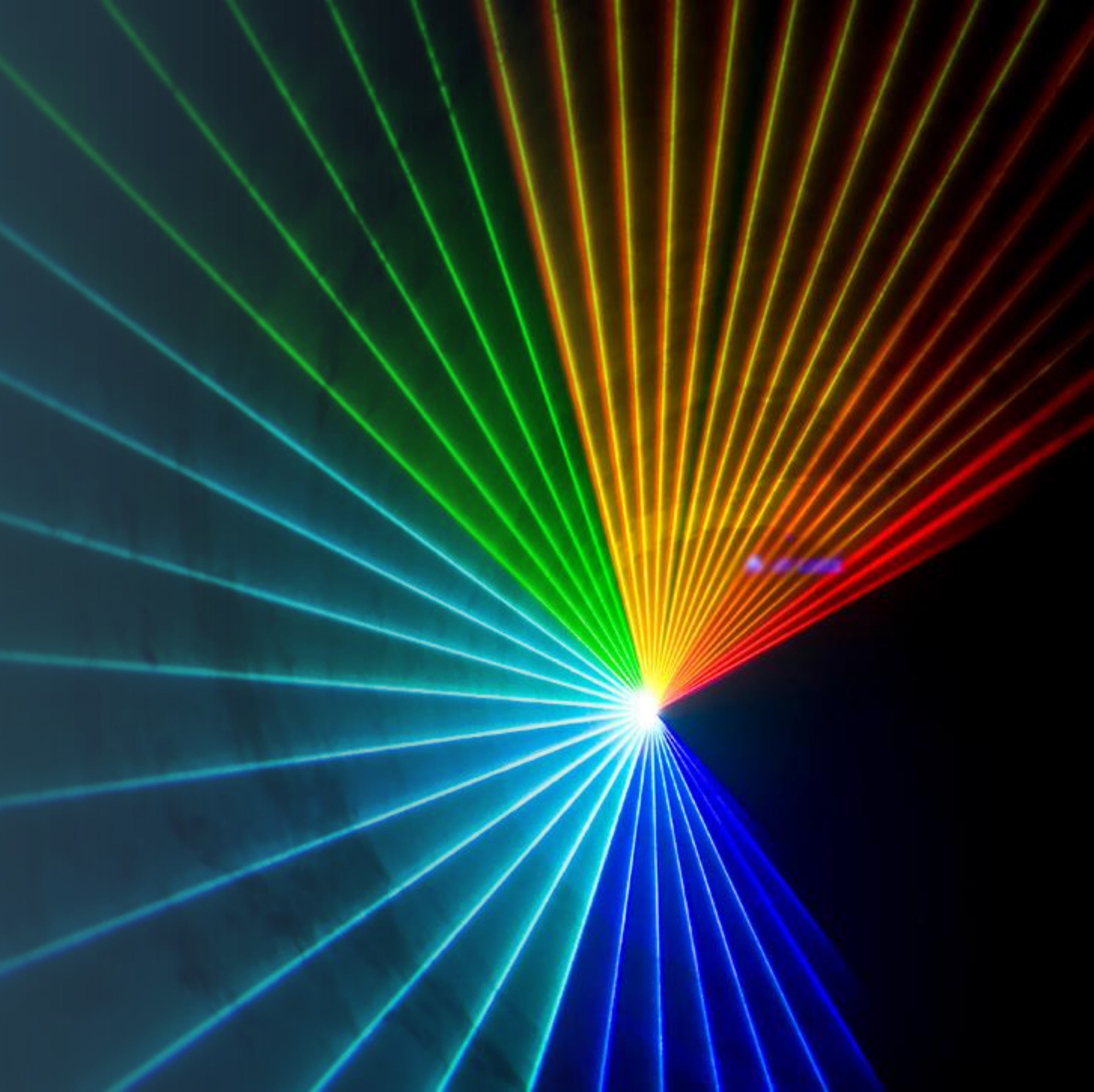
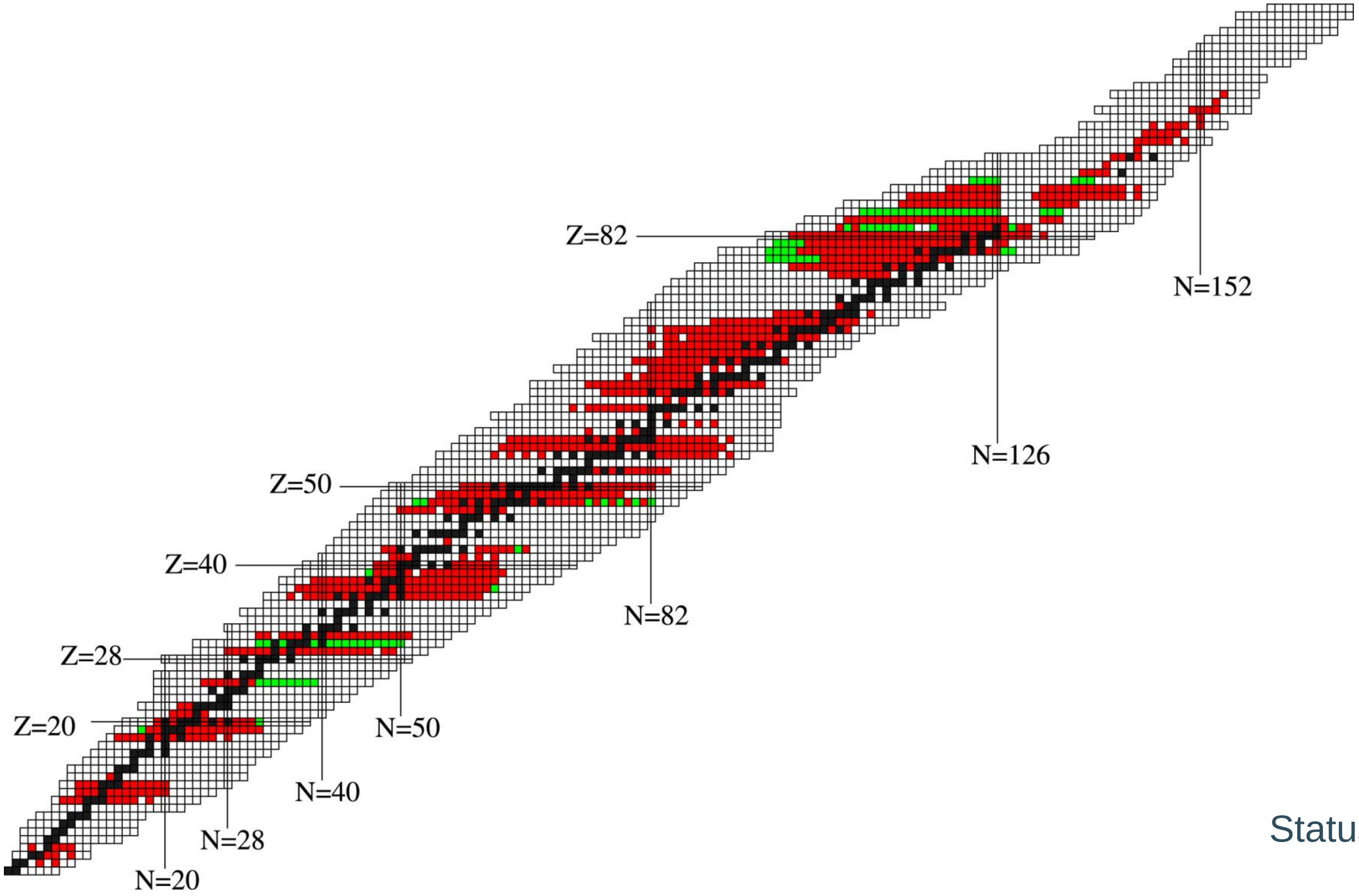
Recent highlights in the measurements of nuclear charge radii of short-lived isotopes



Ruben de Groote

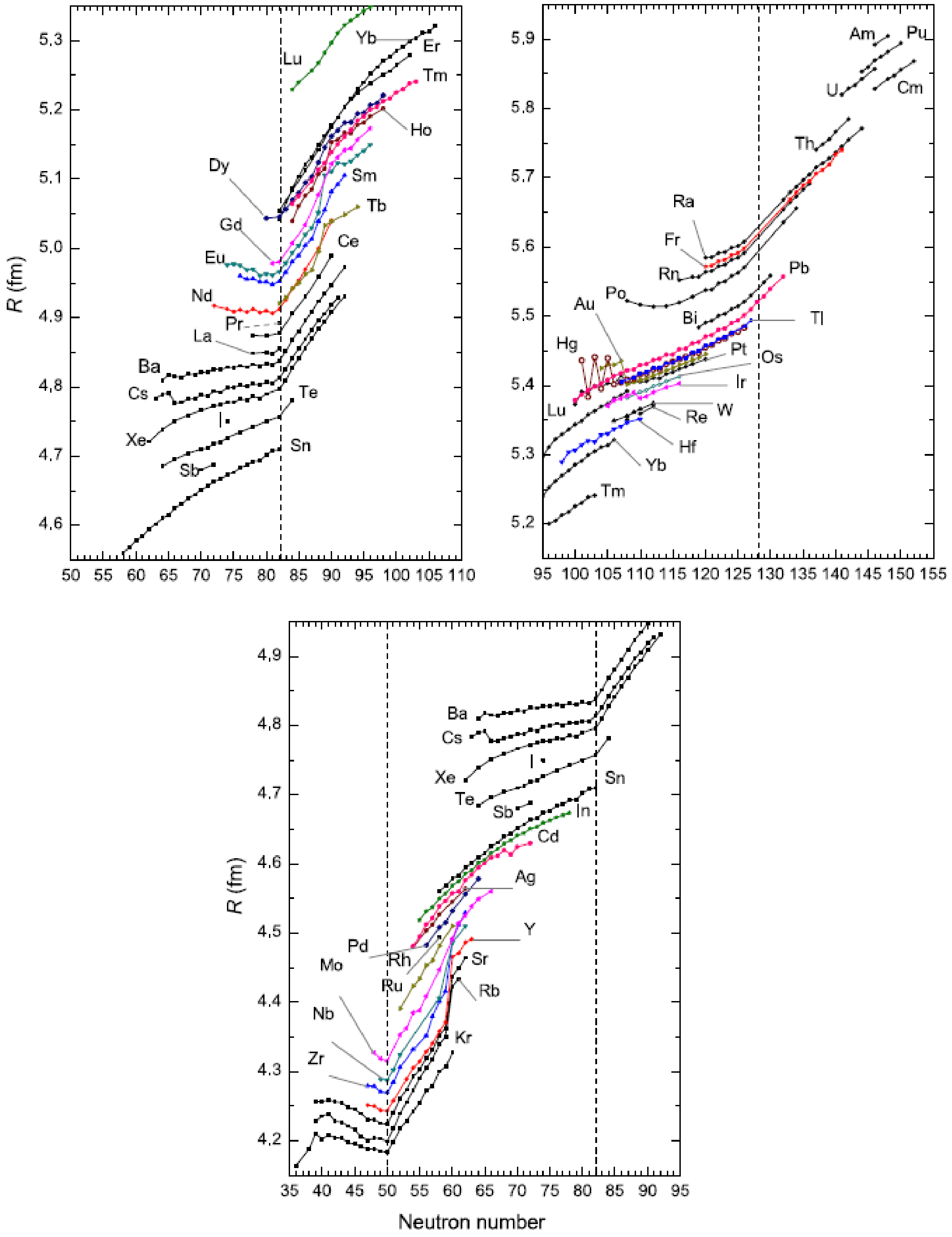
YKIS2022b conference, 23-27 May 2022



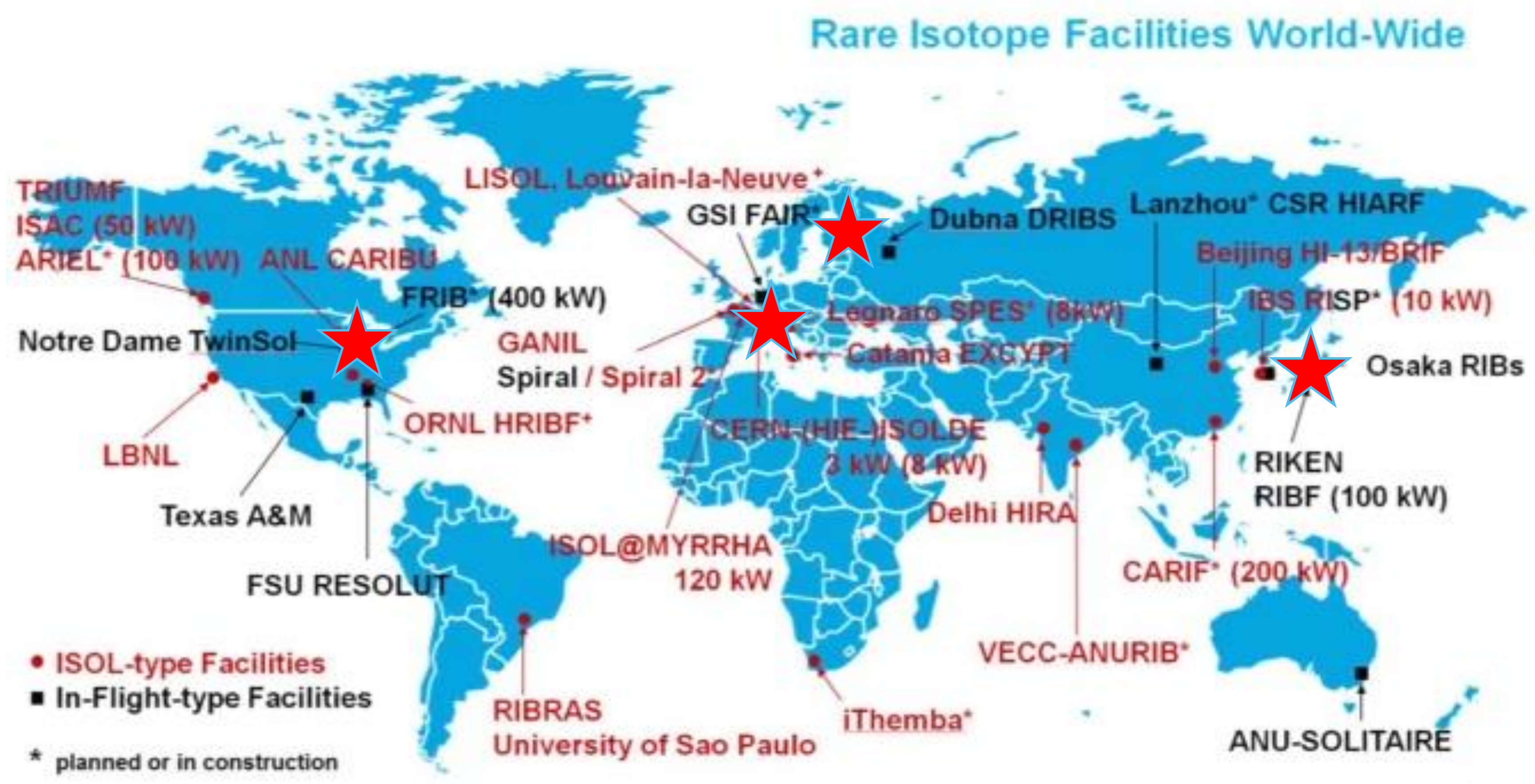
Status ~ 2016

A rich dataset…

- Shell effects
- Odd-even staggering
- Gradual deformation effects
- Sudden shape changes
- …



