PROBING THE STRUCTURE OF EXOTIC NUCLEI WITH PROTON AND ANTIPROTON TARGETS

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CEA Saclay

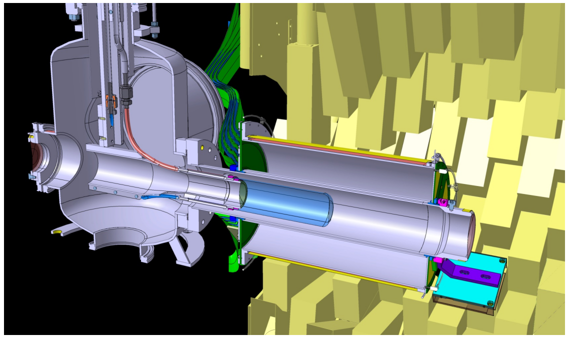
GDS Topical Meeting, Legnaro, 25-27th January 2017

OUTLINE

✧ Challenges in the study of exotic nuclei

✧ A proton target: MINOS

- Method
- Description
- Results at RIKEN
- Perspectives



✧ An antiproton target: PUMA

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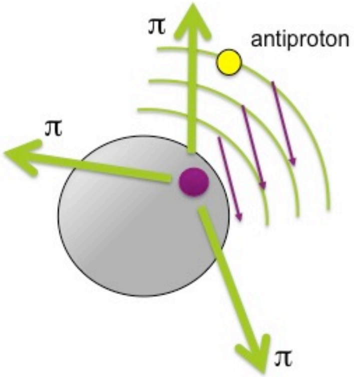
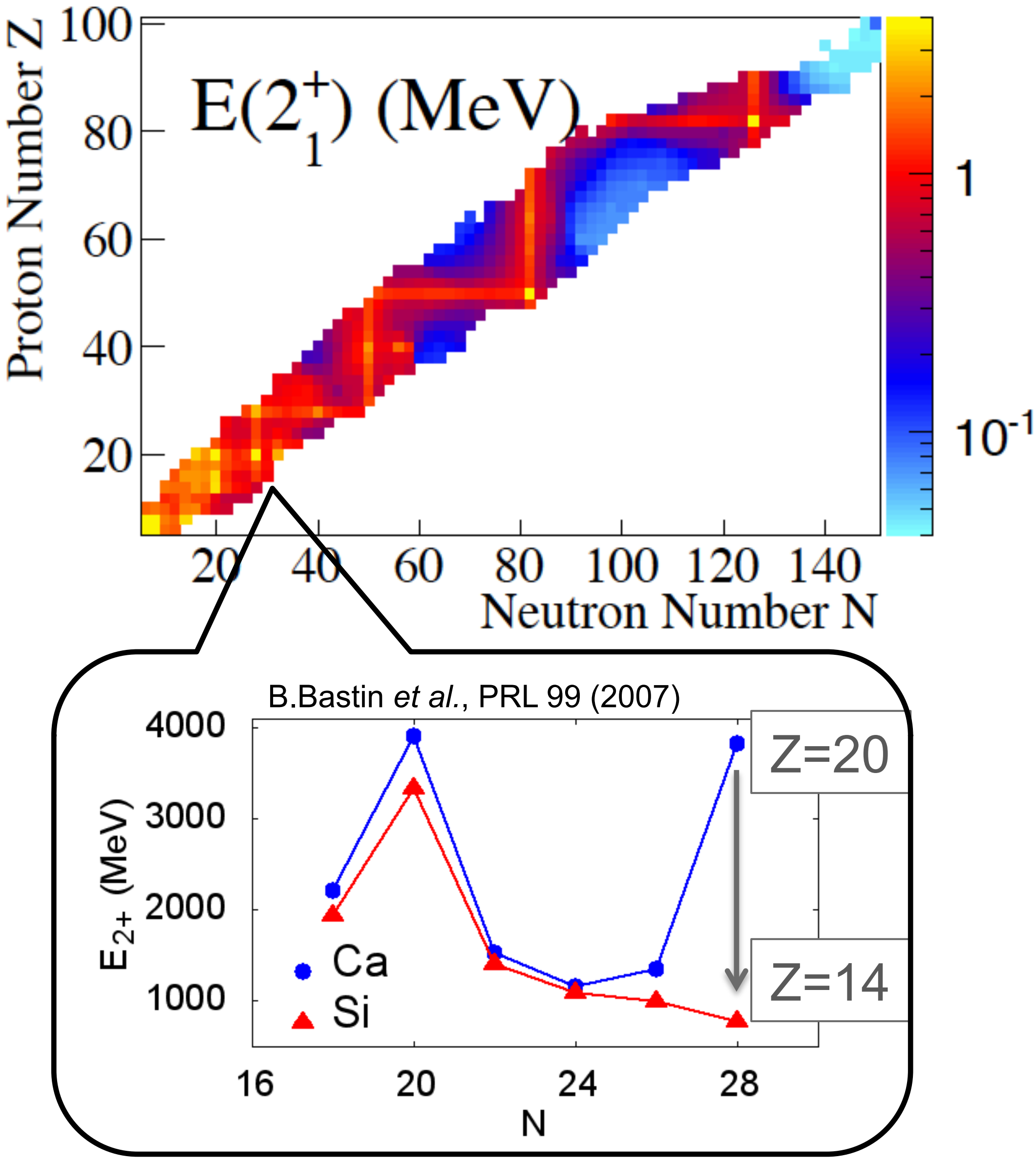


Evolution of shell structure

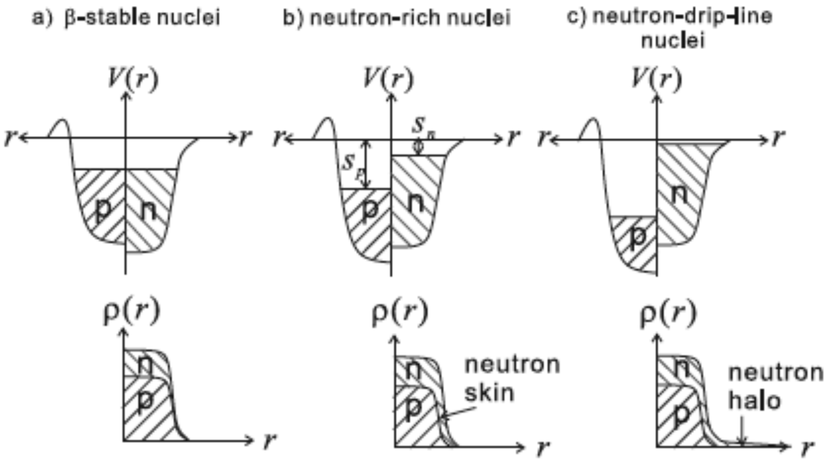
- Energy spectrum sensitive to shell structure
- 2^+ energy most accessible observable
- **High 2^+ energy <=> magic numbers**



- Magic numbers (may) change far from stability e.g. N=28
- Possible diving mechanism:
  Central force T. Otsuka *et al.*, PRL 87 (2001)
  Tensor force T. Otsuka *et al.*, PRL 104 (2010)
  3 body force G. Hagen *et al.,* PRC **80** (2009)

Development of halos and thick neutron skins

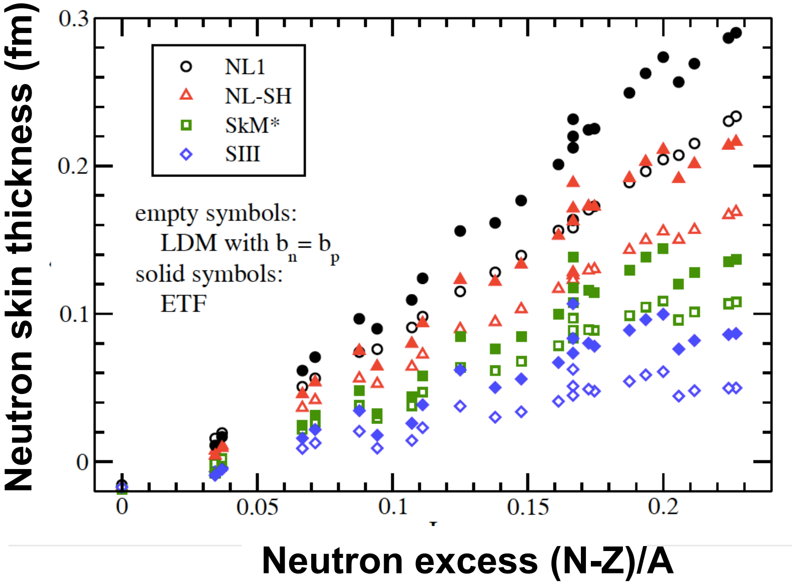
Skins from **matter and charge radius:**
- Electron / hadron elastic scattering
- Coherent pion photoproduction
- Parity violation in electron scattering



Halo measured in **light neutron-rich nuclei**
- No measurement of halo beyond Mg
- Recent hints of proton halo

Relevant to:
- Benchmark **symmetry term of EOS**
- Study **nucleon-nucleon correlations** in dilute matter

Current limitations:
- No data on skins for **unstable nuclei**
- Difficulty to measure **shape/tail of density distribution**



X. Vinas *et al.*, Eur. Phys. J A 50, 27 (2014)

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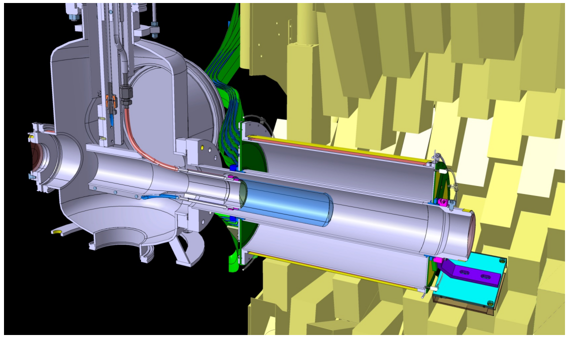

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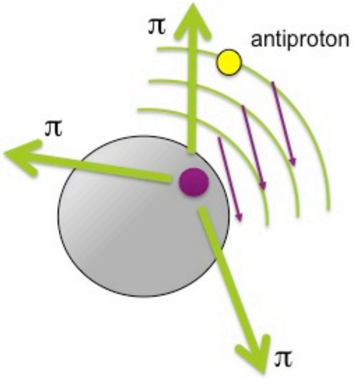
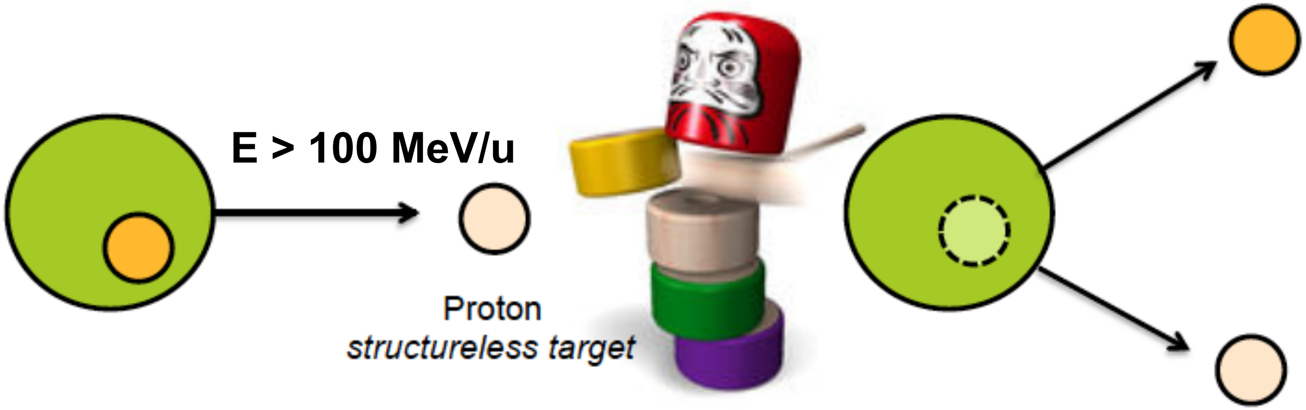


Quasi Free Scattering reactions in inverse kinematics

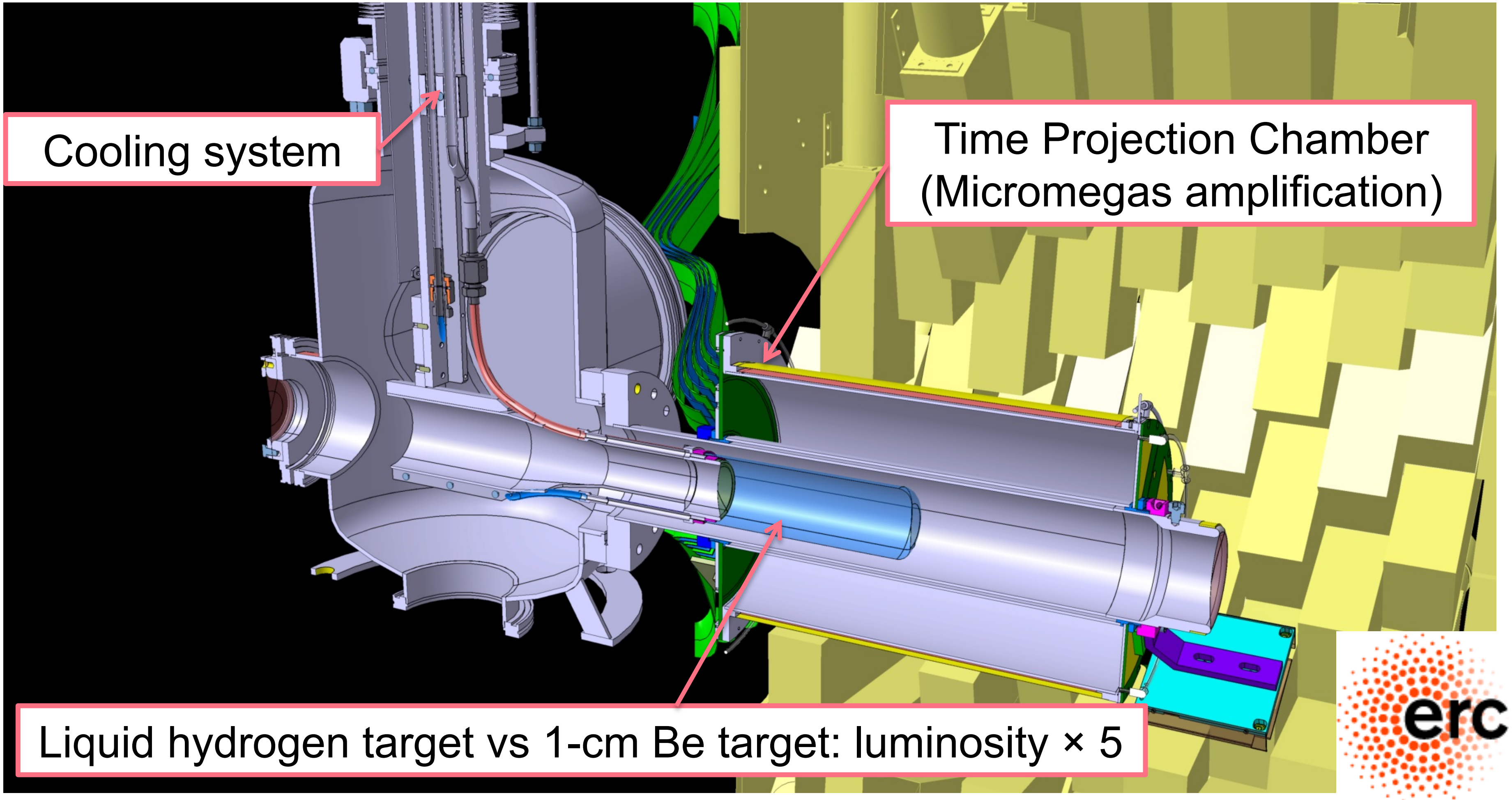
- QFS is a clean experimental probe
- QFS in inverse kinematics compatible with thick target => increase luminosity
- **need vertex** reconstruction for:
  doppler correction
  (gamma spectroscopy)
  energy loss correction
  (invariant mass spectroscopy)

Adapted from I.Sick, ECT*2008

	cleanliness	feasibility
(e,e'p)	++	--
transfer	+	-
HI knockout	-	+
QFS	+	+



MINOS : Magic Numbers Off Stability



Cooling system

Time Projection Chamber (Micromegas amplification)

