QCD Phase Diagrams with Charge and Isospin Axes under Heavy-Ion Collision and Stellar Conditions

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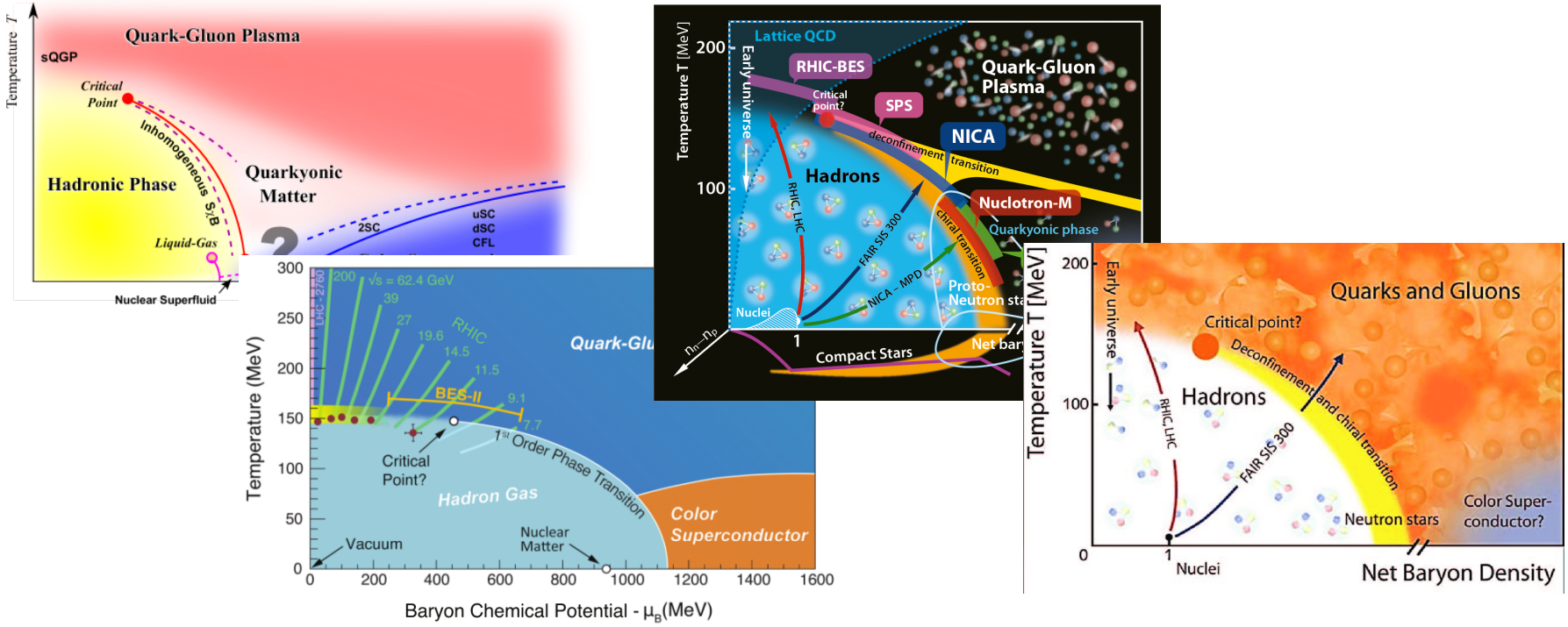
Main references:
Phys. Rev. D 102 (2020) 7, 076016, e-Print: 2004.03039
J. Phys. Conf. Ser. 1602 (2020) 1, 012013, e-Print: 2010.00996
For neutron-star mergers:
Phys. Rev. Lett. 122 (2019) 6, 061101, e-Print: 1807.03684
Eur. Phys. J. A 56 (2020) 2, 59, e-Print: 1910.13893

QCD Phase Diagram



- Phase diagrams with finite μ_B are usually shown in 2D
- How much are they affected by charge and isospin?
- How do charge and isospin quantities relate?
- How much are they affected by strangeness?

