Probing exotic matter in neutron stars

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NP3M
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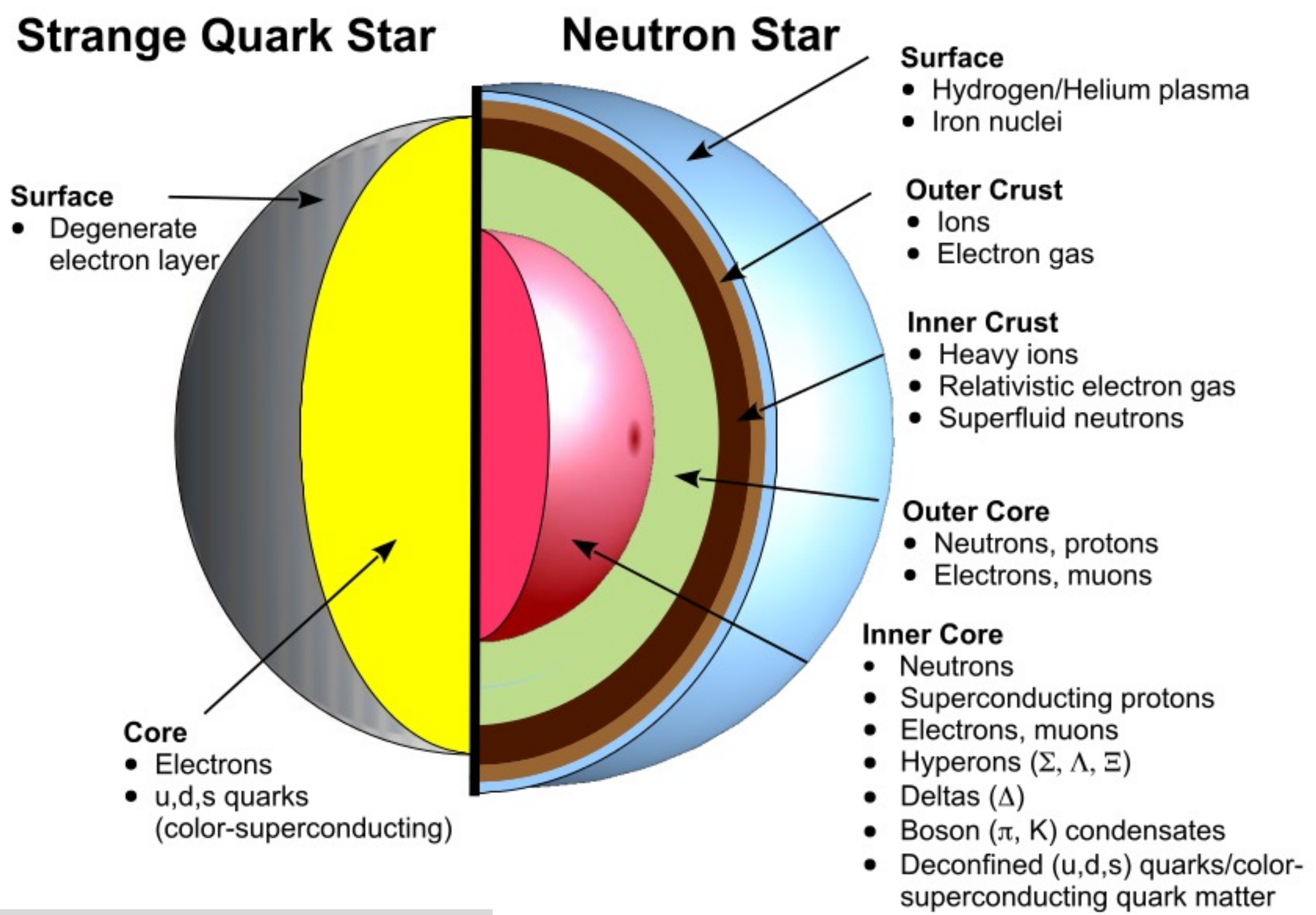
PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS
NSF

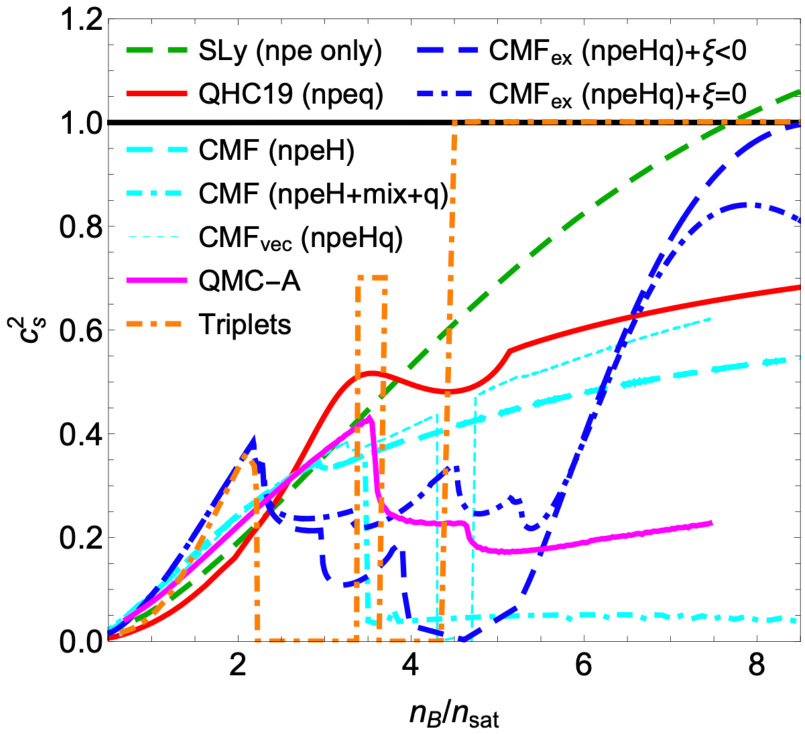
NS vs. Strange Quark Star structure

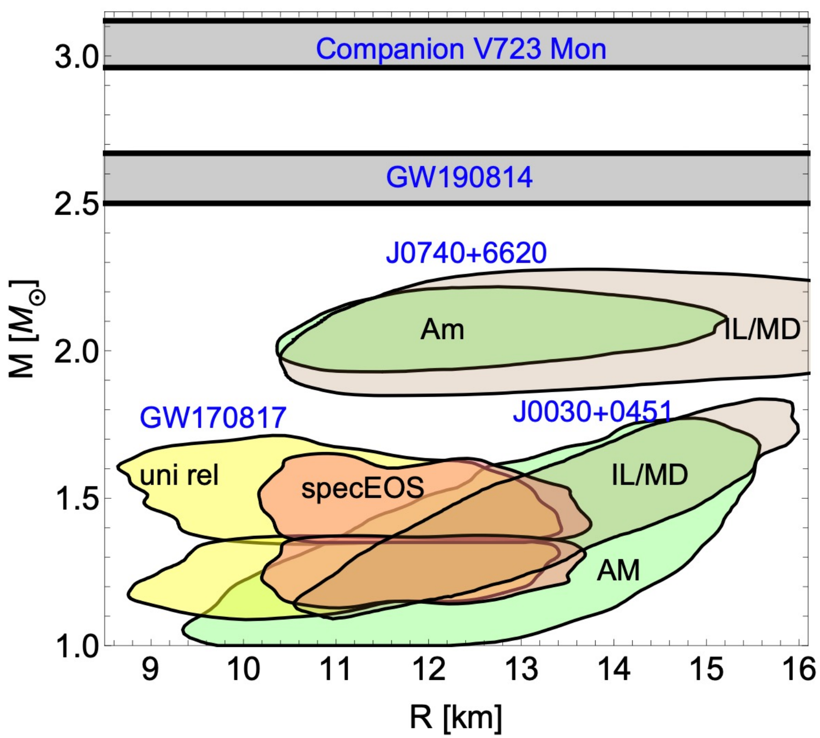


Mod.Phys.Lett.A 29 (2014) 1430022
e-Print: [1408.0079]

Neutron Star Composition

- Different exotic matter associated with different phase transitions
- Can easily be seen in speed of sound but not necessarily in mass-radius



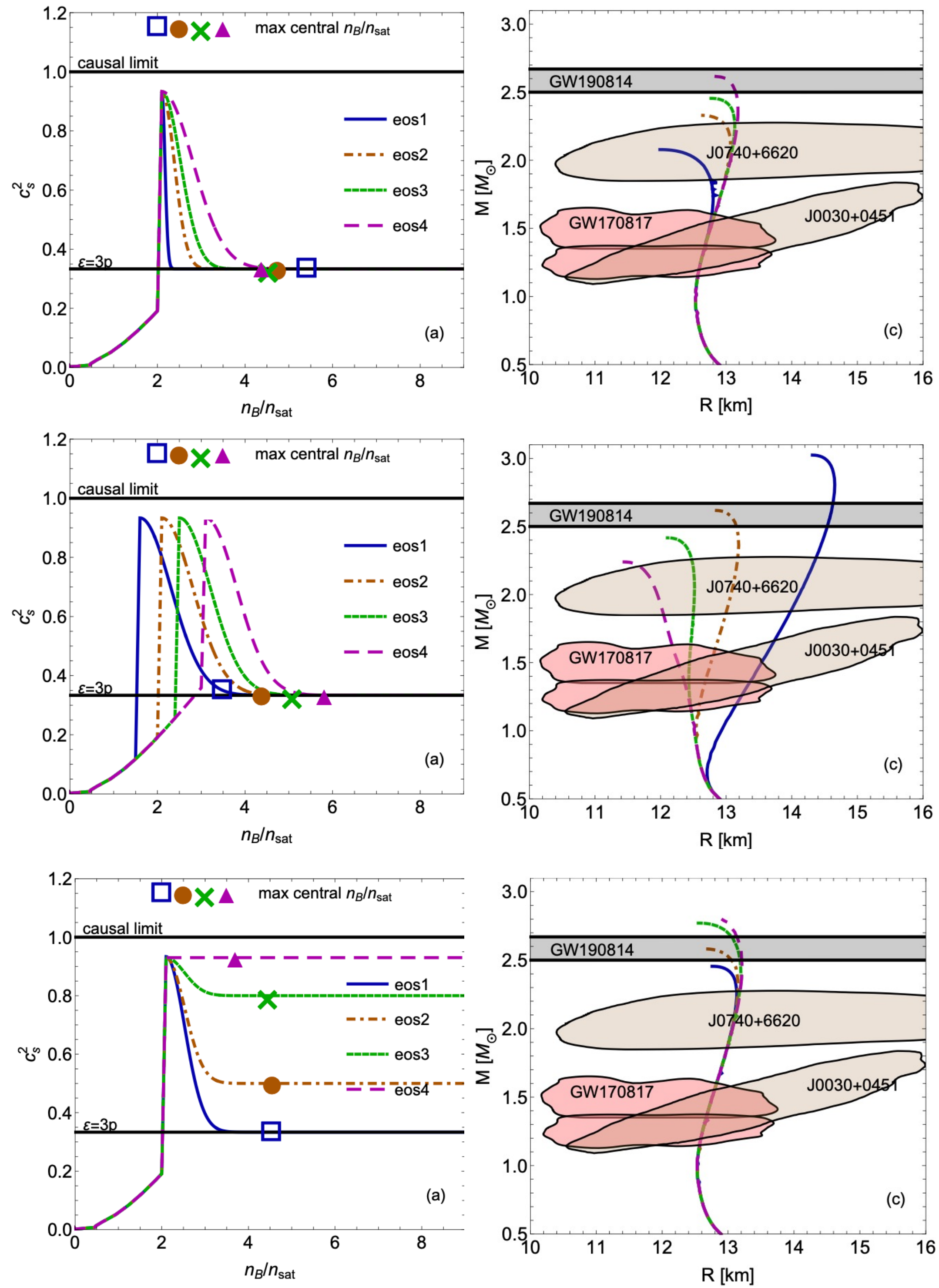


PRD 105 (2022) 2, 023018 e-Print: [2106.03890](2106.03890)

Parametric approach

- ✶ More controlled speed of sound parametric form can help to determine neutron-star composition
- ✶ Maximum stellar mass and radius can determine width, density, and height of bumps

