STRANGE NUCLEAR PHYSICS

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IFIC, València, 14 October 2004

CONVENTIONAL NUCLEAR PHYSICS

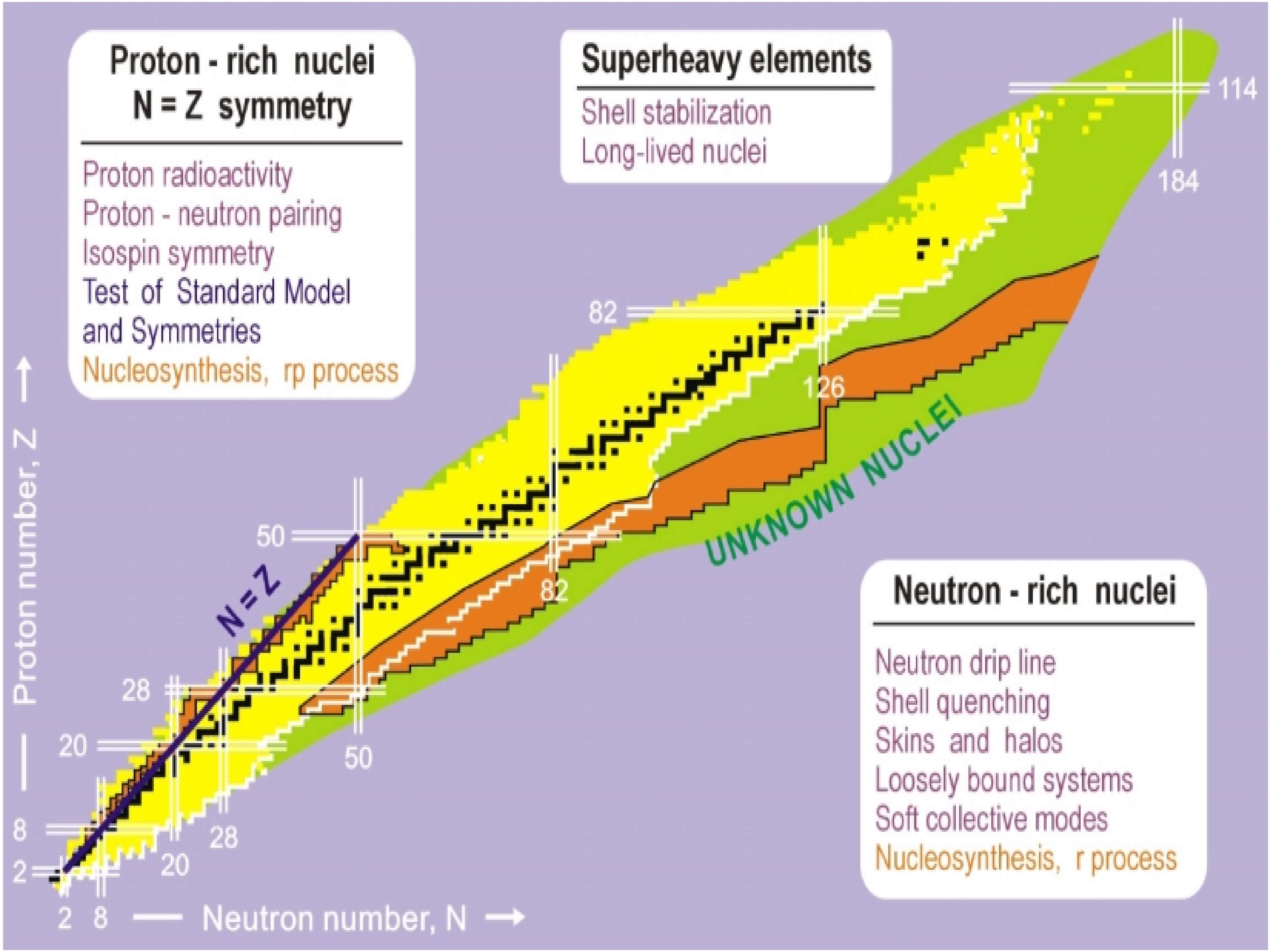
Nuclear Physics aims at the understanding of the structure, dynamics and overall properties of nuclei and nuclear reactions.

Degrees of freedom: baryons (n,p,Δ,…) and mesons (π,ρ,…) made of u,d quarks and antiquarks

More than 50 years of research have tested and established the validity of nuclear models (shell-model, liquid drop, pairing …) in explaining a vast variety of nuclear phenomena

In spite of the impressive progress it is still a very active field….

GSI,COSY,MAMI (Germany), ISOLDE-CERN, CRC (Belgium), KVI (The Netherkands), GANIL (France), JYFL (Finland), Dubna (Russia), LNL,Gran Sasso,LNS,LNF (Italy), MSU,ANL,Oak Ridge (USA), RIKEN (Japan), …



Proton - rich nuclei
N = Z symmetry

Proton radioactivity
Proton - neutron pairing
Isospin symmetry
Test of Standard Model
and Symmetries
Nucleosynthesis, rp process

Superheavy elements

Shell stabilization
Long-lived nuclei

Neutron - rich nuclei

Neutron drip line
Shell quenching
Skins and halos
Loosely bound systems
Soft collective modes
Nucleosynthesis, r process

STRANGE NUCLEAR PHYSICS

Studies nuclear phenomena involving one or more strange particles (containing the s quark or antiquark)

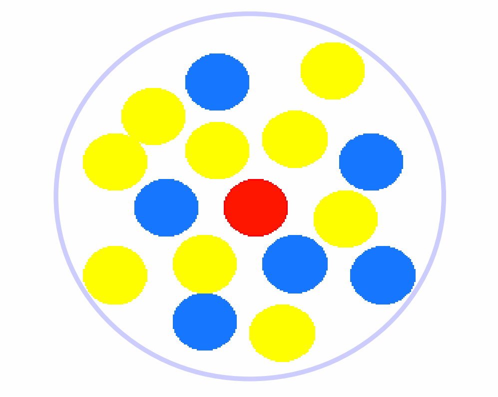
Baryon (Hyperon)	quarks	Isospin	Mass (MeV)
Λ	$u\ d\ s$	0	1115
Σ^+	$u\ u\ s$	1	1189
Σ^0	$u\ d\ s$	1	1193
Σ^-	$d\ d\ s$	1	1197
Ξ^0	$u\ s\ s$	1/2	1315
Ξ^-	$d\ s\ s$	1/2	1321

Meson	quarks	Isospin	Mass (MeV)
$\bar{K}^0$	$\bar{d}\ s$	1/2	498
K^-	$\bar{u}\ s$	1/2	494
K^+	$u\ \bar{s}$	1/2	494
K^0	$d\ \bar{s}$	1/2	498

HYPERNUCLEAR PHYSICS

Hypernuclei are bound systems of conventional baryons (protons, neutrons) plus one or more strange baryons (hyperons →Y)

$^{A}_{Y}Z$

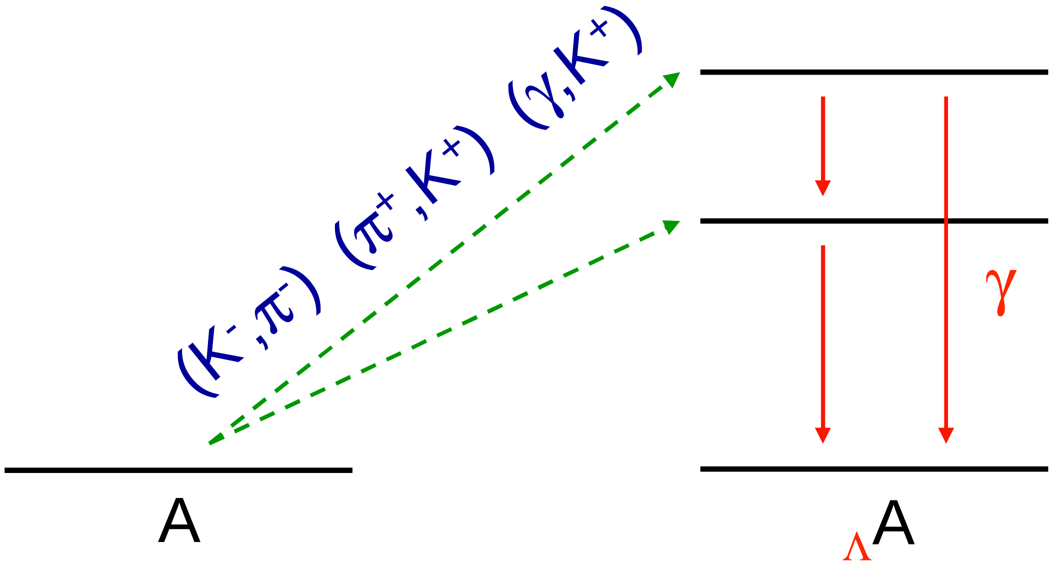


- ✓ New spectroscopy involving a strange baryon
  (hyperon beams are unstable)
  →Learn about the YN interaction
  Is SU(3) enough to understand the new phenomenology?

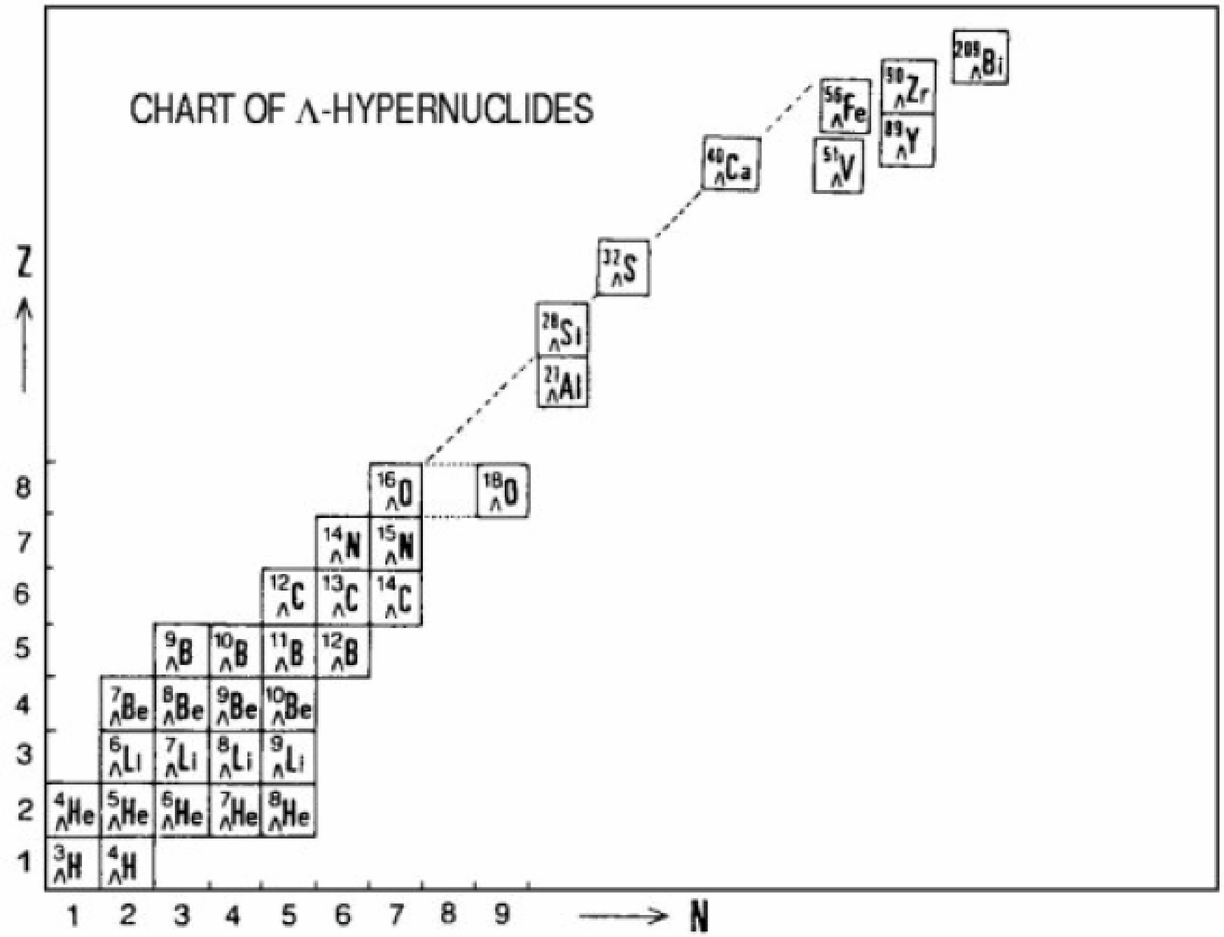
- ✓ Unique source of information for studying the weak YN →NN interaction

How are hypernuclei produced?

