Photoproduction of Λ–Hypernuclei in the Quark-Meson Coupling (QMC) model

Tony 's 60th Birthday Workshop, Adelaide, Feb. 15-19, 2010

K. Tsushima (JLab)

R. Shyam, P. Guichon, A.W. Thomas

PLB, 676, 51 (2009)

NPA 814, 66 (2008), arXiv:0903.5478 [nucl-th]

K. Saito, KT, A.W. Thomas, PPNP, 58, 1 (2007)

Outline

1. **QMC** model, **finite nuclei**
2. **Hypernuclei** in the latest **QMC** model (Σ,Λ,Ξ): **no heavy**

   Σ–hypernuclei as in experiment

3. Photoproduction of Λ–hypernuclei
4. Summary (Discussions)

Introduction, motivation

- **(Heavy) nuclei** in terms of **quarks** and **gluons** (or **QCD**) **???!!!**
- **NN**,**NNN**,NNNN,NNNNN..... interactions
  ⇒ **Nucleus ?** ⇐ shell model, **MF** model,**density** functional theory...**BUT ?**
- **Lattice QCD**: **still** extracting **NN** and **NY** **2-body** interactions, [**Y**=hyperons: **Λ,Σ,Ξ**]
- **Hypernucleus ?** (Nucleus+**Y**) bound states
- **Quark** model based description of **nucleus**

Hypernuclei: SU(3) so bad ?

Λ hypernuclei: **well established** Expts.

up to **Pb** core nucleus, many states

Σ^+ hypernuclei: **only** ${}^{4}_{\Sigma}$**He** **confirmed**

⇒ Probably **no** other Σ **hypernuclei**

Ξ hypernuclei: **hints – not confirmed**

⇒ **Planned** Expts.: **(**JLab**?)**, **J-PARC**,

GSI-FAIR

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

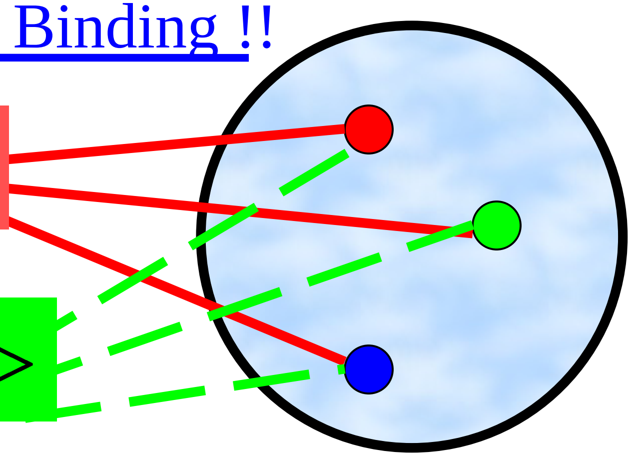
(For a review, PPNP 58, 1 (2007))

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

Nuclear Binding !!

< σ >

< ω >



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

← nonlinear in σ

$M^*_N \cong M_N - g^N_\sigma \sigma + (d/2)(g^N_\sigma \sigma)^2$

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

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

1. Start

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

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

Self-consistent !

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…

$$M^*(\vec{R}) = M - g_\sigma \sigma(\vec{R}) + \frac{d}{2}\left(g_\sigma \sigma(\vec{R})\right)^2 + \ldots$$

Non-linear dependence: **scalar polarizability**

(d)**¼ = 0.22 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**

New saturation mechanism !

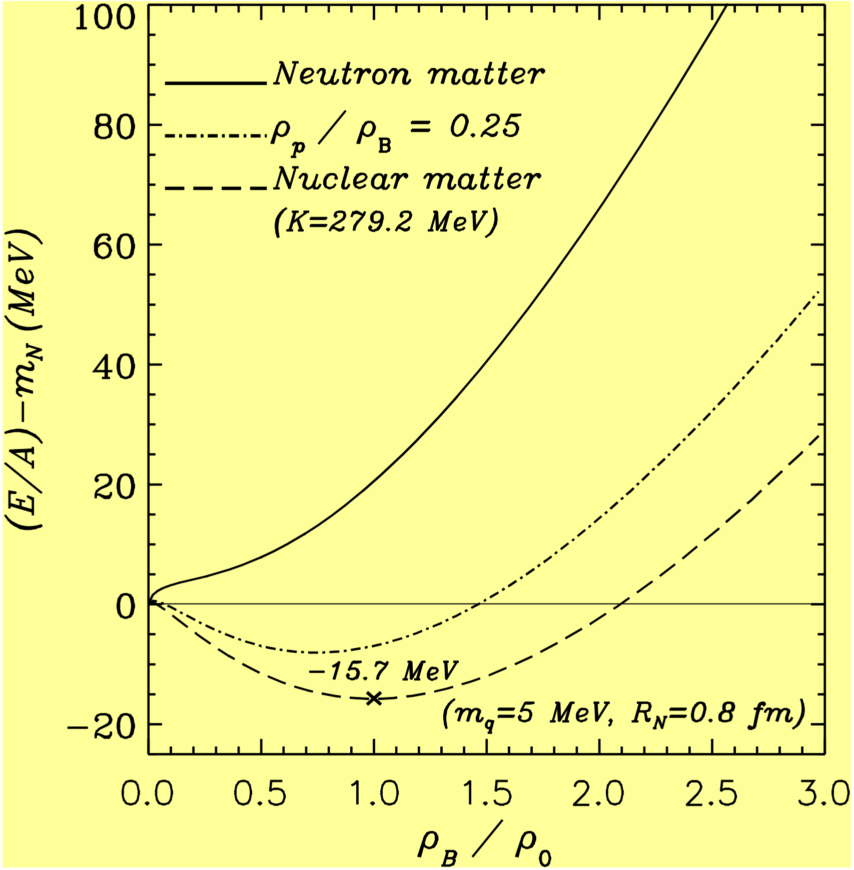
Incompressibility

(~ spring constant)

