NUCLEI AND THE PROPERTIES OF NUCLEAR MATTER

Never at Rest: a Lifetime Inquiry of QGP

February 9-12, 2025, Physikzentrum Bad Honnef

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Bundesministerium für Bildung und Forschung

NUCLEAR FORCES, NUCLEI & STARS

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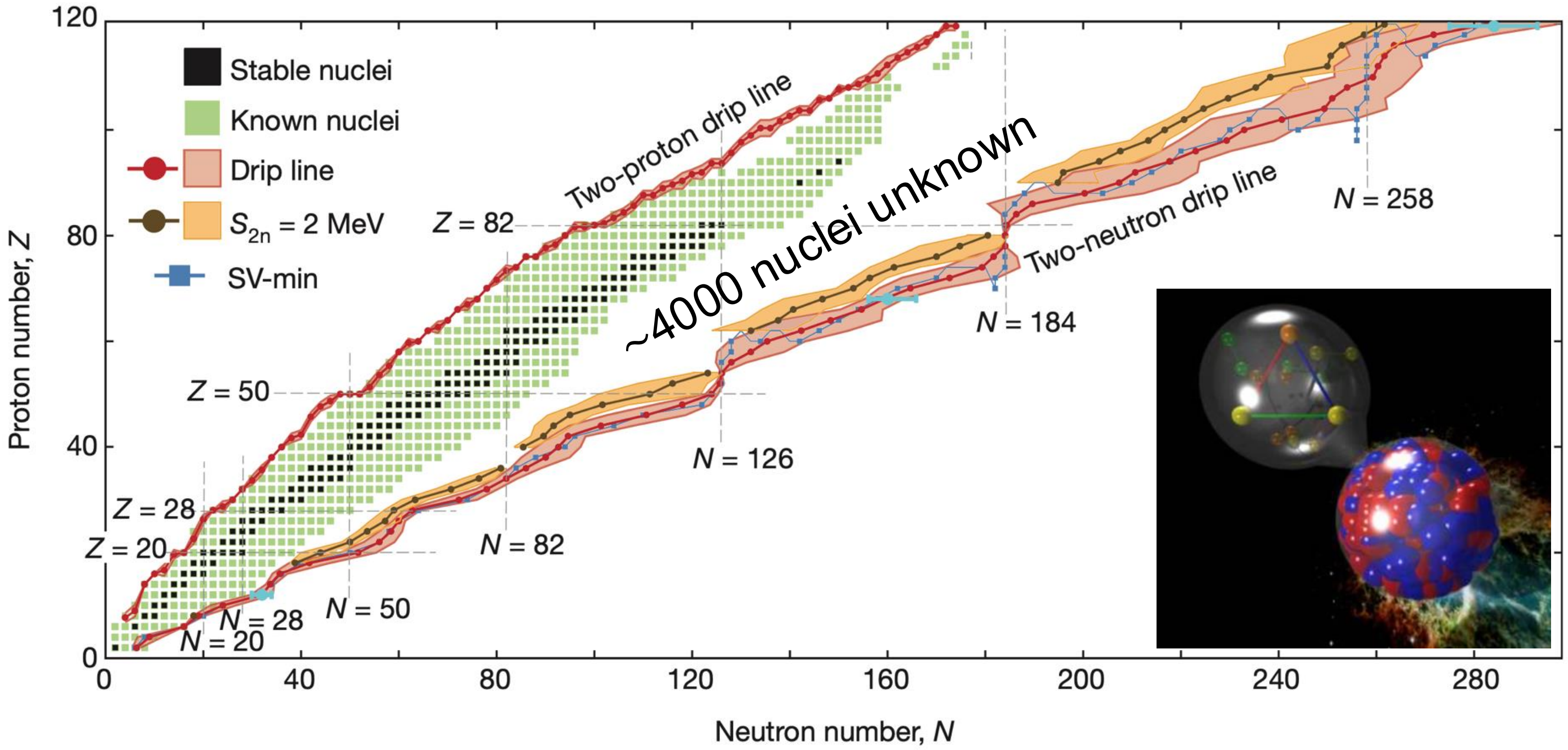
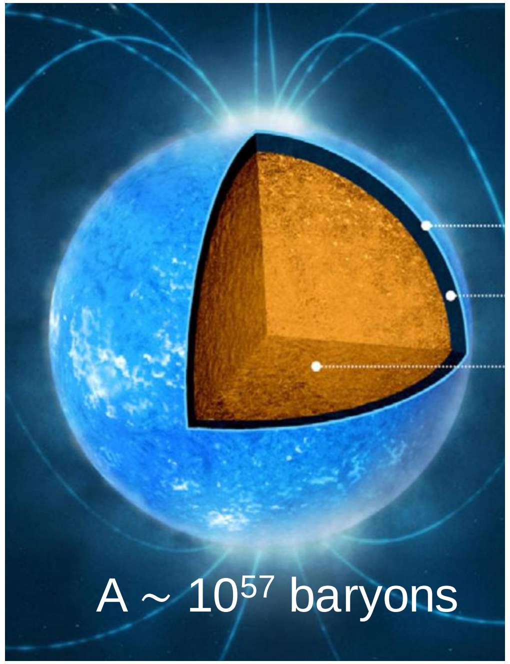


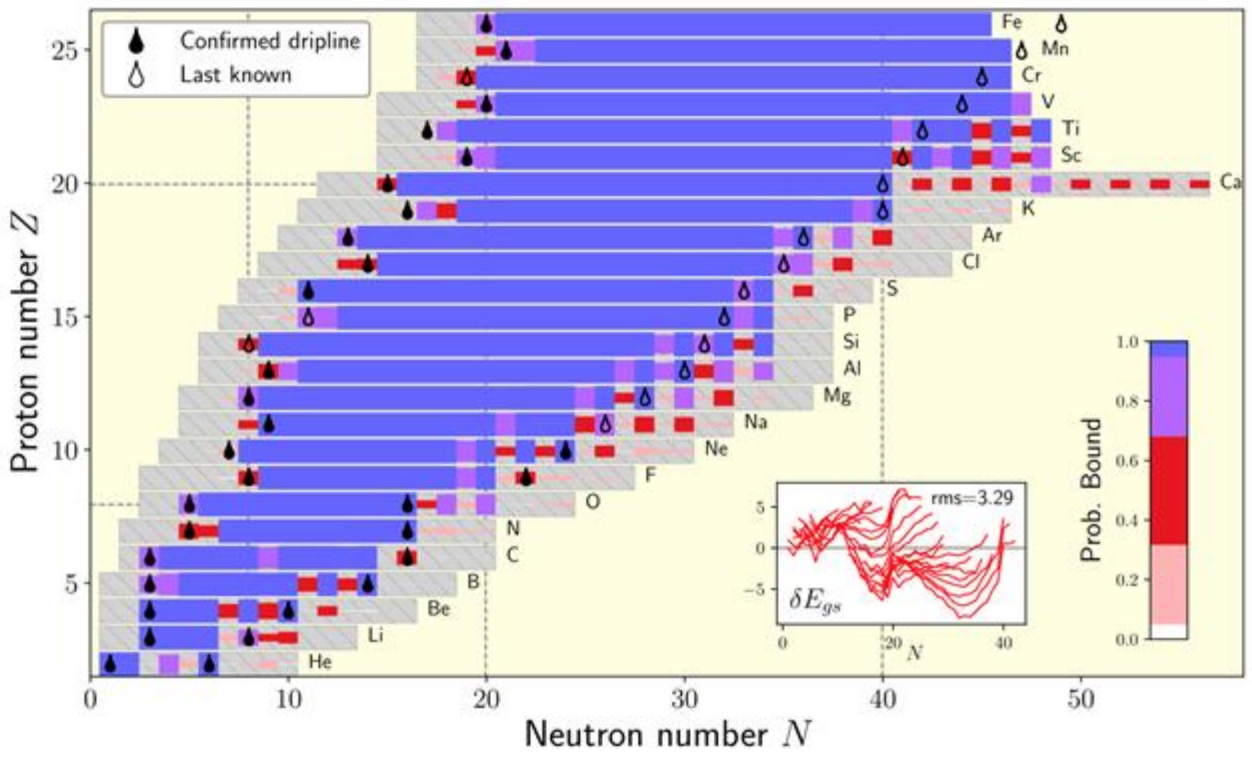


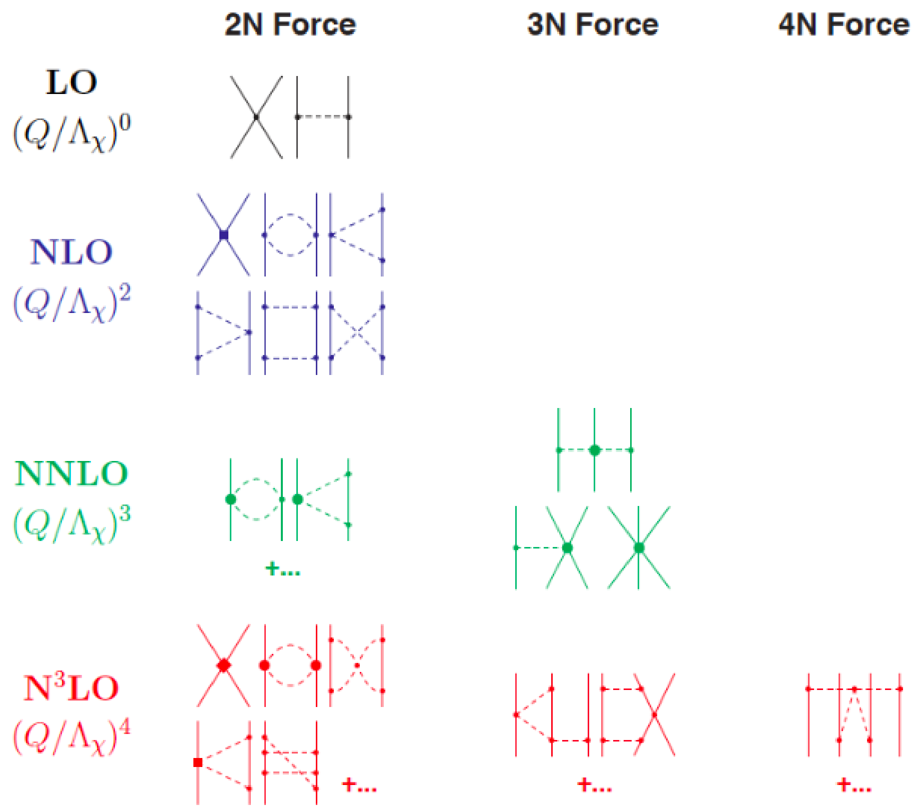
Erler et al., Nature (2012)

from Watts et al., Rev. Mod. Phys. (2016)

