PROBING HALOS VIA NUCLEON REMOVAL

Halo Week, Gothenburg, Sweden
June 10-14, 2024

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DFG
SFB 1245
Alexander von HUMBOLDT STIFTUNG
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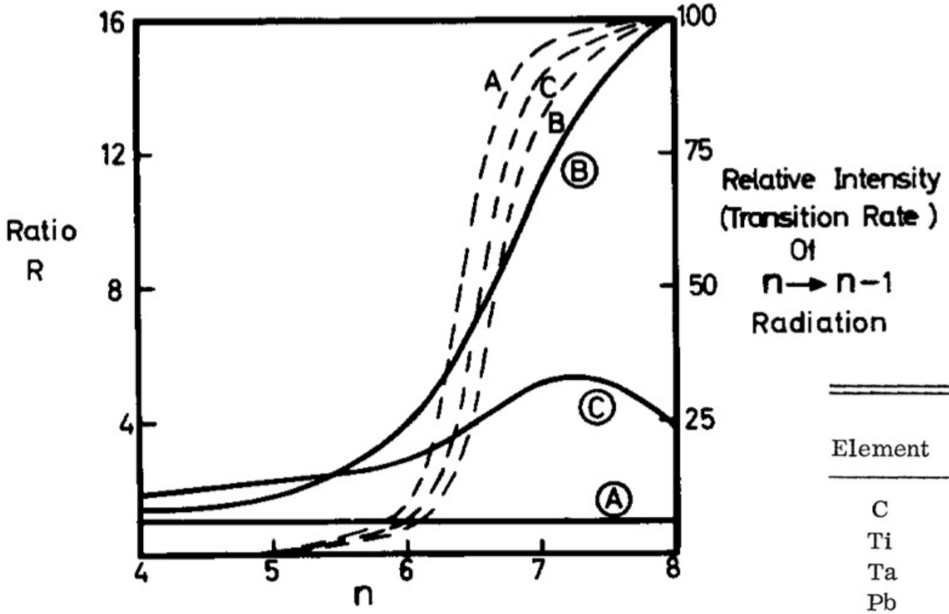
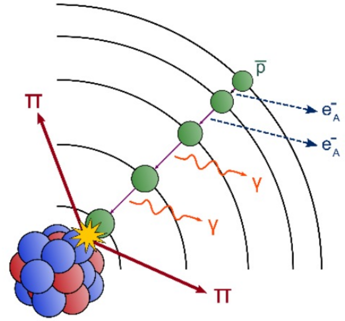
HALOS AND SKINS: PRE-HISTORY

« Neutron atmosphere »
from kaon absorption



Burhop, NPB (1967)

« Neutron halo »
from antiproton annihilation



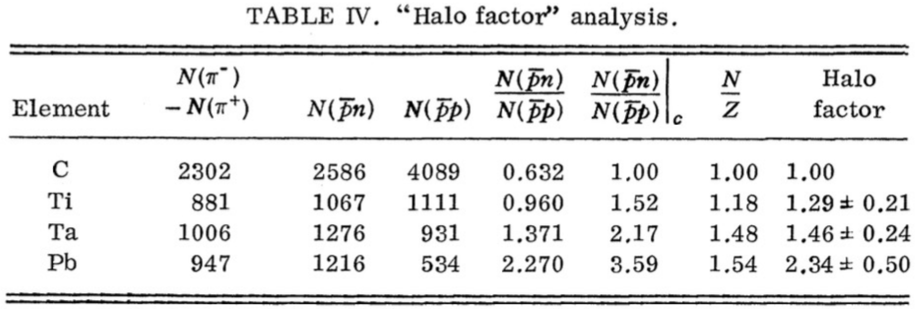
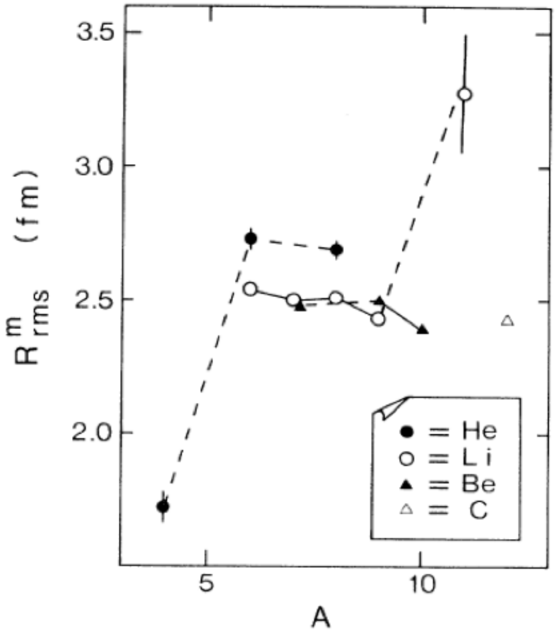


TABLE IV. “Halo factor” analysis.

Element	$N(\pi^-) - N(\pi^+)$	$N(\bar{p}n)$	$N(\bar{p}p)$	$\frac{N(\bar{p}n)}{N(\bar{p}p)}$	$\frac{N(\bar{p}n)}{N(\bar{p}p)}\Big\rvert_c$	$\frac{N}{Z}$	Halo factor
C	2302	2586	4089	0.632	1.00	1.00	1.00
Ti	881	1067	1111	0.960	1.52	1.18	1.29 ± 0.21
Ta	1006	1276	931	1.371	2.17	1.48	1.46 ± 0.24
Pb	947	1216	534	2.270	3.59	1.54	2.34 ± 0.50

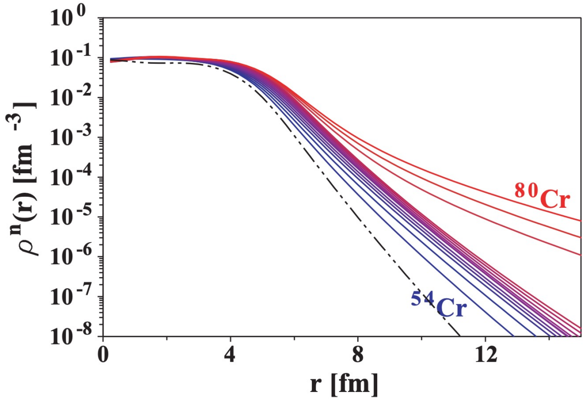
Buggs et al., PRL (1973)
followed up at LEAP, CERN, 90s

« Neutron halo »
from interaction cross section



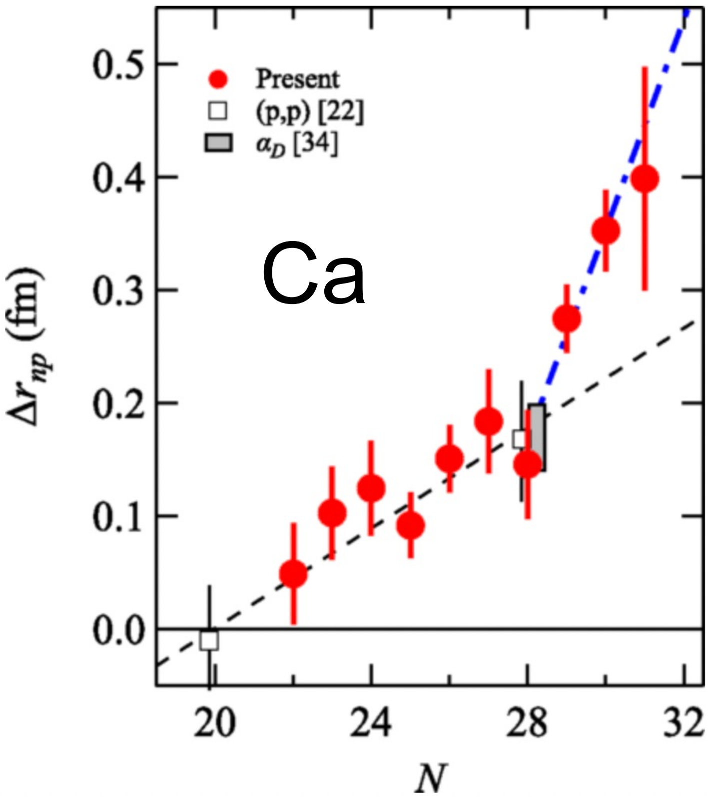
Tanihata et al., PRL (1985)

