Neutron Stars as Nuclear Physics Laboratory

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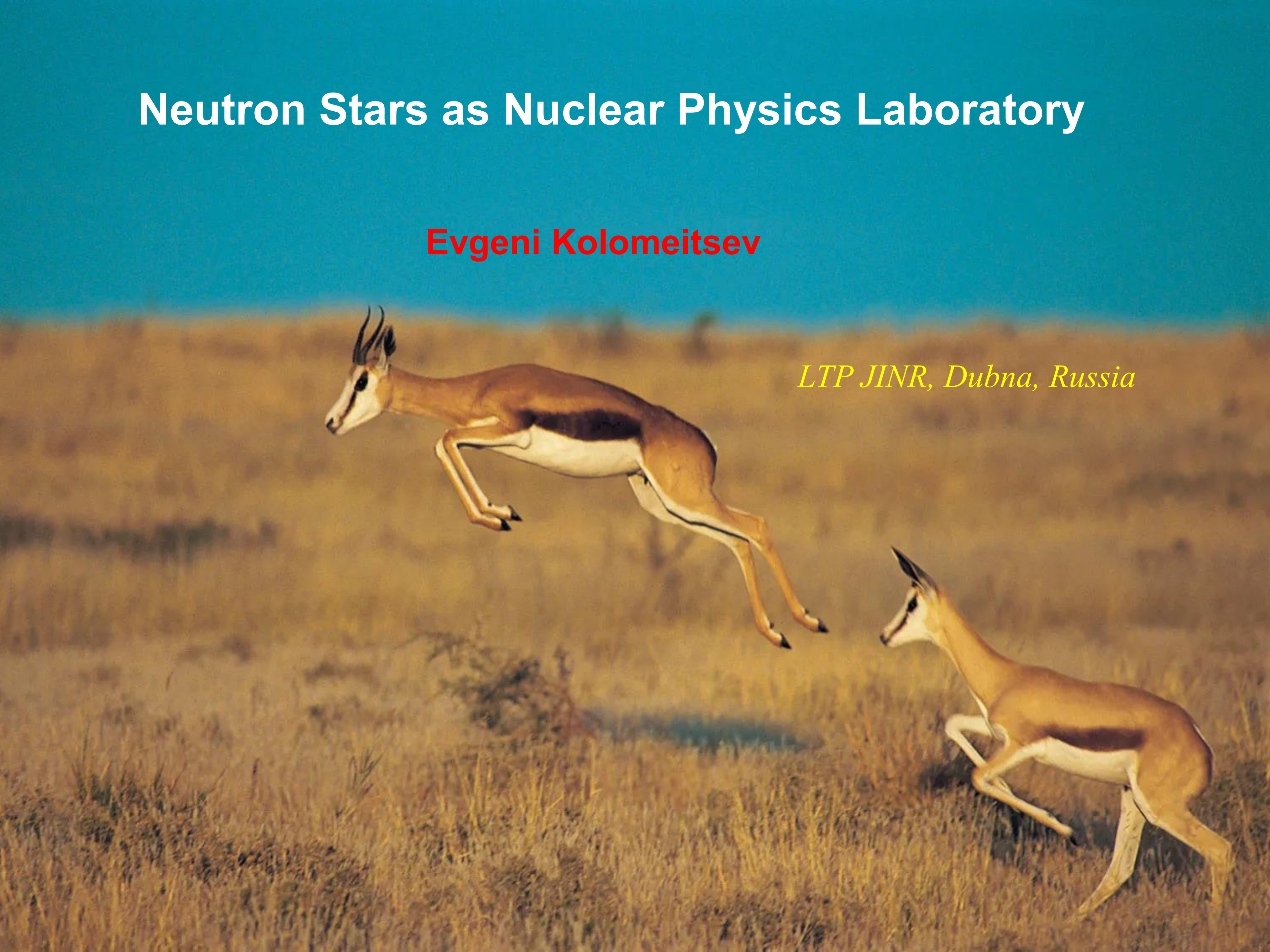
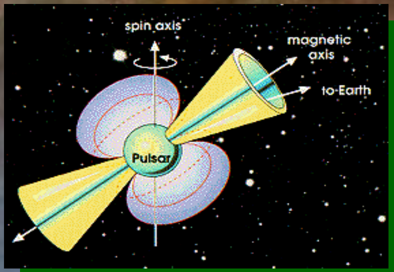
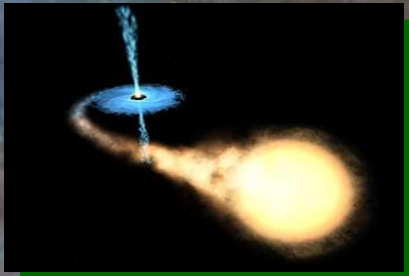


Neutron Star Zoo

>2000 neutron stars in isolated rotation-powered pulsars
~ 30 millisecond pulsars



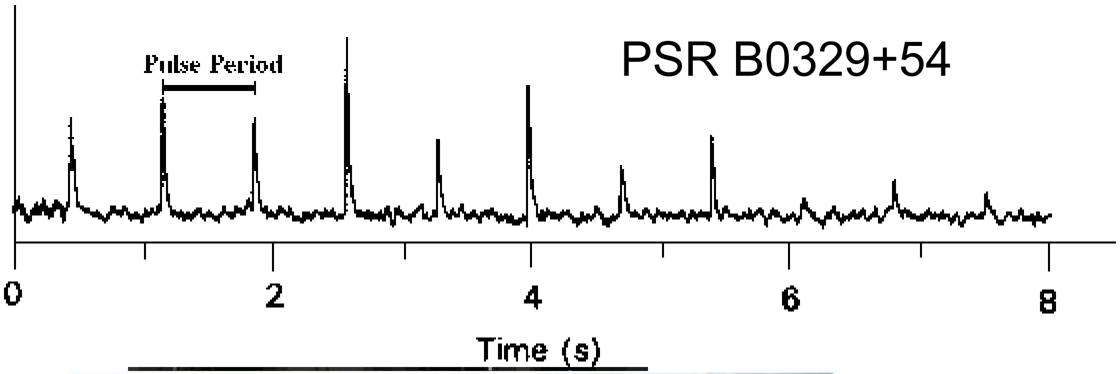
>100 neutron stars in accretion-powered X-ray binaries
~ 50 x-ray pulsar
intense X-ray bursters (thermonuclear flashes)

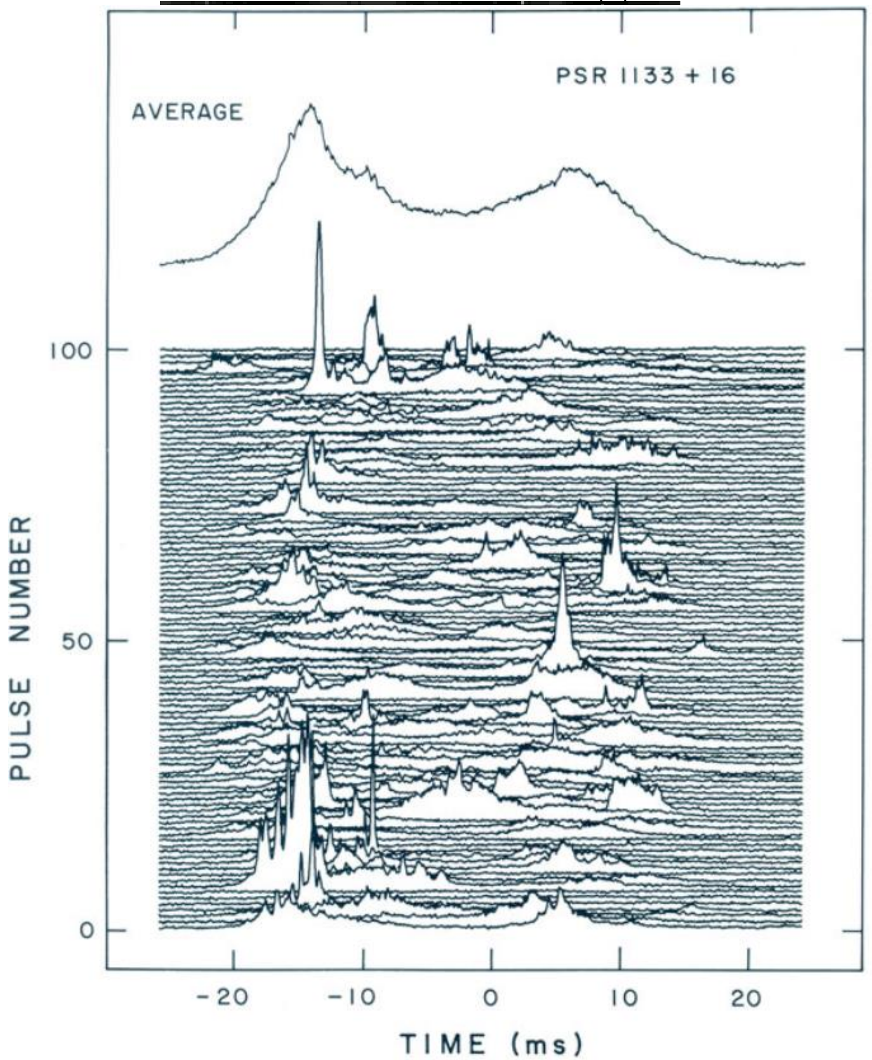


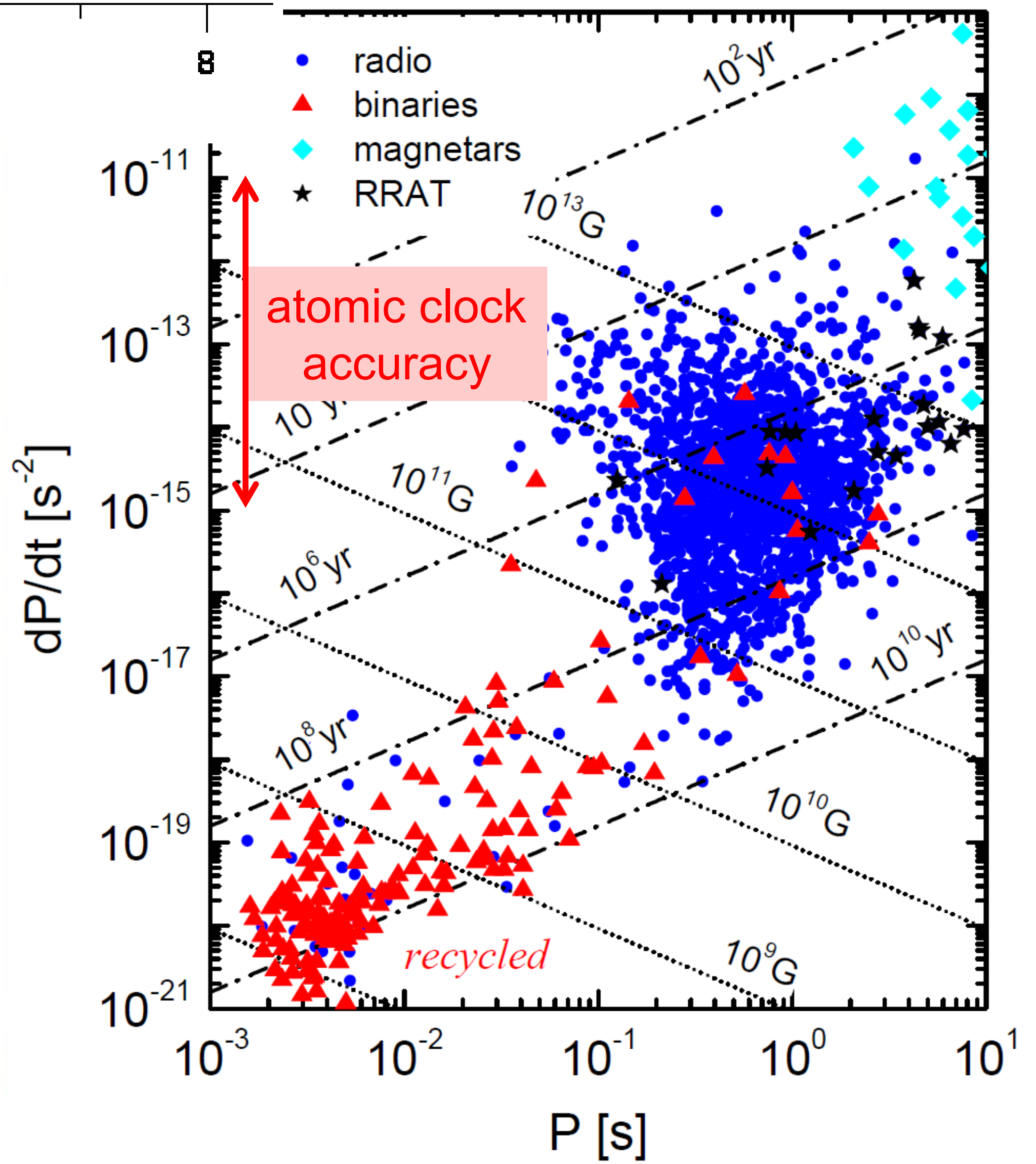
short gamma-ray bursts
neutron star -- neutron star,
neutron star -- black-hole mergers

soft gamma-ray repeaters – magnetars
(super-strong magnetic fields)

Pulsar timing



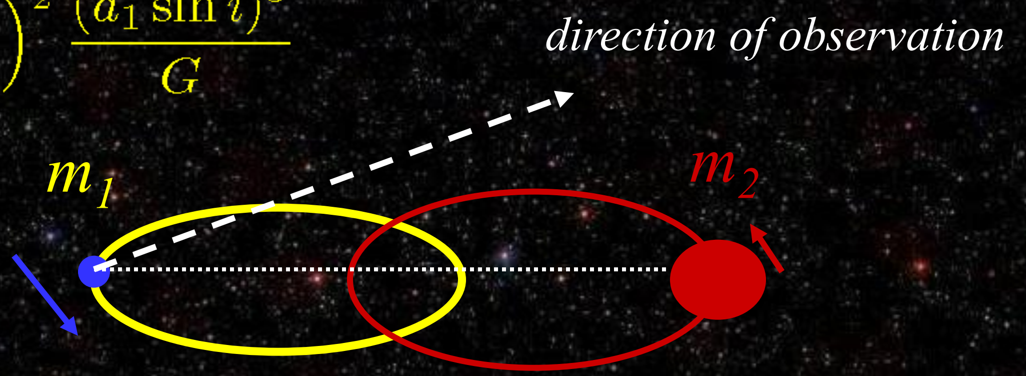




Measuring pulsar mass

Pulsar mass can be measured only in binary systems

$$\frac{(M_1 \sin i)^3}{(M_1+M_2)^2} = \left(\frac{2\pi}{P_b}\right)^2 \frac{(a_1 \sin i)^3}{G}$$



Newton gravity ⟶ 5 Keplerian orbital parameters:
orbital period, semi-major axis length,excentricity, …

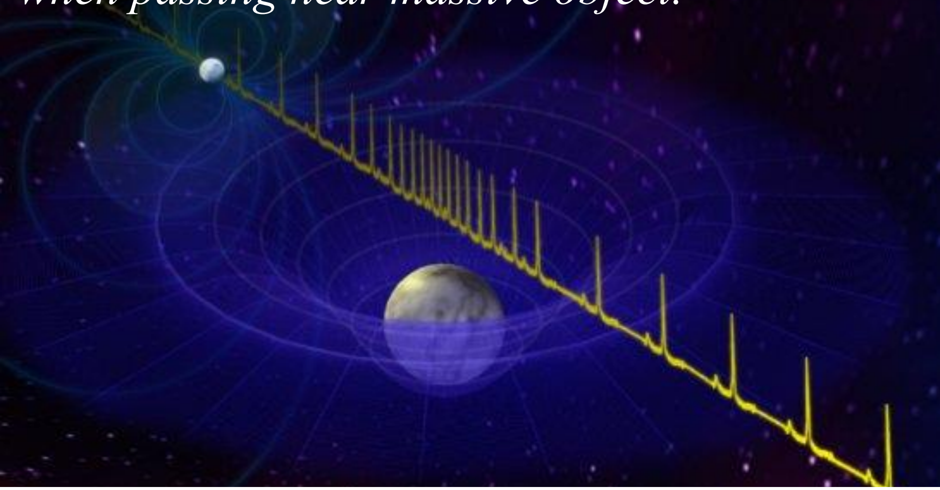
Do not determine individual masses of stars and the orbital inclination.

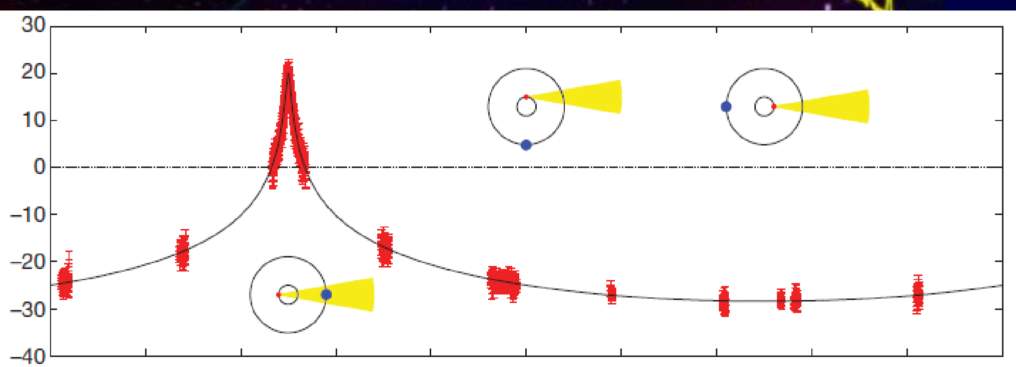
Einstein gravity ⟶ 5 potentially measurable post-Keplerian parameters:
orbit precession, Shapiro delay, gravitational redshift, ….