Chiral Mean Field (CMF) Model

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

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

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

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

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

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

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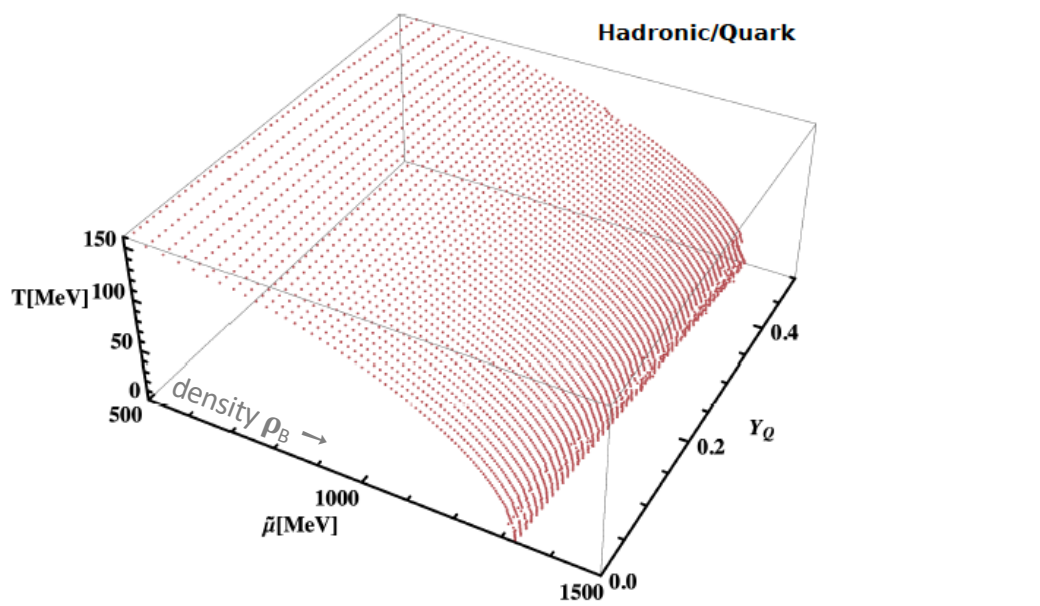
- Larger Y_Q (at fixed T) pushes the phase transition to larger $\widetilde{\mu}$
- Lower Y_Q (at fixed T) pushes the phase transition to lower $\widetilde{\mu}$!
- Changes due to Y_Q effects on the EoS (particle population) on each side



