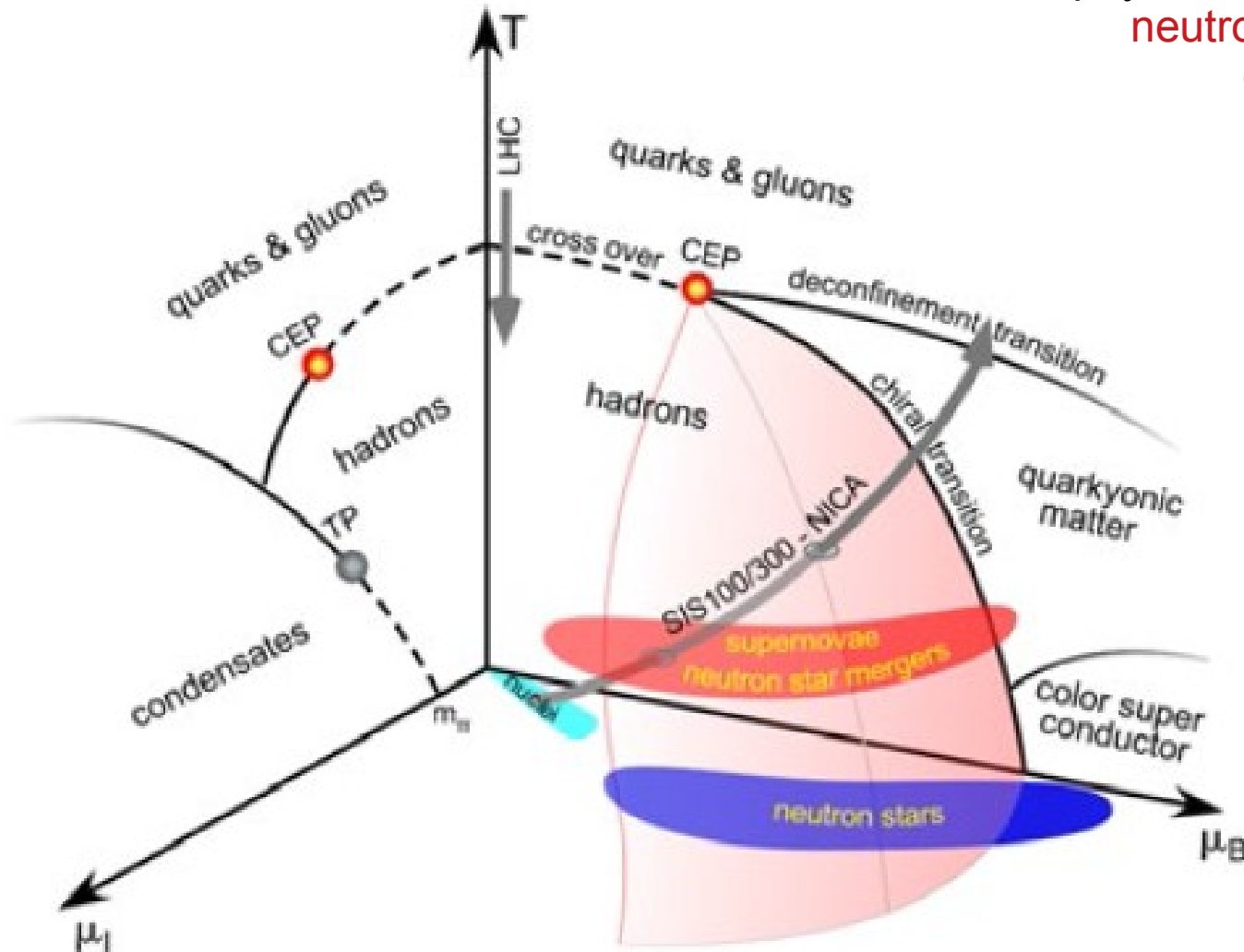


# The QCD Phase Diagram in Astrophysics

Conjectured Phase Diagram highlighting the role of astrophysical phenomena like **supernovae**, **neutron stars** and their **mergers** for exploring the phase boundary  
Limiting the hadronic Matter phase.



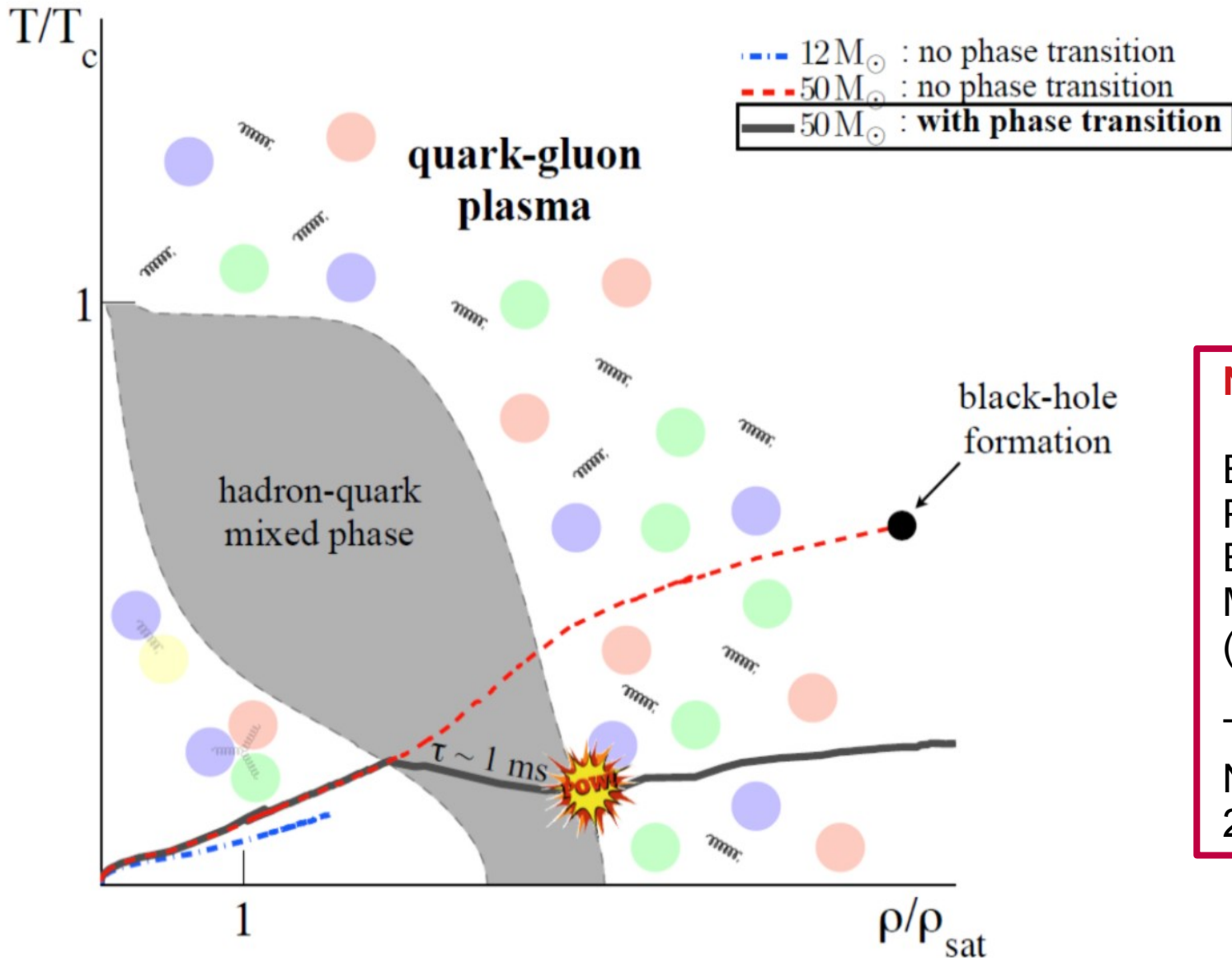
## New:

