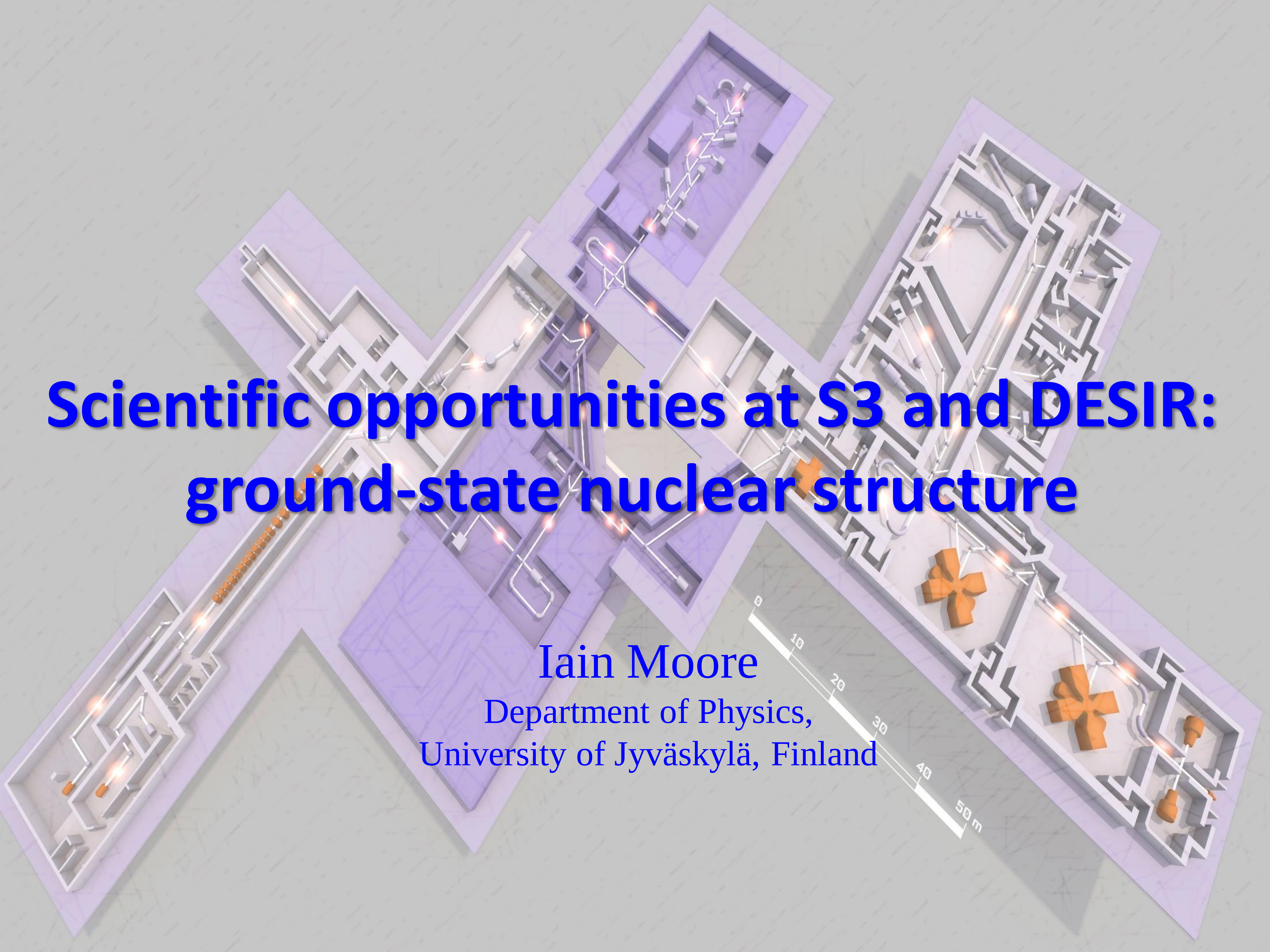


Scientific opportunities at S3 and DESIR: ground-state nuclear structure

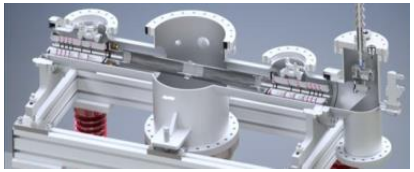
Iain Moore
Department of Physics,
University of Jyväskylä, Finland

Outline

- The atomic mass and nuclear structure
- Trap-assisted spectroscopy
- Nuclear fingerprints on atomic spectra
- Ground- and isomeric state studies below ^{100}Sn
- Proton-rich studies between ^{40}Ca and ^{56}Ni
- Summary

Why do we measure atomic masses?

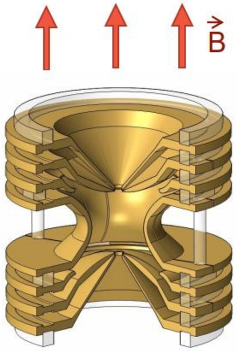
$m(A,Z) = Z \cdot m_p + (A-Z) \cdot m_n + Z \cdot m_e - B(A,Z)$



	$\delta m/m$	δm for m=100 u (μu)	δm for m=100 u (keV)
General physics & chemistry	$\leq 10^{-5}$	1000	1000
Nuclear structure physics - separation of isobars	$\leq 10^{-6}$	100	100
Astrophysics - separation of isomers	$\leq 10^{-7}$	10	10
Weak interaction studies	$\leq 10^{-8}$	1	1
Metrology - fundamental constants Neutrino physics	$\leq 10^{-9}$	0.1	0.1
CPT tests	$\leq 10^{-10}$	0.01	0.01
QED in highly-charged ions - separation of atomic states	$\leq 10^{-11}$	0.001	0.001

MR-TOF

Penning traps



Nuclear structure via mass measurements

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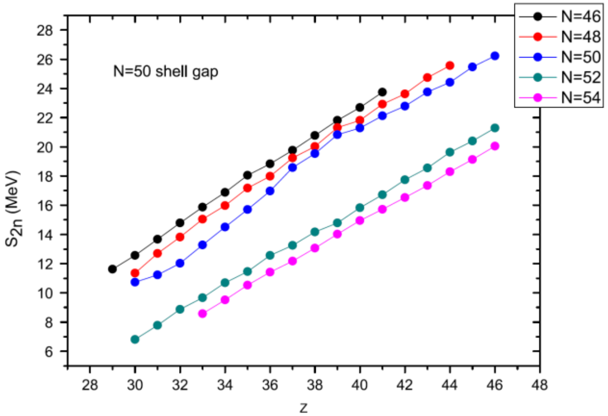
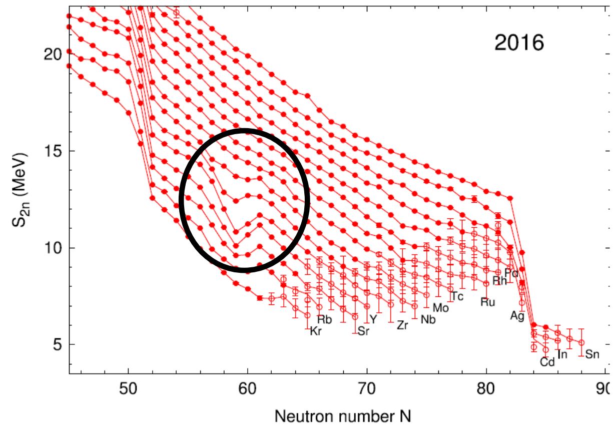
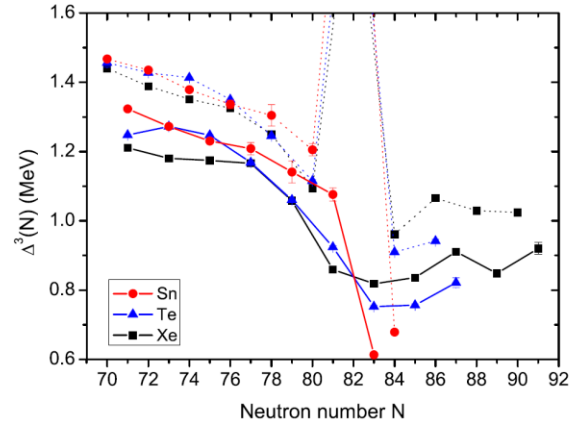