$K \approx 280$ MeV

(200 ~ 300 MeV)

PLB 429, 239 (1998)



Finite nuclei: ^{208} Pb energy levels

NPA 609, 339 (1996)

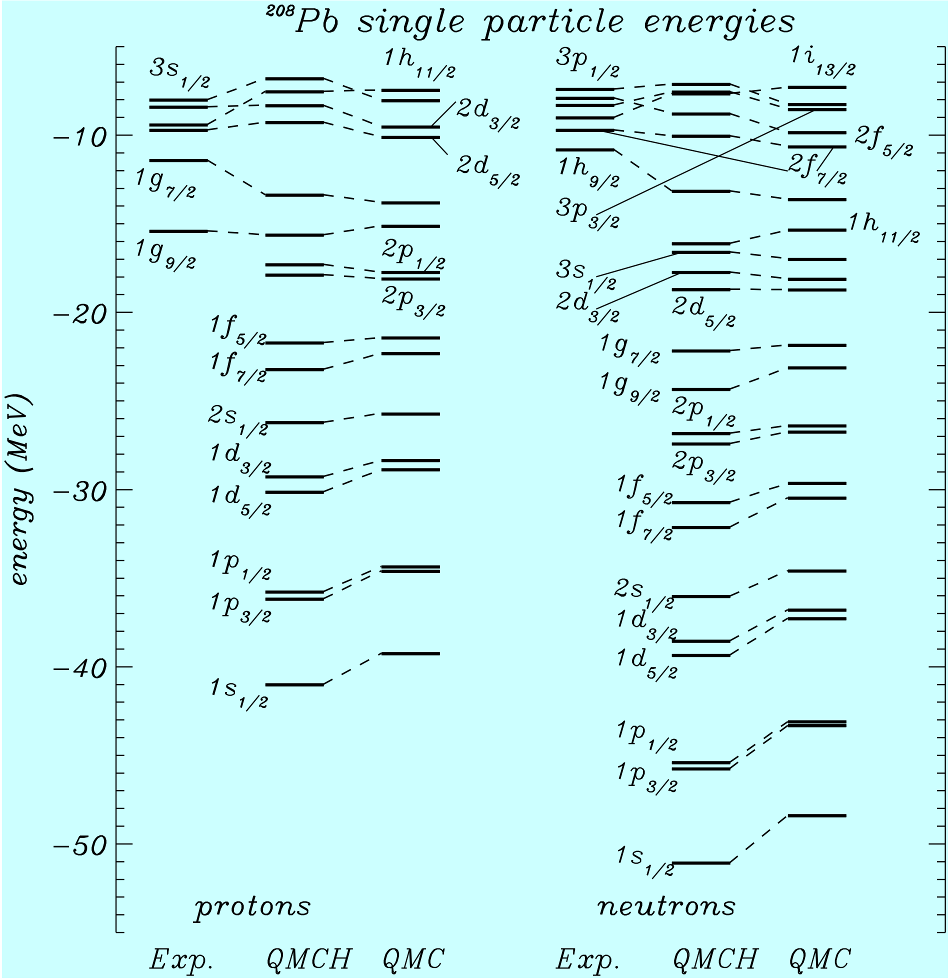
Heavy mass nuclei

Based on quarks !

↓

Hypernuclei

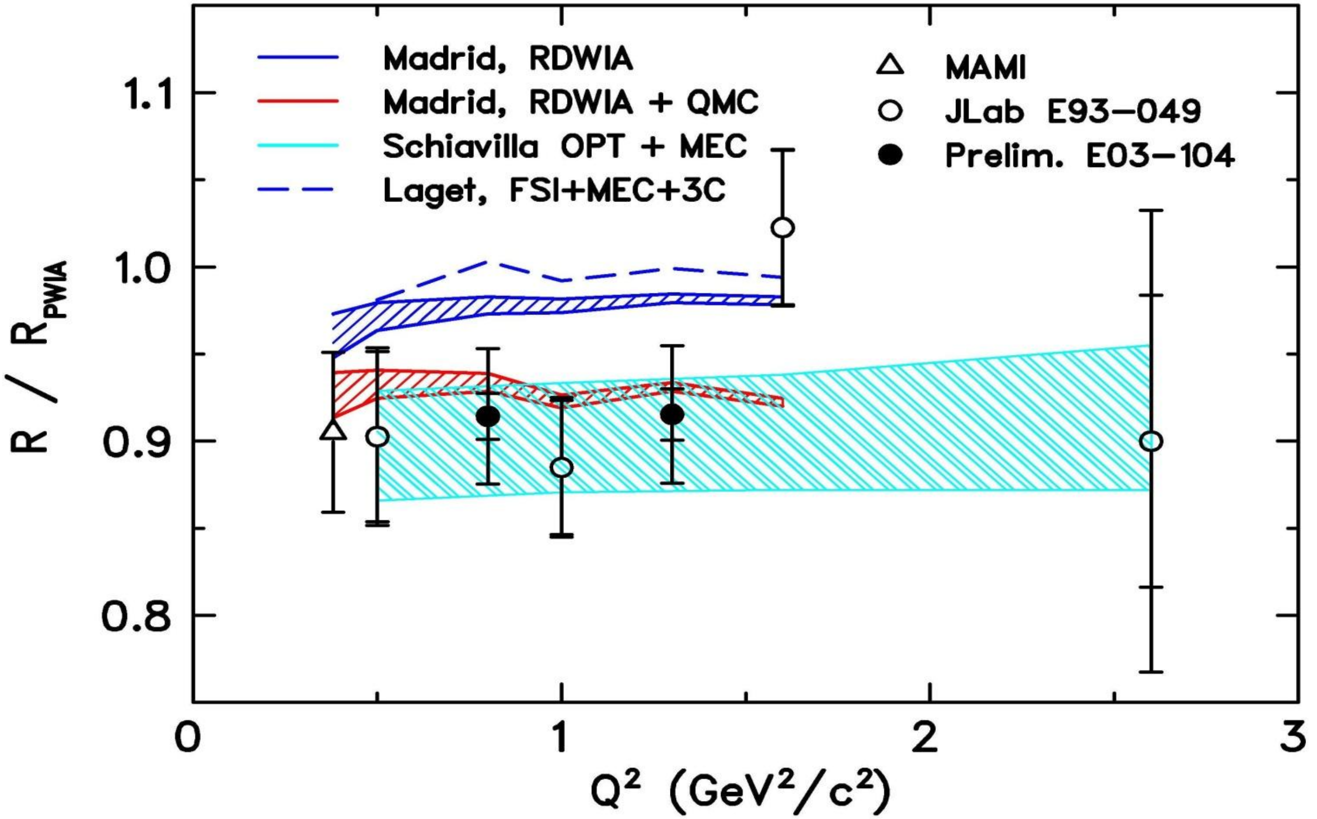
(the latest version of QMC)