… obtained worldwide…



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with too many highlights…

- Constraining equation of state with charge radii data
  - ^{68}Ni,mirror pair ^{54}Fe-^{54}Ni

    S. Kauffmann et al., PRL 124, 132502 (2020)
    S. V. Pineda et al, PRL 127, 182503 (2021)

- Small-scale effects like odd-even staggering
  - Neutron-rich copper isotopes

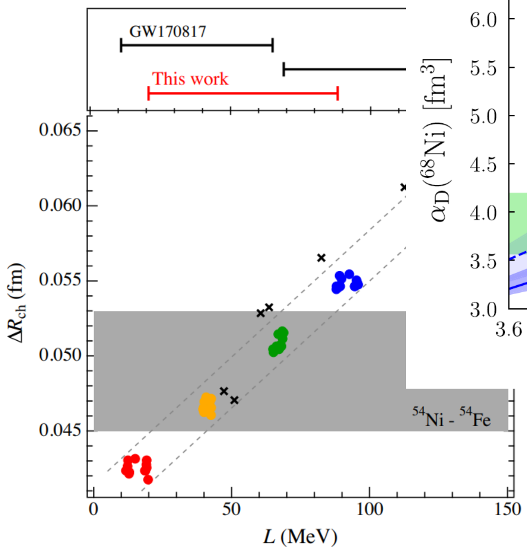
    R. P. de Groote et al., Nat. Phys. 16, 620–624 (2020)

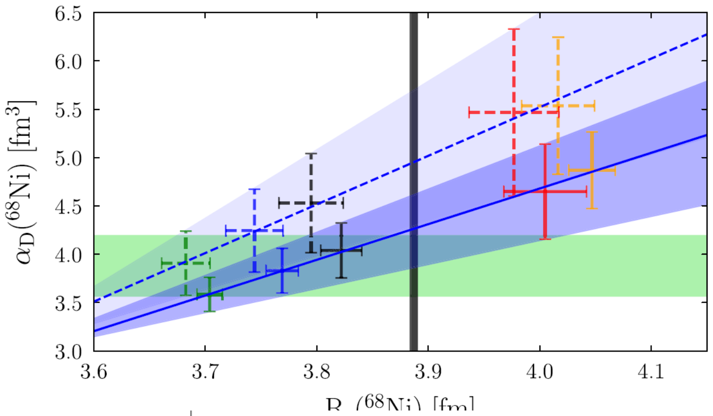
- Understanding charge radius kinks at shell closures
  - Sn, Hg, …

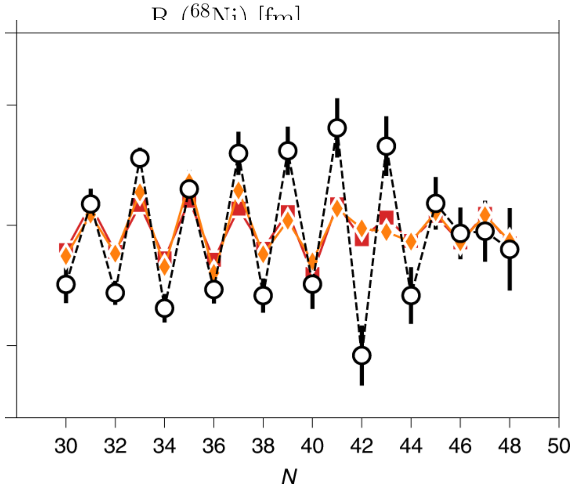
    C. Gorges et al, PRL 122, 192502 (2019)
    T. Day Goodacre et al, PRL 126, 032502 (2021)

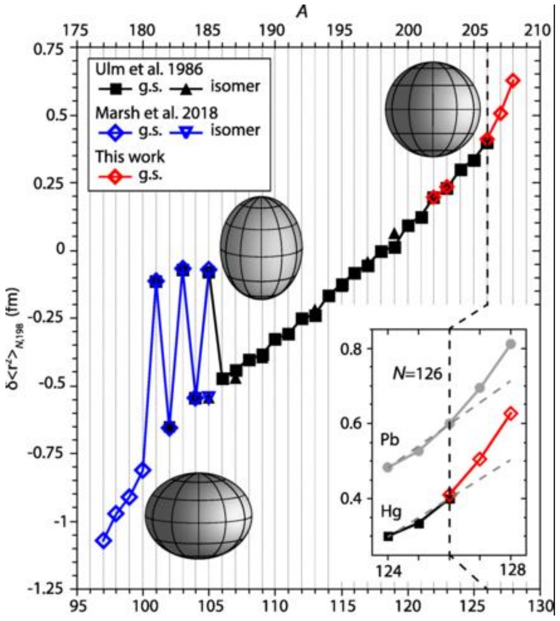
- Interplay of coulomb and strong force in superheavies
  - No   S. Raeder et al., PRL 120, 232503 (2018)

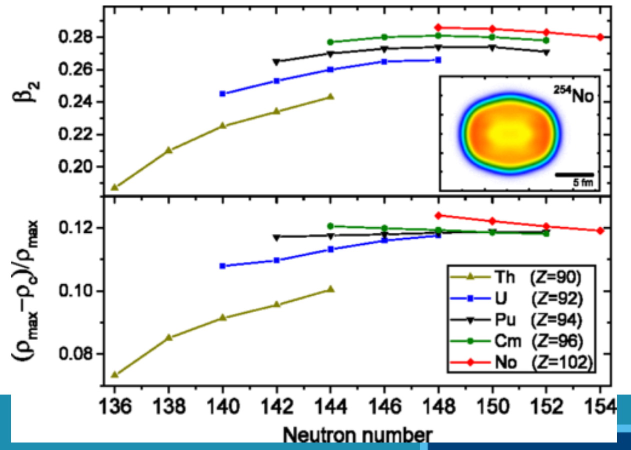
- …… many more…







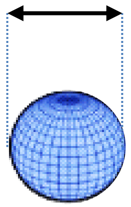




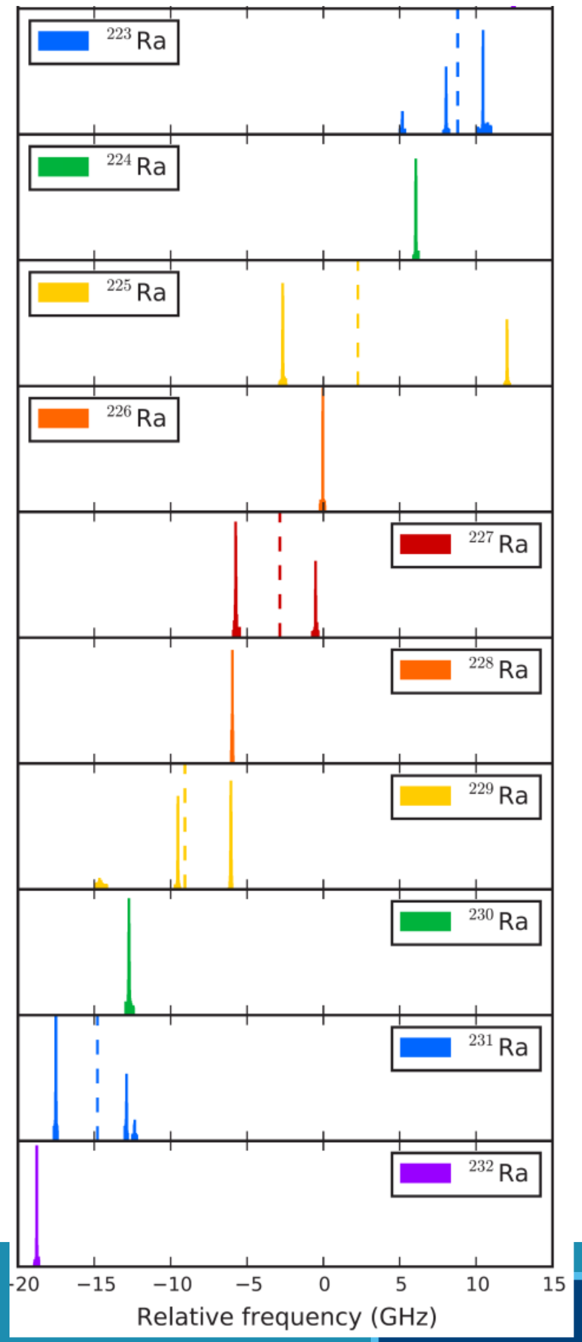
Extracting nuclear charge radii using laser spectroscopy

- Isotope shift:
  - *Atomic* levels shift due to changing mass and size

  - Knowledge of atomic factors enables extraction of nuclear charge radius changes



Charge radii $\delta\langle r^2\rangle$



KM Lynch et al. Physical Review C 97 (2), 024309

The calcium region

Scientific case

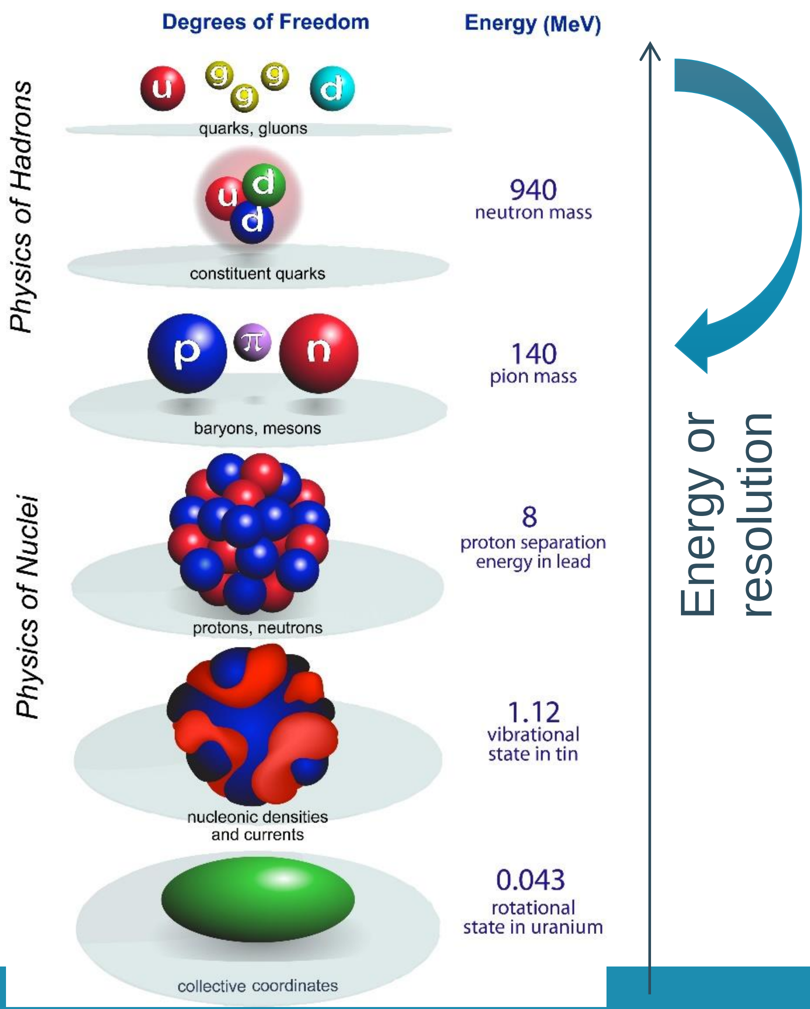
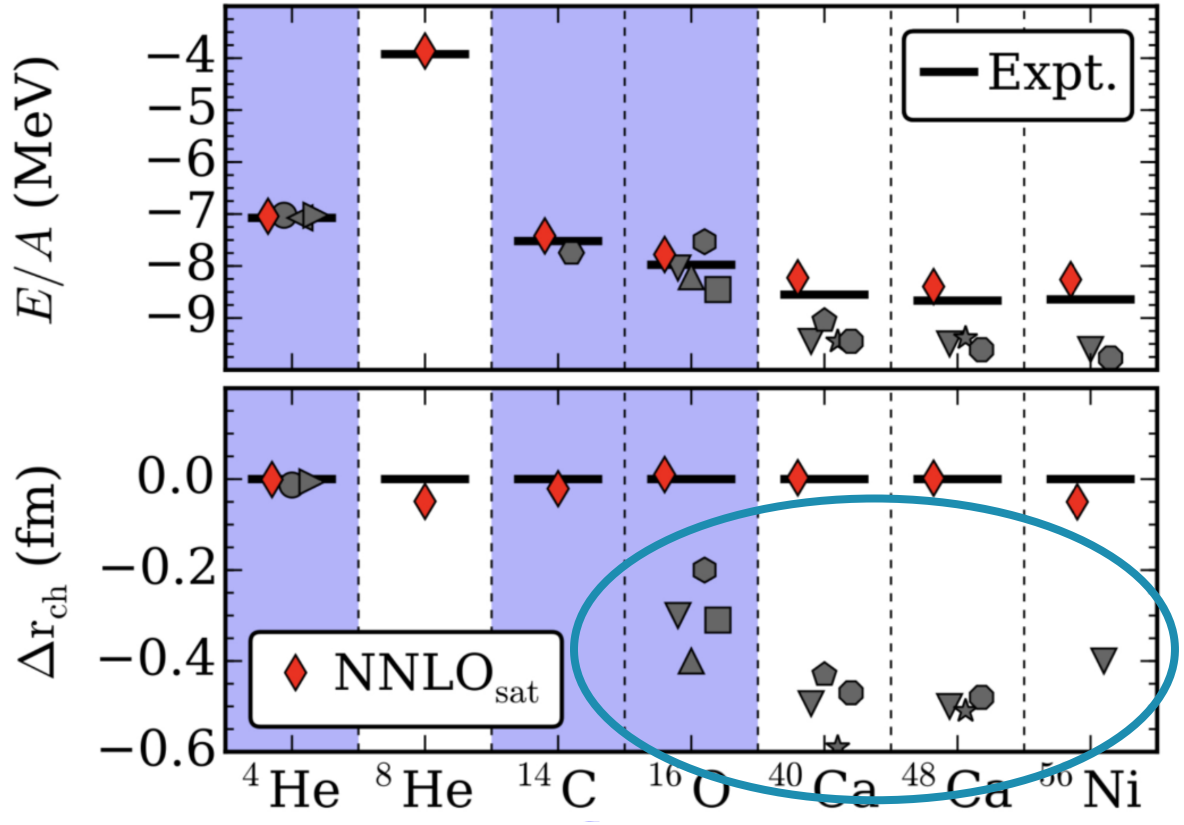


Fig.: Bertsch, Dean, Nazarewicz, SciDAC review (2007)

Chiral Effective Field Theory

A. Ekström, PRC **91**, 051301(R) 2015



Constrained to provide an accurate description of the A=2 and A=3 systems.

