Exotic Matter Produced in Neutron-Star Mergers

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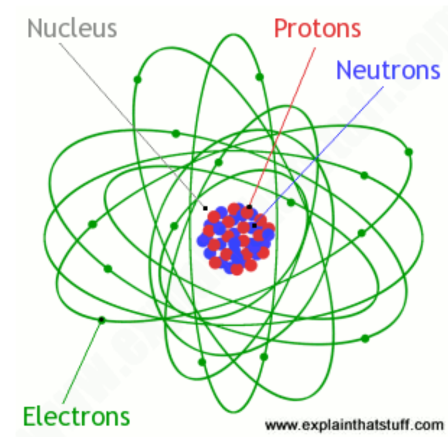
KENT STATE UNIVERSITY

PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

NSF

Neutron-Star Core Modelling

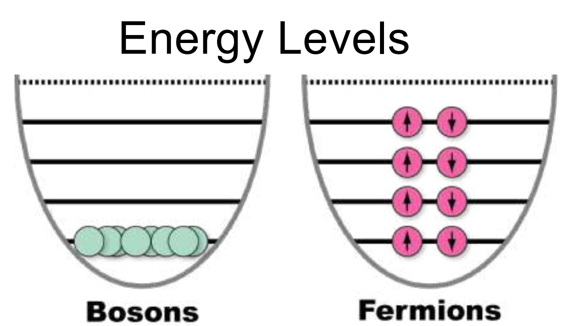
- Landau predicted giant nuclei formed when normal nuclei come in close contact at great density and "laws of ordinary quantum mechanics break down" in 1931



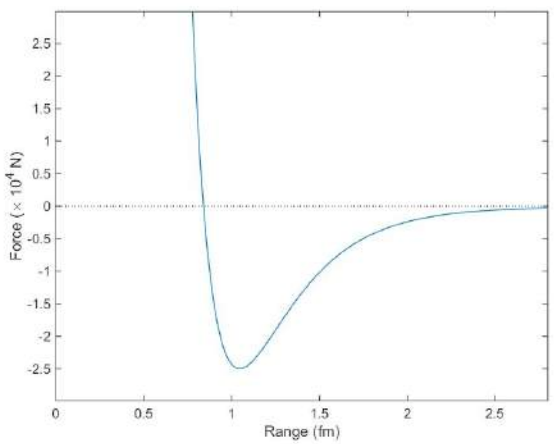
- Chadwick discovered neutron in 1932

- 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

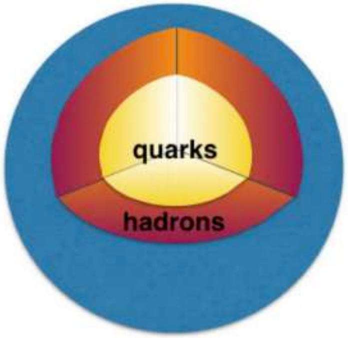
- Higher-order interactions added to better reproduce nuclear saturation properties by Boguta and Bodmer in 1977

- Hyperons included in modeling by Glendenning in 1979

- Negative parity baryons studied in stars by VD in 2008

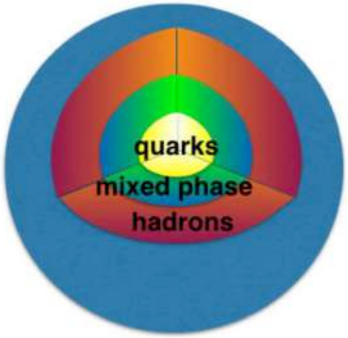
Neutron-Star Core Modelling

- 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

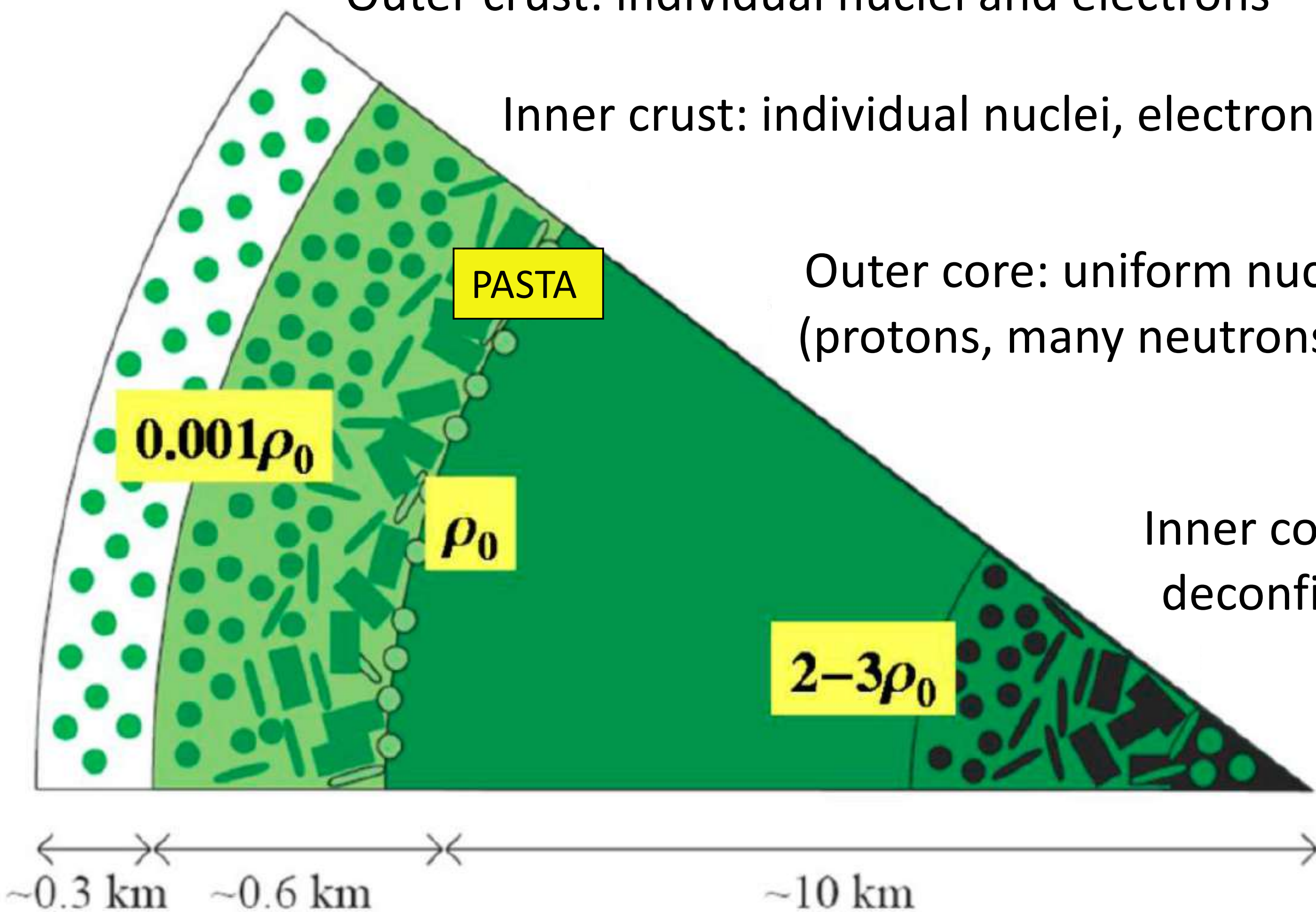
Neutron-Star Structure

Outer crust: individual nuclei and electrons

Inner crust: individual nuclei, electrons, and neutrons

Outer core: uniform nuclear matter (protons, many neutrons, electrons)

Inner core: hyperons, deconfined quarks?



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

CMF (Chiral Mean Field) Model

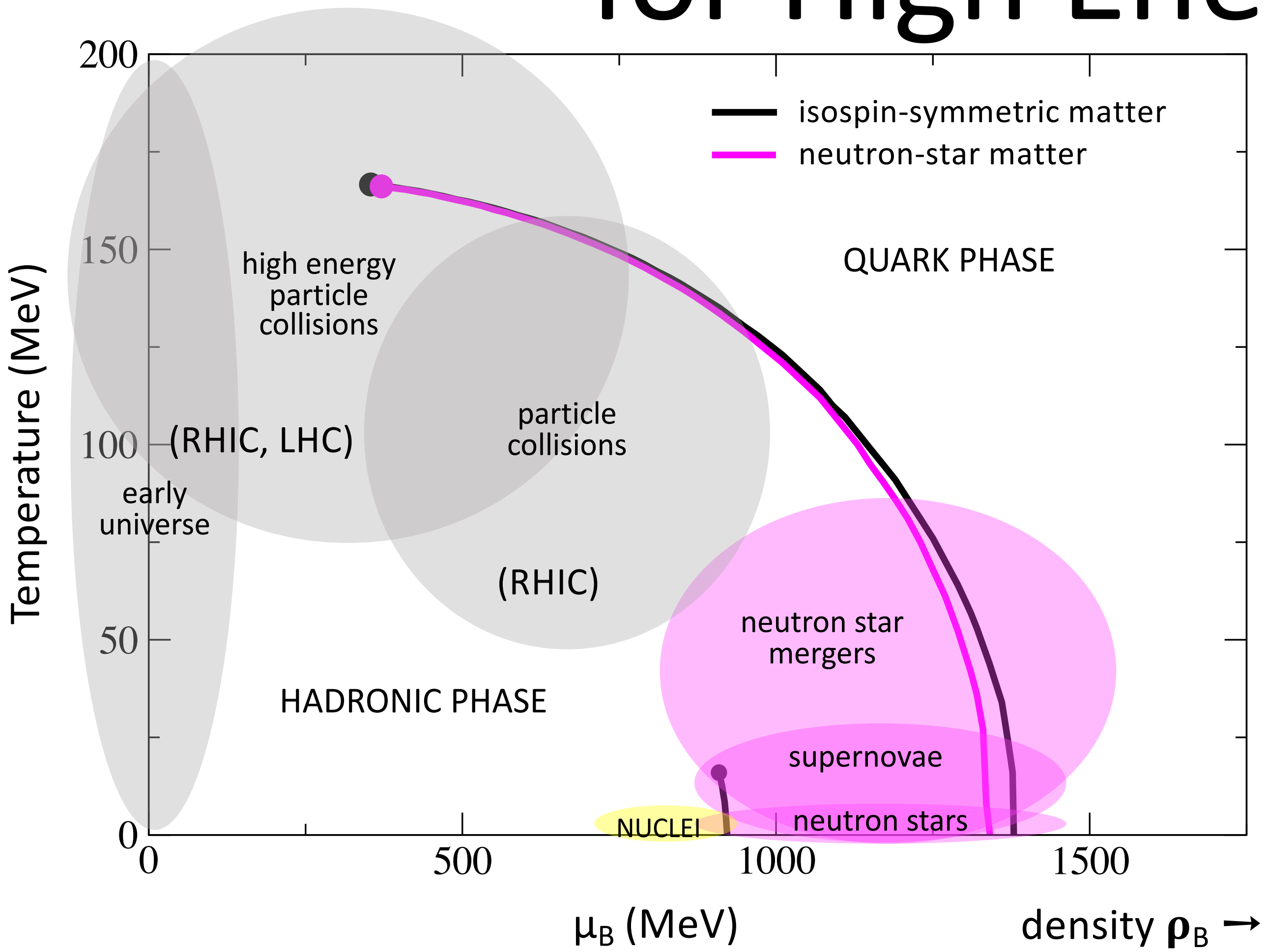
- Non-linear realization of the linear sigma model
- Includes baryons (+ leptons) and quarks
- Fitted to reproduce nuclear, astrophysical, lattice QCD
- Baryon and quark effective masses

