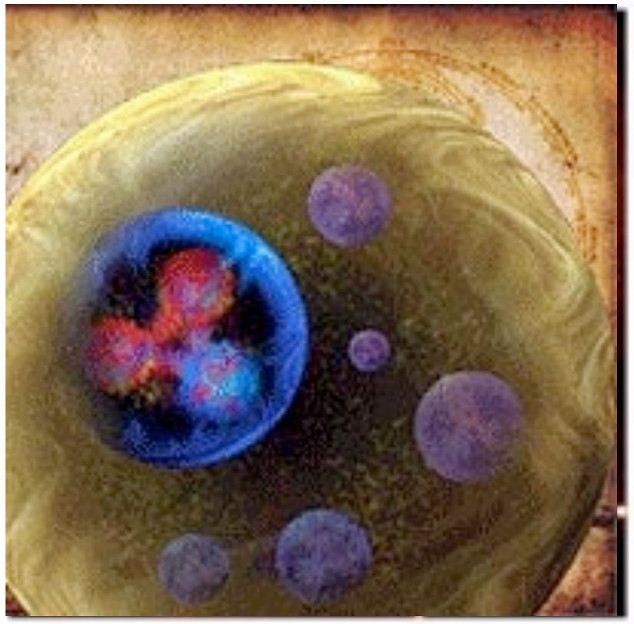


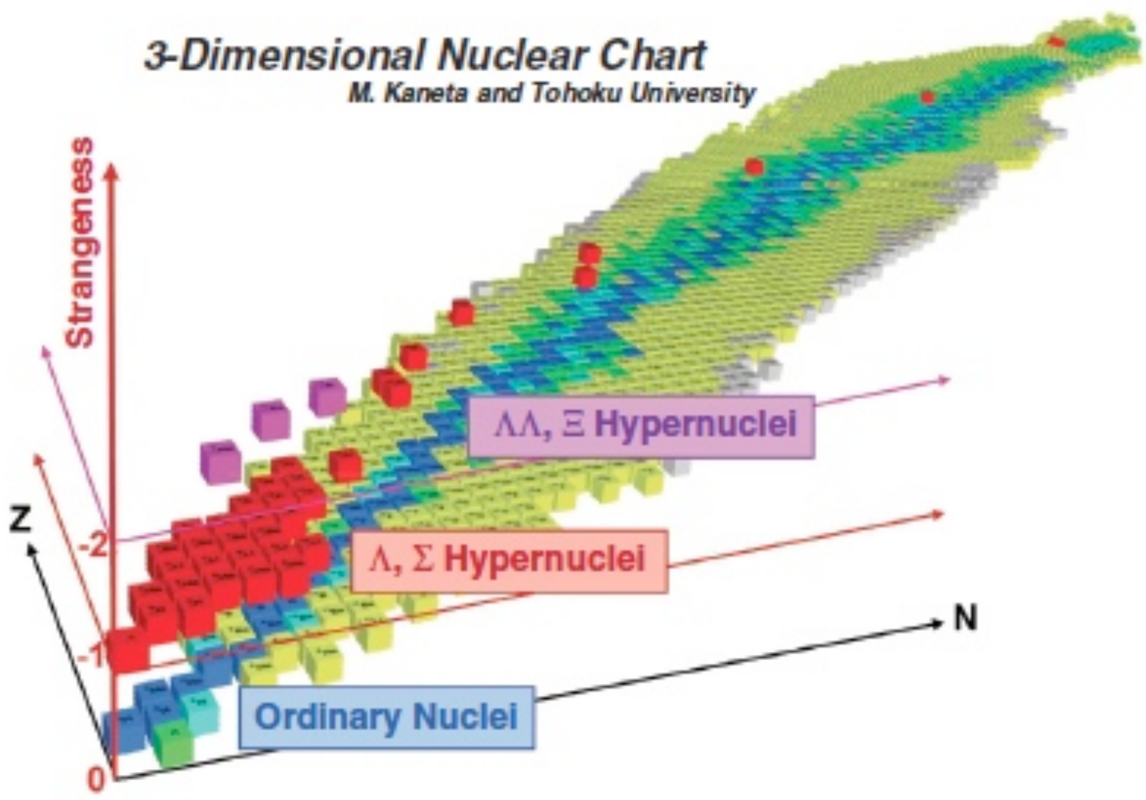



Hyperonic Equation of State and Astrophysical Applications

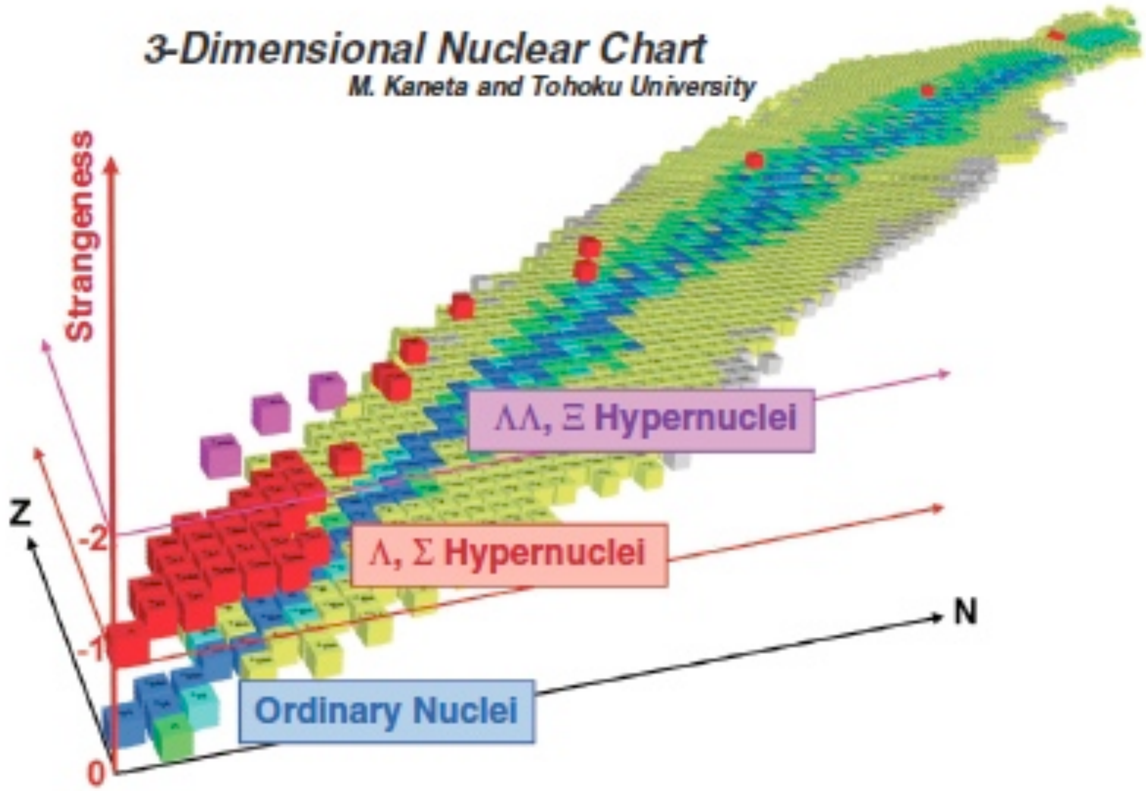
Debarati Chatterjee
Laboratoire de Physique Corpusculaire
Caen, France

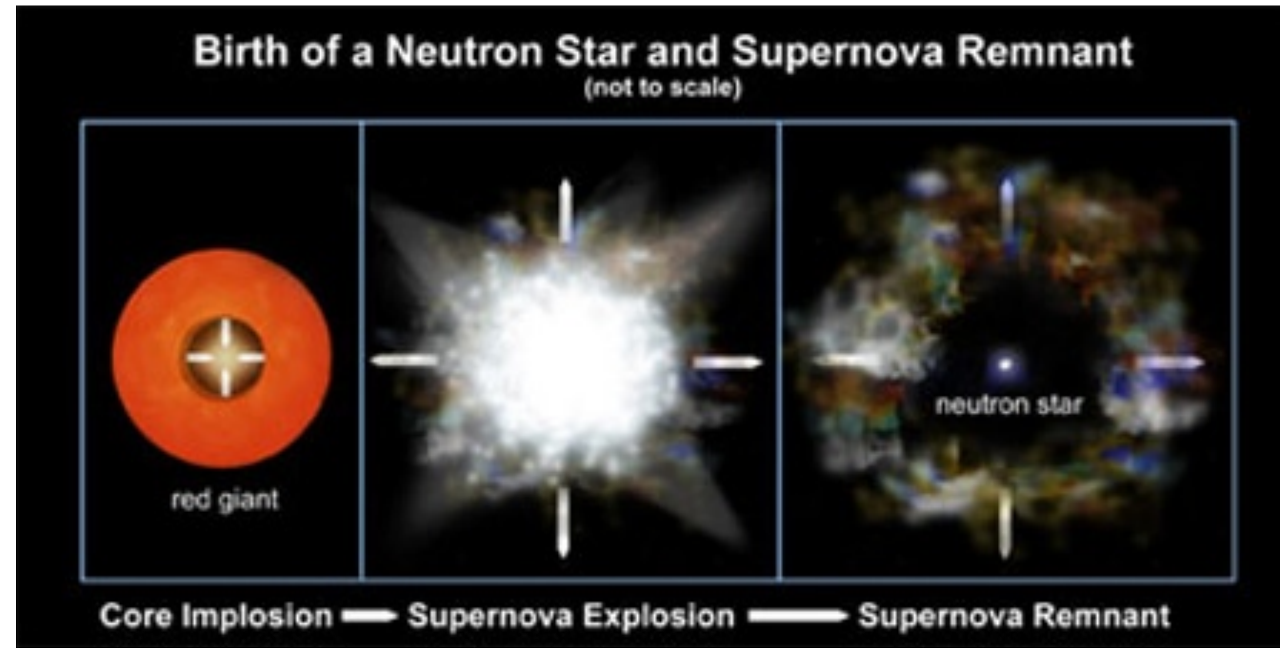
EMMI Workshop, Turin 2017

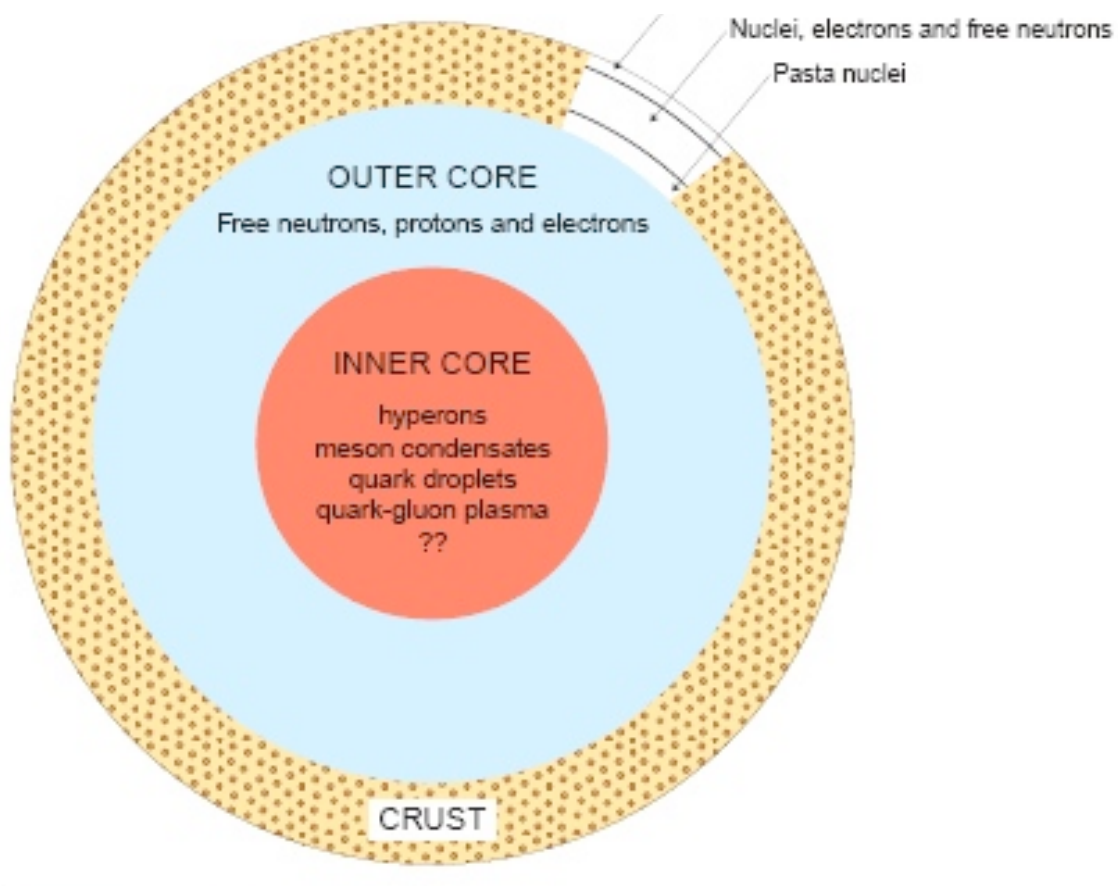
STRANGENESS IN NUCLEAR PHYSICS

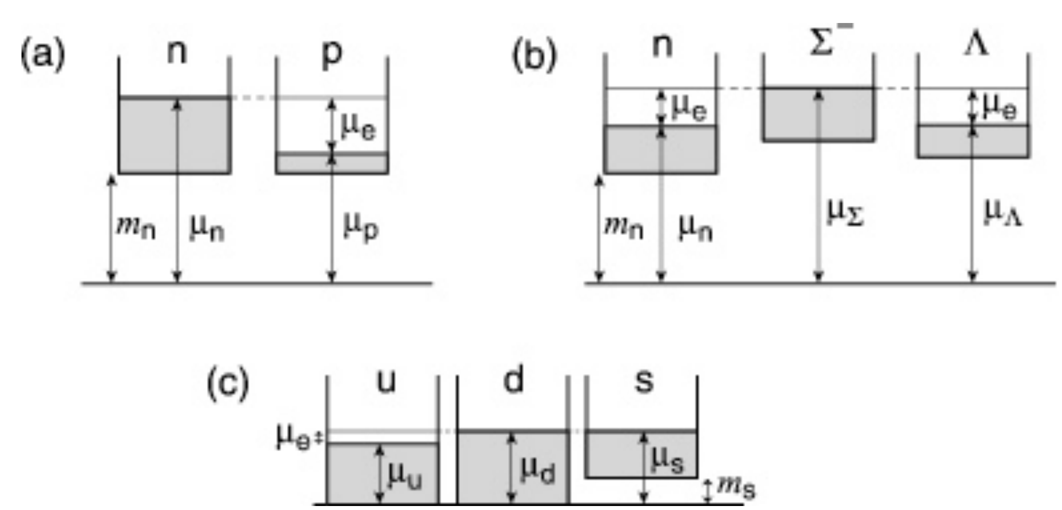


STRANGENESS IN ASTROPHYSICS: NEUTRON STARS









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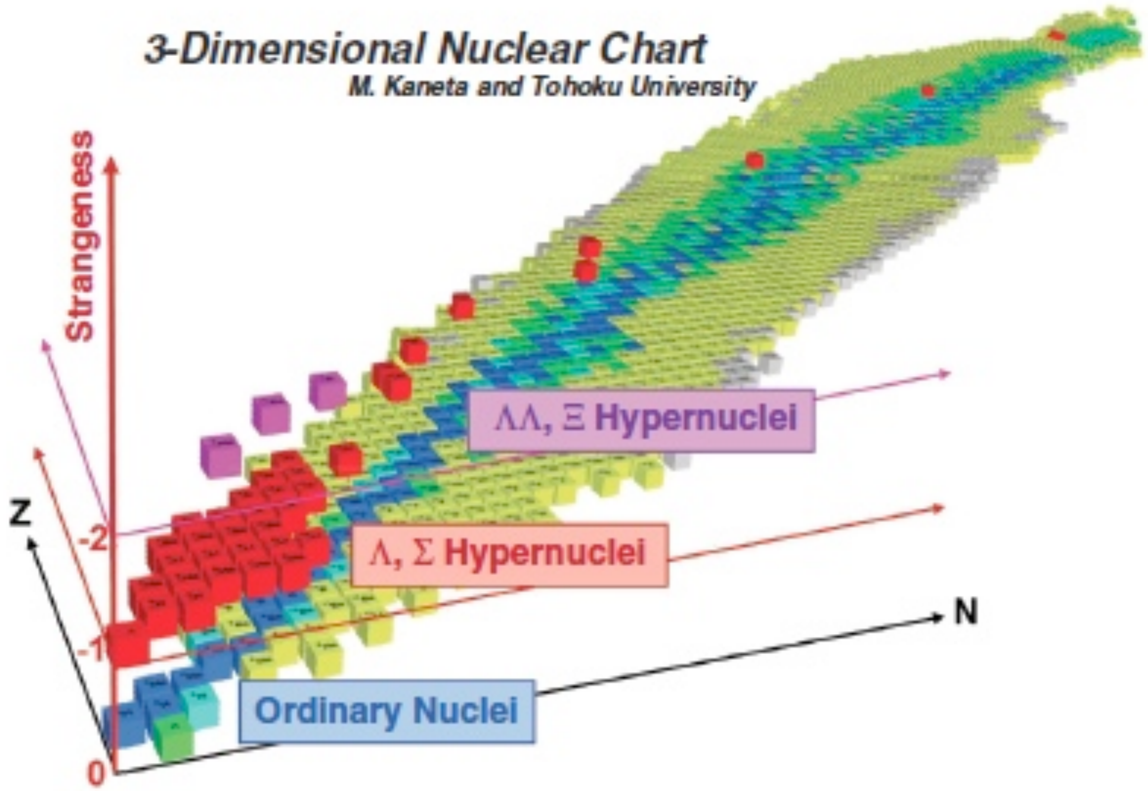
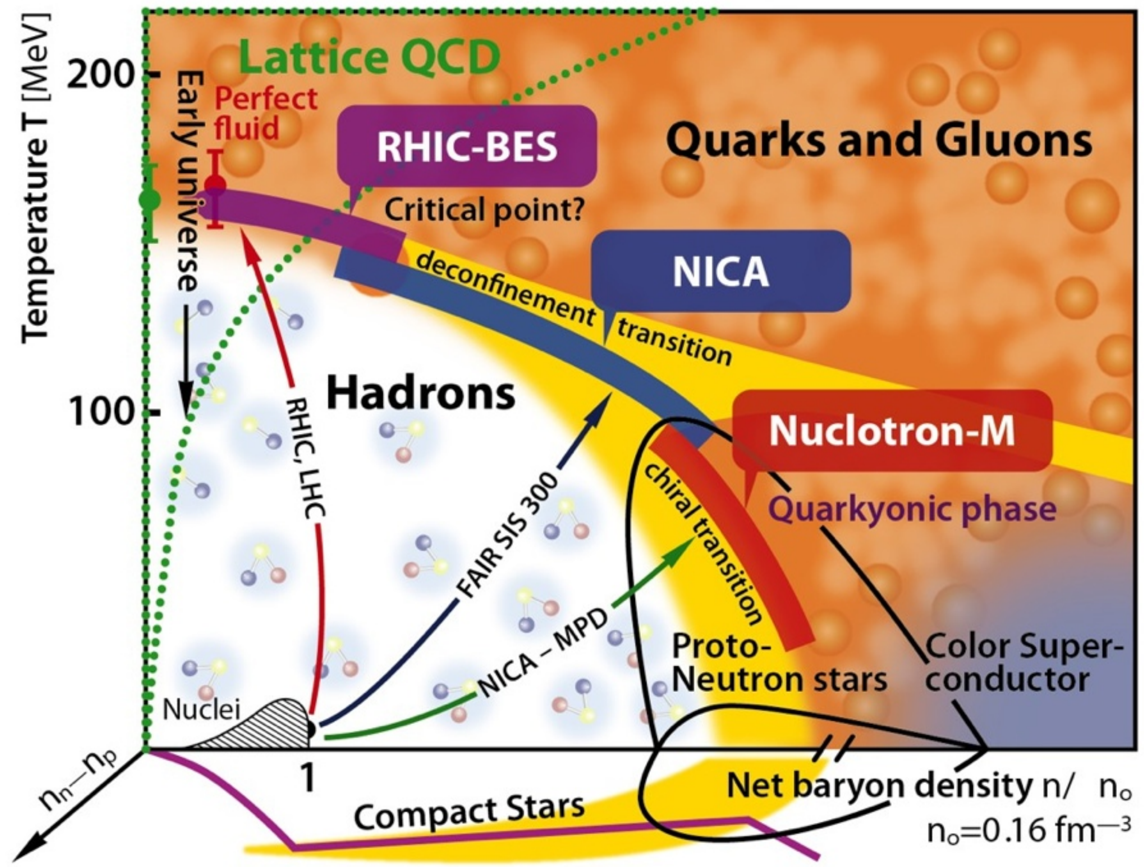
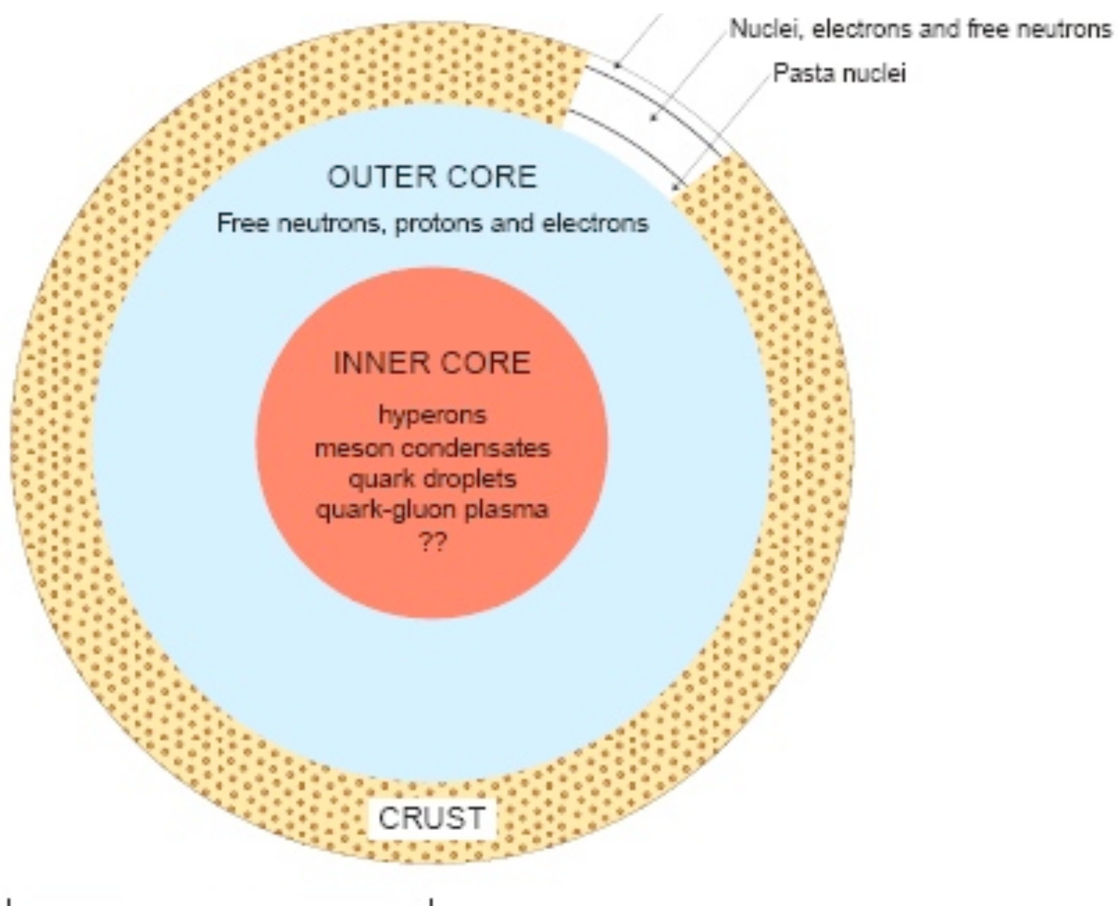
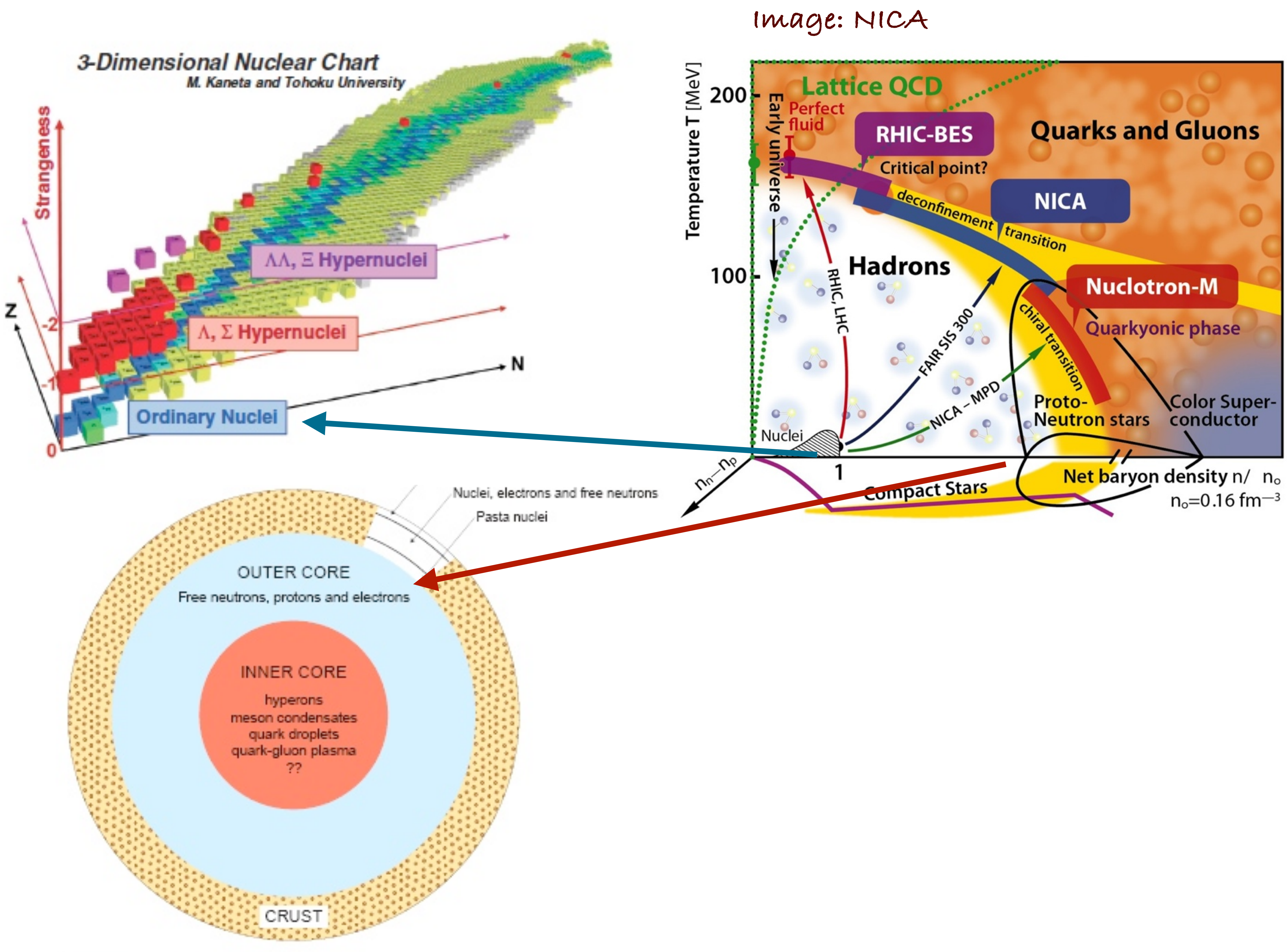