Evidence for strong Phase transition from Existence of exploding Massive blue supergiants ( $M \sim 50 M_{\text{sun}}$ )

T. Fischer et al.,  
Nature Astronomy  
2 (2018) 960

# The QCD Phase Diagram in Astrophysics

Phase diagram from relativistic density functional for hadronic (DD2F) & quark matter (SFM)



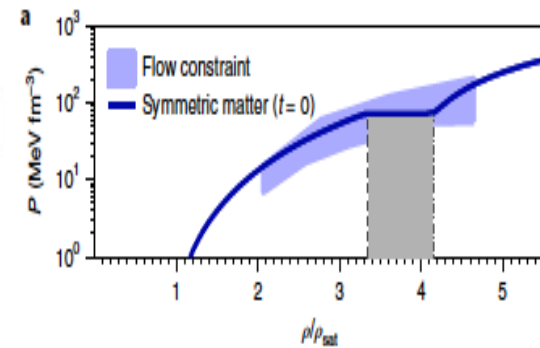
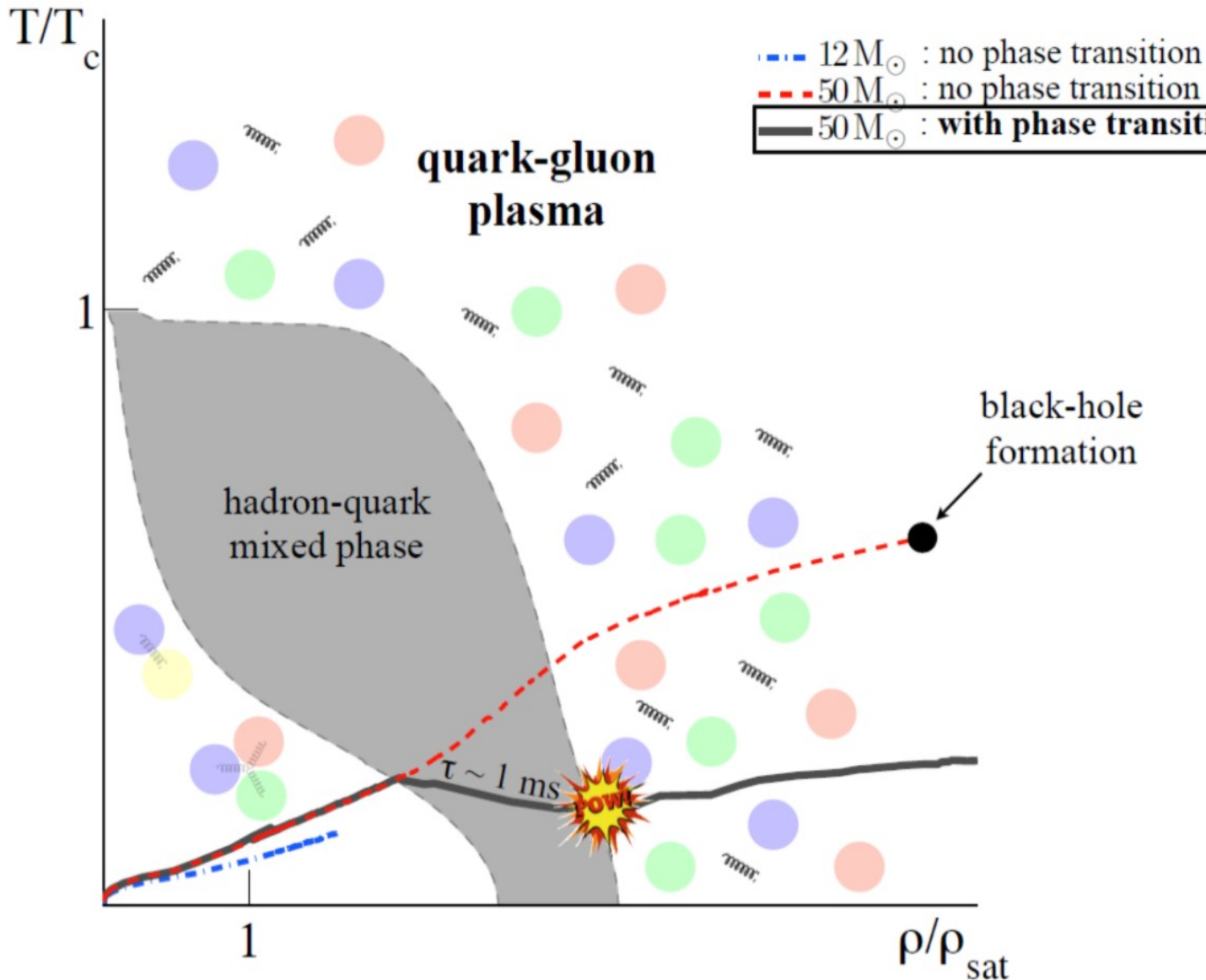
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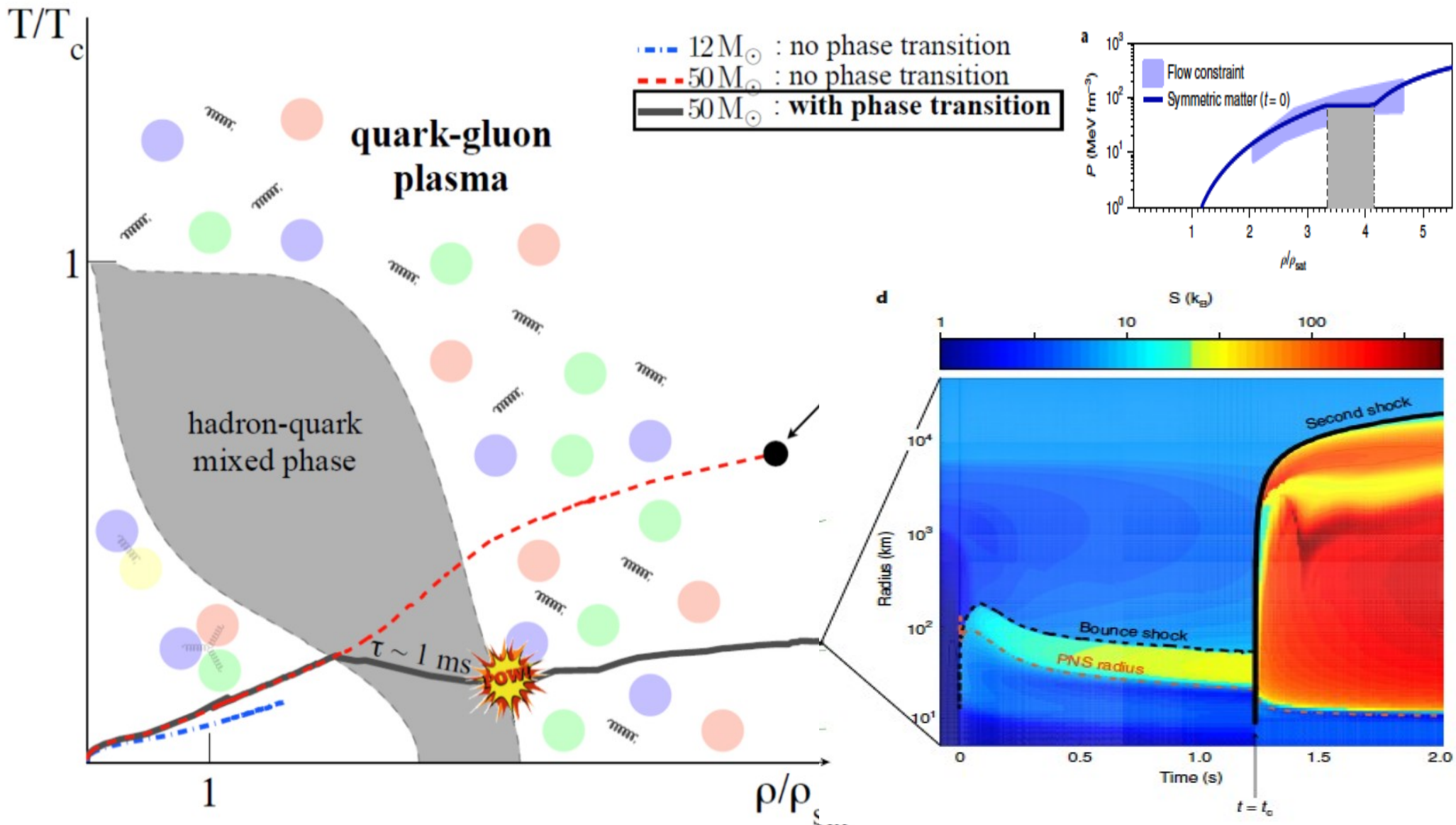
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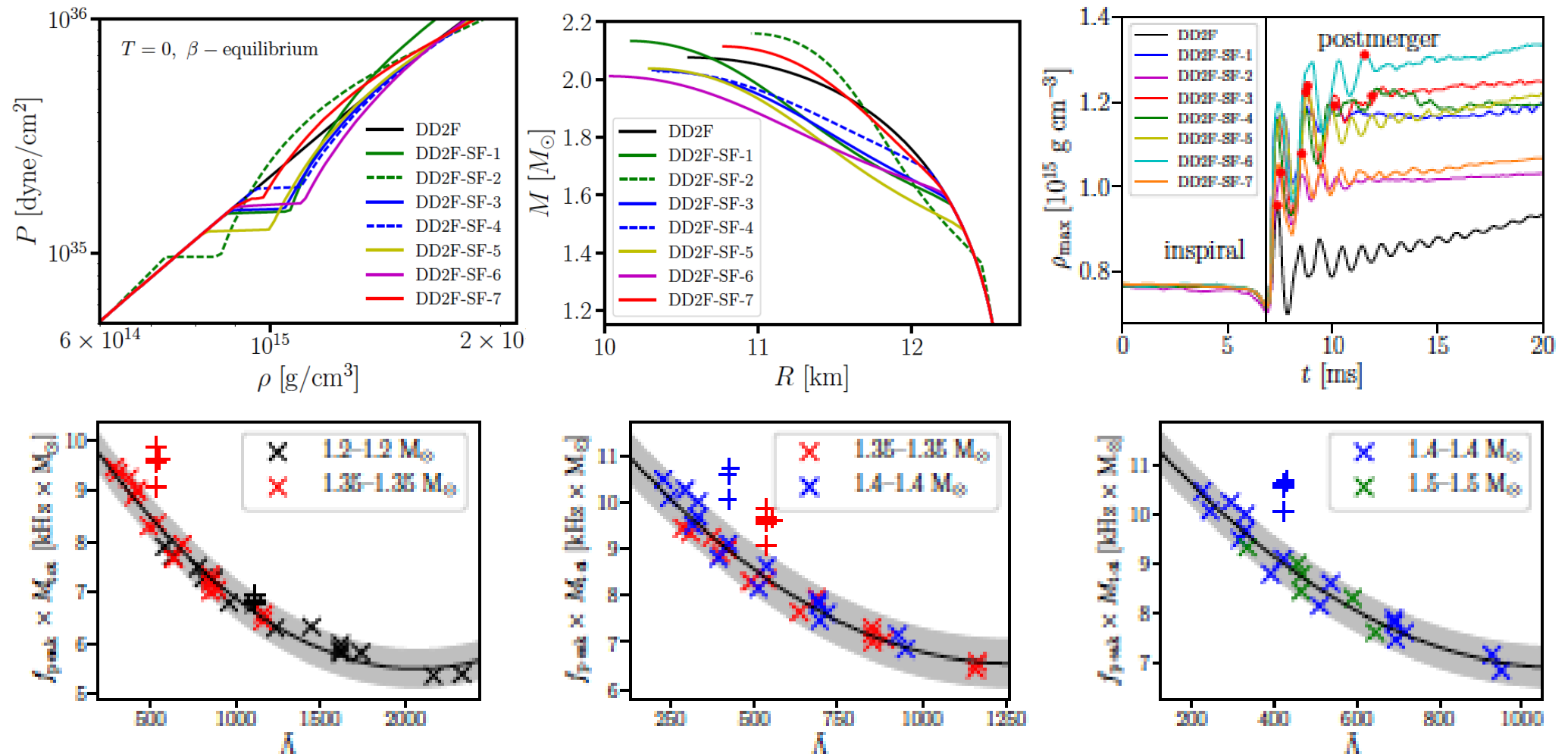
# The QCD Phase Diagram in Astrophysics

