laboratoire commun CEA/DSM CNRS/IN2P3

Composition and clusters in the neutron-star crust

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J. M. Pearson (Université de Montréal)

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

Fustipen Topical Meeting
GANIL, Caen (France), 17 – 19 May 2016

Outline

- Introduction: NS & EoS
- Effective nuclear models
  - Brussels-Montreal BSk model
- NS composition & clusters
  - outer crust
  - inner crust
- Conclusions

NS: general properties

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 ?

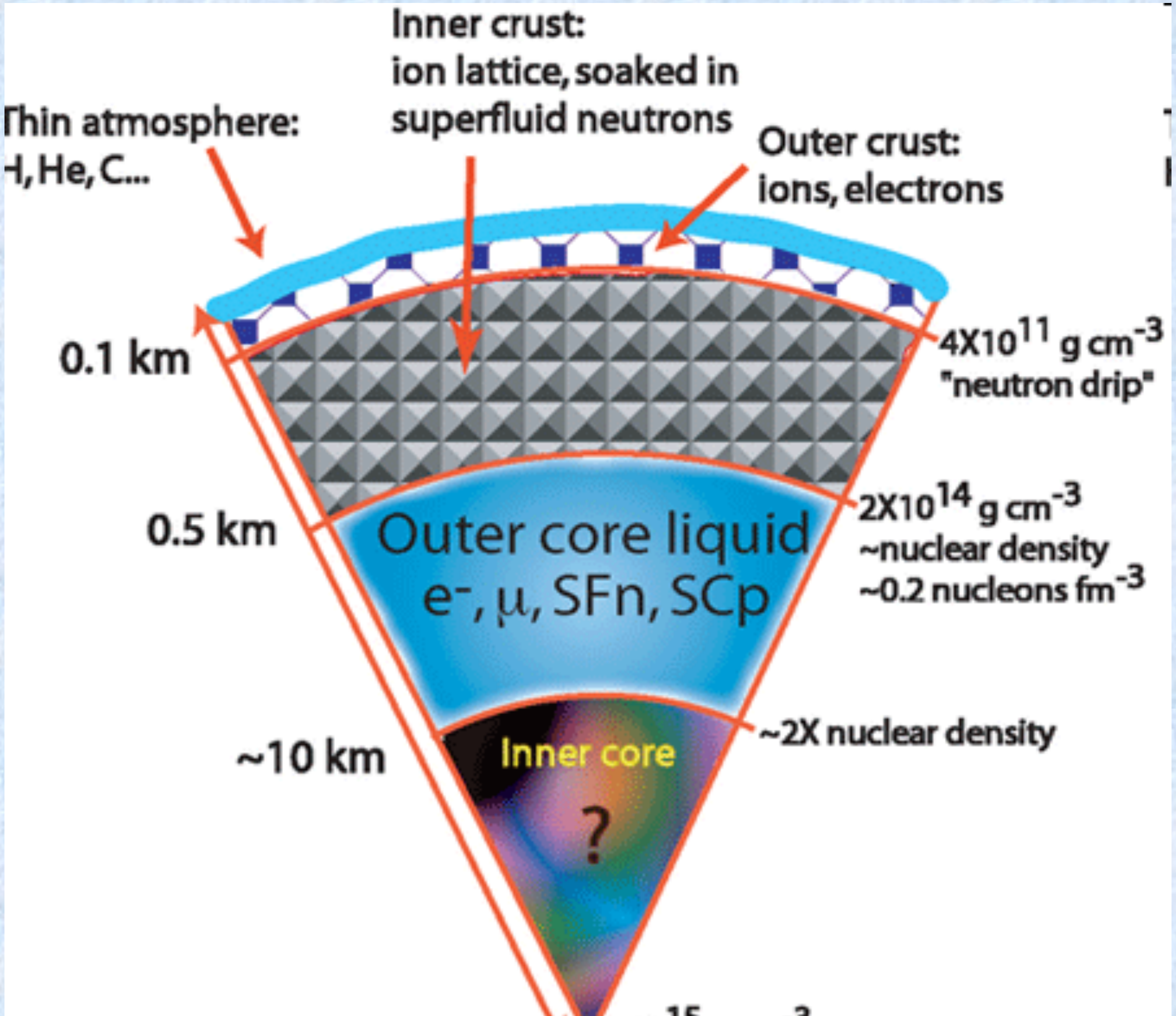
$$M \approx 1 - 2\ M_\odot$$

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

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

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

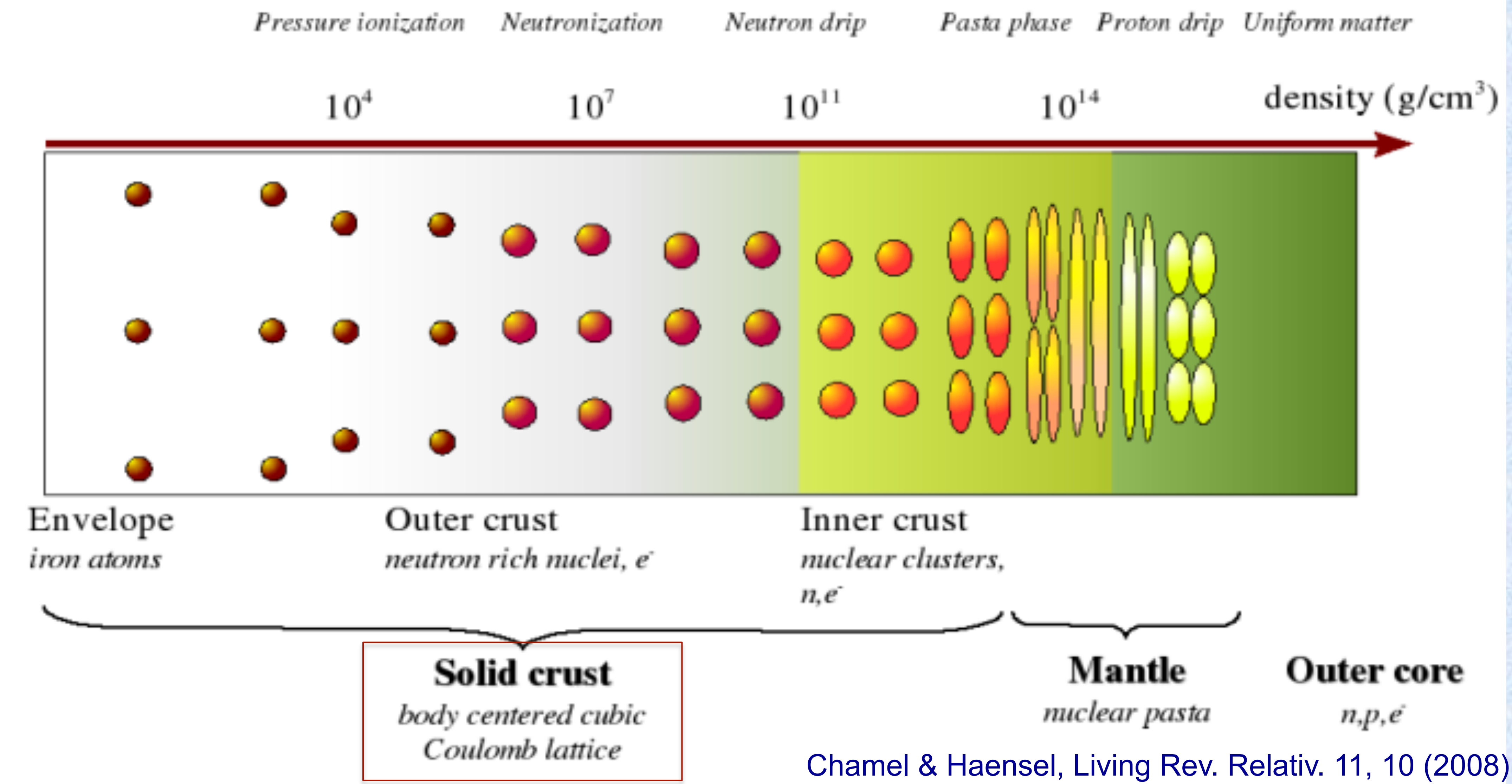
$$B_{\mathrm{surf}}\ \text{up to}\ 10^{14} - 10^{15}\ \mathrm{G} \longrightarrow B_{\mathrm{int}}???$$



http://www.physics.montana.edu

very dense matter, use of GR → UNIQUE “LABORATORIES”!

NS crust structure

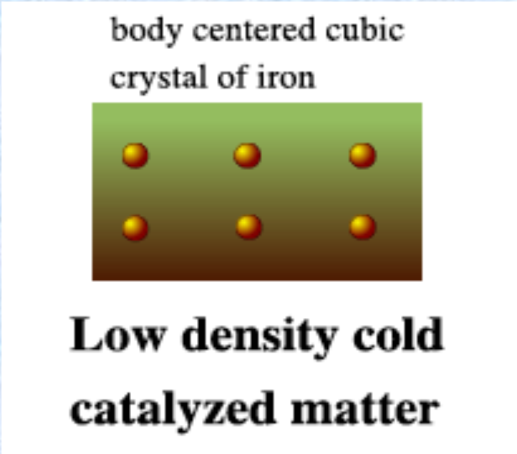


Chamel & Haensel, Living Rev. Relativ. 11, 10 (2008)

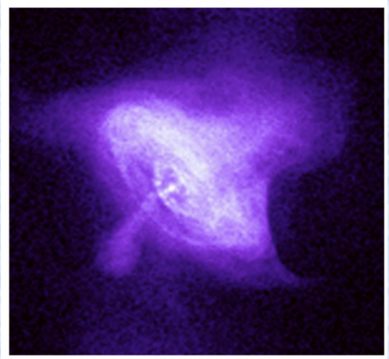
Neutron star crust : ≈ 1% mass, ≈ 10% radius

Different NS crusts

- Catalysed matter

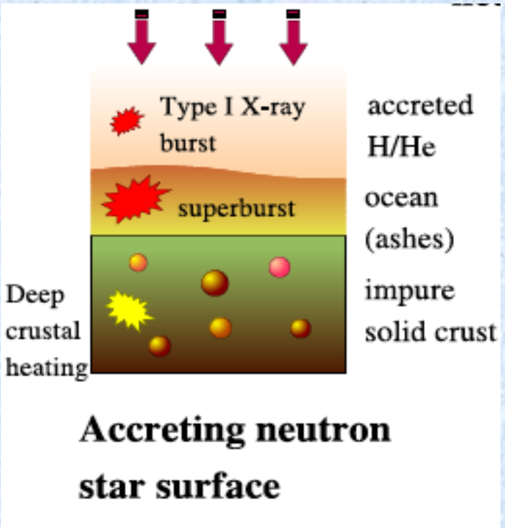


- NS born a high T ≈ 10^{11} K → “hot” scenario
- **full thermodynamical equilibrium at T=0**

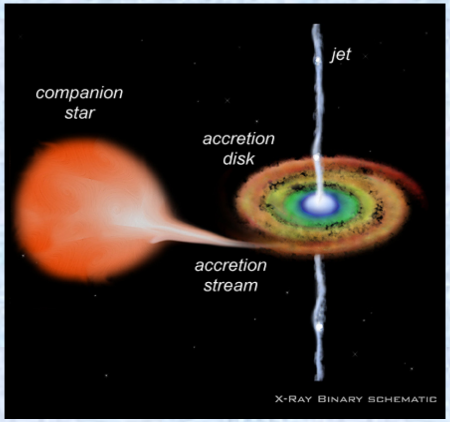


Example of isolated NS
Credits: NASA/CXC/SAO (Crab, X ray)

- Accreted matter



- T < 10^9 K → “cold” scenario
- **matter off-equilibrium** (local min of E)



Artist view of accreting NS

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

Different theoretical approaches

Phenomenological approaches

- Based on effective nuclear interactions
- Parameter adjusted to reproduced nuclear properties

- ➢ Liquid drop models (e.g. BBP 1971, Douchin&Haensel 2001, LS, Oertel *et al*. 2012 T>0)
- ➢ Semi-classical models: (Extended) Thomas-Fermi (e.g. Onsi *et al*. 2008, Shen 1998)
- ➢ Self-consistent mean-field models : Hartree-Fock / Hartree-Fock Bogoliubov (e.g. Negele&Vautherin 1973, Baldo *et al*. 2007, Grill *et al*. 2011)
  RMF (with and w/o hyperons) (e.g. Weissenborn *et al*. 2012, Bednarek *et al*. 2012)
- ➢ Nambu-Jona-Lasinio (quark) (e.g. Zdunik&Haensel 2013, Blaschke *et al*. 2010, Bonanno&Sedrakian 2012)
- ➢ (Modified) Bag Model of quark (e.g. Weissenborn *et al*. 2011)