Image: NICA





STRANGENESS IN ASTROPHYSICS: NEUTRON STARS



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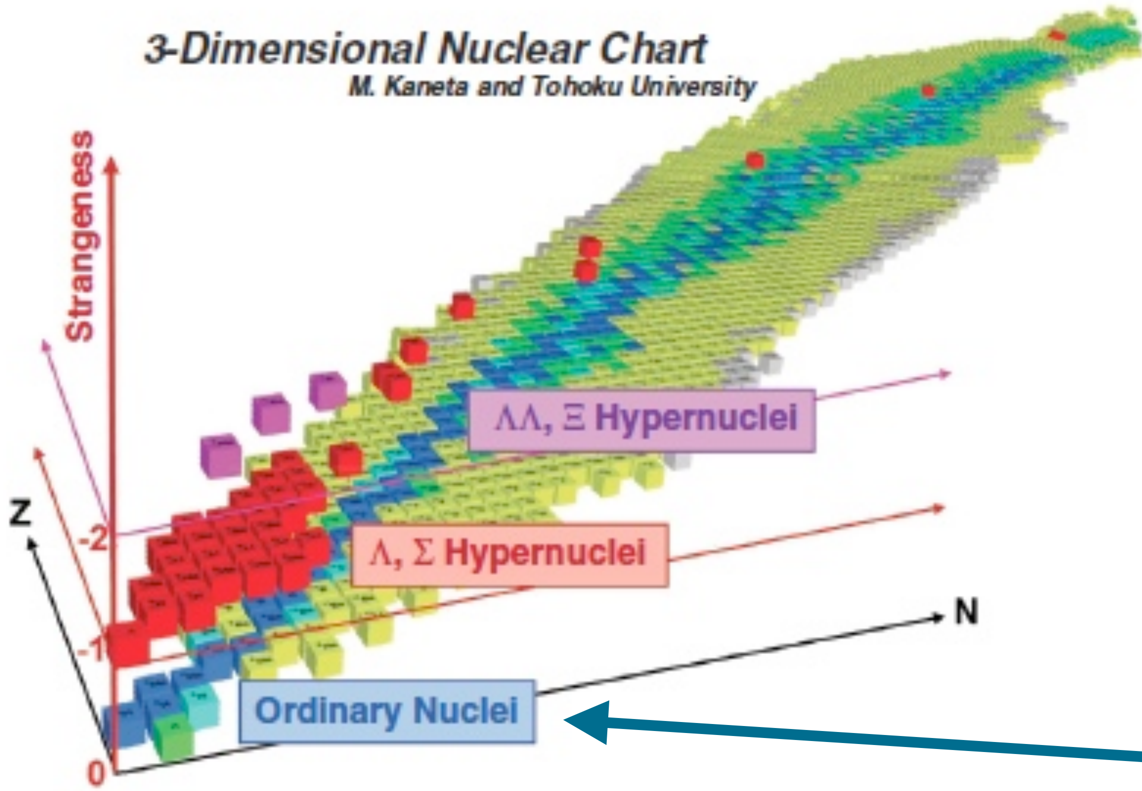

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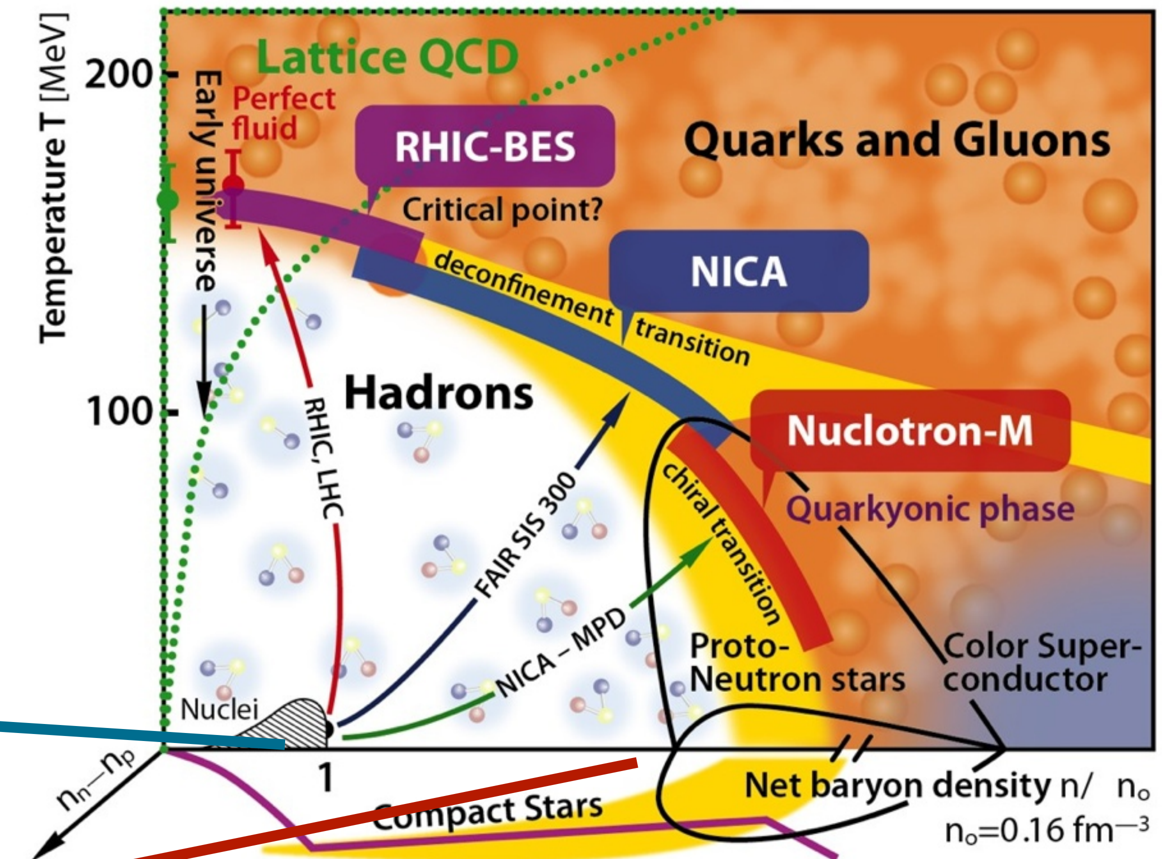
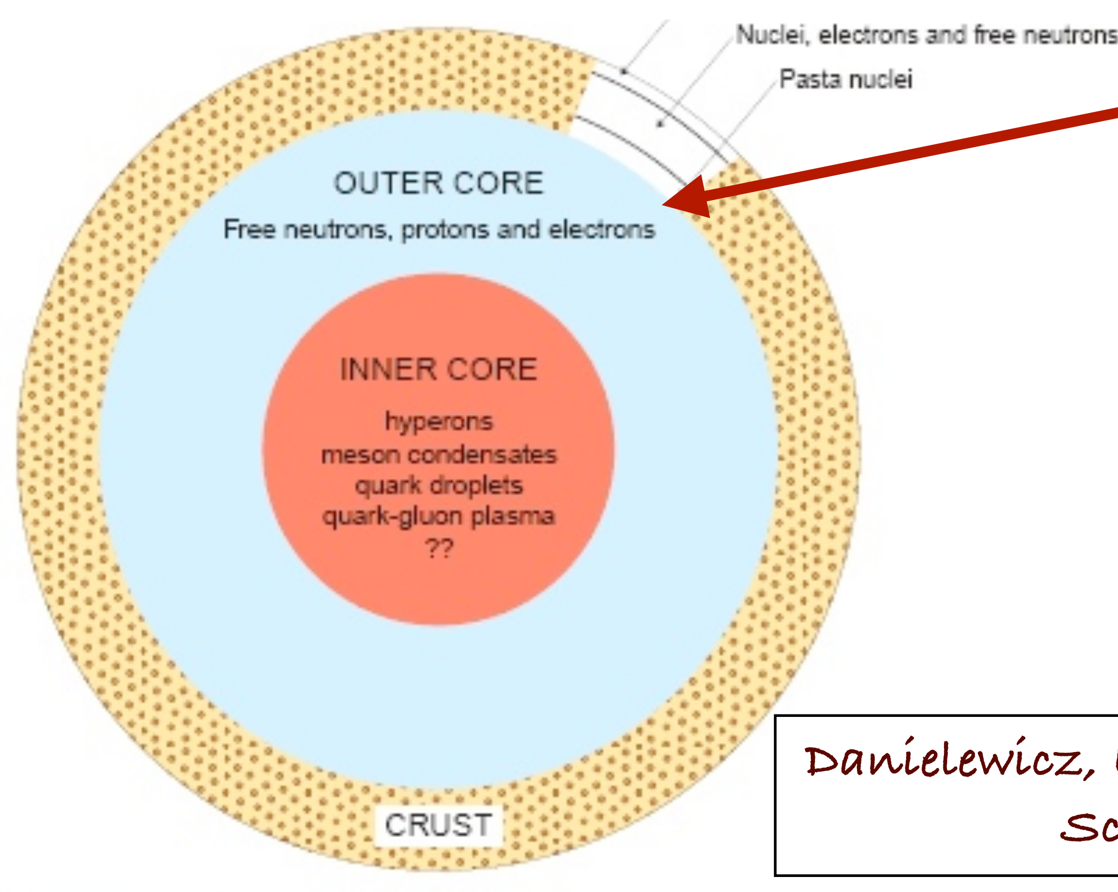
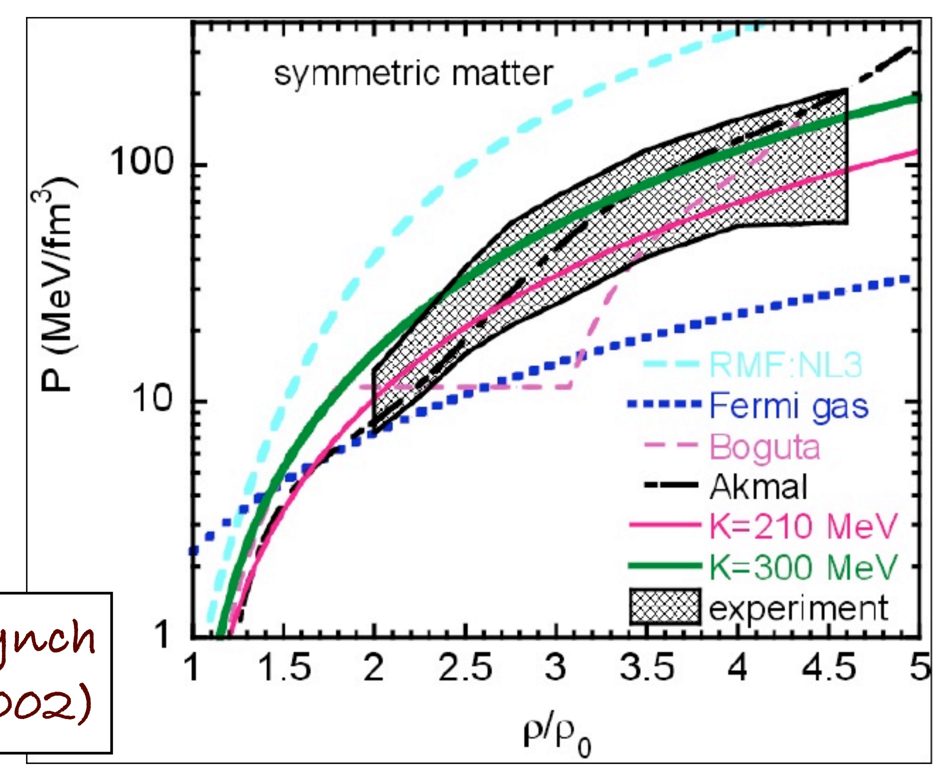
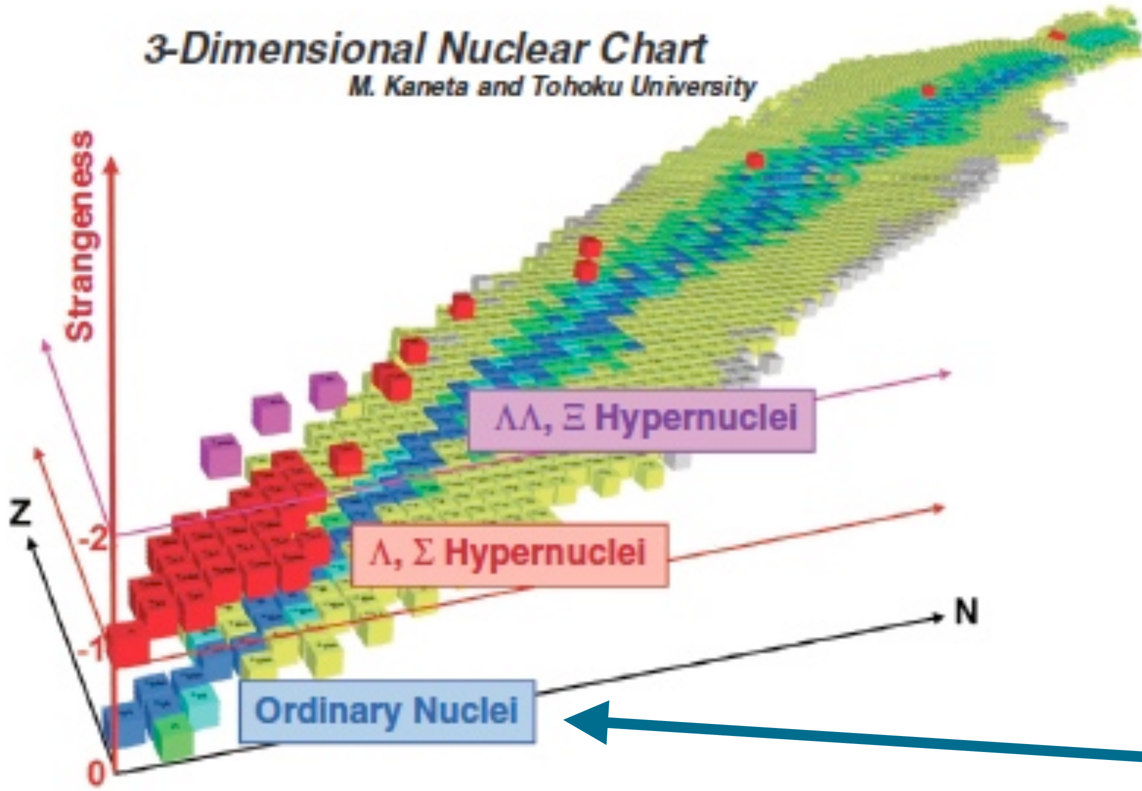




Danielewicz, Lacey and Lynch
Science 298 (2002)



