Institut d'Astronomie et d'Astrophysique
Université Libre de Bruxelles

# Symmetry energy : nuclear mass models and neutron-star structure

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Supernova Remnant 1987A in the Large Magellanic Cloud HUBBLESITE.org

NuSYM15
Krakow (Poland), 29 June – 2 July 2015

# Outline

- Introduction: NS & EoS
  - different models and $M_{max}$ predictions
  - (some) constraints from nuclear and astrophysics
- Effective nuclear models
  - Brussels-Montreal BSk model
- EoSs of dense matter & $E_{sym}$ parameters
  - The model
  - Catalysed matter : structure and composition
  - Accreted crust
- Conclusions & Outlook

# EoS for NS: the challenge

Contrarily to a normal star, in a NS:

✓ matter is highly **degenerate**!
( **T = 0** approximation )

✓ very high density!
composition uncertain

⇩

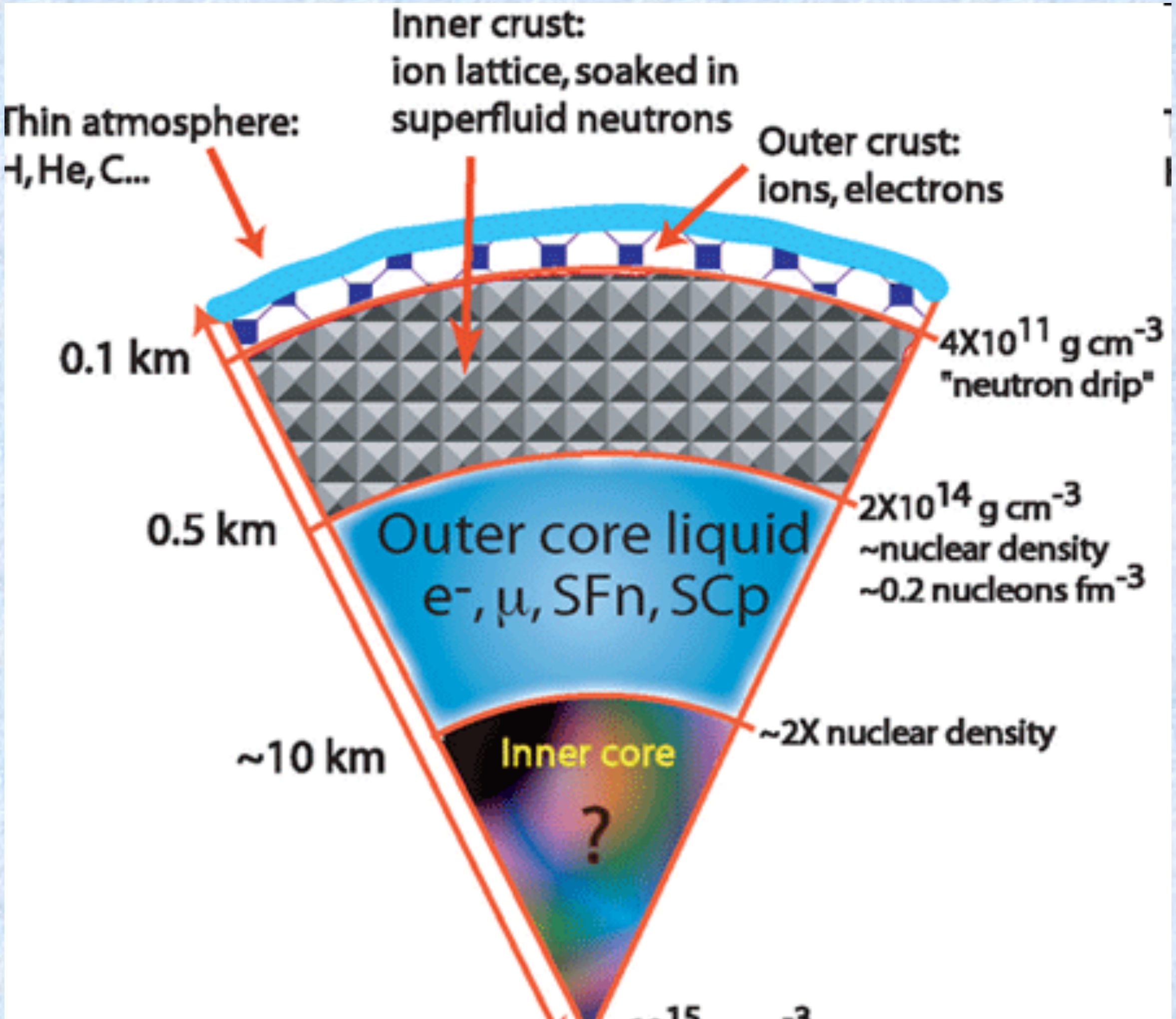
different states of matter :
inhomogeneous, homogeneous,
exotic particles ?

$$M \approx 1-2\ M_\odot$$

$$R \approx 10\ \text{km}$$

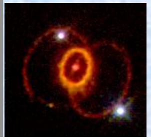
$$\bar{\rho} \approx 10^{14}-10^{15}\ \text{g cm}^{-3}$$