Microscopic approaches

- Based on quantum many-body theories from realistic nuclear interactions (→ *ab-initio* methods)
- But : not (yet) affordable for the crust

- ➢ Variational methods (e.g. APR 1998)
- ➢ (Dirac) Brueckner Hartree-Fock (e.g. Sammaruca 2010, Li&Schulze 2008, Fuchs 2008, Vidaña *et al*. 2011, Burgio *et al*. 2011)
- ➢ Perturbative QCD (e.g. Kurkela *et al*. 2010)
- ➢ Monte Carlo (e.g. Carlson *et al*. 2003, Gandolfi *et al*. 2012)

N.B. : Non-exhaustive list!!!
for a review, e.g. : Haensel, Potekhin, Yakovlev, "*Neutron Stars 1*" (Springer, 2007)

Properties of nuclear matter

In applying nuclear models in astrophysics → two kinds of quantities :

1. **Thermodynamic variables** → physical conditions in the star (e.g. *P, T, B, ...*)
2. **Nuclear parameters** → properties of nuclear matter around saturation at *T=0*

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

$$E(n,\eta) = E(n_0, \eta = 0) + \frac{1}{2} K_\infty \left(\frac{n - n_0}{3 n_0} \right)^2 + E_{\rm sym}$$

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

$$S_1(n) = \frac{1}{2} \frac{\partial^2 (\mathcal{E}/n)}{\partial \eta^2} \bigg|_{\eta=0} \approx J + \frac{1}{3} L \left(\frac{n - n_0}{n_0} \right) + \frac{1}{18} K_{\rm sym} \left(\frac{n - n_0}{n_0} \right)^2$$

$$\neq$$

$$S_2(n) = \frac{\mathcal{E}(n, \eta = 1) - \mathcal{E}(n, \eta = 0)}{n}$$

$$\eta = \frac{n_n - n_p}{n}$$

Properties of nuclear matter

In applying nuclear models in a…

1. **Thermodynamic variables** →…

2. **Nuclear parameters** → prope…

- Energy around saturation (i…

$$E(n,\eta) = E(n_0,\eta = \ldots$$

- In SN & NS → n-rich matte…

$$S_1(n) = \frac{1}{2}\frac{\partial^2(\mathcal{E}/n)}{\partial\eta^2}\Bigg|_{\eta=0} \approx \ldots$$

$\neq$

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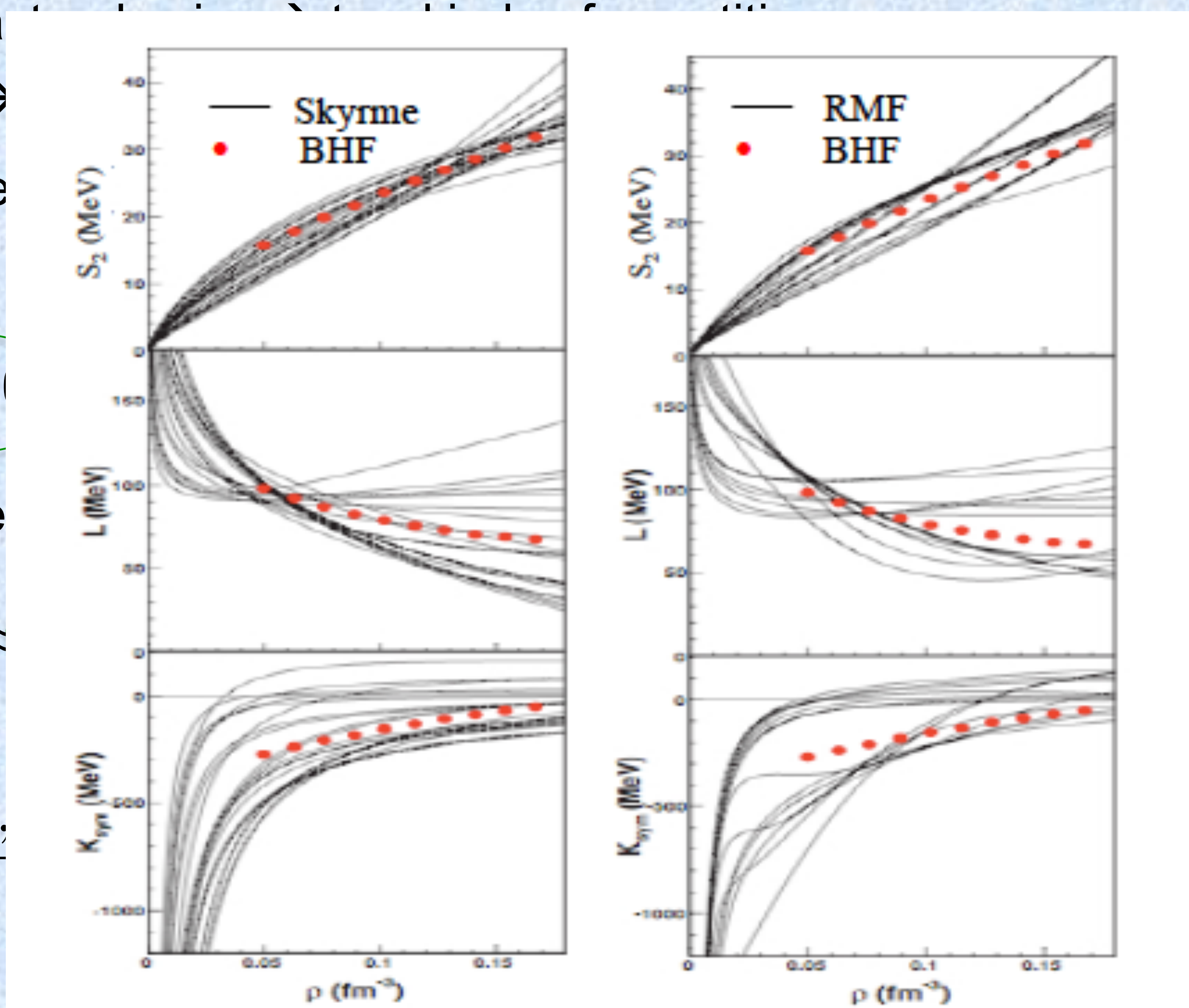


I. Vidana, talk at WG2 meeting NewCompstar(2014)

How can we constrain the EoS ?

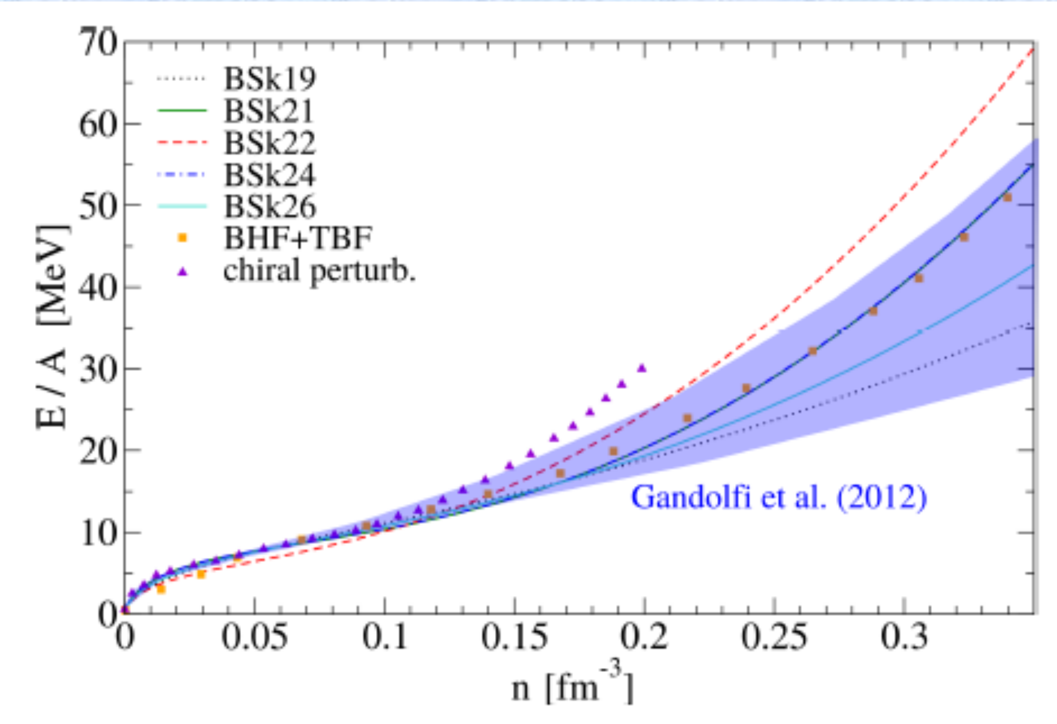
Nuclear physics experiments

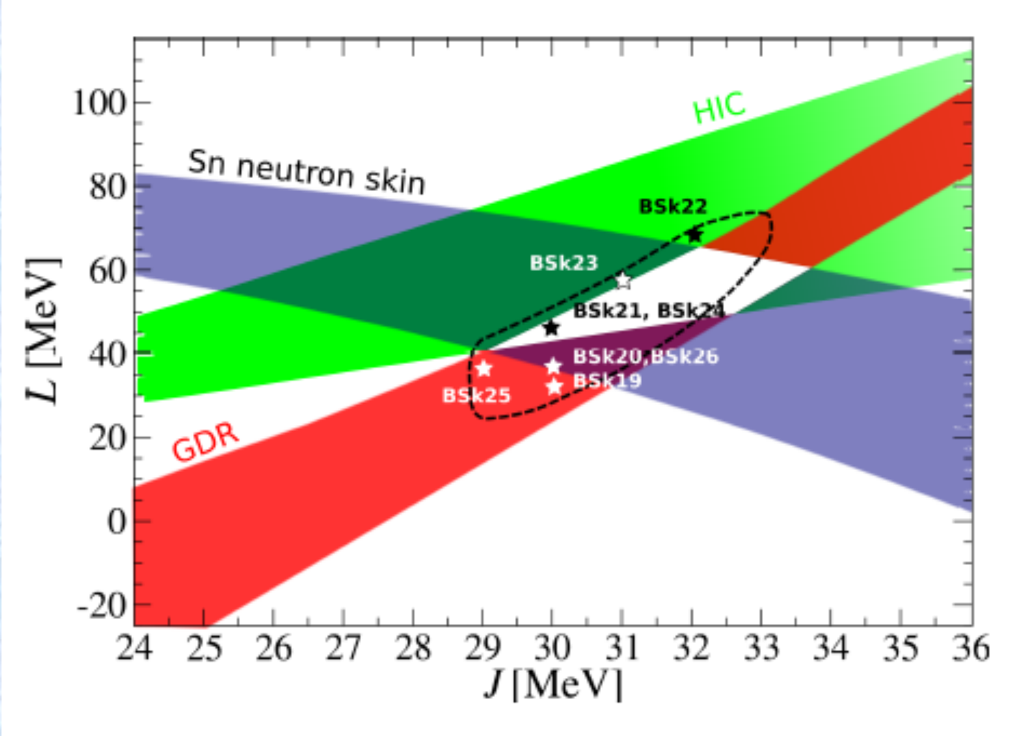
- Measure of **nuclear masses**, radii
- Resonances → K, E_{sym}…
- Heavy ion collision experiments
- ...

\+ *ab-initio* calculations (theory)

Astrophysical observations

- **Measure of NS masses**, radii (!)
- **Rotation**
- Cooling
- moments of inertia, M_b vs M_{grav}
- ...





Fantina *et al.*, EPJ Web of Conf. 66, 07005 (2014); AIP Conf. Proc. 1645, 92 (2015), and Refs. therein

 (see also EPJ 50 (2014) for constraints on symmetry energy)

How can we constrain the EoS ?

