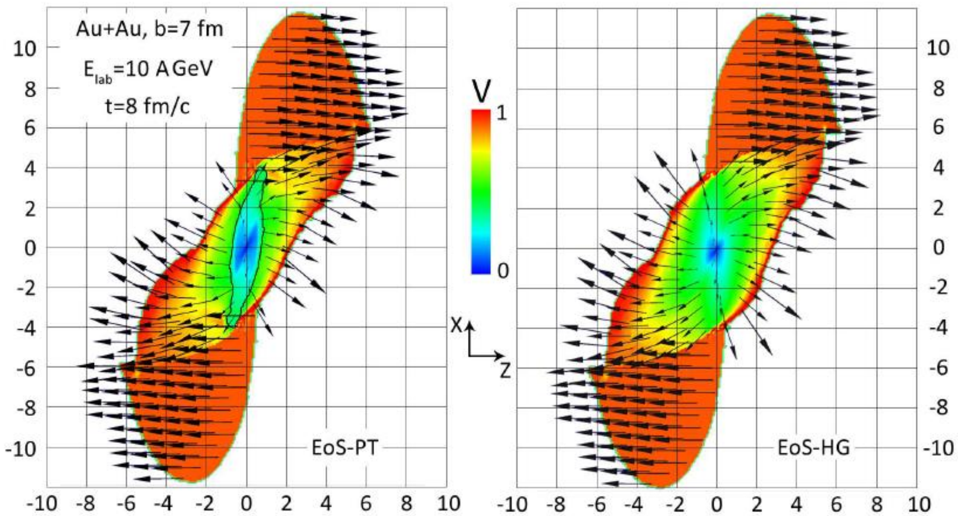
Equations of state of ultra-dense matter

Alessandro Drago
University of Ferrara

- Lab indications of a phase transition
  - Sound velocity
  - Transverse mass
  - Strangeness production
- New experiments proposed
- From labs to stars
  - Isospin dependence
  - Temperature dependence
  - Strangeness (hyperons and quarks)
- One or two M-R relations?
  - Metastability and GRBs
  - The role of LOFT

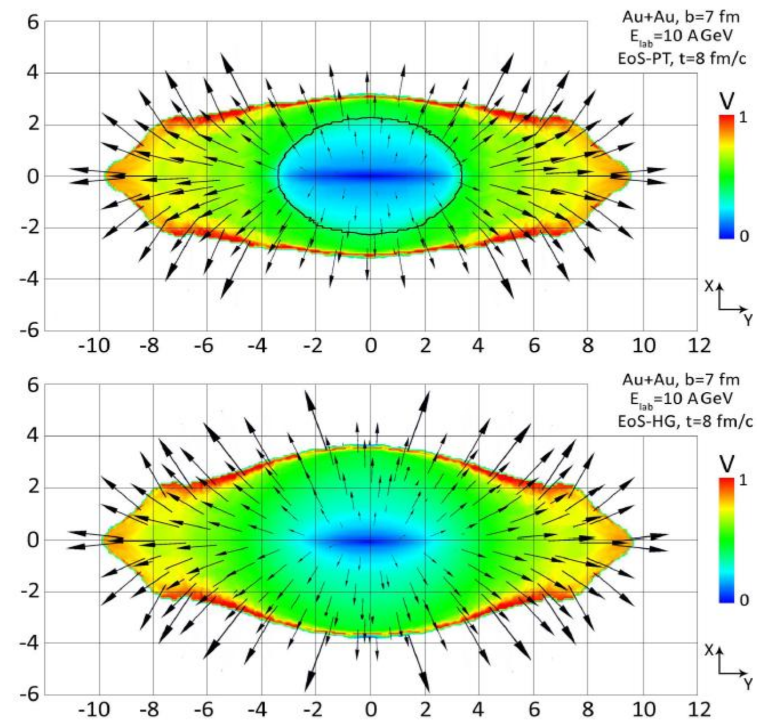
Lab experiments testing matter at high density and temperature