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

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

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



QMC ⇔ QHD

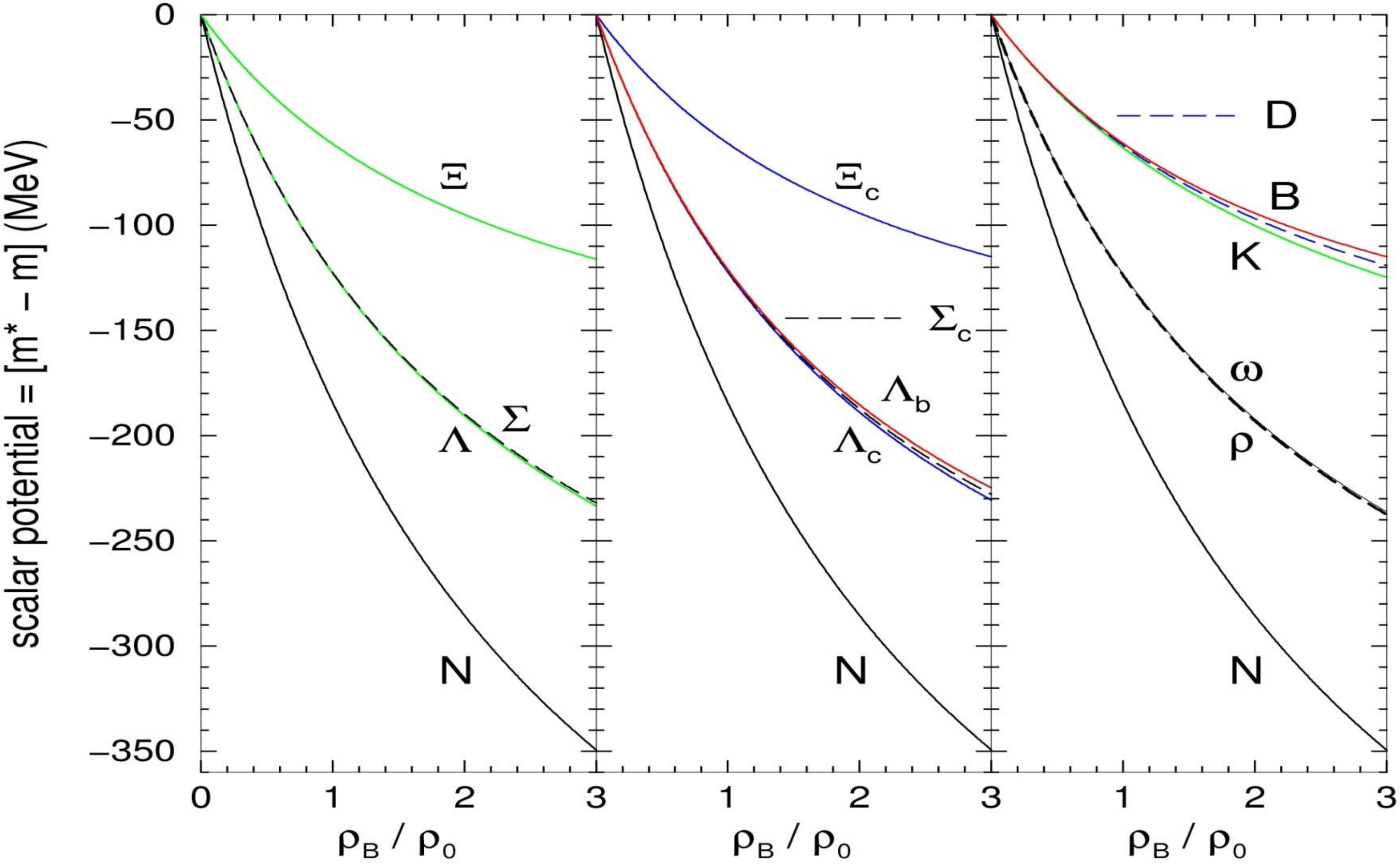
- QHD shows importance of **relativity** :
  mean **σ, ω** and **ρ** fields
- **QMC** goes **far beyond QHD** by incorporating effect of hadron ***internal structure***

- 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 next !

Scalar potentials in QMC respects light quark number !



