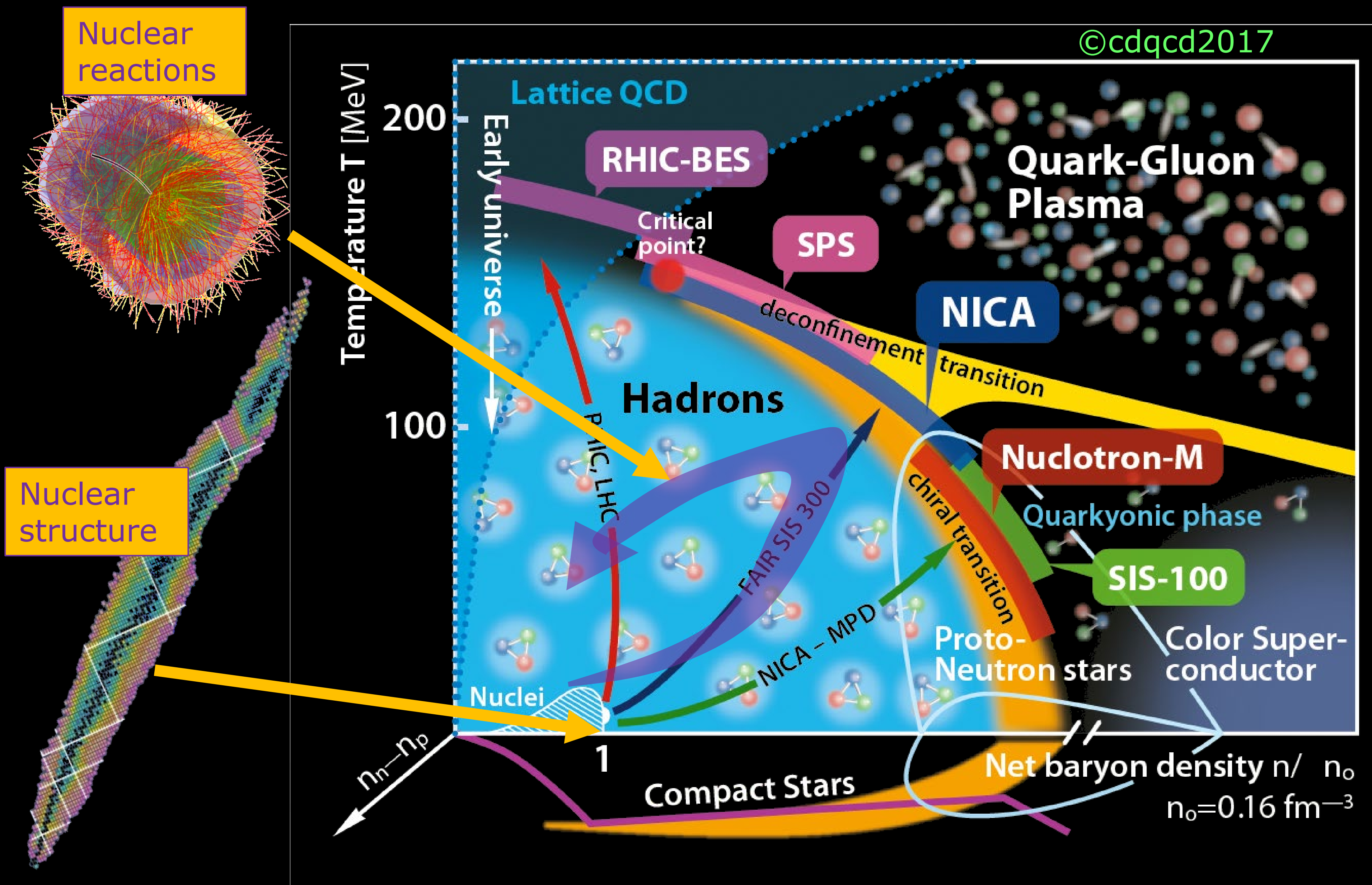
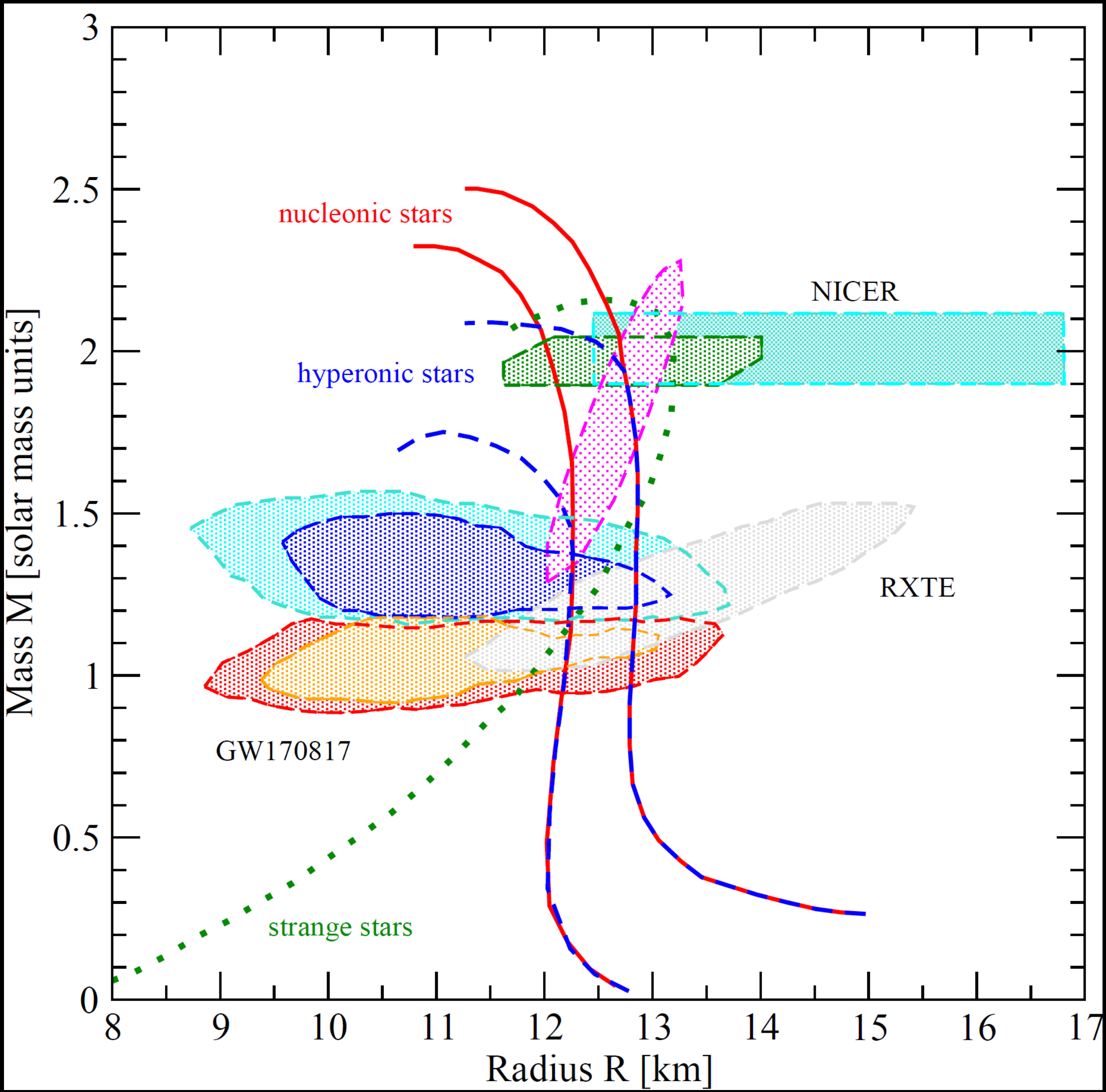
Hadronic EoS in the laboratory



