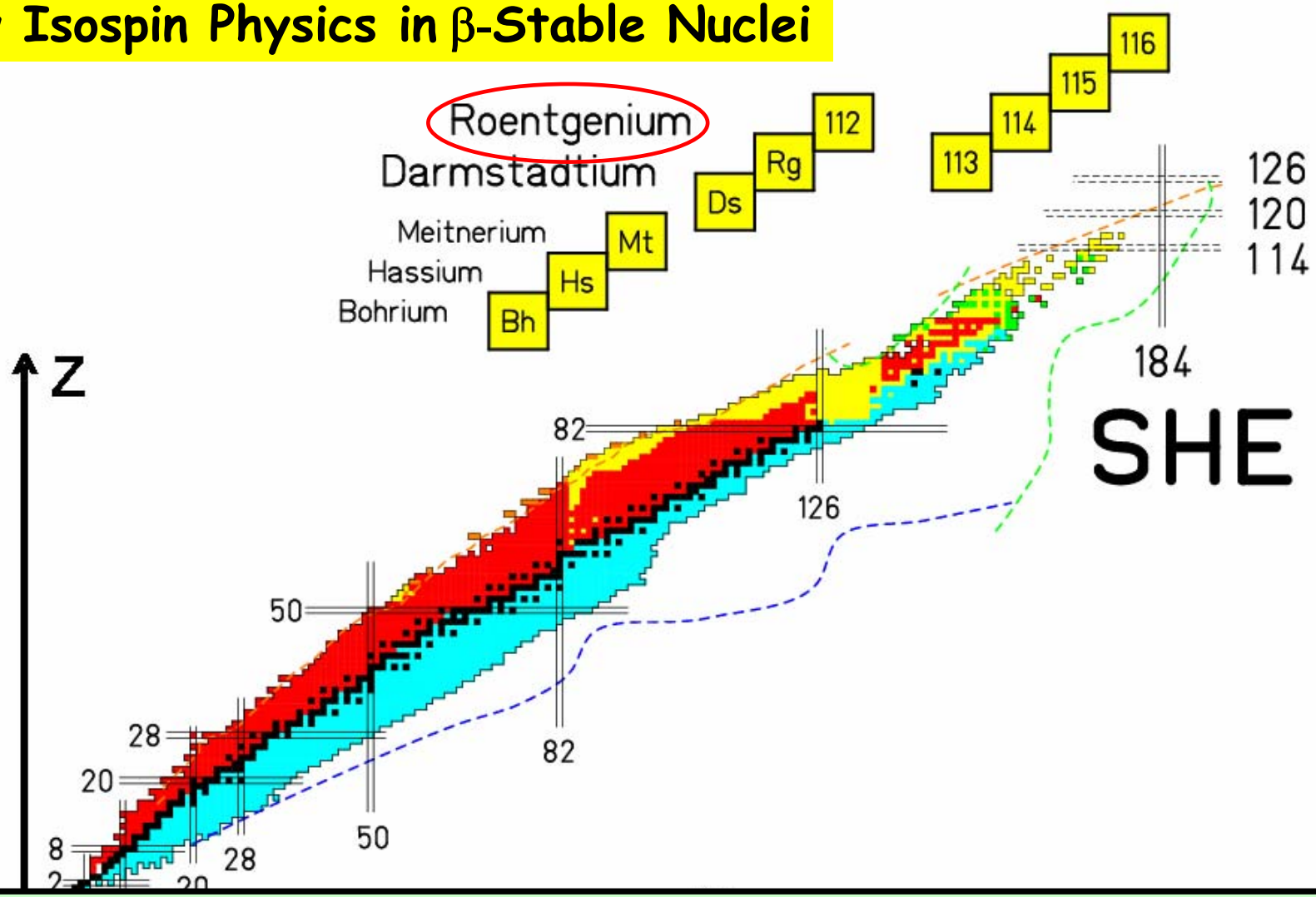
The first Century of Nuclear Physics: Low Isospin Physics in β-Stable Nuclei



$$E(A)/A = -16\text{MeV} + E_{surf}/A^{1/3} + E_{pair} + E_{shell} + E_{coul}$$

$$+ [(N-Z)/A]^2(a_4 + C_{sym}/A^{1/3})$$

From Nuclear Matter to Neutron Stars

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Content:

- Relativistic *ab initio* Approach: The DDRH Field Theory
- Nuclear Matter and Nuclei at extreme Isospin
- Extension to SU(3) Flavor Dynamics and Hypernuclei
- Neutronstars
- Summary

Density Dependent Hadron Field Theory: The DDRH Lagrangian

$$
\begin{aligned}
\mathcal{L}_B &= \overline{\Psi}\left[i\gamma_\mu\partial^\mu - M\right]\Psi \\
\mathcal{L}_M &= \frac{1}{2}\sum_{i=\sigma,\delta,\pi,\eta}\left(\partial_\mu\Phi_i\partial^\mu\Phi_i - m_i^2\Phi_i^2\right) - \\
&\quad \frac{1}{2}\sum_{\kappa=\omega,\rho,\gamma}\left(\frac{1}{2}F_{\mu\nu}^{(\kappa)}F^{(\kappa)\mu\nu} - m_\kappa^2 A_\mu^{(\kappa)}A^{(\kappa)\mu}\right) \\
\mathcal{L}_{int} &= \overline{\Psi}\hat{\Gamma}_\sigma(\hat{\rho})\Psi\Phi_\sigma - \overline{\Psi}\hat{\Gamma}_\omega(\hat{\rho})\gamma_\mu\Psi A^{(\omega)\mu} + \\
&\quad \overline{\Psi}\hat{\Gamma}_\delta(\hat{\rho})\boldsymbol{\tau}\Psi\boldsymbol{\Phi}_\delta - \overline{\Psi}\hat{\Gamma}_\rho(\hat{\rho})\gamma_\mu\boldsymbol{\tau}\Psi\boldsymbol{A}^{(\rho)\mu} - \\
&\quad \overline{\Psi}\hat{\Gamma}_\eta(\hat{\rho})\gamma_5\Psi\Phi_\eta - \overline{\Psi}\hat{\Gamma}_\pi(\hat{\rho})\gamma_5\gamma_\mu\boldsymbol{\tau}\Psi\partial^\mu\boldsymbol{\Phi}_\pi - \\
&\quad e\overline{\Psi}\hat{Q}\gamma_\mu\Psi A^{(\gamma)\mu} \quad .
\end{aligned}
$$

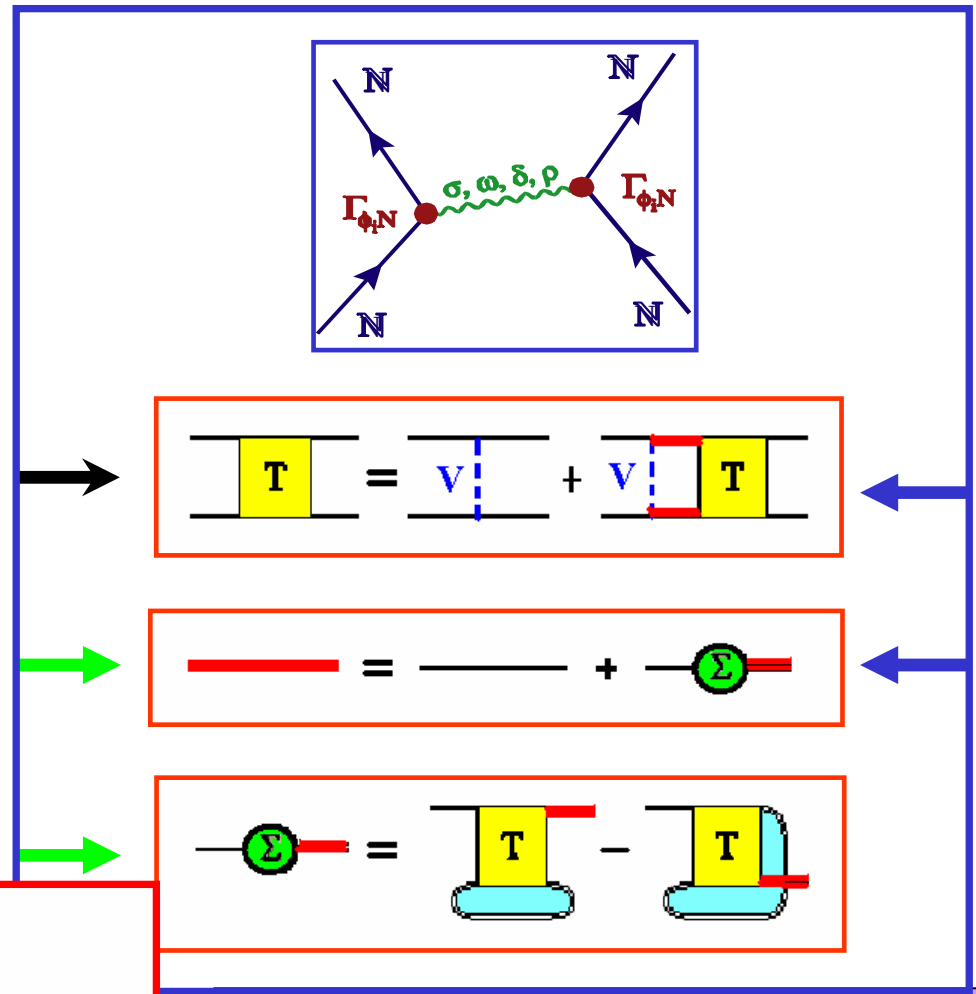
- **Covariance of field equations**
- **Thermodynamical consistency**
- **Systematic Expansion**