HALOS & SKINS IN MEDIUM-MASS NUCLEI

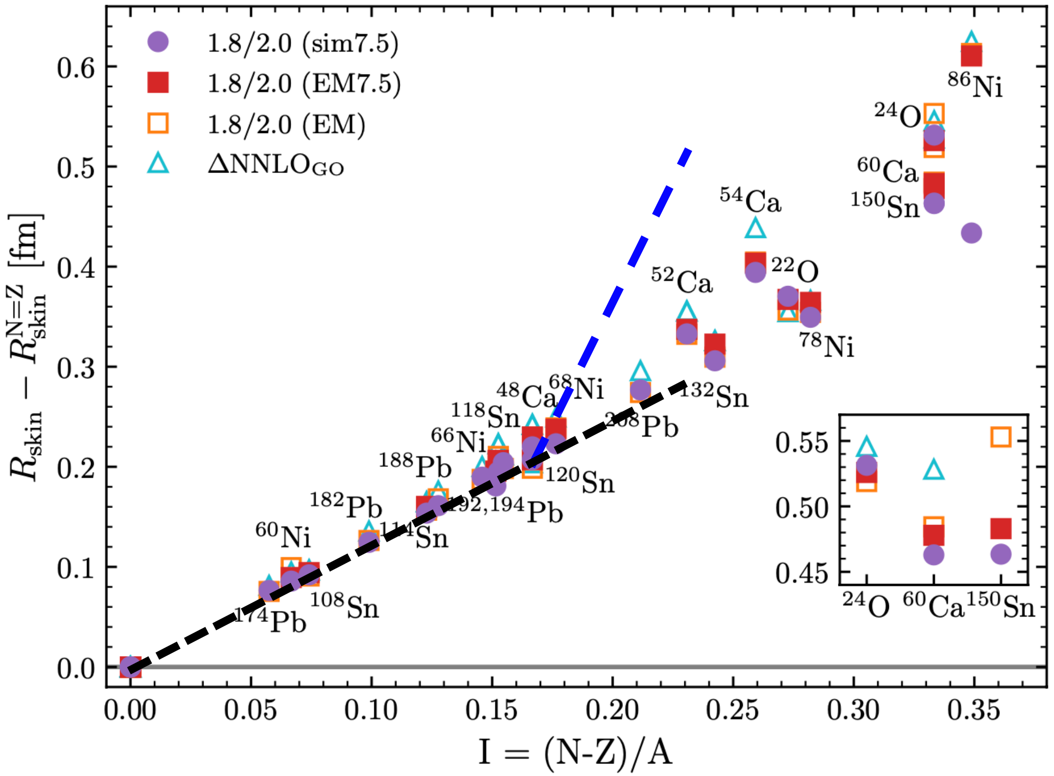


Rotival, Duguet, PRC (2009)

Interaction cross sections



Tanaka et al., PRL (2020)



From Arthuis, Hebeler, Schwenk, arXiv (2024)

OUTLINE

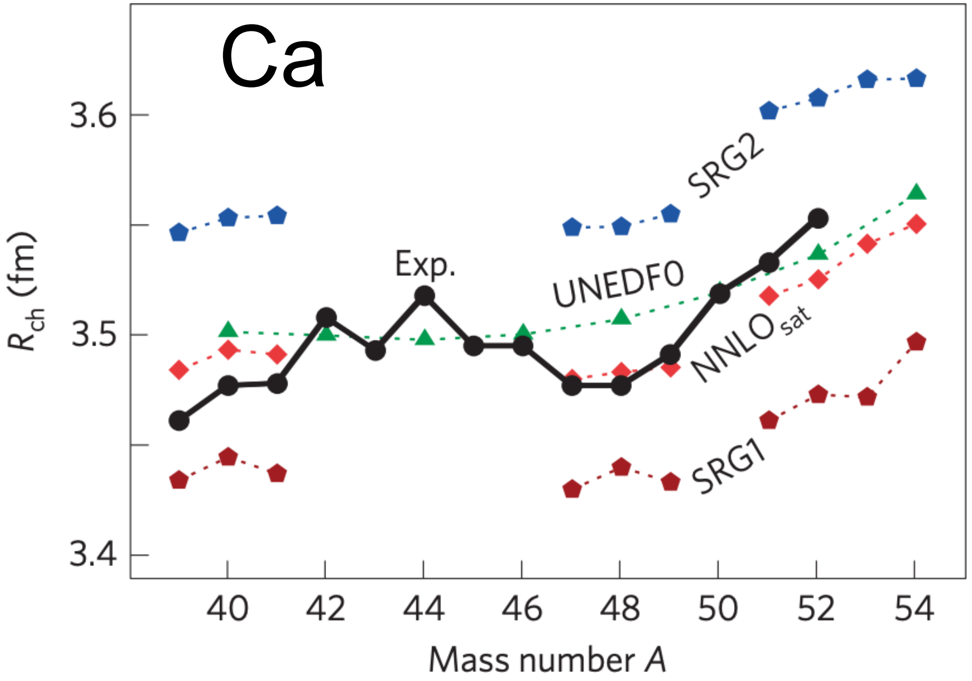
- **Sensitivity of quasifree scattering observables to the size of Ca isotopes**
  Enciu et al., PRL (2022); Enciu et al., work in progress (2024)

- **PUMA: antimatter to probe the radial density tail**
  Aumann et al., EPJA (2022); Fischer et al., NIMB (2024); Schlaich et al., IJMS (2024)

