Structure nucléaire : propriétés statiques du noyau

D. Lunney (CSNSM) pour la collaboration "Physique ISOL Basse Energie France"

Conseil Scientifique de l'IN2P3 – 26 octobre 2017

outline

Introduction and general remarks on:	Relation of this physics to the ISOL technique
nuclear binding energy and the mass surface,	Where and how does IN2P3 contribute?
charge radii, electromagnetic moments,	Recent results involving IN2P3 physicists
physics of shell structure & nuclear deformation	Perspectives and conclusions

Institut national de physique nucléaire et de physique des particules

cnrs dépasser les frontières

mass excess → valley of stability

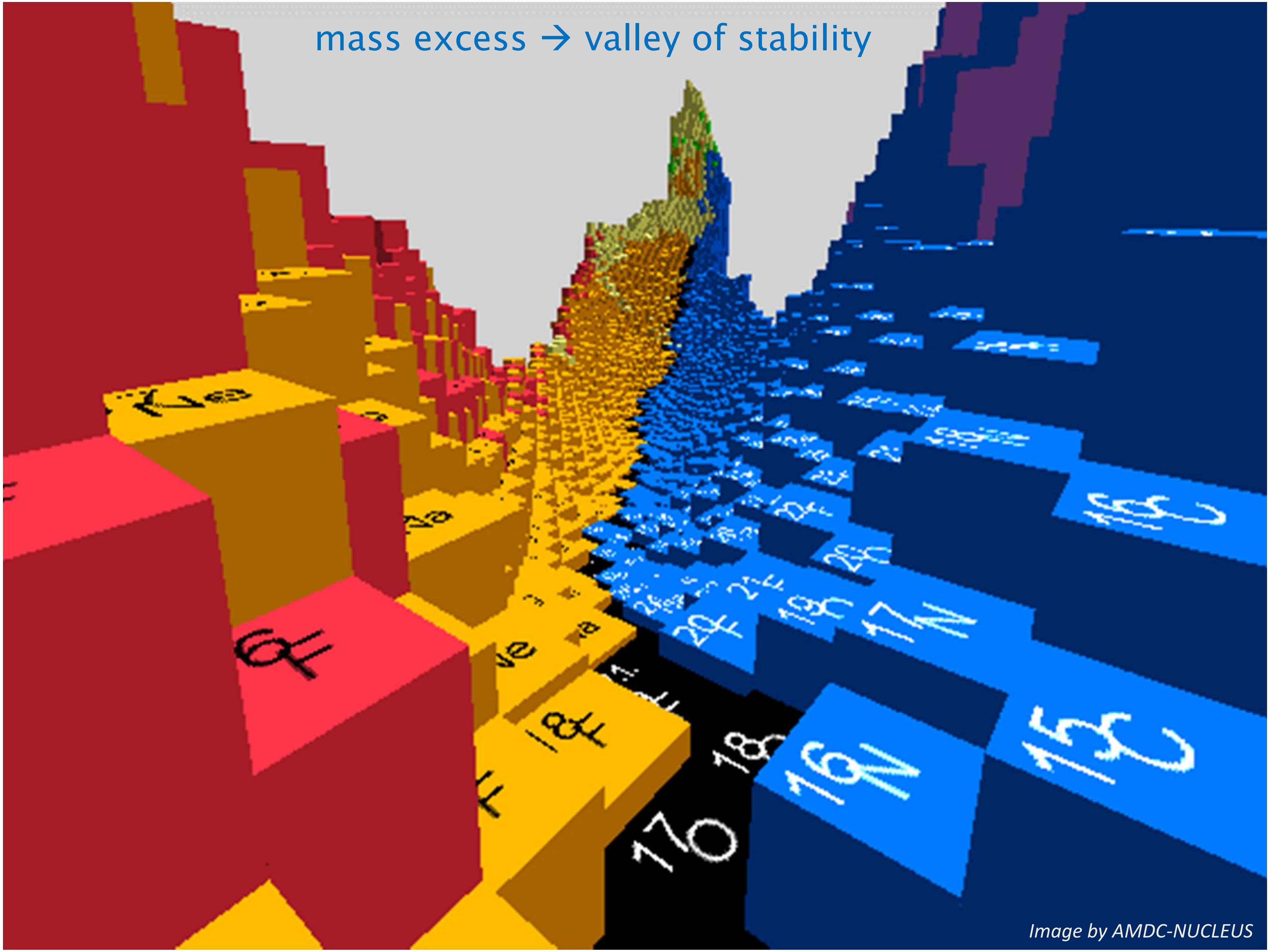
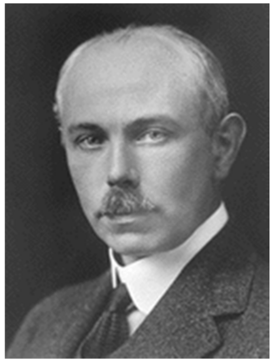


Image by AMDC-NUCLEUS

mass spectrometry and nuclear structure

F.W.Aston (~1920's): 212 isotopes discovered
the *packing fraction*



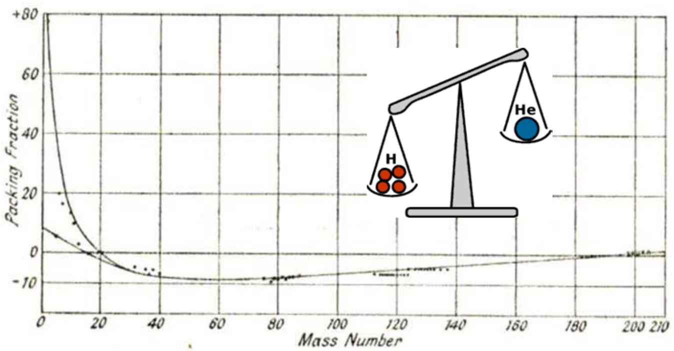
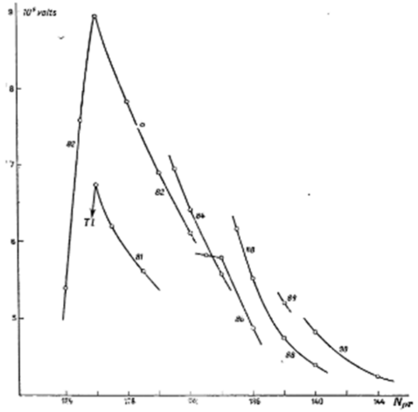
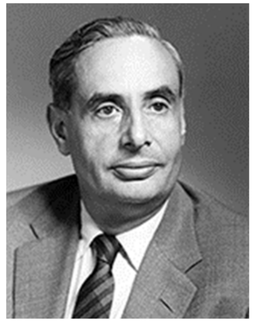
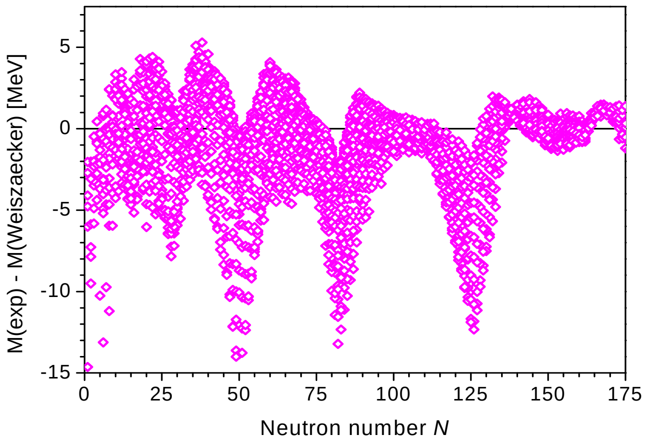


Fig. 20.—Aston's Original Packing Fraction Curve (1927).

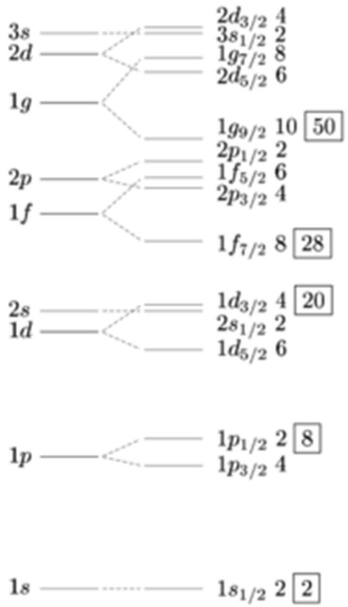
W.M. Elsasser (~1934) magic numbers







C.F. von Weiszaecker (~1935) mass formula



M. Göppert & H. Jensen (~1950) shell model

mass models

- ❑ Finite-Range Droplet Model:
  shells on drop (mic-mac)

- ❑ Hartree-Fock-Bogoliubov
  (Skyrme, Gogny, …)

- ❑ Beyond Mean Field
- ❑ Relativistic Mean Field

- ❑ Large Scale Shell Model

- ❑ (*ab initio*) predictions:
  Gorkov Green's Function
  In-Medium Sym. Renorm. Group
  Coupled-cluster method
  Chiral Effective-Field Theory

Ongoing efforts to calculate binding energy from first Principles (very important!)

PHYSICAL REVIEW C
covering nuclear physics

Volume 96, Issue 4 (partial)
October 2017

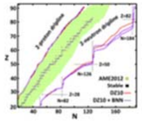
HIGHLIGHTED ARTICLES

Editors' Suggestion

Refining mass formulas for astrophysical applications: A Bayesian neural network approach

R. Utama and J. Piekarewicz

Phys. Rev. C **96**, 044308 (2017) – Published 6 October 2017



The masses of nuclei between the experimentally known region and the neutron drip line are key inputs for a variety of astrophysical applications. Particularly near the drip lines, unstable nuclei are also at the core of fundamental questions about the limits of nuclear binding. The authors use two existing mass models that capture the essential underlying physics and then refine their predictions by training an artificial neural network. The results significantly reduce the root-mean-square deviation relative to experiment. These newly refined mass tables are used to map the neutron drip lines and to study a few critical *r*-process nuclei.