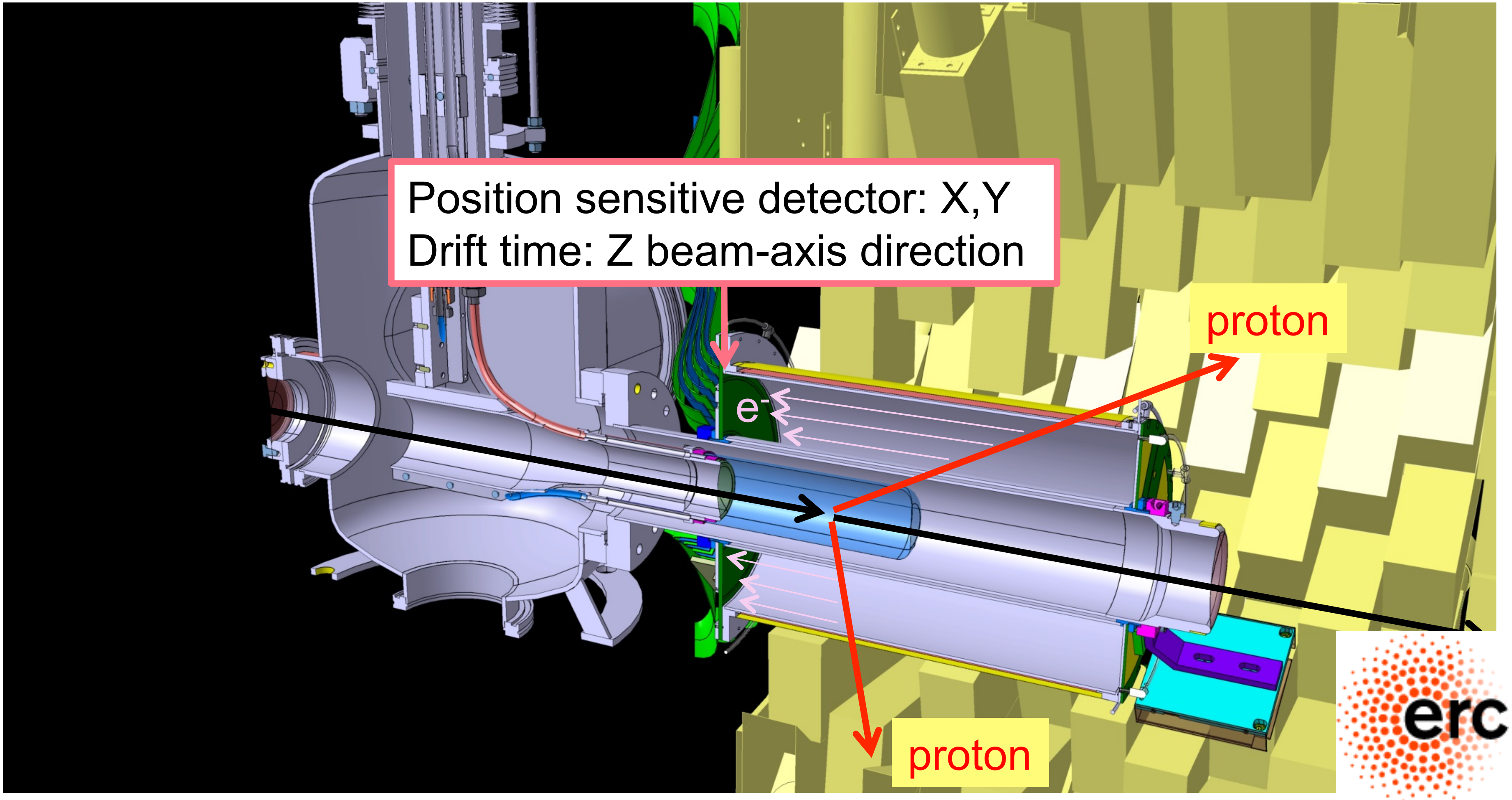
Liquid hydrogen target vs 1-cm Be target: luminosity × 5

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

http://minos.cea.fr

Hosted by Spin-Isospin Laboratory of RIKEN Nishina Center

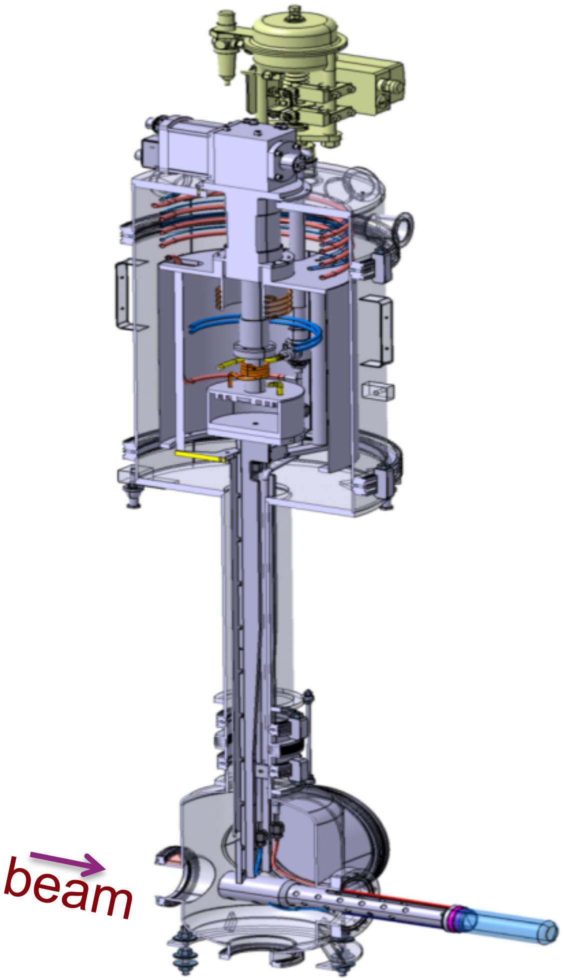
MINOS : Magic Numbers Off Stability



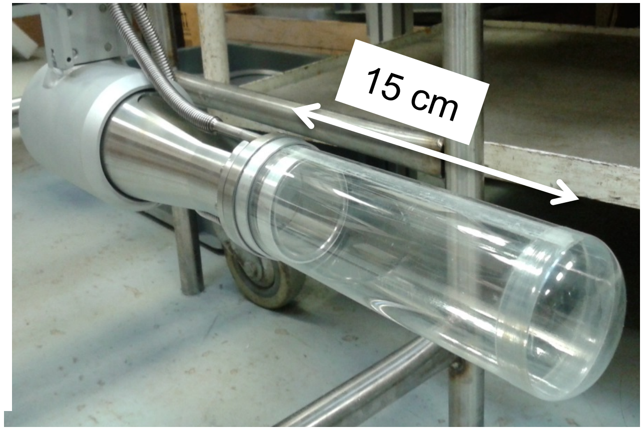
Position sensitive detector: X,Y
Drift time: Z beam-axis direction

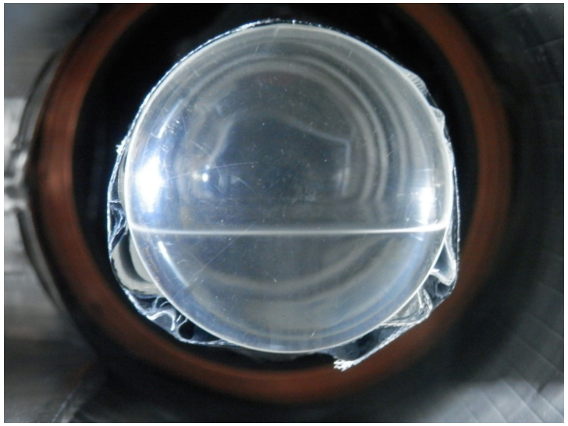
Efficiency: 95% in (p,2p) & resolution on vertex: 5 mm (FWHM)

The MINOS device: LH_2 target

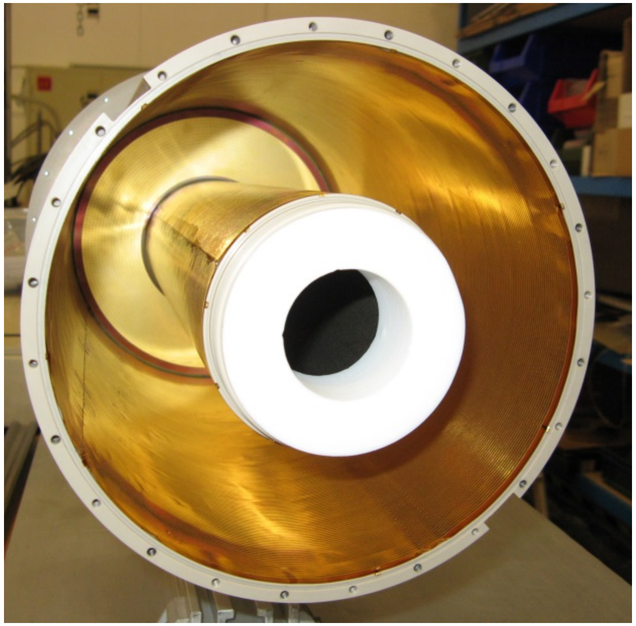


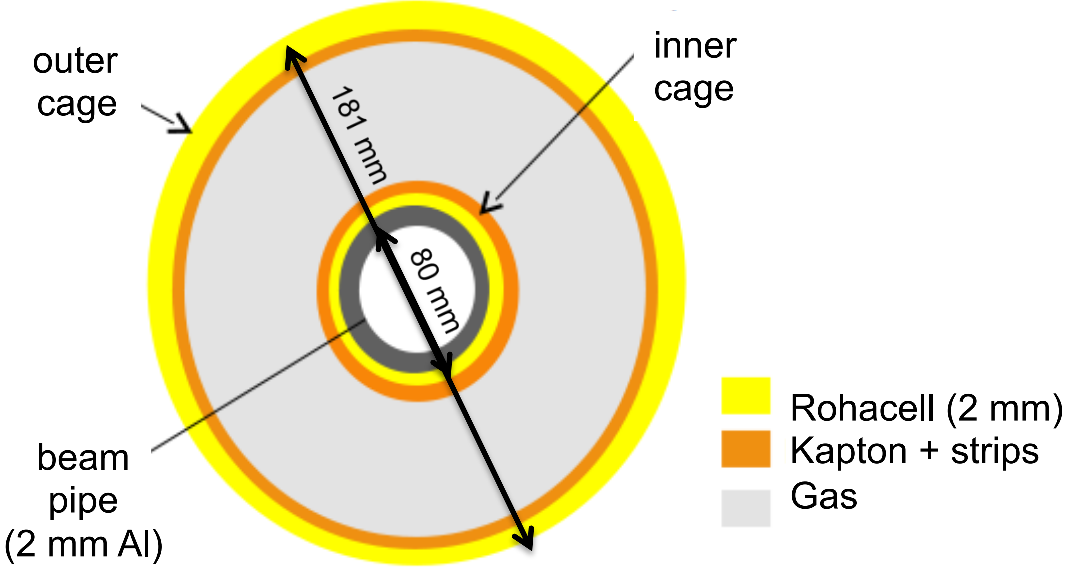
- Cryogenic target (20 K)
- Mylar cell: 200 microns, 38 mm entrance window
- 100-150 mm length, **≈ 1 g/cm^2 H**
- E_{loss}=65 MeV/u for 250 MeV/u ^{78}Ni
- Surrounding space free for detection

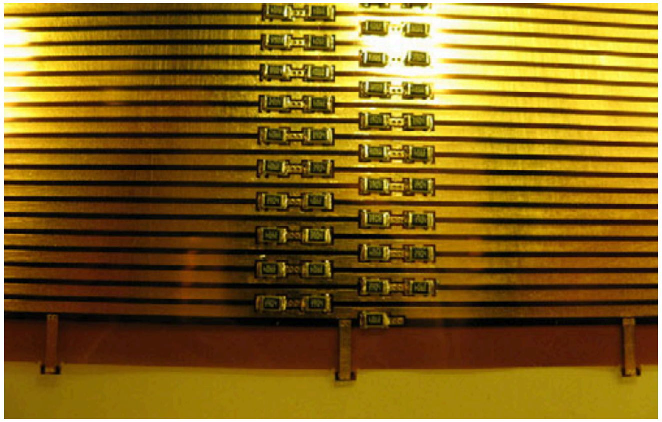




The MINOS device: field cage







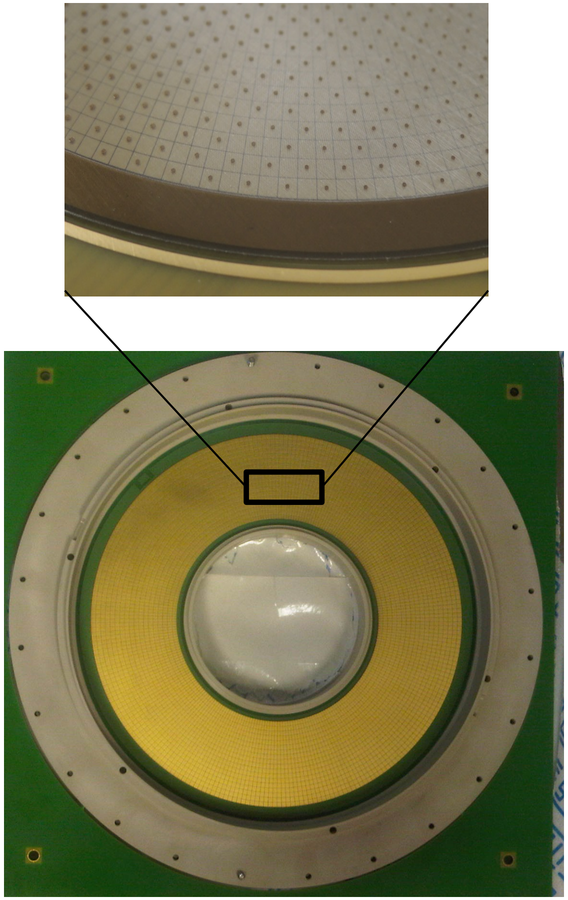
- 30-cm long drift space
- ~400 1-mm strips connected by 800 resistors
- Compact, low-material budget field cage
- Ar (82%) + CF_4 (15%) + C_4H_{10} (3%) gas at 1 ATM
  Drift velocity ~4.5 cm/μs at 180 V/cm
  Transverse diffusion < 200 μm/√cm

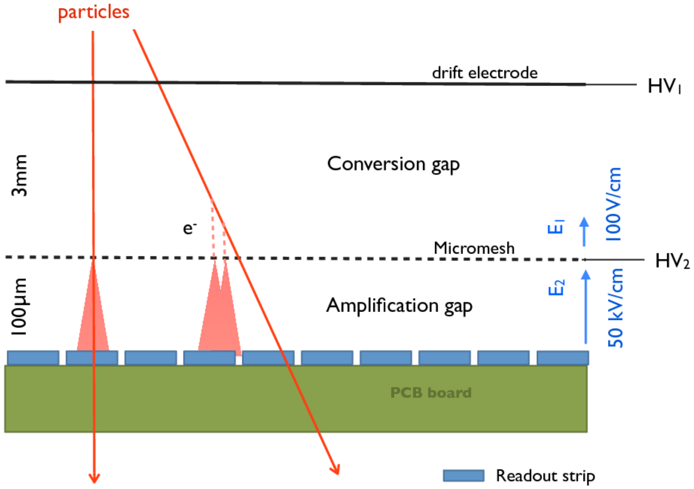
The MINOS device: Micromegas detector

- Micromegas detector

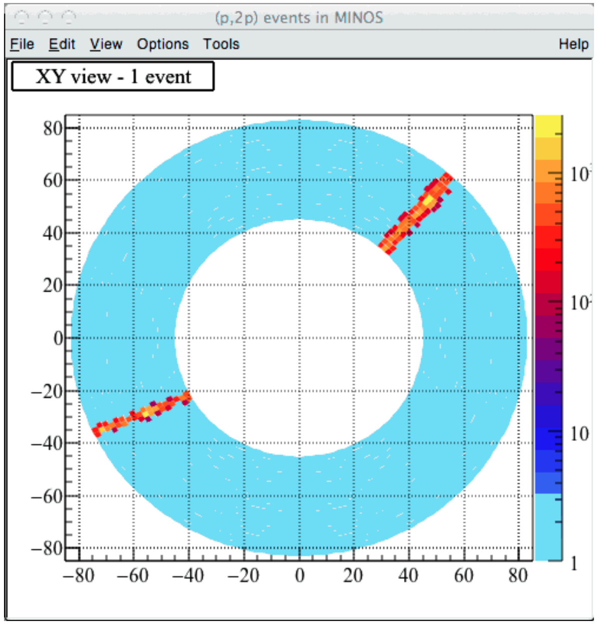
G. Charpak, I. Giomataris, et al., NIMA 376, 29 (1996).

