Physics Highlights and Challenges: Nuclear Physics

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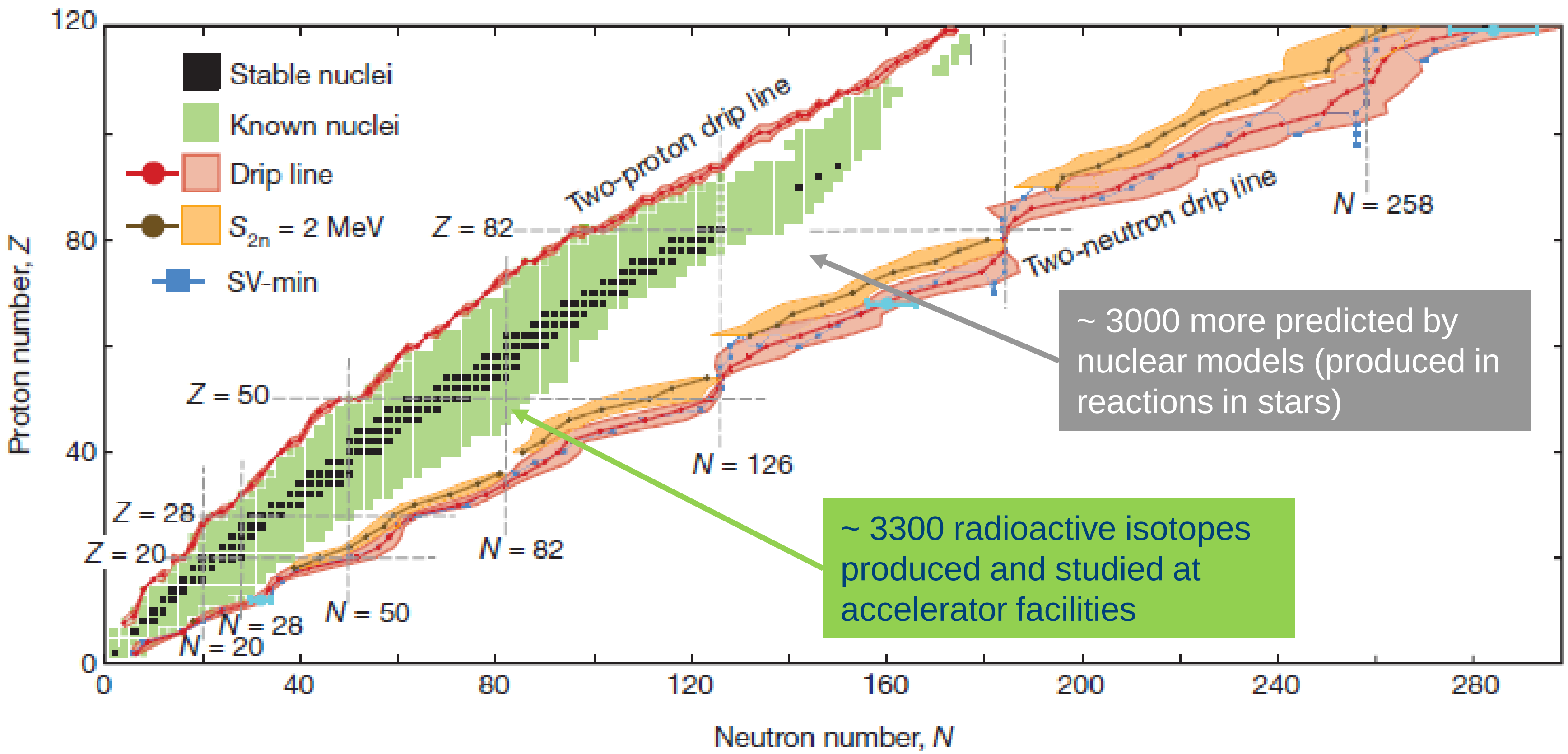
- Nuclear-physics research: aim
- Progress in nuclear theory
- Progress in experiments
- Outlook and perspectives
- Conclusions

Thanks to P. Van Duppen, N. Kalantar, C. Scheidenberger, P. Greenlees, Y. Leifels, P. Roussel Chomaz, W. Korten, … for input

Nuclear-Physics Research - Aim

- Unravel the fundamental properties of nuclei from their basic constituents
- Investigating the strong and weak interaction at work in the nuclear medium
  → competing with the electromagnetic force in the heaviest isotopes
- Establishing the limits of existence

More in talk by Marek Lewitowicz



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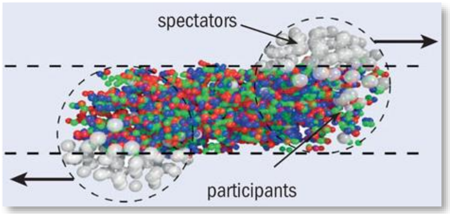
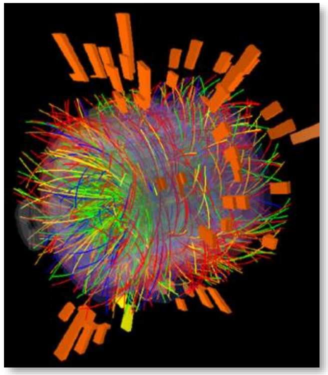
Nuclear-Physics Research - Aim

- Experimental investigations explore 3 extremes:

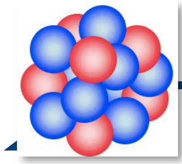


Link to Hadron Physics (see J. D'Hondt, M. Lewitowicz)



Energy

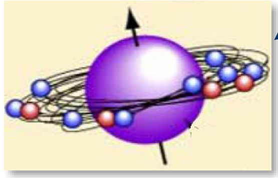
- Strong links to
  - **Nuclear Astrophysics / Nucleosynthesis**
  - **Fundamental Interactions and Symmetries**
  - Atomic Physics / Chemistry (e.g. heavy element region)
  - Societal Aspect (e.g. medical radioisotopes)

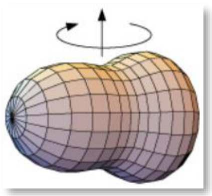


N/Z - isospin

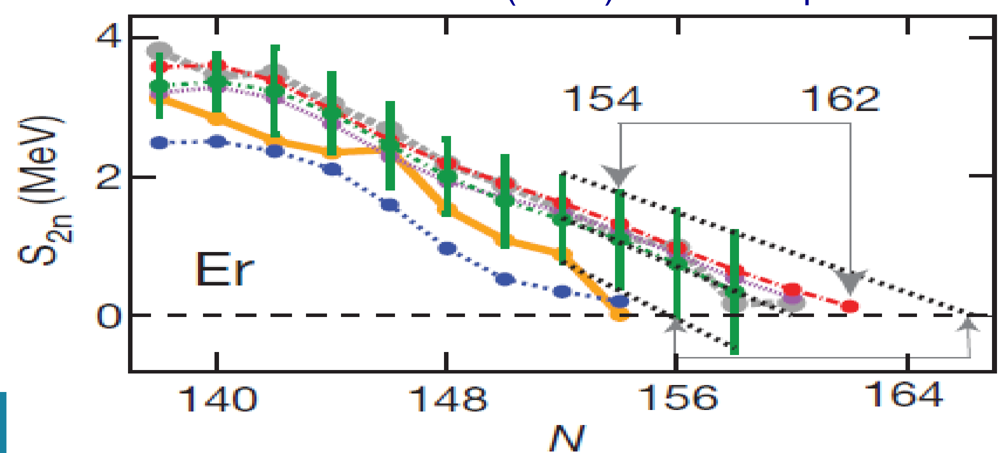
Er (Z=68) neutron drip line: N≈154 - 162

Spin - Deformation





Z

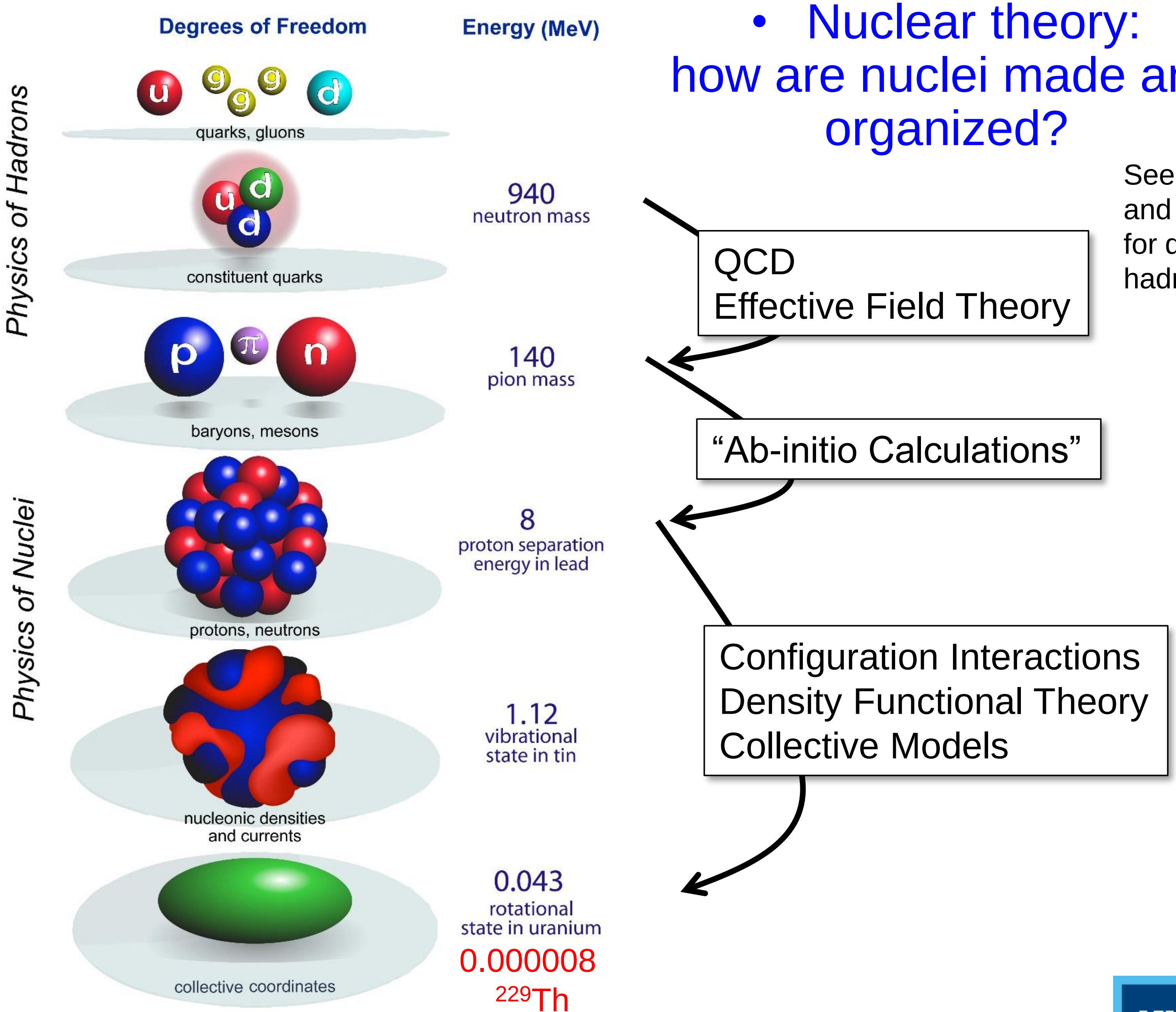


Data up to N=112

Erler,- Nature 486 (2012)

• Nuclear theory: how are nuclei made and organized?

See Jorgen d'Hondt and M. Lewitowicz for quark-gluon and hadron physics



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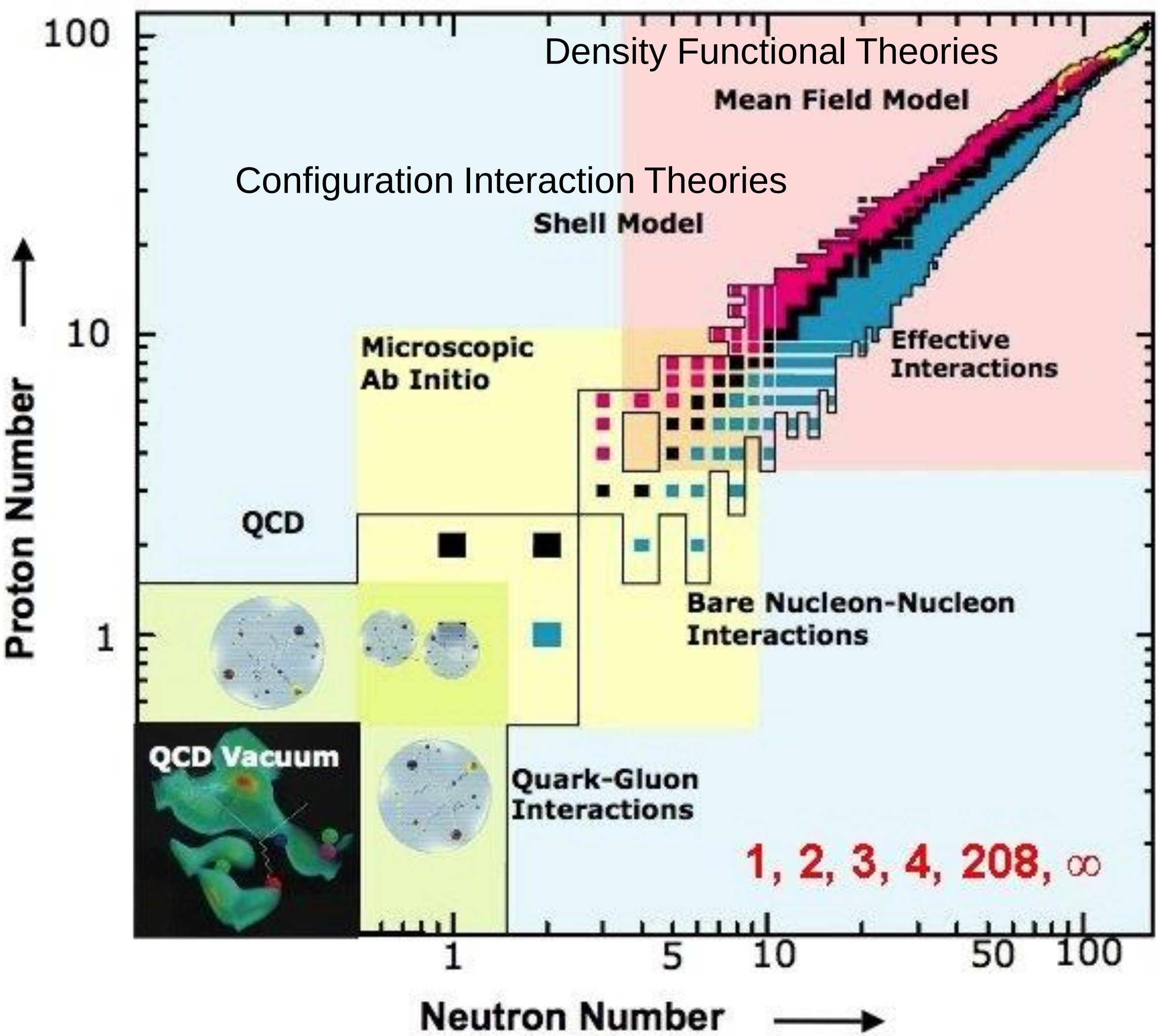
The application domain of nuclear theories

From lattice-QCD towards multi-nucleon systems



DFT: nucleons moving within their own self-consistently-generated mean field

CI: many-body methods using *ab-initio* or empirical nucleon-nucleon interactions

Ab-initio: nn-interaction derived from QCD through chiral EFT + exact solution of the many-body problem

