Hypernuclear Physics with Heavy Ion Beams

Projectile fragmentation reactions

Take R. Saito

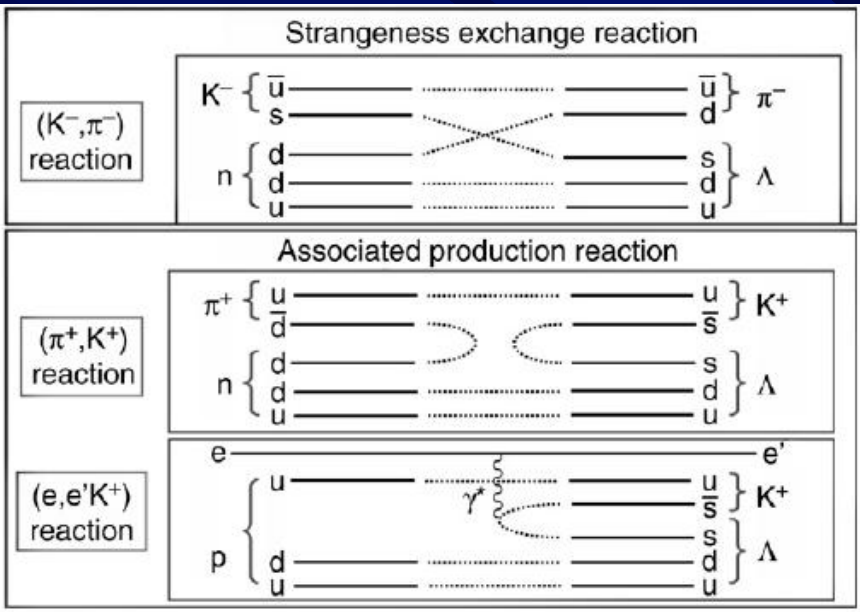
GSI Helmholtz Center for Heavy Ion Research, Germany

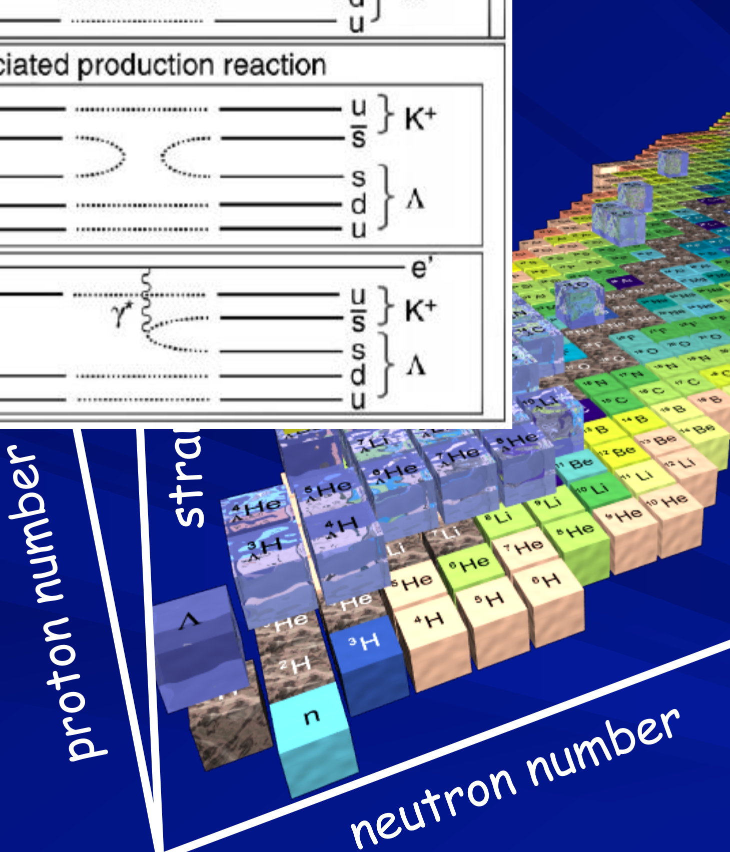
Helmholtz Institute Mainz, Germany

ENSAR2-NUSPRASEN Workshop on Nuclear Reactions (Theory and Experiment) ,

January 22nd – 24th, 2018, Warsaw, Poland

clear chart





Advantage

- Precise spectroscopy
  - Structure in detail
- Clean experiment

Difficulties

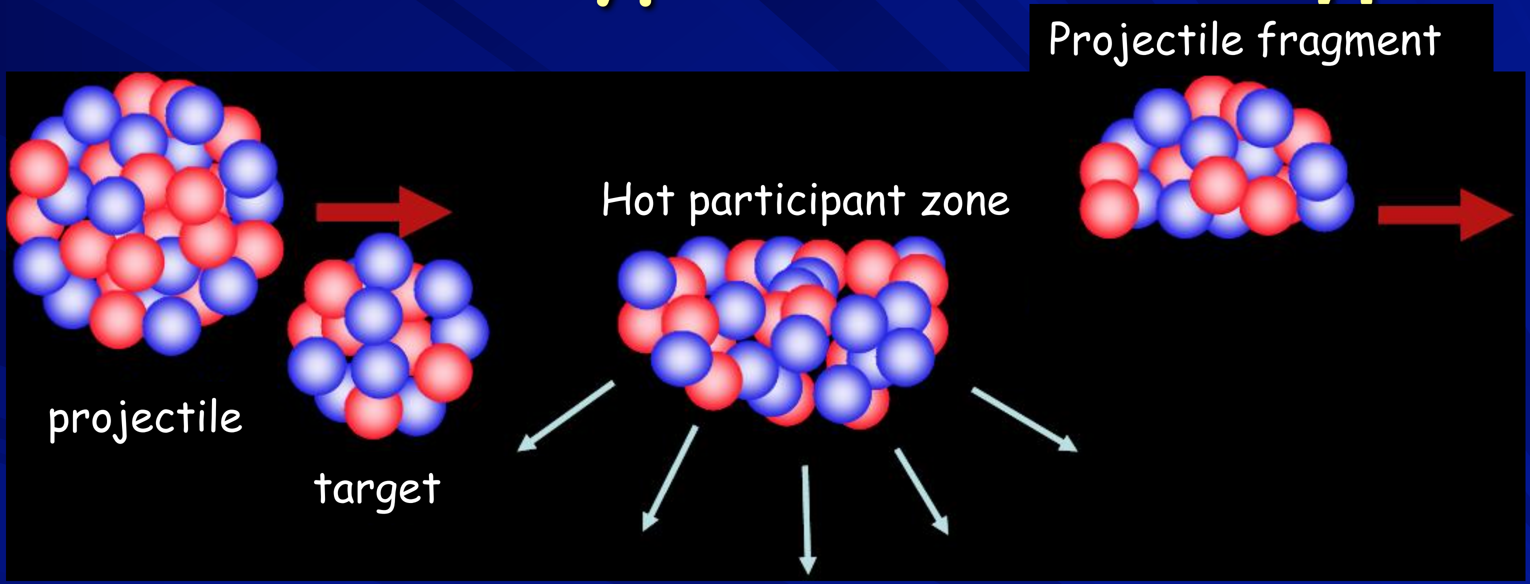
- Limited isospin
- Small momentum transfer to separate hypernuclei
- Difficulties on decay studies
- Only up to double-strangeness

Hypernuclear spectroscopy with heavy ion beams

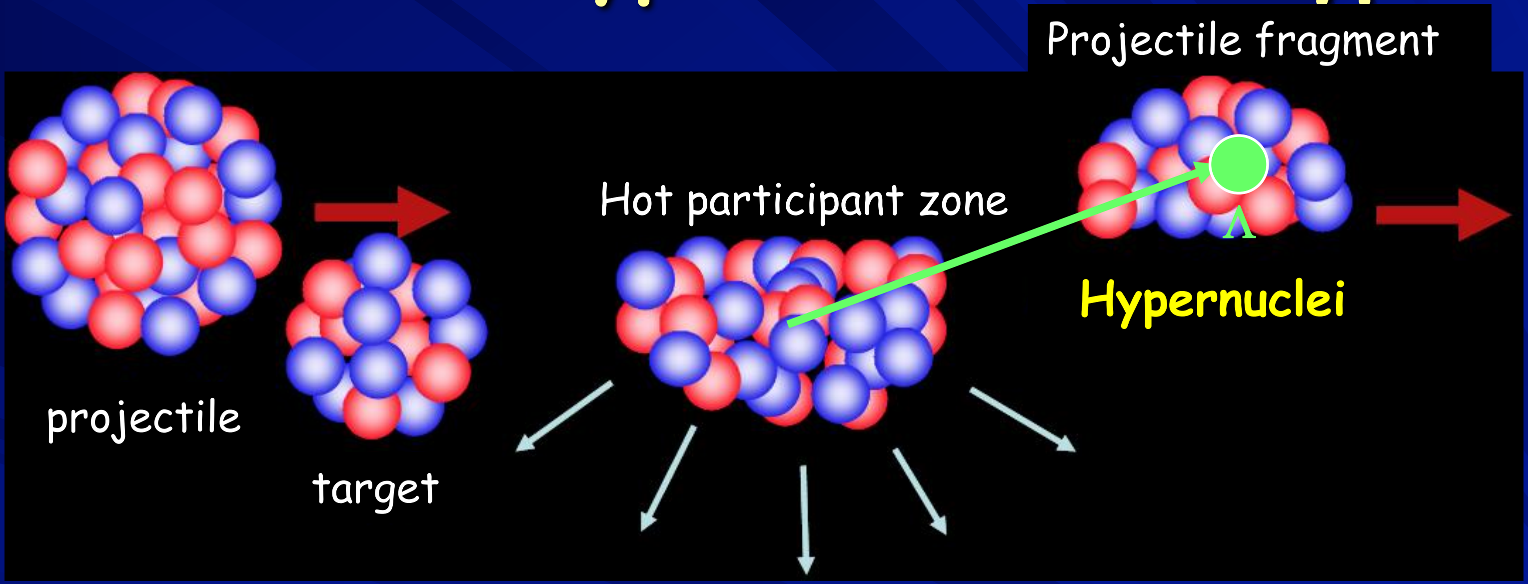
HypHI project, started in 2005

Hypernuclear spectroscoy with **H**eavy **I**on Beam

Production of Hypernuclei with HypHI

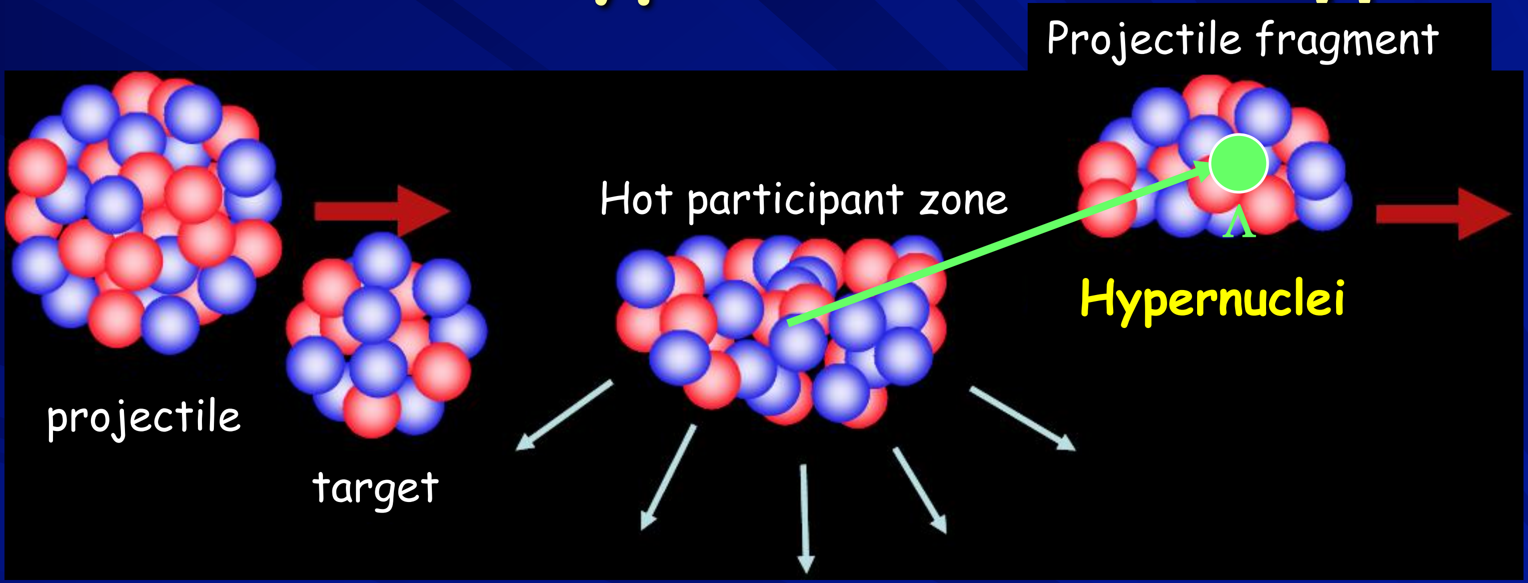


Production of Hypernuclei with HypHI



- **Coalescence of Λ in projectile fragments**

Production of Hypernuclei with HypHI

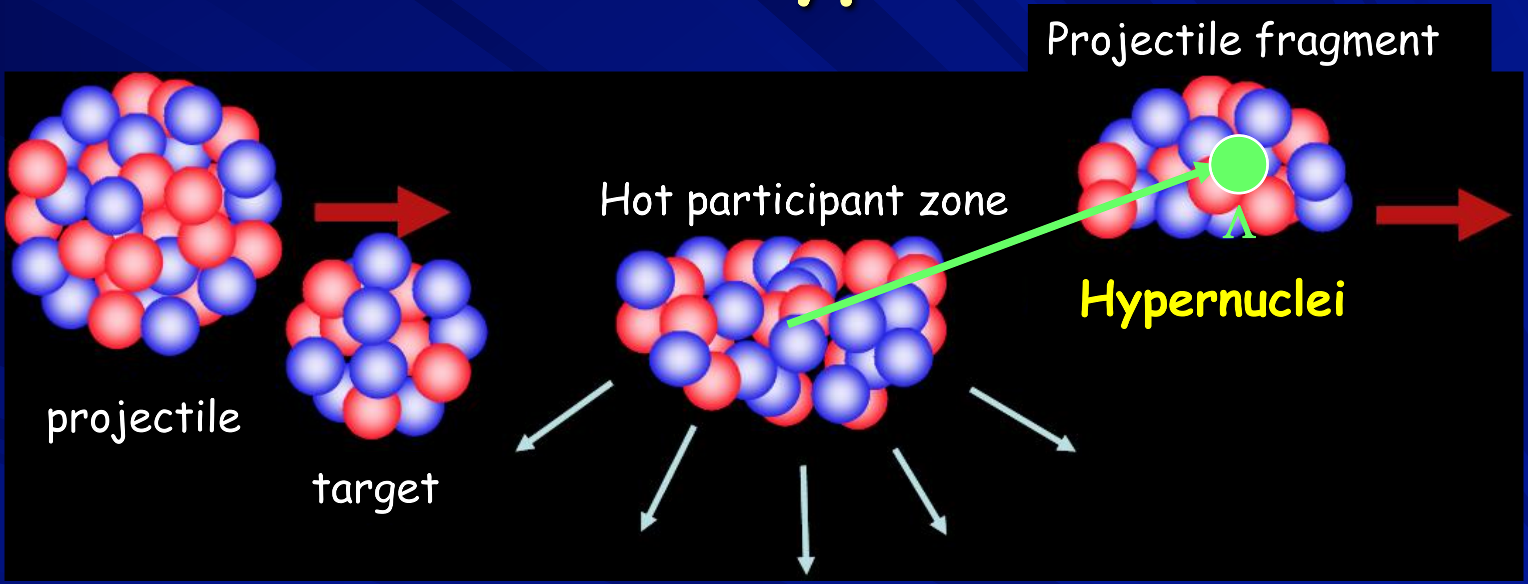


- **Coalescence of Λ in projectile fragments**

- **NN -> ΛKN : Energy threshold ~ 1.6 GeV**
  - Heavy ion beams with E > 1.6 A GeV needed
    - Stable heavy ion beam at GSI
    - Stable heavy ion beam at FAIR
    - **RI-beam from FRS and super-FRS**

Accessible to neutron- and proton rich hypernuclei

Relativistic hypernuclei



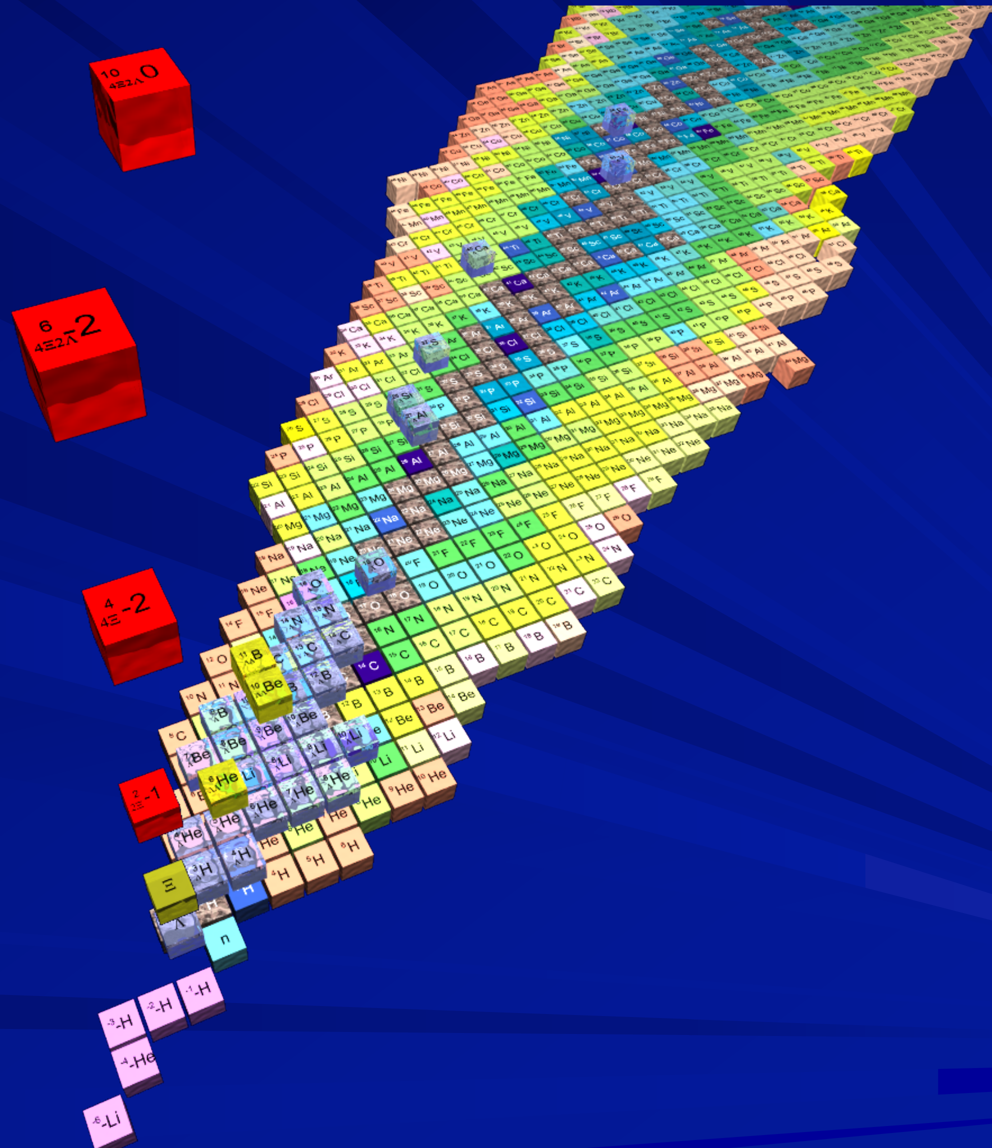
- **Large Lorentz factor** γ (>3)
  - Effective lifetime : Longer by the Lorentz factor