NUCLEAR FORCES, NUCLEI & STARS

Modern theory : effective field theory (**EFT**) from QCD and many-body **ab initio** methods





Stroberg, Holt, Schwenk, Simonis, Phys. Rev. Lett. (2021)

NUCLEAR FORCES, NUCLEI & STARS

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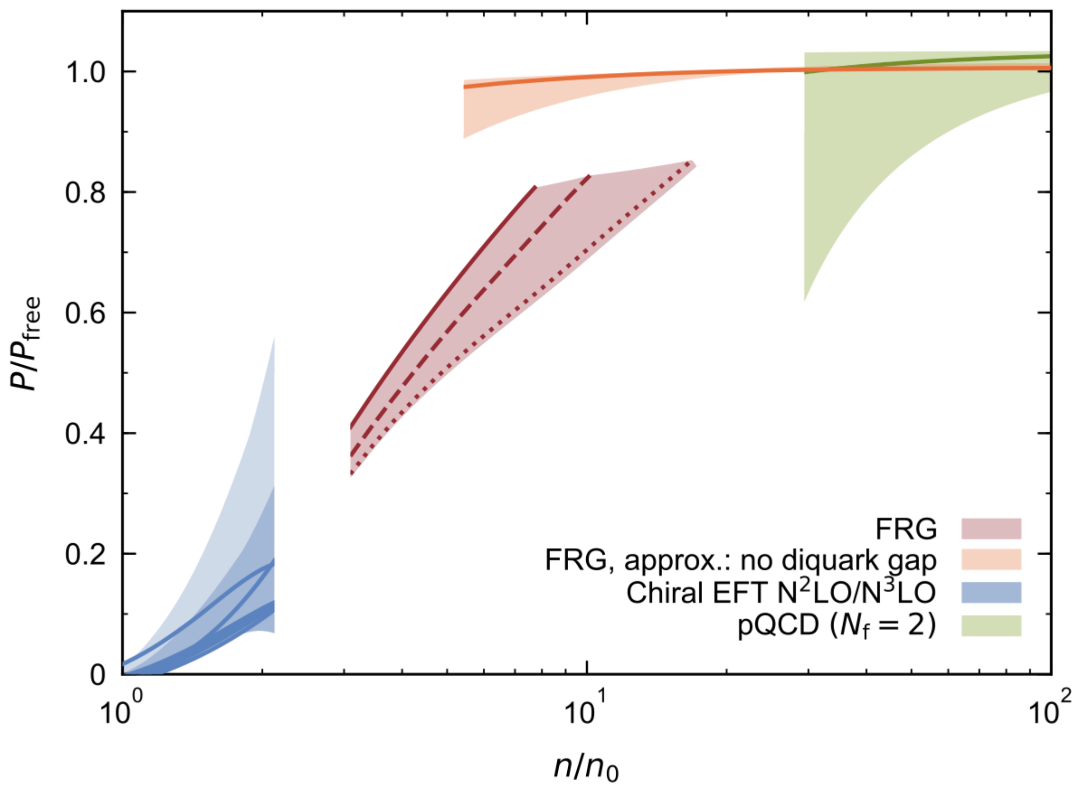
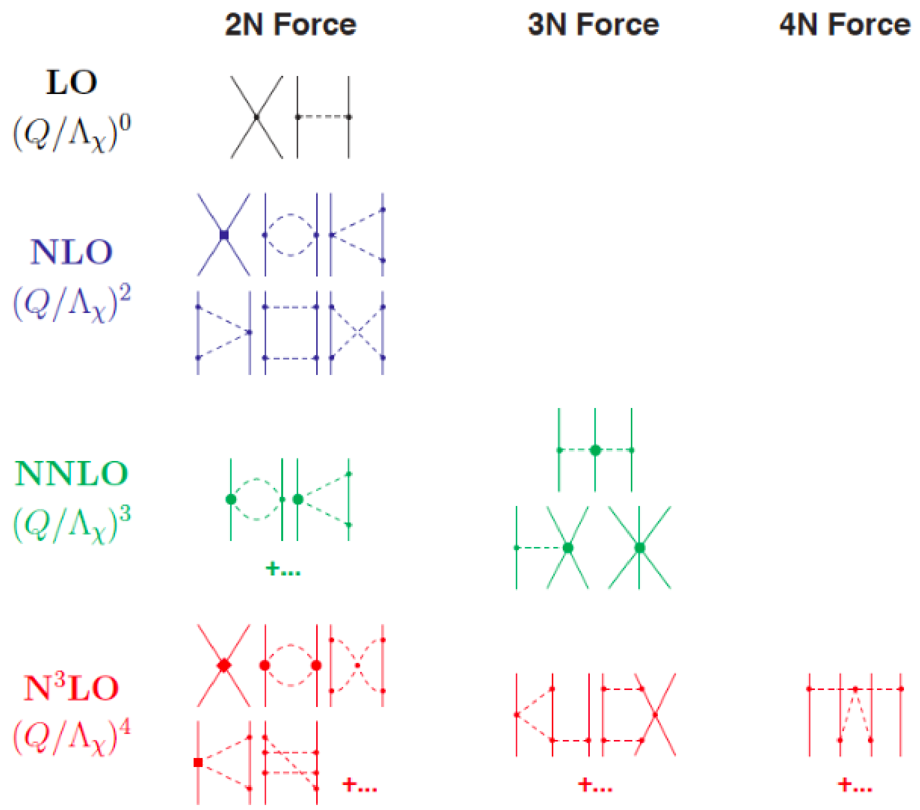
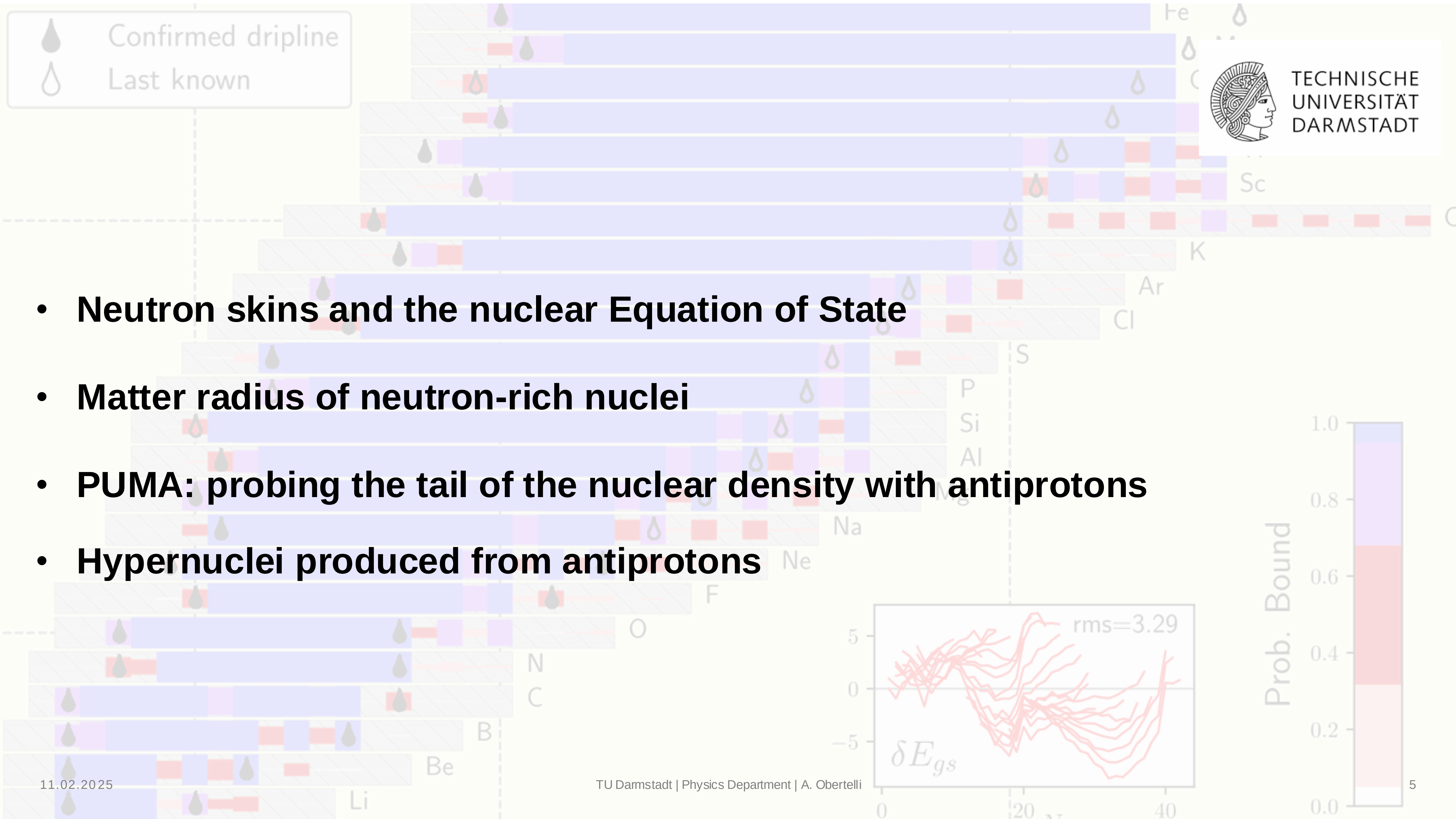


Leonhardt et al., Phys. Rev. Lett. (2020)



- **Neutron skins and the nuclear Equation of State**
- **Matter radius of neutron-rich nuclei**
- **PUMA: probing the tail of the nuclear density with antiprotons**
- **Hypernuclei produced from antiprotons**



