Nuclear Structure with Rare Isotopes
Recent Results and Future Projects

TECHNISCHE UNIVERSITÄT DARMSTADT

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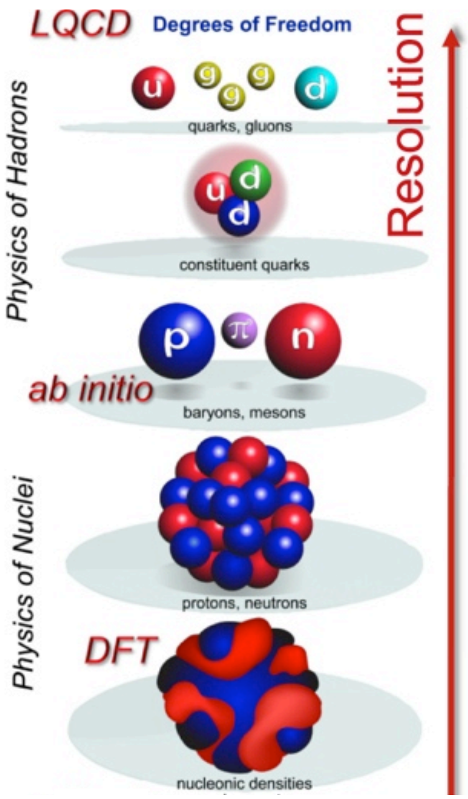
[web version: unpublished results removed]

GSI-FAIR Colloquium
February 5th, 2019

Alexander von Humboldt Stiftung/Foundation erc DFG SFB 1245

The atomic nucleus



- ❑ How far can nuclei be described from ***ab initio* principles**?
- ❑ How do protons and neutrons **interact** with each other to form nuclei?
- ❑ What are the relevant **degrees of freedom** to describe nuclear phenomena?
- ❑ What can nuclei teach us about (neutron) **stars**?

Figure from G. F. Bertsch, D. J. Dean and W. Nazarewicz, SciDAC Rev. 6 (12007)

Neutron-to-proton asymmetry in nuclei: a “new” degree of freedom

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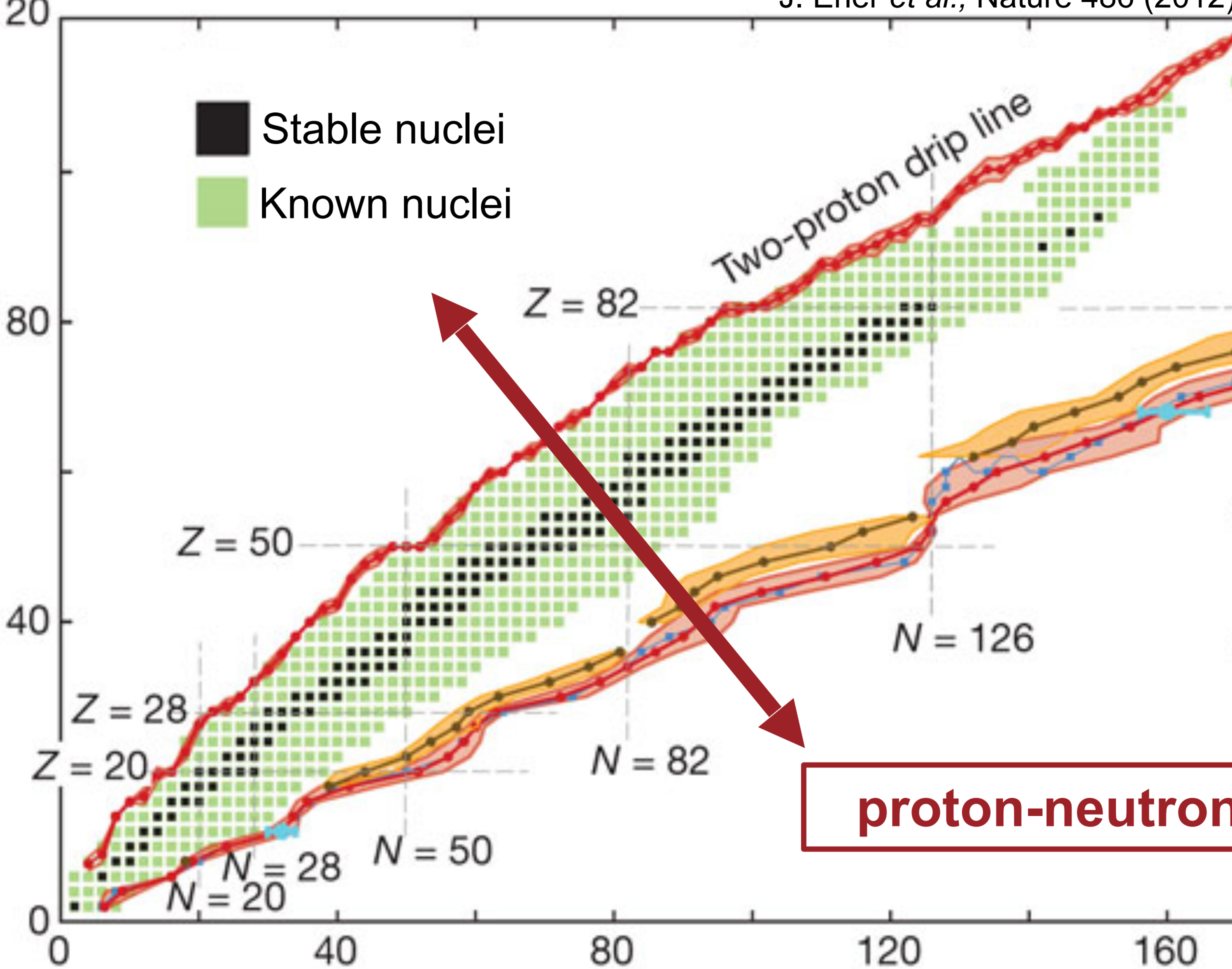
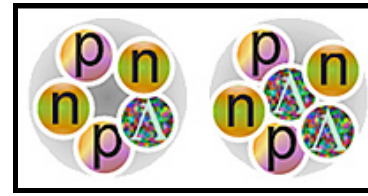
J. Erler *et al.*, Nature 486 (2012)



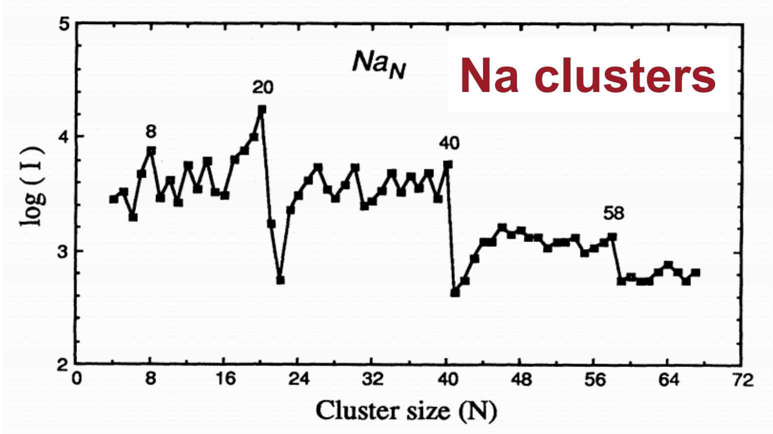
proton-neutron asymmetry

hypernuclei

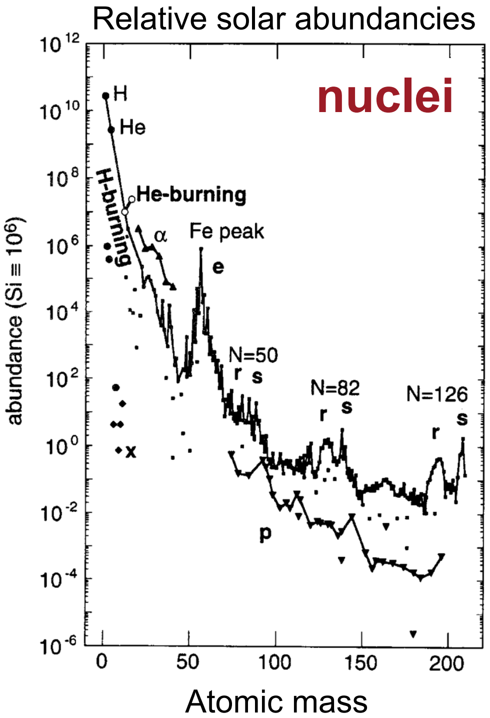


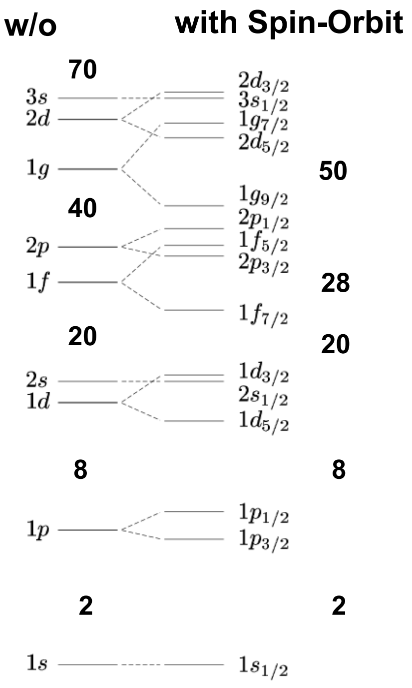
Shells in atomic nuclei

- Basic property of **finite size quantum systems**
- electrons in atoms, in clusters, nucleons in nuclei,…
- **Shell closures / magic numbers** are fingerprints of the **interactions** at play



