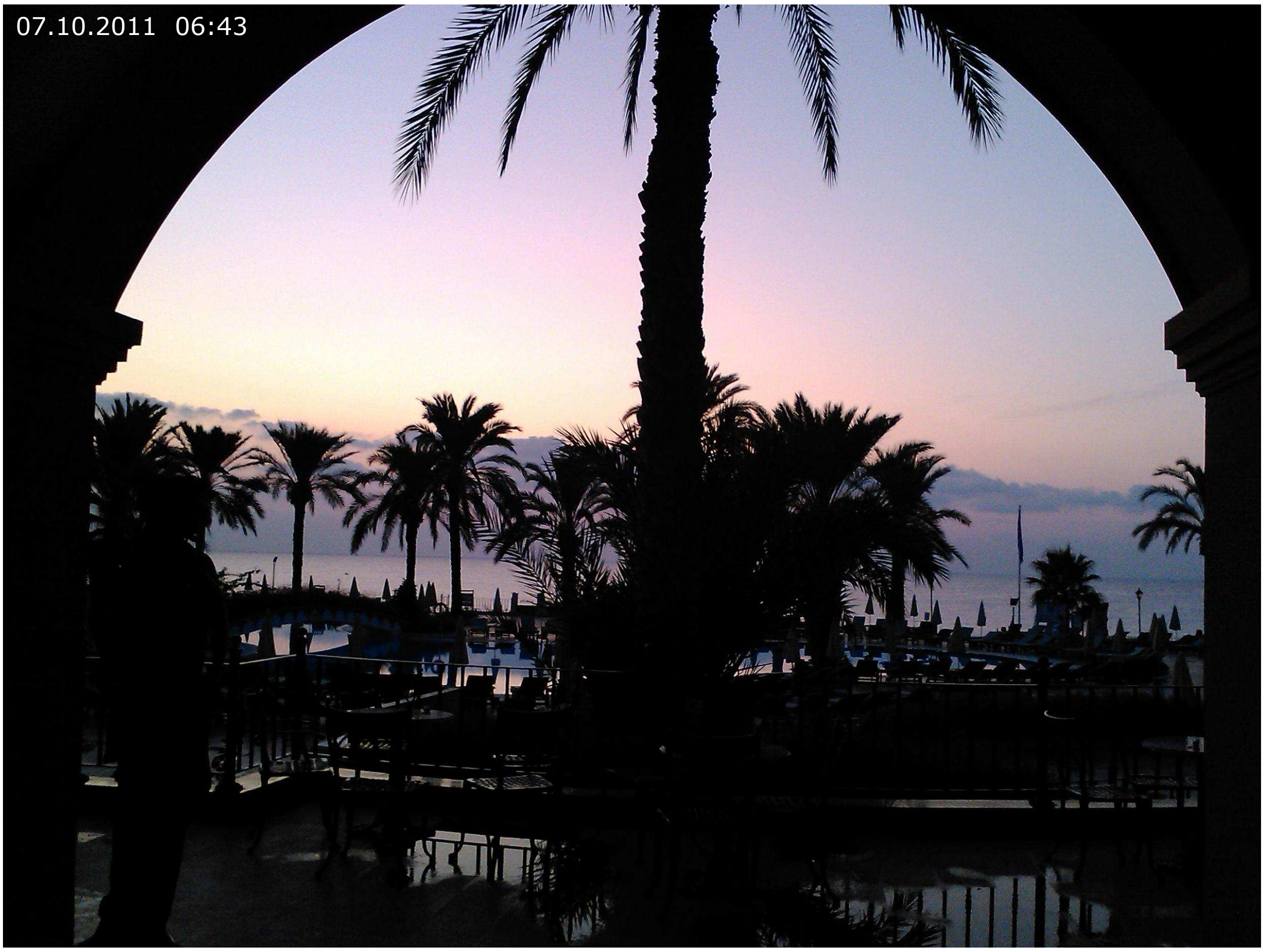


Hypernuclei

Why ?

Why now?

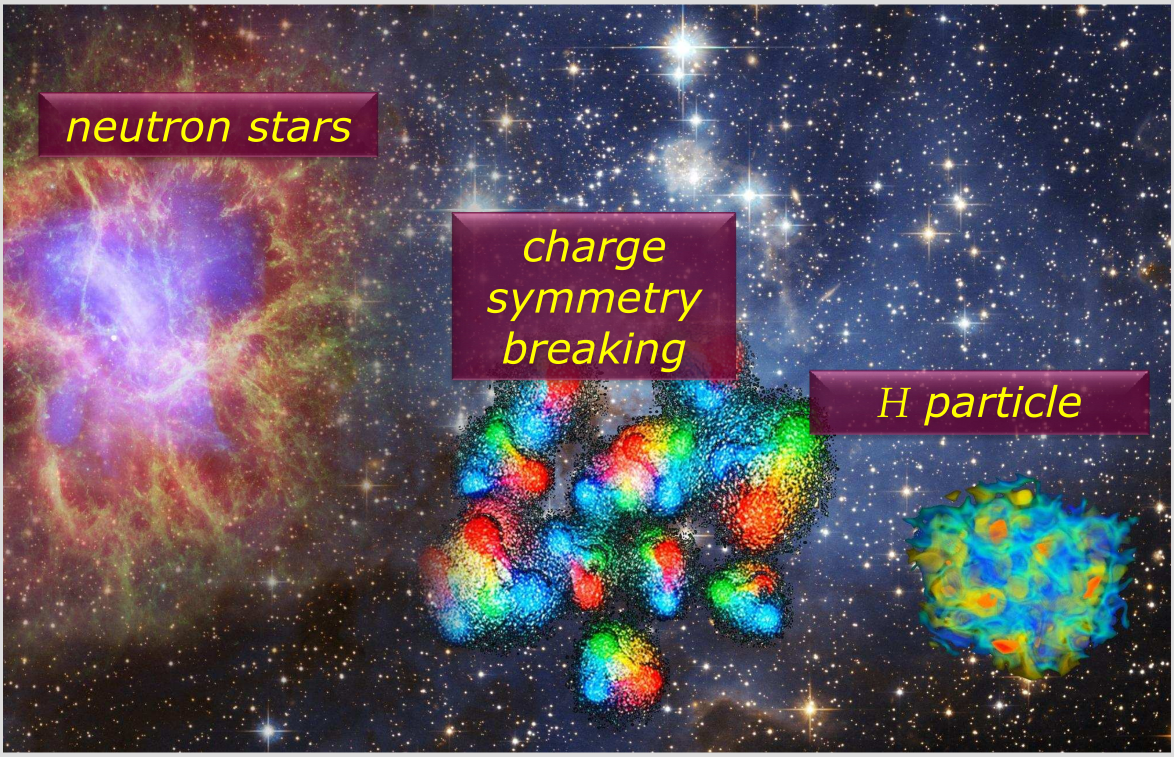
Why now in Mainz?

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
mami MAINZER MIKROTRON
SEVENTH FRAMEWORK PROGRAMME
Bundesministerium für Bildung und Forschung
DFG

Josef Pochodzalla NUFRA 2011

Bridging the gap between Quarks and Stars

Comprehensive description of Nuclei in terms of basic principles (QCD)…



…to allow quantitative predictions in regions not accessible by experiments

5 decades of hyperons in neutron stars

NEUTRON STAR MODELS

A. G. W. Cameron

Atomic Energy of Canada Limited, Chalk River, Ontario, Canada

Received June 17, 1959

Another reason why the writer has not taken into account complications inherent in using a relativistic equation of state is that no such things as pure neutron stars can be expected to exist. The neutrons must always be contaminated with some protons and sometimes with other kinds of nucleons (hyperons or heavy mesons).

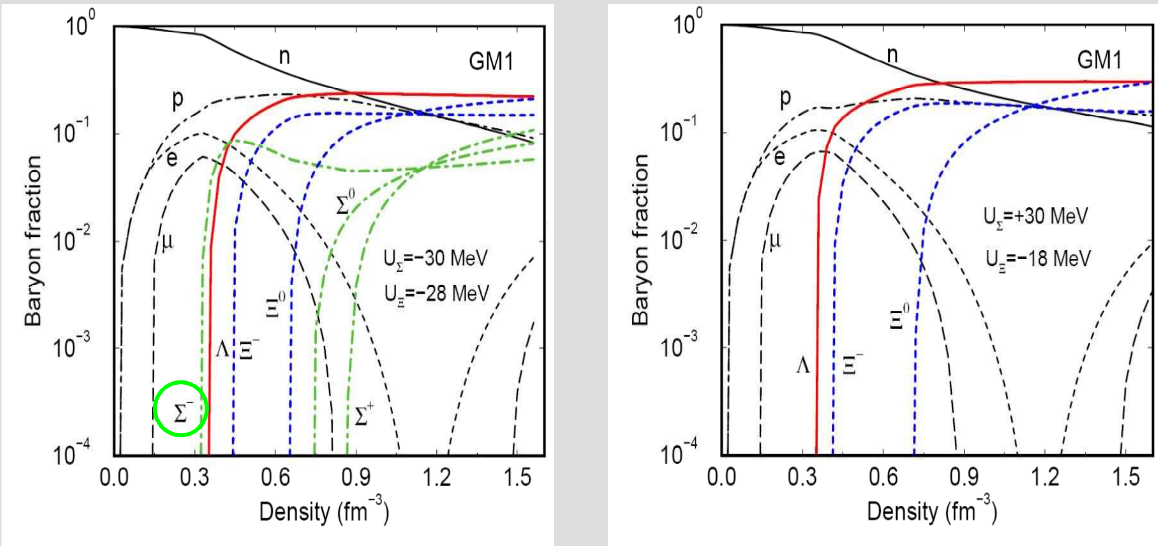
Alastair G.W. Cameron, Astrophysical Journal, vol. 130, p.884 (1959)

Rather than being a surprise to find hyperons it would stretch our understanding of fundamental strong and weak interaction processes to breaking point if they were not to appear. It is certainly inconceivable that a nucleon-only EoS could be realistic at such large densities.

