Rescuing the hyperons in compact stars

[A hypernuclear equation of state for dense matter]

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LNGS, Dec 5th, 2013

More info → PRC 87, 055806 (2013) and A&A 559, A118 (2013)

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

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outline

basic concepts

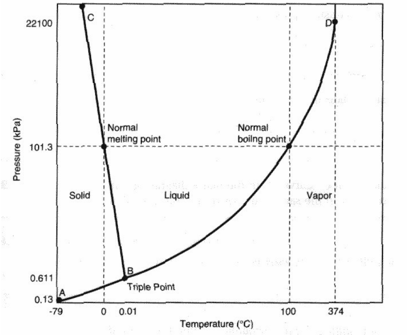
equation of state (EoS)

EoS

relation between thermodynamical quantities $(P, T, \rho, \epsilon, ...)$ which describes the **state of matter** under a given set of physical conditions

example: $PV = nRT$ (ideal gas)

an EoS yields a **phase diagram**



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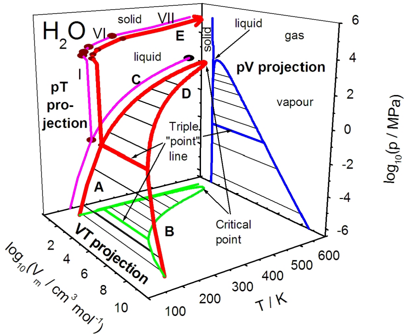
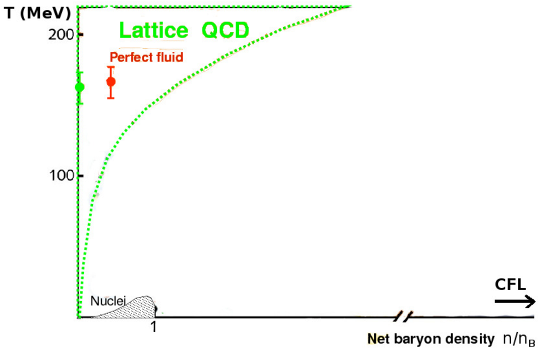


Herráez et al., J. Chem. Educ. (2004), http://biomodel.uah.es/Jmol/plots/phase-diagrams/

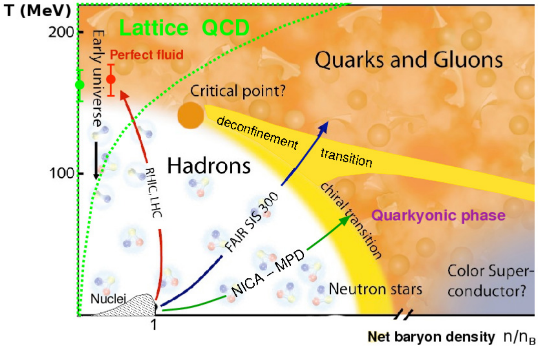
equation of state (EoS)

nuclear matter phase diagram



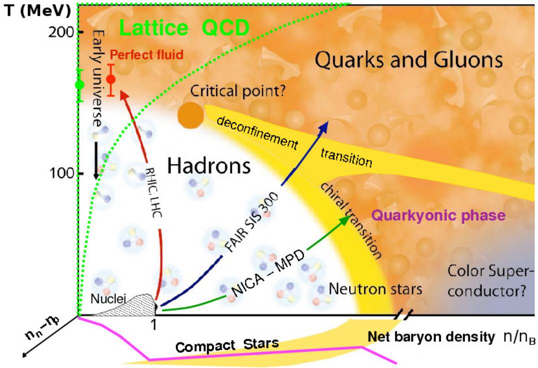
equation of state (EoS)

nuclear matter phase diagram



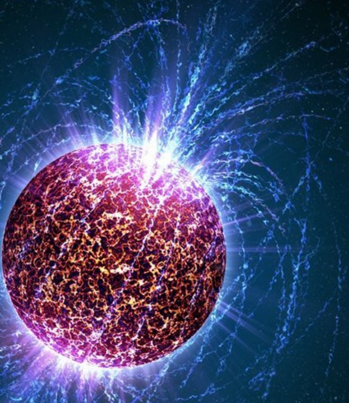
equation of state (EoS)

nuclear matter phase diagram



compact objects:

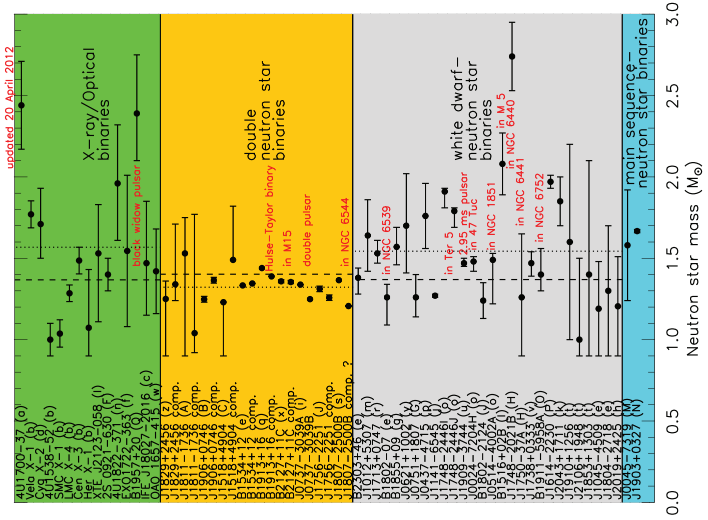
1. do not burn nuclear fuel
2. thermal pressure cannot balance the gravitational collapse (quantum degeneracy pressure)



the "Mario Rossi" compact star:

- mass $M \sim 1.5$ $M_\odot$
- radius $R \sim 12$ km
- density $\rho \sim \rho_0 \equiv 0.16$ fm^{-3}
- magnetic field up to $B \sim 0.01 m_\pi^2 \sim 10^{15}$ G
- rotation period $P \sim 10^{-3} - 1$ s
- temperature $T \sim$ few MeV $\sim 10^{10}$ K (cold objects!)

compact star observations: masses



(Lattimer, arXiv:1305.3510)

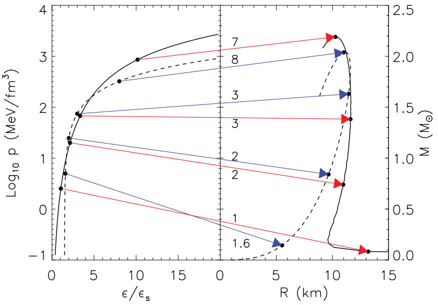
why a nuclear equation of state (EoS)?

GR hydrostatic equilibrium → Tolman-Oppenheimer-Volkoff equations (1939)

$$4\pi r^2 dp(r) = -\frac{M(r)dM(r)}{r^2}\left(1+\frac{p(r)}{\epsilon(r)}\right)\left(1+\frac{4\pi r^3 p(r)}{M(r)}\right)\left(1-\frac{2M(r)}{r}\right)^{-1}$$

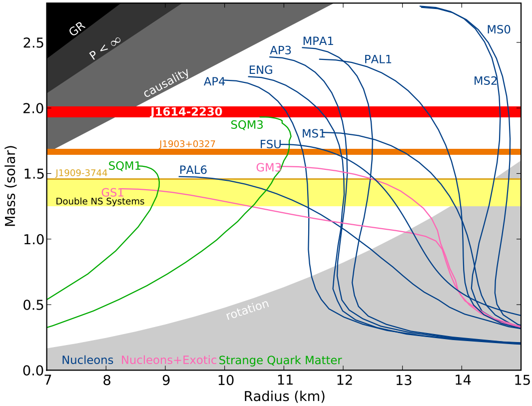
$$dM(r) = 4\pi r^2 \epsilon(r) dr$$

EoS generates a unique M vs. R relation! (Lindblom 1992)



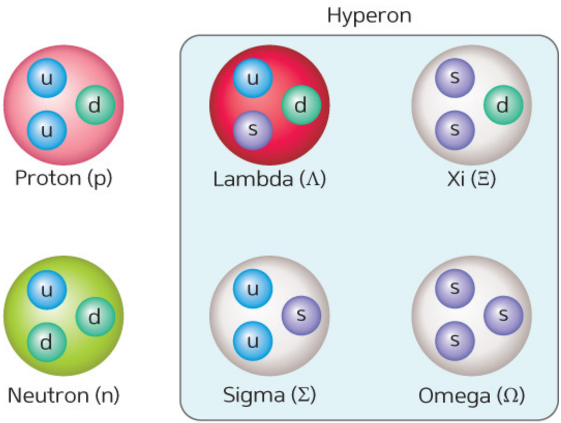
note: high mass configuration produced by *stiff* EoS

why a nuclear equation of state (EoS)?



- GR: $R > 2GM$
- finite pressure (compressible stellar matter): $R > 9GM/4$
- causality: $c_s < 1 \rightarrow R \gtrsim 2.9GM$
- rotation: mass-shedding limit (716 Hz) from fastest rotating pulsar J1748-2446

what is an hyperon



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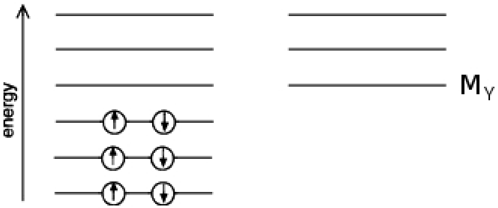
onset of hyperons in dense matter

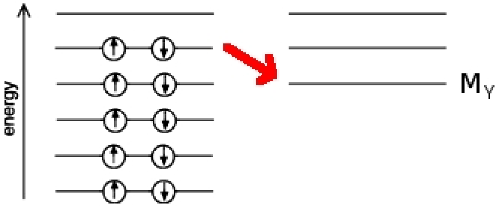


onset of hyperons: $\mu = \sqrt{k_F^2 + M_N^2} \geq M_Y^* - q\mu_e$

consequence (problem...)