NEUTRON SKIN THICKNESS

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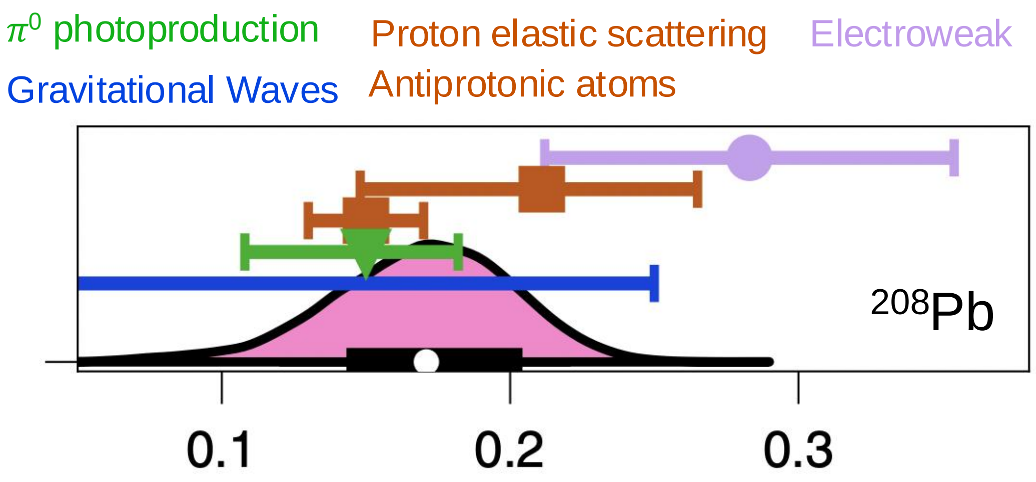
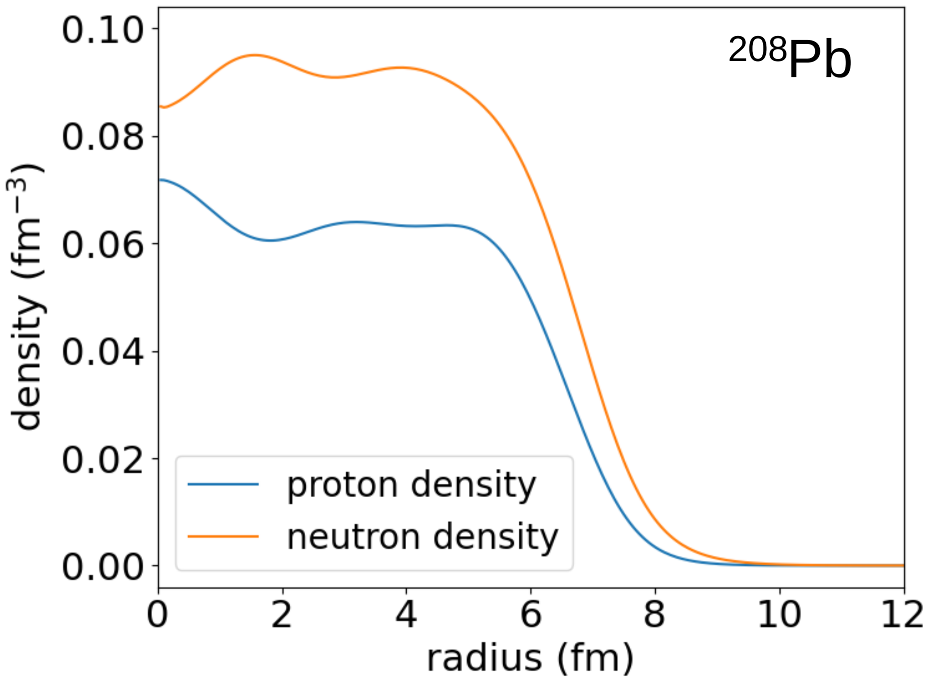
from Hu et al., Nature Phys. (2022)



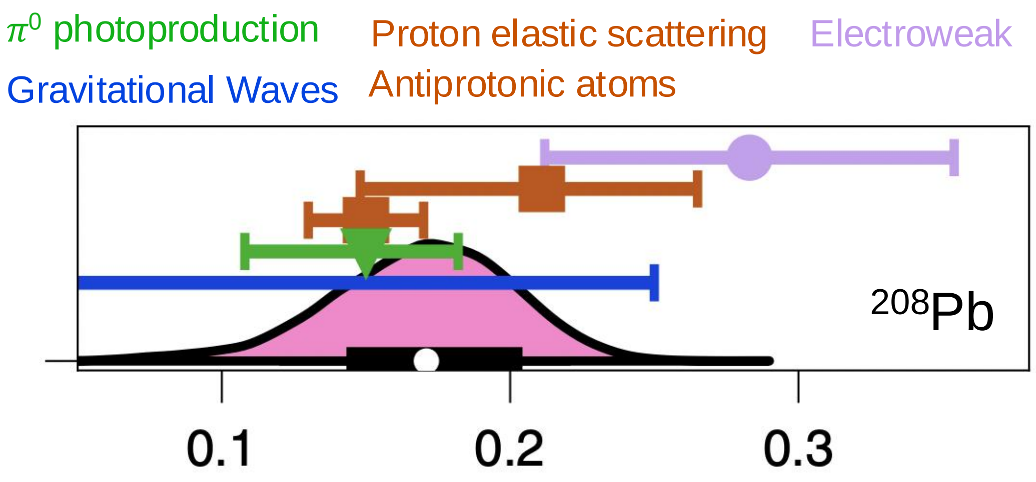
$$\Delta r_{np} = \sqrt{\langle {r_n}^2 \rangle} - \sqrt{\langle {r_p}^2 \rangle} \text{ (fm)}$$



- Charge radius from electron elastic scattering (Coulomb)
- Matter or neutron radius experimentally challenging to access
- Neutron skin thickness linked to nuclear equation of state (EOS) around saturation

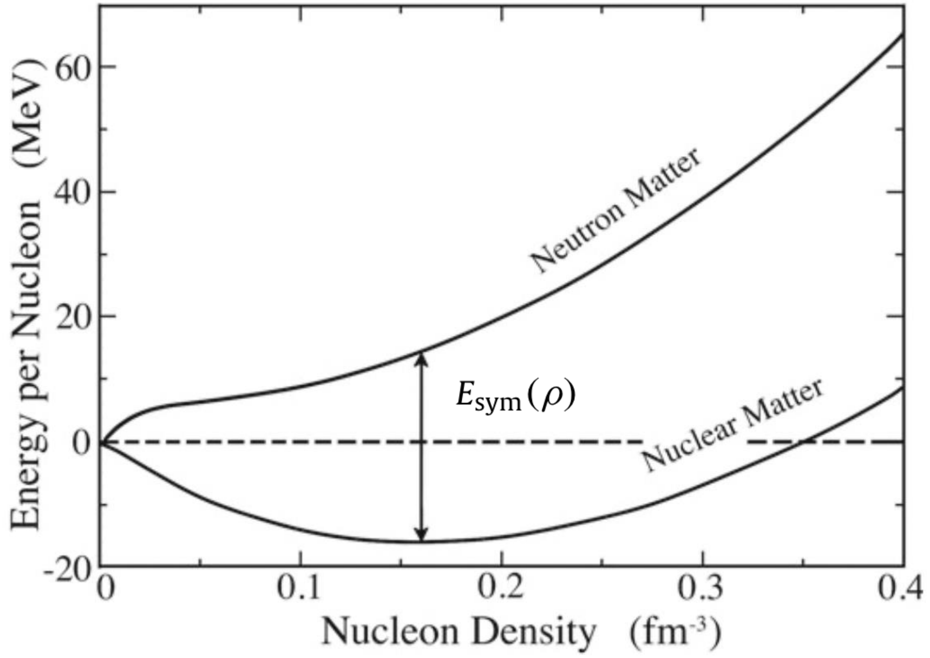
NEUTRON SKIN THICKNESS

from Hu et al., Nature Phys. (2022)



$$\Delta r_{np} = \sqrt{\langle r_n{}^2 \rangle} - \sqrt{\langle r_p{}^2 \rangle} \text{ (fm)}$$

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho - \rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2$$



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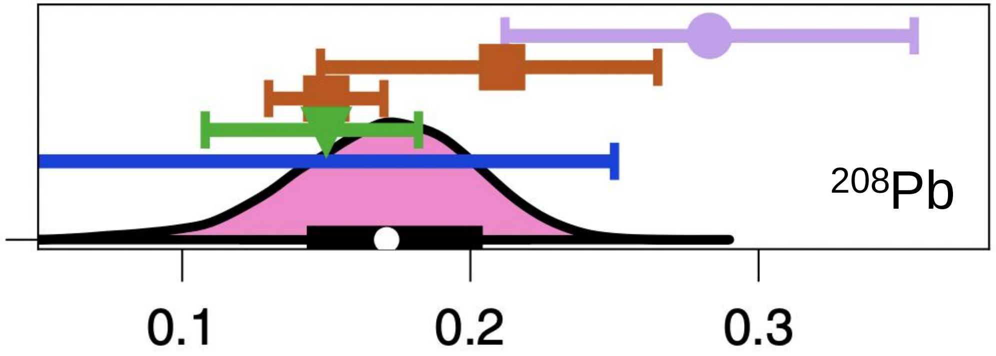
NEUTRON SKIN THICKNESS

from Hu et al., Nature Phys. (2022)

π^0 photoproduction
Proton elastic scattering
Electroweak
Gravitational Waves
Antiprotonic atoms



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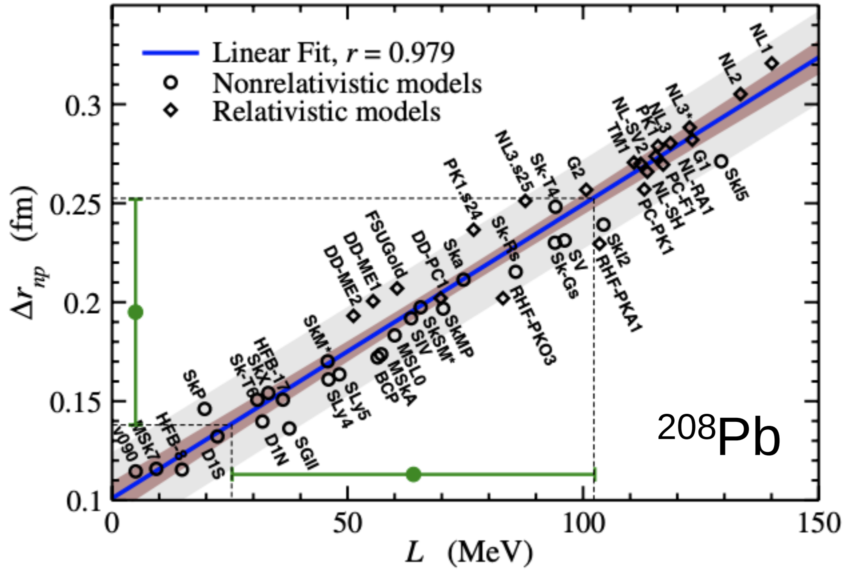

Roca-Maza et al., Phys. Rev. Lett. (2021)

- Charge radius from electron elastic scattering (Coulomb)
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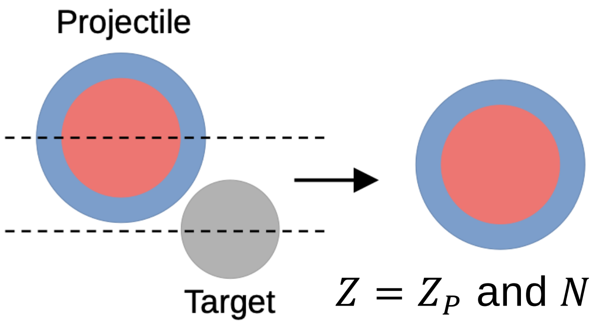
NEUTRON-ONLY REMOVAL REACTIONS