J. R. Stone, P. A. M. Guichon, A. W. Thomas, arXiv:1012.2919v1

Appereance of Hyperons

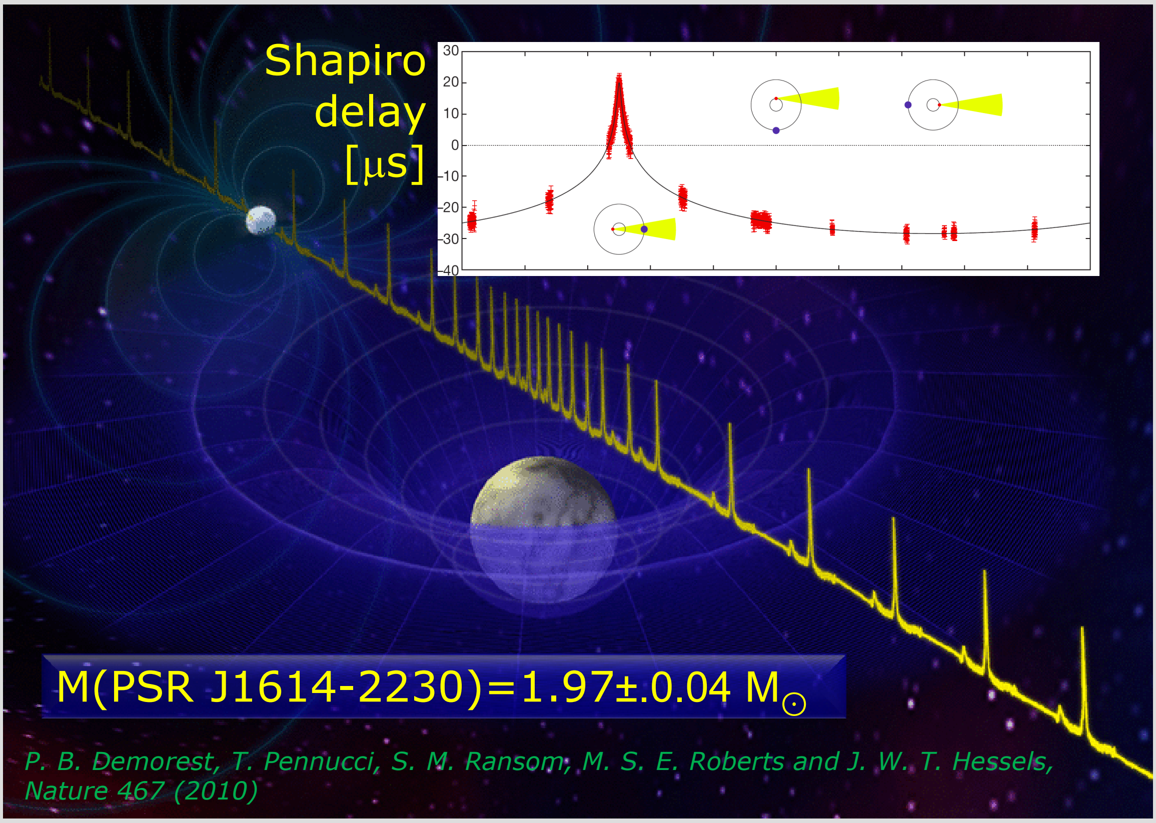
- hyperons appear, when its in-medium energy equals its chemical potential
- Input: Baryons in chemical Equilibrium, conservation laws, interaction



N. K. Glendenning, Phys. Rev. C **64**, 025801 (2001)

- beyond $2\rho_0$ hyperons may play a significant role in neutron stars
- in the core hyperons may even be more abundant than neutrons

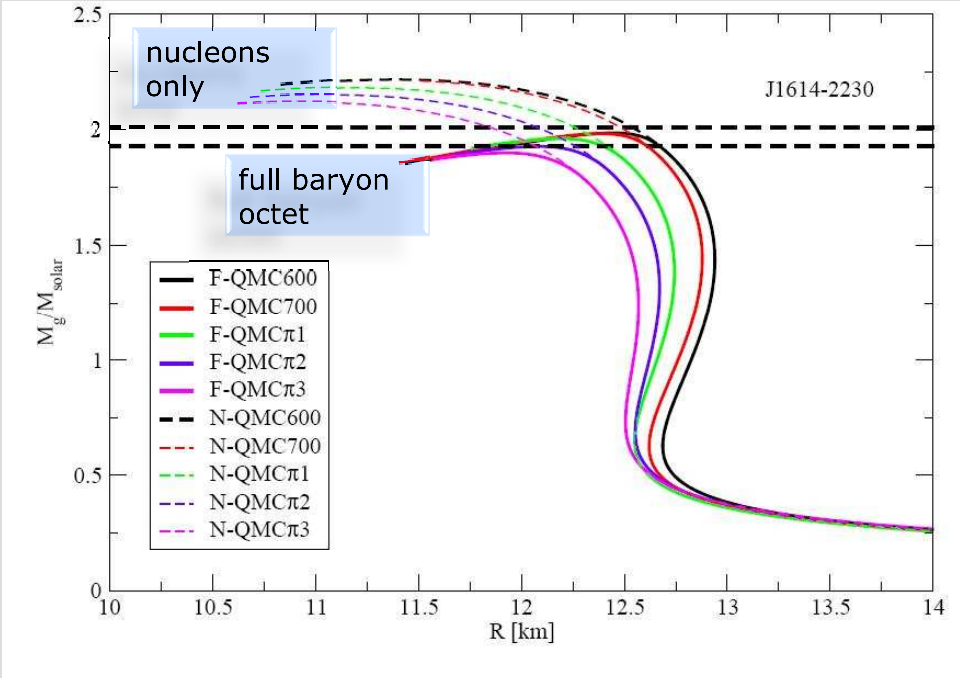
Masses of Neutron Stars



P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts and J. W. T. Hessels, Nature 467 (2010)