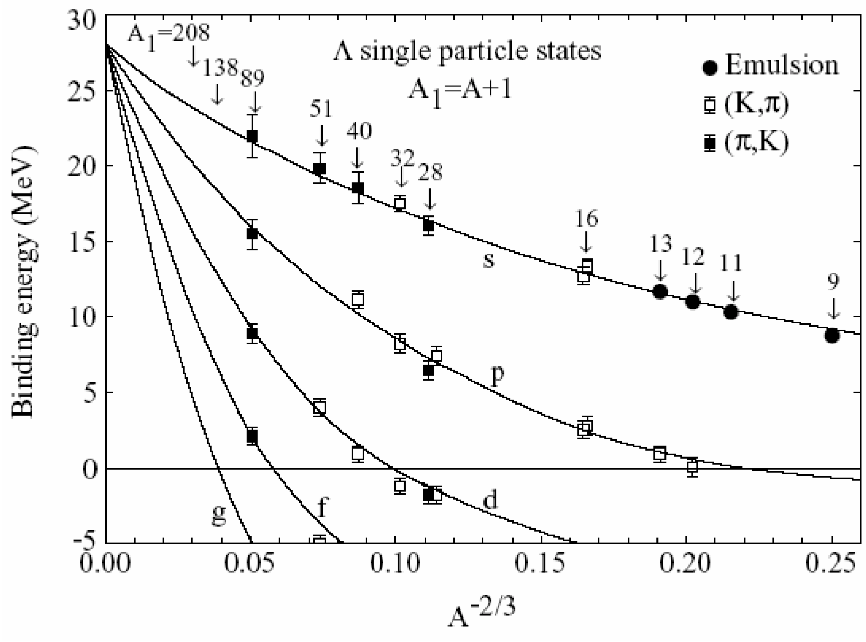
Strangeness exchange:	$n(K^-, \pi^-)\Lambda$ $p(K^-, \pi^\pm)\Sigma^\mp$	CERN, BNL, KEK, DAPHNE
Associated production:	$n(\pi^+, K^+)\Lambda$	BNL, KEK
Electroproduction:	$p(e, e' K^+)\Lambda$	JLab



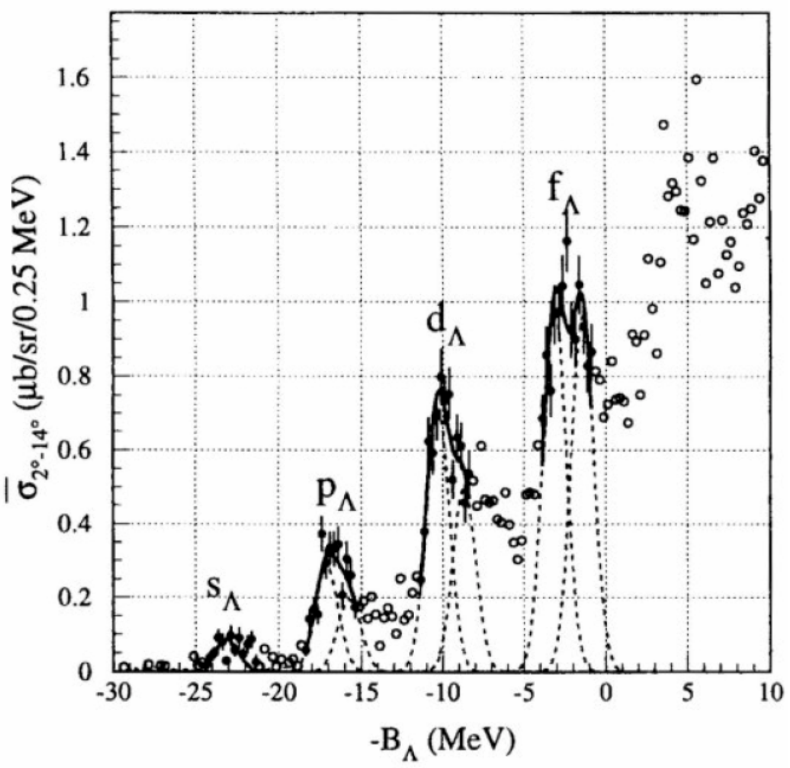
Known Λ hypernuclei

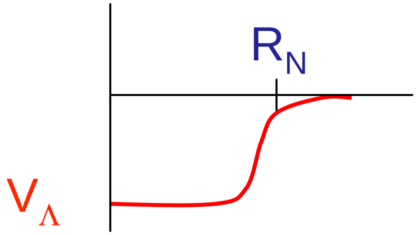


Binding energies of s.p. Λ states



Spectrum of ${}^{89}_{\Lambda}$Y (KEK E369)

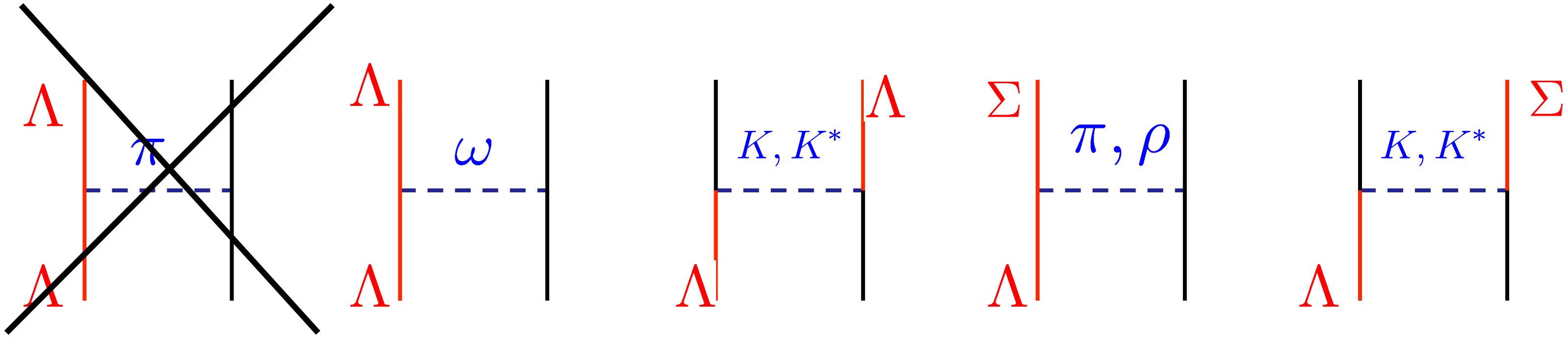




These data reflect the single particle behaviour of the Λ in the nucleus

V_Λ=-28 MeV (V$_N$=-55 MeV)

YN interaction



Isospin Λ = 0
Isospin π = 1

$$V_{\mathrm{YN}} = V_0 + V_{\mathrm{S}}\vec{\sigma}_1\vec{\sigma}_2 + V_{\mathrm{T}}\hat{S}_{12} + V_{\mathrm{LS}}\vec{L}\vec{S}^{+} + V_{\mathrm{ALS}}\vec{L}\vec{S}^{-}$$

Juelich A,B	**B. Hozelkamp, K. Holinde, J. Speth, NPA500 (1989) 485**
Nijmegen NSC89	**M.M. Nagels, Th.A. Rijken, J.J. de Swart, PRC40 (1989) 2226**
Nijmegen NSC97	**Th. A. Rijken, Y. Yamamoto, V.G.J. Stoks, PRC59 (1999) 21**

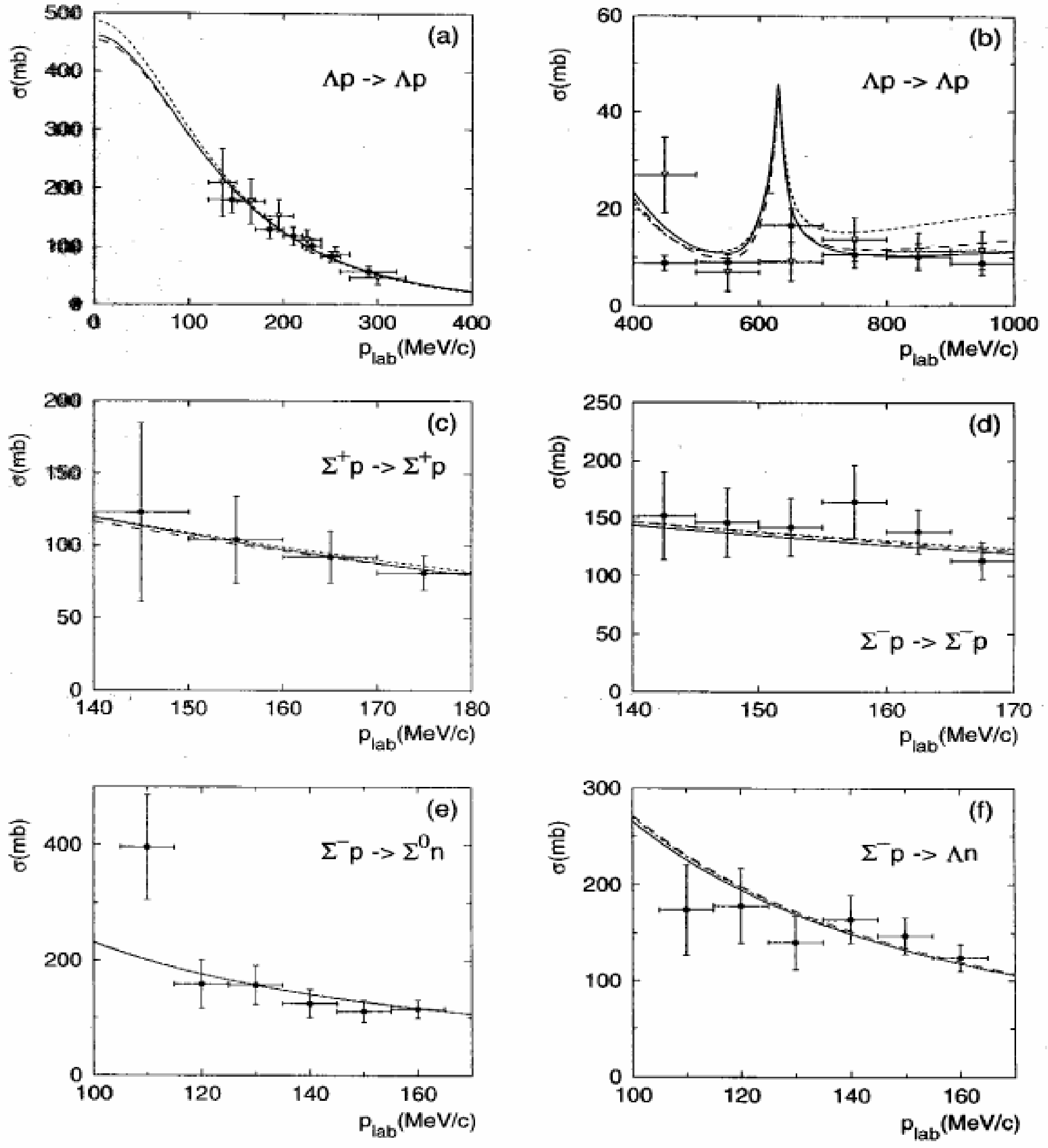
Fitted to: **4300 data on NN scattering**

