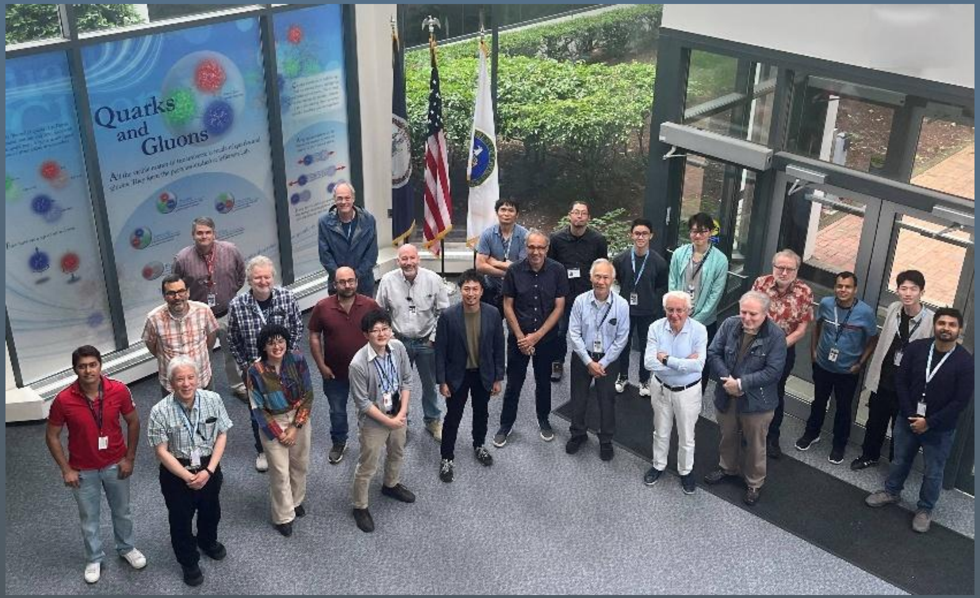


THE UNIVERSITY OF TOKYO

QNSI

Quark Nuclear Science Institute, UTokyo

Spectroscopic study of Lambda hypernuclei with electron and meson beams

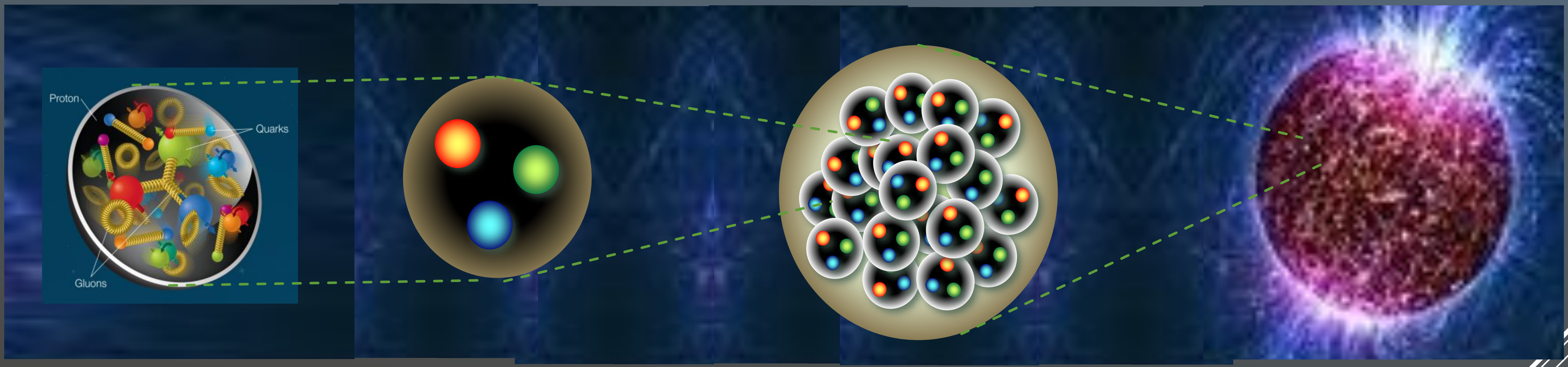
Satoshi Nue Nakamura

The University of Tokyo

27th June 2025

Quantum many-body systems which strong force governs

Nucleon (Hyper)Nucleus Neutron Star



Gluons and Sea Quarks

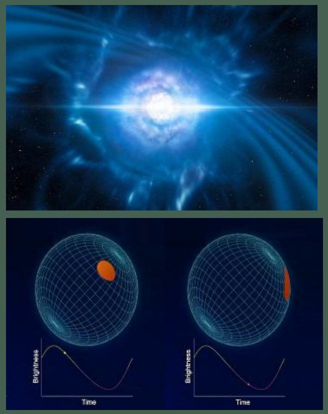
Hadron from Valence Quarks

Nucleus from Hadrons

Materials from Nuclei
incl. **Neutron Stars**

10^{-15}m 10^{4}m

CURRENT PROBLEMS ON Λ HYPERNUCLEI

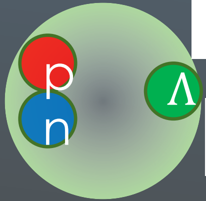


Hypertriton Puzzle

JLab
E12-19-002

MAMI

Shallow bound
Short lifetime



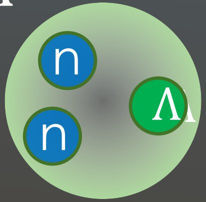
J-PARC

RARiS

$^{3}_{\Lambda}n$ Puzzle

GSI

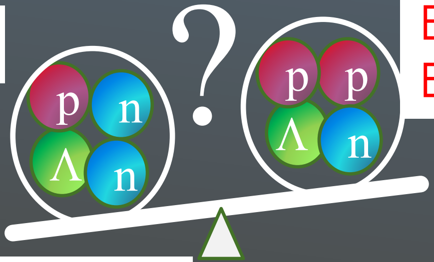
Bound?
Resonance?
Not Exist?



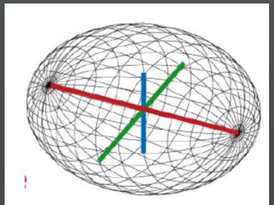
JLab
E12-17-003

CSB of Λ Hypernuclei

E12-24-004



JLab
E12-15-008
E12-20-013



JLab
E12-24-011

Tri-axially deformed nucleus

Hyperon Puzzle

Why massive
NS exists?

Recent
astronomical
observations

A=3
10^{-15} m

A~10^{57}
10^{4} m

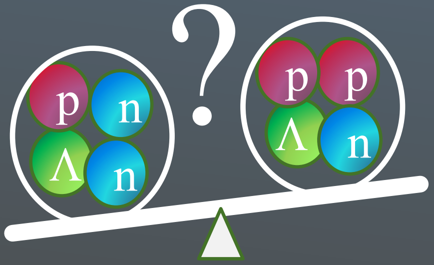
J-PARC HIHR

Approved JLab Hypernuclear Experiments (PAC52, July 2024)

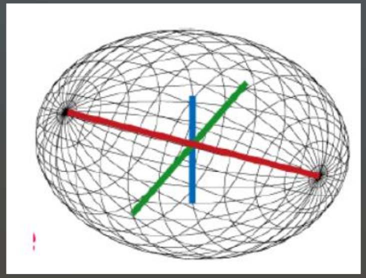
E12-15-008 Isospin dependence study
E12-24-013 $^{40,48}\mathrm{Ca}\,(e, e'K^{+})\,^{40,48}_{\Lambda}\mathrm{K}$

E12-18-013 Large mass number
E12-24-003 ^{208}Pb (e,e'K) $^{208}_{\Lambda}\mathrm{Tl}$

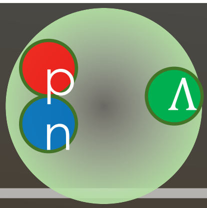
E12-24-004 Study of CSB in p-shell hypernuclei
^{6}Li (e,e'K) $^{6}_{\Lambda}\mathrm{He}$, ^{9}Be (e,e'K) $^{9}_{\Lambda}\mathrm{Li}$, ^{11}B (e,e'K) $^{11}_{\Lambda}\mathrm{Be}$



E12-24-011 Study of triaxial deformed nuclei with a Λ probe
$^{27}\mathrm{Al}\,(e, e'K^{+})\,^{27}_{\Lambda}\mathrm{Mg}$



