Constraints on the Nuclear Equation of State. Hyperon Puzzle of Neutron Stars

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[PLB 748 (2015) 369; PRC 92 (2015) 052801(R), NPA 950 (2016) 64]

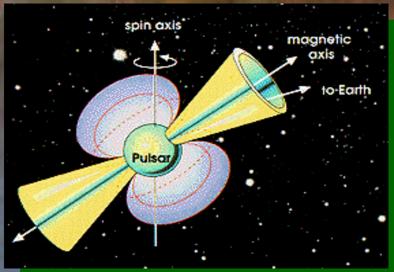
- **Constraints on the nuclear EoS:**
  - **maximum neutron-star mass**
  - **baryon mass vs. gravitational mass**
  - **mass-radius relation**
  - **particle flow in heavy-ion collisions**

- **Making RMF model flexible**

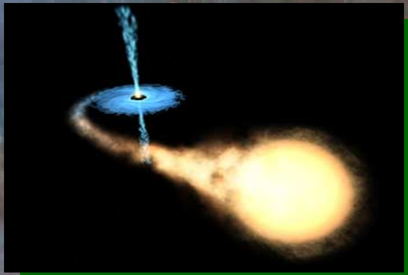
- **Hyperon puzzle**

Neutron Star Zoo

>1400 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)

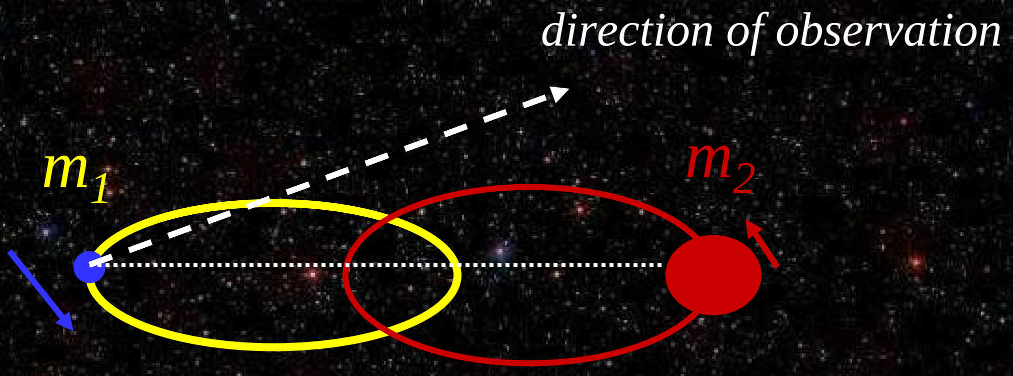


short gamma-ray bursts
neutron star -- neutron star,
neutron star -- black-hole mergers

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

Measuring pulsar mass

Pulsar mass can be measured only in binary systems



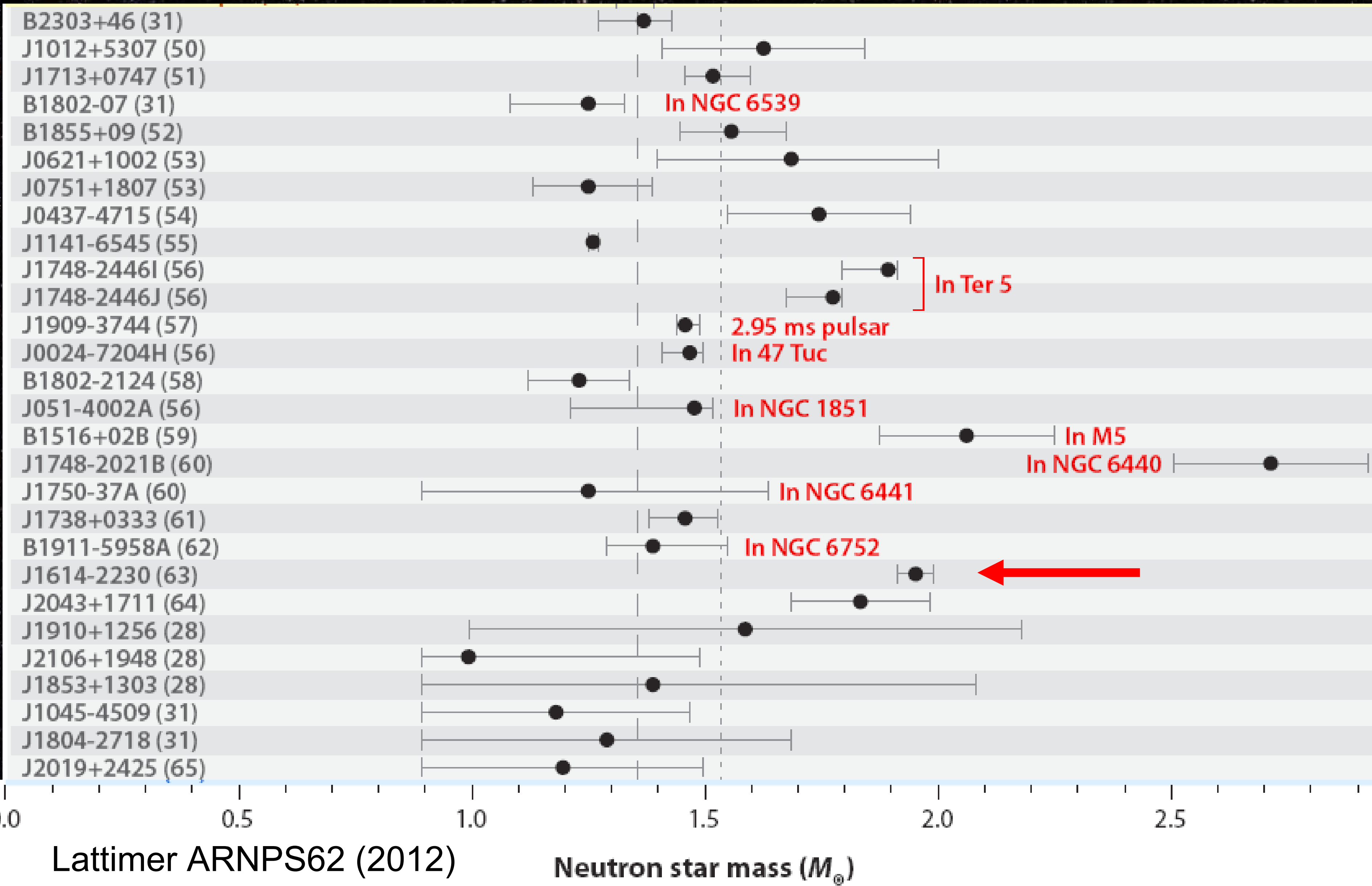
Newton gravity ⟶ 5 Keplerian orbital parameters:
orbital period, semi-major axis length,excentricity, …

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, ….

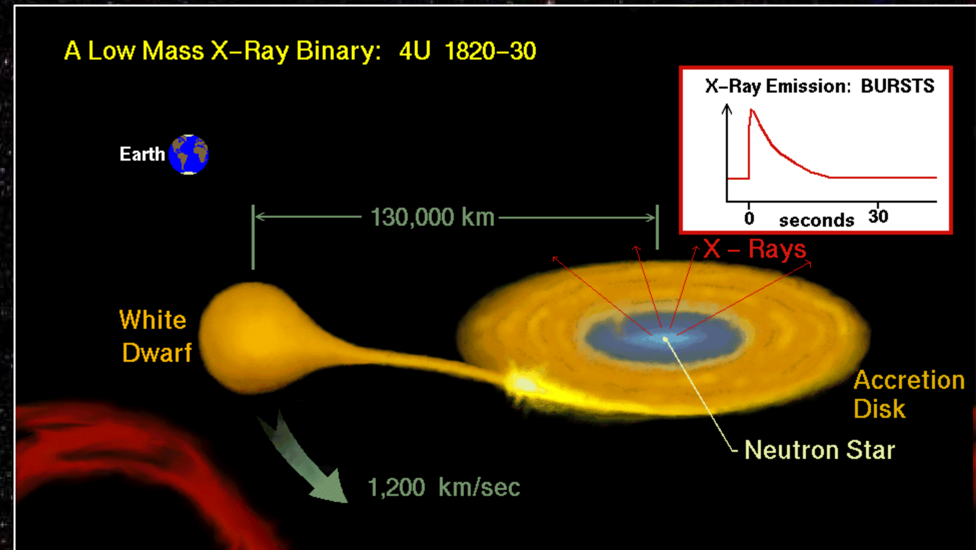
Measurement of any 2 post-Keplerian parameters allows to determine the mass of each star.

White dwarf -- neutron star binaries



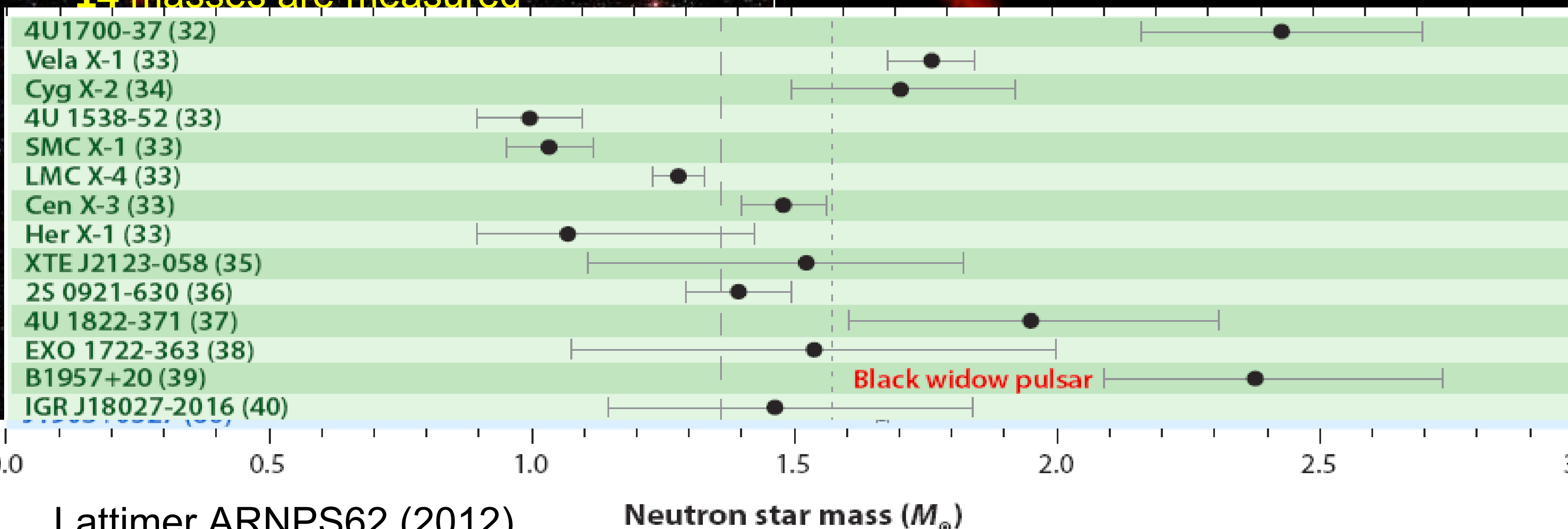
Lattimer ARNPS62 (2012)

Measuring pulsar mass

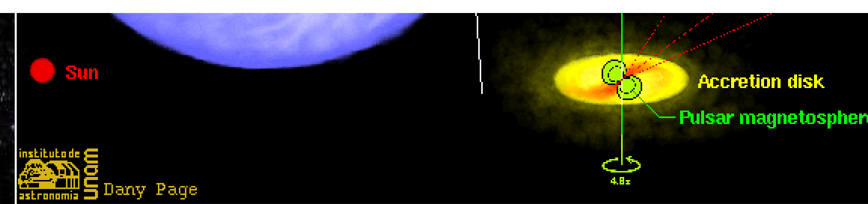


X-ray binaries

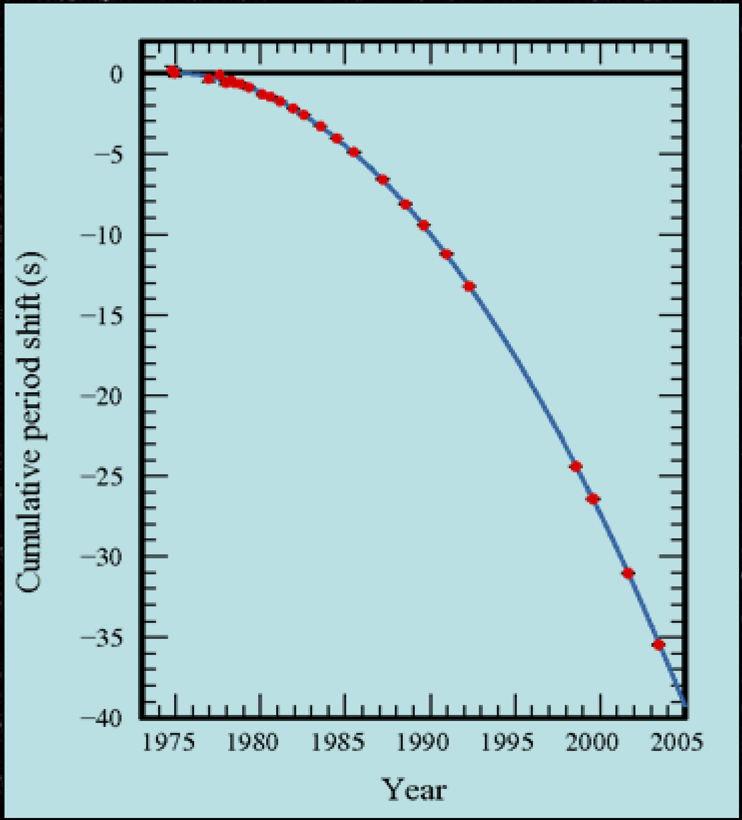
14 masses are measured



Lattimer ARNPS62 (2012)



Measuring pulsar mass

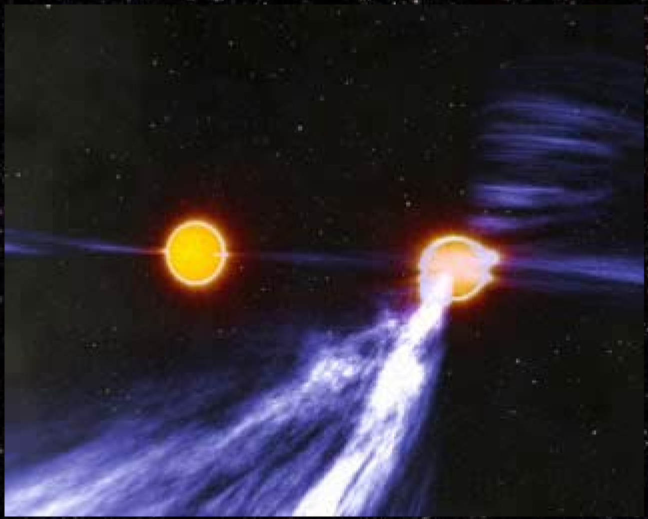


Double neutron star binaries

1974 **PSR B1913+16** Hulse-Taylor pulsar

First precise test of Einstein gravitation theory

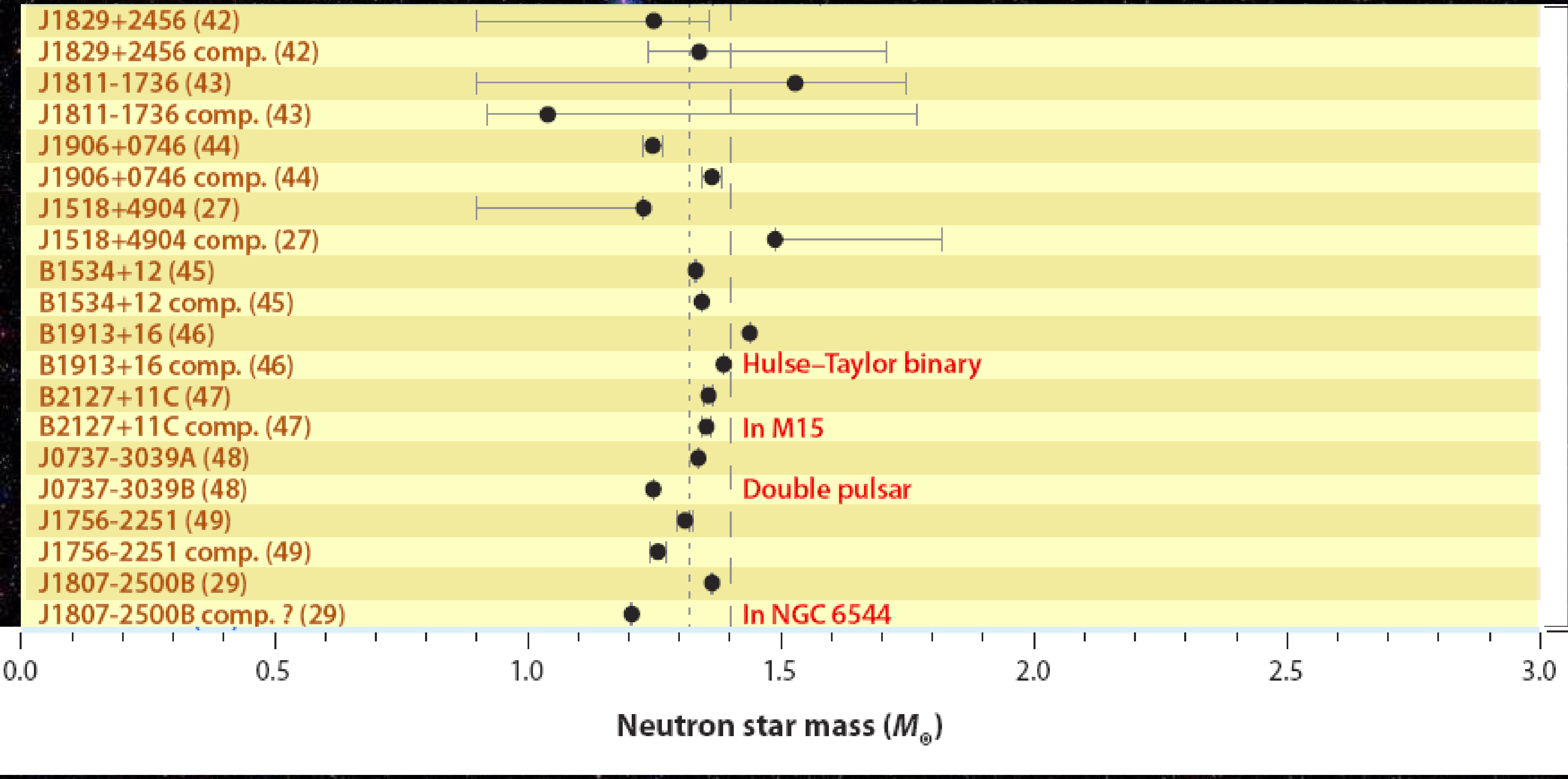
2003 **J0737-3039** first double pulsar



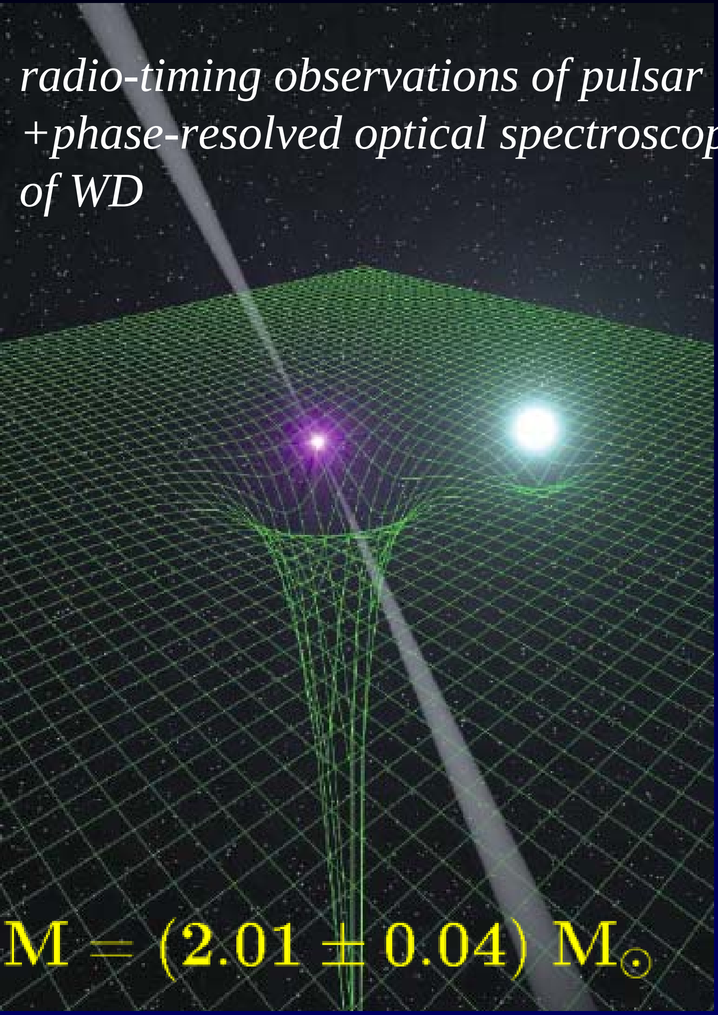
Pulsar A: $P^{(A)}$=22.7 ms, $M^{(A)}$=1.338 M_{sol}
Pulsar B: $P^{(B)}$=2.77 ms, $M^{(A)}$=1.249±0.001 M_{sol}
Orbiting period 2.5 hours