35 data on YN scattering **+ SU(3)**

→ Explain the depth of the Λ nucleus potential

→ But, spin dependence unconstrained

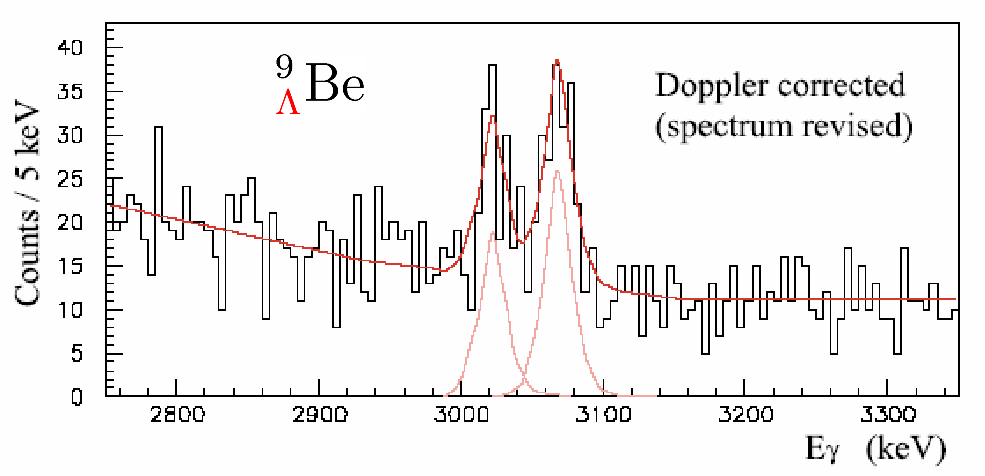
Total cross sections for YN scattering

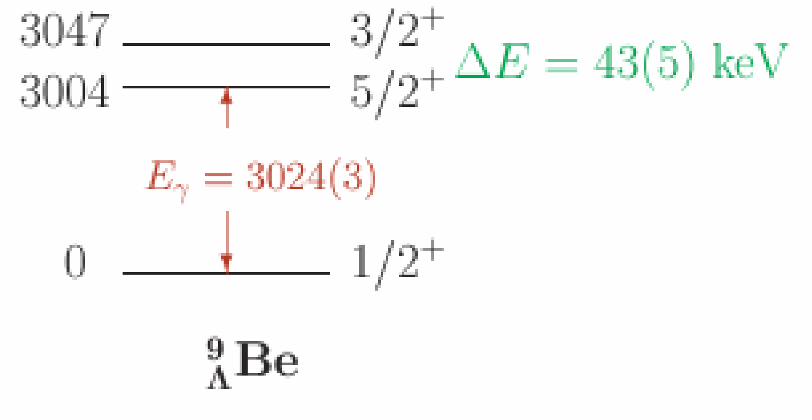


New info from hypernuclei: γ-ray (coincidence) experiments !

BNL E930, Tamura spokeperson

H. Akikawa et al, PRL88 (2002) 082501





Nijmegen NSC97f → spin-orbit splitting in $^{9}{}_{\Lambda}$Be: 150-200 keV

E.Hiyama et al., PRL85 (2000) 270

New! Nijmegen ESC03 → spin-orbit splittings in $^{9}{}_{\Lambda}$Be: ~ 80 keV

The new generation of experiments performed in the last 5 years have disclosed many interesting aspects of hypernuclear structure

→ crucial information for constraining the YN interaction!

Exotic Multistrange systems

Double Lambda hypernuclei $^{A}_{\Lambda\Lambda}Z$

→ strength of the $\Lambda\Lambda$ interaction: $\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2B_{\Lambda}({}^{A-1}_{\Lambda}Z)$

Old data: $\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) \simeq 4-5\ \mathrm{MeV}$

New data: $\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) \simeq 1\ \mathrm{MeV}$

↑

Reproduced by more recent BB forces! NSC97 and consistent with SU(3) expectations

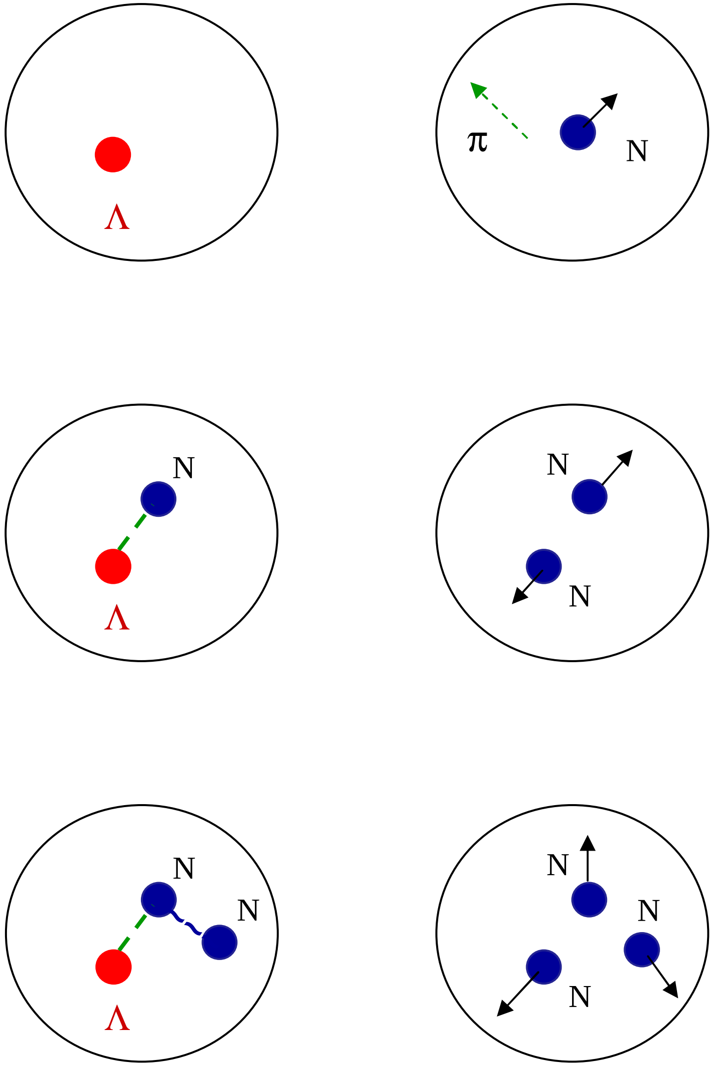
Stable highly strange hypernuclei (S=-3): $^{6}_{\Lambda\Xi}\mathrm{He}$

Pauli blocking on final Λ yields stability against $\Xi N \rightarrow \Lambda\Lambda$

(Q~25 MeV)

Filikhin and Gal (2004) with NSC97

WEAK HYPERNUCLEAR DECAY



MESONIC

$\Gamma_{\pi-}$: Λ g π^- p

$\Gamma_{\pi 0}$: Λ g π^0 n

k_N~100 MeV/c < k_F

↓

Pauli blocked!

NON-MESONIC

Γ_n: Λ n g n n

Γ_p: Λ p g n p

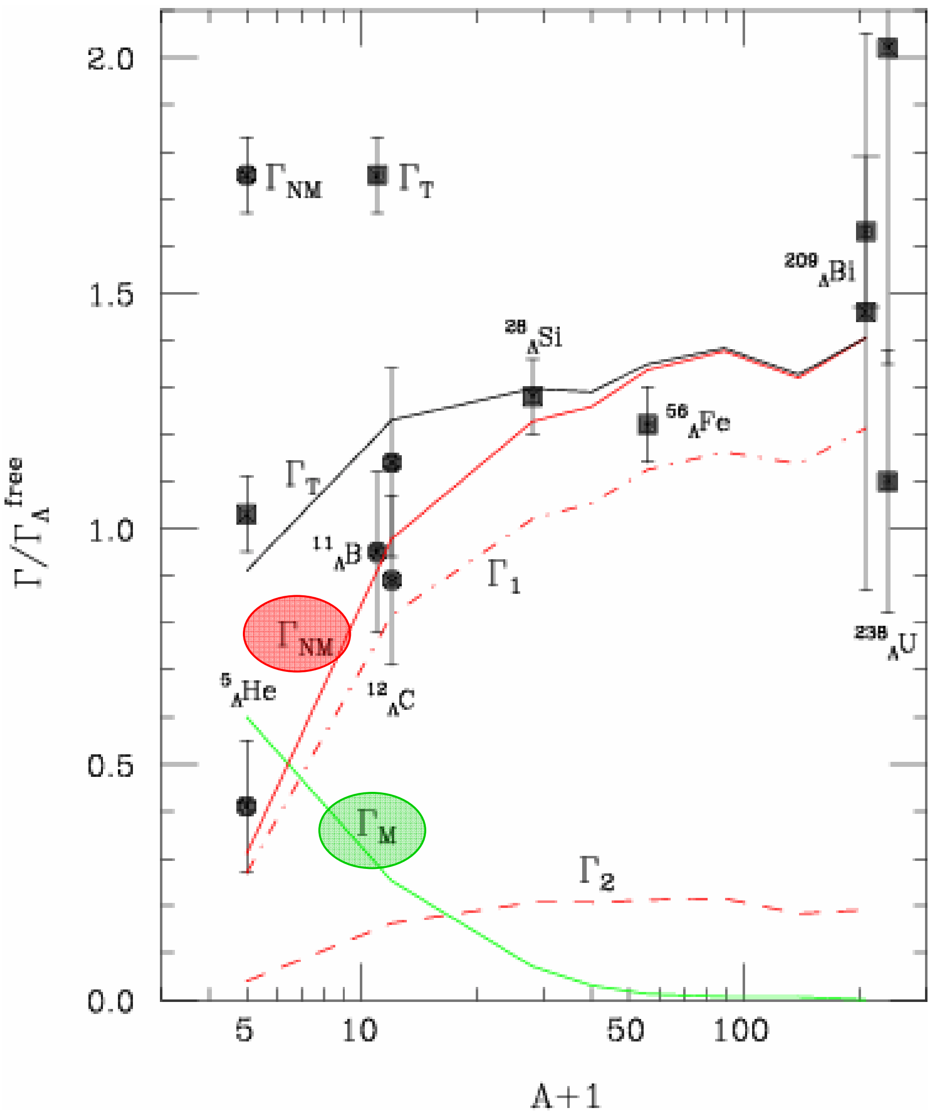
k_N~400 MeV/c

Γ_2: Λ N N g n N N

k_N~340 MeV/c

$$\Gamma_T = \Gamma_M + \Gamma_{NM} = \Gamma_{\pi-} + \Gamma_{\pi 0} + \Gamma_n + \Gamma_p + \Gamma_2$$

Observed decay rates



free Λ : Γ_Λ^{free}= 3.8 10^9 s $^{-1}$

$\Gamma_{\pi-}^{free}$: Λ g π^- p

$\Gamma_{\pi0}^{free}$: Λ g π^0 n

$\Gamma_{\pi-}^{free}/\Gamma_{\pi0}^{free}$ =1.78 ~ 2 → ΔI=1/2 !

Hypernuclear width: $\Gamma_T \sim \Gamma_\Lambda^{free}$

BNL, 91

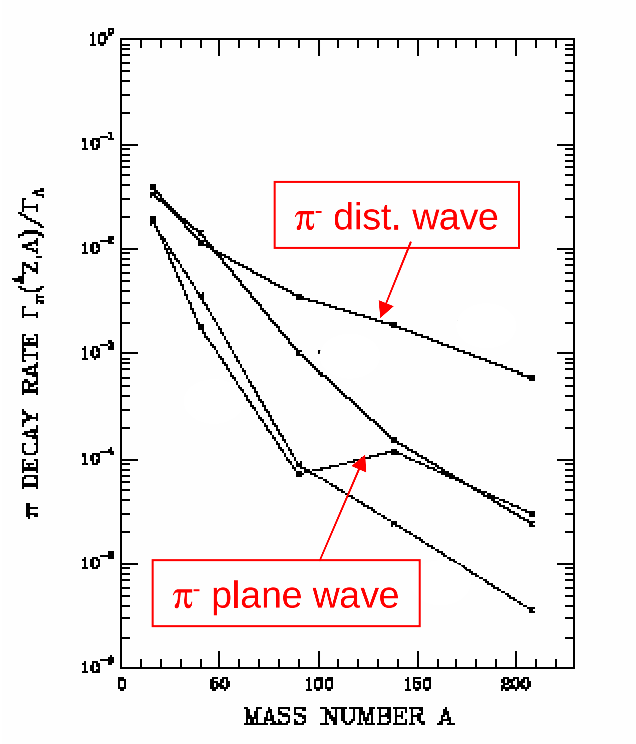
KEK, 95, 98

Jülich, 93, 97, 98

MESONIC DECAY: $\Lambda \rightarrow \pi N$ $Q \sim m_\Lambda - m_N - m_\pi \sim 35$ MeV

The tight energy balance of the reaction makes this process to be very sensitive to:

→ pion-nucleus optical potential:



$$E_\Lambda = E_N + \sqrt{m_\pi^2 + q^2} + U_\pi \leftarrow \text{attractive}$$

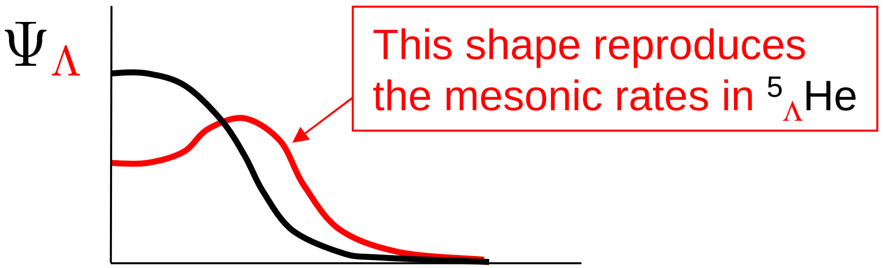
Enhancement of up to two orders of magnitude!