Heavy Ion Collisions
collective velocities of matter



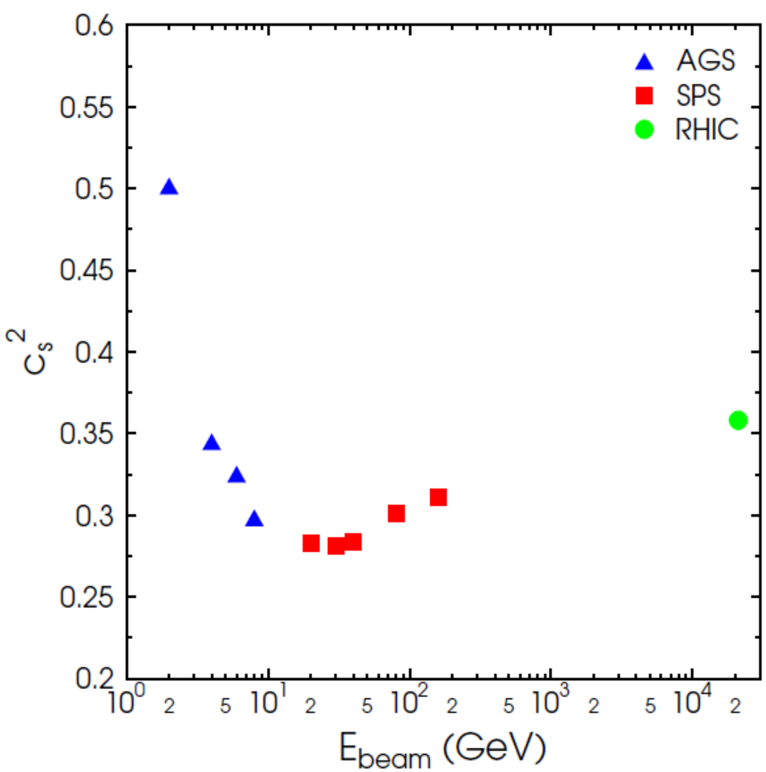
Velocities in the reaction plane

Transverse velocities

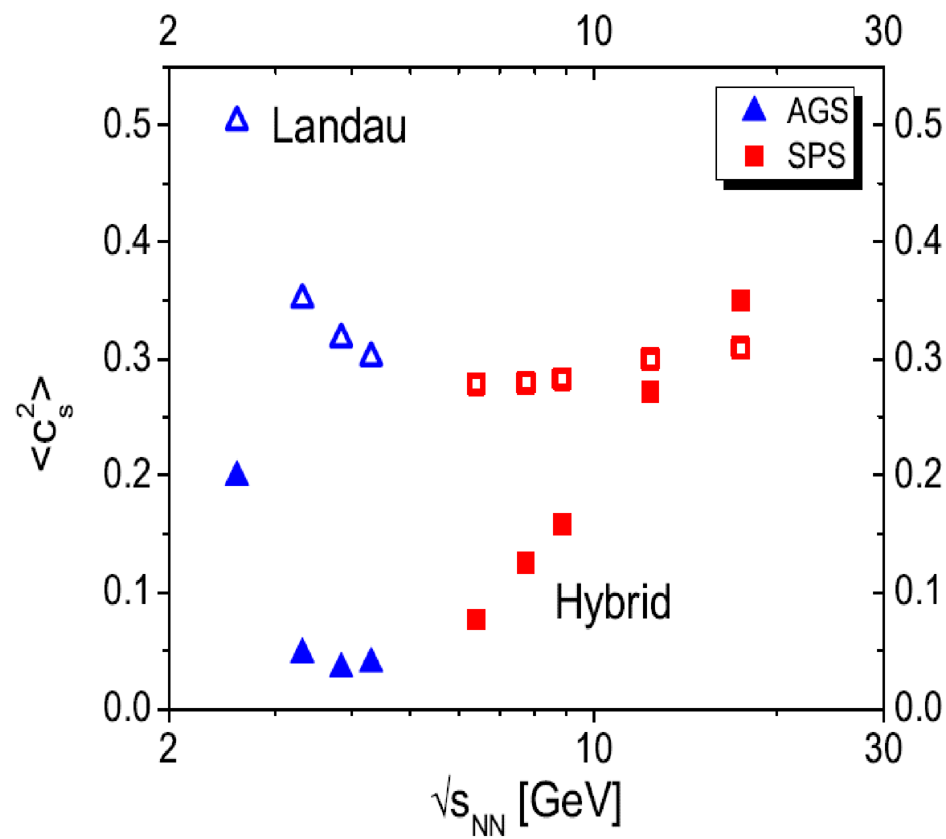


Merdeev, Satarov, Mishustin 2011

Sound velocity



Gazdizicki, Gorenstein, Seyboth 2011



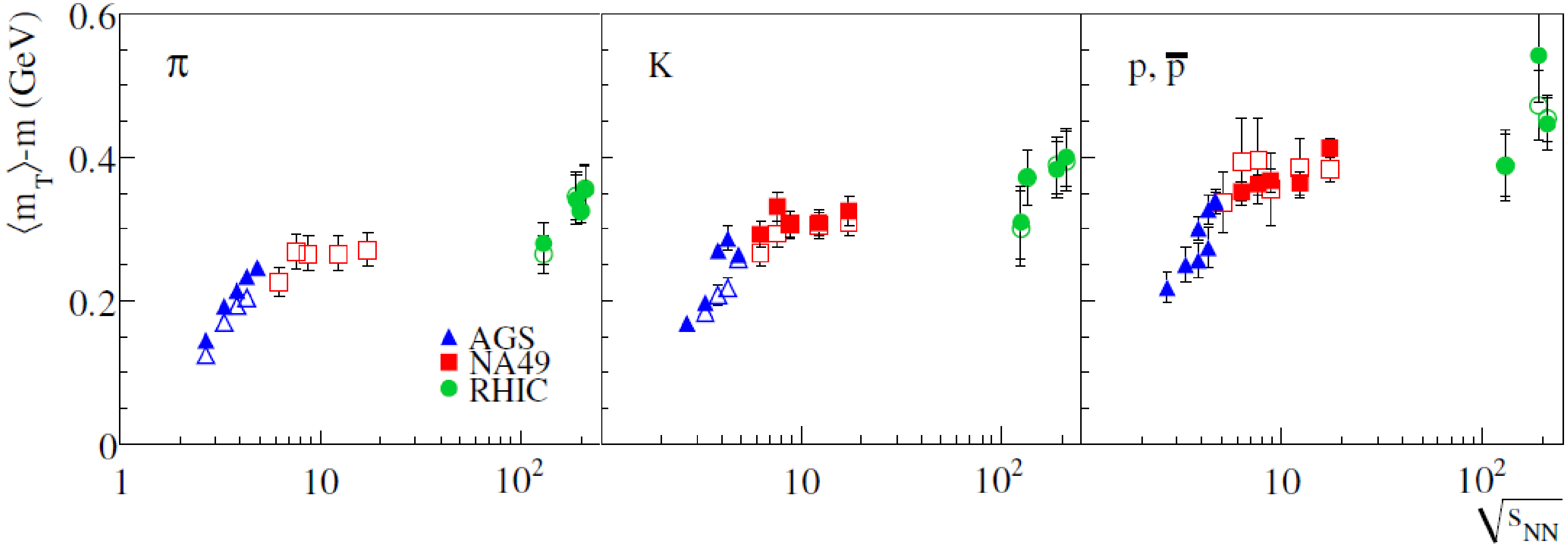
Steinheimer, Bleicher 2012

$S_{NN} = 2\ m\ (E_{beam} + m)$

Also Russkikh & Ivanov 2006

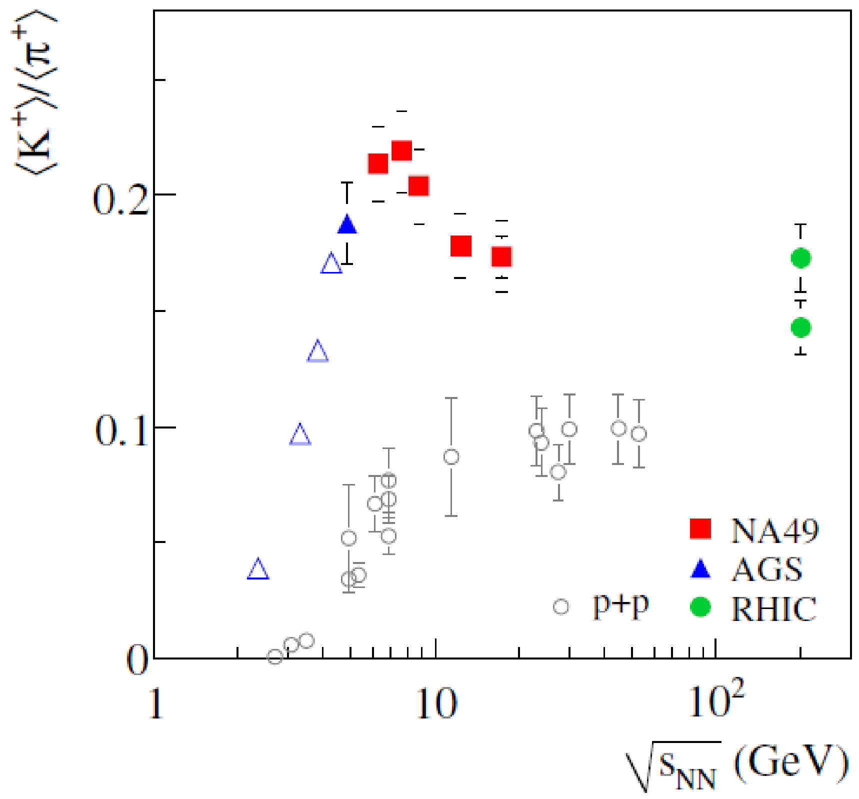
Transverse mass

$$m_T = (m^2 + p_T^2)^{1/2}$$



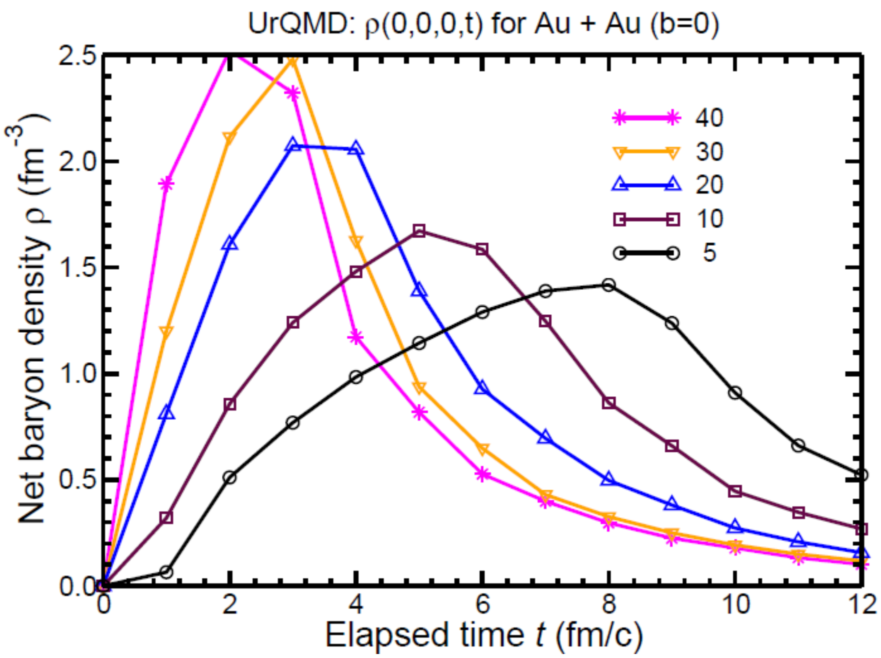
Gazdizicki, Gorenstein, Seyboth 2011

Strangeness production

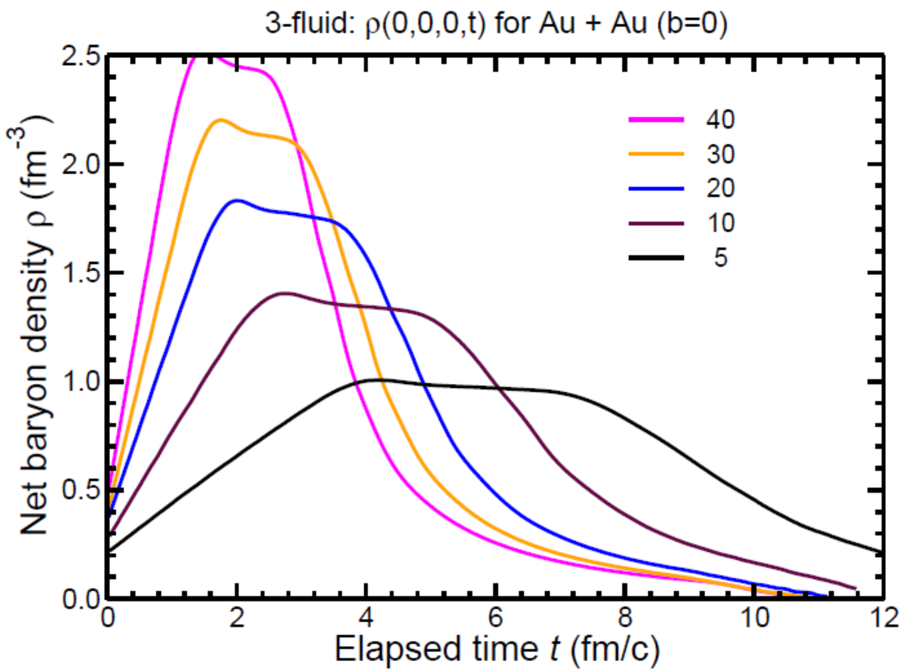


Gazdizicki, Gorenstein, Seyboth 2011

Which densities are tested in HIC?