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)

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

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

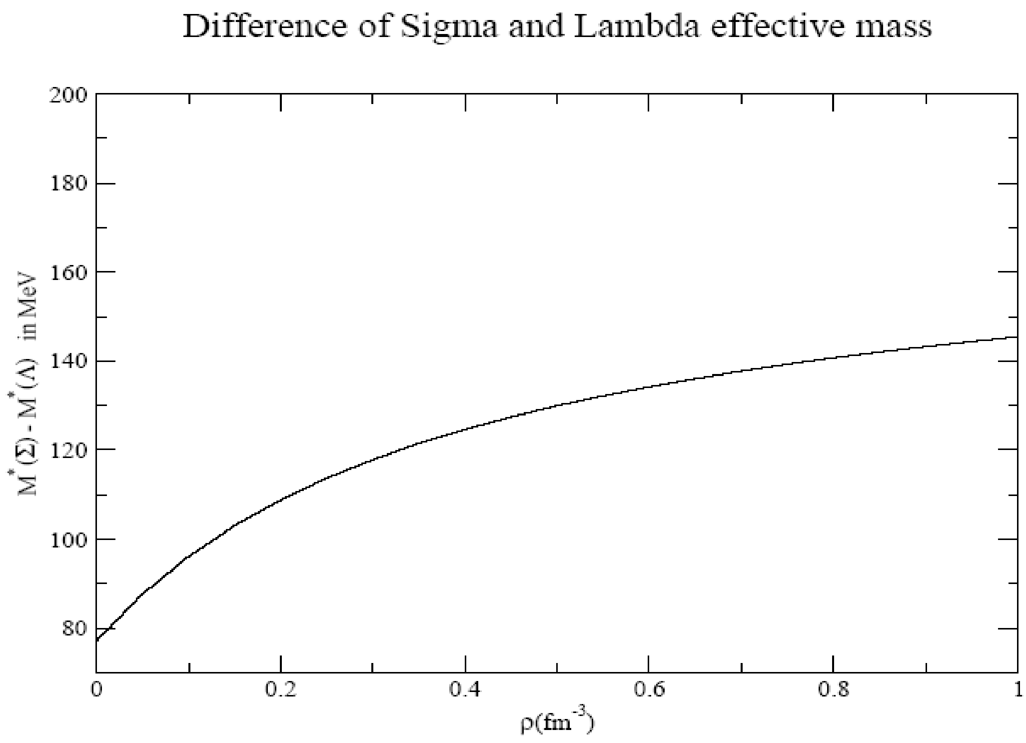
$$\Delta E_M = -3\alpha_c \sum_{a,\, i<j} \lambda_i \lambda_j \vec{\sigma}_i \cdot \vec{\sigma}_j M(m_i, m_j, R)$$

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

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

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!!**

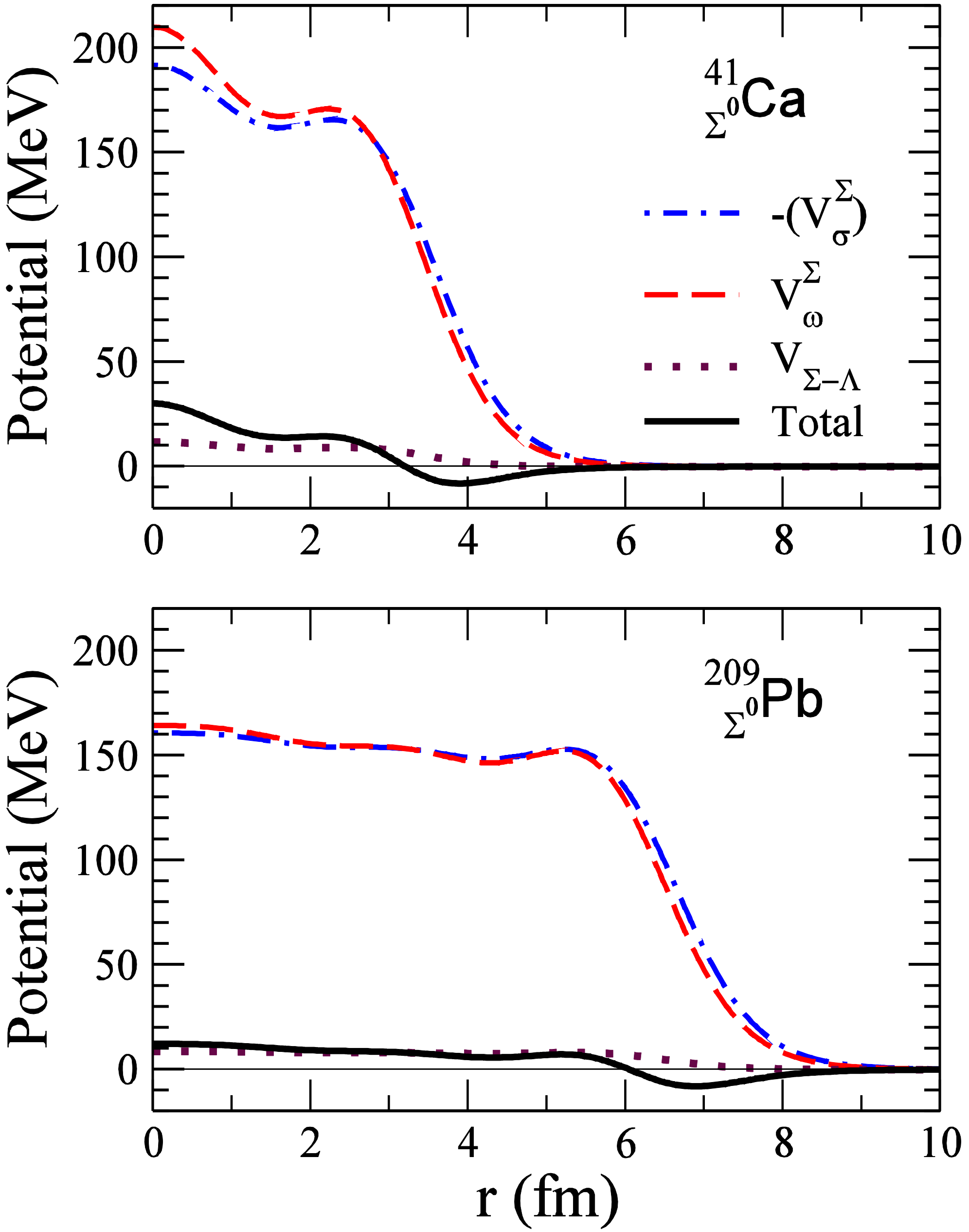
Guichon, Thomas, Tsushima, Nucl. Phys. A841 (2008) 66