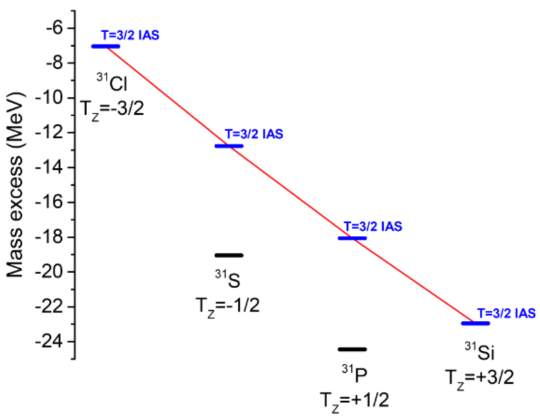
Evolution of shell gaps



Onset of deformation

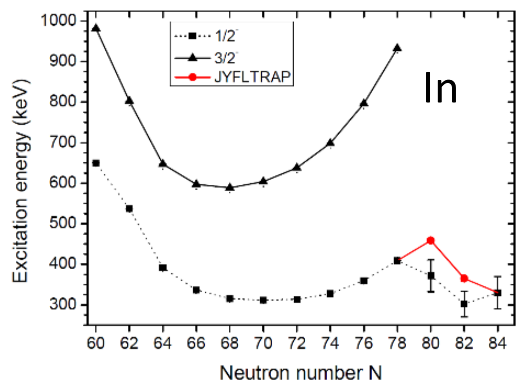


Nucleon pairing energies

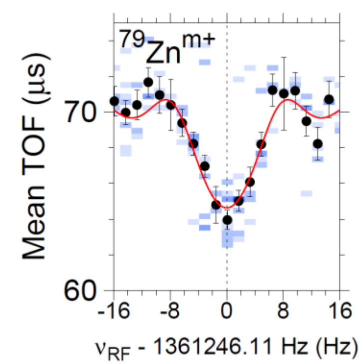


IMME, isospin symmetry

ISOMERS



Single-particle energies



Shape coexistence

Trap-assisted decay spectroscopy

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A=111 fission fragments

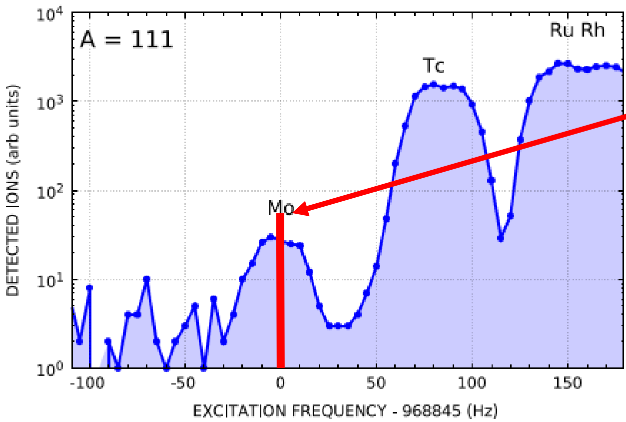
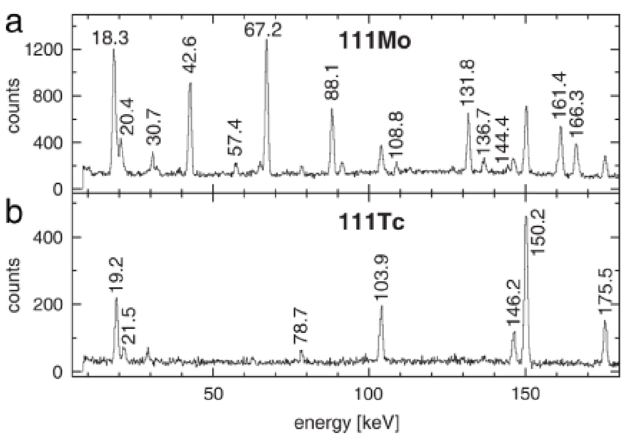
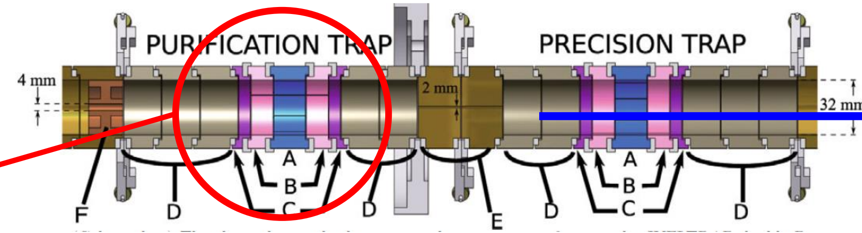
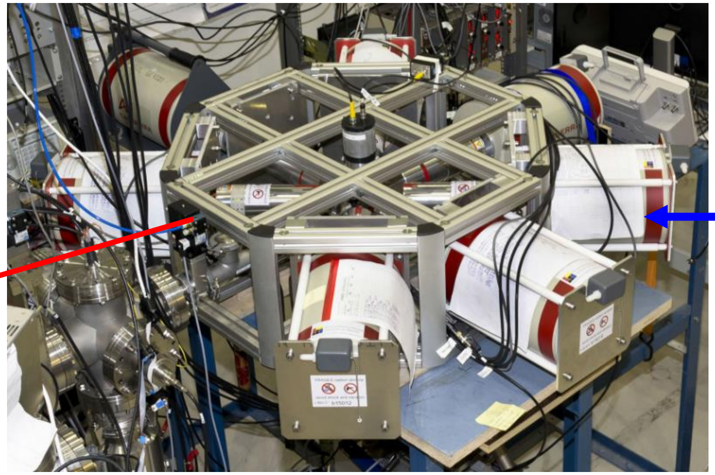


Fig. 24. Mass spectrum of $A = 111$ isobars.







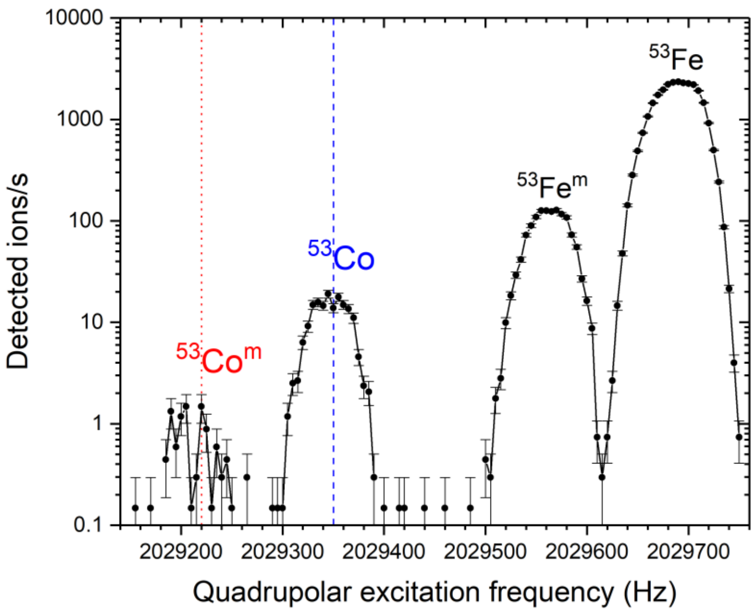
- Focus of decay spectroscopy region at IGISOL on studies of evolution of coexisting shapes around A=100-120
- Monoisotopic beam of ^{111}Mo delivered for post-trap decay spectroscopy

Low-energy Ge array (U-Warsaw) @JYFLTRAP

J. Kurpeta et al., Phys. Rev. C 84 (2011) 044304

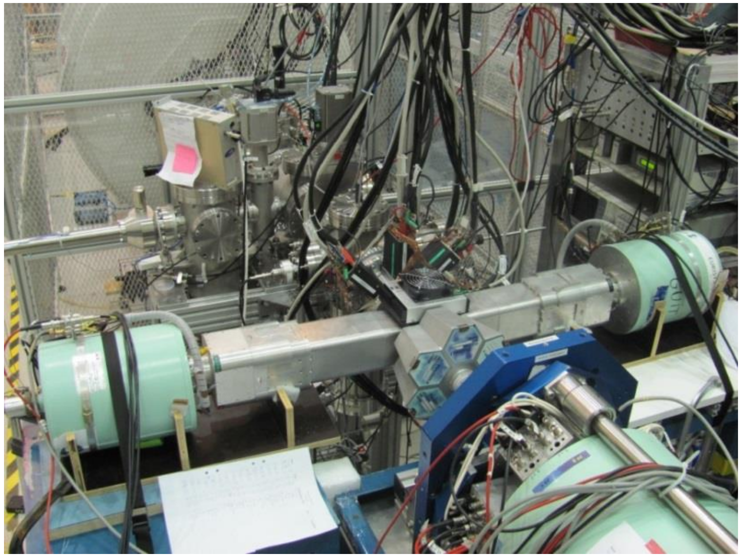
Trap-assisted spectroscopy – proton-rich nuclei

Proton-emission branching with TASISpec



- Revisiting ^{53m}Co 50 years after the discovery of proton radioactivity
- TASISpec: DSSD array with Cluster and 2 Clover detectors
- Complementary studies with ACTAR TPC, LISE 3 @GANIL

L.G. Sarmiento et al., to be submitted



Other post-trap detectors:

- DTAS (total absorption decay spectroscopy)
- BELEN for delayed neutrons
- MONSTER…

~60% of JYFLTRAP experiments are for spectroscopy-related proposals

Post-trap spectroscopy at DESIR & in-trap spectroscopy

Nuclear fingerprint on atomic spectra

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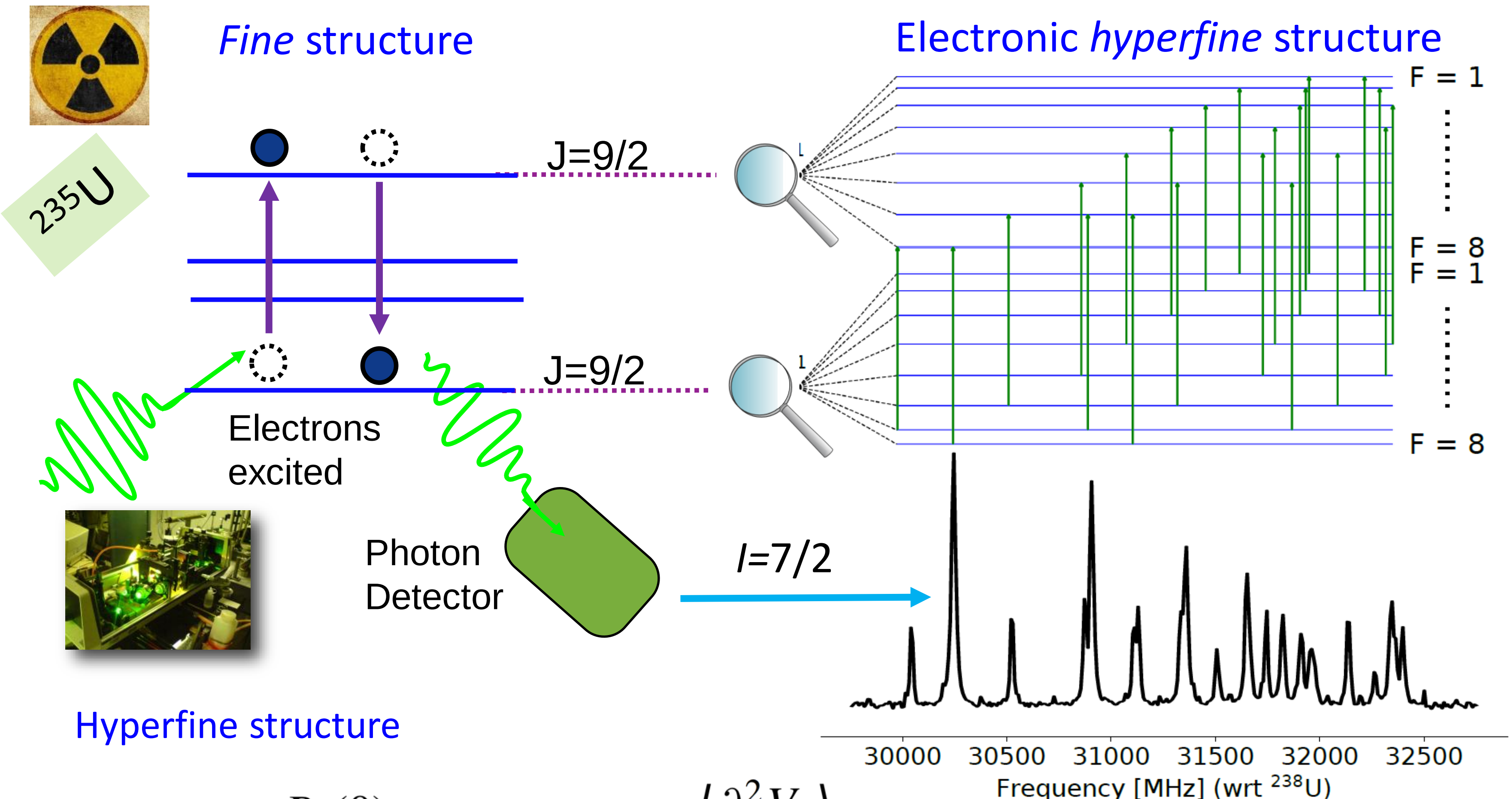
Fine structure