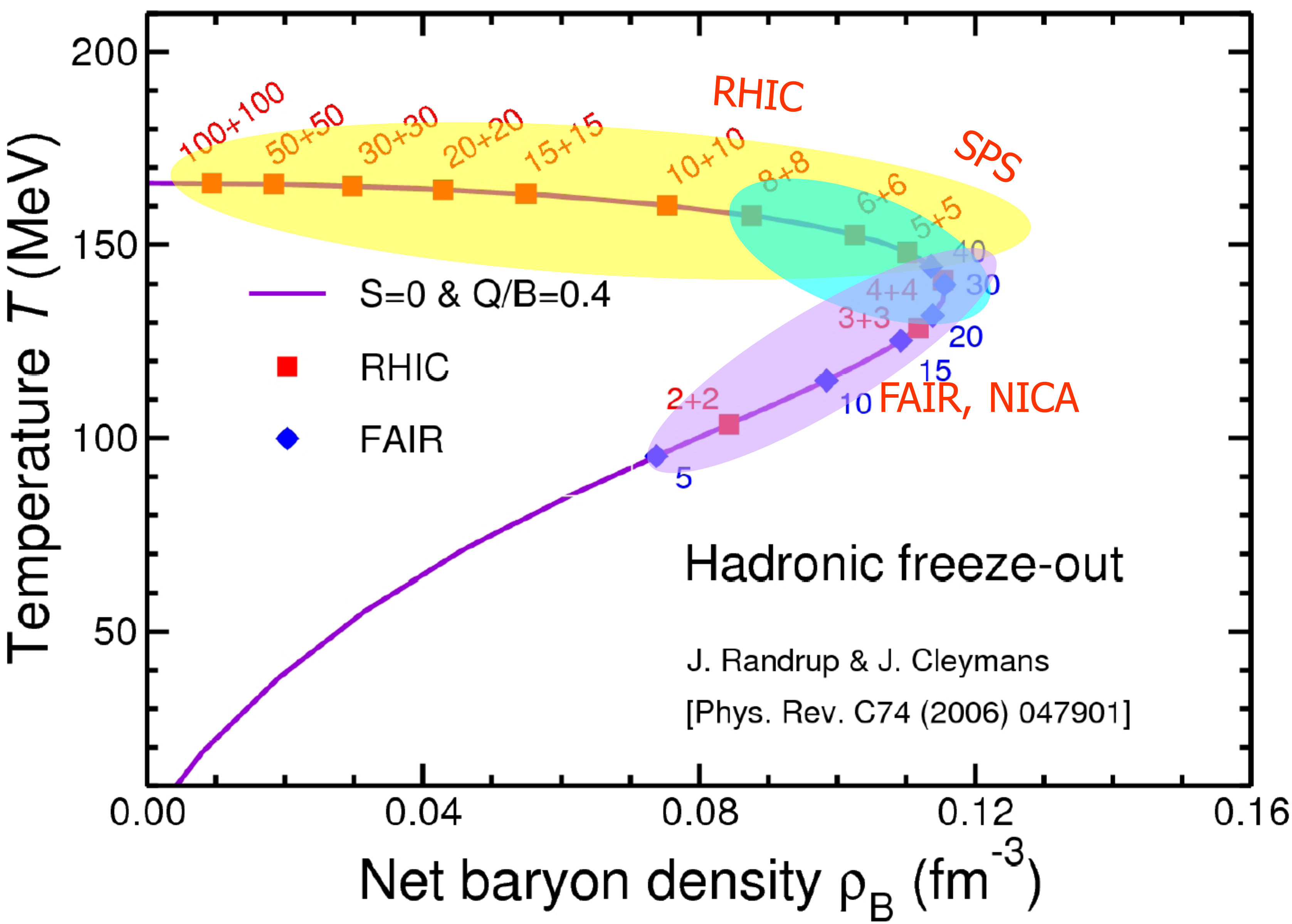
UrQMD



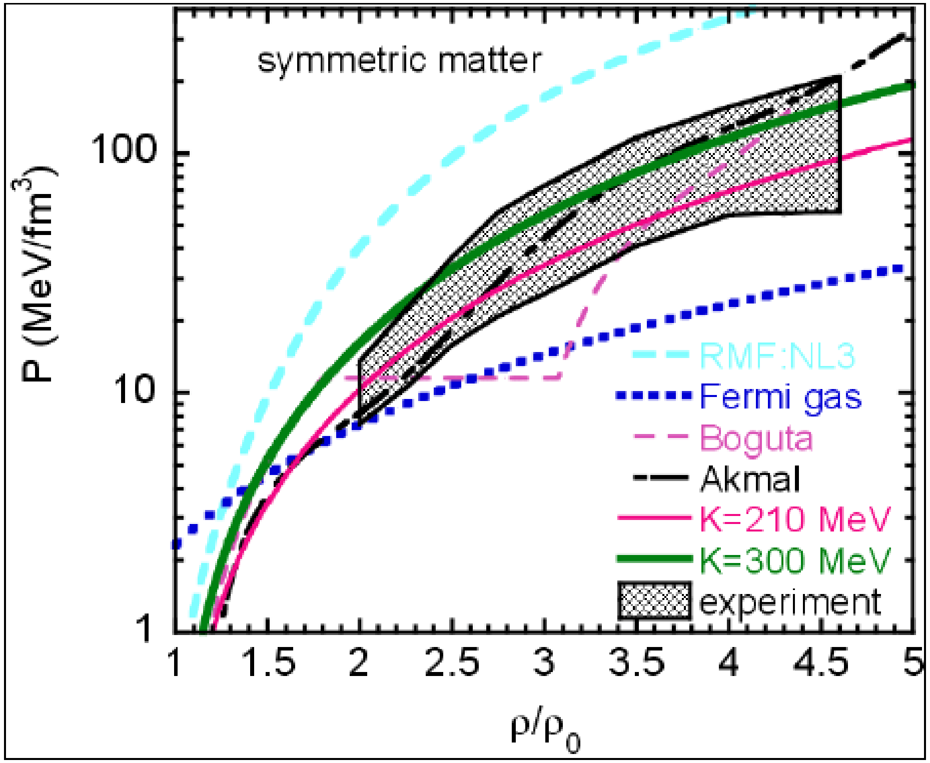
Ivanov, Russkikh, Toneev 2006

Central densities during HIC

Freeze-out conditions

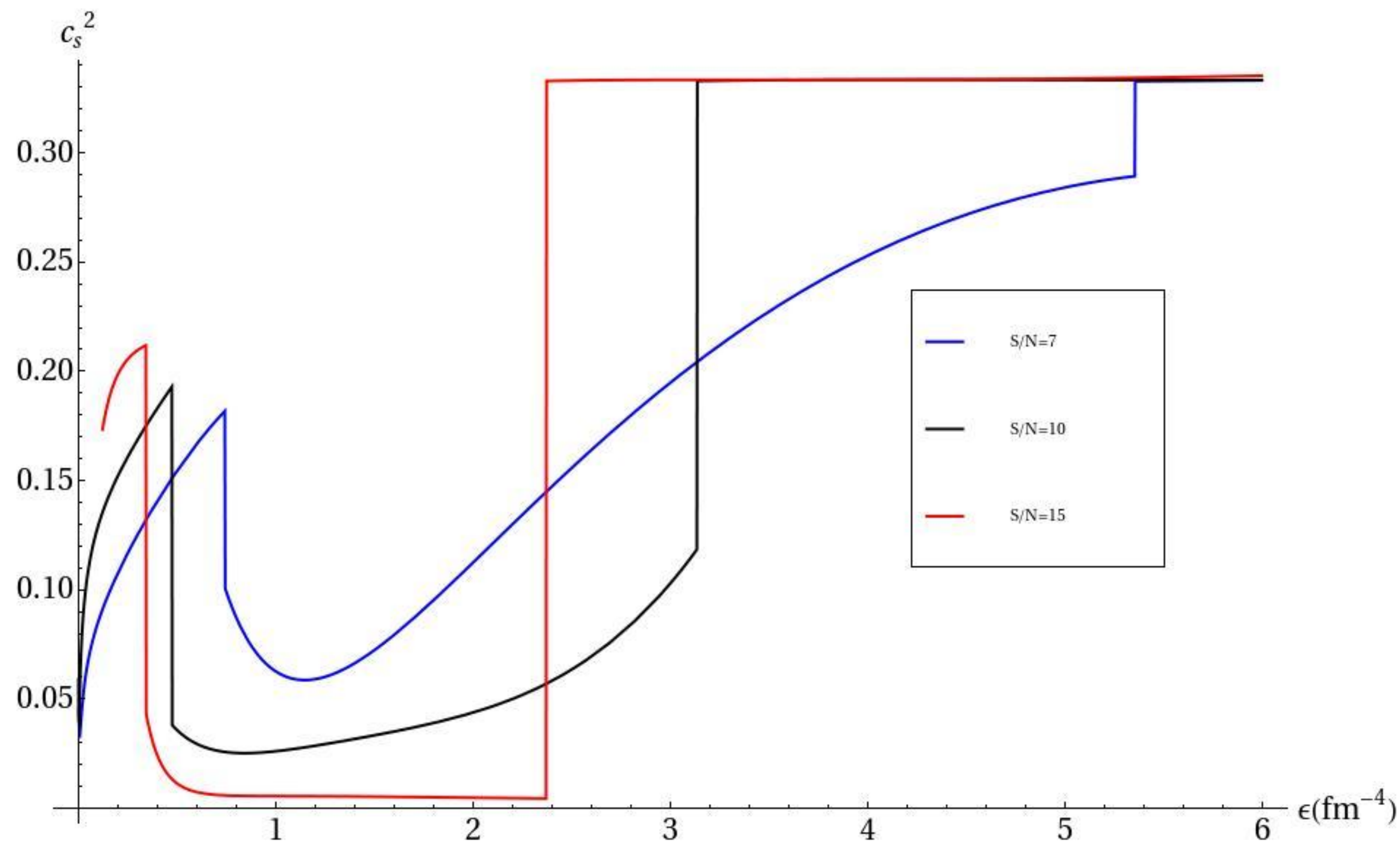


From Danielewicz, Lacey & Lynch 2002

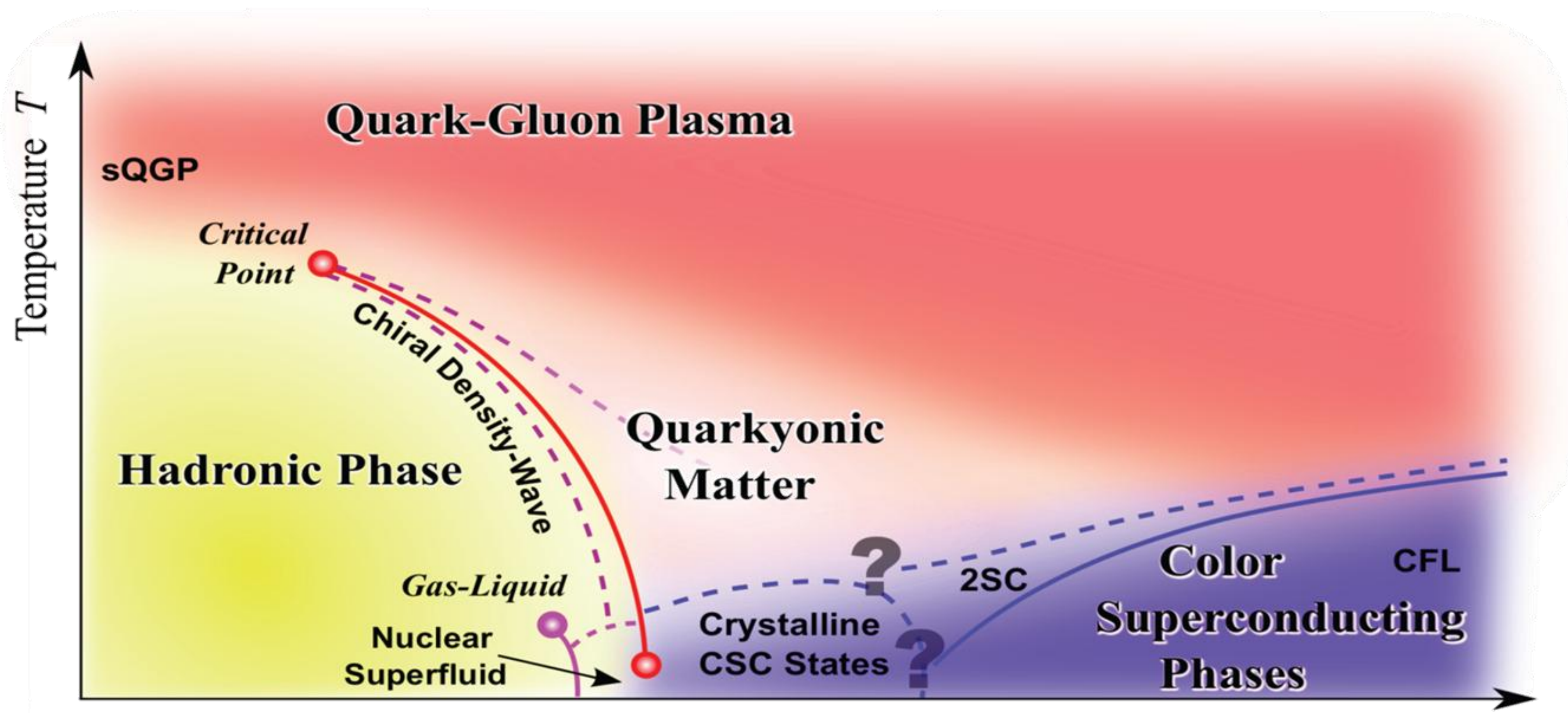


Based on AGS data at E_{lab} <= 10 A GeV

Sound velocity in a mixed quark-hadron phase
(MIT-bag model)



(Possible) phases of matter at high ρ and T



Courtesy of T. Hatsuda

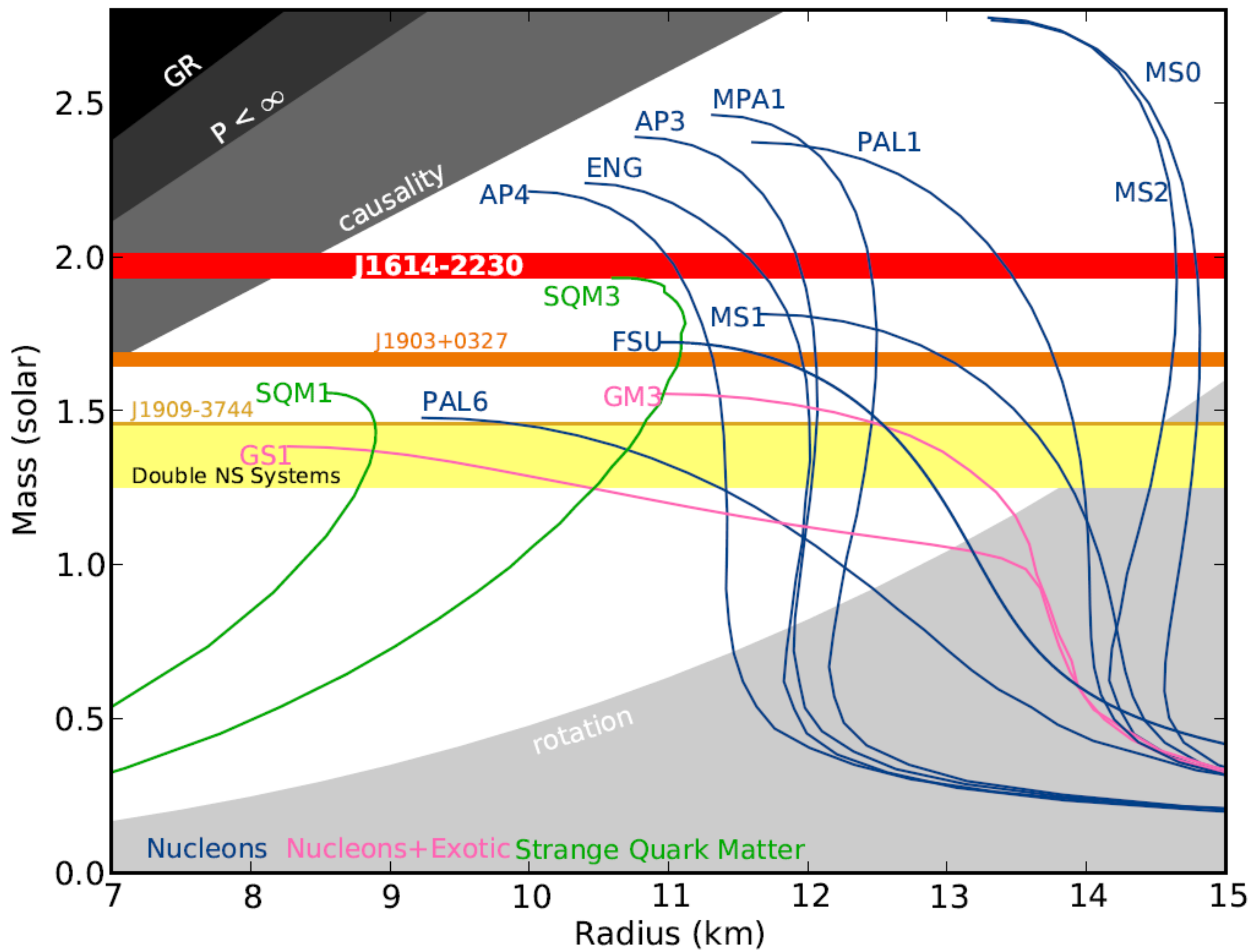
Experiments on superdense nuclear matter

