Introduction, Motivations: QMC model

Motivations

- **(Large) nuclei,** and **nuclear matter** in terms of **quarks** and **gluons**

(**eventually** by **QCD**) **???!!!**

- **NN**,NNN,NNNN... interactions →

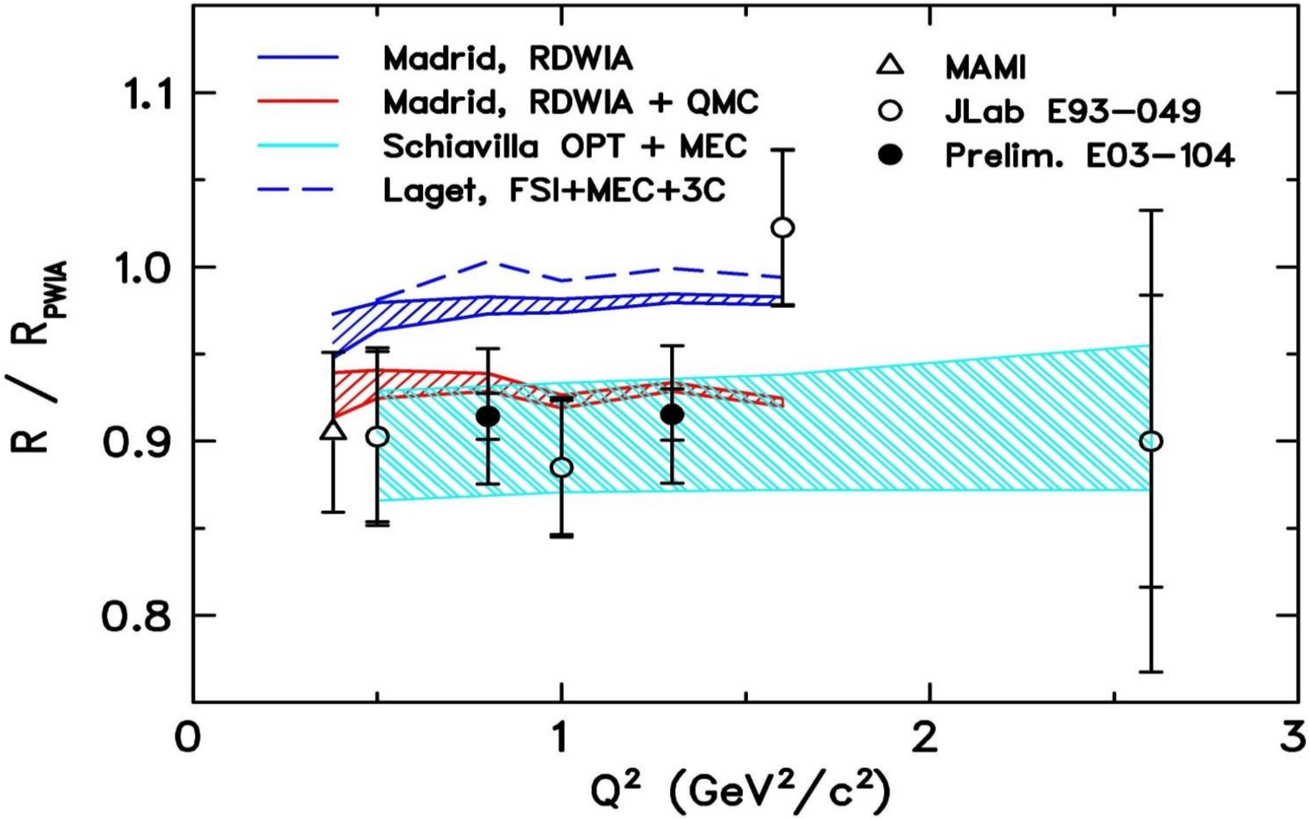
 Nucleus ? ← shell model, MF model,...

- **Lattice QCD**: still extracting **NN, NY and YY** interactions, [**Y**=hyperons:**Λ,Σ,Ξ**]
- **Quark model** based description of **nucleus**
- **Hadron** properties **in a nuclear medium**

$R = (p'_x / p'_z) = (G_E^p / G_M^p)$: $^4He / ^1H$

S. Malace, M. Paolone and S. Strauch, arXiv:0807.2251 [nucl-ex]

S. Strauch *et al., Phys. Rev. Lett.* ***91, 052301 (2003)***

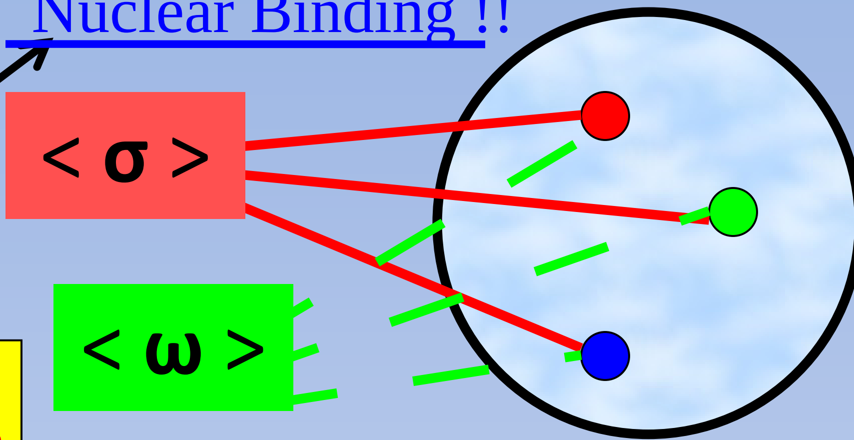


The QMC model P. Guichon, PLB 200, 235 (1988)

(For a review, PPNP 58, 1 (2007))

Light (**u,d**) **quarks** interact **self-consistently** with mean **σ** and **ω** fields

Nuclear Binding !!



$m^*_q = m_q - g^q_\sigma \sigma = m_q - V^q_\sigma$

↓ nonlinear in **σ**

$M^*_N \approx M_N - g^N_\sigma \sigma + \underline{(d/2)\,(g^N_\sigma \sigma)^2}$

$M^*_N = M_N - V^N_\sigma$

$[\, i \gamma \cdot \partial - (m_q - V^q_\sigma) + \gamma_0 V^q_\omega \,]\; q = 0$

1. Start

$[i \gamma \cdot \partial - M^*_N + \gamma_0 V^N_\omega]\, N = 0$

$V^N_\omega = 3 V^q_\omega$

Self-consistent !

(Applied quark model !)

Bound quark Dirac spinor ($1s_{1/2}$)

Quark Dirac spinor in a **bound hadron:**

$$q_{1s}(r) = \begin{pmatrix} U(r) \\ i\sigma\cdot\hat{r}\, L(r) \end{pmatrix} \chi$$

Lower component is **enhanced** !

⇒ $g_{A^*} < g_A$: ~ $|U|^{**}2 - (1/3)\, |L|^{**}2$,

⇒ **Decrease** of scalar density ⇒

Decrease in **Scalar Density**

Scalar density (quark): ~ **|U|**2 - |L|**2**,

⇓

M_N*, **N** wave function, **Nuclear** scalar density etc., are **self-consistently modified** due to the N **internal structure** change !

⇒ **Novel Saturation** mechanism !

At Nucleon Level Response to the Applied Scalar Field is the Scalar Polarizability

Nucleon response to **a chiral invariant scalar field** is then a nucleon property of great interest…

$$M^*(\vec{R}) \approx M - g_\sigma \sigma(\vec{R}) + (d/2)\,(g_\sigma \sigma(\vec{R}))^{**2}$$

Non-linear dependence **scalar polarizability**

0.22 d**¼ R in original QMC (MIT bag)

Indeed, in nuclear matter at mean-field level (e.g. QMC), this is the **ONLY place the response of the internal structure of the nucleon enters.**

Nuclear (Neutron) matter, E/A

Novel saturation mechanism !

