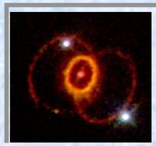
Institut d'Astronomie et d'Astrophysique
Université Libre de Bruxelles

Dense matter in in core-collapse supernova and neutron-star physics

Anthea F. Fantina (afantina@ulb.ac.be)

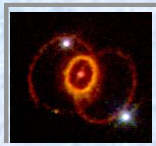
Collaborators: N. Chamel, S. Goriely (IAA, Université Libre de Bruxelles)
J. M. Pearson (Université de Montréal)
E. Khan (IPN Orsay)
G. Colò (Università di Milano)
N. Paar, D. Vretenar (University of Zagreb)
J. Margueron (IPN Lyon)
M. Oertel, J. Novak (LUTh-Meudon)
P. M. Pizzochero (Università di Milano)
P. Haensel, J. L. Zdnunik (CAMK, Warsaw)

Seminar @ LNGS, 23 July 2015

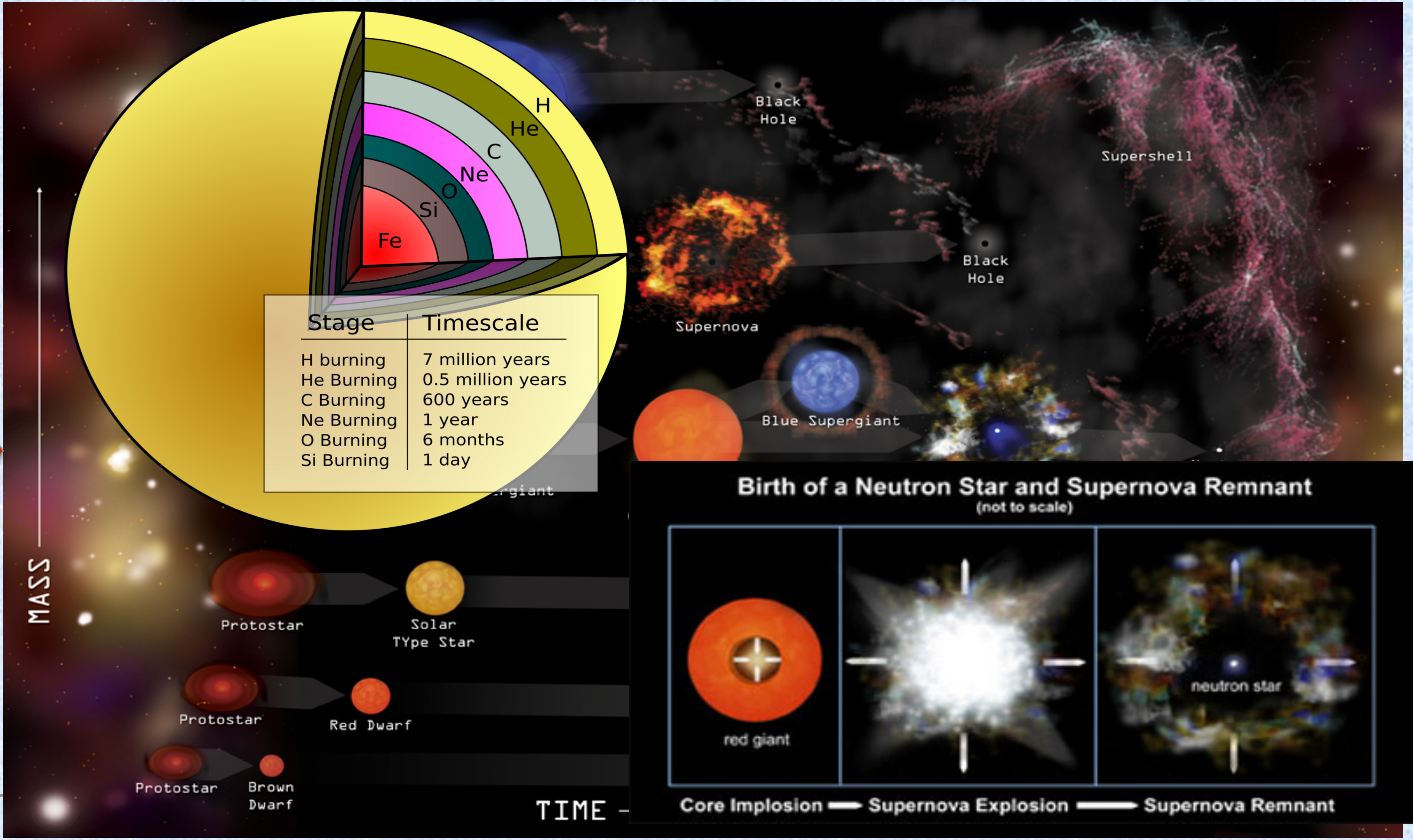


Outline

- Motivation and astrophysical framework
- Equation of state of dense matter:
  - Brussels-Montreal functionals
  - constraints from nuclear physics
  - constraints from astrophysics & neutron star properties
- Weak interaction rates:
  - introduction on electron capture
  - the model
  - results
  - collective modes (GT, IAR)
- Conclusions & Outlooks

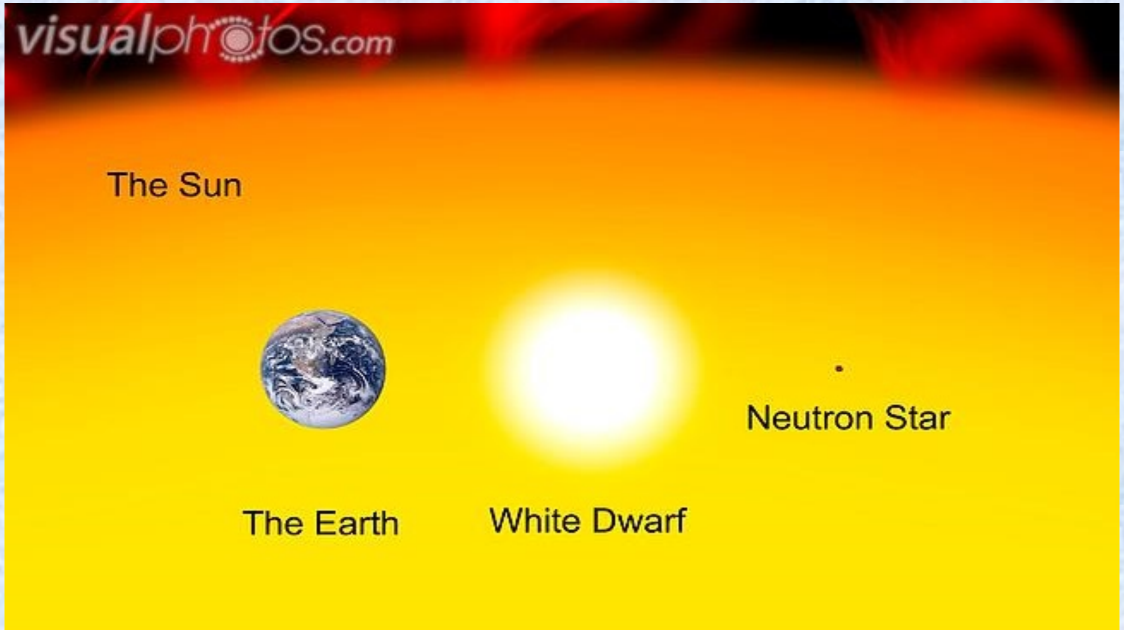


Astrophysical framework: SN & NS



Credits: http://chandra.harvard.edu; http://large.stanford.edu

How compact is a NS?



SUN

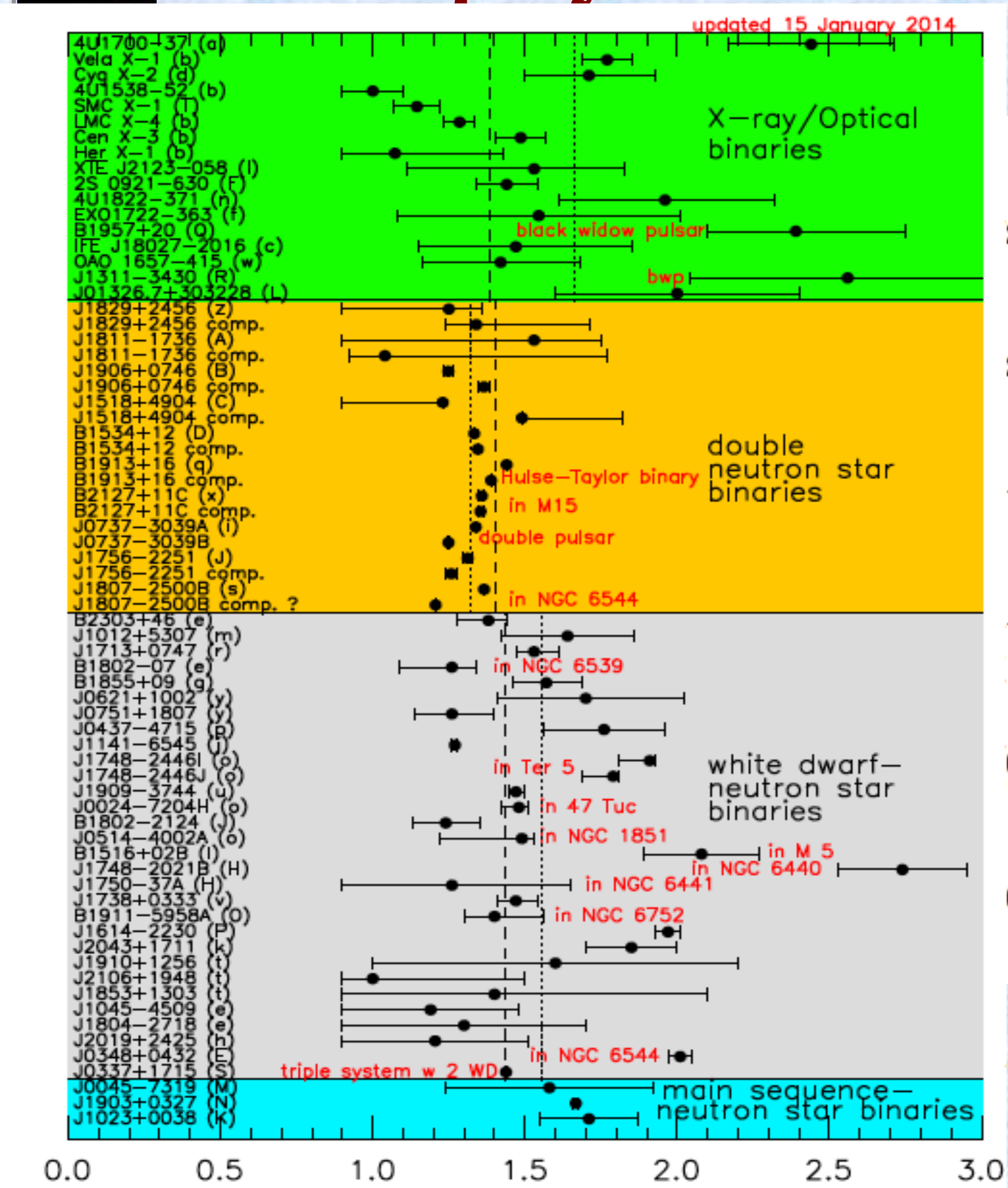
$$
\begin{aligned}
M_\odot &= 1.98855 \times 10^{30}\ \mathrm{kg} \\
R_\odot &= 6.96342 \times 10^{5}\ \mathrm{km} \\
\bar{\rho} &\approx 1.4\ \mathrm{g\ cm^{-3}} \\
\frac{2GM}{Rc^2} &\approx 10^{-6}
\end{aligned}
$$

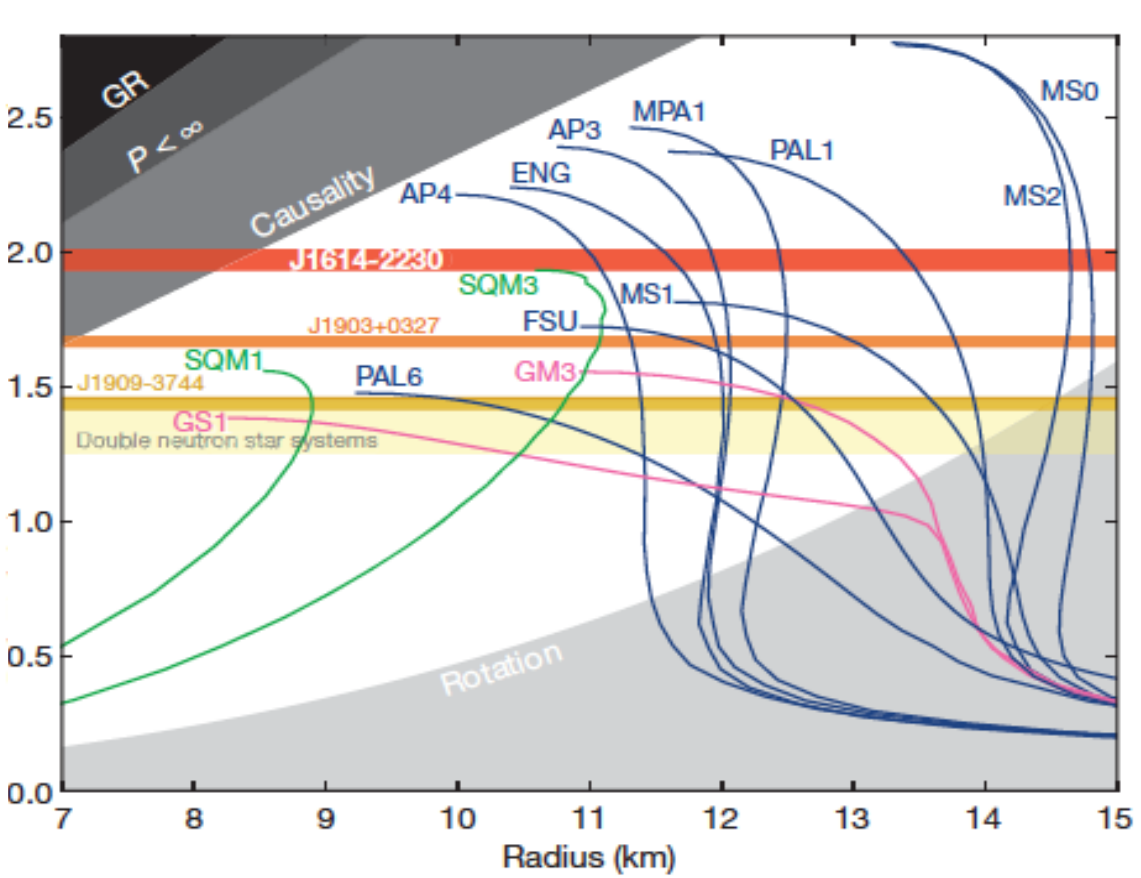
NEUTRON STAR

$$
\begin{aligned}
M &\approx 1 - 2\ M_\odot \\
R &\approx 10\ \mathrm{km} \\
\bar{\rho} &\approx 10^{14} - 10^{15}\ \mathrm{g\ cm^{-3}} \\
\frac{2GM}{Rc^2} &\approx 0.2 - 0.4
\end{aligned}
$$

→ dense matter → need of nuclear physics, interactions very important!
compact → need of general relativity!

Astrophysical framework: SN & NS





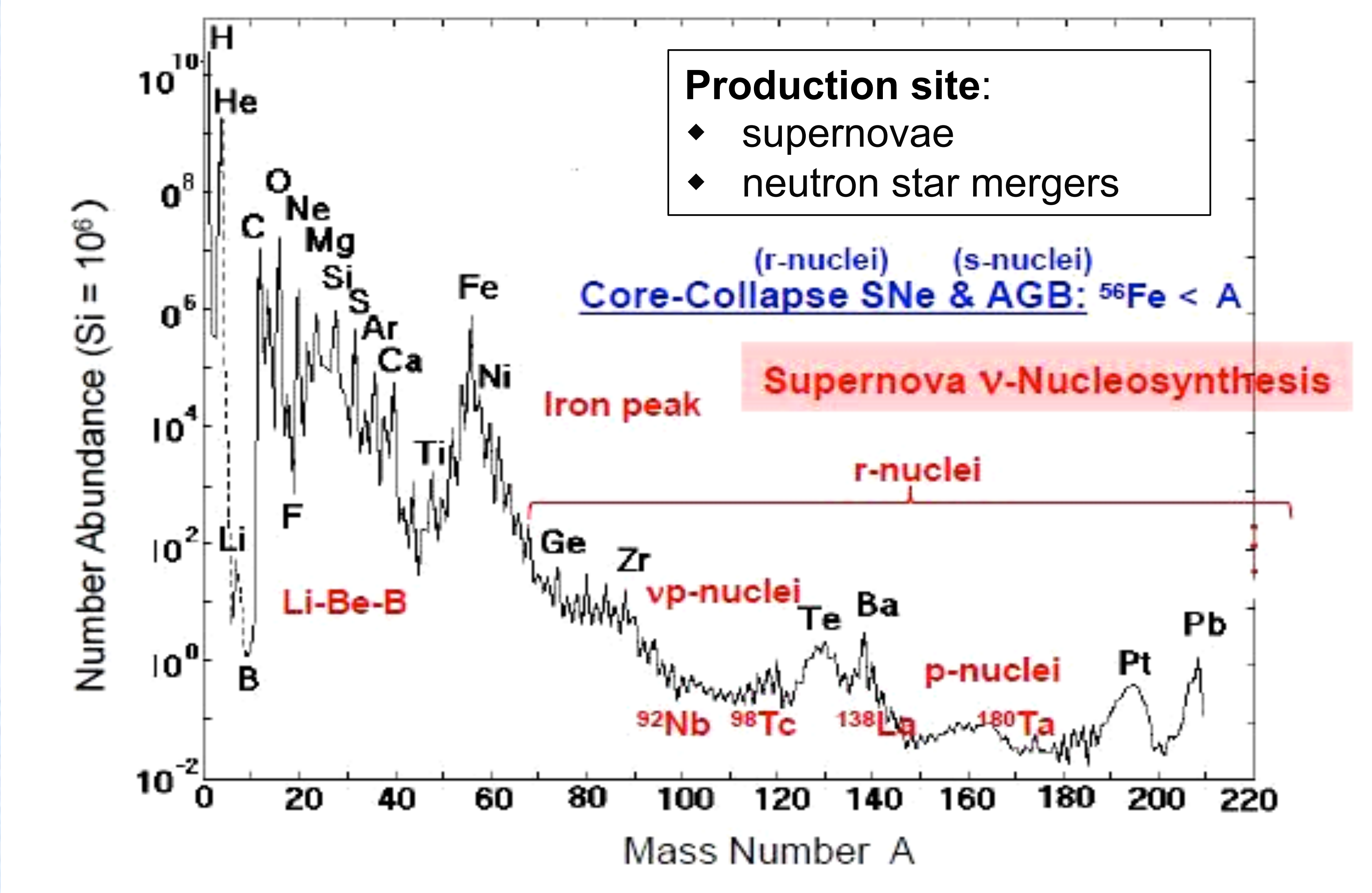
2 M_{sun} NS measurements:

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

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

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

Nucleosynthesis in the Universe



Kajino, talk Russbach School (2013)

Study of compact stars: SN & NS

interdisciplinary study also supported by
COST Action MP1304 (NewCompstar) [1] at European level

Microphysics
nuclear physics

- **equation of state**
- **weak processes**
- neutrino interactions

Macrophysics
hydrodyn. SN & NS models

- multi-D models
- general relativity
- neutrino transport

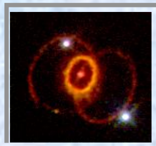
Nuclear physics experiments

- nuclear structure, mass measurement (exotic nuclei, HIC)
- β decays, reaction rates Gamow-Teller transitions
- neutrino cross-sections

Astrophysical observations

- neutrino signal, SN light curves
- gravitational waves
- NS properties (e.g. masses)
- NS cooling (related to pairing)

