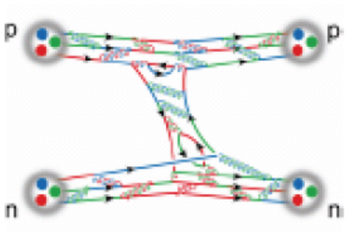
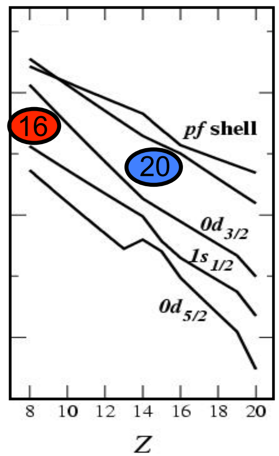
Recent Highlights and Perspectives with Exotic Nuclei

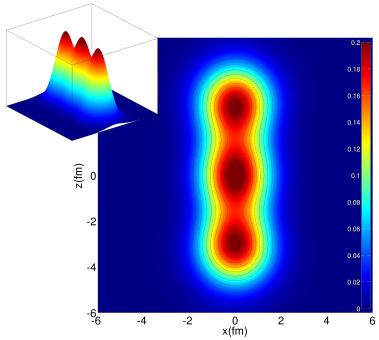
A. Obertelli, *CEA Saclay*

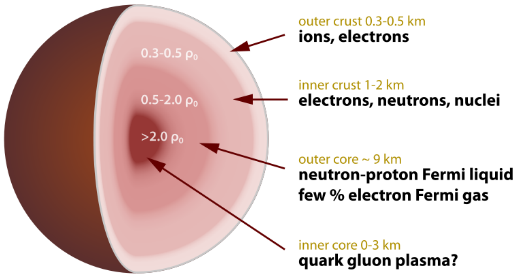
54th Bormio Winter Meeting 2016
Bormio, Italy

Key questions in Nuclear Structure









1- Can we describe nuclei from first principles ?

2- What is the nuclear shell structure ?

3- What is the nuclear matter distribution inside the nucleus ?

Connecting the Nuclear Force and first principles

Ab initio: QCD Lagrangian symmetries / pion relevant DoF (chiral symmetry breaking)
perturbation expansion Λ_π/Q E. Epelbaum et al., Rev. Mod. Phys. 81, 1773 (2009)

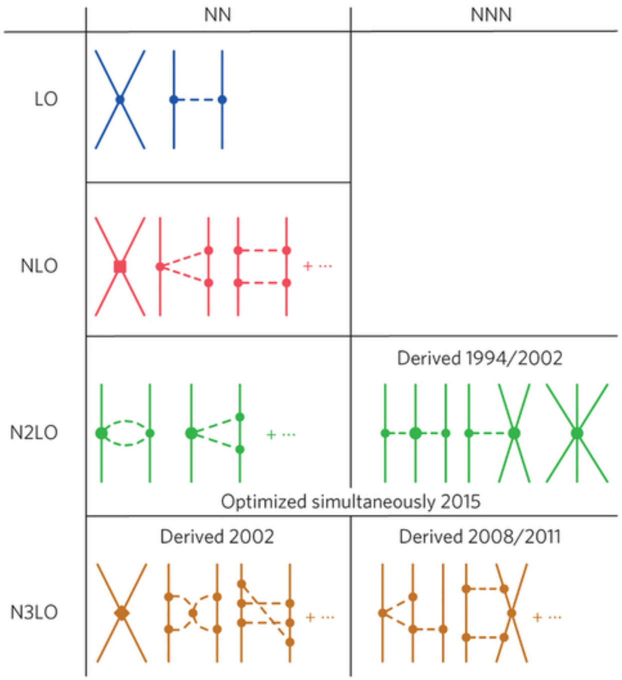
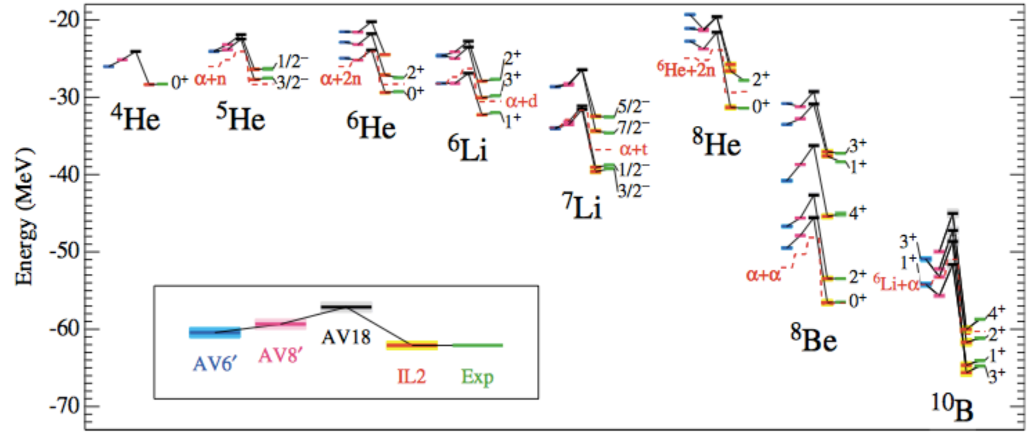


Figure from G. Hagen *et al.*, Nature Physics (2015)

R.B. Wiringa *et al.,* PRL **89** (2002)



Talks by J. Holt, G. Hagen, S. Gandolfi

- *Ab initio* calculations for **open shell** nuclei V. Somà et al., Phys. Rev. C 89, 061301(R) (2014)
- *Ab initio* effective interactions in reduced valence space (**shell model**)
  S.K. Bogner et al., Phys. Rev. Lett. 113, 142501 (2014) (In-Medium Similarity RG)
  G.R. Jansen et al., Phys. Rev. Lett. 113, 142502 (2014) (Coupled Clusters)

Existence of a bound or resonant 4-neutron system

Theory
NK Timofeyuk, JPG 29 (2003)
C. Bertulani, V. Zielevinsky, JPG 29 (2003)
SC Pieper, PRL 90 (2003)
R. Lazauskas, J. Carbonell, PRC 72 (2005)
YA Laskho, GF Filippov, Phys. At. Nuc. 71 (2008)

- Bound ^{4}n cannot exist
- Possible resonance state ~2 MeV

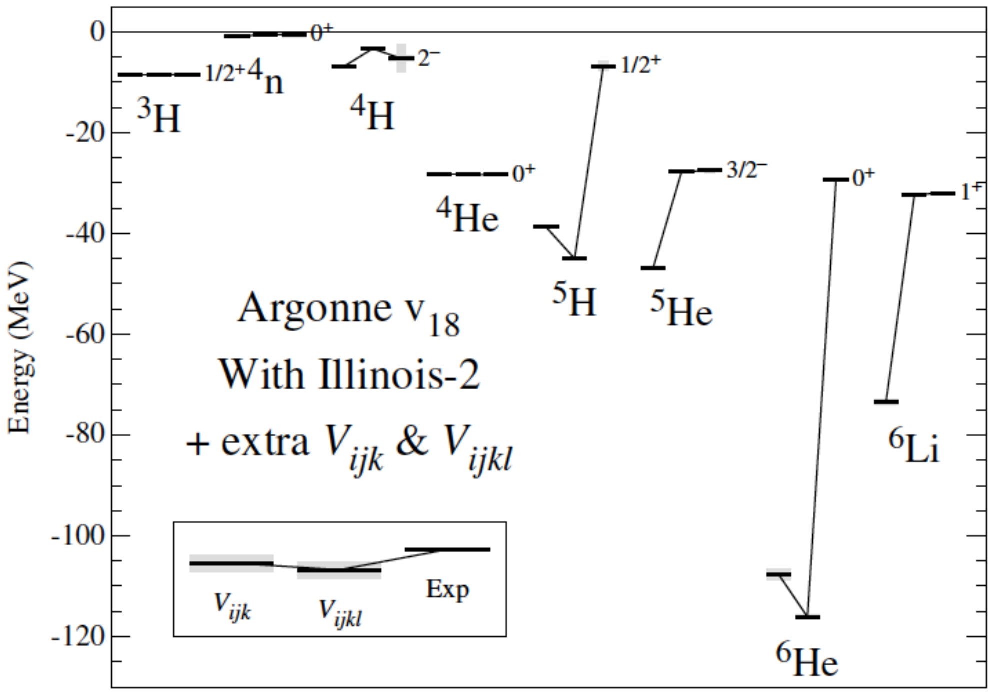
Such a resonance would quantify
- T=3/2 NNN interaction
- T=2 NNNN interaction

Experiment
- Hint for bound 4n in 2002, GANIL
  Breakup ^{14}Be -> ^{10}Be + 4n
  FM Marquez *et al.*, PRC **65** (2002)

- Several attempts since then

- All negative … except recently

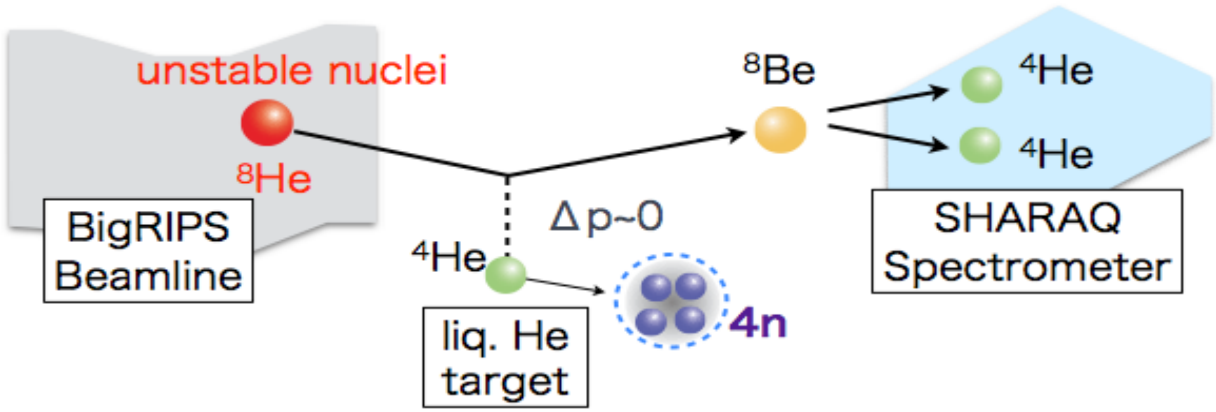
Ab-initio calculation NN, NNN interaction
S. C. Pieper, Phys. Rev. Lett. **90**, 252501 (2003)



Observation of a 4n low-energy resonance

Double-charge exchange (DCX) reaction **$^{4}He(^{8}He,^{8}Be)4n$** at 186 MeV/nucleon, RIBF, 2014

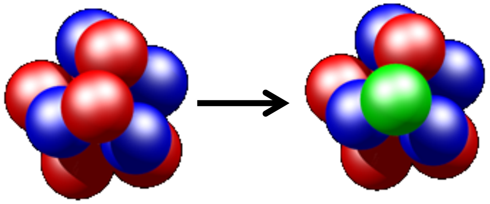
K. Kisamori *et al.,* to be published in Phys. Rev. Lett. (2016)



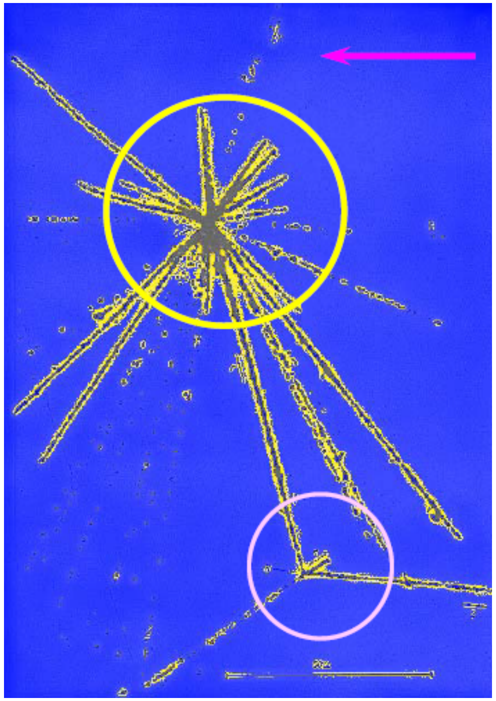
Hypernuclei

Hypernucleus consists of nucleons (n,p) + hyperon (**Y**)

Notation ${}_{Y}^{A}Z$
Y: hyperon
$Z = Zp + (N_Y.q_Y)$
$A = N_n + N_p + N_Y$



First hypernucleus discovered in a stack of photographic emulsions exposed to cosmic rays at about 25 km above ground
M. Danysz and J. Pniewski, Philos. Mag. 44, 348 (1953)



Incoming high energy proton from cosmic ray

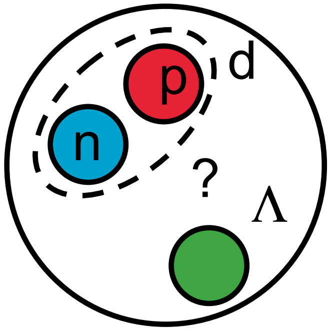
Collision with the nucleus of the emulsion.
Breaks it into fragments.

