Advances In Radioactive Isotope Sciences, Avignon, 8th of June 2023

Recent Nuclear Structure Studies at N=50 Through Masses of Isomeric States

Lukas Nies[1,2] ***for the ISOLTRAP Collaboration***

[1]CERN, Switzerland

[2]University of Greifswald, Germany

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

ISOL TRAP

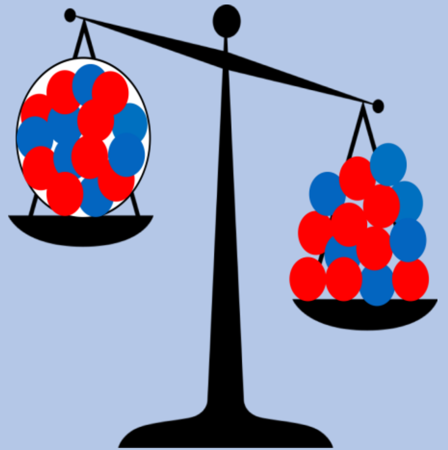
ISOLDE

CERN

ARIS 2023

Atomic physics methods probe nuclear properties

Nuclear Binding Energy



$$M_{atom}(Z,N) = M_{nuc}(Z,N) + Zm_e - B_e(Z)$$

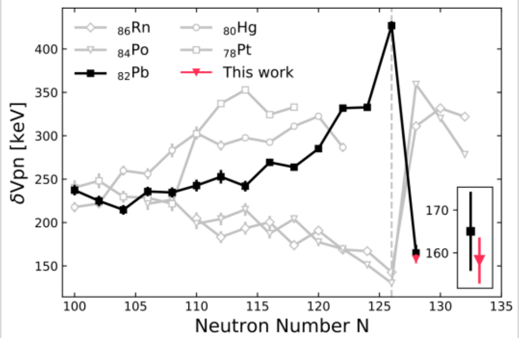
$$M_{nuc}(Z,N) = Zm_p + Nm_n + \frac{E(Z,N)}{c^2}$$

Nuclear Structure

"Mass filters"

Shell model, *ab initio*, etc.

Many-body interactions

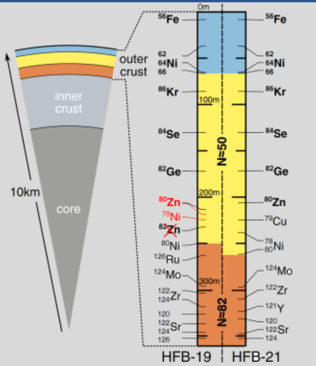


Nuclear Astrophysics

Nucleosynthesis

Light curves

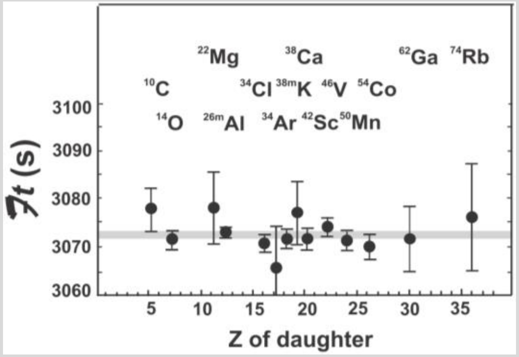
Neutron star compositions



Weak Interaction Physics

Unitarity of CKM Matrix

ν_e mass searches



T. Day Goodacre et al., PRC **104**, 054322 (2021)
R. N. Wolf *et al*., PRL **110**, 041101 (2013)
J. C. Hardy and I. S. Towner, PRC **102**, 045501 (2020)

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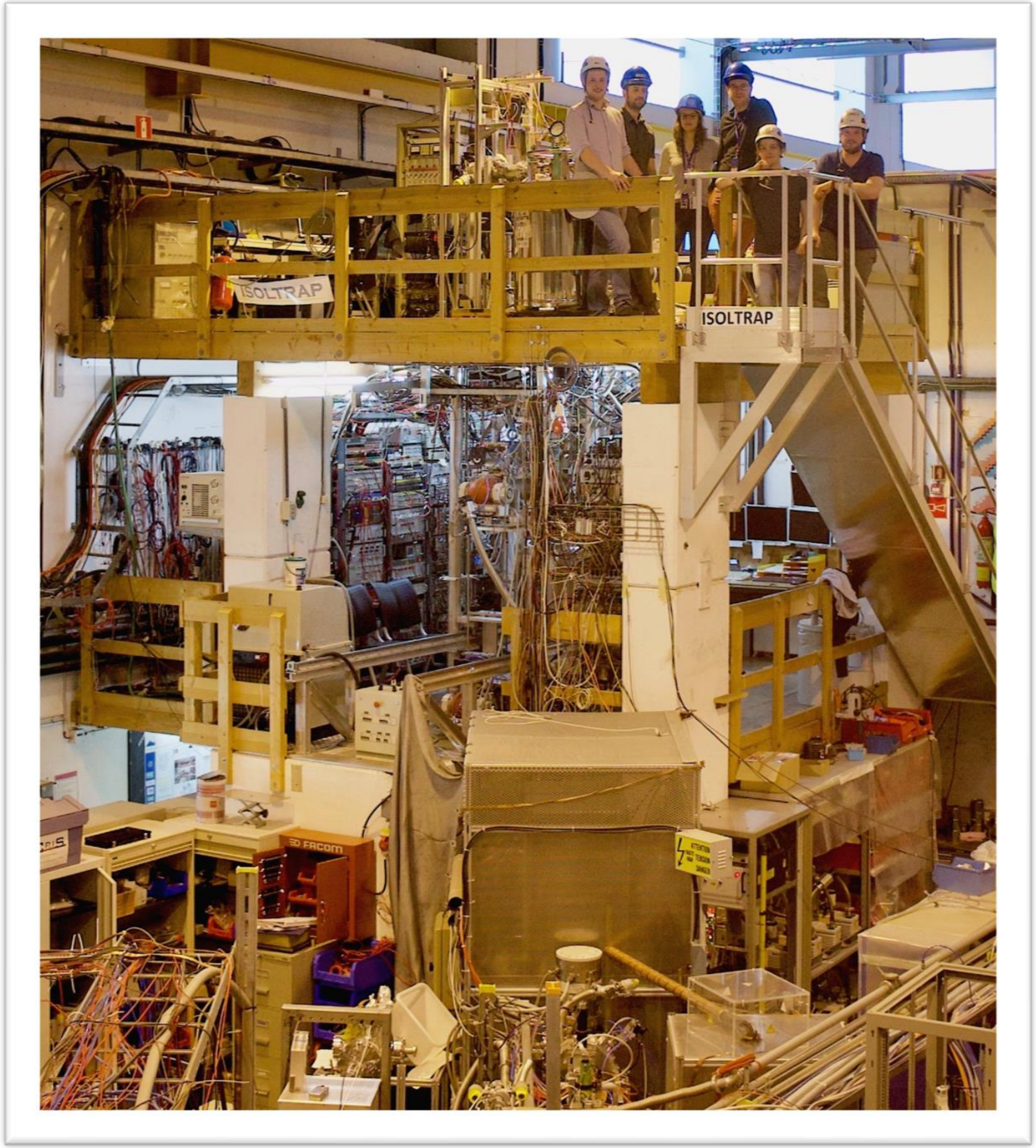
ISOLTRAP at CERN/ISOLDE

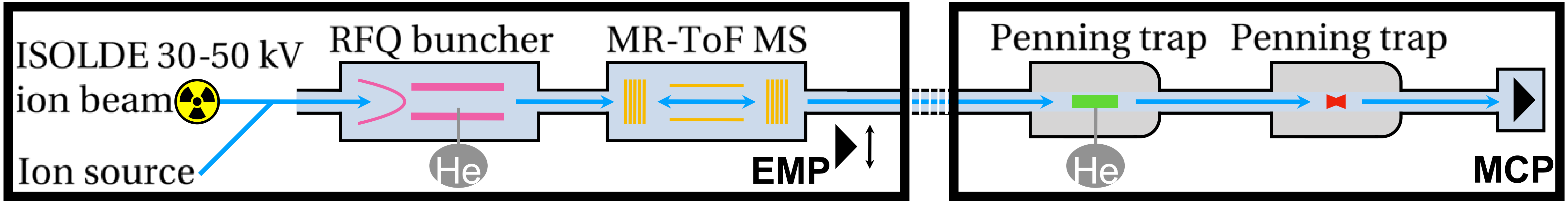
NUCLEAR STRUCTURE OF ^{99}In

SHAPE COEXISTENCE NEAR ^{78}Ni

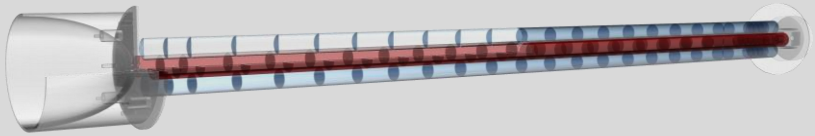


ISOLTRAP Mass Spectrometer

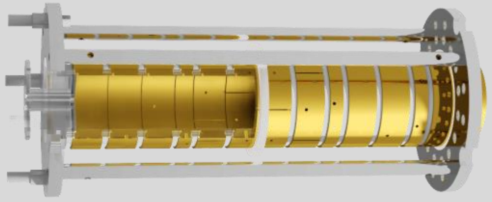
Horizontal section *Vertical section*



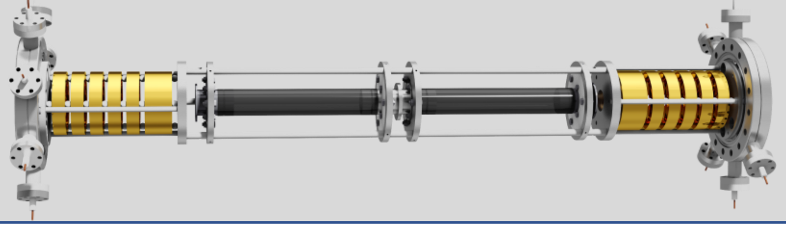
Linear Paul Trap Cooling and Bunching



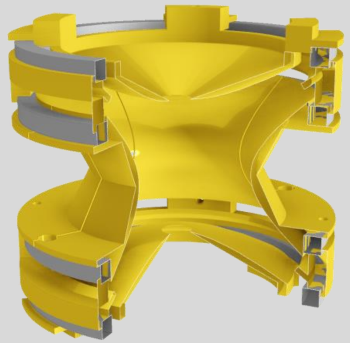
Preparation Penning Trap
Beam preparation and purification



Multi-Reflection Time-of-Flight Mass Spectrometer
Mass separation and mass measurements



Precision Penning Trap
Mass measurements



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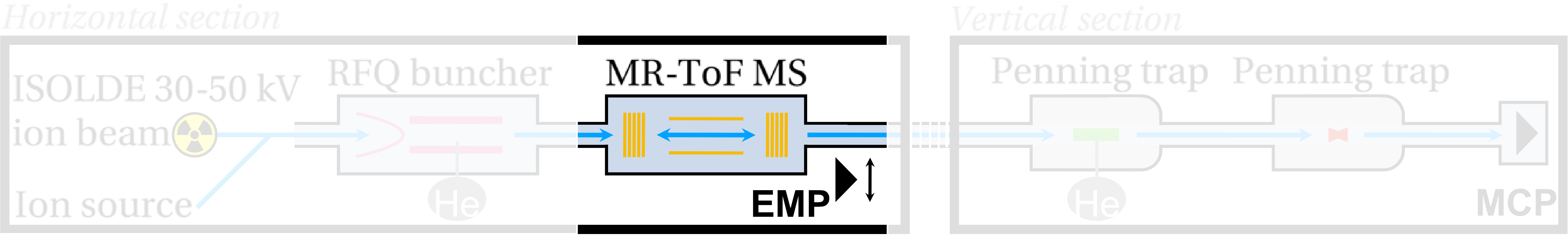
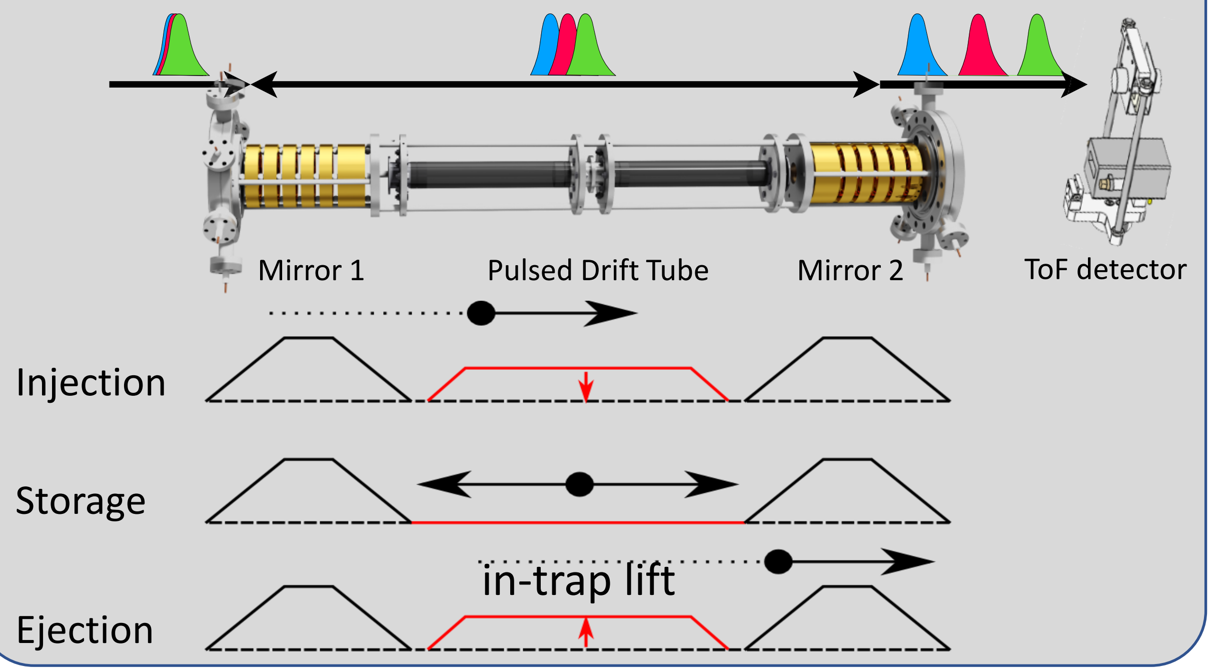
Multi-Reflection Time-of-Flight Device

