Hyperons and Resonances in Nuclei and Neutron Stars

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Agenda:

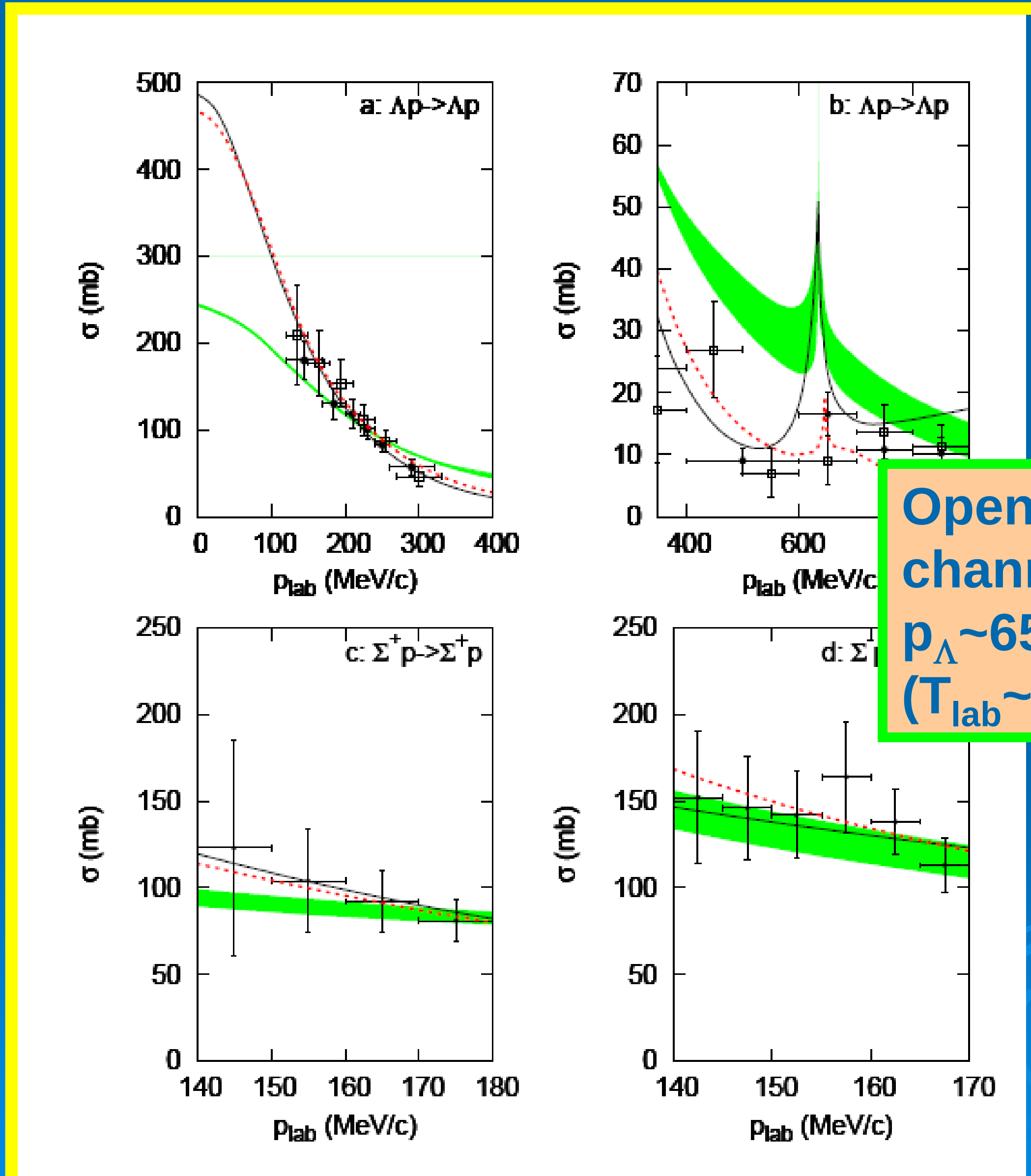
- Hyperon interactions and hypernuclei
- Neutron star matter
- The „hyperonization puzzle“
- Resonances in nuclei and neutron stars

OBE and χEFT NY-Cross Sections:

Results by the Jülich/Bochum Group:

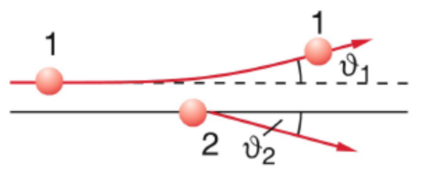
E. Epelbaum et al.

- χEFT (LO)
- Jülich 04
- Nijmwegen SC97



Opening of the ΣN channel at p_Λ~650MeV/c (T_{lab}~175MeV)

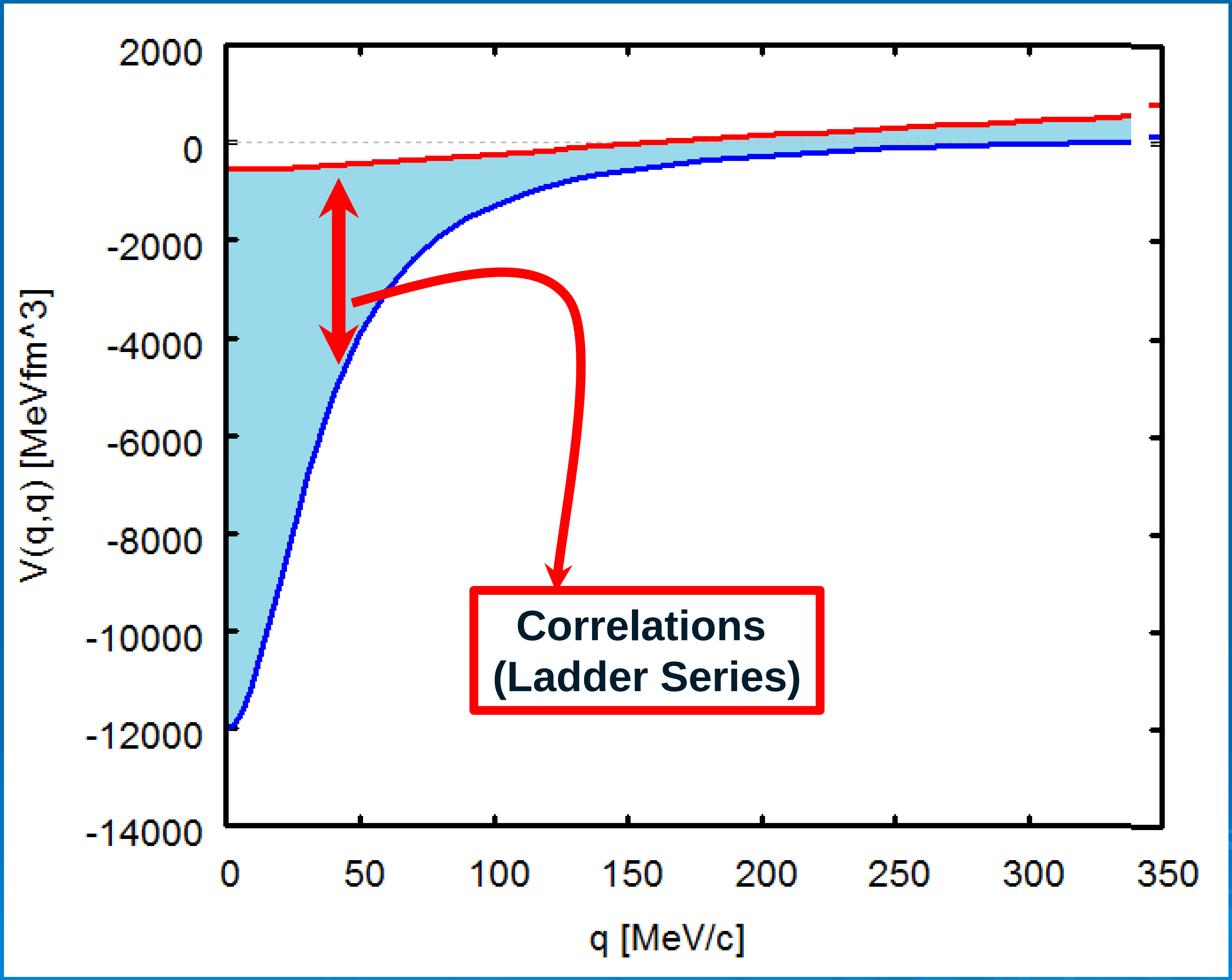
The BB' Scattering Problem:



$$\mathcal{T}\left(q',q|P\right)=\mathcal{V}\left(q',q|P\right)+\int\frac{d^4k}{(2\pi)^4}\mathcal{V}\left(q',q|P\right)\mathcal{G}\left(k|P\right)\mathcal{T}\left(k,q|P\right)$$

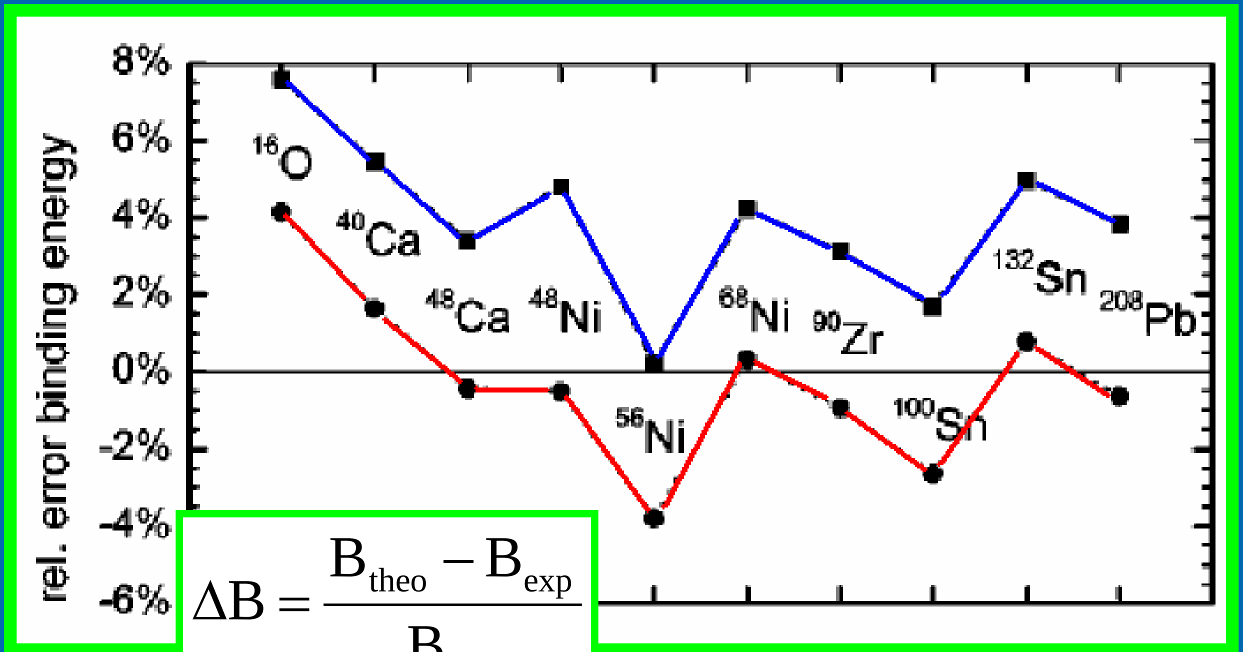
- The Bethe-Salpeter Equation Minkowski-Space
- OBE approach
- 3-D reduction (Thompson, Blankenbecler-Sugar…)
- Phase shifts, scattering lengths…
- DBHF: in-medium self-energies, nuclear properties
- Production of hypernuclei

s-wave SE NN-Potential and K-Matrix



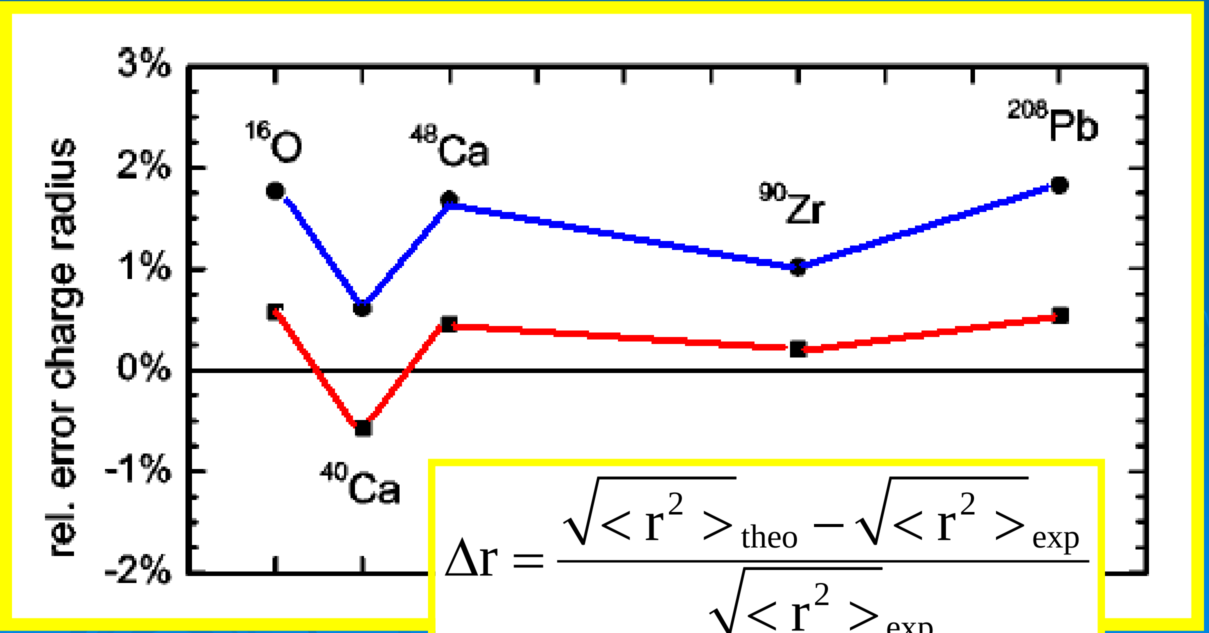
DDRH Results:

B(A) and Charge Radii



$$\Delta B = \frac{B_{theo} - B_{exp}}{B_{exp}}$$

“Hartree” Vertices



$$\Delta r = \frac{\sqrt{<r^2>}_{theo} - \sqrt{<r^2>}_{exp}}{\sqrt{<r^2>}_{exp}}$$

SU(3) coupling of Isospin (T) and Flavour Channels

	$T=0$	$T=\frac{1}{2}$	$T=1$	$T=\frac{3}{2}$	$T=2$
$S=0$	NN		NN		
$S=-1$		$\Lambda N,\ \Sigma N$		ΣN	
$S=-2$	$\Lambda\Lambda,\ \Xi N,\ \Sigma\Sigma$		$\Xi N,\ \Sigma\Lambda,\ \Sigma\Sigma$		$\Sigma\Sigma$
$S=-3$		$\Xi\Lambda,\ \Xi\Sigma$		$\Xi\Sigma$	
$S=-4$	$\Xi\Xi$		$\Xi\Xi$		

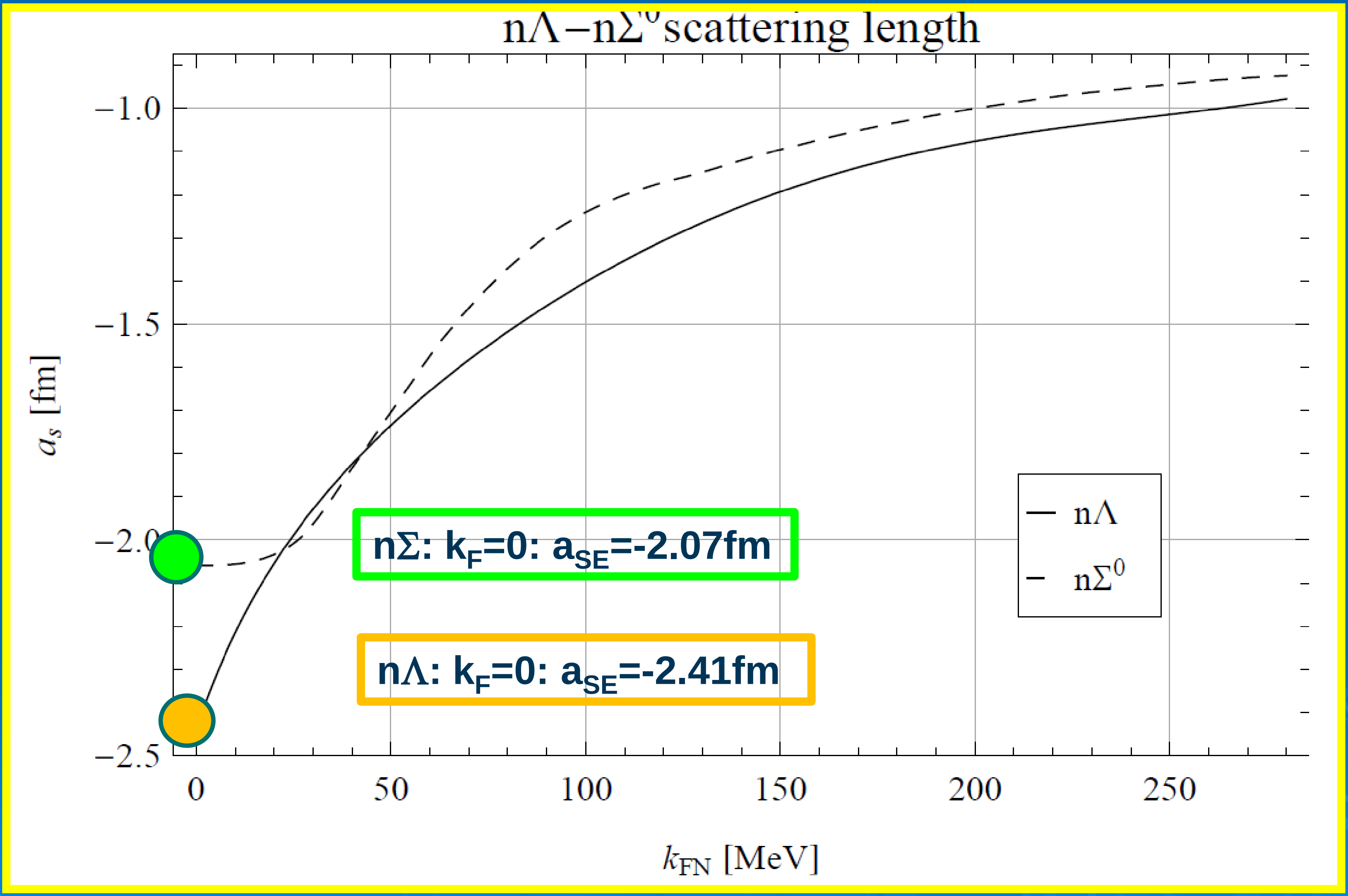
$$Q=+2:\quad \mathrm{p}\Sigma^{+}$$

$$Q=+1:\quad p\Lambda \leftrightarrow p\Sigma^{0} \leftrightarrow n\Sigma^{+}$$

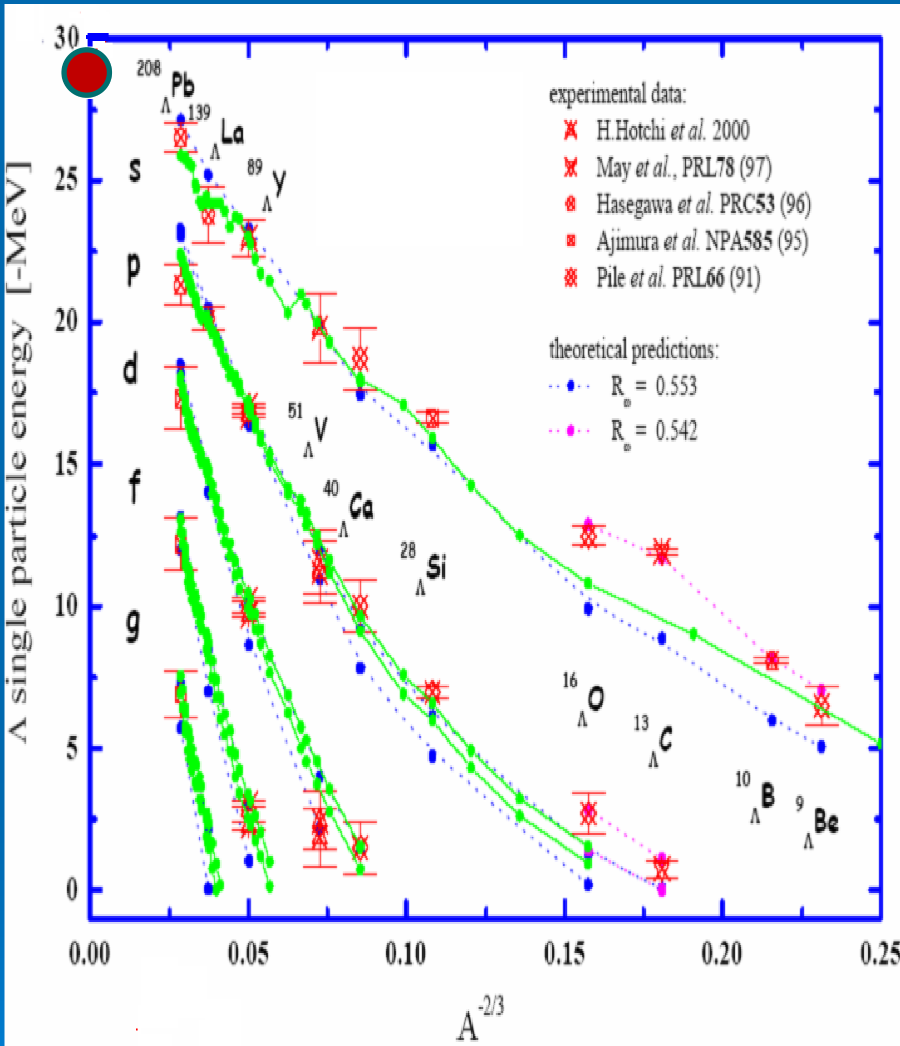
$$Q=\ \ 0:\quad n\Lambda \leftrightarrow n\Sigma^{0} \leftrightarrow p\Sigma^{-}$$

$$Q=-1:\quad \mathrm{n}\Sigma^{-}$$

In-Medium Scattering Lengths (S=-1 Q=0):

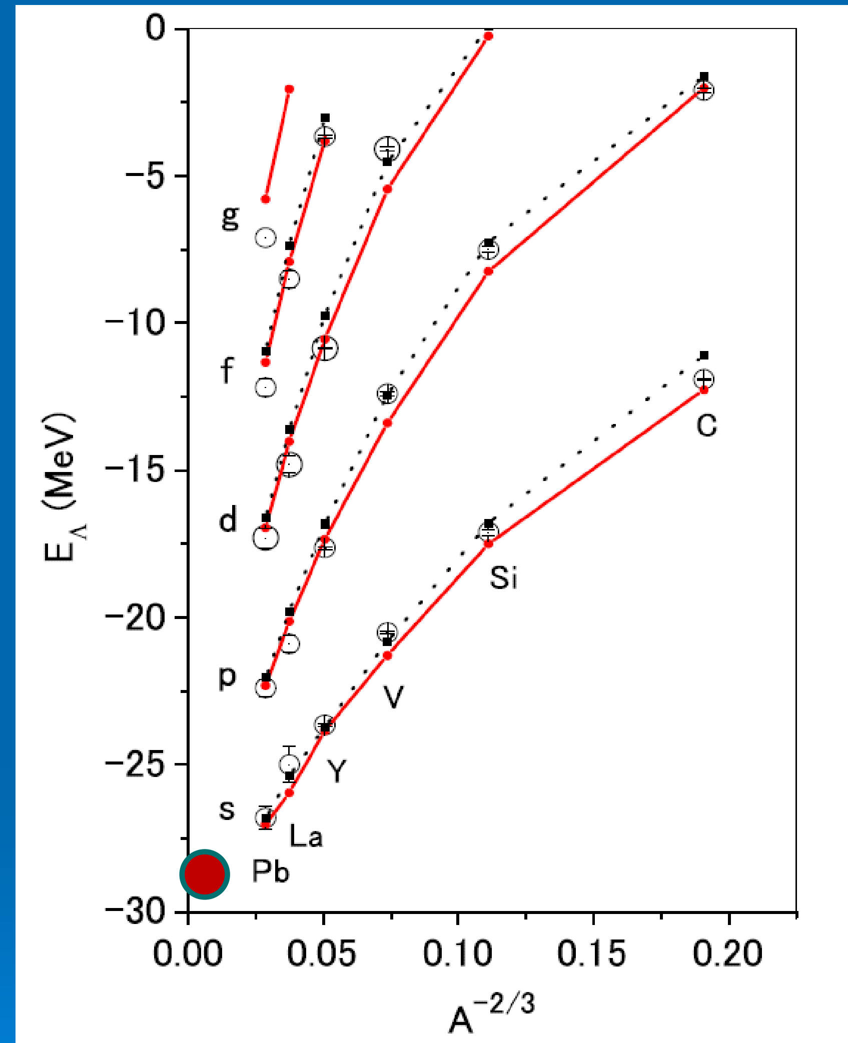


Giessen DBHF



Relativistic DFT
DDRH Vertex Functionals

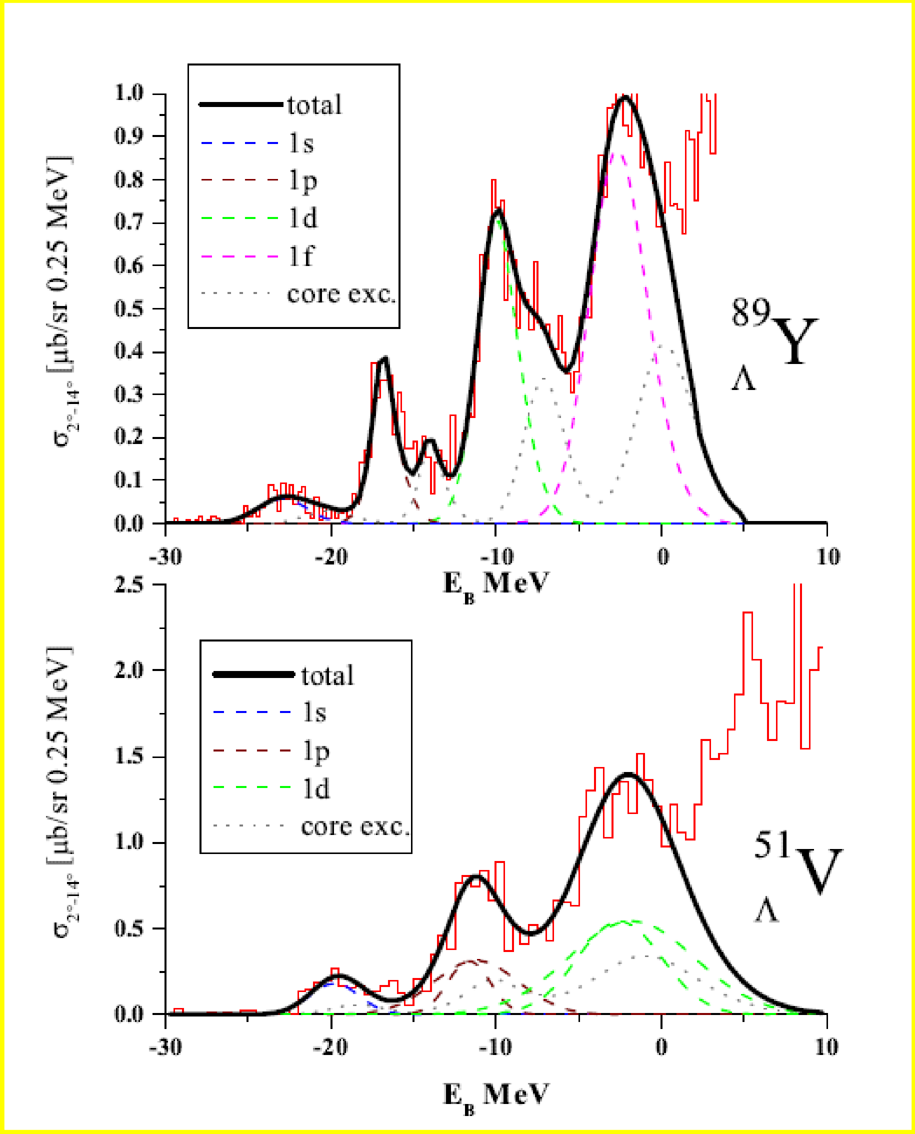
ESC08+MPP



G-matrix Folding Approach
YNN by Multi-Pomeron Forces
+TBA

Application to (π^+,K^+) KEK-Data
(Exp: Hotchi et al.)