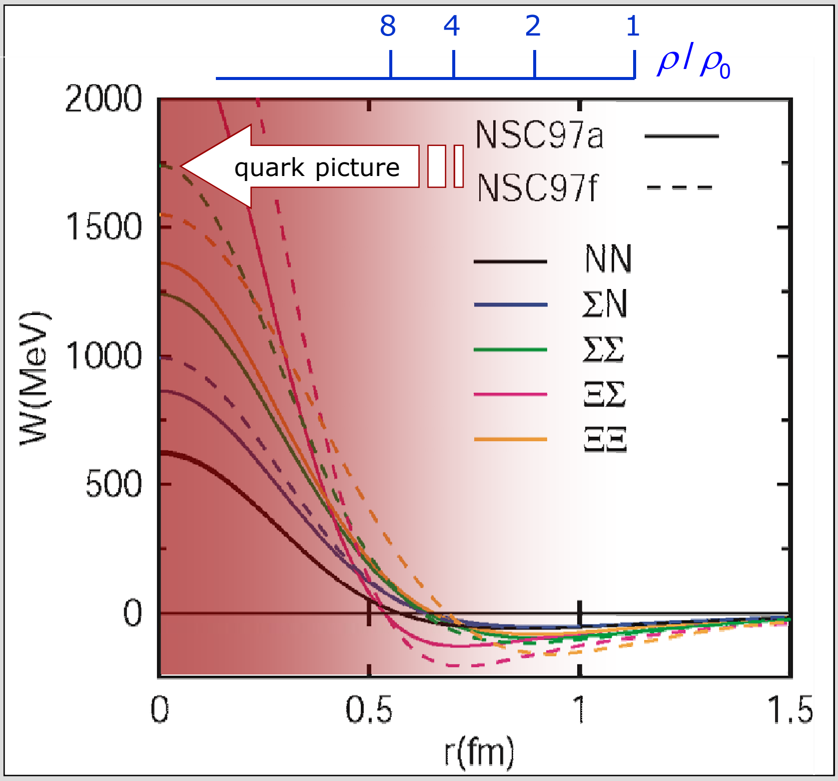
Masses of Neutron Stars

- EOS predicted within Quark-Meson-Coupling model

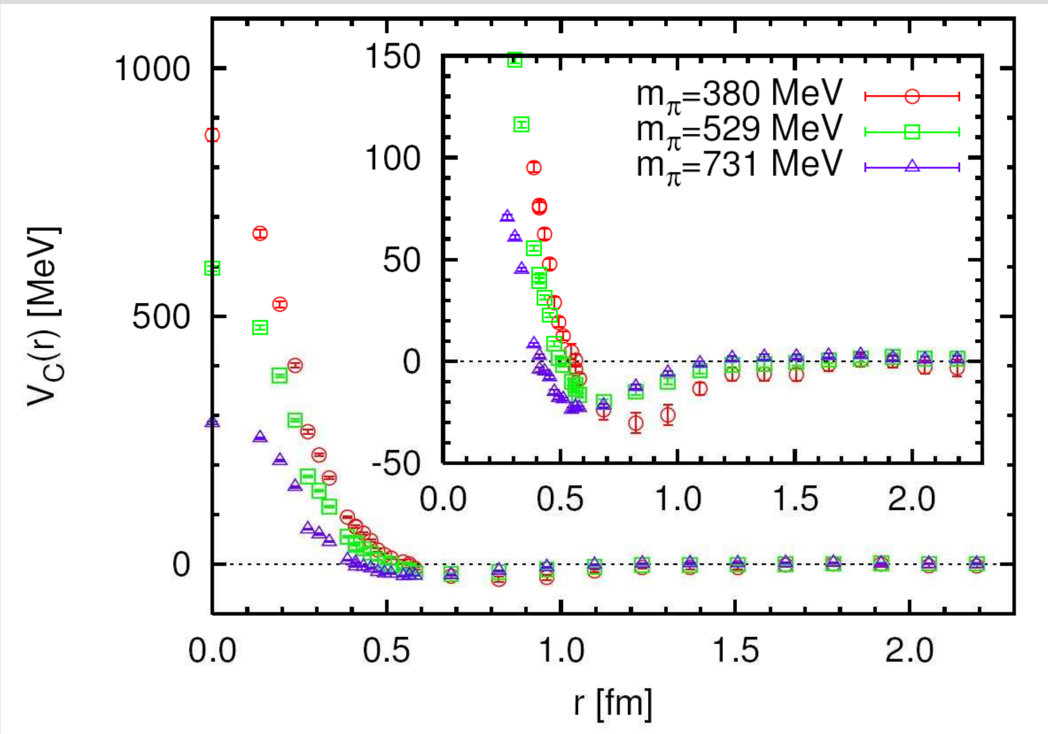


J. R. Stone, P. A. M. Guichon, A. W. Thomas, arXiv:1012.2919v1

Interpolation vs. extrapolation



Nuclear Forces from Lattice QCD



S. Aoki, T. Hatsuda and N. Ishii, Prog. Theor. Phys. 123 (2010) 89

Charge Symmetry Breaking

- Protons and neutrons are the two isospin states of the nucleon
- Protons and neutrons have different masses
- Coulomb interaction would make p (uud) heavier than n (udd)
- The mass difference between up and down quarks is the *only* strong-interaction effect that breaks charge symmetry.

u $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.5$ to 3.0 MeV [a] Charge $= \frac{2}{3}\,e$ $I_z = +\frac{1}{2}$

$m_u/m_d = 0.3$ to 0.6

d $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 3$ to 7 MeV [a] Charge $= -\frac{1}{3}\,e$ $I_z = -\frac{1}{2}$

$m_s/m_d = 17$ to 22

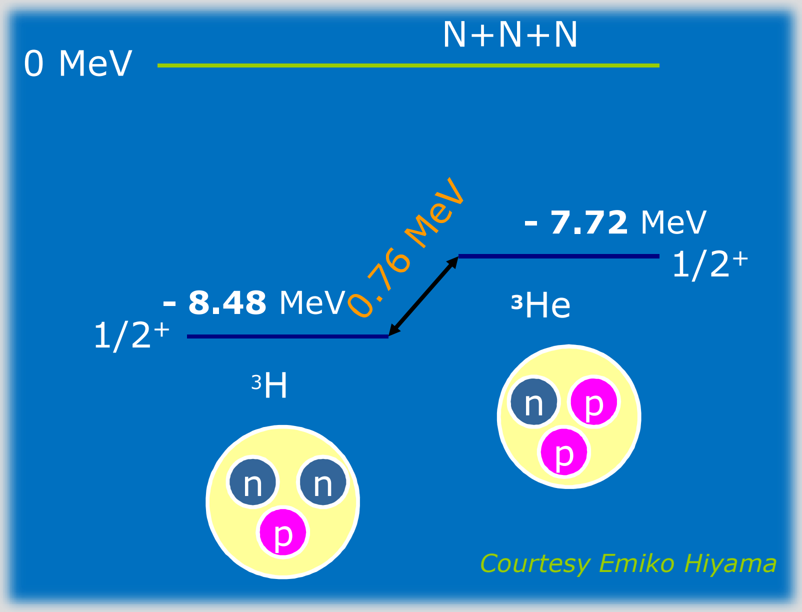
$\overline{m} = (m_u + m_d)/2 = 2.5$ to 5.5 MeV

- Strong CSB in S=0 sector makes neutrons decay into protons and is therefore decisive for the structure of our universe
- Reminder: one has to distinguish between
  - Isospin invariance: $[H_{strong}, T] = 0$
  - Charge independence
  - Charge symmetry: $[H_{strong}, e^{i\pi T_2}] = 0 \quad \leftrightarrow \quad |u\rangle \xrightarrow{CS} -|d\rangle, \; |d\rangle \xrightarrow{CS} +|u\rangle$
    - Example: π^0-π^0 and π^0-π^+ scattering
      - Hamiltonian isospin invariant
      - Clebsch Gordan coefficients are different $|10\rangle|10\rangle \neq |10\rangle|11\rangle$

        $\Rightarrow$ interaction is charge dependent

Charge Symmetry Breaking in Mirror Nuclei

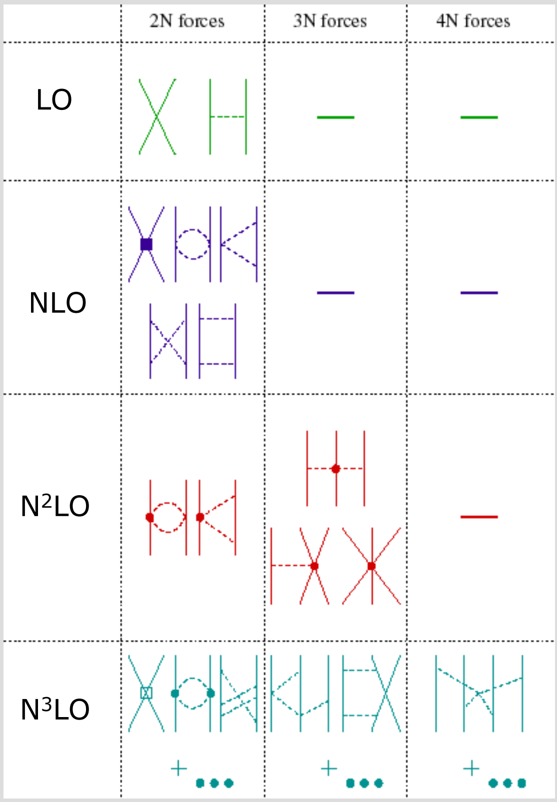
see talk of Hiyama



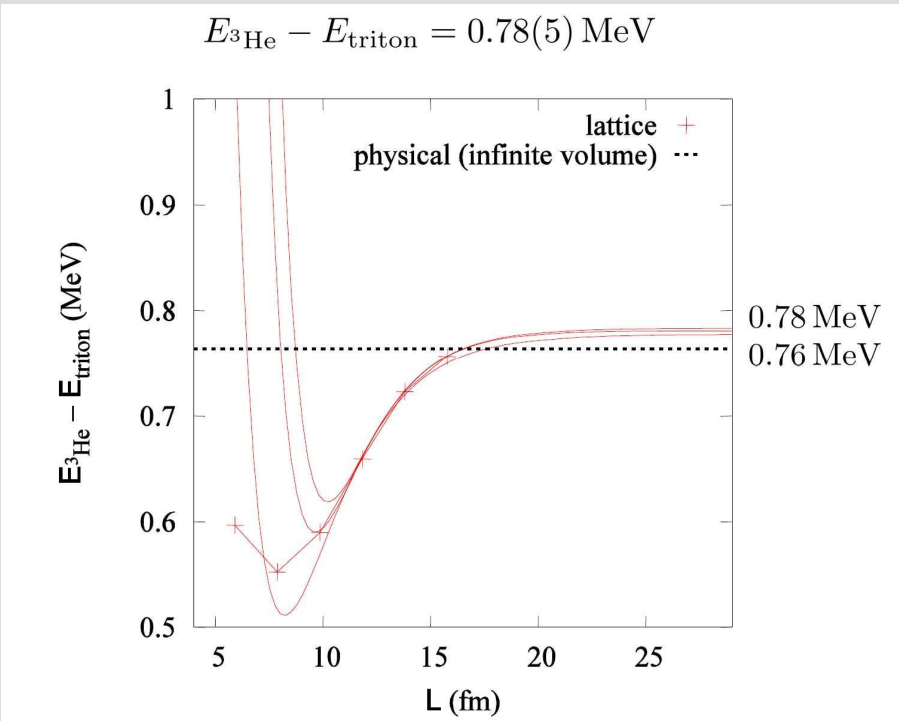
- Coulomb interaction and modifications of nuclear structure due to Coulomb interaction may mask the effect of the strong CSB!