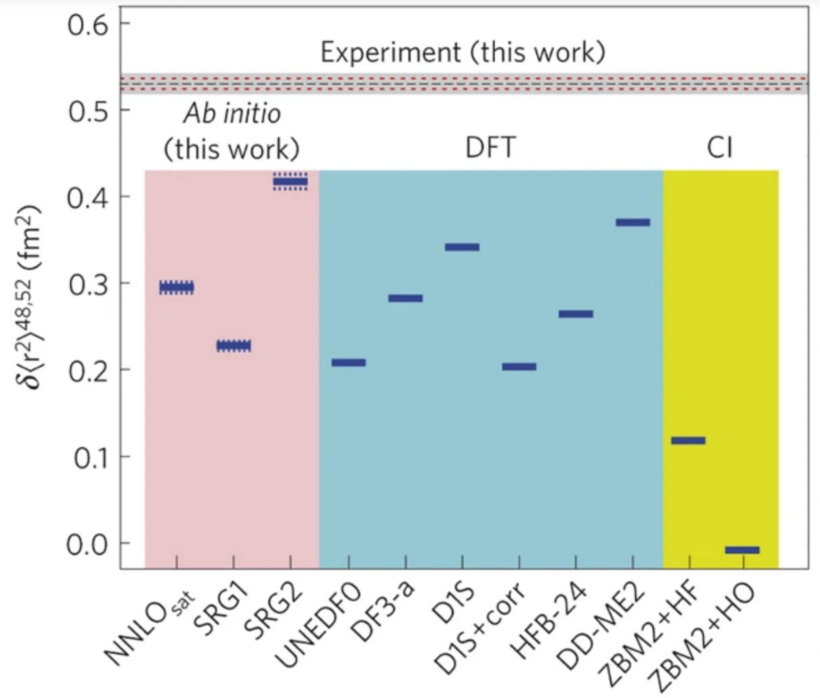
NEUTRON-RICH CALCIUM ISOTOPES

CHARGE RADII OF CA ISOTOPES

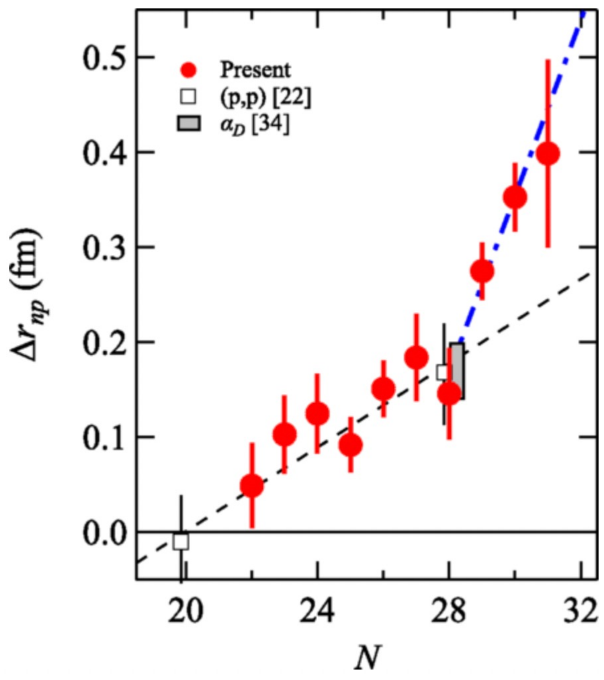
Ca, stable and short lived



Garcia Ruiz et al., Nat. Phys. (2016)



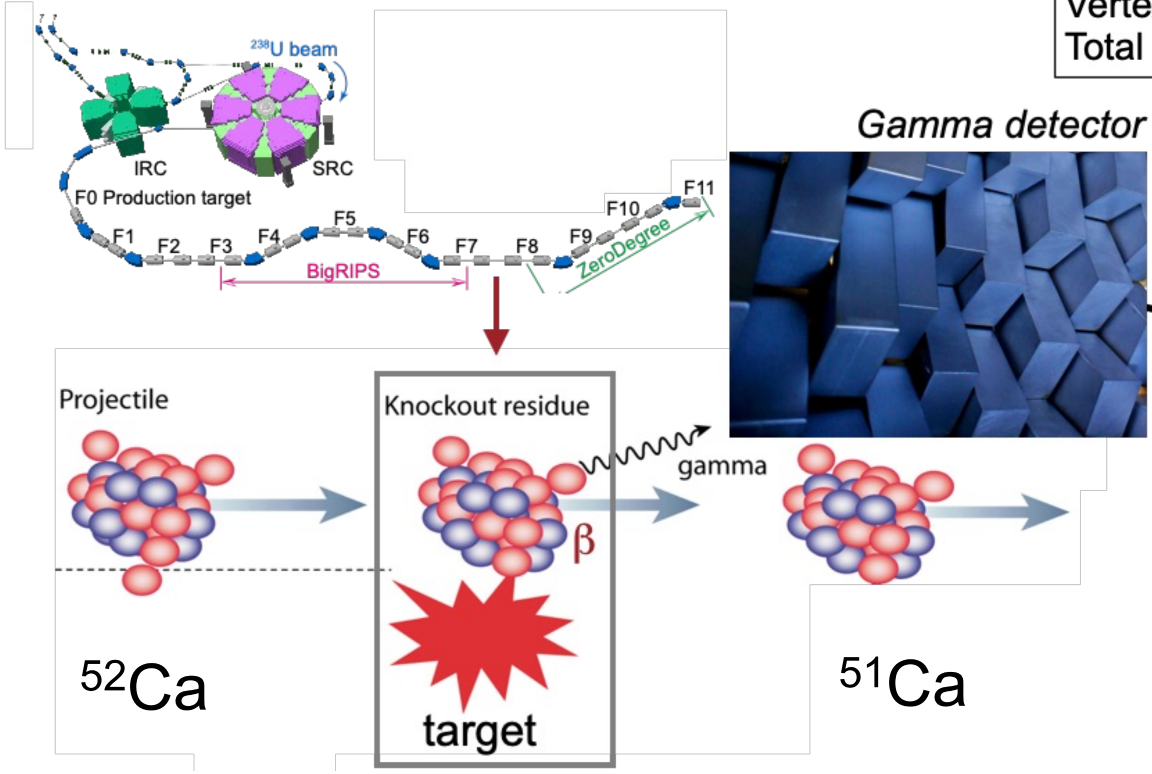
Tanaka et al., PRL (2020)



- electron scattering not yet possible for most RI (**see talk by Suda**)
- Isotopic shifts from laser spectroscopy give access to charge radii
- So far unexplained trend for neutron rich Ca and K isotopes
- Role of neutron distribution suggested to play a role Bonnard et al., PRL (2016)

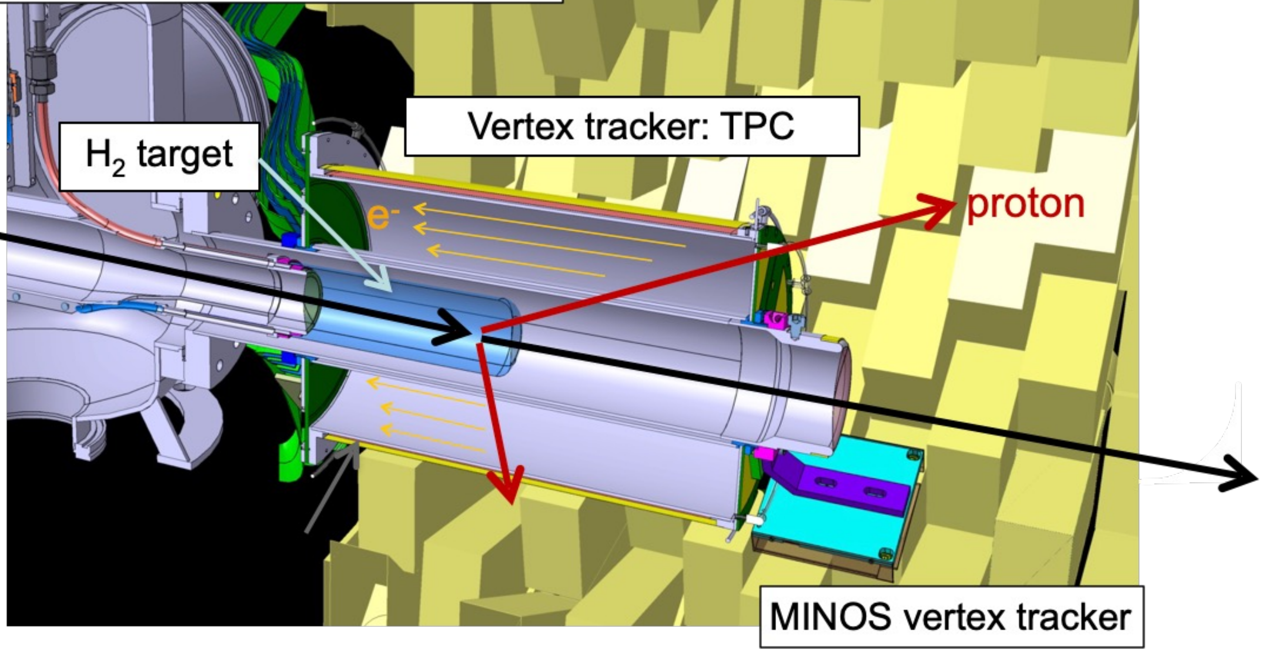
NEUTRON STRUCTURE OF ^{52}CA

- RIBF, RIKEN
- ^{70}Zn primary beam at 345 MeV/nucleon, 200 pnA
- ^{52}Ca(p,pn)^{51}Ca at 200 MeV / nucleon



