Nuclear masses and the equation of state of neutron stars and supernovae

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Matthias Hempel, Basel University

ISOLDE Seminar, CERN, 14.3.2013

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Nuclear masses and the equation of state of neutron stars and supernovae

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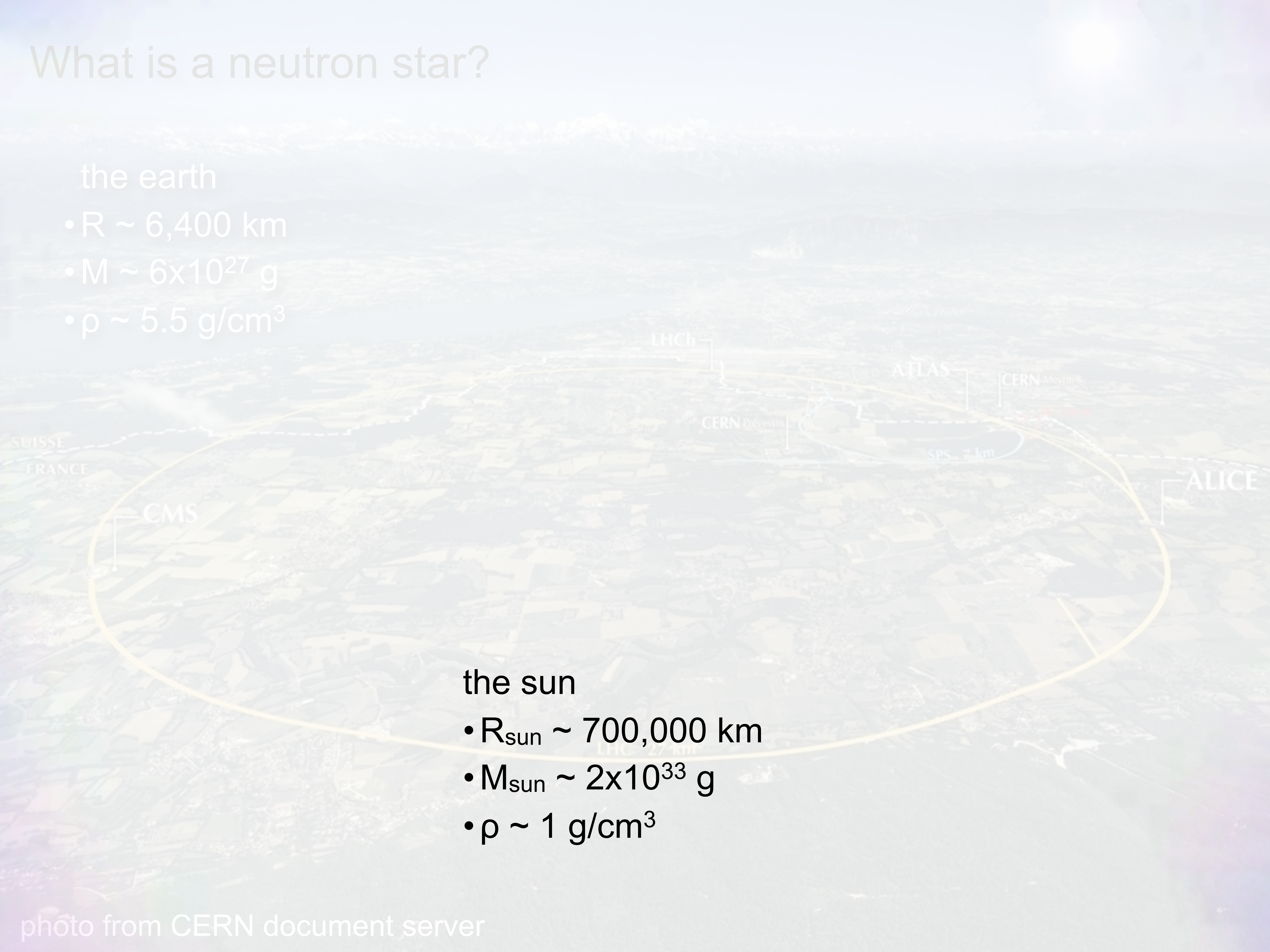
Outline:

1.) structure of neutron stars
2.) the neutron star equation of state (EOS)
3.) experimental and observational constraints
4.) matter in core-collapse supernovae
5.) conclusions

What is a neutron star?



the earth

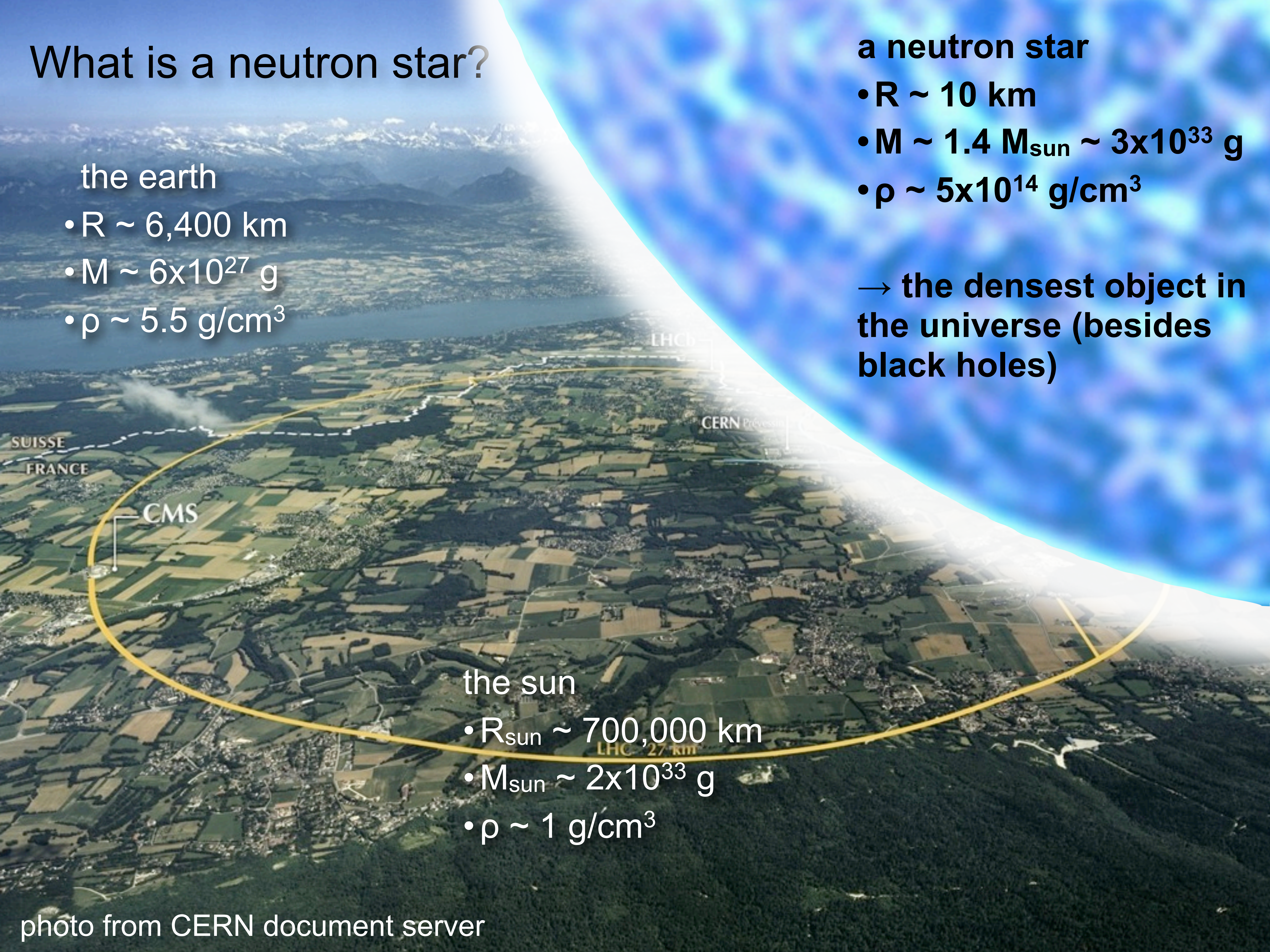
- R ~ 6,400 km
- M ~ 6x10^{27} g
- ρ ~ 5.5 g/cm^3

the sun

- R_{sun} ~ 700,000 km
- M_{sun} ~ 2x10^{33} g
- ρ ~ 1 g/cm^3

photo from CERN document server

What is a neutron star?



the earth

- R ~ 6,400 km
- M ~ $6\mathrm{x}10^{27}$ g
- ρ ~ 5.5 $\mathrm{g/cm^3}$

a neutron star

- **R ~ 10 km**
- **M ~ 1.4 M_{sun} ~ $3\mathrm{x}10^{33}$ g**
- **ρ ~ $5\mathrm{x}10^{14}$ $\mathrm{g/cm^3}$**

→ the densest object in the universe (besides black holes)

the sun

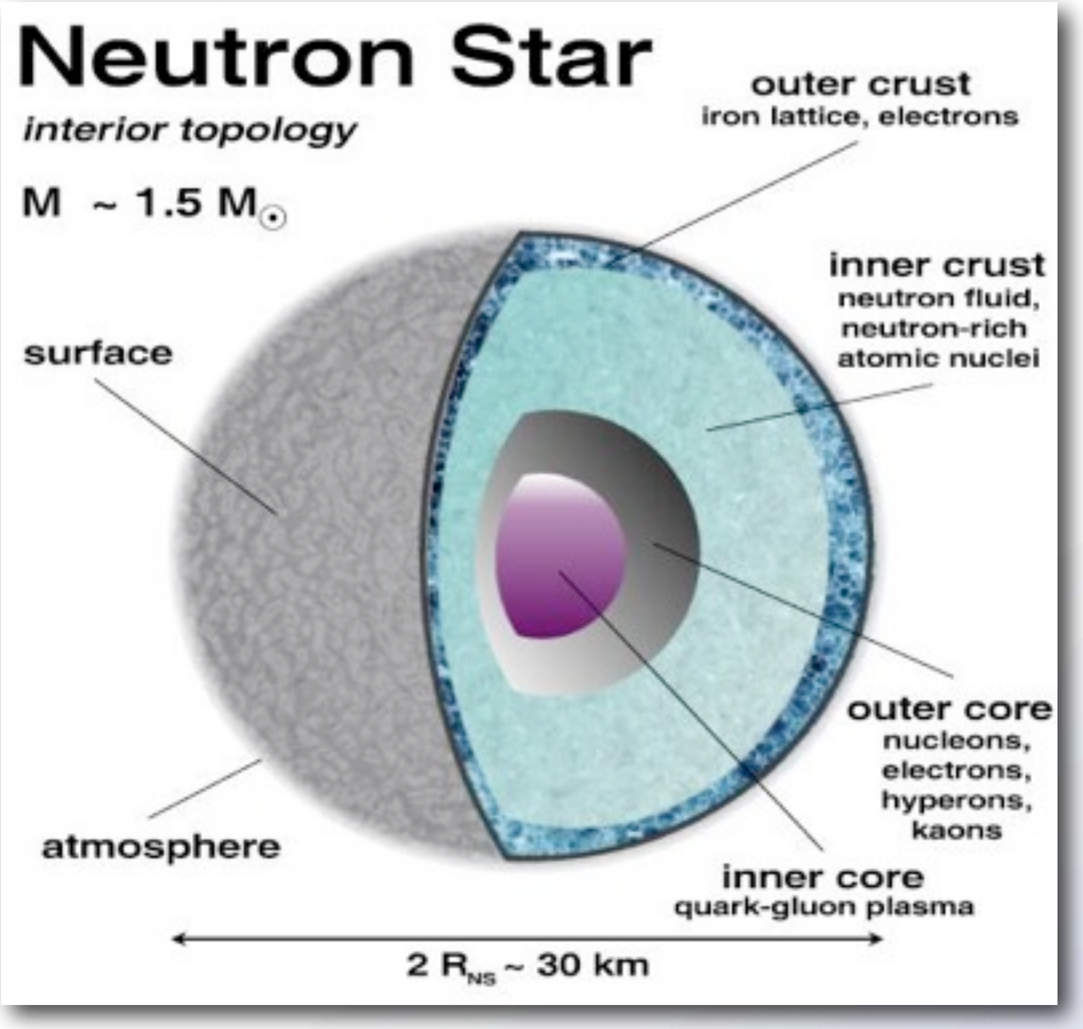
- R_{sun} ~ 700,000 km
- M_{sun} ~ $2\mathrm{x}10^{33}$ g
- ρ ~ 1 $\mathrm{g/cm^3}$

photo from CERN document server

Structure of neutron stars

Structure of a Neutron Star

$\rho_0 \approx 3 \cdot 10^{14}\ \mathrm{g/cm^3} \approx 0.16\ \mathrm{fm^{-3}}$



- atmosphere of electrons, nuclei and atoms (~ cm)