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- Measure of **nuclear masses**, radii
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Astrophysical observations

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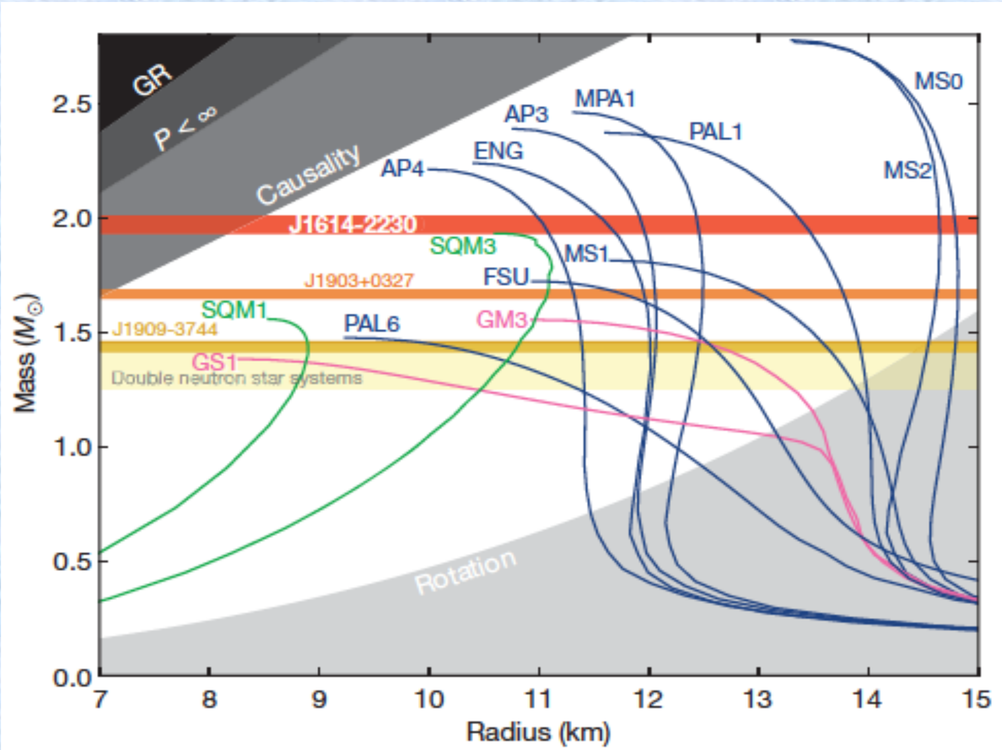

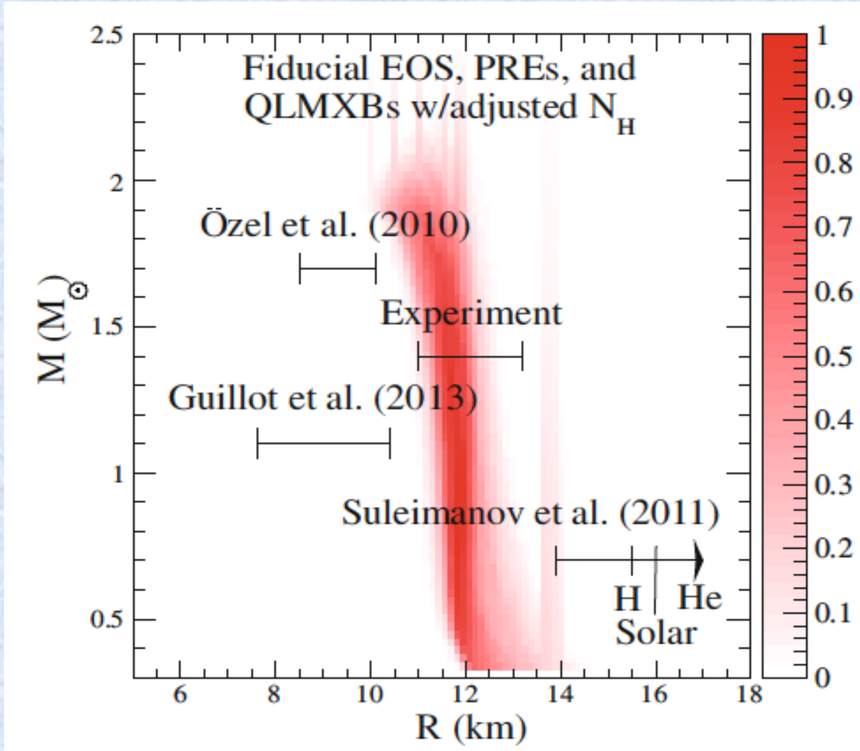

Demorest *et al*., Nature 467, 1081 (2010) ; Lattimer & Steiner, EPJ A50, 40 (2014);
see also Heinke *et al*., MNRAS 444, 443 (2014)

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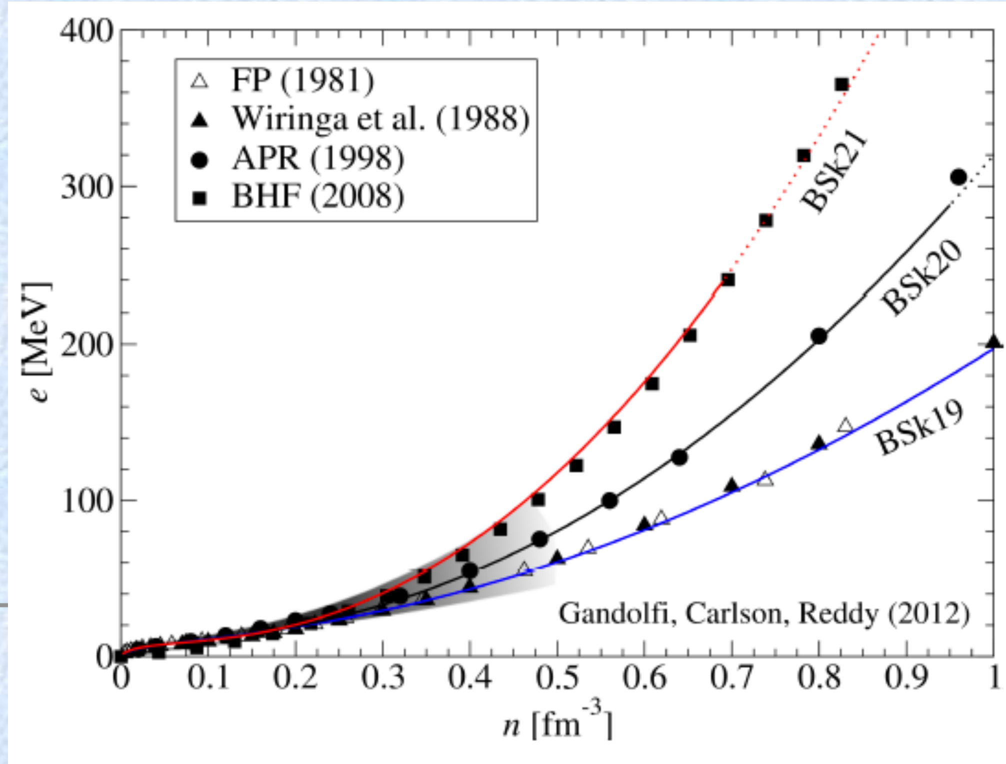
Brussels-Montreal (BSk) functionals

Mass models based on HFB method with Skyrme type energy-density functionals (EDFs) 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_∞ in experimental range (≈ 240 MeV)

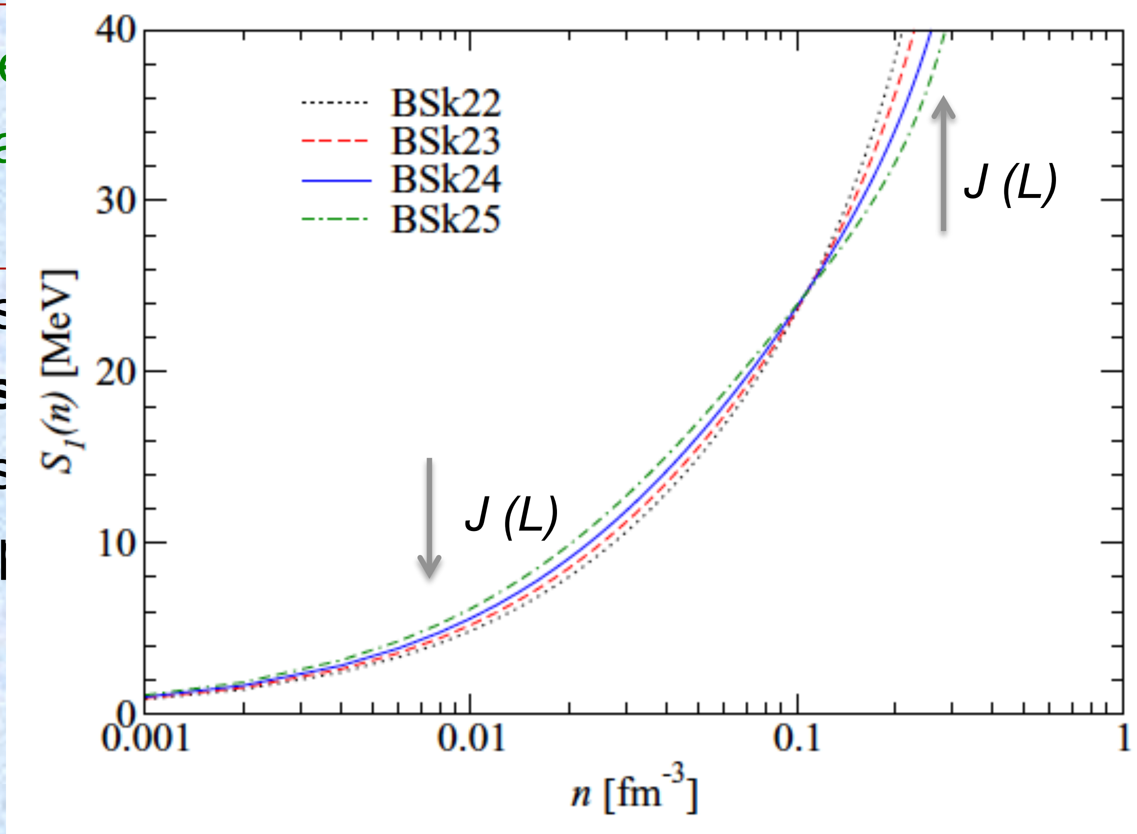
Goriely *et al.*, PRC 82, 035804 (2010)



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

Brussels-Montreal (BSk) functionals

Mass models based on HFB me
functionals (EDFs) and macroscopica
Fitted to experimental data + N-body



BSk19
BSk20
BSk21

- **fit 2010 AME data** (2149 mass
- **different degrees of stiffness**
  constrained to different micros
- all have J = 30 MeV, , K_∞ in exp

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_∞ in experimental range (≈ 240 MeV)

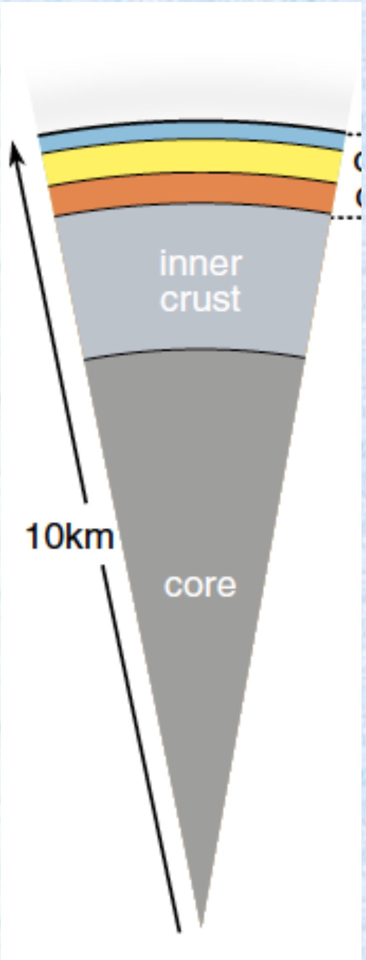
Goriely *et al.*, PRC 88, 024308 (2013)