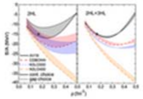
Show Abstract +

Editors' Suggestion

Convergence of the hole-line expansion with modern nucleon-nucleon potentials

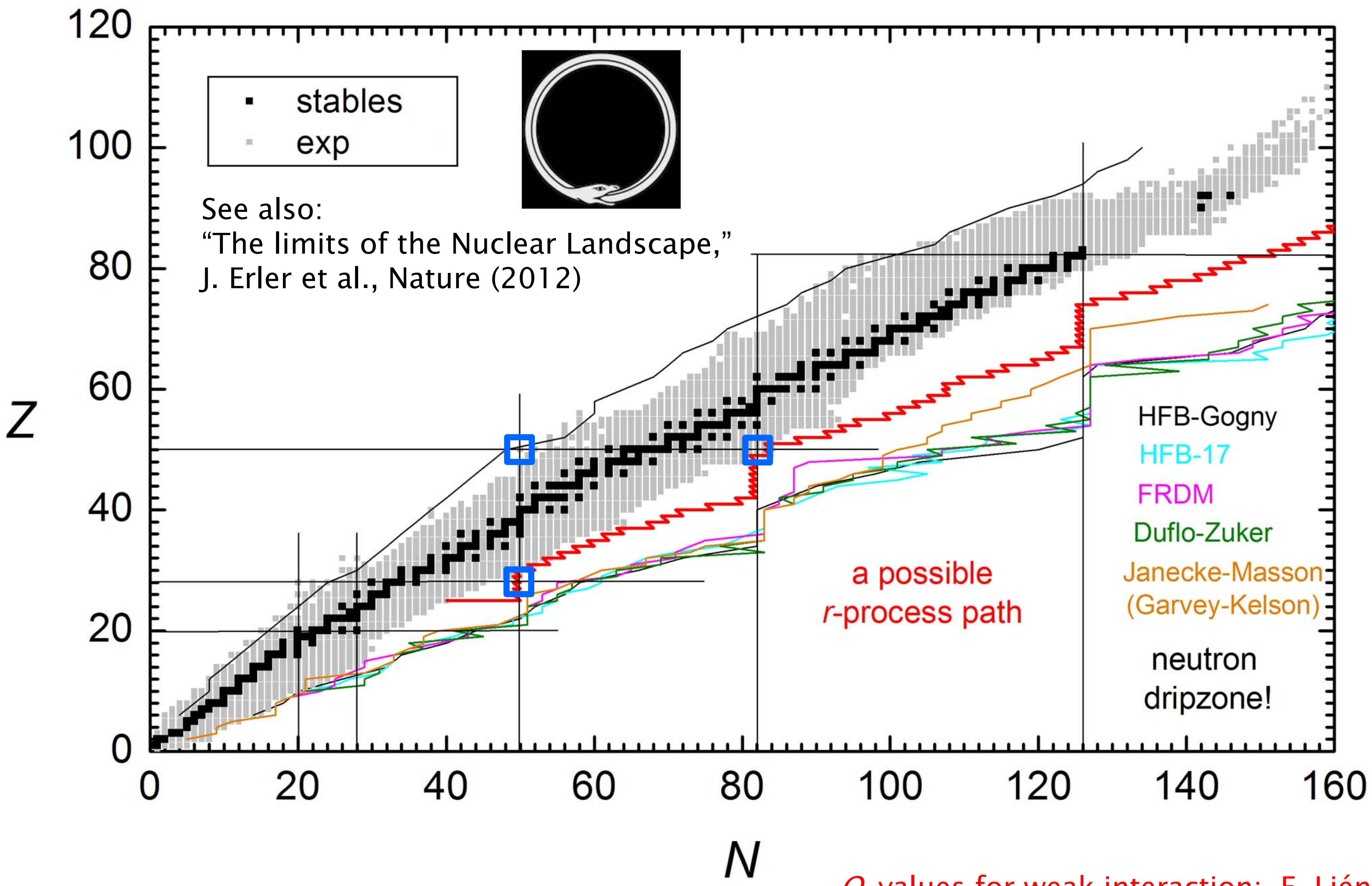
Jia-Jing Lu (陆家靖), Zeng-Hua Li (李增花), Chong-Yang Chen (陈重阳), M. Baldo, and H.-J. Schulze

Phys. Rev. C **96**, 044309 (2017) – Published 6 October 2017



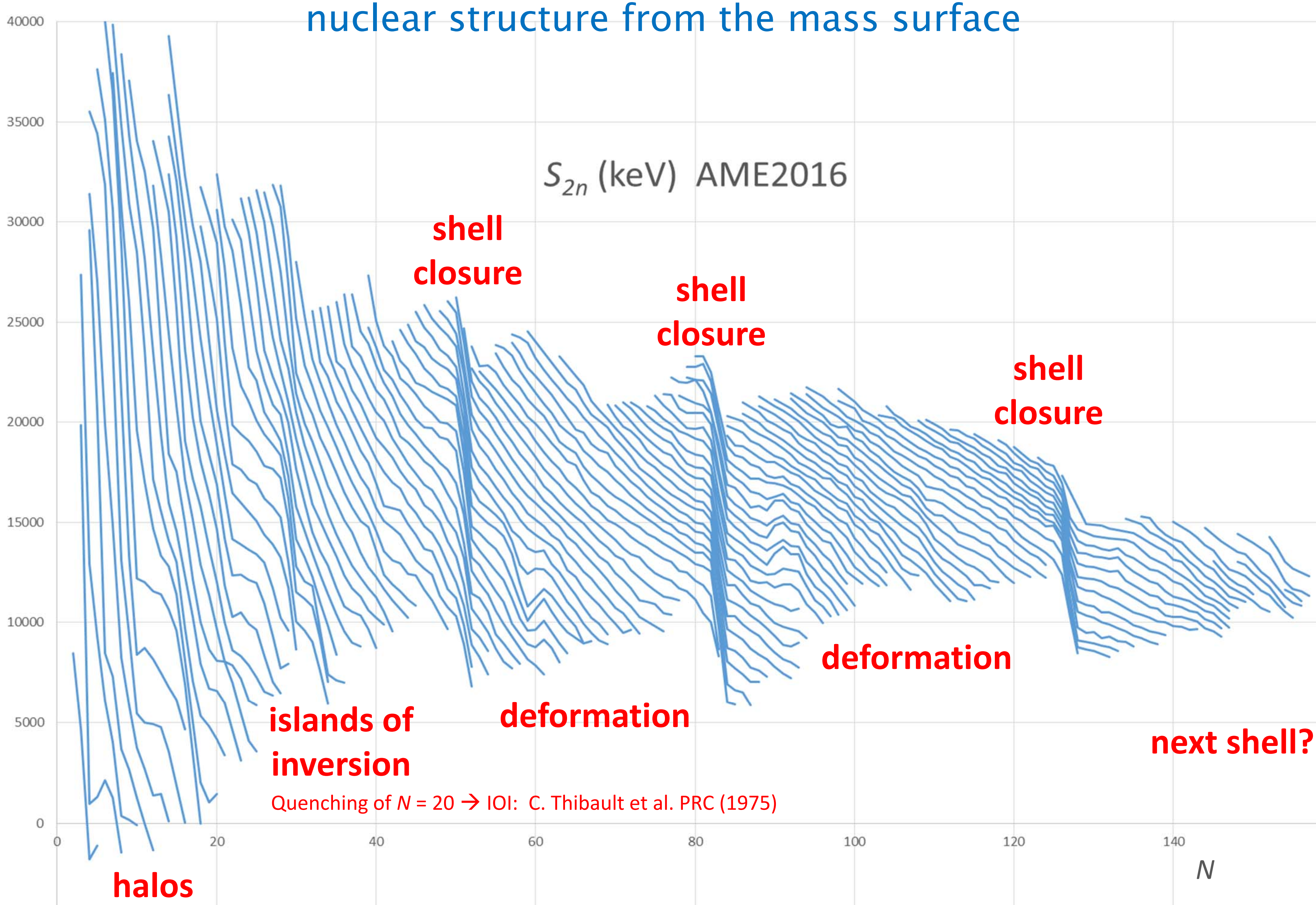
The accurate computation of nuclear matter properties, such as its binding energy, is still a challenge to nuclear theory, largely because the quark substructure of nucleons creates a strong repulsion at short distances that renders a straightforward perturbative calculation impossible. In this work, the authors study the Brueckner-Bethe-Goldstone expansion of dense Fermi systems in terms of hole-line contributions, of the associated Goldstone diagrams, to the binding energy of

mass → reactions/decays and the limits of stability



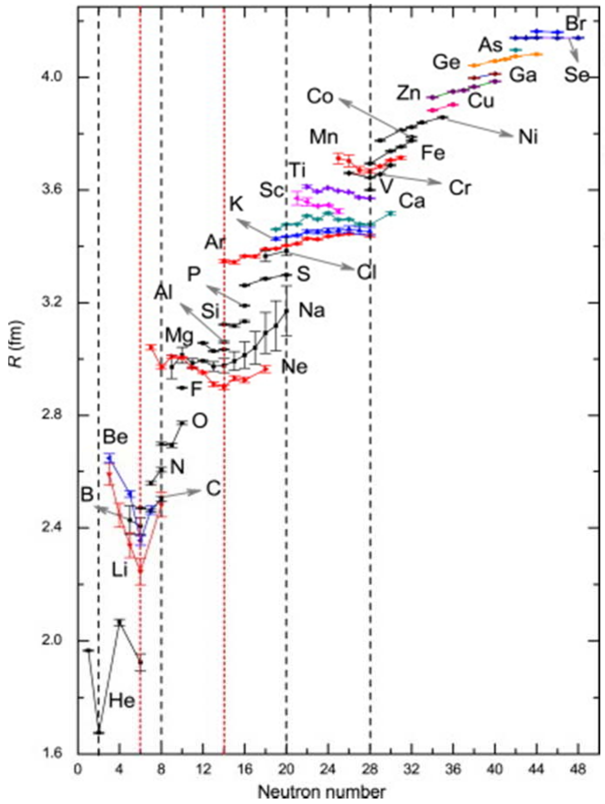
Q–values for weak interaction: E. Liénard
Masses for astrophysics: M. Fallot