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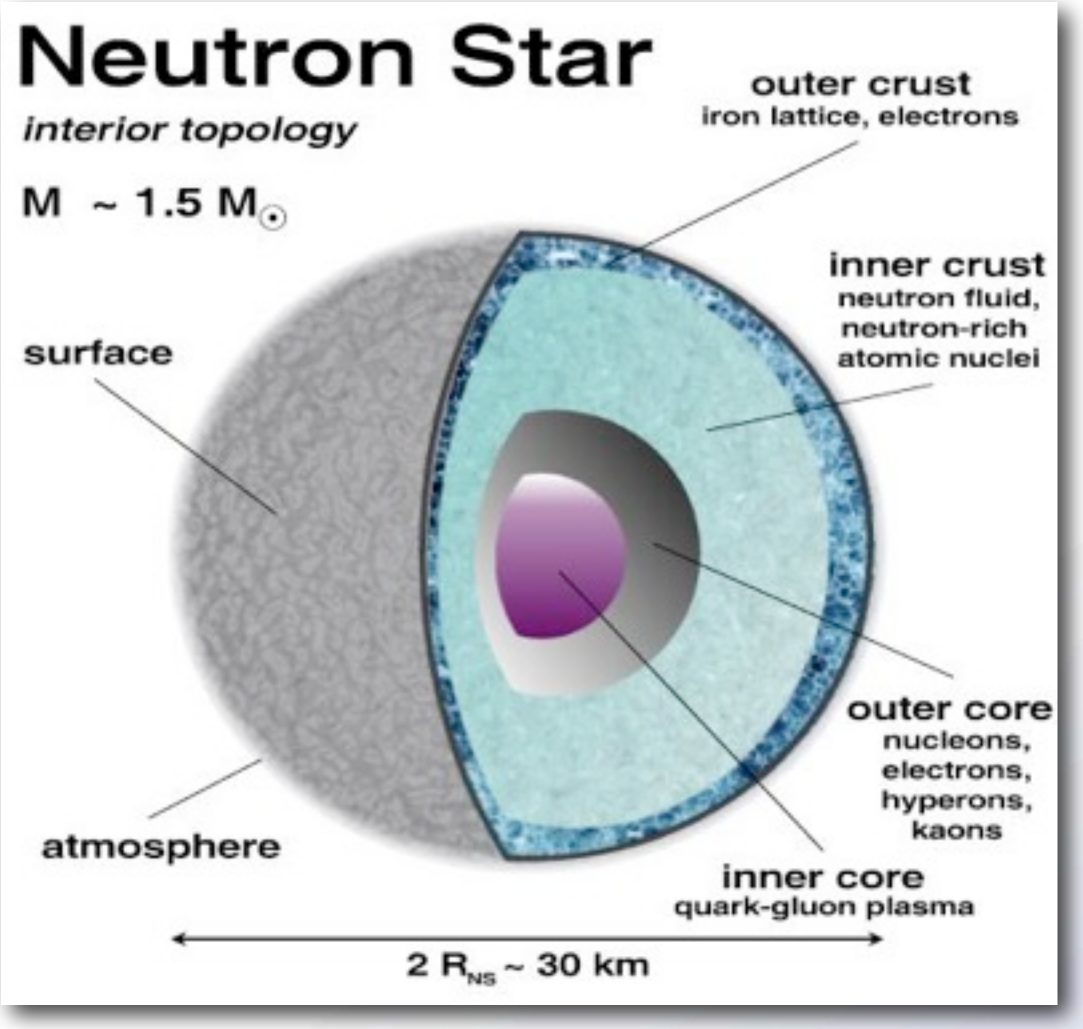
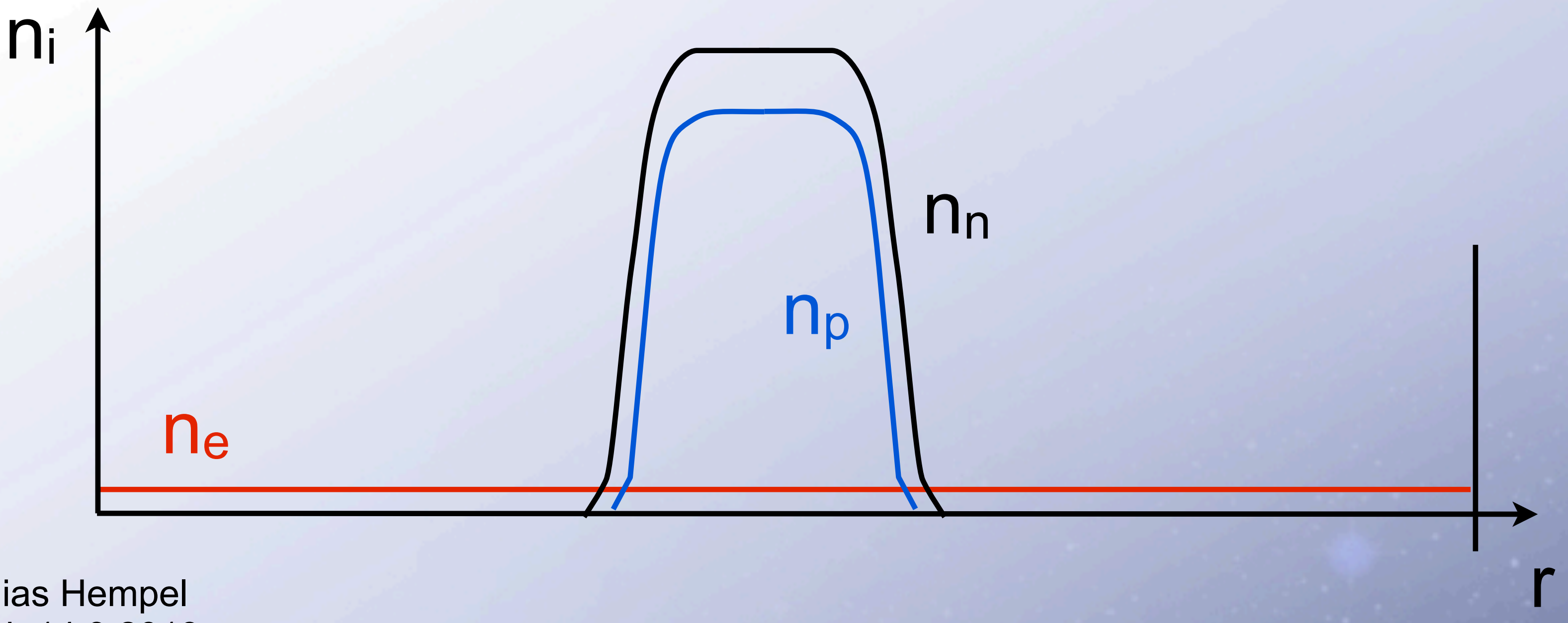


- atmosphere of electrons, nuclei and atoms (~ cm)

- $\rho > 10^4$ g/cm^3 outer crust
- complete ionization of atoms, nuclei arranged in a Coulomb lattice within a free electron gas
- starting from ^{56}Fe, neutronization, asymmetric nuclei

microscopic matter distribution:



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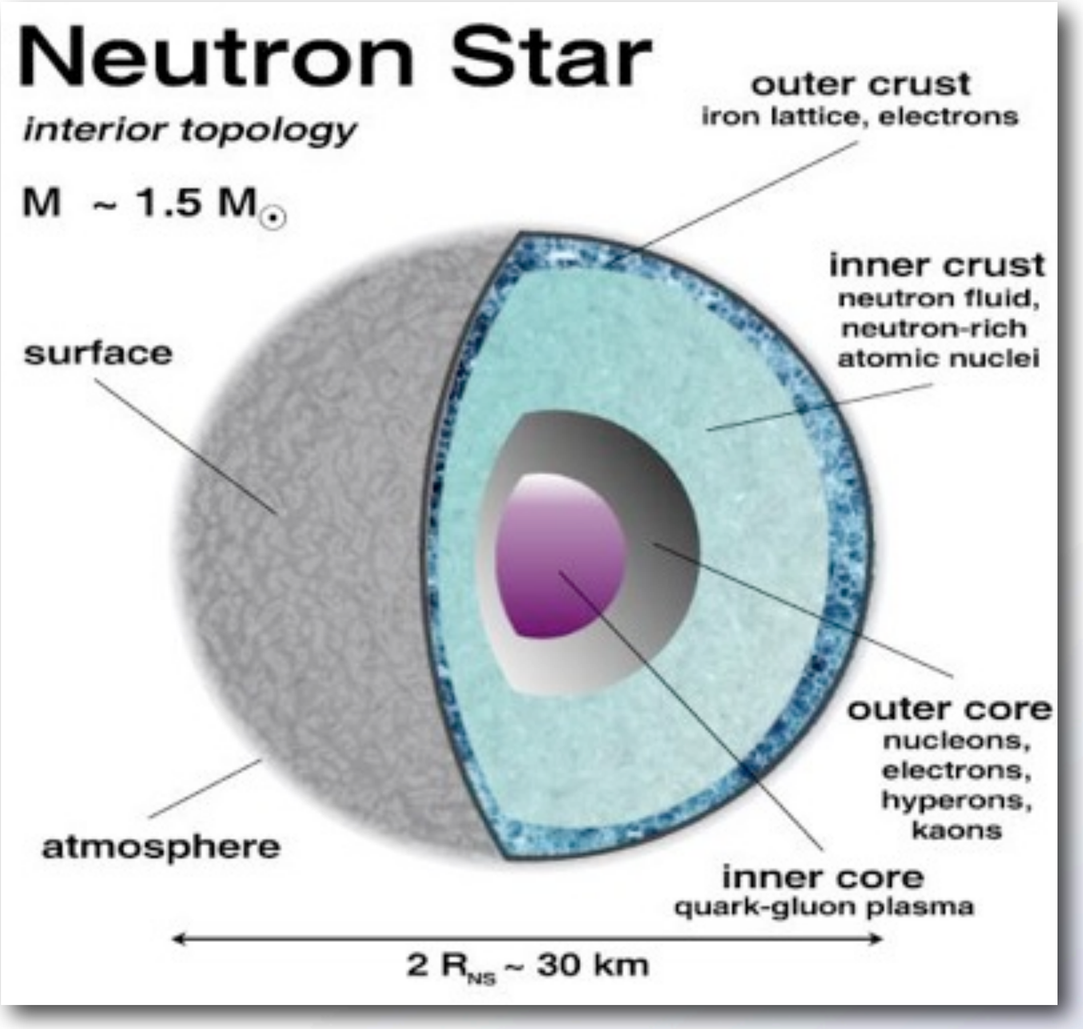
Structure of a Neutron Star



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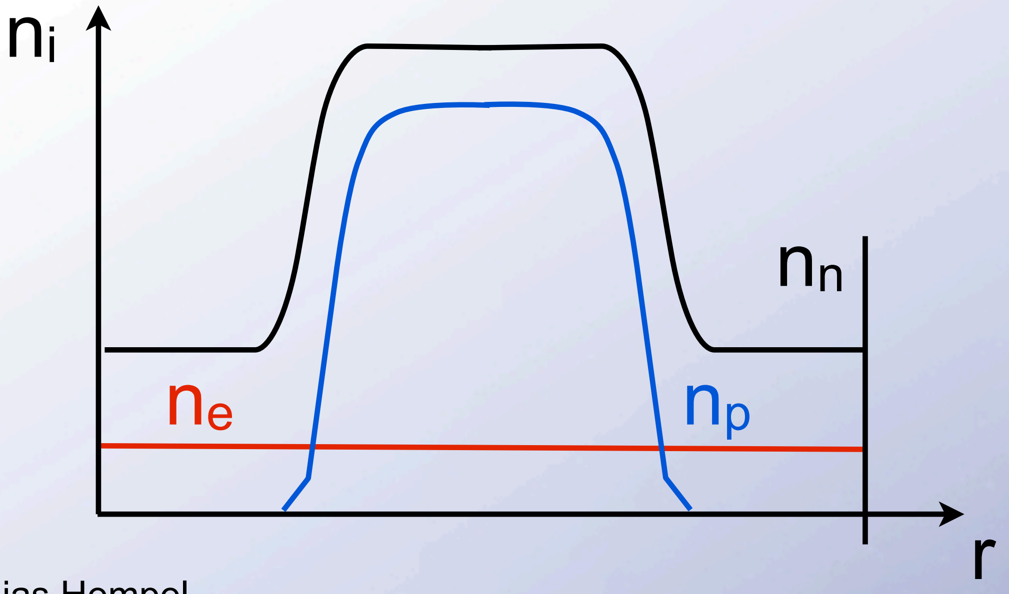

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- complete ionization of atoms, nuclei arranged in a Coulomb lattice within a free electron gas
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- $\rho \approx 4.3 \cdot 10^{11}$ g/cm^3 neutron drip: inner crust (~1 km)
- free neutrons & very neutron-rich nuclei
- $\rho \approx 10^{14}$ g/cm^3 transition to the core, “pasta phases“