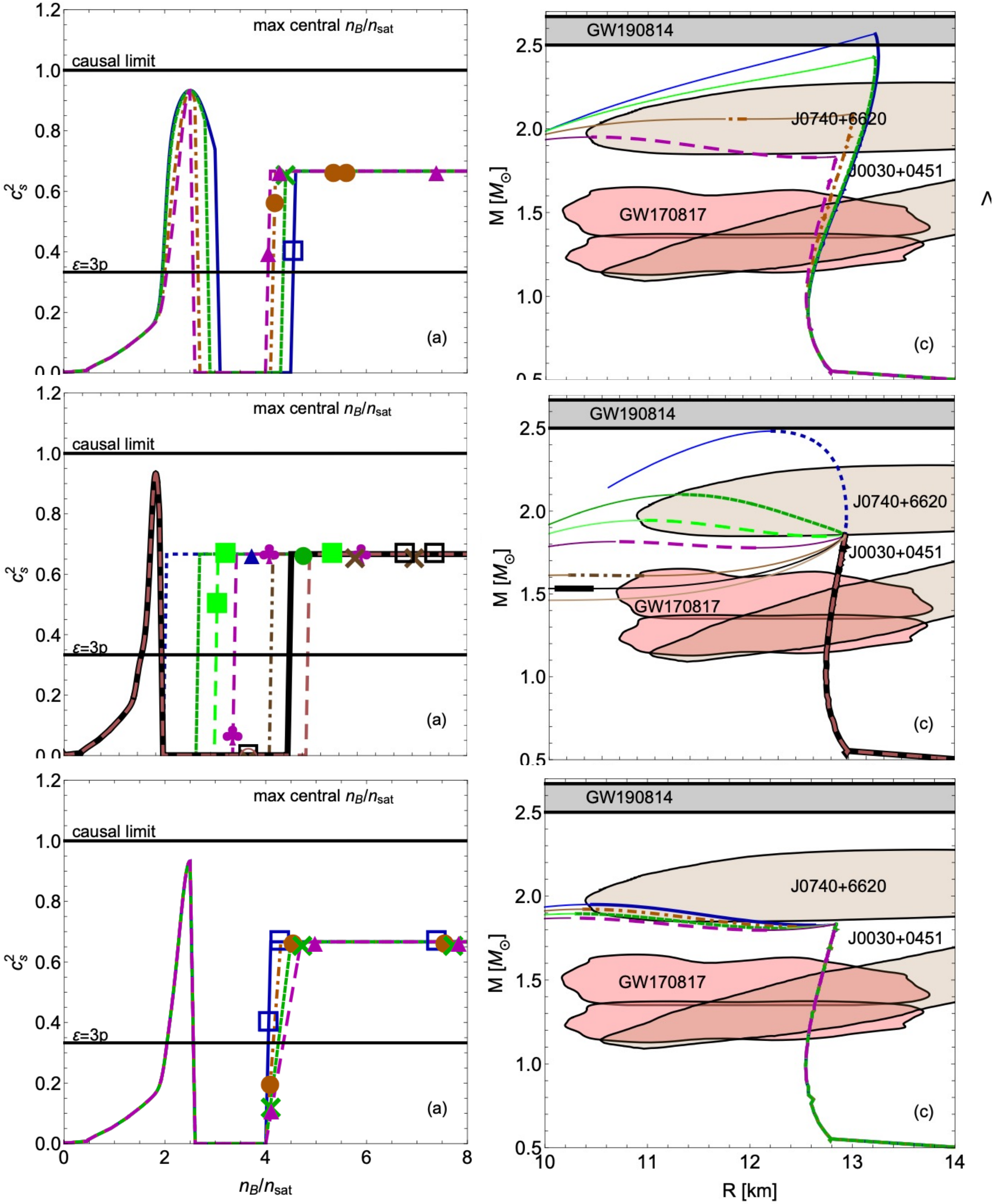
PRD 105 (2022) 2, 023018
e-Print: [2106.03890](https://arxiv.org/abs/2106.03890)



With 1st order Phase Transition

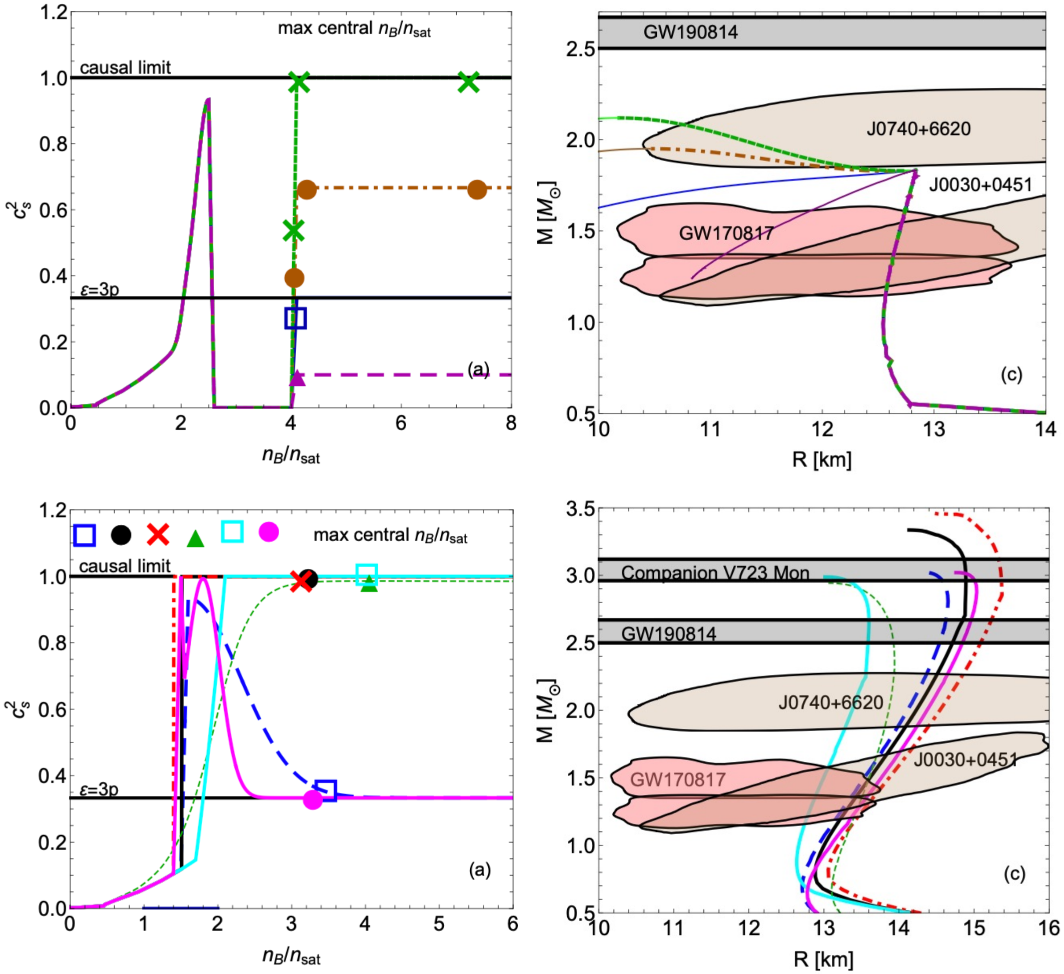
- ✶ Zero speed of sound not ruled by observation of massive stars
- ✶ But constrained by extremely massive objects

PRD 105 (2022) 2, 023018
e-Print: [2106.03890](https://arxiv.org/abs/2106.03890)



High-Density Limit

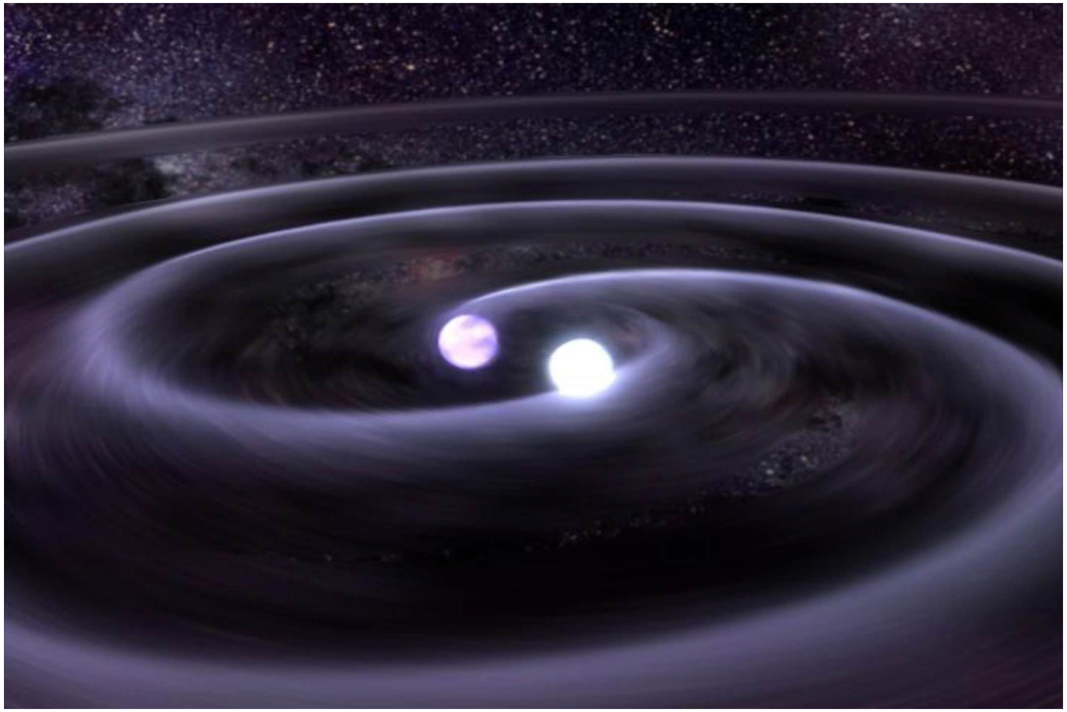
- There are many degeneracies
- But high-density behavior could be determined by large mass, small radius measurement
- $M \geq 2.91 \pm 0.08\ M_{Sun}$ implies $n_{cent} \lesssim 4\ n_{sat}$



PRD 105 (2022) 2, 023018
e-Print: [2106.03890](2106.03890)

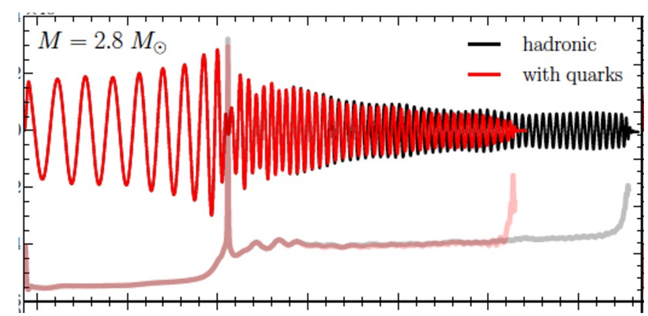
Comparison with Other Systems

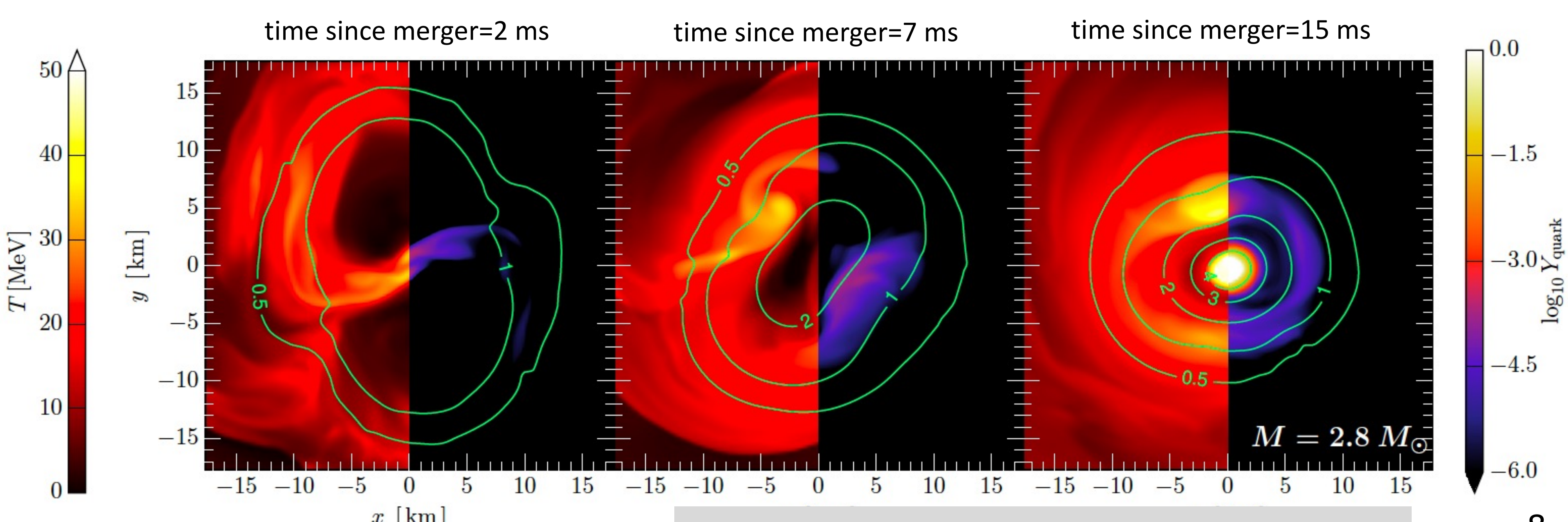
- Cold catalyzed neutron stars cores: $Y_Q = 0 \rightarrow 0.2$ (0.1)
- Heavy-ion collisions: $Y_Q = 0.4 \rightarrow 0.5$ (also have Y_S=0)
- Supernovae explosions/proto-neutron stars: $Y_Q = 0.1 \rightarrow 0.5$ (0.4)
- Neutron-star mergers ?