- 4000 pads of 2 x 2 mm^2





- Typical (p,2p) event



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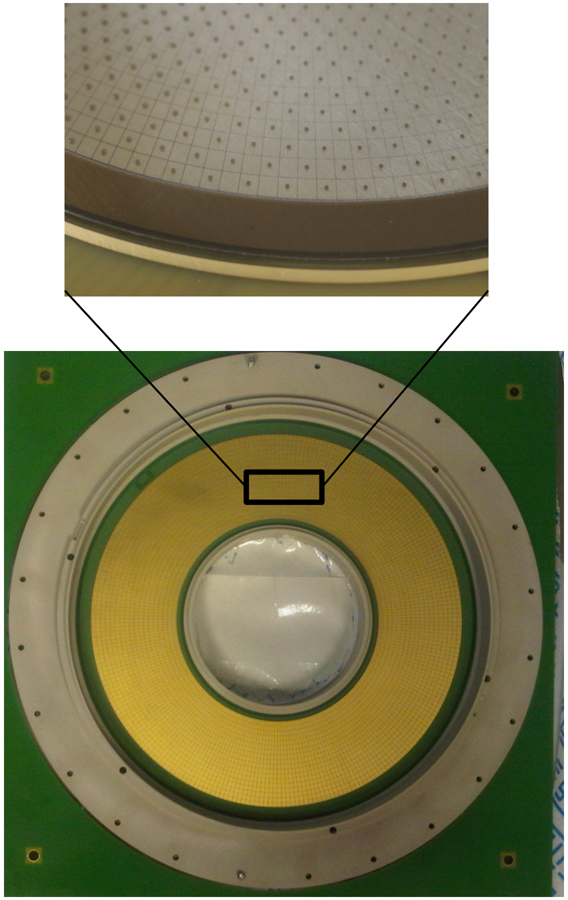
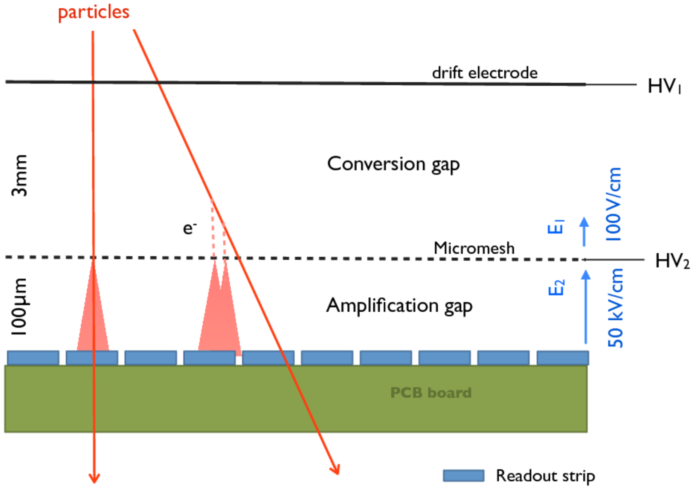
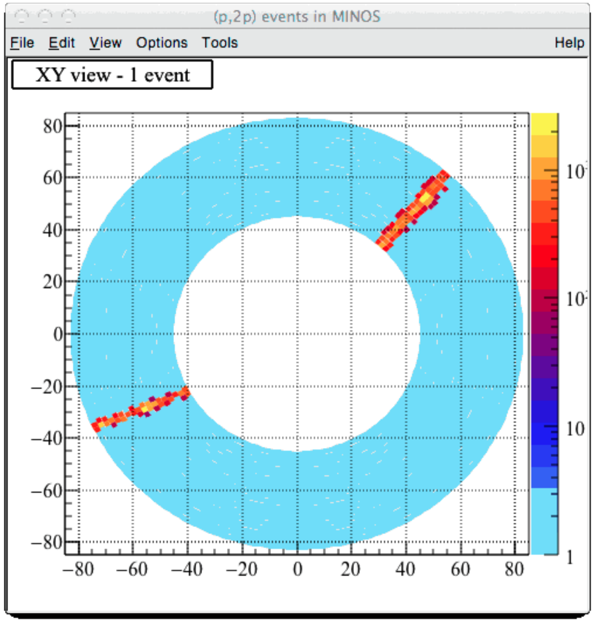




- Noise filtering+tracking algorithm (Hough transform)



GET: Generic Electronics for TPC

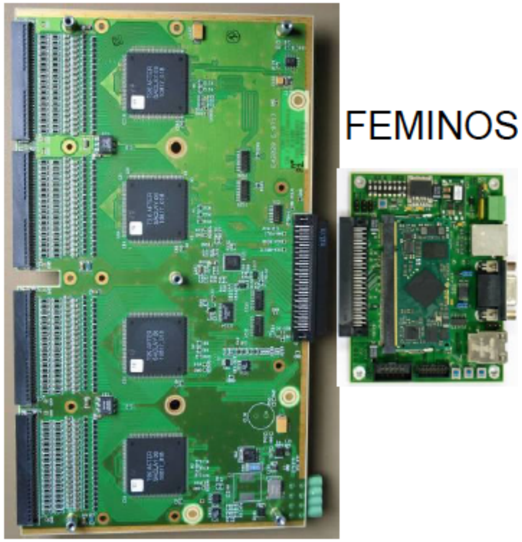
Spokesperson: E.C.Pollacco   CEA/IRFU, CENBG, GANIL, NSCL-MSU, RIKEN collaboration

The MINOS device: electronics

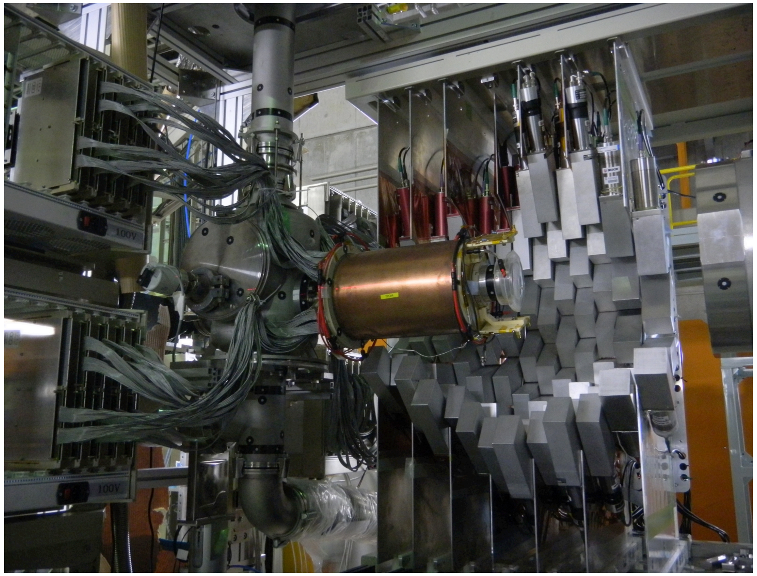
Within MINOS:

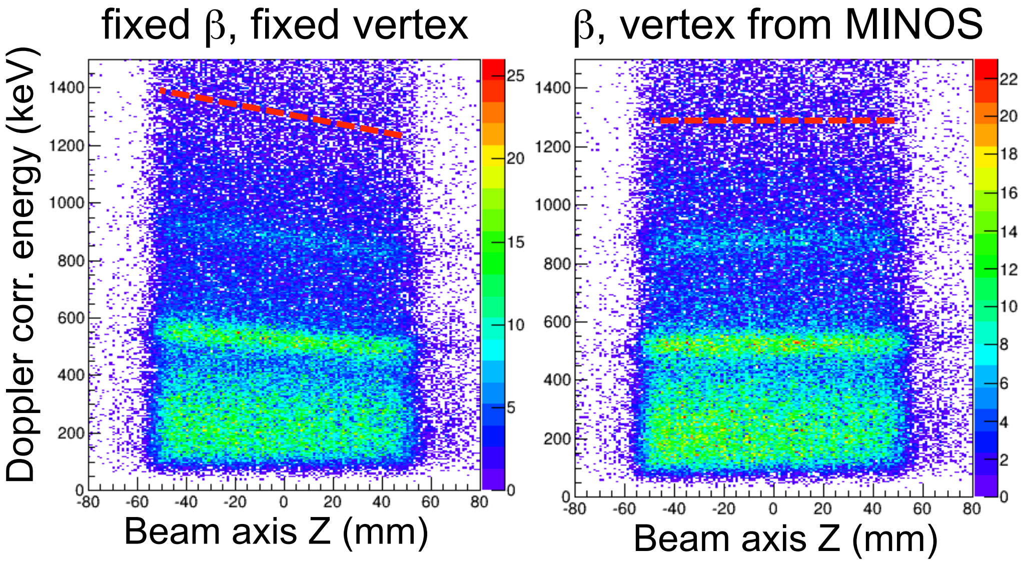
- Feminos readout card
  readout of AGET chip
  dead time ~80 μs at 1 kHz rate

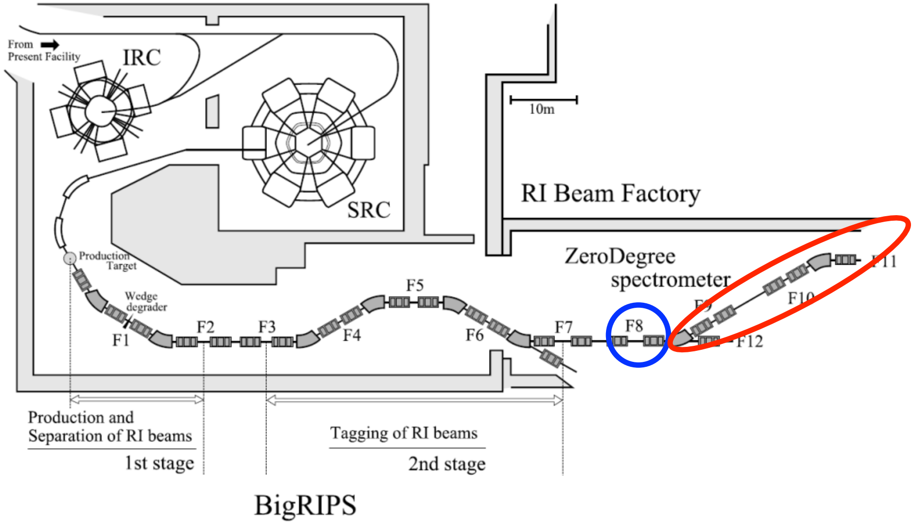
- Dedicated DAQ software



DALI2-MINOS setup at F8







DALI2

- 186 NaI(Tl) crystals
- ε=20% and ΔE/E=10% @ 1 MeV and β=0.6

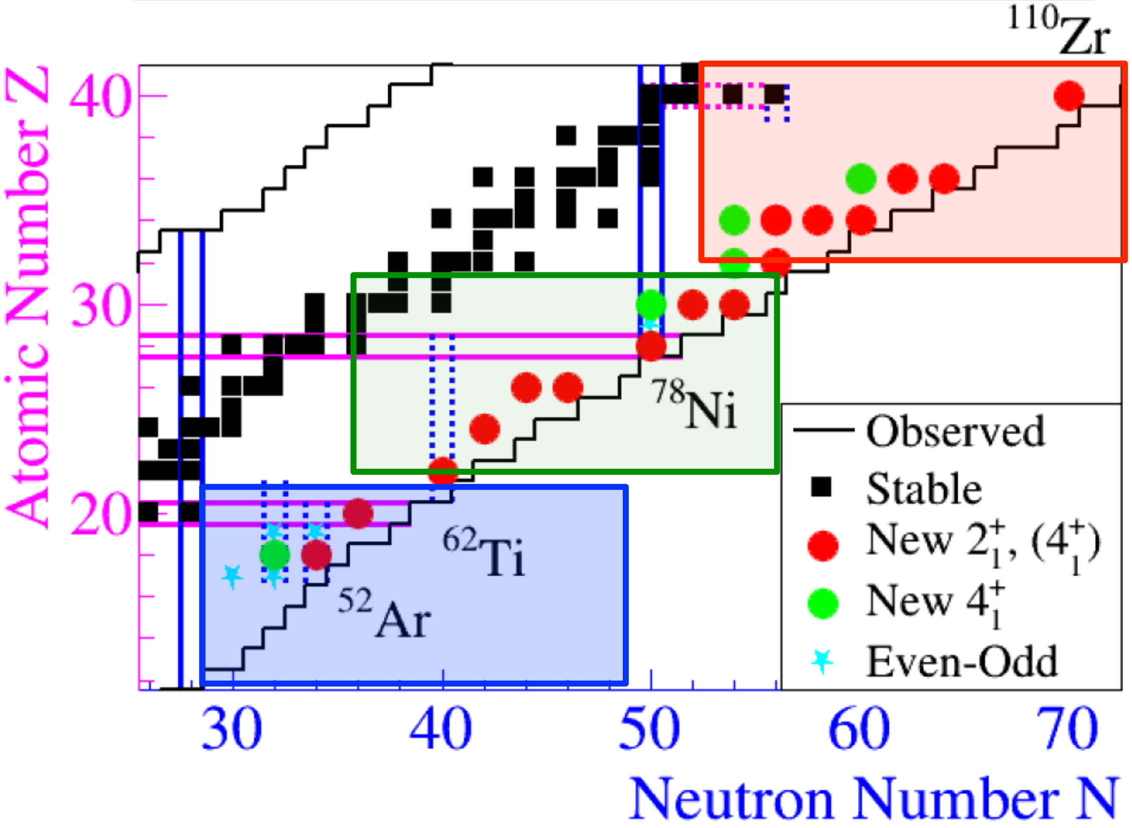
ZeroDegree Spectrometer

- Momentum acceptance: ±3%
- High resolution: P/DP≈6000

Shell Evolution and Search for Two-plus Energies At the RIBF (SEASTAR)

Spokespersons: P. Doornenbal (RIKEN), A. Obertelli (CEA)

Full program: 30 days of beam time



May 2014 SEASTAR1

May 2015 SEASTAR2

To come:

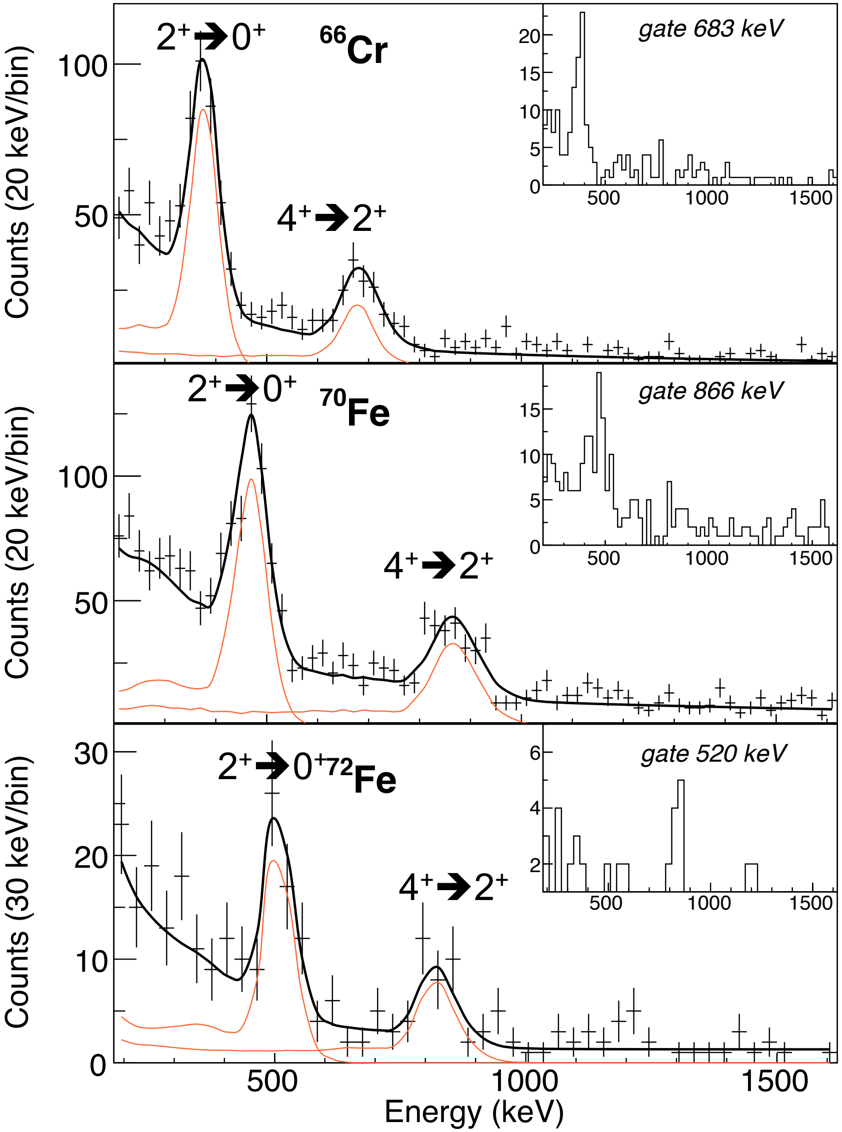
SEASTAR3 (see next)

Follow up:

- Study of N=20 for proton rich nuclei (A.Gillibert, CEA)
- Spectroscopy of ^{100}Sn (J.Lee, HKU, A.Corsi, CEA and K.Wimmer, Tokyo Univ.)

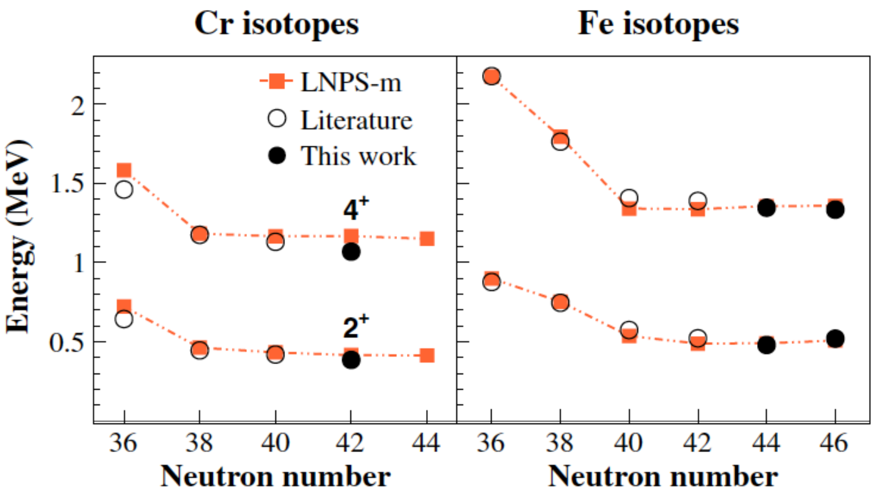
Proposal for a Scientific Program promoted by H.Sakurai (RNC, Univ. of Tokyo) and T.Uesaka (RNC)

SEASTAR1: Collectivity beyond N=40



MOTIVATION

- N=40 and N=50 below Ni isotopes
- Island of collectivity?