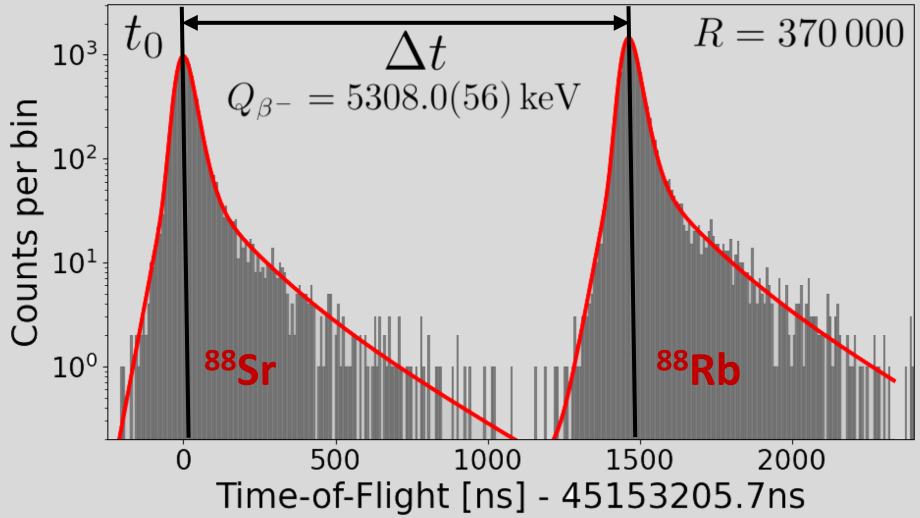


Multi-Reflection Time-of-Flight Mass Spectrometer



$$t_0 = A\sqrt{\frac{m_0}{q}}B$$

$$E = \left[\left(\frac{\Delta t}{t_0}\right)^2 + 2\frac{\Delta t}{t_0}\right] m_0c^2 \approx 2\frac{\Delta t}{t_0}m_0c^2$$



Wolf *et al.*, IJMS 313, 8 (2012)

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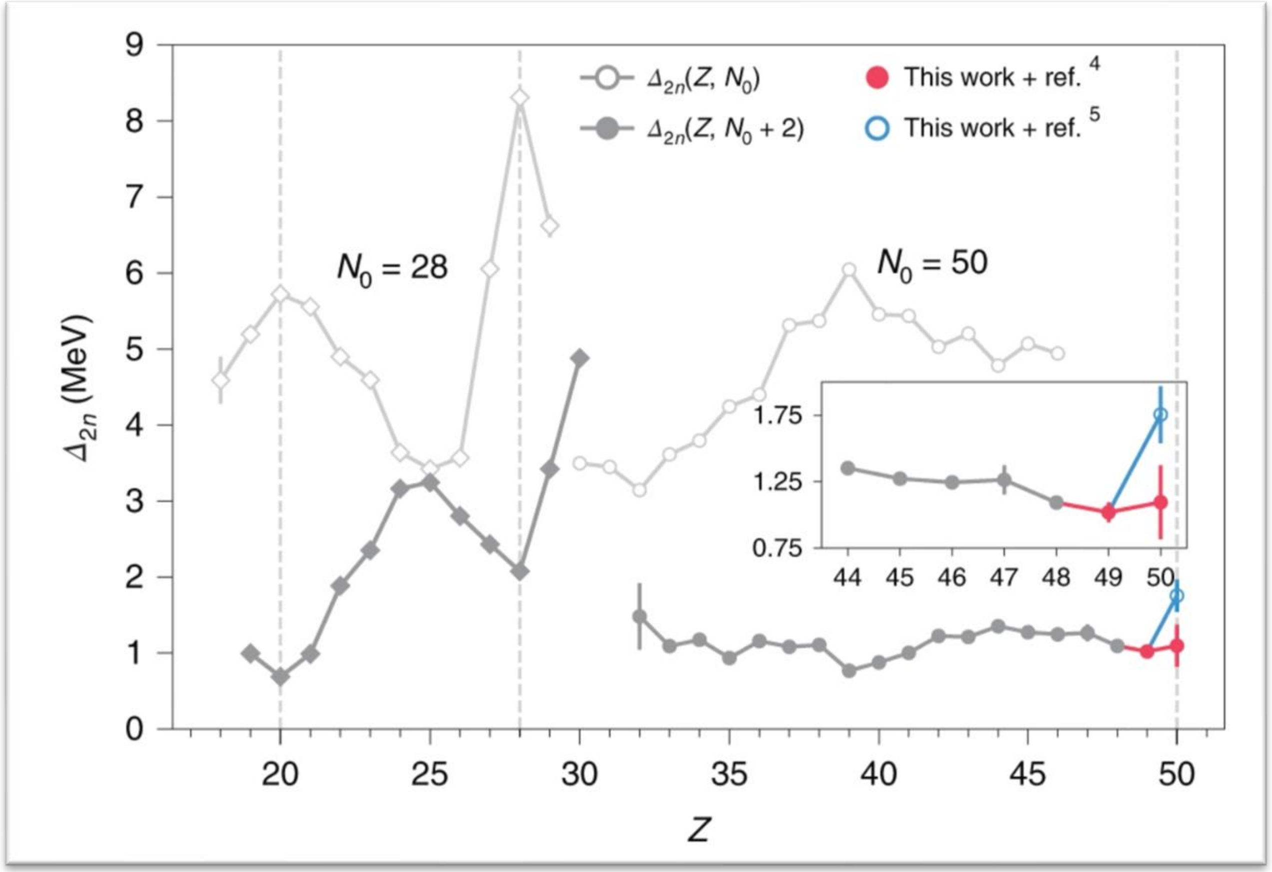
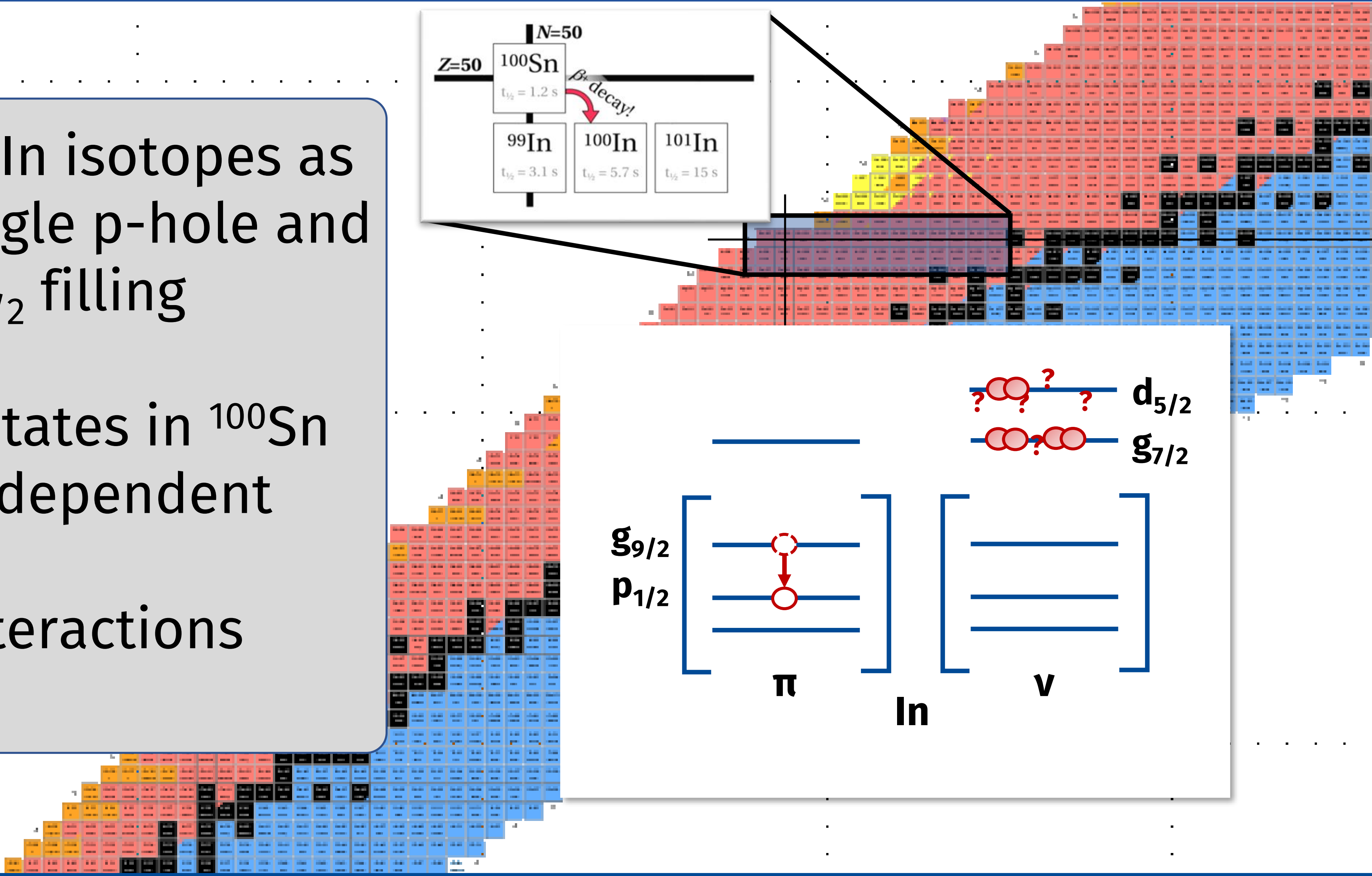


Mougeot *et al.*, *Nature Physics* **17**, p. 1099–1103 (2021)

Excitation energy systematics down to N=50

Neutron deficient In isotopes as ^{100}**Sn** core with single p-hole and gradual $\nu g_{7/2}$ - $\nu d_{5/2}$ filling

- single-particle states in ^{100}Sn
- core-excitation dependent energy shifts
- particle-hole interactions