Neutron-Star Merger Simulation

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

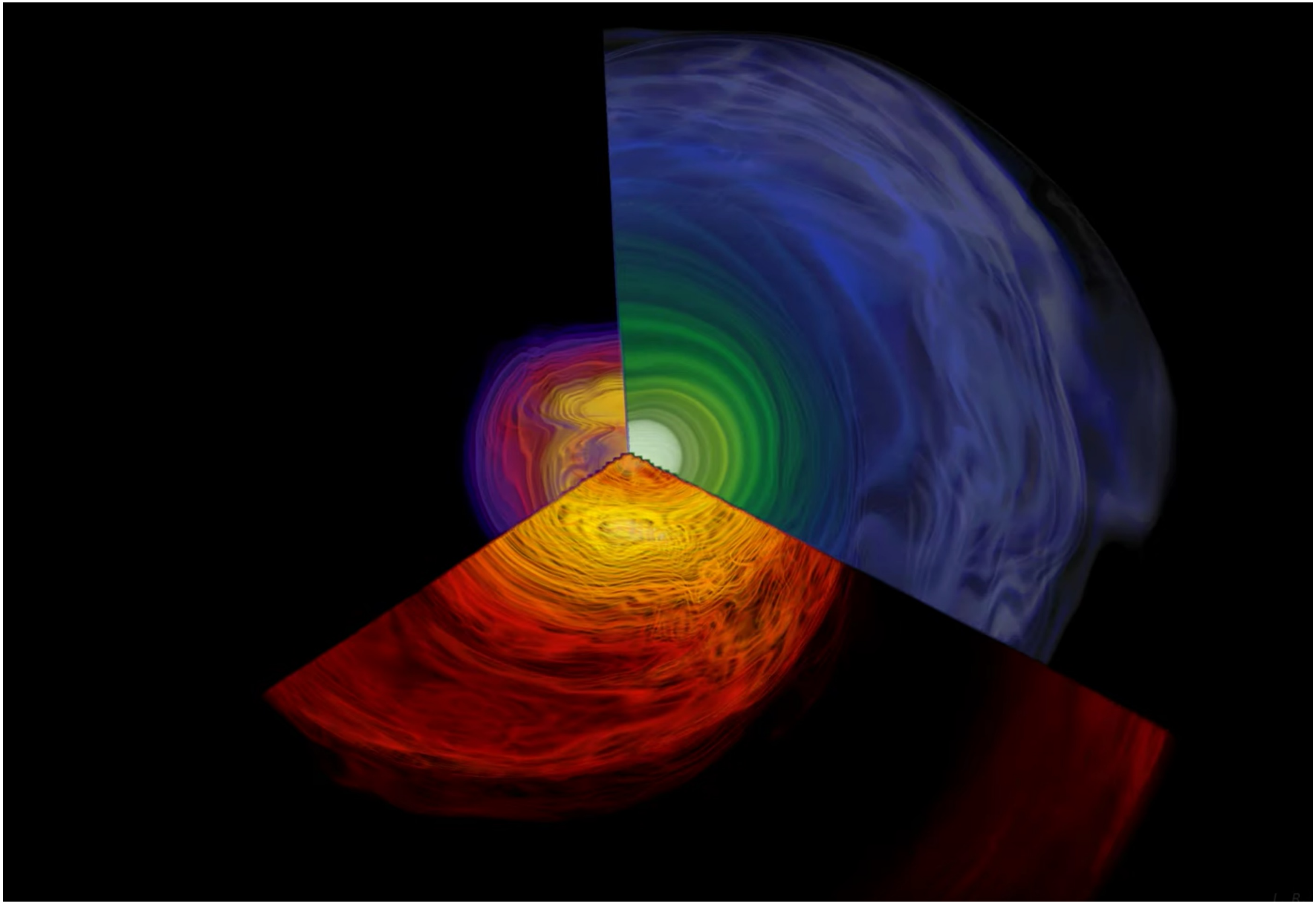




PRL 122 (2019) 6, 061101 e-Print: [1807.03684]

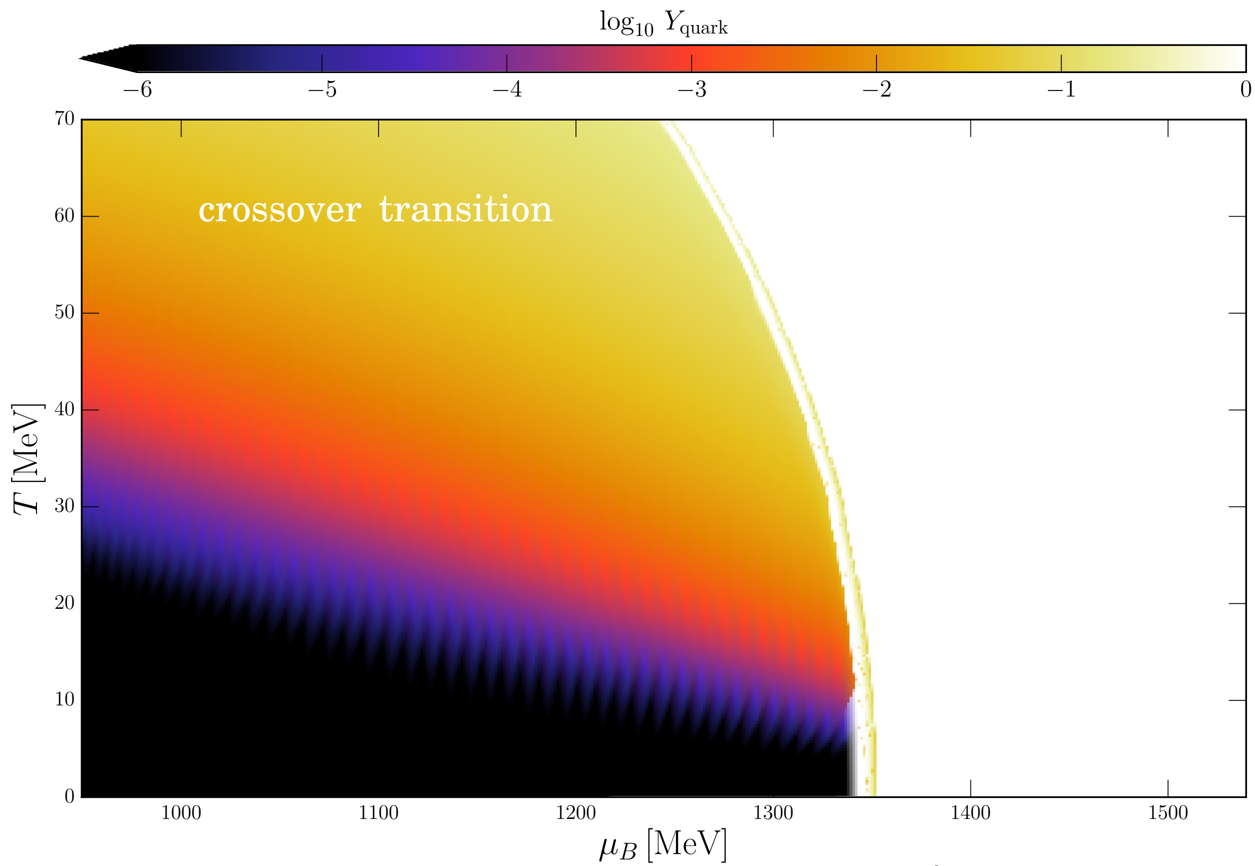
Simulation

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



Merger in the QCD Phase Diagram

- Background: 2D (T,n_B) CMF EoS with 1st order phase transition for Y_Q=Q/B=0.05