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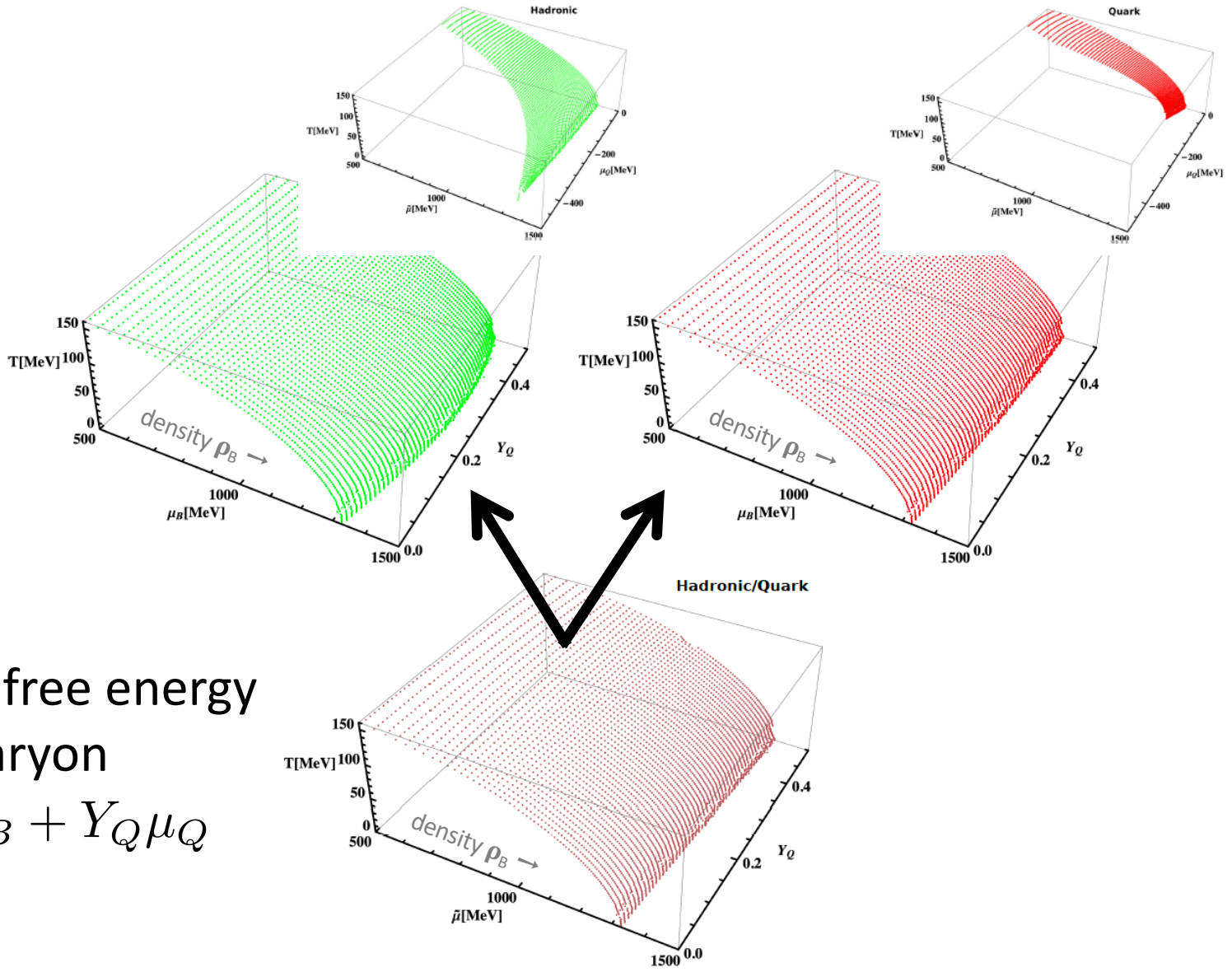
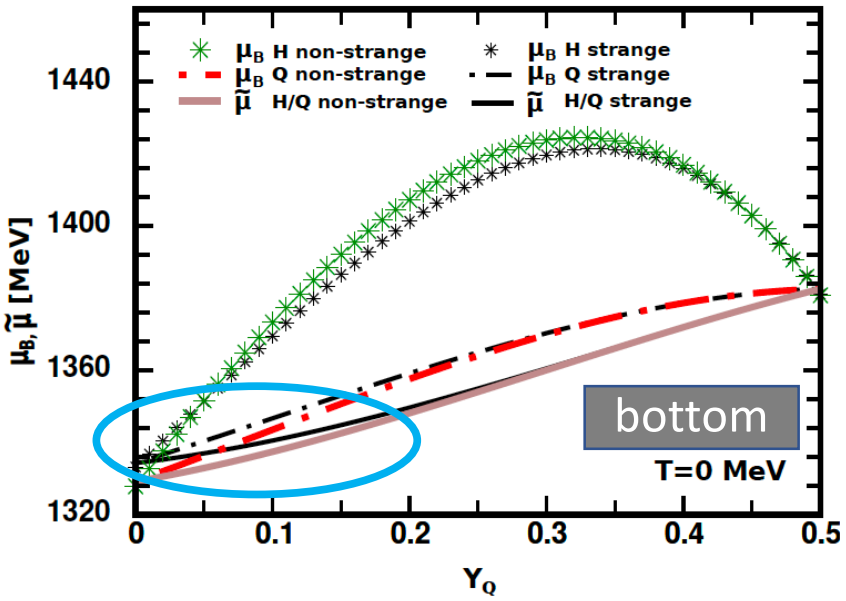


