Exotic Matter in Neutron Stars

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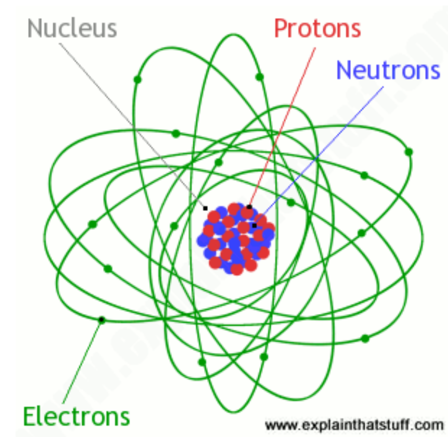
PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

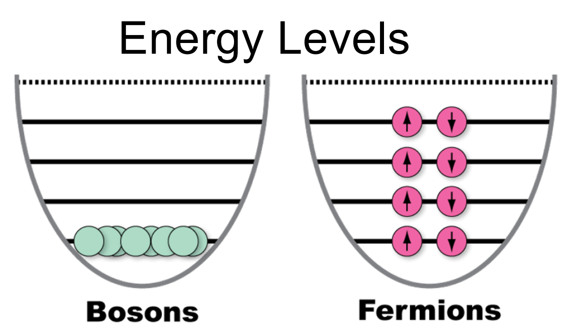
NSF

Neutron-Star Core Modelling

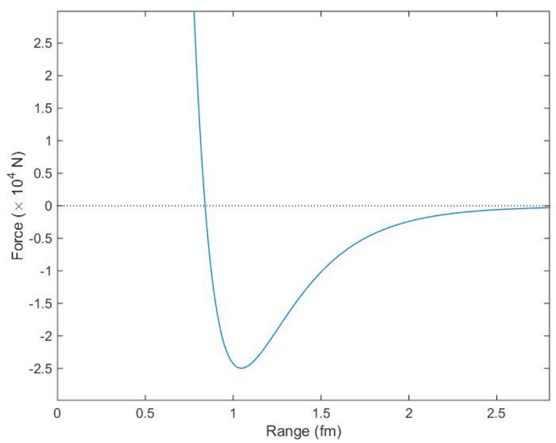
- Landau predicted giant nuclei formed when normal nuclei come in close contact at great density and "laws of ordinary quantum mechanics break down" in 1931



- Chadwick discovered neutron in 1932
- Baade and Zwicky proposed that heavy stars explode as supernovae and give birth to neutron stars in 1939
- Oppenheimer and Volkoff modeled neutron stars as cold, degenerate Fermi gas in 1939



Neutron-Star Core Modelling



- Attractive and repulsive aspects of nuclear force introduced in relativistic model by Walecka in 1974

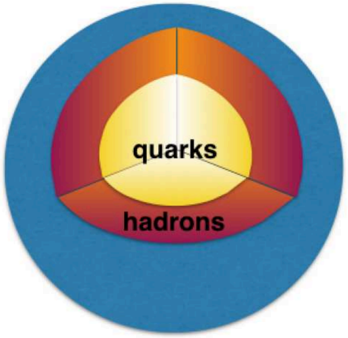
- Higher-order interactions added to better reproduce nuclear saturation properties by Boguta and Bodmer in 1977

- Hyperons included in modeling by Glendenning in 1979

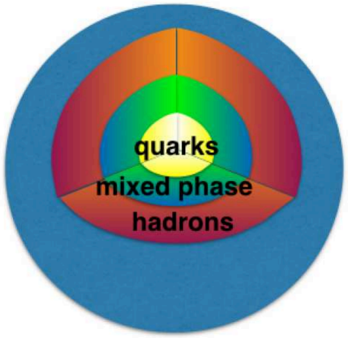
- Negative parity baryons studied in stars by VD in 2008

Neutron-Star Core Modelling

- Hybrid stars with a “quarkian” core suggested by Ivanenko and Kurdgelaidze in 1969

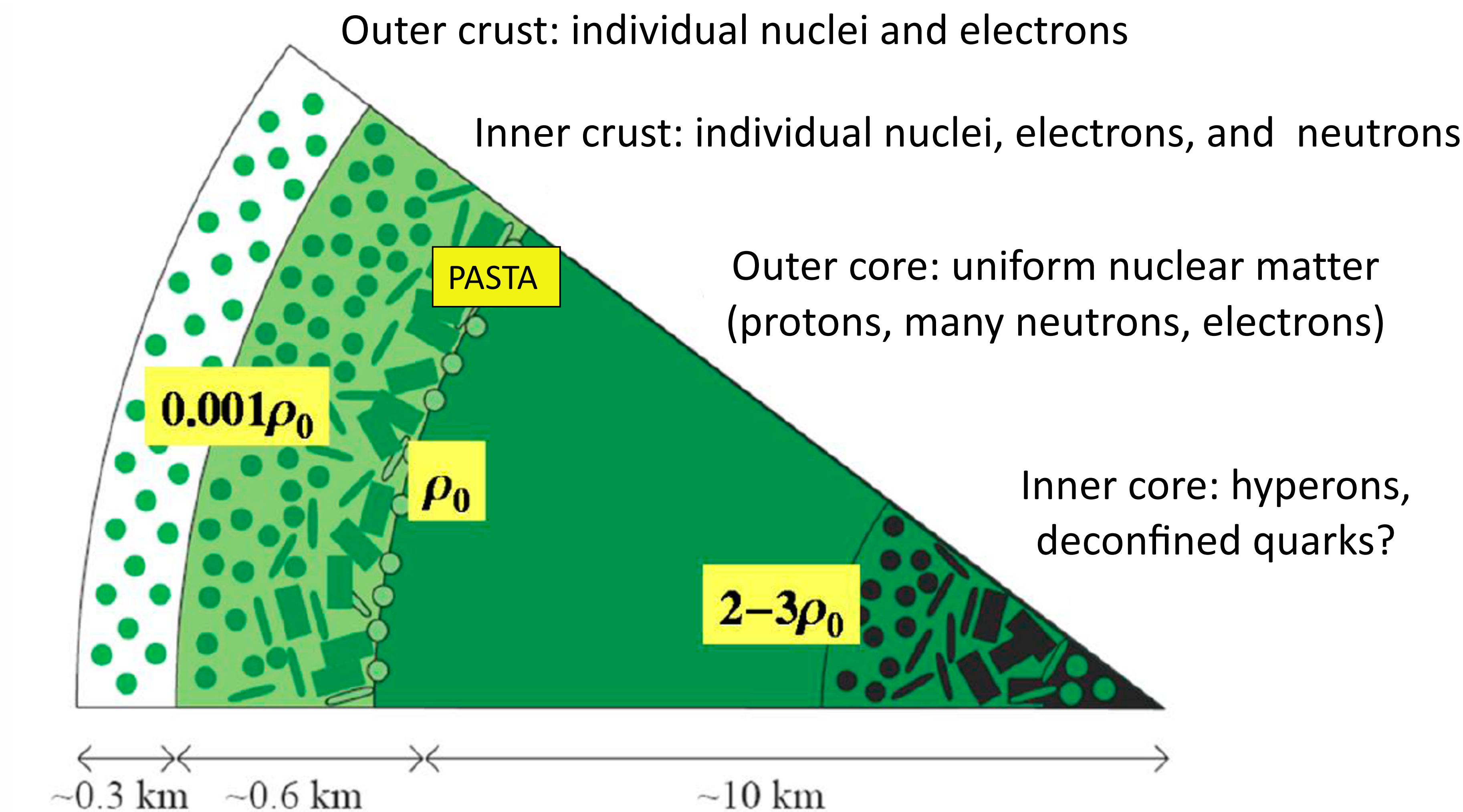


- Pure quark stars proposed by Itoh in 1970
- Presence of a mixed phase (with hadrons and deconfined quarks) inside neutron stars that conserves global charge proposed by Glendenning in 1991



- Presence of a mixed phase inside proto-neutron stars that conserve global charge and global lepton fraction investigated by Roark and VD in 2018