At a given density, the presence of hyperons increases the number of Fermi spheres to be occupied leading to a lower pressure!

onset of hyperons in dense matter



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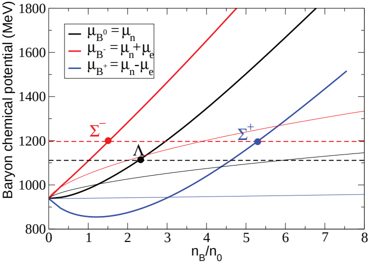
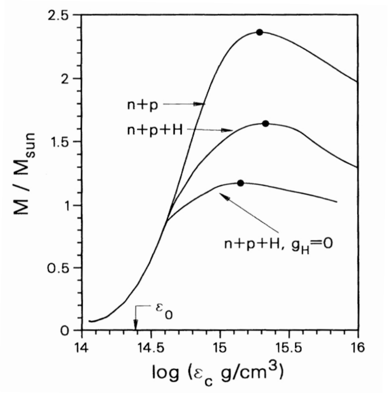


Page and Reddy (2006)

- thin lines: free gas
- thick lines: with mean-field NN potential
- horizontal lines are hyperon vacuum masses

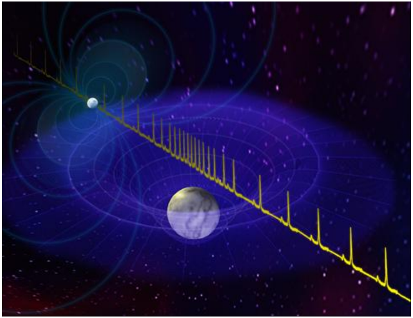


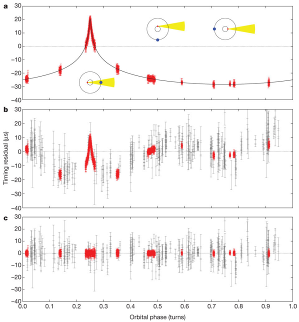
Glendenning and Moszkowski (1991)

hyperon puzzle

heavy mass compact stars

PSR J1614-2230: $M = 1.97 \pm 0.04 M_{\odot}$
(Shapiro delay)



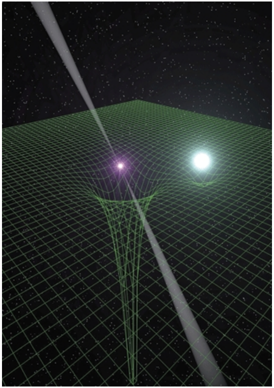


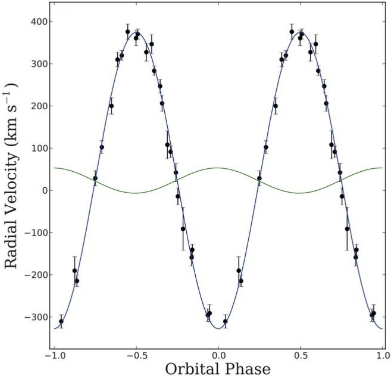
$$\Delta t = -2 M_{\mathrm{WD}} \frac{G M_{\mathrm{P}}}{R^3} \ln \left[1 - \sin i \sin(\Phi - \Phi_0)\right]$$

(Demorest et al., Nature, 2010)

heavy mass compact stars

PSR J1903+0327: $M = 2.01 \pm 0.04 M_\odot$
(radio timing and spectroscopy of the WD companion)



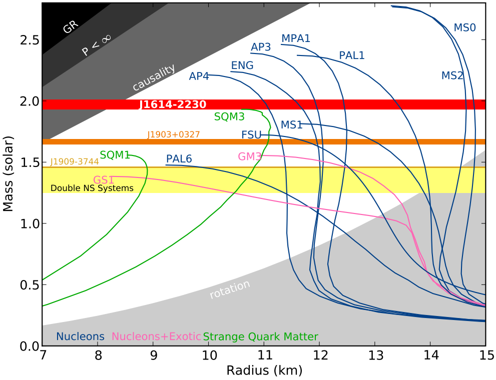


$$M_\mathrm{P}/M_\mathrm{WD} = v_\mathrm{WD}/v_\mathrm{P}$$

(Antoniadis et al., Science, 2013)

hyperon puzzle

EoS strongly dependent on the parametrization!