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

- 1st order phase transitions or crossovers
- Potential for **Φ** deconfinement order parameter

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

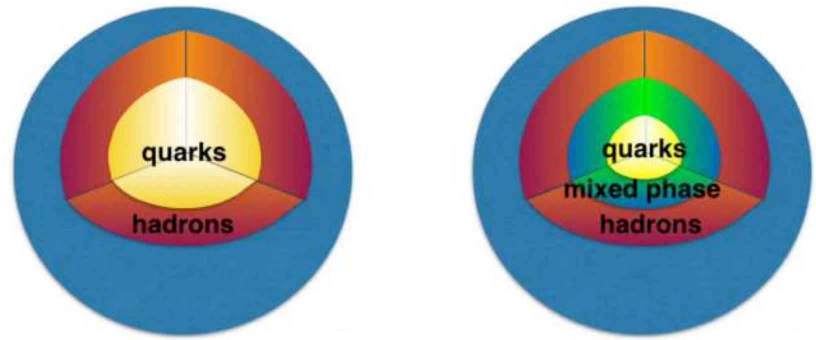
QCD Phase Diagram for High Energy

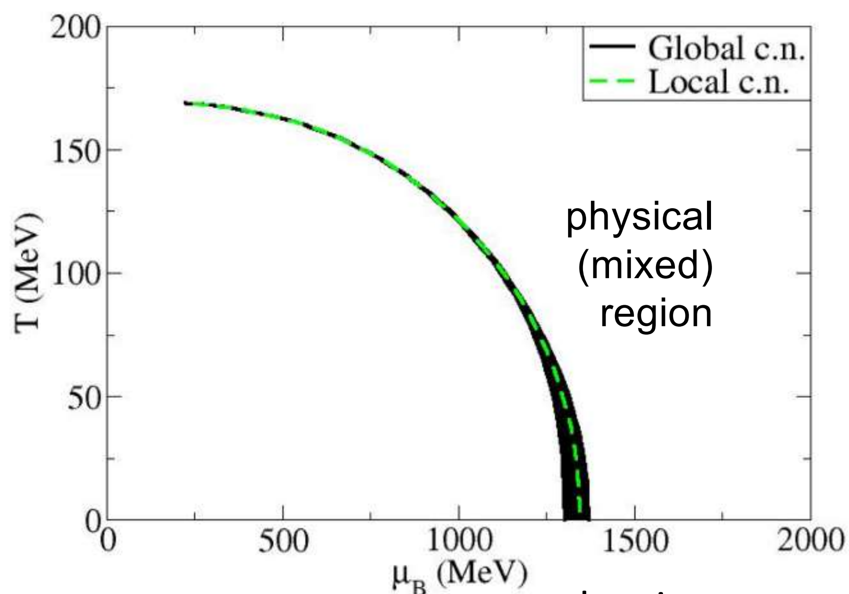


- Results from the CMF model

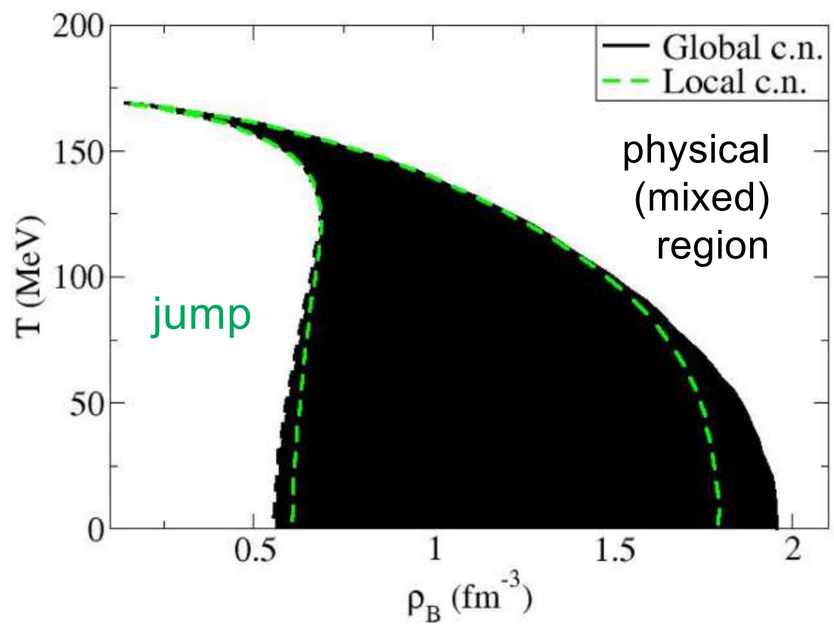
Local vs Global Charge Neutrality

- Absence / presence of mixture of phases: surface tension ???
- "Mixed" quantities like baryon number density



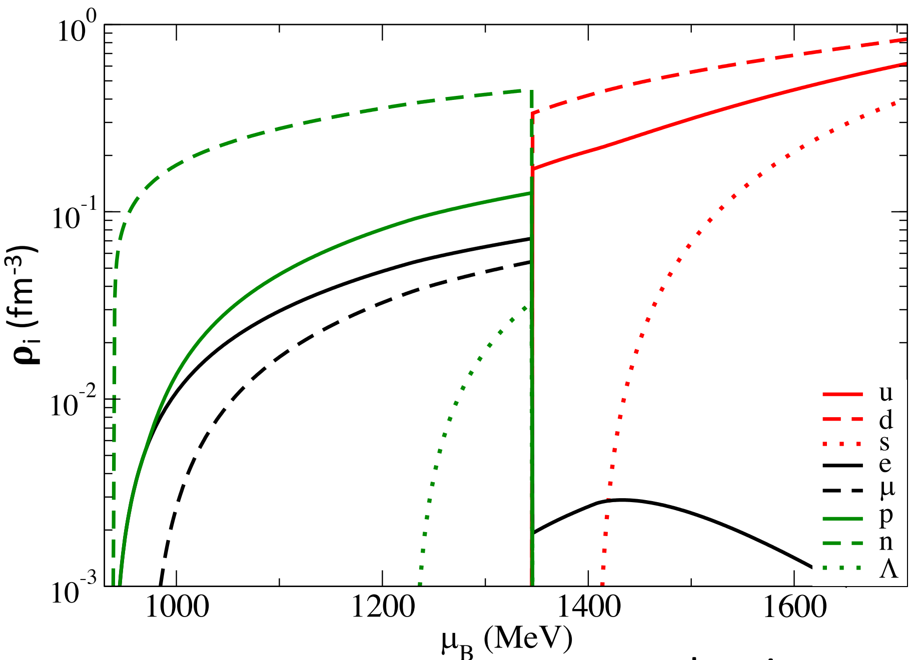


density $\boldsymbol{\rho}_B$ →



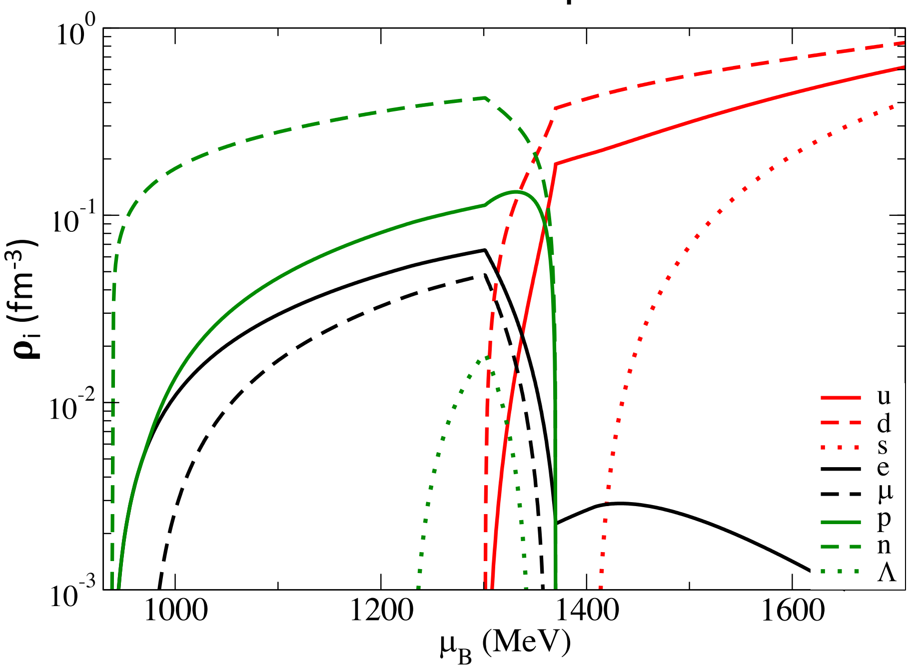
Particle Population from Model

- Hadronic phase: hadrons (neutrons, protons, and Λ hyperons) plus electrons and muons
- Quark phase: quarks (up, down, and strange) plus electrons