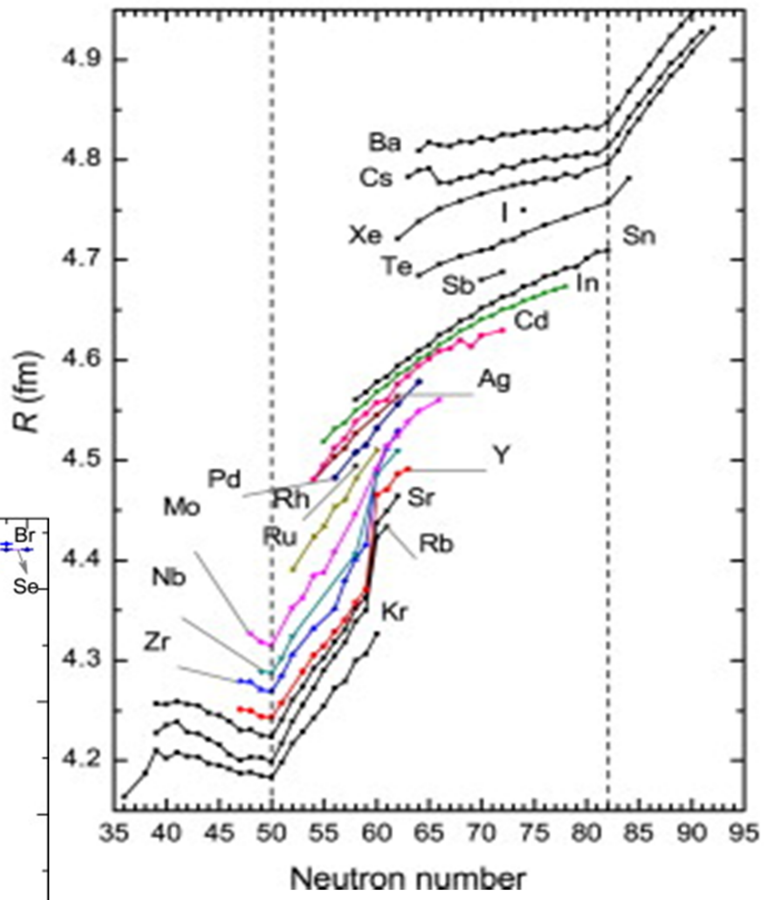
nuclear structure from the mass surface

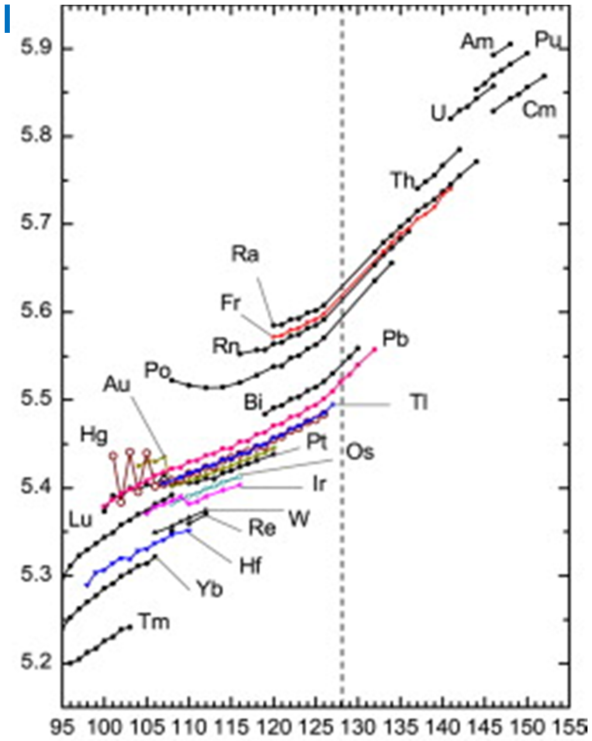


nuclear structure from charge radii

$R \propto A^{1/3}$







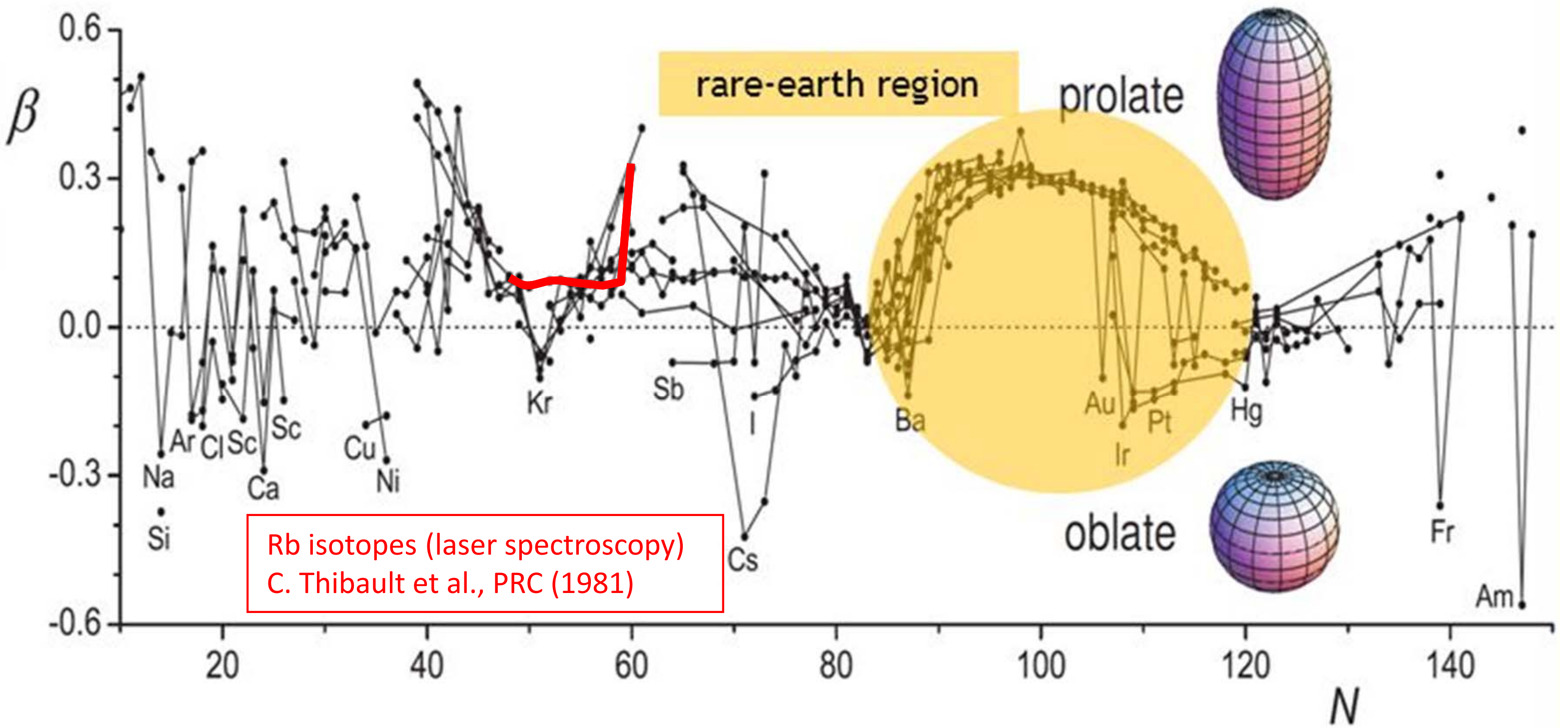
Charge Radii Compilation: I. Angeli and K. Marinova, At. Data Nucl. Data Tables (2013)

charge radii → quadrupole moments

Electric quadrupole moment

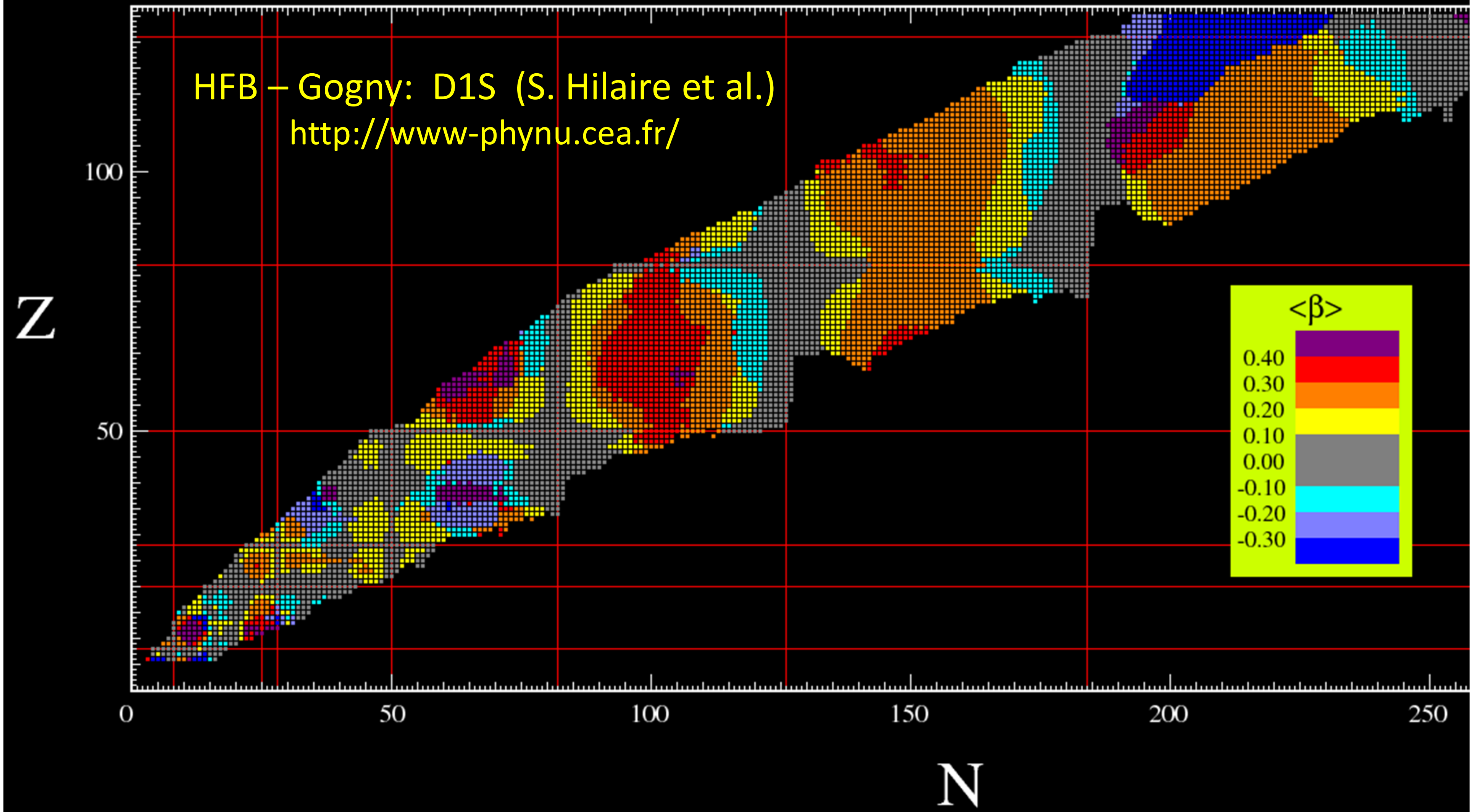
Deformation parameter:

$$\beta_Q = 0.95 \frac{5}{4} \frac{Q_0}{Z R^2} \quad \text{where} \quad \underset{\text{measured}}{Q} = \frac{3K^2 - I(I+1)}{(I+1)(2I+3)} \underset{\text{intrinsic}}{Q_0}$$



Quadrupole moment evaluation: N.J. Stone, ADNDT (2005); ADNDT (2016)

nuclear deformation (from theory)



