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Unified equations of state of dense matter : nuclear-matter properties and neutron-star structure

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"The Structure and Signals of Neutron Stars, from Birth to Death"
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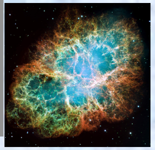
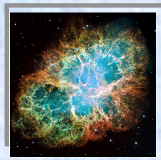


Outline

- Motivation
- Nuclear functionals **BSk****
  - some constraints from nuclear physics
- EoSs:
  - the model
  - NS properties and astrophysical observations
- Conclusions & Outlook



Motivations

- ***Unified*** EoS
  - → based on the same nuclear model from energy-density functional theory
  - → valid in all regions of NS interior
  - → outer / inner crust and crust / core transition described consistently

- EoS both at T = 0 → cold non-accreting NS

  and at finite T → SN cores, accreting NS

- Nuclear physics experiments
- Astrophysical constraints

- Direct applicable for astrophysical application (codes!)

EoS: the challenge

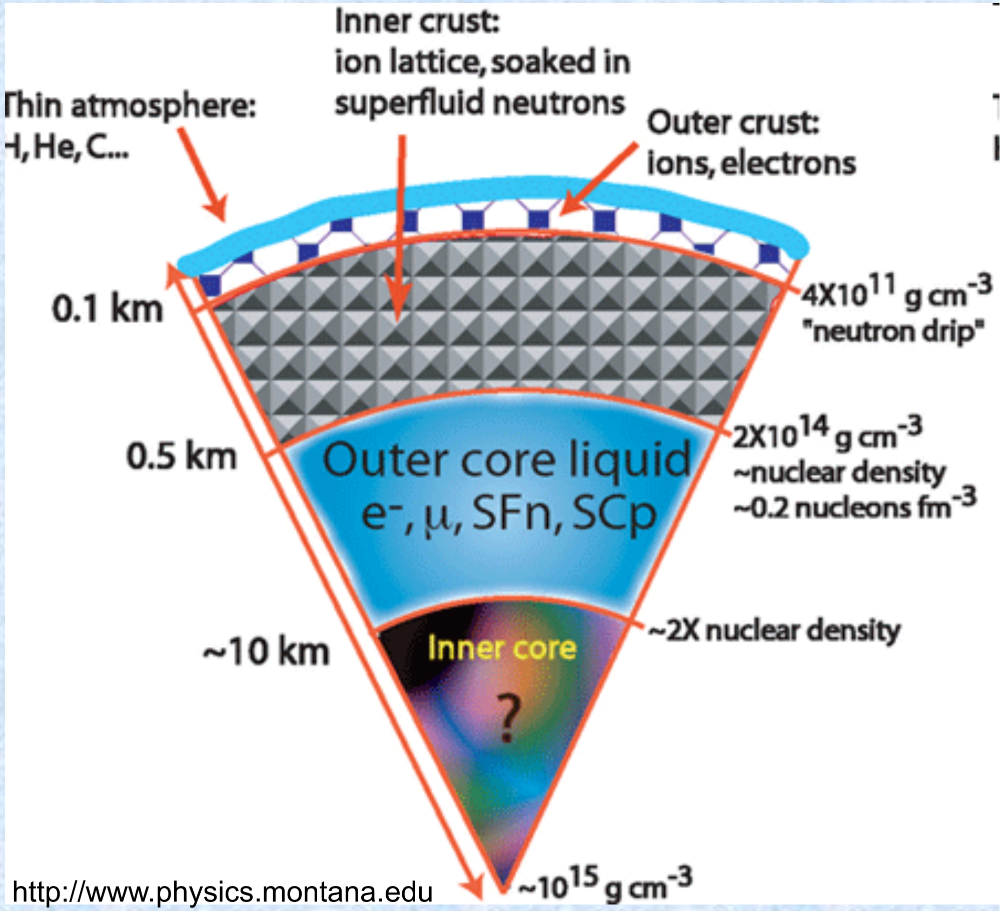
Wide range of ρ, T, Y_e in the core during core collapse and NS formation :

$$\begin{aligned} \rho &\in [10^5 - 10^{15}]\ \mathrm{g\ cm^{-3}} \\ T &\in [0.1 - 100]\ \mathrm{MeV} \\ Y_e &\in [0.05 - 0.5] \end{aligned}$$

In NS: **T = 0** approximation,
but: very high density
→ composition uncertain!

⇓

different states of matter (inhomogeneous, homogeneous, exotic particles?)



http://www.physics.montana.edu

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… a small reminder

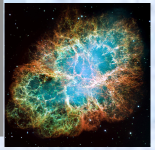
- Energy around saturation (in a liquid drop model):

$$E(n, x = Z/A) = E(n_0, x = 1/2) + \frac{1}{2}K_\infty \left(\frac{n - n_0}{3n_0}\right) + J(1 - 2x)^2$$

- In SN & NS → n-rich matter → symmetry energy important:

$$E_{\rm sym} = \left[J + L\left(\frac{n - n_0}{3n_0}\right) + \frac{1}{2}K_{\rm sym}\left(\frac{n - n_0}{3n_0}\right)^2\right](1 - 2x)^2$$

related to NS crust-core boundary (e.g. Vidaña *et al*., PRC 80, 045806 (2009))



Nuclear model for the EoS

Family of *unified* EoSs:

→ microscopic mass models based on HFB method with Skyrme type functionals and macroscopically deduced pairing force

BSk19
BSk20
BSk21

- **fit 2010 nuclear experimental mass data** (2149 masses, rms = 0.581 MeV)
- reflect current lack of knowledge of high-density behaviour of nuclear matter
- **constrained to microscopic neutron-matter EoS at T = 0** (FP, APR, LS)
- all have J = 30 MeV, K_∞ in experimental range (≈ 240 MeV)

Goriely *et al.*, PRC 82, 035804 (2010)

BSk22
BSk23
BSk24
BSk25
BSk26

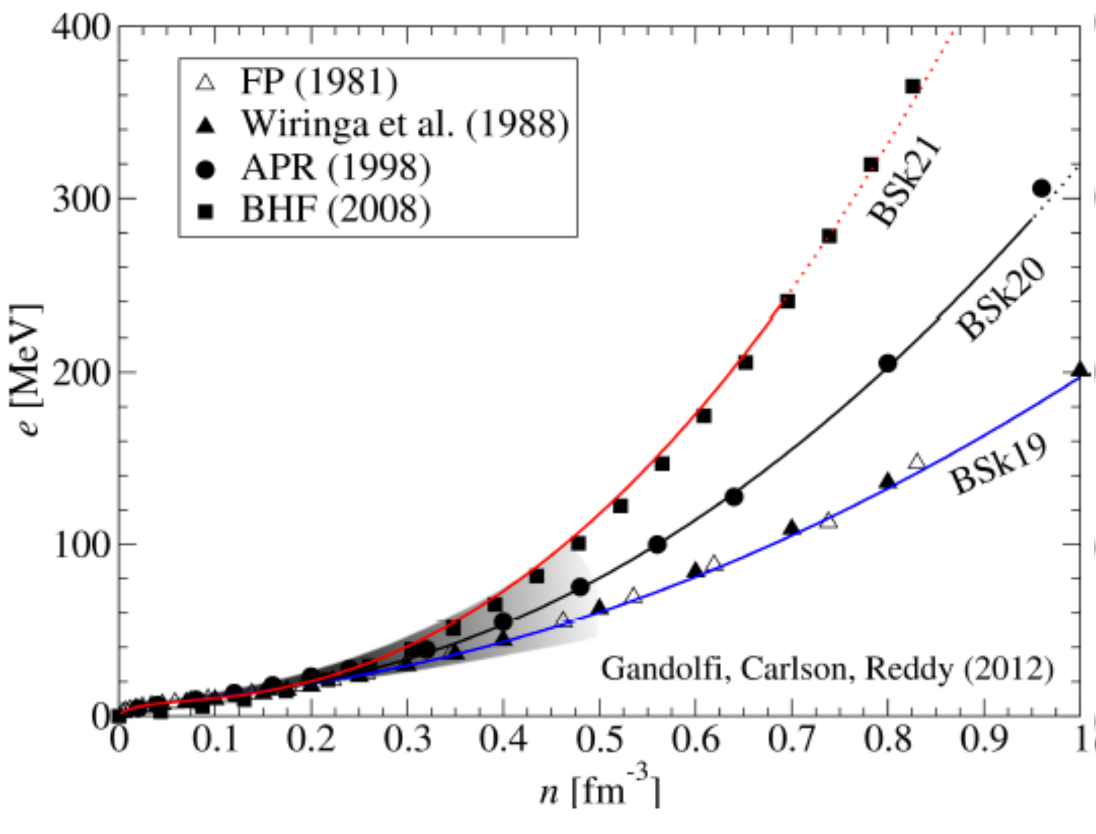
- **fit 2012 nuclear experimental mass data** (2353 masses, rms=0.5-0.6 MeV)
- **constrained to microscopic neutron-matter EoS at T = 0** (LS, APR for BSk26)
- different symmetry energy: J = 32, 31, 30, 29, 30 MeV respectively
- K_∞ in experimental range (≈ 240 MeV)