density ρ_B →

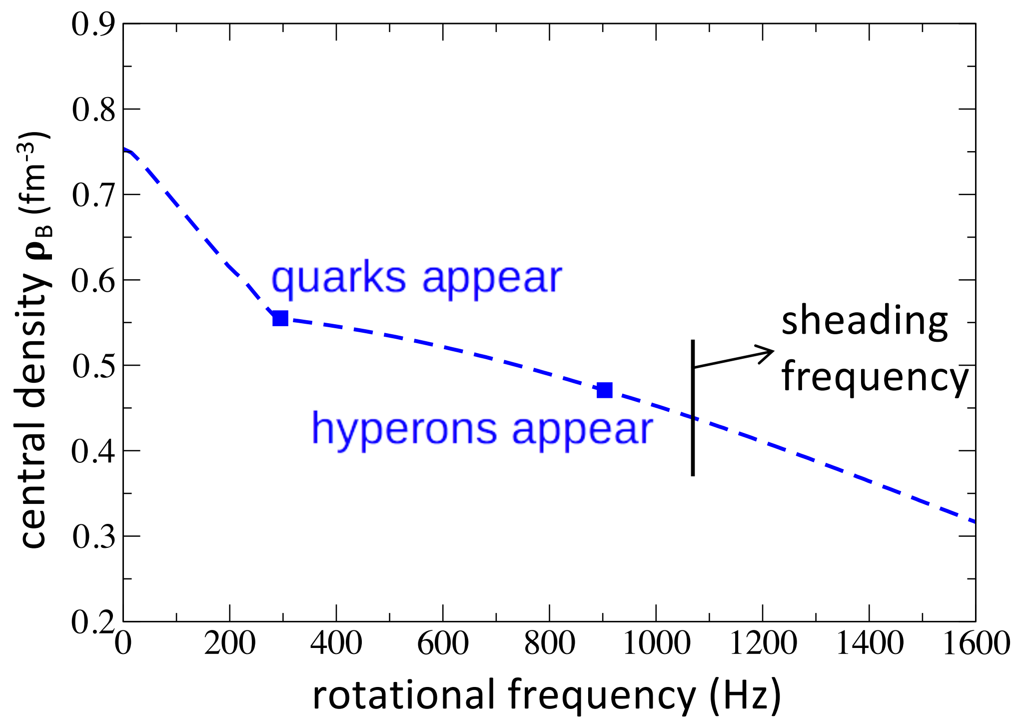
with mixture of phases



density ρ_B →

Stellar Central Density

- Modified General Relativity equations for deformed stars predict lower central stellar density for larger rotational frequencies (at fixed baryon number)
- As massive stars grow old new degrees of freedom appear
- Larger central densities present in mixed phase



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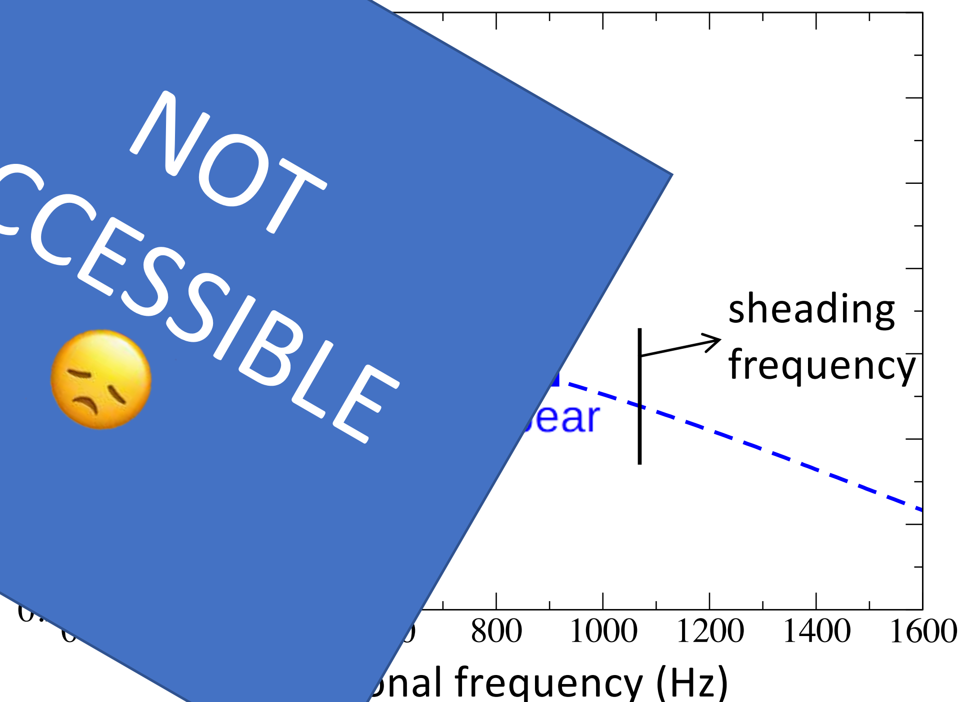
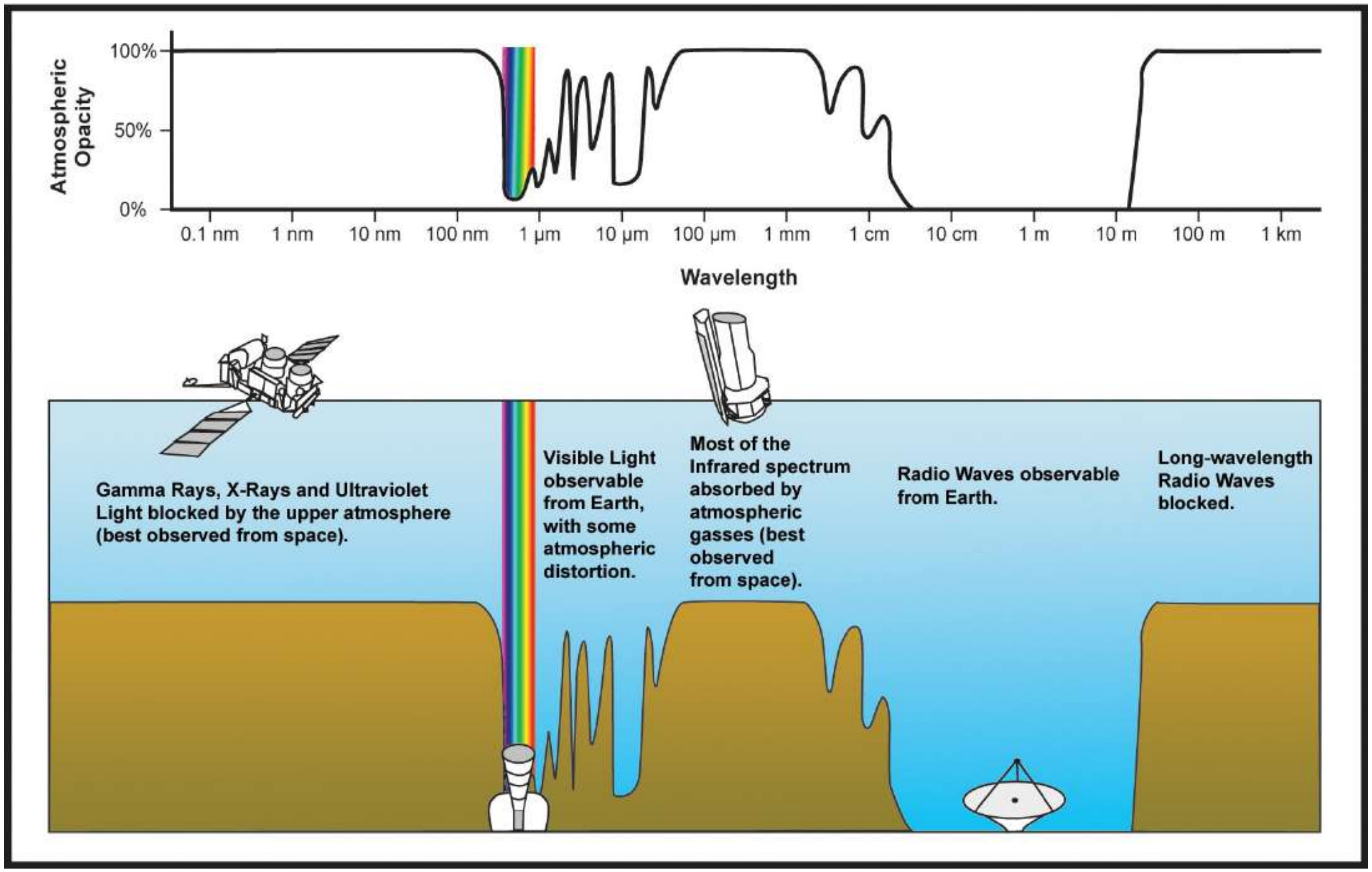
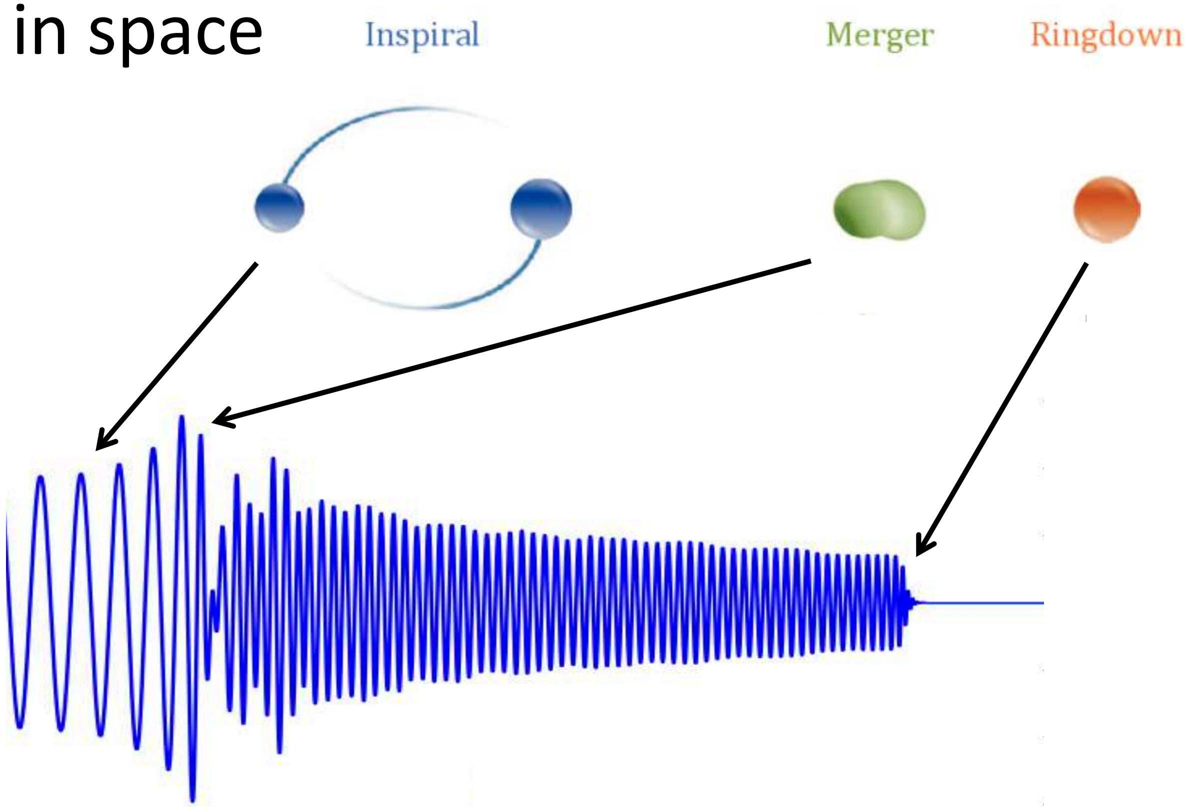


But How Can We Probe the Interiors of Neutron Stars?



