Hypernuclear Physics as a Probe for In-Medium Flavour Dynamics

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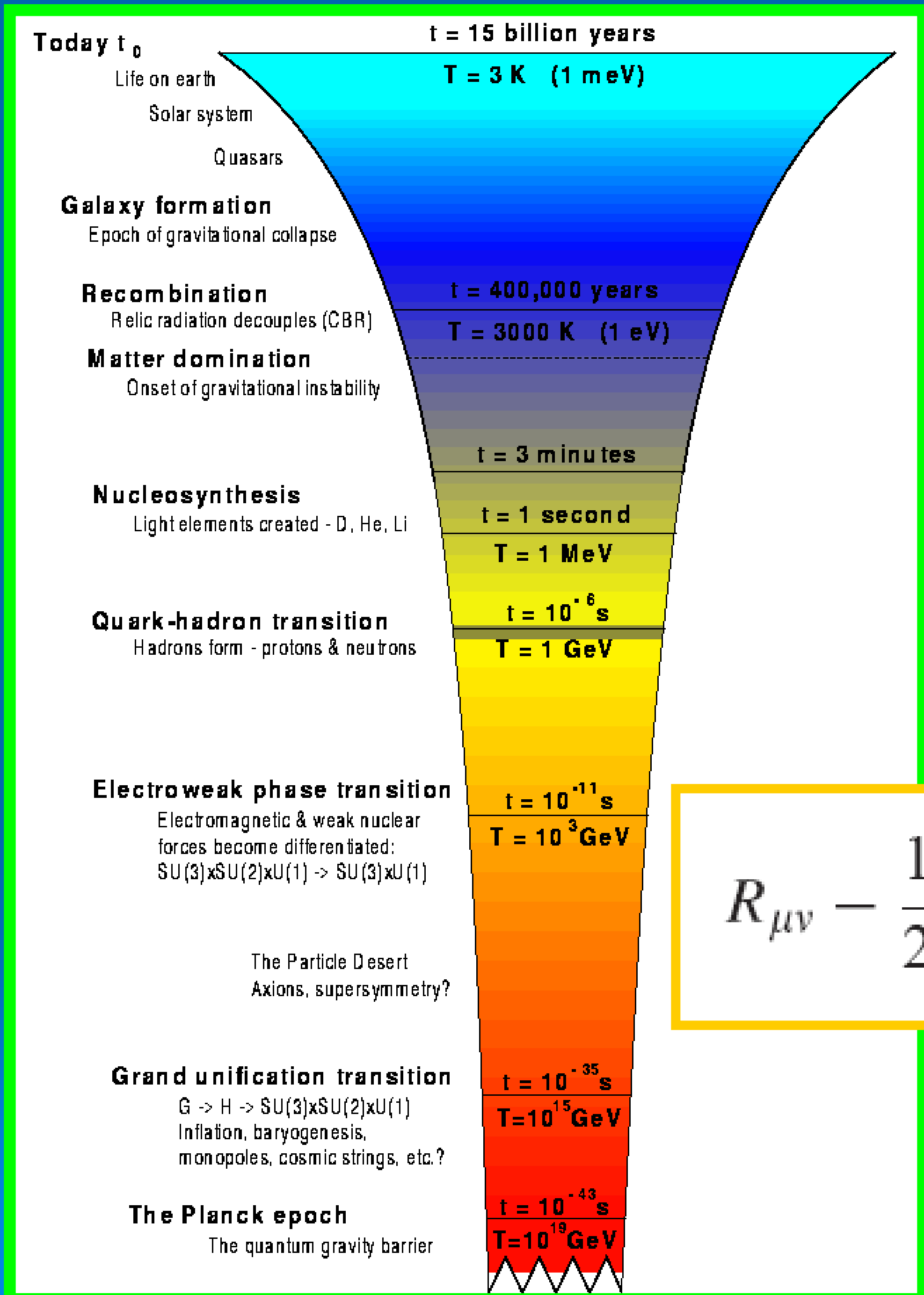
The Topics:

- From Cosmic to Hadronic Scales
- QCD, Hadrons, and Nuclei
- Hadronic Effective Field Theory
- Nuclear Density Functional Theory
- Hypernuclear Matter, Hypernuclei, Neutron Stars
- Summary and Outlook

…and weaving the science net!



$t=t_0$ today

Big Bang Cosmology

time t

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G_N}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

t=0 Big Bang

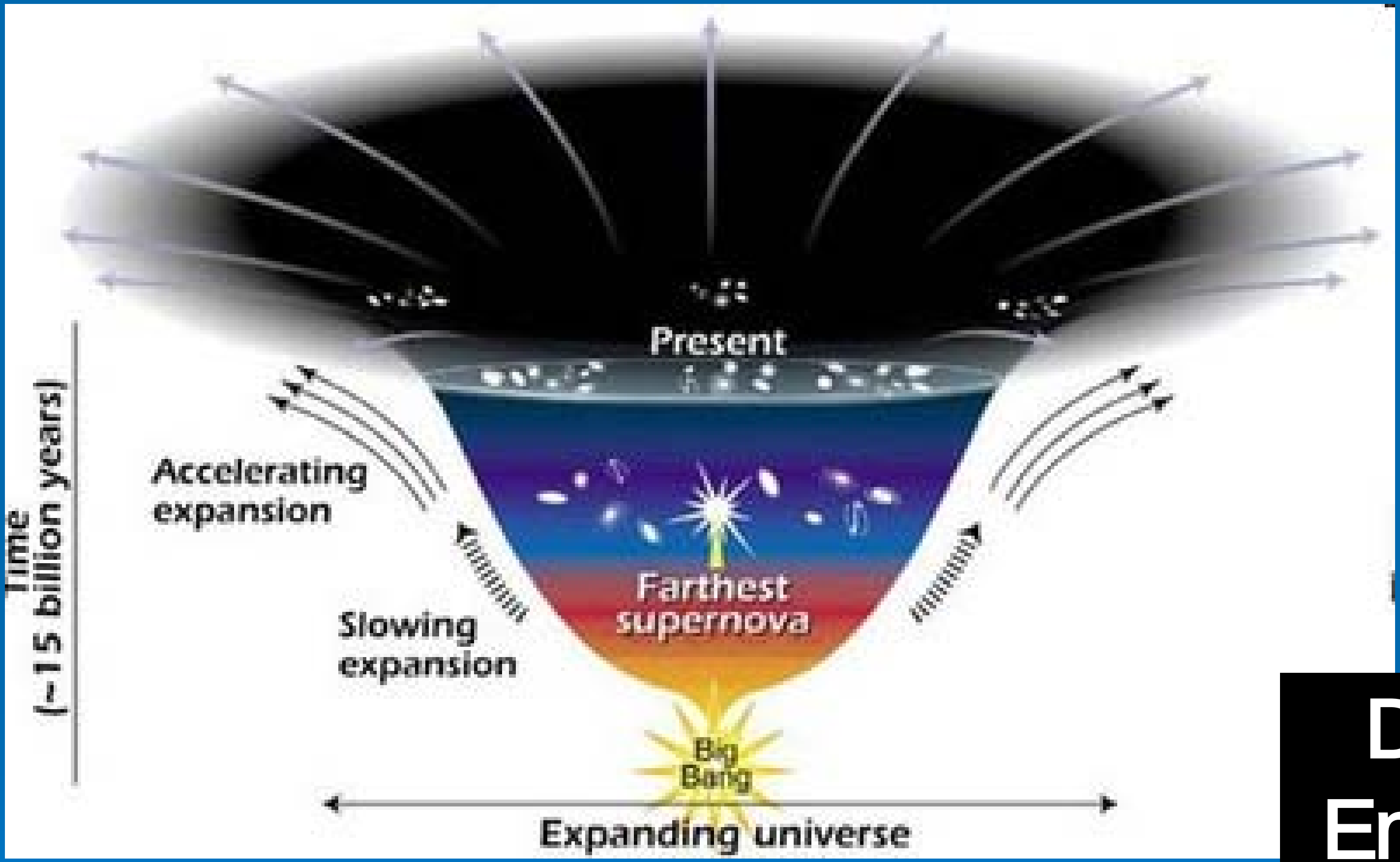
Constituents of the Universe ($\Omega=\rho/\rho_c$):

- Baryonic (luminous) Matter: $\Omega_B\sim0.05$

- Dark Matter: $\Omega_D\sim0.20$

- Dark Energy: $\Omega_\Lambda\sim0.75$

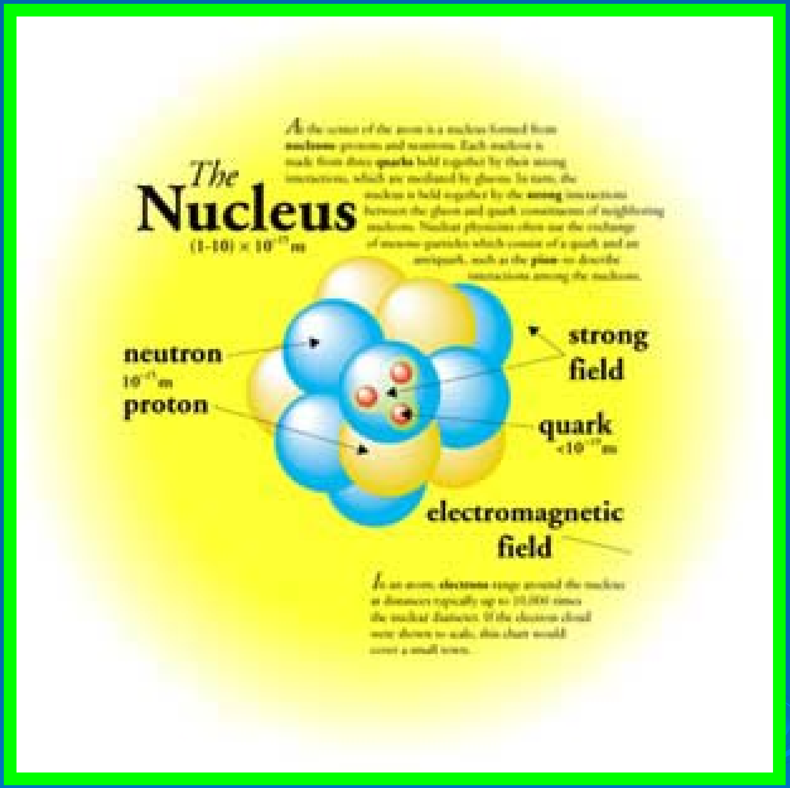
The big Riddle of Cosmology:



$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G_N}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

Dark Energy?

Cosmology, Astrophysics und Atomic Nuclei



Galactic Scales:

100,000 Lightyears (ly)
1ly ~ 10^{18} cm = 10^{16} m = 10^{13} km

Nuclear Scales:
1fm = 10^{-15} m = 10^{-13} cm ~ 10^{-31} ly

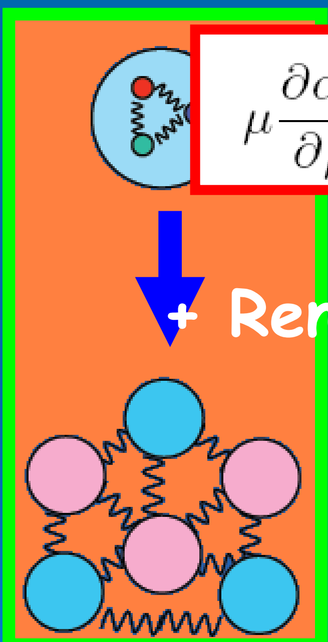
Theory of Strong Interactions: QCD

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}\left(i\gamma^{\mu} D_{\mu} - m\right) q - \frac{1}{4} F^{a}_{\mu\nu} F^{\mu\nu}_{a}$$

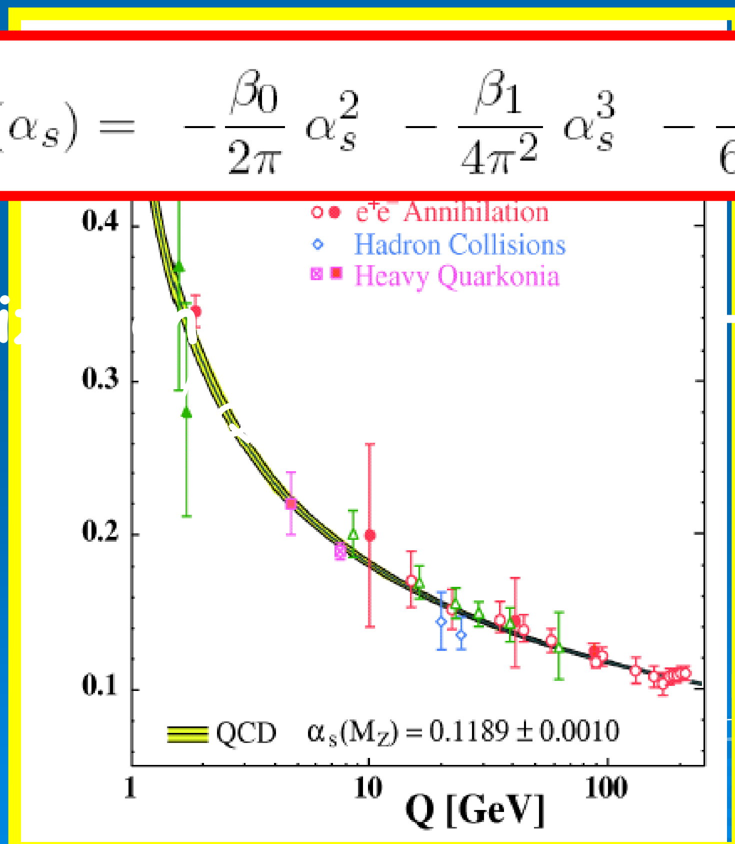
$$= \bar{q}(i\gamma^{\mu}\partial_{\mu} - m)q + g\bar{q}\gamma^{\mu}T_{a}qA^{a}_{\mu} - \frac{1}{4} F^{a}_{\mu\nu} F^{\mu\nu}_{a}$$

$$\mu \frac{\partial \alpha_s}{\partial \mu} = 2\beta(\alpha_s) = -\frac{\beta_0}{2\pi}\alpha_s^2 - \frac{\beta_1}{4\pi^2}\alpha_s^3 - \frac{\beta_2}{64\pi^3}\alpha_s^4 - \cdots$$

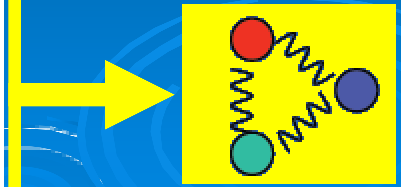
+ Renormali → $\alpha_s(\Lambda_{QCD},\mu)$