	${}^{89}_{\Lambda}$Y
$1s_{1/2}$	-22.94 ± 0.64 MeV
$1p_{3/2}$	-17.02 ± 0.07 MeV
$1p_{1/2}$	-16.68 ± 0.07 MeV
$1d_{5/2}$	-10.26 ± 0.07 MeV
$1d_{3/2}$	-9.71 ± 0.07 MeV
$1f_{7/2}$	-3.04 ± 0.11 MeV
$1f_{5/2}$	-2.26 ± 0.11 MeV

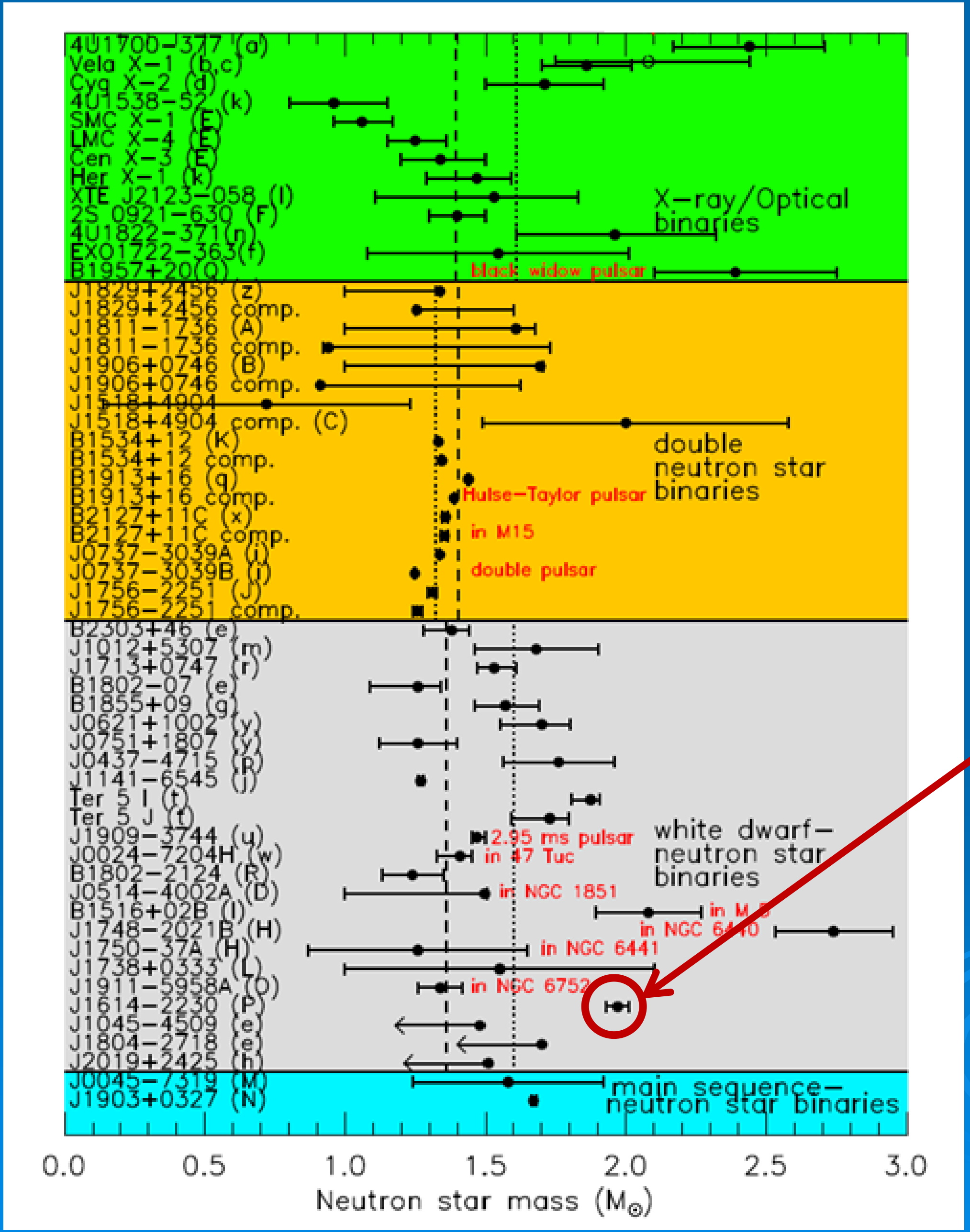


	${}^{51}_{\Lambda}$V
$1s_{1/2}$	-19.8 ± 1.4 MeV
$1p_{3/2}$	-11.8 ± 1.3 MeV
$1p_{1/2}$	-11.4 ± 1.3 MeV
$1d_{5/2}$	-2.7 ± 1.2 MeV
$1d_{3/2}$	-1.9 ± 1.2 MeV

C. Keil, HL (2007); S. Bender, R. Shyam, HL, Nucl.Phys.A839:51-69,2010

Neutron Star Matter in β-Equilibrium

Observed Neutron Star Mass Distribution



J1614-2230

$M = 1.97 \pm 0.04 M_{\odot}$

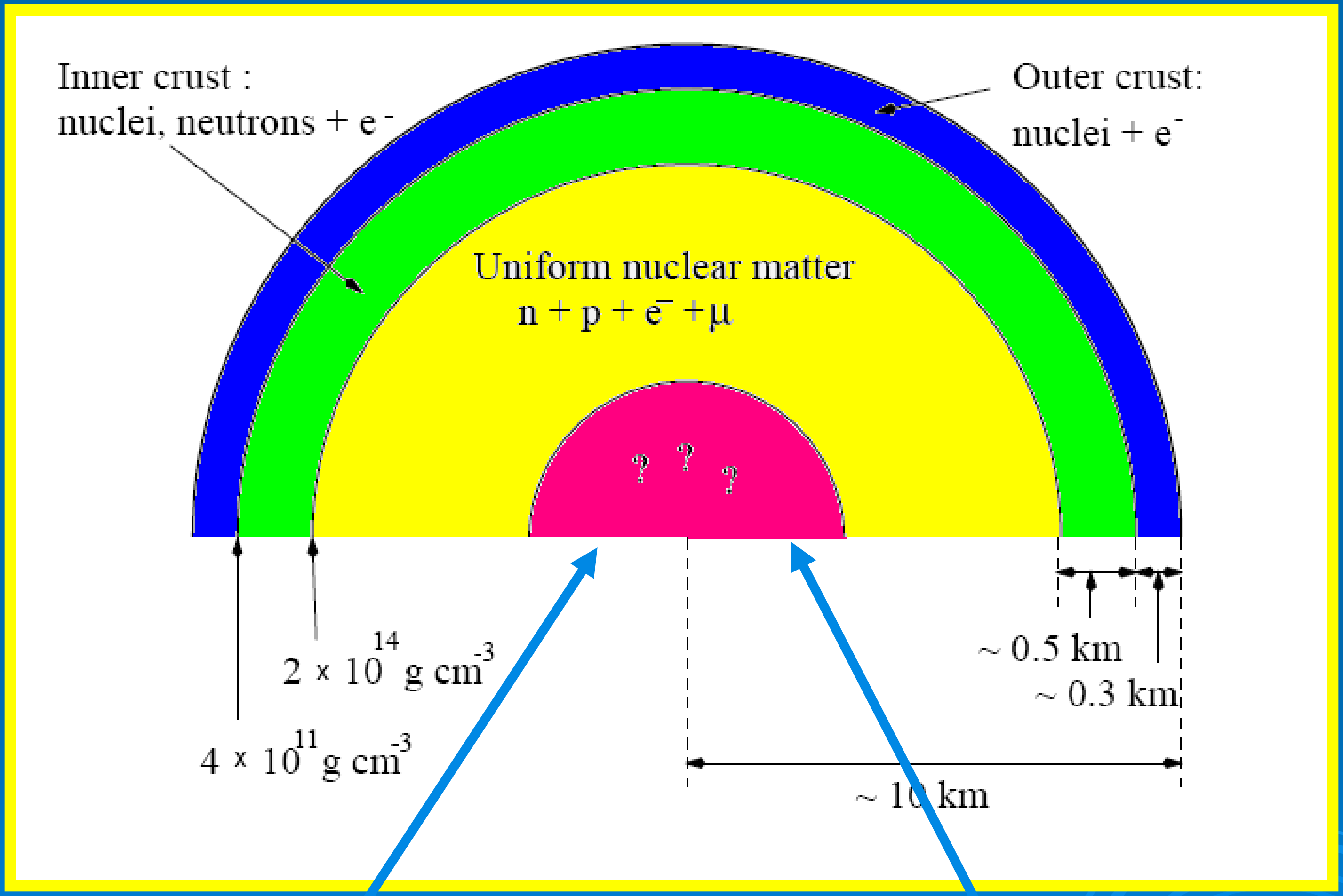
J0348+0432

$M = 2.01 \pm 0.04 M_{\odot}$

J. Lattimer
Annu. Rev. Nucl. Part. Sci. 62, 485 (2012)

Structure of a Neutron Star

(Neutron stars were predicted alreday in 1934 by Walter Baade and Fritz Zwicky)



Baryonic Matter: Λ, Σ, Ξ, Δ,...
Condensates : π, K ....

Quark Matter, QGP, CFL...?

Conditions for β-Equilibrium

$$\boxed{\mu_b = q_b\mu_n - q_e\mu_e}$$

n-p-e-μ Matter:

$$n + \nu_e \leftrightarrow p + e^-$$

$$\boxed{\mu_p = \mu_n - \mu_e}$$

$$e^- \leftrightarrow \mu^- + \nu_e + \bar{\nu}_\mu$$

$$\mu_\mu = \mu_e$$

n-p-Y-e-μ Matter:

$$N + N \to N + \Lambda + K$$

$$\boxed{\mu_\Lambda = \mu_n}$$

$$K^0 \to 2\gamma$$

$$K^- \to \mu^- + \bar{\nu}_\mu$$

$$\mu^- + K^+ \to \mu^- + \mu^+ + \nu_\mu \to 2\gamma + \nu$$

$$\rho_B = \rho_n + \rho_p + \sum_Y \rho_Y \;;\; \rho_\ell = \rho_e + \rho_\mu$$

$$\rho = \rho_B + \rho_\ell$$

$$\mu_B = \varepsilon_B(k_{fB})$$

$$\sqrt{k_{fe}^2 + m_e^2} = \mu_e \,, \; \sqrt{k_{f\mu}^2 + m_\mu^2} = \mu_\mu = \mu_e$$

Baryon chemical potential at T=0
Self-Consistency Problem!

Chemical Potential (T=0):

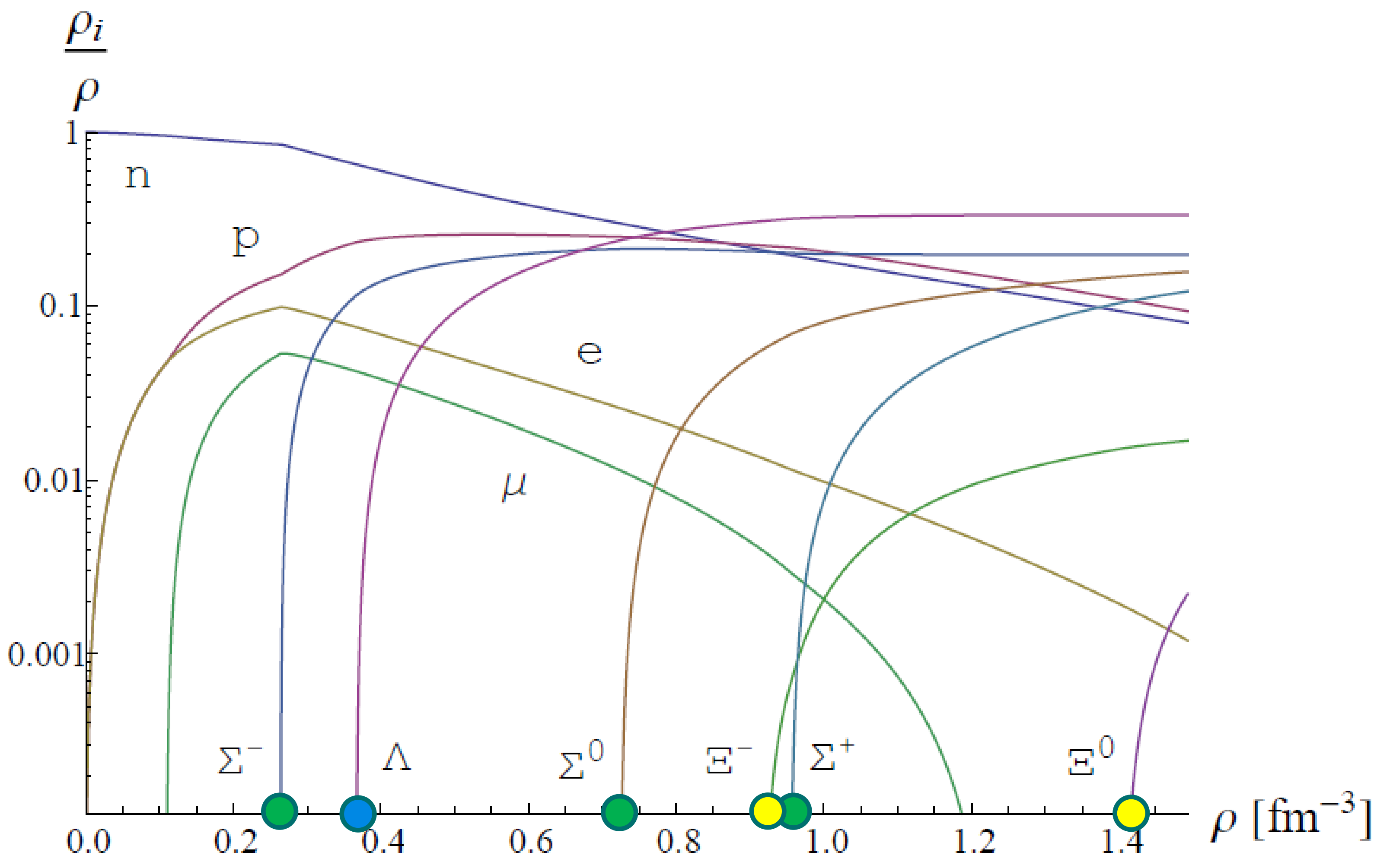
$$\mu_B = g_{\omega B} V_\omega(\rho_b) + g_{\phi B} V_\phi(\rho_b) + g_{\rho B} V_\rho(\rho_b) + \sqrt{k_{Fb}^2 + M_B^{*2}(\rho_s)} \geq M_Y^*$$