Neutron-Star Structure



- Nuclear density $\rho_0 \sim 10^{15}$ g/cm^3

CMF (Chiral Mean Field) Model

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

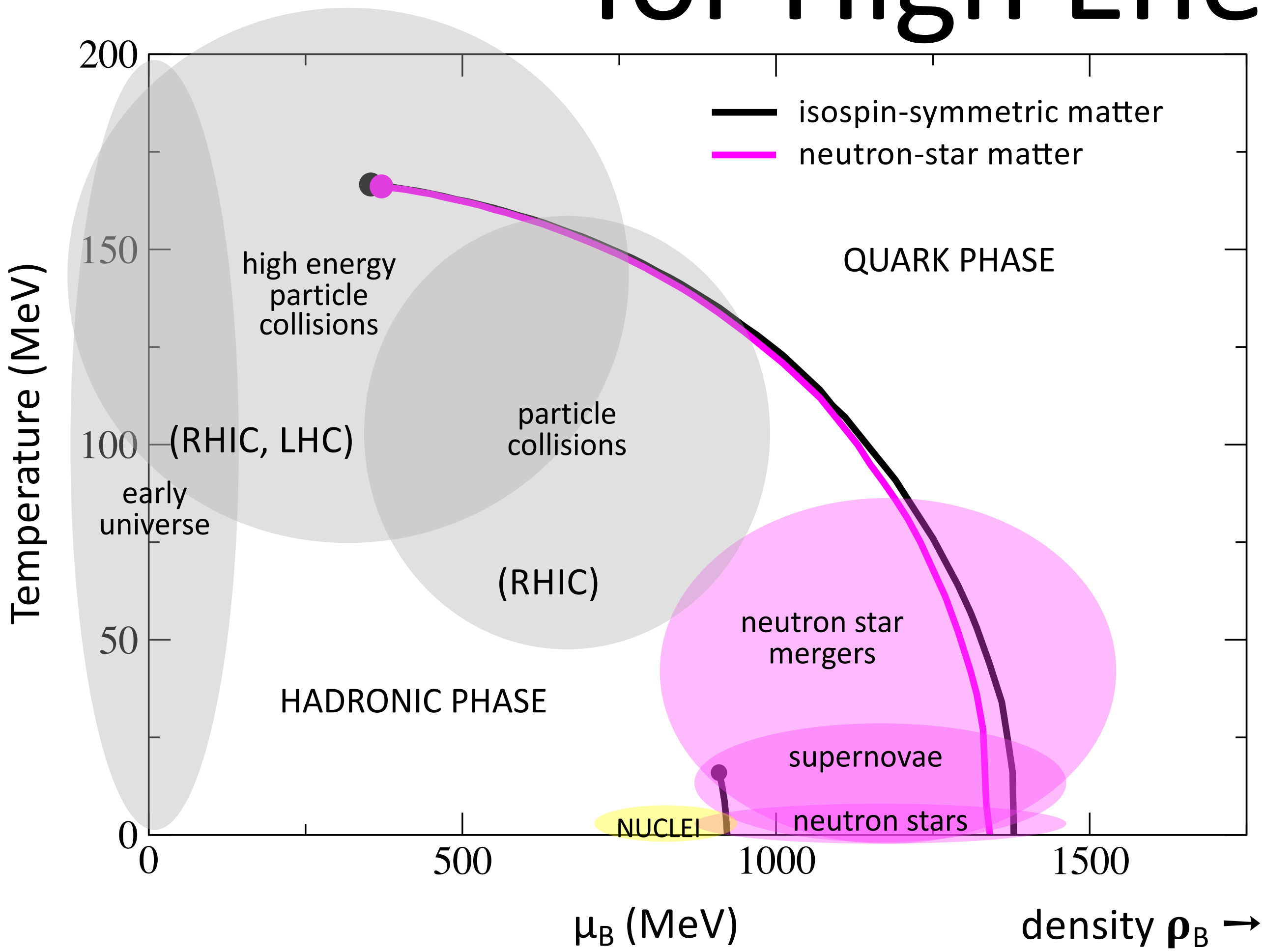
$$M_B^* = g_{B\sigma}\sigma + g_{B\delta}\tau_3\delta + g_{B\zeta}\zeta + M_{0_B} + g_{B\Phi}\Phi^2$$
$$M_q^* = g_{q\sigma}\sigma + g_{q\delta}\tau_3\delta + g_{q\zeta}\zeta + M_{0_q} + g_{q\Phi}(1-\Phi)$$

- 1^{st} order phase transitions or crossovers
- Potential for **Φ** 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, astrophysical, lattice QCD

QCD Phase Diagram for High Energy



- Results from the CMF model

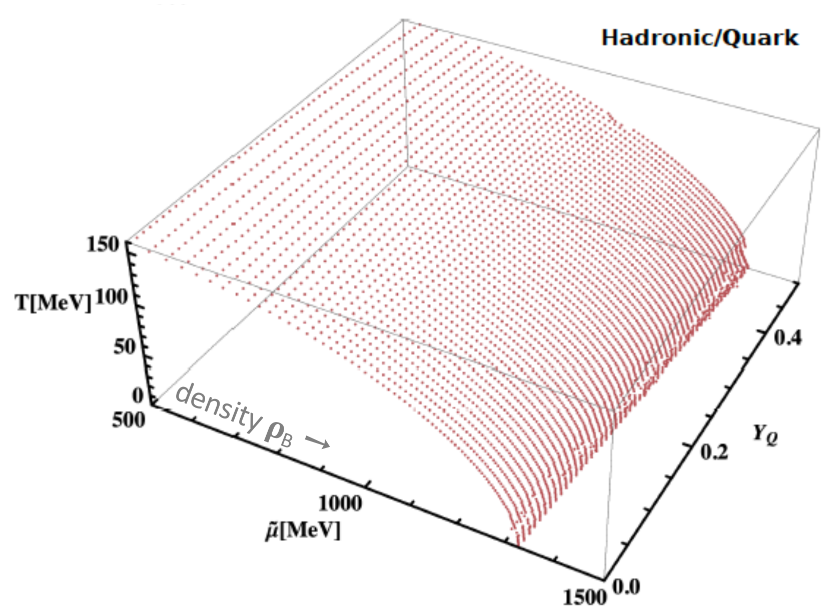
3D QCD Phase Diagrams (Y_S=0)

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

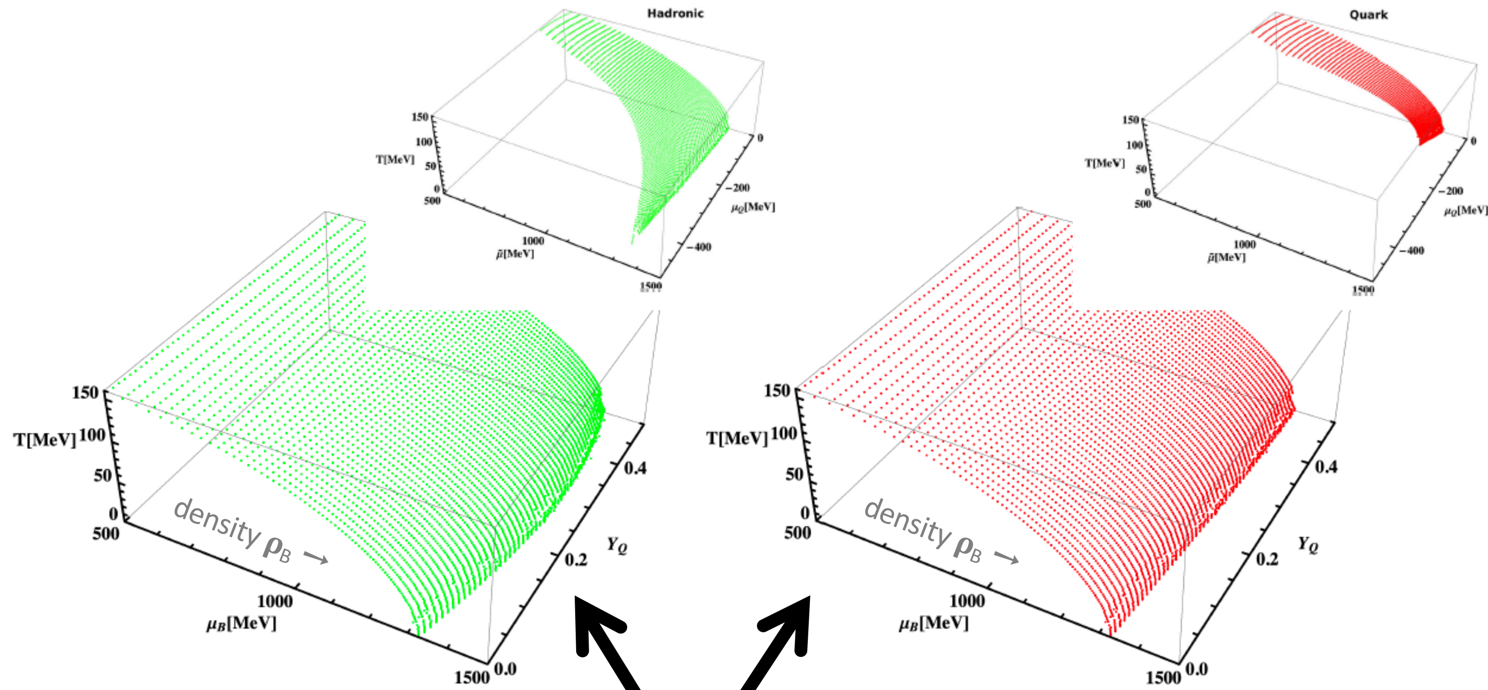
3D QCD Phase Diagrams (Y_S=0)

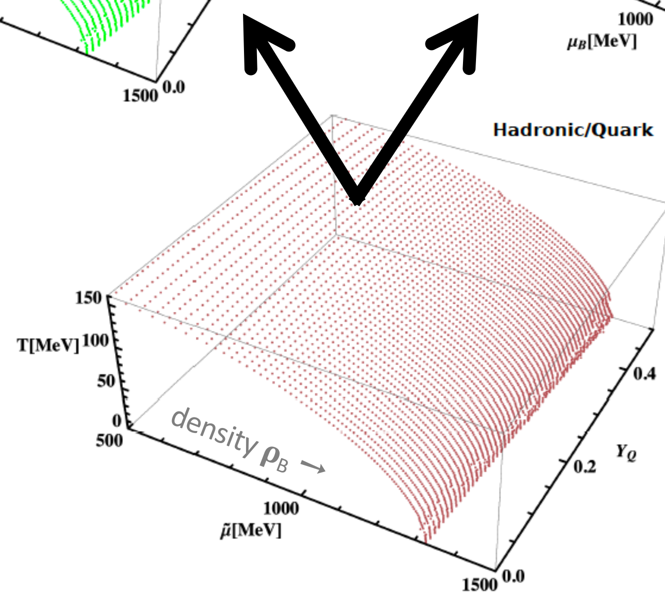
- T, $\widetilde{\mu}$, Y_Q with charge fraction $Y_Q = Q/B$ = 0 → 0.5
  and Gibbs free energy per baryon $\widetilde{\mu} = \mu_B + Y_Q \mu_Q$