Confinement Hadrons and Nuclei



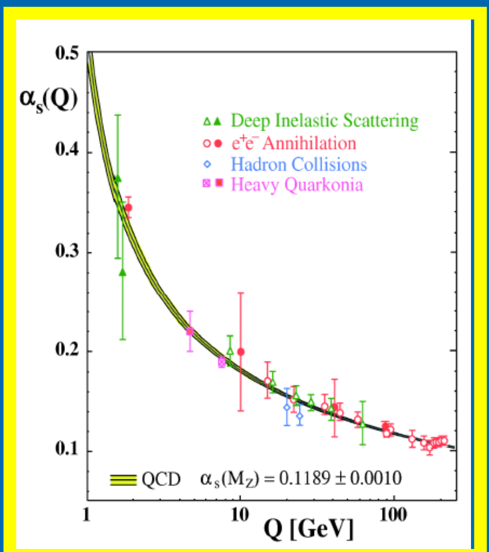
Asymptotic Freedom of Quarks and Gluons

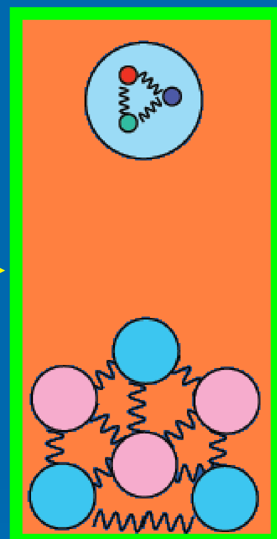


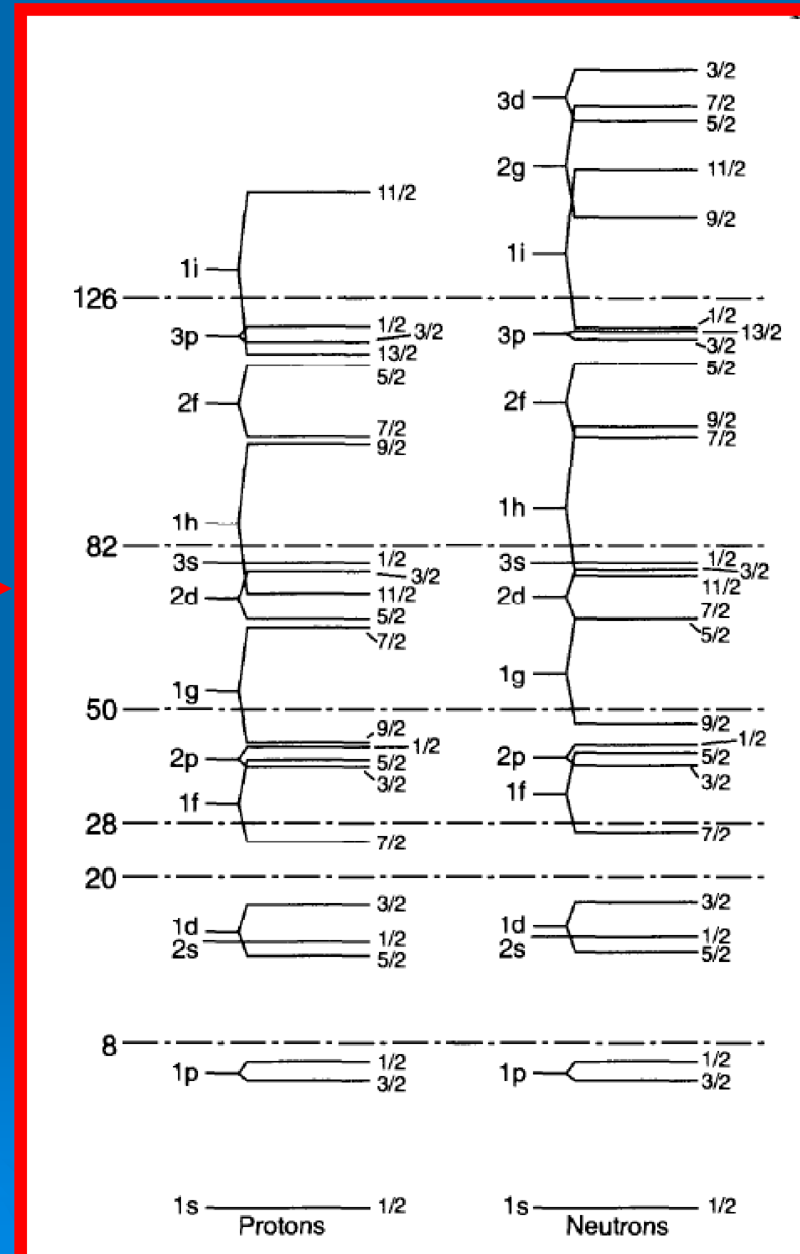
…and from asymptotic freedom…

to confinement…

to the nuclear shell model

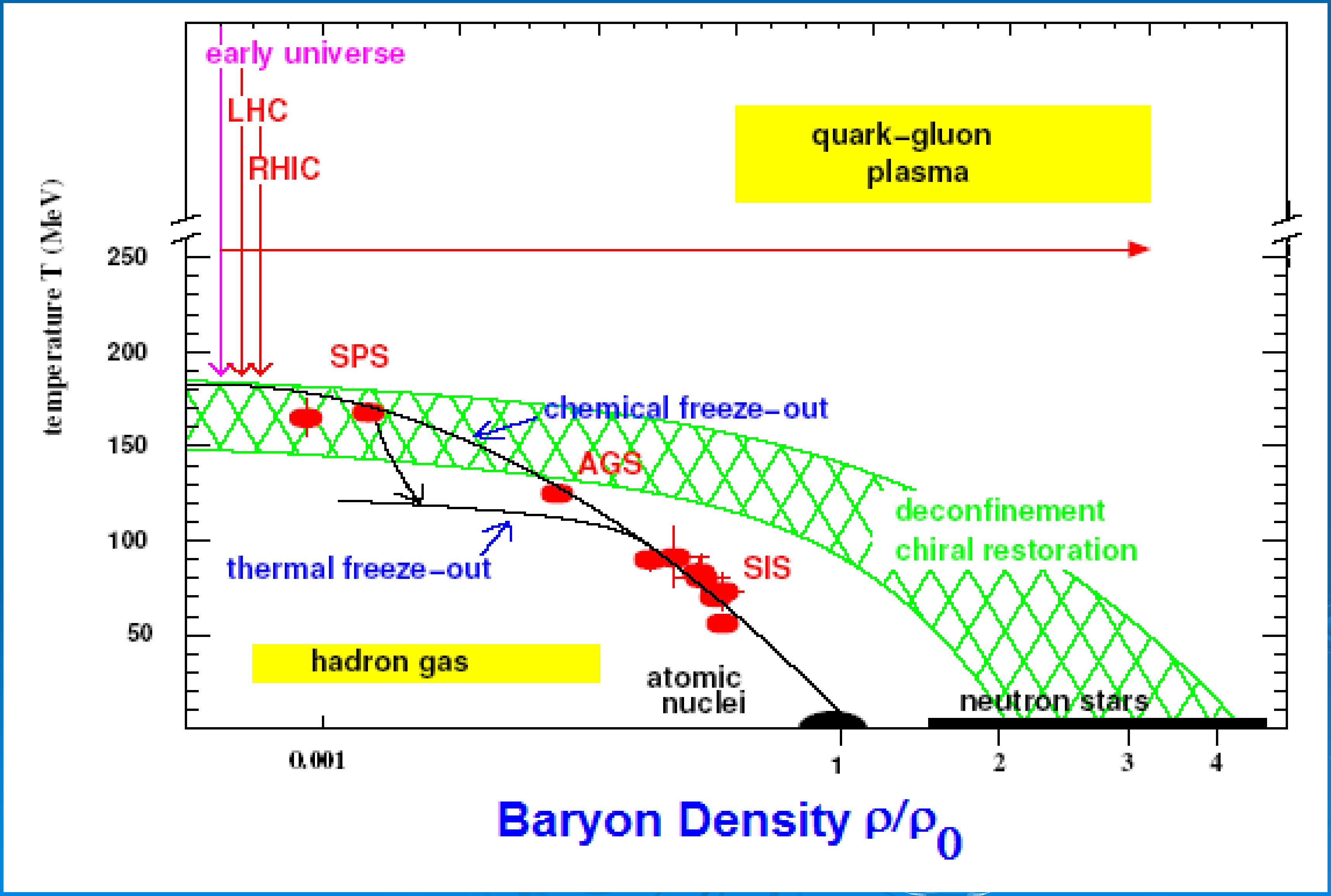




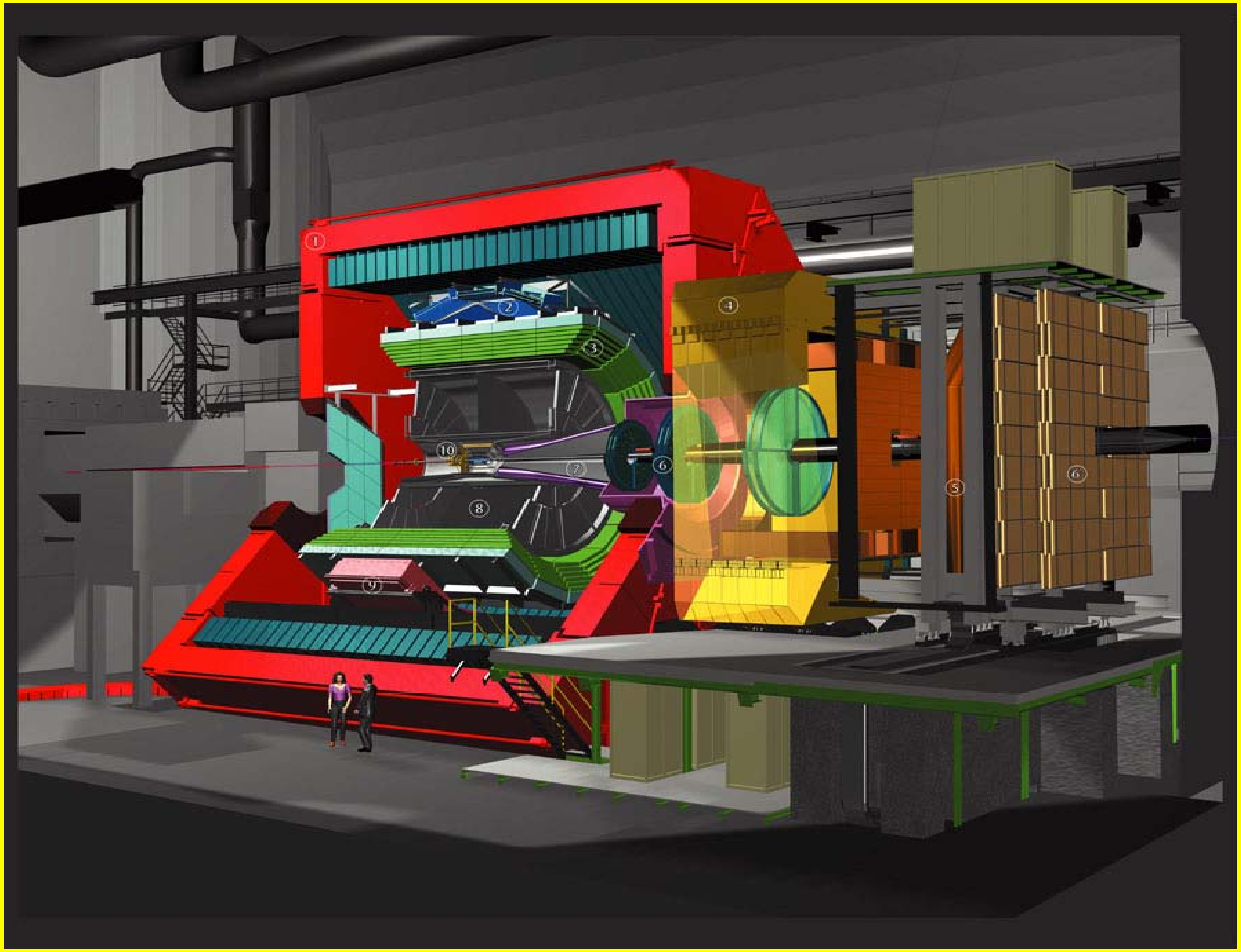


- Nucleus ~ cold, degenerate Fermi-Gas of Quasiparticles
- $U = U_0 + U_{so} \ell \cdot \sigma$

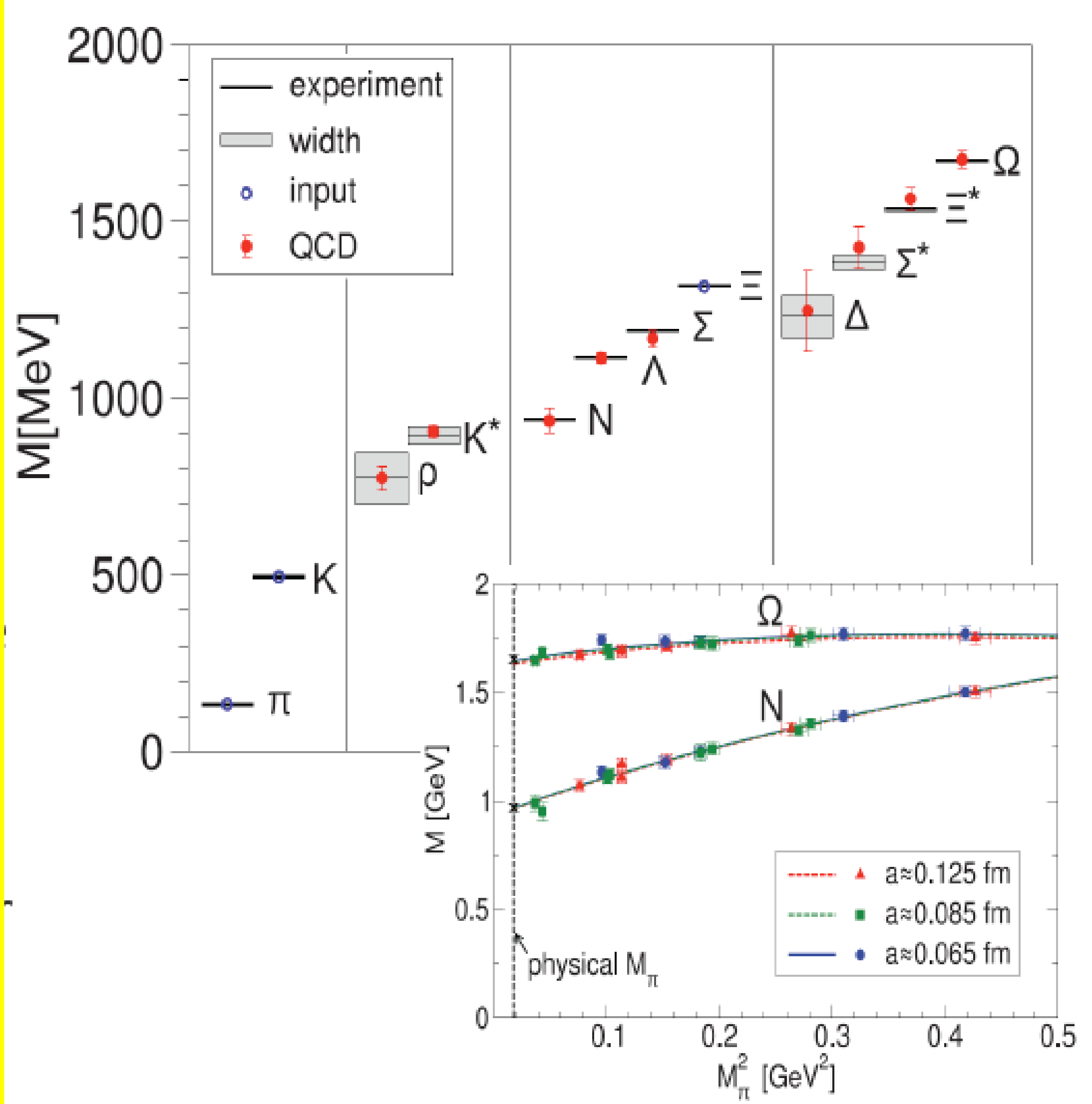
QCD Phase-Diagram



ALICE@LHC



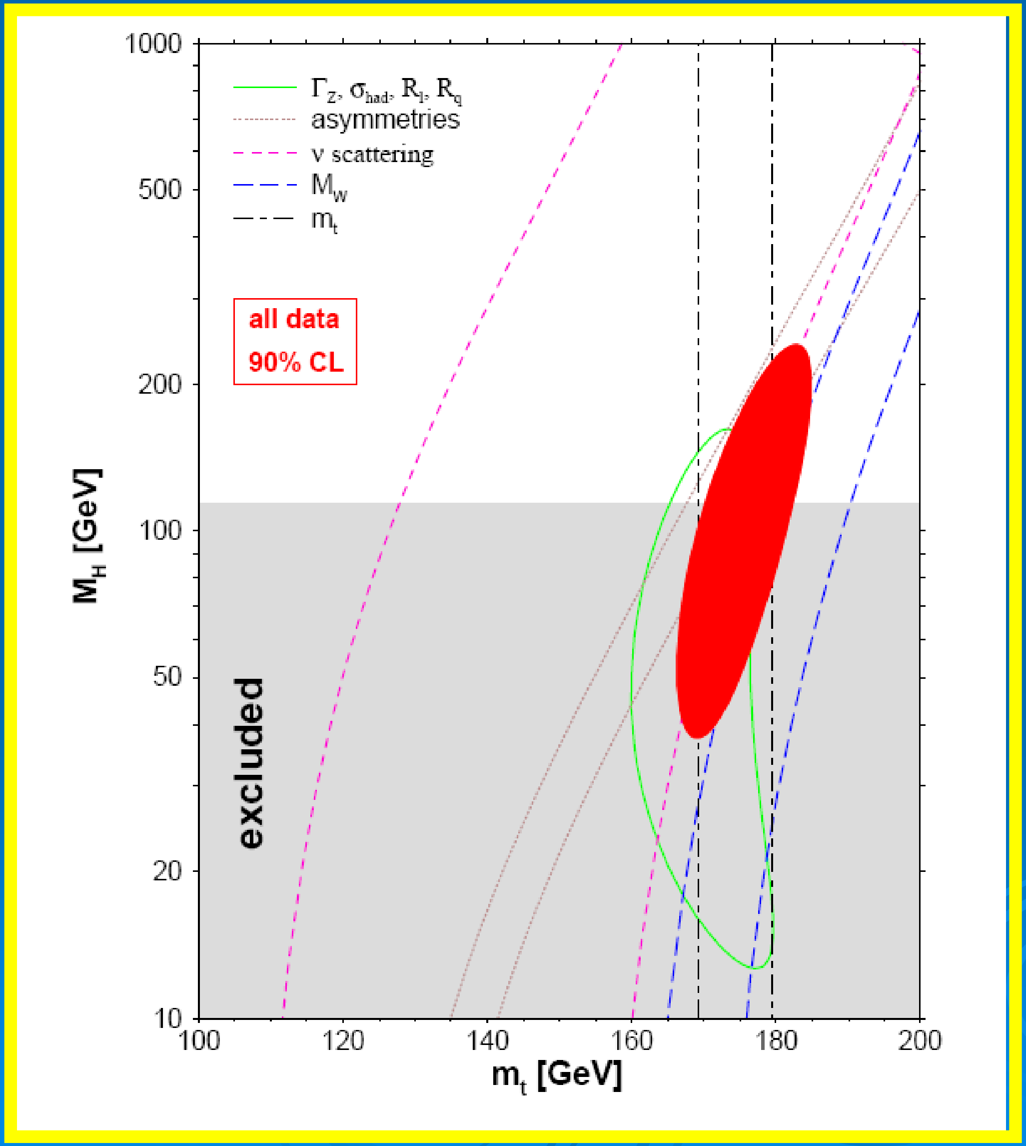
Recent Progress in Lattice QCD - *ab initio* Description of the Baryonic Mass Spectrum:



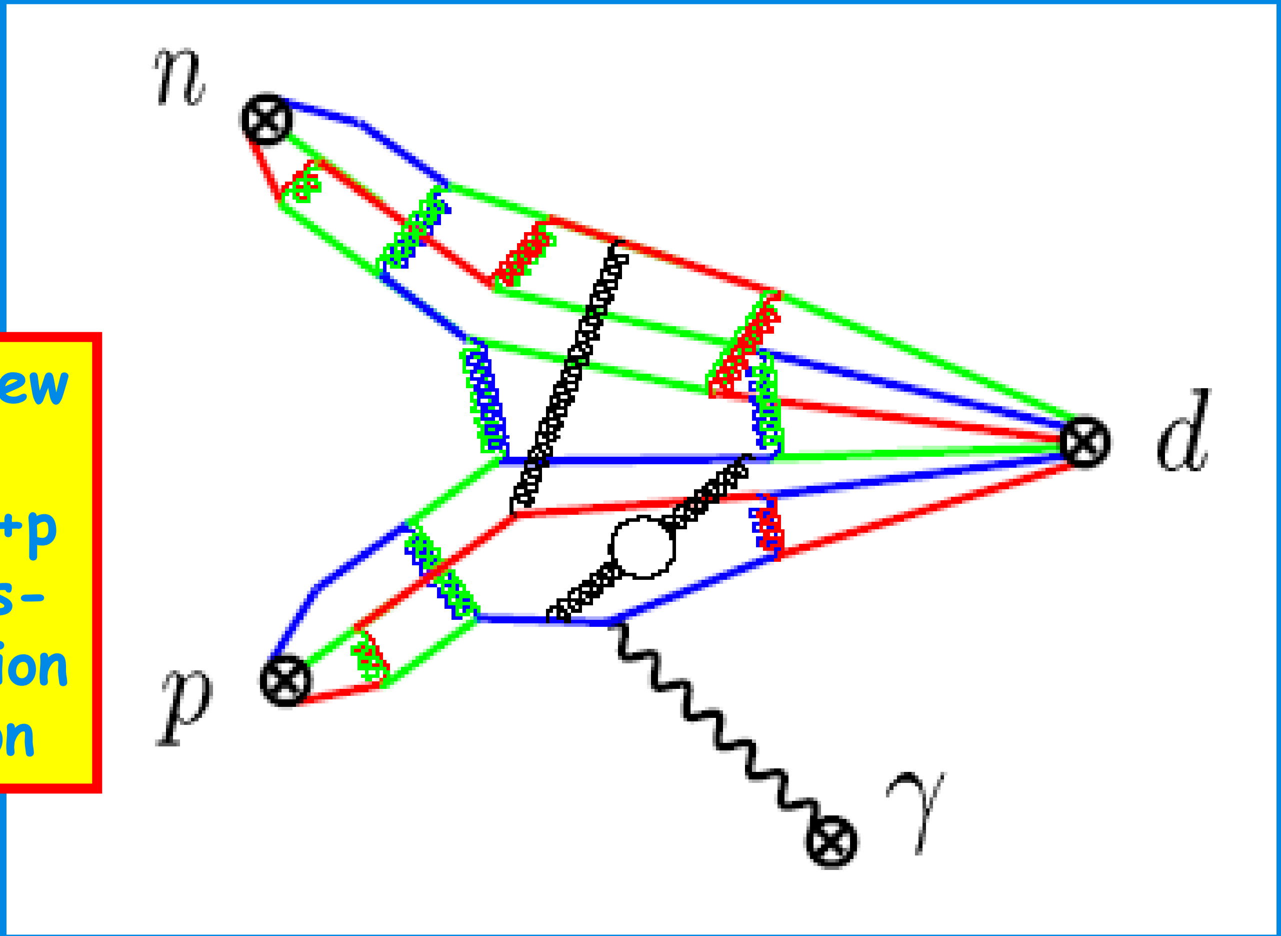
[Wuppertal-Jülich-Gruppe, Science 322 (2008) 1224]

What about mass...?

The Higgs-Field: A massive (complex) scalar field



QCD and Many-Body Physics



QCD View of a (d,γ)→n+p Photodis-integration Reaction

Reduction to the relevant degrees of freedom:

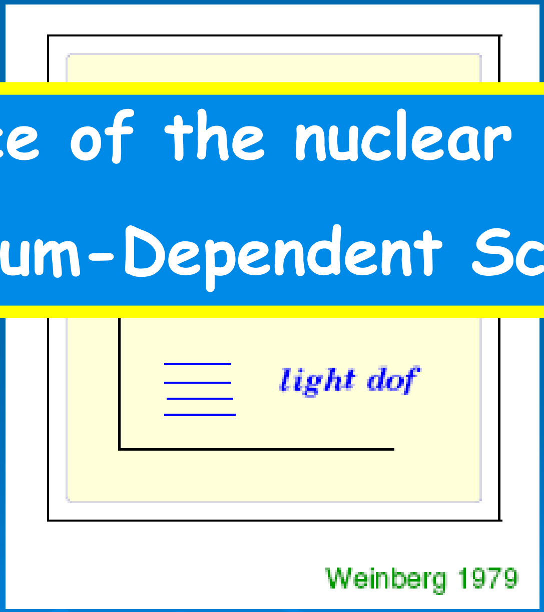
QCD → effective hadronic scales but retaining fundamental symmetries!

Weinberg Hypothesis (~1979):

- Nuclear Physics ≅ EFT of Pions and Nucleons
- Symmetries as the underlying fundamental theory of QCD
- Spontaneously broken chiral symmetry
- Low energy theorems
- Order-by-Order expansion in Q/Λ

Influence of the nuclear medium?