Fermi Momentum:

$$k_{FB}^2 = \left(\mu_B - g_{\omega B} V_\omega(\rho_b) - \ldots\right)^2 - M_B^{*2}(\rho_s) \sim 2\mathrm{M}_B \left(\varepsilon_B(k_{FB}) - U_B(\rho_b)\right) \geq 0$$

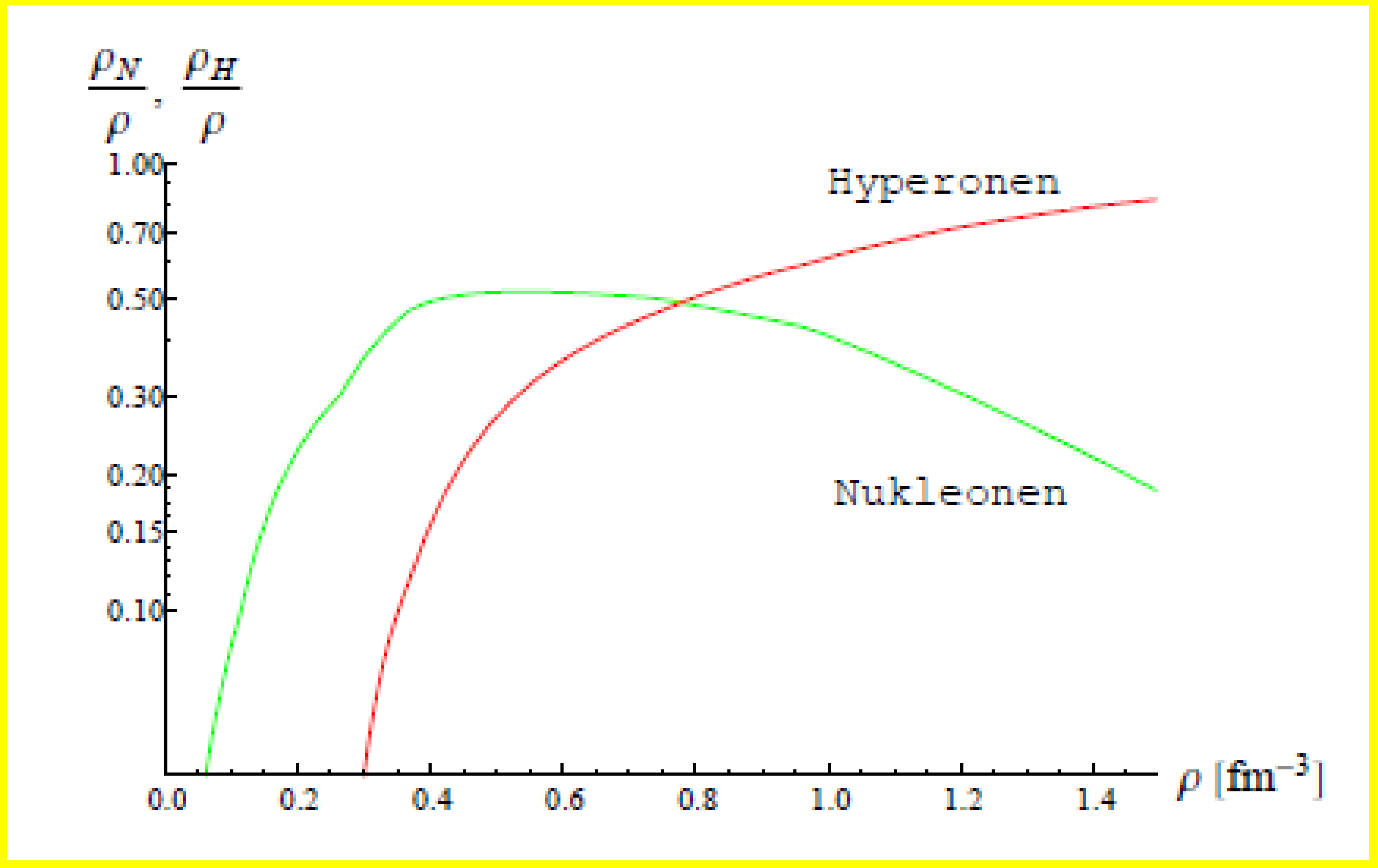
- **Baryon octet: n, p, Λ, Σ, Ξ**
- **Nucleon resonances (which?): Δ_{33}(1232),N*(1440),D_{13}(1520)…**
- **Leptons: e, μ, ν**
- **Three vector (mean-) fields: $V_{\omega,\rho,\phi}$**
- **Three scalar (mean-) fields: $\Phi_{\sigma,\delta,\sigma_s}$**

Baryon fractions as a function of density



J. Wilhelm, H.L.

Composition of Neutron Star Matter: Nucleon and hyperon fractions

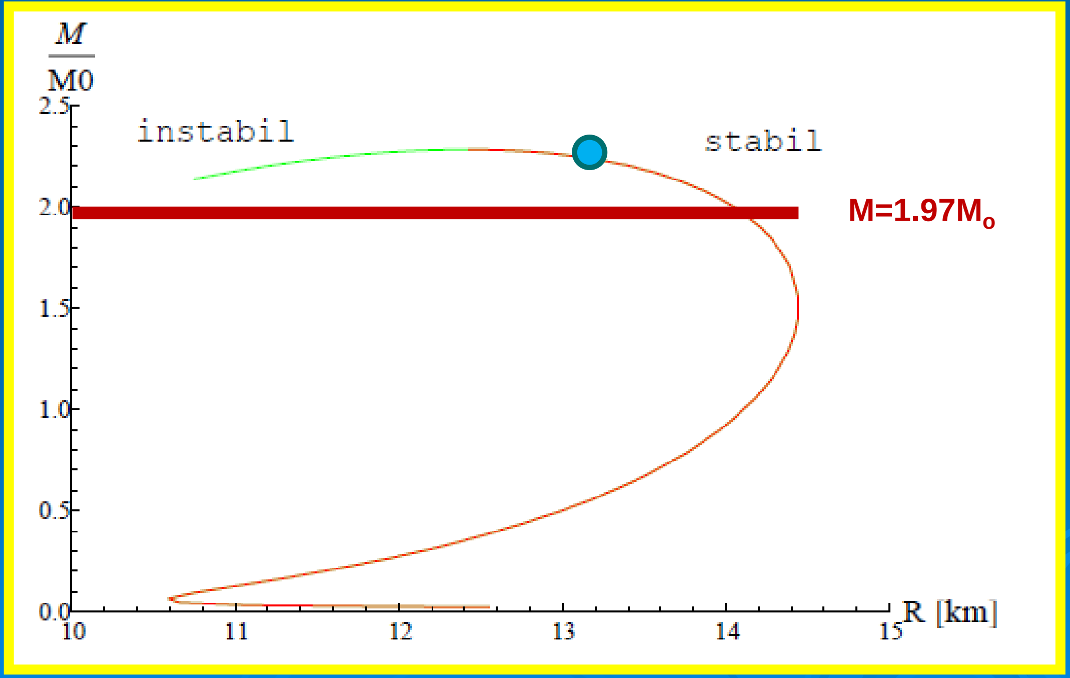


The „EoS“ of a Neutron Star: Mass-Radius Relation from the TOV-equations

$$\frac{dp}{dr} = -\frac{G(\varepsilon + p)(m + 4\pi r^3 p/c^2)}{r(rc^2 - 2Gm)},$$

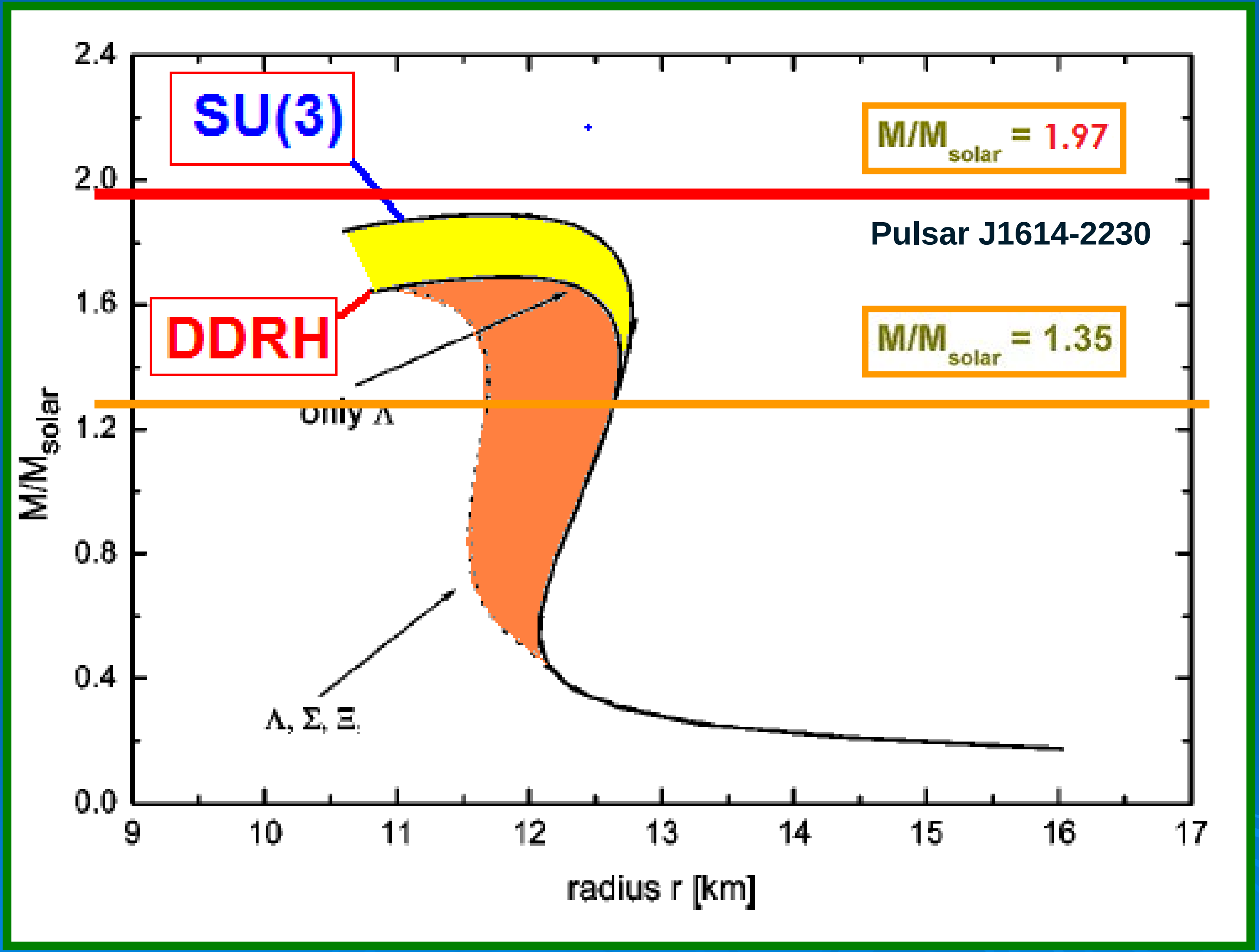
$$\frac{dm}{dr} = 4\pi r^2 \varepsilon / c^2,$$

$$\frac{d\mathcal{N}}{dr} = 4\pi r^2 n \left(1 - \frac{2Gm}{rc^2}\right)^{-1/2},$$