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



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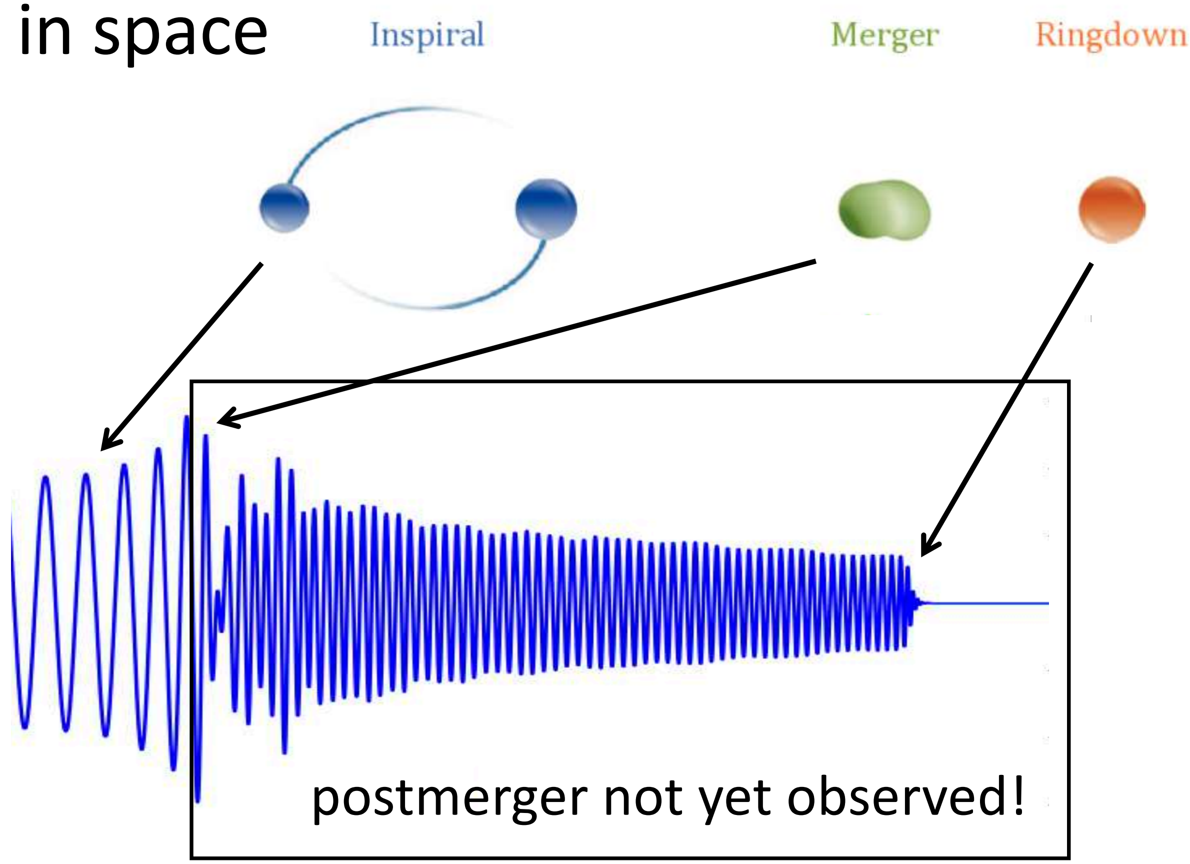
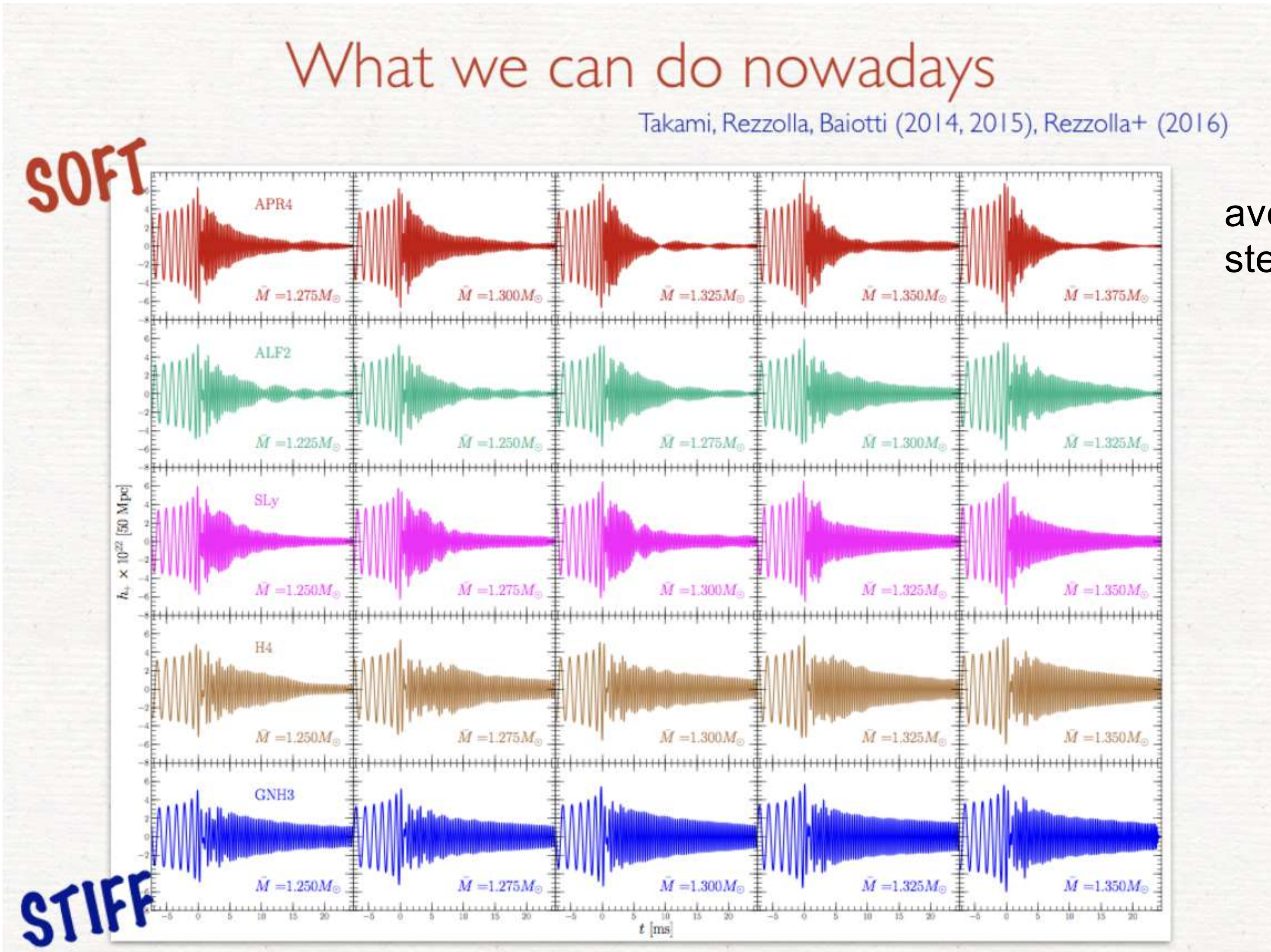


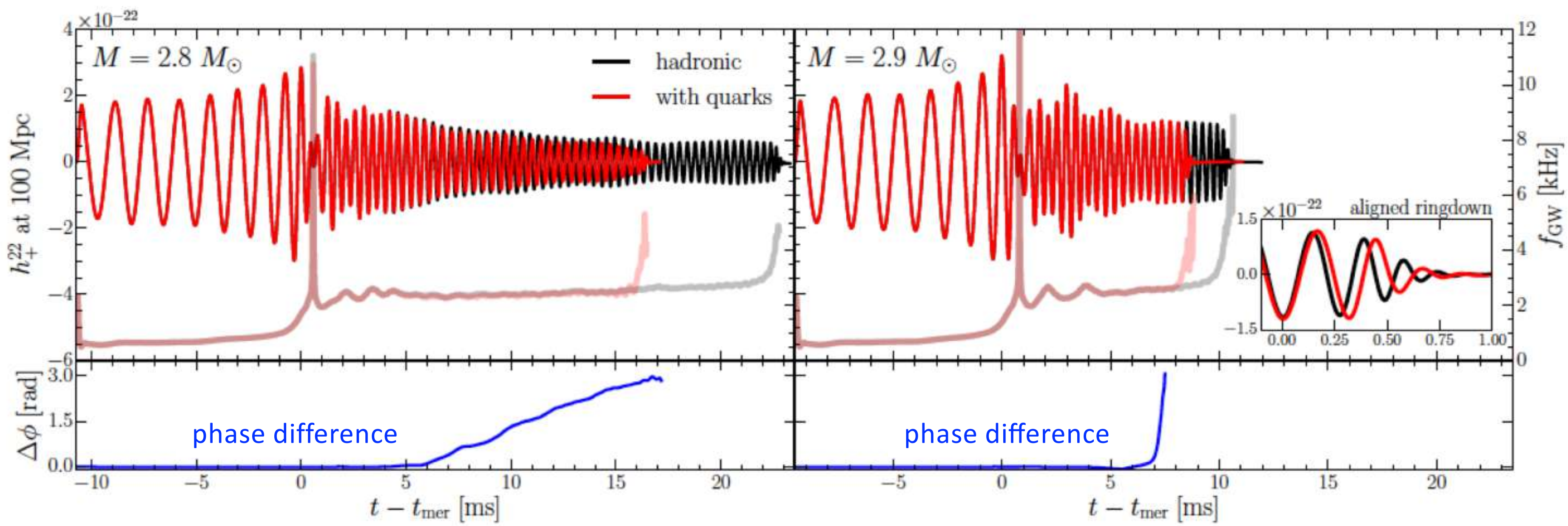
Hadronic Merger Simulations



average
stellar mass

Merger Simulation with Deconf.