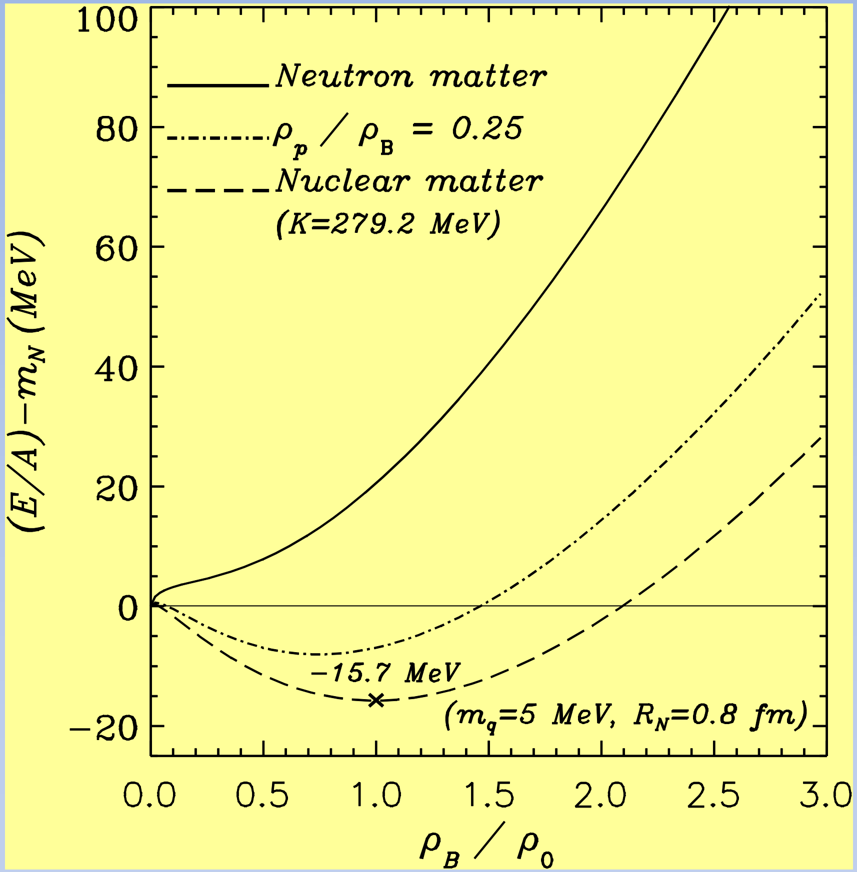
Incompressibility

QHD: K ≈ 500 MeV

QMC: K ≈ 280 MeV

(Exp. 200 ~ 300 MeV)

PLB 429, 239 (1998)



Finite nuclei (^{208}**Pb** energy levels)

NPA 609, 339 (1996)

Large mass **nuclei**

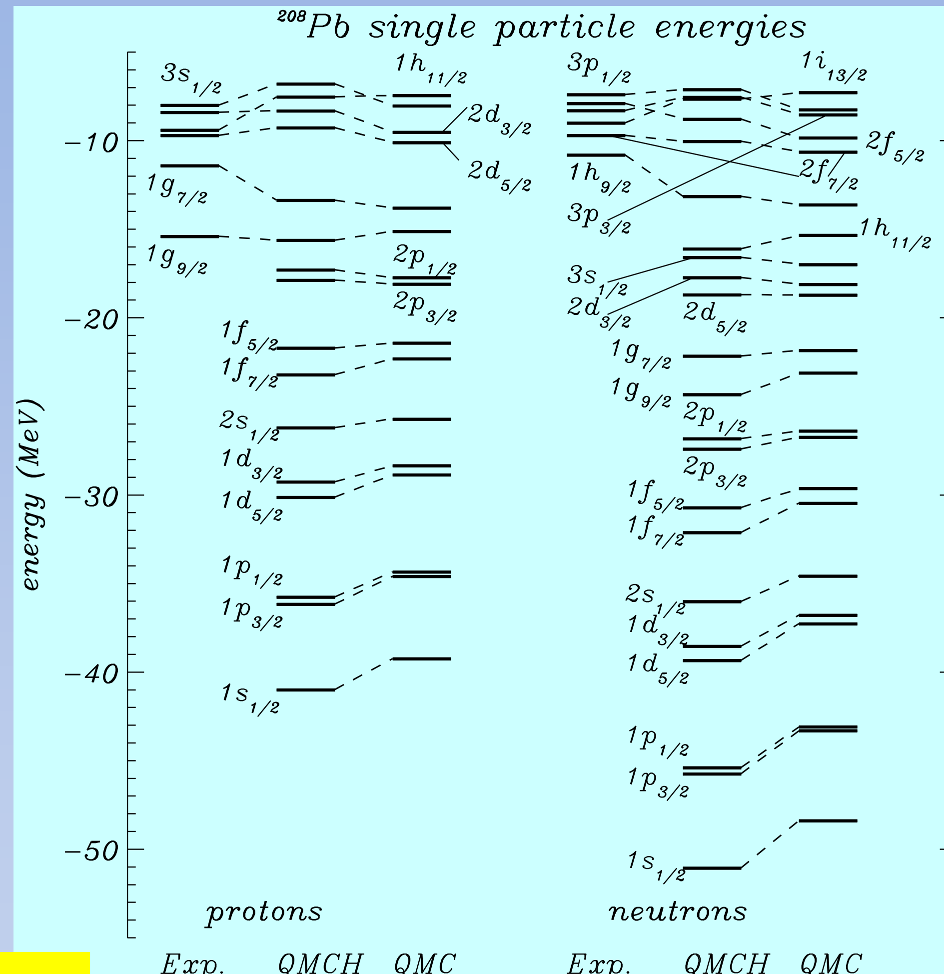
Nuclear matter

<u>Based on **quarks**</u> !

↓

Hadrons

Hypernuclei



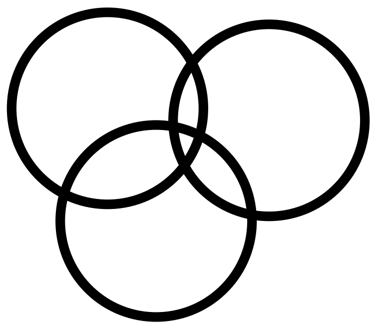
latest QMC, NPA 814, 66 (2008)

Summary : Scalar Polarizability

- Can always rewrite **non-linear coupling** as linear coupling plus non-linear scalar self-coupling – **likely physical origin of <u>non-linear versions of QHD</u>**

- In nuclear matter this is **the only place** the internal structure of the nucleon enters in MFA

- Consequence of **polarizability** in atomic physics is **many-body forces**:



$$V = V_{12} + V_{23} + V_{13} + V_{123}$$

QMC • • QHD

- QHD shows importance of **relativity** :
  mean **σ, ω** and **ρ** fields
- **QMC** goes **far beyond QHD** by incorporating effect of hadron ***internal structure***
- Minimal model couples these mesons to ***quarks*** in relativistic quark model – e.g. MIT bag, or confining NJL
- g_σ^q , g_ω^q, g_ρ^q fitted to ρ_0 , **E/A** and **symmetry energy**

- ***No additional parameters :*** predict change of structure and binding in nuclear matter of **all hadrons**:
  e.g. **ω, ρ, η, J/ψ, N, Λ, Σ, Ξ** • see later !