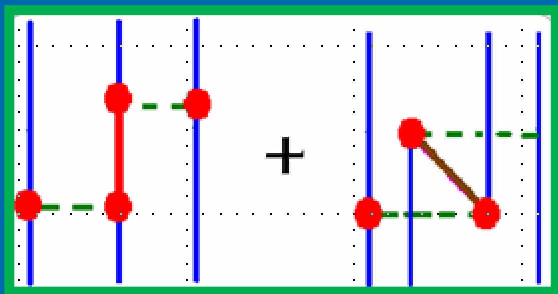
pure n-p matter

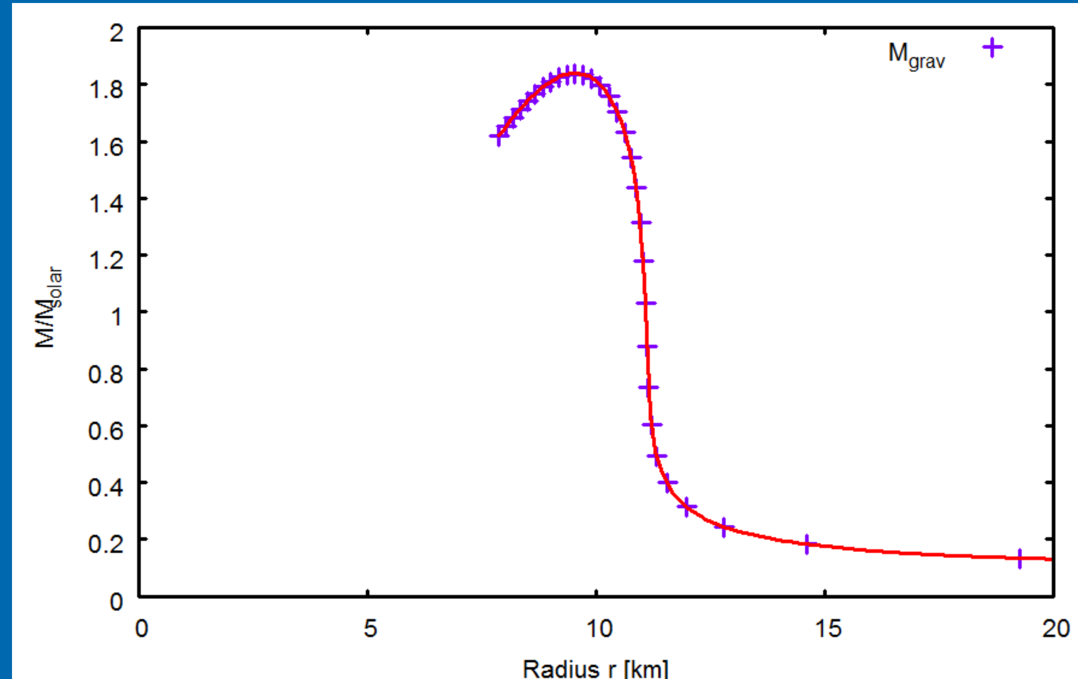
DBHF/DDRH Interactions in a Neutron Star



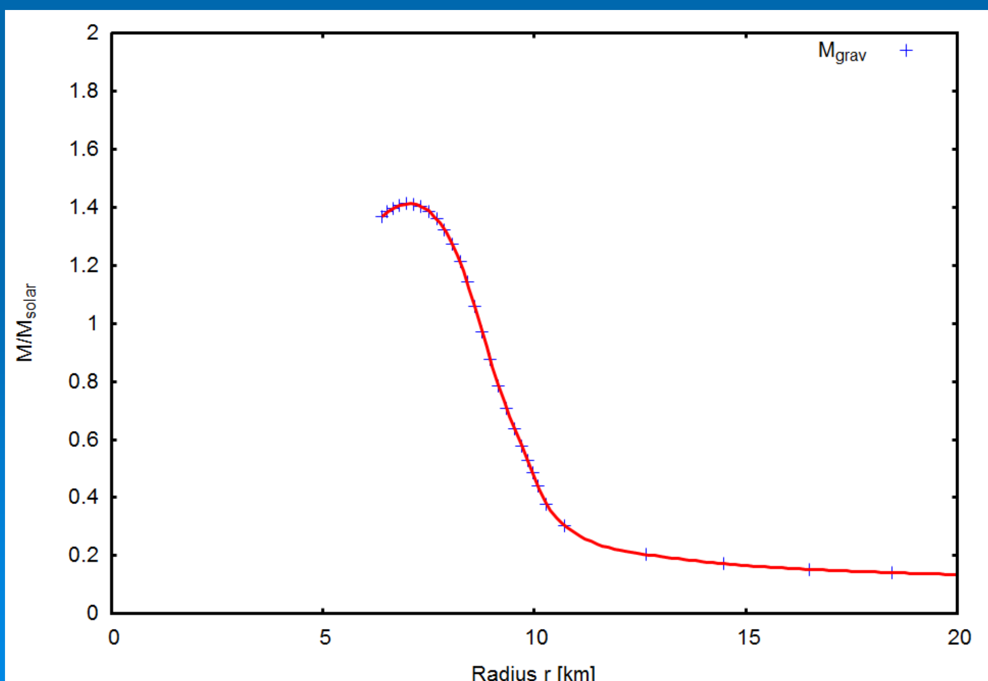
→ „Hyperonization Puzzle“

Hypermatter with 3-body interactions





Urbana V18+3-body
npeμ-matter
(non-relativistic)



Urbana V18+3-body
npYeμ-matter
(non-relativistic)

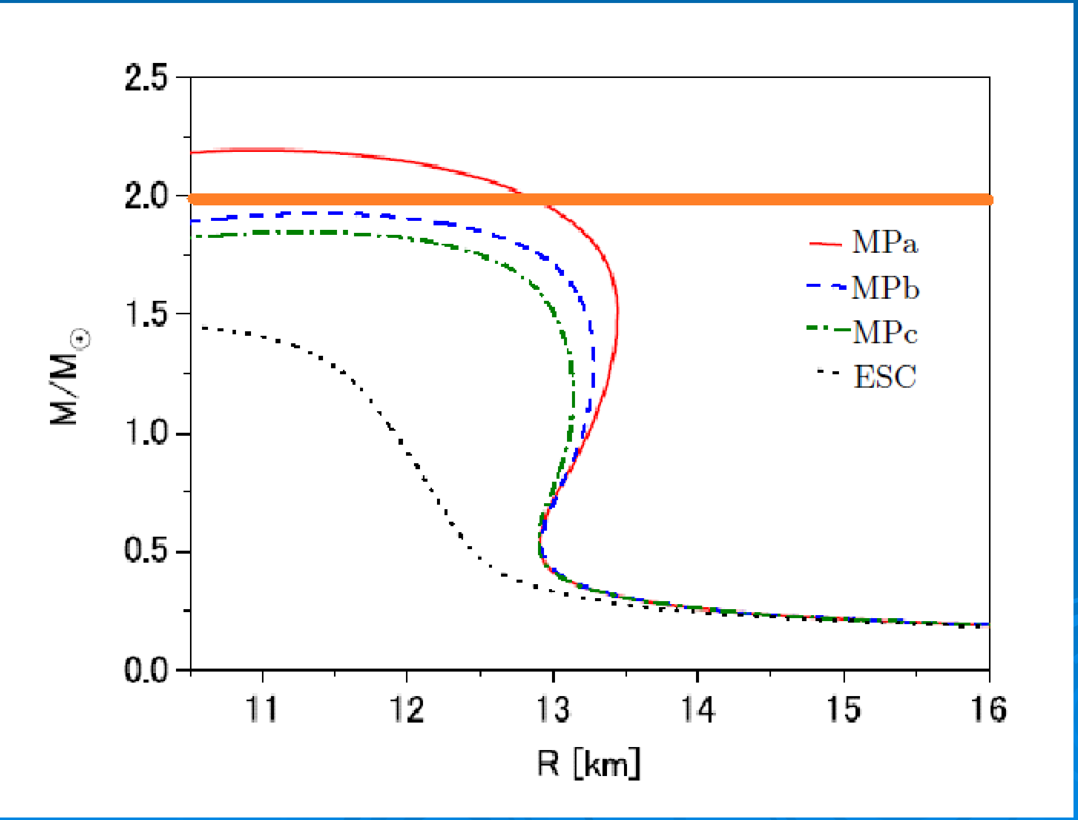
EoS from
Arnett and Bowers (1977) APJS 33, 415

Nijmegen ESC08
TBA and TBR YNN&YNNN from MultiPomeron (MP)

$$V^{(3)}_{eff}(r) = g^{(3)}_P (g_P)^3 \frac{\rho}{\mathcal{M}^5} F(r) \ ,$$

$$V^{(4)}_{eff}(r) = g^{(4)}_P (g_P)^4 \frac{\rho^2}{\mathcal{M}^8} F(r) \ ,$$

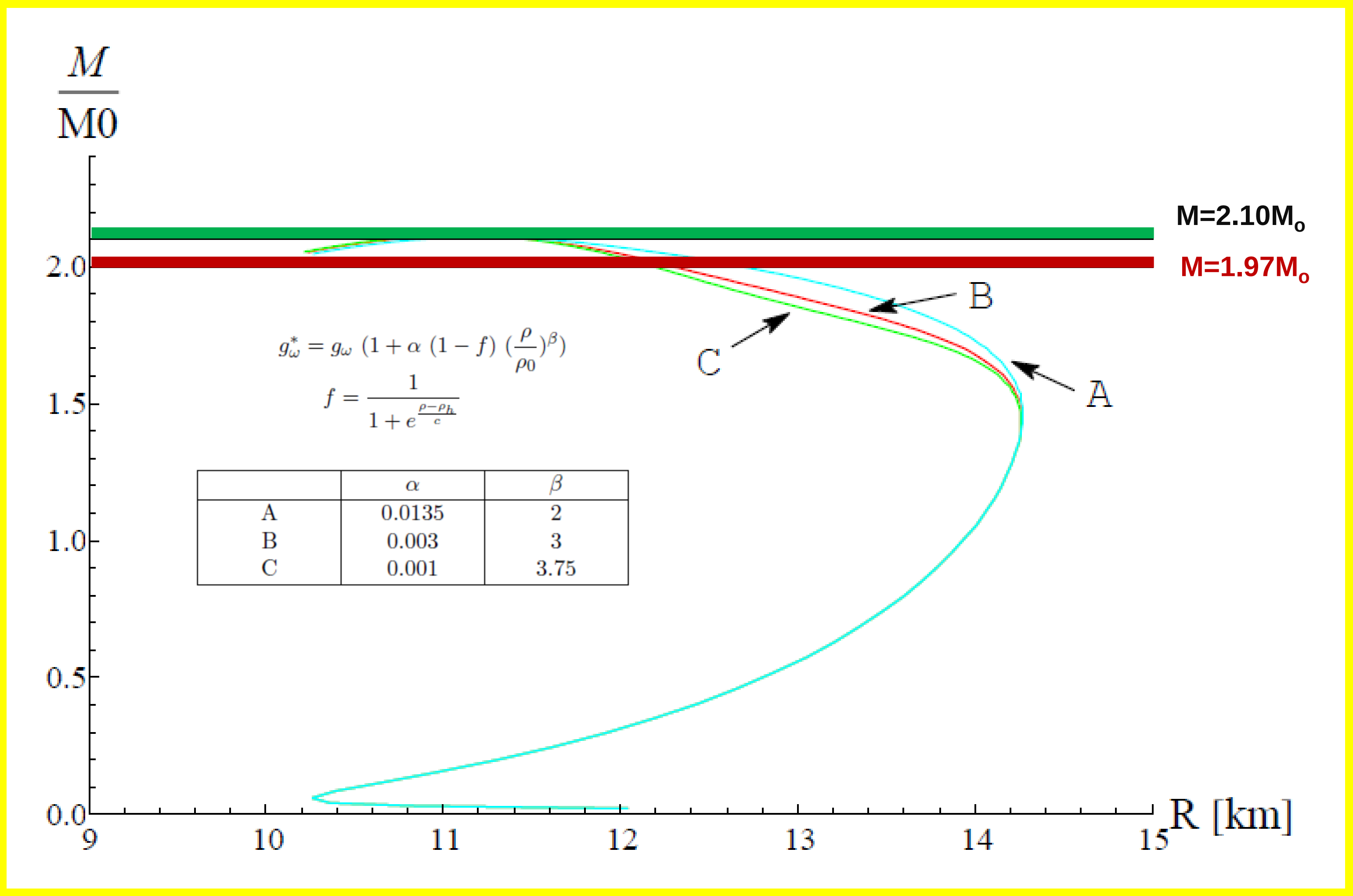
$$F(r) = \frac{1}{4\pi} \frac{4}{\sqrt{\pi}} \left(\frac{m_P}{\sqrt{2}}\right)^3 \exp\left(-\frac{1}{2} m_P^2 r^2\right)$$



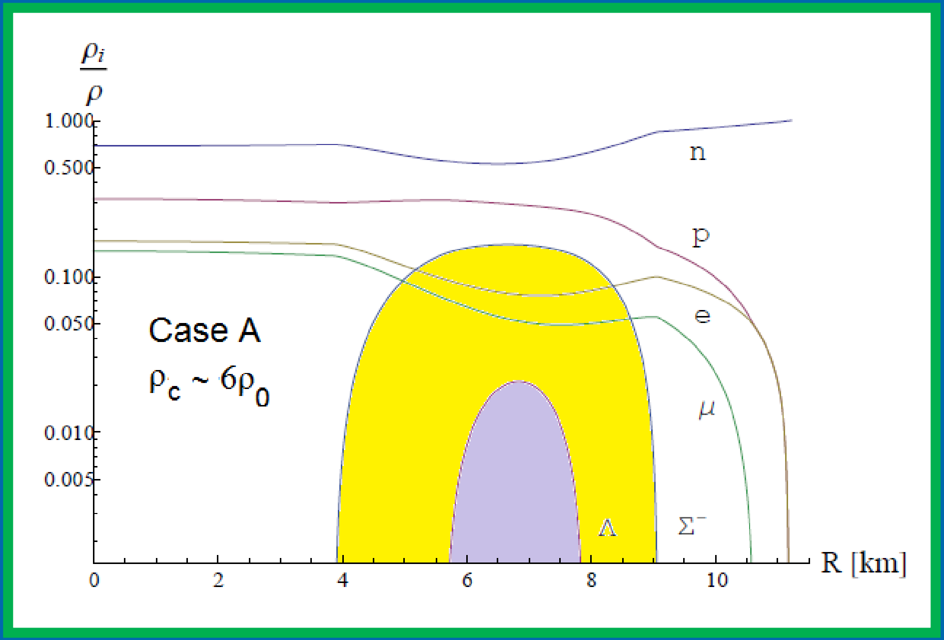
- Y. Yamamoto, T. Furumoto, N. Yasutake, Th.A. Rijken; arxiv:1406.4332