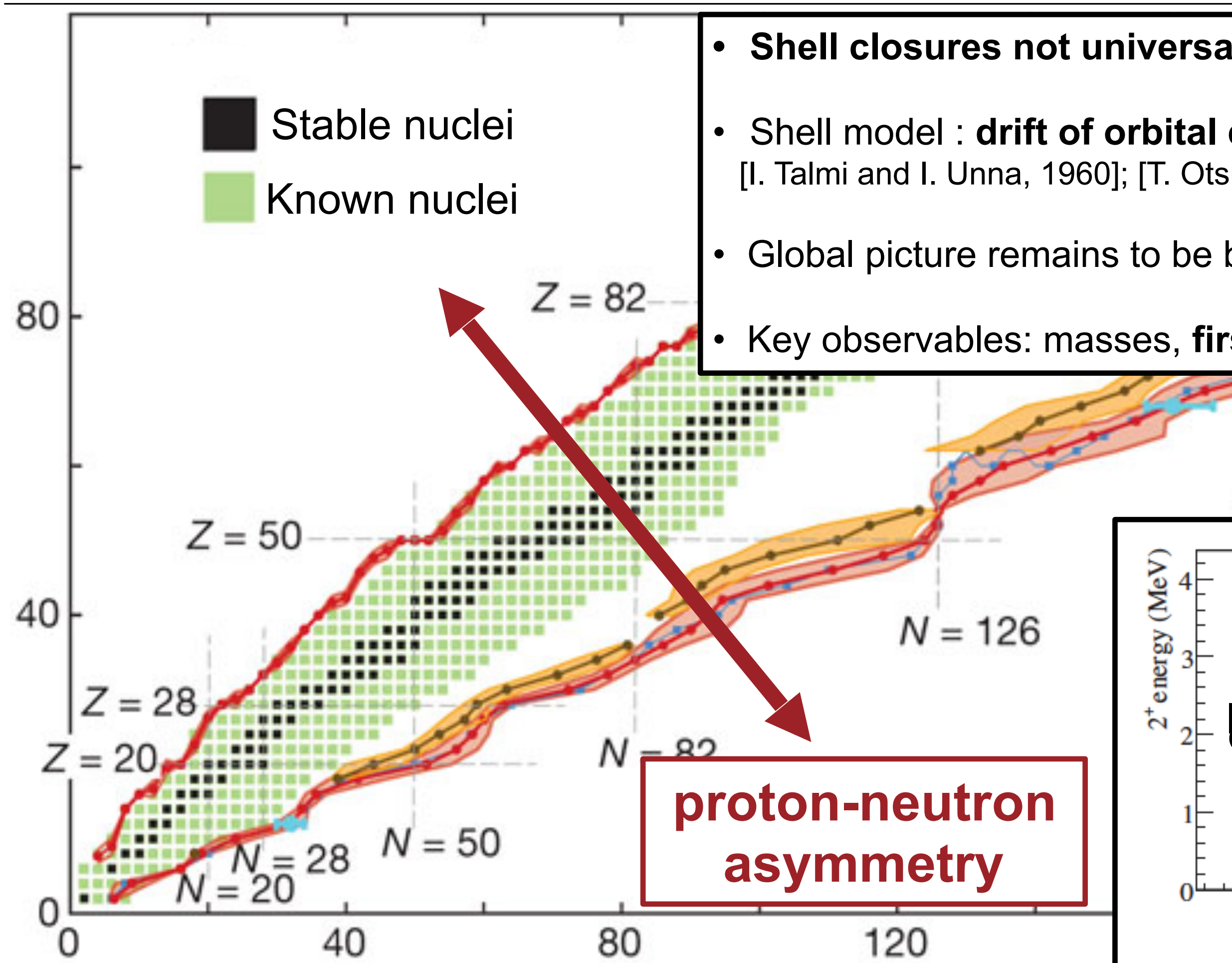
Sodium cluster abundance spectrum from supersonic jet
Walt A. de Herr, Rev. Mod. Phys. 65 (1993)

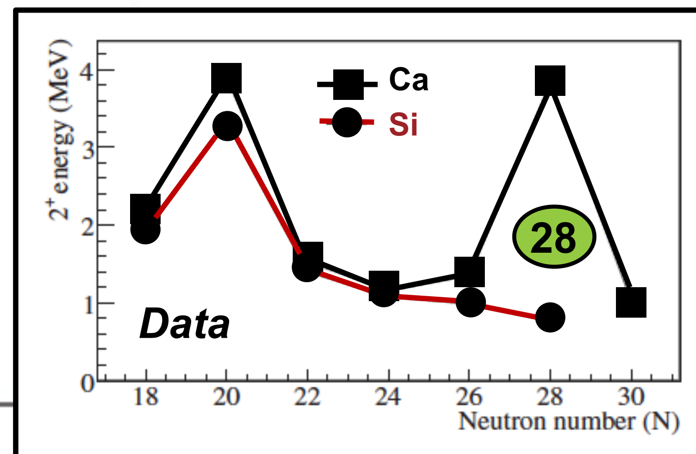




Shell evolution in neutron-rich nuclei

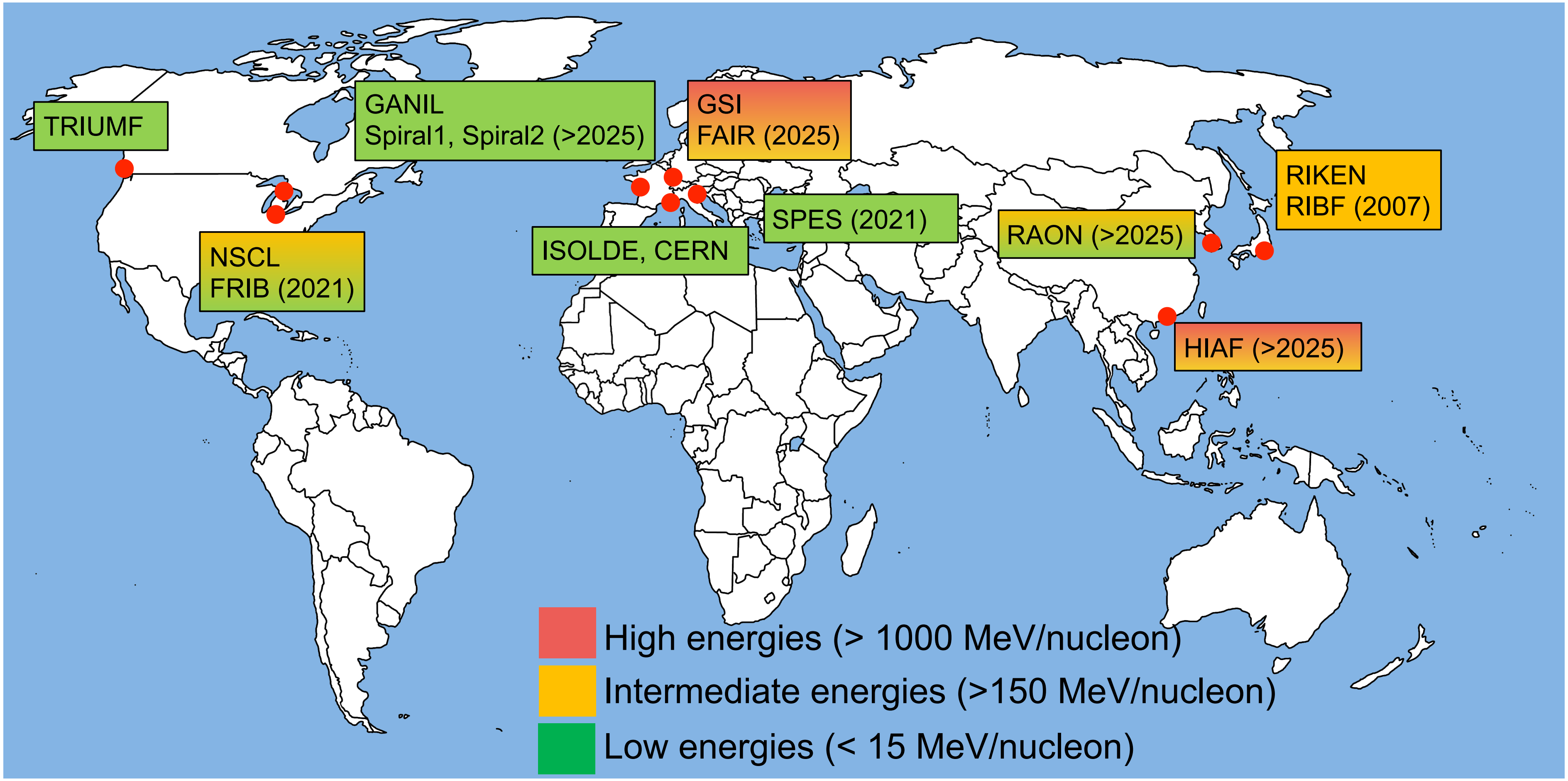
- **Shell closures not universal but local features**
- Shell model : **drift of orbital energies** with number of nucleons [I. Talmi and I. Unna, 1960]; [T. Otsuka *et al.*, 2001]
- Global picture remains to be built (expt. - theory)
- Key observables: masses, **first 2$^+$ energies**, etc…





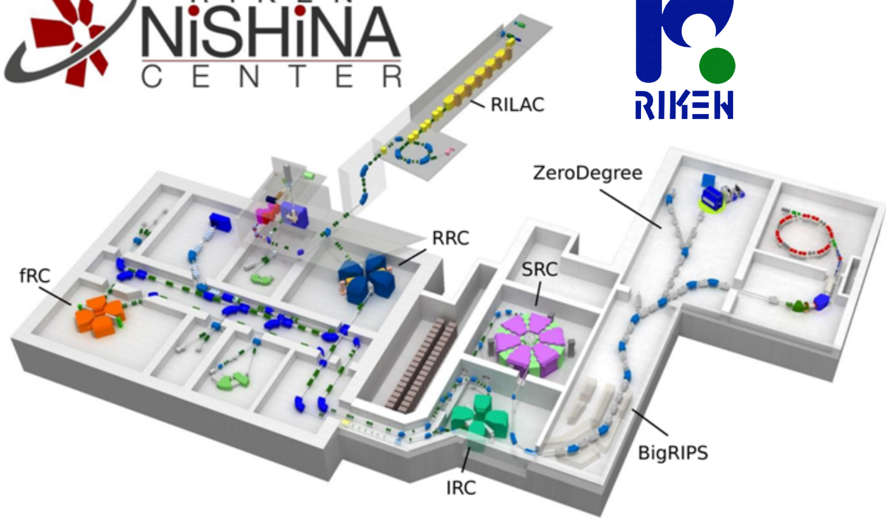
From B. Bastin *et al.*, Phys. Rev. Lett. 99, 022503 (2007)