Experiment	Energy range (Au/Pb beams)	Reaction rates Hz
STAR@RHIC BNL	$\sqrt{s_{NN}}$ = 7 – 200 GeV	1 – 800 (limitation by luminosity)
NA61@SPS CERN	E_{kin}= 20 – 160 A GeV $\sqrt{s_{NN}}$= 6.4 – 17.4 GeV	80 (limitation by detector)
MPD@NICA Dubna	$\sqrt{s_{NN}}$= 4.0 – 11.0 GeV	~1000 (design luminosity of 10^{27} $cm^{-2}s^{-1}$ for heavy ions)
CBM@FAIR Darmstadt	E_{kin}= 2.0 – 35 A GeV $\sqrt{s_{NN}}$= 2.7 – 8.3 GeV	10^5 – 10^7 (limitation by detector)

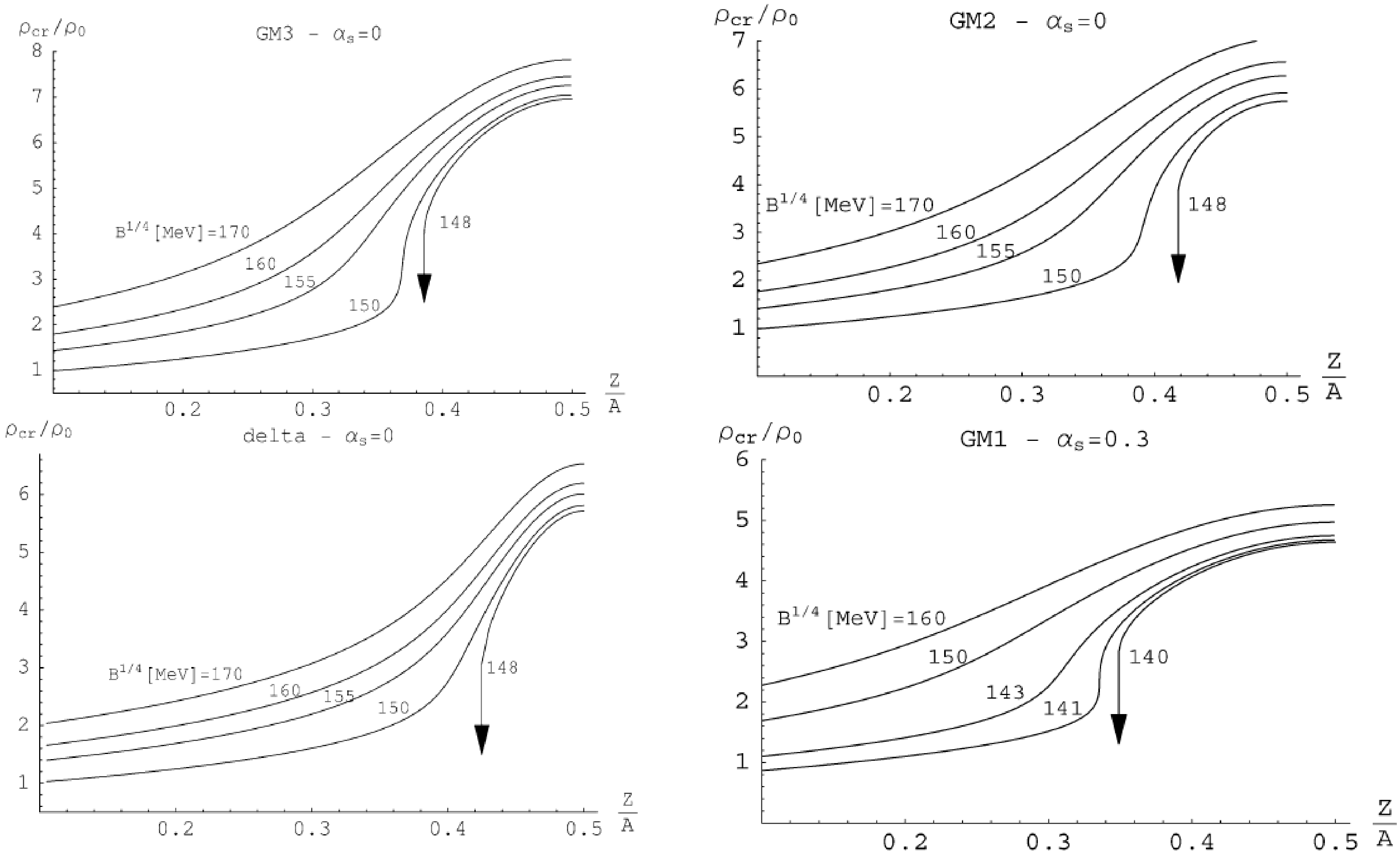
From lab to stars

Shapiro delay measurement of a 2 solar mass neutron star

P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts and J. W. T. Hessels, *Nature*, 467, 1081 (2010)



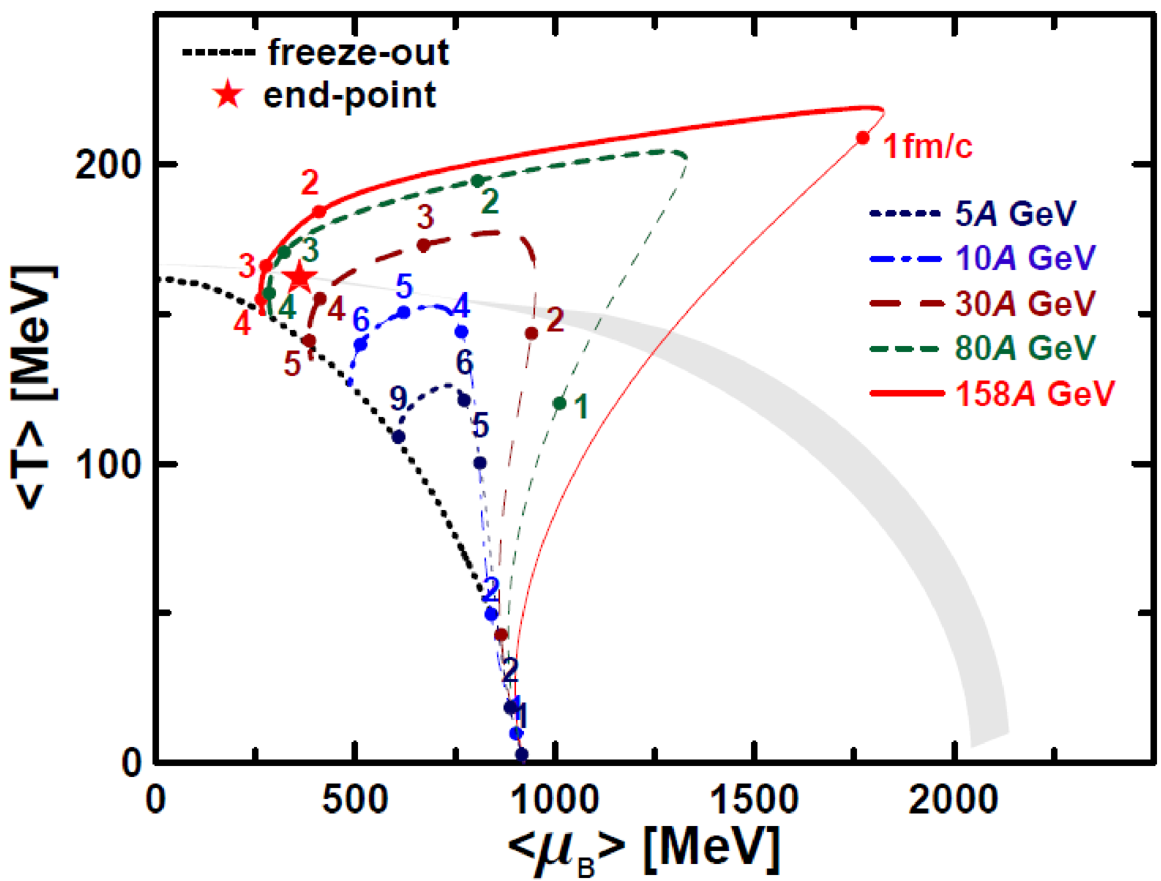
Isospin dependence of critical densities



Di Toro et al. 2006

Temperature in heavy ion collisions

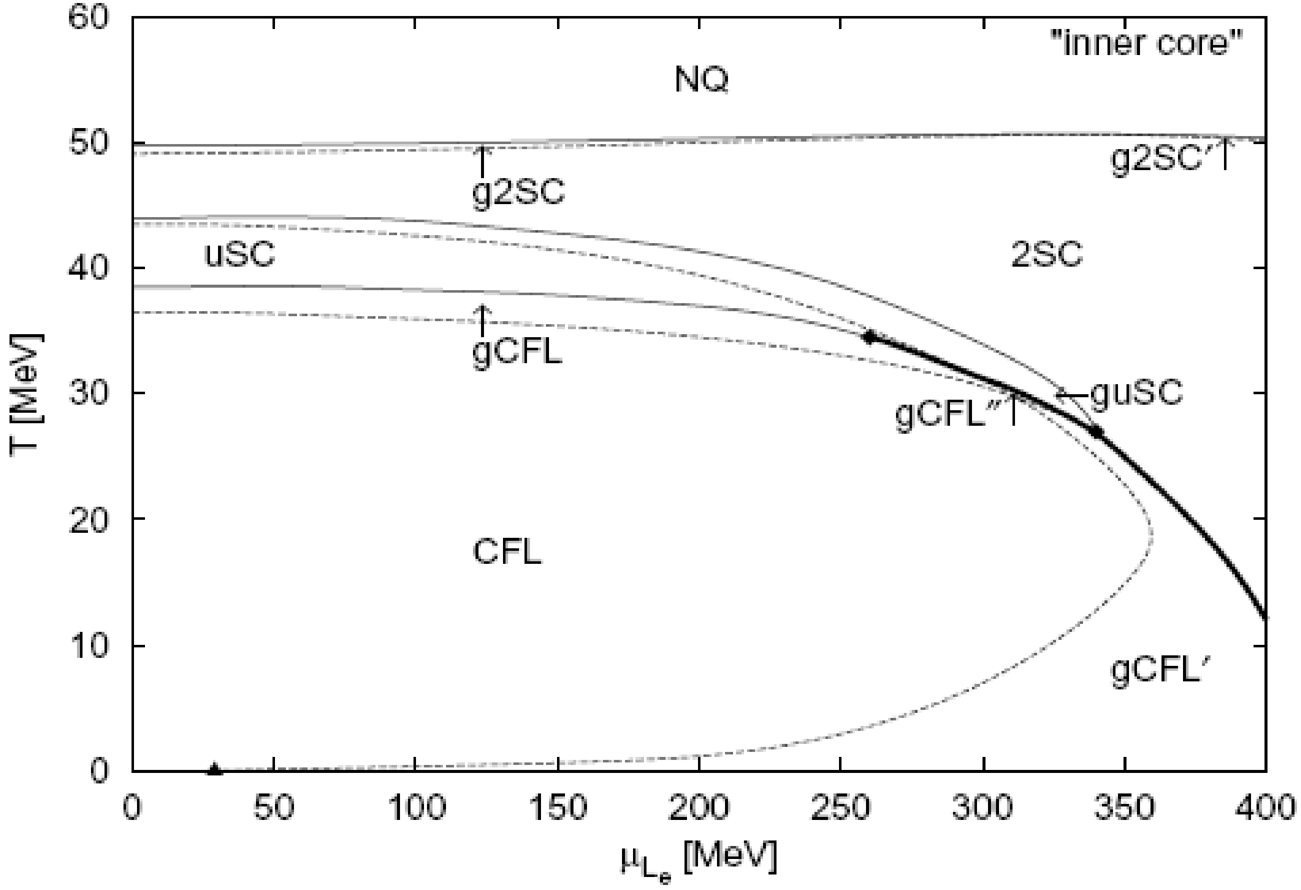
Ivanov, Russkikh, Toneev 2006



In HIC temperatures exceed 100 MeV for energies larger than a few GeV per nucleon