$$\frac{2GM}{Rc^2} \approx 0.2-0.4$$

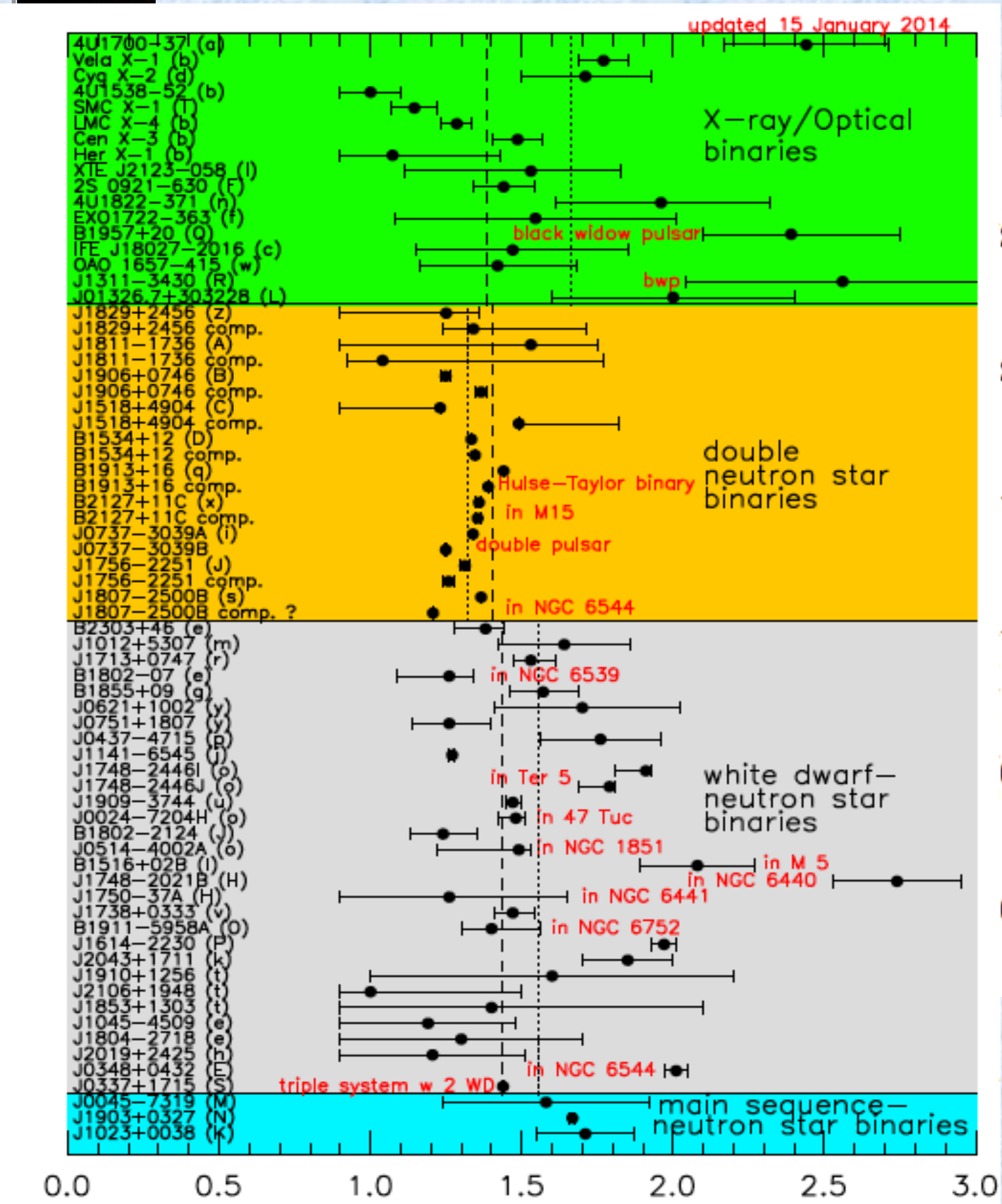


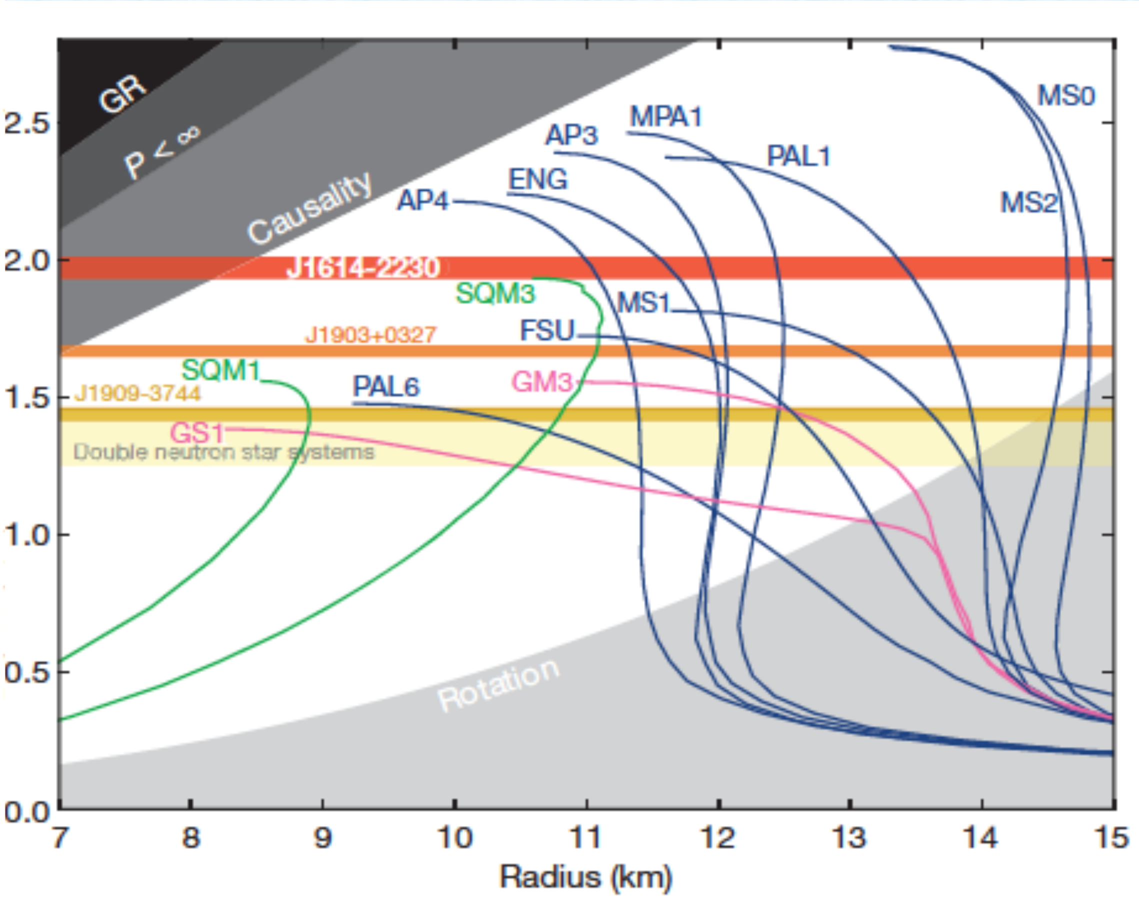
http://www.physics.montana.edu

⇨ very dense matter, use of GR
UNIQUE “LABORATORIES”! (e.g. superfluidity, deformed nuclei, ... )



# NS mass measurement to probe EoS




2 $M_{sun}$ NS measurements:

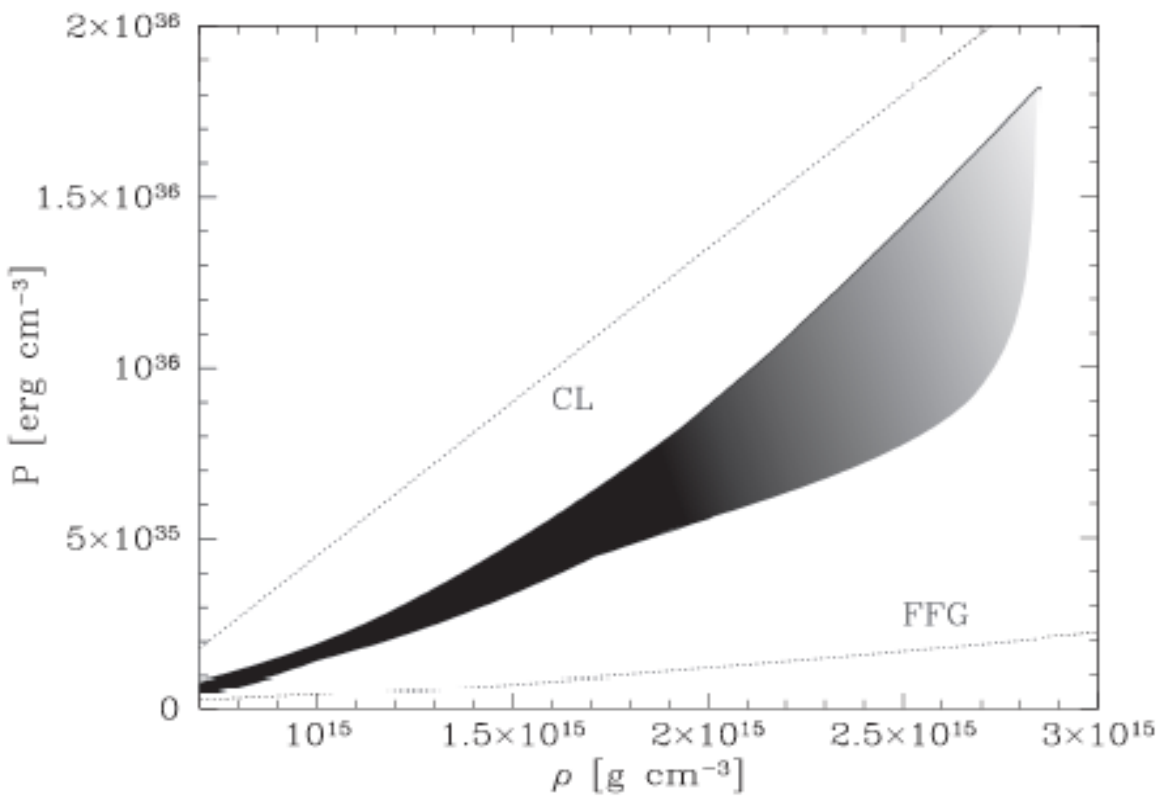
Demorest *et al.*, Nature 467, 1081 (2010)

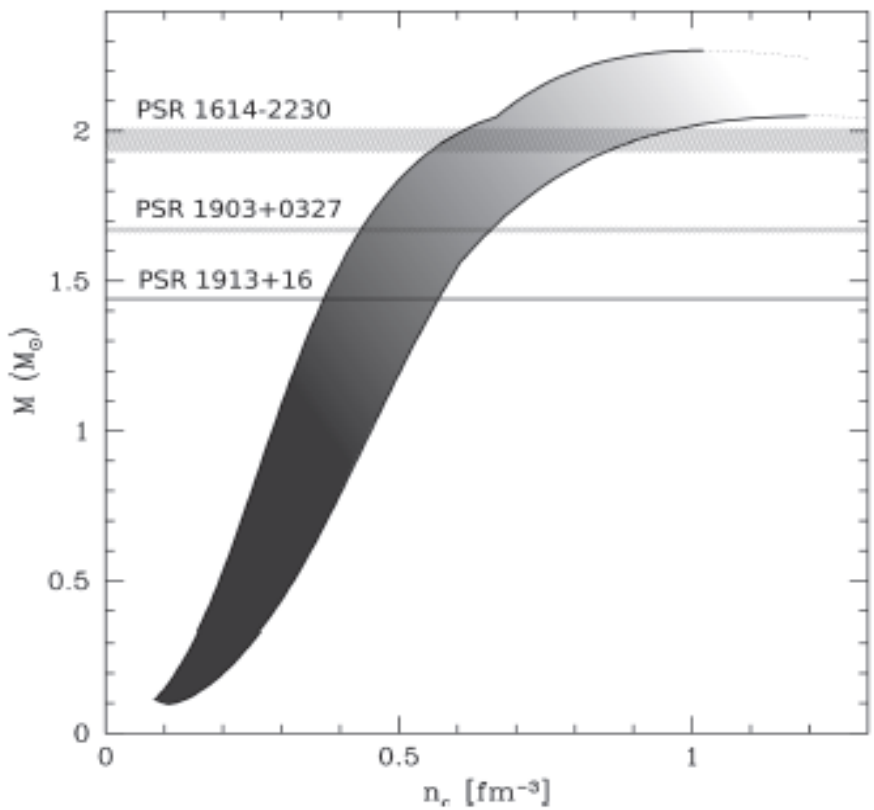
Antoniadis *et al.*, Science 340, 1233232 (2013)

Lattimer, lecture at Carpathian Summer School of Physics (2014)

# Uncertainties in dense-matter EoS

Pressure $P$ versus mass-energy density $\rho$ and corresponding NS mass $M$ versus central density $n_c$ relation, as predicted by various models and consistent with the existence of massive NSs.




Chamel, Haensel, Zdunik, Fantina, Int. J. Mod. Phys. E 22, 1330018 (2013); E 22, 1392004 (2013)

spread mostly at supra-saturation density!

# Maximum mass predictions

The core is assumed to contain nucleons (N), nucleons and hyperons (NH), nucleons and quark (NQ). In some cases, to reach 2 $M_{sun}$ → *fine tuning of parameters*!

- Phenomenological models : start from effective interactions with parameters adjusted on some nuclear properties. E.g. Relativistic Mean Field (RMF), Nambu-Jona-Lasinio (NJL), Modified Bag Model (MBM)

| | RMF (N) | RMF (NH) | RMF/NJL (NQ) | RMF/MBM (NQ) |
|---|---|---|---|---|
| $M_{max}/M_{\odot}$ | 2.1-2.8 | 2.0-2.3 | 2.0-2.2 | 2.0-2.5 |

- Microscopic models : start from realistic interaction (→ *ab-initio*). E.g. (Dirac) Brueckner Hartree-Fock ((D)BHF), variational chain summation method (VCS), perturbative quantum chromodynamics (pQCD)

| | (D)BHF (N) | BHF (NH) | VCS (N) | pQCD (NQ) |
|---|---|---|---|---|
| $M_{max}/M_{\odot}$ | 2.0-2.5 | 1.3-1.6 | 2.0-2.2 | 2.0 |

hyperon puzzle!

Chamel, Haensel, Zdunik, Fantina, Int. J. Mod. Phys. E 22, 1330018 (2013) ; E 22, 1392004 (2013)