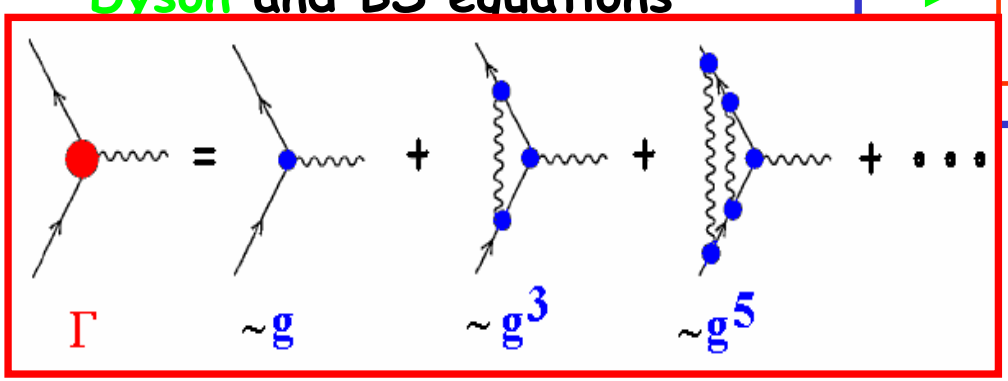
- **Density Dependent Vertices**
- **Static Polarization Self-Energies**
- **Nuclei and Hypernuclei**

PLB345 (1995), PRC52 (1995), PRC57 (1998), PRC64 (2001), PRC66 (2002), Spinger Lect. Notes (2004)

Elements of an *ab initio* Relativistic Nuclear Field Theory

- Baryon-Baryon interactions by meson exchange
- free space and In-medium interactions from the Bethe-Salpeter equation (Ladder Kernel)
- In-medium effects - statistical: Pauli principle
- In-medium effects - dynamical: baryon self-energies
- Self-Consistent solution of Dyson and BS equations

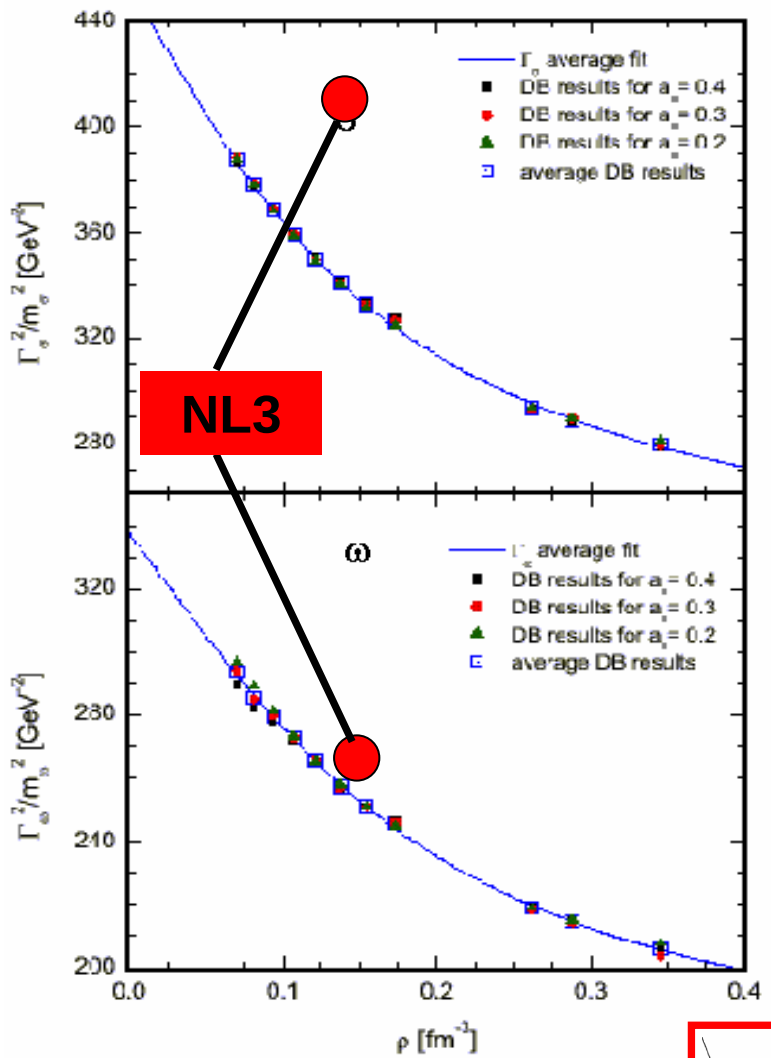


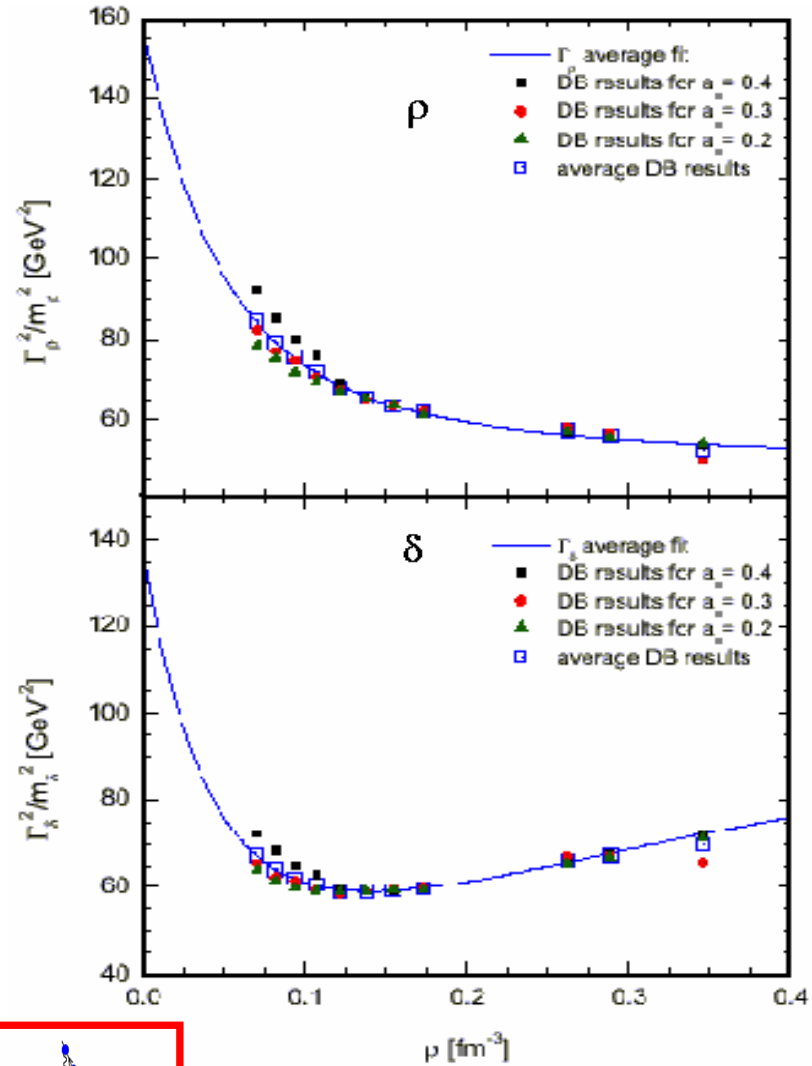


S. Typel, H. Wolter, NPA 1999; P. Rin…; G. H…, PRC…

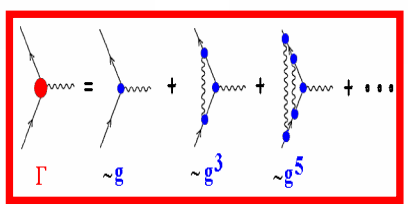
PLB345 (1995), PRC52 (1995), PRC57 (1997), PRC64 (2001), Springer Lecture Notes (2004)

Nuclear Matter DBHF Vertices (Groningen NN-Potential)