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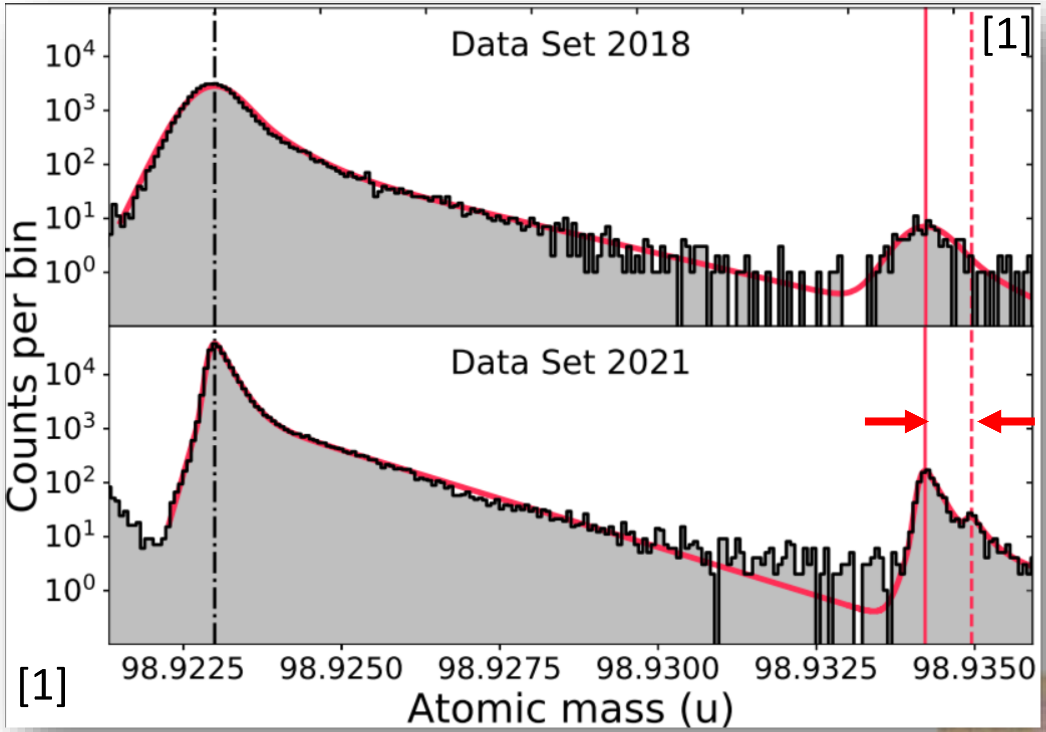
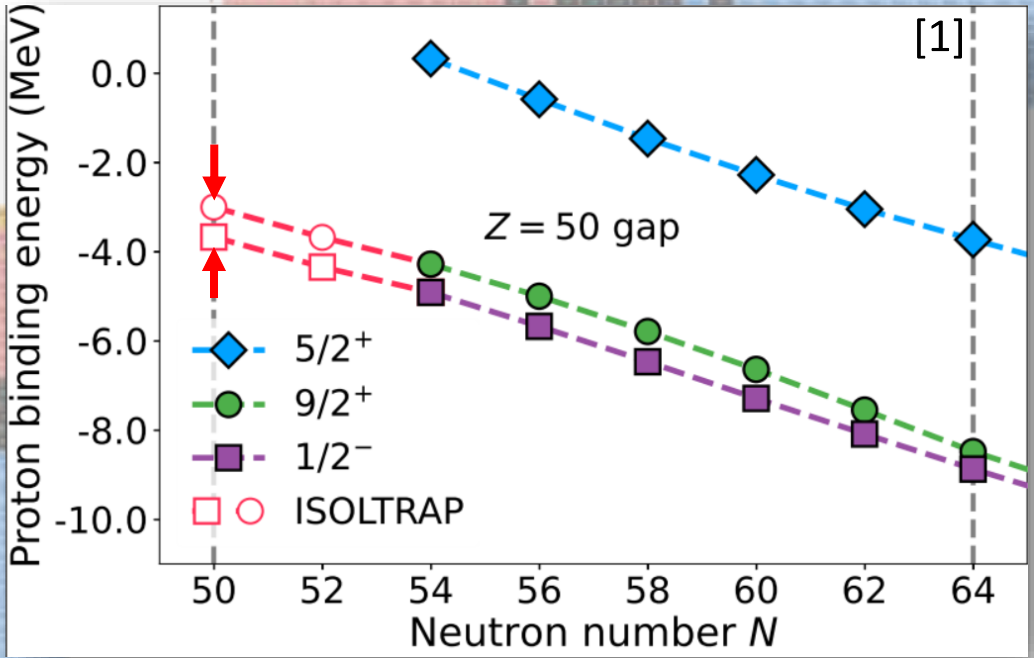


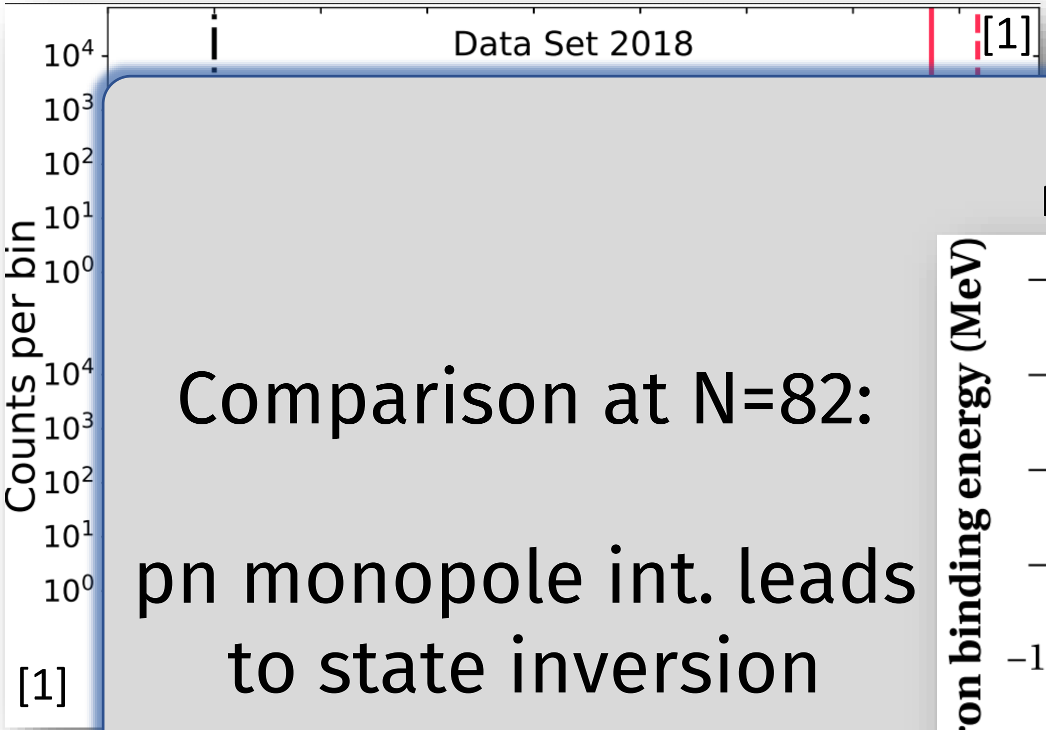
First direct measurement of $^{99m,gs}In$ [1]

Most sensitive experiment at ISOLTRAP yet (~ 10^{-1}/s)



Excitation energy constant over many mass numbers

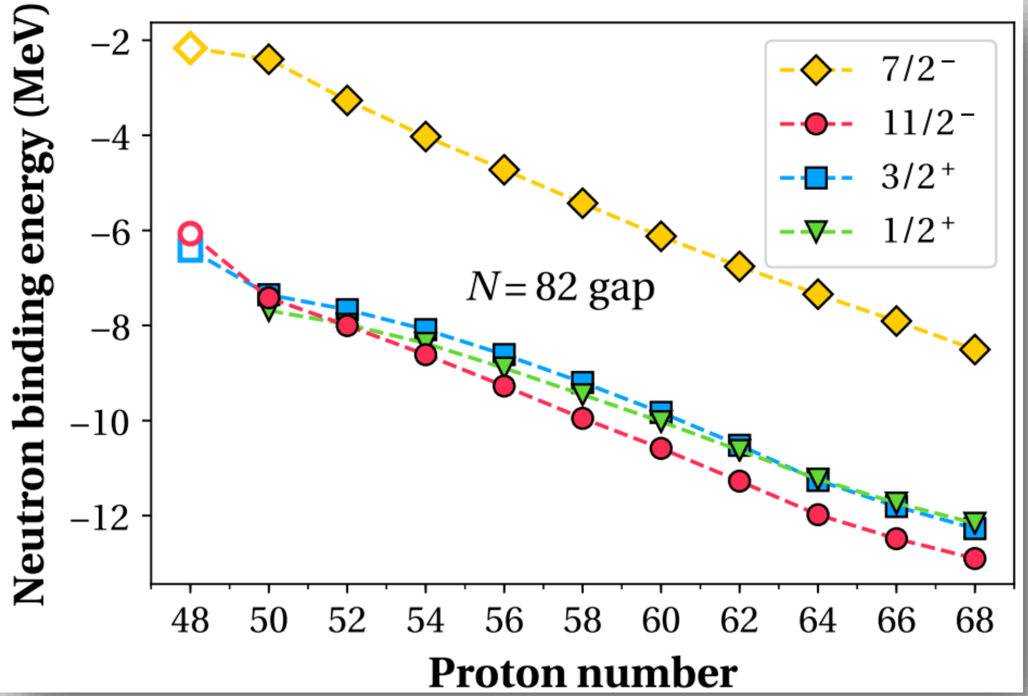
Excitation energy systematics down to N=50



Comparison at N=82:

pn monopole int. leads to state inversion

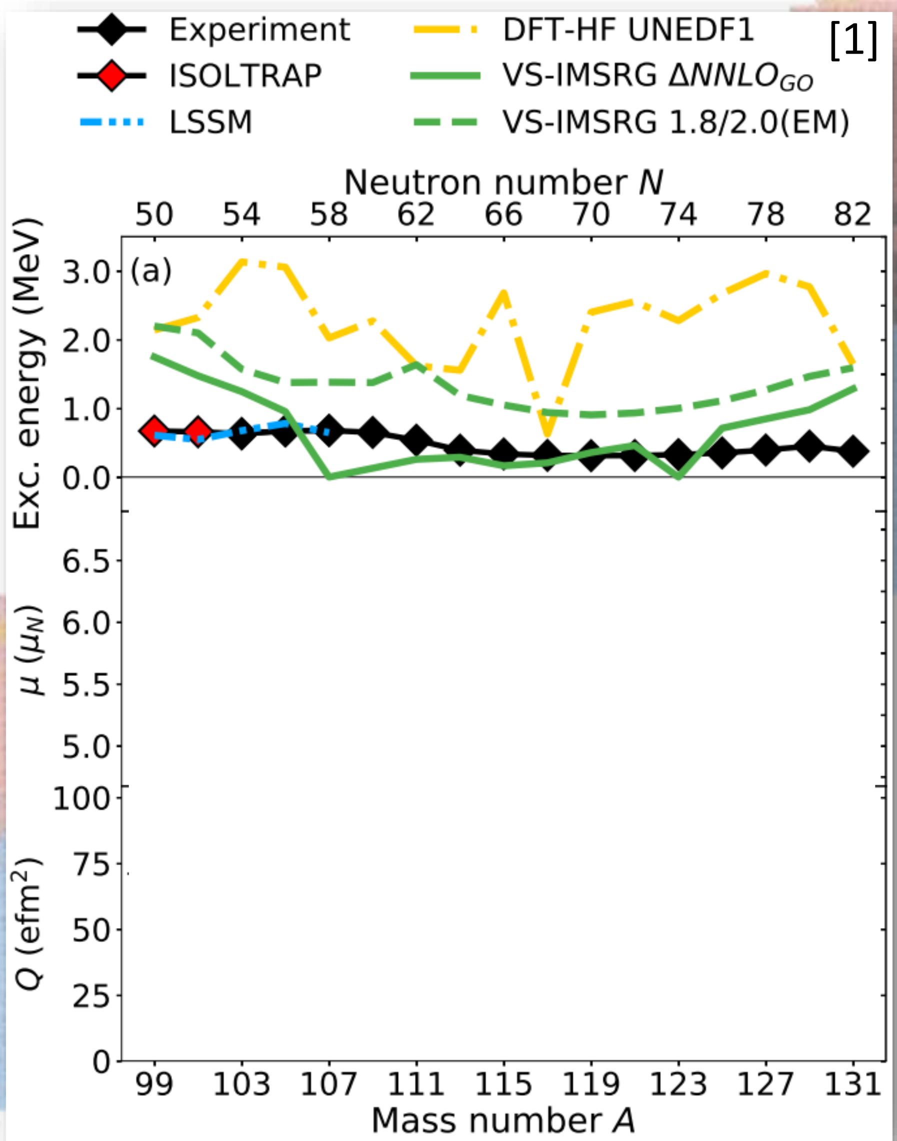
Manea, Karthein et al., PRL **124**, 092502 (2020)



Excitation energy systematics down to N=50

- **LSSM**
  - core-exc. leads to more accurate trend
- ***ab-initio***
  - monopole int. between proton hole and gradual neutron filling in $g_{7/2}$-$d_{5/2}$ orbits important
  - very little variation between N=50 and N=82
- **DFT-HF**
  - Validation of calculations with recent moment measurements from [2]
  - Exc. energy depends directly on spin-orbit interaction

How will magnetic moments evolve towards N=50?