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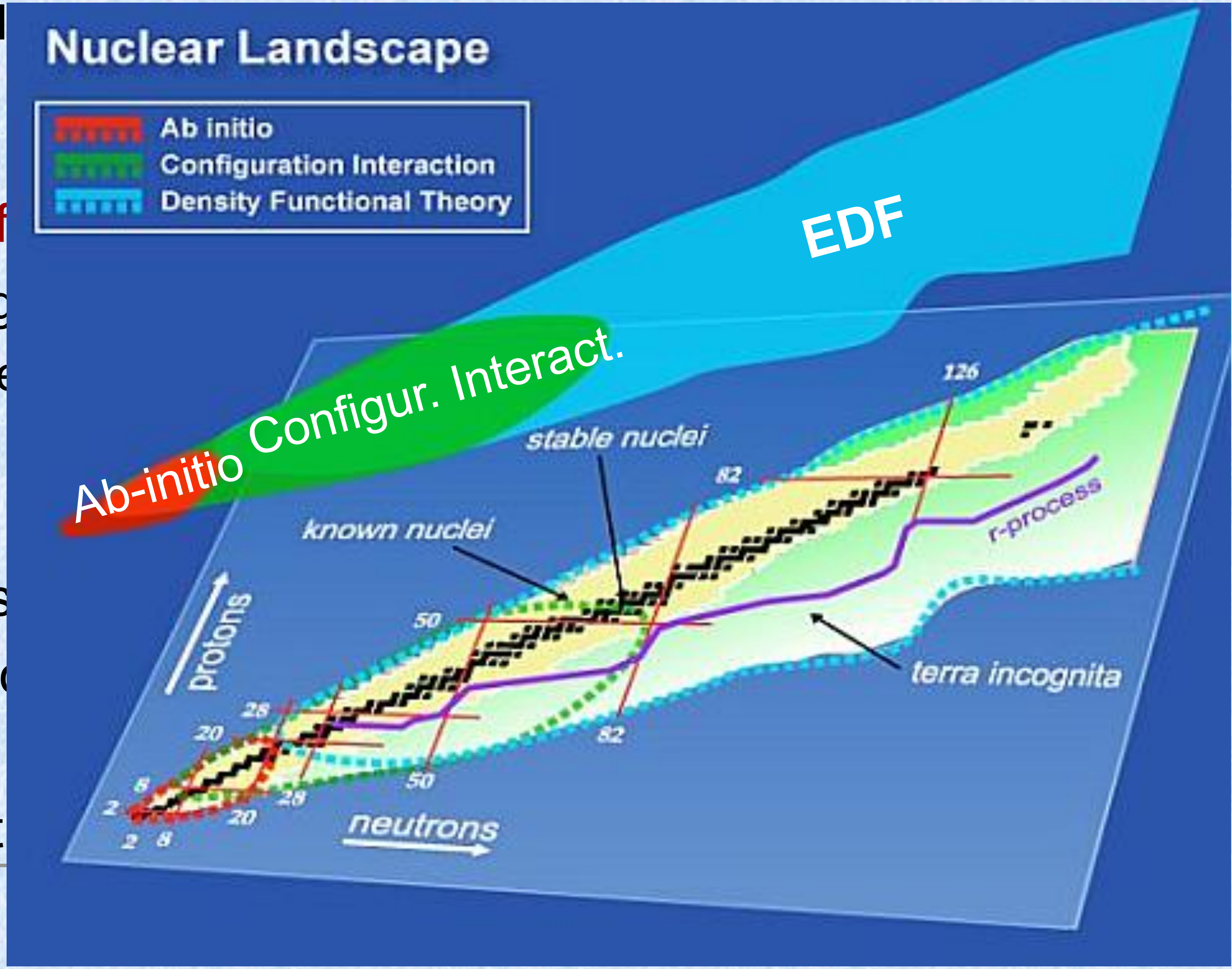
# Our goal : a unified EoS

- Our goal is to construct a ***unified*** EoS
  - → based on the *same nuclear model* from energy-density functional theory
  - → valid in all regions of N
  - → outer / inner crust and
- EoS both at T = 0 and f
  - → cold non-accreting
  - → accreting NS (off-e
  - → SN cores
- Satisfying: - constraints
  - astrophysi
- Direct applicable for ast



# Our goal : a unified EoS

- Our goal is to construct a ***unified*** EoS
  - → based on the *same nuclear model* from energy-density functional theory
  - → valid in all regions of NS (and SN) interior
  - → outer / inner crust and crust / core transition described consistently

- EoS both at T = 0 and finite T
  - → cold non-accreting NS (cold catalysed matter)
  - → accreting NS (off-equilibrium)
  - → SN cores

- Satisfying: - constraints from nuclear physics experiments
  - astrophysical observations

- Direct applicable for astrophysical application

# Brussels-Montreal (BSk) functionals

Mass models based on HFB method with Skyrme type functionals and macroscopically deduced pairing force.
Fitted to experimental data + N-body calculations with realistic forces.

**BSk19**
**BSk20**
**BSk21**

- **fit 2010 AME data** (2149 masses, rms = 0.581 MeV)
- **different degrees of stiffness** (BSk19 softer → BSk21 stiffer) constrained to different microscopic neutron-matter EoSs at T = 0
- all have ***J*** **= 30 MeV**, , $K_\infty$ in experimental range (≈ 240 MeV)

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

**BSk22**
**BSk23**
**BSk24**
**BSk25**
**BSk26**

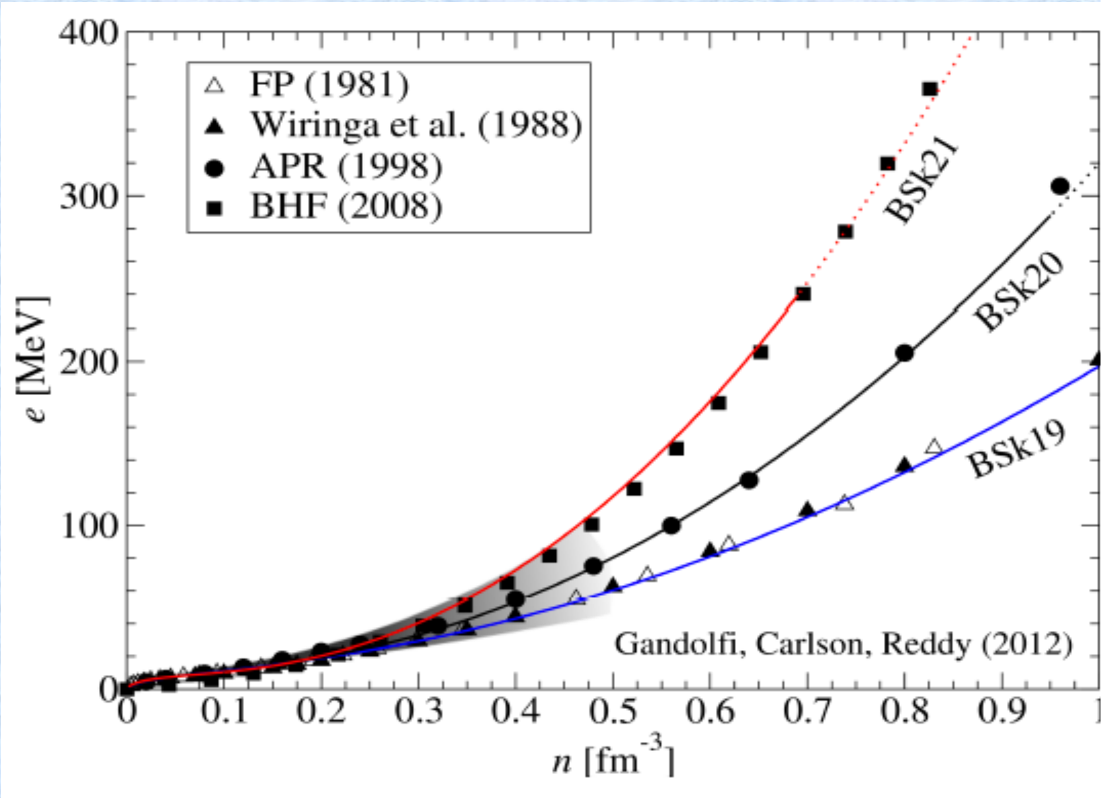
- **fit 2012 AME data** (2353 masses, rms = 0.5-0.6 MeV)
- constrained to microscopic neutron-matter EoSs at T = 0 (rather stiff)
- **different** $E_{sym}$ **coefficient** (***J*** **= 32, 31, 30, 29, 30 MeV**), $K_\infty$ in experimental range (≈ 240 MeV)

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

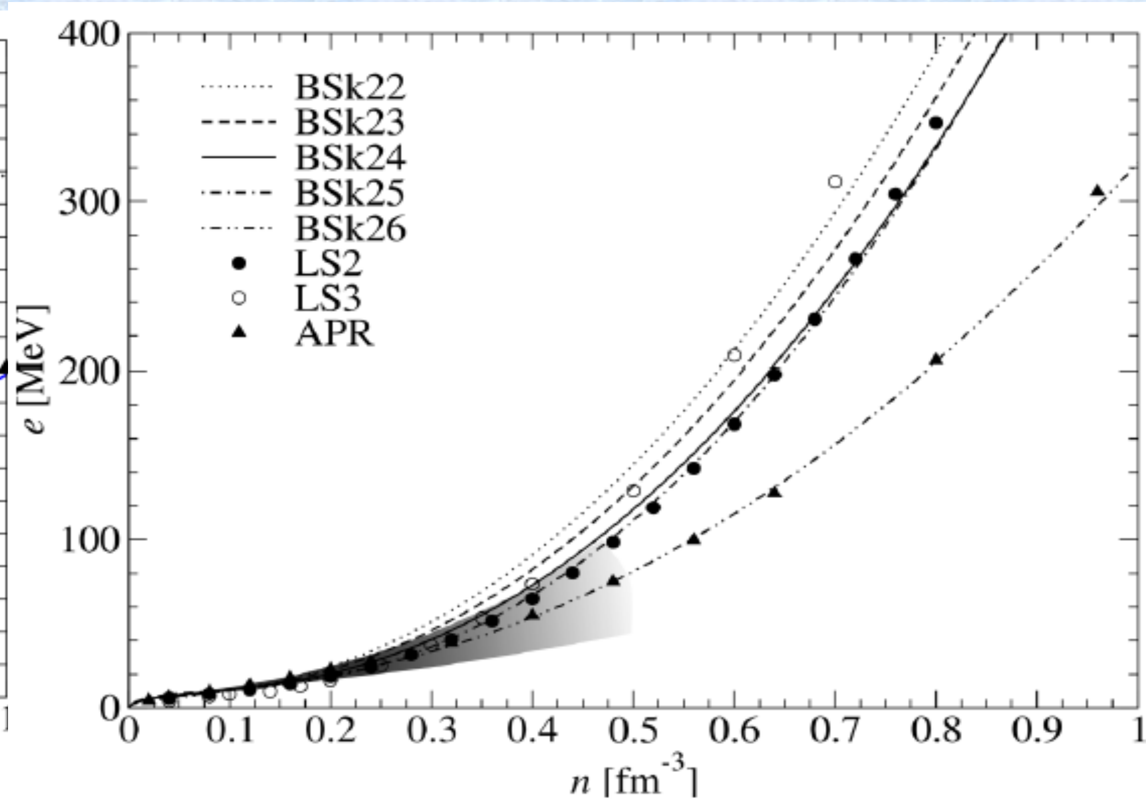
**BSk27*** (2012 AME,rms = **0.5 MeV**), ***J*** **= 30 MeV**: most accurate! Goriely *et al.*, PRC88,061302 (2013)