Effective Field Theories are getting mature

- EFT for relevant degrees of freedom based on symmetries of QCD
- Long range pion dynamics treated explicitely
- Short-range physics absorbed in contact terms
- Low energy constants fitted to experimental data
- Hierarchy of *consistent* NN, 3N, 4N,… interactiopns

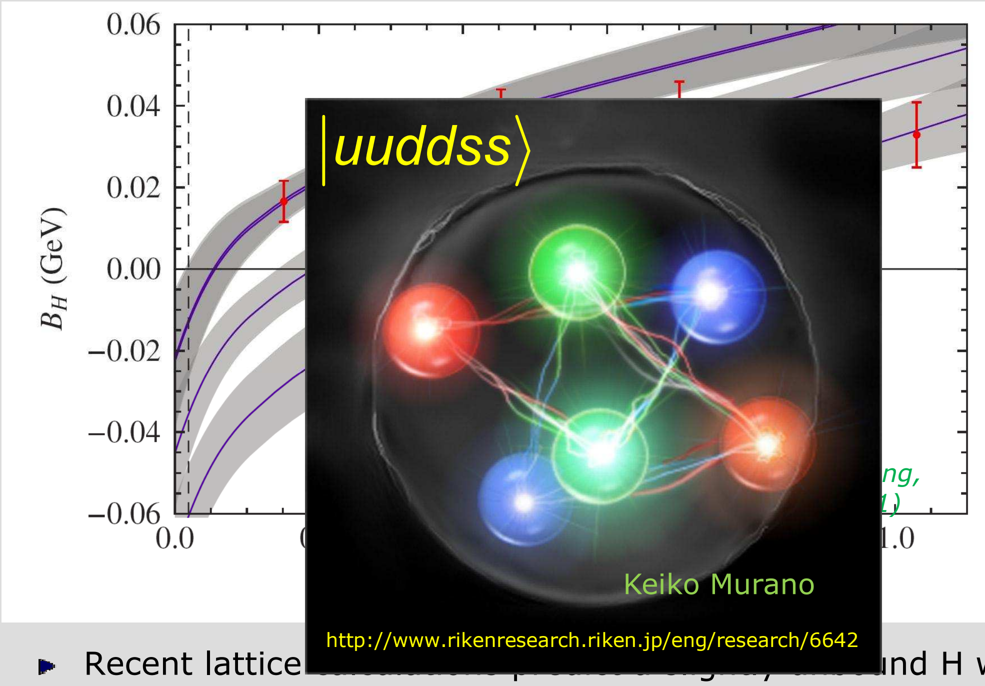


CSB and EFT



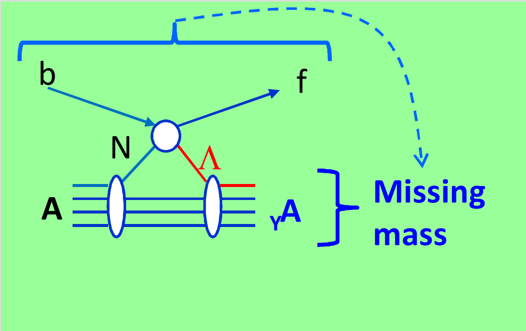
Evgeny Epelbaum, Hermann Krebs, Dean Lee, Ulf-G. Meißner

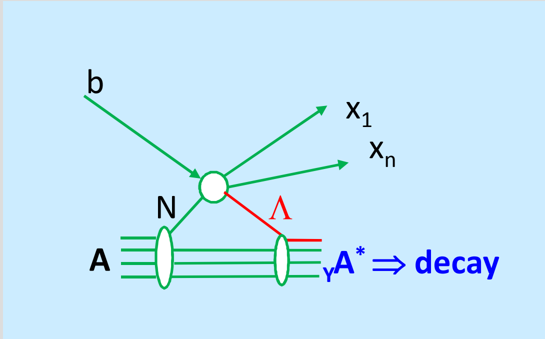
H-Particle



- Recent lattice … und H with B_H=13±14MeV
- That this is so close to the threshold will undoubtedly spur investigations into the consequences for doubly strange hypernuclei as well as the equation of state of dense matter.

The twofold way





- Direct production spectroscopy
- Examples
  - strangeness production (π^+, K^+), (π^-, K^0)
  - strangeness exchange (K^-, π^-) ,(K^-, π^0), (K^-,K^+)
  - electroproduction (e,e´K^+) , (γ,K^+)

Achenbach

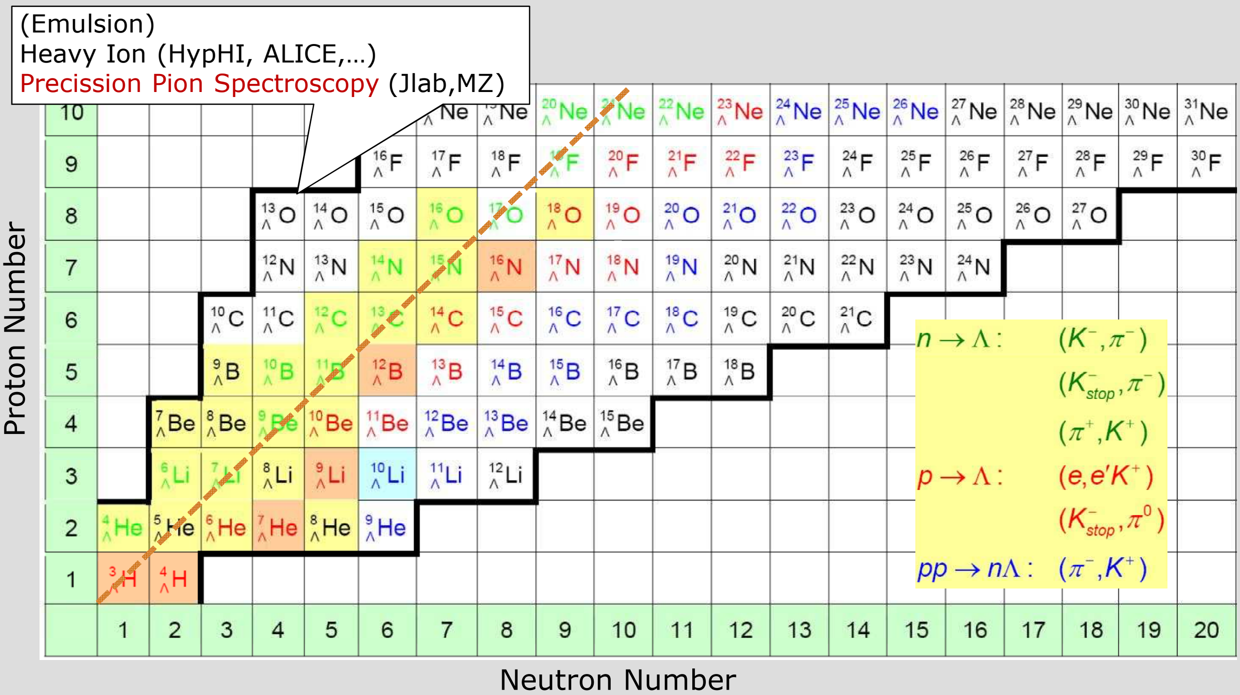
- Decay spectroscopy
  - γ-decay
  - π from weak decay
  - Charged fragments
- Examples
  - nuclear emulsions
  - heavy ion reactions
  - antiproton induced reactions
  - continuum excitation in (e,e´K+)