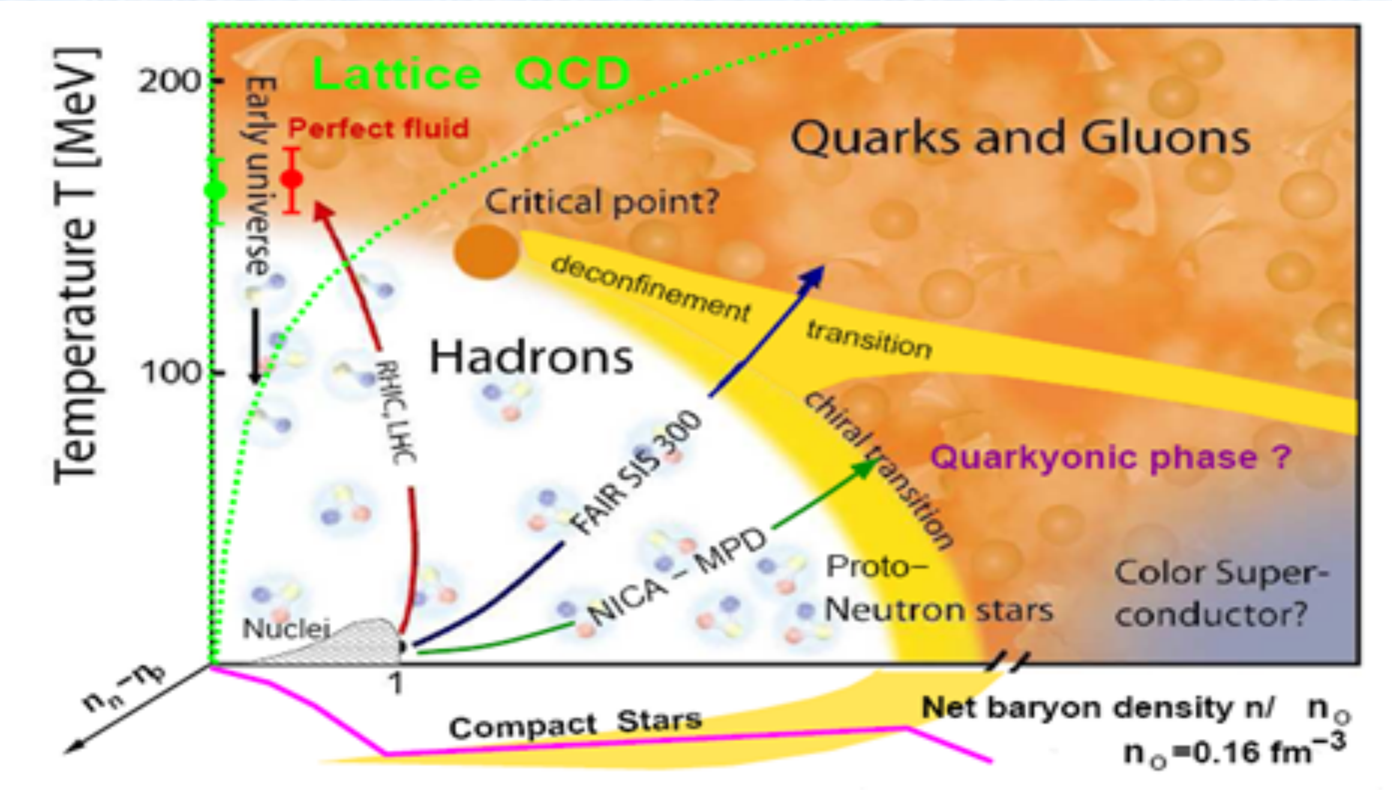
[1] http://www.cost.eu/COST_Actions/mpns/Actions/MP1304



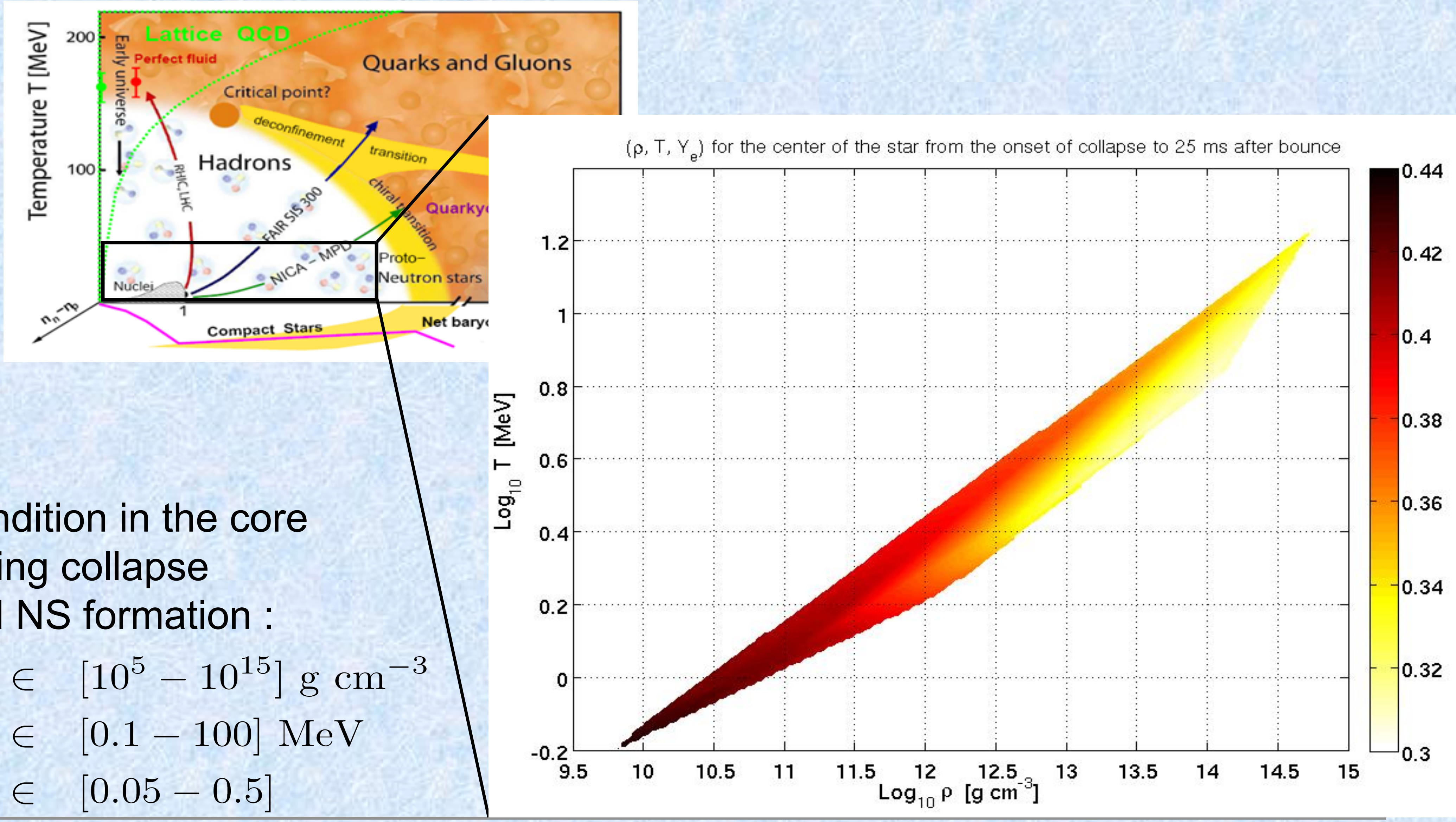
Outline

- Motivation and astrophysical framework
- Equation of state of dense matter:
  - Brussels-Montreal functionals
  - constraints from nuclear physics
  - constraints from astrophysics & neutron star properties
- Weak interaction rates:
  - introduction on electron capture
  - the model
  - results
  - collective modes (GT, IAR)
- Conclusions & Outlook

EoS for SN: the challenge



EoS for SN: the challenge



Condition in the core
during collapse
and NS formation :

$$\rho \in [10^5 - 10^{15}] \text{ g cm}^{-3}$$
$$T \in [0.1 - 100] \text{ MeV}$$
$$Y_e \in [0.05 - 0.5]$$

15 solar mass progenitor, 1D GR simulation
(Fantina, PhD thesis (2010))

EoS for NS: the challenge

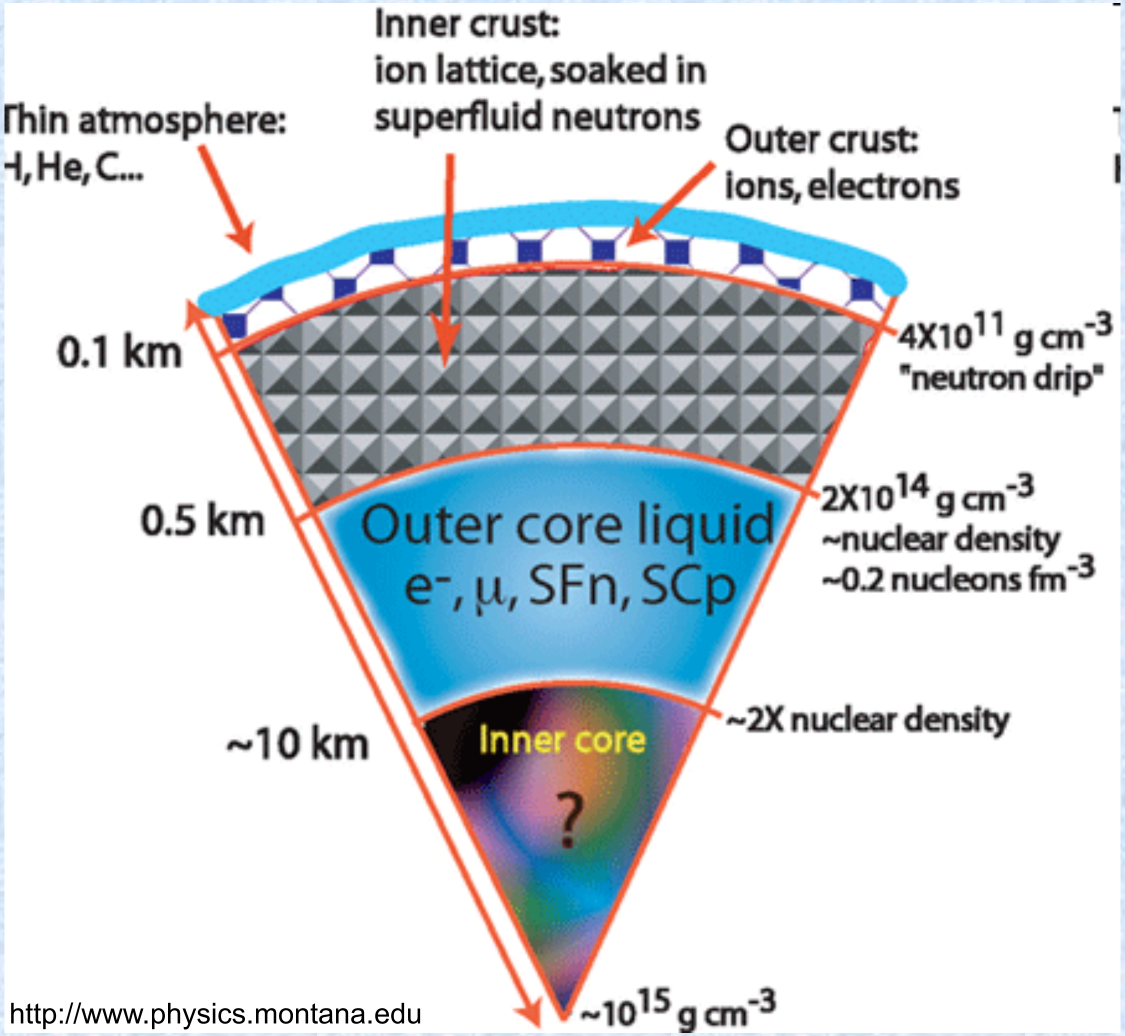
Contrarily to a normal star, in a NS:

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

✓ very high density!
composition uncertain

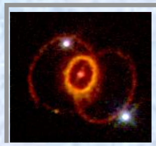
→ NSs are not only made by neutrons!

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



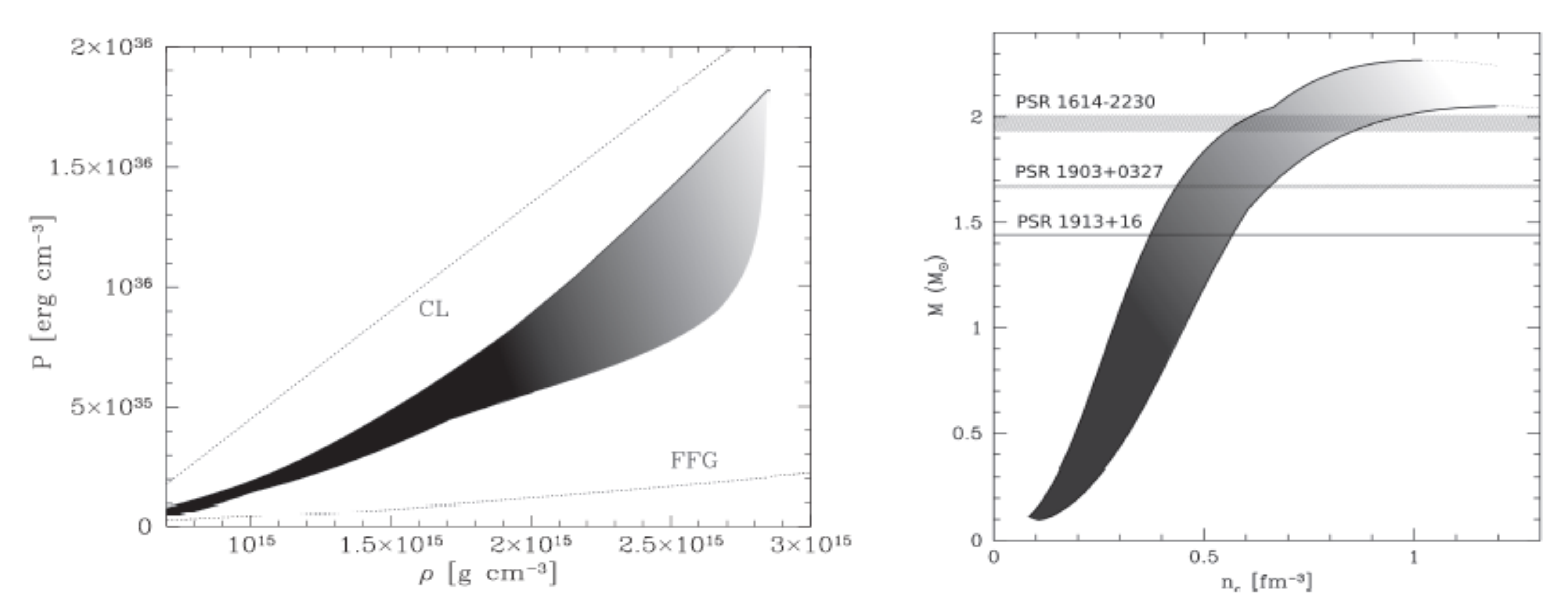
http://www.physics.montana.edu

UNIQUE COSMIC "LABORATORIES"!
(e.g. superfluidity, etc ...)



Uncertainties in dense-matter EoS

Pressure *P* versus mass-energy density ρ 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)

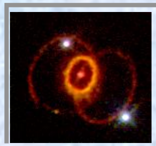
	RMF (N)	RMF (NH)	RMF/NJL (NQ)	RMF/MBM (NQ)
$M_{max}/M_{\odot}$	2.1-2.8	2.0-2.3	2.0-2.2	2.0-2.5

- 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)



EoS: 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):

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

- 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))

Isovector parameters → less certain; large variation of predictions!

EoS: properties of nuclear matter

- 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:

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

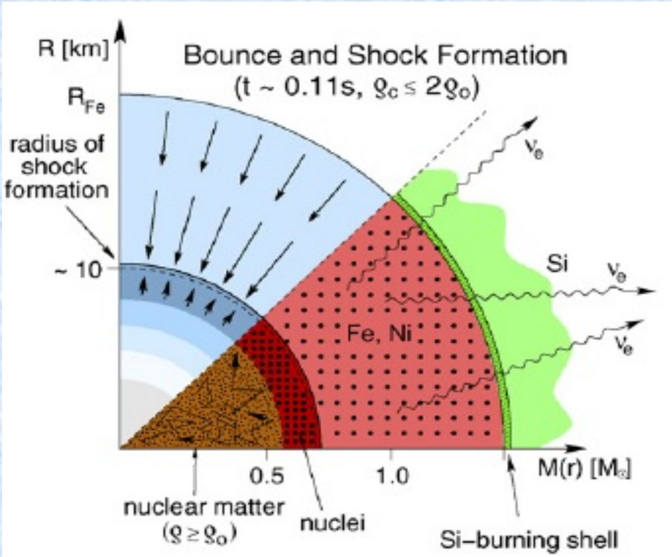
Isovector parameters → less certain; large variation of predictions!

→ Need of experimental information on:

- ❖ GMR (*K_∞*), symmetry energy (*K_{sym}*, *L*) → multifragmentation,
- ❖ nuclear masses and charge radii,
- ❖ nuclear level density (spectroscopic factors) → related to collective excitations and to effective mass

These quantities can have an effect on astrophysical modelling!