- Removal of neutrons only sensitive to neutron skin thickness



$Z = Z_P$ and $N \neq N_P$

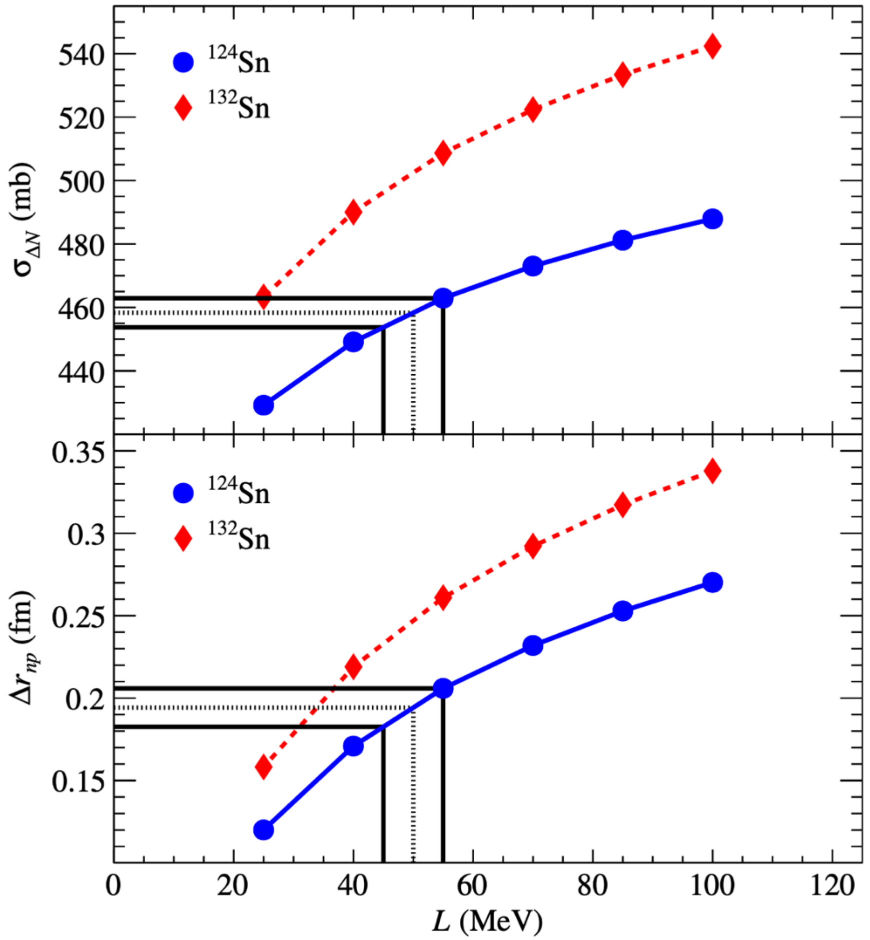
- **Precision of $\pm 1\%$** required

- Eikonal approximation and **Glauber** formalism

$$\sigma_{\Delta N} = \sum_N \binom{N_P}{N} \int d^2 b [1 - P_n(b)]^{N_P - N} P_n^N(b)$$

with

$$P_n(b) = \int dz d^2 s \rho_p^P(\mathbf{s}, z) e^{[-\sigma_{pp} Z_T \int d^2 s \rho_p^T(\mathbf{b}-\mathbf{s},z) - \sigma_{pn} N_T \int d^2 s \rho_n^T(\mathbf{b}-\mathbf{s},z)]}$$

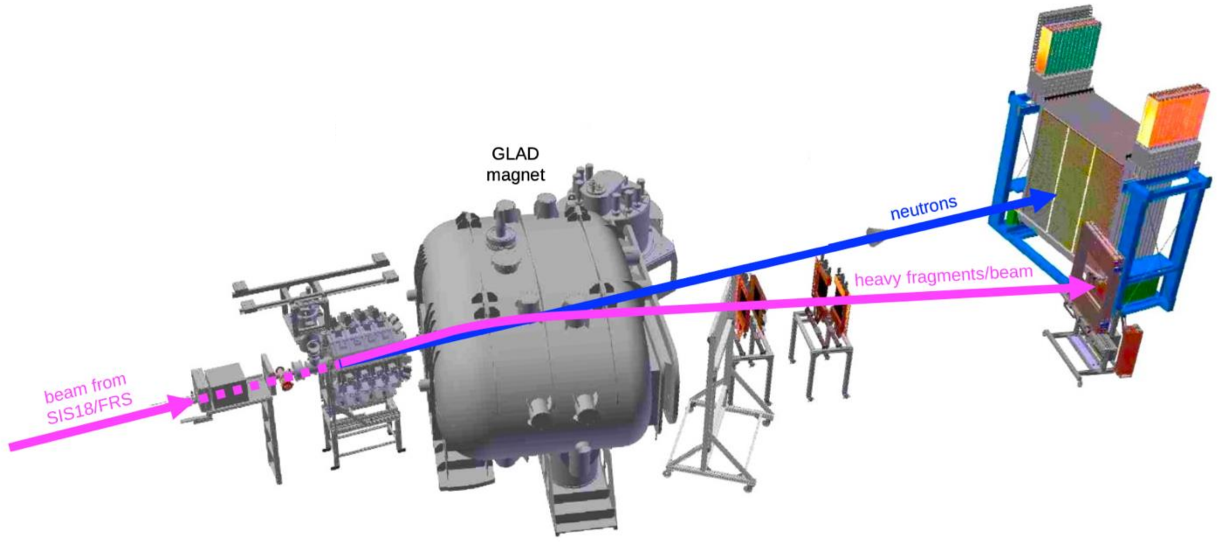


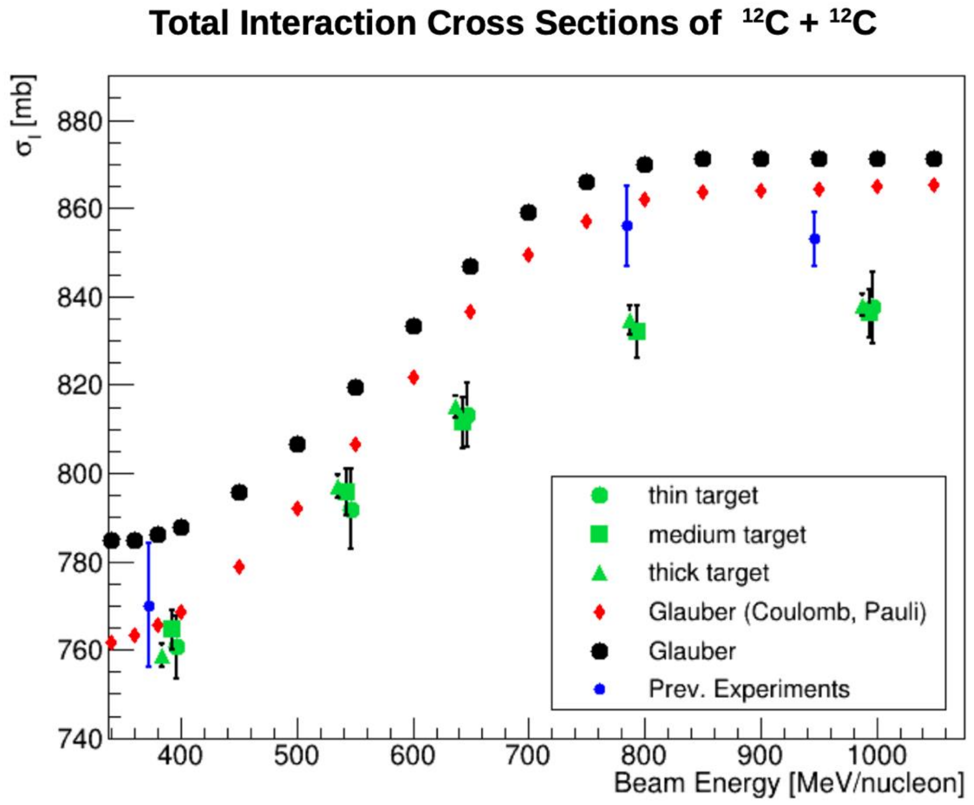
Aumann et al., Phys. Rev. Lett. (2017)

PRECISION MEASUREMENTS AT R3B

- 3 experiments at R^3B, GSI/FAIR
- ^{12}C, ^{120}Sn, $^{124-132}Sn$ beams, ^{12}C, ^{208}Pb targets
- Energies: 400, 550, 650, 800, 1000 MeV/nucleon

- Total interaction cross section $^{12}C+^{12}C$
- **Precision of 0.4 %**
- Glauber theory incl. Coulomb, Pauli blocking
- **Theory overestimates results at high energy by 3%**