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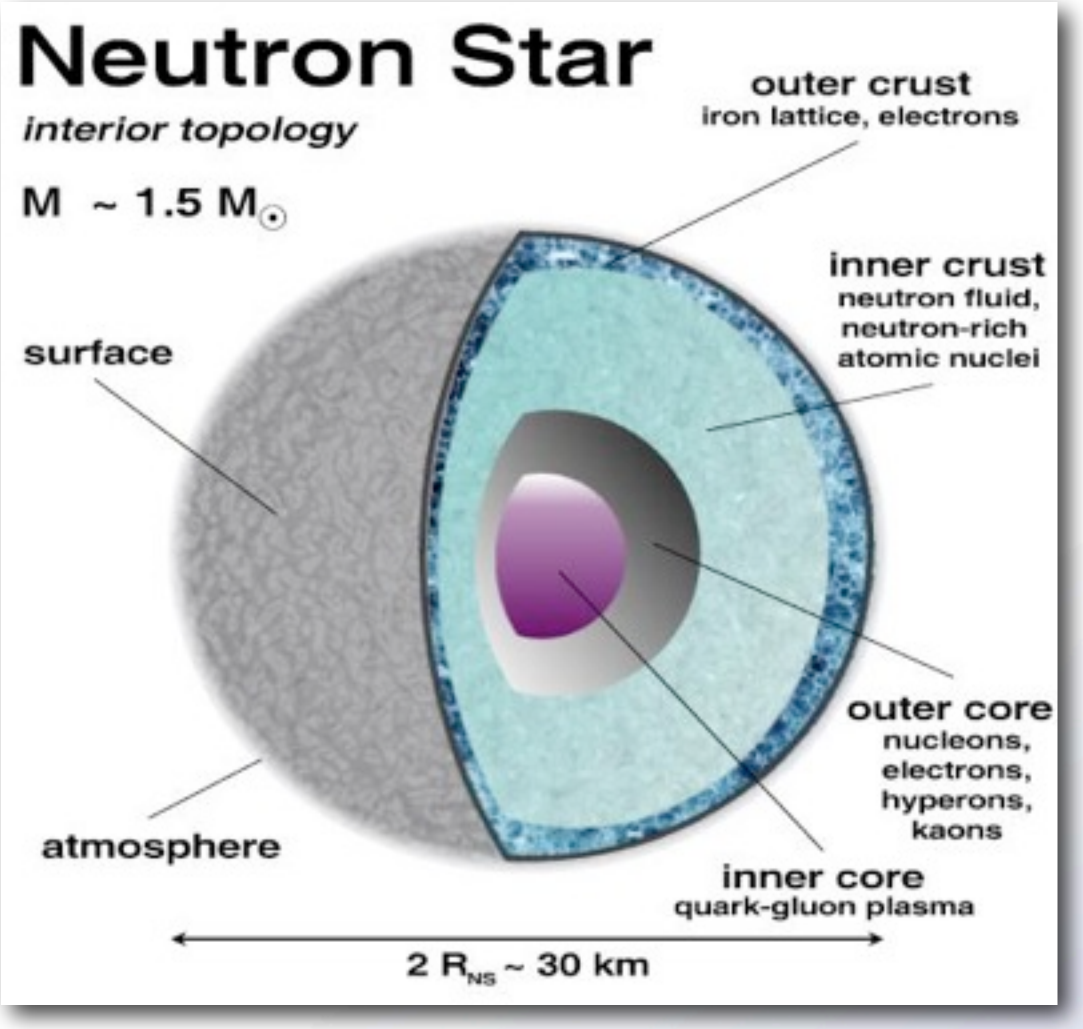

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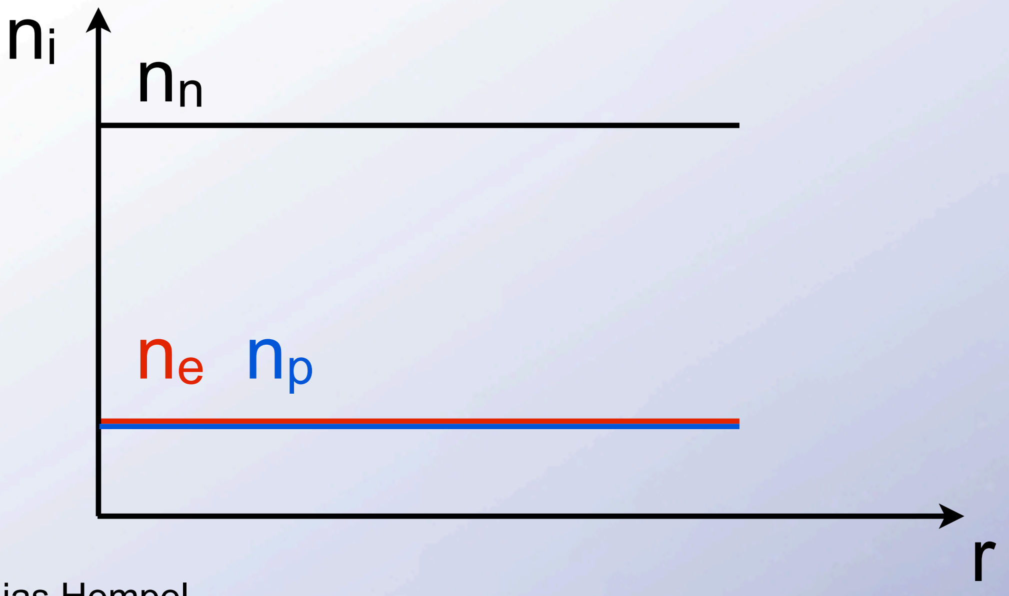

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- $\rho > 2 \cdot 10^{14}$ g/cm^3 core, uniform matter

The outer crust of cold, non-accreting neutron stars

S. Kreim, MH, D. Lunney, J. Schaffner-Bielich, arXiv:1303.1343

Relevance of the outer crust

- moderate thickness ~300 m
- negligible mass ~10^{-5} M_{sun}
- crustal composition relevant for
  - electrical resistivity
  - heat transport
  - starquakes triggering shear mode oscillations (in soft-gamma ray repeaters), see, e.g., Watts & Steiner PRL103 (2009)
  - seed composition for r-process in neutron star merger

The BPS model

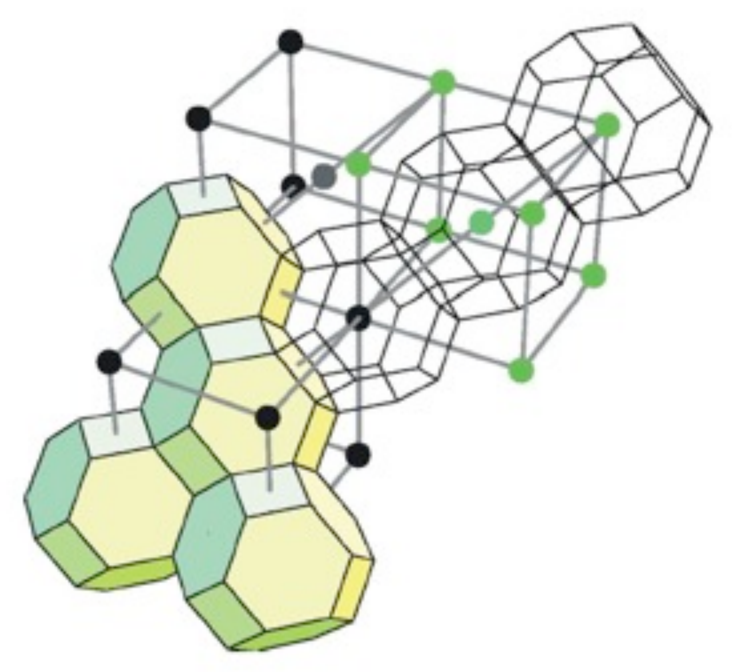
- seminal landmark paper by Baym, Pethick and Sutherland, NPA175 (1971)
- ground-state of matter at T=0 and densities 10^4 g/cm^3 < ρ < 5×10^{11} g/cm^3
- completely ionized nuclei arranged in a body-centered cubic lattice
- using the Wigner-Seitz approximation

$$\epsilon_{\mathrm{tot}}(A,Z,n_B) = \frac{n_B}{A}\left(W_N(A,Z) + W_L(A,Z,n_B)\right) + \epsilon_e$$

W_N: mass of nucleus

W_L: lattice energy per nucleus

ϵ_e: electrons, completely degenerate Fermi-Dirac gas



- required input: masses of (exotic) nuclei

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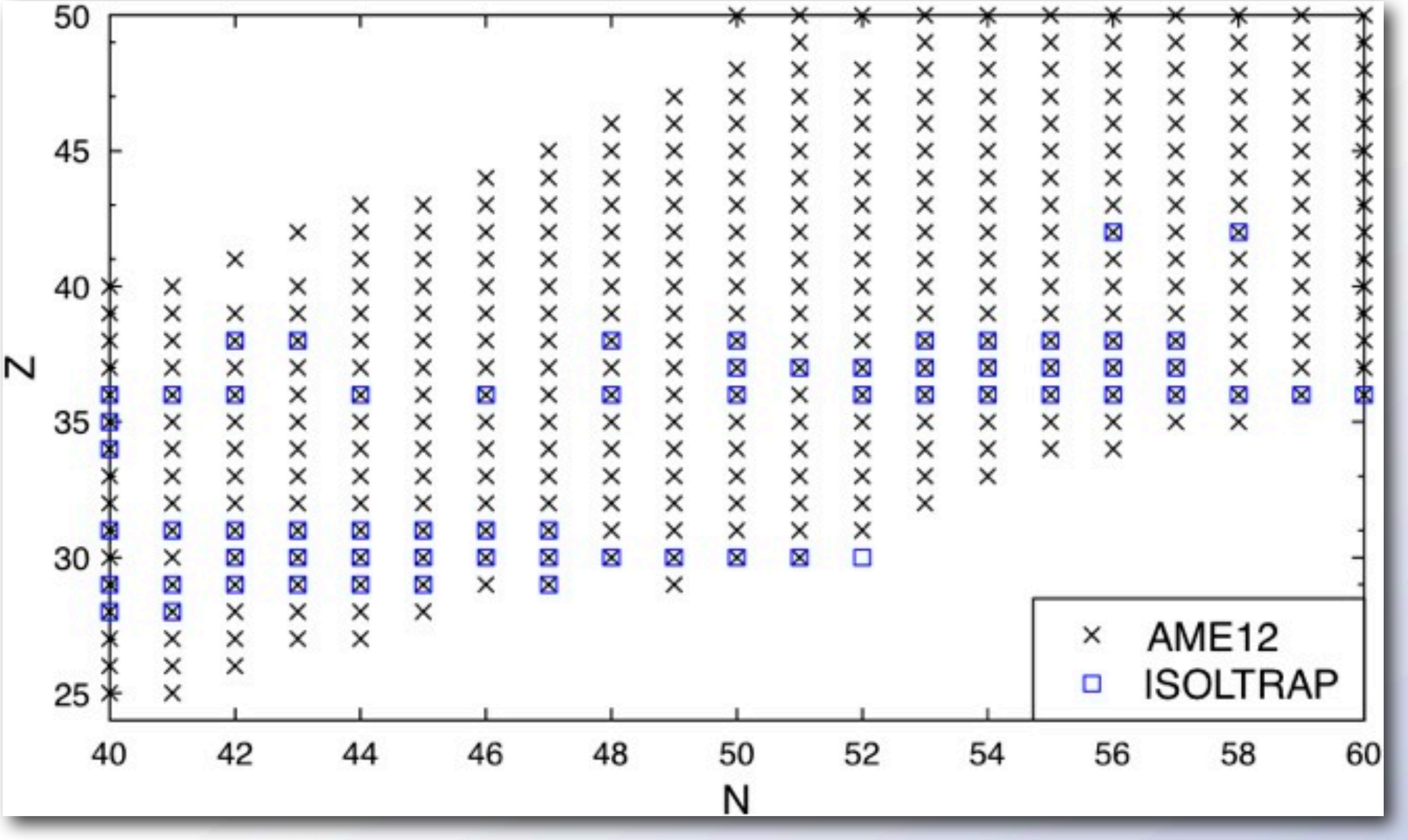
Previous crust studies & nuclear mass tables

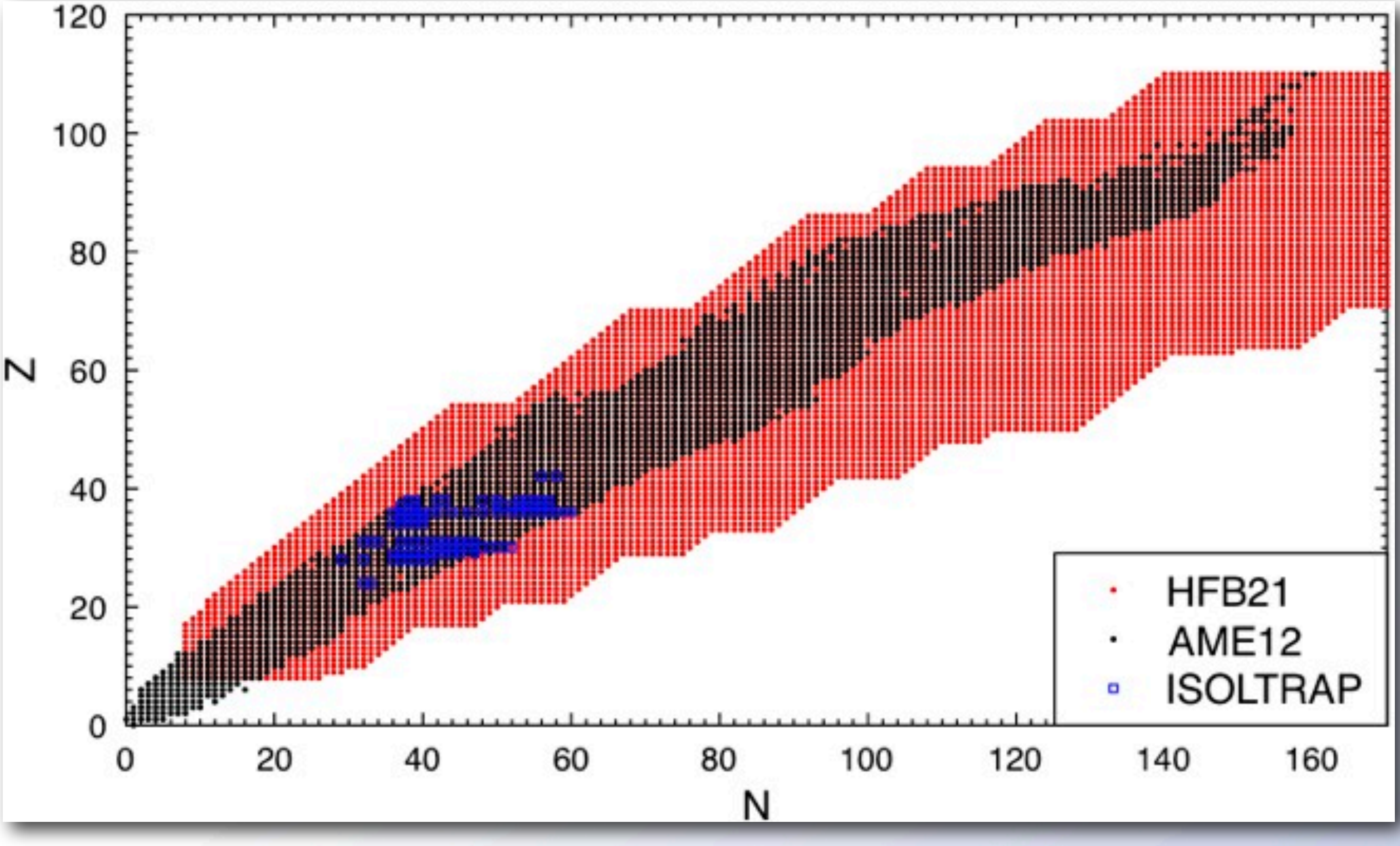
year	authors	used mass tables
1971	Baym, Pethick, Sutherland	liquid-drop model of Myers et al. (1966)
1989	Haensel, Zdunik, Dobaczewski	Skyrme-HFB (SkP), droplet model of Myers (1977)
1994	Haensel, Pichon	AME1992, two droplet models
2006	Rüster, MH, Schaffner-Bielich	AME2003, 21 mass models (relativistic, non-relativistic, effects of deformations)
2011	Pearson, Goriely, Chamel	AME2011, HFB19-HFB21, Gogny D1M
2012	Wang et al.	AME2012 published
2013	Wolf et al.	AME2011, penning trap mass measurement of ^{82}Zn by ISOLTRAP, HFB19-HFB21
2013	Kreim, MH, Lunney, Schaffner-Bielich	AME2012 and ISOLTRAP, extended set of theoretical mass models

