



# (Nuclear) Physics at ISOLDE-CERN (2/2)

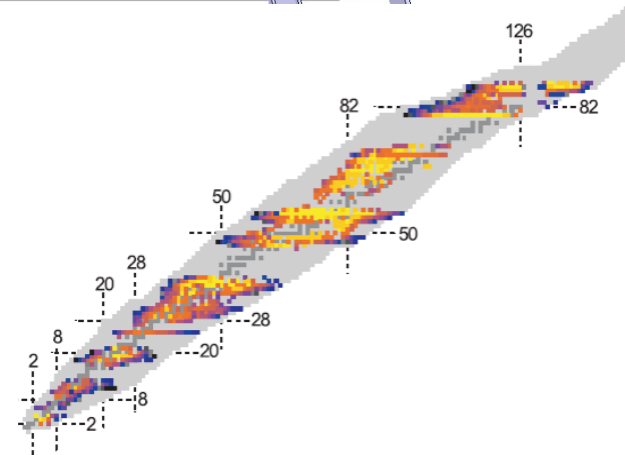
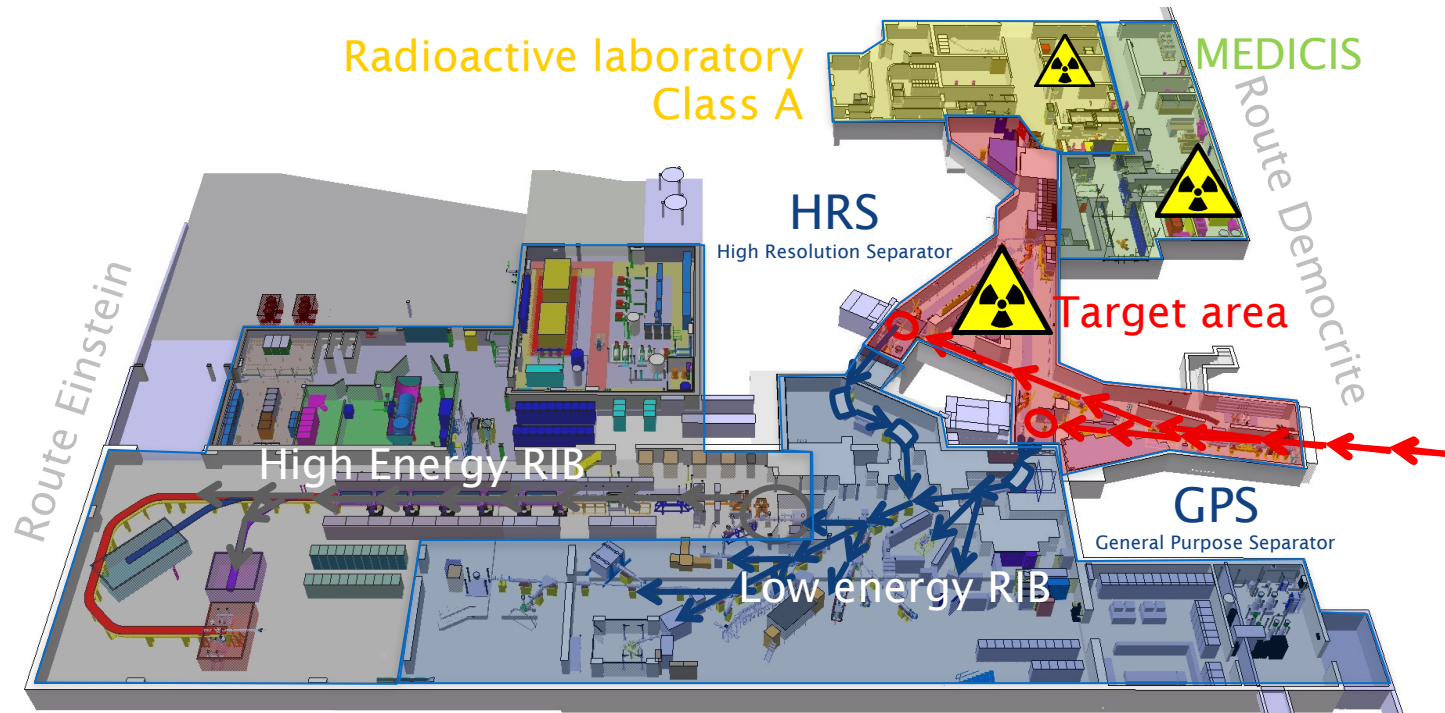
Stephan Malbrunot-Ettenauer  
CERN, TRIUMF, and University of Toronto

on behalf of the ISOLDE-CERN group  
<http://isolde.web.cern.ch>

**ISOLDE**



# The ISOLDE facility - recap





# Homework

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What factors determine ion beam intensity in your set-up?