[1] L. Nies et al., PRL. in press, arXiv:2306.02033
[2] A. Vernon et al, Nature **607**, 260-265 (2022)

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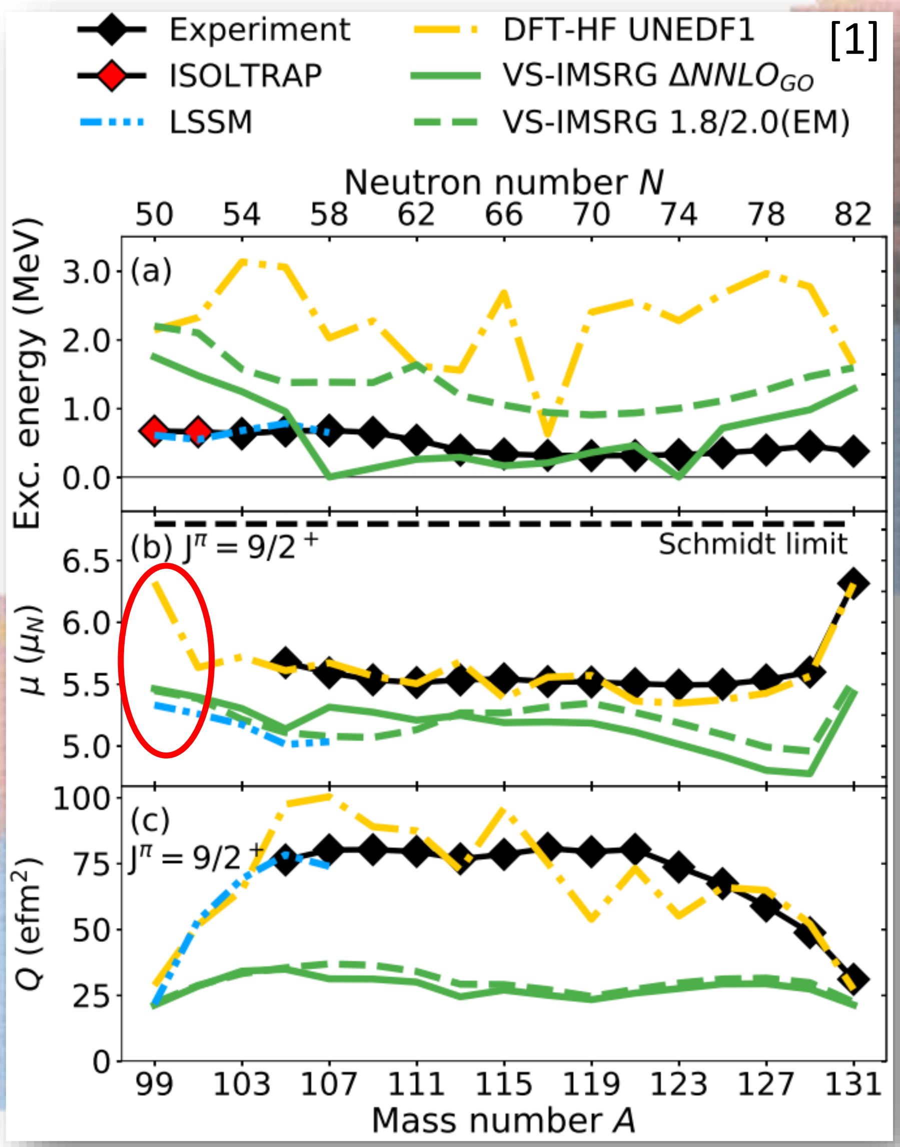
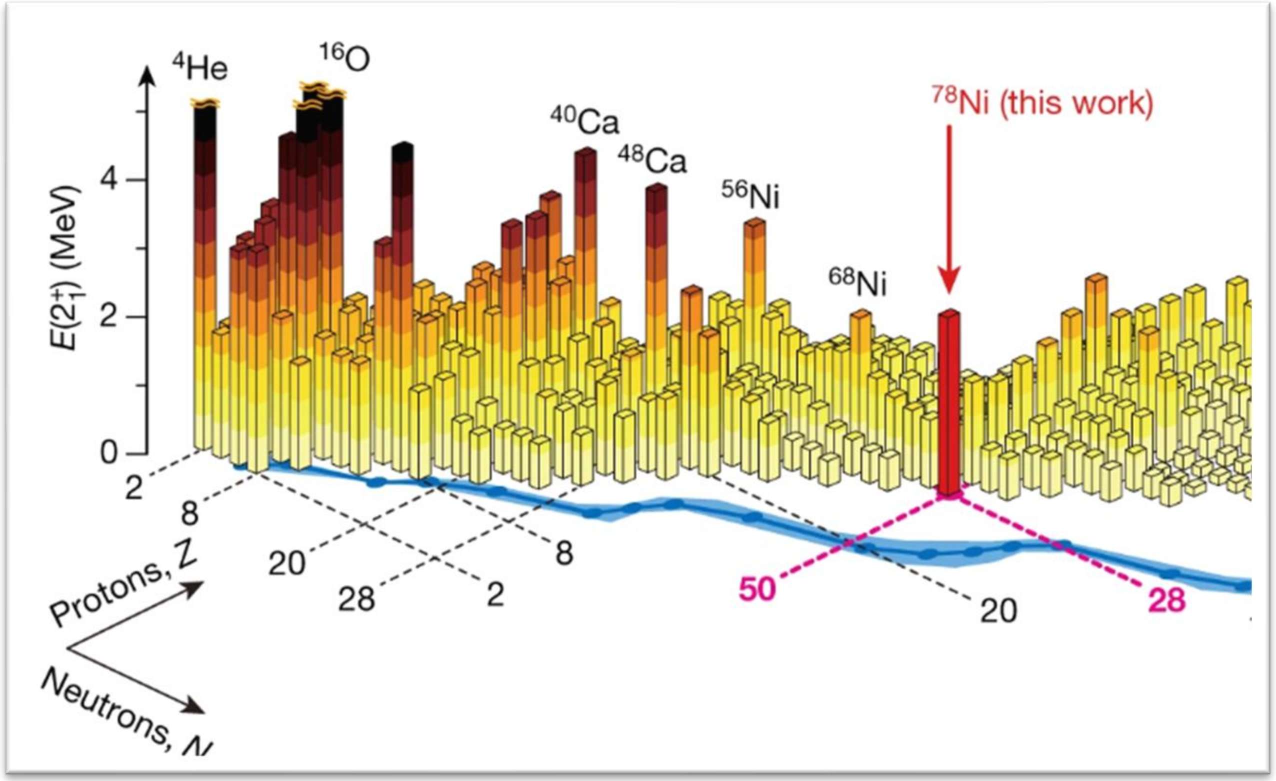


ISOLTRAP at CERN/ISOLDE

NUCLEAR STRUCTURE OF 99In

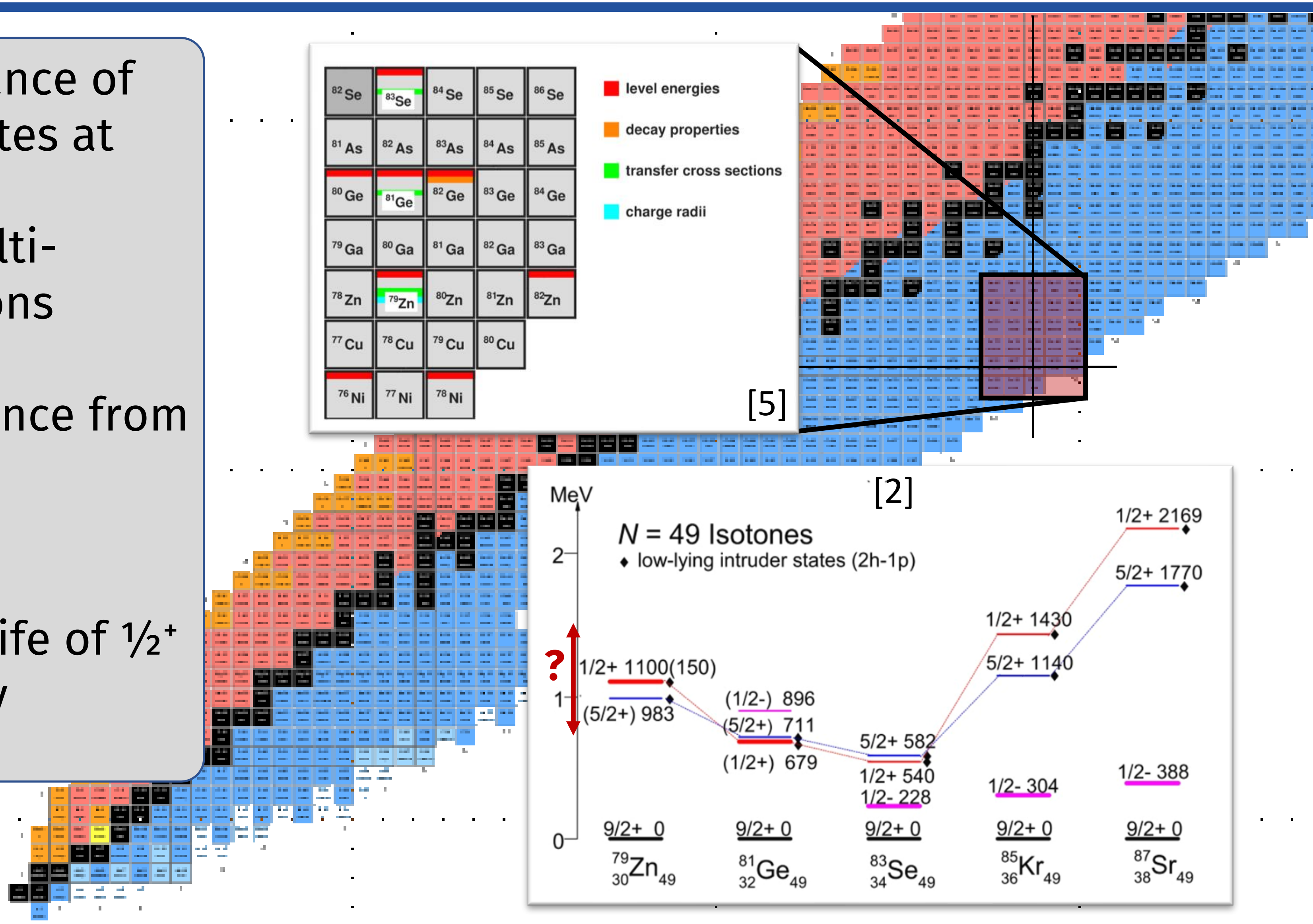
SHAPE COEXISTENCE NEAR ^{78}Ni



Taniuchi *et al.*, *Nature* **569**, p.53–58 (2019)

Evidence for shape coexistence near ^{78}Ni

- Shape coexistence: appearance of spherical and deformed states at similar excitation energies
- Intruder configurations: multi-particle multi-hole excitations across closed shells
- Evidence for shape coexistence from
  - decay spectroscopy [1]
  - laser spectroscopy [2,3]
  - mass measurements [4]
- Excitation energy and half-life of ½$^+$ state in ^{79m}Zn only indirectly measured

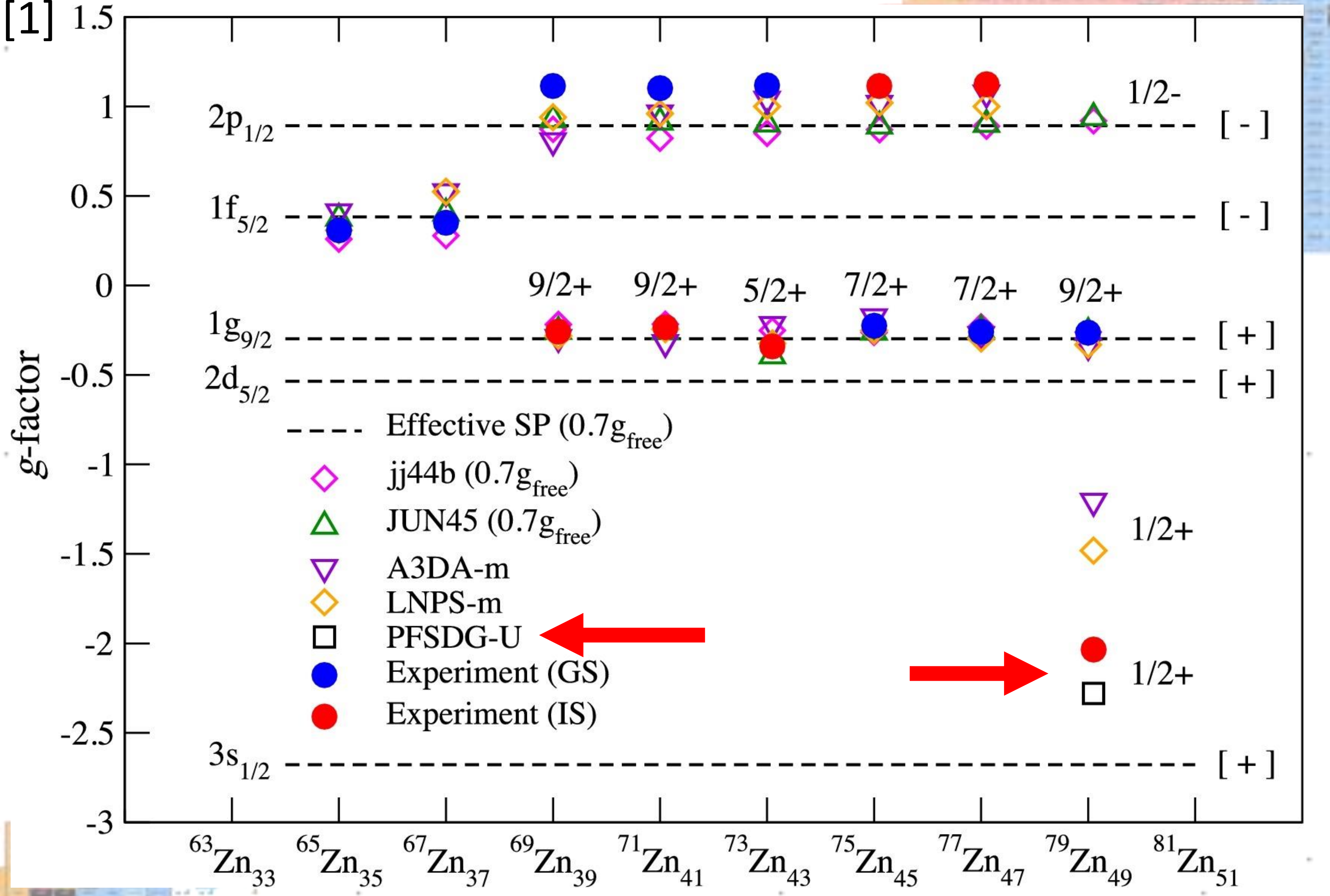


[1] Gottardo et al., PRL **116,** 18201 (2016)
[2] Yang et al, PRL **116**, 182502 (2016)
[3] Wraith et al., PLB **771** (2017) 385-391
[4] Welker et al., PRL **119** 192502 (2017)
[5] Garrett, Zielinska, Clément, PPNP **124** (2022) 103931