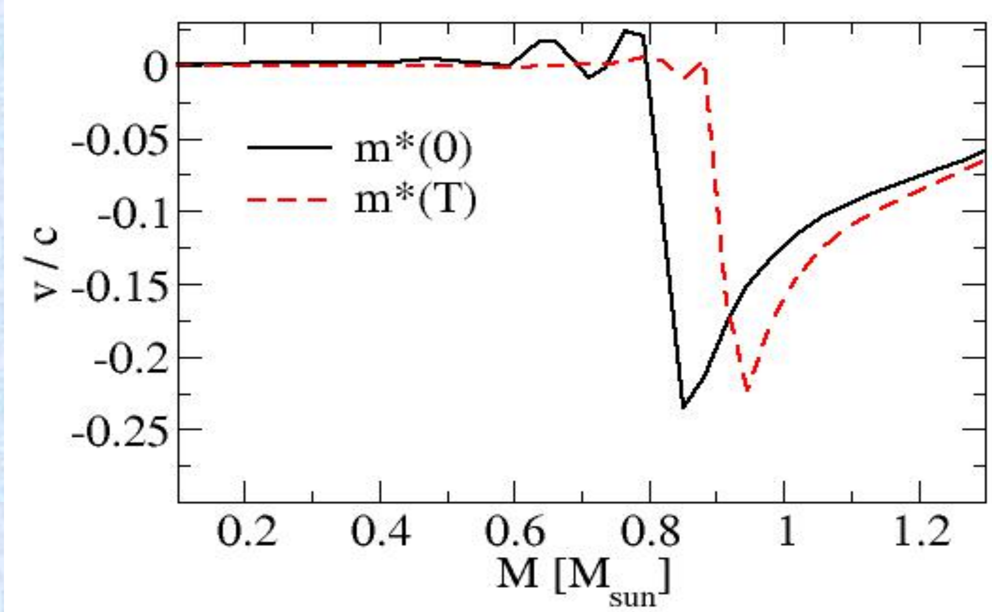
Impact of $E_{sym}(T)$ in SN simulation

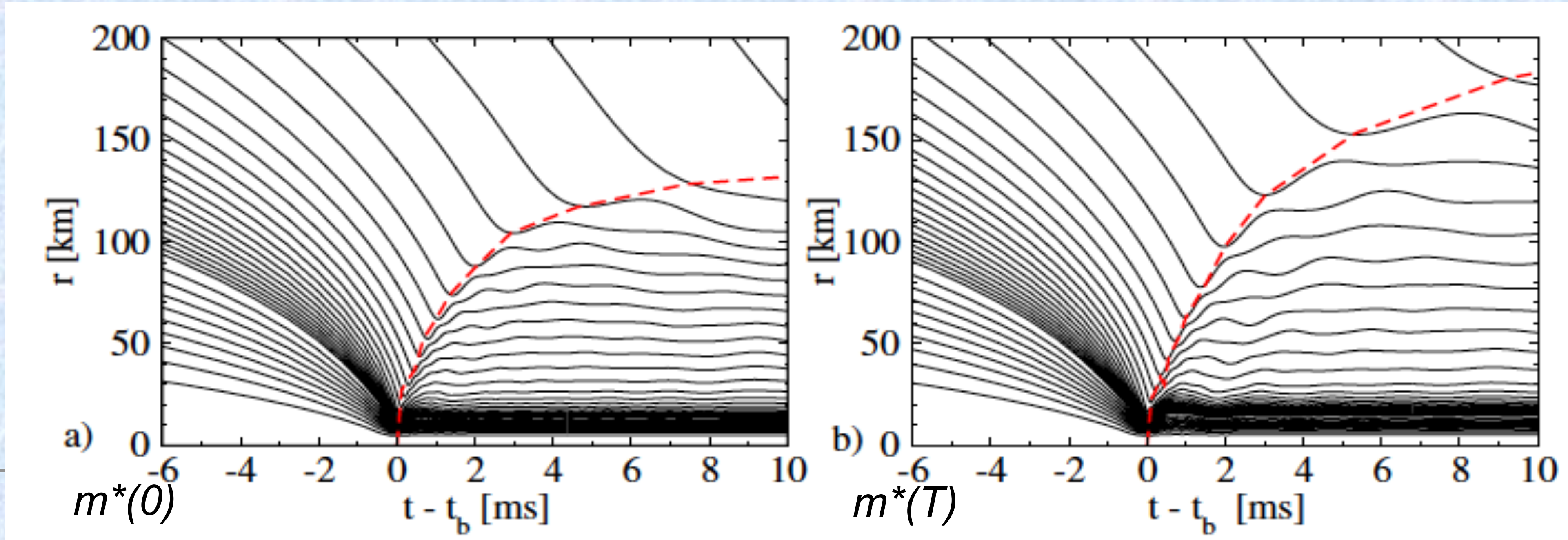


Janka *et al*., Phys. Rep. 442, 38 (2007)

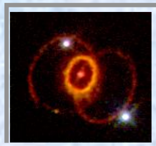
↓

related to *m**



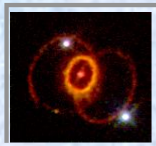


1D Newtonian simulation, 15 M_{sun} progenitor: Fantina *et al*., A&A 541, A30 (2012)



Outline

- ❖ Motivation and astrophysical framework
- ❖ Equation of state of dense matter:
  - Brussels-Montreal functionals
  - constraints from nuclear physics
  - constraints from astrophysics & neutron star properties
- ❖ Weak interaction rates:
  - introduction on electron capture
  - the model
  - results
  - collective modes (GT, IAR)
- ❖ Conclusions & Outlooks



Our goal : a unified EoS

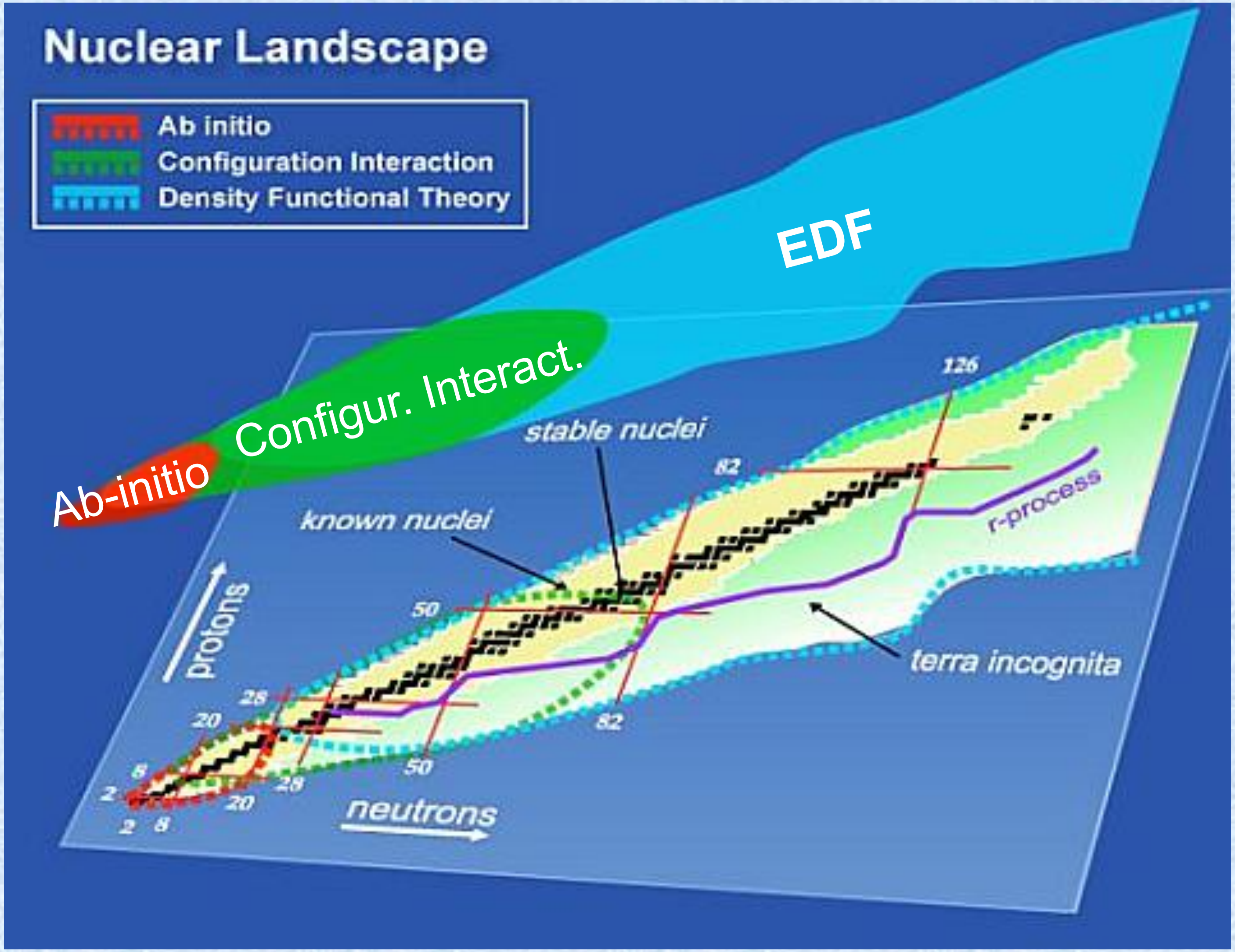
- Our goal is to construct a ***unified*** EoS
  - → based on the *same nuclear model* from energy-density functional theory
  - → valid in all regions of NS (and SN) interior
  - → outer / inner crust and crust / core transition described consistently

- 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

Which theoretical framework?



Bertsch *et al.*, SciDAD Rev. 6 (2007)

To now, no experimental or observational information to probe *all* the regions of SN & NS → need of theoretical models!

Energy-density functional theory

Consistent description of:

- **equation of state**
- **electro-weak processes**

Nuclear EDF in a nutshell

This theory allows for a **consistent** treatment of both *inhomogeneous* (i.e. with nuclei) and *homogeneous* matter as required in compact stars. Successfully applied to describe structure and dynamics of medium-mass and heavy nuclei.

The total energy of the system is expressed as:

$$E = \int d^3\mathbf{r}\ \mathcal{E}\left[\rho_q(\mathbf{r}), \nabla\rho_q(\mathbf{r}), \tau_q(\mathbf{r}), \mathbf{J}_q(\mathbf{r})\right]$$

where ρ_q, τ_q, $\mathbf{J}_q$ (q=n,p) are functionals of the wave functions.
One can obtain ground state by E minimisation procedure (mean-field HF, or HF + BCS / HFB if pairing is included).

Problem : the exact functional E is not known! → one has to rely on **phenomenological functionals** (e.g. non-relativistic Skyrme or Gogny, or relativistic).

→ which functional should we use ?
I will give the example of the BSk functionals

Hohenberg & Kohn, Phys. Rev. B 136, 864 (1964); Kohn & Sham, Phys. Rev. A 140, 1133 (1965);
Skyrme, Phil. Mag. 1, 1043 (1956); Déchargé & Gogny, PRC 21, 1568 (1980);
Stone & Reinhard, Prog. Part. Nucl. Phys. 58, 587 (2007)

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_∞ in experimental range (≈ 240 MeV)

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

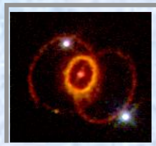
BSk22
BSk23
BSk24
BSk25
BSk26

- **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_∞ in experimental range (≈ 240 MeV)

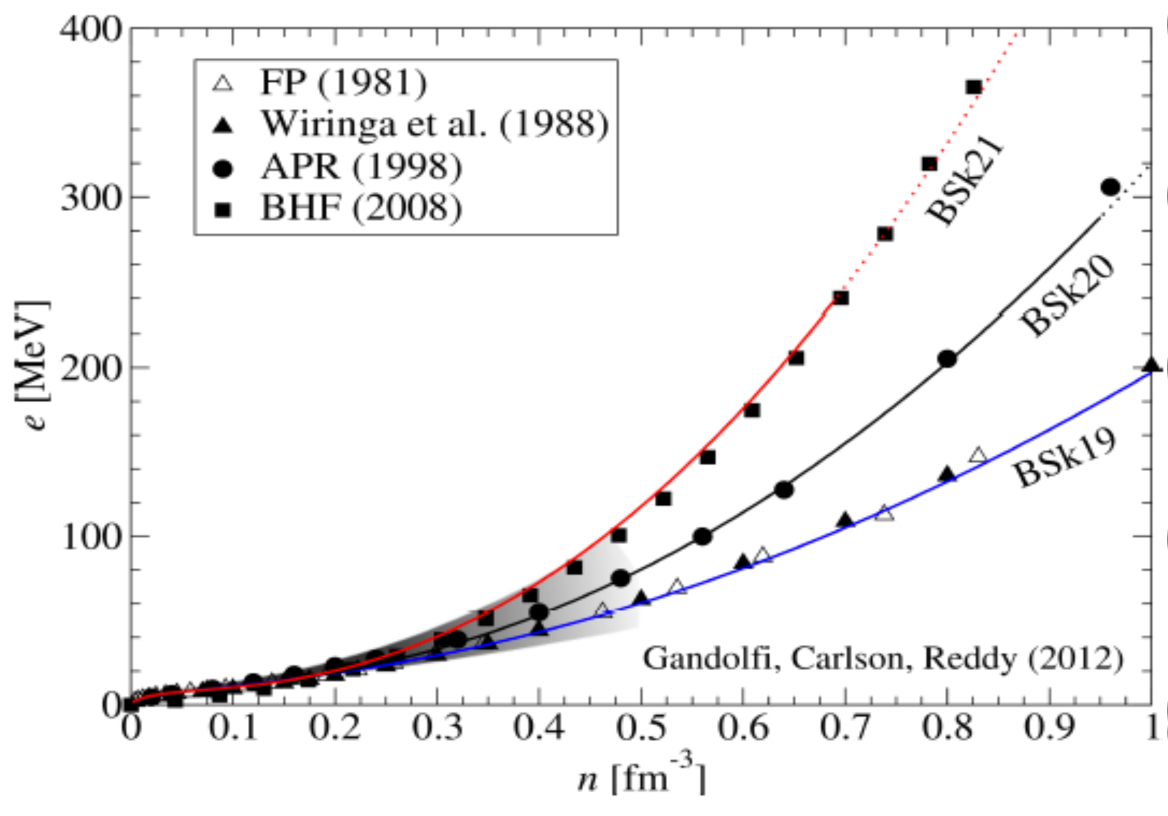
Goriely *et al.*, PRC 88, 024308 (2013)

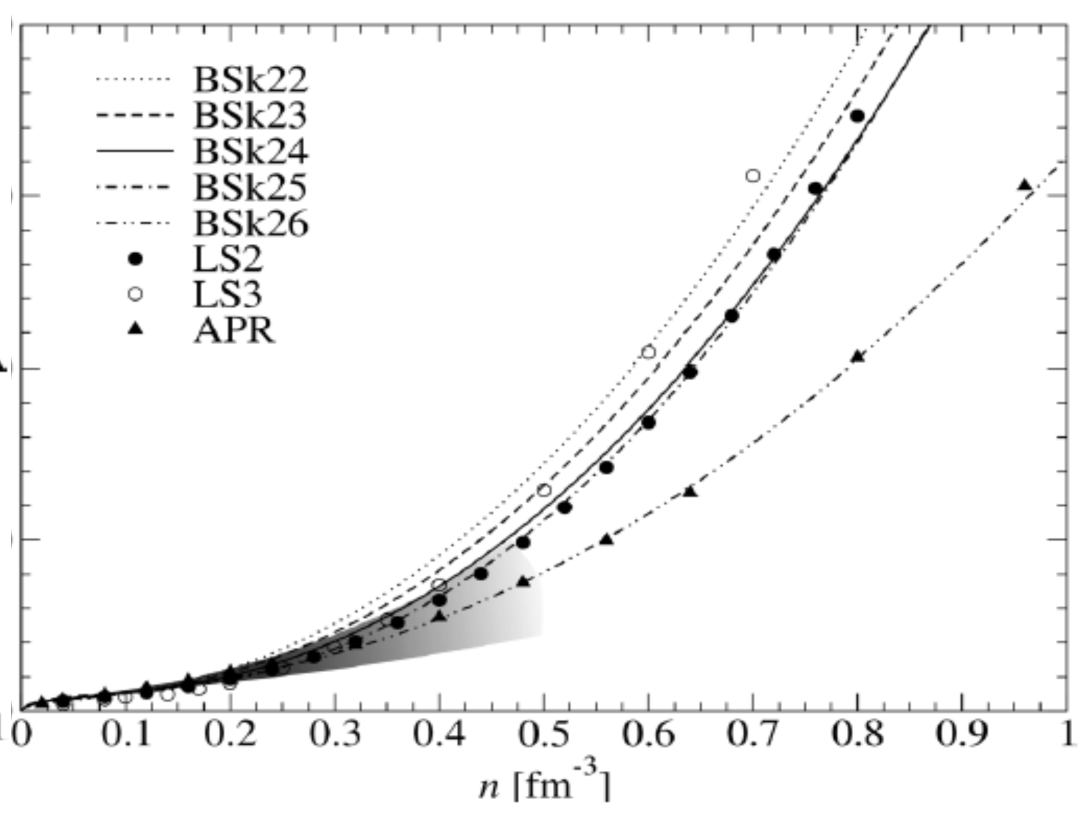
BSk27* (2012 AME), rms = **0.5 MeV** →most accurate! Goriely *et al.*, PRC 88, 061302 (2013)

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



Constraints from nuclear physics: theoretical calculations (neutron matter)



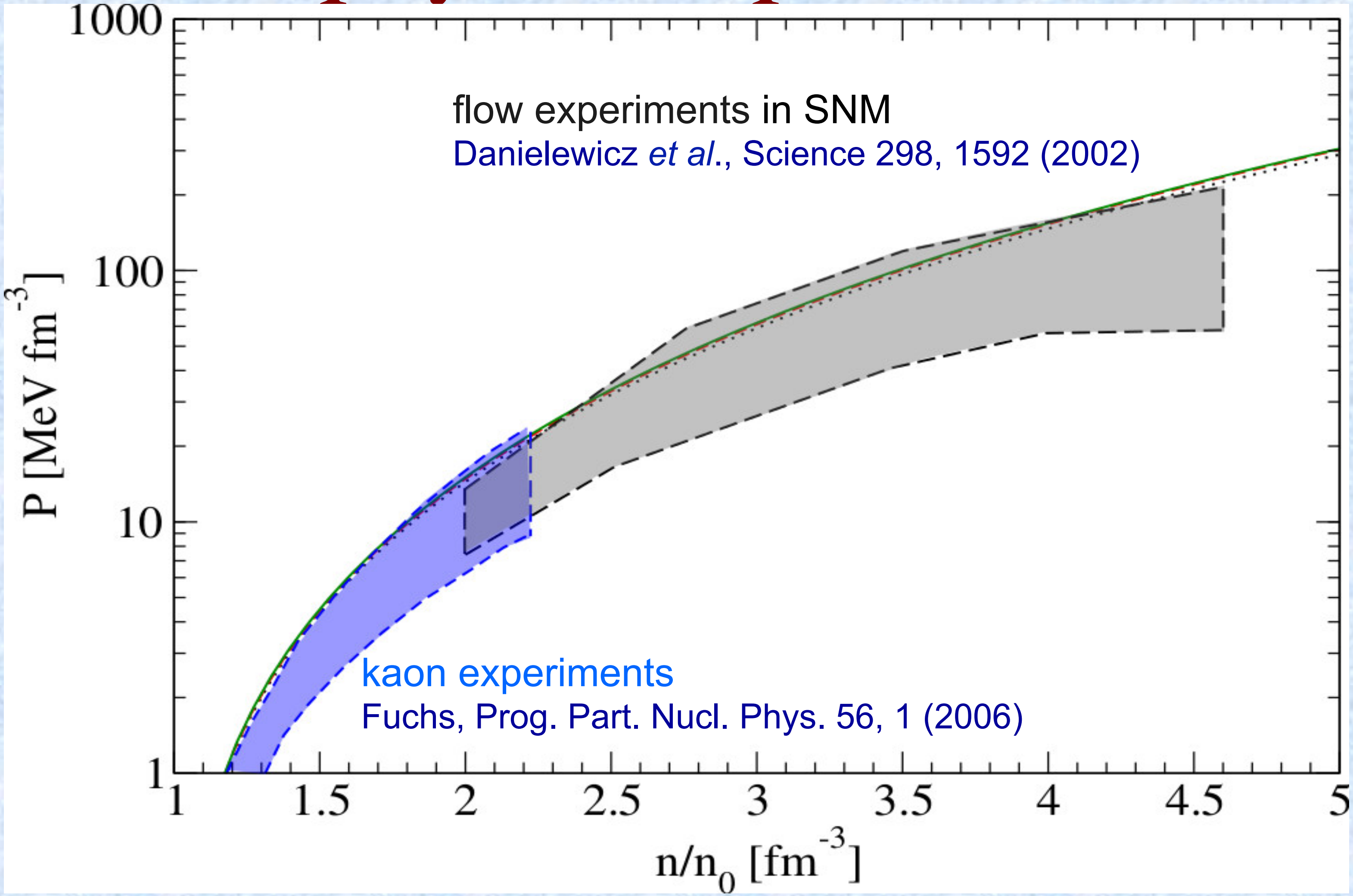


Goriely *et al.*, PRC 82, 035804 (2010)