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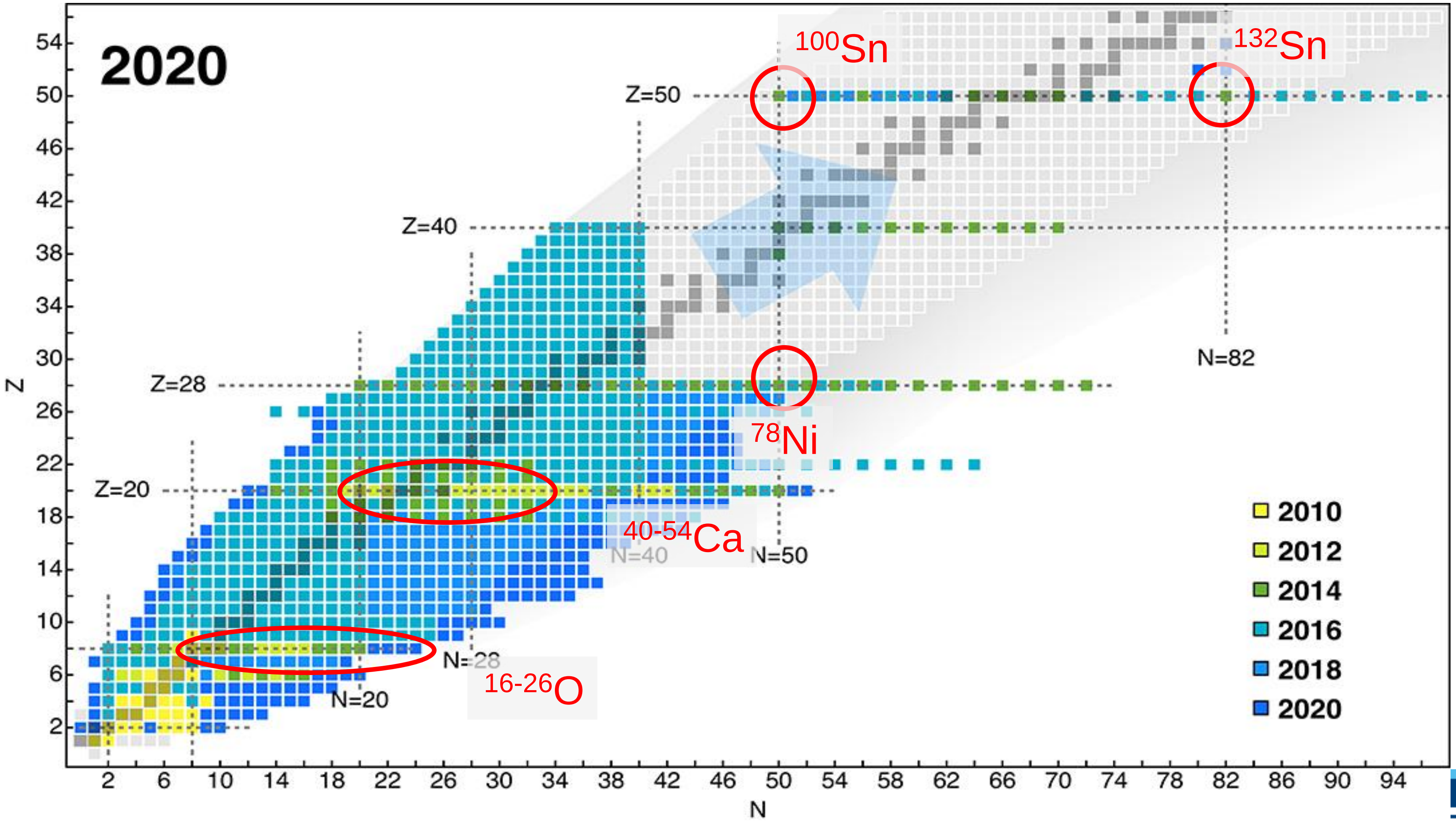
The rising of ab-initio nuclear theories

A-body Schrodinger Equation

- Interactions derived from QCD (Chiral EFT)
- Variety of Quantum Many Body methods

$$H|\Psi_n^A\rangle = E_n^A|\Psi_n^A\rangle$$



H. Hergert, Frontiers in Physics 8 (2020) 379

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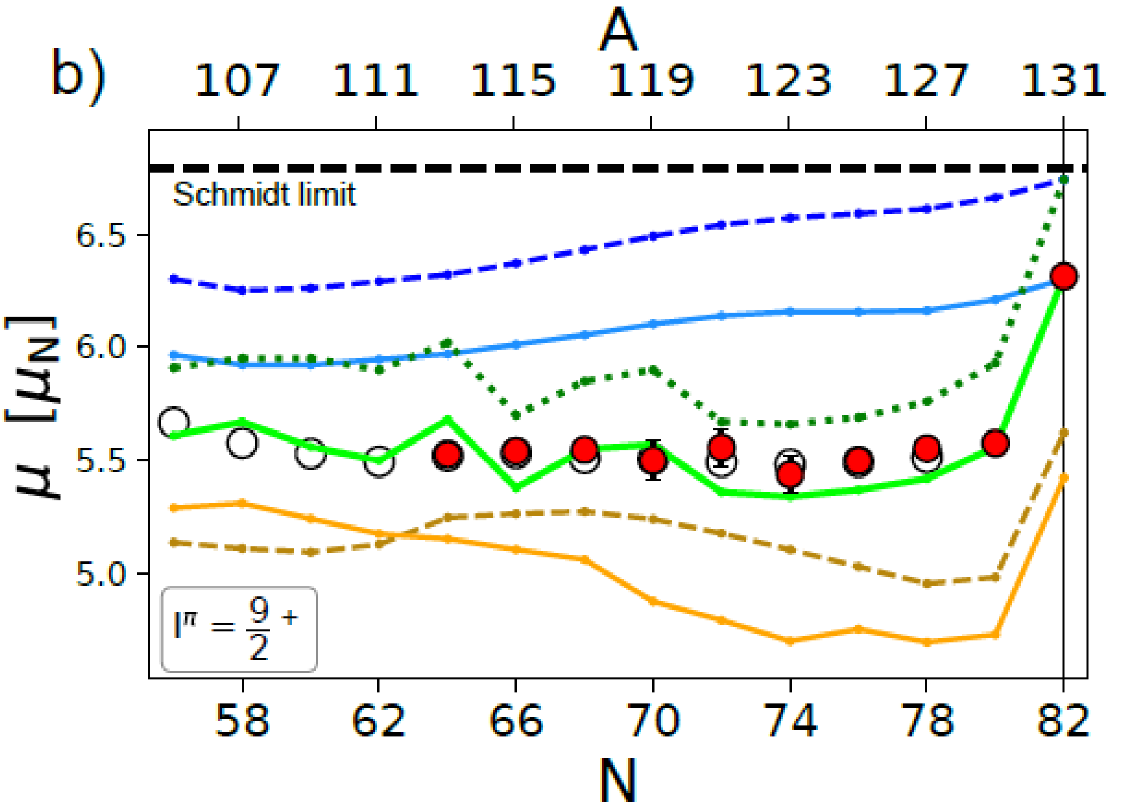
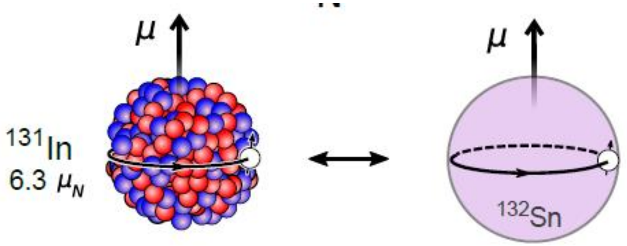
Ab-initio calculations now reach ^{132}Sn

Magnetic moments of **Z=49 indium isotopes** up to magic N=82





Interactions from chiral EFT
Bare magnetic operator derived self-consistently
Bare nucleon g-factors

A textbook example for the nuclear shell model.
BUT ONLY ^{131}In is single-particle like !

Calculations by T. Miyagi, J. Holt and S.R. Stroberg

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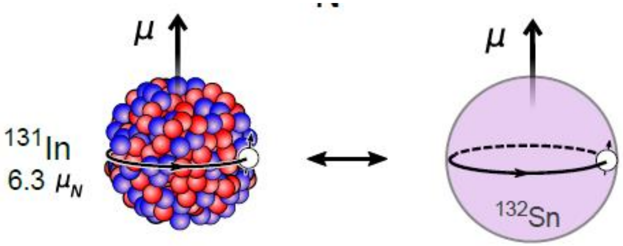
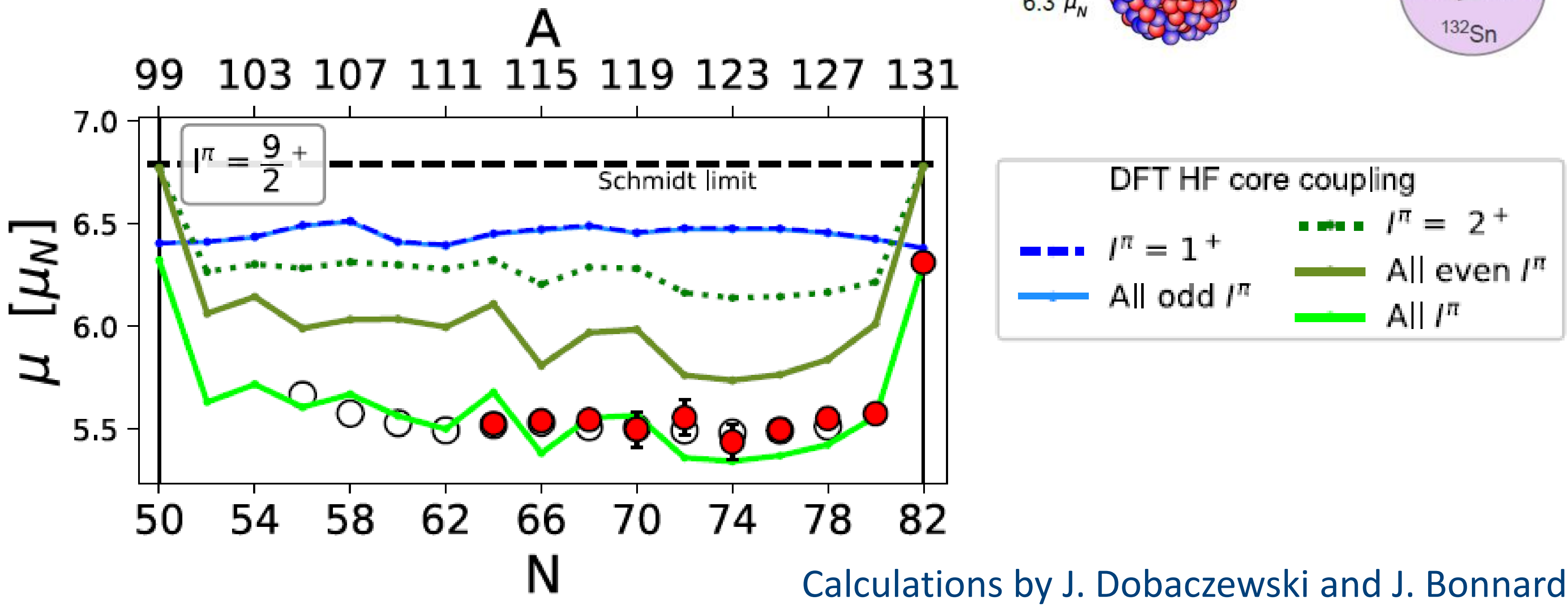
Density functional theories
towards spectroscopic accuracy

Magnetic moments of **Z=49 indium isotopes** up to magic N=82

DFT-HF including time-symmetry breaking contributions to the mean field





Calculations by J. Dobaczewski and J. Bonnard

Ab Initio Limits of Atomic Nuclei

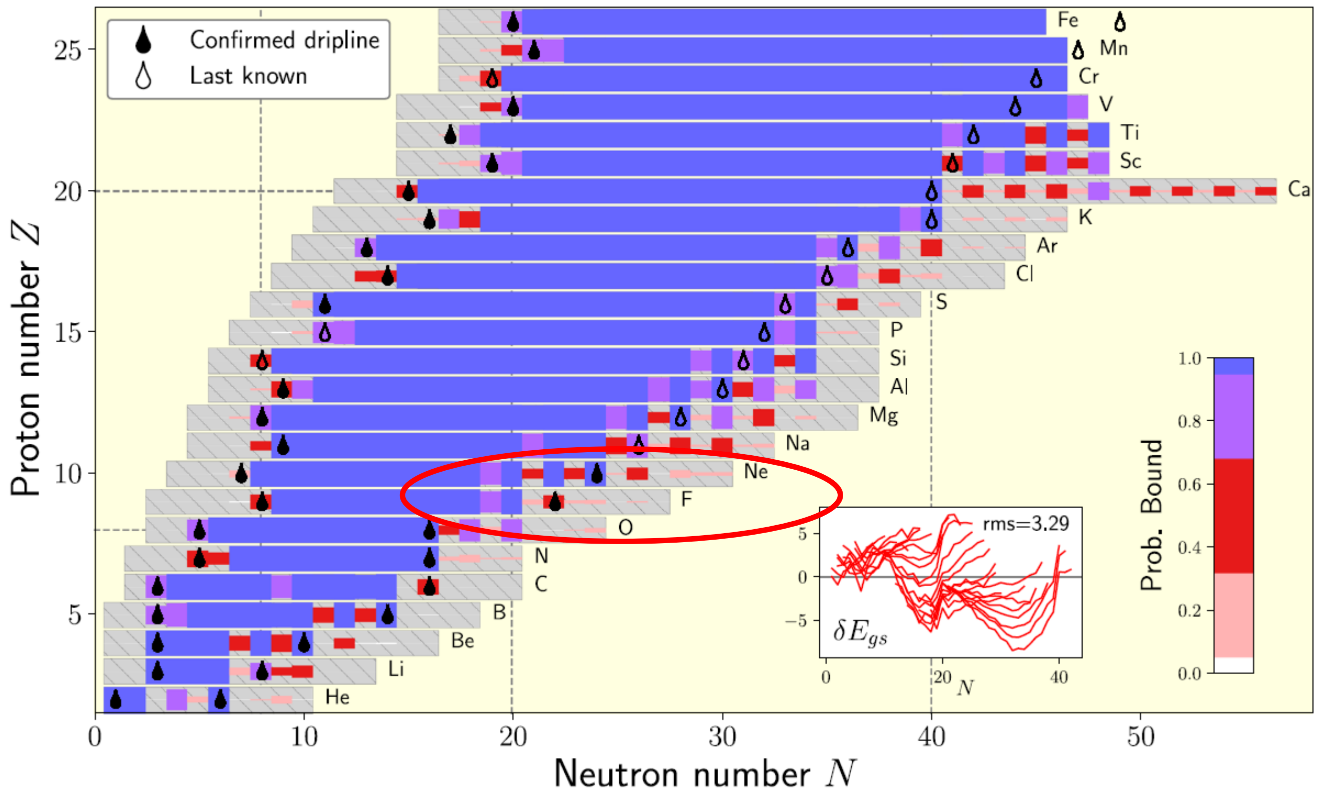
Neutron drip-line experimentally confirmed up to **Z=10 (Ne)**

D.S. Ahn et al., *PRL 123 (2019) 212501*

Proton drip-line experimentally confirmed for all elements on earth (and up to **Z=93 Np** for odd-Z)