Linking QMC to Familiar Nuclear Theory

Since early 70's tremendous amount of work
in nuclear theory is based upon **effective forces**

- Used for everything from nuclear astrophysics to collective excitations of nuclei

- **Skyrme Force**: Vautherin and Brink

In Paper : **Guichon and Thomas, Phys. Rev. Lett. 93, 132502 (2004)**

explicitly obtained **effective force**, 2- plus 3- body, of **Skyrme type**

- **equivalent** to **QMC** model (required expansion around $\sigma = 0$)

Physical Origin of Density Dependent Force of the Skyrme Type within the QMC model

That is, apply new **effective force** directly to calculate nuclear properties using Hartree-Fock (as for usual well known force)

	E_B (MeV, exp)	E_B (MeV, QMC)	r_c (fm, exp)	r_c (fm, QMC)
^{16}O	7.976	7.618	2.73	2.702
^{40}Ca	8.551	8.213	3.485	3.415
^{48}Ca	8.666	8.343	3.484	3.468
^{208}Pb	7.867	7.515	5.5	5.42

» 4%

» 1%

- Where analytic form of (e.g. $H_0 + H_3$) piece of energy functional derived from QMC is:

$$\mathcal{H}_0 + \mathcal{H}_3 = \rho^2 \left[\frac{-3\,G_\rho}{32} + \frac{G_\sigma}{8\,(1 + d\rho\, G_\sigma)^3} - \frac{G_\sigma}{2\,(1 + d\rho\, G_\sigma)} + \frac{3\,G_\omega}{8} \right] + (\rho_n - \rho_p)^2 \left[\frac{5\,G_\rho}{32} + \frac{G_\sigma}{8\,(1 + d\rho\, G_\sigma)^3} - \frac{G_\omega}{8} \right],$$

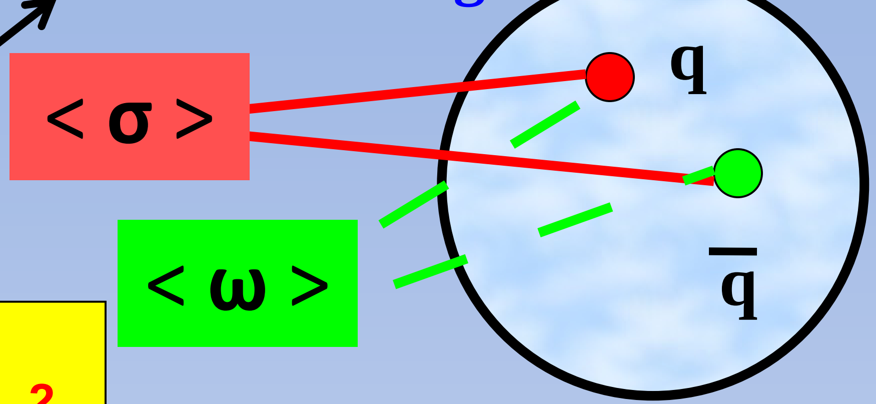
highlights scalar polarizability

Mesons in nuclear medium in **QMC**

(For a review, PPNP 58, 1 (2007))

Light (**u,d**) **quarks** interact self-consistently with mean **σ** and **ω** fields

Nuclear Binding !!