- 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 the EoS (particle population) on each side



3D QCD Phase Diagrams (Y_S=0)





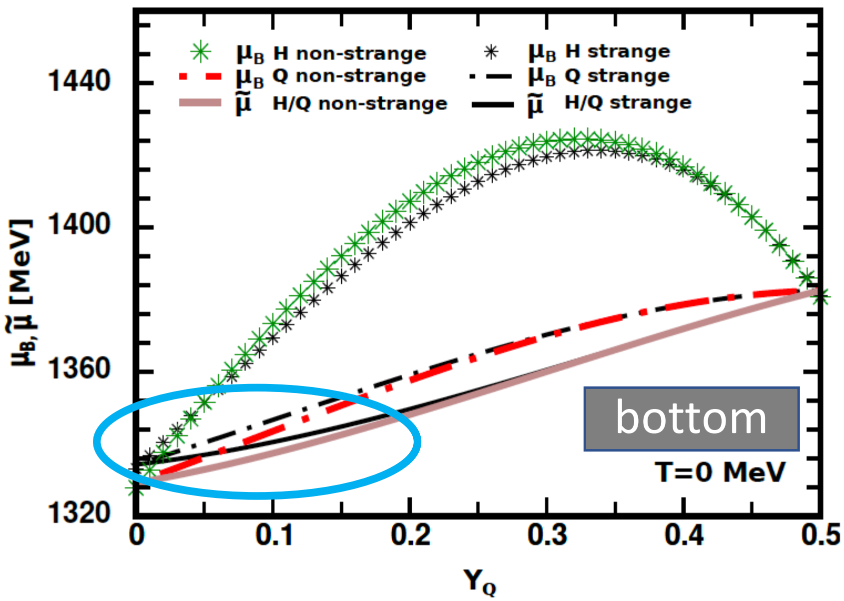
Gibbs free energy per baryon

$\widetilde{\mu}= \mu_B + Y_Q \mu_Q$

Slices of 3D QCD Phase Diagrams

(Y_S=0, $Y_S \neq$/0 in black)

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



Slices of 3D QCD Phase Diagrams
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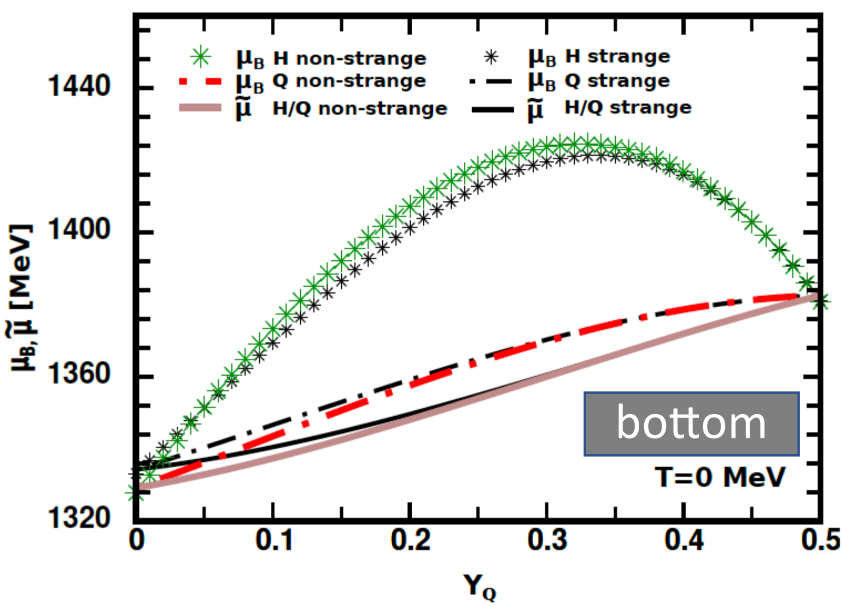
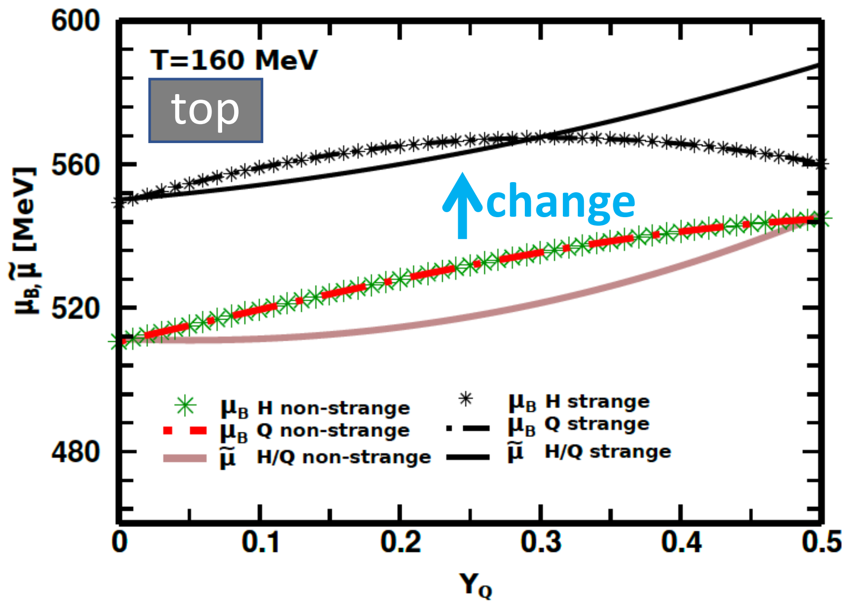
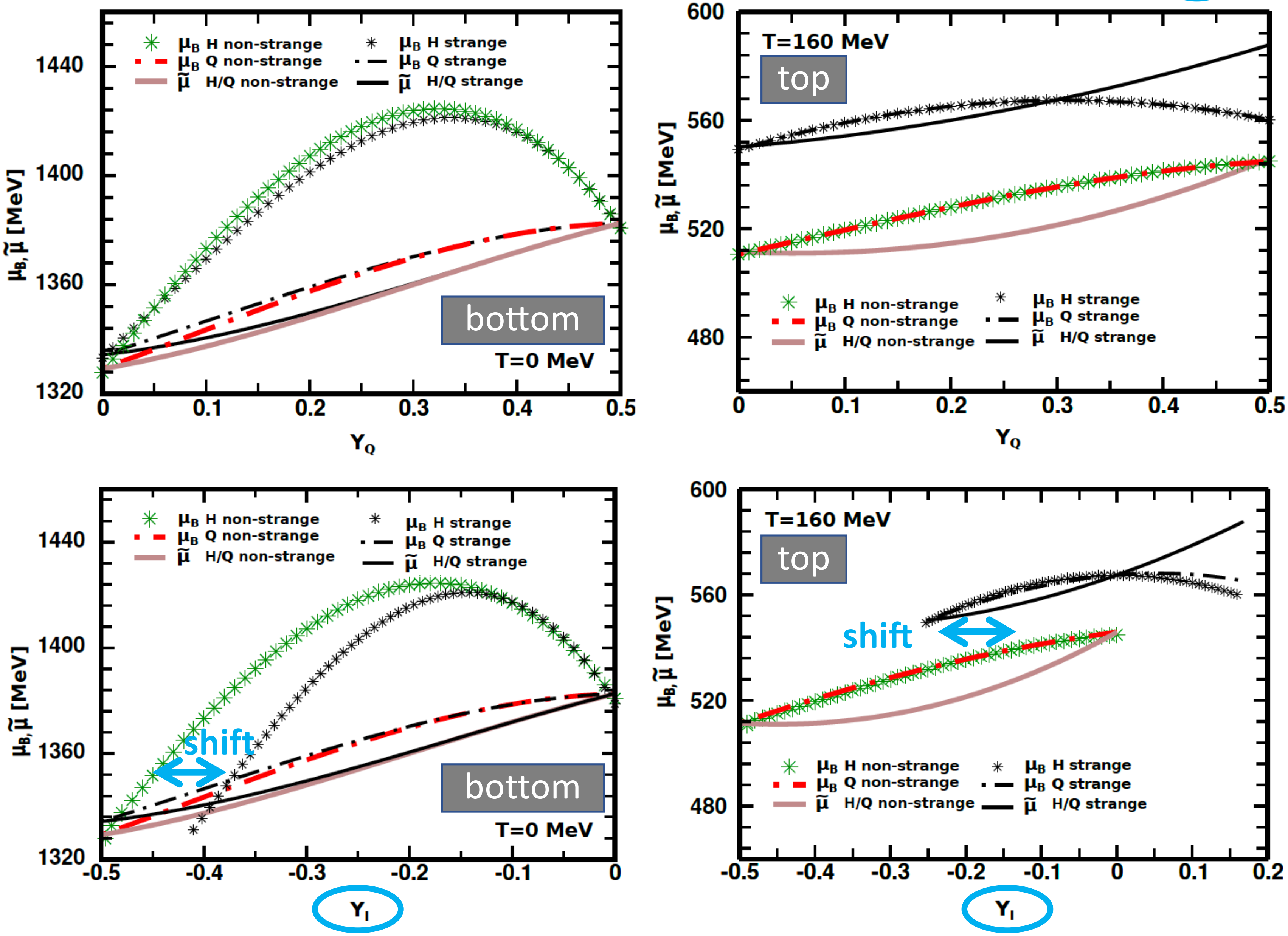