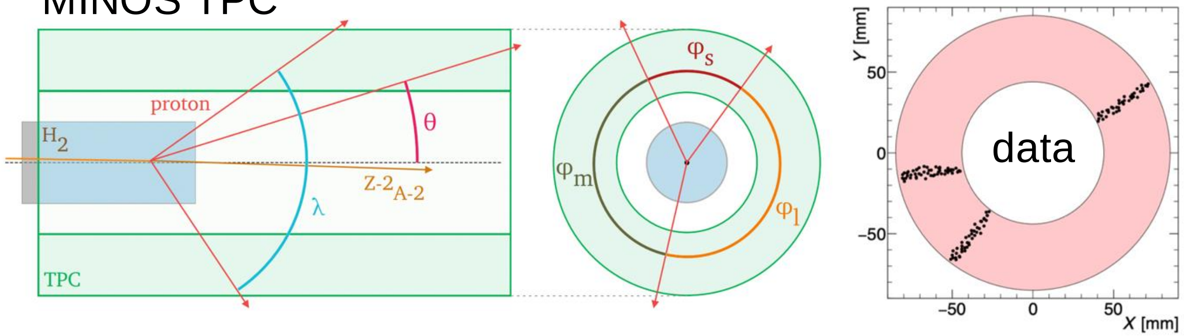




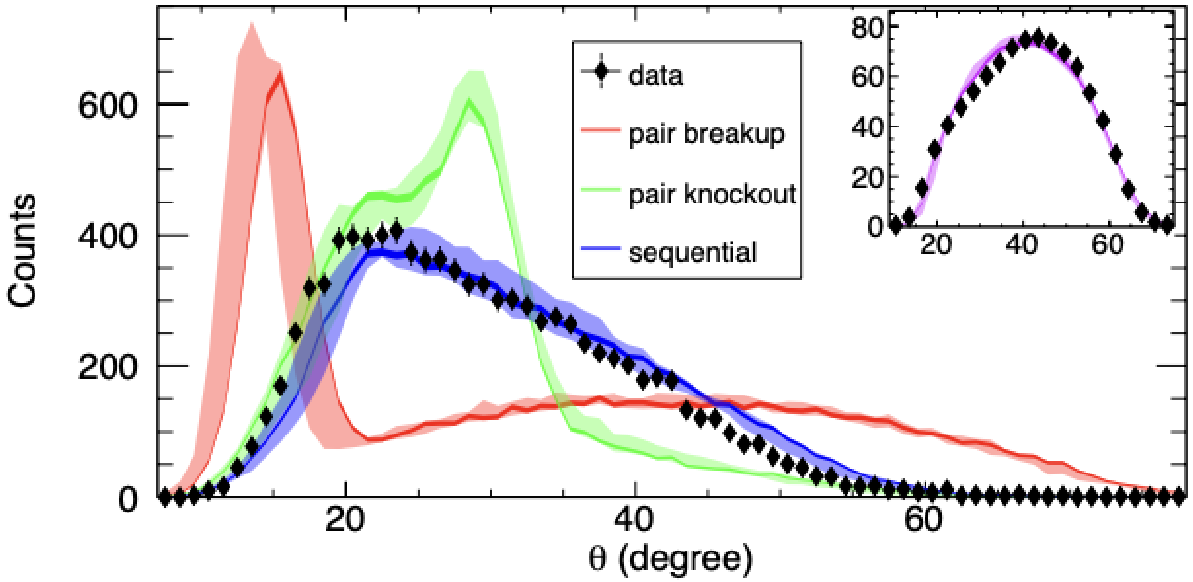
Ponnath et al., Phys. Lett. B (2024)

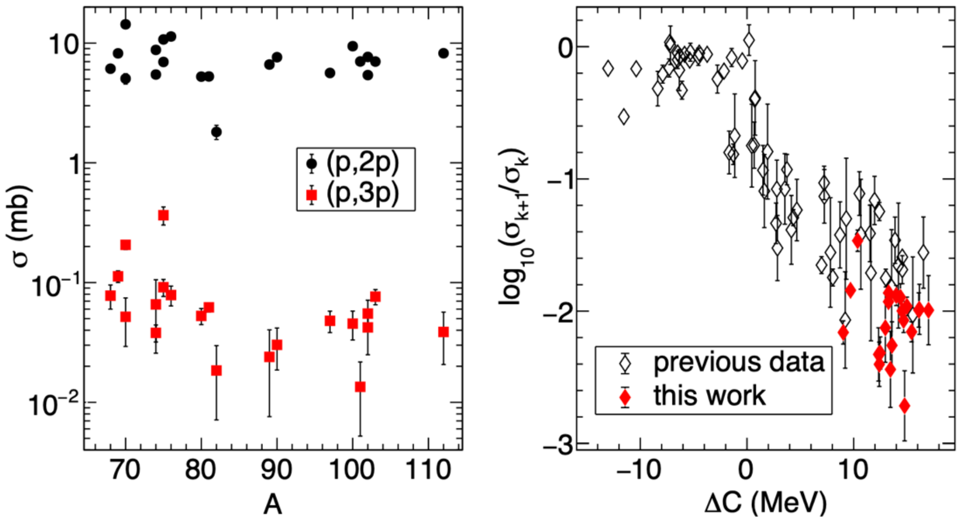
RE-SCATTERING EFFECTS

MINOS TPC



- Two-step two proton knockout from neutron-rich nuclei at 200 MeV/nucleon, RIKEN
- **(p,3p) is about 0.5 to 5% of (p,2p)**

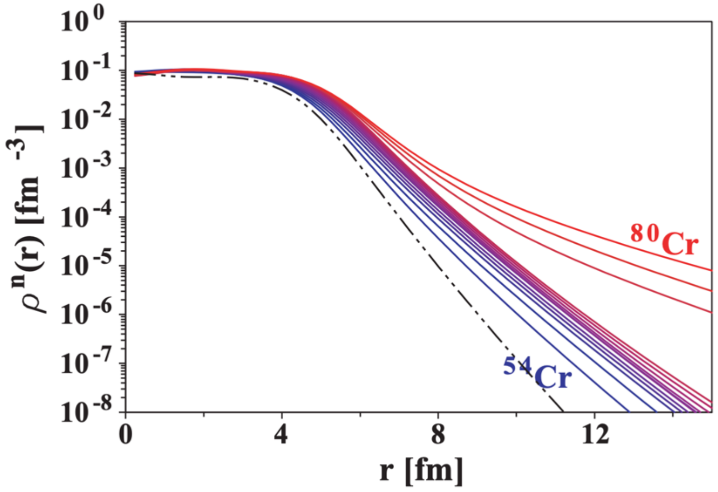


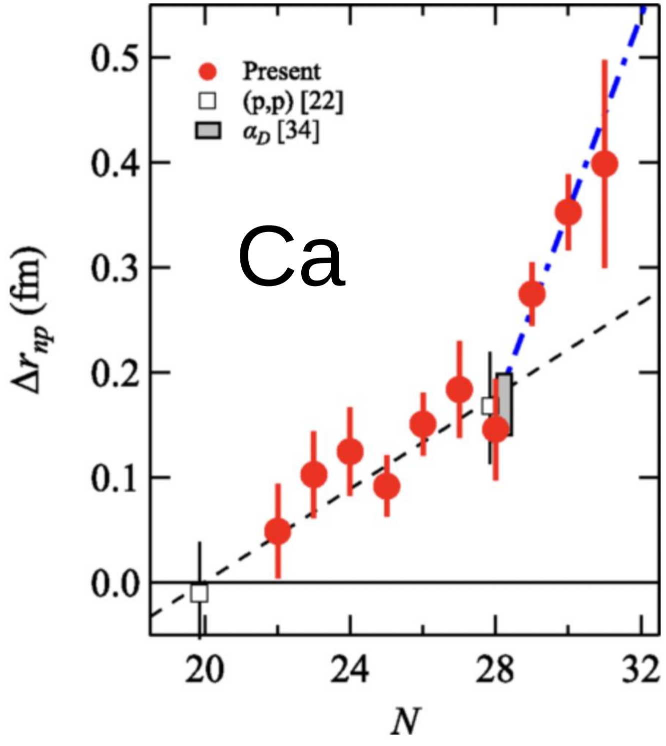


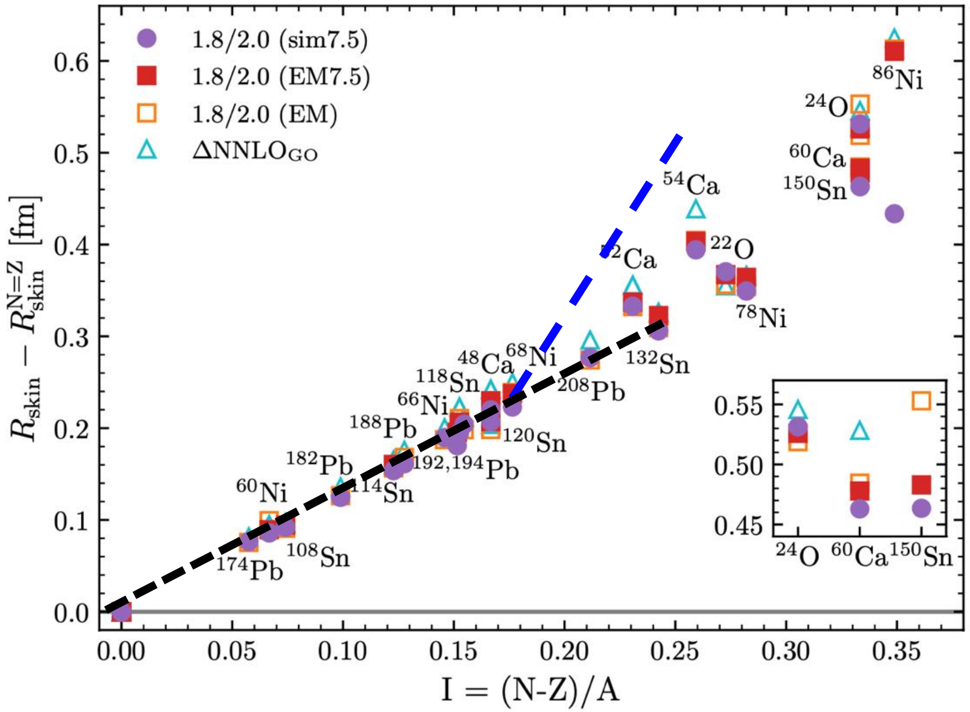
Frotscher et al., Phys. Rev. Lett. (2020)