$m^*_q = m_q - g^q_\sigma \sigma = m_q - V^q_\sigma$

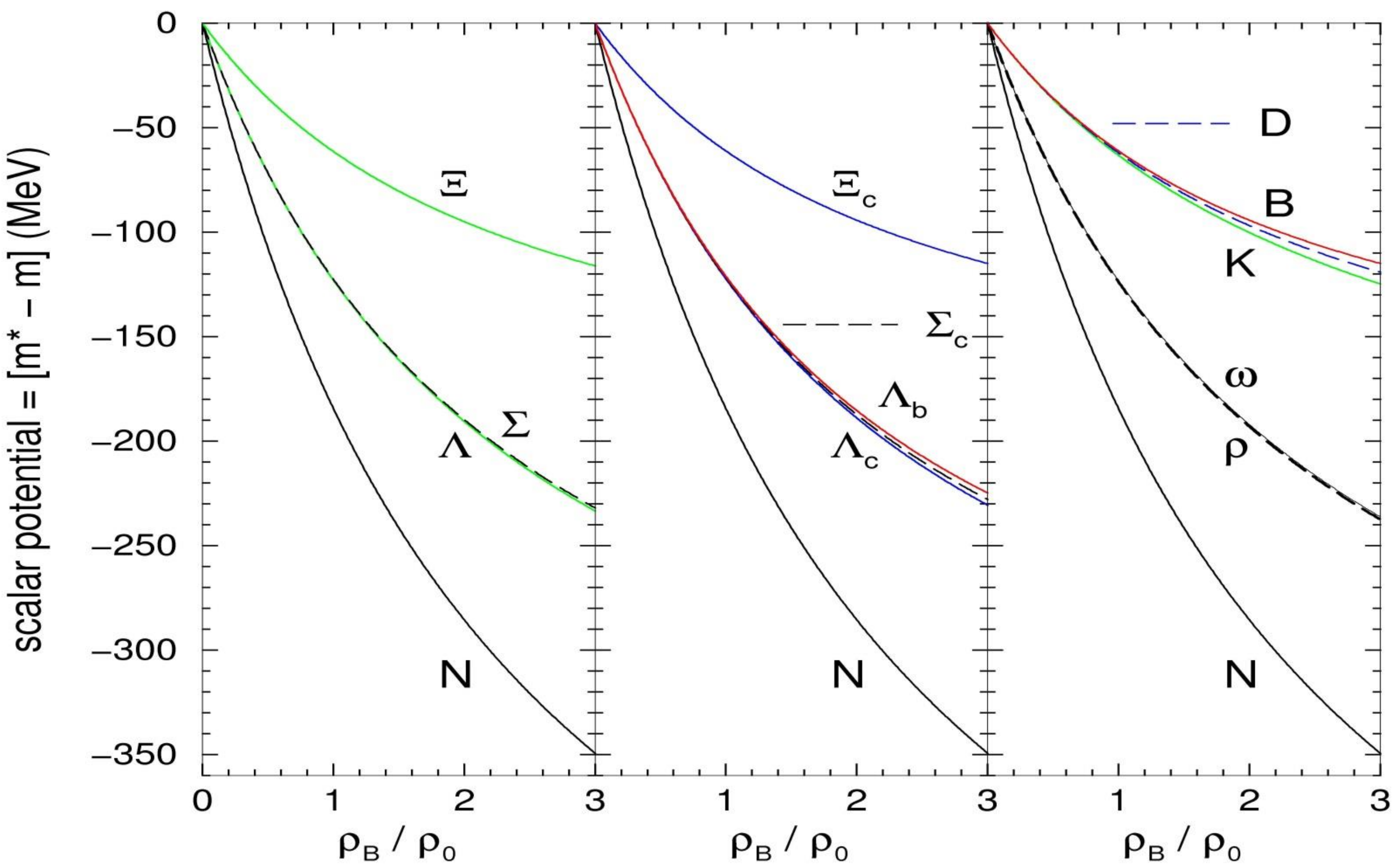
↓ **nonlinear** in **σ**

$M^*_M \approx M_M - g^M_\sigma \sigma + (d^M/2)\ (g^M_\sigma \sigma)^2$

$[\ i\gamma\cdot\partial - (m_q - V^q_\sigma) + \gamma_0 V^q_\omega\ ]\ q = 0$

σ,ω fields: **no couplings** with **s,c,b** quarks**!!**

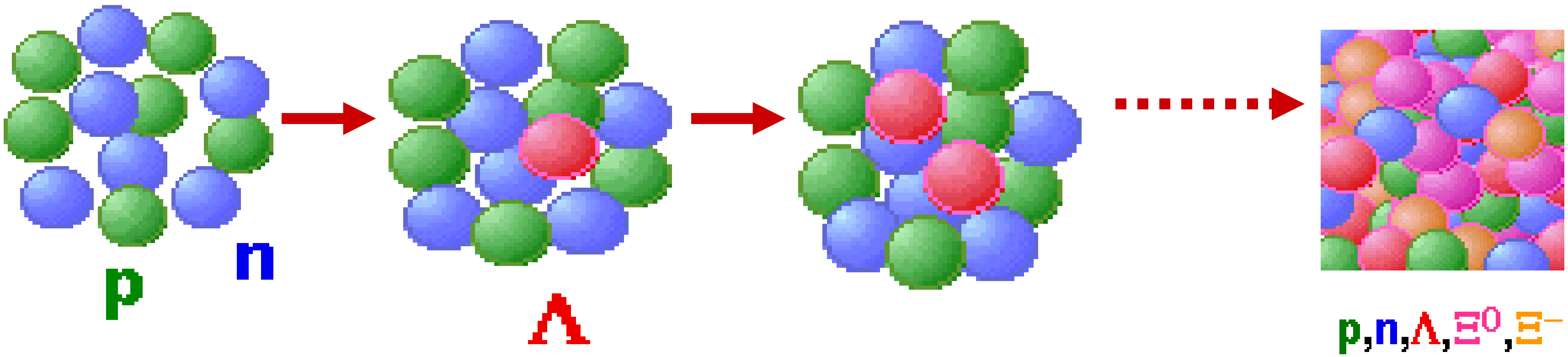
Scalar potentials in **QMC** respects **SU(3)** (**light quark # !**)



Hypernuclei
(Introduction)

What are Hypernuclei ?

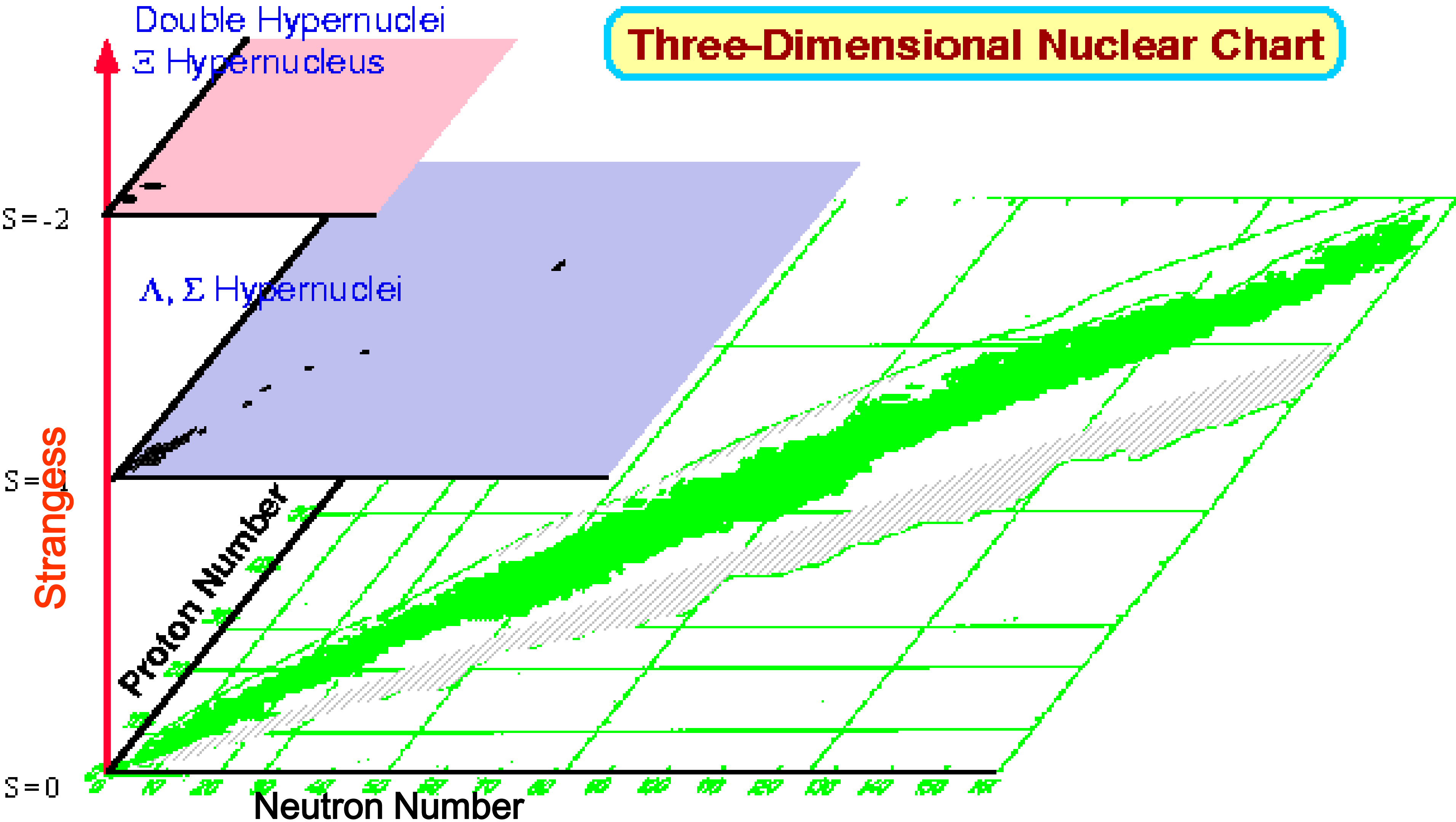
Hypernuclei are nuclear systems where at least one nucleon is replaced by a hyperon (e.g. Λ).

