



# Pairing studies via mass measurements

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ESNT Pairing Workshop

14 June 2025

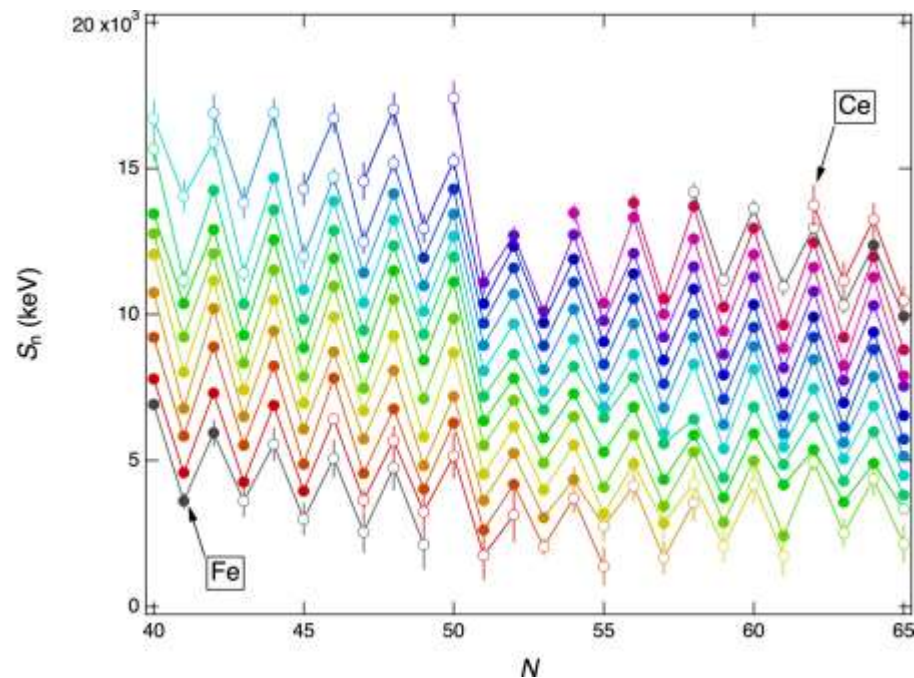
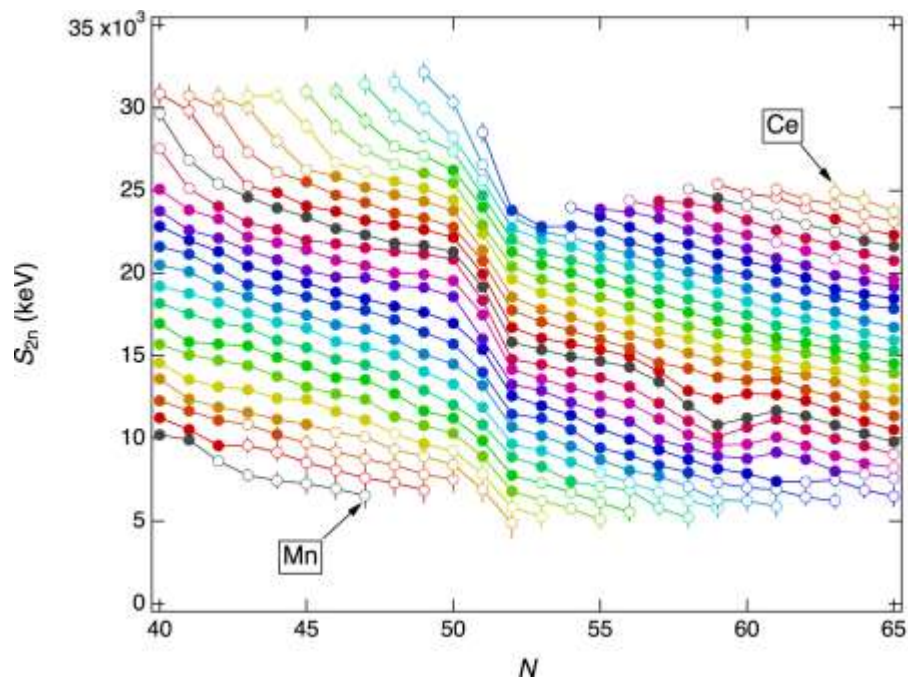




Canada's particle accelerator centre  
is located on the traditional, ancestral, &  
unceded territory of the xwməθkwəyəm People.



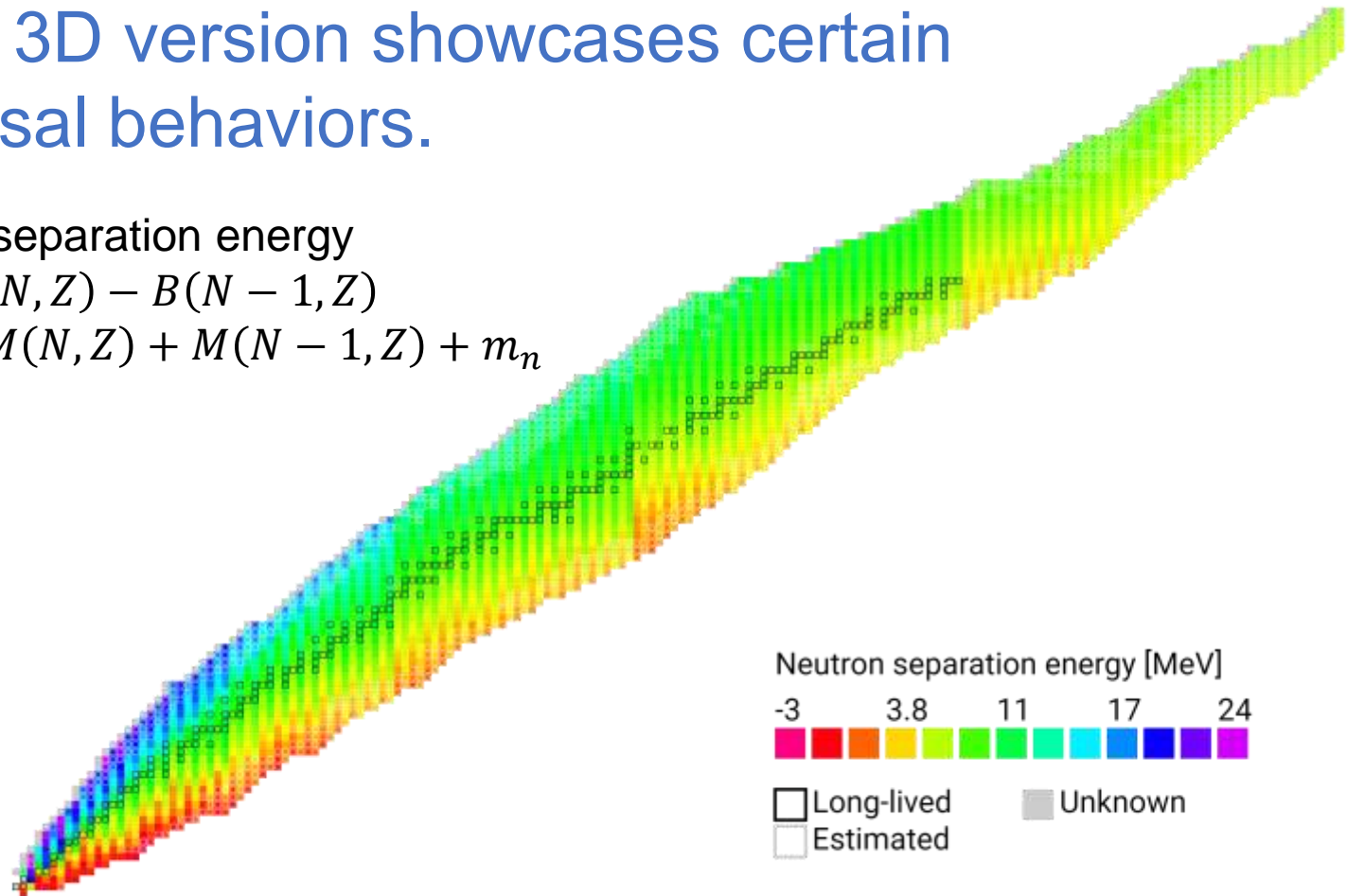
While we tend to 2D plots to surface structure ...



... the 3D version showcases certain universal behaviors.

neutron separation energy

$$\begin{aligned} S_n &= B(N, Z) - B(N - 1, Z) \\ &= -M(N, Z) + M(N - 1, Z) + m_n \end{aligned}$$



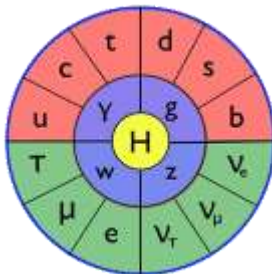
# Yet the uncertainty often differs from what is needed.

Total Binding Energy error [MeV]