Phase diagram of neutral quark matter: effect of neutrino trapping and temperature

Ruster et al. PRD73 (2006) 034025



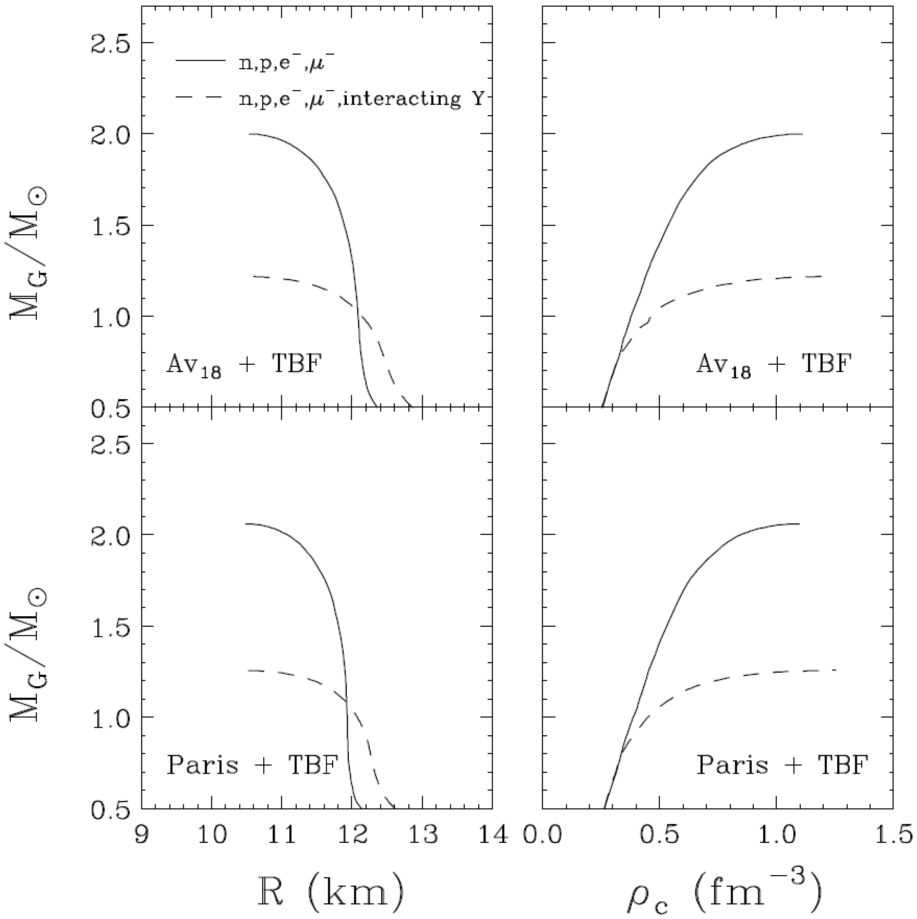
Superconducting gaps vanish at temperatures above 100 MeV (or less…): they are not present in matter tested in heavy ion collisions but they can exist in compact stars

Strangeness production

- In heavy ion experiments strangeness can be produced only by strong-interaction and therefore via associated production. The typical fraction of strangeness is less than 10%
- In a compact star strangeness is mainly produced by weak interaction. Hyperons start appearing at densities above (2.5 – 3) ρ_0
- Hyperons can significantly soften the EoS: is it possible to have a 2 Ms compact star with hyperons? Yes, but…

Hyperonic stars in a non-relativistic BHF

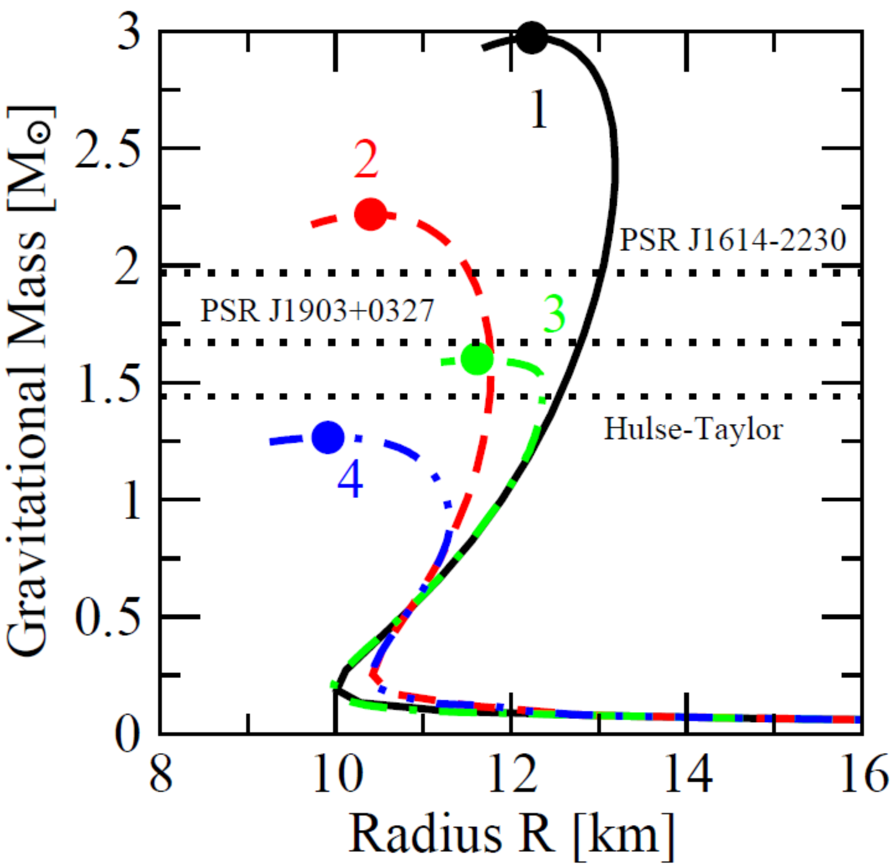
Baldo,Burgio, Schulze Phys.Rev. C61 (2000) 055801

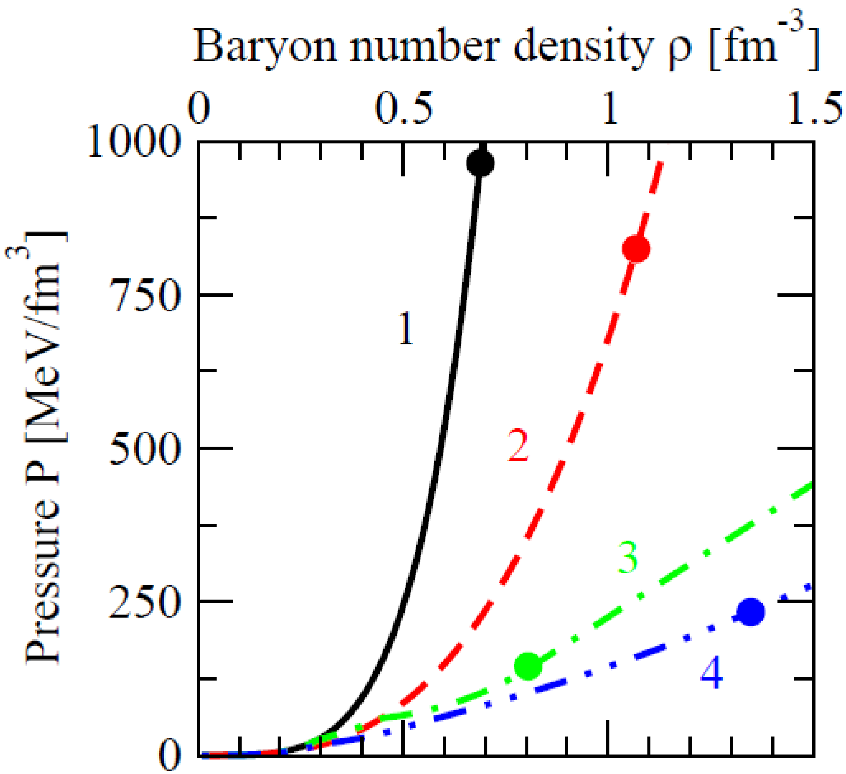


The maximum mass of a hyperonic star in BHF is smaller than 1.4 M_s !

Hyperonic stars in a non-relativistic BHF with parametrised 3-body forces between hyperons

Vidana et al. Europhys.Lett. 94 (2011) 11002





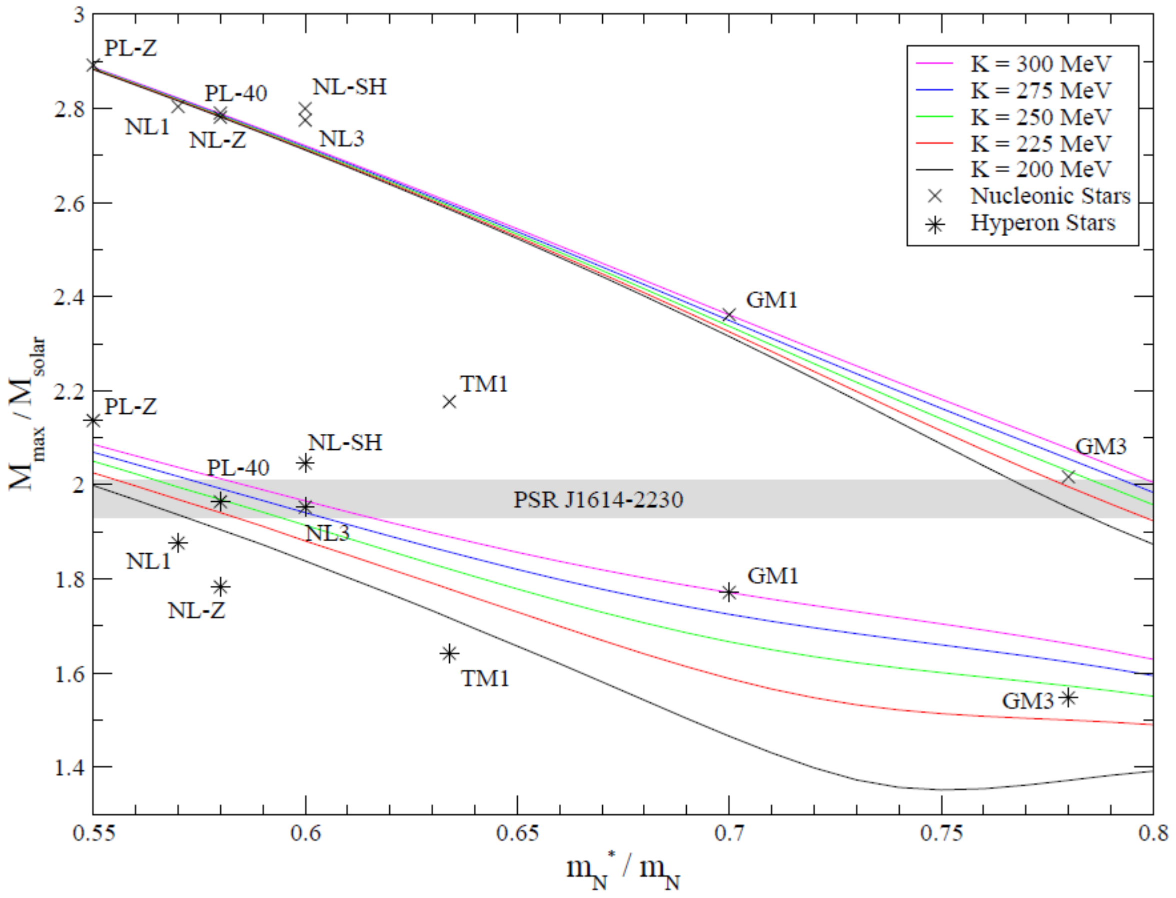
3-body forces are not sufficent to reach two solar masses