[Nature 426, 531 (2003), Science 303, 1153 (2004)]

Double neutron star binaries



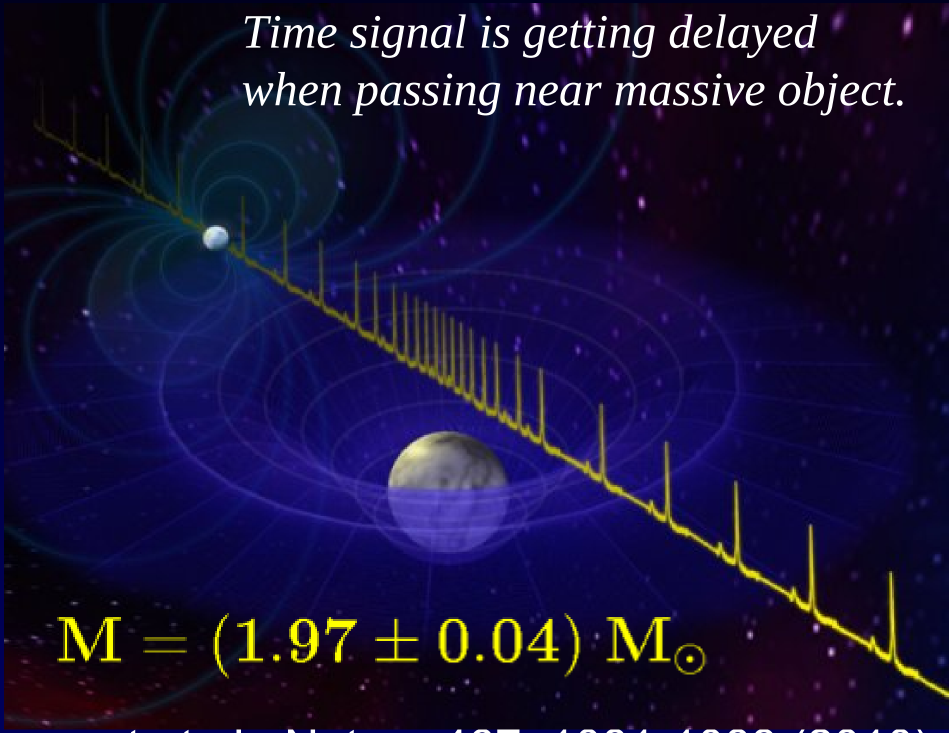
Pulsar J03448+0432



Antonadis et al., Science 340,448

Pulsar J1614-2230

Measured Shapiro delay with high precision



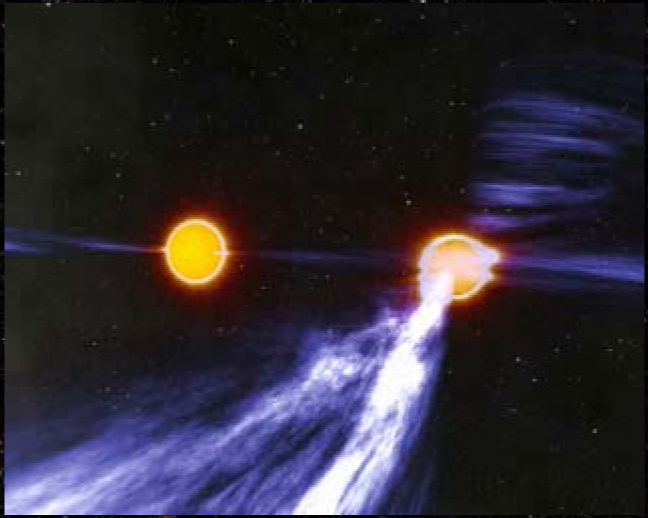
P.Demorest et al., Nature 467, 1081-1083 (2010)

Highest well-known masses of NS

there are heavier, but far less precisely measured candidates

Gravitational mass -- baryon number constraint

first double pulsar system J0737-3039



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[Nature 426, 531 (2003), Science 303, 1153 (2004)]

Pulsar B: progenitor ONeMg white dwarf,
driven hydrodyn. unstable by e− captures on Mg & Ne;

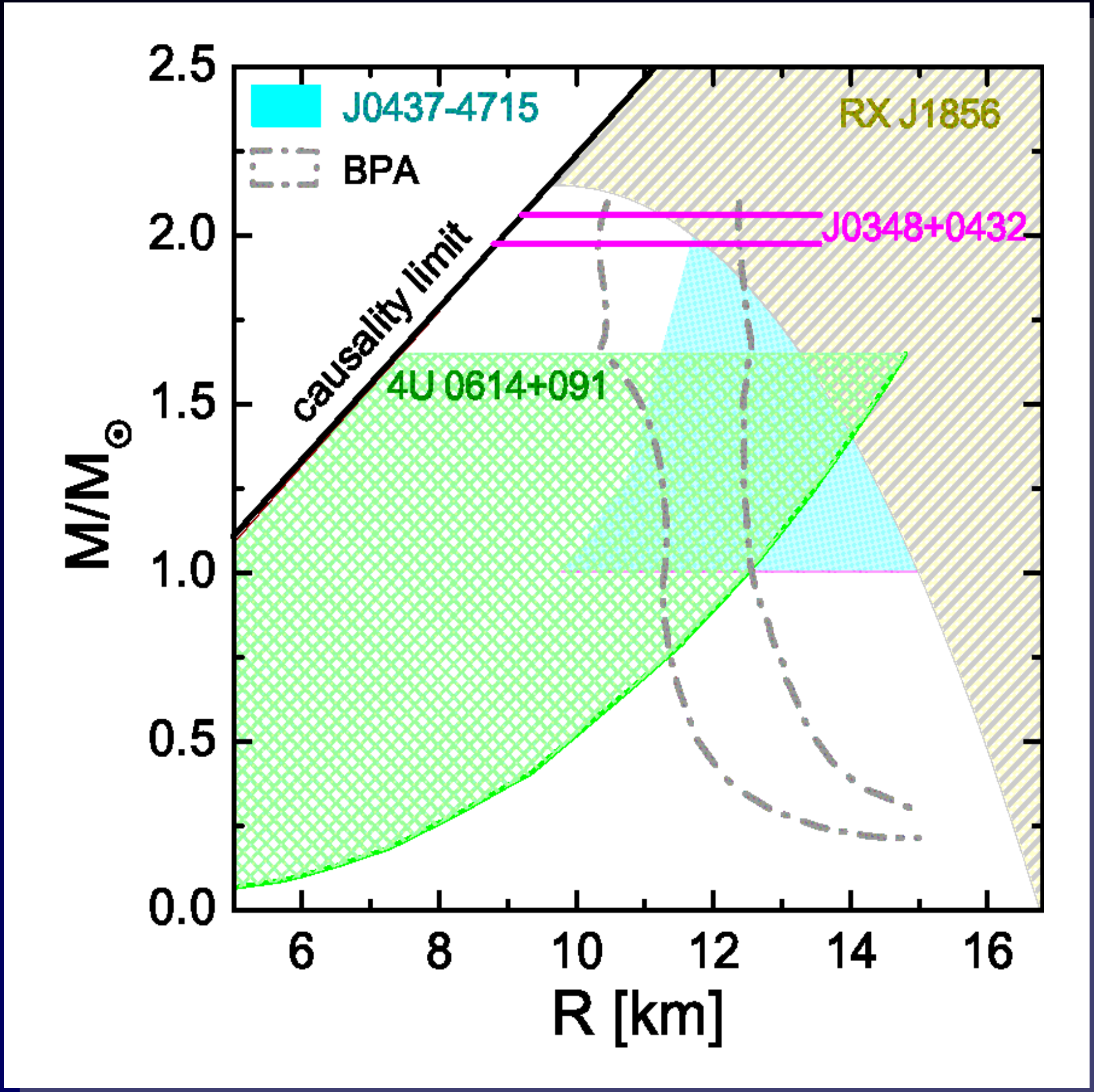
[Podsiadlowski et al., MNRAS 361, 1243 (2005)]

observed NSs gravitational mass (remnant star): 1.248—1.250 M_{sol}

critical baryon mass of progenitor white dwarf: 1.366—1.375 M_{sol}

assume no mass-loss during collapse…

Mass-radius relation



BPA: Bayesian probability analysis [Lattimer,Steiner …]

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

Neutron star cooling data

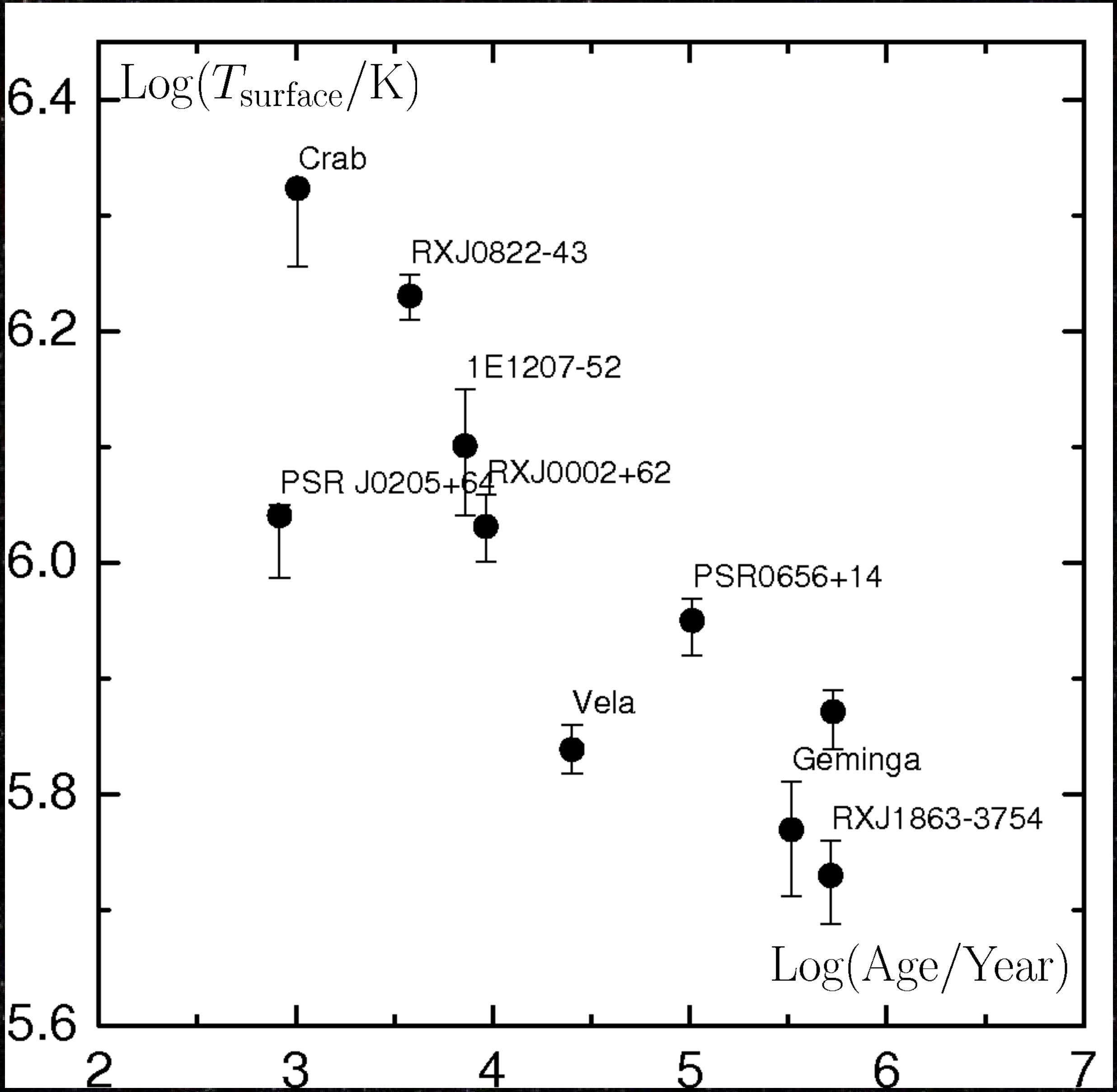
Given:

- **EoS**
- **Cooling scenario**
  [neutrino production]

Mass of NS

↓

Cooling curve



Neutrino emission reactions

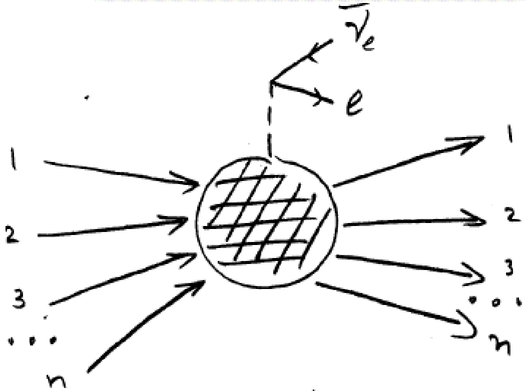
$T < T_{\rm opac} \sim 10^{-1}$—$10^{0}$ MeV

neutron star is transparent for neutrino

$$C_V \frac{\mathrm{d}T}{\mathrm{d}t} = -L$$

C_V - specific heat, L - luminosity

✔ n-nucleon reaction

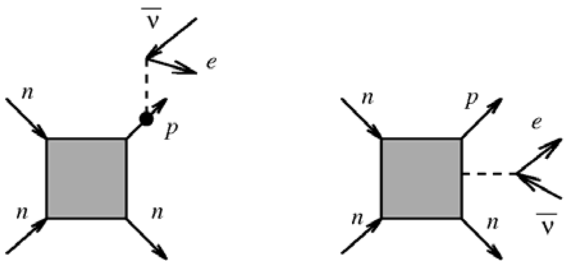


$$L = \int \mathrm{d}V \sum_{\text{reaction r}} \epsilon_\nu^{(r)}$$

emissivity

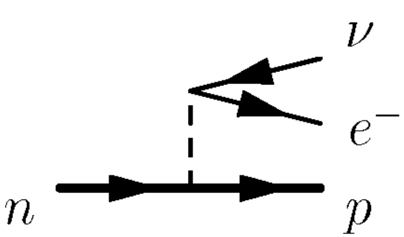
$T \ll \epsilon_{\rm F}$ ➡ $\epsilon_\nu \sim T^{2n+4}$

standard: modified Urca



$$L = 10^{22} \left(\frac{T}{10^9\,\mathrm{K}}\right)^{8} \left(\frac{n_e}{n_0}\right)^{\frac{1}{3}} \quad \frac{\mathrm{erg}}{\mathrm{cm}^3\,\mathrm{s}}$$

exotic: direct Urca



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

$$L = 10^{27} \times \left(\frac{T}{10^9\,\mathrm{K}}\right)^{6} \left(\frac{n_e}{n_0}\right)^{\frac{1}{3}} \quad \frac{\mathrm{erg}}{\mathrm{cm}^3\,\mathrm{s}}$$

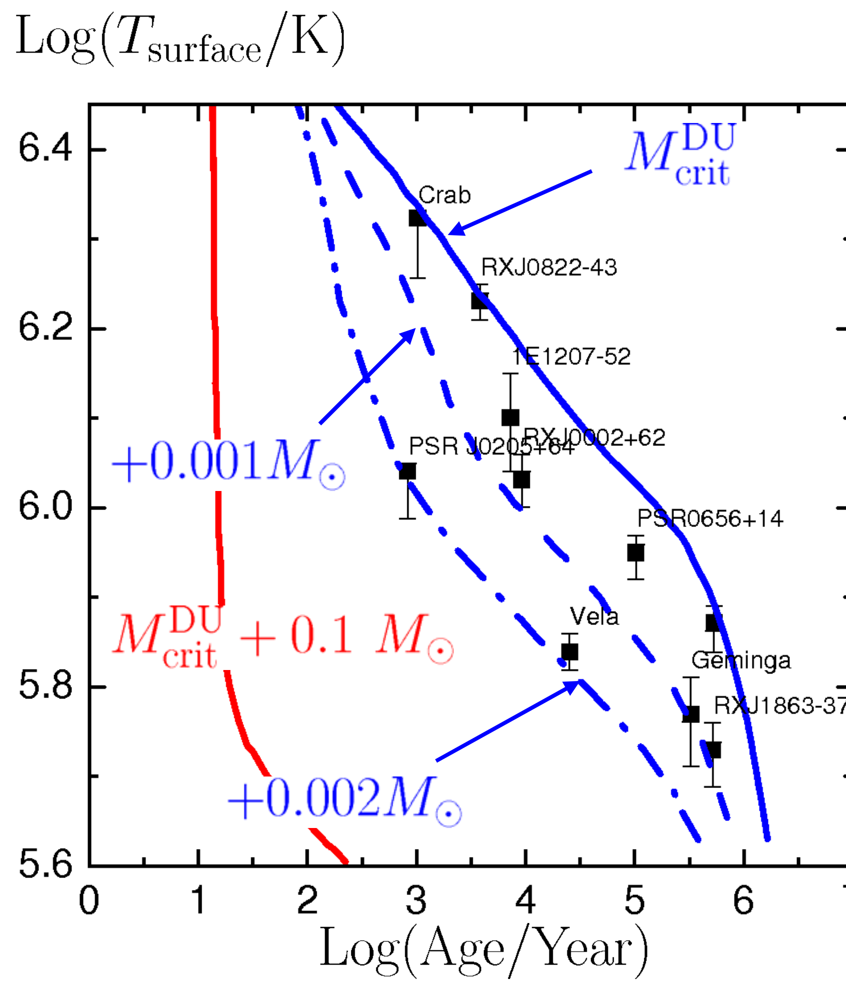
starts at some critical density, i.e. in stars with $M > M^{DU}_{crit}$

Neutron Star Cooling Scenario

standard scenario (MU+pairing)

only "slow" cooling can be described

Neutron stars with $M > M_{\rm crit}^{\rm DU}$ will be too cold



[Blaschke, Grigorian, Voskresensky A&A 424 (2004) 979]

DU process schould be „exotics“

(if DU starts it is dificult to stop it)

$M_{\rm crit}^{\rm DU} \gtrsim 1.3\ M_\odot$ $\quad n_{\rm crit}^{\rm DU} \gtrsim 4\, n_0$

EoS should produce a large DU threshold in NS matter !