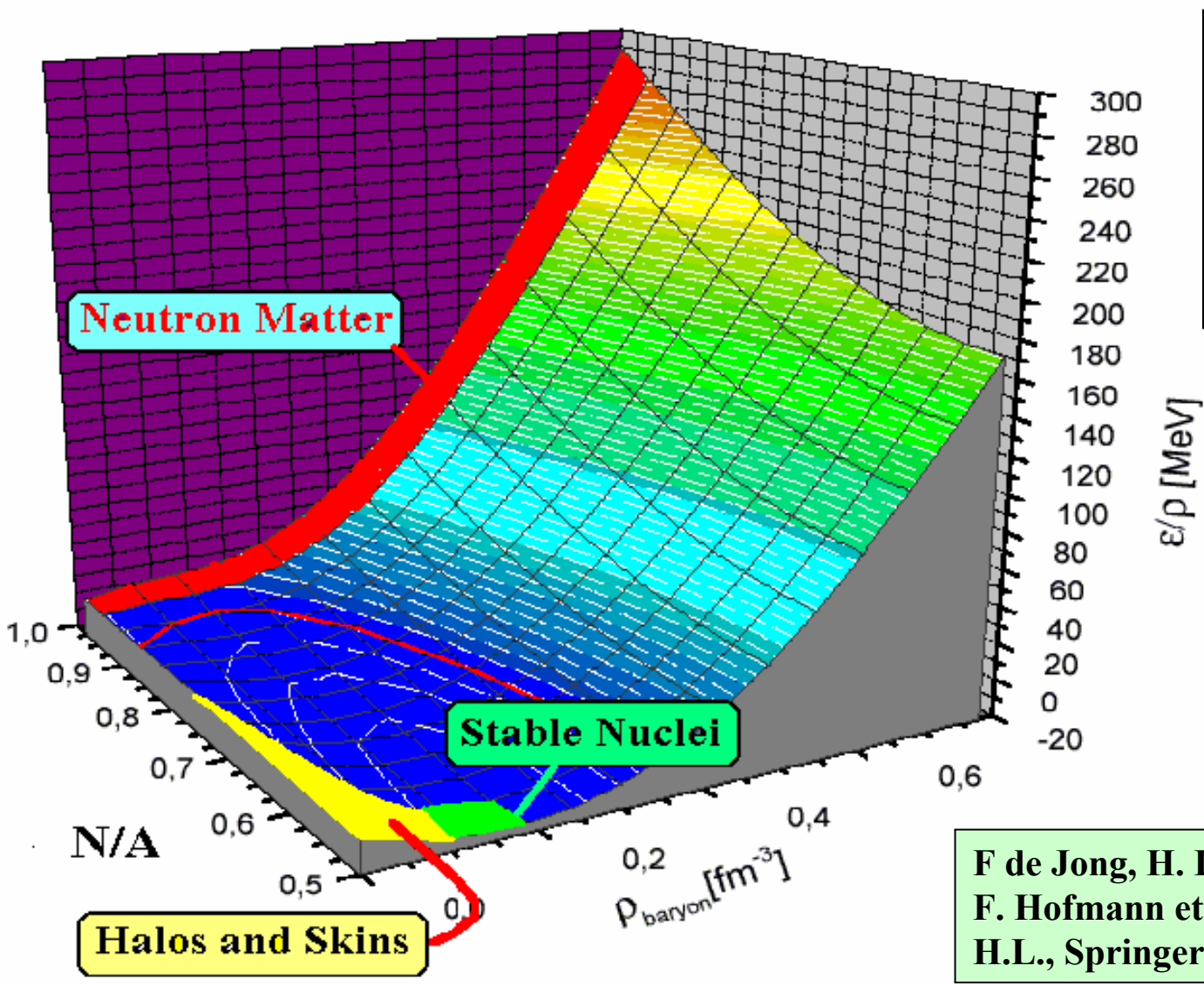


Isoscalar Vertices



Isovector Vertices

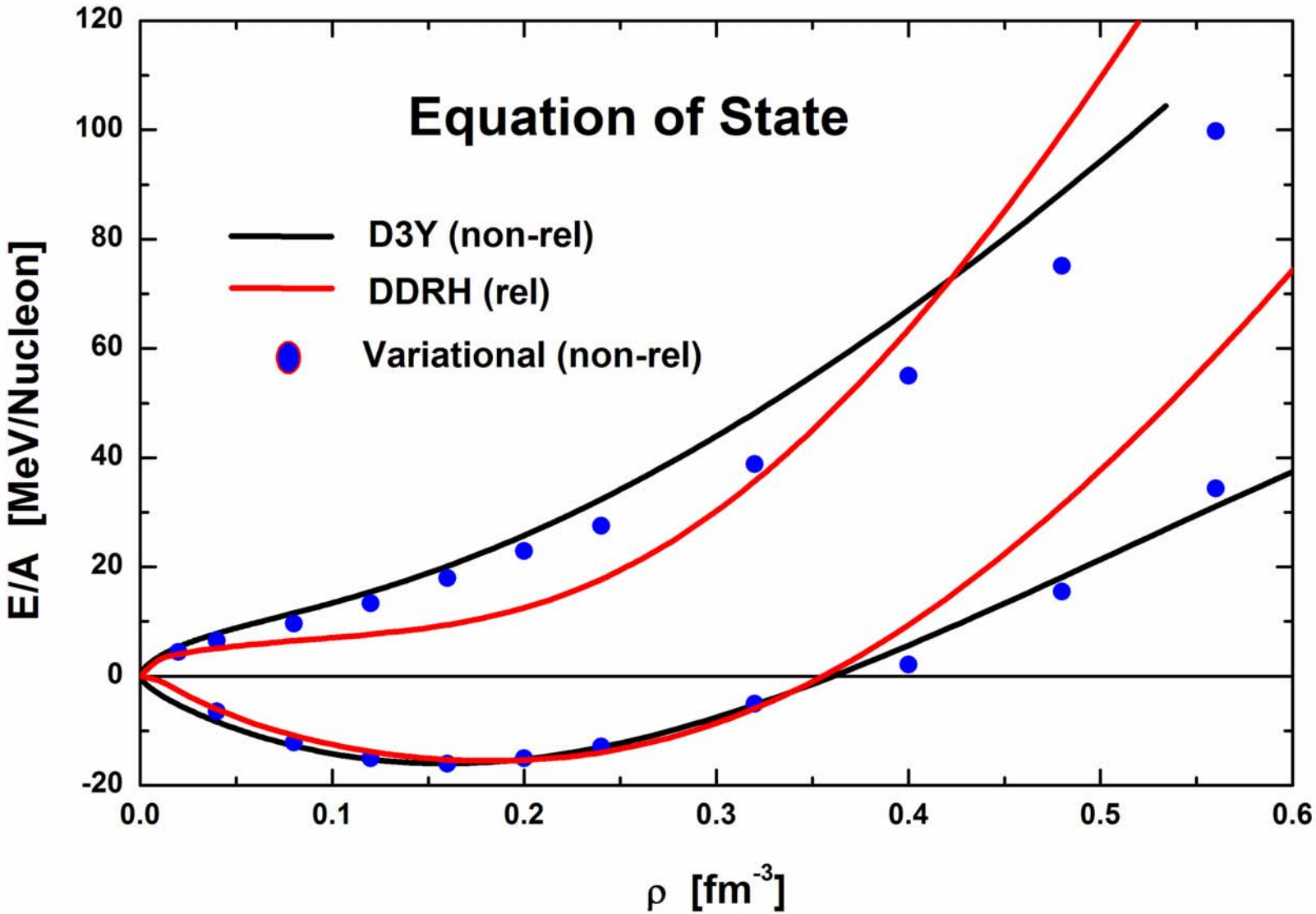
EoS of Asymmetric Nuclear Matter



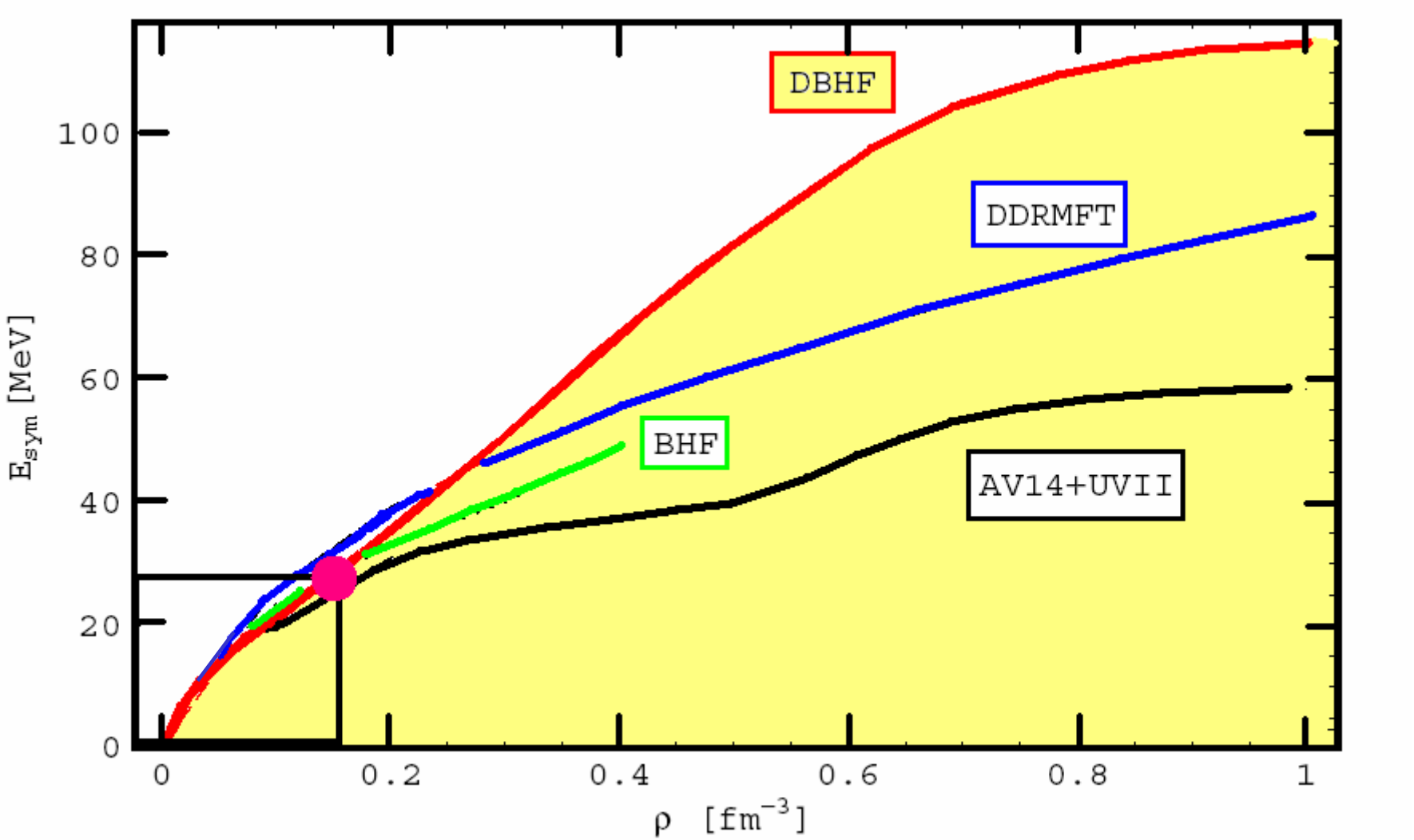
DDRH Calculations (DBHF vertices from Groningen NN-Potential)