Radioactive ion beam facilities worldwide

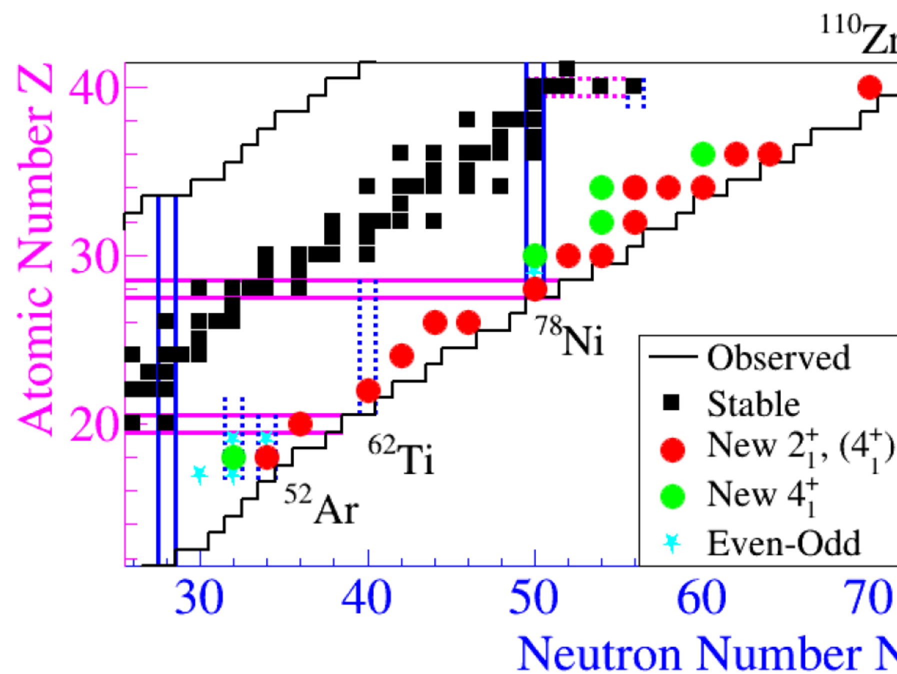


Spectroscopy at the RIBF, RIKEN

RIBF : >100 more intensities than anywhere else
Opened new opportunities in the recent years



SEASTAR: spectroscopy program at RIKEN
(data taking: 2014-2017)



- RIBF exists since 2007
- Accelerator complex: coupled cyclotrons
- Heavy-ions accelerated up to 345 MeV/nucleon
- SRC: largest heavy-ion cyclotron worldwide

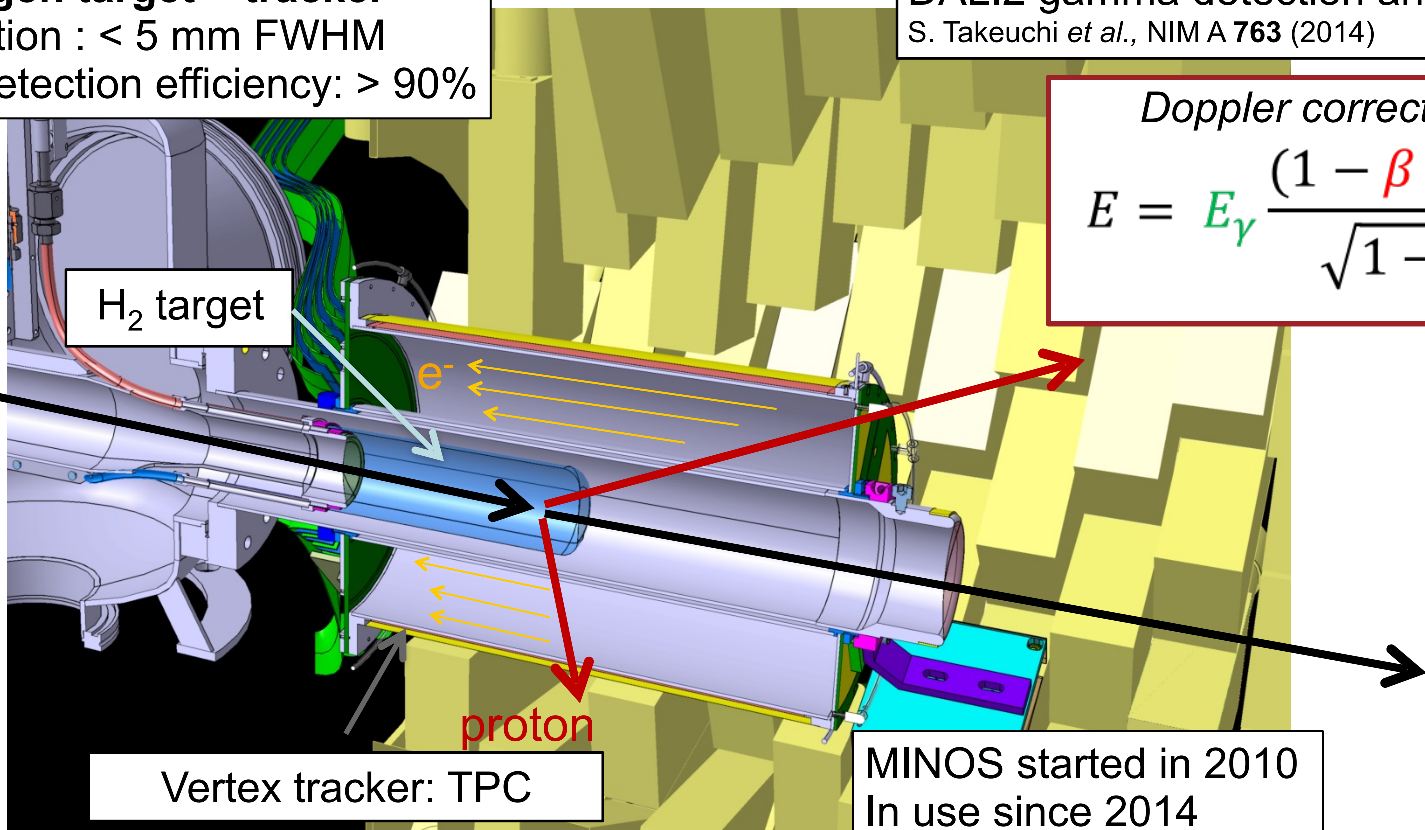
In-beam gamma spectroscopy and MINOS

liquid hydrogen target + tracker
Vertex resolution : < 5 mm FWHM
Total *(p,2p)* detection efficiency: > 90%

DALI2 gamma detection array
S. Takeuchi *et al.*, NIM A **763** (2014)

Doppler correction

$$E = E_\gamma \frac{(1 - \beta \cos\theta)}{\sqrt{1-\beta^2}}$$



Vertex tracker: TPC

MINOS started in 2010
In use since 2014

A. Obertelli *et al.*, EPJA **50** (2014)

MINOS and DALI2 in a nutshell

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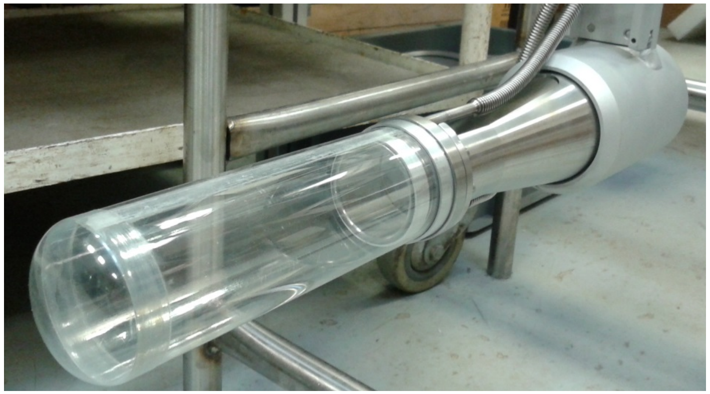
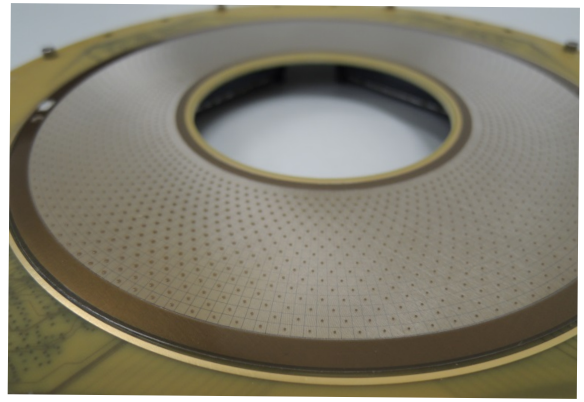
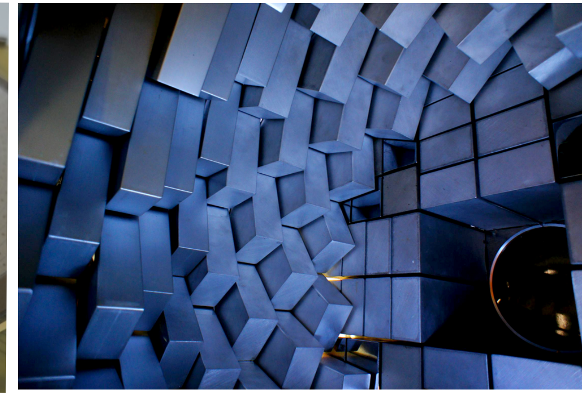