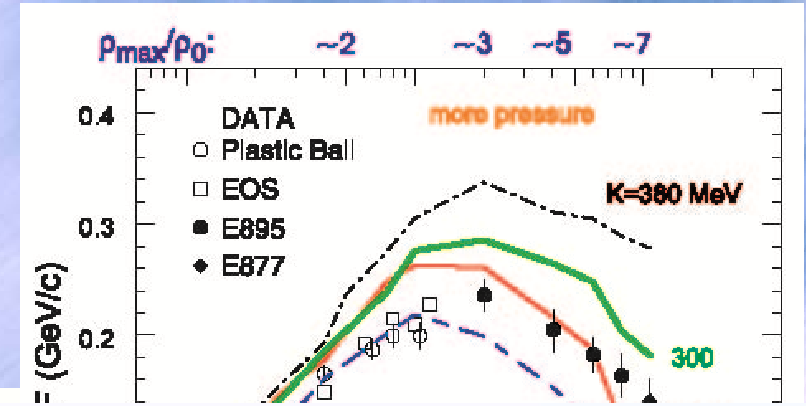
[EEK, Voskresensky NPA759 (2005) 373]

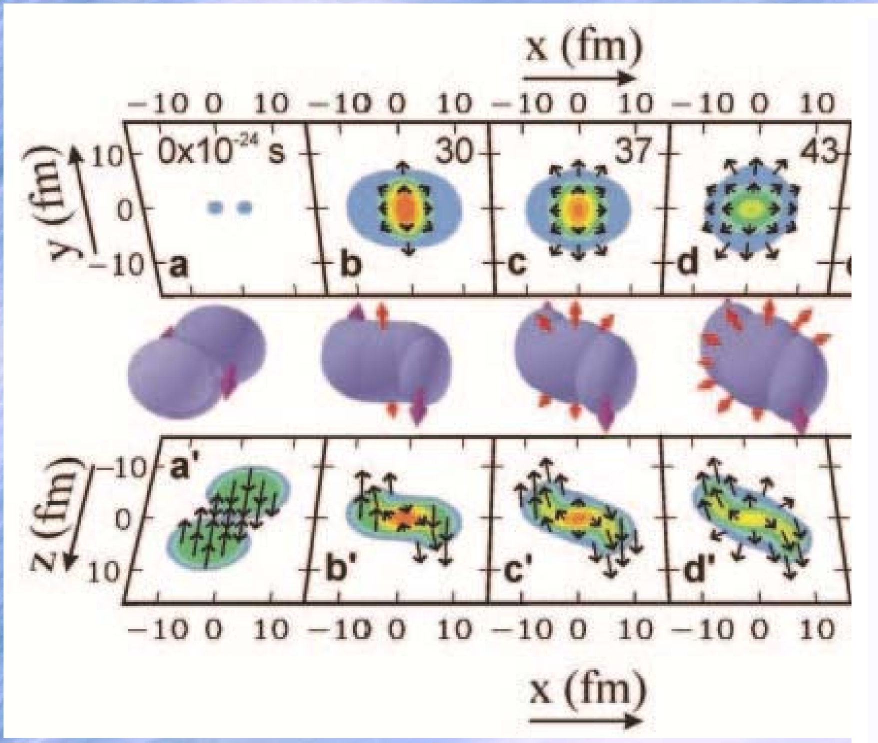
Constraints from heavy-ion collisions

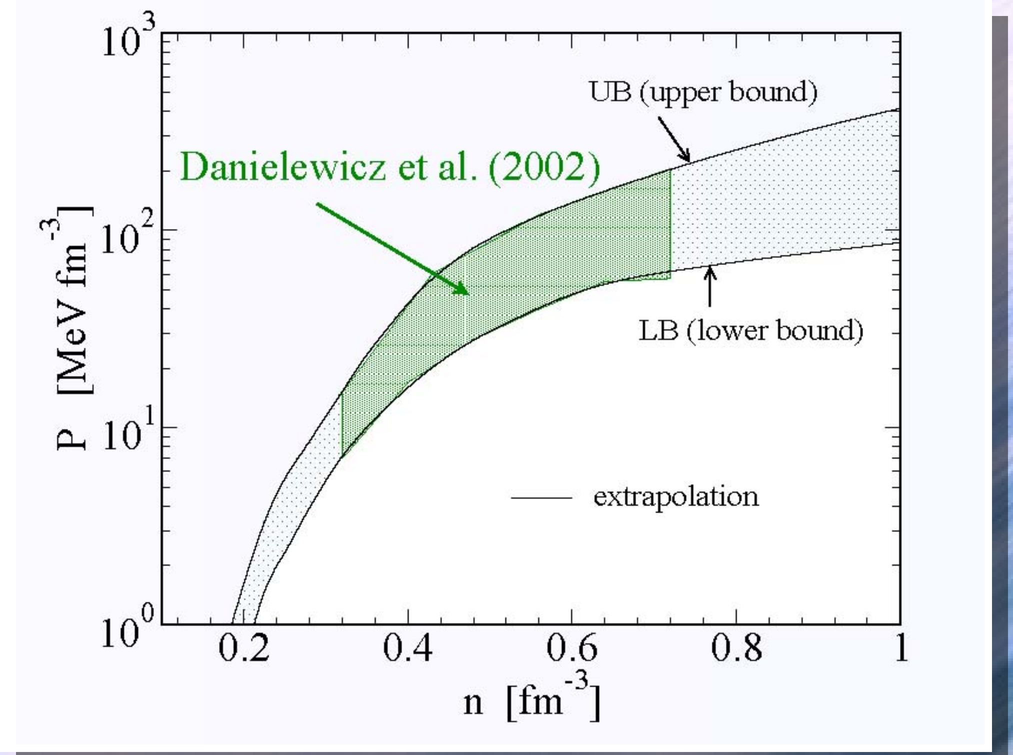
- Boltzmann kinetic equation
- Mean-field potential

$$U = (a\rho + b\rho^{\nu})/[1+(0.4\rho/\rho_0)^{\nu-1}] + \delta U_p$$

fitted to directed & elliptic flow

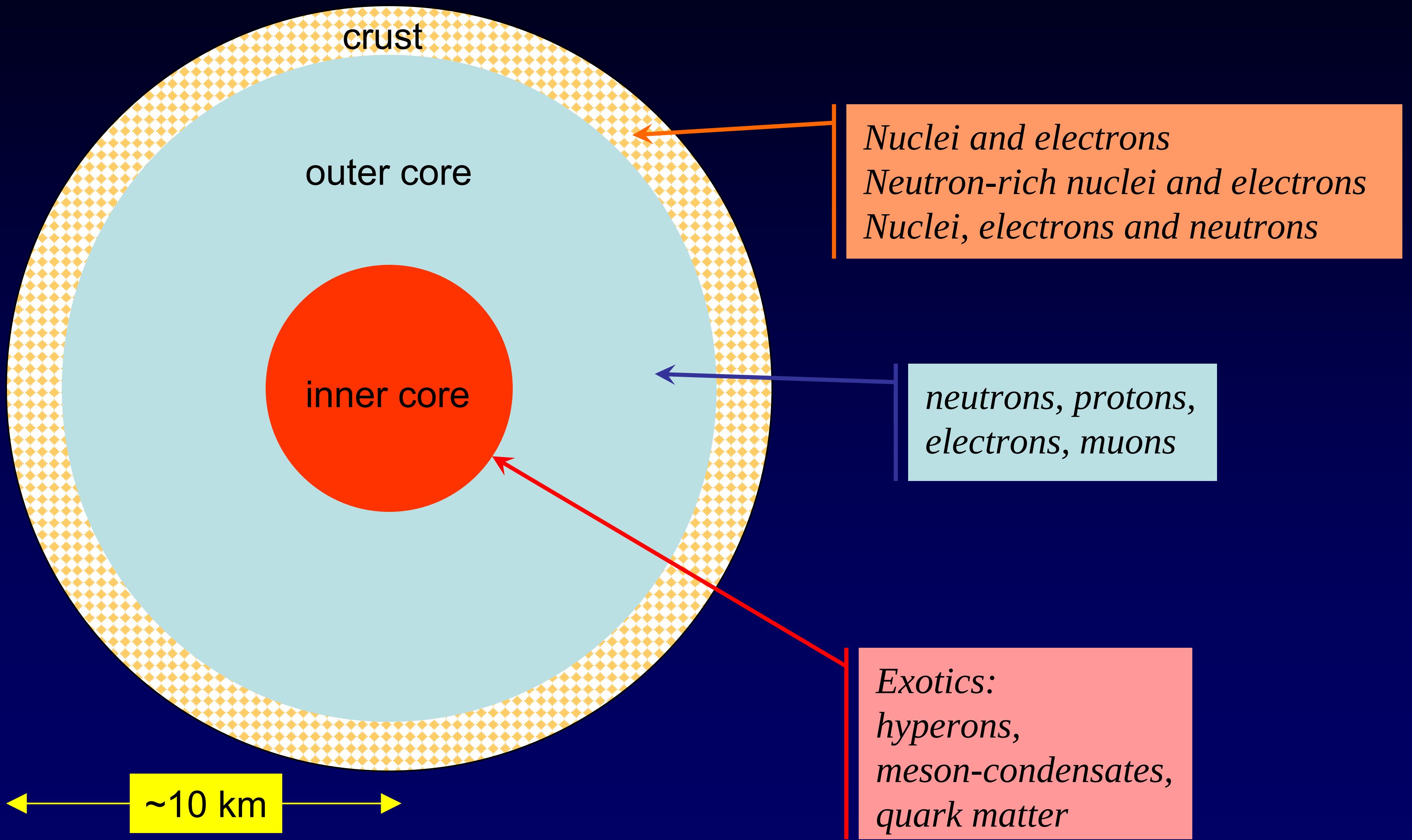






[Danielewicz, Lacey, Lynch, Science 298, 1592 (2002)]

Cross section of a neutron star

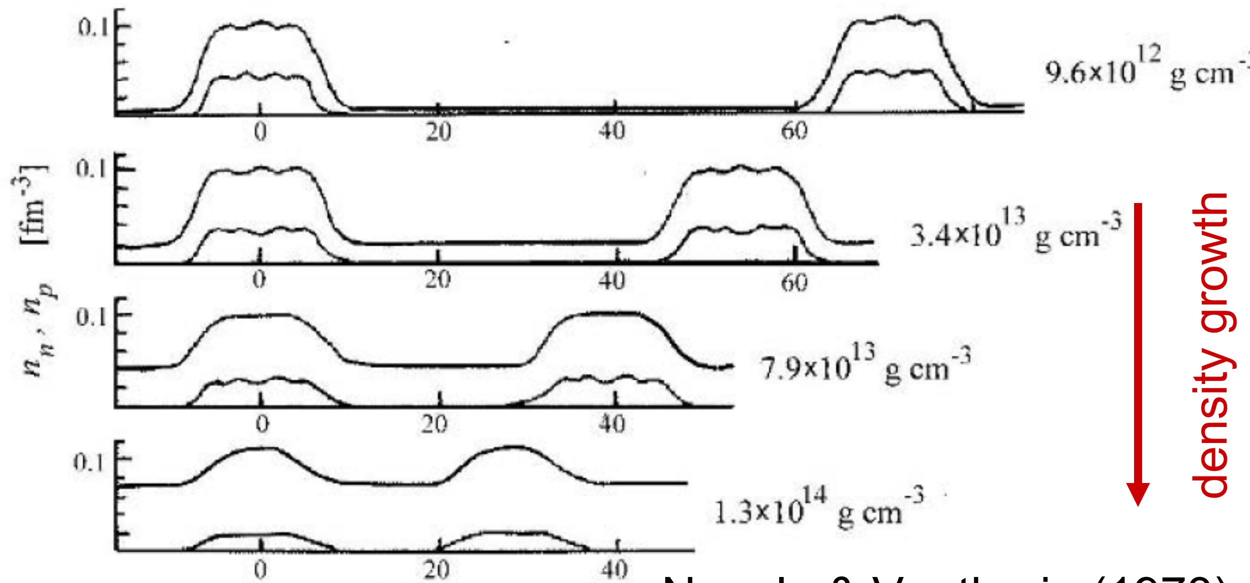


Crust

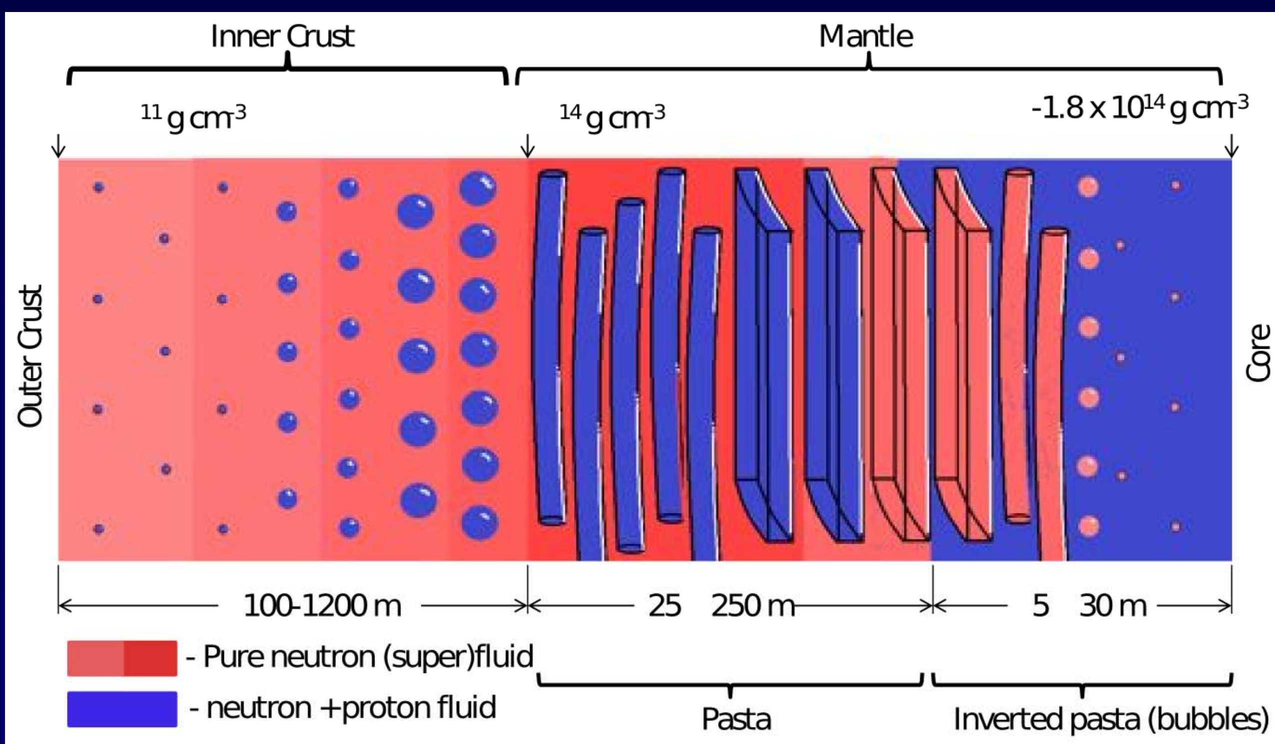
Nucleus melting

Pasta structure

interplay of Coulomb energy and surface tension



Negele & Vautherin (1973)



saturation density

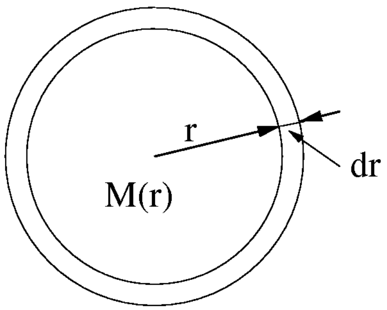
$$\rho_0 = 2.8 \times 10^{14} \frac{\mathrm{g}}{\mathrm{cm}^3}$$

M_{crust} ~0.1M_{sol}

R_{crust}~10^2—10^3 m

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)

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

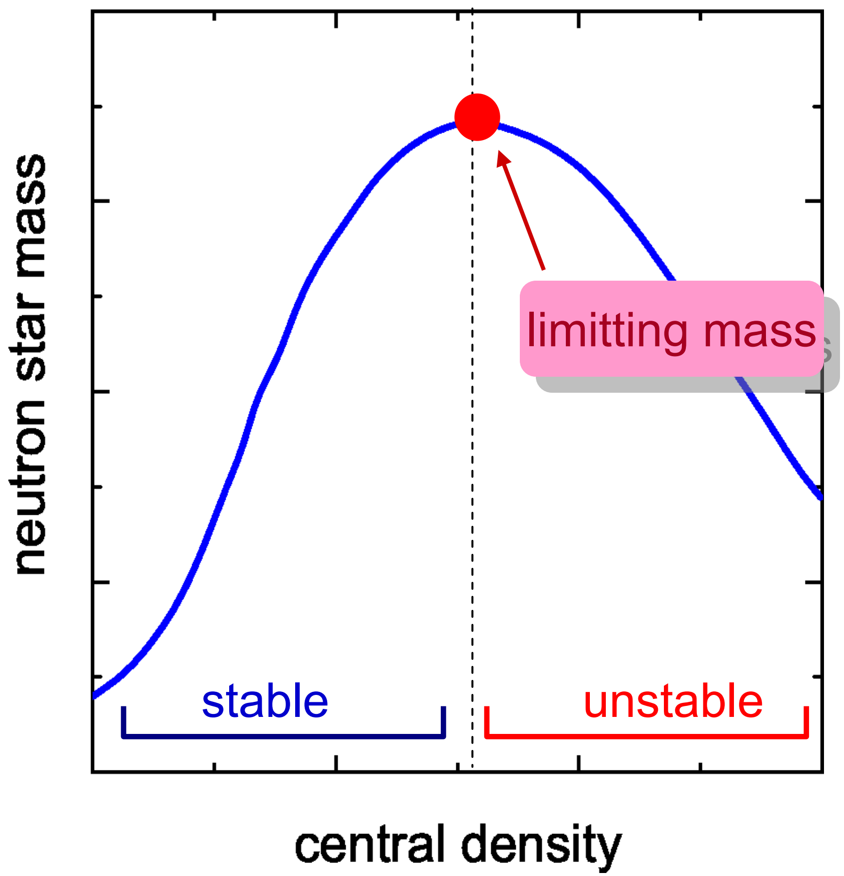
boundary conditions: $\varepsilon(r=0) = \varepsilon_{\rm c}\,, \quad M(r=0) = 0\,, P(r=R) = 0$