F de Jong, H. L. PRC58 (1998),
F. Hofmann et al. PRC64 (2001)
H.L., Springer Lecture Notes 2004

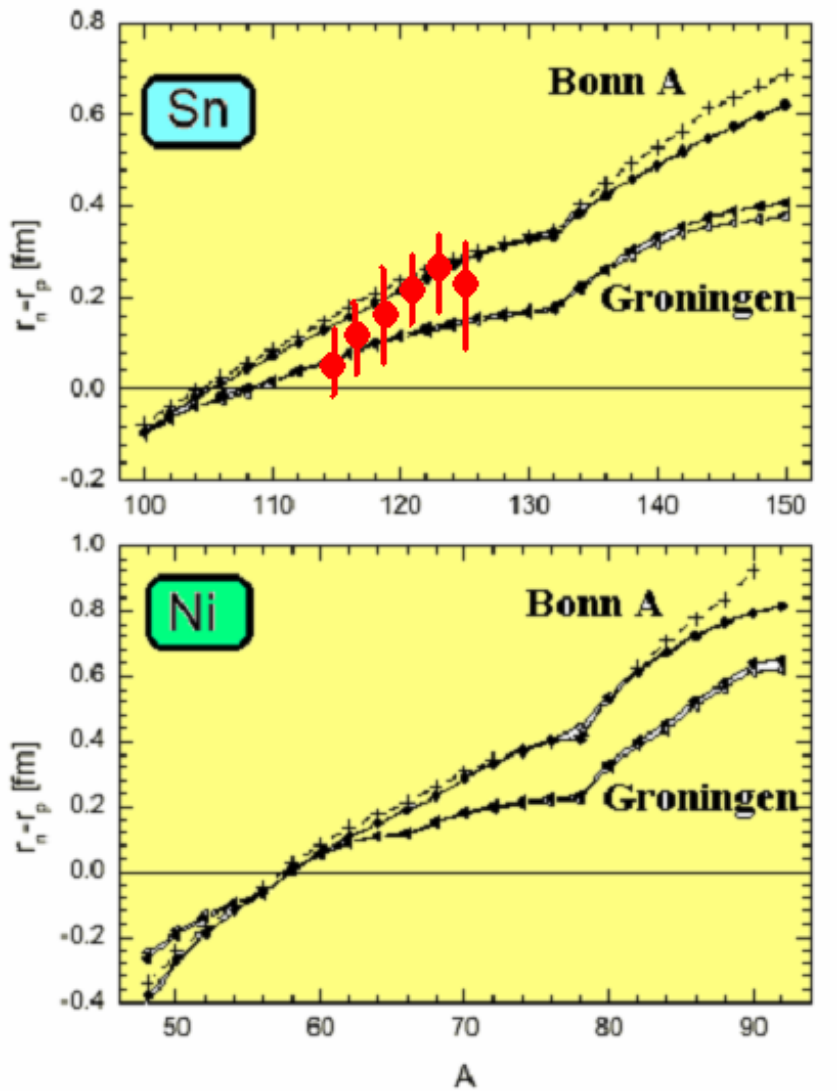
The EoS: DDRH Dirac-Brueckner vs. non-relativistic Brueckner and Urbana V18+UIX



EoS of Asymmetric Nuclear Matter: Symmetry Energy



Neutron Skins in Ni and Sn Isotopes



DDRH RMF-Calculations
Dirac-Brueckner In-Medium Vertices
Bonn-A and Groningen NN-Potentials

Neutron Skin and Symmetry Energy:

Bonn A : a_4 = 32 MeV

Groningen : a_4 = 26 MeV

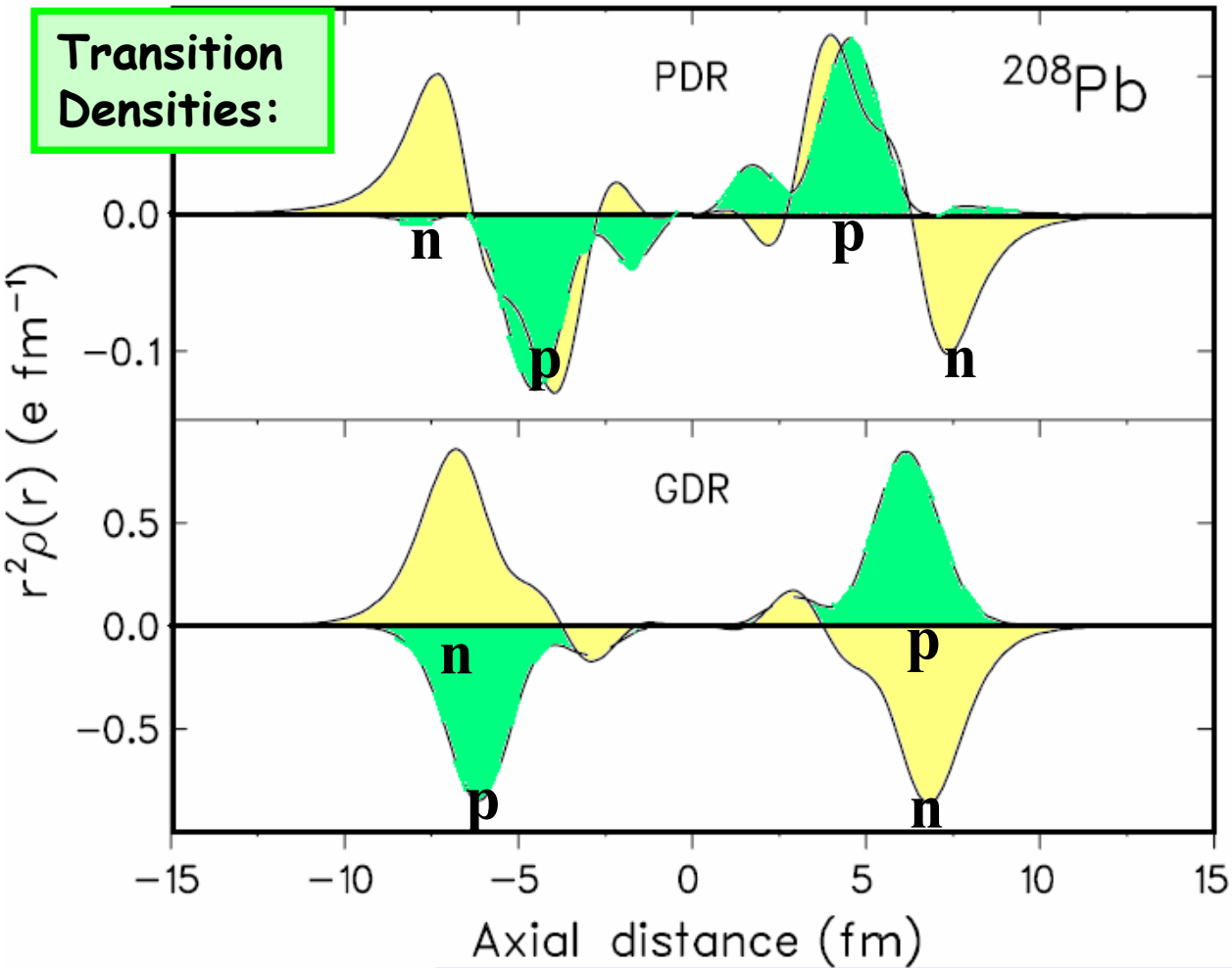
Sn Data: Krasnahorkay et al. PRL 82 (1999) 3216
(from Charge Exchange Spin-Dipole sum rules)