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

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

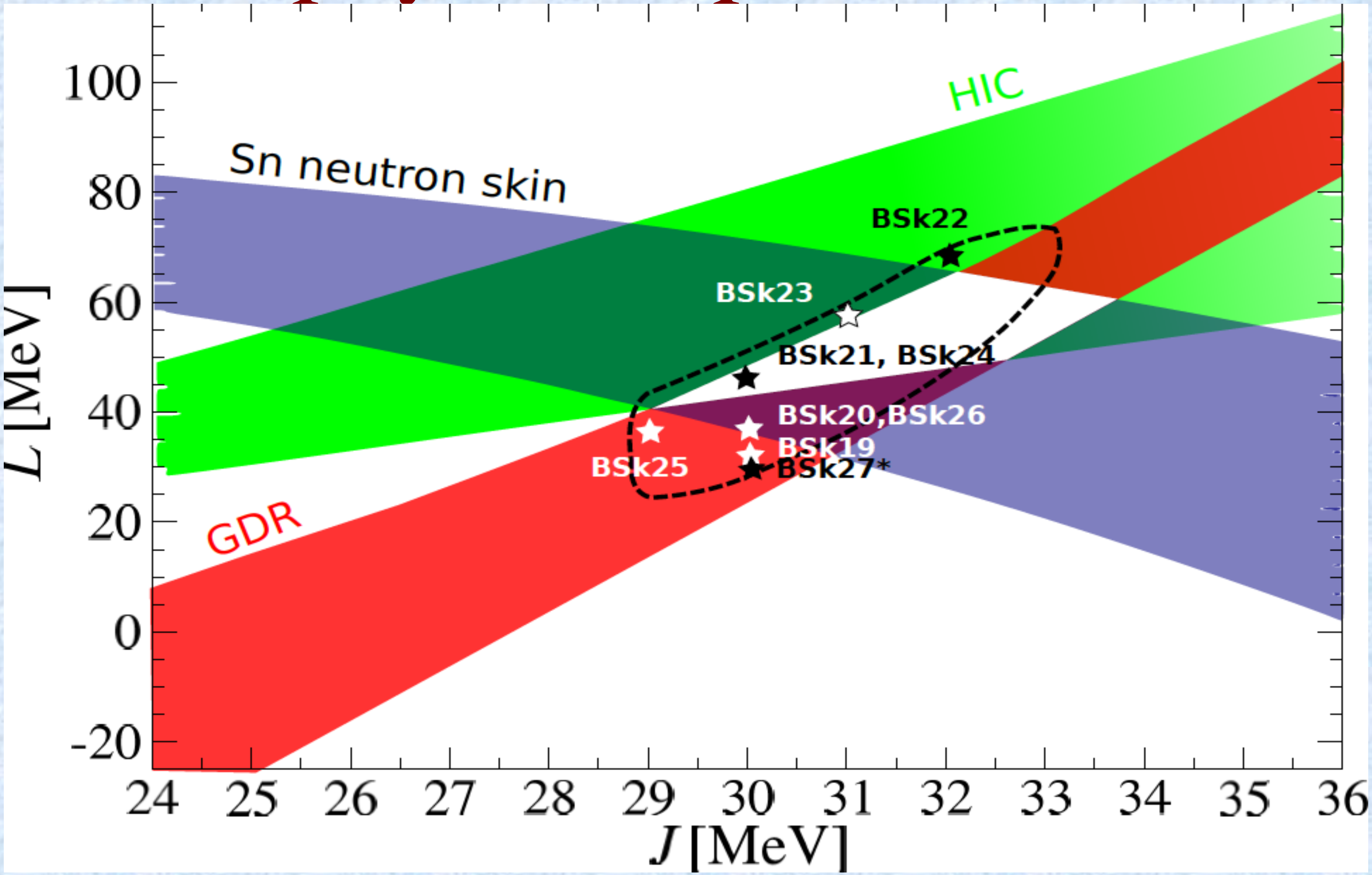
Comparison with observables from nuclear physics experiments



➡ Functionals in good agreement with "experimental" constraints on symm. 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

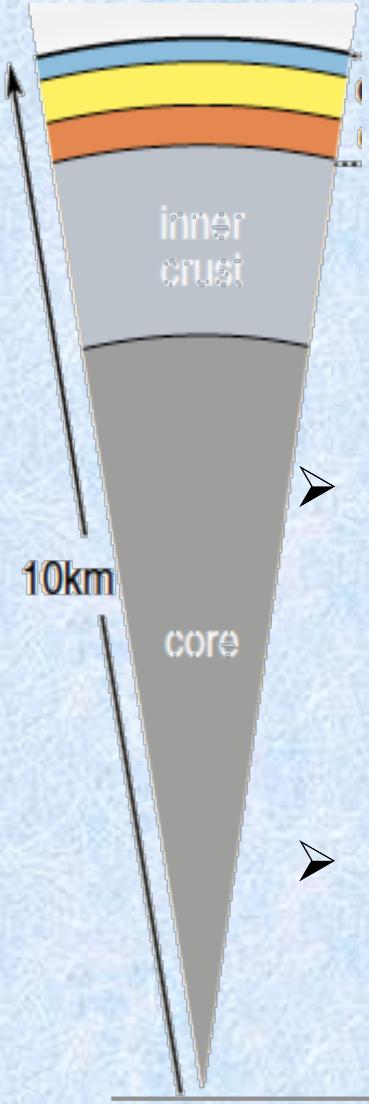
Potekhin, Fantina, Chamel *et al.*, A&A 560, A48 (2013) for BSk19-20-21 models
Fantina, *et al.*, AIP Conf. 1645, 92 (2015)

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

Outline

- Motivation and astrophysical framework
- Equation of state of dense matter:
  - Brussels-Montreal functionals
  - constraints from nuclear physics
  - constraints from astrophysics & neutron star properties
- Weak-interaction rates:
  - introduction on electron capture
  - the model
  - results
  - collective modes (GT, IAR)
- Conclusions & Outlooks

EoS of NS (nucleonic EoSs)



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

  → one nucleus (bcc lattice) + e^- (β equilibrium)

  → minimization of the Gibbs energy per nucleon: <u>BPS model</u>

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

- INNER CRUST (Pearson *et al.*, PRC85, 065803 (2012))

  → one cluster (spherical) + n, e^- (β equilibrium)

  → semi-classical model: <u>Extended Thomas Fermi</u> (4th order in $\hbar$)
  <u>+ proton shell corrections</u>

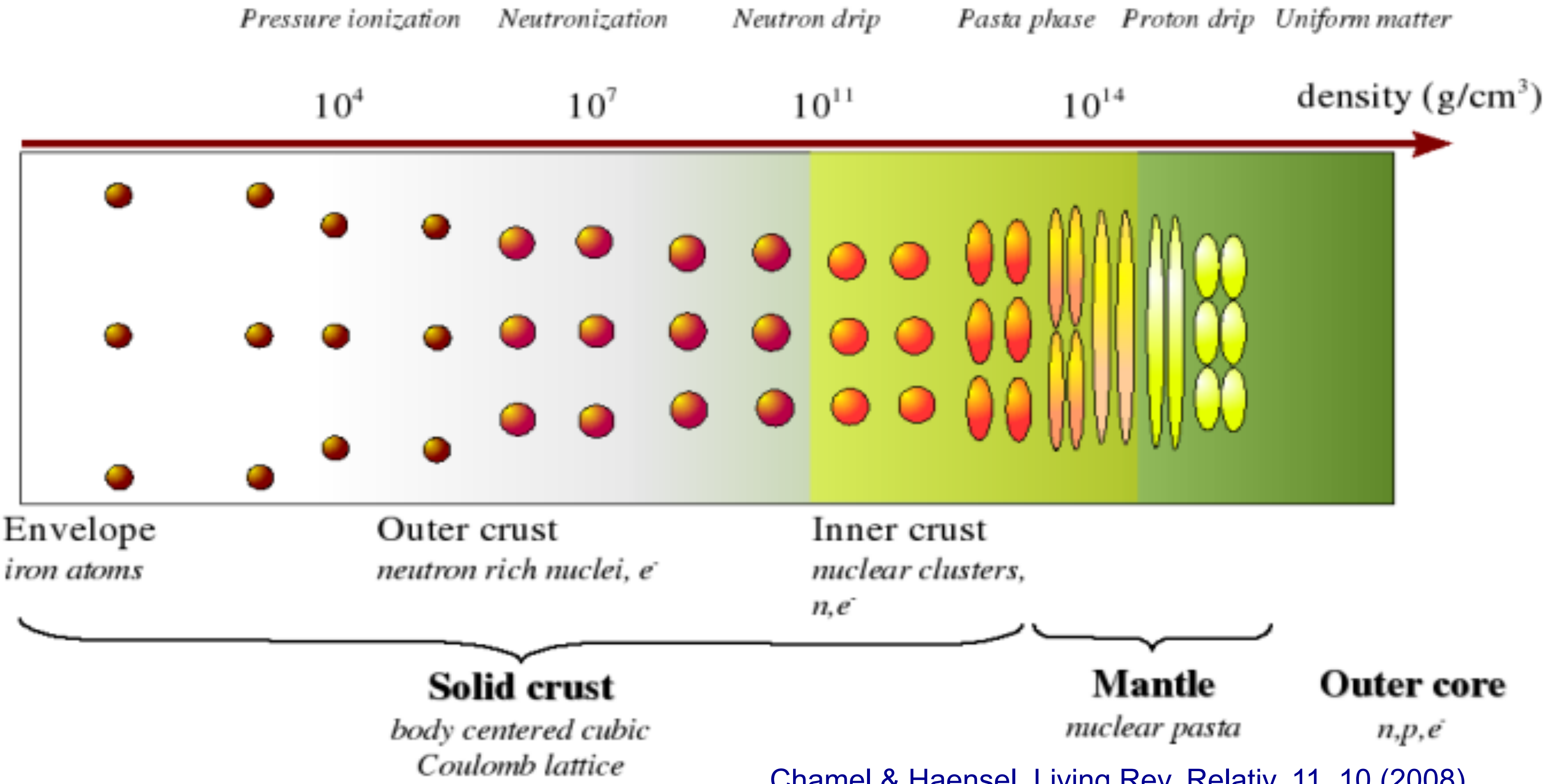
- CORE (Goriely *et al.*, PRC 82, 035804 (2010), Goriely *et al.*, PRC 88, 024308 (2013))

  → homogeneous matter: n, p, e^-, μ (β 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)

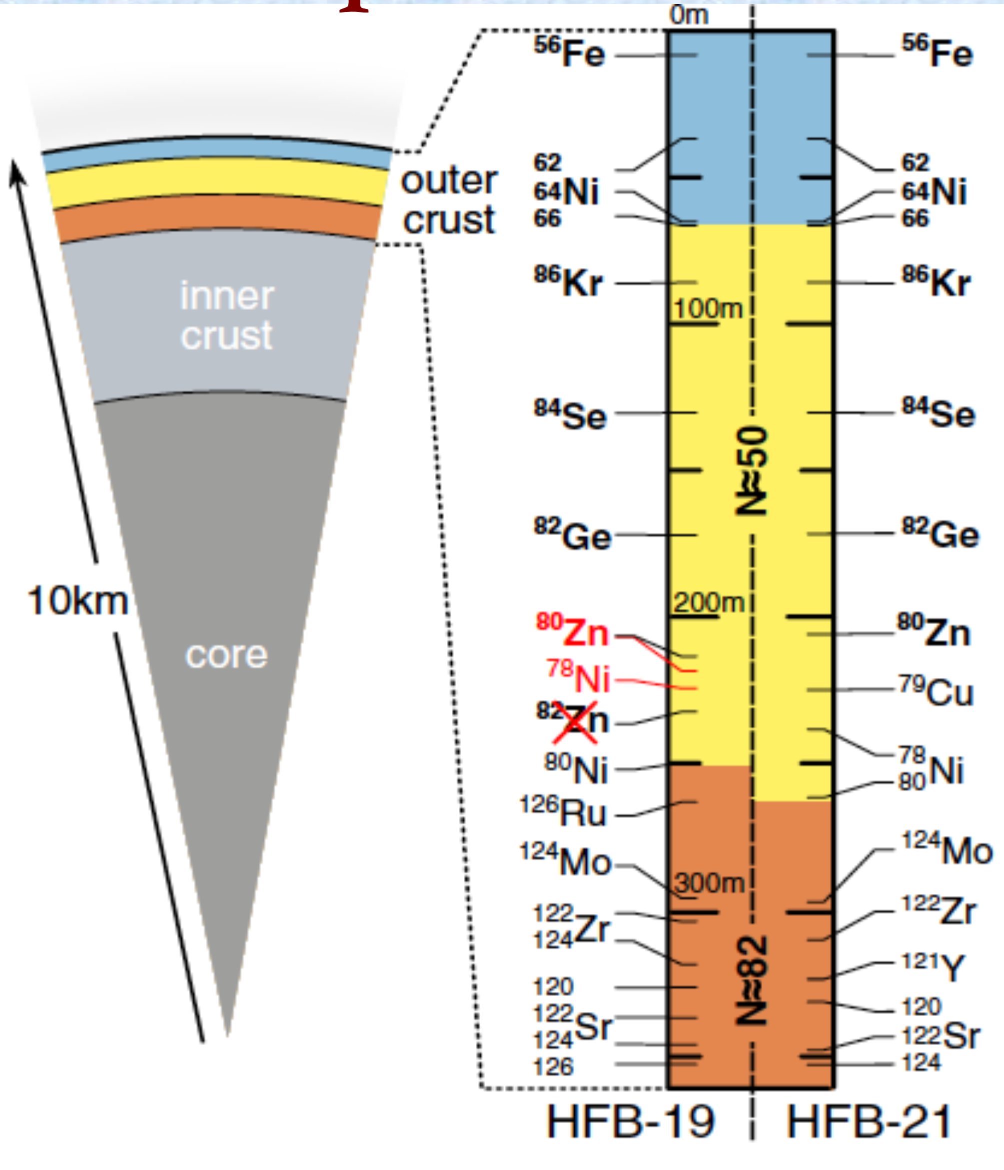
NS crust structure



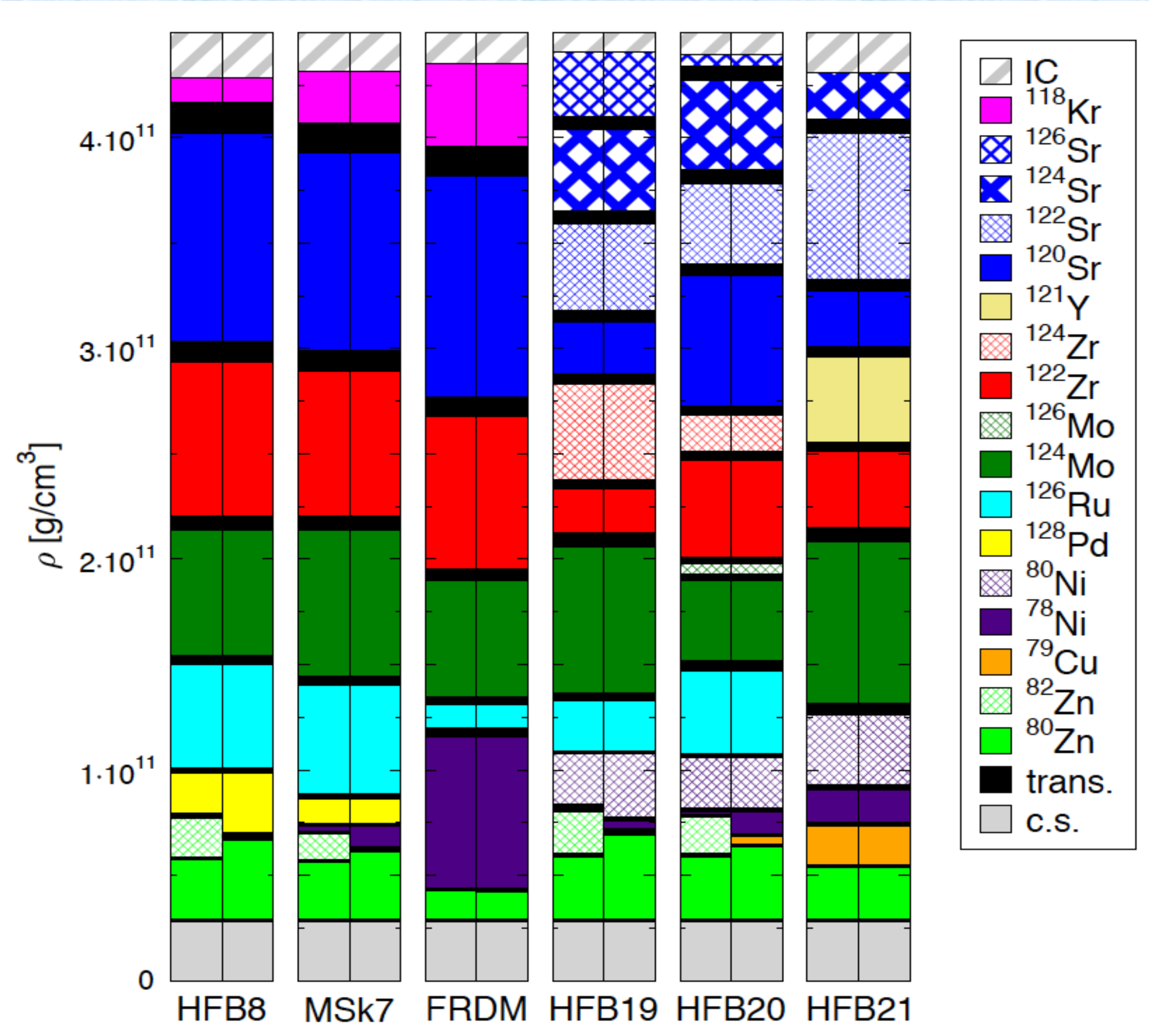
Chamel & Haensel, Living Rev. Relativ. 11, 10 (2008)

NS crust : ≈ 1% mass, ≈ 10% radius
but: related to different phenomena (e.g. glitches, X-ray bursts, etc...)

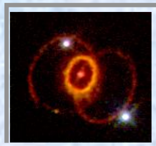
EoS for NS crust: importance of experimental masses



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

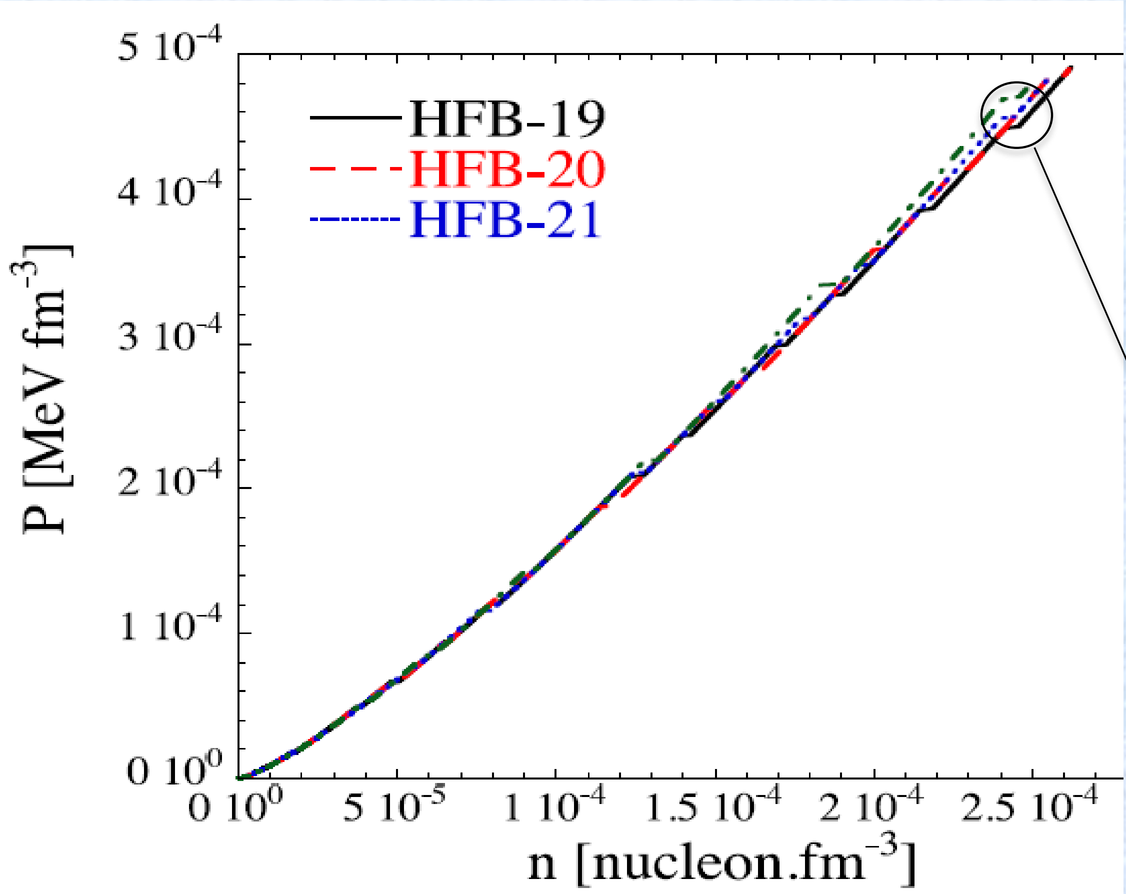


Kreim *et al.* Int. J. Mass Spectrometry (2013)