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

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

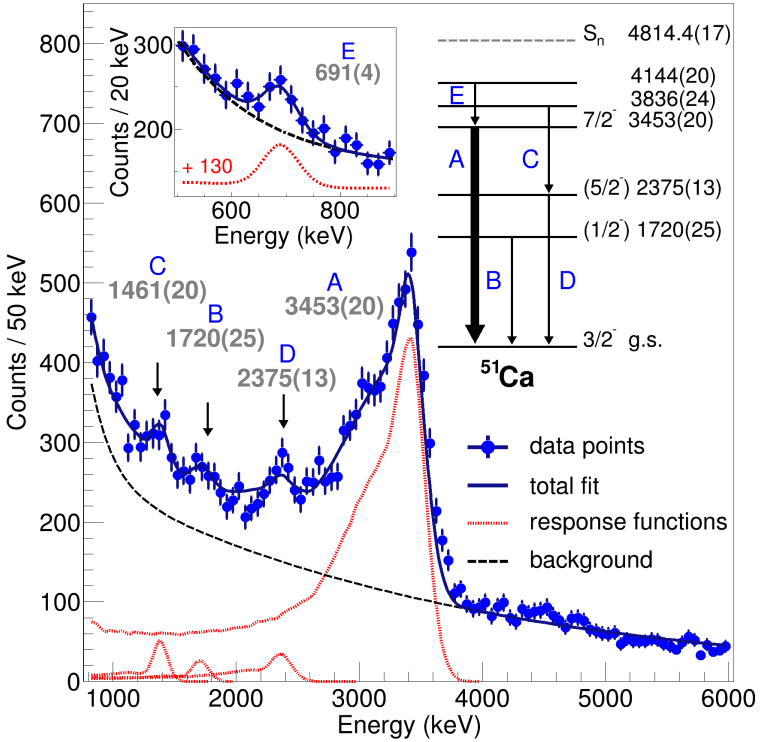


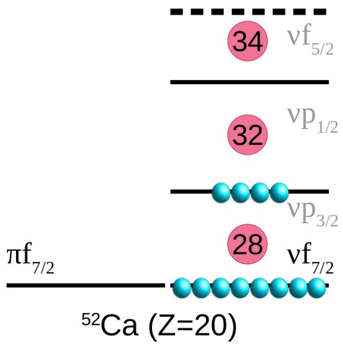
AO et al., EPJA (2014)

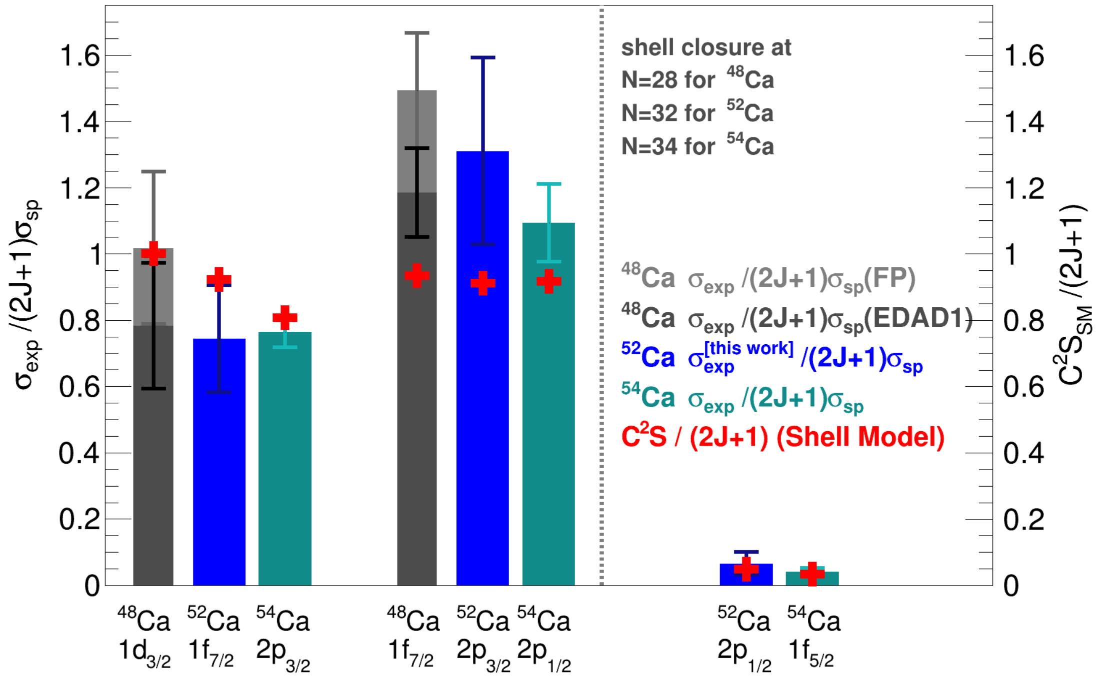
NEUTRON-RICH CALCIUM ISOTOPES

N=32 SHELL CLOSURE IN ^{52}CA

- DWIA single-particle cross sections: K. Ogata, K. Yoshida
- ^{52}Ca presents the features of a neutron closed shell as ^{48}Ca, ^{54}Ca
- proton closed shell as well Sun et al., PLB (2020)

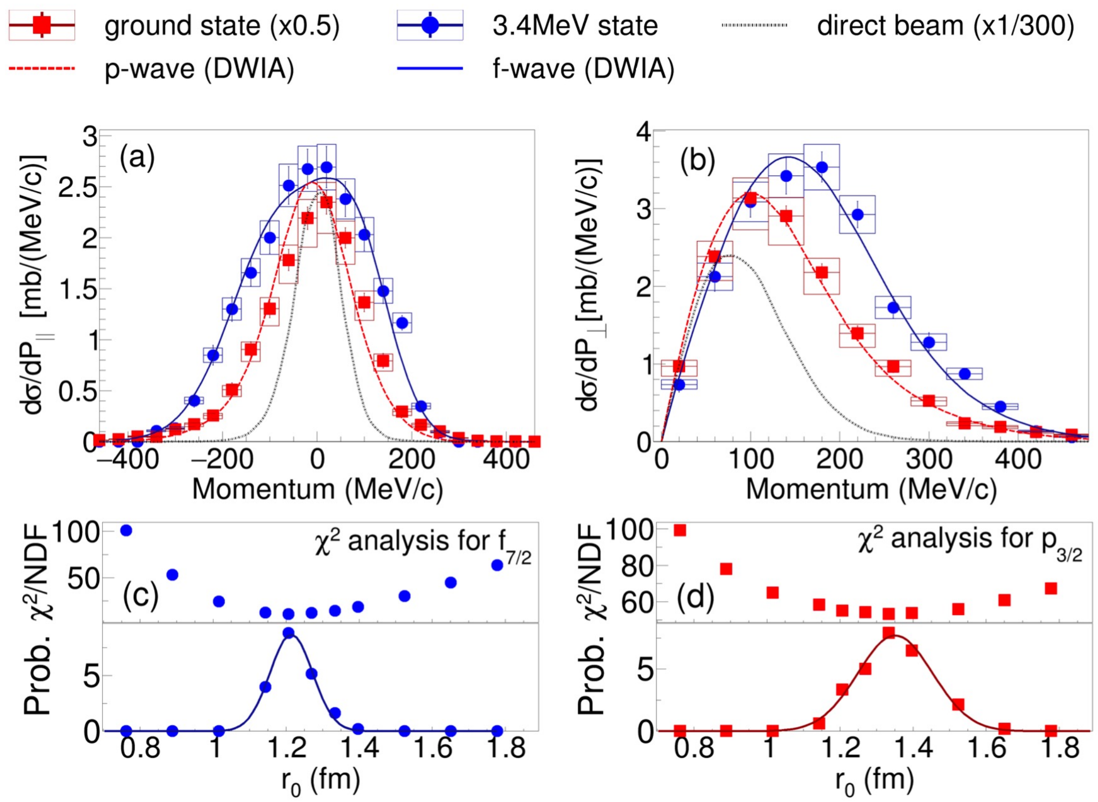






Enciu et al., PRL (2022)

EXCLUSIVE MOMENTUM DISTRIBUTIONS



- Momentum distributions of $\nu p_{3/2}$ and $\nu f_{7/2}$ single particle states, K. Yoshida (JAEA) and K. Ogata (Kuyshu)