goal

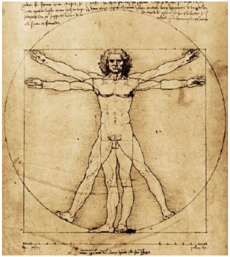
determination of limiting cases for hypernuclear matter

relativistic mean-field model

effective models

analytical, first-principle treatment of QCD is currently a cherished dream. . .

full model



effective model

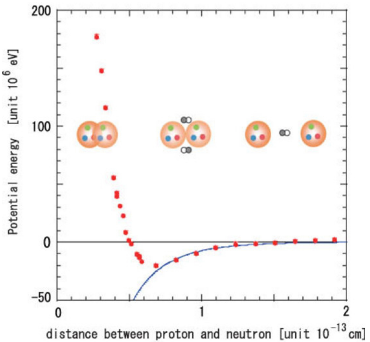
d.o.f.: observable particles (hadrons) instead of quarks and gluons

relativistic mean-field program:

- identify relevant degrees of freedom
- construct a Lagrangian (compatible with symmetries)
- compute the energy-momentum tensor (EoS)

(hyper) nuclear matter

basic assumptions and features for describing nuclear (and hypernuclear) properties:

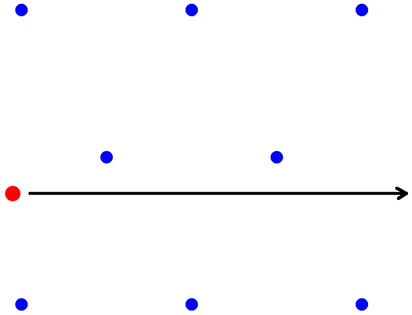


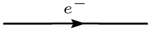
- nucleons (and hyperons) interact through meson exchange
- assume that only low spin, isospin is needed (from OBEP)
- σ–meson: long-range attraction
- ω–meson: repulsive part of the potential
- ρ–meson: isospin asymmetry

RMF

- static uniform matter in its ground state
- constant meson field VEV

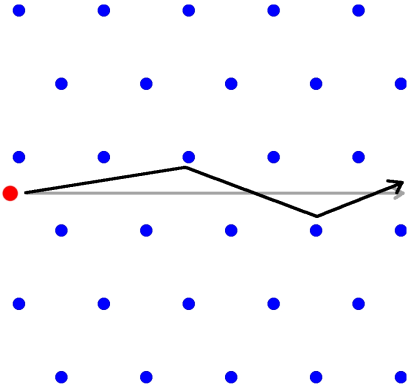
interacting theory

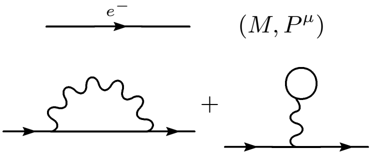




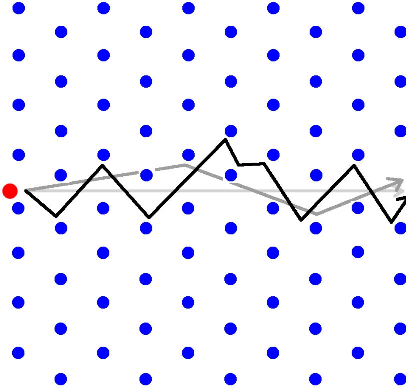
(M, P^μ)

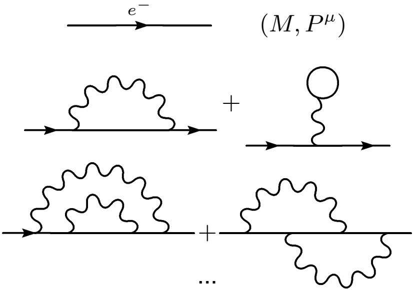
interacting theory



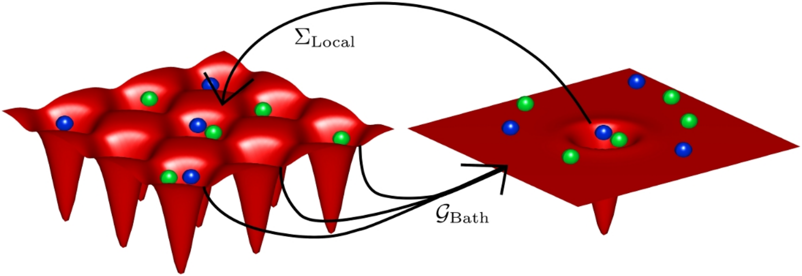


interacting theory





relativistic mean-field model



(http://physics.aalto.fi/groups/comp/qd/research/)