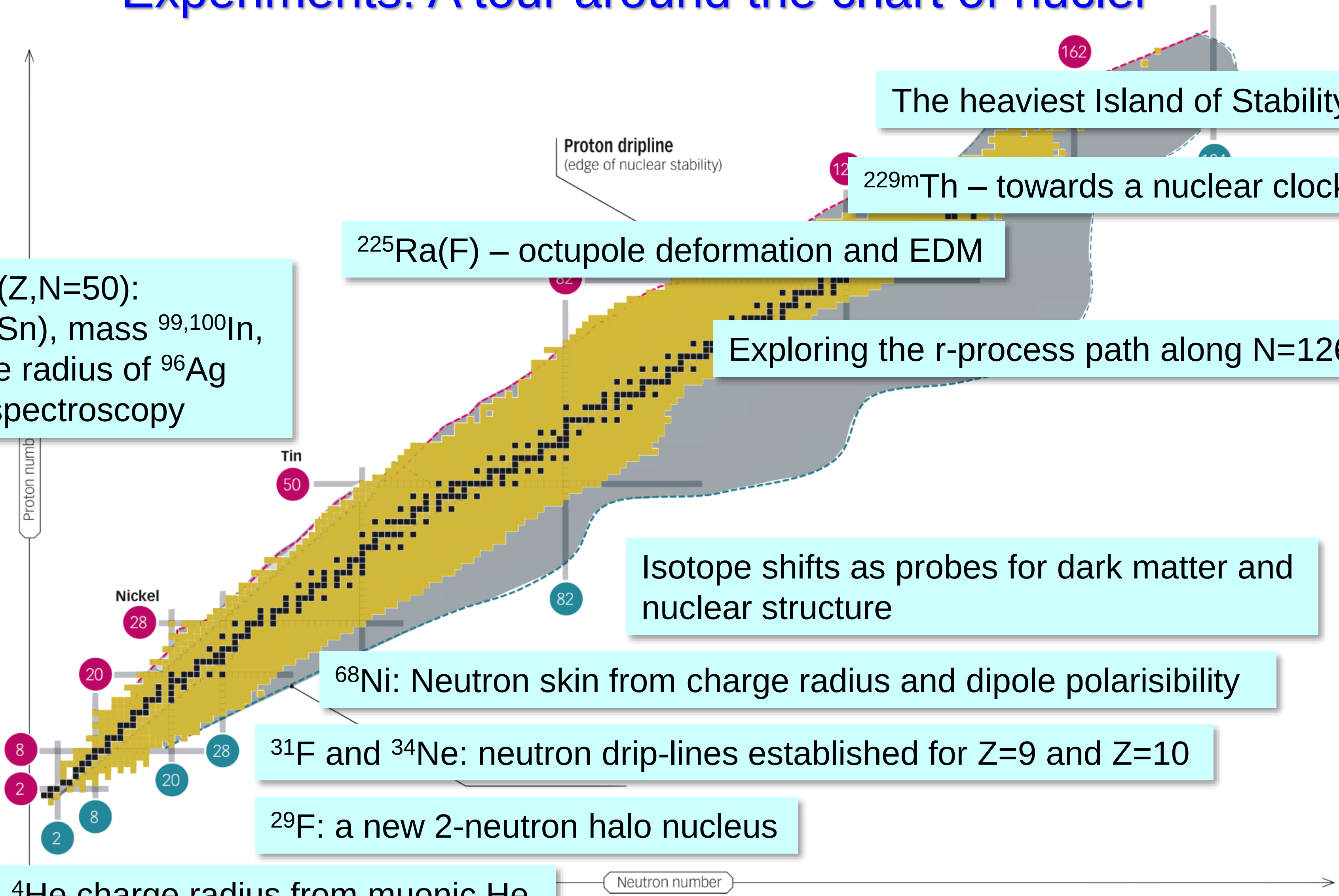
Z.Y. Zhang et al., *PRL 122 (2019) 192503* Lanzhou, China

Ab-initio predicted drip-lines up to Z=26 (Fe)



S.R. Strobergh, J. Holt, A. Schwenk, J. Simonis, PRL 126, 022501 (2021)

Experiments: A tour around the chart of nuclei



The heaviest Island of Stability

^{229m}Th – towards a nuclear clock

^{225}Ra(F) – octupole deformation and EDM

^{100}Sn (Z,N=50):
Q_β(^{100}Sn), mass ^{99,100}In,
charge radius of ^{96}Ag
^{88}Ru spectroscopy

Exploring the r-process path along N=126

Isotope shifts as probes for dark matter and nuclear structure

^{68}Ni: Neutron skin from charge radius and dipole polarisibility

^{31}F and ^{34}Ne: neutron drip-lines established for Z=9 and Z=10

^{29}F: a new 2-neutron halo nucleus

^{4}He charge radius from muonic He

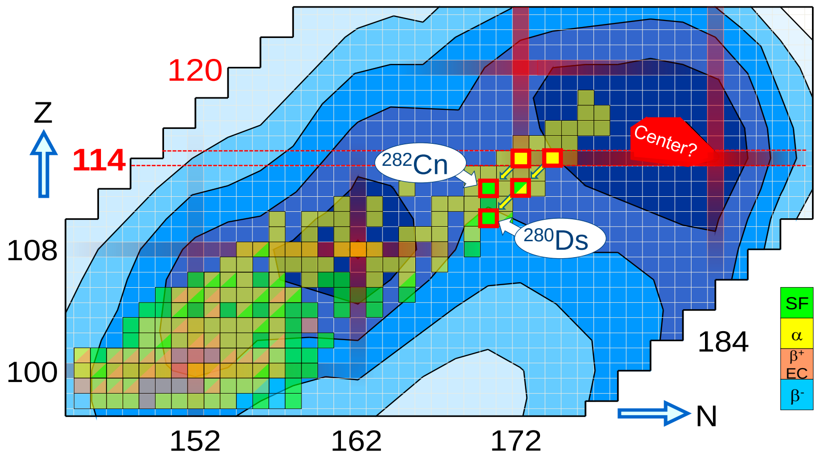
A new limit on the neutron EDM

Antimatter precision experiments

The heaviest island of stability

The center of the Island of Stability: it is not at Z = 114

Chart of nuclei of superheavy nuclei

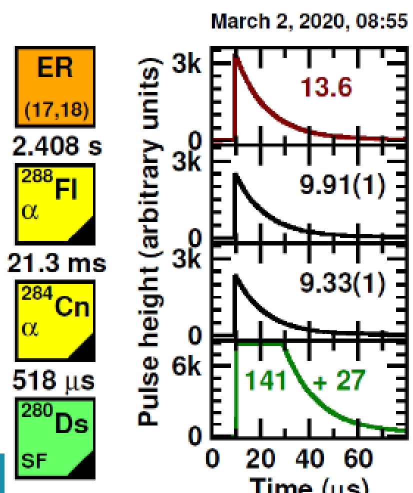


Calculated shell stabilization energy (Sobiczewski *et al.*)
Colored boxes: known nuclei

- First detailed **nuclear spectroscopy** of flerovium (Z=114) decay chains with TASISpec+ at ***TASCA*** recoil separator
- Discovery of **new isotope ^{280}Ds** (Z=110) provides first **sequence of α-decay energies across Z=114** shell gap
- Discovery of **excited 0$^+$ state** in ^{282}Cn (Z=112): **shape coexistence**

➔ together with extensive triaxial beyond mean-field theory these findings suggest that there is **no pronounced shell gap at proton number Z=114**

- Focus shifts to **heavier elements: 120? 126?**



A. Såmark-Roth *et al.*, Phys. Rev. Lett. 126 (2021) 032503
J.L. Egido & A. Jungclaus, Phys. Rev. Lett. 125 (2020) 192504; *ibid.*, 126 (2021) 192501
Spokesperson: D. Rudolph, Lund. Univ.

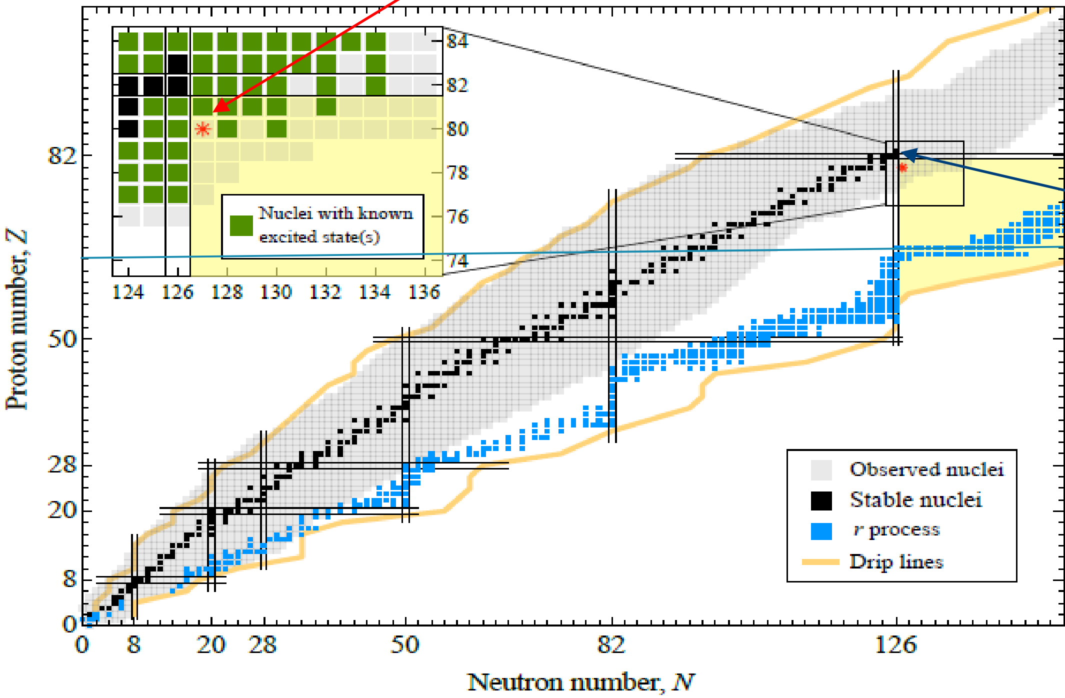
Courtesy: Y. Leifels

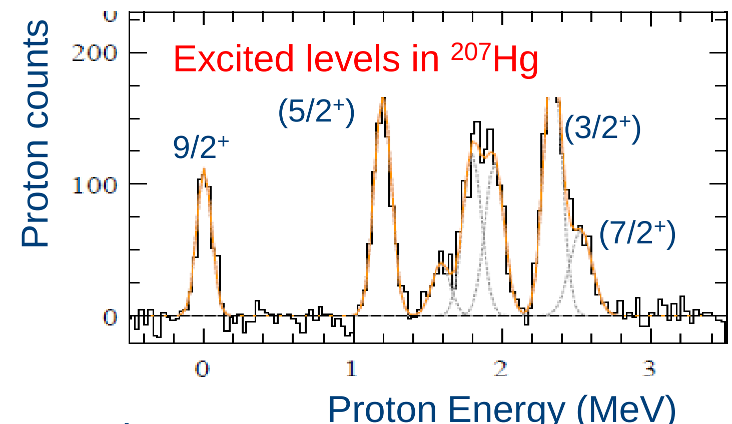
Terra incognita: first spectroscopy south-east of ^{208}Pb

Towards the r-process path along N=126

Study single particle states in ^{207}Hg for the first time using Transfer Reaction:

^{206}Hg (1.52 GeV) + d → ^{207}Hg + p





→ Binding energy of the neutron in different orbits is extracted

→ Allows to predict the last N=127 isotone with bound neutrons: Gd (Z=64)

Tang et al., PRL 124, 062502 (2020)

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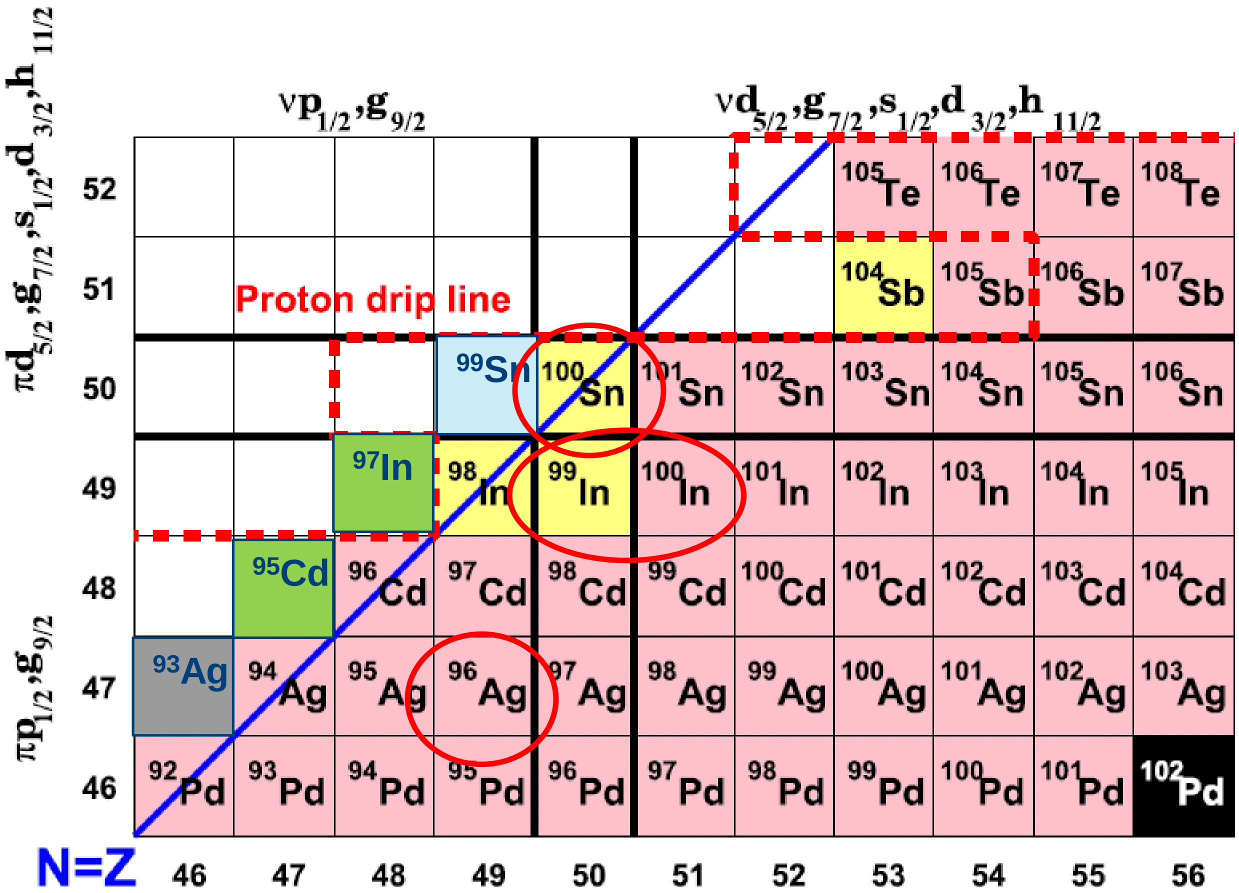
The ^{100}Sn region
self-conjugate and doubly-magic: N,Z=50

➔ Testing ab-initio nuclear theory near the proton drip-line

Q_β and B(GT) ^{100}Sn

Masses of ^{99,100}In

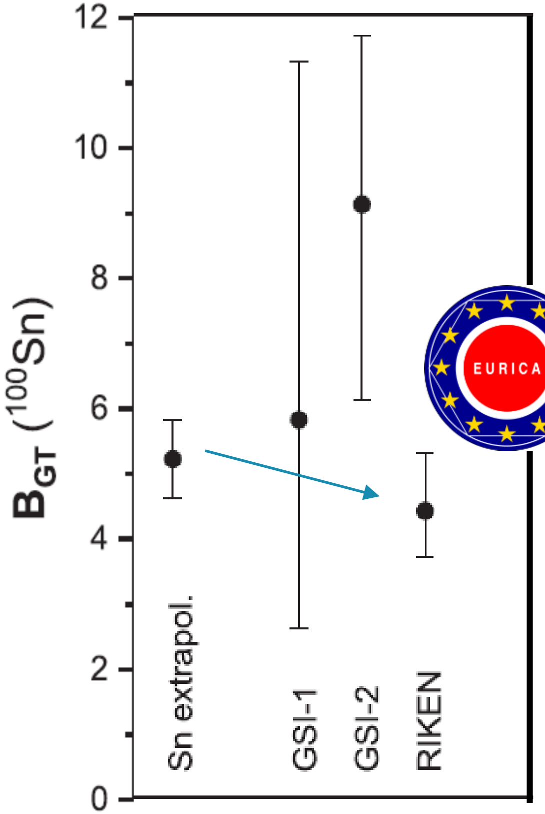
Charge radius of ^{96}Ag

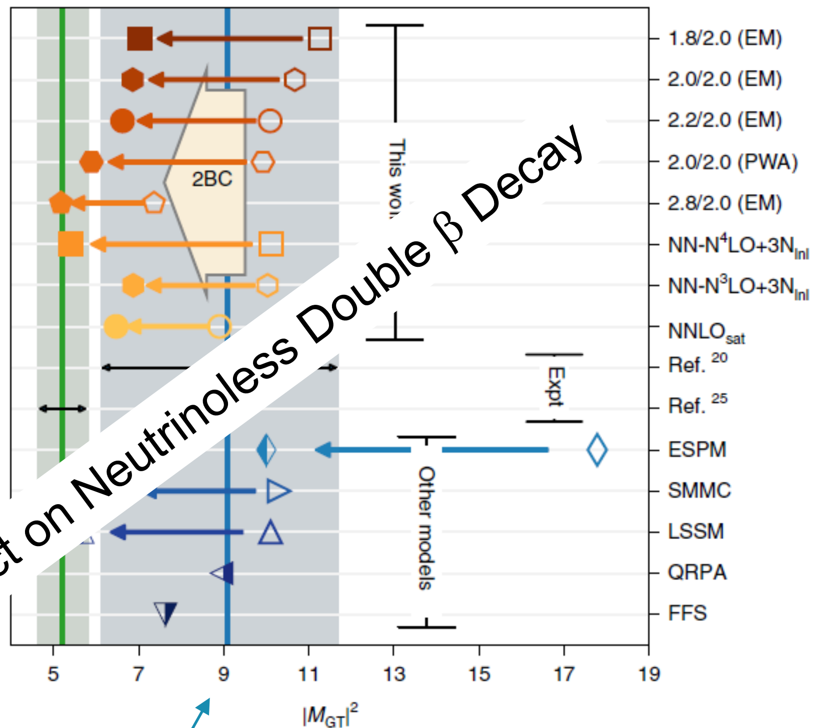


β decay of ^{100}Sn (Z,N=50)