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

# Constraints from nuclear physics: theoretical calculations (neutron matter)



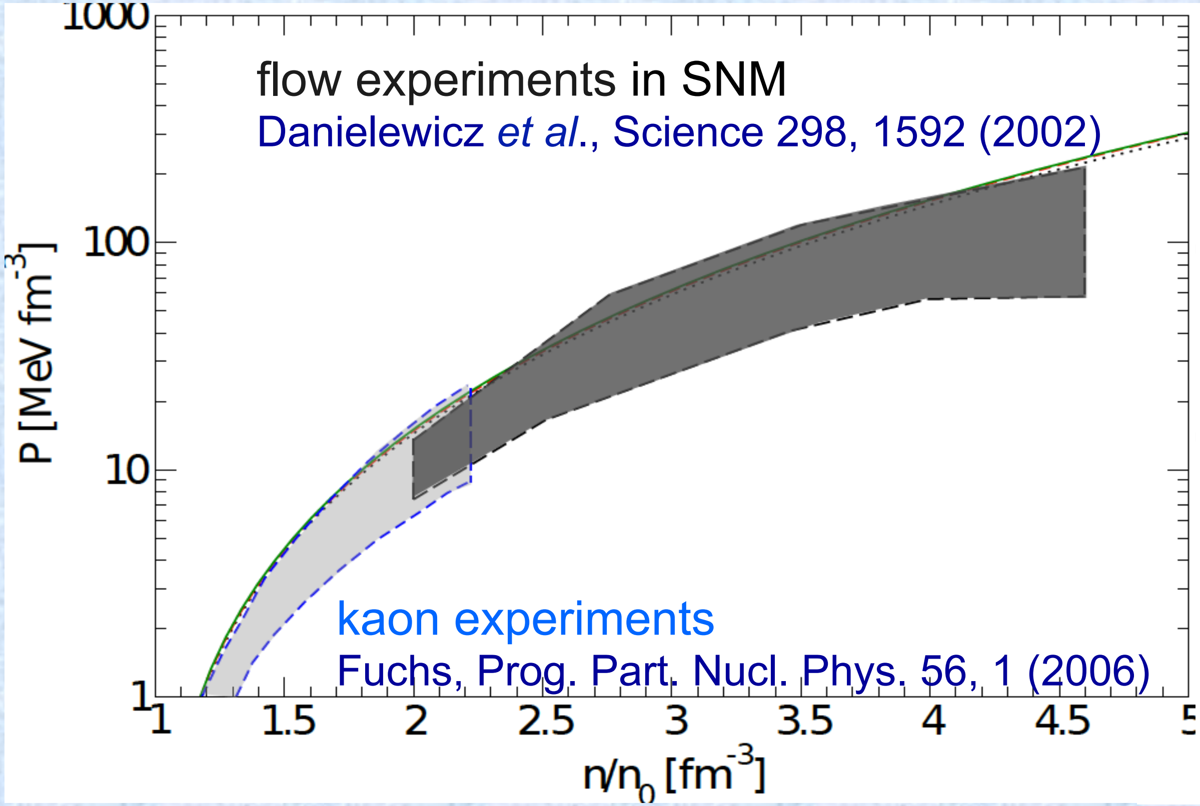

Goriely *et al.*, PRC 82, 035804 (2010)

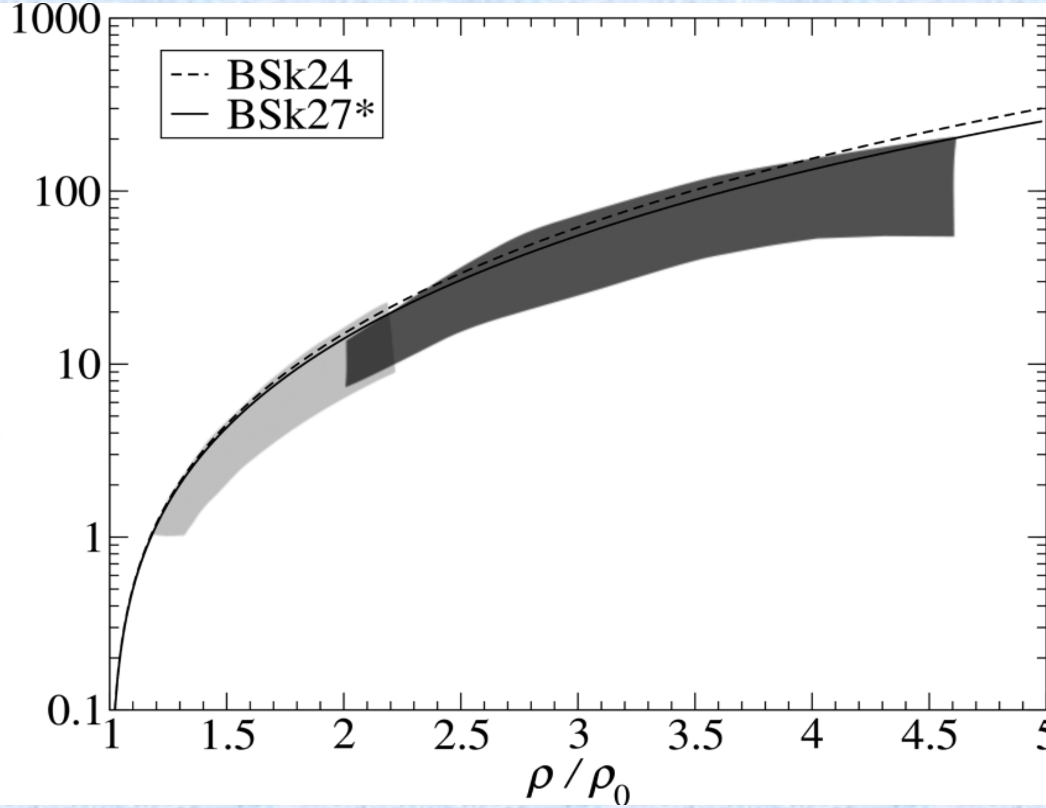



Goriely *et al.*, PRC 88, 024308 (2013)

BSk** fitted to realistic neutron-matter EoSs with different stiffness and agree with more microscopic calculations

# Constraints from nuclear physics: experiments (symmetric nuclear matter)



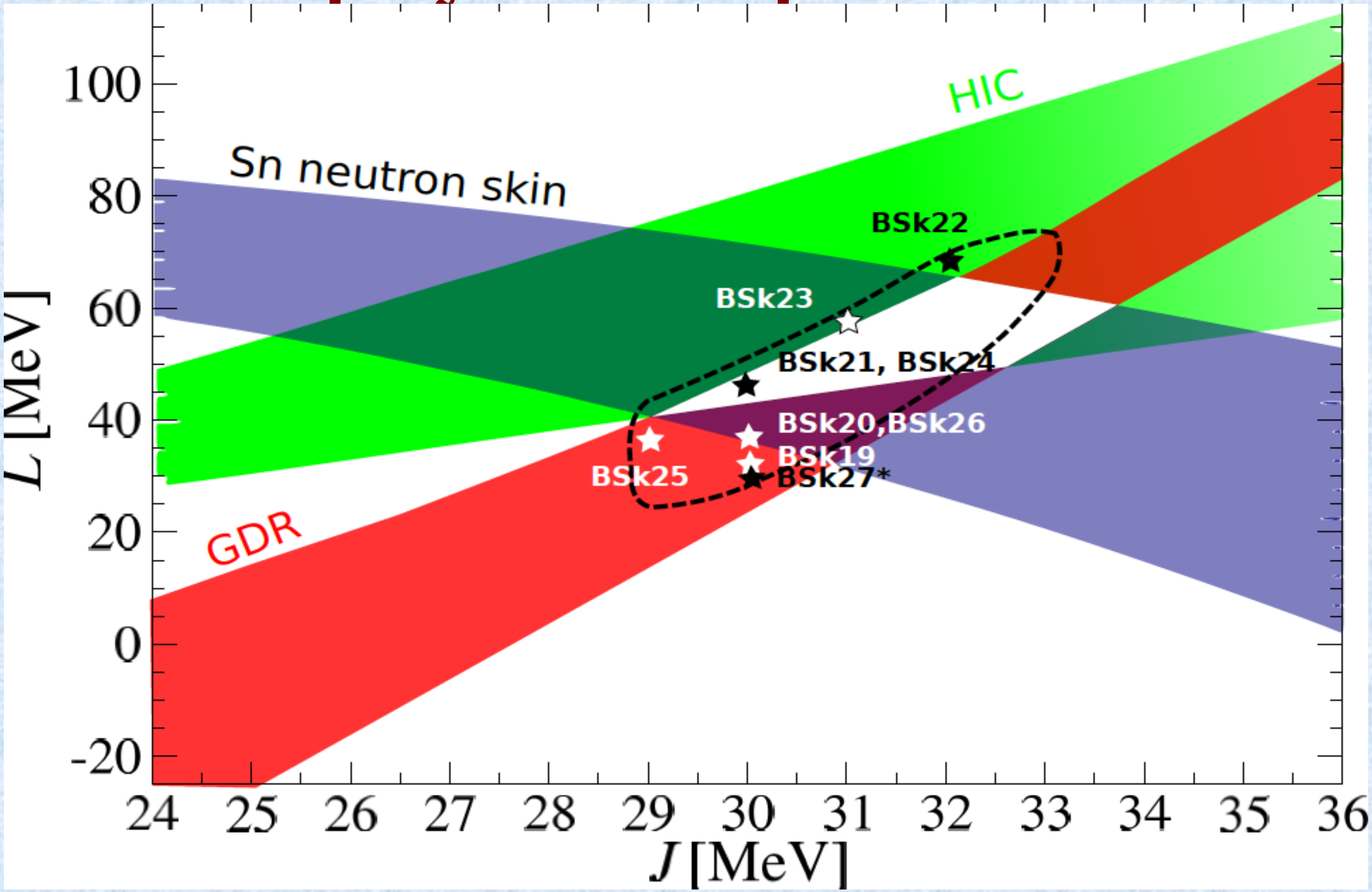




Goriely *et al.*, PRC 88, 061302 (2013)

Functionals in good agreement with "experimental" constraints on symmetric matter

N.B.: deduced constraints are not direct experimental data, are model dependent!

