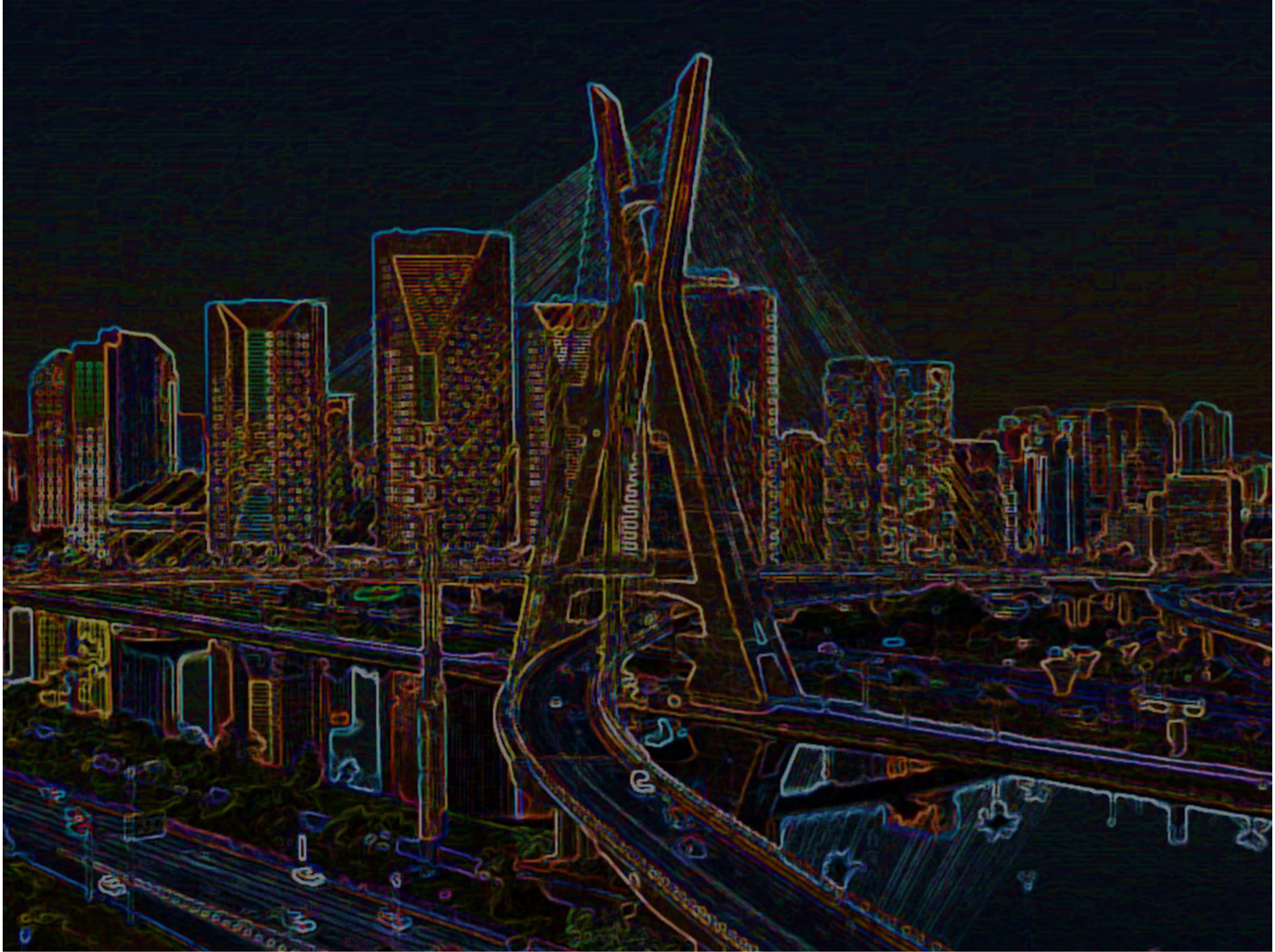

Workshop on Multineutron Clusters in Nuclei and in Stars

Sao Paulo

Juni 2-6, 2025

Measurement of ^{6}H Groundstate Energy at MAMI

Josef Pochodzalla and Tianhao Shao

for A1 Collaboration

Johannes Gutenberg-University Mainz and Fudan University

based on Phys.Rev.Lett.134.162501 (2025)

Workshop on Multineutron Clusters in Nuclei and in Stars
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Measurement of ^{6}H Groundstate Energy at MAMI

- **Tour of neutral systems** – *there may be more than just nnnn*
- **Neutron rich systems: ^{6}H**
- **MAMI experiment**
- **Outlook and Summary**

Josef Pochodzalla and Tianhao Shao
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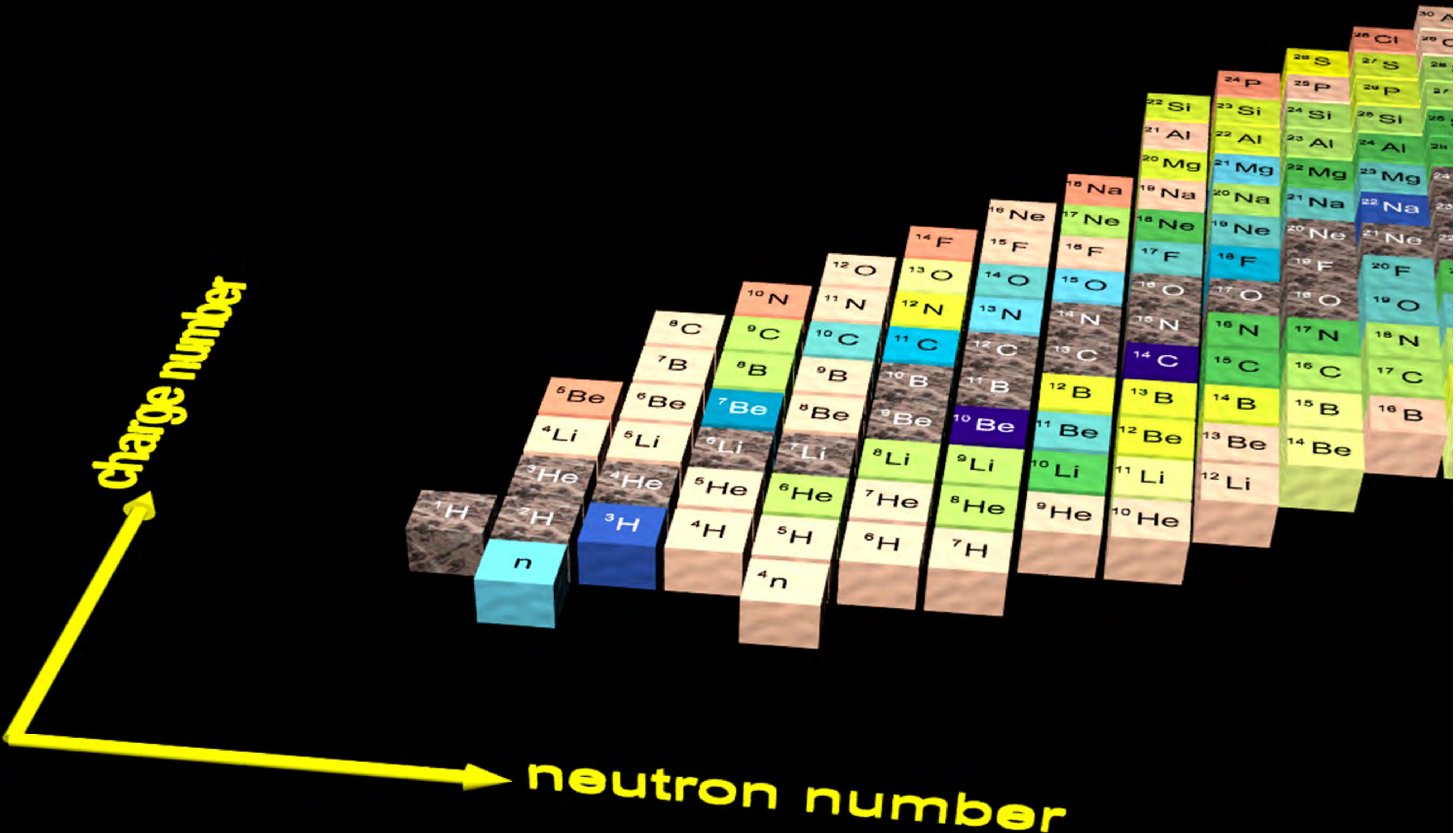
based on Phys.Rev.Lett.134.162501 (2025)

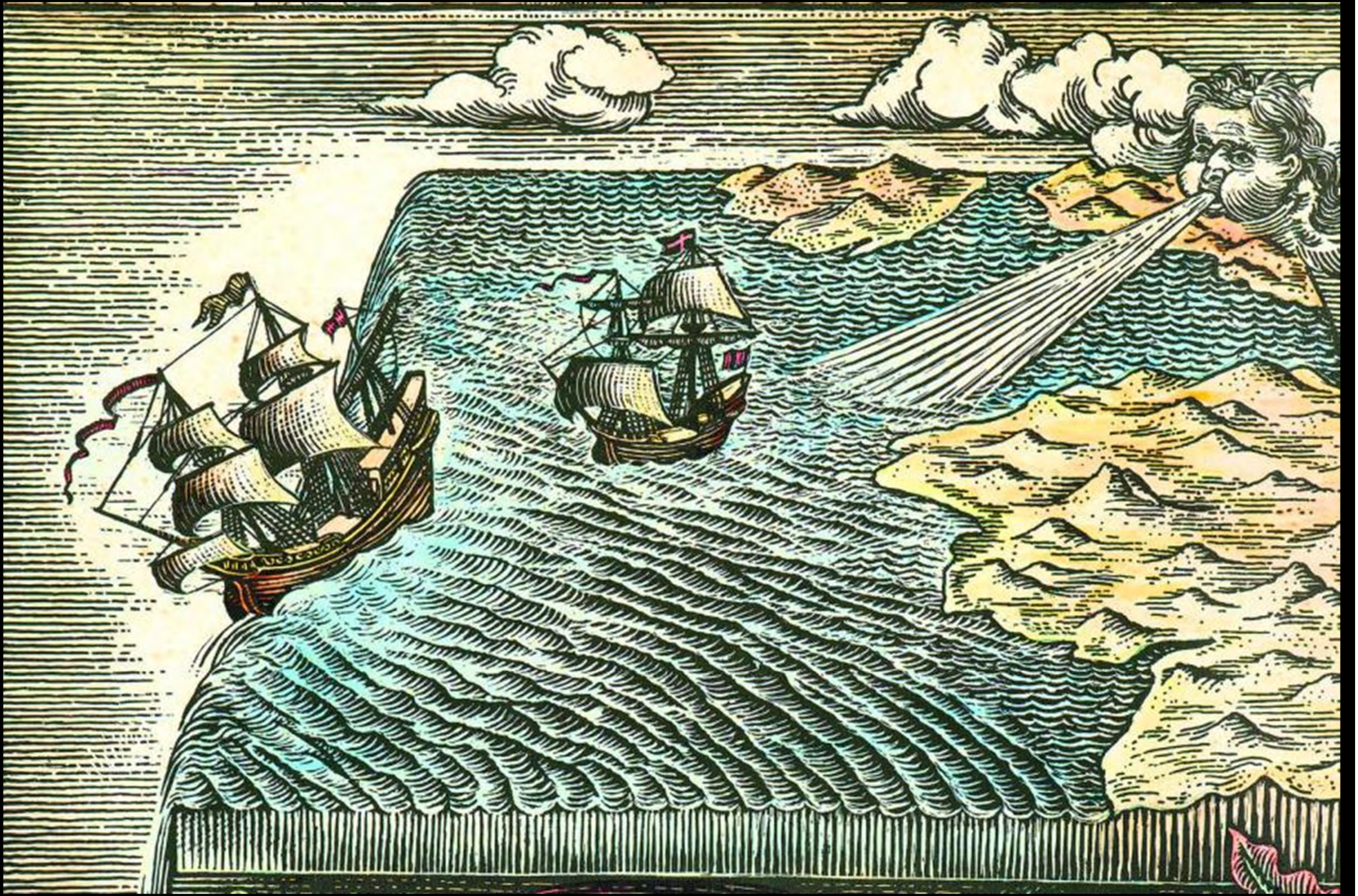
Short tour through neutral systems

(there may be out there than just nnnn)

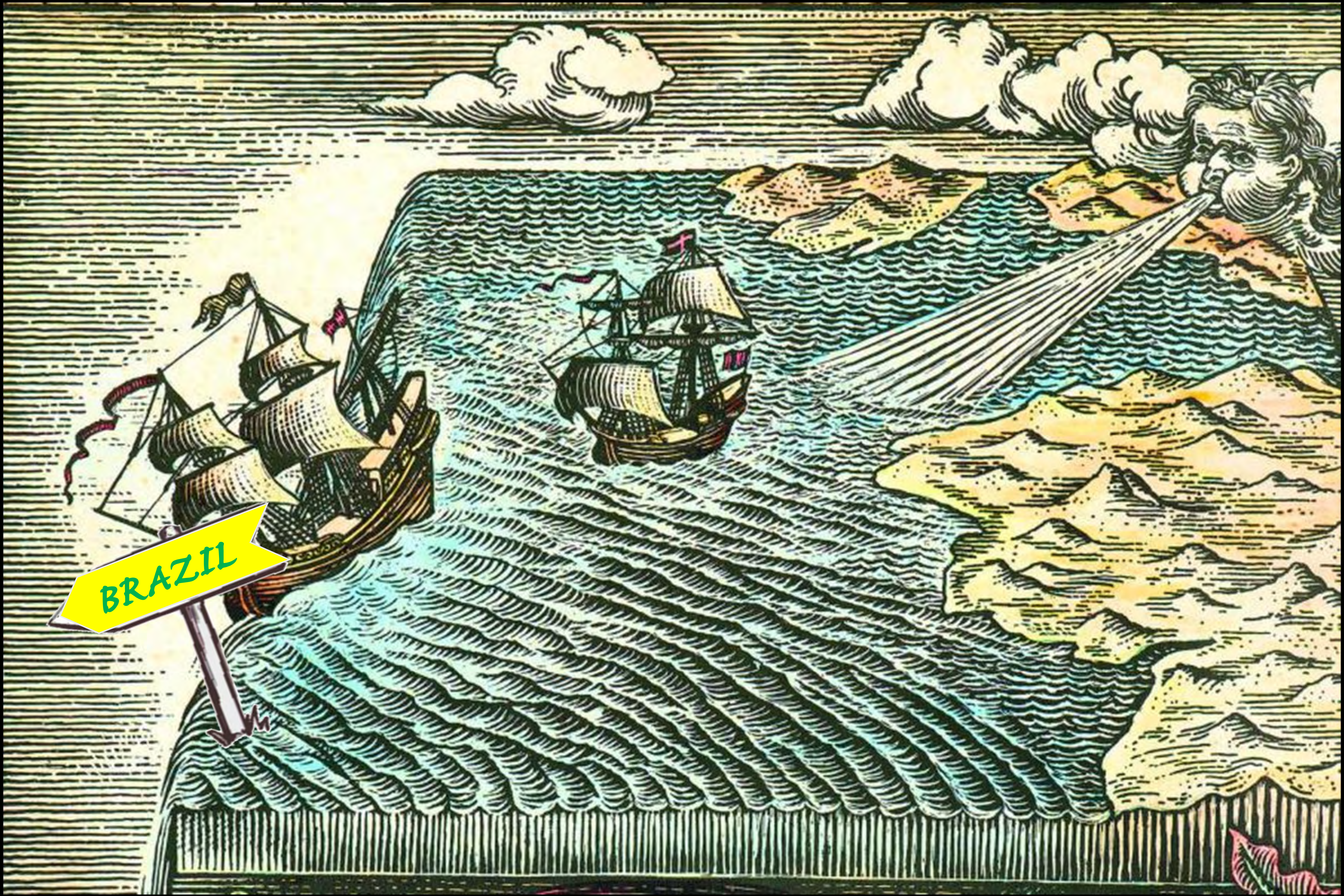
Playground of the Workshop



The World is not flat



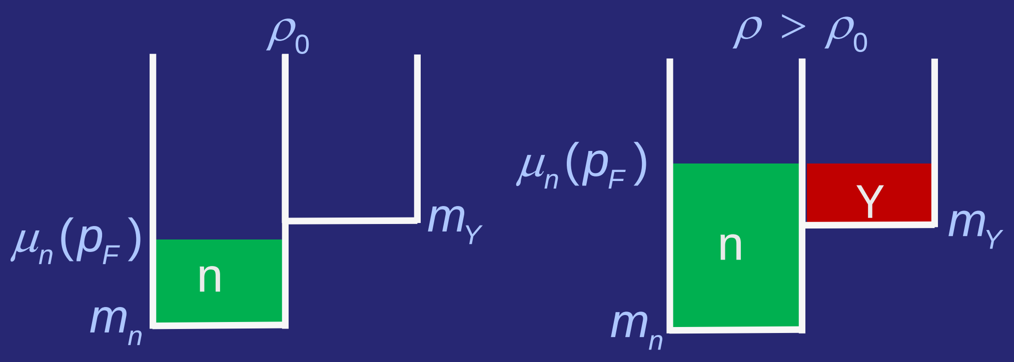
The World is not flat



Hyperos in Neutron Stars

Remember talk of Francesca Bonaiti

Cameron 1959, Ambartsumyan & Saakyan 1960



$e^- + p \rightarrow \nu_e + \Lambda$ $\qquad$ $p_{F,n}^2 + m_n^2 \geq m_\Lambda^2$