STRANGENESS IN HIC



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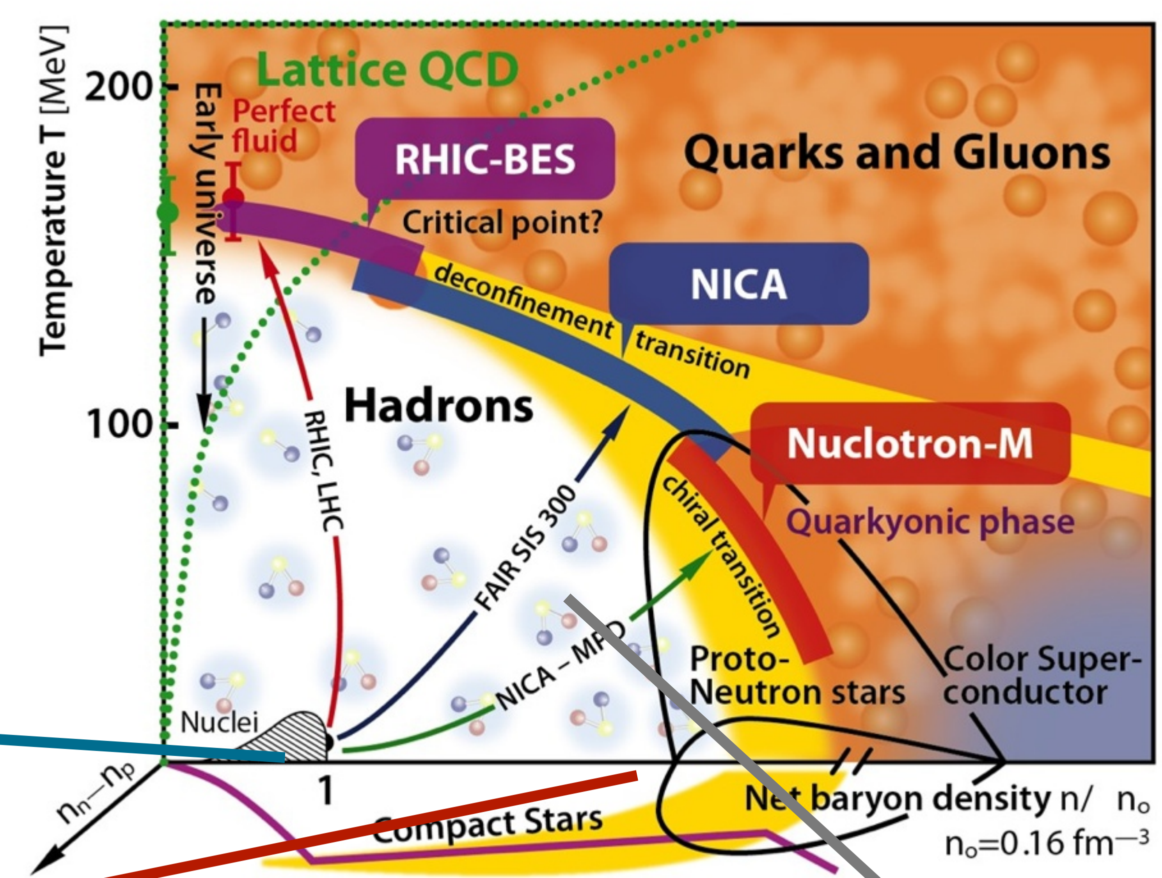
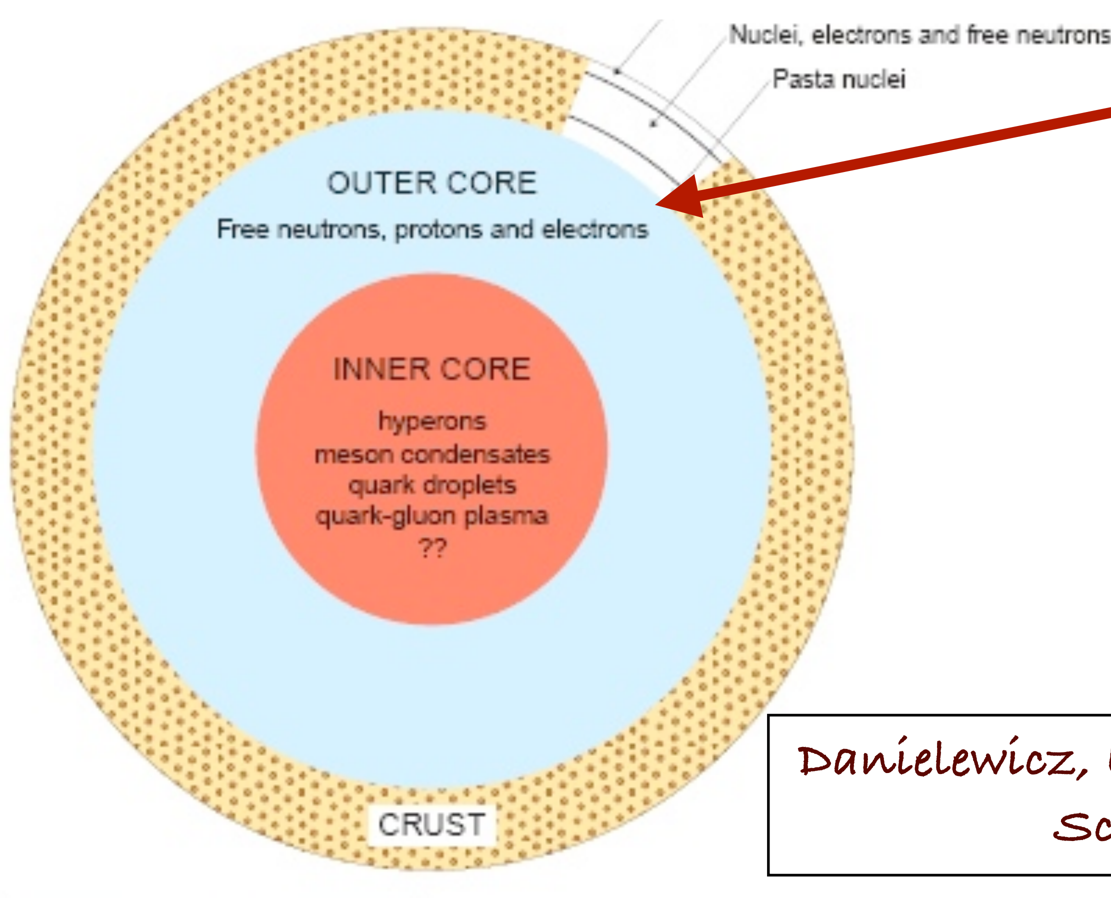
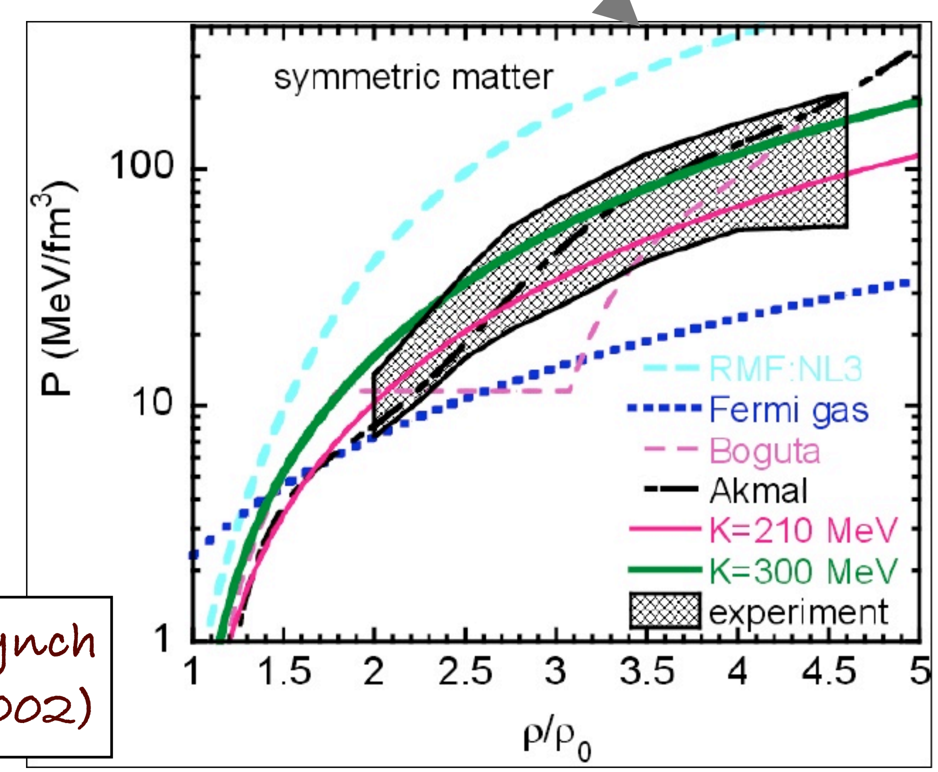
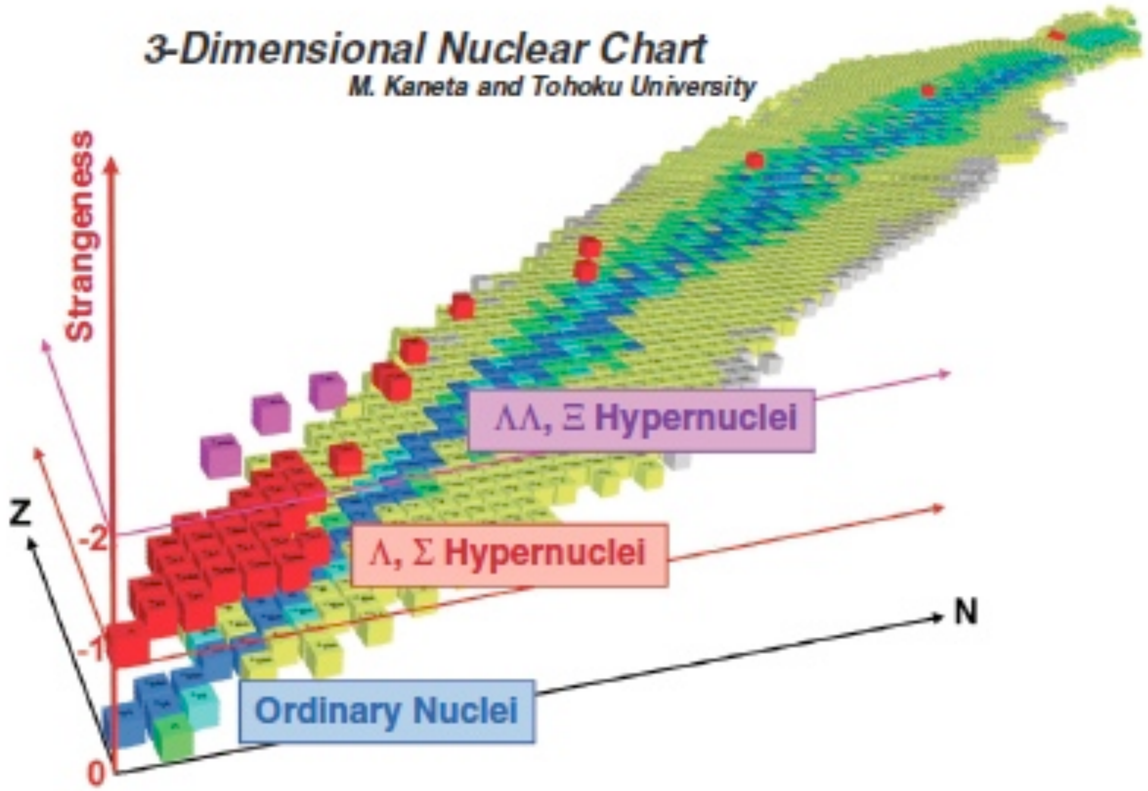






Danielewicz, Lacey and Lynch
Science 298 (2002)

STRANGENESS



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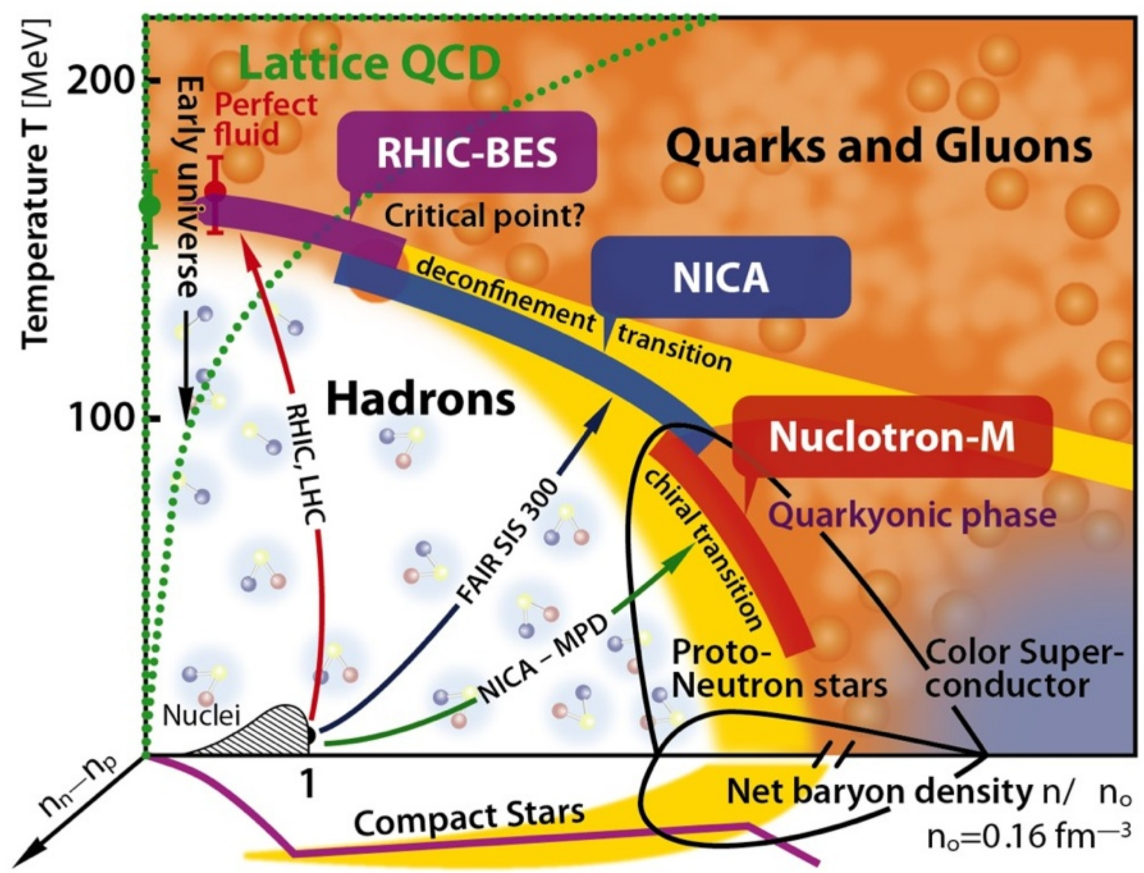
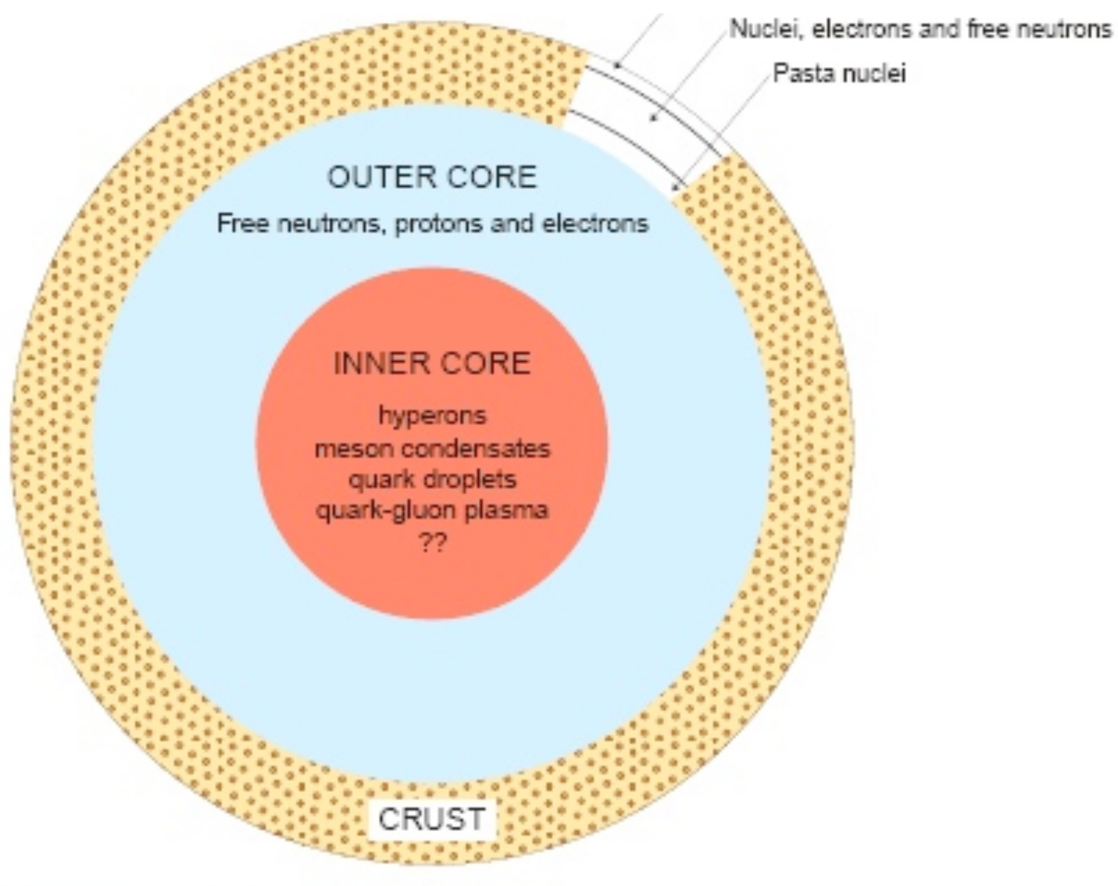
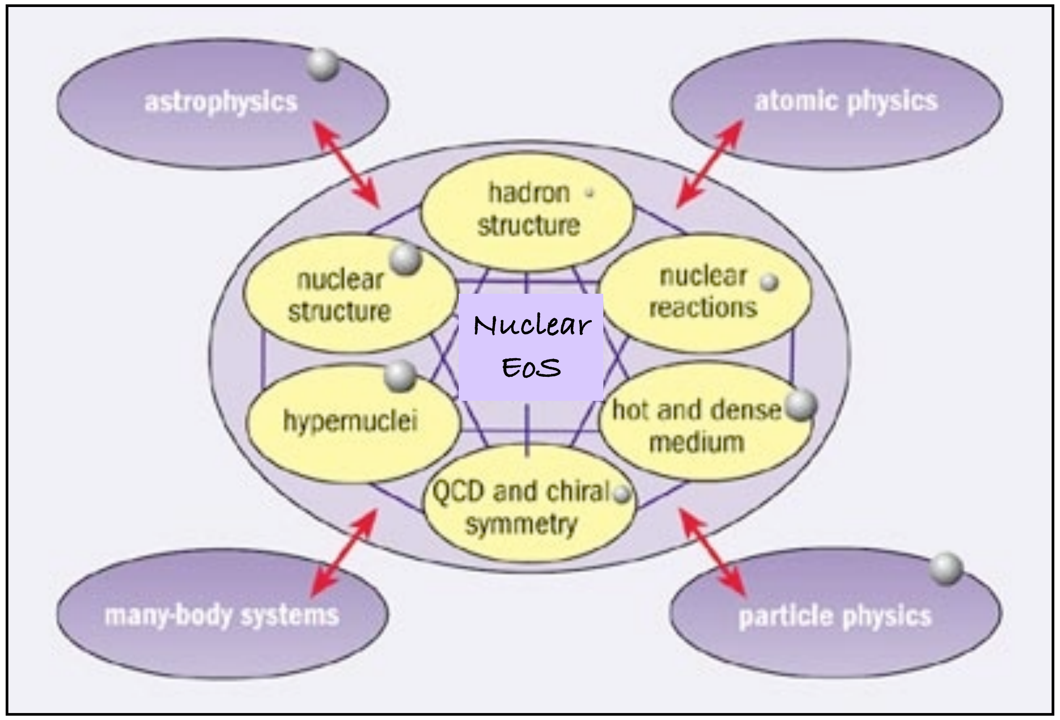






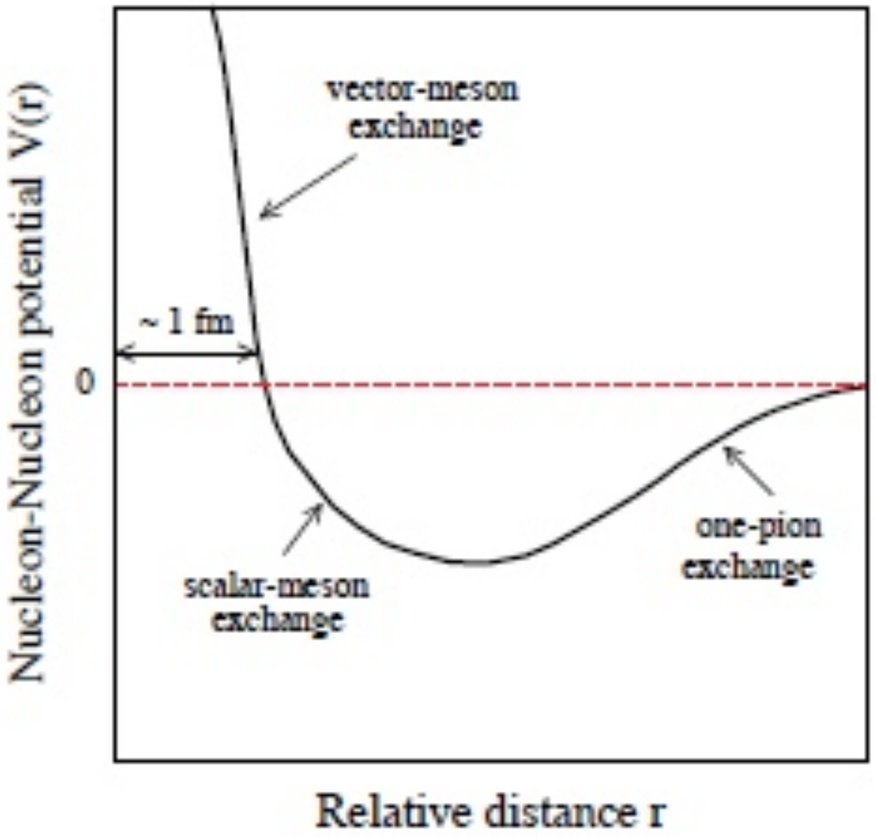
NS EOS: THEORETICAL MODELS

- ***Microscopic models*** *(realistic N-N interactions)*
  - *Meson exchange (e.g. Brueckner Hartree Fock models)*
  - *Chiral perturbation theory*

- ***Phenomenological models***
  - *Effective density dependent interactions*
  - *Parameters adjusted to reproduce nuclear and hypernuclear observables*

- *Non-relativistic (Skyrme interactions)*

- *Relativistic Mean Field Models (RMF)*
  - *baryon-baryon interaction mediated by meson exchange*
  - *nucleonic couplings fitted to properties of bulk nuclear matter (GL, GM1) or to properties of nuclei (NL3, TM1, FSUGold)*
  - *hyperonic couplings fixed by symmetry relations and hypernuclear data*



Radial profile of NN-potential

LABORATORY CONSTRAINTS ON EOS

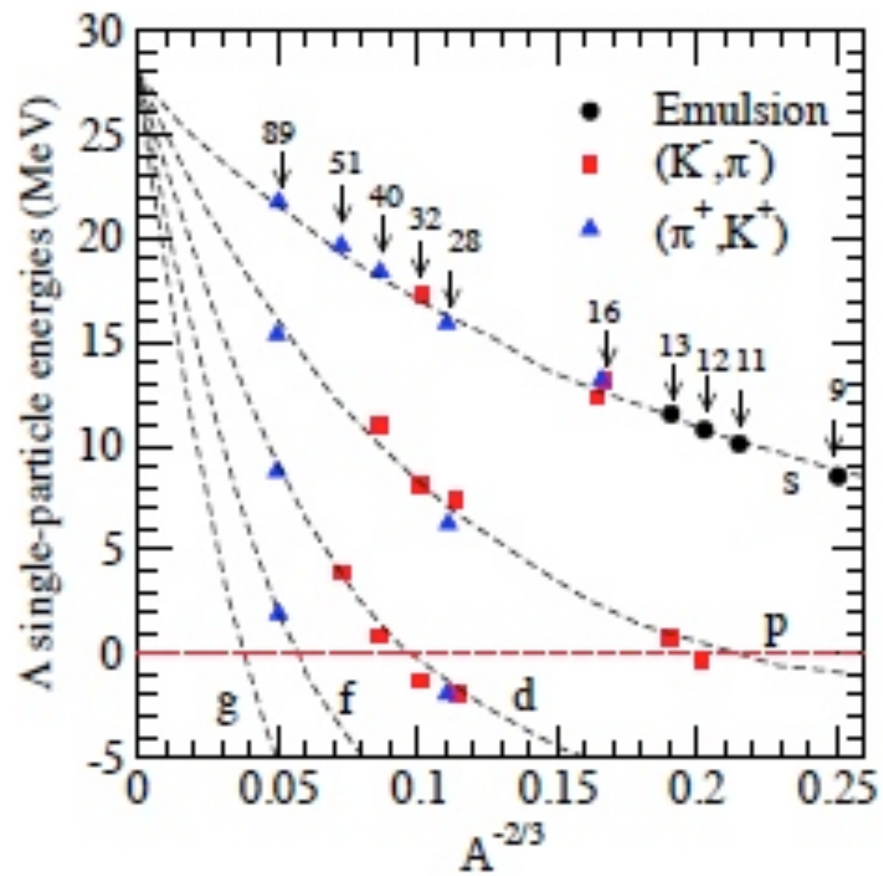
- ***N-N interaction*** *: fairly well known*
  - *scattering data*
  - *measured properties of nuclei*

D.C. and I. Vidaña, EPJA 52 (2016) 29

- ***Y-N interaction*** *: poorly constrained*
  - *short lifetime of Y*
  - *low intensity beam flux*
  - *ΛN and ΣN scattering events ~ 600*

- ***Y-Y interaction*** *: hardly any constraints*
  - *no scattering data*

- *Hypernuclei (YN bound systems)*
  - *40 single Λ-hypernuclei and few double-Λ*
  - *no Σ hypernuclei confirmed yet*



Energy of a hyperon in sp orbits s,p,d,f,g of hypernuclei deduced from (K^-, π^-) and (π^+, K^+) reactions

Strangeness exchange reactions (CERN, BNL, KEK, J-PARC)

$$K^- + {}^AZ \rightarrow {}^A_\Lambda Z + \pi^-$$

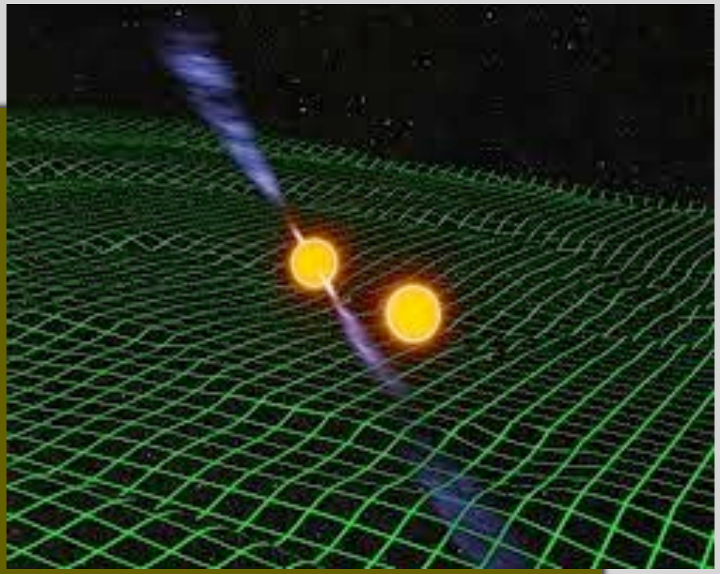
Associate production reactions (BNL, KEK, GSI)