→ New GT-strength: smaller than previous and more precise, consistent with extrapolated value from systematics

Ab-initio CC calculations including 2-body currents (full symbols)





- Impact on Neutrinoless Double β Decay

Exp GSI-2: Hinke,- Nature (2012)

- Increased radioactive beam rates expected at:

FAIR Phase 0 Research Program

GANIL spiral2 laboratoire commun CEA/DRF CNRS/IN2P3

BUT …

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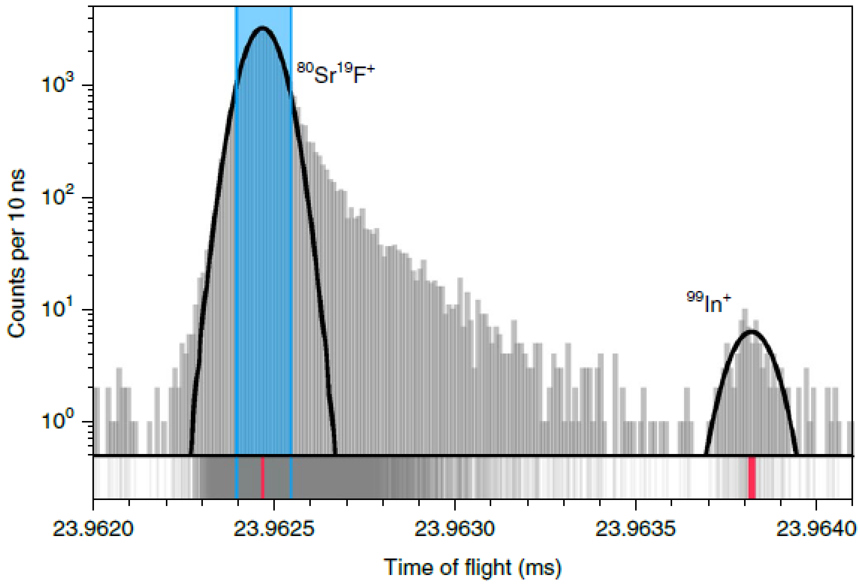
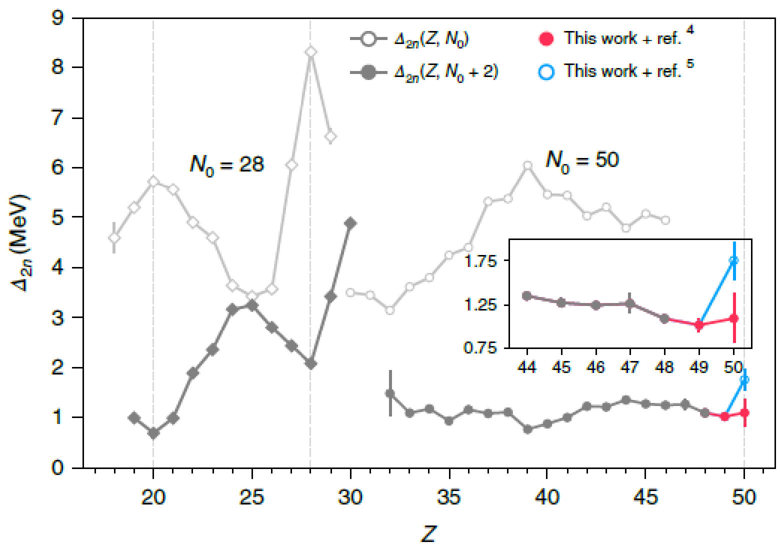
Exp RIKEN: Lubos,- PRL 122 (2019) Theory: Gysbers,- Nature Physics (2019)

Mass of ^{99}In and ^{100}In (Z=49)

ISOLDE
ISOLTRAP





MORE DATA NEEDED !

➔ Use mass of ^{100}In and $Q_\beta(^{100}Sn)$ to improve the mass-value of ^{100}Sn

Conflicting results on beta-decay Q-value of ^{100}Sn:

D. Lubos et al., PRL 122, 222502 (2019) (RIKEN)

Q_β = 3.71(20) MeV

C.B. Hinke et al., Nature 486 (2012) 341 (GSI)

Q_β = 3.29(20) MeV

➔ Trend in the masses indicates that the mass of ^{100}Sn using RIKEN result on GT decay is inconsistent with expected trend

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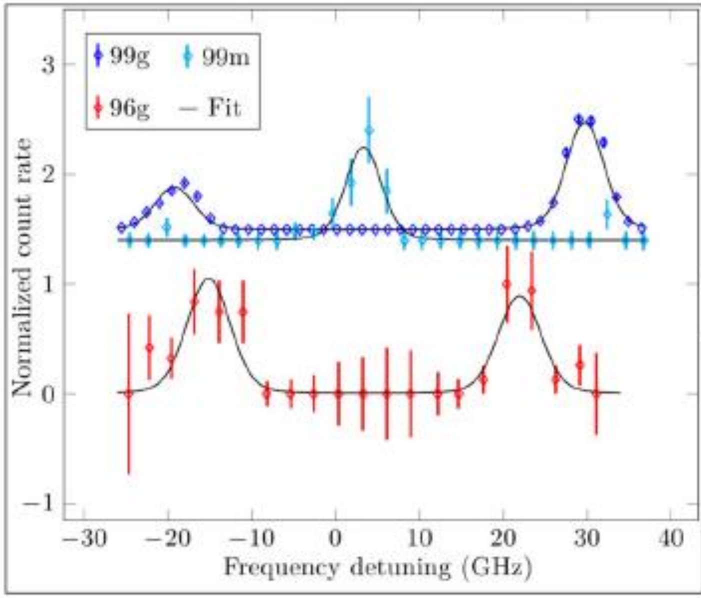
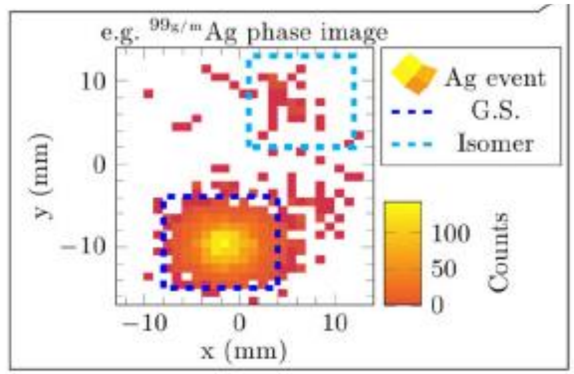
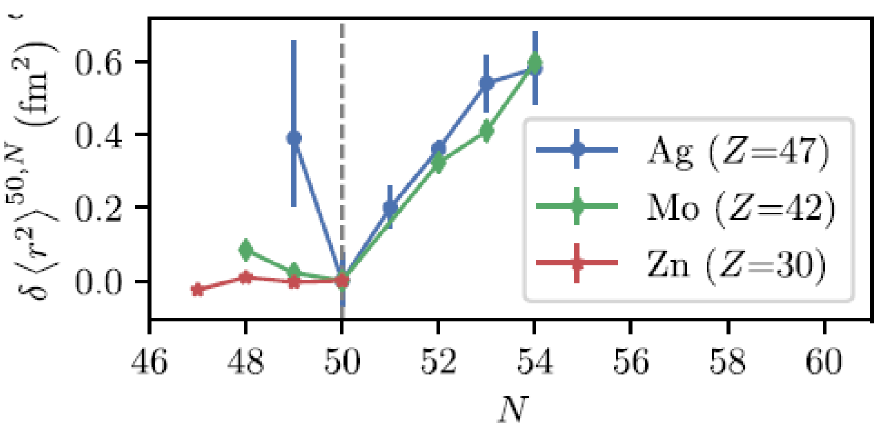
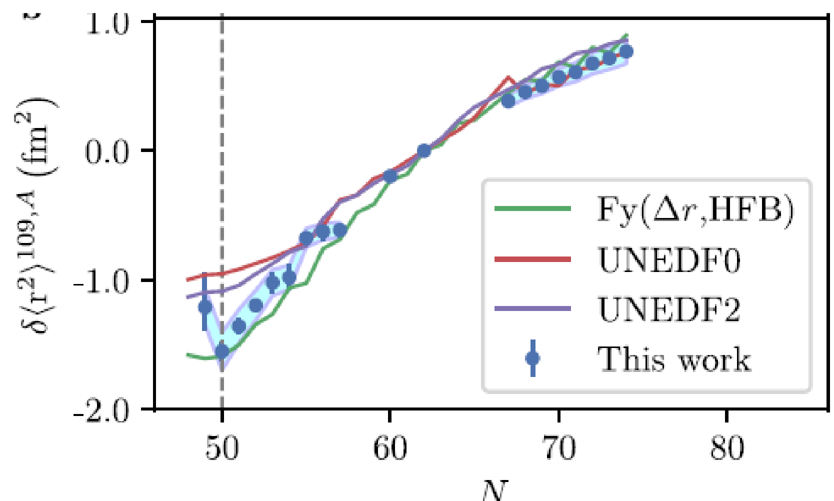
Increase in the charge radius of ^{96}Ag

Trap-assisted laser spectroscopy
- → Towards ultimate sensitivity
- → Detection rate ^{96}Ag: 1 count / 3 minutes
- → Challenges modern DFT approaches near ^{100}Sn

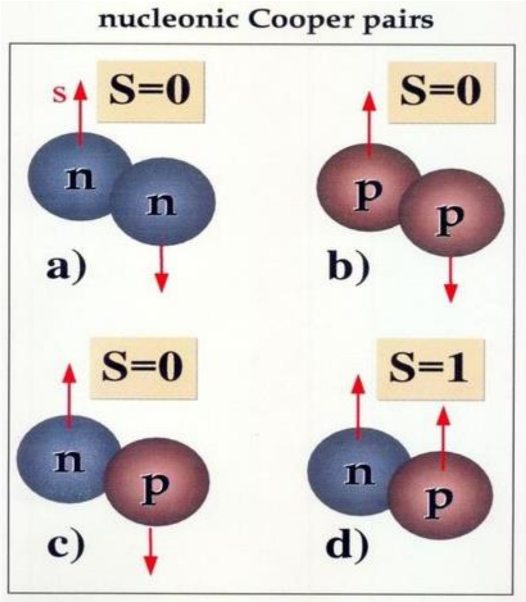








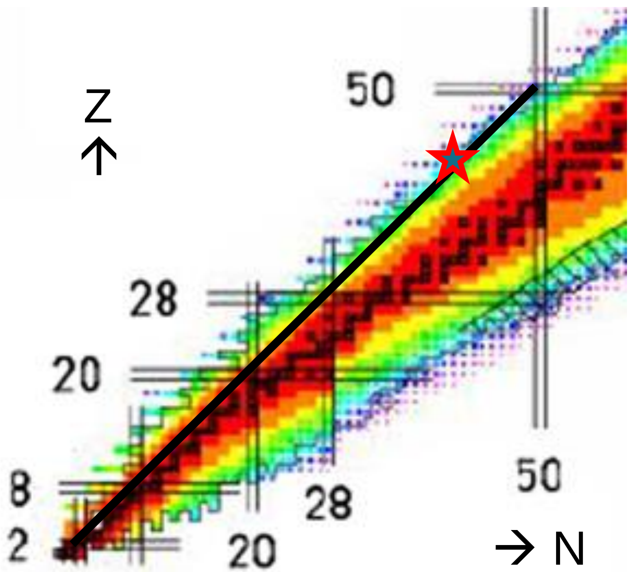
N=Z isotopes: study p-n (iso-scalar) pairing correlations

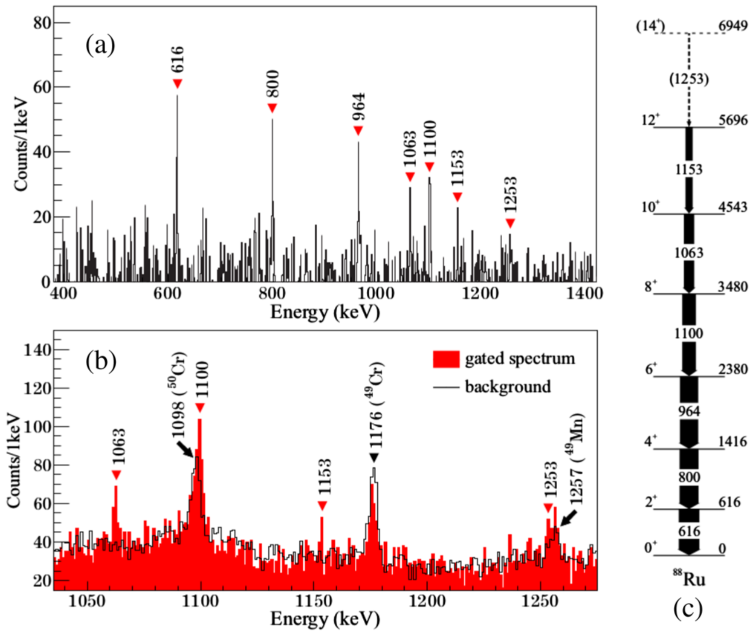


Nucleons can form strongly correlated pairs which impacts strongly on nuclear structure.

Only in N=Z nuclei will the p-n (isoscalar) pairing be important, as protons and neutrons occupy the same orbit.

★ ^{88}Ru: 44 protons and 44 neutrons (near proton dripline)





Rotating deformed nucleus with strong ISO-SCALAR p-n pairing !

B. Cederwall et al., PRL 124, 062501 (2020)

Hyperfine structure, isotope shifts and nuclear charge radii

For nuclear structure studies:
sensitive to shell gaps, deformation, neutron skin

For particle physics studies:
Probes to search for new bosons, EDM's, anapole/Shiff moments

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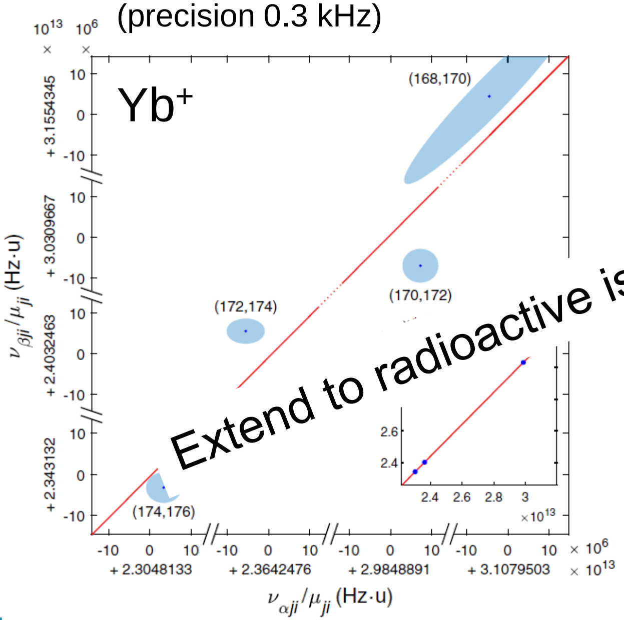
Precision isotope shifts: sensitive to new bosons?