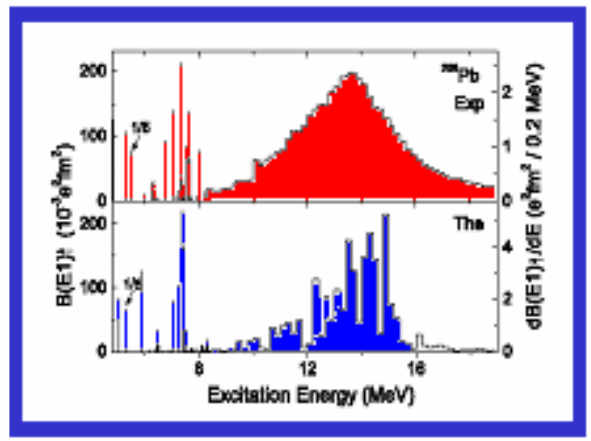
F. Hofmann et al., PR C64 (2001)
N. Tsoneva. H.L., PLB586 (2004)

Pygmy Dipole Strength in ^{208}Pb

(γ,γ') inel.Scattering B(E1) Distributions (PRL 89 (2002)):

Transition Densities:



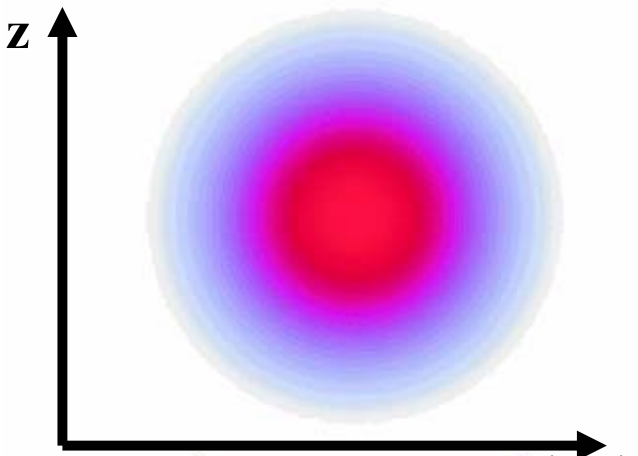


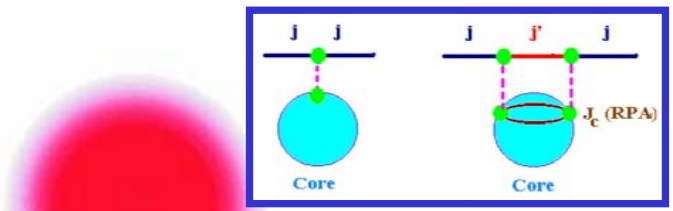
PDR: p/n in phase

GDR: p/n out of phase

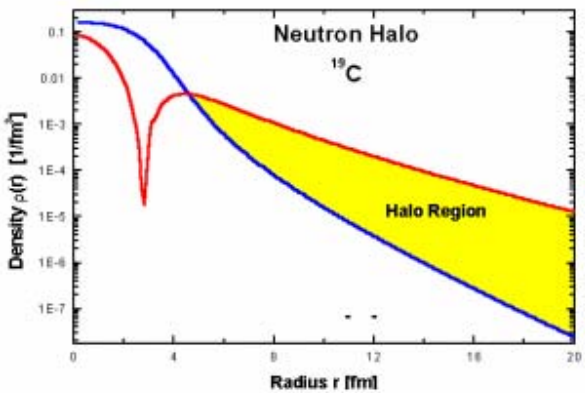
The PDR is a mode of genuine character, NOT the tail of the GDR!

Shape and Size of ^{19}C and ^{16}O : Ground State Densities





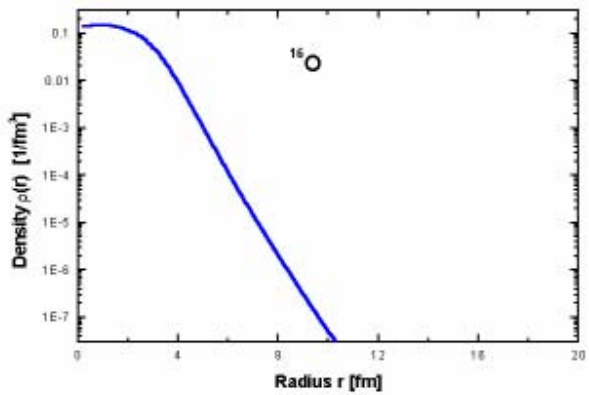
$^{19}C(1/2+, g.s.)$



$\sqrt{<r^2>(1/2+)} = 5.34$ fm

S = 0.47

$^{16}O(0+, g.s.)$



$\sqrt{<r^2>(1/2-)} = 2.96$ fm

S = 0.97

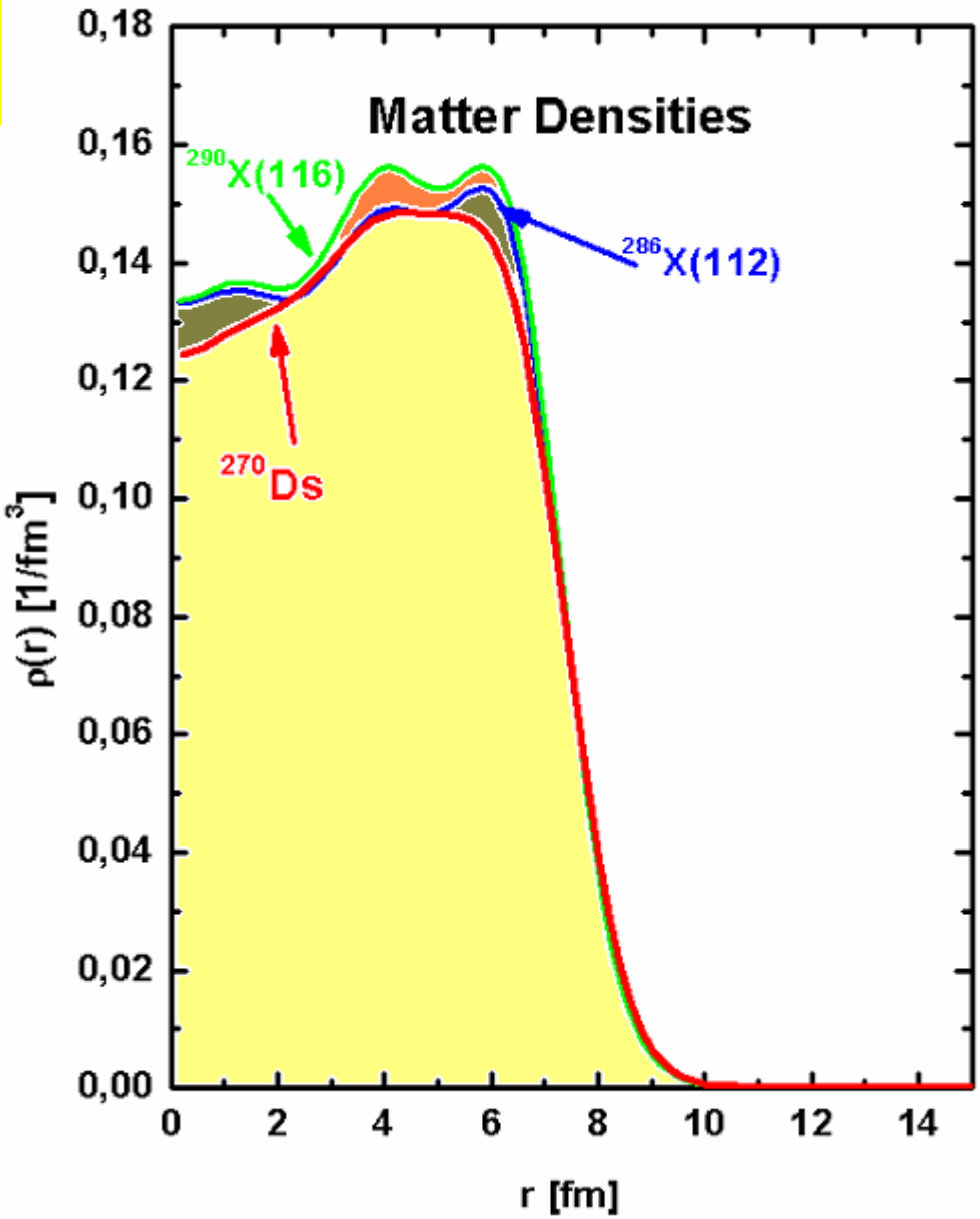
Extreme Shapes of SHE: Bubble Nuclei

- Transitional to Nuclear Matter
- Stabilization by Shell Effects
- Magic Proton Shells:
  Z=114, Z=116, Z=120 ....?
- Crucial for Protons :
  - Coulomb Repulsion
  - Isovector Attraction
- Extreme Shapes: Bubbles

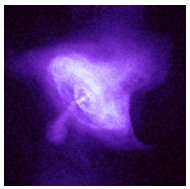
HFB density distributions for ^{A}Ds A=270:

E(HFB): -7.20 [MeV/A]

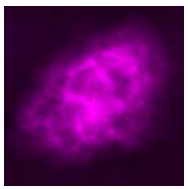
E(Audi'03): -7.25 [MeV/A]