↓

Predictions for nuclear structure and dynamic (A>3).

Why is there the mismatch?
Why does $NNLO_{sat}$ work?

An open problem…

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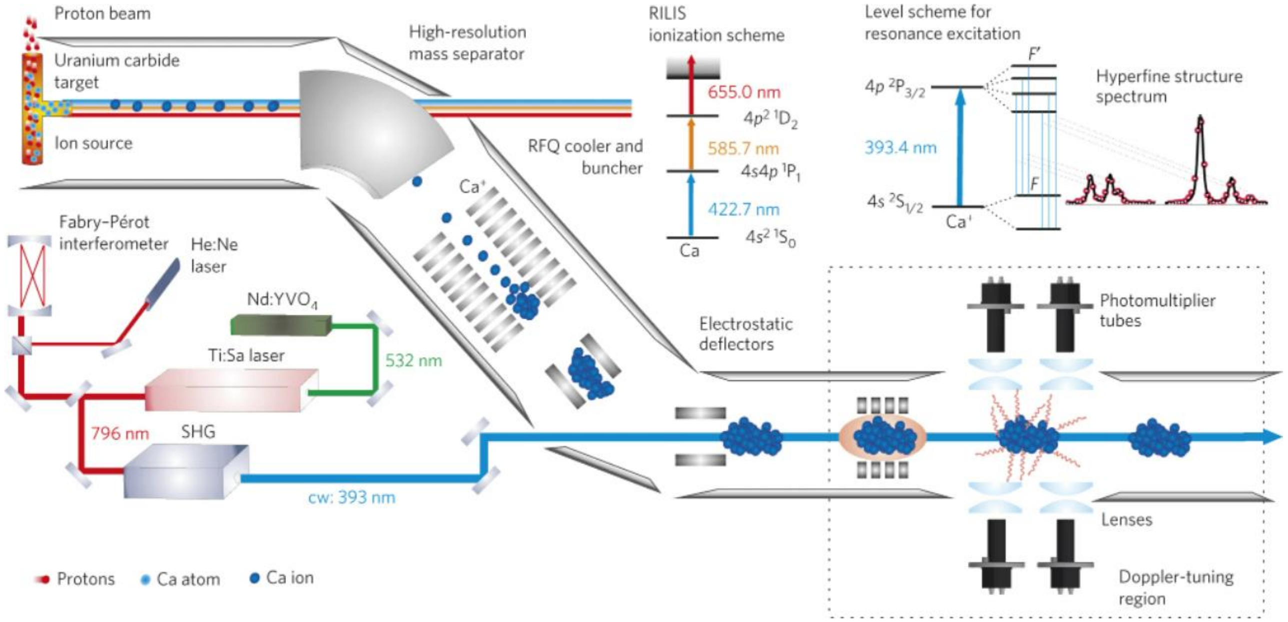
Nuclear radii in the calcium region

- Measurements at ISOLDE
- Collinear laser spectroscopy
  - Velocity spread of thermal ensemble of atoms
    => doppler effect
    => isotope shift not resolved
  - Accelerate to a few keV/u: velocity spread compresses
- Workhorse of the field!



R Garcia Ruiz et al. Nature Phys **12,** 594–598 (2016)

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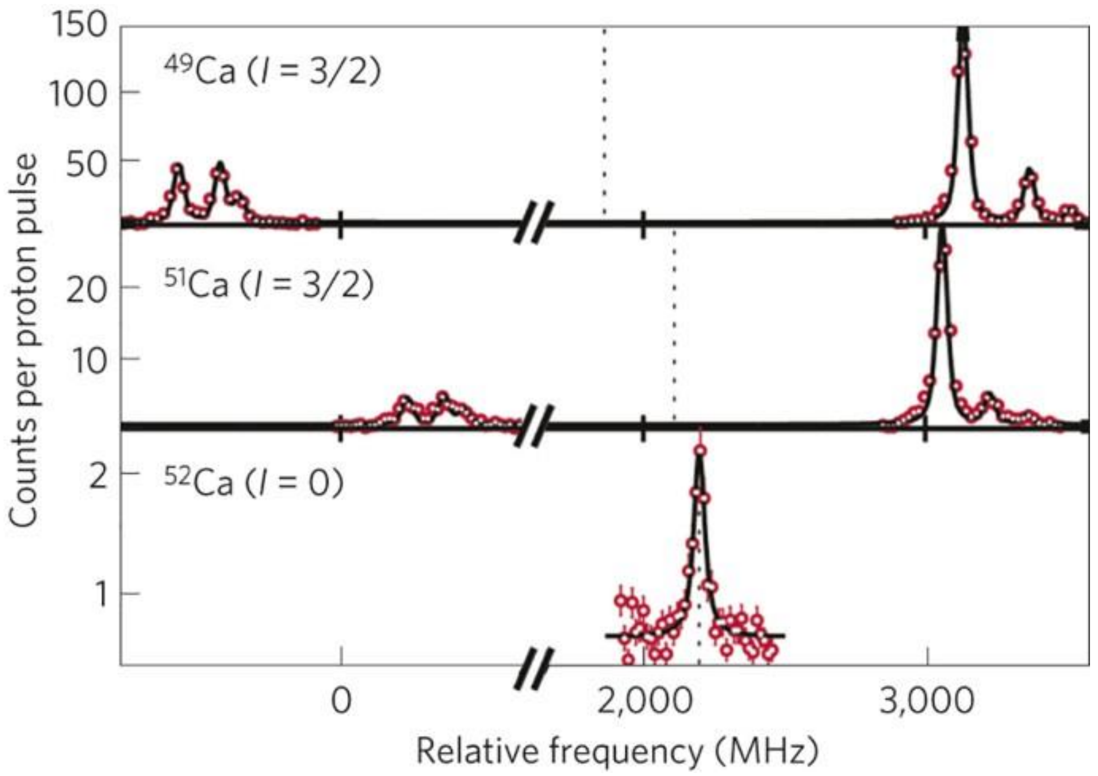
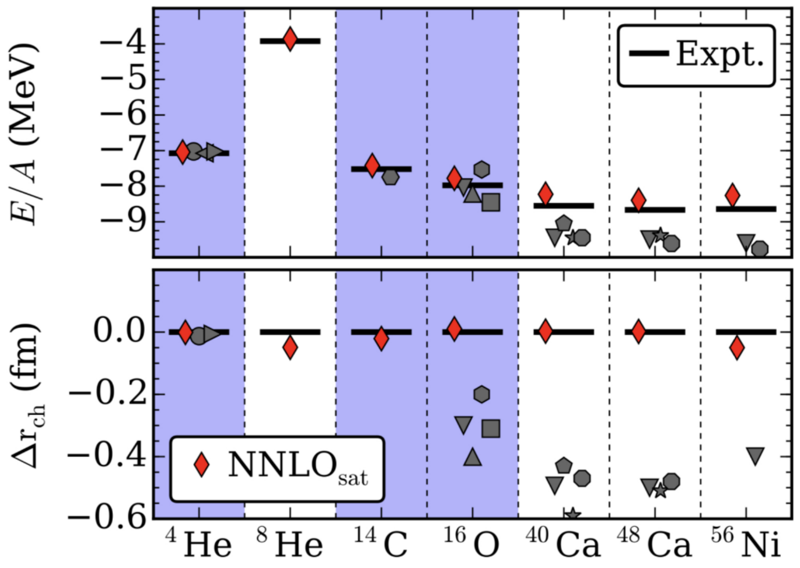
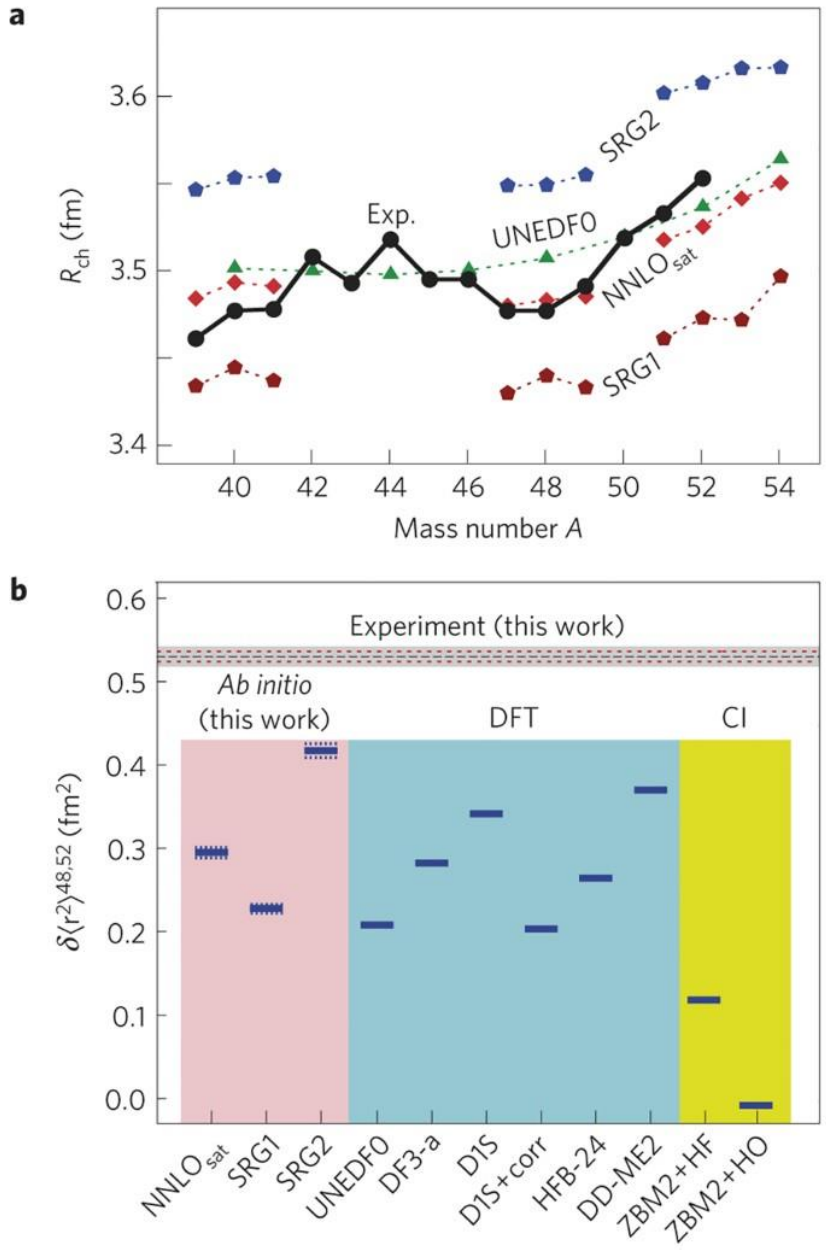


R Garcia Ruiz et al. Nature Phys **12,** 594–598 (2016)

The chain of Ca isotopes

- Extending data to neutron-rich isotopes reveals further discrepancies, even with $NNLO_{sat}$
- This remains an open problem for ab-initio theory





R Garcia Ruiz et al. Nature Phys **12,** 594–598 (2016)