Gibbs free energy per baryon

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

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



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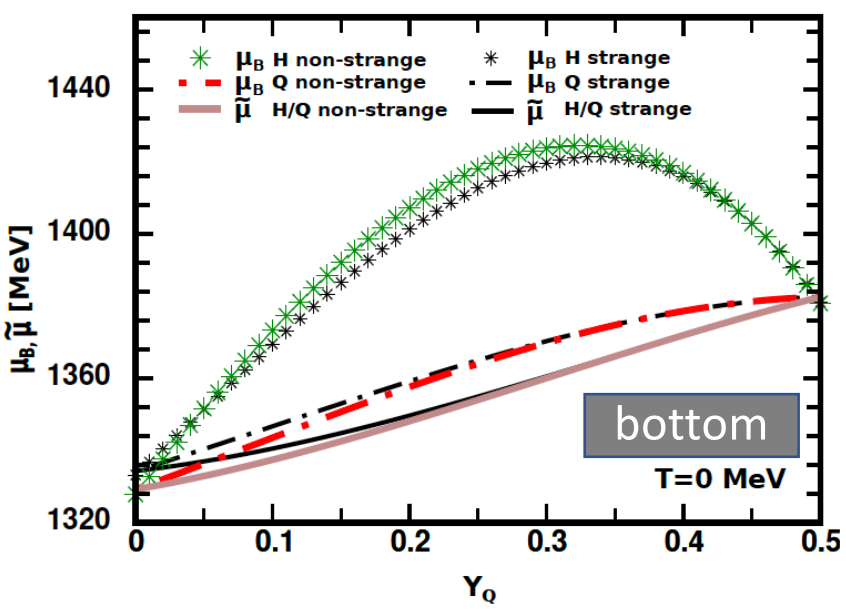
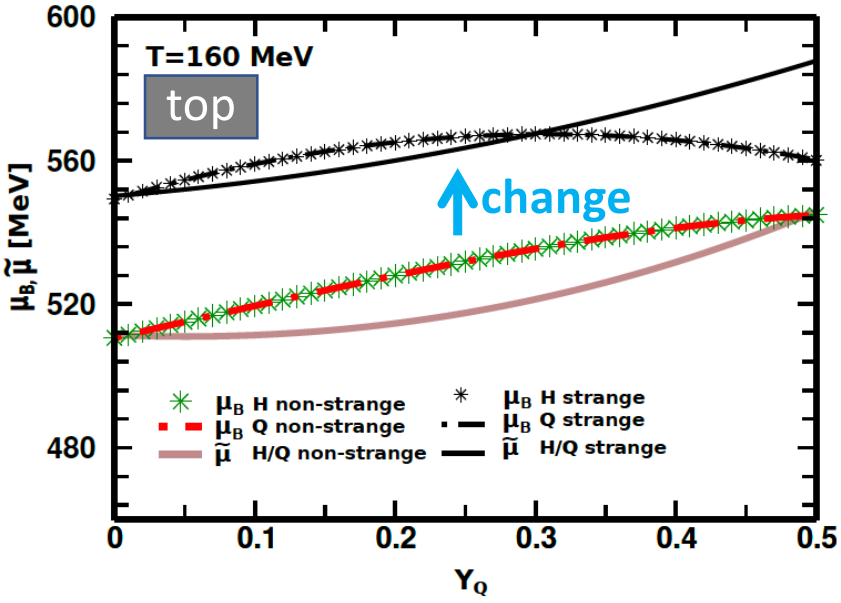
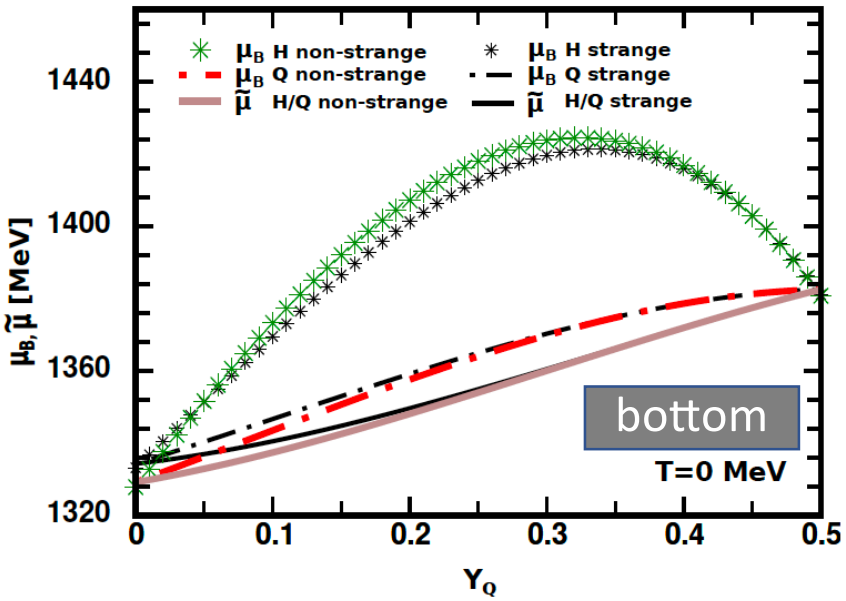
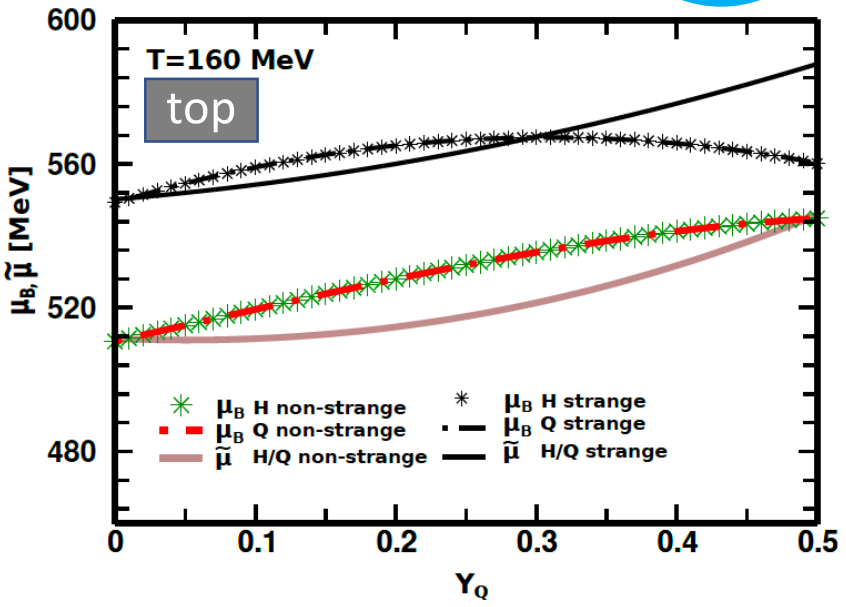
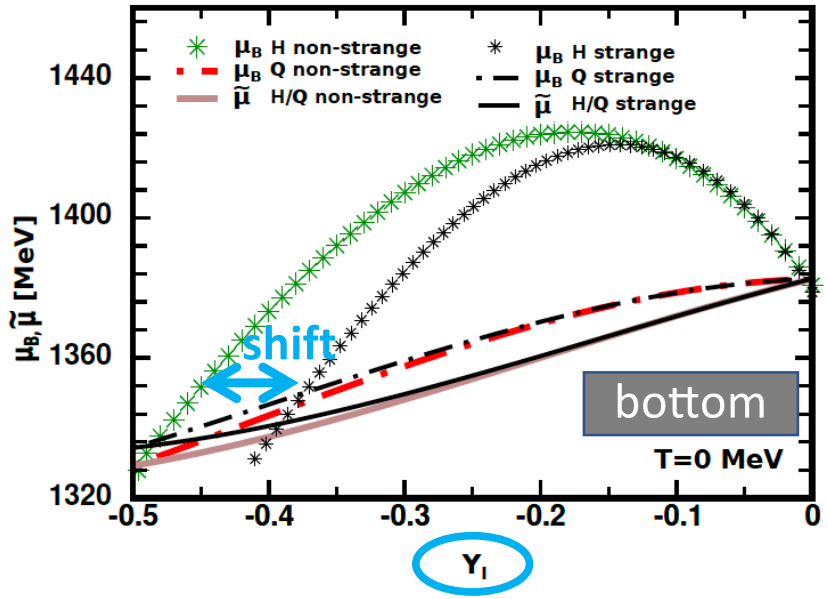