Masses of Neutron Stars: Observations of Radio Pulsars

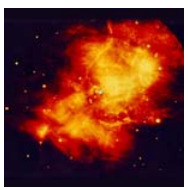


X-ray



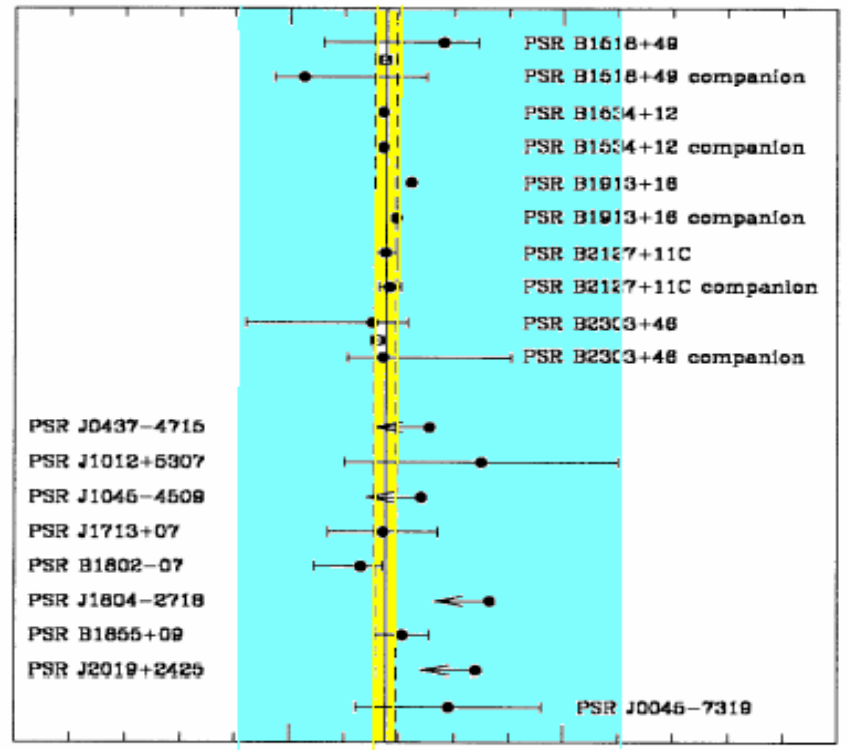
Radio

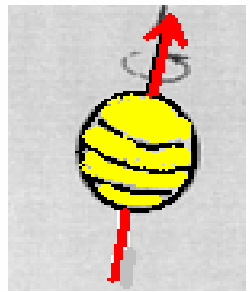
Optical



Infrared

Crab Nebula
Chandra
X-Ray
Observatory

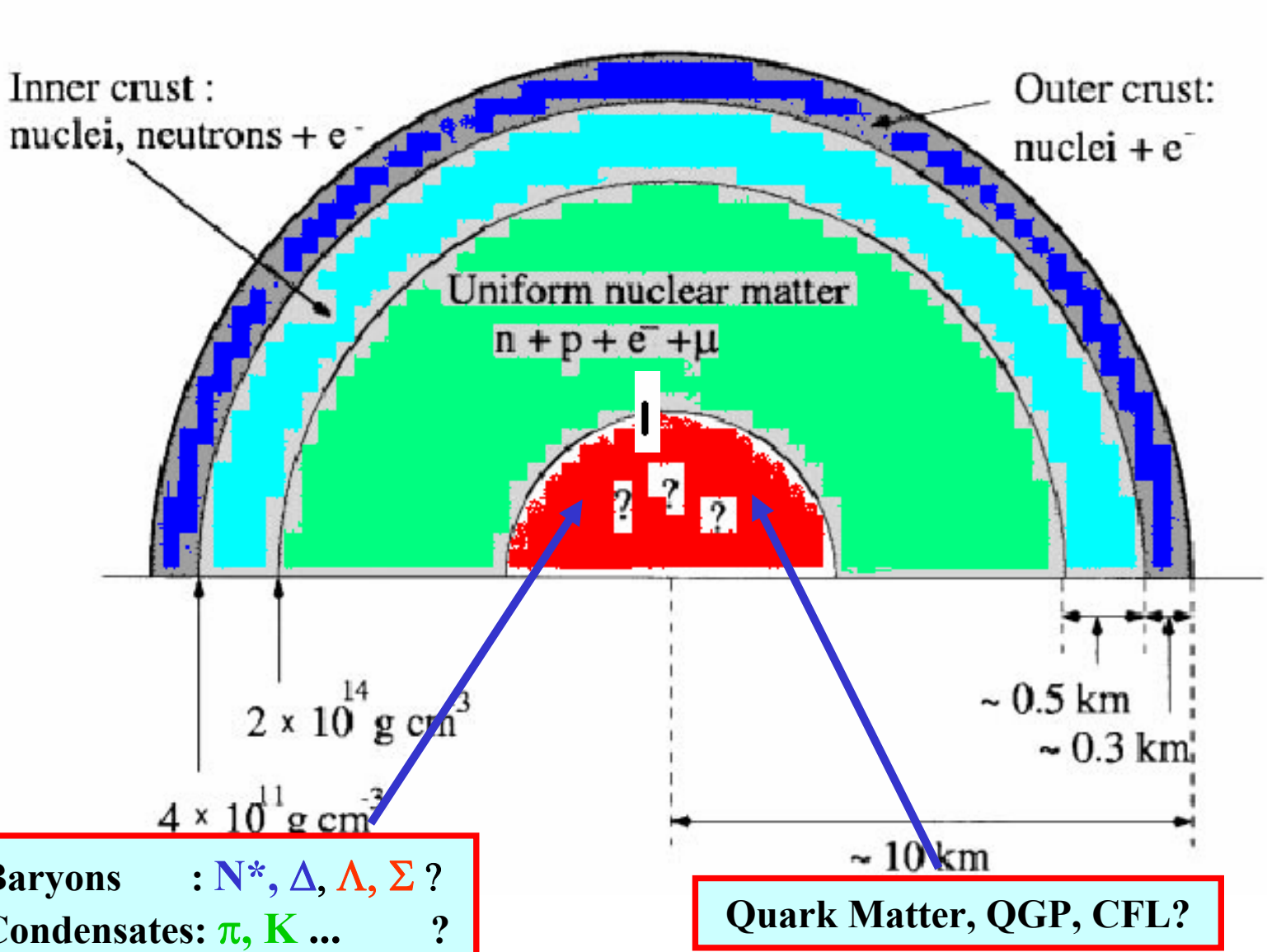




$$M = 1.35 \pm 0.004\ M_{solar}$$

(S.E. Thorsett, D. Chakrabarty, Astrophys. J. 512 (1999) 288.)

Expected Structure of a Neutron Star

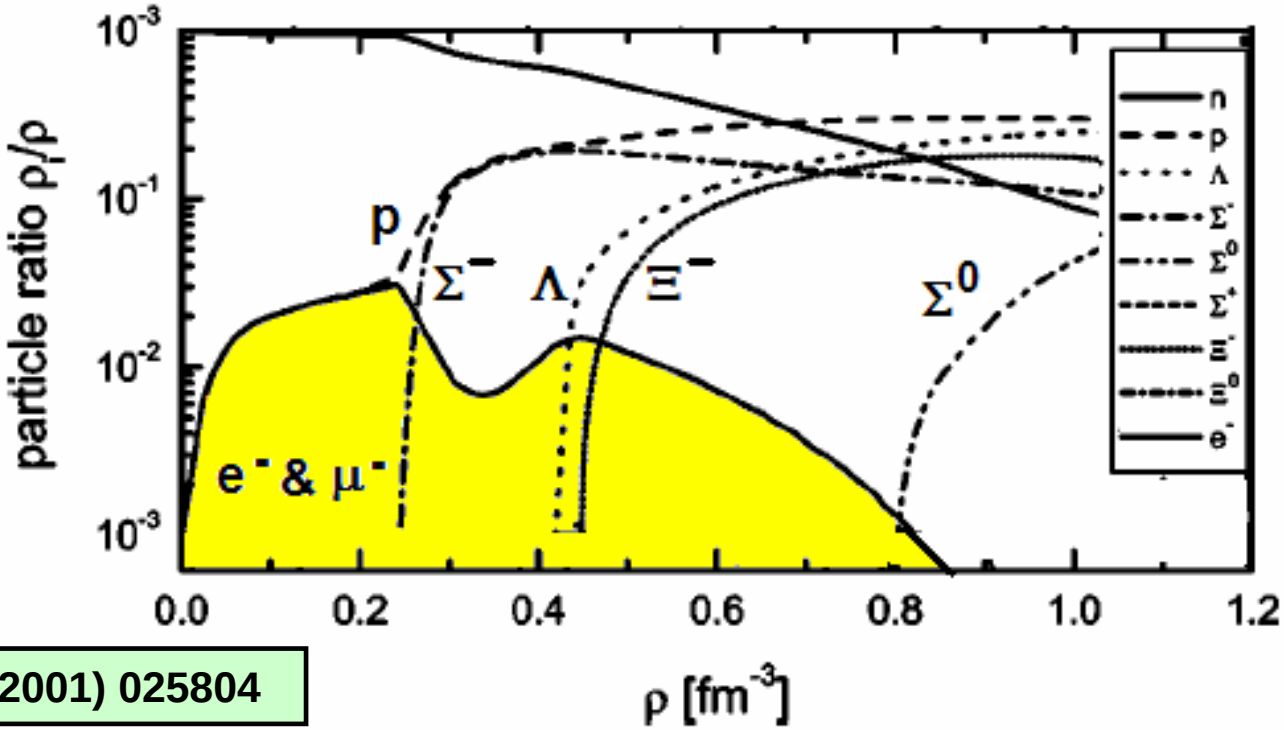


Charge-Neutral Neutron Star Matter in β-Equilibrium

$$n + n \rightarrow \Lambda + n \; ; \; p + n \rightarrow n + e^- \; ; \; \Lambda + \Lambda \rightarrow \Xi^- + p$$