LH2 target

- 100-150 mm thick, 20 K
- Thin Mylar container: 150 µm

MINOS-TPC

- inspired from PANDA TPC prototype
- Iso Ar CF_4, 1 bar
- Micromegas amplification (g=1000)
- 4000 channels, AGET chip
- digital, 512 time bins, 100 MHz
- Individual-channel discriminators

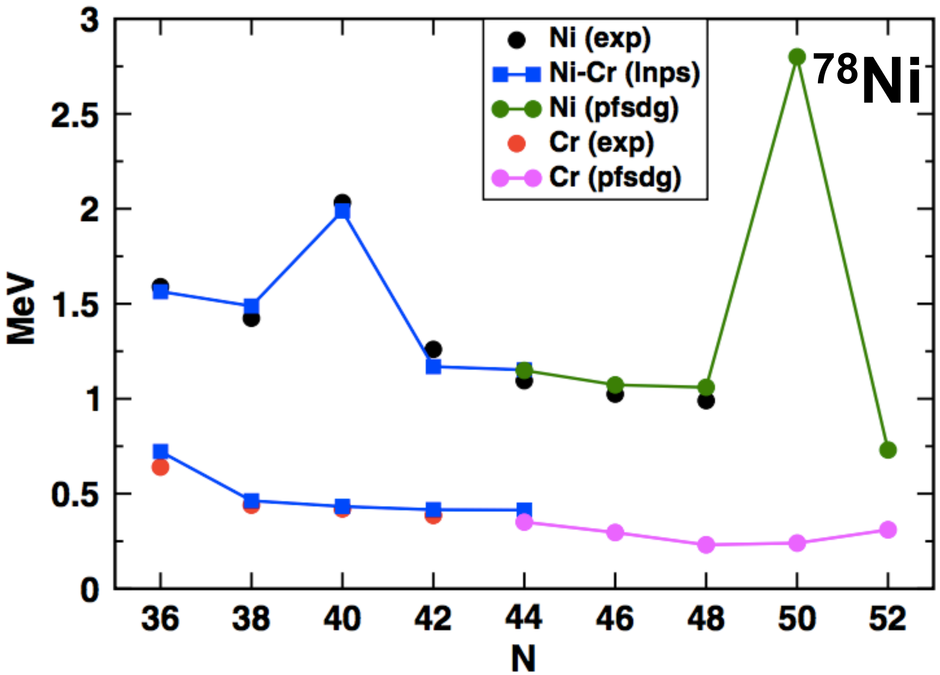
DALI2

- 186 NaI detectors
- upgraded to 226 detectors from 2017
- Efficiency: 30% @ 1 MeV
- Resolution: 9% FWHM @ 1 MeV

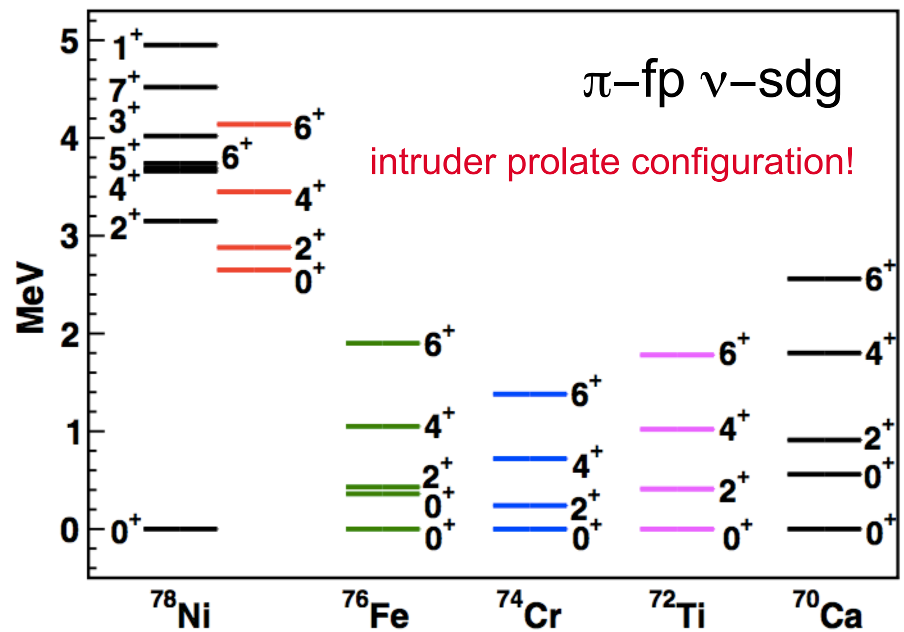
Collaboration

L. Achouri, O. Aktas, G. de Angelis, N. Aoi, T. Aumann, H. Baba, F. Brown, D. Calvet, S. Chen, N. Chiga, L. Chung, M.L. Cortes, A. Corsi, F. Delaunay, A. Delbart, Z. Dombradi, P. Doornenbal, F. Flavigny, S. Franchoo, I. Gasparic, R.-B. Gerst, J.-M. Gheller, J. Gibelin, A. Gillibert, S. Go, M. Gorska, A. Gottardo, K. Hahn, C. Hilaire, A. Jungclaus, D. Kim, N. Kobayashi, T. Kobayashi, T. Koiwai, Y. Kondo, W. Korten, P. Koseglou, Y. Kubota, V. Lapoux, J. Lee, B.D. Linh, H. Liu, T. Lokotko, G. Lorusso, C. Louchart, R. Lozeva, M. Marques, M. Mc Cormick, K. Matsui, Y. Matsuda, M. Matsushita, S. Michimasa, T. Miyazaki, S. Momiyama, K. Moschner, I. Murray, D. Napoli, F. Naqvi, M. Niikura, A. Obertelli, N. Orr, S. Ota, H. Otsu, V. Panin, S.-Y. Park, N. Paul, N. Pietralla, Z. Podolyak, E.C. Pollacco, G. Randisi, F. Recchia, W. Rodriguez, E. Sahin, M. Sasano, Y. Shiga, Y. Shimuzu, P.-A. Soderstrom, D. Sohler, I. Stefan, D. Steppenbeck, L. Stuhl, Y. Sun, M. Tanaka, R. Taniuchi, S. Takeuchi, Y. Togano, V. Vaquero, H. Wang, S. Wang, V. Werner, K. Wimmer, Z. Xu, H. Yamada, D. Yan, M. Yasuda, K. Yoneda, Y. Zaihong

^{78}Ni: shape coexistence ?



Shell Model



F. Nowacki *et al.*, PRL 117 (2016)

Are there signs of harmonic shell gaps in ^{110}Zr ?

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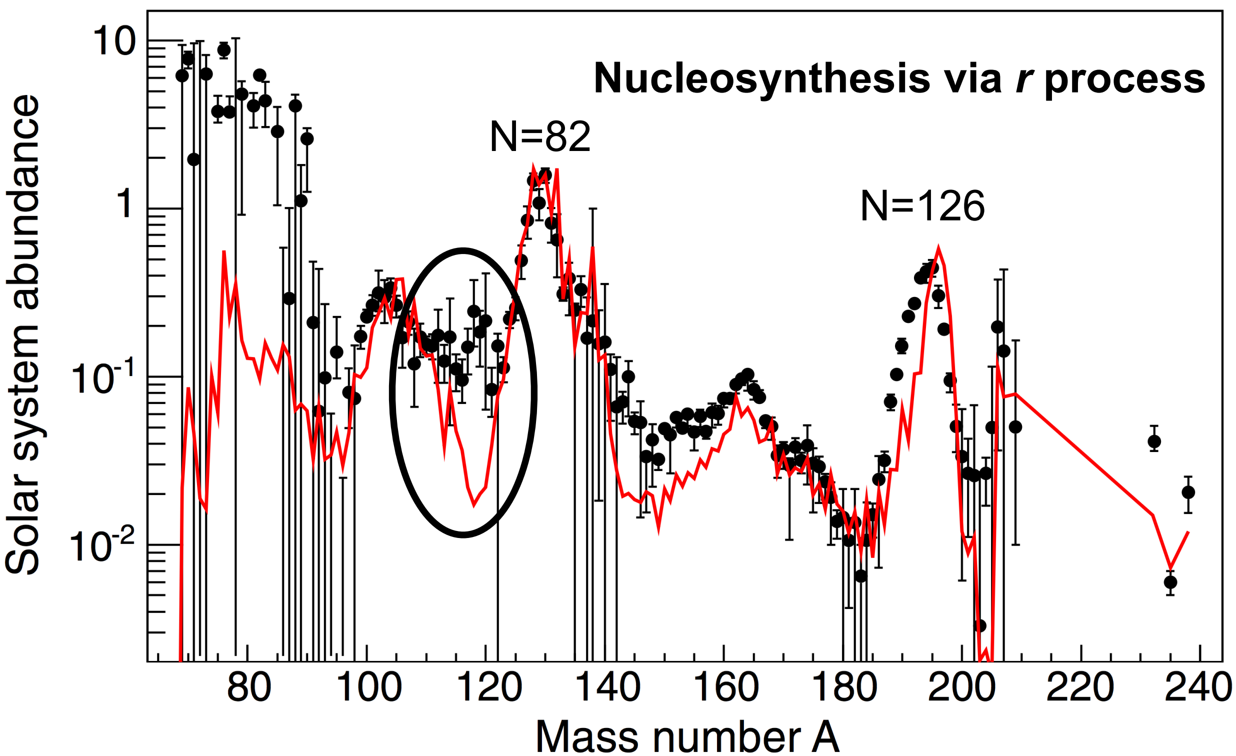
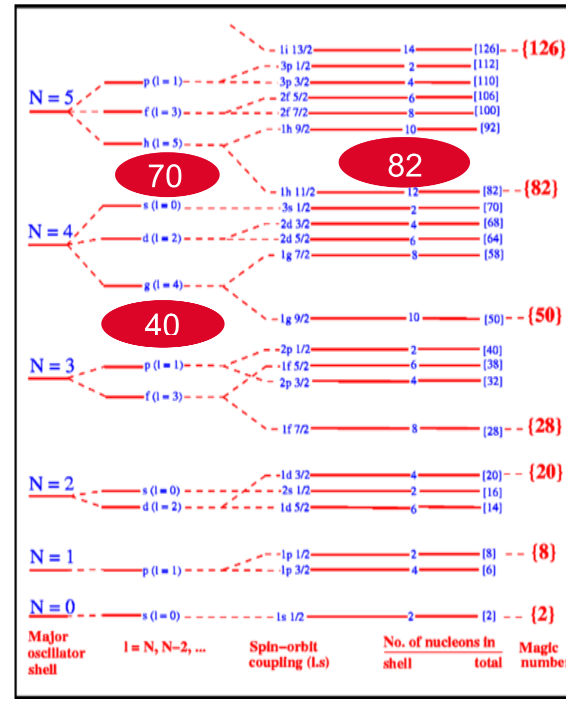
From G. Lorusso *et al.*, PRL 114 (2015)