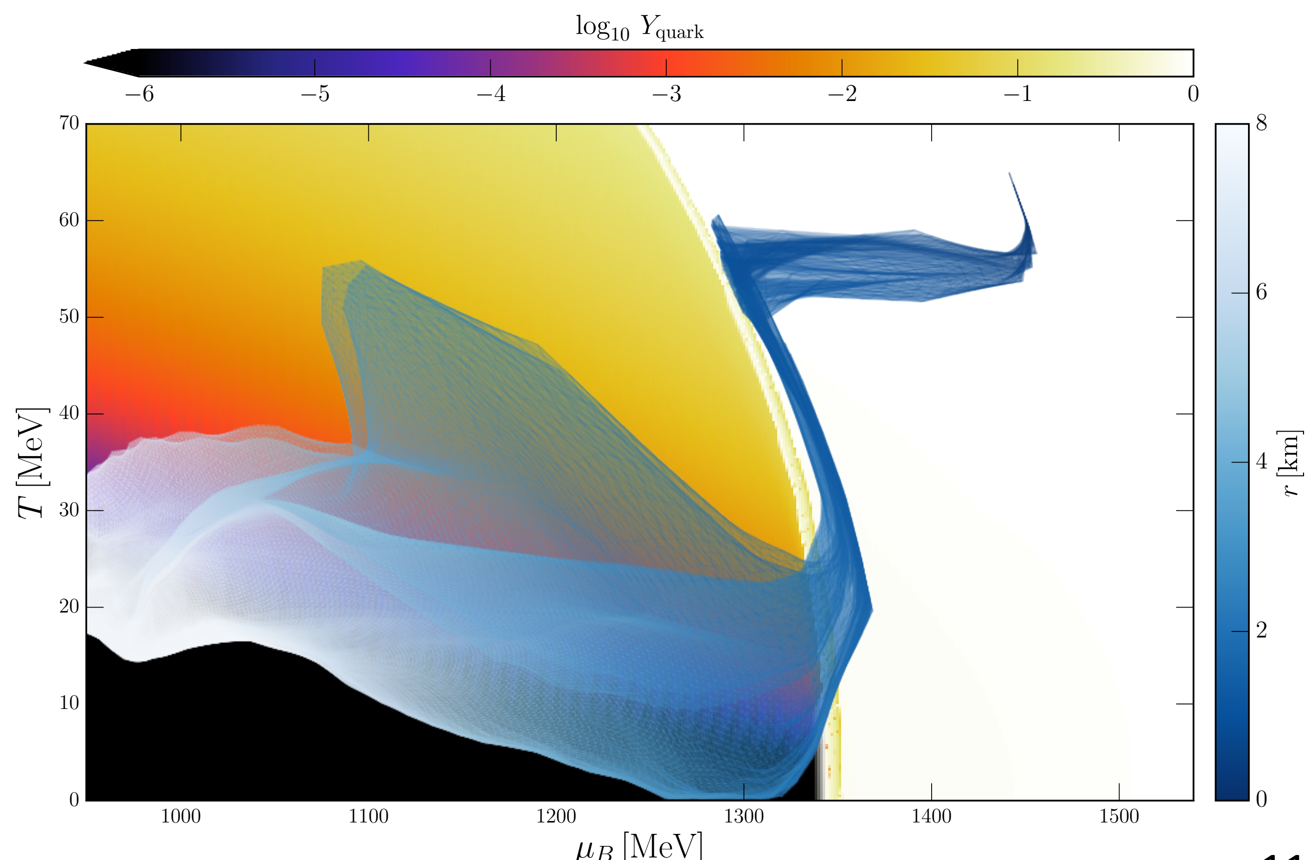


density ρ_B →

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

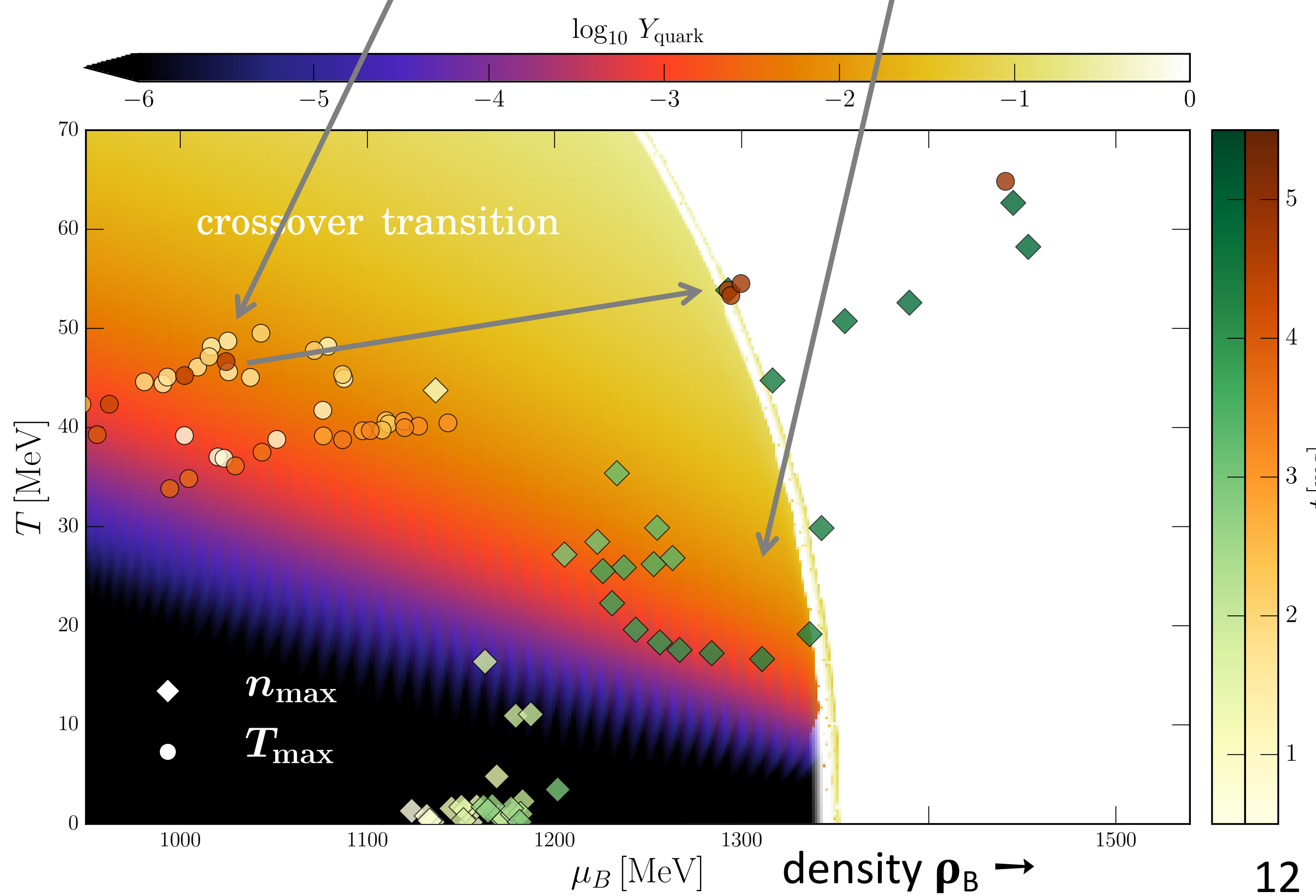


density ρ_B →

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

Merger in the QCD phase Diagram

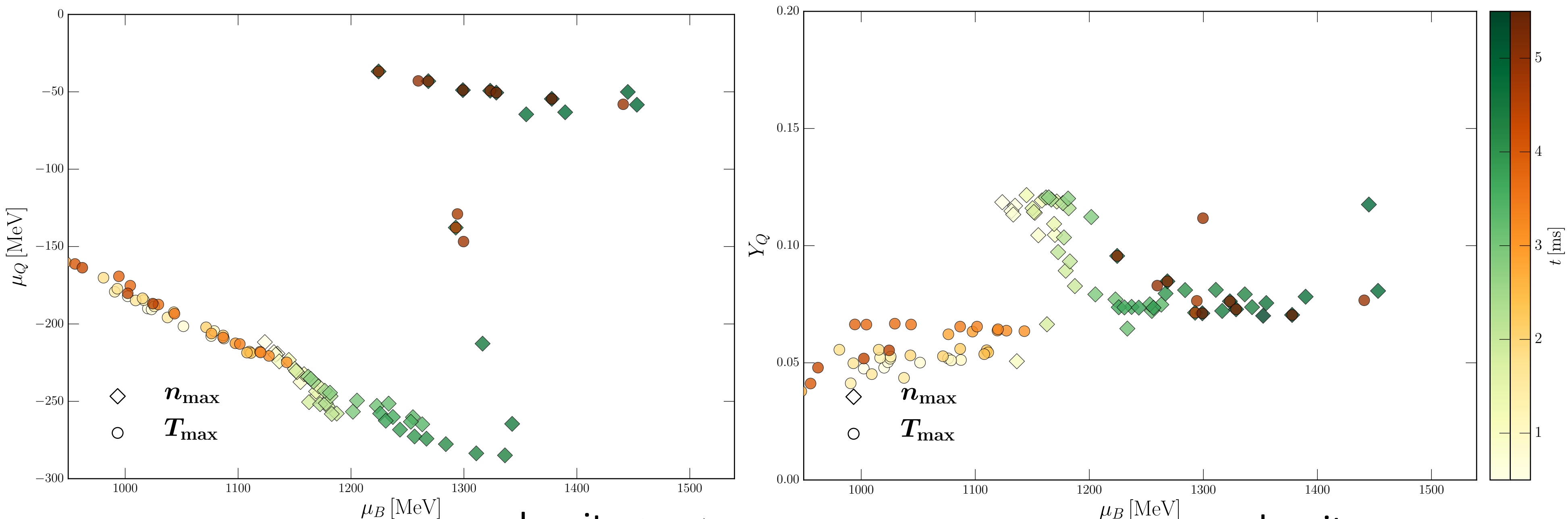
- Tracking maximum temperature ● and density ◆ during merger



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

More Merger Phase Diagrams

- Tracking maximum temperature ● and density ◆



density $\boldsymbol{\rho}_B \rightarrow$ density $\boldsymbol{\rho}_B \rightarrow$

- Increase in abs. value of charged chemical potential until phase transition, when it drops

EPJA 56 (2020) 2, 59 e-Print: [1910.13893](1910.13893)

- Decrease in charge fraction of core when quarks appear (never reaching heavy-ion/supernovae conditions)

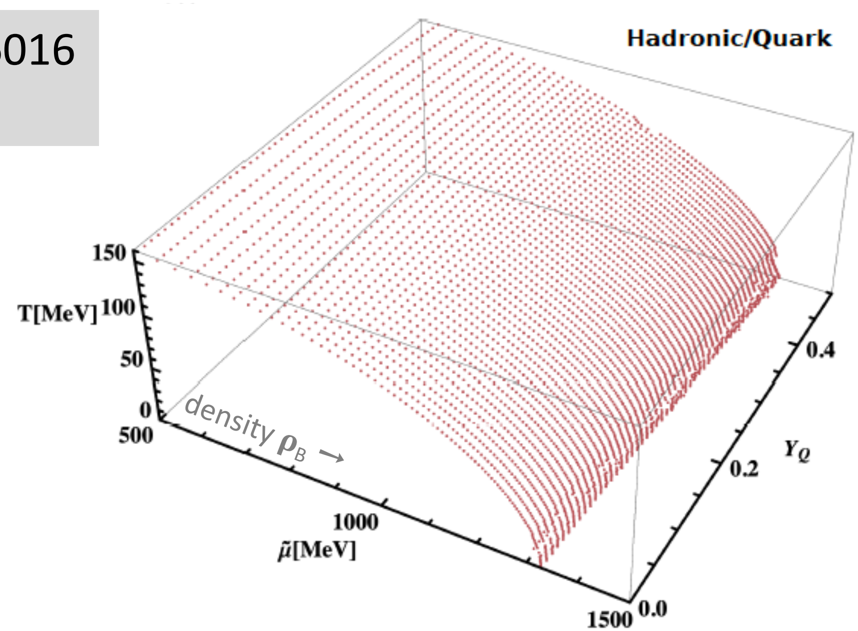
3D QCD Phase Diagrams (Y_S=0)

- T, $\widetilde{\mu}$, Y_Q with charge fraction $Y_Q = Q/B$ = 0 → 0.5
  and Gibbs free energy per baryon $\widetilde{\mu} = \mu_B + Y_Q \mu_Q$

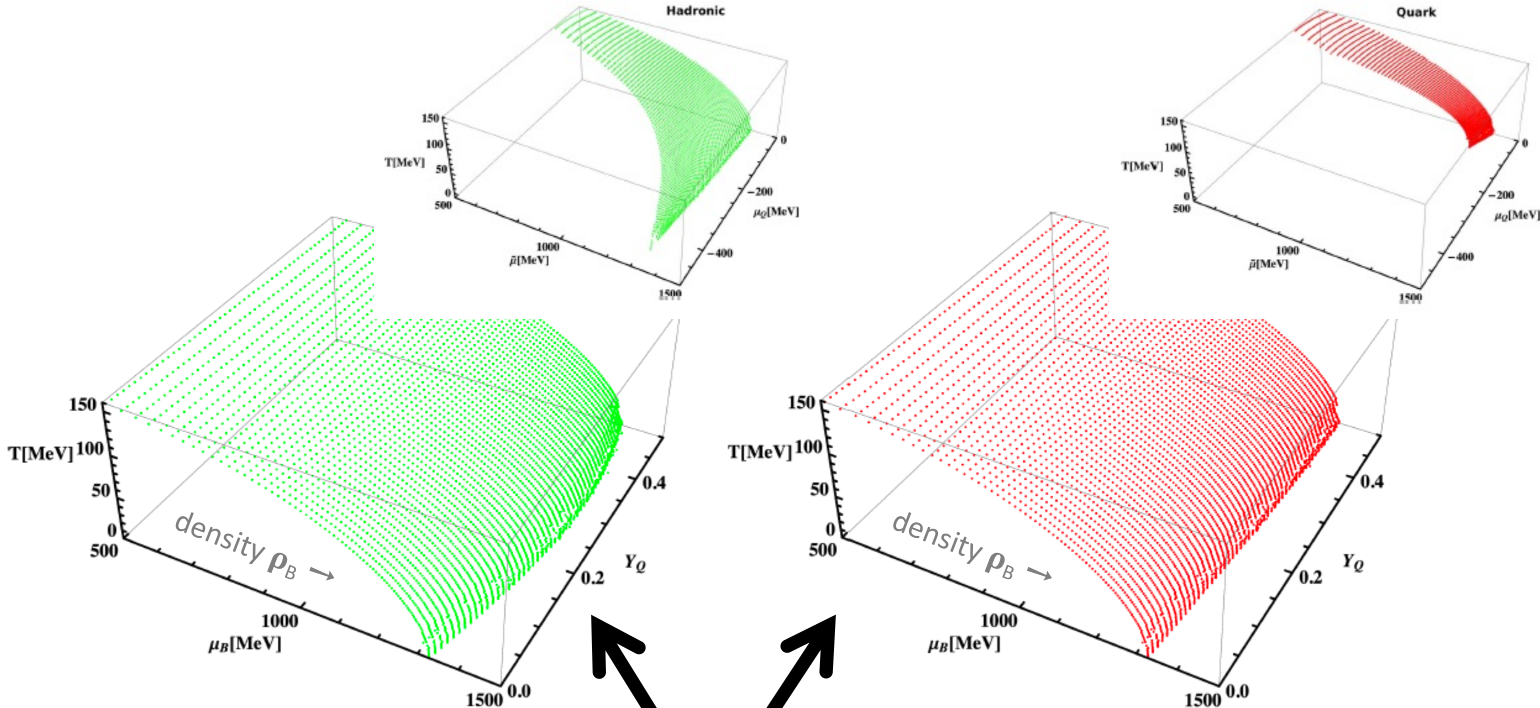
3D QCD Phase Diagrams (Y_S=0)

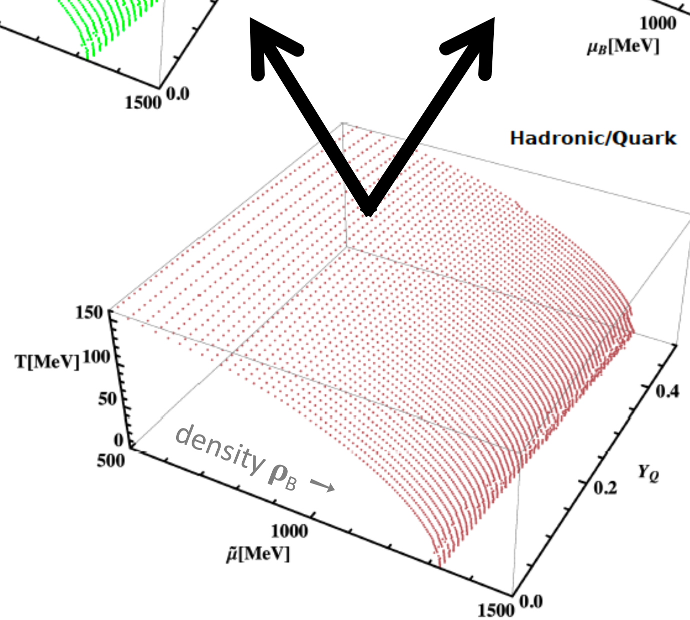
- T, $\widetilde{\mu}$, Y_Q with charge fraction $Y_Q = Q/B$ = 0 → 0.5
  and Gibbs free energy per baryon $\widetilde{\mu} = \mu_B + Y_Q \mu_Q$
- Larger Y_Q (at fixed T) pushes the phase transition to larger $\widetilde{\mu}$
- Lower Y_Q (at fixed T) pushes the phase transition to lower $\widetilde{\mu}$!
- Changes due to Y_Q effects on stiffness (particle population) on each side

PRD 102 (2020) 7, 076016
e-Print: 2004.03039



3D QCD Phase Diagrams (Y_S=0)



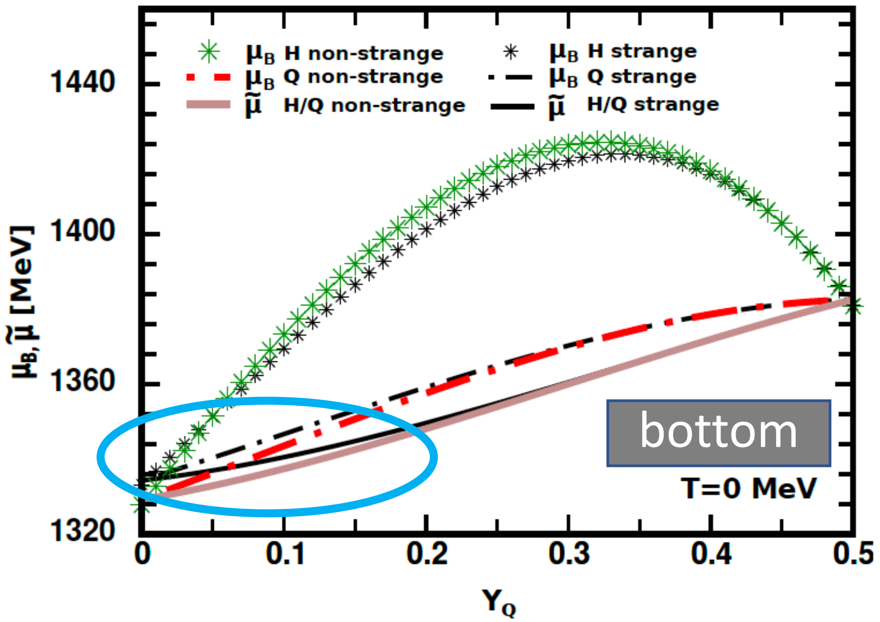


Gibbs free energy per baryon
$\widetilde{\mu} = \mu_B + Y_Q \mu_Q$

PRD 102 (2020) 7, 076016
e-Print: 2004.03039

Slices of 3D QCD Phase Diagrams
(Y_S=0, Y_S ≠/0 in black)

- For finite net strangeness $Y_S \neq 0$, deconfinement takes place at larger free energy/ baryon chemical potential