    200 ps -> 600 ps at GSI (ct ~ 20 cm)

    200 ps -> 4 ns at FAIR (ct ~ 120 cm)

- **Hypernuclear separation and spin precession**

Nuclear matter with multiple-strangeness



HypHI at GSI/FAIR: Concept of Experiments

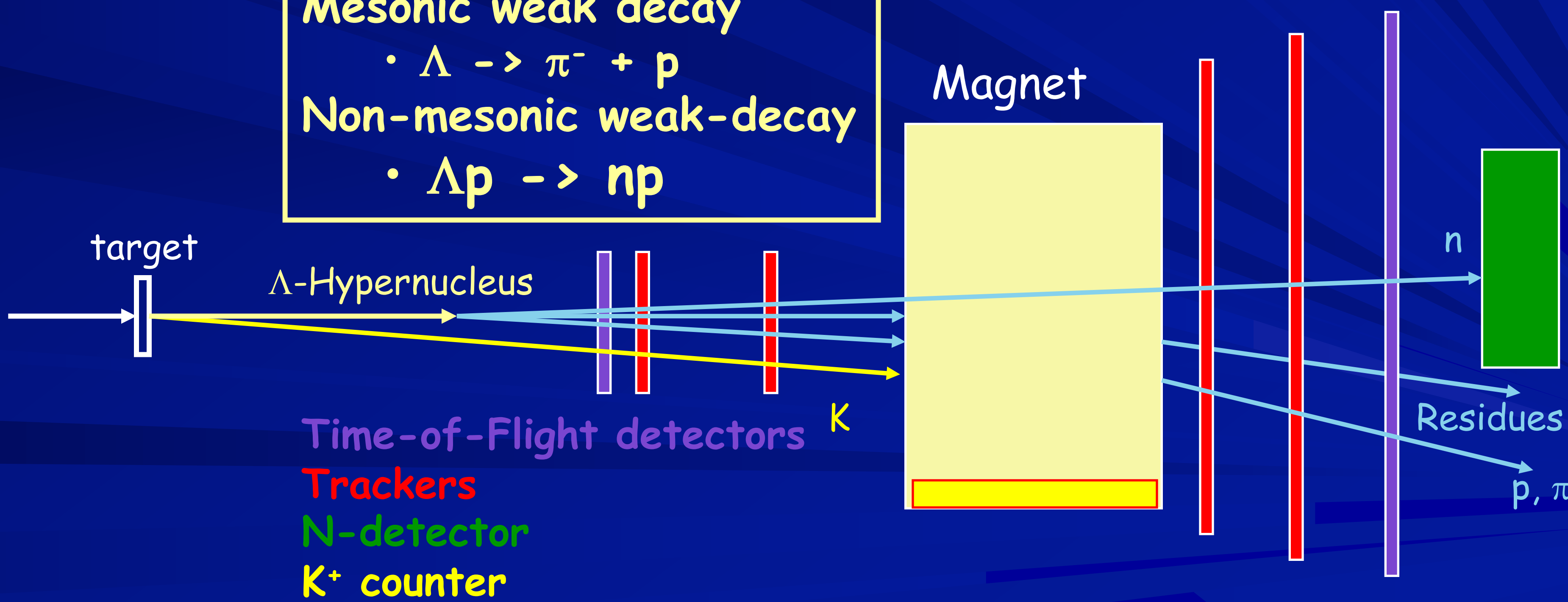
Produced hypernucleus close to projectile velocity

- Large Lorents factor $\gamma > 3$
- $c\tau$ ~ 20 cm at 2 A GeV

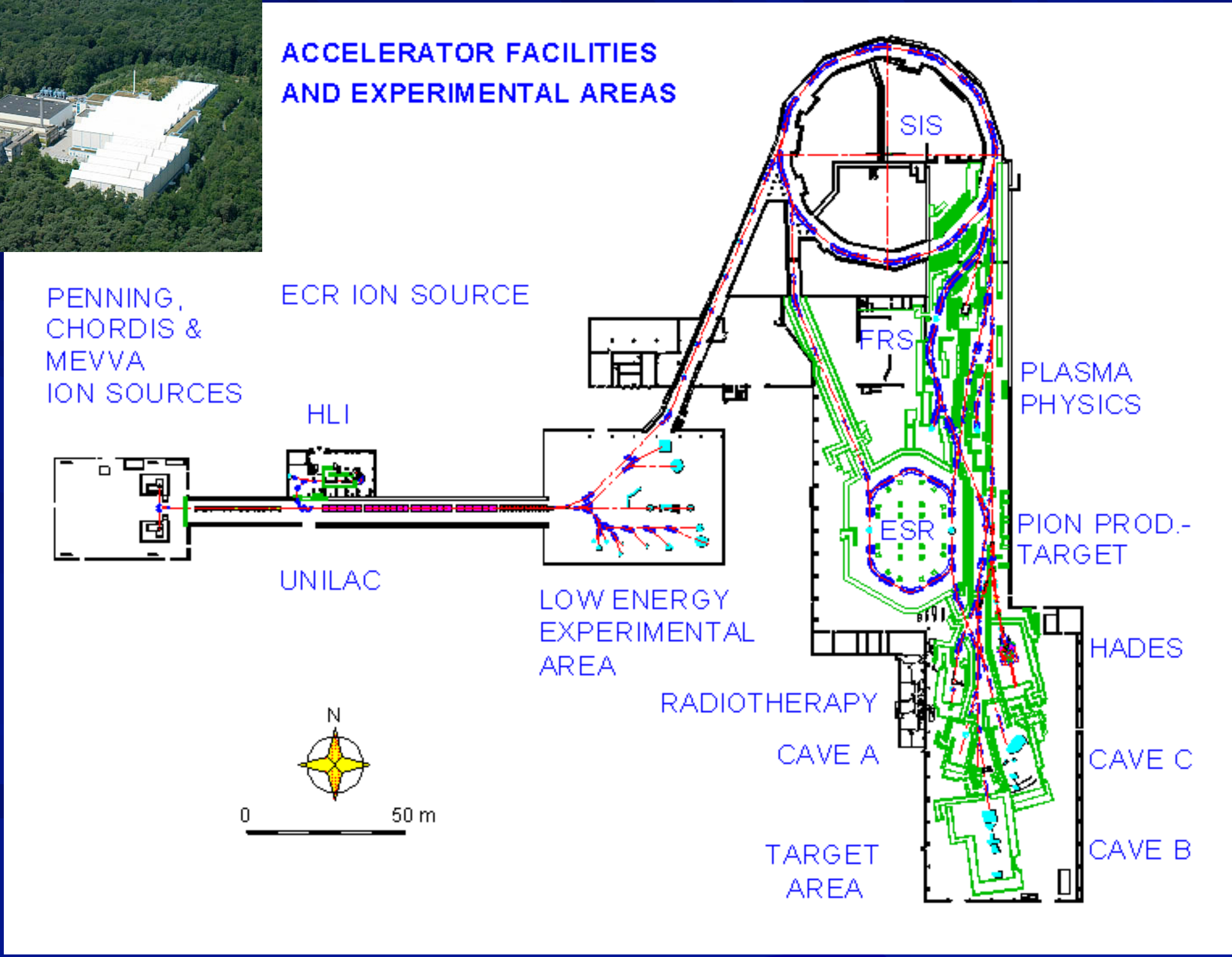
Example : $^{12}C + {}^{12}C \rightarrow {}^{A}{}_{\Lambda}Z + K^{+,0} + X$

Mesonic weak decay
- $\Lambda \rightarrow \pi^{-} + p$

Non-mesonic weak-decay
- $\Lambda p \rightarrow np$



GSI Helmholtz Center for Heavy Ion Research

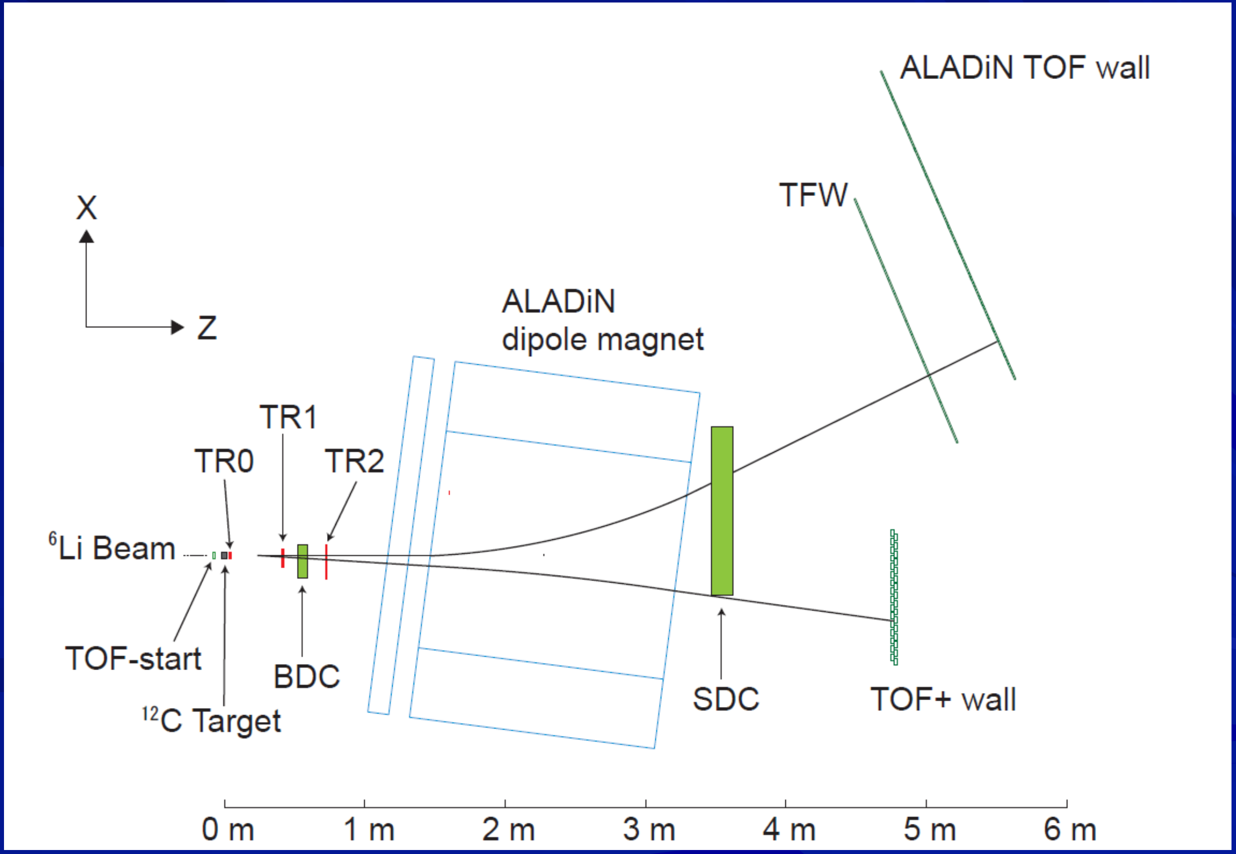


HypHI Phase 0 in October 2009

- **The goal of the Phase 0 experiments**
  - **To demonstrate the feasibility of precise hypernuclear spectroscopy with ^{6}Li primary beams at 2 A GeV : Mesonic decay $\Lambda \rightarrow \pi^- + p$**

$^3_\Lambda H \rightarrow \pi^- + {}^3He$

$^4_\Lambda H \rightarrow \pi^- + {}^4He$



Funding

- Helmholtz-University Young Investigators Group VH-NG-239, 2006-2012
- DFG grant SA1696/1-1 2007-2009, TOF detectors

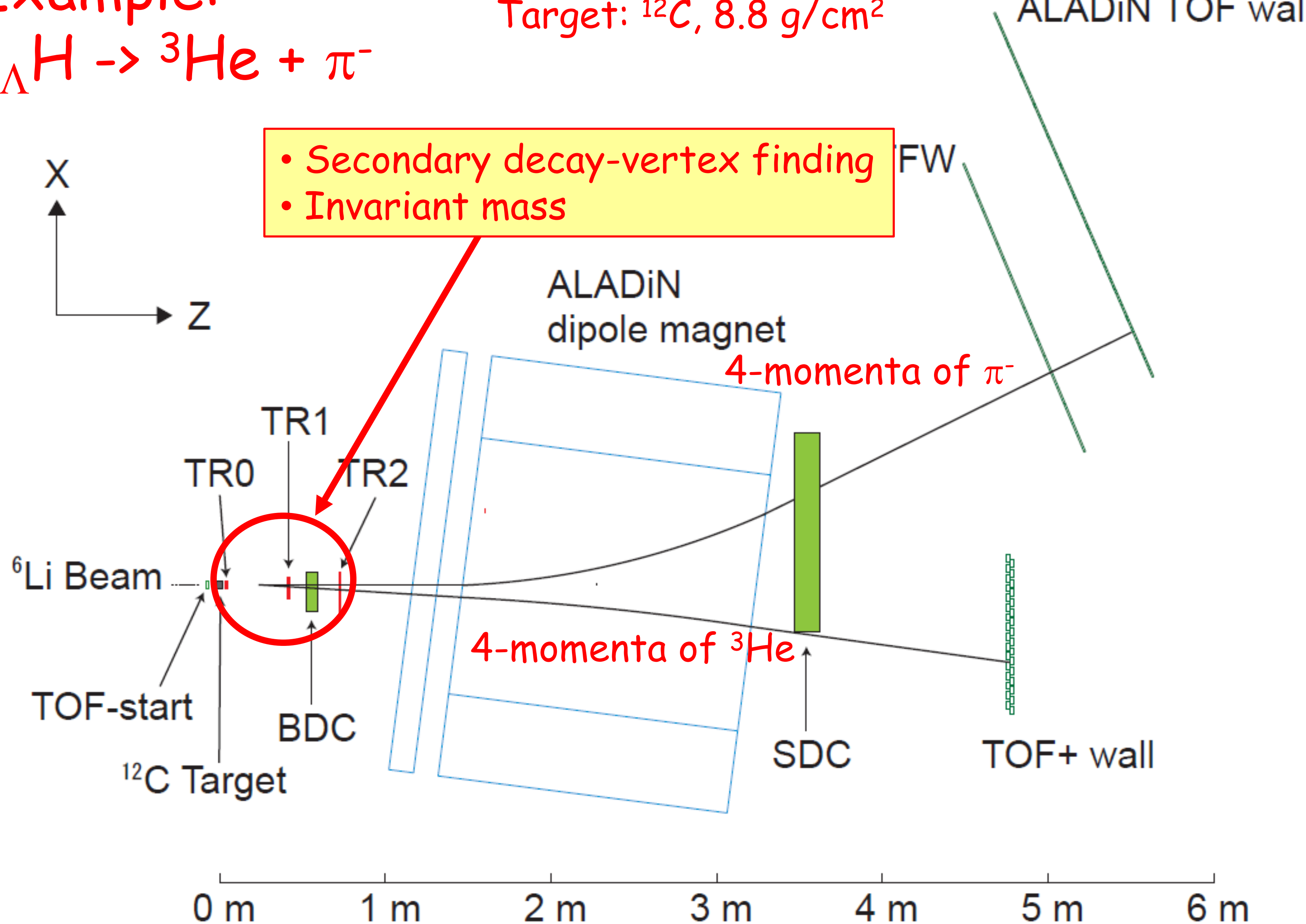
HypHI Phase 0 (2009), $^{6}Li+^{12}C$ at 2 A GeV

Example:

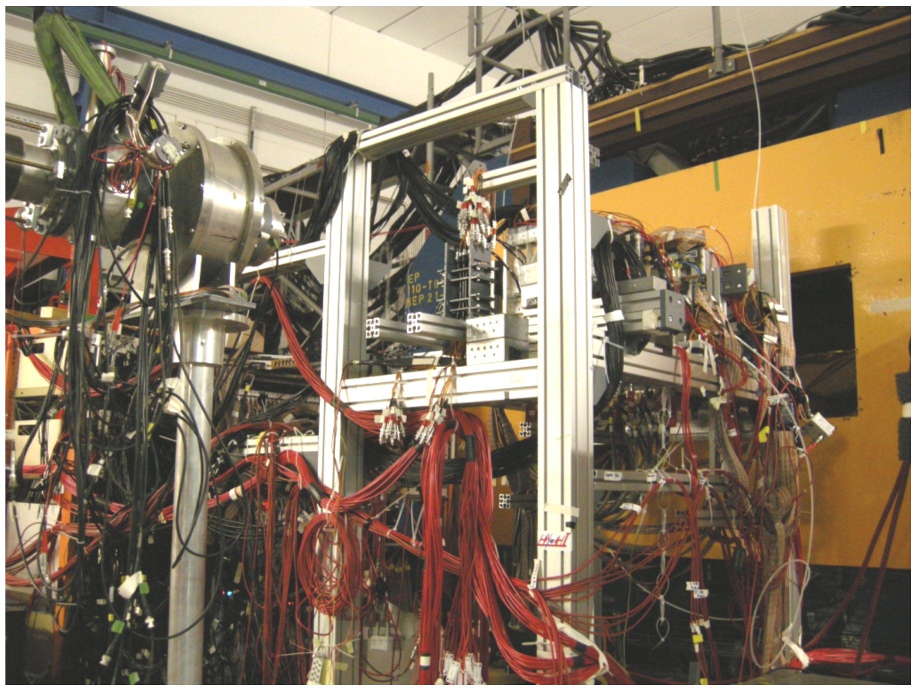
$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$