E12-20-013A/E12-15-008A Decay π spectroscopy

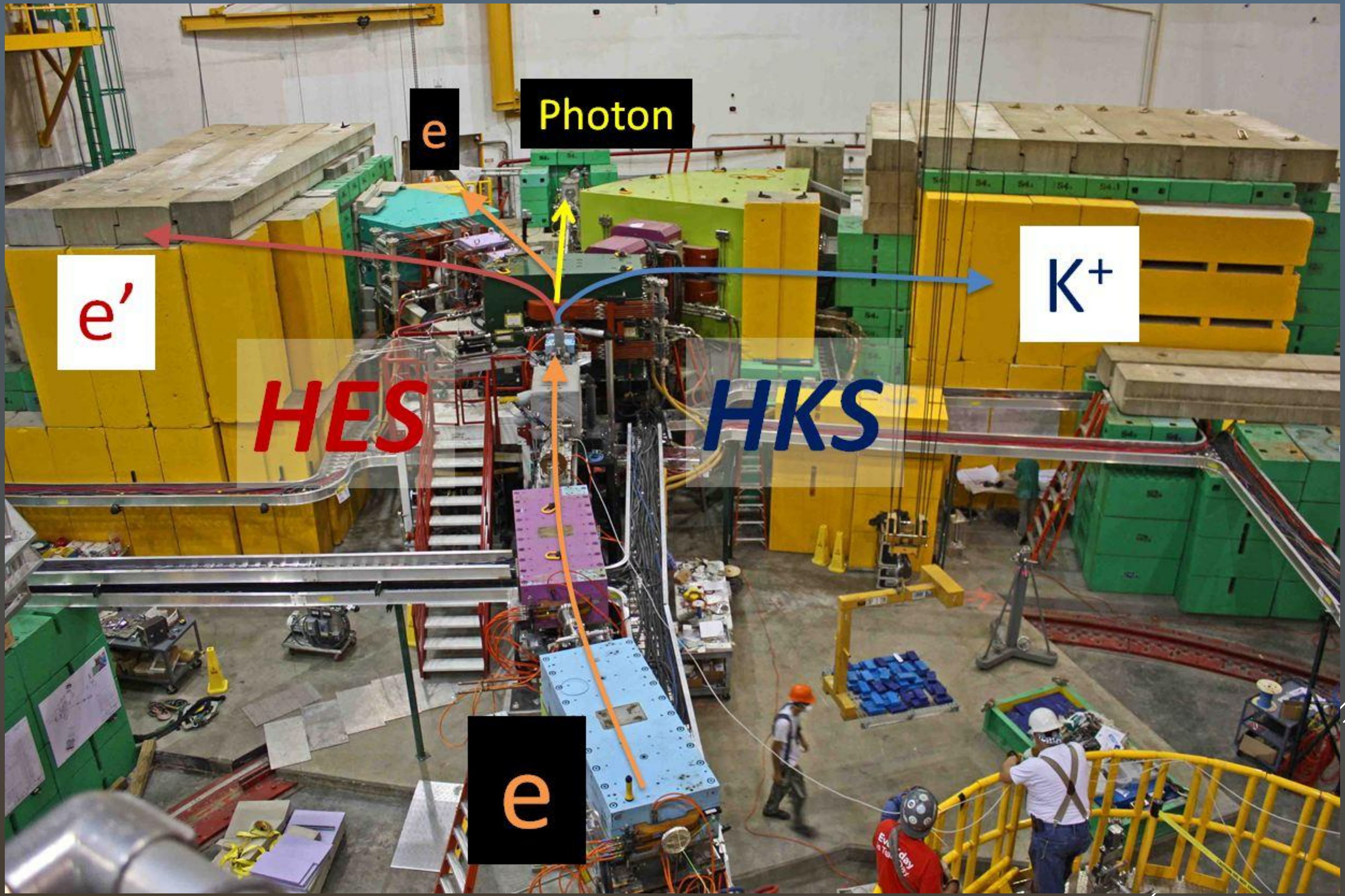


Solid targets
1st Campaign
To be run in 2027

E12-19-002 Cryo. Gas ^{3,4}He (e,e'K) $^{3,4}_{\Lambda}\mathrm{H}$

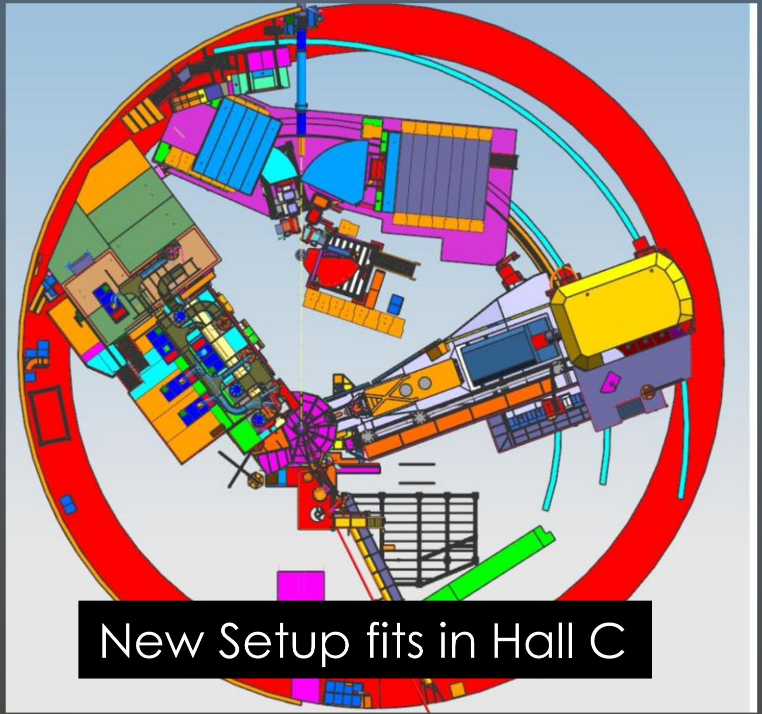
(e,e'K$^+$) reaction spectroscopy

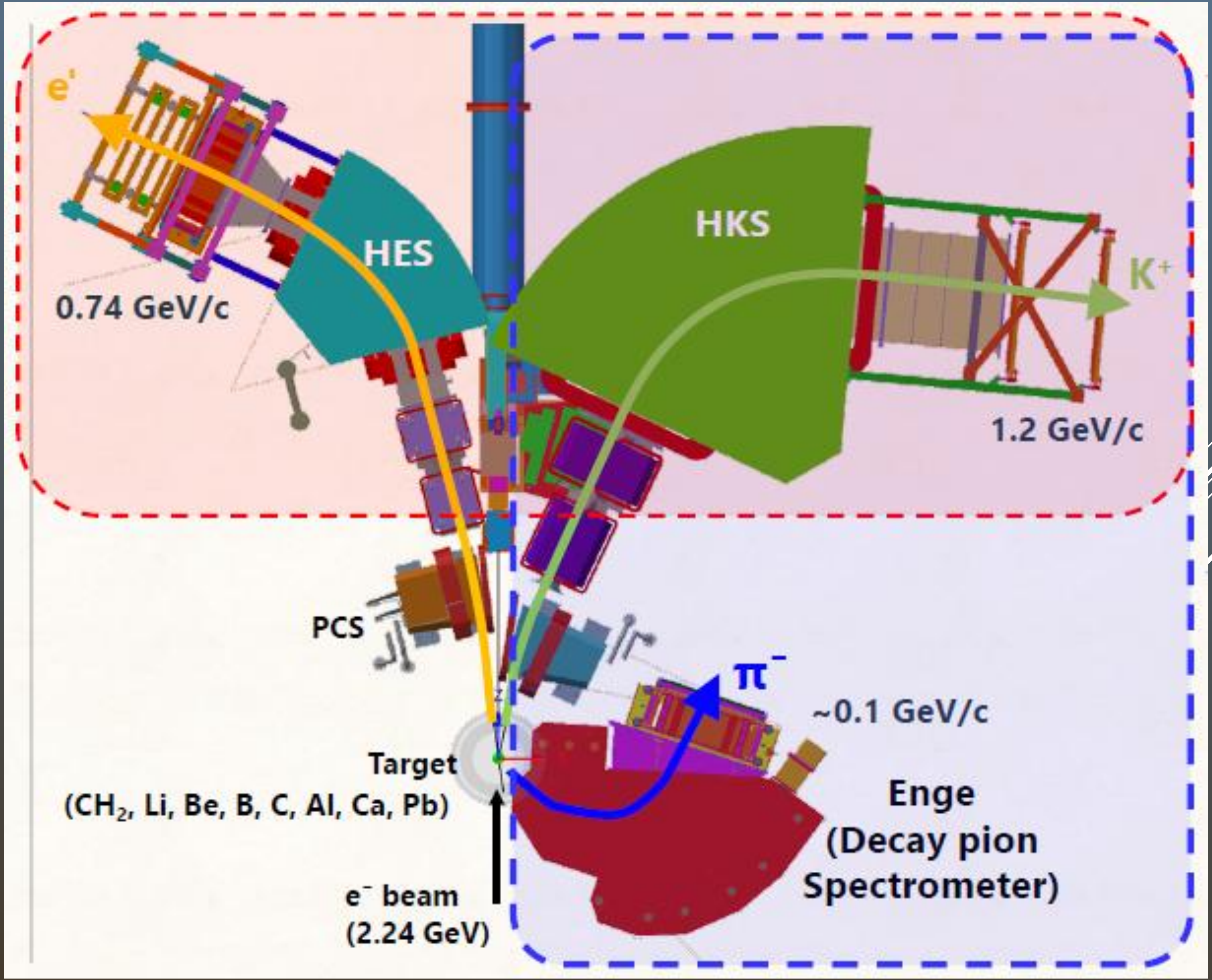
Jefferson Lab
EXPLORING THE NATURE OF MATTER



HKS＋HES＋SPL @JLab Hall-C (2009)

SETUP IN HALL-C

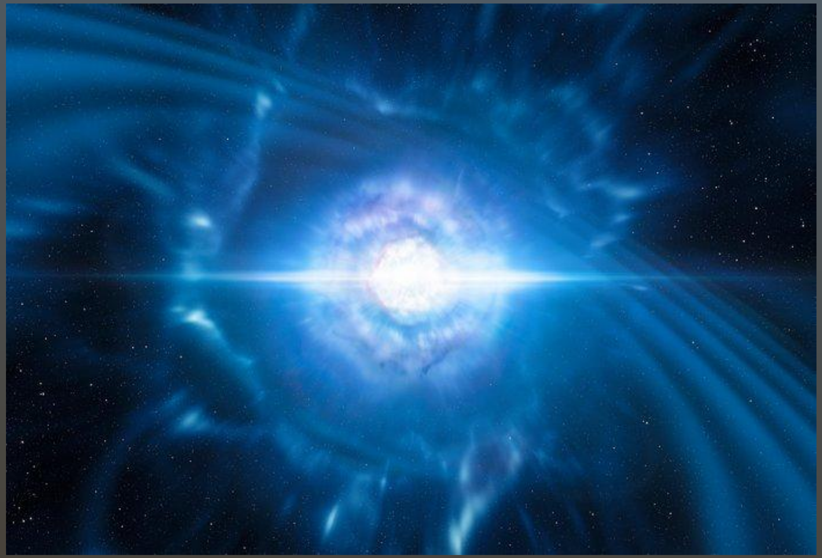




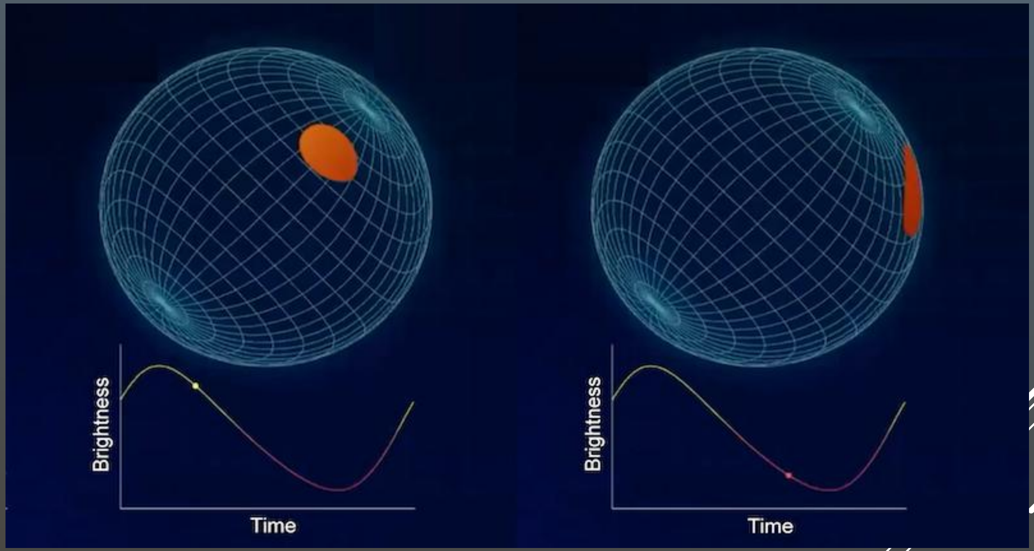
New astronomical observations

New Gravitational Waves from NS mergers and
NICER (Neutron star Interior Compsition ExploreR)

CC4.0 ESO/L. Calçada/M. Kornmesser



Gravitation Wave from neutron star mergers
LIGO/Virgo PRL **119**, 161101 (2017)



Goddard Space Flight Center

NICER : NS x-ray hot spot measurement
Physics 14, 64 (Apr. 29, 2021)

Macropscopic features of NS : Tidal deformability, Radius and Mass

HYPERON Puzzle

Mystery of heavy Neutron Stars.

Based on our knowledge of baryonic force,
Hyperon naturally appear at high density $(\rho \sim 2,3\rho_0)$

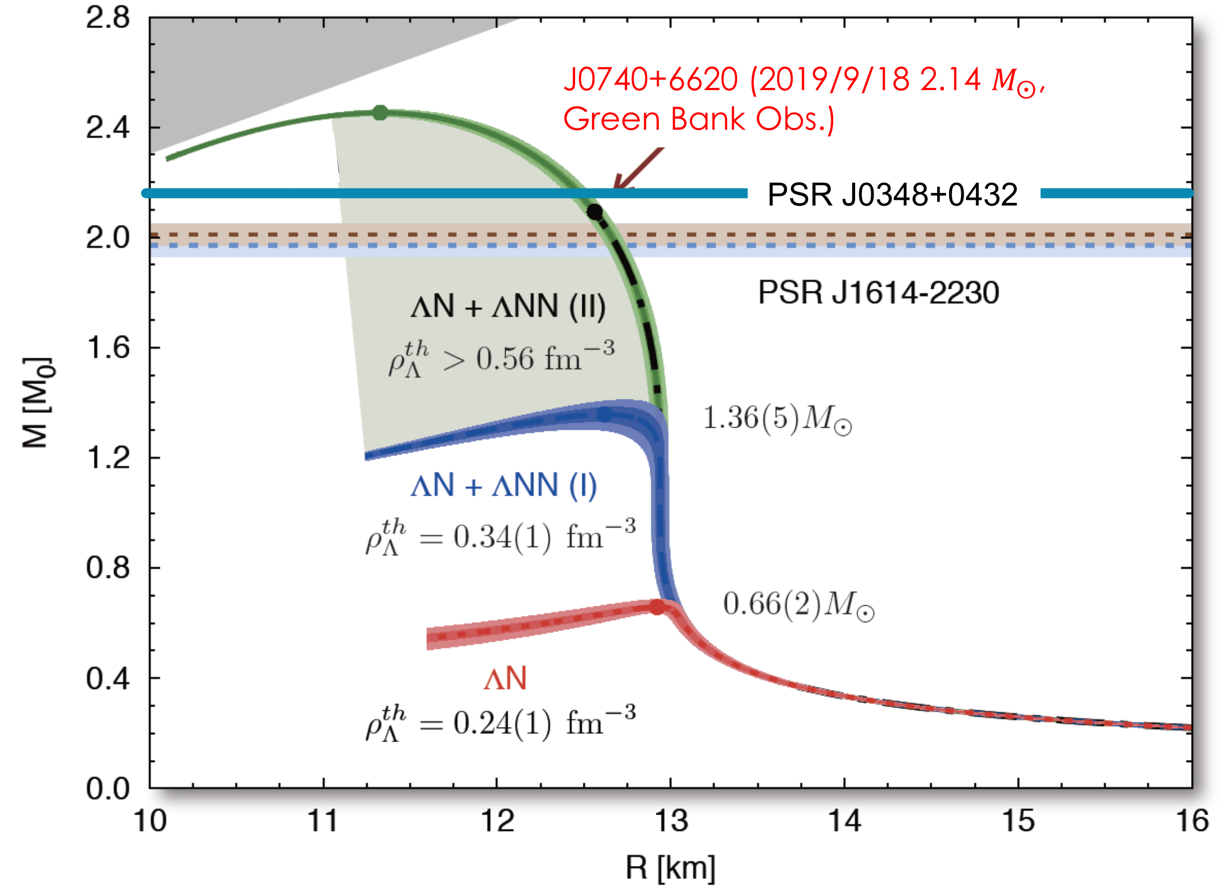
Too soft EOS. **NS cannot support mass of 2** $M_\odot$

Contradict to astronomical observations.