« star » fragments: 21 tracks: 9α + 11 H + ${}_{\Lambda}X$

The fragments ${}_{\Lambda}X$ disintegrates about 10^{-12} sec later (typical for weak decay)

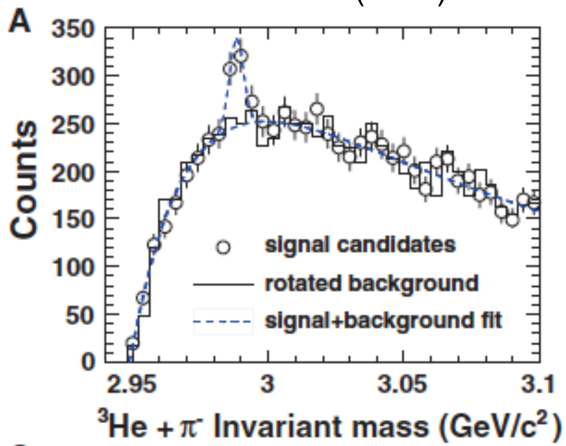
${}_{\Lambda}X$ interpretated as a hypernucleus

The hypertriton ($^3_\Lambda$H) puzzle

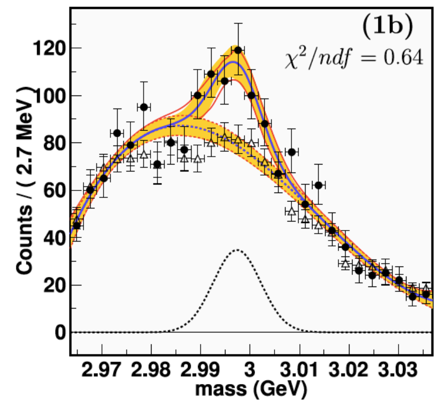


B_Λ = 130(50) keV
(radius > ^{208}Pb)

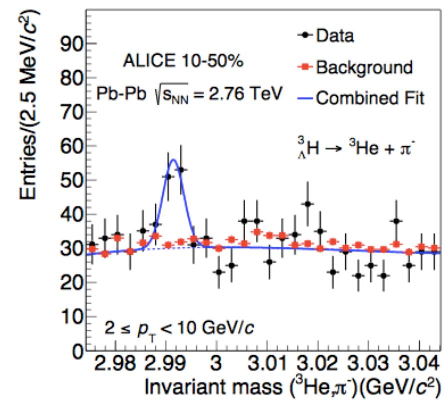
STAR collaboration,
Science **328** (2010)



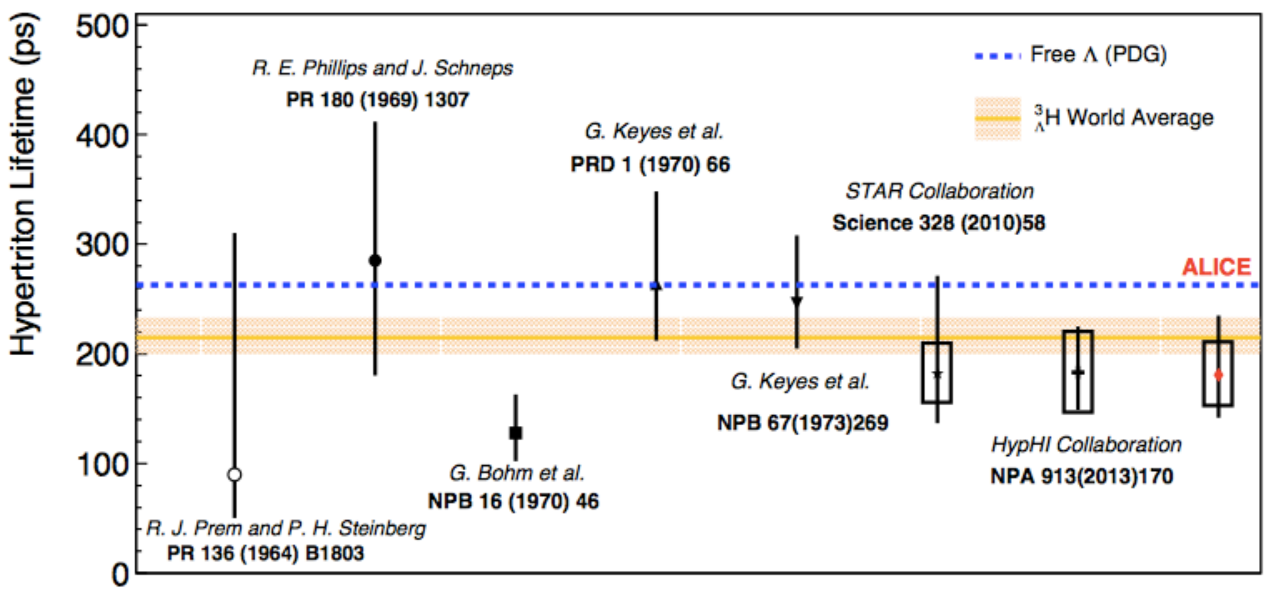
HyPHI collaboration,
Nucl. Phys. A **913**, 170 (2013)



ALICE collaboration,
PLB, **In Press** (2016)



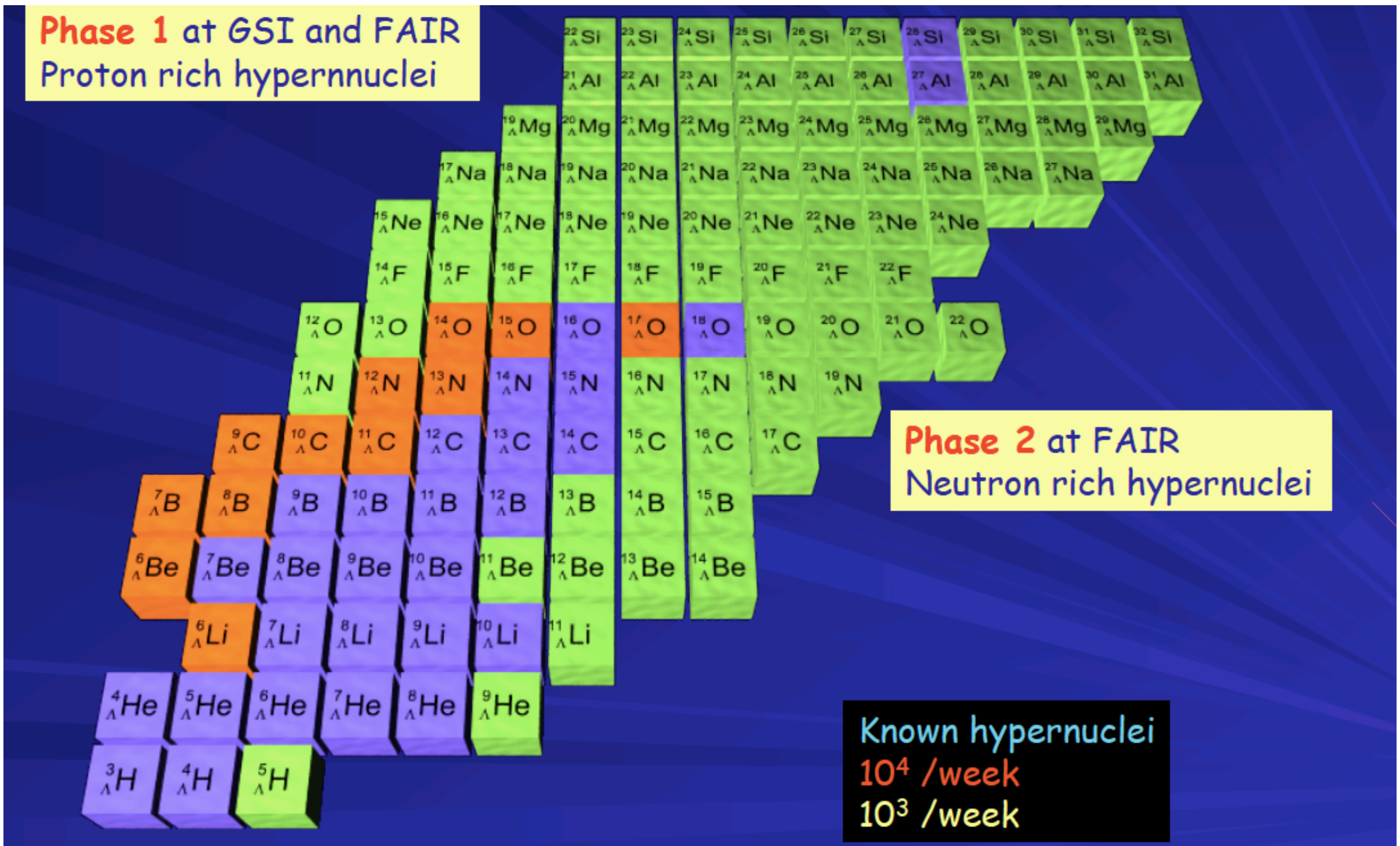
3_ΛH lifetime, **Hyphi: $\tau = 183^{+42}_{-32} \pm 37$ ps, ALICE: $\tau = 181^{+59}_{-39} \pm 33$ ps < τ_{free}=261 ps**



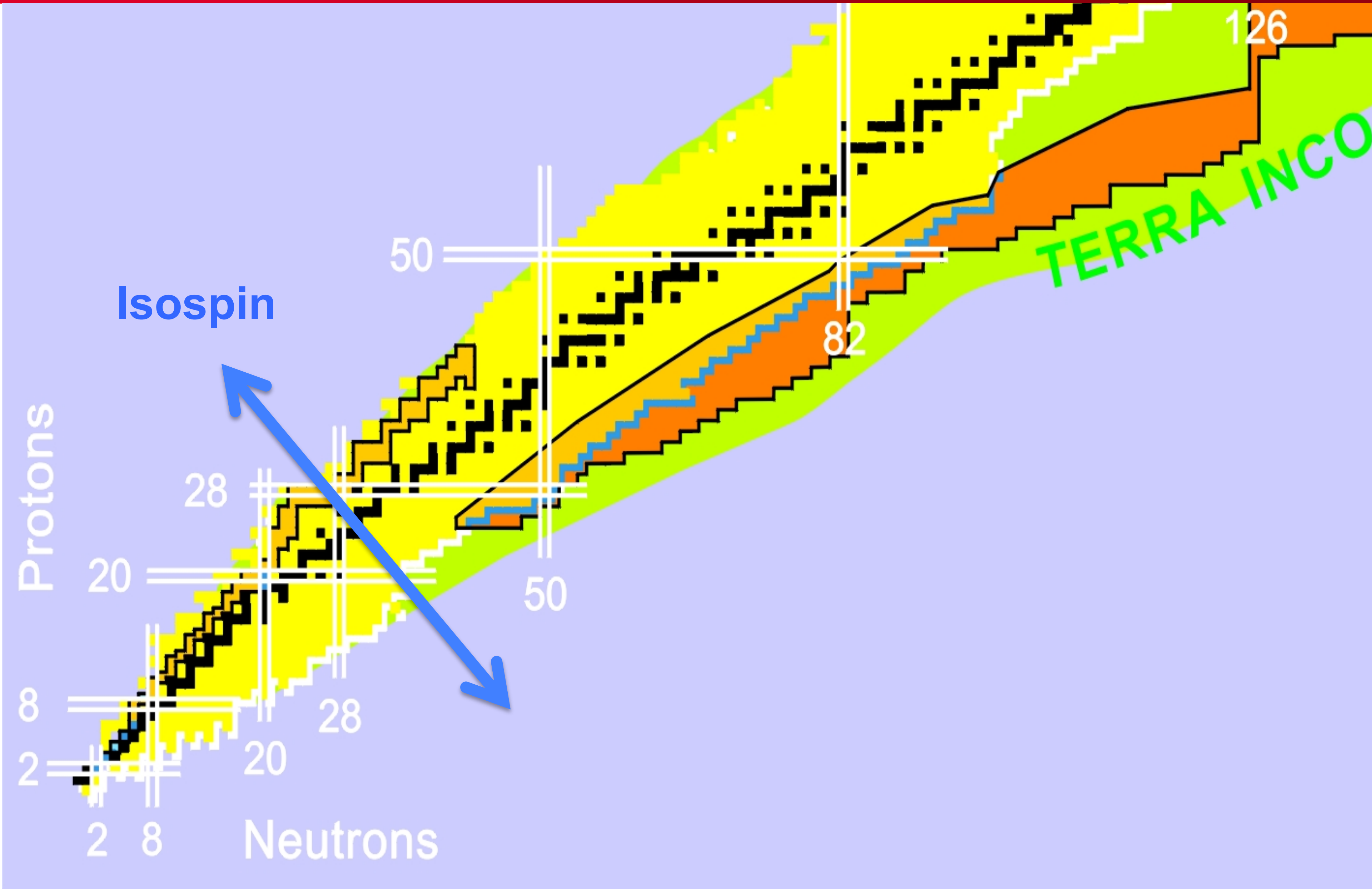
Neutron-rich Hypernuclei @ GSI / FAIR

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)
+ kaon & pion-decay tagging + invariant mass (spectrometer)

Courtesy of T. Saito, GSI



Shell Structure and Shell Evolution

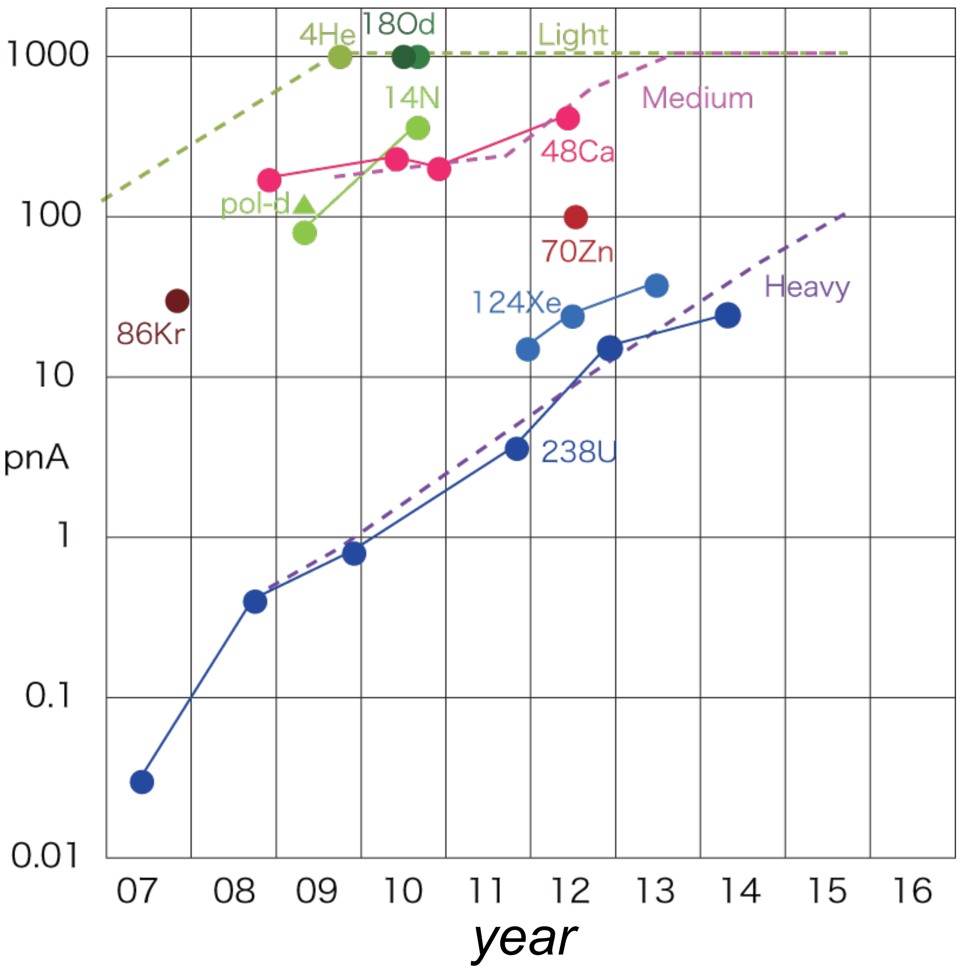


The Radioactive Isotope Beam Factory (RIBF), RIKEN

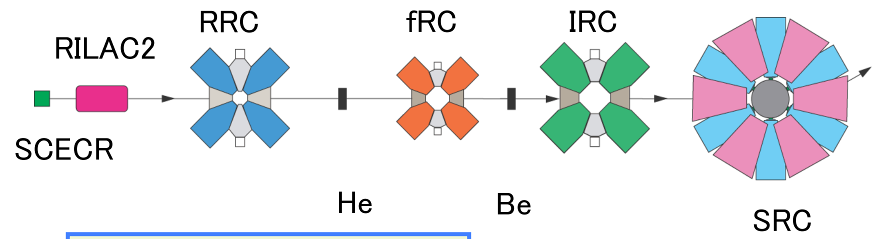
RIBF started operation in **2007**

Worldwide unique intensities

Continuous progression



345 MeV/u



Typical configuration

Maximum primary beam intensities

- ^{48}Ca beam : 415 pnA in 2012
- ^{70}Zn beam : 125 pnA in 2012
- ^{78}Kr beam : 275 pnA in 2015
- ^{124}Xe beam: 40 pnA in 2013
- ^{238}U beam: 40 pnA in 2015