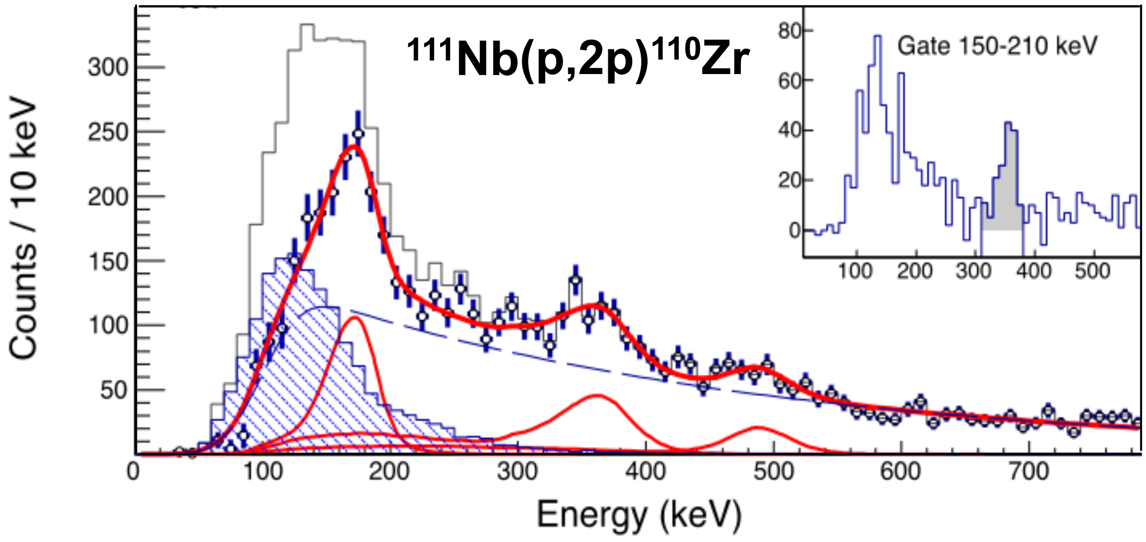
weak spin-orbit

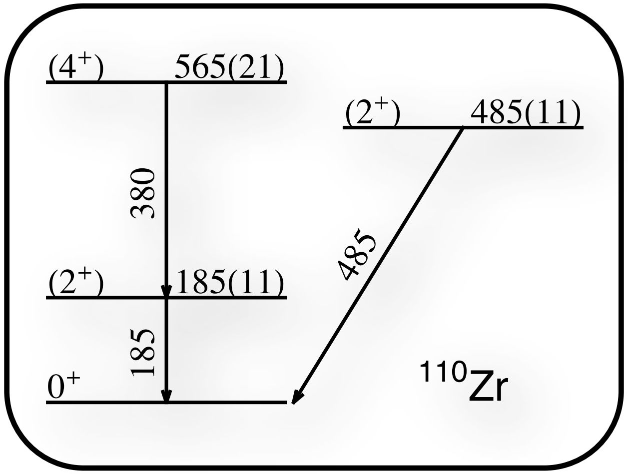
strong spin-orbit stable nuclei



- ❑ **Various theoretical predictions**
  - **Shell gaps at N=70, Z=40? Tetrahedral** symmetry? **Axially deformed**?
- ❑ Important **benchmark for theory**

Spectroscopy of ^{110}Zr





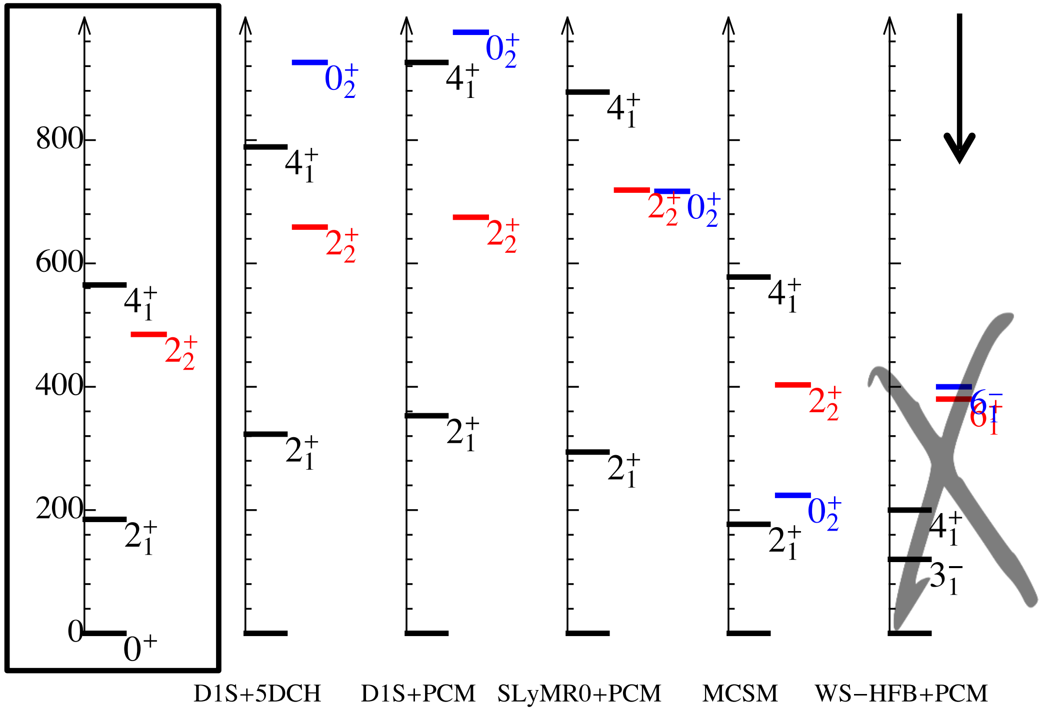
N.Paul *et al.*, PRL 118 (2017)

Spectroscopy of ^{110}Zr

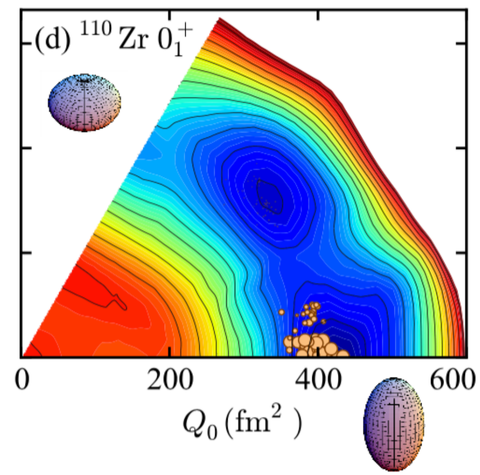
data

Ellipsoidal predictions

Tetrahedral prediction
Tagami *et al.,* PRC 87 (2013)



T. Togashi *et al.*, PRL 117 (2016)



^{110}Zr well deformed, prolate nucleus

N.Paul *et al.*, PRL 118 (2017)

