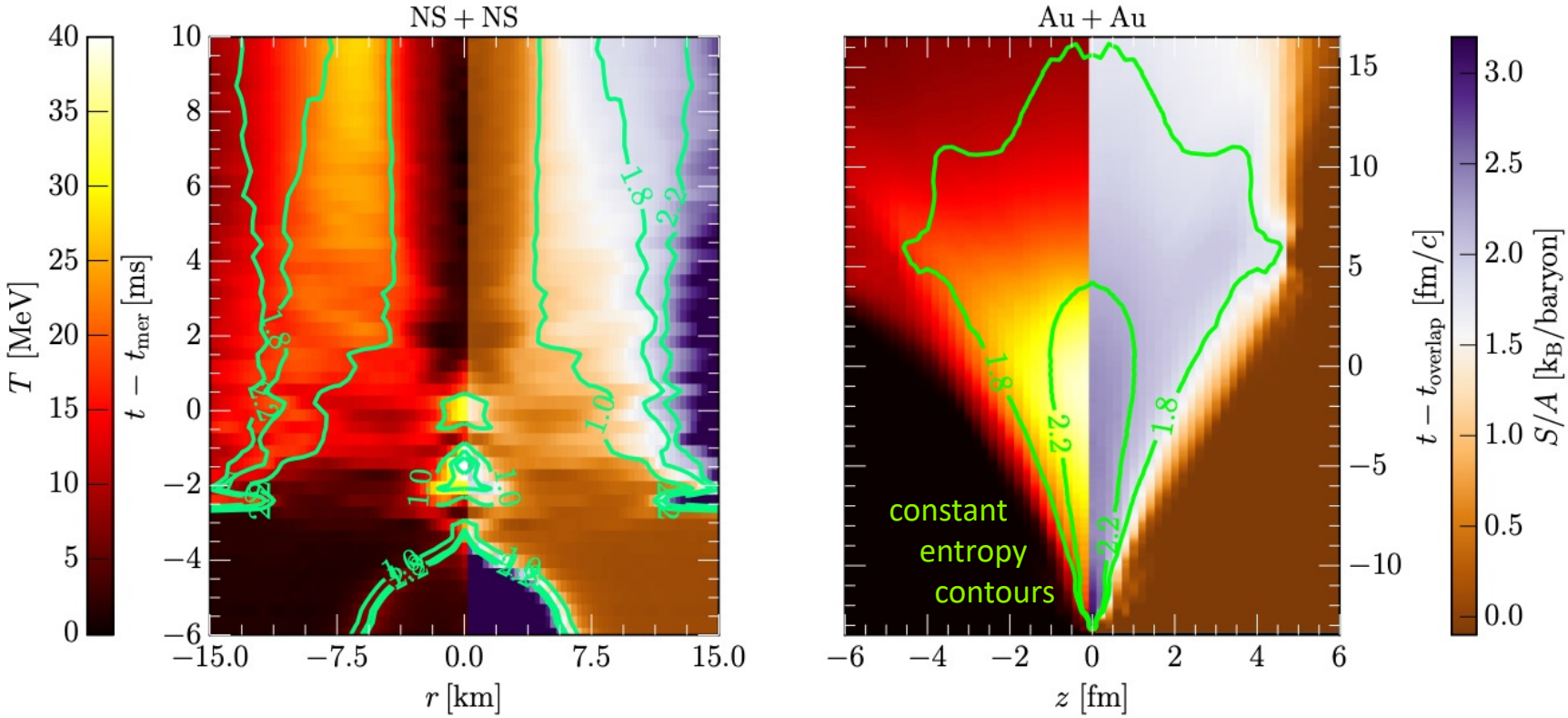
e-Print: 2201.13150

- Similar geometry across 18 orders of magnitude



Comparisons with heavy-ion collisions

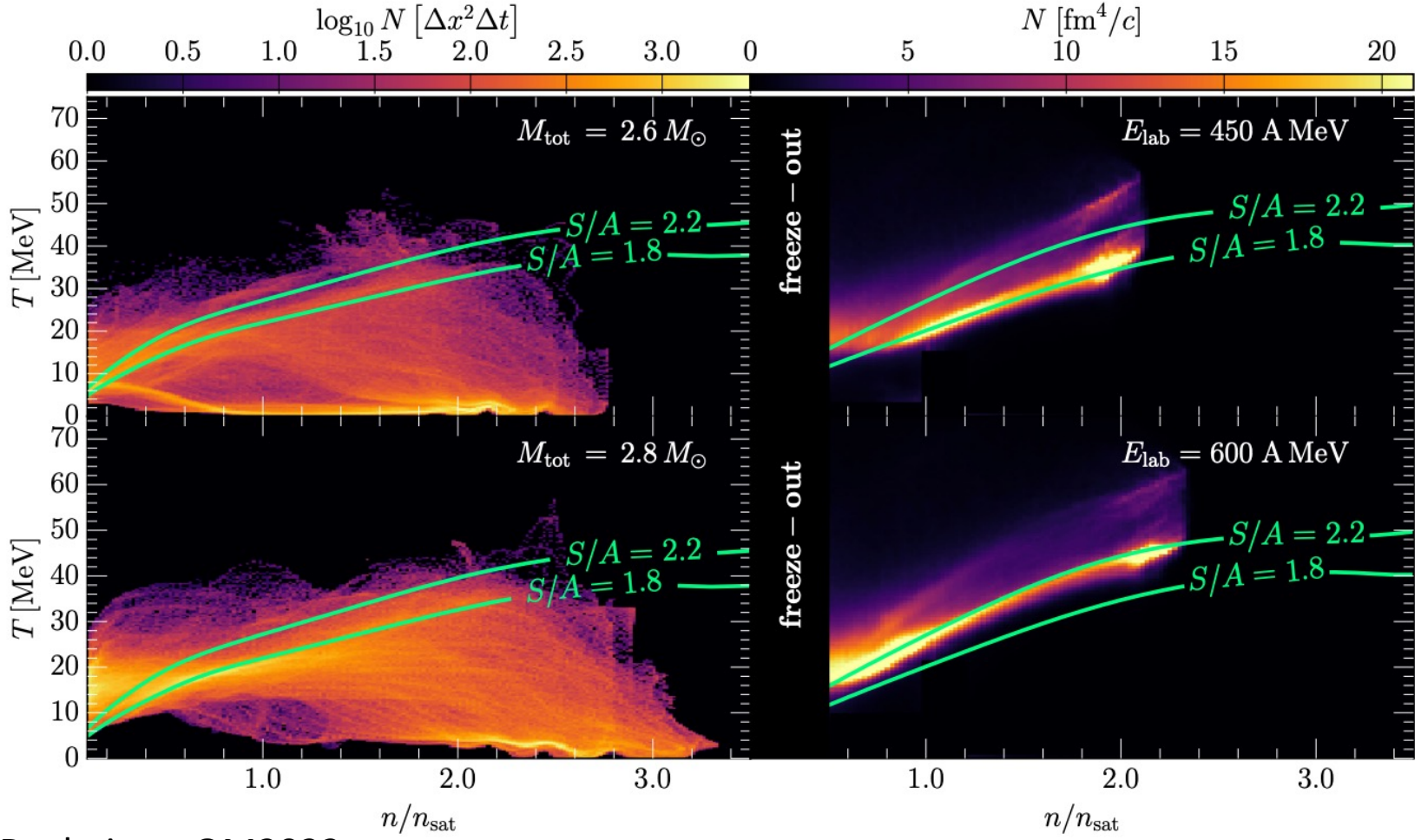
- Time evolution of systems with averaged equatorial and averaged transverse plane