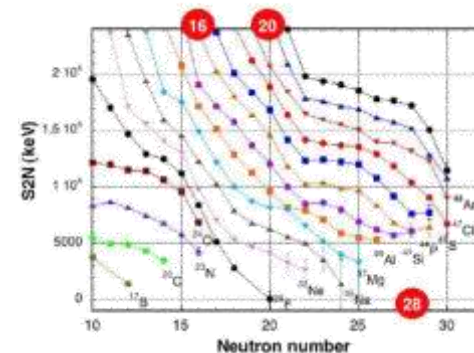
**Fundamental symmetries**

$$\delta m/m < 10^{-8}$$



**Halos and skins**

$$\delta m/m = 10^{-7}$$

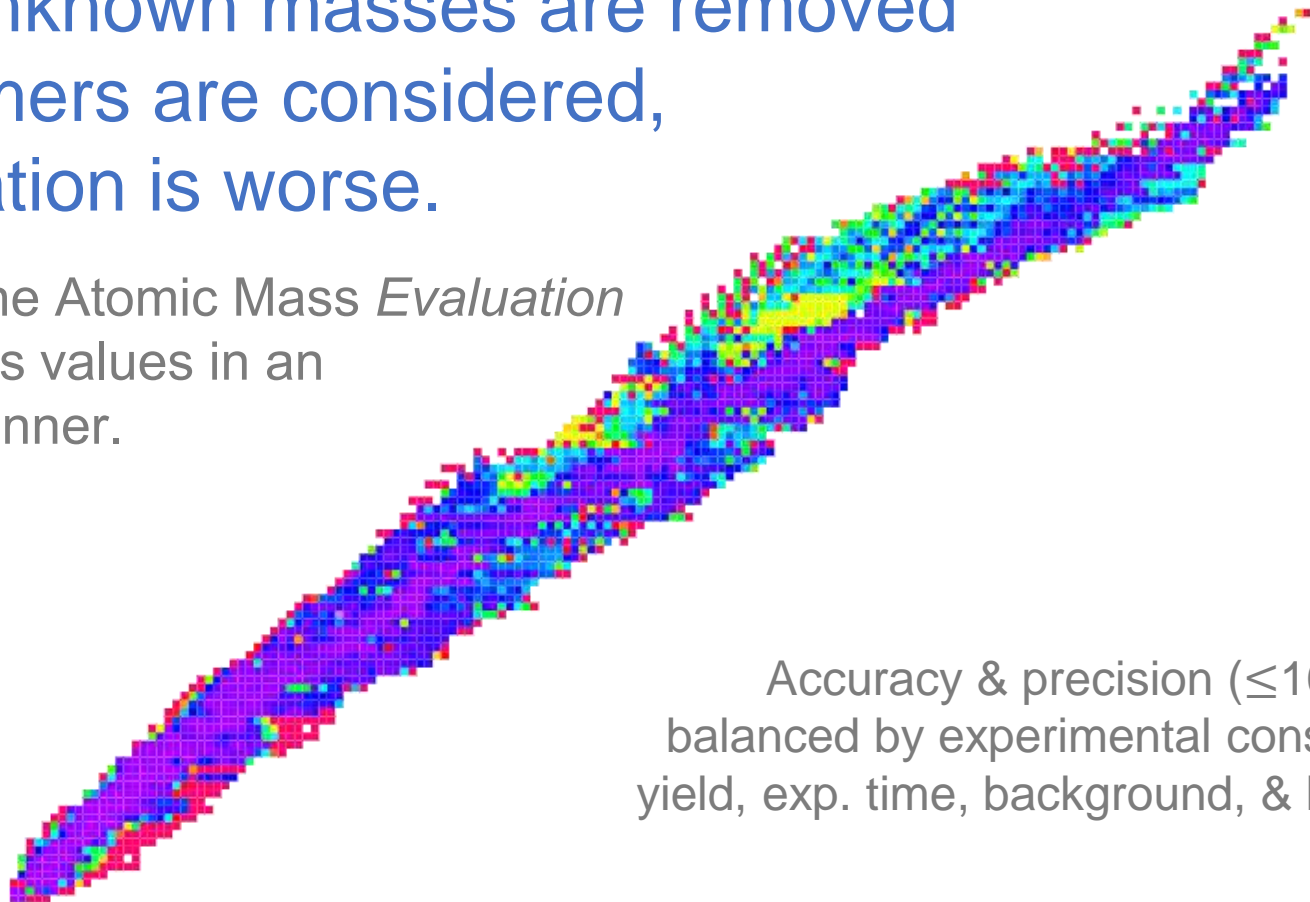


**Evolution of nuclear shell structure**

$$10^{-6} < \delta m/m < 10^{-5}$$

When unknown masses are removed  
and isomers are considered,  
the situation is worse.

Caution: The Atomic Mass *Evaluation*  
extrapolates values in an  
opaque manner.

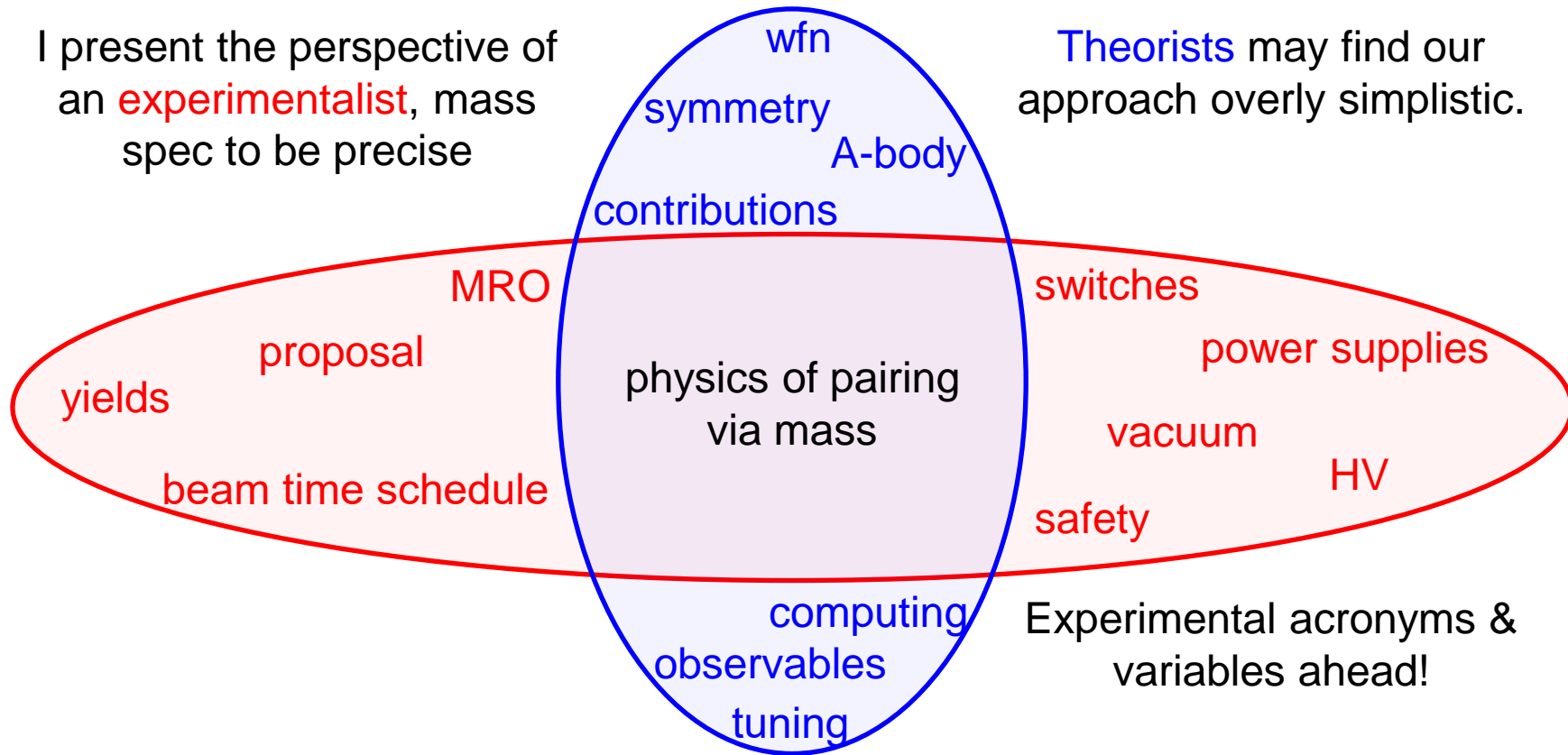


Accuracy & precision ( $\leq 100$  keV)  
balanced by experimental constraints:  
yield, exp. time, background, & half life.

# Caveats:

I present the perspective of  
an **experimentalist**, mass  
spec to be precise

**Theorists** may find our  
approach overly simplistic.



Experimental acronyms &  
variables ahead!

# Outline

Mass differences for nuclear structure

Mass spectrometry of RIB worldwide

- RIB production + mass spec techniques
- ESR @ GSI in 2005
- CSR @ IMP in 2023
- JYFLTRAP @ U Jyväskylä

TITAN: TRIUMF's Ion Trap for Atomic and Nuclear science

- 2 recent studies
- 2 proposed experiments

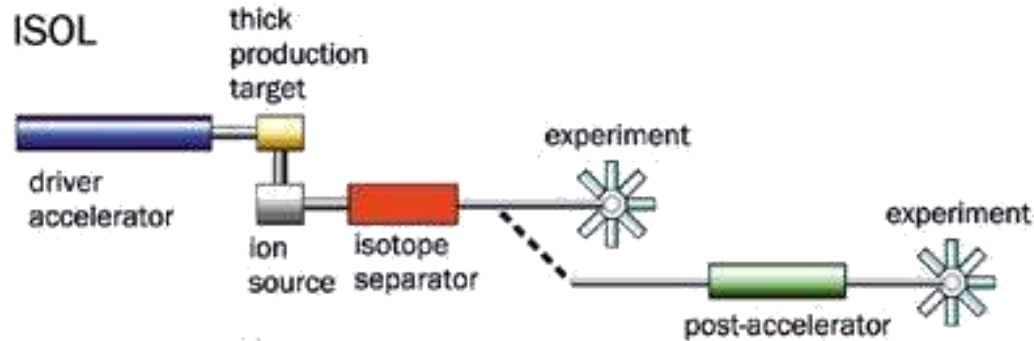
Outlook on mass spectrometry of RIB

Closing thoughts

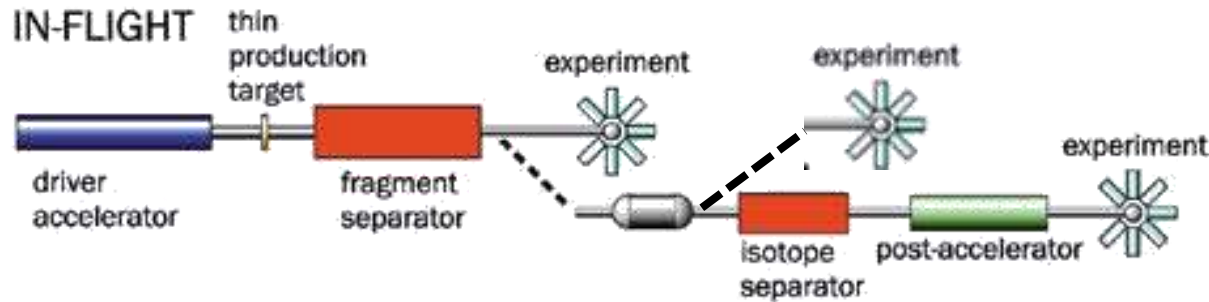


Production of Radioactive Ion Beam (RIB) strongly influences mass spec options and its limitations.

# RIB predominantly produced by in-flight fragmentation or in-target spallation/fragmentation.



- ☺ large amounts
- ☹ low-energy beam
- ☹ chemistry dependent
- ☹  $T_{1/2} > \text{ms}$

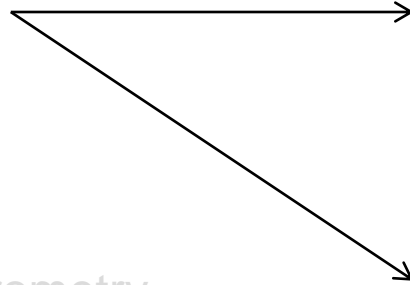


- ☺ make anything
- ☹  $T_{1/2} > 100 \text{ ps}$
- ☹ high(er)-energy beam
- ☹ small amounts

# Indirect techniques struggle with accuracy & precision but are only viable option $T_{1/2} < \mu\text{s}$ .

## Indirect

- Decay measurements & kinematics



### decays:



$$Q_a = M_A - M_B - m_b$$

## Direct

- Conventional mass spectrometry
- Time of flight
- Frequency based

### reactions:



$$Q = M_A + M_a - M_B + M_b$$

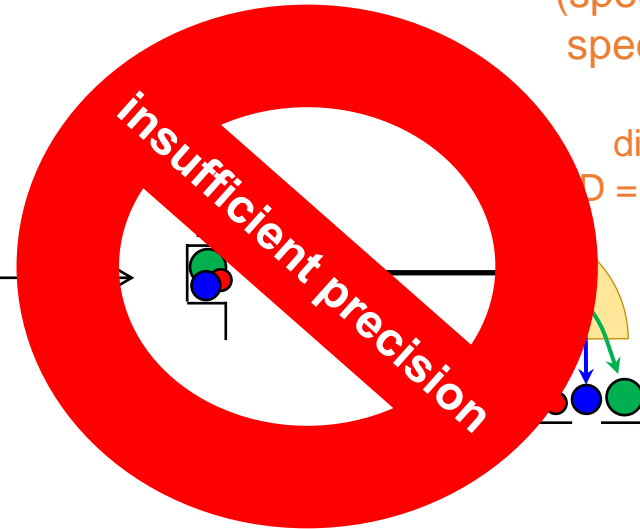
# Magnetic rigidity alone provides insufficient precision for nuclear-structure studies.