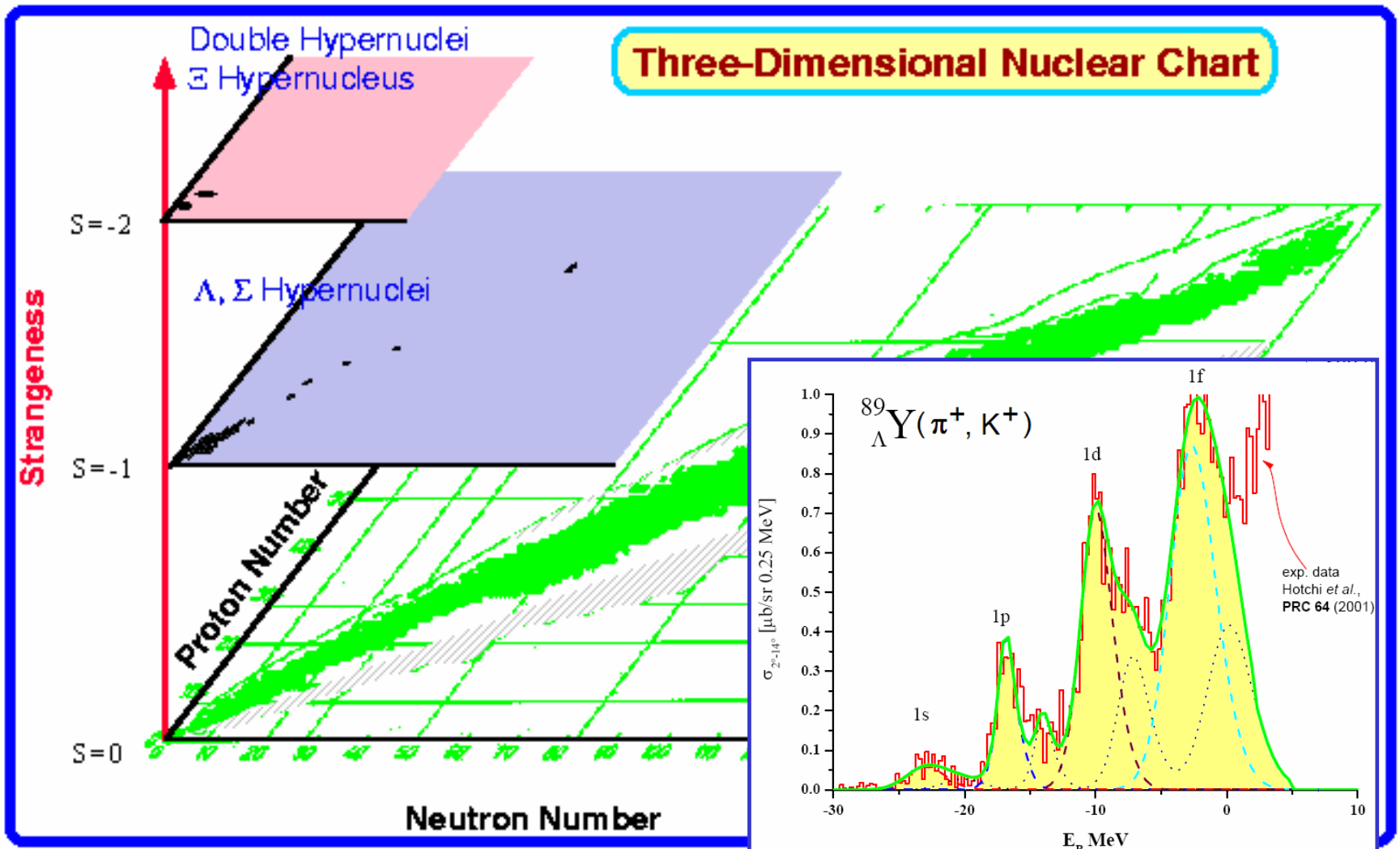
$$\mu_i = b_i \mu_n - q_i \mu_e$$

Creation of Strangeness:
$\rho \sim 2\rho_0$: hyperon threshold (Σ^-, Λ), $\rho > 5\rho_0$: hypermatter dominates



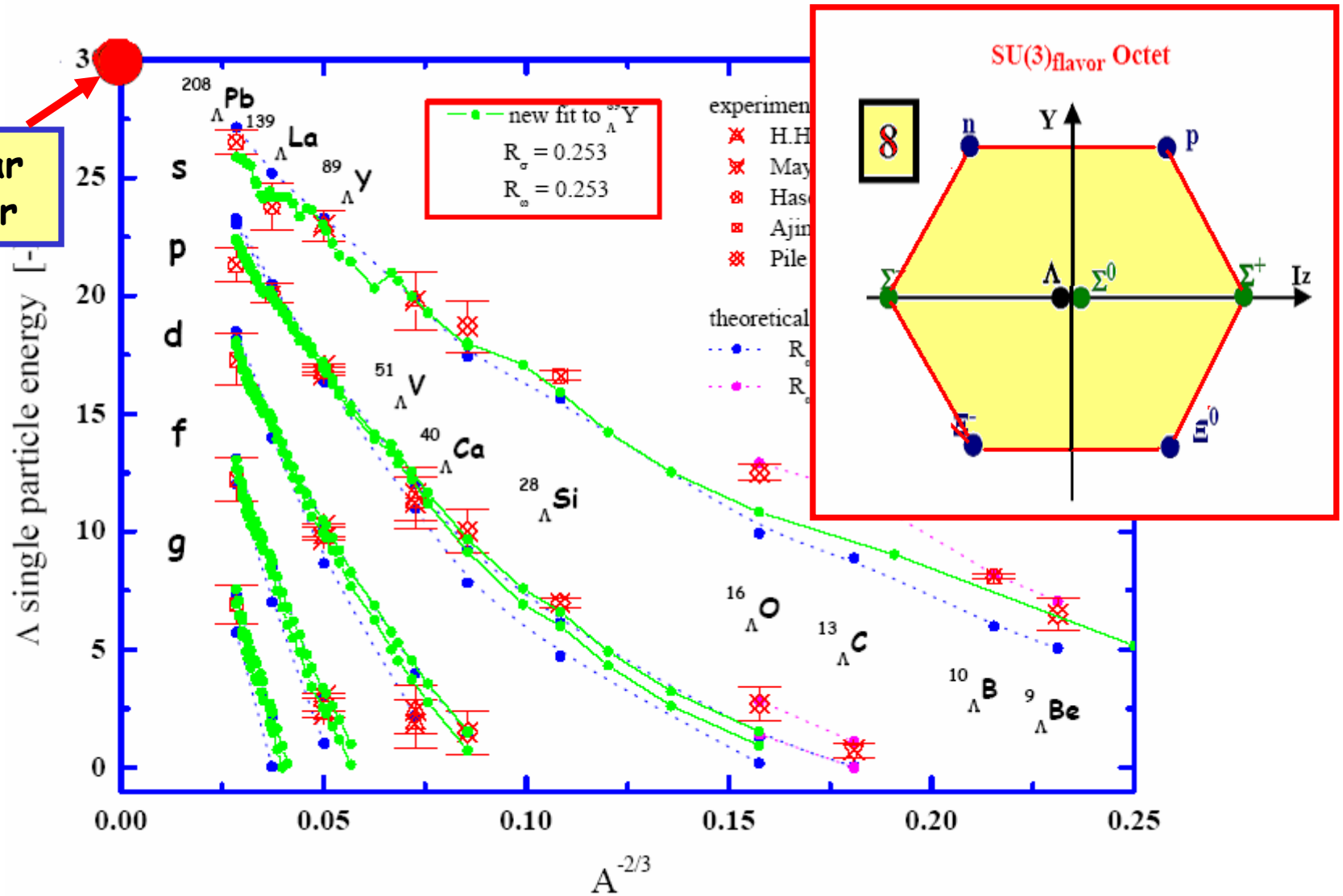
PRC 64 (2001) 025804

Strangeness and Hypernuclear Physics: From SU(2) Isospin to SU(3) Flavour Dynamics