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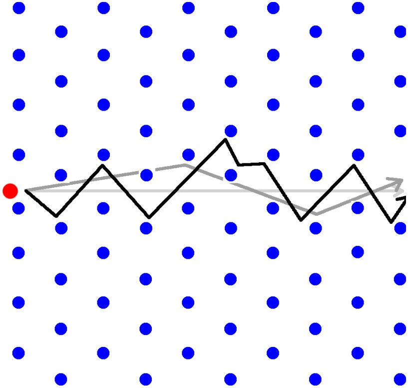
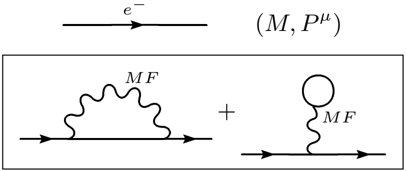


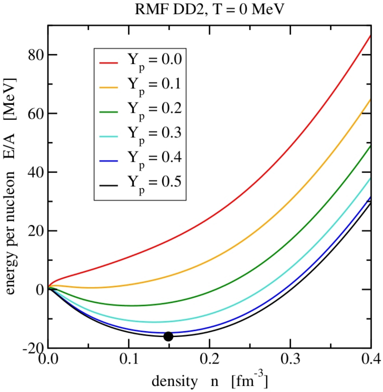


what do we need all this formalism for?

energy-momentum tensor

a model $\mathcal{L}[\phi_i]$ $\rightarrow$ $T_{\mu\nu} = -g_{\mu\nu}\mathcal{L} + \sum_i \frac{\partial \mathcal{L}}{\partial^\mu \phi_i}\partial_\nu \phi_i$ $\rightarrow$ we get a nuclear EoS!

with $T_{\mu\nu} = \mathrm{diag}(\epsilon, p, p, p)$



(Typel S., 2010)

electrically neutral stellar matter in β-equilibrium:
two **conserved charges** and two **Lagrange multipliers**, namely for the particle species i:

$$\mu_i = B_i \mu_B + Q_i \mu_Q$$

constraints on μ_B and μ_Q

$$\sum_i B_i \rho_i = \rho_B, \qquad \sum_i Q_i \rho_i = \rho_Q \equiv 0$$

RMF Lagrangian

full Lagrangian

$$\mathcal{L}_B = \sum_B \bar{\psi}_B[\gamma^\mu(i\partial_\mu - g_{\omega B}\omega_\mu - \frac{1}{2}g_{\rho B}\boldsymbol{\tau}\cdot\boldsymbol{\rho}_\mu) - (m_B - g_{\sigma B}\sigma)]\psi_B$$
$$+ \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu - \frac{1}{4}\boldsymbol{\rho}^{\mu\nu}\cdot\boldsymbol{\rho}_{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}^\mu\cdot\boldsymbol{\rho}_\mu$$
$$+ \sum_{e^-,\mu^-} \bar{\psi}_\lambda(i\gamma^\mu\partial_\mu - m_\lambda)\psi_\lambda$$

baryon octet: p, n, Λ, Σ's and Ξ's
mesons: σ, ω and ρ
leptons: e^-, μ^- (and neutrinos at finite-temperature)
parameters:

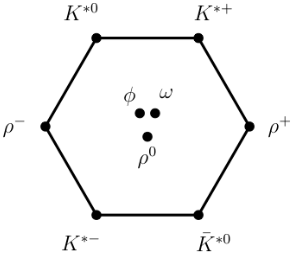
- $g_{iN} \equiv g_{iN}(\rho)$ [DD-ME2, Niksic et al., 2008]
  (symmetric and asymmetric nuclear matter, binding energies, charge and neutron radii of spherical nuclei)
- g_{iY} to be fixed

how to fix g_{iY}

fit to hypernuclear-potential (U_Y) data

$$U_Y = g_{\sigma Y}\sigma^{eq} + g_{\omega Y}\omega^{eq}$$

1) vector octet



VDM: universal coupling of $\boldsymbol{\rho}$

$$g_{\Xi\Xi\rho} = g_{NN\rho} = \frac{1}{2}g_{\Sigma\Sigma\rho}, \quad g_{\Lambda\Lambda\rho} = 0$$

quark model and ideal mixing: mesons

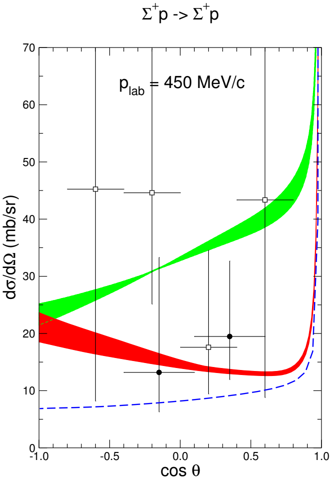
$$\omega \sim \frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d)$$
$$\phi \sim \bar{s}s$$

simple strangeness-content counting

$$g_{\Sigma\Sigma\omega} = g_{\Lambda\Lambda\omega} = 2g_{\Xi\Xi\omega} = \frac{2}{3}g_{NN\omega}$$

how to fix g_{iY}

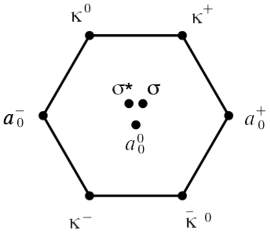
unknown hypernuclear potentials!