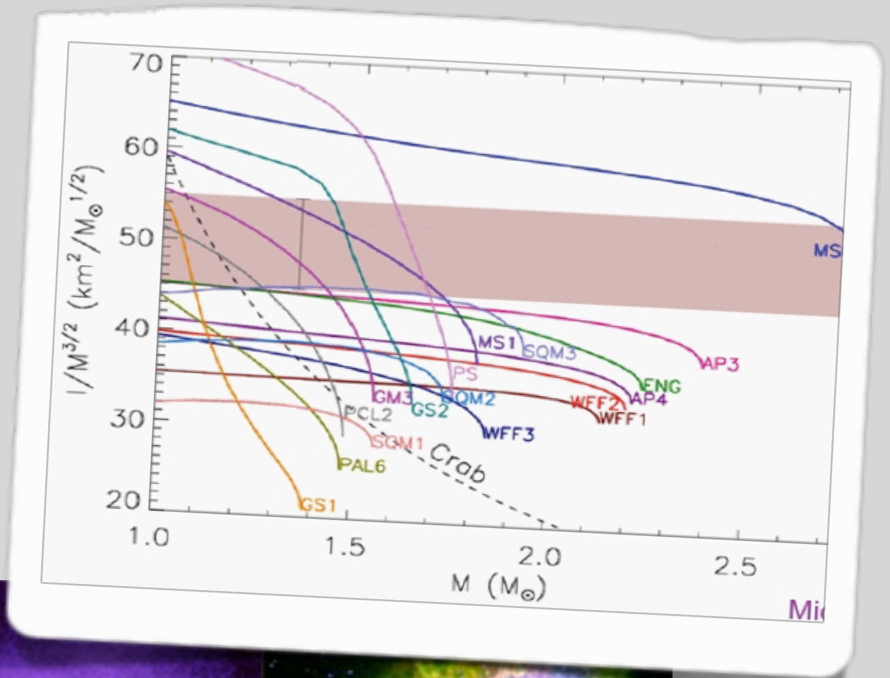
$$\pi^+ + {}^AZ \rightarrow {}^A_\Lambda Z + K^+$$

Electro-production reactions (JLAB, MAMI-C)

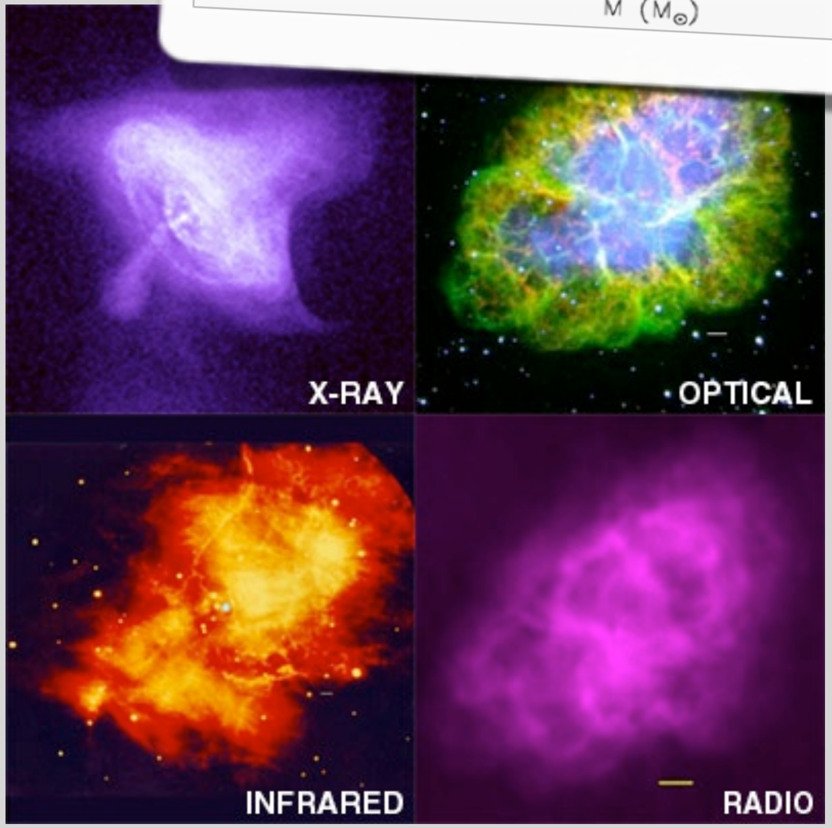
$$e^- + {}^AZ \rightarrow e^- + K^+ + {}^A_\Lambda(Z-1)$$

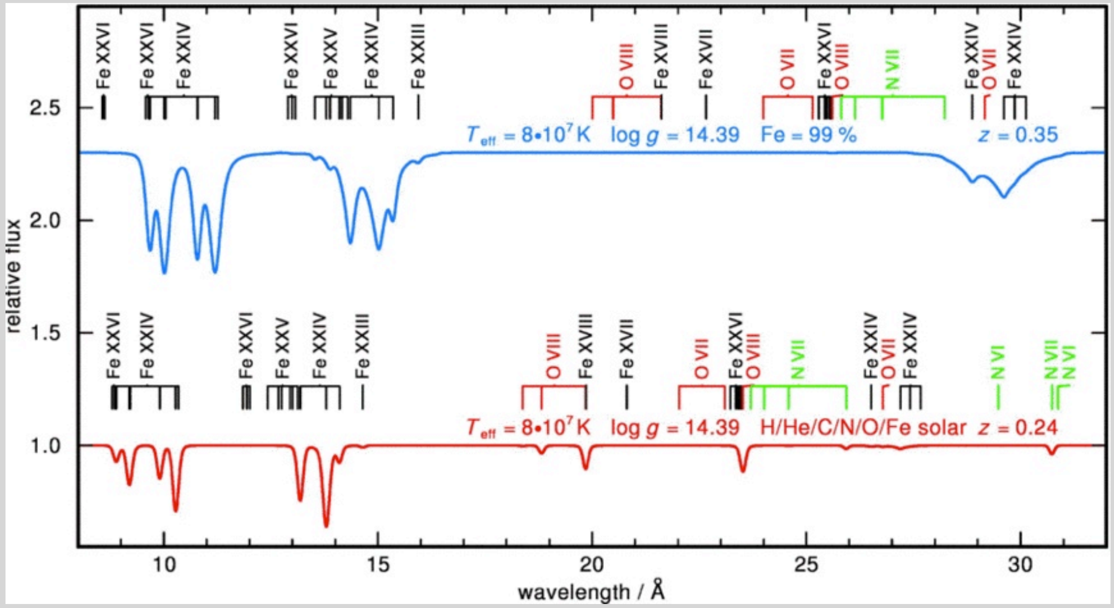
NS Astrophysical Observables





- *Spin frequency*
- *Mass*
- *Radius*
- *Moment of inertia*
- *Gravitational redshift*
- *Cooling*





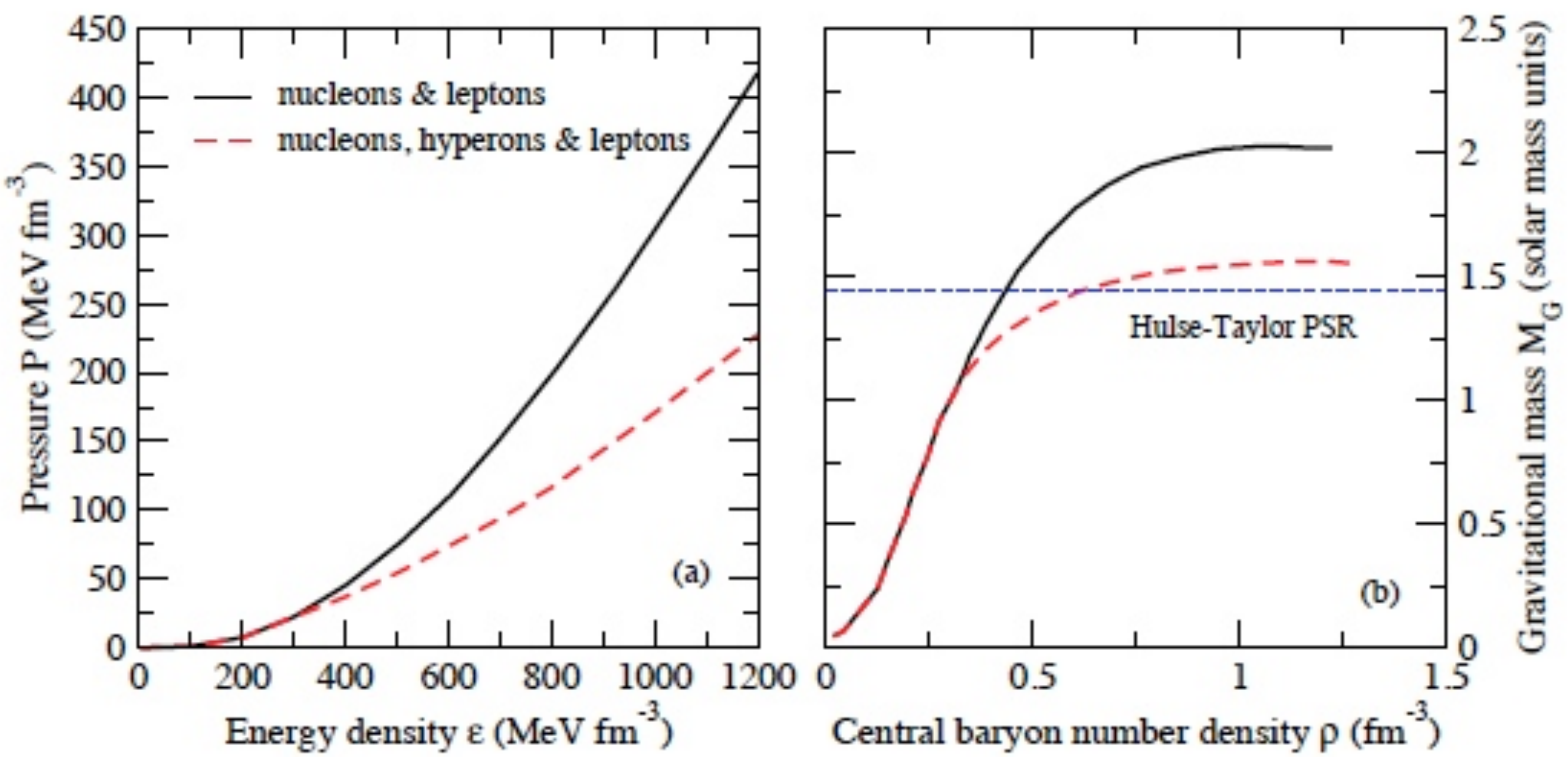
IMPLICATIONS ON ASTROPHYSICS: NS MAXIMUM MASS

Tolman-Oppenheimer-Volkov equations of relativistic hydrostatic equilibrium:

$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(m+4\pi p r^3)(\epsilon+p)}{r(r-2Gm/c^2)}$$

$$\frac{dm}{dr} = 4\pi\frac{\epsilon}{c^2}r^2$$

Effect of presence of hyperons on EoS and mass of a NS



$M^{max}(theo) > M^{max}(obs)$

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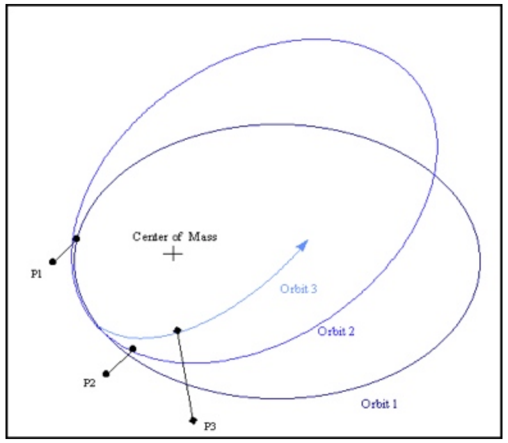
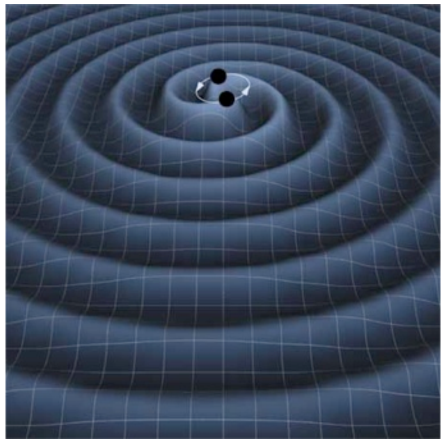
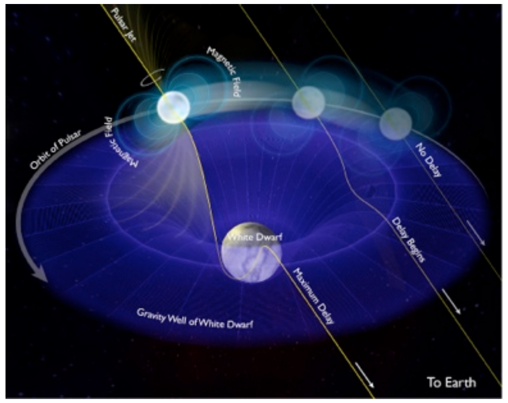
Constraints from Neutron Star masses :
Relativistic binaries





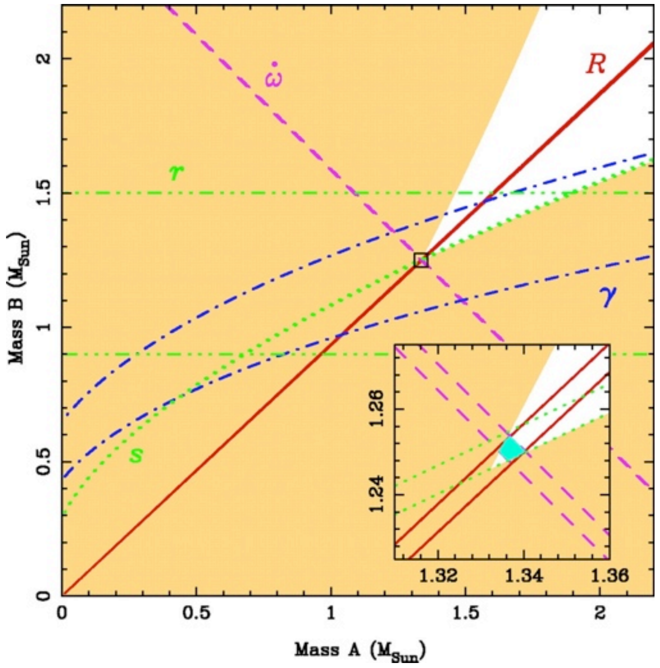


Keplerian parameters

- Orbital period P_b
- Projected semi-major axis $x = (a_p \sin i) / c$
- Orbital eccentricity e
- Longitude of periastron ω
- Epoch of periastron passage T_o

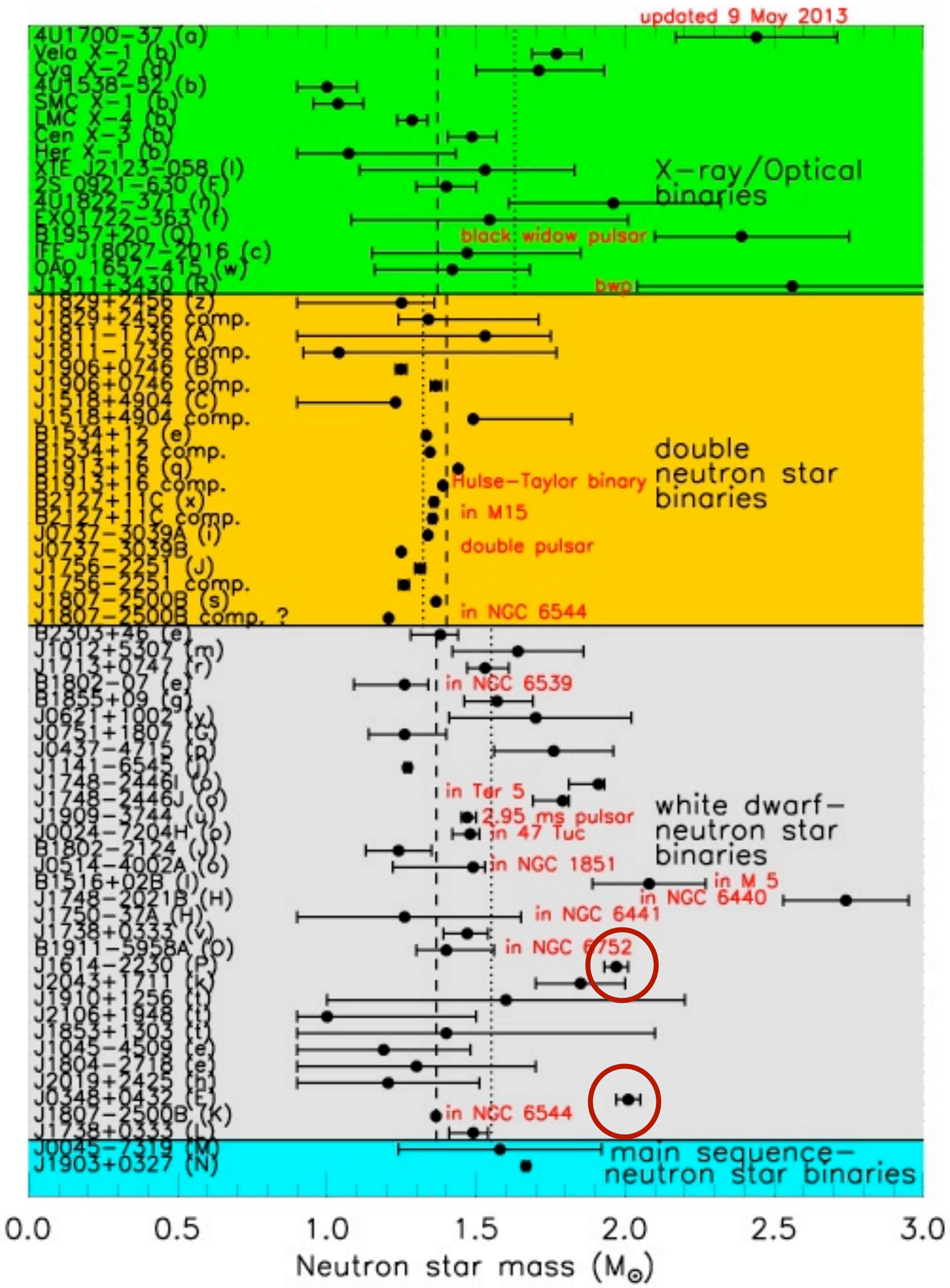
Post-Keplerian Parameters

- *Relativistic advance of periastron* $\dot{\omega}$
- *Gravitational redshift and time dilation* γ
- *Orbital decay in period* $\dot{P}_b$
- *Shapiro time delay (range r and shape s)*



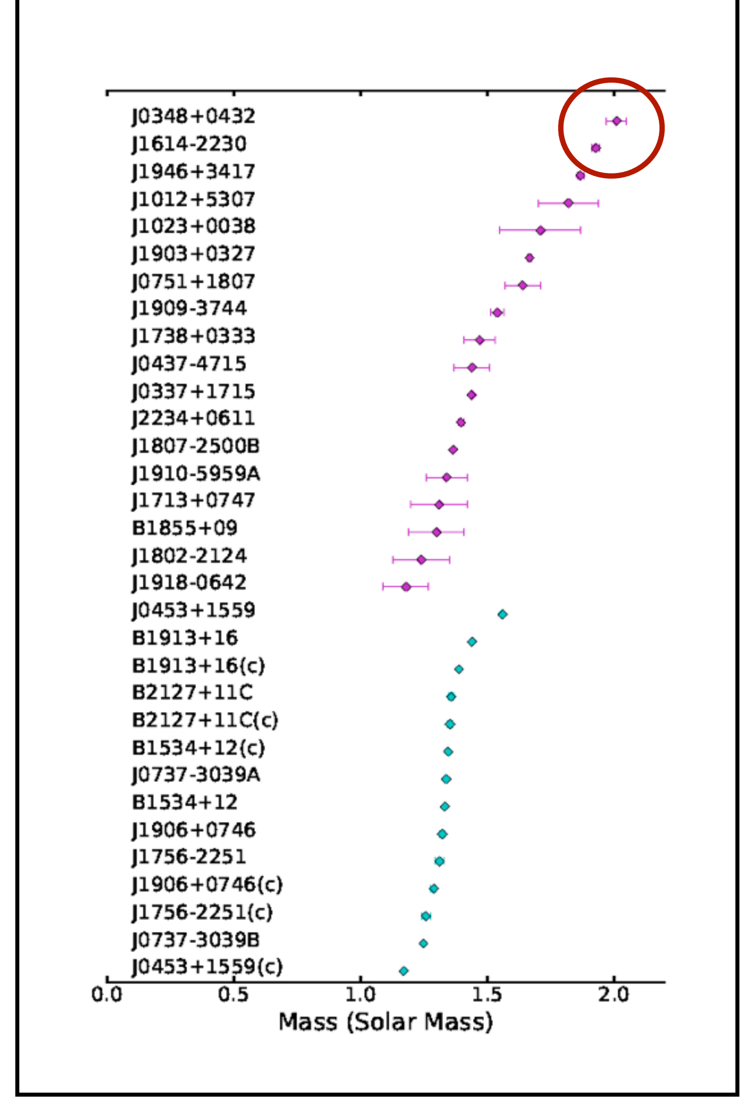
Constraining the EoS

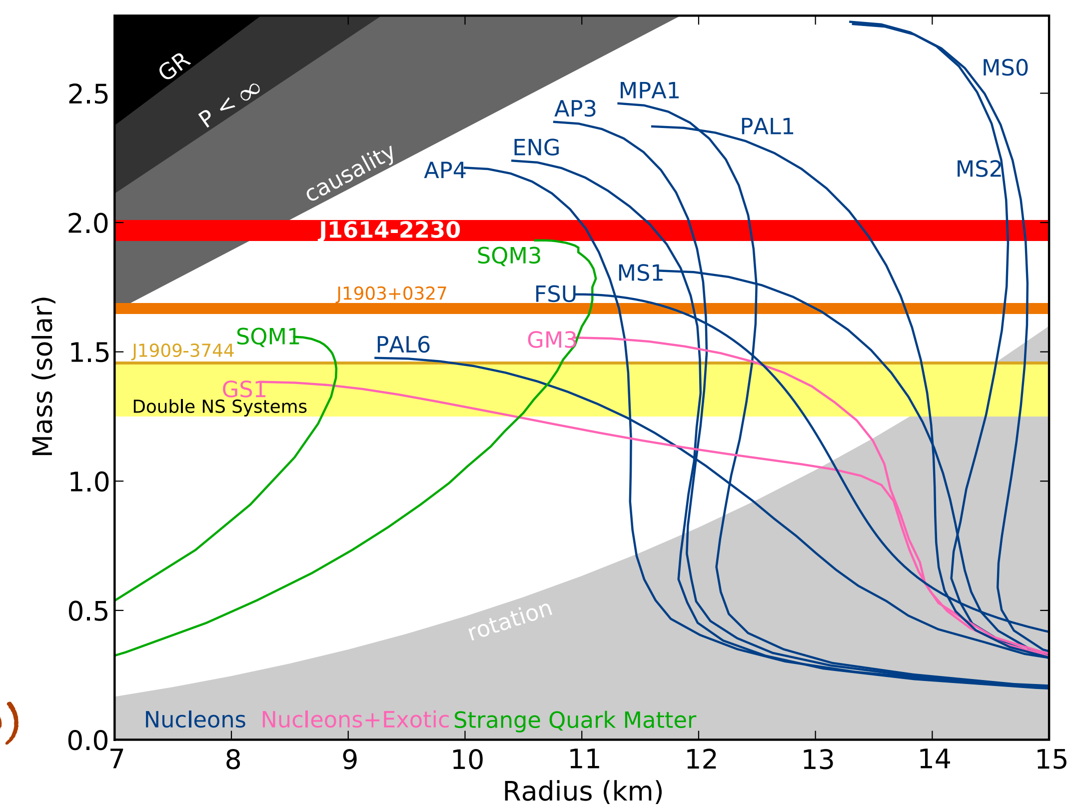
$M^{max}(theo) > M^{max}(obs)$



Prakash, PoS (2013)