Need **additional repulsive force**
(ΛNN 3-body repulsive force)
Make stiffer EOS

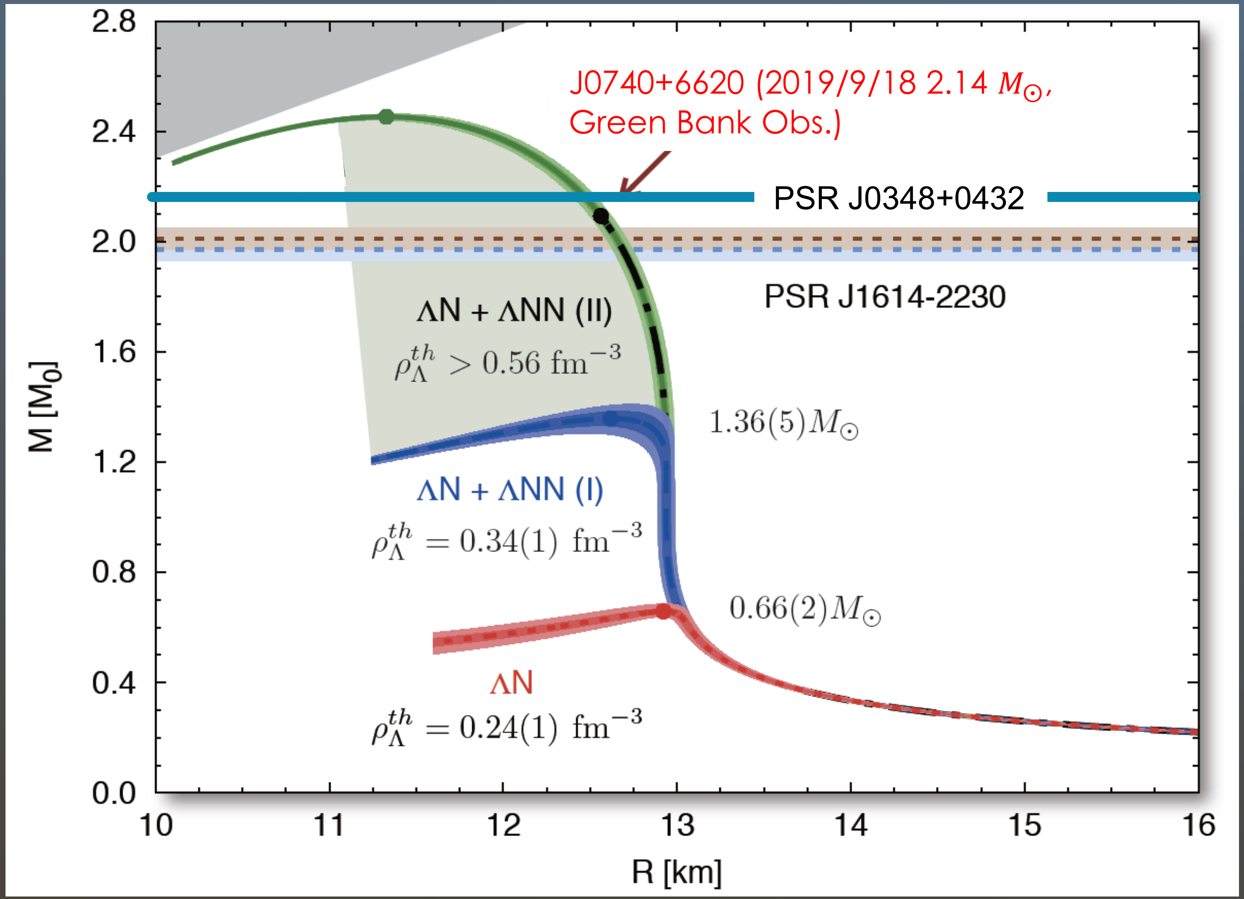
Neutron star : **Large** $(N-Z)/A \geq$ **0.9 and Large A**

Iso-spin dependence **A dependence**

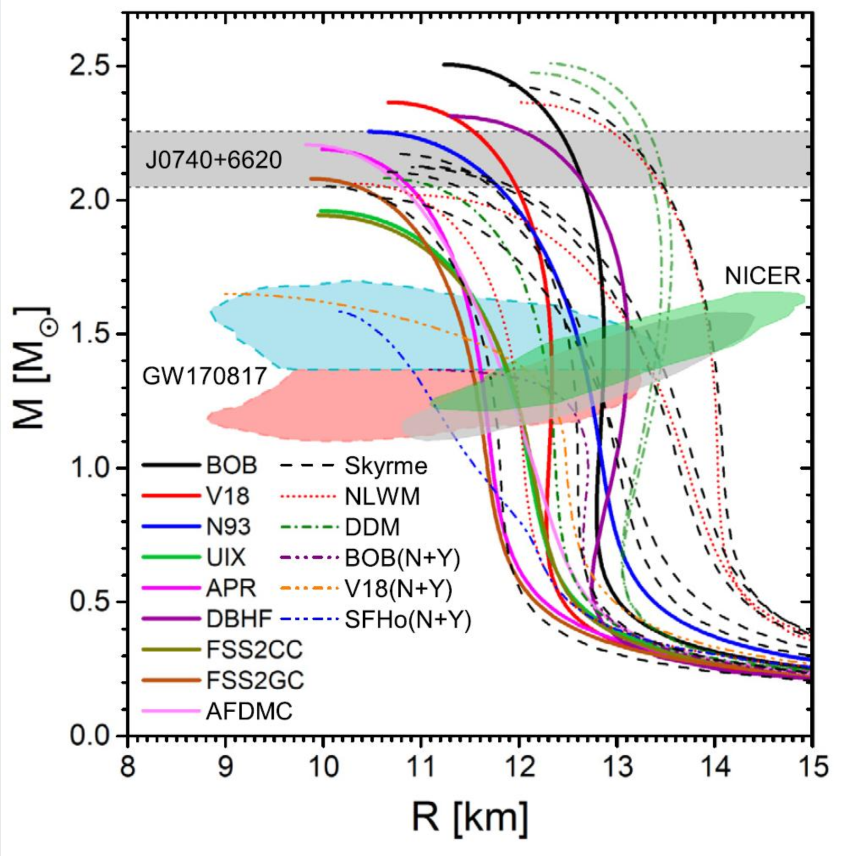


2 solar mass NS

NEW CONSTRAINS FROM ASTRONOMICAL OBSERVATIONS



D.Lonardoni AFDMC

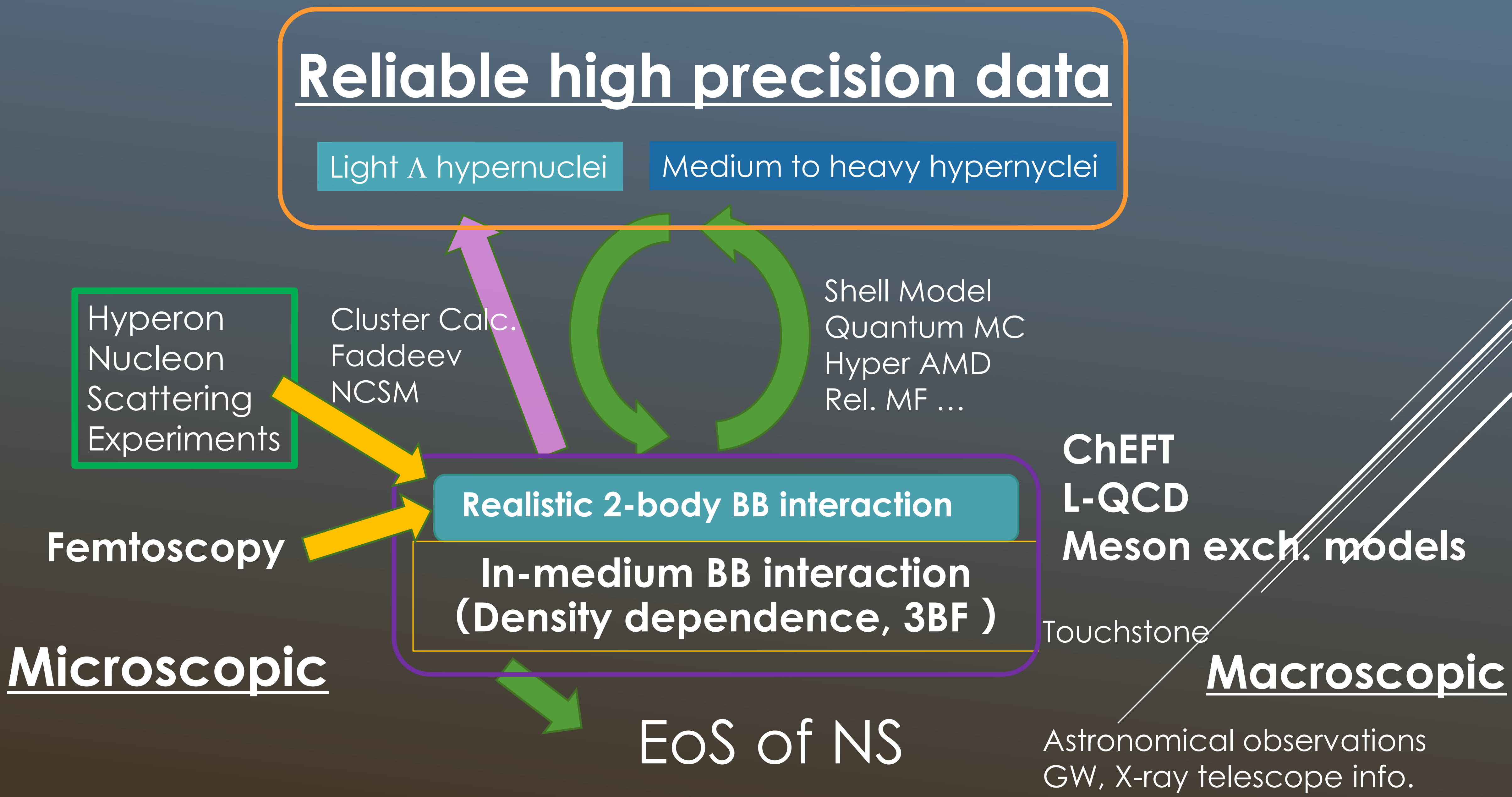


C.F.Burgio et al. Prog. Part. Nucl. Phys 120 (2021) 103879.

Macroscopic understanding of NS made great progresses.
But we would like to know why NS is so heavy and large.

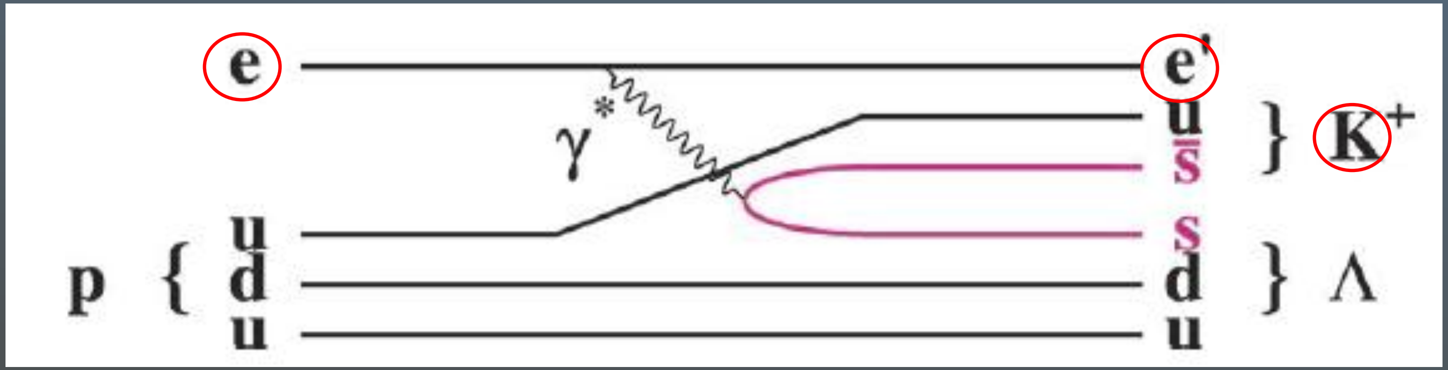
Microscopic study (nuclear physics exp) becomes more important than ever!

Strategy to solve the hyperon puzzle



Lambda production with electron and meson beams

(e,e'K⁺) @ JLab



Excellent mass resolution

~ 0.5 MeV(FWHM)

Absolute energy calibration

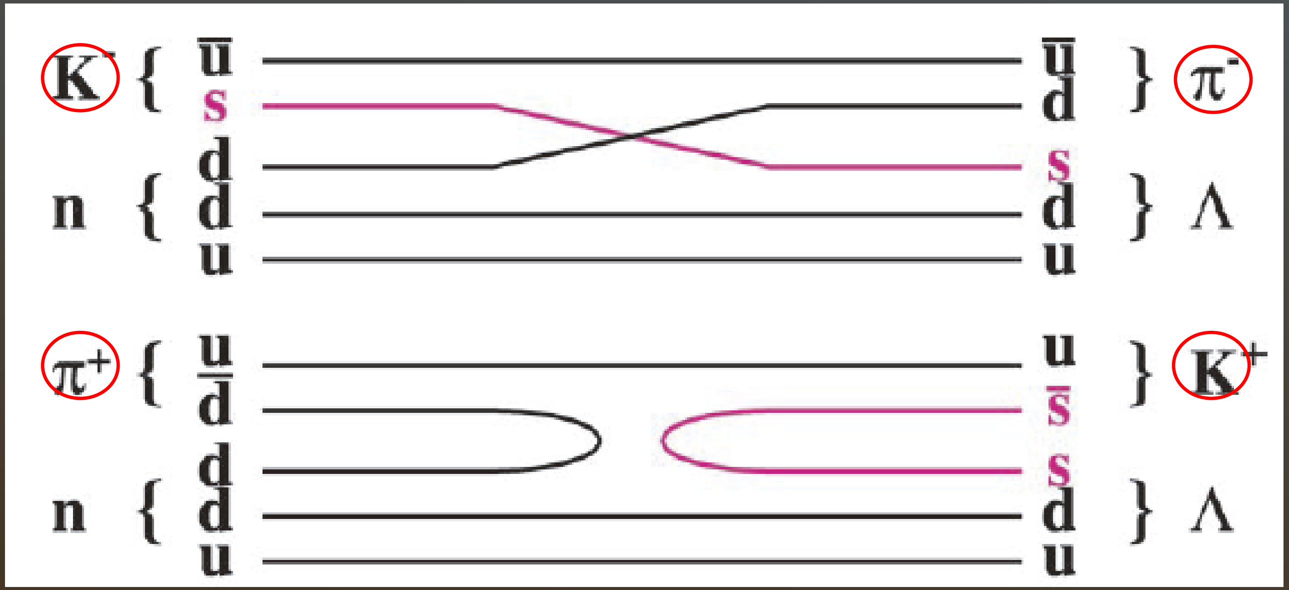
p(e,e'K⁺) Λ, Σ^0

High Intensity

$100\ \mu A = 6 \times 10^{14}$ /s

Thin target (isotopically enriched)

eg. $^{40,48}Ca$



(K^-, π^-)