(Haidenbauer et al., 2013)

future: lQCD and PANDA, HypHI, MAMI C, FINUDA, JLab, J-PARC, ...

2) scalar octet:



$$2(g_{N\sigma} + g_{\Xi\sigma}) = 3g_{\Lambda\sigma} + g_{\Sigma\sigma}$$

parameter study:

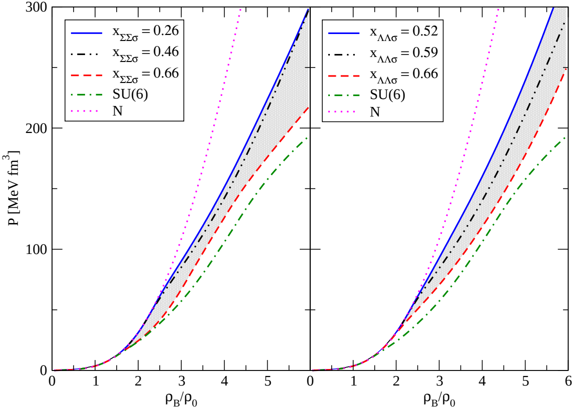
- fix one of the couplings to NSC89
- vary $g_{\sigma\Lambda}$ (or $g_{\sigma\Sigma}$) such that

$$0 < g_{\sigma Y} < g_{\sigma N}$$

results

results for zero-temperature

hyperon coupling constants fixed by NSC89

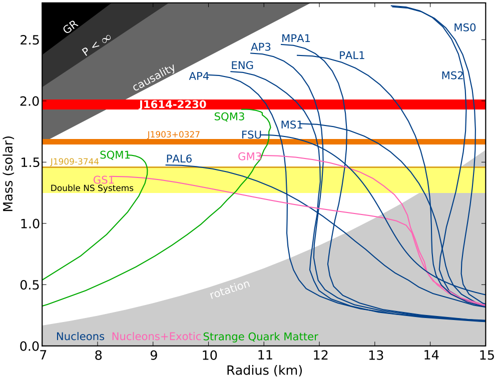


$x_{\Lambda\sigma} = 0.58$ $\qquad$ $x_{\Sigma\sigma} = 0.448$

where $x_{\Lambda\sigma} = g_{\Lambda\sigma}/g_{N\sigma}$

again: hyperon puzzle

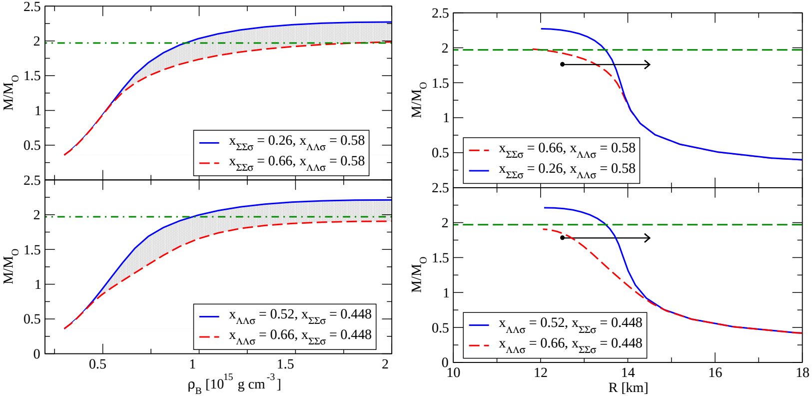
EoS strongly dependent on the parametrization!