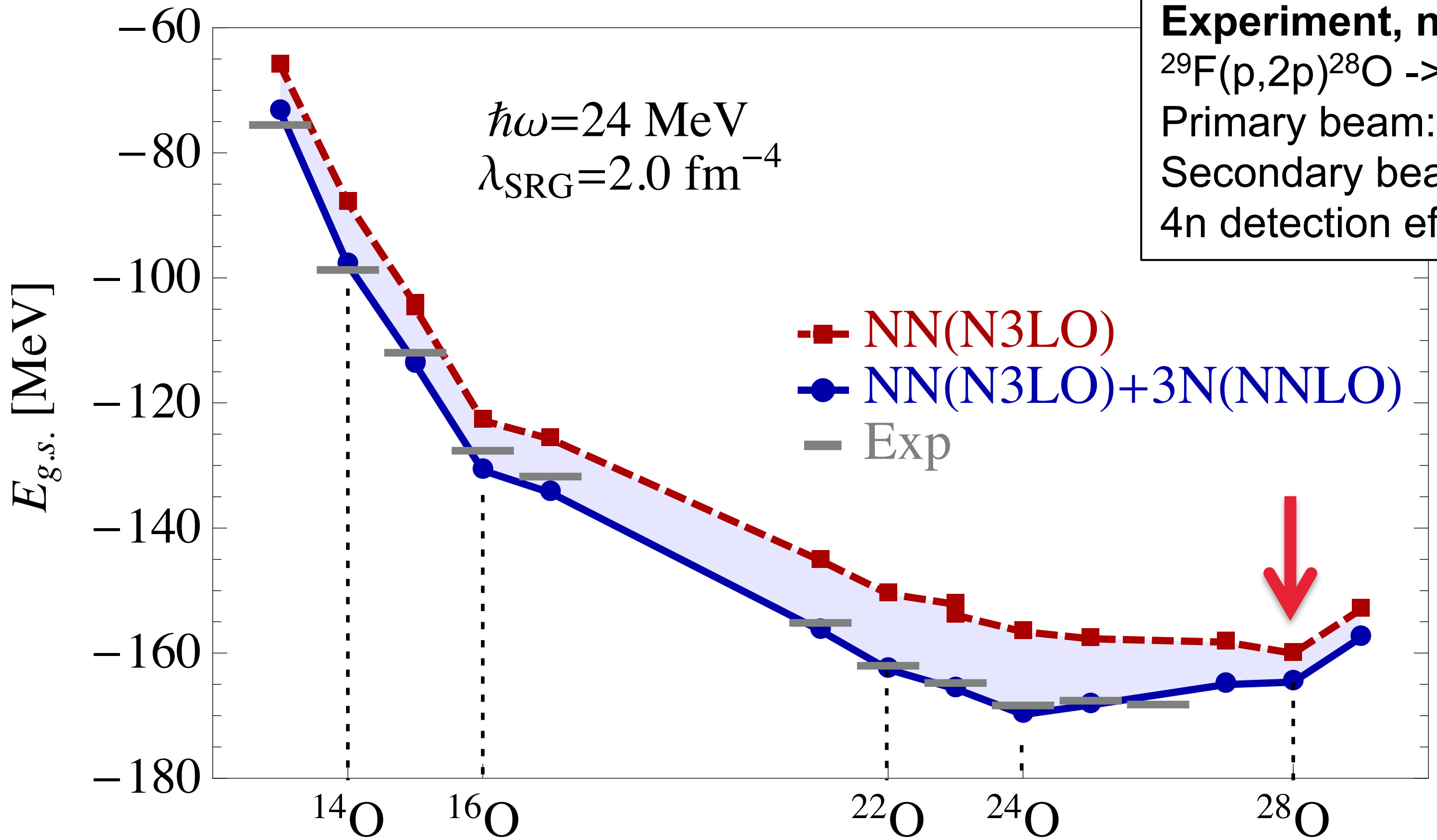
- *2015-2016 upgrade to achieve 100pnA U-beam*

Ex. ^{11}Li at 10^5 pps, ^{24}O at 3000 pps
^{104}Sn at >1000 pps

Connecting the Nuclear Force and first principles

- **Invariant mass measurements at** RIKEN for isotopes beyond the neutron drip line
- ^{26}**O** binding energy, submitted, Y. Kondo (Tokyo Tech) *et al.*
- ^{27,28}**O** binding energy measured in November 2015, under analysis

Experiment, nov. 2015:
^{29}F(p,2p)^{28}O -> ^{24}O+4n
Primary beam: ^{48}Ca @ 500 pnA
Secondary beam intensity: 15 pps
4n detection efficiency: 1-3 %

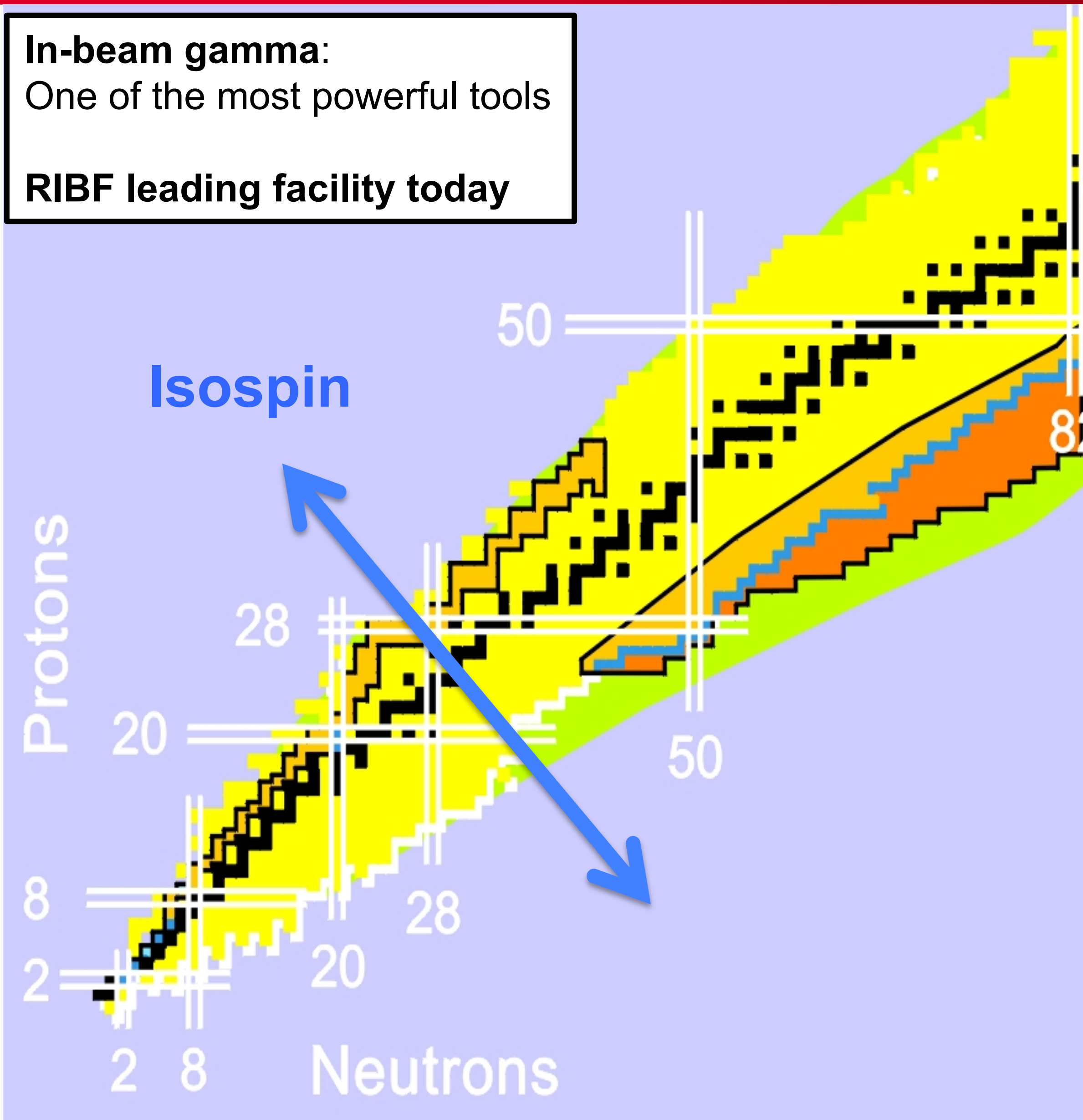


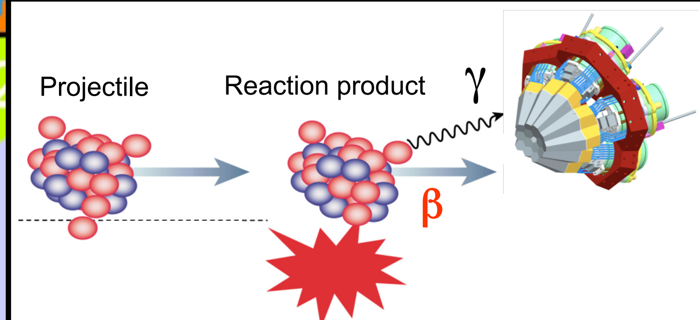
Self-Consistent Green's Function theory
Courtesy C. Barbieri, University of Surrey

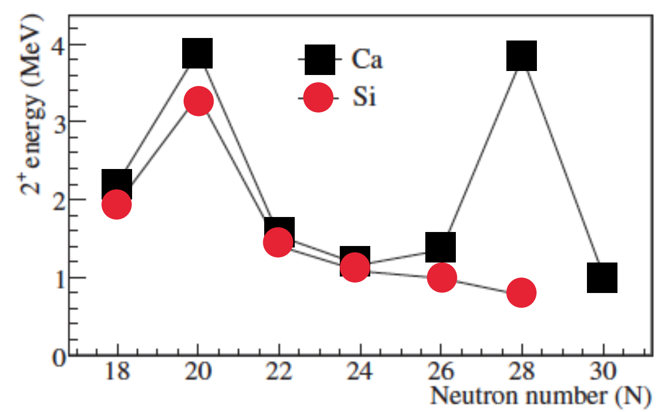
Shell Structure and Shell Evolution

In-beam gamma:
One of the most powerful tools

RIBF leading facility today





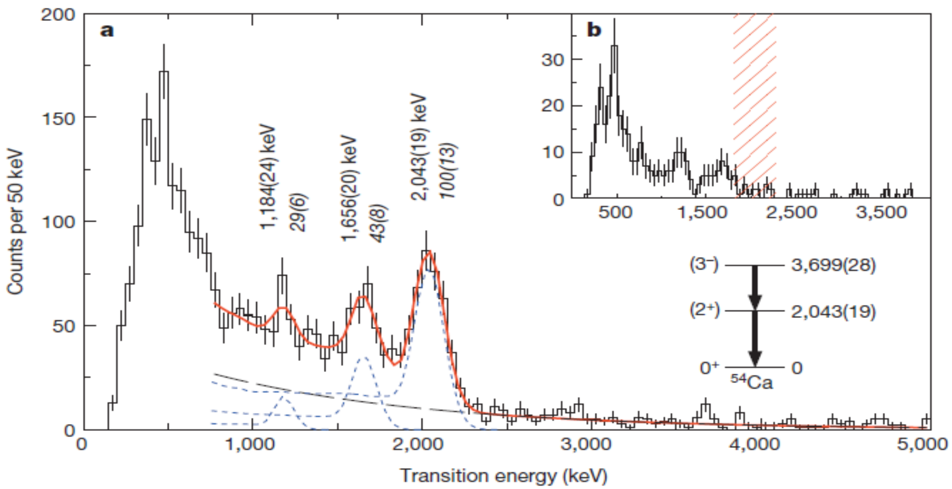


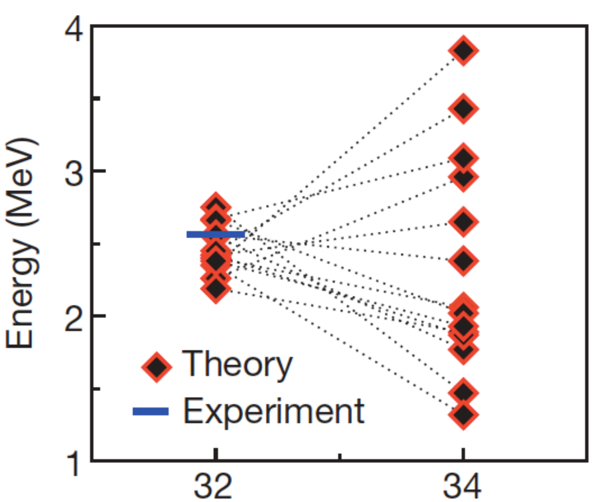
from B. Bastin *et al.*, PRL **99** (2007)