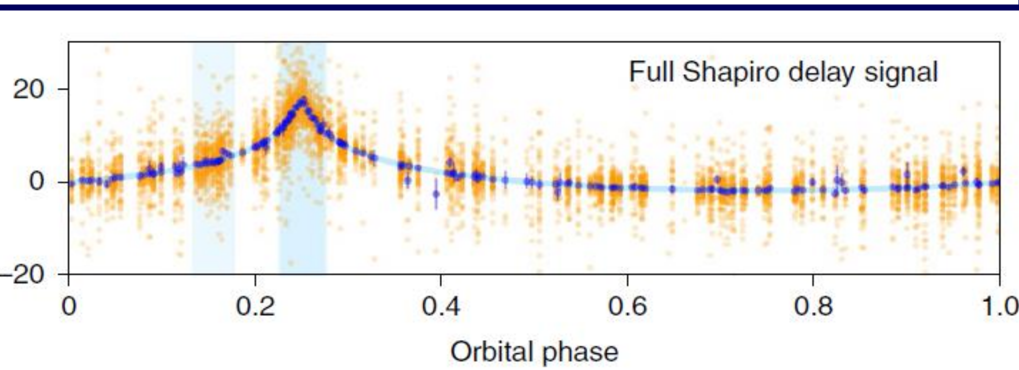
Measurement of any 2 post-Keplerian parameters allows to determine the mass of each star.

Shapiro Delay

Time signal is getting delayed when passing near massive object.

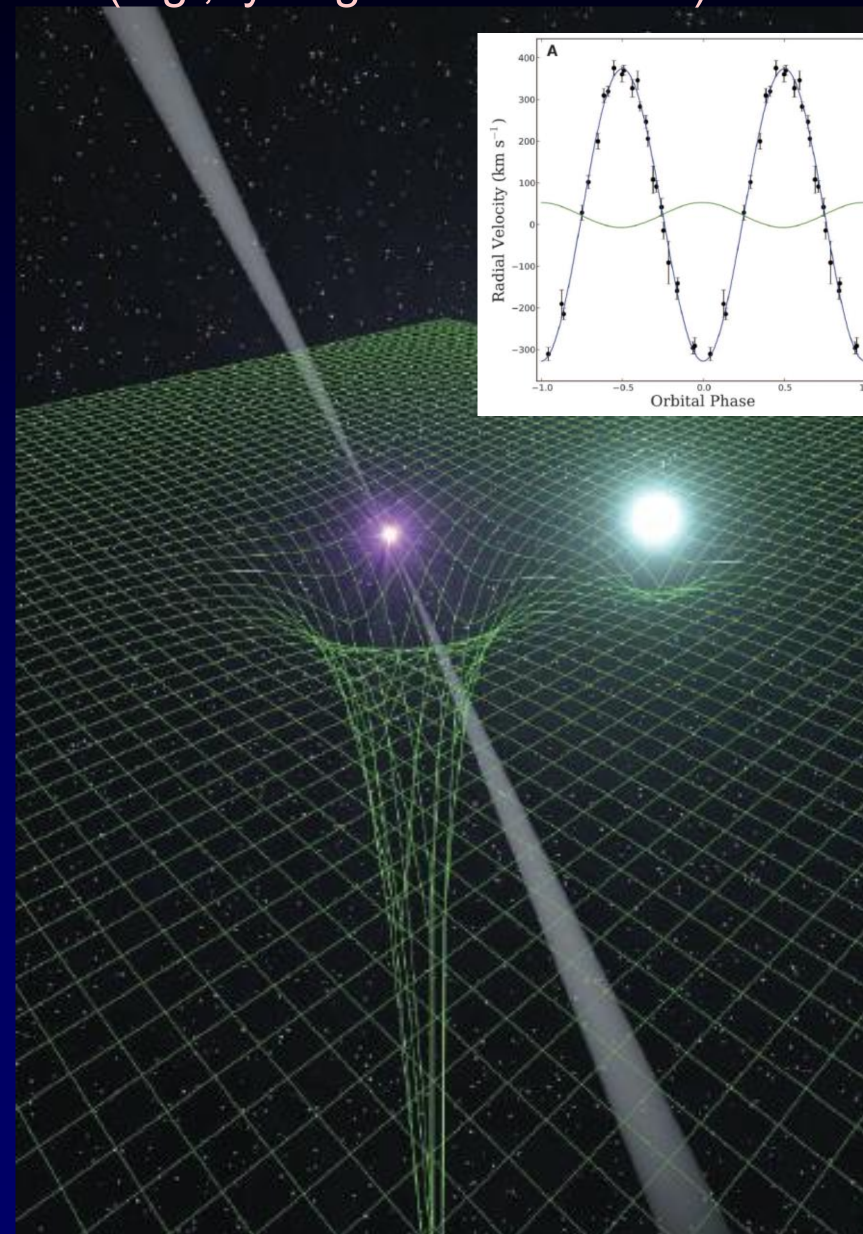






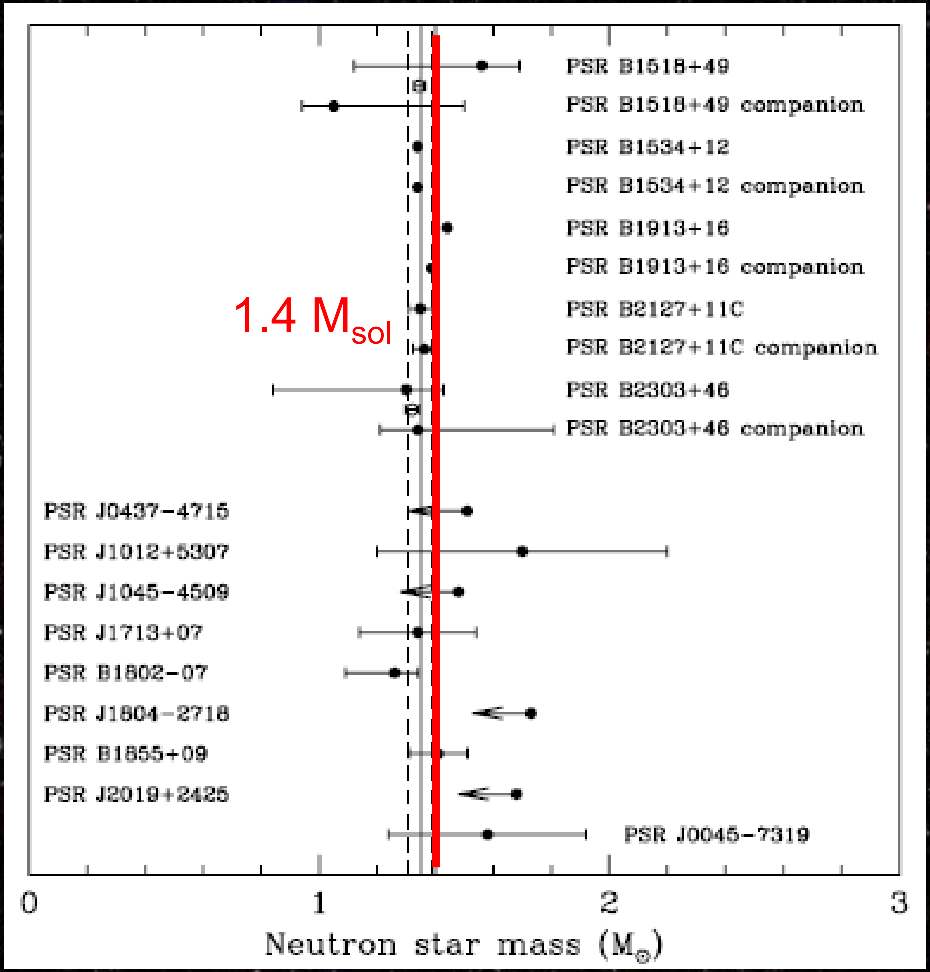
Measured Phase-Resolved Spectra of the optical counterpart.

(e.g.,hydrogen Balmer lines)



Neutron star masses

1999

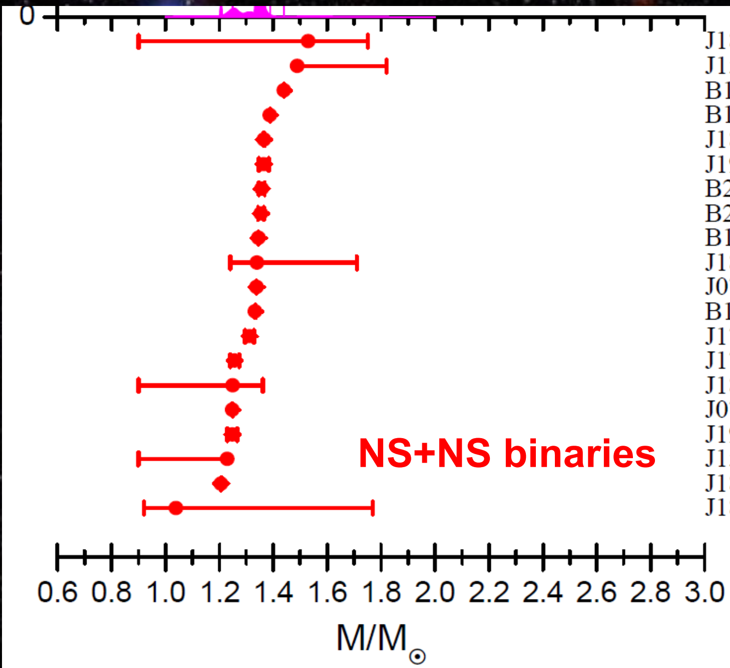


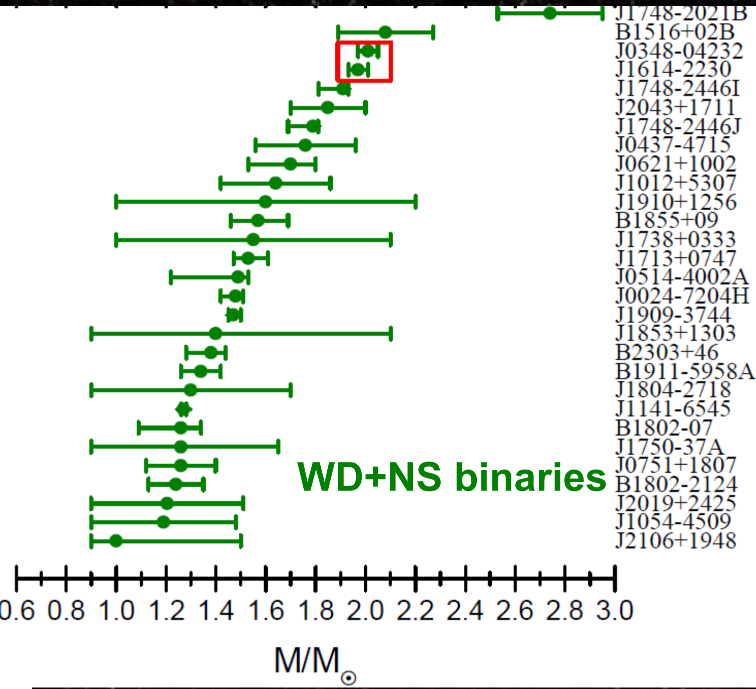
Are masses of all NS the same?

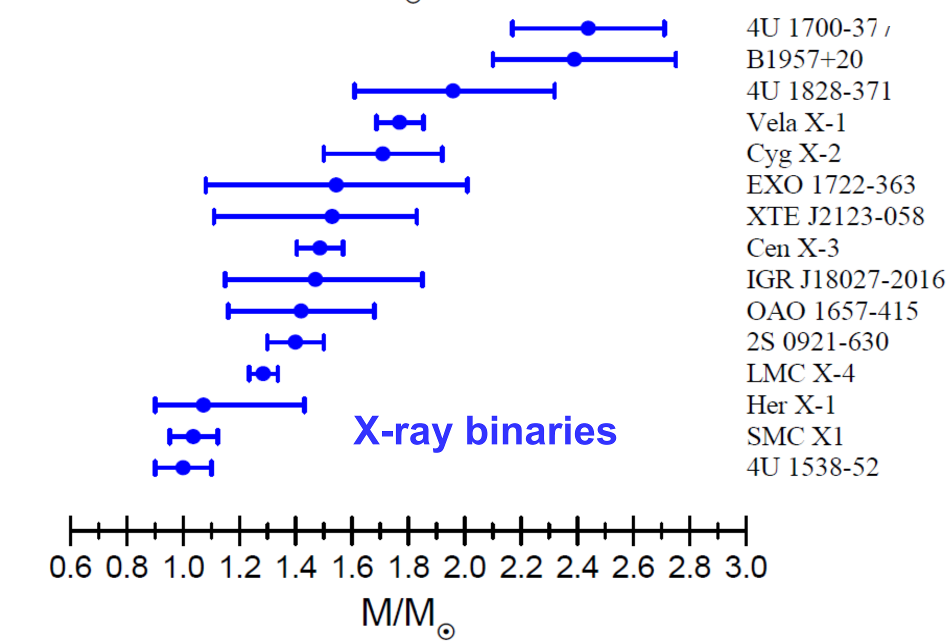
[Thorsett, Chakrabarty, ApJ 512 (1999)288]

Neutron star masses

2020s

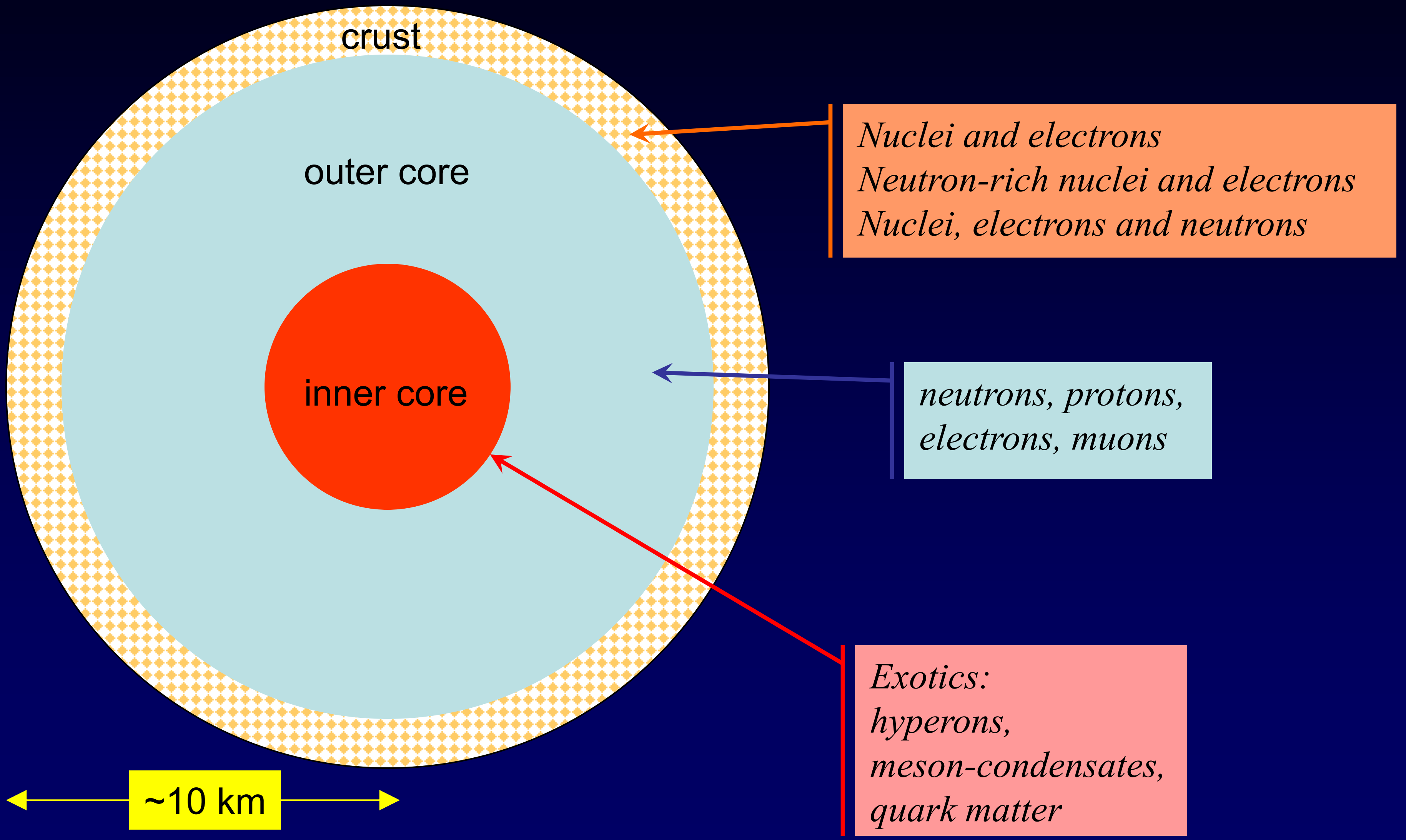






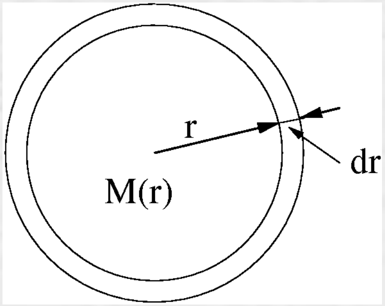
- Neutron star masses can be very different
- A neutron star can be heavier than 2 M_{sol}