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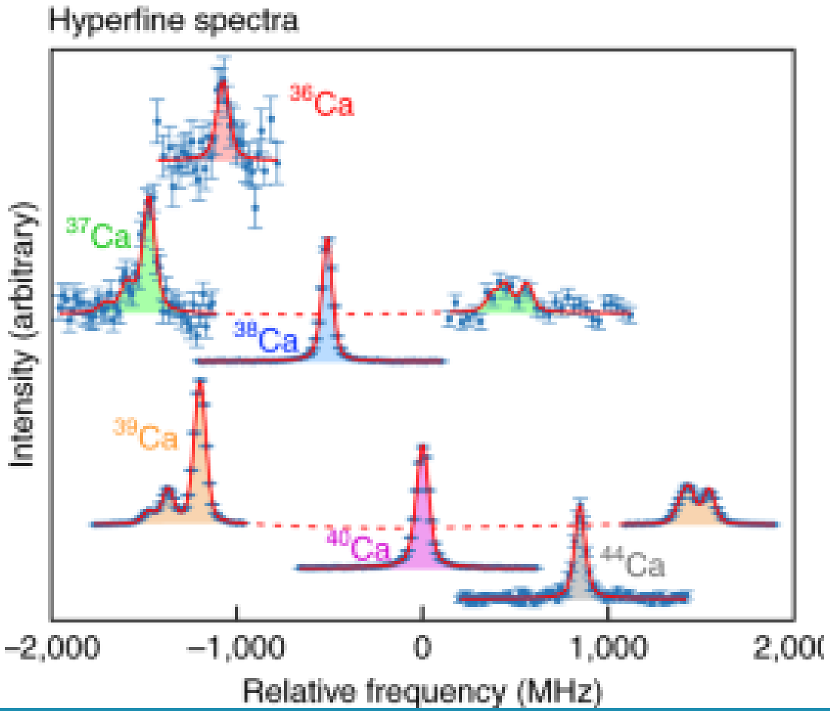
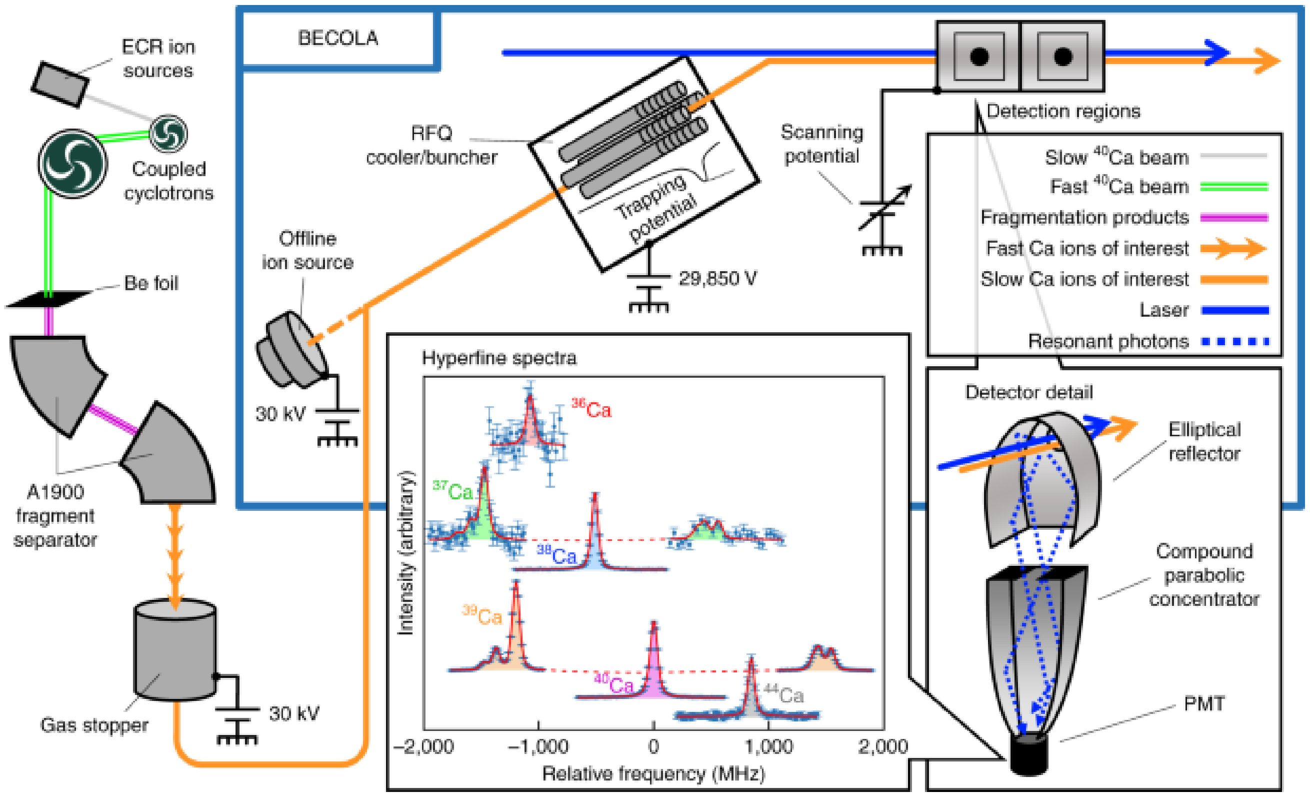
The chain of Ca isotopes

- Proton-rich nuclei not available in ISOLDE…
- NSCL: projectile-fragmentation reaction
- Spectroscopy down to ^{36}Ca!



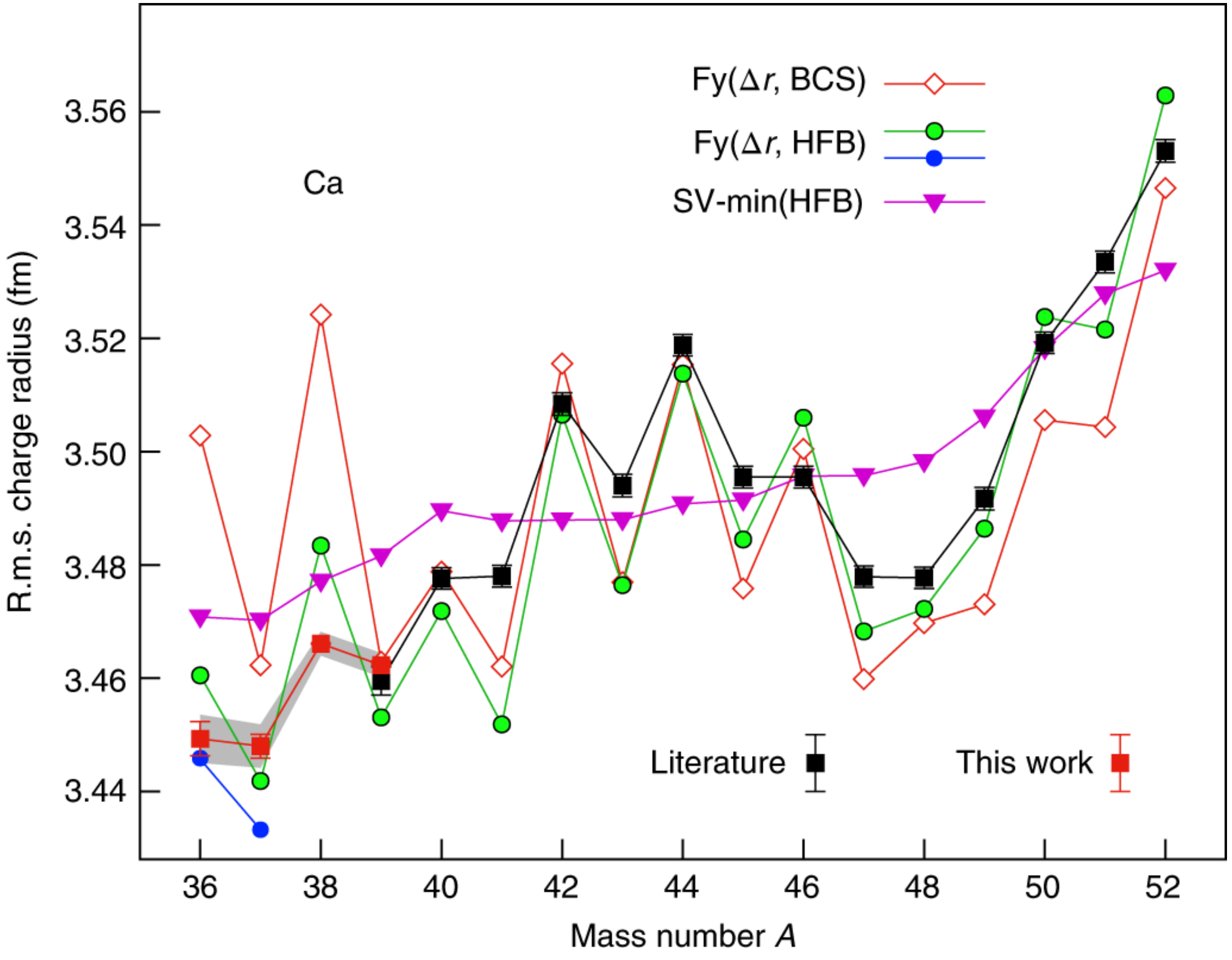


AJ Miller, Nature Physics volume 15, pages 432–436 (2019)

The chain of Ca isotopes

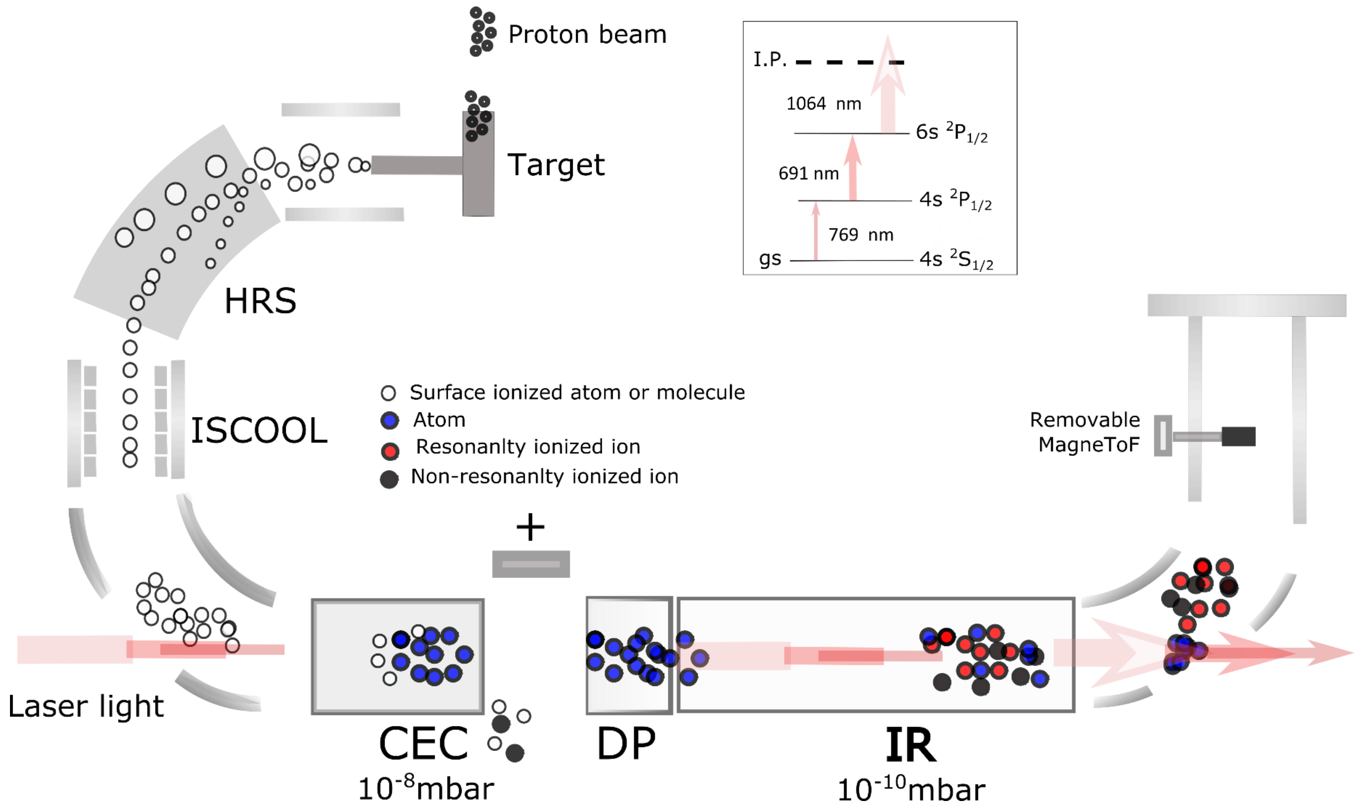
- Proton-rich nuclei not available in ISOLDE…
- NSCL: projectile-fragmentation reaction
- Spectroscopy down to ^{36}Ca!

- Density functional calculations
  - BCS approximation: unbound single-proton orbits get occupied
    => radii too large
  - HFB: spatial localization of nuclear density
    => good match obtained, also n-rich side!



AJ Miller, Nature Physics volume 15, pages 432–436 (2019)

Laser spectroscopy of K (Z=19)



CRIS:

- Collinear = doppler-free
- RIS = versatile, efficient

Challenges:

- Large isobaric contamination
- Low yields
- Changing proton current
  → changing production and background

At mass 52:

- **>10^6 pps contamination**
- 300 pps ^{52}K

- Beta-detection: remove stable contaminants

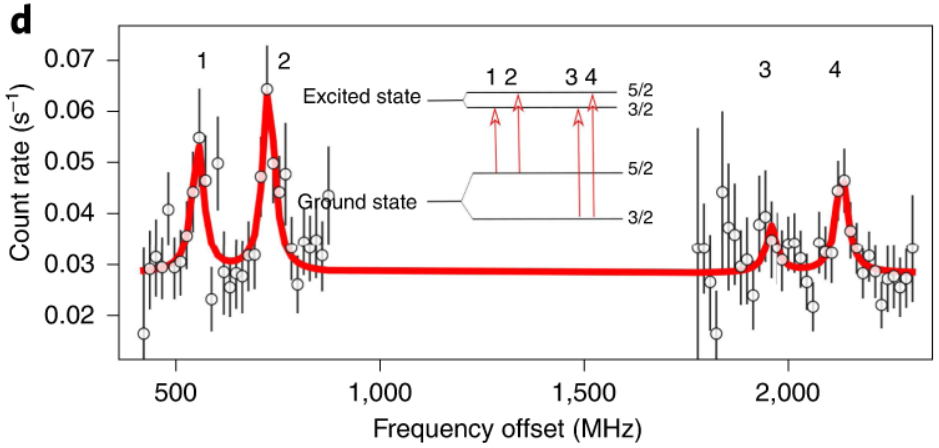
A. Koszorus et al., Nature Physics 17 (2021) 439–443