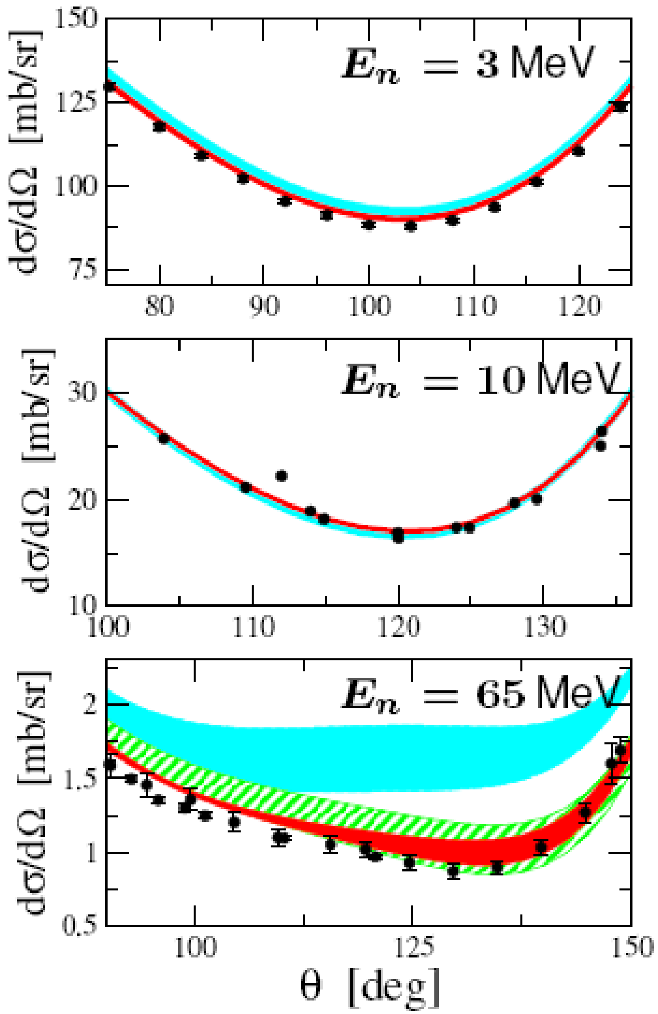
Medium-Dependent Scales?

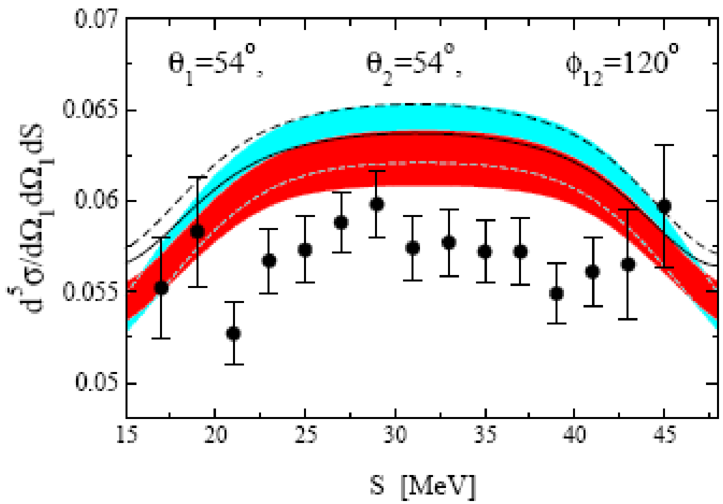


$$L_{QCD} \rightarrow L_{EFT} = L_{\pi\pi} + L_{\pi N} + L_{NN} + \ldots$$

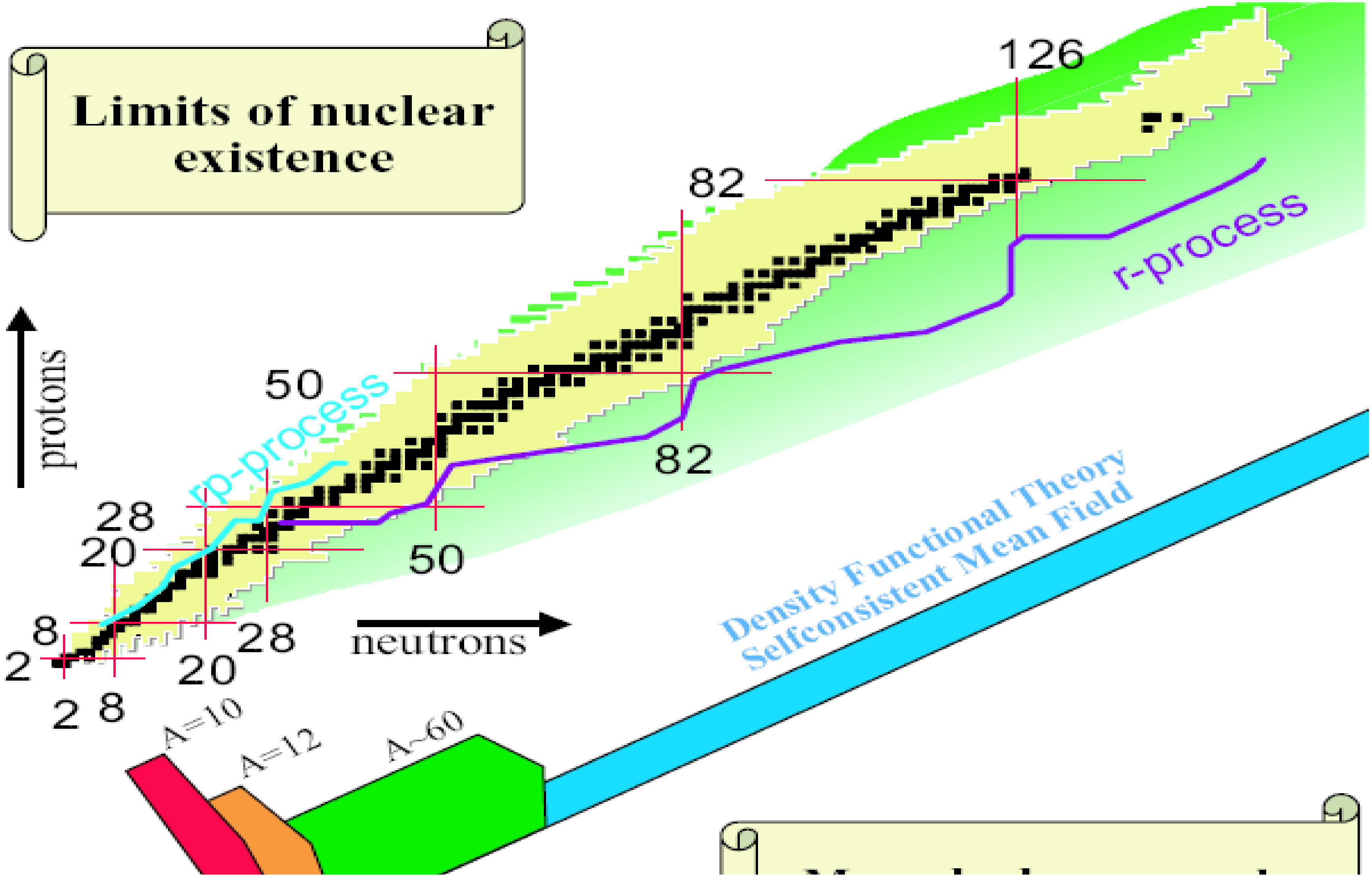
3N INTERACTION to N^{2}LO: PREDICTIONS

$\Rightarrow$ Parameter-free predictions for nd and pd scattering & break-up



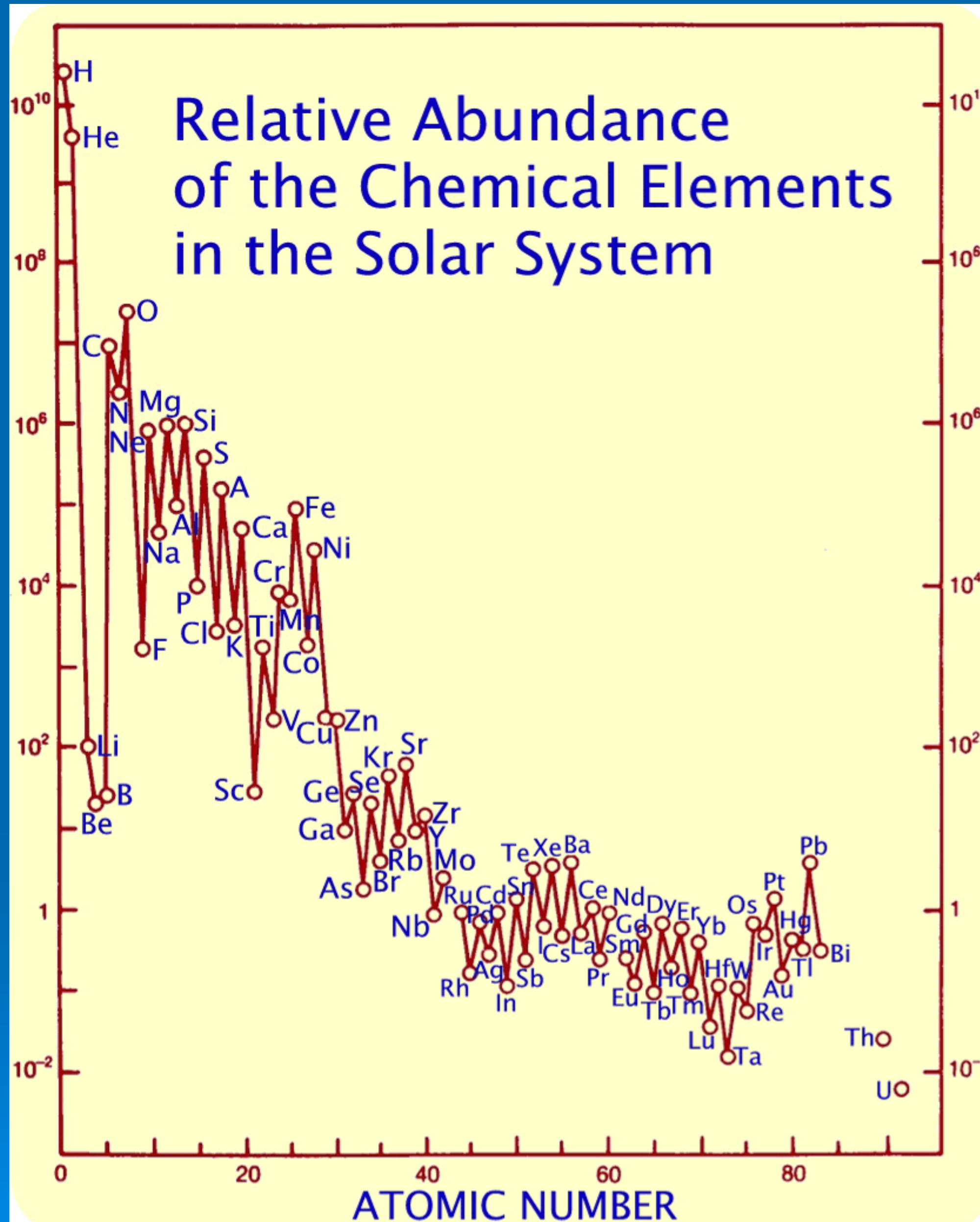


N^{2}LO
NLO
N^{2}LO w/o 3NF
— CD-Bonn w TM'
— — AV18 w UIX



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

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


Relative Abundance
of the Chemical Elements
in the Solar System
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
10^{-2}
0
20
40
60
80
ATOMIC NUMBER
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
A
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 — OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

„B^2FH" Theory

Theorems on the Dynamics of Interacting Quantum Many-Body Systems:

Kohn-Sham (~1960) : QM many-body systems ≅ DFT of E[ρ]

Kohn-Hohenberg (~1963) : DFT → E[ρ,τ]

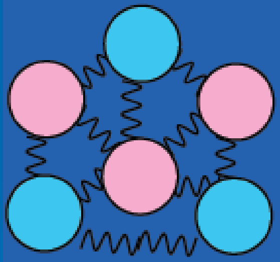
$$E[\rho,\tau]/\rho = \tau + \tfrac{1}{2}E_{int}/\rho \sim \tau + \tfrac{1}{2}\rho(3a_{SE}+a_{TE})/4 + \ldots$$

$$\rho = \left\langle \Psi^{+}\Psi \right\rangle \sim \frac{1}{3}k_F^3 \; ; \; \tau = \left\langle \frac{\hbar^2}{2m}\left|\nabla\Psi\right|^2 \right\rangle \frac{1}{\rho} \sim \frac{3}{5}k_F^2$$

Lagrangian Hadronic

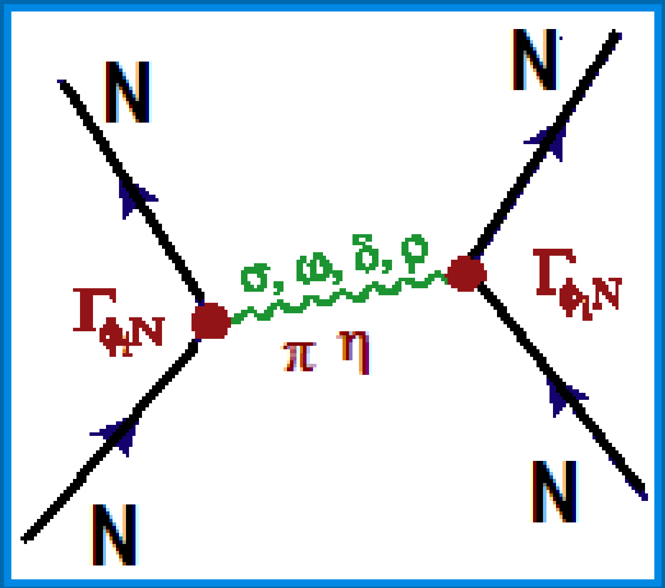
Density Functional Theory

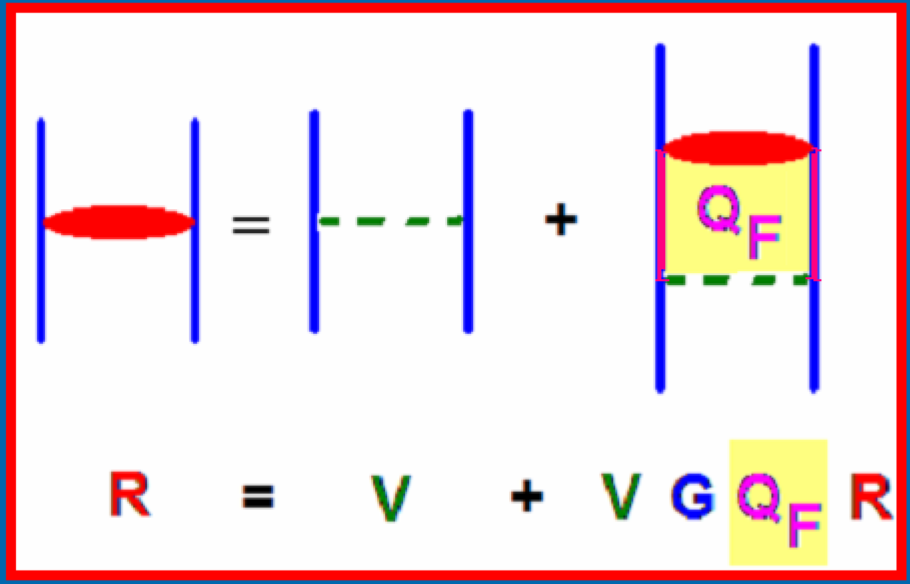
$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_m + \mathcal{L}_{int}$$



$$\begin{aligned}\mathcal{L}_{int} = \; & \bar{\psi} g_\sigma \Phi_\sigma \psi + \bar{\psi} g_\delta \boldsymbol{\tau} \boldsymbol{\Phi}_\delta \psi \\ & + \bar{\psi} g_\pi \gamma^5 \boldsymbol{\tau} \boldsymbol{\Phi}_\pi \psi + \bar{\psi} g_\eta \gamma^5 \Phi_\eta \psi \\ & - \bar{\psi} g_\omega \gamma_\mu A^\mu_\omega \psi - \bar{\psi} g_\rho \gamma_\mu \boldsymbol{\tau} \mathbf{A}^\mu_\rho \psi - e \bar{\psi} \hat{Q} \gamma_\mu A^\mu_\gamma \psi\end{aligned}$$

Giessen DDRH Theory: Covariant Octet Flavour Density Functional Theory

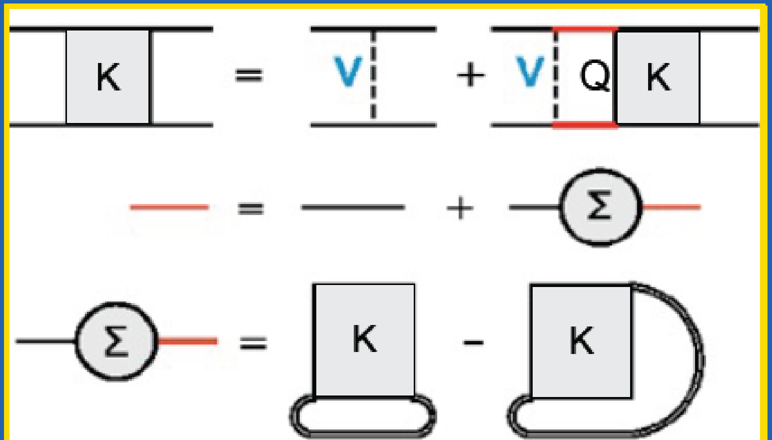




- SU(3) DFT at the Fermi Momentum Scale
- BB Interactions in Free Space by Meson Exchange
- *ab initio* Approach to In-Medium Interactions
- Self-consistence, Thermodynamical Consistence