Gamma spectroscopy of radioactive nuclei

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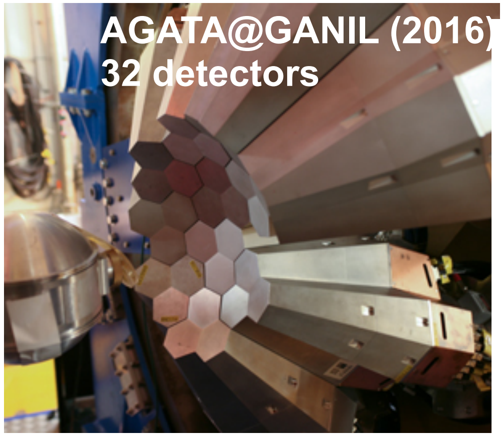
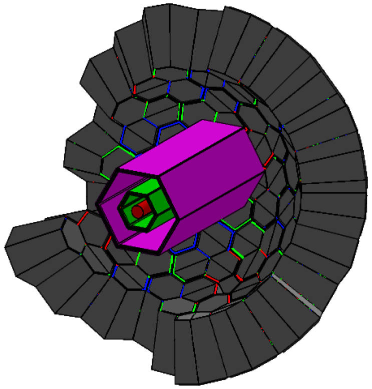
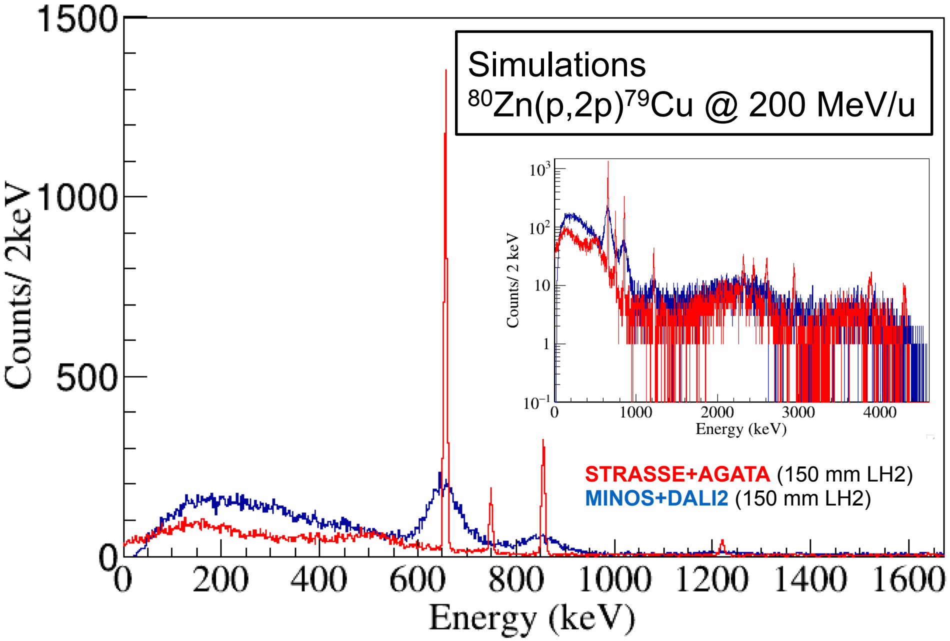
- **Ge** tracking arrays open new opportunities
- High intrinsic resolution (0.2%) and high « granularity » (< 5 mm FWHM, pulse shape)
- Fast beams: exciting future with GRETA at FRIB (>2021) and with **AGATA** at FAIR (>2025)
- **New compact Silicon tracker STRASSE**: vertex resolution 1 mm FWHM
- Prototype under development







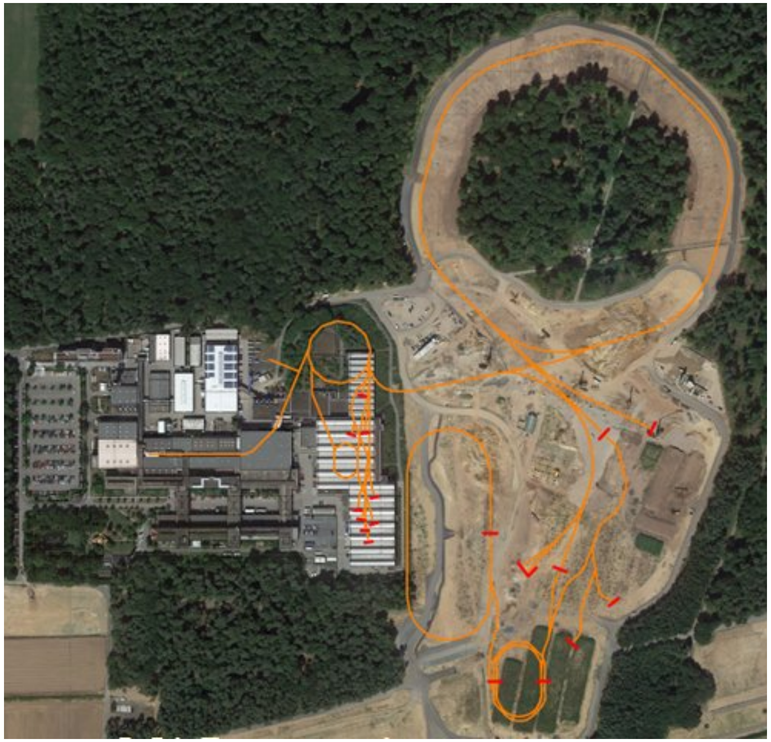
Sensitivity gain: 100

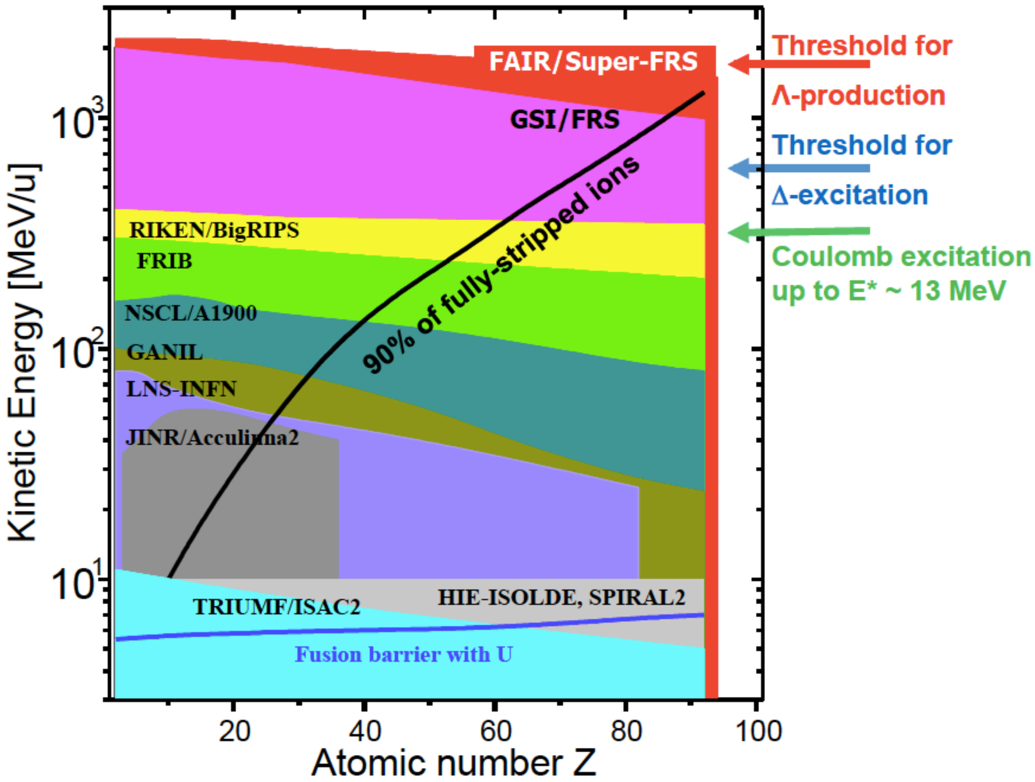
Courtesy H. Liu (TuDa)

Opportunities with RIBs at FAIR

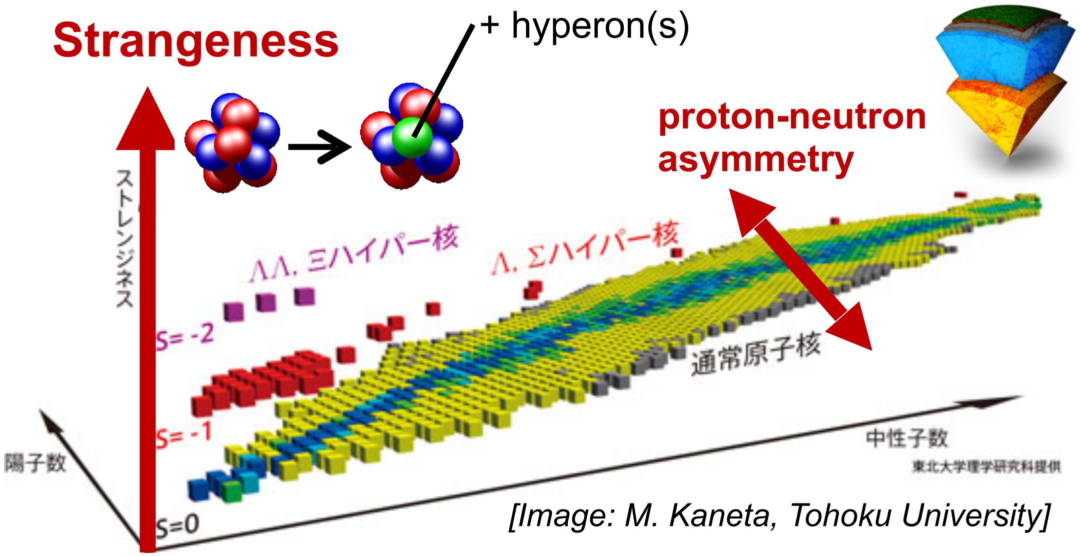
- First beams for physics in 2025
- **NUSTAR**: low-energy nuclear physics pillar

- Beam intensities 1000-10000 larger than GSI
- Unique energy regime of 0.4-2 GeV/nucleon
- Antiprotons

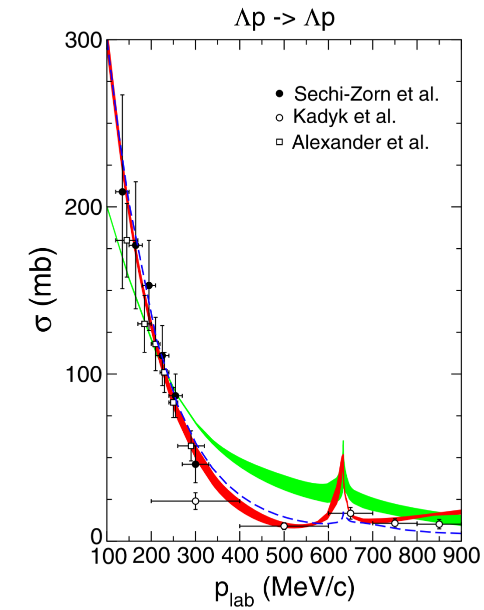




Hypernuclei



[Image: M. Kaneta, Tohoku University]