m_Λ=1116 MeV, m_n= 939MeV $\Rightarrow p_{F,n} \approx 600 MeV \simeq 3fm^{-1}$

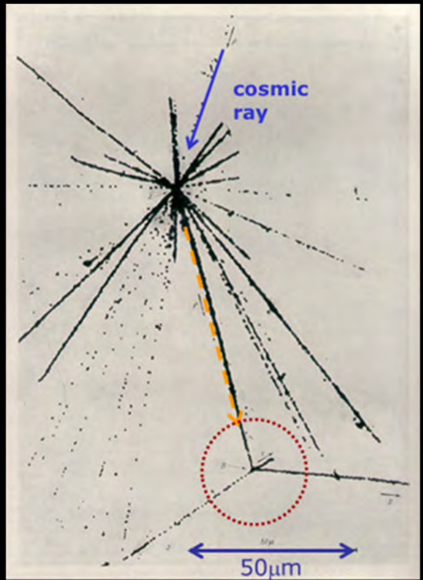
non-interacting Fermi-gas: $\rho = \frac{p_{F,n}^3}{3\pi^2} \Rightarrow p_{F,n}(\rho_0) = 1.7fm^{-1}$

$\Rightarrow$ appearence of hyperons at $\rho_\Lambda \approx 5.5\rho_0$

with interactions $\rho_\Lambda \approx 2-3\rho_0$

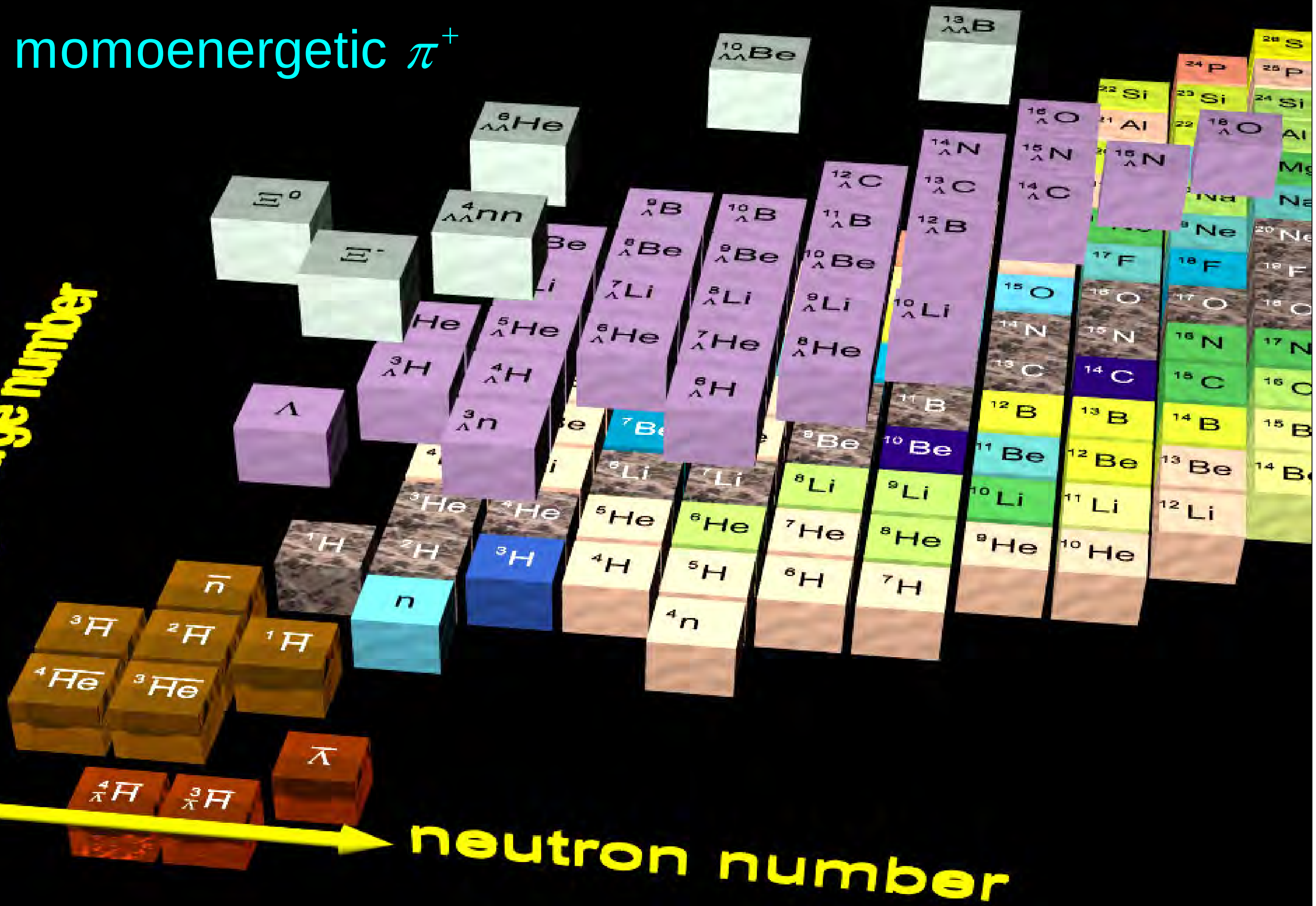
- Baryon density in neutron stars 2-3 ρ_0
- Fermi level of neutrons beyond m_Λ
- Time scale of explosion $\mathcal{O}$(s) $\leftrightarrow$ Weak interaction $\mathcal{O}(10^{-10}$s)
- $\Rightarrow$ hyperons can appear by weak interaction
- Once they appear they are stable because of Pauli supression

Light Nuclear Systems

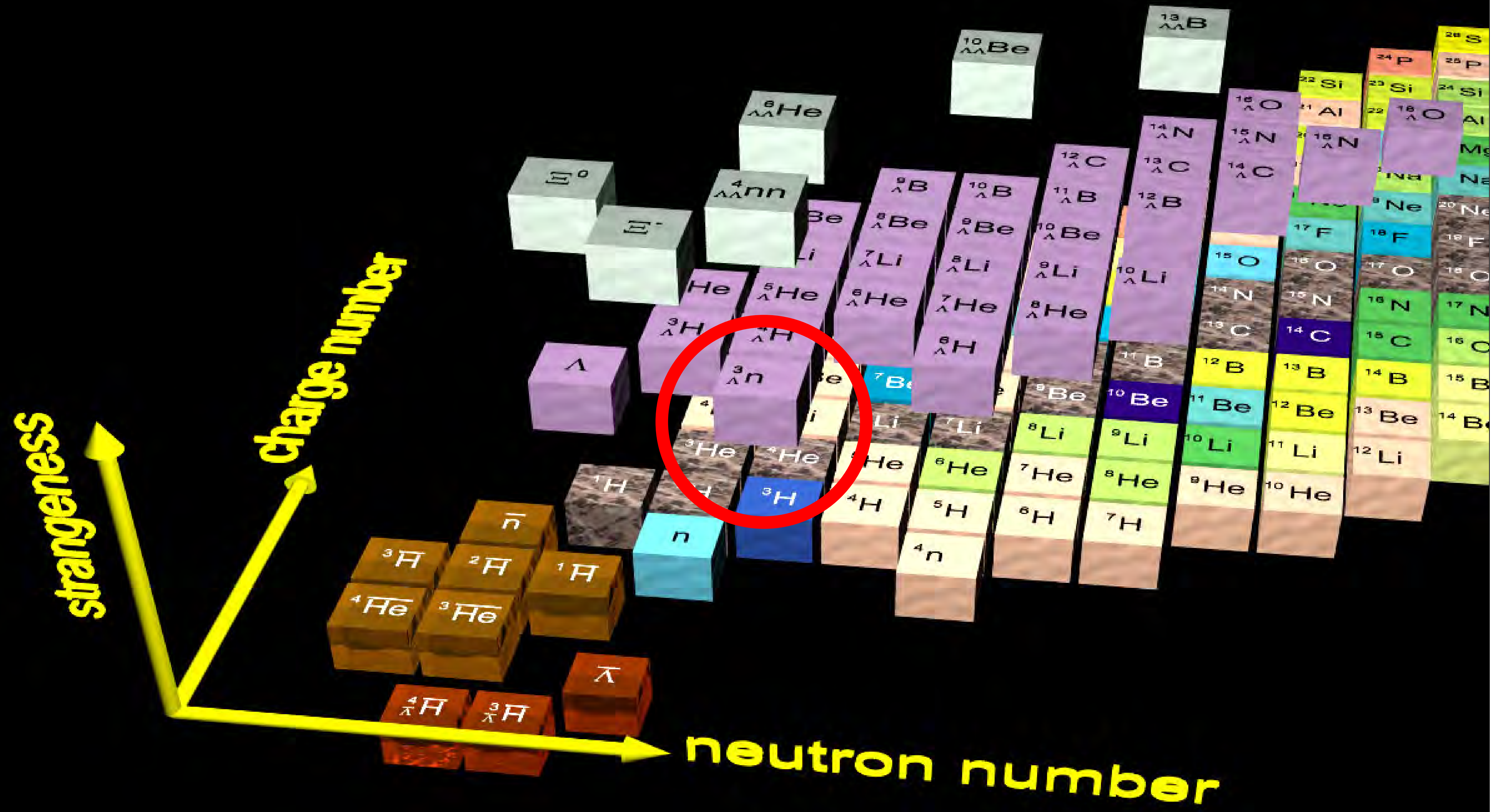


$${}^{4}_{\Lambda}H \rightarrow \pi^{+} + {}^{4}He$$

momoenergetic π^{+}

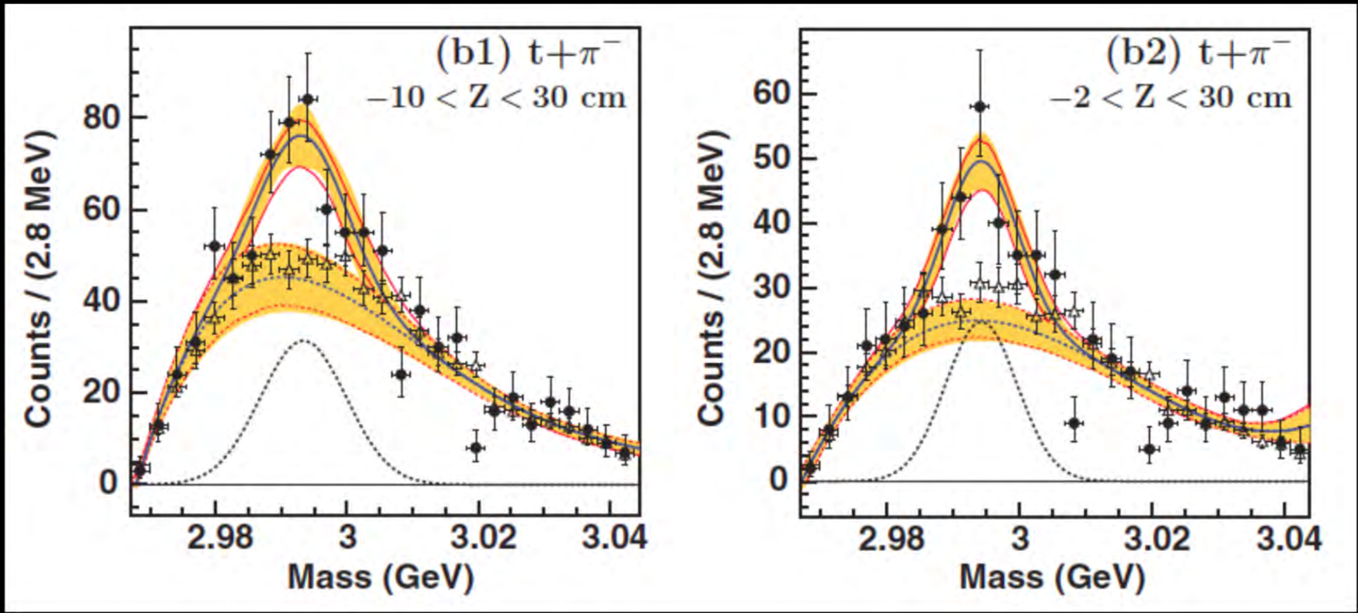


Neutral Systems



The nnΛ Puzzle

- Such a state has been suggested by the HypHI collaboration
- weak decay $nn\Lambda \rightarrow \pi^- {}^3H$ (invariant mass) $\Rightarrow$ bound state
- Lifetime = typical weak decay lifetime $\gg$ strong decay

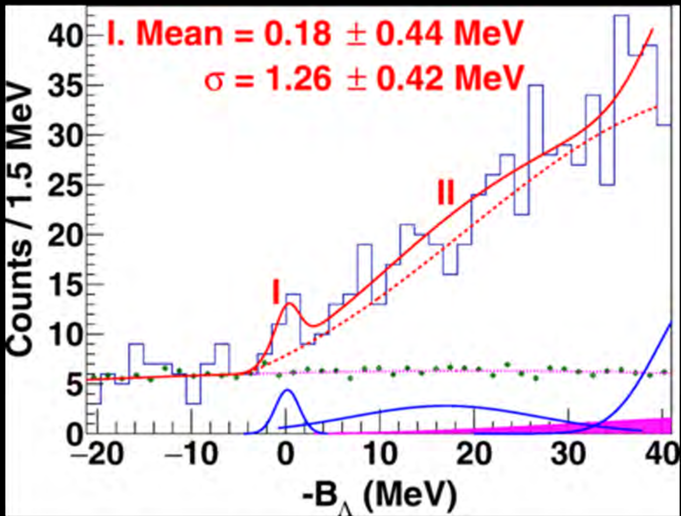


C. Rappold et al., Phys. Rev. C 88 , 041001(R) (2013)

- Statistical Decay Model ${}^6_\Lambda He^*$ at E_x=40MeV
  - Λ 30.7% $nn\Lambda$ 17.3%
  - ${}^3_\Lambda H$ 13.9% ${}^4_\Lambda H$ 29.2%
  - ${}^4_\Lambda He$ 3.9% ${}^5_\Lambda He$ 4.8%
- but:
  - The experiment poses questions
  - all modern state of the art theories do not allow a bound $nn\Lambda$ state