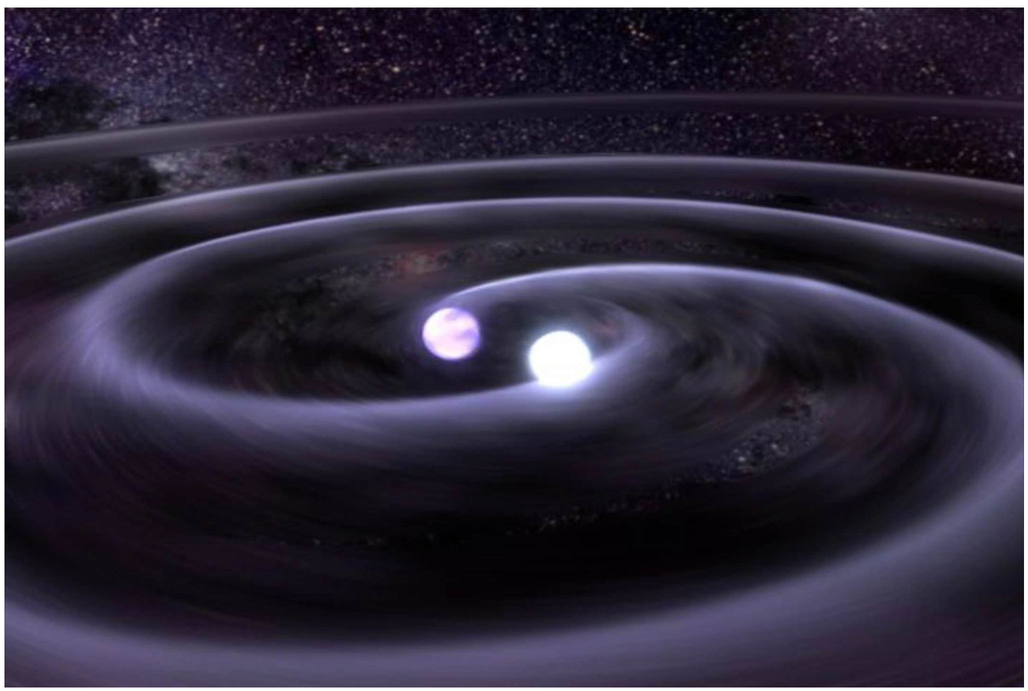


- For finite net strangeness $Y_S \neq 0$, isospin and charge fraction relation is not trivial $Y_I = Y_Q - 0.5 + \frac{1}{2} Y_S$

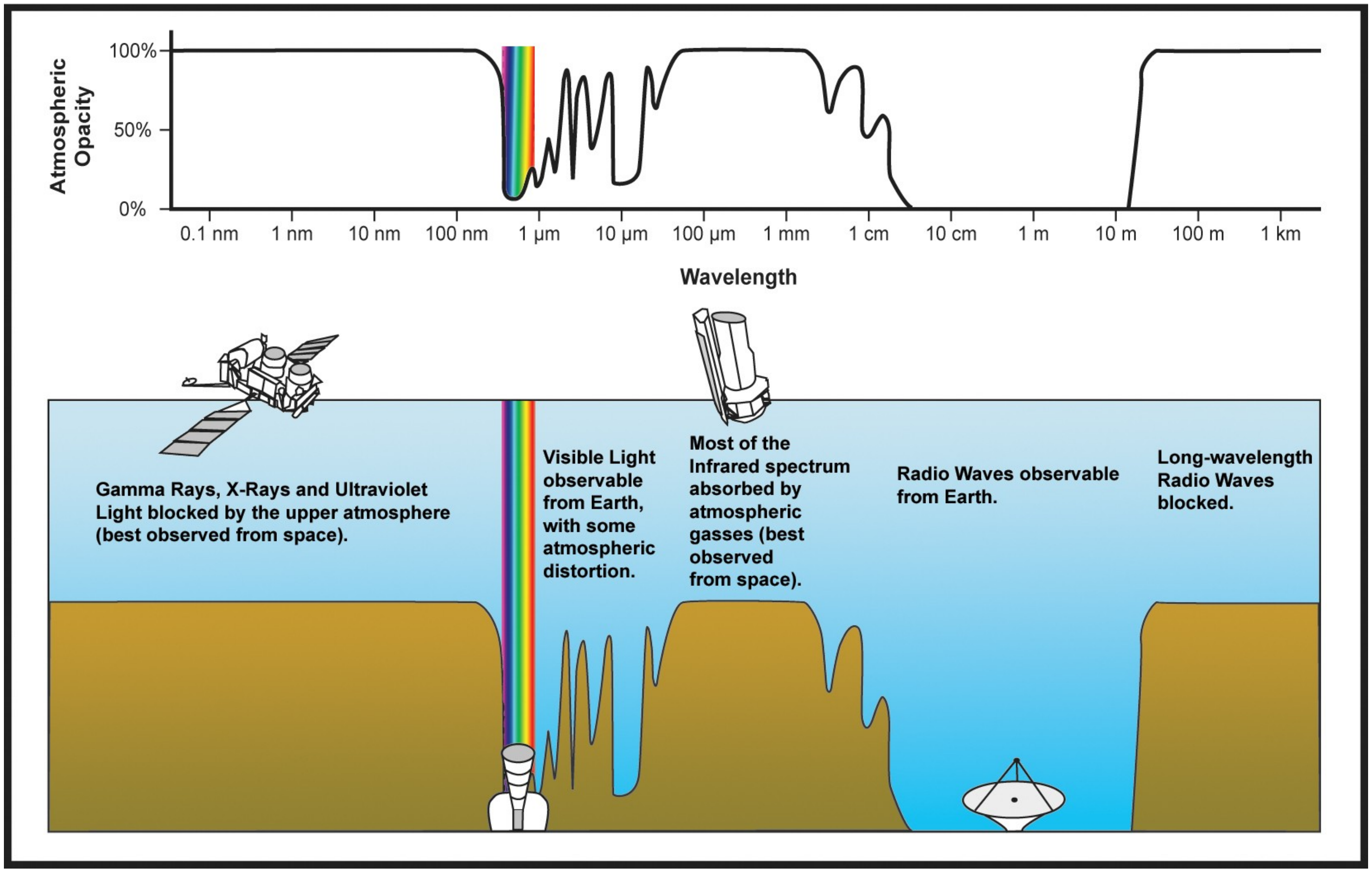


Charge Fraction Y_Q Overview

- Heavy-ion collisions: 0.4 → 0.5
- Cold catalyzed neutron stars cores: 0 → 0.15
- Supernovae explosions and proto-neutron stars: 0.1 → 0.5 (0.4)
- Neutron-star mergers ?

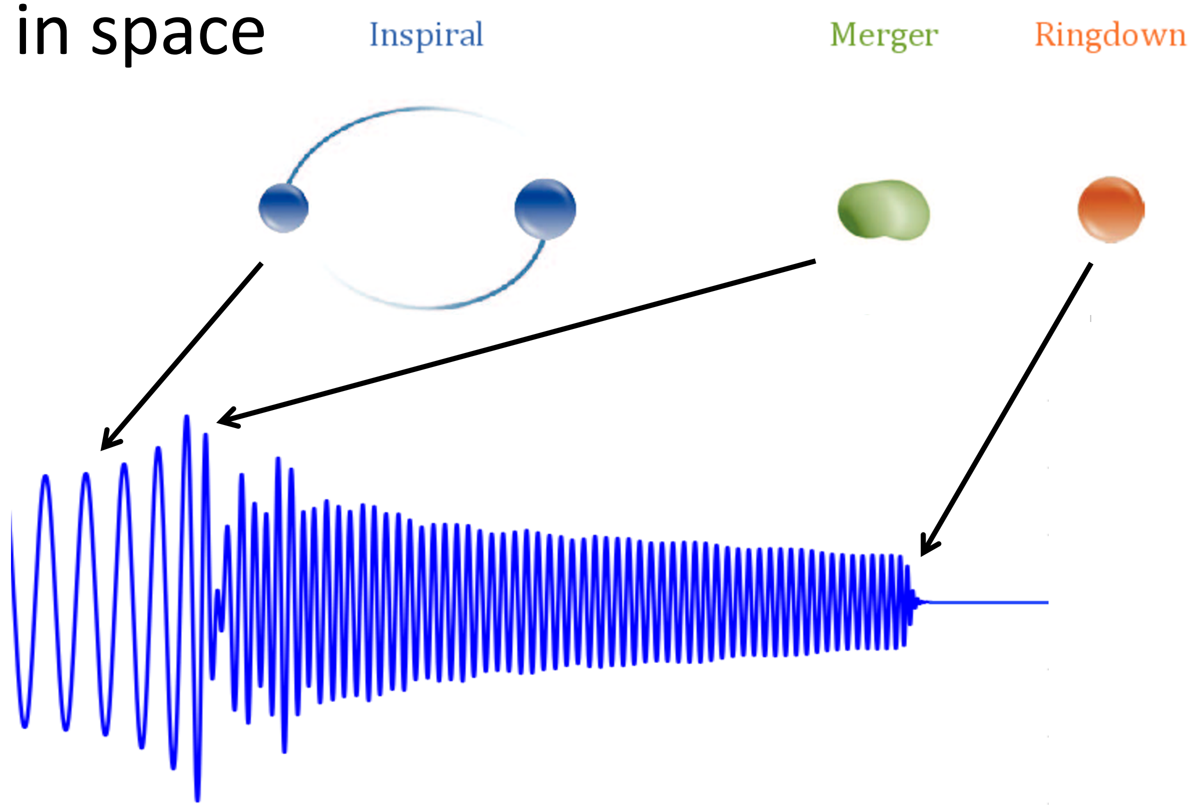


But How Can We Probe the Interiors of Neutron Stars?