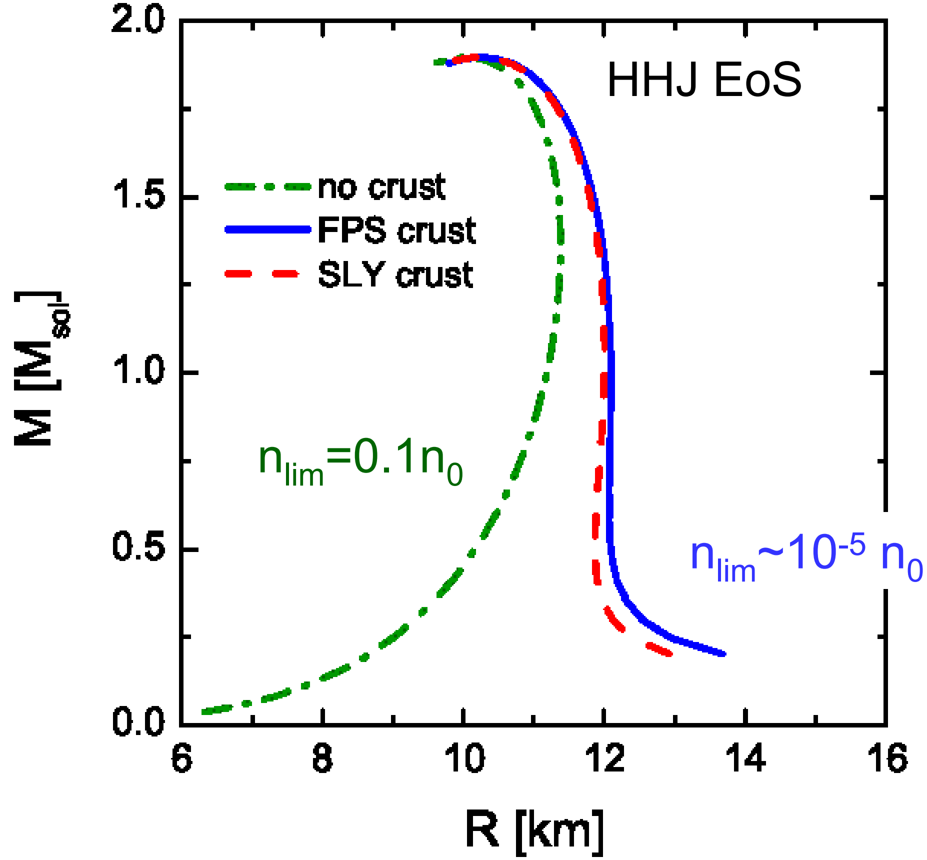
OUTPUT: neutron star density profile, radius R and mass M

relativistic corrections

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

Neutron star configuration

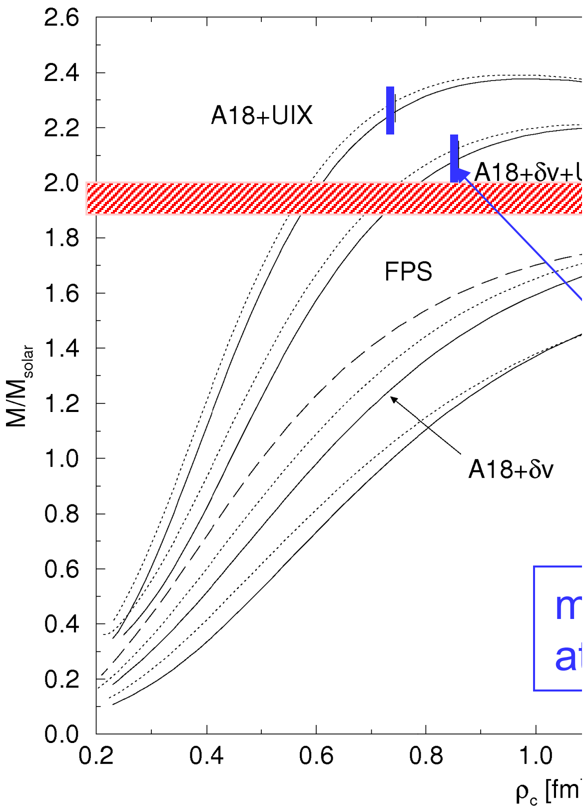




uncertainty in R~10^3 m

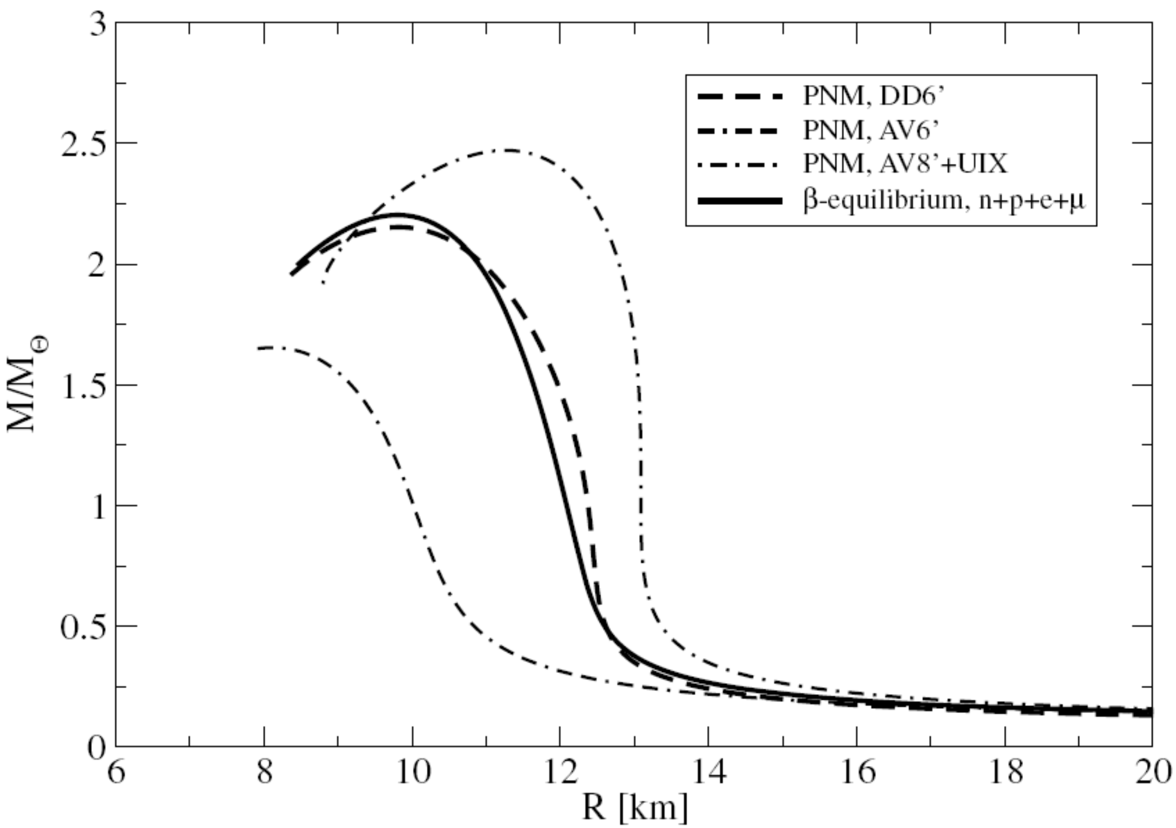
Ab inito calculations of the EoS starting from NN potential

variational chain-summati



[Akmal, Pandharipande, Ravenhall PRC58(98)1804]

auxiliary field diffusion Monte Carlo technique



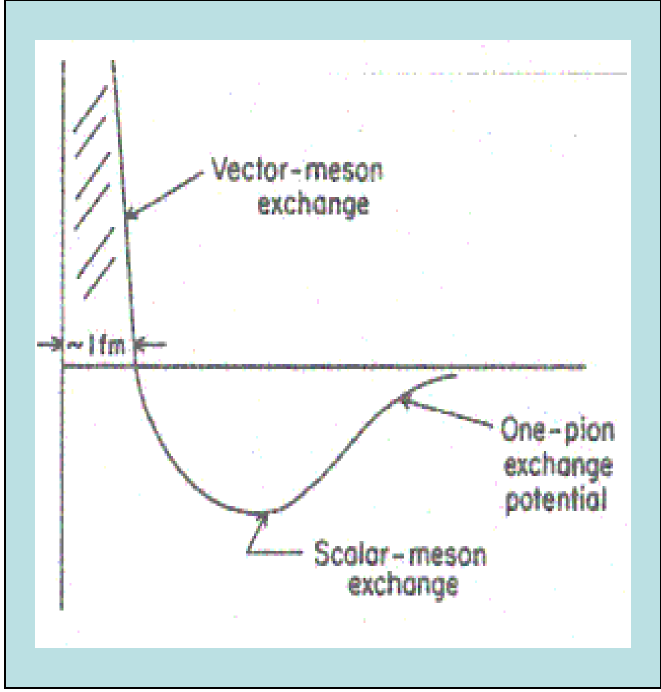
[Gandolfi et al PRC **79**, 054005 (2009)]

non-relativistic EoS!

Relativistic mean-field models

nucleon-nucleon interaction

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



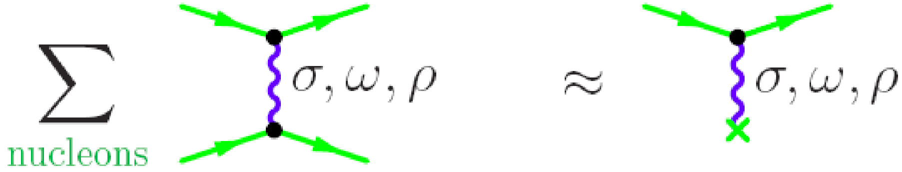
a model

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

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

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

medium: mean-field approximation



$$\sigma(r,t) = \sigma$$

$$\omega_\mu(r,t) = \delta_{\mu,0}\, \omega_0$$

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

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 σ 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

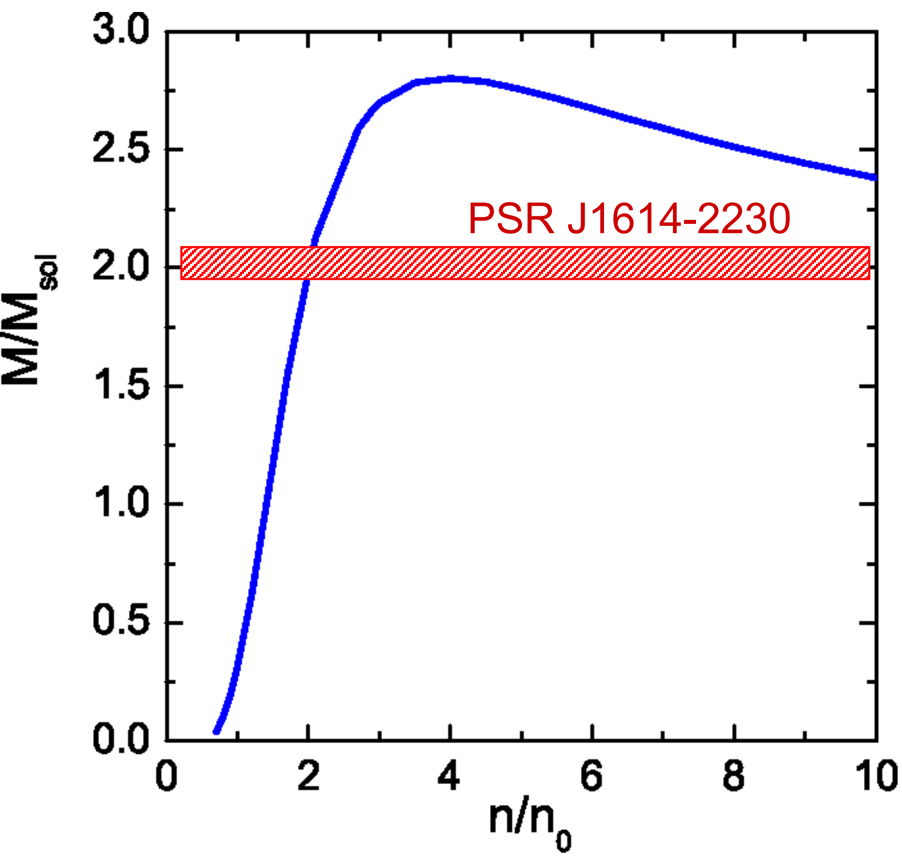
n_0	$\simeq$	$0.16 \pm 0.015\ \mathrm{fm}^{-3}$
E_{bind}	$\simeq$	-15.6 ± 0.6 MeV
$m_N^*(\rho_0)$	$\simeq$	$(0.75 \pm 0.1)\, m_N$
K	$\simeq$	240 ± 40 MeV
a_{sym}	$\simeq$	32 ± 4 MeV

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

(pure) Walecka model U(σ)=0

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

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

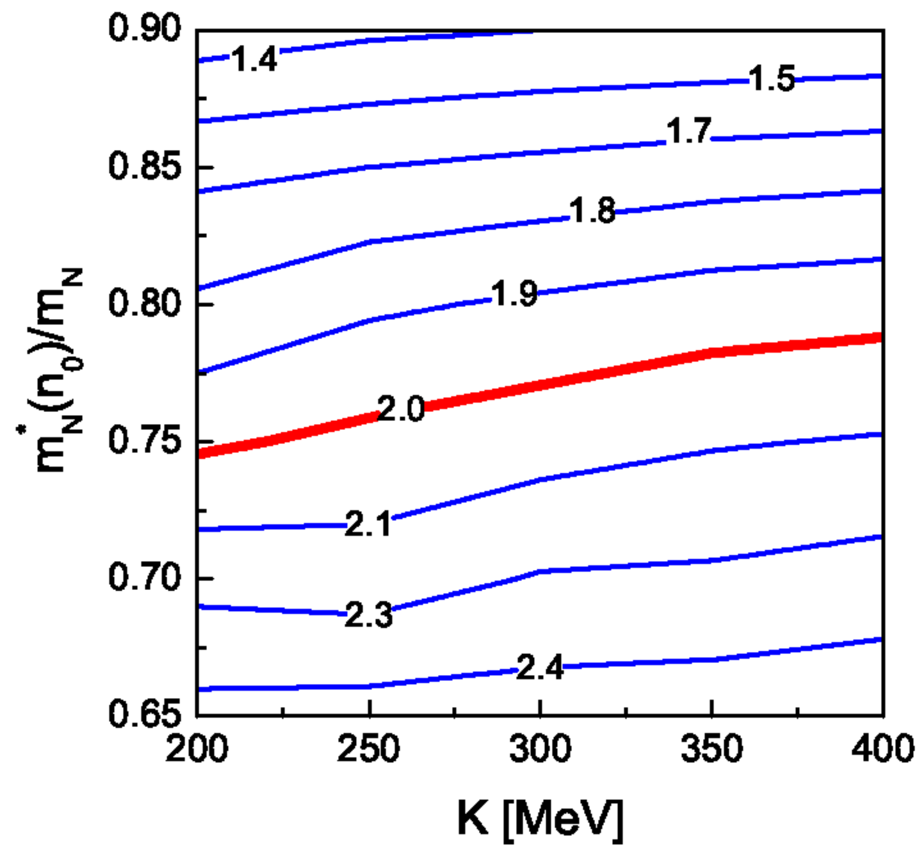


Hardest EoS among all RMF models

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

non-linear Walecka model (NLW)

maximal mass of NS



weak dependence on K !

strong dependence on m^*_N

Nuclear EoS: Examples for illustrations

Relativistic Mean Field Models

NLρ, NLρδ **T. Gaitanos, M. Di Toro, S. Typel, V. Baran, C. Fuchs, V. Greco, H.H. Wolter**

scalar-field dependent couplings [Nucl. Phys. A 732, 24 (2004)]

KVR, KVOR **E.E. Kolomeitsev, D.N.Voskresensky**

reduction of hadron masses in dense medium is included

[Nucl. Phys. A 759, 373 (2005)]

density dependent couplings

DD, D^3C, DD-F **S. Typel** [Phys. Rev. C 71, 064301 (2005)]

Dirac- Bruekner-Hartree-Fock

DBHF **E.N.E. van Dalen, C. Fuchs, A. Faessler**

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

EoS at saturation

$$E(n,\beta) = E_0(n) + \beta^2 E_S(n) \approx a_V + \frac{K}{18}\epsilon^2 - \frac{K'}{162}\epsilon^3 + \ldots + \beta^2\left(J + \frac{L}{3}\epsilon + \ldots\right) + \ldots$$

$$\epsilon = (n - n_{sat})/n \qquad \beta = (n_n - n_p)/(n_n + n_p)$$

[illegible]	n_{sat}	[illegible]	K	K'	J	L	m_D/m
	[fm^{-3}]	[MeV]	[MeV]	[MeV]	[MeV]	[MeV]	
NLρ	0.1459	−16.062	203.3	576.5	30.8	83.1	0.603
NL$\rho\delta$	0.1459	−16.062	203.3	576.5	31.0	92.3	0.603
DBHF	0.1779	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.684
DD	0.1487	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.565
D^{3}C	0.1510	[illegible]	[illegible]	[illegible]	31.9	59.3	0.541
KVR	0.1600	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.800
KVOR	0.1600	−16.000	275.0	[illegible]	[illegible]	[illegible]	0.800
DD-F	0.1469	−16.024	223.1	757.8	31.6	56.0	0.556