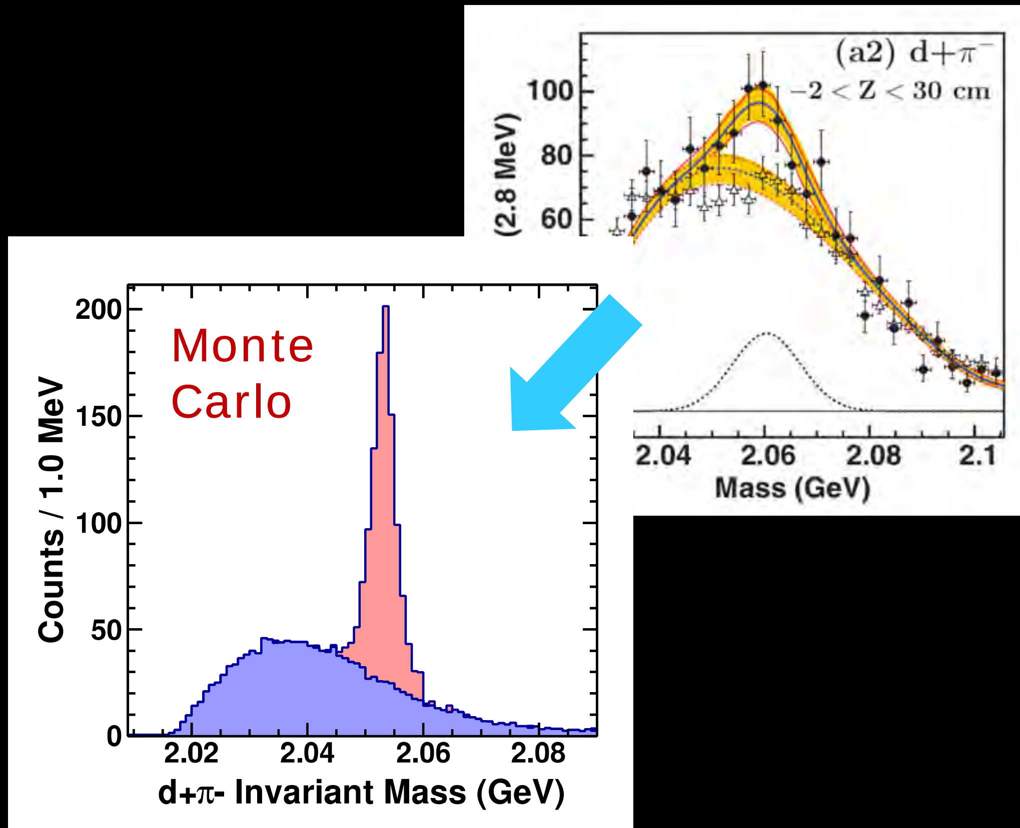
Approaching the nnΛ

- 2018: J-Lab E12-17-003
  - $^{3}H(e,e'K^{+})(nn\Lambda)$
  - missing mass experiment
  - Phys. Rev. C 105, L051001 (2022)



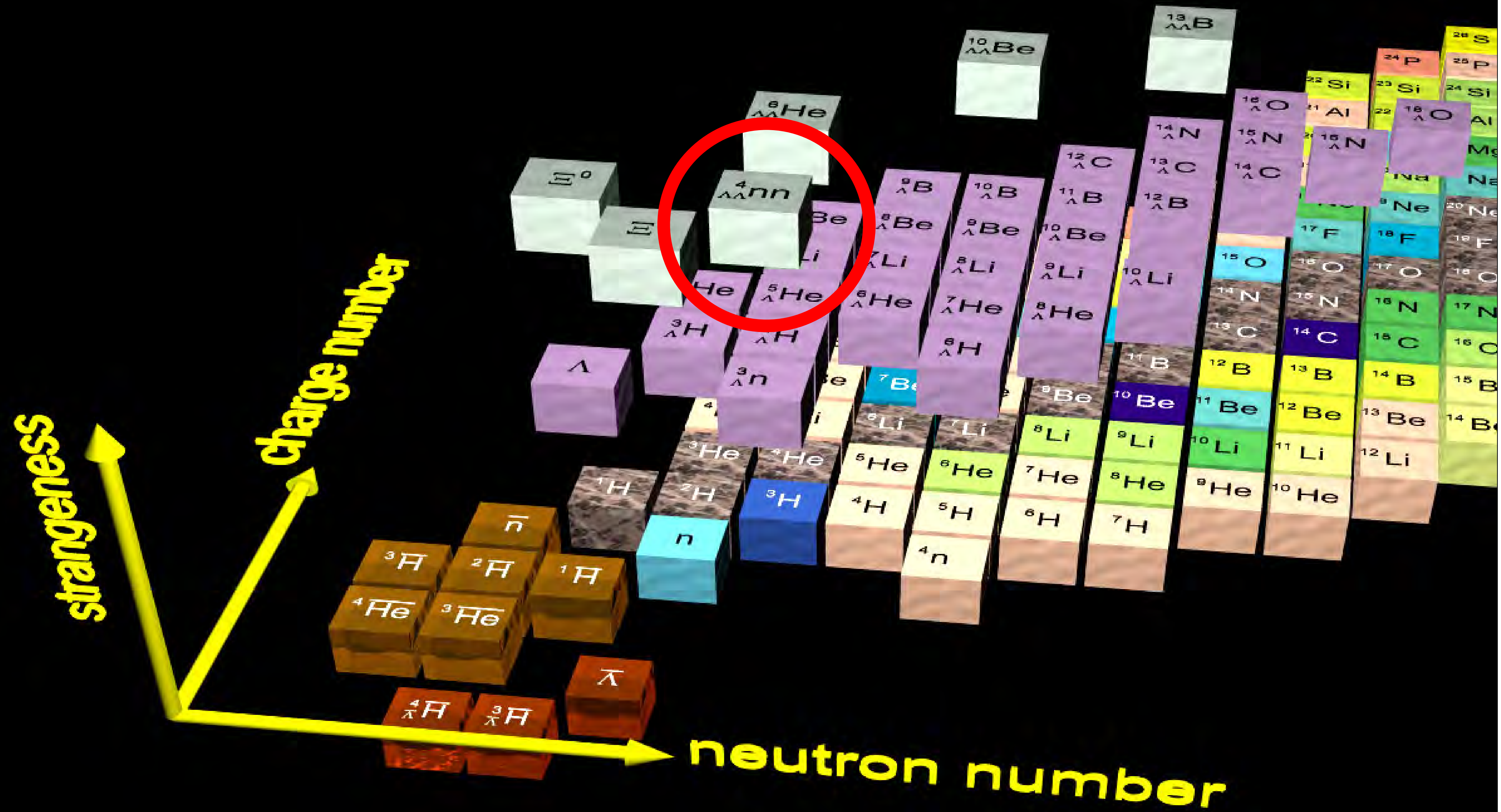
" $^{3}{}_{\Lambda}n$ resonance ....possibly observed. However, to make a definitive identification, improved statistics are required".

- 2022: FRS+WASA for S447
  - $^{6}Li+^{12}C$
  - for d+π 2× better mass resolution
  - 8 times better S/BG ratio expected
  - lifetime



The existence of this state would require to re-think our understanding of three-body interactions

Neutral Systems



E906 – the case of nnΛΛ

- aim: search for ΛΛ hypernuclei by sequential weak π^- decays
- $9 \cdot 10^{11}$ K^- on Be target: $^{9}Be(K^-,K^+)\Xi^- + X$

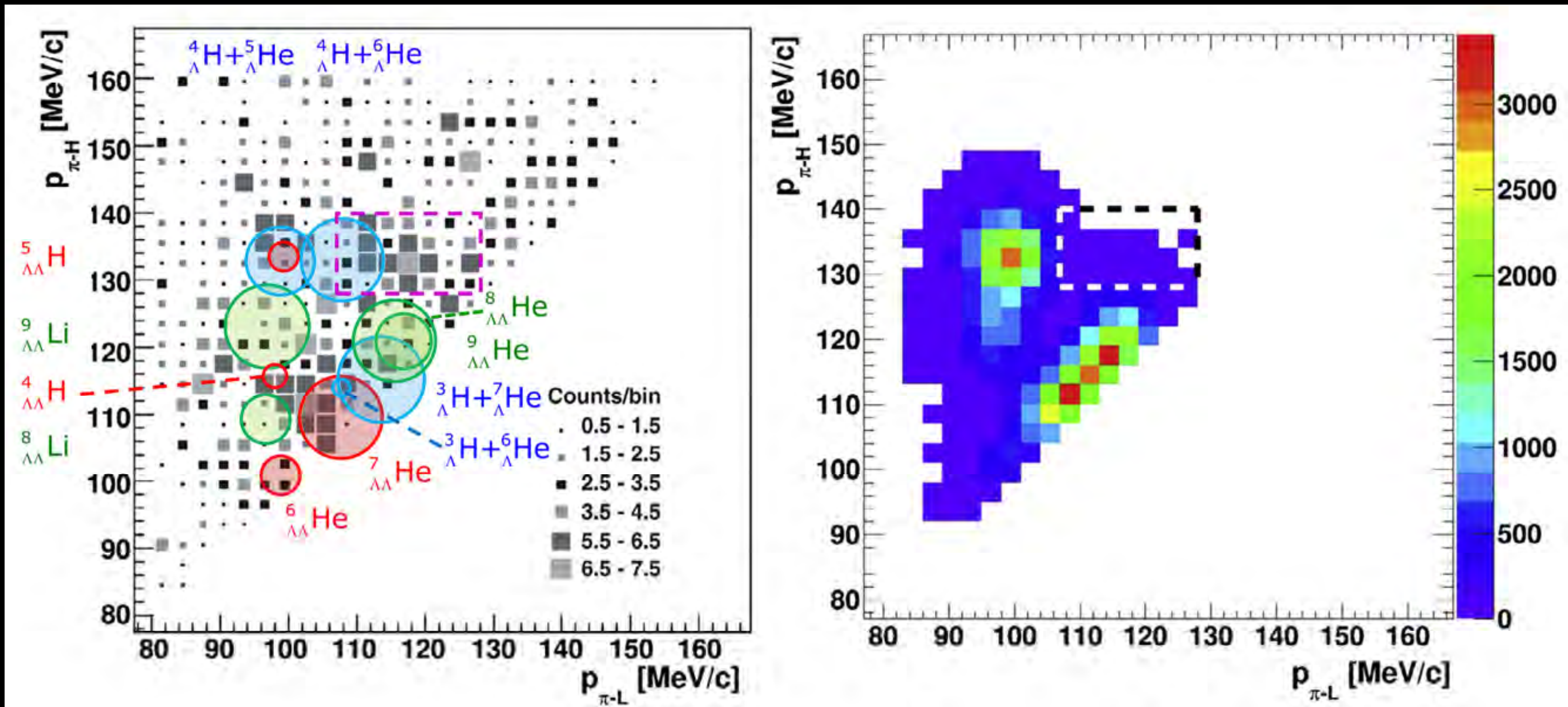
J.K. Ahn, et al., Phys. Rev. Lett. 87 (2001) 132504.

Doube Hypernulei $^{A0}_{\Lambda\Lambda}Z^* \rightarrow {}^{A}_{\Lambda\Lambda}Z + X$

$$\rightarrow \pi^- + {}^{A}_{\Lambda}(Z+1)$$

$$\rightarrow \pi^- + {}^{A}(Z+2)$$

Twin Hypernuclei $^{A0}_{\Lambda\Lambda}Z^* \rightarrow {}^{A1}_{\Lambda}Z_1 + {}^{A2}_{\Lambda}Z_2 + X$



E906 – the case of nnΛΛ

- Explore all energetically possible decay channels by a statiscial model
- Inlclude branching ratios etc.

Physics Letters B 790 (2019) 502–508

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Has the neutral double hypernucleus ${}^{4}_{\Lambda\Lambda}n$ been observed?

Sebastian Bleser[a], Michael Bölting[a], Theodoros Gaitanos[b], Josef Pochodzalla[a,c,*], Falk Schupp[a], Marcell Steinen[a]

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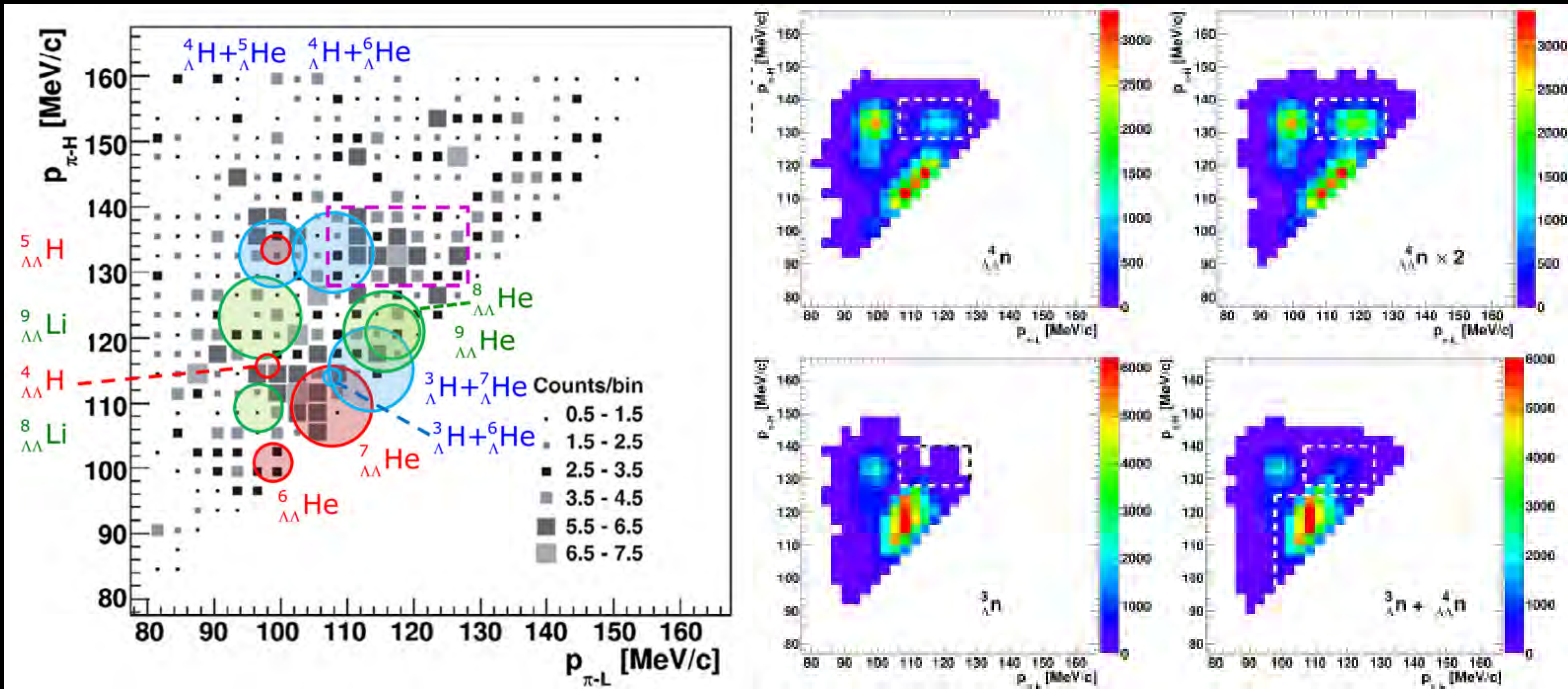
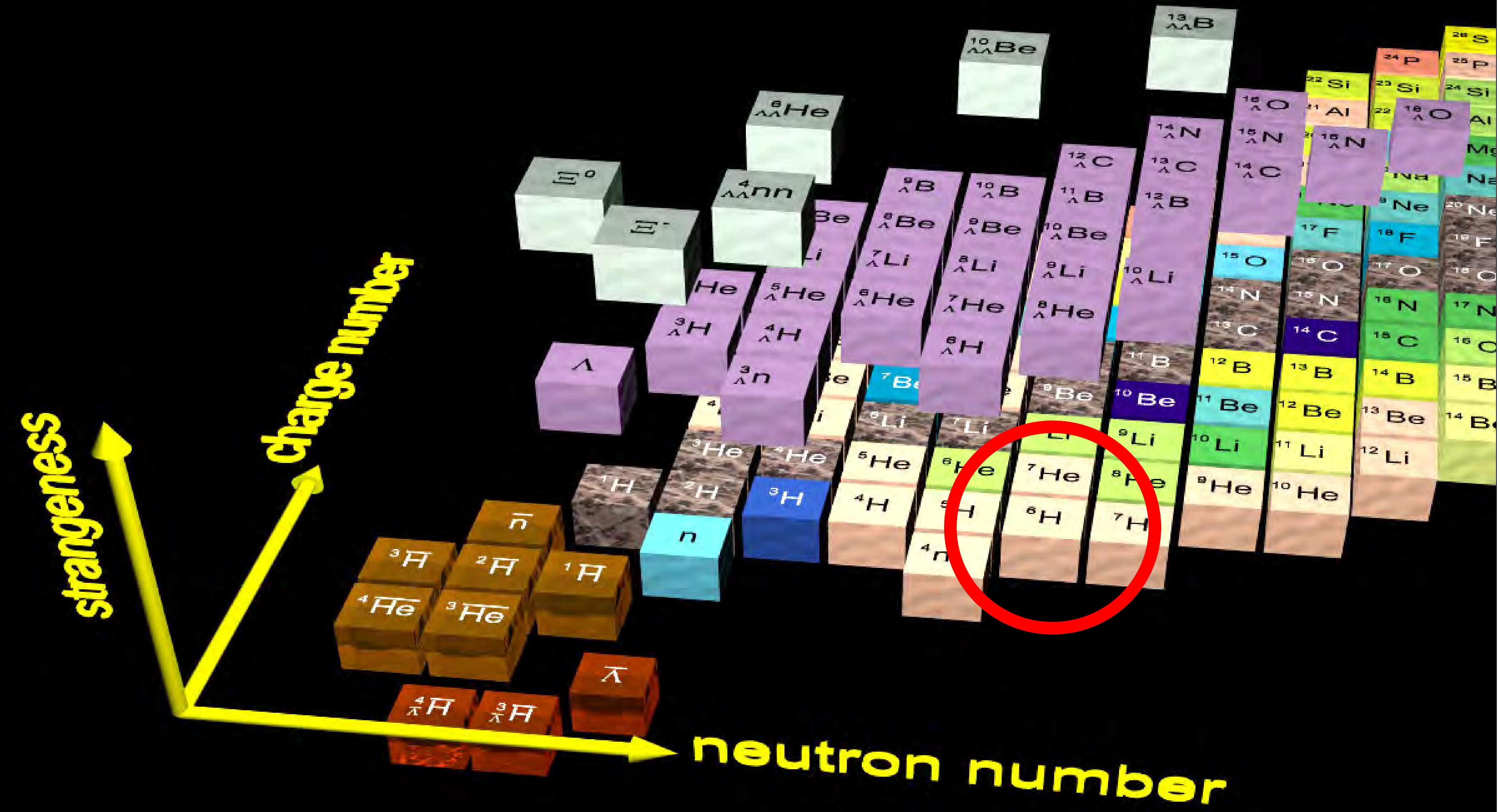