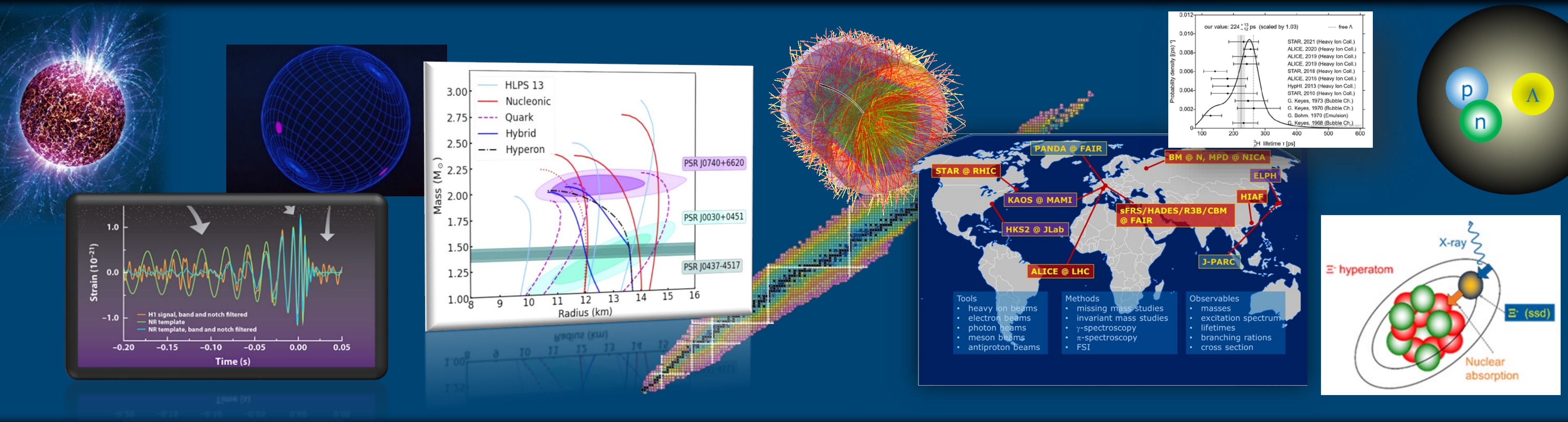
Stellar graveyard meets earth



Isaac Vidana

Kithbühel
14 September 2022

The hypertriton – what we know about and what we want to know



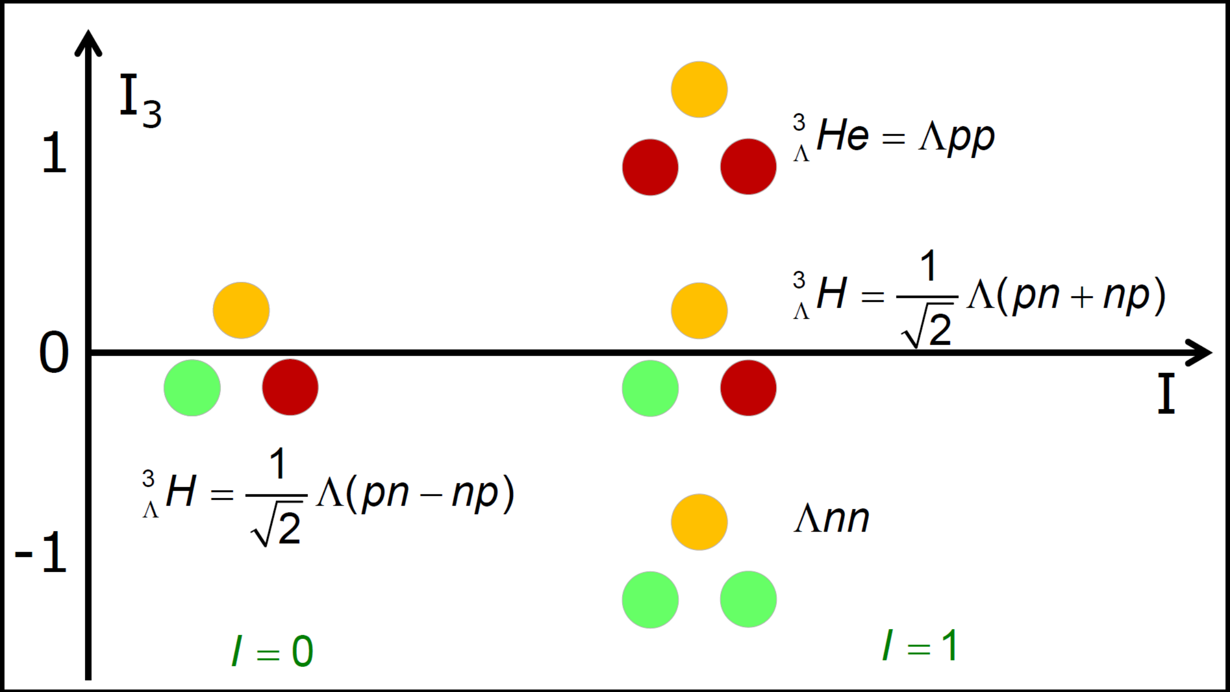
Josef Pochodzalla

JGU Mainz & Helmholtz-Institut – Mainz – European Union

JG|U HIM Helmholtz-Institut Mainz DFG Deutsche Forschungsgemeinschaft German Research Foundation STRONG 2020

A=3 hypernuclei

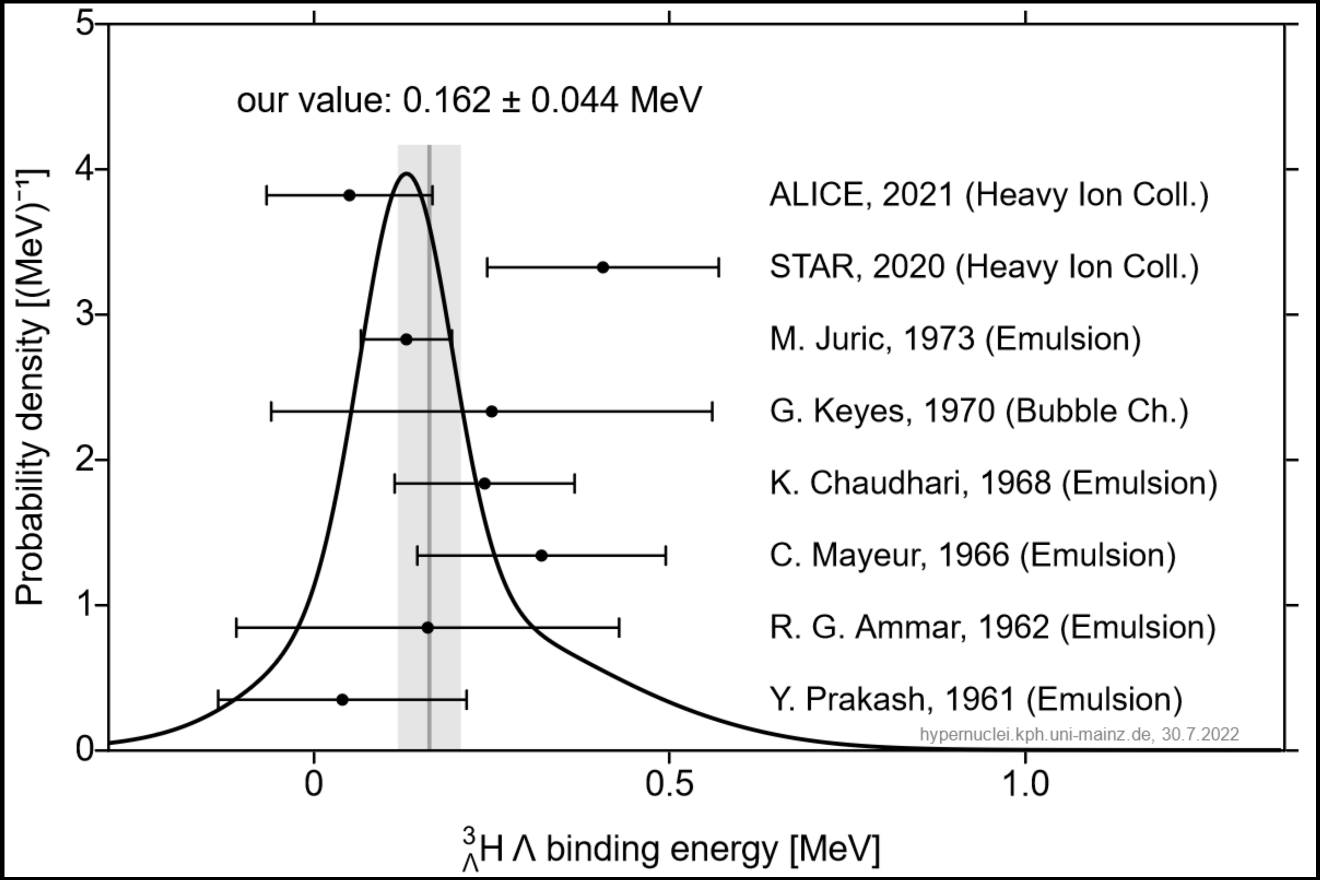
- Three-baryon forces are essential to describe complex nuclei
- A=3 hypernnuclei are important cornerstones



- I=0, $J^{\pi}=1/2^{+}$ is only nucleus known for sure to be bound
- Observed branching ratio $$R_3 = \frac{\Gamma({}^{3}_{\Lambda}H \to {}^{3}He + \pi^-)}{\Gamma({}^{3}_{\Lambda}H \to X + \pi^-)} = 0.35 \pm 0.04$$

  and small binding energy suggest groundstate spin $J^{P}=1/2^{+}$
- No experimental evidence for bound excited state