- DWIA transition amplitude:

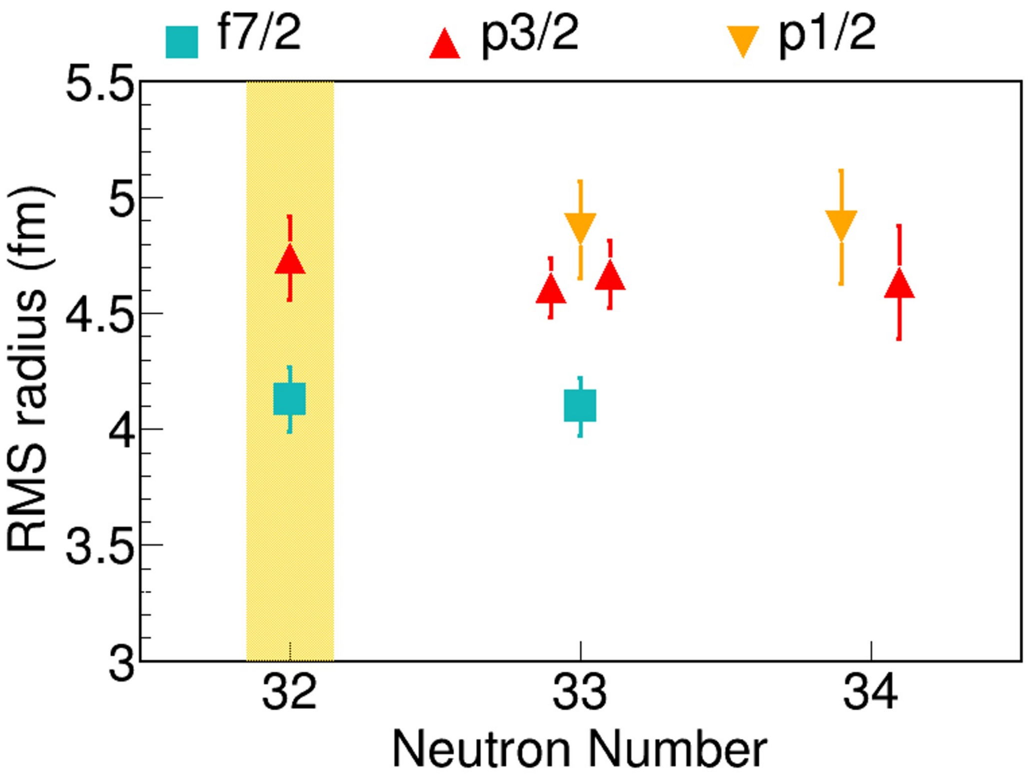
$$T^{jlm} = \sqrt{S} \left\langle \chi_{p'}^{(-)} \chi_N^{(-)} \middle| \tau_{pN} \middle| \chi_p^{(+)} \psi_{jlm} \right\rangle$$

Distorted wavefunctions of the outgoing (-) and incoming (+) protons and knocked-out nucleon and transition form factor $\langle \psi_f | a_{nlj} | \psi_i \rangle$~ s.-p. wavefunction of the knocked-out nucleon.

Model inputs

- W.-S. wavefunctions, parameters with S_n, r_0, a_0 OR microscopic transition amplitude
- Optical potential

NEUTRON TRANSITION AMPLITUDE RMS



- **^{52}Ca**

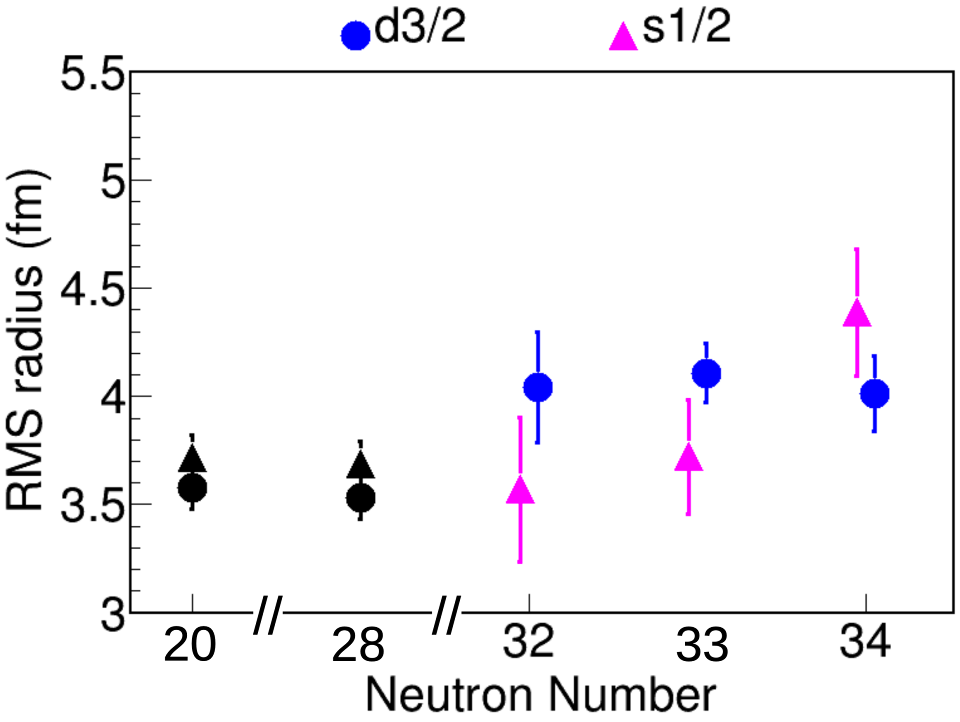
Resulting rms radii:
$\nu f_{7/2}$: 4.13(14) fm
$\nu p_{3/2}$: 4.74(18) fm
Difference: **0.61(23) fm**

from HFB, SKM:
$\nu f_{7/2}$: 4.12 fm
$\nu p_{3/2}$: 4.49 fm
Difference: 0.37 fm

- **^{53,54}Ca**: compatible results
- The approach gives comparable size for $\nu p_{3/2}$ and $\nu p_{1/2}$

NEUTRON-RICH CALCIUM ISOTOPES

PROTON TRANSITION AMPLITUDE RMS



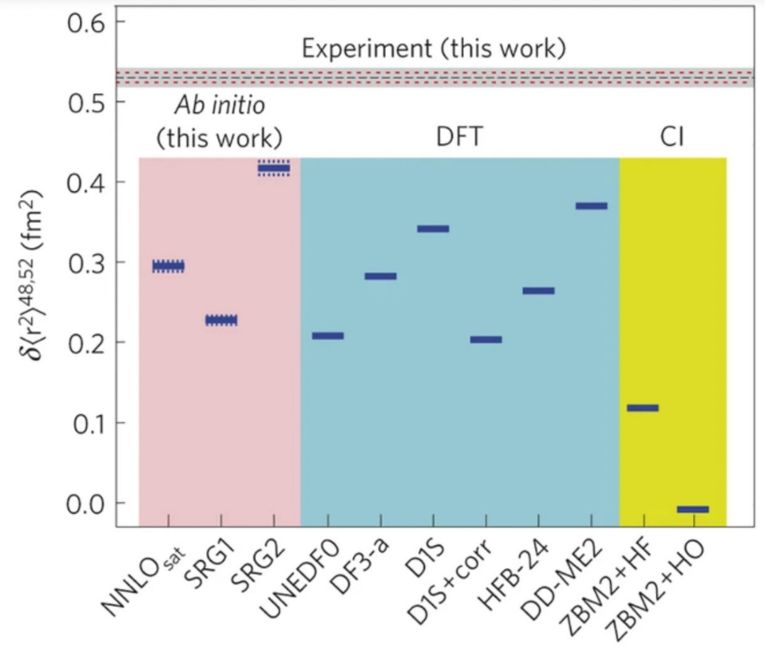
Assuming HF wavefunction and fixed proton orbitals up to $d_{5/2}$ (Si core), one gets:

$$\delta\langle r^2\rangle^{48,52} = 0.76(63)\ \mathrm{fm}^2$$

Inconclusive due to

- systematics
- stat. uncertainties

New experiments accepted at RIBF for O, C, Ca isotopes (Nakamura, Obertelli)