Phase diagram from relativistic density functional for hadronic (DD2F) & quark matter (SFM)



# Hybrid star formation in postmerger phase

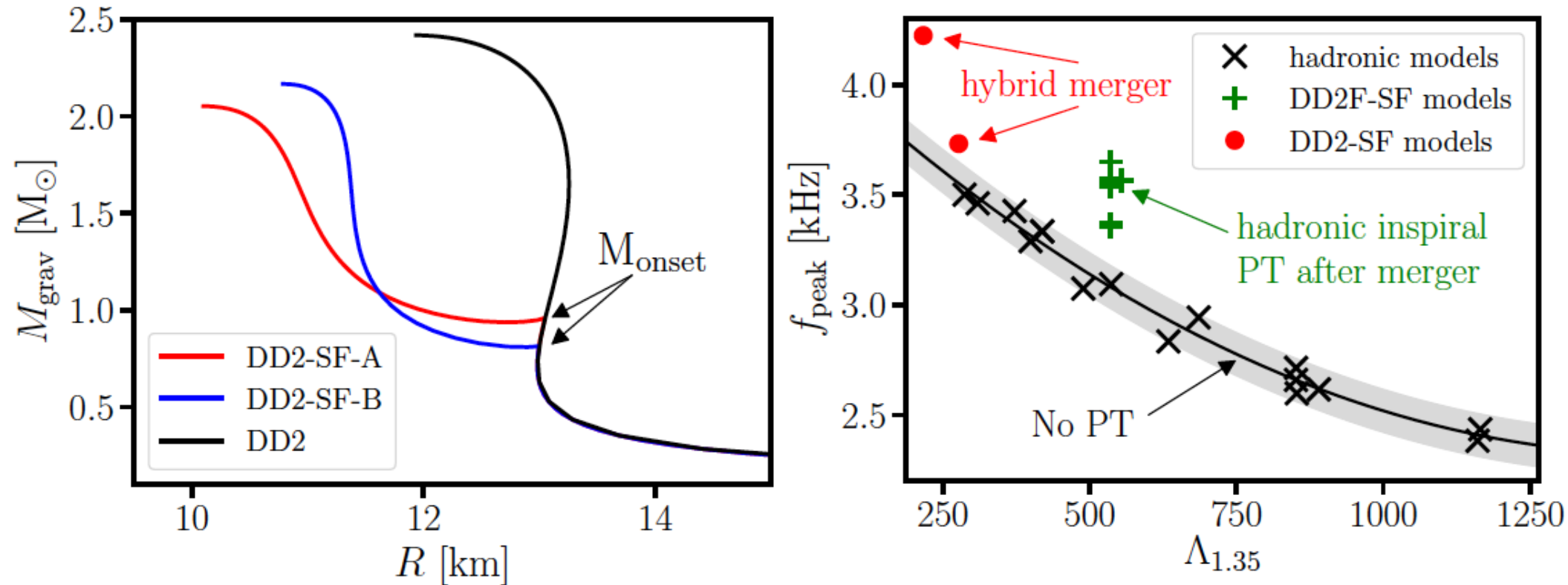
Strong phase transition in postmerger GW signal, S. Blacker et al., arxiv:2006.03789



Dominant **postmerger** frequency  $f_{\text{peak}}$  vs. tidal deformability  $\Lambda_{1.35}$  from **inspiral** phase:  
 Results from hybrid models appear as **outliers** of the grey band (maximal deviation of purely hadronic models from a least squares fit) = signalling a **strong phase transition in NS** !