Hypertriton binding energy



Universality of two-body systems

- Consider near-threshold s-wave state
- Size of bound state ~scattering length

$$|a| \sim \frac{\hbar}{\sqrt{2\mu B}}$$

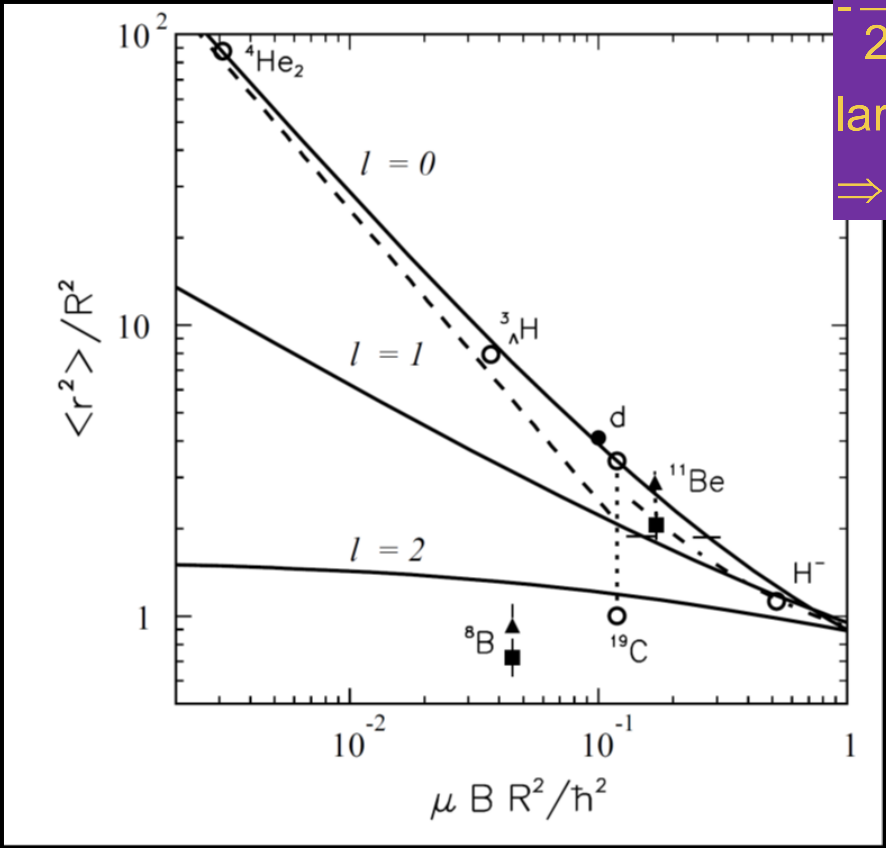
Schrödingerequation

$$-\frac{h^2}{2\mu}\frac{d^2}{dr^2}u(r)+V(r)\cdot u(r)=B\cdot u(r)$$

large distance ($V(r) \to 0$) and $B \to 0$

$\Rightarrow \quad u(r)=C(r-a)$

ratio of halo and core-potential square radii



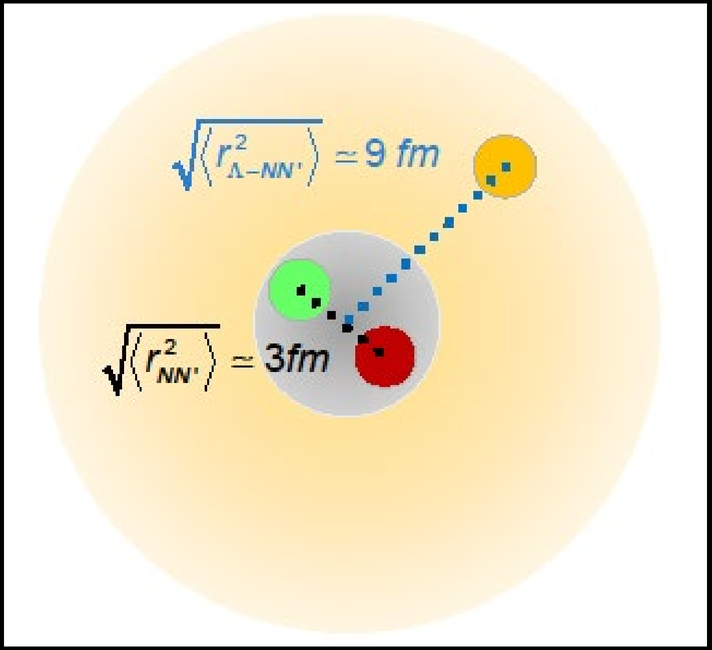
scaled separation energy

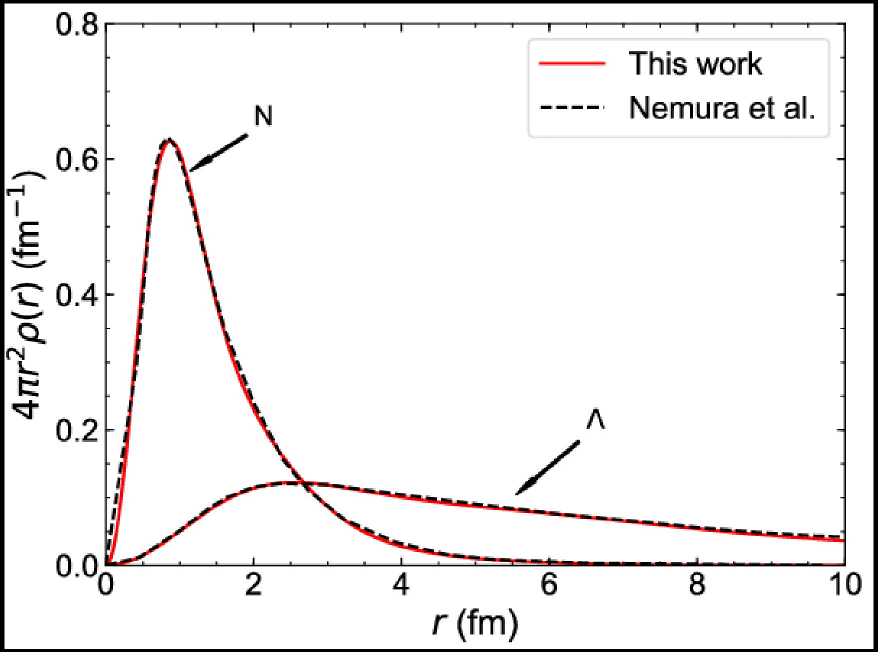
K.Riisager,D.V.FedorovandA.S.Jensen, Europhys. Lett 49, 547 (2000)

$^3_\Lambda$H - a fascinating halo nucleus

- Binding energy ≈162keV $\Rightarrow$ Characteristic length of two-body s-wave halo system

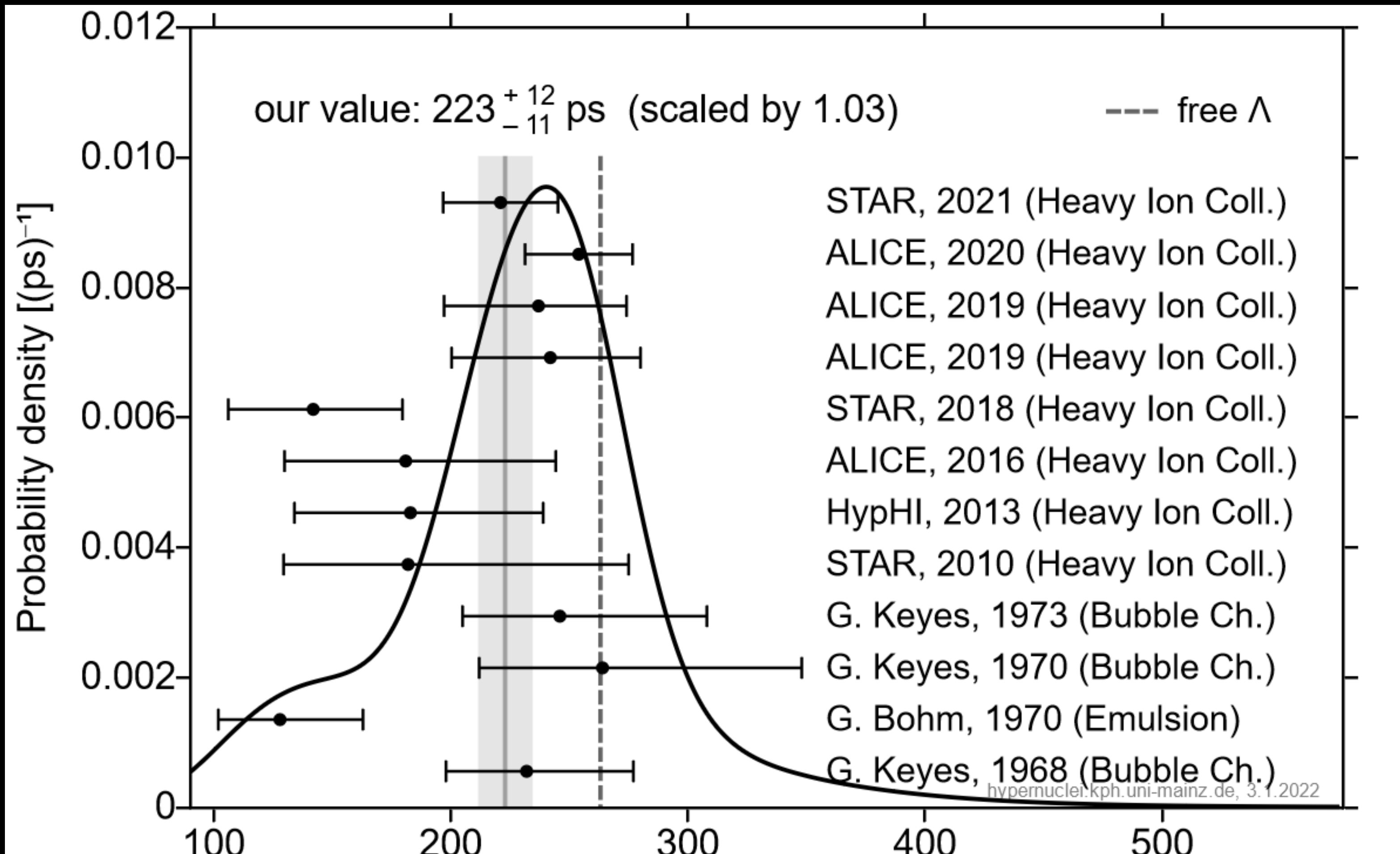
$$\langle \Delta r^2 \rangle = \hbar^2 / (4\mu B) \xrightarrow{^3_\Lambda \mathrm{H}} 9\,\mathrm{fm}$$