In-Medium Vector Repulsion and the „Hyperon Puzzle“

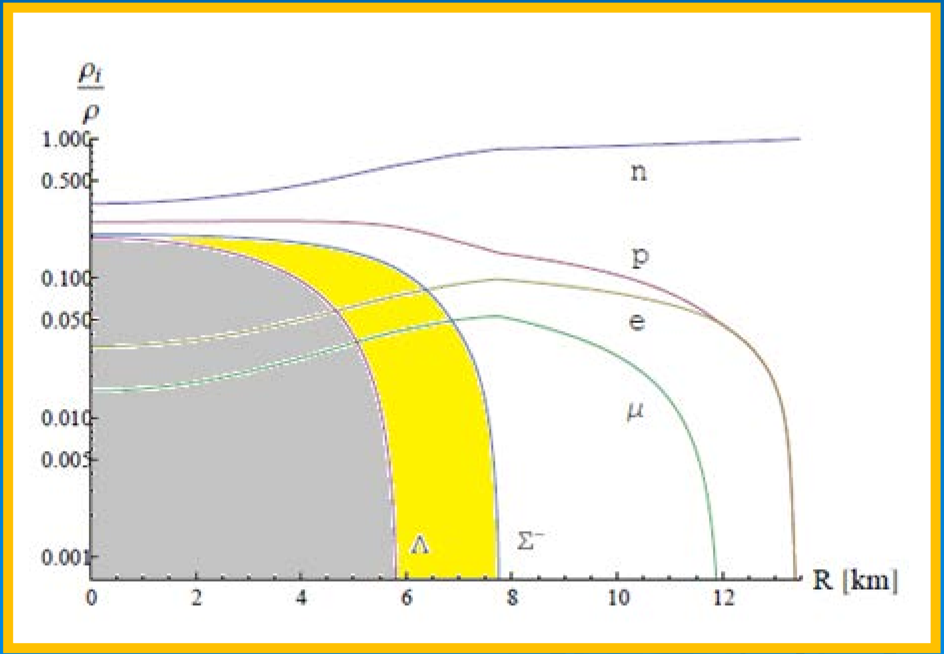
Mass-Radius Relation for a Neutron Star with Hyperon Vector Repulsion



$$g^*_\omega = g_\omega\ (1+\alpha\ (1-f)\ (\frac{\rho}{\rho_0})^\beta)\ ;\ f = \frac{1}{1+e^{\frac{\rho-\rho_h}{c}}}$$



Vector-Repulsion scenario: Hyperon shell in a neutron star

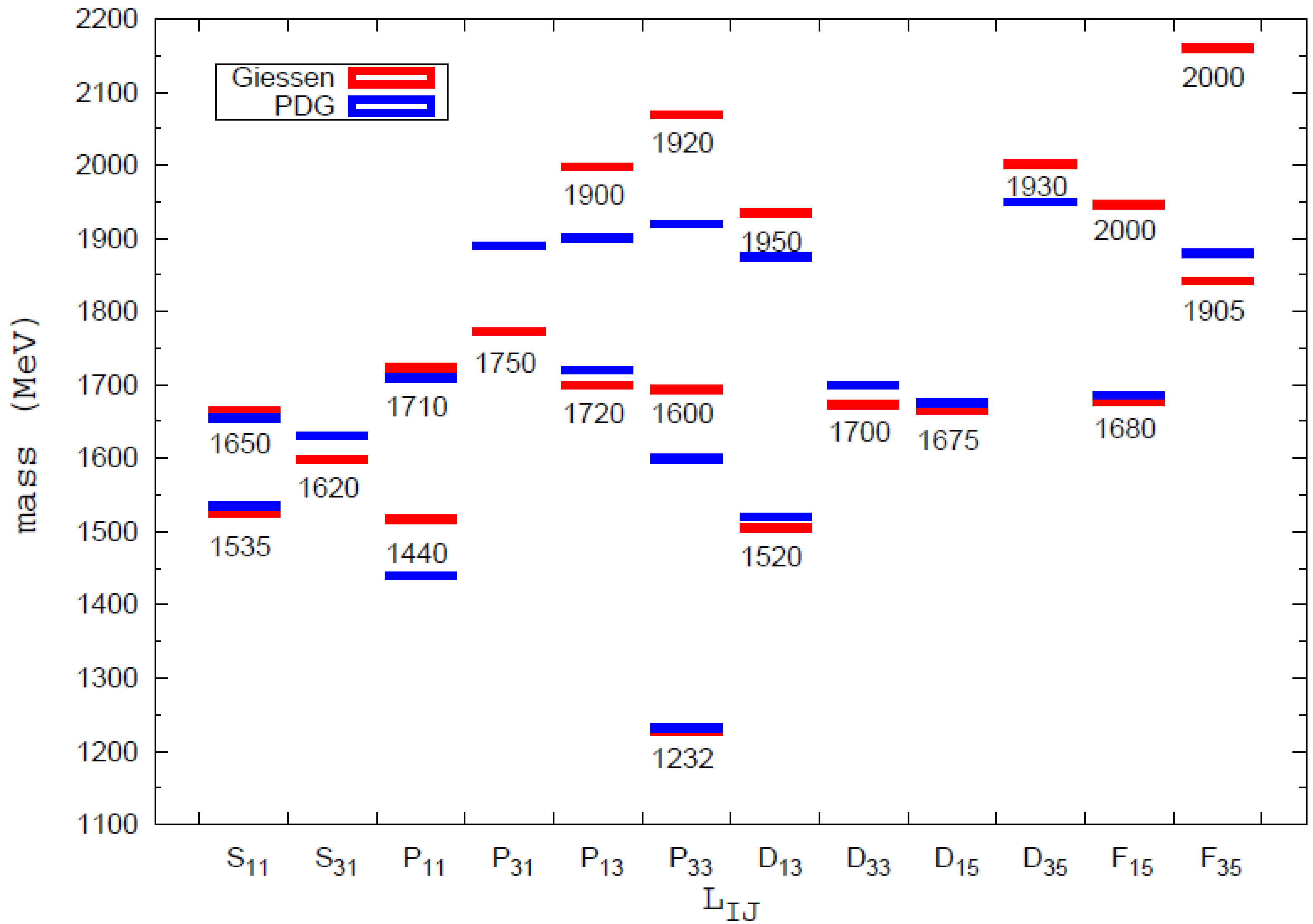


Standard Scenario: Hyperon core in a neutron star

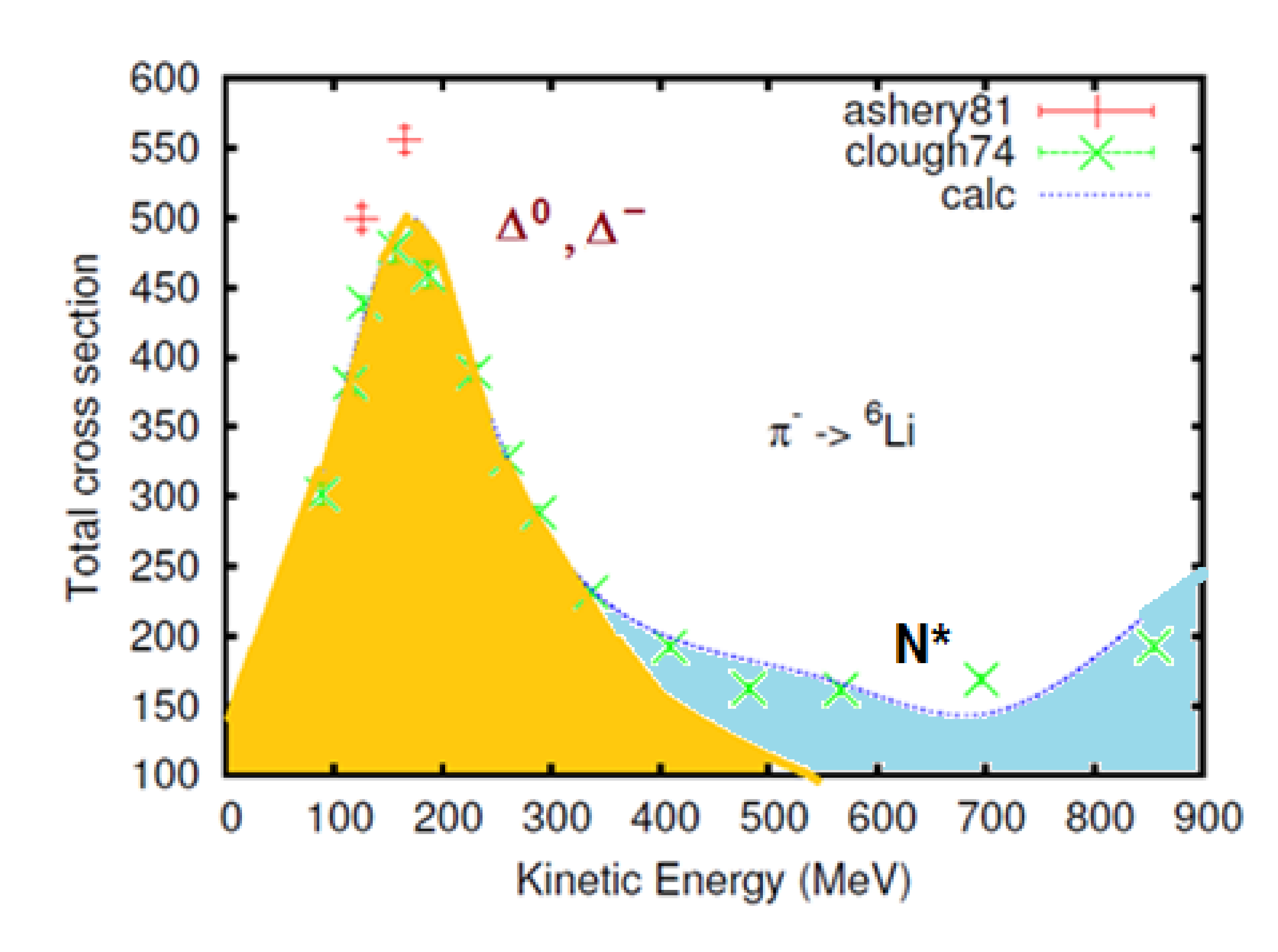
Resonances in Nuclei and Neutron Stars

Level Scheme: GiM coupled channel analysis and PDG

(Xu Cao, V.Shklyar, H.L., Phys. Rev. C 88, 055204 (2013))



$\Delta_{33}(1232)$ and higher N* resonance in $\pi+^6$Li scattering



S. Lourenco, H.L. S. Wycech

FRS@GSI : N* in asymmetric nuclear matter

$^{112}Sn \rightarrow {}^{112}In(p^{-1}n)$ $^{112}Sn \rightarrow {}^{112}\mathrm{Sb}(n^{-1}\mathrm{p})$

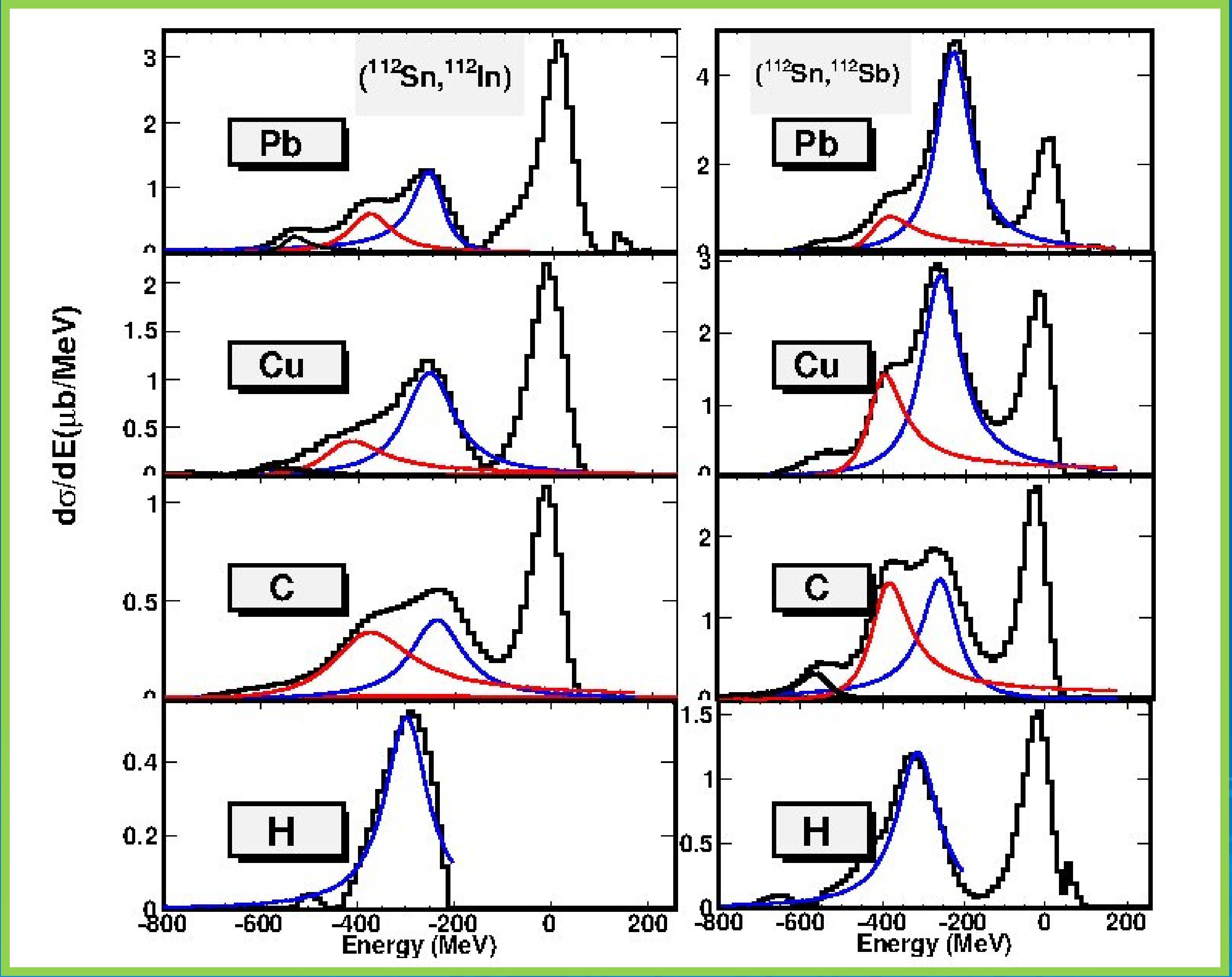
Target:

Bi($n^{-1}N^{*+}$)
Tl($p^{-1}N^{*++}$)

Zn($n^{-1}N^{*+}$)
Ni($p^{-1}N^{*++}$)

N($n^{-1}N^{*+}$)
B($p^{-1}N^{*++}$)

Δ^{++}, N^{*++}



Target:

Tl($p^{-1}N^{*0}$)
Pb($n^{-1}N^{*-}$)

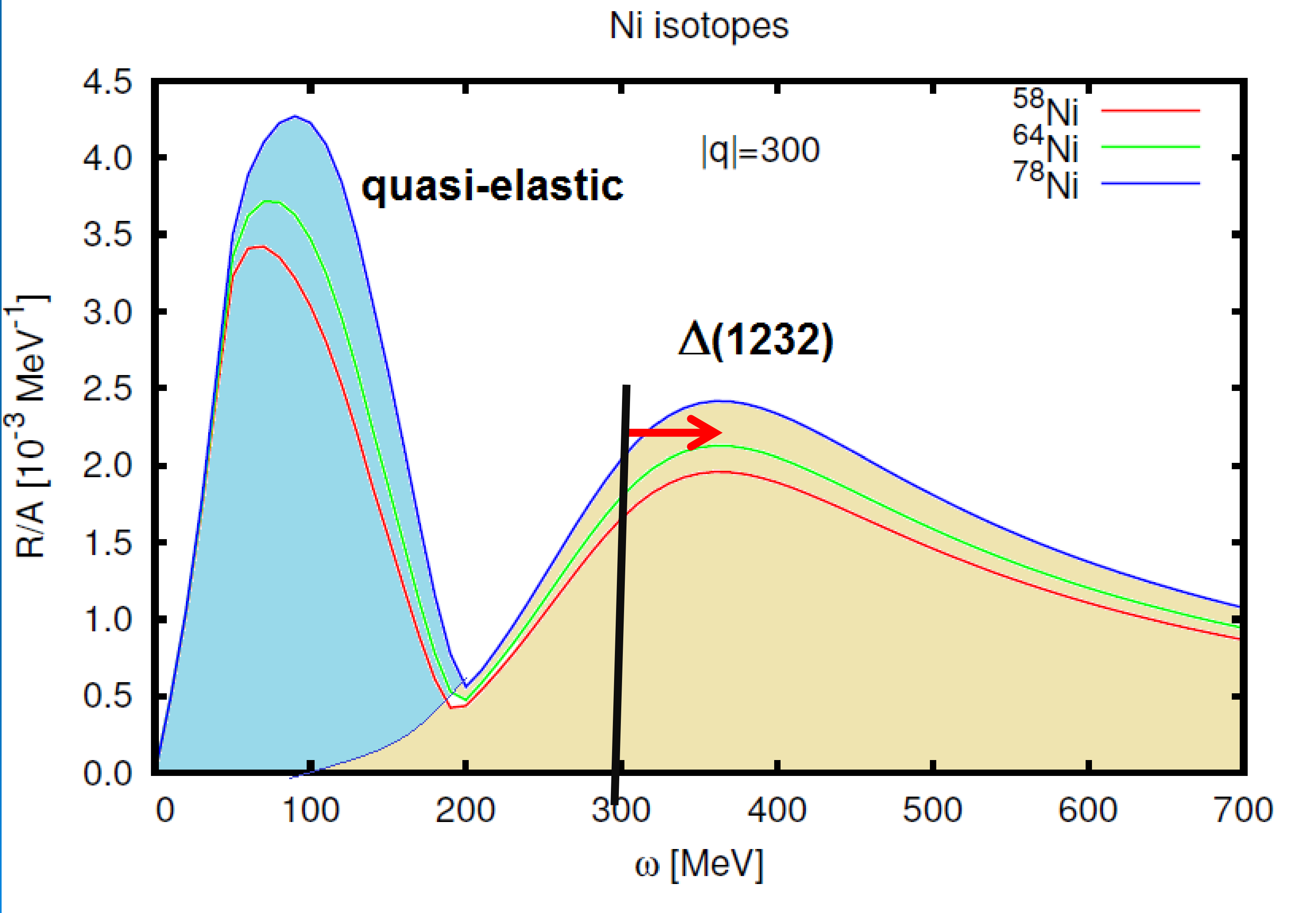
Ni($p^{-1}N^{*0}$)
Cu($n^{-1}N^{*-}$)

B($p^{-1}N^{*0}$)
C($n^{-1}N^{*-}$)

n,Δ^0,N^{*0}

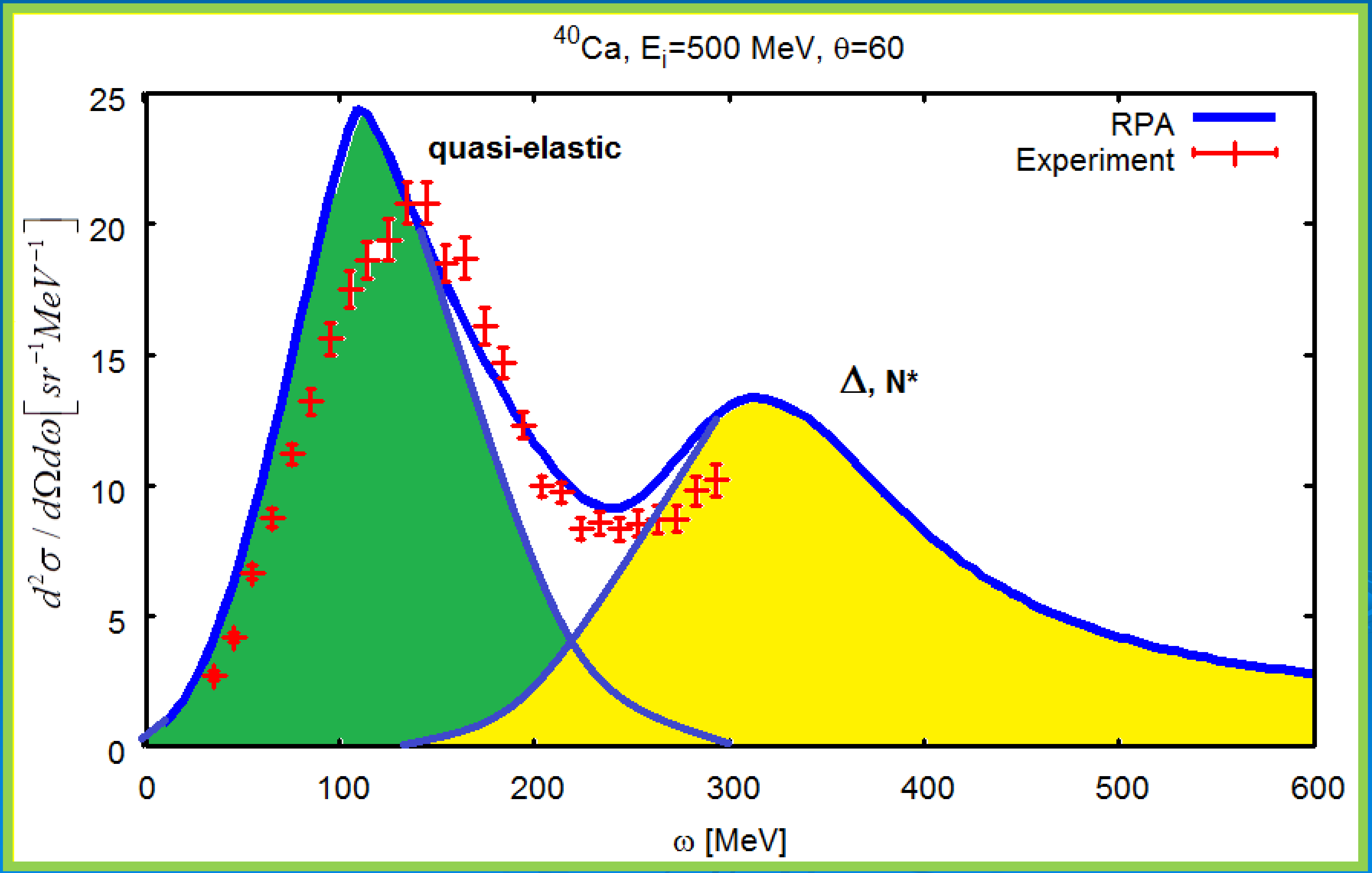
Data and their description: J. Benlliure → Talk on Friday!

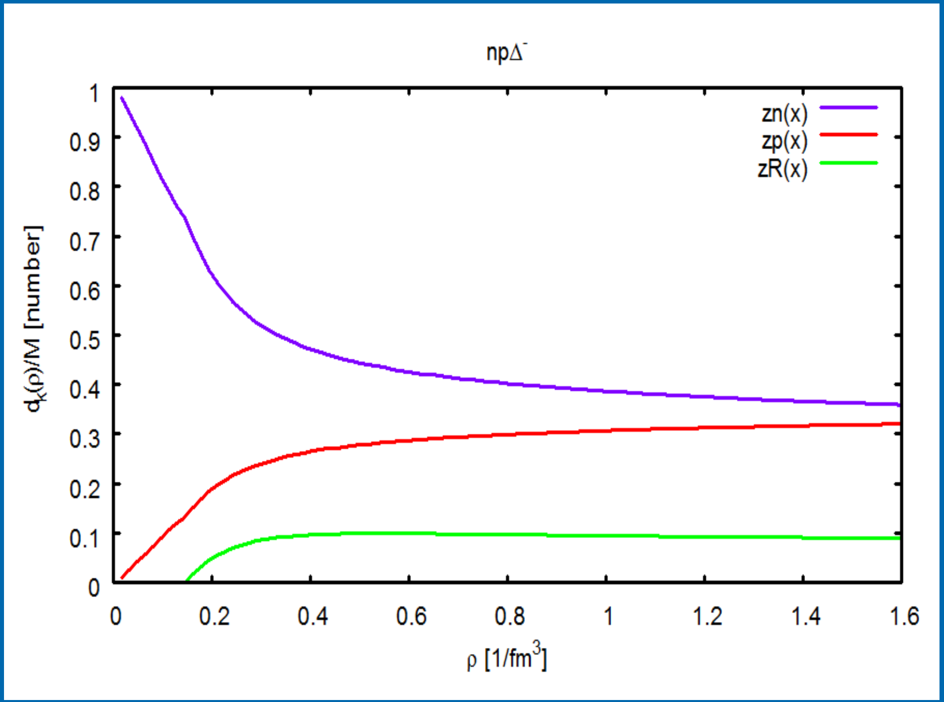
Response Functions (per nucleon!) along the Ni-chain: RPA results for $T_a=\tau_-$ (pn^{-1} & Δn^{-1} transitions)



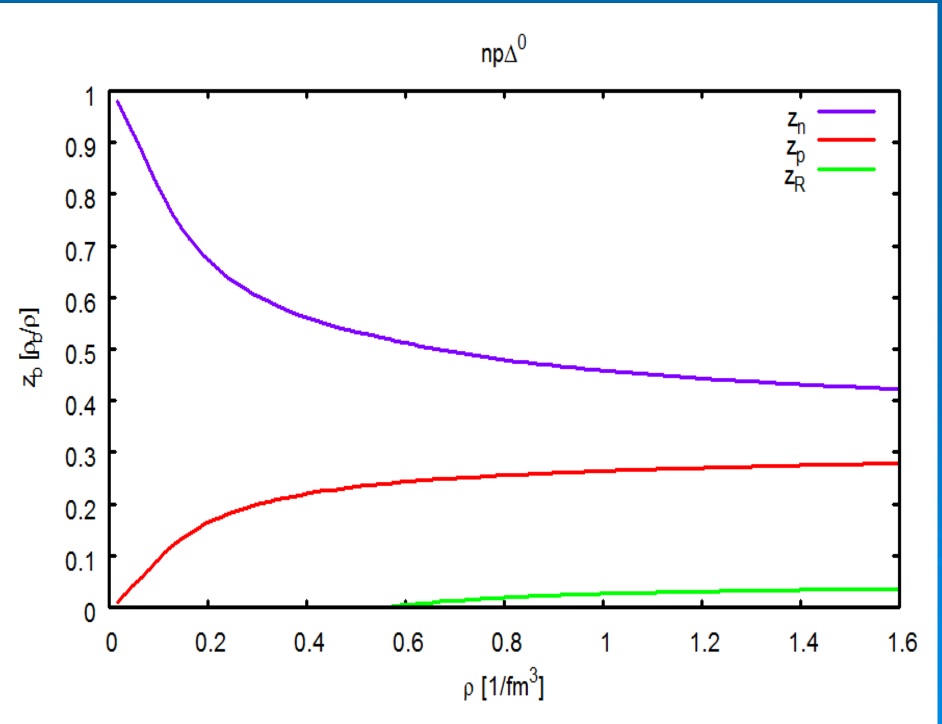
A. Fedoseew, H.L.