HIC

ab initio

atomic nuclei

Urbana Argonne

small

large

isospin diffusion in HIC
62 MeV < L < 107 MeV
B.A. Li, A.W. Steiner
nucl-th/0511064

spin-orbit splitting
RMF Models

single nucleon spectra

similar

similar

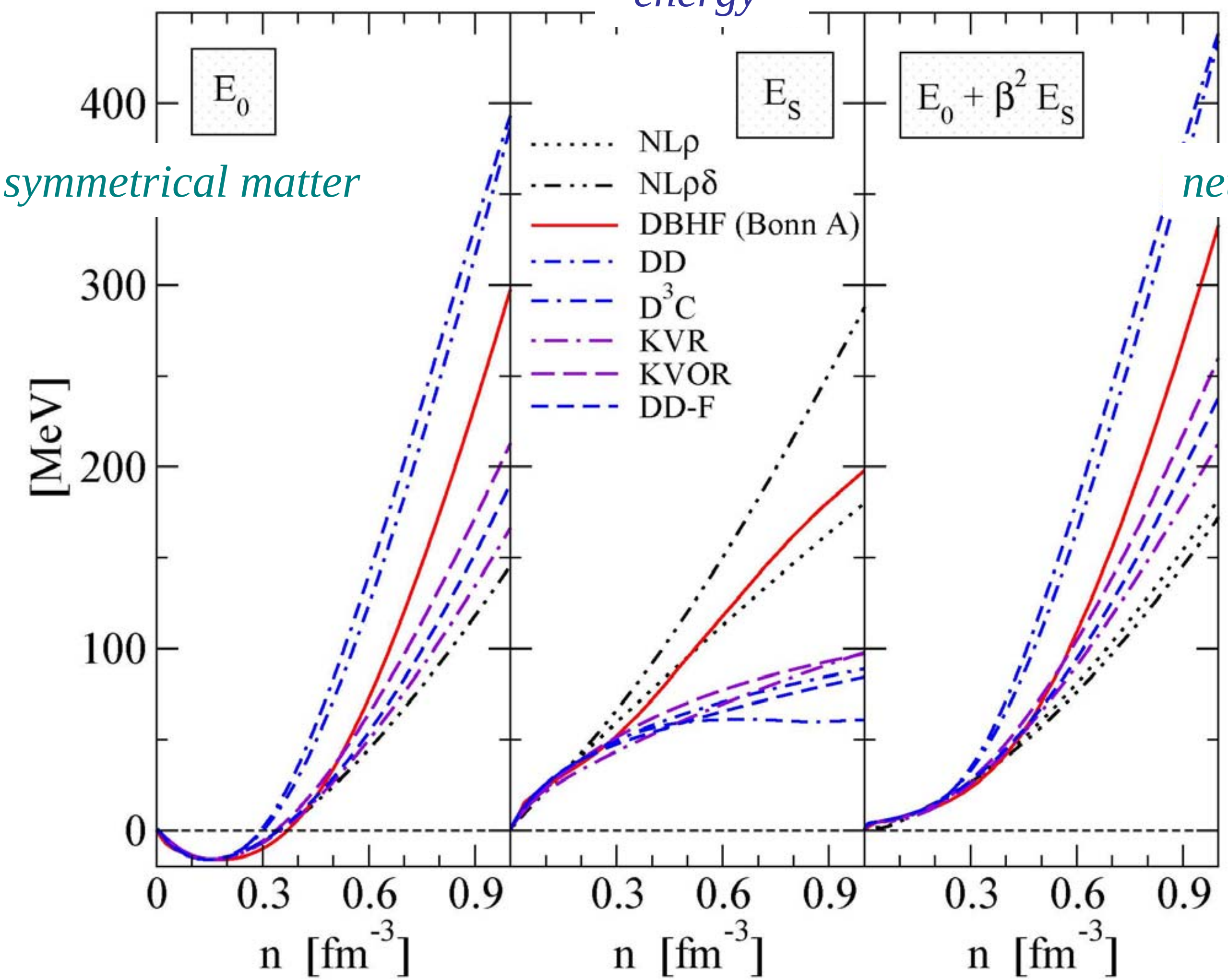
within empirical range

surface in atomic nuclei

symmetry energy

isospin symmetrical matter

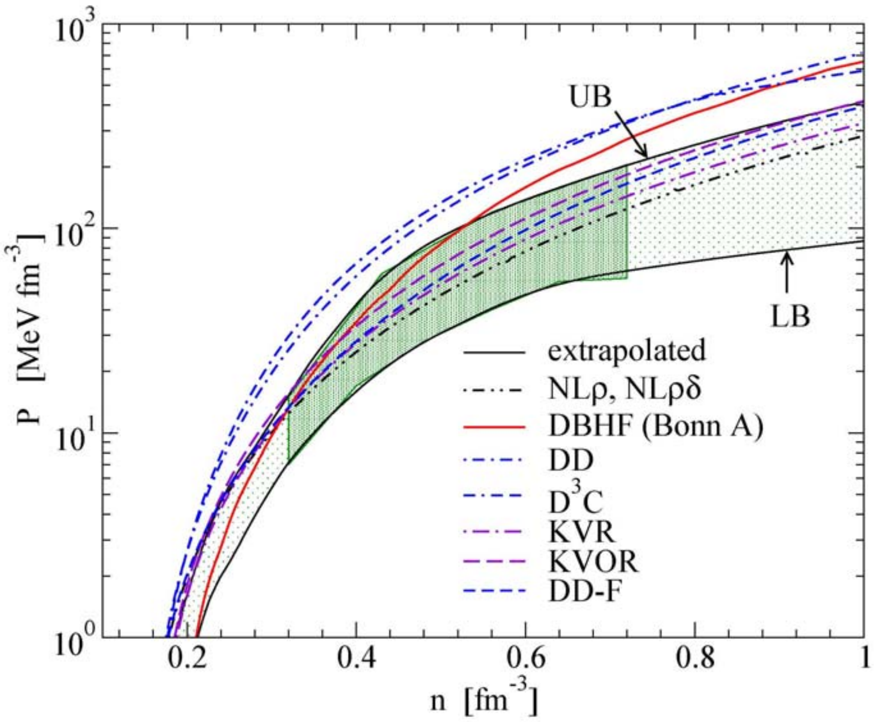
neutron matter

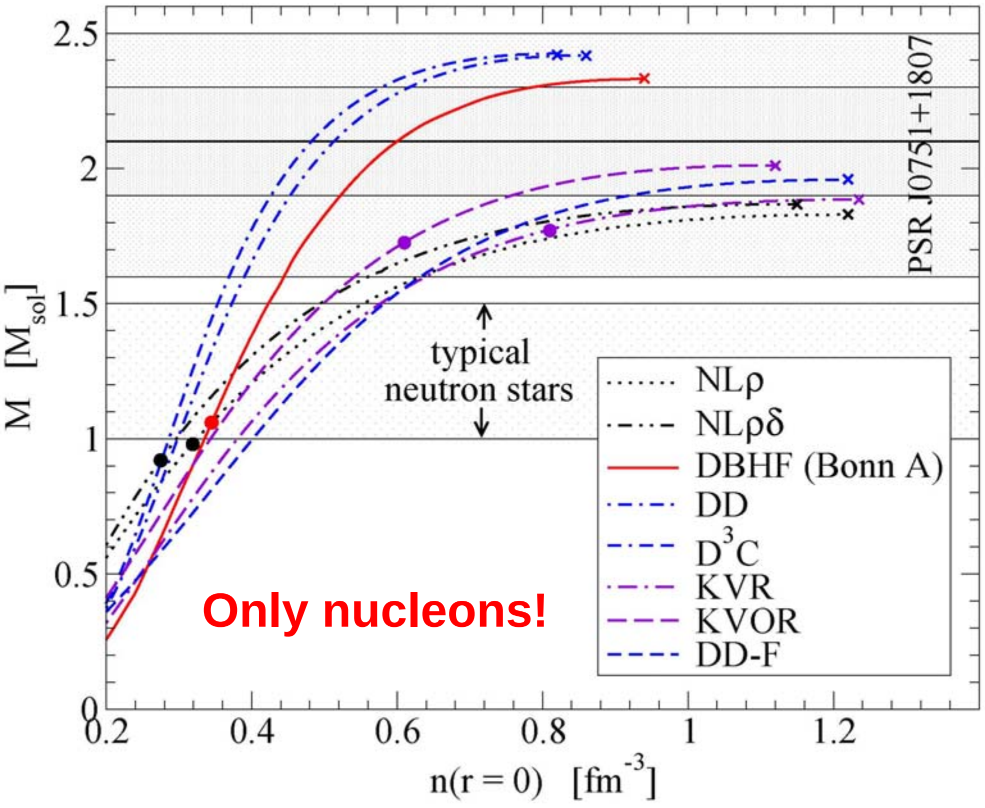


[Klaehn et al., PRC 74 (2006) 035802.]

✔ constraints from heavy-ion collisions

✔ maximum mass constraints



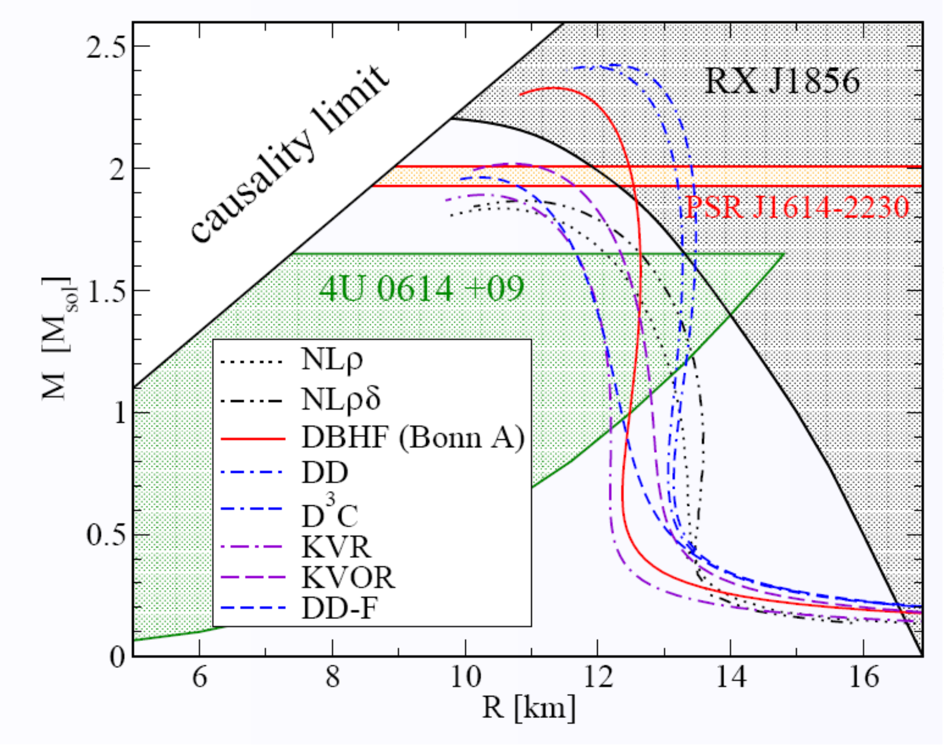


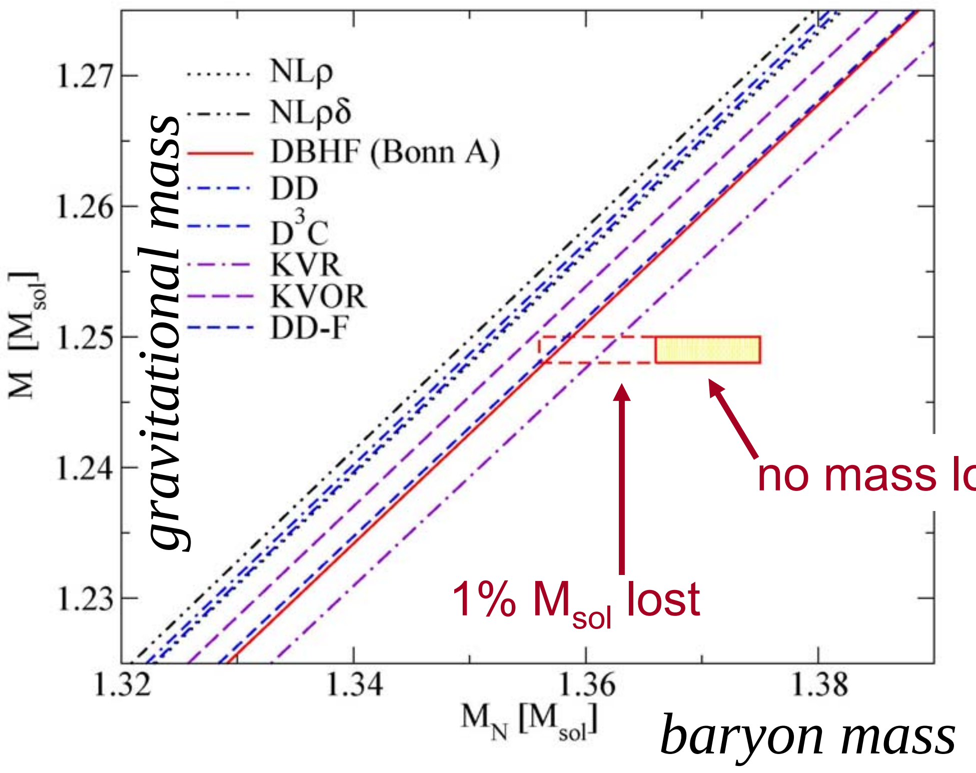
***Dots** indicate star masses and corresponding central densities, at which direct Urca reaction starts.*

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

✔ **maximal NS mass constraint**

✔ **baryon vs. gravitational mass**





$$M_N = 4\pi\, m_N \int_0^R \frac{\mathrm{d}r r^2\, n(r)}{\sqrt{1 - 2G\, m(r)/r}}$$

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

Making RMF EoS flexible

- **Non-linear Walecka model:**
  Play with a scalar-field potential

- **Scaling of meson masses and coupling constants**

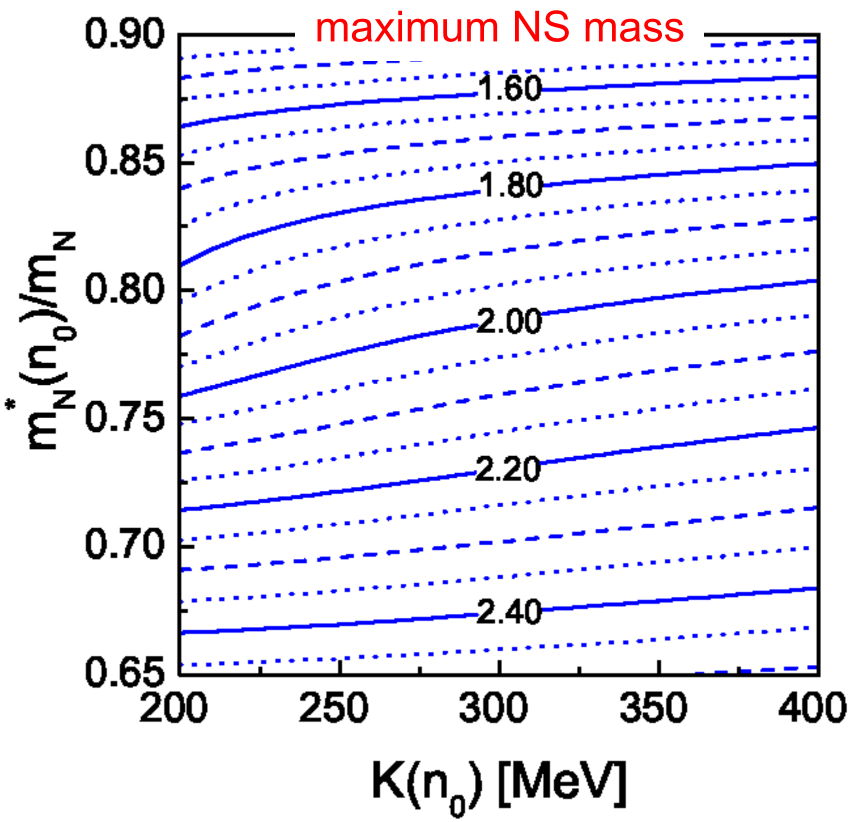
The standard non-linear Walecka (NLW) model

$$\mathcal{L} = \overline{\Psi}_N \left[\left(i\,\partial_\mu - g_\omega \omega_\mu - g_\rho \boldsymbol{t} \boldsymbol{\rho}_\mu \right) \gamma^\mu - m_N + g_\sigma \sigma \right] \Psi_N$$ *nucleons*

$$+ \tfrac{1}{2}[(\partial_\mu \sigma)^2 - m_\sigma^2 \sigma^2] - U(\sigma)$$ *scalar field*

$$- \tfrac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \tfrac{1}{2} m_\omega^2 \omega_\mu^2 - \tfrac{1}{4}\boldsymbol{\rho}_{\mu\nu}\boldsymbol{\rho}^{\mu\nu} + \tfrac{1}{2} m_\omega^2 (\boldsymbol{\rho}_\mu)^2$$ *vector fields*

$$U(\sigma) = \tfrac{b}{3} m_N (g_{\sigma N}\sigma)^3 + \tfrac{c}{4}(g_{\sigma N}\sigma)^4$$



Input parameters

$$n_0 = 0.16\,\mathrm{fm}^{-3},\ \mathcal{E}_0 = -16\,\mathrm{MeV},\ K = 250\,\mathrm{MeV}$$

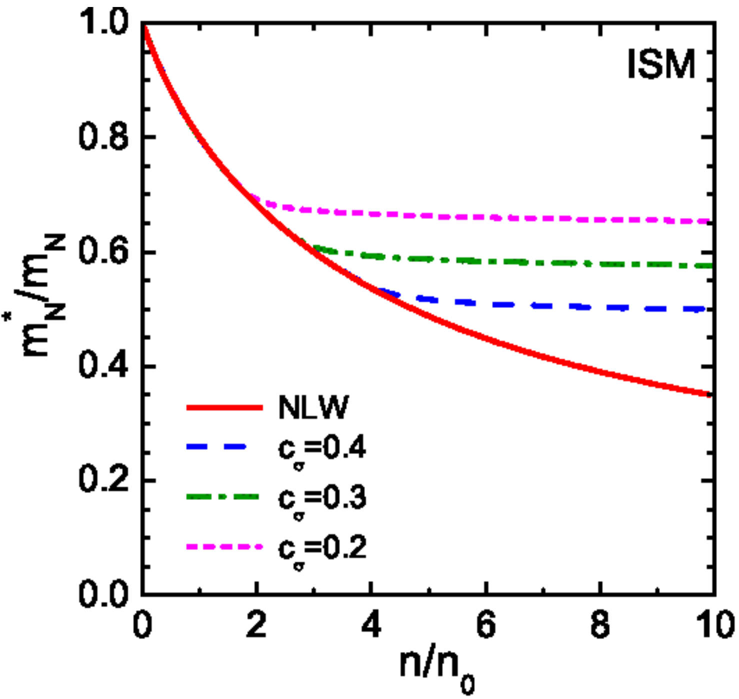
$$\mathcal{E}_{\rm sym} = 30\,\mathrm{MeV},\ m_N^*(n_0)/m_N = 0.8$$

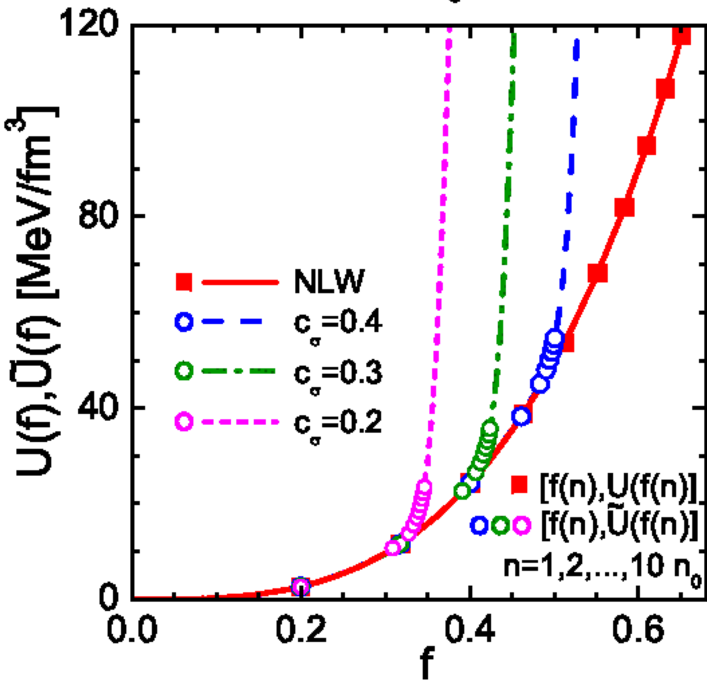
$$\Longrightarrow M_{\rm max} = 1.92\,M_\odot$$

For better description of atomic nuclei one Includes no-linear terms $\omega_\mu^4,\ \omega_\mu^2 \boldsymbol{\rho}_\nu^2$

→ softening of EoS and M_{max} reduction

Maximum mass strongly depends on $m^*_N(n_0)$ and weakly on K.