PRD 102 (2020) 7, 076016 e-Print: 2004.03039

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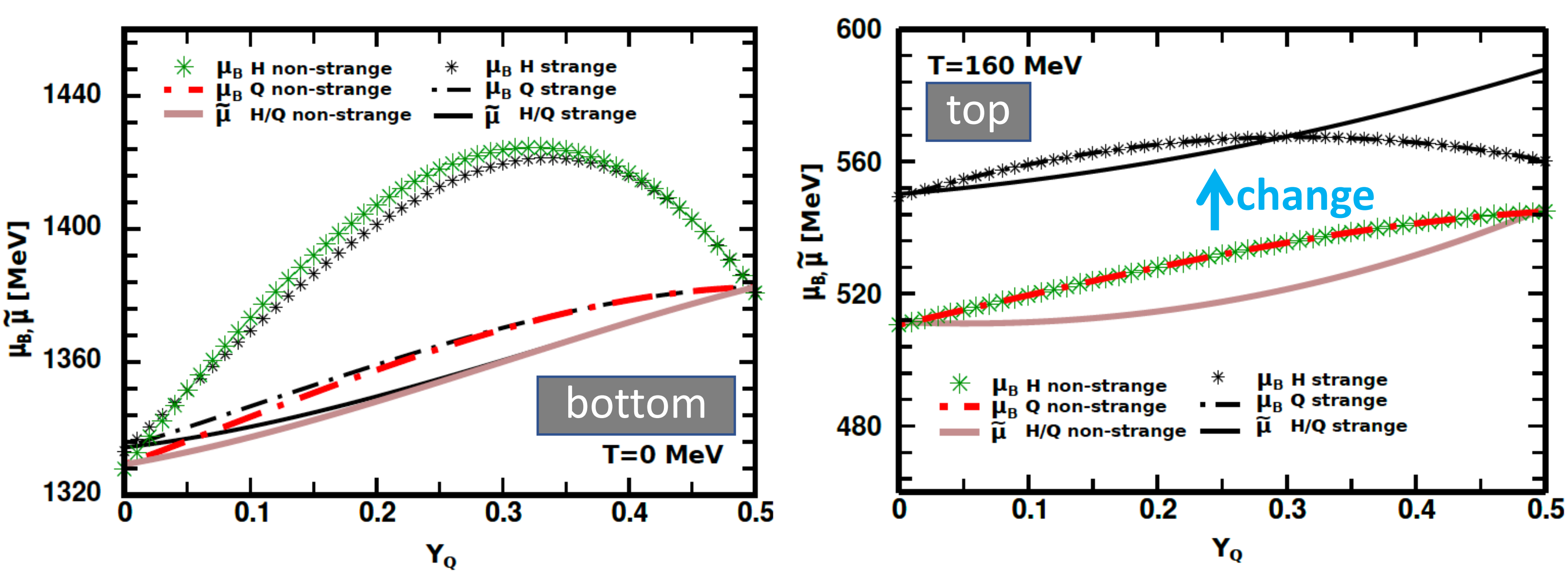
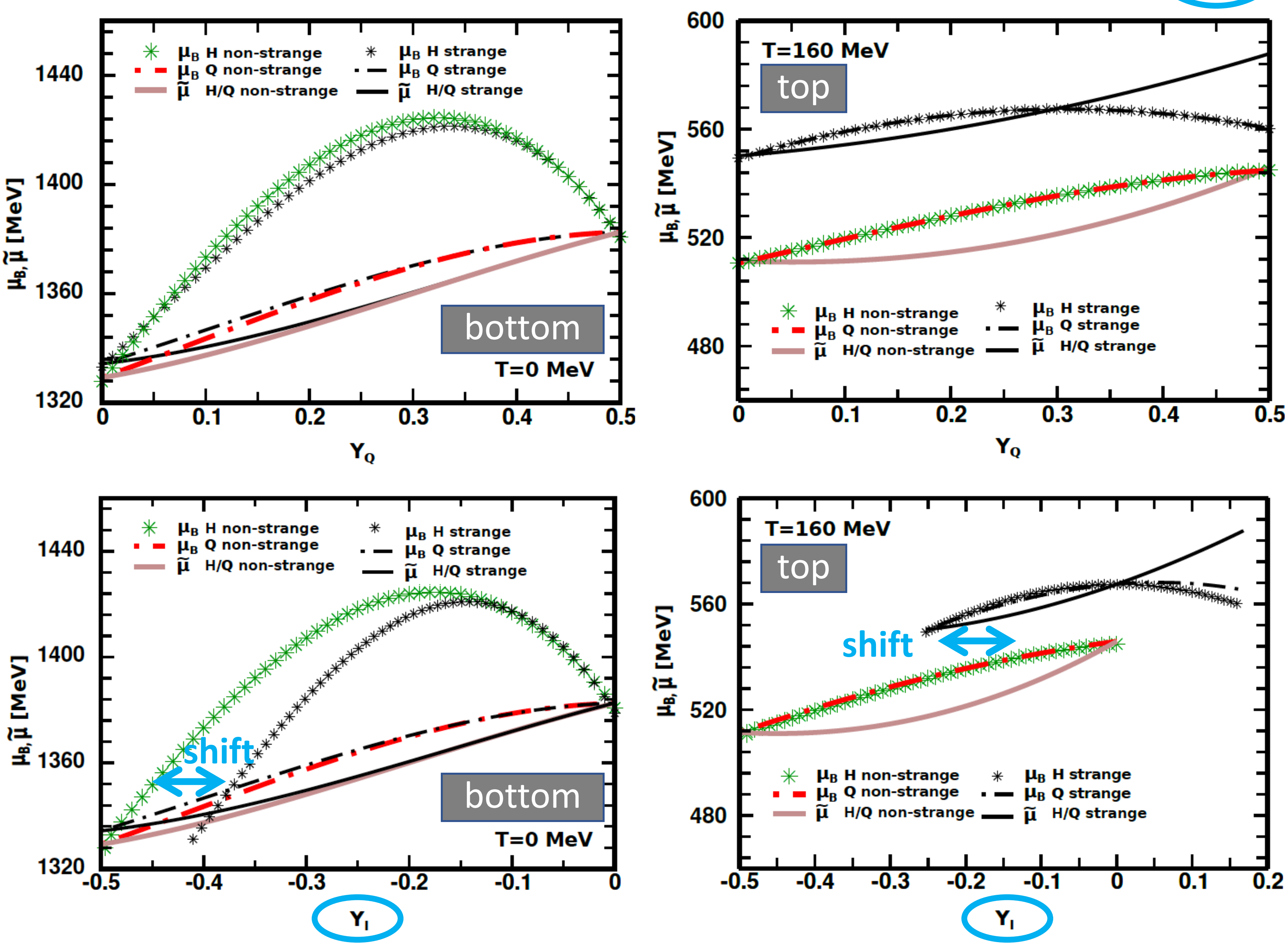


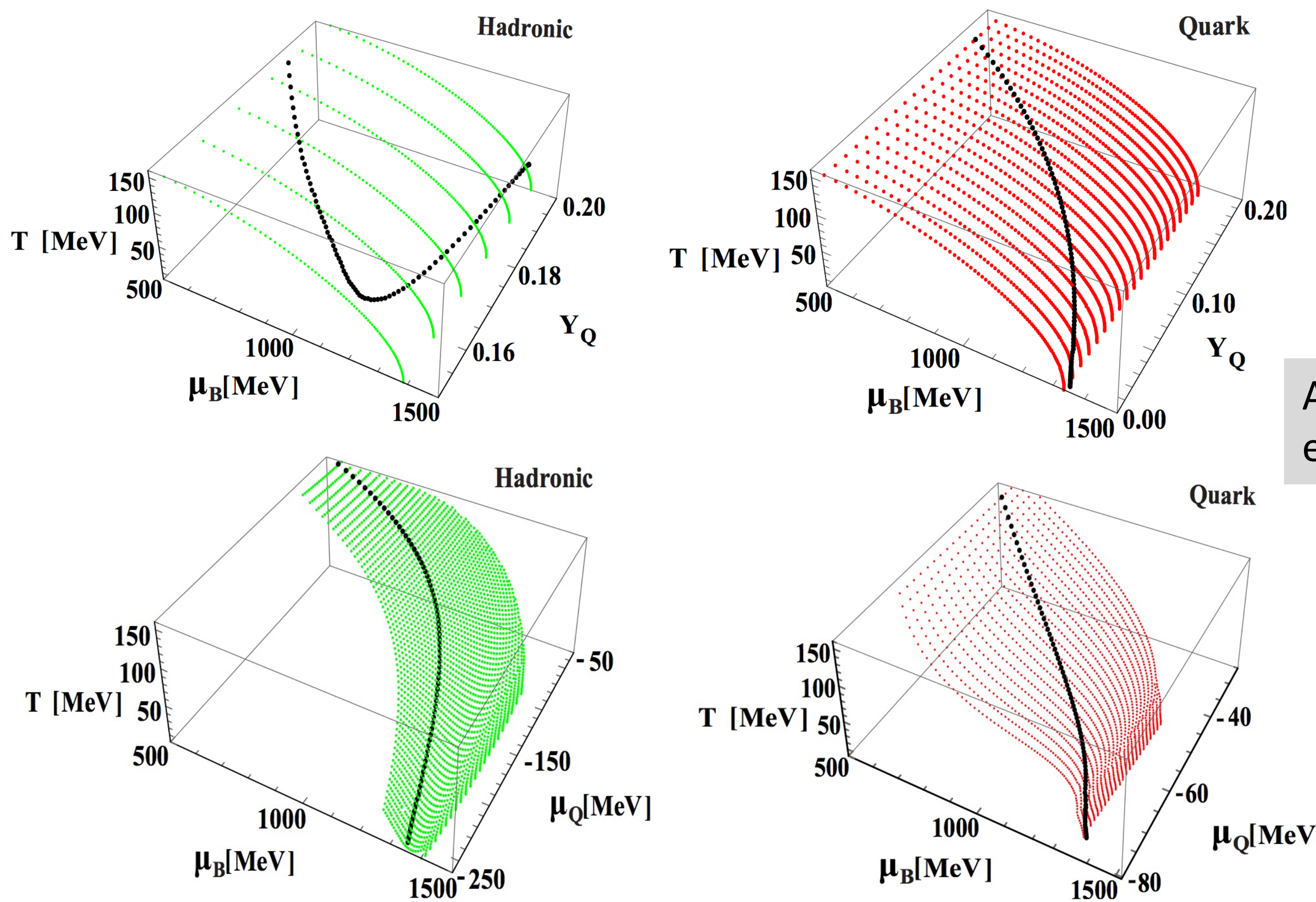
PRD 102 (2020) 7, 076016 e-Print: 2004.03039

- For finite net strangeness $Y_S \neq 0$, isospin and charge fraction relation is not trivial $Y_I = Y_Q - 0.5 + \frac{1}{2} Y_S$



Chemical Equilibrium Lines

- ⋆ Leptons in chemical equil. with baryons/quarks $\mu_Q = -\mu_{e,\mu}$
- ⋆ Charge neutrality $Y_Q = Y_{lepton}$, finite strangeness $Y_S \neq 0$



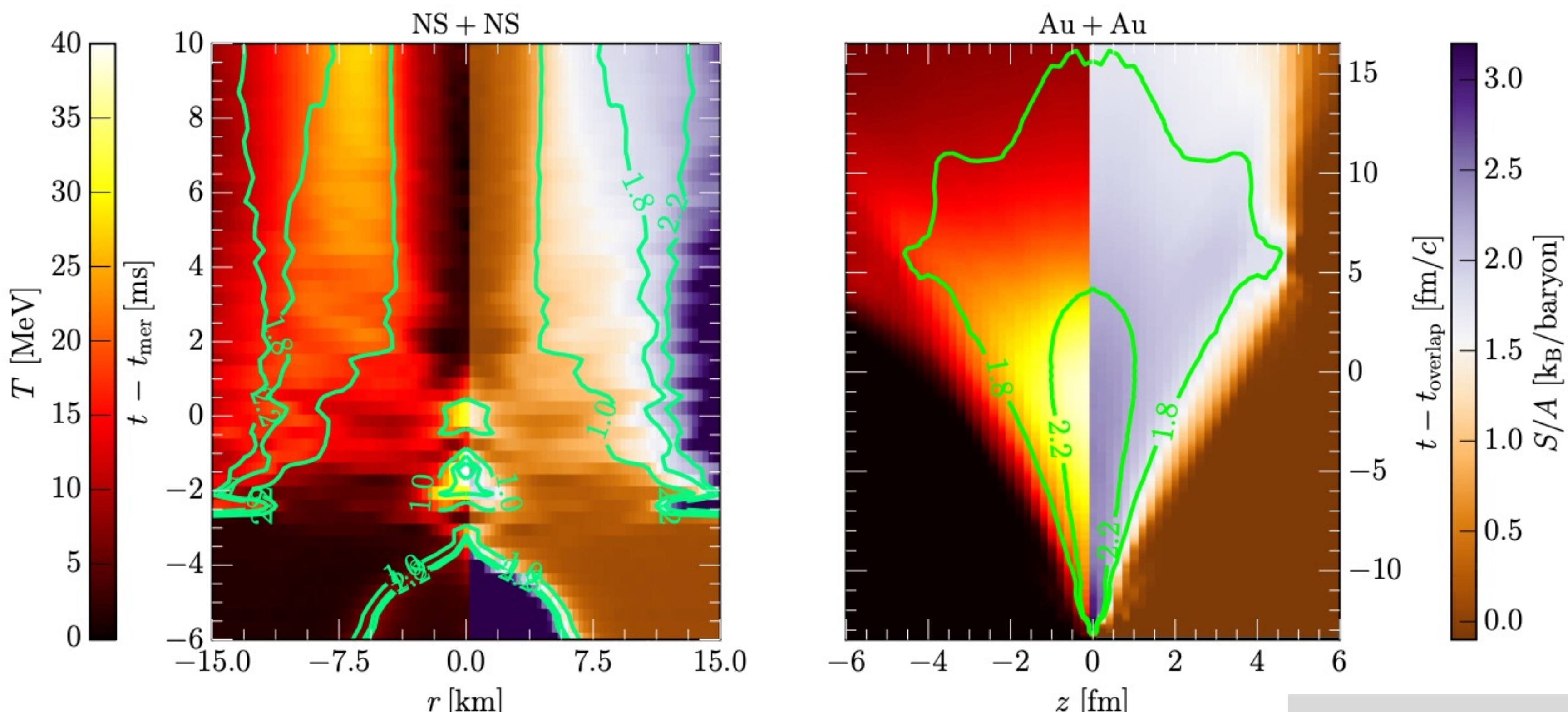
Astron.Nachr. 342 (2021)
e-Print: 2011.11686