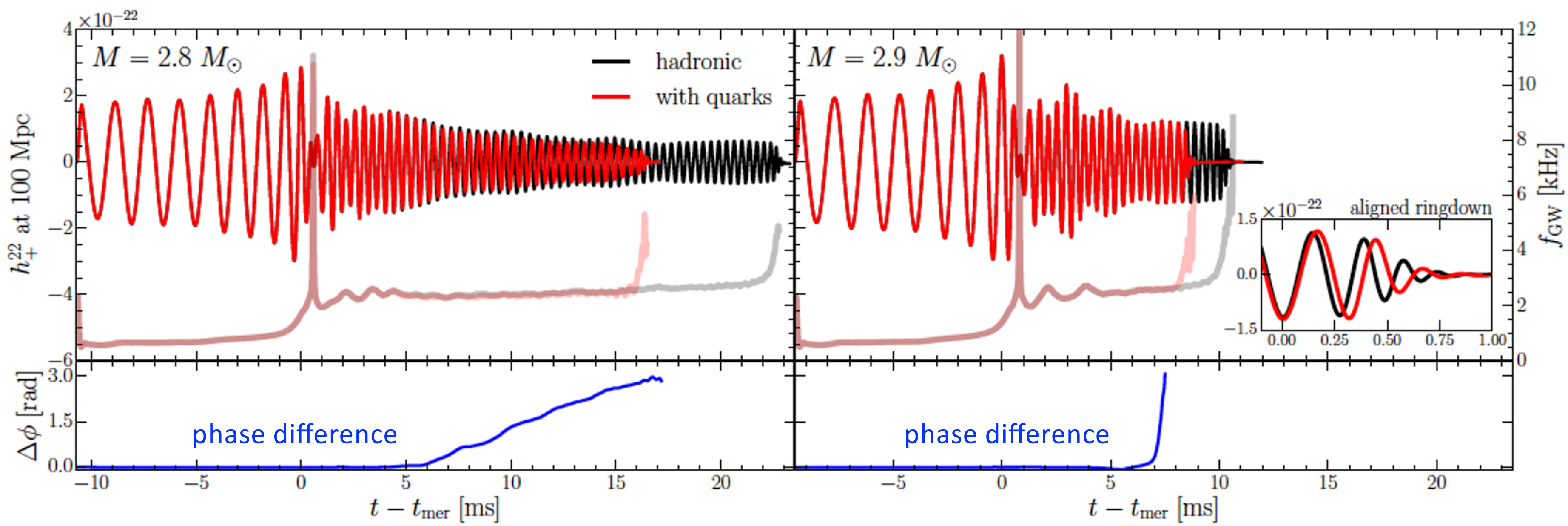
Neutron Star Merger 170817

- 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



Merger Simulation with Deconf.

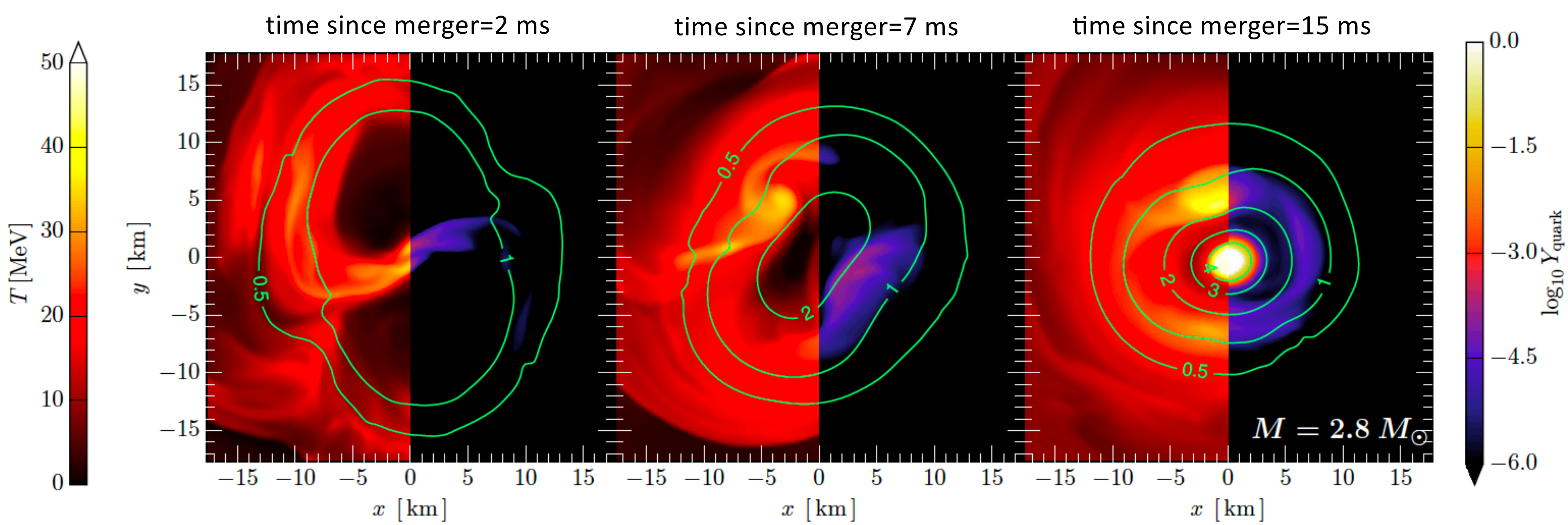
- 3D (T, $\boldsymbol{\rho}_B$, Y_c) CMF EoS with/without quarks
- Solve coupled Einstein-hydrodynamics system using Frankfurt/IllinoisGRMHD code (FIL)
- Interesting results for final masses of 2.8 and 2.9 M_{sun}



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

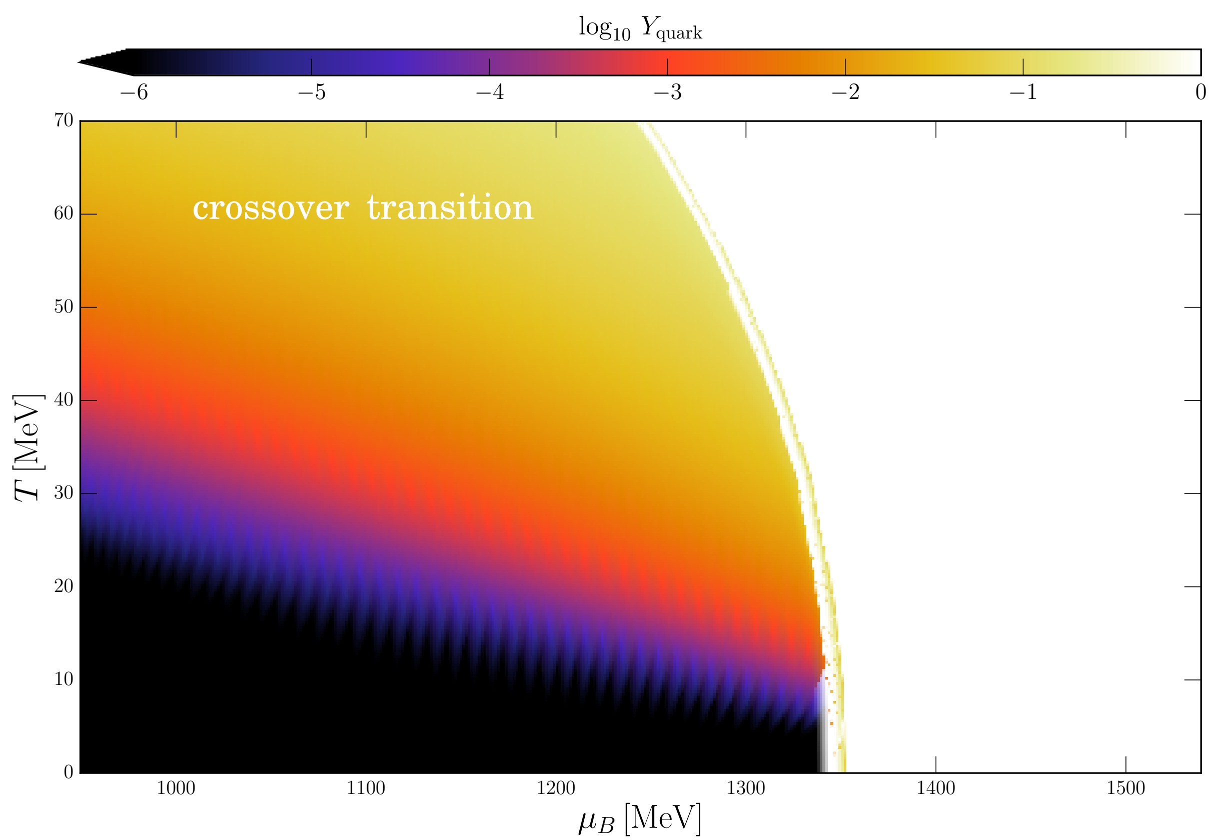
Inside the Neutron-Star Merger

- As neutron stars merge, a hot ring with some quarks forms around the center
- Then a very hot region forms in the center with lots of quarks