Note that the central density is very large, 5 – 9 ρ_0

A relativistic approach could be needed

Hyperonic stars in a relativistic mean-field with a repulsive vector ϕ-meson interaction

Weissenborn, Chatterjee, Schaffner-Bielich Nucl.Phys. A881 (2012) 62

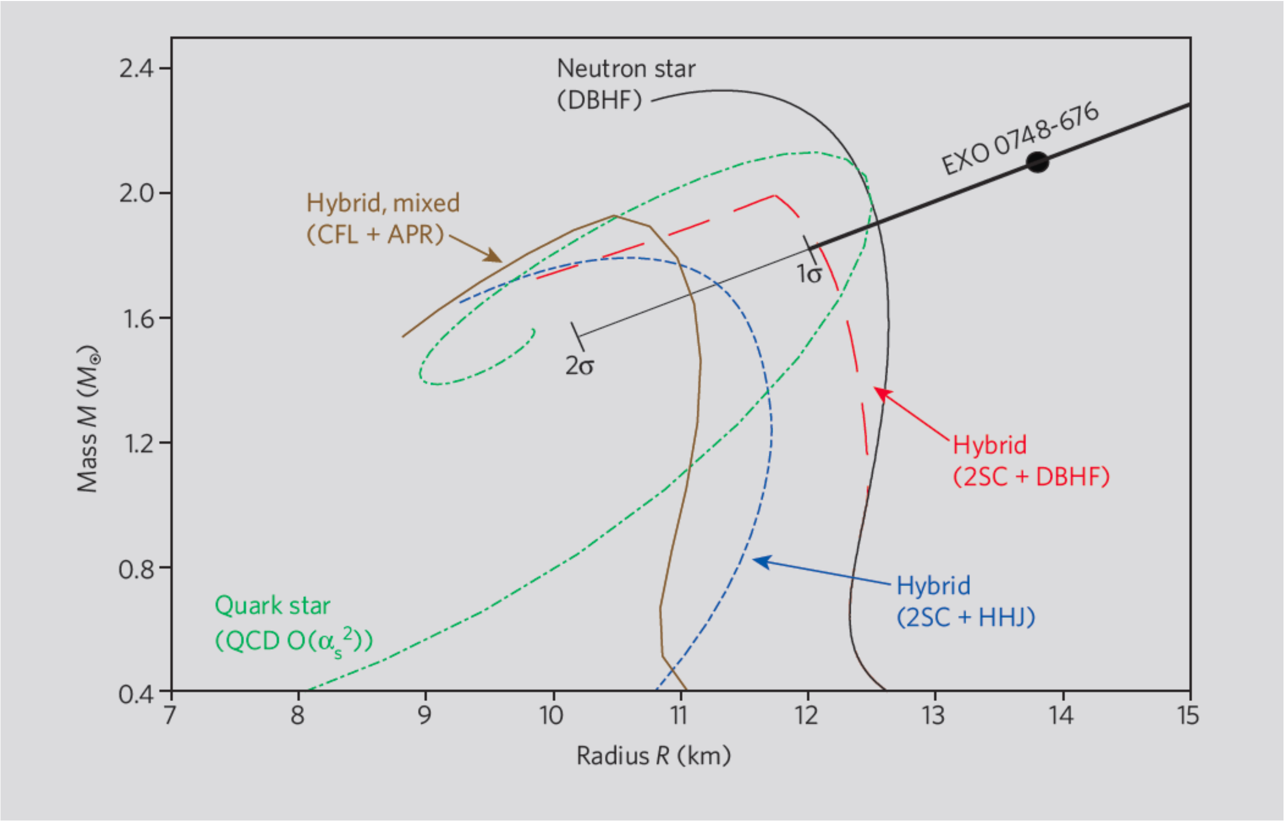


SU(6) symmetry imposed

Large maximum masses can be obtained but only if the effective mass of the nucleon is strongly reduced

Hybrid and quark stars can be massive

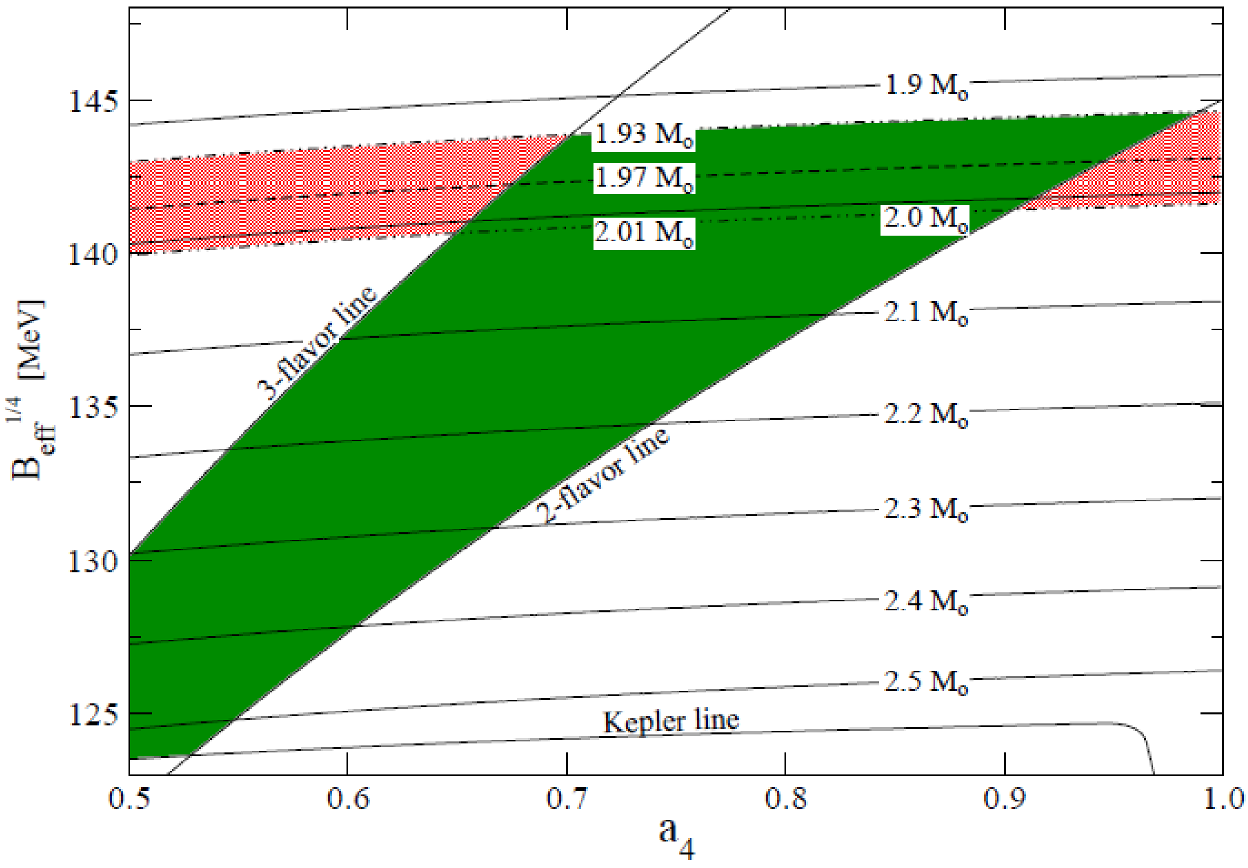
Alford, Blaschke, Drago, Klaehn, Pagliara, Schaffner-Bielich Nature 445, E7 (2007)



Transitions from a purely hadronic configuration to a configuration containing at least in part deconfined quark matter are possible. Energies of the order of a few 10^{53} erg are liberated in the transition

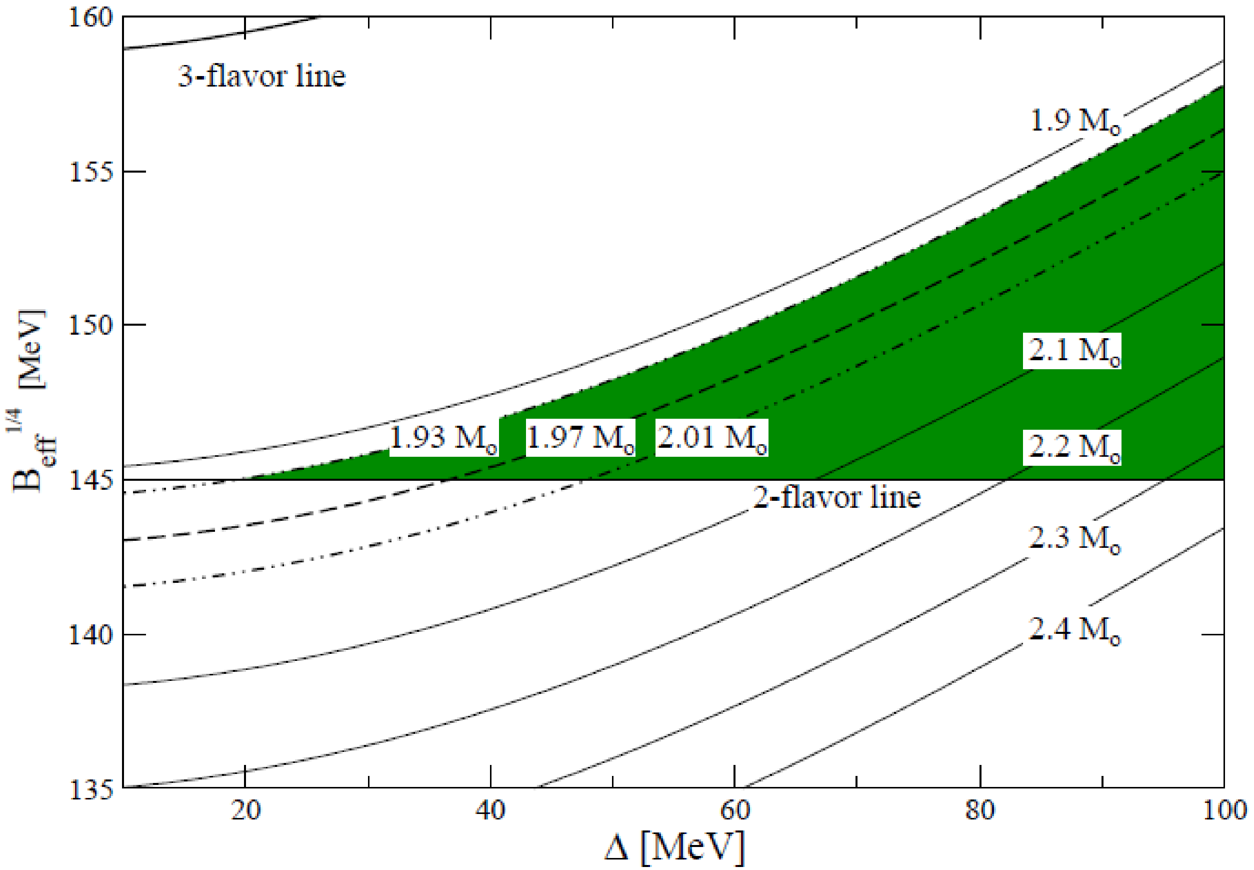
Maximum masses for quark stars
MIT-bag model with gluonic interaction