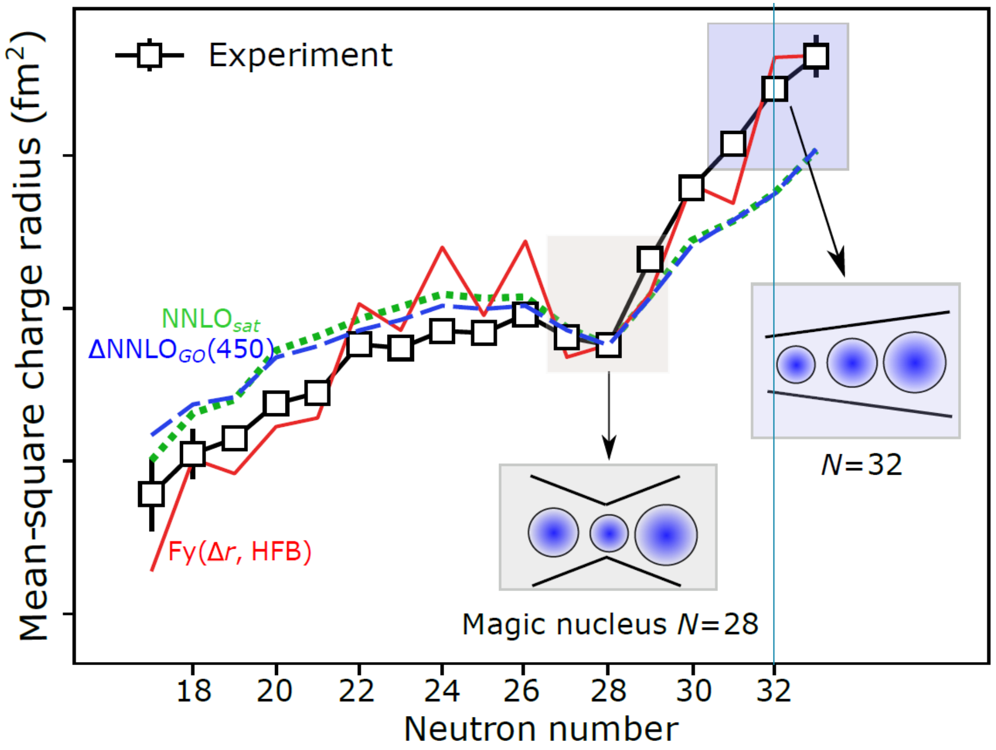
Results

- CRIS: combines collinear geometry with selective laser ionization spectroscopy

- Measurement successful!
  - Spin assigned I=2
  - Smooth continuation of the trend

- Discrepancy for ab-initio work persists
  - Newer $NNLO_{go}$ interaction also does not produce slope of the increase beyond N=28

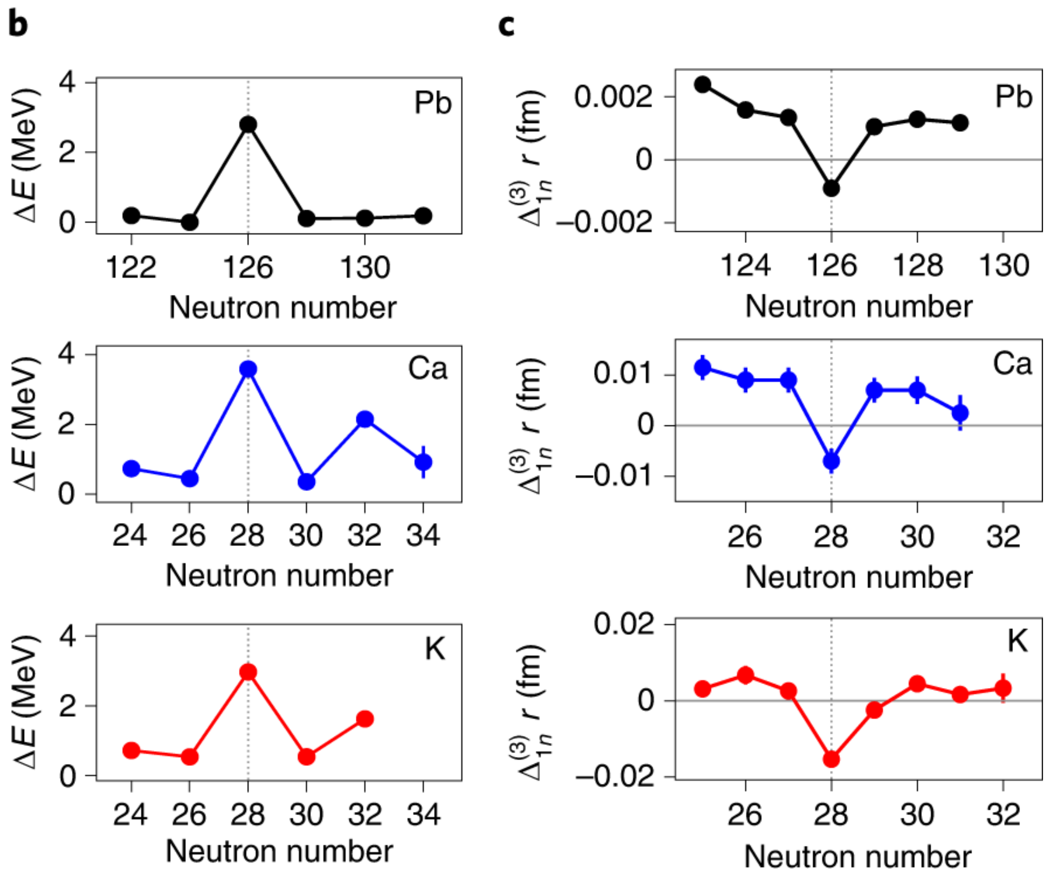




A. Koszorus et al., Nature Physics 17 (2021) 439–443

Further probing with the K (Z=19) chain

- N=32 has been reported as a potential new shell closure near Z=20
  - Energy gaps obtained from binding energies show clear increase at well-established shell closures and N=32 for Ca and K
- Charge radii provide a test here: shell crossing corresponds to change in radius slope
  - Absence of clear effect at N=32…

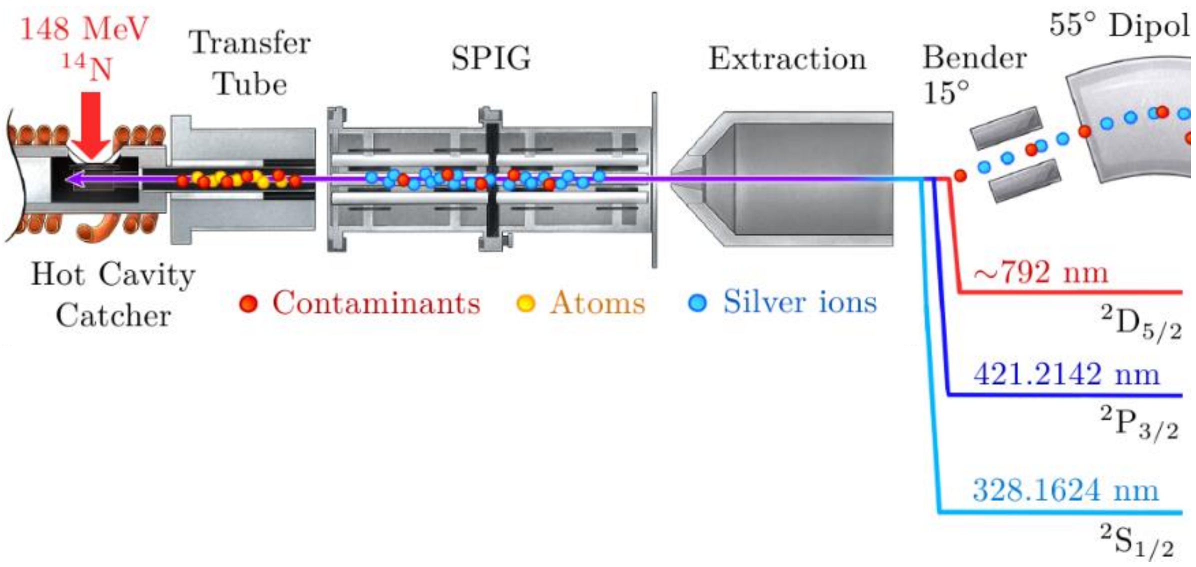


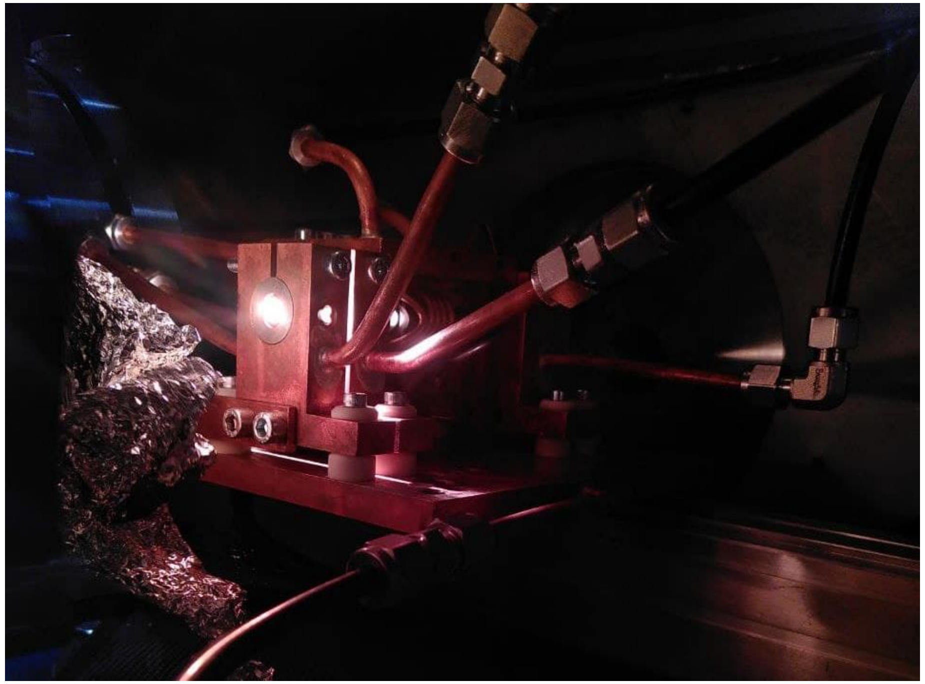
A. Koszorus et al., Nature Physics 17 (2021) 439–443

In-source laser spectroscopy

Pushing methods to short lifetimes and low yields with in-source laser spectroscopy

Pushing far from stability – in-source laser spectroscopy

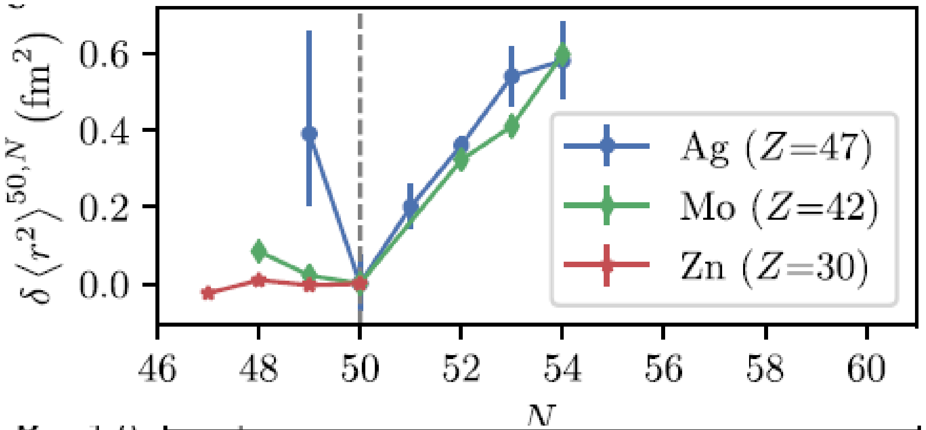


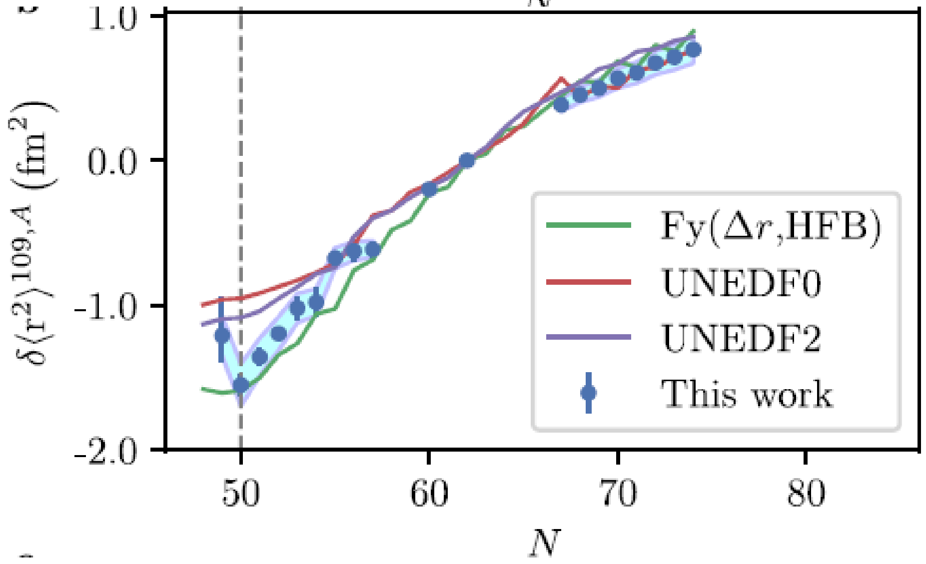


- Introducing lasers into the ion source, to achieve stepwise laser ionization
- Enables the furthest reach from stability
- Price to pay: resolution (limits applicability to particularly lucky elements)