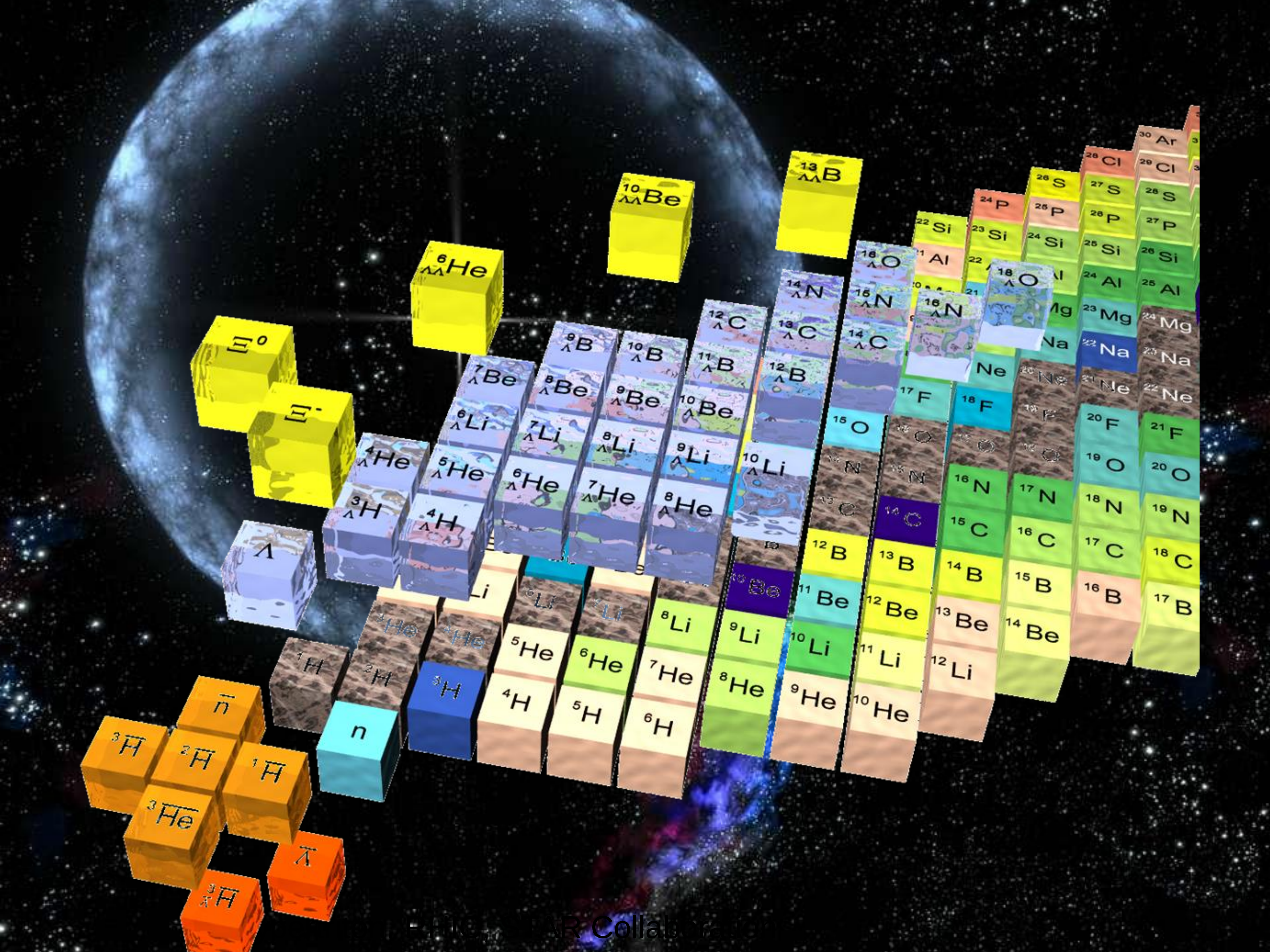


$^{A}_{\Lambda}Z$ is a bound state of Z protons (A-Z-1) neutrons and a Λ hyperon

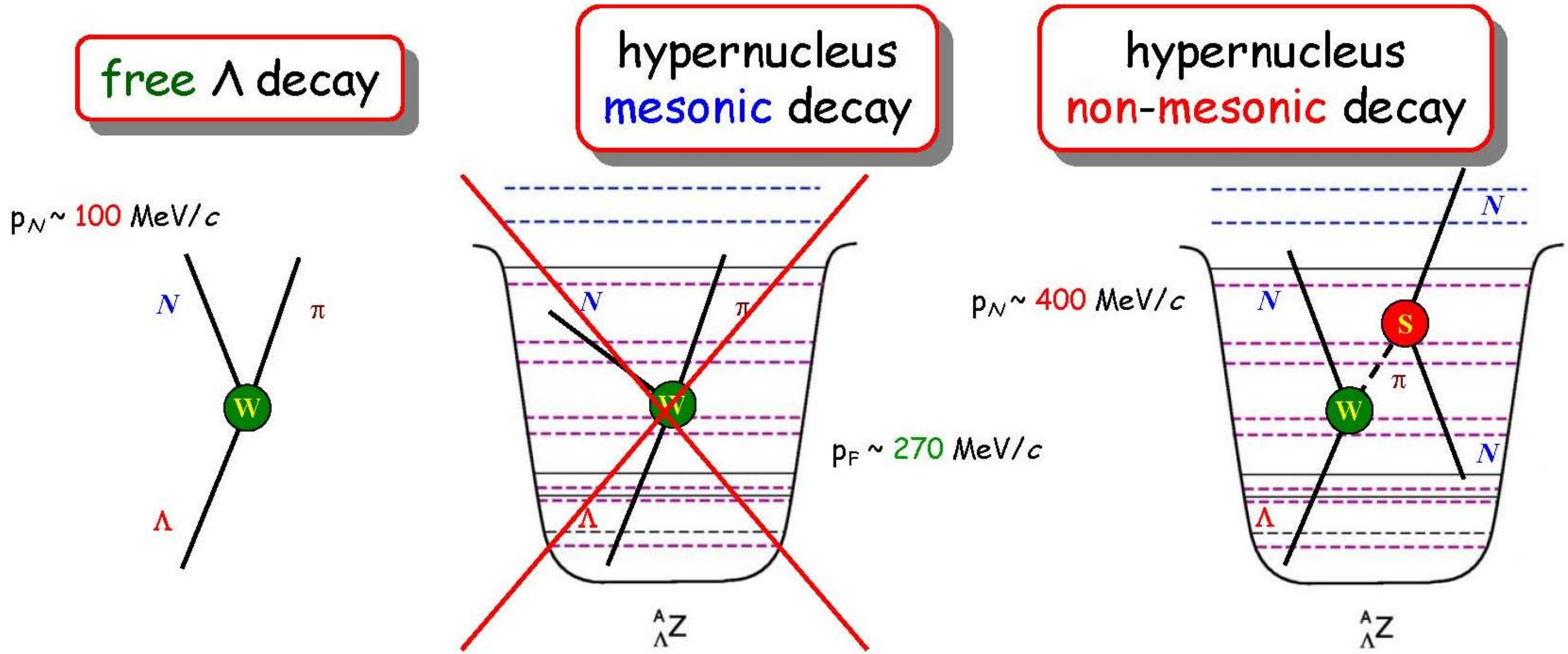
Hypernuclei are a laboratory to study the hyperon-nucleon, Hyperon-hyperon interactions.

S = - 2, Ξ-Hypernuclei at J-PARC, JAPAN by (K^-, K^+) reaction, the first evidence. (KISO Event, Ξ^- - ^{14}N system)




Ξ⁰
Ξ⁻
Λ
n
RHIC, STAR Collaboration

Λ hyperon can stay in contact with nucleons inside a Nucleus



$\Lambda \rightarrow n + \pi^0 + 41$ MeV (36%)

$\Lambda \rightarrow p + \pi^- + 38$ MeV (64%)

$\tau_\Lambda = 263$ ps

suppressed by Pauli blocking

$\Lambda + n \rightarrow n + n + 176$ MeV

$\Lambda + p \rightarrow n + p + 176$ MeV

Why are Hypernuclei interesting!