RESULT:

- **Extension of N=40 island of collectivity towards N=50**
- Interplay of pairing and quadrupole correlations

C.Santamaria, C. Louchart *et al.*, PRL 115 (2015)

SM calculations from F.Nowacki, IPHC Strasbourg

SEASTAR2: spectroscopy of ^{110}Zr

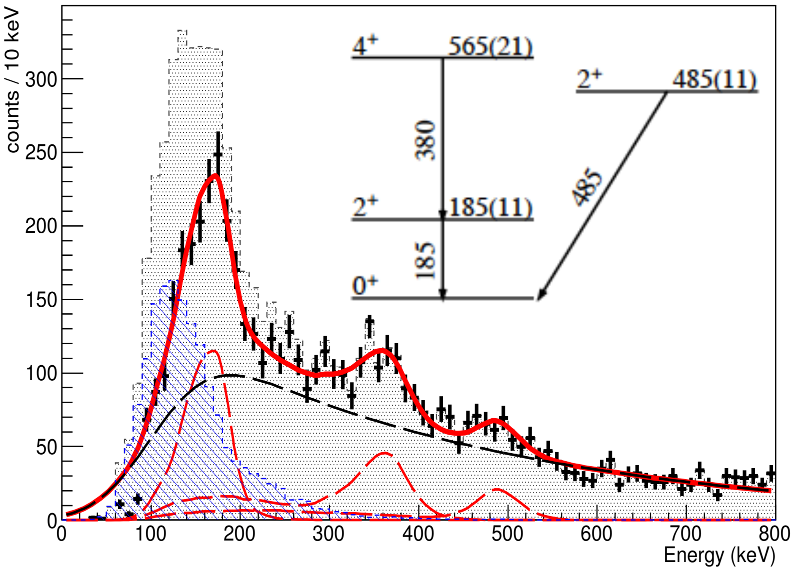
MOTIVATIONS:

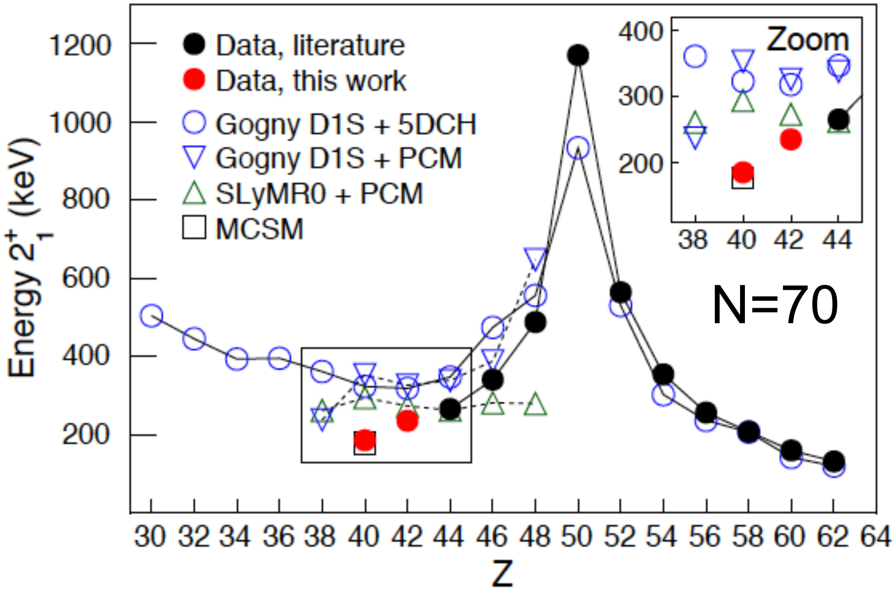
- **Z=40 and N=70 predicted magic** for tetrahedral symmetry and harmonic oscillator
- Deformed ^{110}Zr from beyond-mean field

RESULTS:

- Level scheme not compatible with tetrahedral symmetry (0^+, 3^-, 4^+)
- Lowest 2^+ energy along N=70 chain, and very similar to ^{108}Zr

  ⇒ **well-deformed nucleus**

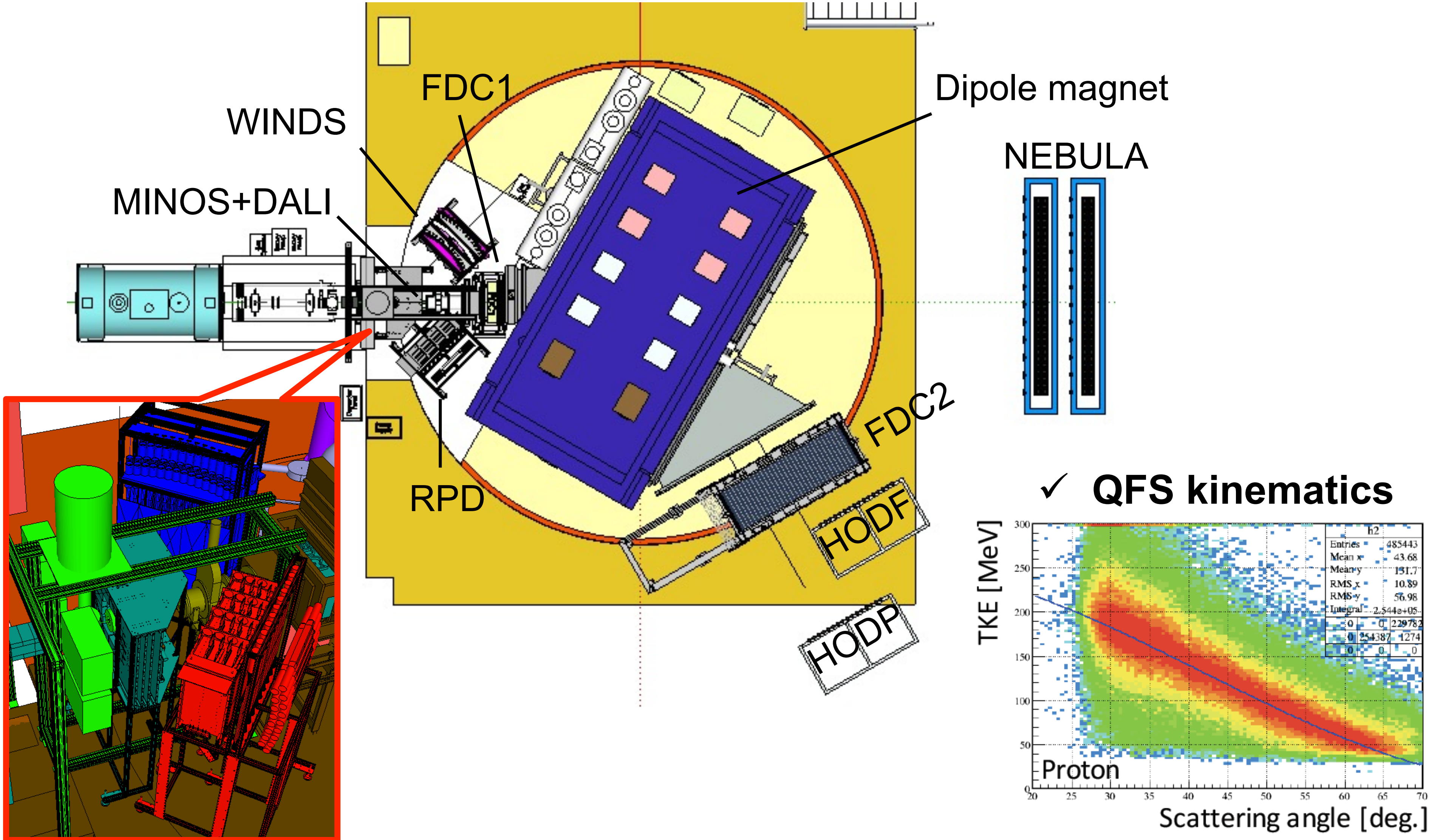




N.Paul *et al.*, Phys.Rev.Lett in press

Particle spectroscopy with MINOS at SAMURAI

- Dineutron correlations in Borromean halo nuclei ^{11}Li, ^{14}Be, ^{15}B
- Missing+Invariant mass measurement: ^{11}Li(p,pn)^{10}Li ➔ ^{9}Li+n



✓ **QFS kinematics**

Particle spectroscopy with MINOS at SAMURAI

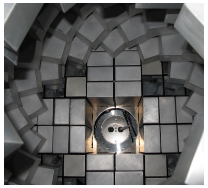
Performed experiments:

- Oct 2014: Dineutron correlation in borromean halo nuclei ^{11}Li, ^{14}Be, ^{15}B
  (A.Corsi, CEA and Y.Kubota, RIKEN)
- Oct 2015: Invariant mass of ^{28}O
  (Y.Kondo, Tokyo Tech.)

To come:

- SEASTAR3: spectroscopy of ^{52}Ar, ^{54}Ca, ^{62}Ti, etc.
  (A.Obertelli, CEA and P.Doornenbal, RIKEN)
- Search for superheavy 7H and its tetraneutron decay
  (Z.Yang, RIKEN and M.Marquez, LPC Caen)
- Investigation of the 4n system at SAMURAI by (p,pα) quasi-free scattering
  (S.Paschalis, Surrey Univ.)
- Search for ^{22}C (2^+), ^{21}B, ^{23}C, ^{25}N: structure at and beyond the N=16 sub-shell closure
  (N.Orr, LPC Caen)
- Invariant Mass Measurement of ^{39}Mg at SAMURAI
  (H.Crawford, LBNL)

Perspectives: high-resolution gamma spectroscopy

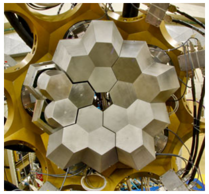


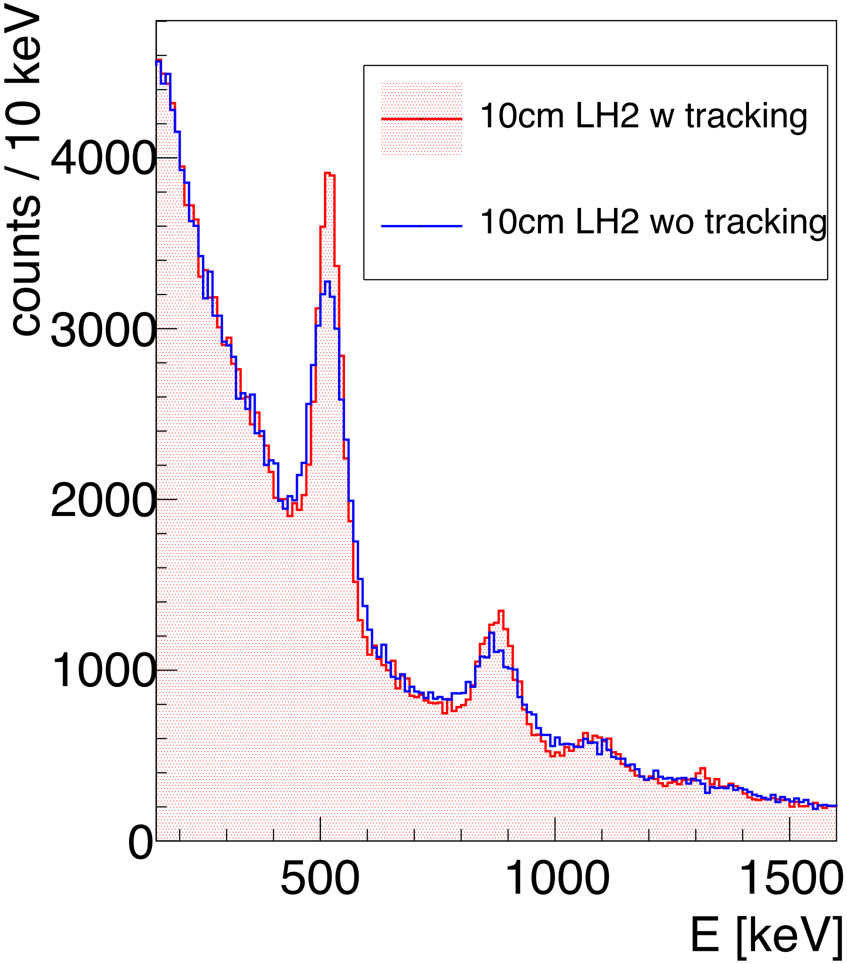
DALI2

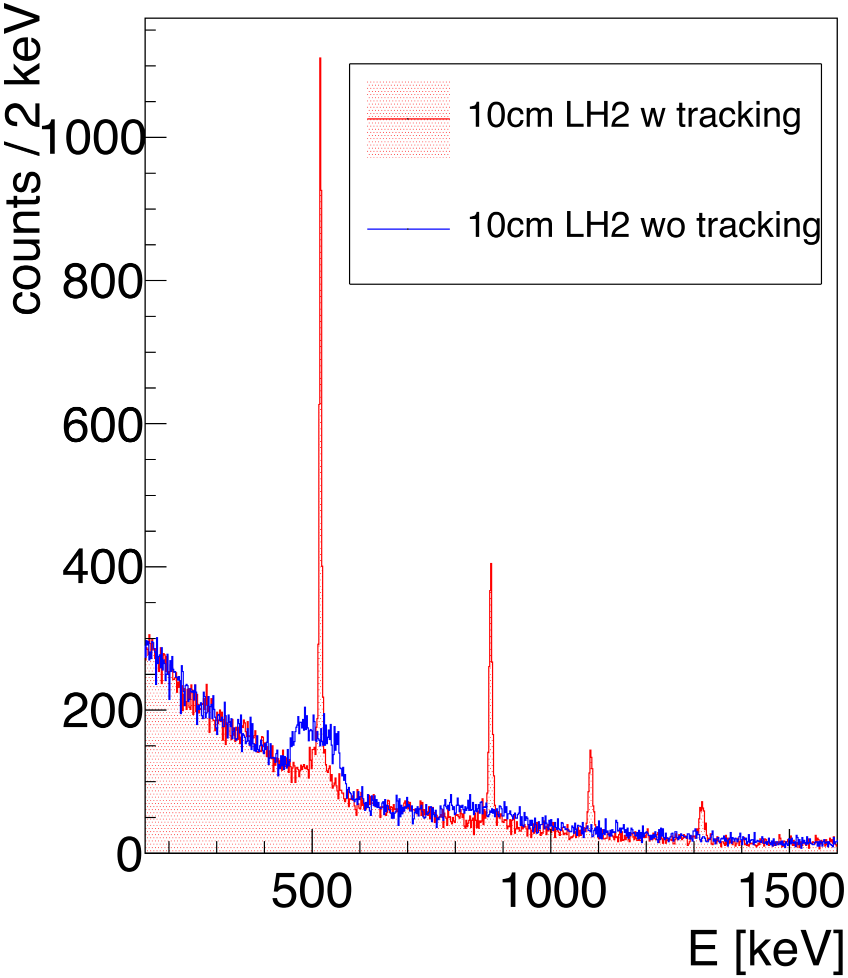
Simulation at 250 MeV/u

High-resolution array

Simulation at 250 MeV/u
5T+5D AGATA clusters







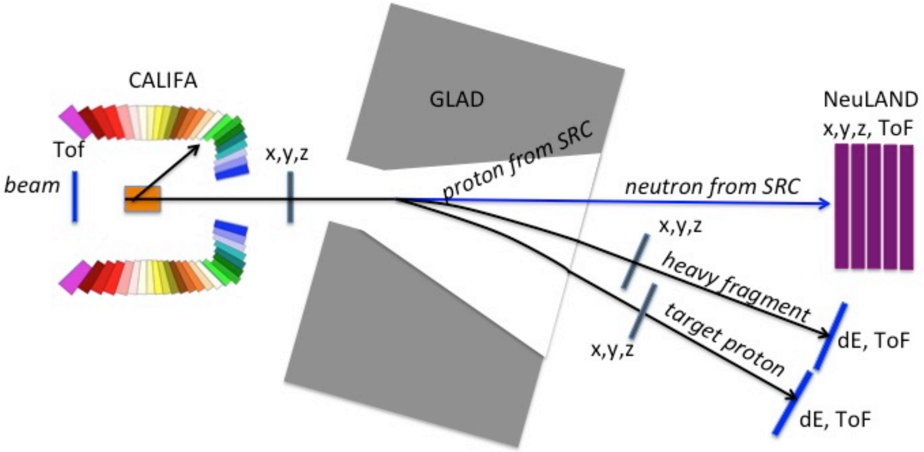
Perspectives: QFS studies at GSI/R^{3}B

Unique features at GSI:

- High beam energy => reduce beam re-interaction, proton straggling
  18 Tm corresponding to 1.9 GeV/u for ^{16}O
- R^{3}B detection system => kinematically complete measurement

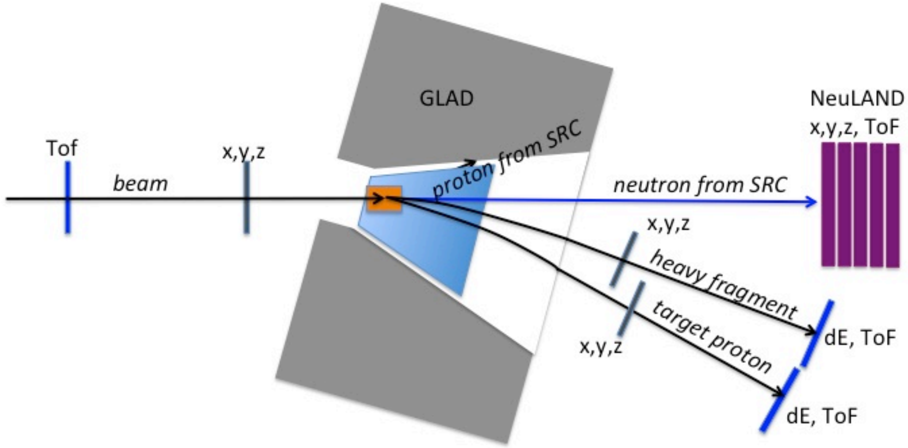
Two possible setups at secondary target:

LH$_2$ target+CALIFA
Protons up to 300 MeV



From 2018

LH$_2$ target+**TPC inside GLAD**
Protons up 1-2 GeV



From 2021

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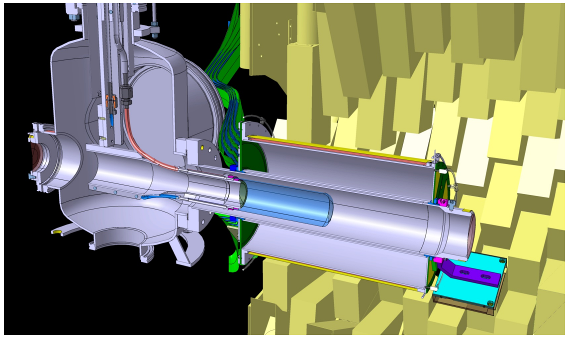
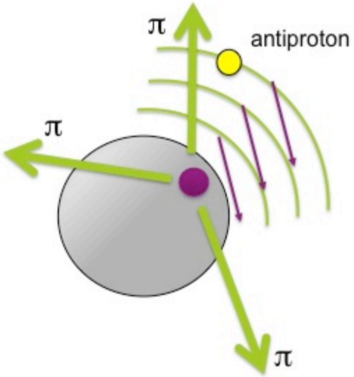