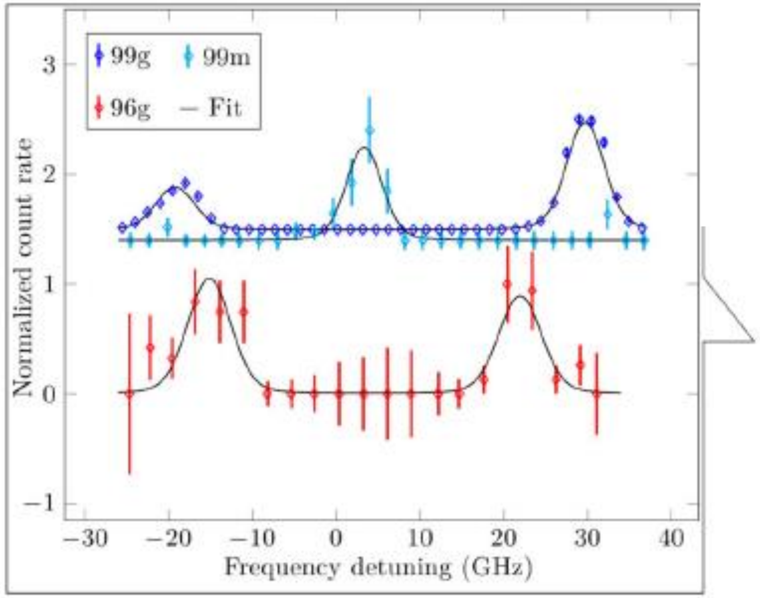
M. Reponen, R.P. de Groote et al., Nature Communications 12 (2021) 4596

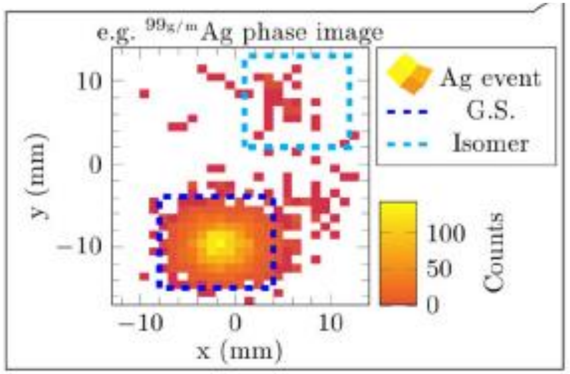
In-source laser spectroscopy of silver





- Trap-assisted laser spectroscopy for mass purification
- Towards ultimate sensitivity
- Detection rate ^{96}Ag: 1 count / 5 minutes!
- Challenges modern DFT approaches near ^{100}Sn





Data: IGISOL laboratory (JYFL)

M. Reponen, R.P. de Groote et al., Nature Communications 12 (2021) 4596

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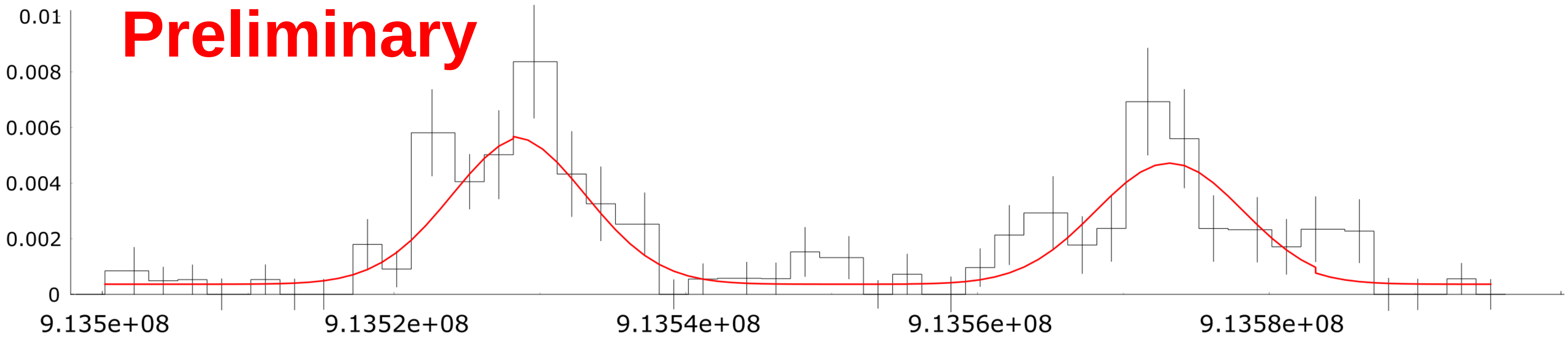
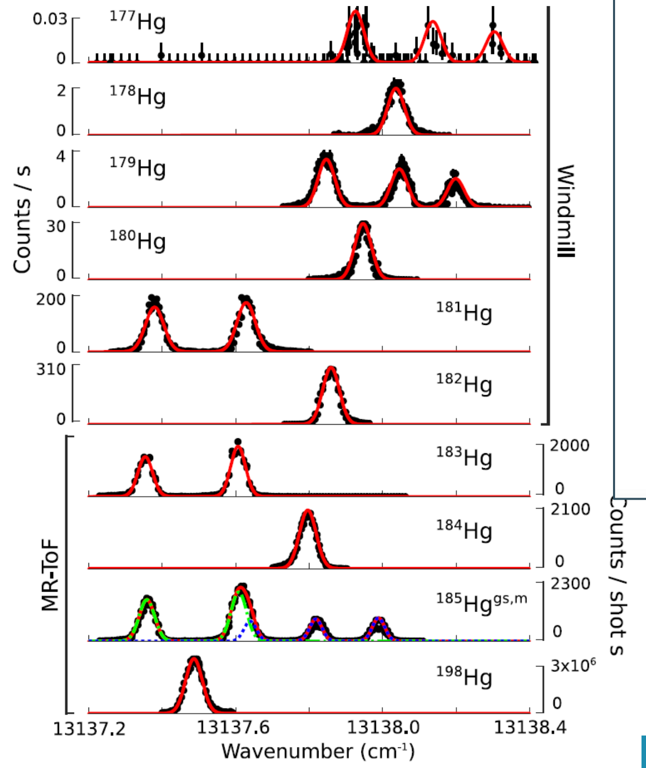


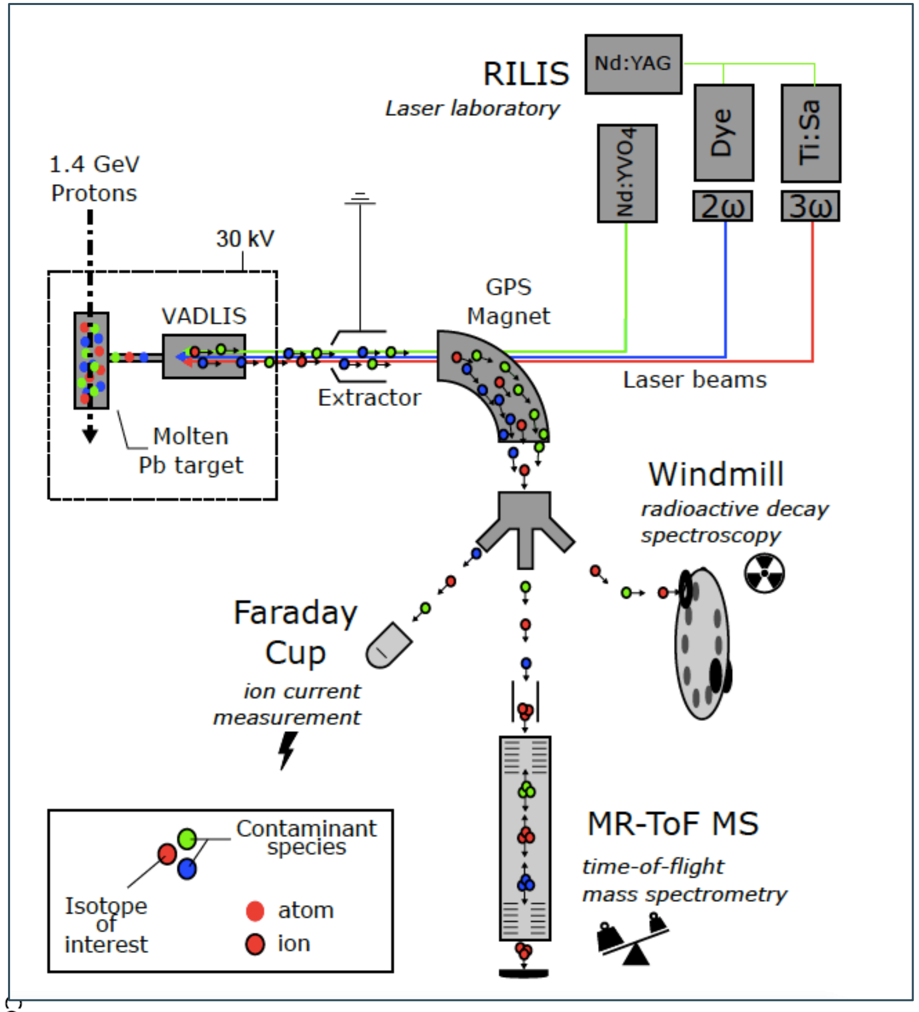
Data: IGISOL laboratory (JYFL)

M. Reponen, R.P. de Groote et al., Nature Communications 12 (2021) 4596

In-source laser spectroscopy of Hg and Bi

- Heavy isotopes: perfect for in-source laser spectroscopy
- Covering >10 orders of magnitude in production rate!
- Requires versatile detection systems to handle different detection rates and S/B conditions
  - alfa-decay
  - fast high-resolution mass separation (10^{-5}) with MR-TOF
  - Faraday cup for stables



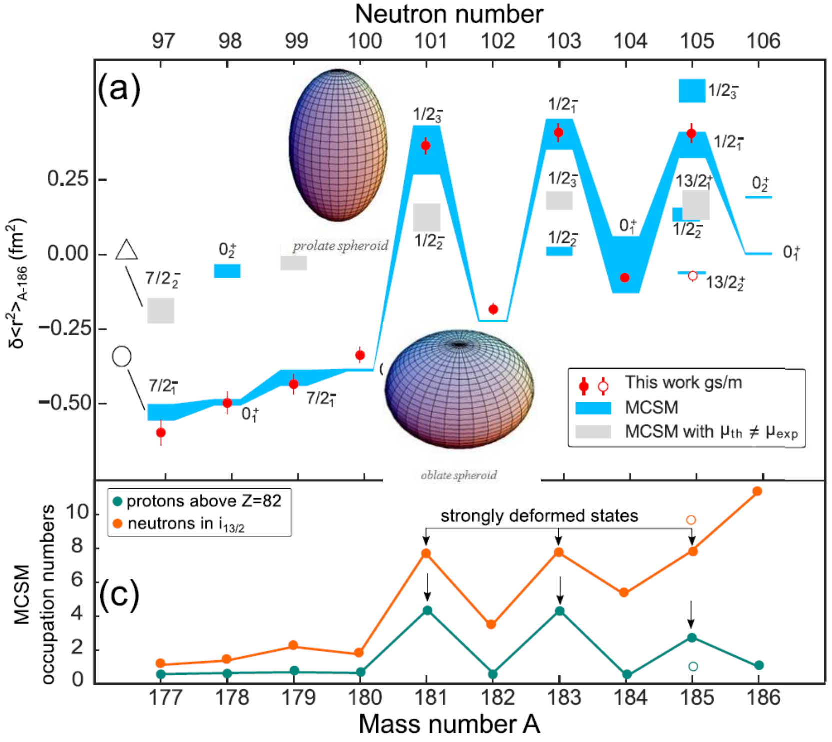


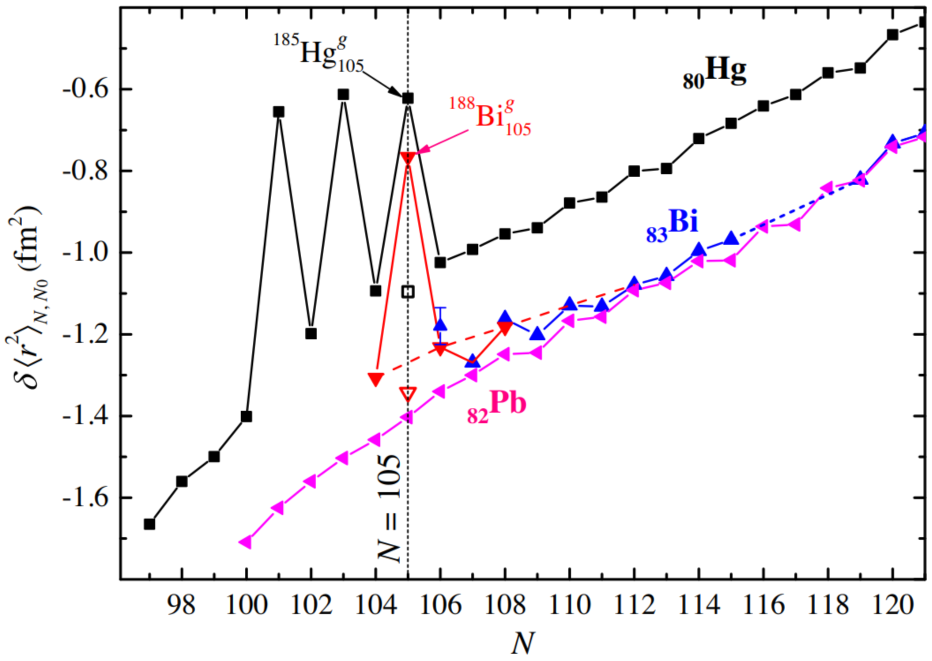
B. March et al., Nature Physics 14, 1163 (2018), S. Sels et al., Phys. Rev. C 99, 044306 (2019)

Shape staggering of Hg and Bi

FIRST large scale shell model calculations in this heavy mass region (Otuska et al.)