Measured binding energies



- AME12: atomic mass evaluation by Wang et al. (2012)
- ISOLTRAP penning trap measurement at CERN of ^{82}Zn
  B/A(^{82}Zn): 8.305(5) MeV → 8.30109(4) MeV (Wolf et al. PRL 110, 2013)
- increased shell gap (two-neutron separation energy)
- N=50 closed neutron shell extremely important for crust

Theoretical mass models

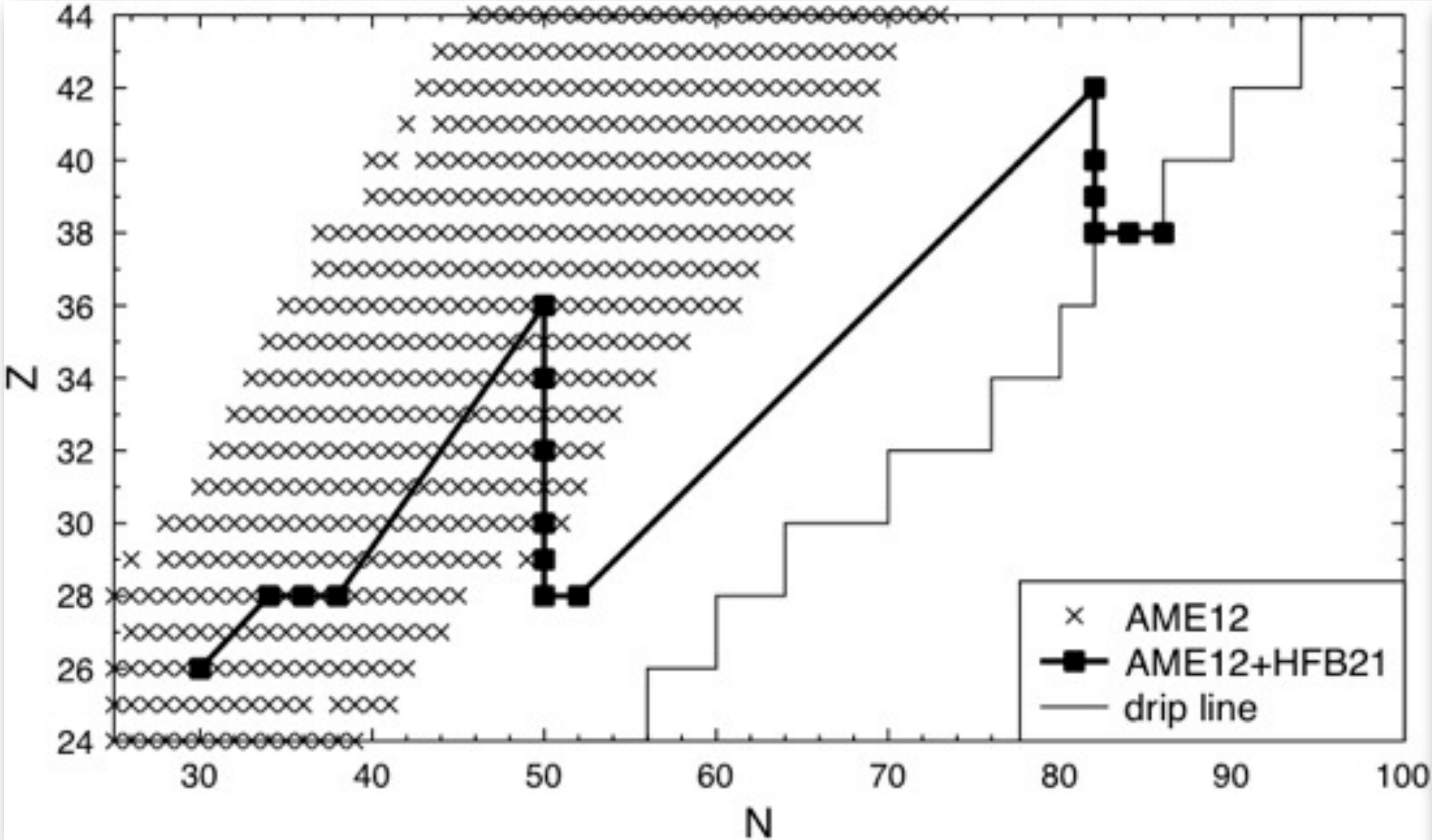


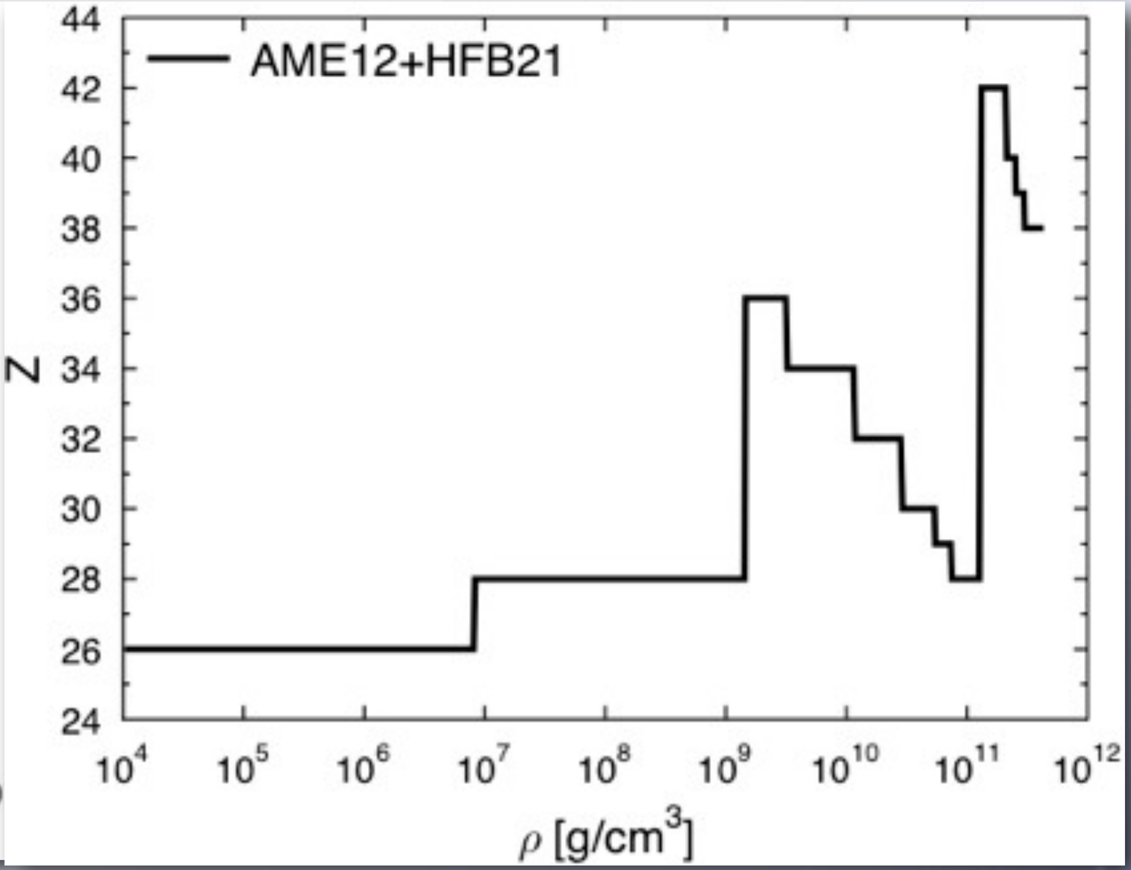
theory

} experiment

- in the crust: extremely degenerate electrons → electron captures, very exotic neutron-rich nuclei
- theoretical mass models to augment measurements
- for each density, determine the equilibrium nucleus which minimizes the thermodynamic potential of all these nuclei

Sequence of nuclei in the crust with HFB21





- using AME12 and HFB21: ^{82}Zn not found
- dominance of N=50 and 82 closed neutron shells
- extremely unstable nuclei in vacuum e.g. $T_{1/2}(^{66}\mathrm{Ni})$ = 54.6h, $T_{1/2}(^{78}\mathrm{Ni})$ = 0.11s
- degenerate electrons change beta-stability
- at 4x10^{11} g/cm^3 neutron drip, beginning of inner crust

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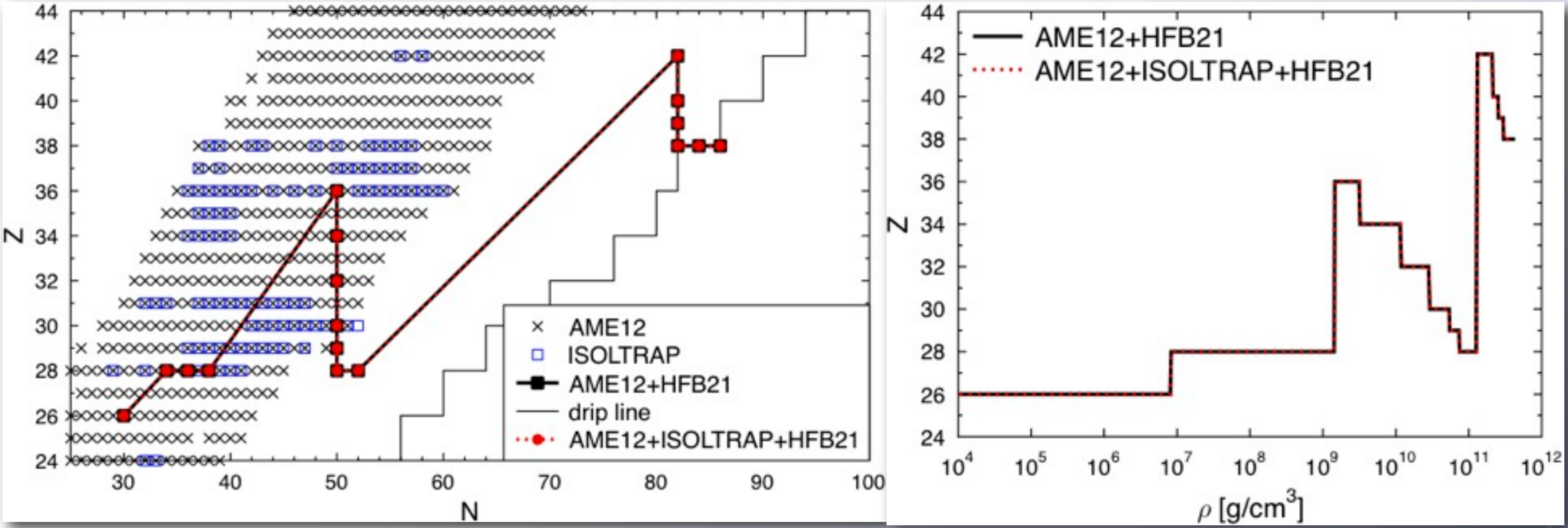