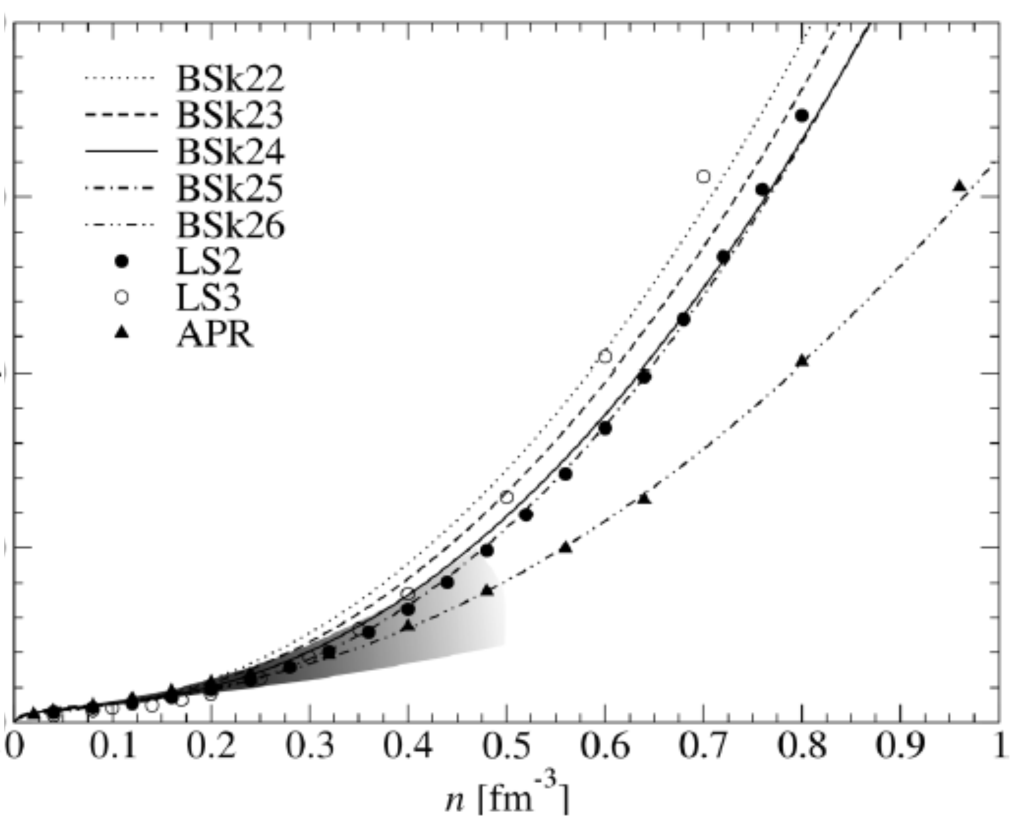
Goriely *et al.*, PRC 88, 024308 (2013)

see also: Chamel *et al.*, PRC 80, 065804 (2009)

→ BSk** suitable to describe all the regions of NS

Constraints from nuclear physics: theoretical calculations (neutron matter)



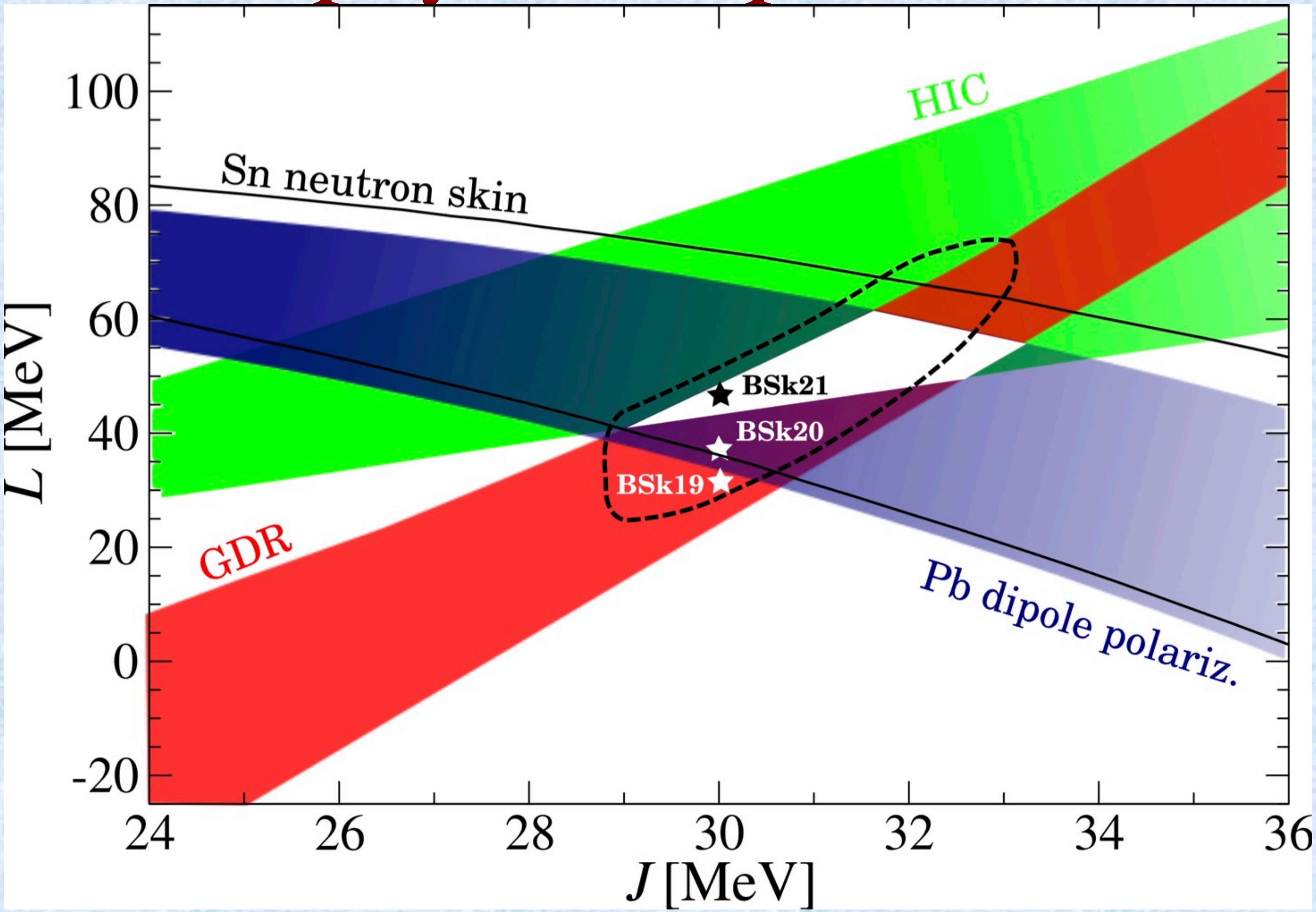


N. Chamel, talk ECT* (2013)

Goriely *et al.*, PRC 88, 024308 (2013)

BSk** fitted to realistic neutron-matter EoSs with different stiffness

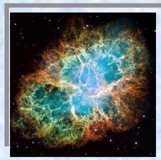
Constraints from nuclear physics experiments