Intensity limitation < a few $\times 10^6$ /s

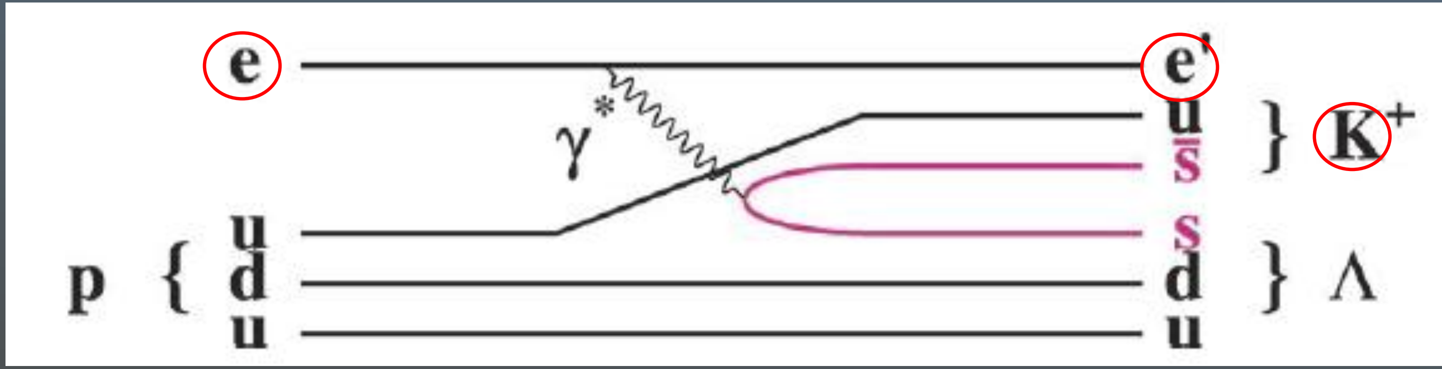
1-2 MeV resolution

Normalized to $^{12}{}_{\Lambda}C$ mass

(π^+, K^+)

Lambda production with electron and meson beams

$(e,e'K^+)$ @ JLab

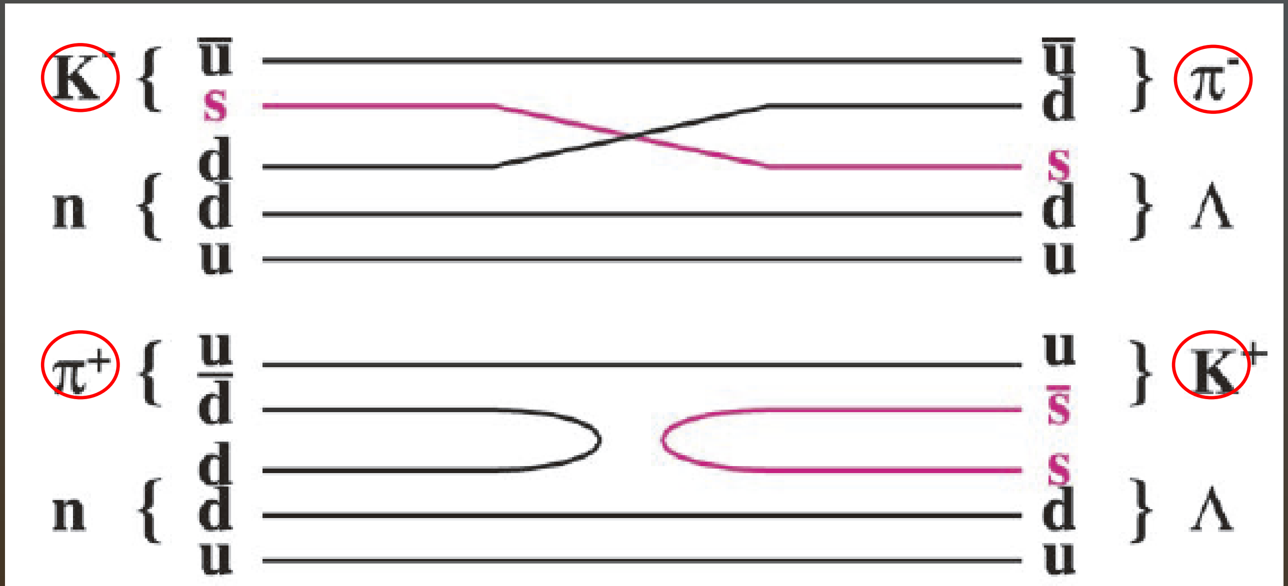


Excellent mass resolution
~ 0.5 MeV(FWHM)

Absolute energy calibration
$p(e,e'K^+)\ \Lambda, \Sigma^0$

High Intensity
$100\ \mu A = 6 \times 10^{14}$ /s

Thin target (isotopically enriched)
eg. $^{40,48}Ca$



(K^-, π^-)

Intensity limitation < a few $\times 10^6$ /s

1-2 MeV resolution
Normalized to $^{12}_{\Lambda}C$ mass

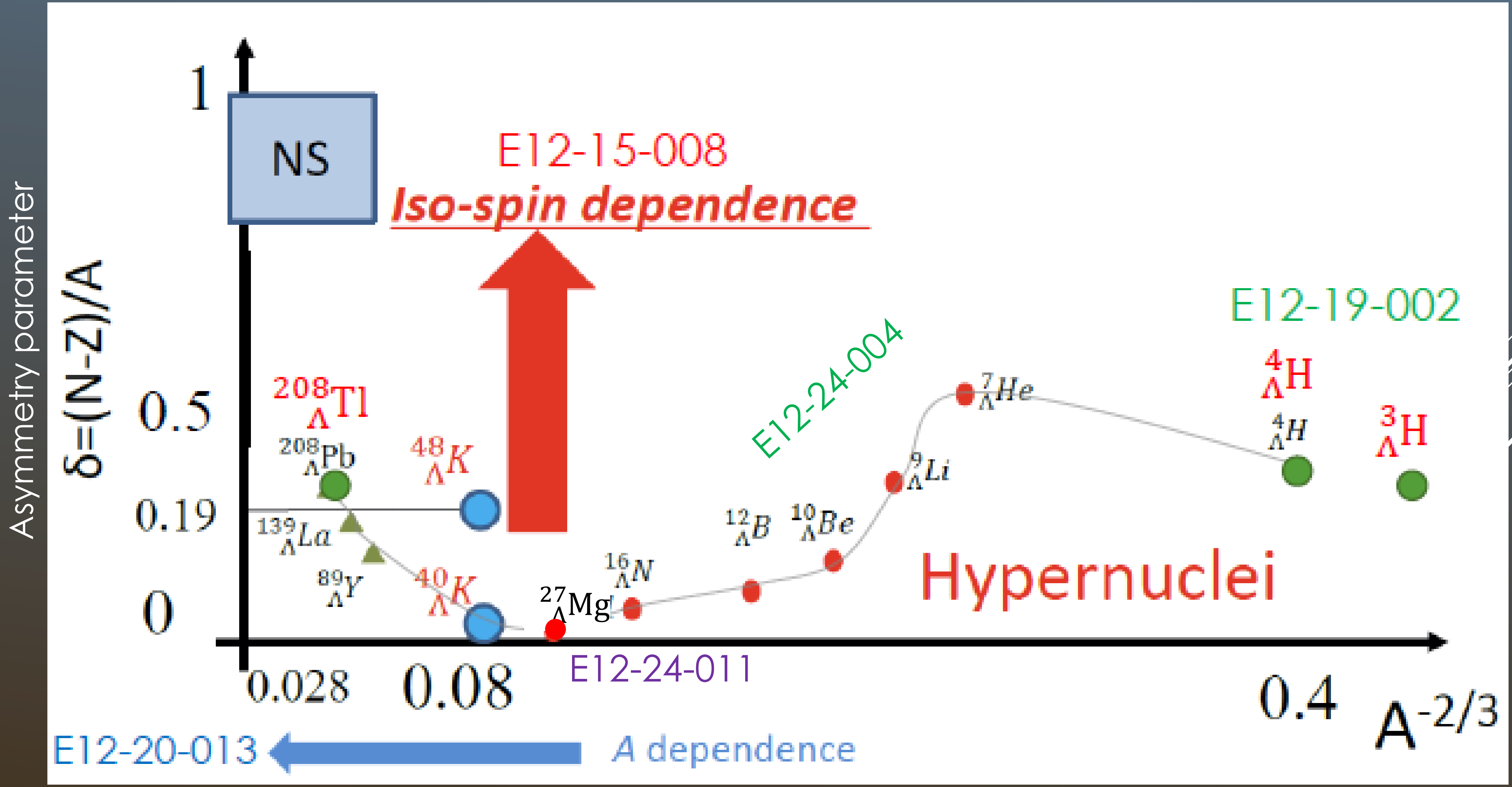
(π^+, K^+)

HIHR@J-PARC HEF Ex

Excellent mass resolution
< 0.4 MeV

Thin target (isotopically enriched)
No limitation for beam intensity

From Hypernuclei to Neutron Stars



Facilities for Lambda hypernuclear spectroscopy

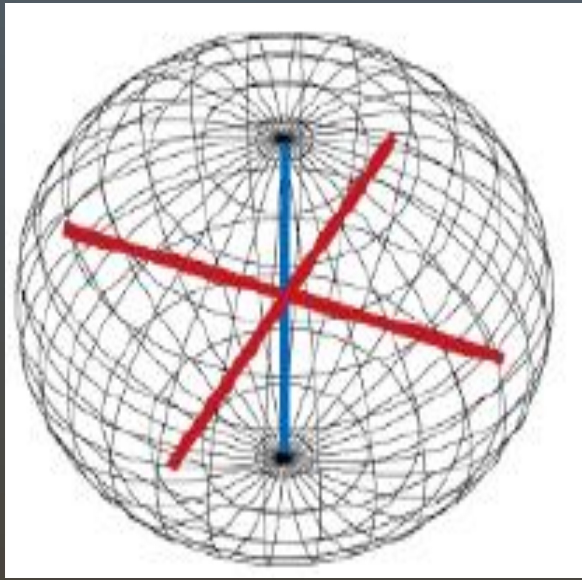
HIHR, JLab and MAMI are possible competitors. But simultaneously complementary!

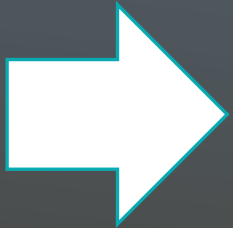
	HIHR	JLab	Mainz/JLab
Reaction	$n(\pi^+, K^+)\Lambda$	p(e,e'K⁺)Λ	Decay π
Achievable Precision (keV)	◎ <100	◎ <100	◎ <100
Applicable hypernuclei	◎ All Z	○ Light – Medium Heavy (Larger Z, higher BG)	× Only Ground states of light hypernuclei
Flexibility of beamtime	◎ Standing Beamline with dedicated spectrometer Hypernuclear Factory	× Large-scale Installation (several months)	○ Kaon Spectrometer Installation
Absolute Energy Calibration	△ $^{12}_{\Lambda}C$, $^{7}_{\Lambda}Li$ $p(\pi^-, K^+)\Sigma^-$ Decay π	◎ $p(e, e'K^+)\Lambda, \Sigma^0$	◎ Elastic e scattering Abs. Ee measure

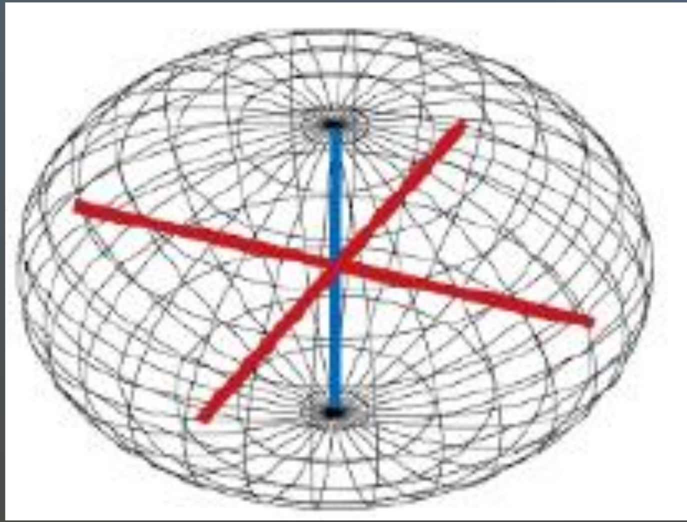
E12-24-011 Study of triaxially deformed nucleus using a Λ particle as a probe