## Indirect

- Decay measurements & kinematics

## Direct

- Conventional mass spectrometry
- Time of flight
- Frequency based



mass separator:  
(spectrograph /  
spectrometer)

dispersion  
 $D = \Delta x \cdot m / \Delta m$

# TOF, esp. MR-TOF mass spec, can provide high precision and accuracy.

## Indirect

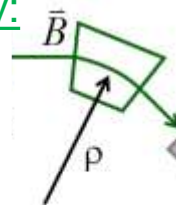
- Decay measurements & kinematics

magnetic rigidity:

$$B\rho = p/q = \gamma m v / q$$

$$\delta m > 100 \text{ keV}$$

$$T_{1/2} > \mu\text{s}$$

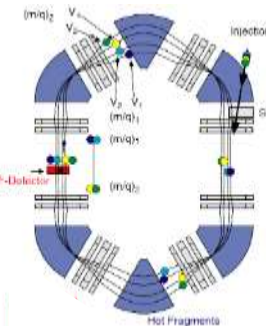


storage rings

$$\gamma_t \rightarrow \gamma$$

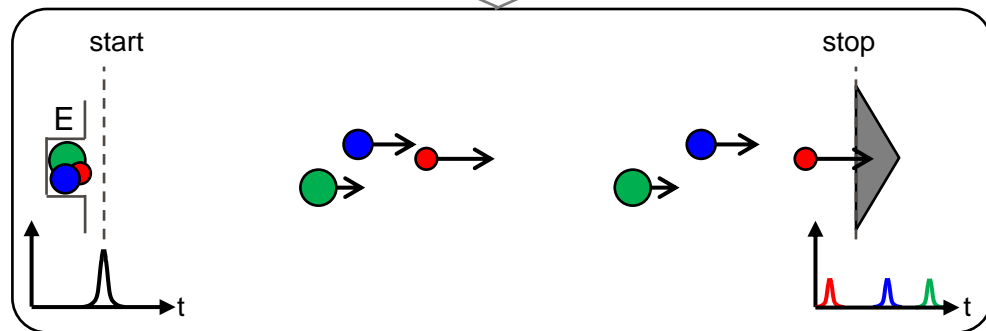
$$\delta m \sim 100 \text{ keV}$$

$$T_{1/2} > 10 \mu\text{s}$$



## Direct

- Conventional mass spectrometry
- Time of flight
- Frequency based



MR-TOF ion traps

$$\delta m \sim 10 \text{ keV}$$

$$T_{1/2} > \text{ms}$$



# Highest precision & accuracy are via frequency-based measurements, esp. Penning trap.

## Indirect

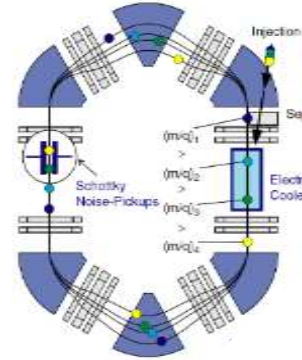
- Decay measurements & kinematics

## Direct

- Conventional mass spectrometry
- Time of flight
- Frequency based

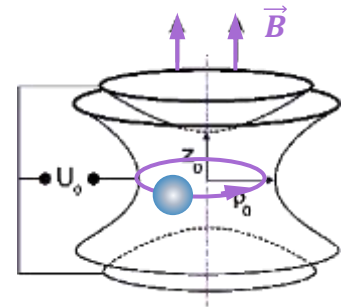
### storage rings

$$\frac{\Delta v}{v} \rightarrow 0$$
$$\delta m > 10 \text{ keV}$$
$$T_{1/2} > \text{s}$$

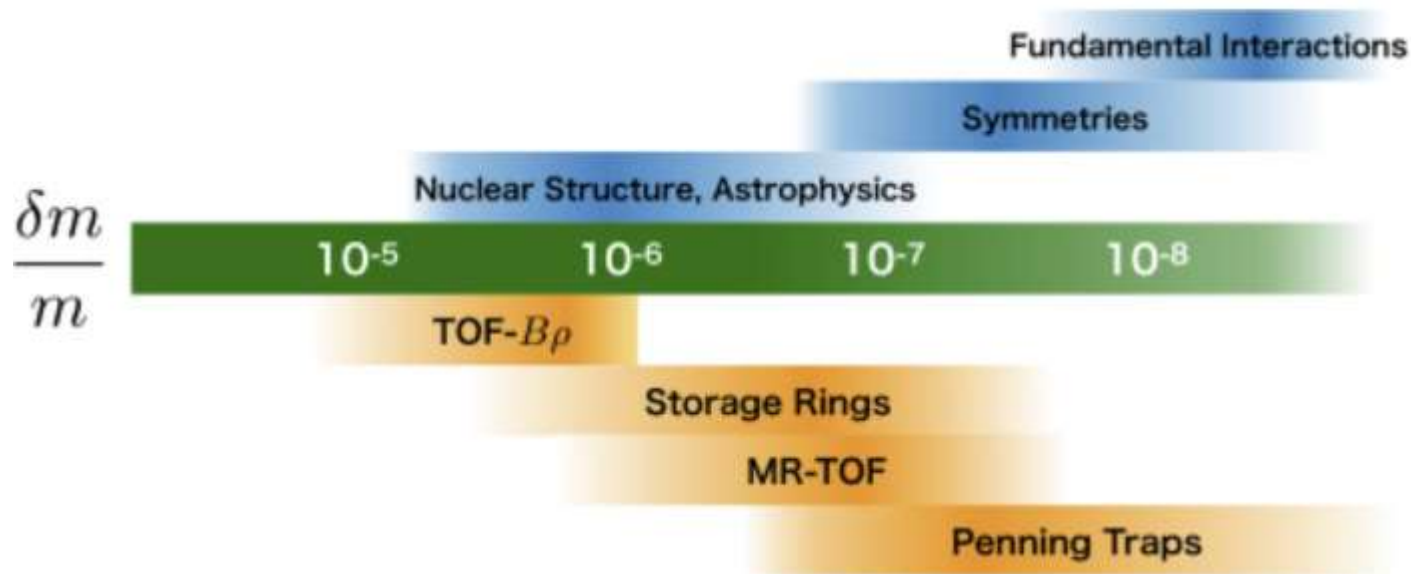


### Penning traps

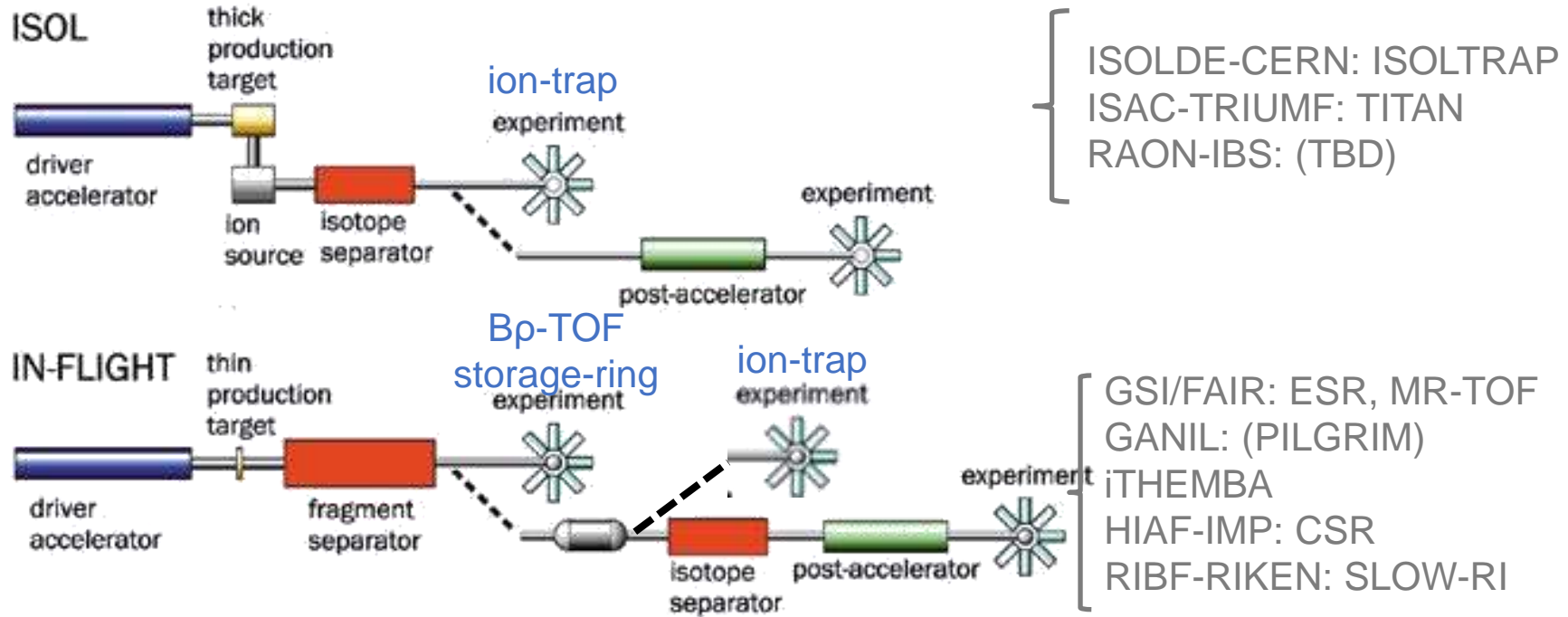
$$\omega_c = \frac{q}{m} \cdot B$$
$$\delta m > 10 \text{ eV}$$
$$T_{1/2} > 3 \text{ ms}$$



A summary, but an experimentalist  
can always worsen the precision.



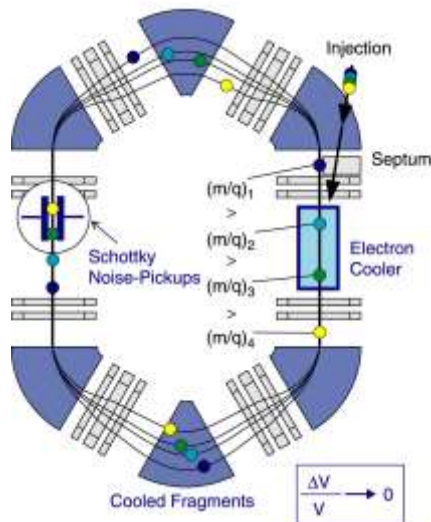
# Precision methodology is determined largely by RIB production.



The ESR @ GSI has defined how storage-ring mass spec developed & continues to be pioneered

# 2005: ESR's 604 masses ( $\delta m \sim 30$ keV, $T_{1/2} > 10$ s) for systematic study of odd-even staggering (OES)

Broadband SMS measurement of p-rich masses for  $Z=50-82$ , 114 1<sup>st</sup> times



To extract exp. pairing correlation, used approximate pairing-gap energy  $\Delta$  in BCS theory:

$$\Delta_n^{(3)} = (-1)^N [BE(Z, N+1) - 2BE(Z, N) + BE(Z, N-1)]$$

$$\Delta_p^{(3)} = (-1)^Z [BE(Z+1, N) - 2BE(Z, N) + BE(Z-1, N)]$$

Near stability, well-known parametrization of  $\Delta \approx 12/\sqrt{A}$  MeV. (N.B. other plots use  $D_{p,n} = 2\Delta_{p,n}$ .)

Connected to strength of pairing interaction  $G$ :

$$\frac{2}{G} = \sum \frac{1}{\sqrt{(\epsilon_\nu - \lambda)^2 + \Delta^2}}$$

where  $\epsilon_\nu$  is single particle energy and  $\lambda$  chemical potential, summing over all single-particle levels  $\nu$  below and above Fermi energy.