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 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 **$1s_{1/2}$ 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

Photoproduction of Λ hypernuclei

R. Shyam, KT, A.W. Thomas, PLB 676, 51 (2009)

Λ and K^+ are produced via **s-channel**

N* excitation (dominant)

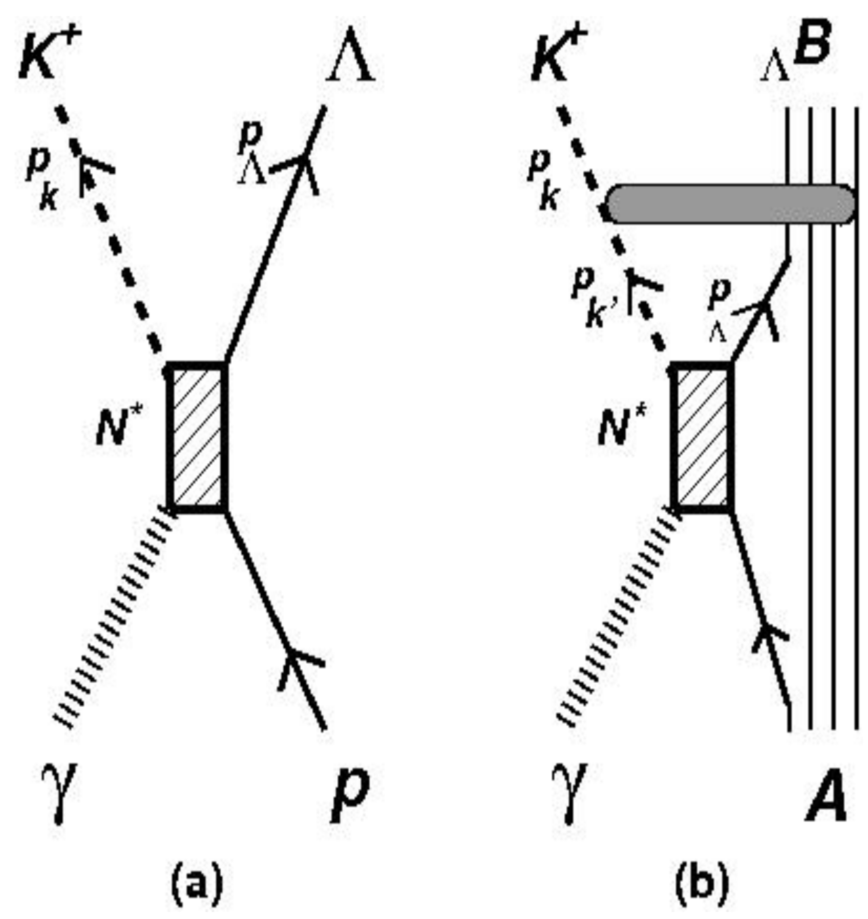
S_{11}(1650), P_{11}(1710)

P_{13}(1720)

⇓

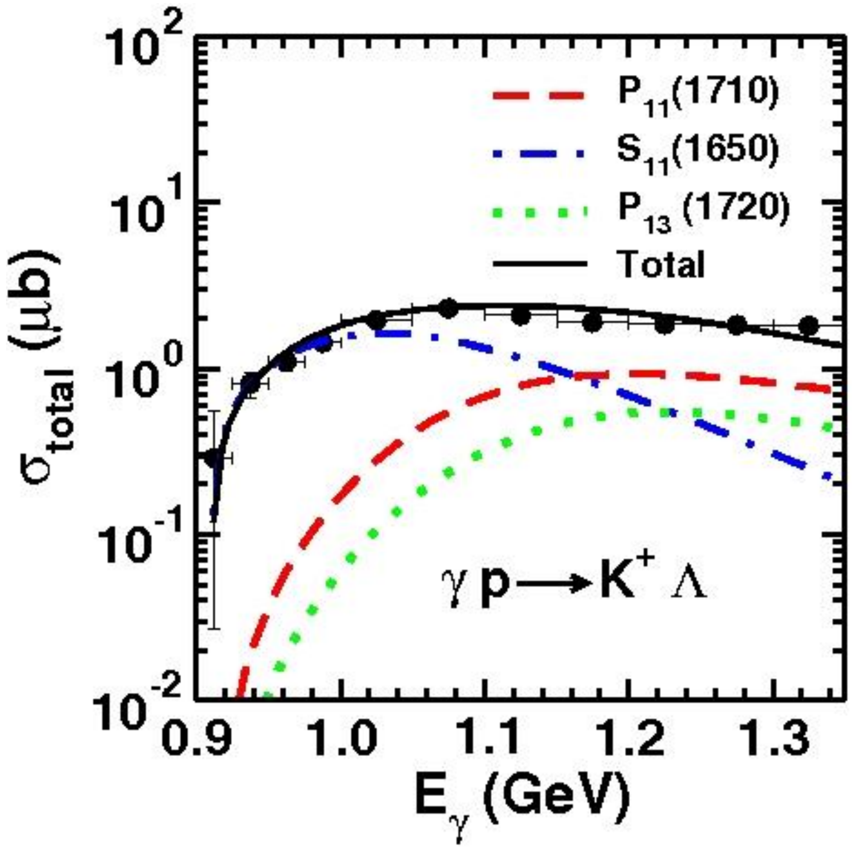
Energy region of interests,
hypernuclei production