Antoniadis et al., (2016)

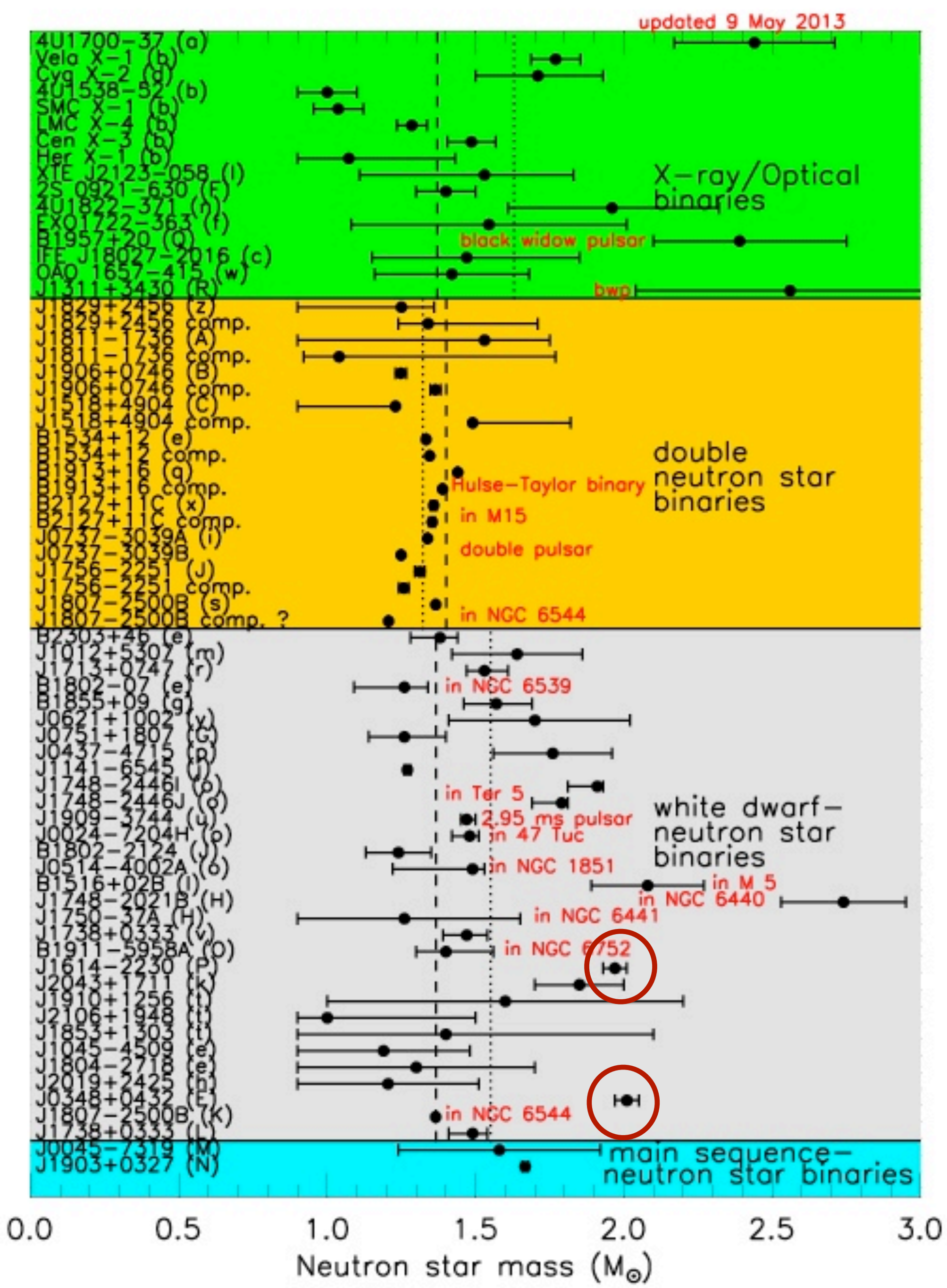




Lattimer and Prakash, (2010)

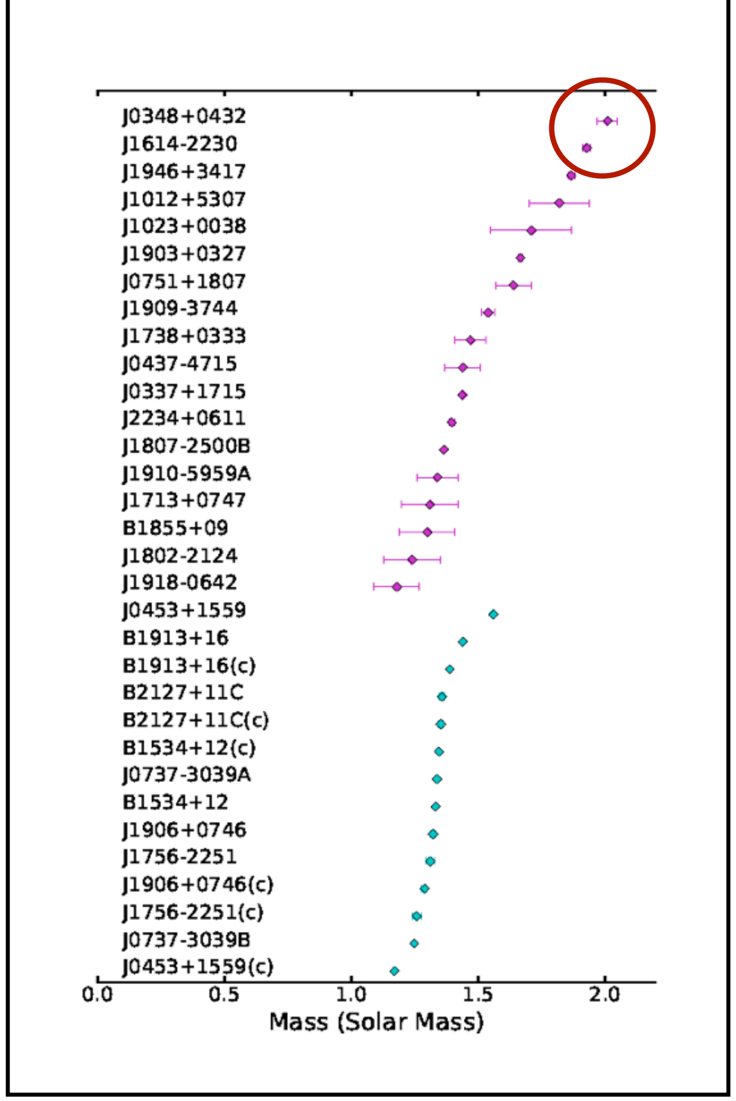
Constraining the EoS

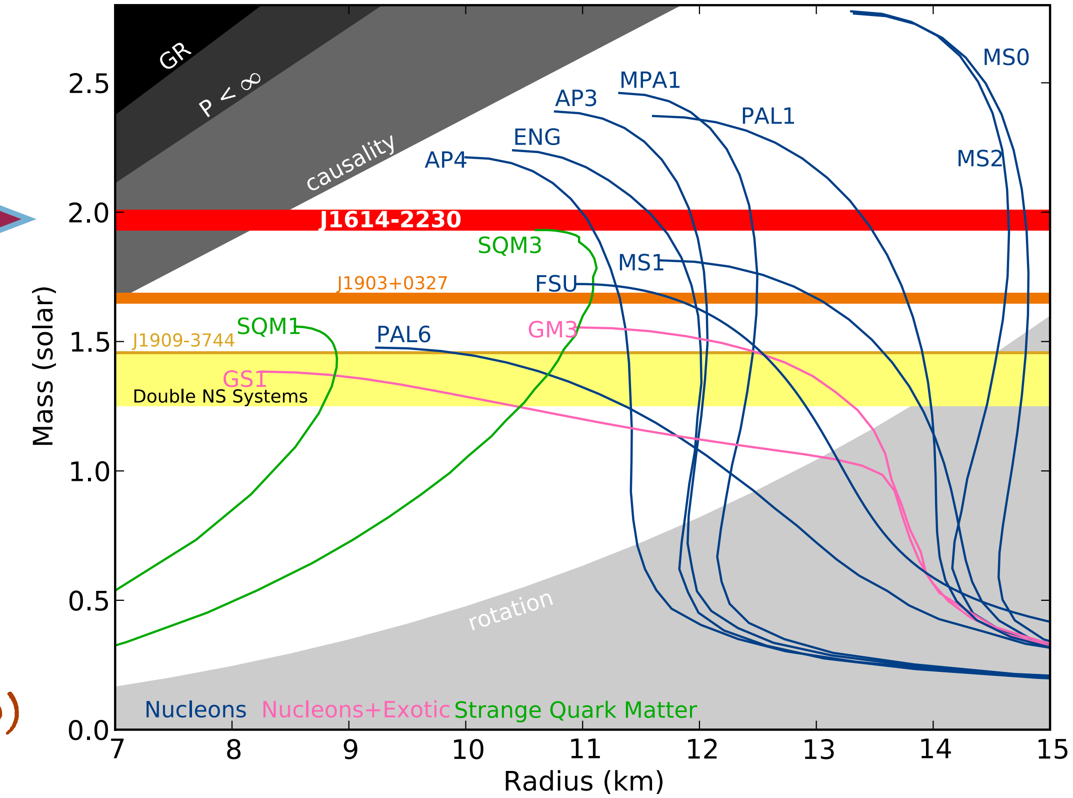
$M^{max}(theo) > M^{max}(obs)$



Prakash, PoS (2013)

Antoniadis et al., (2016)

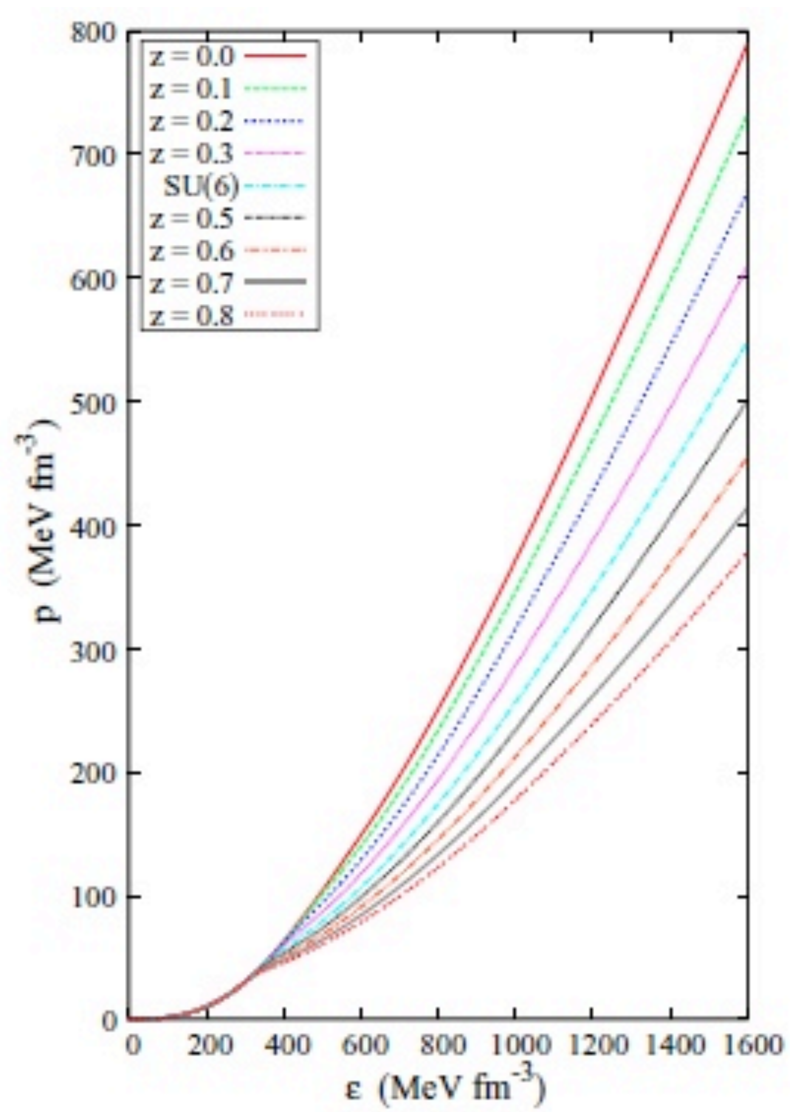


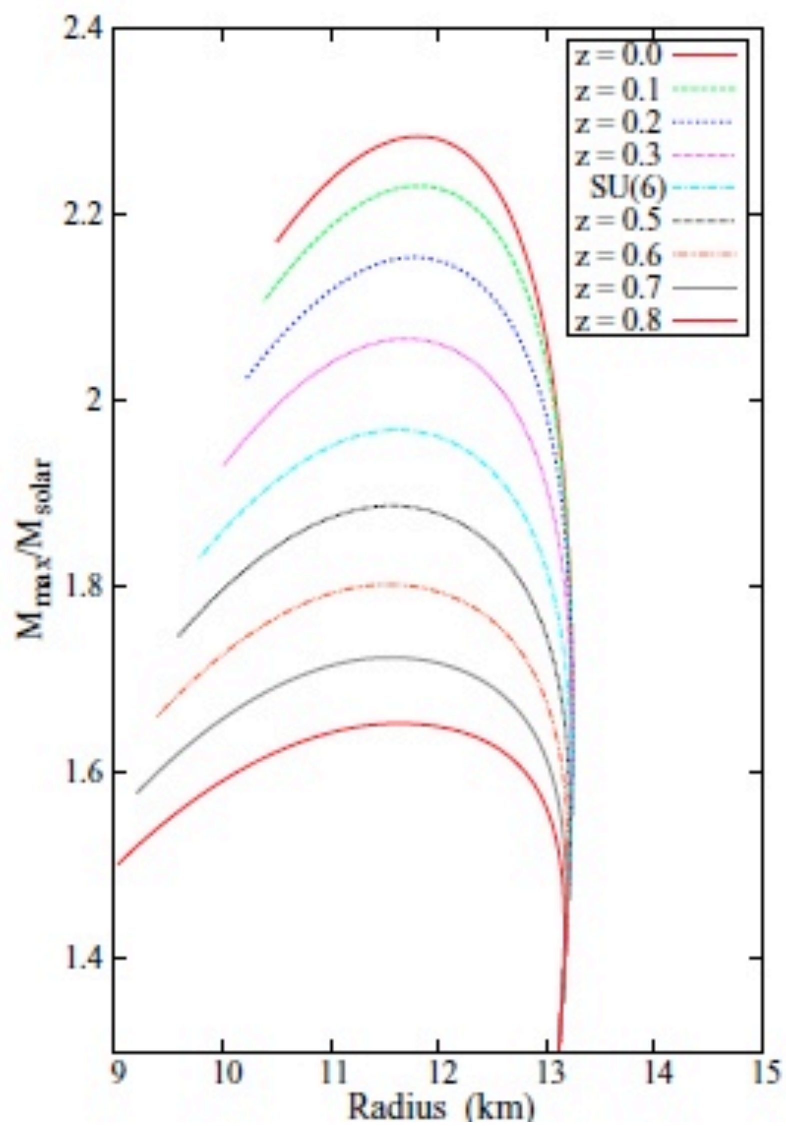


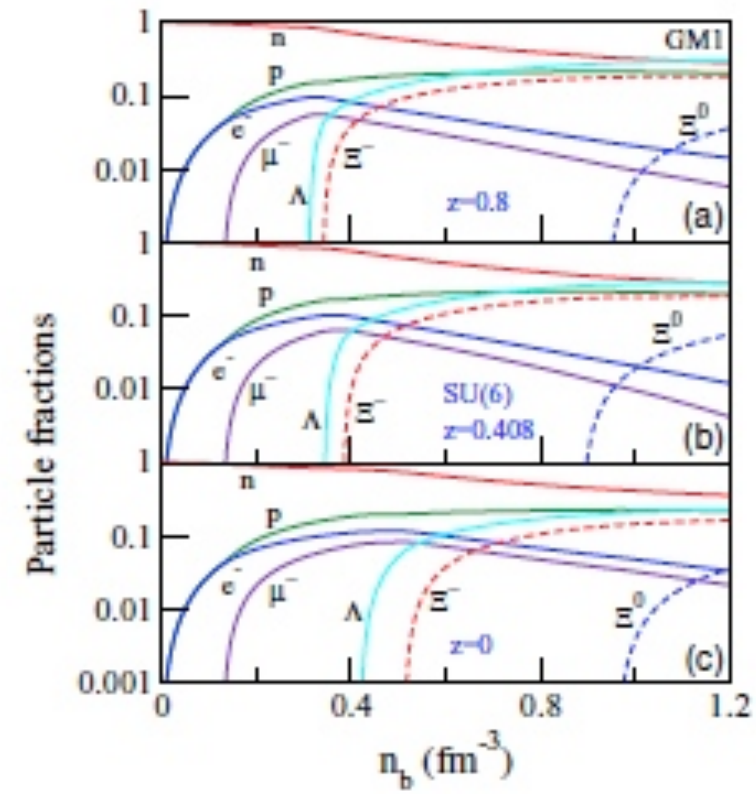
Lattimer and Prakash, (2010)

SOLVING THE HYPERON PUZZLE: HYPERON-HYPERON REPULSION

RMF EoSs including YY-repulsion and M-R relation







$z = \frac{1}{\sqrt{6}} = 0.4082$

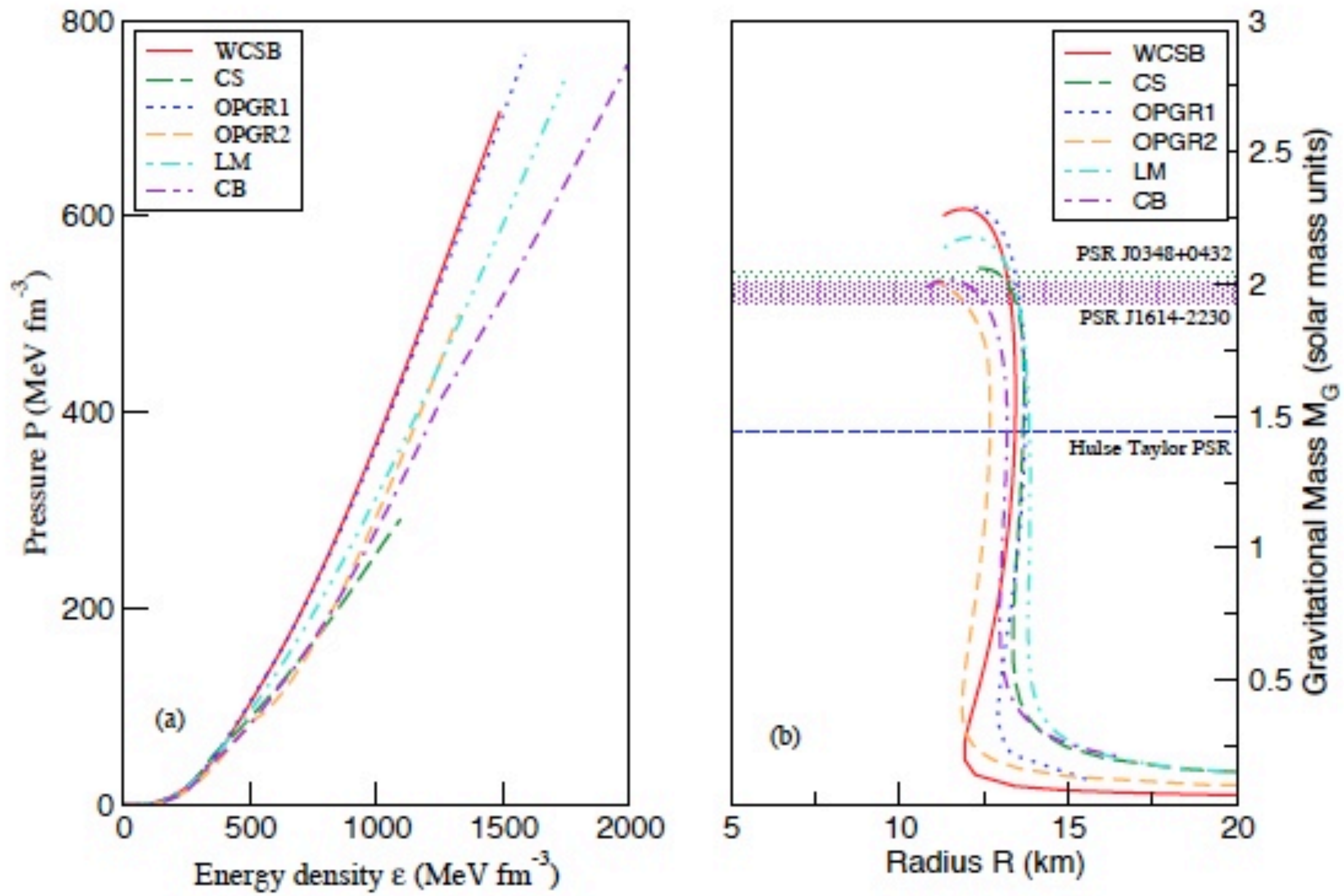
$g_{\omega\Xi} = 0, \frac{g_{\omega\Lambda}}{g_{\omega N}} = \frac{1}{2}, z = \frac{\sqrt{2}}{\sqrt{3}} = 0.8164$

$\frac{g_{\omega\Lambda}}{g_{\omega N}} = \frac{g_{\omega\Xi}}{g_{\omega N}}, z = 0$

S. Weissenborn, D.C. and J. Schaffner-Bielich, PRC 85 (2012); PRC 90 (2014)

SOLVING THE HYPERON PUZZLE: HYPERON-HYPERON REPULSION

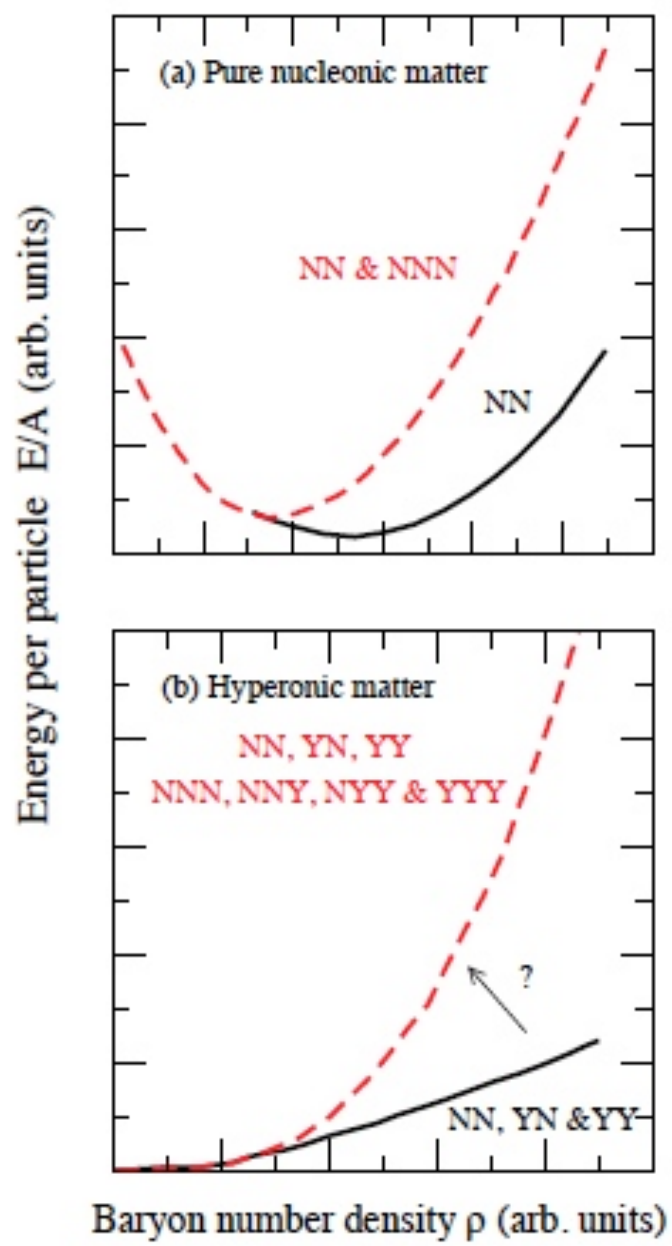
D.C. and I. Vidaña, EPJA 52 (2016) 29



RMF EoSs including YY-repulsion and M-R relation

S. Weissenborn, D.C. and J. Schaffner-Bielich, NPA 881 (2012); PRC 85 (2012)
Colucci and Sedrakian PRC 87 (2013)
Oertel Providencia Gulminelli and Raduta, J.Phys. G 42 (2015)
Lopes and Menezes PRC 89 (2014)
Char and Banik PRC 90 (2014)