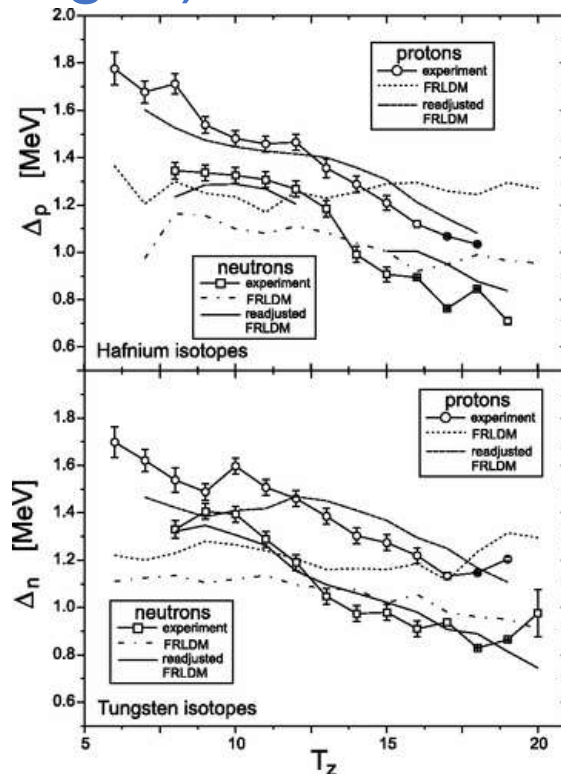


# Isospin dependence required adjusting FRDM pairing (by parameterizing $G$ ).

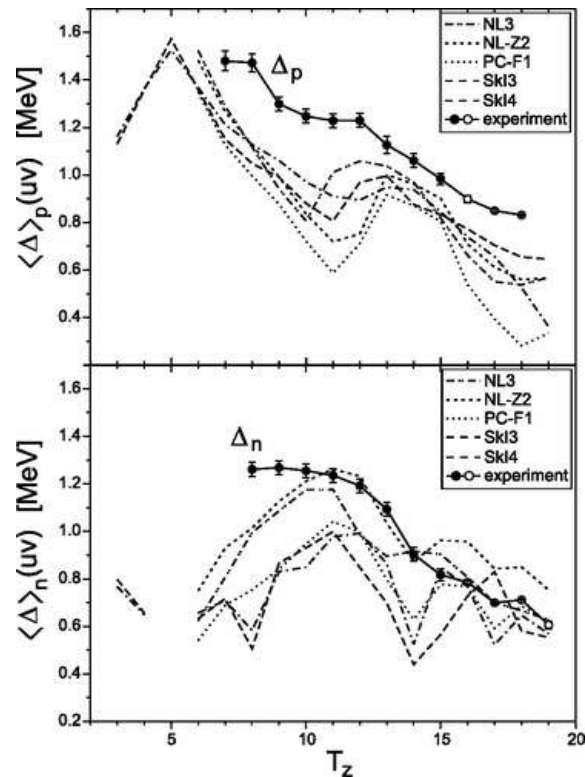
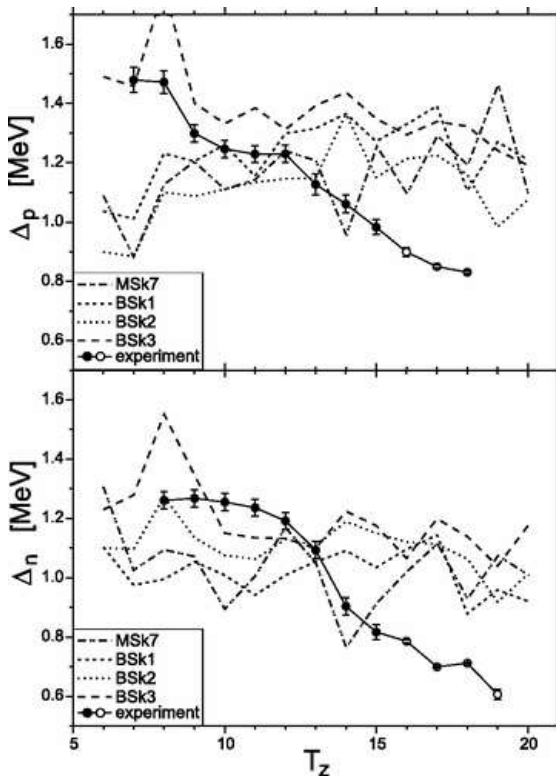
Precision & breadth allowed for systematic study on pairing.  
Focused on even-even nuclides

Exp. isospin dependence not reproduced by original FRDM.

Adjusted FRDM parameterized  $G$  with 2 constants each, with best fit found when corresponding parameter pairs were equal, for 25% improvement in fit.



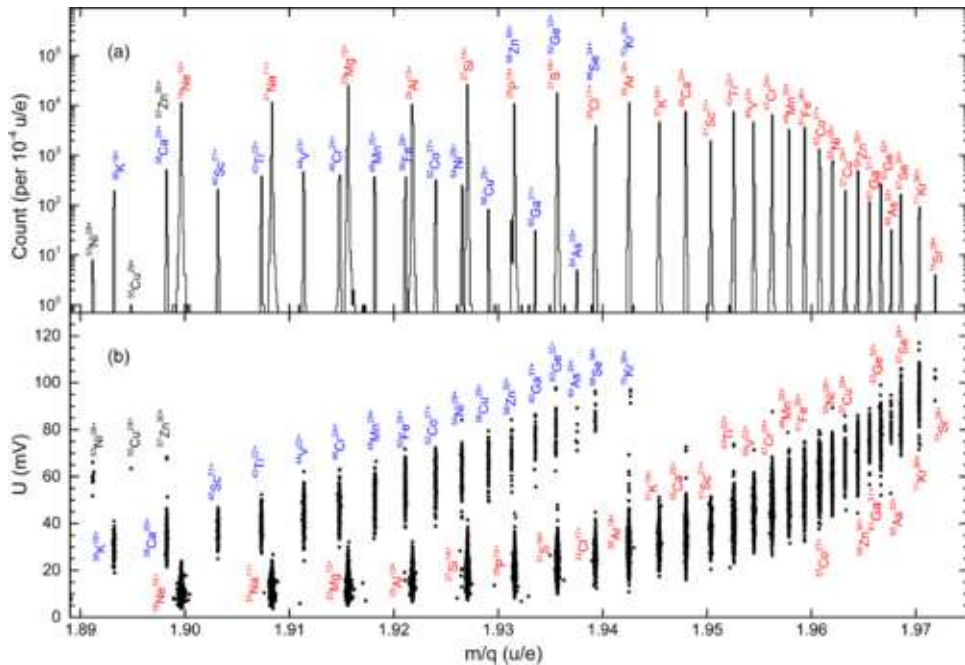
# Microscopic models poorly described e-e Hf.



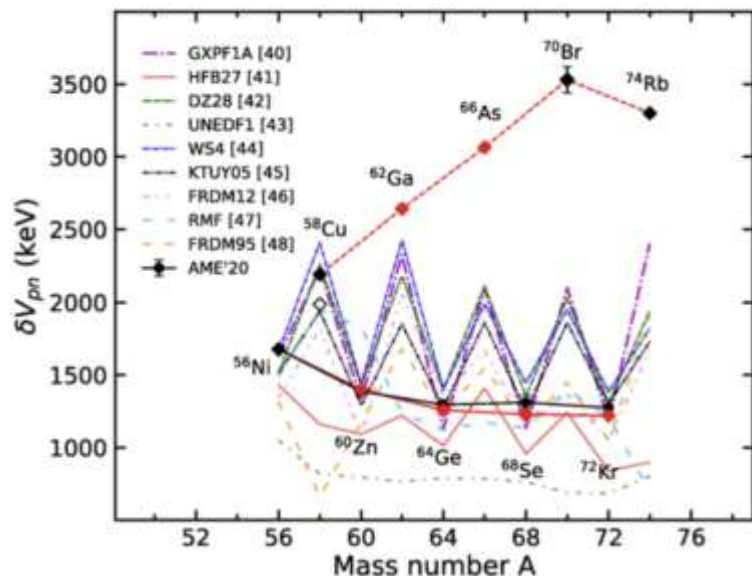
No disentanglement mean-field contributions to OES  
& pairing gap from 2<sup>nd</sup>, 3<sup>rd</sup>, 4<sup>th</sup>-order mass diffs.

CSRe @ IMP data has upped the game.

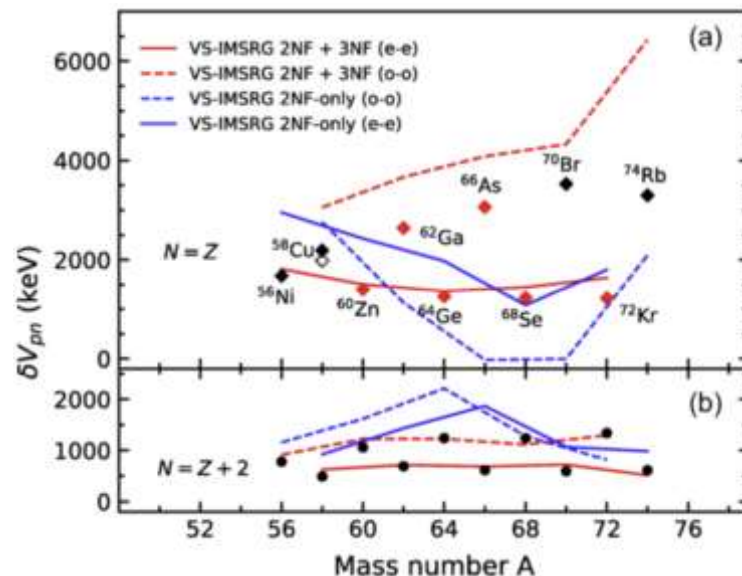
A new IMS technique allowed mass spec close to  $N = Z$  at the dripline.



# IMSRG calculations indicate enhancement of $T = 1$ pn pairing over the $T = 0$ pn pairing in region.



- oo nuclei are  $(1,0^+) \rightarrow$  couple to  $T = 1$  pn pair
- ee nuclei weighted contribution  $T = 1, 0$  & trend is captured by USD interxn