E. Oset, L.L. Salcedo, NPA443 (1985) 704

J. Nieves, E. Oset, PRC47 (1993) 1478

T. Motoba, K. Itonaga, H. Bando, NPA489 (1988) 683

→ Λ wavefunction in the nucleus:



This shape reproduces the mesonic rates in $^5_\Lambda$He

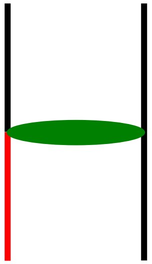
NON-MESONIC DECAY: Λ N → N N $Q \sim m_\Lambda - m_N \sim 175$ MeV

The emerging nucleons are very energetic and this process is not sensitive to nuclear structure details

→ Ideal process to characterize the baryon-baryon weak interaction!

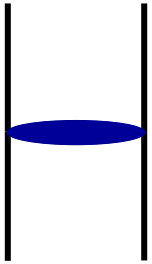
In particular, for processes having $\Delta S=1$ ($\Lambda N \rightarrow NN$), the PC amplitude is not masked by the strong interaction like in the case $\Delta S=0$ ($NN \rightarrow NN$)

$\Delta S=1$



Both PC and PV weak amplitudes can be studied from hypernuclear weak decay

$\Delta S=0$



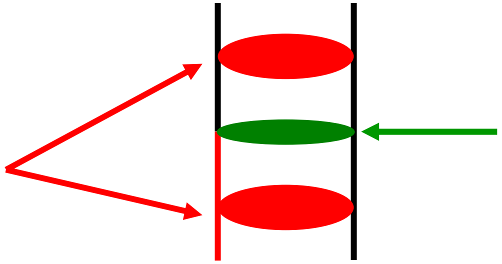
Only the PV amplitudes are accessible

W.M. Alberico and G. Garbarino, Phys. Reports 369 (2002) 1
E. Oset and A. Ramos, Prog. Part. Nucl. Phys. 41 (1998) 191

Non-mesonic processes:

Γ_n: Λ n → n n

Γ_p: Λ p → n p



strong interaction
between initial ΛN
and final NN pair

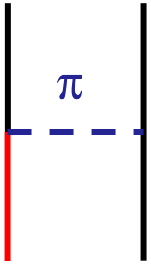
weak interacction:

- meson exchange: $\pi,\eta,K,\rho,\omega,K^*$
- quark models

→ Decay width $\Gamma_1=\Gamma_n+\Gamma_p$ well reproduced by all models but…

→ not the ratio Γ_n/Γ_p !

$$\left[\frac{\Gamma_n}{\Gamma_p}\right]^{\text{theo}} < 0.5 \qquad 0.5 < \left[\frac{\Gamma_n}{\Gamma_p}\right]^{\text{exp}} < 2$$



OPE mechanism dominated by tensor transitions

$^3S_1 \rightarrow {}^3D_1$

$\Lambda N \rightarrow NN$

Antisymmetry requires isospin I=0
nn pairs are in isospin I=1
→ Γ_n: Λn → nn supressed in OPE!

Theoretical models

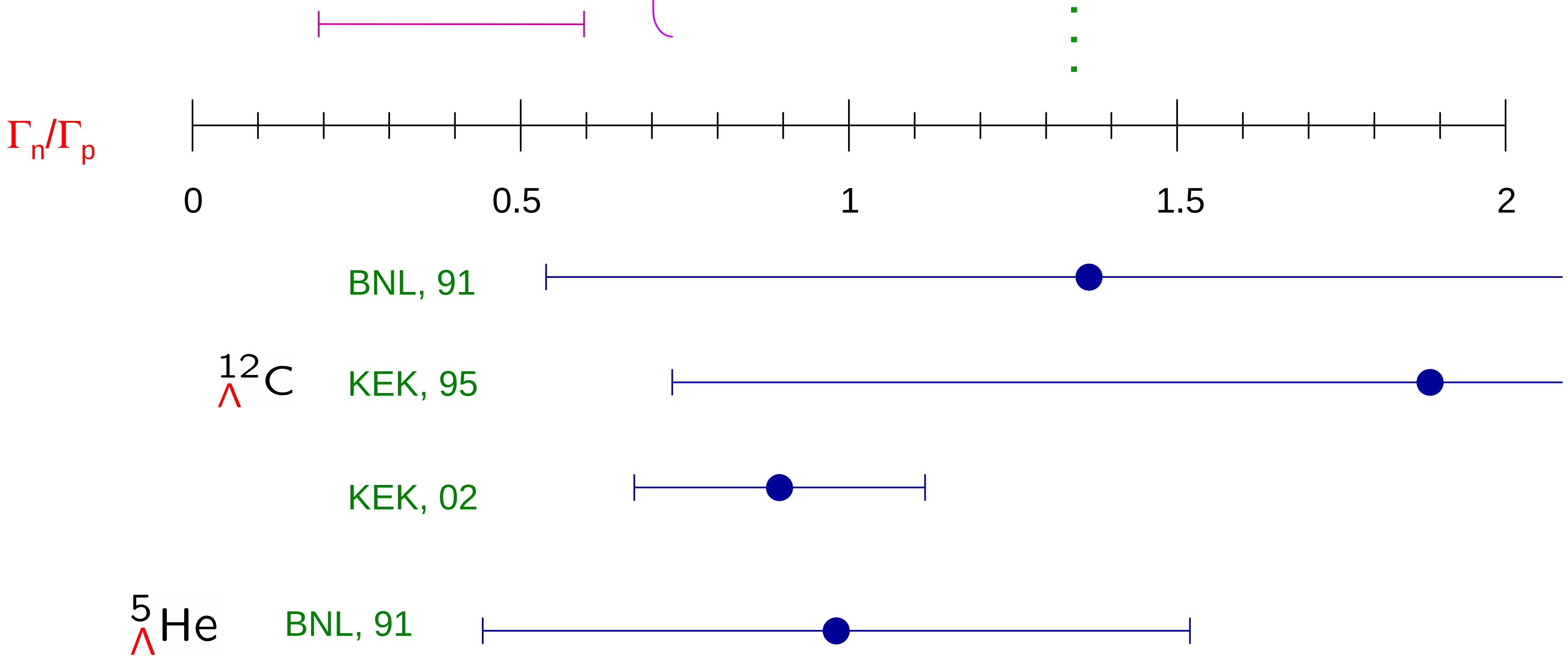
A. Parreño, A. Ramos and C. Bennhold, PRC 56 (1997) 339

K. Sasaki, T. Inoue and M. Oka, NPA 669 (2000) 331

D. Jido, E. Oset and J. E. Palomar, NPA 694 (2001) 525

K. Itonaga, T. Ueda and T. Motoba, PRC65 (2002) 034617

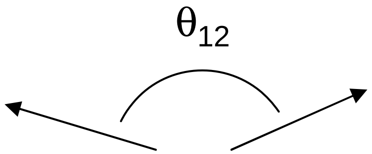
⋮



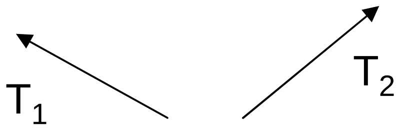
A challenge in hypernuclear weak decay for many years!

Recent development: NN coincidences

Angular correlations

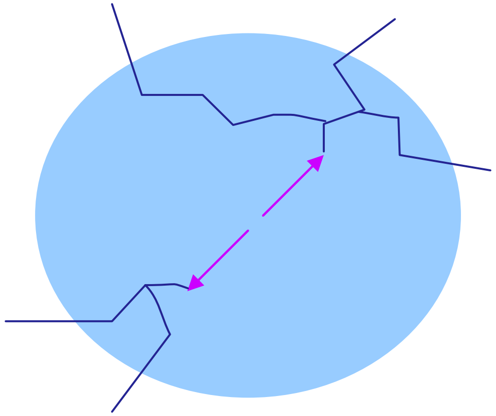


Energy correlations: T_1+T_2



Measuring distributions of NN pairs in coincidence permits a better determination of the ratio Γ_n/Γ_p :

- ✓ Reduces contamination from the process Γ_2: ΛNN → NNN
- ✓ More exclusive measurement of final states → some quantum mechanical interferences are eliminated



Models: must include FSI effects

The primary nucleons produced in the weak decay continuously change energy, direction, charge and new secondary nucleons are emitted.

A. Ramos, M.J. Vicente-Vacas and E. Oset, PRC55 (1997) 735-743; Erratum: ibid. C66 (2002) 039903

No FSI : $$\frac{N_{nn}^{wd}}{N_{np}^{wd}} \equiv \frac{\Gamma_n}{\Gamma_p}$$

Including FSI: $$\frac{N_{nn}}{N_{np}} \neq \frac{\Gamma_n}{\Gamma_p}$$

N_{nn},N_{np}: number of nn, np pairs after FSI

${}^{5}_{\Lambda}$He	$\frac{\Gamma_n}{\Gamma_p}$	$\frac{N_{nn}}{N_{np}}$
OPE	0.09	0.26
OME-a	0.34	0.51
OME-f	0.46	0.61

$(T_N^{\text{th}} = 30\ \text{MeV y}\ \cos\theta_{12} \leq -0.8)$

KEK-E462 (HYP2003) (preliminary)

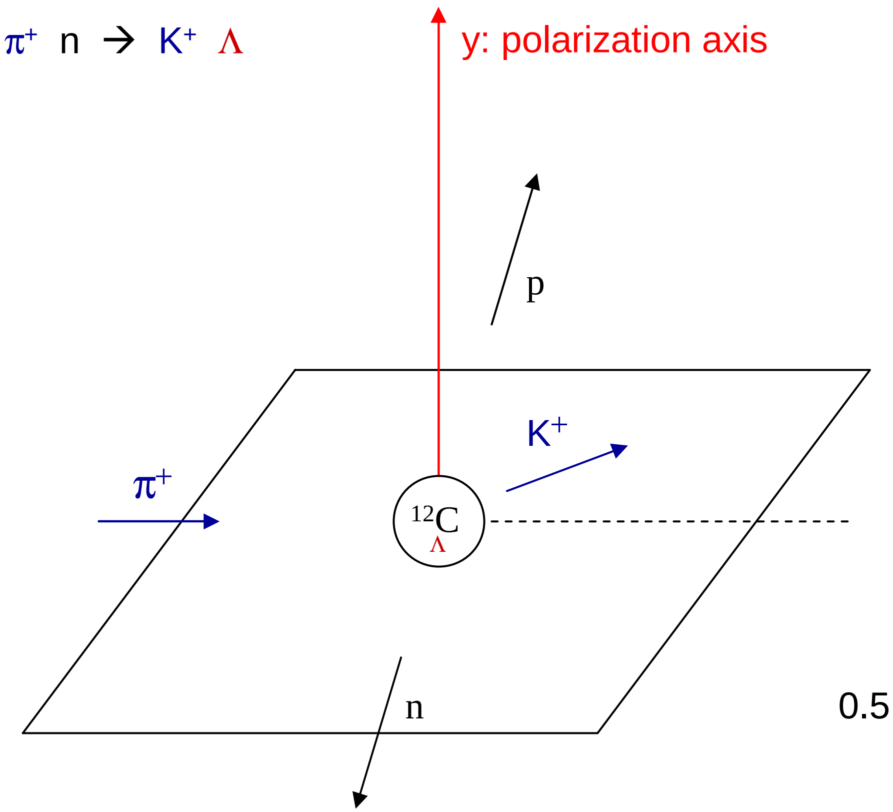
$$\frac{N_{nn}}{N_{np}} = 0.44 \pm 0.14$$