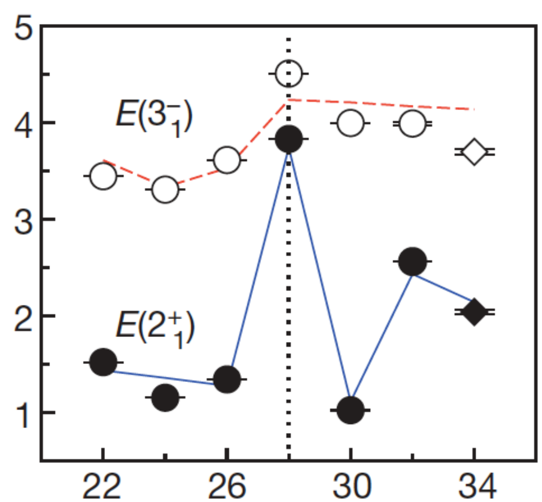
The N=34 new magic number

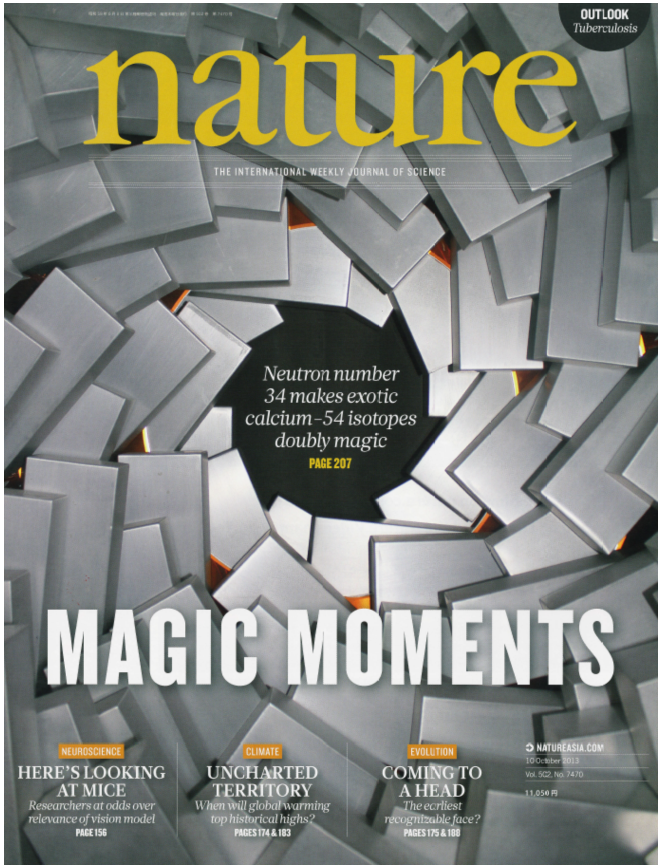
^{56}Ti, ^{55}Sc + Be -> ^{54}Ca + X at the RIBF (DALI2)
^{70}Zn primary beam (100 pnA max)
^{56}Ti 120 pps/pnA, ^{55}Sc 12 pps/pnA

D. Steppenbeck *et al.*, Nature **502** (2013)



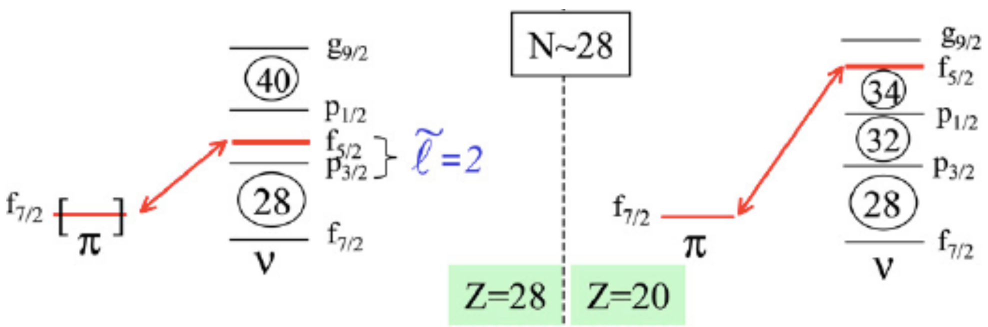






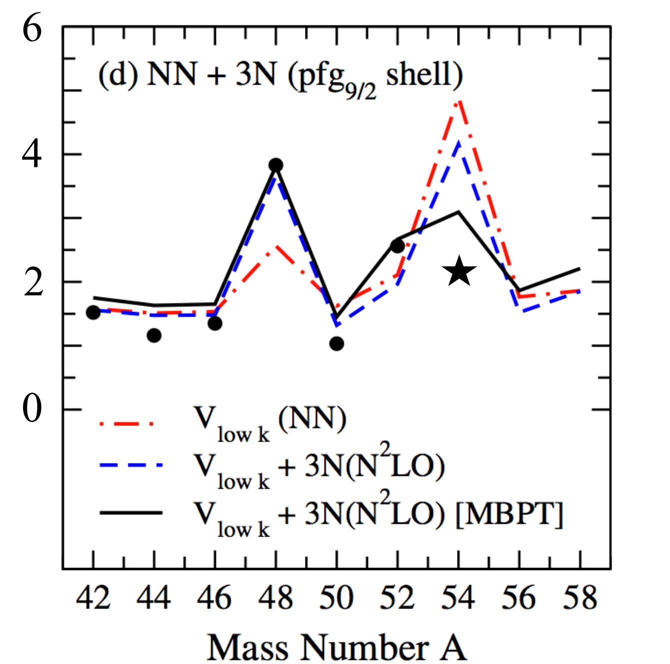
Tensor / spin-isospin terms … and 3-body forces

Role of the **spin-isospin and tensor terms**
T. Otsuka, PRL 87, 082502 (2001)
T. Otsuka et al., PRL 95, 232502 (2005)



O. Sorlin, M.-G. Porquet, Prog. Part. Nuc. Phys. 61, 602 (2008)

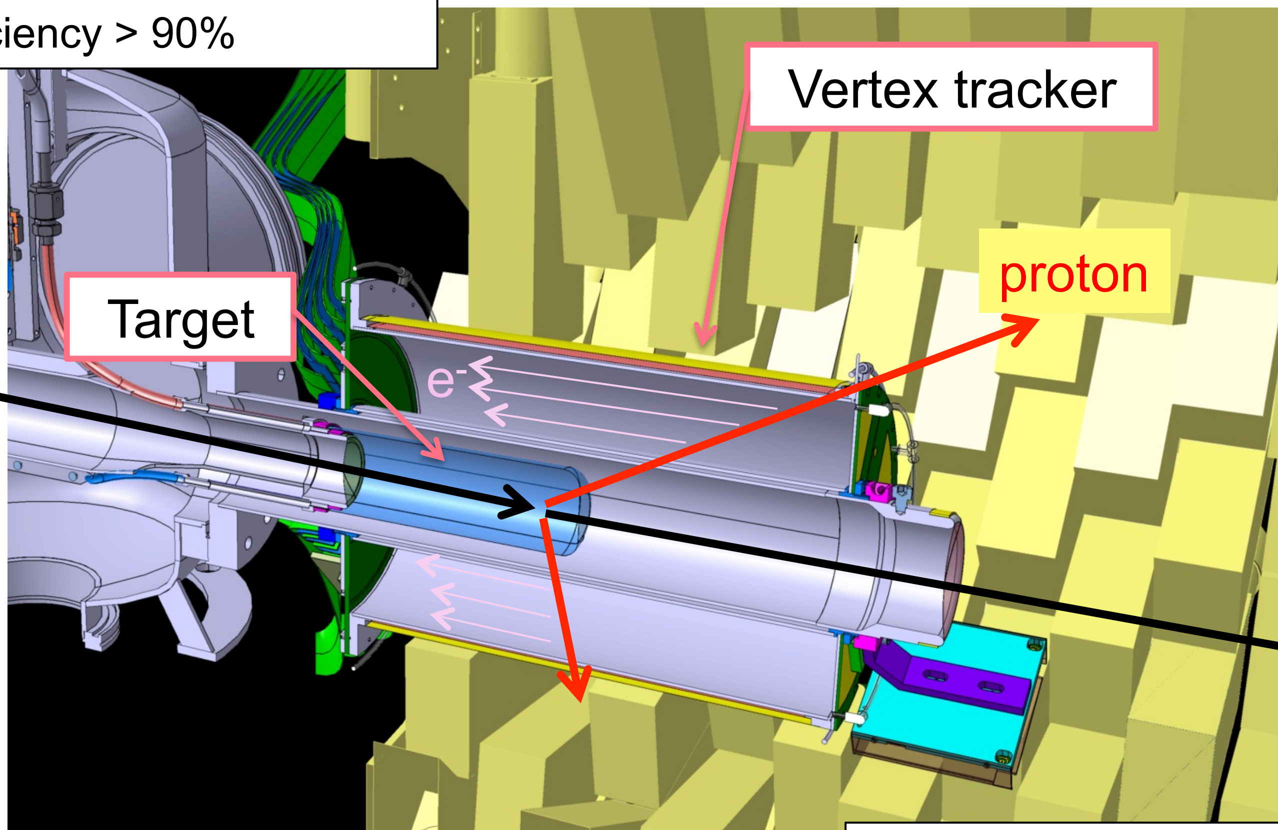
Three body forces



J.D. Holt *et al.*, JPG:NPP **39** (2012) 085111

MINOS at the RIBF

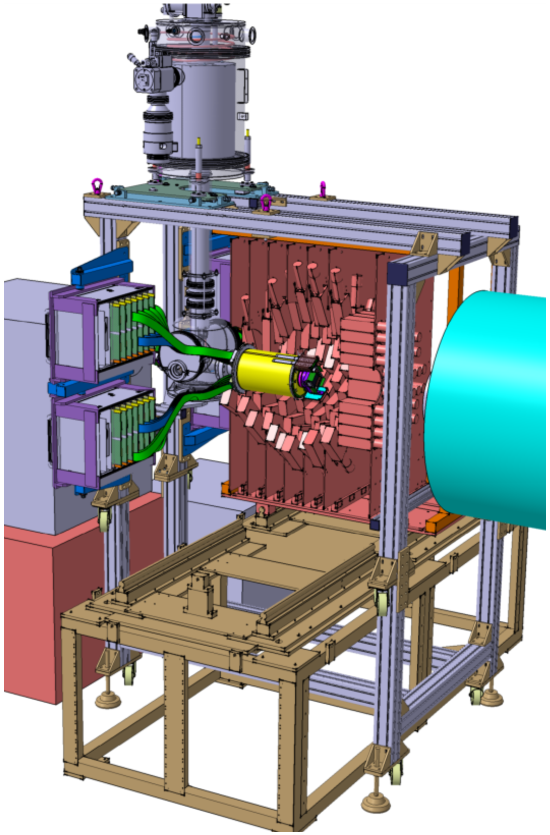
50-150 mm **liquid hydrogen target**
Vertex resolution : < 5 mm FWHM
Detection efficiency > 90%