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

Brussels-Montreal (BSk) functionals

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

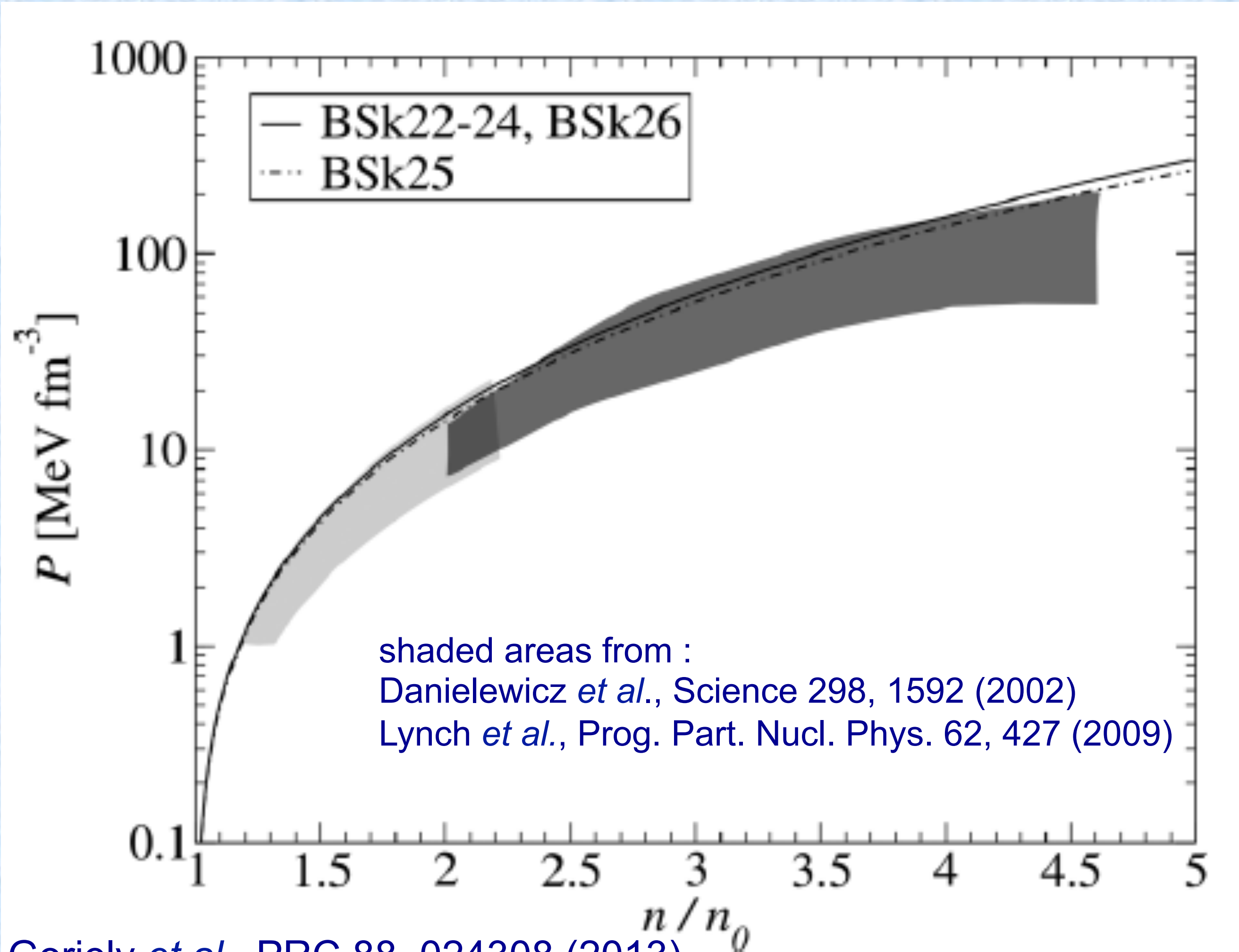
✓ BSk** also used to compute properties of infinite homogeneous nuclear matter



we construct ***unified EoSs*** with these functionals (until now, few unified EoSs! e.g. SLy, BCPM)

- *same nuclear model* to treat different NS regions
- avoid ad-hoc matching procedures at boundaries (see e.g. Fortin *et al*., arxiv:1604.01944v1)
- here: case of "*T = 0*"

Comparison with observables from nuclear physics experiments

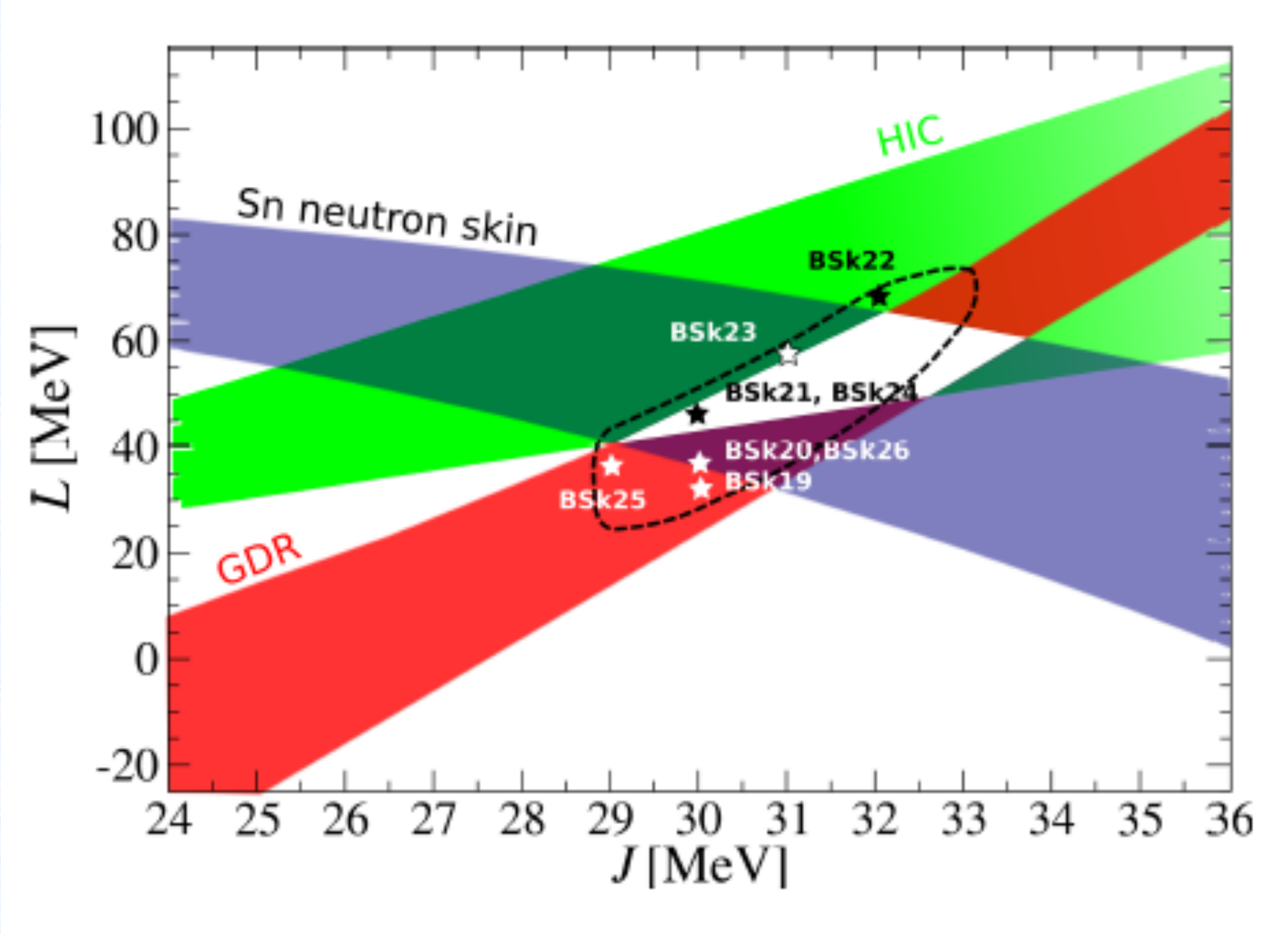


Goriely *et al*., PRC 88, 024308 (2013)

→ Functionals in good agreement with “experimental” constraints on symmetric matter

<u>N.B.</u>: 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)
Fantina *et al.*, AIP Conf. 1645, 92 (2015)
Fantina *et al.*, PRC 93, 015801 (2016)

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

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NS EoS: outer crust (nonaccreting)

Ground state of matter below neutron drip (isolated NSs):

- cold catalysed matter hypothesis → **T = 0**, matter in full thermodynamical equilibrium
- charge neutrality + β equilibrium
- structure made by perfect crystal with ONE nuclear species at lattice sites (e.g. bcc) (A,Z), + electrons (no free neutrons!).

⟶ **BPS** model (Baym, Pethick, Sutherland, ApJ 170, 299 (1971))

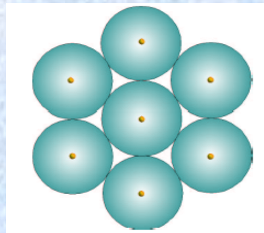
⟶ minimise the Gibbs energy per nucleon: $g = \dfrac{\mathcal{E} + P}{n}$ at constant *P*

where: *n* is the baryon number density,

P is the pressure: $P = P_e + P_L$ (electrons + lattice)

$\mathcal{E}$ is the energy density:

$$\mathcal{E} = n_N M(Z,A)c^2 + \mathcal{E}_e + \mathcal{E}_L$$



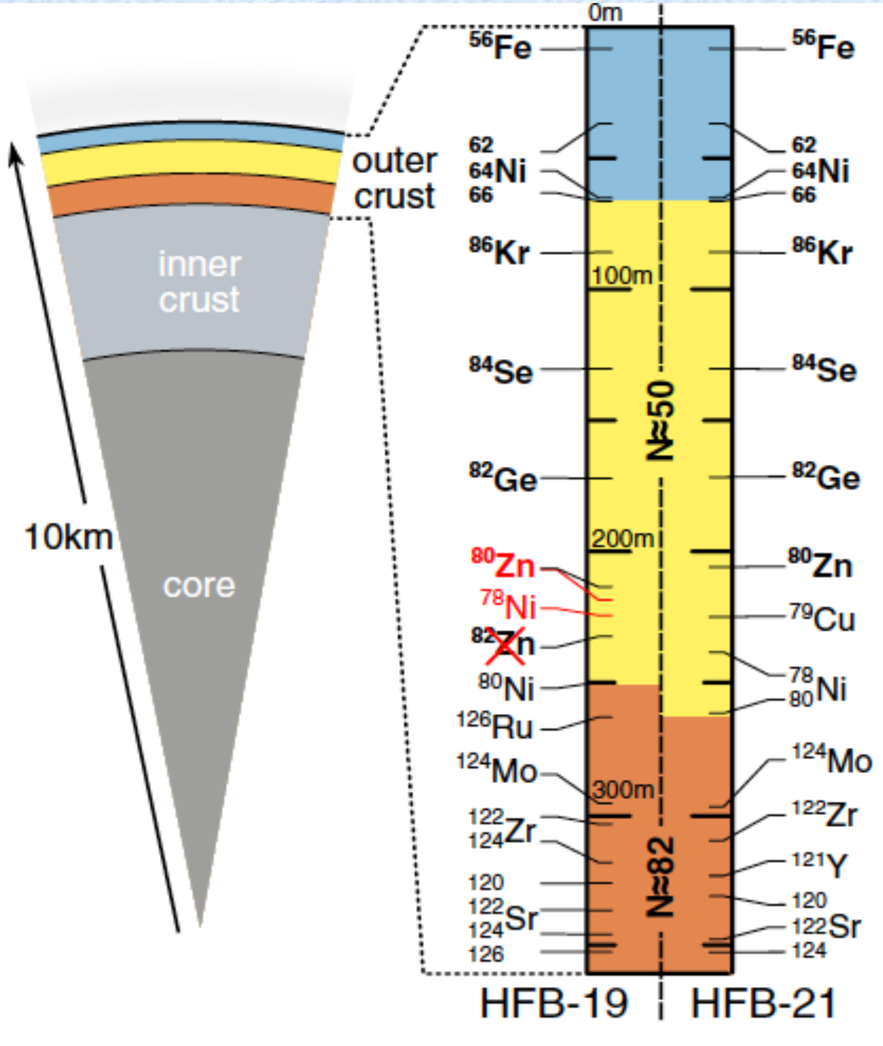
density of nuclei $n_N = n/A$ — **mass of nucleus** (exp or theory) — e^- energy — lattice energy (electrostatic contribution – Wigner-Seitz)

For ref. other calculations of the EoS have been made, e.g.: Harrison & Wheeler (1958), Salpeter, ApJ 134, 669 (1961)