Take home message

- Structure of conventional and strange nuclei should be treated together
- Caveat: information on hypernuclei is much more limited
  - few ten nuclei
  - Ground state masses
  - Lifetime
  - In sime cases excited states
- When it comes to the core of neutron stars non-strange and strange baryons and there multi-body interactions are important

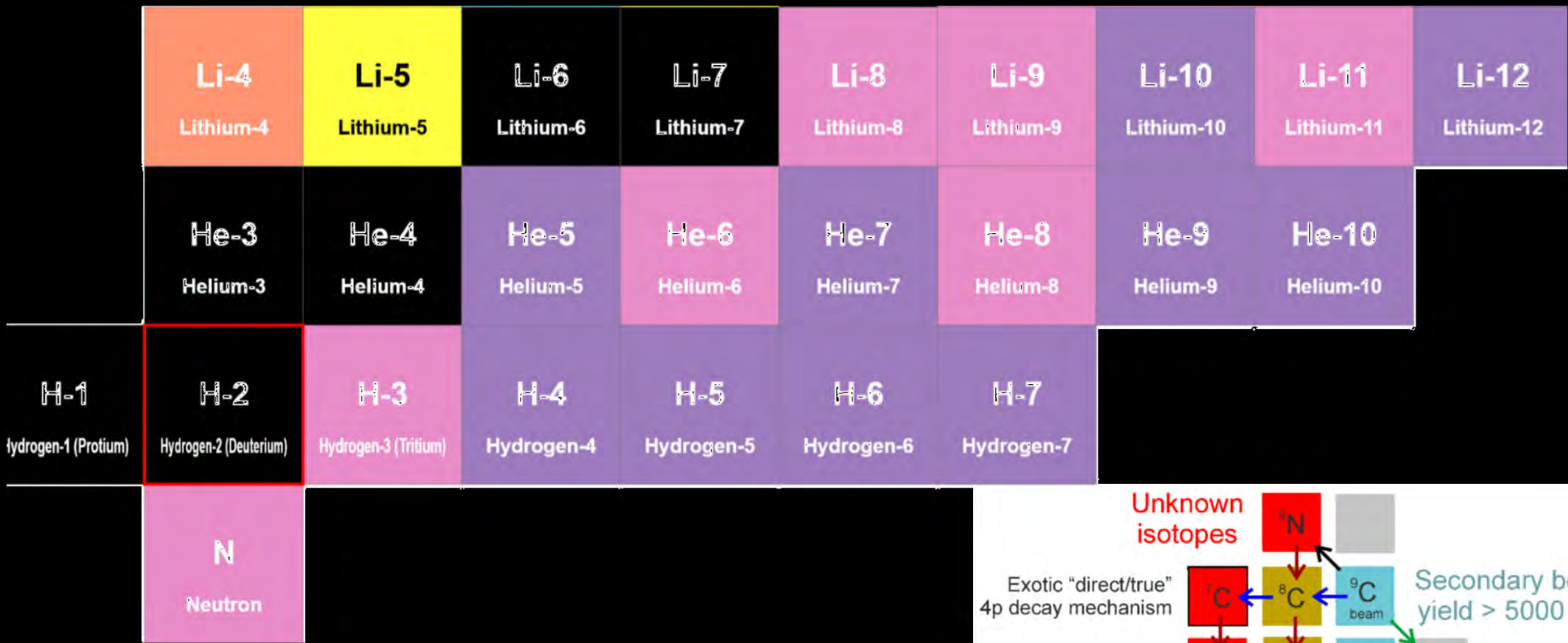
The extremly neutron rich system ^{6}H

Light Neutron Rich Systems

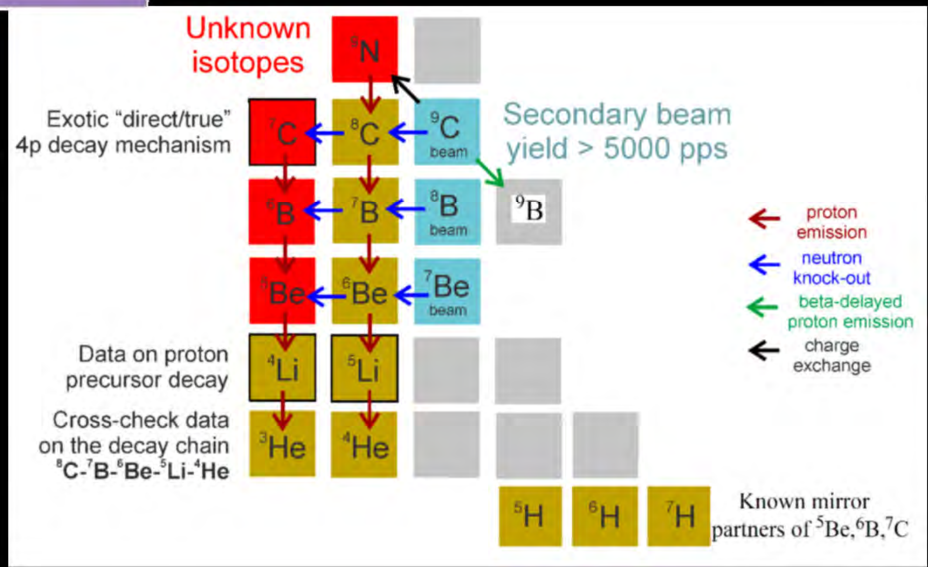


Exotic Hydrogen Isotope

- Largest neutron-to-proton ratios known so far
  - ^{4}H, ^{5}H : clear signal observed
  - ^{6}H, ^{7}H : Indistinct signal, controversial results
- Laboratory for multi-neutron interactions

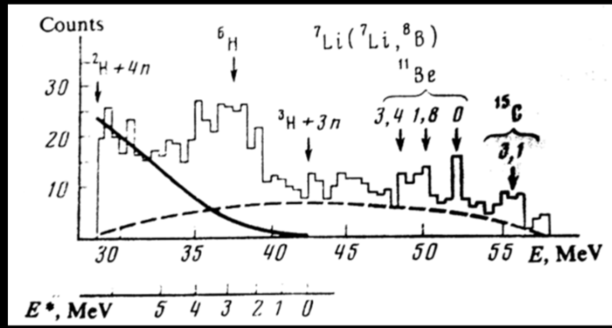


- Mirror nuclei of proton rich systems
  - GSI-Super-RFS Proposal G-22-00111: Towards limits nuclear structure by using a ^{9}C beam

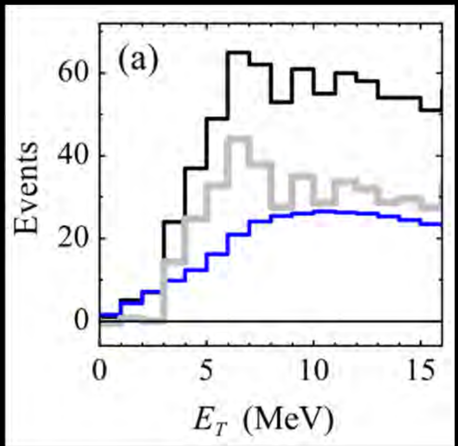


Observed ^{6}H ground state energies

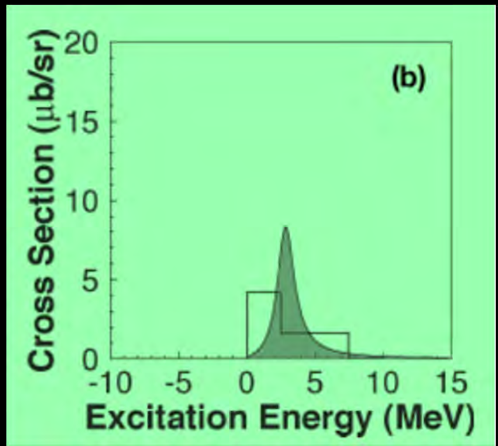
Reaction	E_r [MeV]	Γ [MeV]	year
^{7}Li(^{7}Li,^{8}B)^{6}H	2.7 ± 0.4	1.8 ± 0.5	1984
^{9}Be(^{11}B,^{14}O)^{6}H	2.6 ± 0.5	1.3 ± 0.5	1986
^{9}Be(π^{-},pd)^{6}H	6.6 ± 0.7	5.5 ± 2.0	2003
^{11}B(π^{-},p^{4}H)^{6}H	7.3 ± 1.0	5.8 ± 2.0	2003
^{12}C(^{8}He,^{6}H$\rightarrow$t+3n)^{14}N	$2.91^{+0.85}_{-0.95}$	$1.52^{+1.77}_{-0.35}$	2008
^{2}H(^{8}He,^{4}He)^{6}H	>4.5	5	2022



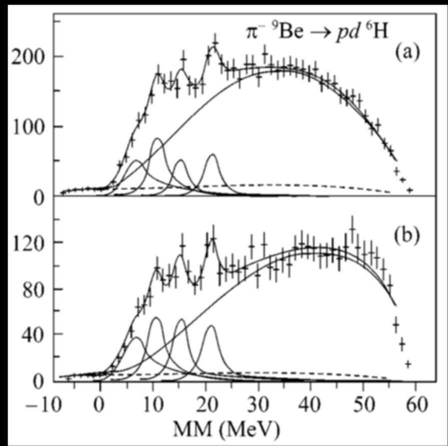
D. Aleksandrov et al. , Yadernaya Fizika 39,513 (1984)



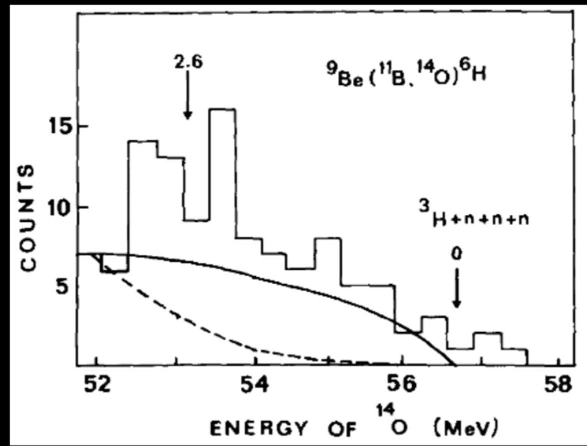
E. Yu. Nikolskii et al. , PRC 105, 064605 (2022)



M. Caamano et al. , PRC **78**, 044001 (2008)



Yu.B. Gurov et al. , JETP Lett. **78**, 183 (2003)

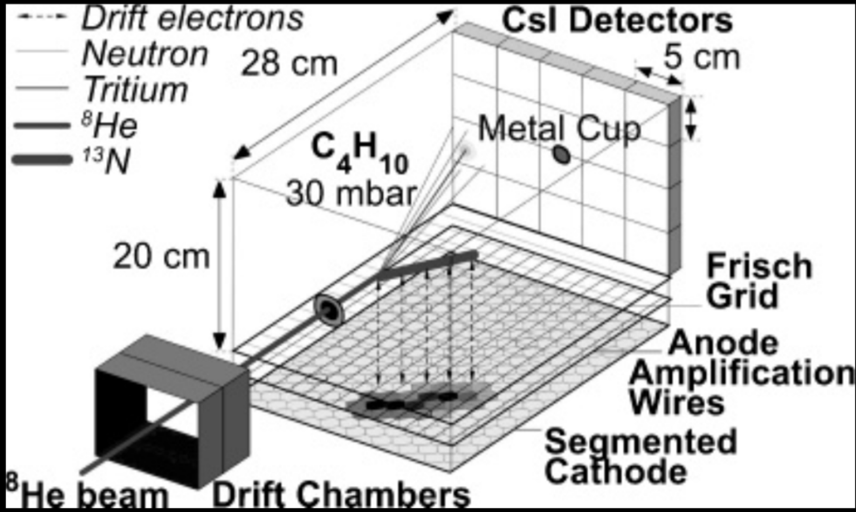


A. Belozyorov et al. , Nucl. Phys.A 460.2, 352 (1986)

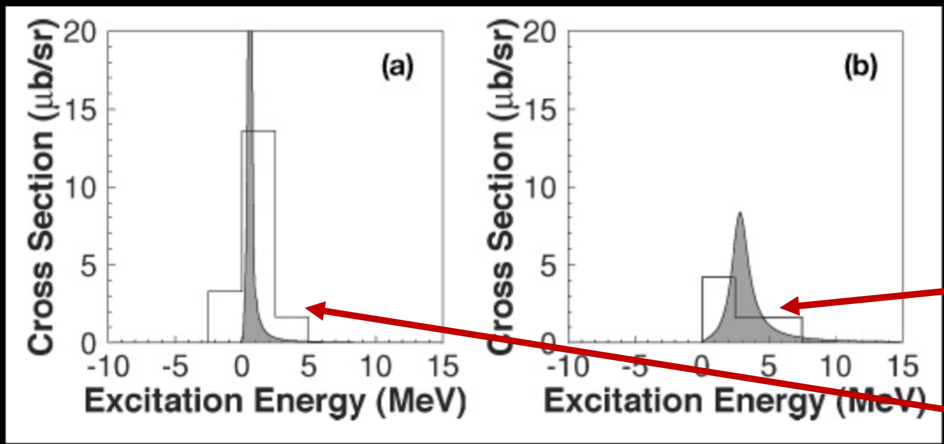
- In most cases: nuclear transfer or kick-out reactions

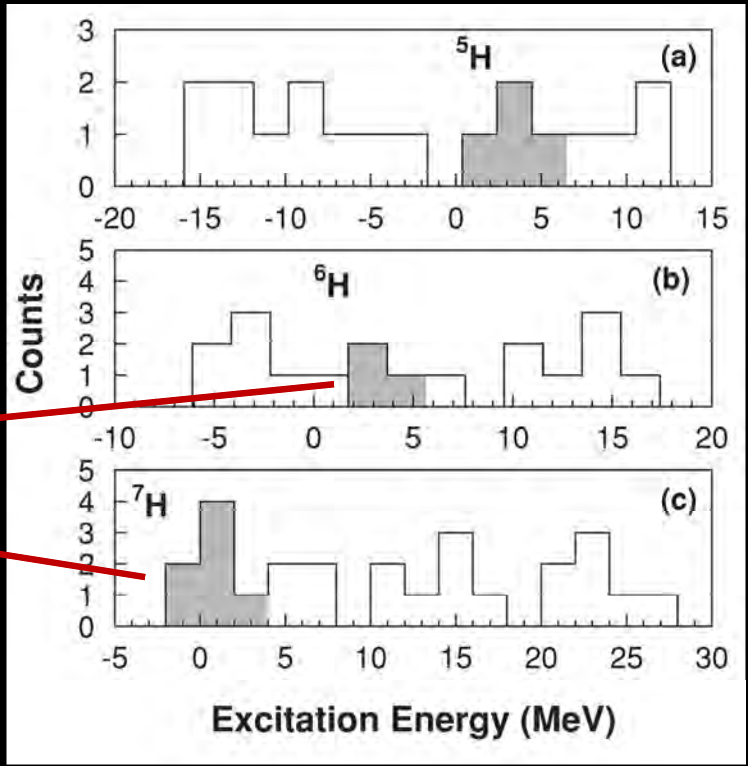
$^{12}C(^{8}He,^{5,6,7}H \rightarrow t + xn)^{17-x}N$