PFSDG-U for accurate observables at N=49

- g-factors of both states well produced for N<49
- At N=49, 1p-2h has 40% neutron occupancy
  - -> larger valence space
  - -> more accurate g-factor (PFSDG-U interaction [2])

[1]



[1] Wraith et al, PLB **771** (2017) 385-391
[2] Nowacki et al, PRL **117**, 272501 (2016)
[3] Nies, Dao, Kankainen, Lunney, Nowacki et al., in preparation

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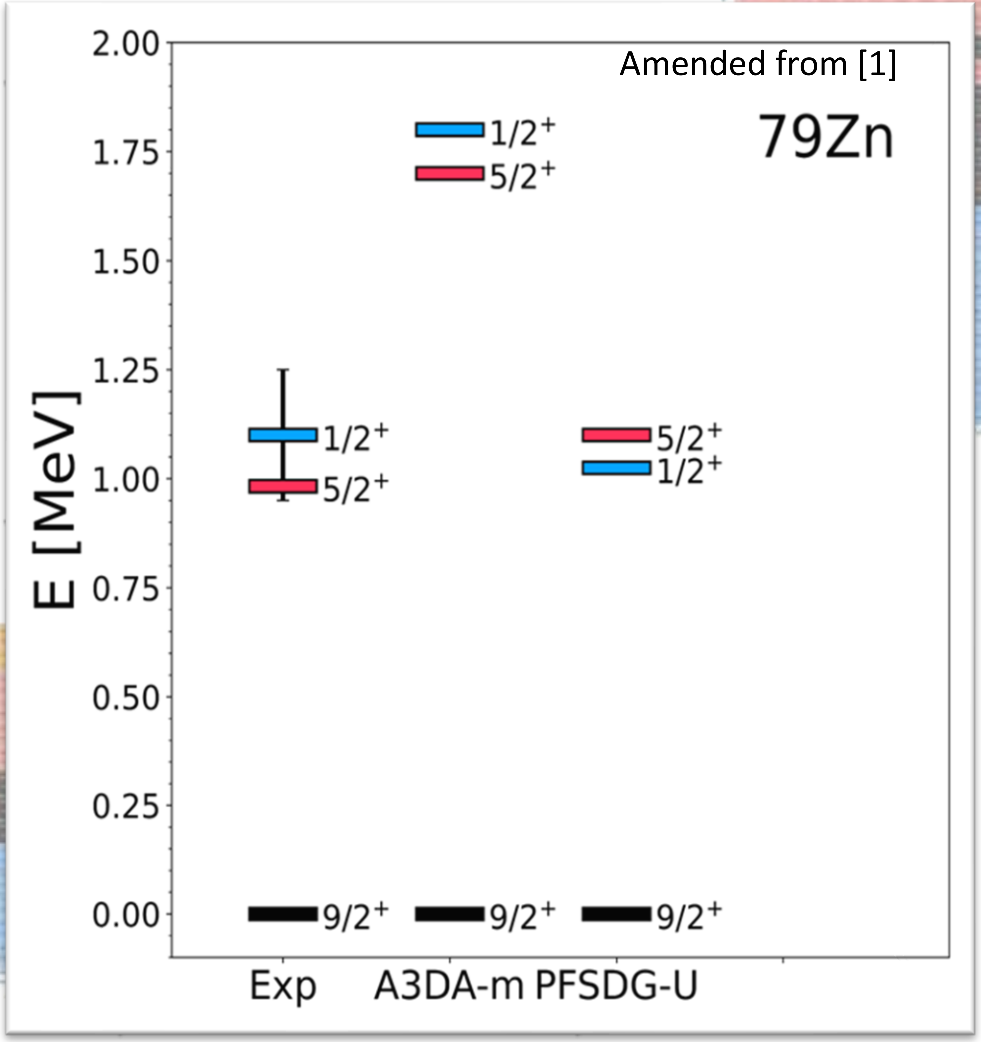

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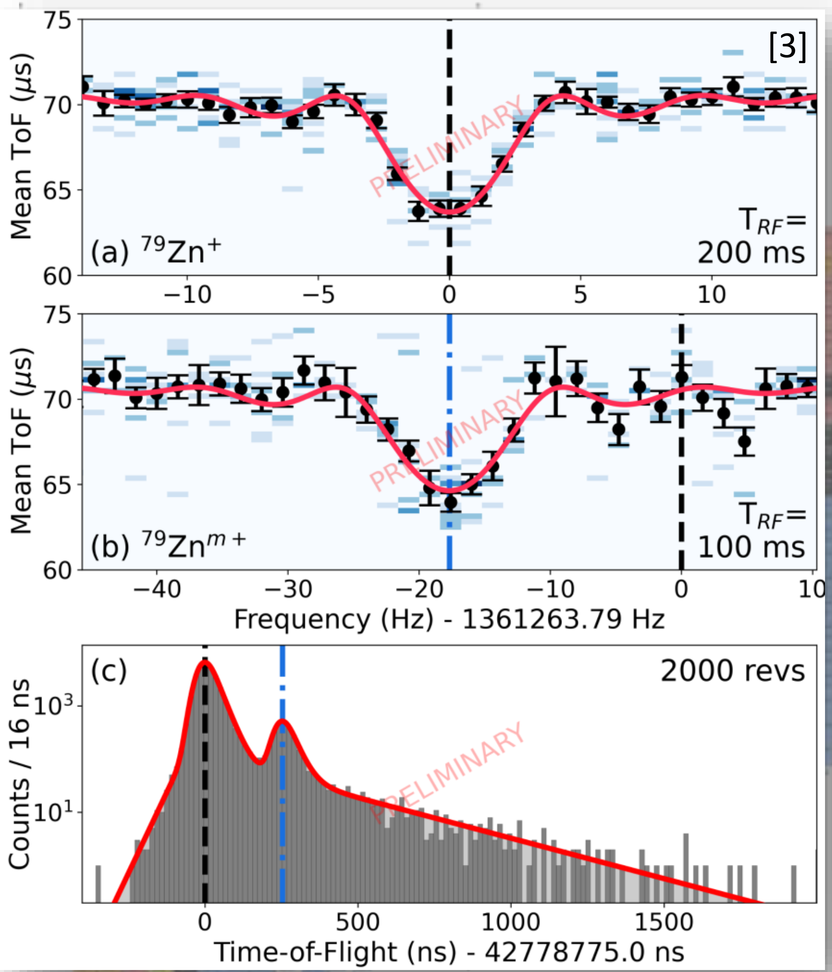

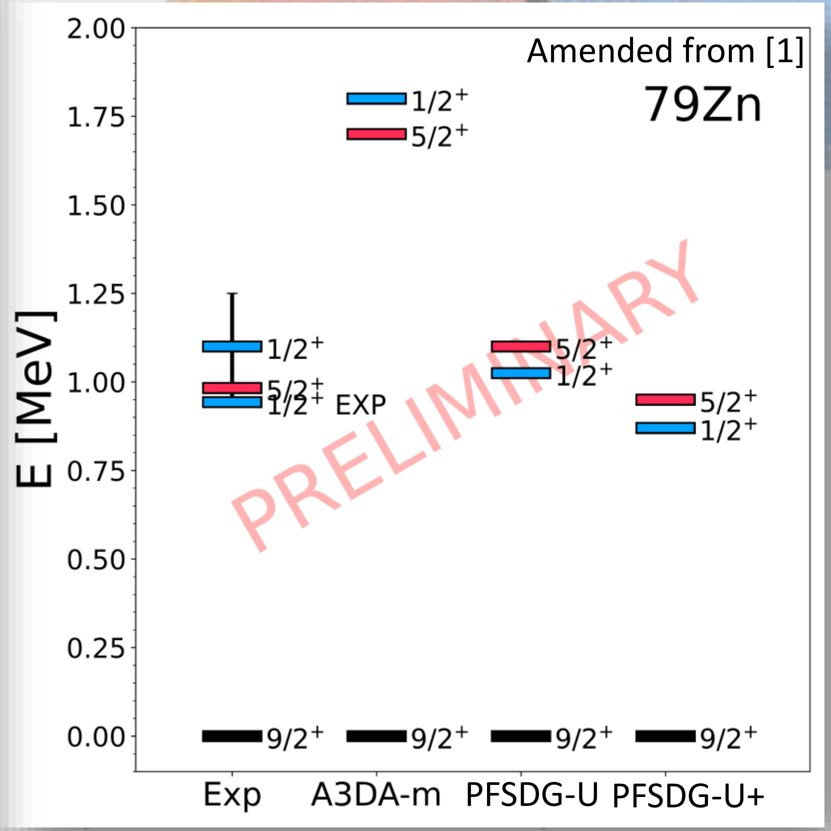

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DNO expansion of SM wave functions

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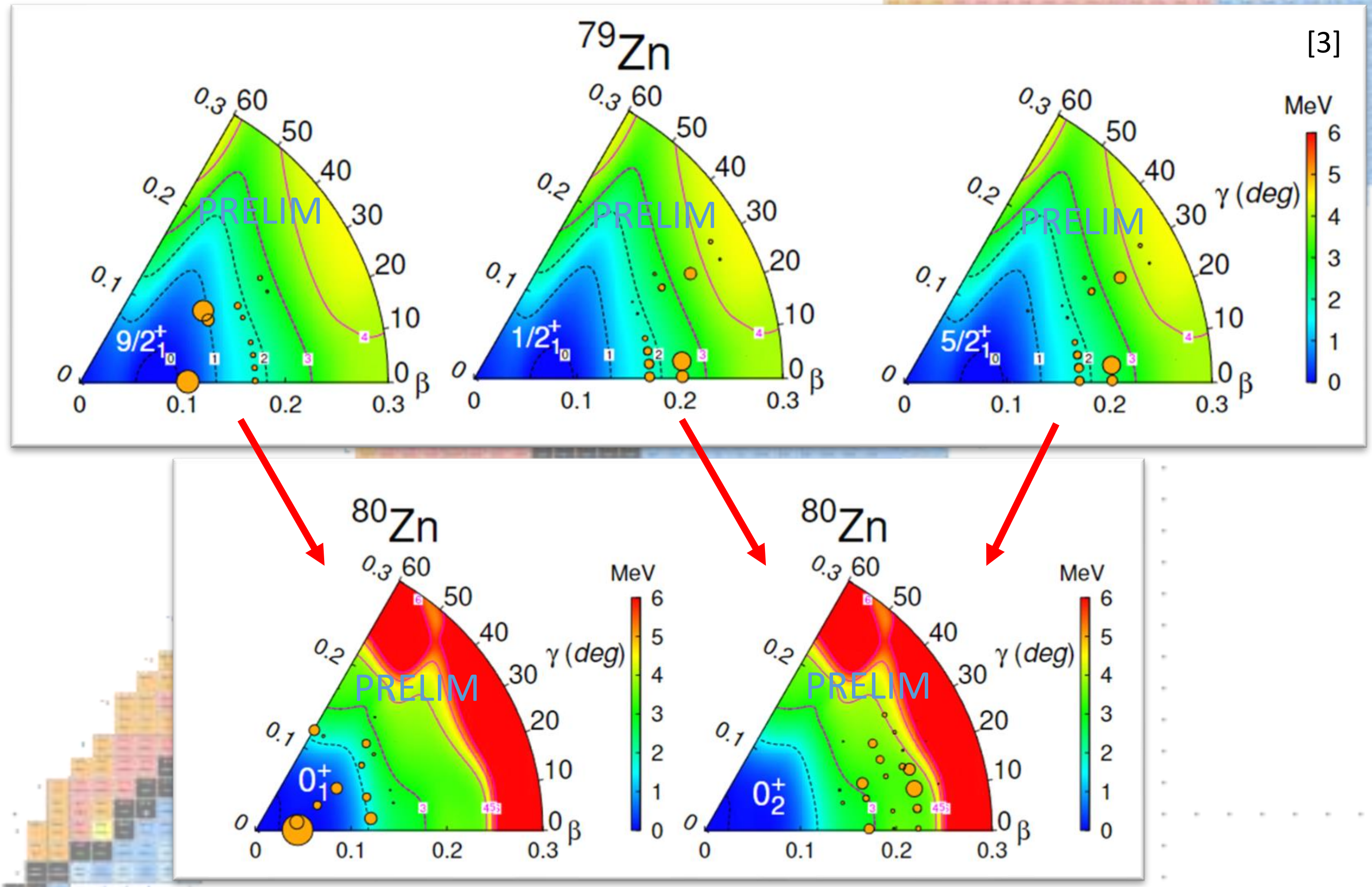