SOLVING THE HYPERON PUZZLE: HYPERONIC 3-BODY FORCES



Effect of 3N and hyperonic 3BF
on energy/particle of NM and HM

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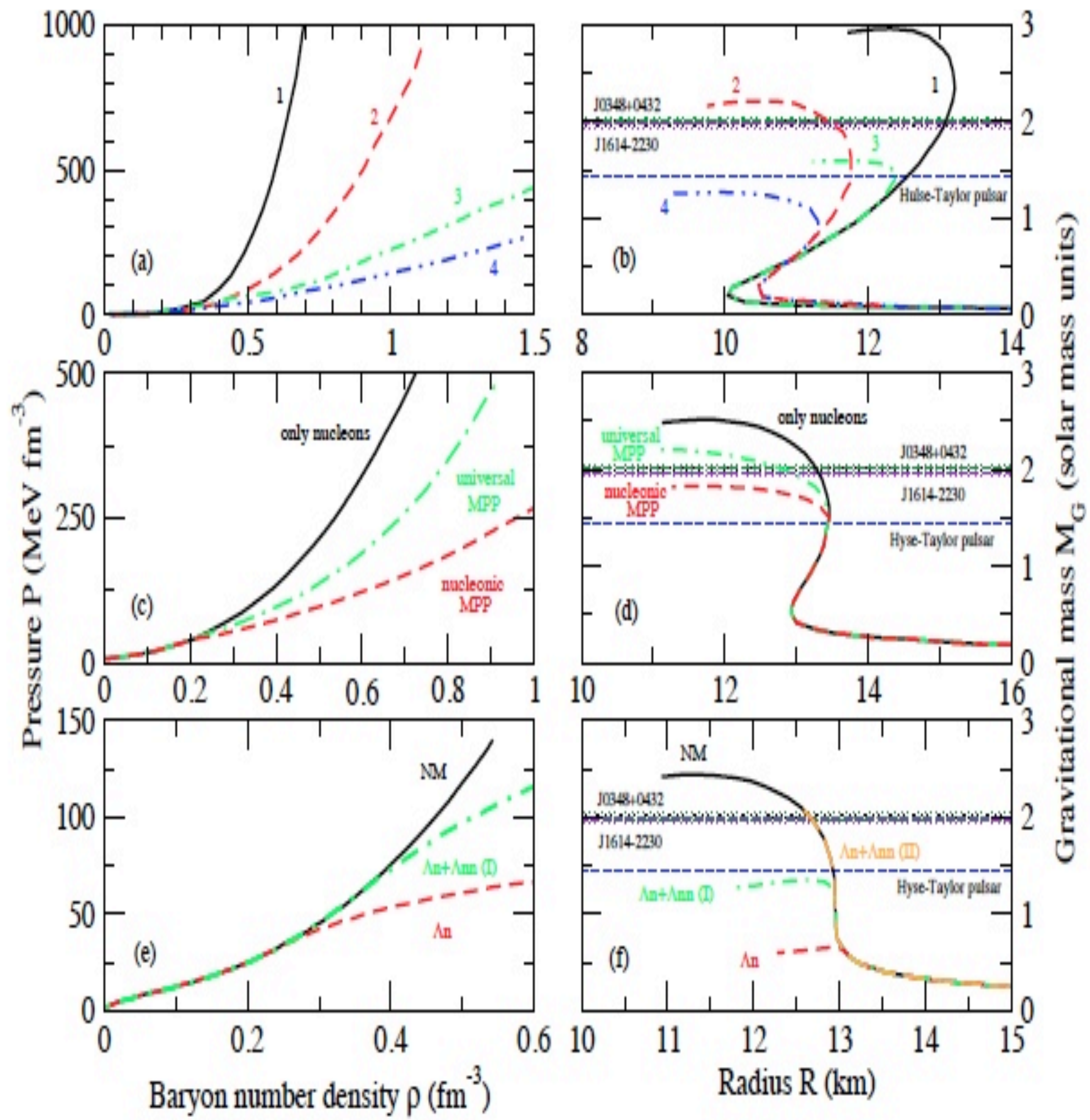
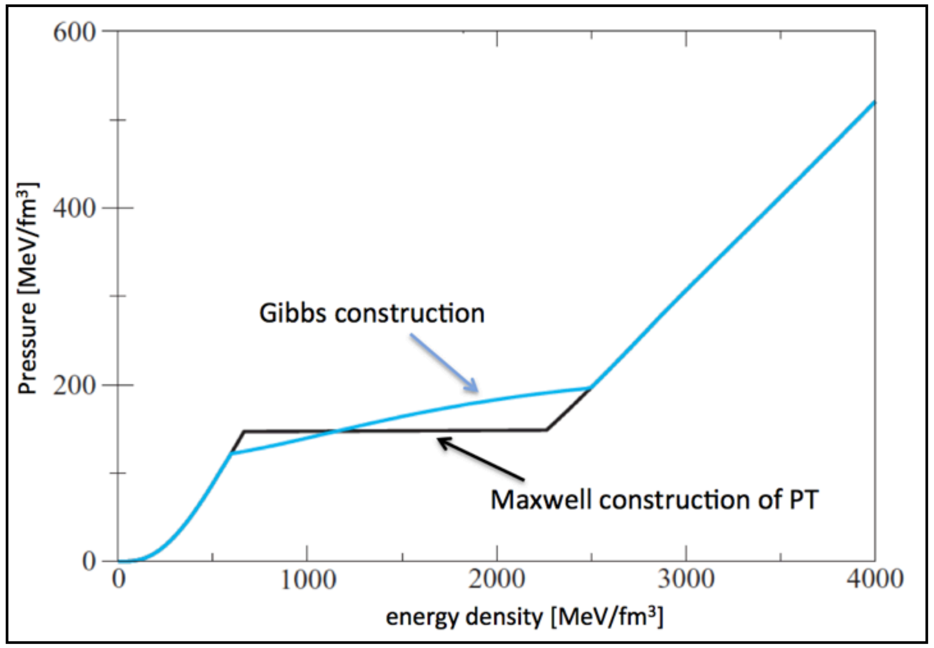


EoS and M-R relations using
(a)-(b) BHF,
(c)-(d) MPP,
(e)-(f) Quantum MC

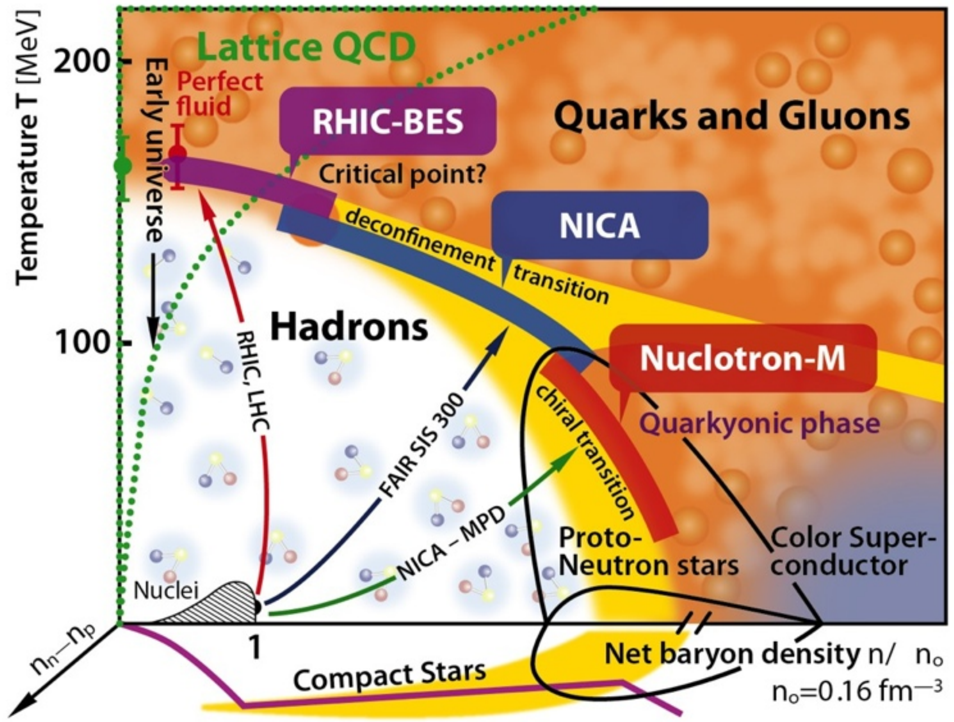
Vidaña+, EPL 94 (2011)
Yamamoto+, PRC 88 (2013)
Lonardoni+, PRL 114 (2015)

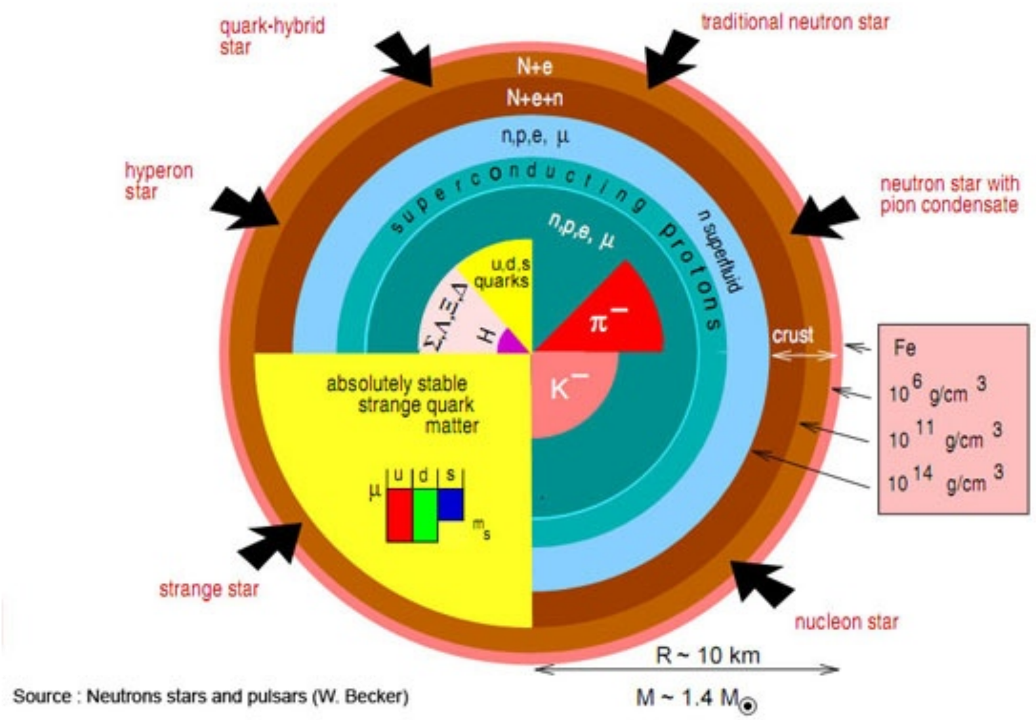
SOLVING THE HYPERON PUZZLE: PHASE TRANSITION TO QM

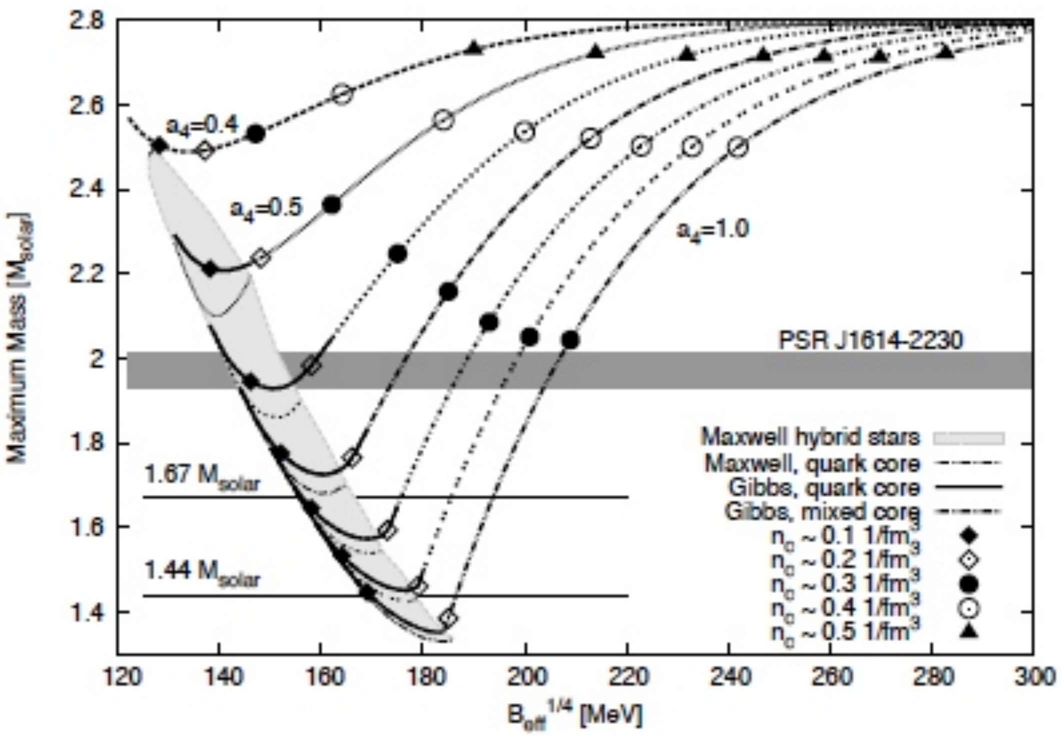
Hadron-Quark phase transition



Schramm, Dexheimer, Negreiros (2016)







Weissenborn, Sagert, Hempel, Pagliara and Schaffner-Bielich, ApJ 740 (2011)

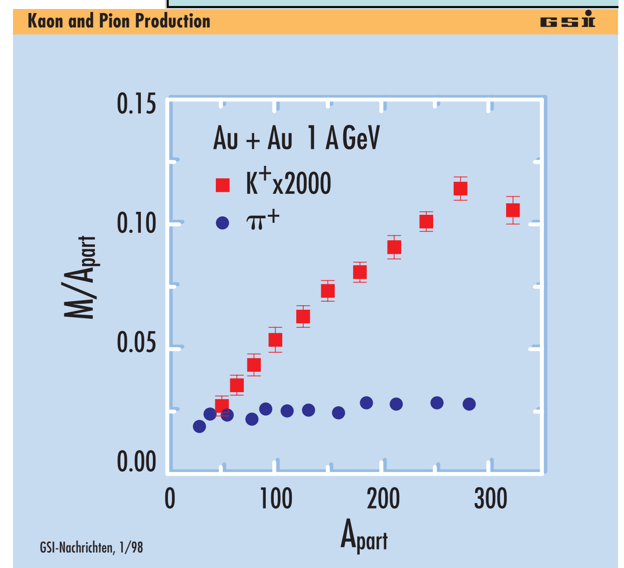
SOFT EOS FROM HEAVY-ION DATA

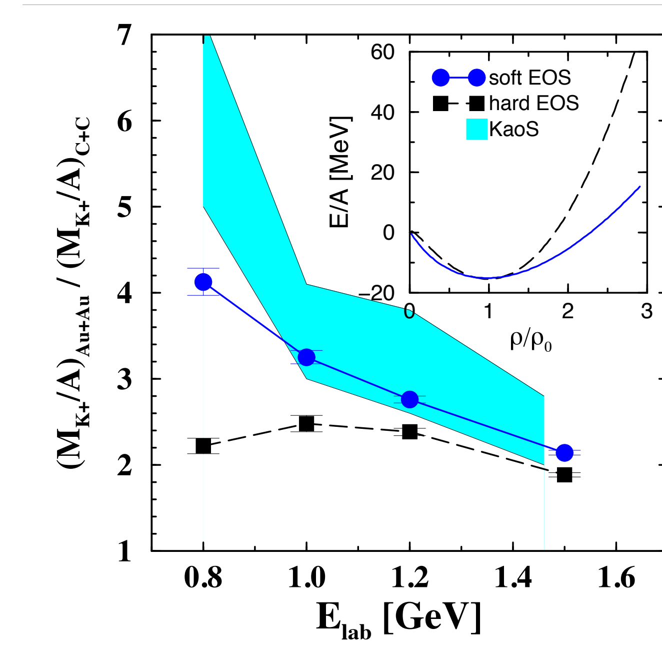
K⁺ meson production in heavy-ion collisions

$NN \rightarrow N\Delta \rightarrow NYK$

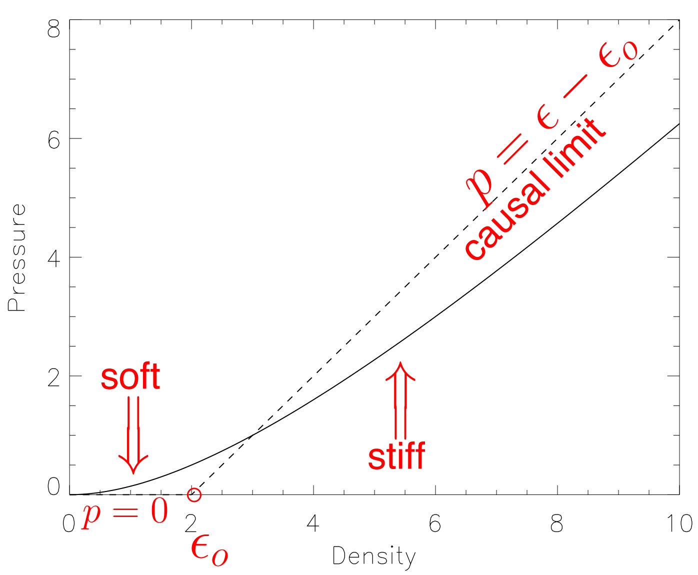
$\hookrightarrow \pi N \rightarrow YK$

KaoS experiment, GSI Darmstadt

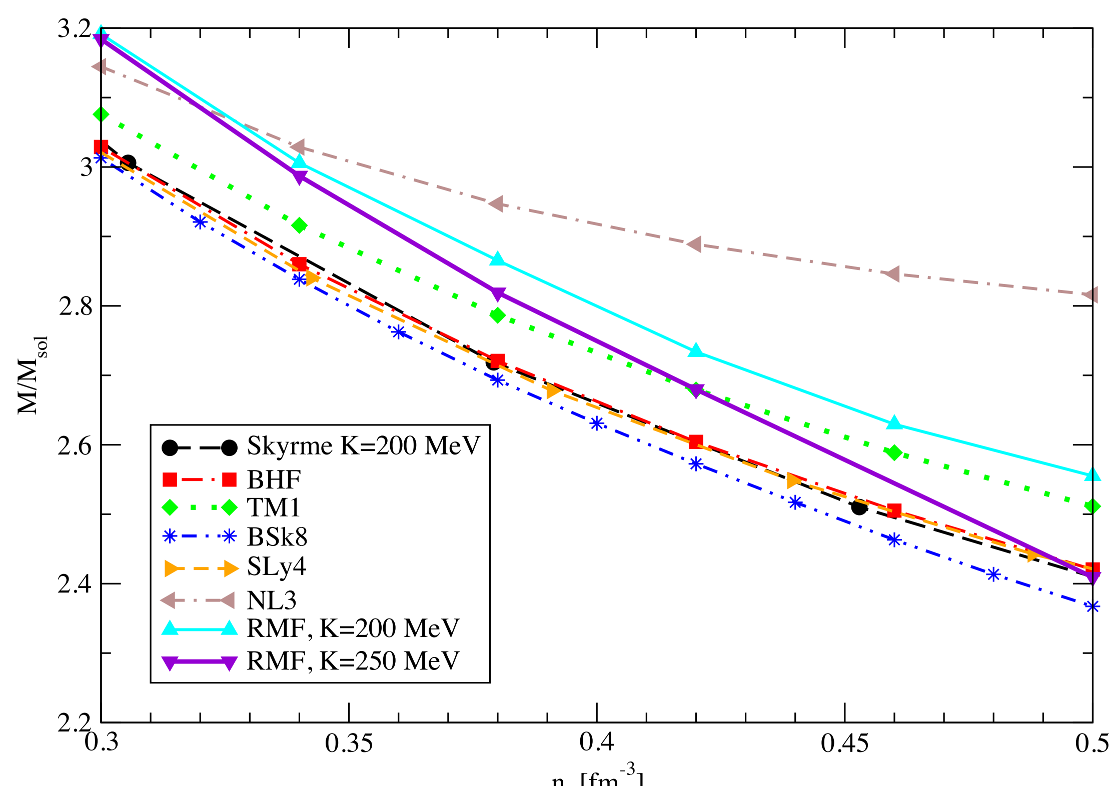




Sturm et al. (KaoS collaboration), PRL 2001

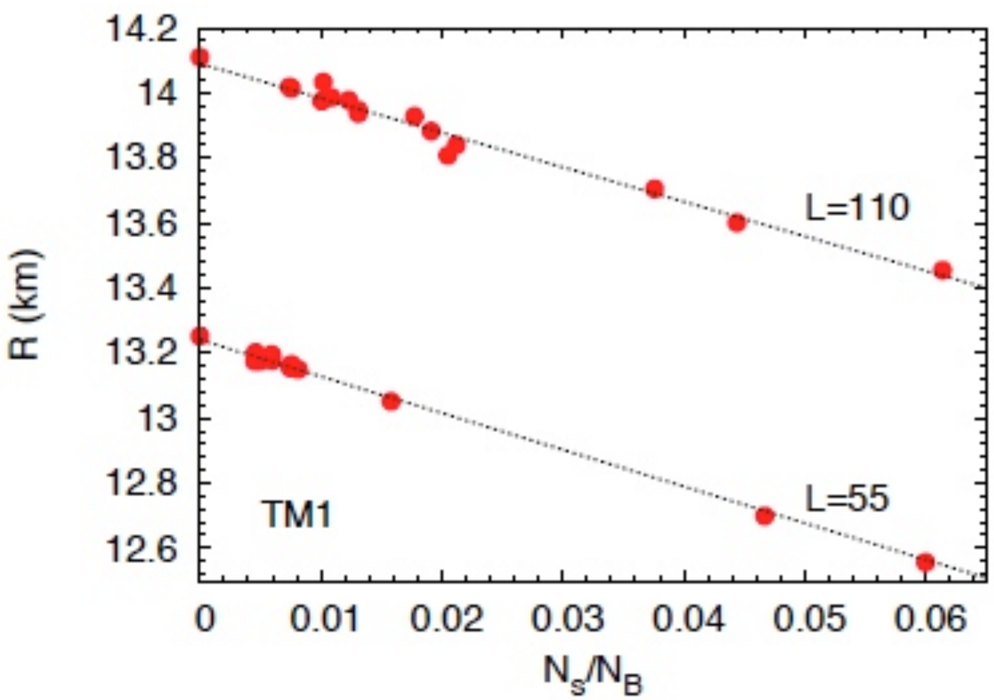


Lattimer, GSI, 2010



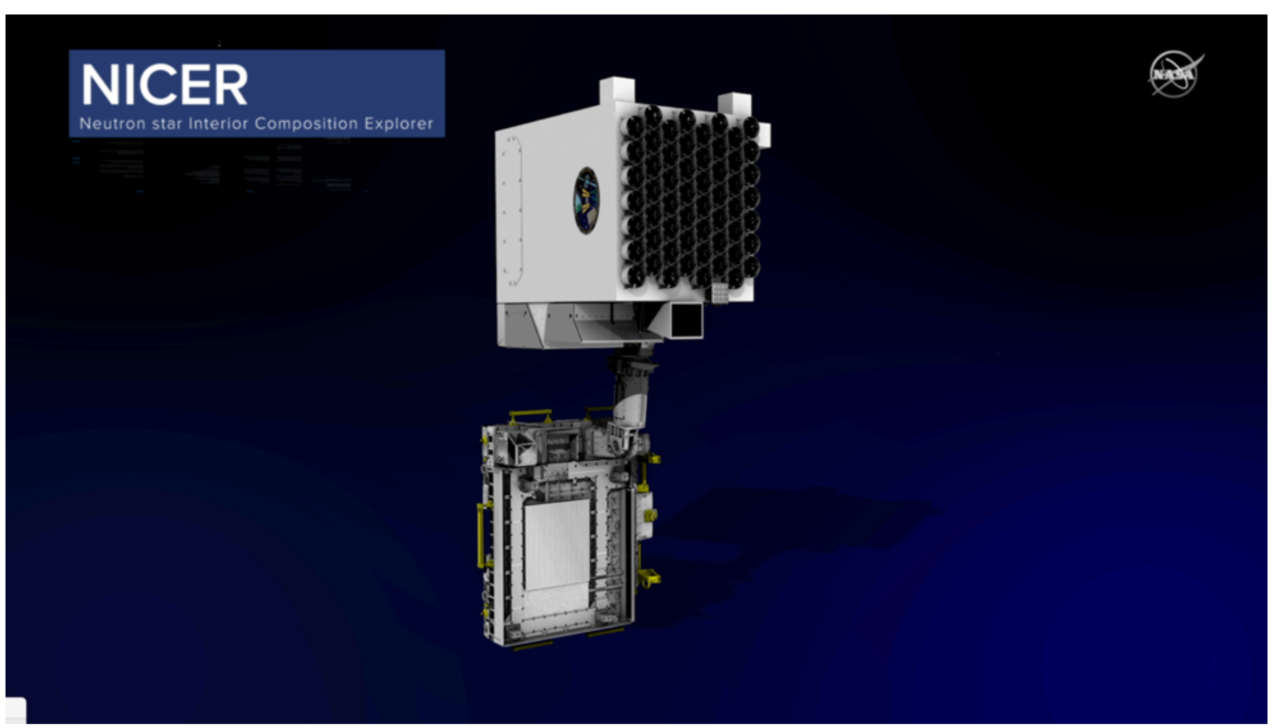
I. Sagert, C. Sturm, D. C., L.Tolos and J. Schaffner-Bielich, PRC 85 (2012)