Merger in the QCD Phase Diagram

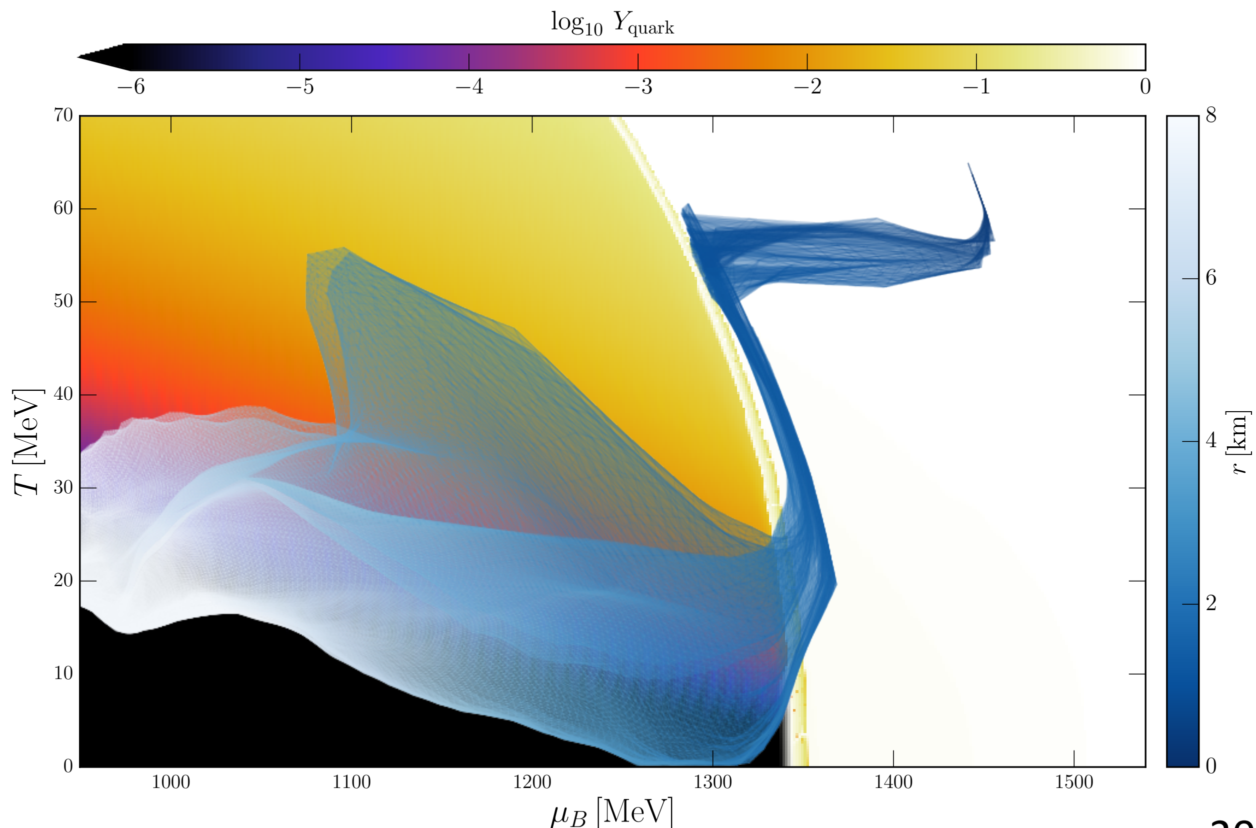
- Background: 2D (T, n_B) CMF EoS with 1st order phase transition for $Y_Q = Q/B = 0.05$



density $\boldsymbol{\rho}_B$ →

Merger in the QCD Phase Diagram

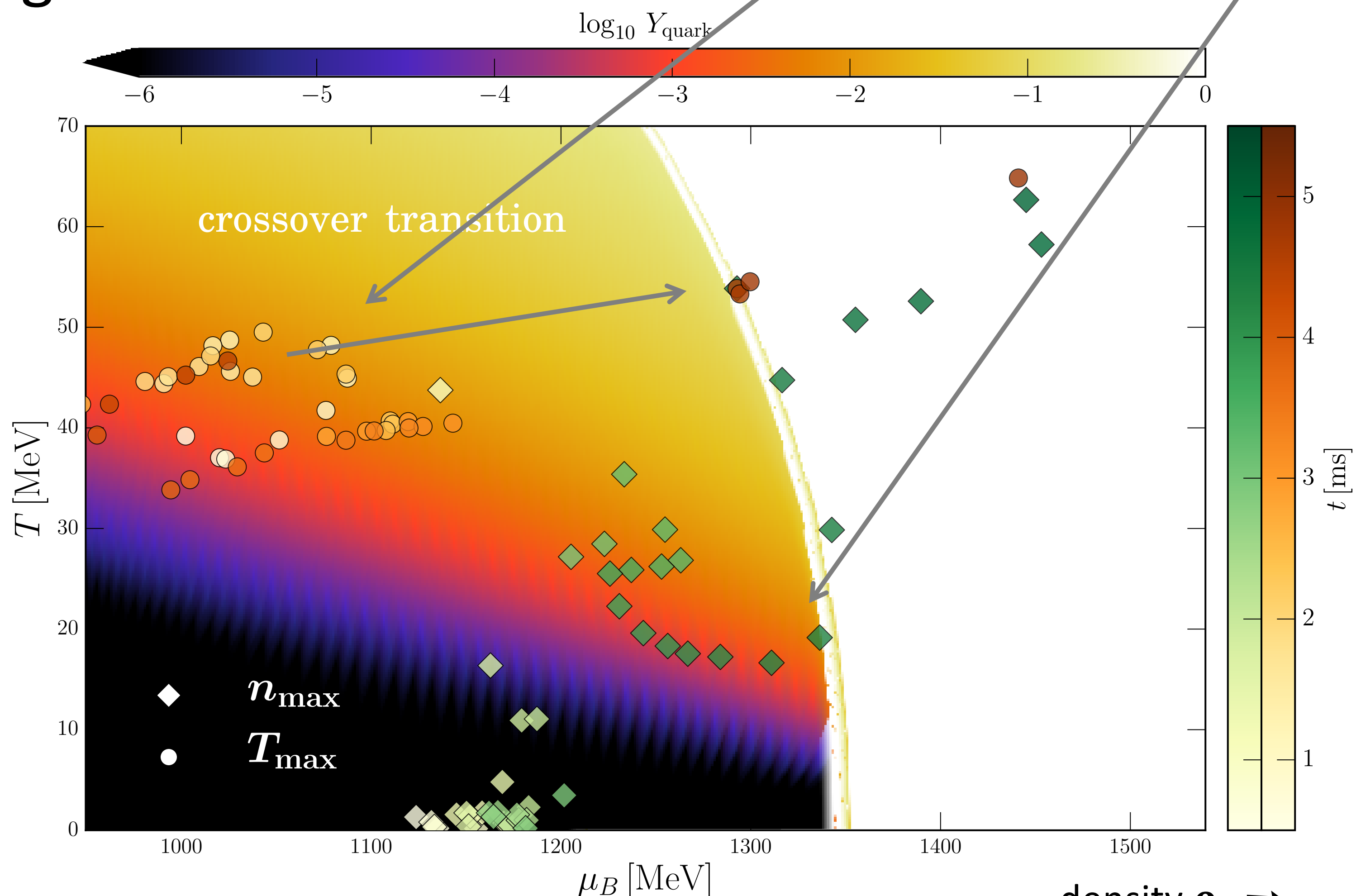
- 3D (T,n_B,Y_Q) CMF EoS with 1st order phase transition for binaries with final mass of 2.9 M_{Sun} after deconfinement (~5 ms) but before collapse to black hole



density ρ_B →

Merger in the QCD phase Diagram

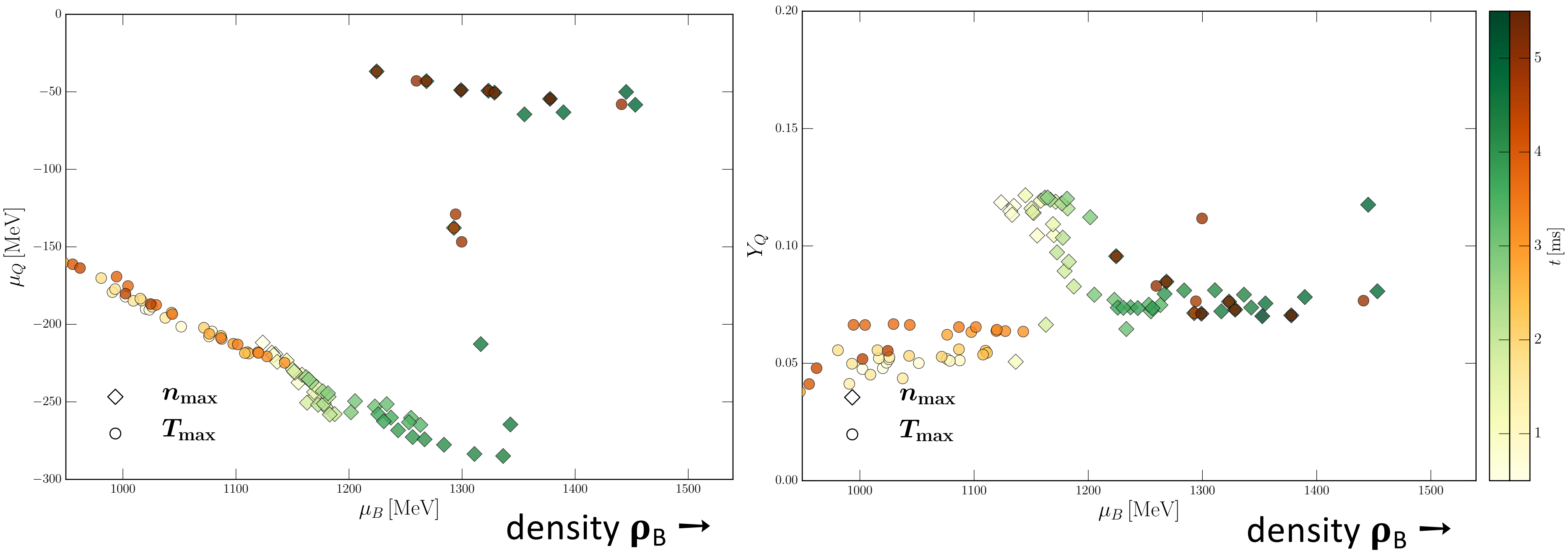
- Tracking maximum temperature ● and density ◆ in merger