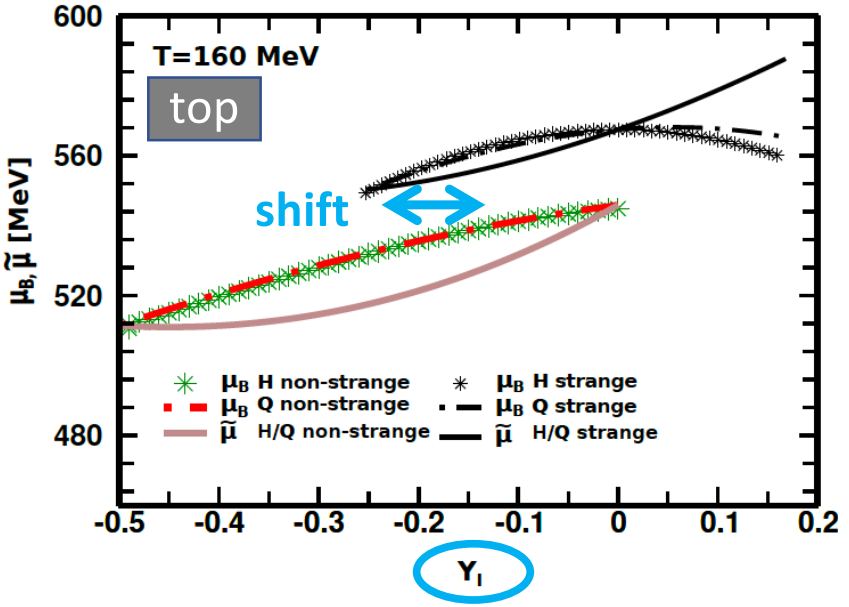


- For finite net strangeness $Y_S \neq 0$, isospin and charge fraction relation is not trivial $Y_I = Y_Q - 0.5 + \frac{1}{2} Y_S$