Electronic *hyperfine* structure



Hyperfine structure

$$A = \frac{\mu_I B_e(0)}{I J}$$

Magnetic dipole interaction

$$B = e Q_s \left\langle \frac{\partial^2 V_e}{\partial z^2} \right\rangle$$

Electric quadrupole interaction

I

Nuclear spin

Isotope shifts of electronic transitions

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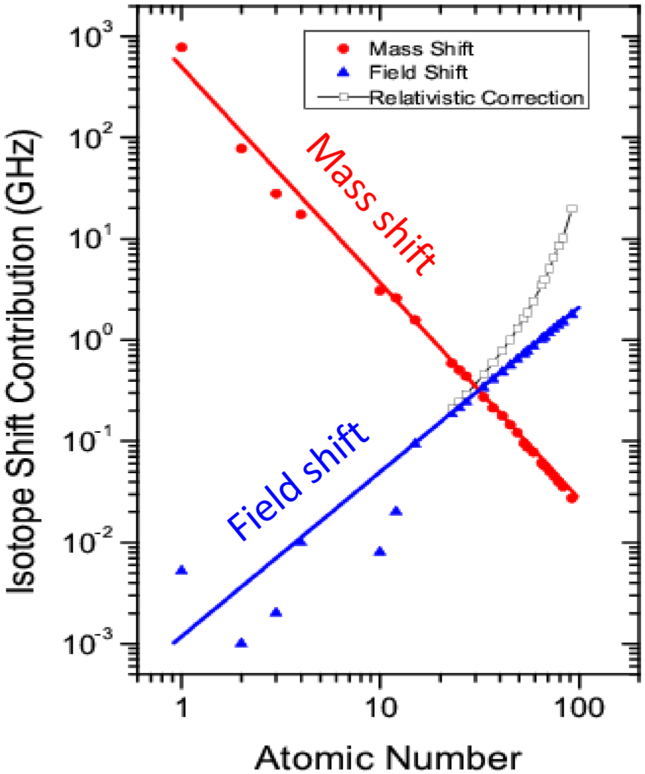
Nuclear mass Nuclear size

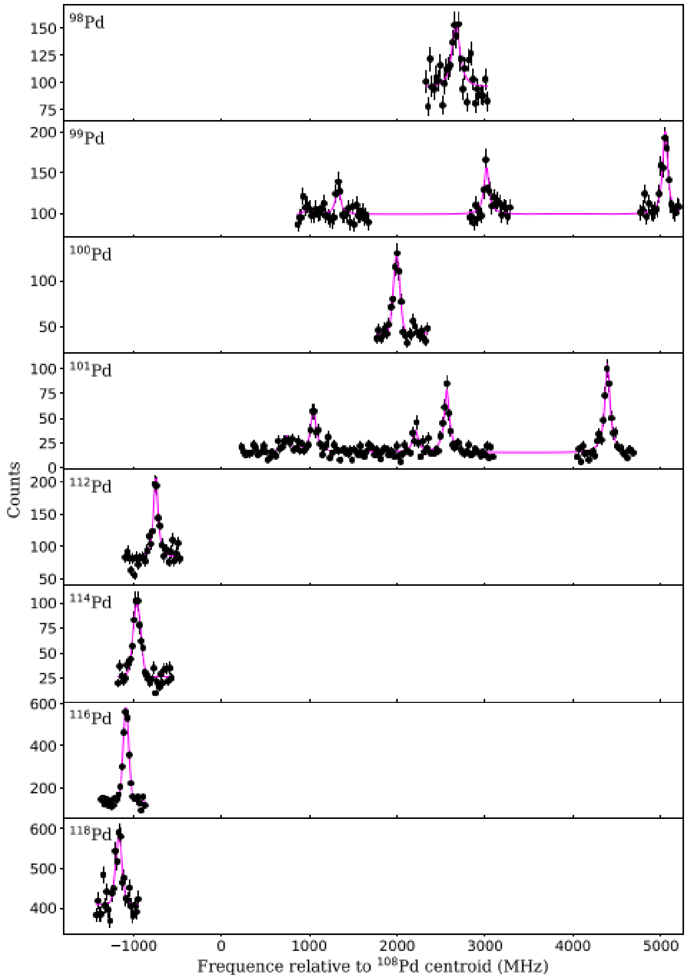
$$\delta\nu_i^{A,A'} = M_i \frac{A'-A}{AA'} + F_i \delta\langle r^2\rangle^{A,A'}$$



Higher *Z* can afford lower resolution methods (RIS @S3)

Lower *Z* requires high resolution (CLS @DESIR)

Pd isotope shifts



S. Geldhof et al., to be submitted

What can the nuclear charge radii tell us?

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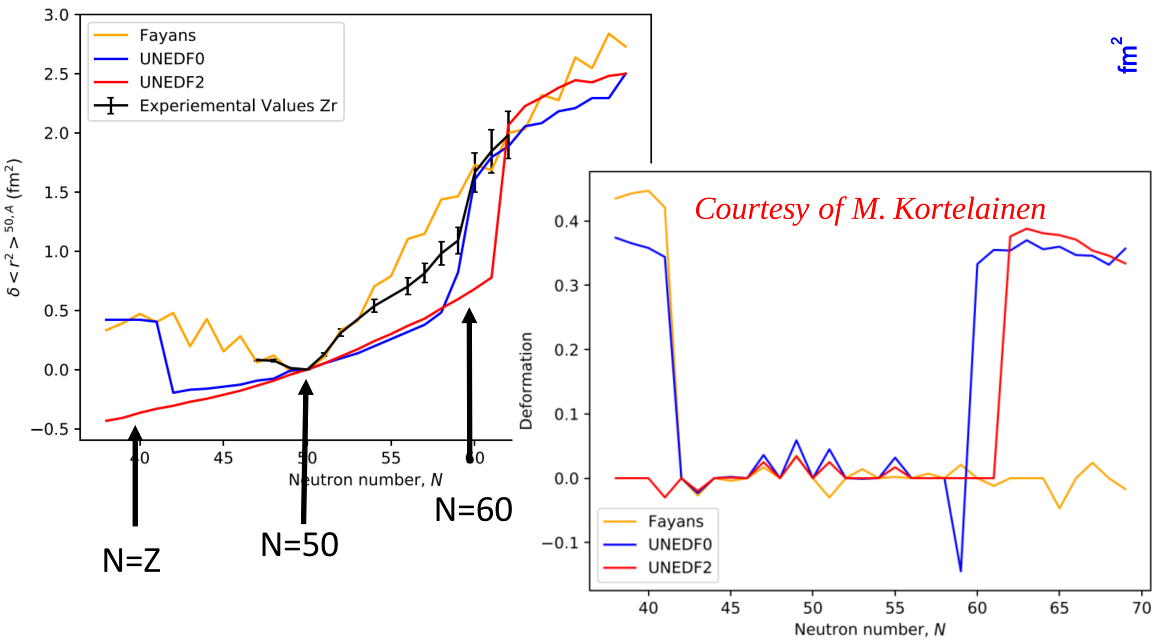
A simple droplet model approach:

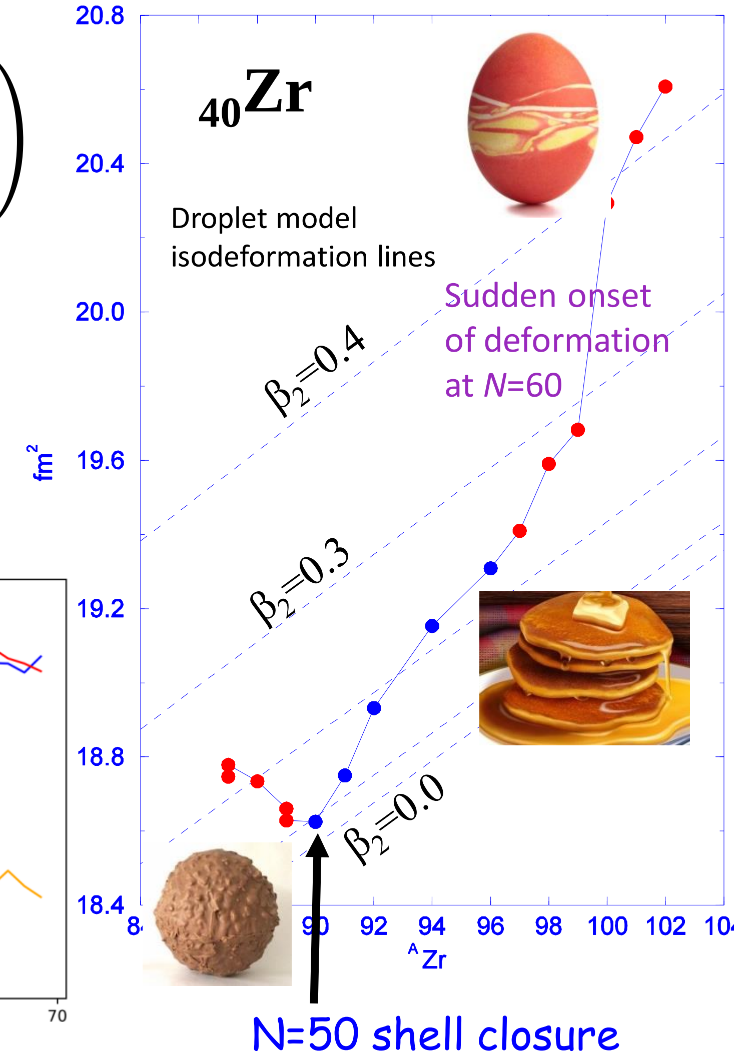
$$\langle r^2 \rangle = \langle r^2 \rangle_{sph} \left(1 + \frac{5}{4\pi} \left(\langle \beta_2^2 \rangle + \cdots \right) \right)$$

Size (liquid droplet model)

Shape (Quadrupole term)