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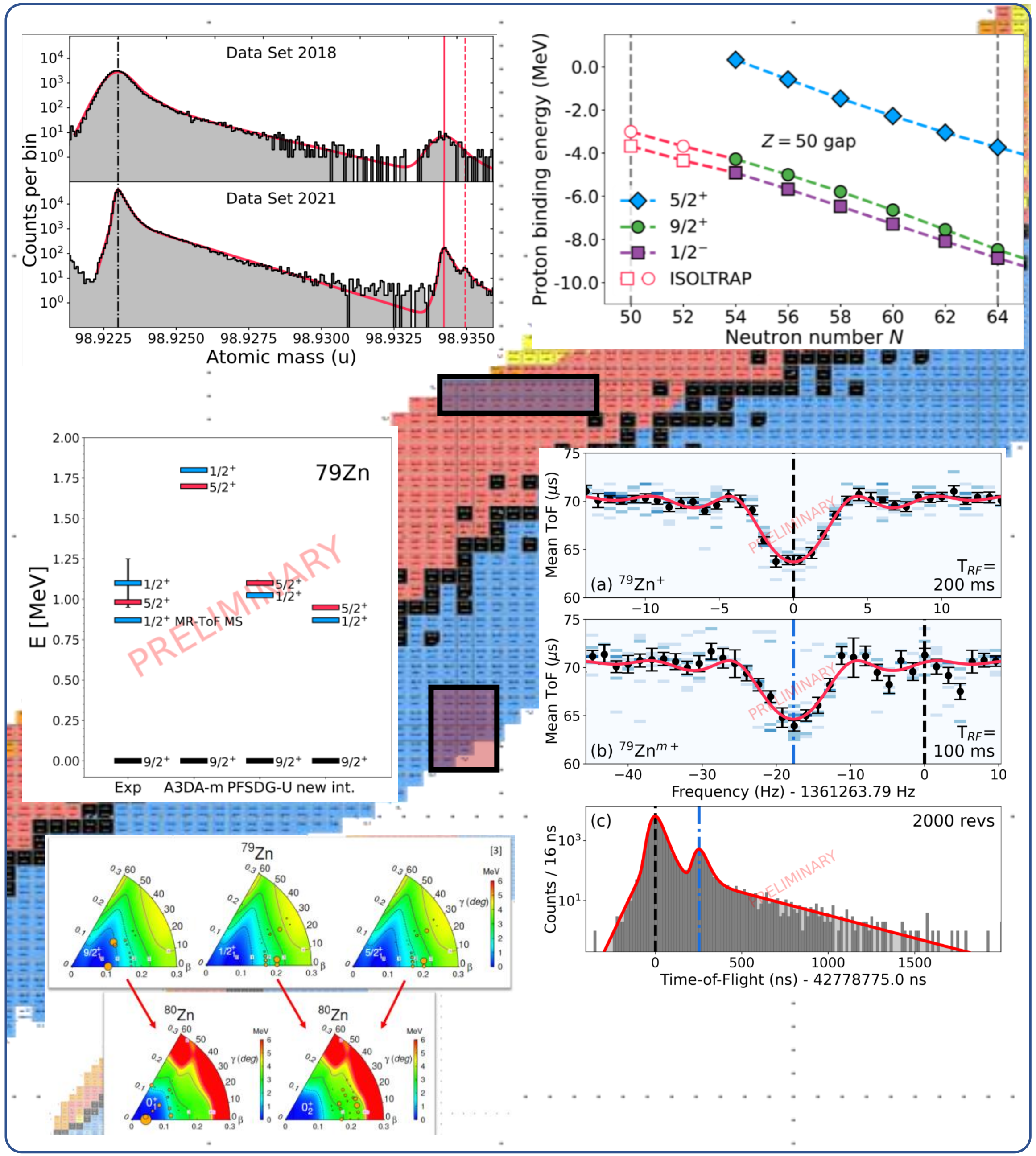
[2] Nowacki et al, PRL **117** 272501 (2016)
[3] Nies, Dao, Kankainen, Lunney, Nowacki et al., in preparation
[4] Dao, Nowacki PRC **105** 054314 (2022)

Summary

- Indium campaigns 2018 and 2021 highly successfull, **first-time measurement of ^{99m}In**
- Nuclear theory calculations challenged through **^{99m}In and ^{101m}In,** revealing constant excitation energy behavior across N=50
- Direct excitation energy measurement of intruder ½⁺ isomeric state in **^{79}Zn** validates **PFSDG-U** interaction and DNO-SM expansion reinforces evidence for **shape coexistence in ^{78}Ni region**



D. Atanasov, K. Blaum,
J. Karthein, **D. Lange**,
Yu. Litvinov,
D. Lunney, V. Manea,
M. Mougeot, L. Nies,
Ch. Schweiger,
L. Schweikhard, F. Wienholtz, *et al.*

Max-Planck-Institut für Kernphysik
IJCLab Irène Joliot-Curie
GSI
Universität Heidelberg Zukunft seit 1386
Universität Greifswald Wissen lockt. Seit 1456
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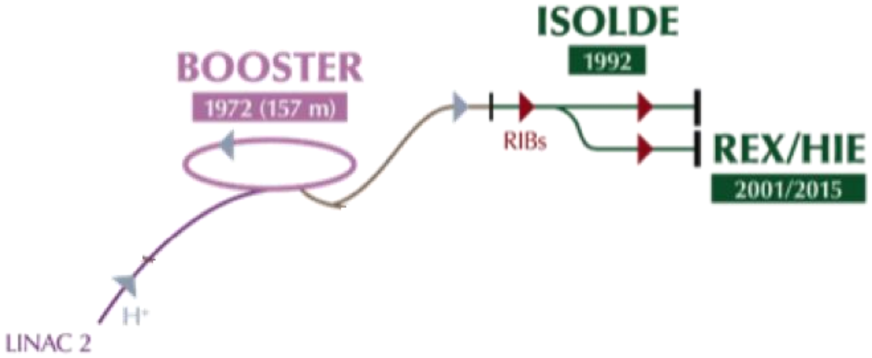
ISOLDE
CERN
Max-Planck-Gesellschaft
ENSAR
Federal Ministry of Education and Research
Grants No.: 05P15ODCIA 05P15HGCIA
CNRS IN2P3 Les deux infinis

2020

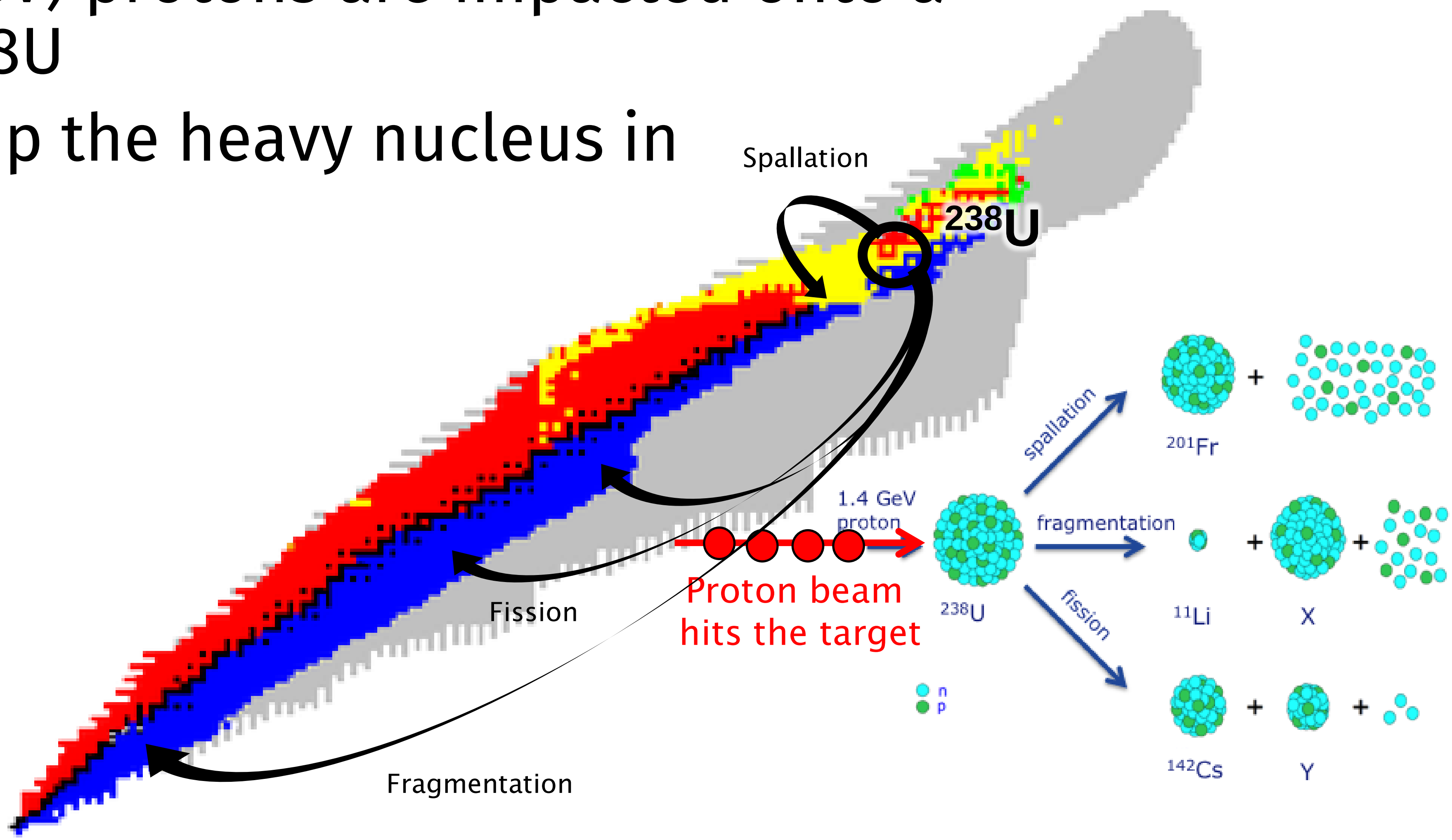
ISOLDE at CERN

- Isotope Separator OnLine DEvice
- Produces Radioactive Ion Beams (RIBs)
- Approved by the CERN council in 1964
  - Initially used 600 MeV protons from SC
  - Then used 1.0 GeV (later 1.4 GeV) protons from the PSB
- ~0.1% of the CERN budget
- ~7% of the CERN scientists
- ~50% of the CERN protons



Production: Modern-day alchemy

- High energy (1.4 GeV) protons are impacted onto a thick target e.g. 238U
- The protons split up the heavy nucleus in one of three ways
  - Fission
  - Fragmentation
  - Spallation