^{40}Ca and ^{48}Ca data from:
G. J. Kramer, “The proton spectral function of ^{40}Ca and ^{48}Ca studied with the (e,e'p) reaction”, PhD, Amsterdam Univ., 1990

NEUTRON-RICH CALCIUM ISOTOPES

COMPARISON TO THEORY

[preliminary, removed from slides]

[1] HF calculations, HFBRAD code, SKM interaction

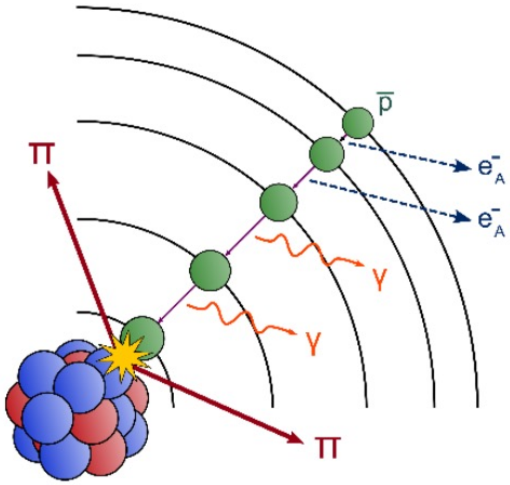
[2] W. Horiuchi, private communication
based on: W. Horiuchi et al., Phys. Rev. C (2020)

[3] J. Liu, private communication
based on: J. Liu et al., Phys. Lett. B (2020)
[Relativistic Hartree-Fock calculations]

IMSRG: **preliminary**, ongoing work
M. Heinz, T. Miyagi, A. Schwenk, A. Tichai

So far, unevolved one-body annihilation operator
Extension to transformed (many-body) operator ongoing

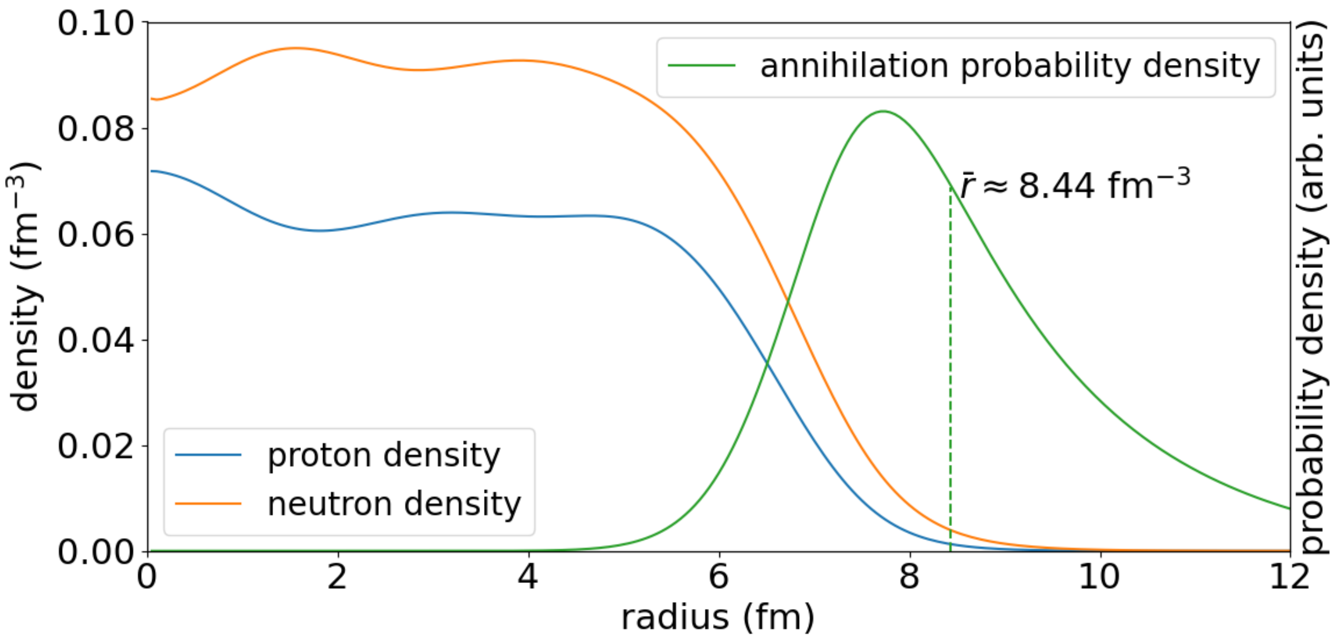
LOW ENERGY ANTIPROTONS AS PROBE



- $\bar{p}$ captured in antiprotonic orbital (~QED)
- then annihilate in tail $\rho_{n/p}(r)$ (QCD)
- Conservation of total charge

$$\sum_{\pi} q_\pi = \begin{cases} 0 \text{ for } \bar{p}p \\ -1 \text{ for } \bar{p}n \end{cases}$$

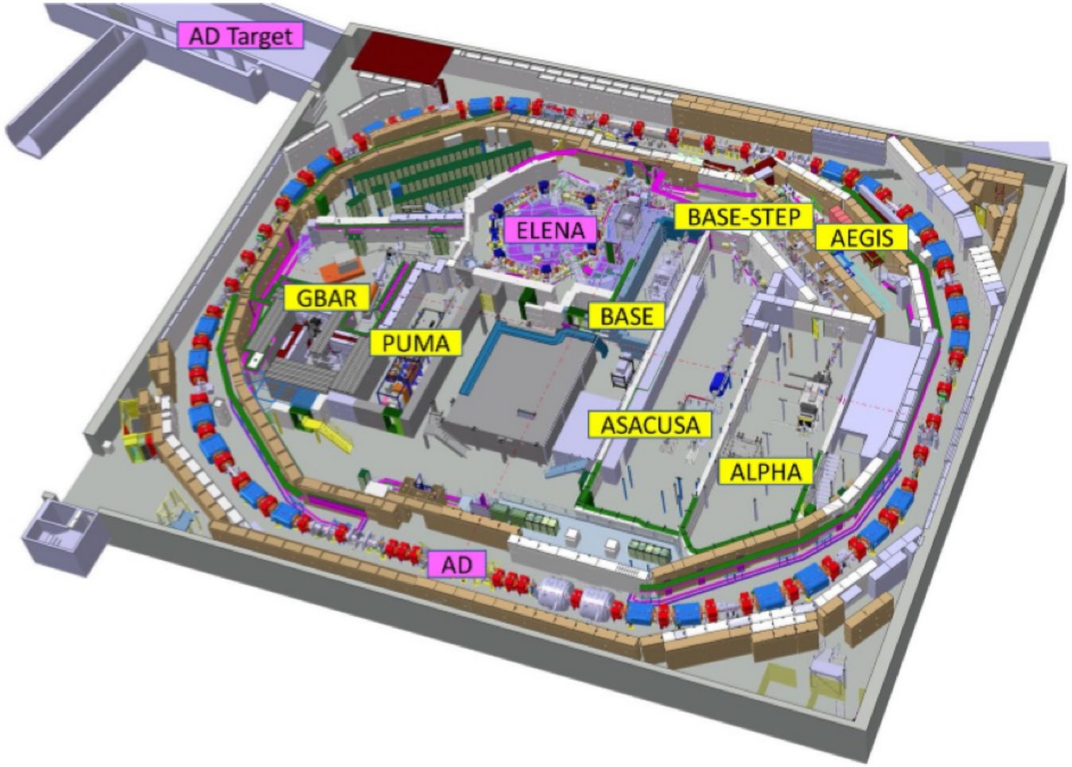
- Collaboration with Lazauskas, Hupin et al. (theory)