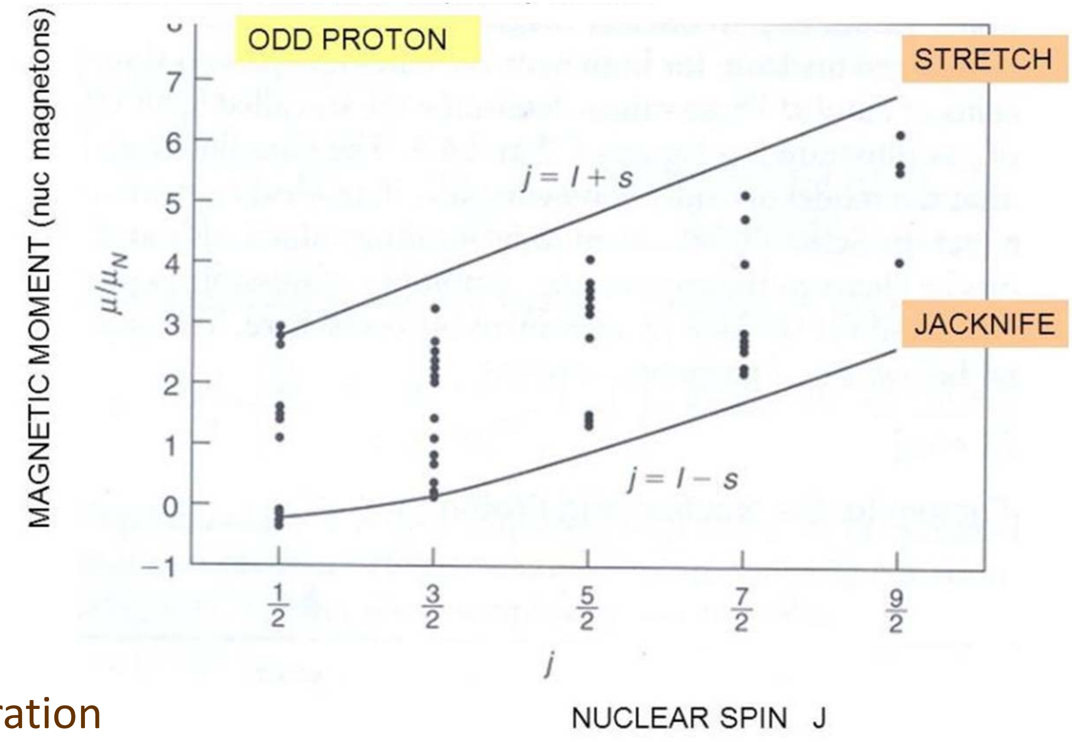
magnetic dipole moment

Magnetic moment operator

$$\vec{\mu}=\sum_{k=1}^{A} g_l^{(k)}\vec{l}^{(k)}+\sum_{k=1}^{A} g_s^{(k)}\vec{s}^{(k)}$$

Free-nucleon g factors

$$g_s^{\pi} = 5.585 \qquad g_l^{\pi} = 1$$
$$g_s^{\nu} = -3.826 \qquad g_l^{\nu} = 0$$

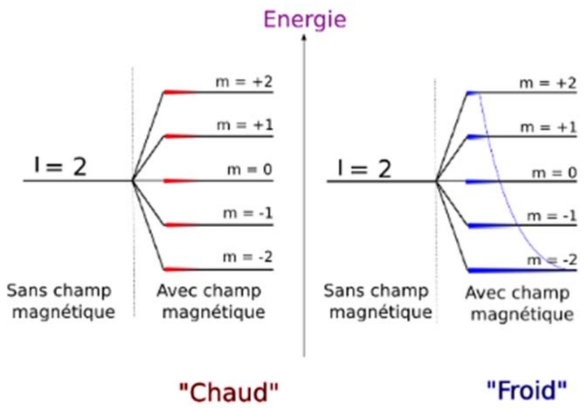


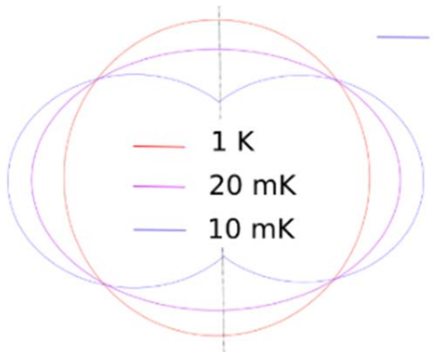
valence (single-) particle configuration

→ in-nucleus effects
(meson exchange)
→ configuration mixing
→ sensitive shell model tests

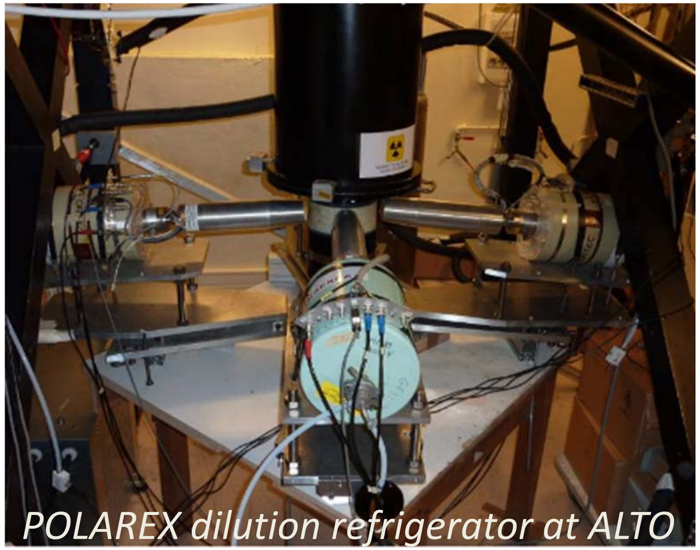
Data: magnetic dipole (and electric quadrupole) moment evaluation: N.J. Stone, ADNDT (2005)

magnetic moments: low-temperature orientation





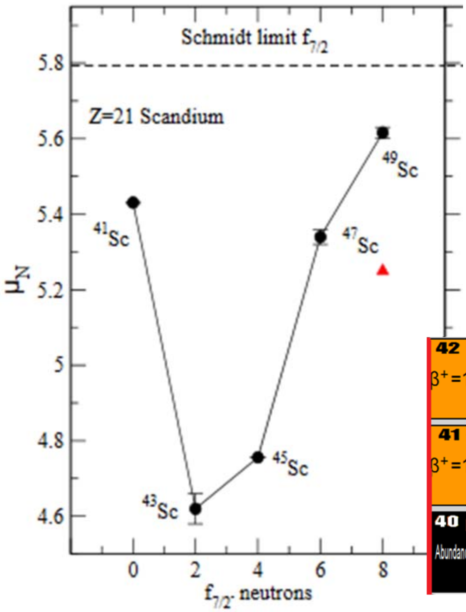
$$h\nu_0 = \frac{|\mu|}{I}(B_{hf} + B_{applied}).$$



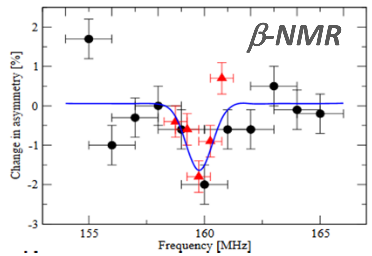
POLAREX dilution refrigerator at ALTO

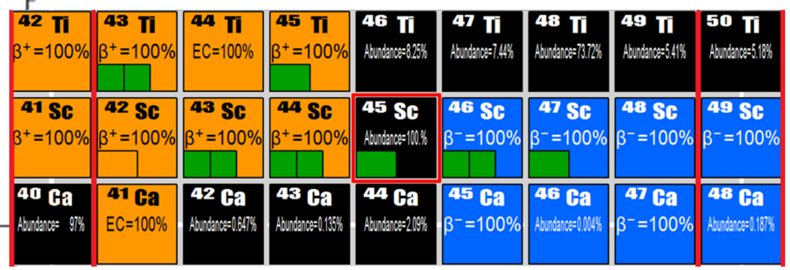
IN2P3: CSNSM, LPSC

NICOLE dilution refrigerator at ISOLDE

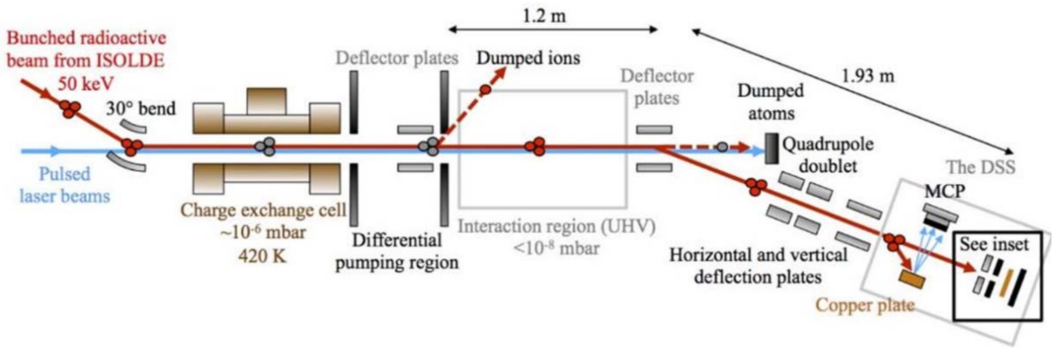


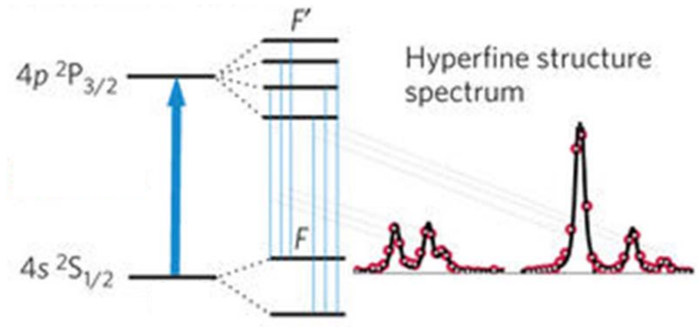
From: Ohtsubo et al. Phys. Rev. Lett. (2012)