H. Nemura *et al.* (2000)
Z. Zhang *et al.* (2018)

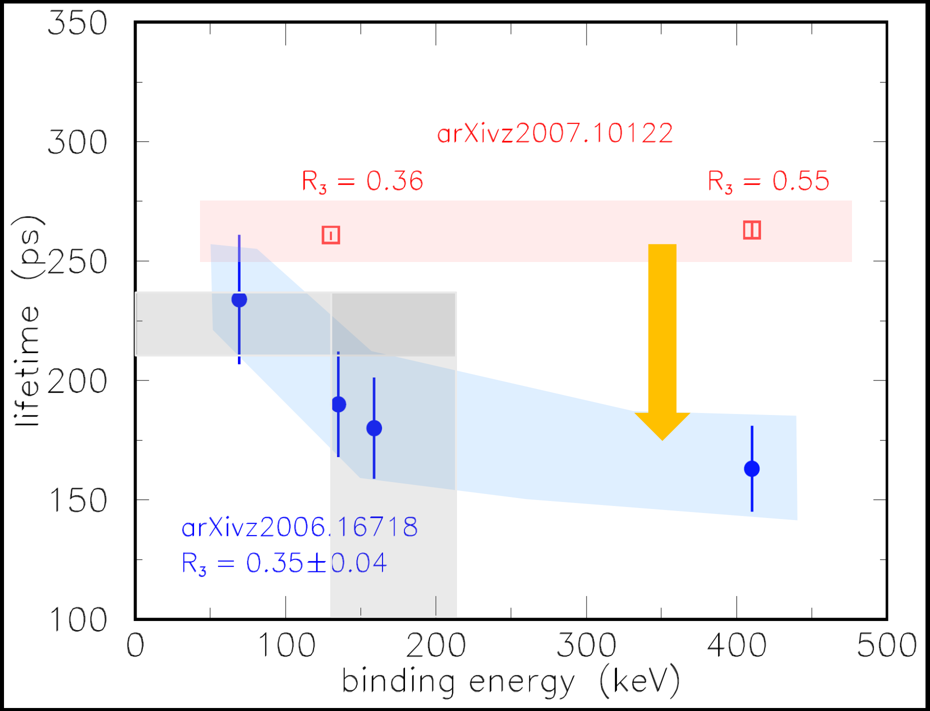
Lifetime of $^{3}_{\Lambda}H$



Is there still a puzzle?

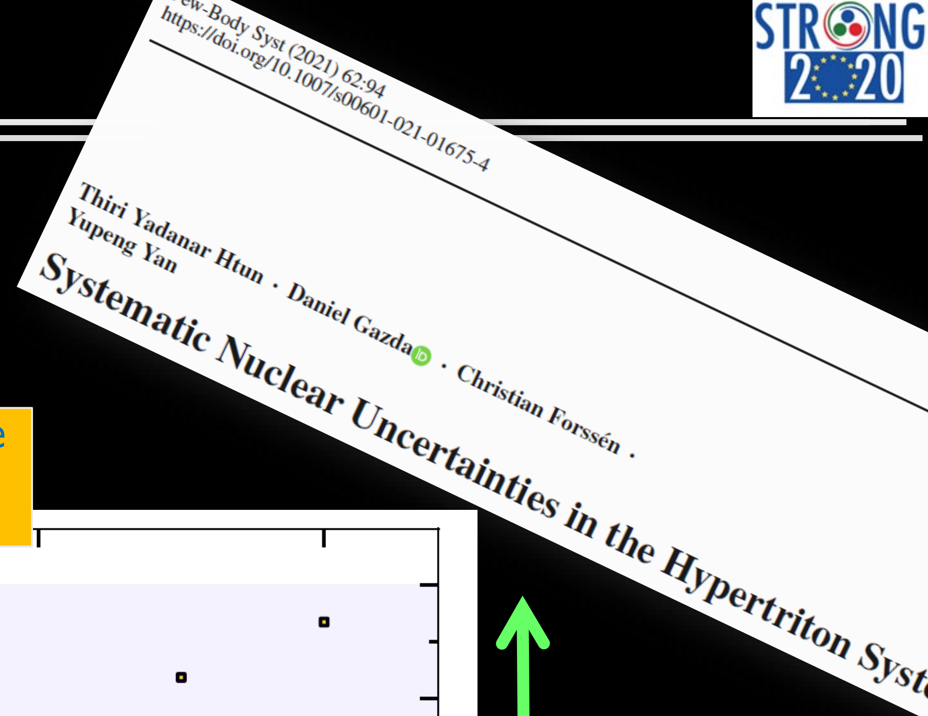
- Hildebrand & Hammer, EFT
  PRC 102, 064002 (2020)
  - exp. $R_3 \approx 0.35$ favors small BE

- Obiol et al., EFT
  PLB 811, 135916 (2020)
  - π distorted waves and
  - ΣNN admixture important
  - $\Rightarrow$ strong relation between BE and τ
- Precise measurements of BE *and* τ will provide a stringent test of models



Quest for precision

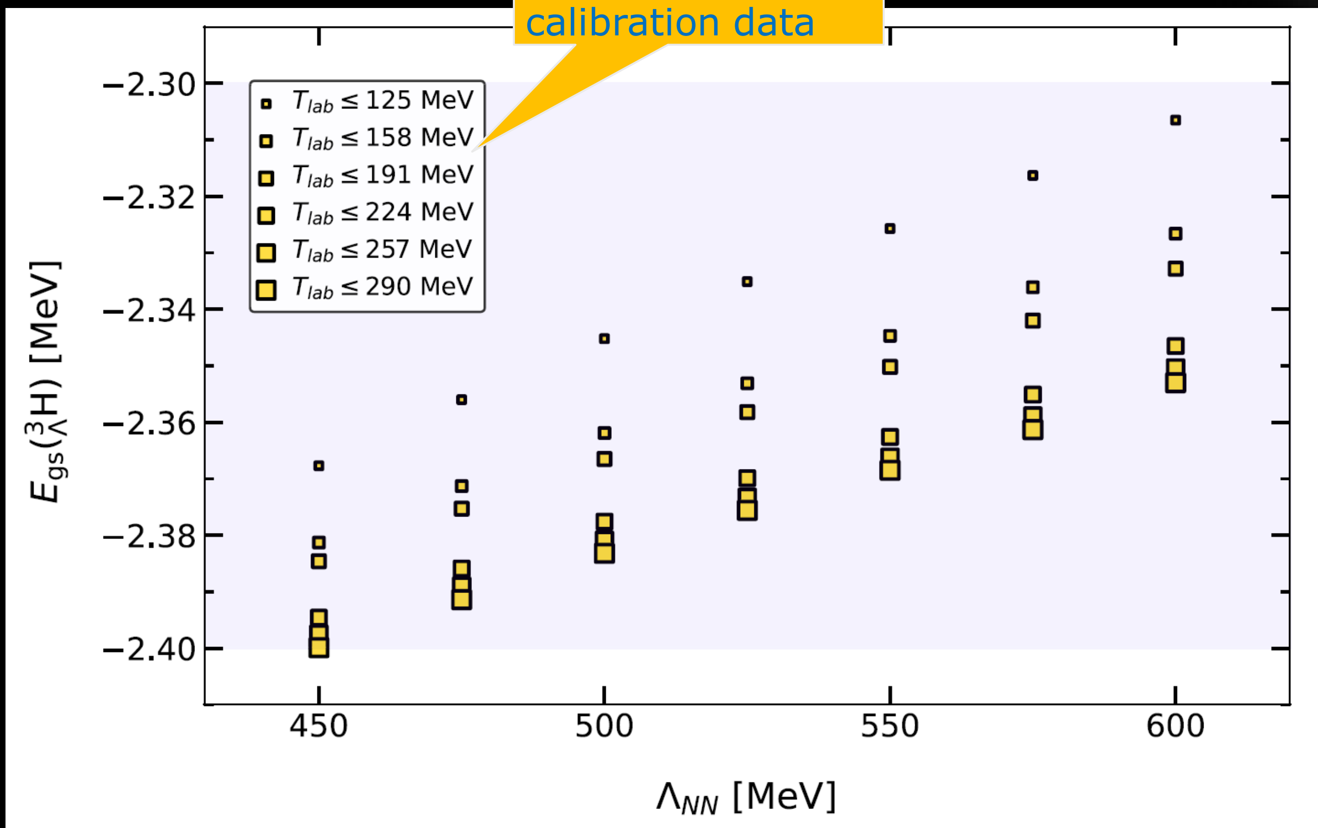
- Systematic study of hypertriton binding energy in 42 different NNLO interactoin models