NEUTRON-RICH NUCLEI: CA ISOTOPES

Interaction cross sections



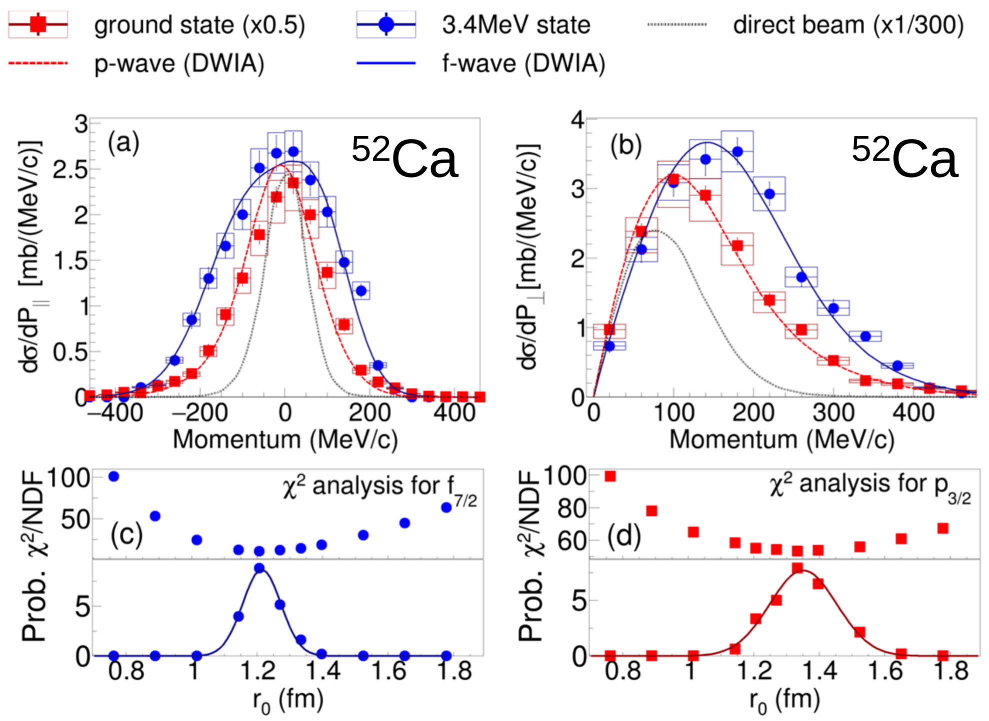




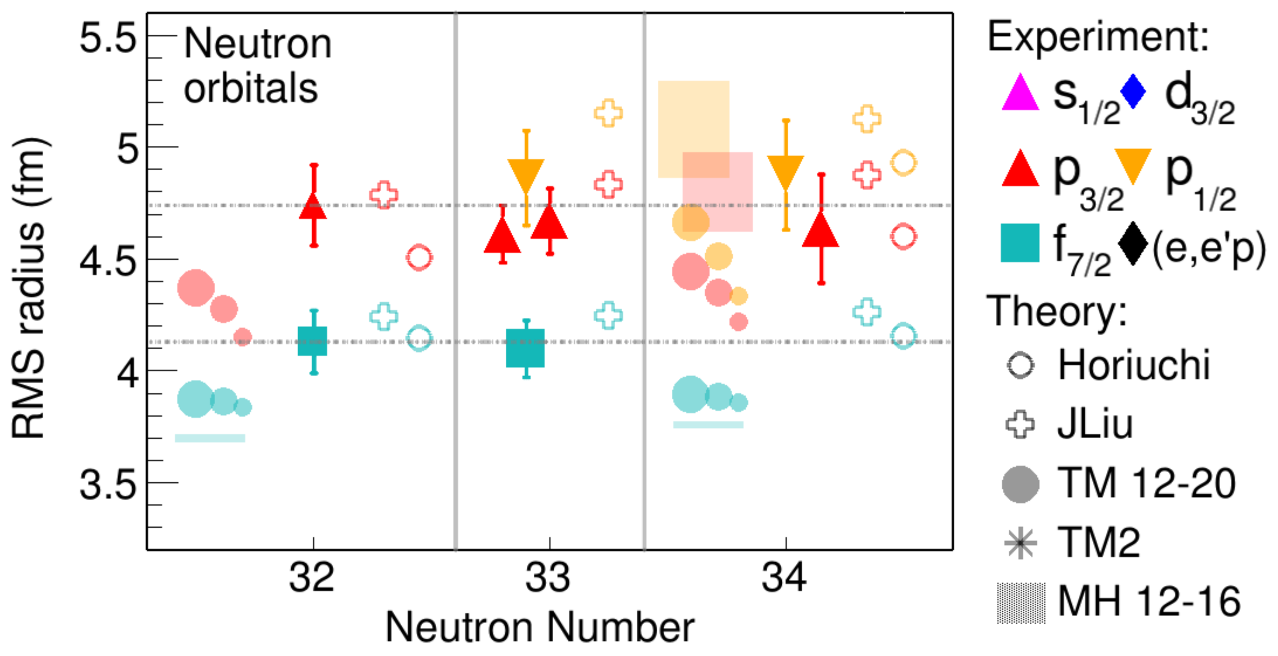
Rotival, Duguet, Phys. Rev. C (2009) Tanaka et al., Phys. Rev. Lett. (2020) Arthuis, Hebeler, Schwenk, arXiv (2024)

PROBING NEUTRON WAVE FUNCTIONS

- Neutron knockout (p,pn) from ^{52,53,54}Ca at 200 MeV/nucleon, RIKEN
- DWIA analysis of momentum distributions for single-particle $p_{1/2,3/2}$ and $f_{7/2}$ orbitals
- **Agreement with mean-field calculations** which predict a large neutron radius for Ca isotopes



Enciu et al., Phys. Rev. Lett. (2022)



Enciu et al., in preparation (2025)

LOW ENERGY ANTIPROTONS AS PROBE

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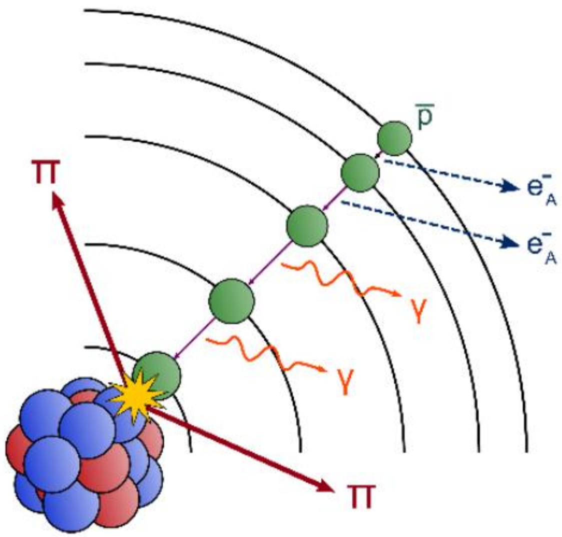
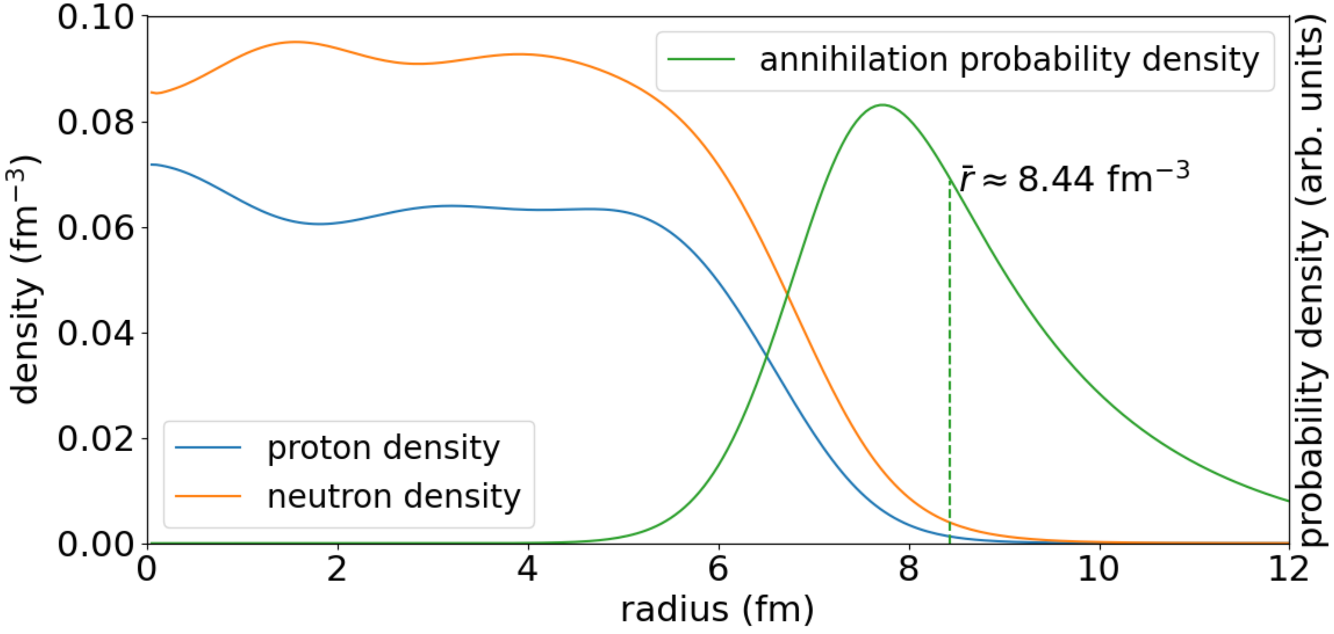


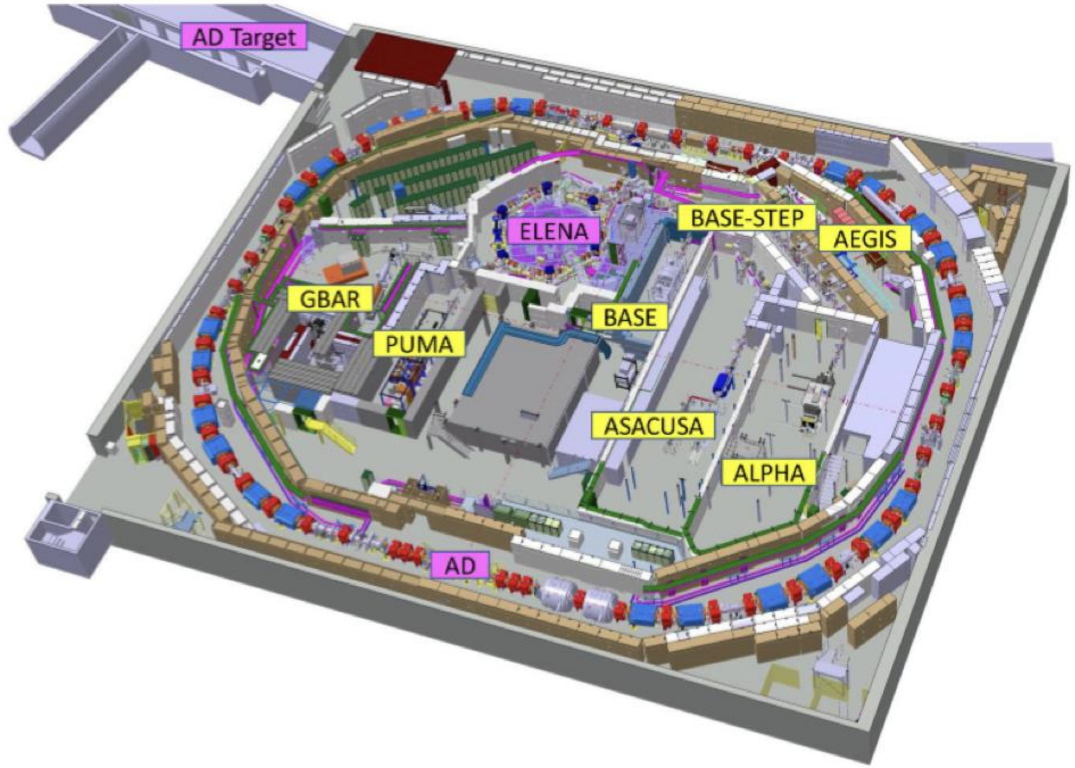


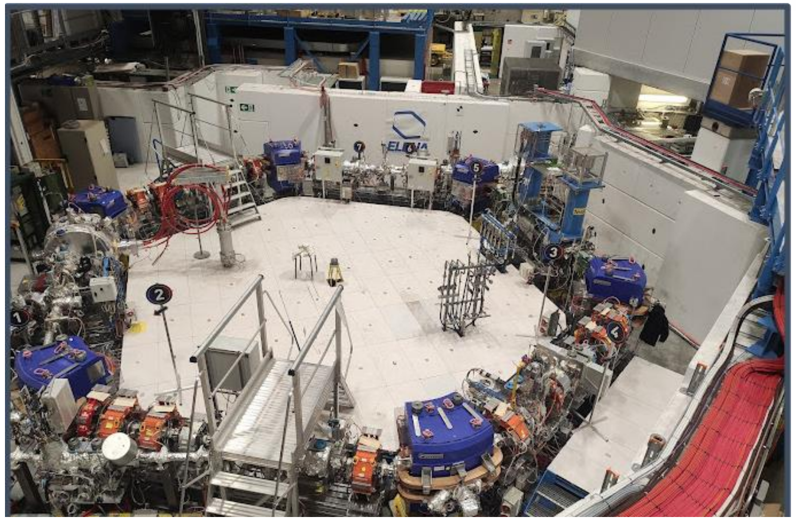
- $\bar{p}$ captured in antiprotonic orbital (~QED)
- then annihilate in tail $\rho_{n/p}(r)$ (QCD)
- Conservation of total charge