Non-Perturbative Approach to BB Interactions…

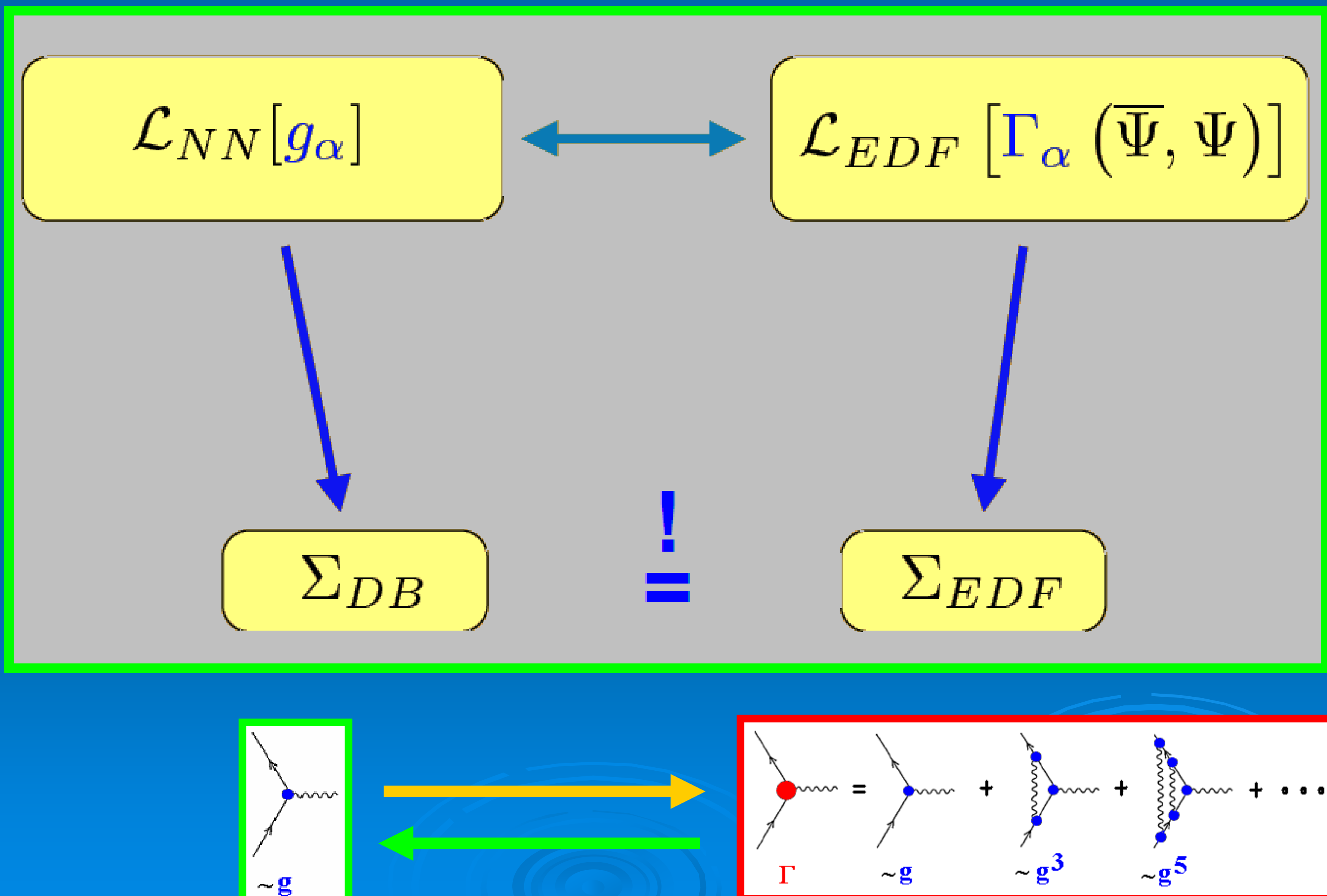
$$K = V + \int V g_{NN} Q_F K$$



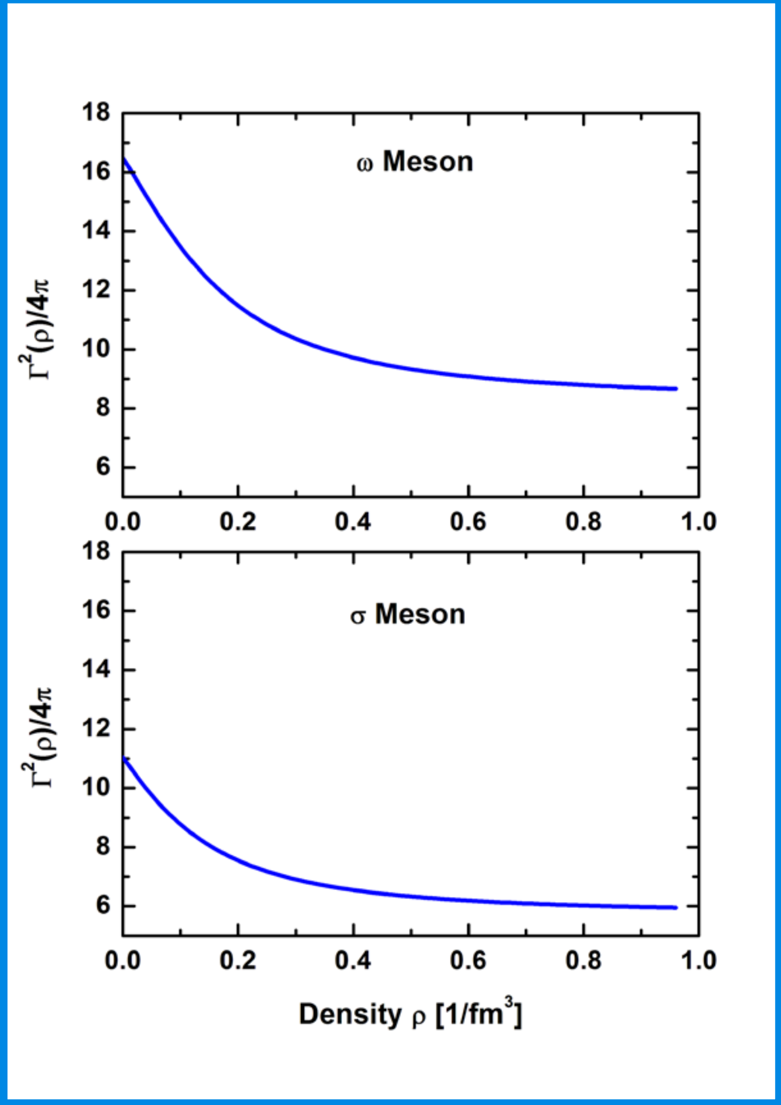
- Ladder Kernel
- Map the ab-initio calculations on an effective Lagrangian
- Medium dependent renormalization

$$V_{OBE} = \sum_{\alpha} g_{\alpha}^{2} D_{\alpha}(t) \langle \overline{u}_1 \hat{O}_{\alpha} u_3 \rangle \langle \overline{u}_2 \hat{O}_{\alpha} u_4 \rangle$$

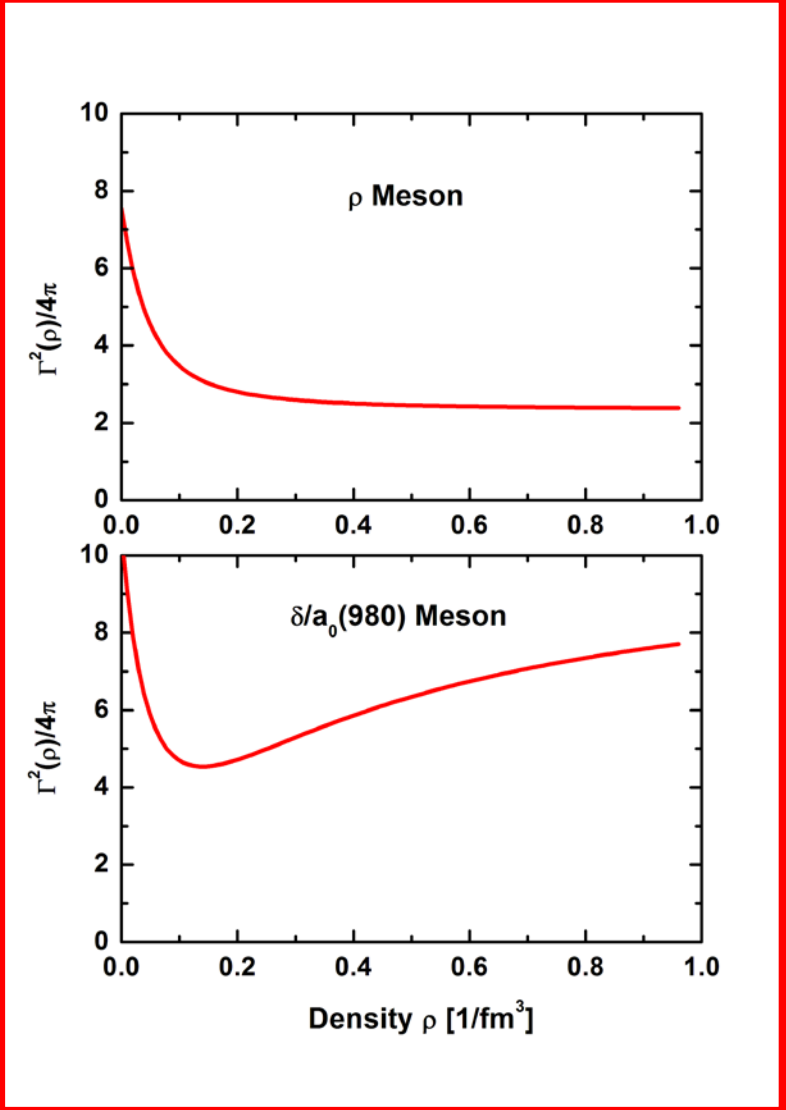
Building blocks for a covariant nuclear DFT…



Nuclear Matter DBHF Vertices



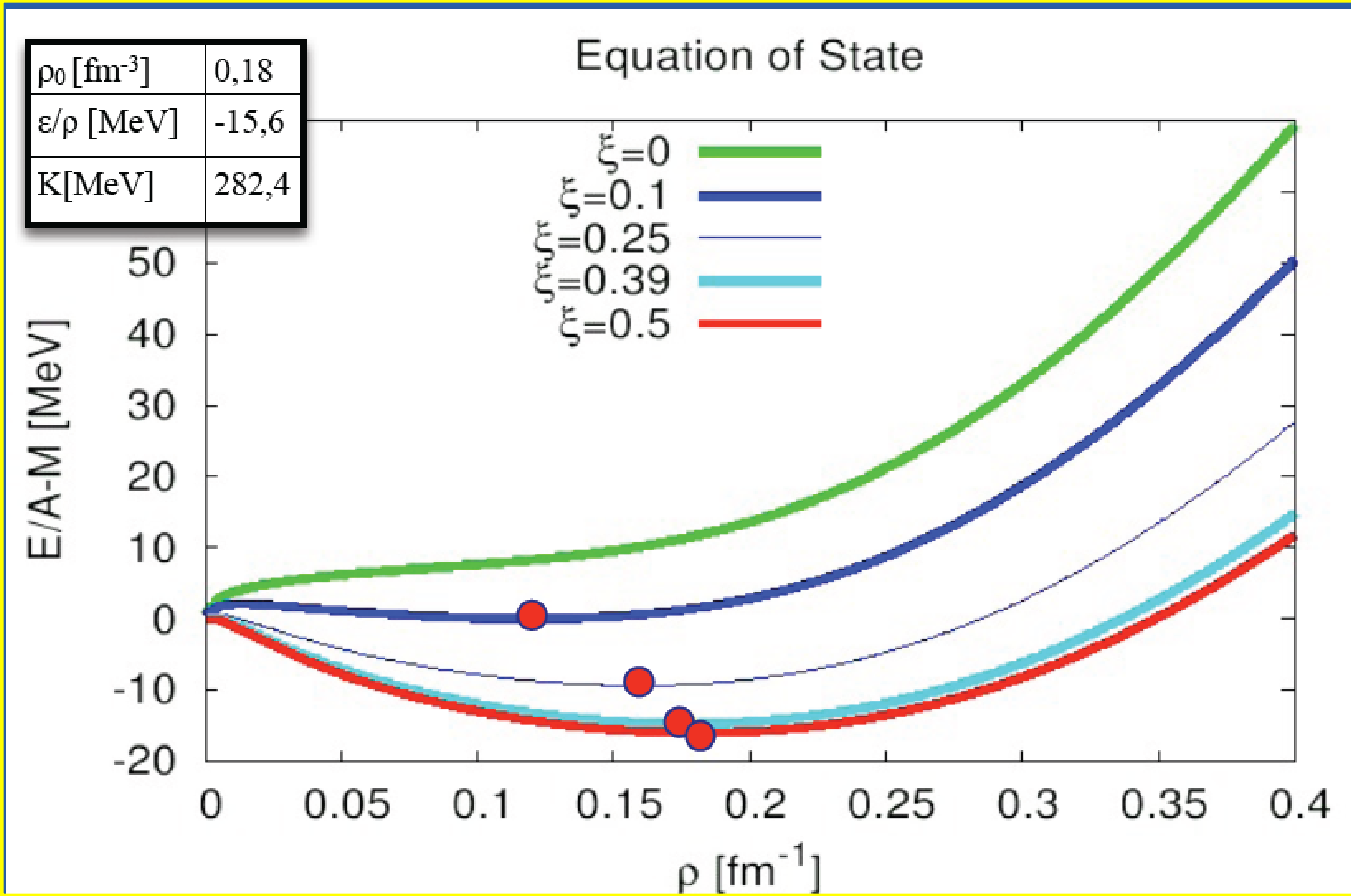
Isoscalar Vertices



Isovector Vertices

The Nuclear Equation of State

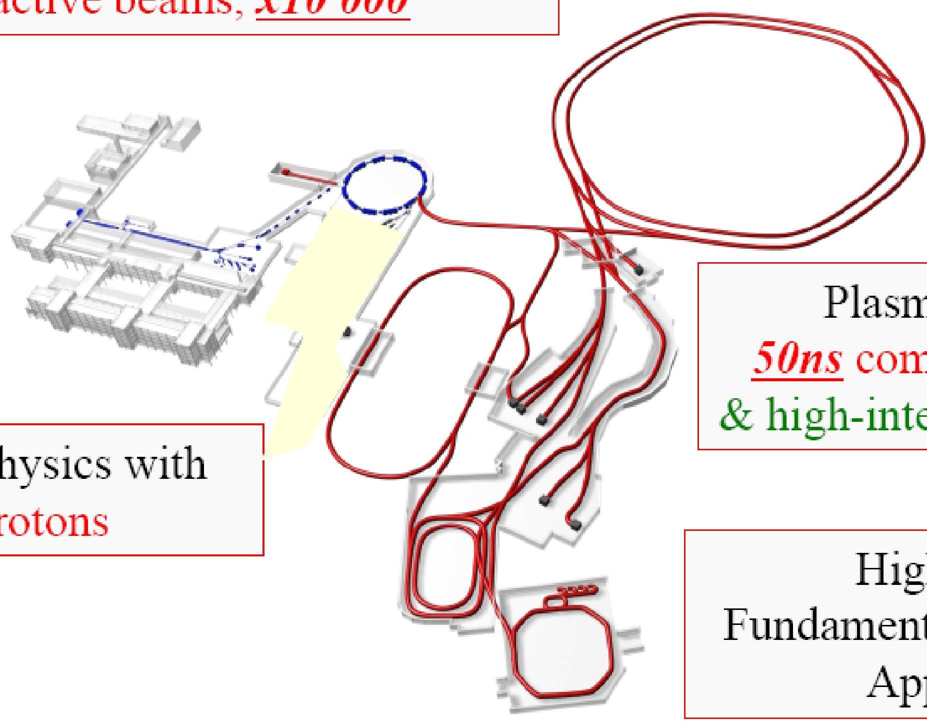
ρ_0 [fm^{-3}]	0,18
ε/ρ [MeV]	-15,6
K[MeV]	282,4



Five Fields of Research at FAIR

Nuclear Structure & Astrophysics with
radioactive beams, ***x10 000***

Nuclear Matter Physics with
35-45 GeV/u HI beams, ***x1000***



Plasma Physics with
50ns compressed ion beams
& high-intensity petawatt- laser

Hadron Physics with
antiprotons

High EM Field (HI)
Fundamental Studies (HI & p)
Applications (HI)

100 m

Status: Dec 2008

ab initio covariant Nuclear Many-Body Theory:

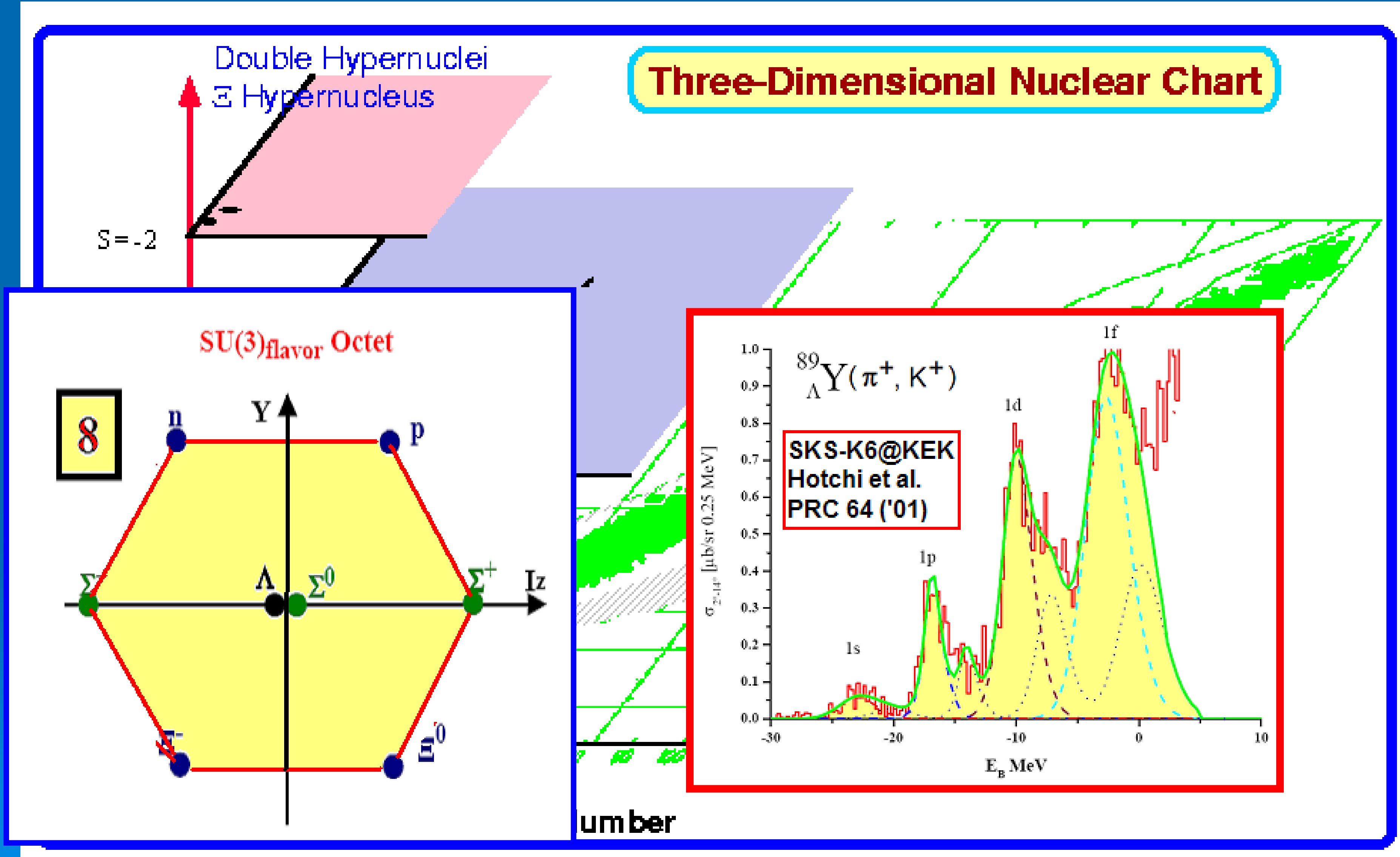
Energy Density Functional (EDF) - Diagrammatic Order Scheme

$$E(\rho) \approx E(\rho_0) + \sum_{q=p,n} \frac{\partial E(\rho)}{\partial \rho_q}\Big|_{\rho_0} \delta\rho_q + \sum_{q,q'=p,n} \frac{\partial^2 E(\rho)}{\partial \rho_q \partial \rho_{q'}}\Big|_{\rho_0} \delta\rho_q \delta\rho_{q'} + \ldots$$

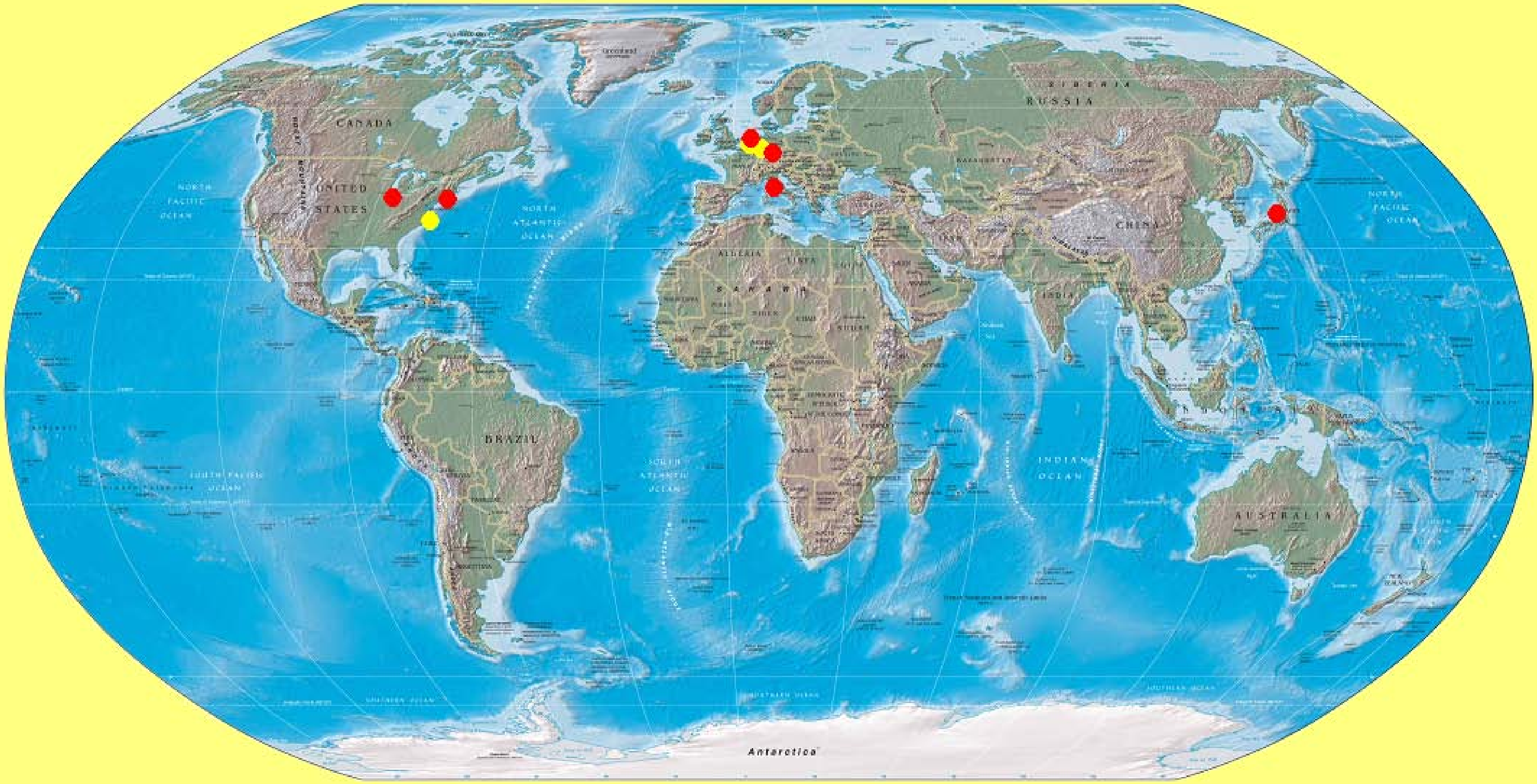
$$E(\rho) \approx E(\rho_0) + \sum_{q=p,n} U_q(\rho_0)\delta\rho_q + \sum_{q,q'=p,n} F_{qq'}(\rho_0)\delta\rho_q \delta\rho_{q'} + \ldots$$