A Test Case:
Quasi-free Inclusive (e,e') Scattering



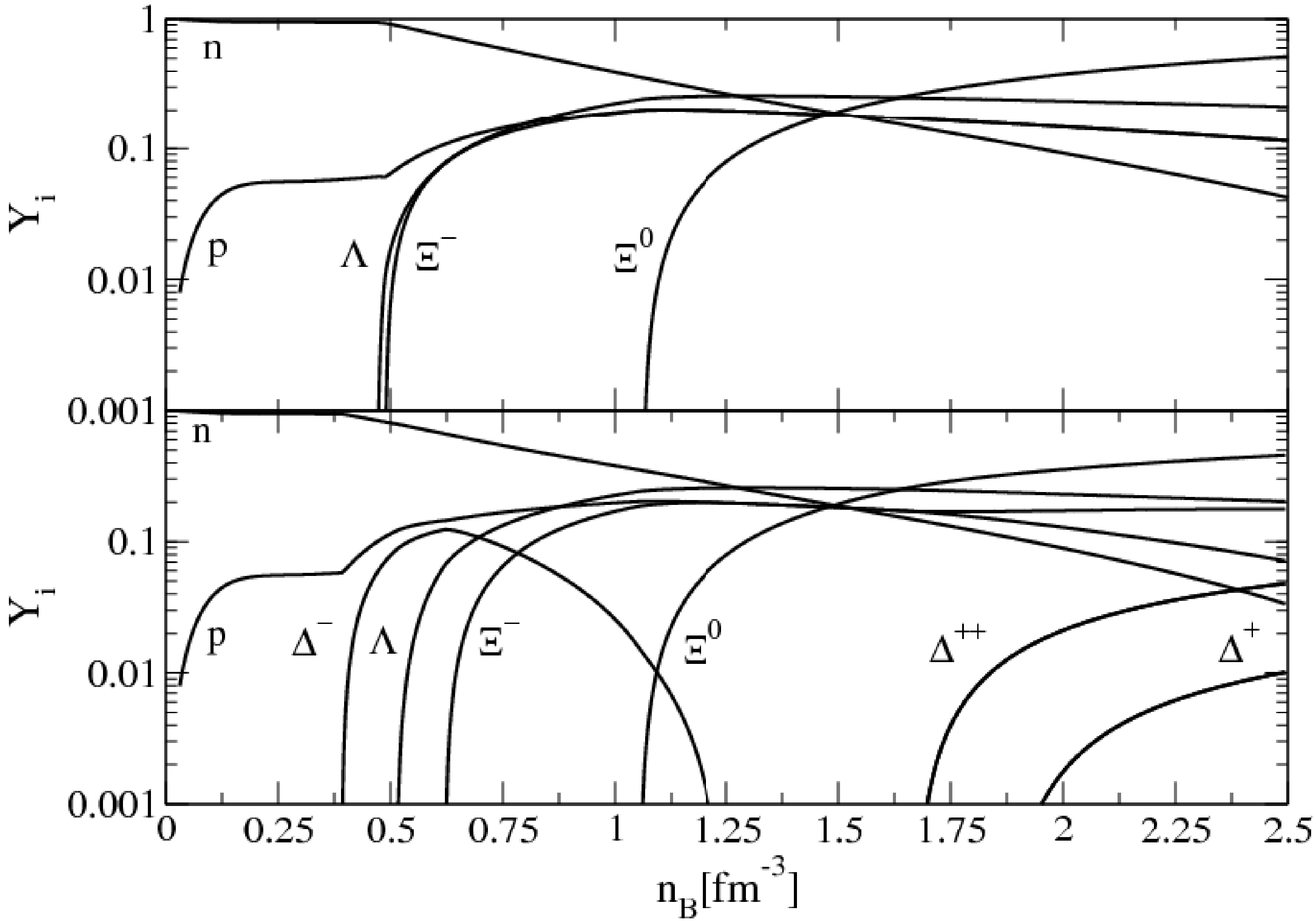


Composition of npeμΔ⁻-matter $\rho_{th}=0.18fm^{-3}$



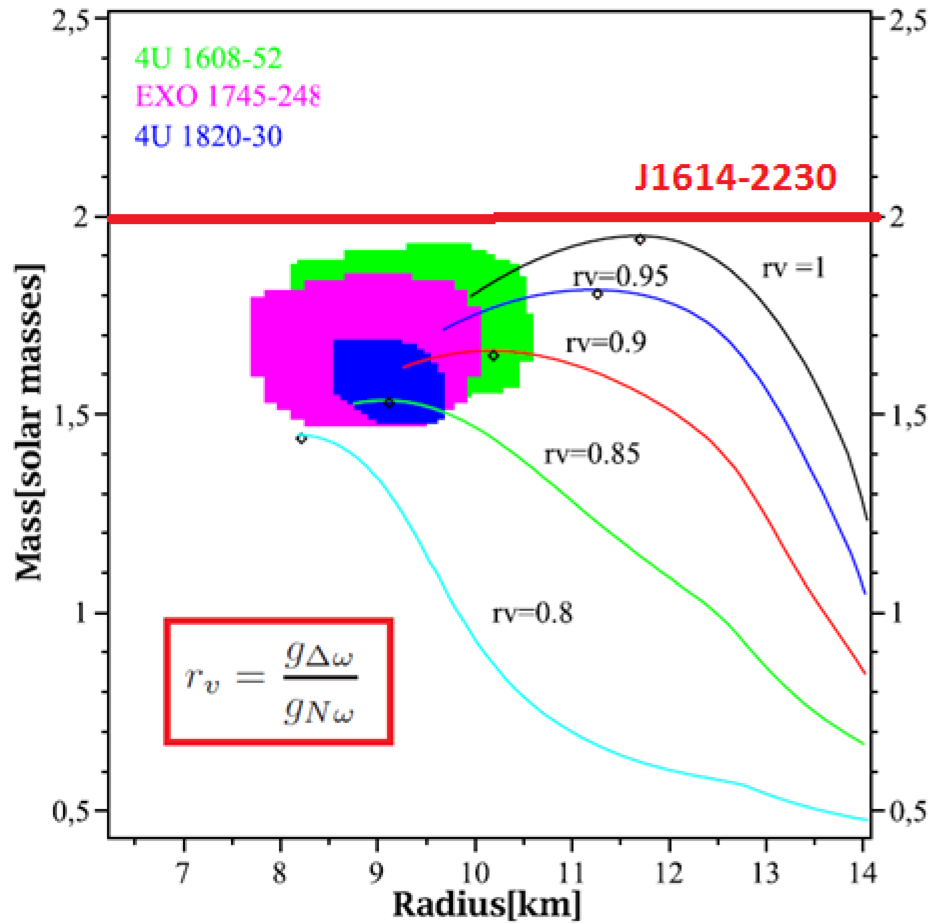
Composition of npeμΔ⁰-matter $\rho_{th}=0.61fm^{-3}$

Populations with and without deltas



c/o Alessandro Drago, Ferrara

Δ's in Neutron Stars



Mass-Radius-relationship of Neutron stars for various couplings of the Δ resonances, starting from $r_v = 1$ (upper line) to 0.8 (lowest line). Also included are the 1-σ errorbars for measured neutron stars . The black diamond on each curve represents the maximum stable configuration

Schürhoff, Schramm,Dexheimer, 2010

Summary and Outlook

- Hyperons and nucleon resonances in nuclei
- Interactions and composition of neutron star matter
- Unsolved: properties of exotic matter, its composition and dynamics
- FRS and Super-FRS: NY and NNY interactions – HypHI Experiment
- FRS and Super-FRS: resonances in asymmetric nuclear matter and NN* interactions – Exp. S363
-

- Credits to
- Madhumita Dhar, Andreas Fedoseew, Theo Gaitanos, and Jonas Wilhelm
- Supported by DFG, BMBF, HIC for FAIR, and GSI

Open Problems for npYR-Matter

- N*N and N*Y 2-body interactions
- N*NY,N*N*Y,N*N*N*…. 3-body interactions
- Resonances in asymmetric nuclear matter
- In-medium properties of interactions at $\rho \sim 2 \ldots 10\rho_0$

Theoretical and experimental information on Delta – meson couplings

$X_\sigma = g_{\sigma\Delta} / g_{\sigma N}$
$X_\omega = g_{\omega\Delta} / g_{\omega N}$

Theoretical analysis:

QCD sum rules $x_\omega << 1$	PRC 51 (1995) 2260
$\Sigma_\Delta = \Sigma_N - 30$ MeV at $0.75\,\rho_0$	NPA 468 (1987) 631

Electron scattering:

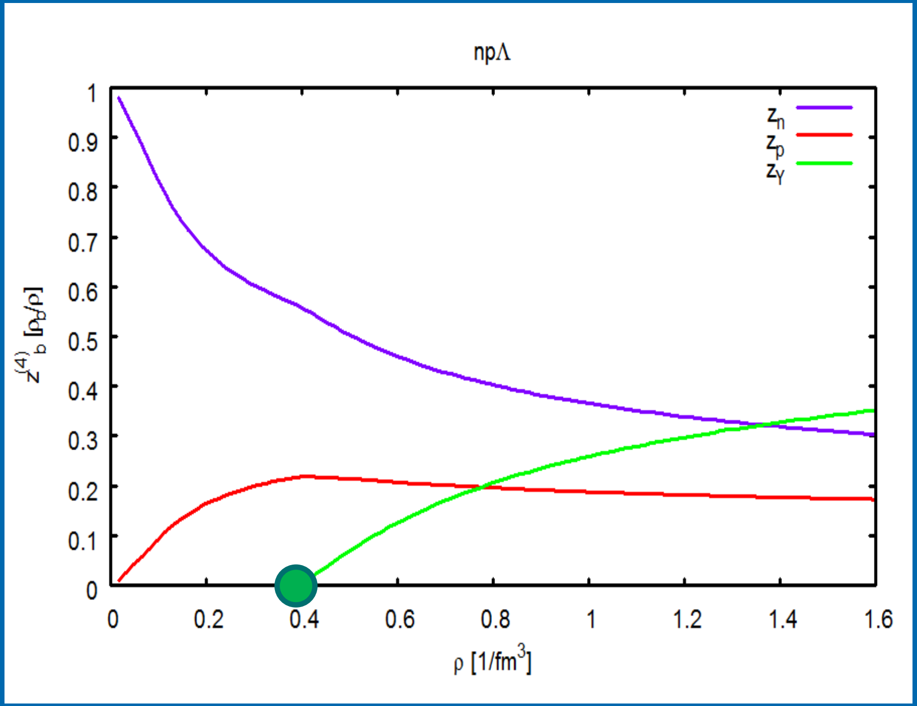
$\Sigma_\Delta = -75\,\rho/\rho_0$ MeV	NPA 435 (1985) 765
$0 < x_\sigma - x_\omega < 0.2$	PRC 42(1990) 2290

Pion scattering:

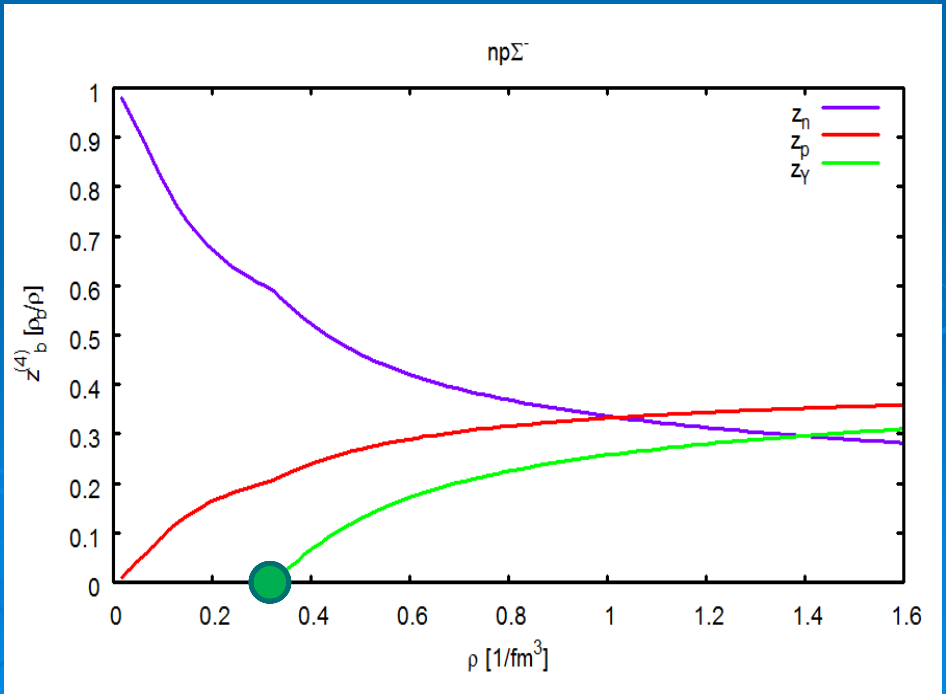
$\Sigma_\Delta = -30$ MeV at $\rho_{surface}$	NPA 345 (1980) 386
$\Sigma_\Delta = \Sigma_N$	PRC 81(2010) 035502

Photo-absorption:

$\Sigma_\Delta = -80$ MeV	PLB 321 (1994) 177



Composition of npeμΛ-matter ρ_{th}=0.4fm^{-3}



Composition of npeμΣ$^-$-matter ρ_{th}=0.33fm^{-3}

β-Equilibrium with Resonances
npYReμ Matter:

$$N + N \to N + N^*$$

$$N^* = \Delta_{33}(1232), P_{11}(1440), \mathrm{D}_{13}(1520), S_{11}(1535)\ldots$$

$$N^* \to \begin{cases} N + \pi & \to N + \{\ell\,\overline{\ell}, \gamma\gamma, \ell\,\overline{\nu}\ldots\} \\ Y + K^{0,+} & \to Y + \{\ell\,\overline{\ell}, \gamma\gamma, \ell\,\overline{\nu}\ldots\} \end{cases}$$

Thermodynamical equilibrium:

$$\mu_R = \mu_n - q_R \mu_e$$

Charge neutrality:

$$\sum_{b=n,p,Y} q_b x_b + \sum_{R=\Delta,N^*(1440)\ldots} q_R x_R = x_\ell$$

Baryon density $\mathrm{x}_b = \dfrac{\rho_b}{\rho}$:

$$x_B = \sum_{b=n,p,Y} x_b + \sum_{R=\Delta,N^*(1440)\ldots} x_R = 1 - x_\ell$$