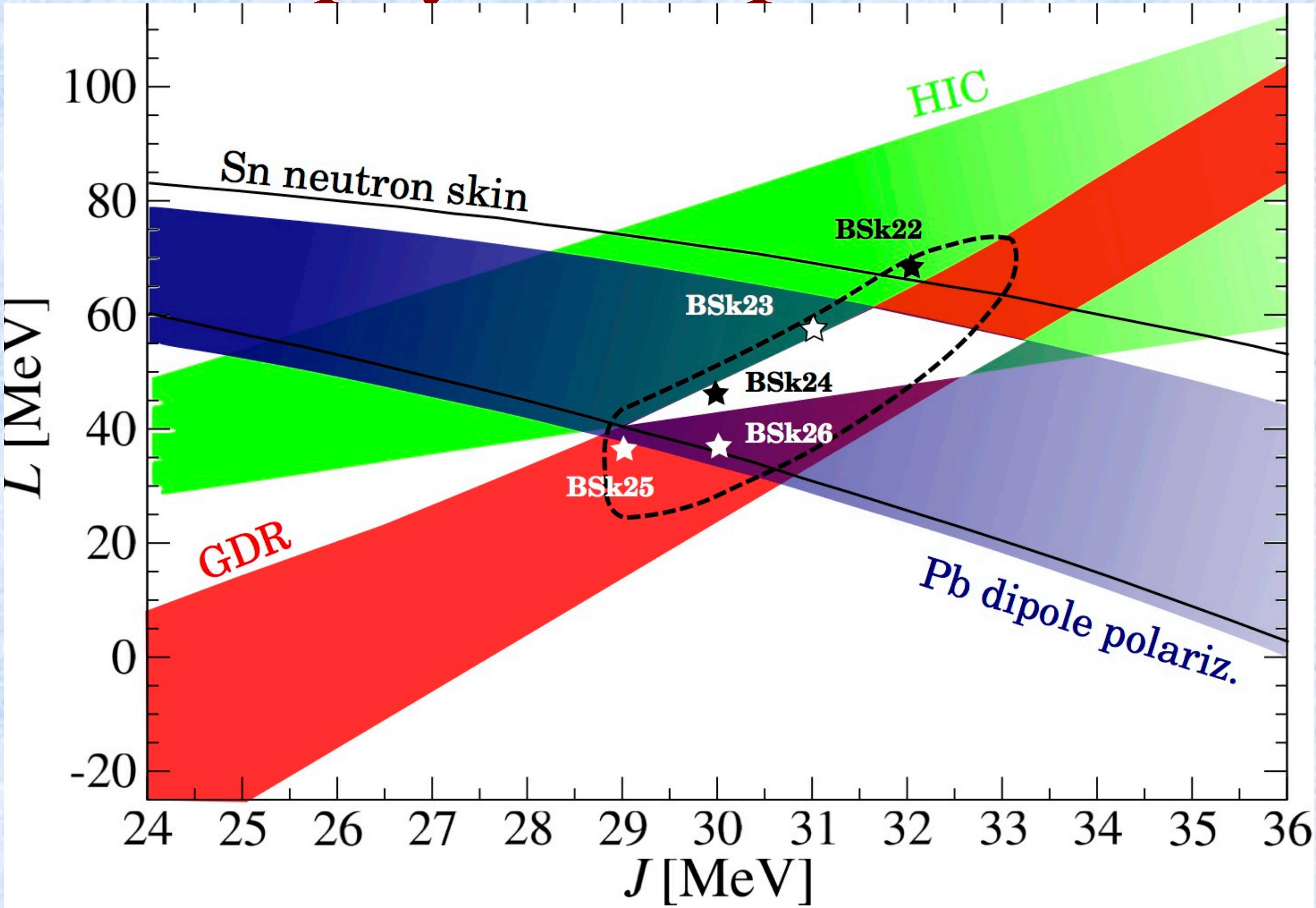
⇒ *J*,*L* consistent with experimental constraints

Potekhin *et al.*, A&A 428, 191 (2013)

for experim. constraints see also:
Tsang et al., PRC 86, 015803 (2012);
Lattimer and Lim , A&A 771, 51 (2013)



Constraints from nuclear physics experiments



➡ *J*,*L* consistent with experimental constraints

Courtesy of N. Chamel

for experim. constraints see also:
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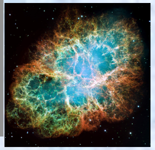

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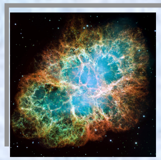


EoS of neutron star

- **OUTER CRUST** (up to neutron drip) (J. M. Pearson *et al.*, PRC83, 065810 (2011))

  → one nucleus (bcc lattice) + electrons, in charge neutrality and β equilibrium

  → minimization of the Gibbs energy per nucleon: BPS model $g = e + \dfrac{P}{n_B}$

  Only microscopic inputs are nuclear masses
  → Experimental or microscopic mass models HFB19-26

- **INNER CRUST** (Onsi *et al.*, PRC77, 065805 (2008), Pearson *et al.*, PRC85, 065803 (2012))

  → one cluster (Wigner-Seitz cell, spherical) + n, e^-

  → semi-classical model: Extended Thomas Fermi (4th order in *ħ*)
  + proton shell corrections (Strutinski Integral theorem)

- **CORE** (Goriely *et al.*, PRC 82, 035804 (2010), Goriely *et al.*, PRC 88, 024308 (2013))

  → homogeneous matter: n, p, e^-, muons in β equilibrium *

  → *same* nuclear model to treat the interacting nucleons

* here we do not consider possible phase transition!
transition to exotic matter in Chamel, Fantina, Pearson, Goriely, A&A 553, A22 (2013)

NS structure

Using the EoSs **BSk 19-20-21** and **BSk 22-24-26**

→ computing NS structure

for **non-rotating** and **rigidly rotating** NSs.

Method: solve Einstein equations in GR for stationary axi-symmetric configurations.

Code: **LORENE** library (http://www.lorene.obspm.fr)

Refs: Gourgoulhon, arXiv: 1003.5015 (lectures given at 2010 CompStar school)

Gourgoulhon *et al.*, A&A 349, 851 (1999)

Grandclément & Novak, Liv. Rev. Relativ. 12, 1 (2009)

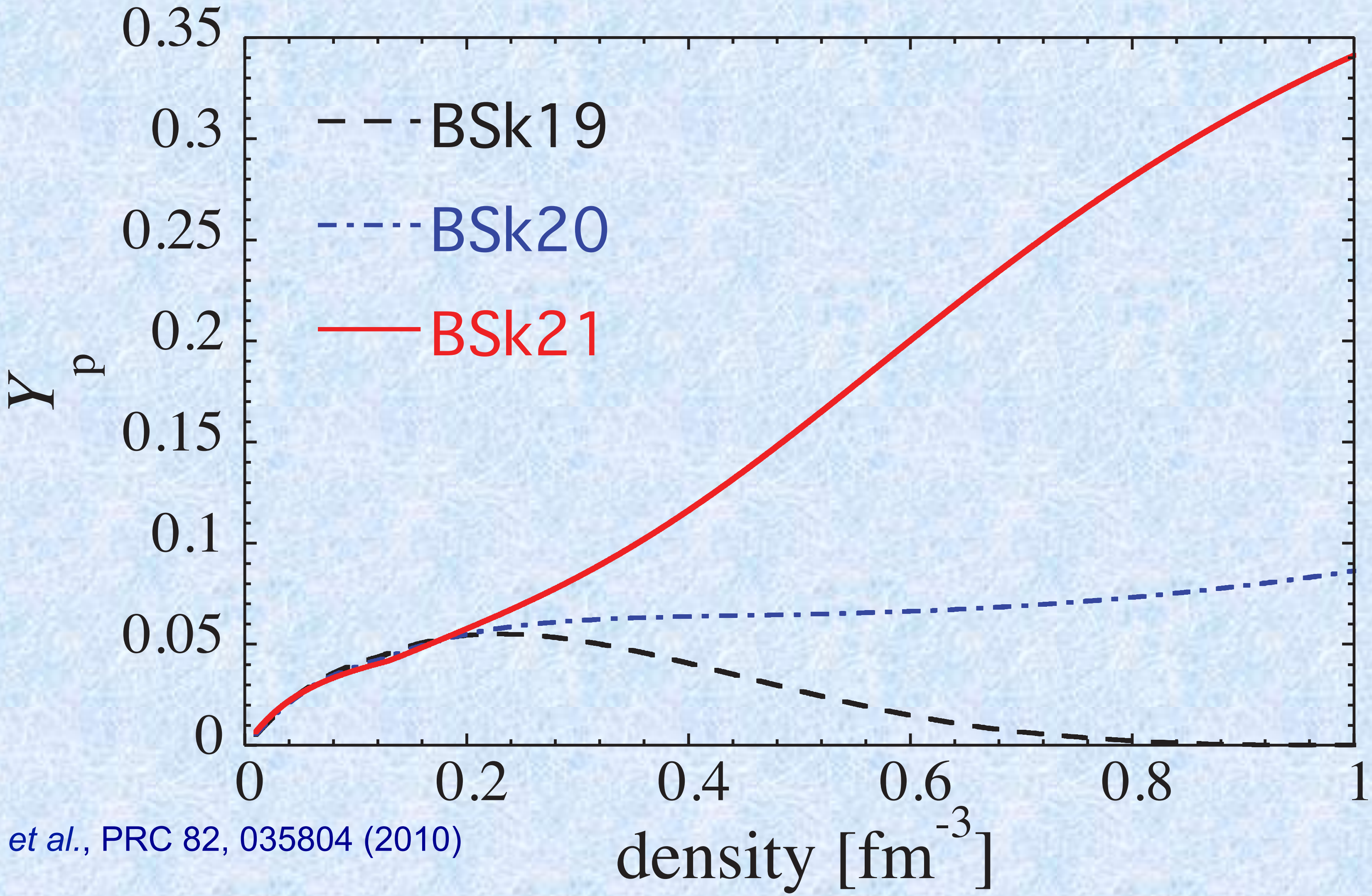
Non-rotating NS → solve TOV equations:

$$\frac{dP}{dr} = -\frac{G\rho\mathcal{M}}{r^2}\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi P r^3}{\mathcal{M}c^2}\right)\left(1-\frac{2G\mathcal{M}}{rc^2}\right)^{-1},$$

$$\frac{d\mathcal{M}}{dr} = 4\pi r^2\rho$$

➡ EoS $P(\rho)$ to close the system

NS properties: *dURCA process*

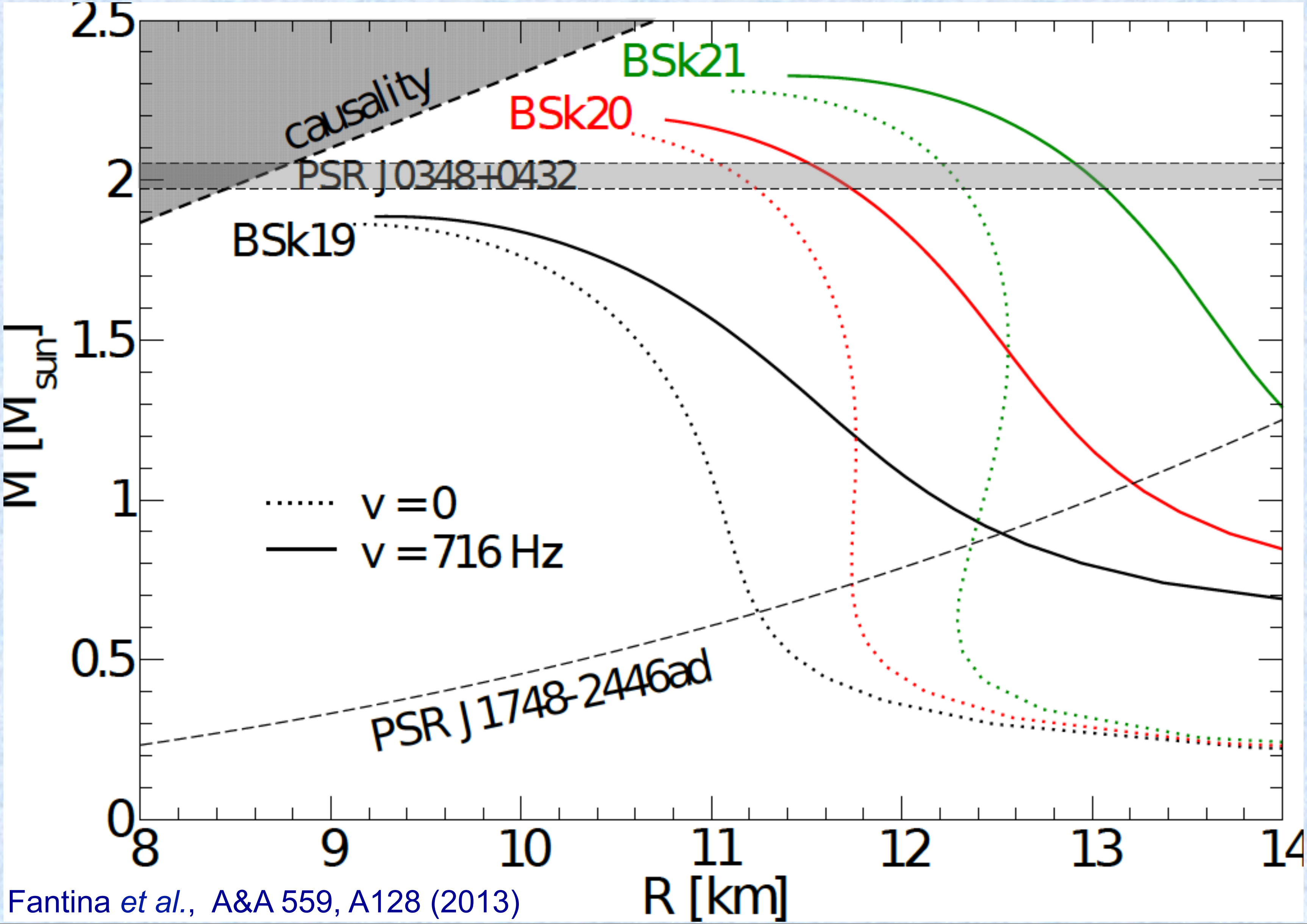


Goriely *et al.*, PRC 82, 035804 (2010)

direct URCA possible if $Y_p \approx$ 11-15%

BSk21 compatible with existence of direct URCA process for n > 0.45 1/fm^3, or M > 1.59 M_{sun}

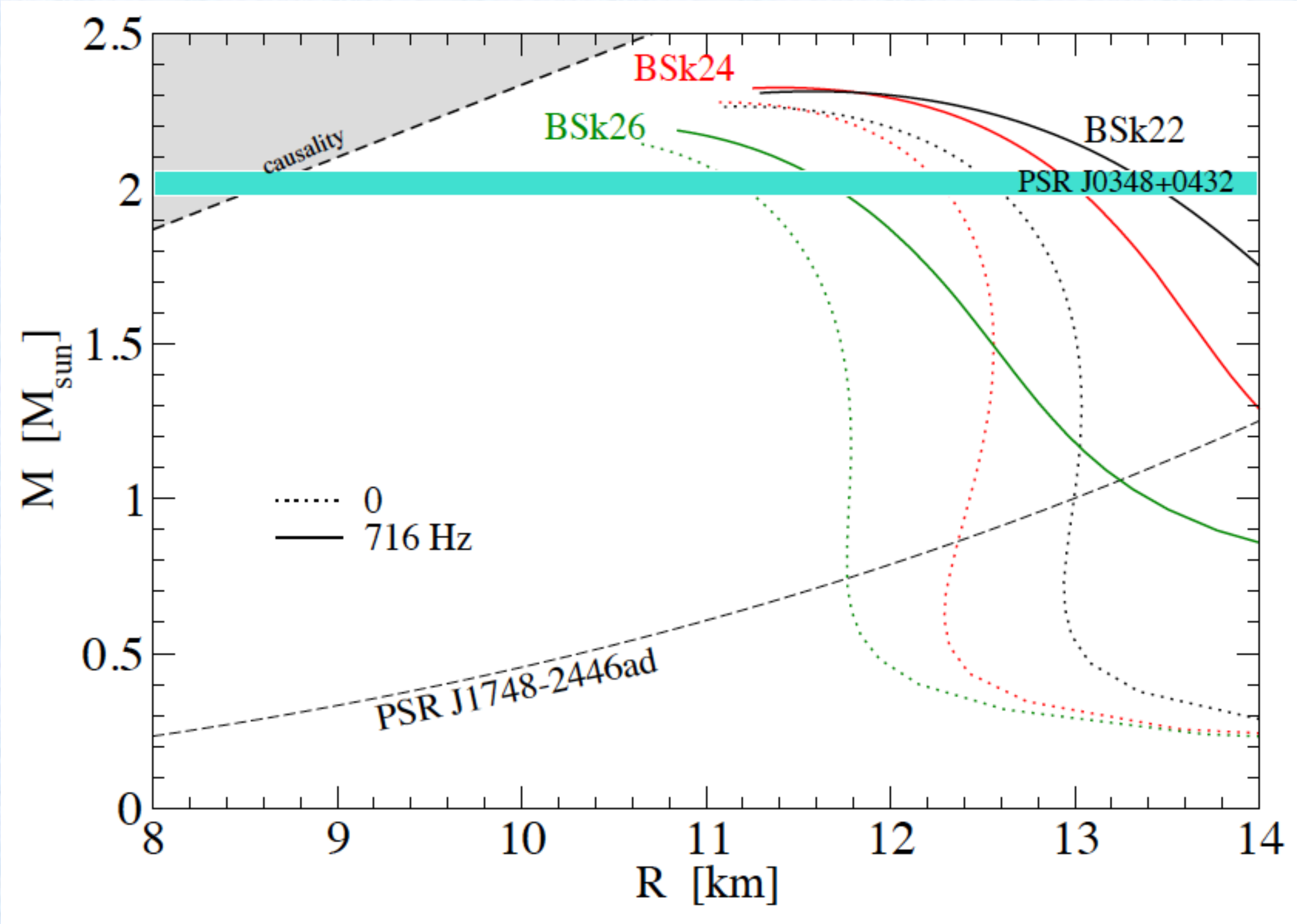
NS properties: *M-R relation with rotation*