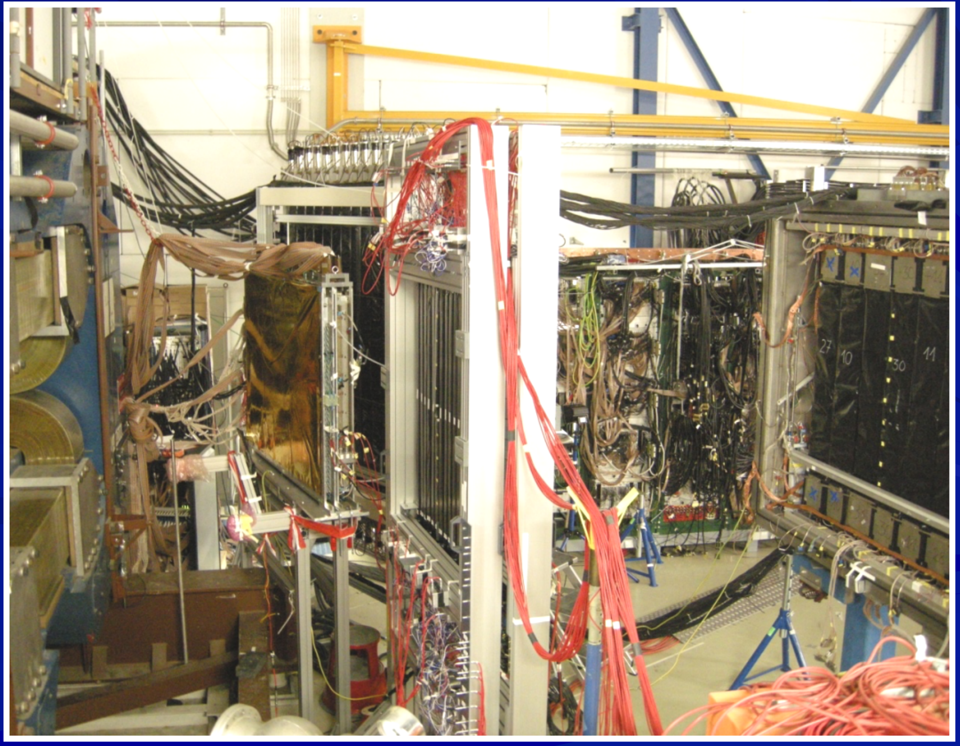
Beam: ^{6}Li at 2 A GeV, $3X10^{6}$ /s

Target: ^{12}C, 8.8 g/cm^{2}

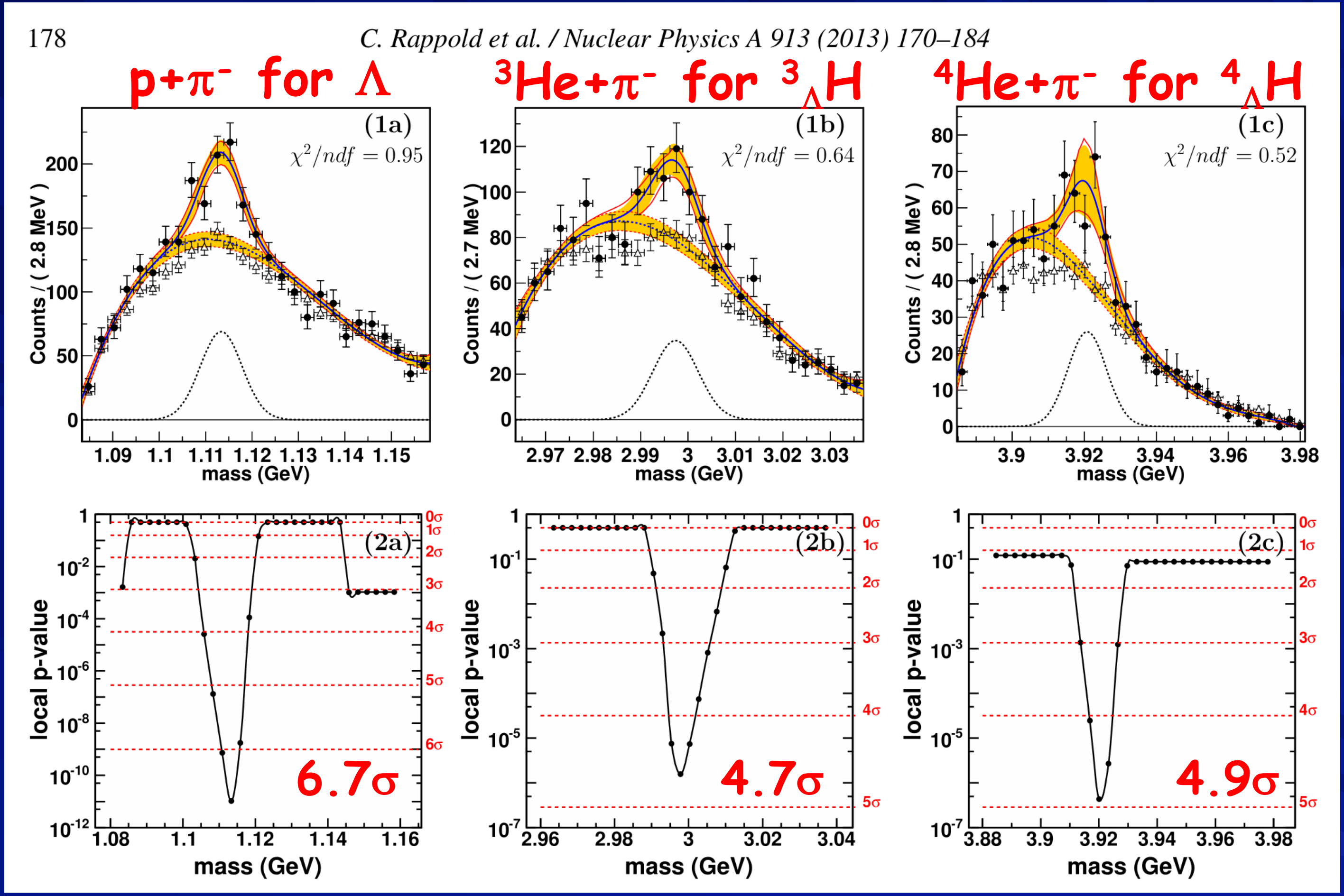


Setup in 2009



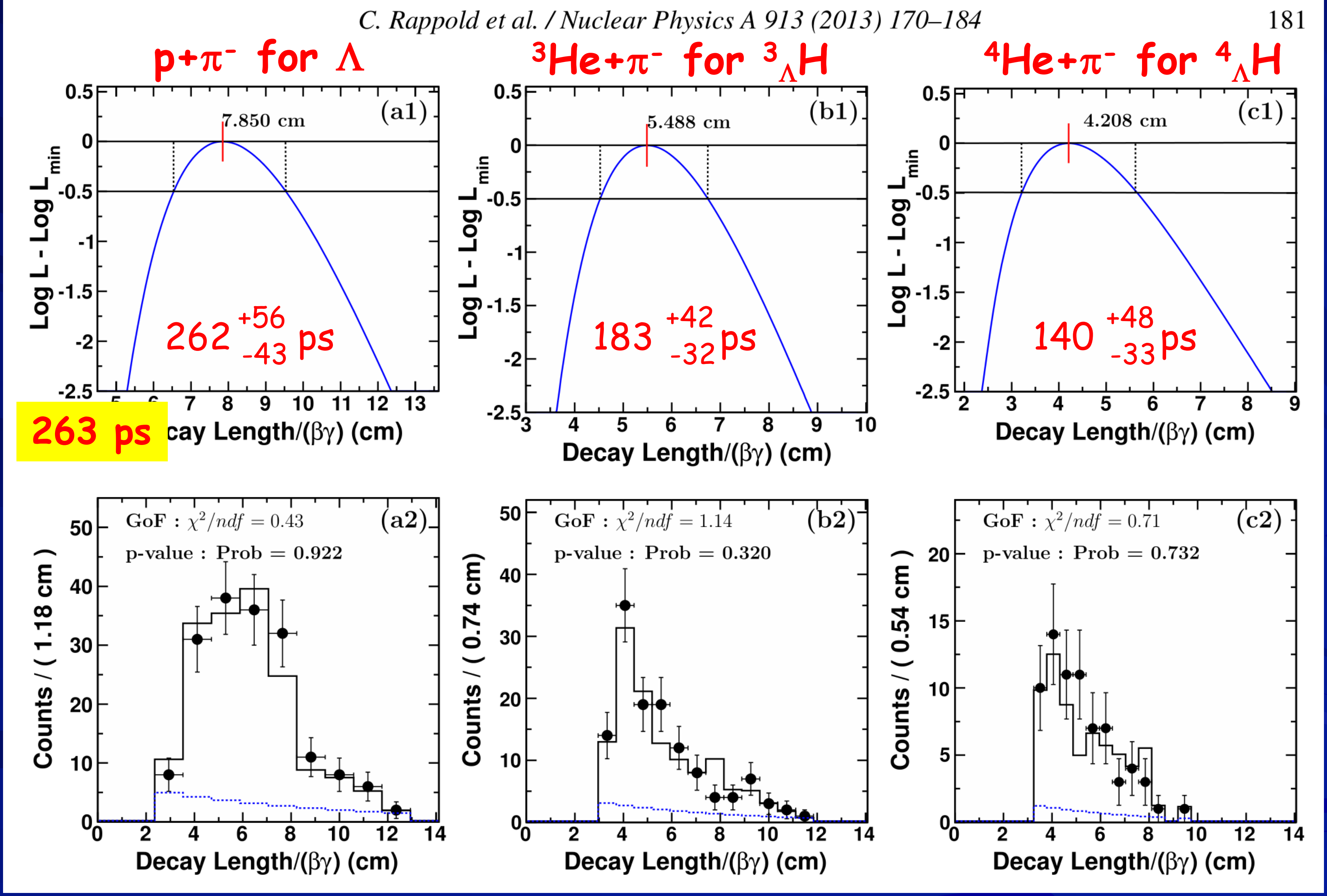


Invariant mass distribution



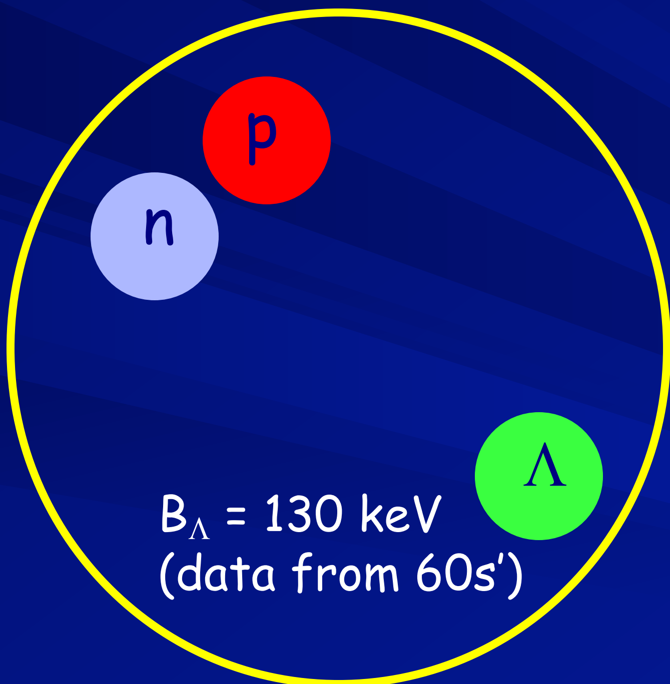
- Statistical analysis of Λ invariant mass (-100 mm < Vertex Z < 300 mm) with RooStats and RooFit package
- Fitting model = n_s *(Gaus: sig_m, sig_s)* + n_b *(Chebychev: a0, a1, a2)*

Lifetime: Unbineed maximum likelihood fitting



$^{3}_{\Lambda}$H (hypertriton)

Benchmark in hypernuclear physics



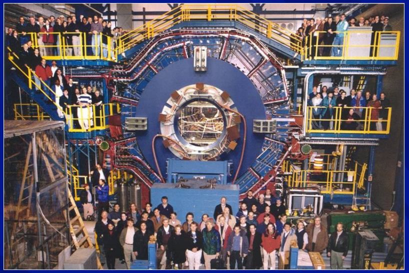
HypHI Phase 0

$$183^{+42}_{-32}\ \text{ps}$$

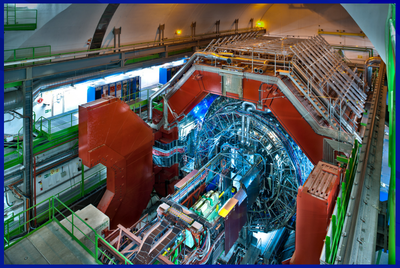
$\tau(^{3}_{\Lambda}\text{H})$ should be equal to $\tau(\Lambda$, 263 ps)

$^{3}_{\Lambda}H$ Lifetime till Summer 2017

- **HypHI**
  - $^{6}Li+^{12}C$ and $^{20}Ne+^{12}C$ at 2 A GeV at GSI
  - Phase 0 ($^{6}Li+^{12}C$), 183^{+42}_{-32} ps (Λ: 263 ps)
- **STAR at BNL RHIC**
  - $^{197}Au+^{197}Au$
  - Observation of short lifetime of $^{3}_{\Lambda}H$
  - Two/three-body decays combined: 155^{+25}_{-22} ps



- **ALICE at LHC CERN**
  - $^{208}Pb+^{208}Pb$
  - 181^{+54}_{-39} ps

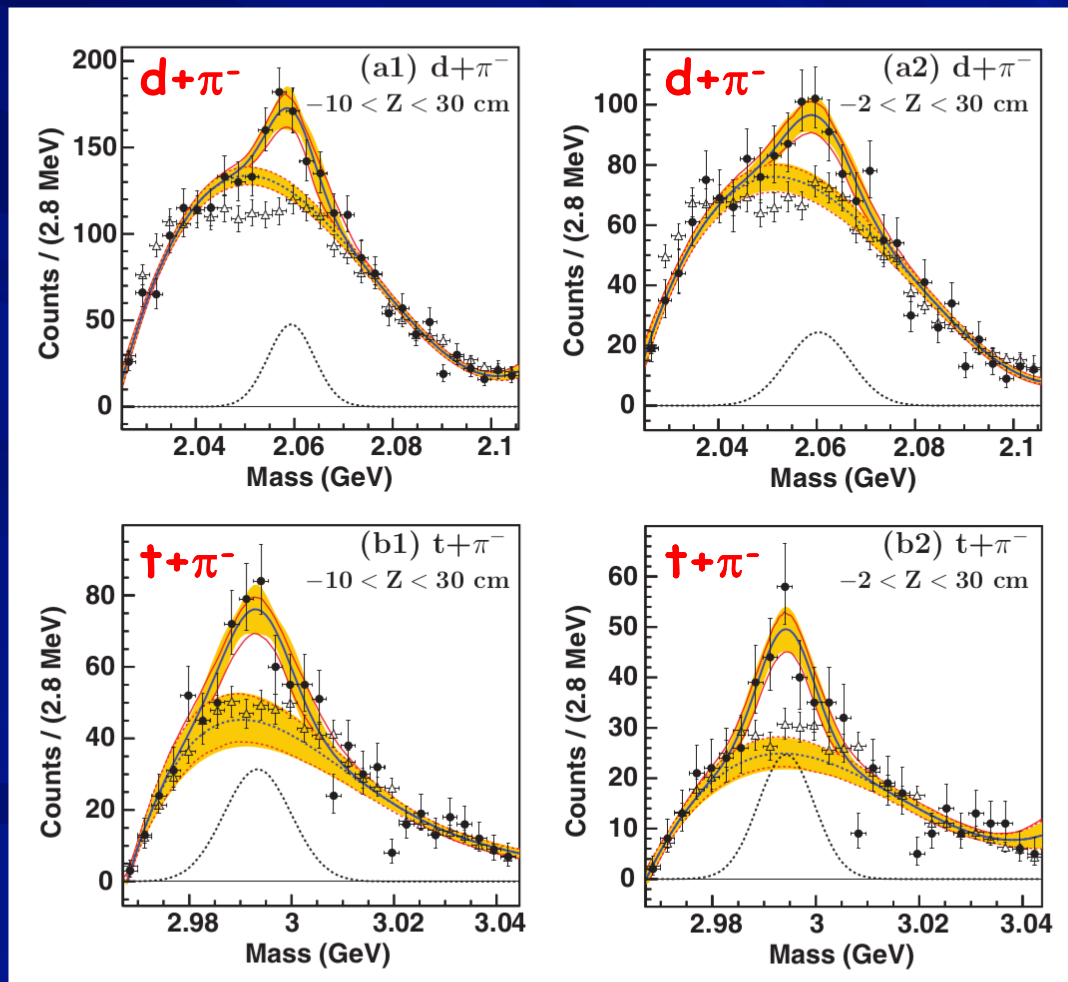


No theories to explain the short lifetime of $^{3}_{\Lambda}H$

d+π⁻ and t+π⁻ : Invariant mass

RAPID COMMUNICATIONS

C. RAPPOLD *et al.* PHYSICAL REVIEW C **88**, 041001(R) (2013)



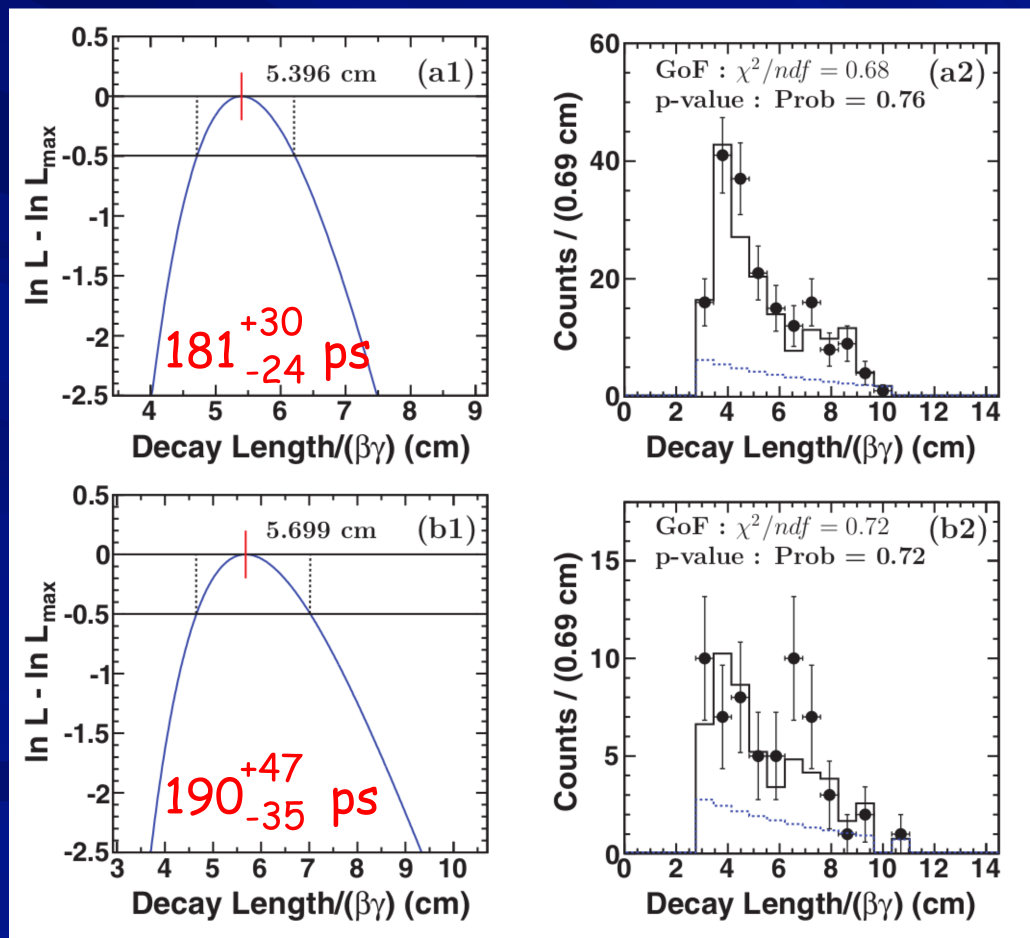
$d+\pi^-$ and $t+\pi^-$: Lifetime

RAPID COMMUNICATIONS

SEARCH FOR EVIDENCE OF $^3_\Lambda n$ BY . . . PHYSICAL REVIEW C **88**, 041001(R) (2013)