## **ISOLDE**

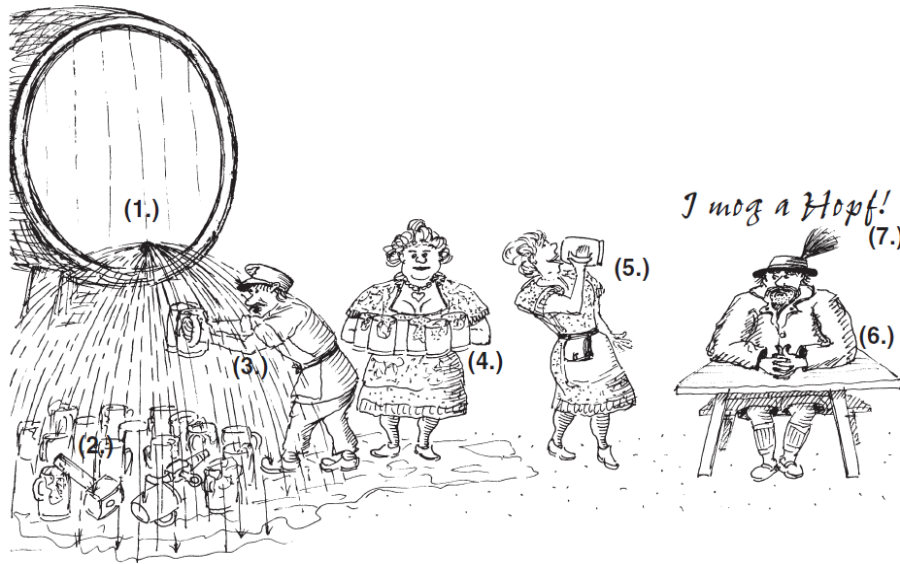
- 1.4 GeV protons
- 2  $\mu\text{A}$  maximal proton intensity
- Isol facility

# Homework

 Number of extracted ions (yield) is governed by:

$$r = \Phi \cdot \sigma \cdot N \cdot \epsilon_{\text{target}} \cdot \epsilon_{\text{source}} \cdot \epsilon_{\text{sep}} \cdot \epsilon_{\text{transp}} \cdot \epsilon_{\text{det}}$$

primary particle flux x reaction cross section x number of target particles x efficiencies



## ISOLDE



- Energy loss of protons in thick target ( $\sigma(E)$ )
- Secondary reactions in target
- Selectivity  $\leftrightarrow$  loss in yield
- Effusion/Diffusion out of target
- Release from target  $\leftrightarrow$  half-life
- How much time do we spend on optimizing (gain in intensity  $\leftrightarrow$  available beam time)
- ...





# Outline

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-  Lecture 1: ISOLDE-CERN: radioactive ion beam production
-  **Lecture 2: Nuclear Physics and Applications at ISOLDE**

## EU officials warn UK over radioactive isotopes

Government denies Brexit will disrupt access to materials used to diagnose and treat disease

CANADA

### Doctors fear shortage as Chalk River reactor halts production of isotope



## HAMILTON THE SPECTATOR

How Canadian isotopes are playing a role in the fight against COVID-19

The New York Times

## Inside the Global Relay Race to Deliver Moly-99

The isotope is a cancer-detecting necessity, but it decays within day and isn't made in North America. A company is rushing to build a plant in Wisconsin to change that.

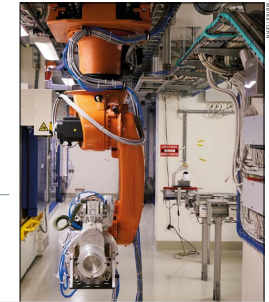
nature  
International journal of science

## Accelerating production of medical isotopes

Thomas Ruth

The global problem of a safe and reliable supply of radioactive isotopes for use in critical hospital procedures can be solved with accelerators, not nuclear reactors, says Thomas Ruth.

## Isotopes for precision medicine



The CERN-MEDICIS facility has produced its first radioisotopes for medical research, targeting novel diagnostic agents and treatments for diseases such as brain and pancreatic cancers.

## Two Birds With One Proton Beam: CERN Now Makes Radioisotopes For Medical Research



Fiona McMillan, CONTRIBUTOR  
FULL BIO  
Opinions expressed by Forbes Contributors are their own.

Forbes

NATURE | NEWS

### Reactor shutdown threatens world's medical-isotope supply

Canada's Chalk River reactor, which makes large amounts of technetium-99m, will end production next month.