# Comparison with observables from nuclear physics experiments

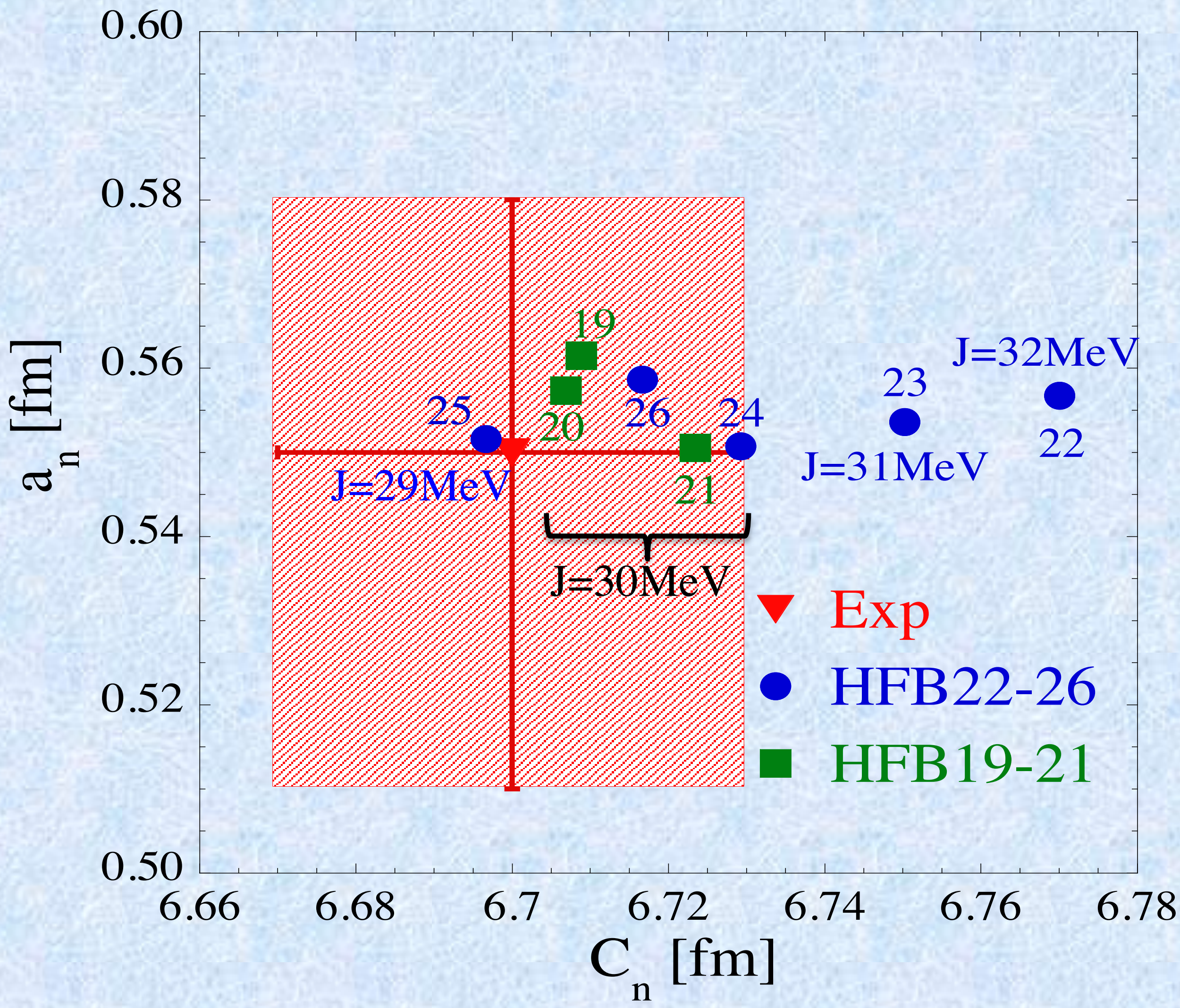



→ *J*,*L* consistent with experimental constraints

Potekhin, Fantina, Chamel *et al.*,
A&A 560, A48 (2013) for BSk19-20-21 models
Fantina *et al.*, AIP Conf. 1645, 92 (2015)

Tsang et al., PRC 86, 015803 (2012);
Lattimer and Lim , ApJ 771, 51 (2013);
Lattimer & Steiner, EPJ A 50, 40 (2014)

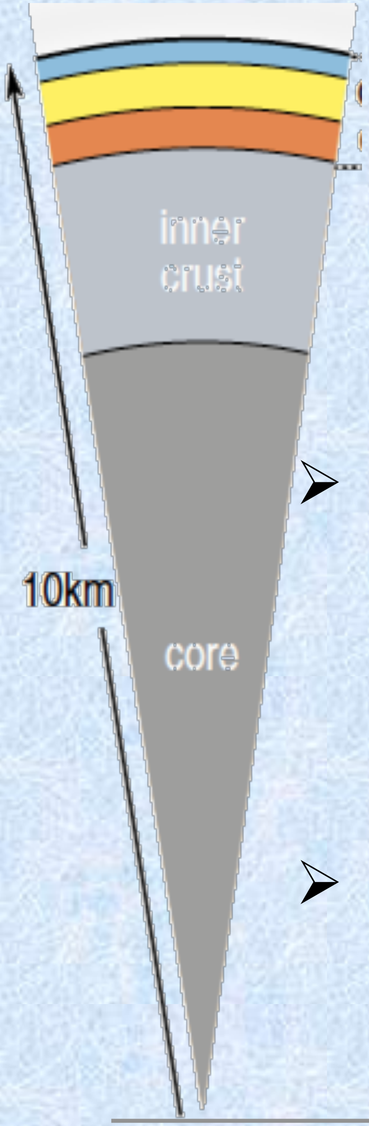
# Comparison with observables from nuclear physics experiments




diffuseness vs. half-height radius in $^{208}$Pb (Tarbert et al., PRL 112, 242502 (2014))

high values of *J* seem disfavoured

# EoS of neutron star




- OUTER CRUST (up to neutron drip) (J. M. Pearson *et al.*, PRC83, 065810 (2011))
  - → one nucleus (bcc lattice) + $e^-$ ($\beta$ equilibrium)
  - → minimization of the Gibbs energy per nucleon: <u>BPS model</u>

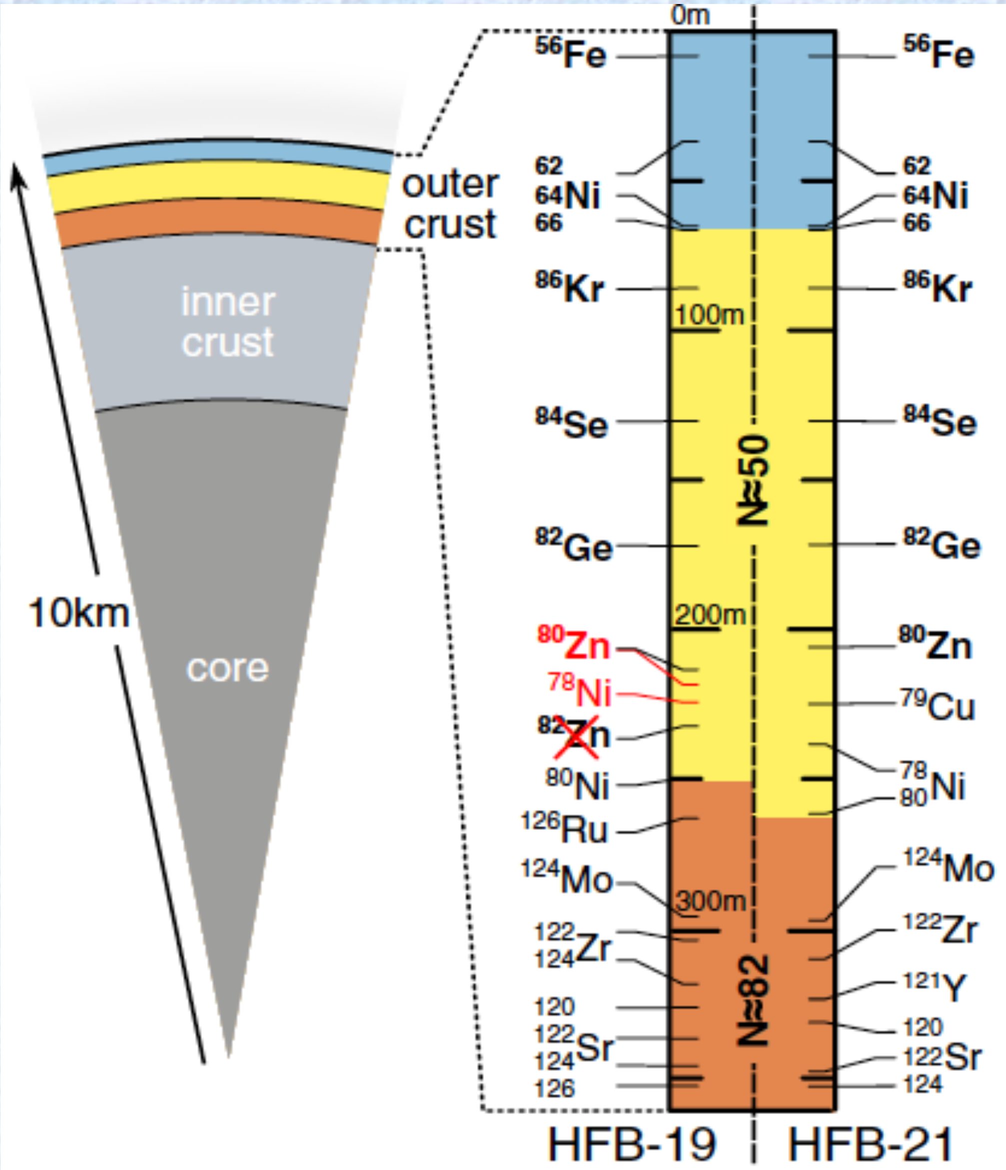
Only microscopic inputs are nuclear masses
→ Experimental or microscopic mass models HFB19-27

- INNER CRUST (Pearson *et al.*, PRC85, 065803 (2012))
  - → one cluster (spherical) + n, $e^-$ ($\beta$ equilibrium)
  - → semi-classical model: <u>Extended Thomas Fermi</u> (4th order in $\hbar$) <u>+ proton shell corrections</u>

- CORE (Goriely *et al.*, PRC 82, 035804 (2010), Goriely *et al.*, PRC 88, 024308 (2013))
  - → homogeneous matter: n, p, $e^-$, $\mu$ ($\beta$ equilibrium) *
  - → <u>*same*</u> 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)