Nakamura

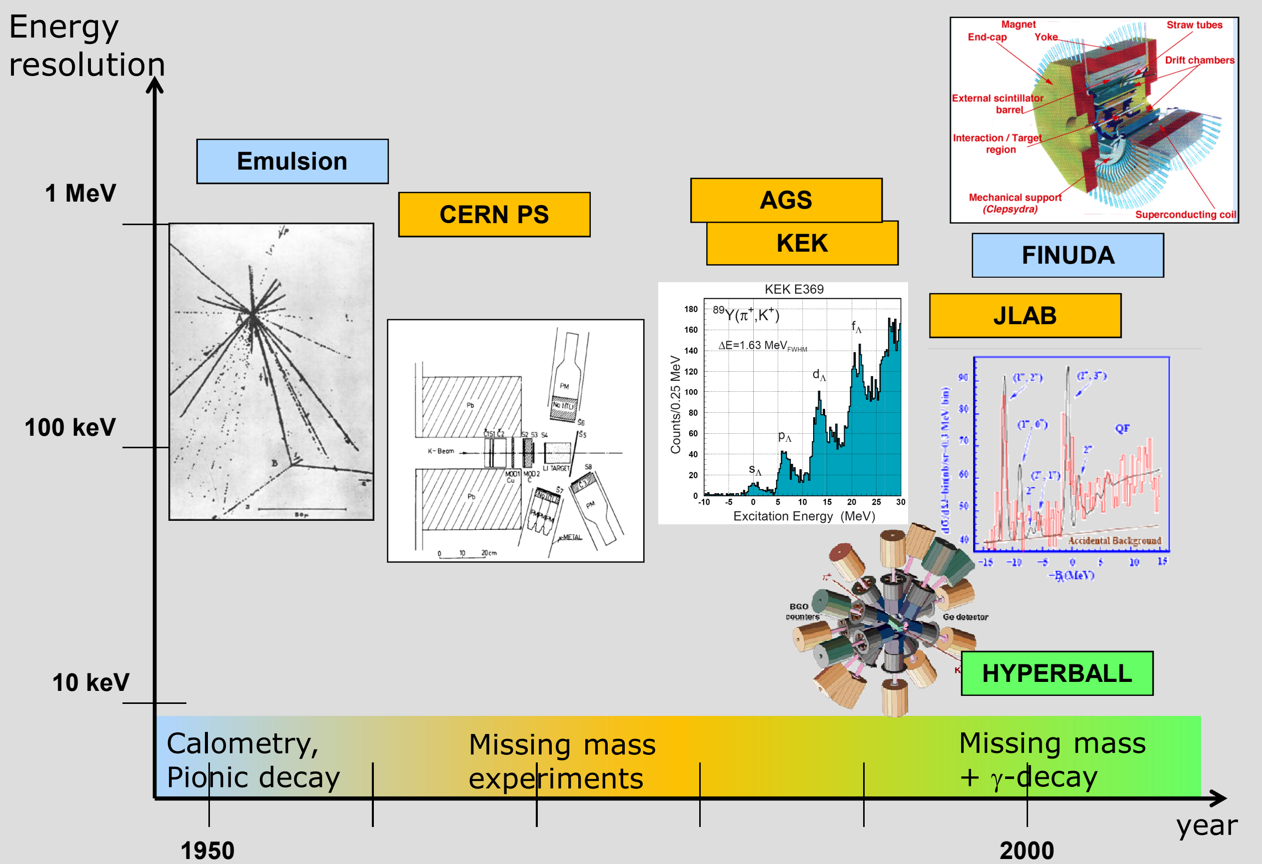
Saito, Leifels, Gaitanos

Sanchez

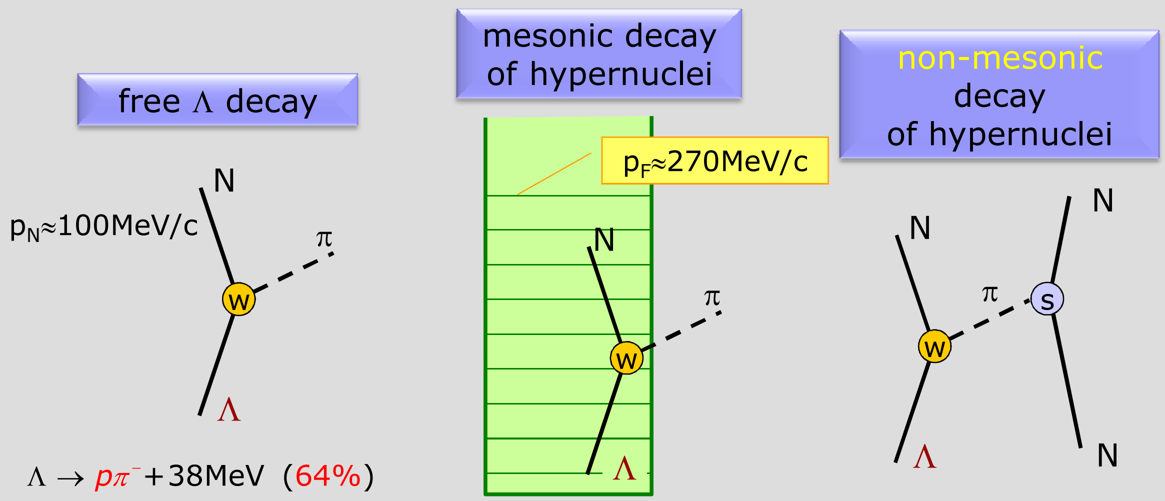
Missing Mass Experiments



Past and Presence of Hypernuclei



Weak decay of hypernuclei



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

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

$\tau_\Lambda = 263ps$

$\Delta I=1/2$ rule

In heavy nuclei suppressed by Pauli blocking

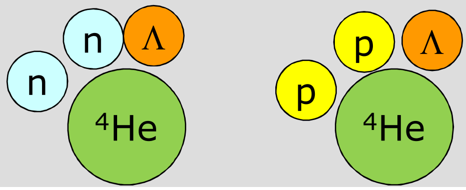
$\Lambda p \rightarrow np + 176\text{MeV}$

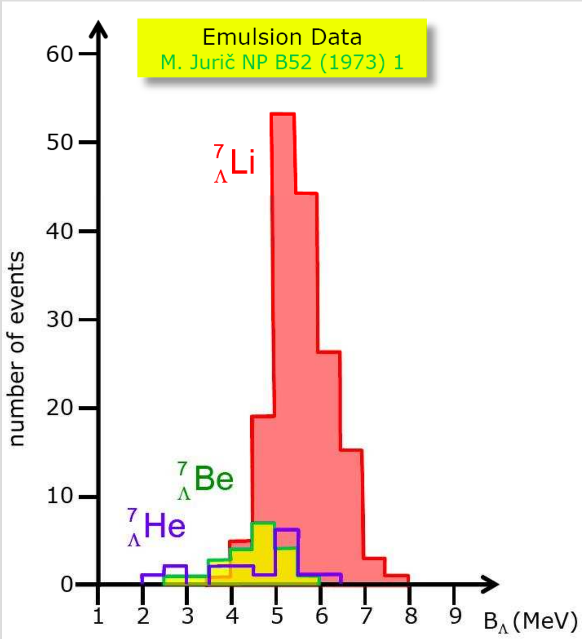
$\Lambda n \rightarrow nn + 176\text{MeV}$

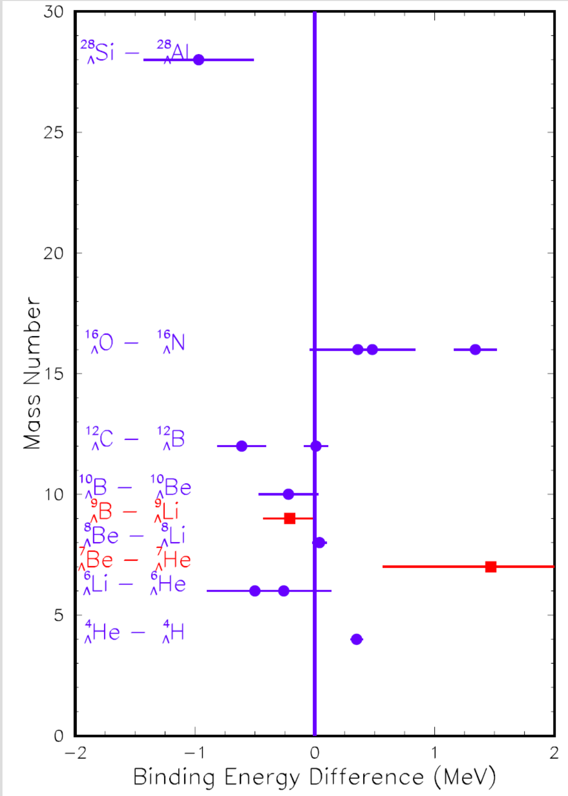
dominant in all but the lightest hypernuclei

- q~400 MeV/c ⇒ probes short distances of baryon-baryon weak interaction

Strange Mirror Nuclei

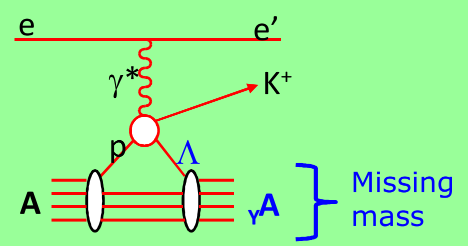




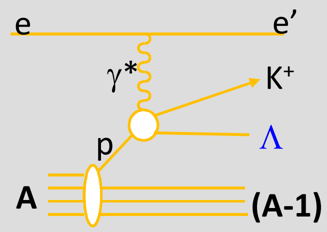


Electro-production of Hypernuclei

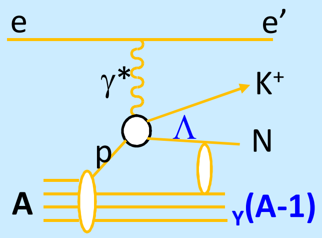
Courtesy
Liaung Tang

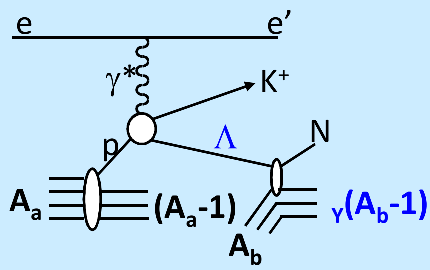


Direct production of Hypernuclei



Quasi-free Λ production (Continuum)