- Active ^{12}C target detector MAYA
- Nitrogen and tritium identified



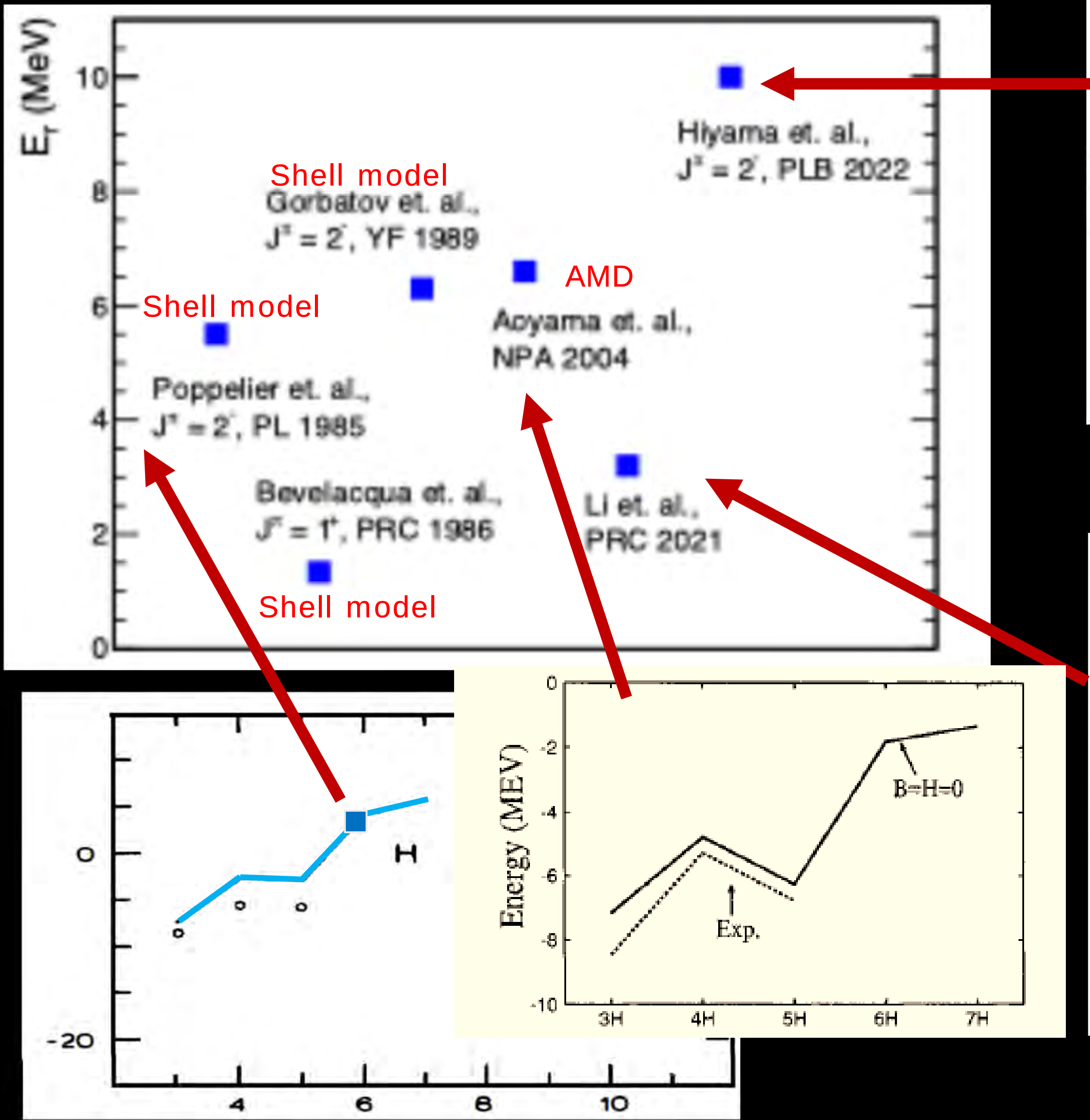
- *Assuming* detected nitrogen is
  - $^{15}N \Rightarrow {}^{5}H$
  - $^{14}N \Rightarrow {}^{6}H$
  - $^{13}N \Rightarrow {}^{7}H$

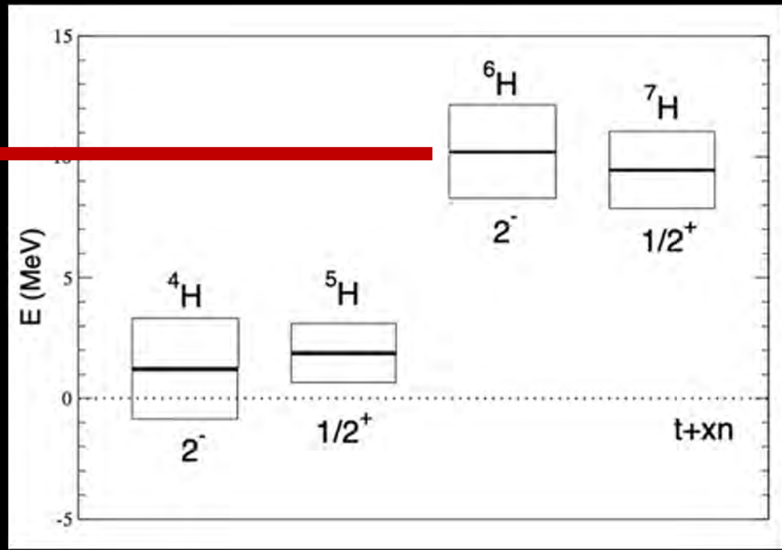




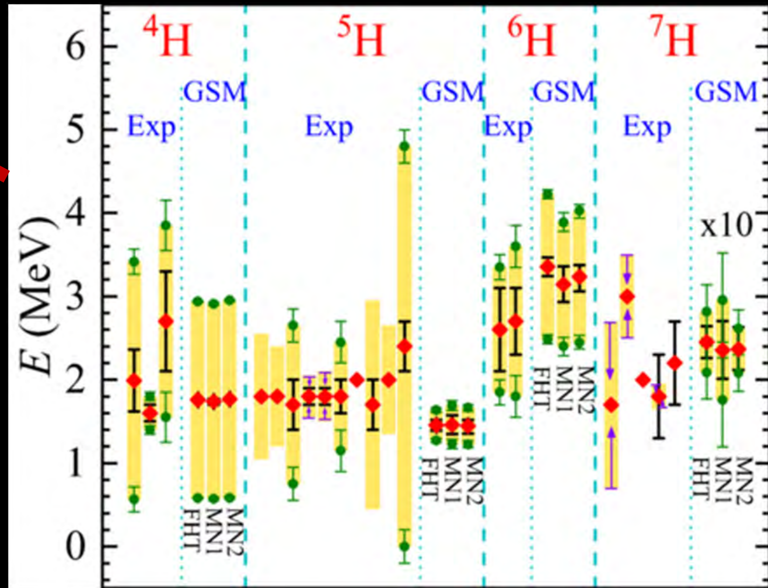
Theoretical situation of ^{6}H

- note: E_r = Energy above t+3n





E. Hiyama et. al., P L 833 (2022) 137367
with an effective n-t potential

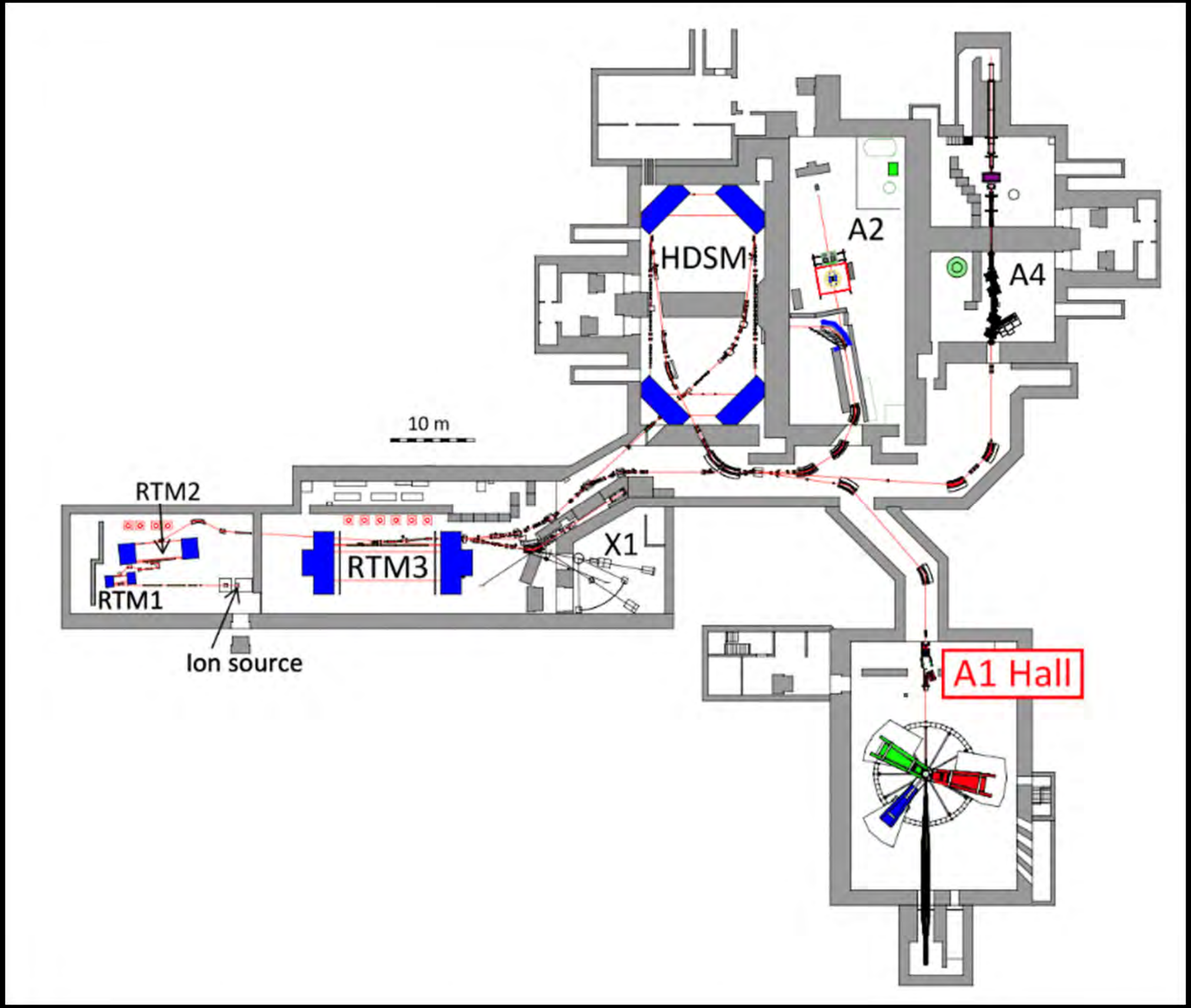


IMP group, PRC 104 (2021) L061306
Gamow shell model

The MAMI Measurement

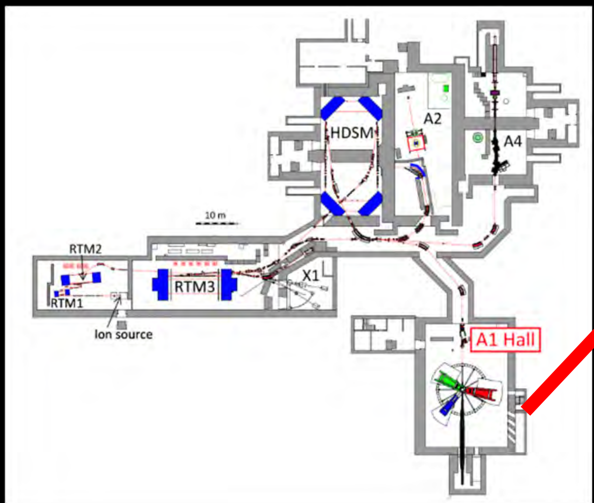
MAMI-A1 Setup

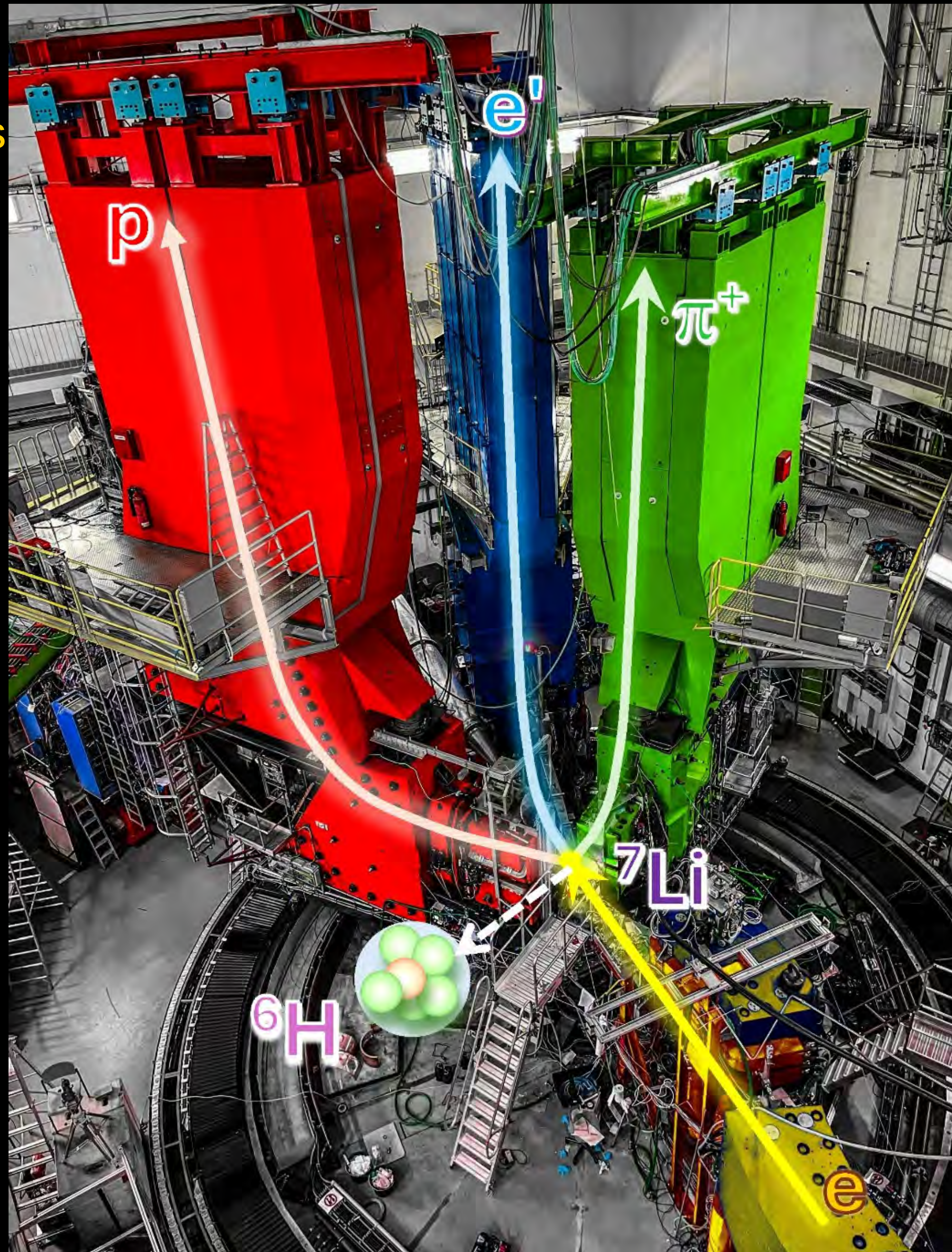
- MAMI is an electron accelerator with E_e=1.5GeV
  - Oacted at the Institut für Kernphysik, Mainz Univ.
  - Sequence of 4 microtrons
  - MAMI-B: 855 MeV electron beam