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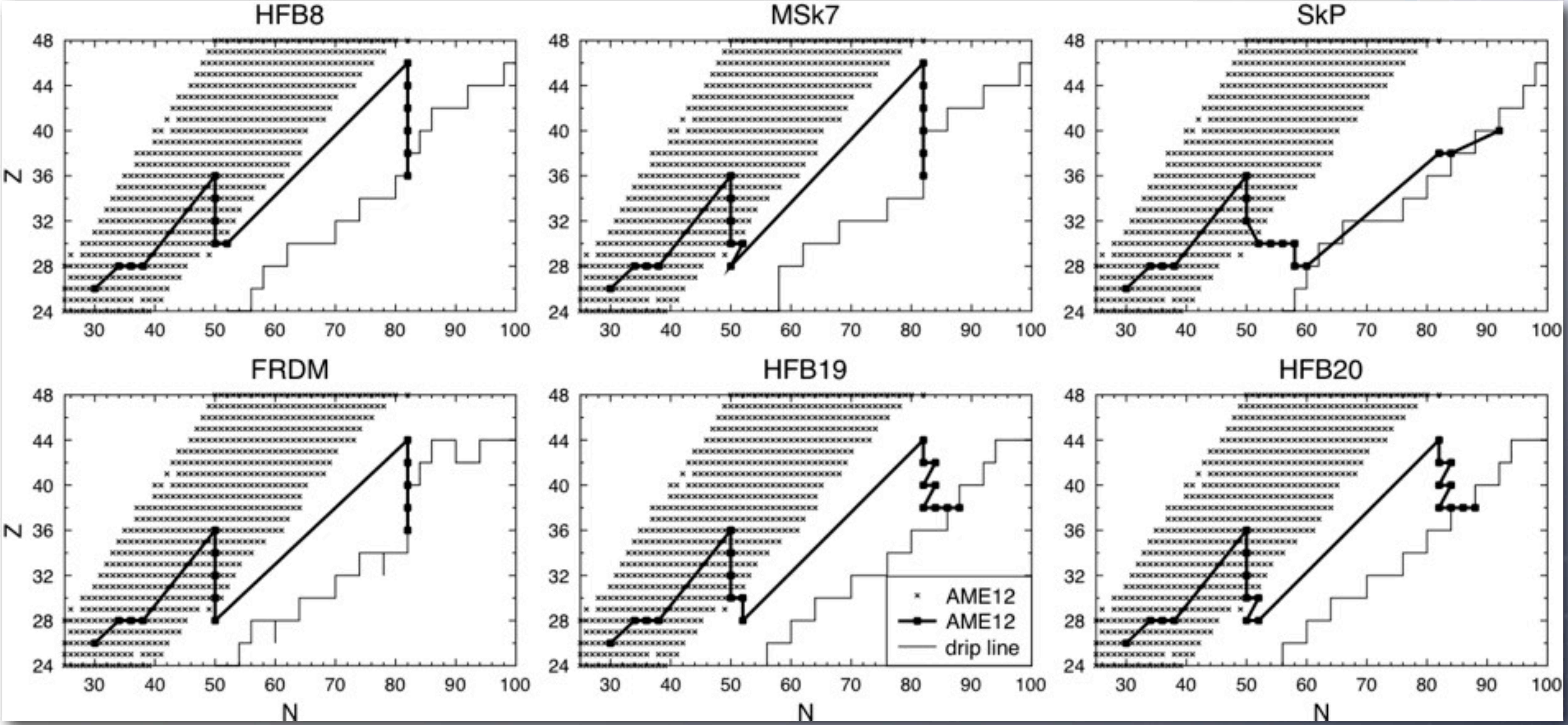
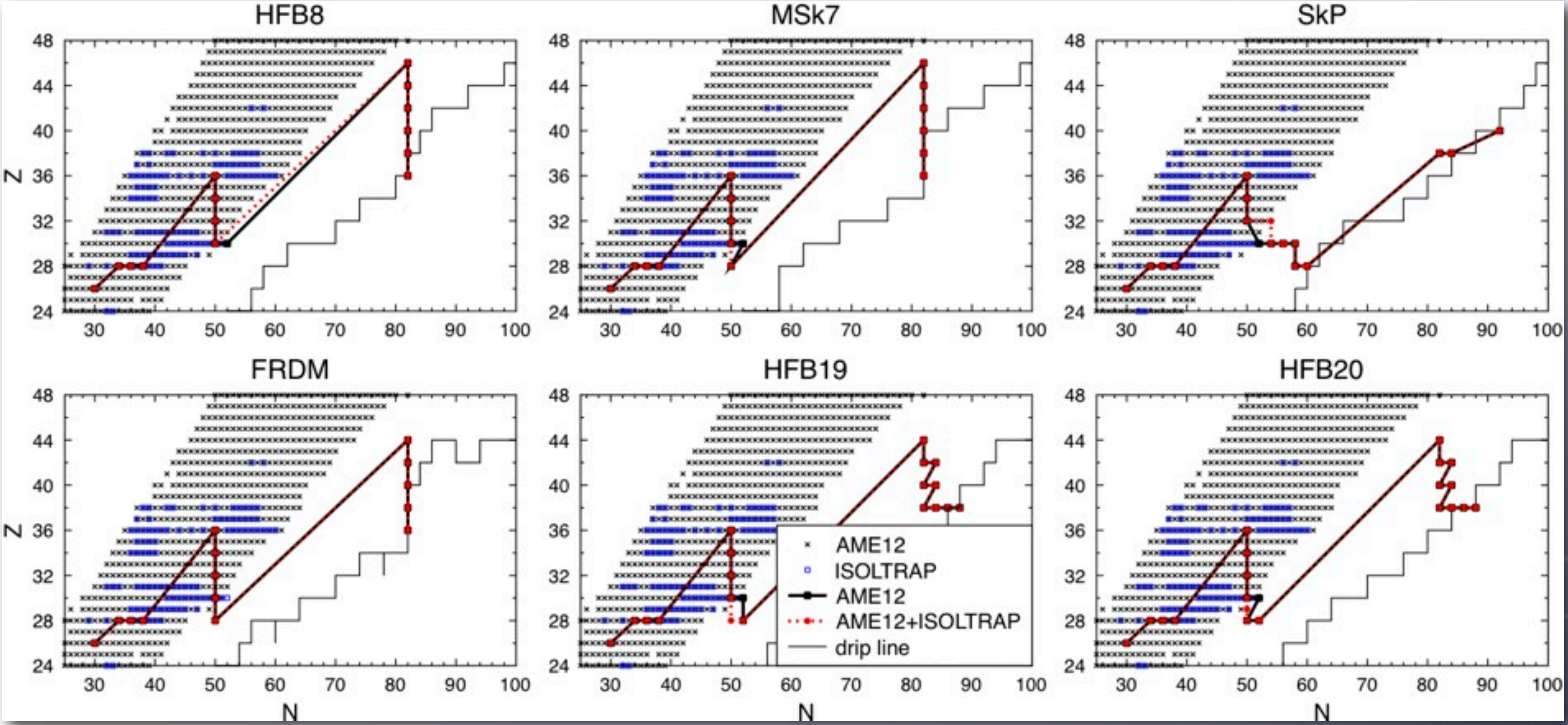
- at 4x10^{11} g/cm^3 neutron drip, beginning of inner crust
- no effect of ISOLTRAP data for HFB21

The fate of ^{82}Zn



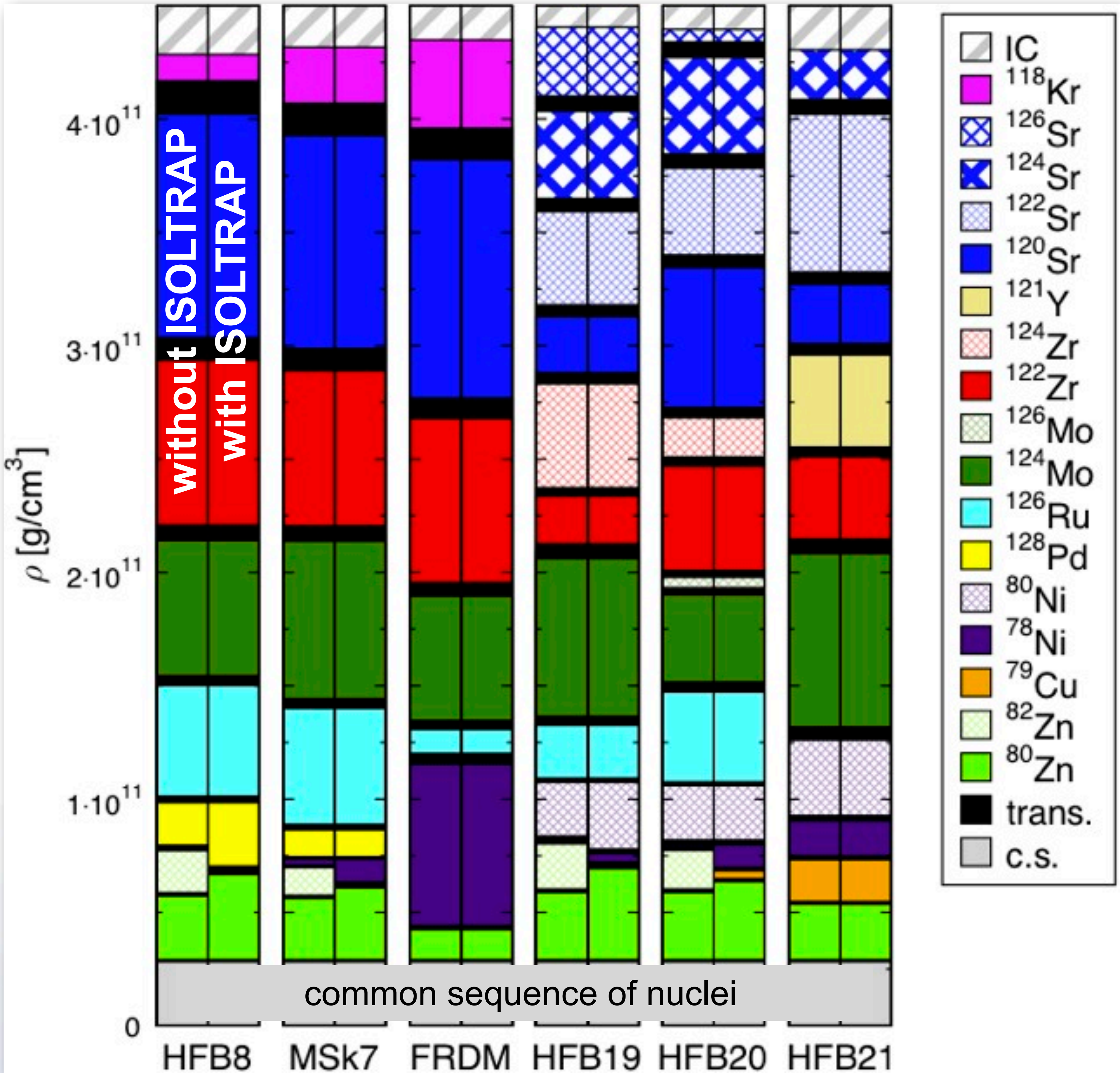
- 5 of 25 tested models predicted ^{82}Zn in the crust

The fate of ^{82}Zn



- 5 of 25 tested models predicted ^{82}Zn in the crust
- the new measurement rules out the appearance of ^{82}Zn for all models
- ^{82}Zn is replaced by N=50 nuclei, shell effects strengthened further
- further validation of results by Wolf et al. PRL110, 2013

Drilling deeper into the NS crust



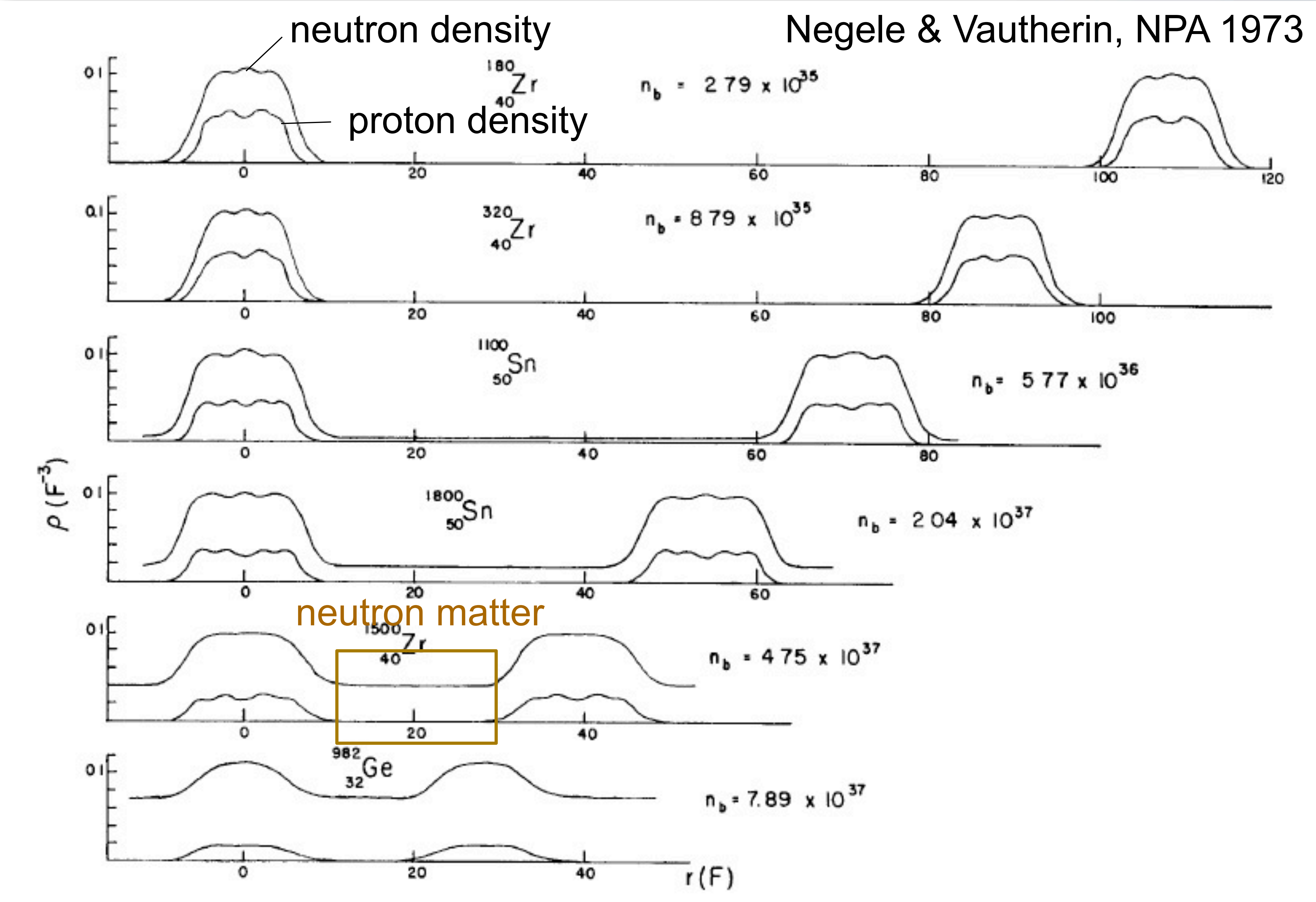
full colors without pattern: N=50 or 82

- the last common nucleus with measured binding energy is ^{80}Zn
- the composition of the crust is known up to ~ 5x10^{10} g/cm^3
- corresponding to a depth of ~ 220 m (Wolf et al. PRL 2013)