# EoS for NS: importance of exp. masses



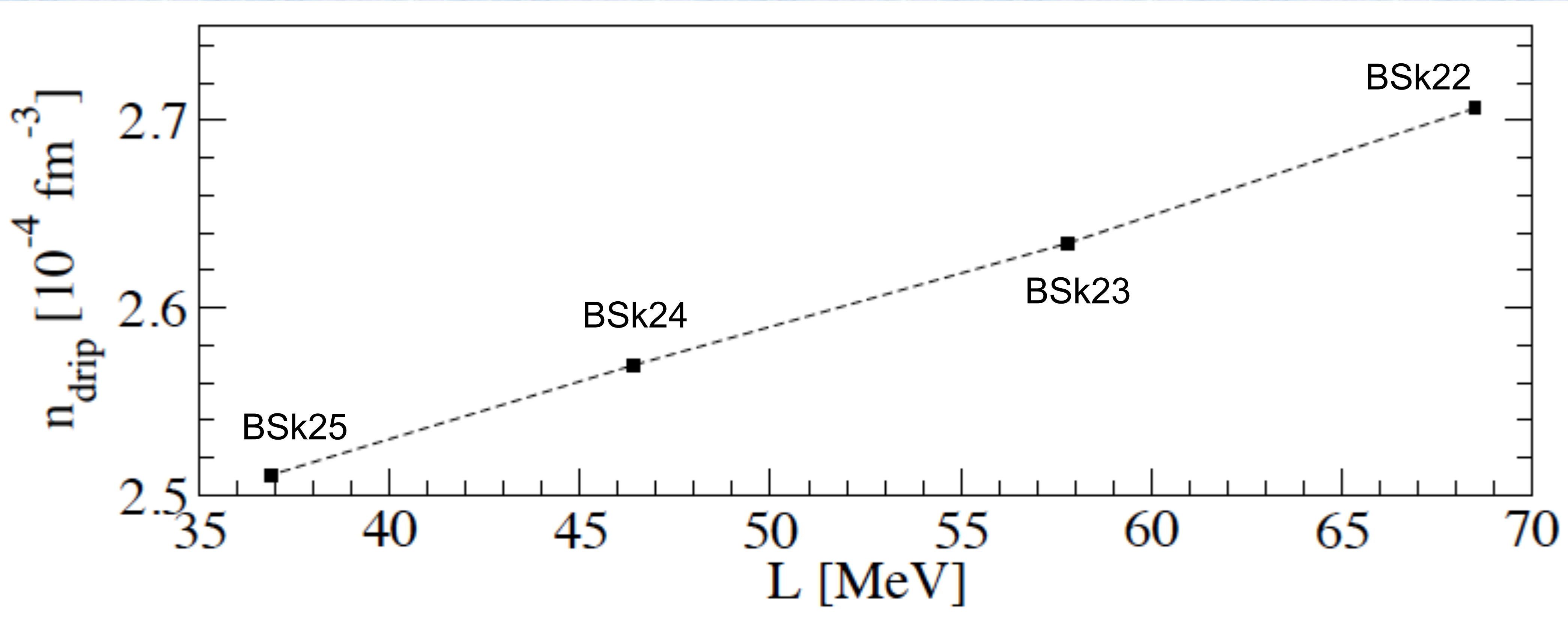

Wolf *et al.*, PRL 110, 041101 (2013); see also Kreim *et al.* (2013)

≈ 200 m (first eight rows)

| HFB-19 | HFB-20 | HFB-21 | HFB-27* |
|---|---|---|---|
| $^{56}$**Fe** | $^{56}$**Fe** | $^{56}$**Fe** | $^{56}$**Fe** |
| $^{62}$**Ni** | $^{62}$**Ni** | $^{62}$**Ni** | $^{62}$**Ni** |
| $^{64}$**Ni** | $^{64}$**Ni** | $^{64}$**Ni** | $^{64}$**Ni** |
| $^{66}$**Ni** | $^{66}$**Ni** | $^{66}$**Ni** | $^{66}$**Ni** |
| $^{86}$**Kr** | $^{86}$**Kr** | $^{86}$**Kr** | $^{86}$**Kr** |
| $^{84}$**Se** | $^{84}$**Se** | $^{84}$**Se** | $^{84}$**Se** |
| $^{82}$**Ge** | $^{82}$**Ge** | $^{82}$**Ge** | $^{82}$**Ge** |
| $^{80}$**Zn** | $^{80}$**Zn** | $^{80}$**Zn** | $^{80}$**Zn** |
| $^{82}$Zn | $^{82}$Zn | - | - |
| - | - | $^{79}$Cu | - |
| | $^{78}$Ni | $^{78}$Ni | $^{78}$Ni |
| $^{80}$Ni | $^{80}$Ni | $^{80}$Ni | - |
| $^{126}$Ru | $^{126}$Ru | - | $^{126}$Ru |
| $^{124}$Mo | $^{124}$Mo | $^{124}$Mo | $^{124}$Mo |
| - | $^{122}$Mo | - | - |
| $^{122}$Zr | $^{122}$Zr | $^{122}$Zr | $^{122}$Zr |
| $^{124}$Zr | $^{124}$Zr | - | $^{124}$Zr |
| - | - | $^{121}$Y | - |
| $^{120}$Sr | $^{120}$Sr | $^{120}$Sr | $^{120}$Sr |
| $^{122}$Sr | $^{122}$Sr | $^{122}$Sr | $^{122}$Sr |
| $^{124}$Sr | $^{124}$Sr | $^{124}$Sr | - |
| $^{126}$Sr | $^{126}$Sr | - | - |

Pearson *et al.*, PRC83, 065810 (2011)
Chamel, Pearson, Fantina, *et al.*, Acta Phys. Pol. B 46, 349 (2015)

# NS outer-inner crust boundary: *n drip*



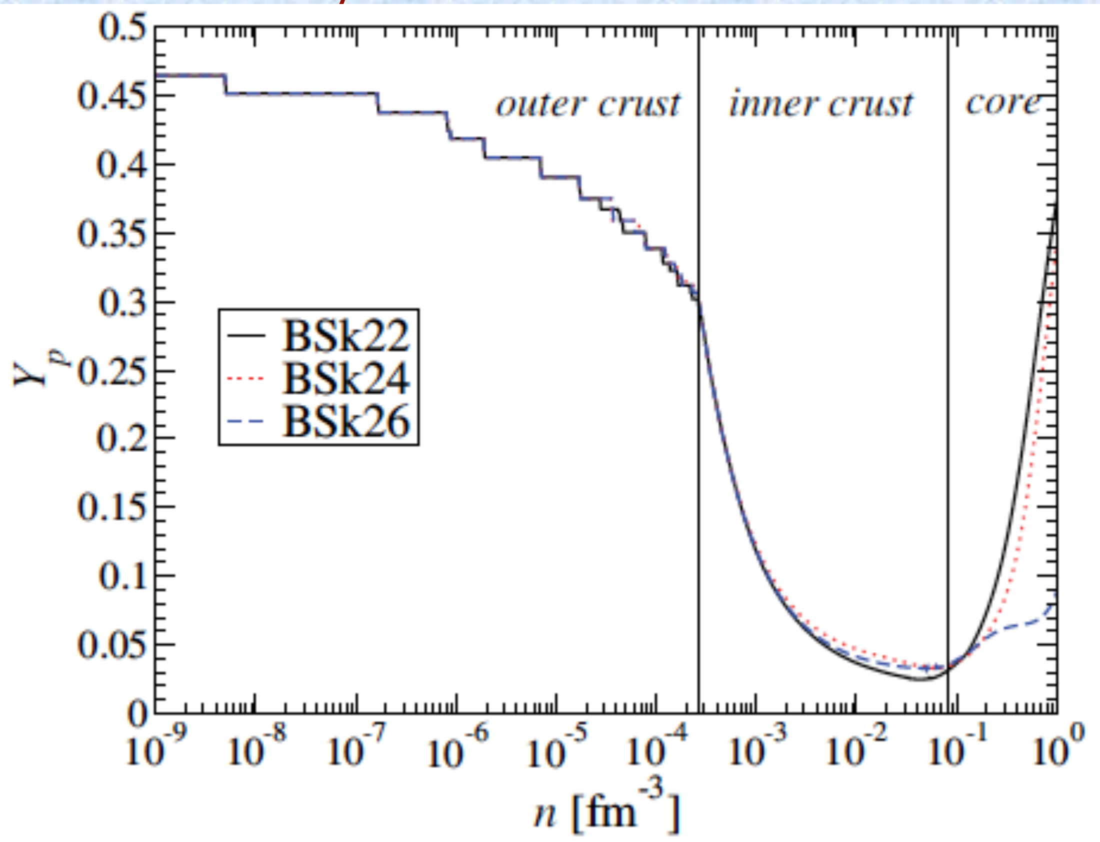

PRELIMINARY! (article in preparation)

see also: Chamel, Fantina, Zdunik, Haensel, PRC 91, 055803 (2015)

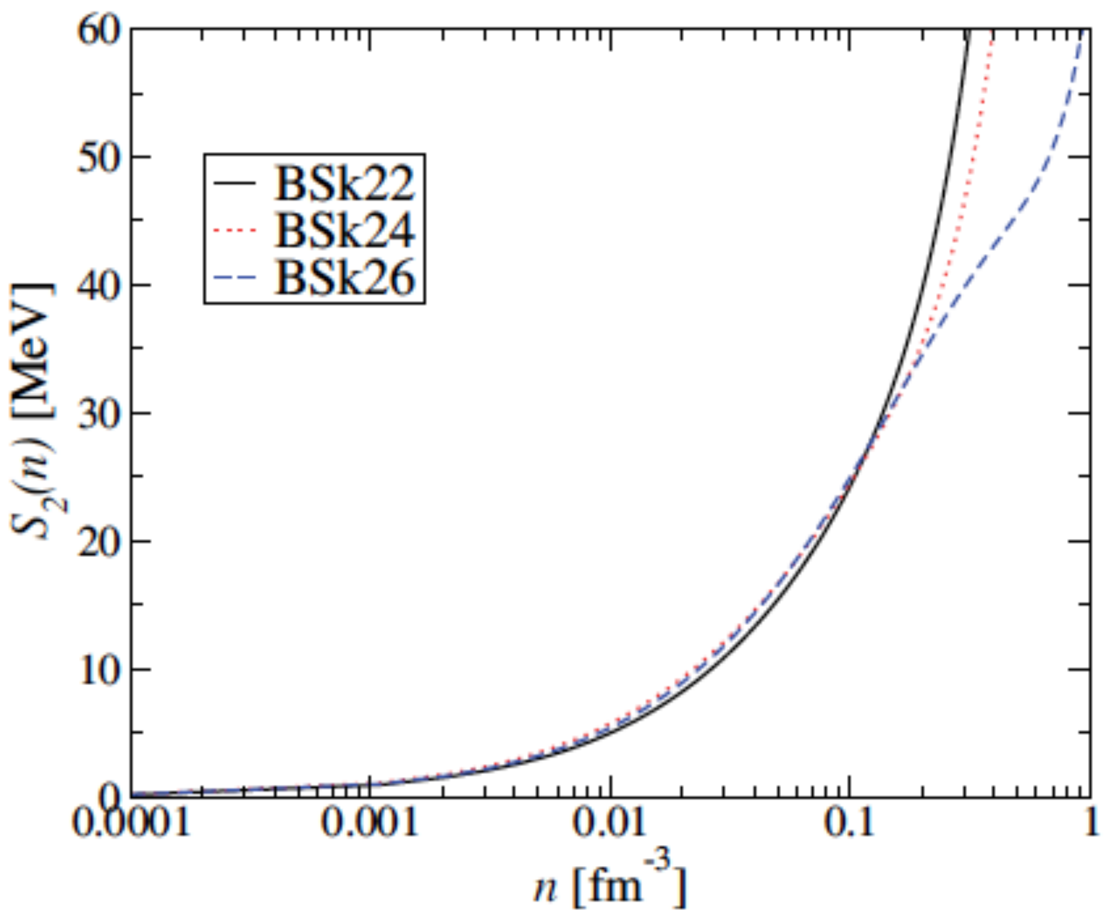
# $Y_p$ and Direct URCA process

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

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




| | $n_{du}$ | $\mathcal{M}_{du}/\mathcal{M}_\odot$ |
|---|---|---|
| BSk22 | 0.33 | 1.14 |
| BSk24 | 0.45 | 1.59 |
| BSk26 | 1.46 | – |