- Present similar temperatures/entropies per baryon with different distributions

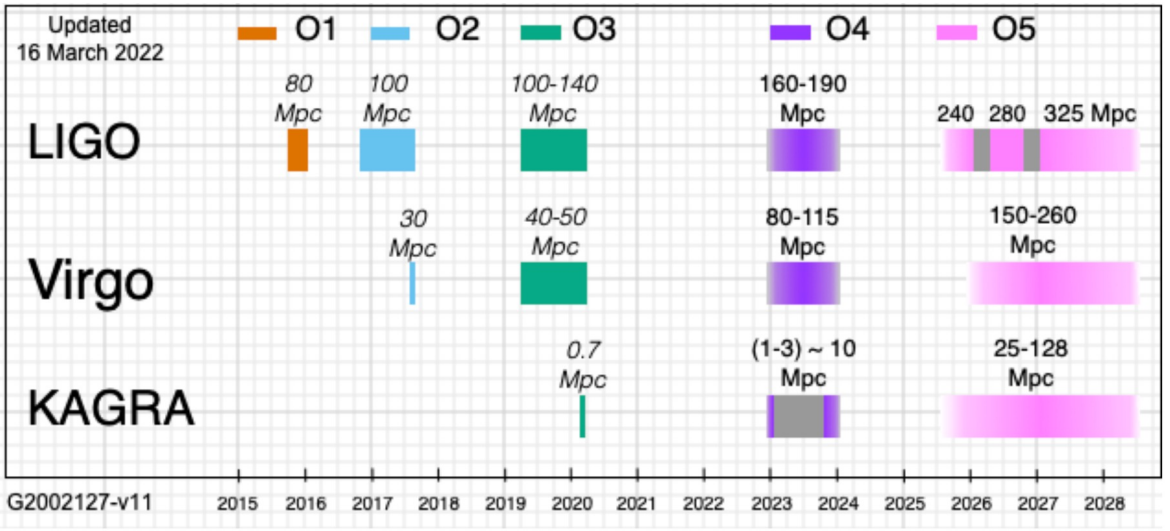
Comparisons with heavy-ion collisions

- Similar trajectories in phase diagram (other than stellar cold center dominated by gravity) allow connection of merger mass with lab energy