MAMI-A1 Setup

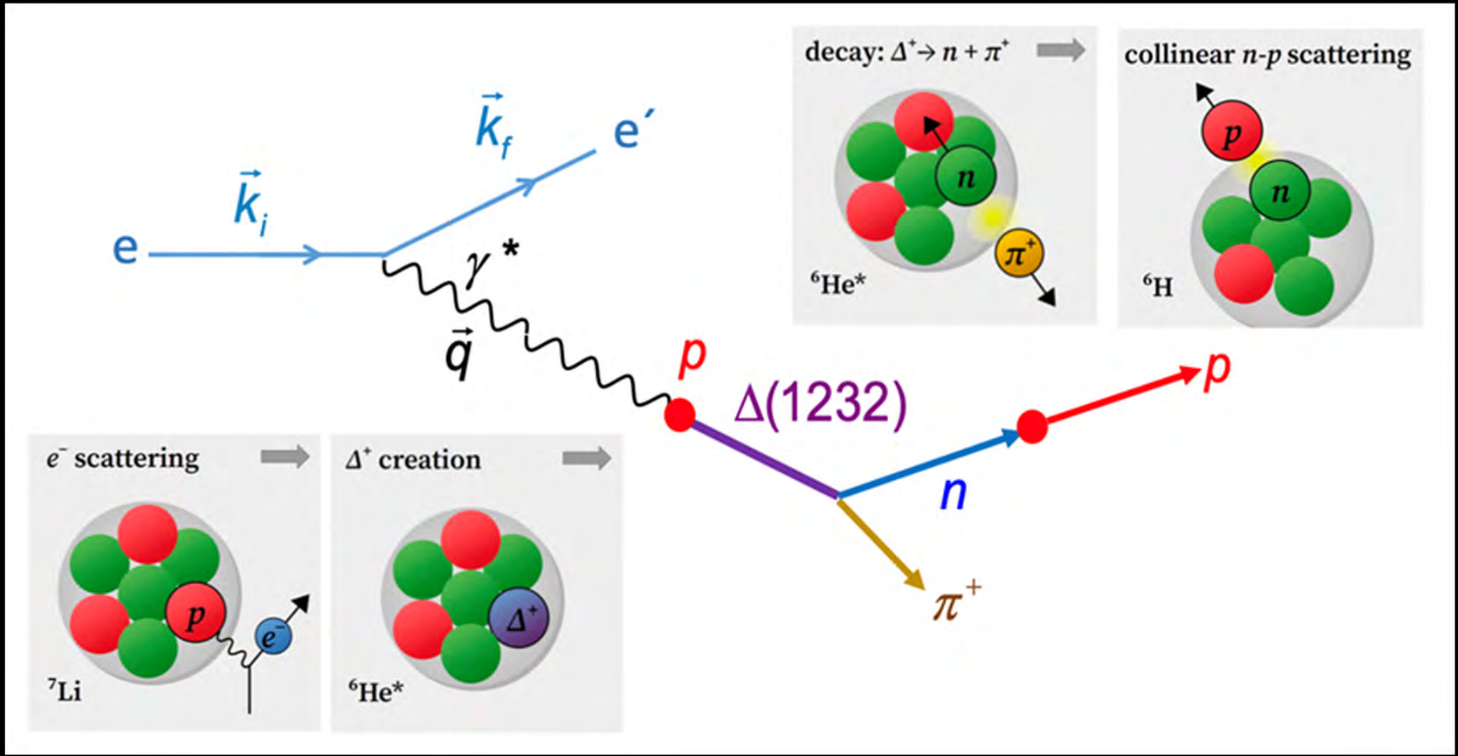
- Experimet A1
  - 4 magnetic focussing spectrometers
  - Resolution: $\delta p/p$ < 10-4
  - Angular acceptance: <30 mrad
- Missing Mass experiment
  - $^{7}\mathrm{Li}(e,e'p\pi^{+})^{6}\mathrm{H}$





Experimental Principals

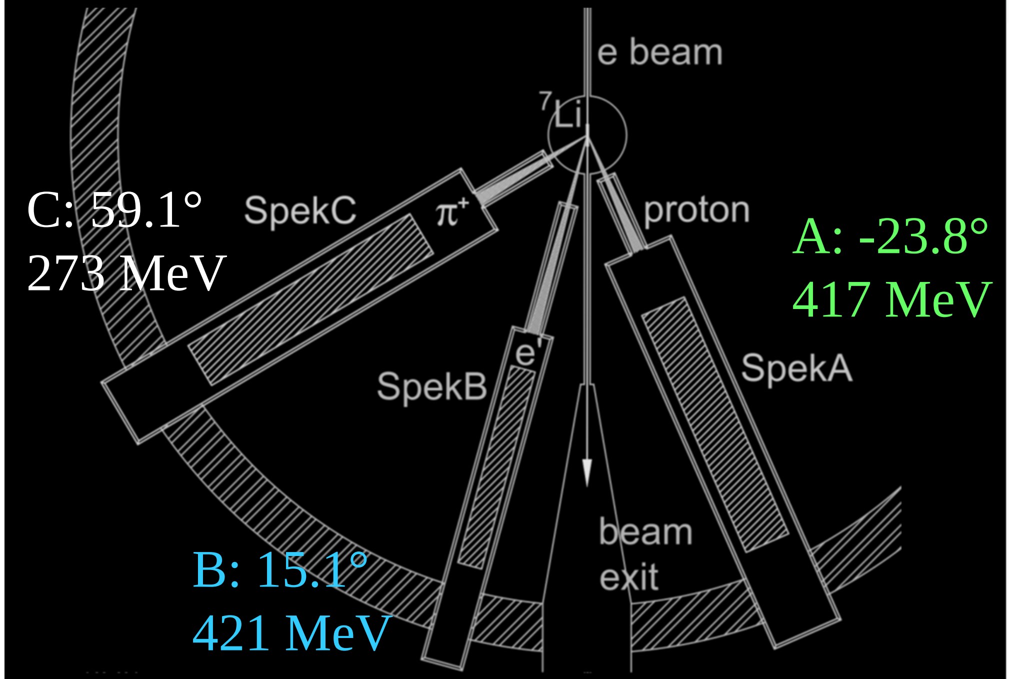
- Measure the momenta of the
  - scattered electron
  - the produced proton and
  - The produced π+
- Then reconstruct the miss-mass spectrum $^{7}Li(e,e'p\pi^{+})^{6}H$
- For the planning educated guess for reaction scheme is needed

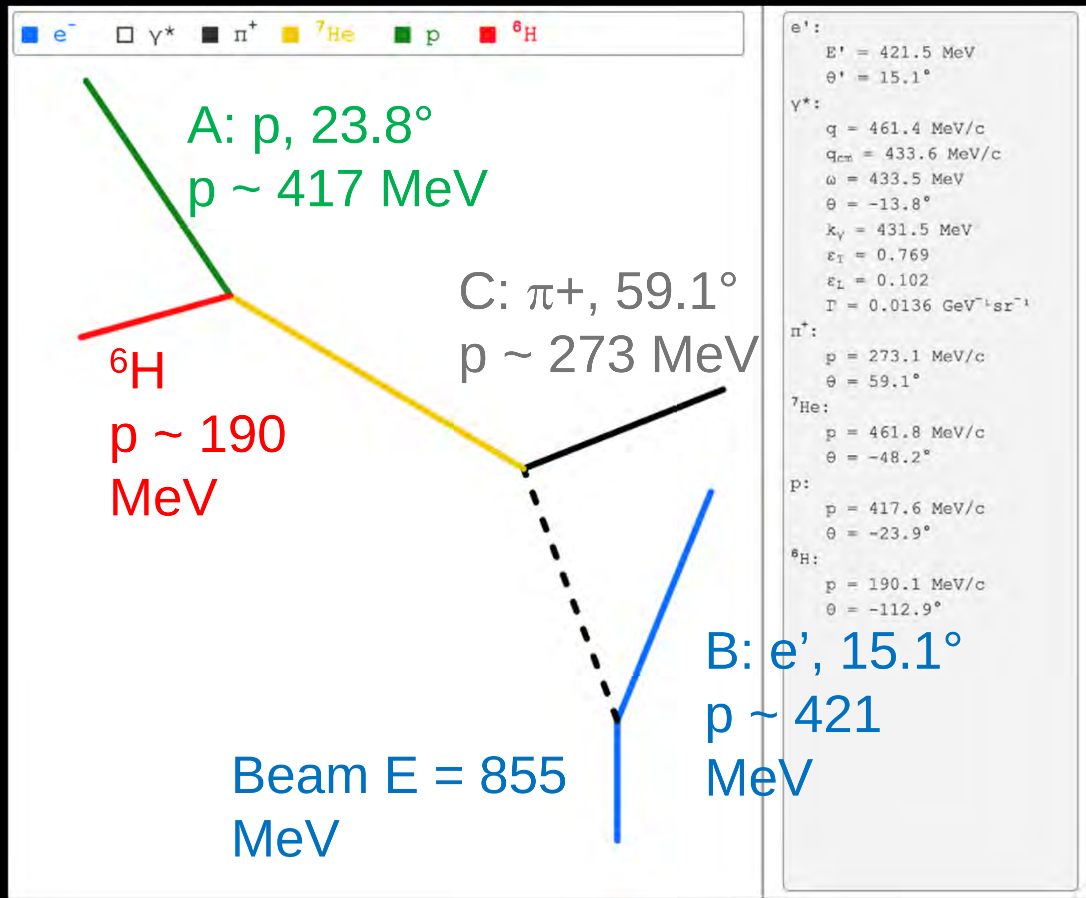


- Expected rate: 1 count in the region of interest per day
  - Confirmed by experiment
- Expected missing mass resolution: 1.2 MeV with 1mm thick target

Choice of kinematics

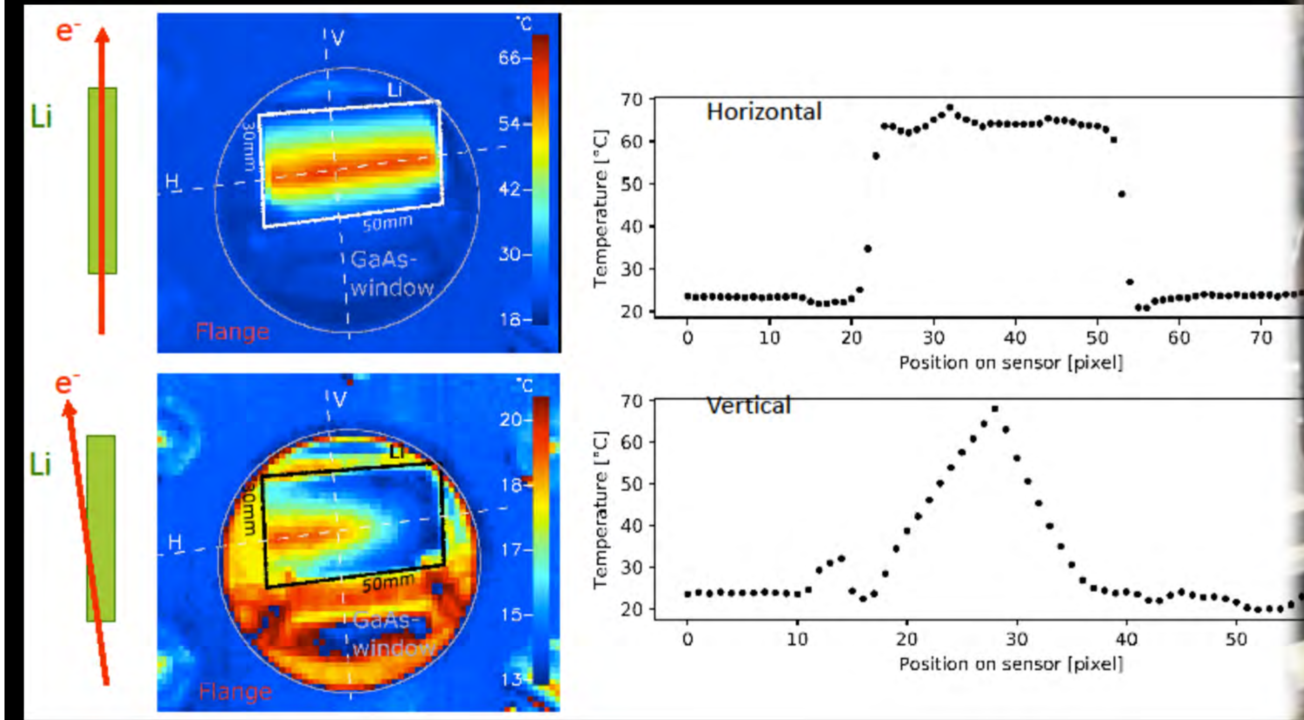
- feasible with the setups of three spectrometers
- MAMI energy
- W ~ 1200 MeV for proton to produce Delta(1232)
- low momentum transfer to ^{6}H