Cross section of a neutron star



Tolman-Oppenheimer-Volkov equation

Equilibrium condition for a shell in a non-rotating neutron star



$$S_\Omega(r)\, dp = dF_G$$ Newton's Law

$$4\,\pi\, r^2\, dp = G\,\frac{M(r)\, dM}{r^2} \qquad dM = 4\,\pi\, r^2\, \varepsilon(p)\, dr$$

INPUT: equation of state (EoS)

$$\varepsilon = \varepsilon(p) \quad \text{or} \quad \begin{cases} p = p(n) \\ \varepsilon = \varepsilon(n) \end{cases}$$

boundary conditions: $\varepsilon(r=0) = \varepsilon_c\,, \quad M(r=0) = 0\,, P(r=R) = 0$

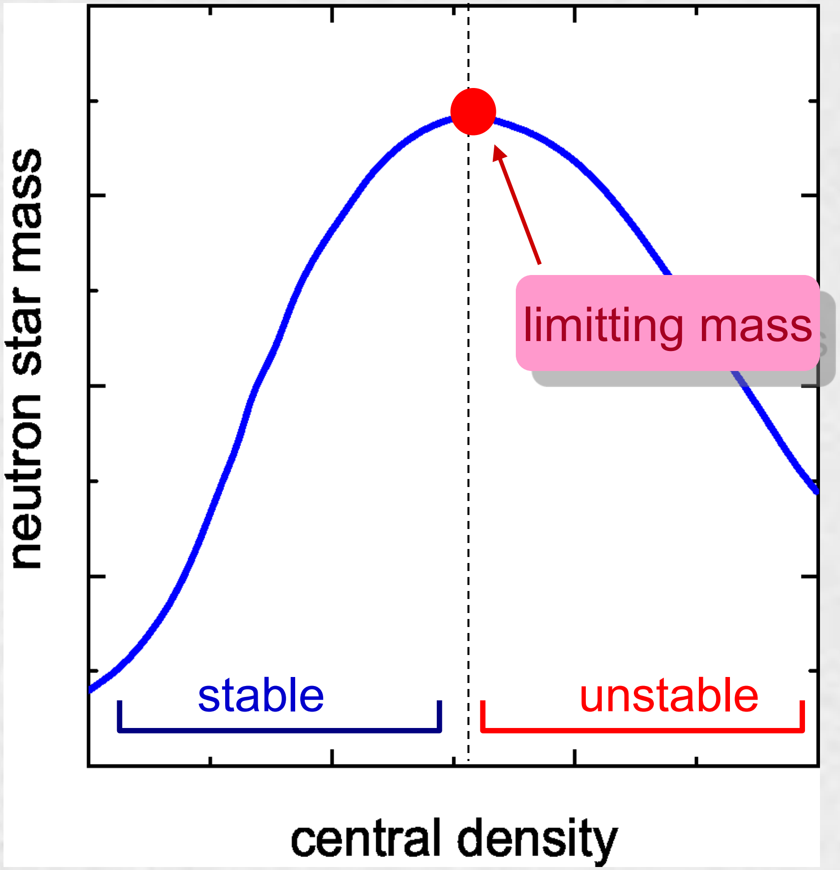
OUTPUT: neutron star density profile, radius R and mass M

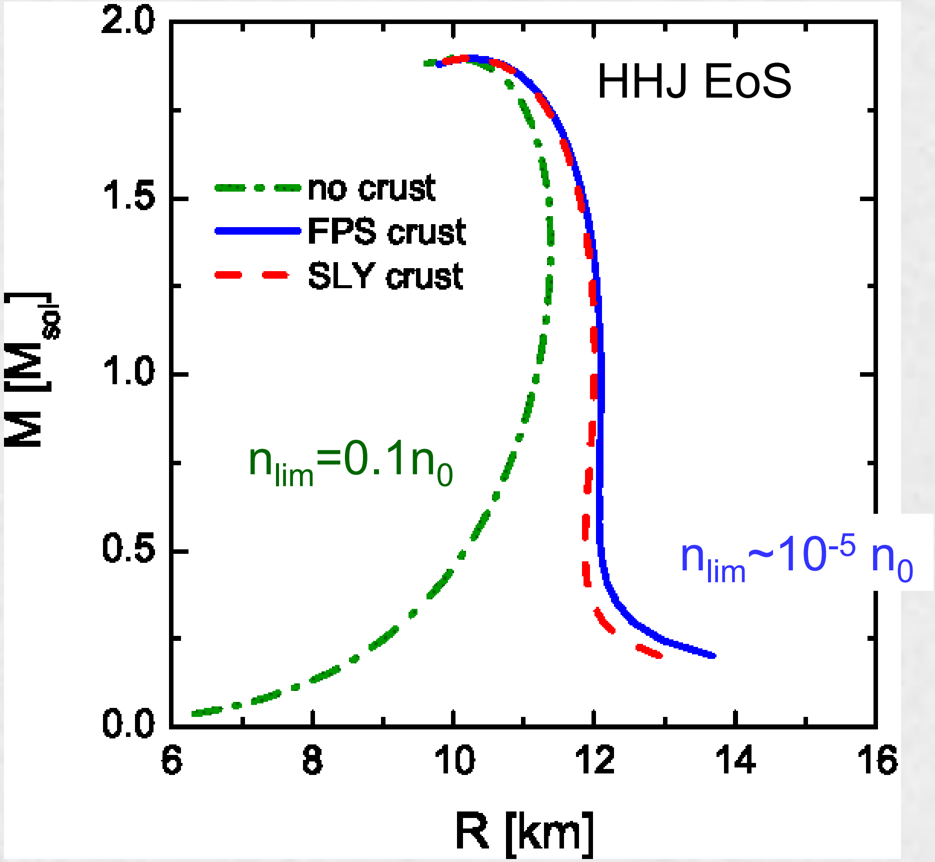
relativistic corrections

$$\frac{dp}{dr} = -\frac{G\,\varepsilon\, M}{r^2}\left(1+\frac{p}{\varepsilon}\right)\left(1+\frac{4\pi P r^3}{M}\right)\left(1-\frac{2GM}{r}\right)^{-1}$$

$$\rho = \varepsilon/c^2$$

Neutron star configuration





uncertainty in R~10^3 m

Oppenheimer-Volkoff mapping

[Lindblom ApJ 398 (1992) 569]

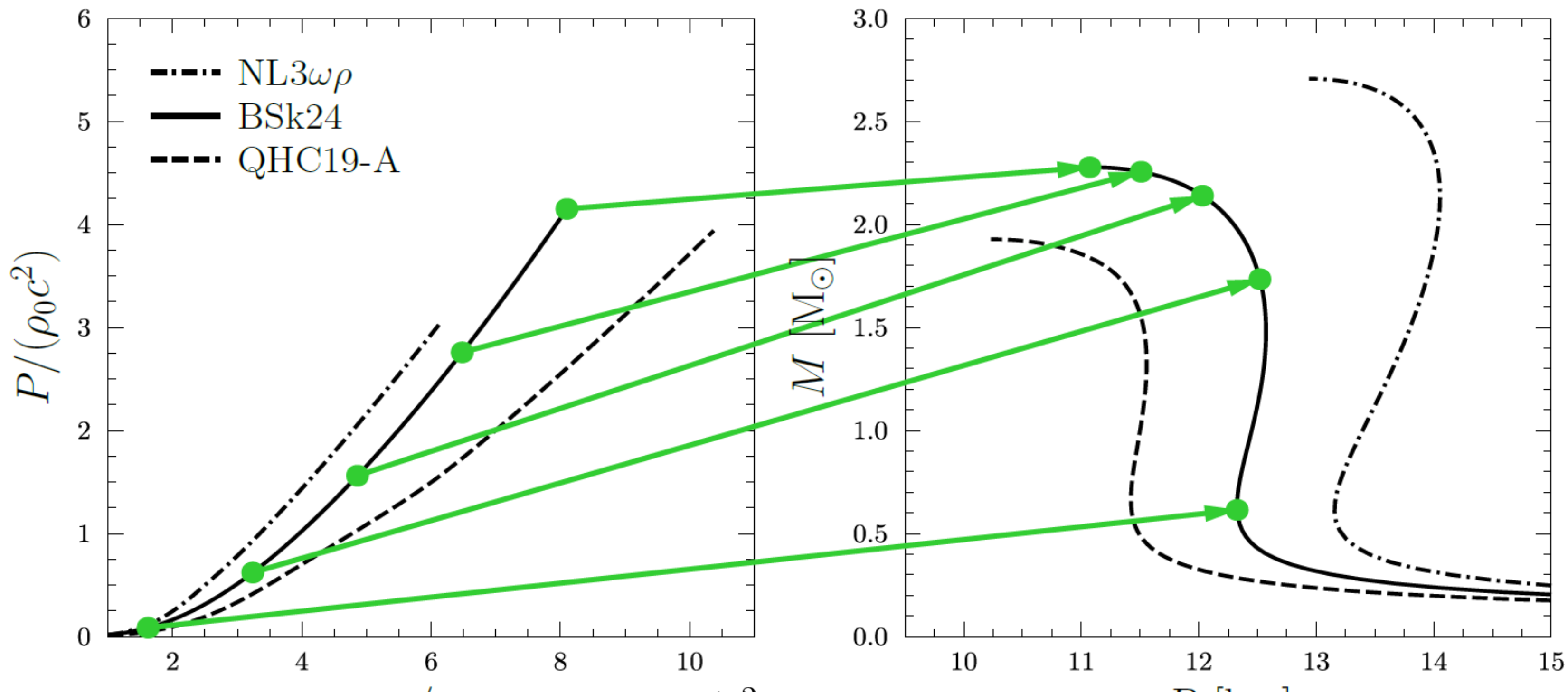
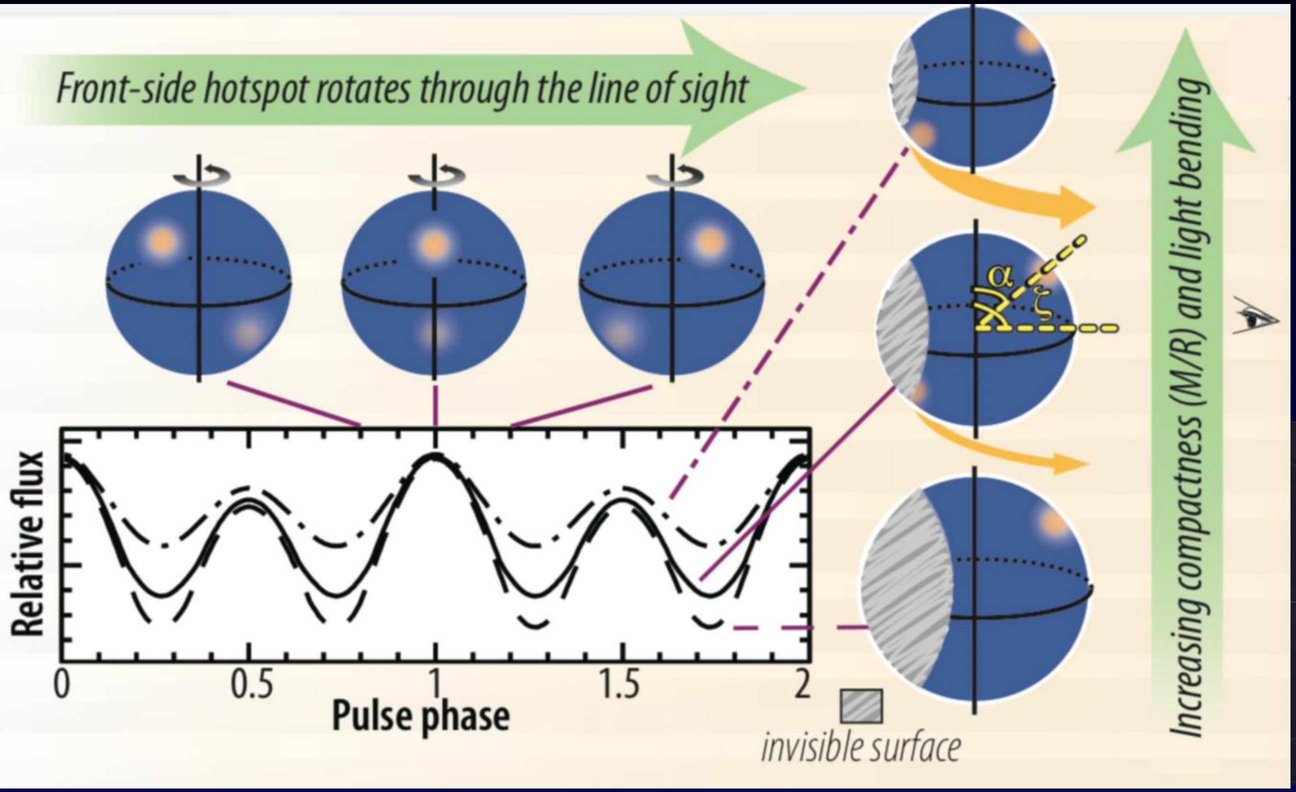


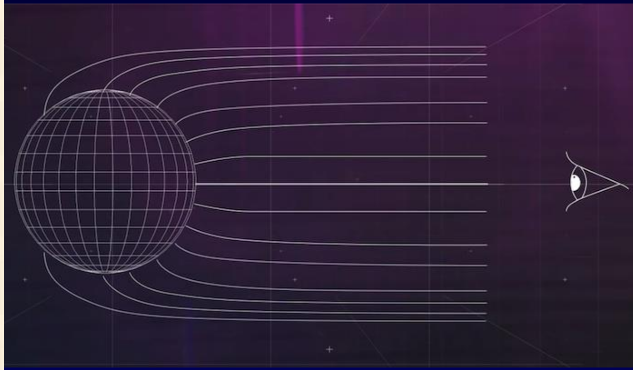
Fig. by D.D. Ofengeim

- *One can unambiguously restore the P(ρ) function from the M − R relation, if the latter is known for every mass*
- *The maximum NS mass (TOV limit) exists for every EoS*
- *Stiffer EoSs shift the M − R curve to higher masses and radii*

The Neutron Star Interior Composition Explorer Mission (NICER)



Lightcurve modeling constrains the compactness (GM/Rc^2) and viewing geometry of a non-accreting millisecond pulsar

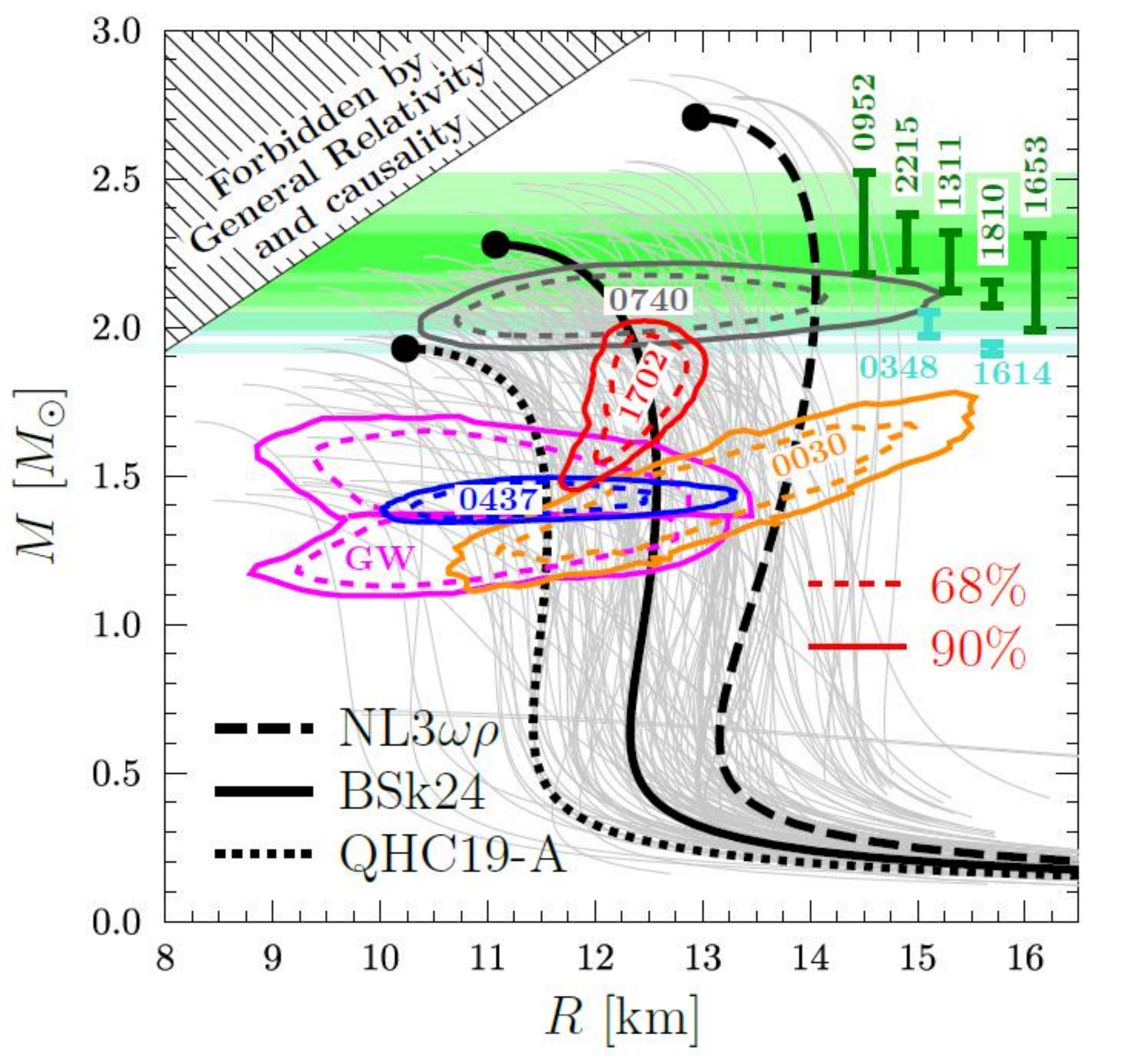


PSR J0740+6620

Thomas E. Riley *et al* 2021 *ApJL* **918** L27 — $R = 12.39^{+1.30}_{-0.98}$ km and $M = 2.072^{+0.067}_{-0.066}\, M_{sol}$