$d+\pi^-$

$t+\pi^-$



$d+\pi^-$ and $t+\pi^-$:Signals from others

RAPID COMMUNICATIONS

SEARCH FOR EVIDENCE OF $^{3}_{\Lambda}n$ BY . . . PHYSICAL REVIEW C **88**, 041001(R) (2013)

Decay channel	Counts
$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{p}+\mathrm{d}+\pi^-$	8 to $\mathrm{d}+\pi^-$
$^{4}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d}+\mathrm{d}+\pi^-$	1 to $\mathrm{d}+\pi^-$
$^{4}_{\Lambda}\mathrm{H} \rightarrow \mathrm{t}+\mathrm{p}+\pi^-$	6 to $\mathrm{t}+\pi^-$
$^{6}_{\Lambda}\mathrm{He} \rightarrow {}^{4}\mathrm{He}+\mathrm{d}+\pi^-$	15 to $\mathrm{d}+\pi^-$
$^{4}_{\Lambda}\mathrm{He} \rightarrow \mathrm{p}+\mathrm{p}+\mathrm{d}+\pi^-$	8 to $\mathrm{d}+\pi^-$
$^{5}_{\Lambda}\mathrm{He} \rightarrow \mathrm{d}+{}^{3}\mathrm{He}+\pi^-$	14 to $\mathrm{d}+\pi^-$

Observed $d+\pi^-$: 202
Observed $t+\pi^-$: 181

Neutral nucleus with Λ, nnΛ ??

$^{3}_{\Lambda}n \rightarrow t + \pi^-$
$^{3}_{\Lambda}n \rightarrow t^* + \pi^- \rightarrow n + d + \pi^-$

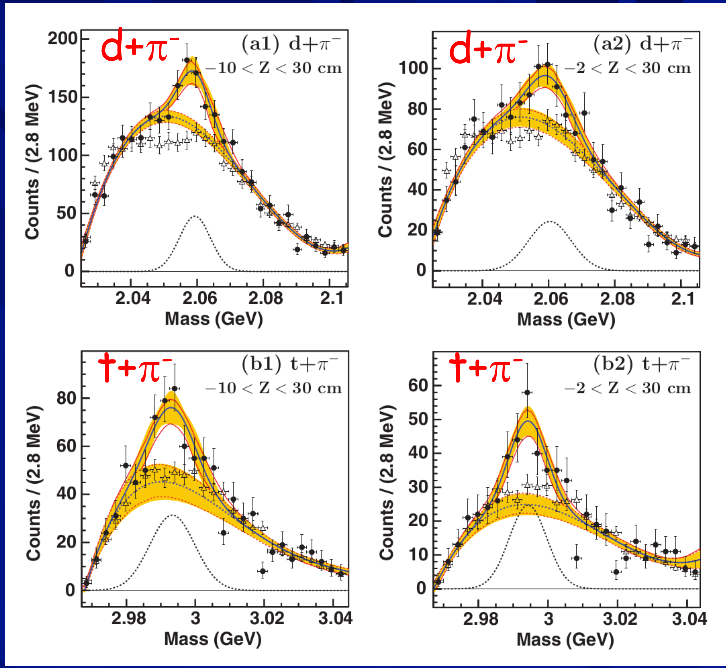
?

Solving two puzzles

Signals indicating nnΛ bound state

All theoretical calculations are negative

- E. Hiyama et al., Phys. Rev. C89 (2014) 061302(R)
- A. Gal et al., Phys. Lett. B736 (2014) 93
- H. Garcilazo et al., Phys. Rev. C89 (2014) 057001



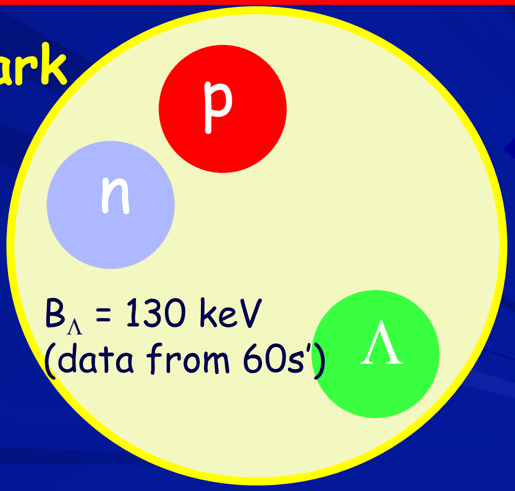
C. Rappold et al., PRC 88 (2013) 041001

Short lifetime of $^{3}_{\Lambda}H$

- HypHI Phase 0: 183^{+42}_{-32} ps
- STAR at RHIC: ~~155^{+25}_{-22} ps~~ **142^{+24}_{-21}**
- ALICE at LHC: ~~181^{+54}_{-39} ps~~ **237^{+33}_{-36}**

No theories to reproduce the short lifetime

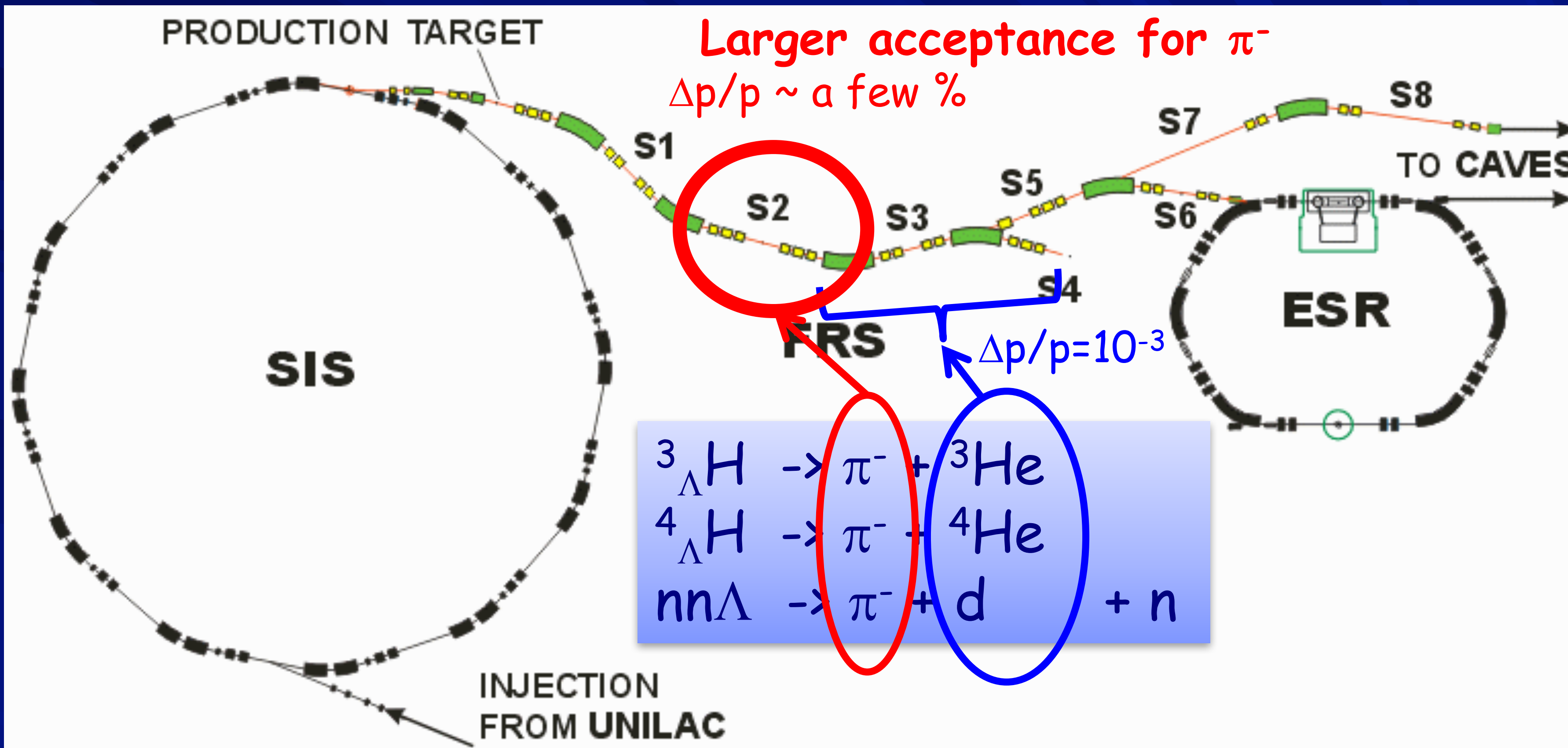
Benchmark



$\tau(^{3}_{\Lambda}H)$ should be equal to $\tau(\Lambda$, 263 ps)

New novel technique with FRS at FAIR Phase 0 (GSI)

Accelerator complex and FRS at GSI

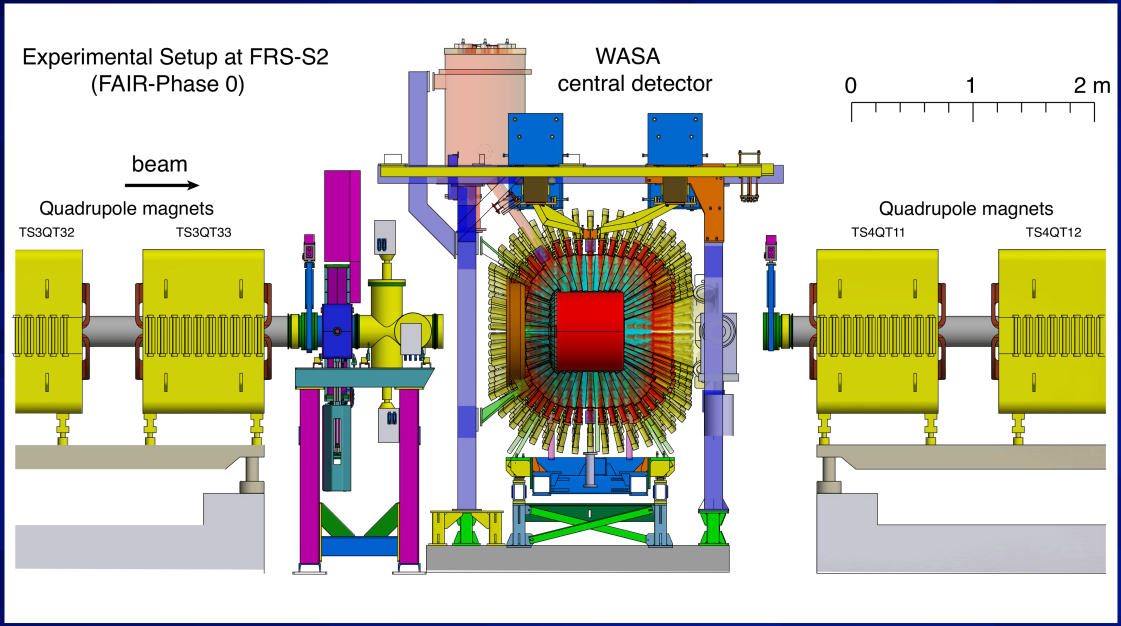


$^{3}_{\Lambda}H \rightarrow \pi^- + {}^{3}He$

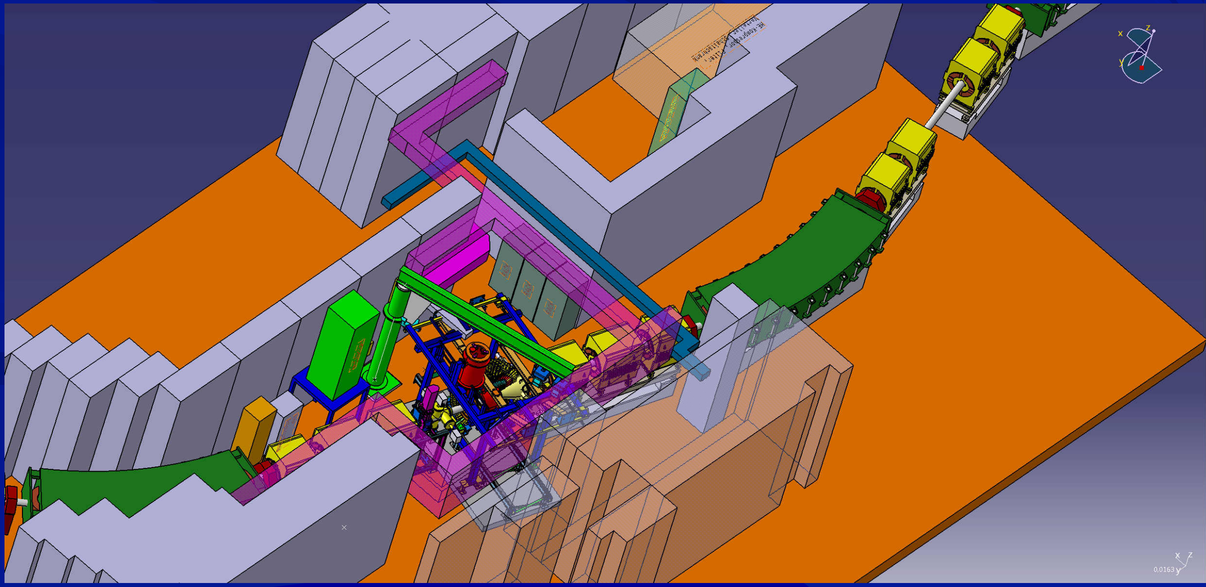
$^{4}_{\Lambda}H \rightarrow \pi^- + {}^{4}He$

$nn\Lambda \rightarrow \pi^- + d + n$

WASA to S2 of FRS at GSI



Experiment planed in 2019



Rate estimation and Simulated invariant mass distribution

Table 2: Summary of the channels of interest, magnetic rigidity setup of FRS, requested shifts for each setup and corresponding expected signal integrals after the event reconstructions.

Channel of interest	FRS rigidity [Tm]	Duration of beams on target	Estimated signal integral
$d+\pi^-$	16.675	24 shifts (8 days)	4.0×10^3
${}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He}+\pi^-$	12.623	9 shifts (3 days)	1.5×10^3
${}^{4}_{\Lambda}\mathrm{H} \to {}^{4}\mathrm{He}+\pi^-$	16.675	together with $d+\pi^-$	5.0×10^3

10 ~ 40 times more

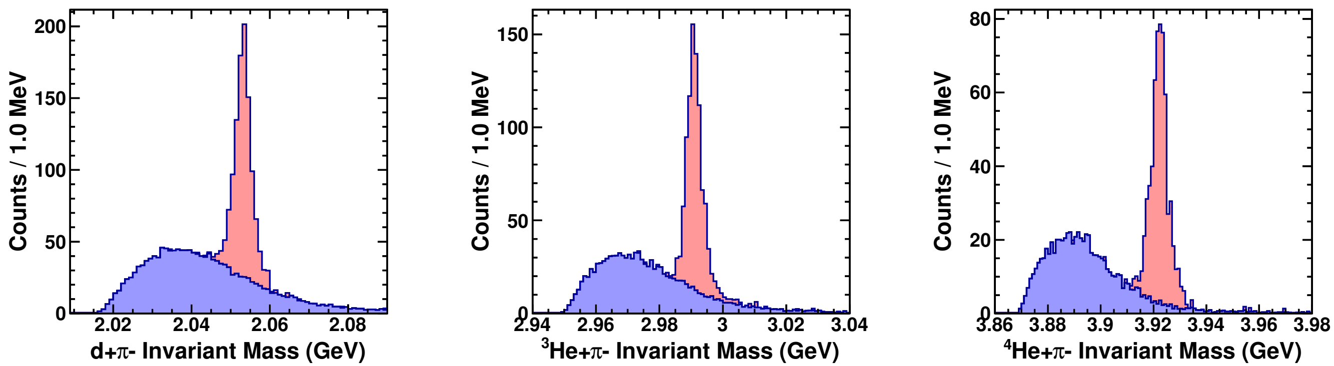


Figure 8: Expected invariant mass distributions of d+π^- from ${}^{3}_{\Lambda}$n, 3He+π^- from ${}^{3}_{\Lambda}$H and 4He+π^- from ${}^{4}_{\Lambda}$H, together with signals (red) and backgrounds (blue)

5 times better resolution

Approval by the GSI G-PAC in 2017

FAIR
GSI

FAIR - Facility for Antiproton and Ion Research in Europe GmbH

GSI Helmholtzzentrum für Schwerionenforschung GmbH

Planckstrasse 1
64291 Darmstadt
Germany

FAIR/GSI · Planckstr. 1 · 64291 Darmstadt · Germany

Takehiko Saito

- GSI -

Scientific Managing Director
Professor Dr. Paolo Giubellino
Phone +49-6159-71-2649
P.Giubellino@gsi.de

11.10.2017

S447: "Studies of the d+π^-- signa...
hypernuclei by new spectroscop...

Takehiko Saito et al.

Dear Colleague,

The management of GSI/FAIR would like ... our latest 'Call for Proposals for Beam Ti... Advisory Committee met on Septembe... evaluate a total of 64 proposals requ... considerations of the G-PAC were base... importance of the proposed research, its... the GSI/FAIR facility that are unique. Prop... experiments of category A recommended ... of great scientific interest but due to th... recommended to run only if beam t... Experiments of category B are those tha... proposal to a future call, and for cate... recommended. In total, the G-PAC recom... 311 shifts are at UNILAC, 317 shifts at S... CRYRING. Shifts granted as experiments category A in this Call will be scheduled between 2018 and 2019 and will expire after that period.