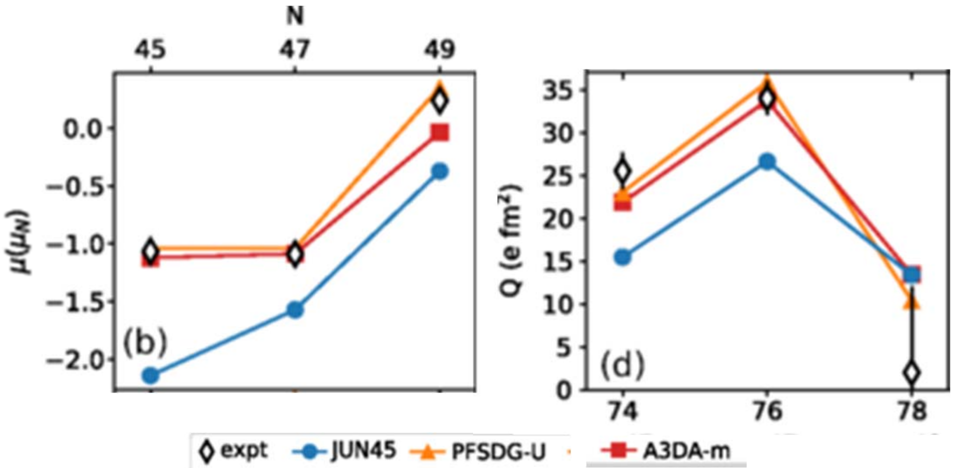
magnetic moments with laser spectroscopy: ^{78}Cu





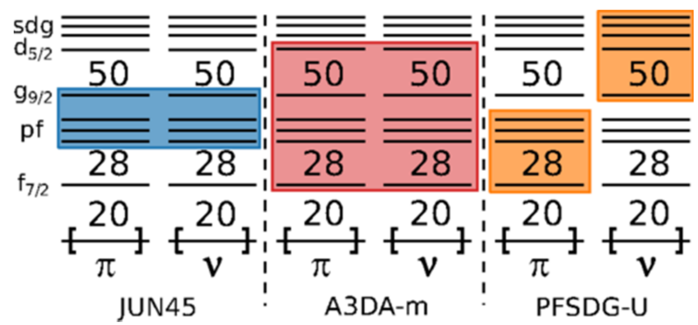
$$A = \frac{\mu_I H_e(0)}{I \cdot J} \qquad B = eQV_{zz}(0) \quad \longleftarrow \quad \Delta E_{HFS} = \frac{A}{2}K + B\frac{\frac{3}{4}K(K+1) - I(I+1)J(J+1)}{2(2I-1)(2J-1)I \cdot J}$$

where $K = F(F+1) - I(I+1) - J(J+1)$



R.P. de Groote et al., Phys. Rev. C (2017)

Large-scale (Monte Carlo) Shell Models



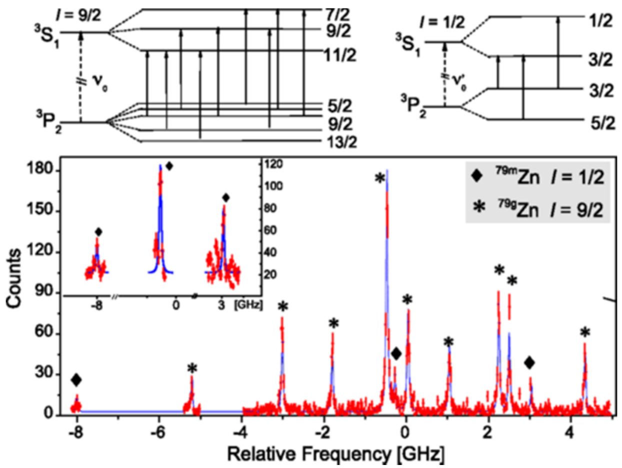
CRIS

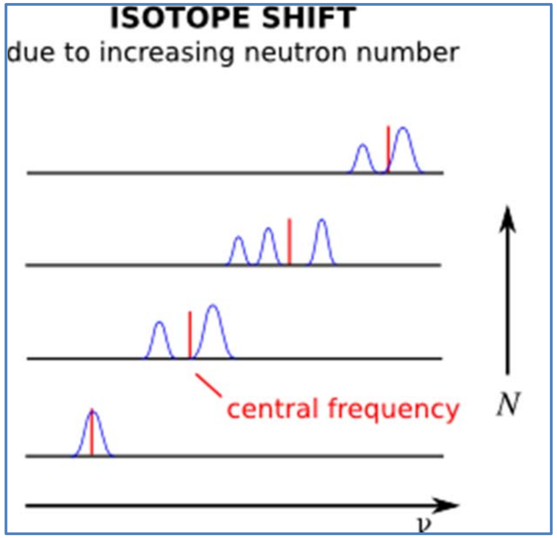
IN2P3: IPN

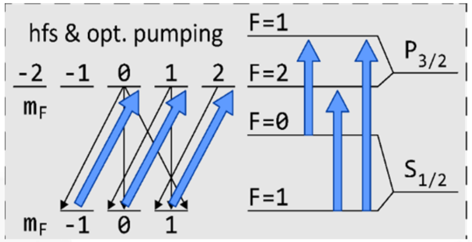
PFSDG-U: Strasbourg -Madrid

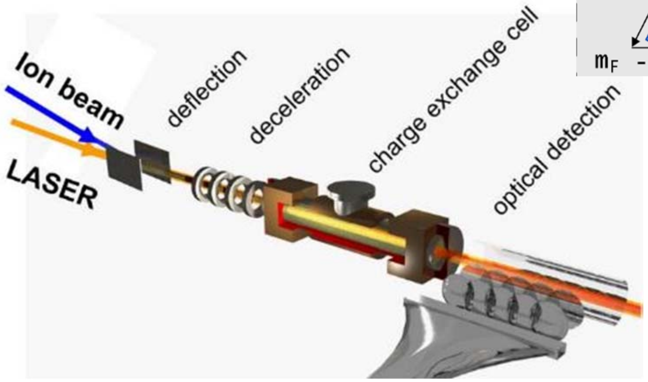
ISOLDE

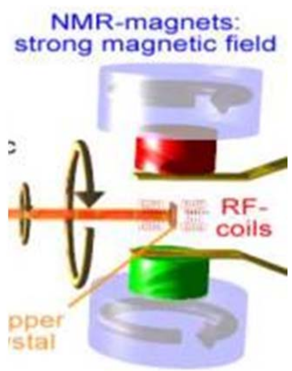
measuring moments from hfs → charge radii

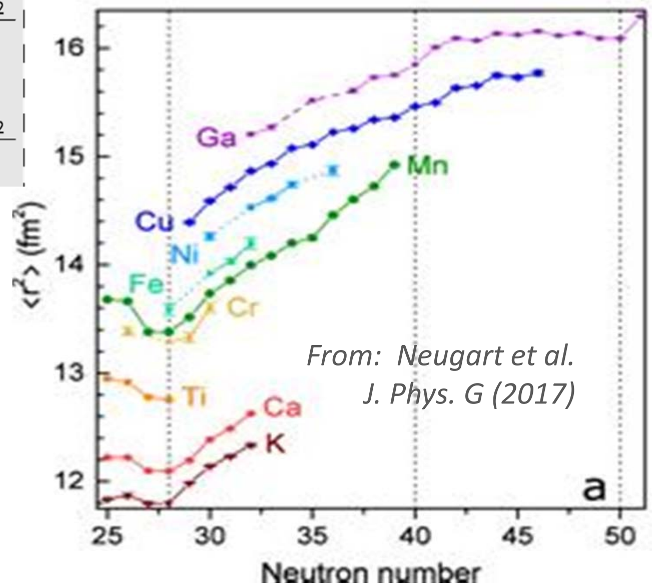










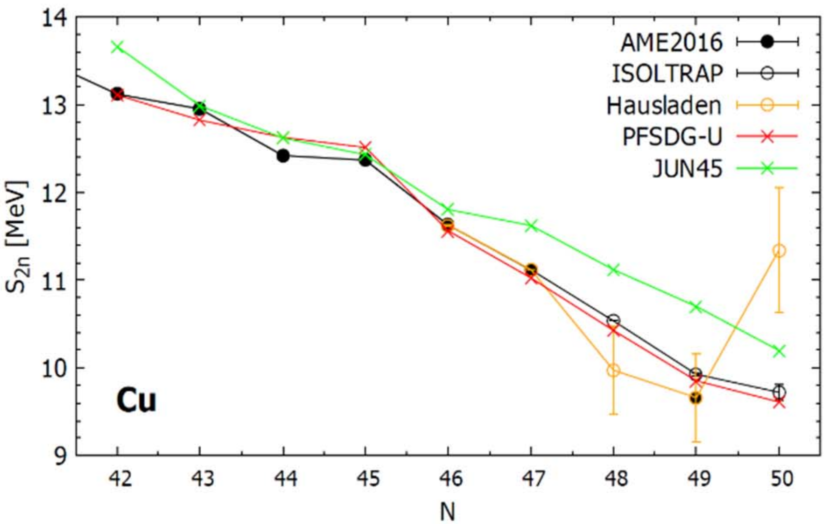


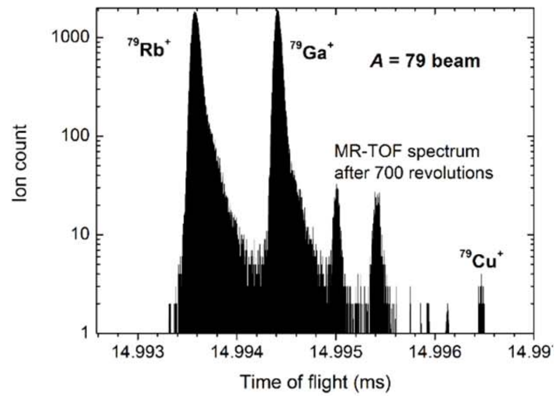
From: Neugart et al. J. Phys. G (2017)

IN2P3: IPN, CSNSM

mass measurement of ^{79}Cu: just 1 proton away from ^{78}Ni!