goal

determination of limiting cases for hypernuclear matter

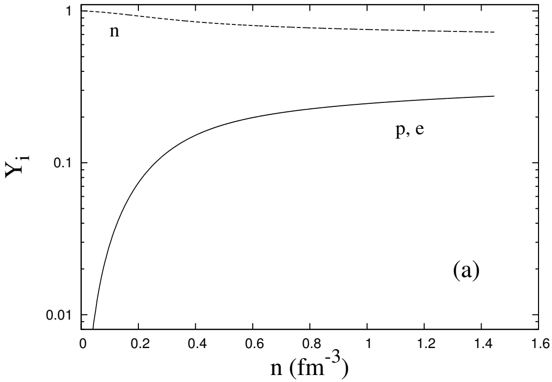
mass-radius relation



particle fractions: zero temperature

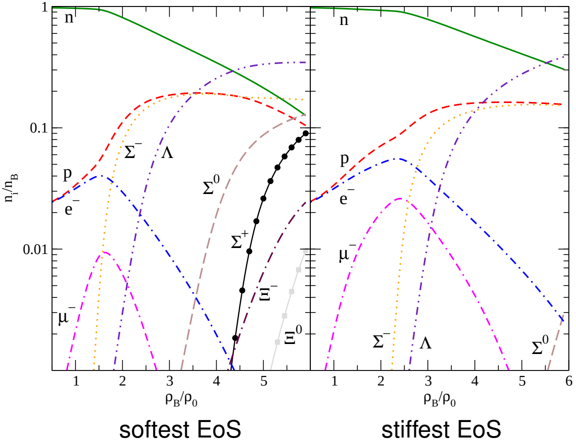
no hyperons

- charge neutrality
- β-equilibrium



(Lopes, 2012)

particle fractions: zero temperature



- deleptonization due to negative hyperon onset
- shift of hyperon onset in case of small *attractive* couplings ($g_{Y\sigma}$)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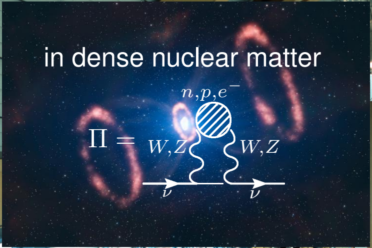
neutrinos in proto-neutron stars

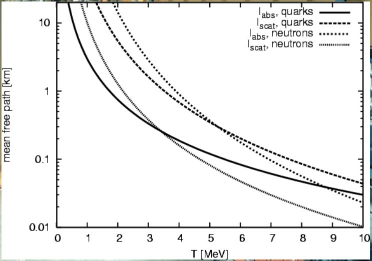


mean-free path

$$\lambda \sim 1/\sigma(T)$$

cross-section

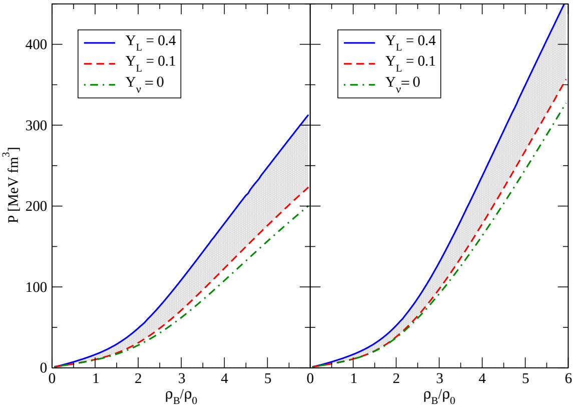
$$d\sigma(T) \sim \Pi(T)$$



(Sagert, 2008)

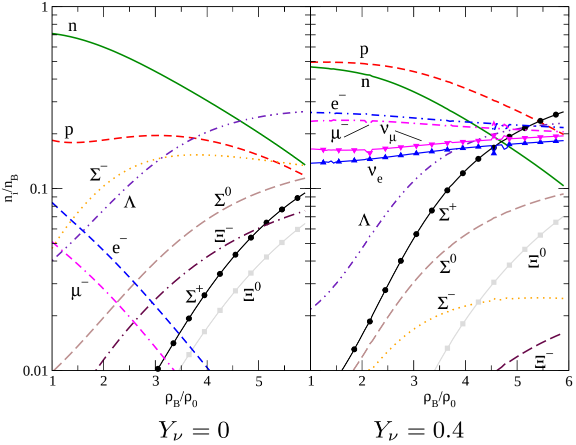
non-zero temperature and neutrino trapping