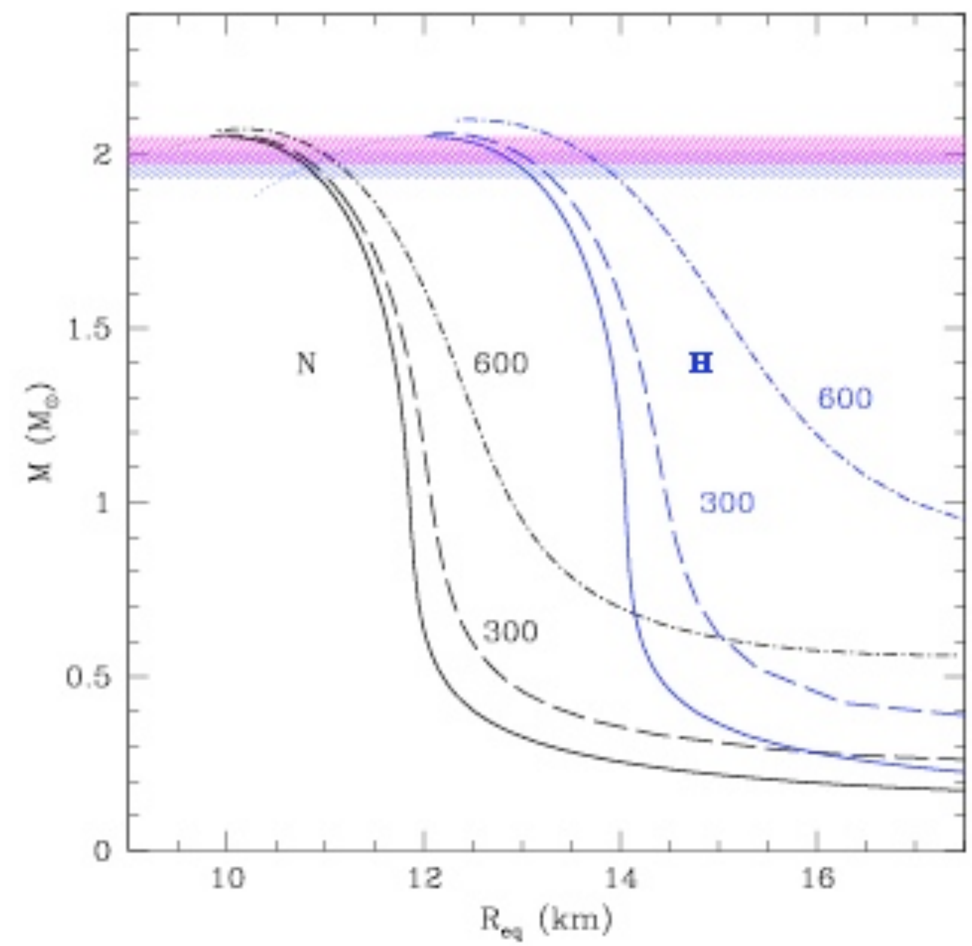
IMPLICATIONS ON ASTROPHYSICS: NS RADII



Providencia and Rabhi, PRC (2013)

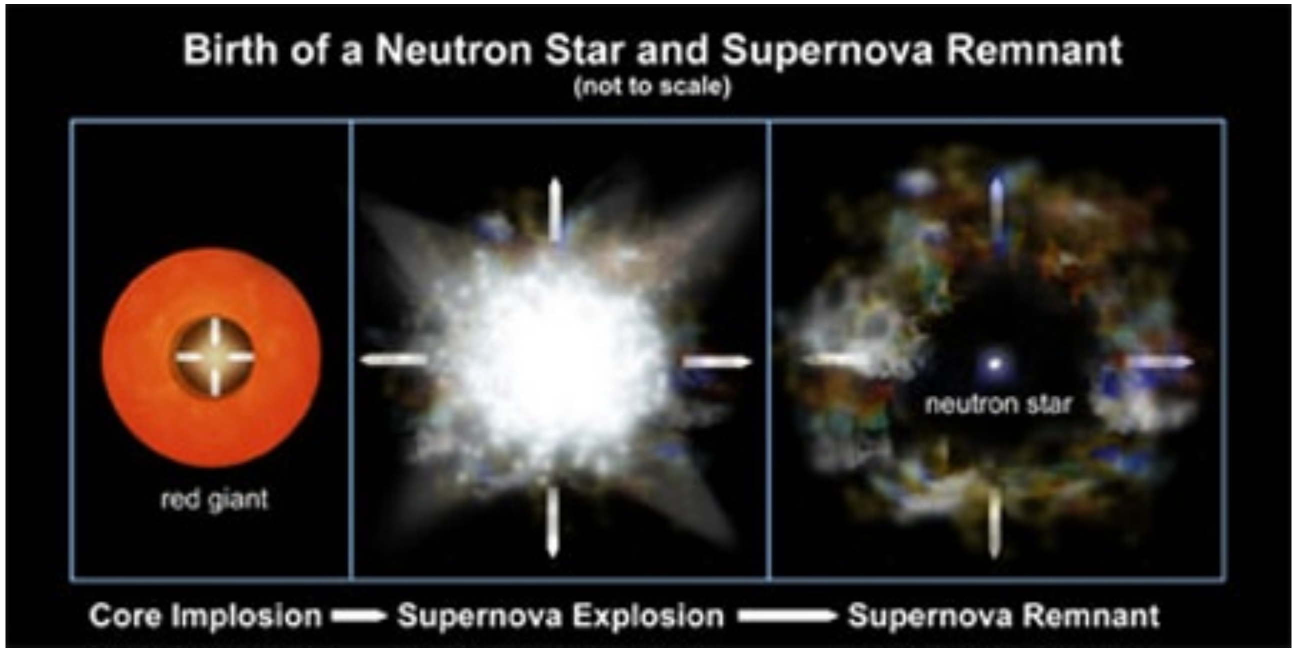
- Measurement of R can also serve to constrain EoS and estimate strangeness content N_s/N_B
- For a given M, R decreases linearly with increase in total hyperon content
- $M = 1\text{-}1.6\ M_{sol}$, R_{HS} >13 km due to pre-hyperon stiffening required for the EoS

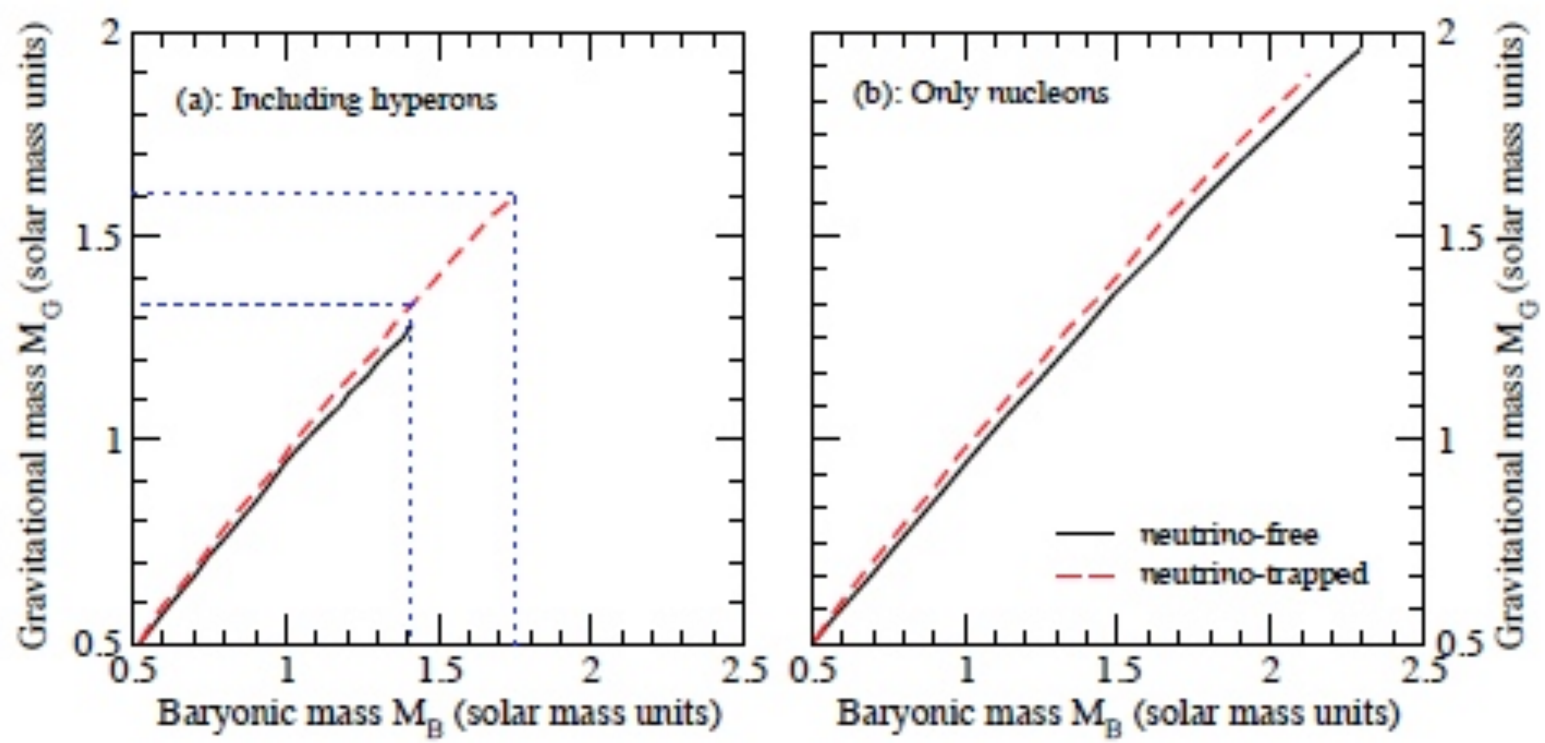




Fortin et al., (2015)

IMPLICATIONS ON ASTROPHYSICS: BH FORMATION





M_G vs M_B for neutrino-free and neutrino-trapped matter

D.C. and I. Vidaña, EPJA 52 (2016) 29

IMPLICATIONS ON ASTROPHYSICS: PNS COOLING

Possible sources of cooling

- *Leptonic weak processes*

direct Urca process:

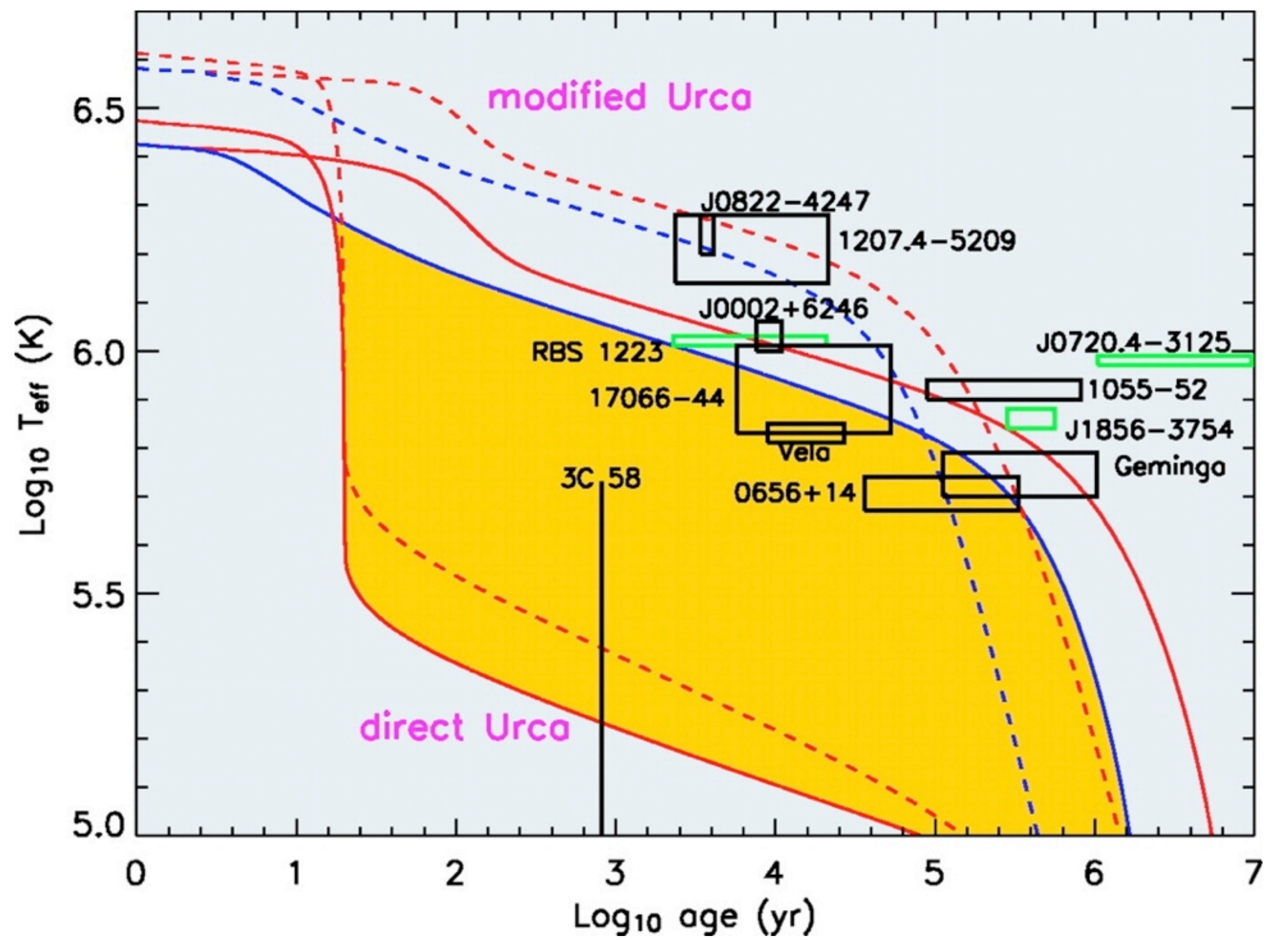
$$n \to p + e^- + \bar{\nu}_e$$
$$p + e^- \to n + \nu_e$$

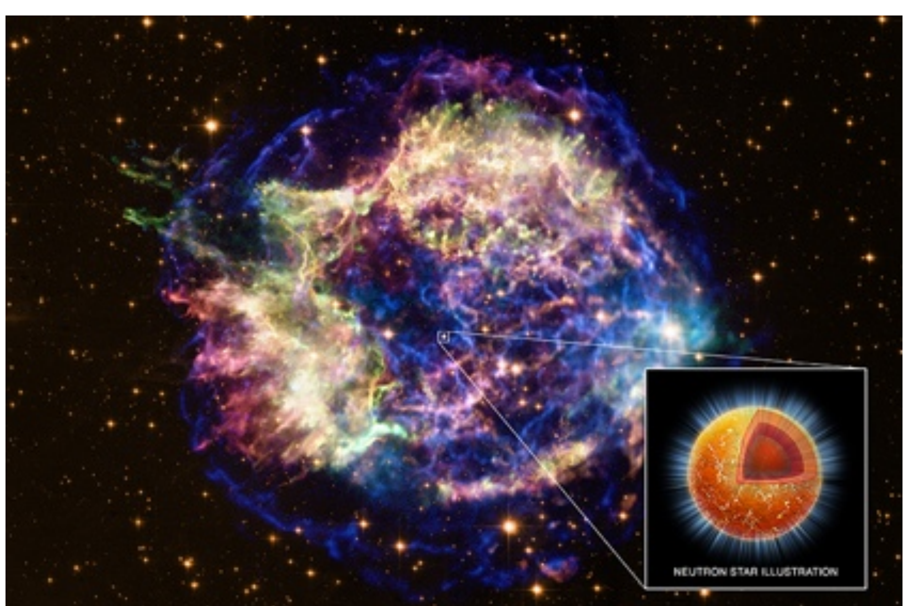
modified Urca process:

$$n + N \to p + e^- + \bar{\nu}_e + N$$
$$p + e^- + N \to n + \nu_e + N$$

hyperon Urca process :

$$Y \to B + l + \bar{\nu}_l$$





IMPLICATIONS ON ASTROPHYSICS: R-MODES

Possible sources of bulk viscosity

- *Leptonic weak processes*

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- *Non-leptonic processes involving hyperons*

$$n + p \leftrightarrow p + \Lambda$$
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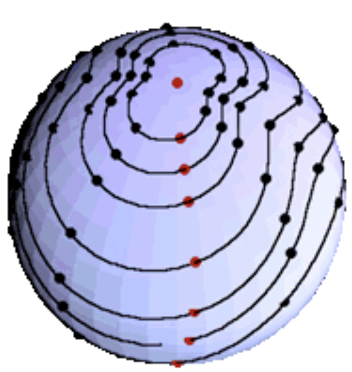
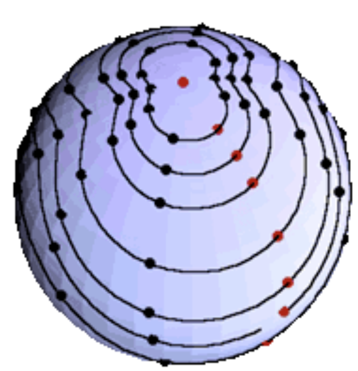


co-rotating



inertial

- *Generic to all rotating NSs*
- *Unstable by CFS mechanism: amplitude grows due to own gravitational radiation-reaction; sources of GW*
- *Damped by (shear, bulk) viscosity, depends on the composition of NS interior*
- *Shear viscosity: from momentum transport due to particle scattering*
- *Bulk viscosity: from variation in pressure and density when the system is driven away from chemical equilibrium*
- *timescale associated with growth/dissipation*
  $\tau_{\zeta,\eta} \gg \tau_{GW}$ *: r-mode unstable, star spins down*
  $\tau_{\zeta,\eta} \ll \tau_{GW}$ *: r-mode damped, star can spin rapidly*

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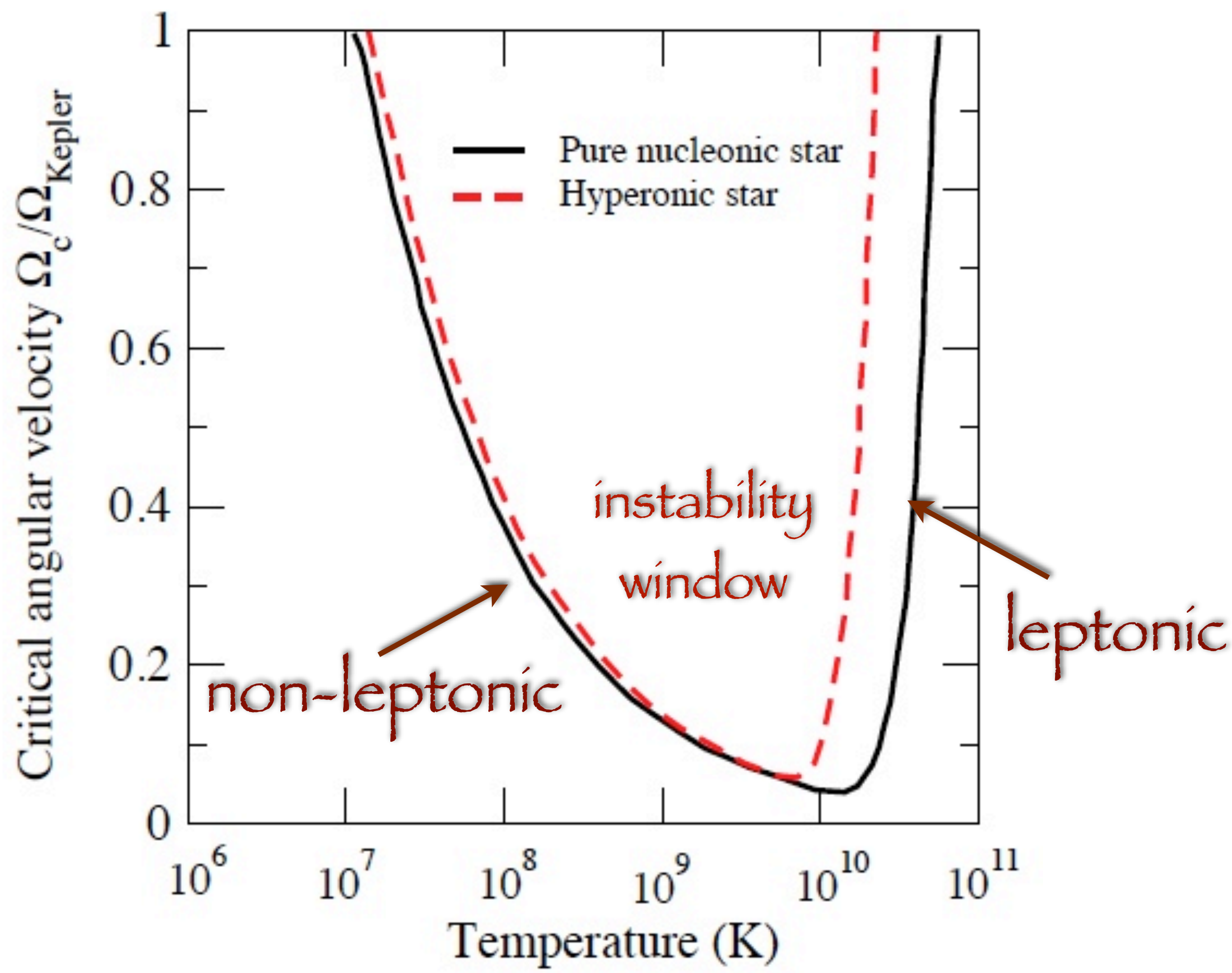