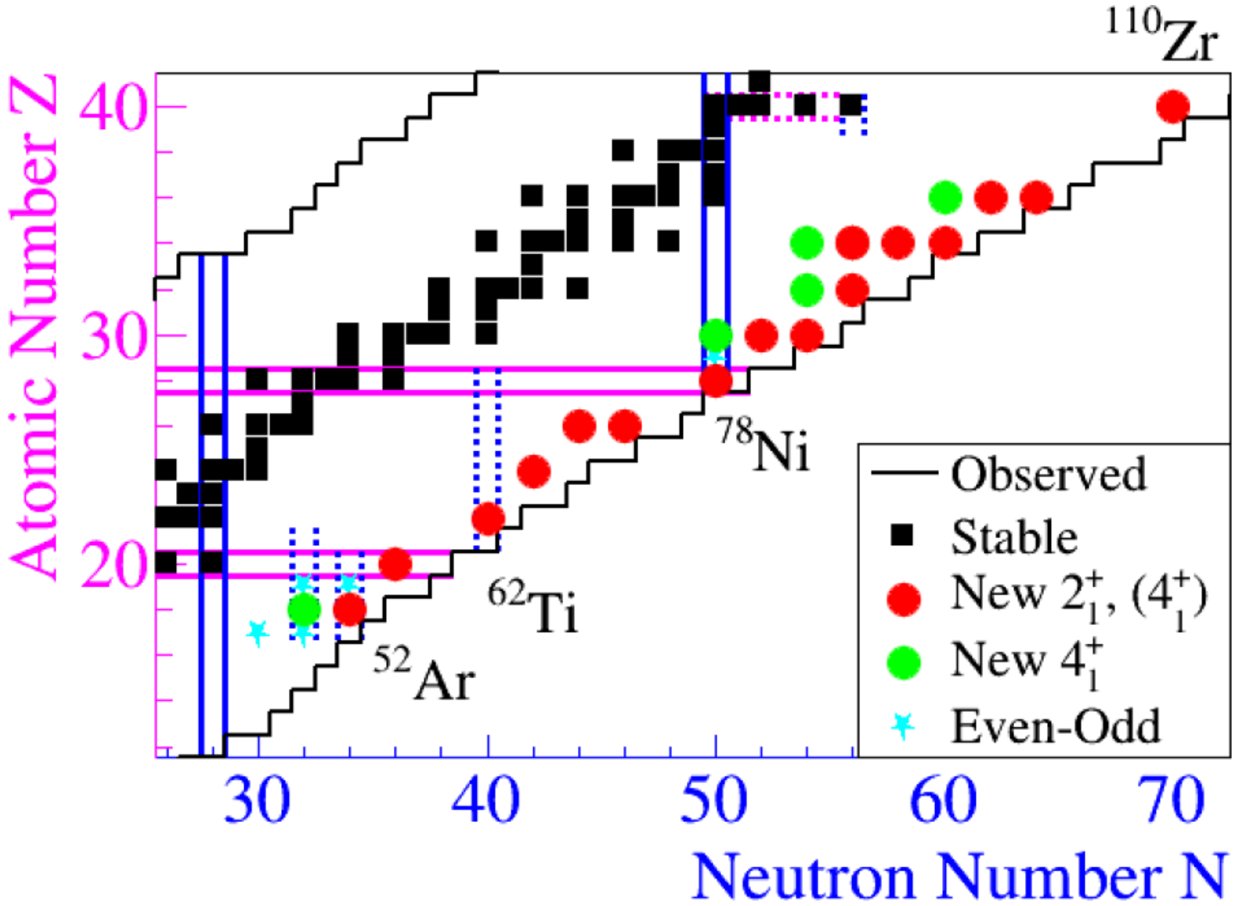


Project started in November 2010
In use at the RIBF since 2014

A. Obertelli *et al.*, Eur. Phys. Jour. A **50**, 8 (2014)

SEASTAR
Shell Evolution and Search for 2⁺ Energies At the RIBF





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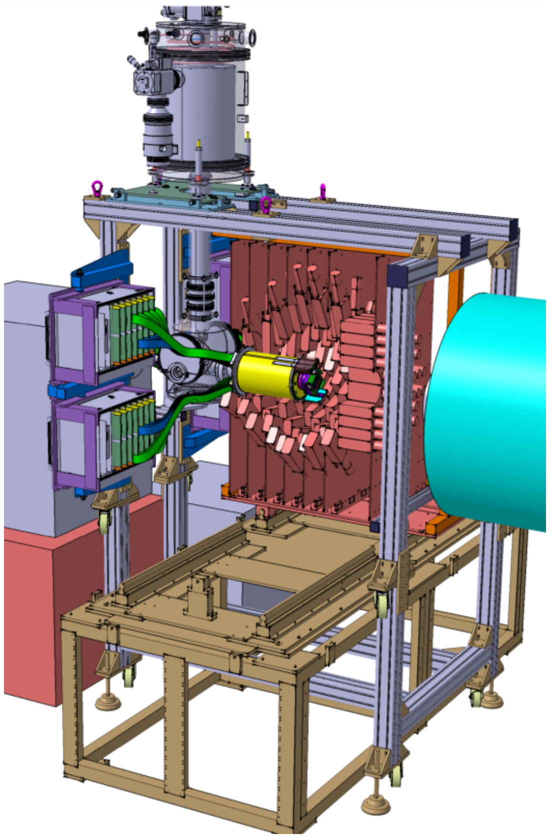
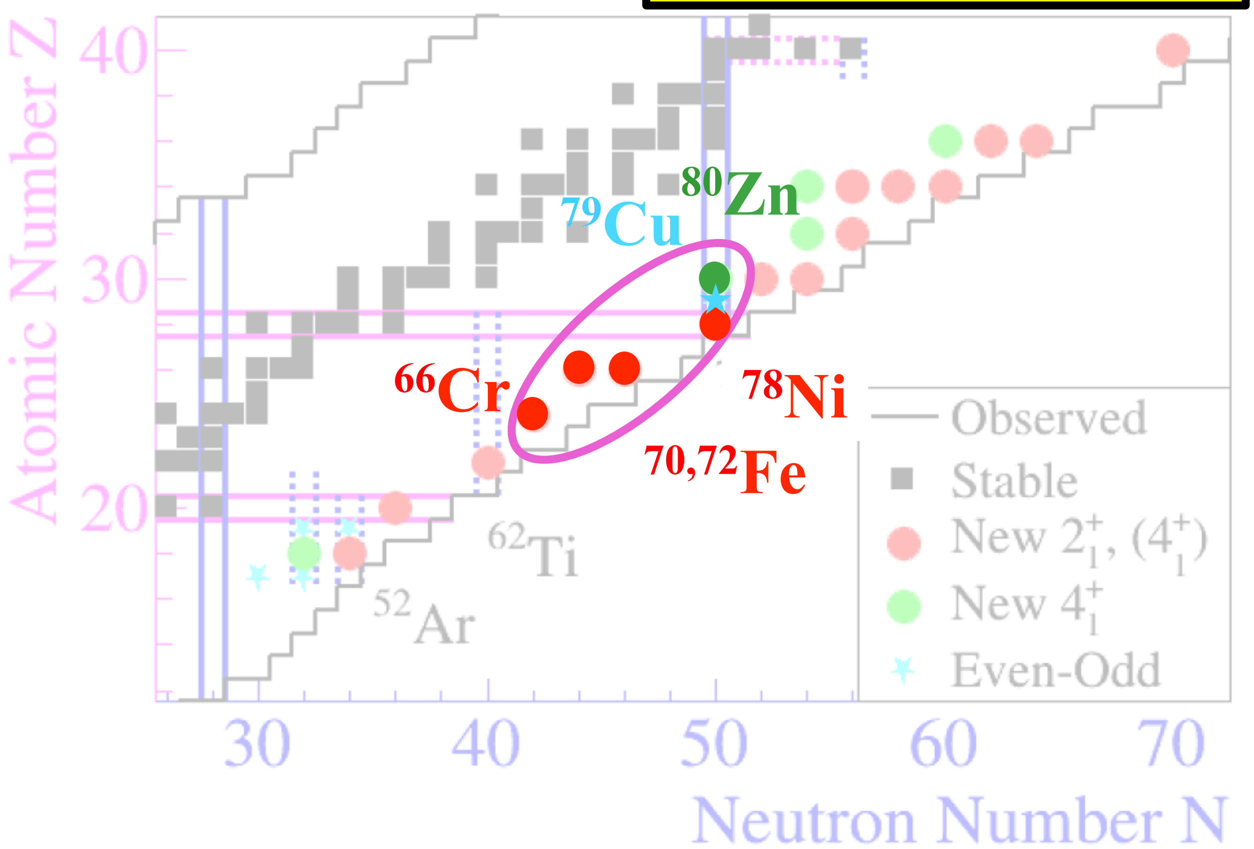
Shell Evolution and Search for 2⁺ Energies At the RIBF

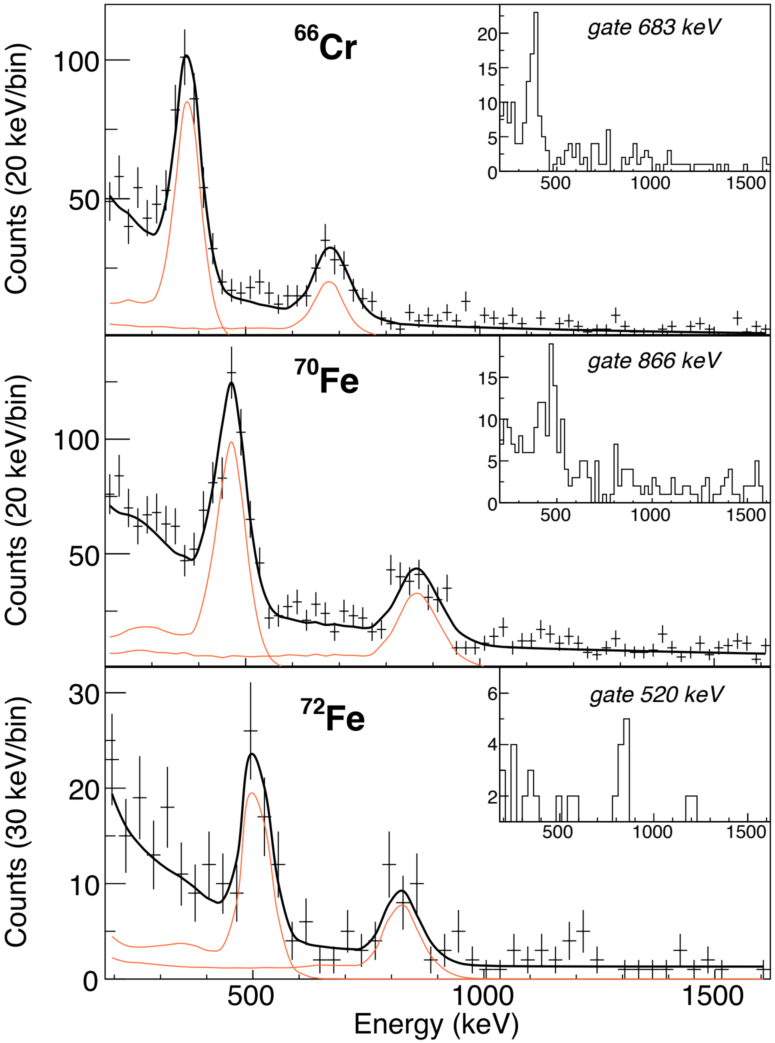


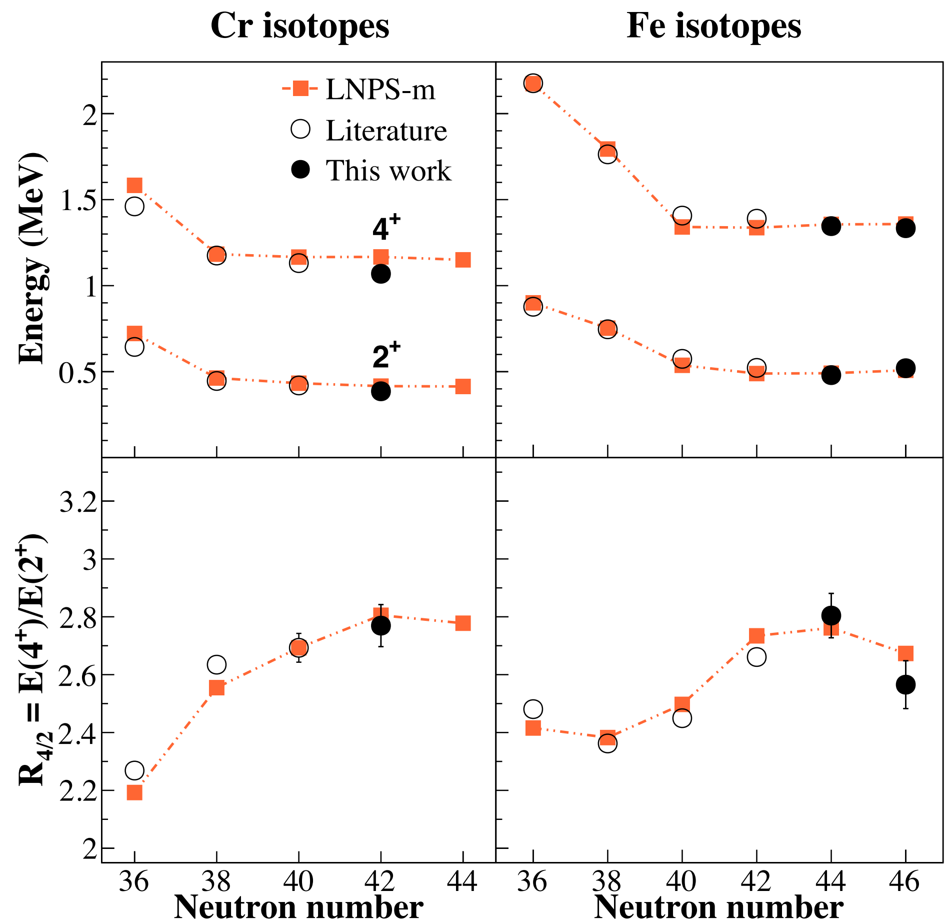
First campaign: May 2014



Primary beam ^{238}U at 345 MeV/nucleon, **mean intensity = 13 pnA**
Secondary beams at 250 MeV/nucleon, 100-mm target, $\Delta\beta/\beta$ = 20%

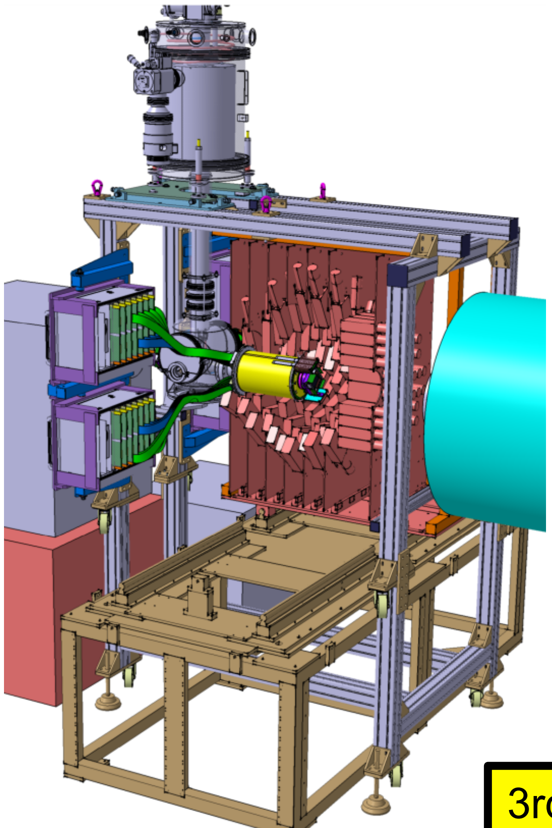
Collectivity beyond N=40 in Cr, Fe isotopes