G. Garbarino, A. Parreño and A. Ramos, PRL 91, 112501 (2003)

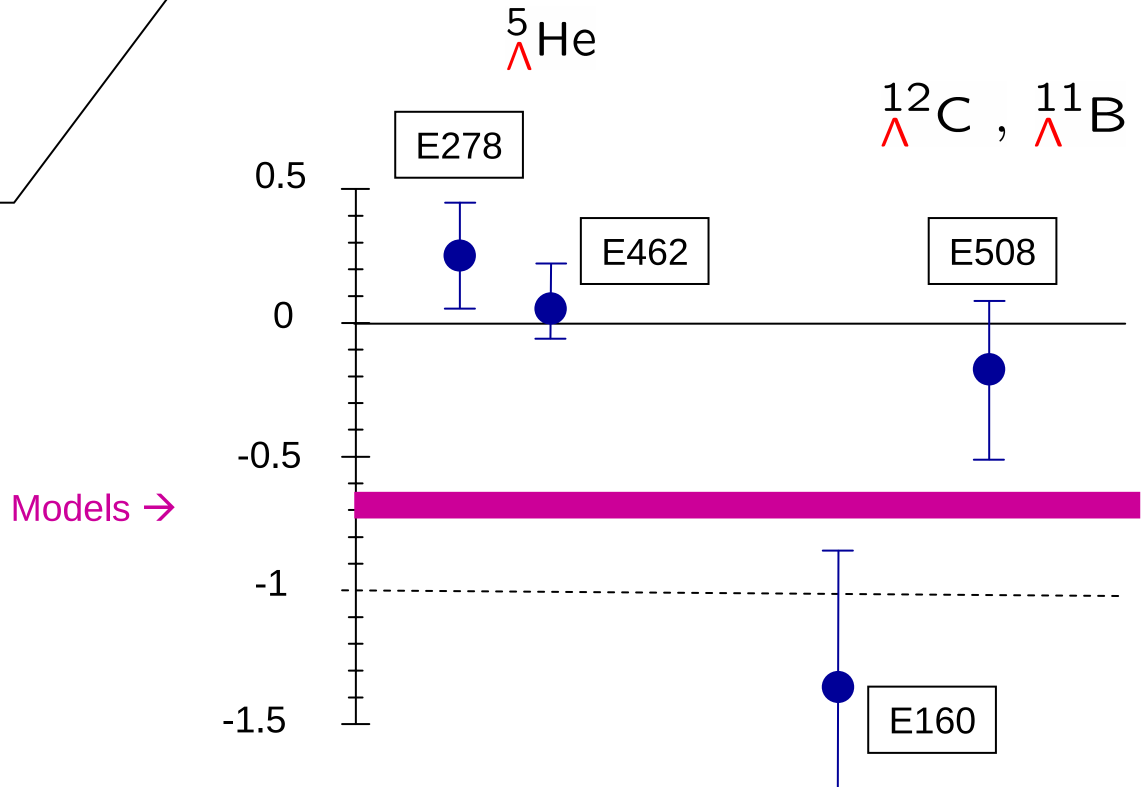
The Γ_n/Γ_p problem has been solved!

New challenge in hypernuclear decay: Asymmetry

$\pi^+ \; n \rightarrow K^+ \; \Lambda$



$$\mathcal{A} = \frac{N_p^{\uparrow} - N_p^{\downarrow}}{N_p^{\uparrow} + N_p^{\downarrow}}$$

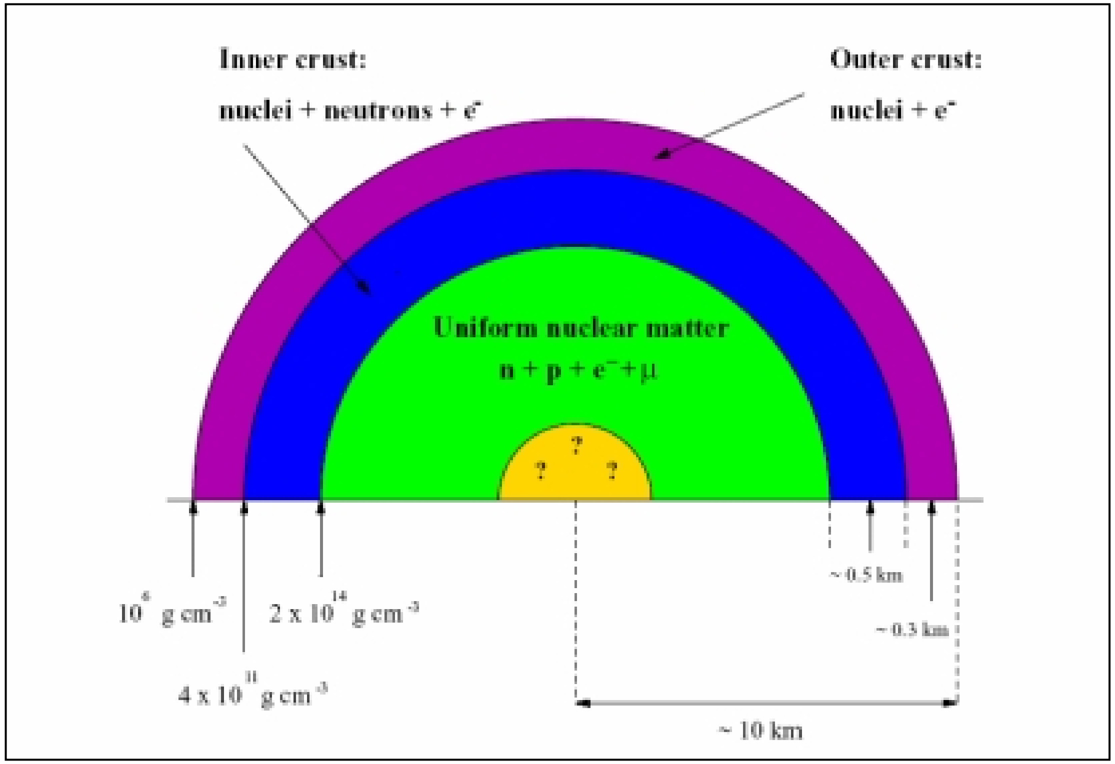


STRANGENESS IN NEUTRON STARS

Mass ~ 1.4 to 2.2 M⇠

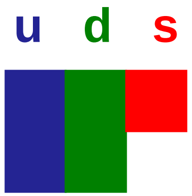
Radius ~ 10 km

Central density ~ $\rho_c = (4 – 8)\ \rho_0$
$(\rho_0 = 0.17\ \mathrm{fm}^{-3} = 2.8\ 10^{14}\ \mathrm{g/cm}^3)$



Strangeness

- *confined* form
  - hyperons: Σ^-, Λ
  - kaons: K^-
- *deconfined* form → strange quark matter



HYPERONS IN NEUTRON STARS → HYPERONIC MATTER

First proposed in 1960: **V.A. Ambartsumyan, G.S. Saakyan, Sov. Astron. AJ. 4 (1960) 187**

The core of a neutron star is a fluid of neutron rich matter in equilibrium with respect to the weak interactions (β-stable nuclear matter)

Why is it likely to have hyperons?

- ✓ The central density of a neutron star is high

$\rho_c = (4 - 8)\,\rho_0$ ($\rho_0 = 0.17$ fm^{-3} $= 2.8\ 10^{14}$ g/cm^3)

- ✓ The nucleon chemical potential increases very rapidly with density

→ Above a threshold density, $\rho_T = (2-3)\,\rho_0$, hyperons are created in the stellar interior!

β-stable hadronic matter

- Equilibrium with respect to weak interaction processes:

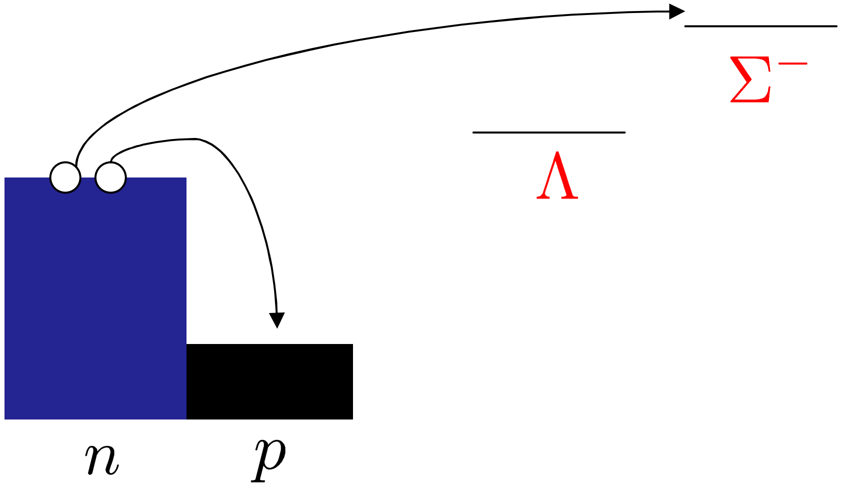
$$n \leftrightarrow p\, e^- \,\bar{\nu}_e \qquad (\mu_n = \mu_p + \mu_{e^-})$$

$$n\, n \leftrightarrow p\, \Sigma^- \quad (\text{or} \;\; e^-\, n \leftrightarrow \Sigma^-\, \nu_e) \qquad (\mu_{e^-} + \mu_n = \mu_{\Sigma^-})$$

$$n\, n \leftrightarrow p\, \Lambda \quad (\text{or} \;\; e^-\, p \leftrightarrow \Lambda\, \nu_e) \qquad (\mu_n = \mu_\Lambda)$$

- Charge neutrality:

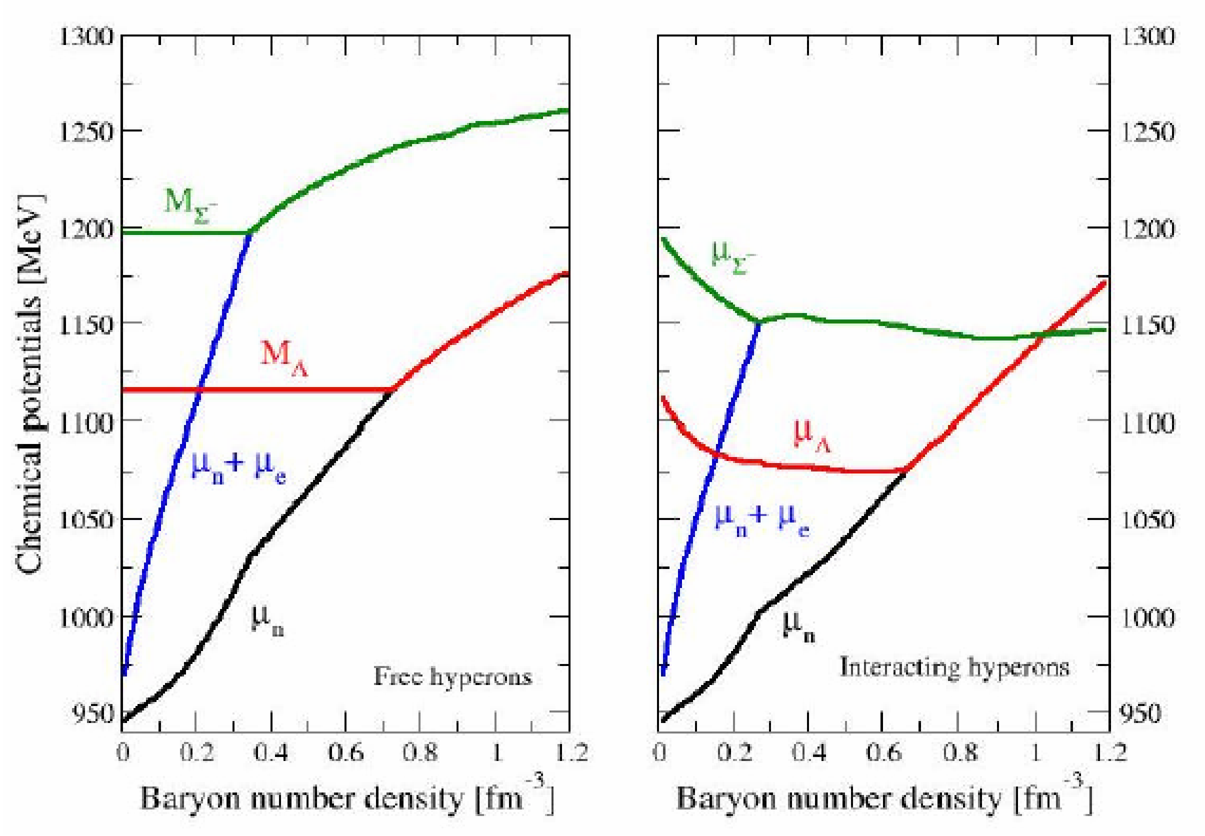
$$n_p + n_{\Sigma^+} = n_{e^-} + n_{\mu^-} + n_{\Sigma^-} + n_{\Xi^-}$$