M. C. Miller *et al* 2021 *ApJL* **918** L28 — $R = 13.7^{+2.6}_{-1.5}$ km and $M = 2.08 \pm 0.07\, M_{sol}$

- Selected NS mass and radius measurements in comparison with M − R relations for various EoSs



Equation of state of nuclear matter

The energy per nucleon of the nuclear matter

$$E(n_p, n_n) = E_0(n) + E_S(n)\frac{(n_p - n_n)^2}{n^2}$$

n_p – proton number density
n_n – neutron number density

$n = n_p + n_n$

- **nuclear matter parameters**

$$E_0(n) = E_0 + 0 + \frac{K}{18}\frac{(n-n_0)^2}{n_0^2} + \frac{Q}{162}\frac{(n-n_0)^3}{n_0^3} + O\left(\frac{(n-n_0)^4}{n_0^4}\right)$$

$$n_0 \approx 0.16\,\mathrm{fm}^{-3}, \;\; E_0 \approx -16\,\mathrm{MeV}\,, \;\; K \approx 230 \pm 30\,\mathrm{MeV}\,, \;\; Q < 0$$

symmetry energy

$$E_S(n) = J + \frac{L}{3}\frac{n-n_0}{n_0} + \frac{K_{\mathrm{sym}}}{18}\frac{(n-n_0)^2}{n_0^2} + \frac{Q_{\mathrm{sym}}}{162}\frac{(n-n_0)^3}{n_0^3} + O\left(\frac{(n-n_0)^4}{n_0^4}\right)$$

$J \leftrightarrow S_0$

There is a correlation among parameters: J, L, K_{sym}

- *Correlations among parameters L-J*

$$\varepsilon_S[n] = J + \frac{L}{3}\frac{n-n_0}{n_0} + \frac{K_{\rm sym}}{18}\frac{(n-n_0)^2}{n_0^2} + \dots$$

Masses: UNEDF0 Skyrme DF+BHF
[Kortelainen *et al.*, PRC **82**, 024313 (2010)]

Isobaric analog states+isovector skin:
[Danielewicz et al. NPA 958, 147 (2017)]

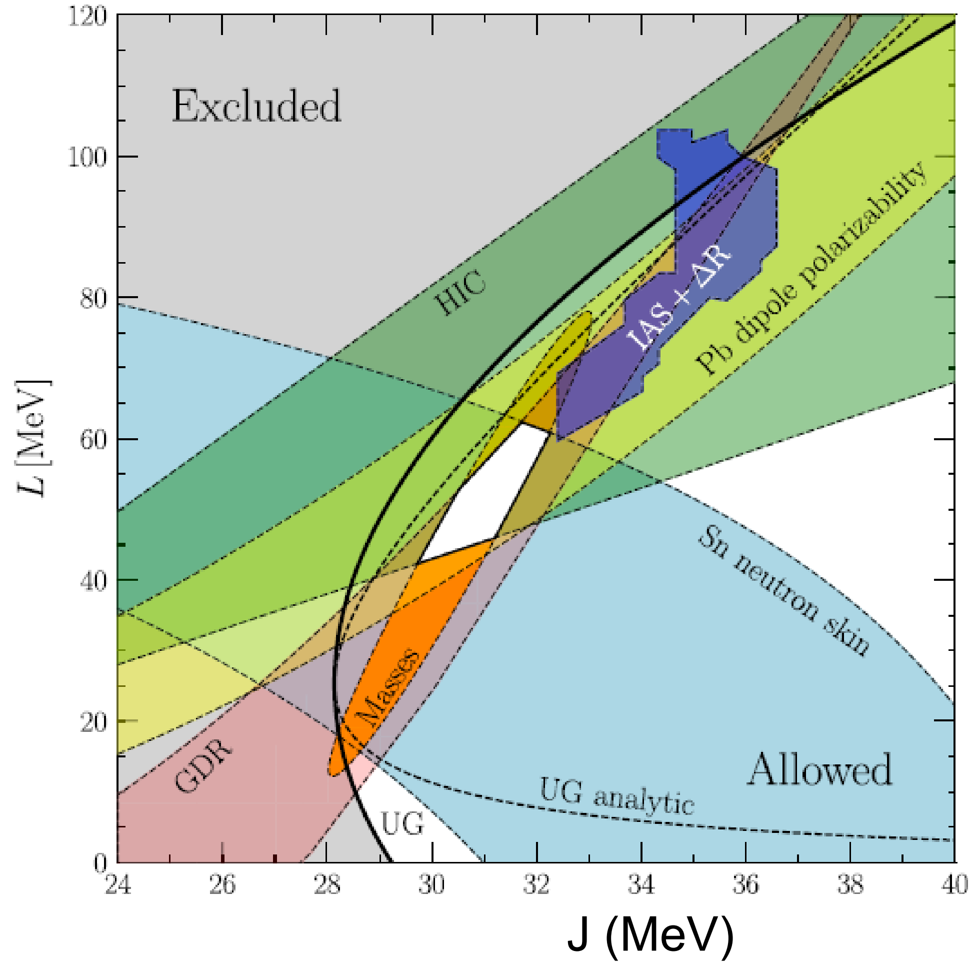
Pb dipole polarizability:
[Roca-Maza *et al.*, PRC **88**, 024316 (2013)]

Sn neutron skin:
[Chen et al., PRC **82**, 024321 (2010)]

GDR:
[Trippa et al., PRC **77**, 061304 (2008)]

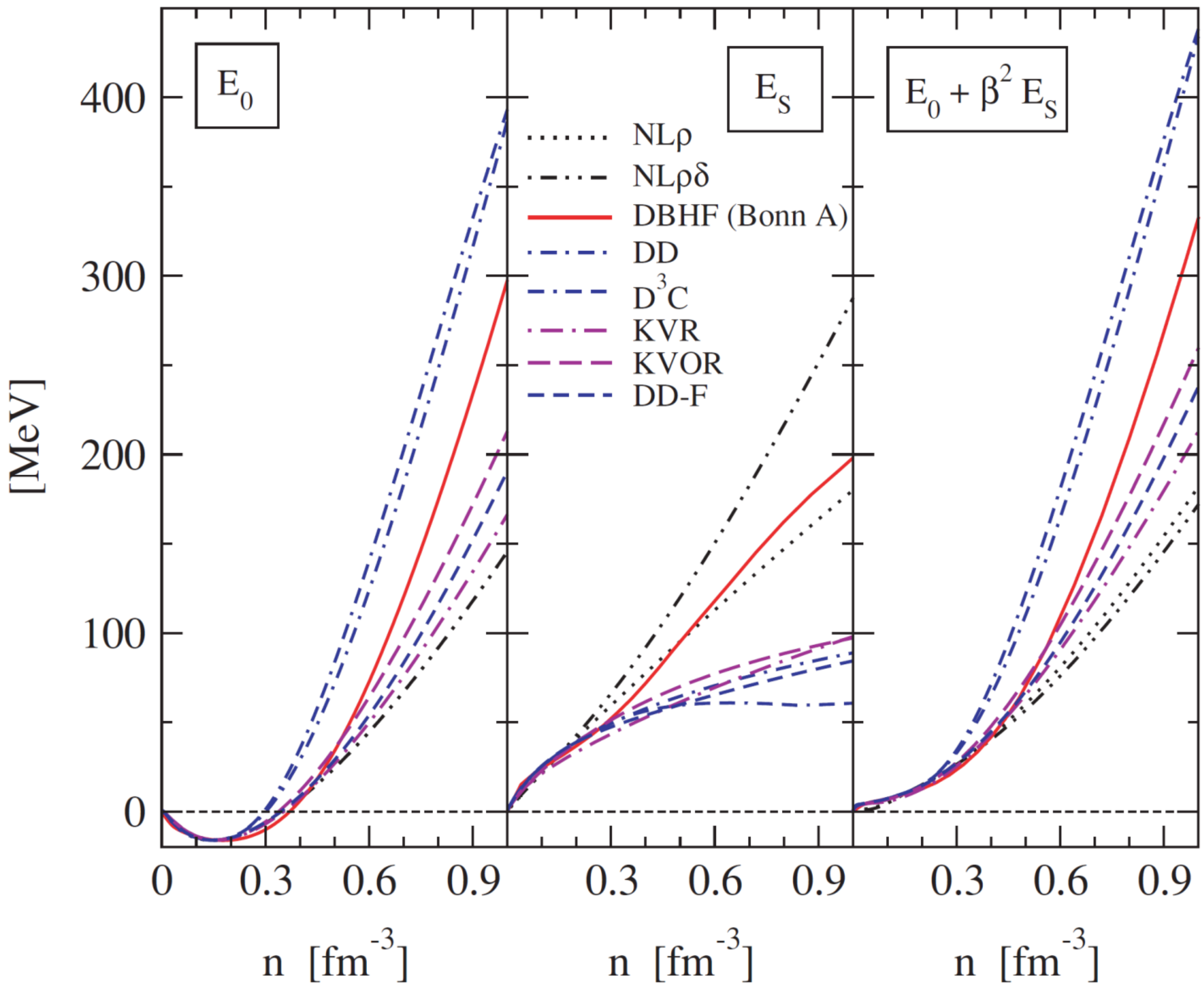
Isospin defusion in HIC
[Tsang et al., PRL 102, 122701 (2009)]

Lattimer Lim plot



Behind all calculation are particular models for NN interactions and many-body techniques

Equation of state of nuclear matter



Neutron star composition

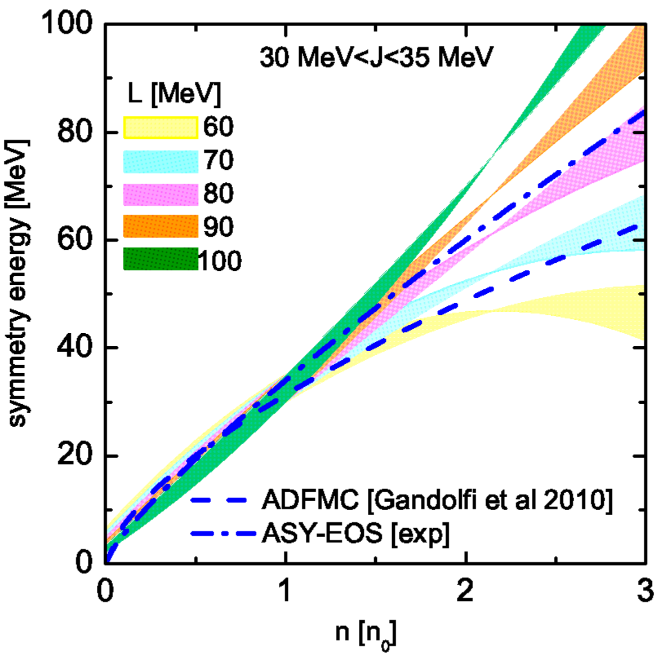
chemical potentials: $\mu_n = \frac{\partial E(n_p, n_n)}{\partial n_n} = \frac{\partial E(n,x)}{\partial n} - \frac{x}{n}\frac{\partial E(n,x)}{\partial x}$ $\quad \mu_p = \frac{\partial E(n_p, n_n)}{\partial n_p} = \frac{\partial E(n,x)}{\partial n} + \frac{1-x}{n}\frac{\partial E(n,x)}{\partial x}$

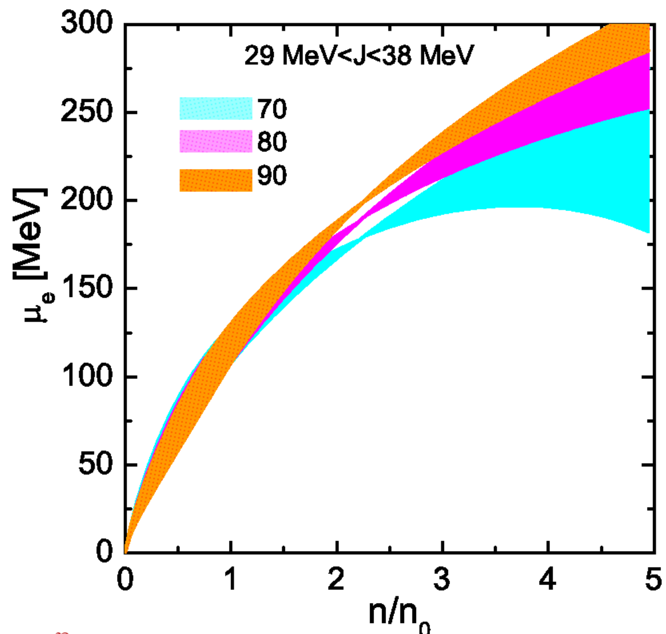
Condition of the beta equilibrium $\quad n \leftrightarrow p + e^- \quad n \leftrightarrow p + \mu^- \quad \mu^- \leftrightarrow e^- \quad x = n_p/n$

$\mu_n = \mu_p + \mu_e \qquad \mu_\mu = \mu_e \qquad \mu_e = \mu_n - \mu_p = -\frac{1}{n}\frac{\partial E(n,x)}{\partial x} = 4\,E_{\mathrm{S}}(n)\,(1-2\,x)$

equation for the proton concentration

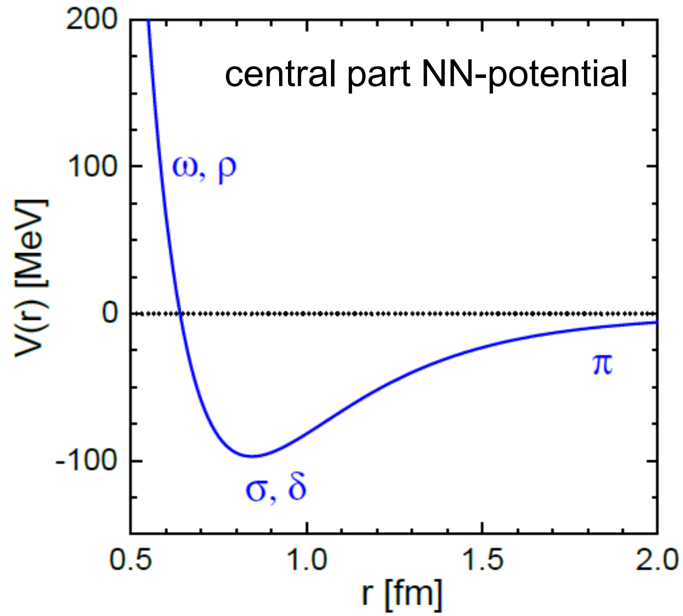
$$n_e(\mu_e) + n_\mu(\mu_e) = \frac{(\mu_e^2 - m_e^2)^{3/2}}{3\pi^2} + \frac{(\mu_e^2 - m_\mu^2)^{3/2}}{3\pi^2} = n_p = x\,n$$





$$E_{\mathrm{tot}} = E_{\mathrm{nucl}} + E_{\mathrm{lept}} = E_{\mathrm{nucl}} + \sum_{l=e,\mu} \int_0^{p_{\mathrm{F},l}} \frac{2\mathrm{d}^3 p}{(2\pi)^3}\sqrt{m_l^2 + p^2}$$

Relativistic mean-field models



nucleon-nucleon interaction

vacuum: one boson-exchange for NN-potential
+ Lippmann-Schwinger equations

a model

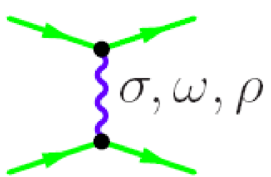
$$\mathcal{L} = \sum_N \bar{N} \Big[i \left(\hat{\partial} + i\, g_{\omega N} \hat{\omega} + i\, g_{\rho N} \boldsymbol{\tau}\, \hat{\boldsymbol{\rho}} \right) \Big] - \left(m - g_{\sigma N}\, \sigma \right) \Big] N$$

$$+ \underbrace{\frac{1}{2} \left(\partial_\mu \sigma\, \partial^\mu \sigma - m_\sigma^2\, \sigma^2 \right) - U(\sigma)}_{\text{scalar}}$$

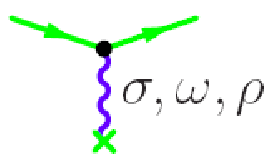
$$- \underbrace{\frac{1}{4} \omega_{\mu\nu}\, \omega^{\mu\nu} + \frac{1}{2} m_\omega\, \omega_\mu\, \omega^\nu}_{\text{vector}} - \underbrace{\frac{1}{4} \boldsymbol{\rho}_{\mu\nu}\, \boldsymbol{\rho}^{\mu\nu} + \frac{1}{2} \boldsymbol{\rho}_\mu\, \boldsymbol{\rho}^\mu}_{\text{iso-vector}}$$

medium: mean-field approximation

$\sum_{\text{nucleons}}$



$\approx$



$$\sigma(r,t) = \sigma$$
$$\omega_\mu(r,t) = \delta_{\mu,0}\, \omega_0$$
$$\rho_\mu^a(r,t) = \delta^{a,3}\, \delta_{\mu,0}\, \rho_0^{(3)}$$

constant fields

[Serot, Walecka]

pion dynamics falls out completely in this approx.