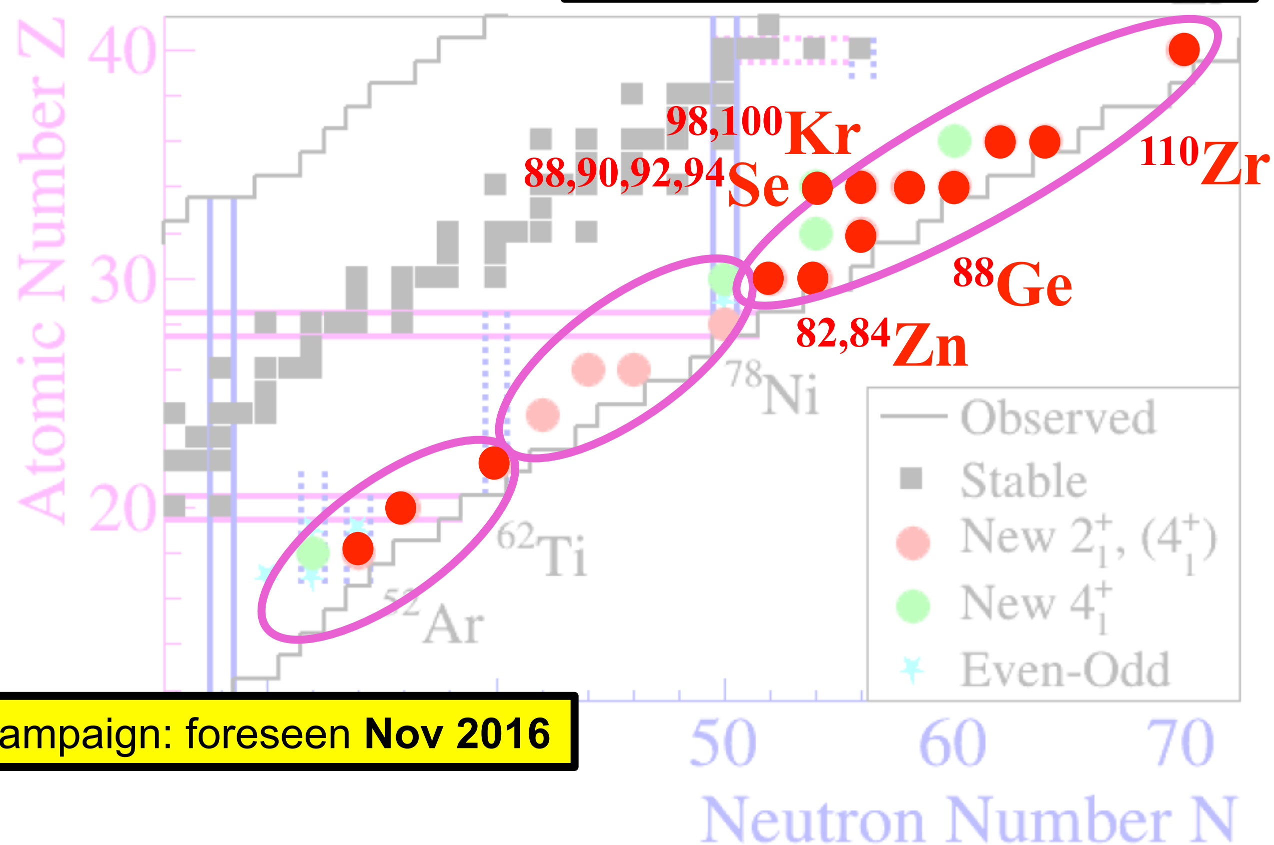


C. Santamaria *et al.*, Phys. Rev. Lett. **115**, 192501 (2015)

SEASTAR continuation

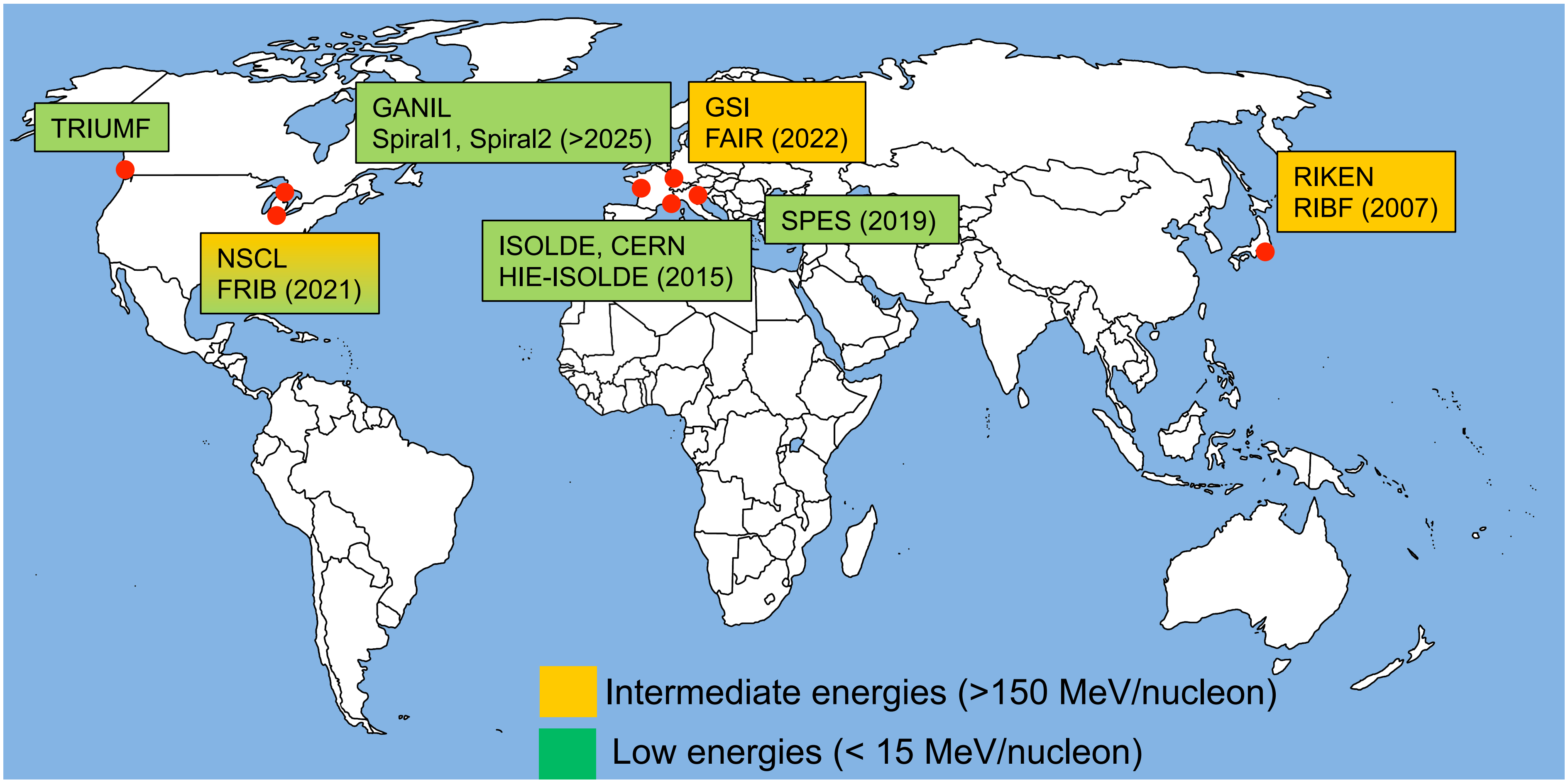


Second campaign: **May 2015**



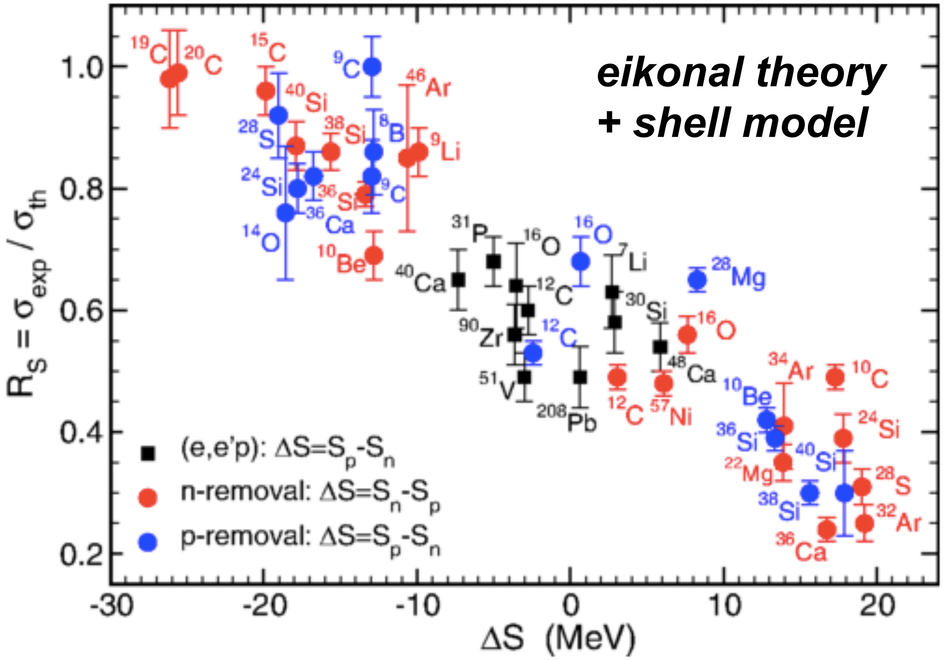
3rd campaign: foreseen **Nov 2016**

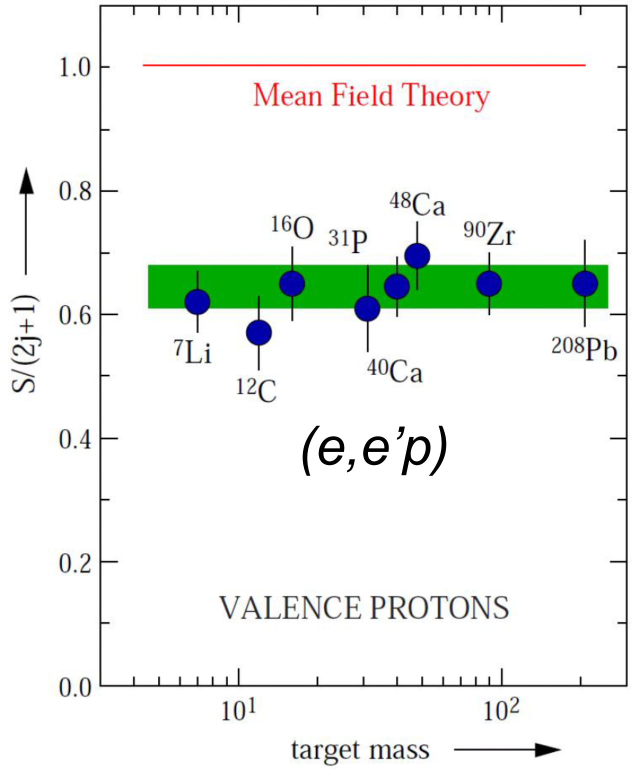
New-generation Rare Isotope Beam facilities



Probing the wave function via nucleon removal

A. Gade *et al.*, Phys. Rev. C **77**, 044306 (2008)
J.A. Tostevin and A. Gade, Phys. Rev. C **90**, 057602 (2014)





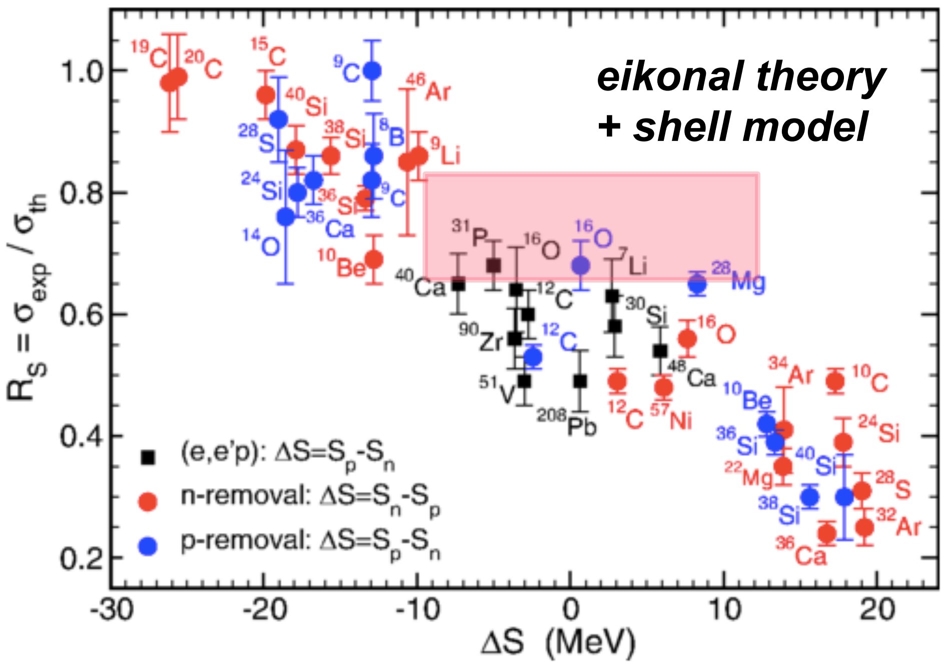
$$\frac{d\sigma_{\alpha\beta}}{d\Omega} = \sum_{n\ell j} S_{n\ell j} \left.\frac{d\sigma_{\alpha\beta}}{d\Omega}\right|_{n\ell j}$$

Intermediate-energy knockout

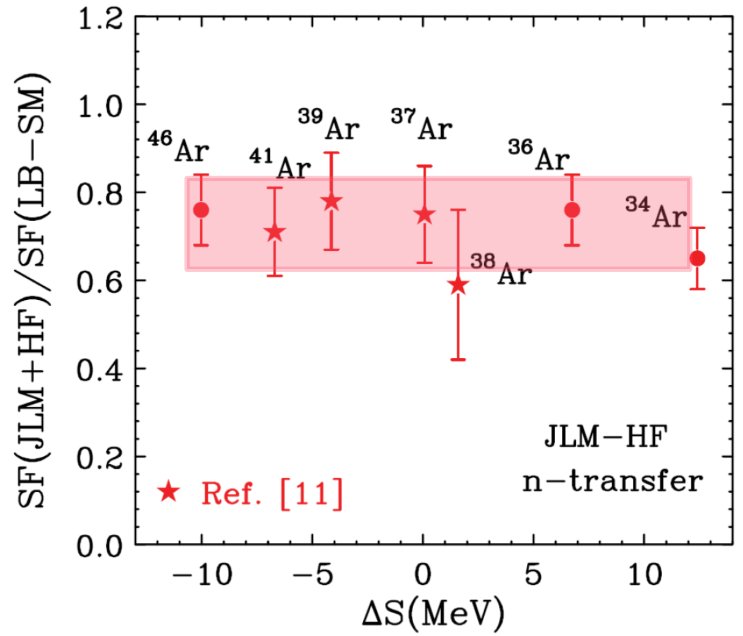
Disagreement between theory and experiment