Baryon chemical potentials in dense hyperonic matter

$$\mu_{e^-} + \mu_n = \mu_{\Sigma^-}$$

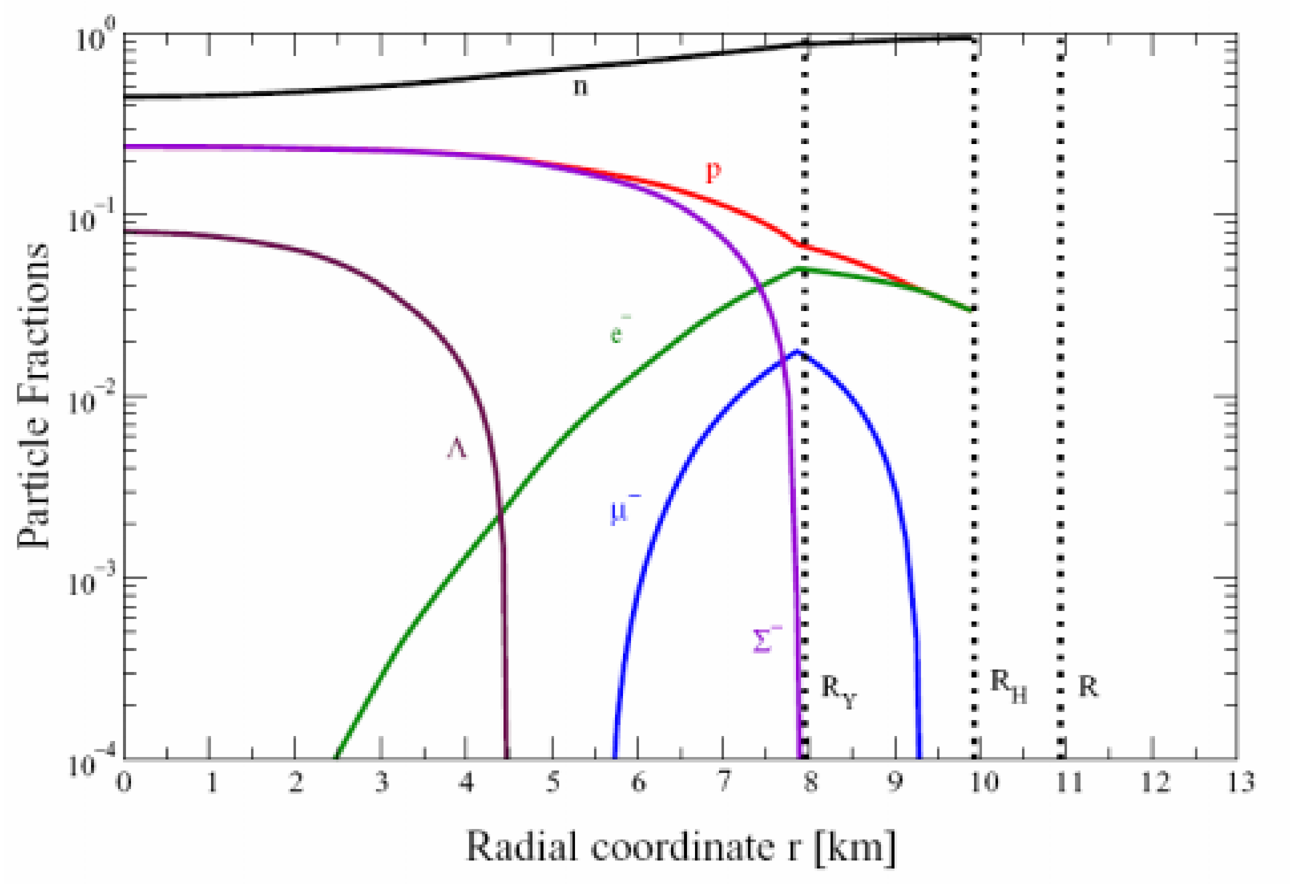
$$\mu_n = \mu_\Lambda$$



Thesis Isaac Vidaña, 2001

The composition of a neutron star depends on the hyperon properties in the medium (i.e. on the YN and YY interactions)

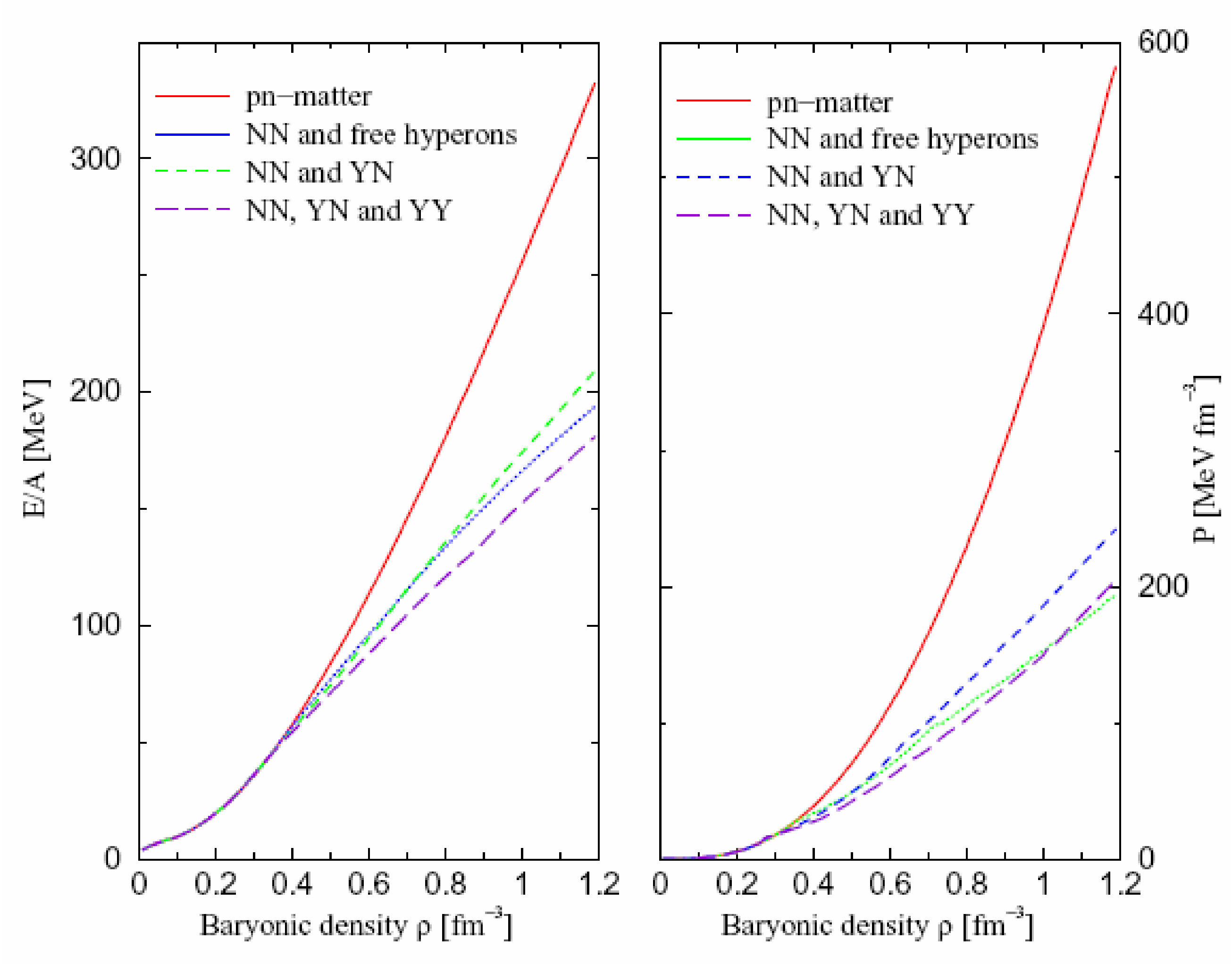
Profile of a neutron star with hyperons



I. Vidaña, A. Polls, A. Ramos, L. Engvik and M. Hjorth-Jensen, Phys. Rev. C62 (2000) 035801

Neutron stars are “giant hypernuclei” under the influence of gravity and strong interactions

The Equation-of-State (EoS) of hyperonic matter



The presence of hyperons produces a softening in the EoS!

Properties of a compact star

Hydrostatic equilibrium in General relativity:
Tolman-Oppenheimer-Volkov (TOV) equations

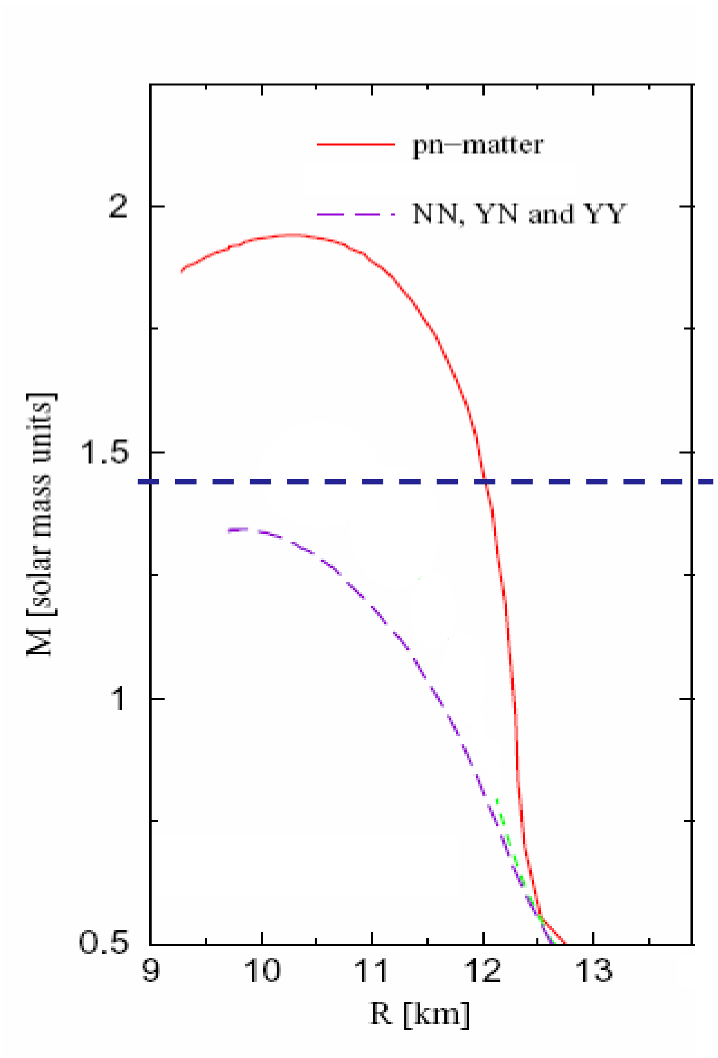
$$
\begin{aligned}
\frac{dP}{dr} &= -G\frac{m(r)\rho(r)}{r^2}\left(1+\frac{P(r)}{\rho(r)}\right)\left(1+4\pi r^3 P(r) m(r)\right)\left[1-\frac{2Gm(r)}{r}\right]^{-1} \\
\frac{dm}{dr} &= 4\pi r^2 \rho(r)
\end{aligned}
$$

imposing the boundary conditions

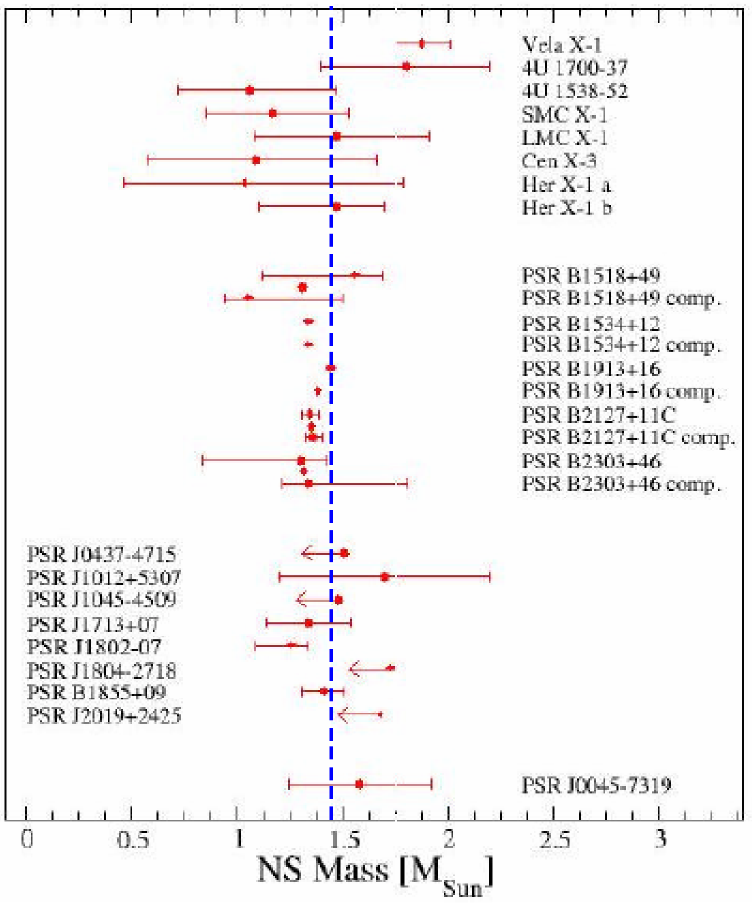
$$
\begin{aligned}
m(r=0) &= 0 \\
P(r=R) &= P_{\text{surf}}
\end{aligned}
$$

and assuming a central density $\rho(r=0) = \rho_c$

The mass M and radius R of the compact star is determined from a given EoS, $P=P(\rho)$ → $M(\rho_c)$, $R(\rho_c)$