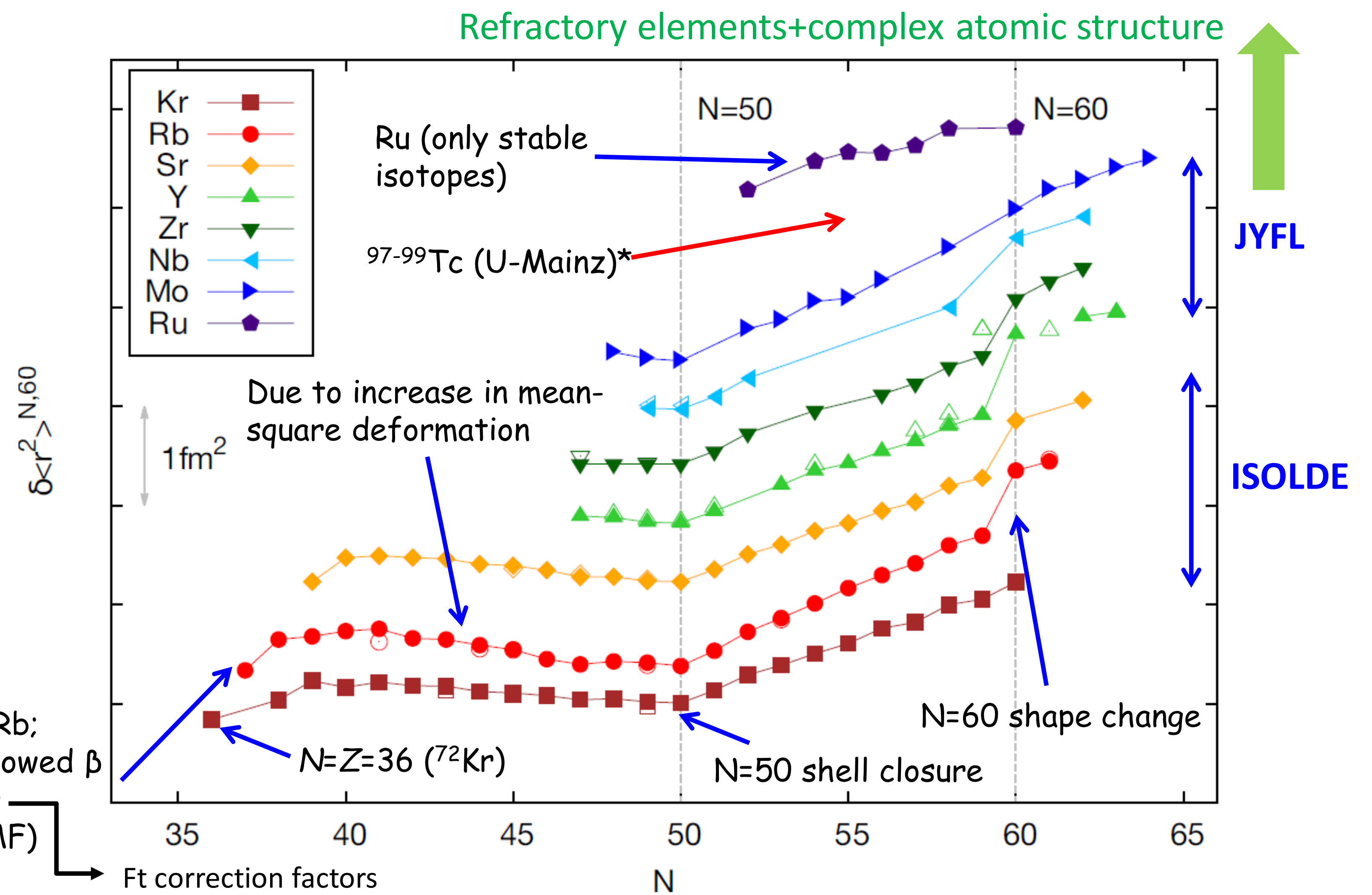
Charge radii and deformation from density functional theory





- Of high interest to probe towards N=Z

Charge radii systematics



N=Z=^{74}Rb; superallowed β Emitter (TRIUMF) → Ft correction factors

E. Mane et al., PRL (2011) 212502

**T. Kron et al., Phys. Rev. C 102 (2020) 034307*

Laser spectroscopy towards the *N=Z* line

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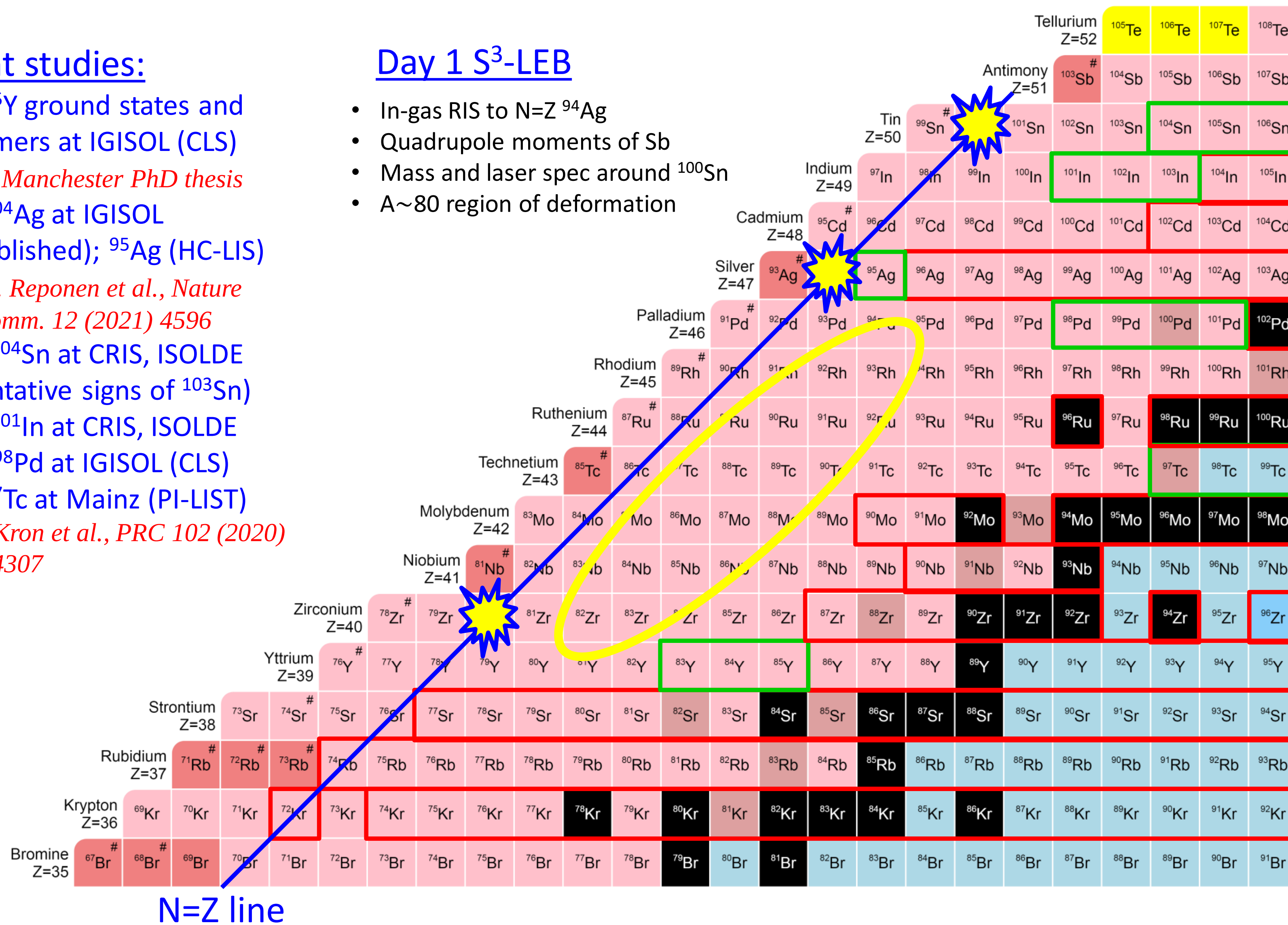
Recent studies:

- $^{83-85}$Y ground states and isomers at IGISOL (CLS)
  - *U. Manchester PhD thesis*
- $^{96-104}$Ag at IGISOL (published); ^{95}Ag (HC-LIS)
  - *M. Reponen et al., Nature Comm. 12 (2021) 4596*
- To ^{104}Sn at CRIS, ISOLDE (tentative signs of ^{103}Sn)
- To ^{101}In at CRIS, ISOLDE
- $^{101-98}$Pd at IGISOL (CLS)
- $^{99-97}$Tc at Mainz (PI-LIST)
  - *T. Kron et al., PRC 102 (2020) 034307*

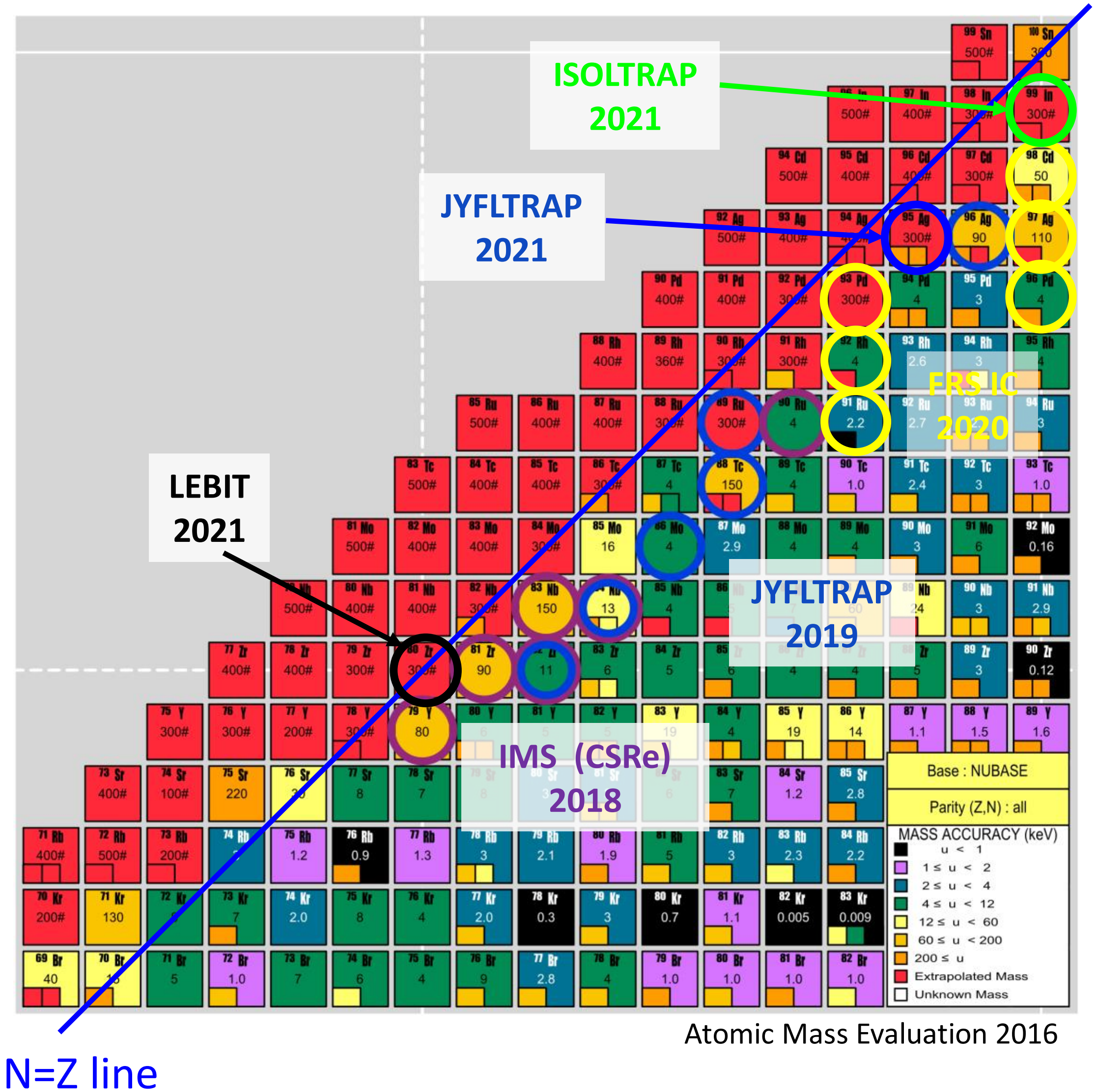
Day 1 S^3-LEB

- In-gas RIS to N=Z ^{94}Ag
- Quadrupole moments of Sb
- Mass and laser spec around ^{100}Sn
- A~80 region of deformation