Pearson, Chamel, Fantina, Goriely, Eur. Phys. J. A 50, 43 (2014)

# Computing the NS structure

- Nuclear models: **BSk 19-20-21** & **BSk 22-23-24-25-26**

  → microscopic mass models that fit:

  - available nuclear experimental mass data
  - nuclear-matter properties from microscopic calculations

- Build the NS:

  - **non-rotating NS** → solve Tolman-Oppenheimer-Volkoff (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

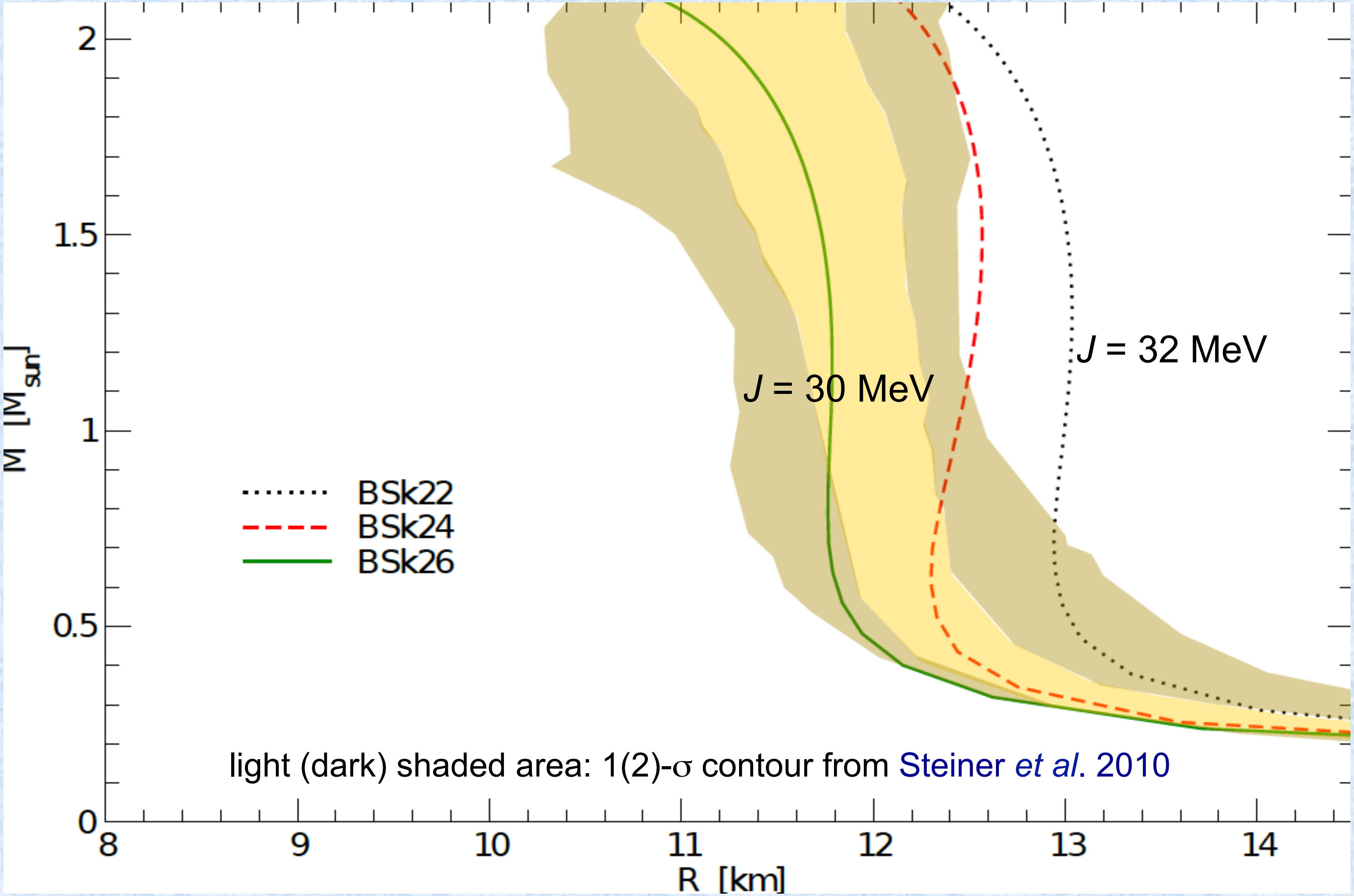
  - **rigidly rotating** NSs

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

*Code*: **LORENE** library (http://www.lorene.obspm.fr)
developed at Observatoire de Paris-Meudon

Refs on LORENE: Gourgoulhon, arXiv: 1003.5015 (lectures given at 2010 CompStar school)
Gourgoulhon *et al.*, A&A 349, 851 (1999)
Granclément & Novak, Liv. Rev. Relativ. 12, 1 (2009)

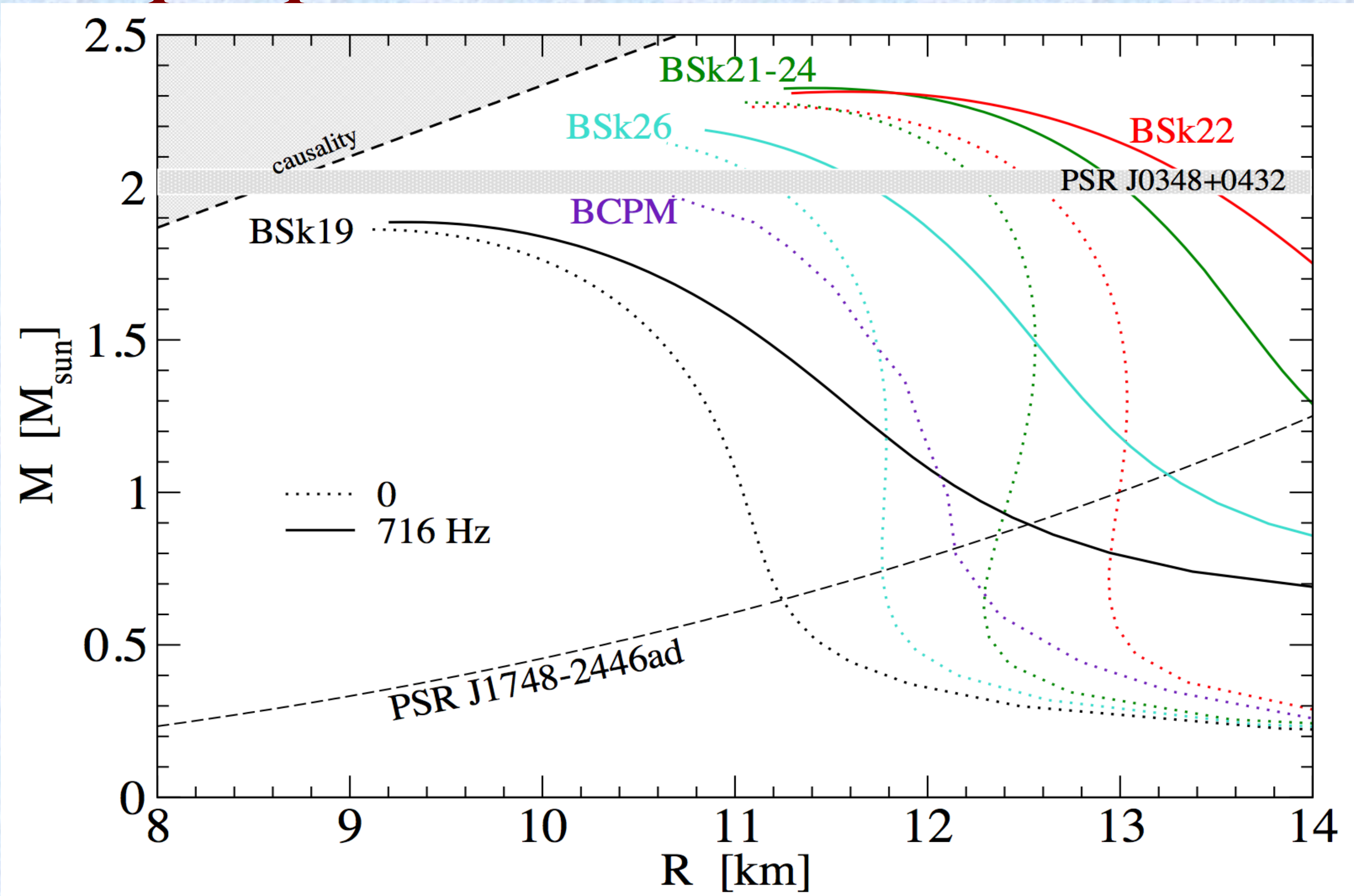
# NS properties: *M-R relation*




Pearson, Chamel, Fantina, Goriely, Eur. Phys. J. A 50, 43 (2014)

BSk24, 26 compatible with astrophysical "observations"

# NS properties: *M-R relation with rotation*




for BSk19-20-21, see Fantina *et al.*, Astron. Astrophys. 559, A128 (2013)

BSk21-22-24-26 compatible with observations

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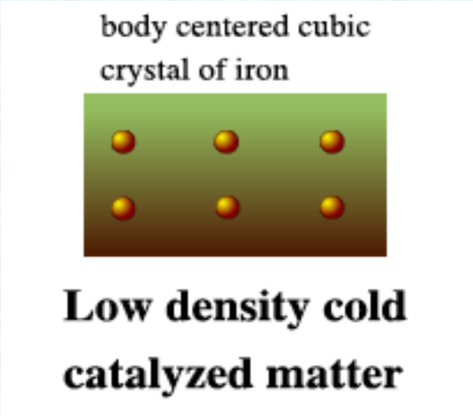
# NS crust: catalysed vs accreted