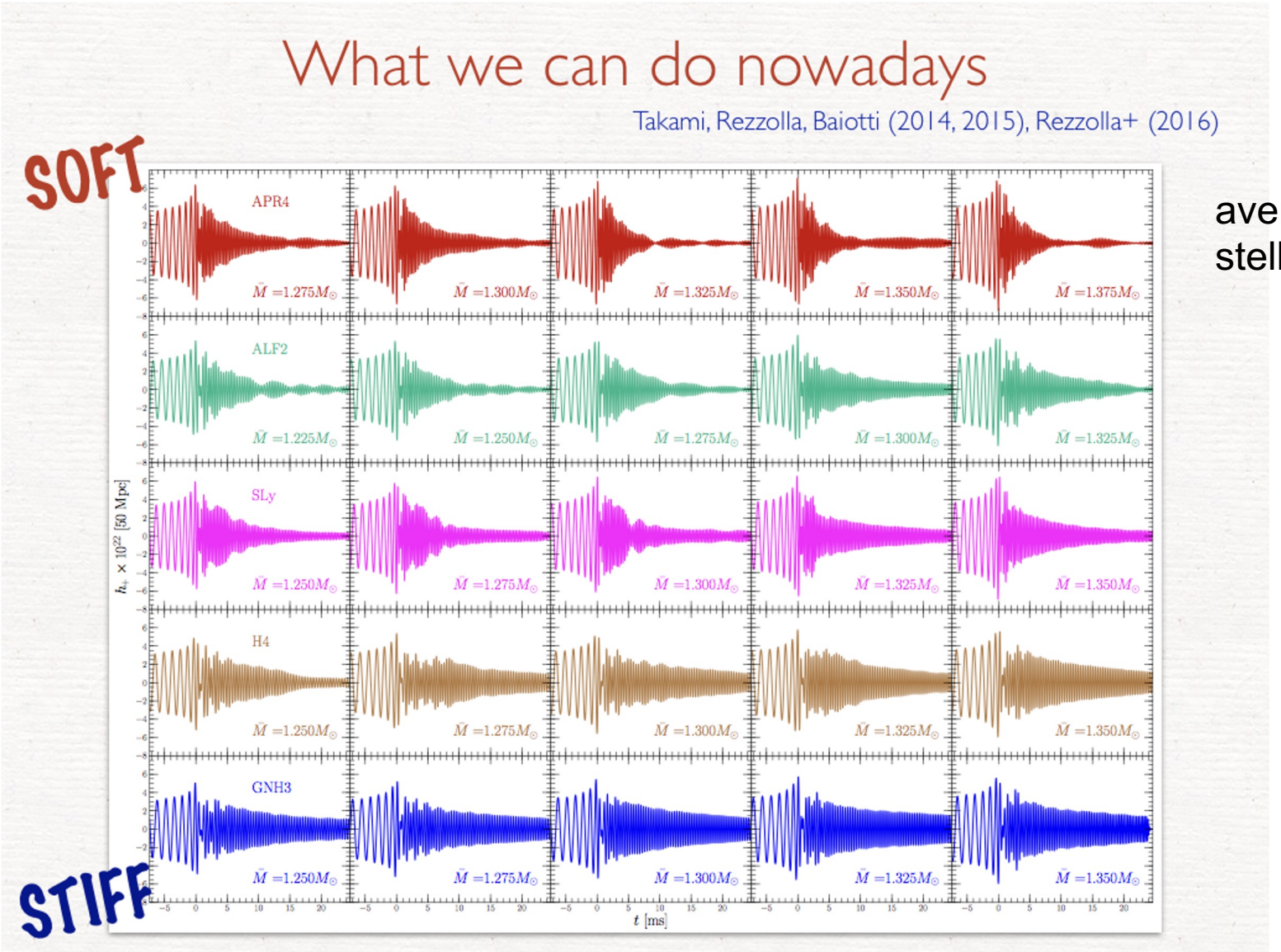


Conclusions

- New tight constraints from experiment, observation, and theory are slowly determining dense matter and neutron-star core properties
- EoS repositories help speeding up understanding of dense matter
- Neutron-star mergers create unique ideal conditions to create and detect deconfinement to quark matter in astrophysics
- LIGO, Virgo, and KAGRA are closely coordinating to start O4 Observing run together in mid-December 2022 (March 2022 update; next update May 2022)