High density quantum many-body system

NUCLEUS







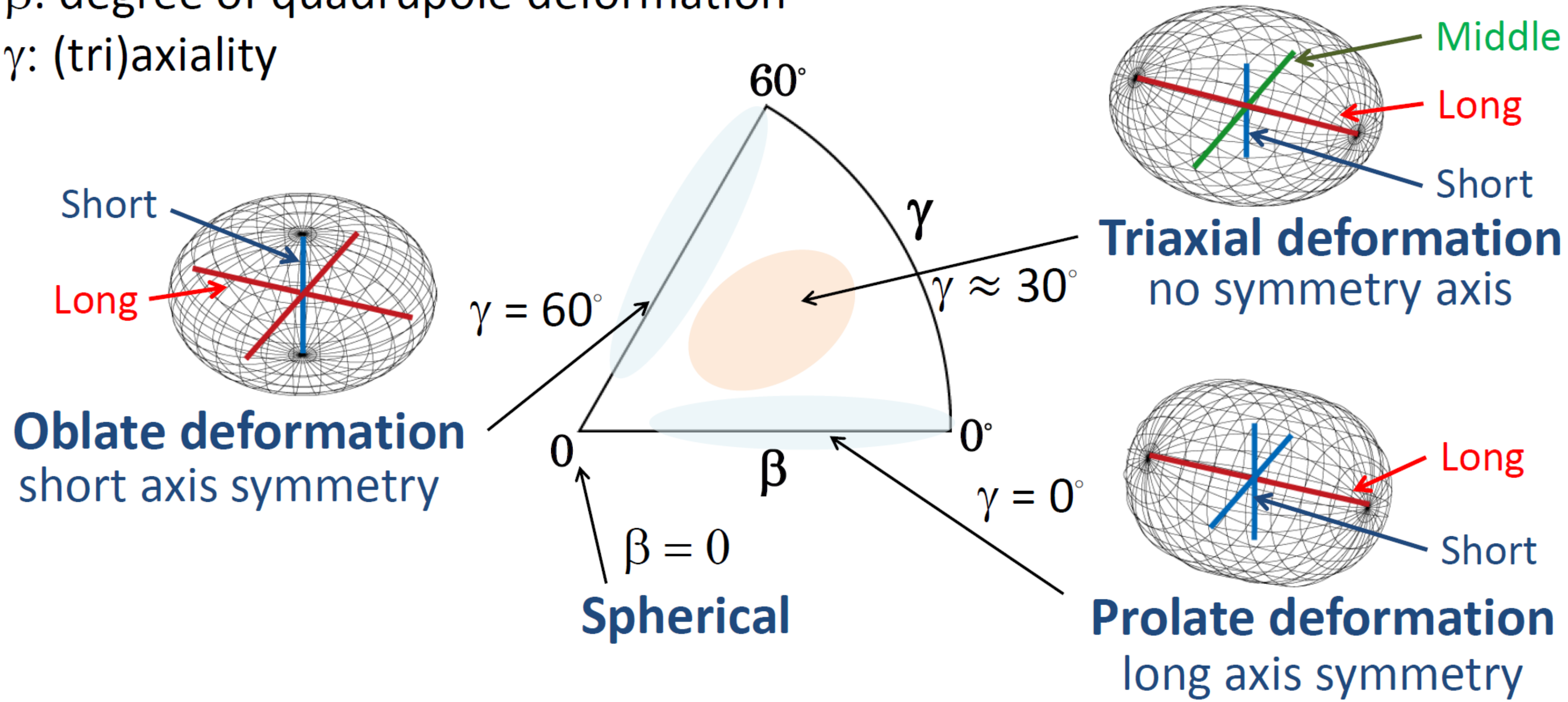
Extremely dense, but its shape can be changed with a relatively small energy.

PARAMETERS TO DESCRIBE DEFORMATION

Gamma-ray measurement is usual experimental technique to study deformed nuclei

Nuclear quadrupole deformation (β,γ)

- β: degree of quadrupole deformation
- γ: (tri)axiality

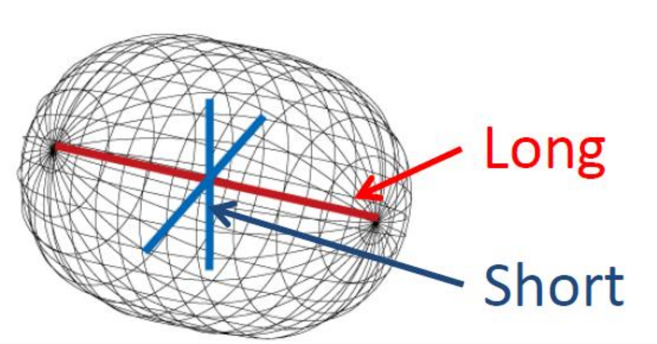


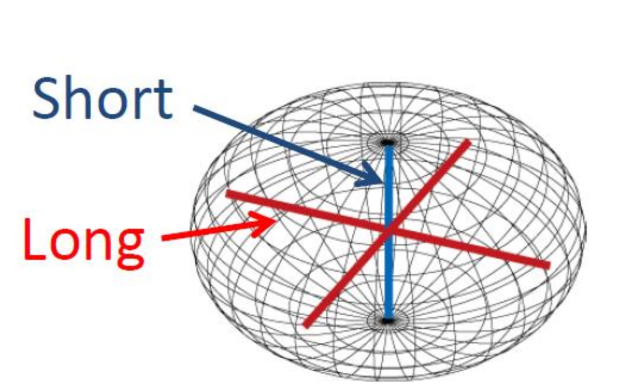
M.Isaka, Hypernuclear Physics Workshop 2023 at JLab

^{26}Mg is interesting candidate for triaxially deformed nucleus

Proton Z=12 Prolate

Neutron N=14 Oblate



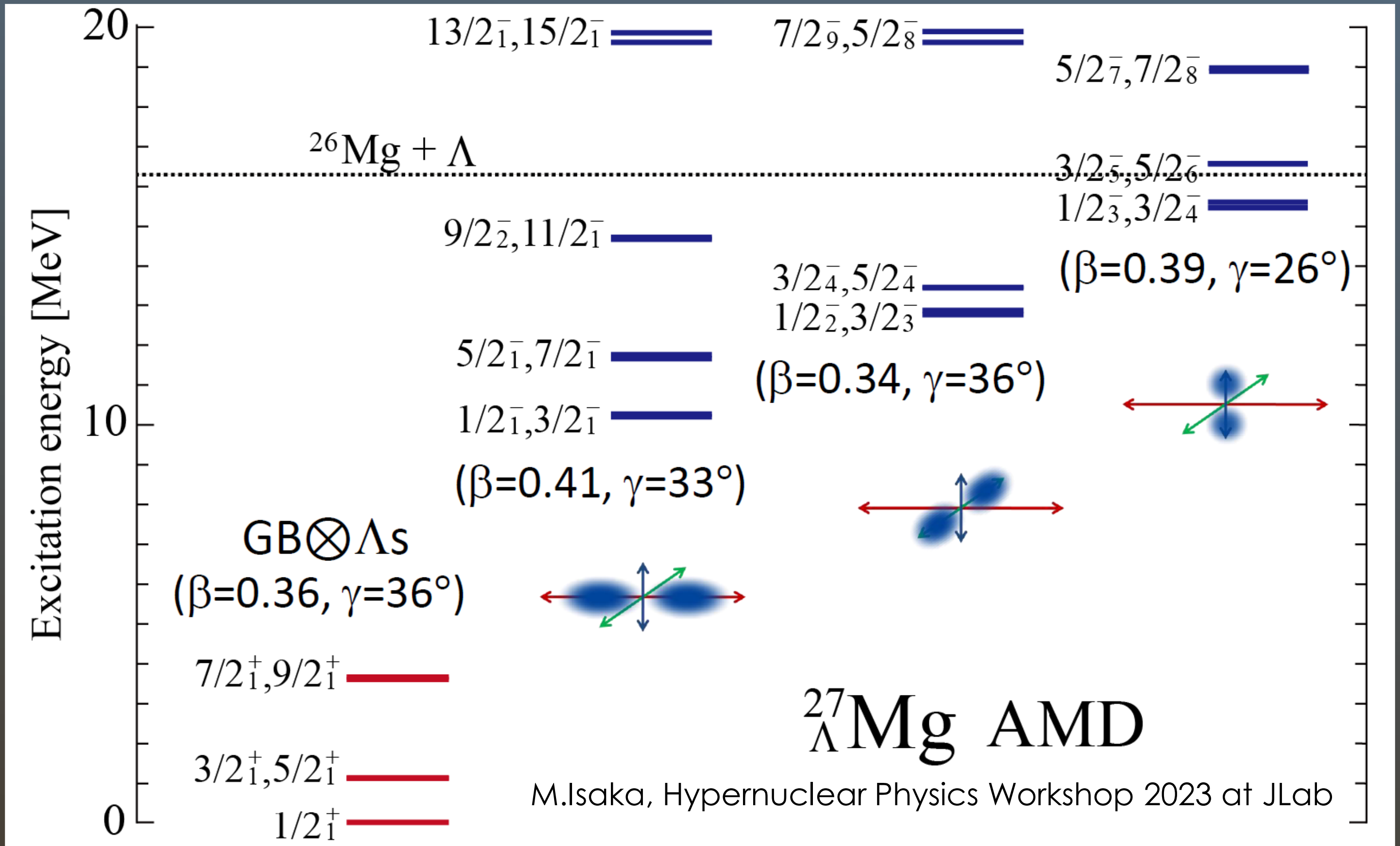


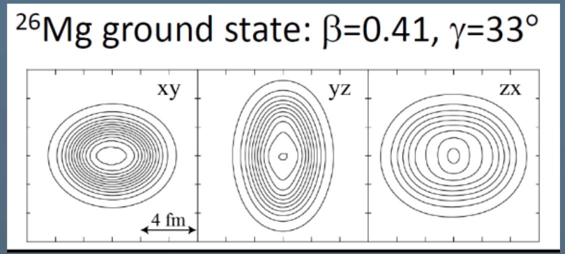
Co-existence of different deformations

Terasaki et al. NPA**621**(1997)
Rodrıguez-Guzman et al. NPA**709** (2002)
Peru et al PRC**77** (2008)
Hinohara, Kanada-En'yo PRC**83** (2011)

ADDING A Λ PARTICLE

$^{27}\mathrm{Al}(e,e'K^{+})^{27}_{\Lambda}\mathrm{Mg}$



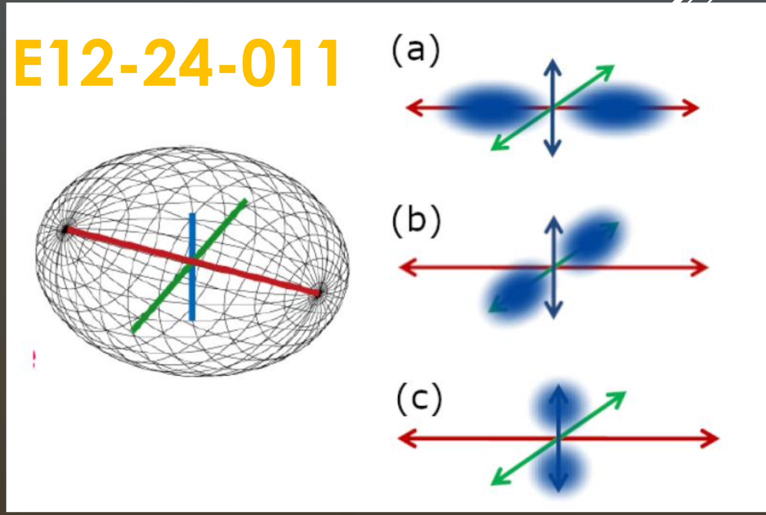


ΛN interaction is attractive

WF of Λ in p-orbit is straight

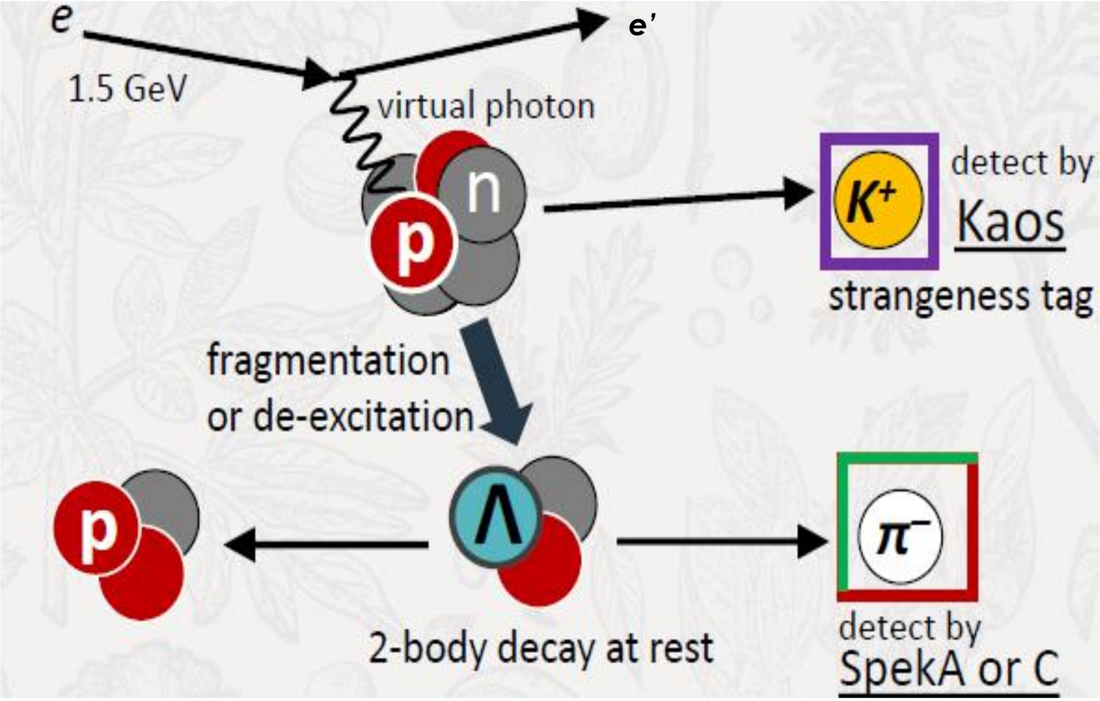
Overlap between Λ and ^{26}Mg core depends on axis direction

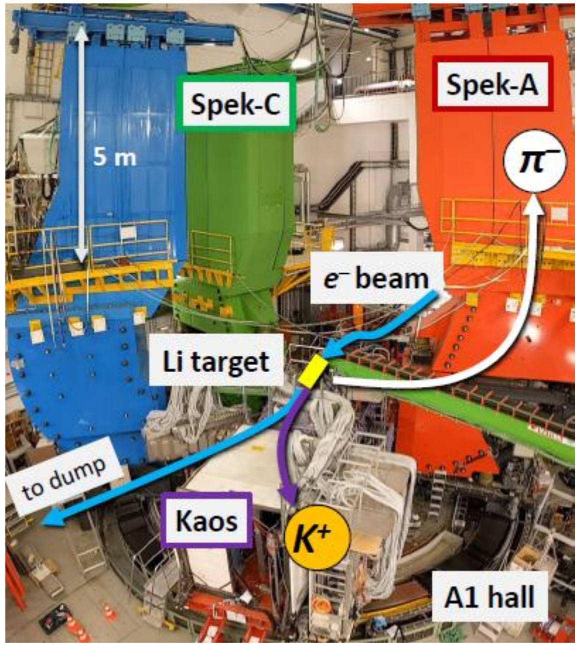
$^{26}\mathrm{Mg} \otimes \Lambda(p)$ splits in 3 states



(Hyper) Anti-symmetrized Molecular Dynamics
M. Isaka et al. PRC 83 (2011) 044323.
PRC 83 (2011) 054304.