I.D. Moore, Colloque GANIL, 28 Sept. 2021

Current status of masses below ^{100}Sn



Atomic Mass Evaluation 2016

Courtesy of W. Plass & C. Hornung (updated last week)

- Penning trap, storage ring and MR-TOF devices used
- Generally, large shifts in the mass surface in A=80-90 region for N=Z+1 → validity of extrapolation to N=Z?
- Significant discrepancies between Penning traps and IMS (CSRe)

M. Vilen et al., PRC 100 (2019) 054333

- FRS Ion Catcher, GSI, MR-TOF, ^{97}Ag
  - discovery of long-lived (1/2$^-$) isomeric state

C. Hornung et al., PLB 802 (2020) 135200

- FRS Ion Catcher, GSI, MR-TOF, ^{93}Pd
  - connected to ^{94}Ag via 1-p decay
- JYFLTRAP, ^{95,96g,m}Ag (2021)
- ISOLTRAP, $^{99\text{-}101g,m}$In
  - amplifies discrepancy in existing β-decay Q values used to derive the mass of ^{100}Sn

M. Mougeot et al., Nature Phys. (2021) https://doi.org/10.1038/s41567-021-01326-9

- LEBIT, ^{80}Zr
  - compelling evidence for deformed shell closure

arXiv:2108.13419v1 (30 Aug. 2021)

Spin-gap isomers below ^{100}Sn

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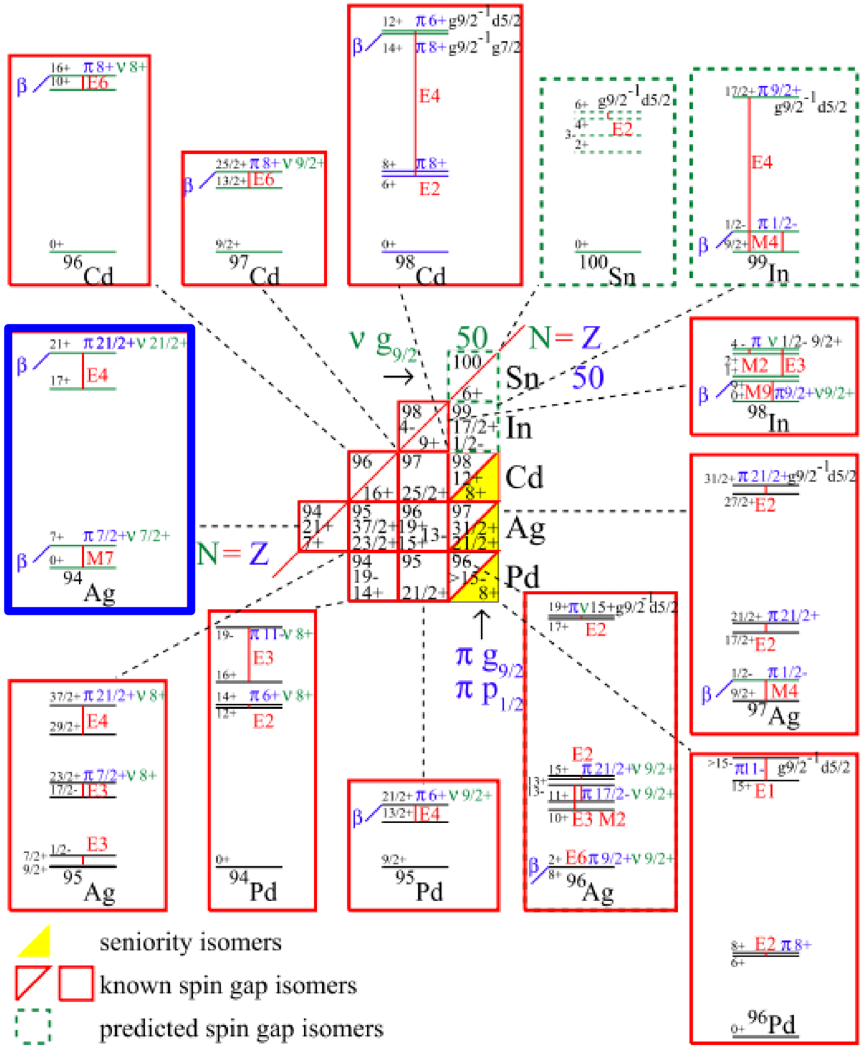


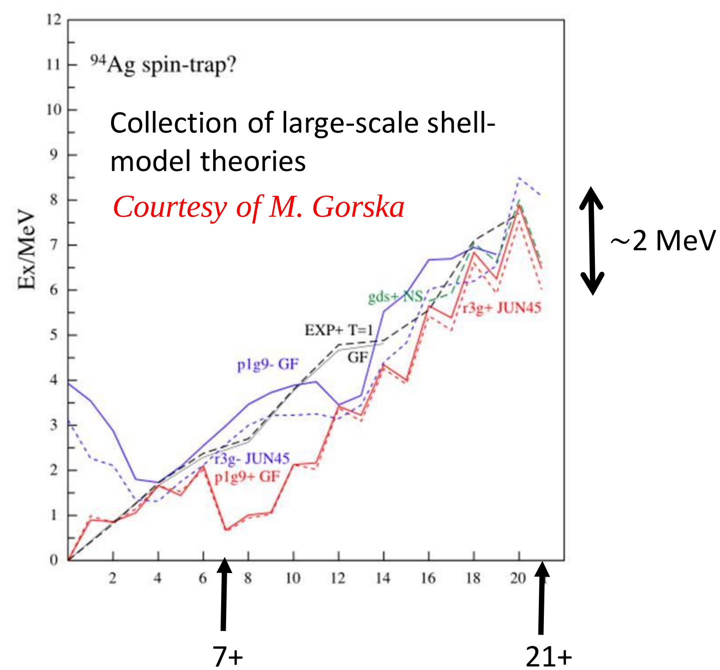
T. Faestermann et al., PPNP 69 (2013) 85

Nucleon-Nucleon interactions

- Effective single particle energy levels (^{101}Sn, ^{99}In)
- T=0 T=1 pairing interaction (^{98}In)
- Spin-aligned coupling scheme (^{94}Ag, ^{90}Rh)

Comprehensive set of Q_β, $T_{1/2}$, $b_{\beta p}$ and γ data for p-rich nuclei 43 ≤ N, Z ≤ 51 from RIKEN.

J. Park et al., Phys. Rev. C 99 (2019) 034313



~15 years of developments for Ag at IGISOL

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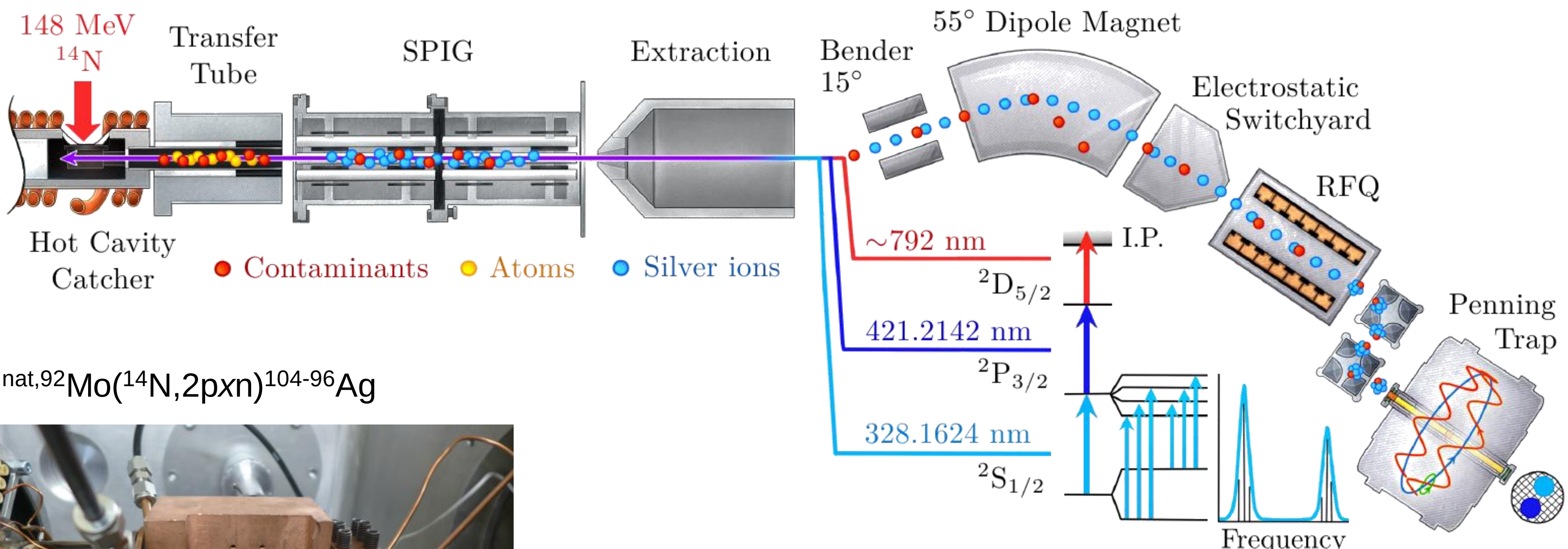
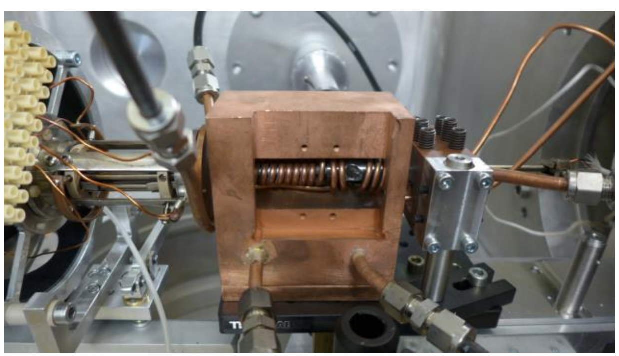
An inductively-heated hot cavity catcher laser ion source at IGISOL



$^{nat,92}Mo(^{14}N,2pxn)^{104-96}Ag$



**M. Reponen et al., Rev. Sci. Instrum 86 (2015) 123501*

- GSI work (Kirchner) – Ag has excellent extraction from graphite
- In collaboration with ECR team, a new inductively-heated cavity source*
- Tested online, confirming ~1% total efficiency for Ag
- Three-step resonance laser ionization and spectroscopy