Hadronic Merger Simulations

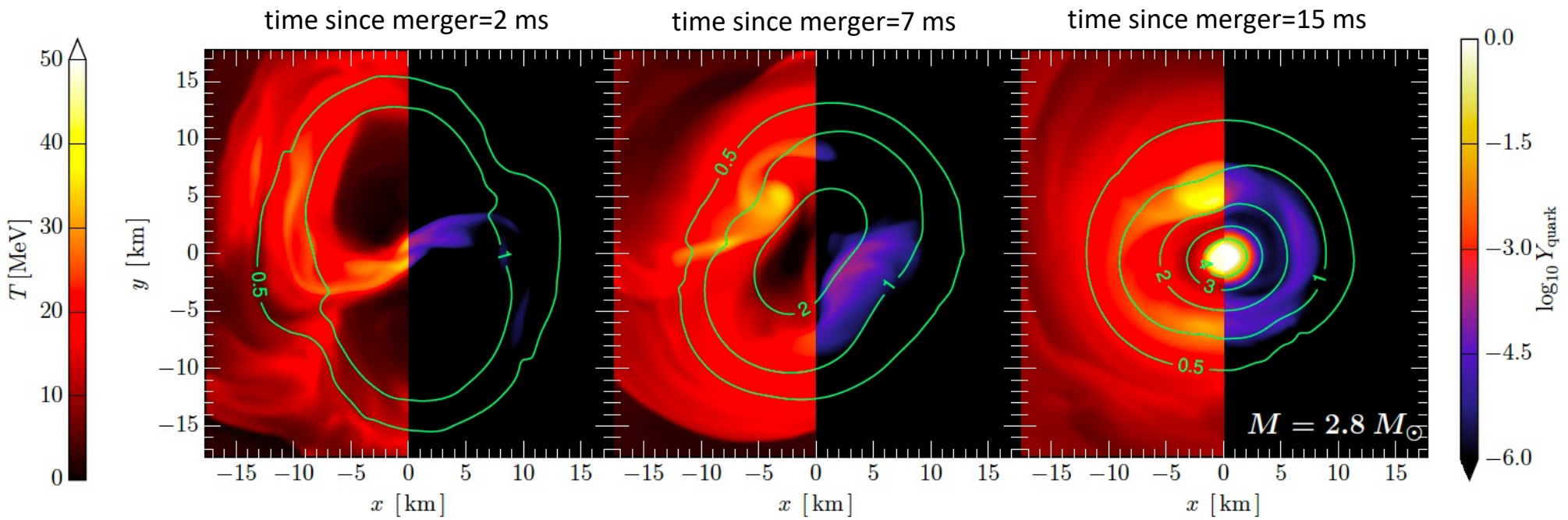


average stellar mass

Neutron-Star Merger Simulation

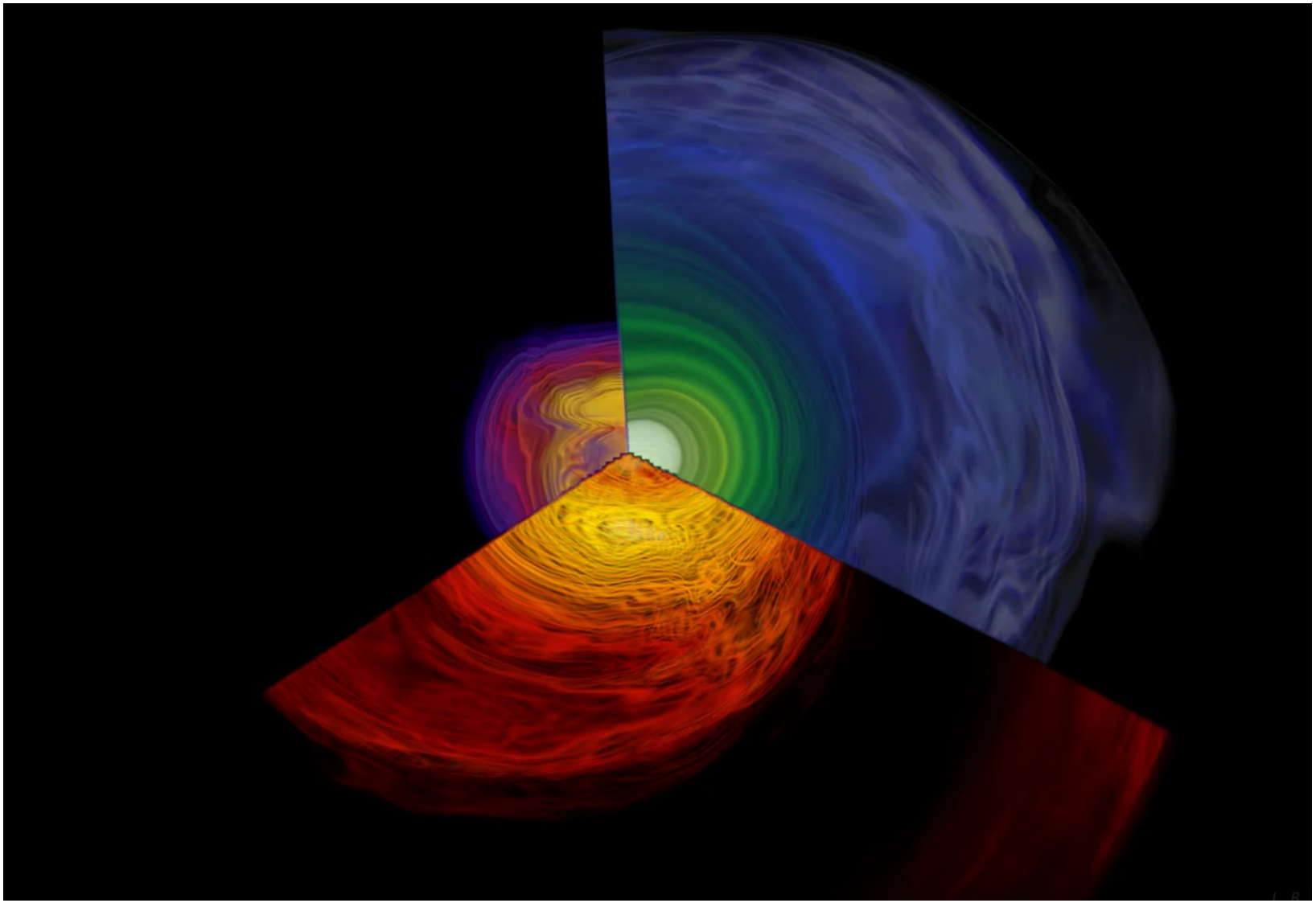
- 3D (T, n_B, Y_Q) CMF tables with 1st order phase transition
- Coupled Einstein-hydrodynamics system (*Frankfurt/IllinoisGRMHD* code)