Weissenborn et al. Astrophys.J. 740 (2011) L14



Maximum masses for quark stars MIT-bag model with CFL condensate

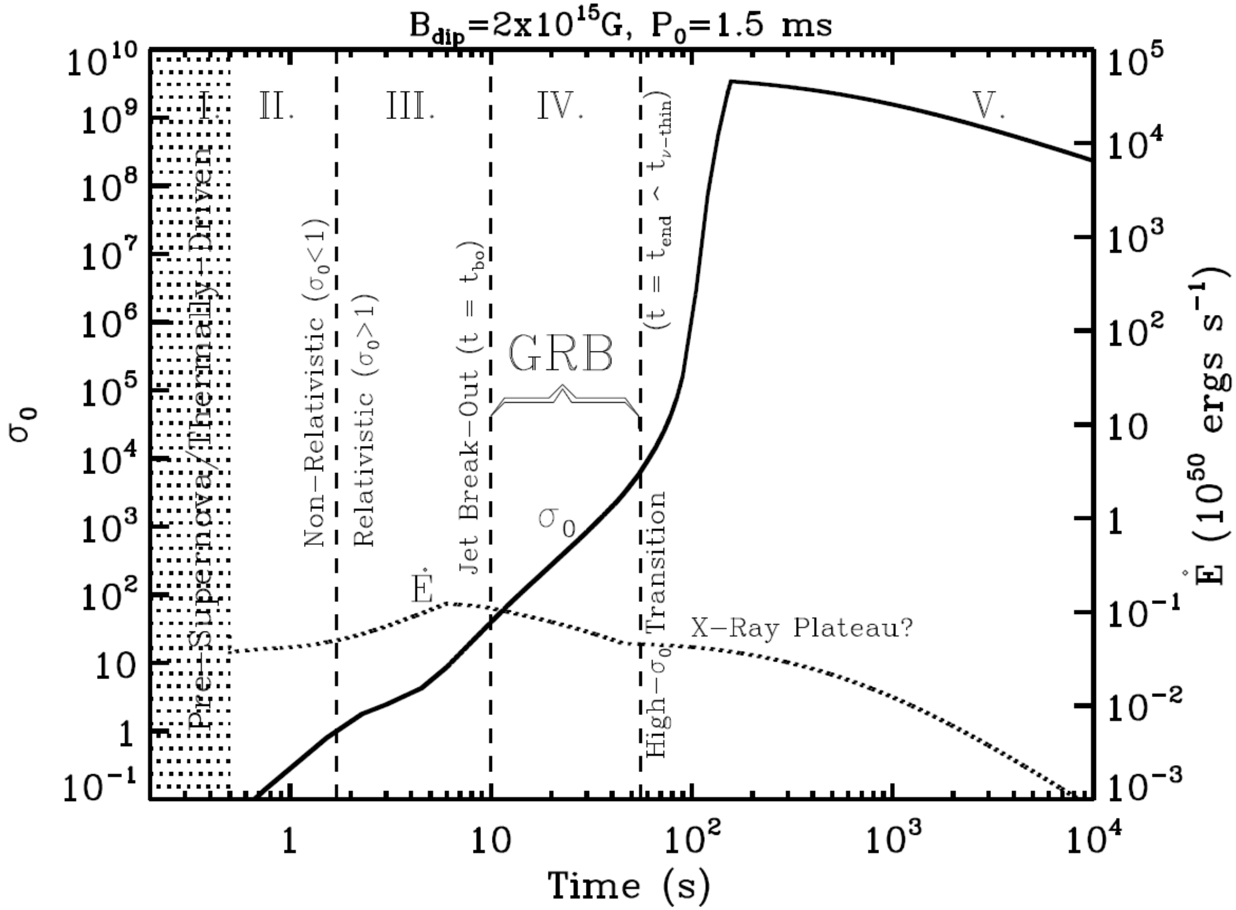
Weissenborn et al. Astrophys.J. 740 (2011) L14



Maximum masses up to 2.2 Ms can be obtained

Metastability of compact stars and GRBs

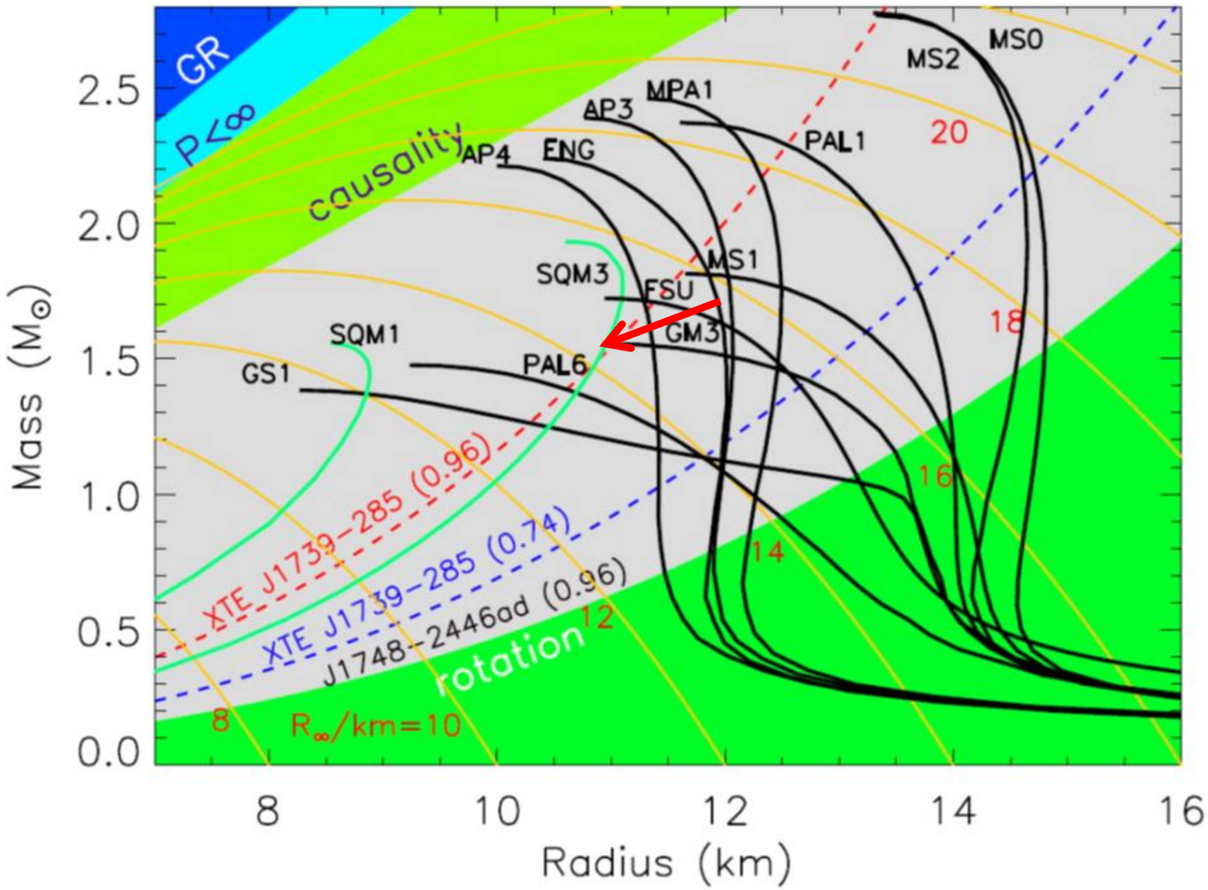
Magnetar model of GRBs (Metzger et al.)



$$\sigma_0 \equiv \frac{\phi^2\Omega^2}{\dot{M}c^3} \qquad \phi \equiv B_r r^2$$

Quark deconfinement would reheat the star and generate a new mass ejection

Transition from a neutron star to a strange (or hybrid) star



Excess of long quiescent times in GRBs

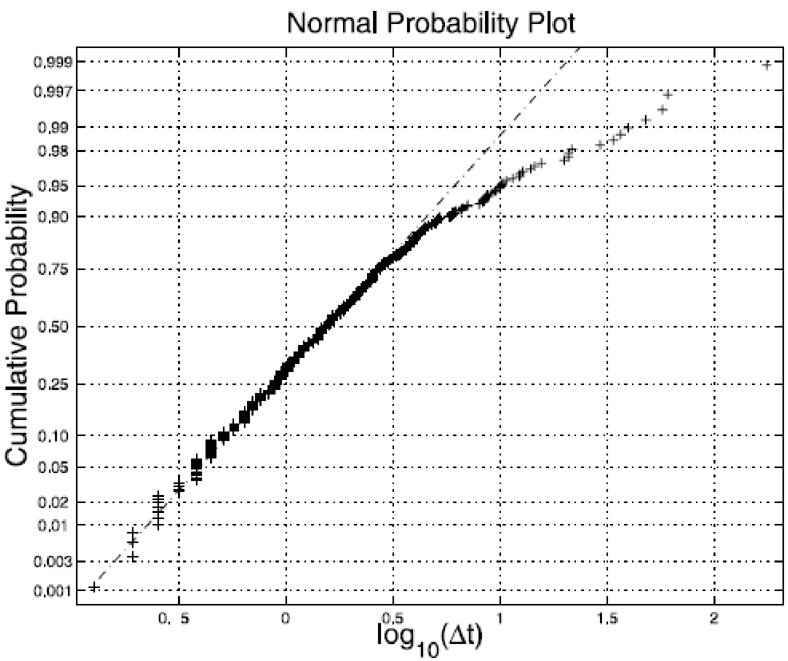


Figure 5. The cumulative distribution of $\log_{10}(\Delta t)$. Δt is taken from the sample of 24 dimer bursts. The cumulative distribution is compared to this of a normal distribution with the best-fitting parameters.

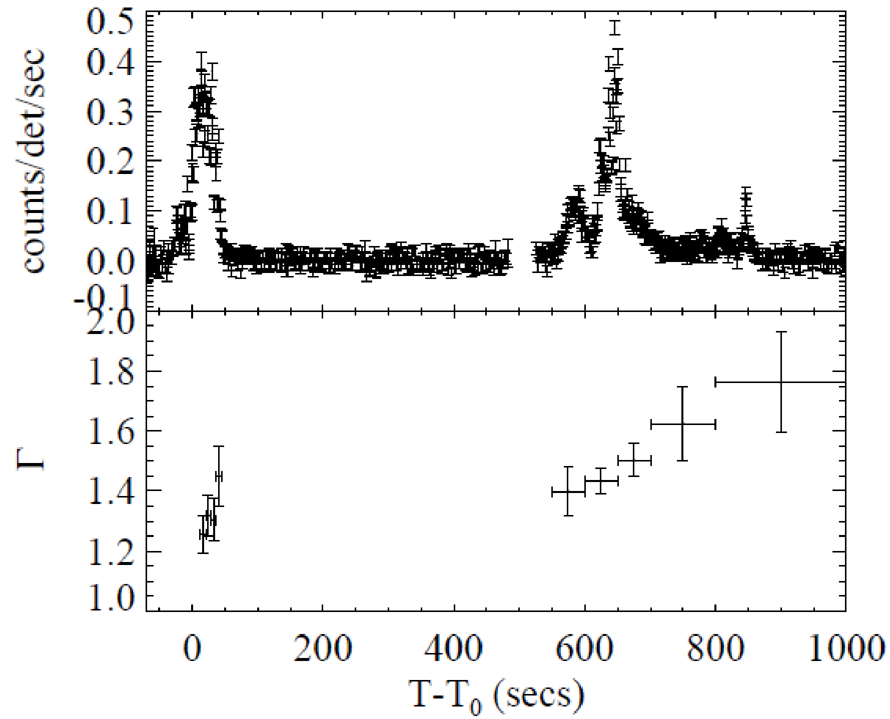


FIG. 1.— BAT count rates (upper panel) and photon index evolution (lower panel) of GRB 110709B. The spectral model is a simple power law.