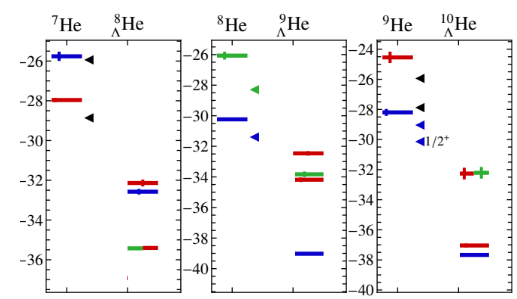


J. Haidenbauer *et al.*, NPA 915 (2013)

- hyperon-nucleon interaction loosely known
- hypernuclei: spectroscopic close to stability and light nuclei [ex. JPARC, Jlab, Mainz]

- core physics program of PANDA at FAIR

- enhanced three-body force effects
- ab initio formalism for hypernuclei exists
- few data for neutron-rich / deficient hypernuclei



R. Wirth, R. Roth, PLB 779 (2018)

Hypernuclei from heavy ion collisions

- **Light and medium mass hypernuclei,** HYPHI program at GSI/FAIR
- **Heavy ion collisions at E > 2 GeV/nucleon NN -> Λ K N (thr.: 1.6 GeV)**
  pion-decay tagging + invariant mass (spectrometer)
- complementary to high resolution / multi-strangeness program at PANDA

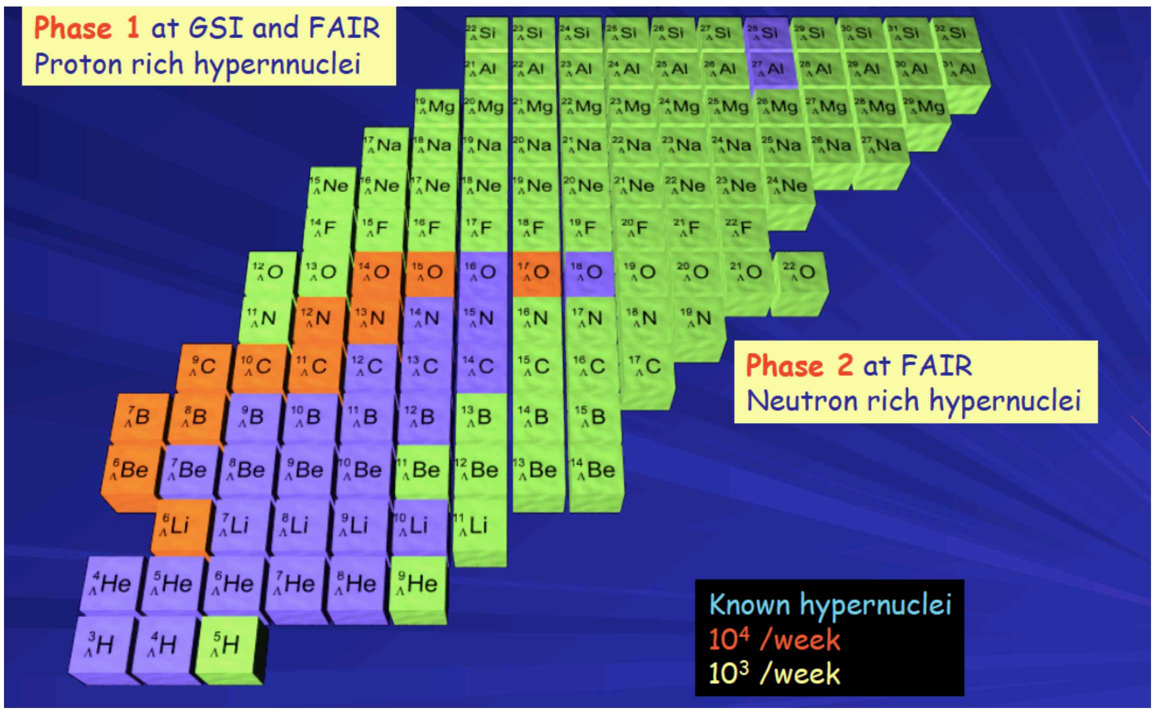
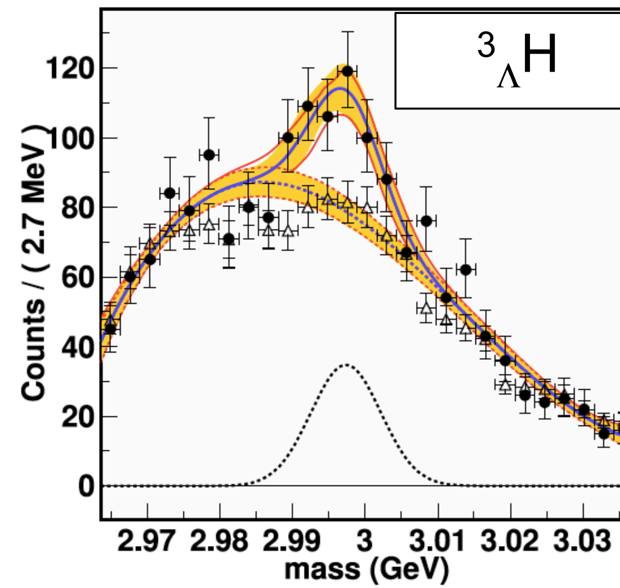


Figure from T. Saito, GSI / RIKEN / IMP



HyPHI collaboration,
Nucl. Phys. A 913 (2013)

Neutron-rich hypernuclei at R3B

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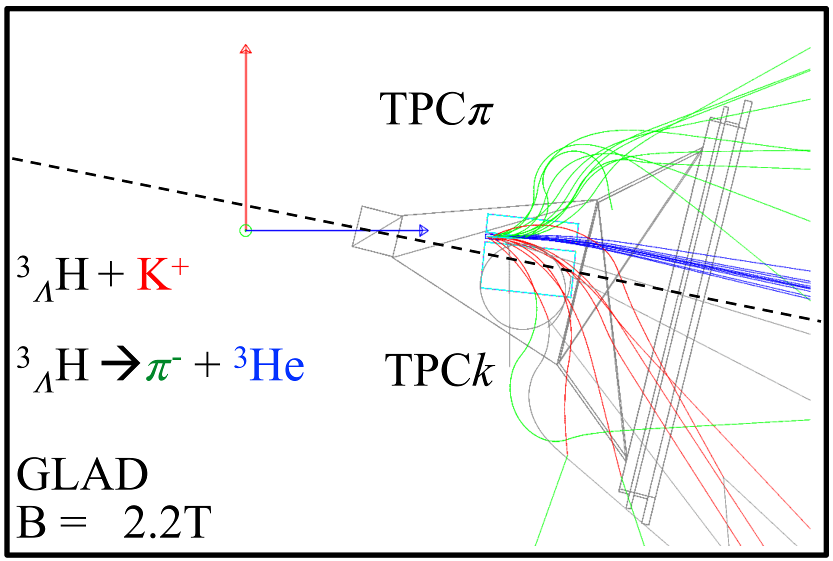
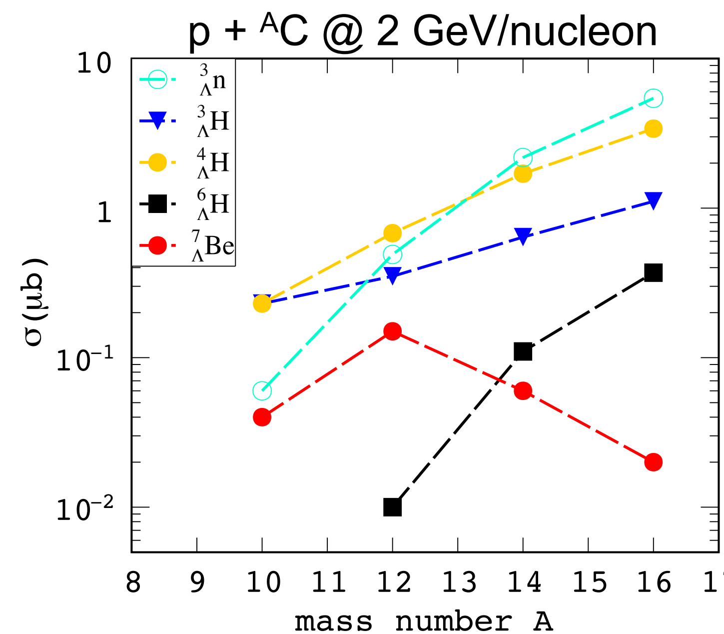
- hypernuclei with radioactive beams at R3B:
  - synthesise new hypernuclei
  - spectroscopy of bound and unbound states
  - precise lifetimes

- production (K^+) and decay (π^-) vertices tagging
- invariant mass measurements
- tracking array inside the GLAD dipole



Courtesy Y. Sun (TuDa)