Note: IPHC Strasbourg development of inductive micro-oven for GANIL ECR sources

Penning trap-assisted in-source RIS

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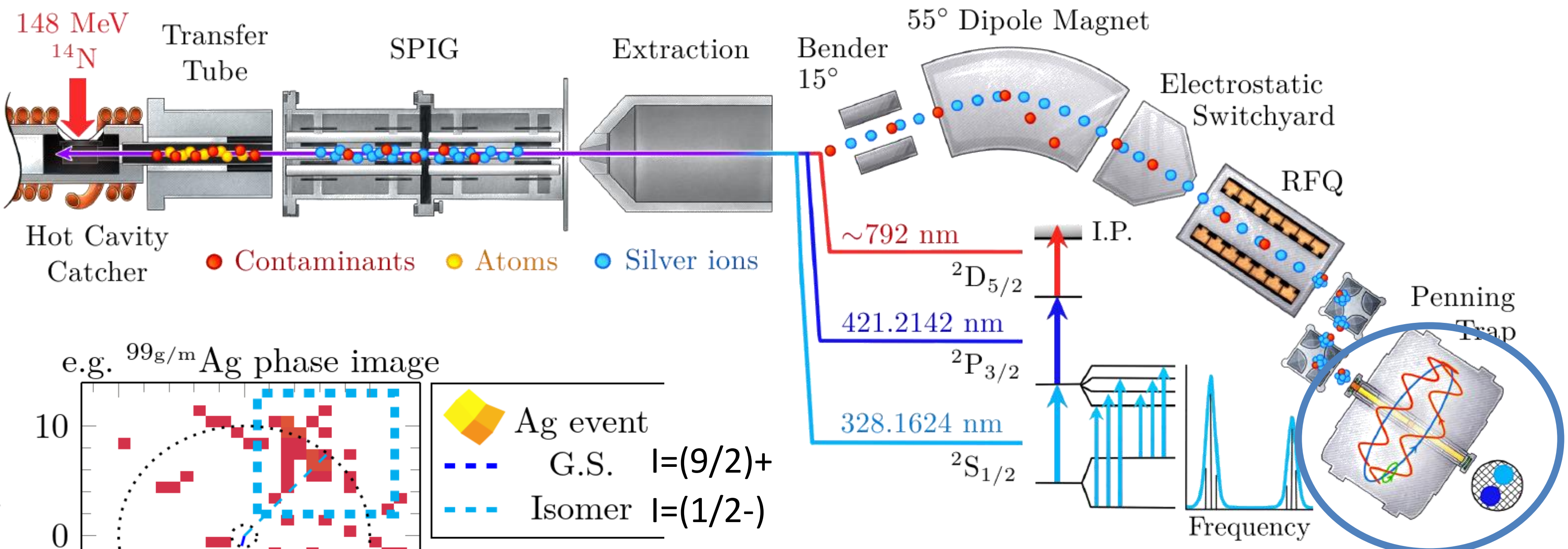
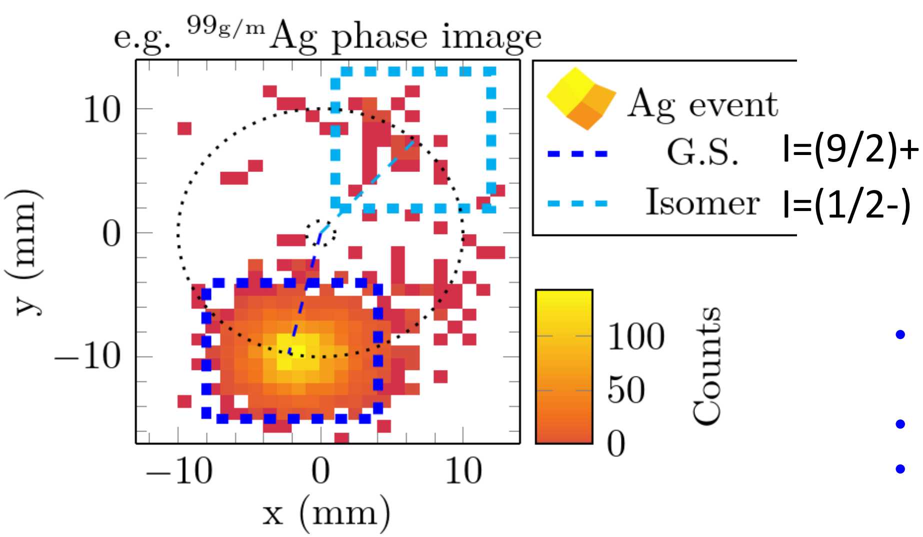
An inductively-heated hot cavity catcher laser ion source at IGISOL



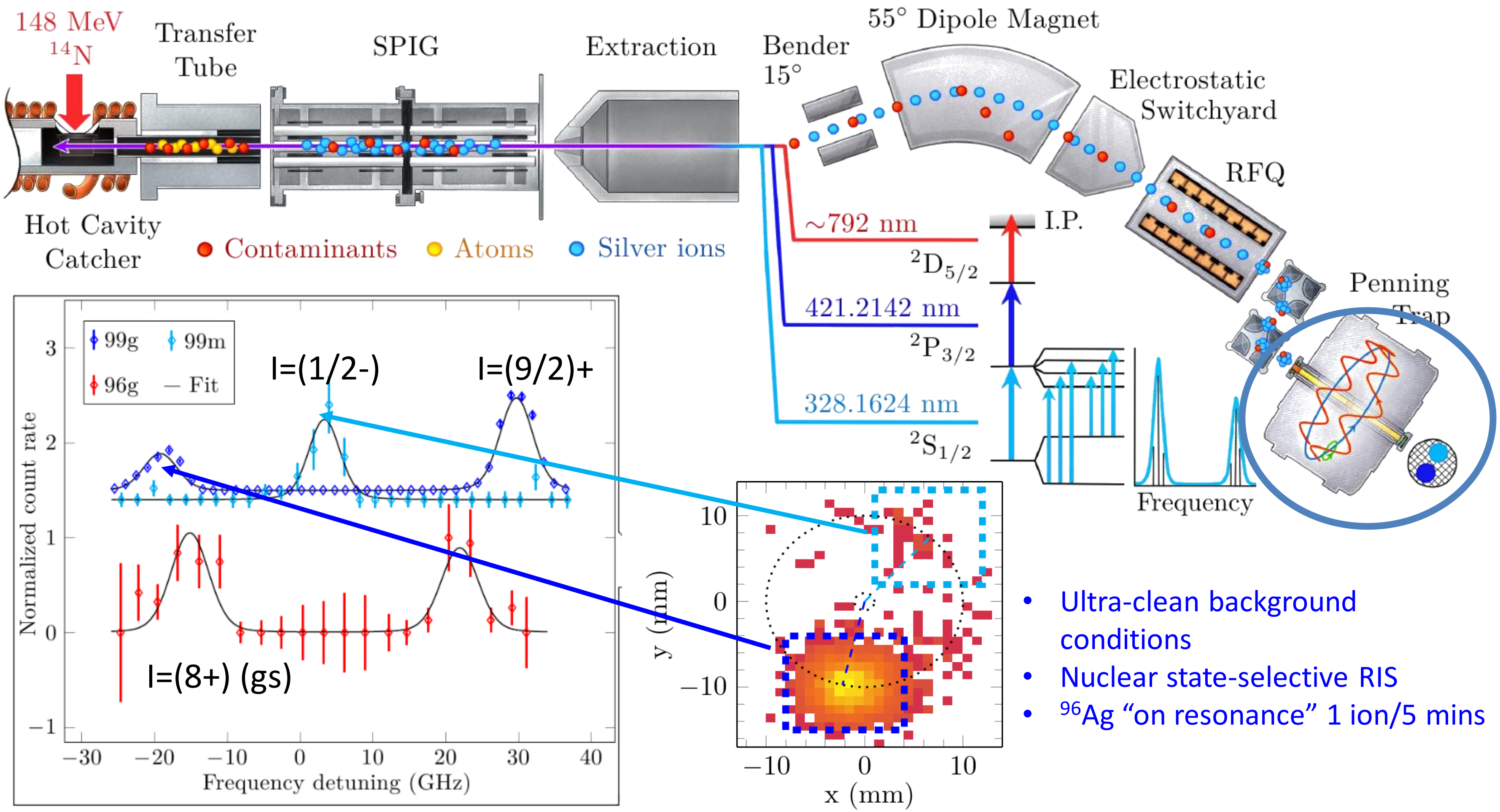


Trap-assisted spectroscopy + laser selectivity

- Ions are mass-separated, bunched and injected into the JYFLTRAP Penning trap
- Isobaric purification applied
- PI-ICR method used for state identification (and mass measurements)
- Information on isomeric yield ratios

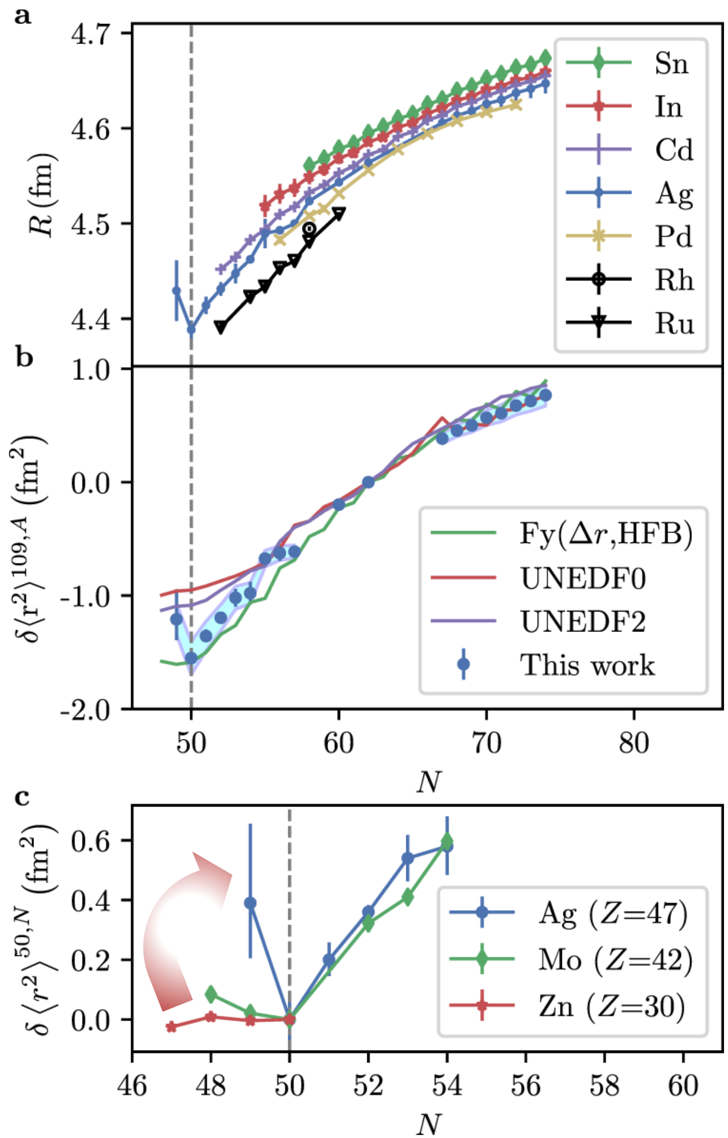
Penning trap-assisted in-source RIS

An inductively-heated hot cavity catcher laser ion source at IGISOL



- Ultra-clean background conditions
- Nuclear state-selective RIS
- ^{96}Ag "on resonance" 1 ion/5 mins

Evolution of charge radii near ^{100}Sn



- New measurements cross *N*=50 shell closure in the region of ^{100}Sn
- UNEDF functionals predict a rather smooth behaviour; Fayans EDF better reproduces local variations
- None of the models reproduces the pronounced increase in crossing *N*=50
- Fayans functional also applied to recent Pd charge radii data; exploration of the strength of pairing correlations (publication to be submitted)