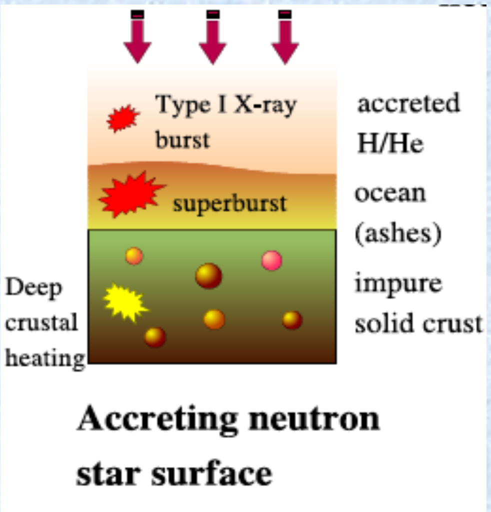
## ➢ Catalysed matter




- NS born a high T ≈ $10^{11}$ K → "hot" scenario
- **full thermodynamical equilibrium at T=0**
- ground state of matter
  → minimise Gibbs energy wrt Z,A
- no exothermic reactions possible

see e.g. Baym *et al*., ApJ 170, 299 (1971)

## ➢ Accreted matter

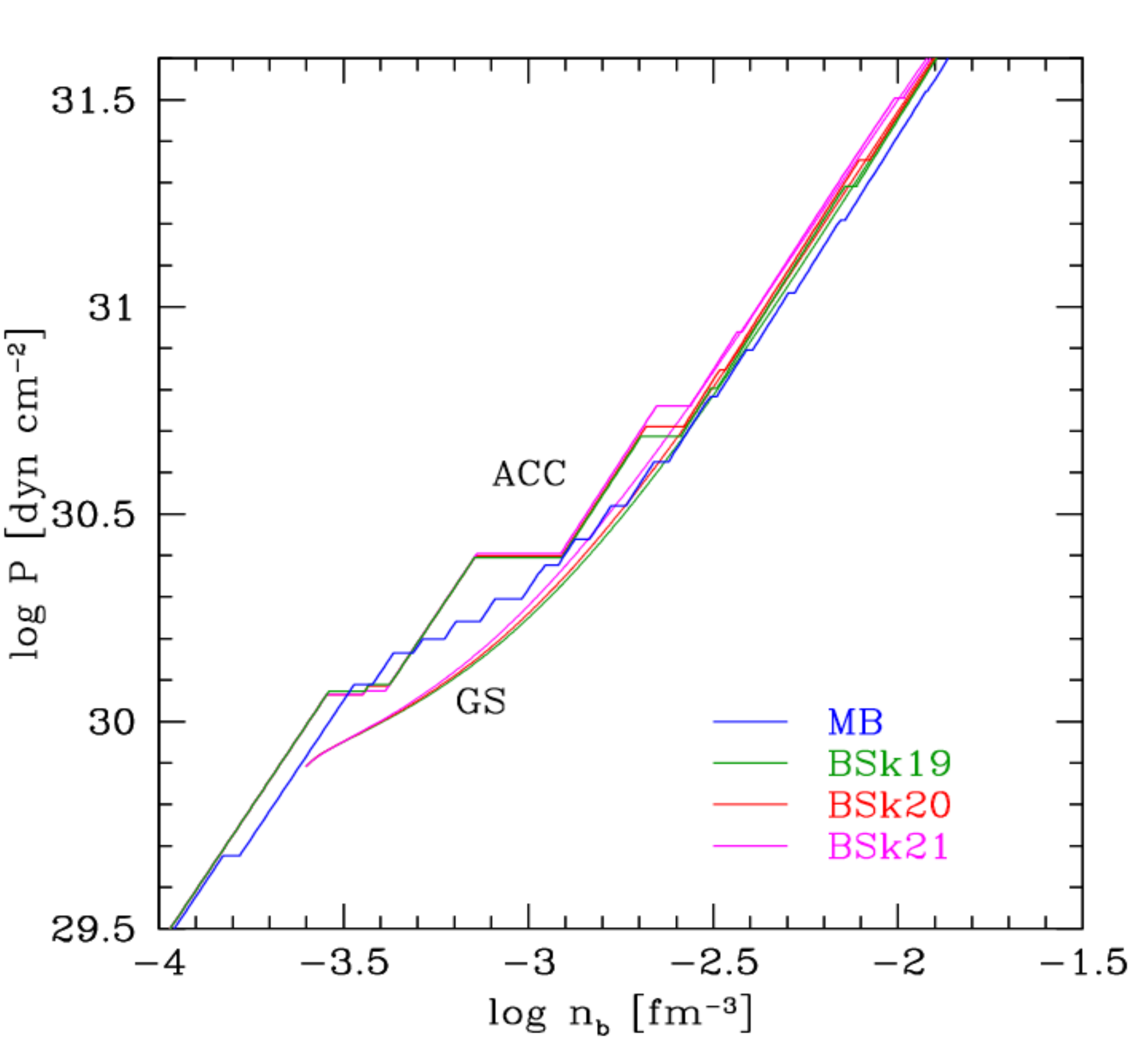



- T < $10^9$ K → "cold" scenario
- **matter off-equilibrium** (local min of E)
  → minimum wrt neighbours N,Z at const. A
- EC, n emission, pycnonuclear possible
- exothermic reactions possible → energy sources
  → can explain thermal radiation in SXTs in quiescence

see e.g. Haensel & Zdunik, A&A 227, 431 (1990);
A&A 229, 117 (1990); A&A 404, L33 (2003) and Refs. therein

for a review: Chamel & Haensel, Living Rev. Relativ. 11, 10 (2008)

# Accreted NS: EoS




EoS for catalysed (GS) and accreted (ACC) crust.

Initial composition: $^{56}$Fe ahes

**Accreted crust EoS significantly stiffer than GS one for :**
**$\rho = 5 \times 10^{11} - 6 \times 10^{12}$ g/cm$^3$**

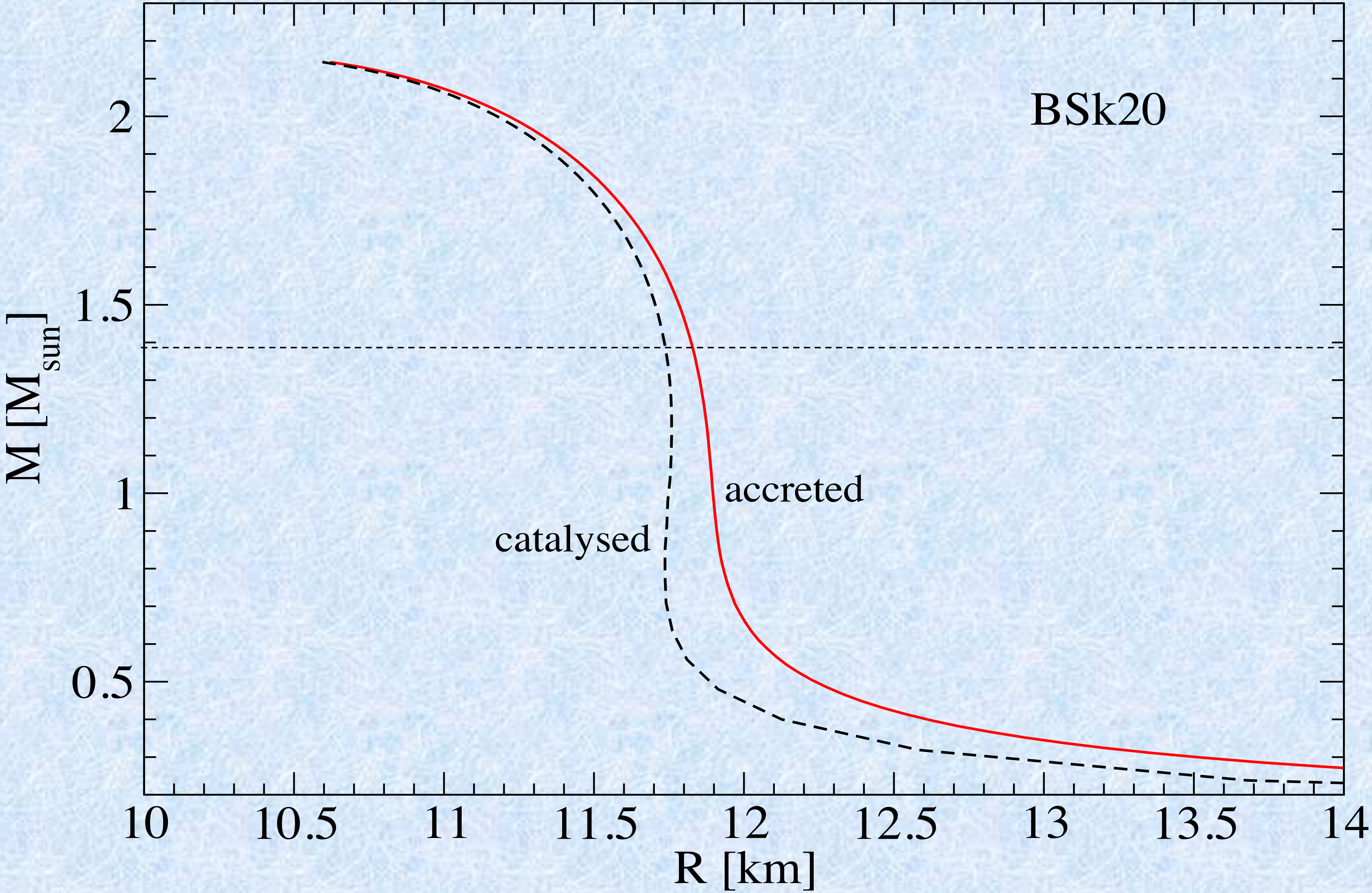
↓

Typically, for 1.4 $M_{sun}$ NS, one expects : $R_{ACC} - R_{GS} \approx 100$ m

(see e.g. Haensel&Zdunik, A&A, 1990)

PRELIMINARY! (Article in preparation). Figure by J. L. Zdunik

# Accreted NS: EoS




PRELIMINARY!

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# Conclusions & Outlooks

- Unified EoSs for NS matter → same nuclear model to describe all regions of NS fitted on *experimental nuclear data* and *nuclear matter properties*
  EoSs based on BSk 21-24-26 consistent with astrophysical observations!

- **Nuclear physics experiments + Astrophysical observations can put constraints on the EoS of dense matter!**
- **Most favoured values seem to be $J \approx 30$ MeV, $L \approx 37 - 46$ MeV**

- EoSs BSk 19-20-21 at T=0 for catalysed matter available as:
  - ***tables*** : Fantina *et al.*, A&A 559, A128 (2013), doi: 10.1051/0004-6361/201321884
  - ***fit*** : Potekhin *et al.*, A&A 560, A48 (2013) at: http://www.ioffe.ru/astro/NSG/BSk/

    Fit: EoS, density profiles, electrical conductivities → can be used in NS calculations!

- Finite T for SN cores
  work in progress with J. M. Pearson, N. Chamel, S. Goriely

- Accreting NS properties
  work in progress with N. Chamel, P. Haensel, J. L. Zdunik


Thank you!
Supernova Remnant 1987A in the Large Magellanic Cloud. HUBBLESITE.org