Fantina *et al.*, A&A 559, A128 (2013)

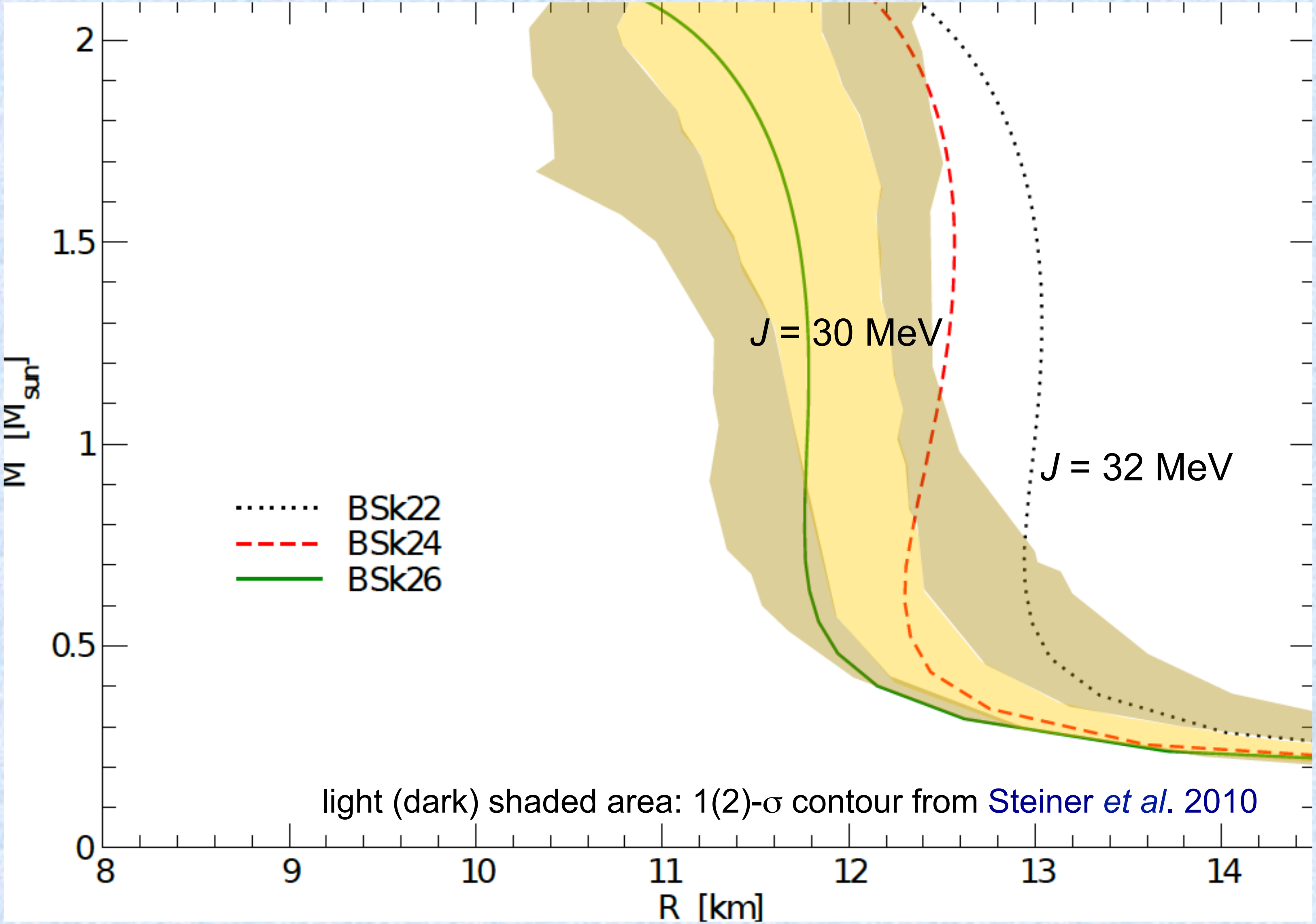
BSk20, BSk21 compatible with observations, BSk19 too soft,
(but if we consider a possible phase transition to exotic phase…)

NS properties: *M-R relation with rotation*



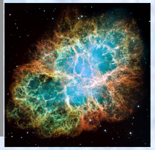
BSk22-24-26 compatible with observations

NS properties: *M-R relation*



Pearson, Chamel, Fantina, Goriely, Eur. Phys. J. A 50 (2014)

→ astrophysical observations agree with J = 30 MeV



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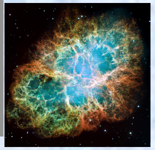


Conclusions

❖ Unified EoSs for NS matter

→ <u>same</u> nuclear model to describe <u>all</u> regions of NS interior

❖ Nuclear models fitted on *experimental nuclear data*

and *nuclear-matter properties*

❖ EoSs based on BSk21-24-26 consistent with astrophysical observations!

BSk21-24 functional favoured by mass measurements Chamel *et al*., PRC 84,062802 (2011)

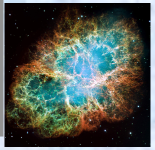
Both mass measurements and astro observations favours $J \approx 30$ MeV

The softest EoS BSk19 seems to be ruled out by astrophysical observations, but BSk19 functional favoured by the analysis of HIC experiments.

→ discrepancy could be resolved by considering the occurrence of a transition to an "exotic" phase in neutron star cores (Chamel *et al*., A&A 553, A22 (2013))

❖ EoSs <u>available</u> as:

- ***tables*** (for BSk19-20-21) at CDS (doi: 10.1051/0004-6361/201321884)
- ***fit*** (for BSk19-20-21) at: http://www.ioffe.ru/astro/NSG/BSk/



Outlooks

- EoSs for NS (T=0) and SN cores (finite T)

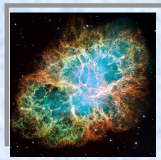
  → **T = 0**: EoSs : AVAILABLE!
  - table
  - analytical fit (easy to implement!)

  → **T ≠ 0**: work in progress → generate tables for SN cores
  → implement in hydro codes