- Hot ring forms first, then very hot region in the center with quarks

PRL 122 (2019) 6, 061101 e-Print: 1807.03684



Simulation

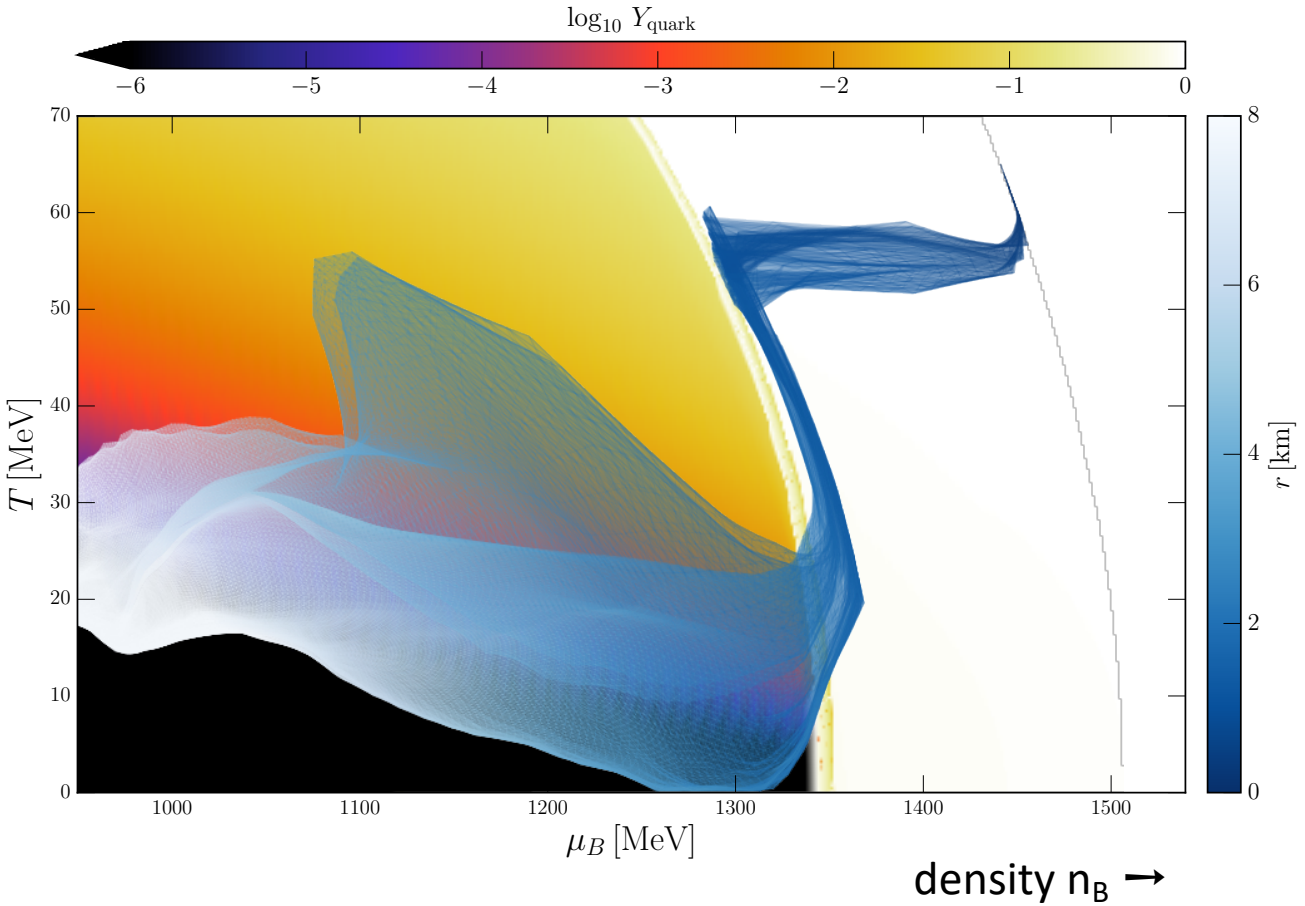
- Our simulation (Youtube) *PRL* 122 (2019) 6, 061101 e-Print: 1807.03684