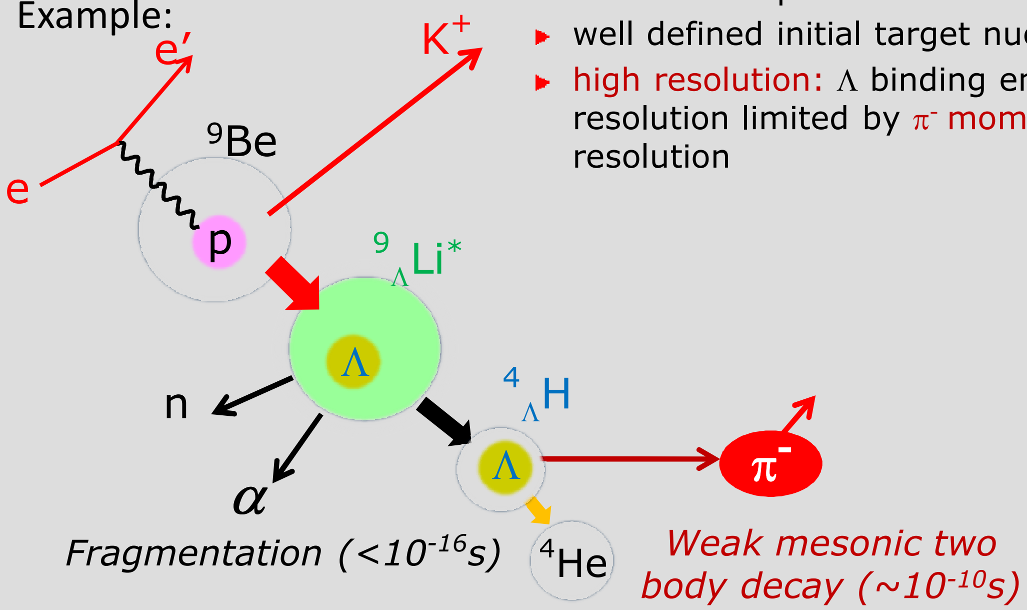


Production of Hyperfragment (Continuum)

Decay pion spectroscopy

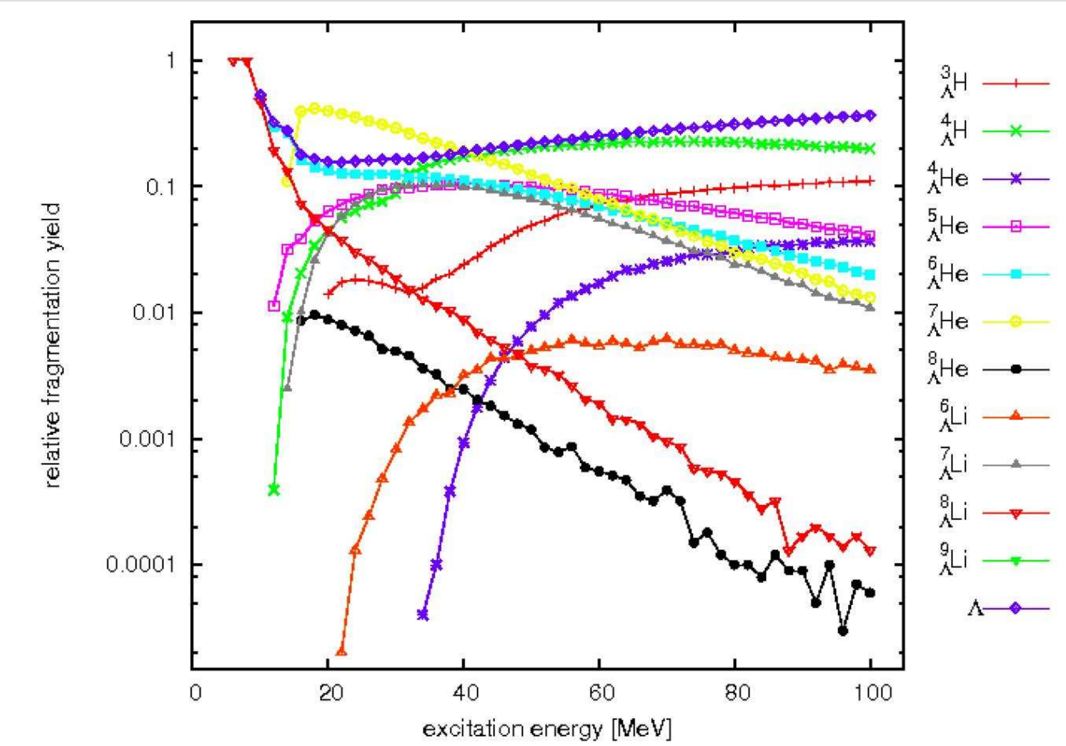
- Two-body decay ⇒ mono-energetic pions
- Like in emulsion access to variety of light and exotic hypernuclei, but
  - electronic experiment
  - well defined initial target nucleus
  - high resolution: Λ binding energy resolution limited by π^- momentum resolution

Example:

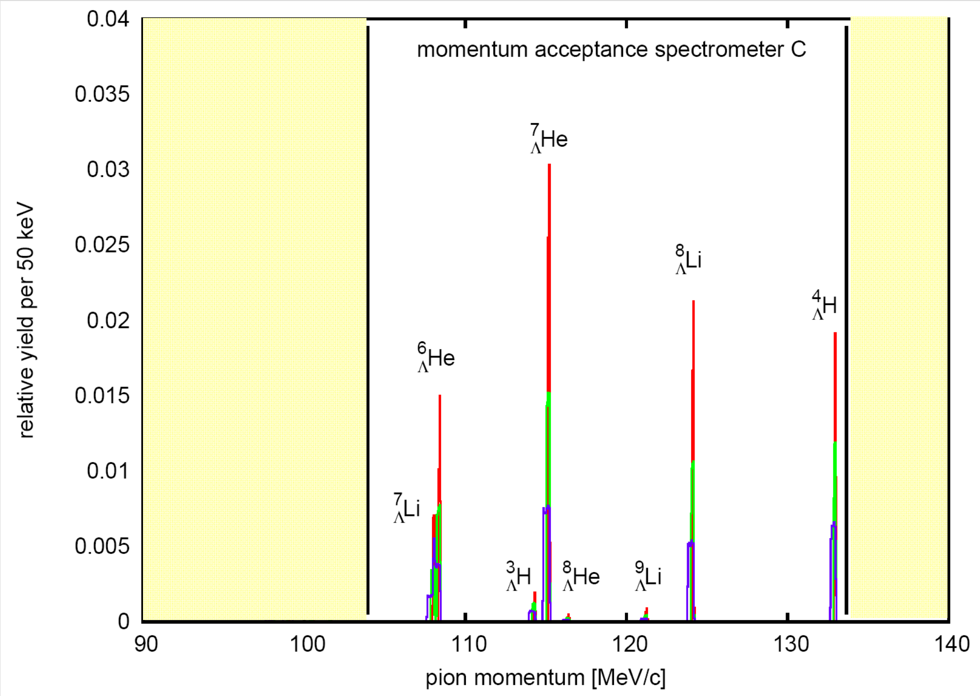


Fermi breakup of excited hypernuclei

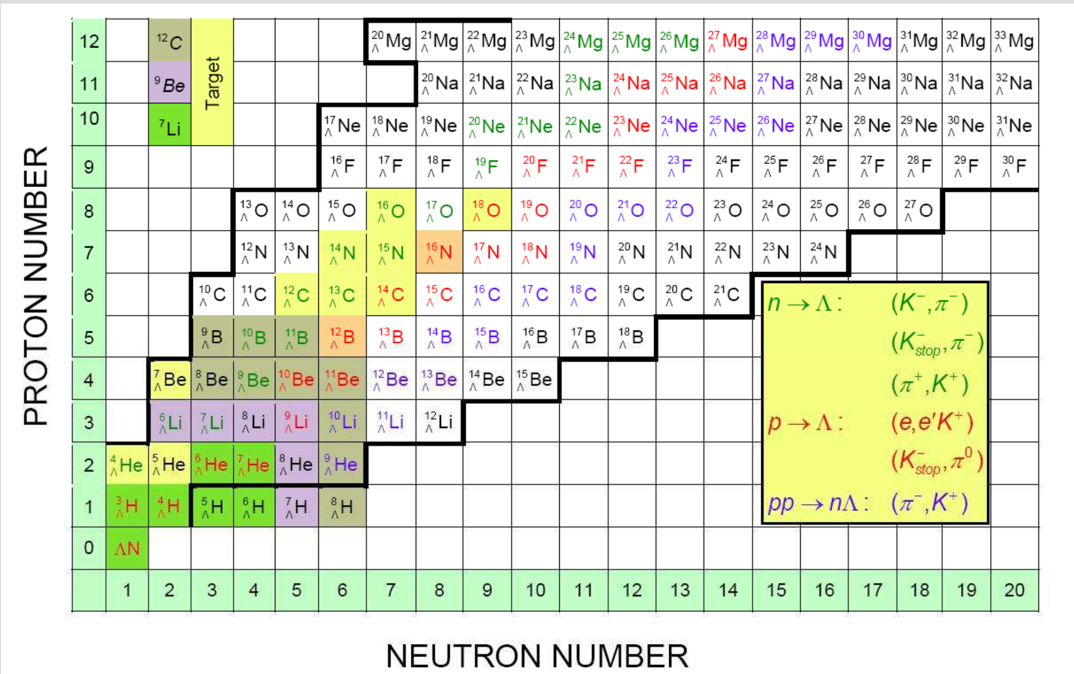
- Decay of $^{9}_{\Lambda}$Li* (A. Botvina, A. Sanchez, J. P.)