nucleon spectrum in MF approximation

$$E_N(p) = \sqrt{m_N^{*2} + p^2} + g_{\omega N}\,\omega_0 + g_{\rho N}\, I_N\, \rho_{03} \qquad m_N^* = m_N - g_{\sigma N}\,\sigma$$

Energy-density functional

$$E[n_p, n_n; \sigma] = \frac{m_\sigma^2\,\sigma^2}{2} + U(\sigma) + C_\omega^2 \frac{(n_n + n_p)^2}{2\,m_N^2} + C_\rho^2 \frac{(n_n - n_p)^2}{8\,m_N^2} + \sum_N \int_0^{p_{\mathrm{F},N}} \frac{dp\,p^2}{\pi^2} \sqrt{(m_N - g_{\sigma N}\,\sigma)^2 + p^2}$$

evaluated for ¾ field followed from the equation $\frac{\delta E[n_p, n_n, \sigma]}{\delta\sigma} = 0$

Paremeters $C_i^2 = \frac{g_{iN}^2\, m_N^2}{m_i^2}$ are adjusted to properties of nuclear matter at saturation

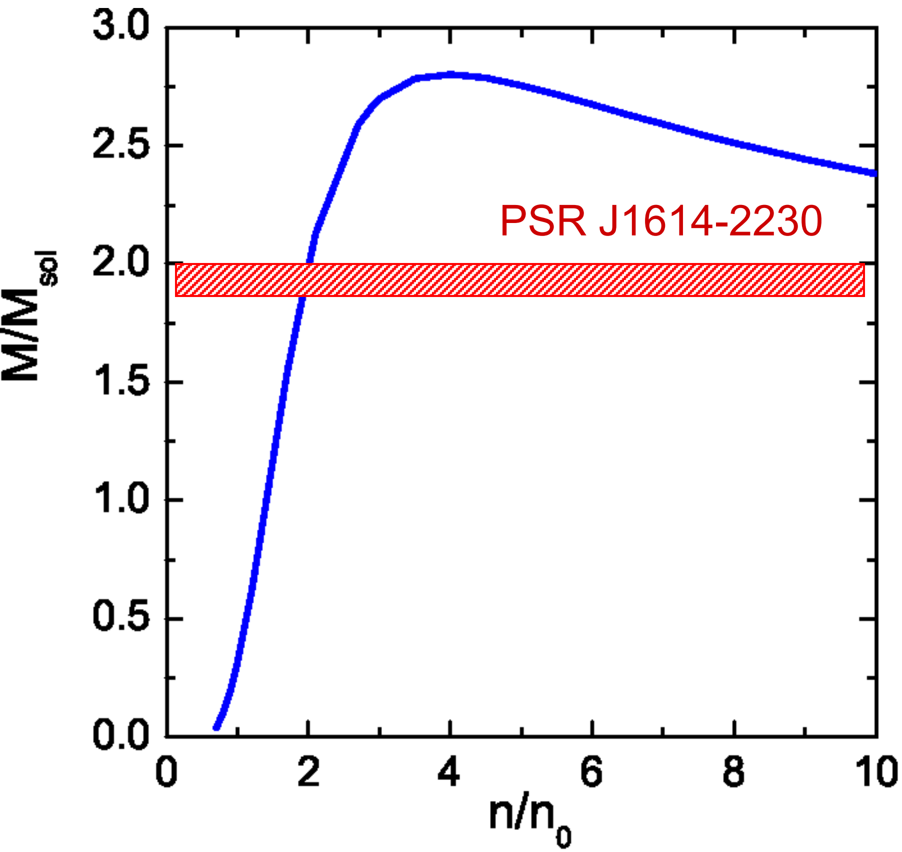
n_0	$\simeq$	$0.16 \pm 0.015\ \mathrm{fm}^{-3}$
E_{bind}	$\simeq$	$-15.6 \pm 0.6\ \mathrm{MeV}$
$m_N^*(\rho_0)$	$\simeq$	$(0.75 \pm 0.1)\, m_N$
K	$\simeq$	$240 \pm 40\ \mathrm{MeV}$
a_{sym}	$\simeq$	$32 \pm 4\ \mathrm{MeV}$

If we add gradient terms this energy density functional can be used for a description of properties of atomic nuclei.

(pure) Walecka model $U(\sigma)=0$

$n_0 = 0.16\text{fm}^{-3}\,,\ E_{\text{bind}} = -16\ \text{MeV}$

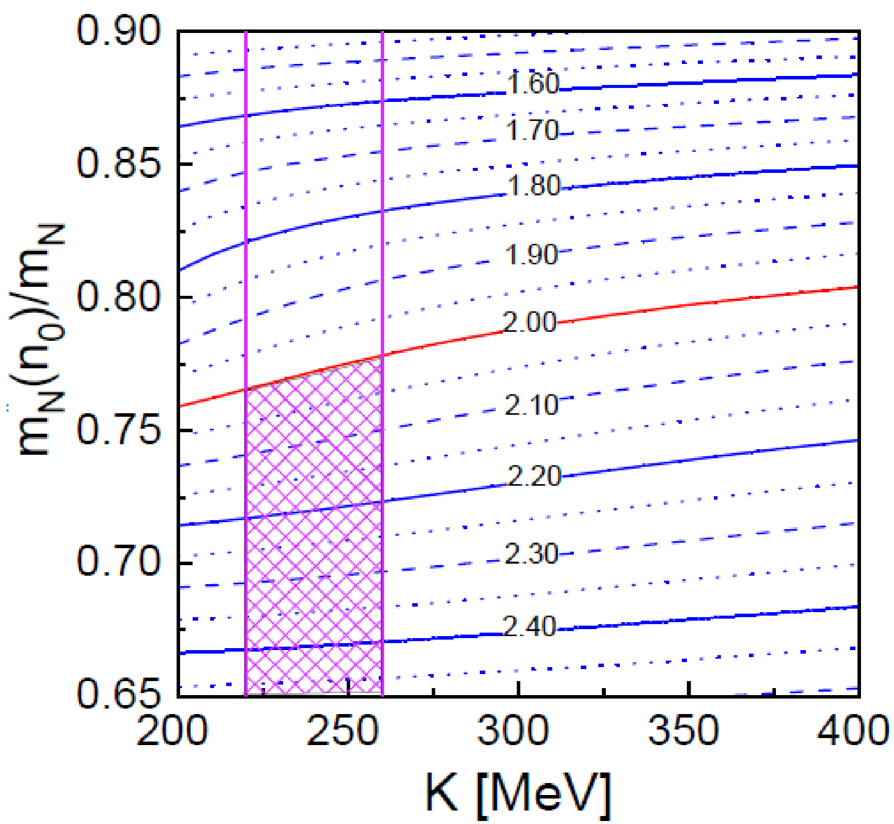
$K = 553\ \text{MeV}\,,\ m_N^*(n_0) = 0.54 m_N$



Hardest EoS among RMF models

modified Walecka $U(\sigma)=a\sigma^3+b\sigma^4$

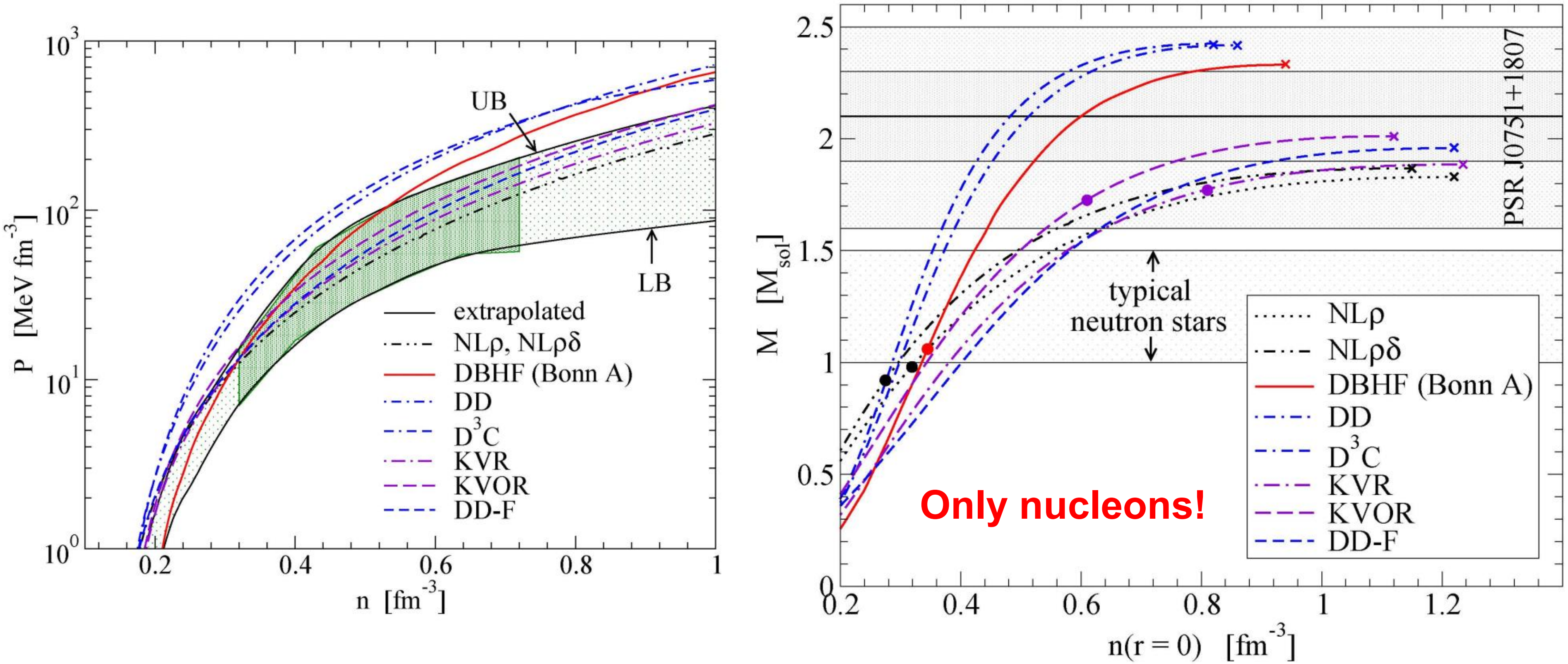
maximal mass of NS



weak dependence on K !

strong dependence on m^*_N

✔ constraints from heavy-ion collisions ✔ maximum mass constraints



Puzzle

Nucleon part of EoS should be sufficiently stiff.
Pressure in isospin symmetric matter should be no to high. (particle flow in HIC)

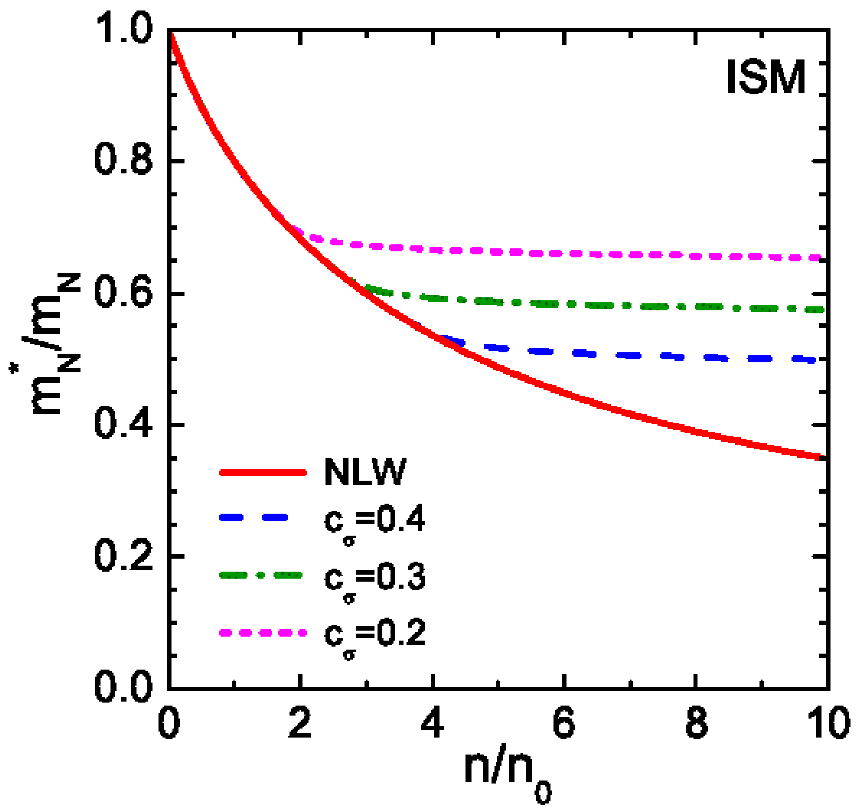
[Klaehn et al., PRC 74 (2006) 035802.]

The standard non-linear Walecka (NLW) model and the cut mechanism

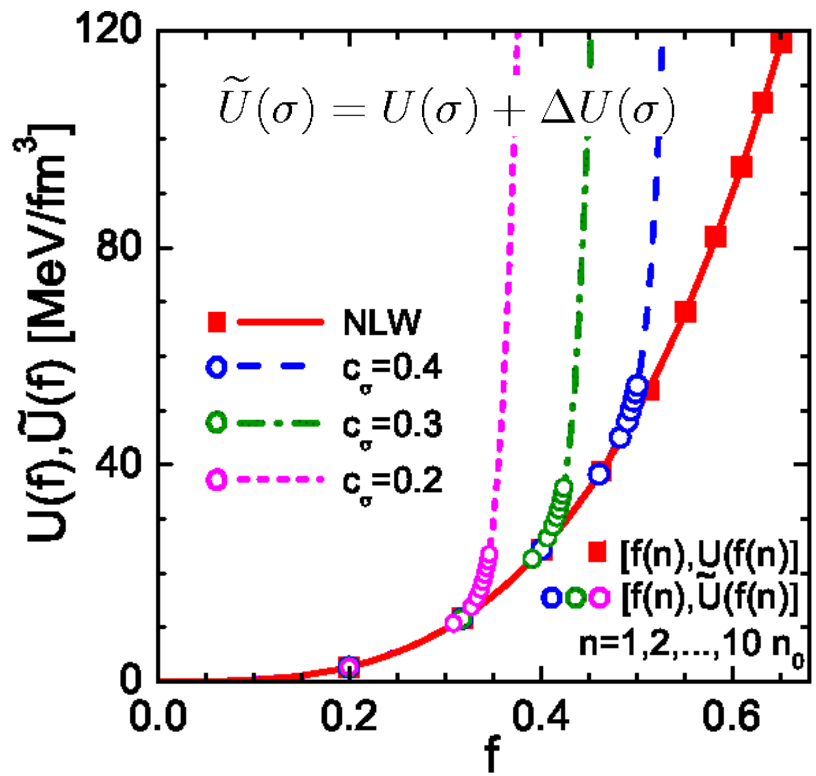
$$\mathcal{L} = \overline{\Psi}_N \left[(i\,\partial_\mu - g_\omega \omega_\mu - g_\rho \boldsymbol{t}\boldsymbol{\rho}_\mu)\,\gamma^\mu - m_N + g_\sigma \sigma \right] \Psi_N + \tfrac{1}{2}[(\partial_\mu \sigma)^2 - m_\sigma^2 \sigma^2] - U(\sigma)$$
$$- \tfrac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \tfrac{1}{2} m_\omega^2 \omega_\mu^2 - \tfrac{1}{4}\boldsymbol{\rho}_{\mu\nu}\boldsymbol{\rho}^{\mu\nu} + \tfrac{1}{2} m_\omega^2 (\boldsymbol{\rho}_\mu)^2 \qquad U(\sigma) = \tfrac{b}{3} m_N (g_{\sigma N}\sigma)^3 + \tfrac{c}{4}(g_{\sigma N}\sigma)^4$$

$n_0 = 0.16\,\mathrm{fm}^{-3}$, $\mathcal{E}_0 = -16\,\mathrm{MeV}$, $\mathcal{E}_{\mathrm{sym}} = 30\,\mathrm{MeV}$

cut mechanism [Maslov et al. PRC 92]