Comparison with Low-Energy Collision

- ⋆ CMF with excluded volume that reproduces crossover

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

- ⋆ Final merger mass of 2.9 M_{Sun} and collision with E_{lab} = 450 MeV

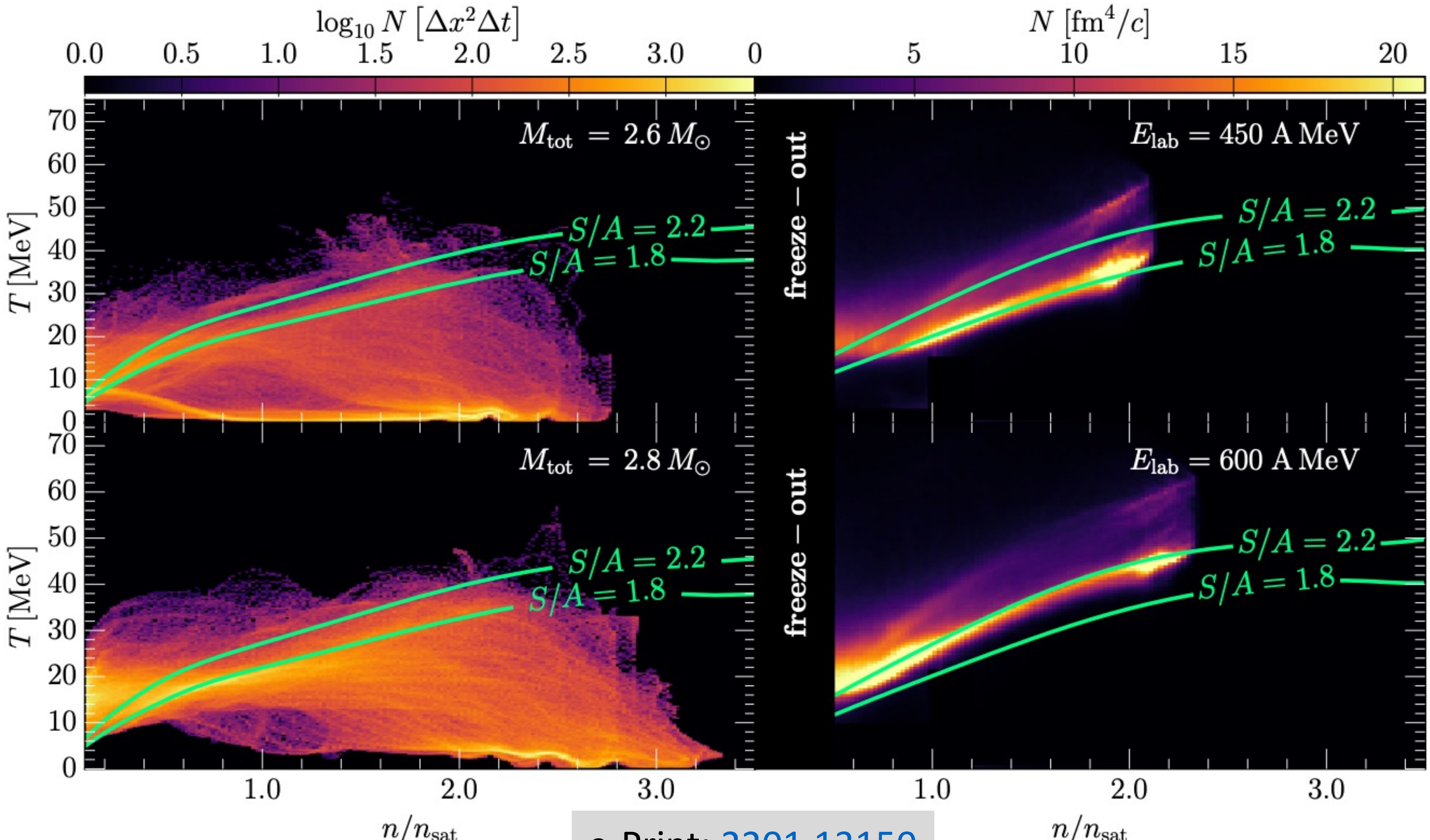


e-Print: [2201.13150]

- ⋆ Present similar temperatures/entropies per baryon

Comparison of Phase Diagrams

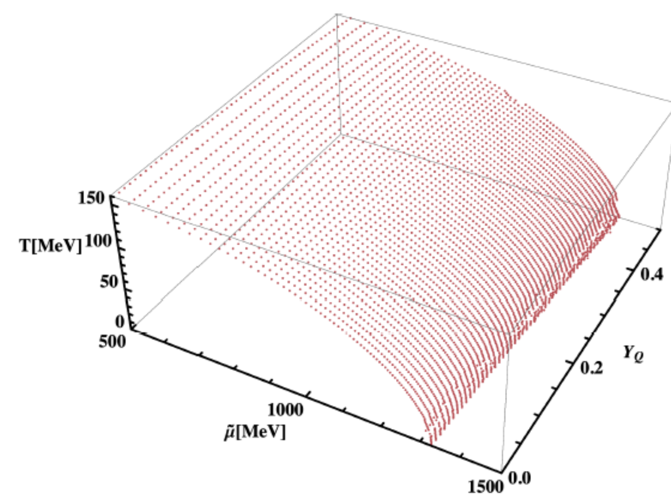
- Similar trajectories (other than stellar cold center and hot ring) allow connection of merger mass with lab energy



e-Print: [2201.13150](https://arxiv.org/abs/2201.13150)

Conclusions and Outlook

- ✶ New tight constraints on neutron-star masses and radii can inform us about dense neutron-star matter
- ✶ Neutron-star mergers create unique ideal conditions to achieve and detect deconfinement to quark matter in astrophysics
- ✶ Comparisons among heavy-ion collisions and neutron stars can be very useful but must be done with care (Y_Q , Y_S , leptons, …)
- ✶ Charge/isospin fractions affect significantly the deconfinement to quark matter: μ_B at deconfinement can change by up to 130 MeV and $\mu_{Q,I}$ by up to 330 MeV



Equation of state: from heavy-ion collisions to neutron stars

Veronica Dexheimer

<u>3D phase diagrams:</u>
Phys. Rev. D 102 (2020) 7, 076016, e-Print: 2004.03039
J.Phys.Conf.Ser. 1602 (2020) 1, 012013, e-Print: 2010.00996
Astron.Nachr. 342 (2021), e-Print: 2011.11686
<u>Neutron-star mergers:</u>
Phys. Rev. Lett. 122 (2019) 6, 061101, e-Print: 1807.03684
Eur. Phys. J. A 56 (2020) 2, 59, e-Print: 1910.13893
<u>Dense matter from GWs:</u>
J.Phys.G 46 (2019) 3, 034002, e-Print: 1810.06109
Phys.Rev.C 103 (2021) 2, 025808, e-Print: 2007.08493
Accepted for Publication in ApJ, e-Print: 2104.05950
e-Print: 2106.03890

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PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

NSF

CMF (Chiral Mean Field) Model

- Non-linear realization of the linear sigma model
- Includes baryons (+ leptons) and quarks
- Baryon and quark effective masses

$$M_B^* = g_{B\sigma}\sigma + g_{B\delta}\tau_3\delta + g_{B\zeta}\zeta + M_{0_B} + g_{B\Phi}\boxed{\Phi}^2$$
$$M_q^* = g_{q\sigma}\sigma + g_{q\delta}\tau_3\delta + g_{q\zeta}\zeta + M_{0_q} + g_{q\Phi}(1 - \boxed{\Phi})$$

- 1st order phase transitions or crossovers
- Potential for $\mathbf{\Phi}$ (deconfinement order parameter)

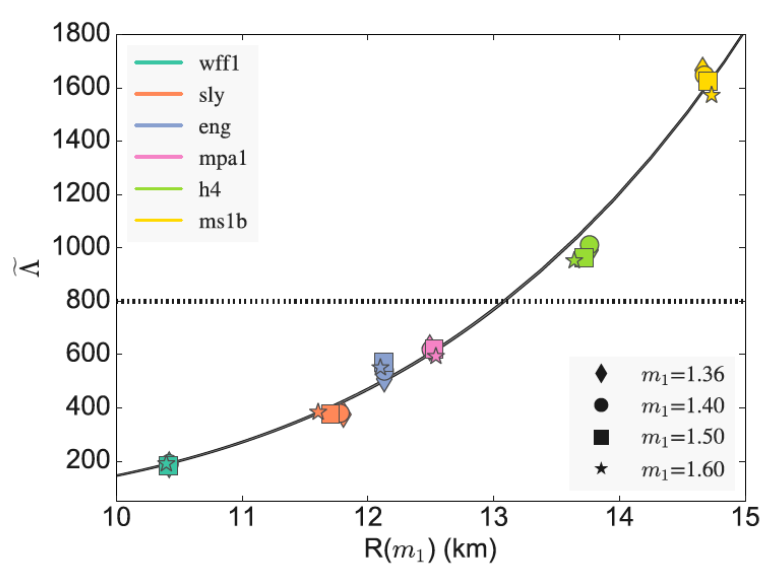
$$U = (a_o T^4 + a_1 \mu_B^4 + a_2 T^2 \mu_B^2)\Phi^2 + a_3 T_o^4 \ \ln(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4)$$

- Fitted to reproduce nuclear physics, astrophysics, lattice QCD
- In agreement with perturbative QCD

Tidal Deformability

- Normalized stellar quadripole deformation by companion

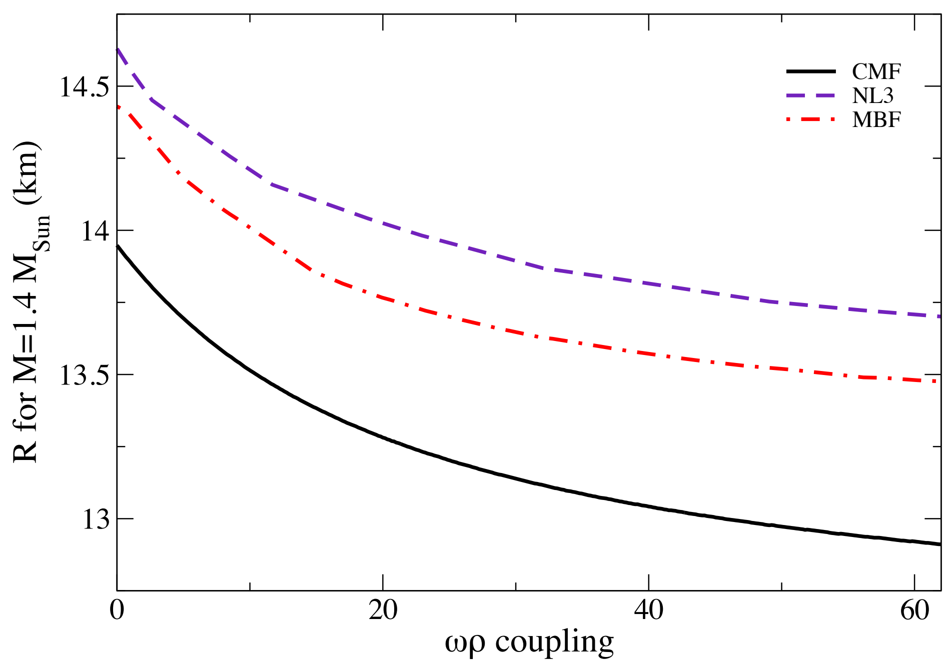
- Calculated from finite-size effects in end of inspiral: 76 $\rightarrow$ 1045 with 90% confidence (De et. al 2018)
- Related to NS radius of M=1.4 M_{sun} (Raithel et. al 2018)
- Universal relation?