ew-Body Syst (2021) 62:94
https://doi.org/10.1007/s00601-021-01675-4

Thiri Yadanar Htun · Daniel Gazda · Christian Forssén ·
Yupeng Yan

Systematic Nuclear Uncertainties in the Hypertriton Syst

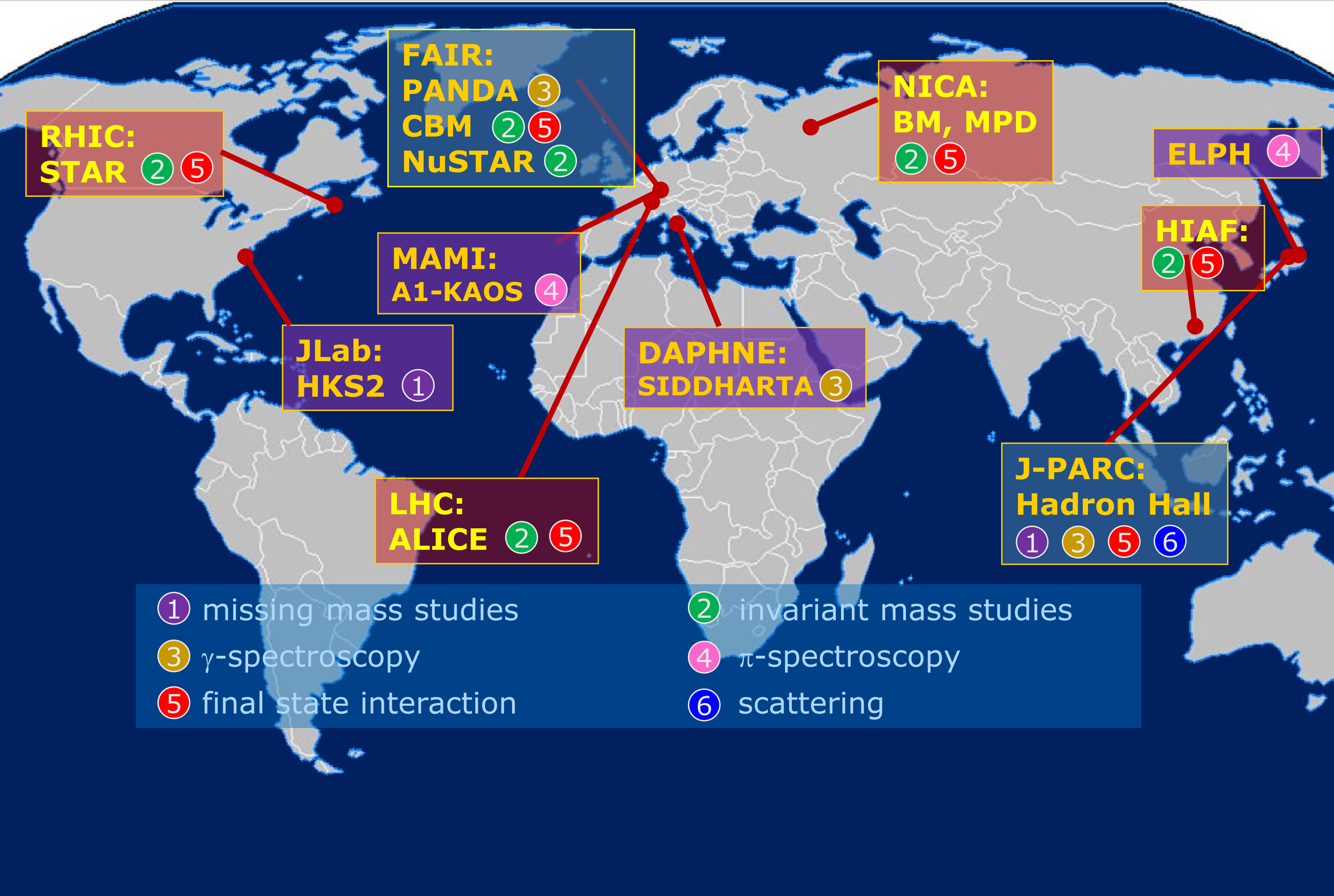
truncations of the NN scattering calibration data



~100 keV

regulator cutoff parameter

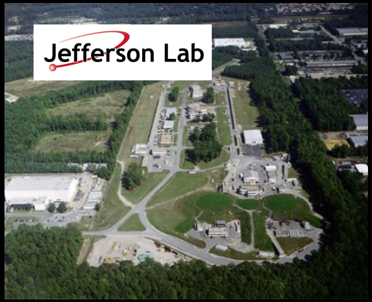
Activities across the world



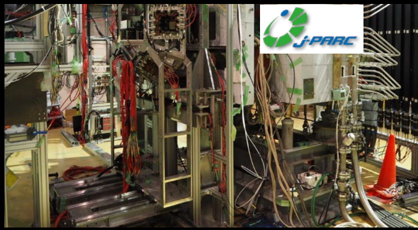
Upcoming mass measurements

- A the Mainz Mikrotron (MAMI), a new high precision pion spectroscopy experiment aims at a measurement with a systematic uncertainty which is comparable to the statistical error of ≤ 20 keV

- At JLab, a missing-mass measurement of the hypertriton mass with a accuracy of less than 100 keV has been proposed.

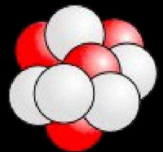


- The J-PARC E07 collaboration plans to analyse hypertriton decays in their emulsion plates. Using Monte Carlo simulations, the statistical and systematic errors for the hypertriton binding energy in this emulsion measurement has been estimated to be approximately 30 keV each. (*see Take Saito*)

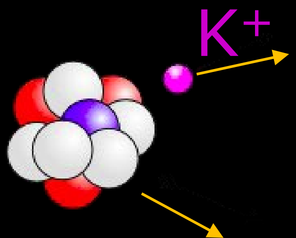


- Improved measurements by heavy ion experiments ALICE and STAR expected

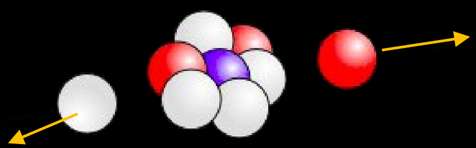
High resolution pion spectroscopy



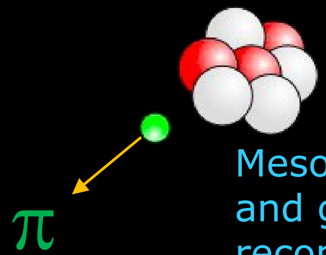
Electroproduction of excited hypernuclei on ^{9}Be Target



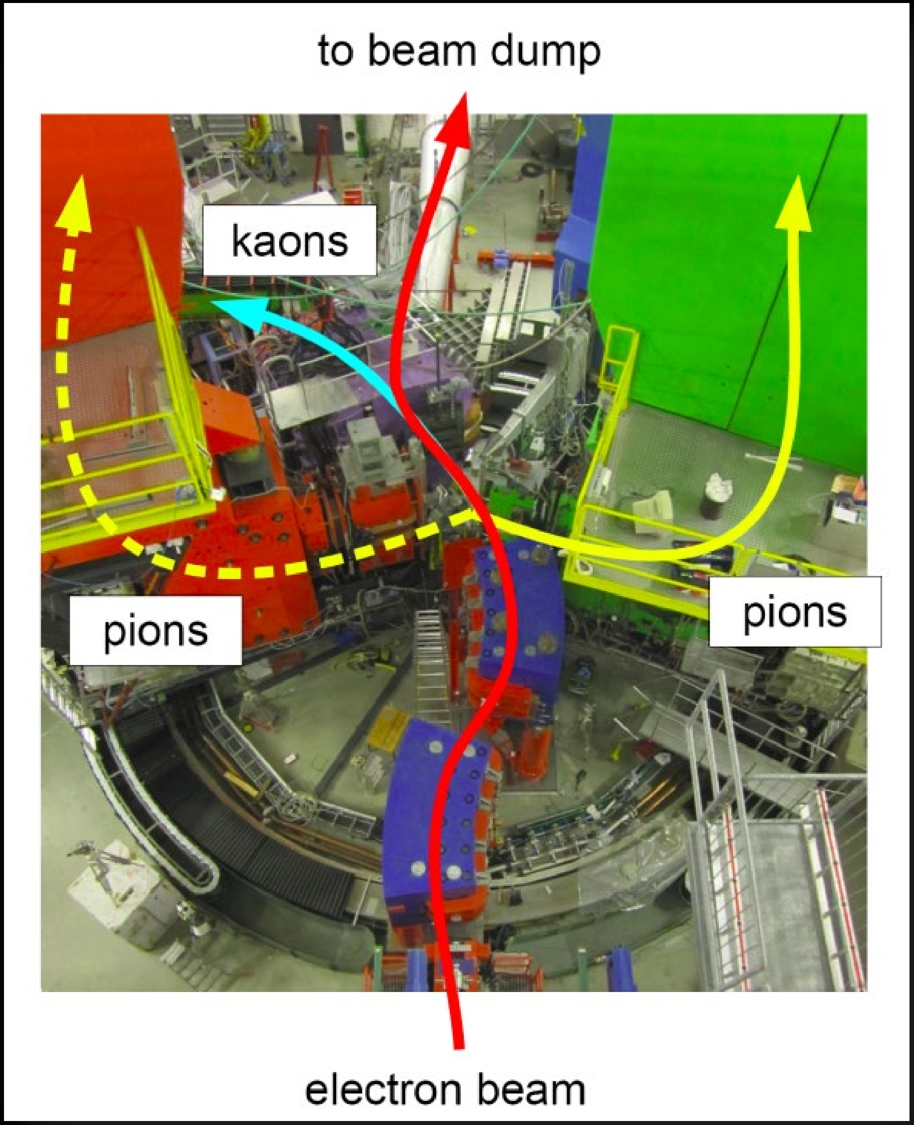
Event tagging by kaon detection



Fragmentation produces several light hypernuclei



Mesonic weak decay and groundstate mass reconstruction by spectroscopy of pions from two-body decay