Established at MAMI





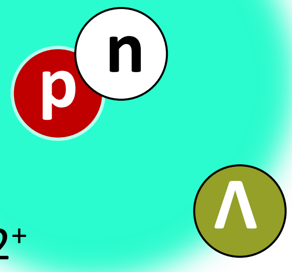
Measure monochromatic π– with K⁺ tag

DECAY π SPECTROSCOPY OF ELECTROPRODUCED HYPERNUCLEI

HYPERTRITON PUZZLE

Hypertriton – a benchmark in hypernuclear physics

d-Λ binding system



d-Λ bound state
Isospin $I = 0$
spin-parity $J^P = 1/2^+$

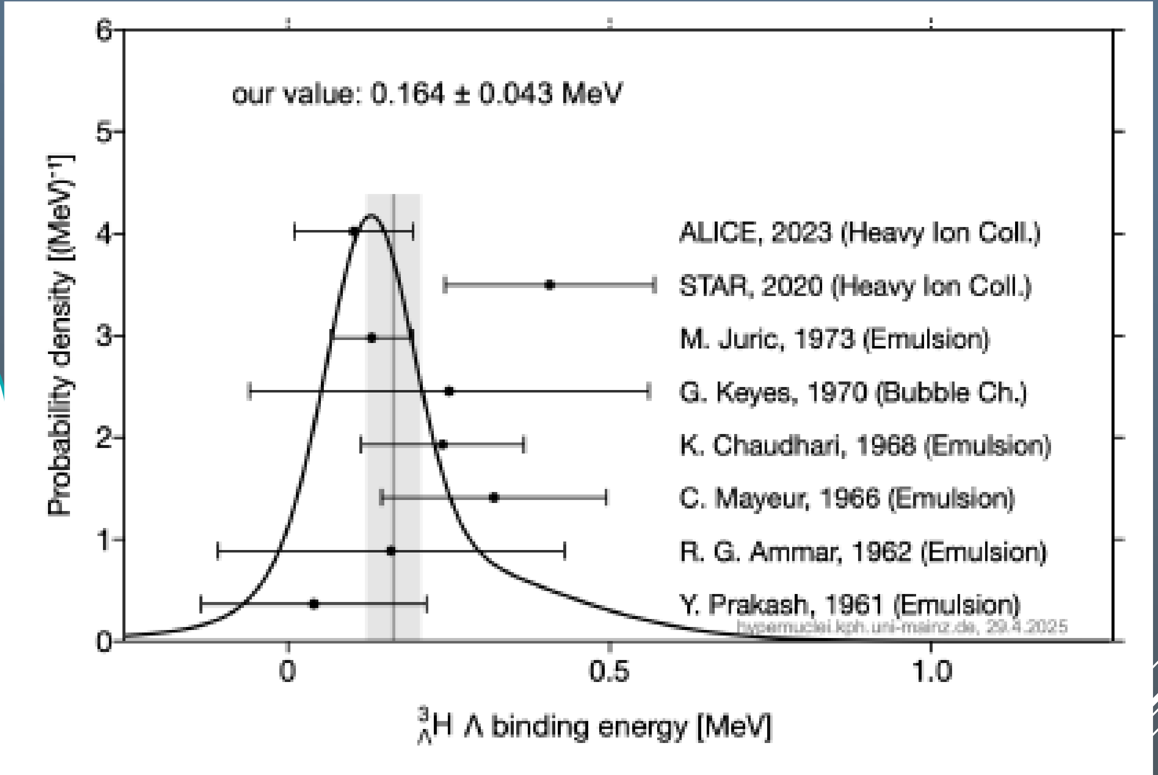
Shallow binding?
or
Deeply bounded?

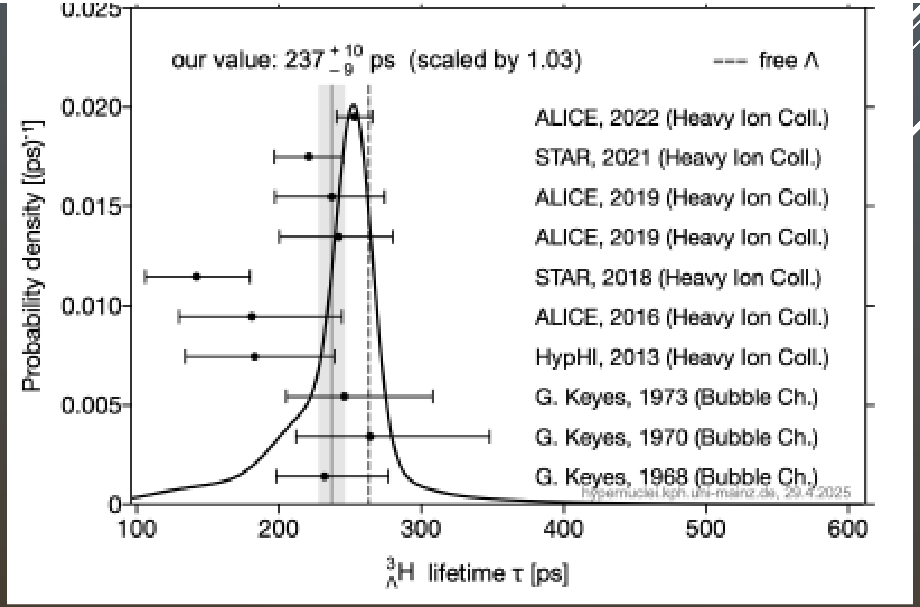
- Still large experimental uncertainties:

  STAR 2020 : $0.41 \pm 0.12_{(stat.)} \pm 0.11_{(syst.)}$ MeV
  ALICE 2023 : $0.10 \pm 0.06_{(stat.)} \pm 0.07_{(syst.)}$ MeV

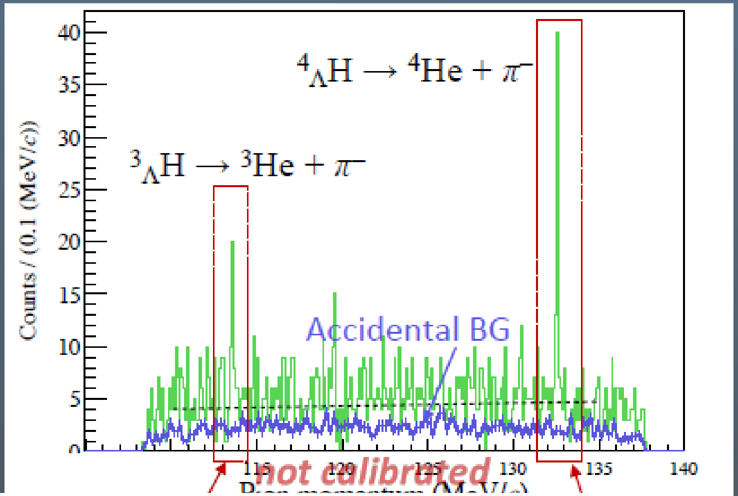
- Need to clarify with the lifetime

→ Decay-pion spectroscopy at MAMI

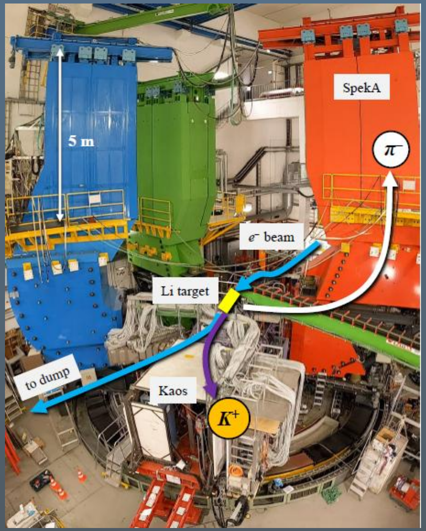


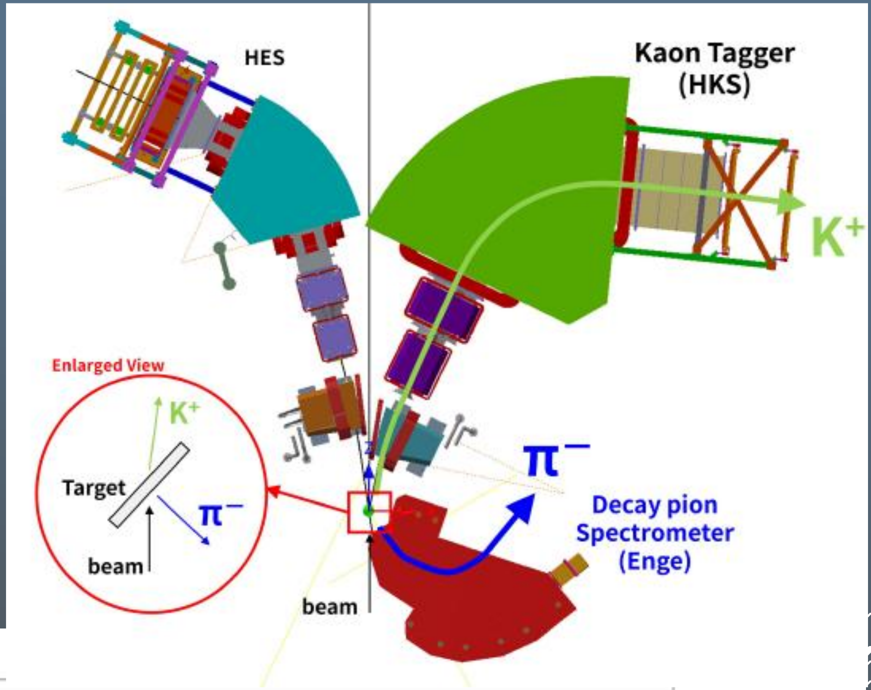


Deeper binding suggests shorter lifetime.



MAINZ(preliminary analysis)
R. Kino @ INPC 2025





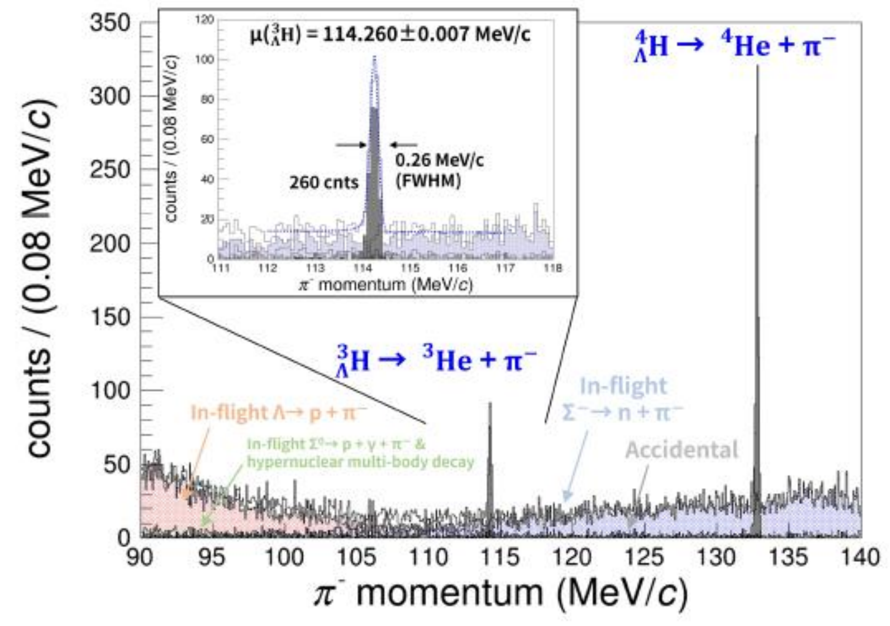
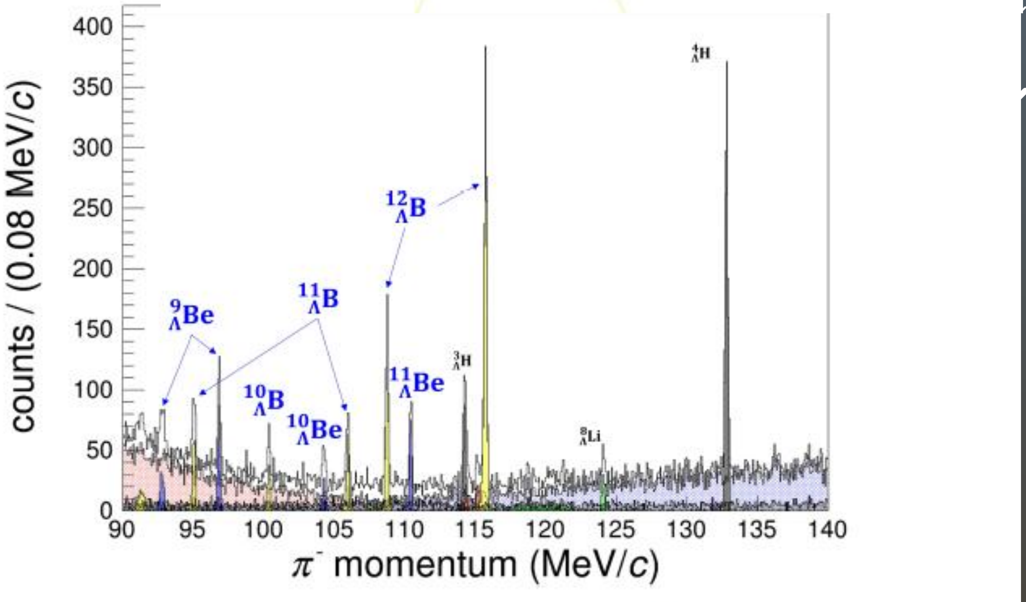


Figure 22: Pion spectrum of the Li target (5 days).