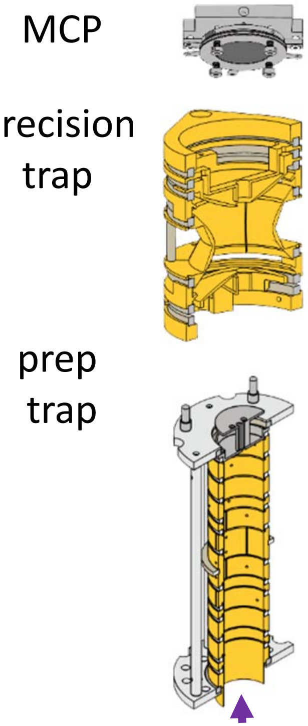
Comparison to PFSDG-U (complements the moments)





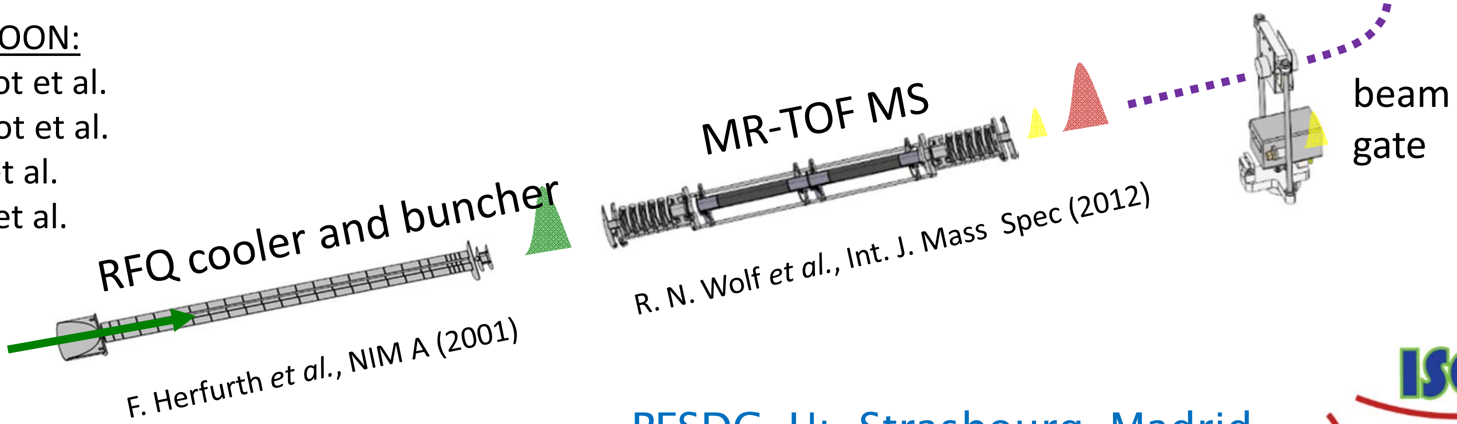
~ 5 ions/s

A. Welker *et al.*, Phys. Rev. Lett. (2017) in print



M. König *et al.*, IJMS (1995)

G. Savard *et al.*, Phys. Lett. A (1991)



COMING SOON:

^{63}Cr: M. Mougeot et al.

^{48}Ar: M. Mougeot et al.

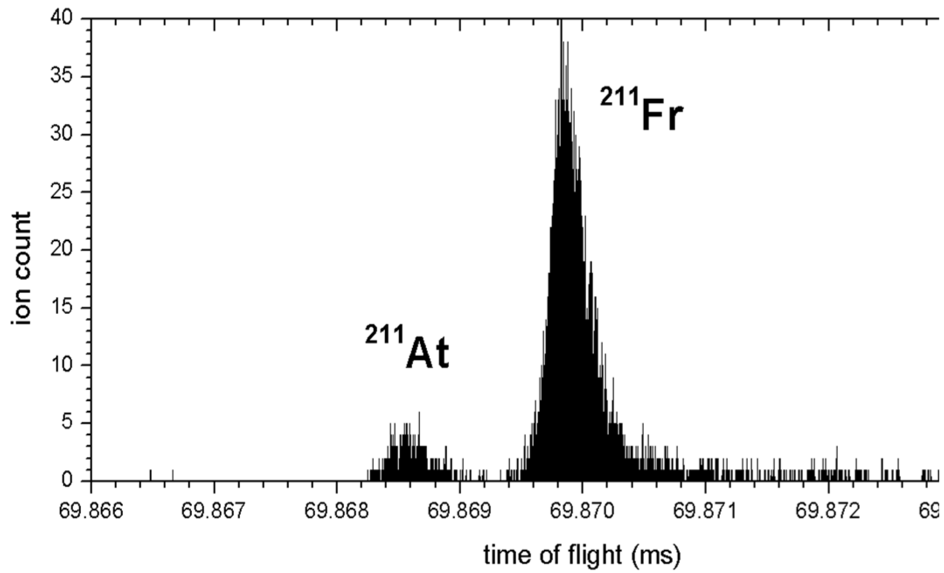
^{98}Kr: V. Manea et al.

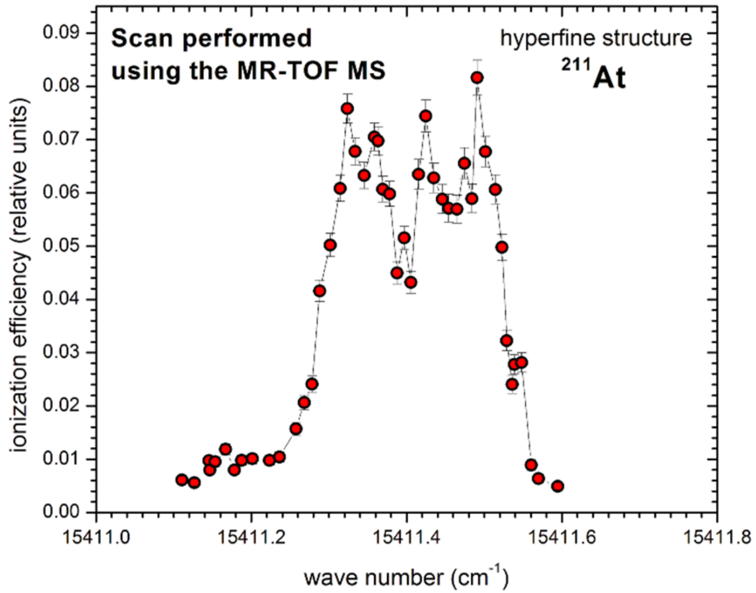
^{132}Cd: V. Manea et al.

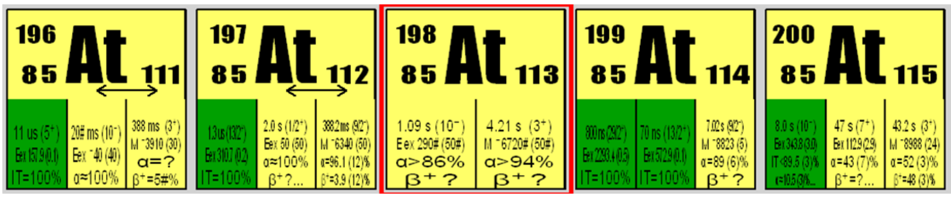
PFSDG-U: Strasbourg-Madrid

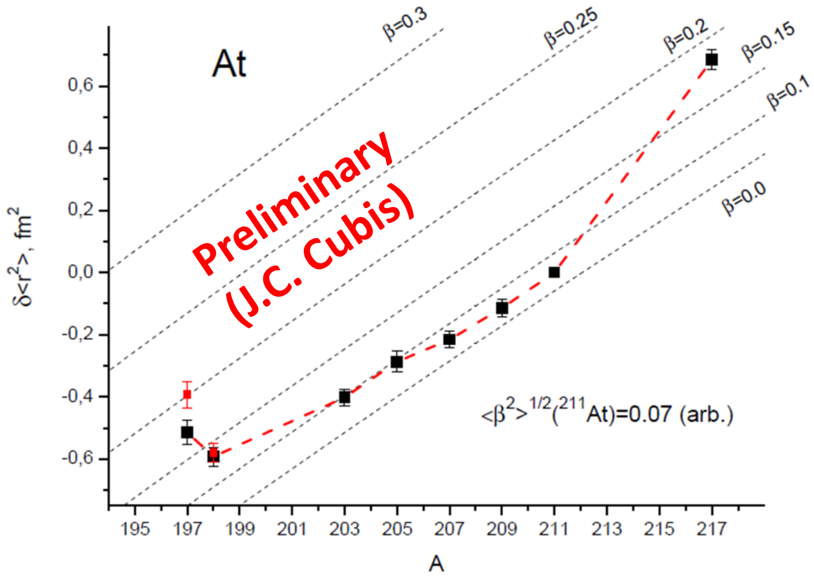
IN2P3: CSNSM, CENBG

MR-TOF mass spectrometer: new laser synergy → charge radii!









195Po alpha-decay & masses with ISOLTRAP: N. Althubiti et al. PRC (2017)

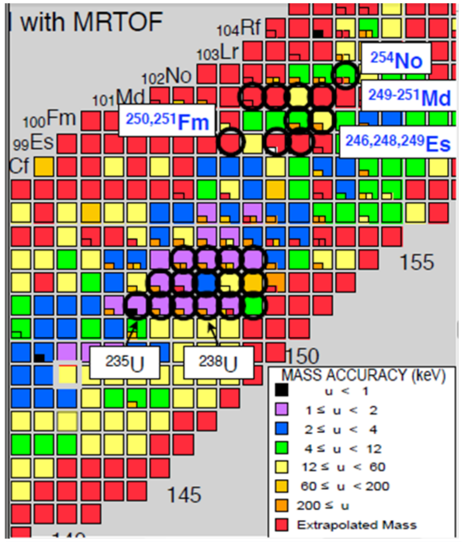
masses/radii/moments/spins: physics publications involving IN2P3

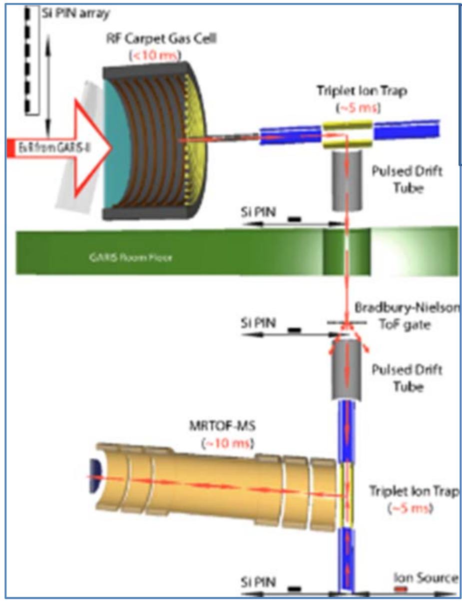
ISOLTRAP (CSNSM, CENBG)
2017: Phys. Rev. Lett., Welker et al.
2017: Phys. Rev. C, Althubiti et al.
2017: Eur. Phys. J. A, Welker et al.
2017: Phys. Rev. C, Manea et al.
2017: Phys. Rev. C, de Roubin et al.
2017: J. Phys. G, Atanasov et al.
2015: Phys. Rev. Lett., Rosenbusch et al.
2015: Phys. Rev. Lett., Atanasov et al.
2014: Phys. Rev. C, Kreim et al.
2014: Phys. Rev. C, Boehm et al.
2013: Phys. Rev. Lett. Wolf et al.
2013: Nature, Wienholtz et al.
2013: Phys. Rev. C, Stanja et al.
2013: Phys. Rev. C, Manea et al.
2012: Phys. Rev. C, Naimi et al.
2012: Eur. Phys. J. A, Herlert et al.
2012: Phys. Rev. Lett., Fink et al.
2011-1998: >40 publications

COLLAPS (IPN, CSNSM)
2017: J. Phys. G, Yordanov et al.
2017: Phys. Lett. B, Wraith et al.
2016: Phys. Rev. Lett., Yang et al.
2016: Nat. Phys., Garcia Ruiz et al.
2016: Phys. Rev. C, Bissel et al.
2016: Phys. Rev. Lett., Yordanov et al.
2015: Eur. Phys. J. D, Froemmgen et al.