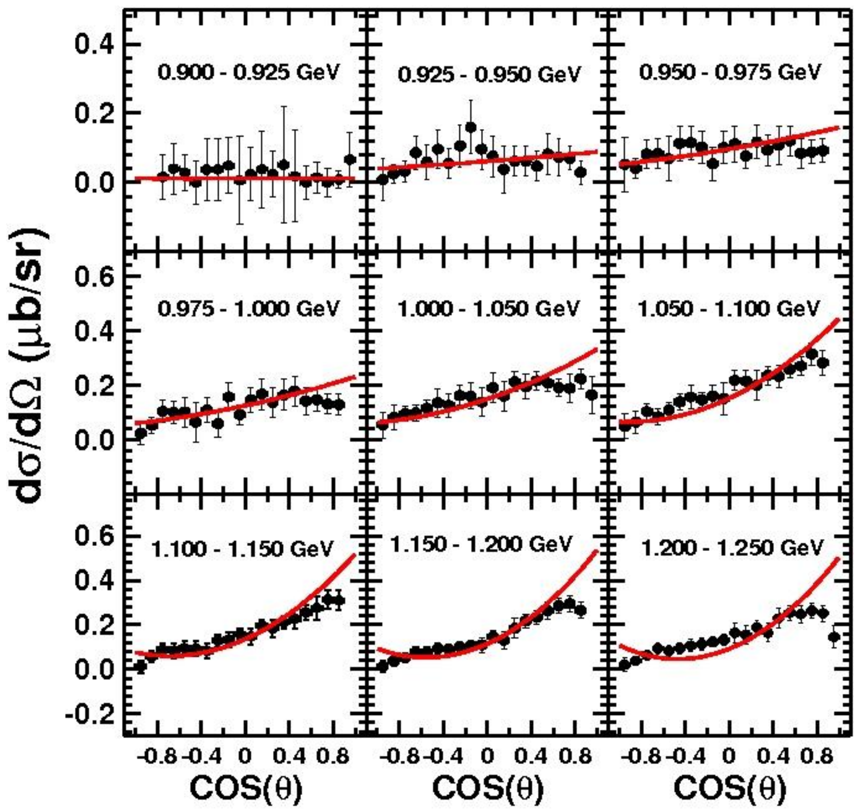
(~ **10 % ambiguity** due to the other background ⇒)



Elementary $\gamma\, p \rightarrow K^+ \Lambda$ reaction

R. Shyam, KT, A.W. Thomas, PLB 676, 51 (2009)





Differential cross sections: $^{12}C(\gamma,K^+)^{12}_{\Lambda}B$

PLB 676, 51 (2009)

$E_{th} \sim 695$ MeV

$d\sigma/d\Omega$ at

Kaon angle $\theta = 10°$

$1^-, 2^- \Leftrightarrow (1p^{-p}_{3/2}, 1s^{\Lambda}_{1/2})$

(wave functions!) $\Rightarrow$

$2^+, 3^+ \Leftrightarrow (1p^{-p}_{3/2}, 1p^{\Lambda}_{3/2})$

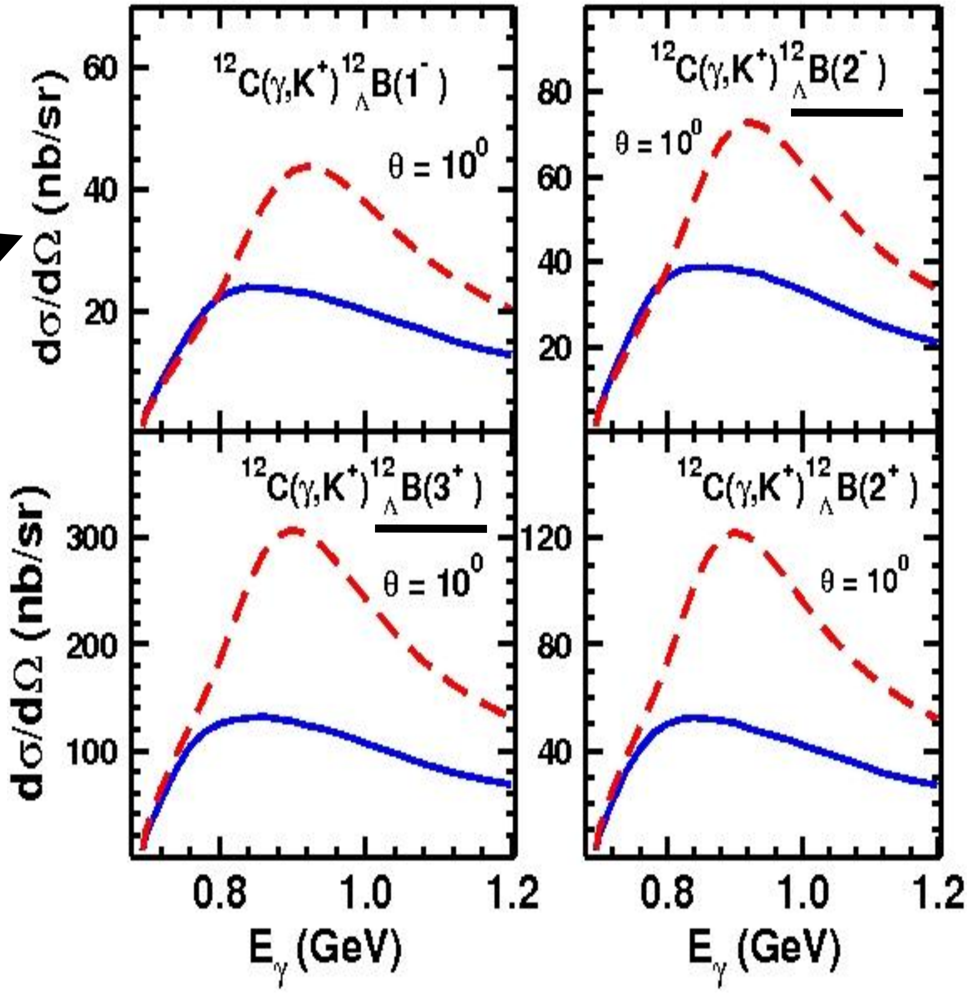
(potentials!) $\Rightarrow$

Diracp

(phenomenological)