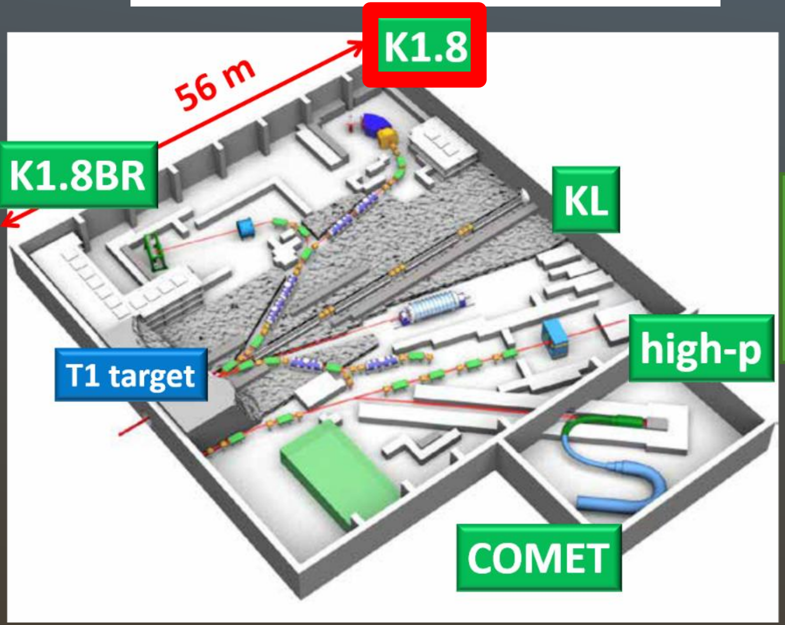


4: Pion spectrum of the C target (7 days in 100 mg/cm^2 + 21 days in 50 mg/cm^2).

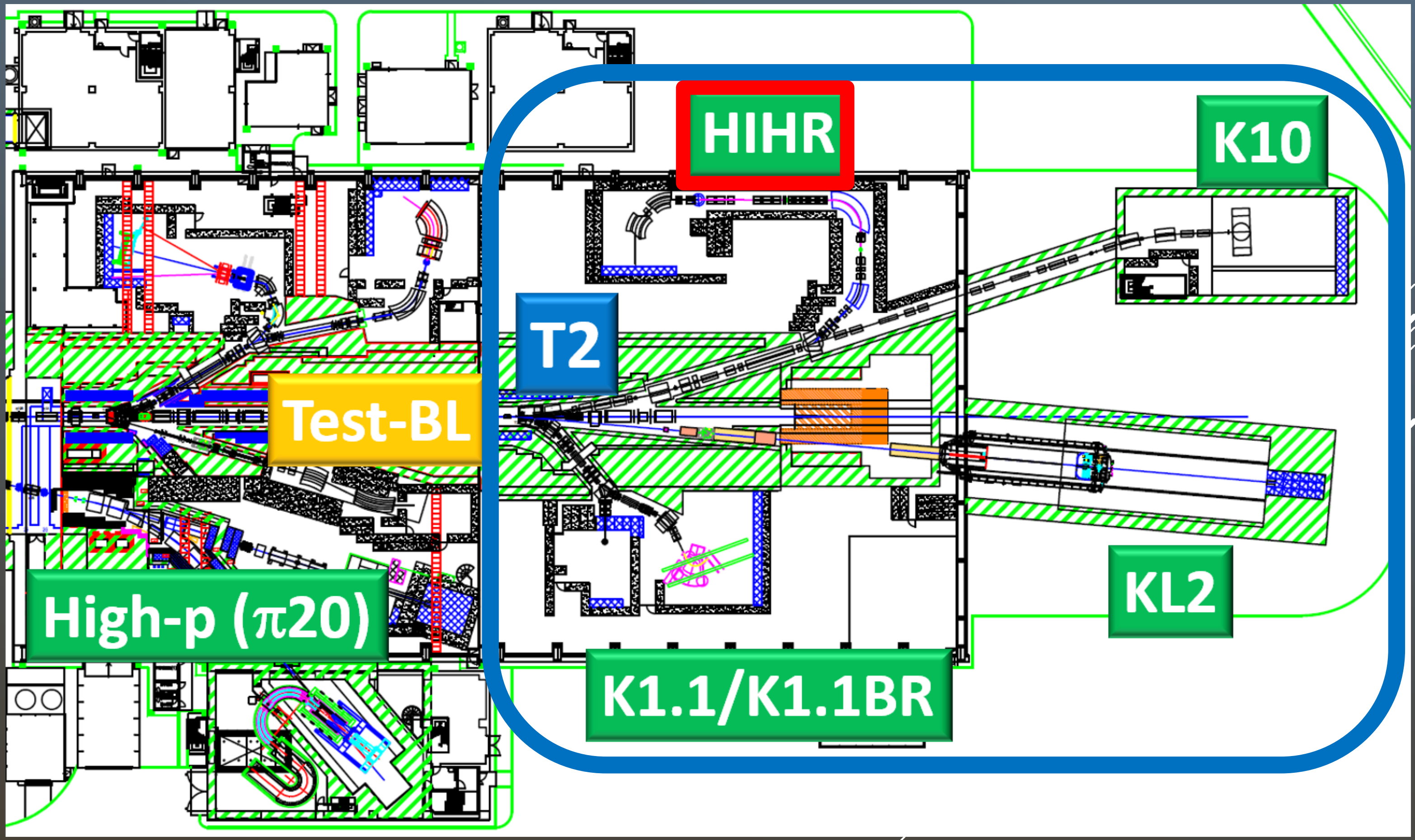
JLab expectations Run Gr. Experiment (Parasitic data taking)

Hadron Experimental Facility EXtension (HEF-EX) Project @J-PARC

Present facility



1 production target (T1) +
2 charged beamlines (K1.8/1.8BR, High-p)
1 neutral beamline (KL)
1 muon beamline (COMET)



1 new production target (T2) +
4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10) +
2 modified beamlines (High-p (π20), Test-BL)

HIHR

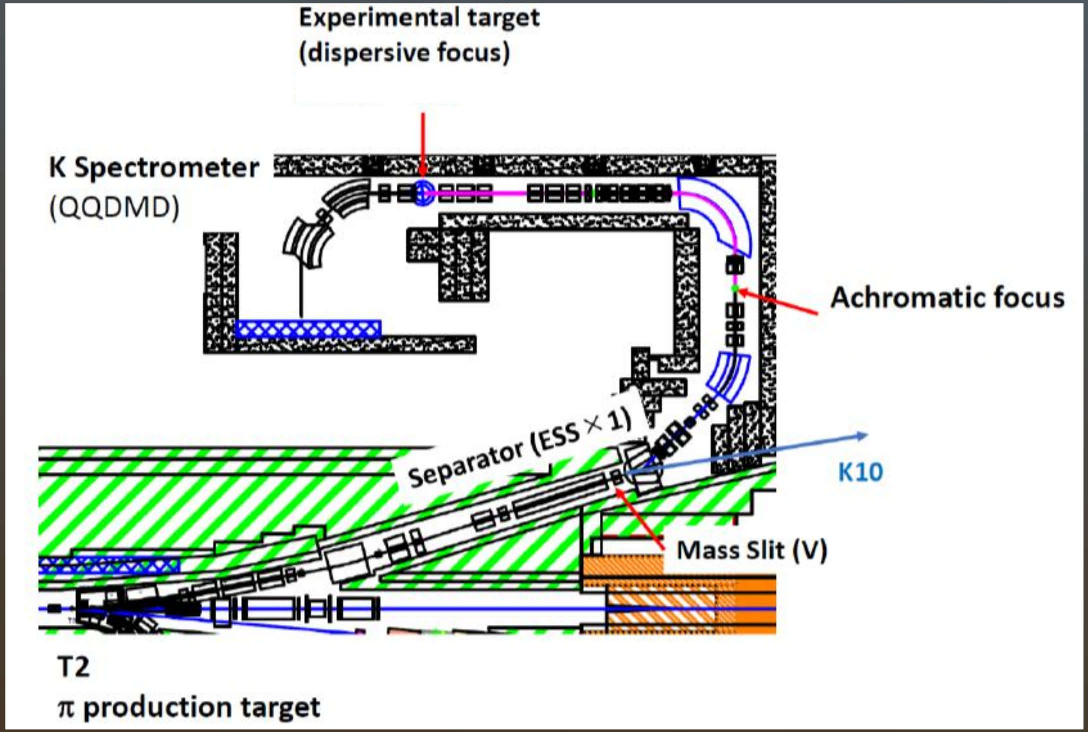
High-Intensity High-Resolution Beamline for High Precision (π, K) Spectroscopy

Exist beamlines:
~10^6 pions/pulse, $\Delta p/p$ ~ 1/1000

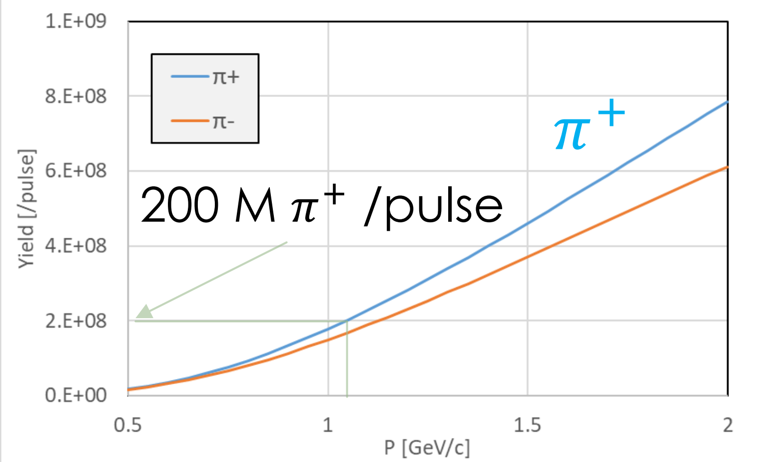
200 x 10^6 pions/pulse, $\Delta p/p$ ~ 1/10000

- Momentum dispersion matching

no beam tracking = **NO limit for π rate** from detectors



HR beamline (P_{max} = 2 GeV/c)
+ High Res. Kaon sectrometer

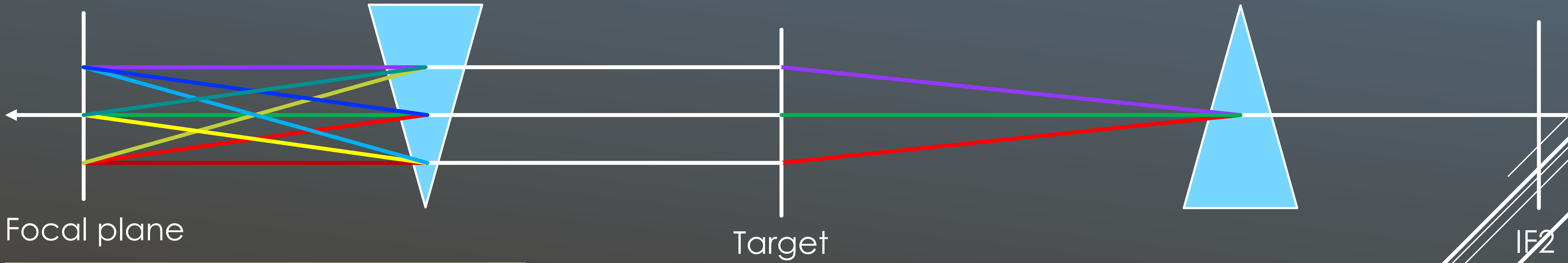


3deg. Ext. angle, 5.0×10^{13} ppp on 50% loss target (T2) 46kW, 5.2s (92kW on T1)
1.4msr%, (From T. Takahashi)

MOMENTUM DISPERSION MATCH

Scattered spectrometer — Reaction — Beam line

$$\begin{pmatrix} x_f \\ \theta_f \\ \delta_f \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} & s_{16} \\ s_{21} & s_{22} & s_{26} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} T & 0 & 0 \\ 0 & \theta/\theta_1 + 1 & 0 \\ 0 & 0 & (K\theta + DQ)/\theta_0 + C \end{pmatrix} \begin{pmatrix} b_{11} & b_{12} & b_{16} \\ b_{21} & b_{22} & b_{26} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_0 \\ \delta_0 \end{pmatrix}$$



$$\begin{aligned} \theta_1 &= b_{21}x_0 + b_{22}\theta_0 + b_{26}\delta_0, \\ K &= (\partial p_{scat}/\partial\theta)(1/p_{scat}), \\ C &= (\partial p_{scat}/\partial p_{beam})(p_{beam}/p_{scat}), \\ D &= (\partial p_{scat}/\partial Q)(1/p_{scat}). \end{aligned}$$