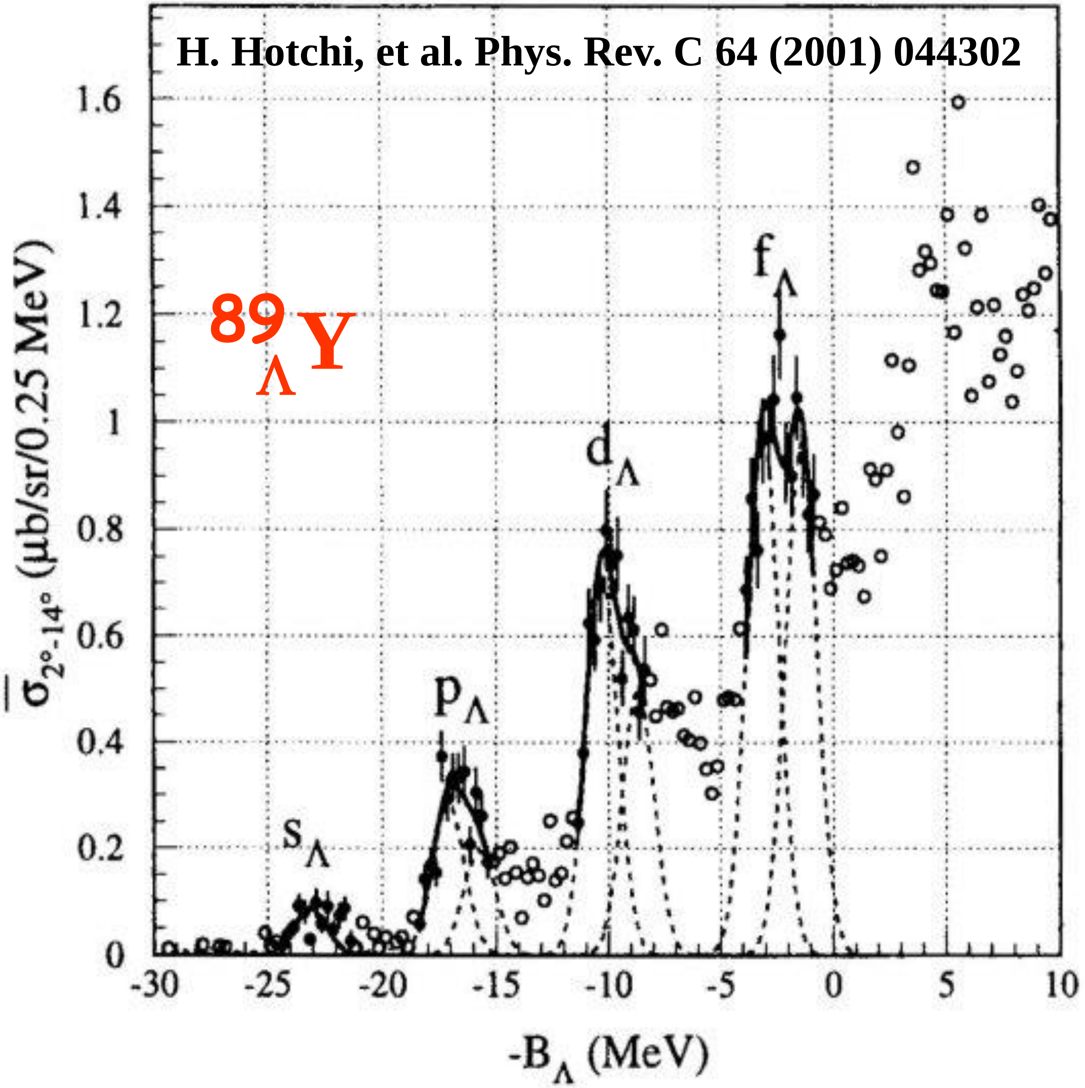
New type of nuclear matter, new symmetries, New selection rules. First kind of flavored nuclei.

Hyperons are free from Pauli principle restrictions

Can occupy quantum states already filled up with nucleons

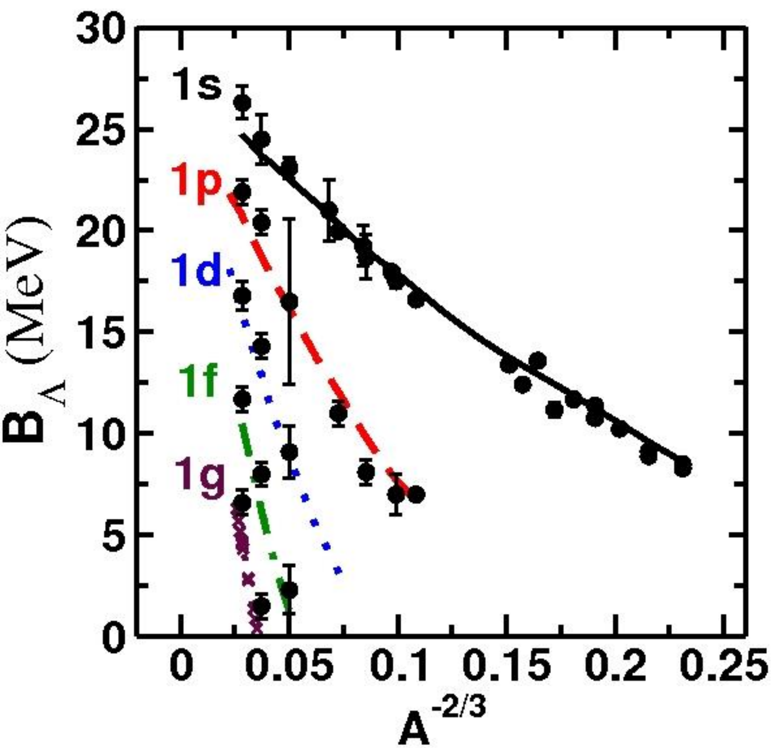
This makes a hyperon embedded in the nucleus a unique tool for exploring the nuclear structure.

Good probe for deeply bound single particle states.



Study of S = -1 hypernuclei (Λ or Σ)

The nuclear structure and the many body nuclear dynamics is extended to new non conventional symmetries, due to the inclusion of an S≠ 0 degree of freedom in the nucleus, YN interaction



The Skyrme type ΛN interaction from the known BE of Λ hypernuclei.

Neelam Guleria, S.K. Dhiman and R. Shyam, Nucl. Phys. A 886, 71 (2012)

The role played by quark degrees of freedom in nuclear phenomena: Quark-Meson coupling model, extended for hypernuclei

Guichon, KT, Saito, Thomas

The study of four fermion, strangeness changing, baryon-baryon weak interaction YN→NN, which can occur only inside hypernuclei

S = -2 systems

New Physics items

Neutron star composition

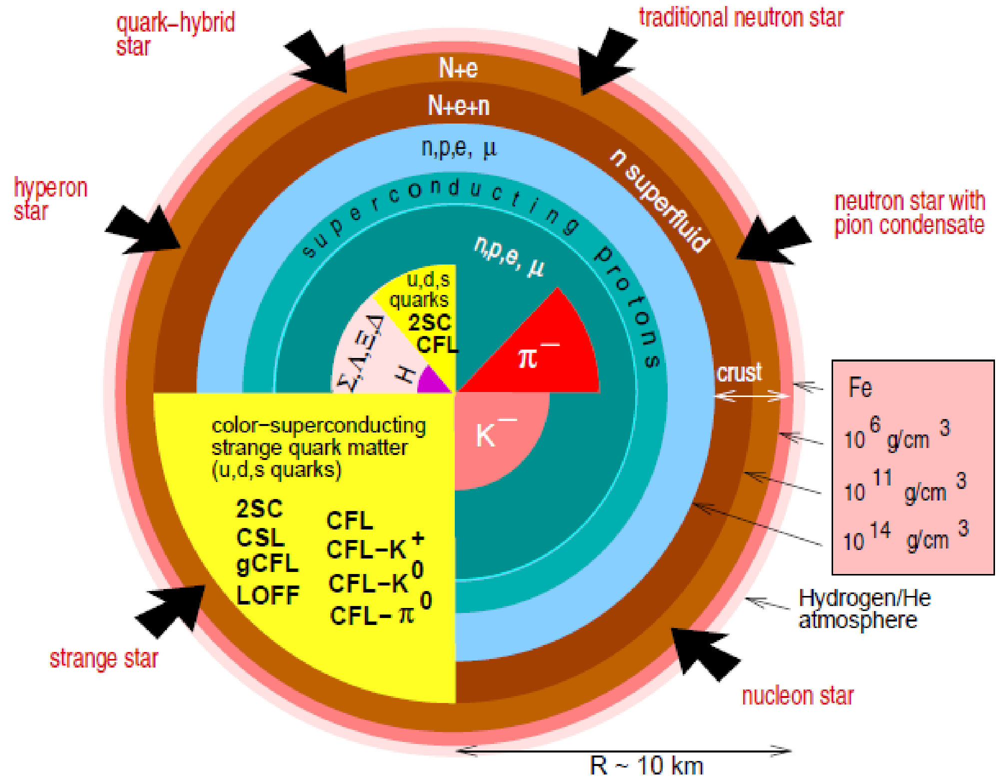
• For a detailed understanding of the quark aspect of the baryon-baryon forces in the SU(3) space, information on the YY channel is essential.