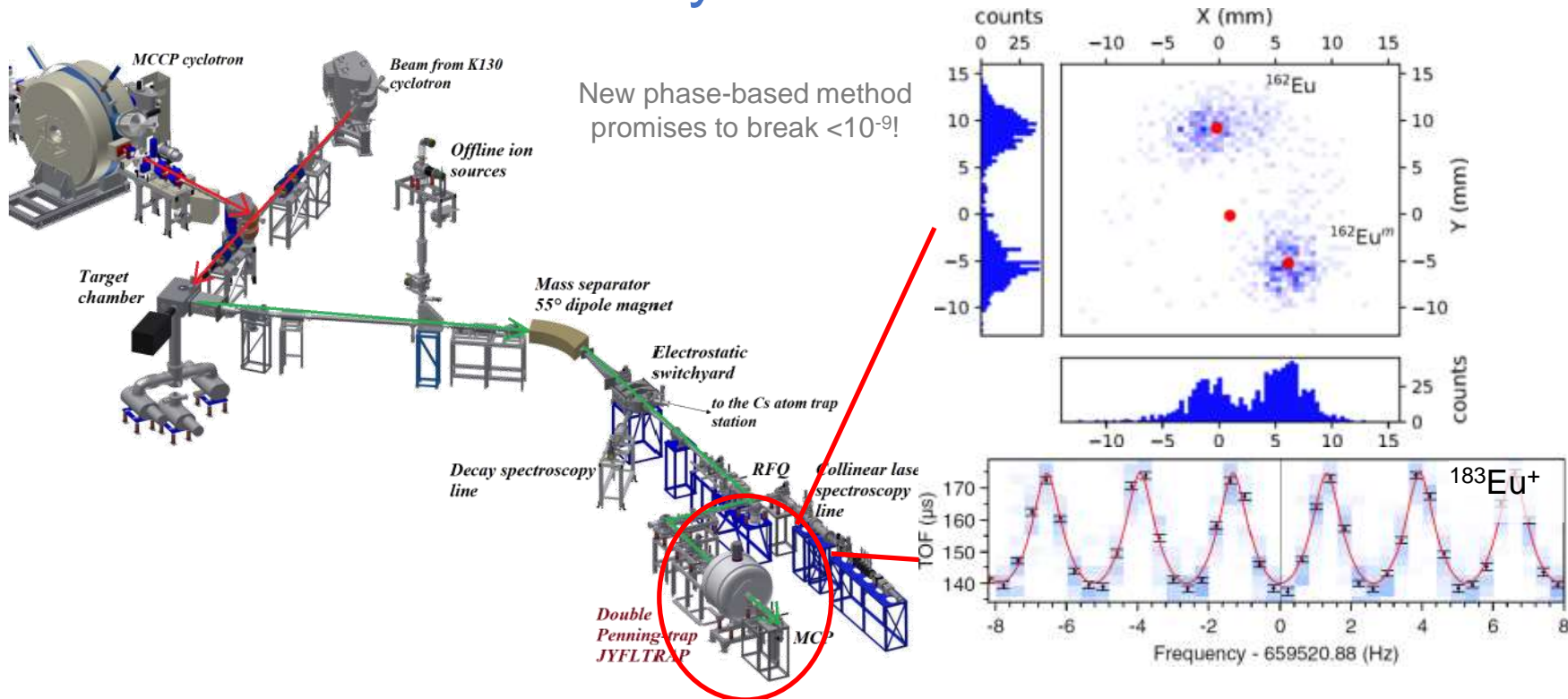


- 3NF enhances pn correlations along  $N=Z$  w/  $T=1$  enhancement  $\rightarrow \delta V_{pn}^{oo}$  more significant  $\rightarrow$  isospin inversion of g.s.

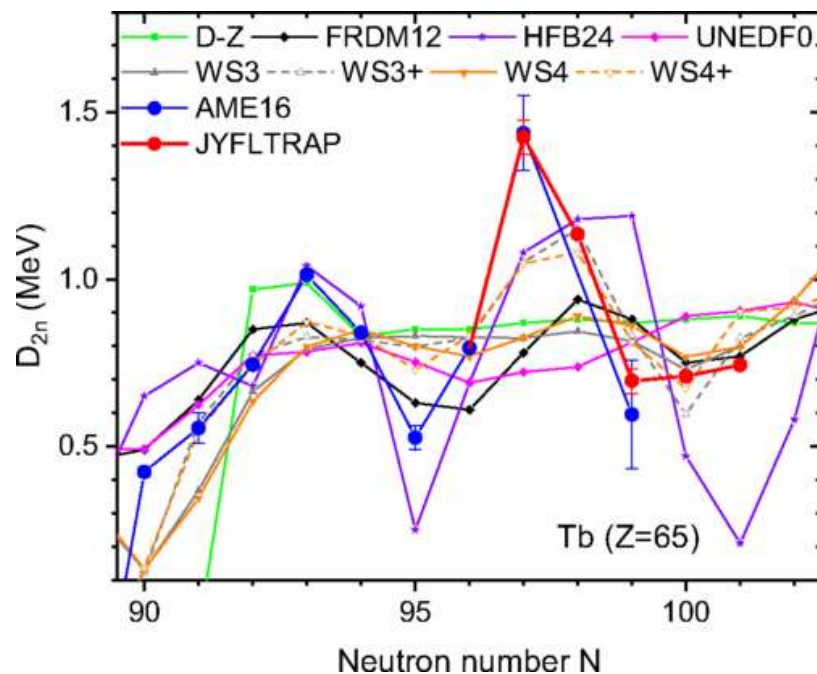
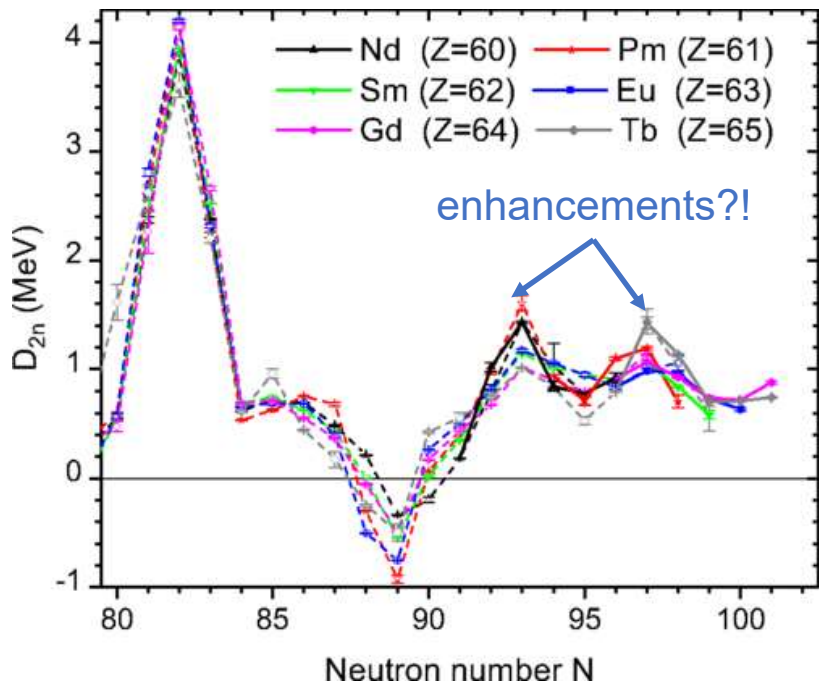


JYFLTRAP @ U Jyväskylä for the rare-earth region

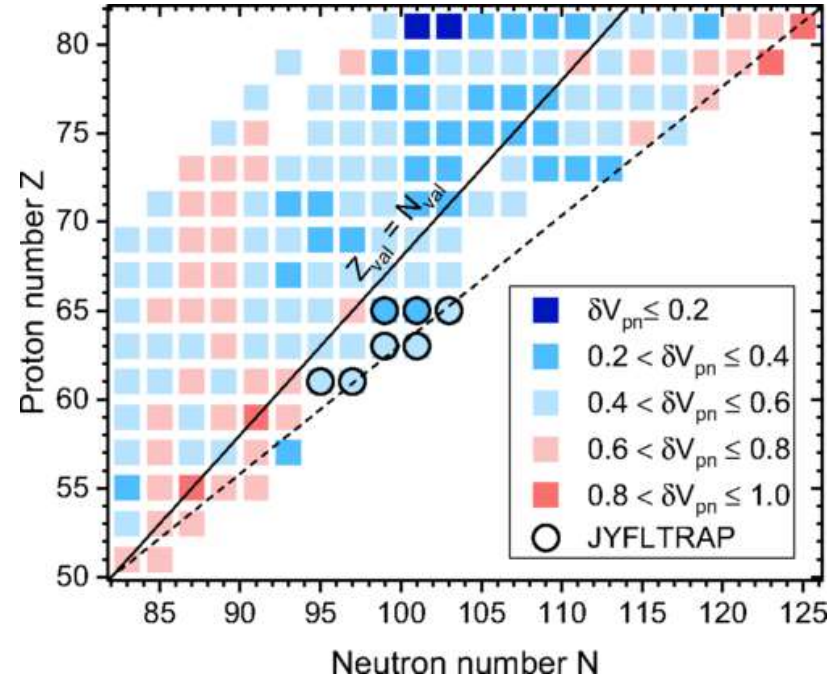
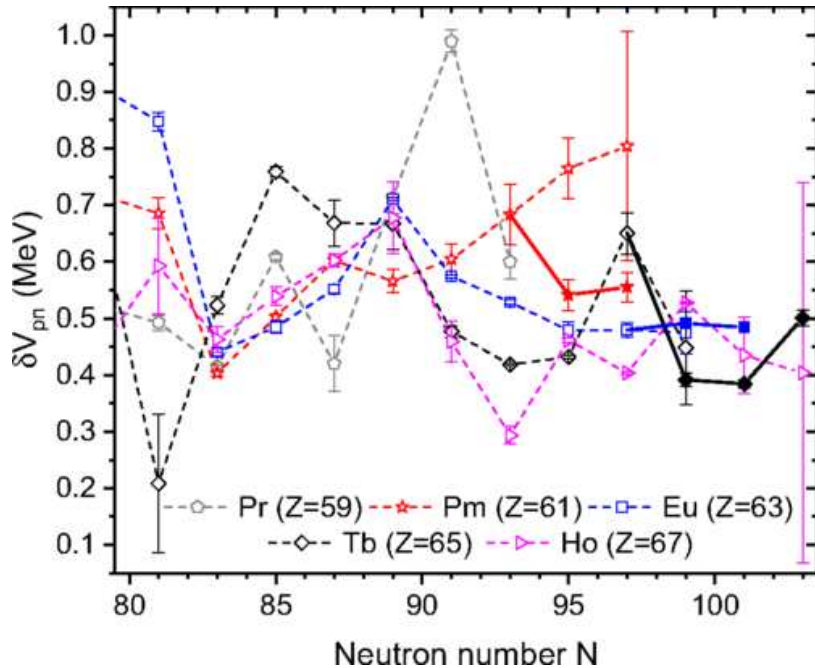
# Penning traps allow highest precision & accuracy: JYFLTRAP added many n-rich rare-earth nuclides.



# Experimental neutron-pairing energy found to be weaker than contemporary models.



Local maxima in avg. p-n interaction (Pm@N=93, Tb@N=97) suggest p-n pairing may explain high  $D_{2n}$ .



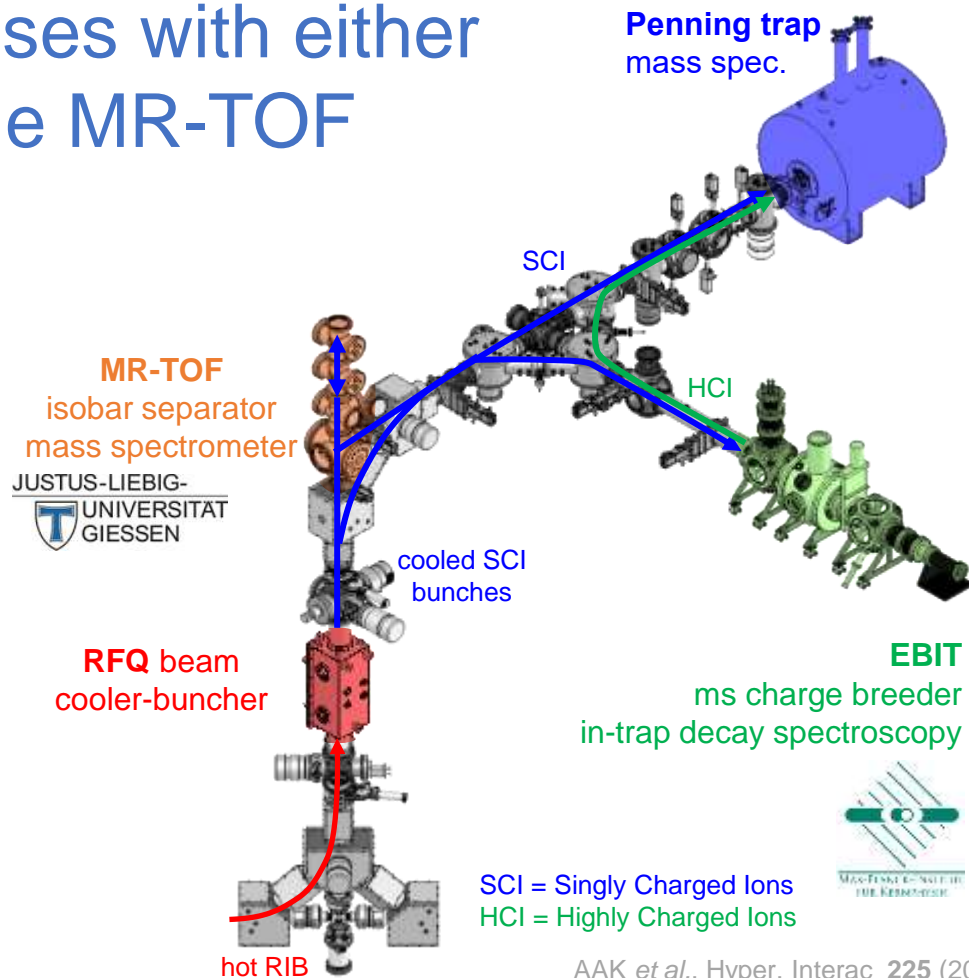
# TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN)