EoS : outer crust

≈ 200 m



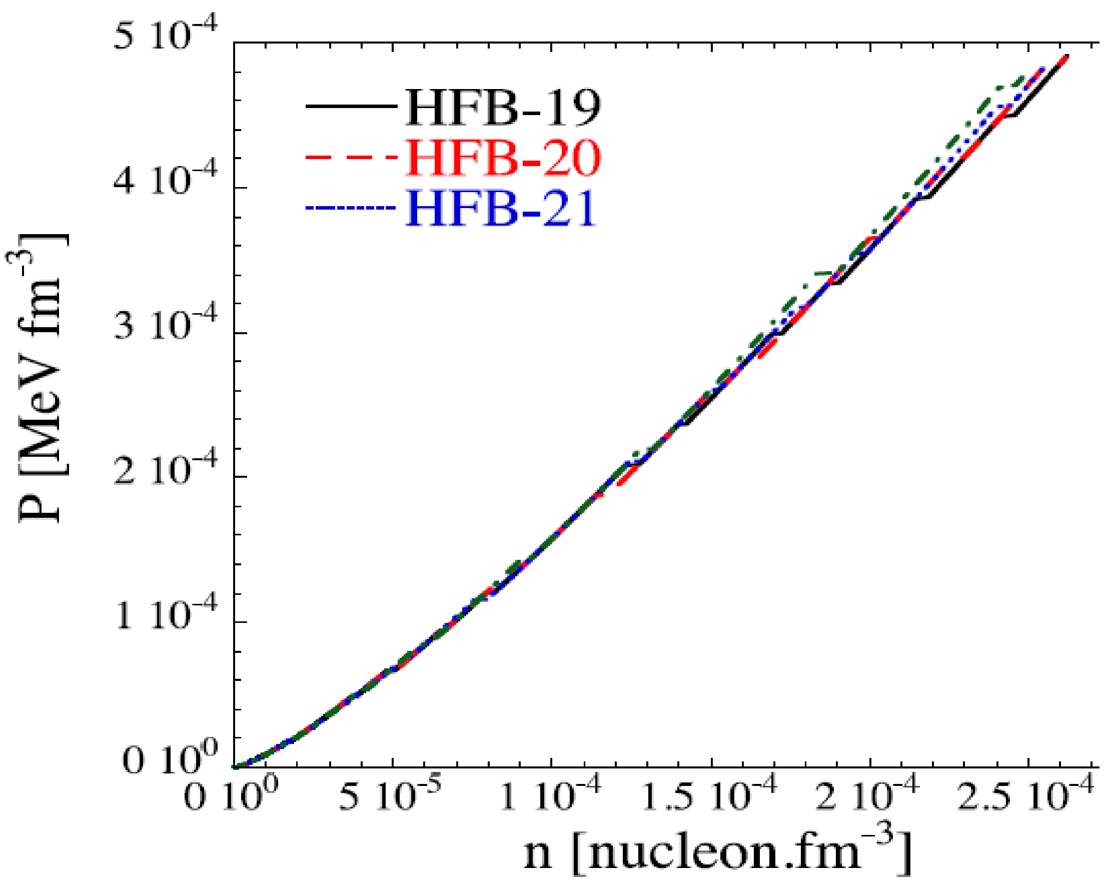
HFB-19	HFB-20	HFB-21	HFB-27*
^{56}Fe	**^{56}Fe**	**^{56}Fe**	**^{56}Fe**
^{62}Ni	**^{62}Ni**	**^{62}Ni**	**^{62}Ni**
^{64}Ni	**^{64}Ni**	**^{64}Ni**	**^{64}Ni**
^{66}Ni	**^{66}Ni**	**^{66}Ni**	**^{66}Ni**
^{86}Kr	**^{86}Kr**	**^{86}Kr**	**^{86}Kr**
^{84}Se	**^{84}Se**	**^{84}Se**	**^{84}Se**
^{82}Ge	**^{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	-	-

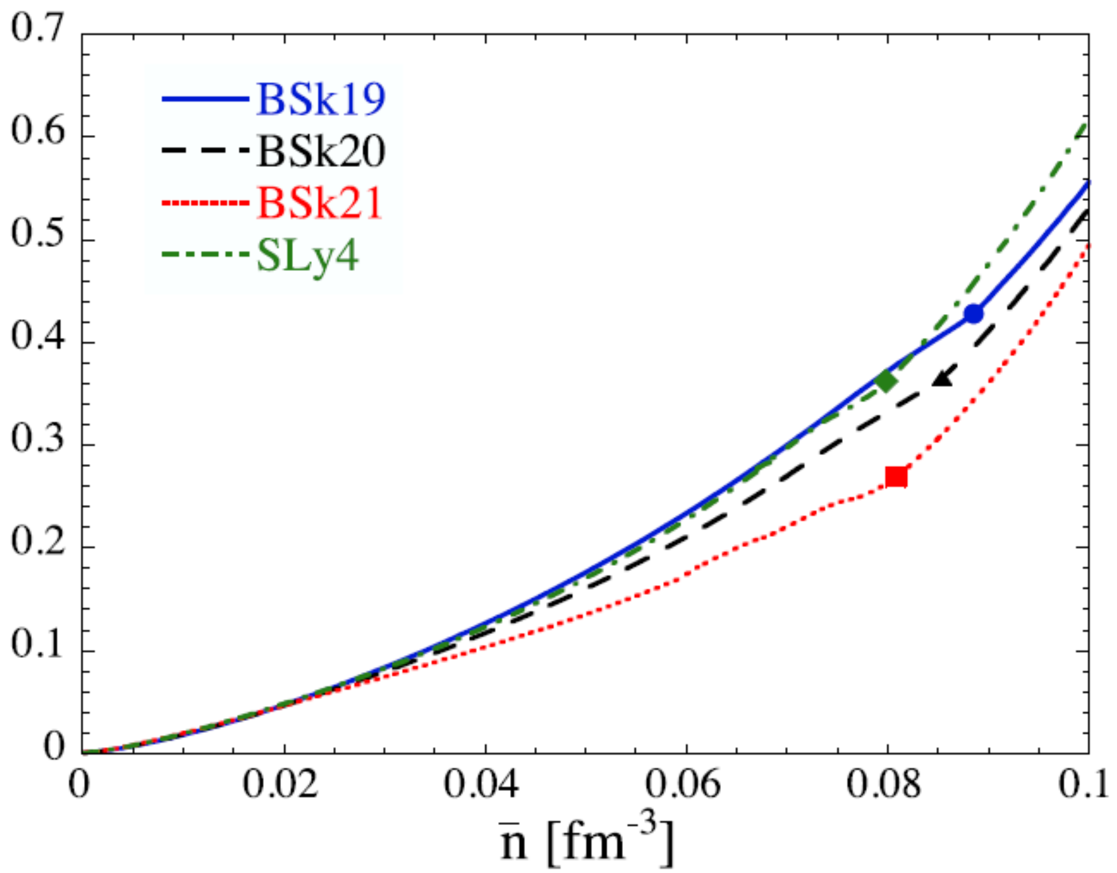
Pearson *et al.*, PRC83, 065810 (2011)
Chamel, Pearson, Fantina, *et al.*, Acta Phys. Pol. B 46, 349 (2015)

EoS for some Brussels-Montreal models (BSk19-20-21)

OUTER CRUST

INNER CRUST & CORE



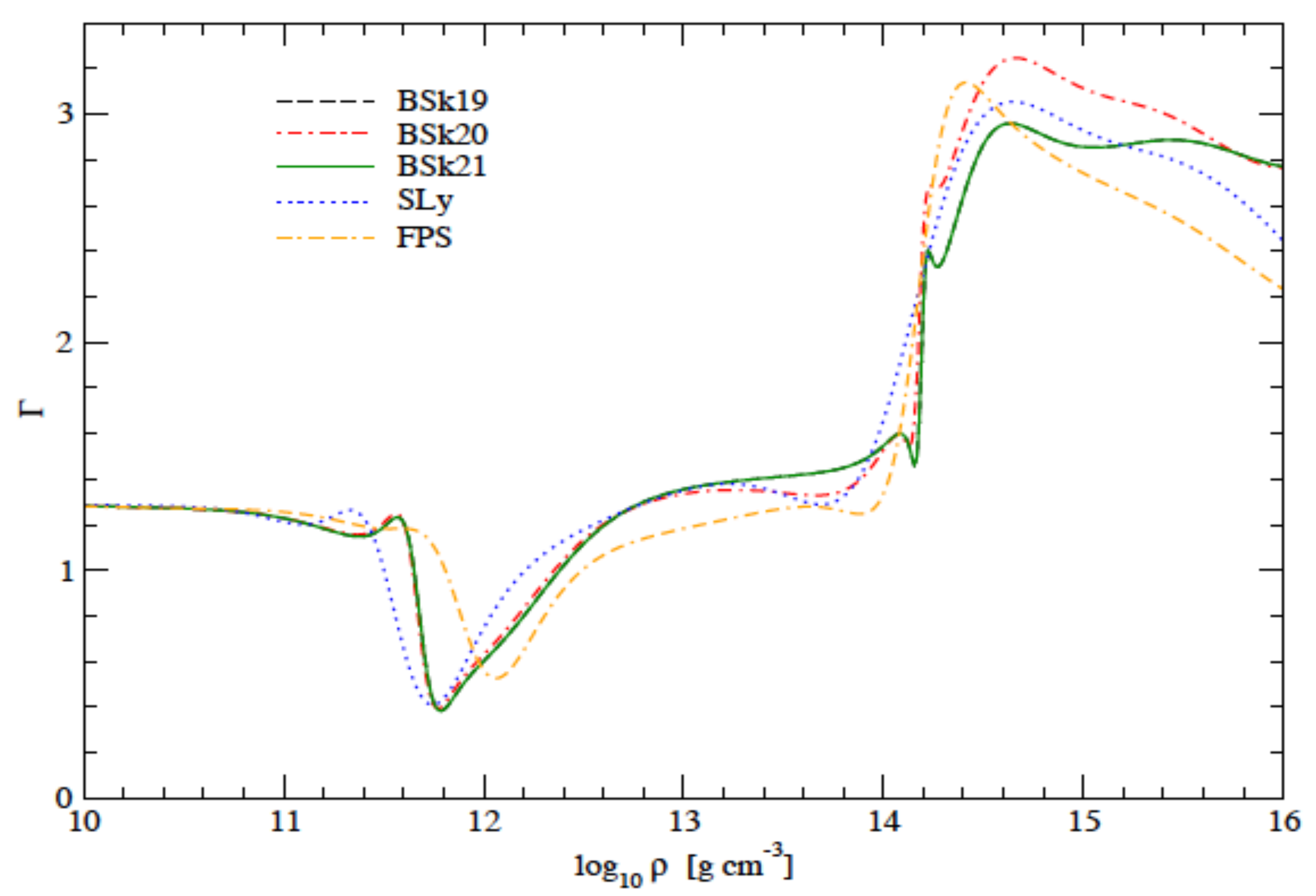


Pearson *et al.*, PRC83, 065810 (2011)

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

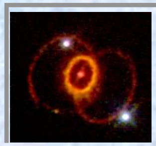
EoSs very different from ideal Fermi gas!

EoS of NS: adiabatic index



Potekhin, Fantina, Chamel, Pearson, Goriely, A&A 560, A48 (2013)

Realistic EoSs hardly parametrised by polytropes!



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

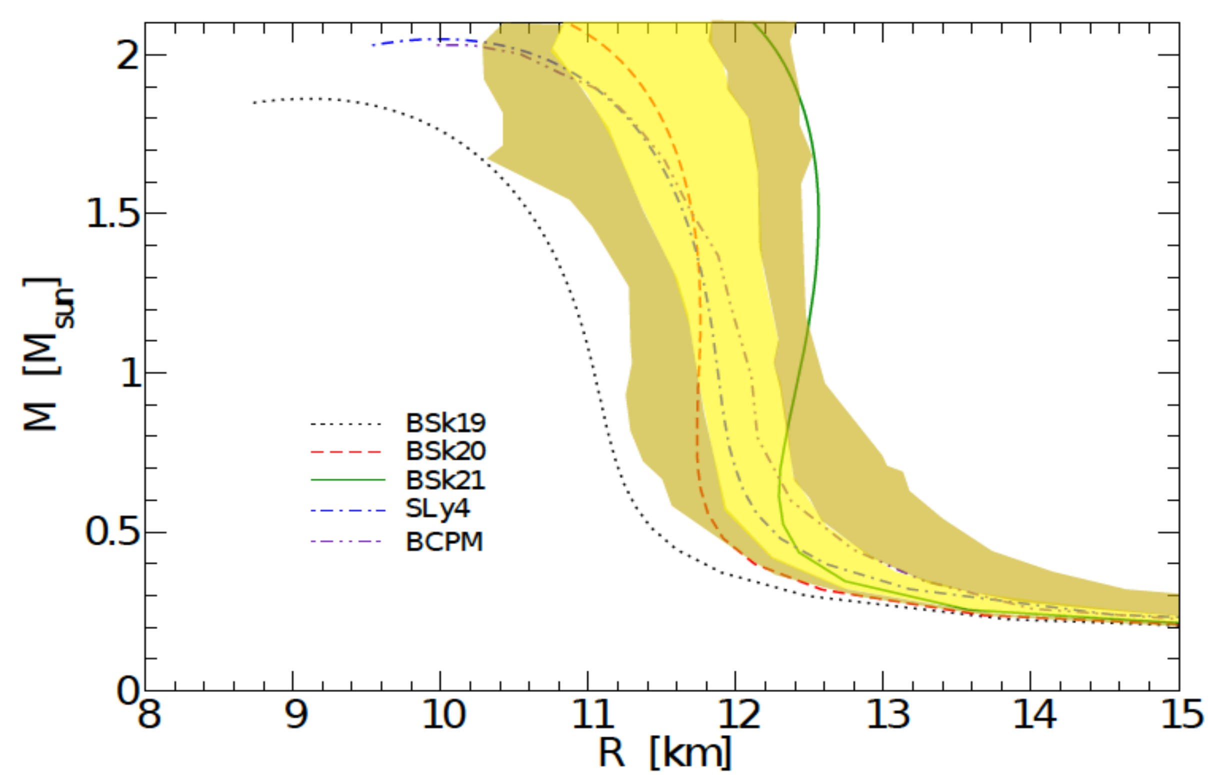
  - ✧ **rigidly rotating** NSs

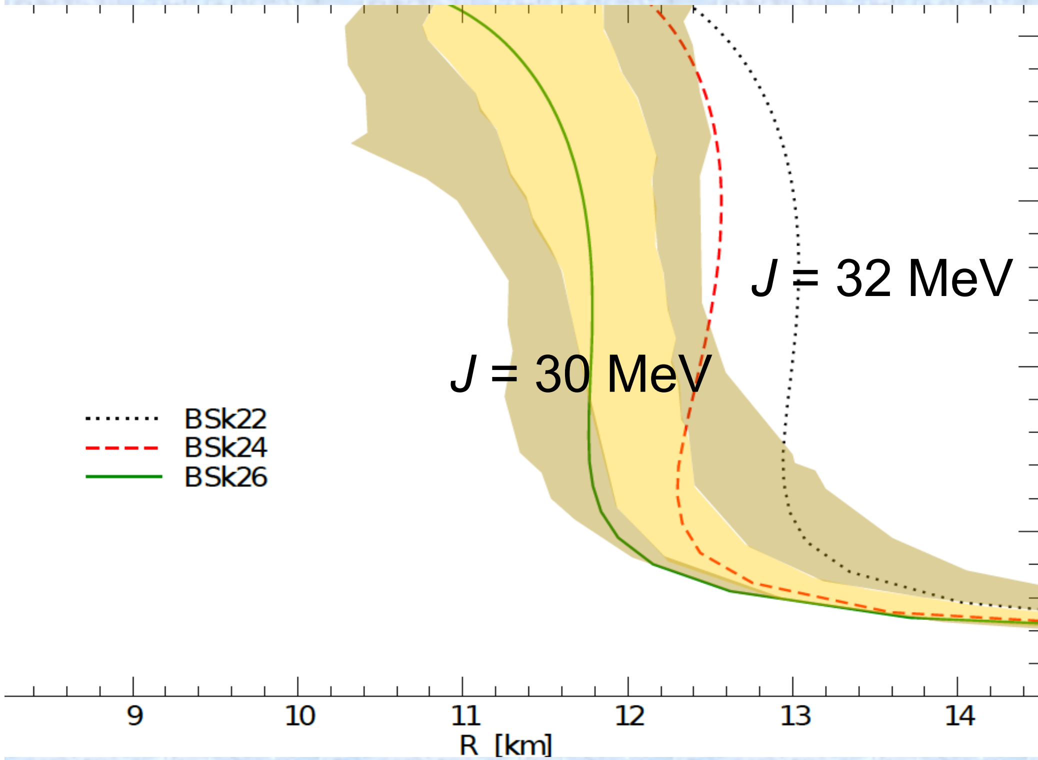
    Method: solve Einstein eqs. in GR for stationary axi-symmetric configurations.

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

NS properties: *M-R relation*



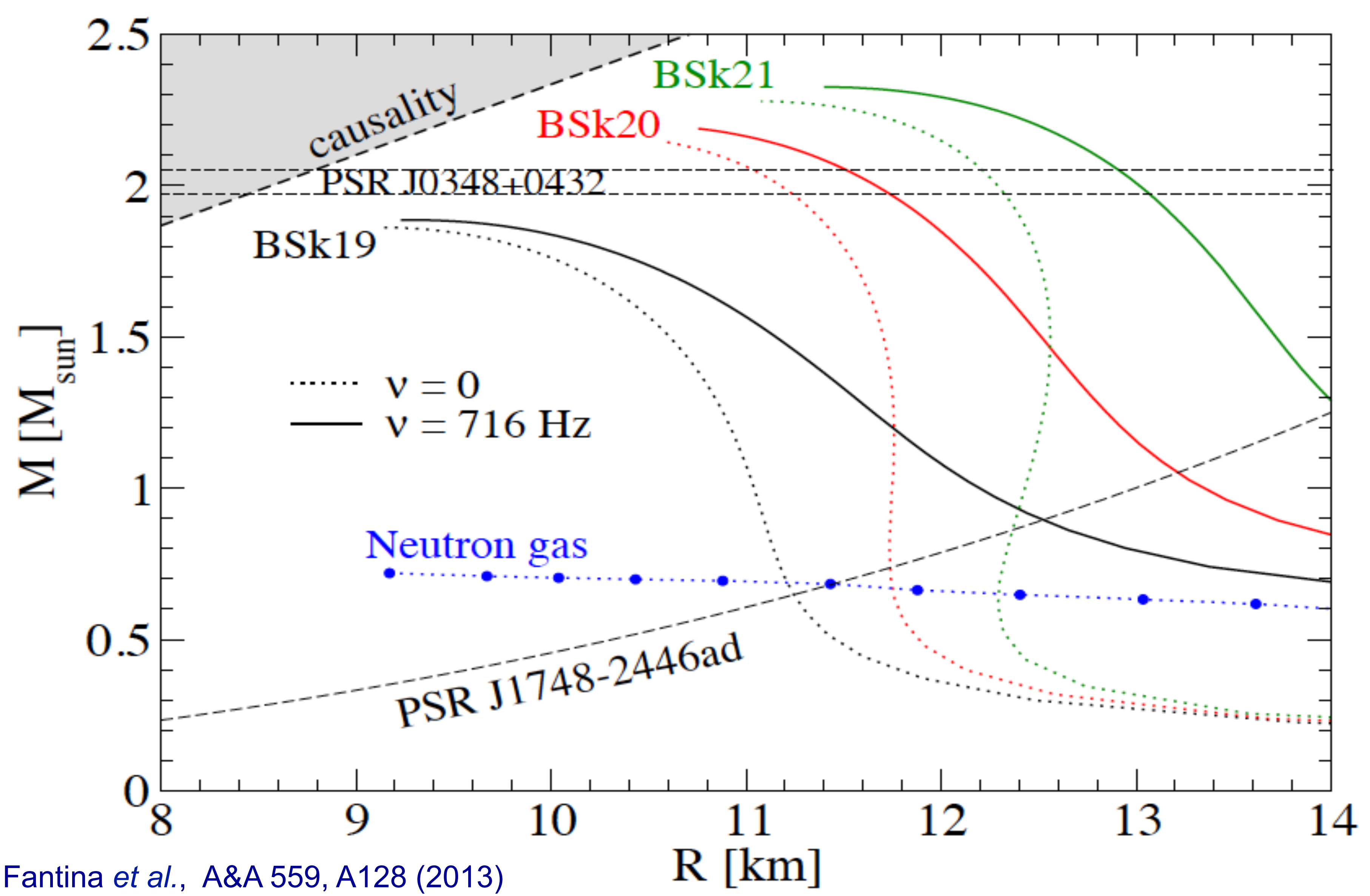


light (dark) shaded area: 1(2)-σ contour from Steiner *et al*. 2010

Fantina *et al.*, Astron. Astrophys. 559, A128 (2013)
Pearson, Chamel, Fantina, Goriely, EPJ A 50, 43 (2014)