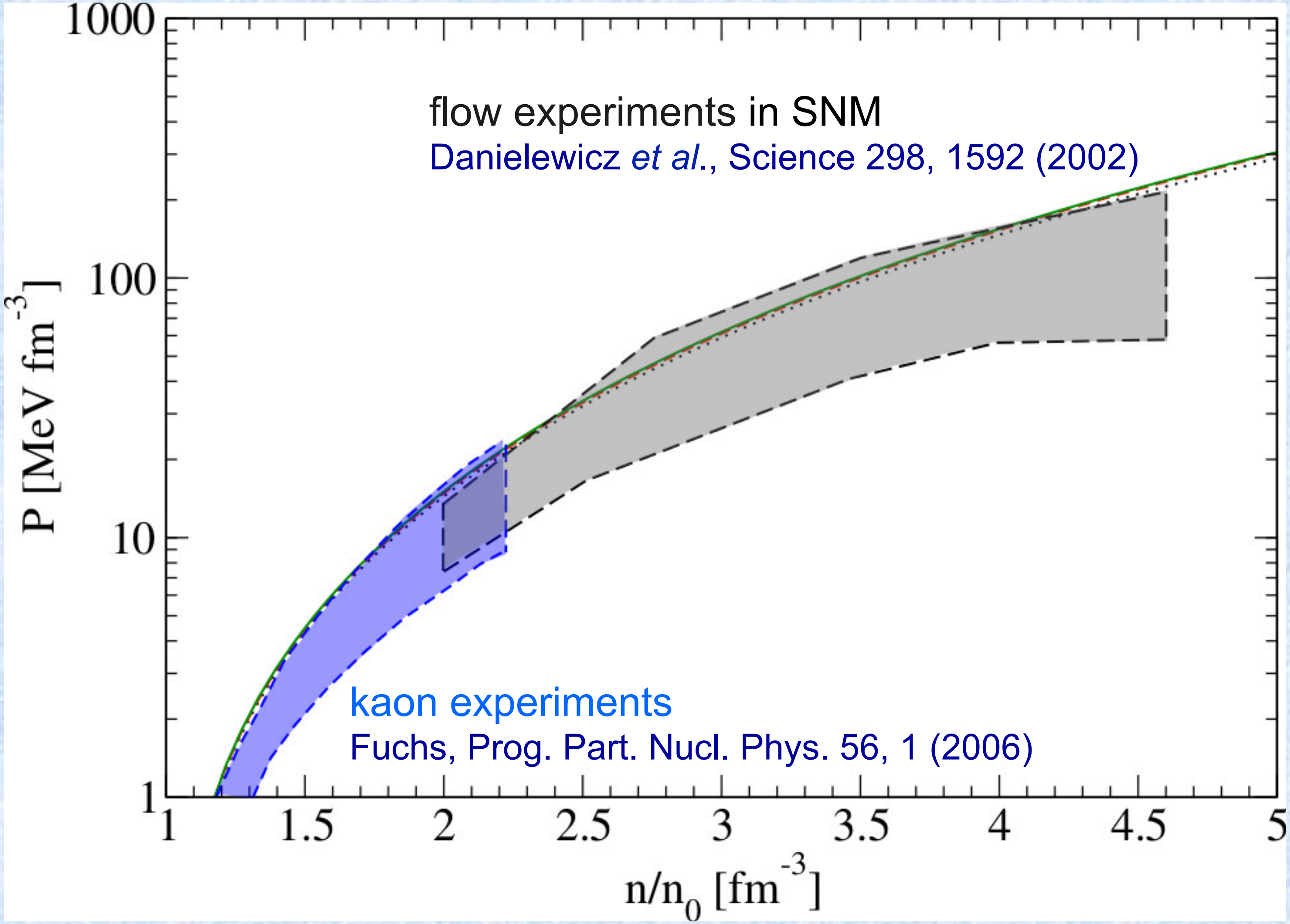
- Application to accreting NSs


Grazie

Back up slides



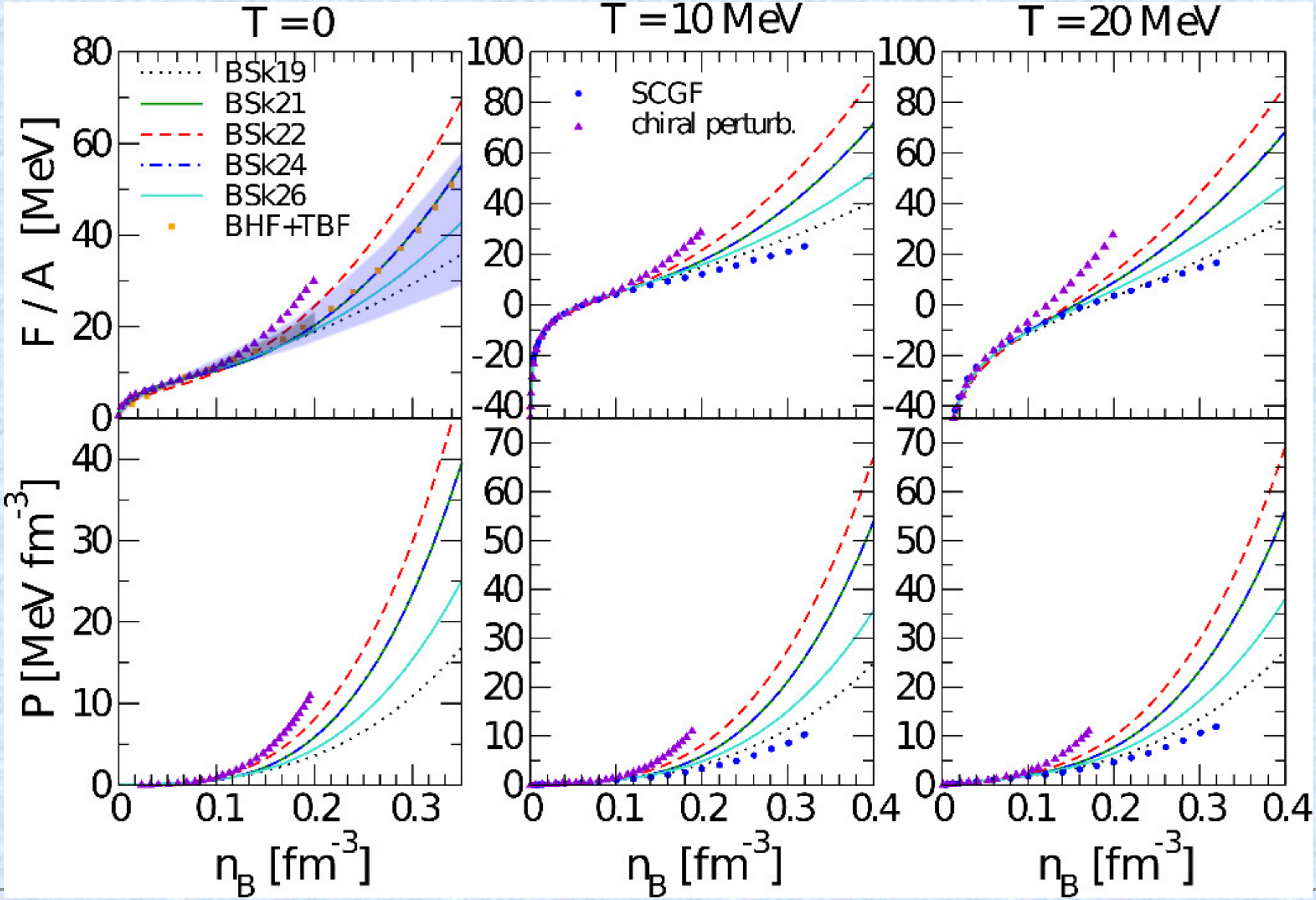
Constraints from nuclear physics experiments (Y_p=0.5)



Functionals in good agreement with “experimental” constraints on symm. matter

<u>N.B.</u>: deduced constraints are not direct experimental data, are model dependent!

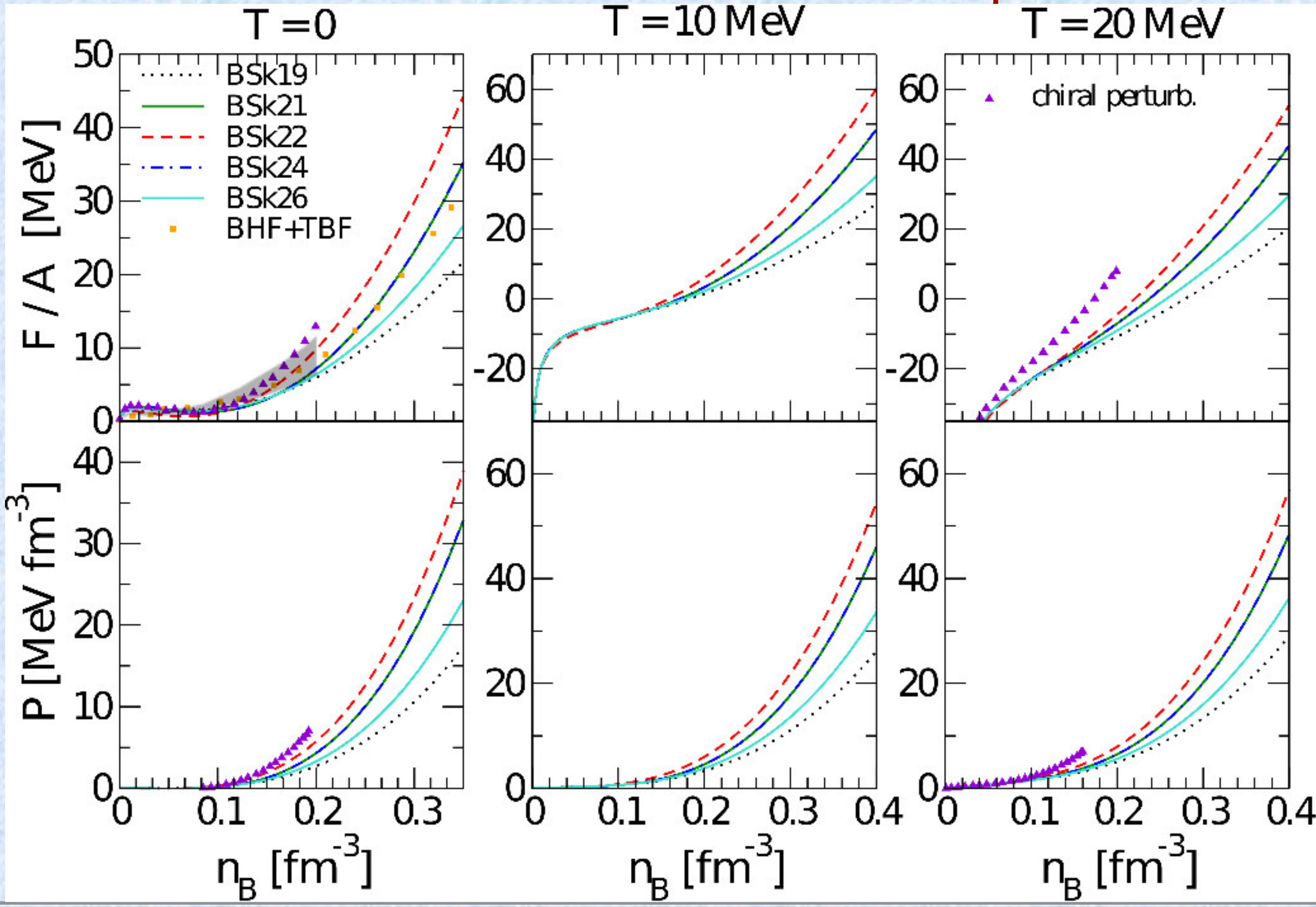
Constraints from nuclear physics: theoretical calculations (neutron matter)