Credit: J. Hur/Massachusetts Institute of Technology

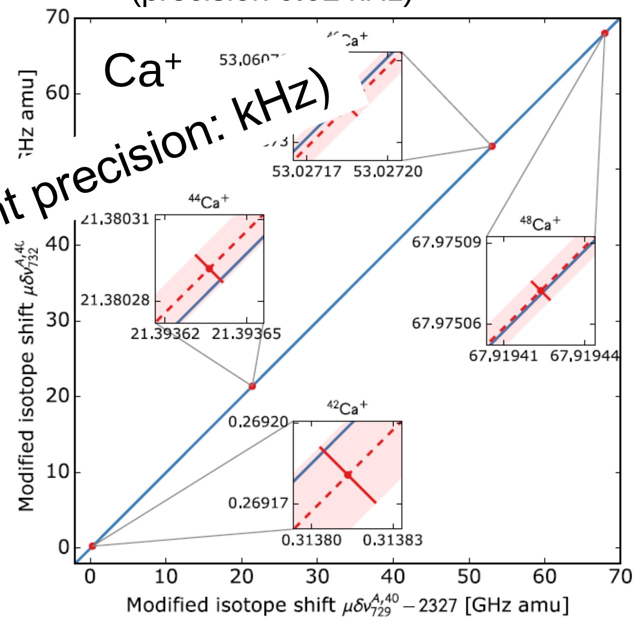
A nonlinearity of the King plot can indicate:

- 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.

5 **stable** Yb isotopes: **deviation observed** (precision 0.3 kHz)



5 **stable** Ca isotopes: **no deviation** (precision 0.02 kHz)



Extend to radioactive isotopes (current precision: kHz)

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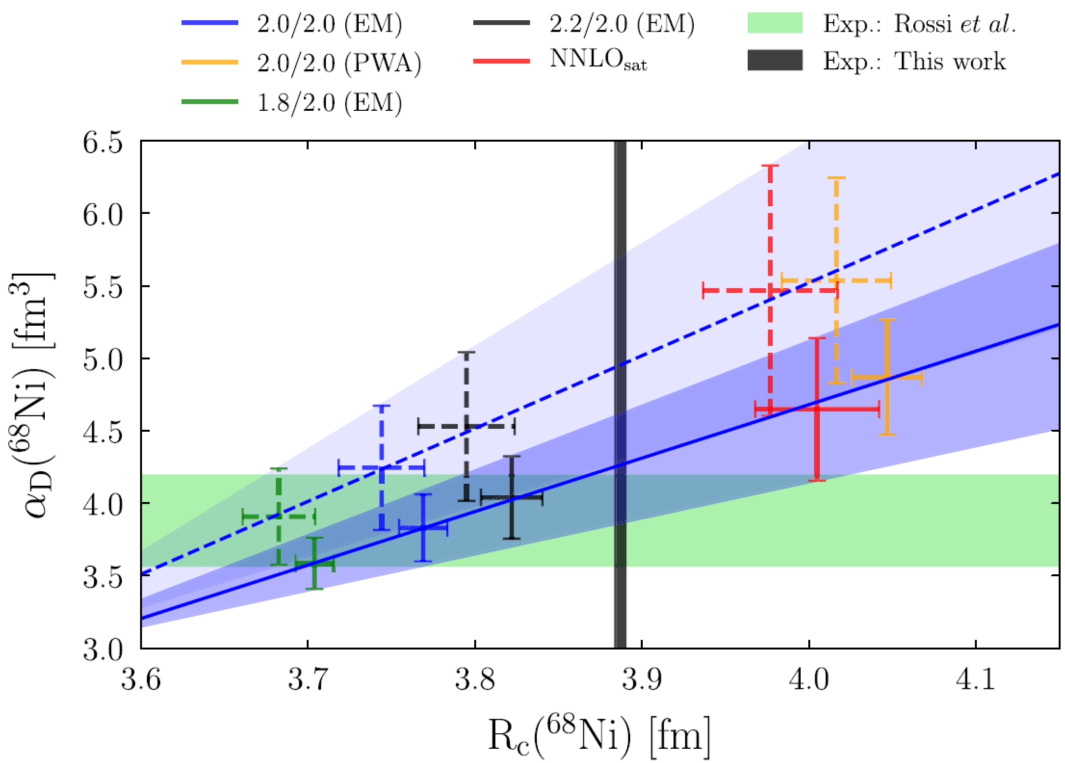
I. Counts et al., PRL 125, 123002 (2020) C. Solaro et al., PRL 125, 123003 (2020)

Charge radius of ^{68}Ni: constraining neutron skin

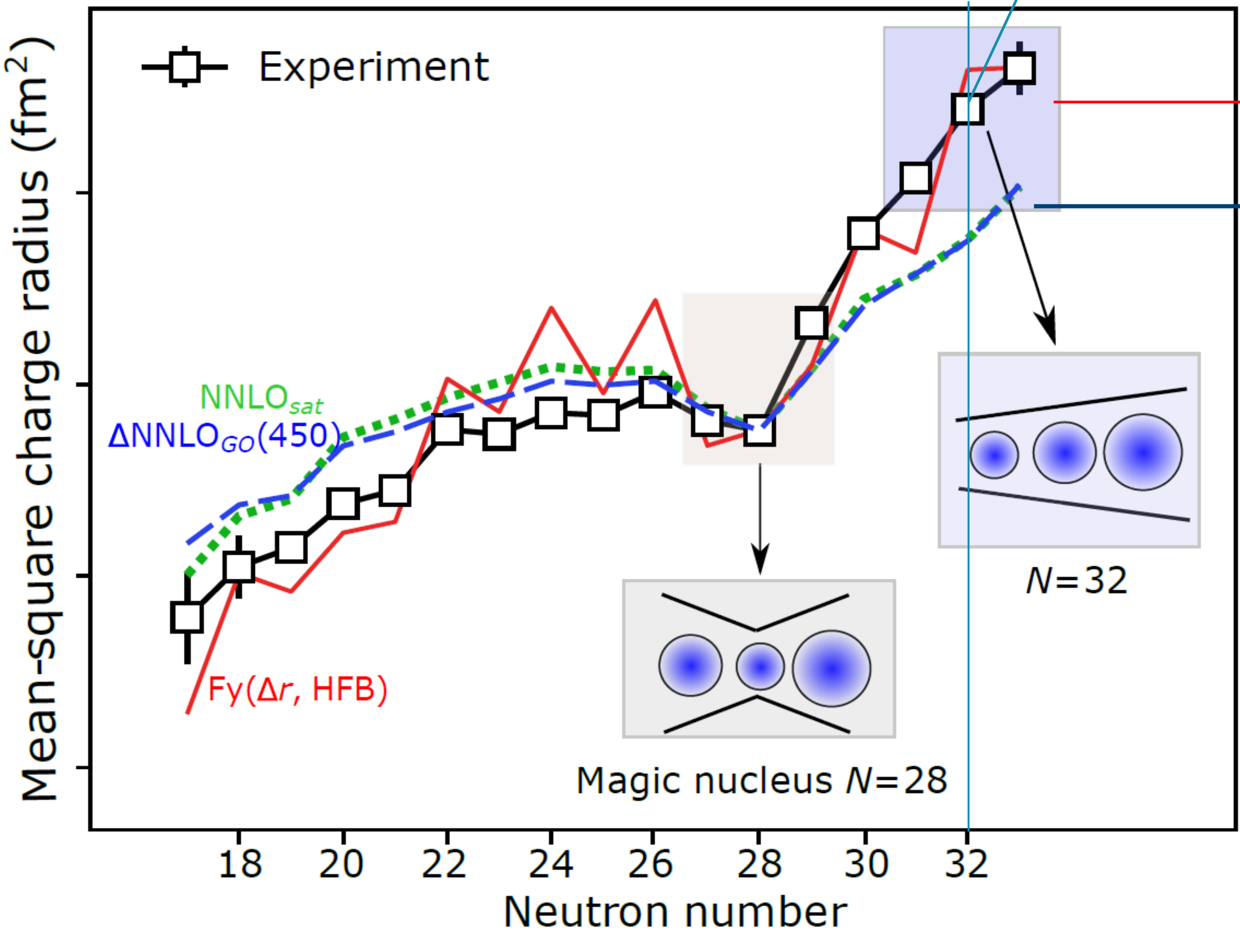
- Coupled Cluster calculations using interactions from chiral-EFT
  - ➔ **correlation between dipole polarizability and charge radius**
  - → including 3 particle -3 hole correlations (full line) leads to softer dipole polarizability and slightly larger charge radius
  - → constrain the neutron radius and the neutron skin of ^{68}Ni



Coupled Cluster calculations Schwenk, Hagen et al.

S. Kauffmann et al., PRL 124, 132502 (2020)

Charge radius of ^{52}K (Z=19):
Challenging the magic nature of N=32
and ab-initio nuclear theories



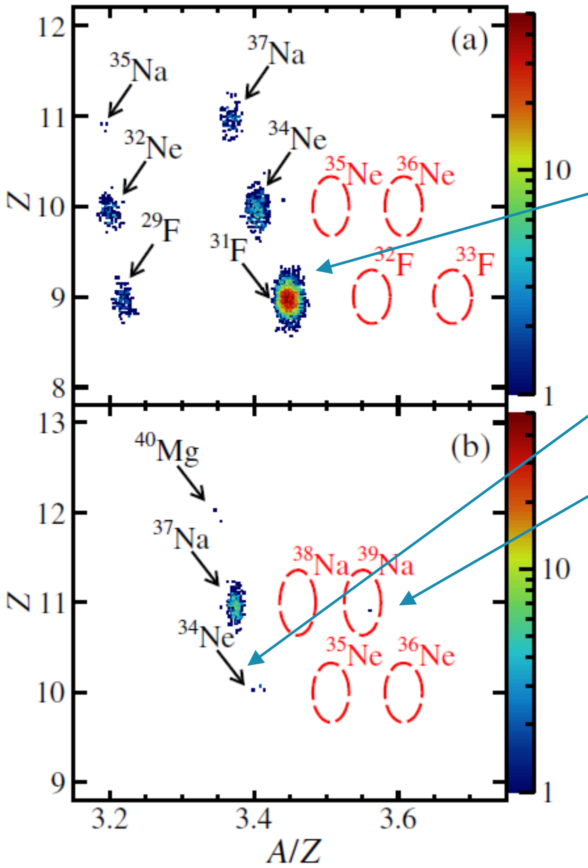
→ No signature of magicity at N=32 !

→ DFT reproduces the trend but overestimates the staggering

→ Ab-initio coupled-cluster underestimate the increase in the size of the radii

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

The neutron drip-line: extended to Fluorine and Neon



31F and 34Ne are the last bound isotopes of these elements

39Na seems bound, drip-line not yet reached

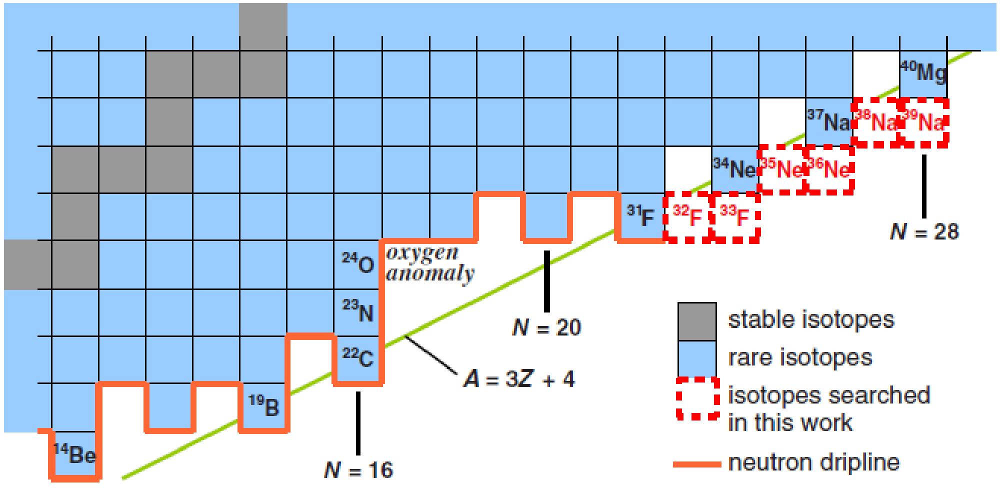
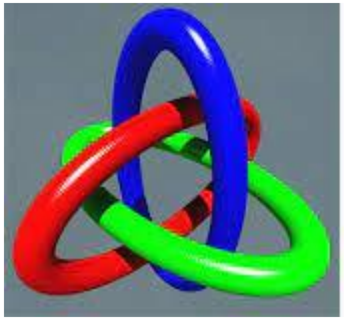
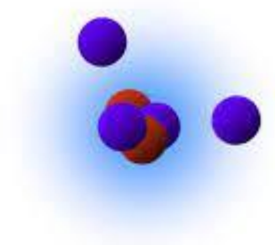


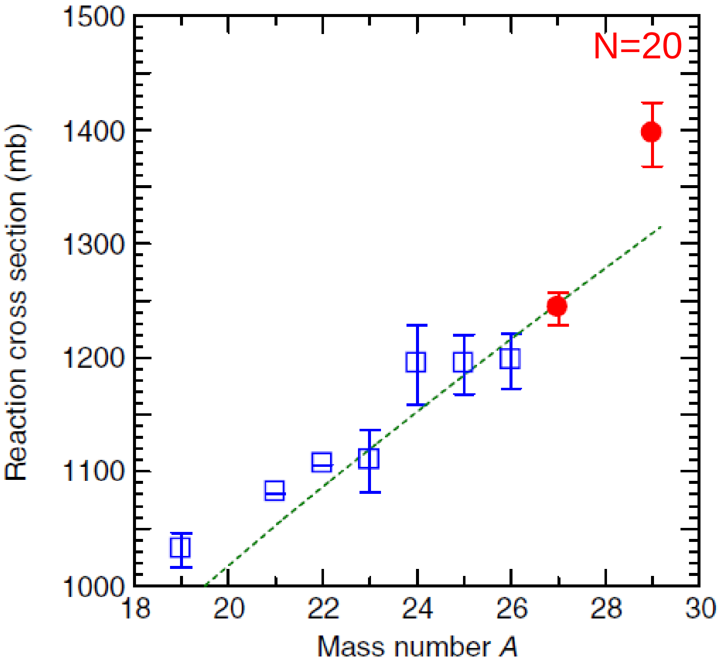
FIG. 1. Section of the nuclear chart showing the location of the isotopes studied in this work (red dotted squares).