# GW signal of deconfinement in merger of hybrid stars

Merger of hybrid stars with early phase transition: A. Bauswein et al., EPJ ST (2020) submitted

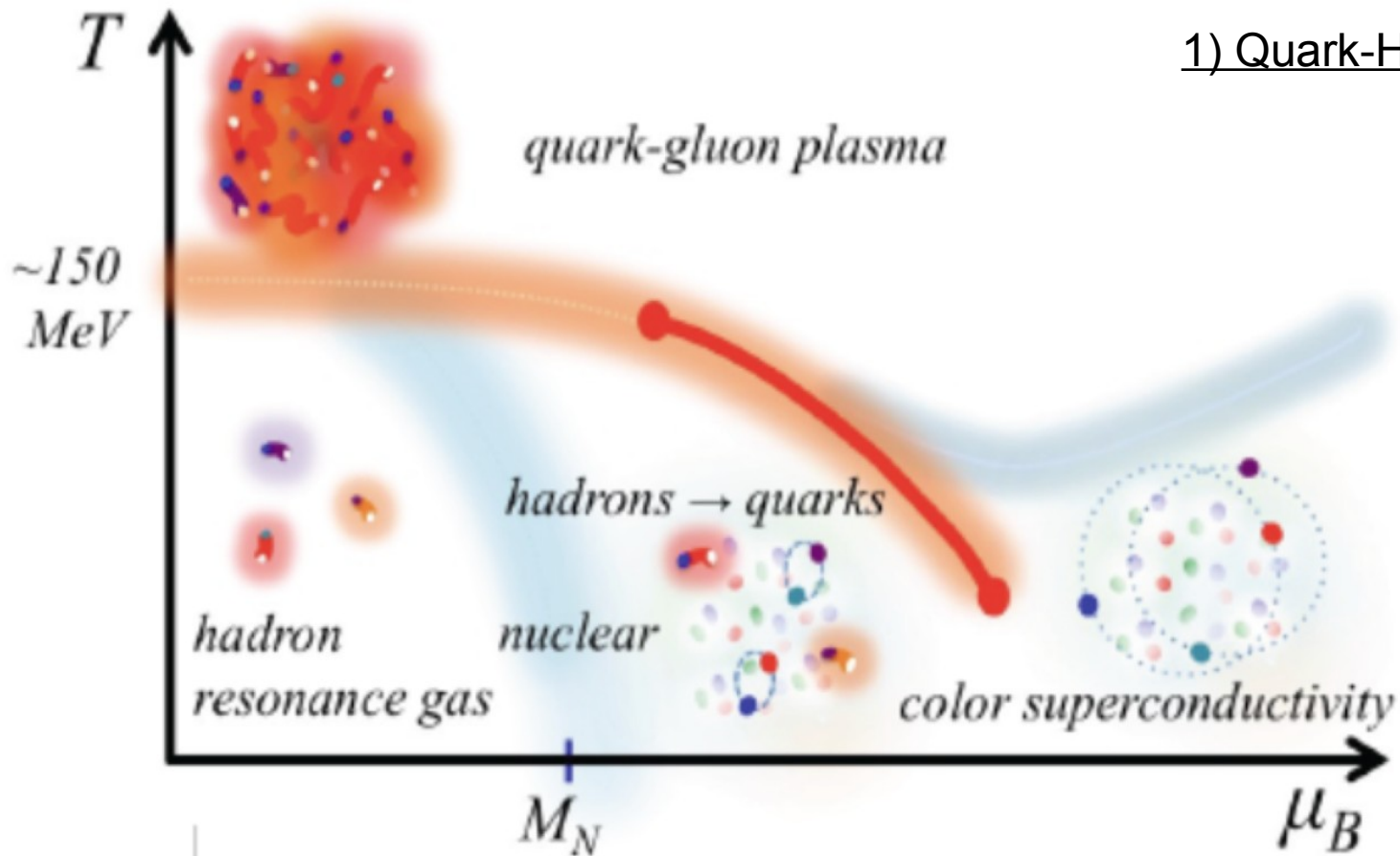


The combination of stiff hadronic EoS (DD2) and string-flip (SF) model allows for early onset of deconfinement in low-mass neutron stars and even third-family solutions (mass twins). For these cases, the event GW170817 could have been a **merger of two hybrid stars!** Also in these cases (red dots in above figure) a **significant deviation** from the grey band of Purely hadronic star mergers without a phase transition is obtained!



# The QCD Phase Diagram in Astrophysics

If the transition looks like a crossover – what can it mean ??



1) Quark-Hadron continuity (duality)

Schaefer – Wilczek  
Wetterich  
Baym – Hatsuda et al.

Interplay of:  
Hadrons (ChSB) &  
Quark pairing (CSC)

# The QCD Phase Diagram in Astrophysics

If the transition looks like a crossover – what can it mean ??

## 2) Inhomogeneous chiral condensates (ICC)

Buballa – Carignano

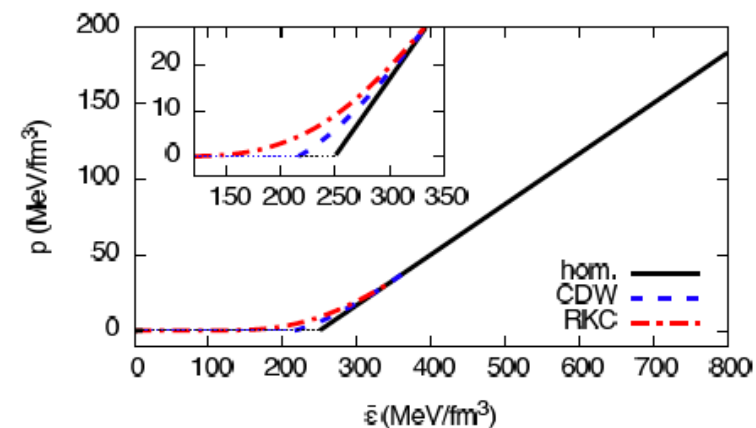
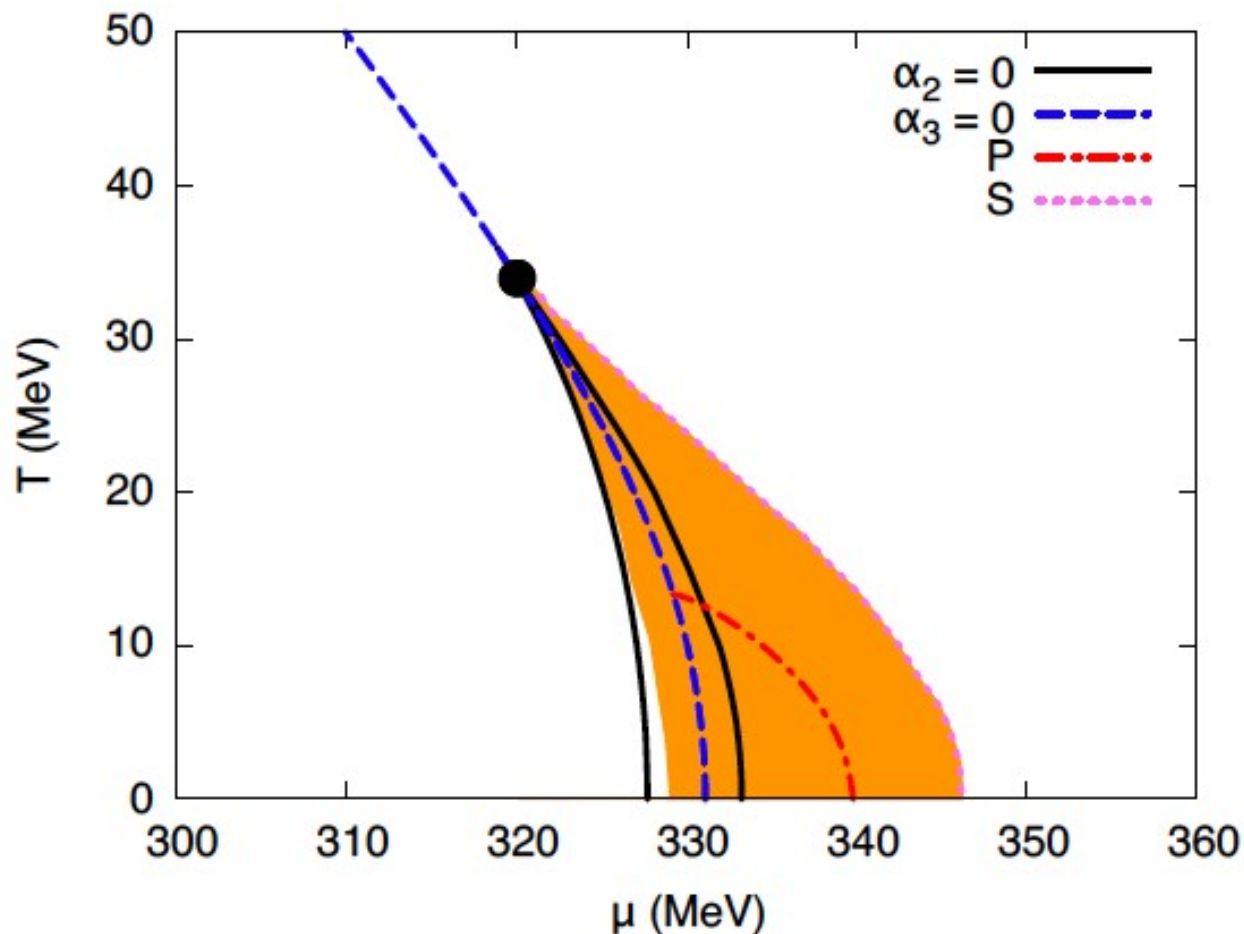
Arxiv:1809.10066