K.A. Maslov et al., PRD92 (2015) 052801(R)

If we modify the scalar potential $\widetilde{U}(\sigma) = U(\sigma) + \Delta U(\sigma)$ so that the $m^*_N(n)$ levels off then the EoS stiffens

$$\frac{\mathrm{d}f}{\mathrm{d}n} = \frac{2(\partial n_{\mathrm{S}}/\partial n)}{m_N^3 C_\sigma^{-2} + \widetilde{U}''(f)/m_N - 2(\partial n_{\mathrm{S}}/\partial f)}$$

$$f = g_\sigma \sigma / m_N \qquad n_S - \text{scalar density}$$

$$\frac{\partial n_{\mathrm{S}}}{\partial n} = \frac{m_N^*}{2\sqrt{p_{\mathrm{F}}^2 + m_N^{*2}}} \qquad -\frac{\partial n_S}{\partial f} = \int_0^{p_{\mathrm{F}}} \frac{m_N p^4 \mathrm{d}p/\pi^2}{(p^2 + m_N^{*2})^{3/2}}$$

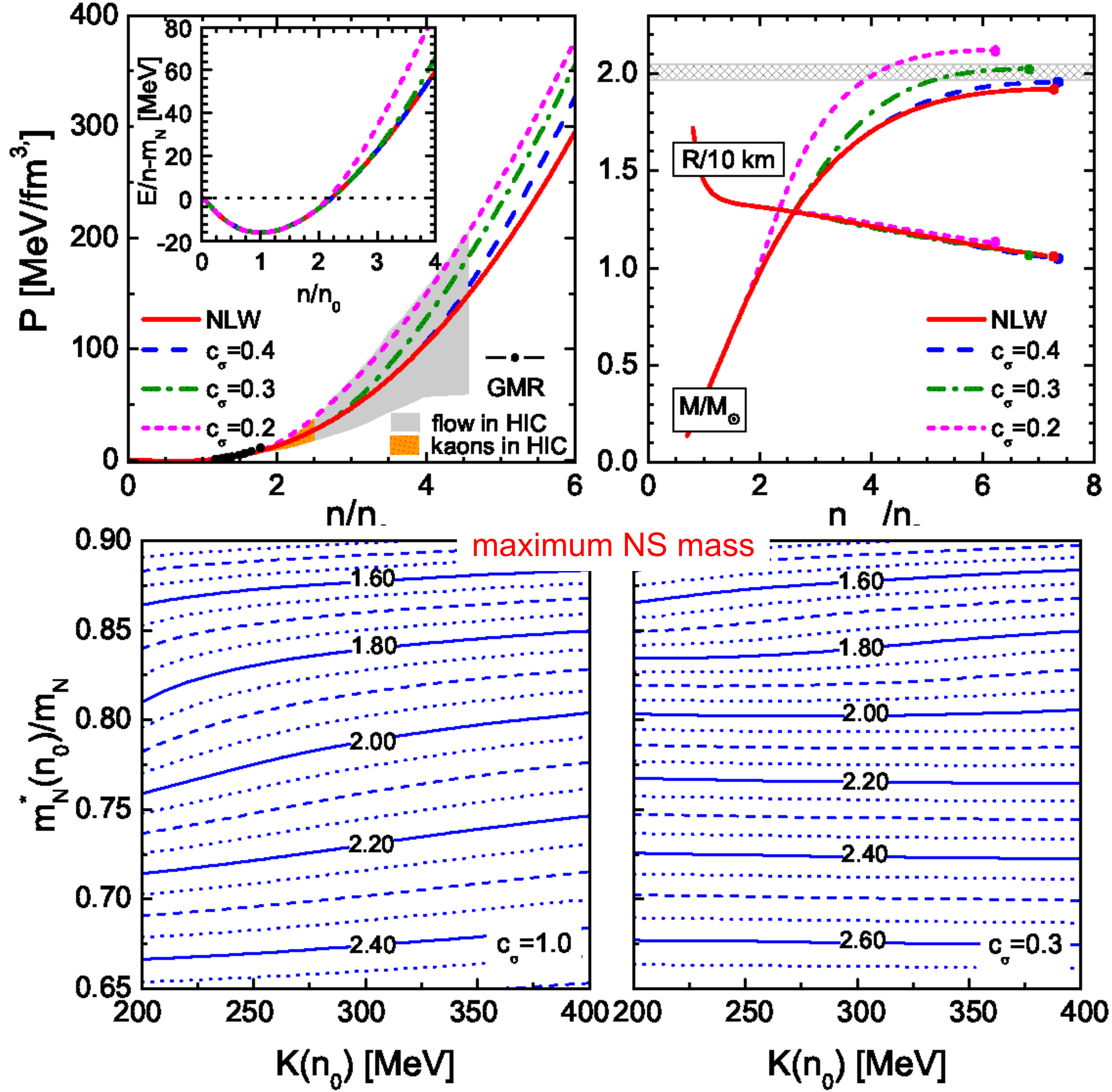
NLWcut model

soft core: $\Delta U(f) = \alpha \ln[1 + \exp(\beta(f - f_{\mathrm{s.core}}))]$

hard core: $\Delta U(f) = \alpha \left[\delta f / (f_{\mathrm{h.core}} - f)\right]^{2\beta}$

$$f_{\mathrm{s.core}} = f_0 + c_\sigma (1 - f_0)$$

$$m_N^*(n_0) = m_N\,(1 - f_0)$$


P [MeV/fm^3]
n/n$_0$
E/n-m$_N$ [MeV]
NLW
c_σ=0.4
c_σ=0.3
c_σ=0.2
GMR
flow in HIC
kaons in HIC
R/10 km
M/M$_\odot$
n$_{max}$/n$_0$
maximum NS mass
$m^*_N(n_0)/m_N$
K(n$_0$) [MeV]
1.60
1.80
2.00
2.20
2.40
2.60
c_σ=1.0
c_σ=0.3

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??

- Song, Brown, Min, Rho (1997) $m^*_\sigma/m_\sigma \approx m^*_\omega/m_\omega \approx m^*_\rho/m_\rho = \Phi(n)$

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

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

  results in *increase* of ρ an ω masses

- σ field dependent masses and couplings constant

→ **KVOR EoS** successfully tested in Klaehn at al., PRC74 (2006) 035802

Aim: Construct a better parameterization which satisfies new constraints on the nuclear EoS
Inclusion of hyperons. “Hyperon puzzle”.
Increase of hyperon-hyperon repulsion due to phi-meson exchange (phi-mass reduction)

Generalized RMF Model

Nucleon and meson Lagrangians

$$\mathcal{L}_N = \bar{\Psi}_N \left(i\, D \cdot \gamma \right) \Psi_N - m_N \, \Phi_N \, \bar{\Psi}_N \, \Psi_N \, ,$$

$$D_\mu = \partial_\mu + i\, g_\omega \, \chi_\omega \omega_\mu + \frac{i}{2} g_\rho \, \chi_\rho \, \boldsymbol{\rho}_\mu \, \boldsymbol{\tau} \, ,$$

$$\mathcal{L}_M = \frac{\partial^\mu \sigma \partial_\mu \sigma}{2} - \Phi_\sigma^2 \frac{m_\sigma^2 \, \sigma^2}{2} - U(\sigma)$$

$$-\frac{\omega_{\mu\nu} \, \omega^{\mu\nu}}{4} + \Phi_\omega^2 \, \frac{m_\omega^2 \, \omega_\mu \omega^\mu}{2} - \frac{\boldsymbol{\rho}_{\mu\nu} \, \boldsymbol{\rho}^{\mu\nu}}{4} + \Phi_\rho^2 \, \frac{m_\rho^2 \, \boldsymbol{\rho}_\mu \boldsymbol{\rho}^\mu}{2} \, ,$$

$$\omega_{\mu\nu} = \partial_\nu \omega_\mu - \partial_\mu \omega_\nu \, , \quad \boldsymbol{\rho}_{\mu\nu} = \partial_\nu \boldsymbol{\rho}_\mu - \partial_\mu \boldsymbol{\rho}_\nu + g_\rho' \, \chi_\rho' \, [\boldsymbol{\rho}_\mu \times \boldsymbol{\rho}_\nu] \, ,$$

effective masses: $m_i^* / m_i = \Phi_i(\chi_\sigma \sigma)$

Energy-density functional

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

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

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

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

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

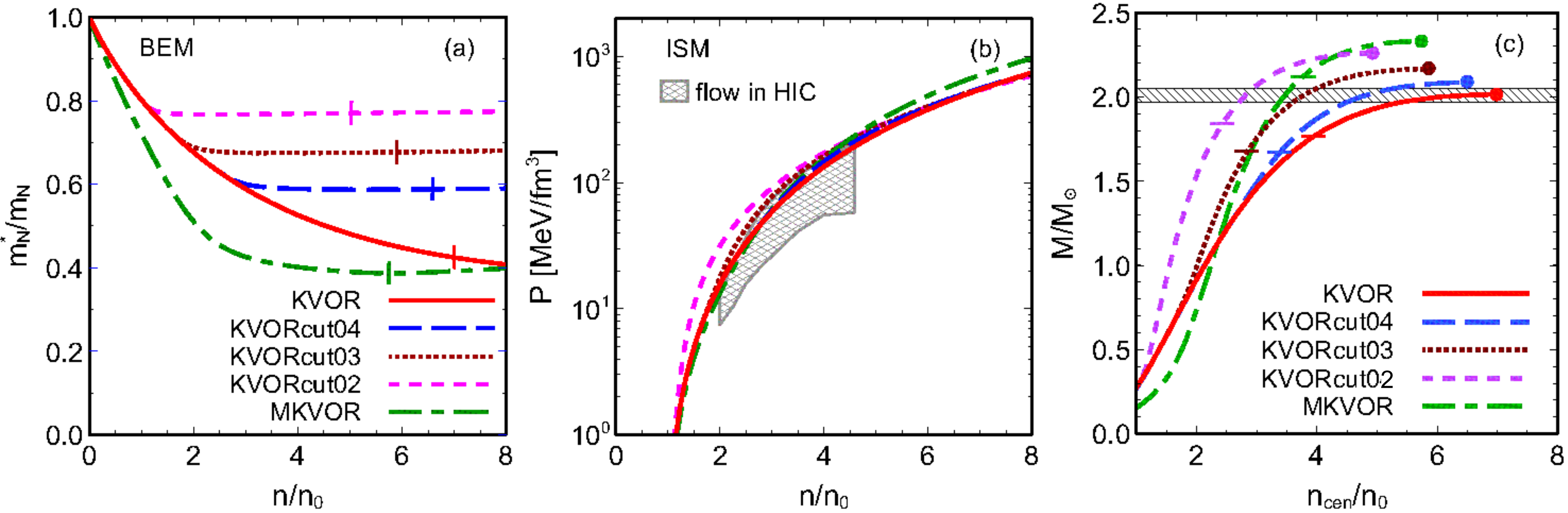
$$\eta_i(f) = \frac{\Phi_i^2(f)}{\chi_i^2(f)}, \quad i = \sigma\,,\, \omega\,,\, \rho$$

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

KVORcut model

Apply cut-scheme to η_ω function

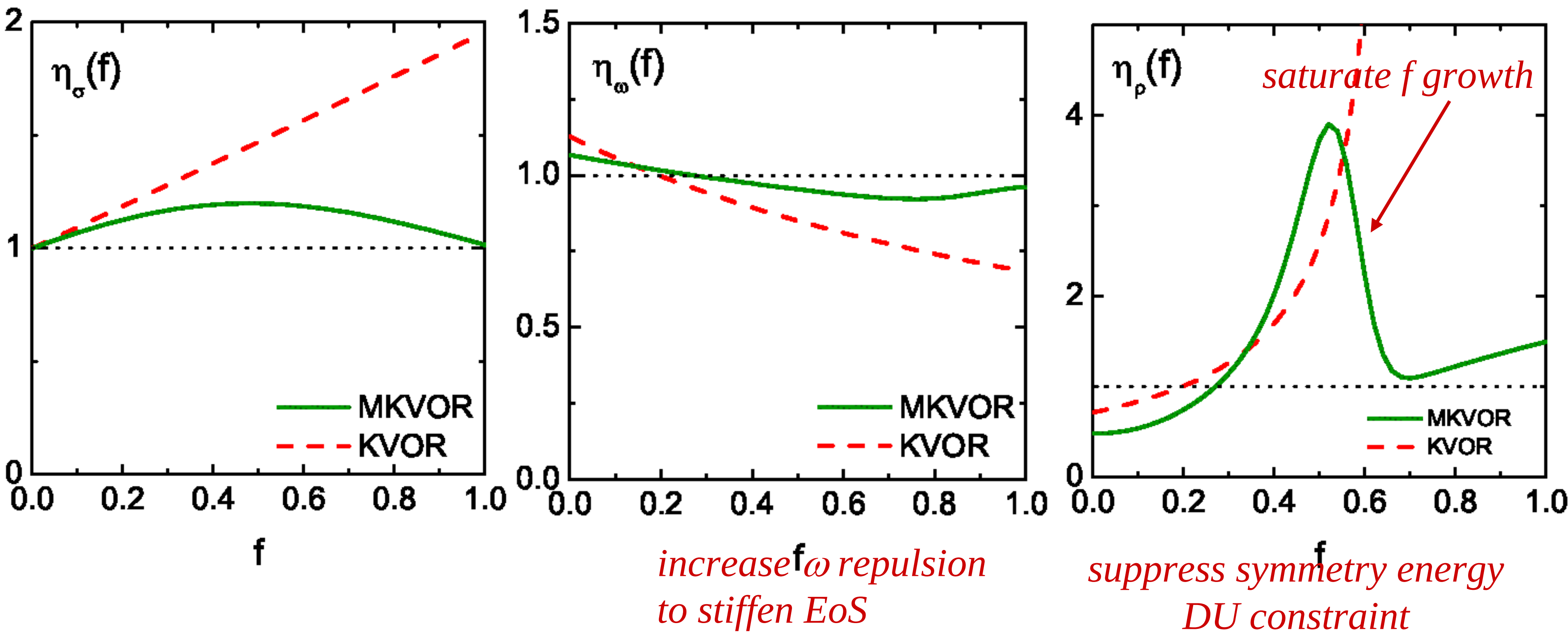
$$\eta_\omega^{\mathrm{KVOR}}(f) \to \eta_\omega^{\mathrm{KVOR}}(f) + \frac{a_\omega}{2}\left[1 + \tanh(b_\omega(f - f_{\mathrm{cut},\omega}))\right]$$



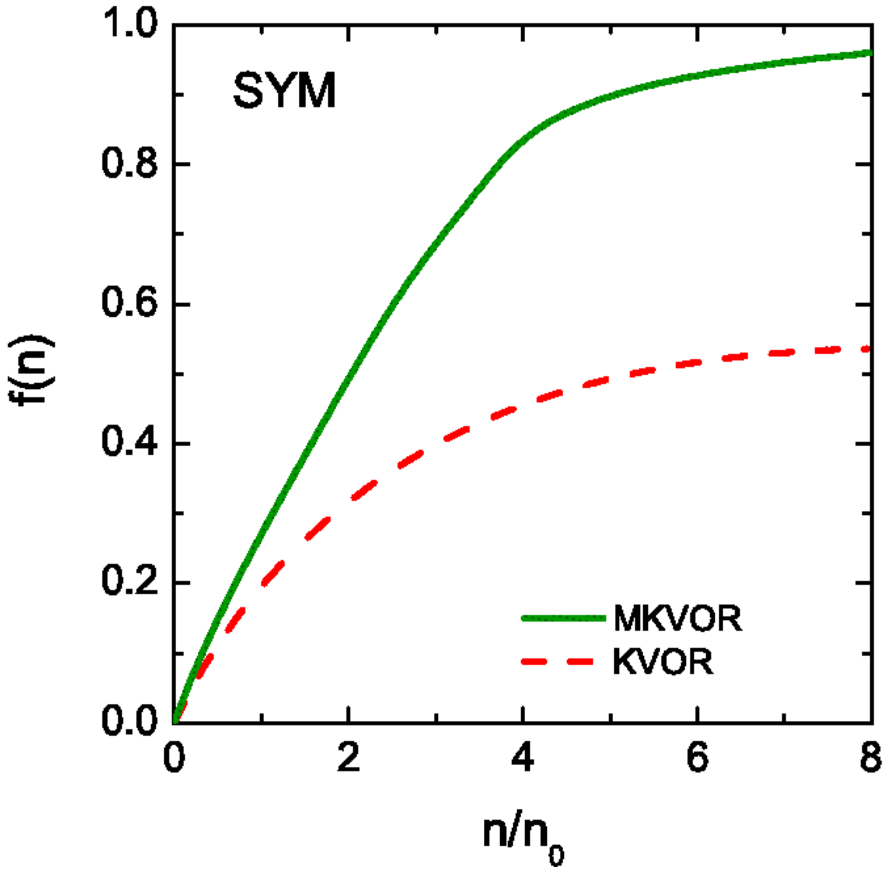
C_σ^2, C_ω^2, C_ρ^2 and parameters of η_σ are fitted to reproduce

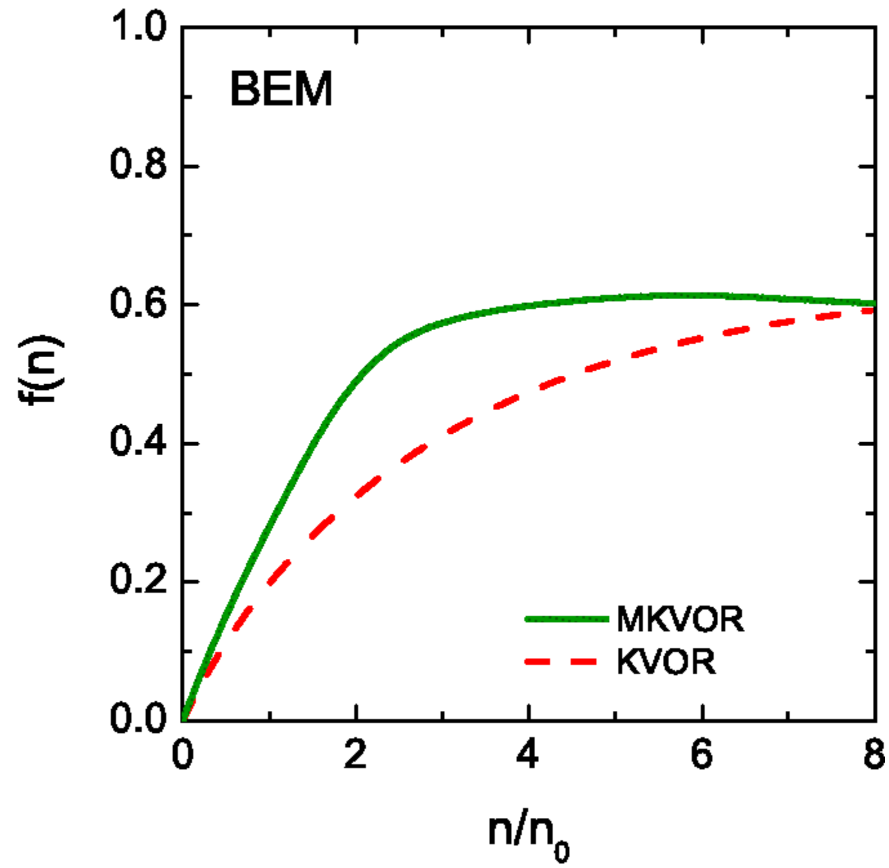
EoS	$\mathcal{E}_0$ [MeV]	n_0 [fm^{-3}]	K [MeV]	$m_N^*(n_0)$ [m_N]	$\widetilde{J}_0$ [MeV]	L [MeV]	K' [MeV]	K_{sym} [MeV]
KVOR	-16	0.16	275	0.805	32	71	423	-85
MKVOR	-16	0.16	240	0.73	30	41	557	-159

scaling functions for coupling constants vs scalar field:

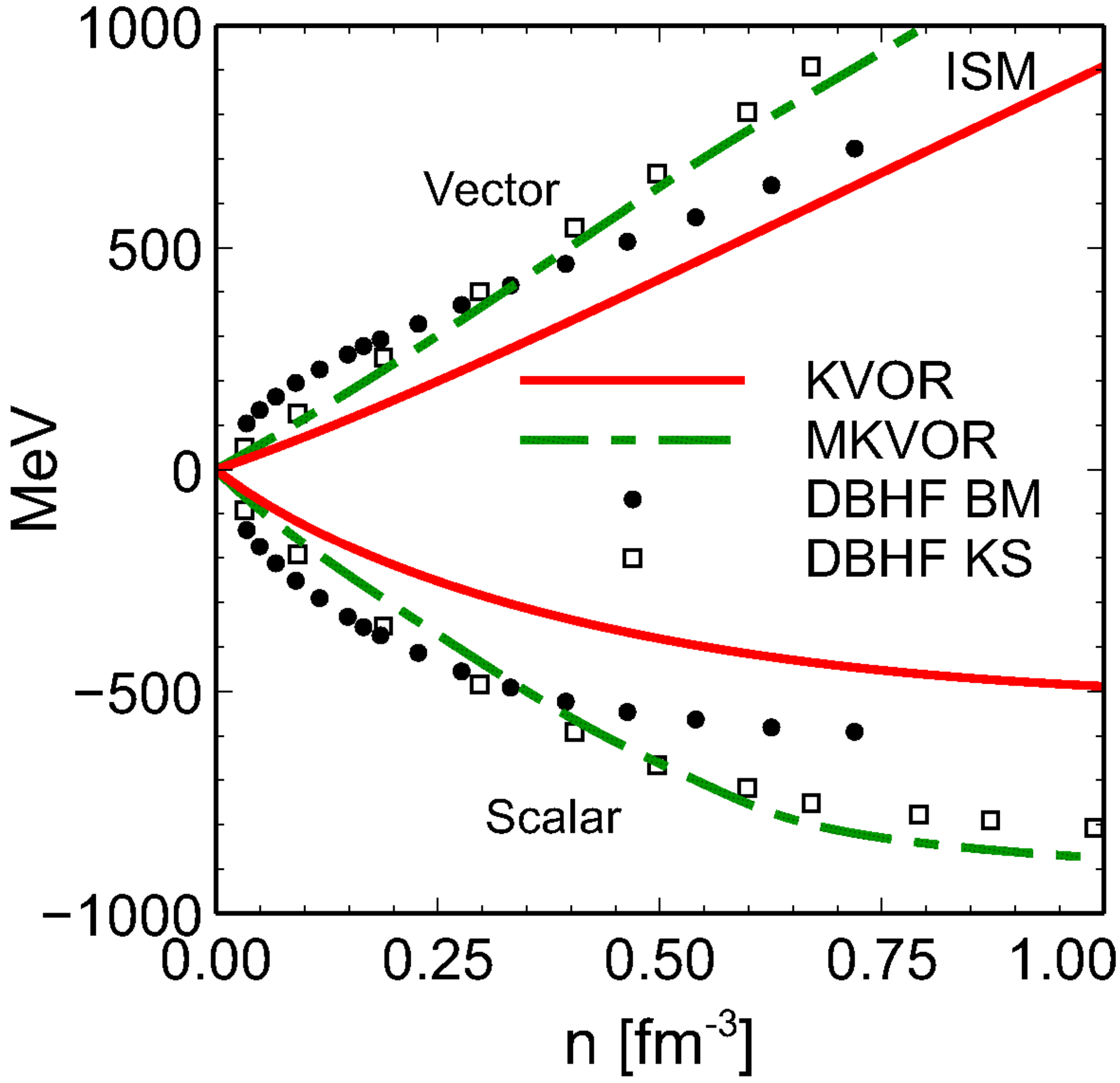


Scalar field in dense matter





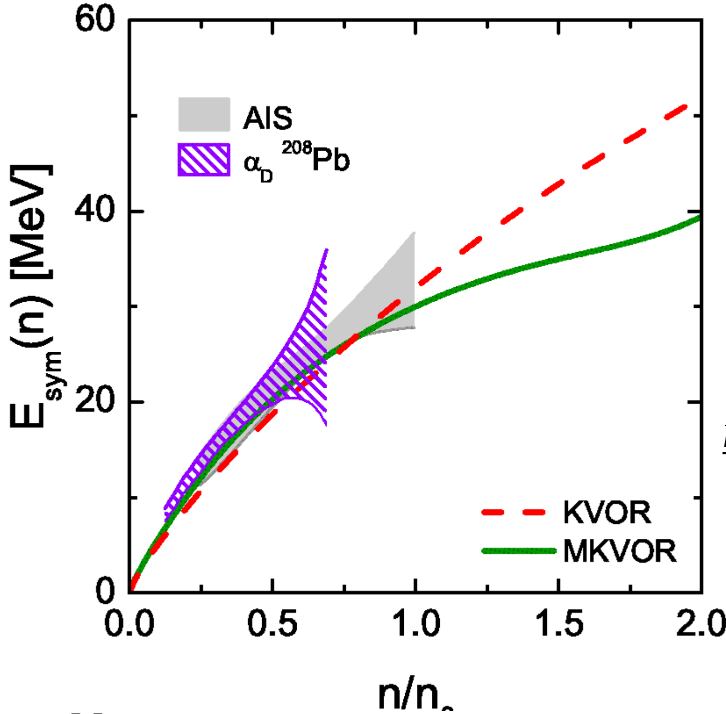
Scalar and vector potentials in KVOR and MKVOR models vs. DBHF calculations



BM: Brockmann – Machleidt
PRC42 (1990)

KS: Katayama-Saito
PRC88 (2013)

Neutron matter EoS



<u>*empirical constraints on symmetry energy*</u>

-- (AIS) analog isobar states

[Danielewicz, Lee NPA 922 (2014) 1]

-- α_D electric dipole polarizability ^{208}Pb

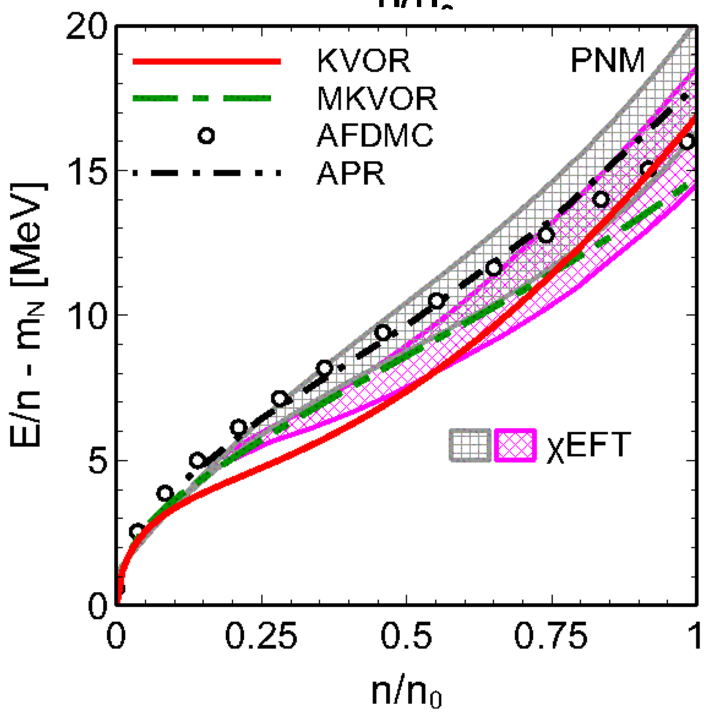
[Zhang, Chen 1504.01077]

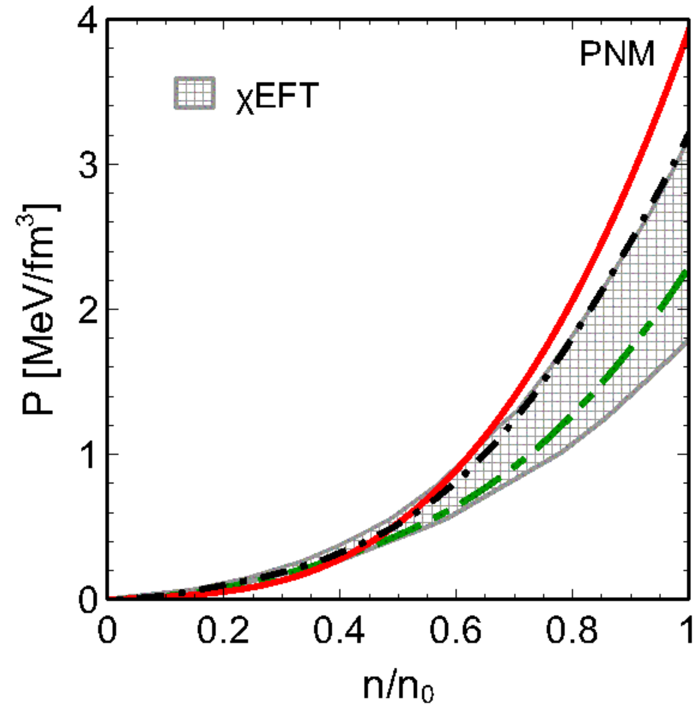
<u>*microscopic calculations*</u>

-- (APR) Akmal, Pandharipande, Ravenhall

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

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

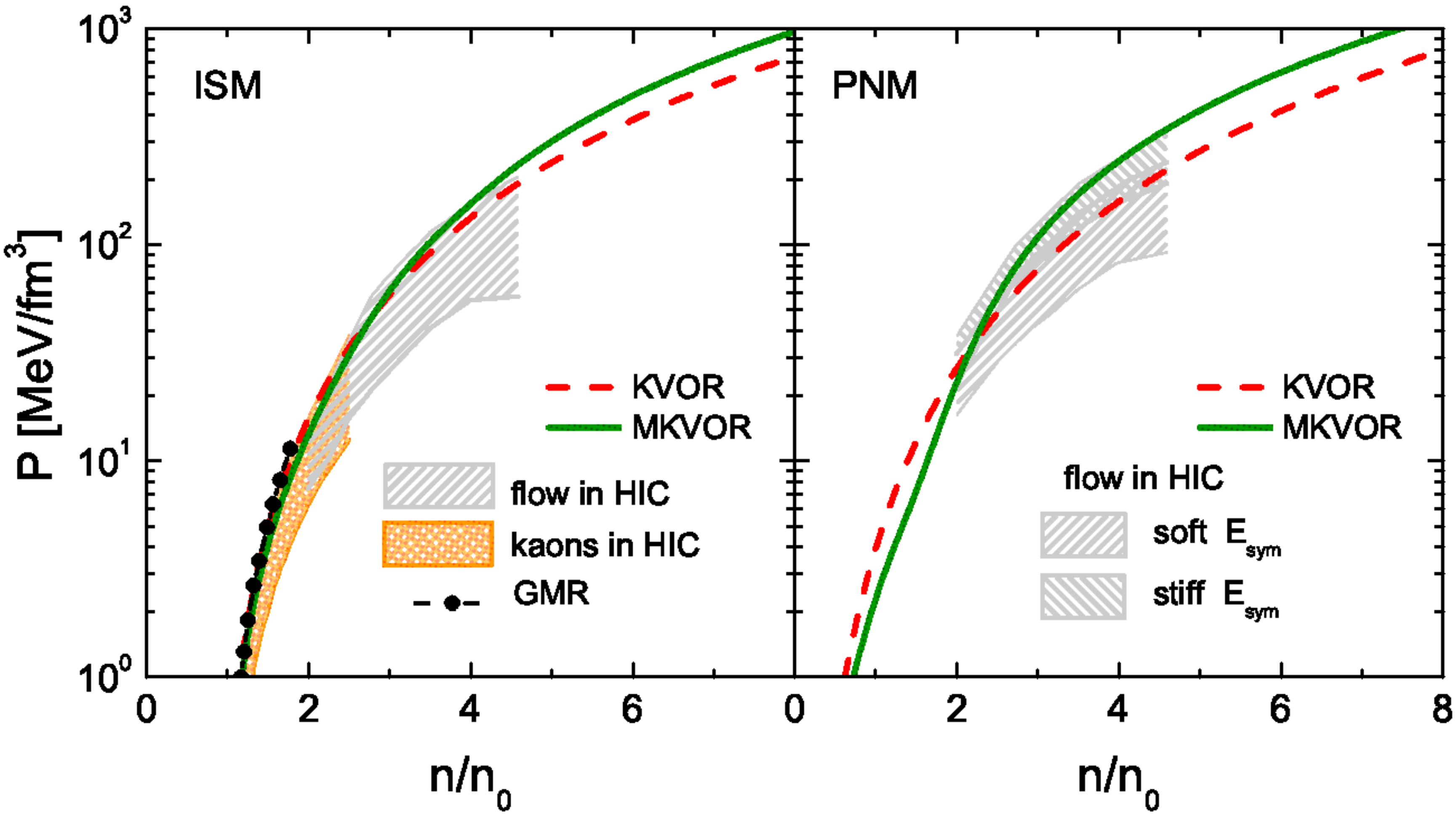




Constraints on EoS from HICs

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

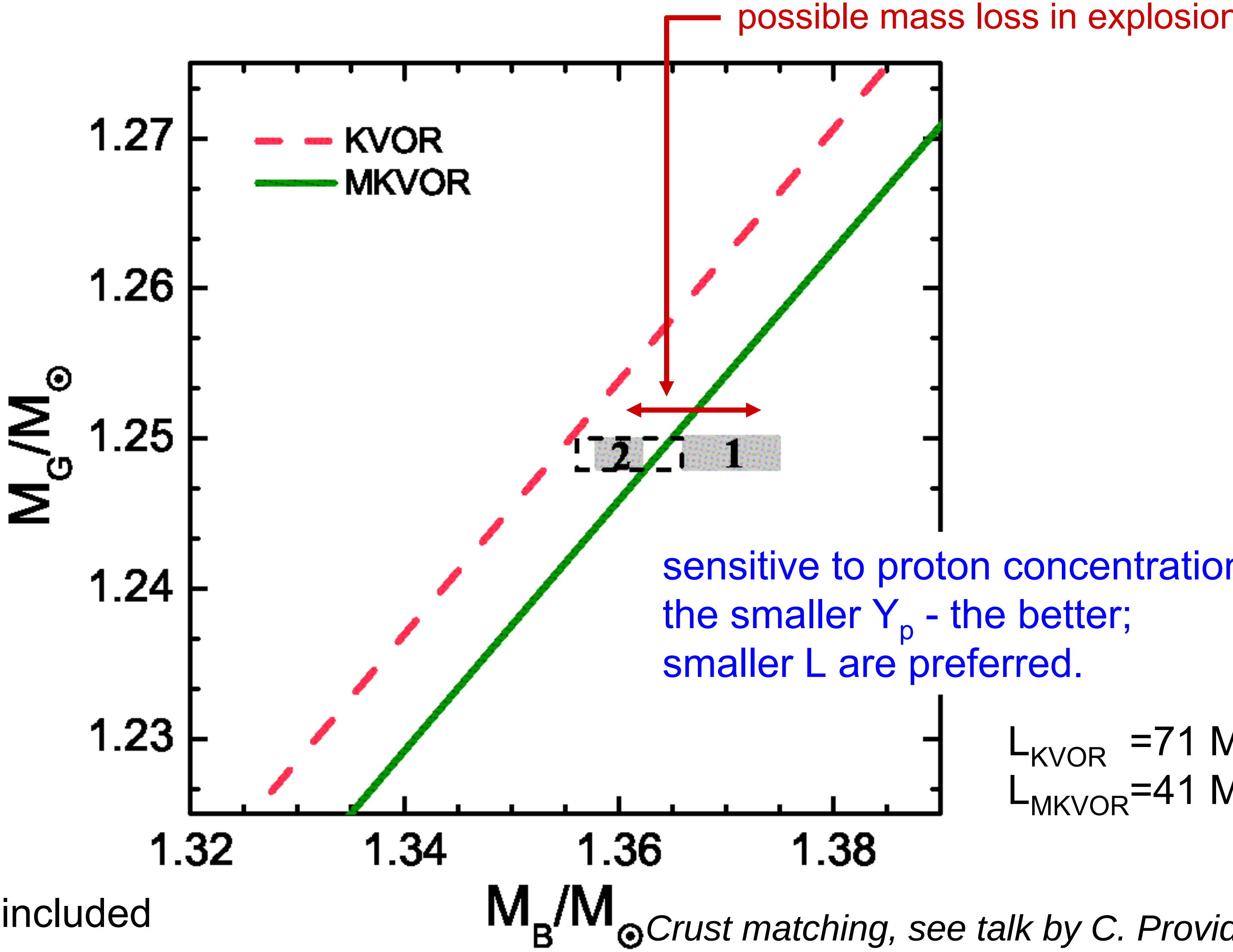
Kaon production: Fuchs, Prog. Part. Nucl. Phys. 56 (2006) 1



Gravitational vs baryon mass of PSR J0737-3039(B)

PSR J0737-3039(B): double pulsar system

1. Podsiadlowski et al., MNRAS 361 (2005) 1243
2. Kitaura et al., A&A 450 (2006) 345

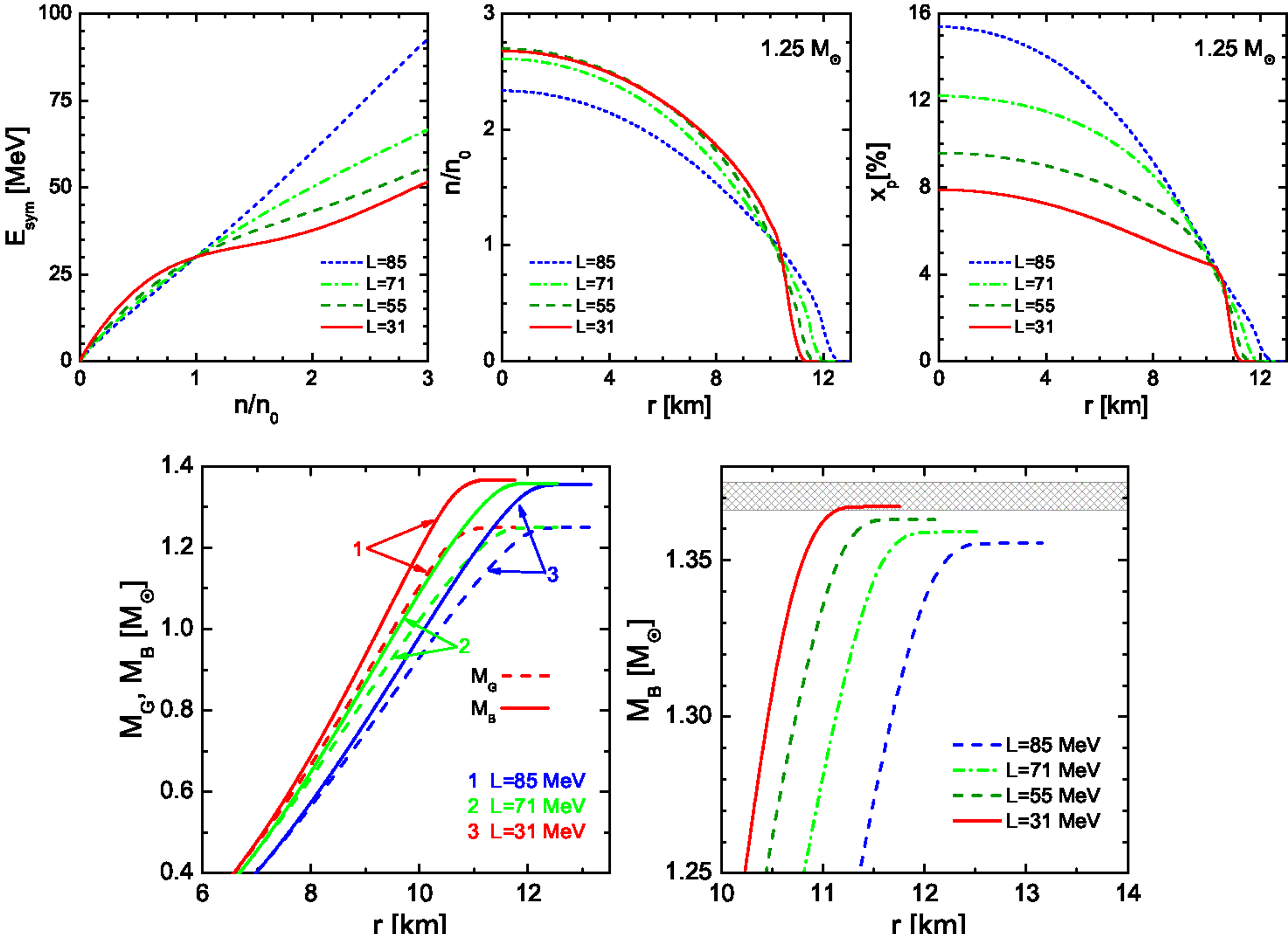


sensitive to proton concentration Y_p
the smaller Y_p - the better;
smaller L are preferred.