Merger in the QCD Phase Diagram

- 3D CMF EoS with 1st order phase transition
- Hypermassive star with final mass of 2.9 M_{Sun} at ~5 ms (after deconfinement but before collapse to black hole)

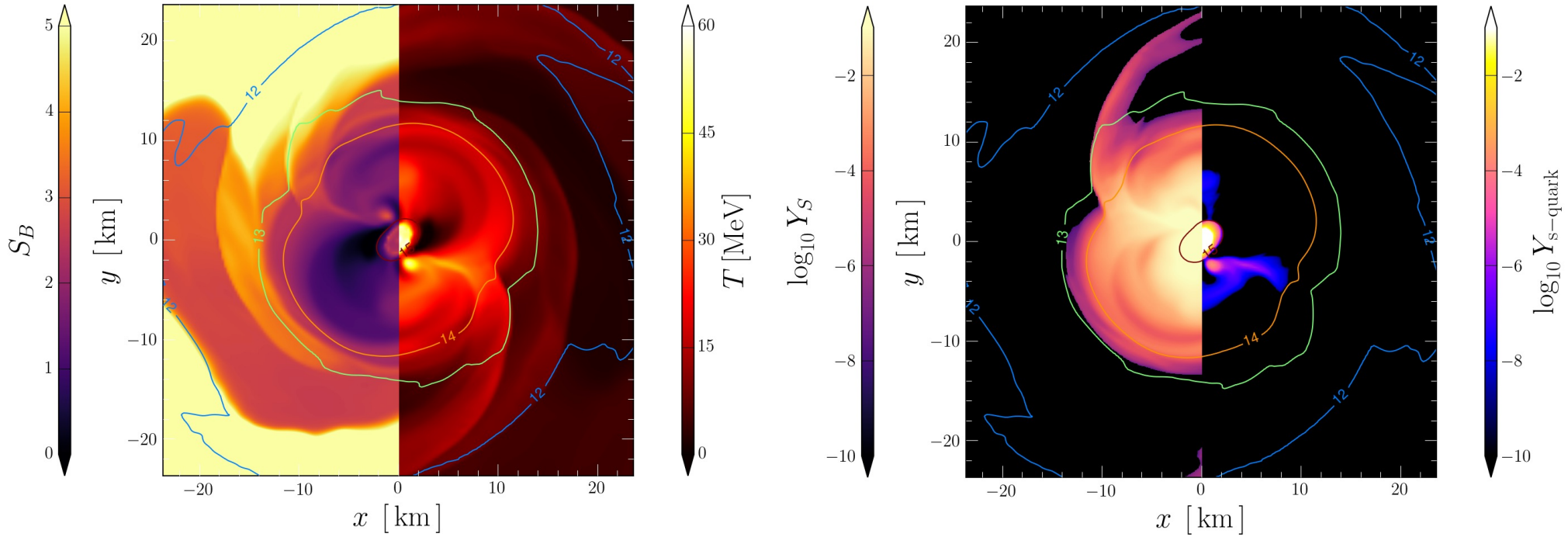
Eur.Phys.J.A 56 (2020) 2, 59
e-Print: 1910.13893