Momentum matching condition

$x_f = (s_{11}b_{11}T + s_{12}b_{26})x_0$ -------- total magnification → minimize

$+(s_{11}b_{12}T + s_{12}b_{22})\theta_0$ -------- point-to-point focus → 0

$+(s_{11}b_{16}T + s_{12}b_{26} + s_{16}C)\delta_0$ --- momentum matching → 0

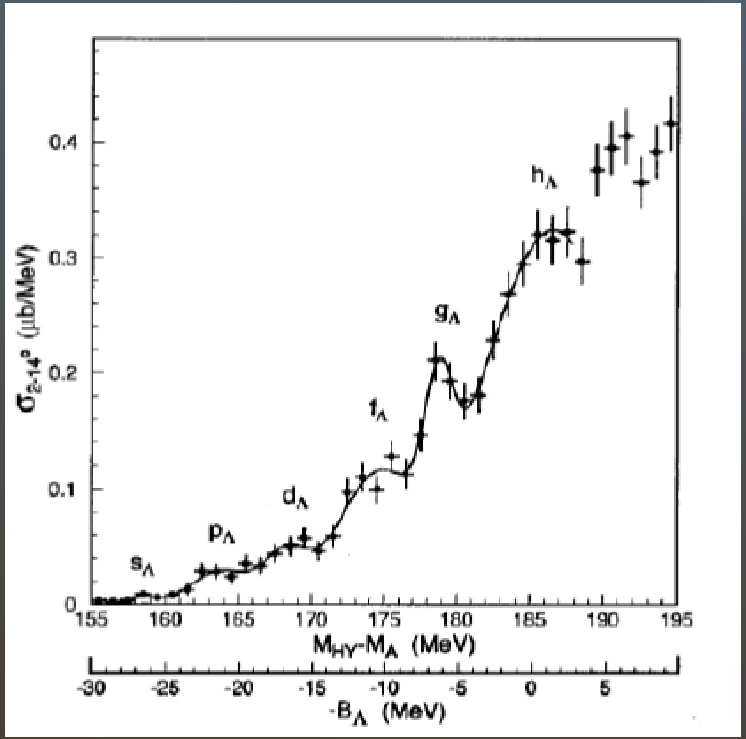
$+(s_{1s} + s_{16}K)\theta$ -------- kinematical correction → 0

$+s_{16}DQ$ -------- a position shift by the excitation energy

Super high resolution (π^+,K^+) spectroscopy

^{12}C, $^{6,7}Li$, ^{9}Be, $^{10,11}B$, ^{28}Si, ^{40}Ca, ^{51}V, ^{89}Y, ^{139}La, ^{208}Pb

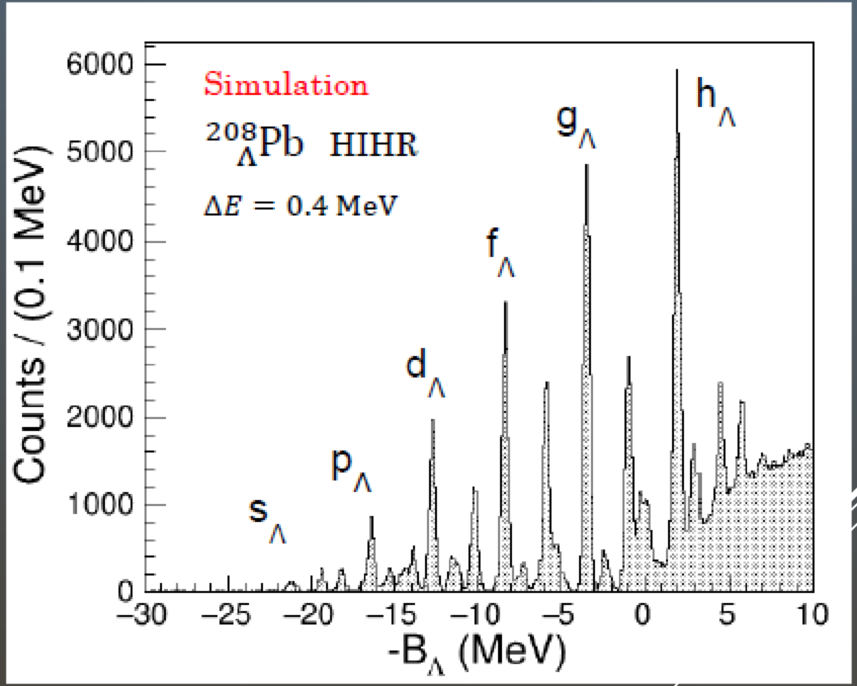
KEK-PS E369 with SKS



60 days × 3M π/spill @ KEK K6

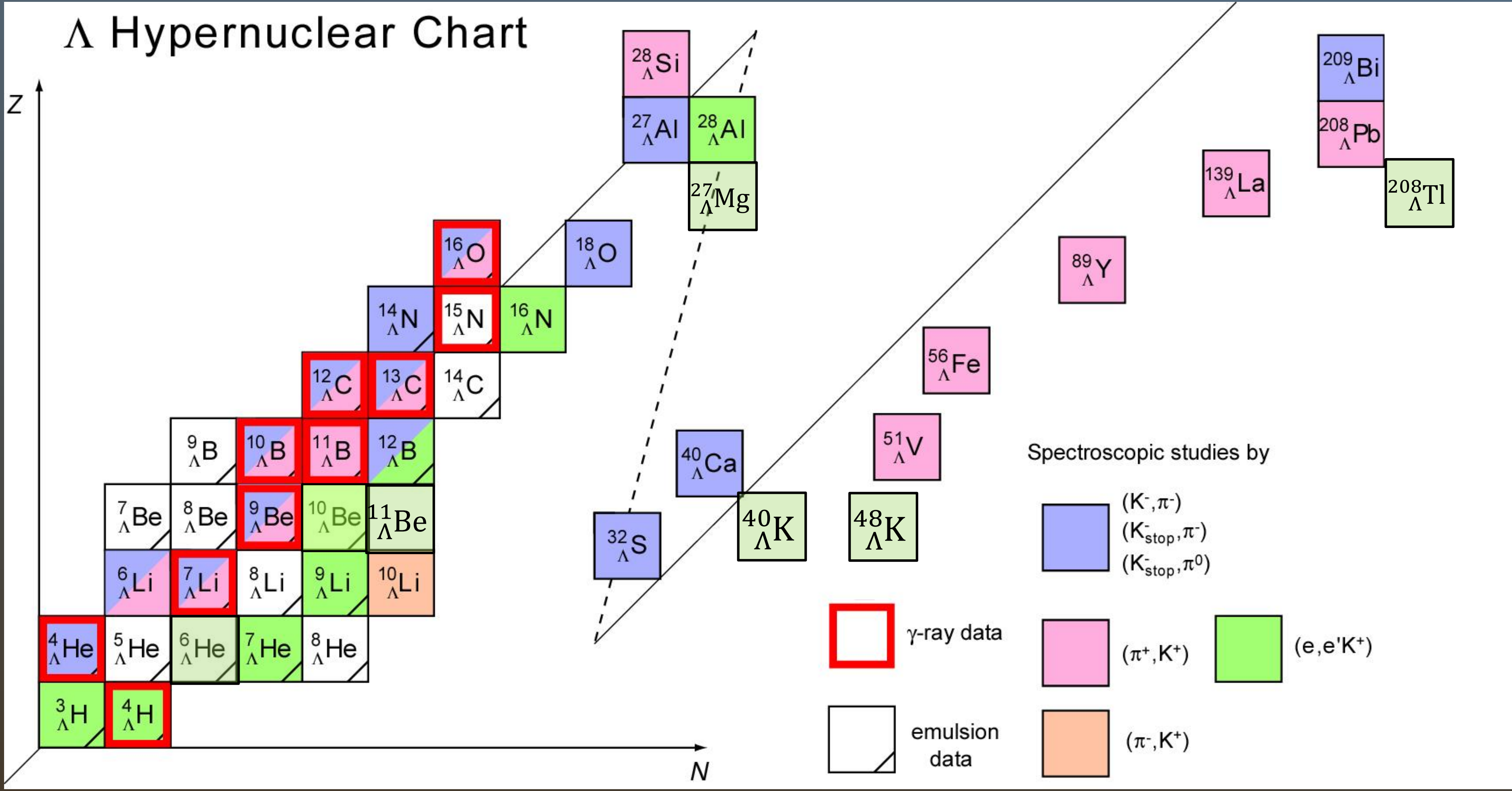
ΔE~2.3 MeV(FWHM)

Expected at HIHR beamline



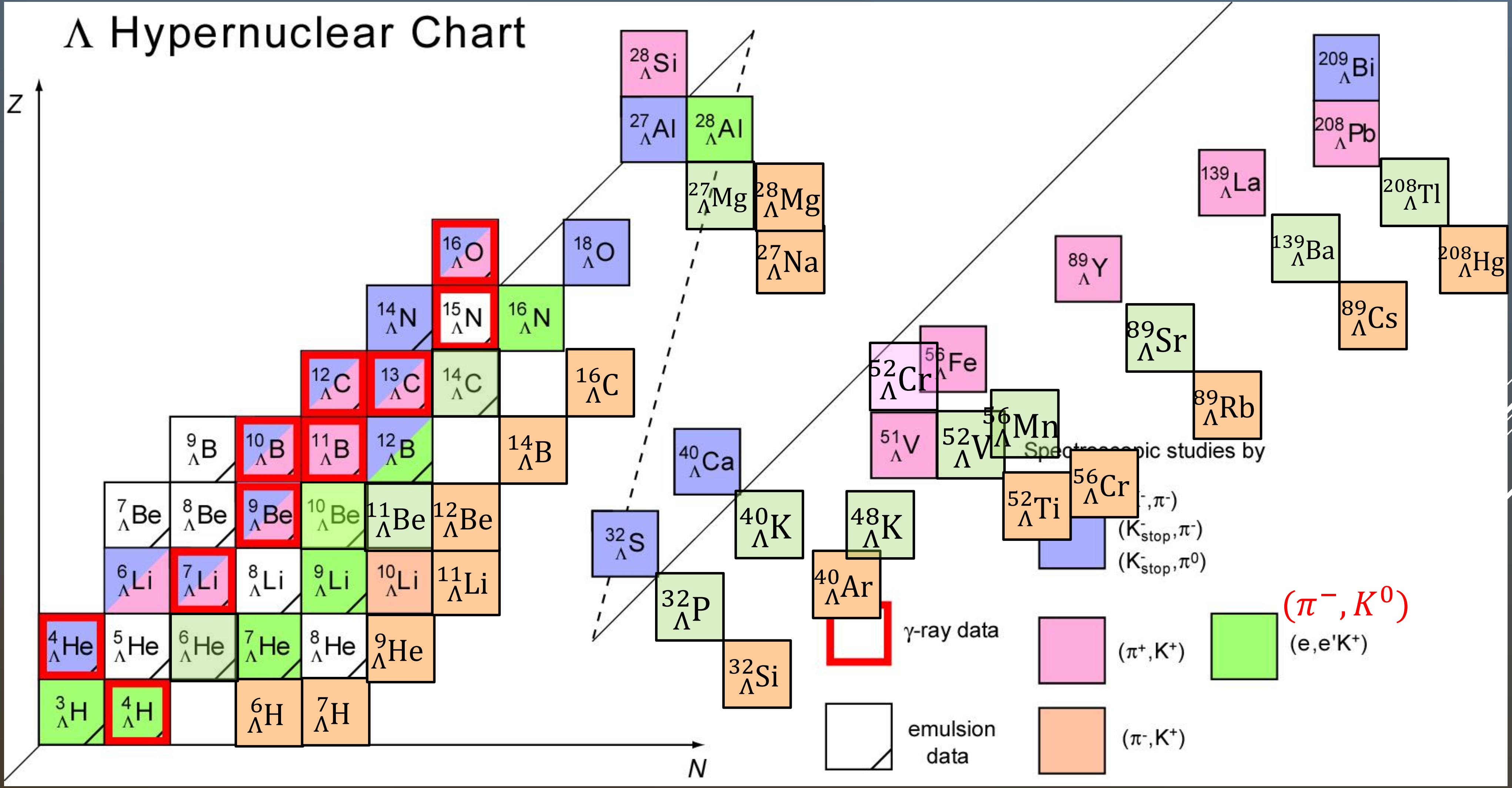
60 days × 200M π/spill @ HIHR

ΔE~**0.4 MeV(FWHM)**



Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

Hypernuclear Factory at HIHR



Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

SUMMARY

- ***Spectroscopy of hypernuclei is now more important than previous. Key to solve the hyperon puzzle.***
- At JLab,$(e, e'K^+)$: ${}^{40,48}_{\Lambda}\mathrm{K}$, ${}^{208}_{\Lambda}\mathrm{Tl}$, ${}^{6}_{\Lambda}\mathrm{He}$, ${}^{9}_{\Lambda}\mathrm{Li}$, ${}^{11}_{\Lambda}\mathrm{Be}$, ${}^{27}_{\Lambda}\mathrm{Mg}$, Decay π in Hall-C

  A campaign of 5 experiments will run in 2027
- At MAMI, Decay π spectroscopy was established
- New HIHR beamline at J-PARC Hadron Hall Extension Project

  Hypernuclear Factory

Complimentary studies of Λ hypernuclear study at JLab and J-PARC

Decay π spectroscopy established at MAMI will be developed at JLab

HYP2025

The 15th International Conference on Hypernuclear and Strange Particle Physics (HYP2025) will take place in **Tokyo**, Japan, from **September 29** (Monday) through **October 3** (Friday), 2025.

Abstract submission is now open (until end of June)!