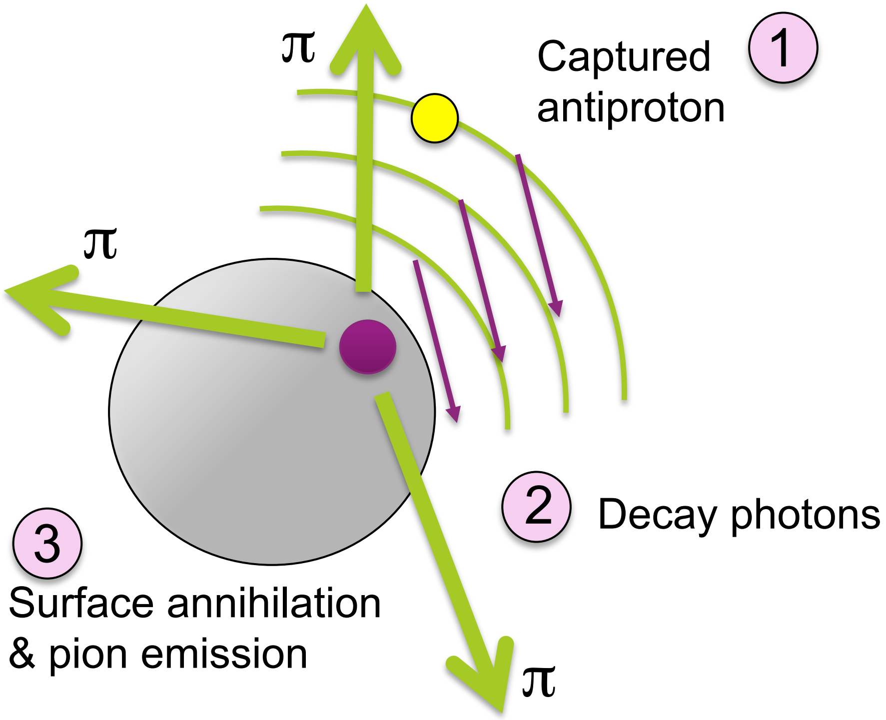
✧ **An antiproton target: PUMA**

- **Method**
- **Description**
- **Perspectives**



The concept: antiproton annihilation

Annihilation with both protons and neutrons



Features:

- **High cross section** (Mbarns) **at low relative energy** (100 eV)
- **Net electric charge conservation**
  - **-1**: neutron annihilation
  - **0**: proton annihilation
- Sensitive to neutron-proton ratio at surface

calculated
1/0.63

$$\left.\frac{\rho_n}{\rho_p}\right|_{surface} = \frac{N_n}{N_p} \times \frac{\sigma_{\bar{p}p}}{\sigma_{\bar{p}n}} \times \varepsilon$$

measured

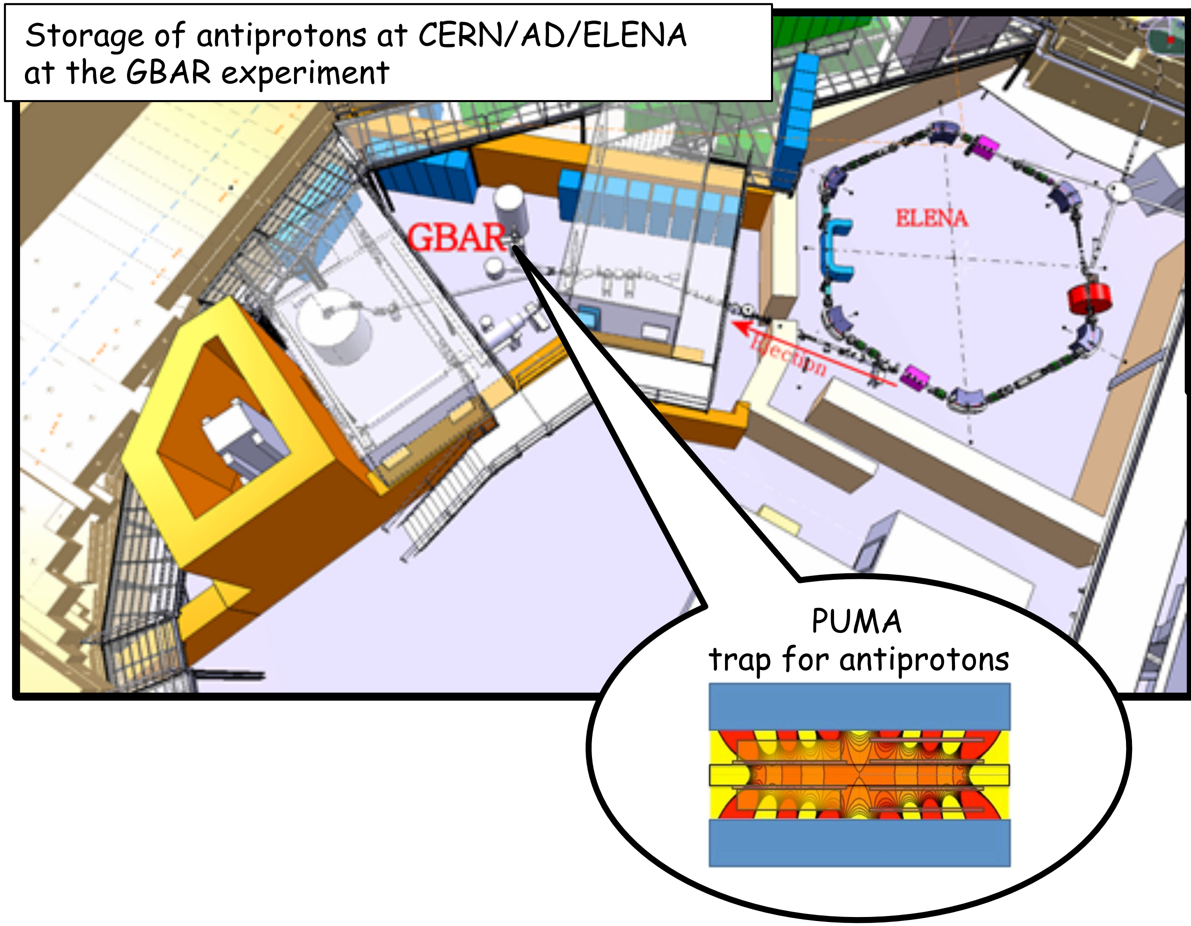
simulated / measured

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

PUMA: Pbar Unstable Matter Annihilation

Bringing the antiprotons from AD (CERN) to ISOLDE (and other RIB facilities)

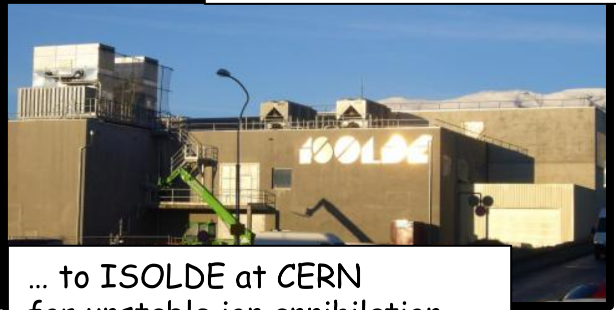
First experiment at ISOLDE foreseen in 2022



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

PUMA
trap for antiprotons

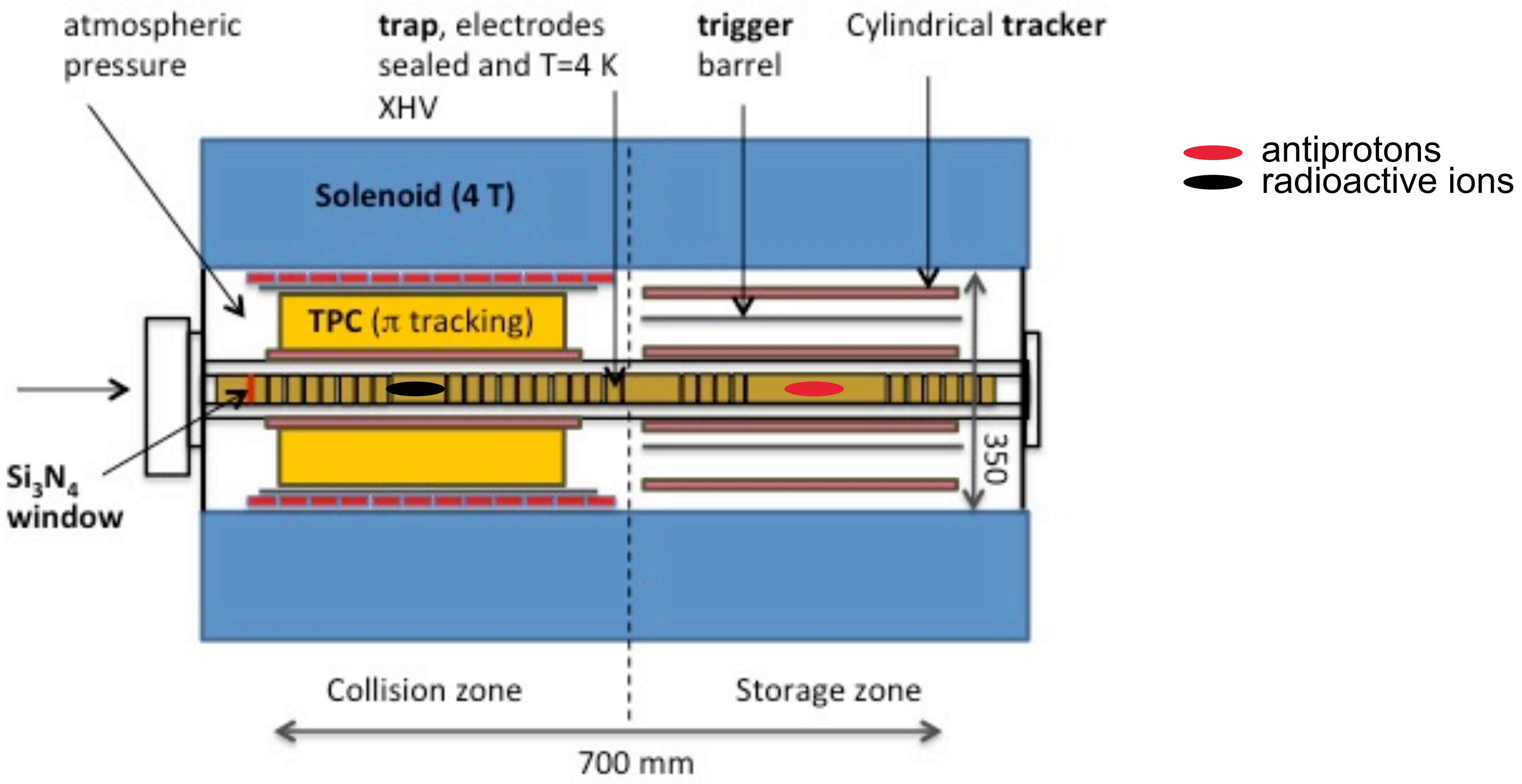
Transport the antiprotons…



… to ISOLDE at CERN
for unstable ion annihilation.

A. Obertelli, ERC CoG 2016

The PUMA device

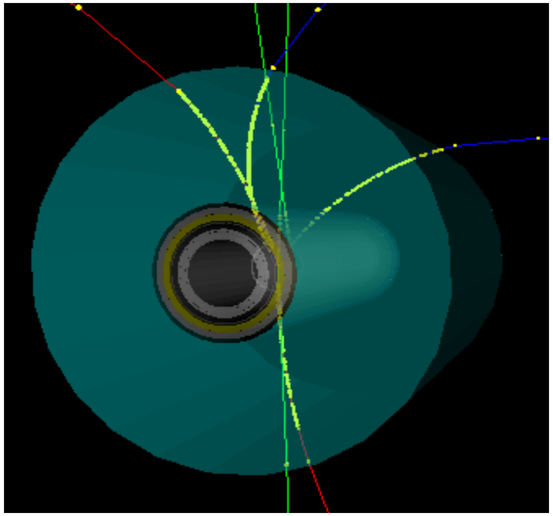


Technical challenges:

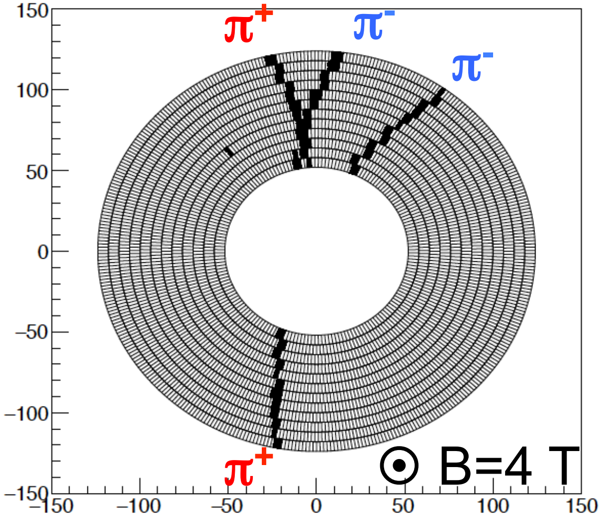
- Store a large number of antiproton ($<10^8$) for a long time
  ⇒ **sealed cryogenic (4 K) trap for extreme vacuum (10^{-16} mbar)**
- Transport ions through a **nanometric window**
- Reconstruct net charge of annihilation via pion detection

PUMA detection system

TPC (π+/π- identification, vertex tracking)

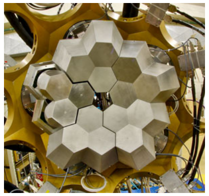


GEANT4 simulation



- 4500 pads, 3x3 mm^2
- 98% efficiency for ≥1 π with its charge
- ~5mm resolution on vertex
- MINOS-like electronics

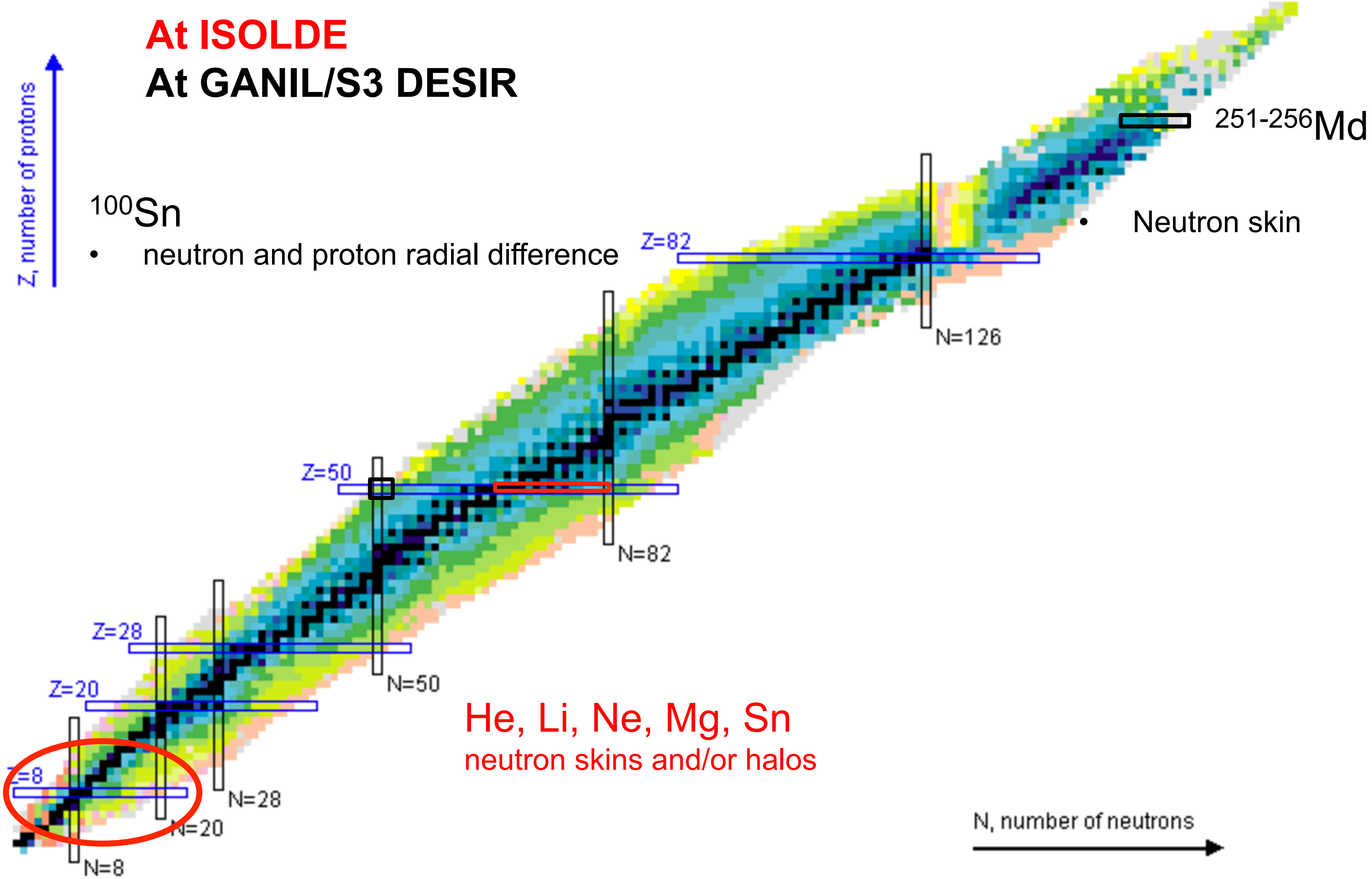
Upgrade: gamma array for spectroscopy after annihilation