BHF+TBF: Zuo *et al.*, J.Phys.Conf.Ser. 420, 012089 (2013)
Chiral effective theory: Drischler *et al.*, arxiv:1310.5627v1(2013)
Monte Carlo: Gandolfi *et al.*, PRC 85, 032801(2012)

Chiral perturb. : Fiorilla *et al.*, Nucl. Phys. A880, 65 (2012)
SCGF: Rios *et al.*, PRC 79, 025802 (2009)

Constraints from nuclear physics: theoretical calculations (Y_p=0.1)



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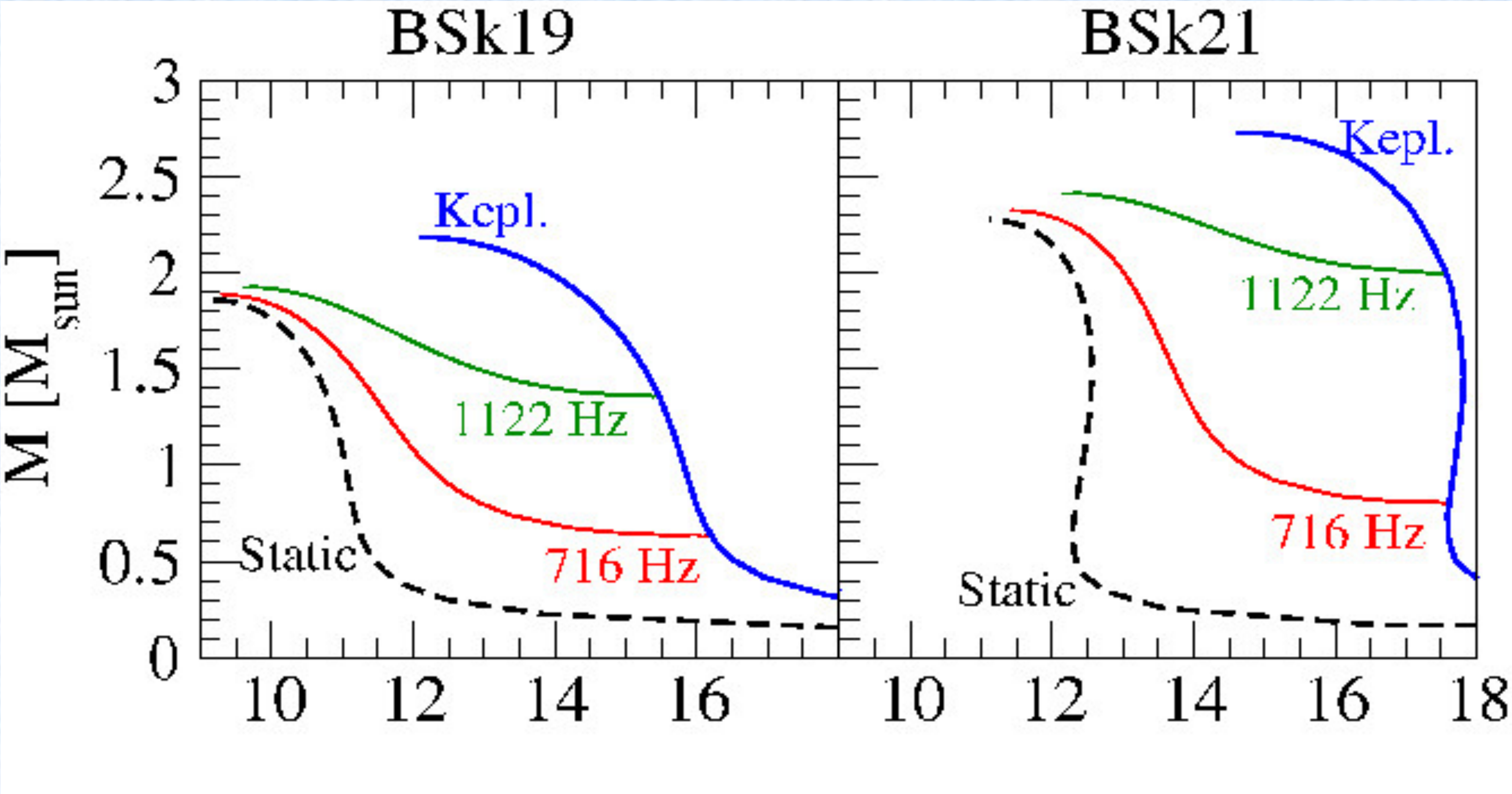
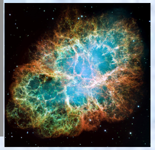
Chiral effective theory: Drischler *et al.*, arxiv:1310.5627v1(2013)
Chiral perturb. : Fiorilla et al., Nucl. Phys A880, 65 (2012)