density ρ_B →

More Phase Diagrams

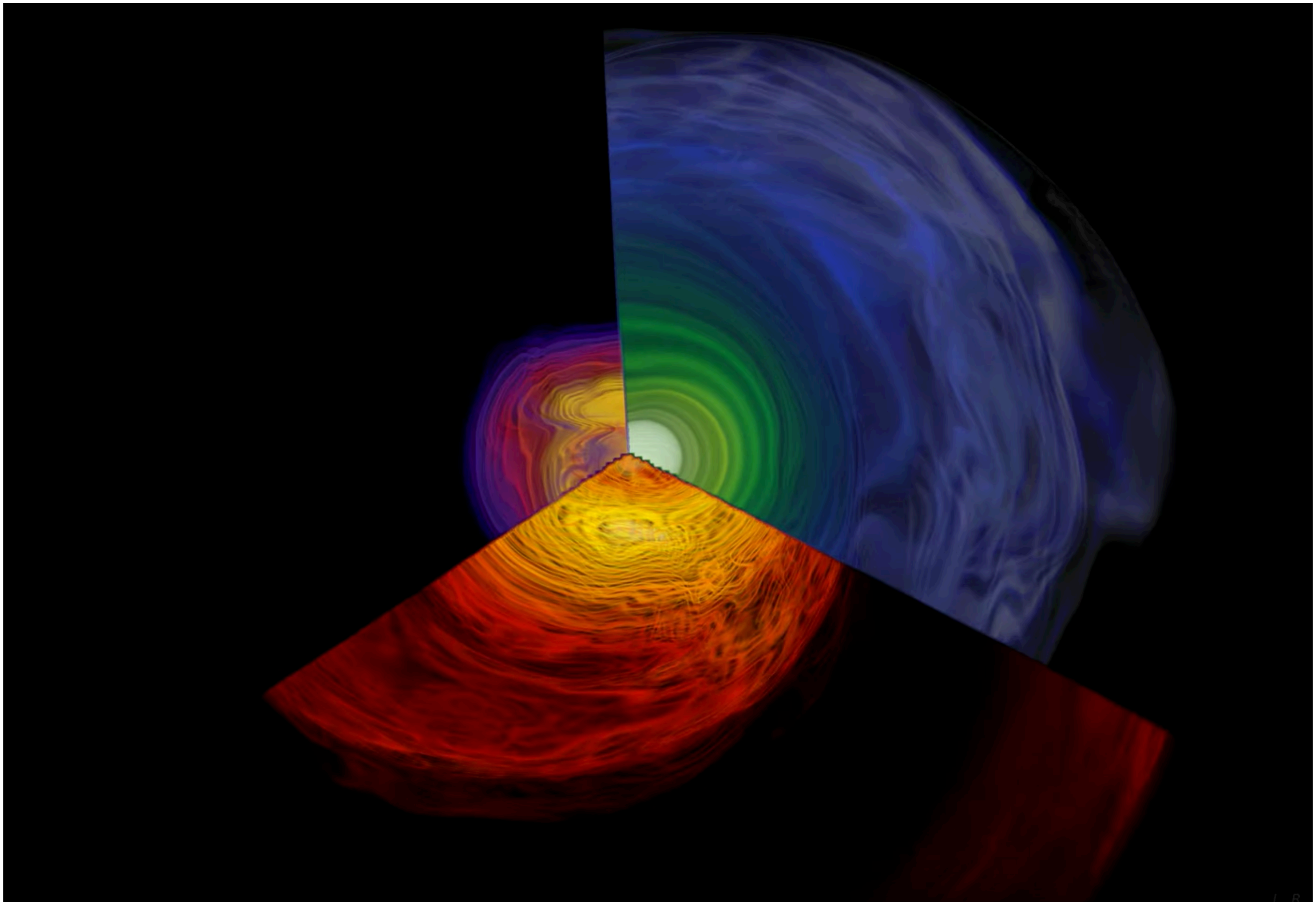
- Tracking maximum temperature ● and density ◆



- Increase in abs. value of charged chemical potential until phase transition, when it drops
- Decrease in charge fraction of core when quarks appear (not reaching heavy-ion/supernovae conditions)

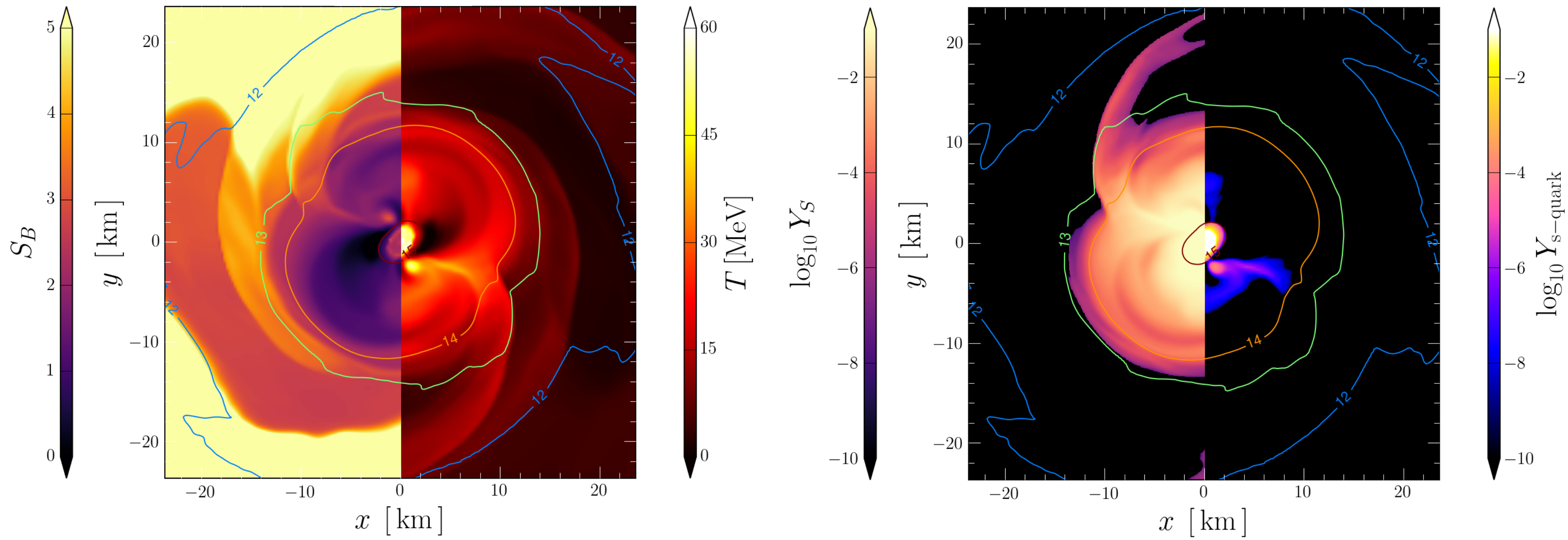
Simulation

- [Our simulation on Youtube]



Inside Hypermassive Neutron Star

- At 5 ms after merger



- Increase of temperature, entropy per baryon, and s-quark fraction at phase transition
- Total strangeness (hyperons ➜ s-quarks) remains ~ same