Phys. Rev. Lett. **115**, 222501 (2015)

Previous Decay Pion Spectroscopy

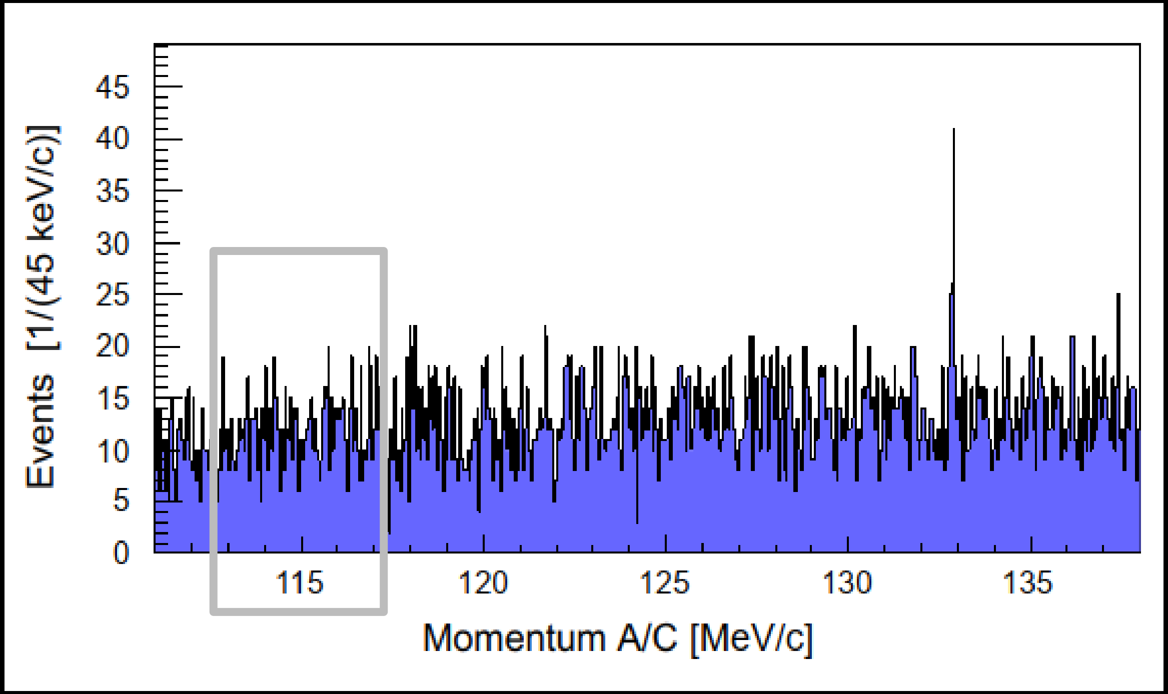
- Two body decays of hypernuclei:

$$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-} \quad 114\,\mathrm{MeV/c}$$

$$^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-} \quad 133\,\mathrm{MeV/c}$$

- B_{Λ} = 2157 ± 5 (stat.) ± 77 (syst.) keV[1]
- However: Hypertriton not observed
- From fragmentation model: 1/10 of $^{4}_{\Lambda}$H yield

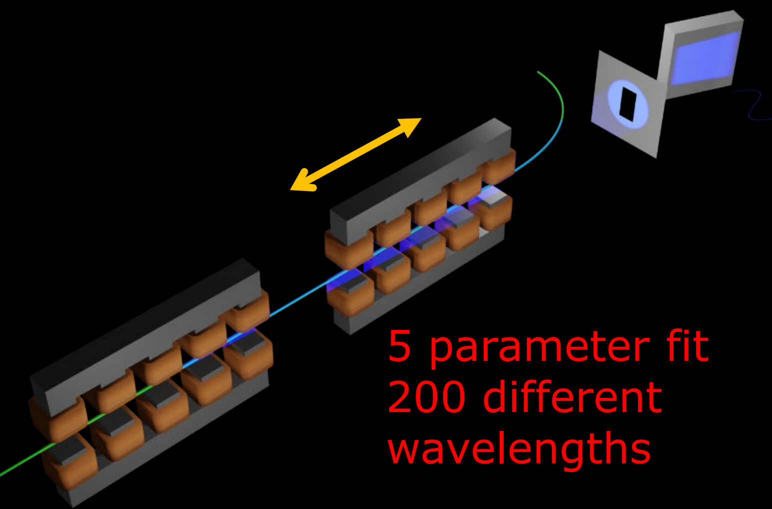
Decay pion momentum



[1] F. Schulz, NPA 954, 149 (2016)

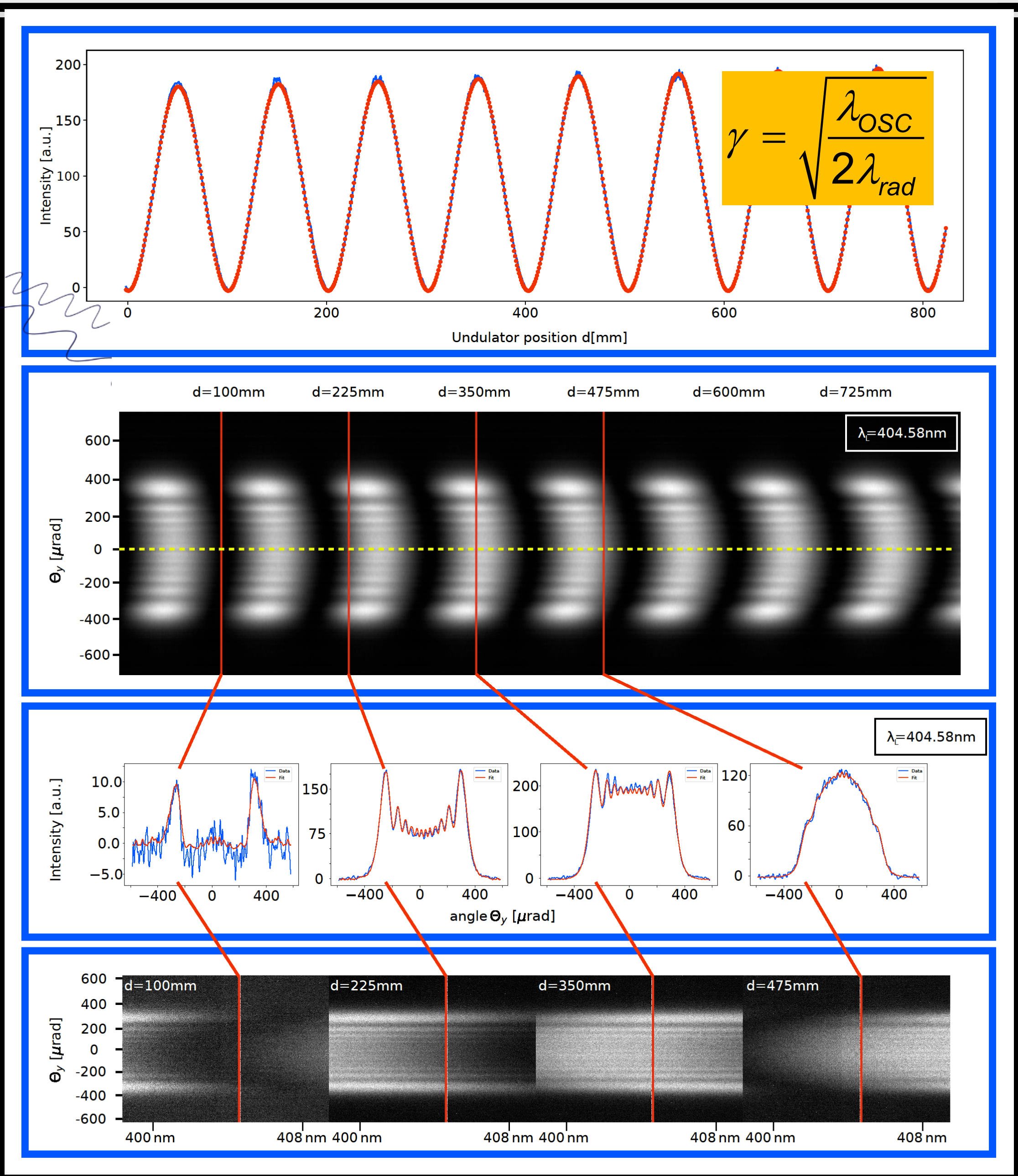
Absolute beam energy measurement

PhD Pascal Klag

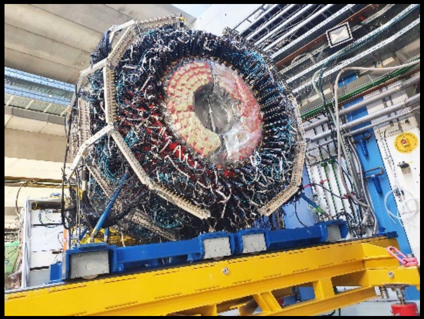


5 parameter fit
200 different wavelengths

Hypertriton measurement running right now!