RKC – real kink crystal

CDW – chiral density wave

CEP  $\rightarrow$  PLP

(Pseudo Lifshitz Point)

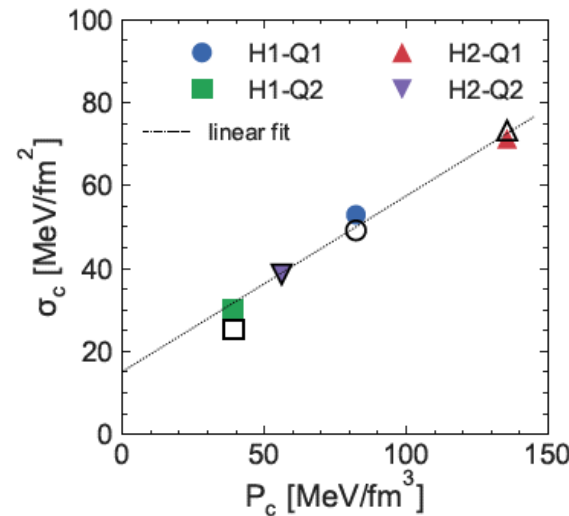
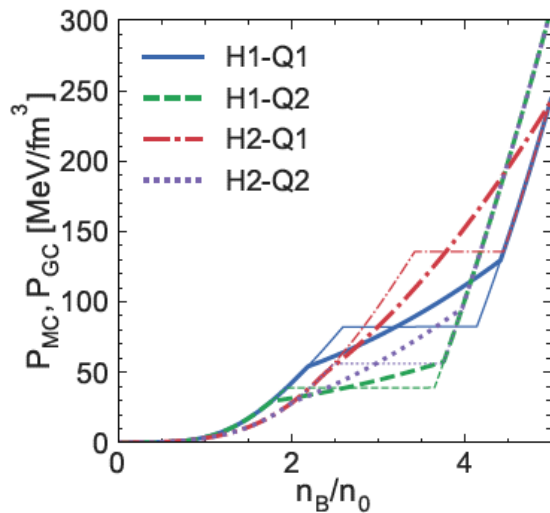


Buballa & Carignano, arxiv:1508.04361



# The QCD Phase Diagram in Astrophysics

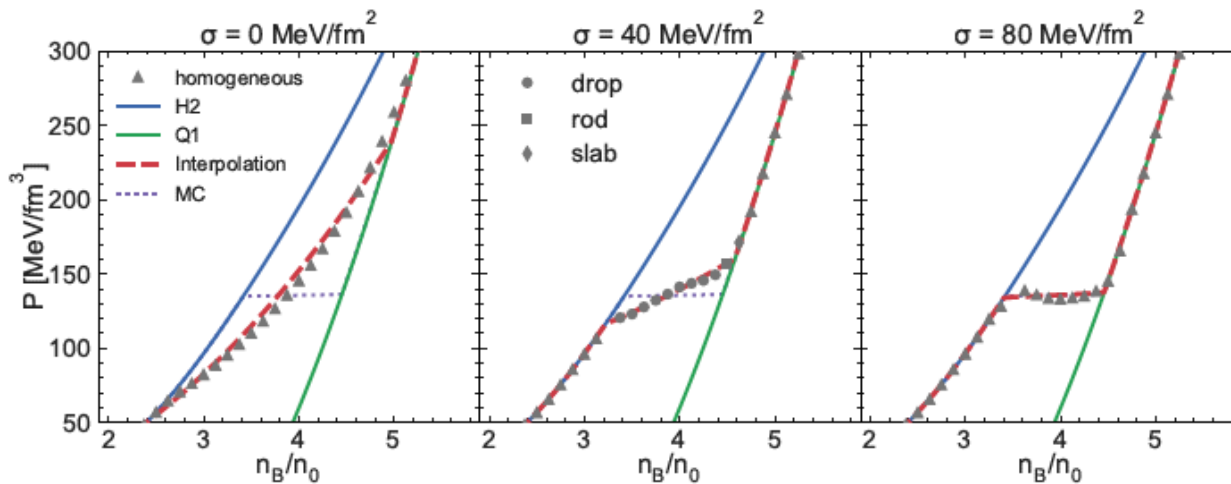
If the transition looks like a crossover – what can it mean ??



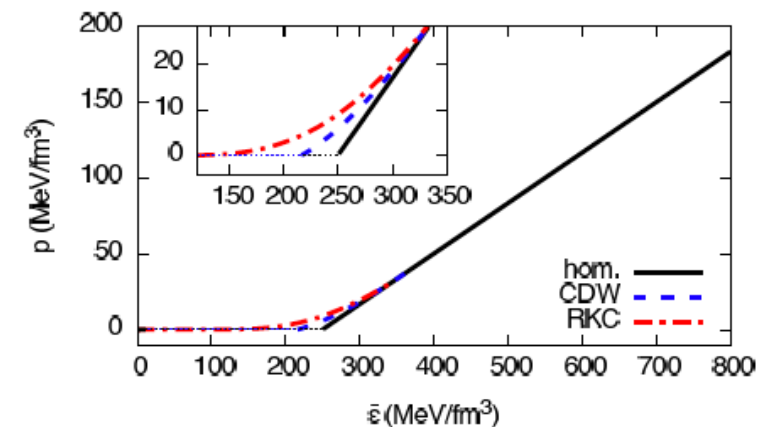
### 3) Structured mixed phase (pasta)

Yasutake et al.  
Arxiv:1812.11889

surface tension effects:  
 $\sigma = 0$  : Gibbs construction  
 $\sigma > \sigma_c$  : Maxwell constr.