• Formation of compact stars depends On the nature of the YY interaction.

• Are there S=-2 deeply bound multi $\overline{K}$ states??

• Search for *H particle*
six-quark system uuddss

Conjectured
composition of a neutron star



Juergen Schaffner-Bielich, Nucl. Phys. A804 (2008) 309

Experiments

No! Σ-Hypernuclei

Naïve SU(3) based model

yield Σ-Hypernuclei !

→ QMC ?

Λ, Σ ⇔ Self-consistent OGE color hyperfine interaction

Λ and Σ hypernuclei are more or less similar (channel couplings) ⇔ **improve !**

Ξ potential: **weaker (~1/2)** of Λ and Σ (**Light quark #**)

Very **small spin-orbit splittings** for Λ hypernuclei ⇔ **SU(6) quark model**

Bag mass and **color** **mag.** **HF** int. contribution (**OGE**)

T. DeGrand *et al*., PRD 12, 2060 (1975)

$$M = [N_q\Omega_q + N_s\Omega_s]/R - Z_0/R + 4\pi BR^3/3$$

$$+ (F_s)^n \Delta E_M (f) \qquad (f = N, \Delta, \Lambda, \Sigma, \Xi \ldots)$$

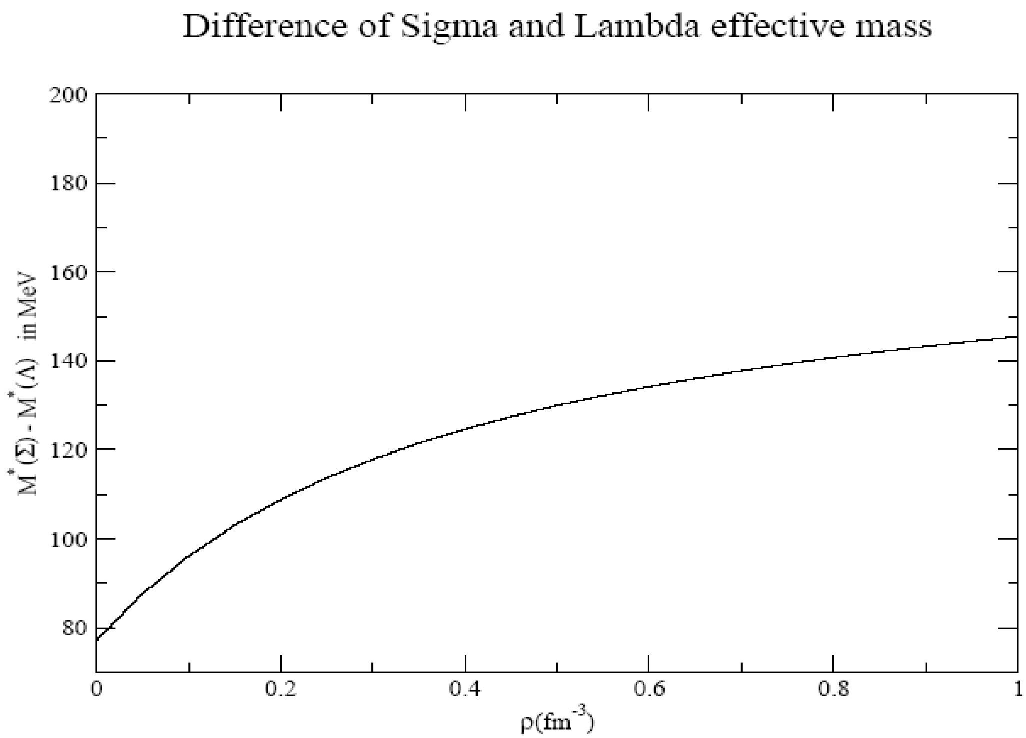
$$\Delta E_M = -3\alpha_c \sum_{a,\, i<j} \lambda_i \lambda_j \vec{\sigma}_i \cdot \vec{\sigma}_j \, M(m_i, m_j, R)$$

$$\Delta E_M(\Lambda) = -3\alpha_c \, M(m_q, m_q, R), \quad (q = u, d)$$

$$\Delta E_M(\Sigma) = \alpha_c M(m_q, m_q, R)$$
$$-4\alpha_c M(m_q, m_s, R)$$

Latest QMC: Includes Medium Modification of Color Hyperfine Interaction

N - Δ and Σ - Λ splitting arise from **one-gluon-exchange** in MIT Bag Model : as "**σ**" so does this splitting…



Σ - Λ splitting

→ **Σ-hypernuclei unbound!!**

Guichon, Thomas, Tsushima, Nucl. Phys. A841 (2008) 66

Σ^0 potentials ($1s_{1/2}$)