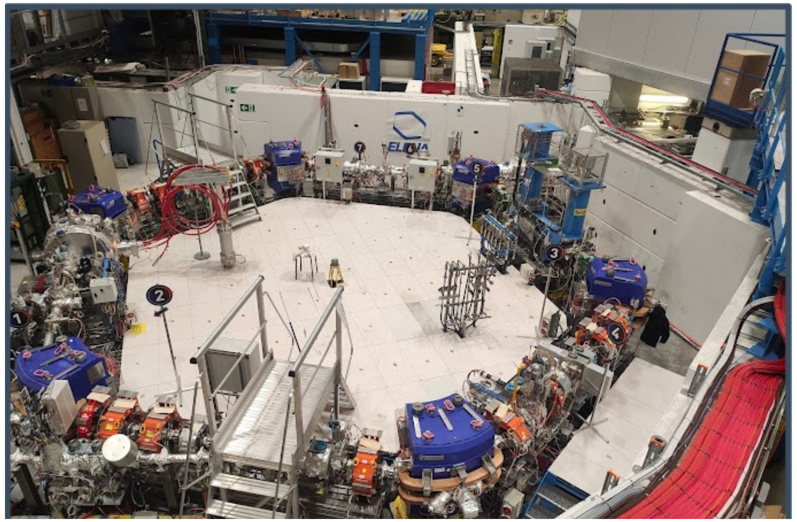


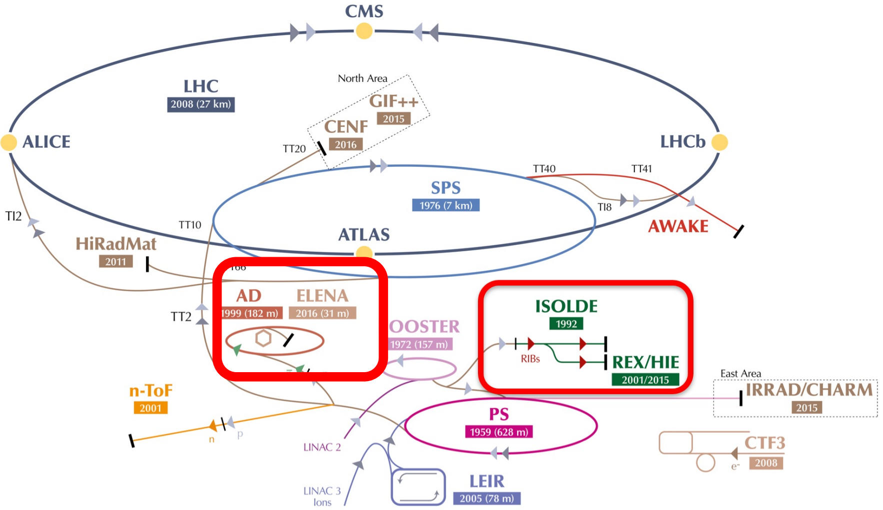
- First application of method: Bugg et al., PRL (1973)
- Application to rare isotopes first proposed by: Wada and Yamazaki, NIM B (2004)
- First experiments at PUMA, CERN, in 2025

PUMA AT CERN

THE ANTIMATTER FACTORY AT CERN

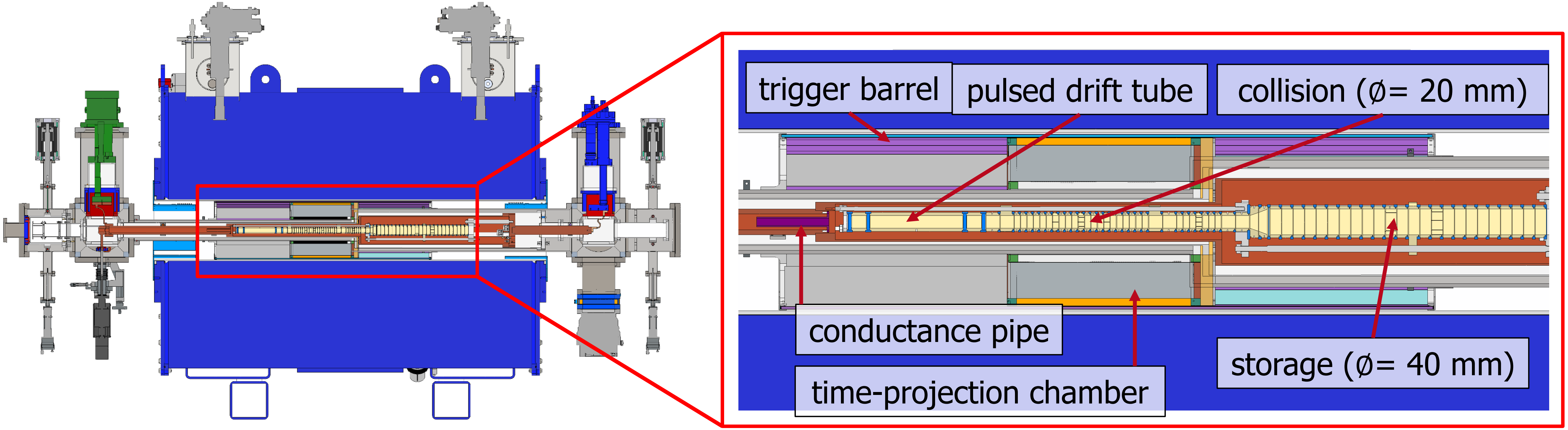






- 1.5 10^{13} protons at 26 GeV/c from PS
- 3. 10^{7} antiprotons at AD
- Deceleration: 5.3 MeV (AD), 100 keV (ELENA)
- Experiments: 4. 10^{6} antiprotons every 110 s

THE PUMA EXPERIMENT



Objectives:

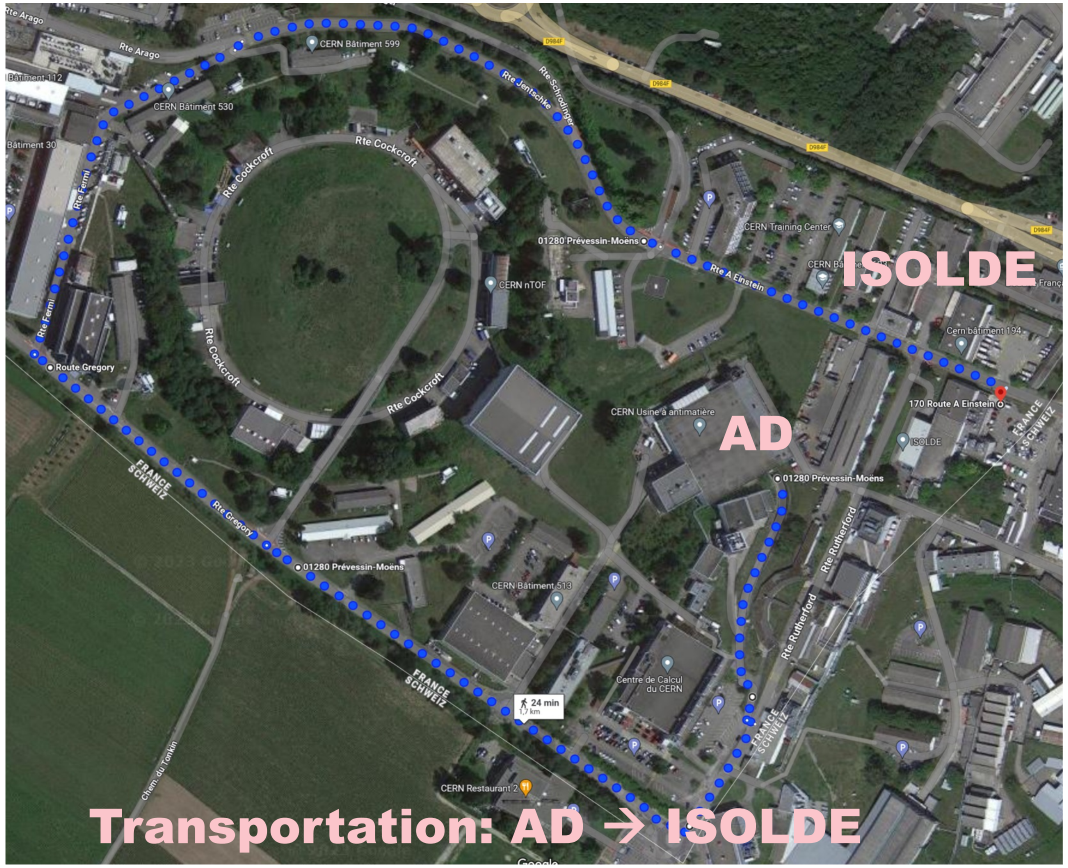
- store few 10^7 antiprotons (stage 1), 10^9 antiprotons (stage 2, $\equiv 10^7$ antiprotons / cm^3)
- Injection bunches of $10^{4\text{-}5}$ ions