Upcoming lifetime studies

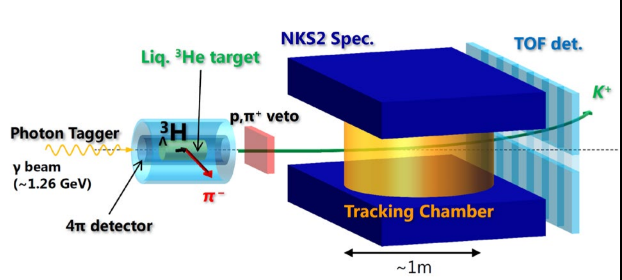


- Data taken by WASA-FRS Collaboration in March 2022 at GSI/FAIR might provide an improved lifetime measurement of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ analyzing decay vertices.

- During the LHC RUN3 and Run4 in the coming decade 2022-2030, ALICE will increase the data rates by a factor larger than 50.

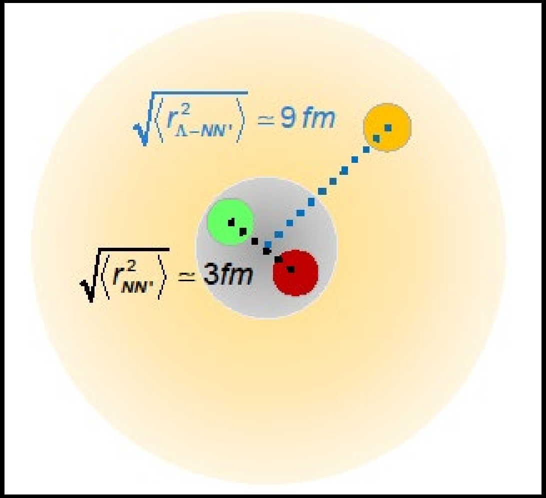
- The P73/P77 collaboration at J-PARC plans to measure the ${}^{3}_{\Lambda}H$ lifetime with a K^{-} beam. The lifetime is determined event-by-event by the time difference between the starting time and the decay product pion of ${}^{3}_{\Lambda}H$. The collaboration aims at a uncertainty of about 20%.

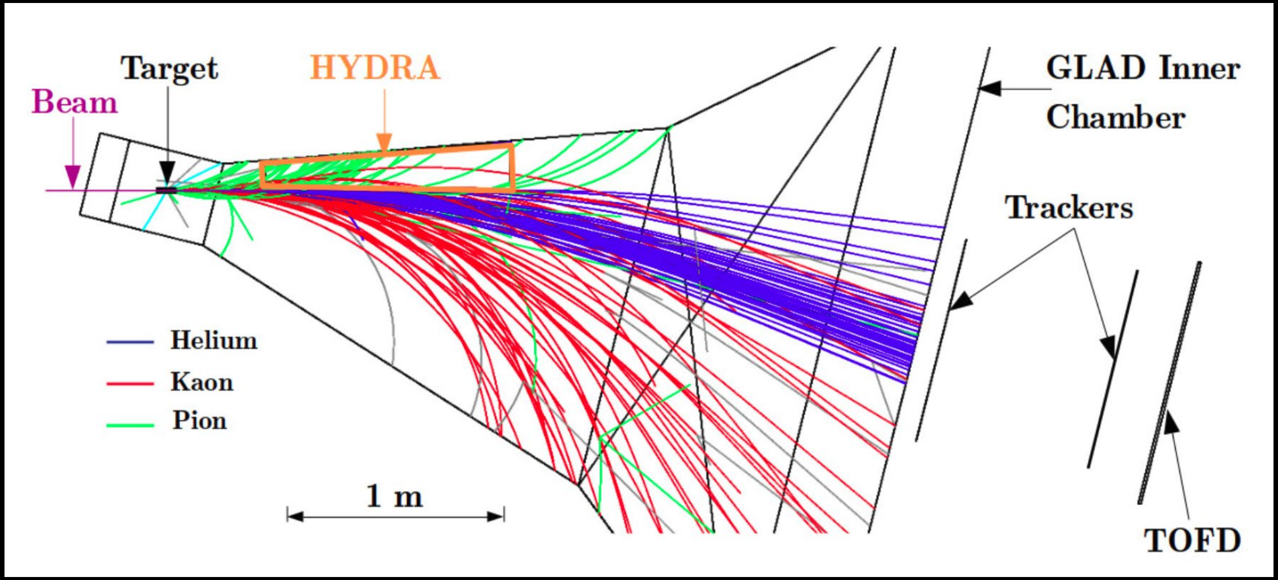
- An experiment at the Tohoku University at ELPH plans to employ a photon beam to produce ${}^{3}_{\Lambda}H$ and measure the decay time spectrum. Goal $\Delta t = 10 ps$

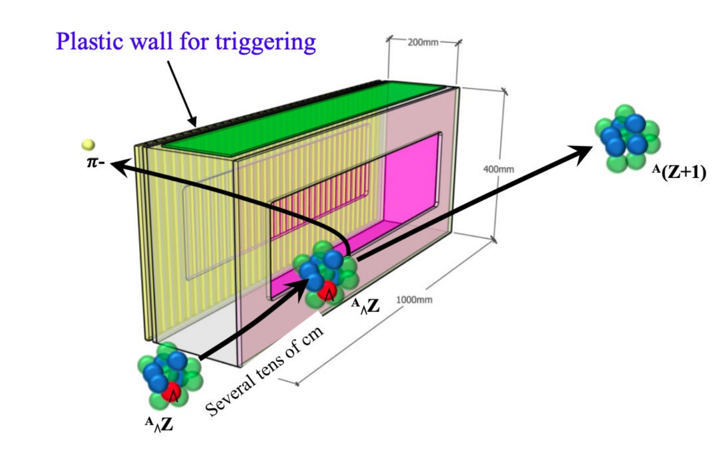


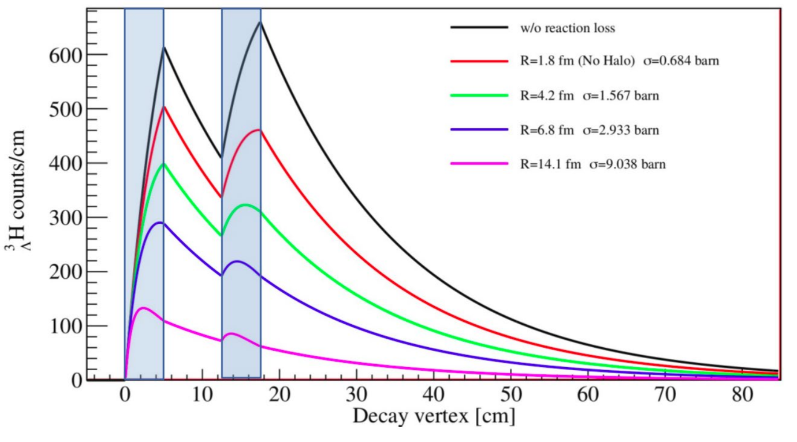
Hypernuclei Decay at R3B Apparatus

- HYDRA: Measure reaction cross section of ${}^{3}_{\Lambda}H$
- Primary production and secondary reaction target