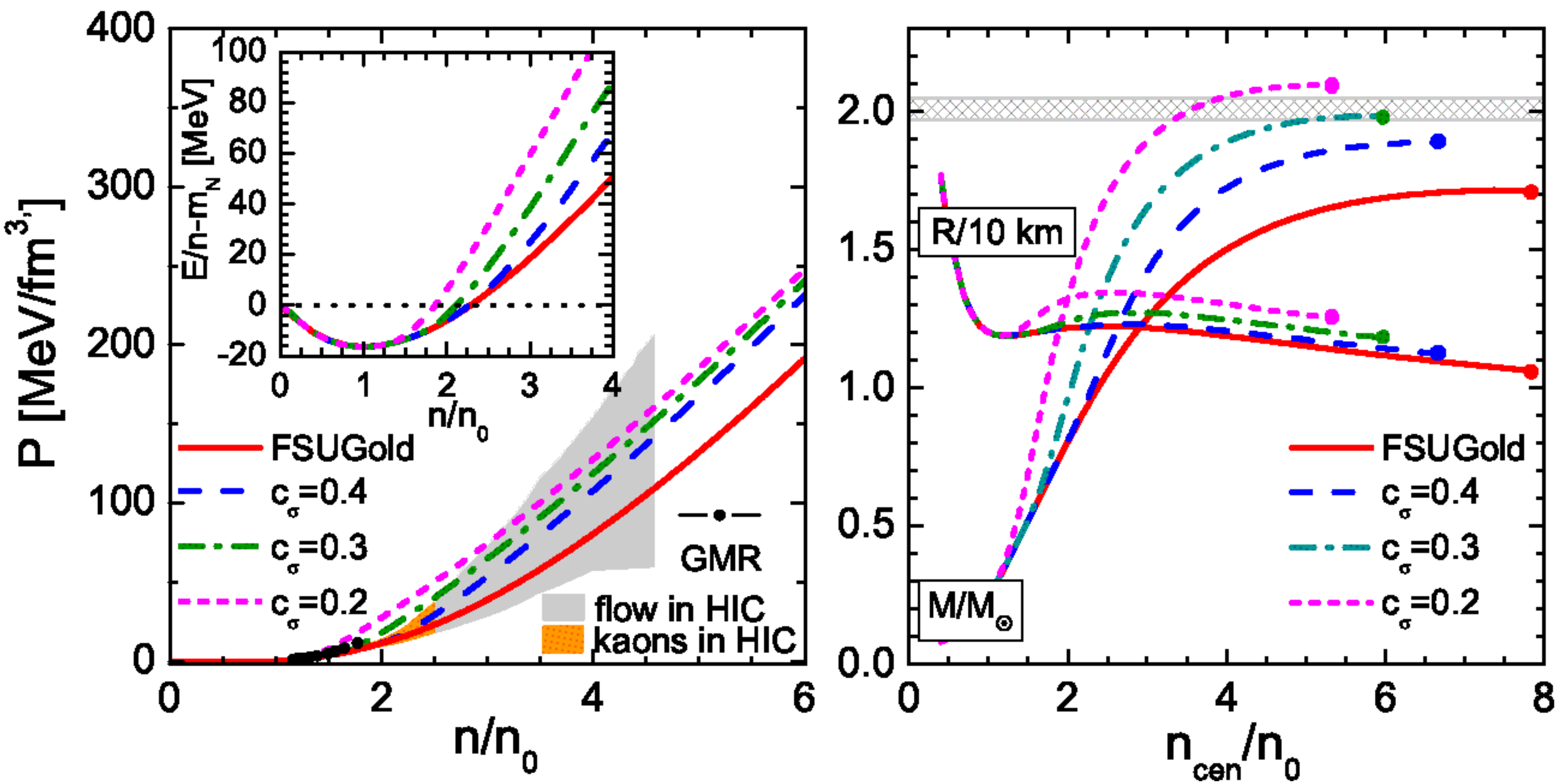


If $m^*_N(n)$ saturates then the EoS stiffens



$$f_{\mathrm{s.core}} = f_0 + c_\sigma (1 - f_0)$$
$$m_N^*(n_0) = m_N\,(1 - f_0)$$

[FSUGold model](#) Todd-Rutel, Piekarewicz, Phys. Rev. Lett. 95 (2005) 122501



Alternative FSUGold2 model: W.-Ch. Chen, Piekarewicz, Phys. Rev. C 90 (2014) 044305

$M_{\rm max} = 2.1\, M_{\odot}$

KVOR model [EEK and D.Voskresensky NPA 759 (2005) 373]

- in standard RMF model m_σ, m_ω, and m_ρ do not change

  Can the in-medium modification (decrease) of meson masses be included in an RMF model??

- σ field dependent masses and couplings constant
- decreasing functions of σ: $m^*_\omega(\sigma)$, $m^*_\rho(\sigma)$ $\longleftarrow$ self-consistent σ field

  results in *increase* of ρ an ω masses

- universal scaling $m^*_\sigma/m_\sigma \approx m^*_\omega/m_\omega \approx m^*_\rho/m_\rho = \Phi(n)$

Lattice QCD (SC-QCD): common drop of meson masses
[Ohnishi Miura Kawamoto Mod.Phys.Lett A23, 2459]

Sliding vaccua and double decimation concept [Brown, Rho PR396(2004)1]

"vector manifestation" [Harada, Yamawaki]

Half-skyrmion model of dense nuclear matter [Vento; Rho, Hyun Kyu Lee 1704.02775]

$$\mathcal{L} = \bar\Psi_N\big(\partial\cdot\gamma - g_\omega\chi_\omega\omega\cdot\gamma - \frac{1}{2}g_\rho\chi_\rho\boldsymbol{\rho}\cdot\gamma\boldsymbol{\tau}\big)\Psi_N - m_N\Phi_N\bar\Psi_N\bar\Psi_N$$

$$+\frac{\partial^\mu\sigma\partial_\mu\sigma}{2} - \Phi_\sigma^2\frac{m_\sigma^2\sigma^2}{2} - U(\sigma) - \frac{\omega_{\mu\nu}\omega^{\mu\nu}}{4} + \Phi_\omega^2\frac{m_\omega^2\omega_\mu\omega^\mu}{2} - \frac{\boldsymbol{\rho}_{\mu\nu}\boldsymbol{\rho}^{\mu\nu}}{4} + \Phi_\rho^2\frac{m_\rho^2\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu}{2}$$

Energy-density functional

$B \in \mathrm{SU}(3)$ ground state multiplet

scalar field $f = g_\sigma \chi_\sigma \sigma / m_N$

$$E[f,\{n_\mathrm{B}\}] = \sum_B E_\mathrm{kin}\left(p_{\mathrm{F},B}, m_B \Phi_B(f)\right) + \sum_{l=e,\mu} E_\mathrm{kin}(p_{\mathrm{F},l}, m_l)$$

$$+ \frac{m_N^4 f^2}{2C_\sigma^2}\eta_\sigma(f) + \frac{1}{2m_N^2}\left[\frac{C_\omega^2 \widetilde{n}_B^2}{\eta_\omega(f)} + \frac{C_\rho^2 \widetilde{n}_I^2}{\eta_\rho(f)} + \frac{C_\phi^2 \widetilde{n}_S^2}{\eta_\phi(f)}\right],$$

$C_i = \frac{g_{iN} m_N}{m_i}$, $i = \sigma, \omega, \rho$ $\quad C_\phi = m_\omega C_\omega / m_\phi$

effective densities: $\widetilde{n}_B = \sum_B x_{\omega B} n_B \quad \widetilde{n}_I = \sum_B x_{\rho B} t_{3B} n_B \quad \widetilde{n}_S = \sum_H x_{\phi H} n_H$

with coupling constant ratios $\quad x_{\omega(\rho)B} = \frac{g_{\omega(\rho)B}}{g_{\omega(\rho)N}} \quad x_{\phi H} = \frac{g_{\phi H}}{g_{\omega N}}$

mass scaling:

$$\Phi_m(f) \approx \Phi_N(f) = 1 - f$$

$$\Phi_H(f) = 1 - x_{\sigma H}\frac{m_N}{m_H}\xi_{\sigma H} f$$

scaling functions

$$\eta_i(f) = \frac{\Phi_i^2(f)}{\chi_i^2(f)}, \quad i = \sigma\,,\,\omega\,,\,\rho$$

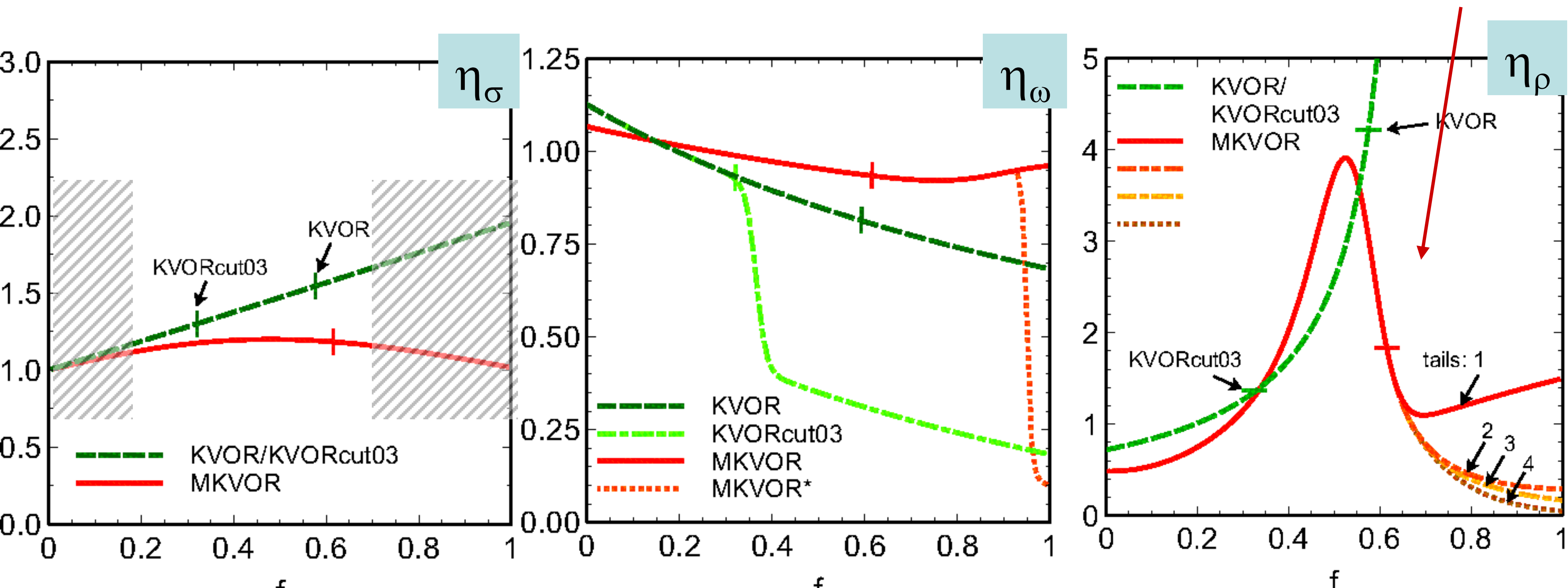
The standard sigma potential can be introduced as $\eta_\sigma(f) = 1 + \frac{2\,C_\sigma^2}{m_N^4 f^2}U(f)$

[MKVOR model]   [Maslov, EEK Voskresensky, PLB748,369 (2015); NPA950,64(2016)]

EoS	$\mathcal{E}_0$ [MeV]	n_0 [fm^{-3}]	K [MeV]	$m_N^*(n_0)$ [m_N]	$\widetilde{J}_0$ [MeV]	L [MeV]	K' [MeV]	$K_{\rm sym}$ [MeV]
MKVOR	-16	0.16	240	0.73	30	41	557	-159

scaling functions for coupling constants vs scalar field:

saturate f growth

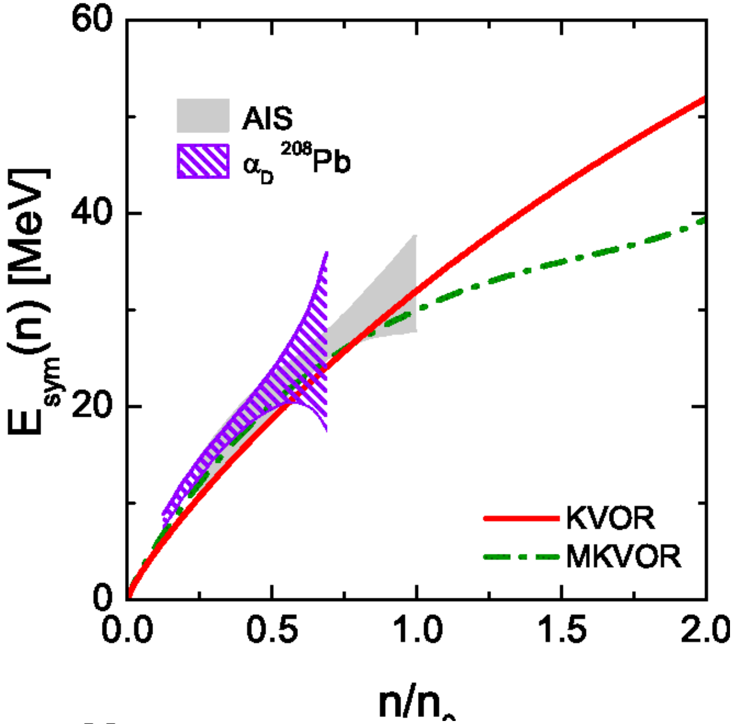


ticks – max. values of f reached in neutron star

increase ω repulsion to stiffen EoS

suppress symmetry energy DU constraint

Neutron matter EoS



empirical constraints on symmetry energy

-- (AIS) analog isobar states

[Danielewicz, Lee NPA 922 (2014) 1]

-- α_D electric dipole polarizability ^{208}Pb

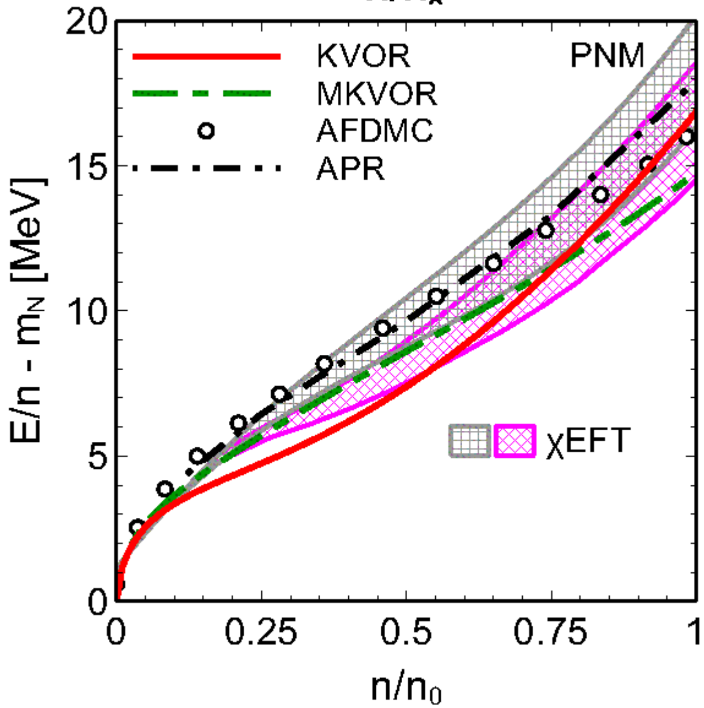
[Zhang, Chen 1504.01077]