BIC HELA DE FF

For your proposal S447[1] the G-PAC formulated the following evaluation with which I concur:

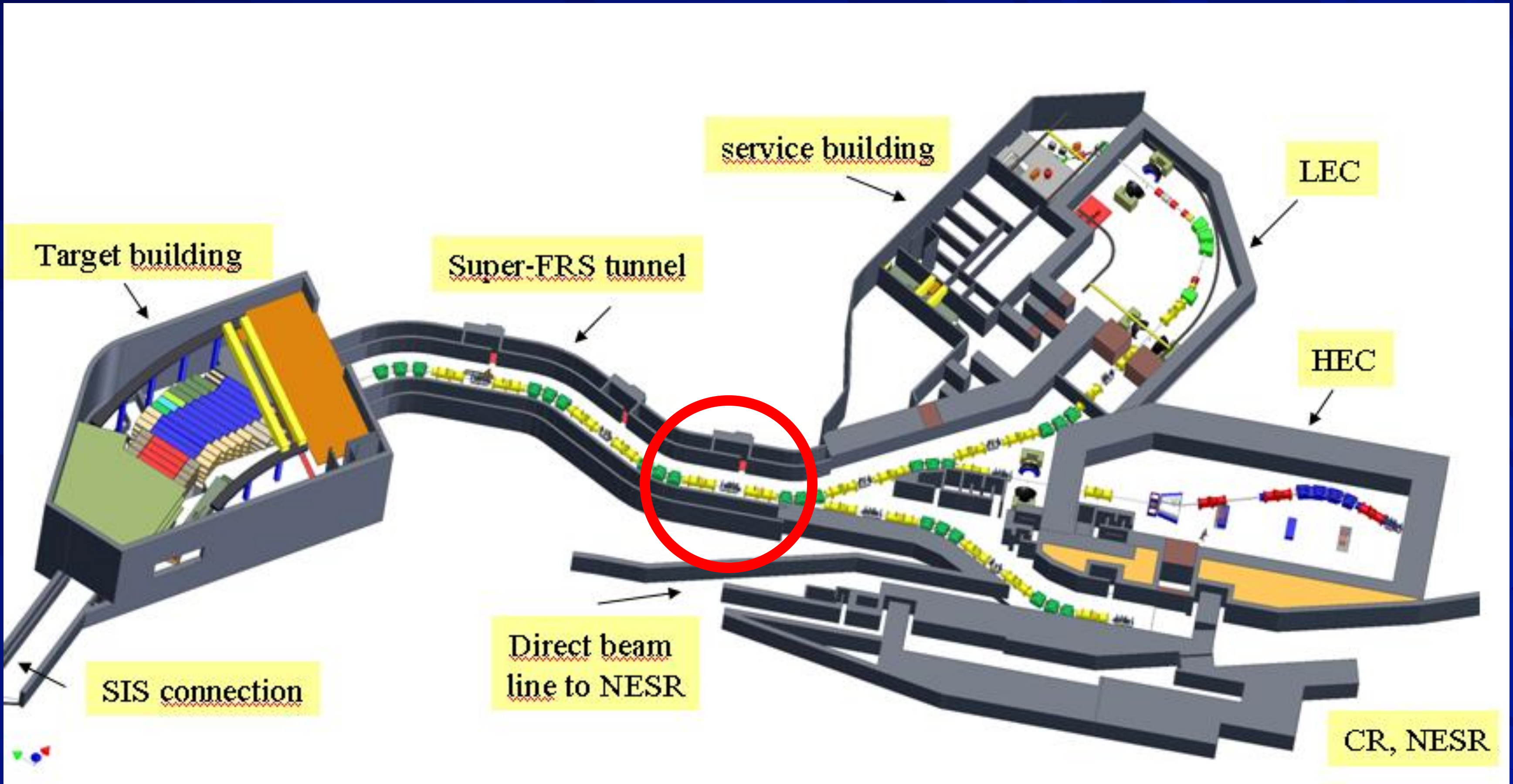
Regarding the proposal "Studies of the d+π^- signal and lifetime of the ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H hypernuclei by new spectroscopy techniques with FRS" (Proposal S447), the G-PAC recommends this proposal with ***highest priority (A)*** *and that* ***27 shifts of main beam time and 18 shifts of parasitic beam time*** *for WASA commissioning be allocated, including 24 shifts for the study of Λnn and ${}^{4}_{\Lambda}$H. In view of the shortage of beam time and the availability of three independent measurements the study of ${}^{3}_{\Lambda}$H was considered of less importance.*

Regarding the proposal "Studies of the d+π^- signal and lifetime of the ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H hypernuclei by new spectroscopy techniques with FRS" (Proposal S447), the G-PAC recommends this proposal with ***highest priority (A)*** *and that* ***27 shifts of main beam time and 18 shifts of parasitic beam time*** *for WASA commissioning be allocated, including 24 shifts for the study of Λnn and ${}^{4}_{\Lambda}$H. In view of the shortage of beam time and the availability of three independent measurements the study of ${}^{3}_{\Lambda}$H was considered of less importance.*

In 2019

FAIR in Germany

Super-FRS at FAIR



Precise hypernuclear spectroscopy with RI-beams

We can still go further


Huizhou
China
INNER MONGOLIA
JILIN
LIAONING
North Korea
Pyongyang
평양
Seoul
서울
South Korea
Busan
부산
Fukuoka
福岡
Yellow Sea
East China Sea
Beijing
北京
Tianjin
天津
HEBEI
SHANXI
SHANDONG
GANSU
NINGXIA
SHAANXI
QINGHAI
Xi An
西安
HENAN
JIANGSU
Shanghai
上海
ANHUI
Hangzhou
杭州
ZHEJIANG
HUBEI
Chengdu
成都
SICHUAN
Chongqing
重庆
TIBET
ARUNACHAL PRADESH
SIKKIM
Bhutan
ASSAM
NAGALAND
MEGHALAYA
BIHAR
MANIPUR
Bangladesh
TRIPURA
WEST BENGAL
MIZORAM
GUIZHOU
HUNAN
JIANGXI
FUJIAN
Taipei
臺北市
Taiwan
Kaohsiung City
YUNNAN
GUANGXI
GUANGDONG
Hong Kong
Myanmar (Burma)
Naypyitaw
နေပြည်တော်
Chiang Mai
เทศบาลนคร
เชียงใหม่
Laos
Hanoi
HAINAN
Paracel

HIAF in Huizhou/China

High Intensity Heavy Ion Accelerator Facility

View of the HIAF campus

New Hypernuclear Project
Spokesperson: Take Saito

@ 2023

Approved by Chinese government in December 2015
Under construction

Courtesy of Xinwen Ma

HIAF

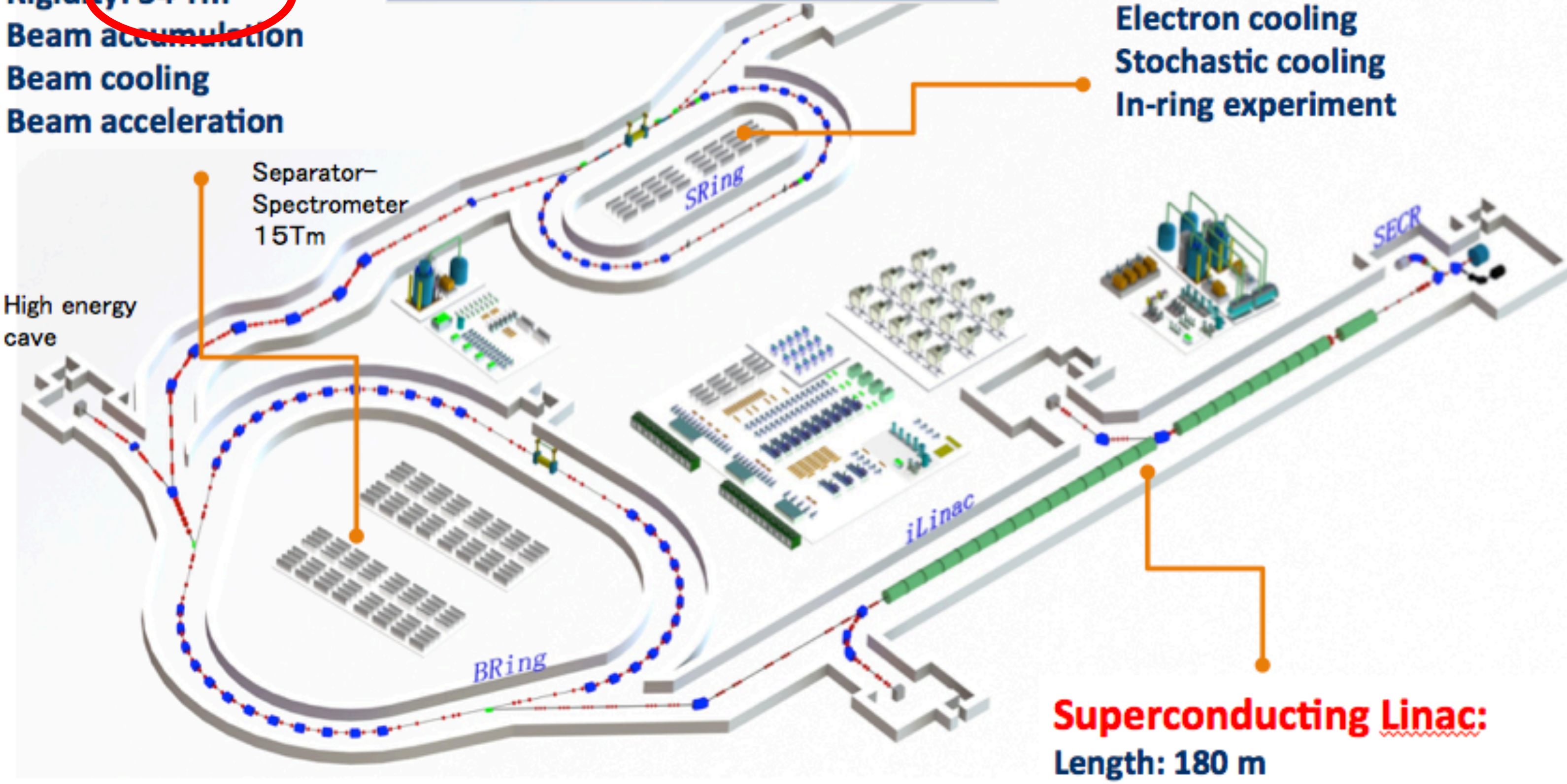
Configuration of the Facility

	Ions	Energy	Intensity
BRing	U^{34+}	0.8 GeV/u	~1.0×10^{11} ppp

4.25 A GeV for A/q=2

Booster Ring:
Circumference: 471
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration

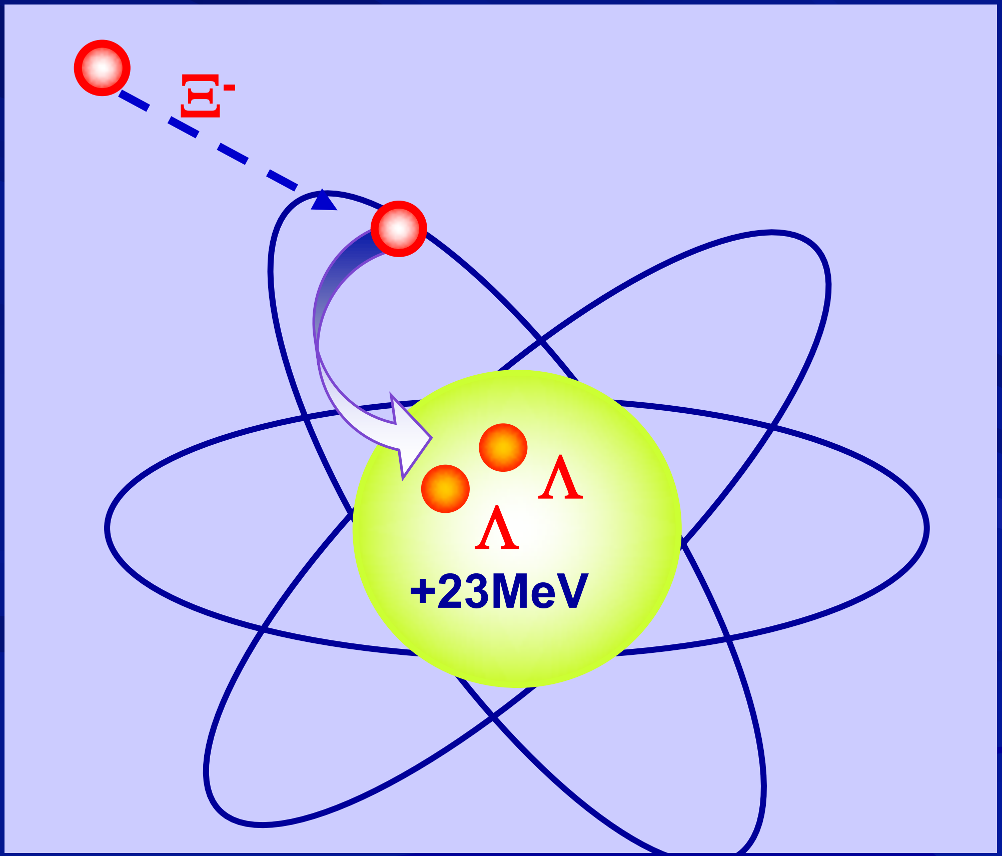
Spectrometer Ring:
Circumference:188.7 m
Rigidity: 13T m
Electron cooling
Stochastic cooling
In-ring experiment



Superconducting Linac:
Length: 180 m
Energy: 17 MeV/u (U^{34+})
CW and pulse modes

Hypernuclei with double-strangeness

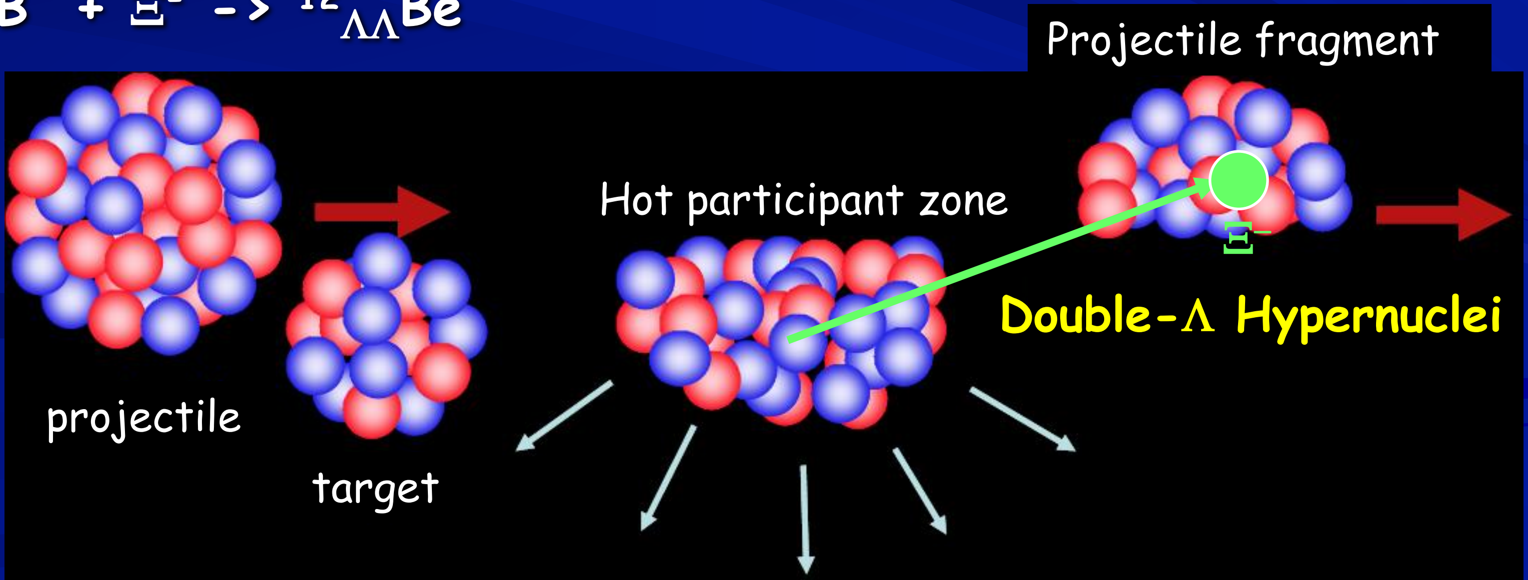
- Heavy ion beams at 4.25 A GeV
- Above threshold of Ξ^- hyperon (dss) production: 3.747 A GeV
- $\Xi^- p \rightarrow \Lambda\Lambda$