Measured neutron star masses



Influence of hyperons:

lower maximum masses
higher central densities
more compact (smaller radius)

Too “soft” EoS

→ need extra pressure at high density

Improved two-body YN, YY interactions

Three-body forces: YNN, YYN, YYY

(ANTI)KAONS IN THE MEDIUM

The K- feels attraction in the medium

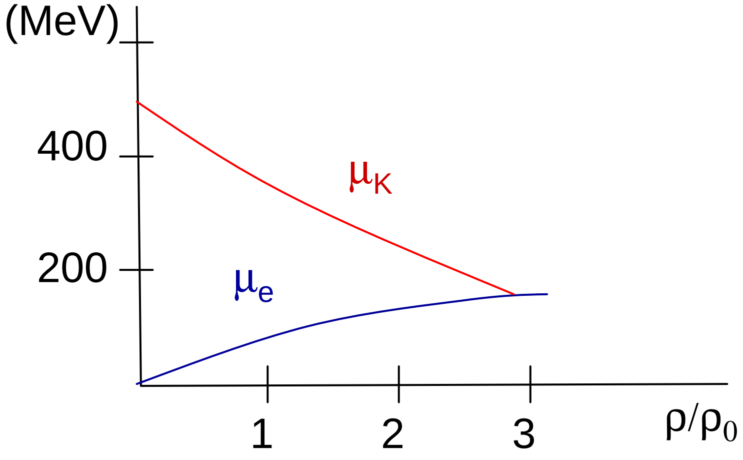
→ Kaon condensation in neutron stars?

D.B. Kaplan and A.E. Nelson, Phys. Lett. B175 (1986) 57

G. E. Brown and H. A. Bethe, Astrophys. Jour. 423 (1994) 659

$$n \leftrightarrow p\, e^-\, \bar{\nu}_e \quad \rightarrow \quad \mu_n = \mu_p + \mu_{e^-}$$

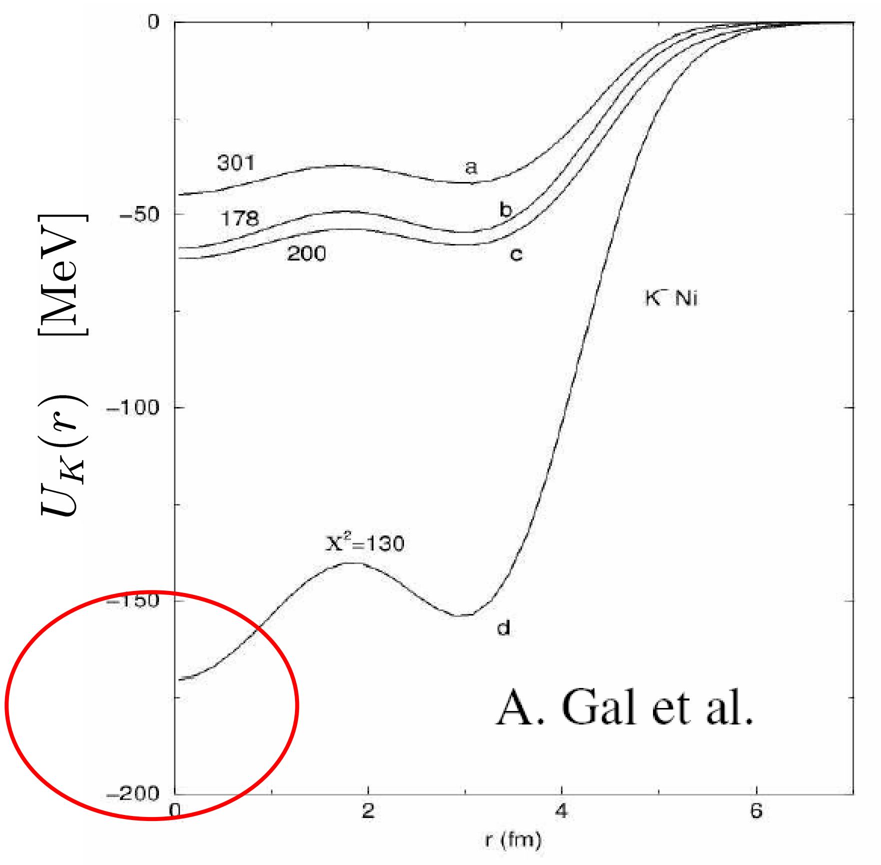
$$n \leftrightarrow p\, K^- \quad \rightarrow \quad \mu_n = \mu_p + \mu_{K^-}$$

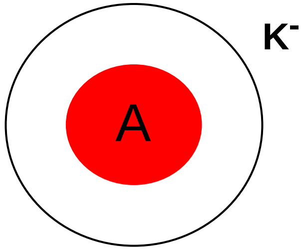


Kaons are bosons → a condensate of (anti)kaons would appear

Best fits to kaonic atoms seem to prefer $U_K \sim -200$ MeV at ρ_0

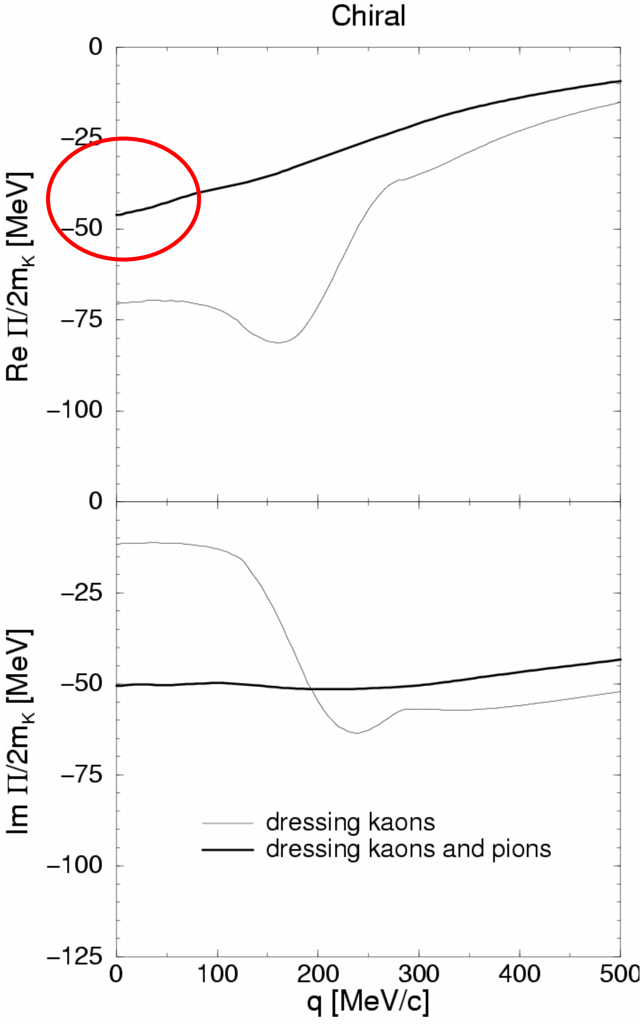
E. Friedman, A. Gal, and C.J. Batty, NPA 579 (1994) 518



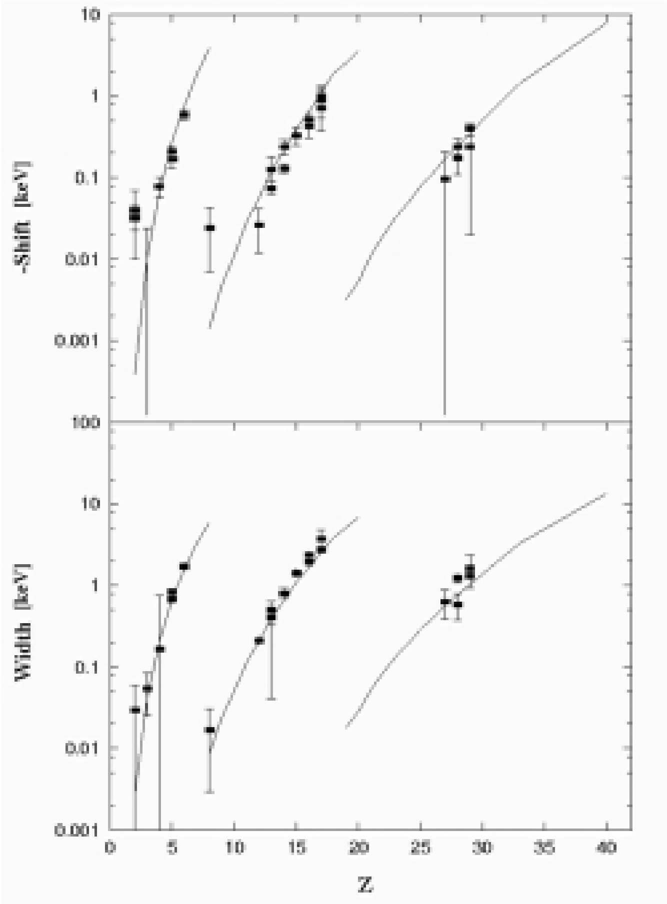


$$\left(-\nabla^2 + m_K^2 + 2m_K U_K(r) + V_{\text{Coul.}}\right)\Psi_K(r) = {E_K}^2\,\Psi_K(r)$$

However, theoretical models based on the KN interaction plus appropriate many-body effects → moderate attraction for the K-nucleus potential



A. Ramos and E. Oset, NPA 671 (2000) 481



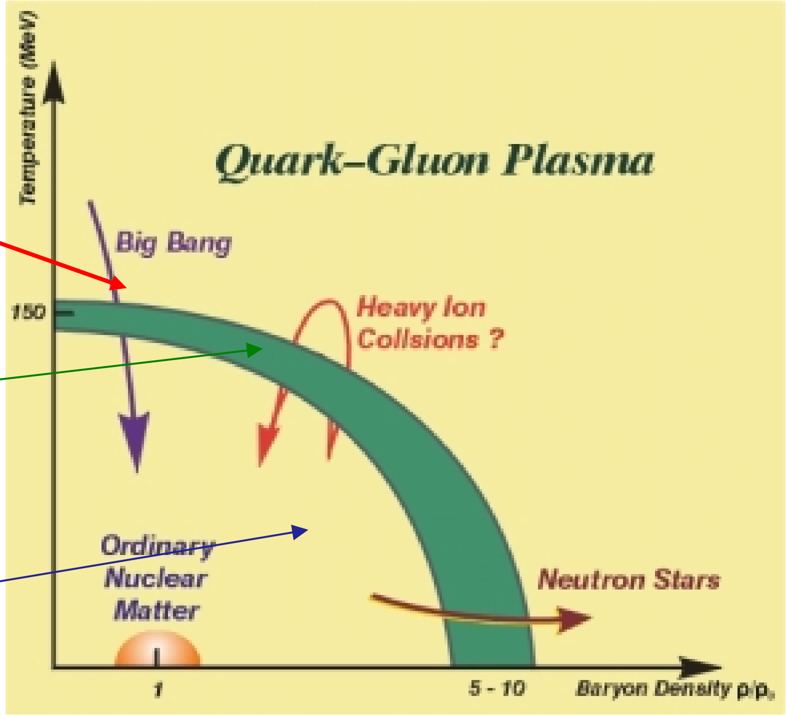
kaonic atom data are also well described!