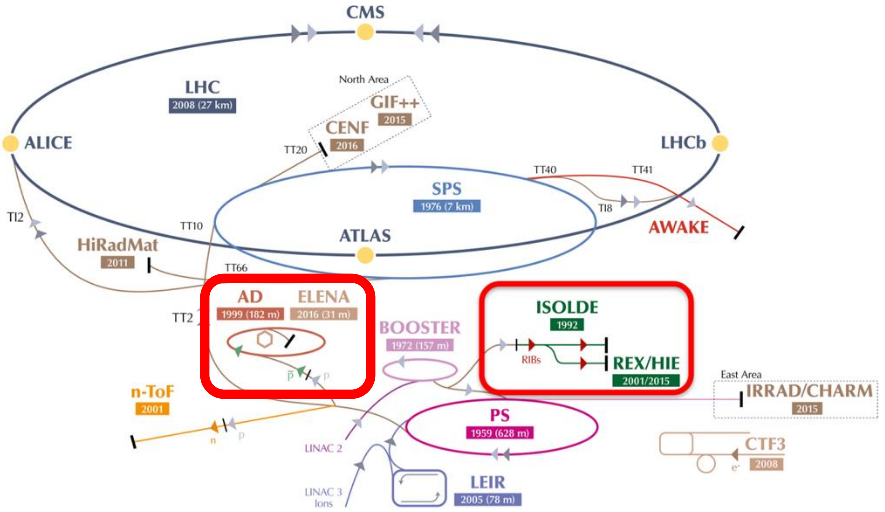
$$\sum_\pi q_\pi = \begin{cases} 0 \text{ for } \bar{p}p \\ -1 \text{ for } \bar{p}n \end{cases}$$

- First application of method: Bugg et al., PRL (1973)
- Application to rare isotopes first proposed by: Wada and Yamazaki, NIM B (2004)
- **Expected sensitivity: 10%,** dominated by FSI

THE ANTIMATTER FACTORY AT CERN

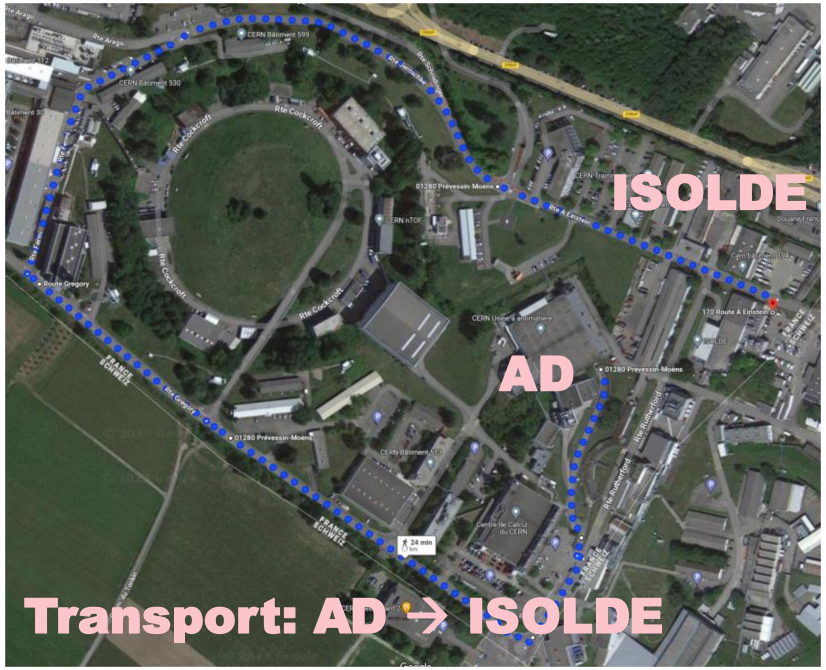


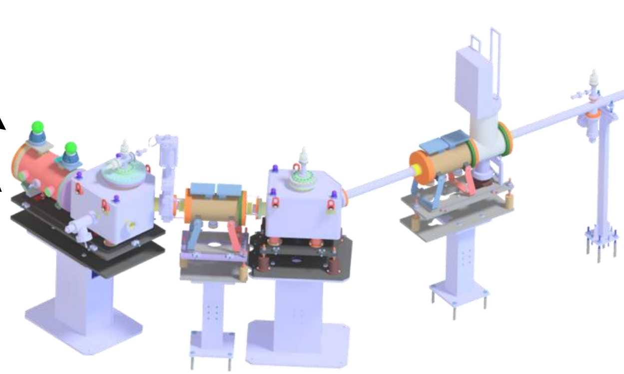
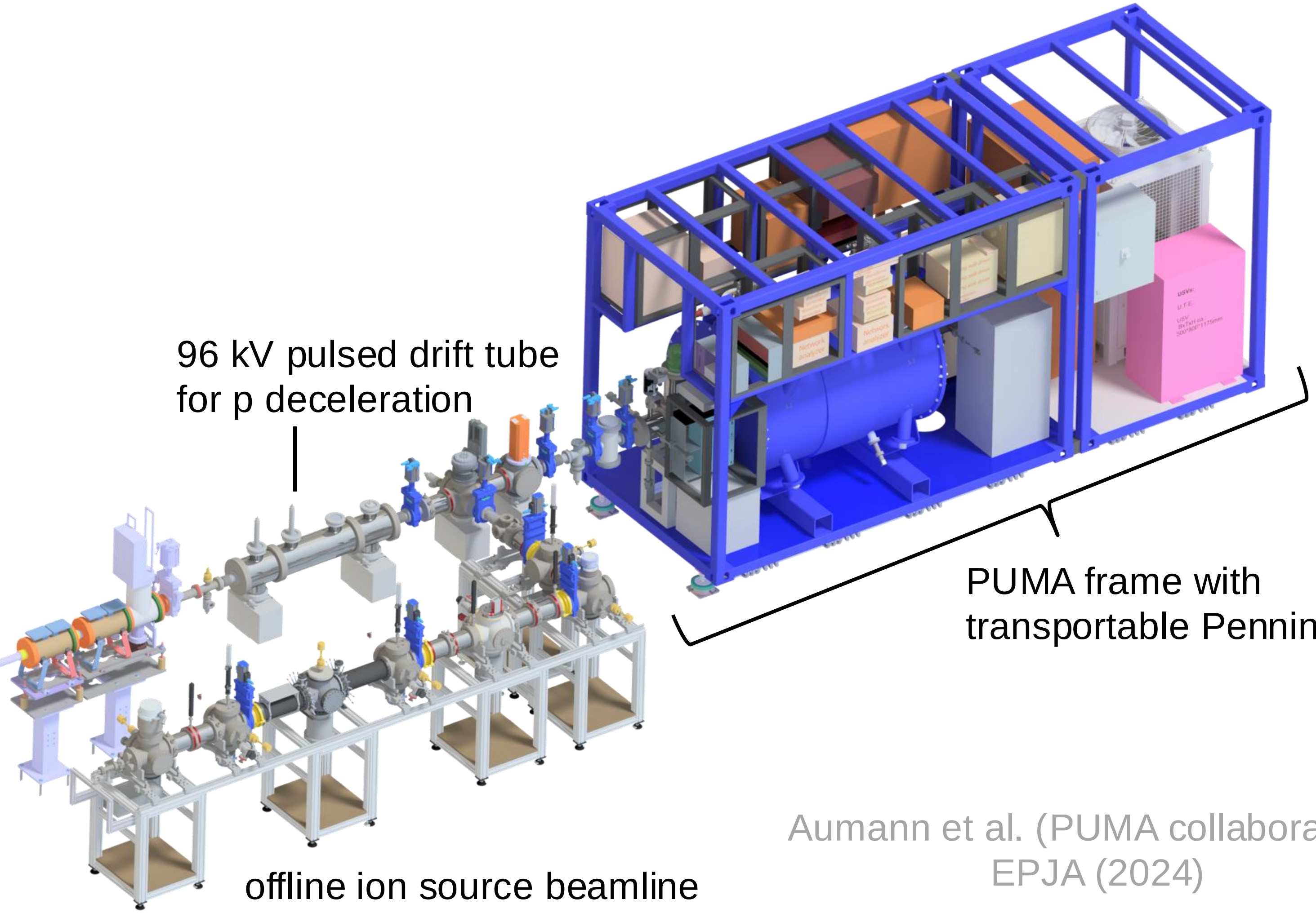




- 1.5 10^{13} protons at 26 GeV/c from PS
- 3. 10^{7} antiprotons at AD
- Deceleration: 5.3 MeV (AD), 100 keV (ELENA)
- Experiments: ~8. 10^{6} antiprotons every 110 s

THE PUMA EXPERIMENT



Aumann et al. (PUMA collaboration),
EPJA (2024)