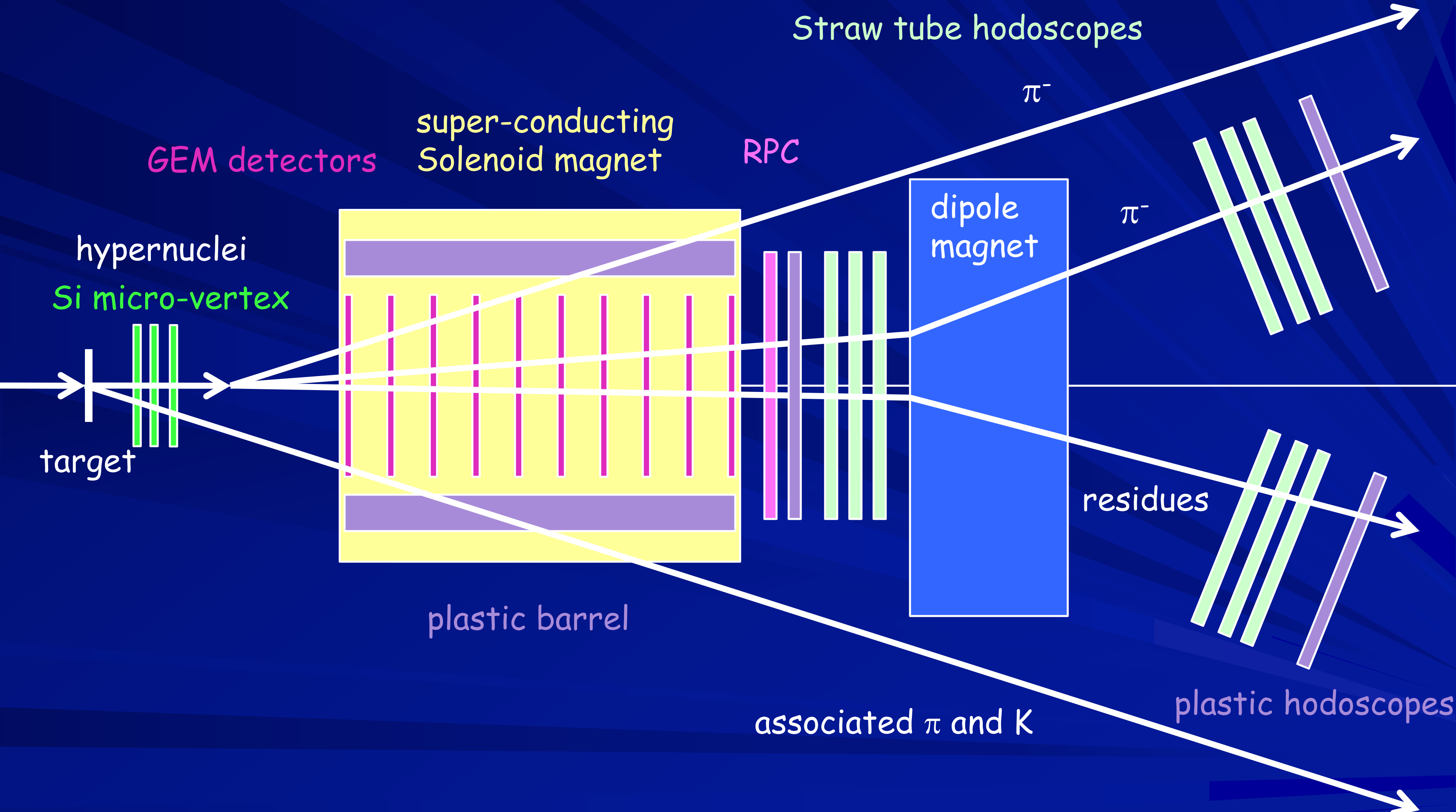
Production of double-Λ hypernuclei

- d + Ξ^- -> $n\Lambda\Lambda$
- t + Ξ^- -> $nn\Lambda\Lambda$
- ^3He + Ξ^- -> $^4_{\Lambda\Lambda}H$
- ^4He + Ξ^- -> $^5_{\Lambda\Lambda}H$
- ^6Li + Ξ^- -> $^7_{\Lambda\Lambda}He$
- ^7Li + Ξ^- -> $^8_{\Lambda\Lambda}He$
- ^9Be + Ξ^- -> $^{10}_{\Lambda\Lambda}Li$
- ^{10}Be + Ξ^- -> $^{11}_{\Lambda\Lambda}Li$
- ^{10}B + Ξ^- -> $^{11}_{\Lambda\Lambda}Be$
- ^{11}B + Ξ^- -> $^{12}_{\Lambda\Lambda}Be$

Examples with only up to Boron fragments

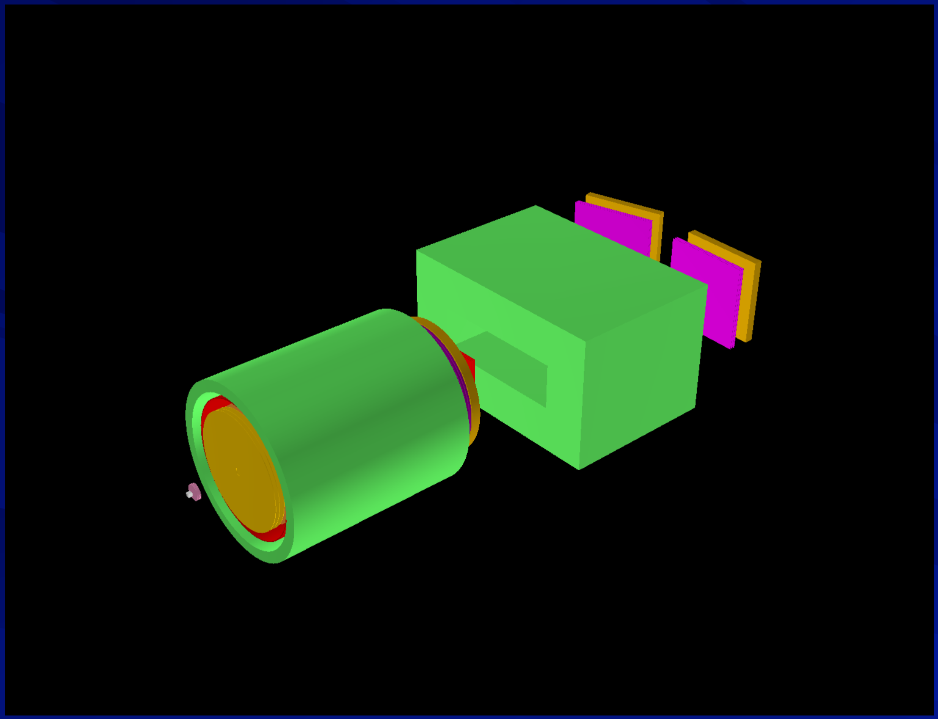


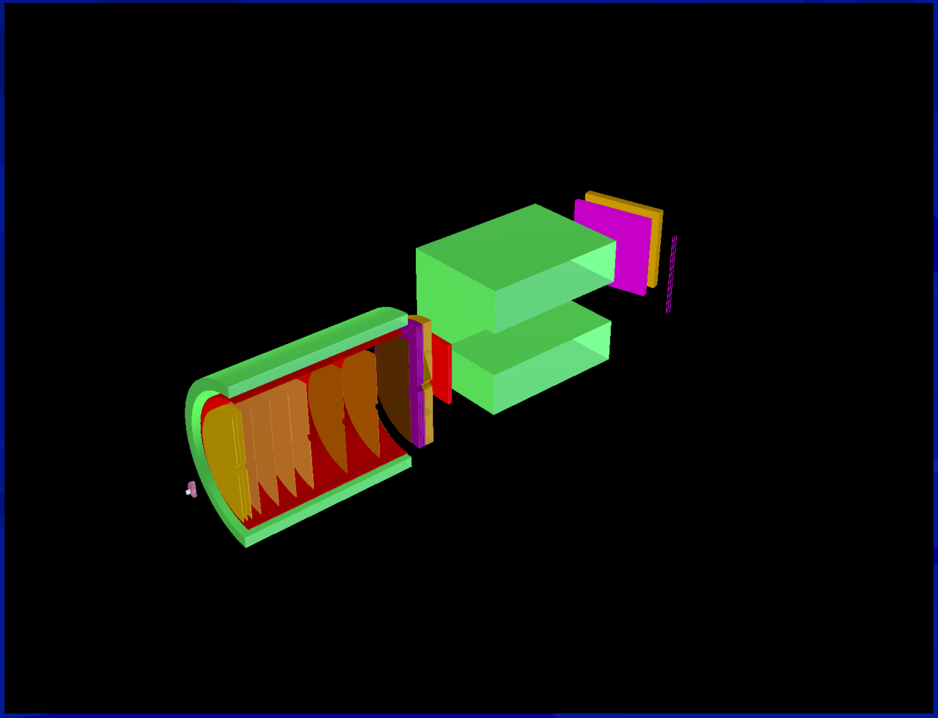
Current considerations for HIAF



< 10 M Euro

Current considerations for HIAF





Expected reconstructed rate

- $^{20}Ne + ^{12}C$ at 4.25 A GeV
- Beam intensity: 10^7 /s

- Small Beam intensity
- Independent to other complexes

Day-1 experiment at HIAF

	Single-Λ (Σ) hypernuclei	Double-Λ hypernuclei
per day	8×10^5	9×10^1
per week	6×10^6	6×10^2
per month	2×10^7	3×10^3

Hypernuclear scattering experiments with
- Polarized target(H, HD) + TPC
- Polarized projectiles

$^3_\Lambda H + p \rightarrow {}^3_\Lambda H' + p'$
$^3_\Lambda H + p \rightarrow \Lambda d + p'$
$^3_\Lambda H + p \rightarrow \Lambda pn + p'$