The inner crust

Matter in the inner crust

- nuclear clusters immersed in a gas of neutrons


neutron density

proton density

Negele & Vautherin, NPA 1973

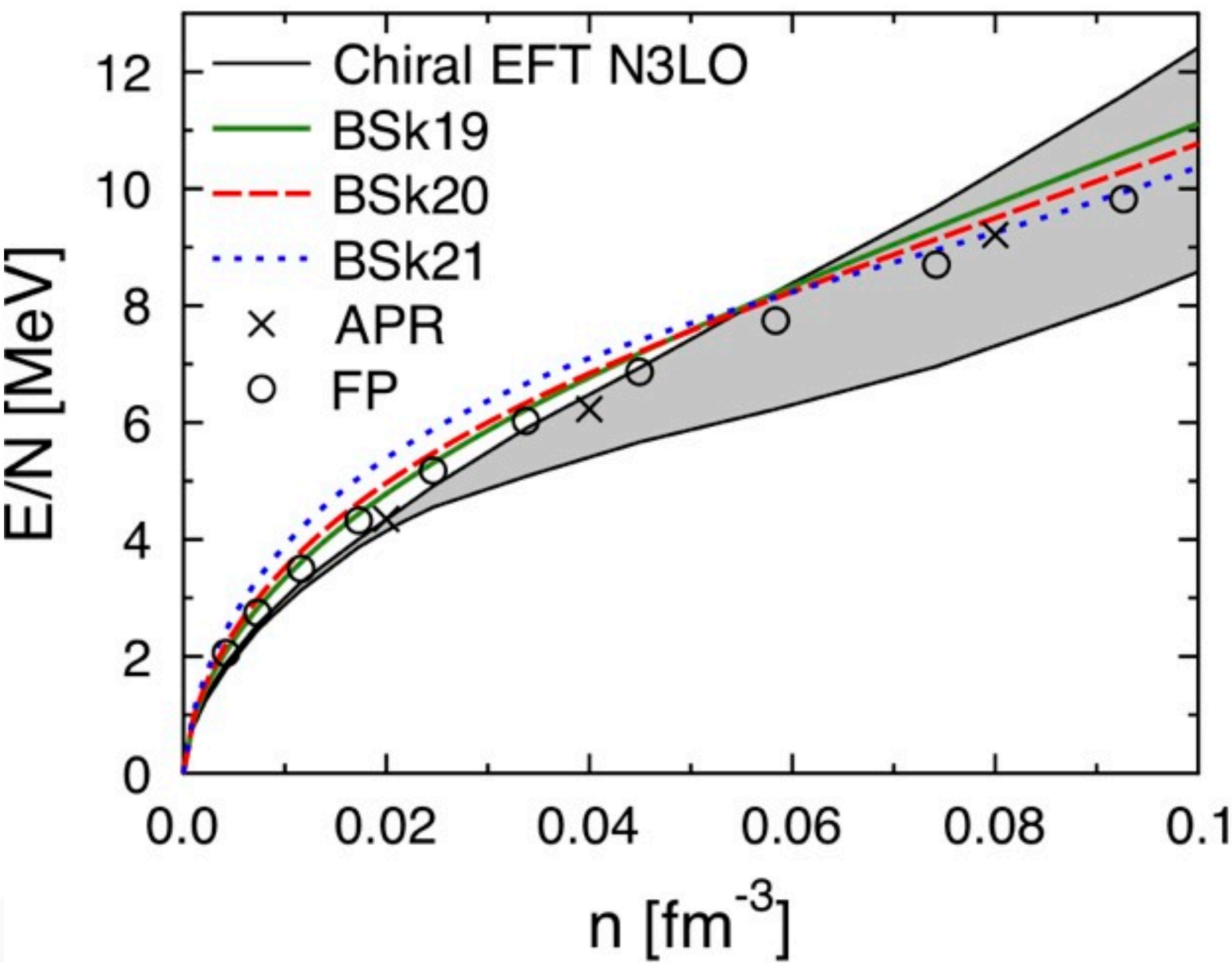
neutron matter

neutron drip

density, depth

core

Neutron matter equation of state from theory



Kreim, MH, Lunney, Schaffner-Bielich arXiv:1303.1343

- BSk (2012): effective parameterization of the nuclear interactions, fitted to binding energies
- APR(1998), FP(1981): variational calculations, based on measured nucleon phase shifts
- Chiral effective field theory (Schwenk et al.): systematic expansion, only few coupling constants fitted to light nuclei

→ consistency of various theoretical approaches

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The core

The outer core

- $\rho > 10^{14}$ g/cm^3 ~ 1/2 ρ_0
- uniform nuclear matter, electrons and muons
- very neutron-rich, proton fraction $Y_p \sim 0.01 - 0.1$

The inner core

- $\rho > 5\ 10^{14}$ g/cm^3 ~ 2 ρ_0 (?)
- hyperons, kaon or pion condensation, deconfined quark matter, color-superconducting phases, ... (?)

The nuclear matter EOS

- expansion of the nuclear matter EOS around the saturation point:

$$E(x,\beta) \simeq E(x,0) + \beta^2 E_{\mathrm{sym}}(x),$$
$$\beta = 1 - 2Y_p, \; x = \frac{n_B}{n_0} - 1$$
$$E(x,0) \simeq -B_0 + \frac{1}{18} K x^2 + \frac{1}{162} K' x^3 + \ldots \,,$$
$$E_{\mathrm{sym}}(x) \simeq J + \frac{1}{3} L x + \frac{1}{18} K_{\mathrm{sym}} x^2 + \ldots$$

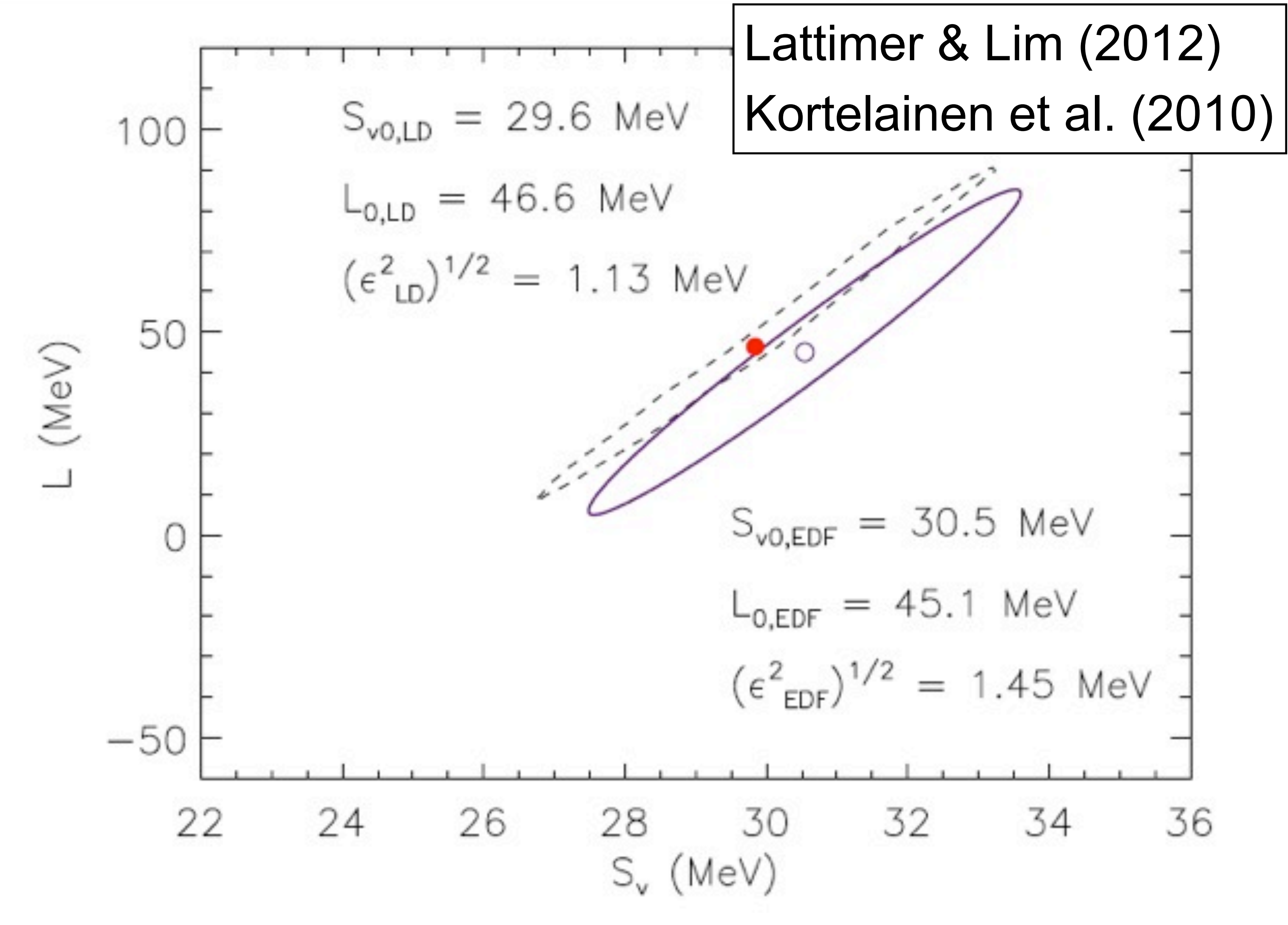
- binding energy B_0, incompressibility K, symmetry energy J, slope parameter L
- typical approaches for nuclear matter
  - – microscopic models, based on realistic nuclear interaction potentials (phase shifts) and many-body techniques
  - – non-relativistic Skyrme forces
  - – relativistic mean-field approach, interactions via meson-exchange

↓

interactions fitted to nuclear observables, e.g., binding energies

Constraints

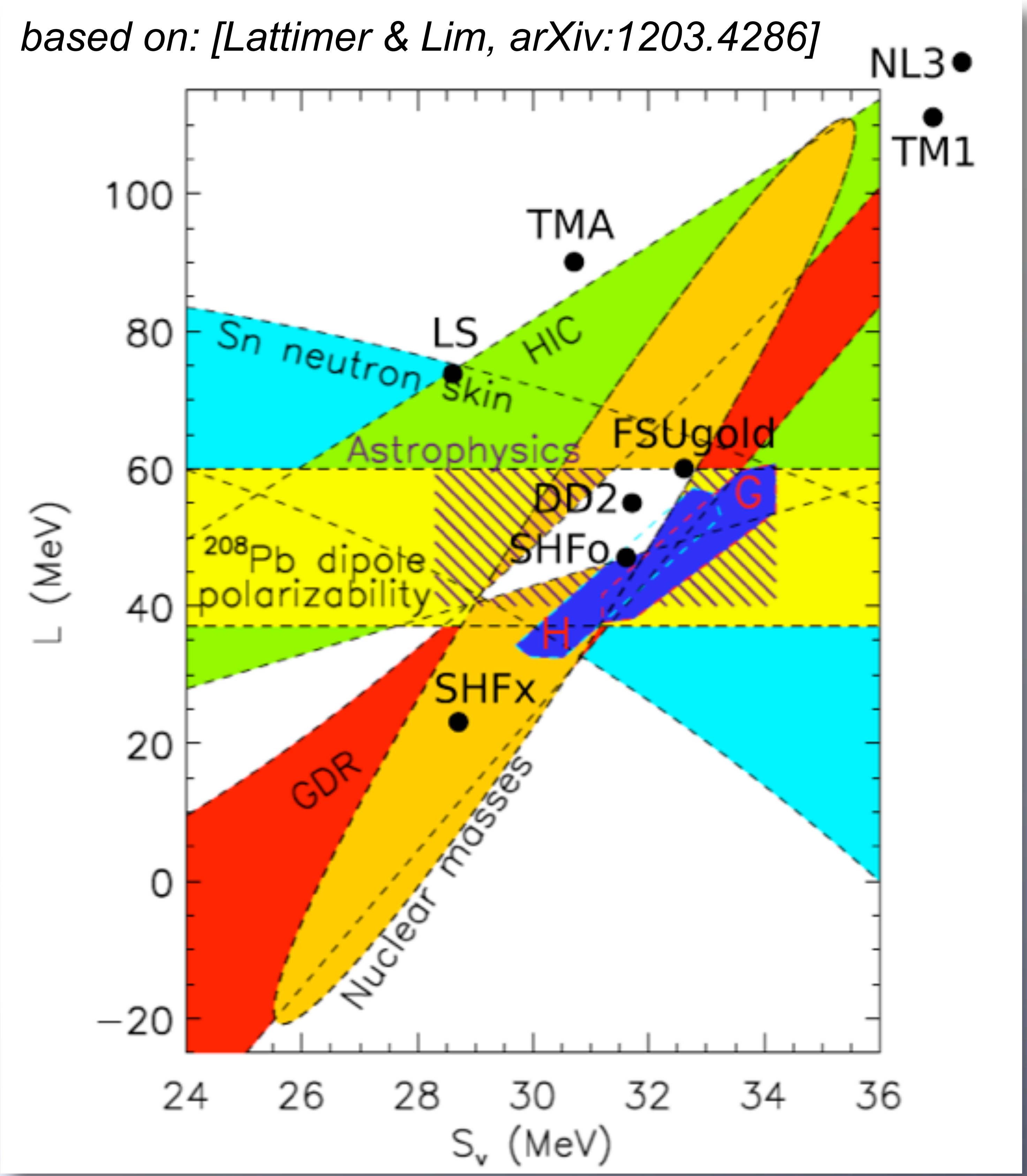
Nuclear masses and the symmetry energy



Lattimer & Lim (2012)
Kortelainen et al. (2010)