CRIS (IPN)
2017: Phys. Rev. Lett. de Groote et al.
2016: Phys. Rev. C, Farooq-Smith et al.
2016: Phys. Rev. C, Lynch et al.
2015: Phys. Rev. Lett., de Groote et al.
2014: Phys. Rev. C, Budincevic et al.
2014: Phys. Rev. X, Lynch et al.
2013: Phys. Rev. Lett., Flanagan et al.

From: Y. Ito, ARIS 2017





more than 100!

ISAC (CSNSM, GANIL)
2017: Phys. Rev. C, Gallant et al.
2015: Phys. Rev. C, Malbrunot et al.
2015: Phys. Rev. C, Kwiatkowski et al.
2013: Eur. Phys. J. A, Brunner et al.
2013: Phys. Rev. C, Chaudhuri et al.
2012: Phys. Rev. C, Simon et al.
2012: Phys. Rev. C, Lapierre et al.
2012: Phys. Rev. Lett., Gallant et al.
2012a: Phys. Rev. Lett., Brodeur et al.
2012b: Phys. Rev. Lett., Brodeur et al.
+ 10 prior publications (2008 - 2011)

NICOLE (CSNSM)
2014: Phys. Rev. C, Stone et al.
2012: Phys. Rev. Lett. Ohtsubo et al.

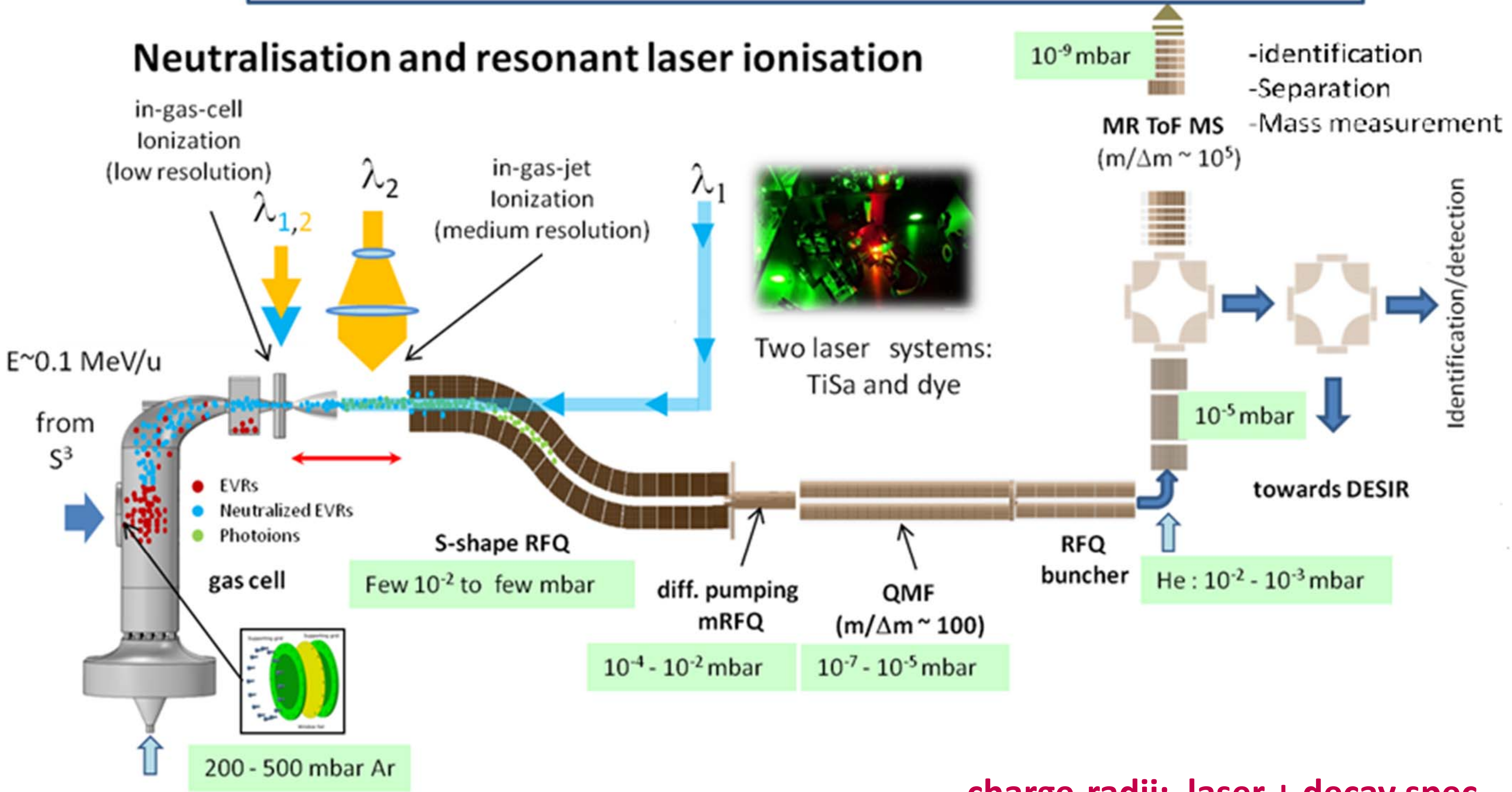
MRTOF@GARIS (IPN)
2017: Ito et al. Phys. Rev. Lett. (sub)
2017: Kimura et al. Phys. Rev. C
2016: Schury et al. Phys. Rev. C

HIRFL (CSNSM)
2017: Phys. Rev. C
2017: Phys. Lett. B
2016: Phys. Rev. Lett.
2015: Chin. Phys. C
2014: Phys. Lett. B
2013: Astro. J. Lett.
2012: Phys. Rev. Lett.
2011: Phys. Rev. Lett.

JYFL (CENBG, GANIL):
2017: Ascher et al. (proposal)
2016: Bastin et al. (proposal)

S³-LEB @ SPIRAL2

KU LEUVEN (Gas cell studies, laser system) | IPN ORSAY (Gas cell) | LPC Caen (RFQs) | GANIL (mr-TOF-ms, laser system, infractructure, safety) | LARISSA, JGU, University of Jyväskylä (narrow band-width laser pre-studies at MARA)

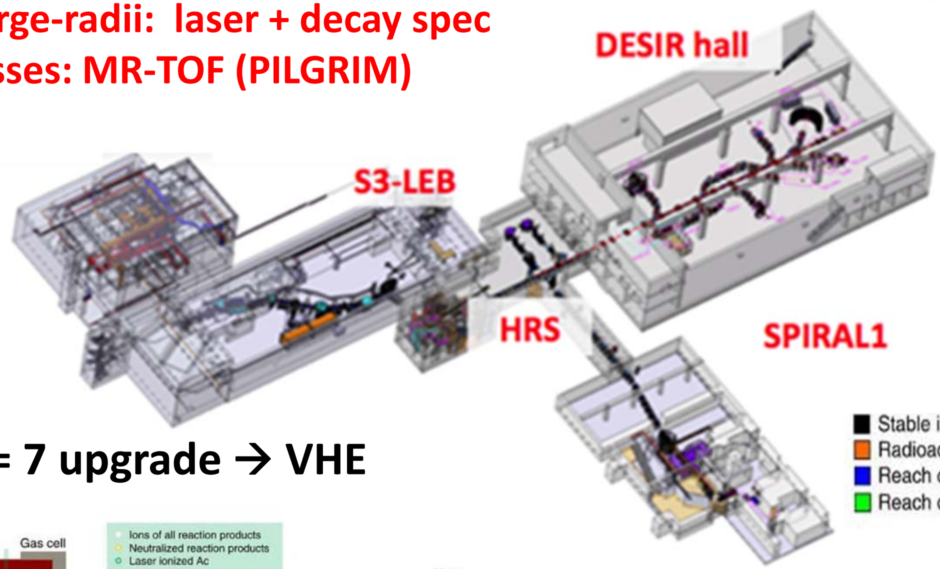


charge-radii: laser + decay spec

masses: MR-TOF (PILGRIM)

masses/radii/moments/spins: physics opportunities at GANIL

S^{3}LEB (REGLIS)
charge-radii: laser + decay spec
masses: MR-TOF (PILGRIM)



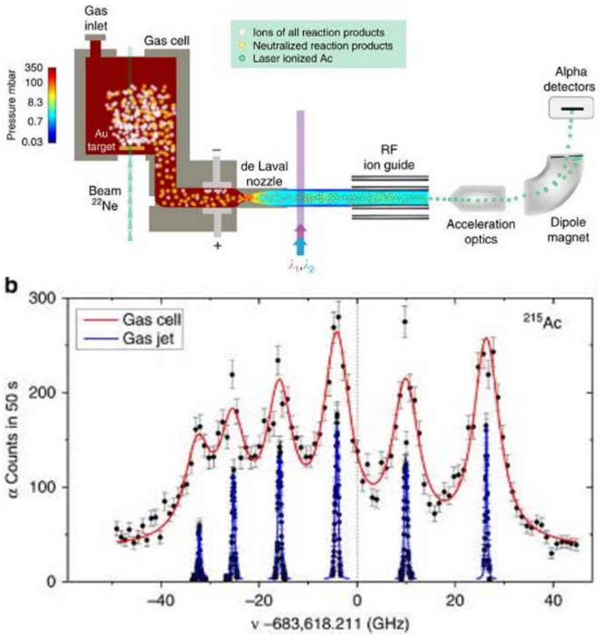
DESIR (S3) Mass LOIs (MLLTRAP & PIPERADE):

Z **= 104 (P. Thirolf et al.);**
A **= 160 p-dripline, ^{100}Sn,**
lighter *N* = *Z* (D. Lunney et al.)