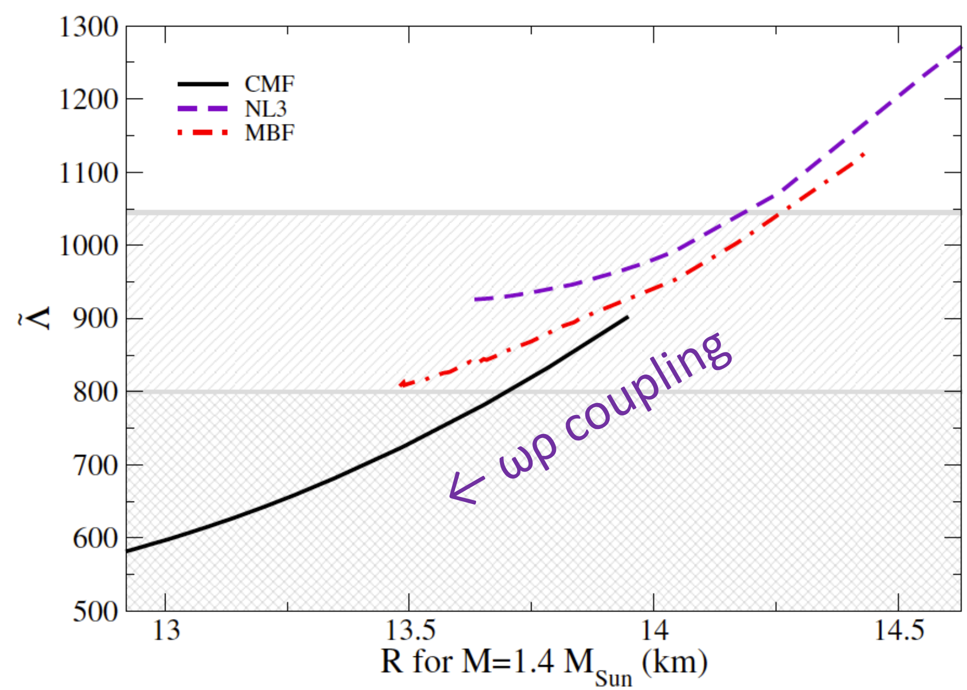


Exploring Isovector Coupling

- Using 3 relativistic EoS's that fulfil standard nuclear and astrophysical constraints: NL3, MBF, and CMF
- New vector-isovector channel $L_{\omega\rho} = g_{\omega\rho} g_\omega^2 g_\rho^2 \omega_\mu \omega^\mu \boldsymbol{\rho_\mu \rho^\mu}$ suggested by Horowitz and Piekarewicz

ωρ coupling

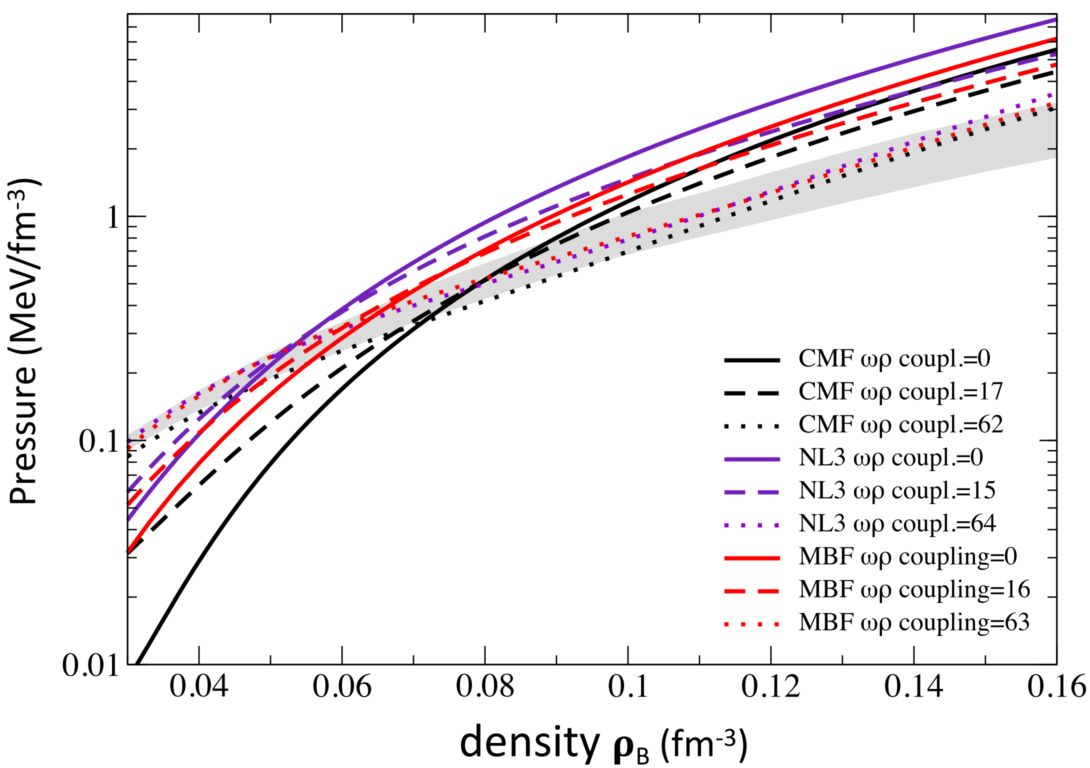




- Non-trivial relation between $\tilde{\Lambda}$ and $R_{1.4M_{Sun}}$

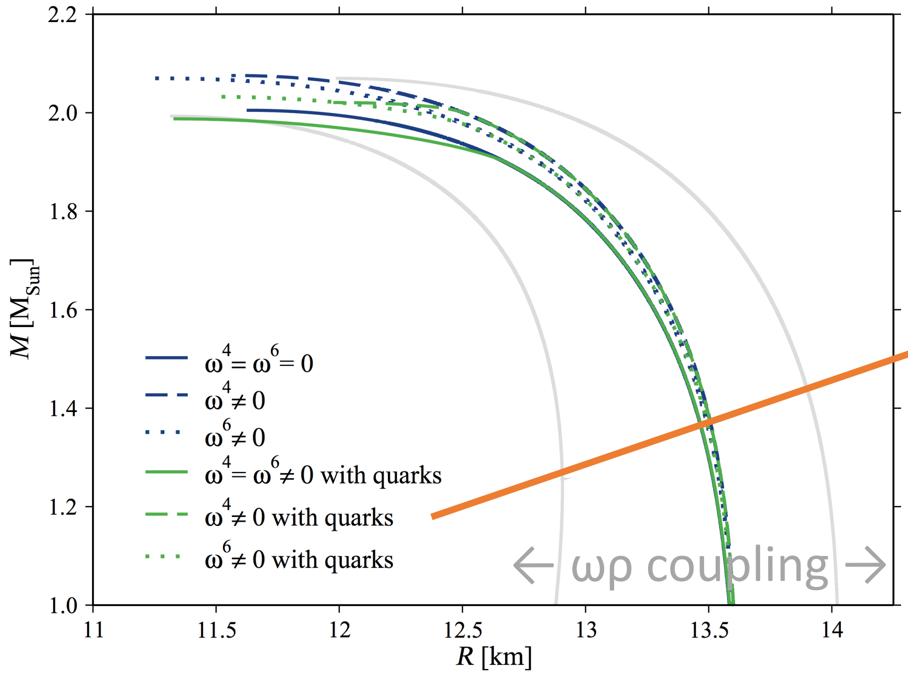
Exploring Isovector Coupling

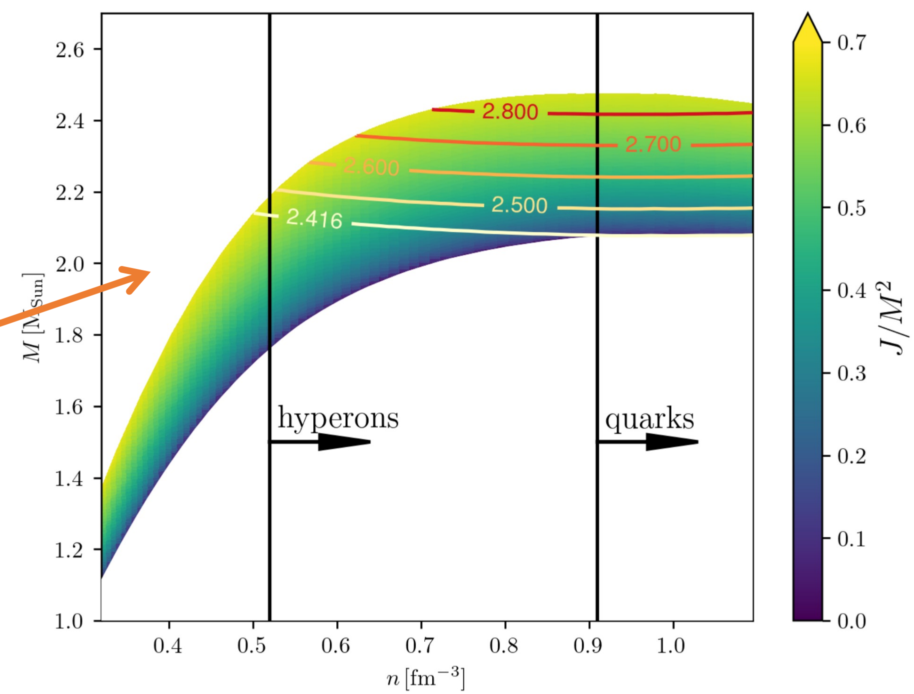
- New vector-isovector channel also in much better agreement with Effective Field Theory calculations from Hebeler et. al (2013) available for low densities



What have we learned about dense matter from GW190814

- Merger of $23.2^{+1.1}_{-1.0}$ M_{Sun} black hole and a $2.59^{+0.08}_{-0.09}$ M_{sun} object
- New quark-vector interactions increase masses to >2 M_{sun}
- Rotation close to the Kepler frequency reproduces ~ 2.5 M_{sun} stars with hyperons and quarks

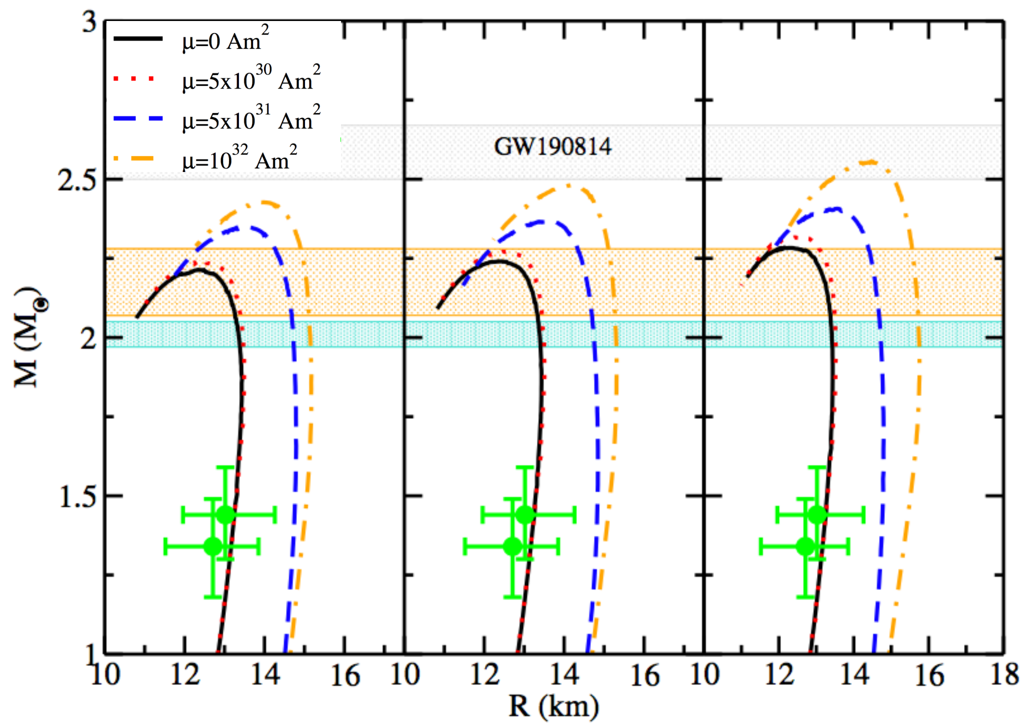




- Exotic degrees of freedom are not excluded

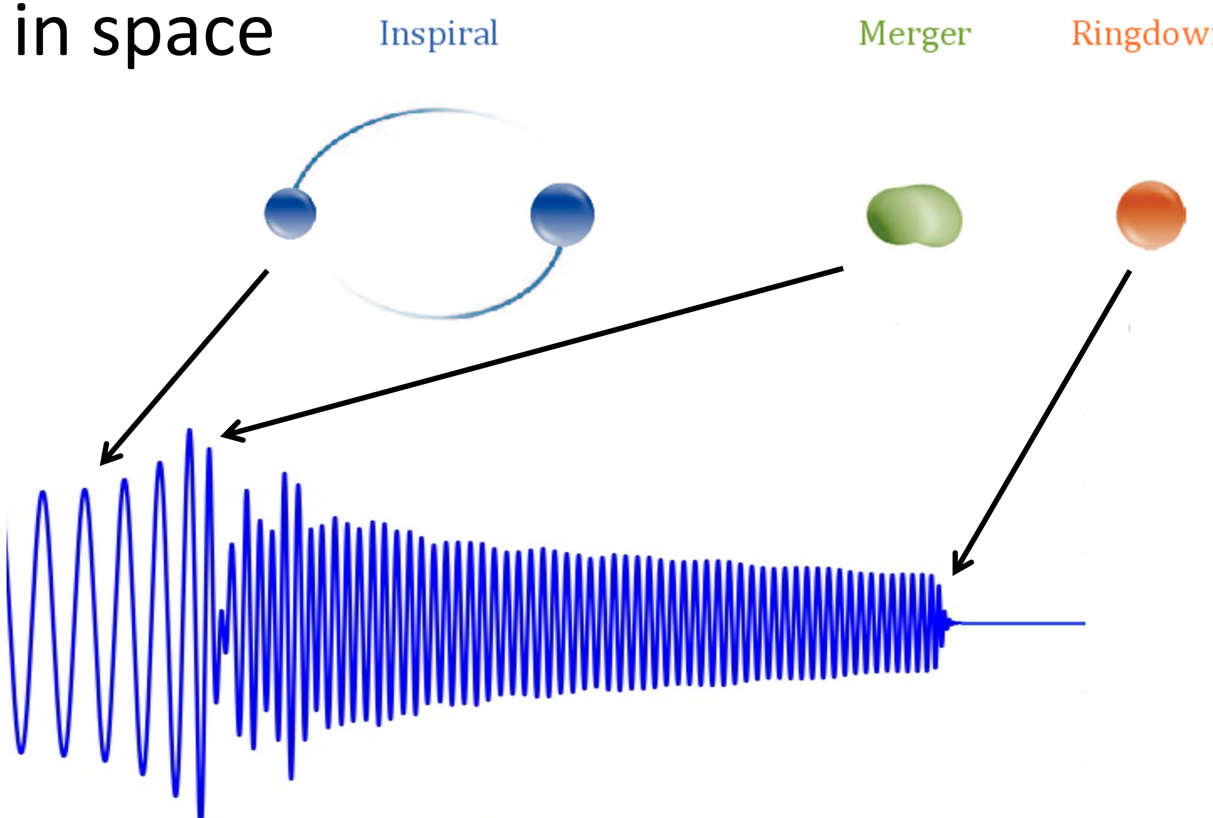
Magnetic massive stars

- Maximum fields allowed by axi-symmetric GR codes not enough to change significantly equation of state
- But decrease in hyperon fraction could increase stellar masses enough to explain GW190814 without rotation
- Stellar radius becomes much larger
- Still, exotic degrees of freedom are not excluded!