new dof (neutrinos) $\rightarrow$ new constraint: fixed lepton fraction

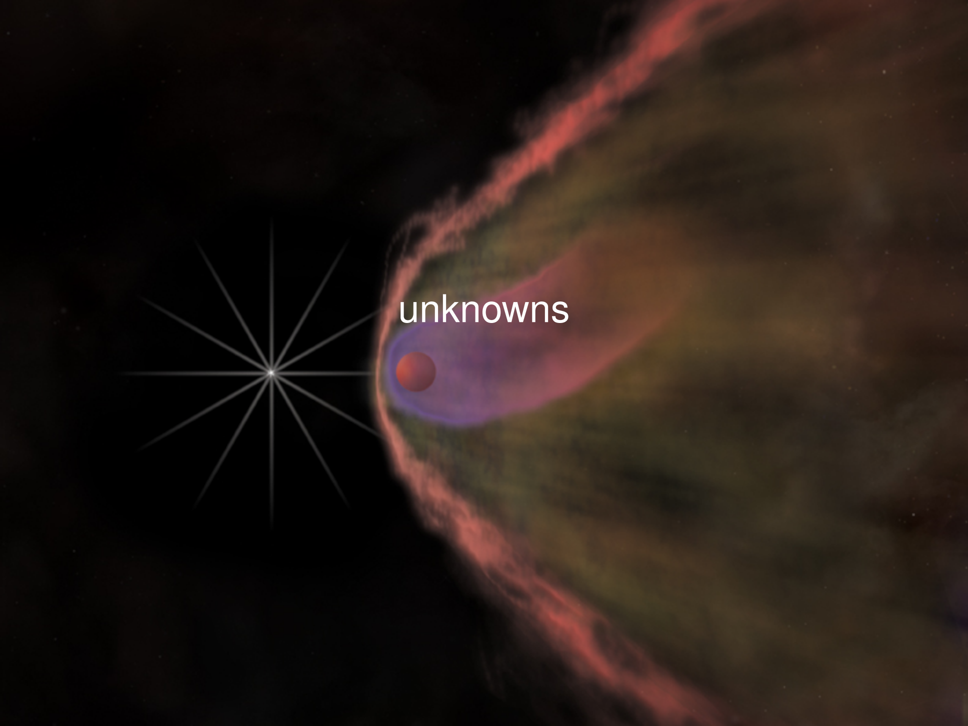


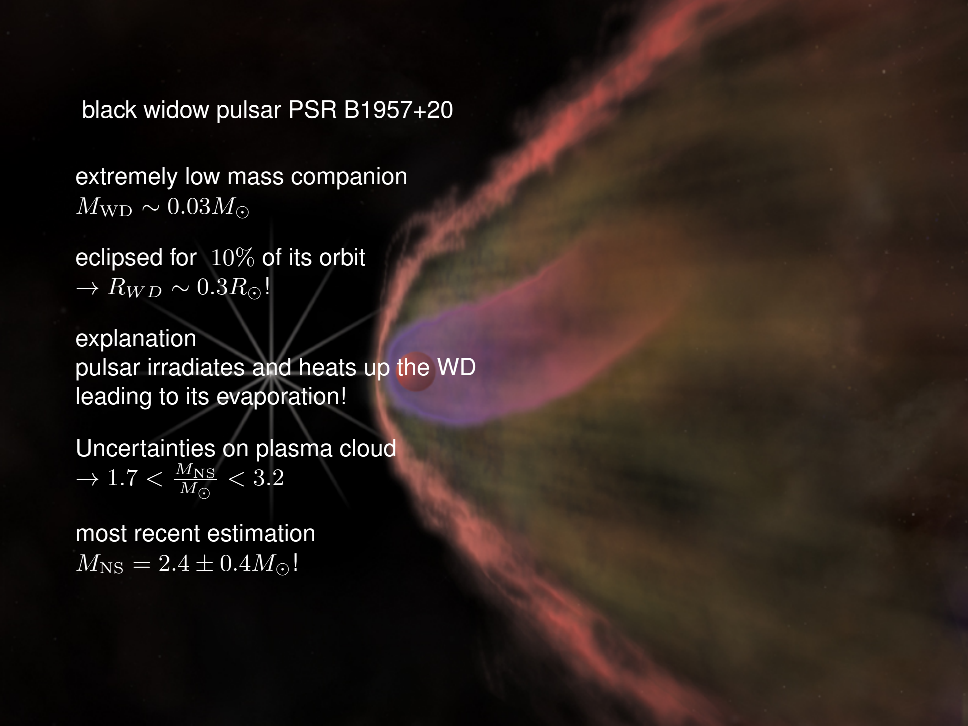
($T = 30$ MeV)

particle fractions: non-zero temperature



- no deleptonization due to fixed lepton fraction
- positive charged hyperons favored due to the presence of electrons
- inversion of charged hyperon onset


unknowns



black widow pulsar PSR B1957+20

extremely low mass companion
$M_{\mathrm{WD}} \sim 0.03 M_{\odot}$

eclipsed for 10% of its orbit
$\rightarrow R_{WD} \sim 0.3 R_{\odot}$!

explanation
pulsar irradiates and heats up the WD
leading to its evaporation!

Uncertainties on plasma cloud
$\rightarrow 1.7 < \frac{M_{\mathrm{NS}}}{M_{\odot}} < 3.2$

most recent estimation
$M_{\mathrm{NS}} = 2.4 \pm 0.4 M_{\odot}$!

what about rotation?

what about strong magnetic fields?

what about inhomogeneous phases at high densities?

what about GR at 10 times ρ_0?

what about dark matter?

...

summary

summary

take-home message

- NS are weird, therefore interesting for physicists!
- high mass NS ($M \sim 2M_\odot$) constraints on EoS
- uncertainties on hyperon parameters allow for their onset
- need for constraints (lQCD or experiments)

future

- rotation and magnetic field contributions to the EoS
- constraints from other observations (cooling, radii)
- merger simulations $\rightarrow$ possible signatures from GW
- hybrid models (hadrons + quarks)

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Thanks for your attention!

backup

International Hypernuclear Network