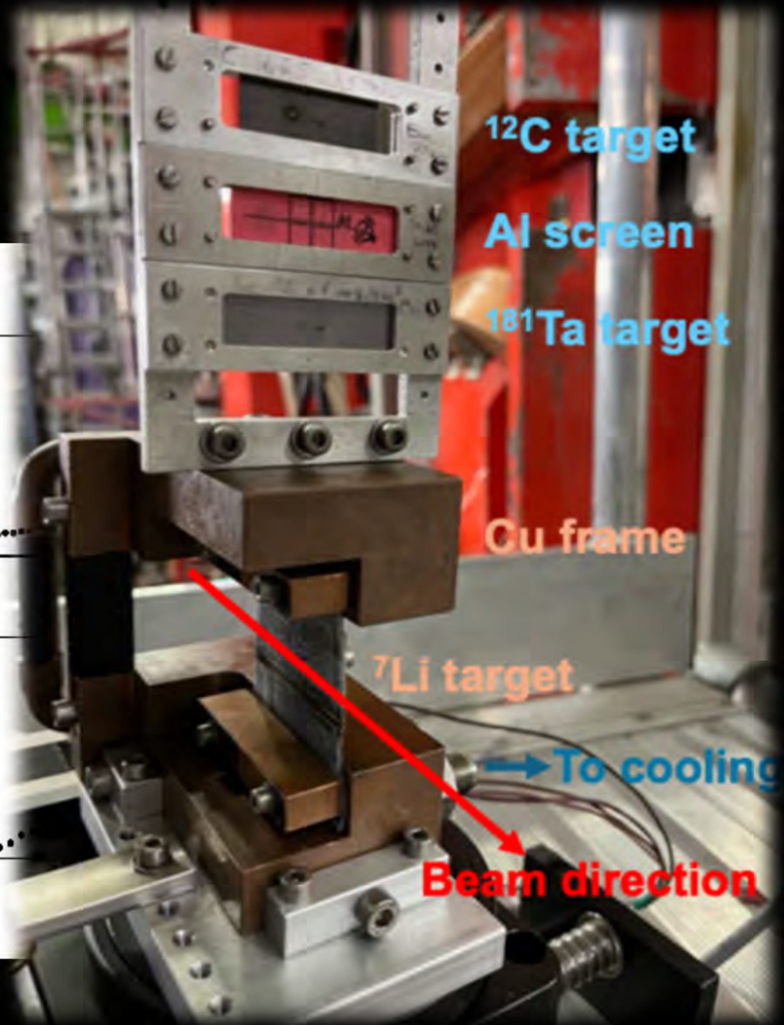




Li Target

- Lithium
  - low melting point 180°C
  - Low density 0.53 g/cm³

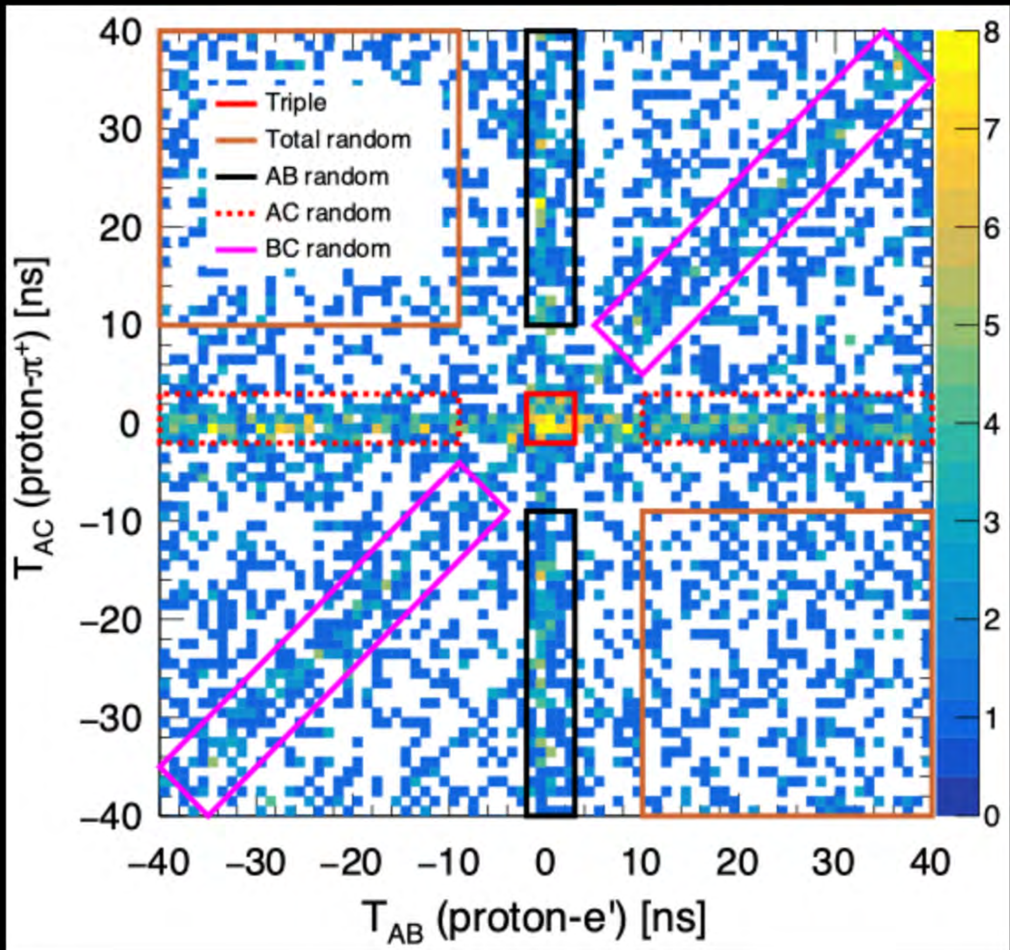




- run_2023: 92.7% natural Lithium (7.4% ^{6}Li, 92.6% ^{7}Li)
- run_2024: 99.99% enriched ^{7}Li

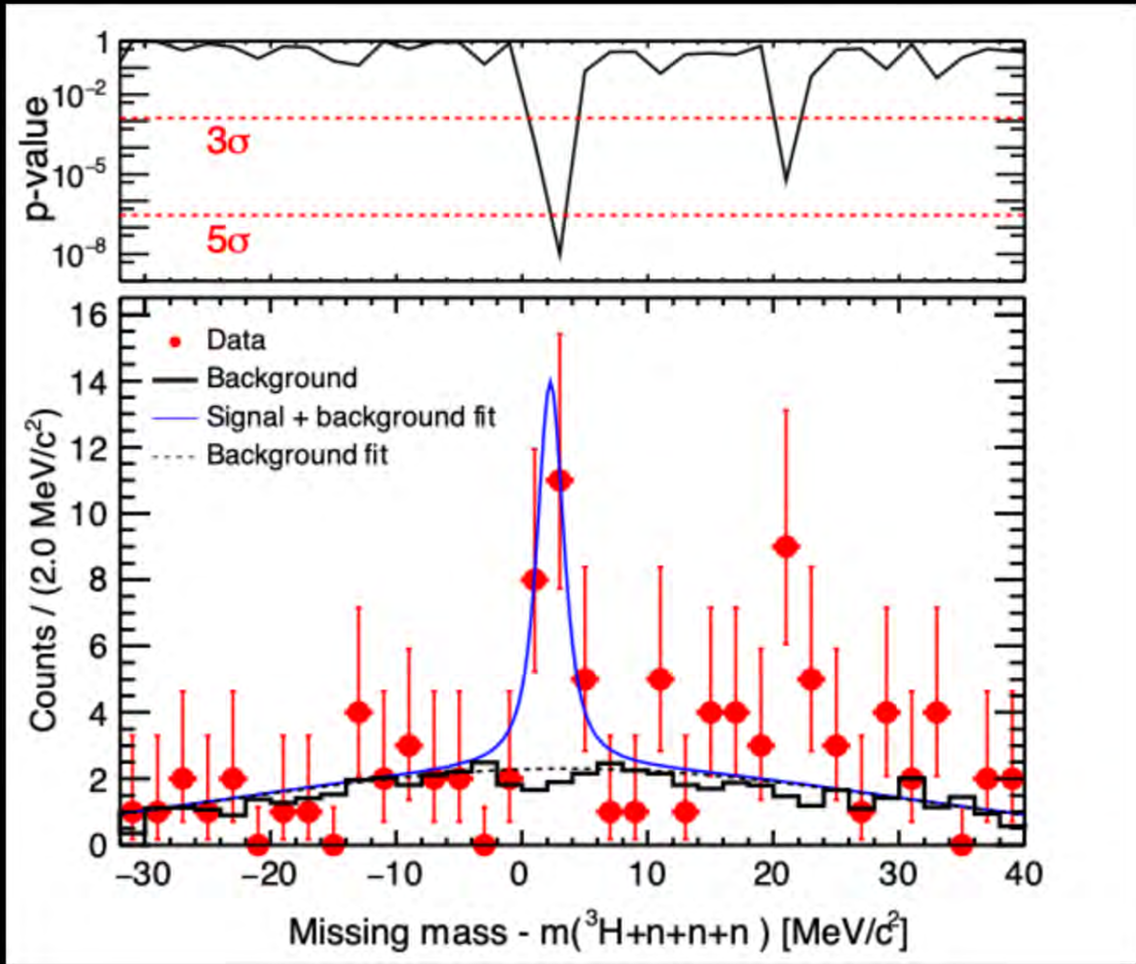
Data analysis

- Signal data: triple coincidence between 3 spectrometers
- Random background =
- AB random + AC ramdom + BC random – 2 × total random
- weighted according to the areas of the selected regions
- no further normalization neede



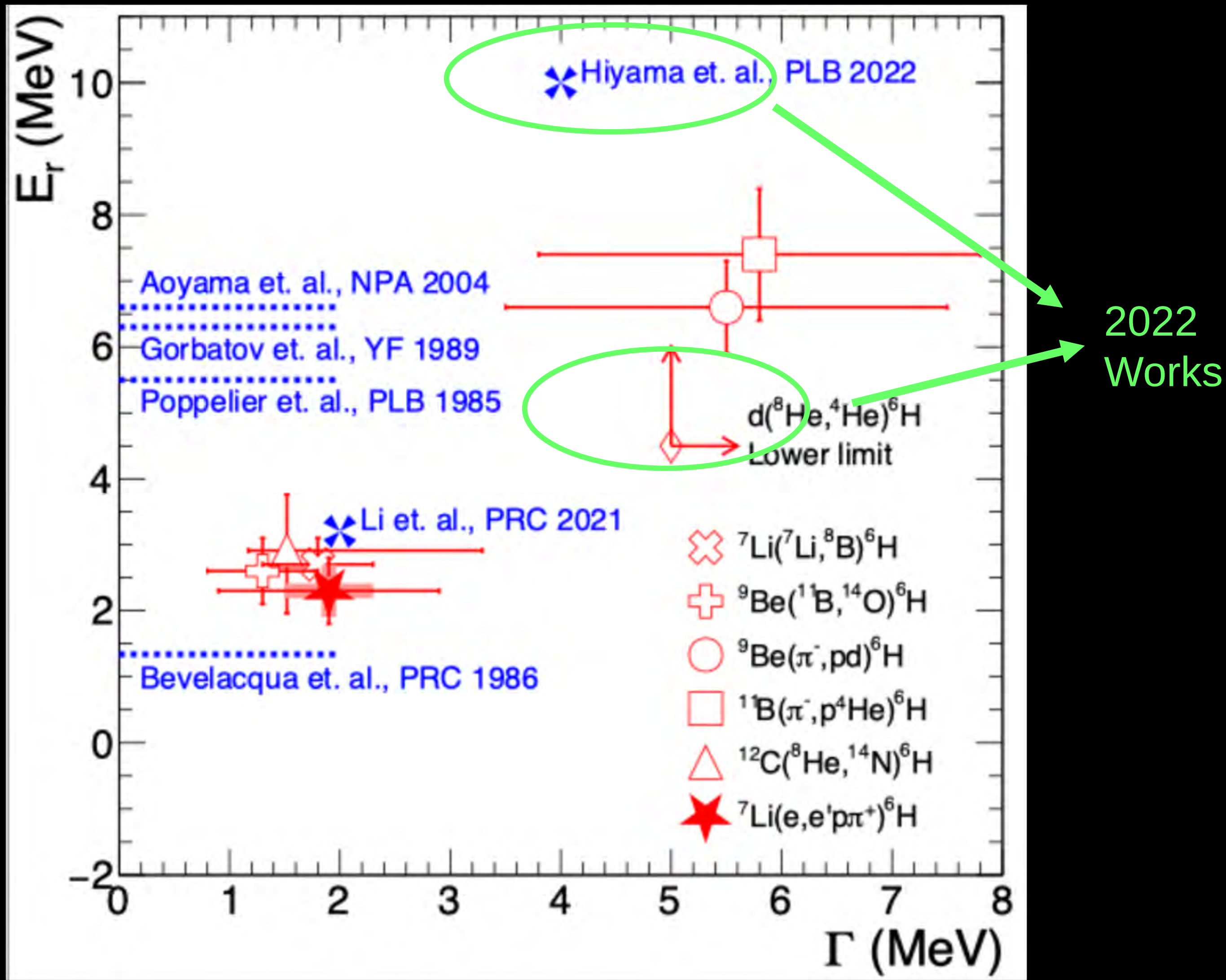
Result

- ^6H spectrum：Missing mass – 3H+n+n+n



- Support ^6H ground-state energy and width should be small
  - E = 2.3 ± 0.5 (stat.) ± 0.4 (syst.) MeV,
  - Γ = 1.9 ± 1.0 (stat.) ± 0.4 (syst.) MeV

Result

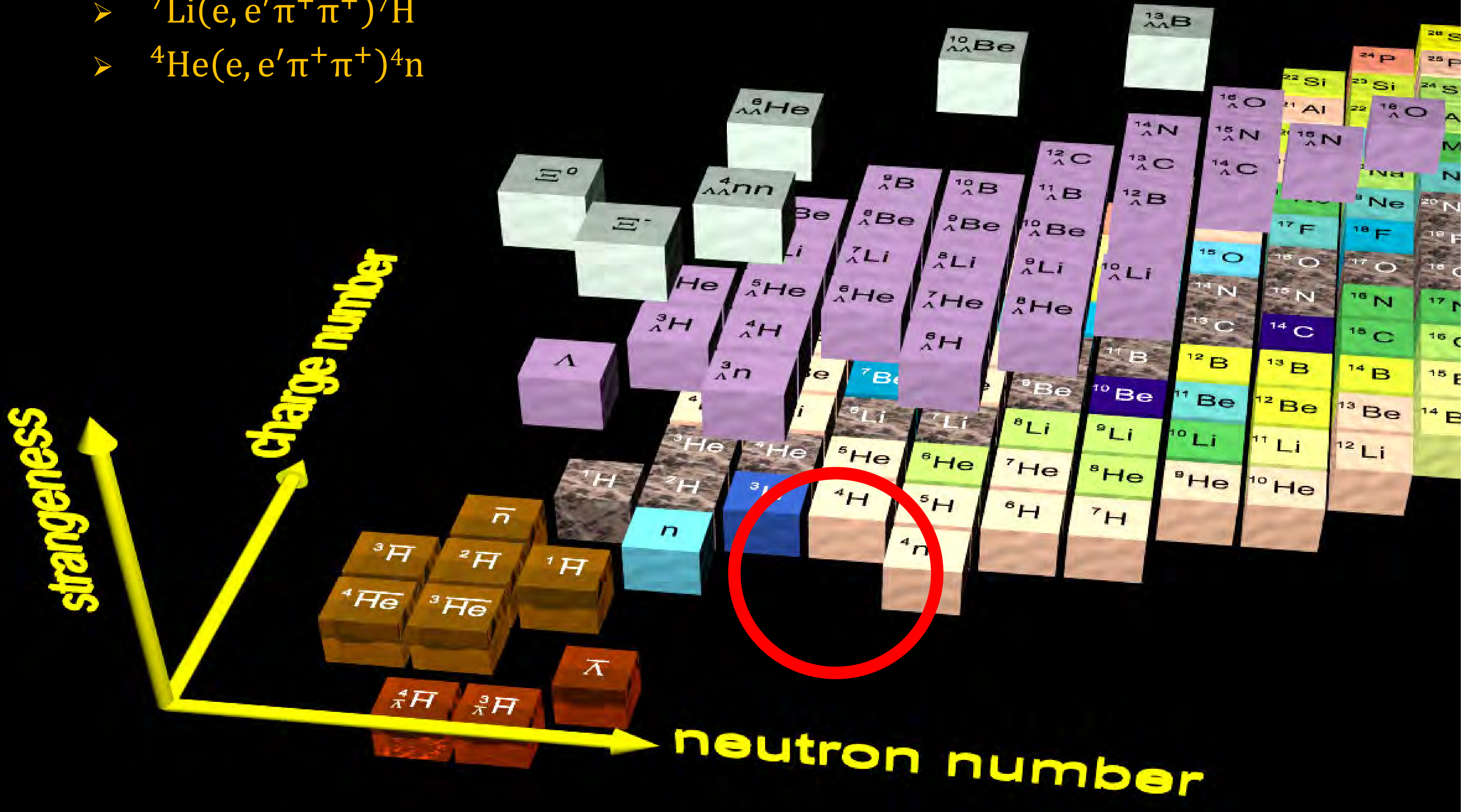


- First time to observe ^{6}H in an electron scattering experiment
- Measured ^{6}H ground-state energy and width are much smaller than 2022 works. Neutron interactions in ^{6}H maybe stronger than expect

Outlook

Future options

- Electron scattering experiment can be used to study neutron nuclei
- $^{6}\mathrm{Li}(e, e'p\pi^{+})^{5}\mathrm{H}$
- $^{4}\mathrm{He}(e, e'p\pi^{+})^{3}n$
- $^{7}\mathrm{Li}(e, e'\pi^{+}\pi^{+})^{7}\mathrm{H}$
- $^{4}\mathrm{He}(e, e'\pi^{+}\pi^{+})^{4}n$



Is there a nnn state?