### Similarity with ICC

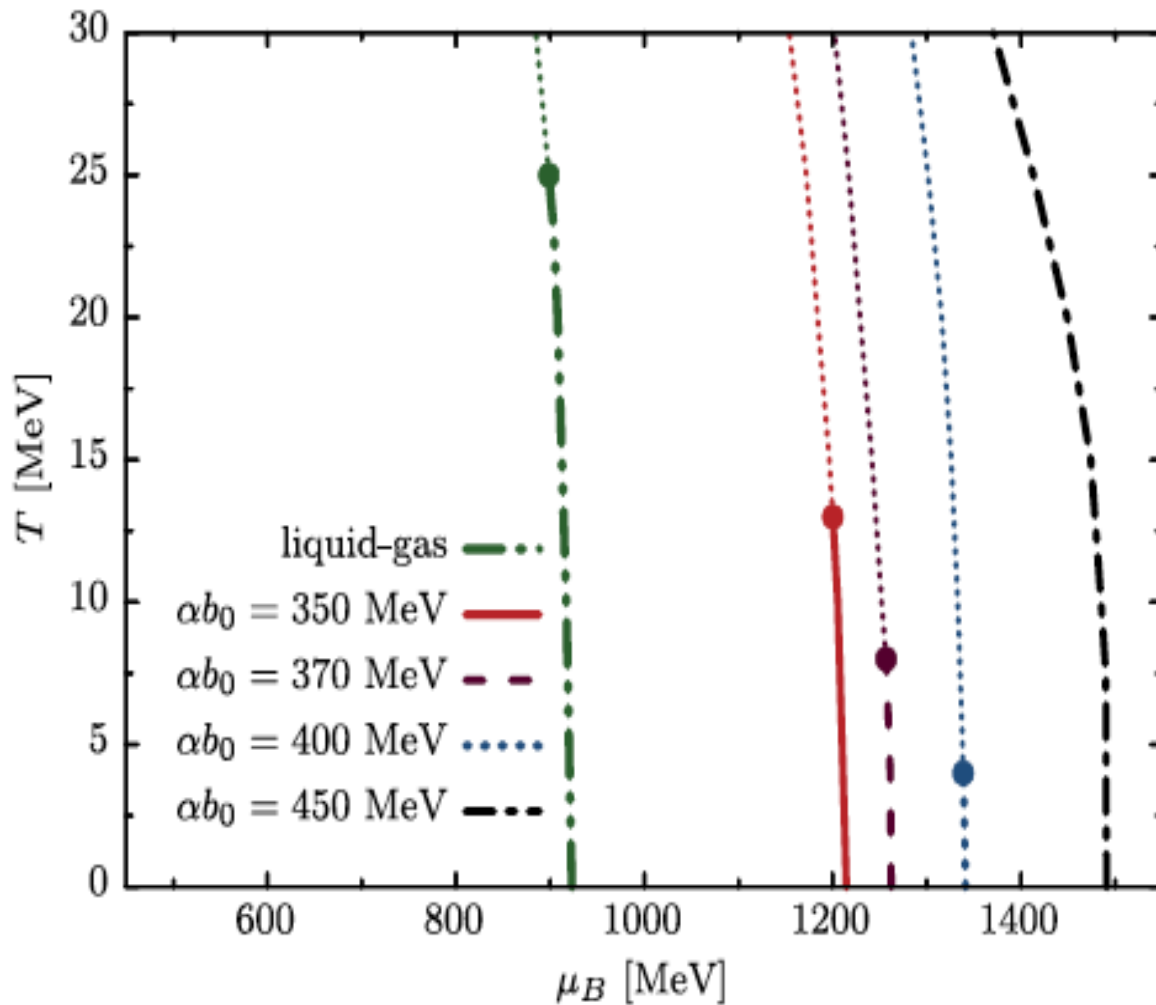


Buballa & Carignano, arxiv:1508.04361

# The QCD Phase Diagram in Astrophysics

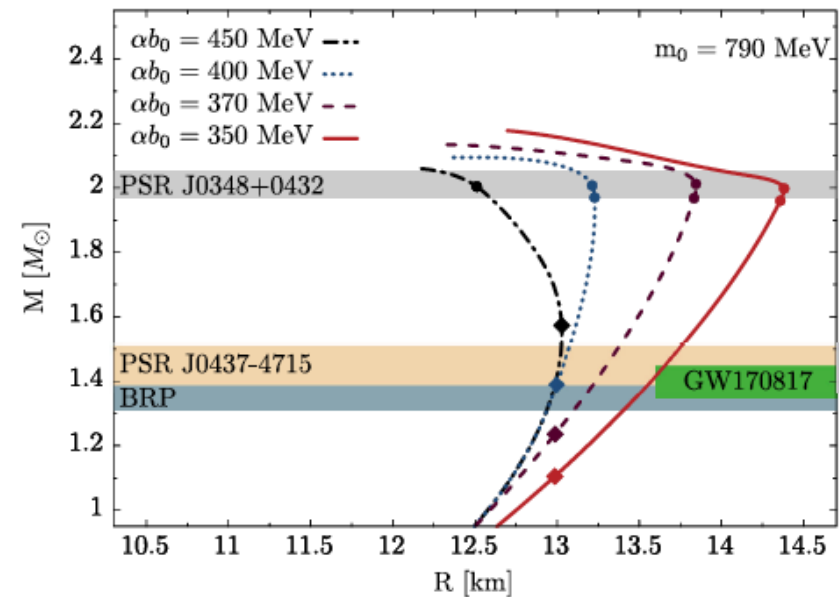
If the transition looks like a crossover – what can it mean ??

4) Parity doubling (equal mass for chiral partners)



Marczenko et al.  
PRD 98 (2018) 103021  
crossover or weak 1<sup>st</sup> order PT  
Fulfills neutron star constraints

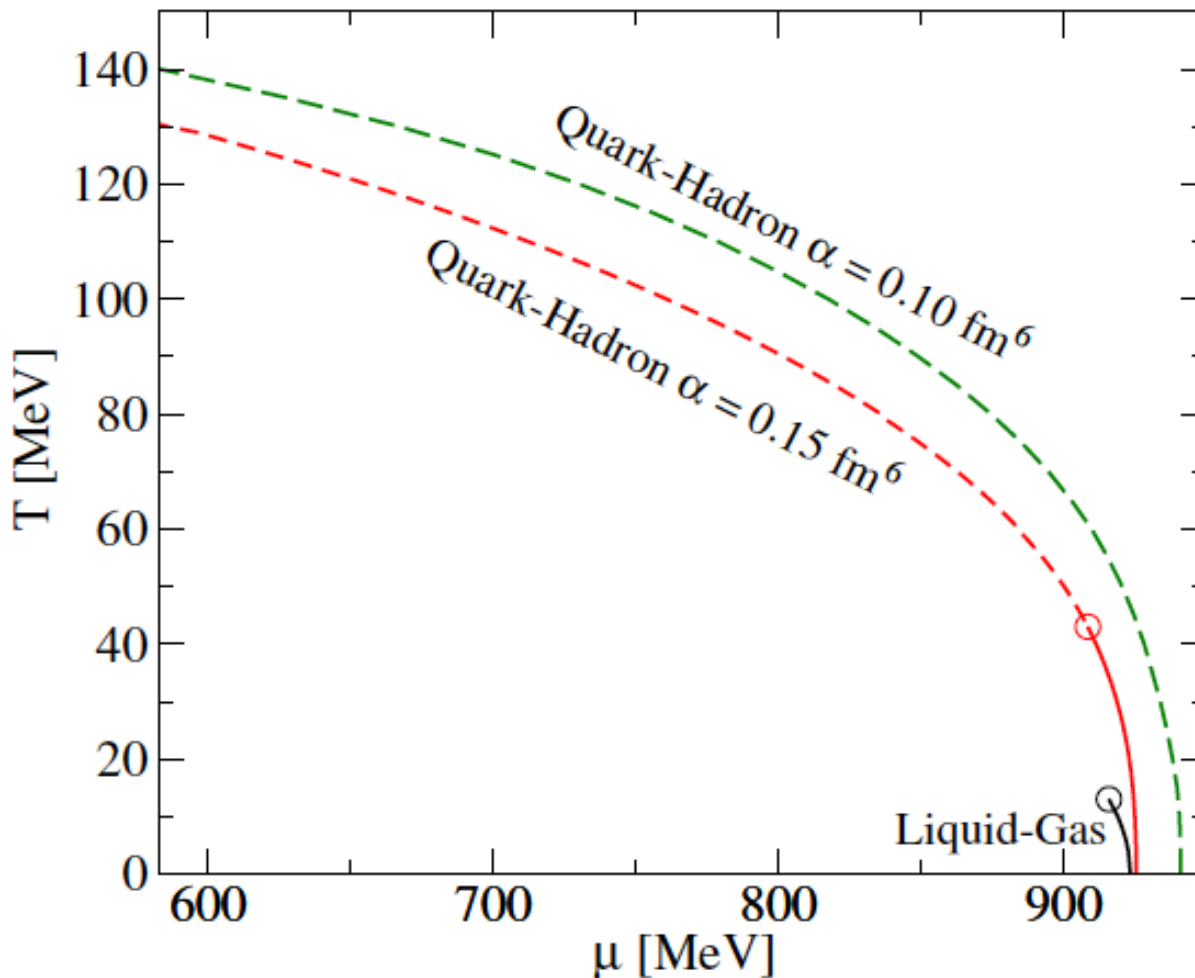
Purely hadronic matter!