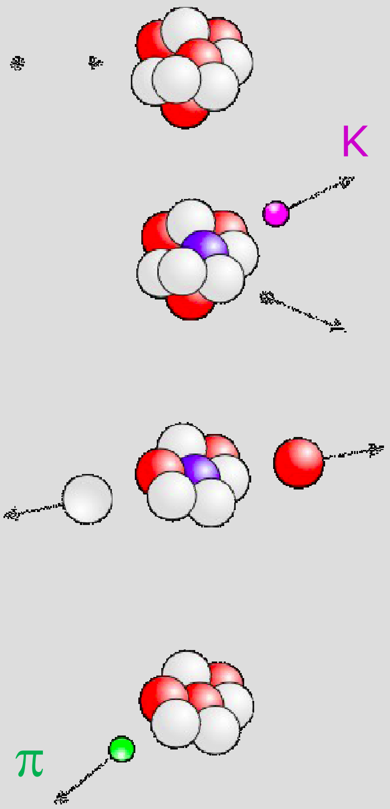
What can be expected



The prospects



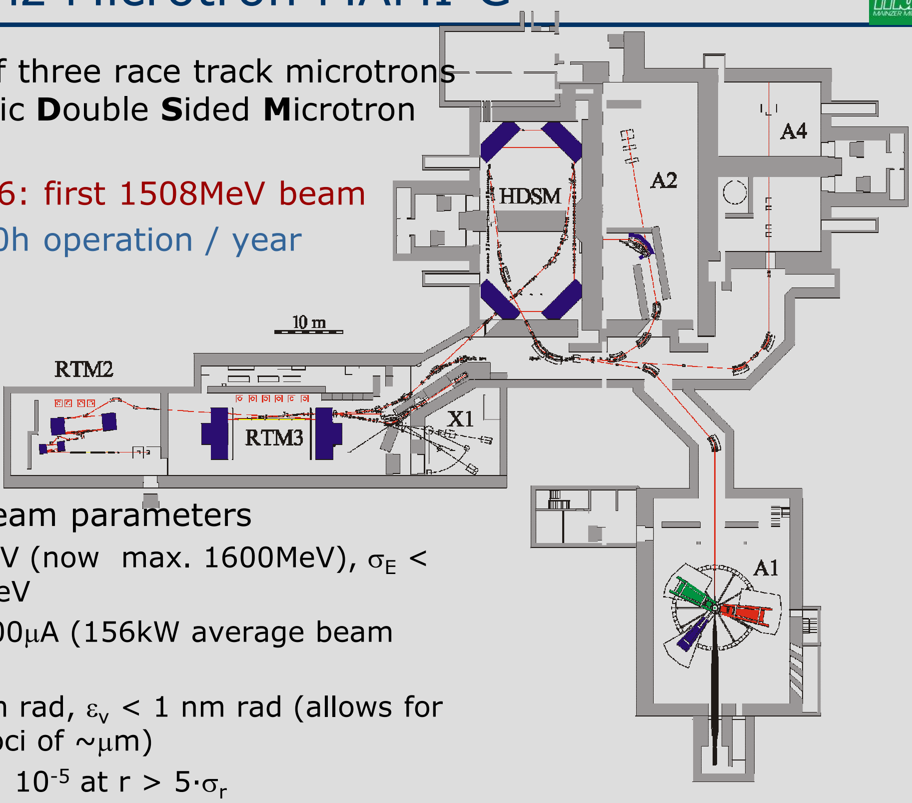
The experiment in a nutshell



- Electroproduction of excited hypernuclei on ^{9}Be Target
- Event tagging by kaon detection
- Fragmentation produces several light hypernuclei
- Mesonic weak decay and groundstate mass reconstruction by spectroscopy of pions from two-body decay

The Mainz Microtron MAMI-C

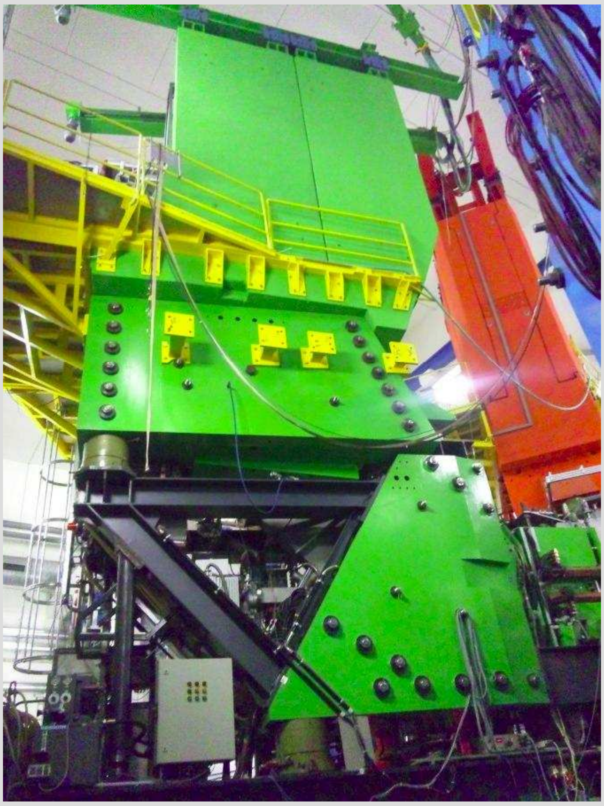
- Cascade of three race track microtrons + **H**armonic **D**ouble **S**ided **M**icrotron (HDSM)
- 19.12.2006: first 1508MeV beam
- Up to 7000h operation / year



- MAMI-C beam parameters
  - 1508MeV (now max. 1600MeV), σ_E < 0.100MeV
  - max. 100μA (156kW average beam power)
  - ε_h=9 nm rad, ε_v < 1 nm rad (allows for beam foci of ~μm)
  - halo: < 10^{-5} at r > $5 \cdot \sigma_r$