Microscopic relativistic Fermi-Liquid Theory

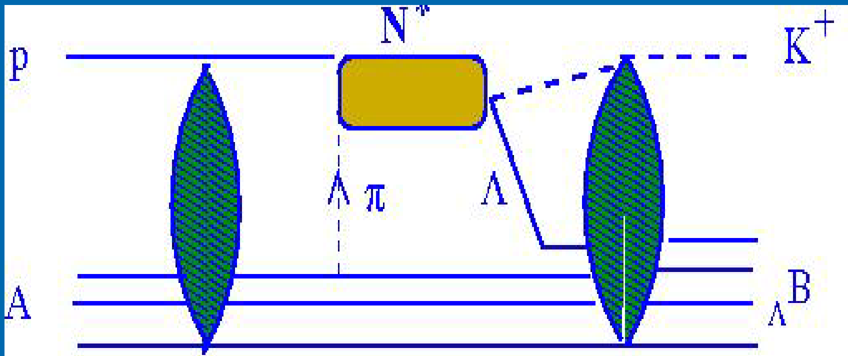
Strangeness and Hypernuclear Physics: From SU(2) Isospin to SU(3) Flavour Dynamics

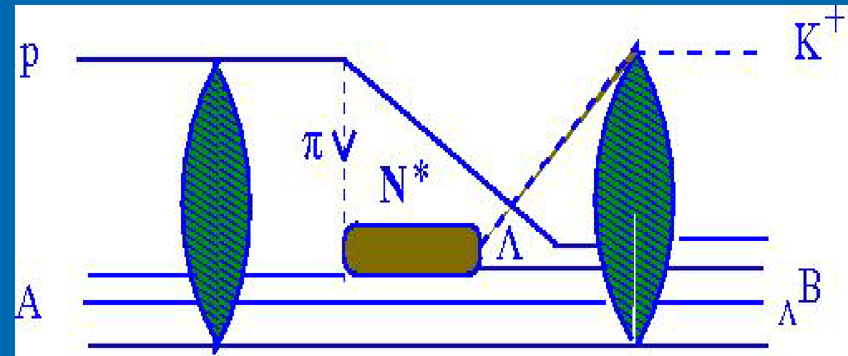


World Map of Hypernuclear Physics



Dynamics of strangeness production

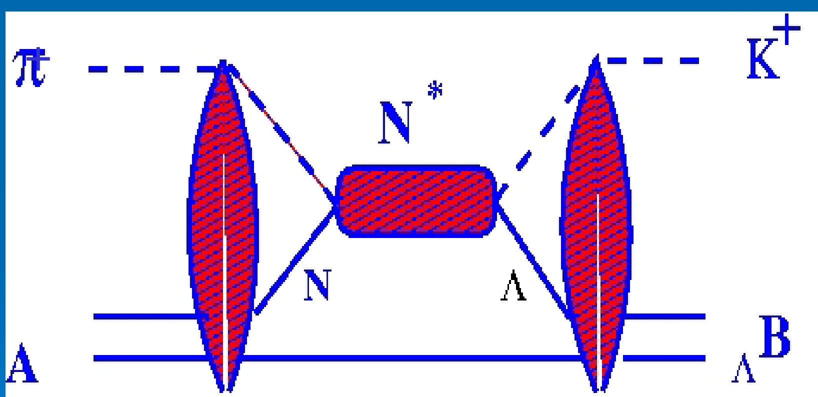


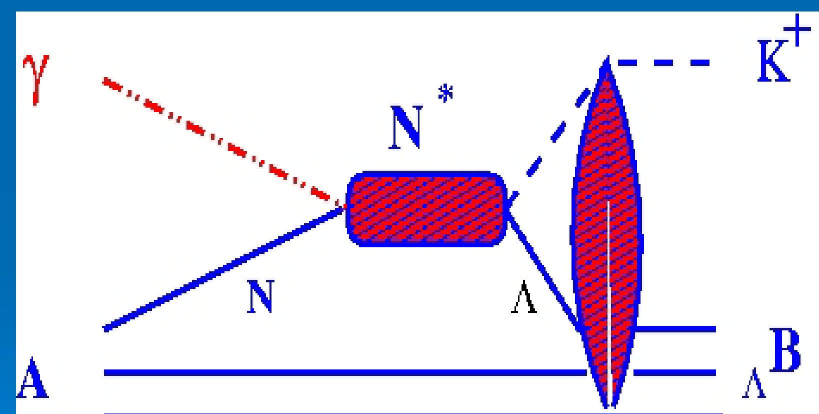


Target emission

$A(p,K^+)_\Lambda B$

Projectile emission



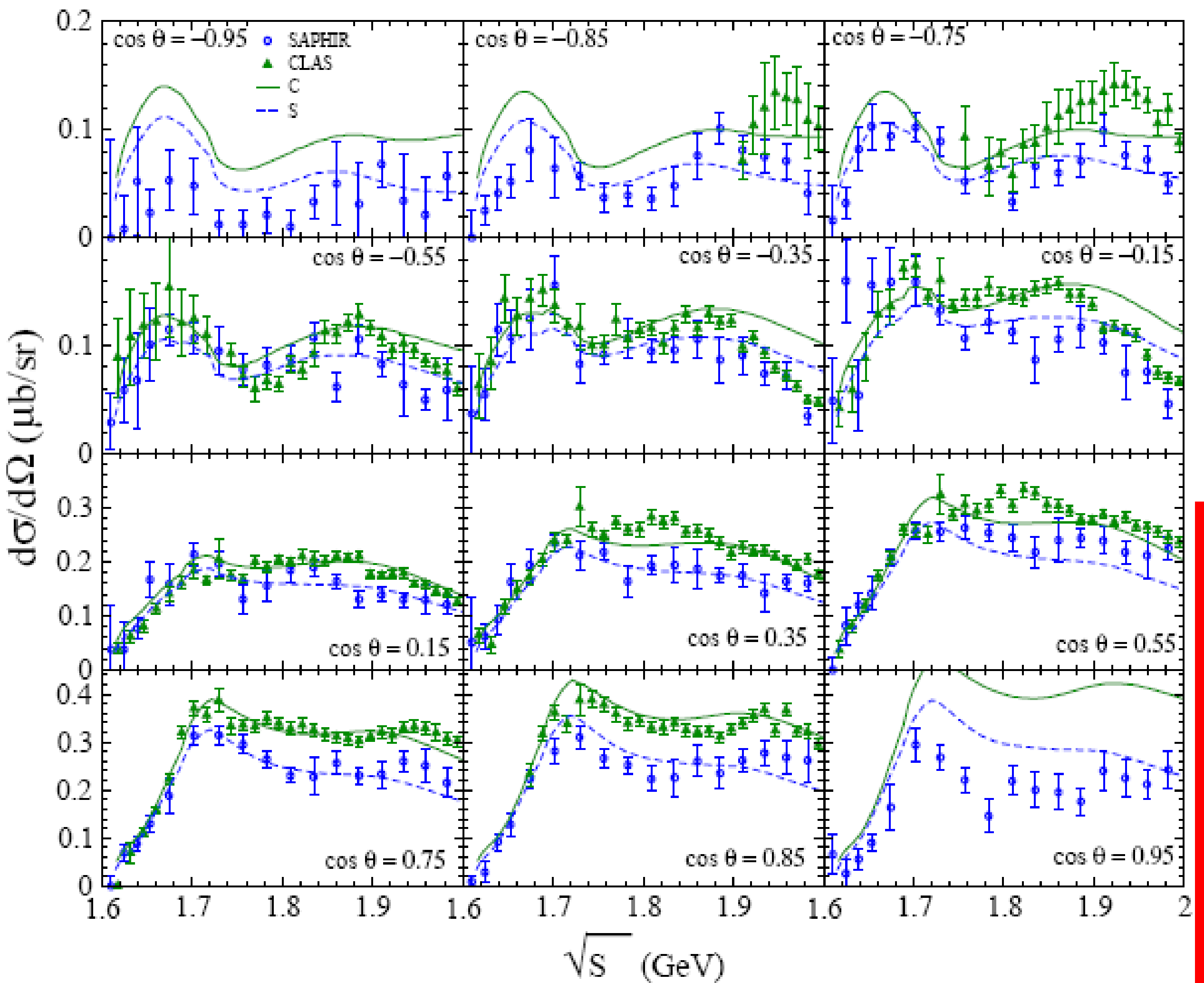


$A(\pi^+,K^+)_\Lambda B^*$

$A(\gamma,K^+)_\Lambda B'$

N * (1650), N*(1710), N*(1720) baryonic resonances.

γp → KΛ Results from the Giessen CC Model



- separate fits to SAPHIR and CLAS data
- constraints from other hadronic and γ channels

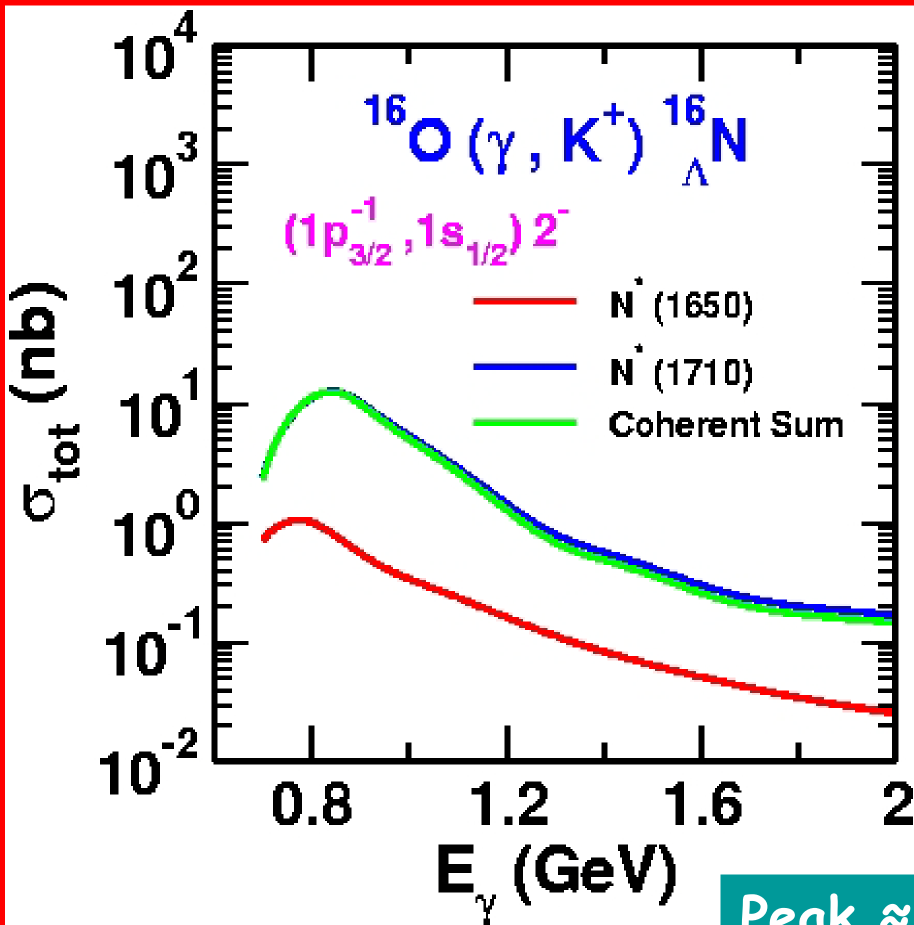
$\pi N \to K\Lambda$

+

$\gamma N \to \gamma N$	$\pi N \to \pi N$
$\gamma N \to \pi N$	$\pi N \to 2\pi N$
$\gamma N \to \eta N$	$\pi N \to \eta N$
$\gamma N \to \omega N$	$\pi N \to \omega N$
$\gamma N \to K\Sigma$	$\pi N \to K\Sigma$

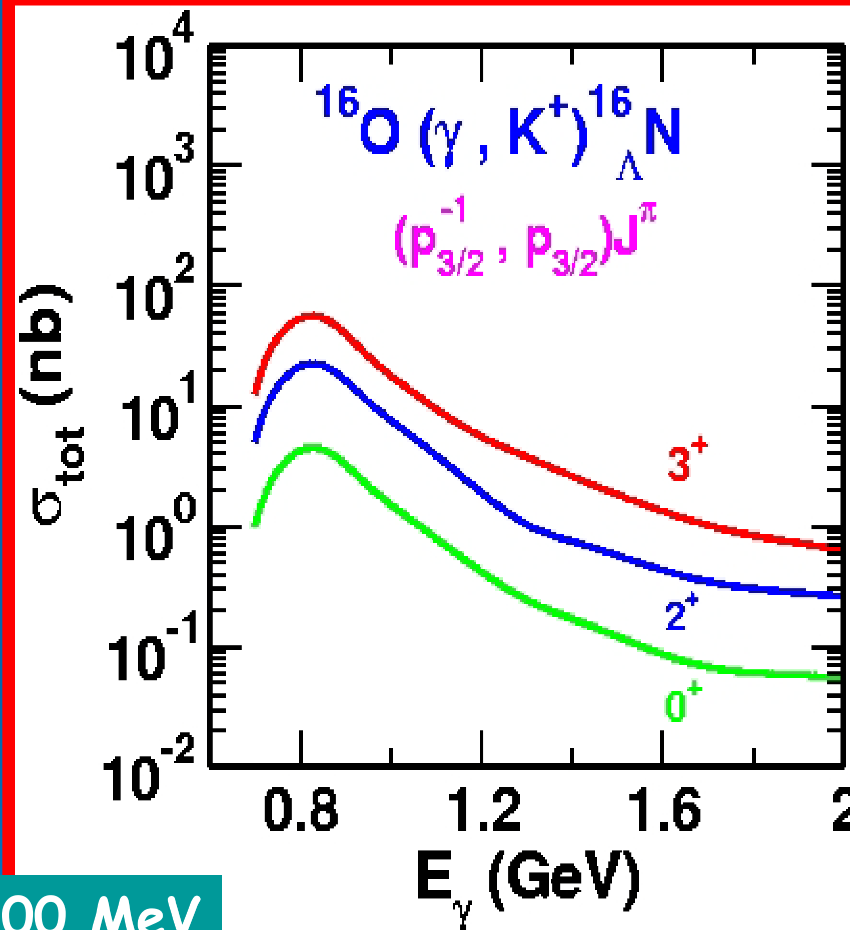
nucl-th/0505010/PRC 72:015210 (2005)

Relative Contribution of various Resonances



(N*(1720) weaker by a factor 1000)