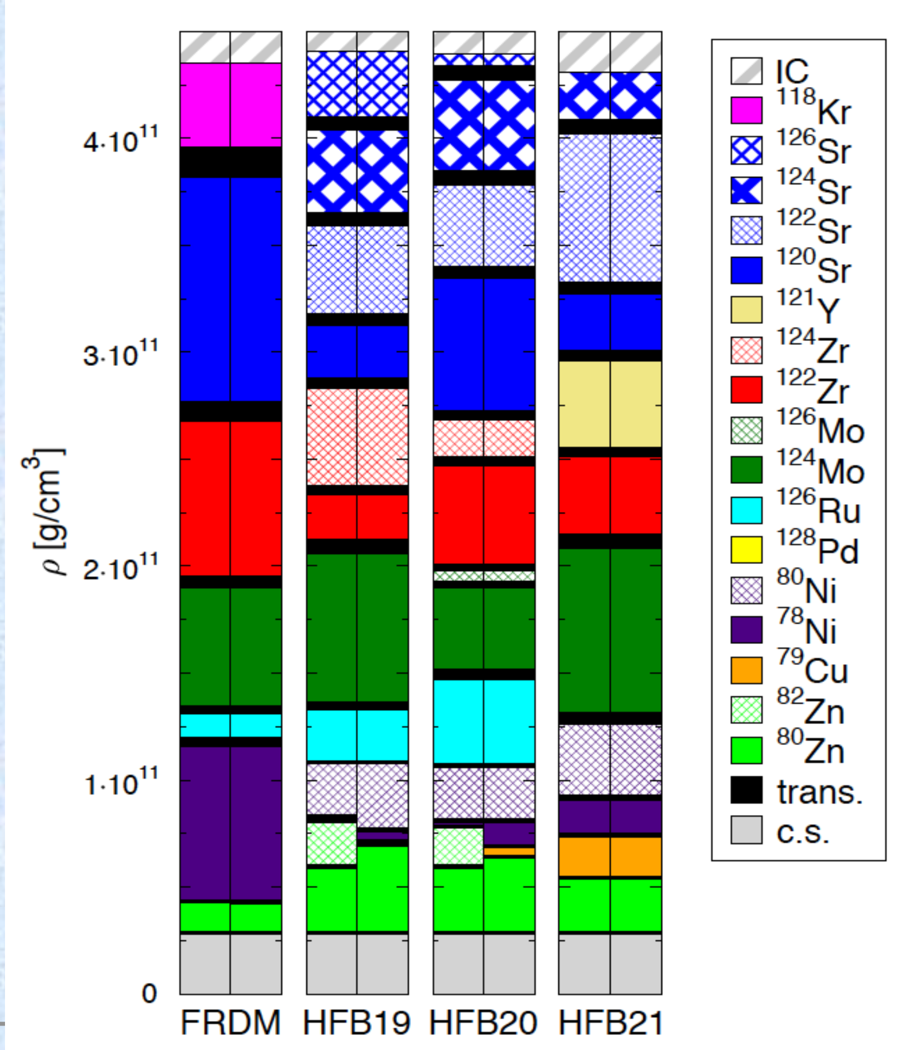
NS EoS: outer crust

$$\mathcal{E} = n_N M(Z,A) c^2 + \mathcal{E}_e + \mathcal{E}_L$$

outer crust structure determined by (measured) masses of n-rich nuclei



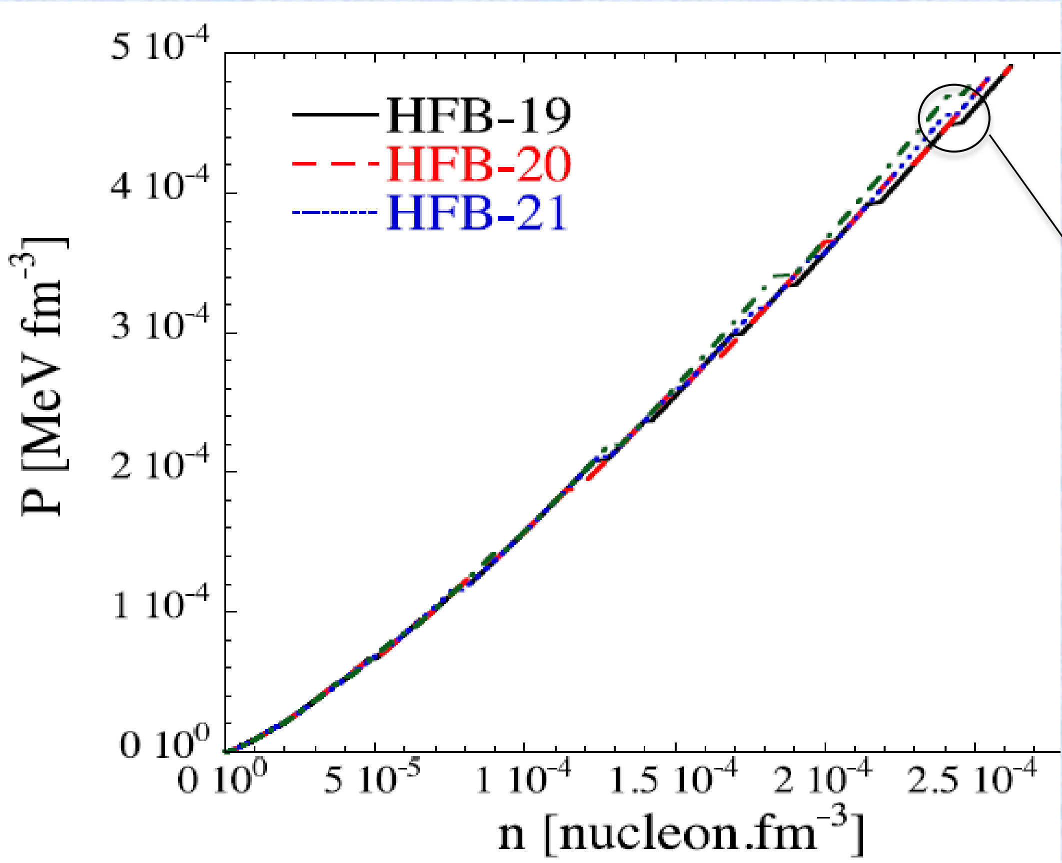
Wolf *et al.*, PRL 110, 041101 (2013)



Kreim *et al.*, Int. J. Mass Spectr. 349, 63 (2013)

NS EoS: outer crust

Mass models: HFB (no approximations!)



J. M. Pearson *et al*., PRC 83, 065810 (2011)

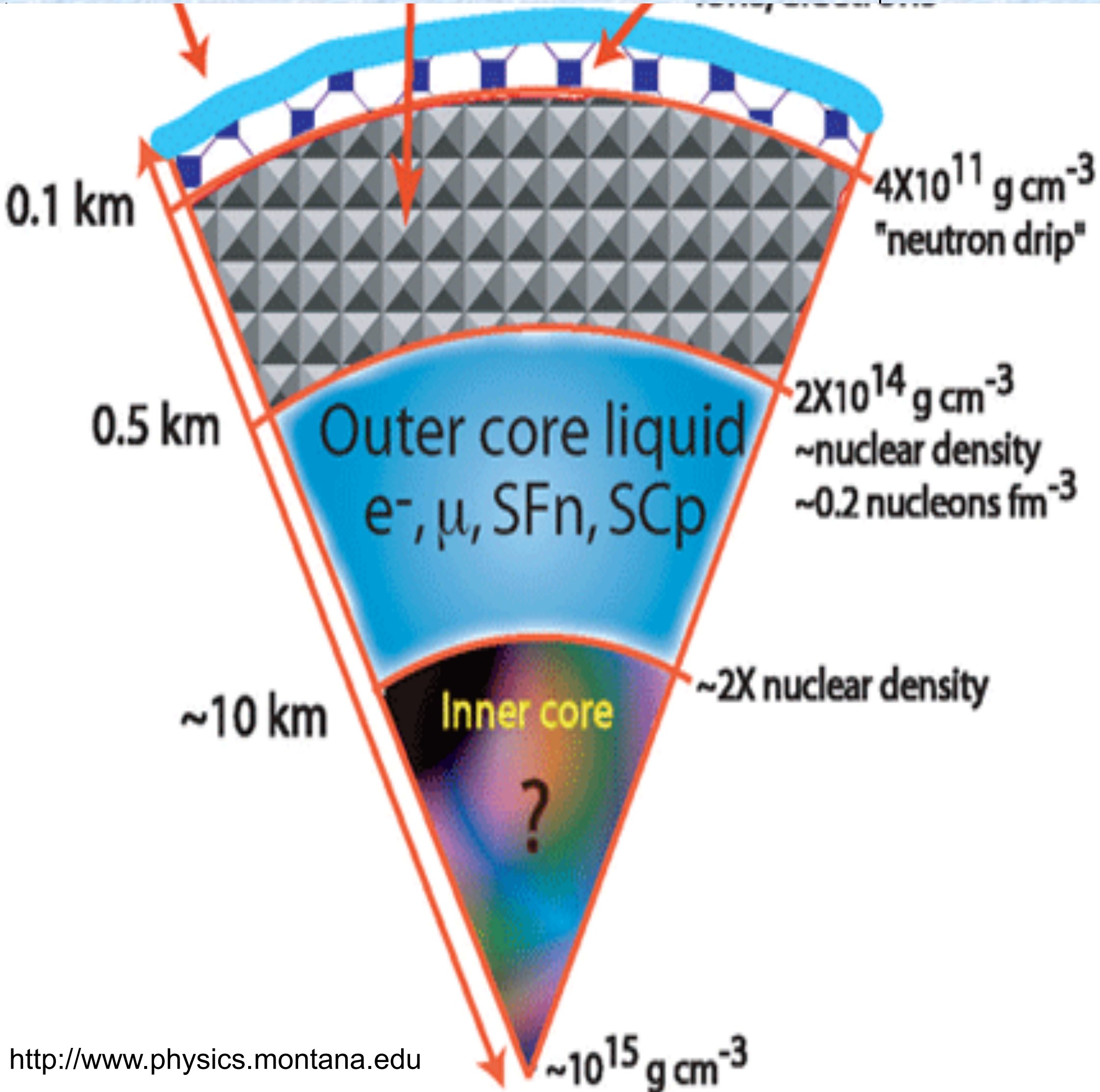
≈ 200 m (first eight rows)

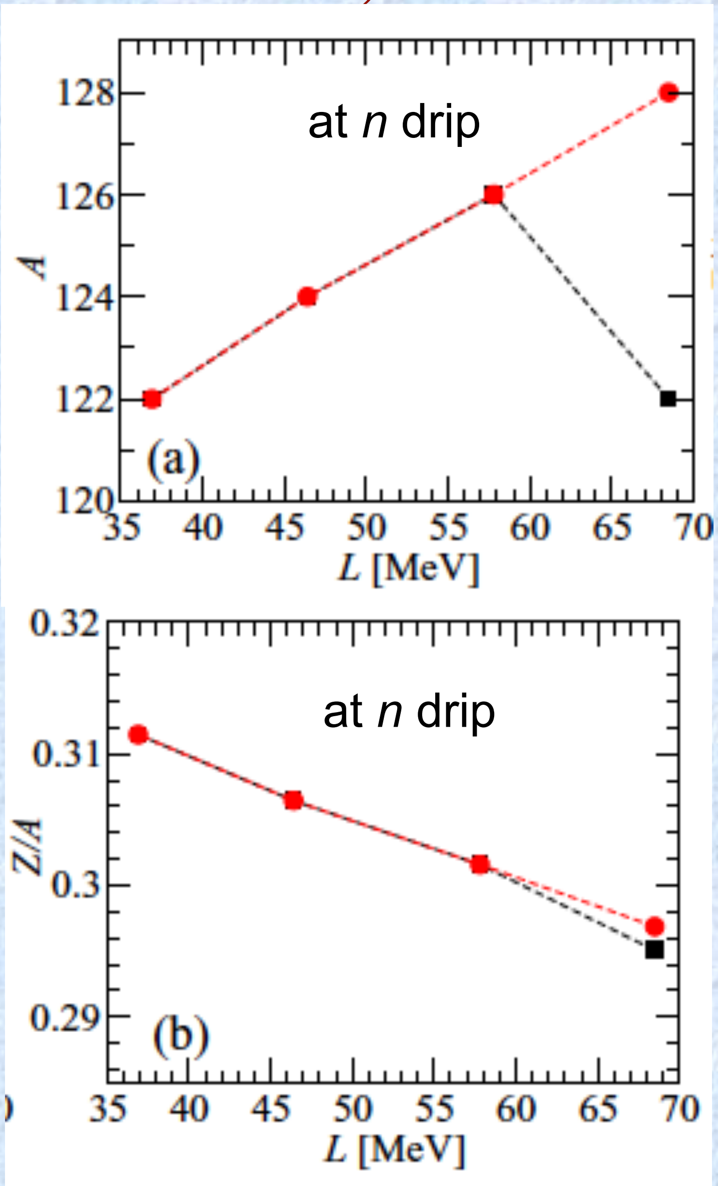
HFB-19	HFB-20	HFB-21
^{56}**Fe**	^{56}**Fe**	^{56}**Fe**
^{62}**Ni**	^{62}**Ni**	^{62}**Ni**
^{64}**Ni**	^{64}**Ni**	^{64}**Ni**
^{66}**Ni**	^{66}**Ni**	^{66}**Ni**
^{86}**Kr**	^{86}**Kr**	^{86}**Kr**
^{84}**Se**	^{84}**Se**	^{84}**Se**
^{82}**Ge**	^{82}**Ge**	^{82}**Ge**
^{80}**Zn**	^{80}**Zn**	^{80}**Zn**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