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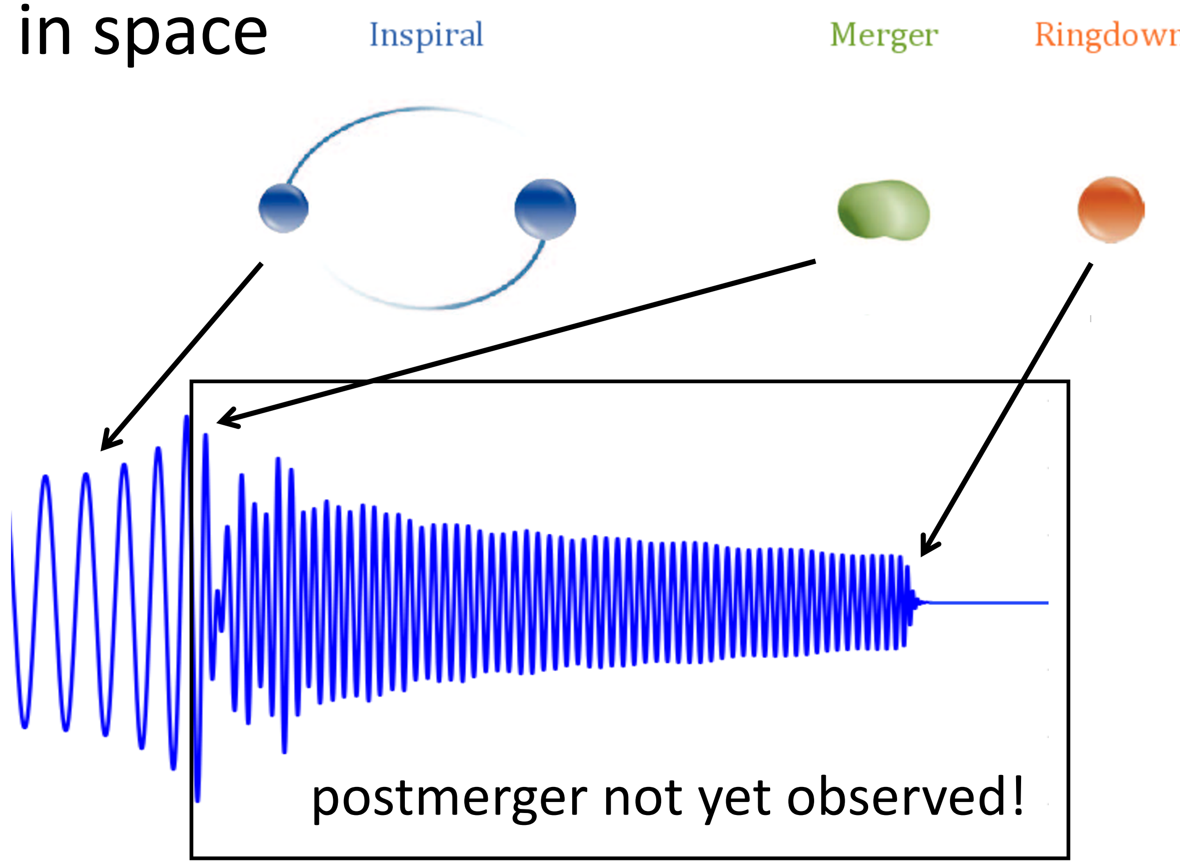
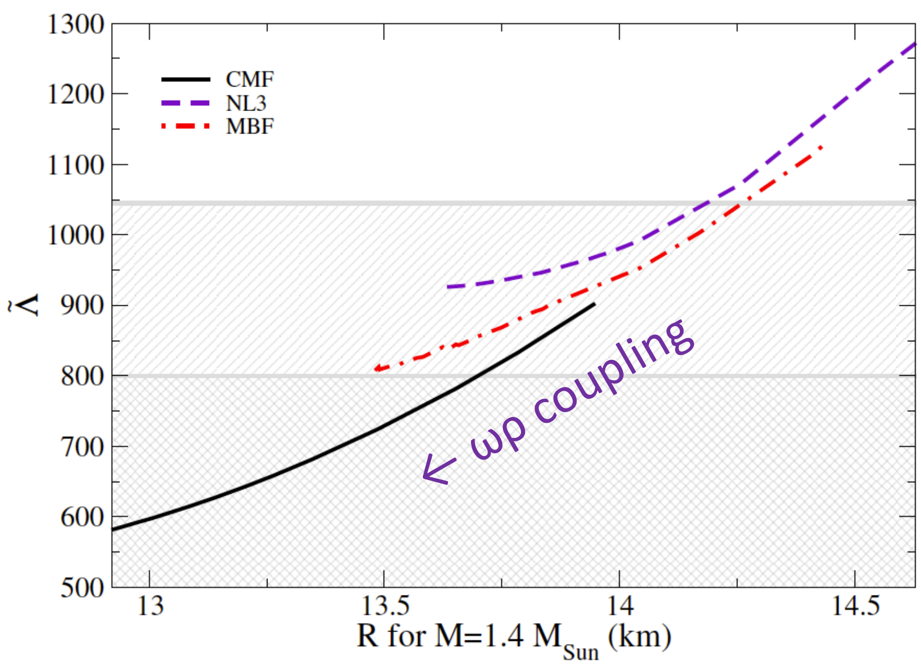


What have we learned from GW170817?

- Tidal deformability (finite-size effects in end of inspiral): 76 $\rightarrow$ 1045 with 90% confidence (De et. al 2018)
- New vector-isovector channel that can be added to any model

$$L_{\omega\rho} = g_{\omega\rho} g_\omega^2 g_\rho^2 \omega_\mu \omega^\mu \boldsymbol{\rho_\mu \rho^\mu}$$

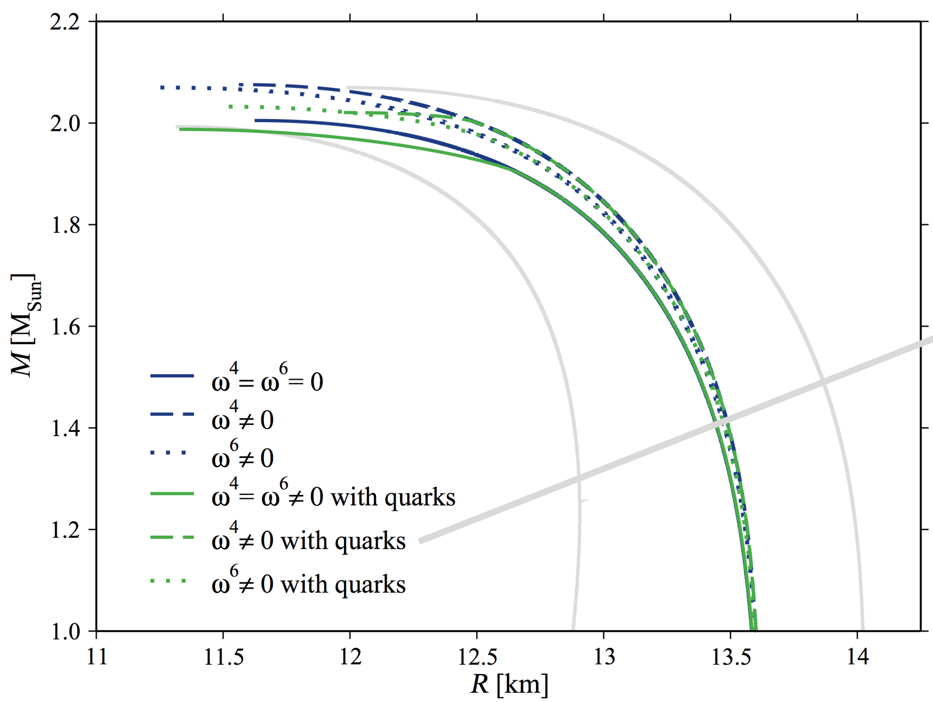
ωρ coupling

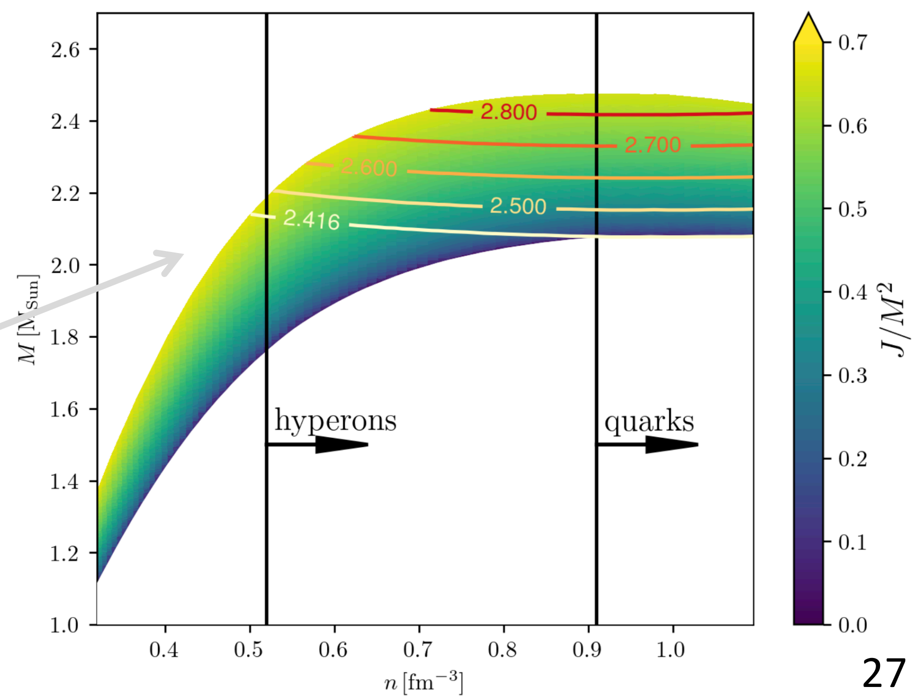


- Results in better agreement with Effective Field Theory calculations for low densities

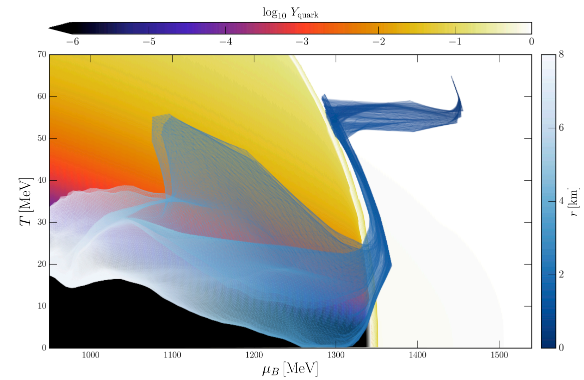
What have we learned from GW190814?

- Merger of $23.2^{+1.1}_{-1.0}$ M_{Sun} black hole and a $2.59^{+0.08}_{-0.09}$ M_{sun} "?"
- New vector interactions increase masses to ~2.1 M_{sun}
- With phase transitions, rotation close to the Kepler frequency reproduces ~2.5 M_{sun} stars with hyperons and quarks





Conclusions and Outlook



- Astrophysics provides an ideal testing ground for nuclear physics
- Conditions created in neutron-star mergers are unique (Y_Q, Y_I, Y_S, leptons, …)
- Y_Q, Y_I affect significantly the deconfinement to quark matter: μ_B can change by up to 130 MeV and $\mu_{Q,I}$ by up to 330 MeV
- Now, we can also see the universe through gravitational waves so, maybe, there will be a clear first signature for quark deconfinement phase transition from astrophysics!
- More realistic models with temperature/exotic degrees of freedom needed to study
  - relation between tidal deformability and nuclear physics
  - realistic neutron-star merger simulations