# The QCD Phase Diagram in Astrophysics

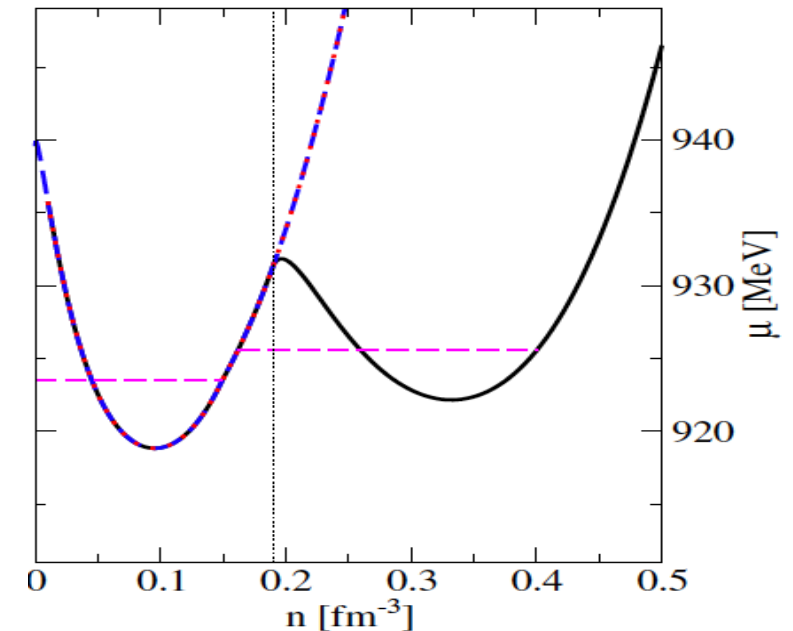
If the transition looks like a crossover – what can it mean ??

5) Unified quark-hadron matter model

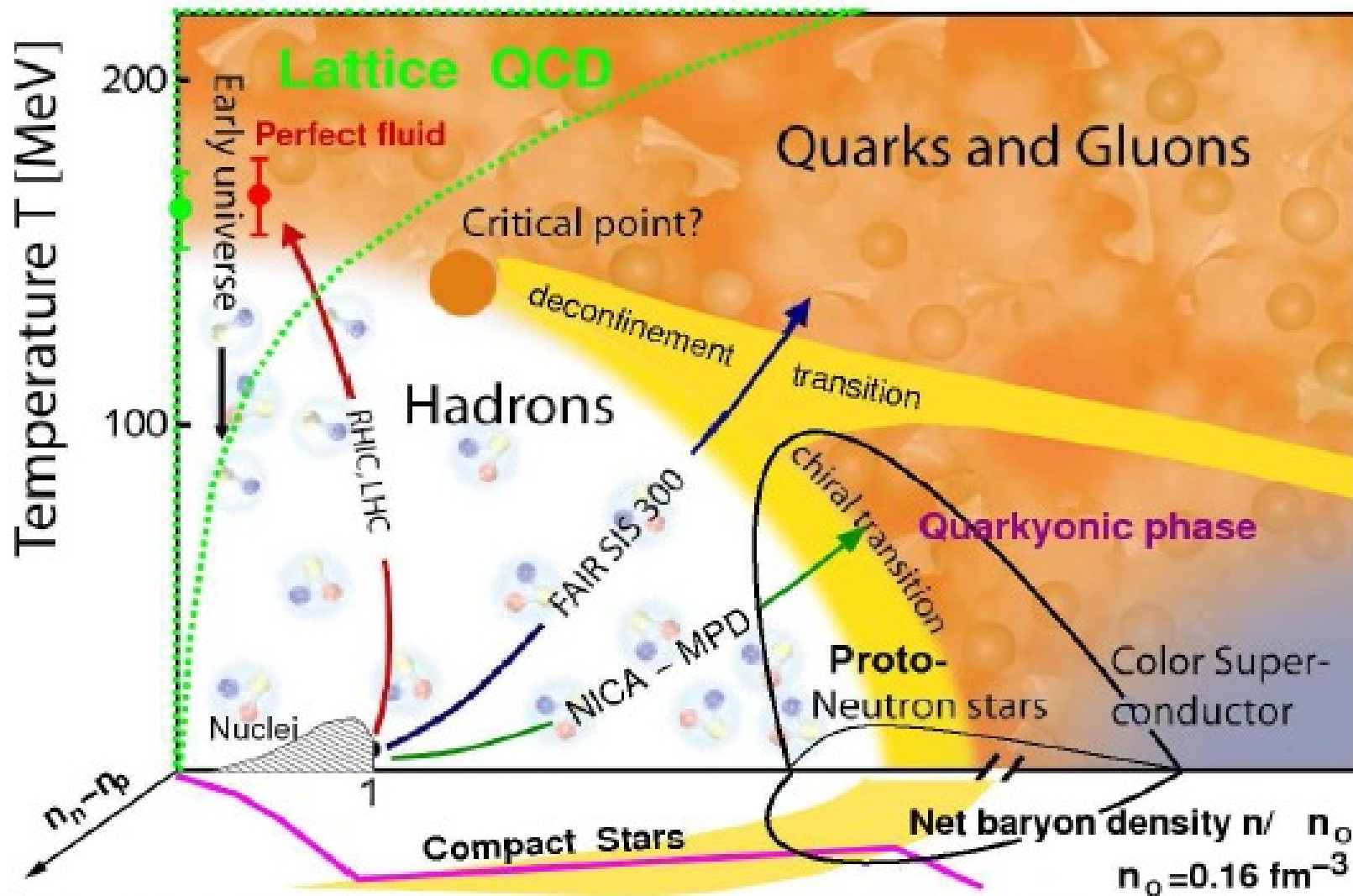


Bastian & Blaschke  
Arxiv:1812.11766  
crossover or 1<sup>st</sup> order PT + L-G

Mott transition for hadrons!