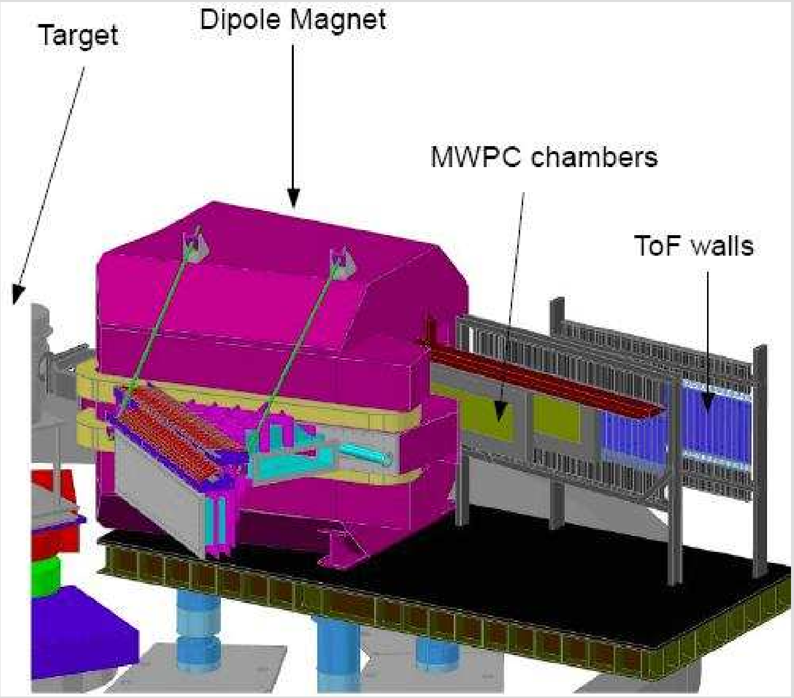
Pion detection

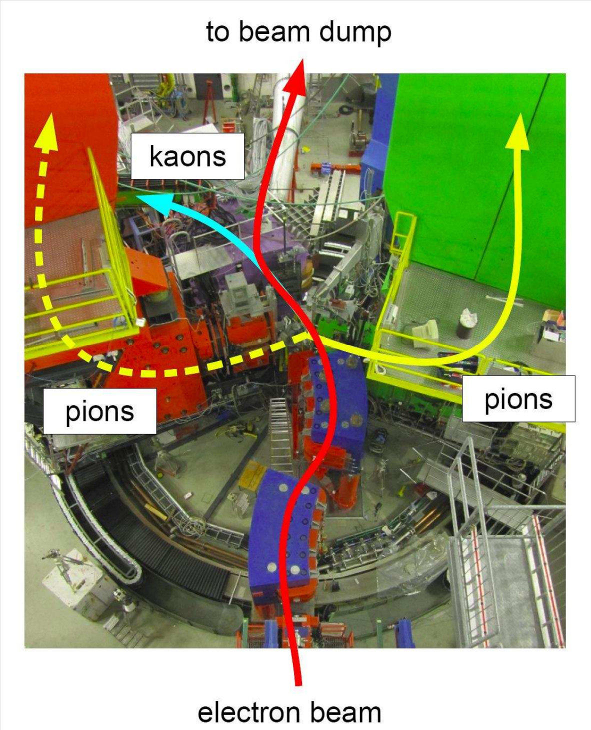
- Spectromter C (green)
- Spectrometer A (red)
- Momentum resolution $\Delta p/p = 10^{-4} \Rightarrow \Delta m < 20keV/c$
- Solid angle: 28 msr
- Momentum acceptance
  - Spec A: 20%
  - Spec C: 25%
- Length of trajectories
  - Spec A:10.75m
  - Spec C: 8.53m
- Gas threshold Cherenkov detectors for pion/electron separation

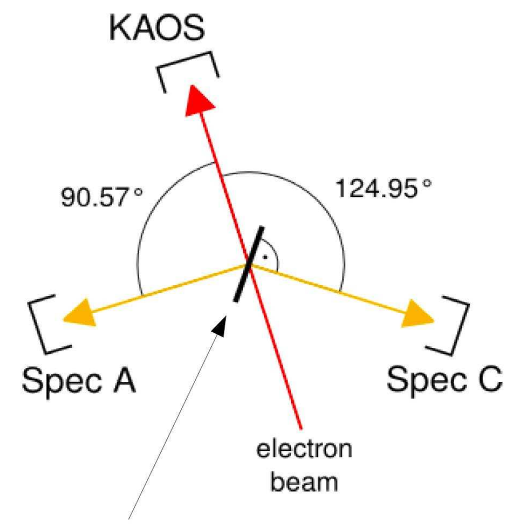


Kaon Tagger

- Double arm, short orbit spectrometer
- Placed at 0°
- Momentum acceptance 50%
- Flight path 7m

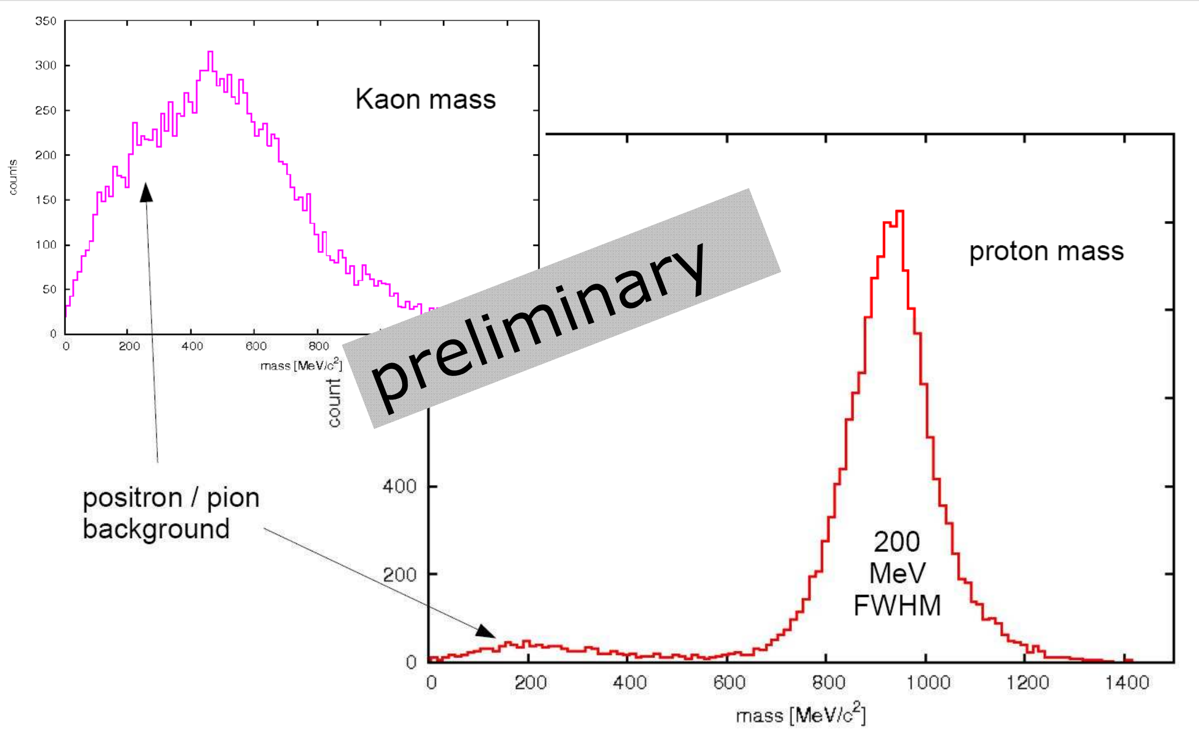




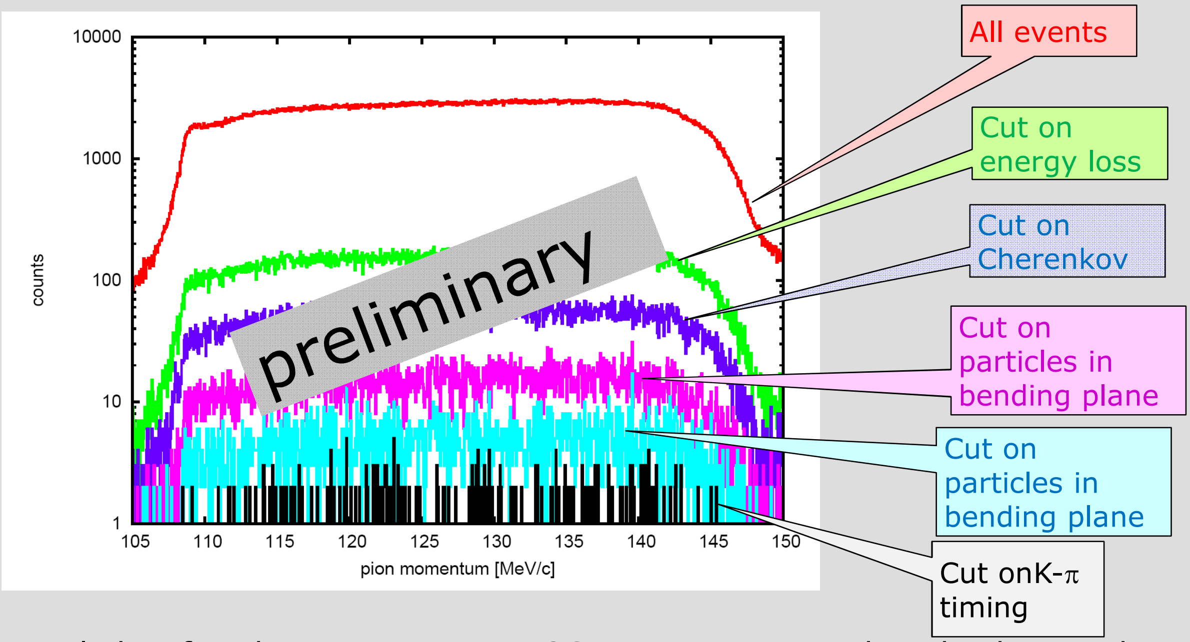


Target rotated 54° wrt beam:
→ Reduced energy loss variation for pions

Pilot run: June/Juli 2011



Status of the analysis



- Flight of path correction in KAOS ⇒ reduce background
- Correlated cut conditions ⇒ reduce background
- Use full data sample ⇒ × 3-4
- Use less stringent cuts on energy loss ⇒ × 2

A1 Collaboration

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University of Ljubljana and Institut "Josef Stefan", Ljubljana, Slovenia:
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Toshiyuki Gogami, Sho Nagao

GSI, Darmstadt, Germany:
Olga Borodina, Vakkas Bozkurt, Eunhee Kim, Christophe Rappold

Hypernuclear physics: a multicultural activity

nuclear reaction

- Hypernuclei offer a bridge between traditional nuclear physics , hadron physics and astrophysics

- It helps to explore fundamental questions like
  - How do nucleons and nuclei form out of quarks?
  - Can nuclear structure be derived *quantitatively* from QCD?
  - Properties of strange baryons in nuclei and structure of QCD vacuum?
  - Baryon-baryon weak interaction $\Lambda N \rightarrow NN$, $\Lambda\Lambda \rightarrow \Lambda N$
  - H-dibaryon {uuddss} in nuclei ?
  - Can we constrain the interior of neutron stars?

astrophysics