Inside Hypermassive Neutron Star

- At 5 ms after merger

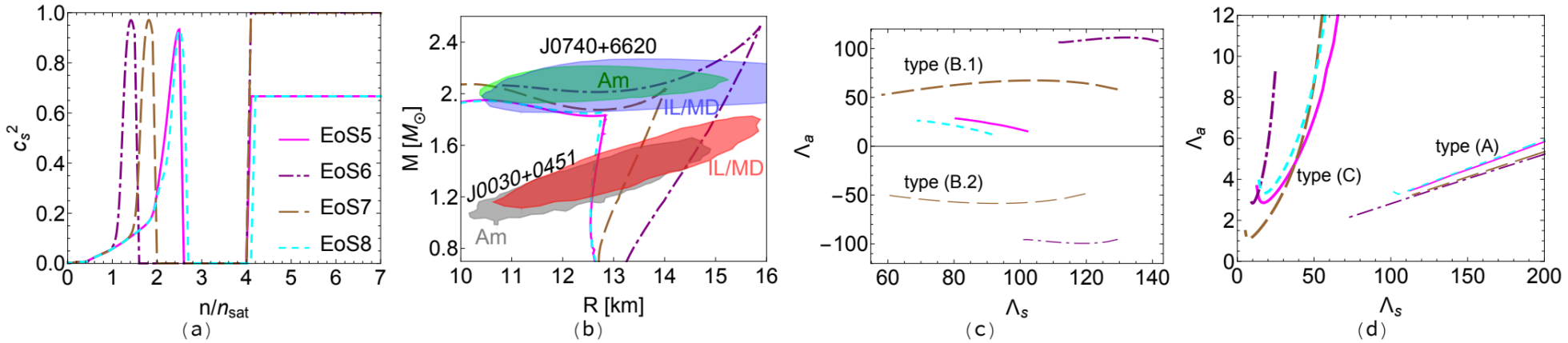
Eur.Phys.J.A 56 (2020) 2, 59
e-Print: 1910.13893



- Increase of temperature, entropy per baryon, and s-quark fraction at phase transition
- Reaching heavy-ion entropies but with lots of net strangeness

Deconfinement in the Tidal Deformability

- 1st–order phase transitions tilt the mass-radius diagram



- Can create structure in the binary Love relations: slope, hill, drop, and swoosh
- Evident swoosh for twin stars

e-Print: 2111.10260

The Mass Distribution of Neutron Stars in Gravitational-Wave Binaries

Philippe Landry[1] and Jocelyn S. Read[1]