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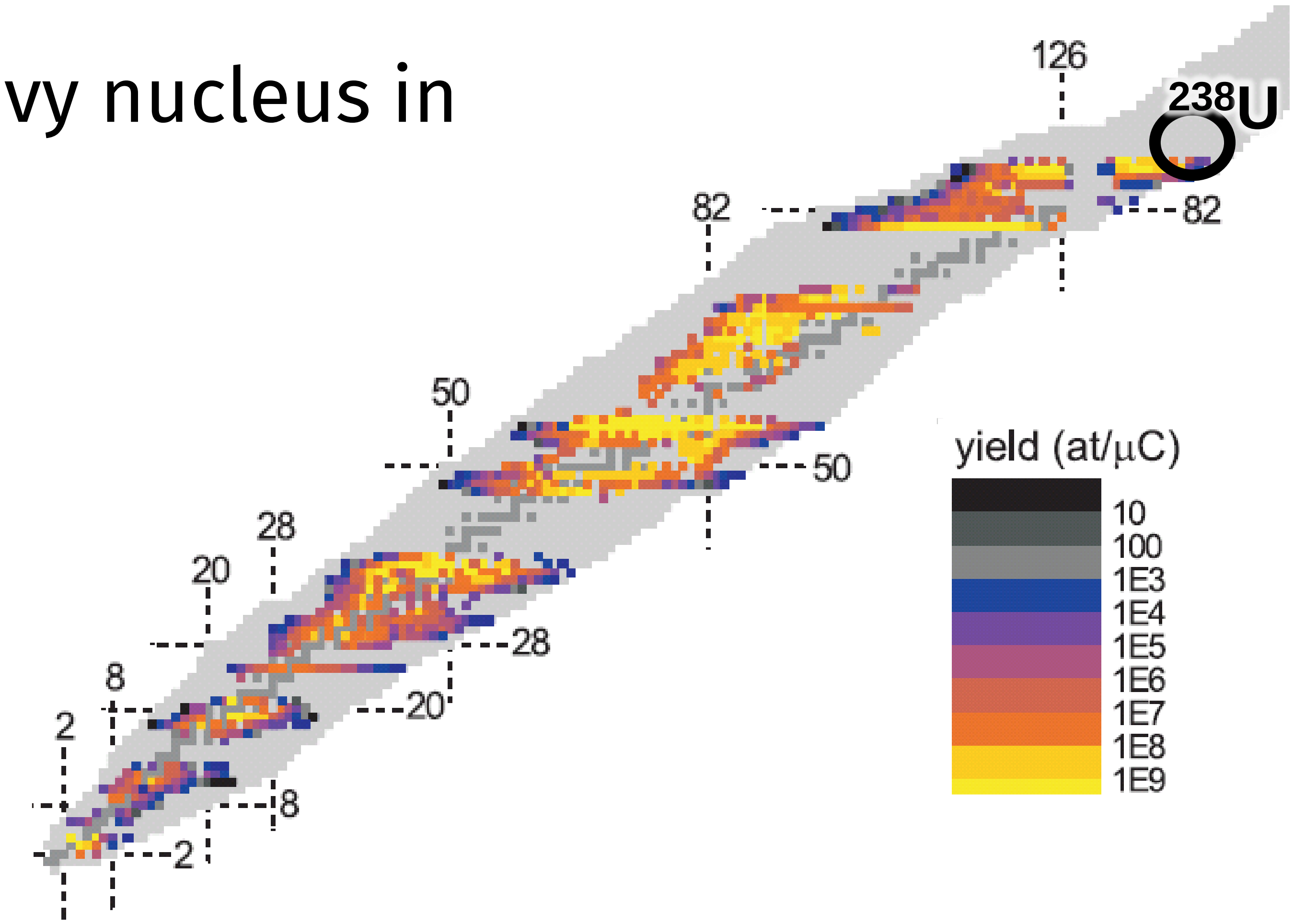
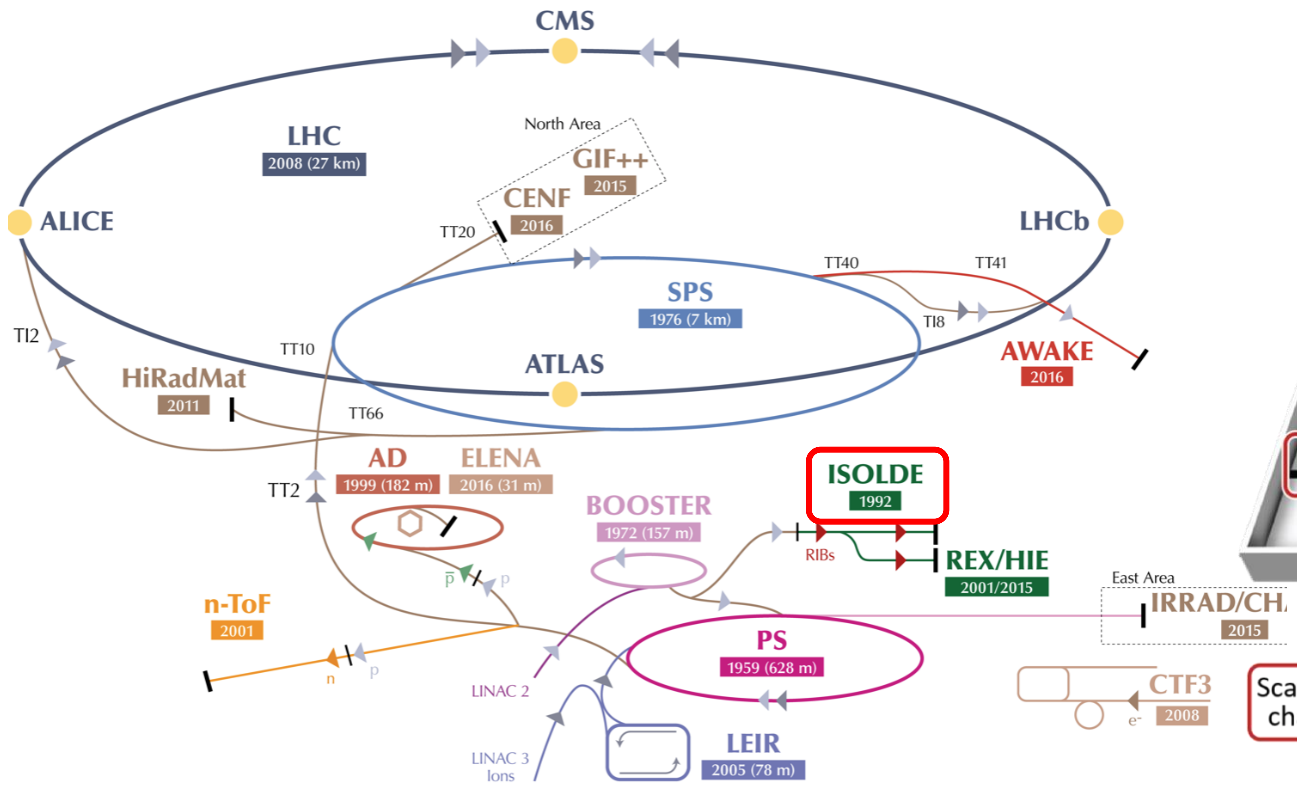
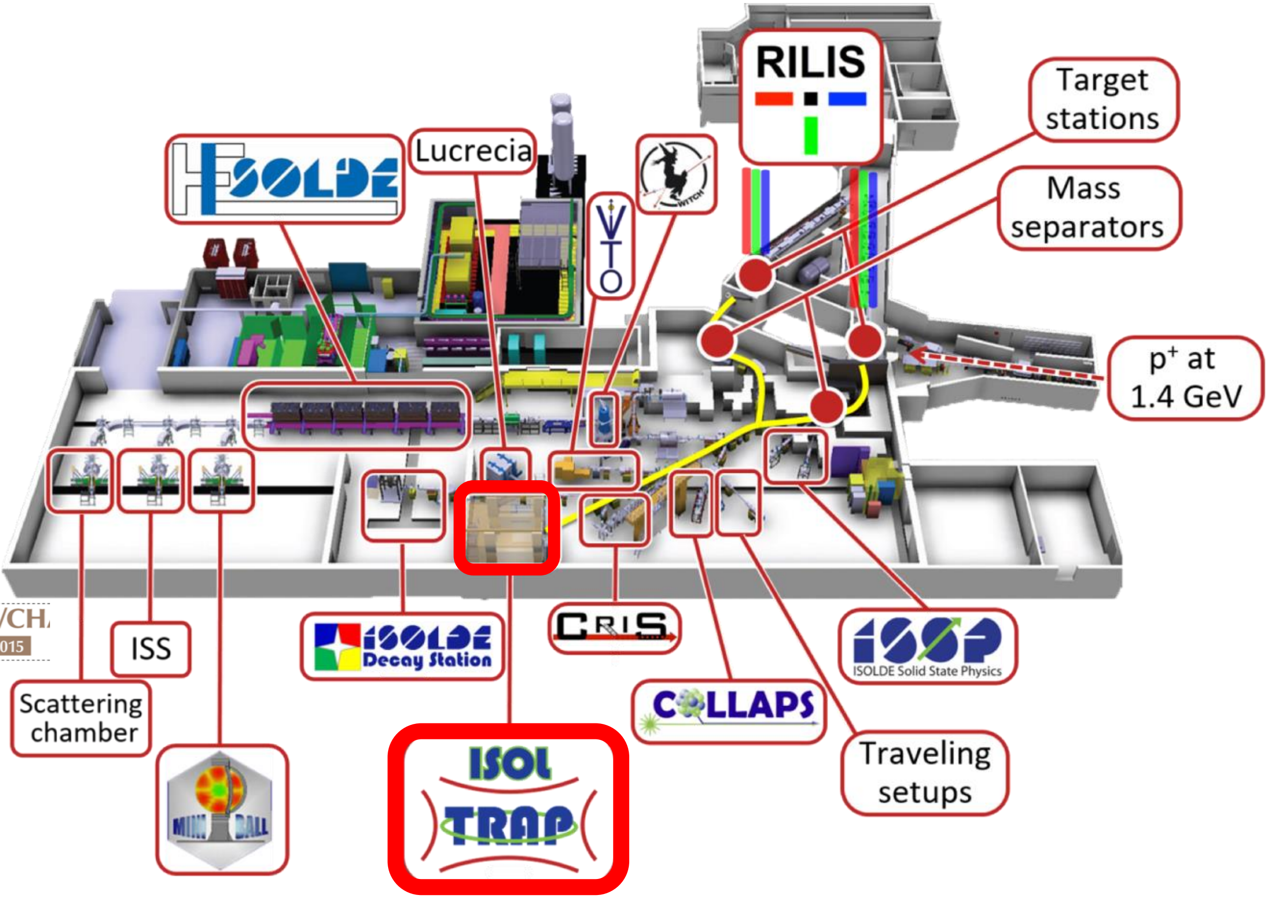


~6000 isotopes predicted by theory
~3000 isotopes already discovered
~1000 isotopes produced by ISOLDE
74 different elements available

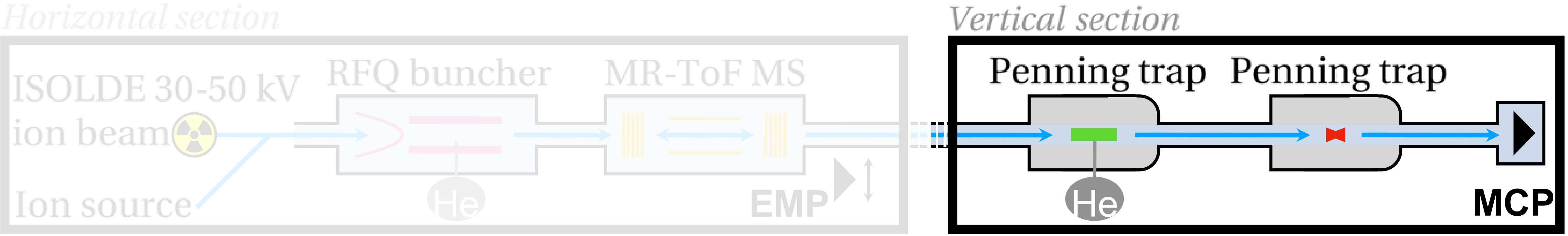
Production: Modern-day alchemy

ISOLDE at CERN



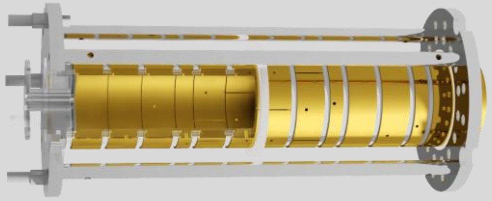


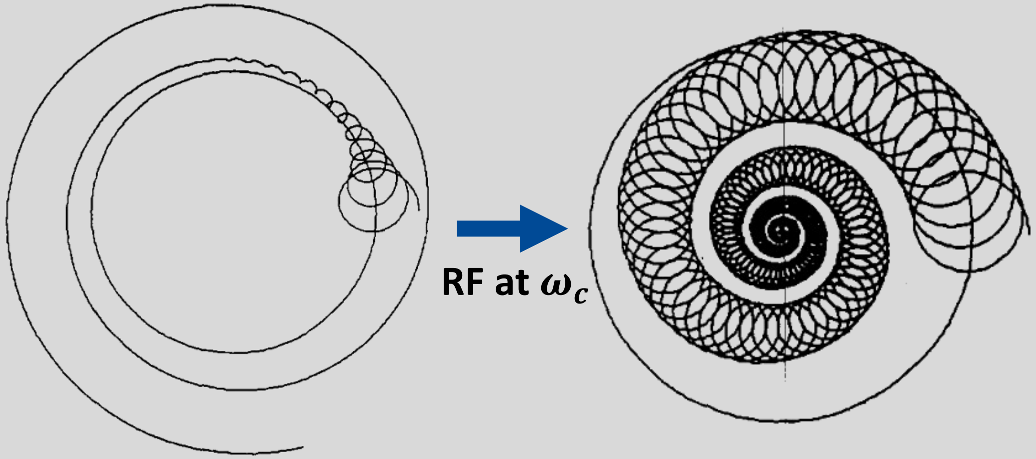
Tandem Penning Trap



Preparation Penning Trap

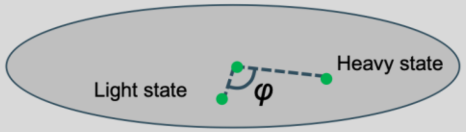
Beam preparation and purification with buffer gas