PUMA physics program

At ISOLDE

At GANIL/S3 DESIR



^{100}Sn

- neutron and proton radial difference

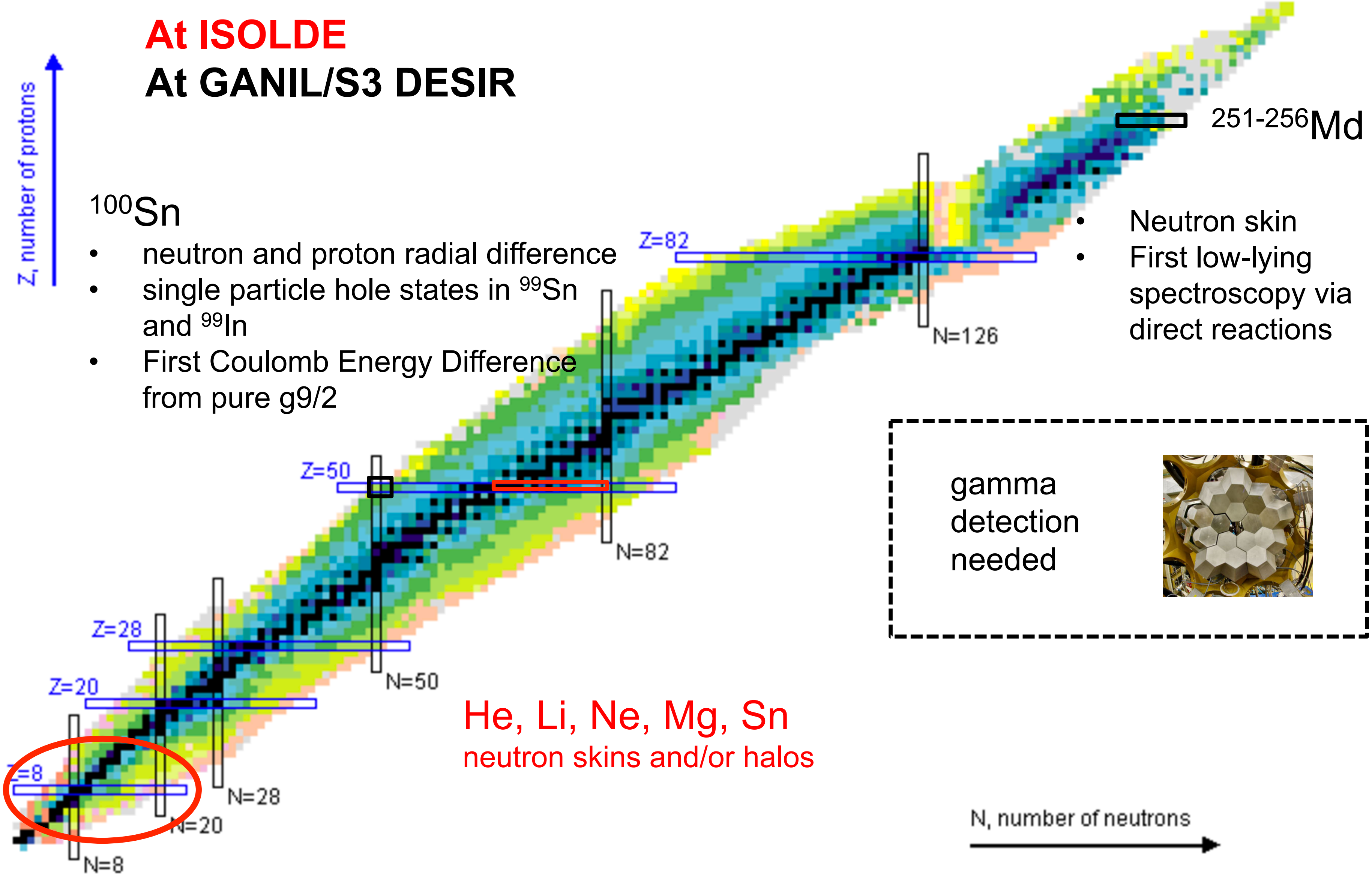
$^{251\text{-}256}$Md

- Neutron skin

He, Li, Ne, Mg, Sn

neutron skins and/or halos

PUMA physics program



At ISOLDE

At GANIL/S3 DESIR

^{100}Sn

- neutron and proton radial difference
- single particle hole states in ^{99}Sn and ^{99}In
- First Coulomb Energy Difference from pure g9/2

$^{251-256}$Md

- Neutron skin
- First low-lying spectroscopy via direct reactions

gamma detection needed

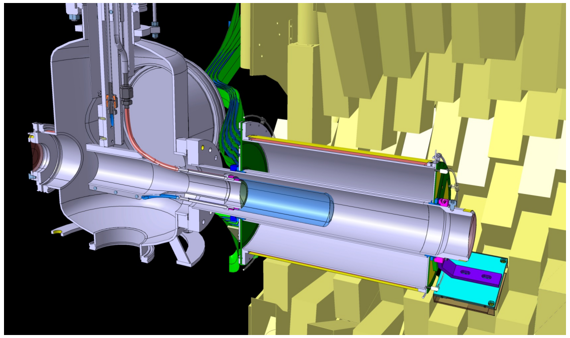
He, Li, Ne, Mg, Sn

neutron skins and/or halos

Summary

✧ MINOS device successfully operated at RIKEN

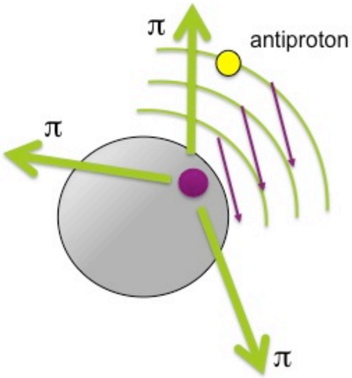
- 4 experiments performed since 2014
- More experiments to come
- Perspectives:
  1. high-resolution gamma spectroscopy
  2. exclusive QFS reactions at GSI/R^{3}B



✧ Construction of new PUMA device beginning

- Technical challenges
- Perspectives:
  1. Measure neutrons skins and halo at ISOLDE (>2022)
  2. Spectroscopy of exotic nuclei at S^3/DESIR (>2025)

…you are welcomed to join!



Collaborations

MINOS development team

S. Anvar, L. Audirac, G. Authelet, H. Baba, B. Bruyneel, D. Calvet, F. Chateau, A. Corsi, A. Delbart, P. Doornenbal, J.-M. Gheller, A. Giganon, T. Isobe, Y. Kubota, C. Lahonde-Hamdoun, D. Leboeuf, D. Loiseau, M. Matsushita, A. Mohamed, J.-Ph. Mols, T. Motobayashi, M. Nishimura, A. Obertelli, S. Ota, H. Otsu, C. Péron, A. Peyaud, E.C. Pollacco, G. Prono, J.-Y. Rousse, H. Sakurai, C. Santamaria, M. Sasano, R. Taniuchi, S. Takeuchi, T. Uesaka, Y. Yanagisawa, K. Yoneda

Physics collaborations

Di-neutron correlations Uesaka, Sasano, Zenihiro, Yoneda, Sato, Otsu, Shimizu, Baba, Isobe, Sako, Stul, Panin (RNC), **Kubota**, Dozono, Ota, Kobayashi M., Kiyokawa (CNS), **Corsi**, Obertelli, Santamaria, Pollacco, Lapoux, Gillibert, Calvet, Delbart, Gheller, Authelet, Roussé (CEA), Kobayashi N., Koyama, Miyazaki (Tokyo Univ.), Kobayashi T., Hasegawa, Sumikama (Tohoku Univ.), Nakamura, Kondo, Togano, Shikata, Tsubota, Saito, Ozaki (Tokyo Tech), Yasuda, Sakaguchi, Shindo, Tabata, Ohkura, Nishio (Kyushu Univ.), Nakatsuka (Kyoto Univ.),Yukie, Kawakami, Kanaya (Miyazaki Univ.), Marques, Gibelin, Orr (LPC Caen), Flavigny (IPNO), Yang, Feng (Peking Univ.), Caesar, Paschalis (TUD), Reichert (TUM), Kim (Ehwa Womans University)

SEASTAR N. Alamanos, G. de Angelis, N. Aoi, H. Baba, C. Barbieri, C. Bertulani, A. Corsi, F. Delaunay, Z. Dombradi, **P. Doornenbal**, T. Duguet, S. Franchoo, J. Gibelin, A. Gillibert, S. Go, M. Gorska, A. Gottardo, S. Grévy, J.D. Holt, E. Ideguchi, T. Isobe, A. Jungclaus, N. Kobayashi, T. Kobayashi, Y. Kondo, W. Korten, Y. Kubota, I. Kuti, V. Lapoux, S. Leblond, J. Lee, S. Lenzi, H. Liu, G. Lorusso, C. Louchart, R. Lozeva, F.M. Marques, I. Matea, K. Matsui, Y. Matsuda, M. Matsushita, J. Menendez, D. Mengoni, S. Michimasa, T. Miyazaki, S. Momiyama, P. Morfouace, T. Motobayashi, T. nakamura, D. Napoli, F. Naqvi, M. Niikura, **A. Obertelli**, N. Orr, S. Ota, H. Otsu, T. Otsuka, N. Pietralla, Z. Podolyak, E.C. Pollacco, G. Potel, G. Randisi, F. Recchia, E. Sahin, H. Sakurai, C. Santamaria, M. Sasano, A. Schwenk, Y. Shiga, Y. Shimuzu, S. Shimoura, J. Simonis, P.A. Soderstrom, S. Sohler, V. Soma, I. Stefan, D. Steppenbeck, T. Sumikama, H. Suzuki, M. Tanaka, R. Taniuchi, K.N. Tuan, T. Uesaka, J. Valiente Dobon, Zs. Vajta, D. Verney, H. Wang, V. Werner, Zh. Xu, R. Yokoyama, K. Yoneda

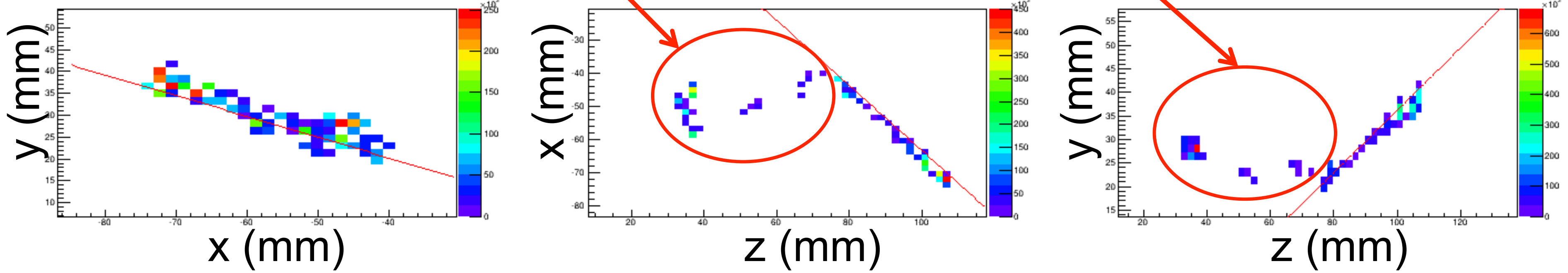
PUMA development team

D.Calvet, A.Corsi, A.Delbart, J.M.Gheller, P.Legou, A.Obertelli, N.Paul, J.Y. Roussé, (CEA Saclay), F.Flavigy (IPNO), D.Lunney (CSNSM), S.Naimi, T.Uesaka (RIKEN),….

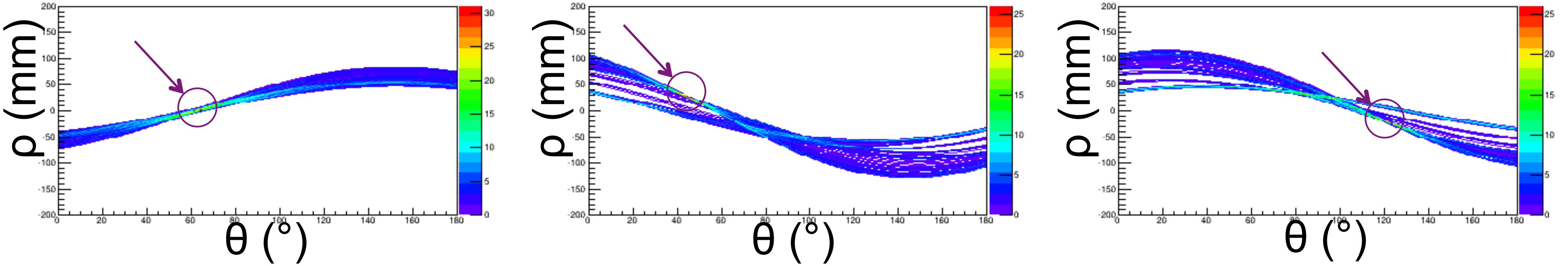
BACKUP

TRACKING ALGORITHM

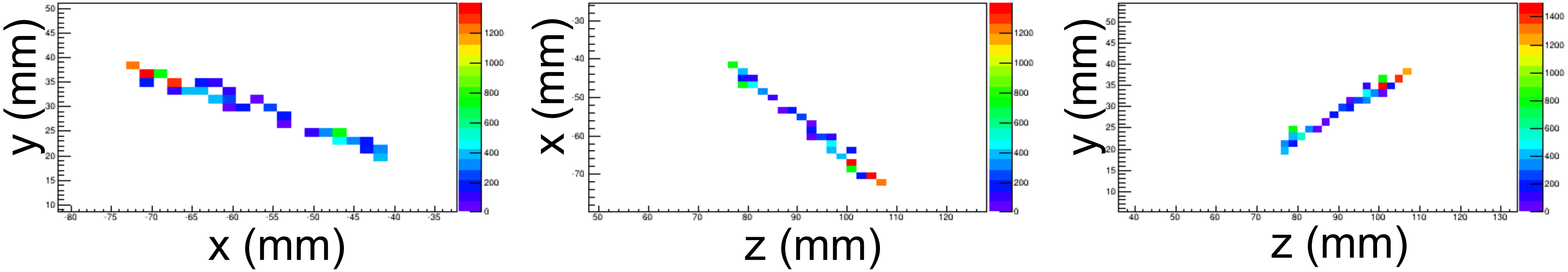
(xy) plane Δ e^- **(xz) plane** Δ e^- **(yz) plane**



Hough spaces

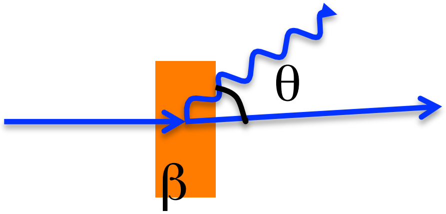


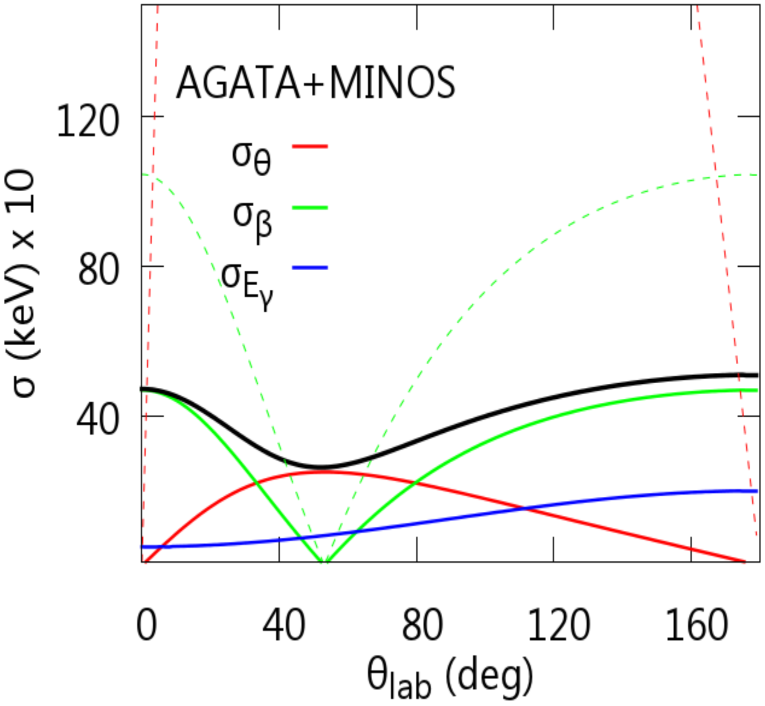
AFTER Hough transform

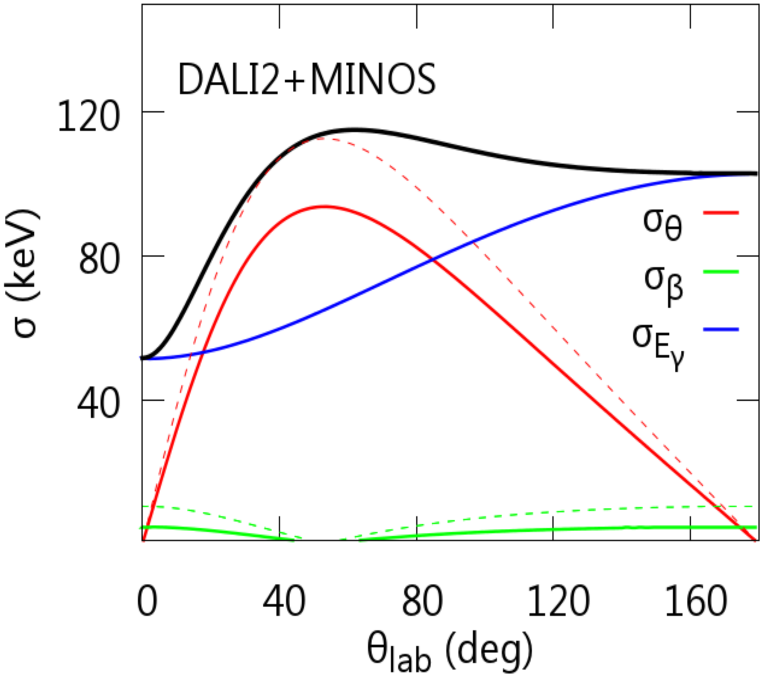


Energy resolution in in-flight gamma spectroscopy

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







Status: spectroscopy of ^{54}Ca at RIBF

New sub-shell closure at N=34

Steppendbeck *et al*., Nature 502 (2013)