QMC

$|q| \cong [1.4, 1.7]\ \mathrm{fm}^{-1}$



Summary: Λ hypernuclei photoproduction

1. **First attempt** to study photoproduction of Λ hypernuclei ($^{12}C(\gamma,K^{+})^{12}_{\Lambda}B$ reaction) via **quark-based** model (**QMC**)
2. **$d\sigma/d\theta$** at Kaon angle **θ = 10°** shows **distinguishable difference!**
3. **Back ground** inclusion (higher energies)
4. **Heavier Λ** hypernuclei

Discussions

1. Study of Ξ hypernuclei
   ⇑ ⇒ $A(K^-, K^+)_\Xi B$ reaction
2. Elementary $K^- N \to \Xi K^+$ reaction
3. Heavier Λ hypernuclei **photoproduction**
4. Electroproduction of Λ hypernuclei
5. Λ_c hypernuclei **???!!!**

Happy Birthday Tony!

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** !

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

⇒ **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 !

Hypernuclei spectra 1

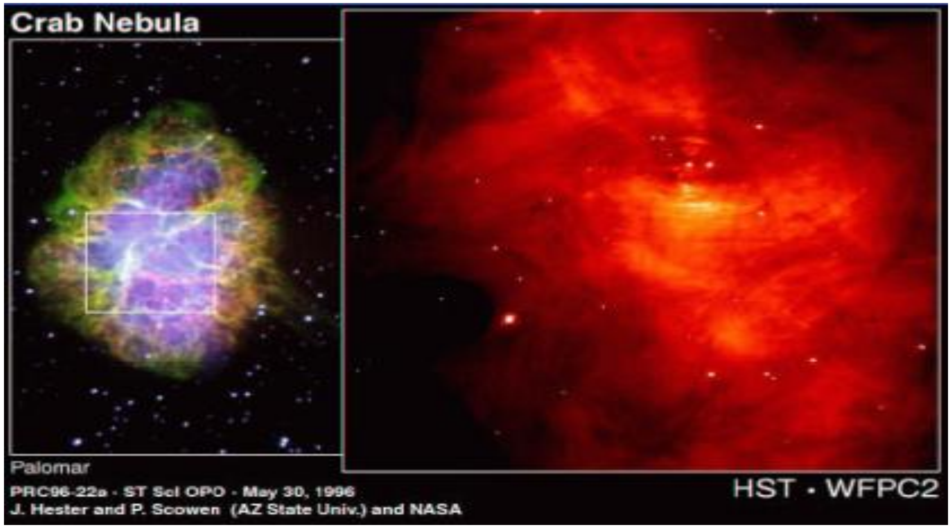
NPA 814, 66 (2008)

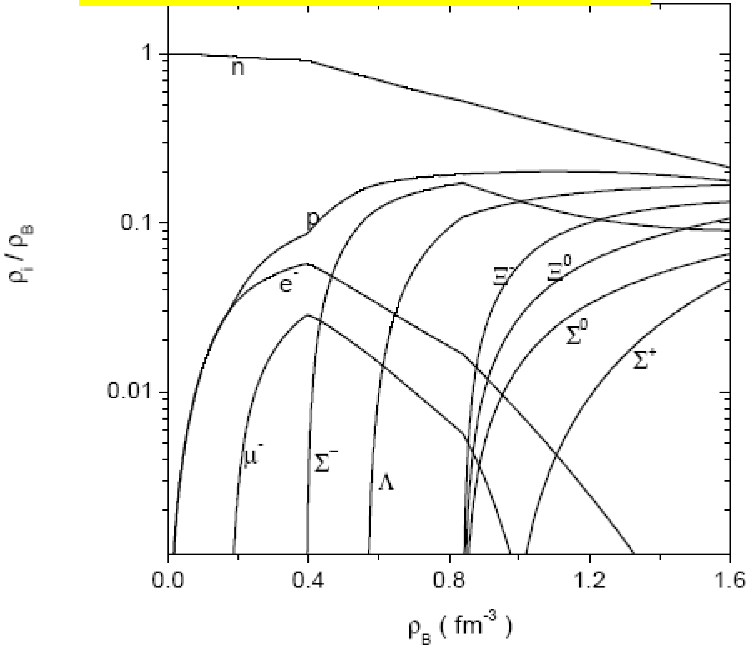
	${}^{16}_{\Lambda}$O Exp.	${}^{17}_{\Lambda}$O	${}^{17}_{\Xi^0}$O	${}^{40}_{\Lambda}$Ca Exp.	${}^{41}_{\Lambda}$Ca	${}^{41}_{\Xi^0}$Ca	${}^{49}_{\Lambda}$Ca	${}^{49}_{\Xi^0}$Ca
$1s_{1/2}$	-12.4	-16.2	-5.3	-18.7	-20.6	-5.5	-21.9	-9.4
$1p_{3/2}$		-6.4			-13.9	-1.6	-15.4	-5.3
$1p_{1/2}$	-1.85	-6.4			-13.9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

$^{12}_{\Lambda}$B hypernucleus (MeV)

State	**Exp.**	**QMC**	V_V (W.S)	V_S (W.S)
$^{12}_{\Lambda}$B $1s_{1/2}$	**11.37**	**14.93**	171.78	-212.69
$^{12}_{\Lambda}$B $1p_{3/2}$	**1.73**	**3.62**	204.16	-252.28
$^{12}_{\Lambda}$B $1p_{1/2}$	**1.13**	**3.62**	227.83	-280.86
$(p1p_{3/2})^{-1}$ ^{12}C	15.96 Sep. energy	(≅OK)	382.60	-472.34