N.B.: Pressure continous function of star radius
→ density jump if transition from one stable nuclide to the other

NS EoS: outer crust and E_{sym}

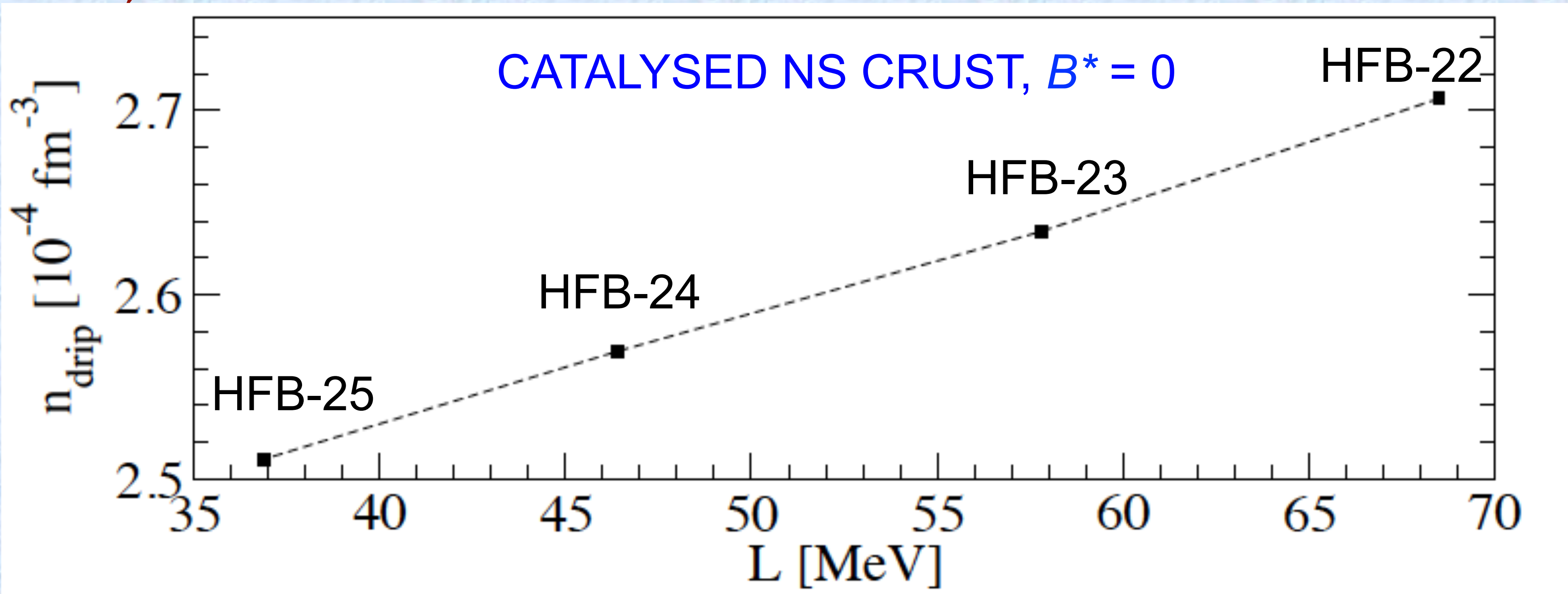
HFB-22	HFB-23	HFB-24	HFB-25





$$\frac{Z}{A} \approx \frac{1}{2}\sqrt{1 + \frac{a_{\text{eff}}}{J_{\text{eff}}}}$$

E_{sym} and inner-outer crust boundary



$$n_{\rm drip}(A,Z) \approx \frac{A}{Z}\frac{\mu_e^{\rm drip}(A,Z)^3}{3\pi^2(\hbar c)^3}\left[1+\frac{4C\alpha}{(81\pi^2)^{1/3}}Z^{2/3}\right]^{-3}$$

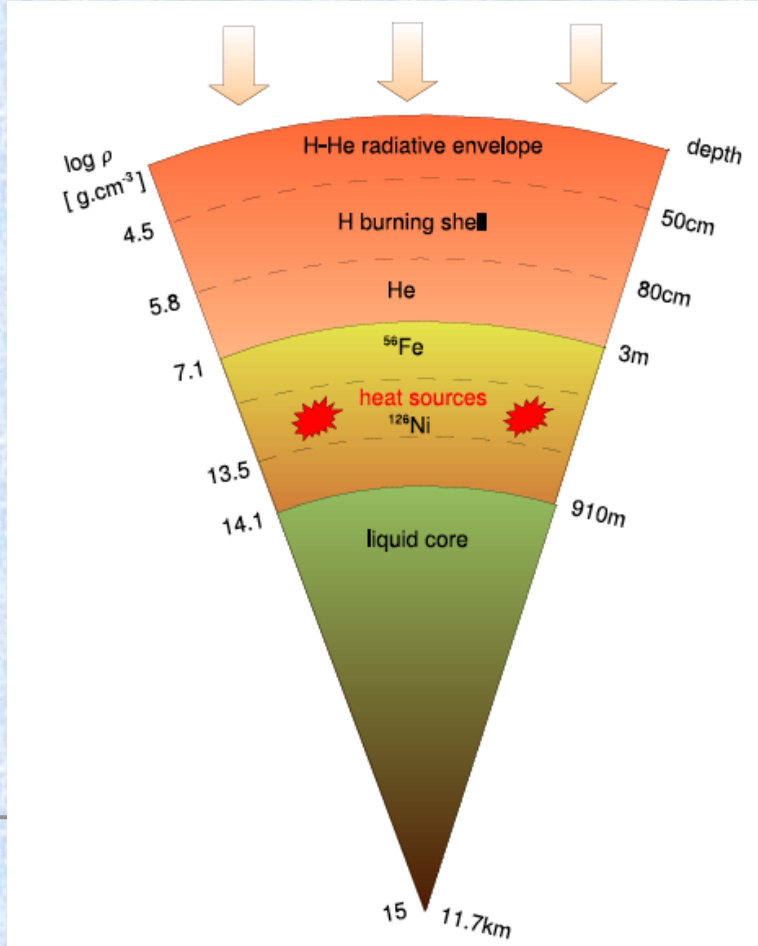
$$\mu_e^{\rm drip}(A,Z) \equiv \frac{-M'(A,Z)c^2 + Am_nc^2}{Z} + m_ec^2 \,.$$

Fantina *et al*., PRC 93, 015801 (2016)
Chamel, Fantina, Zdunik, Haensel, PRC 91, 055803 (2015)

NS EoS: outer crust for accreting NS

For **catalysed** NS crust → initial composition around Fe → $A \approx 50\text{-}60$
(determined by full minimisation of g)

For **accreting** NS crust → initial composition depend on ashes
produced by *rp*-process during x-ray bursts → A from ≈ 60 to ≈ 106
and in steady state H and He burning during superbursts → $A \approx 60$



Chamel & Haensel, Living Rev. Relativ. 11, 10 (2008)

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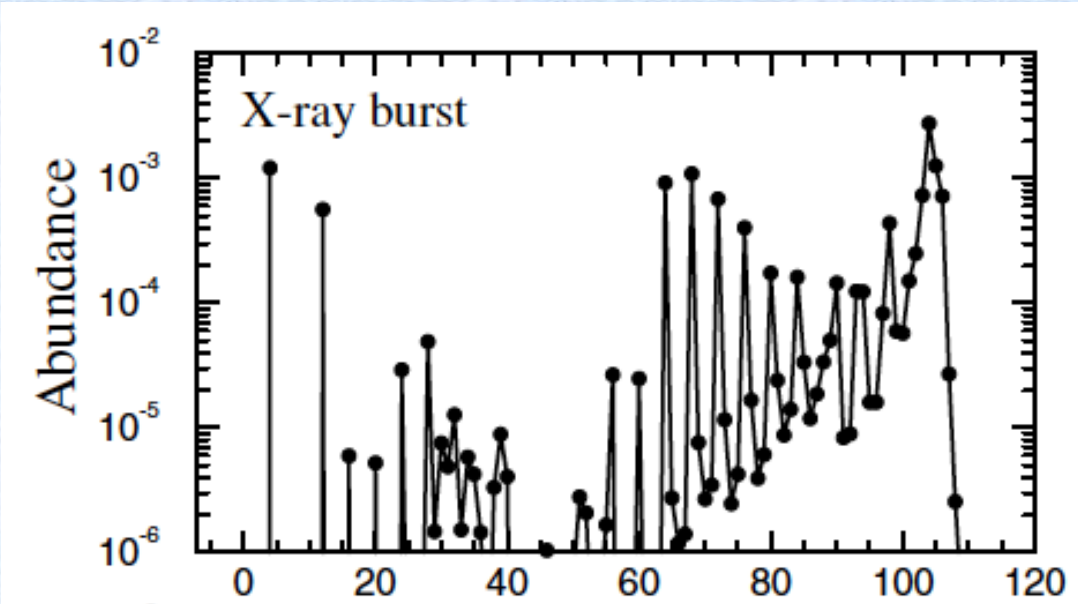
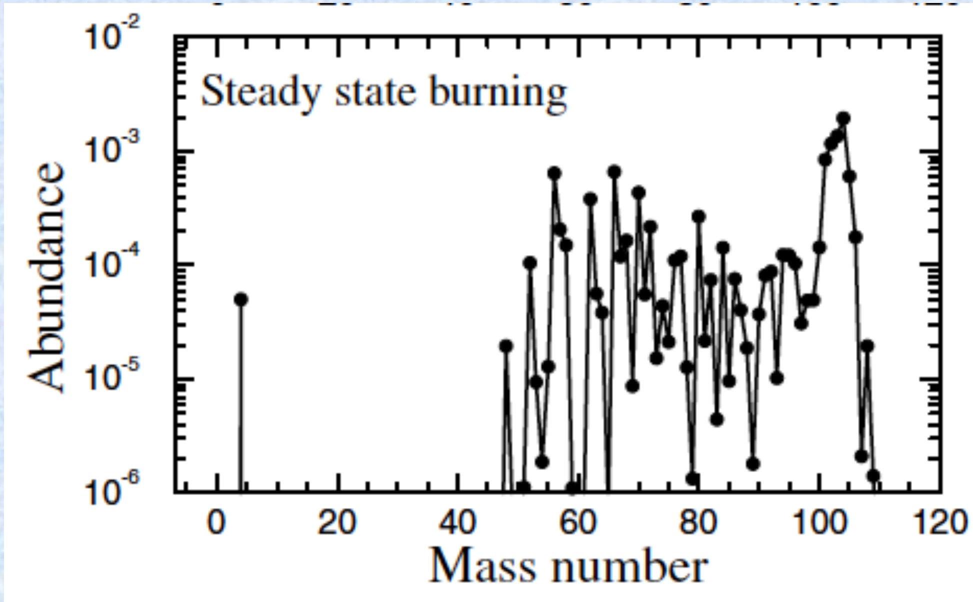
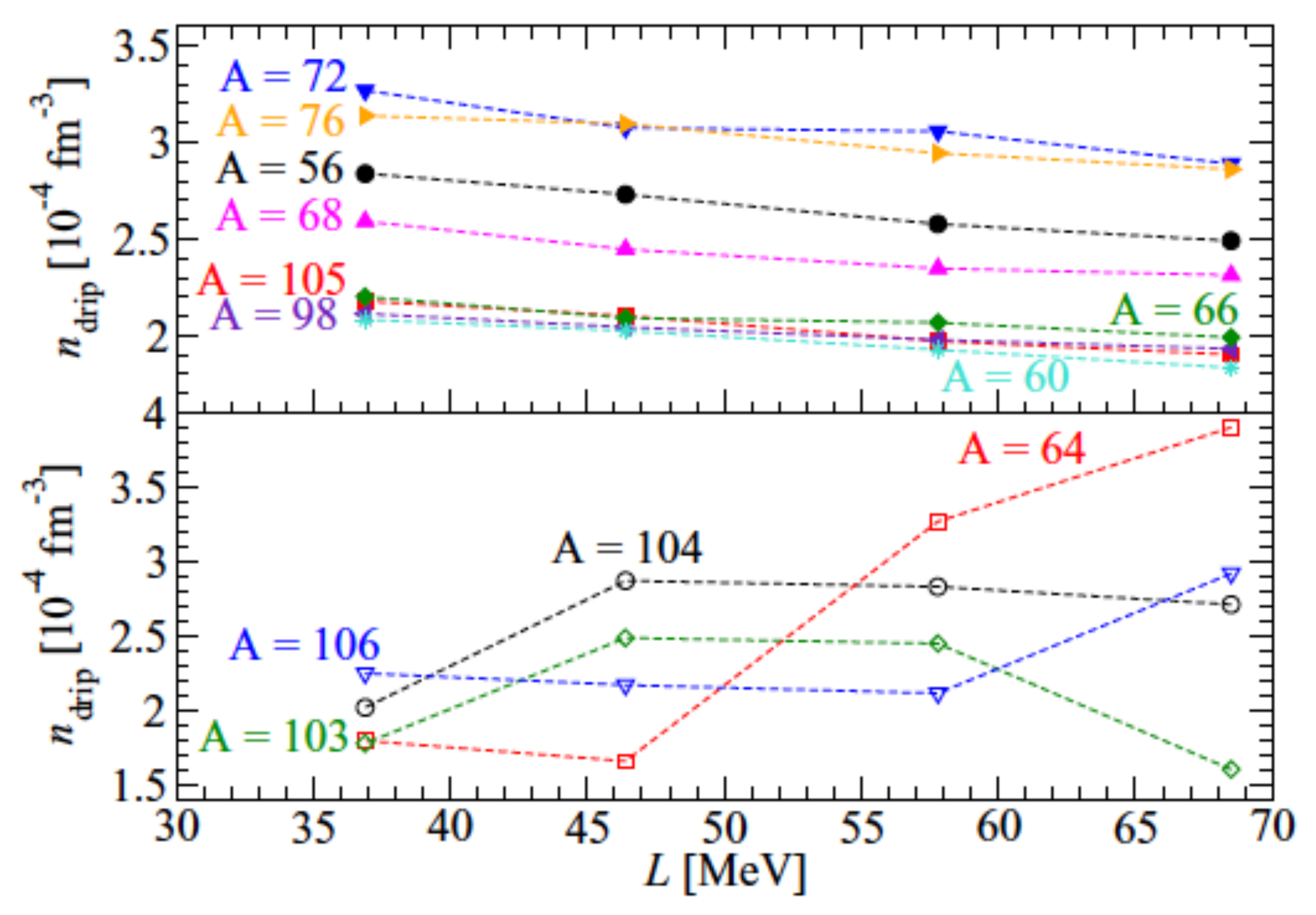