BSk20, 24, 26, SLy4, BCPM compatible with observations
BSk21 marginally compatible

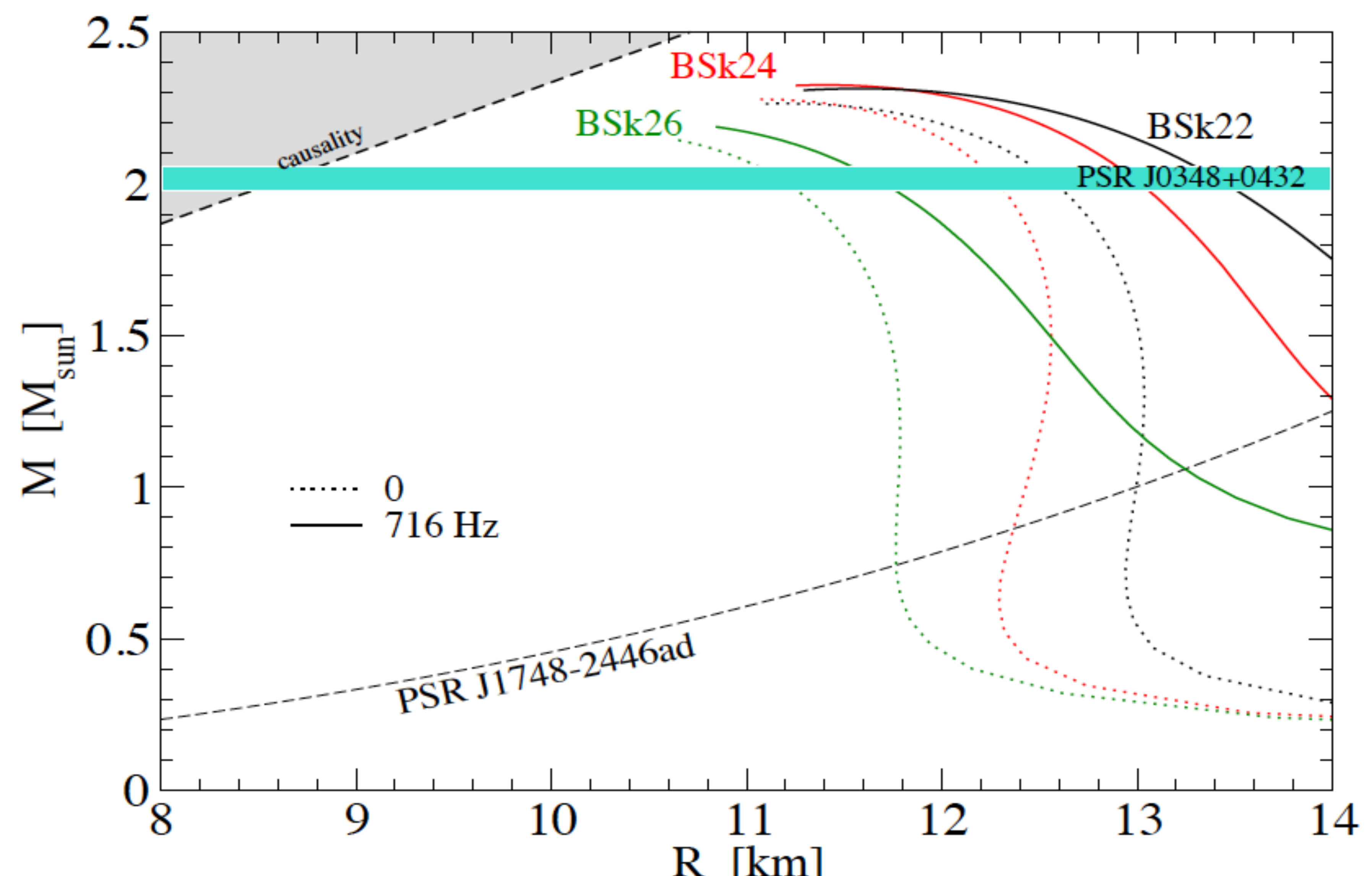
NS properties: *M-R relation with rotation*



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

BSk20-21 compatible with observations
BSk19 seems to soft, but if phase transition → still ok!

NS properties: *M-R relation with rotation*

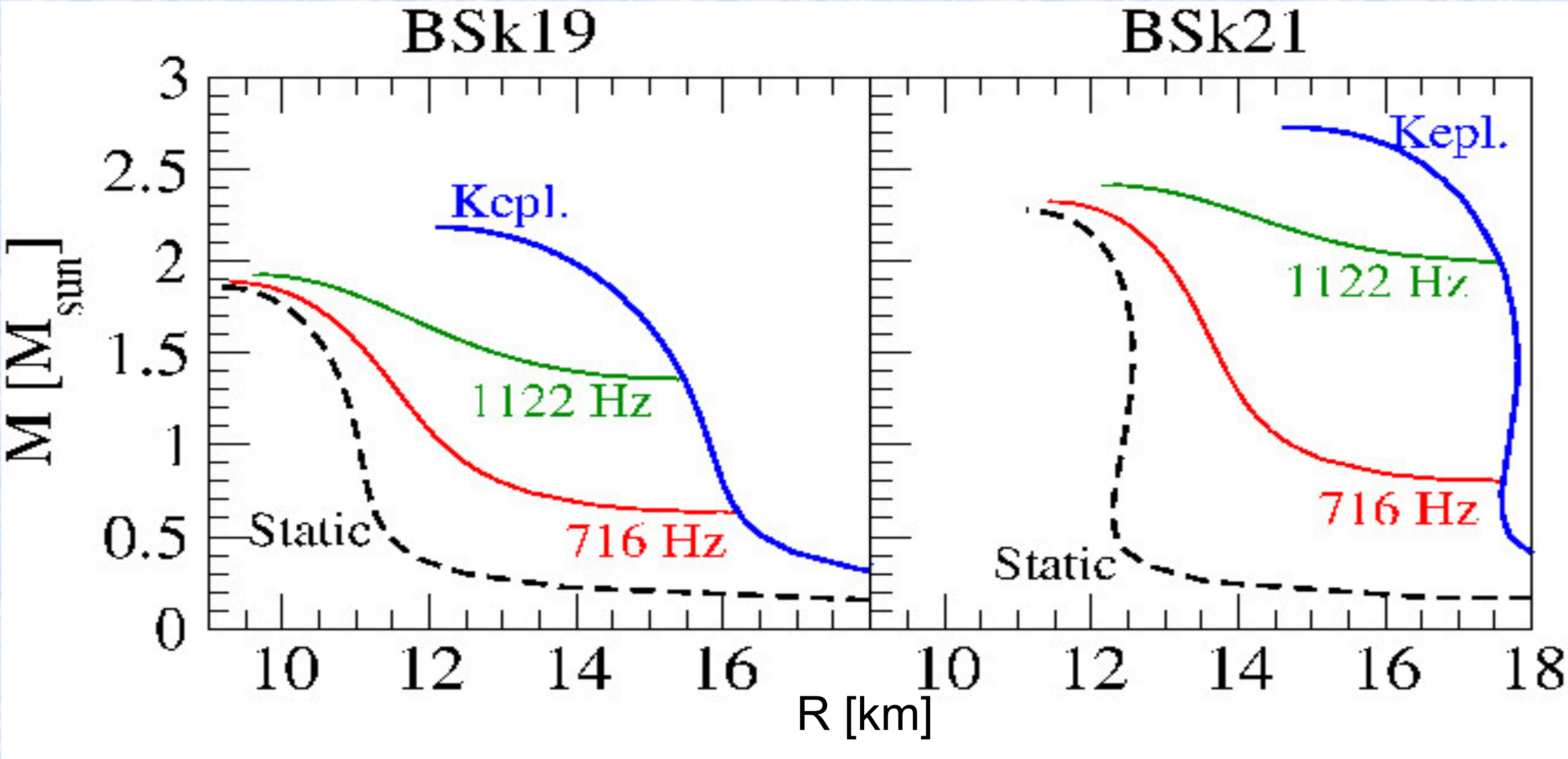


Fantina *et al.*, AIP Conf. Proc. 1645, 92 (2015)

➡ BSk22-24-26 compatible with observations of M_{max}

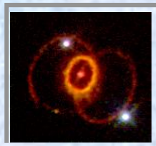
NS properties: *keplerian velocity*

The rotational frequency of a stable NS is limited by the keplerian frequency above which the NS will be disrupted as a result of mass shedding



Fantina *et al.*, Astron. Astrophys. 559, A128 (2013)

only fast rotation increases considerably maximum mass (≈ 17-20%)
but: rotation can affect structure of low-mass NSs



Conclusions & Outlooks on EoSs

❖ **Nuclear physics experiments + Astrophysical observations can put constraints on the EoS of dense matter!**

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

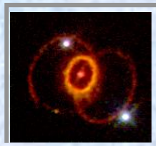
➢ ***fit*** : Potekhin *et al.*, A&A 560, A48 (2013) at: http://www.ioffe.ru/astro/NSG/BSk/

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

\+ ***Love number*** : Damour, Nagar, Villain, PRD 85, 123007 (2012)

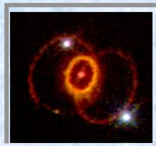
❖ Finite T for SN cores
work in progress with J. M. Pearson, N. Chamel, S. Goriely

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



Outline

- Motivation and astrophysical framework
- Equation of state of dense matter:
  - Brussels-Montreal functionals
  - constraints from nuclear physics
  - constraints from astrophysics & neutron star properties
- Weak interaction rates:
  - introduction on electron capture
  - the model
  - results
  - collective modes (GT, IAR)
- Conclusions and Outlooks



Motivations for weak processes in SN

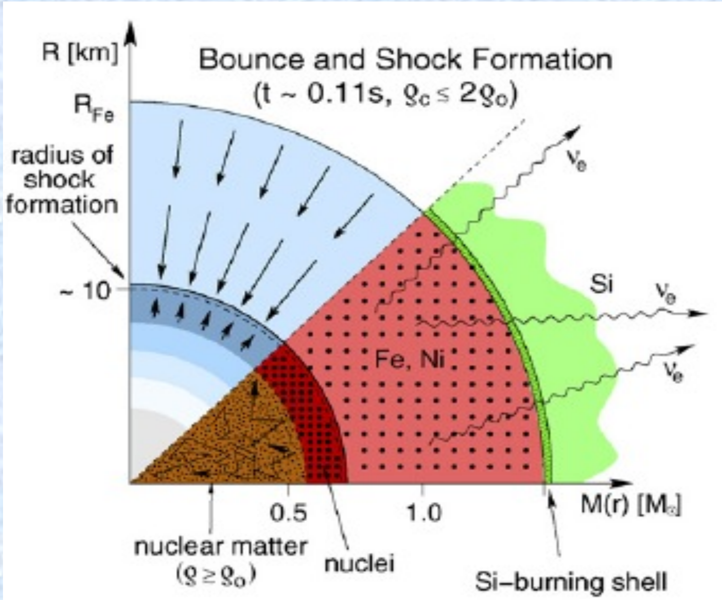
- Weak processes crucial all along the life of a star

- Electron-capture and beta decays crucial in pre-supernova phase
  - ⟶ determines electron fraction Y_e and entropy s in the core
  - ⟶ formation of neutron-rich nuclei

- Electron-capture governs the deleptonization phase
  - ⟶ Y_e at trapping
  - ⟶ shock wave formation

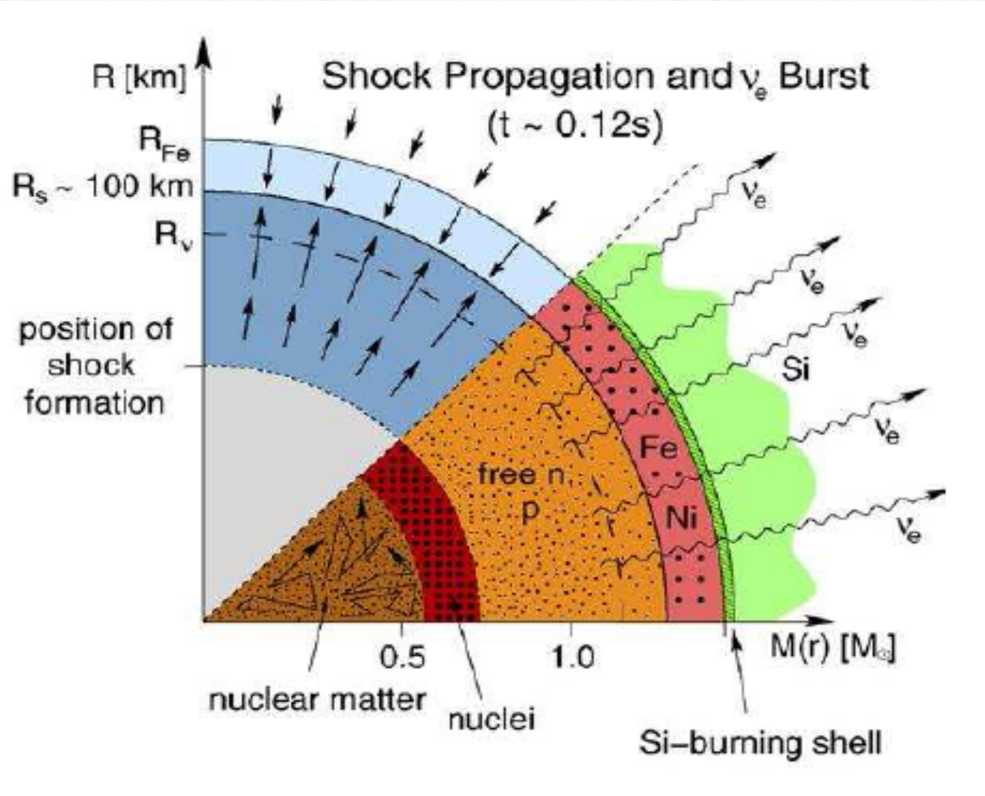
$$M_{ch} = 5.8\ Y_{lept}^2$$

- Here: calculations on Fe, Ge, Ni isotopes

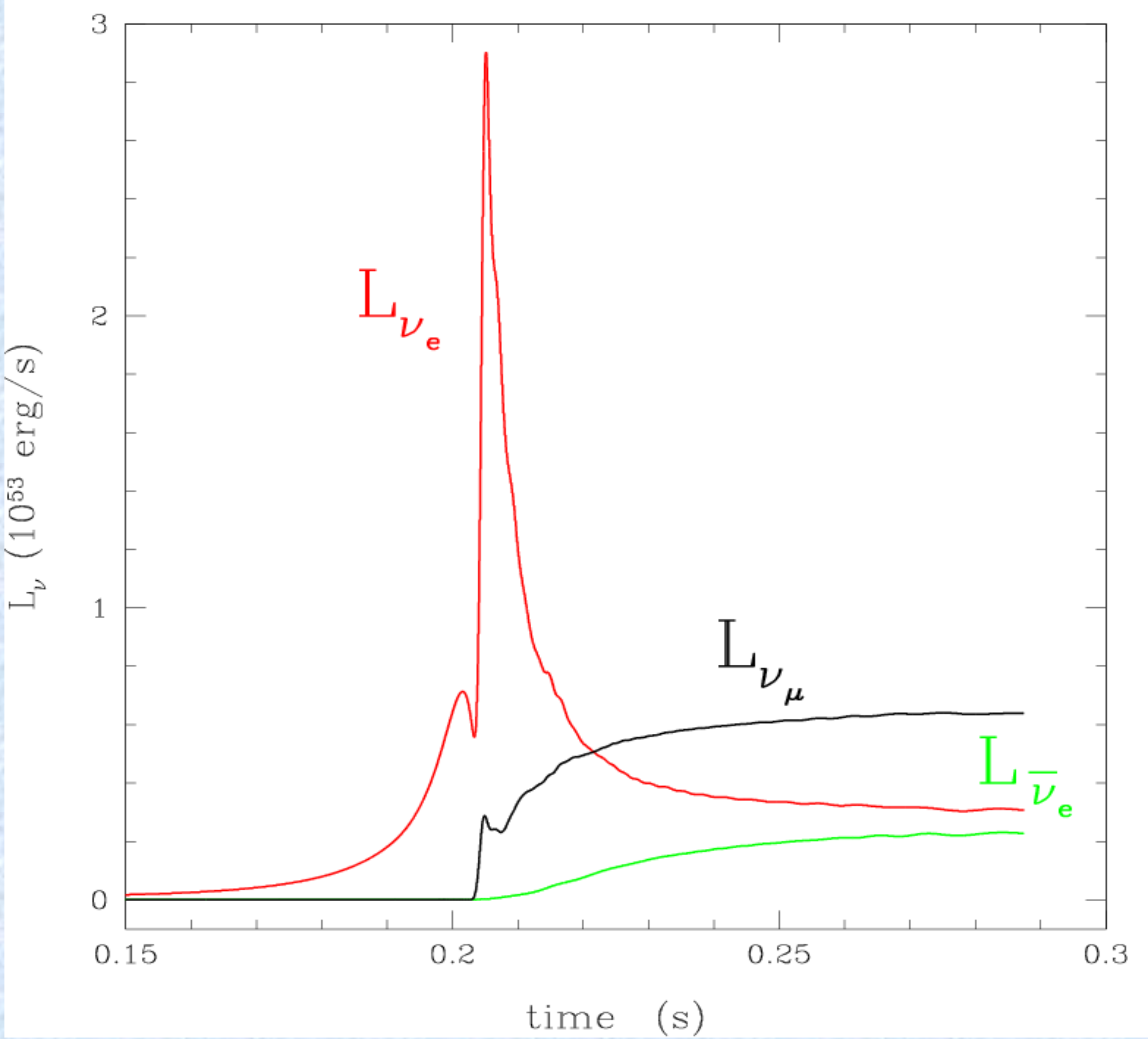


Janka *et al.*, Phys. Rep. 442, 38 (2007)

Neutrino burst at shock break-out



Janka *et al.*, Phys. Rep. 442, 38 (2007)



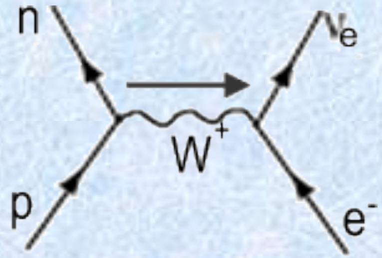
Thompson *et al.*, Ap.J. 592, 434 (2003) , 11 M_{sun} progenitor

for a review, e.g. Janka, Annu. Rev. Nucl. Part. Sci. 62, 407 (2012); Burrows, Rev. Mod. Phys. 85, 245 (2013) Mezzacappa, Rev. Nucl. Part. Sci. 55, 467 (2005)

Introduction on electron capture

$$p + e^- \rightarrow n + \nu_e$$ on free protons

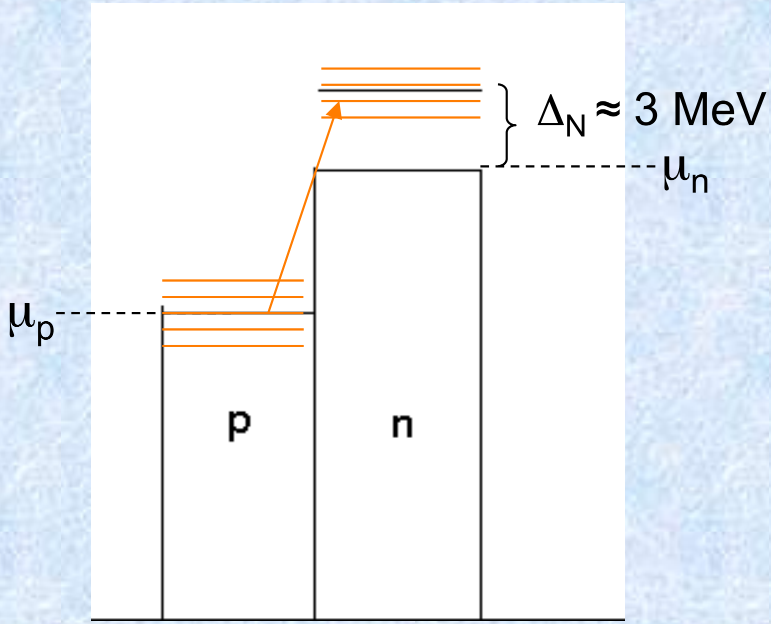
$$(Z, A) + e^- \rightarrow (Z-1, A) + \nu_e$$ on nuclei



Condition during supernova collapse:

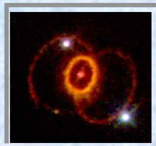
$$\rho \in [10^5 - 10^{15}] \text{ g cm}^{-3}$$
$$T \in [0.1 - 100] \text{ MeV}$$
$$Y_e \in [0.05 - 0.5]$$

⟶ capture allowed!