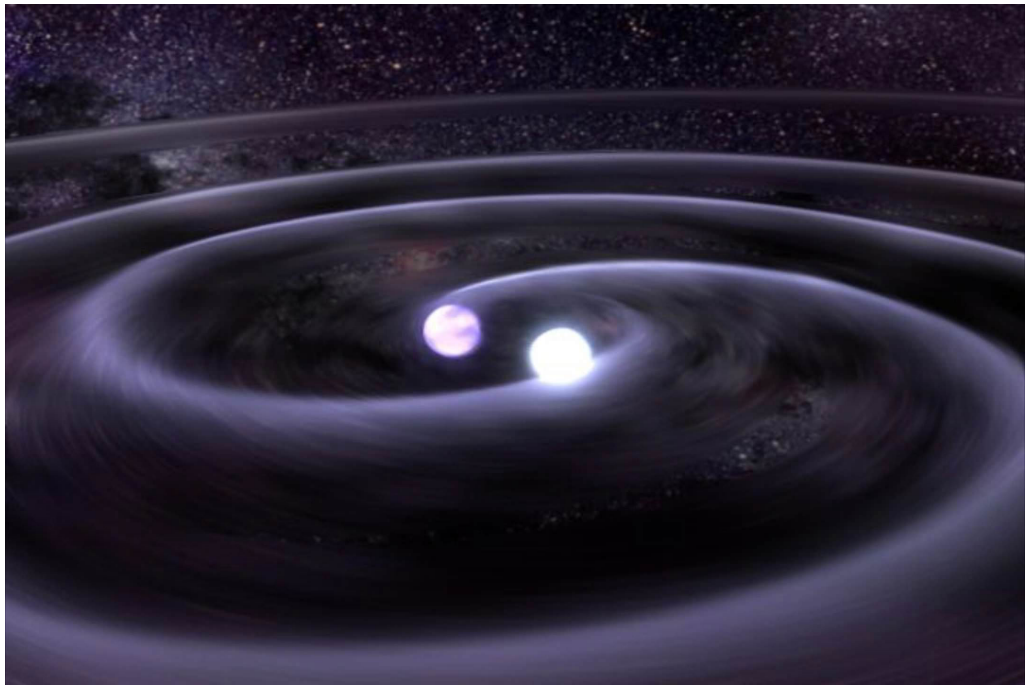






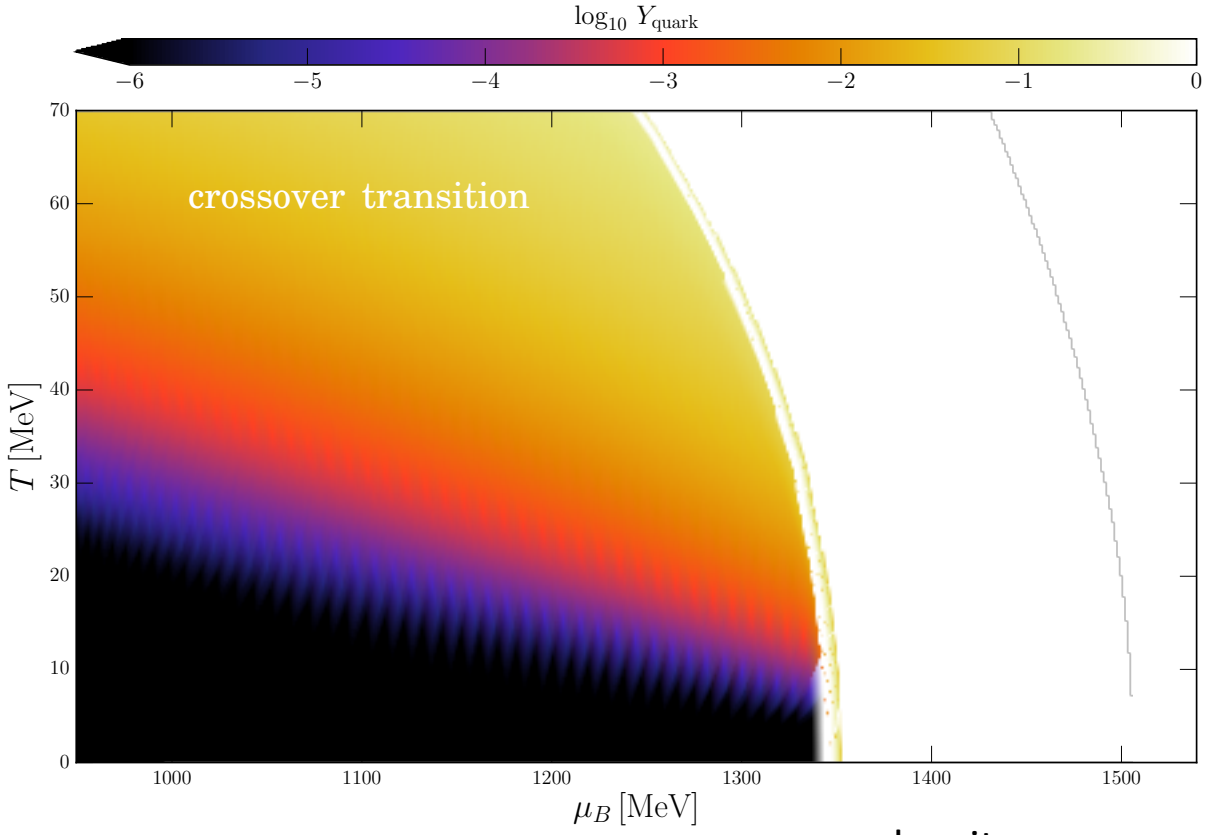
Charge Fraction Y_Q Overview

- 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 ?