# TITAN measures masses with either the Penning-trap or the MR-TOF mass spectrometer

**MR-TOF** is superior in:  
speed  
dynamic range  
sensitivity  
being non-resonant  
cost

**Penning trap** is superior in:  
precision  
accuracy  
resolving power

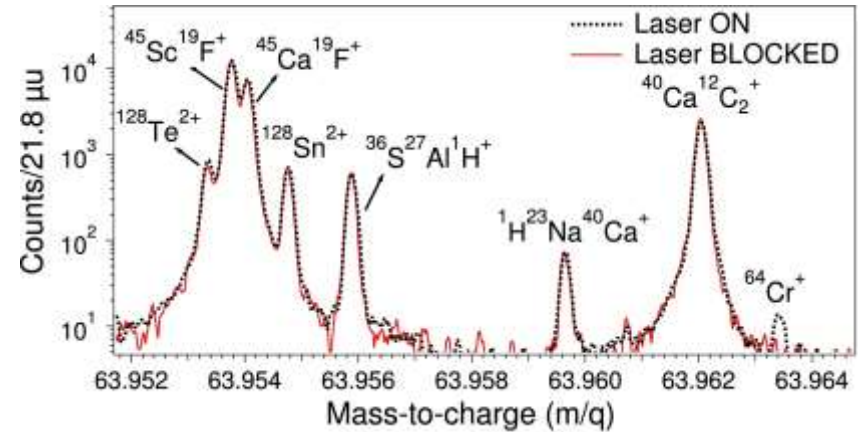


# Ongoing developments demonstrated unparalleled capabilities useful for structure studies.



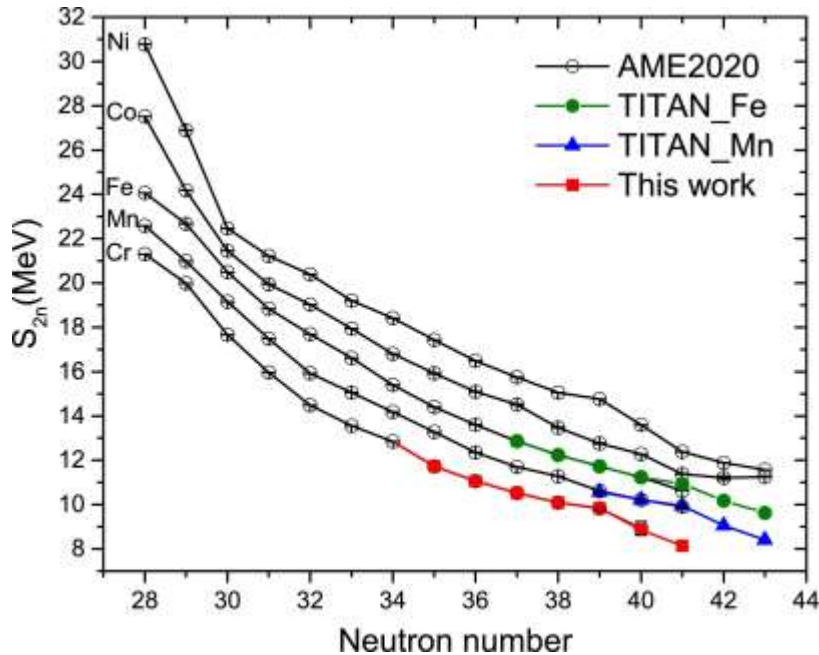
Its in-situ beam purification improves its dynamic range and sensitivity, even for isomers

Simultaneous half-life measurements add value for either science or identification purposes.



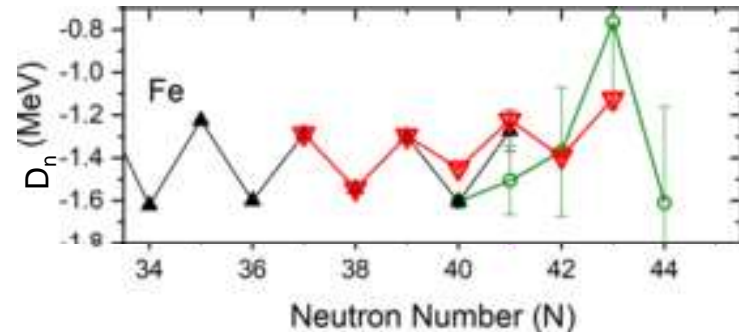
The tool of choice at nearly all RIB facilities, current or planned

# Study of suspected subshell $N = 40$ found smoother OES of pairing gap approaching $N=42$ .

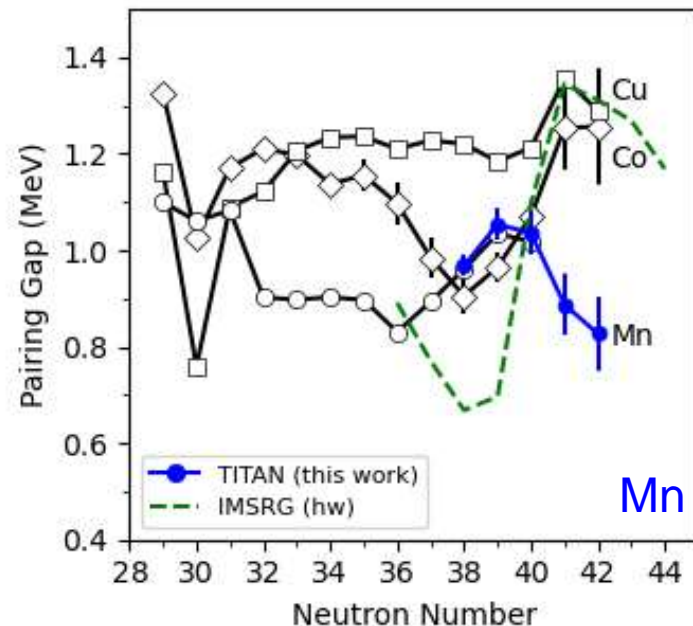
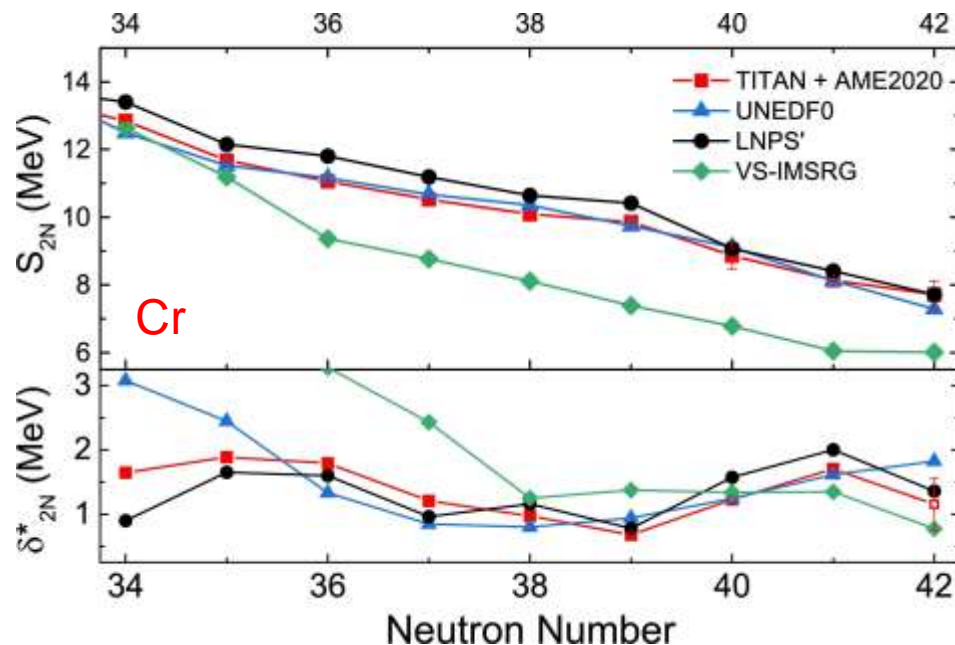


Gradual onset of collectivity in Cr, Mn, Fe observed

Support spectroscopy results for quadrupole & pairing correlation

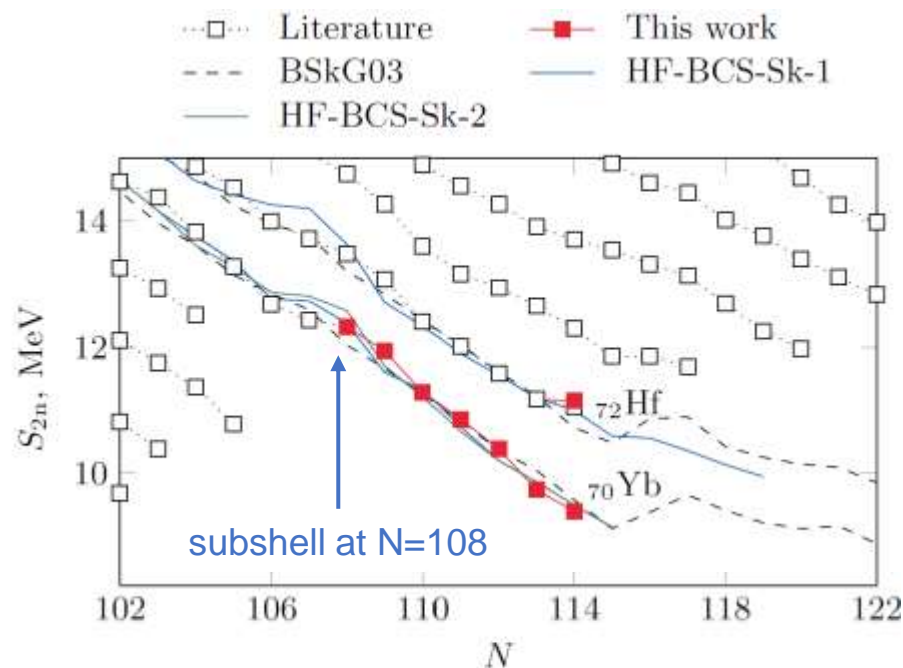


IMSRG would benefit from multiparticle-multihole excitations, as supported by pairing gap energies.



Switching to n-rich Yb ...