Excitation of states with different J

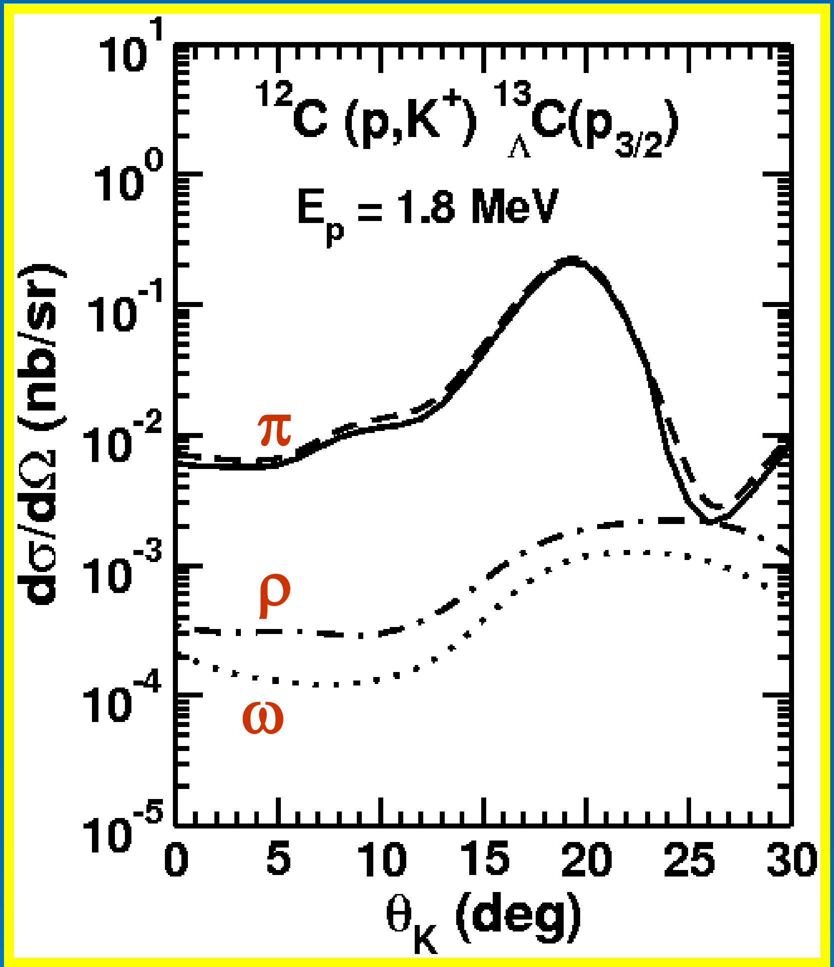


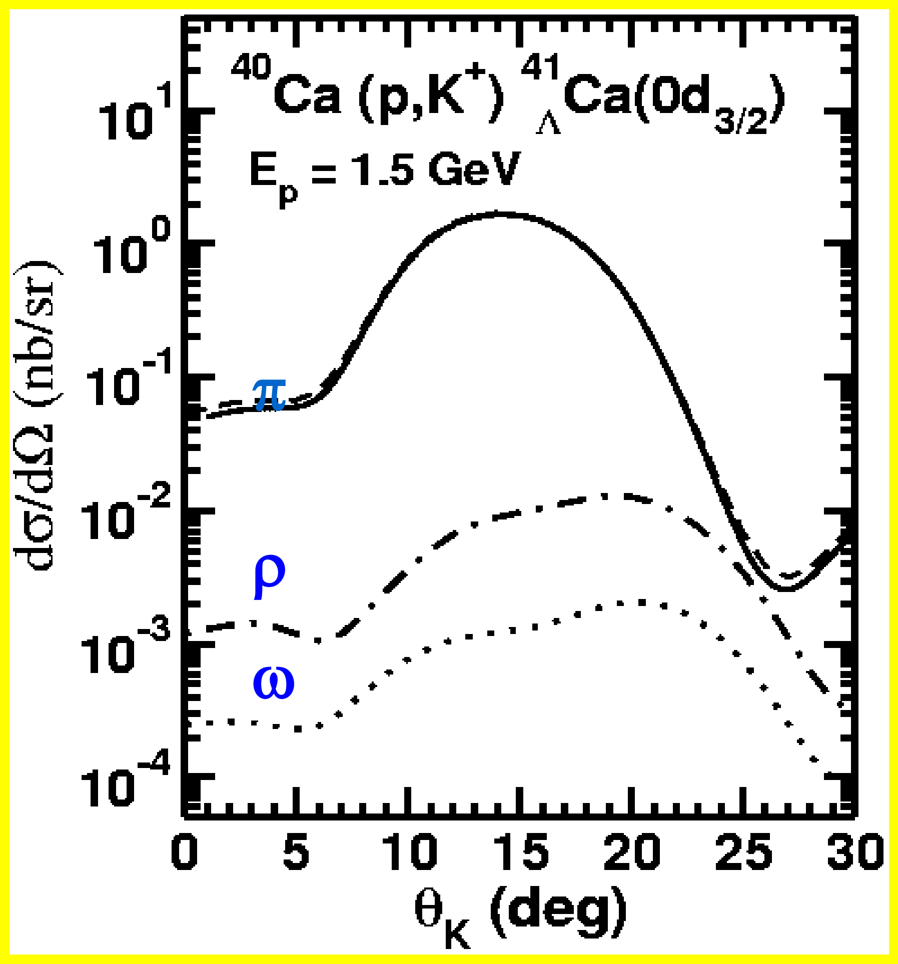
Largest J state is dominant

Peak ≈ 900 MeV

Phys.Rev.C77:052201,2008

Proton-induced Strangeness Production

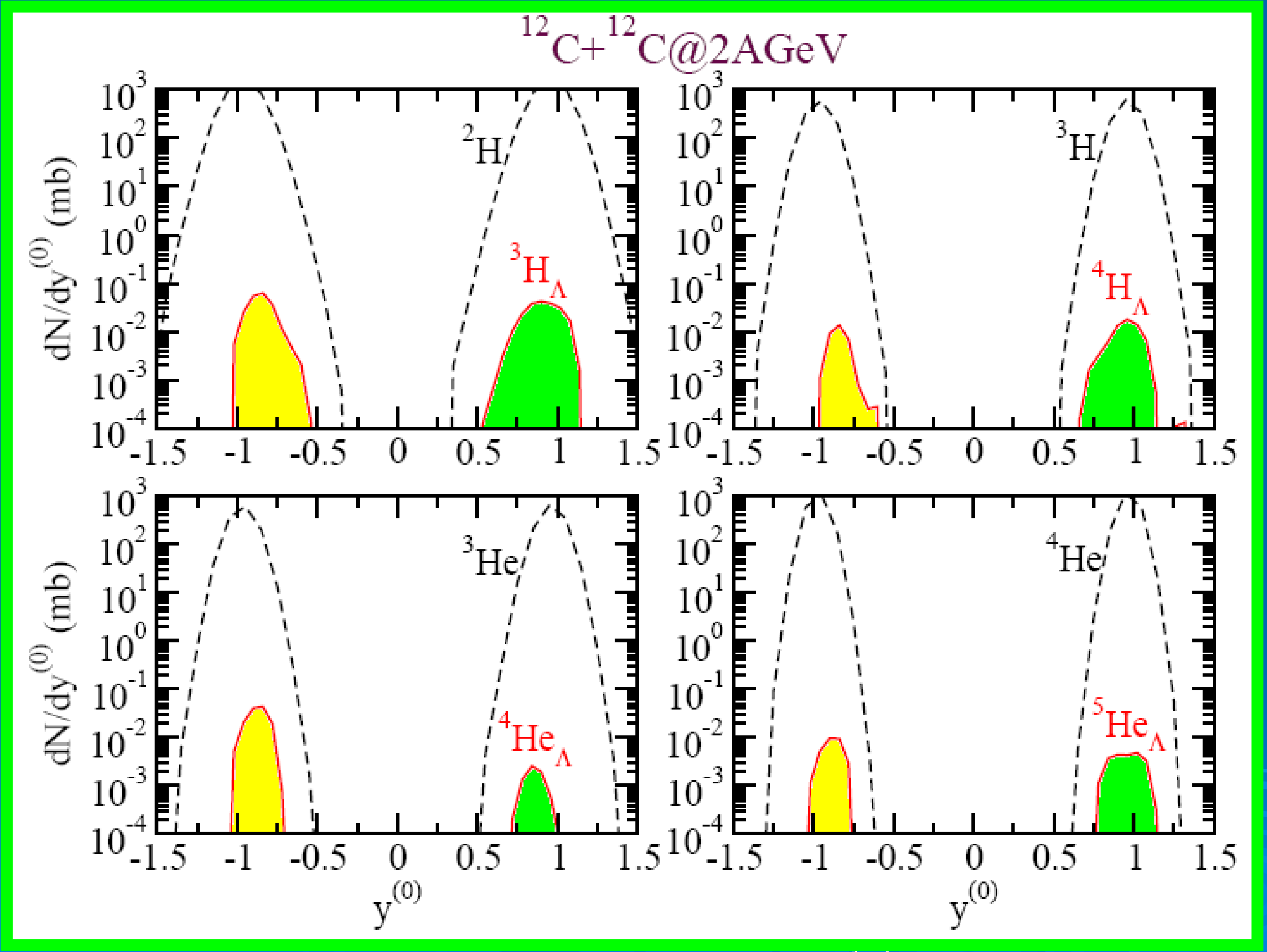




π exchange dominates, ρ and ω exchange more important at back angles due to large momentum transfers.

R. Shyam, H. L. and U. Mosel, Phys. Rev.C 69 (2004) 065205

Exploratory Case Study:
Production of Hypernuclei in Heavy Ion Collisions
The HypHI Project@GSI & FAIR (T. Saito)



GiBUU+Coalescence+SMM, PLB 2009; arXiv:0811.3506; Phys.Lett.B663:197-201,2008

What do we learn from hypernuclei?

- baryon-meson octet coupling constants and vertices

$g_{N\sigma}$, $g_{N\omega}$, $g_{N\rho}$,

Free space NN scattering and nuclei

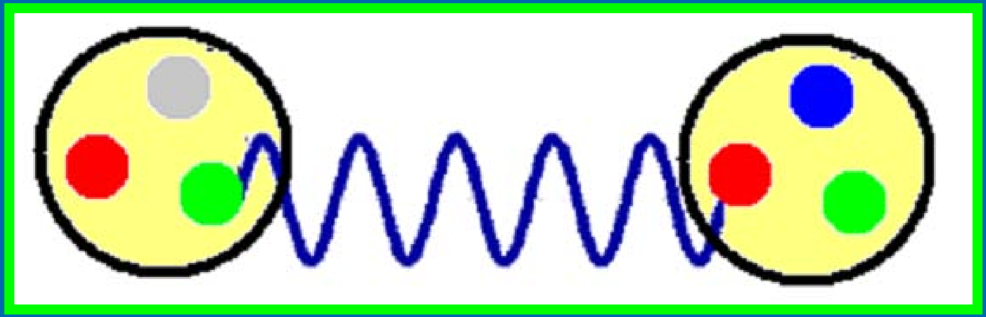
$g_{\Lambda\sigma}$, $g_{\Lambda\omega}$, $f_{\Lambda\omega}$

Accessible in hypernuclei

- YA mean-field $V(g_{Ym})=V_0+V_{ls}$
- +dynamical correlations?

Direct Observation? → Hyperon „Beams“ at J-PARC!

DDRH-Scaling of In-Medium Hyperon Interactions



Naïve Quark Model Scaling:

$g_{m\Lambda} = 2/3\; g_{mN}$

but...

$$K_{\Lambda N} = \frac{1}{1 - z V_{NN} G Q_F} z V_{NN} = R K_{NN}$$

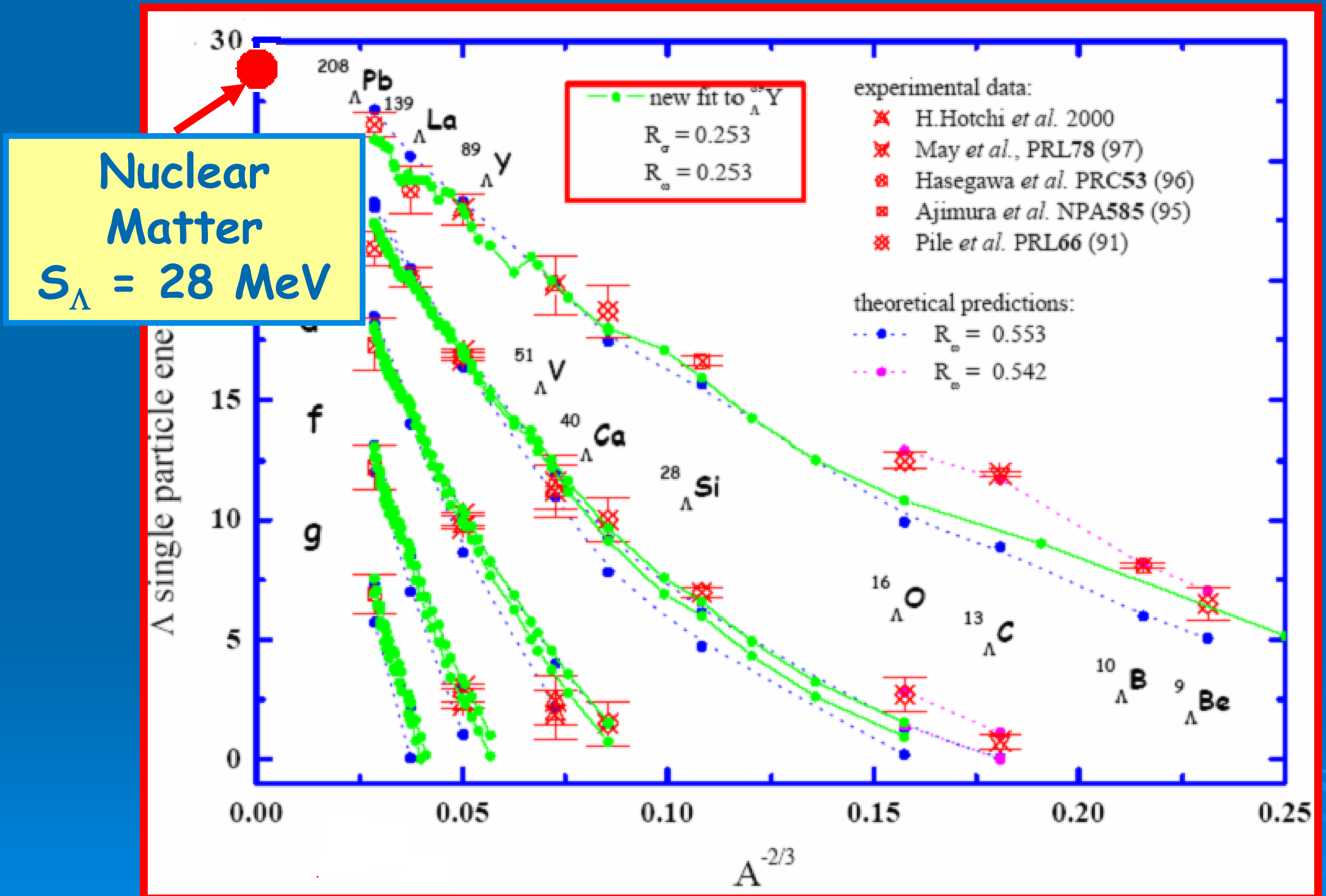
Hyperon-Nucleon Vertices at the Mean-Field Level:

$$\Sigma_{mY} = g_{mY}\Phi_m(\rho_B) \Leftrightarrow \Sigma_{mN} = g_{mN}\Phi_m(\rho_B)$$

$$R_m = \frac{g_{mY}}{g_{mN}} = \frac{\Sigma_{mY}}{\Sigma_{mN}}$$

$$R_m = \frac{g_{mY}}{g_{mN}}\left[1 + O\left(\left(\frac{k_F^Y}{k_F^N}\right)^2\right) + O\left(1 - \frac{M_N}{M_Y}\right)\right]$$

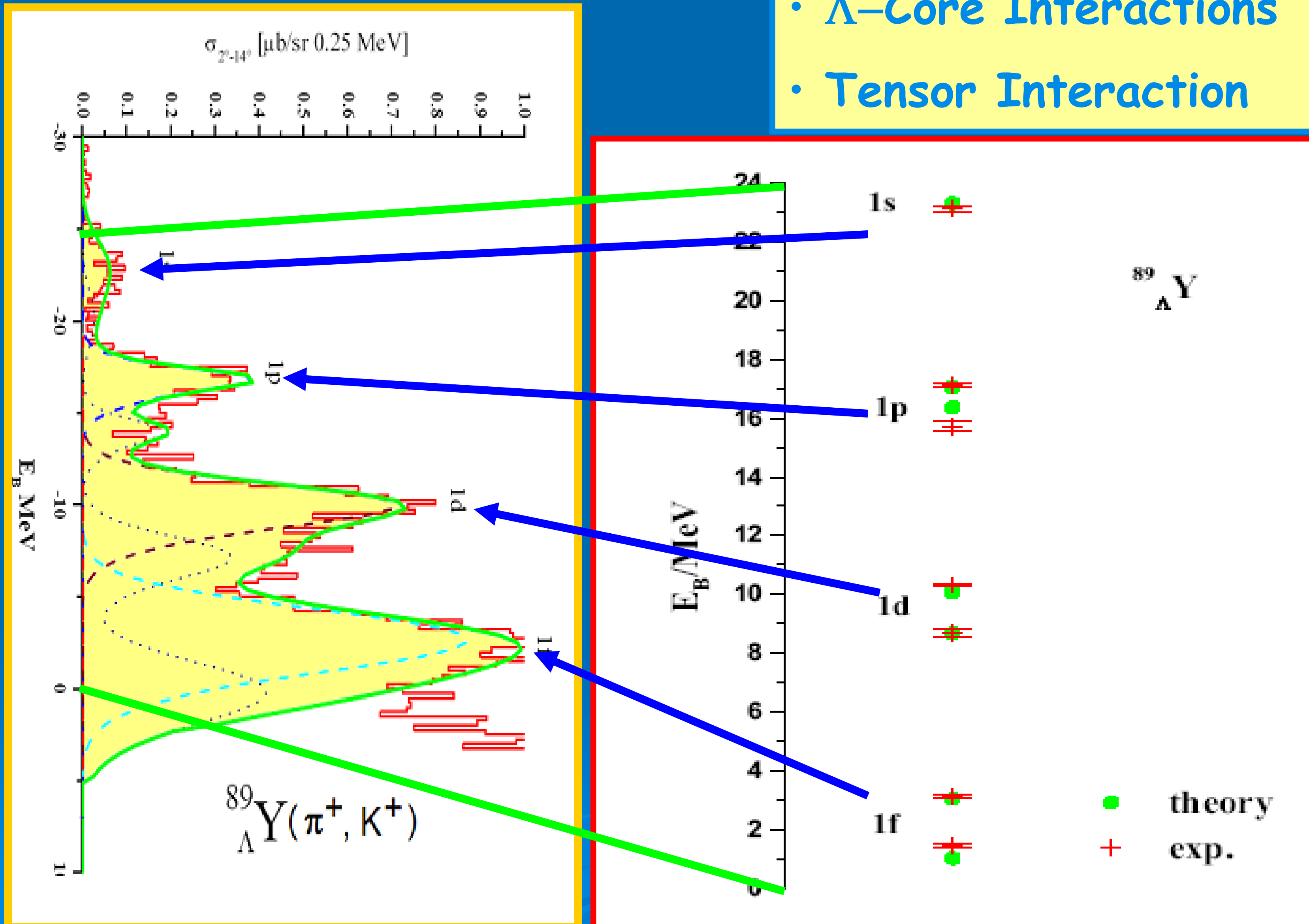
DDRH Flavour Dynamics: Λ Single Particle Energies



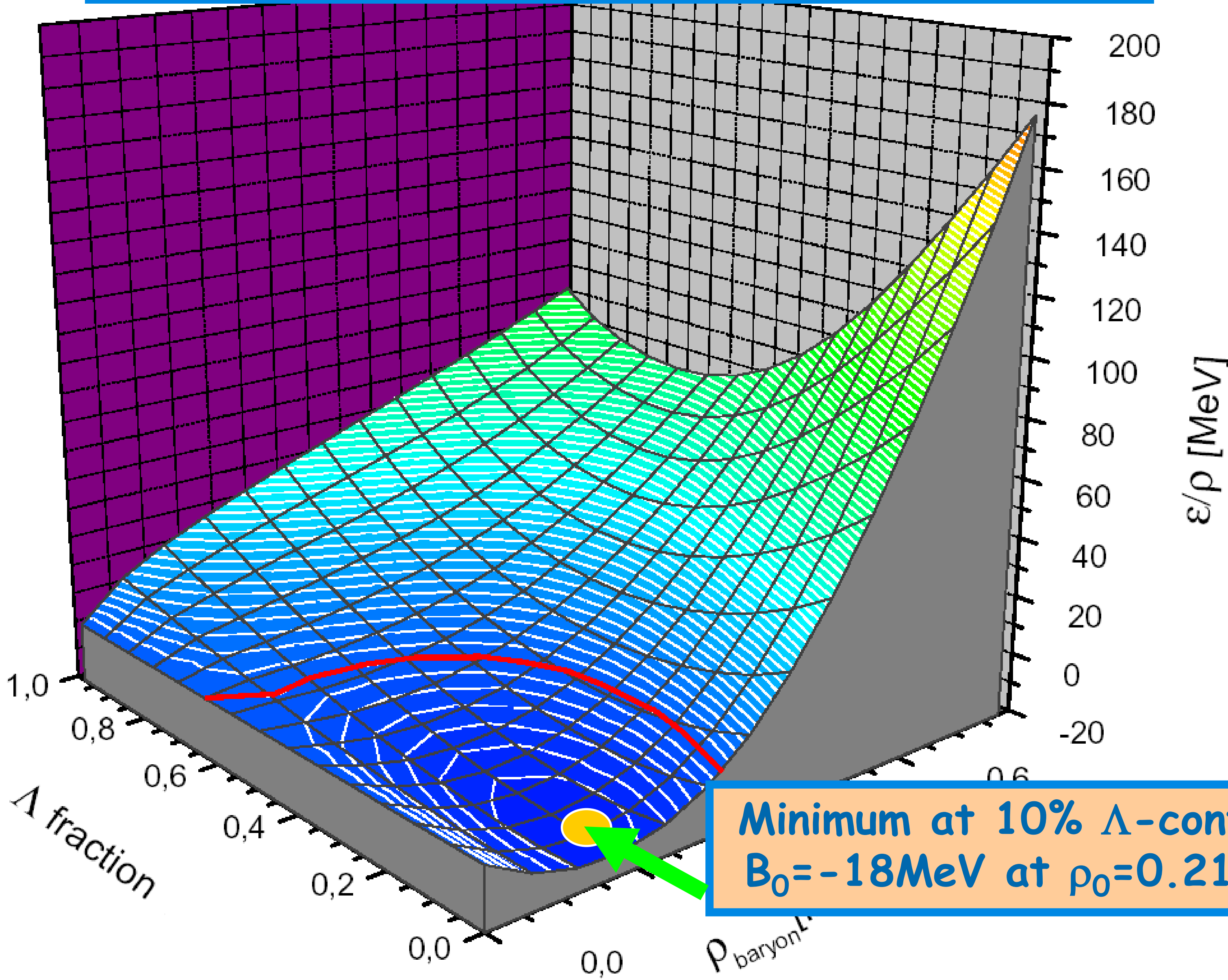
Density Dependent NN and NΛ Dirac-Brueckner Vertices

DDRH Spectrum for ^{89}Y:

- $^{89}Y = \Lambda + {}^{88}Y(4-, g.s.)$
- Λ–Core Interactions
- Tensor Interaction