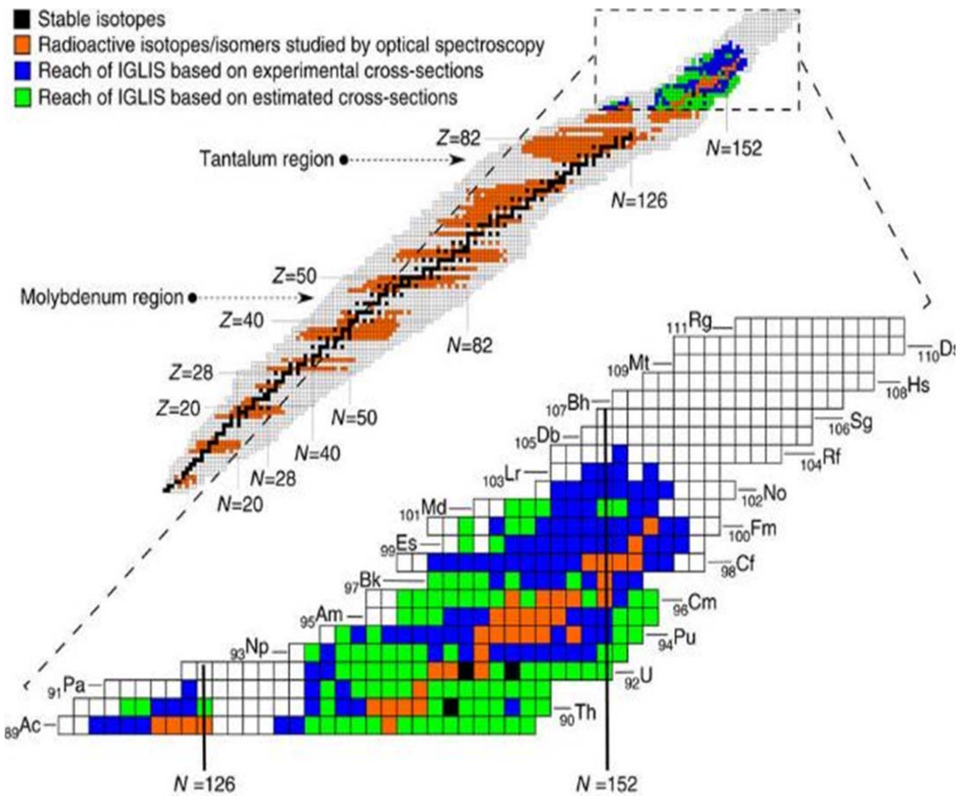
DESIR (S1) Mass LOI:
n-rich O, F, P, Cl (P. Ascher et al.)

+ DESIR LUMIERE LOIs

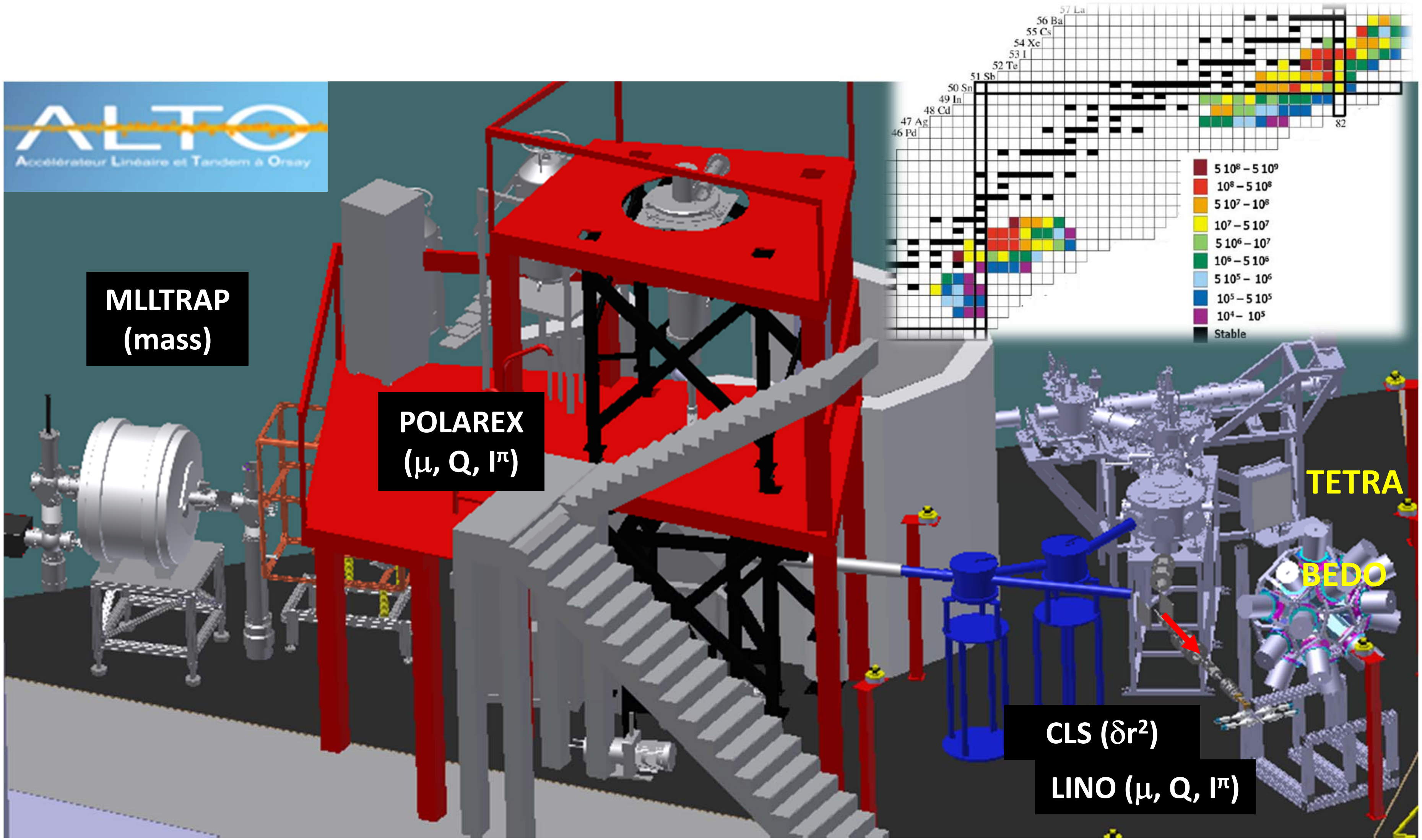
A/q = 7 upgrade → VHE



R. Ferrer et al., Nature Comm. (2017)



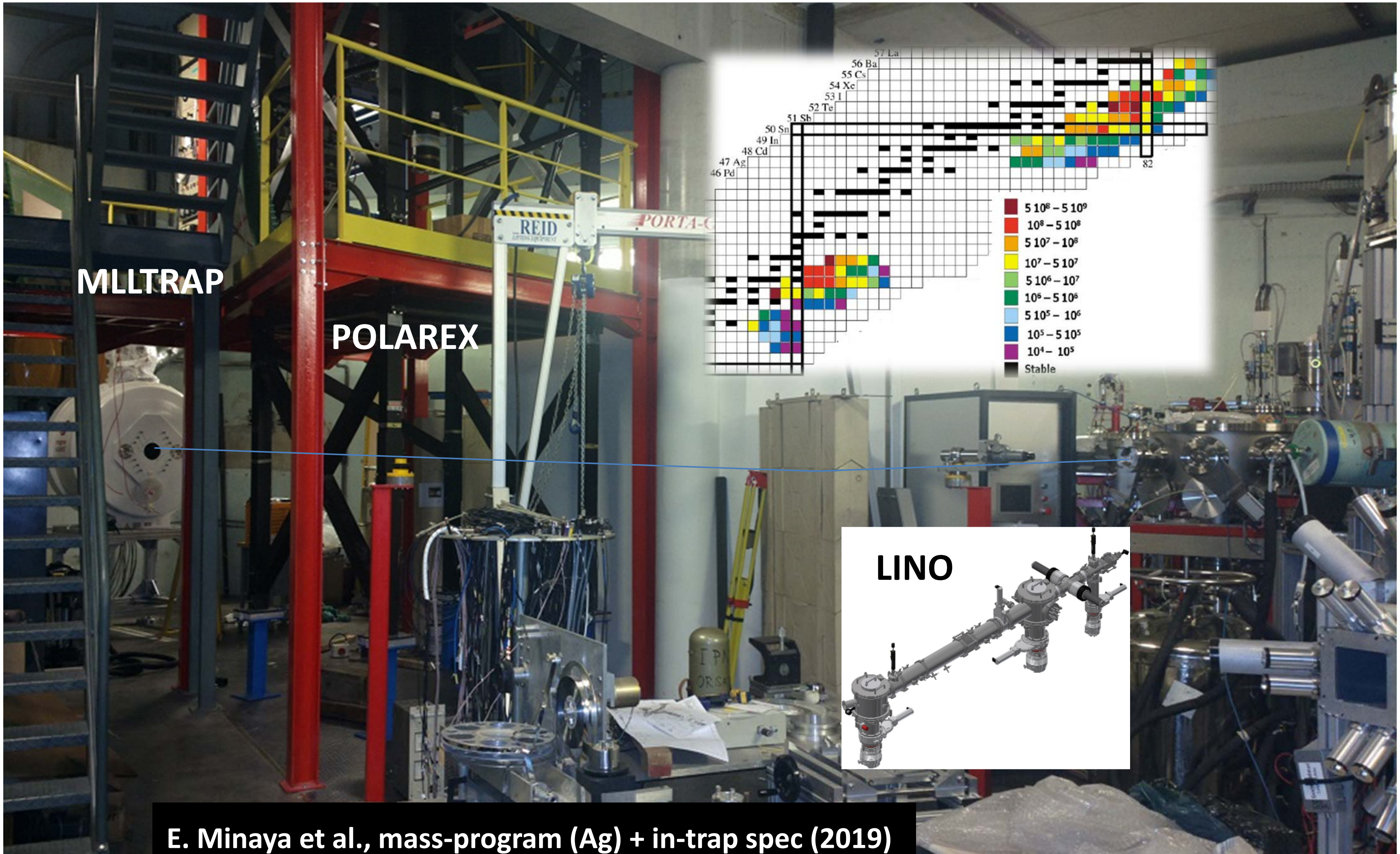
P2IO Projet Emblematique “Terra Incognita”



2017-2019; fort soutien de l’IN2P3

IPN – CSNSM – SPhN *+ GANIL, CENBG, LPSC…*

ALTO experimental area



E. Minaya et al., mass-program (Ag) + in-trap spec (2019)
D. Yordanov et al. charge radii of Ag and moments (2018)
C. Gaulard et al. spins/moments of Pm (2017)

Structure nucléaire : propriétés statiques du noyau

conclusions

Ground-state property (lab)	Now	(Near) Future
masses (CENBG, CSNSM, GANIL, IPN)	ISOLTRAP-ISOLDE TITAN-ISAC, GARIS	MLLTRAP-ALTO/DESIR S^3LEB-PILGRIM, PIPERADE-DESIR
charge radii, moments & spins (IPN, GANIL)	COLLAPS-ISOLDE CRIS-ISOLDE	CLS-ALTO, LINO-ALTO S^3LEB-REGLIS, LUMIERE-DESIR
moments & spins (CSNSM, LPSC, IPN)	NICOLE-ISOLDE	POLAREX-ALTO

- Studies of ground-state properties important & complementary – results (involving IN2P3) of high quality
- Instrumentation developed for ISOL experiments → coupled via gas cell to in-flight facilities (also post-acc)
- Implication of many IN2P3 physicists in present experimental programs concerning *all* gs properties
- France now developing many ISOL-based instruments (especially traps) for the national facilities