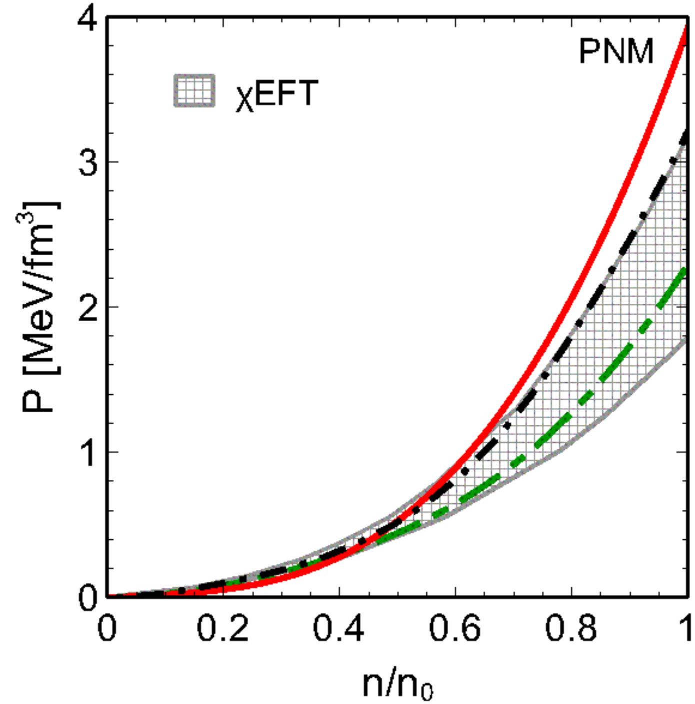
microscopic calculations

-- (APR) Akmal, Pandharipande, Ravenhall

-- (AFDMC) Gandolfi et al.MNRAS 404 (2010) L35

--(χEFT) Hebeler, Schwenk EPJA 50 (2014) 11

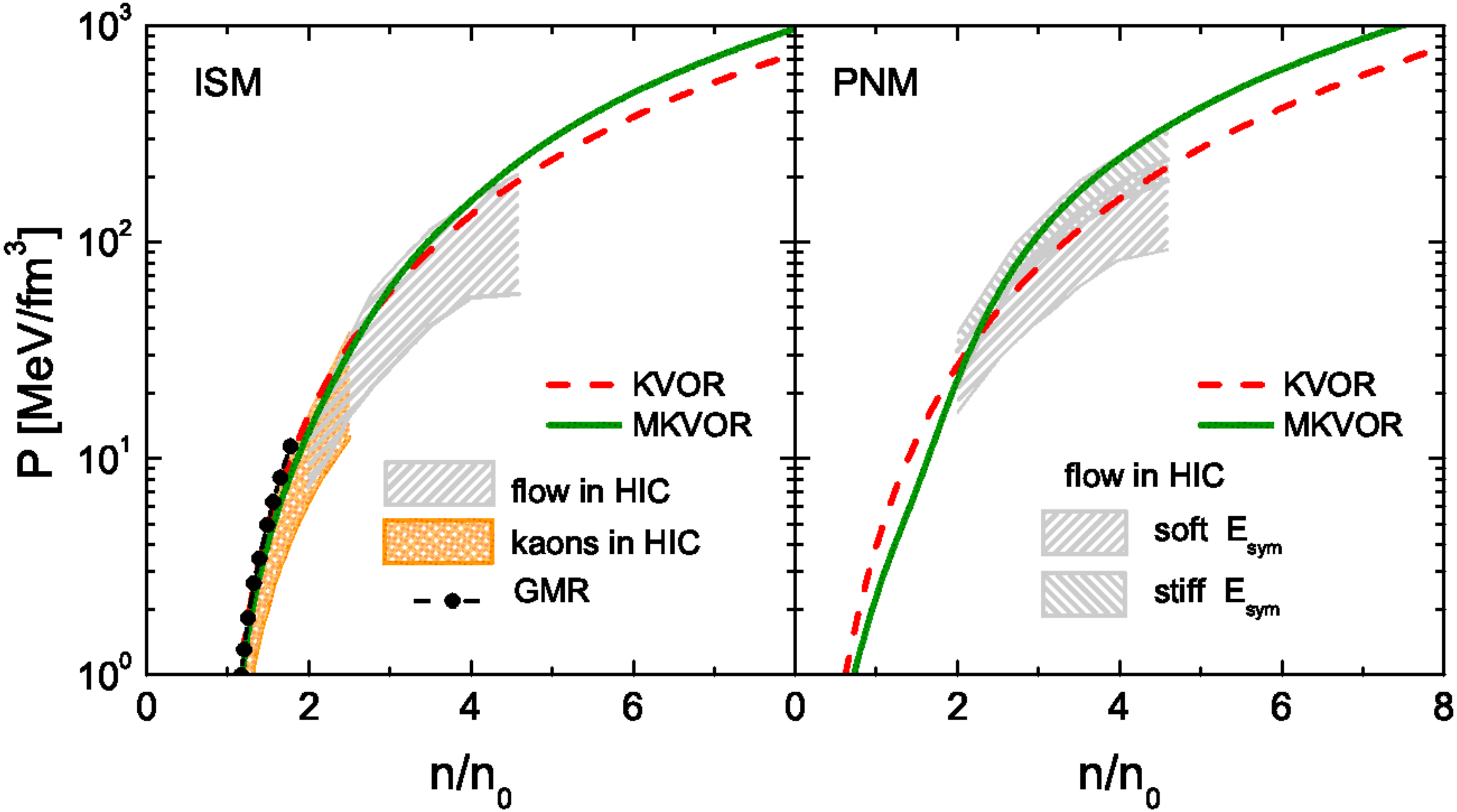


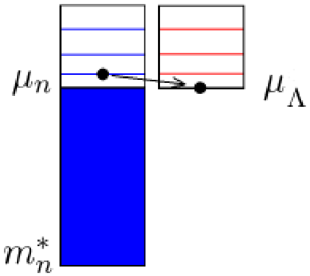


Constraints on EoS from HICs

Particle flow: Danielewicz, Lacey and Lynch, Science 298 (2002) 1592

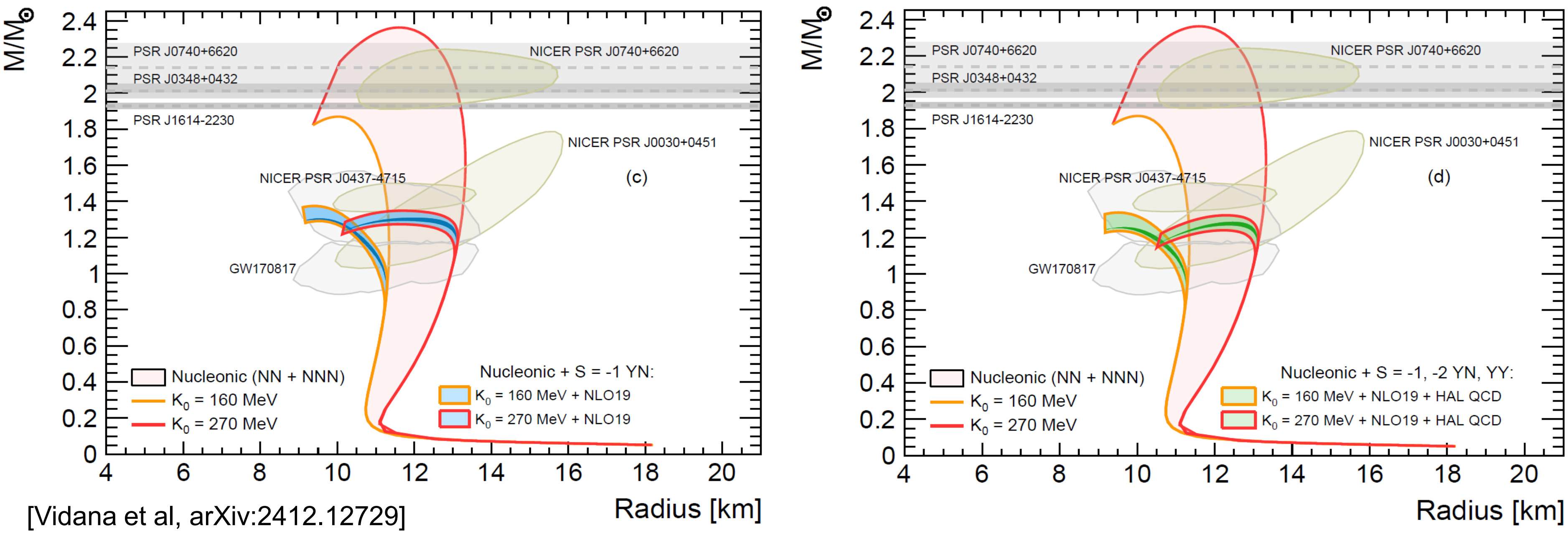
Kaon production: Fuchs, Prog. Part. Nucl. Phys. 56 (2006) 1





"Hyperon puzzle"

If we allow for a population of new Fermi seas (hyperon, Δ baryons, …)
EoS will be softer and the NS will be smaller



[Vidana et al, arXiv:2412.12729]

Simple solutions: **-- make nuclear EoS as stiff as possible** [flow constraint]
-- suppress hyperon population (increase repulsion/reduce attraction)

against phenomenology of YN,NN,YY interaction in vacuum +hypernuclear physics

Attempts to solve the hyperon puzzle

play with hyperon coupling constants $x_{mH} = \frac{g_{mH}}{g_{mN}}$

quark counting SU(6) for vector couplings:

$$g_{\omega N} : g_{\omega \Lambda} : g_{\omega \Sigma} : g_{\omega \Xi} = 3 : 2 : 2 : 1$$

$$g_{\rho N} : g_{\rho \Lambda} : g_{\rho \Sigma} : g_{\rho \Xi} = 1 : 0 : 2 : 1$$

scalar couplings:

$$x_{\sigma H} = \frac{x_{\omega H} n_0 C_\omega^2 / m_N^2 - U_H(n_0)}{m_N - m_N^*(n_0)} \longleftarrow \begin{cases} U_\Lambda(n_0) = -28\,\mathrm{MeV} \\ U_\Sigma(n_0) = +30\,\mathrm{MeV} \\ U_\Xi(n_0) = -15\,\mathrm{MeV} \end{cases}$$

extensions

phi meson: HH' repulsion

$$g_{\phi N} : g_{\phi \Lambda} : g_{\phi \Sigma} : g_{\phi \Xi} = 0 : 2 : 2 : 1 \qquad g_{\phi \Lambda} = -\frac{\sqrt{2}}{3} g_{\omega N}$$

[J. Schaffner et al., PRC71 (1993), Ann.Phys. 235 (94),PRC53(1996)]

SU(3) coupling constants: extra parameters to tune.

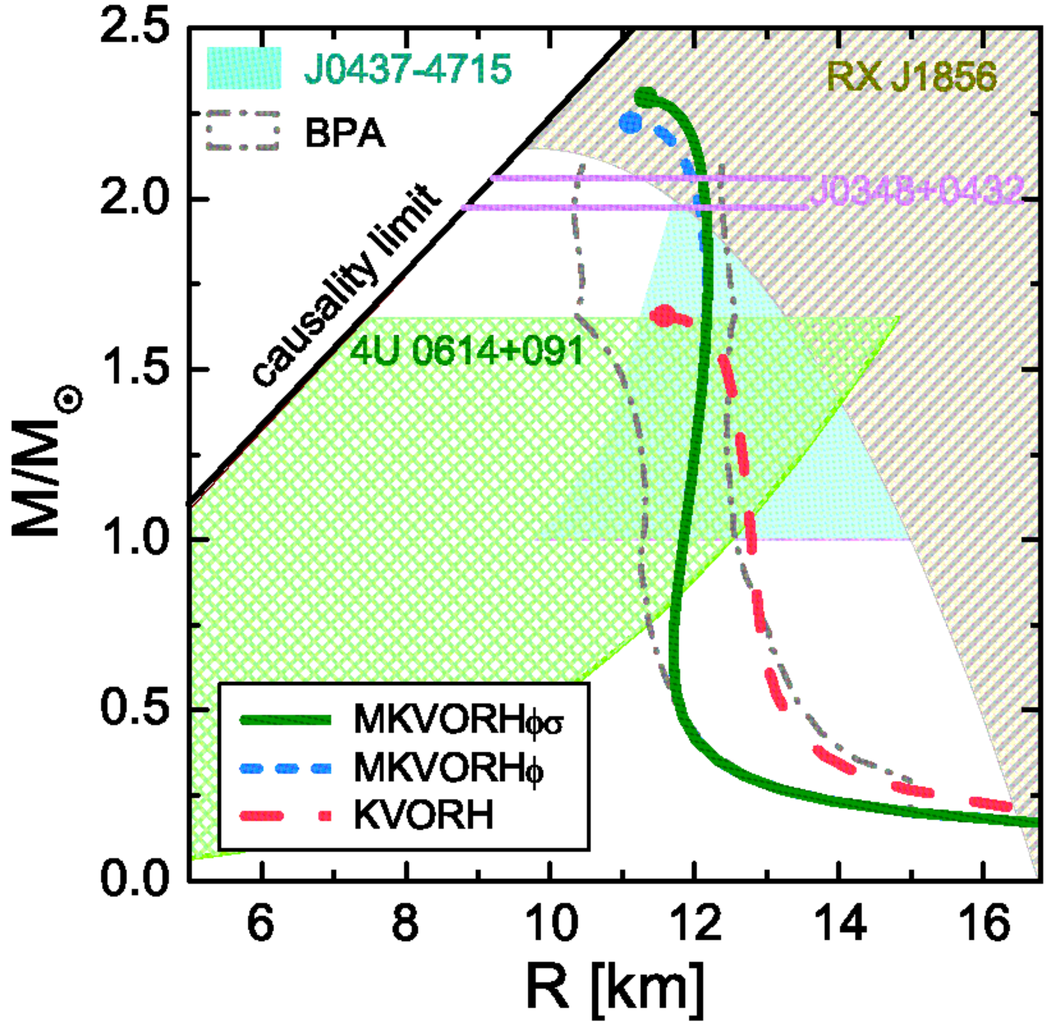
two effects: $|g_{\omega H}|$ increases; $g_{\phi N}$ non zero

[Weissenborn et al., PRC85 (2012);NPA881 (2012); NPA914(2013)]

alternative

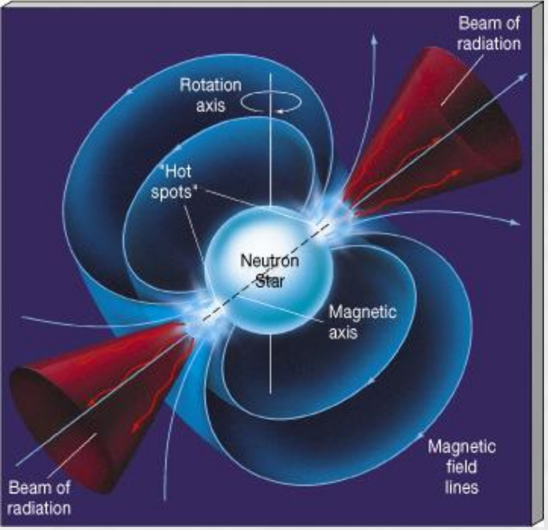
mass of ϕ meson — If we take into account a reduction of the ϕ mass in medium we can increase a HH repulsion

Mass-radius constraints



BPA: Bayesian probability analysis [Lattimer,Steiner …]

msp PSRJ0437-4715: 3σ confidence Bogdanov ApJ 762, 96 (2013)



Pulsar age

Pulsar rotation period/frequency changes with time:

$$\dot{\Omega} = -\frac{B^2 R^6}{6\, c^3 I} \sin^2\alpha\, \Omega^3 - G\frac{32\varepsilon^2}{5c^5} I\, \Omega^5$$

e.m. wave emission — **grav. wave emission**

α angle between rotation a and magnetic axes

ε neutron star eccentricity

$$\dot{\Omega} = \varkappa \Omega^n$$

$$P = 2\pi/\Omega$$

→

$$(n-1)\frac{\dot{P}(t)}{P(t)}t = 1 - \left(\frac{P_0}{P(t)}\right)^{n-1}$$

initial period (P_0)

current period ($P(t)$)

$$P_0/P \ll 1$$

spin-down age:

$$\tau_{\rm sd} = \frac{1}{n-1}\frac{P}{\dot{P}}$$

braking index:

$$n = \frac{\ddot{\Omega}\,\Omega}{\dot{\Omega}^2}$$

kinematic age:

1) age of the associated SNR

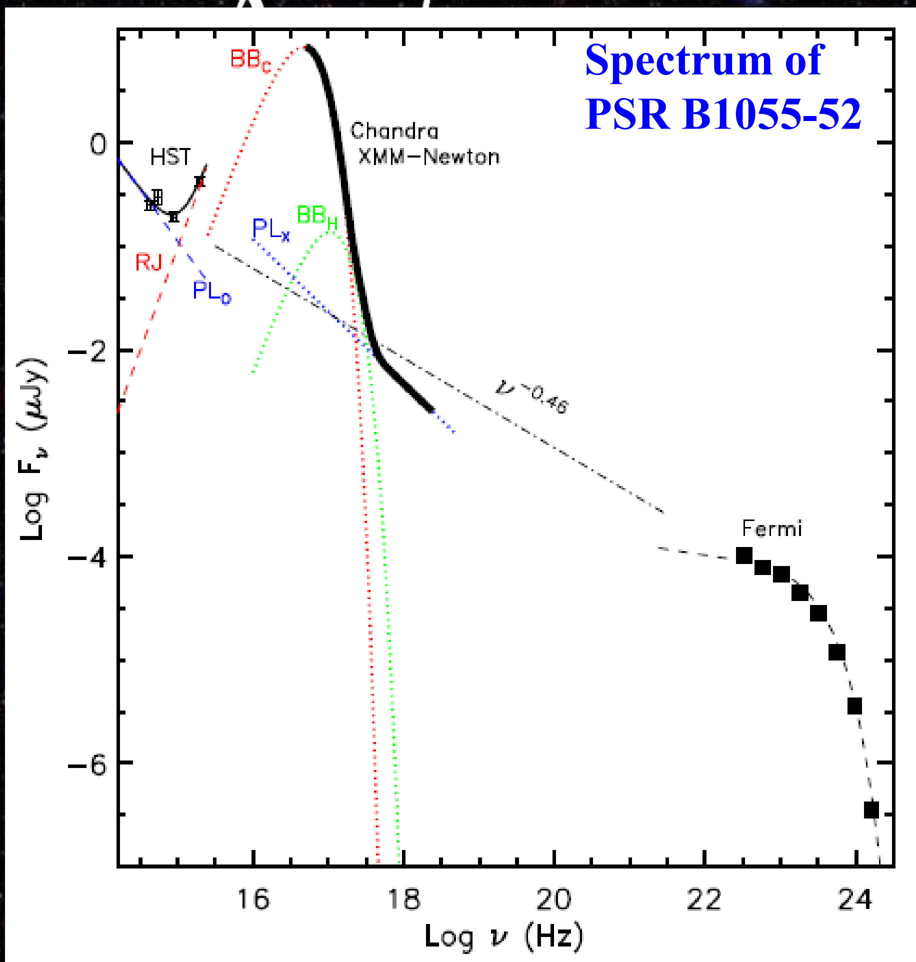
2) pulsar speed and position w.r. to the geometric center of the associated SNR

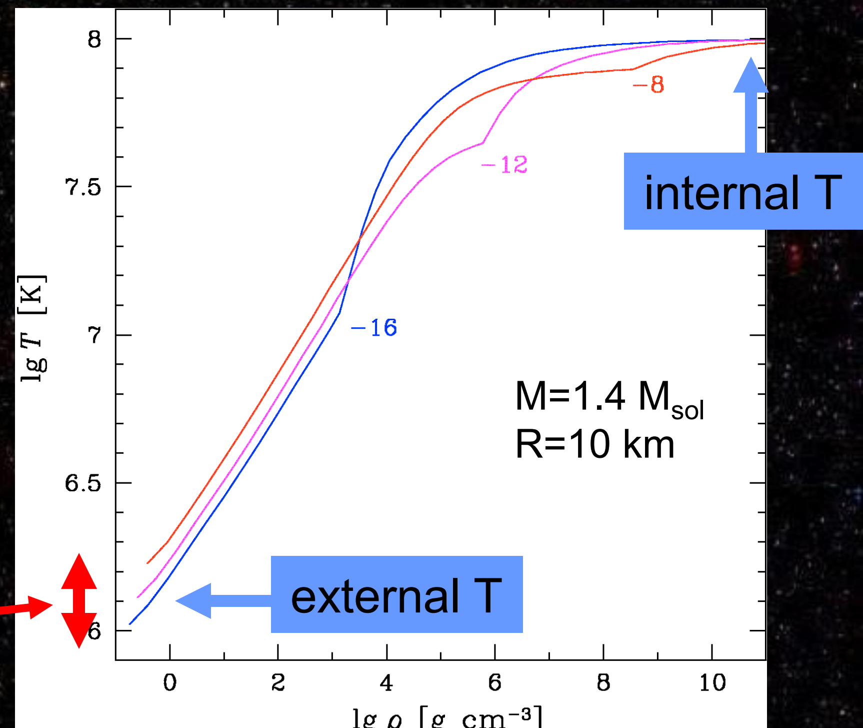
3) historical events

Crab : 1054 AD
Cassiopeia A: 1680 AD
Tycho's SN: 1572 AD

Measuring pulsar temperature

- radiation spectrum and source geometry
- internal vs. external temperature
- heat transfer in envelop





debris of supernova explosion;
accreted "nuclear trash"