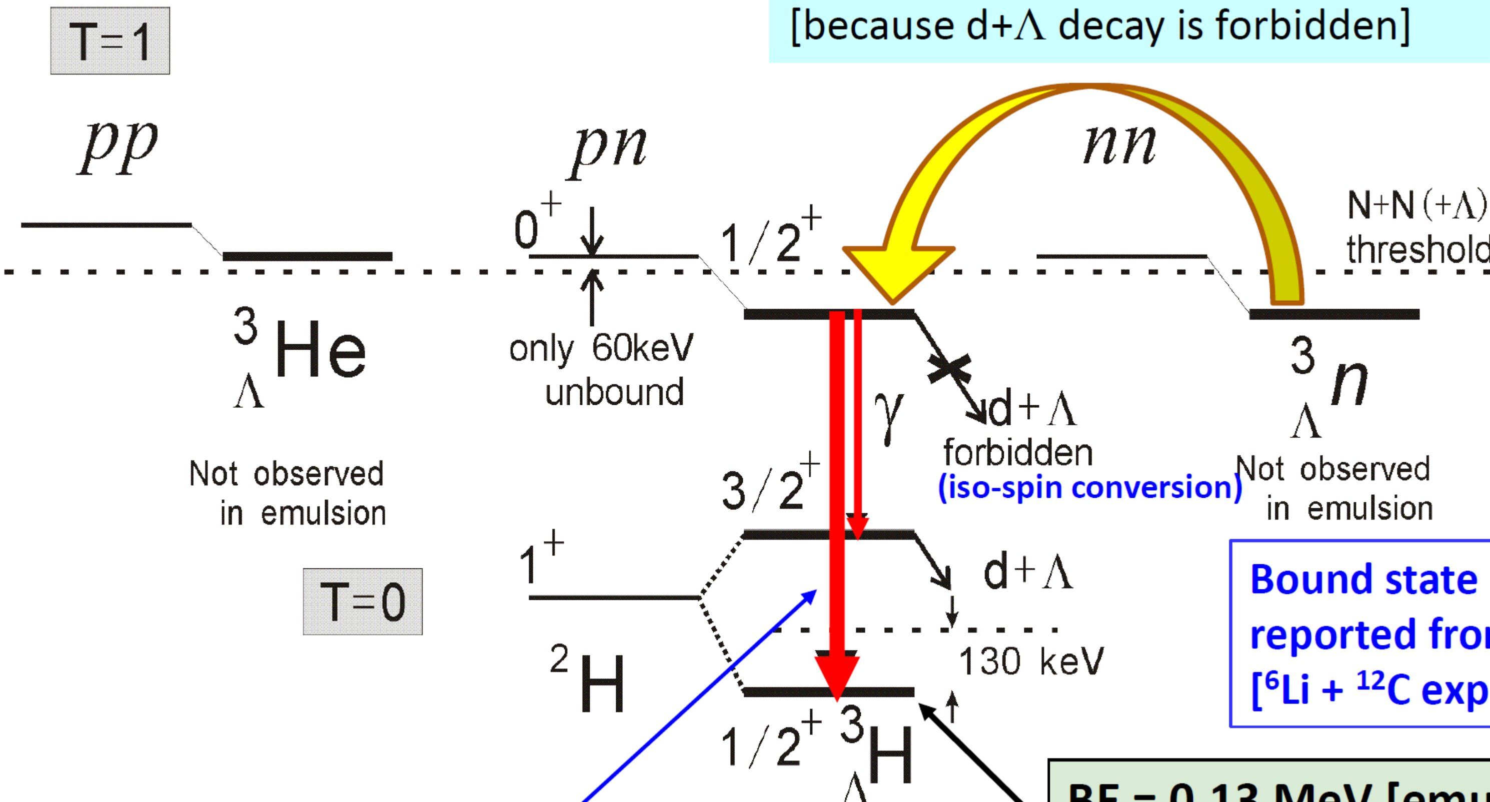


Alexandre Obertreille *et al.*

Does an excited state exist?

Present status of $^3_\Lambda$H

Same isospin group
→ $^3_\Lambda$H (1/2⁺, T=1) is particle bound state?
[because d+Λ decay is forbidden]



Bound state reported from GSI [^{6}Li + ^{12}C exp.]

BE = 0.13 MeV [emulsion]
BE = 0.41 MeV [STAR, 2019]

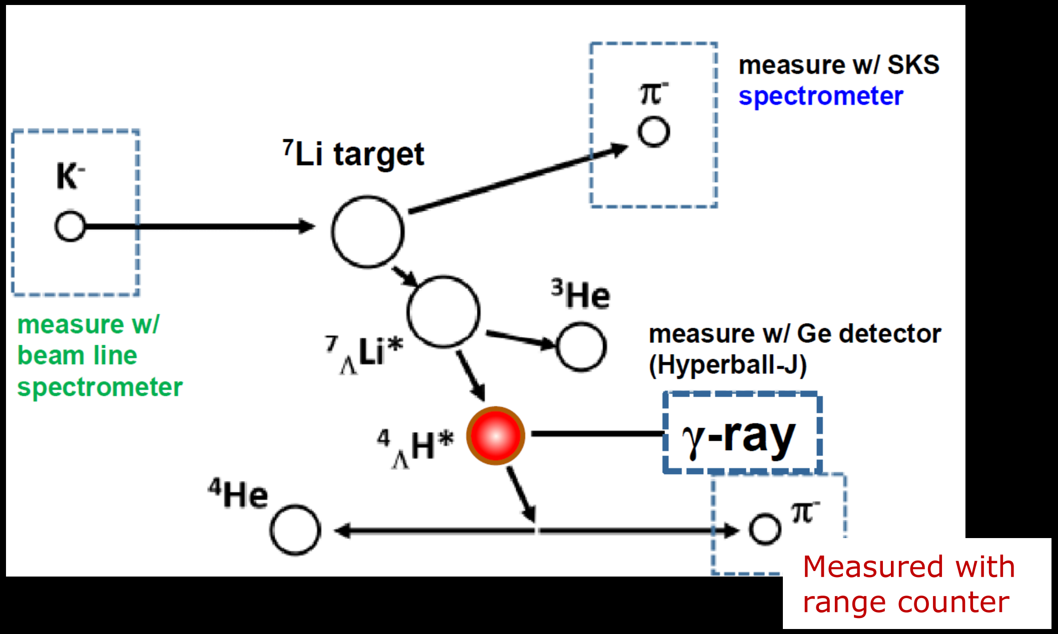
If $^3_\Lambda$H (1/2⁺, T=1) is particle bound state, we can observe γ transition (1/2⁺, T=1) → (1/2⁺)

Deeper bound?

Slide from T.O.Yamamoto

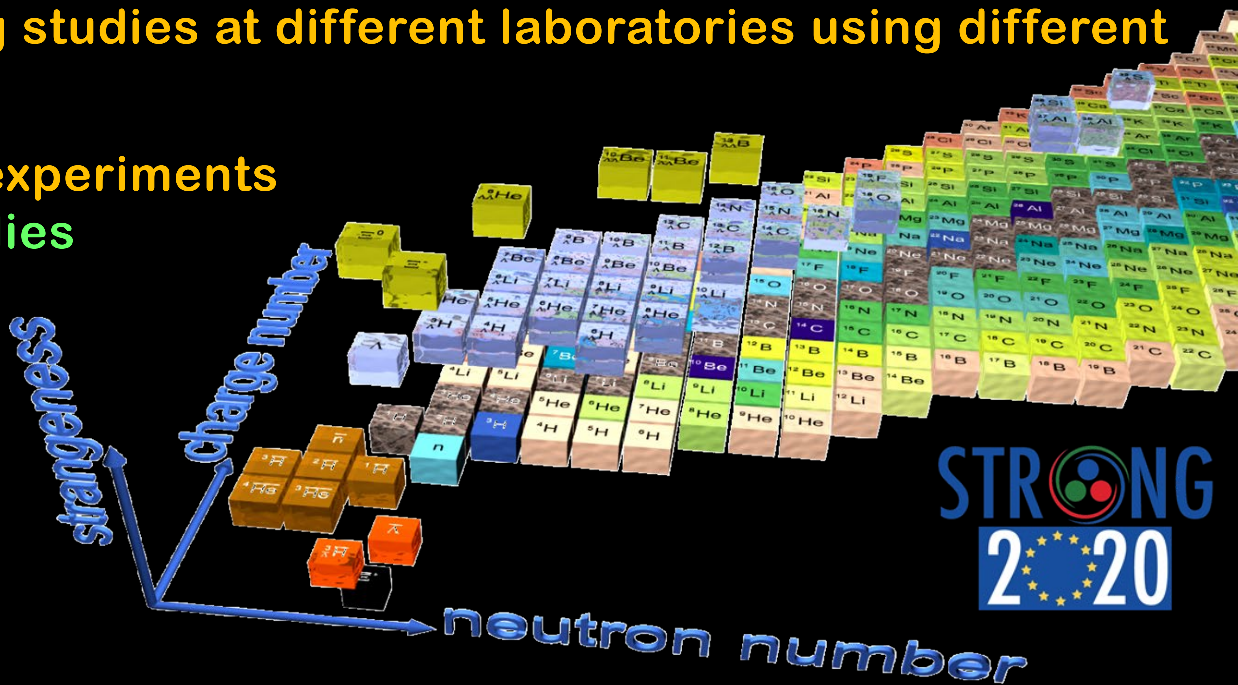
Does an excited state exist?

- Combine missing mass + π-spectroscopy + γ-spectroscopy
- γ-ray spectroscopy of hypernuclei at the K1.1 beamline of J-PARC
- Selecting in the ^{7}Li(K^{-},π^{-}) missing mass reaction the unbound region and by tagging the 2-body weak decay $^{3}_{\Lambda}$H$\rightarrow$ ^{3}He by the monoenergetic π^{-}
- A high resolution Ge array can then be used to search for the γ-ray transitions of $^{3}_{\Lambda}$H.



Take-home message

- **Strangeness nuclear physics is embedded in the quest to determine the EOS of dense stellar systems**
- **Hypernuclei and hyperatoms are femto-laboratories for Y^nN^m interaction**
- **After 60 years still many puzzles: hypertriton, existence of neutral hypernuclei nnΛ, nn$\Lambda\Lambda$, ...hyperon puzzle of NS...**
- **Several complementing studies at different laboratories using different techniques**
- **Coming generation of experiments focus on precision studies**
- Worldwide activities offer a wide variety of unique and highly relevant opportunities for studying strangeness nuclear physics



- Guidance by nuclear theory (EFT, Lattice,...) is indispensible!