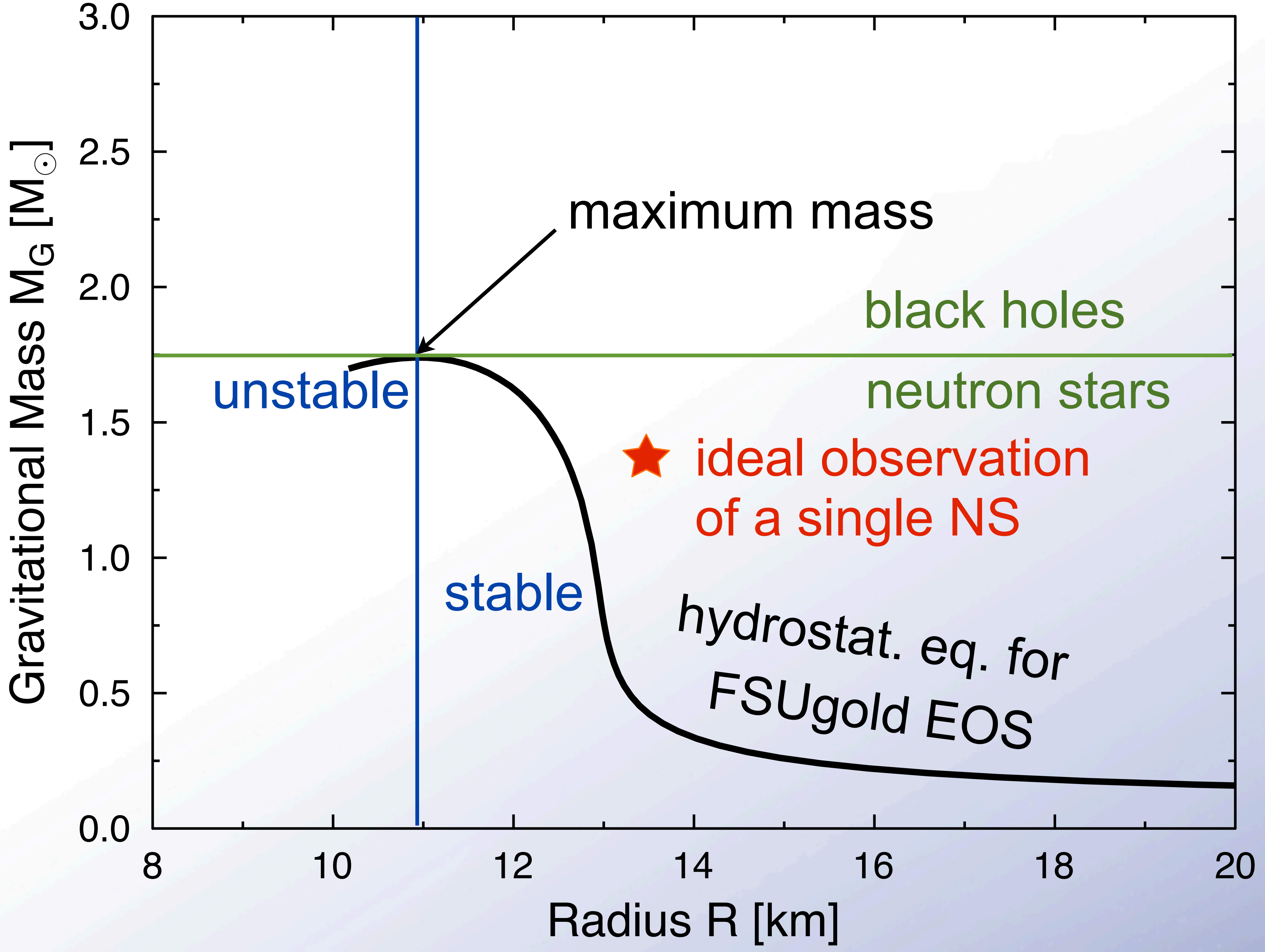
- systematics of nuclear binding energies do not determine E_{sym} uniquely

EOS constraints – symmetry energy


based on: [Lattimer & Lim, arXiv:1203.4286]

- G & H: constraints from neutron matter, theory
- convergence of observational, experimental and theoretical constraints
- black dots: selection of supernova EOS, i.e., available also for finite temperature
- besides LS and TMA: directly fitted to binding energies

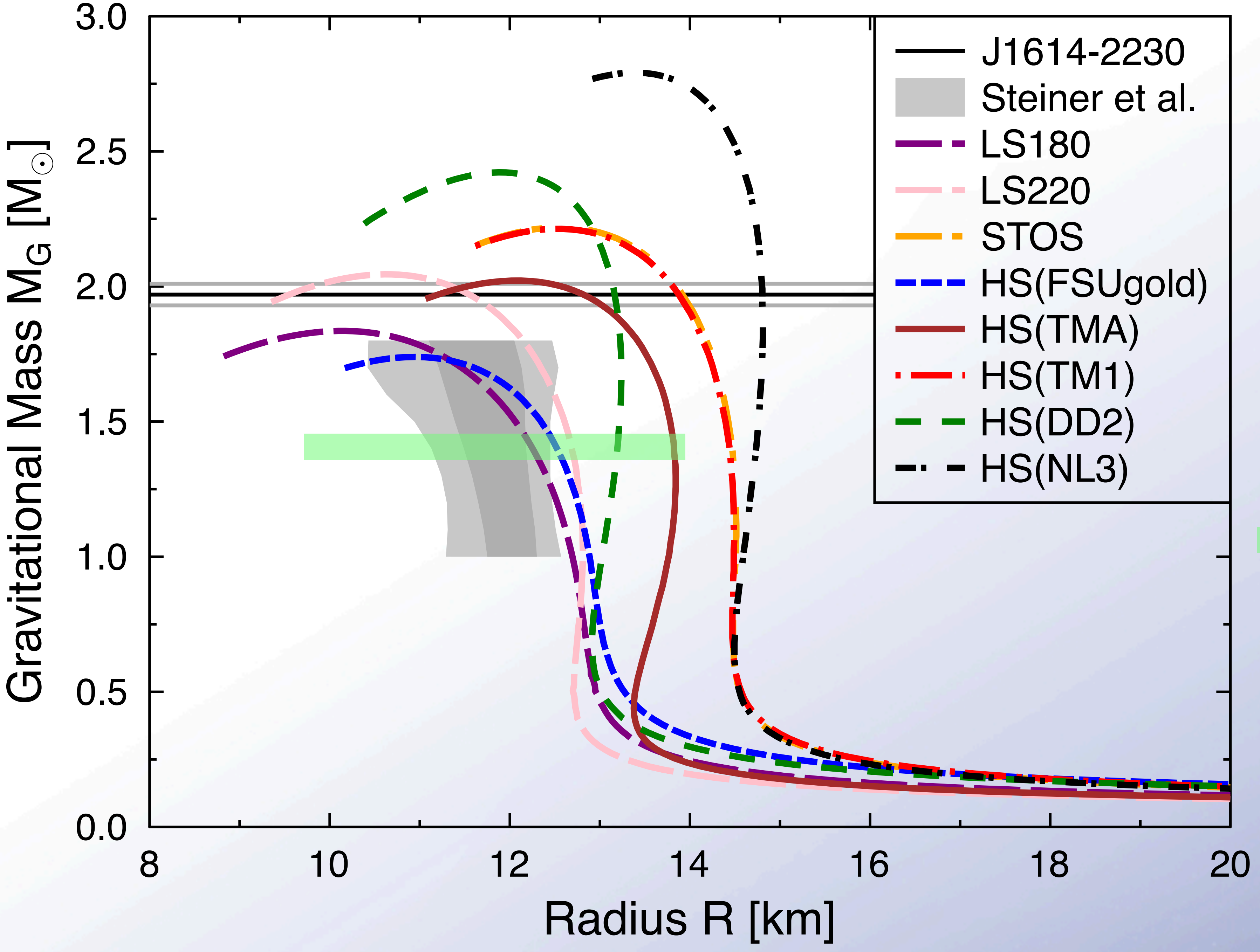
The mass-radius relation of neutron stars



- given EOS, e.g. „FSUgold“
- hydrostatic equilibrium in general relativity (Tolman-Oppenheimer-Volkoff Eqs.)

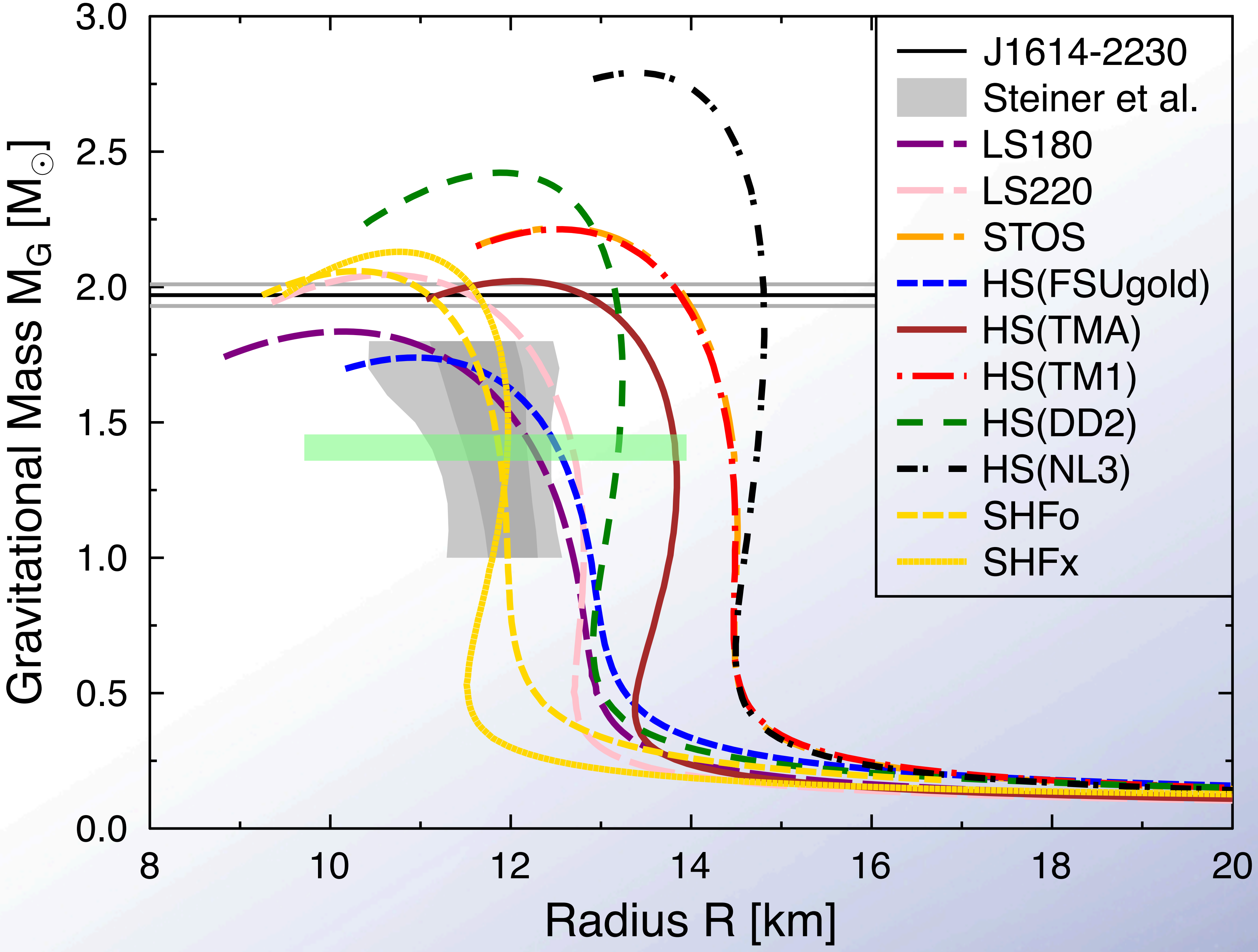
→ (un-)stable neutron star configurations & maximum mass

EOS constraints – neutron star observations



- PSR J1614-2230: Demorest et al. Nature 2010
- bayesian analysis of observations of seven NS, Steiner et al. ApJ 2010, Steiner et al. arXiv 2012
- 🟩 theoretical constraints from Chiral EFT (Hebeler et al. 2010)
- new EOS fitted to observations: Andrew Steiner(Seattle) Tobias Fischer (GSI)