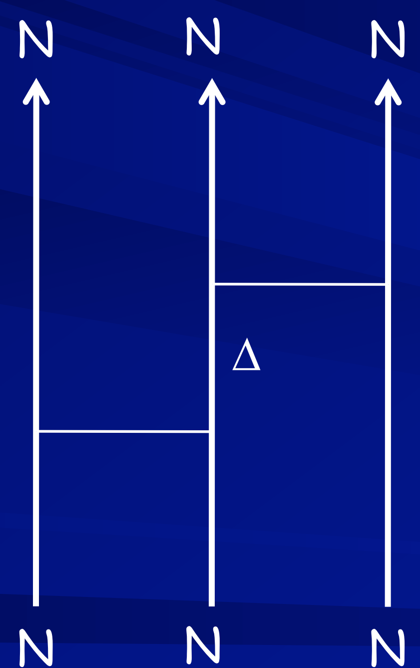
Three-body force in hypernuclei

$m_\Sigma - m_\Lambda$: 75 MeV

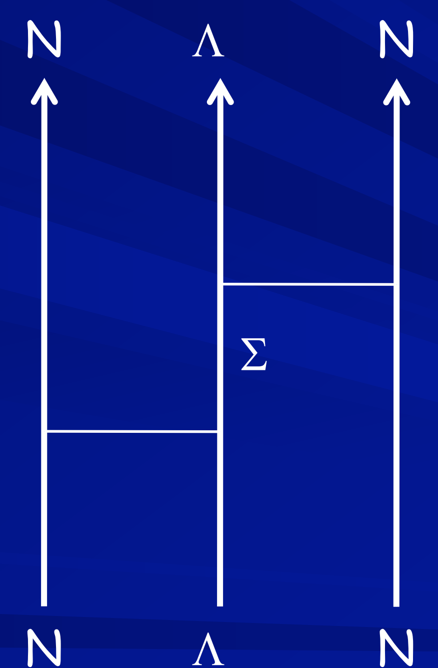
- Large amplitude for ΛN-ΣN coupling

$m_{\Xi N} - m_{\Lambda\Lambda}$: 28 MeV

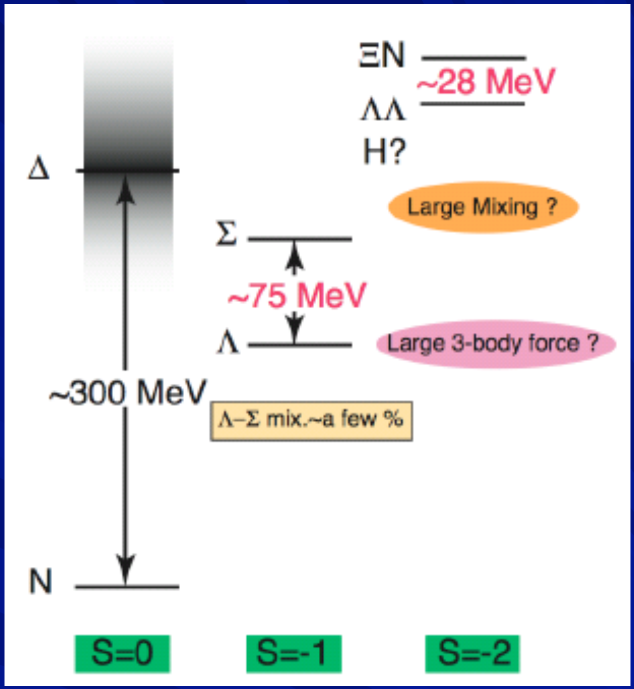
- Large amplitude for ΛΛN-ΞΣN coupling



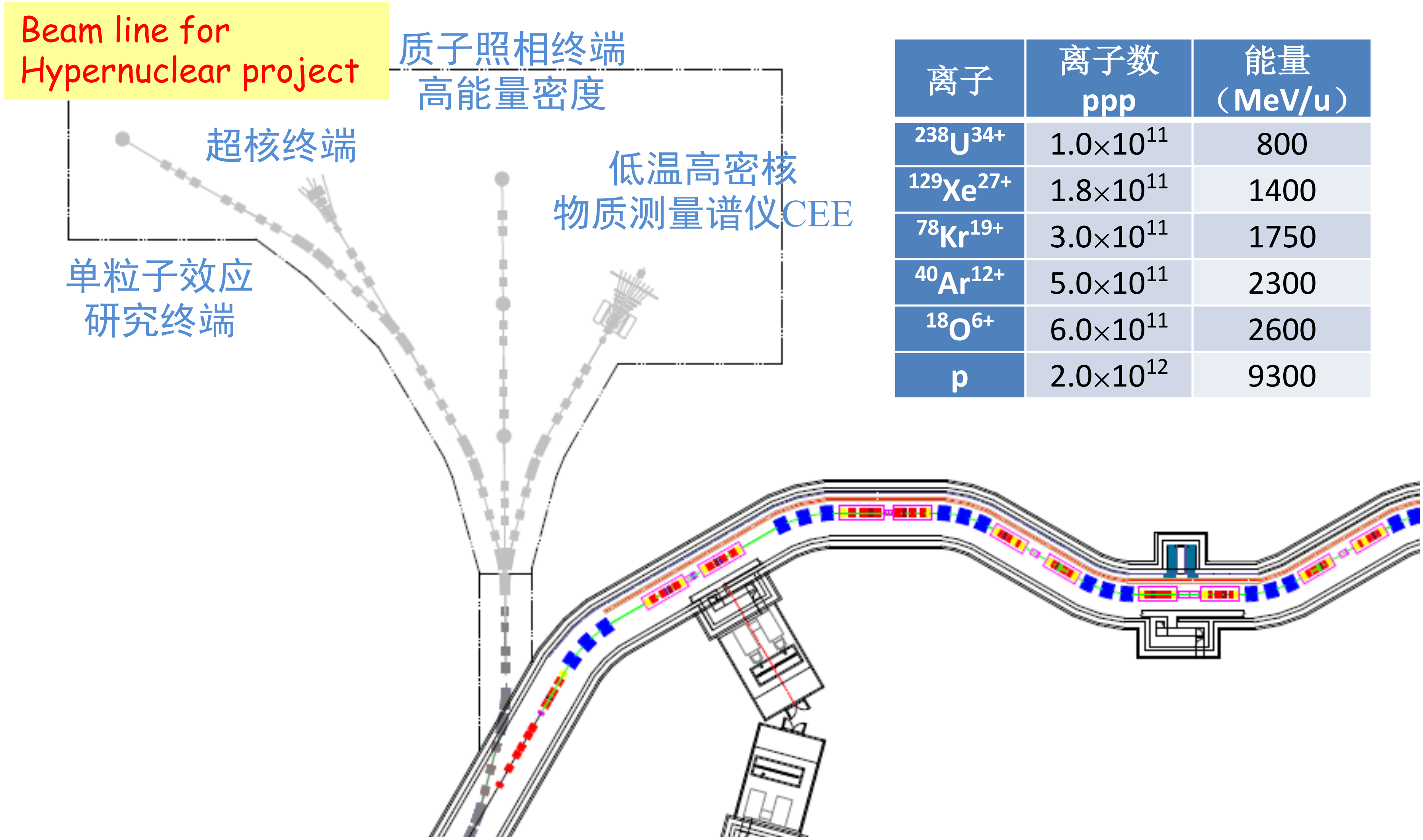
Ordinary nuclei
Suppressed



Hypernuclei nuclei
Large amplitude

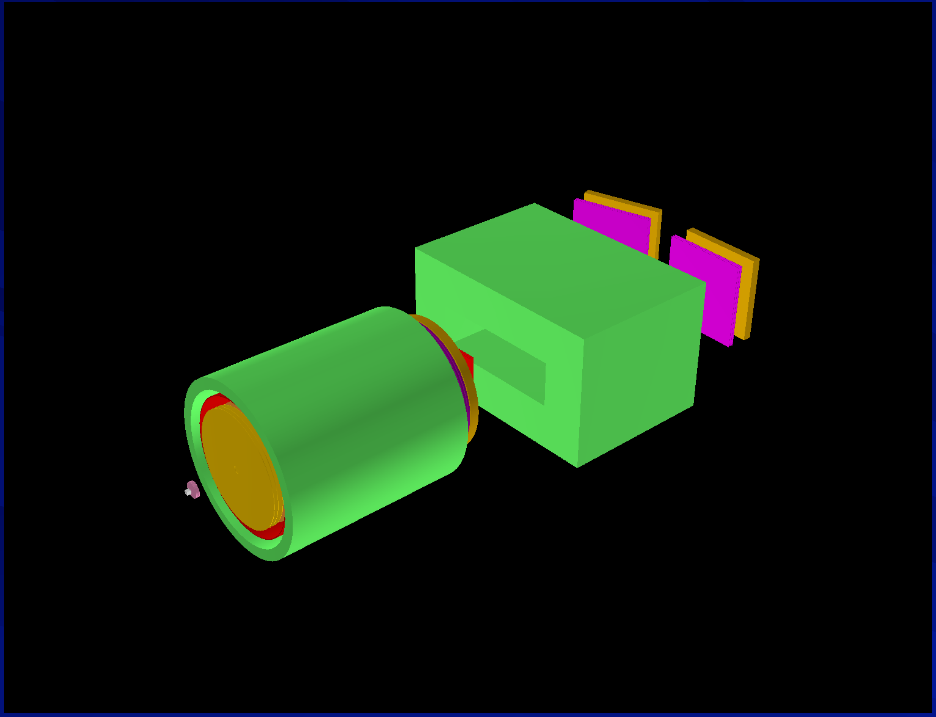


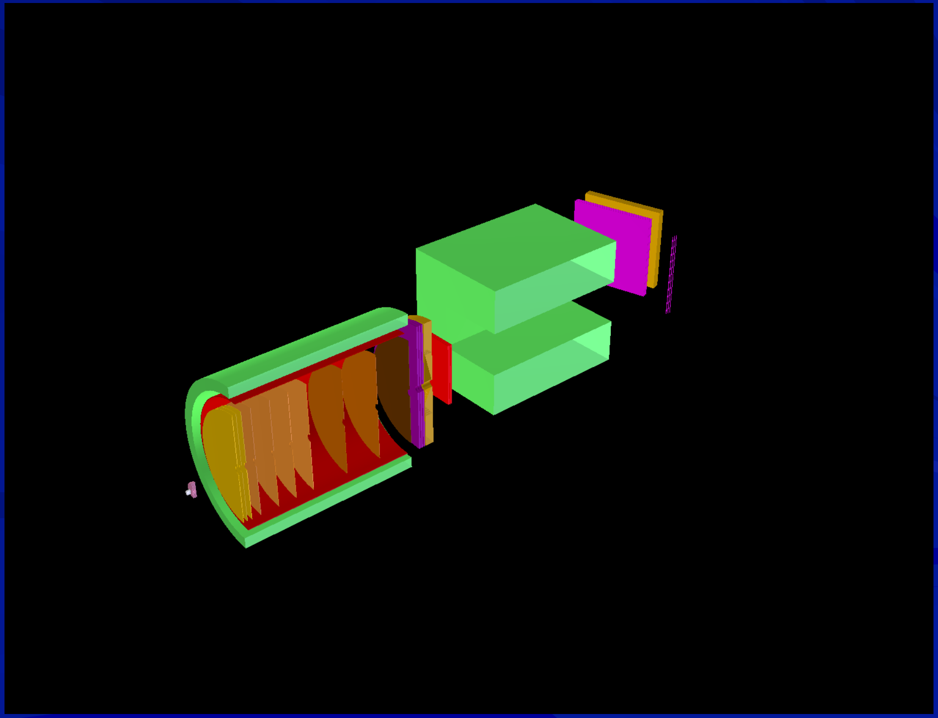
终端-- 高能综合终端



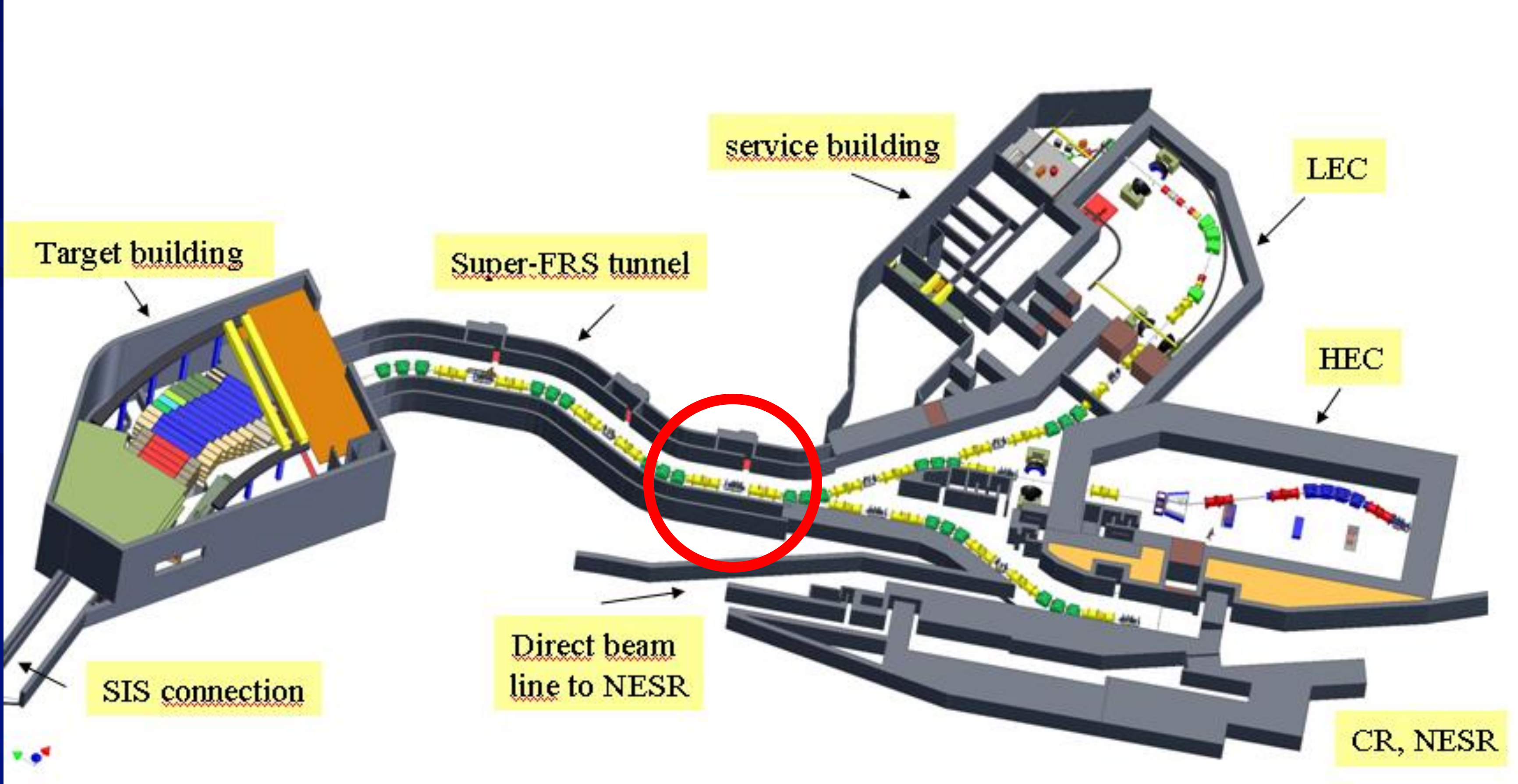
离子	离子数 ppp	能量（MeV/u）
$^{238}U^{34+}$	1.0×10^{11}	800
$^{129}Xe^{27+}$	1.8×10^{11}	1400
$^{78}Kr^{19+}$	3.0×10^{11}	1750
$^{40}Ar^{12+}$	5.0×10^{11}	2300
$^{18}O^{6+}$	6.0×10^{11}	2600
p	2.0×10^{12}	9300

Current considerations for HIAF





Super-FRS at FAIR



Precise hypernuclear spectroscopy with RI-beams

Hypernuclear Physics with Heavy Ion Beams

- Nuclear structure
- Nuclear reaction
- EOS
- Hadronic interactions under $SU(3)_f$
- Interior of neutron stars

If you are interested in, please contact

Take Saito
t.saito@gsi.de

HypHI Phase 0 and 0.5 collaboration

- **GSI Helmholtz-University Young Investigators Group VH-NG-239**
  - S. Bianchin
  - O. Borodina (Mainz Univ.)
  - V. Bozkurt (Nigde Univ.)
  - E. Kim (Seoul Nat. Univ.)
  - D. Nakajima (Tokyo Univ.)
  - B. Özel-Tashnov
  - C. Rappold (Strasbourg Univ.)
  - K. Yoshida (Osaka Univ.)
  - T.R. Saito (Spokes person)
- **Mainz University**
  - P. Achenbach, J. Pochodzalla
- **GSI HP2 and Mainz University**
  - D. Khaneft, Y. Ma, F. Maas
- **GSI HP1**
  - W. Trautmann
- **GSI EE department**
  - J. Hoffmann, K. Koch, N. Kurz, S. Minami, W. Ott, S. Voltz
- **GSI Nuclear reaction**
  - T. Aumann, C. Caeser, H. Simon
- **GSI Detector Lab.**
  - C. Schmidt
- **KEK**
  - T. Takahashi, Y. Sekimoto
- **KVI**
  - E. Guliev, M. Kavatsyuk, G.J. Tambave
- **Nigde University**
  - B. Goekuezuem, Z.S. Ketenci, S. Erturk
- **Osaka University**
  - S. Ajimura, A. Sakaguchi
- **Osaka Electro-Communication University**
  - T. Fukuda, Y. Mizoi
- **Seoul National University**
  - H. Bhang, M. Kim, S. Kim, C.J. Yoon
- **Tohoku University**
  - H. Tamura

Take Saito
t.saito@gsi.de

PhD thesis completed
PhD thesis in progress

Summary

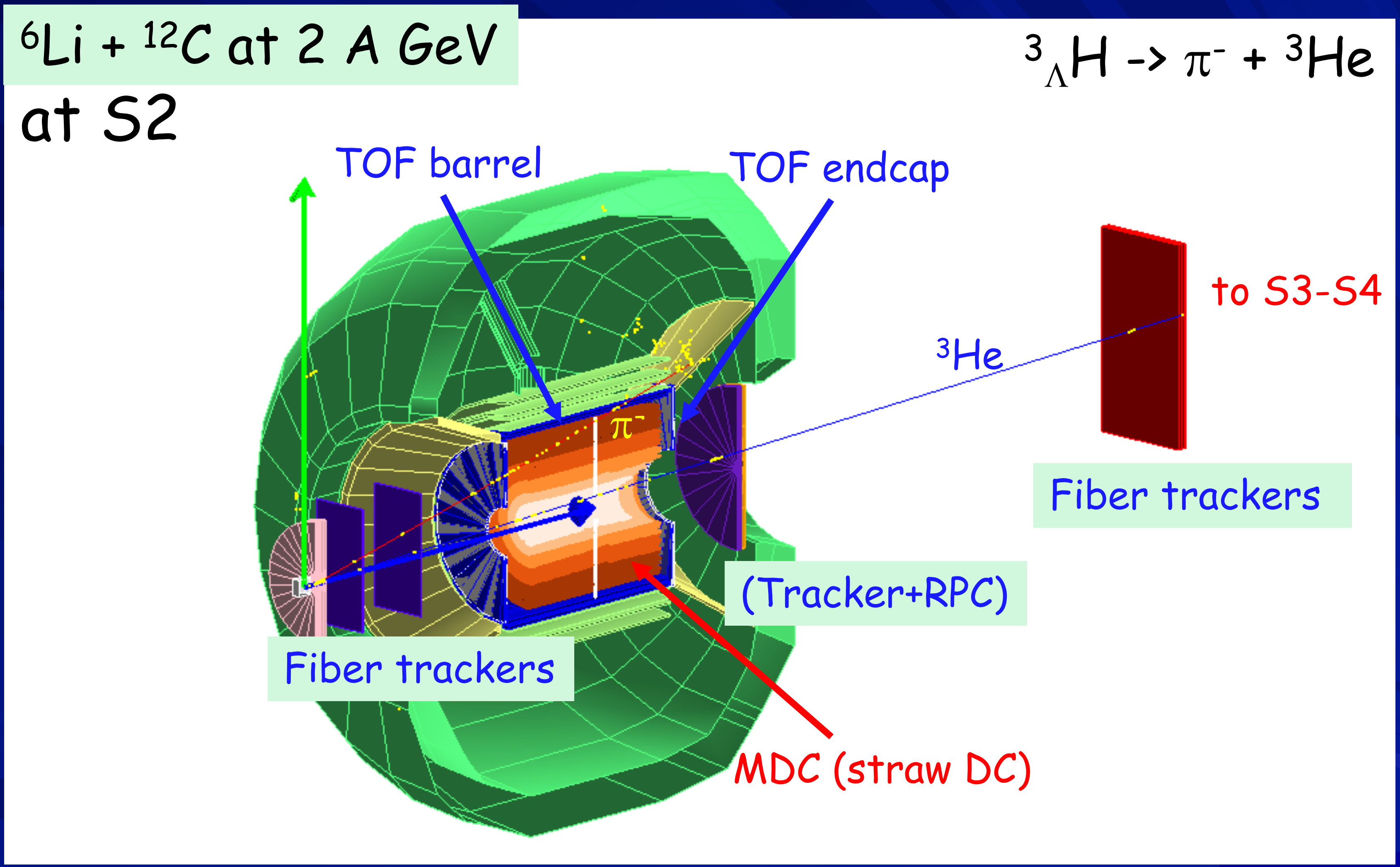
- Hypernuclear spectroscopy with heavy ion beams
- Two puzzles by HypHI Phase 0
  - Signals indicating nnΛ
  - Short hypertriton lifetime

- Near future project with heavy ions
  - FRS + WASA at GSI (FAIR Phase 0) in Germany, 2019
    - nnΛ and hypertriton lifetime
  - Super-FRS at FAIR in Germany, 2023+X
    - Exotic hypernuclei with RI beams
  - HIAF in China
    - Single- and double-strangeness hypernuclei

Take Saito
t.saito@gsi.de

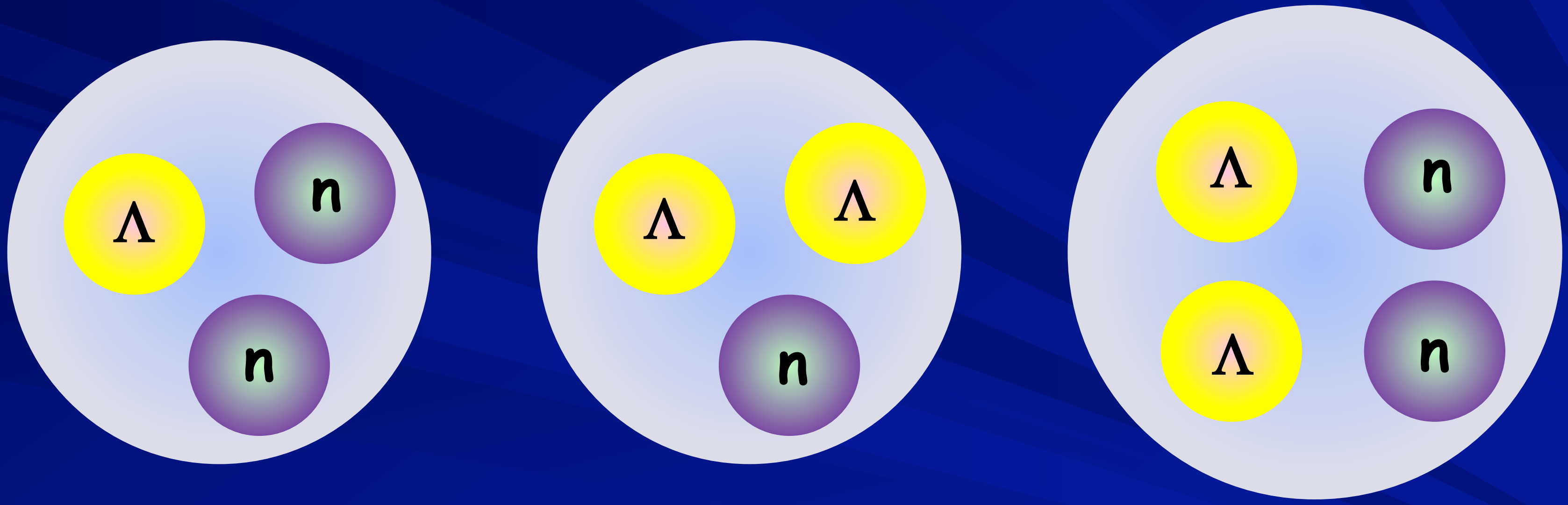
Spare slides

Monte Carlo simulations with WASA at S2 and FRS



GEANT 4, Kalman filter reconstruction and MOCADI,

Femto Neutron Stars???
(named by Josef Pochodzalla)

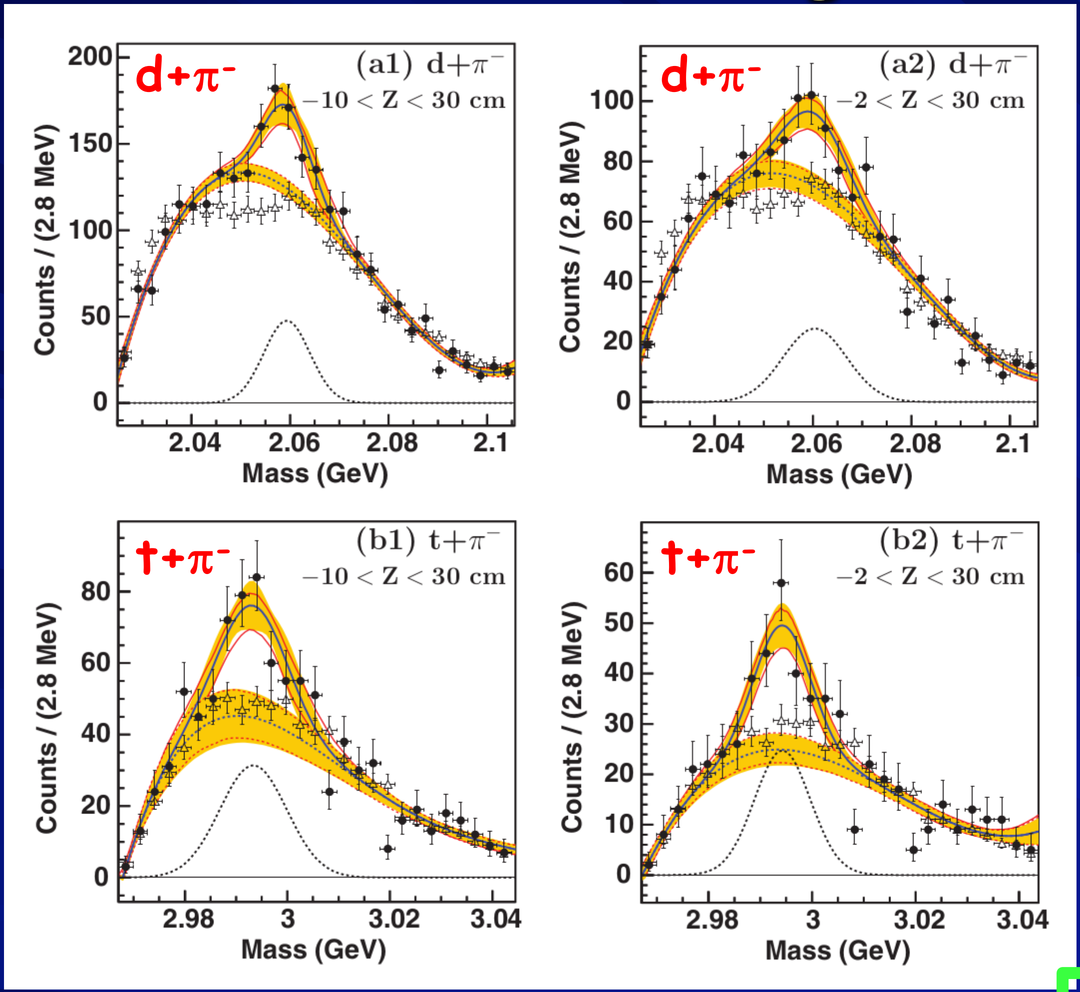


GSI/FAIR
J-Lab
HIAF

HIAF

HIAF

Invariant mass signals of HypHI Phase 0



PRC 88 (2013) 041001(R)

- Poor mass resolution
- Poor S/B ratio
- Signals on top of the bump of the background

Neutral nucleus with Λ, nnΛ ??

$^{3}_{\Lambda}n \rightarrow t + \pi^{-}$

$^{3}_{\Lambda}n \rightarrow t^{*} + \pi^{-} \rightarrow n + d + \pi^{-}$

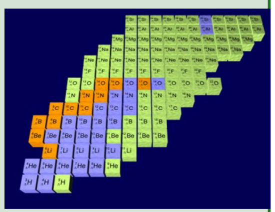
NuPECC Long Range Plan

Hadron physics

Page 65

Box 5: Hypernuclei

Recently, hypernuclear spectroscopy with heavy ion induced reactions has been successfully performed by the HypHI collaboration at GSI. They have shown that the lifetime of the lightest hypernucleus, $^{3}_{\Lambda}$H, is significantly shorter than the Λ-hyperon, also reported by hadron-collider collaborations. A short $^{3}_{\Lambda}$H lifetime has not yet been explained by any theory so far and remains as a puzzle. A signal indicating the existing a neutral strange nucleus, $^{3}_{\Lambda}$n (nnΛ), has been reported, which is still under debate and it requires experimental confirmation. By solving these puzzles with more data on exotic hypernuclei toward nucleon drip-lines, one can deduce essential information on the baryon-baryon interaction under SU(3) including three-body forces. Exotic hypernuclei can only be studied with heavy ions at GSI and FAIR. With these experiments, Europe will play an essential role in nuclear physics with strangeness.