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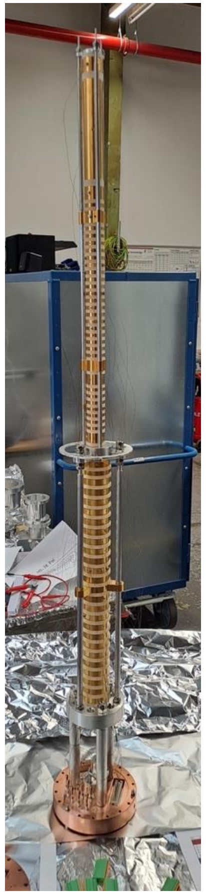
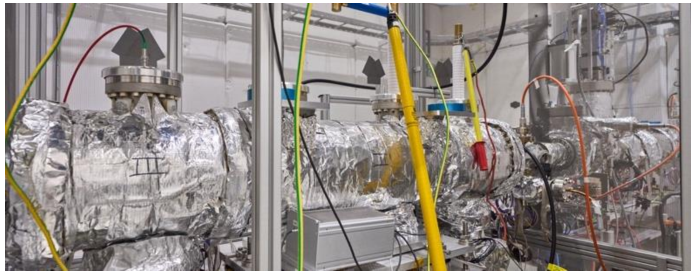
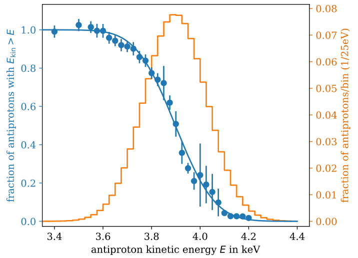
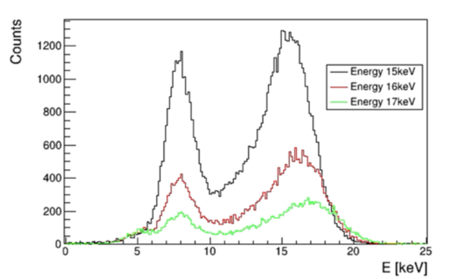
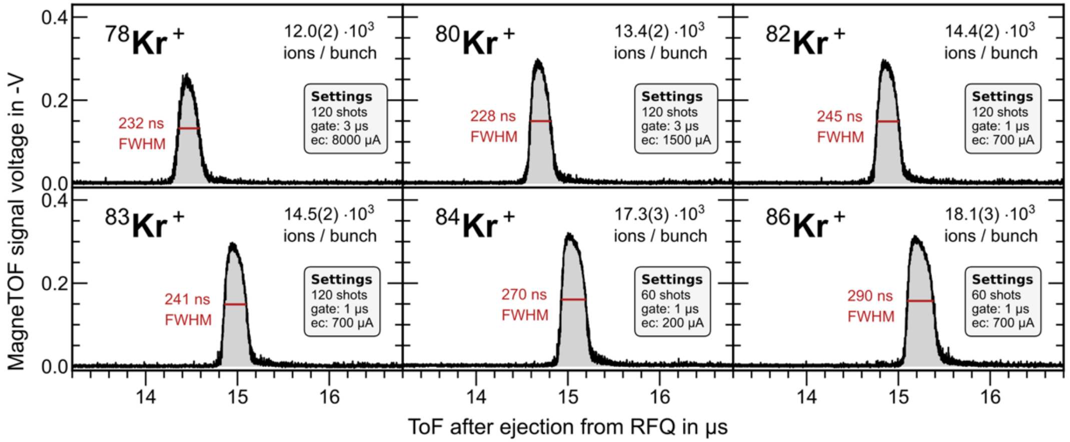
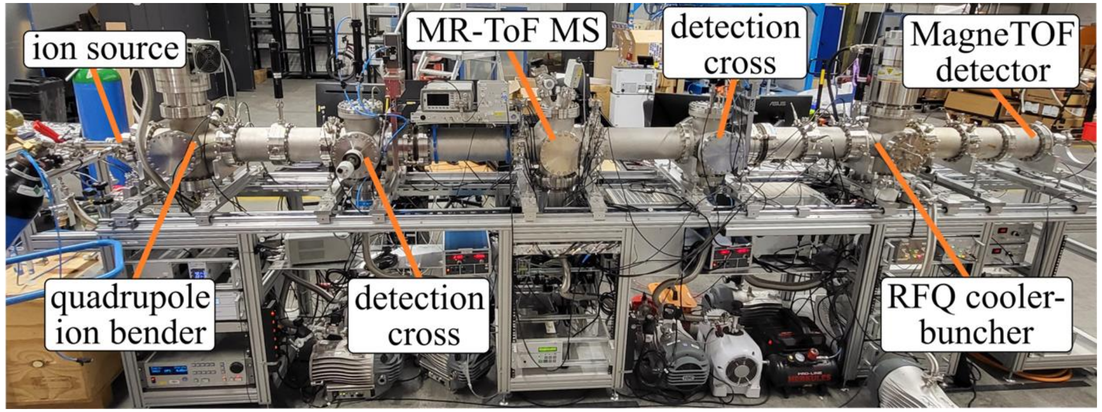








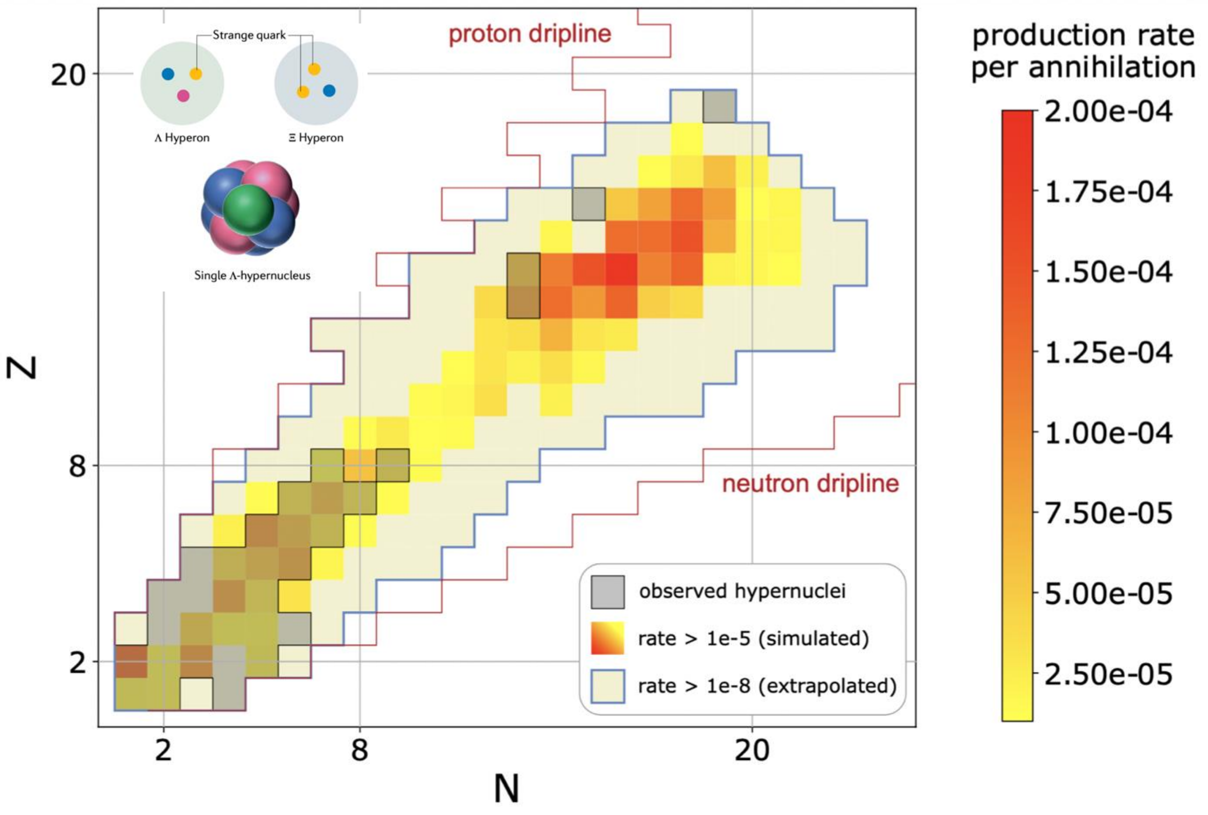




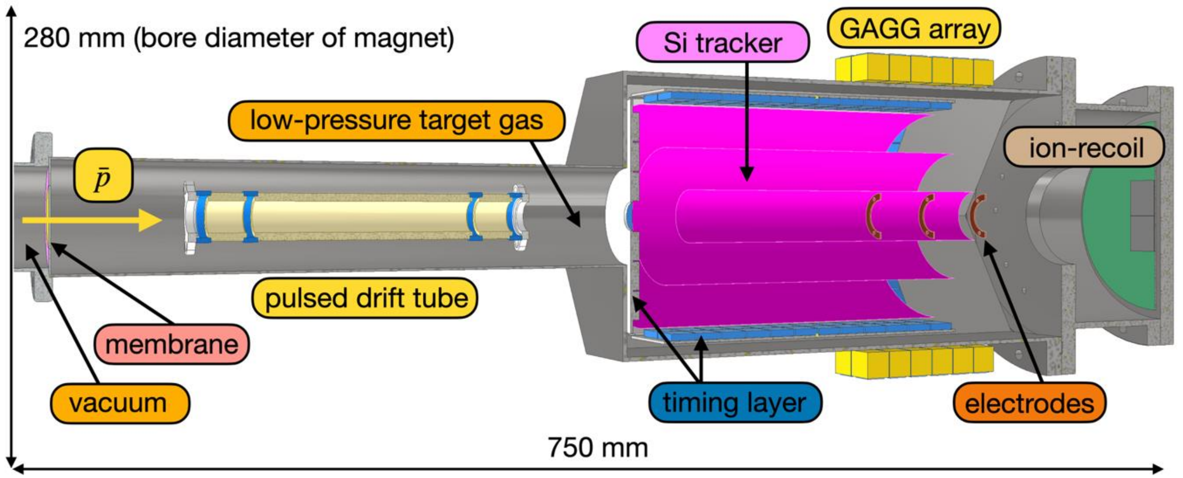
HYPERNUCLEI FROM ANTIPROTONS

- kaons in 3% of antiproton-nucleon annihilations
- 1% of annihilations lead to a hypernucleus

- **hypernuclei factory** at the Antimatter Factory
- proposal to SPSC
- relies on ALICE / ITS3 development



Schmidt et al., EPJA (2024)



SUMMARY

- **NN, YN interactions and EOS** are a focus of modern low-energy nuclear physics

- **Matter radii** of stable and unstable nuclei remain a challenge to measure

- **High precision cross sections** with radioactive beams at R3B, GSI/FAIR
  Glauber theory agrees within 3%, while below 1% is required

- Reactions may indicate **large matter radii in very neutron-rich isotopes**

- **Low-energy antiprotons** to probe the tail of the nuclear density distribution
  The **PUMA** experiment will start at CERN in 2025

- Captured antiprotons lead to **hypernuclei** in 1% of the annihilations
  Potential seed for a hypernuclei factory at CERN (proposal to be submitted)