EOS constraints – neutron star observations



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A. Steiner, MH, T. Fischer; arXiv1207.2184

Core-collapse supernova EOS

Supernova EOS – introduction

	neutron stars	supernovae	heavy ion collisions
timescales	(d - yrs)	ms	fm/c
equilibrium	full	only partly weak eq.	only strong eq.
temperatures	0	0 - 100 MeV	10 - 200 MeV
charge neutrality	yes	yes	no
asymmetry	high	moderate	low

- matter in SN: no weak equilibrium, finite temperature
  → somewhere between cold neutron stars and heavy-ion collisions
- challenge of the supernova EOS:
  - temperatures T = 0 – 100 MeV
  - electron fractions $Y_e = 0 – 0.6$
  - densities $\rho = 10^4 – 10^{15}$ g/cm^3
  - EOS in tabular form, ~1 million configurations (T, Y_e, ρ)
  - nuclei/clusters and non-uniform matter
- SN EOS: multi-purpose EOS

Available supernova EOS

Lattimer & Swesty (1991) (LS)	Skyrme interactions, compressible liquid-drop model, three different compressibilities, and tabulated variants
H. Shen et al. (1998) (STOS)	table for TM1, relativistic mean-field (RMF), Thomas-Fermi approximation
MH & Schaffner-Bielich (2010) (HS)	tables for NL3, TM1, TMA, FSUgold, DD2, SHFo, SHFx, IUFSU: NSE, RMF, excluded volume
G. Shen, Horowitz, Teige (2010)	tables for NL3 and FSUgold: virial expansion, RMF, Hartree

nucleonic EOS

Nakazato et al. 2008	quark matter with large n_c added to STOS
Ishizuka et al. 2008	hyperons added to STOS
Sagert et al. 2009	quark matter with low n_c added to STOS → explosions in 1D
H. Shen et al. 2010	lambdas added to STOS

strange physics
at high densities

principle (open) questions:

- how does the EOS affect the explosion dynamics?
- influence on nucleosynthesis conditions (r-process)?
- possible observables?

EOS model: excluded volume NSE with interactions

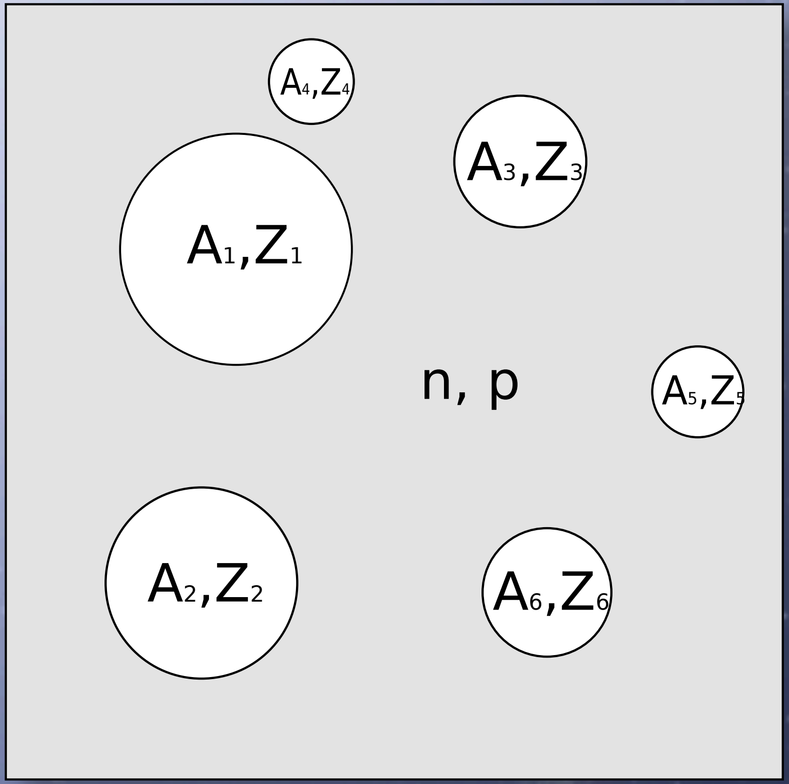
MH, J. Schaffner-Bielich; NPA837(2010) (HS)

- chemical mixture of nuclei and interacting nucleons in nuclear statistical equilibrium
- subsaturation densities: finite temperature generalization of outer crust EOS
  - nuclear mass tables, medium effects, Coulomb energies, excited states, excluded volume
- supersaturation densities: finite temperature RMF/covariant density functional theory
- smooth and continuous change of composition and thermodynamic quantities

- eight EOS tables for different RMF interactions:

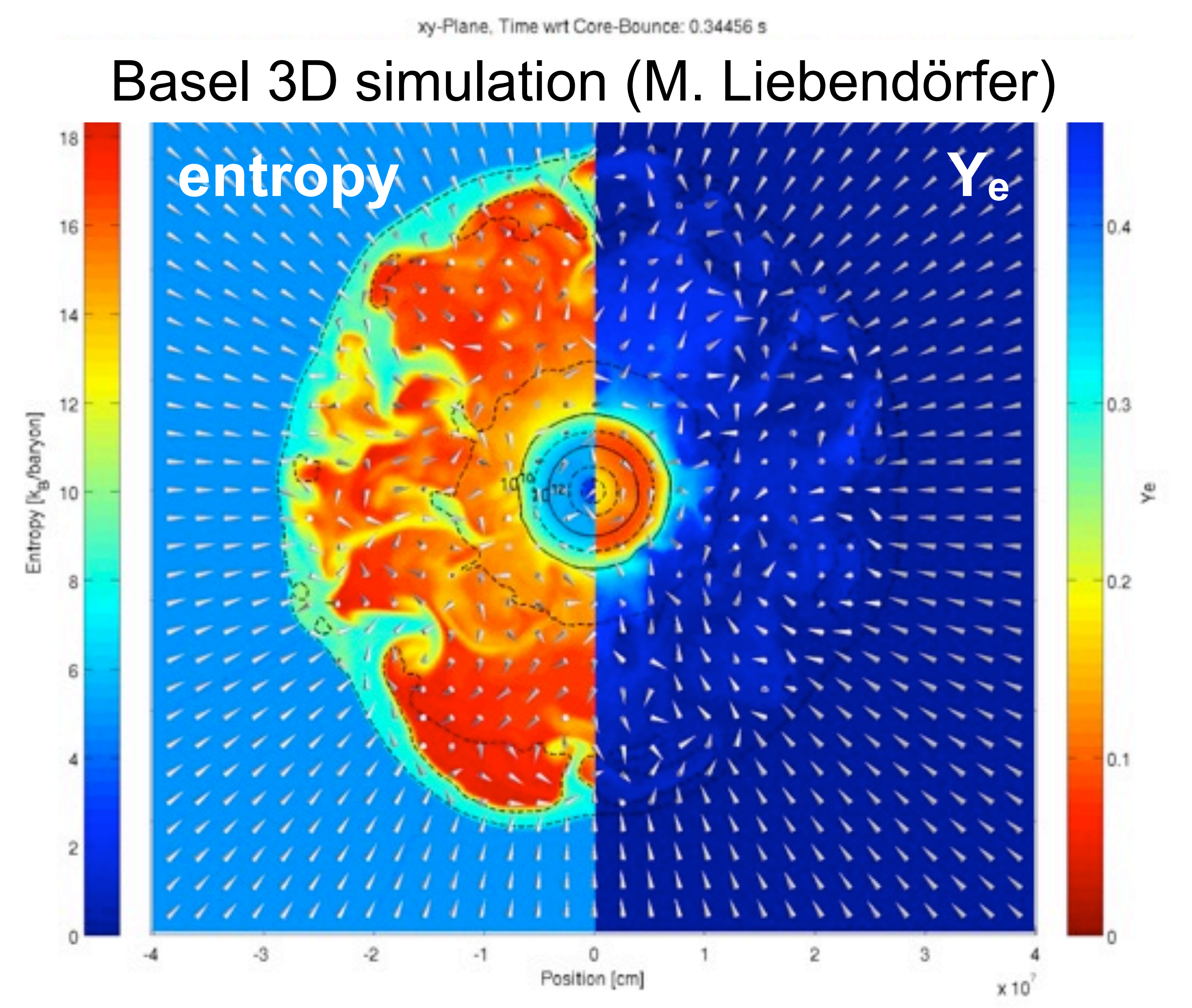
  NL3, TM1, TMA, FSUgold, DD2, SHFo, SHFx, IUFSU

  http://phys-merger.physik.unibas.ch/~hempel/eos.html



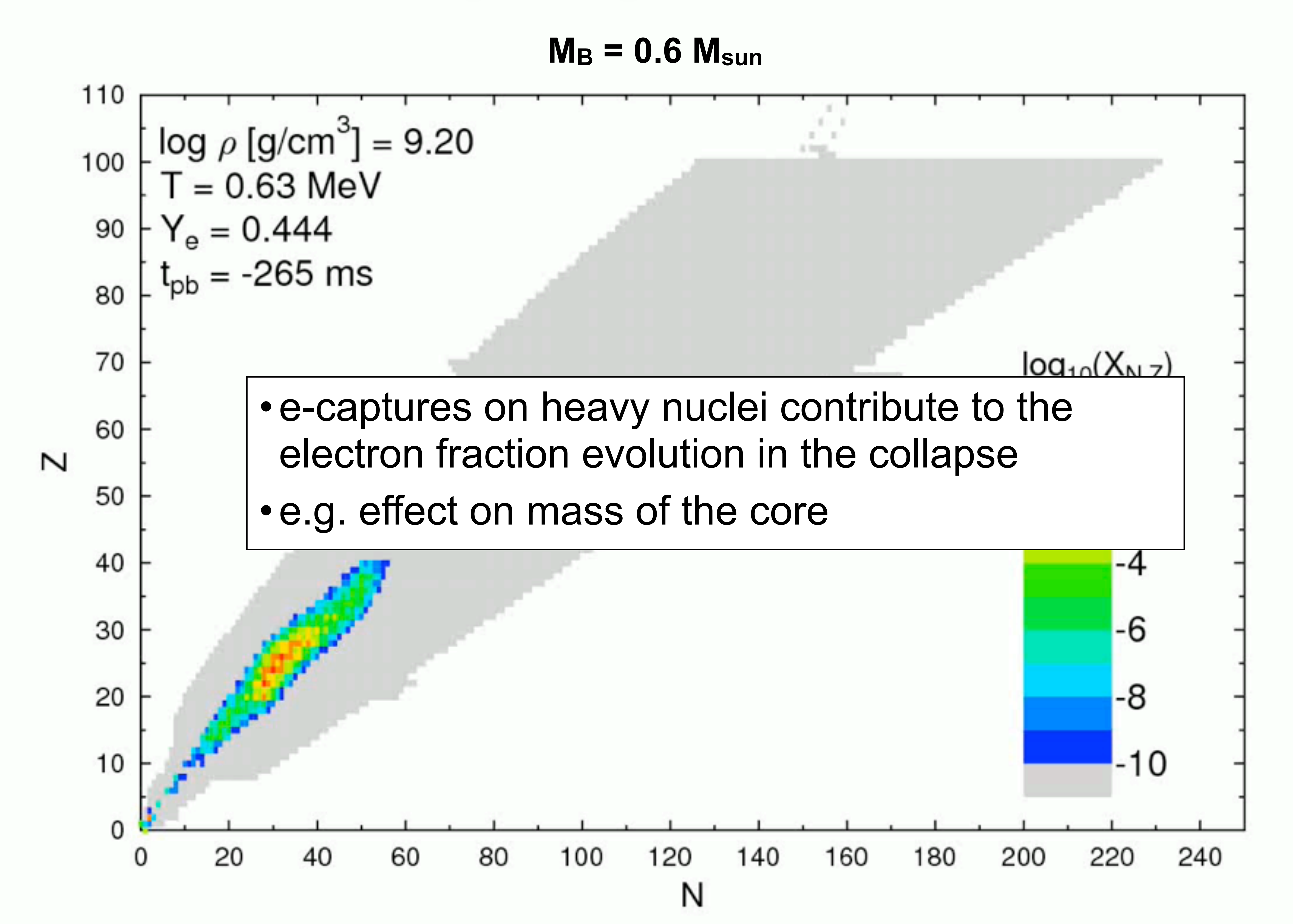
Core-collapse supernovae

- birthplace of neutron stars
- collapse of the iron core of a massive star at the end of its evolution
- the explosion mechanism is not fully understood yet
- collapse -> bounce shock -> standing accretion shock -> explosion (?)



Basel 3D simulation (M. Liebendörfer)

Nuclei in a core-collapse supernova



- e-captures on heavy nuclei contribute to the electron fraction evolution in the collapse
- e.g. effect on mass of the core

Conclusions

- the outer crust is well understood:
  - new mass measurement of ^{82}Zn by ISOLTRAP: enhanced N=50 shell gap (Wolf et al. PRL110, 2013)
  - outer crust known experimentally to a depth of ~220 m, density of ~5x10^{10} g/cm^3, the last known nucleus is ^{80}Zn
  - dominant role of N=50 and 82 neutron shell closures

- theoretical progress for the neutron matter EOS (inner crust)

- convergence of constraints for the nuclear matter EOS (experiment, binding energies, astrophysics, theory)

- important limits for neutron stars and matter in supernovae

- properties of matter at 10^{15} g/cm^3 is still terra incognita

- open questions regarding the role of the EOS in core-collapse supernovae