S. Hirenzaki et al., PRC61 (2000) 055205
A. Baca, C. García-Recio, J. Nieves, NPA 673 (2000) 335

Kaonic atom data are not sensitive to the K-nucleus potential at ρ_0

→ only the nuclear surface (up to $\rho \sim \rho_0/4$) is explored!

Heavy Ion Collisions (HIC) are a possible source of information for determining the in medium properties of antikaons

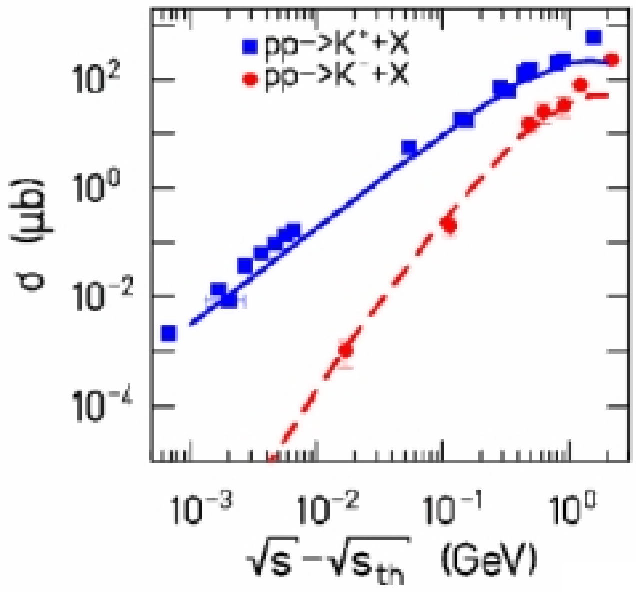


SPS(CERN)/RHIC(BNL)
>100AGeV

AGS-BNL
10AGeV

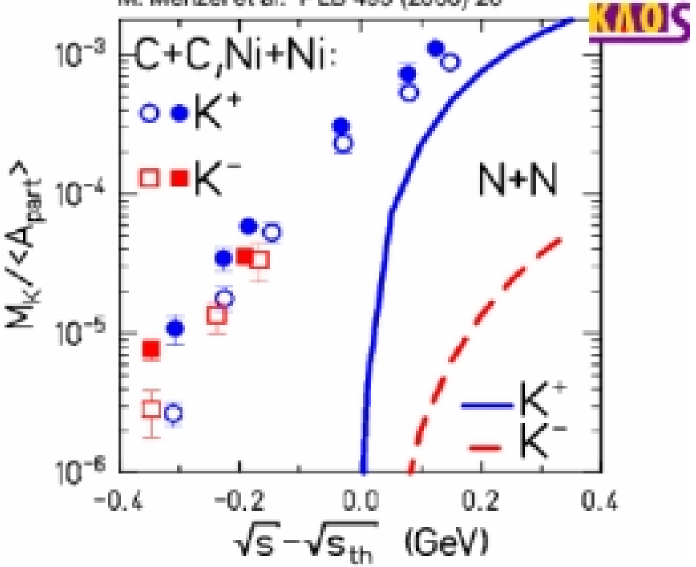
SIS-GSI
1AGeV

Appropriate for studying medium effects on hadrons



NN collisions: $\sigma(K^-) <= \sigma(K^+)/10$

F. Laue, C. Sturm et al. PRL 82 (1999) 1640
M. Menzel et al. PLB 495 (2000) 26



Heavy Ion collisions: $\sigma(K^-) \sim \sigma(K^+)$

K^-/K^+ ratio: increases 1-3 orders of magnitude with respect to NN collisions

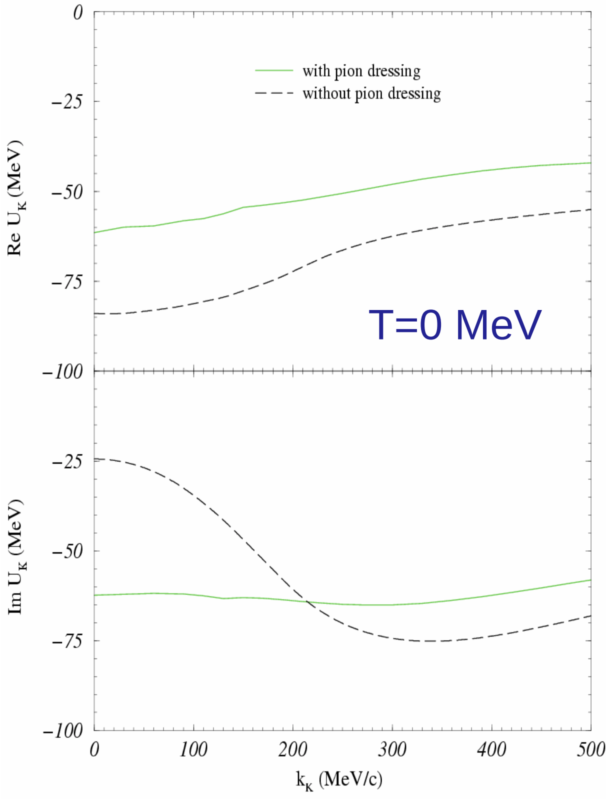
$N N \rightarrow K^+ \Lambda N$ 2.55 GeV
$N N \rightarrow K^+ K^- N N$ 2.87 GeV

→ manifestation of a reduced mass for the K^- !

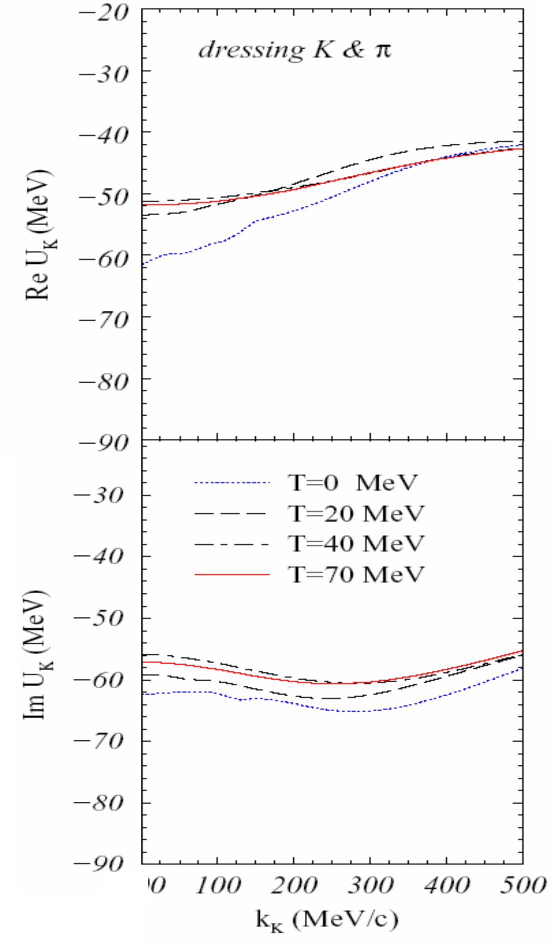
In SIS-GSI: densities up to 2-3ρ_0
finite T: 70 MeV
K- produced at finite momentum

In neutron stars: densities up to 8ρ_0
T ~ 0 MeV
K- at 0 momentum

L. Tolós et al, NPA690 (2001) 547



L. Tolós, A. Ramos and A. Polls, PRC65 (2002) 054907



Moderate dependence of U_K on momentum and on temperature

While enhancement of K^-/K^+ ratio in heavy-ion collision data seem to suggest an attractive K- nucleus potential, the size of the attraction has not yet been determined.

HIC messy:
K^- production linked to K^+ production through NN → K^+YN followed by YN → NK^-
(Ch. Hartnack, H.Oeschler, J.Aichelin, PRL90 (1993) 102302)
→ K- yield depend on medium effects for bot K^+ and K^- !

Data on K^- nucleus scattering/absorption is cleaner and may provide some answers **A. Ohnishi, Y. Nara, V. Koch, PRC56 (1997) 2767**

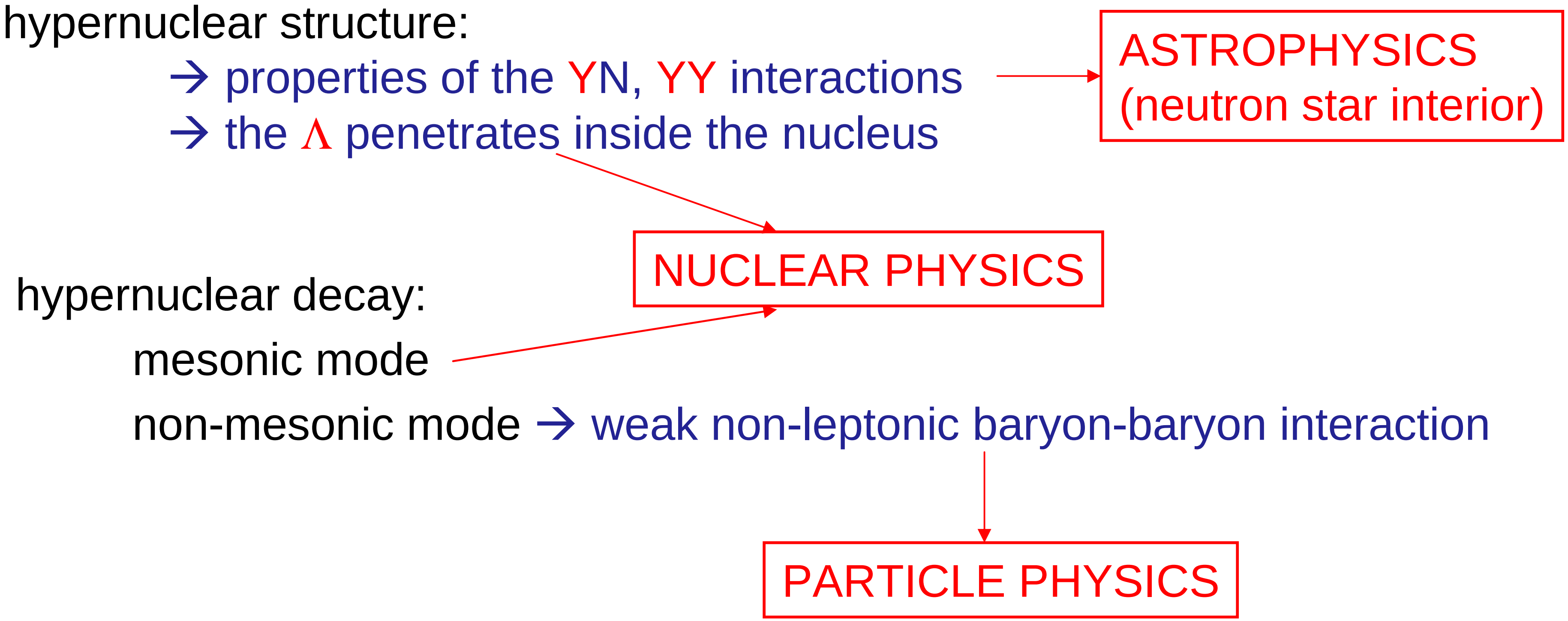
In any case, the more sophisticated theoretical models predict a moderate attraction

M. Lutz, Phys. Lett. B426 (1998) 12
A. Ramos and E. Oset, NPA 671 (2000) 481
L. Tolós et al, NPA690 (2001) 547

→ Kaon condensation is very unlikely !

STRANGE NUCLEAR PHYSICS is a fascinating field that, by adding a new dimension (strangeness) into conventional nuclear physics, opens the door to investigate new phenomena associated to the enlarged field of flavour SU(3) dynamics

Interdisciplinary field !



hypernuclear structure:

→ properties of the YN, YY interactions → ASTROPHYSICS (neutron star interior)

→ the Λ penetrates inside the nucleus → NUCLEAR PHYSICS

hypernuclear decay:

mesonic mode → NUCLEAR PHYSICS

non-mesonic mode → weak non-leptonic baryon-baryon interaction → PARTICLE PHYSICS