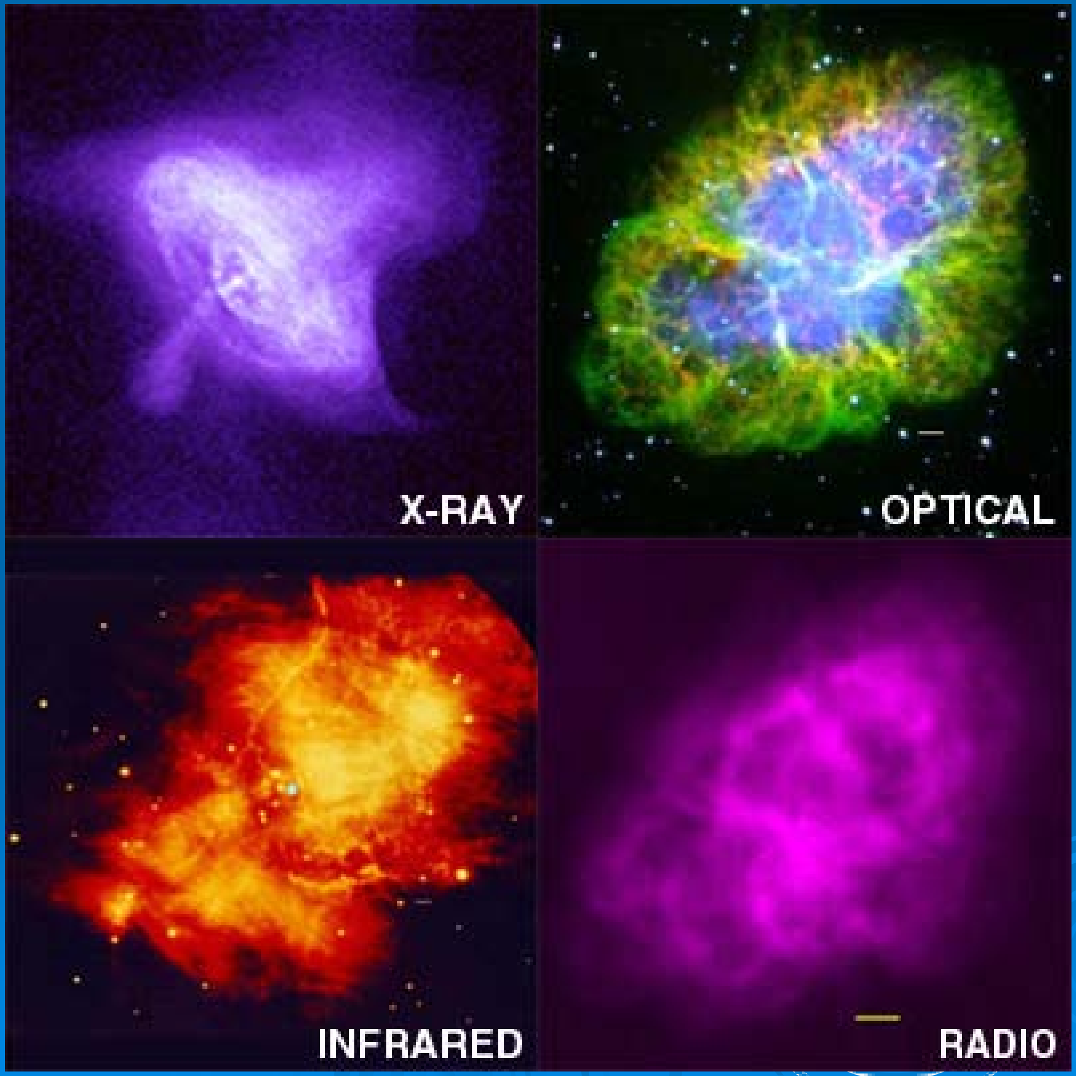
DDRH Hypermatter Equation of State (Binding Energy per Baryon)



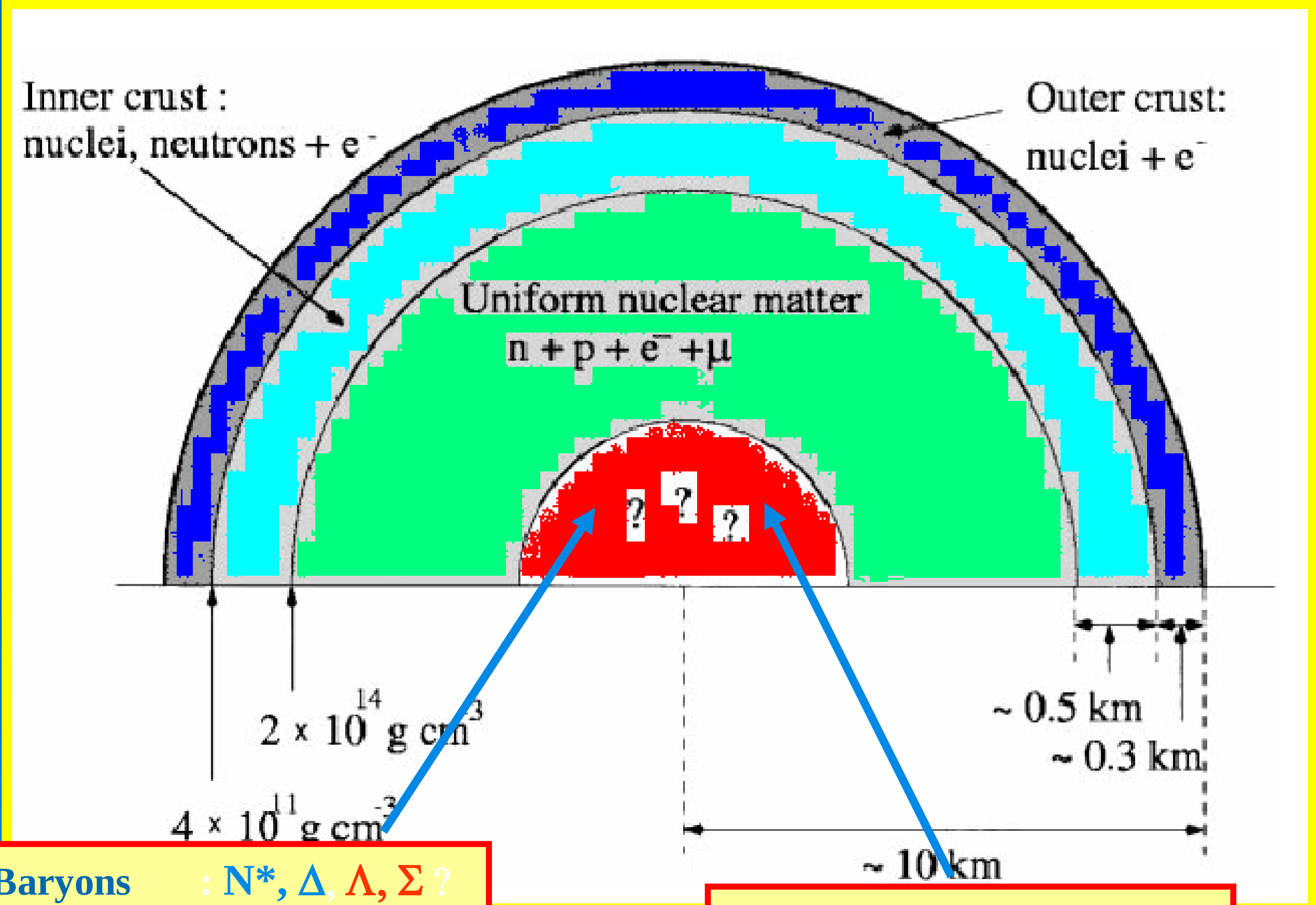
Minimum at 10% Λ-content: B_0=-18MeV at ρ_0=0.21fm^{-3}

Fall in Beauty - the End of a Star ($M>8M_S$):

The Crab Nebula Neutron Star



Expected Structure of a Neutron Star



Baryons : N*, Δ, Λ, Σ ?
Condensates: π, K ... ?

Quark Matter, QGP, CFL?

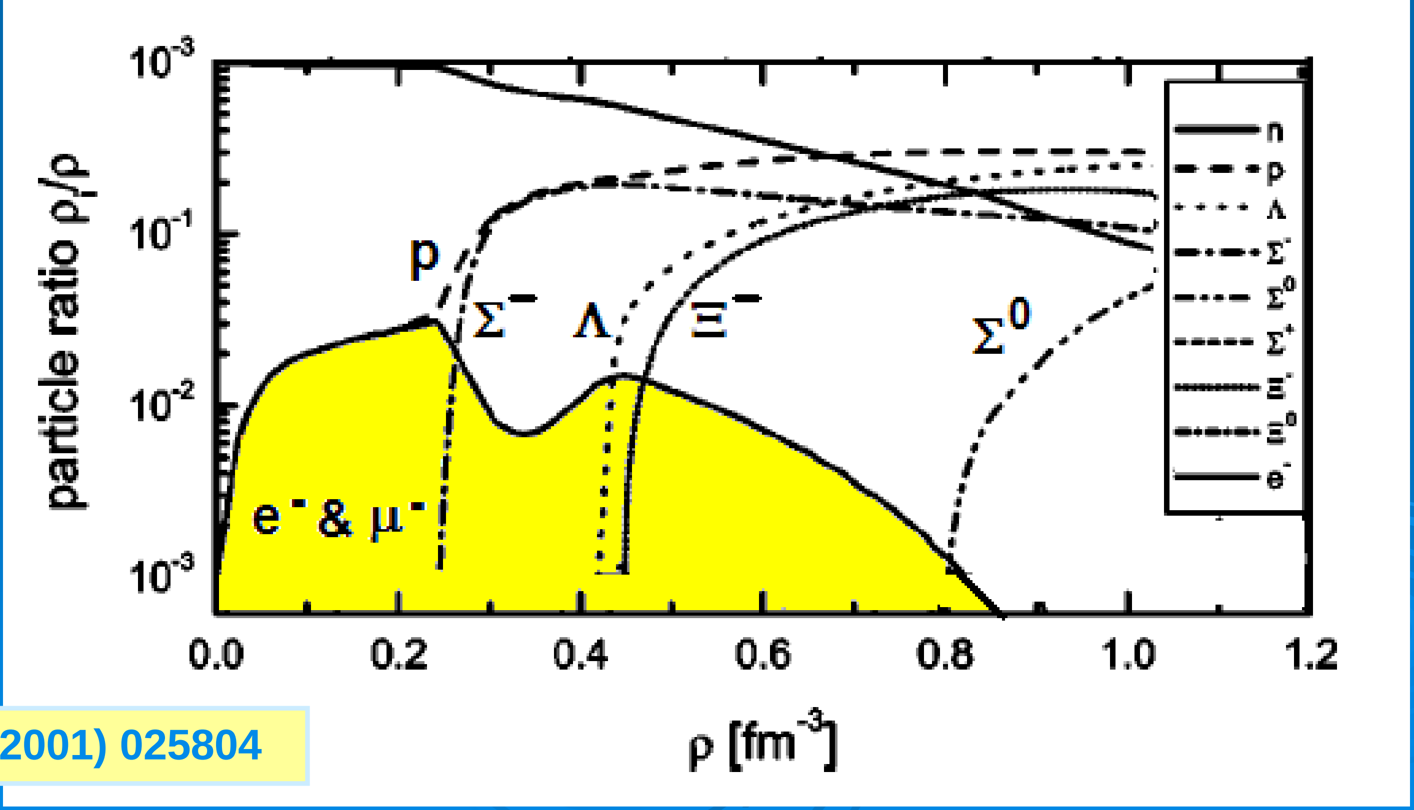
Charge-Neutral Neutron Star Matter in β-Equilibrium

$$n \leftrightarrow p + e^- + \bar{\nu}_e \quad ; \; N+N \leftrightarrow N+Y+\bar{K} \; ; \Delta \leftrightarrow N + \pi$$

$$\lambda_n = \lambda_p + \lambda_{e^-} + \lambda_{\bar{\nu}}; \qquad \bar{K} \rightarrow 2\gamma, \mu + \nu$$

Appearance of Strangeness:

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



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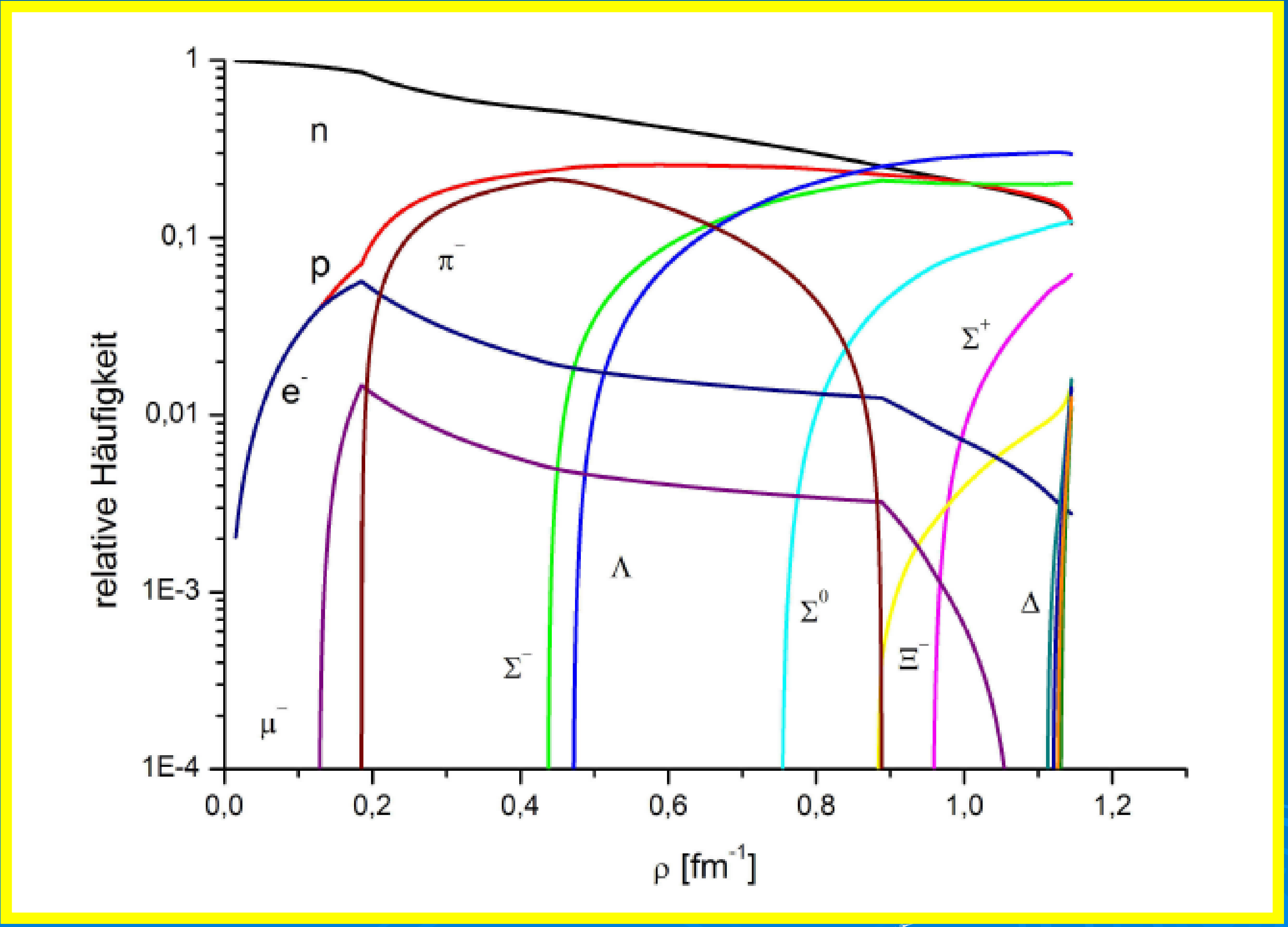
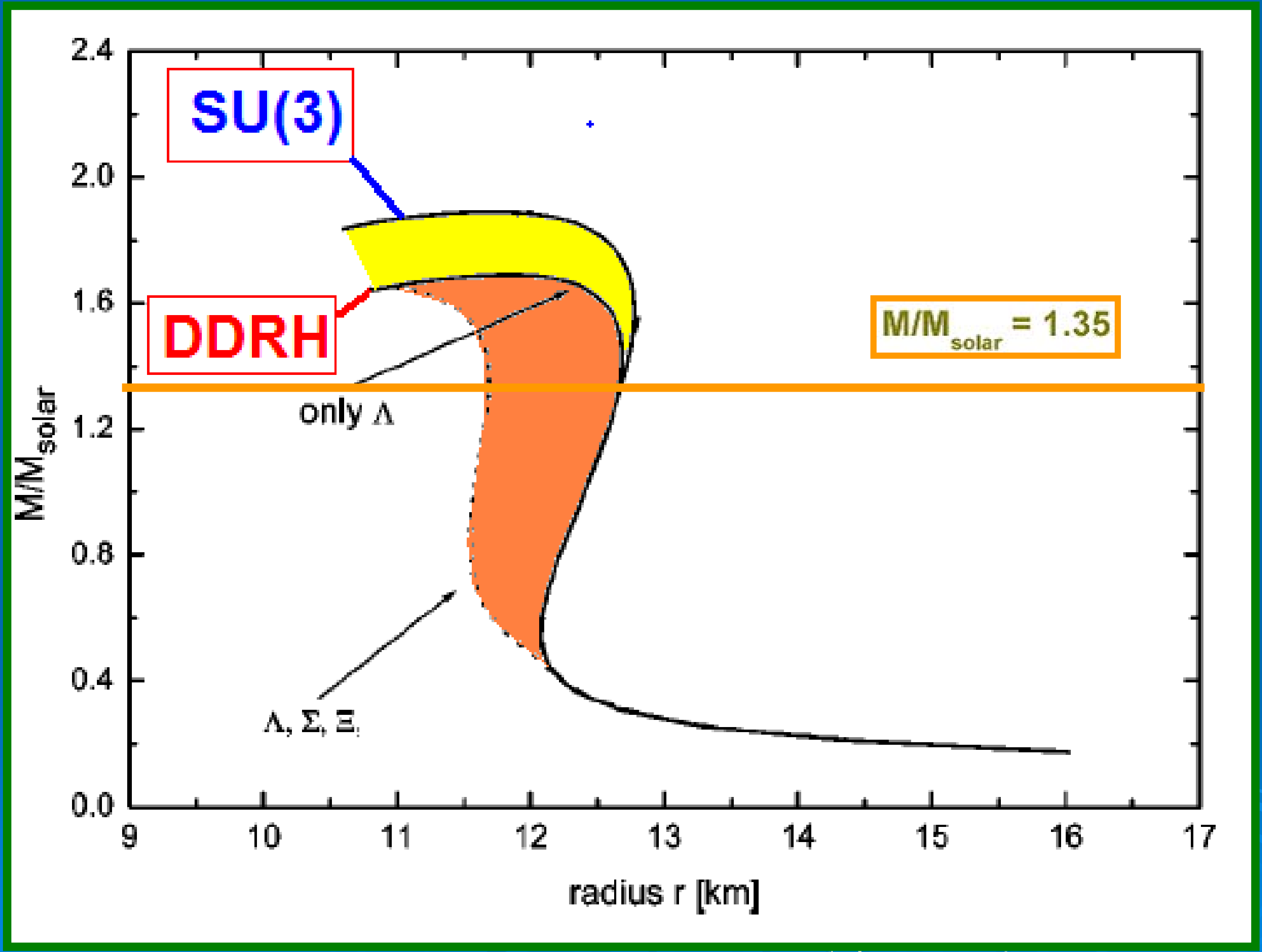
Baryon Resonances in Neutron Stars?