Schatz *et al*., PRL 86, 3471 (2001)

E_{sym} and inner-outer crust boundary

ACCRETED NS CRUST



Fantina *et al*., PRC 93, 015801 (2016)
Chamel, Fantina, Zdunik, Haensel, PRC 91, 055803 (2015)

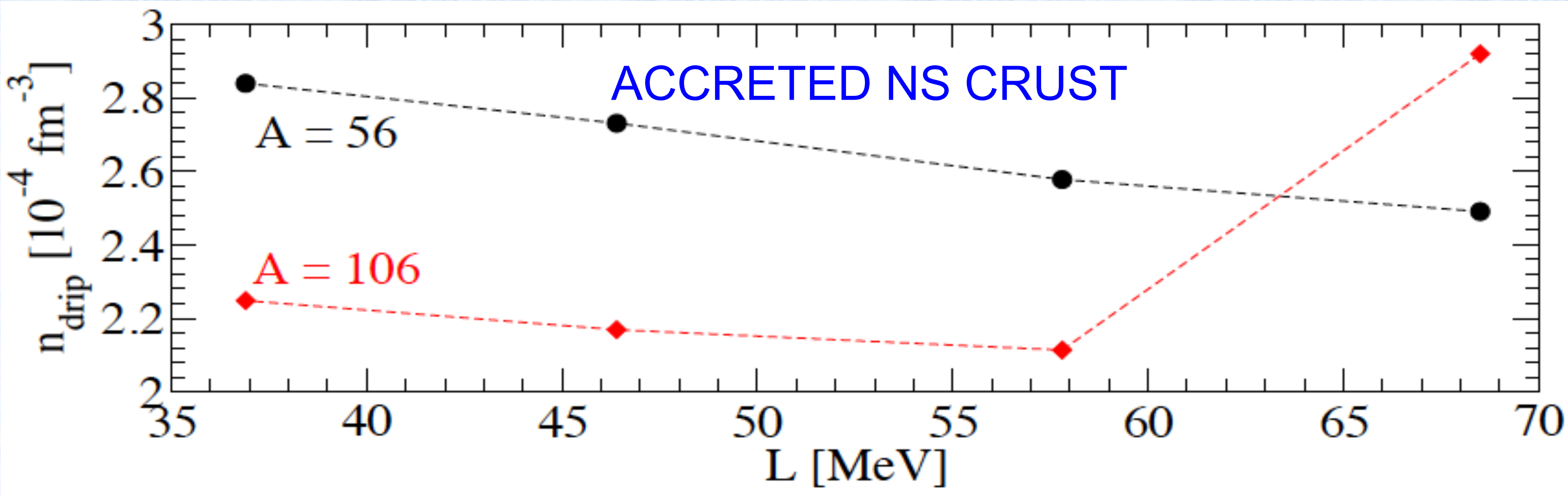
E_{sym} and inner-outer crust boundary

$$n_{\text{drip-acc}}(A,Z) \approx \frac{A}{Z}\frac{\mu_e^{\text{drip-acc}}(A,Z)^3}{3\pi^2(\hbar c)^3}\left[1+\frac{C\alpha}{(3\pi^2)^{1/3}}\left(Z^{5/3}-(Z-1)^{5/3}+\frac{Z^{2/3}}{3}\right)\right]^{-3}$$

$$\mu_e^{\text{drip-acc}} = S_{\Delta N n}(A,Z-1) + M'(A,Z-1)c^2 - M'(A,Z)c^2 + m_e c^2$$

$$S_{\Delta N n}(A,Z-1) = M(A-\Delta N, Z-1)c^2 - M(A,Z-1)c^2 + \Delta N m_n c^2$$

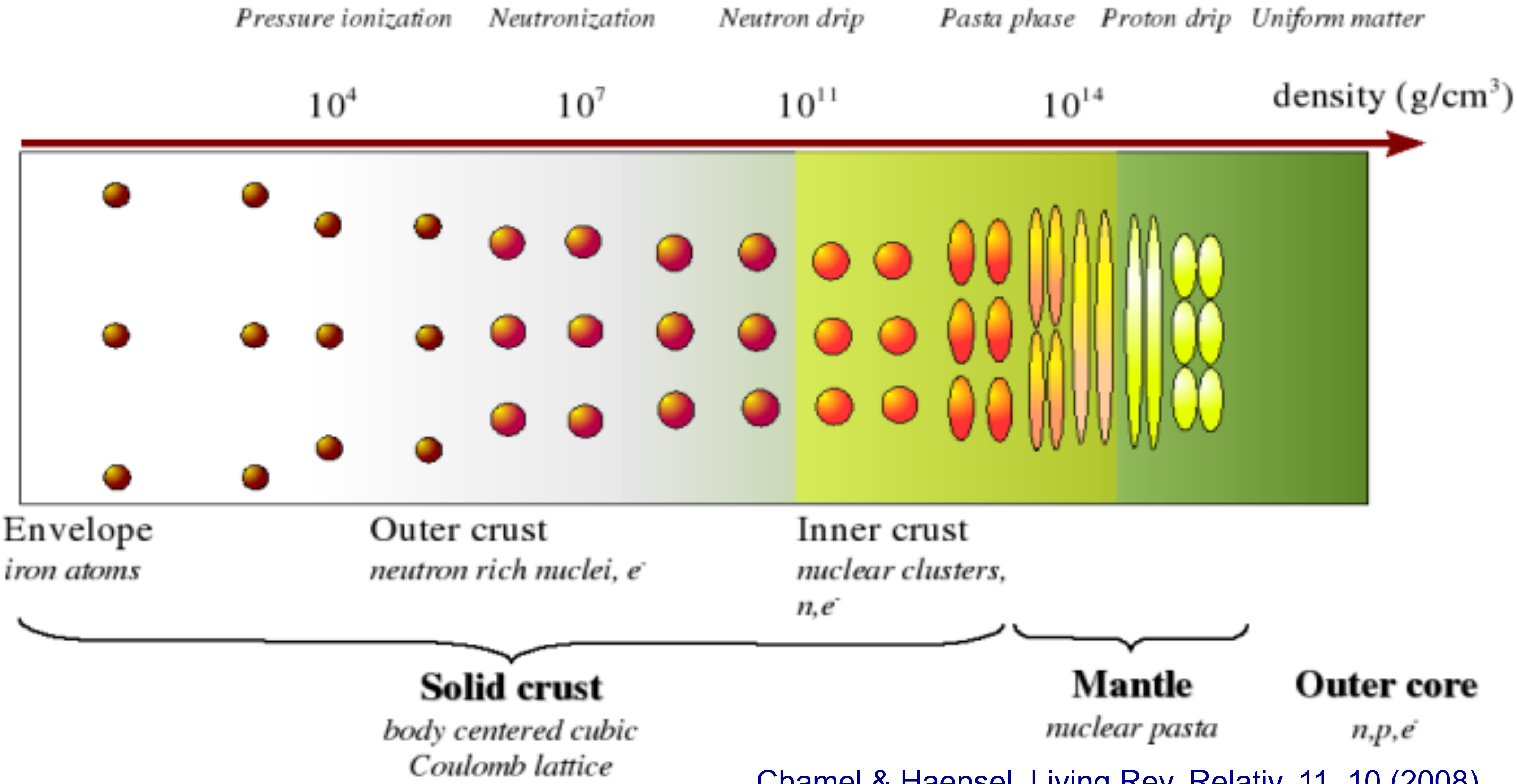
$$(\ll \Delta M' c^2)$$



Fantina, *et al.*, PRC 93, 015801 (2016)
Chamel, Fantina, Zdunik, Haensel, PRC 91, 055803 (2015)

sensitivity also to the details of nuclear structure far from stability!
→ **multiple neutron separation energy & isobaric mass difference**

NS crust structure



Chamel & Haensel, Living Rev. Relativ. 11, 10 (2008)

Neutron star crust : ≈ 1% mass, ≈ 10% radius

NS EoS: inner crust

Beyond n drip ($\rho \approx 4\ 10^{11}$ g cm^{-3}) → n-rich nuclei + e$^-$ + free n!

i.e. when: $$\mu_n = g(T=0) = \frac{M(A,Z) + Z\mu_e + Z\mu_L}{A} \geq m_n c^2$$

→ *E(Z,A)* has to be extrapolated → which approach to use?

1. Compressible liquid-drop model (e.g. Baym, Bethe & Pethick, Nucl. Phys. A 175 225 (1971); Douchin & Haensel Astron. Astrohys. 380, 151 (2001))

- nuclei have sharp surface
- nuclear energy given by sum of contribution (bulk, surface, Coulomb)
- separation of nuclear matter "inside" and "outside" nuclei into two homogeneous phases

2. (Extended) Thomas-Fermi (e.g. Onsi *et al*., PRC 77, 065805 (2008) and refs. therein)

- nuclei have smooth surface (smooth density profiles)
- nuclear energy as a functional of the density (and density gradients) of species
- consistent treatment nucleons "inside" and "outside" nuclei

3. Hartree-Fock / Hartree-Fock Bogoliubov (e.g. Negele & Vautherin, Nucl. Phys. A 207, 298 (1973); Grill *et al*., PRC 84, 065801 (2011))

- quantum calculations: indipendent particle/quasiparticle → shell / pairing effects
- also 3D calculations! e.g. Magierski & Heenen, PRC 65, 045804 (2002); Newton & Stone, PRC 79, 055801 (2009)

NS EoS: inner crust: ETFSI

- **ETF**: Extended (4th order in $\hbar$) Thomas-Fermi (for the **T=0** case!)
  Onsi *et al.*, PRC 77,065805 (2008); PRC 55, 3139 (1997); PRC 50, 460 (1994) and Refs. therein

→ semi-classical model → fast approximation to HF equations!