Precise Spectroscopy of the 3*n* and 3*p* Systems via the ^{3}H(t,^{3}He)3n and ^{3}He(^{3}He,t)3p Reactions at Intermediate Energies

K. Miki,[1,2] K. Kameya,[1,2] D. Sakai,[1,2] R. Urayama,[1,2] N. Imai,[3] S. Ishikawa,[4] S. Michimasa,[3] S. Ota,[3] M. Sasano,[2] H. Takeda,[2] T. Uesaka,[2] H. Haba,[2] M. Hara,[5] Y. Hatano,[5] T. Hayamizu,[2] N. Kobayashi,[6] A. Tamii,[6] S. Adachi,[7] T. Chillery,[3] M. Dozono,[2,8] Y. Fujikawa,[8] H. Fujita,[6] N. Fukuda,[2] T. Furuno,[6] J. Gao,[9] S. Goto,[10] S. Hanai,[3] S. Hayakawa,[3] Y. Hijikata,[2,8] K. Himi,[7] Y. Hirai,[10] J. W. Hwang,[11] M. Ichimura,[2,*] D. Inomoto,[10] M. Inoue,[1,2] H. Kasahara,[10] T. Kawabata,[2,7] K. Kishimoto,[2,10] S. Kitayama,[1,2] K. Kusaka,[2] J. Li,[3] Y. Maeda,[12] Y. Maruta,[1,2] T. Matsui,[1,2] T. Matsuzaki,[2] S. Nakai,[1,2] H. Nishibata,[2,10] M. Otake,[2] Y. Saito,[1,2] H. Sakai,[2] A. Sakaue,[3] H. Sato,[2] K. Sekiguchi,[1,2] Y. Shimizu,[2] S. Shimoura,[3] L. Stuhl,[2,11] T. Sumikama,[2] H. Suzuki,[2] R. Tsuji,[2,8] S. Tsuji,[7] H. Umetsu,[1] Y. Utsuki,[1,2] T. Wakasa,[10] A. Watanabe,[1,2] K. Yako,[3] Y. Yanagisawa,[2] N. Yokota,[2,10] C. Yonemura,[2,10] K. Yoshida,[2] and M. Yoshimoto[2]

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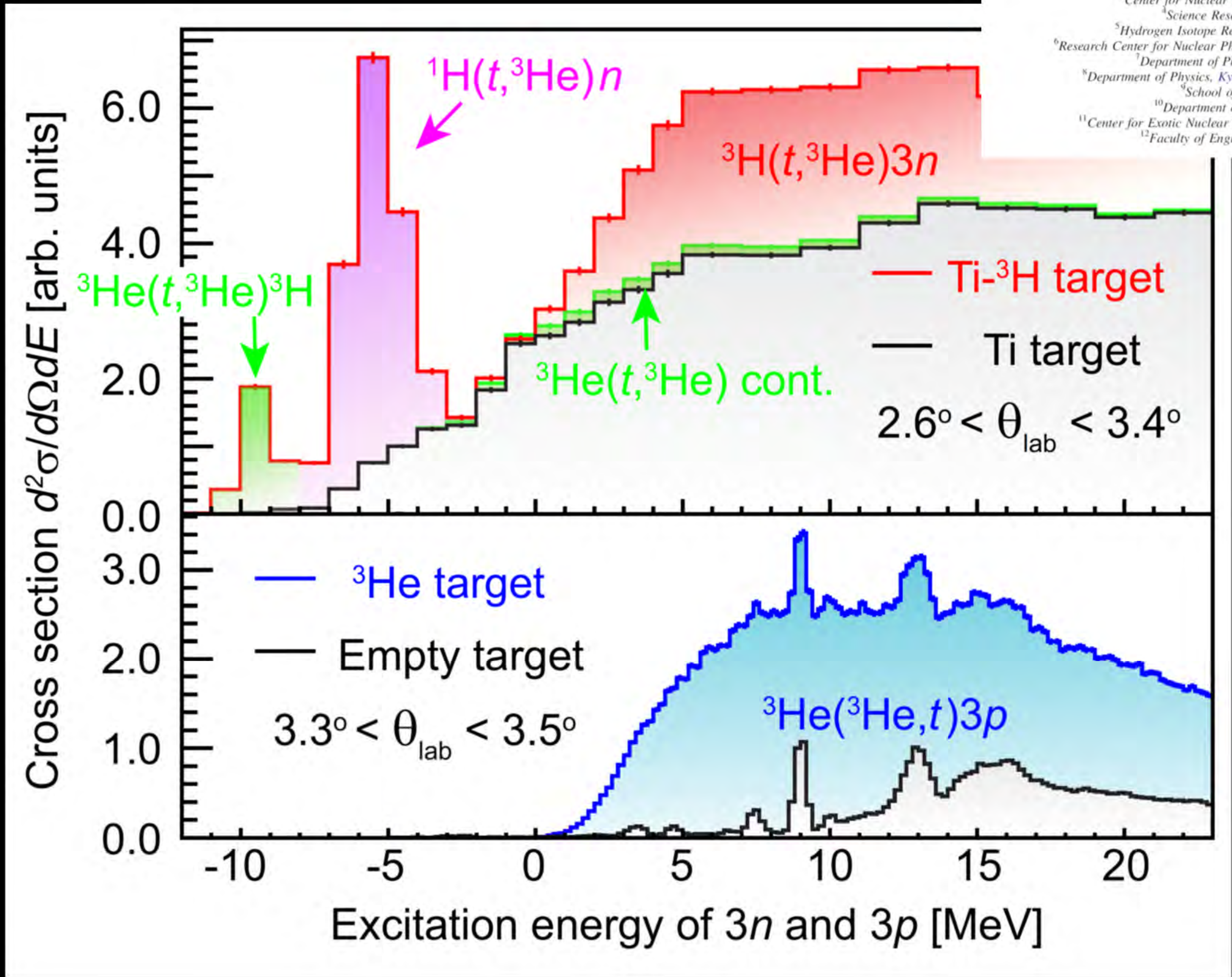

Expectations for the Trineutron

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Trineutron resonances in the SS-HORSE extension of the no-core shell model

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TABLE II. Energies E_r and widths Γ of trineutron resonant states obtained with soft NN interactions Daejeon16 [23], JISP16 [22], and SRG-evolved Idaho N^{3}LO [46]. Uncertainties are presented in parentheses. All values are in MeV.

	$3/2^-$		$1/2^-$	
Interaction	E_r	Γ	E_r	Γ
Daejeon16	0.48(6)	0.96(21)	0.48(8)	0.96(17)
JISP16	0.35(8)	0.70(9)	0.35(11)	0.67(22)
N^{3}LO, SRG, $\Lambda = 2$ fm^{-1}	0.34(8)	0.70(19)	0.35(9)	0.68(16)

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***Ab initio* no-core Gamow shell-model calculations of multineutron systems**

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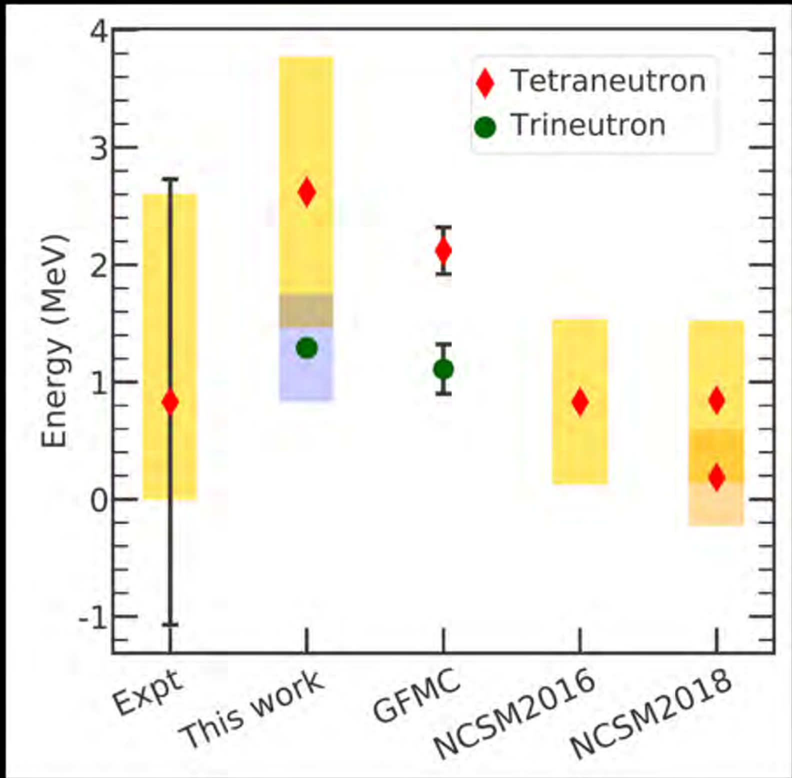
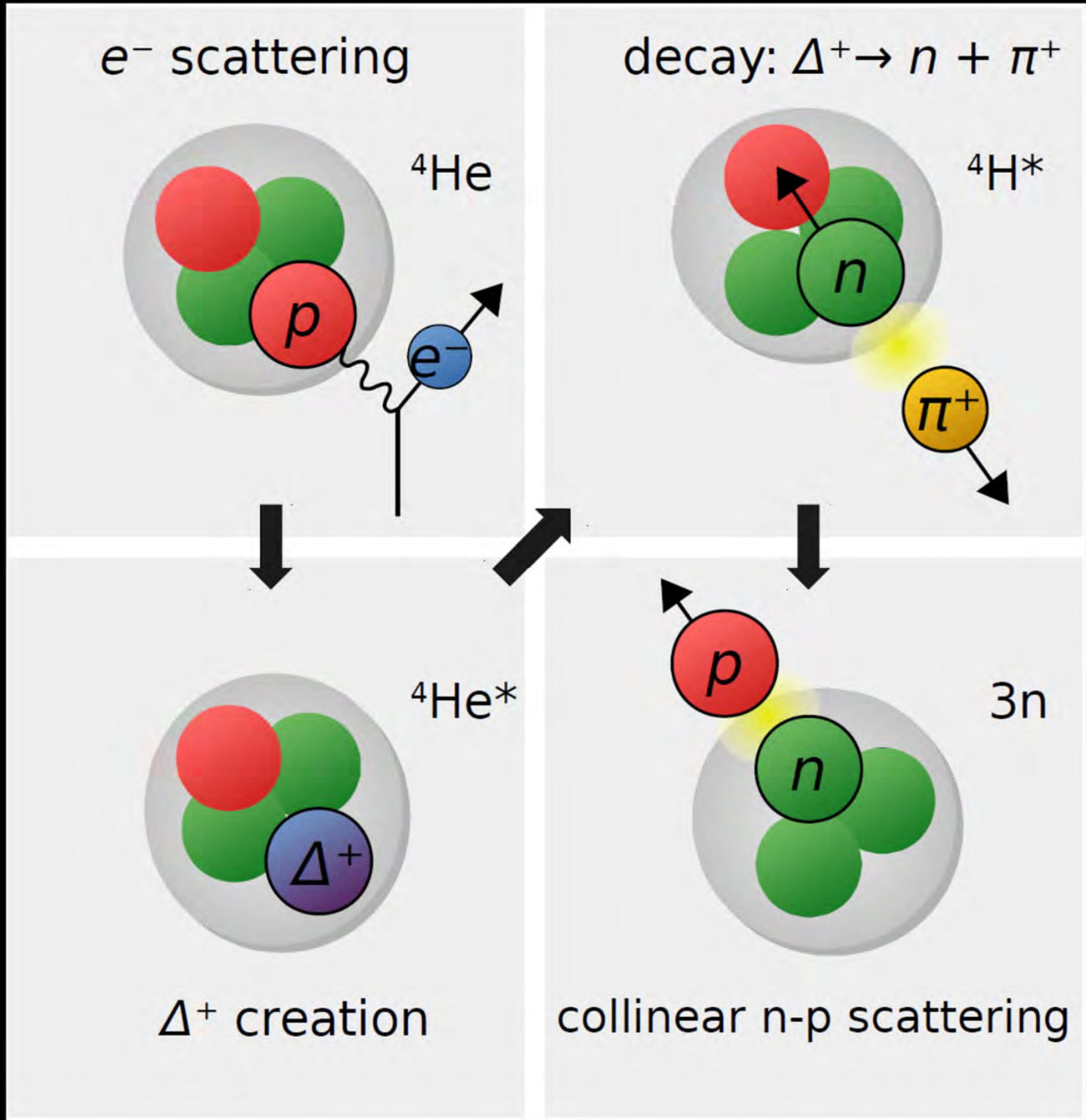


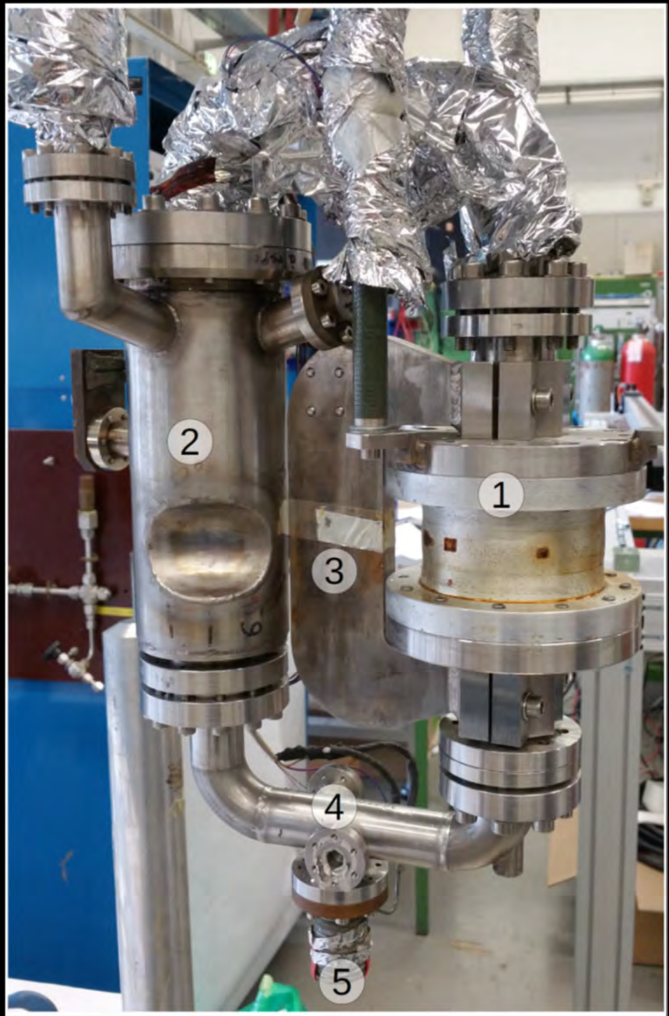
Reaction scheme to produce nnn



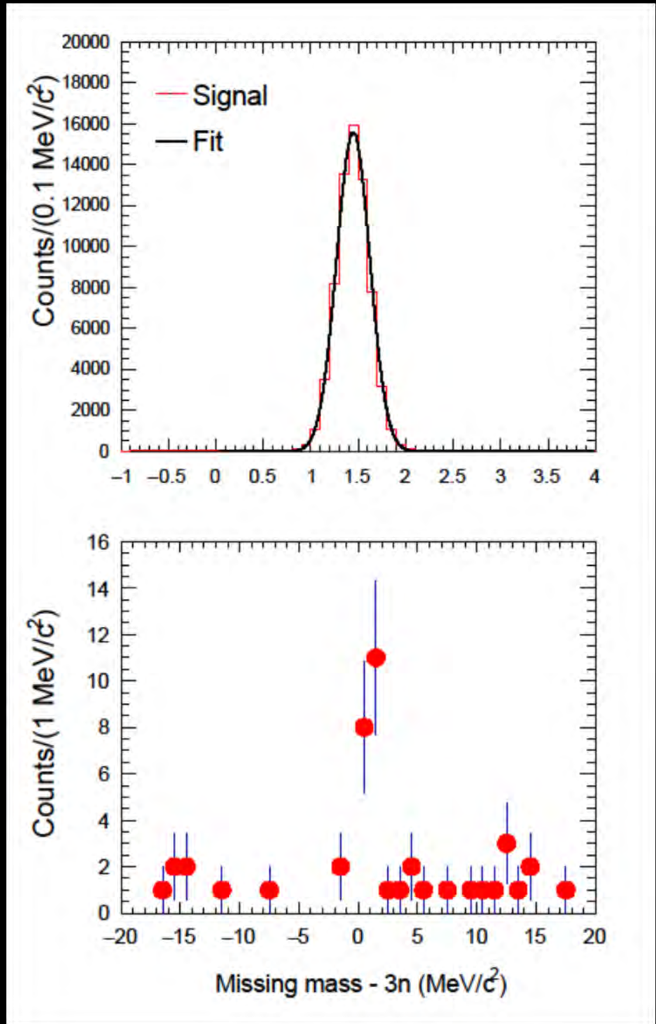
- Helium target needed

Possible nnn search

- ^{4}He target
  - Temperature T = 21K
  - pressure p = 15 bar
  - $\Rightarrow$ density ρ = 33,843 mg/cm^3



Diploma thesis Matthias Heilig



Summary

- For the first time we produced ^{6}H in an electron scattering experiment at MAMI-A1.
- The measured ^{6}H ground-state energy and width are much smaller than the latest experimental and theoretical works
- Electron scattering experiment can be used to search for nnn

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