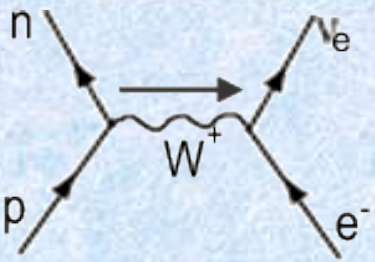


✧ *Electron capture on free protons*: quite well known!

✧ *Electron capture on nuclei*: requires knowledge of nuclear structure → difficult!

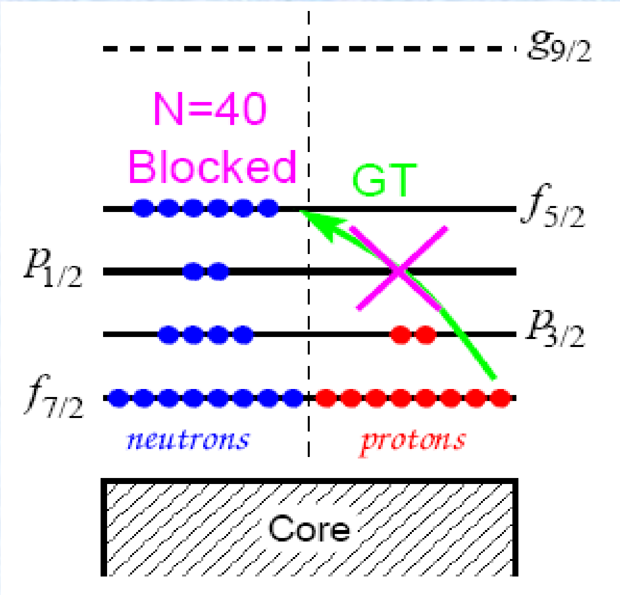


Electron-capture rates: (some) existing calculations (1)



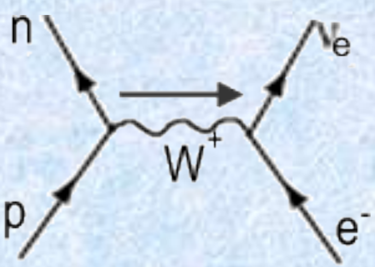
Up to now, in SN simulations, no self-consistent models:

- Fuller, Fowler & Newmann (1982, 1985): independent particle model
  → 2 level-transitions, no configuration mixing and *T* effects



for a review, e.g. Langanke & Martinez-Pinedo, Rev. Mod. Phys. 75, 819 (2003); Nucl. Phys. A928, 305 (2014)

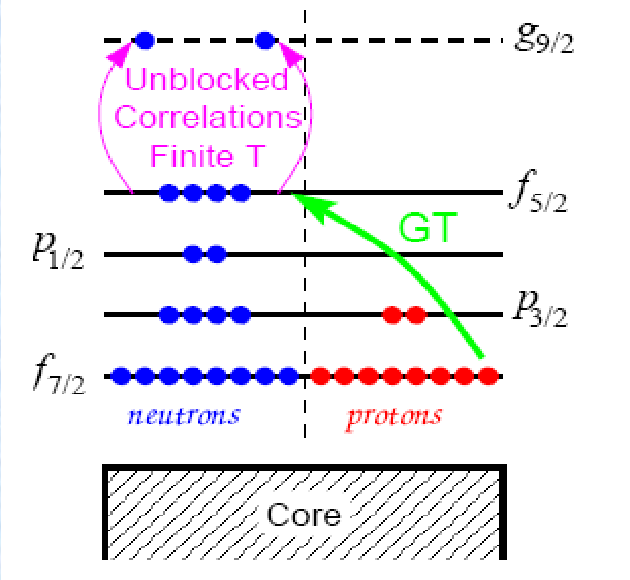
Electron-capture rates: (some) existing calculations (2)



Up to now, in SN simulations, no self-consistent models:

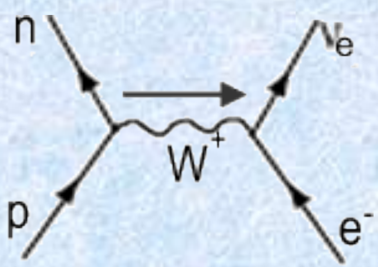
- Fuller, Fowler & Newmann (1982, 1985): independent particle model
  → 2 level-transitions, no configuration mixing and *T* effects

- Langanke & Martínez-Pinedo (2000, 2001): SMMC, SMMC + RPA



for a review, e.g. Langanke & Martínez-Pinedo, Rev. Mod. Phys. 75, 819 (2003); Nucl. Phys. A928, 305 (2014)

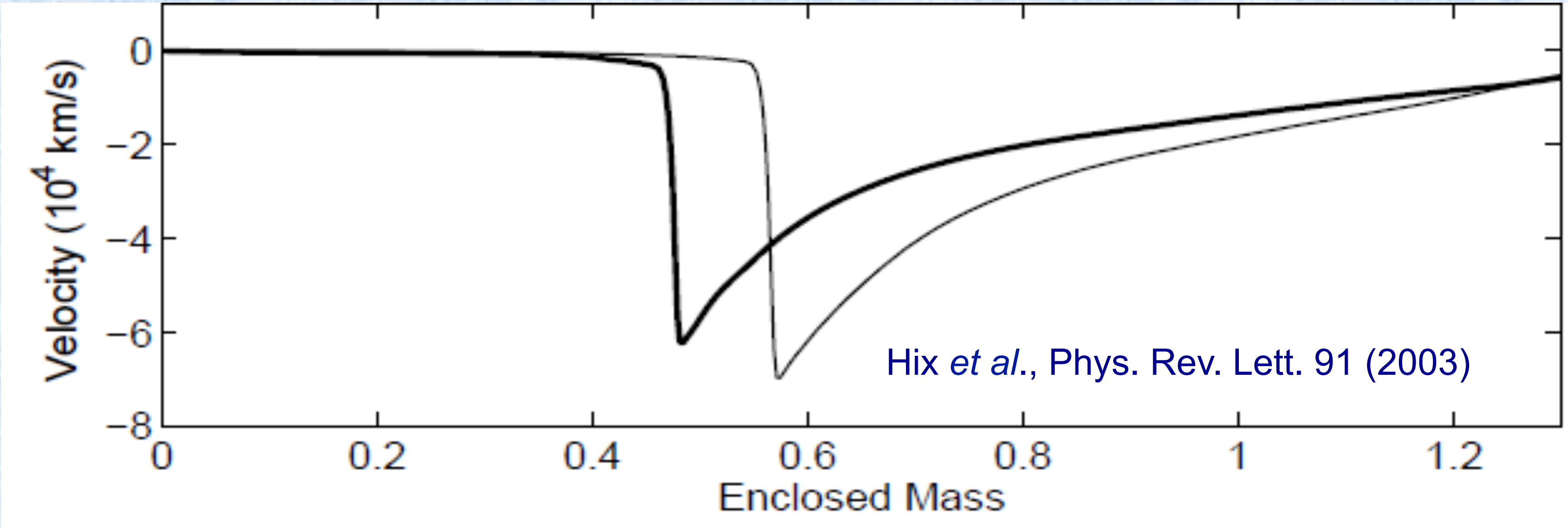
Electron-capture rates: (some) existing calculations (2)



Up to now, in SN simulations, no self-consistent models:

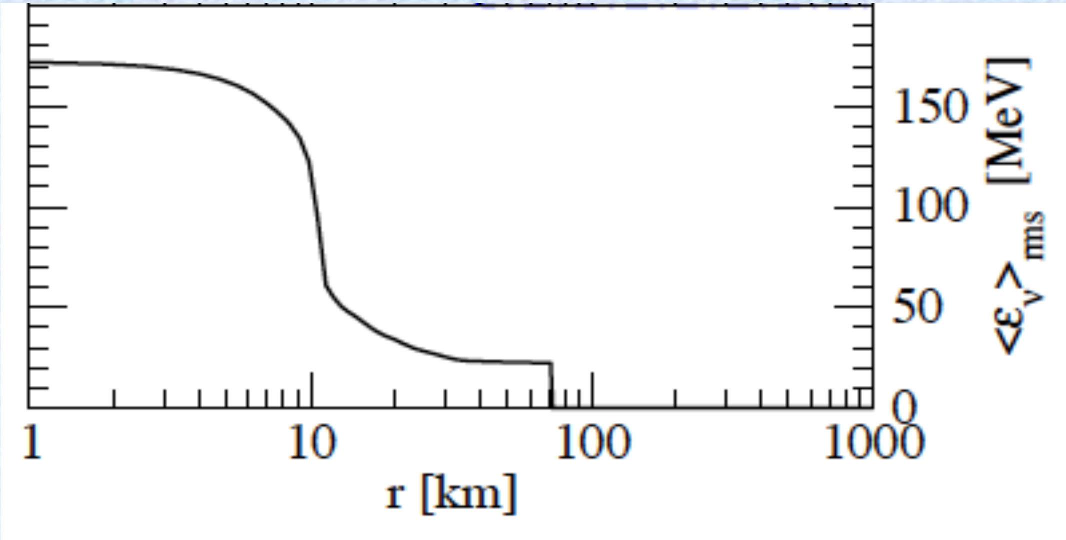
- Fuller, Fowler & Newmann (1982, 1985): independent particle model
  → 2 level-transitions, no configuration mixing and *T* effects

- Langanke & Martínez-Pinedo (2000, 2001): SMMC, SMMC + RPA



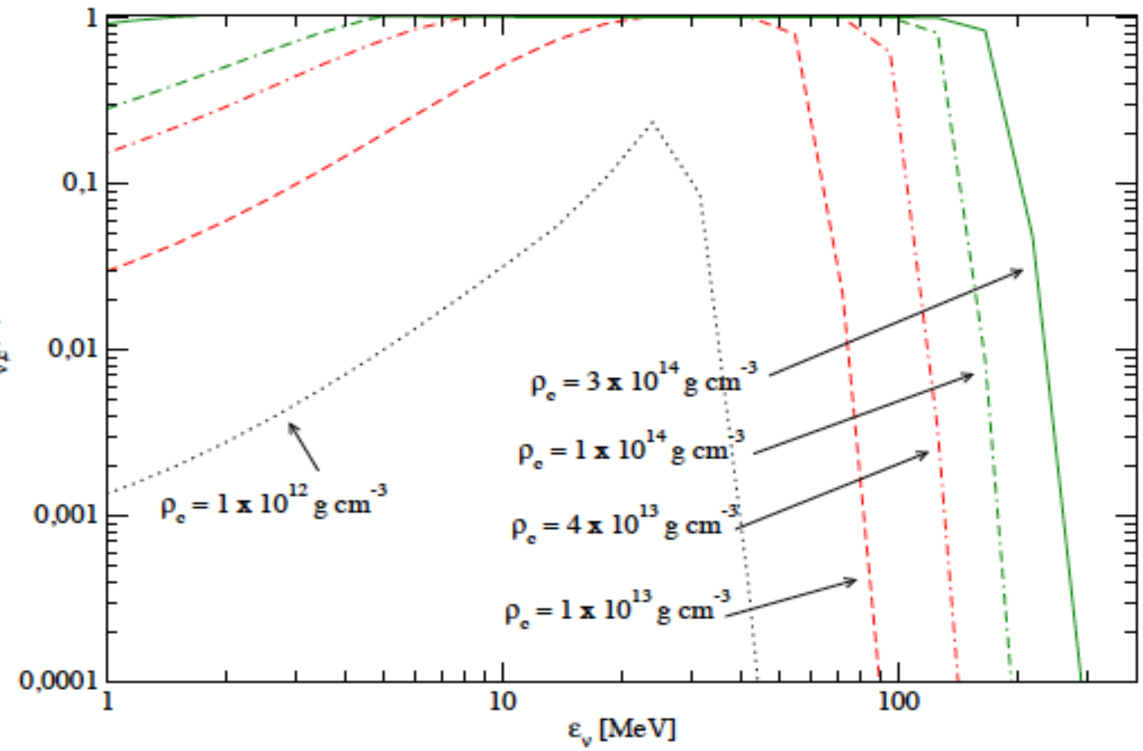
for a review, e.g. Langanke & Martínez-Pinedo, Rev. Mod. Phys. 75, 819 (2003); Nucl. Phys. A928, 305 (2014)

Neutrinos from CCSN: an example



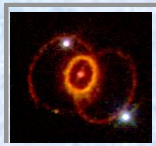
rms neutrino energy at bounce

neutrino distribution function in the core



Electron capture from Bruenn 1985 (FFN)
Trapping scheme based on a threshold density criteria

15 solar mass progenitor, 1D GR simulation
(Fantina, PhD thesis (2010))



Electron-capture rates: (some) existing calculations (3)

➢ <u>Mean-field based models:</u>

- Paar *et al*., Phys. Rev. C 80, 055801 (2009) : FTSHF + RPA
  Skyrme Hartree-Fock + charge-exchange RPA
- Niu *et al*., Phys. Rev. C 83, 045807 (2011) : FTRRPA
  Relativistic RPA
- Dzhioev *et al*., Phys. Rev. C 81, 015804 (2010) : TQRPA
  thermal quasi-particle RPA
- Sarriguren, Phys. Rev. C 87, 045801 (2013) :
  deformed Skyrme Hartree-Fock + QRPA

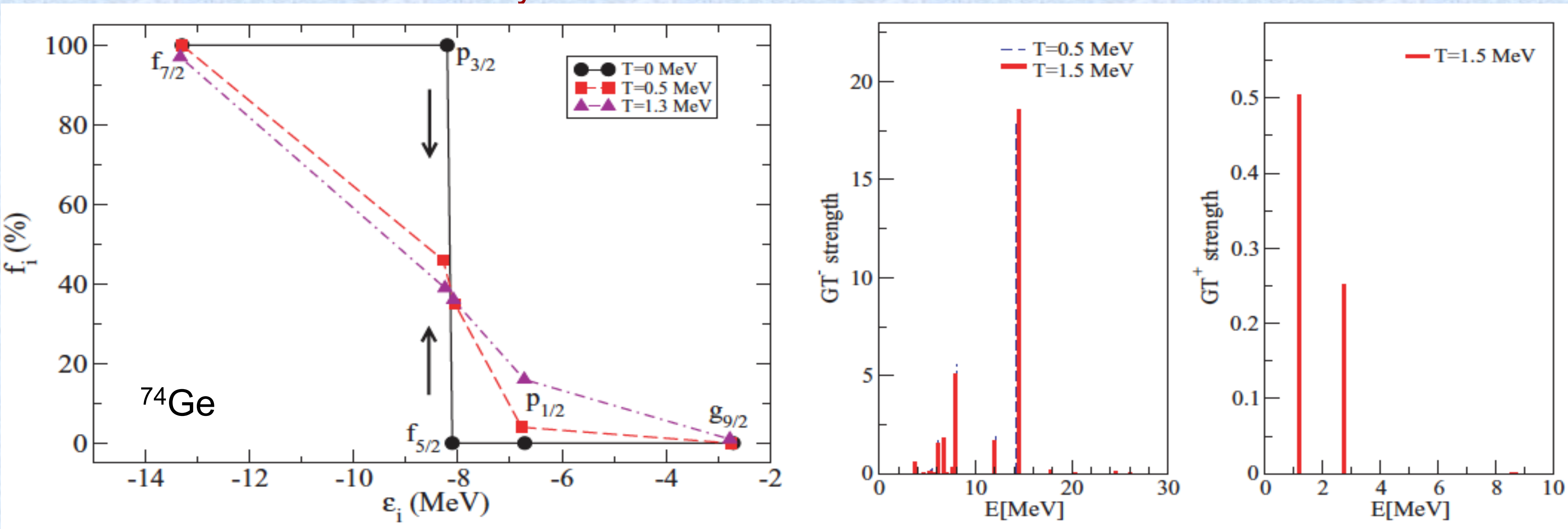
→ *not yet implemented in astrophysical codes*

FTSHF+FTRPA model (sketch)

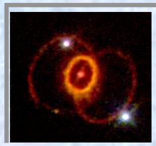
- **FTSHF** → single-nucleon basis, occupation factors and wave function of initial state
- **FTRPA** (finite T, charge-exchange) → excitation energies,
  transition energy and strengths (e.g. GT, IAR)

(Paar *et al.*, PRC 80, 055801 (2009))

N.B.: The model is self-consistent: both HF eqs. and RPA matrix based on the *same* Skyrme functional



Paar *et al.*, PRC 80, 055801 (2009)



FTSHF+FTRPA model (sketch)

- **FTSHF** → single-nucleon basis, occupation factors and wave function of initial state
- **FTRPA** (finite T, charge-exchange) → excitation energies,
  transition energy and strengths (e.g. GT, IAR)

(Paar *et al*., PRC 80, 055801 (2009))

N.B.: The model is self-consistent: both HF eqs. and RPA matrix based on the *same* Skyrme functional

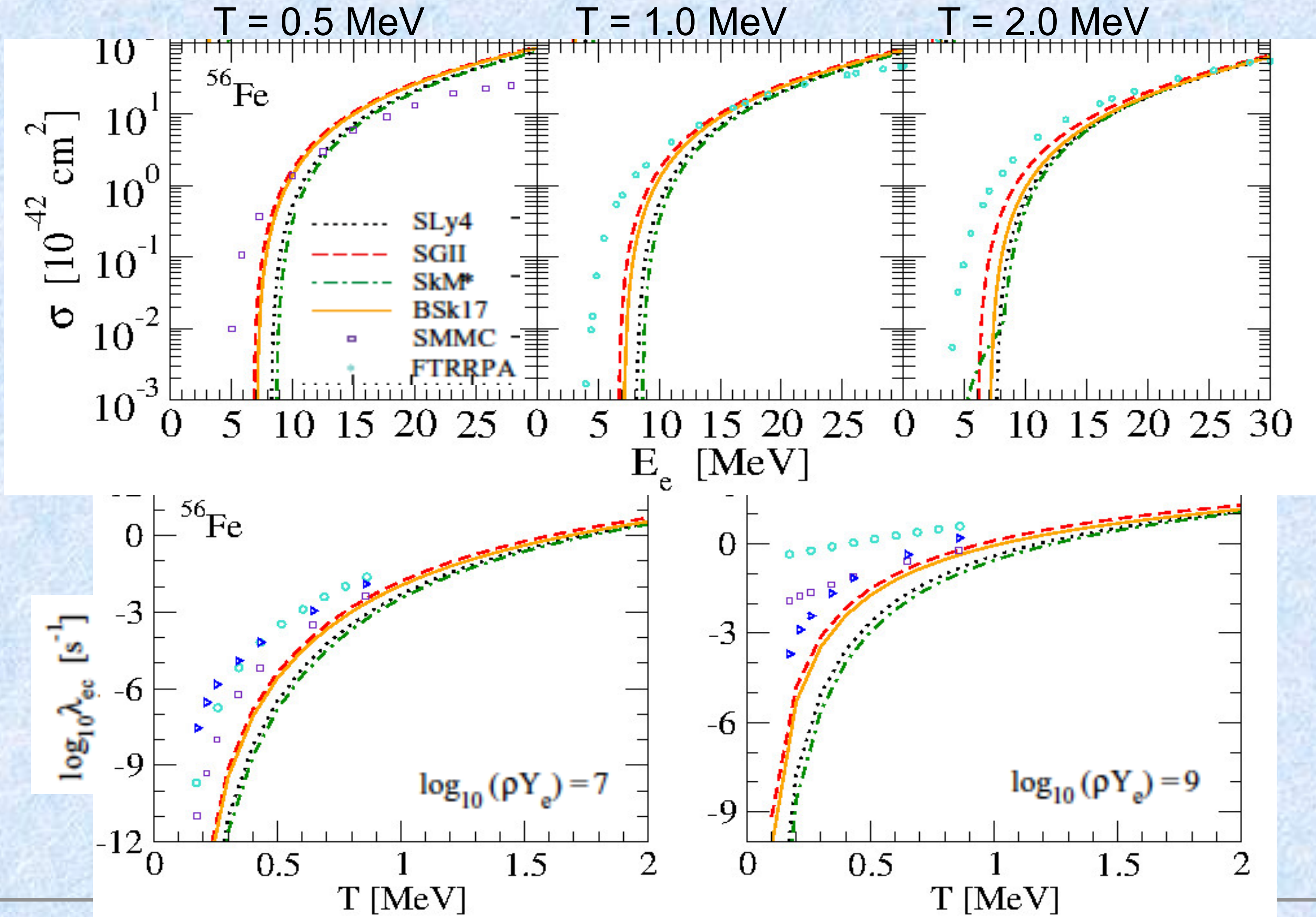
➢ Cross-section for electron-capture in $0.5 < T < 2$ MeV range