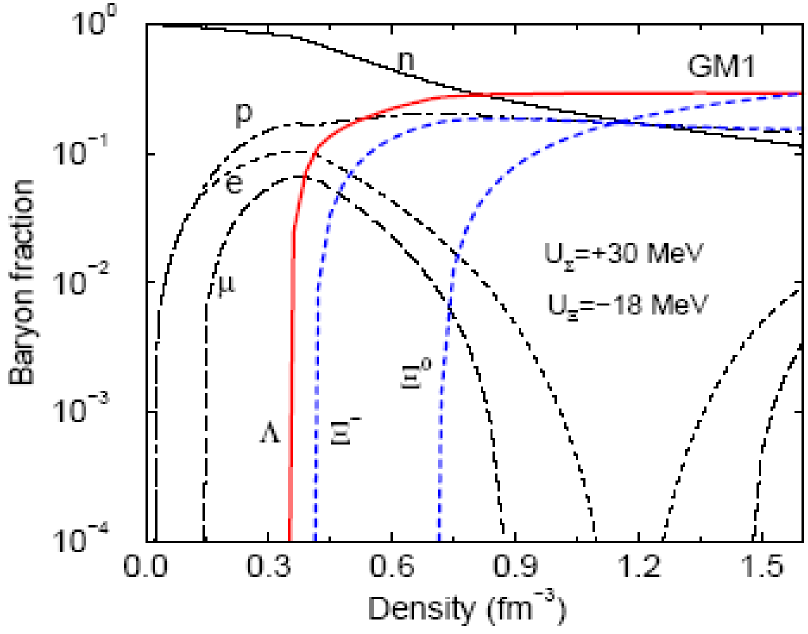
- **Hyperons** enter at just 2-3 ρ_0
- Hence need effective **Σ-N** and **Λ-N** forces in this density region!
- **Hypernuclear data is important input** (J-PARC, FAIR, JLab)





Σ

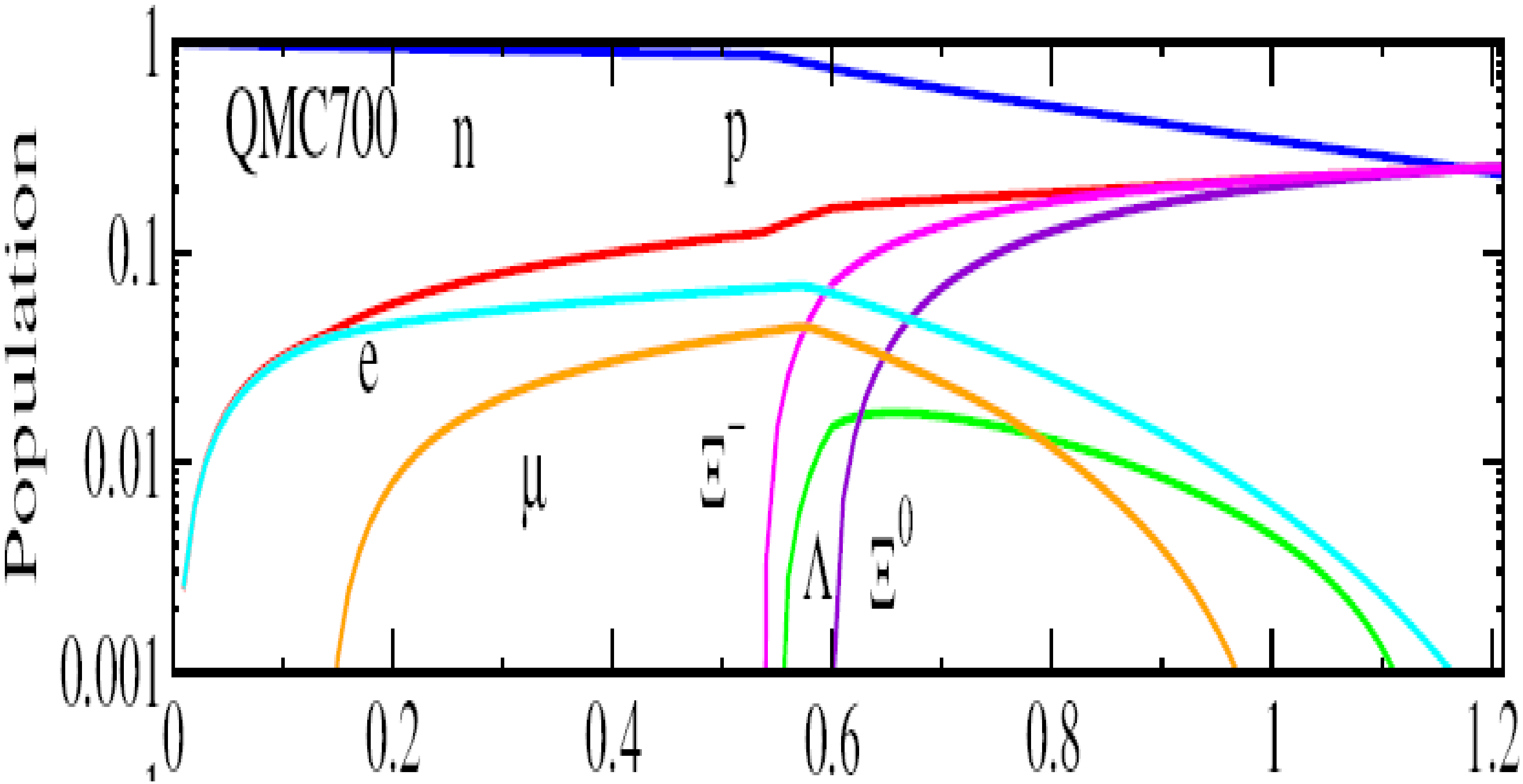
?



From Schaffner-Bielich (2005)

Consequences for Neutron Star ⇒ J. Carroll

New QMC model, fully relativistic, Hartree-Fock treatment



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