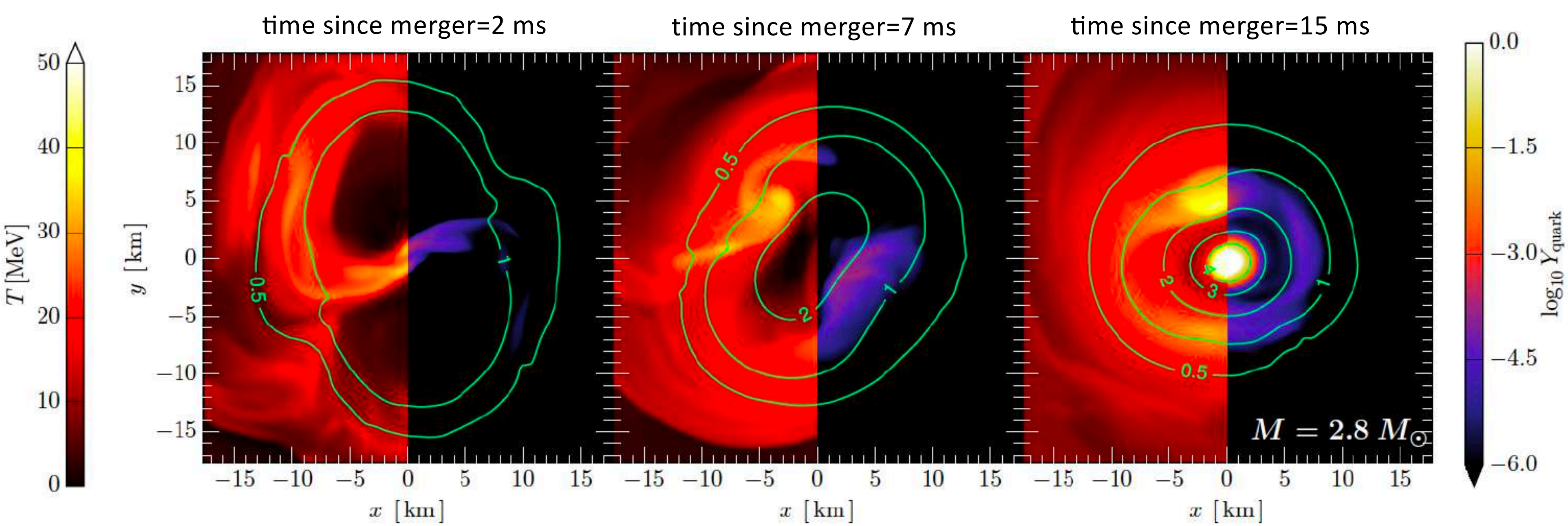
- 3D (T, $\boldsymbol{\rho}_B$,Y_c) CMF EoS with/without quarks
- Solve coupled Einstein-hydrodynamics system using Frankfurt/IllinoisGRMHD code (FIL)
- Interesting results for final masses of 2.8 and 2.9 M_{sun}



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

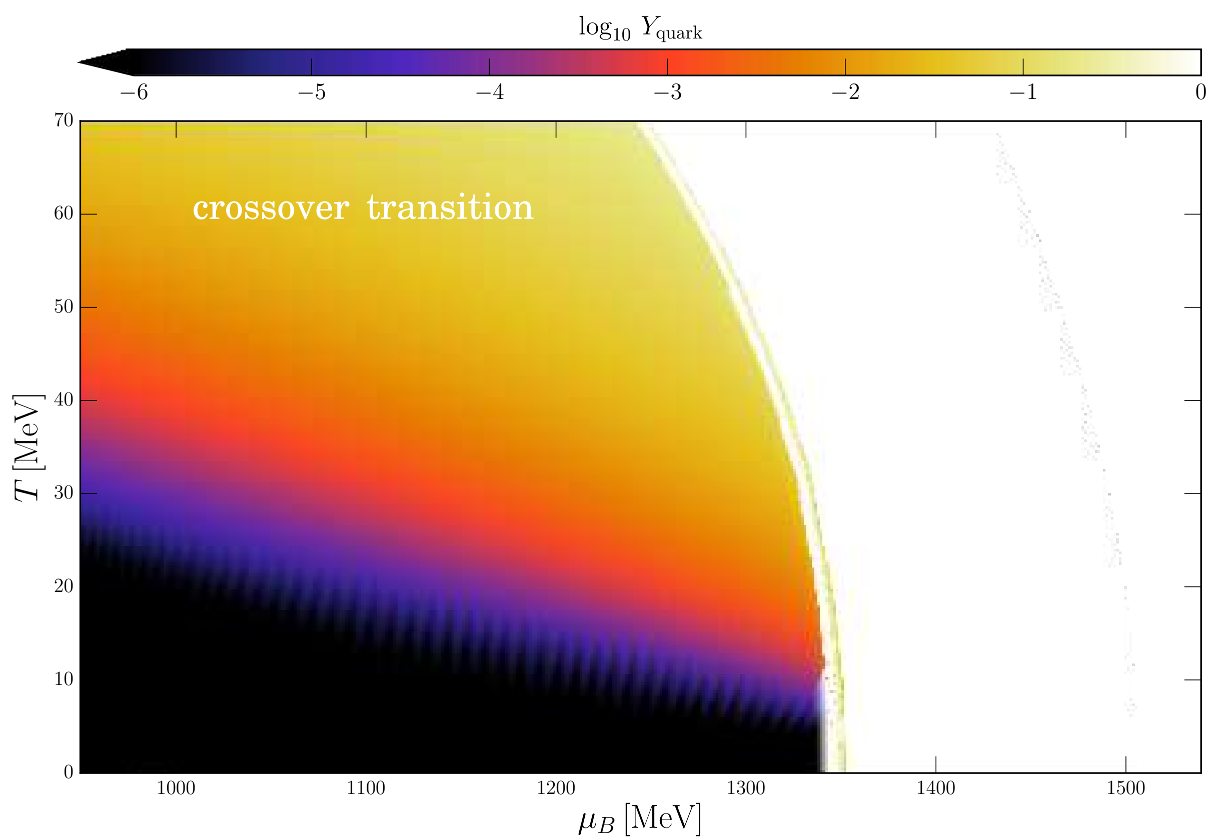
Inside the Neutron-Star Merger

- 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

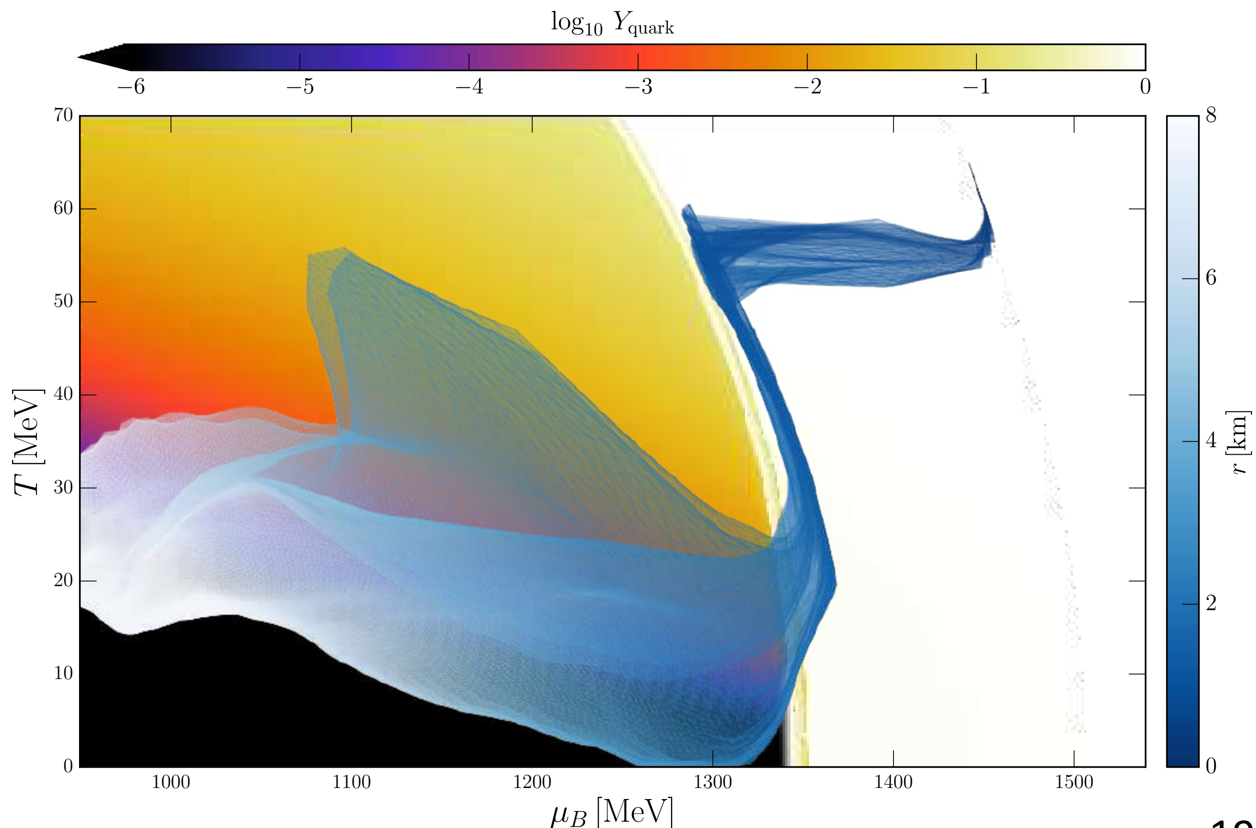
- Background: 2D (T,n_B) CMF EoS with 1^{st} order phase transition for Y_Q=Q/B=0.05