Hypernuclear chart expected to be synthesized and studied at GSI and FAIR. Blue boxes indicate known hypernuclei while orange and green coloured boxes show cases to be populated with 10^4 and 10^3 reconstructed events per week, respectively.

Generalised Parton Distributions (GPDs) and Transverse Spin and Momentum-Dependent Distributions (TMDs)

Our knowledge of nucleon structure has drastically improved in the last few years thanks to the vigorous activity revolving around Generalised Parton Distributions (GPDs) and Transverse

increased the energy of its electron beam from 6 to 12 GeV. Accurate cross-section measurements have shown indications of leading-twist dominance in the accessible kinematic regions. The high precision of the data has stimulated further theoretical analyses to understand the fine details. A variety of beam and target spin asymmetries has been used to constrain models

Nuclear structure and reaction dynamics

continuum degrees of freedom are required.

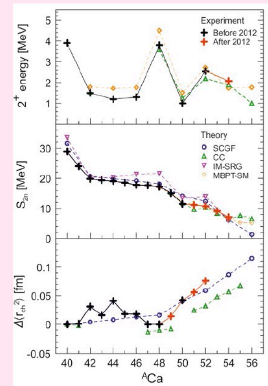
Focused research on constructing improved nuclear EDF that would allow for a precise description of nuclear properties across the nuclear chart, including the spin and isospin channels, restored symmetries, and spectroscopic data is required.

Hypernuclei

Understanding of the nuclear force can be extended to the flavoured-SU(3) symmetry by studying hypernuclei, nuclei with bound hyperon(s) (baryons with strange quarks where Λ (usd) is the lightest). Hyperons in hypernuclei can

Box 3. Structure of Ca isotopes

Standard magic numbers, well established for stable nuclei, fade away in neutron-rich systems where new ones may appear. How do we determine their location? A shell closure cannot be established from a single experimental signature but rather has to emerge from the concurrence of several features, e.g. in energies of the lowest 2+ excited state, two-nucleon separation energies and charge radii isotopic shifts. Hence, different experiments are typically necessary to assess the evolution of magic numbers, as testified by recent studies of neutron-rich calcium isotopes. Penning-trap measurements at TRIUMF and ISOLDE have extended our knowledge of nuclear masses up to ^{54}Ca (central panel) and pointed to the appearance of a new magic number at *N*=32. More recently, charge radii obtained via laser spectroscopy at ISOLDE (lower panel) weakened this conclusion. In parallel, the measurement of the lowest 2+ excited state in ^{54}Ca at RIKEN (upper panel) has opened the same debate on *N*=34. Ab initio calculations (coloured curves) have started to access medium-mass isotopic chains systematically. Comparisons between these calculations and current and future experiments in the region, e.g. up to ^{56}Ca, will help unveil how such magic numbers emerge from underlying complex nucleon dynamics.

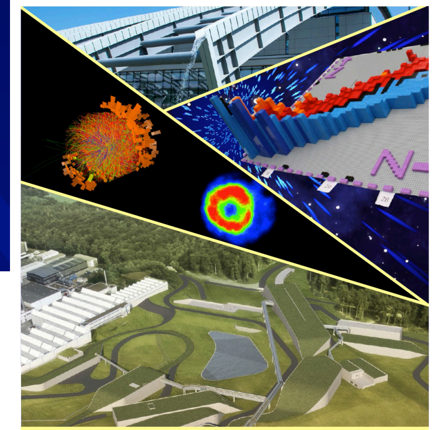


be used as probes of the inside core of nuclei since the hyperon is not subject to the Pauli principle. Hypernuclei close to stability were studied mainly using reactions of meson- and electron-beams. A recent hypernuclei spectroscopic study of $^{3}_{\Lambda}$H is discussed in chapter 1. These studies open a new degree of freedom related to strangeness, which could be combined with exotic nuclei. For instance few-body systems such as 2n+Λ remain to be explained by first principles. These studies are also appealing for future developments.

Testing and constraining three-neutron forces is in turn crucial for neutron-rich nuclei and the equation of state of neutron-rich matter, which is key for understanding and predicting properties of neutron stars. In addition, few-neutron resonances are also considered a milestone calculation in lattice QCD.

Electroweak reactions

Electromagnetic and weak interactions play a crucial role in nuclear physics. On the theoretical

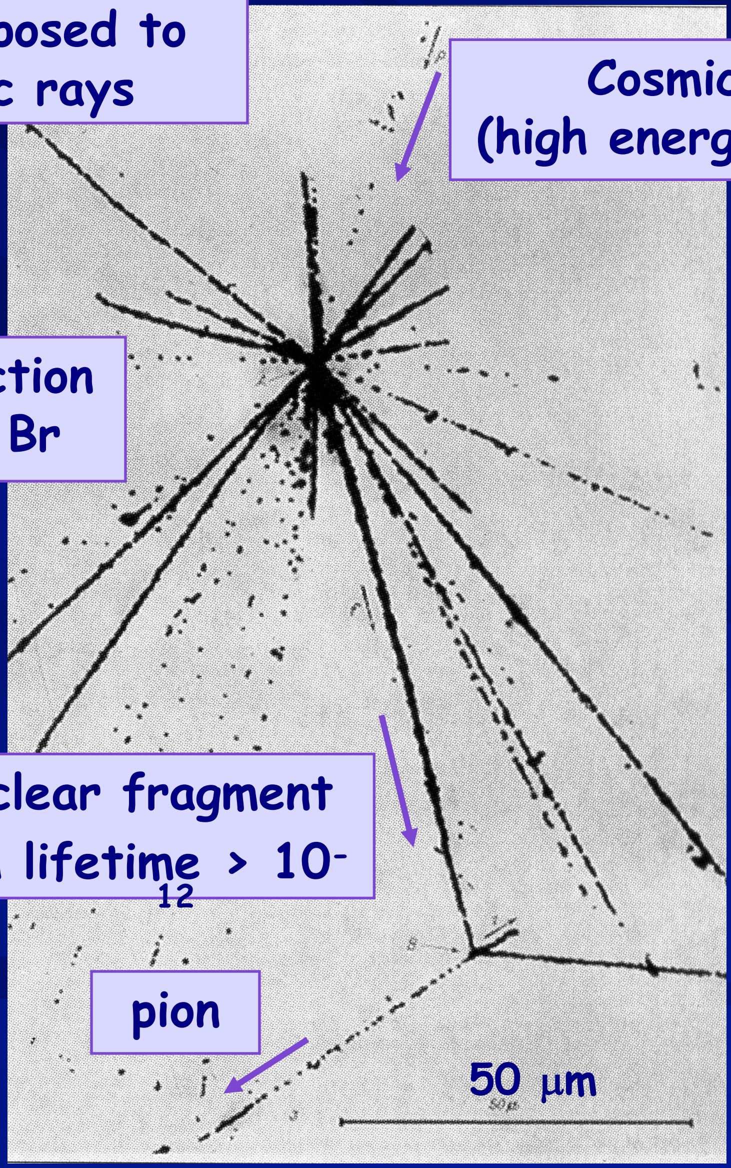


NuPECC Long Range Plan 2017 Perspectives in Nuclear Physics

European Science Foundation

One of day-1 experiments of NuSTAR at FAIR

Hypernuclear physics: How it began



Marian Danysz (left) and Jerzy Pniewski, who first observed a hypernucleus.

"Delayed Disintegration of a Heavy Nuclear Fragment"
M. Danysz and J. Pniewski,
Phil. Mag. 44 (1953) 348.

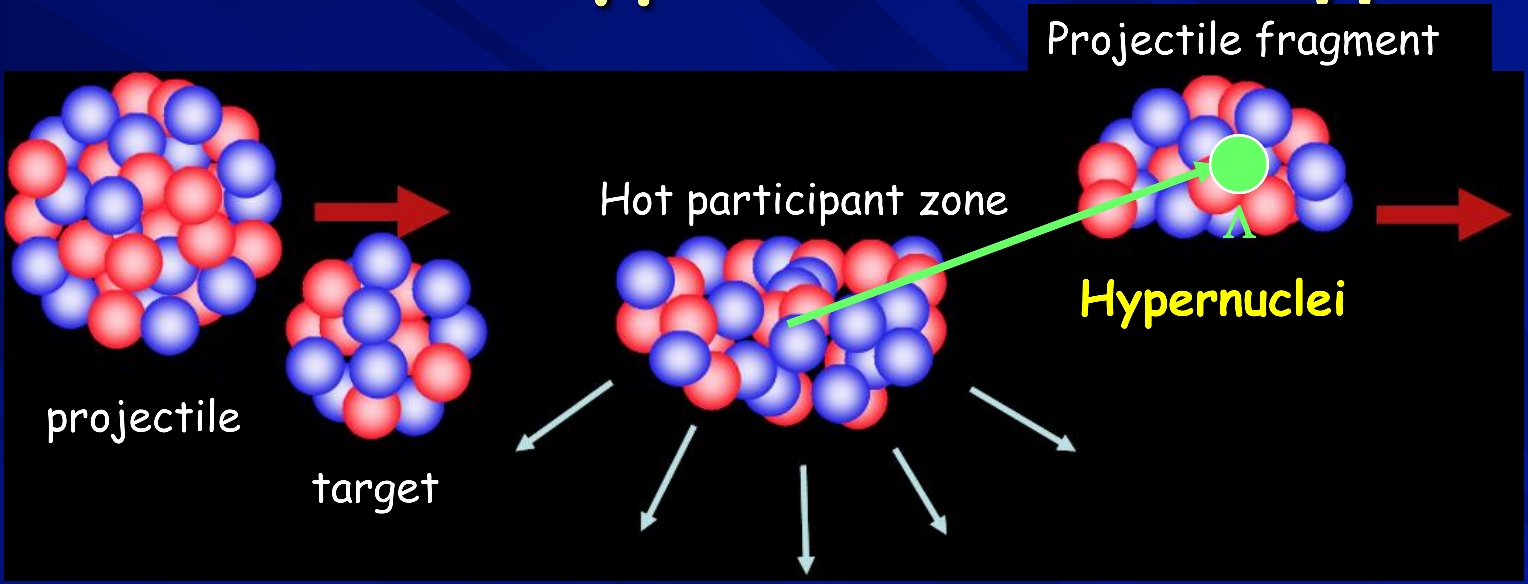
Hypernuclear physics: How it began

- Postmark for 20th International Physics Olympiad in Warsaw, 1989

Hypernuclear physics: How it began

- Postcard issued by Polish office in May 1993

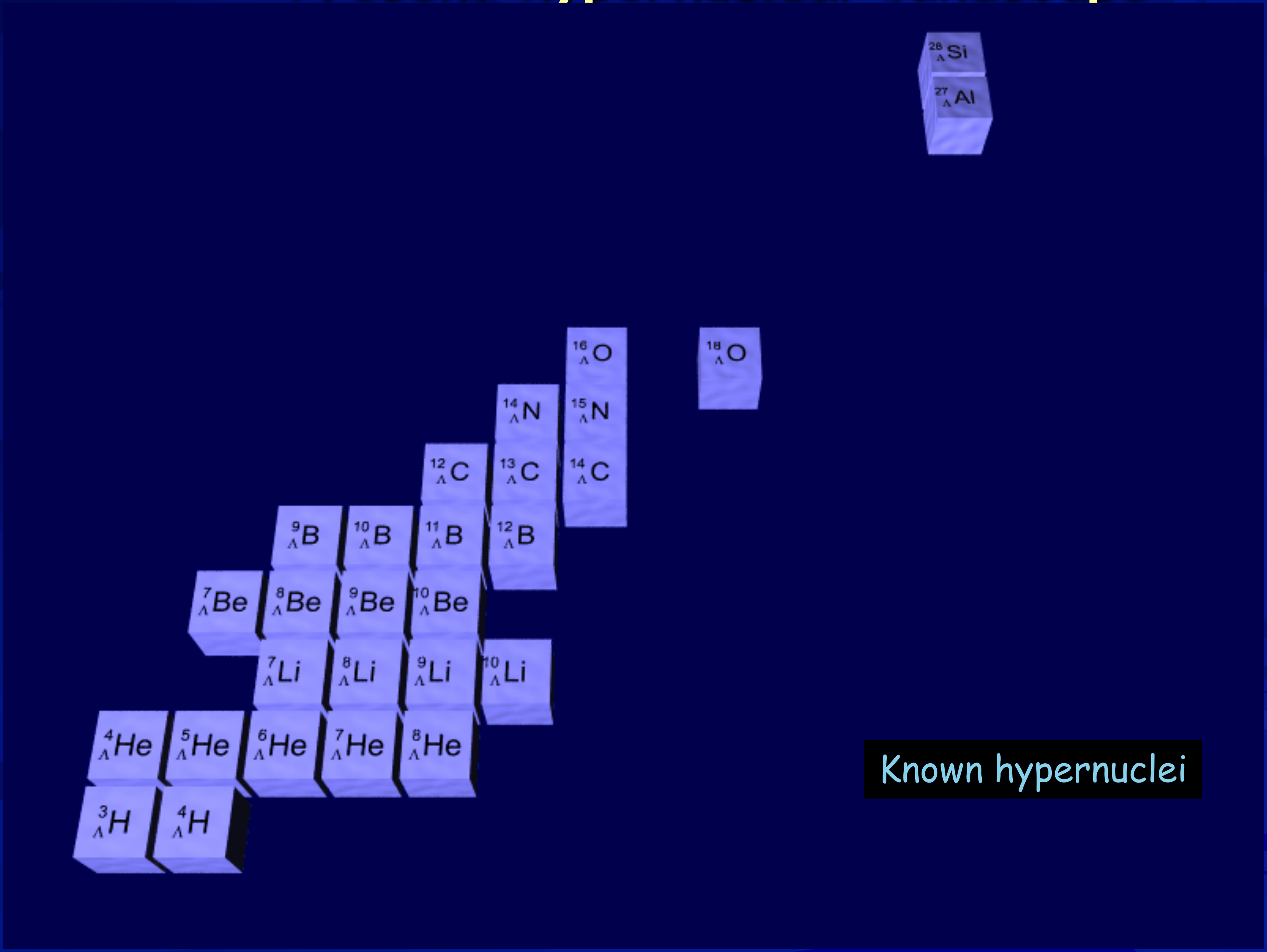
Production of Hypernuclei with HypHI



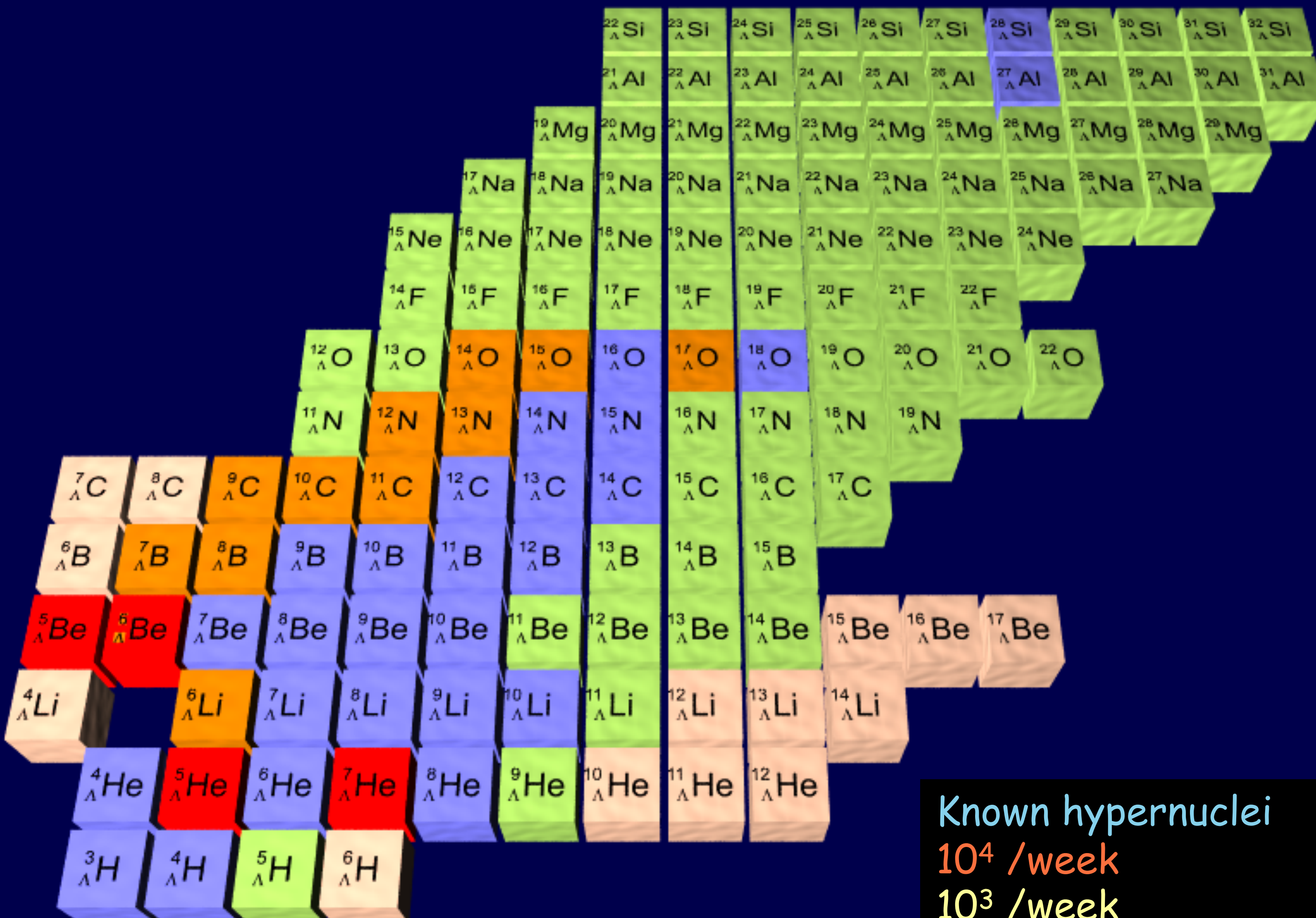
- **Coalescence of Λ in projectile fragments**

Contributing to nuclear reaction studies

Present hypernuclear landscape



Hypernuclear landscape with HypHI



Known hypernuclei
10^4 /week
10^3 /week
With hypernuclear separator
Magnetic moments

HypHI Phase 0 (2009), $^{6}Li+^{12}C$ at 2 A GeV

Example:

$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$