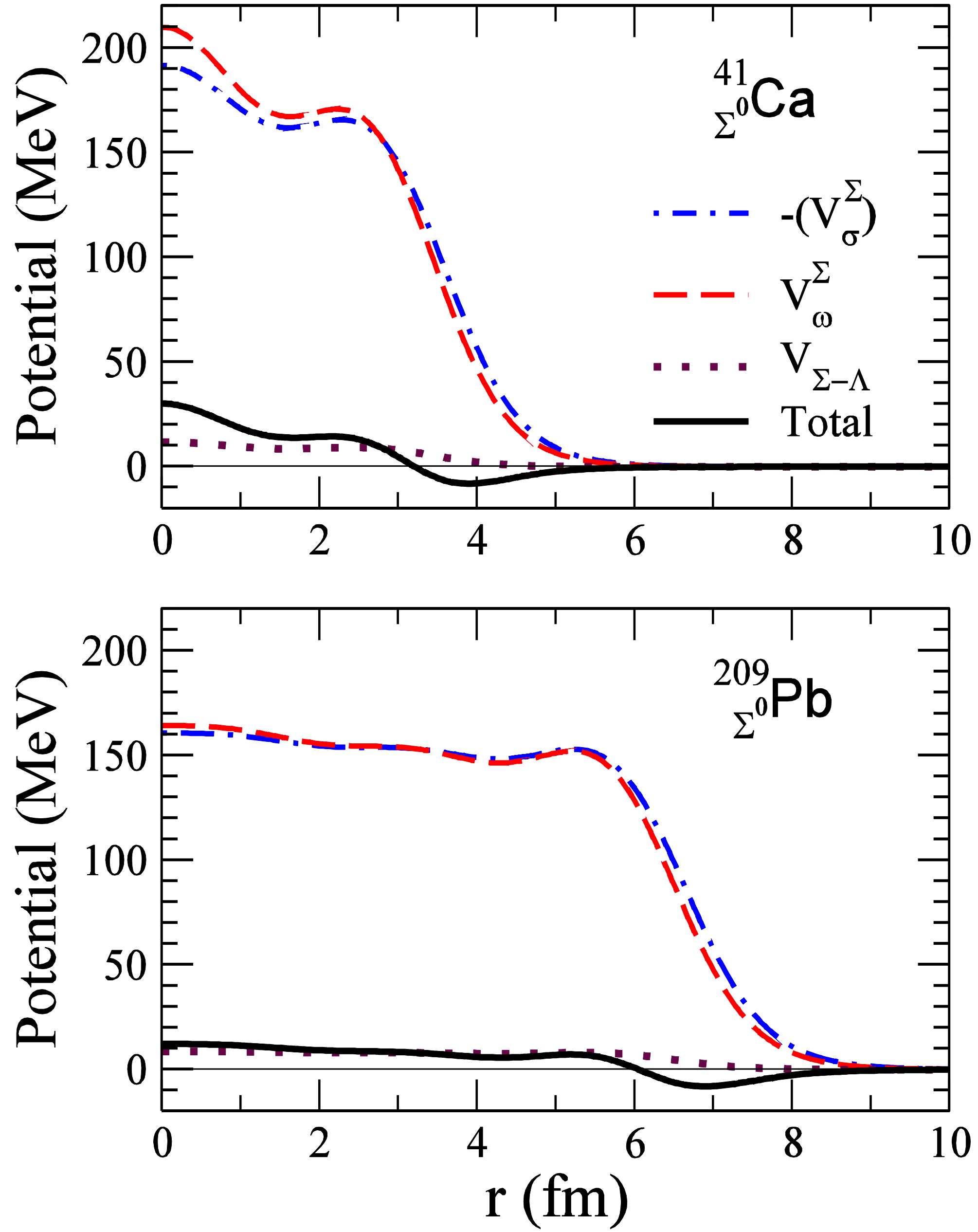
Repulsion in center

Attraction in surface

No Σ nuclear bound state!

HF couplings for hyperons ⇔ successful for high density neutron star

(NPA 792, 341 (2007))



Hypernuclei spectra 1

NPA 814, 66 (2008)

	$^{16}_{\Lambda}O$ Exp.	$^{17}_{\Lambda}O$	$^{17}_{\Xi^0}O$	$^{40}_{\Lambda}Ca$ Exp.	$^{41}_{\Lambda}Ca$	$^{41}_{\Xi^0}Ca$	$^{49}_{\Lambda}Ca$	$^{49}_{\Xi^0}Ca$
$1s_{1/2}$	-12.4	-16.2	-5.3	-18.7	-20.6	-5.5	-21.9	-9.4
$1p_{3/2}$		-6.4			-13.9	-1.6	-15.4	-5.3
$1p_{1/2}$	-1.85	-6.4			-13.9	-1.9	-15.4	-5.6
$1d_{5/2}$					-5.5		-7.4	
$2s_{1/2}$					-1.0		-3.1	
$1d_{3/2}$					-5.5		-7.3	

Hypernuclei spectra 2

NPA 814, 66 (2008)

	$^{89}_{\Lambda}$Yb Exp.	$^{91}_{\Lambda}$Zr	$^{91}_{\Xi^0}$Zr	$^{208}_{\Lambda}$Pb Exp.	$^{209}_{\Lambda}$Pb	$^{209}_{\Xi^0}$Pb
$1s_{1/2}$	-23.1	-24.0	-9.9	-26.3	-26.9	-15.0
$1p_{3/2}$		-19.4	-7.0		-24.0	-12.6
$1p_{1/2}$	-16.5	-19.4	-7.2	-21.9	-24.0	-12.7
$1d_{5/2}$	-9.1	-13.4	-3.1	-16.8	-20.1	-9.6
$2s_{1/2}$		-9.1	–		-17.1	-8.2
$1d_{3/2}$	(-9.1)	-13.4	-3.4	(-16.8)	-20.1	-9.8

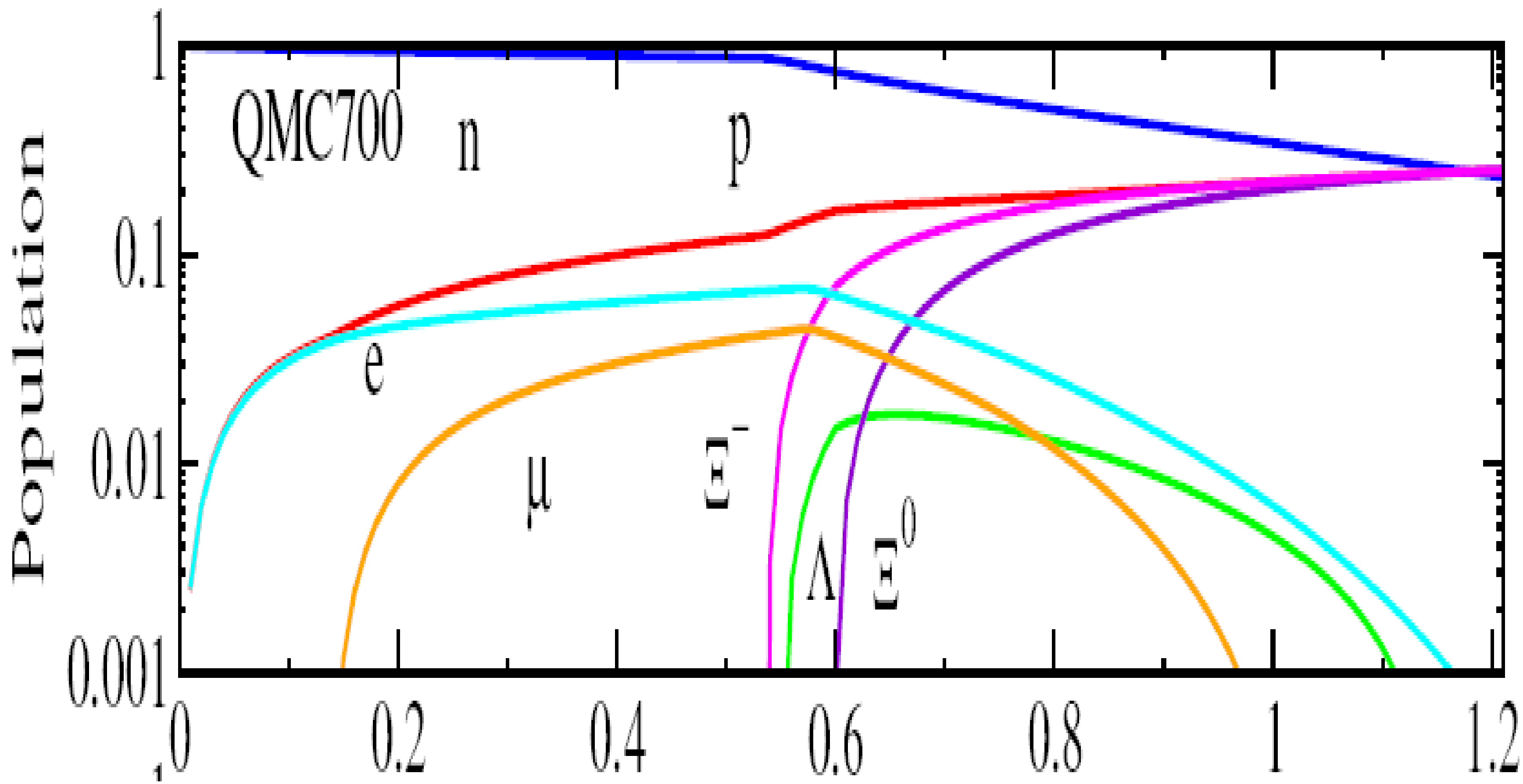
Summary: hypernuclei

- The latest version of QMC (**OGE** color **hyperfine** interaction included self-consistently in matter) ⇒
- Λ single-particle energy **1s1/2 in Pb** is **-26.9** MeV (Exp. **-26.3** MeV) ⇐ **no extra parameter!**
- **Small** spin-orbit splittings for the Λ
- **No Σ nuclear bound state !!**
- Ξ is expected to form nuclear bound state

Consequences for Neutron Star ⇒

D.L.Whittenbury et.al., Phys.Rev. C89 (2014) 06580

New QMC model, relativistic, Hartree-Fock treatment



Stone et al., Nucl. Phys. A792 (2007) 341