- *r-mode instability damped by leptonic bulk viscosity at high T and non-leptonic bulk viscosity at low T*

- *In the intermediate T regime, there exists an Instability window*

D.C. and D. Bandyopadhyay, PRD 74 (2006)

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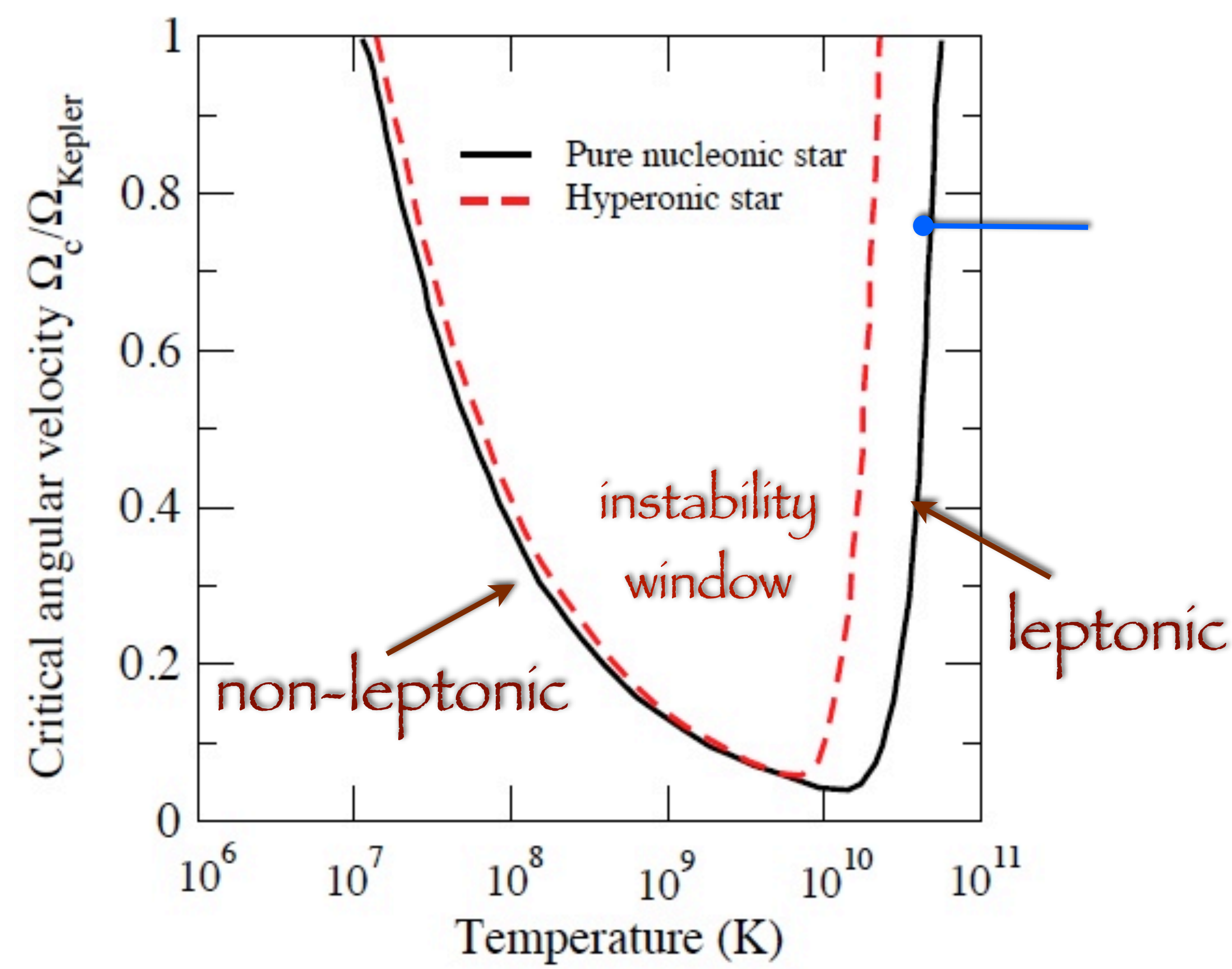

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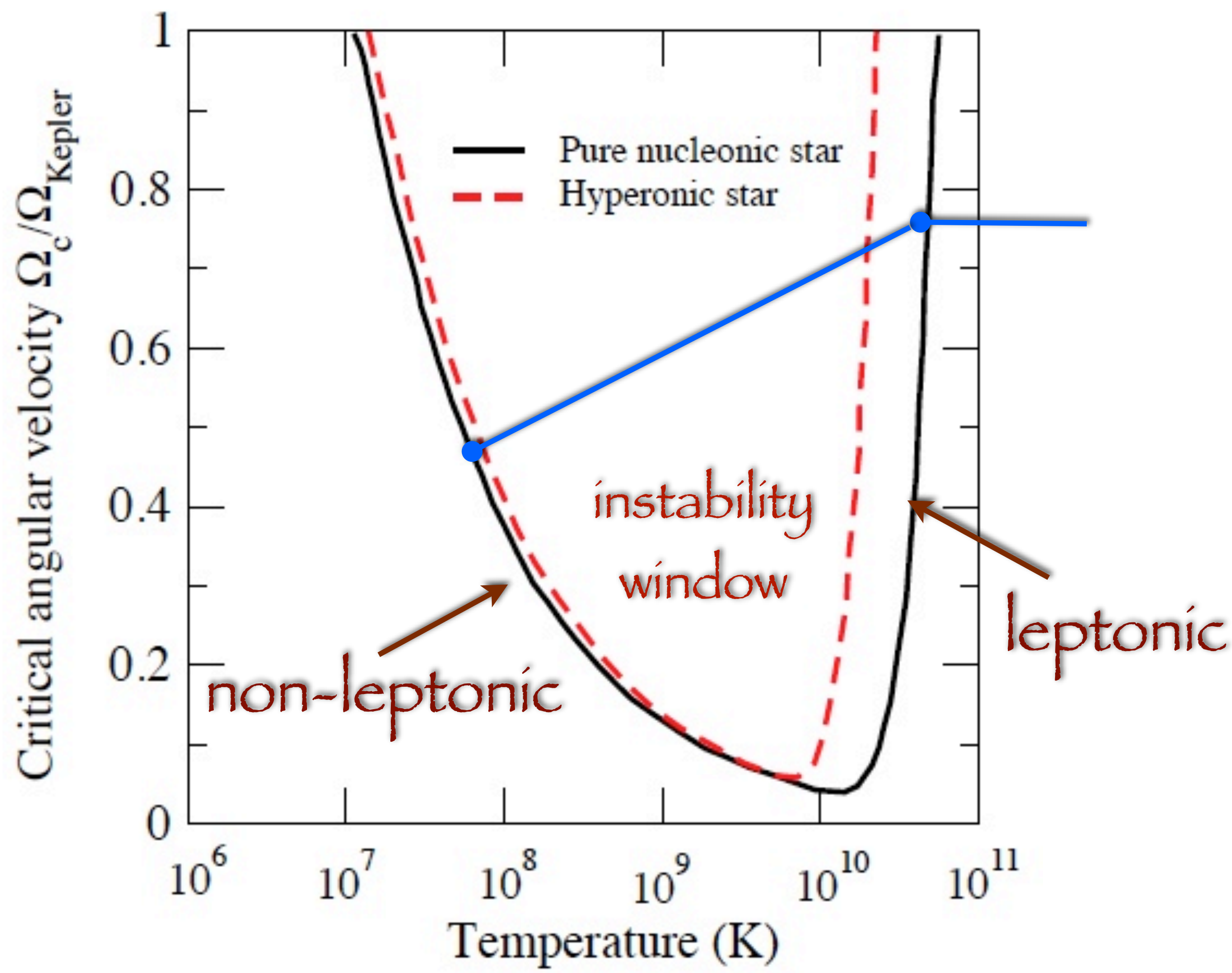

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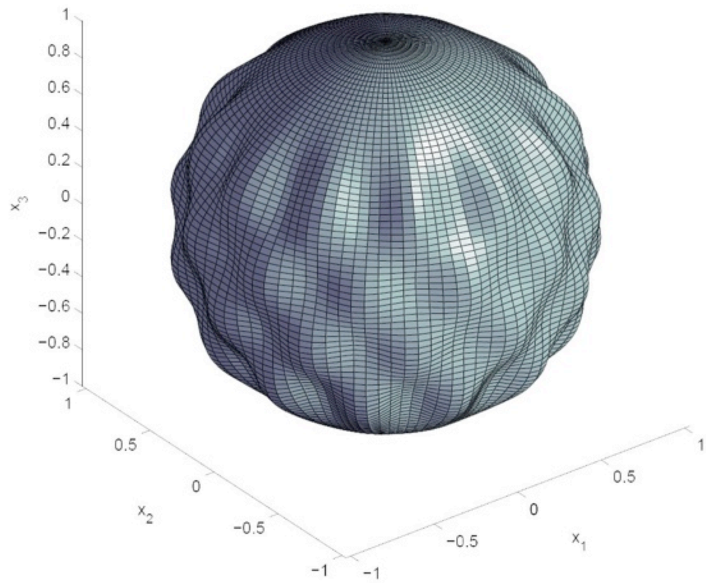
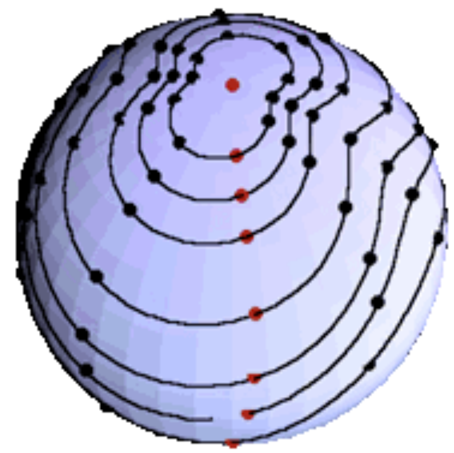
IMPLICATIONS ON ASTROPHYSICS: GW EMISSION



p-mode

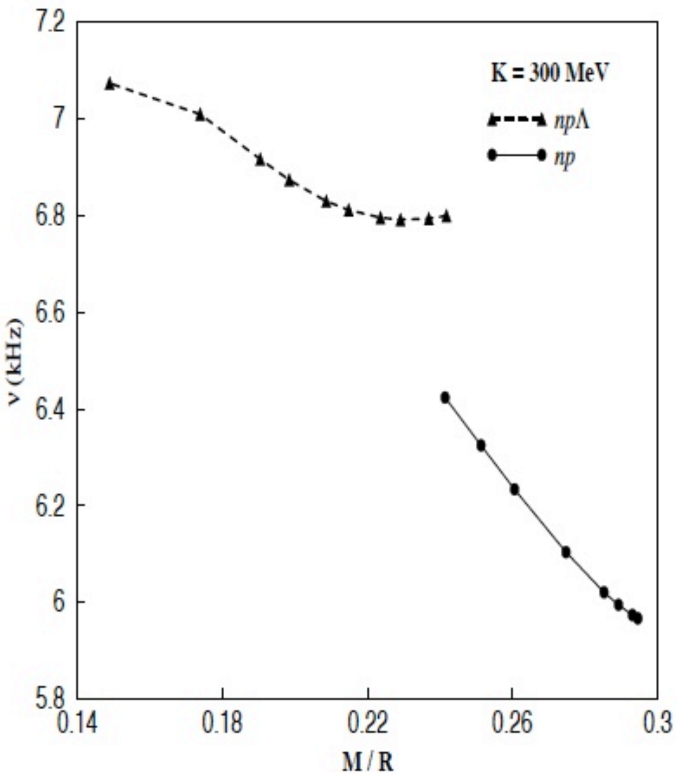


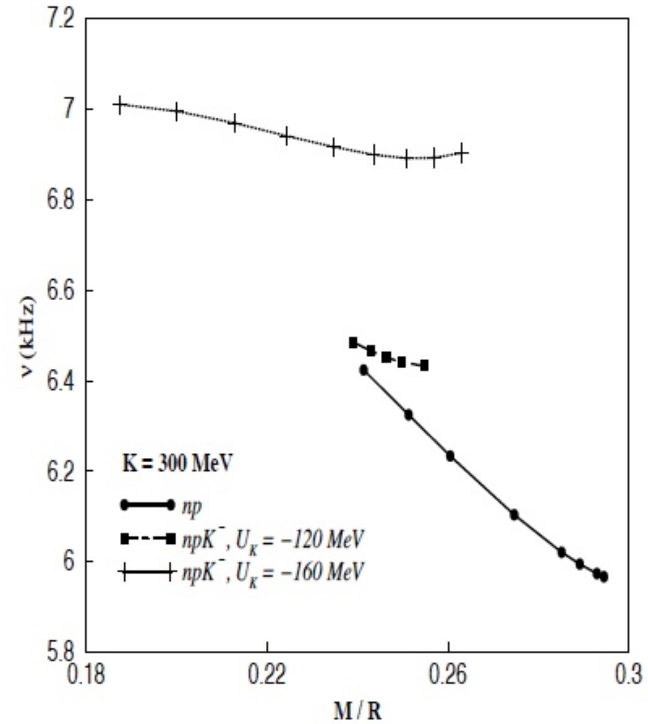
r-mode

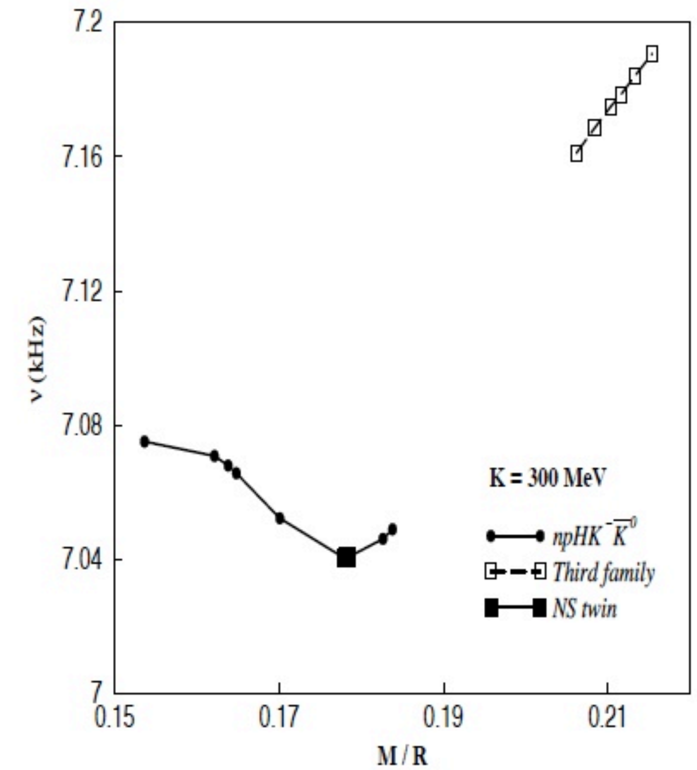
Non-radial Oscillations:
f-modes: fundamental
g-modes: buoyancy
p-modes: pressure
R-modes: Coriolis force
w-modes: space-time

G W detectors

IMPLICATIONS ON ASTROPHYSICS: AXIAL-W MODES



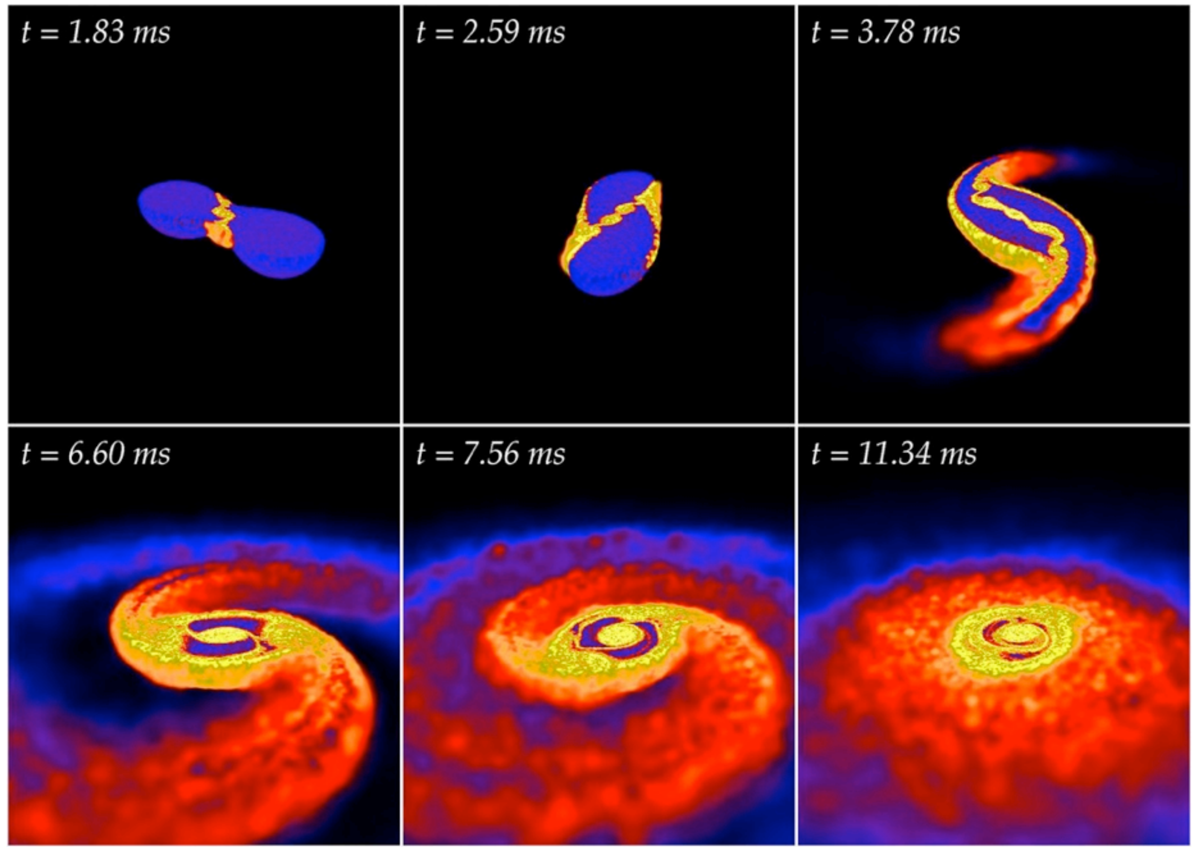


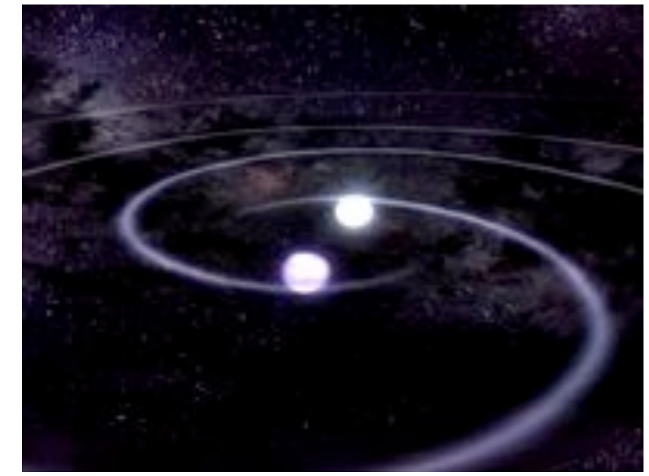


- Detection of w-mode frequencies can constrain composition of NSs
- Frequency and damping time for different EoSs can be calculated as functions of NS structure parameters such as M, R and compactness M/R
- First order phase transition can lead to a stable third family branch of compact stars with higher compactness (smaller radii) than NSs. Axial w-mode frequencies can be used to discriminate between a neutron star and its compact twin.

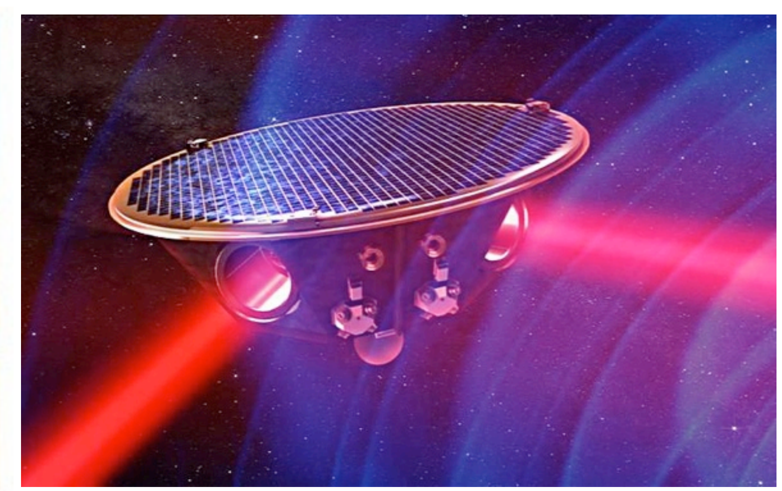
D.C. and D. Bandyopadhyay, PRD 80 (2009)

IMPLICATIONS ON ASTROPHYSICS: GW EMISSION





NS mergers



GW detectors

SUMMARY

- The presence of hyperons in finite nuclear systems is well established experimentally, and it is conjectured that hyperons should also be present in NSs
- As NSs possess large densities and n-p asymmetries beyond the reach of nuclear and hypernuclear experiments, one must rely on theoretical models, with parameters fitted to properties of SNM at nuclear saturation density and then extrapolated
- If present, hyperons should display particular signatures in astrophysical phenomena involving NSs. Thus astrophysical observables may provide constraints on properties of hyperons in dense matter
- The appearance of hyperons relieves the Fermi pressure, softens the Equation of State and reduces the maximum M. Thus observations of large NS masses puts stringent constraints on models of hyperons
- NS Radii may provide estimates on maximum strangeness fraction in NSs
- Urca processes involving hyperons should contribute to additional fast cooling in NSs, unless suppressed by hyperon SF
- Hyperon non-leptonic weak reactions may provide additional bulk viscosity, that may help to damp out unstable R-modes in rapidly rotating young NSs, thus limiting the emission of GWs during spindown to slowly rotating NSs

OUTLOOK

- Future experiments on Ξ-hypernuclei planned at J-PARC will help constrain the Ξ-N interaction as well as double Λ-hypernuclei produced by decay of Ξ^- captured in atomic orbit
- Future experiments planned in BNL, KEK, J-PARC with K beams and at FAIR with protons and antiprotons will study double-strange hypernuclei which may constrain Λ-Λ interaction
- Forthcoming HIC experiments will provide information on compressed baryonic matter at intermediate energies, densities relevant for NS interior where exotic components can appear
- Investigations using ions with varying Z/N ratios may allow the possibility to probe isospin asymmetry of dense matter
- Lattice QCD (HAL QCD) calculations may provide high precision predictions in future, in particular for channels where only few experimental data are available, e.g., the hyperon-nucleon interaction

THANK YOU! MERCI! VIELEN DANK! GRAZIE!