Outlook for PI-ICR-assisted RIS at IGISOL

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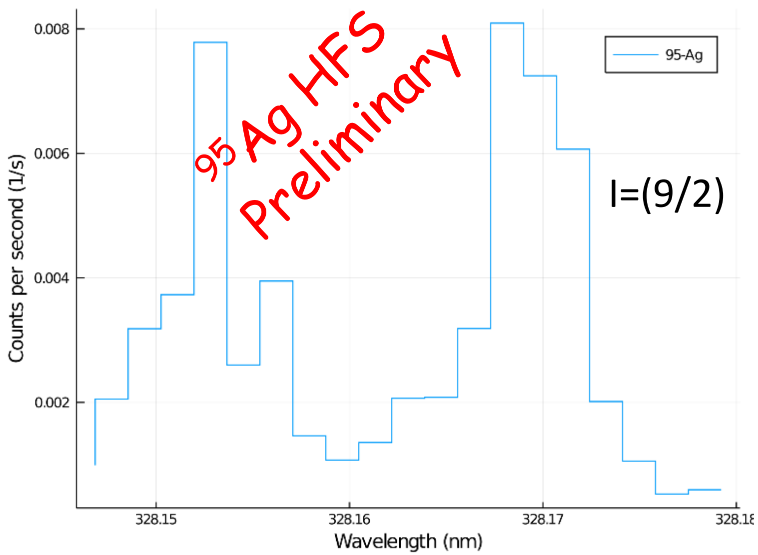
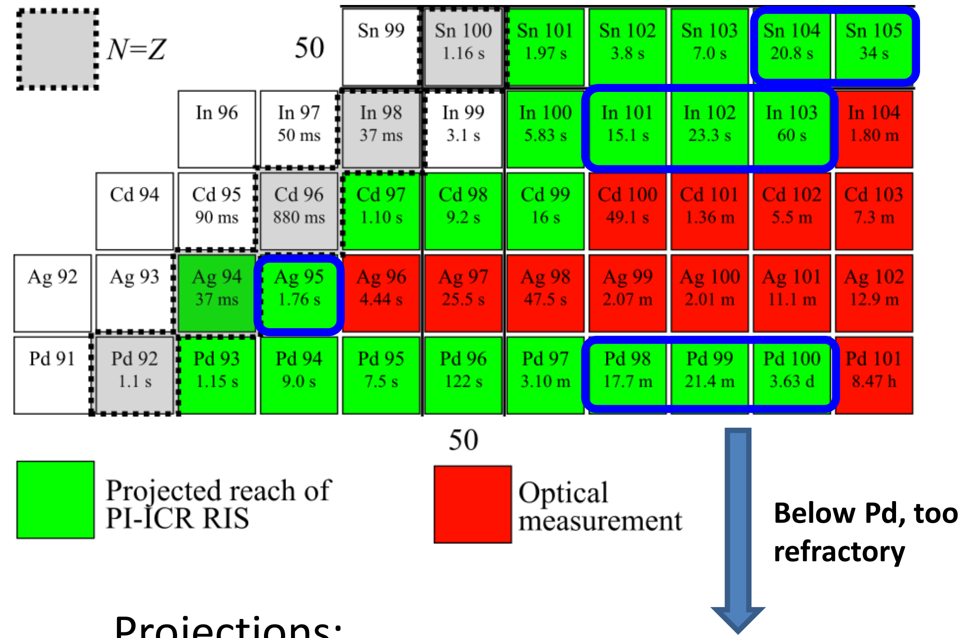
May 2021: ^{58,60}Ni(^{40}Ca,pxn)$^{103\text{-}95}$Ag



- Ca beam intensity 40-50 pnA (average)
- Repeated ^{96}Ag: maximum rate 0.04/s
- Charge radius and dipole moment of ^{95}Ag extracted
- Mass measurements of ^{95,96,96m}Ag
- Tentative signs for (7^{+}) isomer in ^{94}Ag



Projections:

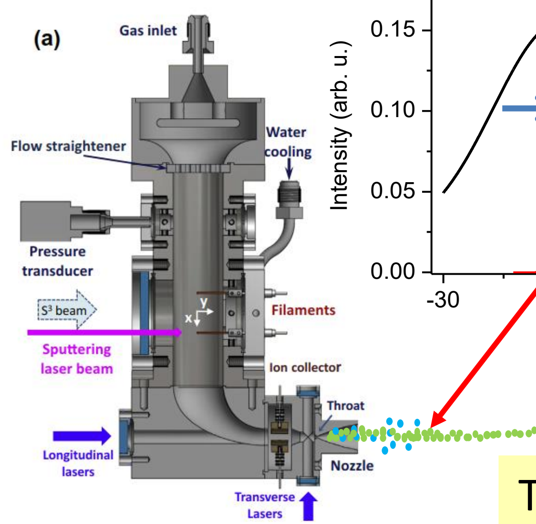
- LISE++ simulations and Gemini++ cross sections
- Assume 0.5% efficiency after mass separation, 10% transmission RFQ and trap
- Laser ionization efficiency ~10%
- ^{40}Ca or ^{58}Ni primary beam, 50 pnA
- Similar statistics as for ^{96}Ag (0.005 ions/s) in <12h

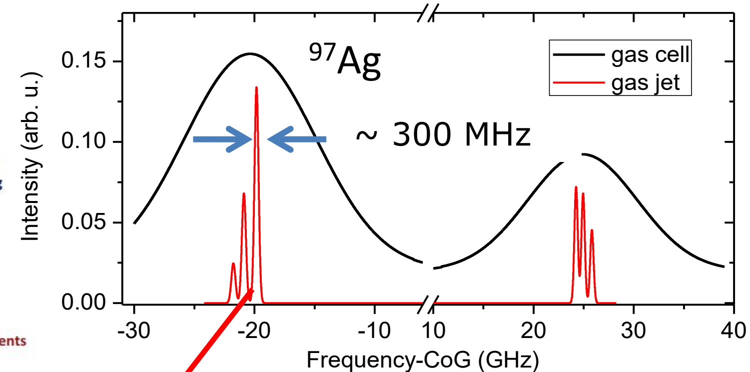
Possibilities for S^3-LEB

	Rates Hz	S3	S3-LEB
N=Z	^{100}Sn	7	0,6
	^{101}Sn	170	14
N=Z	^{98}In	2.6	0,13 (Iso)
	^{99}In	80	7,5
	^{100}In	740	36
	^{98}Cd	3600	352
	^{97}Cd	19	1,6
N=Z	^{96}Cd	4	0,25 (gs) / 0,06 (iso)
N=Z	^{94}Ag	680	0,01 (gs) / 35 (7+) / 1 (21+)
	^{95}Ag	870	77
N=Z	^{92}Pd	810	67
N=Z	^{80}Zr	1300	124

Maximum production rates given for existing SPIRAL2 injector (A/q = 3)

- Primary beam intensity will depend on target capabilities
- NEWGAIN injector project (A/q=7) will boost these rates by *5-10





Resolve hyperfine peaks –
access to Q moments

Talk by Vladimir Manea

Y. Kudryavtsev et al., NIMB 376 (2016) 345

- Provide pure & low energy beams from S^3
- Spectroscopy with only 0,1 pps
- Perform medium-resolution laser spectroscopy 100-300 MHz & Eff > 10%
- MR-TOF-MS, >20-keV precision

Exploring p-rich nuclei between ^{40}Ca and ^{56}Ni

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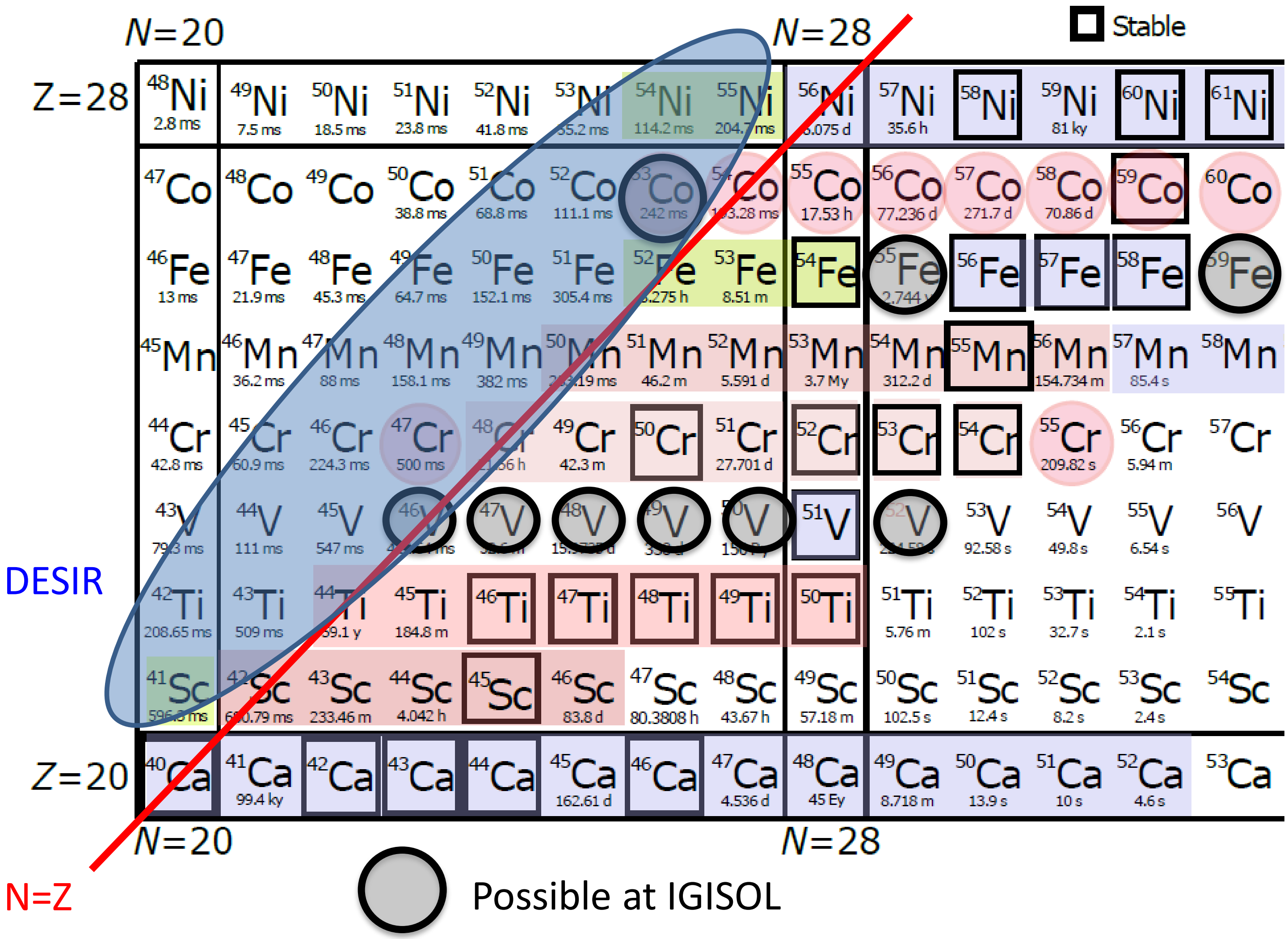
Proposed at IGISOL | Measured at IGISOL | Measured at NSCL | Measured at ISOLDE



Only stable isotopes known for V, Cr and Co

$^{48\text{-}55}$Cr measured at IGISOL (2021)

Offline test performed on V, Fe and Co

Proposal accepted for $^{54\text{-}60}$Co

Many candidates could be studied at DESIR.