Neutron Star Merger 170817

- Observed by LIGO/VIRGO in 17 August 2017
- From galaxy NGC 4993 140 million light-years away
- Observed electromagnetically by 70 observatories on 7 continents and in space



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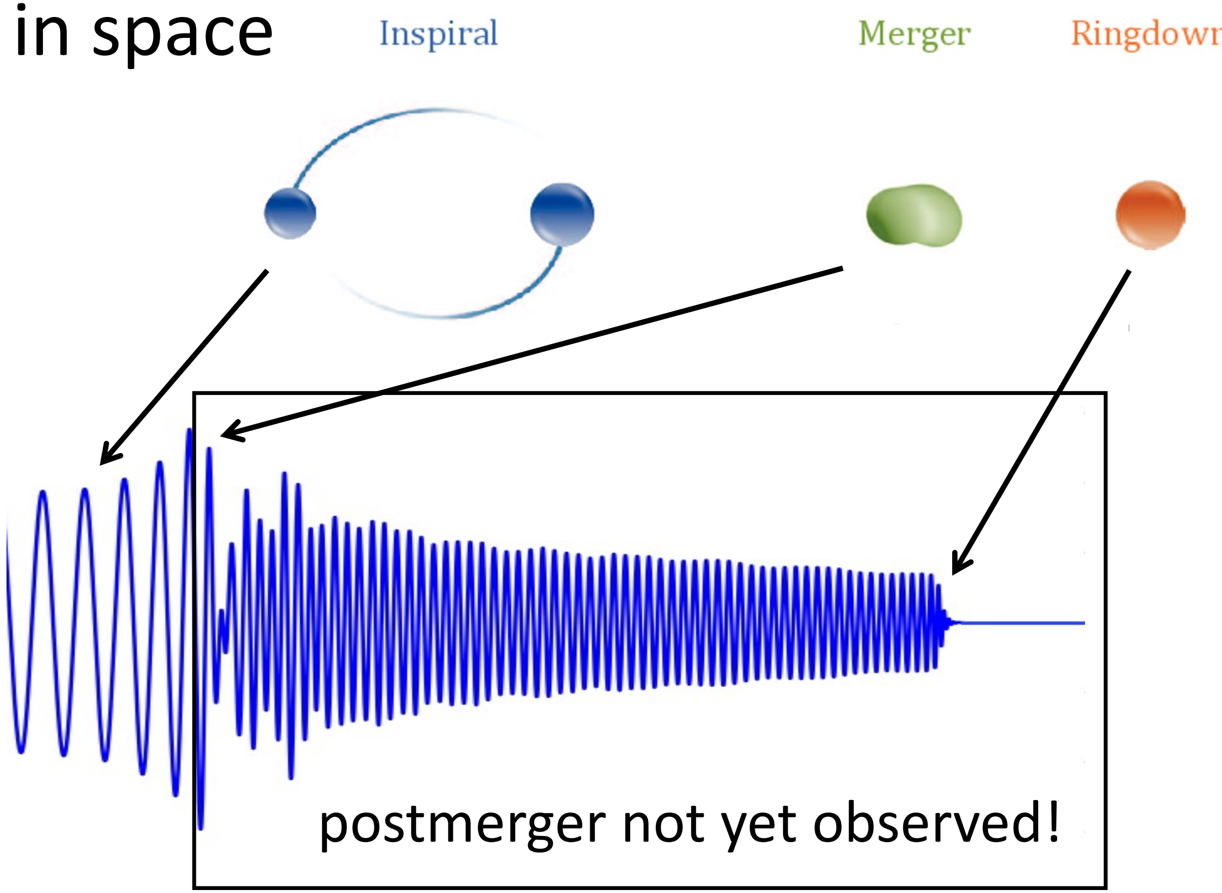
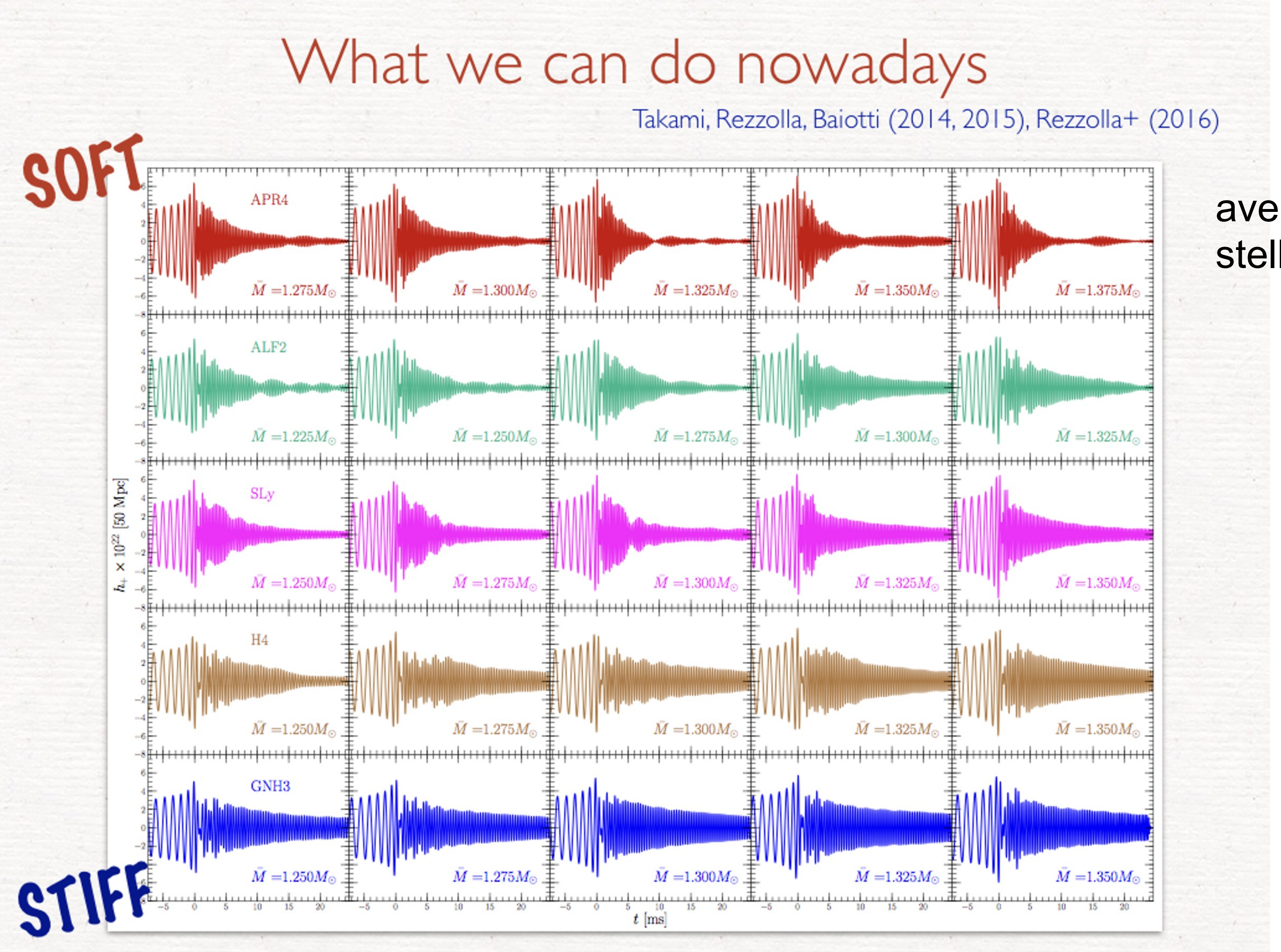


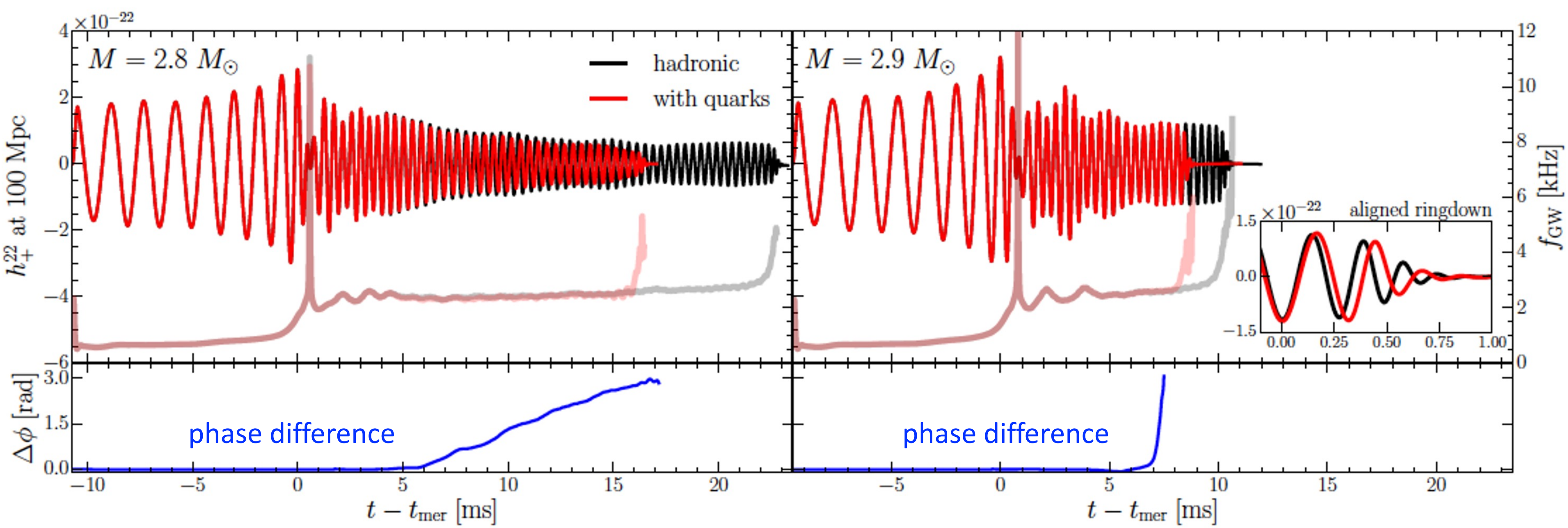
Hadronic Merger Simulations



average
stellar mass

Merger Simulation with Deconf.

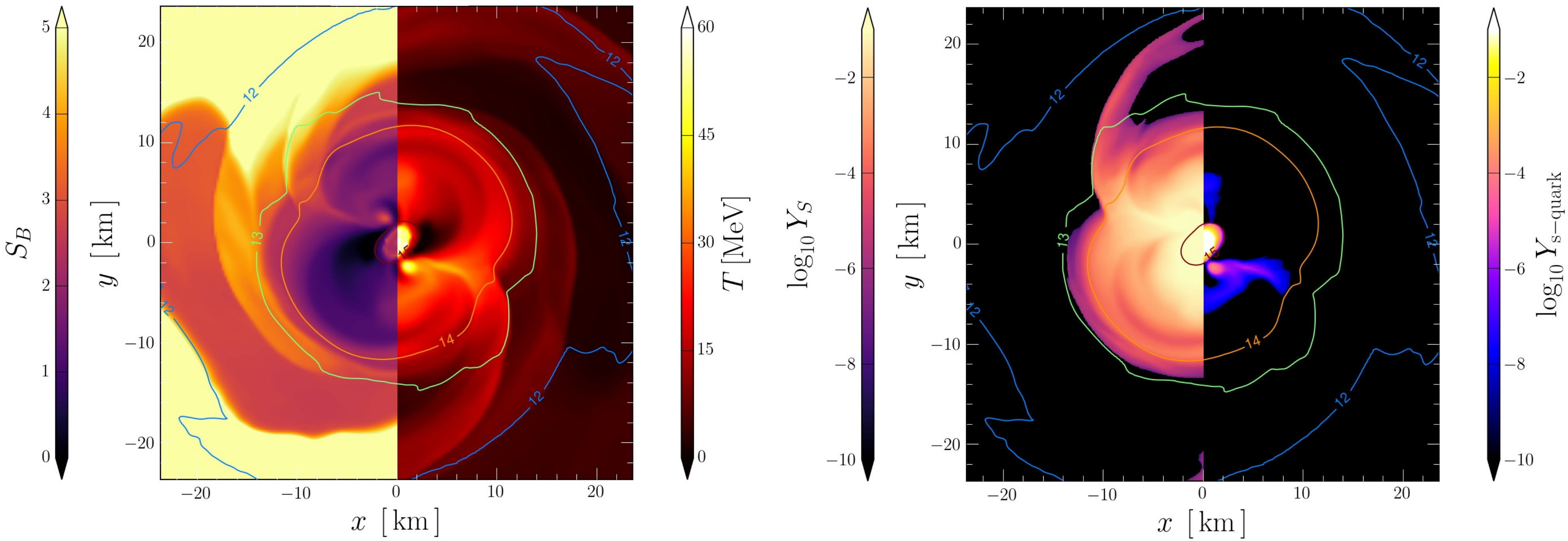
- 3D (T, $\boldsymbol{\rho}_B$,Y_c) CMF EoS with/without quarks
- Solve coupled Einstein-hydrodynamics system using Frankfurt/IllinoisGRMHD code (FIL)
- Interesting results for final masses of 2.8 and 2.9 M_{sun}



- Effects from quarks (h, f, phase) only after the merger

Inside Hypermassive Neutron Star

- At 5 ms after merger



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