- → **origin of the staggering is understood microscopically !**
- → **Shape change from oblate to prolate**



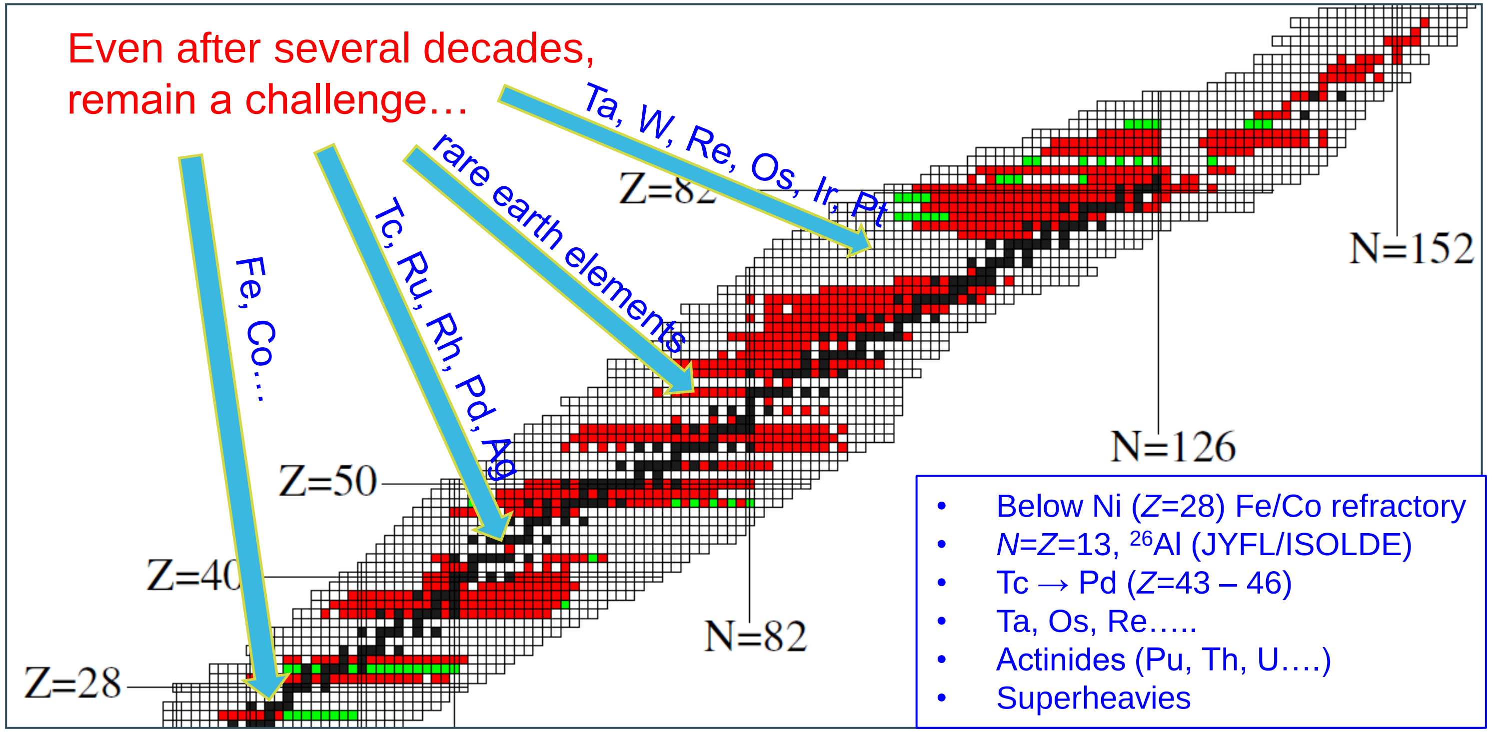


B. March et al., Nature Physics 14, 1163 (2018), A. Barzakh et al, PRL 127, 192501 (2021)

To wrap up…

Some concluding remarks

- Nuclear chart has been successfully explored extensively with optical techniques
  - **Challenges remain**: the most exotic, most short-lived, challenging chemistry, complex or unknown atomic structure, …
- New and efficient techniques are being developed to **access to the most exotic isotopes** (gas-jet, PI-LIST, …)
  - Collaboration between different specialists of different low energy beam techniques is *vital*
  - Use of diverse techniques is *vital*
- Exploration of different facilities opens new frontiers
  - e.g. IGISOL: access refractory isotopes
  - e.g. NSCL/FRIB: fragmentation reactions
  - e.g. GANIL/S3LEB
- With precision comes additional information!
  - Measurement schemes and setups tailored to specific goals are very worthwhile



- Below Ni (Z=28) Fe/Co refractory
- N=Z=13, ^{26}Al (JYFL/ISOLDE)
- Tc → Pd (Z=43 – 46)
- Ta, Os, Re…..
- Actinides (Pu, Th, U….)
- Superheavies

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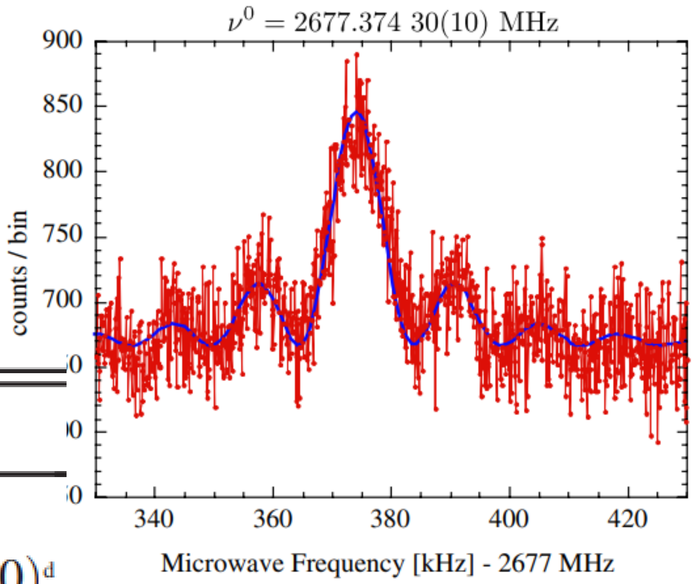
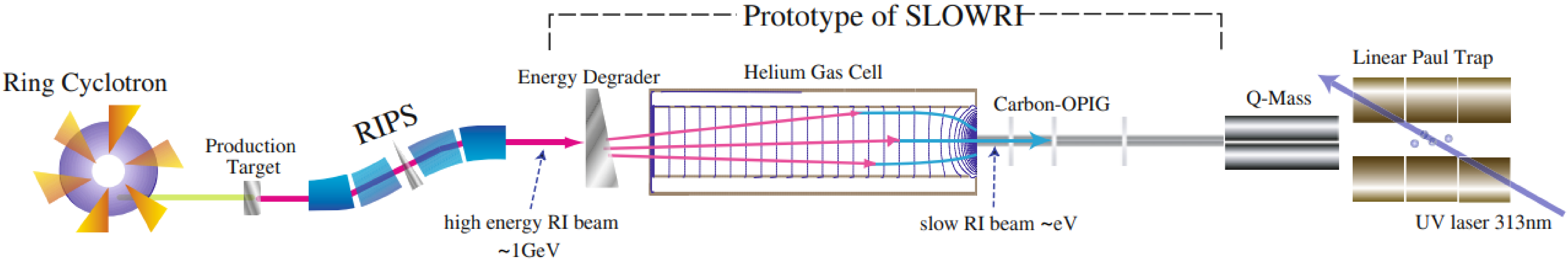
Spectroscopy in ion traps

- Injecting ions into an ion trap enables much longer interaction times
- More careful and delicate spectroscopy enables much higher precision measurements
- So far, however, no radii...

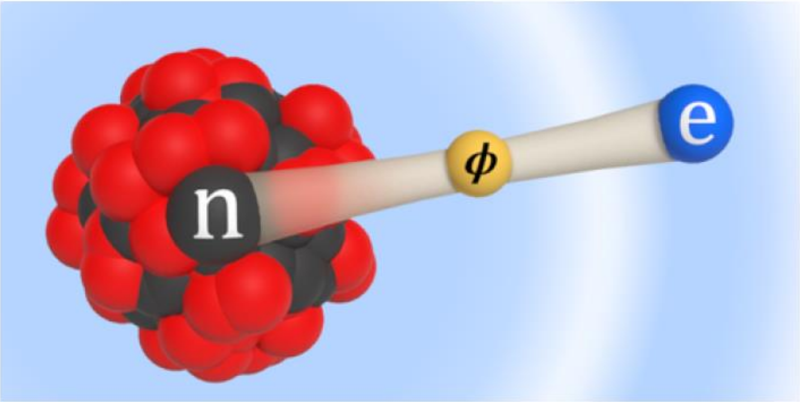
ppb accuracy!

Isotope	A [MHz]
^{7}Be	−742.772 28(43)[c]
^{9}Be	−625.008 837 048(10)[d]
^{11}Be	−2677.302 988(72)[b]





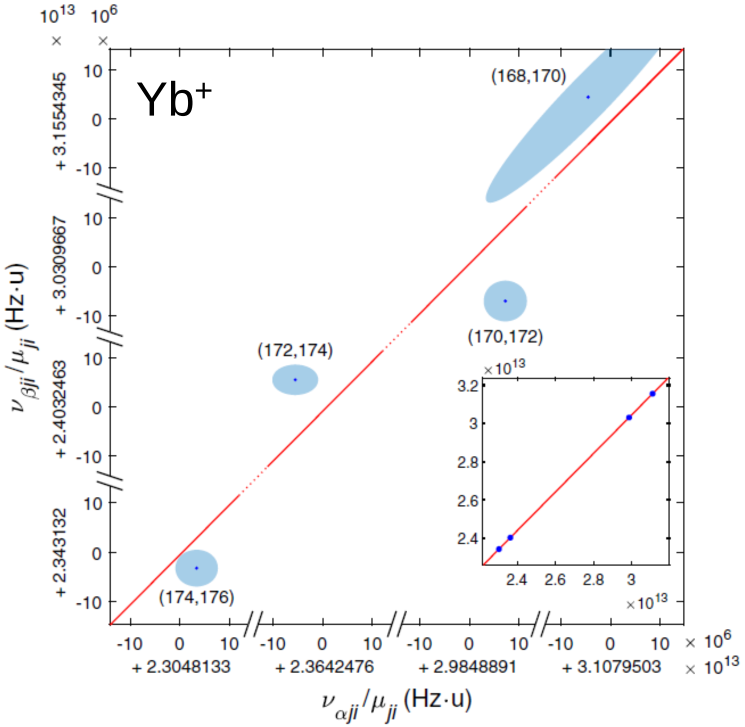
A. Takamine et al., PRL **112**, 162502 (2014)

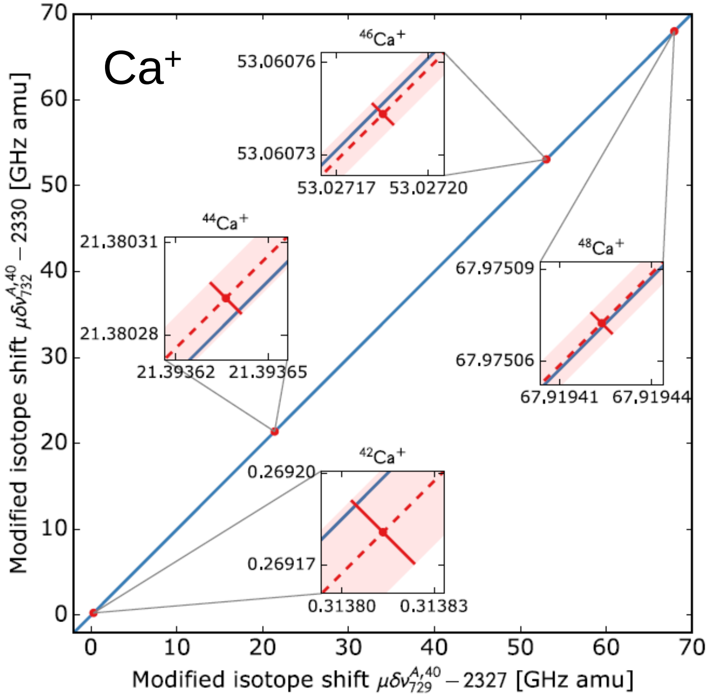


Credit: J. Hur/Massachusetts Institute of Technology

A nonlinearity of the King plot can indicate:

- physics beyond the Standard Model (SM) in the form of a new bosonic force carrier (a **possible candidate for Dark Matter**)
- or arise from higher-order nuclear effects within the SM.
- Precision requirements: sub-Hz! (current RIB application: typically 100 kHz)

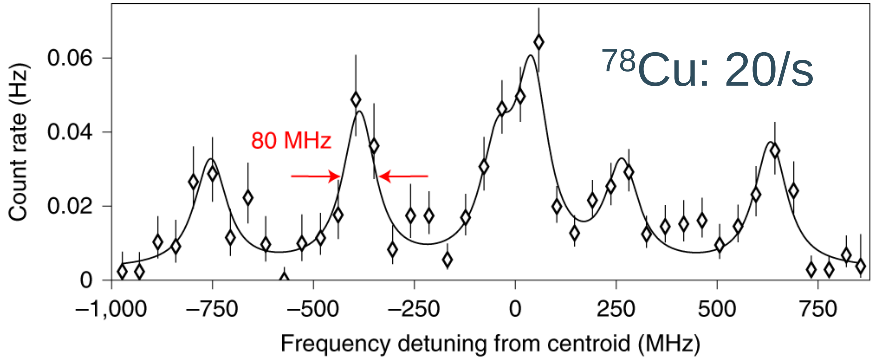


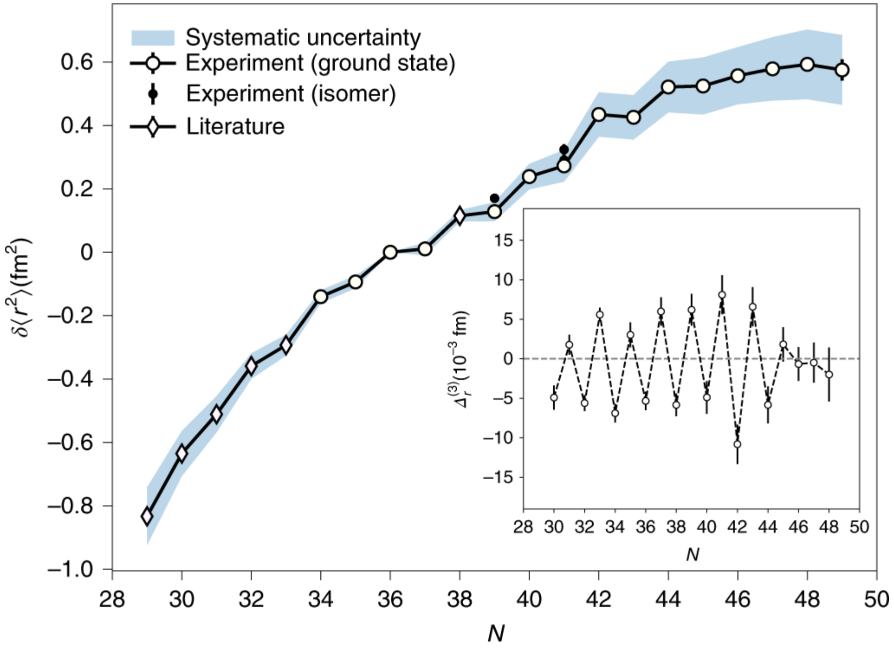


I. Counts et al., PRL 125, 123002 (2020) C. Solaro et al., PRL 125, 123003 (2020)

Small detour past Z=29…

- Neutron-rich isotopes $^{76\text{-}78}$Cu studied for the first time in high-resolution
    - Three additional isotopes in reach due to superior efficiency and S/B ratio
    - Background-free measurements achieved for ^{75,76,77}Cu
    - ^{78}Cu could be studied (half life 330 ms):
      < 20 pps, with **>10^7 contaminants** in the beam!
- Detailed investigation of odd-even staggering…