Probing the wave function via nucleon removal

A. Gade *et al.*, Phys. Rev. C **77**, 044306 (2008)
J.A. Tostevin and A. Gade, Phys. Rev. C **90**, 057602 (2014)



J. Lee *et al*, PRC **83**, 014606 (2011).

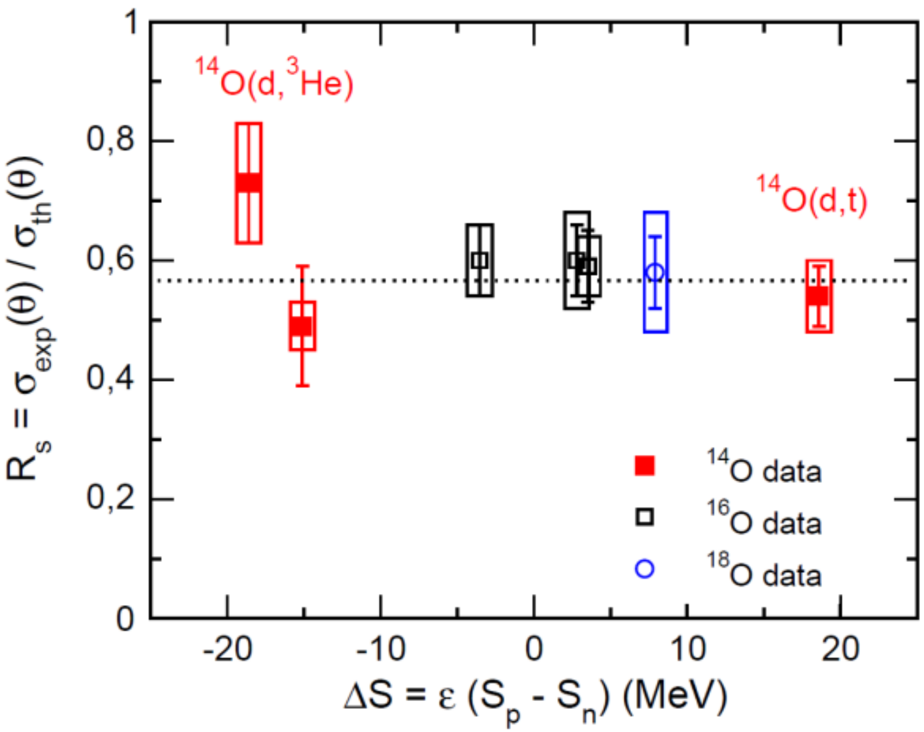


$$\frac{d\sigma_{\alpha\beta}}{d\Omega} = \sum_{n\ell j} S_{n\ell j} \left.\frac{d\sigma_{\alpha\beta}}{d\Omega}\right|_{n\ell j}$$

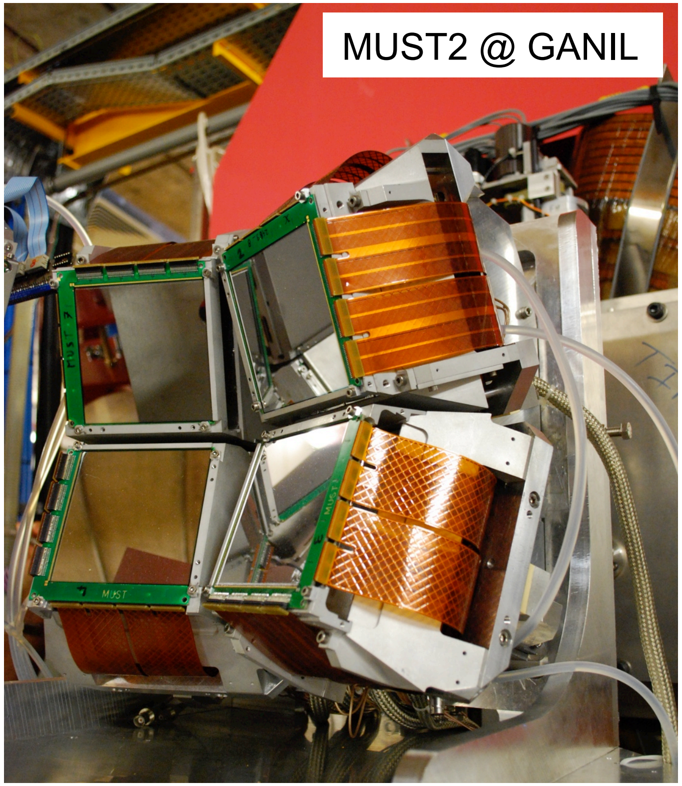
Intermediate-energy knockout
Disagreement between theory and experiment

Oxygen isotopes via transfer

^{14}O(d,t) , (d,^{3}He) and elastic scattering, 19 MeV/nucleon, SPIRAL (GANIL) **ΔS~19 MeV**



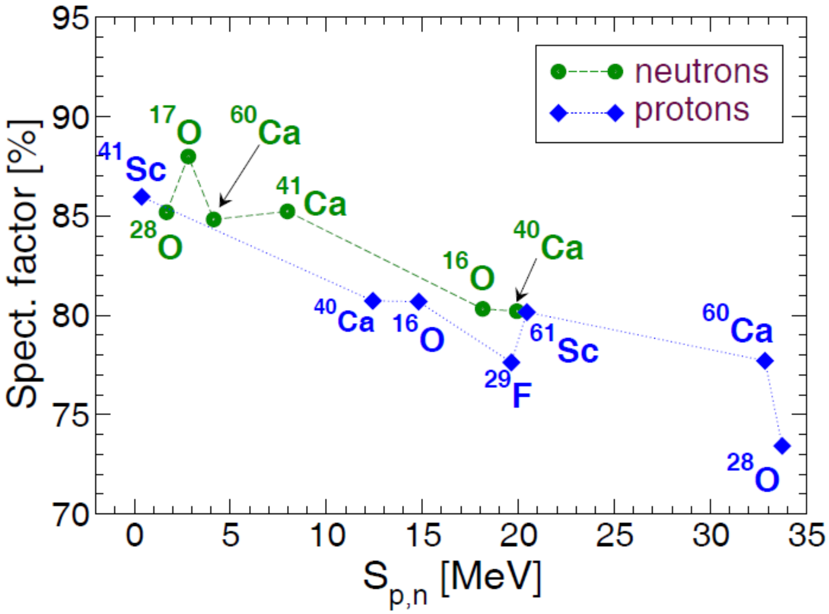
F. Flavigny *et al.,* Phys. Rev. Lett. **110**, 122503 (2013)



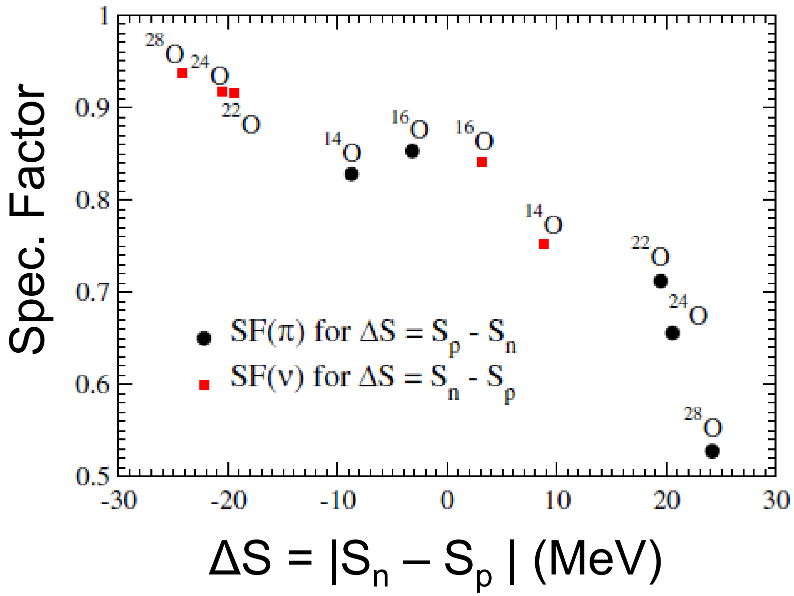
Conclusion

- **weak ΔS dependence**
- **Disagreement** between intermediate-energy nucleon removal and transfer analysis
- **A consistent treatment of structure and reaction mechanism still missing!**

Ab initio theory: very weak dependence



C. Barbieri, W.H. Dickhoff, Int. Jour. Mod. Phys. A **24**, 2060 (2009)



O. Jensen *et al.*, Phys. Rev. Lett. **107,** 032501 (2011)

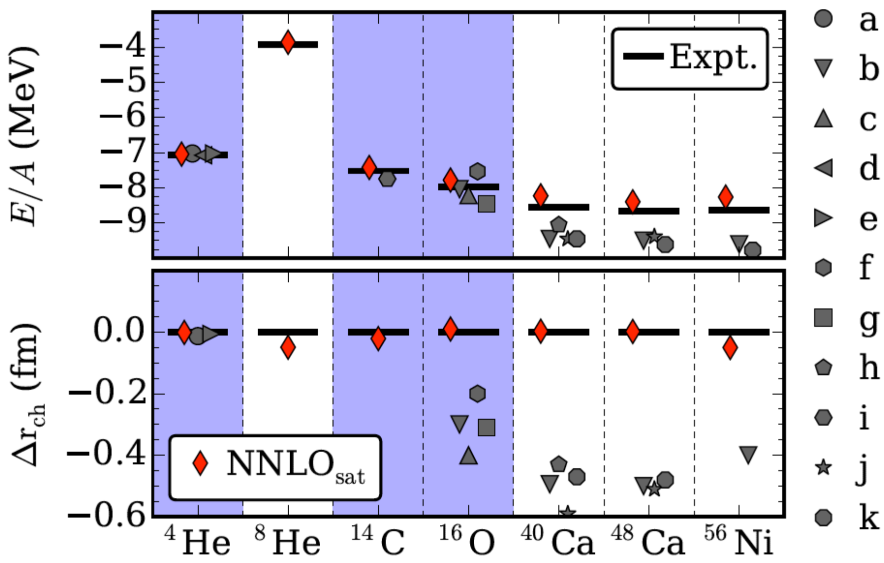
Conclusion

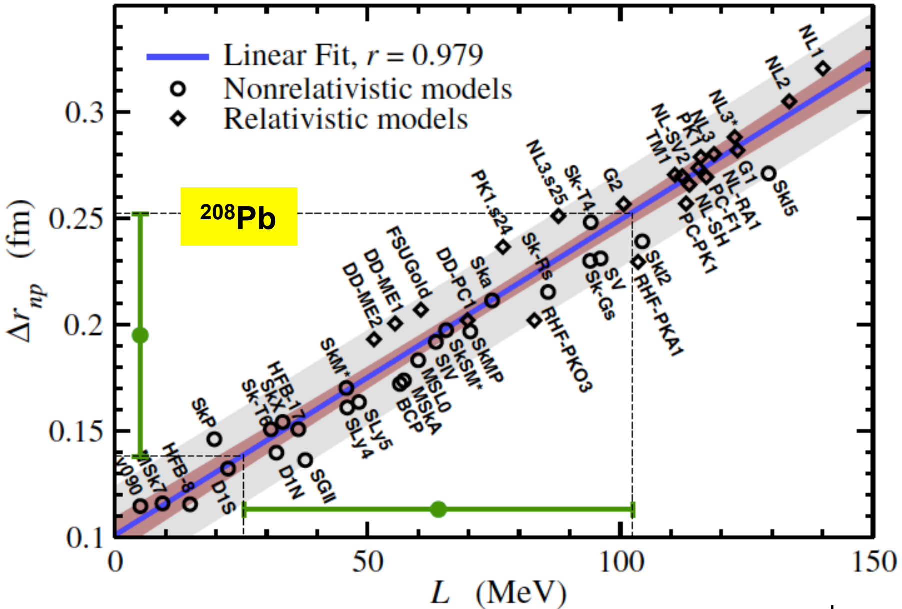
- *Ab initio* prediction of a **weak ΔS dependence** from 0.7 to 0.9
  in **agreement** with **transfer**
  in disagreement with eikonal analysis of heavy-ion induced knockout

Nuclear matter distributions

EoS and symmetry energy **S**:
energy penalty for breaking N=Z symmetry

$$\frac{E}{A}(\rho_n,\rho_p)=\frac{E_0}{A}(\rho)+S(\rho)\left(\frac{\rho_n-\rho_p}{\rho}\right)^2$$





$$L \propto \left.\frac{\partial S(\rho)}{\partial \rho}\right|_{\rho_0}$$

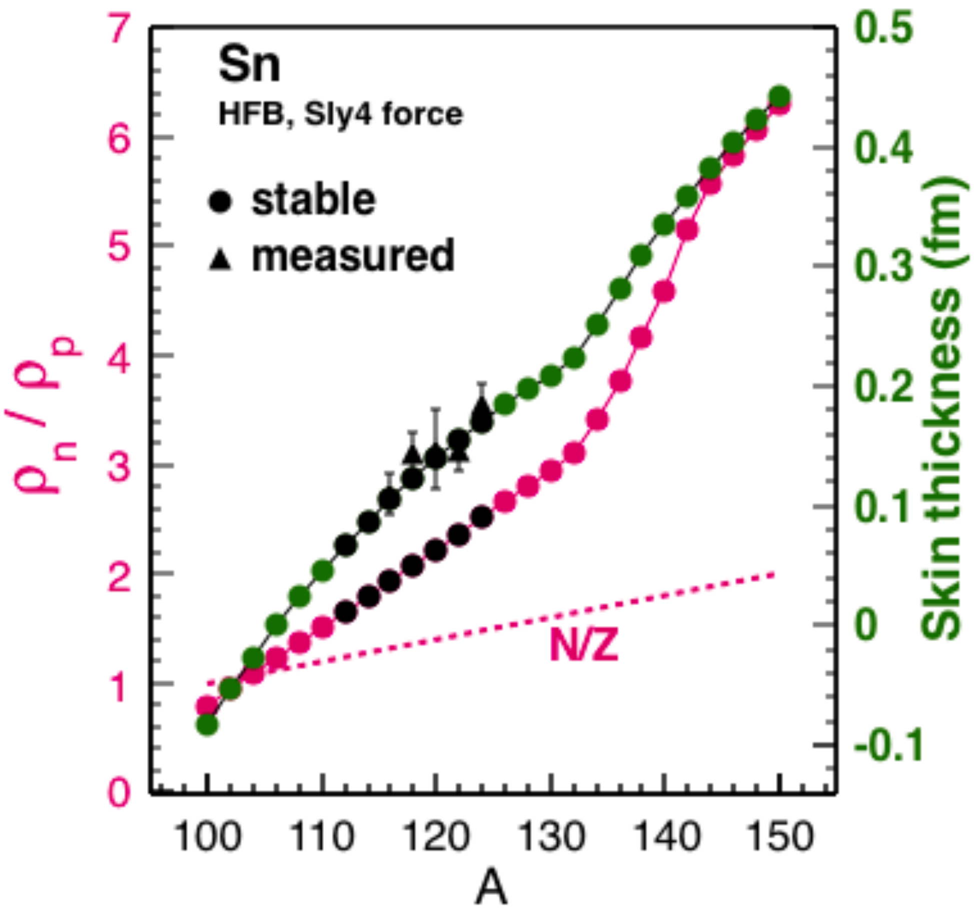
A. Ekström *et al*, Phys. Rev. C **91**, 051301(R) (2015)