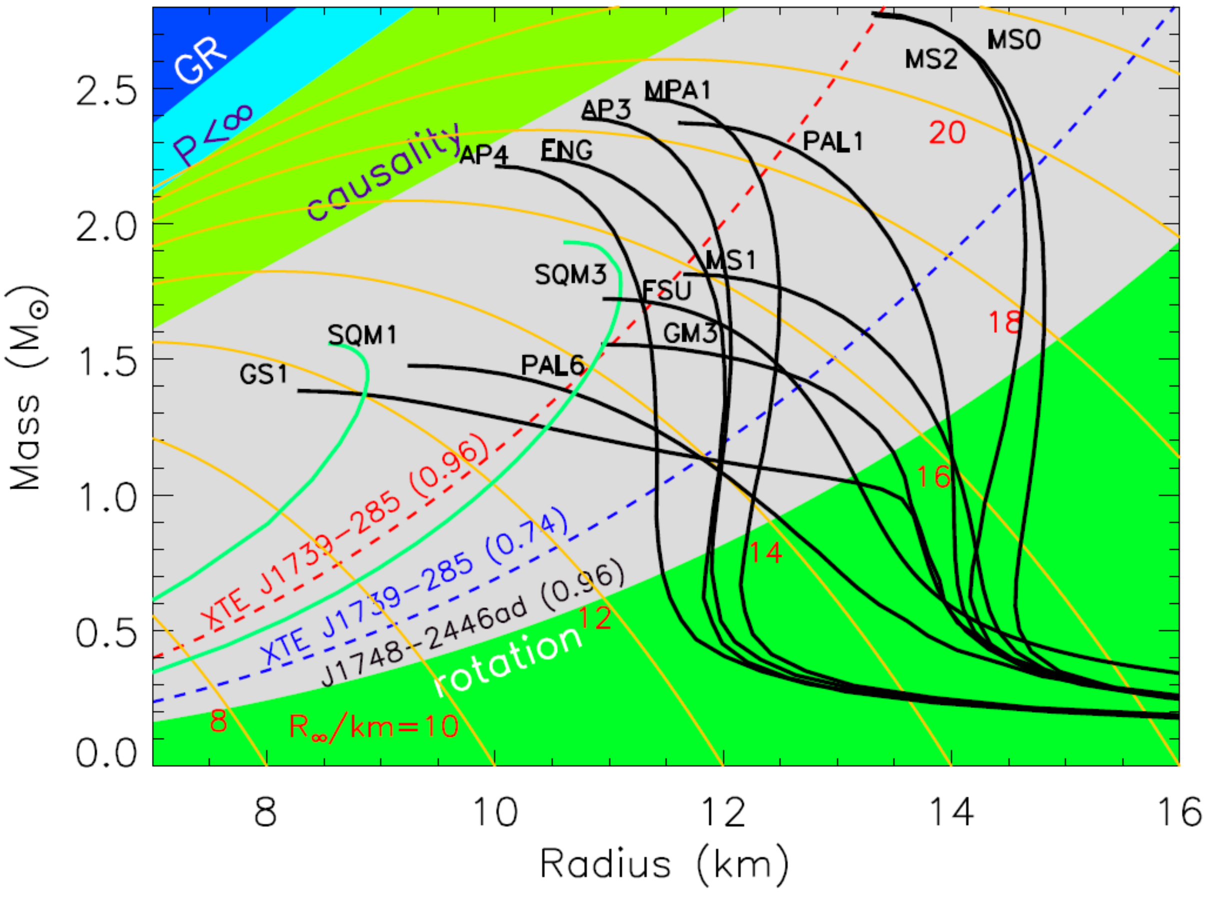
Nakar & Piran 2002

Zhang et al.2012

The role of LOFT

Theoretical M-R relations

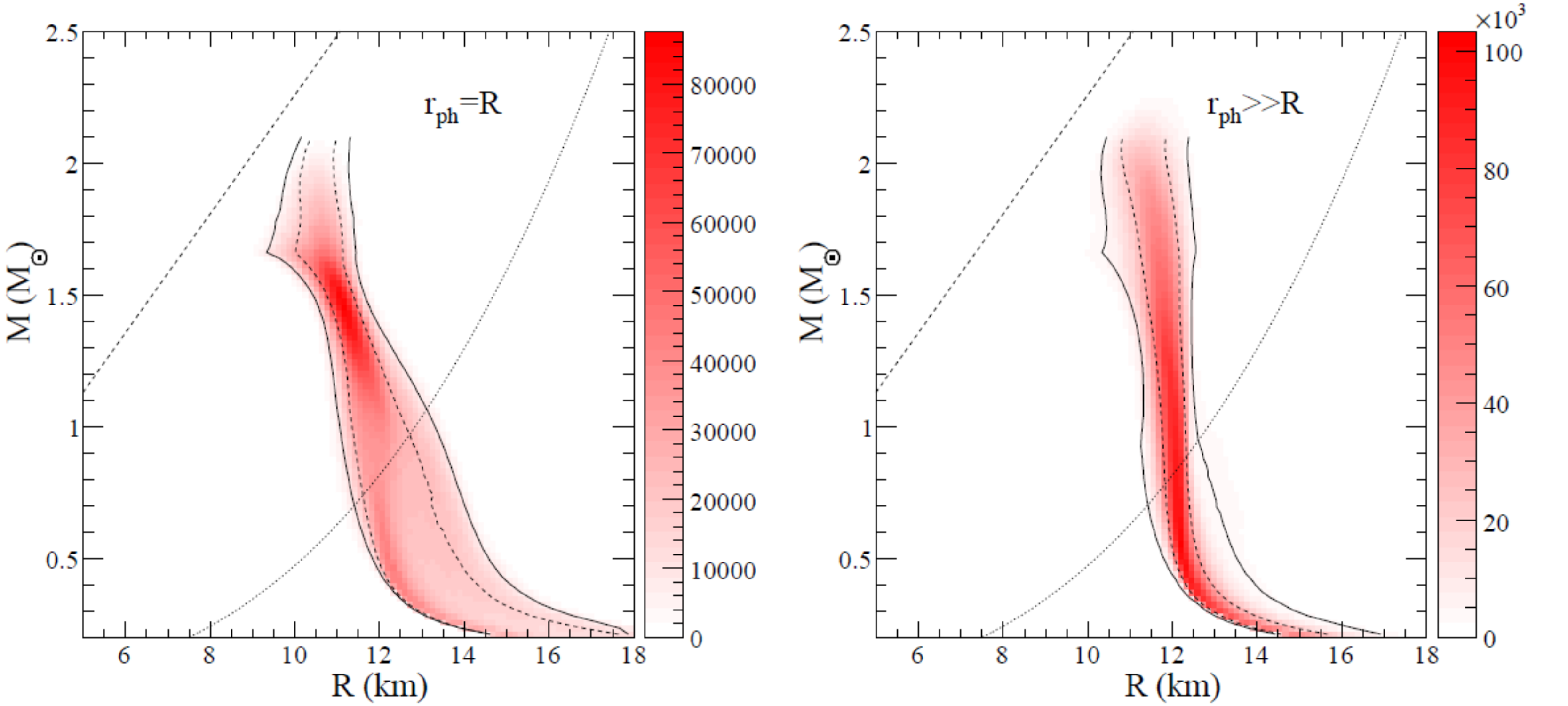
Lattimer & Prakash Phys.Rept.2007



The Equation of State from Observed Masses and Radii of Neutron Stars

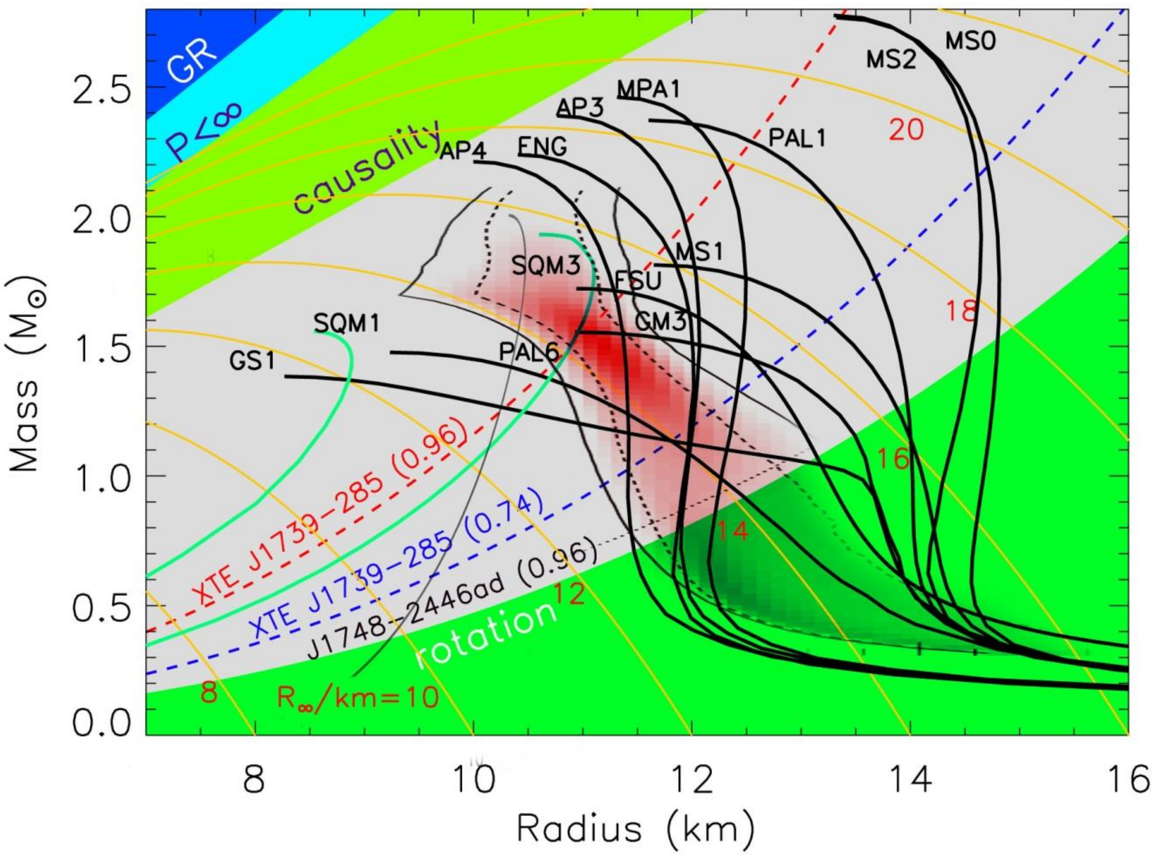
Steiner, Lattimer, Brown 2011

Bayesian analysis based on LMXBs and on x-ray bursts data



assumption that all neutron stars must lie on the same mass–radius curve

LOFT: measuring masses and radii with (5-10)% precision



Conclusions

- HIC lab results indicate «new physics» at energies between highest AGS and lowest SPS data
- Data are compatible with quark deconfinement or with chiral symmetry restoration
- New experiments are under development in Europe, Russia and maybe USA
- It is highly non trivial to extrapolate from (almost) symmetric matter tested by HIC to β-stable matter inside compact stars (isospin and temperature dependence largely unknown)
- hyperonic stars are maybe possible: hyperons are almost certainly present in a 2 M_s star
- A transition from nuclear matter to quark matter could be able to explain long quiescent times in GRBs (magnetar model followed by quark deconfinement)
- (Time separation between SN and GRB, allowing Fe absorbtion lines)
- Precise data on M and R would complement lab data in providing a mapping of the high density EOS of matter