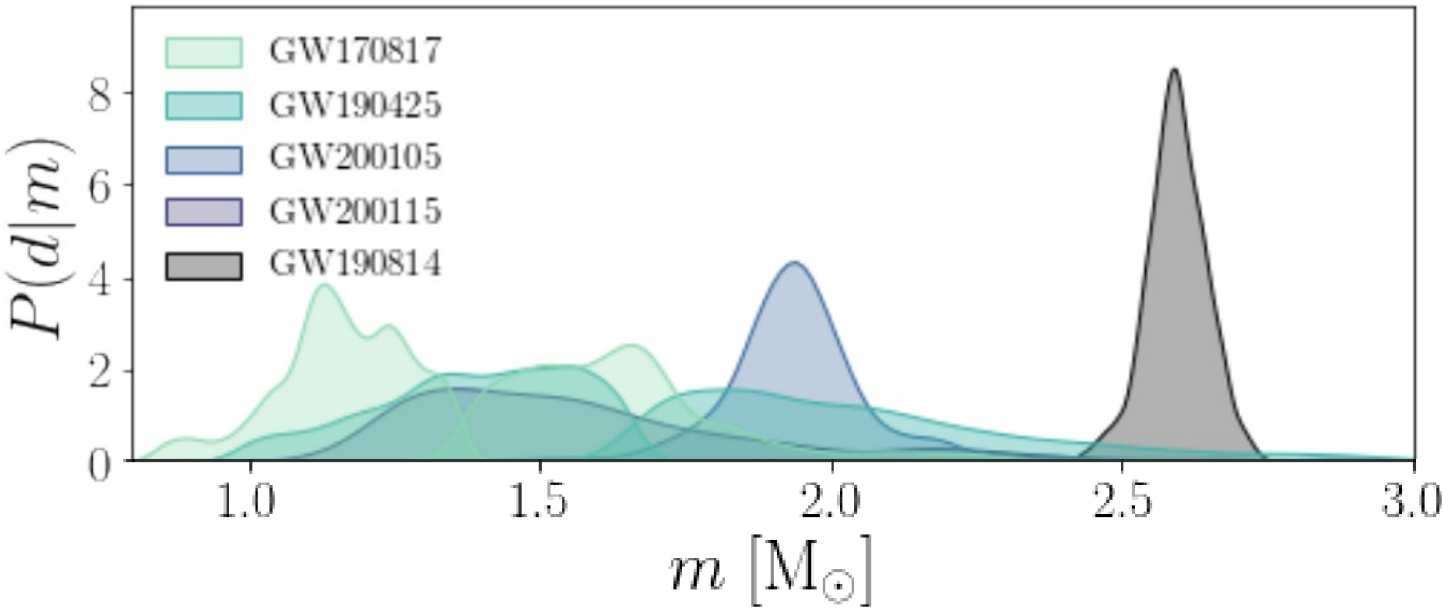


Figure 1. Measured masses and inferred mass distribution for NSs in GW binaries. *Top:* Marginal one-dimensional mass likelihoods $P(d|m)$ for the NSs in the BNS mergers GW170817 and GW190425, the NSBH mergers GW200105 and GW200115, and the candidate NSBH merger GW190814. *Bottom:* Median and symmetric 90%

3D QCD Phase Diagrams

- Example: temperature vs. free energy vs. charge fraction

$$Y_Q = Q_B/B$$

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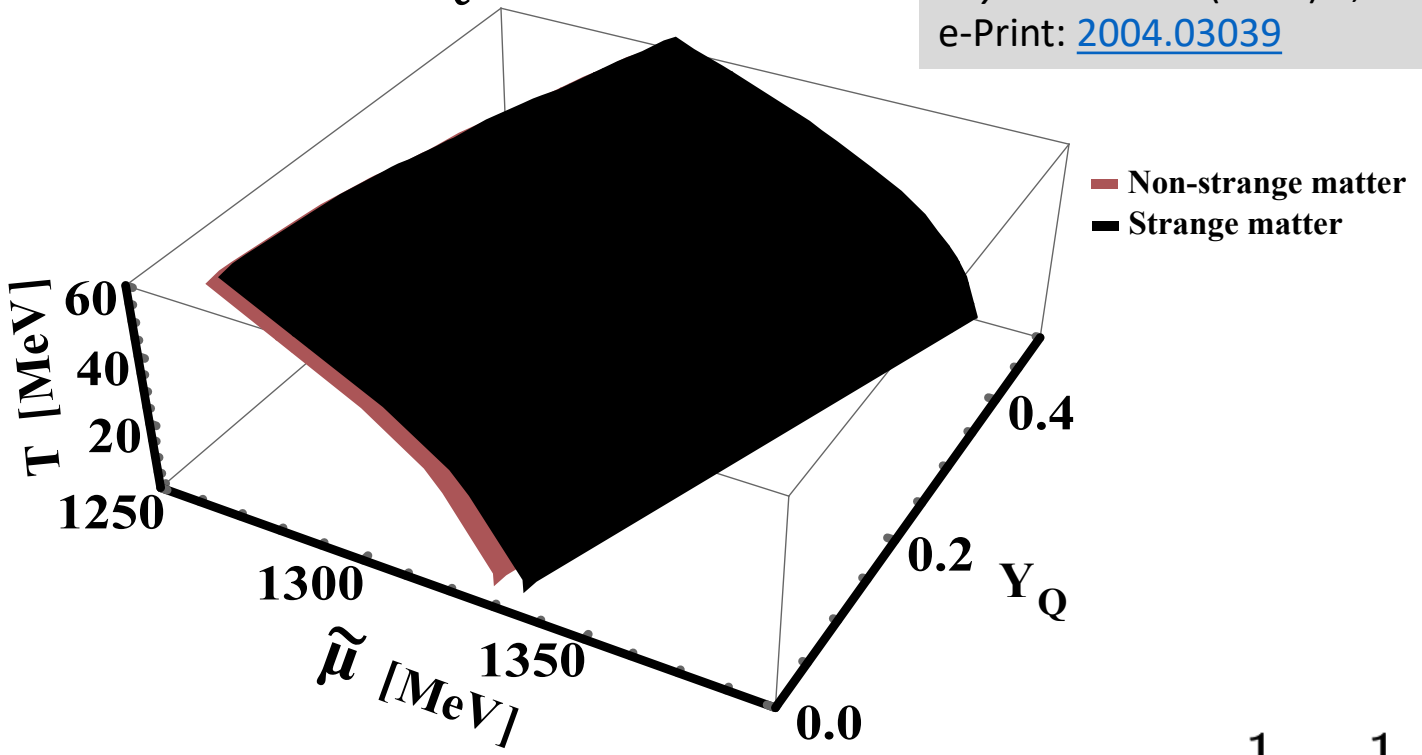

$$\tilde{\mu} = \mu_B + Y_Q\mu_Q + Y_S\mu_S$$

$$Y_Q = Y_I + \frac{1}{2} - \frac{1}{2}Y_S$$

- Other possibilities: strangeness, magnetic field, …