NS properties: *keplerian velocity*

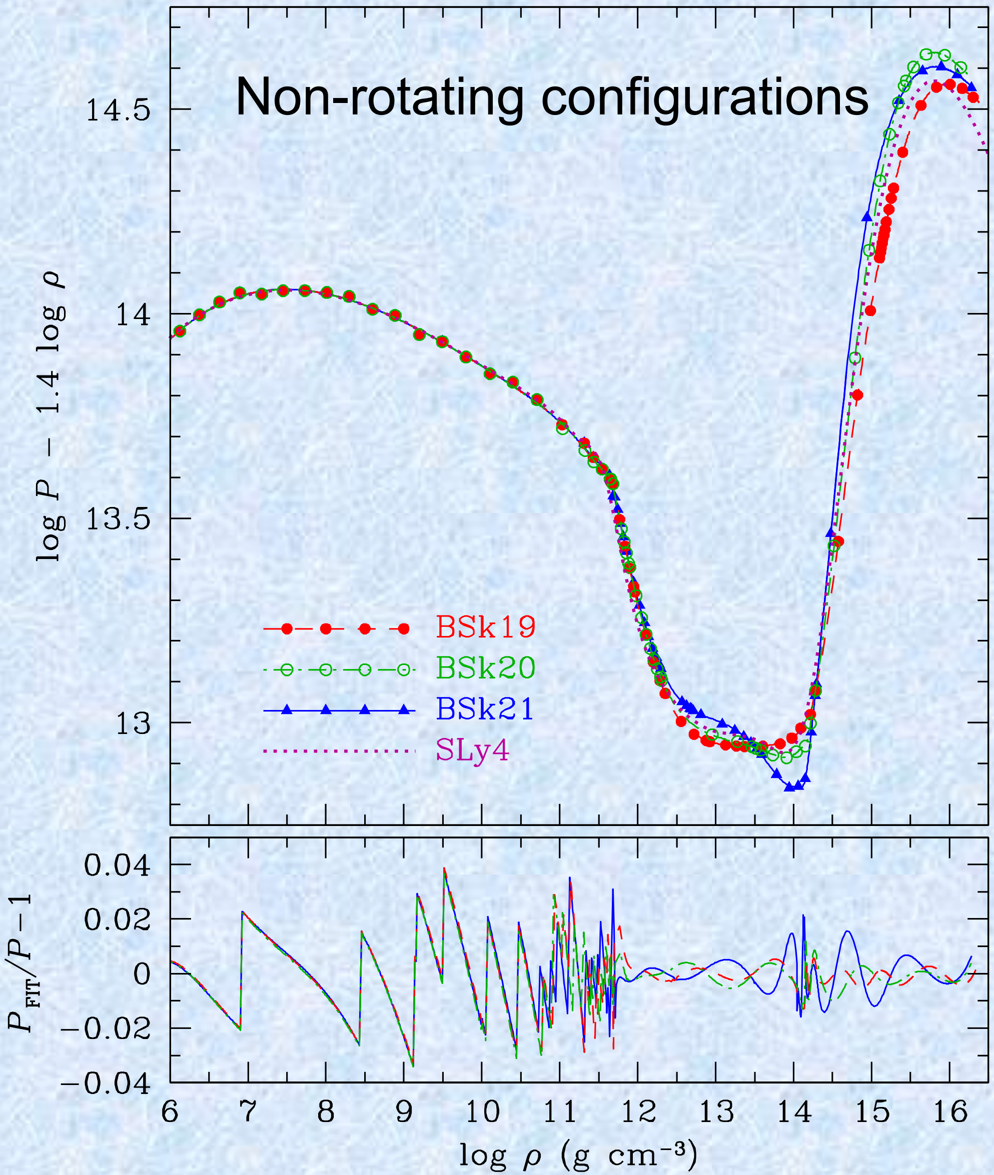


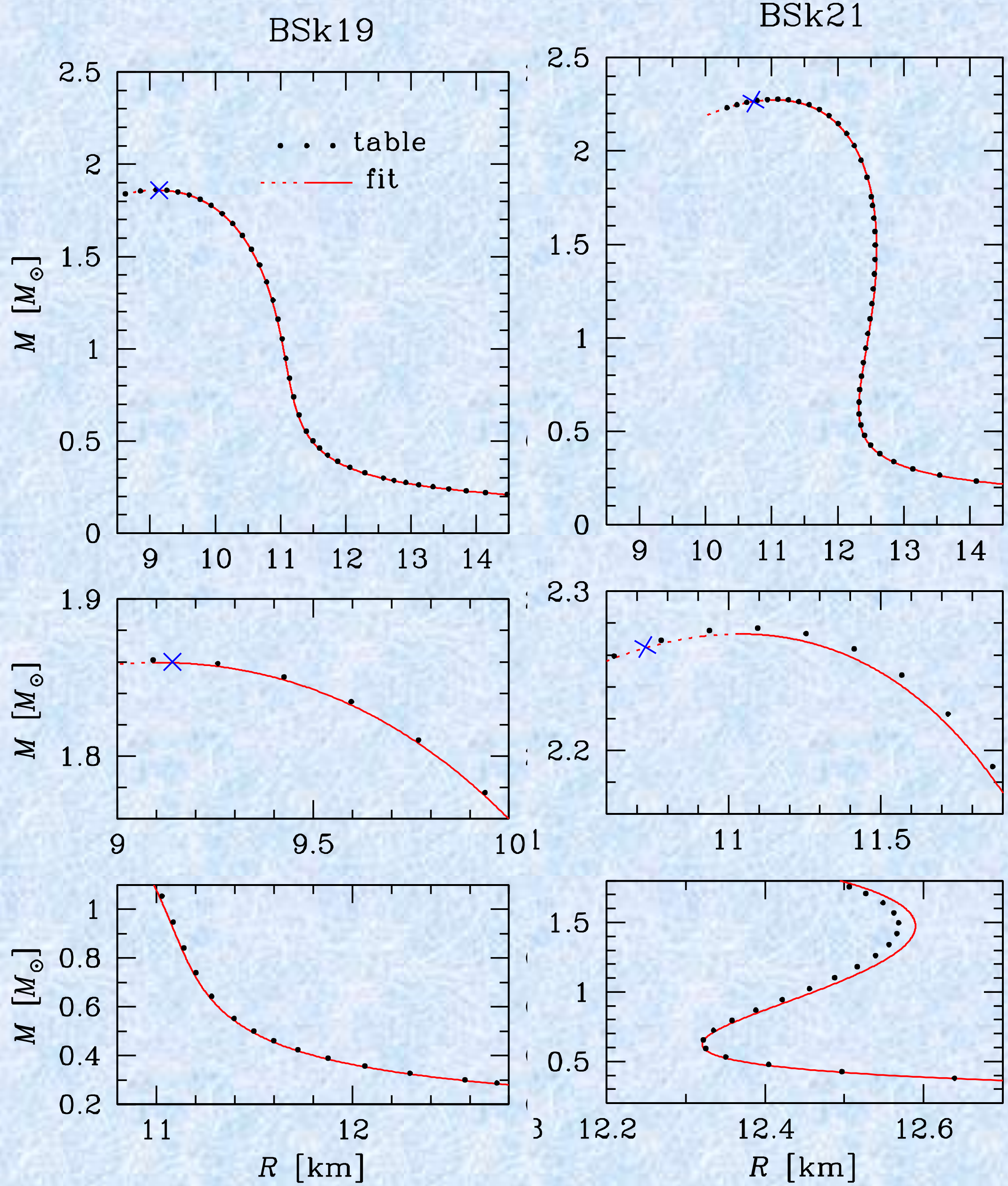
Fantina *et al.*, A&A 559, A128 (2013)

→ only fast rotation increases maximum mass in an important way (≈ 17-20%)

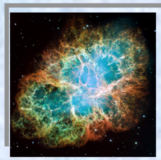


Analytical fit

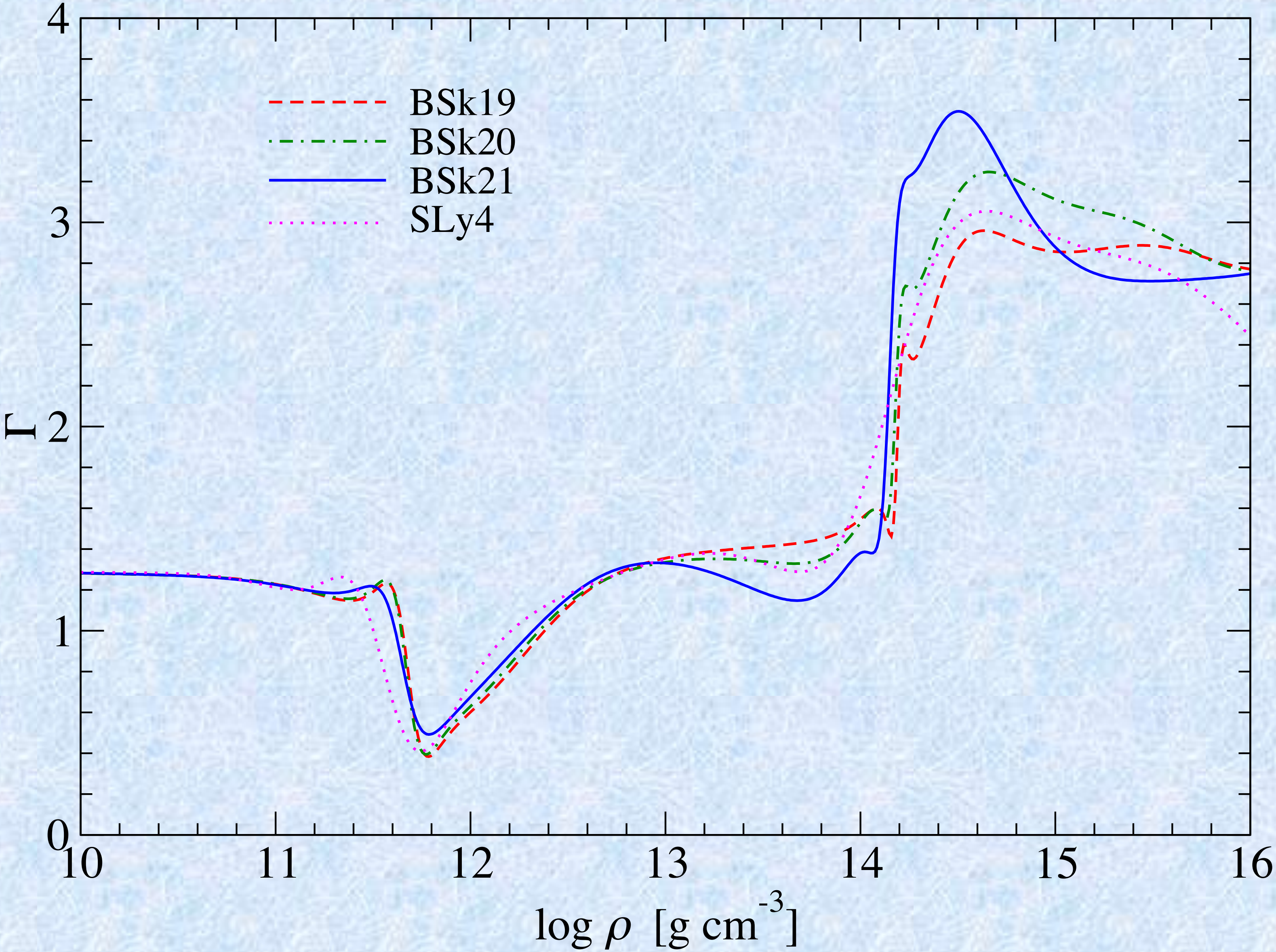




Potekhin *et al.*, A&A 560, A48 (2013)



Analytical fit (adiabatic index)



Potekhin *et al.*, A&A 560, A48 (2013)