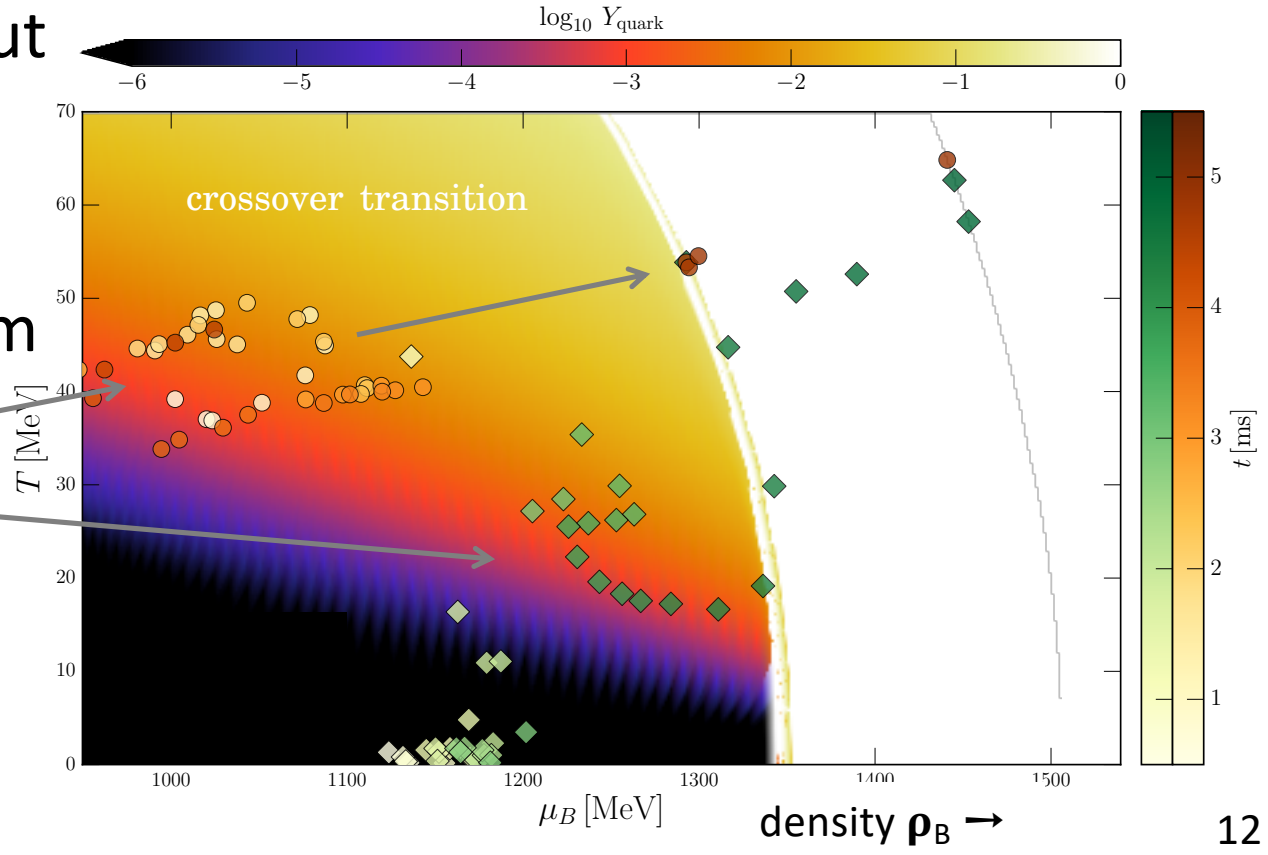
Merger in the QCD Phase Diagram

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



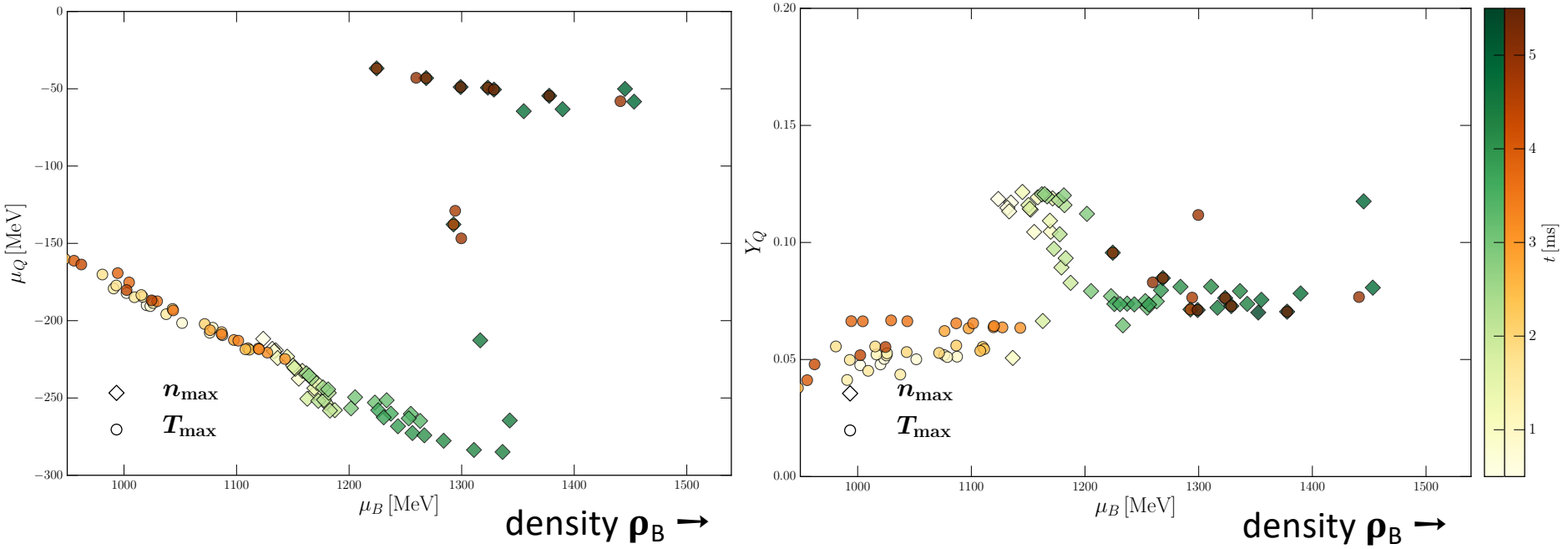
Merger in the QCD phase Diagram

- CMF 3D (T, μ_B, Y_Q) EoS with 1st order phase transition
- Solve Einstein-hydrodynamics using *Frankfurt/IllinoisGRMHD* code
- Hypermassive star with final mass of 2.9 M_{Sun} at ~5 ms (after deconfinement but before collapse to black hole)
- Tracking maximum temperature ● and density ◆ during merger



More Merger Phase Diagrams

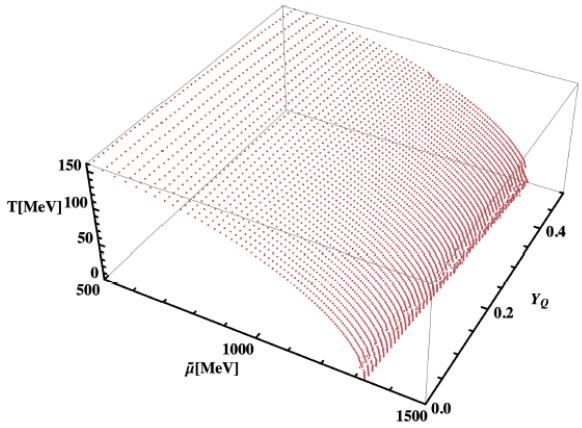
- Tracking maximum temperature ● and density ◆



- Increase in abs. value of charged chemical potential until phase transition, when it drops
- Decrease in charge fraction of core when quarks appear (never reaching heavy-ion/supernovae conditions)

Conclusions and Outlook

- 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



- Comparisons among HI collisions and astrophysics must be done with care (Y_Q, Y_S, leptons, …)
- Neutron-star mergers create ideal conditions to achieve deconfinement
- Now, in addition to observe light, we can also understand the universe through gravitational waves so, maybe, there will be a clear signature for a quark deconfinement phase transition from astrophysics!