Fast gas cell needed!

Courtesy of A. Koszorus

Why is this region interesting?

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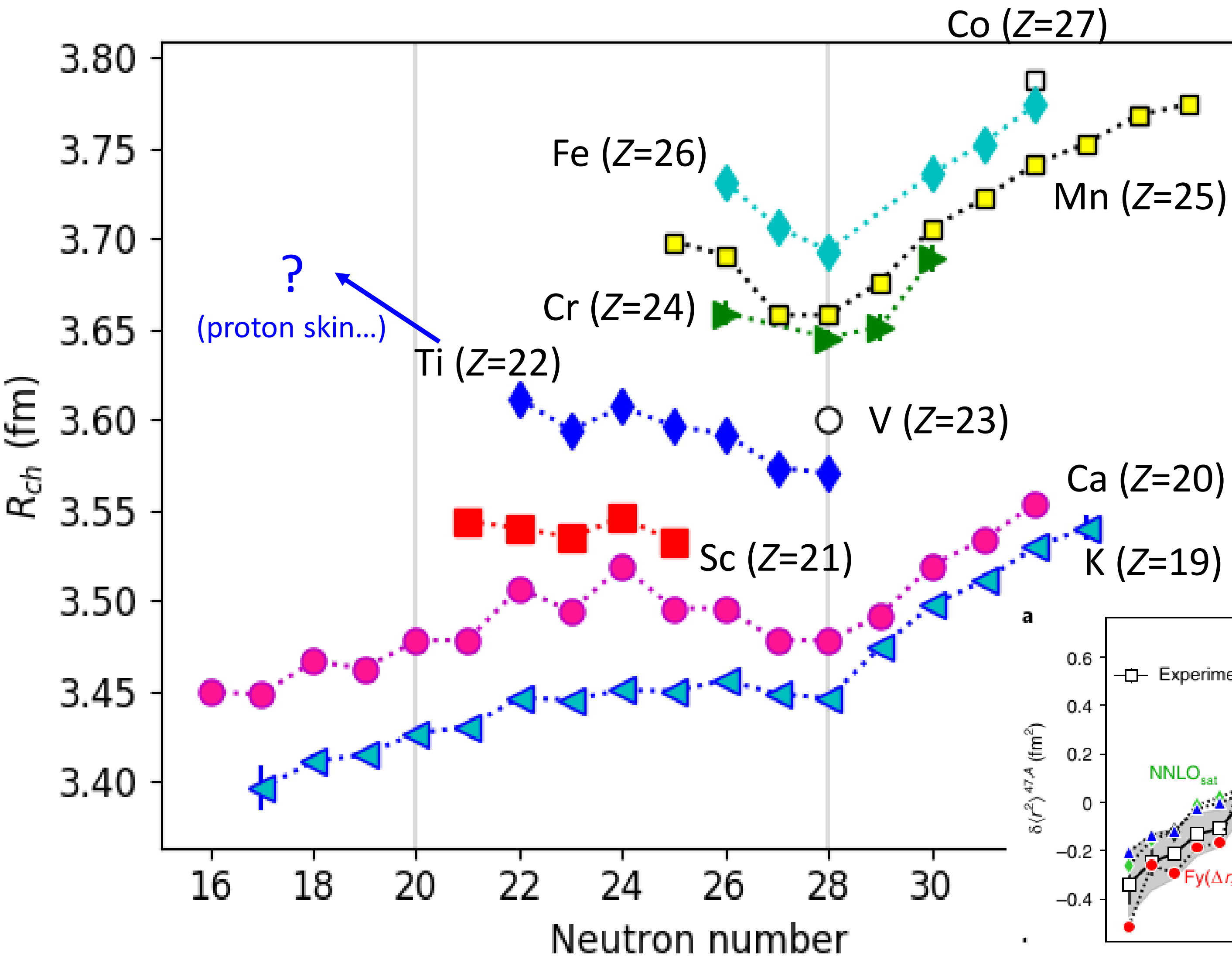
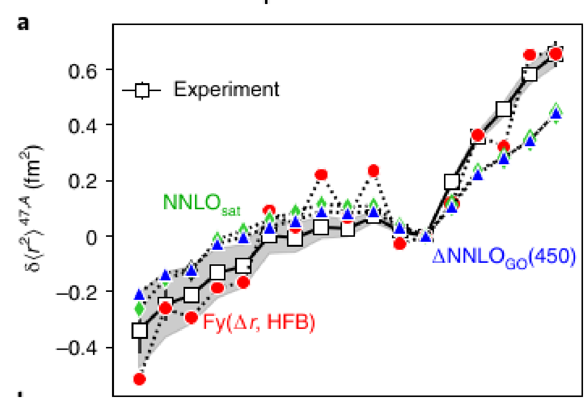


Only stable isotopes known for V, Cr and Co (until recently)

Laser spectroscopy of Co will pave the way for an investigation of the proton-emitting isomer in ^{53}Co!!

Exploring magicity and challenging theory from nuclear sizes



A. Koszorus et al., Nature Phys. 17 (2021) 439

Exploring proton-neutron pairing correlations

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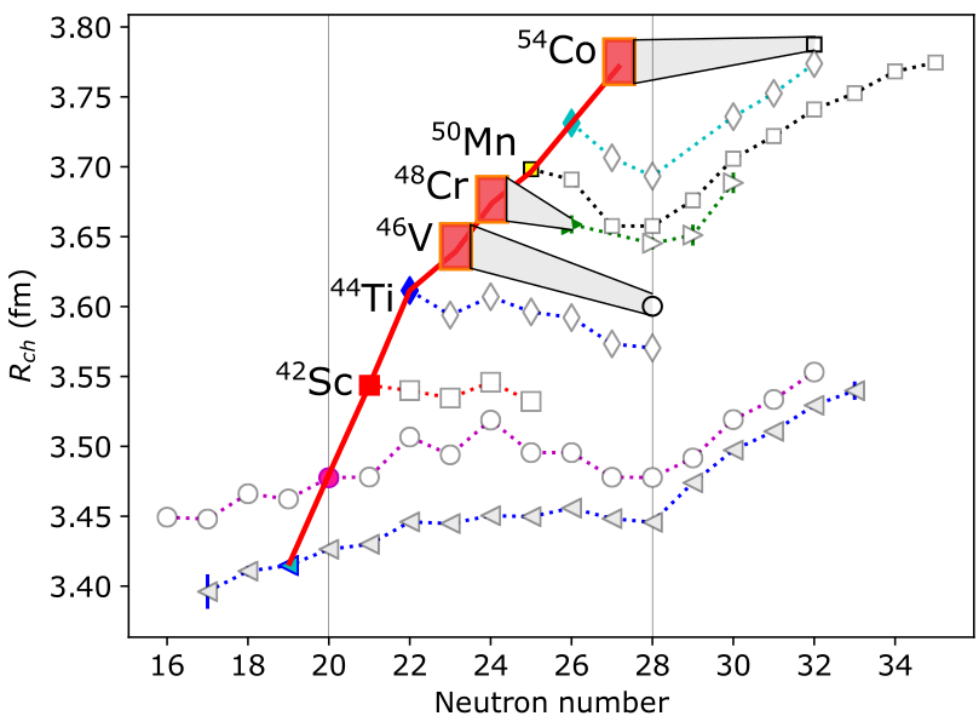
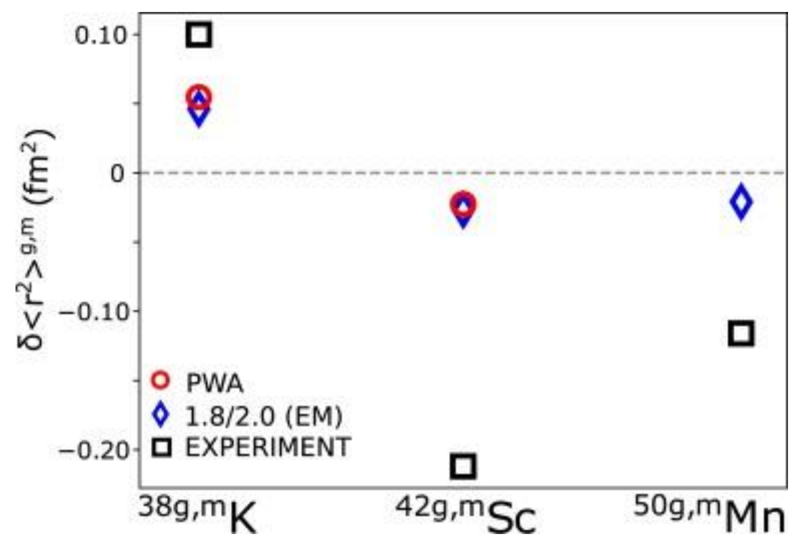
- Odd-odd self-conjugate nuclei provide an ideal testing ground for proton-neutron pairing studies
- Charge radius will be greater for a state with I=0, T=1 than for such a state with I≠0, T=0
- ^{26}Al (5^+ ground state, 0^+ isomer) measured at IGISOL in 2021.



Talk by Bo Cederwall (isoscalar pairing)

Comparing shell model and ab-initio calculations



A. Koszorus et al., Phys. Lett. B 819 (2021) 136439

More widely, isospin-related studies are of particular interest at and past the N=Z line (@DESIR):
Eg. breakdown of isospin symmetry (IMME via masses), the origin of the Wigner energy, pairing condensates…

Summary

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- I hope to have given a flavor of the physics opportunities and current topical interests with a focus along the N=Z line (although much has yet to be studied along the way to N=Z!!)
- Laser spectroscopy and mass spectrometry nowadays are fruitfully combined to provide a wealth of complementary nuclear structure
- Trap-assisted spectroscopy is an extremely powerful tool and (personally) I think is the future direction for facilities hosting traps and decay stations
- S3 and DESIR are very complementary with unique opportunities/strengths
- To take advantage of the beams and intensities available, a fast gas cell needs to be developed
- Not discussed: actinides, the high-precision frontier (octupole moments, hyperfine anomalies…), weak interaction studies (CVC, exotic currents, triple correlations…), in-trap decay studies…
- Future opportunities with MNT reactions, fission fragments…?

Acknowledgements

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The IGISOL group, circa late 2019

Several wonderful (local & non-local) people for material and patient explanations:

Herve Savajols, Nathalie Lecense, Lucia Caceres, Pauline Ascher, Pierre Delahaye, Vladimir Manea, Magda Gorska, Agi Koszorus, Ruben de Groote, Mikael Reponen, C. Hornung

Thanks for your ”online” attention!