DDRH Flavour Dynamics: Λ Single Particle Energies

Nuclear Matter



DDRH Theory: Density Dependent NN and NΛ Dirac-Brueckner Vertices

Neutron Stars and General Relativity:
The Tolman-Oppenheimer-Volkov (TOV) equations

$$\frac{dm(r)}{dr} = 4\pi\, r^2\, \varepsilon(r)$$

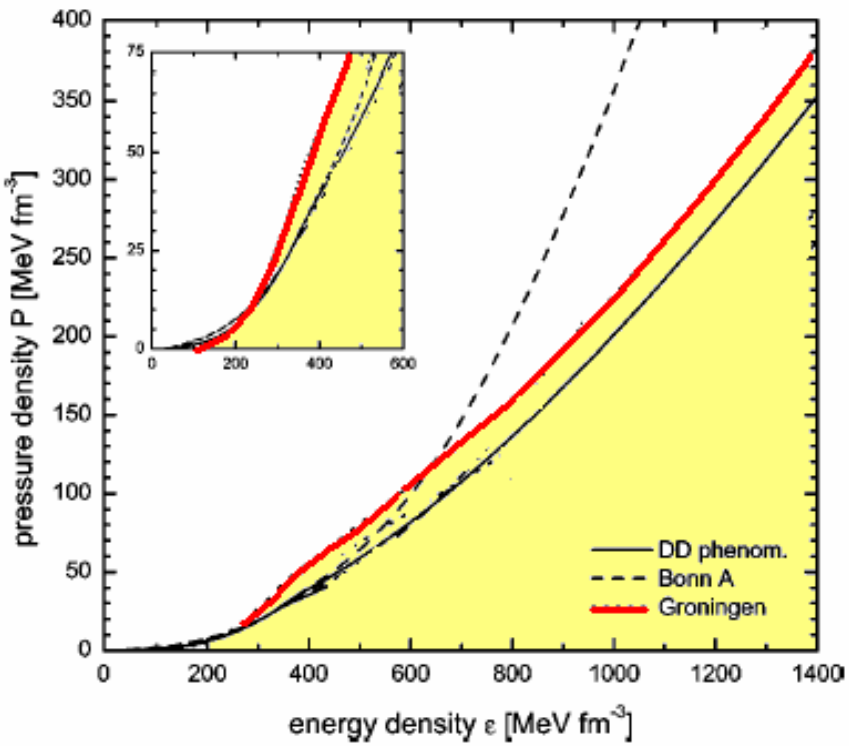
$$\frac{dP(r)}{dr} = -\frac{[\varepsilon(r) + P(r)][m(r) + 4\pi P(r)\, r^3]}{r^2\left[1 - \frac{2m(r)}{r}\right]}$$

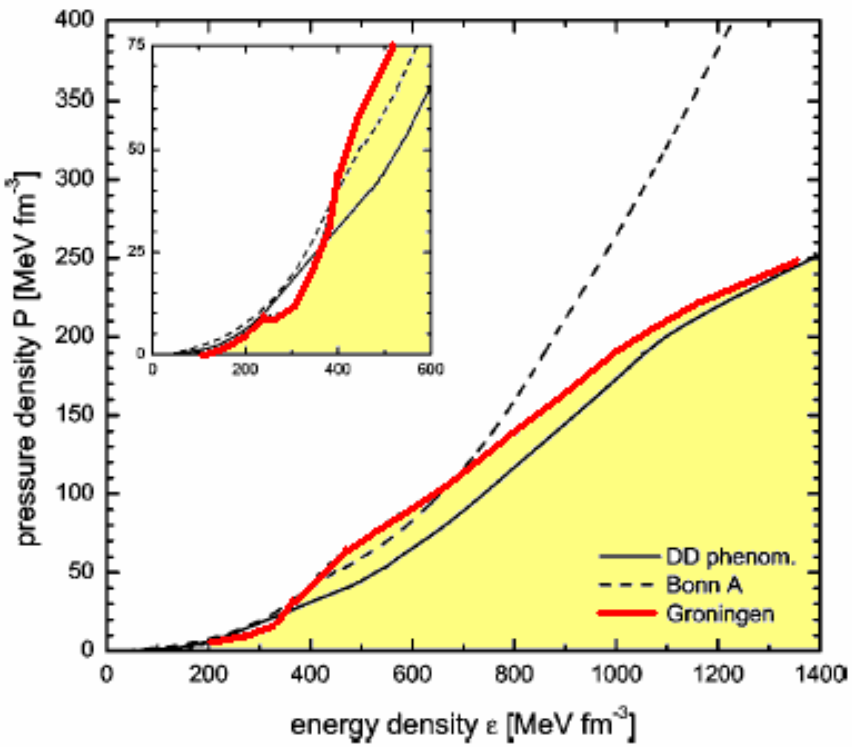
- **m(r): the mass inside a sphere of radius r**
- **Nuclear Matter EoS (β-equil.) : $\varepsilon = \varepsilon(r)$ ➔ $P(\varepsilon) = P(\varepsilon(r))$**
- **integration up to r=R where P(R) = 0 ➔ M(R)**

DDRH Equation of State (➔TOV equations)

EoS for neutron star matter with nucleons and Λ only

EoS for neutron star matter with all octet baryons





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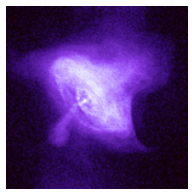
At $\rho < 0.001 fm^{-3}$: matching to BPS EoS

DDRH Neutron Star Mass-Radius Relation:



X-ray

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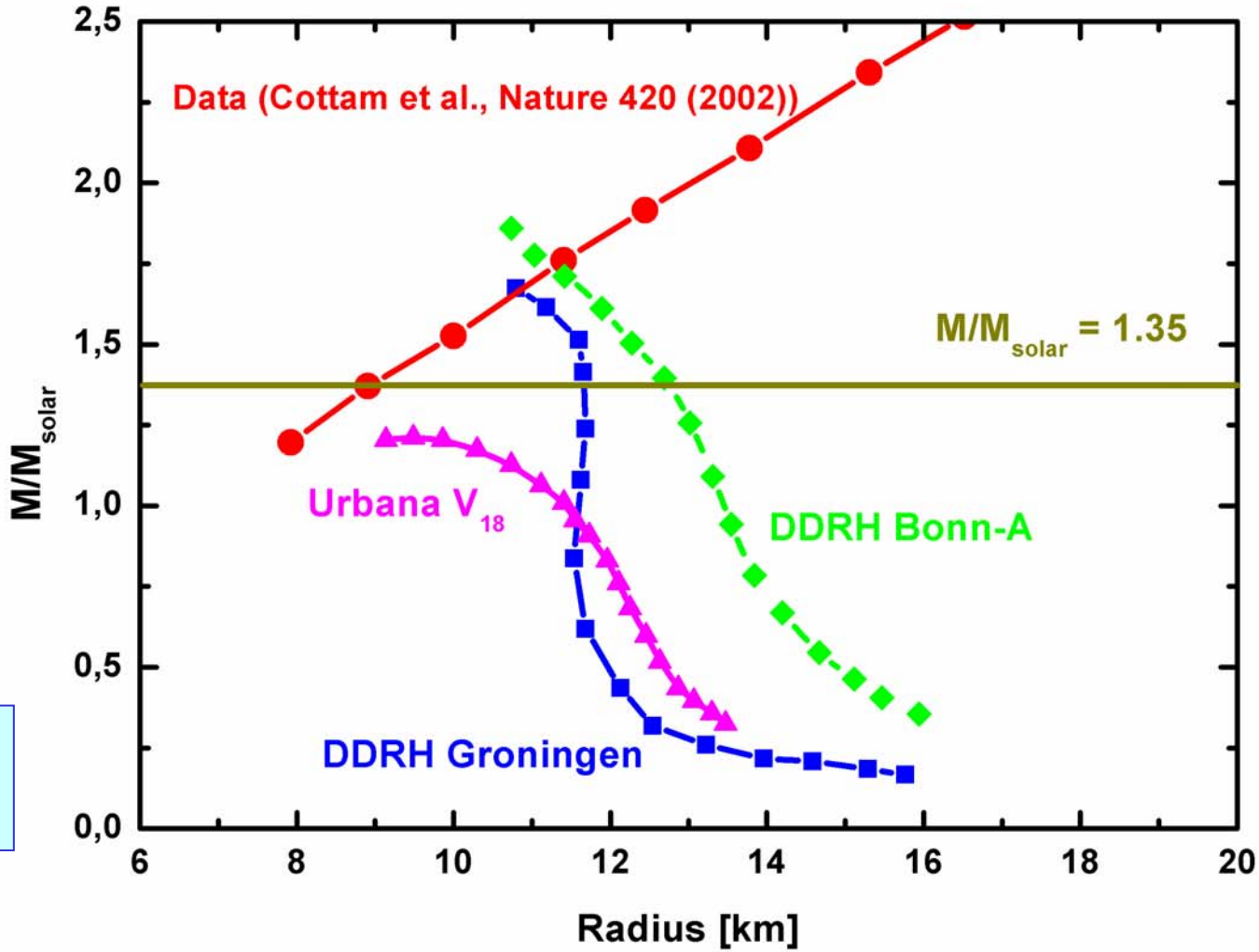

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(2001)
025804

X-ray data from the XMM-Newton observatory:
Red-Shift z ~ M/R
(Fe-Lines from a series of 28 X-ray bursts from EXO07481676)

Summary:

- **Nuclear Many-Body Theory:**

  In-Medium interactions, tadpoles, loops, correlations...

- **DDRH Relativistic field theory with DD vertices**
- ***ab initio* RMF description of stable and unstable Nuclei**
- **Dynamical Correlations in Nuclear Matter**
- **Extension to SU(3) flavor and hypernuclei**
- **Neutron Star Matter and Neutron Stars**

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