density $\boldsymbol{\rho}_B$ →

Merger in the QCD Phase Diagram

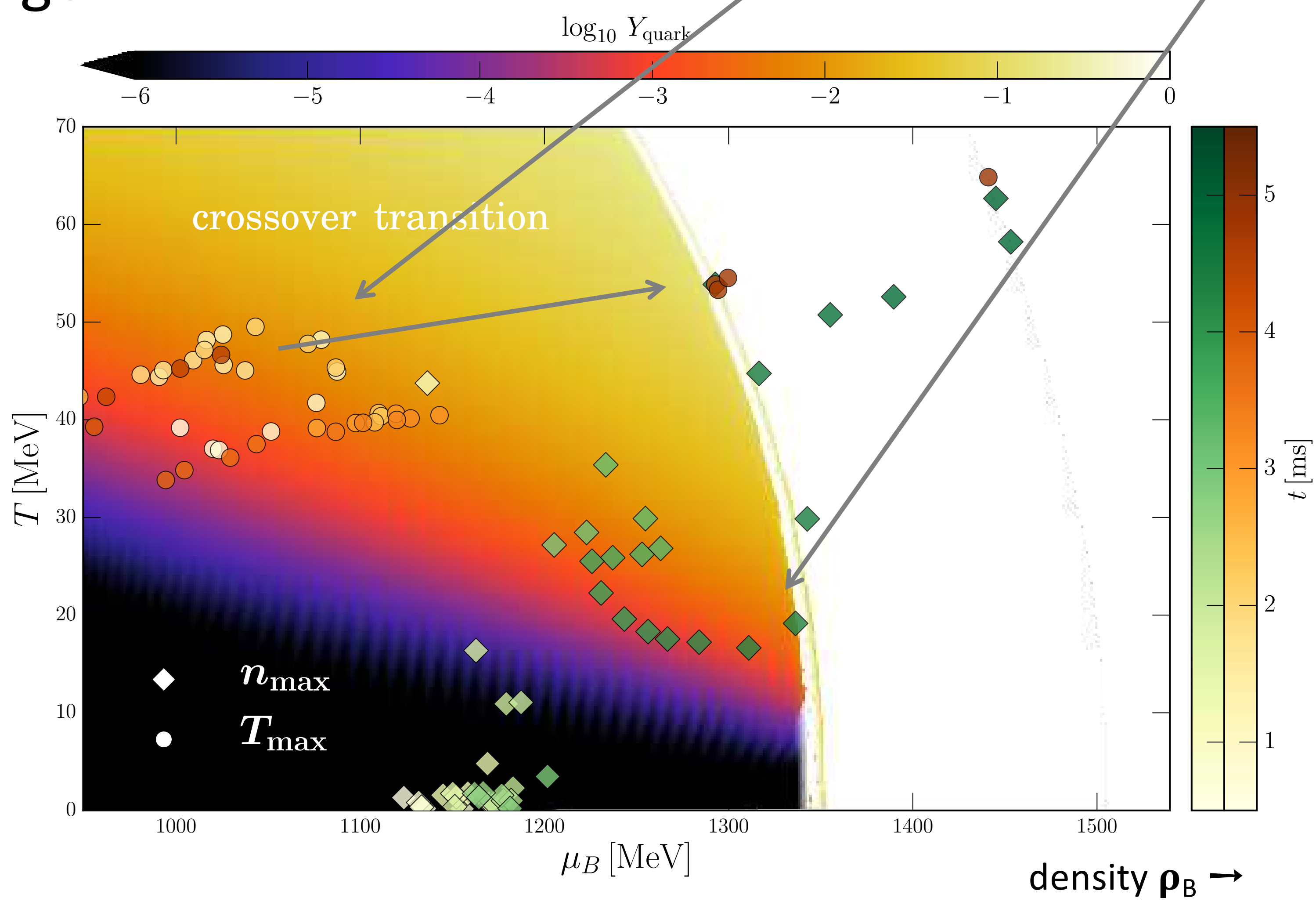
- 3D (T,n_B,Y_Q) CMF EoS with 1st order phase transition for binaries with final mass of 2.9 M_{Sun} after deconfinement (~5 ms) but before collapse to black hole