R. P. de Groote, et al. Nat. Phys. 16, 620–624 - 2020

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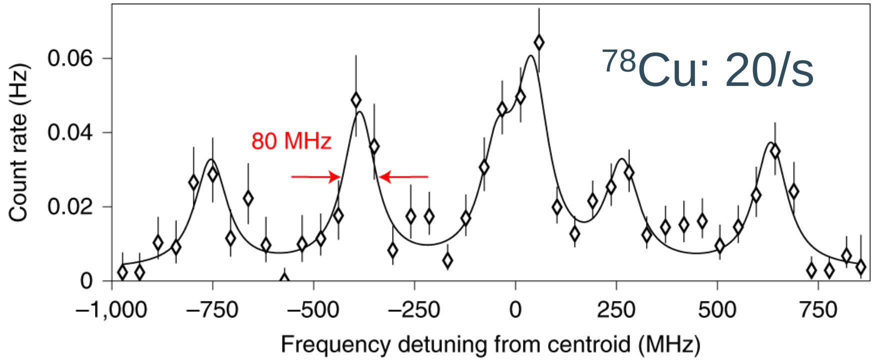
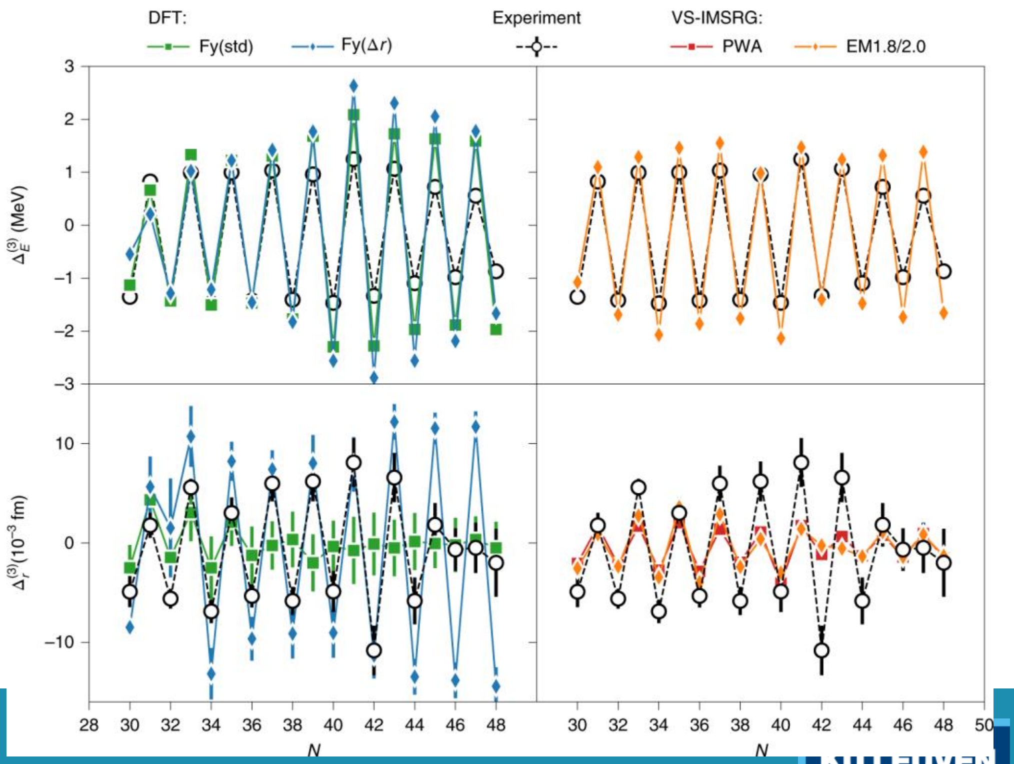
  - ^{78}Cu could be studied (half life 330 ms):
    < 20 pps, with **>10^7 contaminants** in the beam!
- Detailed investigation of odd-even staggering…
  - OES strongly reduced beyond N=46
  - Can understood microscopically from Fayans DFT and IM-SRG with interactions from χ-EFT (fitted to A<4 properties)
    => emerges automatically

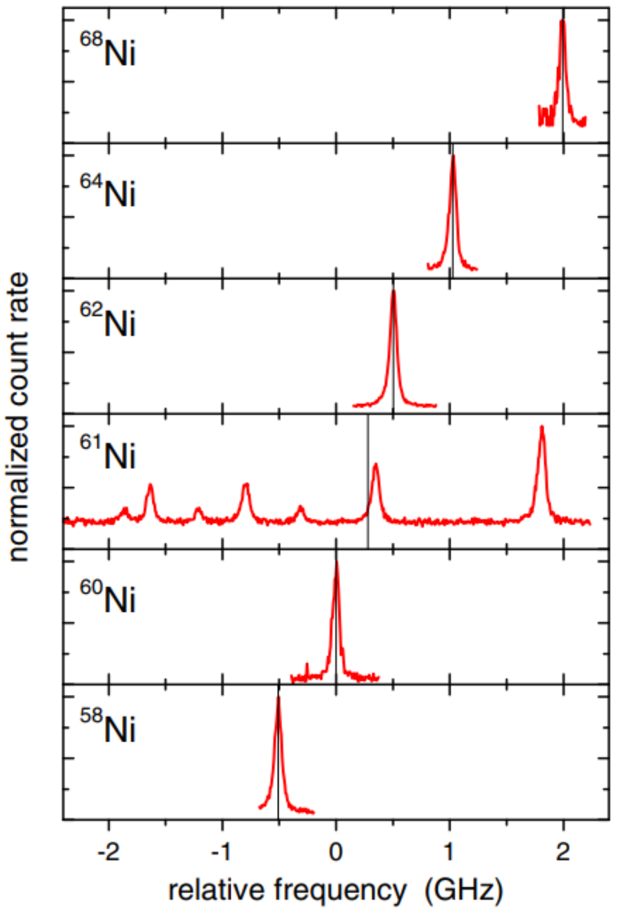




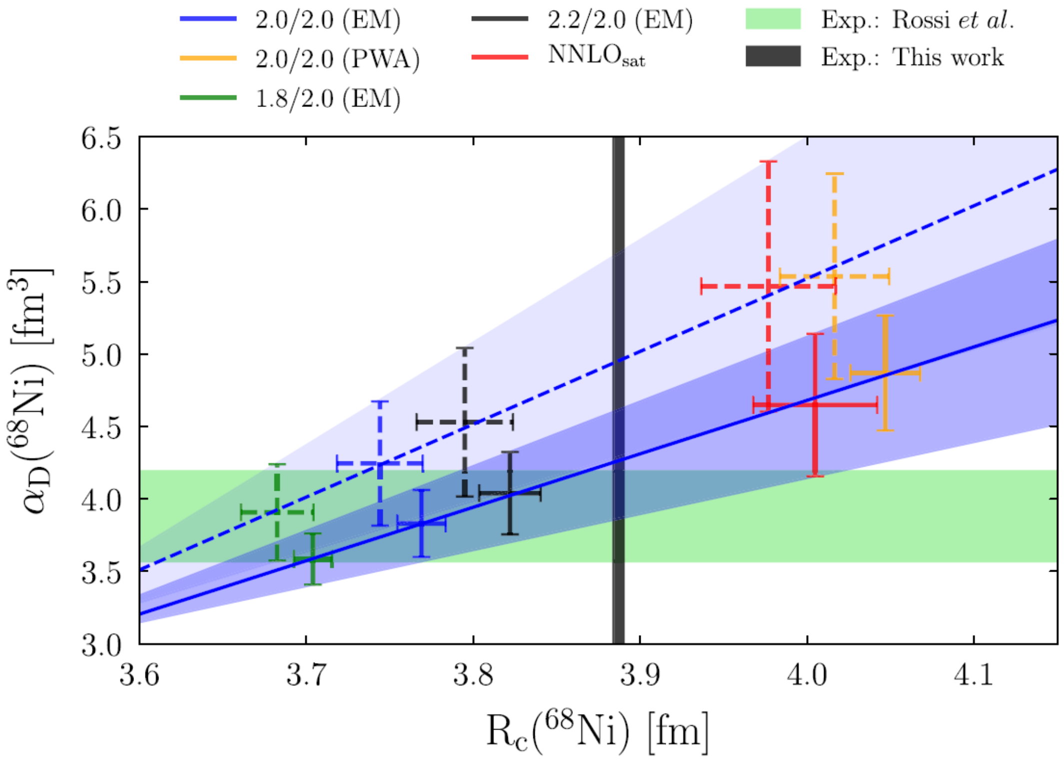
R. P. de Groote, et al. Nat. Phys. 16, 620–624 - 2020

Charge radii of nickel: constraining the neutron skin

Data: obtained at ISOLDE



- Theoretical coupled-cluster calculations with chiral-EFT interactions
  - correlation between dipole polarizability and charge radius
  - including 3 particle -3 hole correlations (full line) leads to softer dipole polarizability and slightly larger charge radius



=> measure the charge radius, exploit the correlation to find polarizability.
Then, constrain neutron radius and neutron skin of ^{68}Ni!

S. Kauffmann et al., PRL 124, 132502 (2020),
Coupled Cluster calculations Schwenk, Hagen et al.

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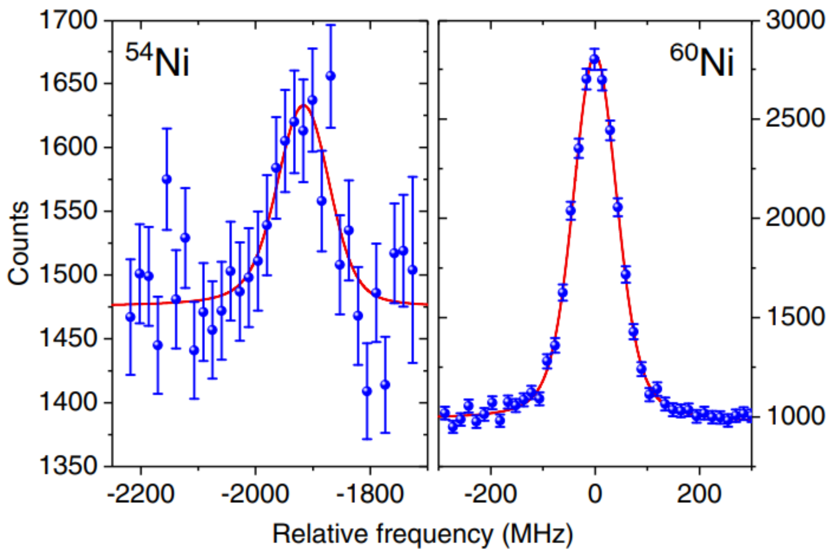
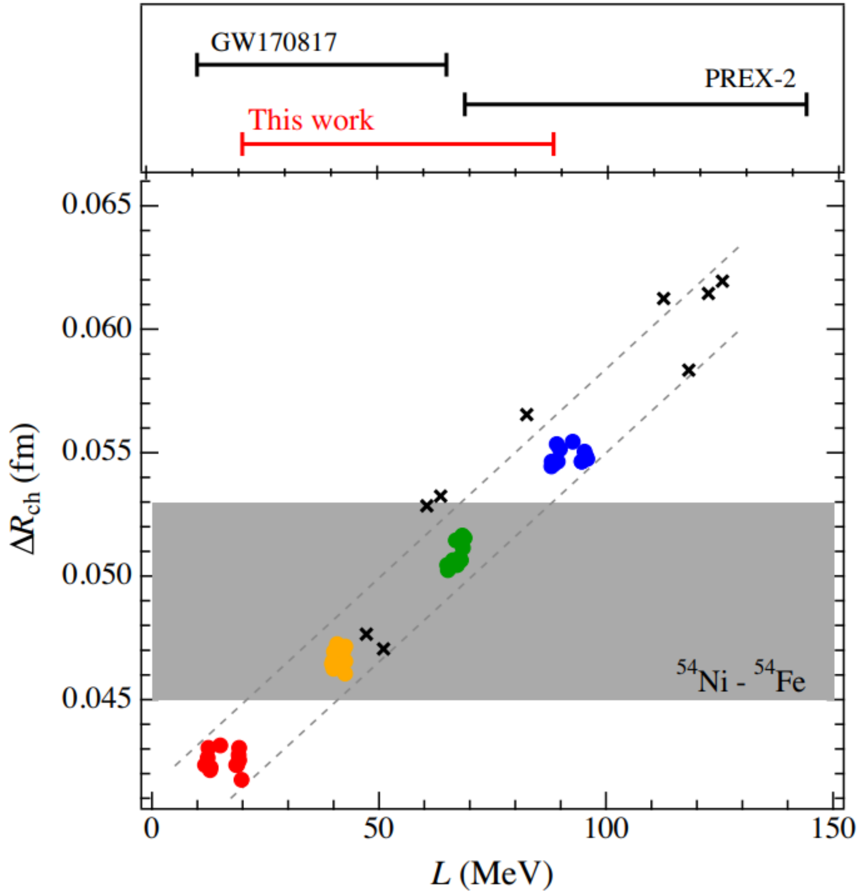
Charge radii of nickel: constraining the neutron skin

- Exploiting correlation between charge radius difference of ^{54}Ni-^{54}Fe, and the symmetry energy parameter *L* in the equation of state
- Constraint is consistent with PREX measurements and neutron star merger GW170817data



Data: obtained at NSCL



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