# New Yb mass determinations influence calculated Hf $S_{2n}$ & $\delta V_{pn}$ , and hint at subshell at $N = 108$ .



BCS pairing constants determined to reproduce  $E_{2+}/6$  moment of inertia factor of  $2+$  states in ground bands of ee nuclei

Distinct  $\beta_2$  max at  $^{172}\text{Yb}$  and  $E_{2+}$  min at  $^{174}\text{Yb}$  led to HF-BCS-Sk-1 and HF-BCS-Sk-2, respectively.

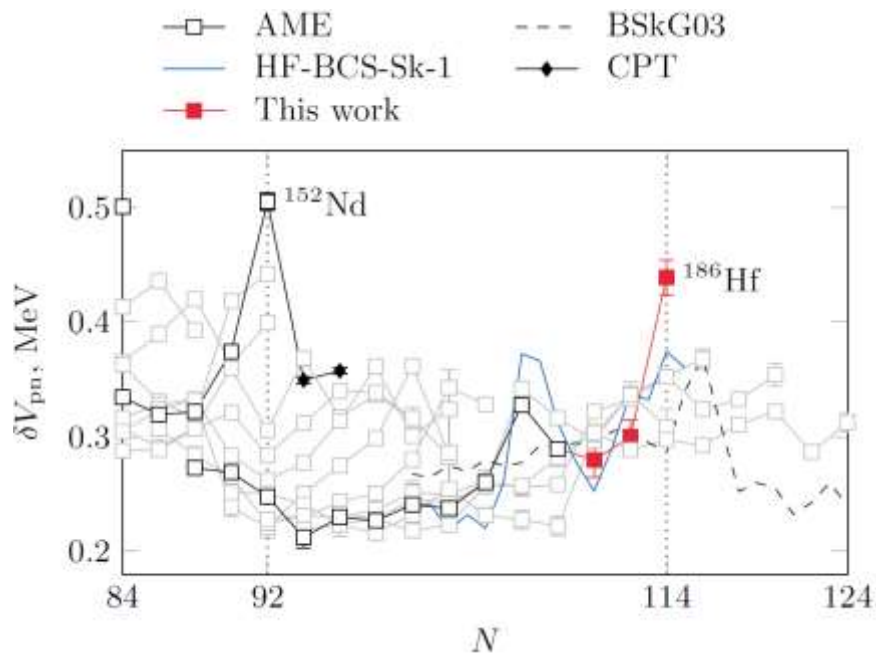
HF-BCS-Sk better predicts trends than without pairing effects, w/in 200 keV for four most exotic isotopes

# $\delta V_{pn}$ suggests prolate-to-oblate shape transition.

Upward tick of  $S_{2n}$  at  $^{186}\text{Hf}$  represents onset of elevated binding for 2 valence neutrons associated with 2 valence protons.

Flattening  $\delta V_{pn}$  of BSkG03 model towards  $N=115$  is transition from prolate ( $N=114$ ) to oblate ( $N=115$ ).

Peak in  $\delta V_{pn}$  at  $N = 114$  indicates prolate-to-oblate shape transition from  $N=113$  to  $114$  in Hf and from  $Z = 70$  to  $72$  in  $N=114$  isotones.



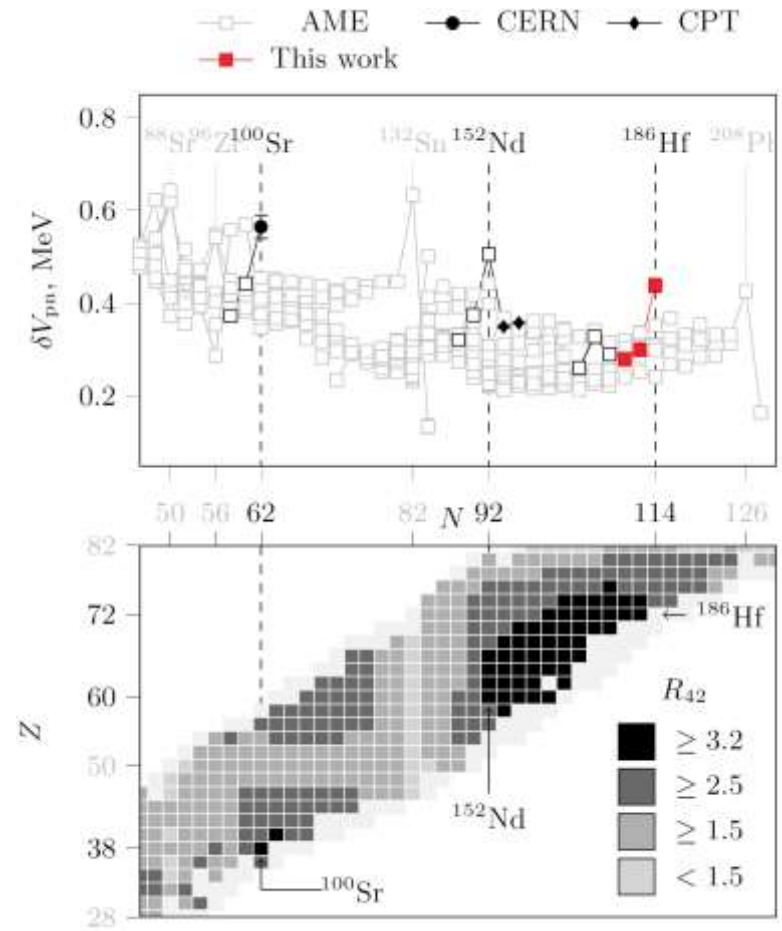


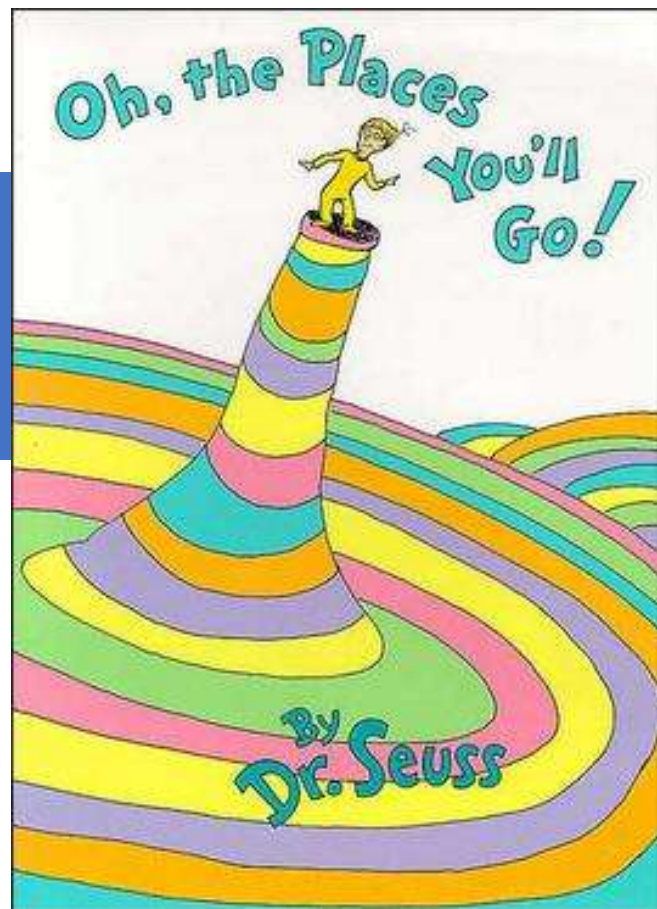
# Comparison of $\delta V_{pn}$ & its $R_{42}$ indicate shape effects.

$$R_{42} = E_{4+}/E_{2+}$$

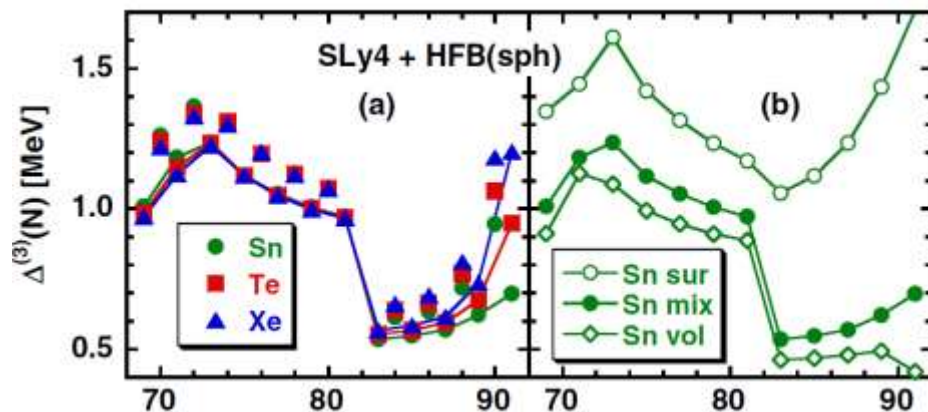
Prominent  $\delta V_{pn}$  peaks in midshell regions, where more interplay between pairs

Elevation at  $^{186}\text{Hf}$  interpreted to be equally prominent to other peaks in region: double magicity ( $^{100}\text{Sn}$ ,  $^{96}\text{Zn}$ ) or shape transition ( $^{152}\text{Nd}$ )





# One horizon is to continue JYFLTRAP and TITAN's exploration for Sn & its neighbors.



Interest in exploring possible subshell closure at  $N = 90$

Larger asymmetry in pairing-gap energy around  $N=82$  for Sn than Te & Xe.

JYFLTRAP calculated SLy4 EDF + HFB pairing in spherical approximation. Data requires volume & mixing pairing, not only surface.

Structure is of relevance to r-process nucleosynthesis calculations

# TITAN takes inspiration from A. Gezerlis and G. Palkanoglou ...

PRL **106**, 252502 (2011)

PHYSICAL REVIEW LETTERS



## Mixed-Spin Pairing Condensates in Heavy Nuclei

Alexandros Gezerlis,<sup>1</sup> G. F. Bertsch,<sup>1,2</sup> and Y. L. Luo<sup>1</sup>

<sup>1</sup>*Department of Physics*

<sup>2</sup>*Institute for Nuclear Theory  
(Rutgers University)*

PHYSICAL REVIEW C **93**, 014312 (2016)

## Probing mixed-spin pairing in heavy nuclei

Brendan Bulthuis and Alexandros Gezerlis

*Department of Physics*

(Received ...)