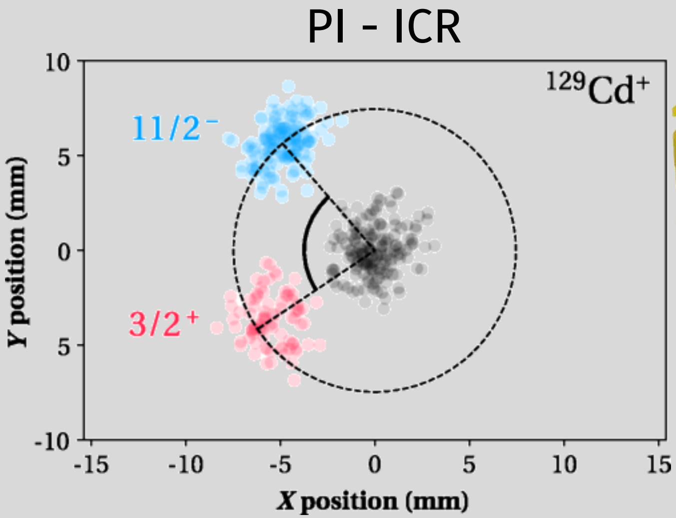


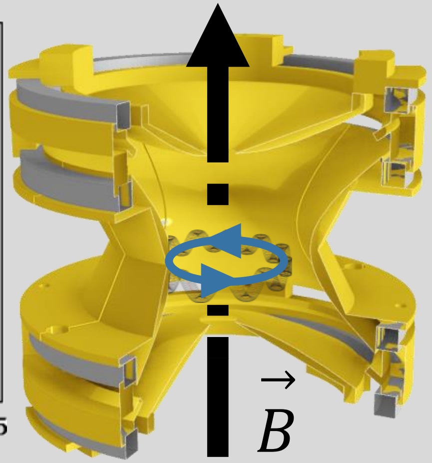


Precision Penning Trap

Mass measurements



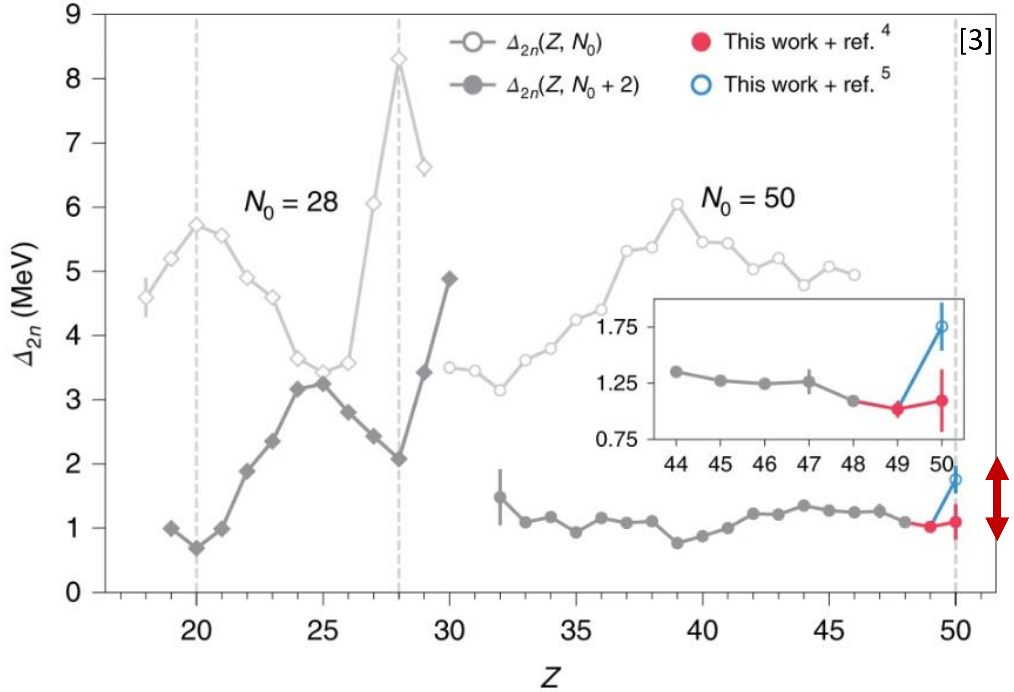




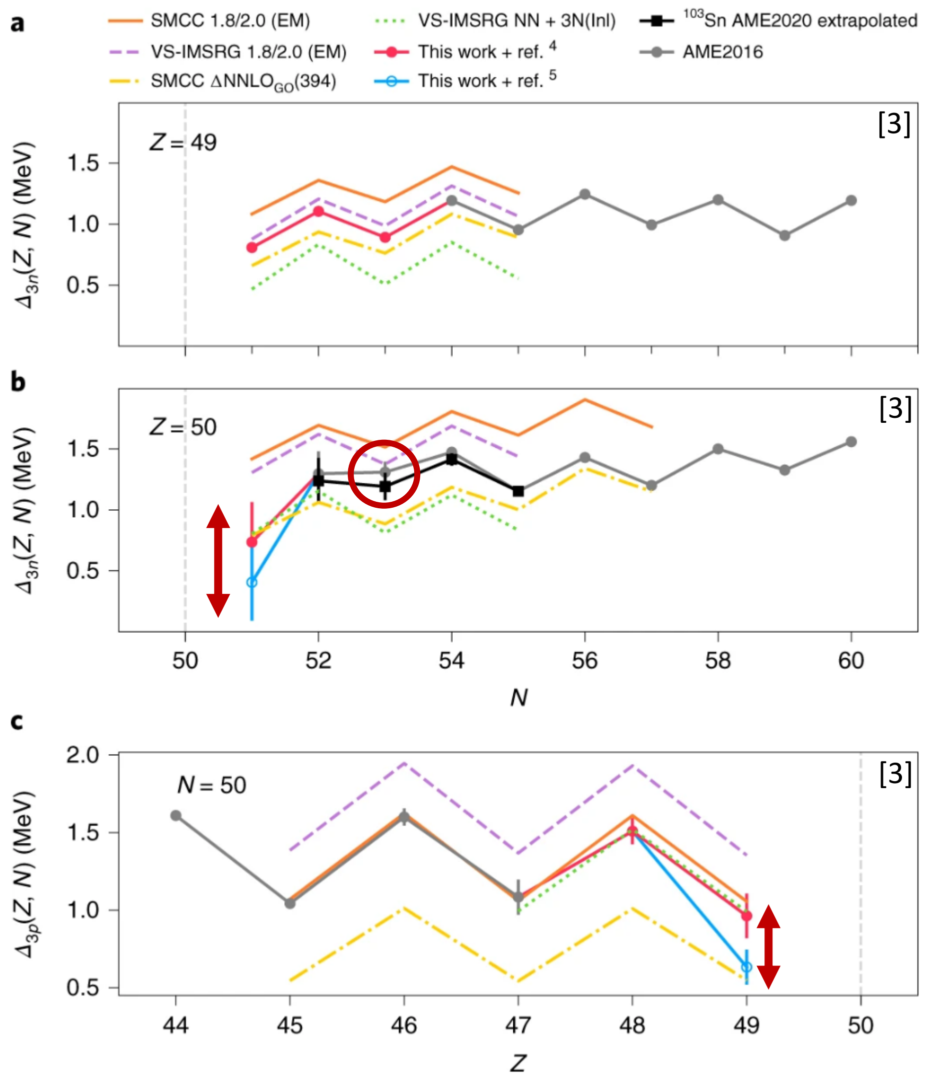
G. Savard, PLA **158**, 5 (1991), p 247-252
M. König, Int. J. Mass. Spec. **142**, 1–2 (1995), p 95-116
S. Eliseev et al., Appl. Phys. B **114:107–128** (2014)

Back to binding energies: Q-value questions…

- Mass of **^{100}Sn** improved by 60 keV based on Q-value to ^{100}In [1-2]
- in-accurate **mass** for ^{103}Sn derived from Q-values **rejected** from AME2020
- extrapolated masses yield more consistent behavior
- direct mass-measurement to confirm expected behavior of mass filters



$$\Delta_{3n}(Z,N) = 0.5\times(-1)^N\,[B(Z,N-1) - 2B(Z,N) + B(Z,N+1)]$$



[1] Hinke et al., Nature **486,** 341-345 (2012)
[2] Lubos et al, PRL **122**, 222502 (2019)
[3] M. Mougeot et al., Nature Physics 17, 1099–1103 (2021)

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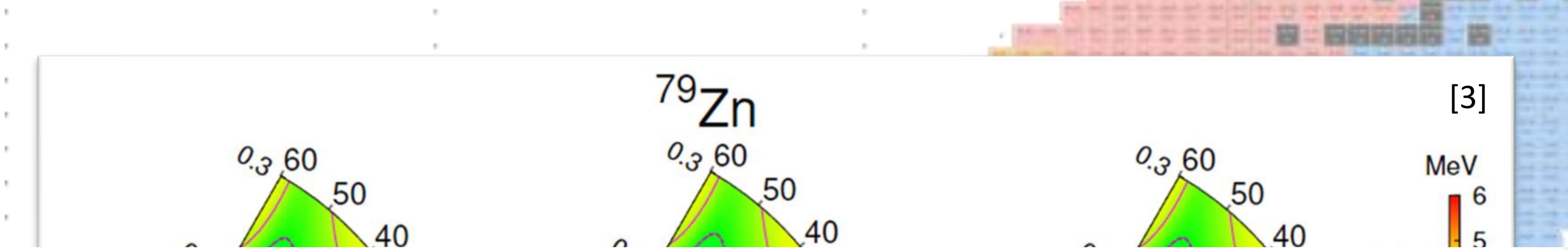
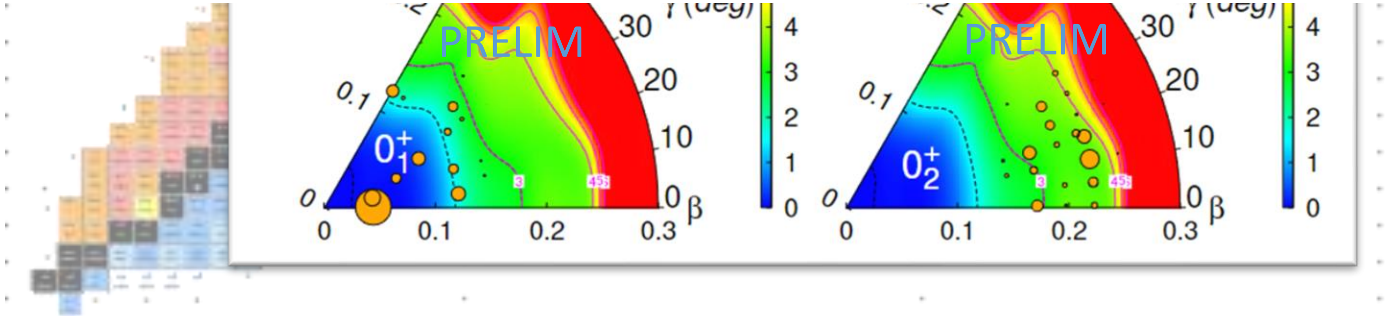


TABLE II. SM ...

PRELIM

Nuclide	J^π	$E^*_{exp.}$	E^*_{theo}	E^*_{corr}	$\nu_{g9/2}$	$\nu_{d5/2}$	$\nu_{s1/2}$	$\nu_{g7/2}$	$\nu_{d3/2}$	$\pi_{f7/2}$	$\pi_{f5/2}$	$\pi_{p3/2}$	$\pi_{p1/2}$
^{79}Zn	$9/2^+$	0.0	0.0	0.0	8.47	0.27	0.04	0.18	0.04	7.51	1.79	0.50	0.20
	$1/2^+$	0.94	0.83	1.83	7.17	0.81	0.54	0.34	0.15	7.18	1.45	0.95	0.42
	$5/2^+$	0.98	0.94	2.32	7.18	1.06	0.31	0.33	0.12	7.20	1.51	0.87	0.41
^{80}Zn	0_1^+	0.0	0.0	0.0	9.50	0.23	0.03	0.19	0.04	7.52	1.90	0.44	0.14
	0_2^+	-	2.16	1.66	7.26	1.20	0.71	0.52	0.31	6.92	1.28	1.33	0.47



[1] Wraith et al, PLB **771** (2017) 385-391
[2] Nowacki et al, PRL **117** 272501 (2016)
[3] Nies, Dao, Kankainen, Lunney, Nowacki et al., in preparation
[4] Dao, Nowacki PRC **105** 054314 (2022)