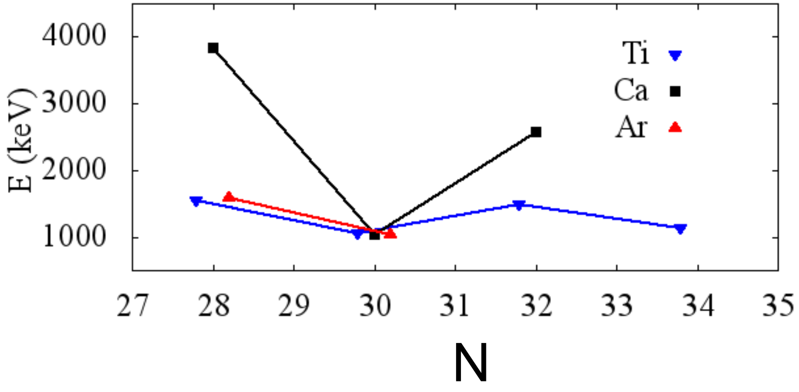
Driving mechanism:

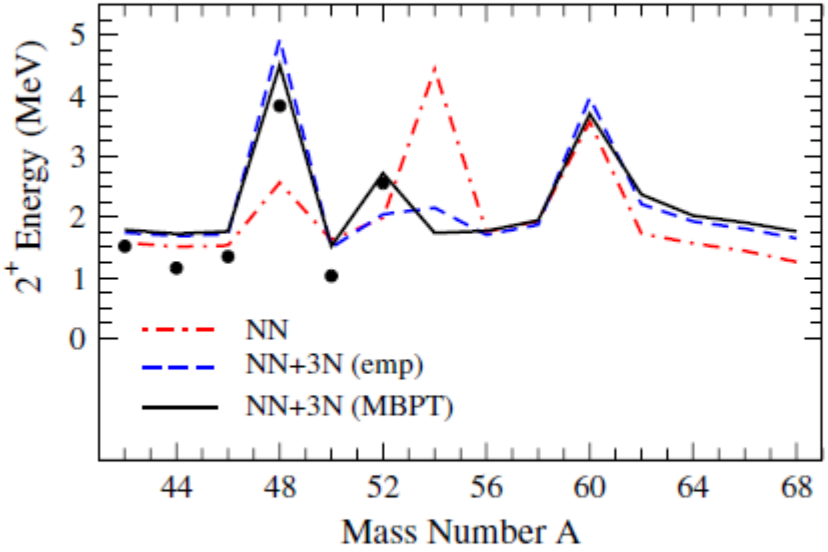
- tensor force

  T. Otsuka et al.

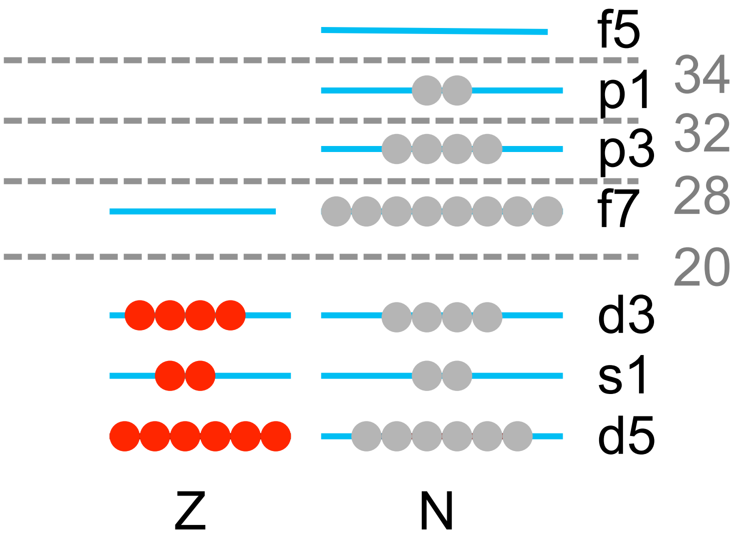
- 3 body force

  J.D.Holt et al., G. Hagen et al.





J.D.Holt *et al.*, J. Phys. G 40, 075105 (2013)



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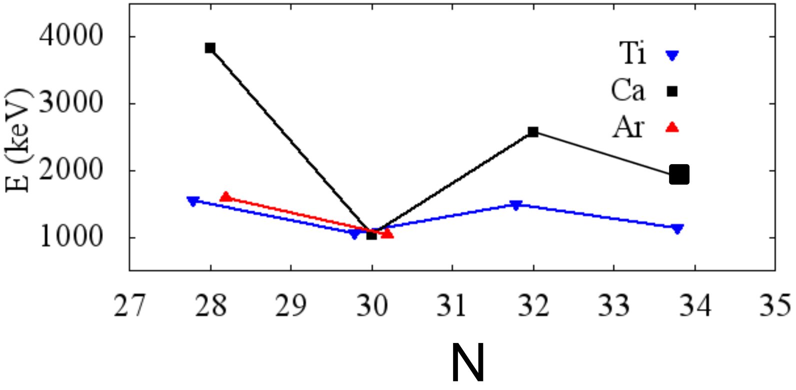
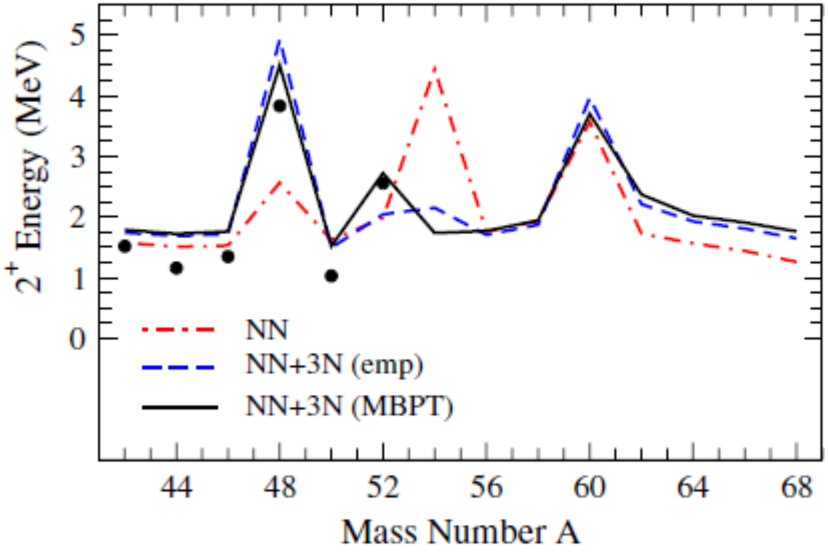
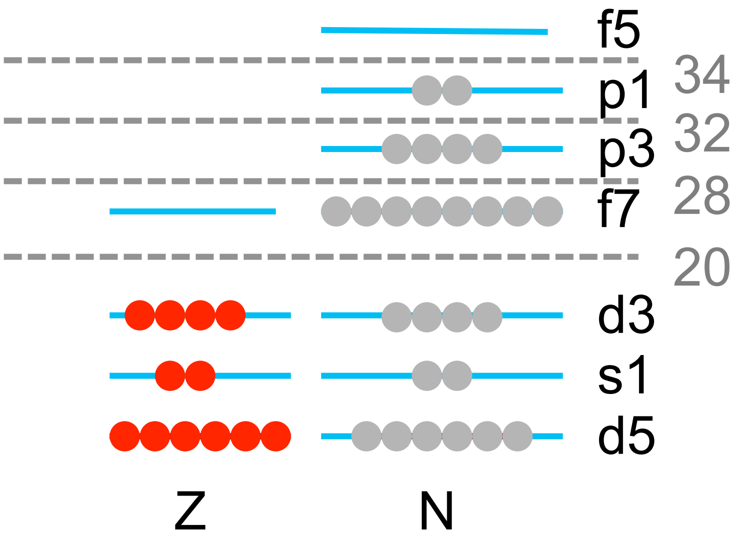


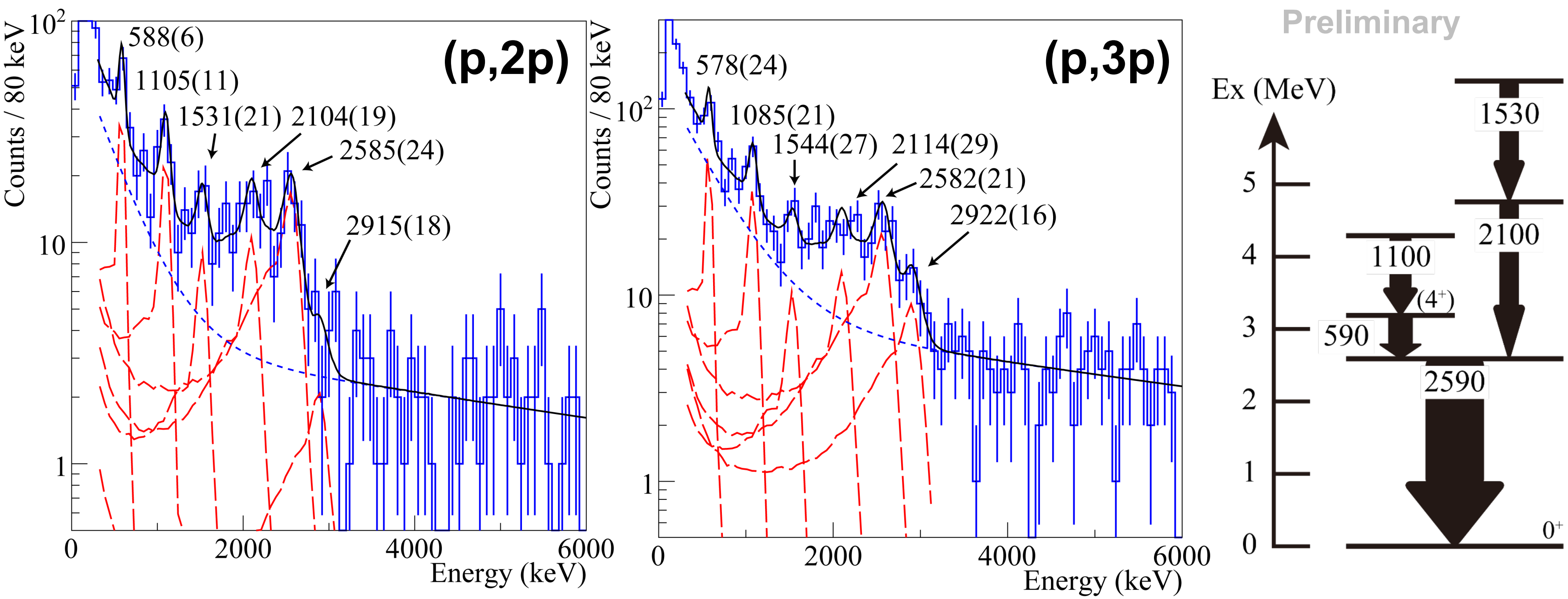


J.D.Holt *et al.*, J. Phys. G 40, 075105 (2013)

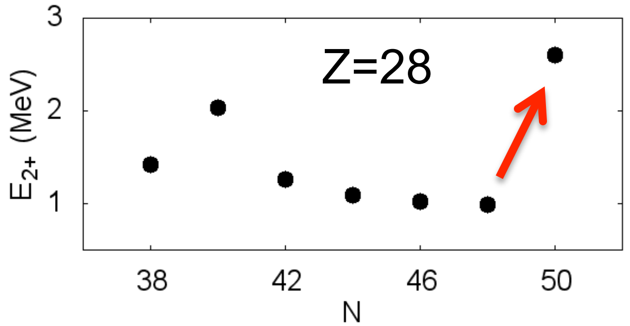


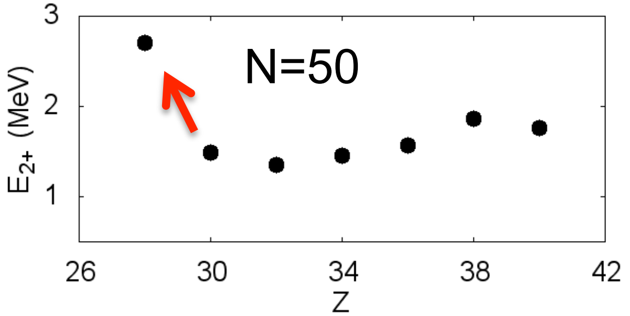
^{54}Ca

SEASTAR1: spectroscopy of ^{78}Ni



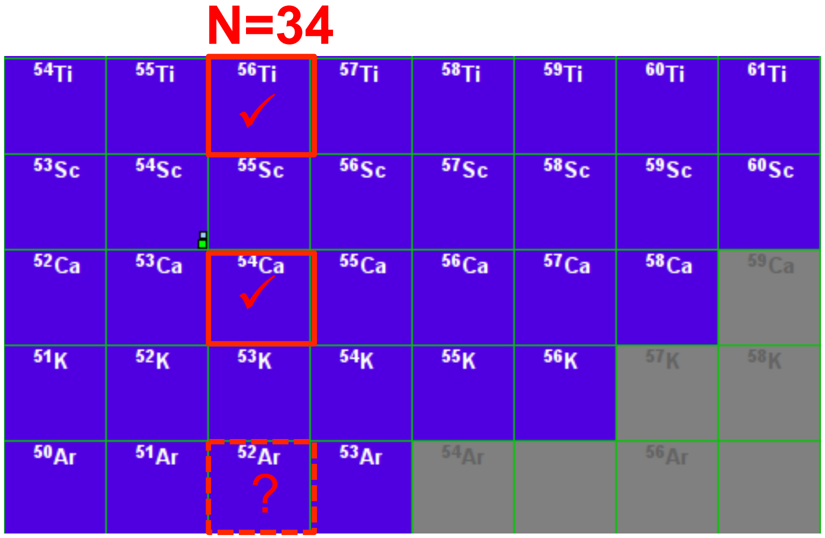
R.Taniuchi *et al.*, in preparation (2017); Collaboration with T.Otsuka (Tokyo Univ.), A. Schwenk (TU Darmstadt)

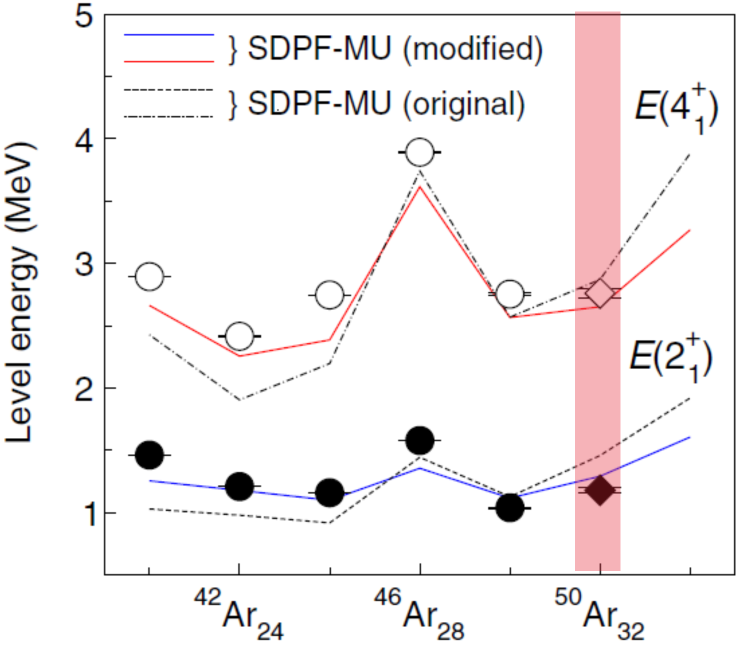




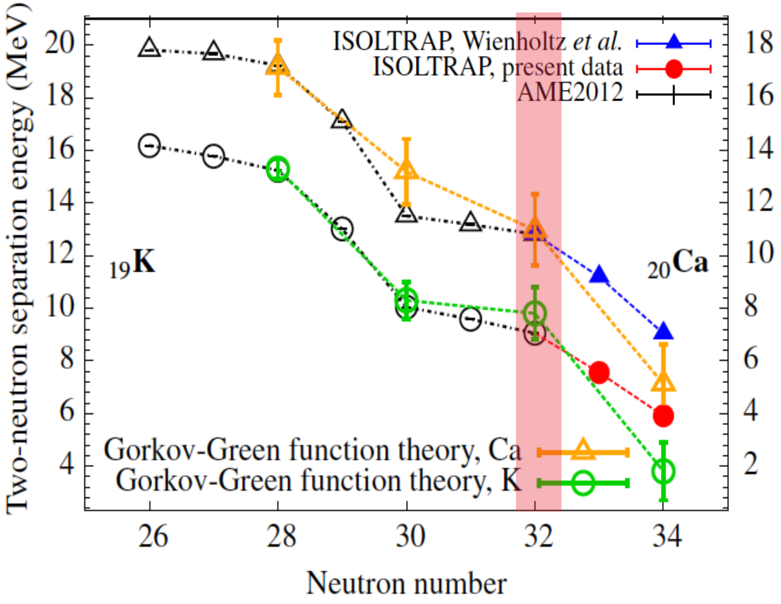
SEASTAR 3/3: Spectroscopy of ^{52}Ar

Does N=34 persist south of ^{54}Ca (as N=32)?