^{29}F: heaviest two-neutron halo nucleus (so far)





^{6}He (N=4)
^{11}Li, ^{14}Be (4n) (N=8)
^{17}B, ^{22}C (N=16)



Matter radius ~ $A^{1/3}$
Halo nuclei: loosely-bound nucleon(s)

Profound test of modern reaction and structure theories:

* effective shell model interactions: good reproduction of cross section and matter radius increase in ^{29}F
* ab-initio interactions with CC: no increase in matter radius of ^{29}F

Alfa-particle charge radius measured using muonic ^{4}He

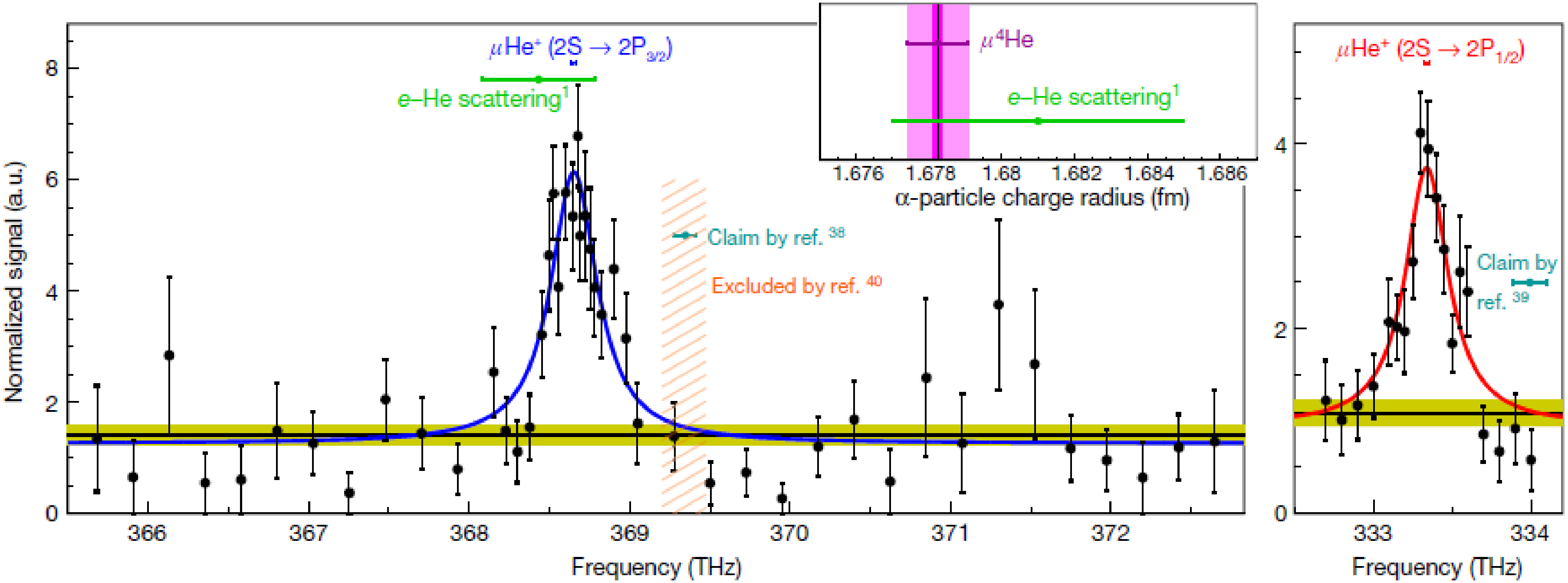
PAUL SCHERRER INSTITUT

Precision improved by almost factor of 5

$$r_\alpha = 1.67824(13)_{\text{exp}}\,(82)_{\text{theo}}\ \text{fm}.$$

In agreement with results from electron-He scattering experiments
In agreement with recent determinations of the proton charge radius
Leads to x10 improvement in the ^{6}He and ^{8}He halo nuclei radii

➔ Established light **muonic atoms** and ions as **precision tools for nuclear structure**



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J.J. Krauth et al., Nature 589 (2021) 527

A new limit on the neutron-EDM

the neutron EDM is $d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26}$ e.cm.

New limit: $|d_n| < 1.8\ 10^{-26}$ e.cm (90% C.L.)

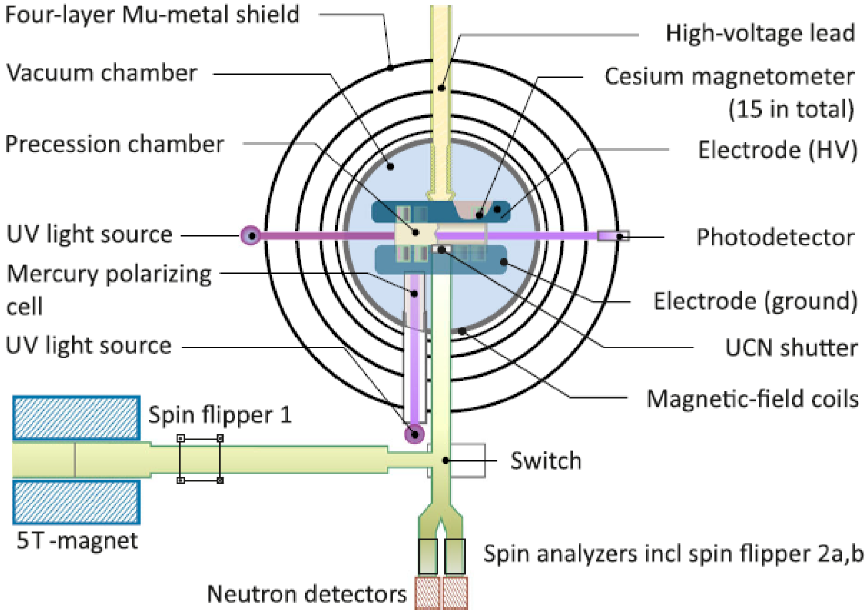


FIG. 1. Scheme of the spectrometer used to search for an nEDM. A nonzero signal manifests as a shift of the magnetic resonance frequency of polarized UCNs in a magnetic field B_0 when exposed to an electric field of strength E.

➔ Improvement of almost a factor 2 compared to the previous best value (PRD92, 092003 (2015)
$|d_n| < 3.0\ 10^{-26}$ e.cm

➔ systematic error improved by factor of 5

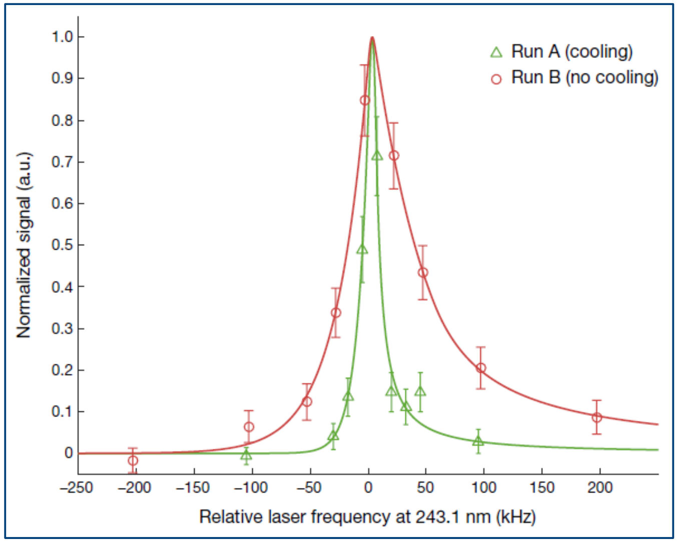
➔ With more statistics (n2-EDM) the n-EDM value can reach the 10^{-27} e.cm sensitivity

Laser-cooling of anti-hydrogen atoms and Sympathetic cooling of antiprotons using laser-cooled Be^+

Towards precision anti-matter research

Anti-hydrogen laser cooling using 121.6 nm laser to excite 1S-2P
- red detuned for cooling → transverse energy < 6 μeV
- bleu detuned for heating

Linewidth of the 1S-2S transition reduced by factor 4 ➔ **opens possibilities for high-precision laser spectroscopy on anti-H**



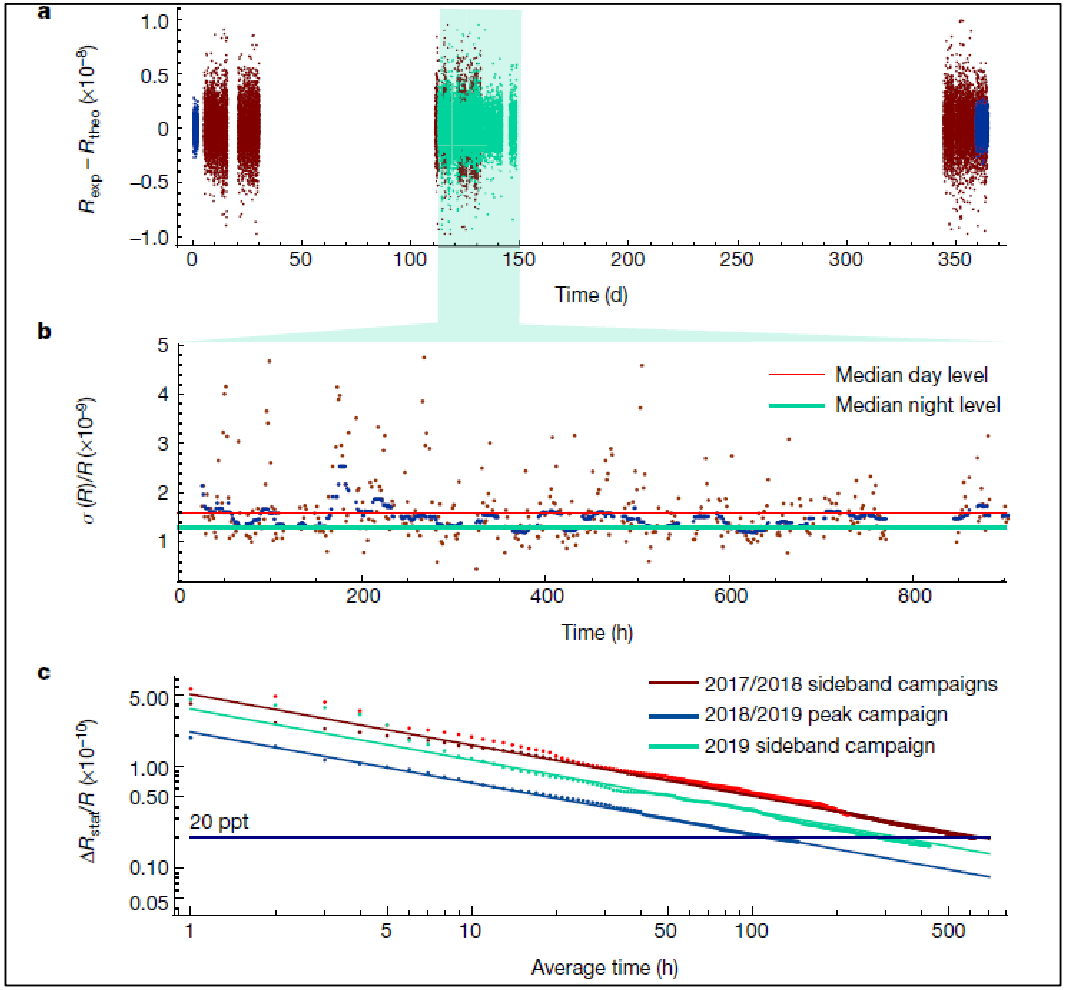
Sympathetic cooling of a single proton using laser-cooled Be+ ions in spatially separated Penning traps

➔ Towards improved precision in matter–antimatter comparisons and dark matter searches

 ALPHA collaboration, Nature 592 (2021) 35 BASE collaboration, Nature 596 (2021) 514

Improved precision on the e/m ratio for antiprotons compared to protons

Testing the Standard Model at the 1.96 × 10^{-27} GeV



4 measurements campaigns in 1.5 years different measurement techniques

- The result: $-(q/m)_{\bar{p}}/(q/m)_p$ = 1.000000000003(16)

  (16 parts in a trillion)

- The result is **consistent with the fundamental charge–parity–time reversal (CPT) invariance** and improves the precision of their previous best measurement by a factor of 4.3.

BASE collaboration, Nature 601 (2022) 53

Outlook and perspectives (very limited selection)

Radioactive molecules as probes for new physics ?
Hypernuclei as new probes to test nuclear models ?
^{229m}Th: a new standard for time / a new probe for fundamental constants?

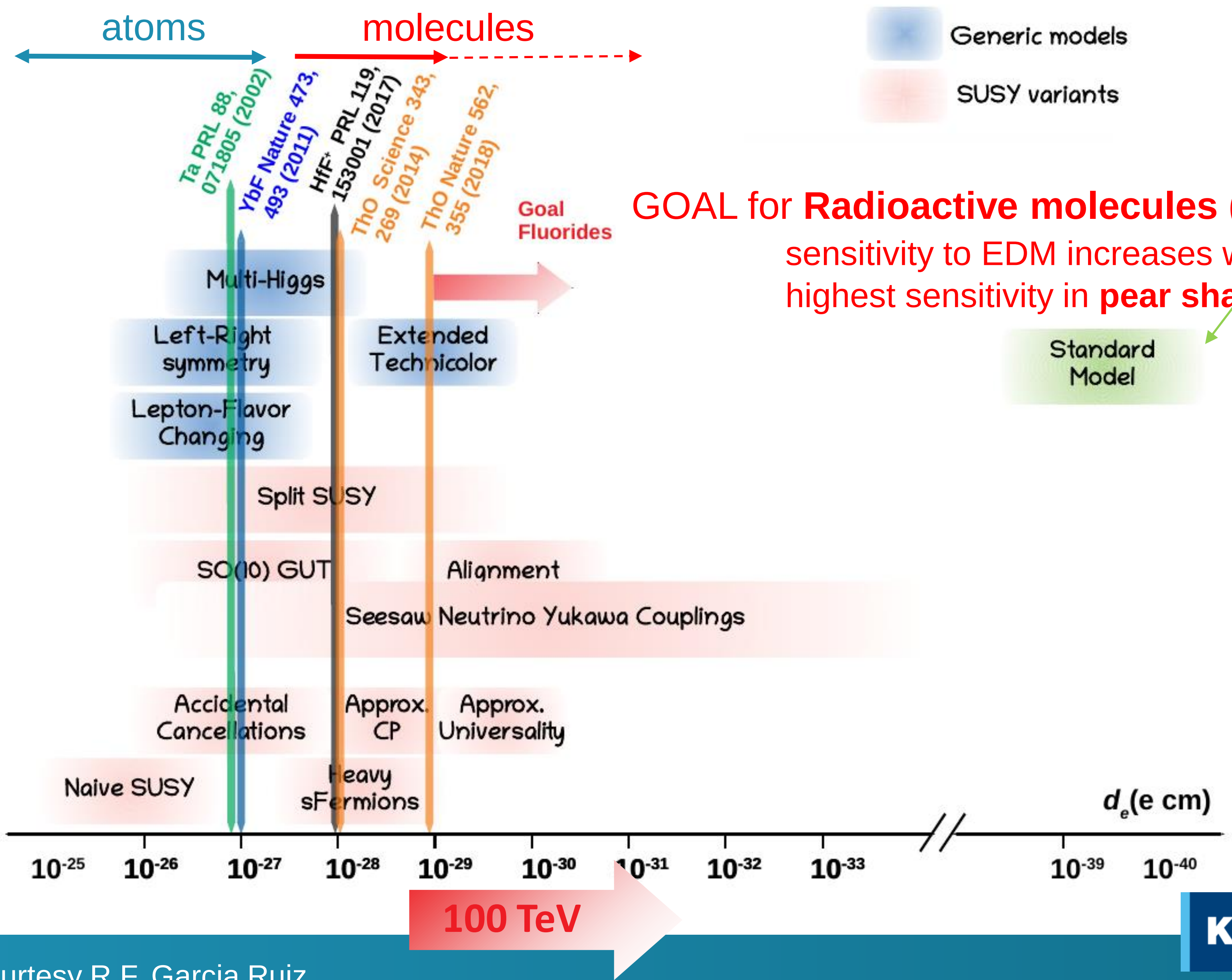
Not covered:

- Link to neutrinoless double beta-decay
- Search for CP violation and new weak currents in precision beta-decay
- Link to neutron-star mergers and gravitational waves