L_{KVOR} =71 MeV
L_{MKVOR}=41 MeV

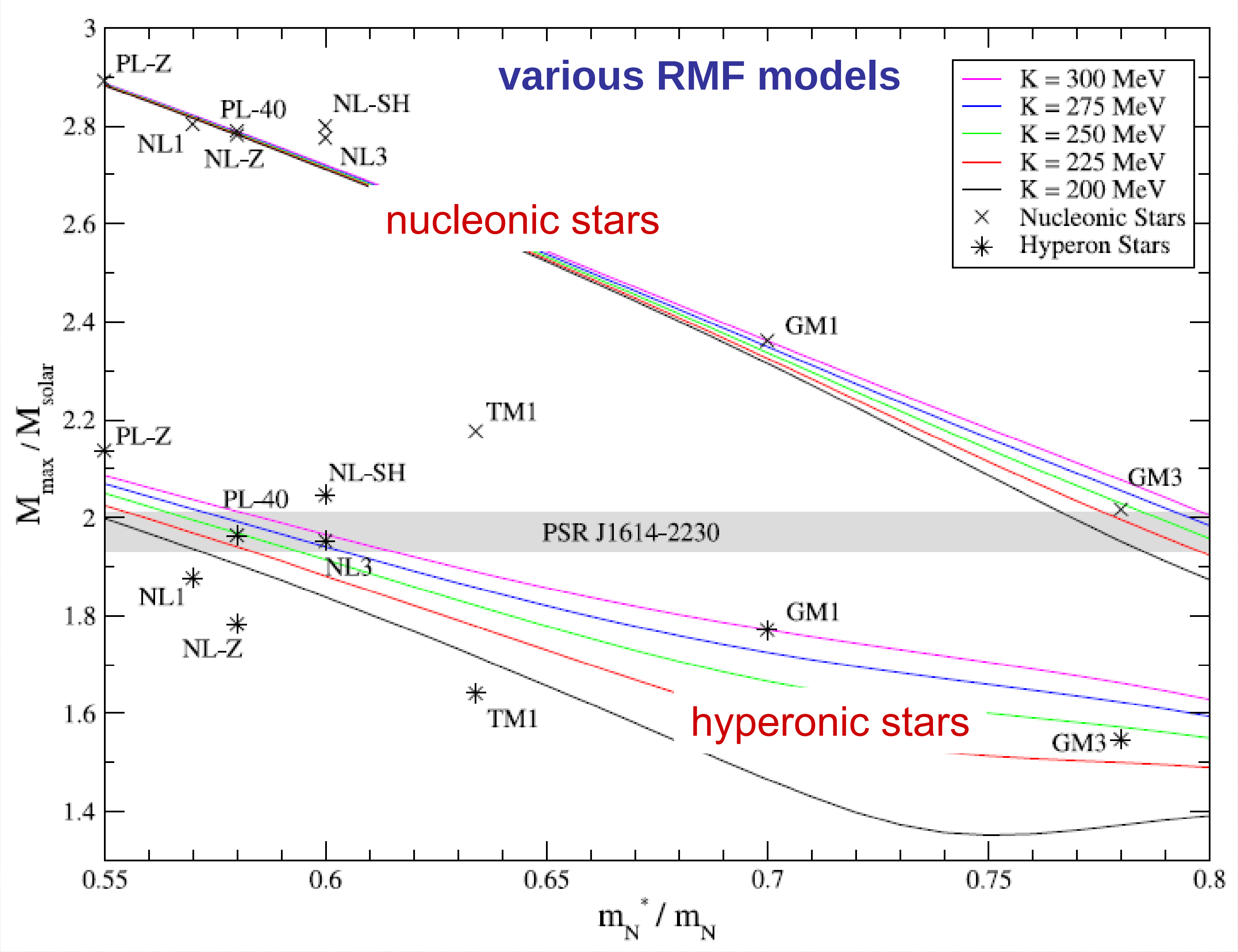
BPS crust is included

Crust matching, see talk by C. Providencia



E_sym [MeV]
n/n_0
L=85
L=71
L=55
L=31
1.25 M_⊙
r [km]
x_p [%]
M_G, M_B [M_⊙]
M_G
M_B
1 L=85 MeV
2 L=71 MeV
3 L=31 MeV
M_B [M_⊙]
L=85 MeV
L=71 MeV
L=55 MeV
L=31 MeV

Hyperon puzzle



[Weissenborn et al., NPA 881 (2012) 62]

Inclusion of hyperons

1) standard. extension: **H**

Vector coupling constants from SU(6) symmetry:

$$g_{\omega\Lambda} = g_{\omega\Sigma} = 2g_{\omega\Xi} = \frac{2}{3} g_{\omega N}\,, \quad g_{\rho\Sigma} = 2g_{\rho\Xi} = 2g_{\rho N}\,,$$
$$2g_{\phi\Lambda} = 2g_{\phi\Sigma} = g_{\phi\Xi} = -\frac{2\sqrt{2}}{3} g_{\omega N}\,, \quad g_{\rho\Lambda} = g_{\phi N} = 0\,.$$

Scalar coupling constants from hyperon binding energies

data on hypernuclei

$$\mathcal{E}^{\Lambda}_{\rm bind}(n_0) = -28\,\mathrm{MeV}$$
$$\mathcal{E}^{\Sigma}_{\rm bind}(n_0) = +30\,\mathrm{MeV}$$
$$\mathcal{E}^{\Xi}_{\rm bind}(n_0) = -15\,\mathrm{MeV}$$

$$\mathcal{E}^{H}_{\rm bind}(n_0) = C^2_\omega m_N^{-2} x_{\omega H} n_0 - (m_N - m^*_N(n_0)) x_{\sigma H}$$

$$x_{\omega(\rho)B} = g_{\omega(\rho)B} / g_{\omega(\rho)N}$$

2) +phi mesons. extension: **Hϕ**

$$\Phi_\phi = 1 - f, \quad \chi_{\phi H} = 1 \qquad \eta_\phi = \frac{\Phi^2_\phi}{\chi^2_\phi} = (1-f)^2$$

Phi meson mediated repulsion among hyperons is enhanced

3) + hyperon-sigma couplings reduced. extension: **Hϕσ**

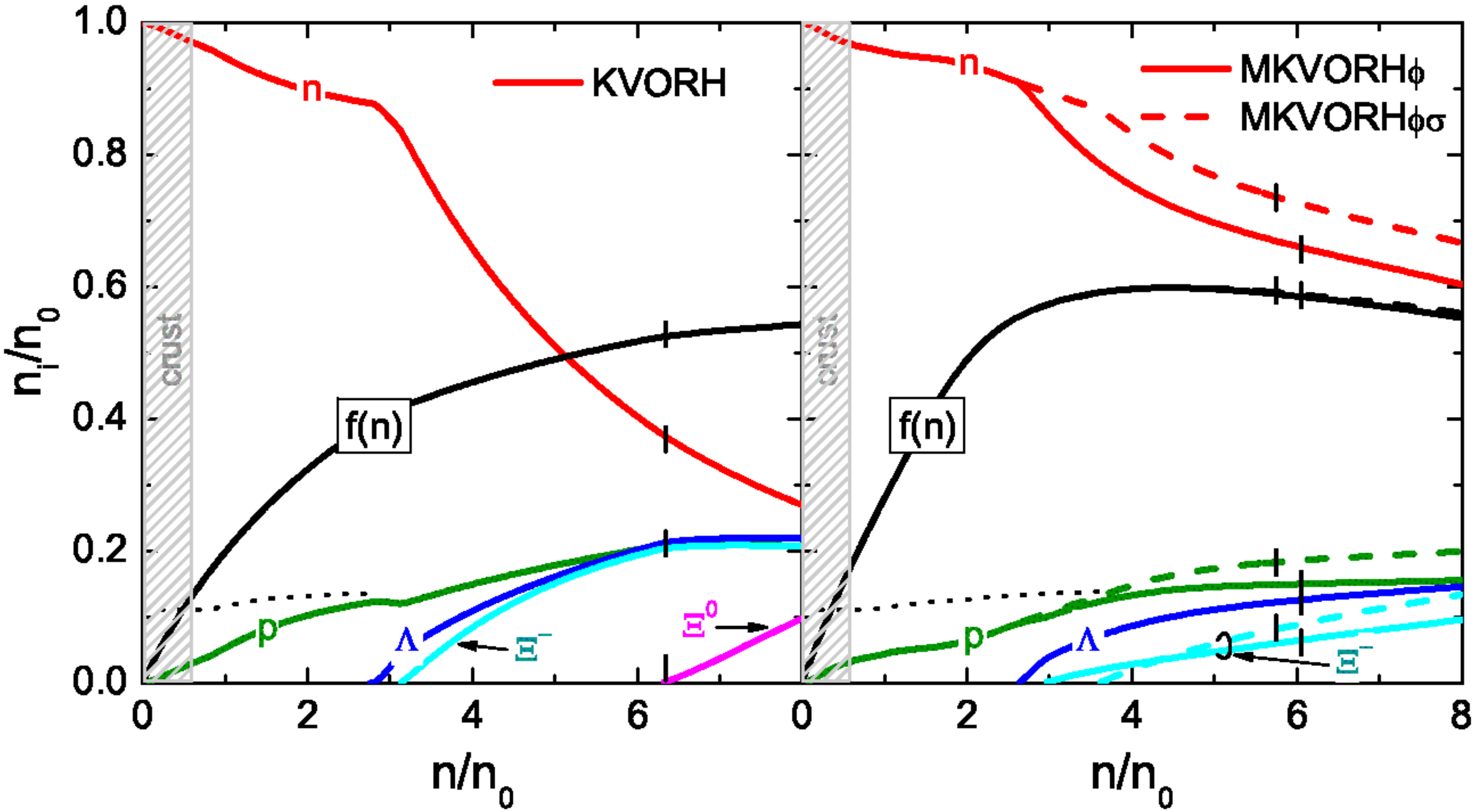
$$\Phi_H(f) = 1 - x_{\sigma H} \frac{m_N}{m_H} \xi_{\sigma H} f$$

$$\xi_{\sigma H}(n \le n_0) = 1 \quad \text{but} \quad \xi_{\sigma H}(n \gtrsim n_\Lambda) \to 0$$

QMC model: Guichon, Thomas

hyperon-nucleon mass gap grows with density

Strangeness concentration



KVORH: n_Λ=2.81n_0, M_Λ=1.37M_{sol},
n_Ξ=3.13n_0 M_Ξ=1.48 M_{sol}

KVOR: n_{DU}=3.96 M_{DU}=1.77 M_{sol}

MKVORHϕ: n_Λ=2.63n_0, M_Λ=1.43M_{sol},
n_Ξ=2.93n_0, M_Ξ=1.65M_{sol}

MKVORHϕσ: n_Ξ=3.61n_0, M_Ξ=2.07M_{sol}

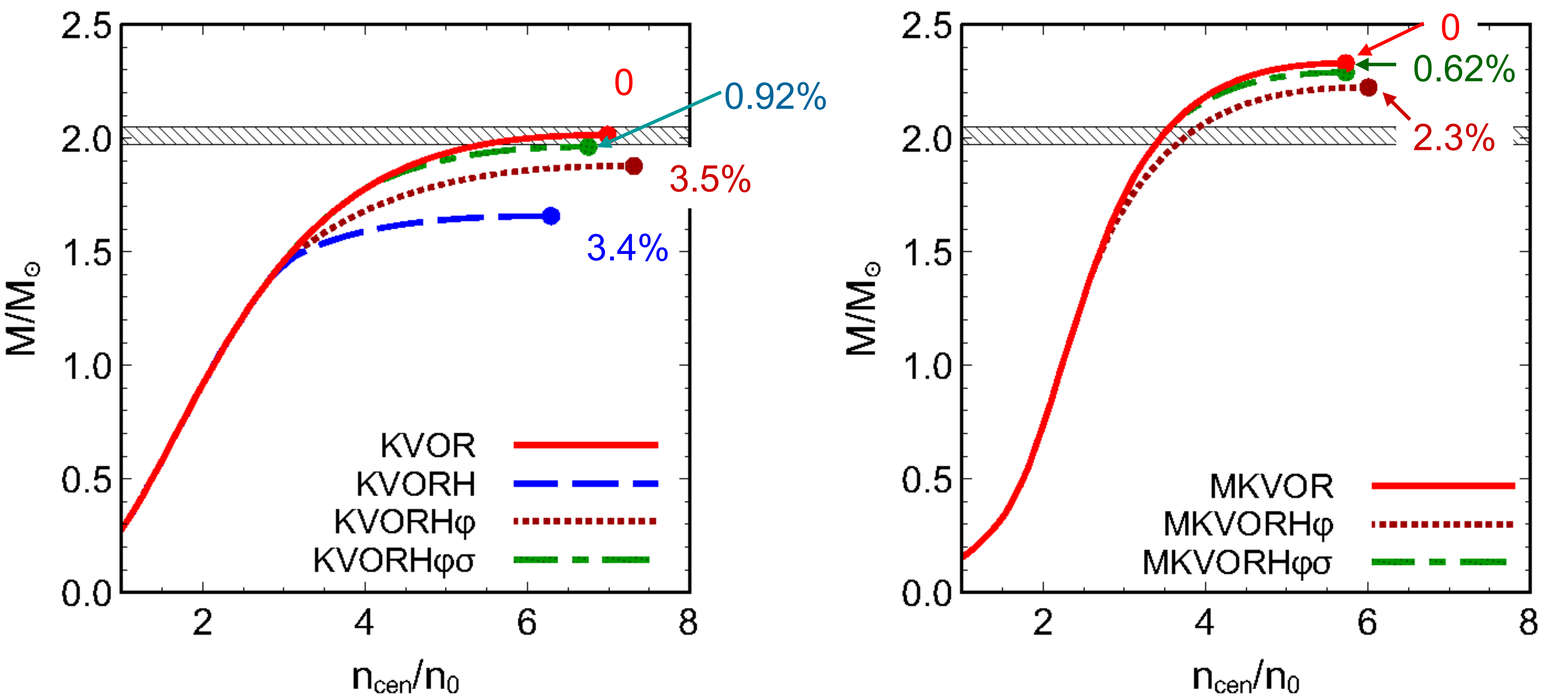
fulfill DU constraint

no Lambdas!

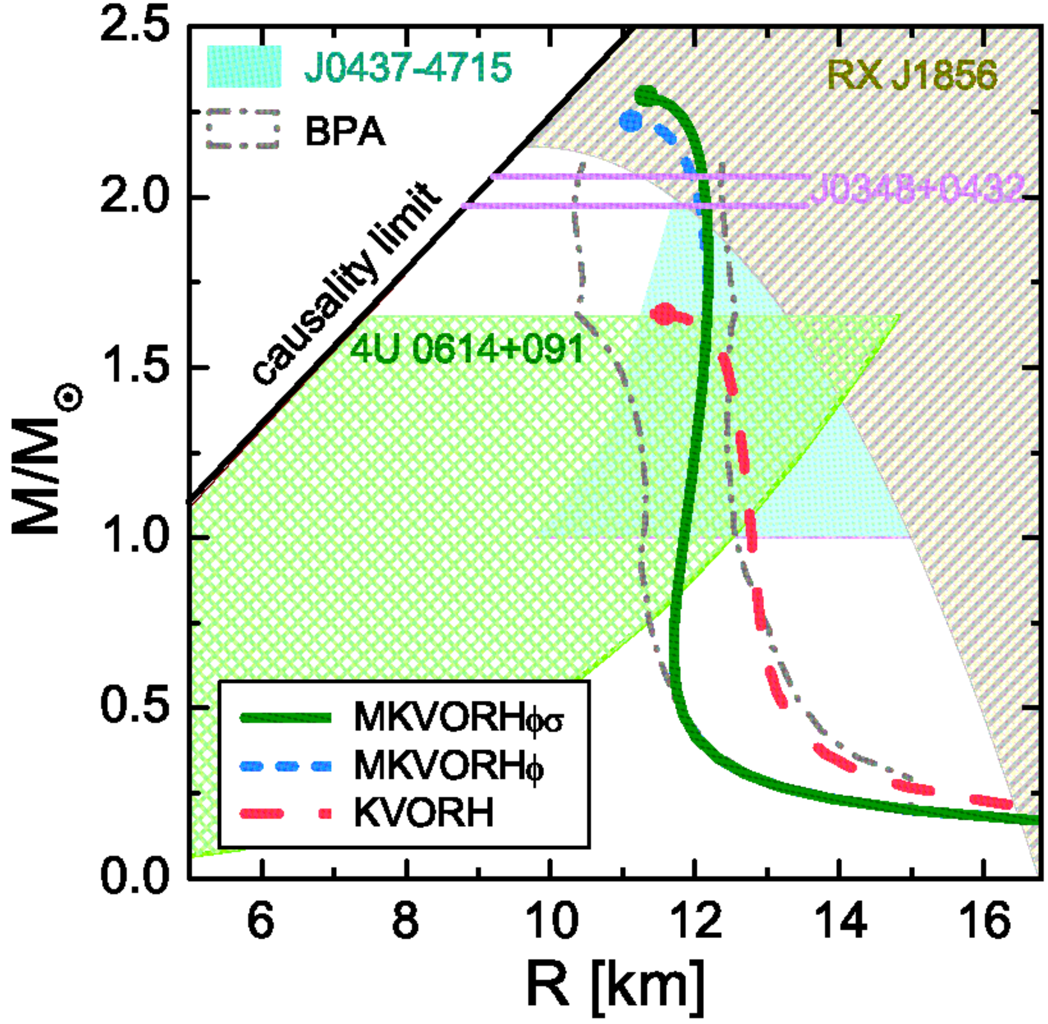
Maximum NS mass and the strangeness concentration

f_S –# strange quarks / # all quarks

Weissenborn, Chatterjee Schafner-Bielich



Mass-radius constraints



BPA: Bayesian probability analysis [Lattimer,Steiner …]

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

Compact stars do provide some constraints on the nuclear EoS

RMF model with with scaled meson masses and coupling constants

- ✓ **Universal scaling of hadron masses. Not universal scaling of coupling constants**

- ✓ **The model is flexible enough to satisfy many astrophysical constraints, constraints from HIC and microscopic calculations.**

- ✓ **Hyperon puzzle can be partially resolved if the reduction of phi meson mass is taken into account**