Y. Sun *et al.*, PRC 98 (2018)
in collaboration with A. Botvina (FIAS)

Neutron skins and equation of state

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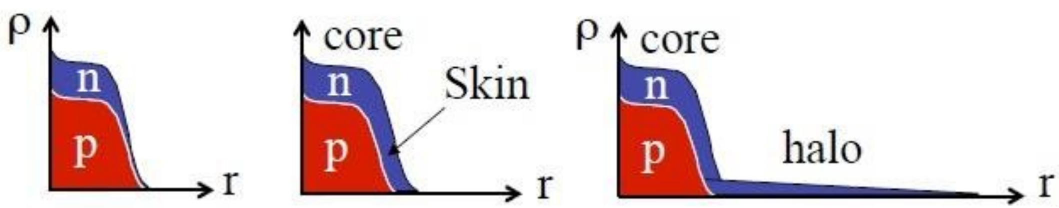
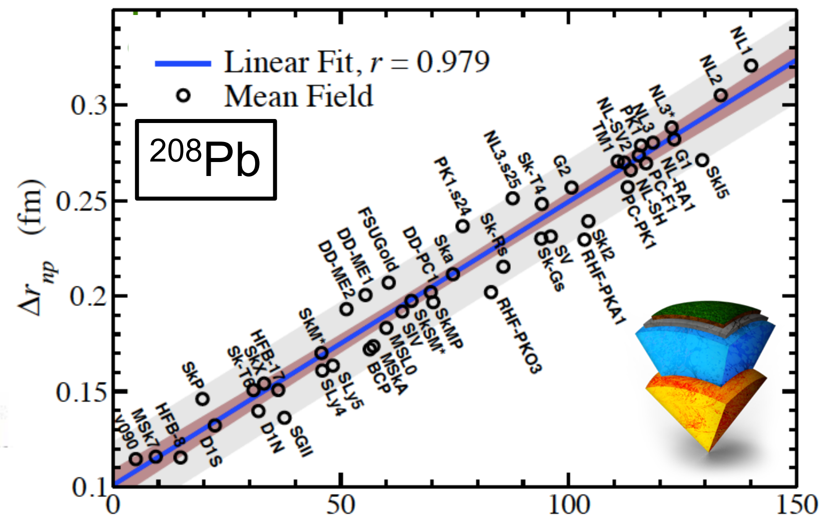
neutron skin thickness

$$\Delta r_{np} = \langle r_n \rangle - \langle r_p \rangle$$



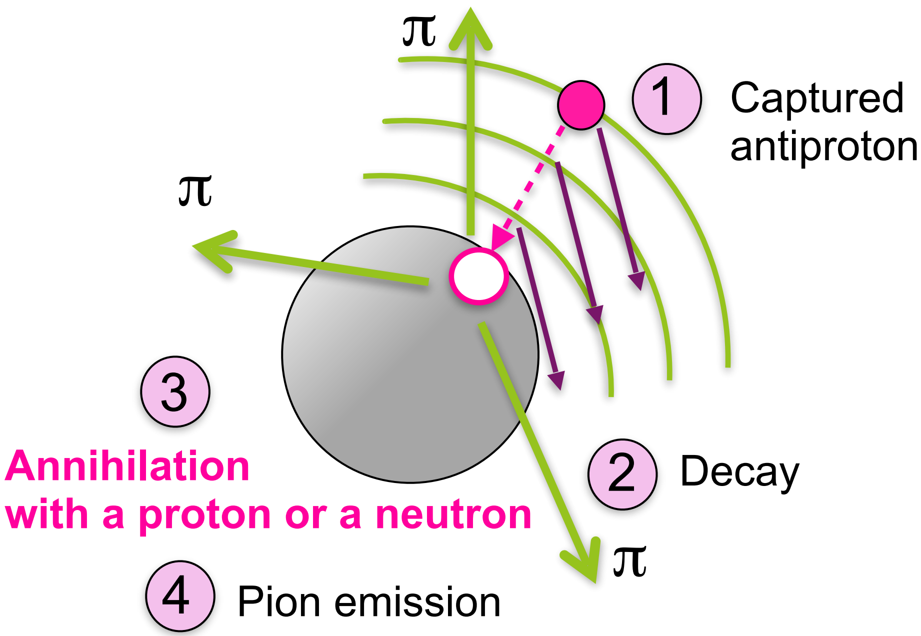
X. Roca-Maza *et al.*, PRL 106 (2011)



Density dependence of the cost of proton-to-neutron asymmetry (MeV)

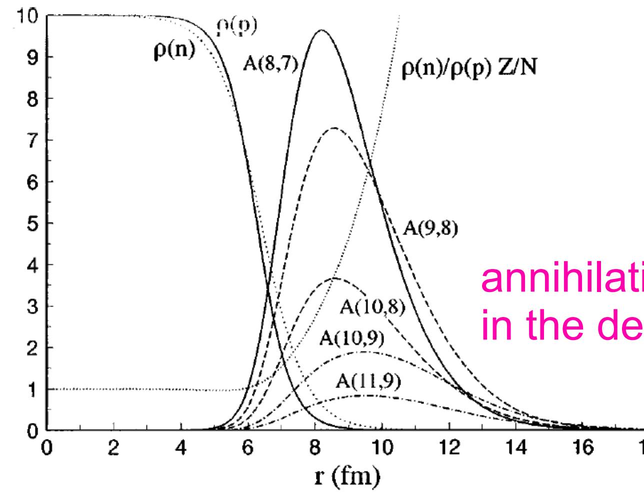
- **neutron skins and halos:** low density “pure” neutron matter at the surface
- extensively studied
- still, little is known experimentally for very neutron-rich nuclei
- motivated by the Nuclear Equation of State and neutron stars

Antiprotons to probe the density tail



Total electric charge conserved during annihilation
Neutron annihilation: Q = -1
Proton annihilation: Q = +1

^{172}**Y @ CERN**, R. Schmidt *et al.*, PRC 58 (1998)



annihilation occurs in the density tail

from experiment

$$\frac{N_n}{N_p} \longleftrightarrow \left.\frac{\rho_n}{\rho_p}\right|_{surface}$$

M. Wada, Y. Yamazaki, NIM B 214 (2004)

PUMA: Pbar Unstable Matter Annihilation

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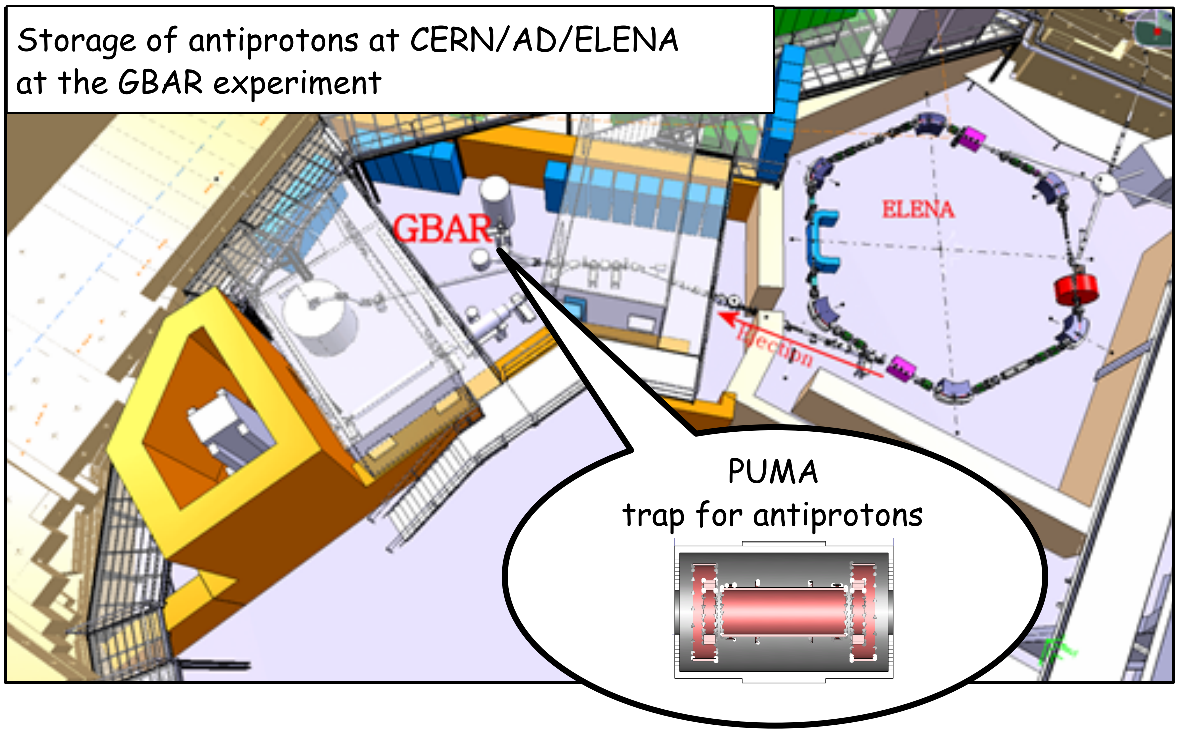
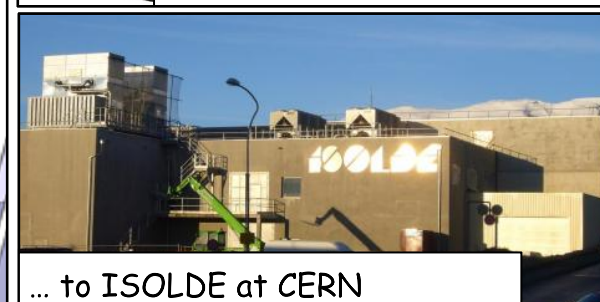
- Transport antiprotons from AD/ELENA (CERN) to ISOLDE
- Device to be build, methodology to be developed
- First experiment at ISOLDE foreseen in 2022
- Pioneer experiment with antiprotons as a probe of rare isotopes
- Opportunities at GSI / FAIR (FLAIR program)



Storage of antiprotons at CERN/AD/ELENA at the GBAR experiment


Transport the antiprotons…



… to ISOLDE at CERN for unstable ion annihilation.

Summary

- ❑ **Explore the proton-to-neutron asymmetry in nuclei**
  - **Shell structure is a local feature** and still to be discovered experimentally
  -
  - N=34 established as a shell closure beyond ^{54}Ca in ^{52}**Ar**
  - no sign of harmonic oscillator shell closures in ^{110}**Zr** (Z=40, N=70)

- ❑ New opportunities with radioactive beams and (anti)proton targets at and towards FAIR
  - **High-resolution spectroscopy** of *r-process* nuclei with AGATA at **HISPEC**
  - Explore neutron-deficient / rich **hypernuclei** at **R3B**
  - PUMA: **low-energy antiprotons** (CERN) to probe **neutron skins and halos**, as was proposed in **FLAIR**