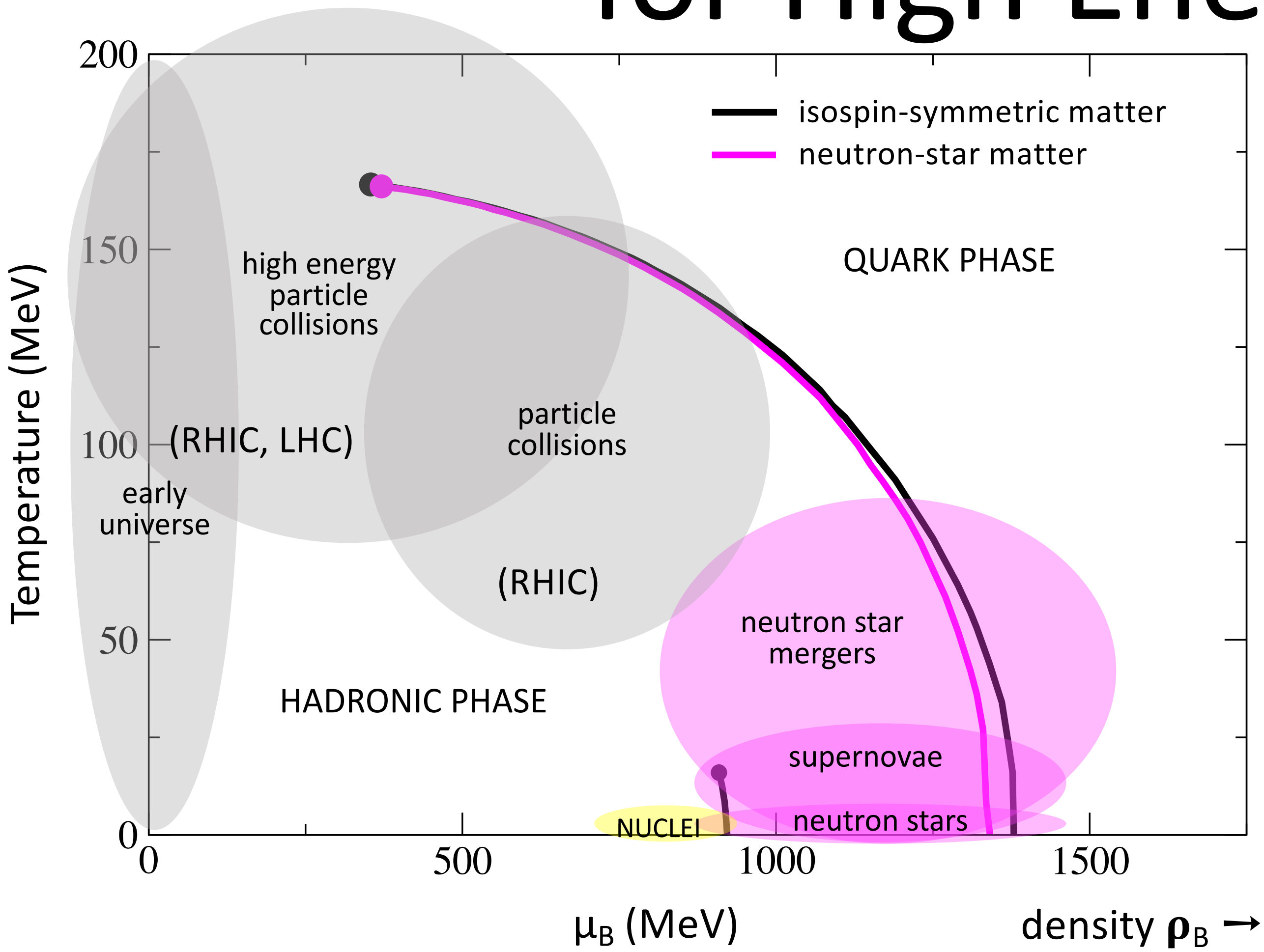
density $\boldsymbol{\rho}_B$ →

Merger in the QCD phase Diagram

- Tracking maximum temperature ● and density ◆ in merger



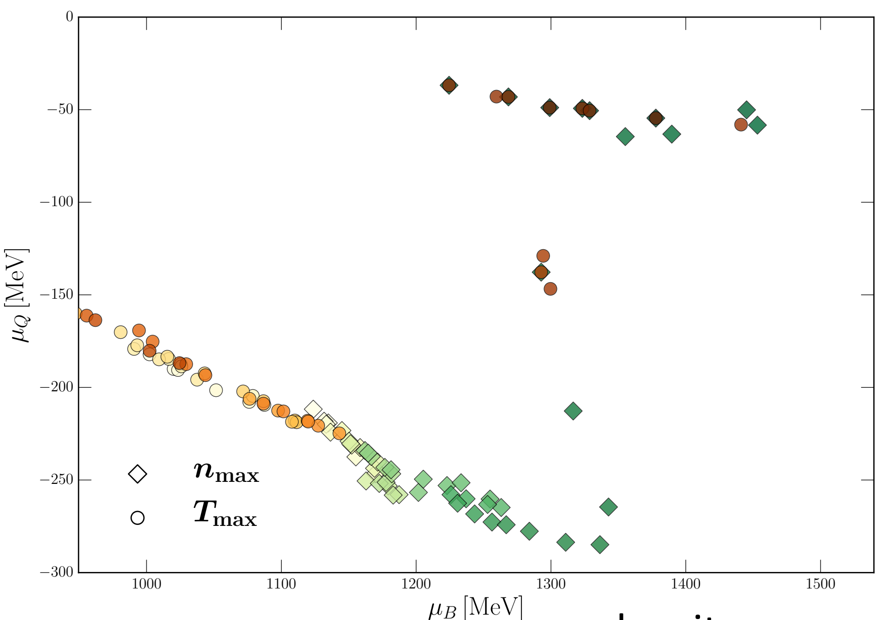
QCD Phase Diagram for High Energy



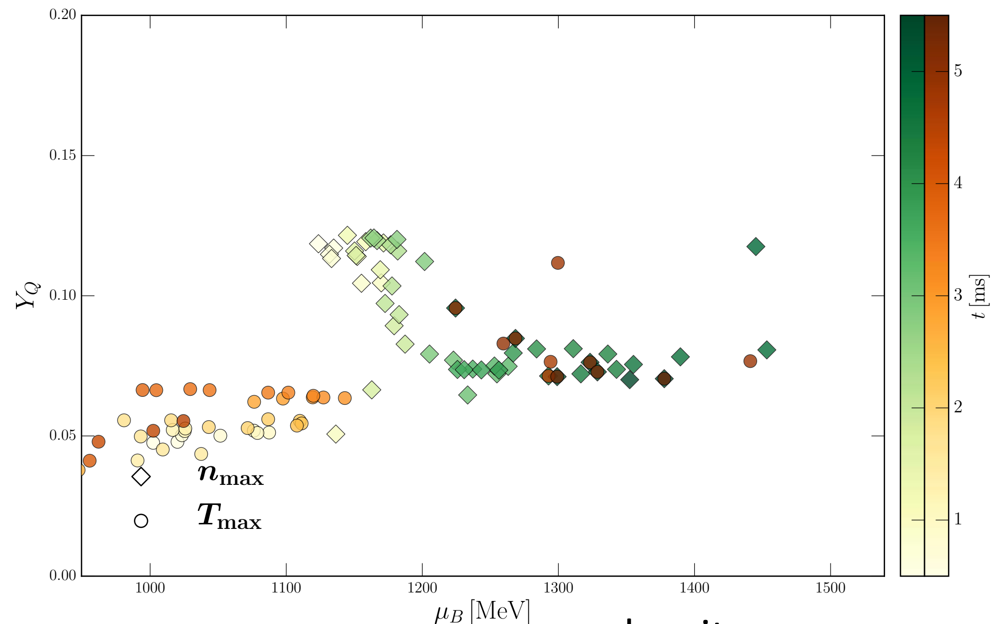
- Results from the CMF model

More Phase Diagrams

- Tracking maximum temperature ● and density ◆



density ρ_B ⟶



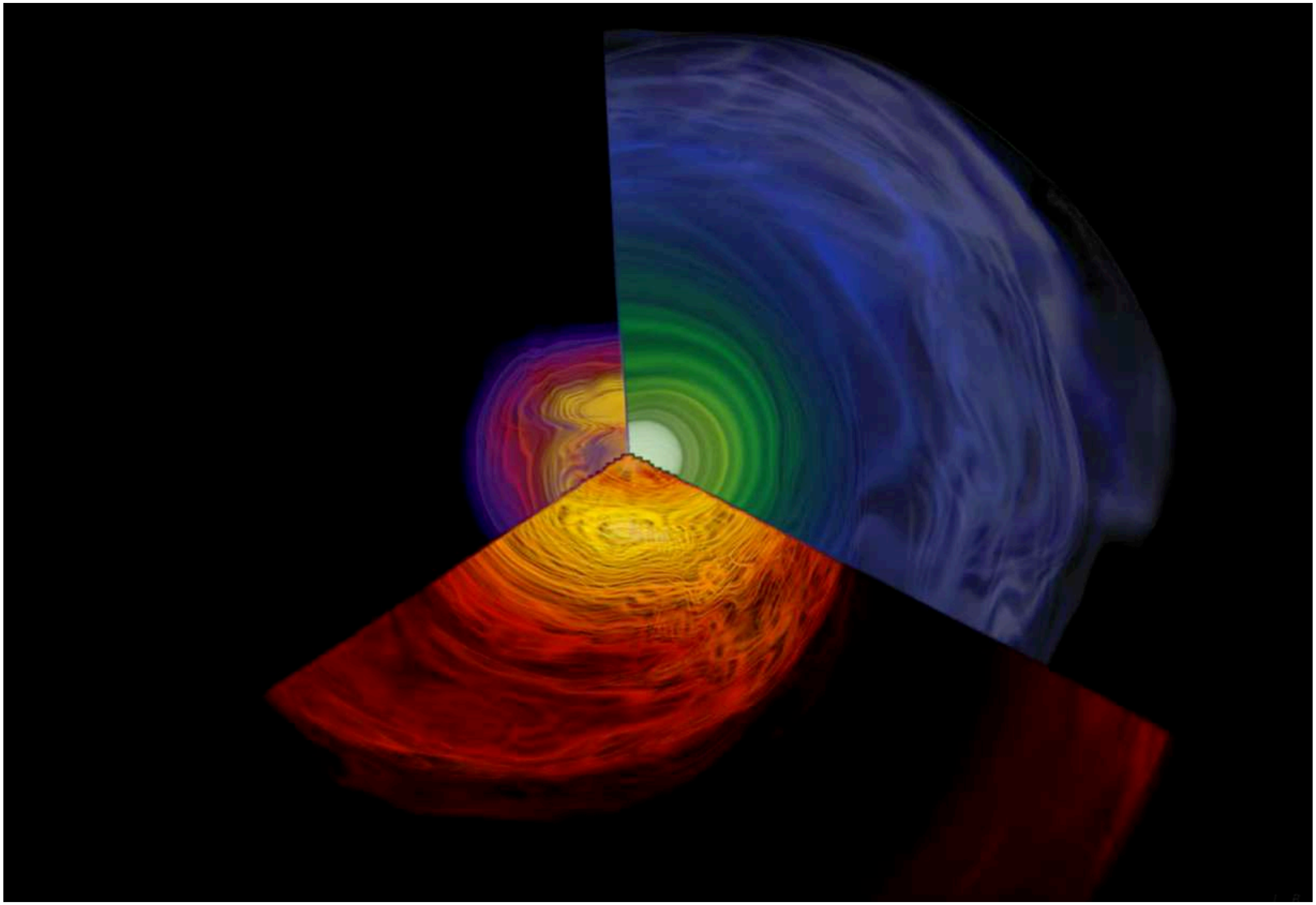
density ρ_B ⟶

- 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)

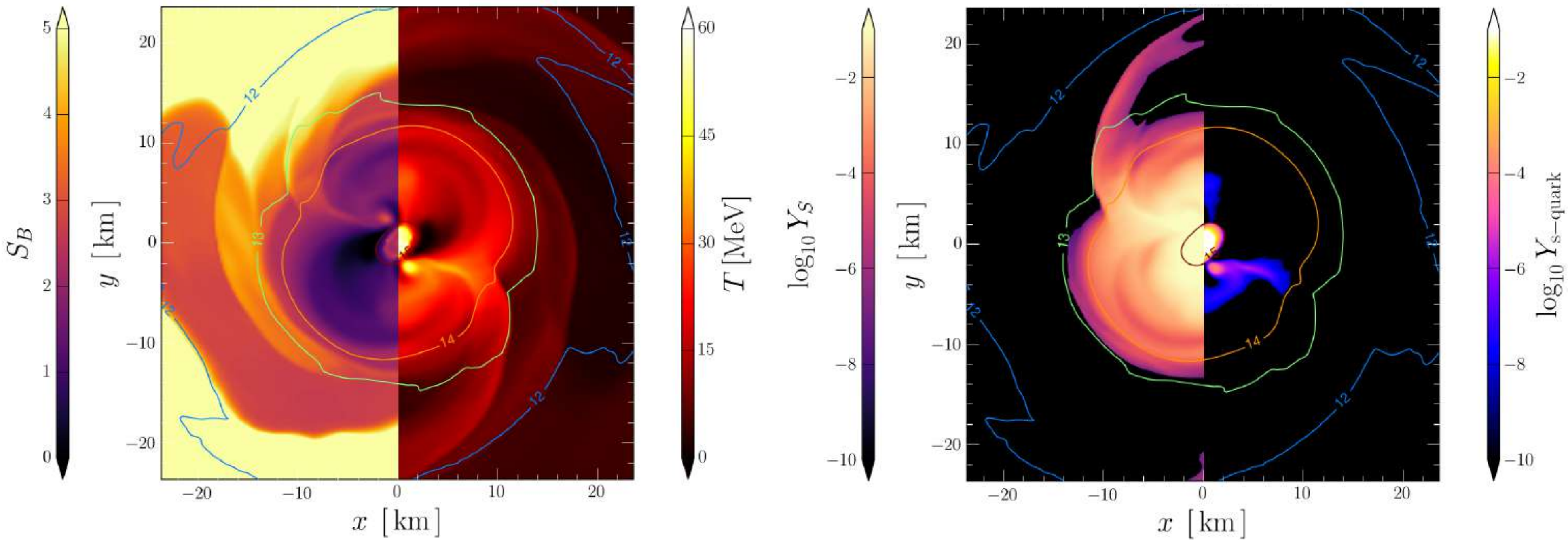
Simulation

- 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

Neutron Star Merger 170817

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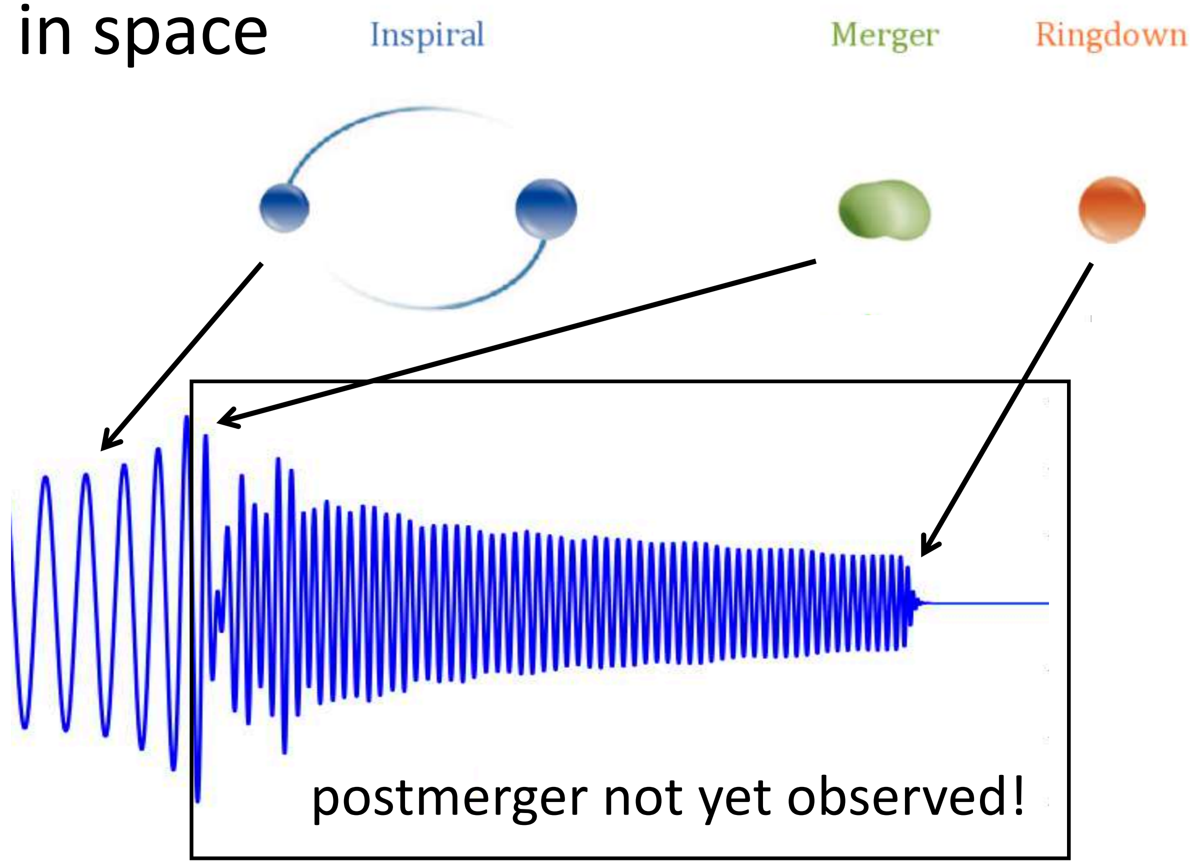
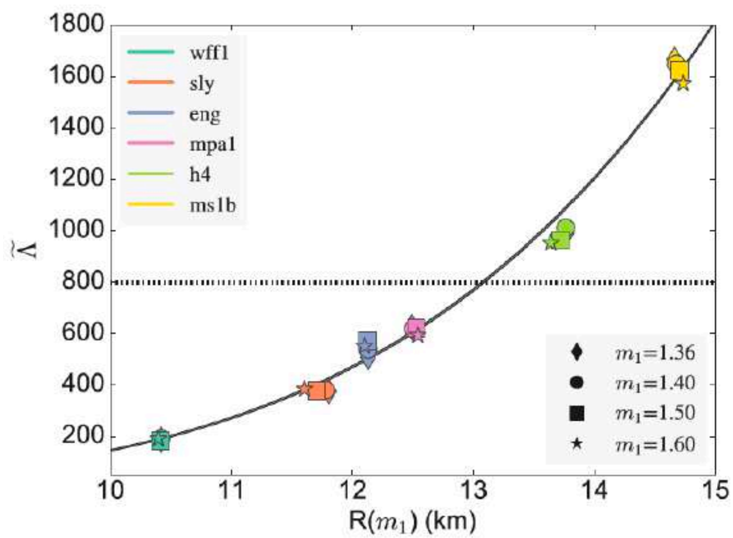