Hyperon Interactions and Neutron Stars

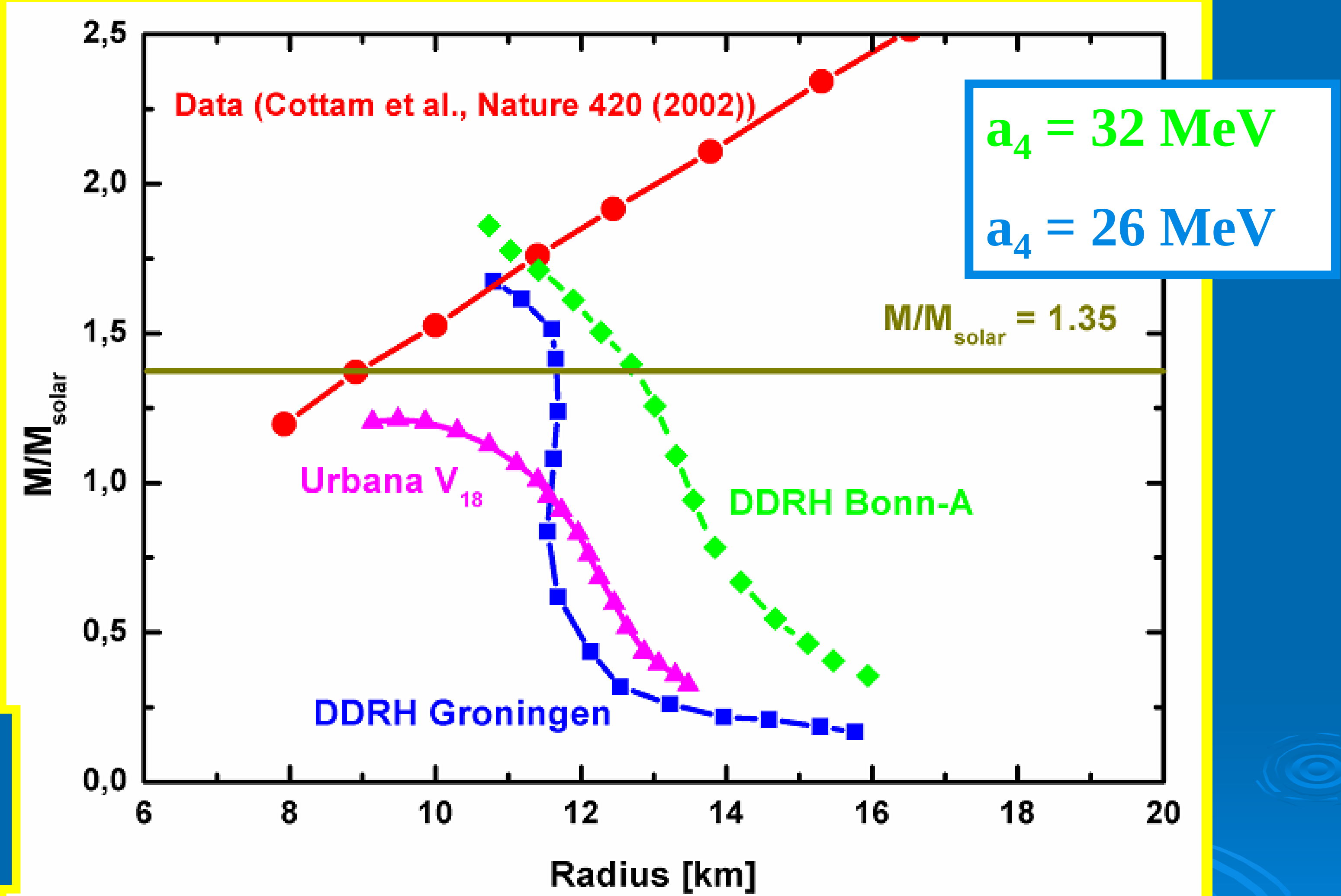


DDRH Neutron Star Mass-Radius Relation (TOV Eq.):

X-ray

Optical

Crab Nebula
Chandra X-Ray
Observatory
and HST



Data: XMM-Newton X-ray space observatory

Gravitational Red-Shift z =0.35 ~ (-G/c^2)M/R

(Fe-Lines from a series of 28 X-ray bursts from EXO07481676)

$\Lambda\Sigma^0$ Mixing in Asymmetric Nuclear Matter

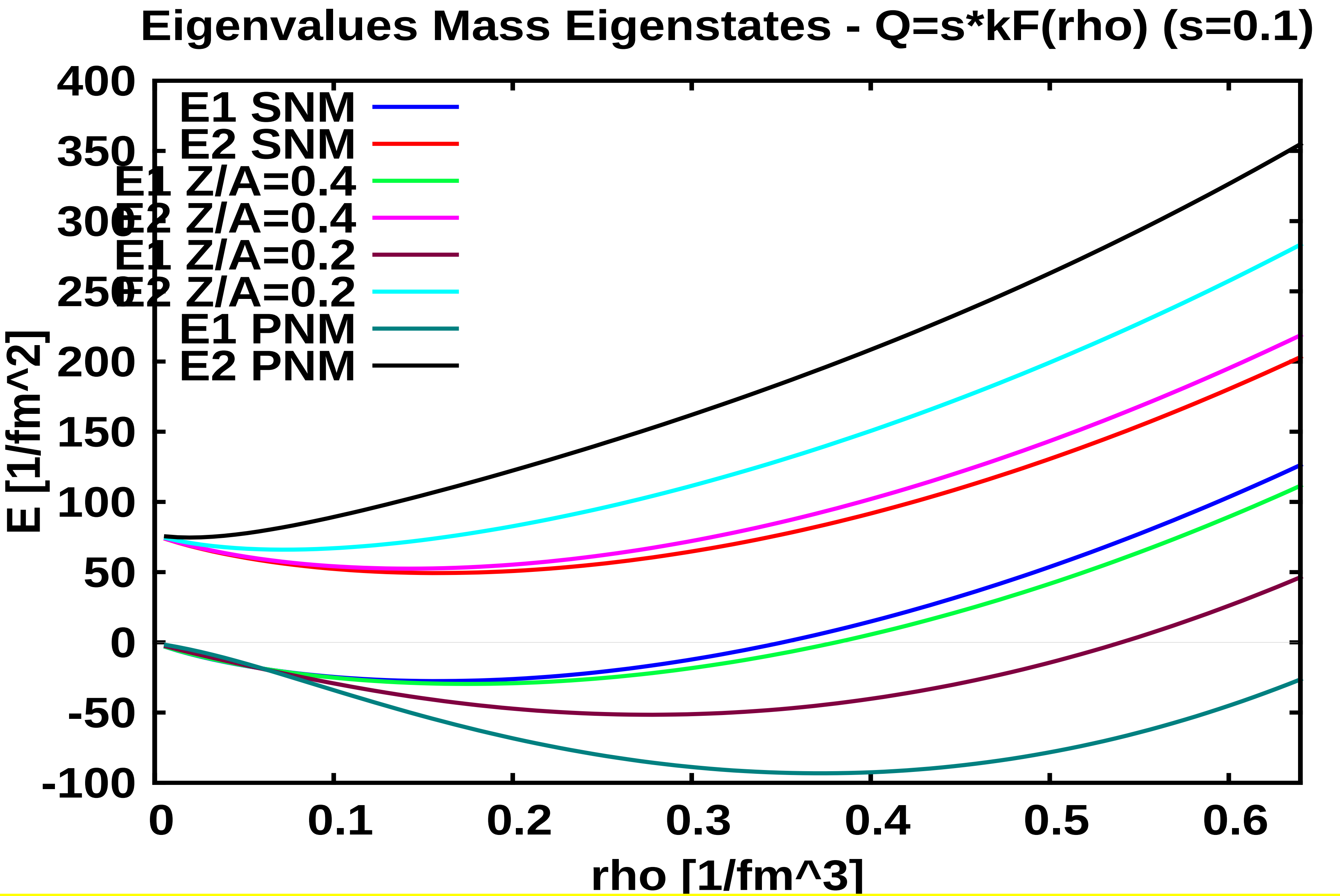
$$M_{\Lambda\Sigma} \equiv \langle N,Z | V_\rho^0 \tau_3 | N,Z \rangle \cong \frac{g^\rho_{\Lambda\Sigma}}{g^\rho_{NN}} \left(\frac{g^\rho_{NN}}{m_\rho} \right)^2 (\rho_n - \rho_p)$$

- $\Lambda\Sigma^0$ *CC* Problem → *Mass* Eigenstates (Δm~77MeV):

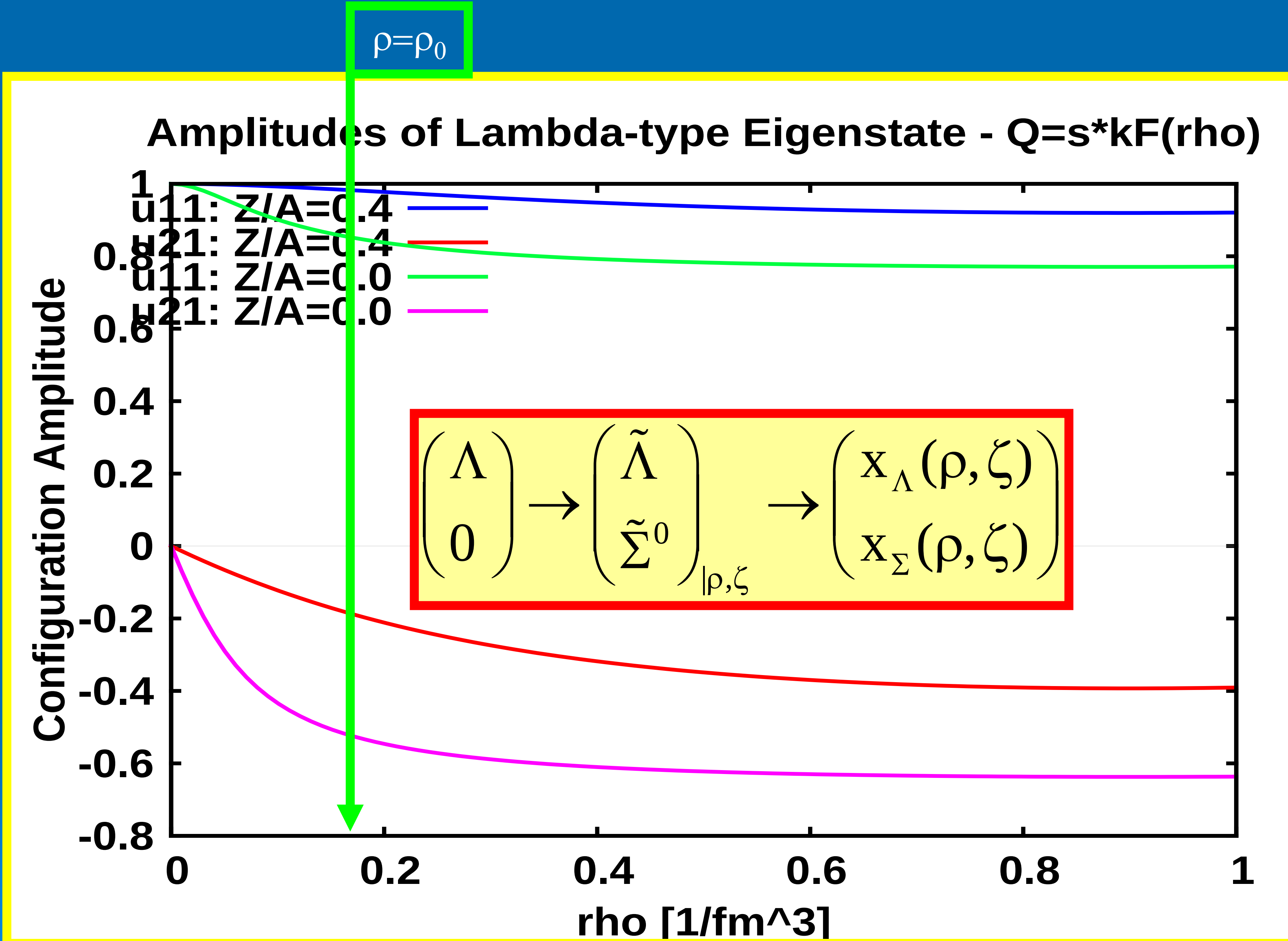
$$\begin{pmatrix} h_\Lambda - E & M_{\Lambda\Sigma} \\ M^\dagger_{\Lambda\Sigma} & h_\Sigma + \Delta m - E \end{pmatrix} \begin{pmatrix} \Psi_\Lambda \\ \Psi_\Sigma \end{pmatrix} = 0$$

- Flavor Eigenstates Φ → *Mass* Eigenstates Ψ:

$$\begin{pmatrix} \Psi_\Lambda \\ \Psi_\Sigma \end{pmatrix} = \begin{pmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{pmatrix} \begin{pmatrix} \Phi_\Lambda \\ \Phi_\Sigma \end{pmatrix} \quad ; \quad \tan 2\varphi = \frac{2M_{\Lambda\Sigma}}{h_\Lambda - h_\Sigma - \Delta m}$$



Eigenvalues Mass Eigenstates - Q=s*kF(rho) (s=0.1)
E1 SNM
E2 SNM
E1 Z/A=0.4
E2 Z/A=0.4
E1 Z/A=0.2
E2 Z/A=0.2
E1 PNM
E2 PNM
E [1/fm^2]
400
350
300
250
200
150
100
50
0
-50
-100
0
0.1
0.2
0.3
0.4
0.5
0.6
rho [1/fm^3]



ρ=ρ0
Amplitudes of Lambda-type Eigenstate - Q=s*kF(rho)
u11: Z/A=0.4
u21: Z/A=0.4
u11: Z/A=0.0
u21: Z/A=0.0
Configuration Amplitude
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
0.2
0.4
0.6
0.8
1
rho [1/fm^3]
$\begin{pmatrix}\Lambda\\0\end{pmatrix} \to \begin{pmatrix}\tilde{\Lambda}\\\tilde{\Sigma}^0\end{pmatrix}_{|\rho,\zeta} \to \begin{pmatrix}x_\Lambda(\rho,\zeta)\\x_\Sigma(\rho,\zeta)\end{pmatrix}$

Summary, Conclusions and Outlook

- Hadrons on Cosmic Scales
- QCD in Nuclei: EFT at the Fermi-Momentum Scale
- Relativistic Field Theory for Nuclei and Hypernuclei
- Productions of Hypernuclei
- Investigations of Nuclei, Hypernuclei and Neutron Stars
- Λ–Σ^0 Flavor Mixing in Asymmetric Matter
- Open Problem: YY Interactions
- Dynamical Correlations and Hyperon Spectral Functions

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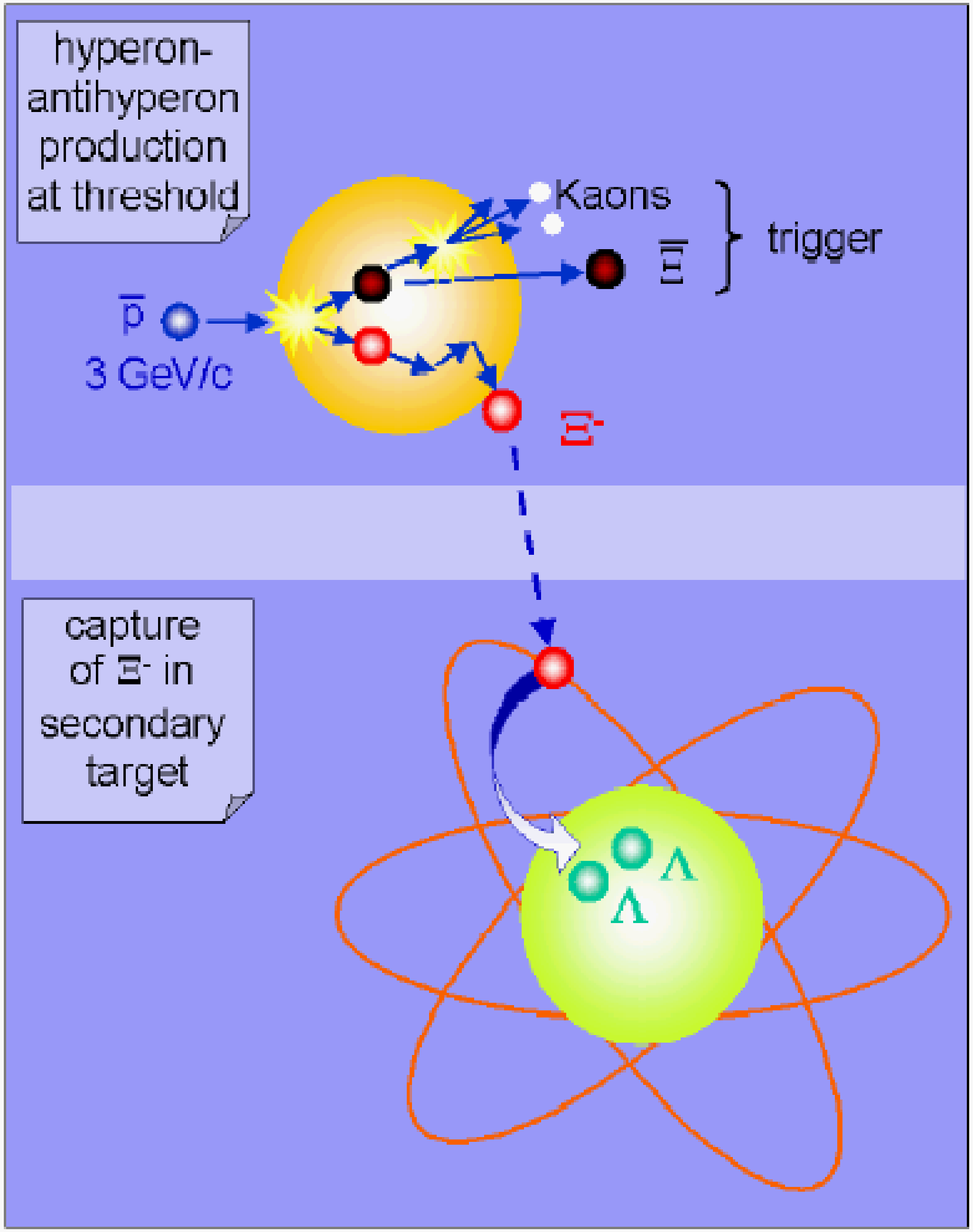
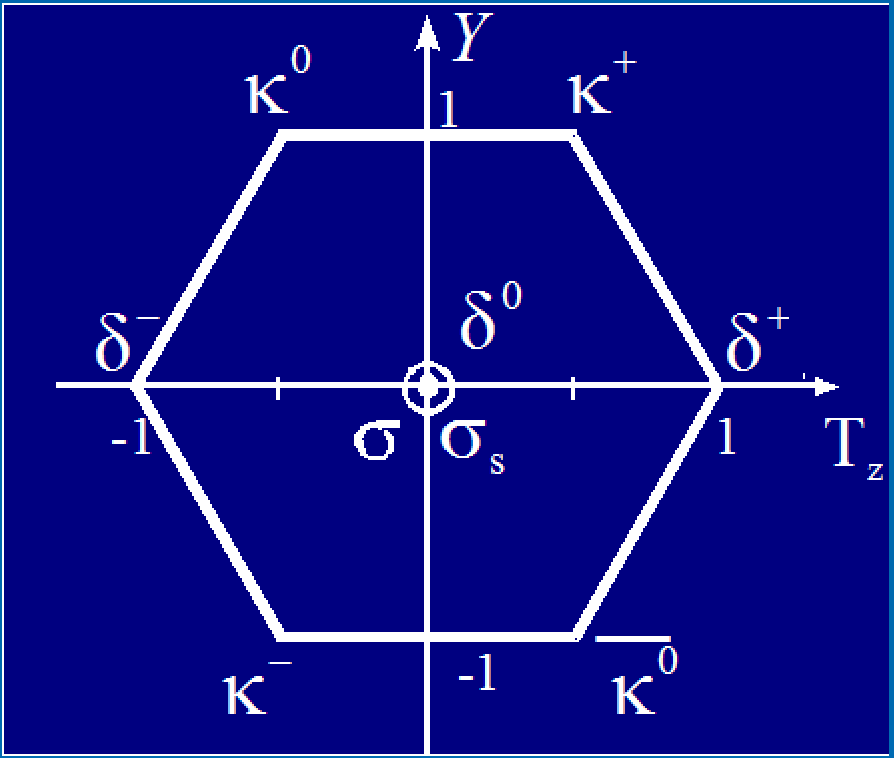
Hypernuclear Physics with PANDA at FAIR@GSI:

Production of Double-Λ Hypernuclei by Ξ^- Capture and subsequent Decay in a 2-step Process



The 0^+ Scalar Meson Nonet



PDG:

- σ/f0(600); Γ ~ 600-1000MeV: → $\pi\pi$
- **δ/a_0(980); Γ~50…100MeV: → $\eta\pi, K\bar{K}$**
- f_0(975); Γ~40…100MeV: → $\pi\pi, K\bar{K}$

Strange Mesons and ΛΛ Binding

$^{6}_{\Lambda\Lambda}$He

DDRH **without** ϕ, σ_s:

$\Delta B_{\Lambda\Lambda}$ = -0.1 MeV
$B_{\Lambda\Lambda}$ = 3.26 MeV

experimental finding:
$\Delta B_{\Lambda\Lambda}$ = 1.01±0.3 MeV
$B_{\Lambda\Lambda}$ ~ 7.14±0.3 MeV

adding ϕ:

SU(3): $$g_{\Lambda\Lambda\phi} = -\frac{\sqrt{2}}{3} g_{NN\omega}$$

and σ_s:
no theoretical constraints

$^{6}_{\Lambda\Lambda}$He

DDRH **with** ϕ, σ_s:

$$-\frac{\sqrt{2}}{3} g_{NN\omega}(\rho = 0) = 10.6$$

$$-\frac{\sqrt{2}}{3} g_{NN\omega}(\rho = \rho_0) = 5.3$$

$g_{\phi\Lambda\Lambda}$	$g_{\sigma s\Lambda\Lambda}$	$B_{\Lambda\Lambda}$	$\Delta B_{\Lambda\Lambda}$
10.6	11	2.1196	0.4862
	11.5	3.1647	1.0939
	12	4.7123	2.1149
7.47	8.5	2.4496	0.6718
	8.85	3.0385	1.0203
	9	3.333	1.2028
5	6	1.8368	0.3362
	6.3	2.1209	0.4885
	7	2.9751	0.9833