Molecules: most sensitive probes to an eEDM

Electric Dipole Moment

SM value is extremely small



GOAL for **Radioactive molecules (RaF)**

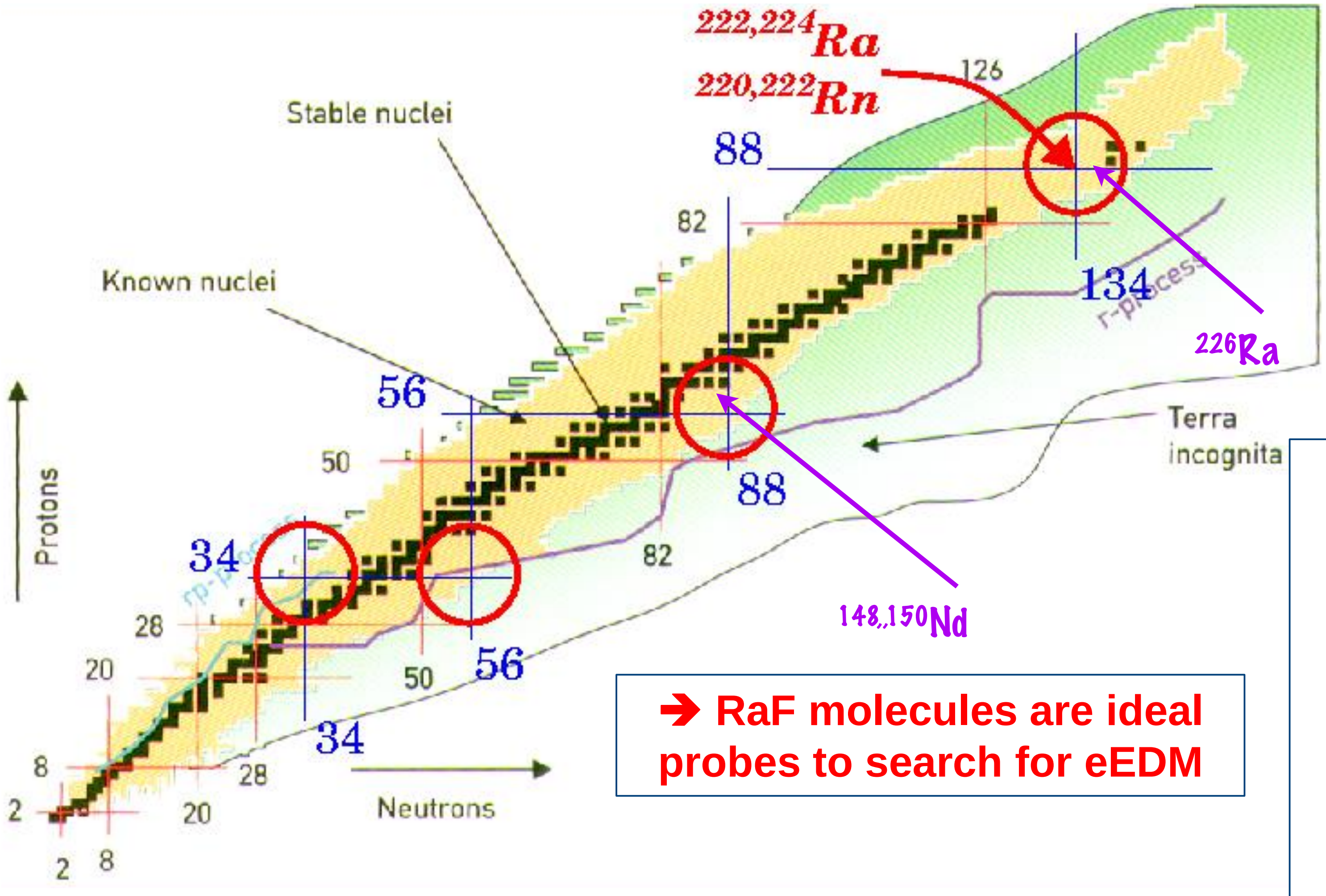
sensitivity to EDM increases with **Z (Z=86)**

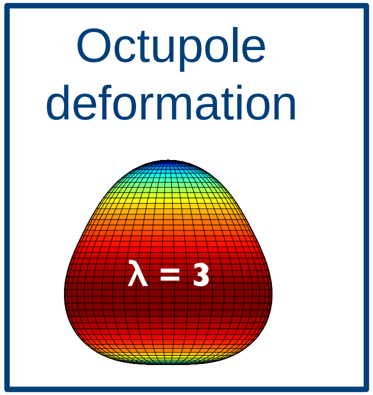
highest sensitivity in **pear shaped nuclei**

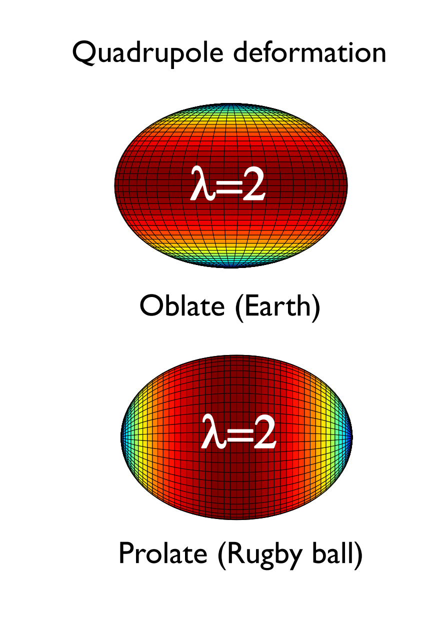
Pear-shaped nuclei: many are radioactive !

Experimental evidence: $^{222–226}$Ra are pear shaped

^{228}Ra and $^{218-224}$Rn are vibrating pears





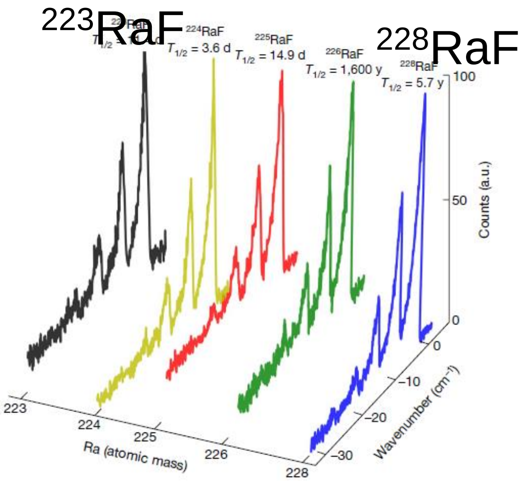


➔ **RaF molecules are ideal probes to search for eEDM**

P.A. Butler, L.P. Gaffney et al., PRL 124, 042503 (2020)
Nature Communications 10 (2019) 2473

RaF radioactive molecules: first spectroscopy established suitability for laser cooling

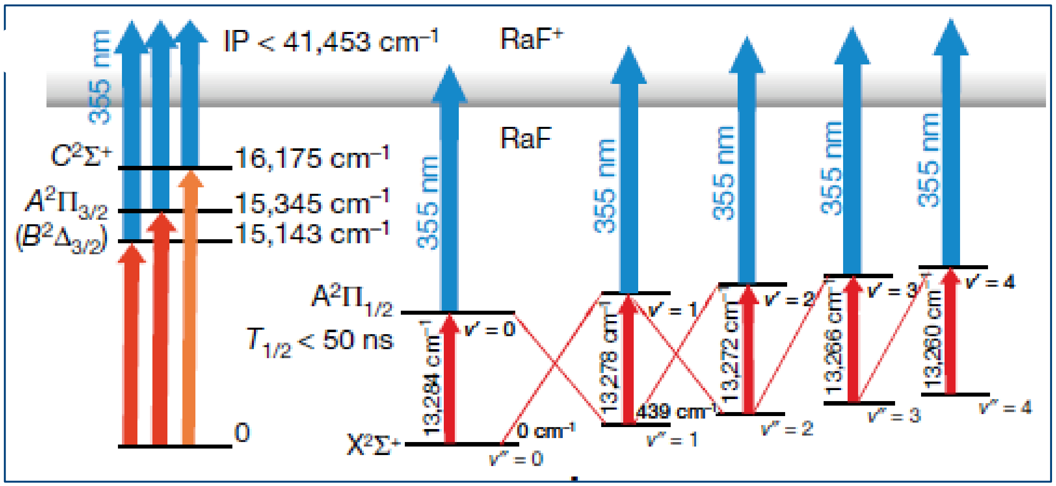
allows for ultra-precise measurements of nuclear-spin-dependent PV effects (e.g. nuclear anapole moment or Shiff moment)

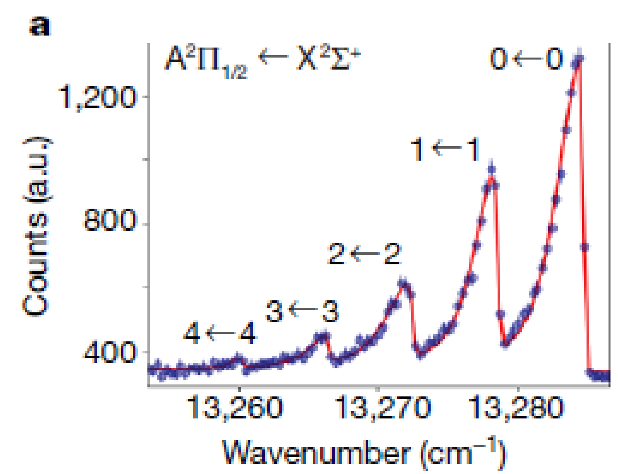


Conditions for efficient laser cooling ➔ Towards eEDM

- ✓ decay back into ground state (feeding into the other vibrational level is < 5%)
- ✓ lifetime of first excited state is < 50 ns (fast for cooling)
- ✓ other electronic levels appear > 2000 cm^{-1} higher in energy ➔ closed cycle

Experimentally established level scheme





Exotic n-rich hypernuclei: stringent tests for (nuclear) theories

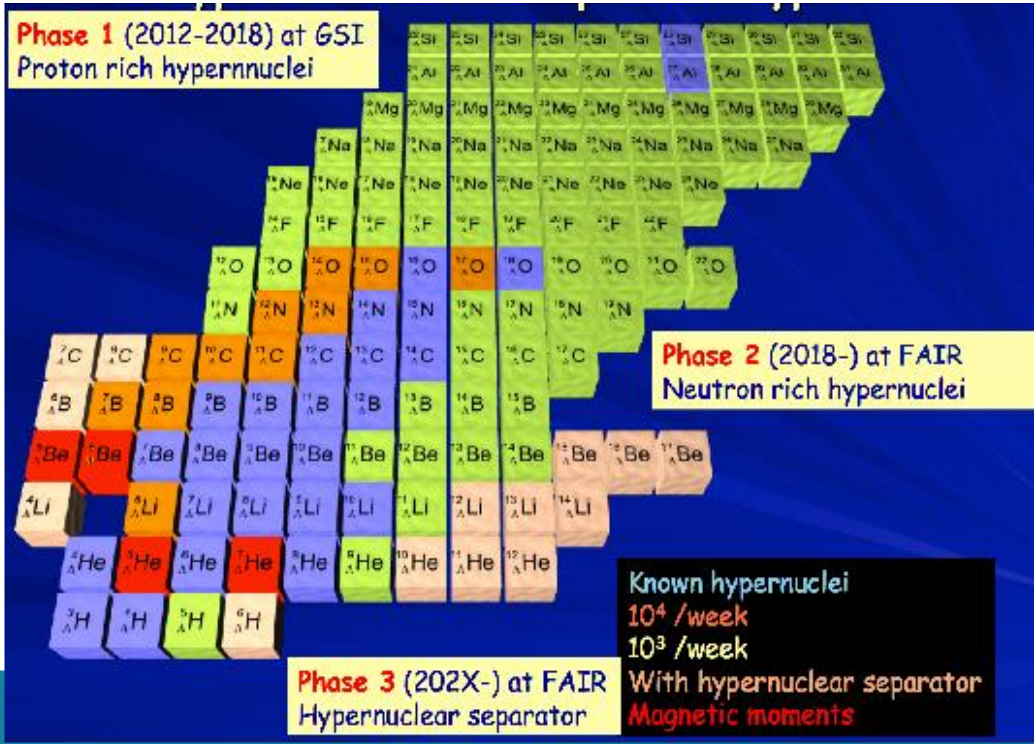
Hyperon puzzle appearance of hyperons in neutron stars

Λnn puzzle existence of a neutral hyper nucleus

Hypertriton puzzle low binding energy ↔ short lifetime

- Pilot experiment at GSI (HypHI) ➔ evidence of ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$, $3_{\Lambda}n$
- The lifetimes have also been determined
- Next goals: binding energies via invariant mass spectroscopy; using the high resolution of FRS will lead to δE~1MeV

now: WASA coupled to FRS



C.Rappold et al., Phys. Rev. C 88(2013)041001

A.Botvina et al., Phys Rev C 88(2013)054605

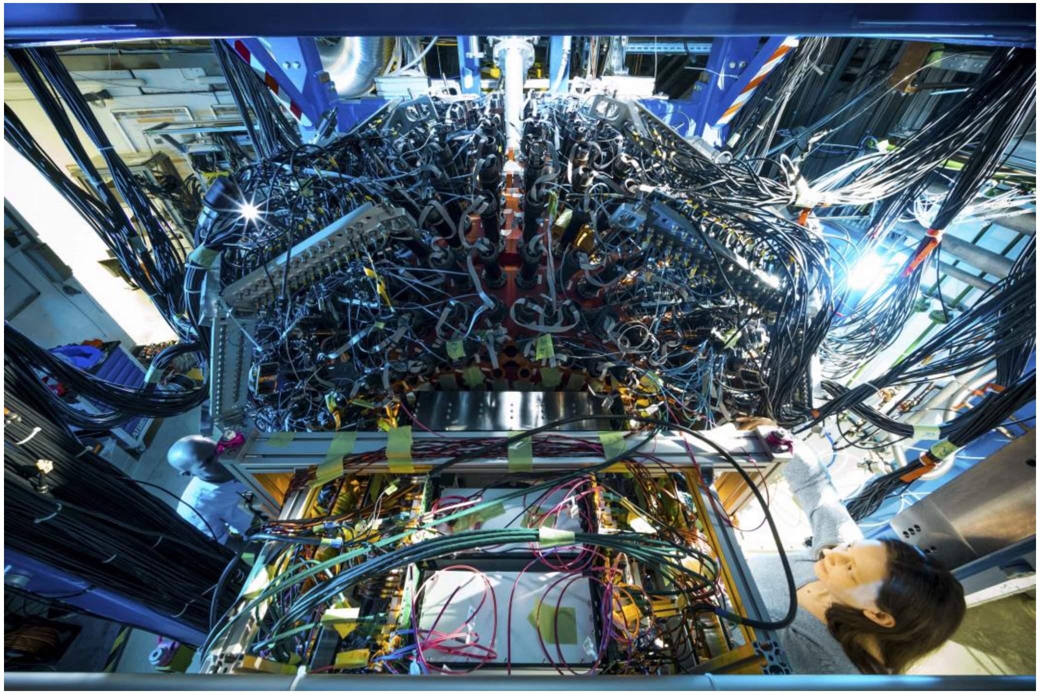
Courtesy C. Scheidenberger, N. Kalantar

WASA@FRS 2022

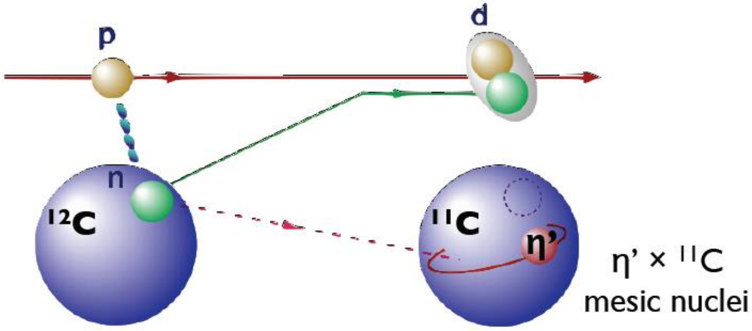
Pilot experiments for Super-FRS

- Search for eta'-mesic nuclei (S490, K.Itahashi et al., 22.-28.2.2022)
- Hypernuclei spectroscopy (S447, T.Saito et al., 10.-19.3.2022)

photo credit: © J. Hosan/GSI/FAIR



η' transfer reaction + Missing mass measurement

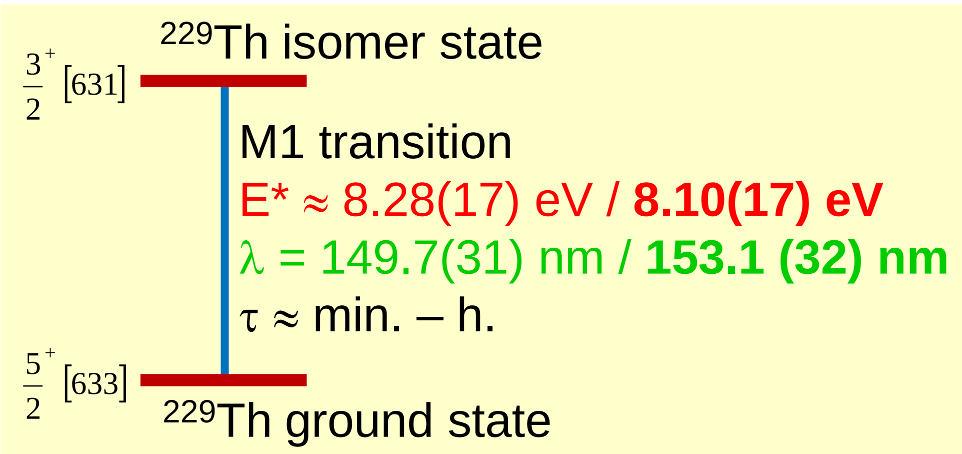


- Novel spectroscopic techniques are explored to study exotic nuclei and exotic atoms
- For the first time a calorimeter is coupled to a high-resolution spectrometer for relativistic beams

The ^{229m}Th Isomer: progress since 2019

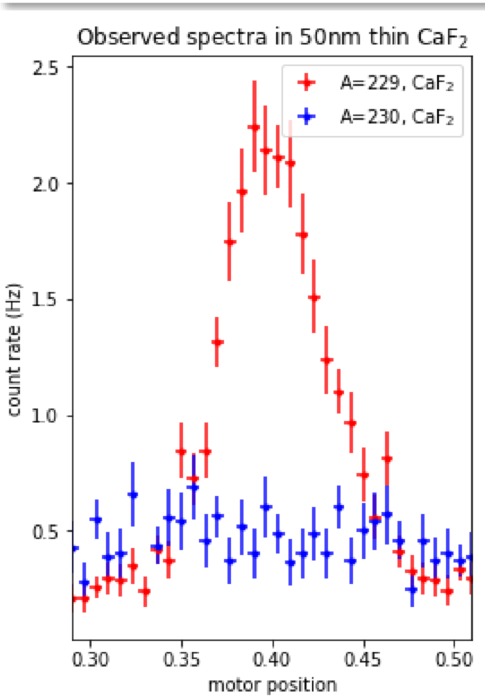
towards a Nuclear Clock and a new probe for precision physics

- Bridge between nuclear physics / atomic physics / laser physics/ metrology / solid state physics



→ $\Delta E/E \sim 10^{-20}$: extremely stable nuclear frequency standard: ‘nuclear clock’

Need better precision on the excitation energy/wavelength to allow for **optical excitation with deep UV laser light.**
(all indirect determinations so far)
Newest: T. Sikorsky et al., PRL 125, 142503 (2020)



Newest approach:
Produce isomer via the beta-decay of ^{229}Ac (62 min) at ISOLDE
Implant in CaF_2 or MgF_2 to block internal conversion.
Observe the **radiative UV photon decay** for first time !
➔ **Precision improved by factor 5-10 !**
➔ This will make search for resonant laser excitation for the first time feasible (1 year → 30-40 days)!