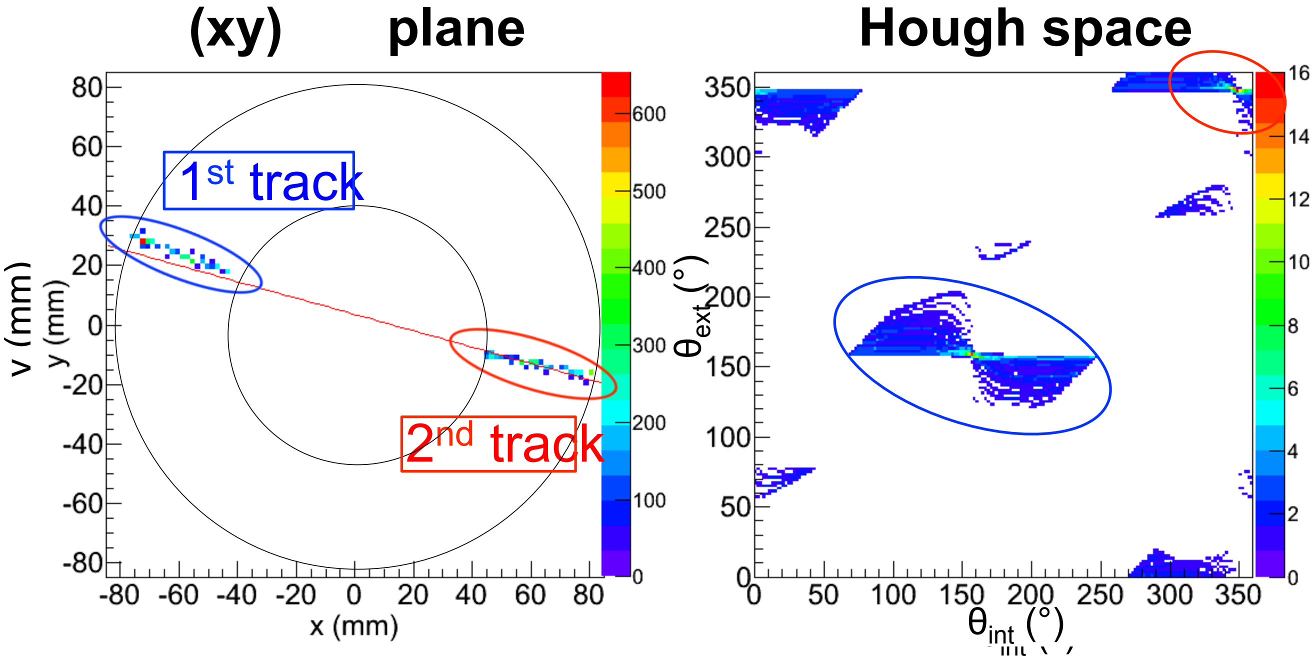
D.Steppendbeck *et al.*, PRL 114 (2015)



Rosenbush et al., PRL 114, 202501 (2015)

Tracking algorithm

Hough transform: pattern extraction technique
✓ Fast algorithm
✓ Pattern recognition & track fitting



How to determine net electric charge

Pion production:

pbar + p

$\pi^+ + \pi^- + 3\pi^0$ (23.3%)

$2\pi^+ + 2\pi^- + \pi^0$ (19.6%)

$2\pi^+ + 2\pi^- + 2\pi^0$ (16.6%)

……

pbar + n

$2\pi^- + \pi^+ + n\pi^0$ (59.7%)

$3\pi^- + 2\pi^+ + n\pi^0$ (23.4%)

$2\pi^- + \pi^+ + \pi^0$ (17%)

……

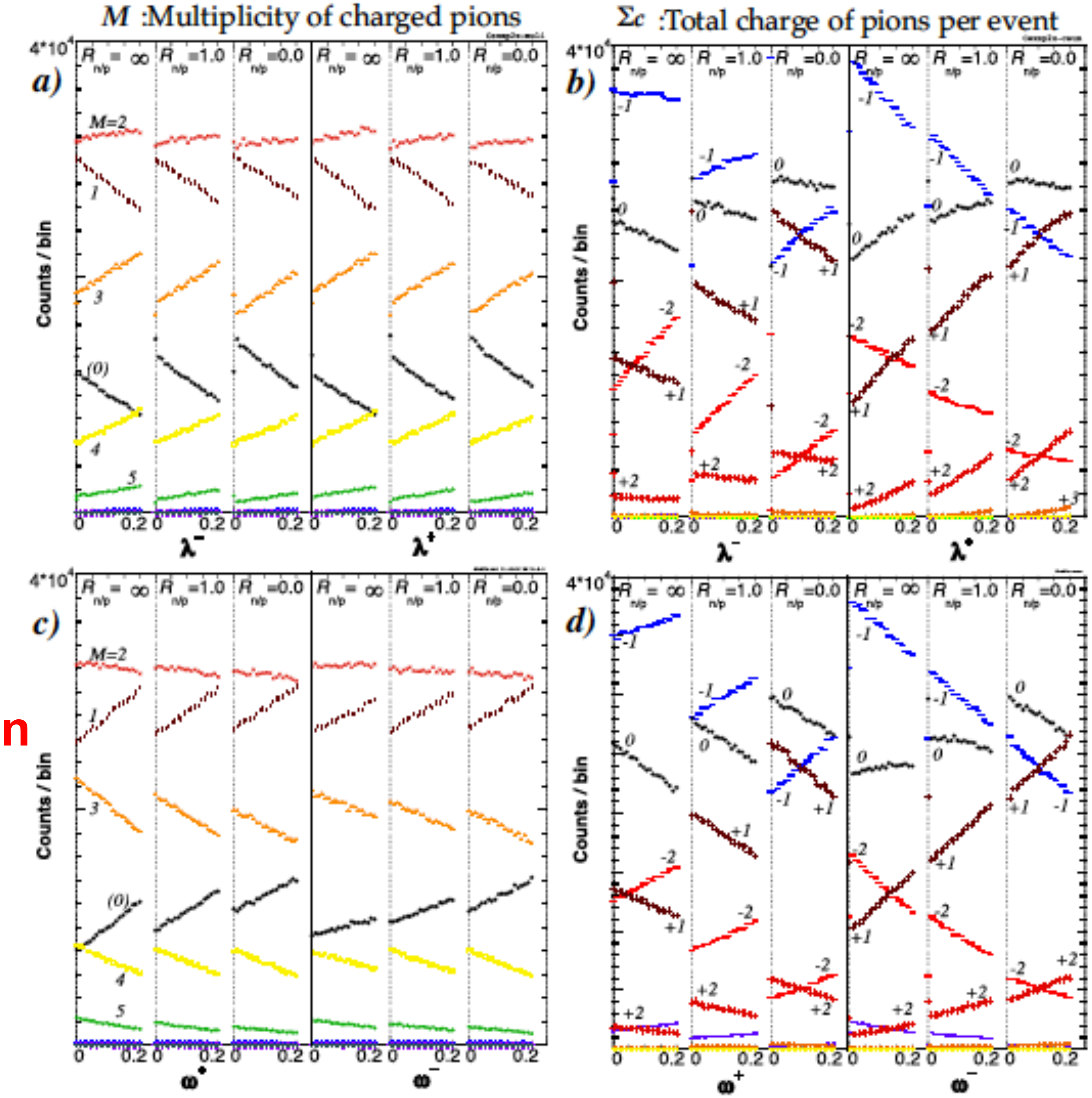
Pions scattering, absorption

$\lambda^+ : \pi^0+N \rightarrow \pi^++N$

$\lambda^- : \pi^0+N \rightarrow \pi^-+N$

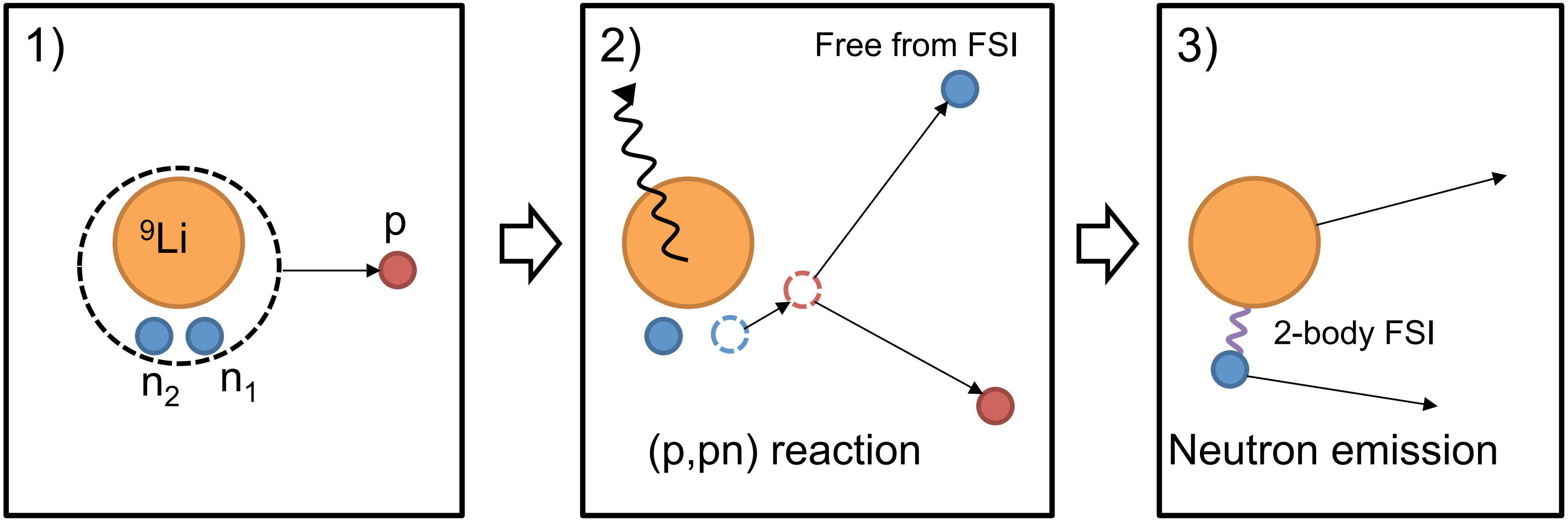
$\omega^+ : \pi^++N \rightarrow \pi^-+N$

$\omega^- : \pi^-+N \rightarrow \pi^++N$

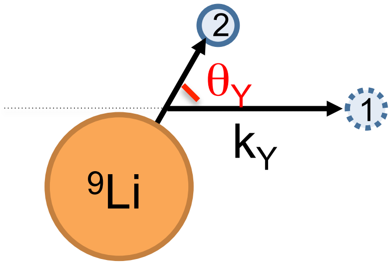


Wada and Yamazaki, unpublished

Dineutron correlation in Borromean halo nuclei



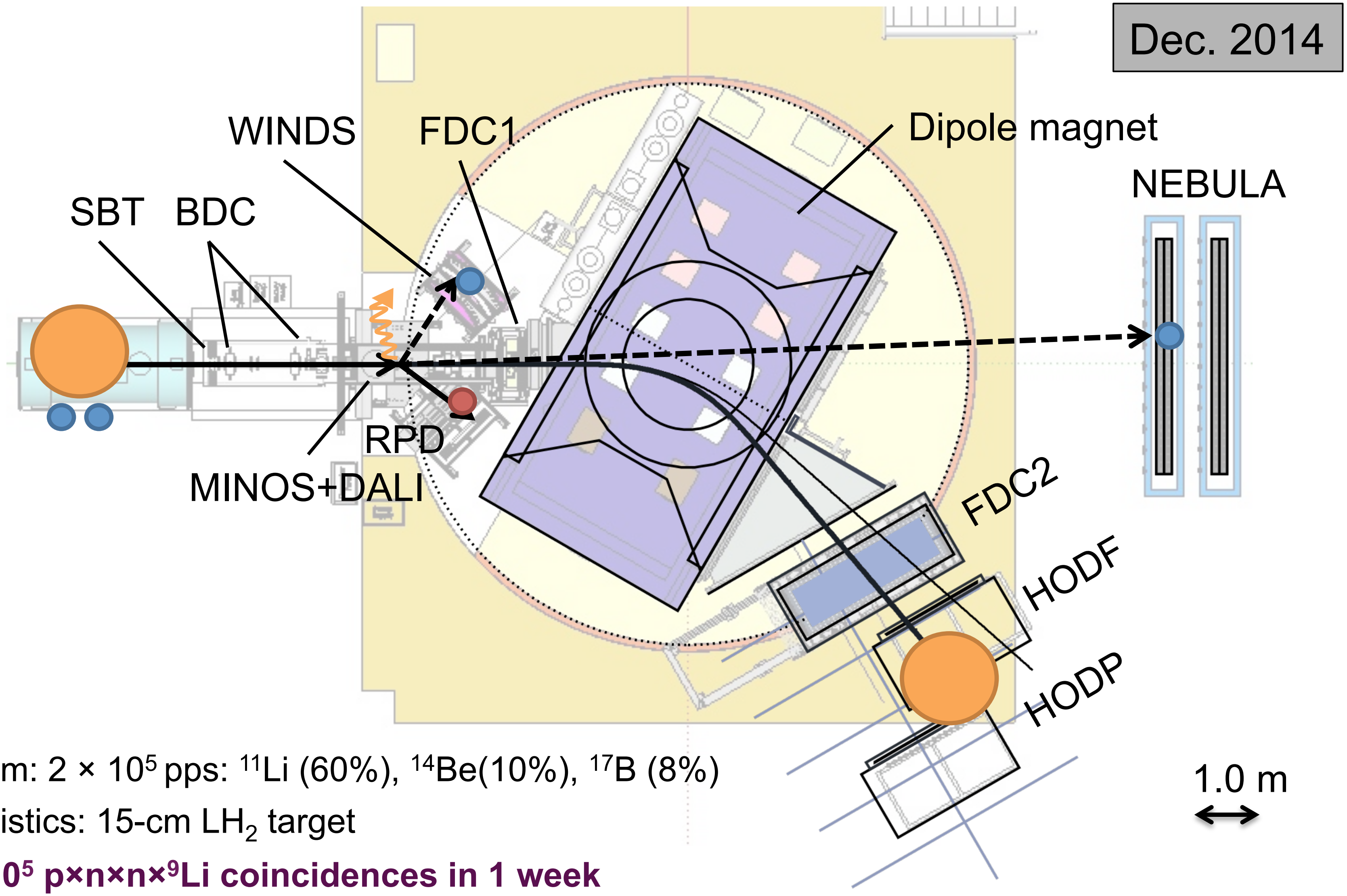
- QFS on Hydrogen to **minimize Final State Interaction (2)**
- **Kinematically complete** measurement
- Core excitation via γ **detection**
- **Observable sensitive to dineutron: θ_Y**



➔ Need high statistics : RIBF + MINOS thick target = x 100 in statistics

Setup at SAMURAI

Spokespersons: Y.Kubota (CNS, RNC) and A.Corsi (CEA Saclay)



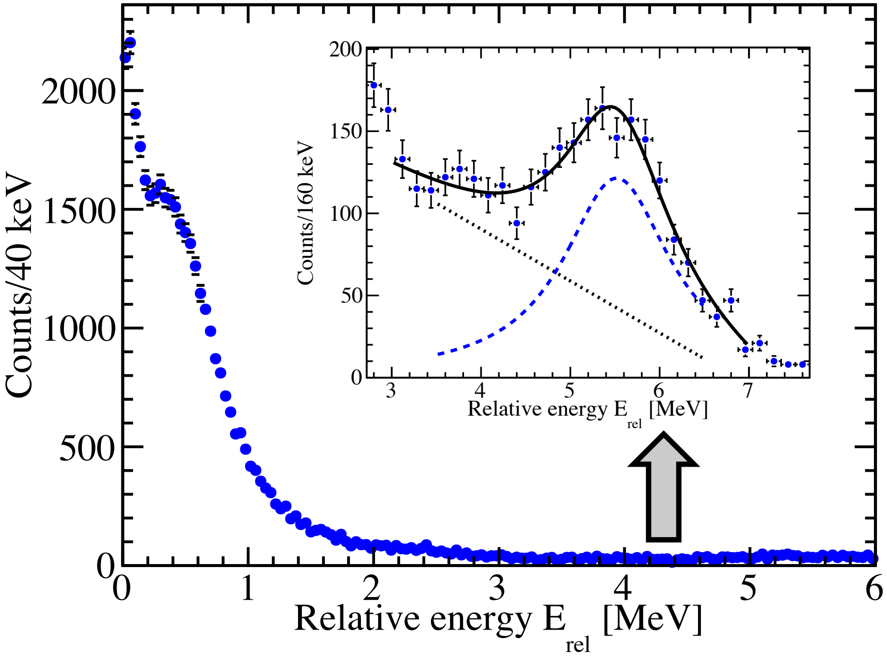
Beam: 2 × 10^5 pps: ^{11}Li (60%), ^{14}Be(10%), ^{17}B (8%)

Statistics: 15-cm LH_2 target

→10^5 p×n×n×^{9}Li coincidences in 1 week

Results from ^{11}Li(p,pn) reaction

Spectroscopy of ^{10}Li

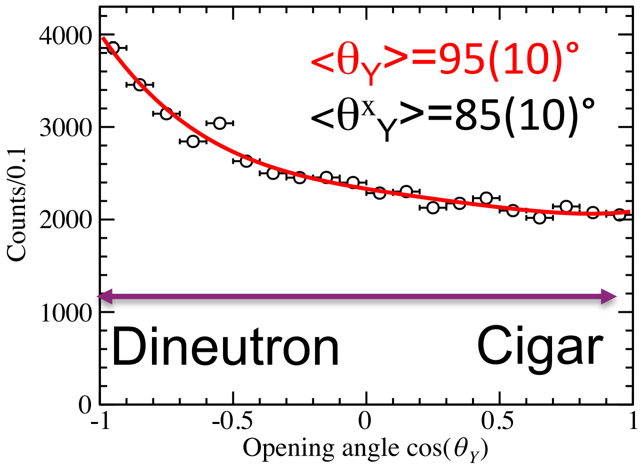


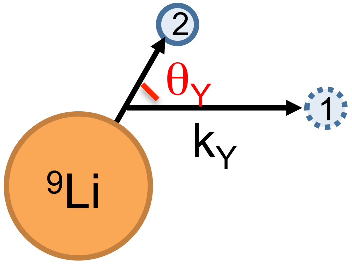
New resonance:

- E_r = 5.52±0.04 MeV
- Γ = 0.72±0.10 MeV
- *d*-wave resonance

Plots: courtesy of Y.Kubota, RNC

Dineutron correlation in ^{11}Li





- Θ_y distribution signals dineutron correlation
- To be quantified via comparison with theoretical model

Collaboration with Y.Kikuchi *et al.*, PTEP 216 (2016)