[Yakovlev et al., A&A 417, 169]

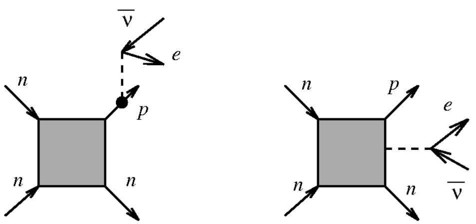
Neutron star cooling

$\underline{T < T_{\rm opac} \sim 10^{-1}\text{–}10^{0}\ {\rm MeV}}$ neutron star is transparent for neutrino

neutrino emissivity

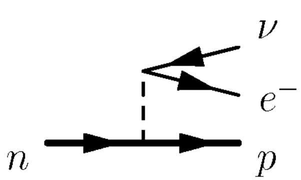
modified Urca (MU)

$$T_9 = T/10^9\,{\rm K} \ll 1$$



$$10^{22} \times \left(\frac{m_N^*}{m_N}\right)^4 T_9^8 \left(\frac{n_e}{n_0}\right)^{\frac{1}{3}} \quad \frac{\rm erg}{{\rm cm}^3\,{\rm s}}$$

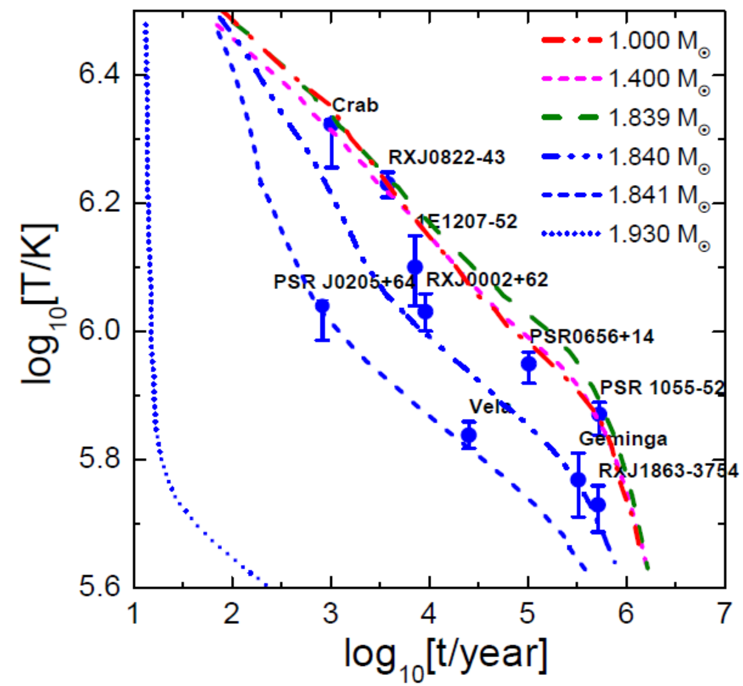
direct Urca (DU)



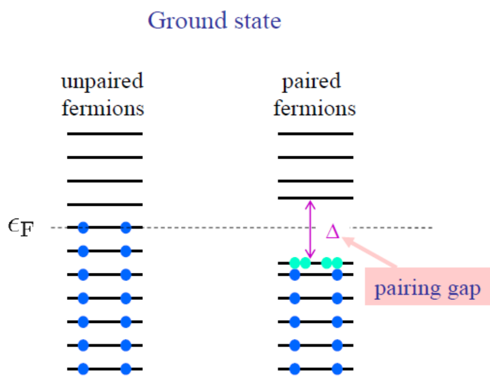
$$10^{27} \times \left(\frac{m_N^*}{m_N}\right)^2 T_9^6 \left(\frac{n_e}{n_0}\right)^{\frac{1}{3}} \quad \frac{\rm erg}{{\rm cm}^3\,{\rm s}}$$

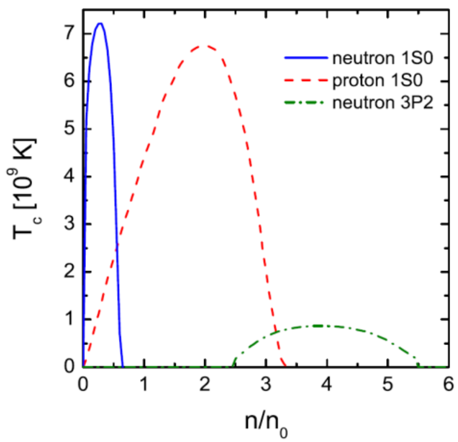
allowed if $|p_{{\rm F},n} - p_{{\rm F},p}| < p_{{\rm F},e}$

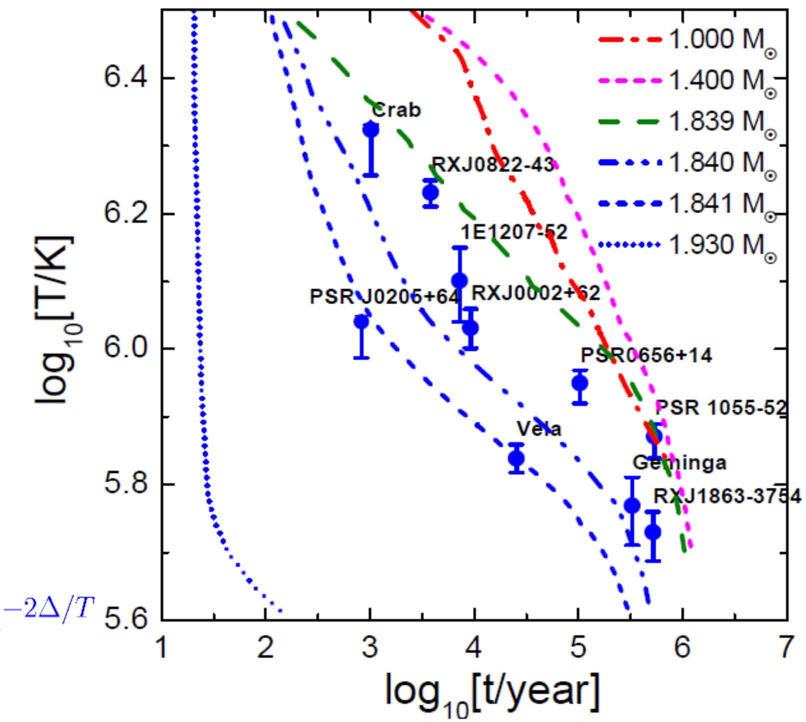
$$x = \frac{n_p}{n} \gtrsim 11\%$$



Neutron star cooling

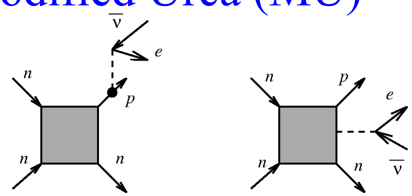






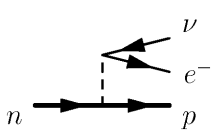
modified Urca (MU)

neutrino emissivity



$$10^{22} \times \left(\frac{m_N^*}{m_N}\right)^4 T_9^8 \left(\frac{n_e}{n_0}\right)^{\frac{1}{3}} \frac{\text{erg}}{\text{cm}^3\,\text{s}} \times e^{-2\Delta/T}$$

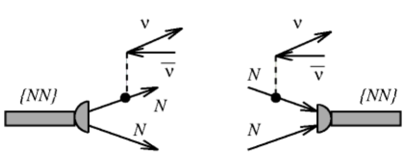
direct Urca (DU)



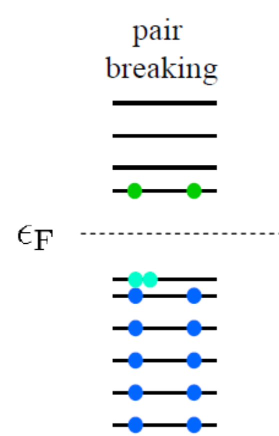
$$10^{27} \times \left(\frac{m_N^*}{m_N}\right)^2 T_9^6 \left(\frac{n_e}{n_0}\right)^{\frac{1}{3}} \frac{\text{erg}}{\text{cm}^3\,\text{s}} \times e^{-\Delta/T}$$

allowed if $|p_{F,n} - p_{F,p}| < p_{F,e}$

pair-breaking-formation (PBF)



$$10^{29} \times \left(\frac{m_N^*}{m_N}\right) \left(\frac{\Delta}{\text{MeV}}\right)^7 \left(\frac{T}{\Delta}\right)^{\frac{1}{2}} e^{-2\Delta/T} \frac{\text{erg}}{\text{cm}^3\,\text{s}}$$



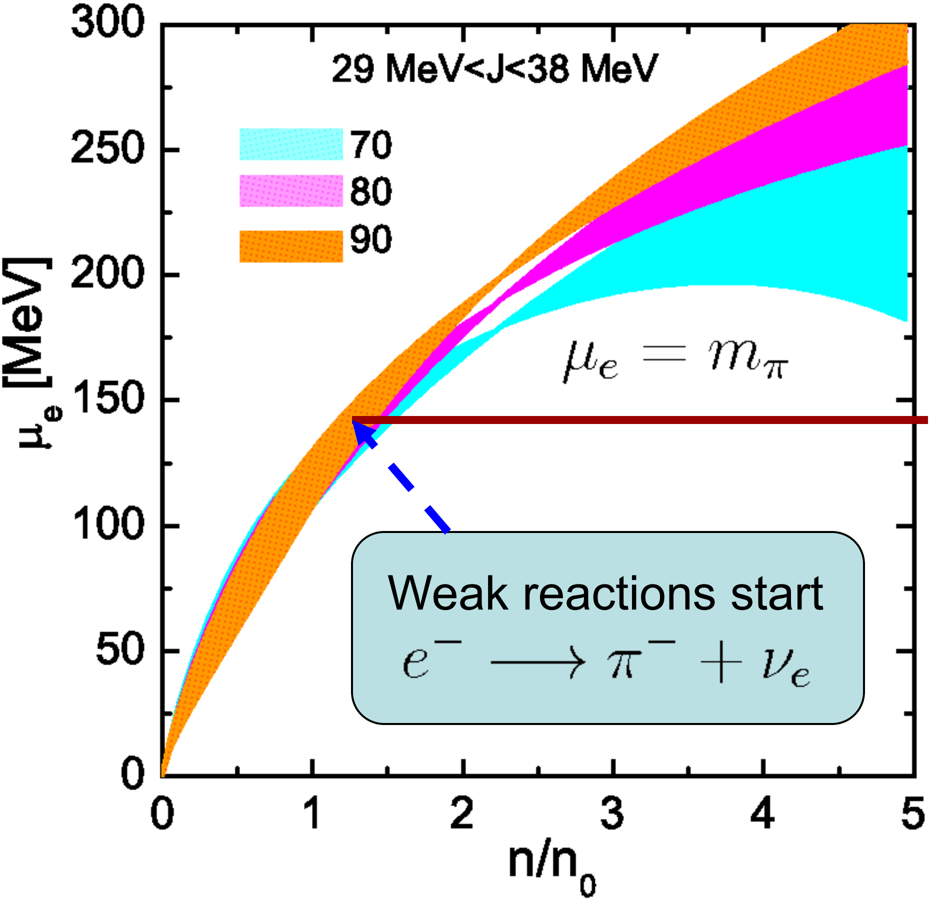
Simple model for NS matter

n+p+e+μ matter

Proton concentration $x = n_p/n$ follows from equations

$$\mu_e = \mu_n - \mu_p = \frac{\partial E}{\partial n_n} - \frac{\partial E}{\partial n_n} = 4\,E_S(n)\,(1-2\,x)$$

$$\frac{(\mu_e^2 - m_e^2)^{3/2}}{3\,\pi^2} + \frac{(\mu_e^2 - m_\mu^2)^{3/2}}{3\,\pi^2} = x\,n$$



Lightest negatively charged bosons: π^-

$$m_\pi = 140 \text{ MeV}$$

$\sqrt{m^2 + k^2}$ → minimum at k=0

Pionization of neutron star matter

Chiral symmetry for pion-nucleon interaction

isospin even and odd amplitudes $$T^{(\pm)} = \frac{1}{2}\left[T(\pi^- p) \pm T(\pi^- n)\right]$$

Chiral symmetry: for forward scattering amplitude: $T^{(\pm)}(\omega, q^2)$

on mass-shell $q^2 = \omega^2 - \mathbf{k}^2 = m_\pi^2$

$$\lim_{\omega \to 0} \omega^{-1}\, T^{(-)}(\omega, m_\pi^2) = \frac{1}{2\, f_\pi^2}$$ Weinberg Tomazawa theorem

$$T^{(-)}(\omega) \approx \frac{\omega}{2\, f_\pi^2}$$

- **polarization operator**

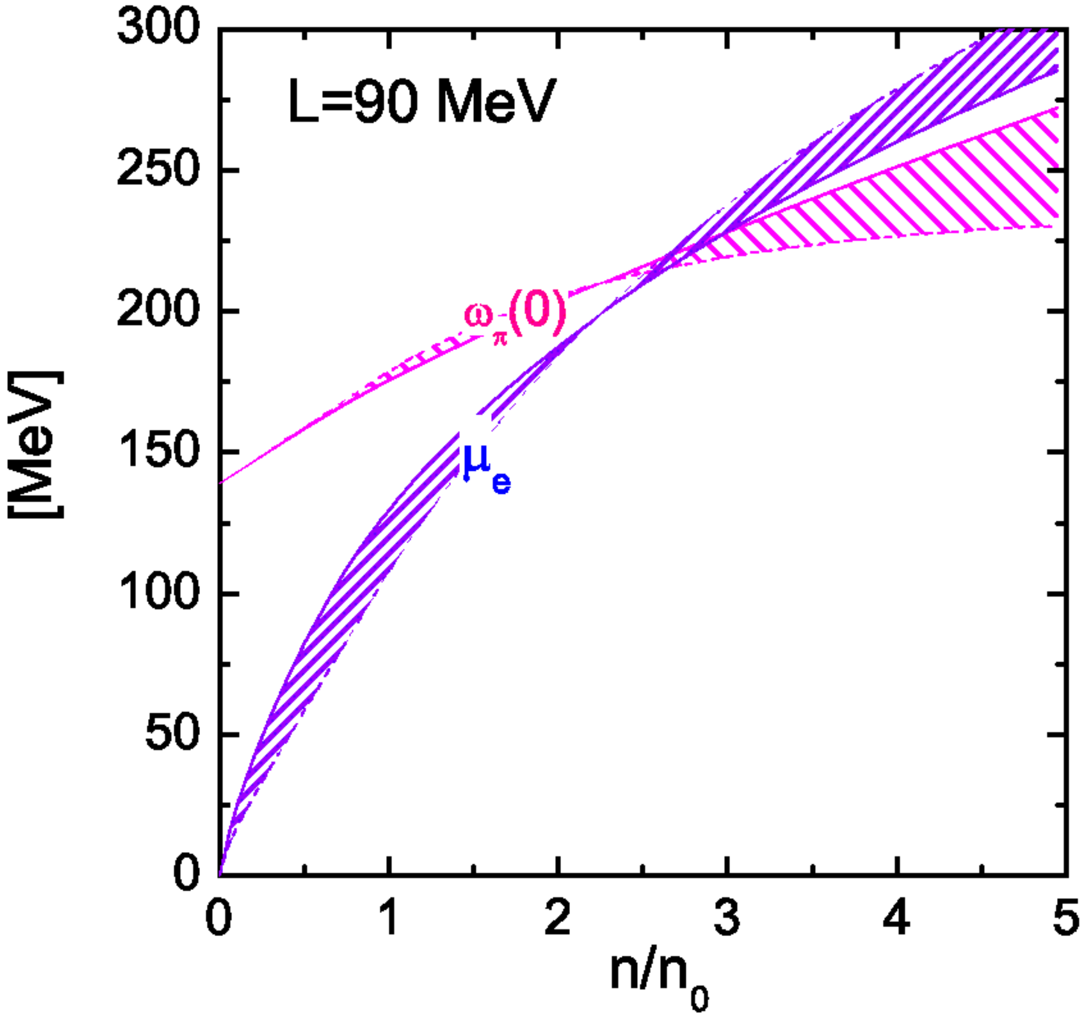
$$\Pi_S(\omega) = -T^{(-)}(\omega)\,(\rho_p - \rho_n)$$

repulsive in neutron reach matter

- **spectrum** $$D^{-1}(\omega, k=0) = \omega^2 - m_\pi^2 - \Pi_S(\omega) = 0$$

29 MeV<J<38 MeV

chiral shield against pionization



Detailed analysis of the possibility of the s-wave pion condensation in Onishi, Jido et al, PRC 80, 038202 (2009)

Conclusion

NSs and HICs are the only sources of the information about properties of the strongly interacting matter under extreme condition.

They provide test for our theories and models in dynamical systems.

Problems in discussion:

Relativistic equation of state?
Inclusion of new particles (hyperons, Deltas)?
Meson in medium?