- Energy density and energy per nucleon of a unit Wigner-Seitz cell is given by:

$$\mathcal{E} = \mathcal{E}_{nuc} + \mathcal{E}_e + \mathcal{E}_{\text{Coul}} + (\rho_n m_n + \rho_p m_p + n_e m_e)c^2$$

$$e = \frac{1}{A}\int_{\text{cell}} \mathcal{E}(\mathbf{r}) d^3\mathbf{r} \qquad e_{nuc} = \frac{1}{A}\int_{\text{cell}} \mathcal{E}^{\text{ETF}}_{\text{Sky}}(\mathbf{r}) d^3\mathbf{r}$$

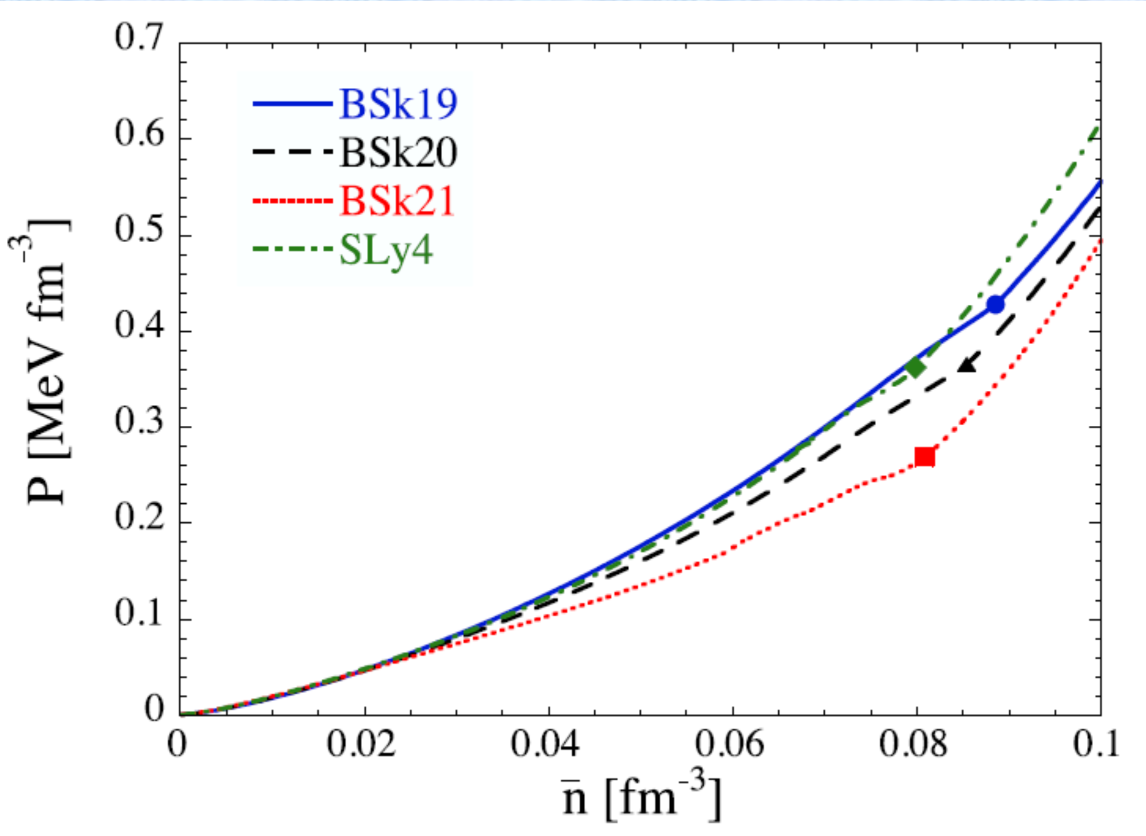
- spherical neutron-proton clusters + n liquid + uniform relativistic e⁻ gas
  in Wigner-Seitz cells, using parameterised density distributions:

$$n_q(r) = n_{B,q} + n_{\Lambda,q} f_q(r)$$

$$f_q(r) = \frac{1}{1 + \exp\left[\left(\frac{C_q - R_{\text{cell}}}{r - R_{\text{cell}}}\right)^2 - 1\right] \exp\left(\frac{r - C_q}{a_q}\right)}$$

First applied by Buchler & Barkat (e.g. Buchler & Barkat, PRL 27, 48 (1971))
Many further applications, e.g. Ogasawara & Sato, Prog. Theor. Phys. 68, 222 (1982); Oyamatsu, NPA 561, 431 (1993);
Centelles *et al.*, Nucl. Phys. A 537, 486 (1992); Cheng *et al.*, PRC 55, 2092 (1997): relativistic ETF

NS EoS: inner crust / core with BSk models

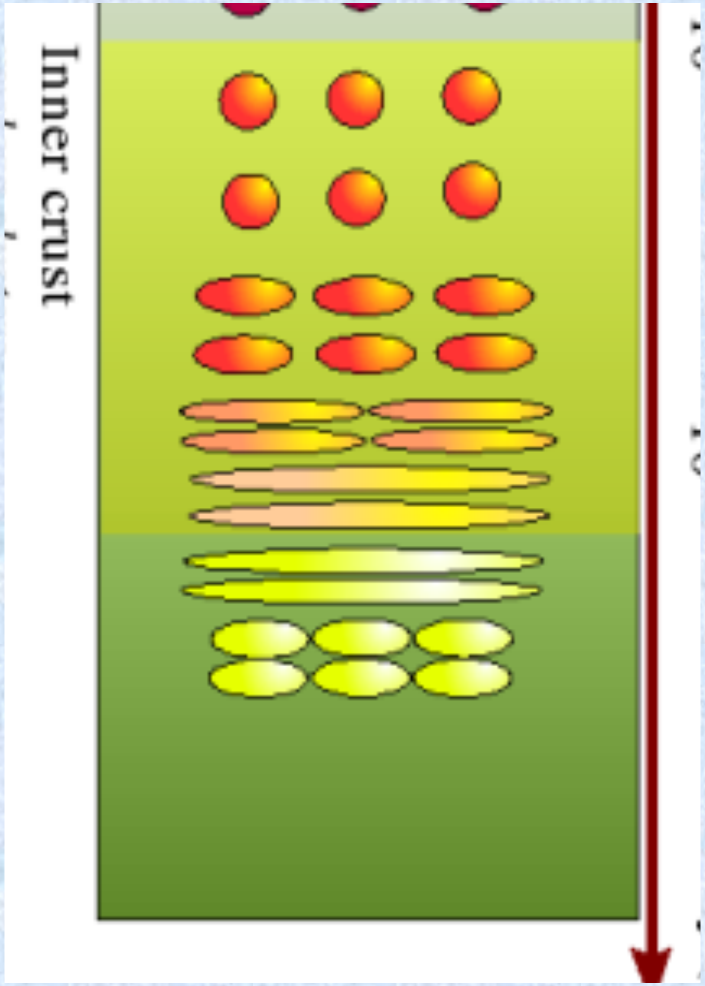


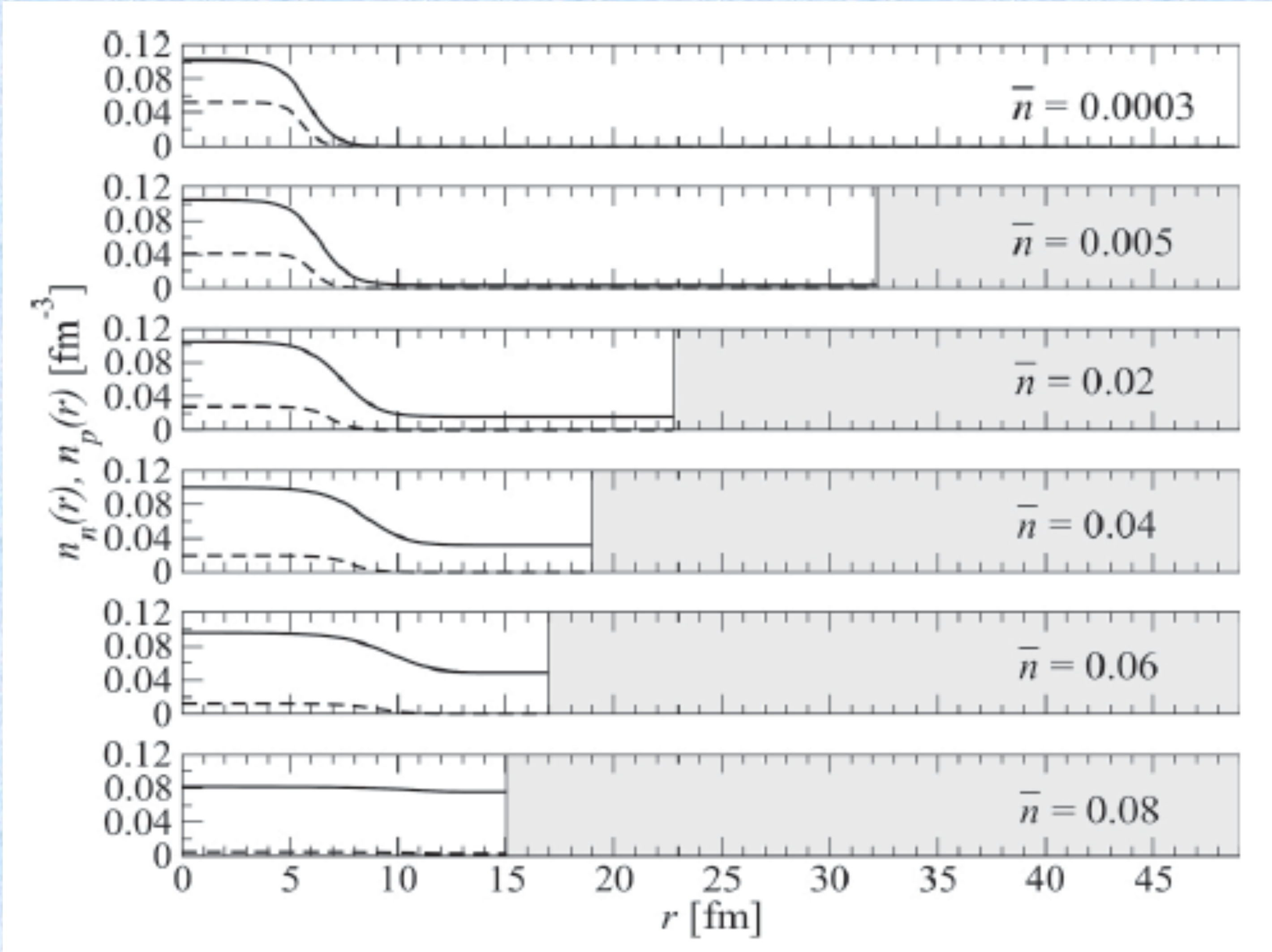
Force	n_{trans} [fm^{-3}]	P_{trans} [MeV fm^{-3}]
BSk19	0.0885	0.428
BSk20	0.0854	0.365
BSk21	0.0809	0.268
SLy4	0.0798	0.361

Pearson *et al.*, PRC 85, 065803 (2012)

Role of pairing with BSk19-20-21 discussed in Pearson *et al.*, PRC 91, 018801 (2015)

NS EoS: inner crust / core with BSk models





Pearson *et al.*, PRC85, 065803 (2012)

→ very smooth crust-core transition: crust dissolves continously into a uniform mixture of nucleons and electrons

Outline

- Introduction: NS & EoS
- Effective nuclear models
  - Brussels-Montreal BSk model
- NS composition & clusters
  - outer crust
  - inner crust
- Conclusions

Conclusions

❖ Composition of NS crusts with *unified* EoSs for NS matter
→ same *EDF* nuclear model to describe all regions of NS
fitted on *experimental nuclear data* and *nuclear matter properties*
→ smooth transition from inhomogeneous matter (with cluster)
to homogeneous nuclear matter

❖ Masses of nuclei in deeper region of NS crust experimentally unknown
→ need of (microscopic) theoretical mass models

❖ Composition in deeper layers of the NS outer crust very sensitive to details of nuclear structure far from valley of stability
→ *masses* of very n-rich Sr and Kr isotopes in *nonaccreting* NS
→ *combination of nuclear masses* (multiple n-separation energy and isobaric 2point mass difference) in *accreting* NS


Merci!
Supernova Remnant 1987A in the Large Magellanic Cloud.
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