KU LEUVEN

S. Kramer, P. Van Duppen, L. Pereira et al., in preparation

CONCLUSIONS

- Ab-initio models as well as density functional theories are progressing fast and will have a strong impact on the predictability of nuclear properties (important for neutrinoless double-beta decay, astrophysics, …).

- Upcoming facilities (and upgrades) like e.g. FAIR, SPIRAL2, HIE-ISOLDE, SPES, ISOL@MYRRHA, … and developments/improvements of instrumentation is boosting the field (see M. Lewitowicz, I. Shipsey, J. D'Hondt)

- Nuclear-physics research is a multi-facetted research area reaching out to many different fields of science and applications

- Precision measurements become more and more important and make the link towards particle physics and fundamental symmetry studies (see talk K. Jakobs)

Thanks to P. Van Duppen, N. Kalantar, C. Scheidenberger, P. Greenlees, Y. Leifels, P. Roussel Chomaz, W. Korten, … for input

KU LEUVEN

Coordinated action between different Radioactive Ion Beams Facilities

GANIL spiral2 – laboratoire commun CEA/DSM CNRS/IN2P3

MYRRHA

FRIB

ISOLDE

SPES – exotic beams for science

TRIUMF

GSI

FAIR

JYFL

RIKEN NISHINA CENTER

BACKUP

Octupole enhanced atomic EDM

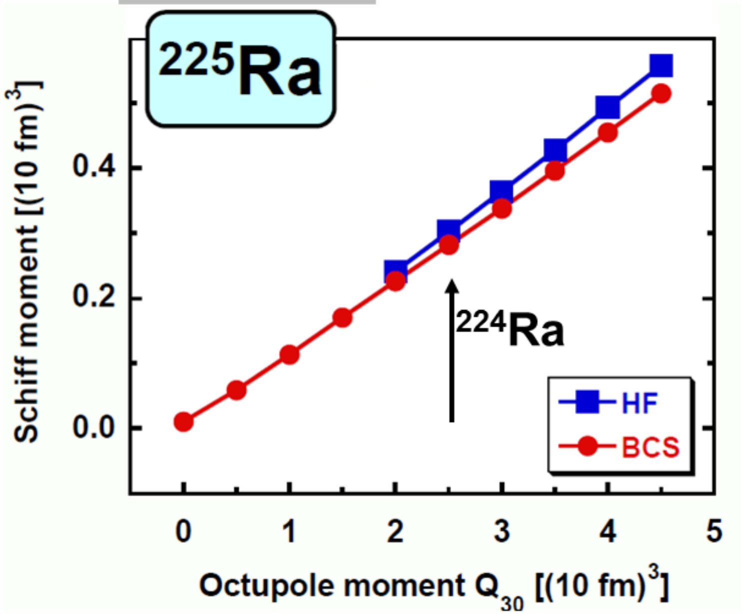
related to Q_3 — P,T-violating n-n interaction

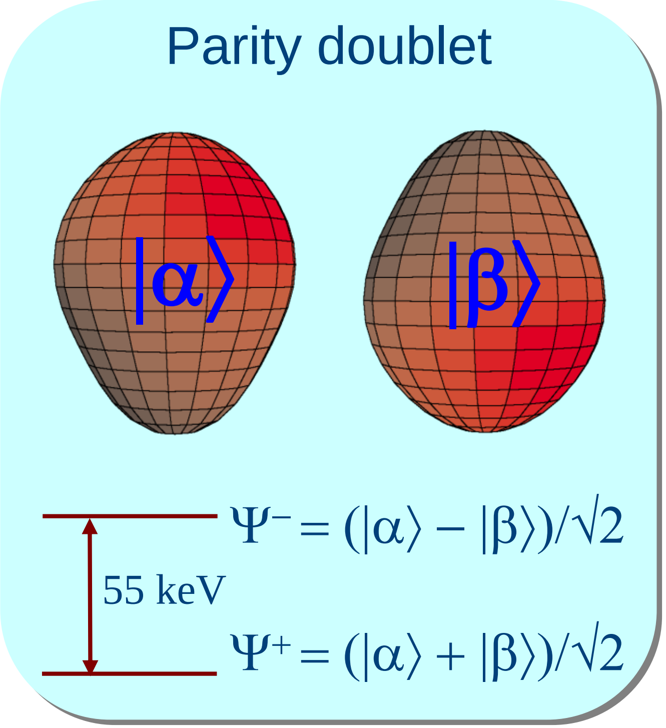
Schiff moment:

$$S = -2\frac{J}{J+1}\frac{<\hat{S}_z><\hat{V}_{PT}>}{\Delta E}$$

$I = ½$

$t_{1/2} = 15$ d





Shiff moment enhanced by ~ 3 orders of magnitude in pear-shaped nucleir

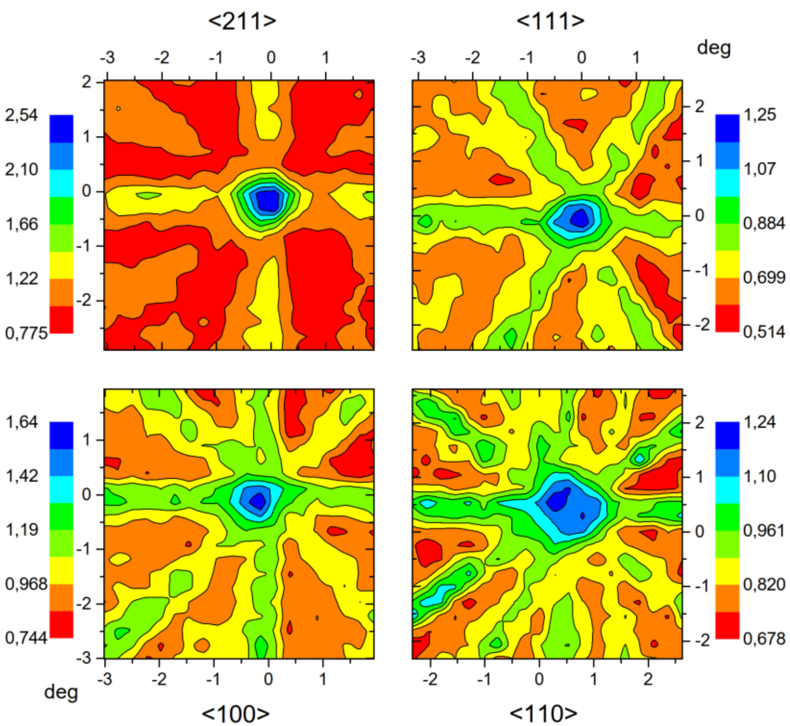
^{229m}Th in CaF crystal - block internal conversion decay

M. Verlinde et al., PRC 100, 024315 (2019)

Exp. Nov 2018

Requirement: 229Ac should take substitutional site in CaF

Method: Emission Channeling



Idea to measure radiative decay energy:

✓ Produce intense beam of 229Ac (RILIS)

✓ 229Ac decays into the 229mTh isomer (~13%)

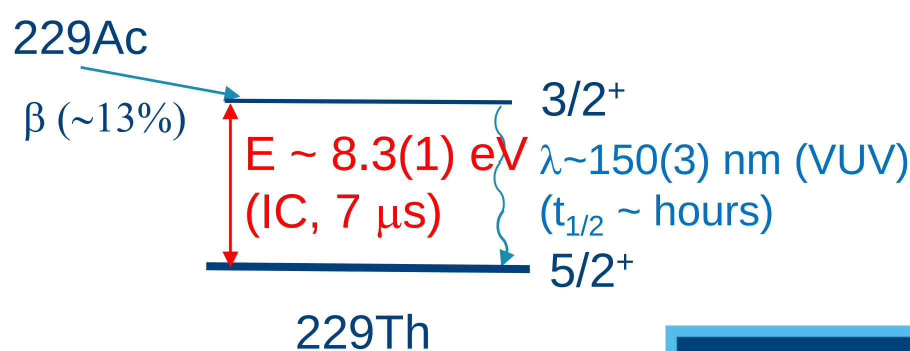
To block Internal Conversion decay

➔ implantation in wide bandgap material CaF (12 eV)

→ radiative decay dominates !

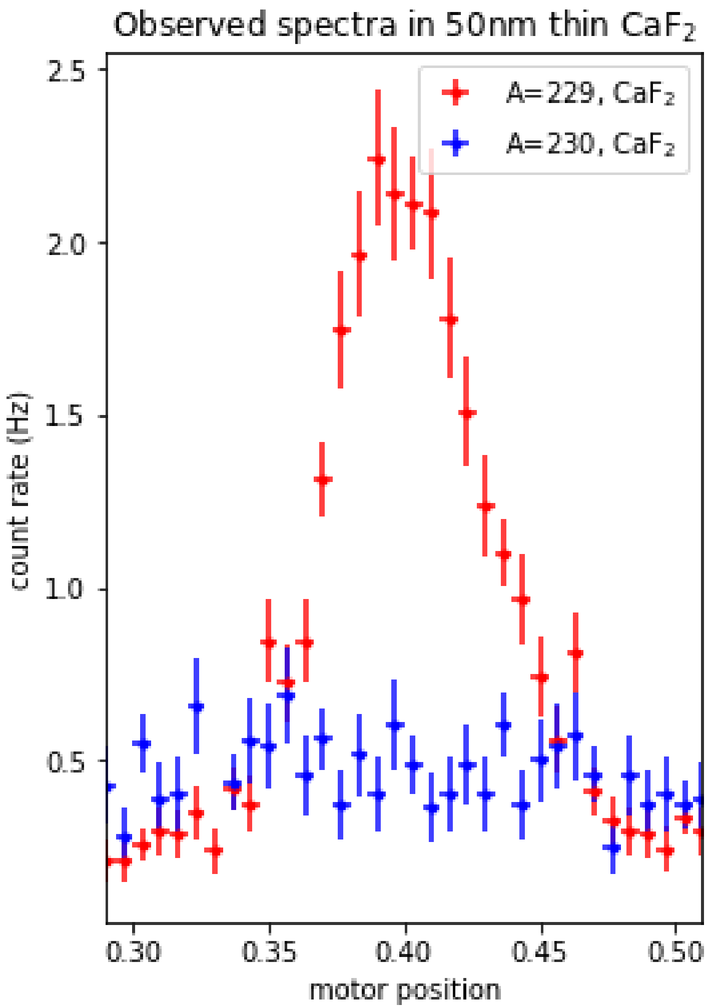
* Measure the radiative decay energy (VUV)

CaF is transparent for VUV radiation

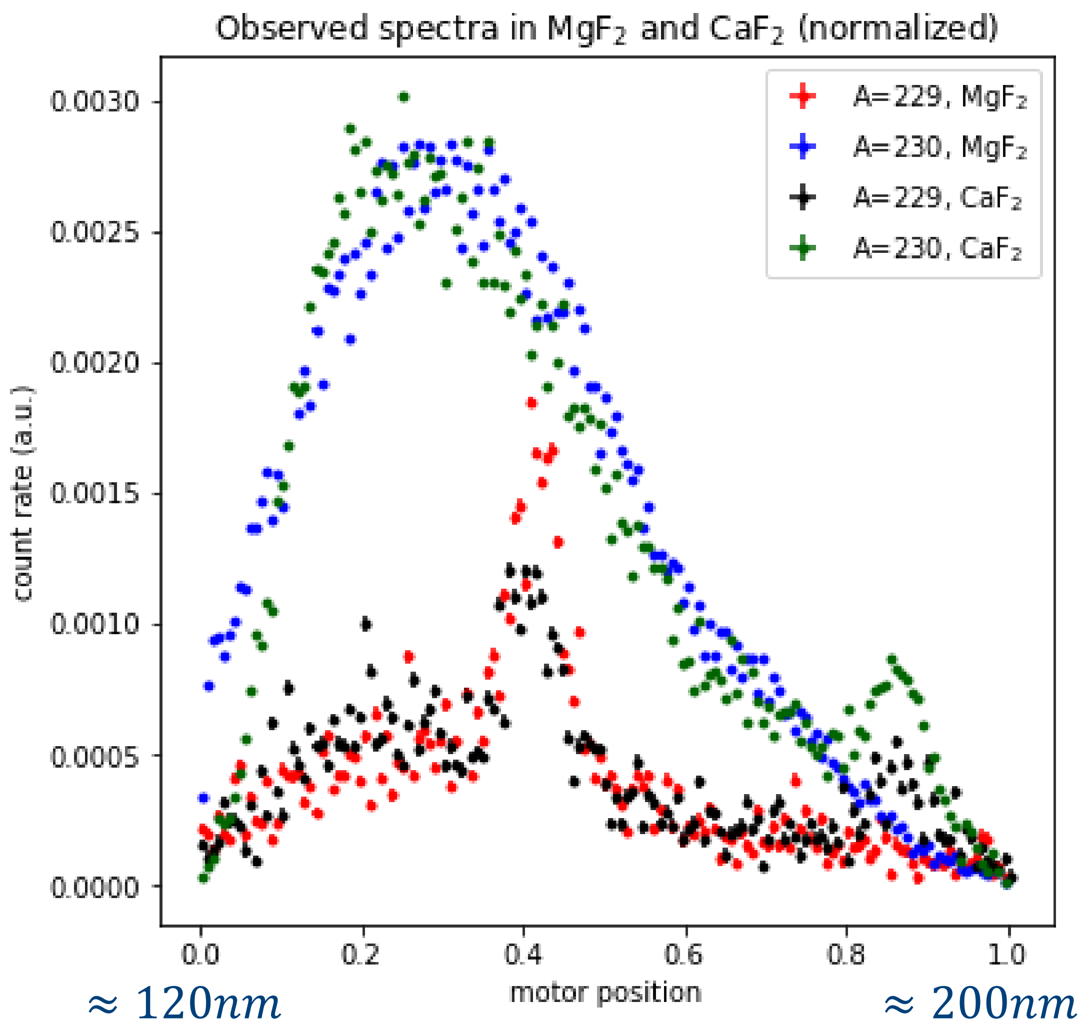


Courtesy P. Van Duppen, L. Pereira et al., KU Leuven

Observation of VUV photon decay from ^{229m}Th



3mm slit, raw count rate



3mm slit, normalized to total $LaBr_3$ count rate

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Courtesy S. Cramer, P. Van Duppen