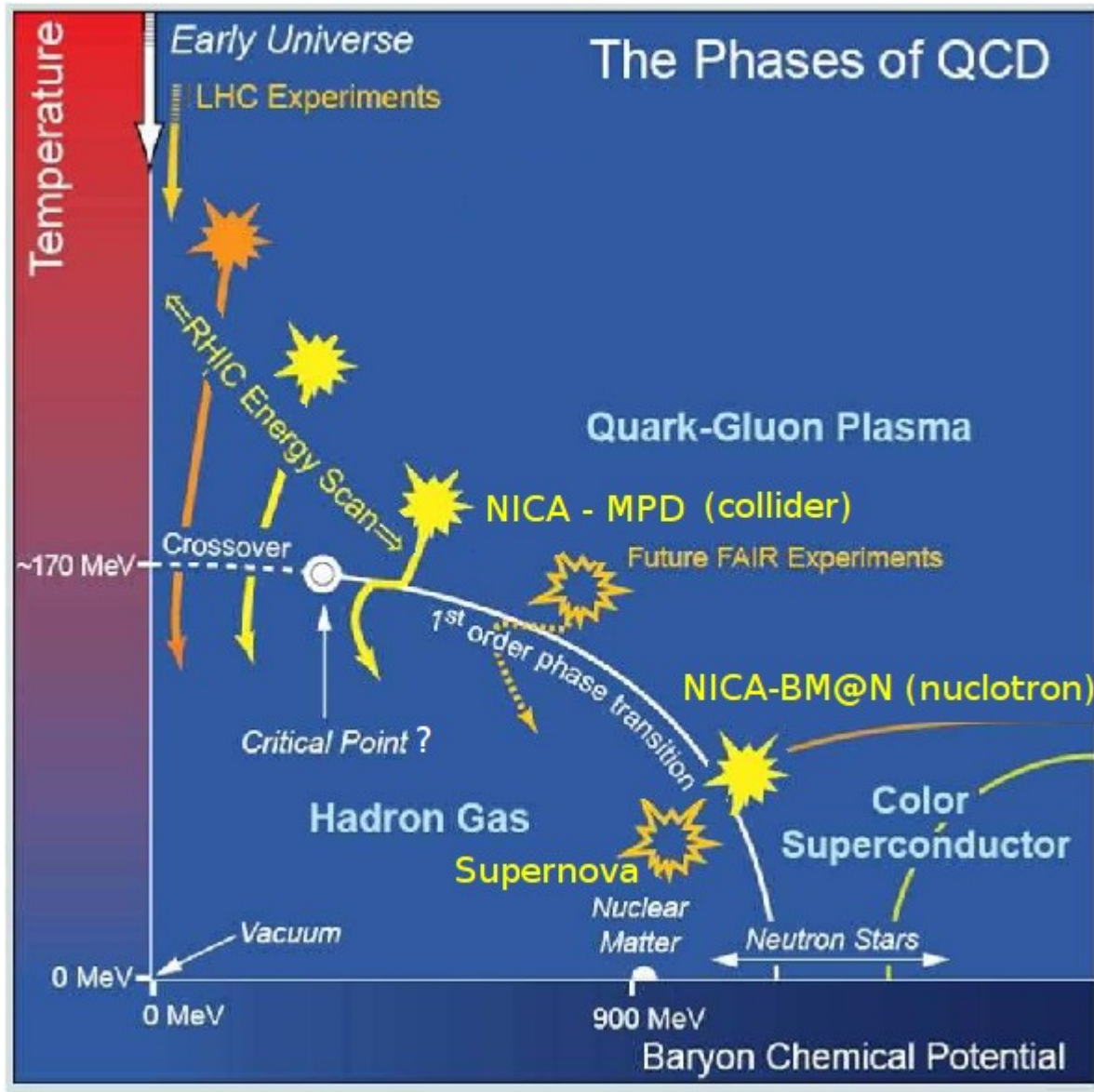
# Support a CEP in QCD phase diagram with Astrophysics?



NICA White Paper, <http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome>

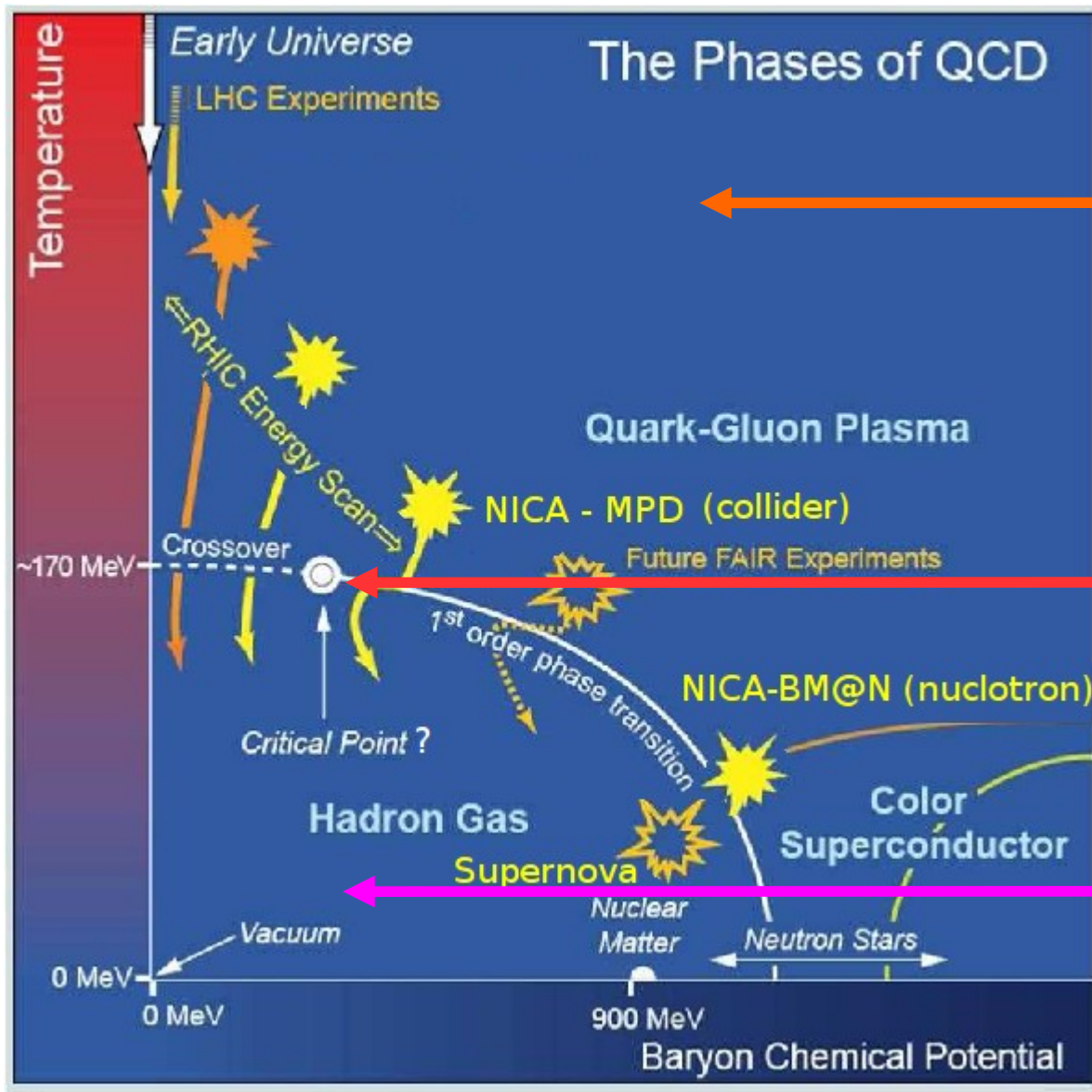
Crossover at finite  $T$  (Lattice QCD) + First order at zero  $T$  (Astrophysics) = Critical endpoint exists!

# The Goal: Theory of the QCD Phase Diagram





# The Goal: Theory of the QCD Phase Diagram



## Perturbative QCD

Approximately selfconsistent HTL resummation  
( $T > 2.5 T_c$ ,  $\mu > 1500$  MeV)

## QCD Phase transition(s)

Mott dissociation of hadrons,  
Deconfinement,  $\chi$ SR

## Statistical Model of Hadron Resonance Gas

Well established for  
Description of chemical  
freezeout