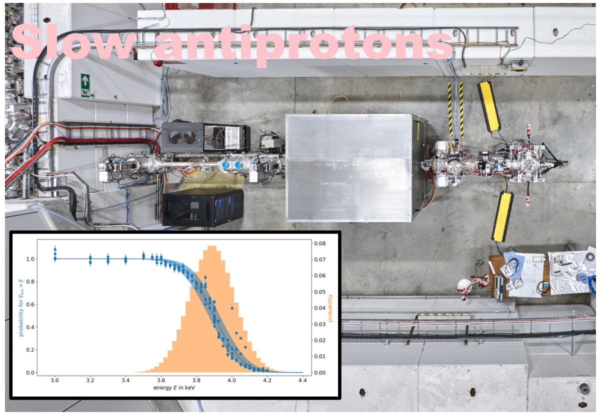
Expected yields:

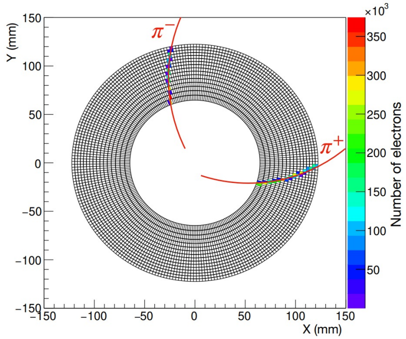
10^5 ions and 10^7 antiprotons in collision trap = 100 Hz of annihilations

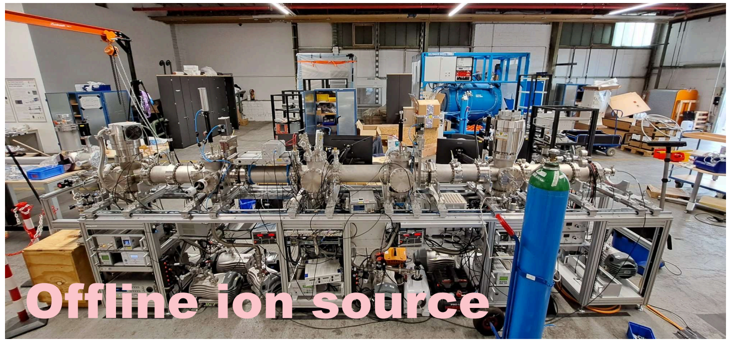
PUMA AT CERN

THE PUMA EXPERIMENT





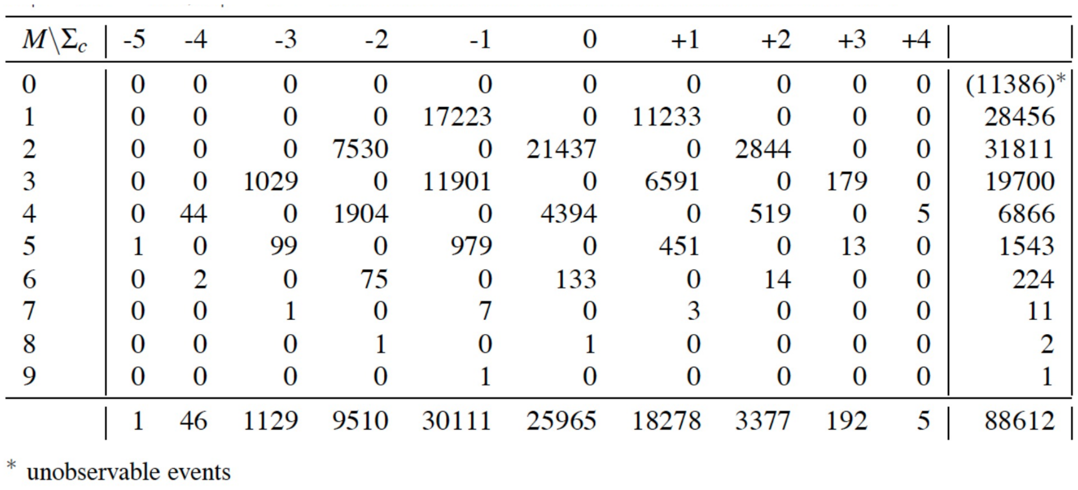




- Long antiproton trapping time already achieved. *Record:* BASE: > 50 years
- Transportation of antiprotons is also part of BASE-STEP (PI: C. Smorra)

FINAL STATE INTERACTIONS

M. Wada, Y. Yamazaki, NIMB (2004)



$M\backslash\Sigma_c$	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	
0	0	0	0	0	0	0	0	0	0	0	(11386)*
1	0	0	0	0	17223	0	11233	0	0	0	28456
2	0	0	0	7530	0	21437	0	2844	0	0	31811
3	0	0	1029	0	11901	0	6591	0	179	0	19700
4	0	44	0	1904	0	4394	0	519	0	5	6866
5	1	0	99	0	979	0	451	0	13	0	1543
6	0	2	0	75	0	133	0	14	0	0	224
7	0	0	1	0	7	0	3	0	0	0	11
8	0	0	0	1	0	1	0	0	0	0	2
9	0	0	0	0	1	0	0	0	0	0	1
	1	46	1129	9510	30111	25965	18278	3377	192	5	88612

* unobservable events

[preliminary, removed from slides]

- 4-parameter model for FSIs S. Wychech
  ω^+, ω^-: absorption of π^+, π^-, λ^+, λ^-: charge exchange π^+, π^-, π^0

- Neural network Kubota et al., in preparation (2024)
  Precision ~ 9%, Accuracy ~ 6 % benchmarked against INC simulations

- Room to improve performances

COLLABORATIONS

SAMURAI

RIKEN
cea SACLAY
TOKYO TECH Pursuing Excellence
RIKKYO UNIVERSITY
TOHOKU UNIVERSITY
TECHNISCHE UNIVERSITÄT DARMSTADT
RCNP
CNS
GSI
IPN ORSAY
vinAtom
lpc caen
KTH VETENSKAP OCH KONST
MTA atomki DEBRECEN
CSIC
IMP

PUMA

TECHNISCHE UNIVERSITÄT DARMSTADT
CERN
IJCLab Irène Joliot-Curie
LKB
IPHC
TRIUMF

Theory (Ca isotopes) TUDa: M. Heinz, T. Miyagi, A. Schwenk, A. Tichai, JAEA: K. Yoshida, Kyushu: K. Ogata

SUMMARY AND PERSPECTIVES

- Investigation of **momentum distributions from quasifree-scattering** as observable sensitive to the spatial distribution of nucleons

  Enciu et al., PRL (2022) & work in progress (2024)

- Low-energy antiprotons to measure the **ratio of neutron-to-proton annihilations**

  PUMA collab., EPJA (2022); Kubota et al., in preparation (2024)

- Both observables require a reaction framework to extract nuclear structure theory
- Despite this limitation they may give access to information along isotopic chains not accesible otherwise