X. Roca-Maza et al., Phys. Rev. Lett. **106**, 252501 (2011)

Nuclear matter distributions in unstable nuclei

- Several high-precision techniques to determine neutron skin thicknesses
  Ex. ^{208}Pb, Δr_{np} = 0.15 fm ±
  - Antiprotonic atoms
    B. Klos *et al.*, PRC 76 (**2007**)
  - Proton scattering
    A. Tamii *et al.*, PRL 111 (**2011**)
  - Parity violation e$^-$ scattering
    S. Abrahamyan *et al.*, PRL 108 (**2012**)
  - Coherent pion photoproduction
    C.M. Tarbert *et al.*, PRL 112 (**2014**)

- … but high luminosity required
  [Stable nuclei only]



For short-lived nuclei:

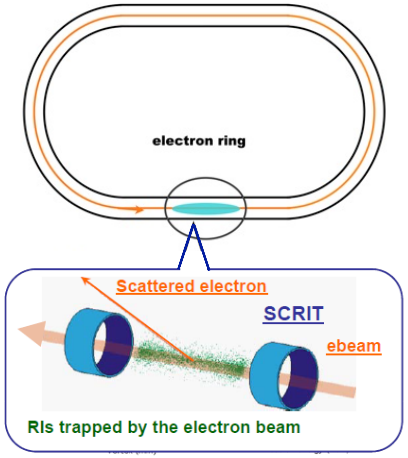
- nuclear density distribution from proton elastic scattering at high energy

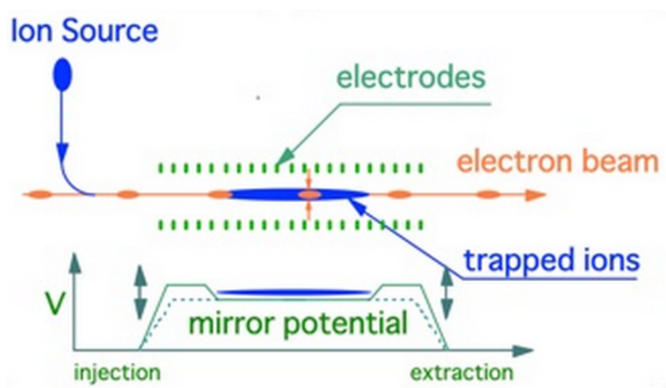
  Programs at RIBF, GSI/FAIR

- **New:** electron – rare isotope elastic scattering
  SCRIT (RIBF), ELISE (planed at FAIR)

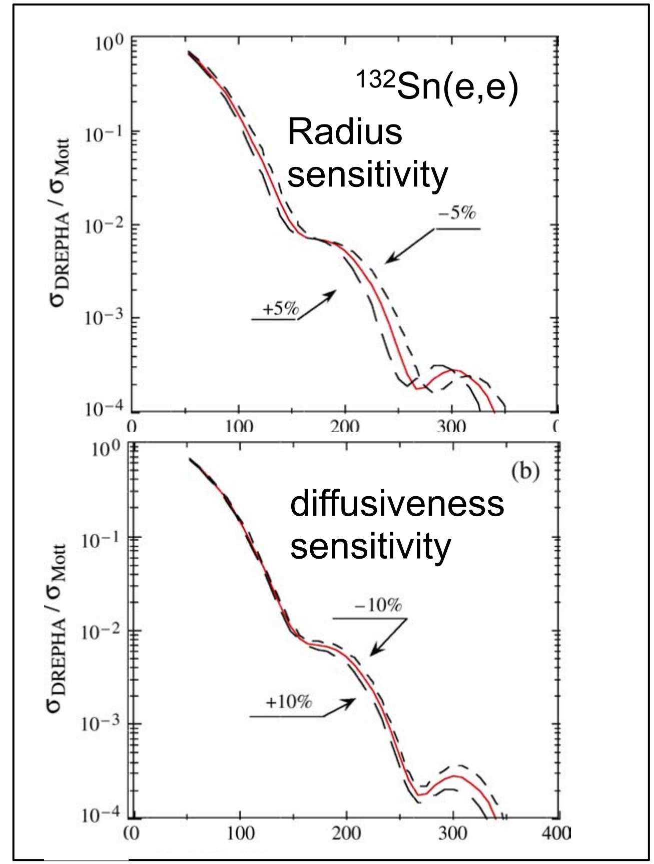
Electron-unstable ion collisions

SCRIT @ RIKEN





M. Wakasugi, T. Suda, Y. Yano, NIM A 532 (2004)



Concept

Use ion-trapping phenomena present in electron storage rings to form “targets” of short-lived nuclei

T. Suda, M. Wakasugi, Prog. Part. Nucl. Phys. **55**, 417 (2005)

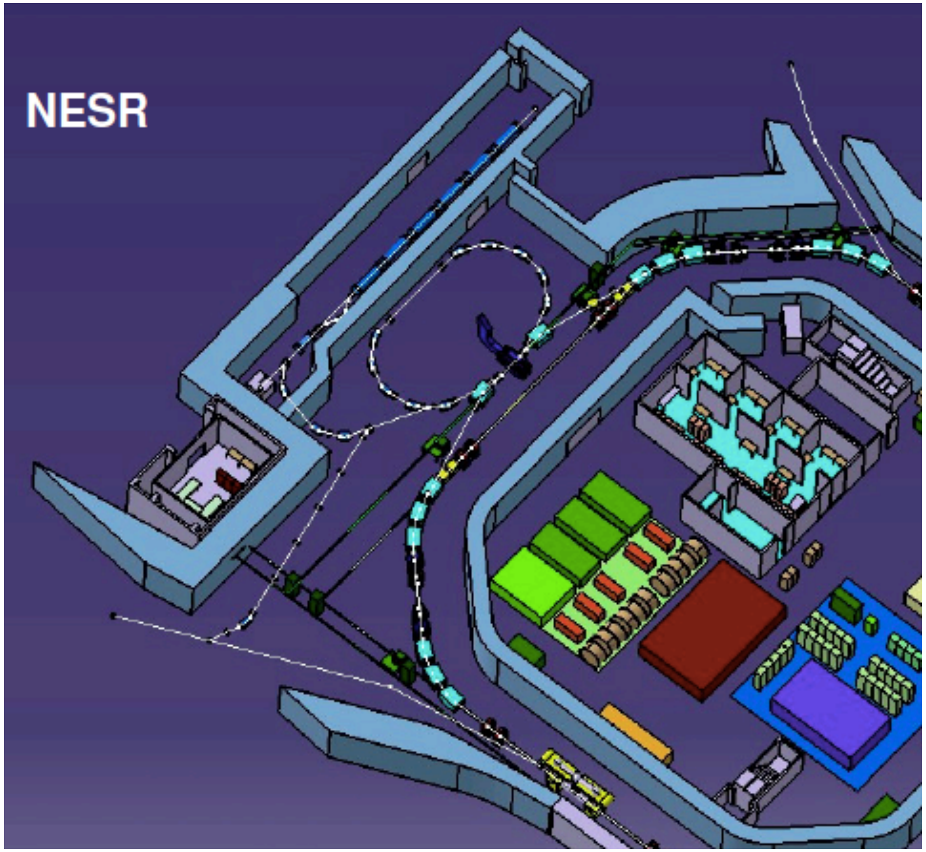
Goal: charge radii and diffusiveness

10^{27} cm^{-2}s^{-1} luminosity (for 10^7 stored ions)

T. Suda *et al.*, Phys. Rev. Lett. **102**, 102501 (2009)

First physics experiments (^{132}Sn region) in 2016

ELISe at FAIR: an electron – Radioactive Ion collider



Part of the FAIR facility (**expected >2025**)

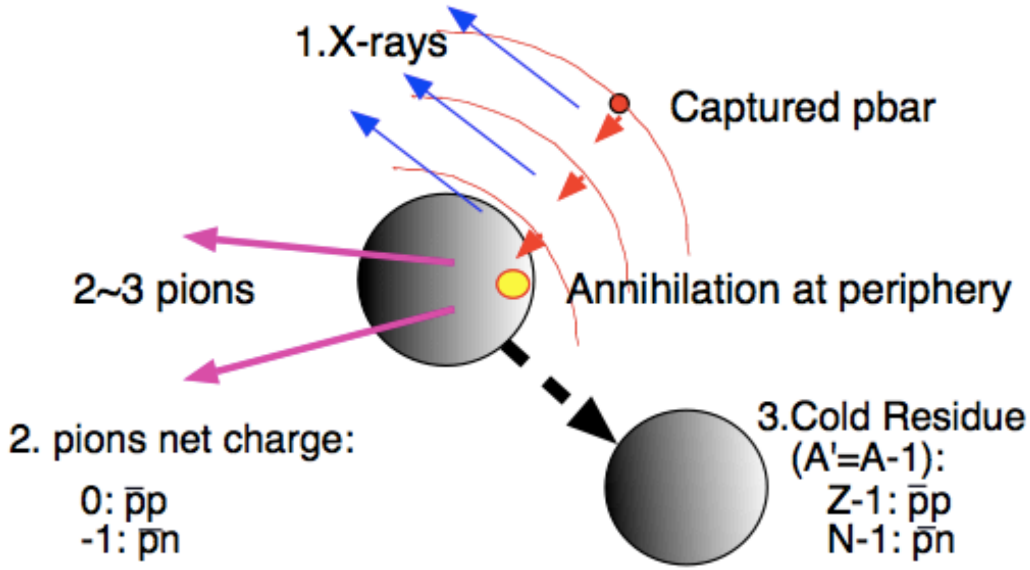
- 125-500 MeV electrons
- 200-700 MeV/u RIBs

Luminosity <10^{28} $cm^2 s^{-1}$ / Lorentz focusing

- charge distributions
- e.m. transitions/modes
- access to nuclear interior
- spectral functions

Antiproton unstable ion annihilation: perspectives

Antiprotonic radioactive atoms (Exo+pbar)



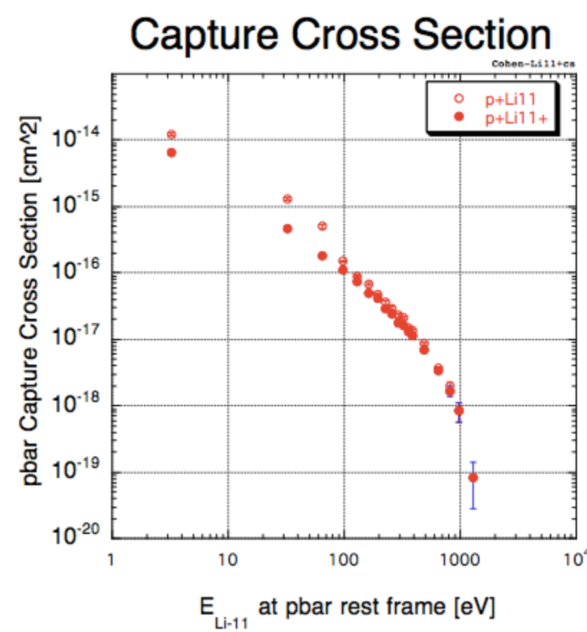
A new probe for nuclear structure study of unstable nuclei

*** annihilation at** $\rho \approx \rho_0\, 1/1000$

*** pbar distinguishes p and n**

$$\left.\frac{\rho_n}{\rho_p}\right|_{surface} = \underbrace{\frac{N_n}{N_p}}_{\text{measured}} \times \overbrace{\frac{\sigma_{\bar{p}p}}{\sigma_{\bar{p}n}}}^{=\,1/0.63} \times \underbrace{\varepsilon}_{\text{simulated / measured}}$$

M. Wada, Y. Yamazaki, Nucl. Instr. Meth. B **214** (2004).



Cohen PRA69(2004)022501

Higlights and Perspectives with Exotic Nuclei

Can we describe nuclei from first principles?

- **Ab initio** treatment of nuclei / improvement of input interaction needed
- Benchmark systematics, *ex.* **oxygen isotopes**
- Isospin dependence of 3N forces, *ex.* **4n low-lying resonance**
- ΛN, ΛNN interactions via **neutron-rich hypernuclei** studies (*ex*. puzzle of ${}_{\Lambda}^{3}\mathrm{H}$ **half-life**)

What is the nuclear shell structure and its origins?

- **Access to new regions of the nuclear chart at the RIBF** and soon at new generation facilities
- Systematic search **for 2^+ states in neutron rich even-even nuclei**
  ex. **N=34 "magic number" (tbc) in ^{54}Ca, first spectroscopy of ^{78}Ni**

- **Limited predictive power for direct reactions**: qualitative use of measured cross sections
  Theory: consistent treatment of structure & reaction needed

What is the nuclear matter distribution inside the nucleus?

- **Neutron skin thickness** strongly related to the EoS (symmetry energy)
- Precision skin thickness measurements in stable nuclei
- **Neutron and proton radial densities of unstable nuclei** not measured yet
  ex. **Electron –unstable ion scattering** (SCRIT @ RIKEN, ELISE @ FAIR) + **p elastic scattering**
  ex. **Antiproton – unstable ion collisions**: ratio of ρ_n and ρ_p at nuclear surface

Due to time or my own limits many topics/observables were not covered:
Exotic radioactivities, beta decay, HI collisions for high density studies, collective modes, nuclear deformation, search for super-heavy elements…