➢ Electron-capture rates:

$$\lambda^{ec}(T)[\mathrm{s}^{-1}] = \frac{V_{ud}^2 g_V^2 c}{\pi^2 (\hbar c)^3} \int_{E_{min}}^{\infty} \sigma(E_e, T)\ E_e\ p_e c\ f_e(E_e)\ \mathrm{d}E_e$$

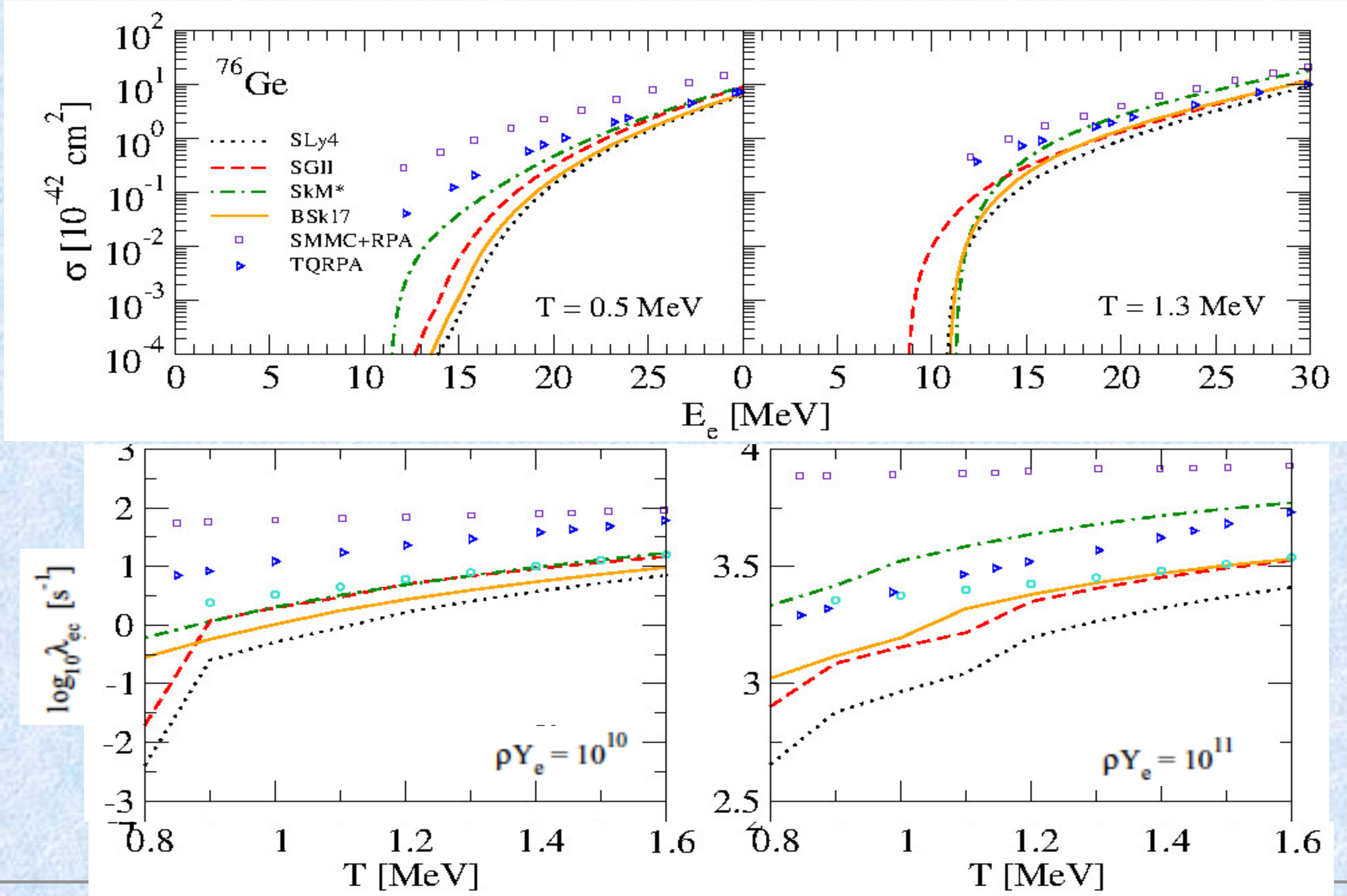
N.B. : I will show results on λ^{ec} for only three nuclei, but we studied :
$^{54\text{-}56}$**Fe**, $^{70\text{-}80}$**Ge**, $^{60\text{-}64}$**Ni** (even-even)

Results on Fe



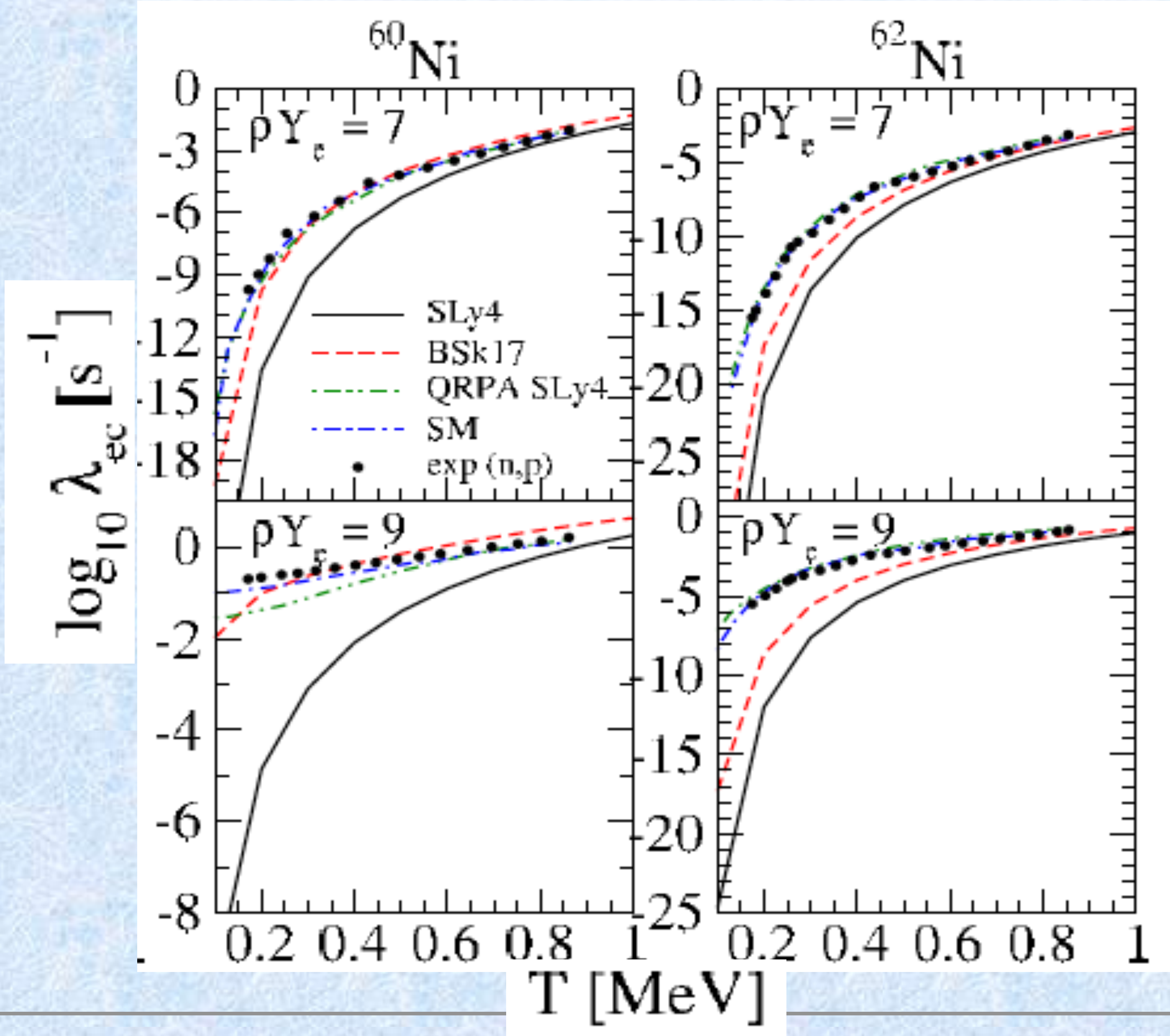
Fantina *et al.*, Phys.Rev. C 86, 035805 (2012)

Results on Ge



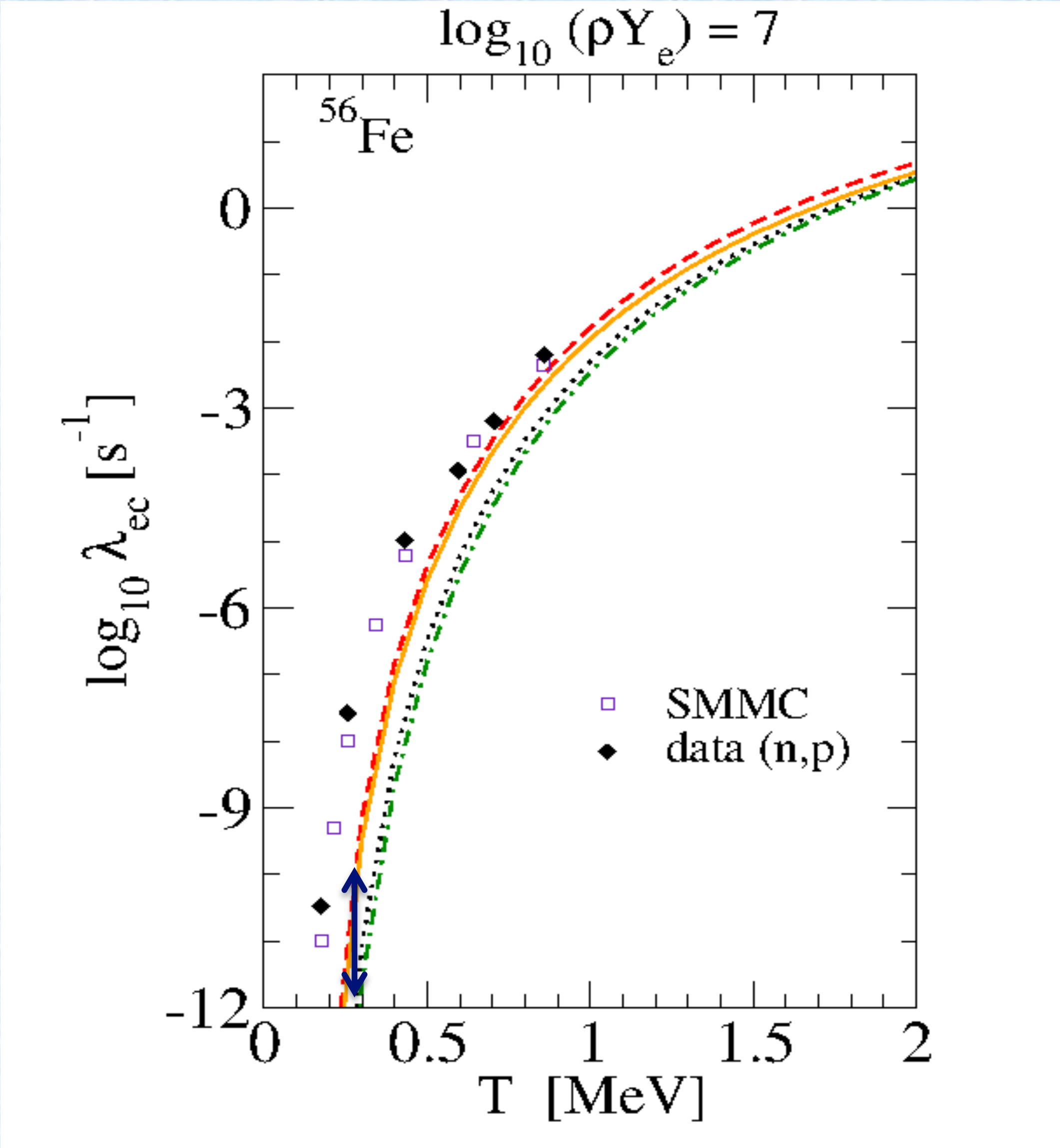
Fantina *et al*., Phys.Rev. C 86, 035805 (2012)

Results on Ni



Fantina *et al.*, EPJ Web of Confer. 66, 02035 (2014)

How to compare with experiments?



Study of beta-decays

→ β decay study and *ft*-values

→ GT strength distributions

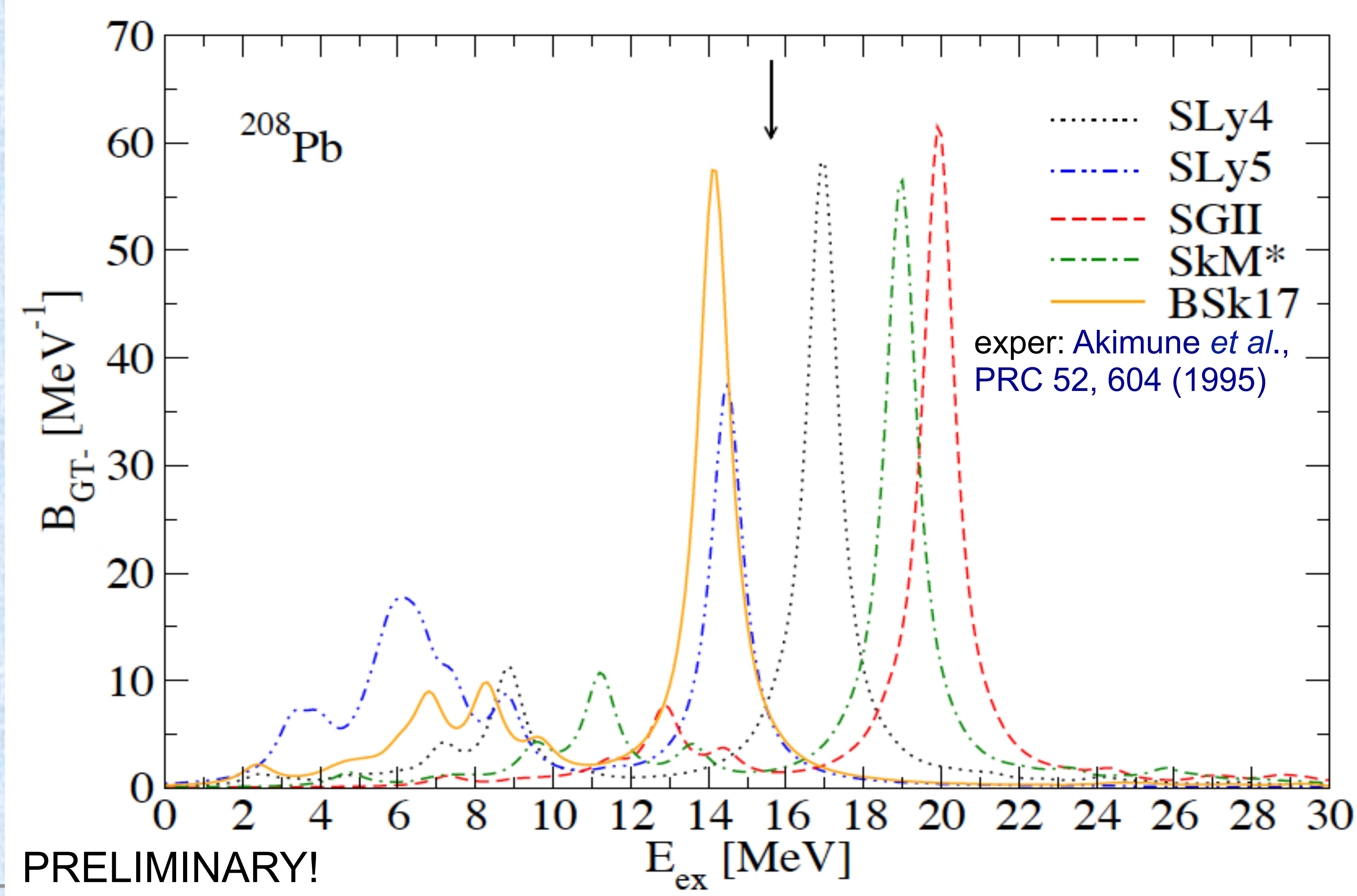
➡ *n-rich nuclei, A ≈ 70, 80, 130*

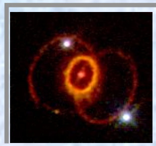
- importance for EC process:
  - ❖ constrain theoretical model (reduce "error bars")
  - ❖ select best functional

- importance for *r*-process
  - ❖ infer abundance of nuclei
  - ❖ constrain duration of *r*-process → site of *r*-process

rather than directly compare the rates, we can look at the transitions that contributes to those rates and can be measured!

Properties of collective modes: GT with (FT)HF + RPA (e.g. ^{208}Pb)





Conclusions on the electron capture

- First calculation of electron-capture rates for stellar conditions within fully self-consistent approach for some selected nuclei

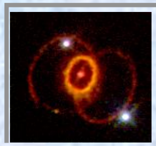
- Calculations on some isotopes (^{54,56}Fe, $^{70\text{-}80}$Ge, $^{60\text{-}64}$Ni)

- Total spread evaluated at about a few orders of magnitude

- Choose "best" functional(s) → constraints from e.g. β-decay experiments

- More systematic calculations on an ensemble of nuclei → TABLES for application to astrophysics (implementation in stellar codes)
  (e.g. core-collapse SN → ANR SN2NS project with E. Khan, J. Margueron, J. Novak, M. Oertel)

- Application of (Q)RPA for studying collective modes, half-life e.g. in Sn isotopes, and some correlations (e.g. n skin vs energy of GT-IAS)



Conclusion on compact-star study

→ Interdisciplinary!

Microphysics
nuclear physics

- ❖ equation of state
- ❖ weak processes
- ❖ neutrino interactions

↔

Macrophysics
hydrodyn. SN & NS models

- ❖ multi-D models
- ❖ general relativity
- ❖ neutrino transport

Nuclear physics experiments

- ❖ nuclear structure, mass measurement (exotic nuclei, HIC)
- ❖ β decays, reaction rates Gamow-Teller transitions
- ❖ neutrino cross-sections

Astrophysical observations

- ❖ neutrino signal, SN light curves
- ❖ gravitational waves
- ❖ NS properties (e.g. masses)
- ❖ NS cooling (related to pairing)


126
82
terra incognita
Grazie
50
82
28
20
50
8
2
28
20
2
8
Supernova Remnant 1987A in the Large Magellanic Cloud. HUBBLESITE.org