PHYSICAL REVIEW LETTERS **134**, 032501 (2025)

## Spin-Triplet Pairing in Heavy Nuclei Is Stable against Deformation

Georgios Palkanoglou<sup>1,2</sup>, Michael Stuck<sup>1</sup>, and Alexandros Gezerlis<sup>1</sup>

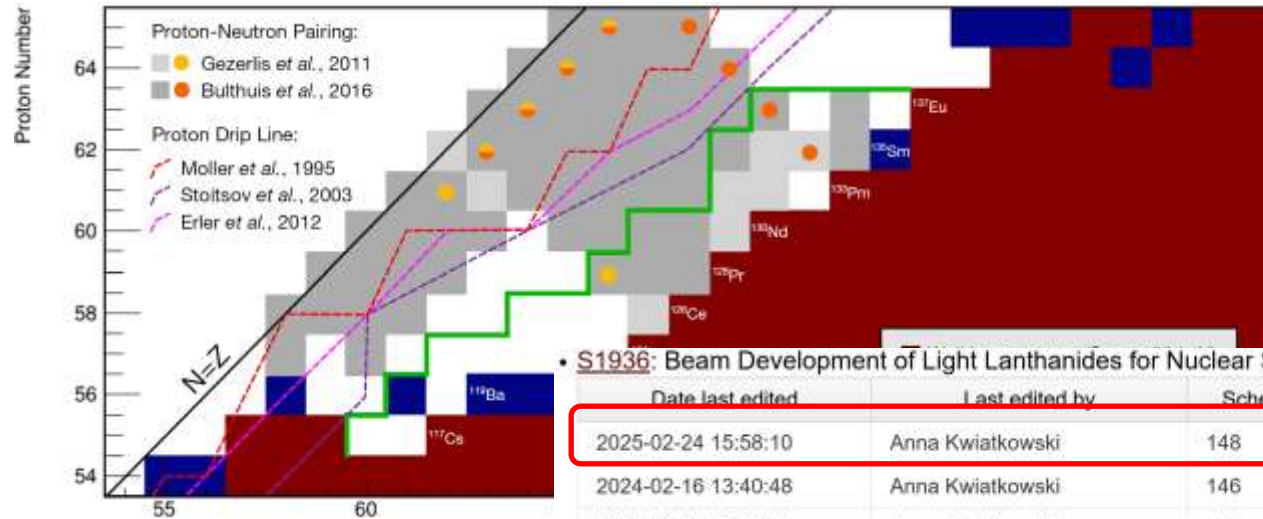
<sup>1</sup>*Department of Physics, University of Guelph, Guelph, Ontario N1G 2W1, Canada*

<sup>2</sup>*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*



(Received 22 February 2024; accepted 4 December 2024; published 23 January 2025)

# TITAN will examine pairing and the proton dripline among the lanthanides.



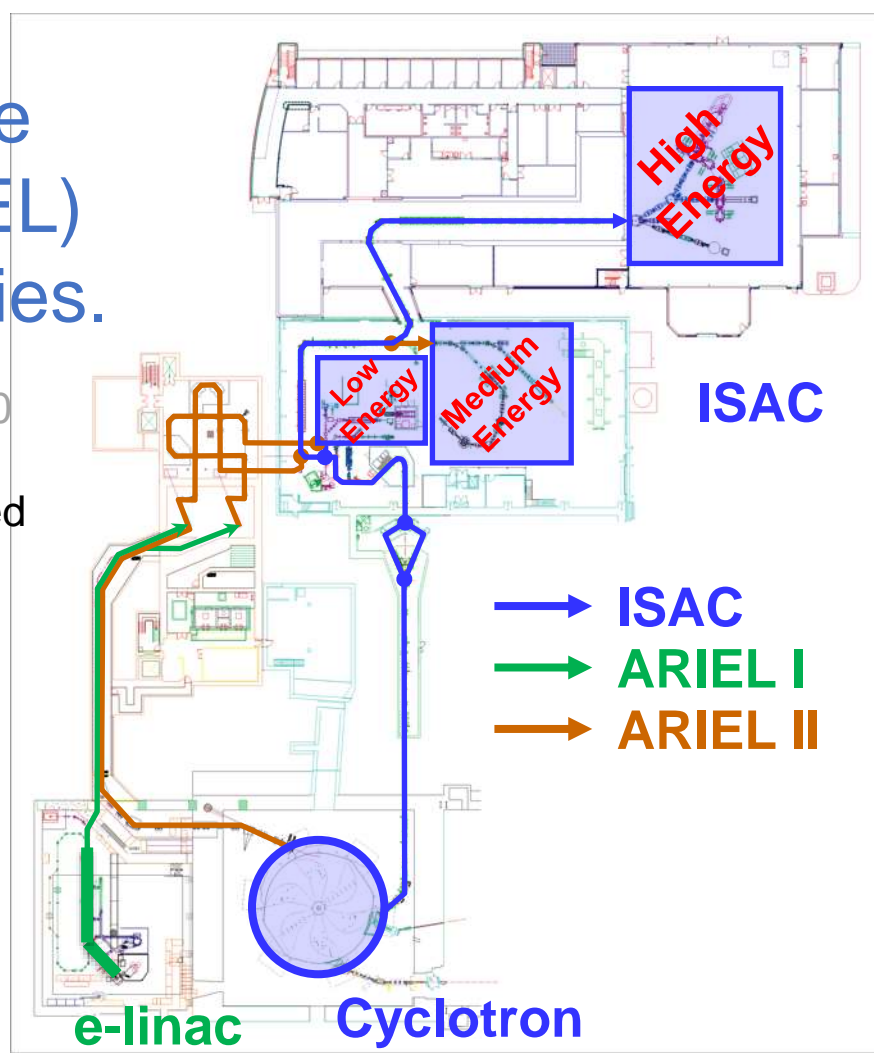
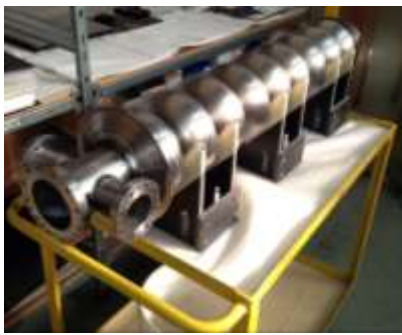
## • S1936: Beam Development of Light Lanthanides for Nuclear Structure Investigations Approaching $N=Z$

Date last edited	Last edited by	Schedule	Facility	Shifts	View	
2025-02-24 15:58:10	Anna Kwiatkowski	148	TITAN	6	<a href="#">View</a>	(Su
2024-02-16 13:40:48	Anna Kwiatkowski	146	TITAN	6	<a href="#">View</a>	(Su
2023-02-22 15:13:31	Anna Kwiatkowski	144	TITAN	6	<a href="#">View</a>	(Su
2022-08-09 00:59:56	Erich Leistenschneider	143	TITAN	6	<a href="#">View</a>	(Su
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2020-02-11 07:13:58	Erich Leistenschneider	138	TITAN	6	<a href="#">View</a>	(Su
2019-07-15 21:17:11	Erich Leistenschneider	137	TITAN	6	<a href="#">View</a>	(Su

Beyond 2025, there will be upgrades  
to RIB production and to facilities.

# TRIUMF's Advanced Rare IsotopE Laboratory (ARIEL) triples science opportunities.

- AETE:  $\leq 100$  kW, 35 MeV, electrons
- APTW / ITE / ITW:  $\leq 50$  kW, 500 MeV,  $\leq 100$   $\mu$ A protons
- e-linac under operation; proton line installed
- online 2027, full specs 2029
- > 9000 hours of RIB per year





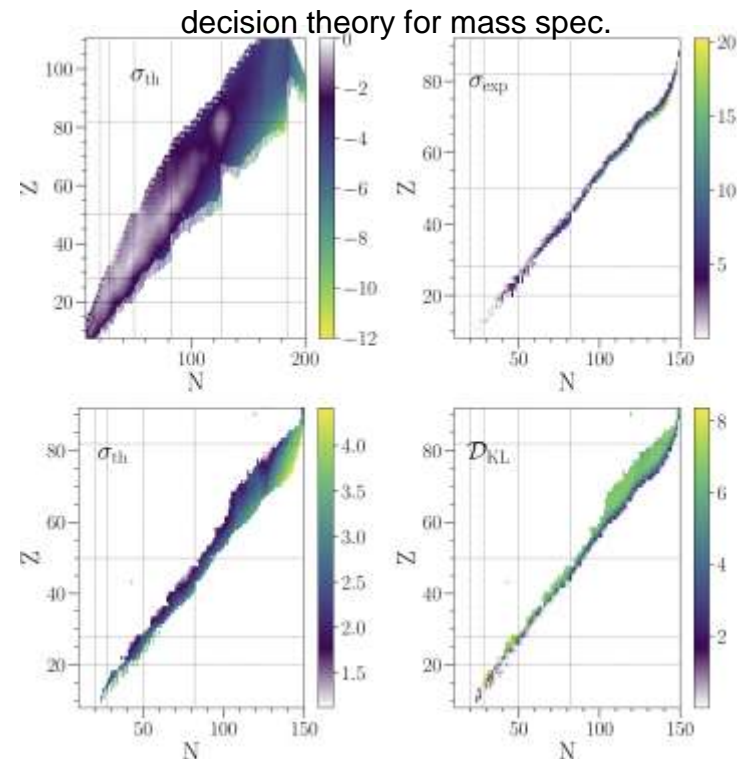
# Ongoing or planned RIB facility upgrades will extend experimental reach of all programs.

Upgrade → benefit:

- higher-energy drivers → further from stability
- new production mechanisms → producing nuclides of interest &/or reduce background
- higher rates → better precision
- multi-user capability → simultaneous science, longer experiments

Other facility upgrades:

- RIBF and FRIB are online (driver)
- HIAF, SPIRAL, FAIR, iThemba, & ISOLDE-CERN (driver) will be complemented by vCARIBU+ N=126 factory and Jyvaskyla (MNT) and Cyclotron Institute (IGISOL)
- RAON (new) adds an Asian competitor



# Next-gen mass spectrometer & techniques are being developed in preparation for new opps.

New  $B\rho$ -TOF spectrometers are being built (superFRS-FAIR and HRS-FRIB)

Storage rings:

- SMS+IMS technique demonstrated at CSRe-IMP  $\rightarrow$  higher precisions
- Planned at CR-FAIR and SRing-HIAF

Penning traps

- PI-ICR should achieve  $\delta m/m \sim 10^{-10}$  & should improve sensitivity  $\rightarrow$  further from stability
- FT-ICR developed for RIB (LEBIT & SHIPTRAP)  $\rightarrow$  improve sensitivity  $\rightarrow$  further from stability

MR-TOF

- mass-selective “re-trapping”/in-situ beam purification demonstrated at TITAN  $\rightarrow$  higher dynamic range, better sensitivity  $\rightarrow$  further from stability
- Simultaneous  $T_{1/2}$  at TITAN and SLOW-RI
- induced-current detection (ongoing at Weizmann Institute) could be coupled to other experiments to “double” science output
- value vs. cost make MR-TOF the tool of choice

## Mass spec improved precision & accuracy for RIB.

- B $\rho$ -TOF (FRIB, GANIL-SPIRAL) & Storage rings (ESR-GSI, CSR-IMP)
- Penning trap (TITAN, JYFLTRAP, ISOLTRAP, CPT, LEBIT)
- MR-TOF (TITAN, FRS, ISOLTRAP, SLOW-RI, *St Benedict-ANL*, *LEBIT*)

## TITAN's broad portfolio allows a broad scope.

- masses & highly-charged-ion spectroscopy
- pioneering ion-trap techniques
- for studies in pairing, shell evolution, special shapes, ...

## Synergy of exp. & theory ...

- leveraged but fully realized?

# Some observations on exp-th collaborations:

## Differences in practices

- Experimental timelines > 0.25-3 yrs from setup to completed analysis vs. theoretical calculations
- PAC proposal & scheduling add months to years
- Exp. tied to the “machine”

## Authorship practices vary

- Co-authorship in experiment (N=5-50) vs. in theory (N=1-5)
- First authorship is exp or th, esp for students & postdocs? Or, by who writes how much up?

## Not full overlap of exp. & th feasibility

- Sensitivity studies similar to Mumpower *et al.*, 2016? Specific nuclides/isotopic chains like halos, Ca dripline?
- Holistic approaches like many observables, including mass, for a specific region?

## Understanding trustworthiness of data isn't straightforward.

- AME is not sacrosanct, especially extrapolations
- Exp like “model-independent” results
- Th calcs can move faster than exp
- Personal opinion: Penning trap > MR-TOF > storage ring > Bp-TOF > indirect (decays, rxns) >  $\beta$ -endpoint

## Uncertainties

- Ion trappers measurements begin to disagree  $>1\sigma$ !
- Theory/model error bars?

## Involvement on the other side, esp by students & PDFS?

- Exp PDFs sometimes are *not* nuclear physicists
- Can there be an equivalent to when experimentalists ran NSM codes? What?



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