Tidal Deformability

- Normalized stellar quadripole deformation by companion

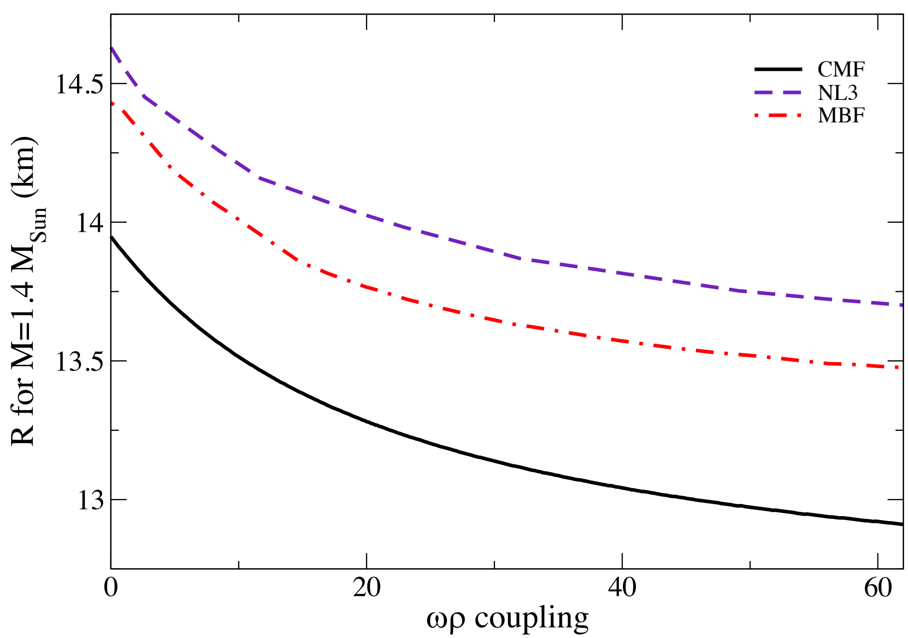
- Calculated from finite-size effects in end of inspiral:
  76 $\rightarrow$ 1045 with 90% confidence (De et. al 2018)
- Related to NS radius of $M=1.4\ M_{sun}$ (Raithel et. al 2018)
- Universal relation?

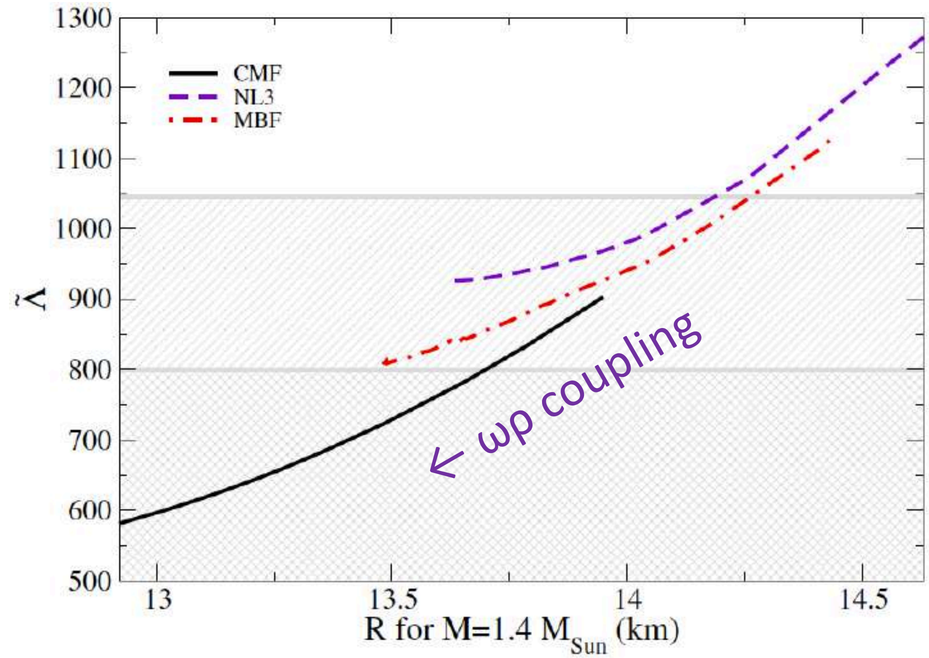


Exploring Isovector Coupling

- 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

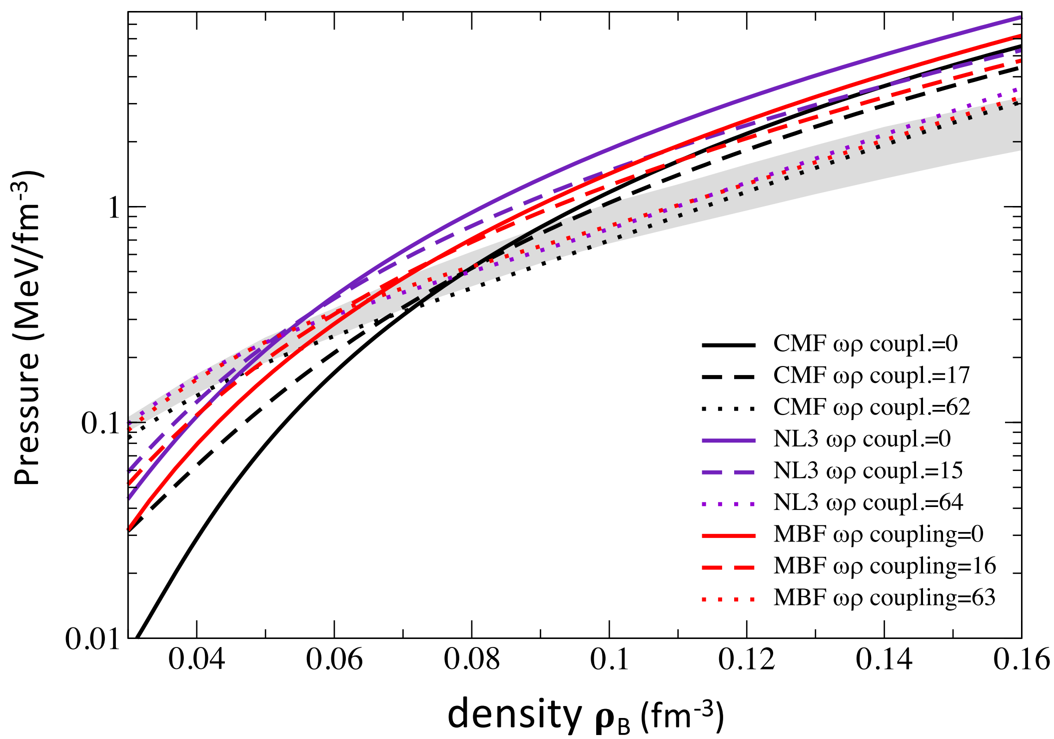




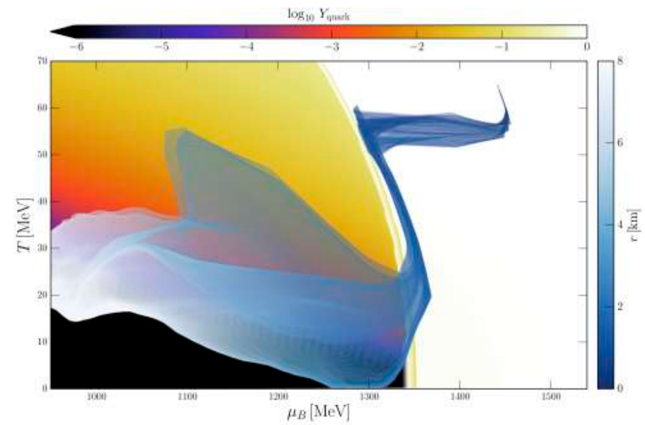
- Non-trivial relation between $\tilde{\Lambda}$ and $R_{1.4M_{Sun}}$

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



Conclusions and Outlook



- Astrophysics provides an ideal testing ground for nuclear physics
- Unique conditions created in neutron-star mergers
- Now, in addition to observe light, we can also understand the universe through gravitational waves
- More realistic models with temperature/exotic degrees of freedom needed to study
  - relation between tidal deformability and nuclear physics
  - realistic neutron-star merger simulations
- More merger data coming … so, maybe, there will be a clear first signature for quark deconfinement phase transition will from astrophysics!