Jeff Tollefson

12 September 2016 | Corrected: 30 November 2016

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nature



## Frankfurter Allgemeine

TUMORTHERAPIE

### Mit seltenen Erden gegen Krebs

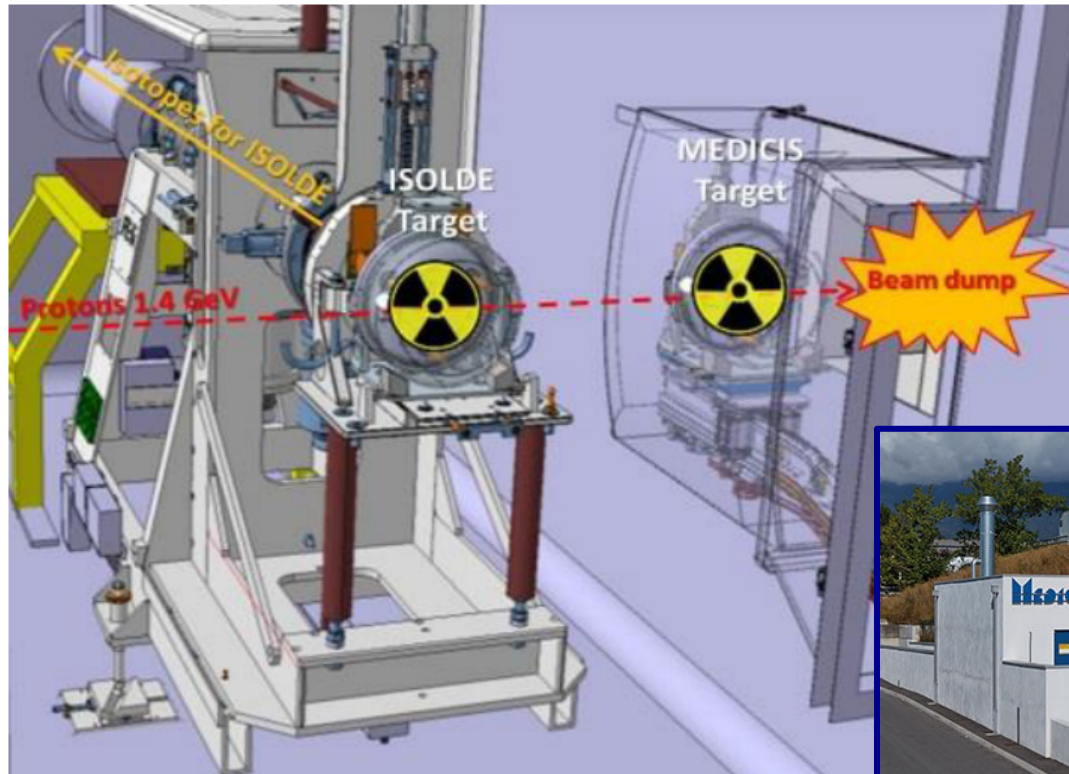
VON JAN HATTENBACH · AKTUALISIERT AM 15.03.2013 · 12:03



Europäische Forscher produzieren in einem Beschleuniger vier Radionuklide, die eine bessere Diagnose und eine effiziente Therapie versprechen. Versuche mit Mäusen lieferten vielversprechende Ergebnisse.

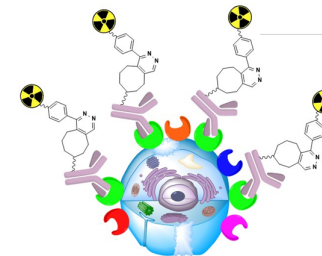
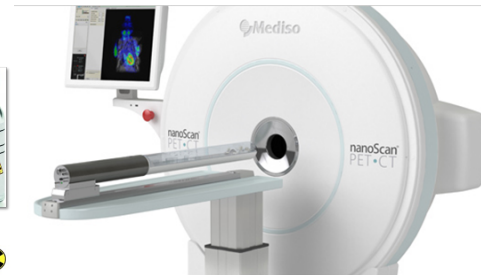
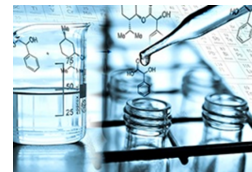
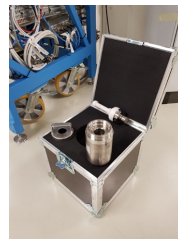
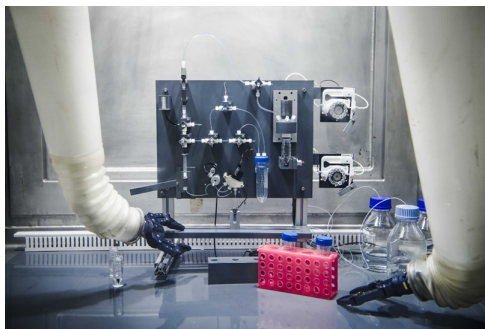
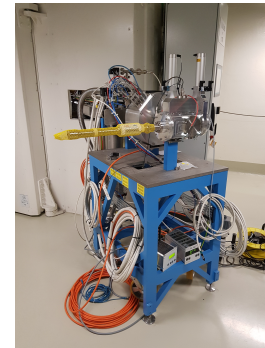
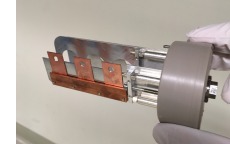
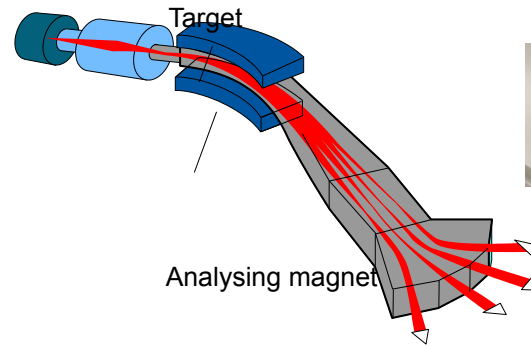
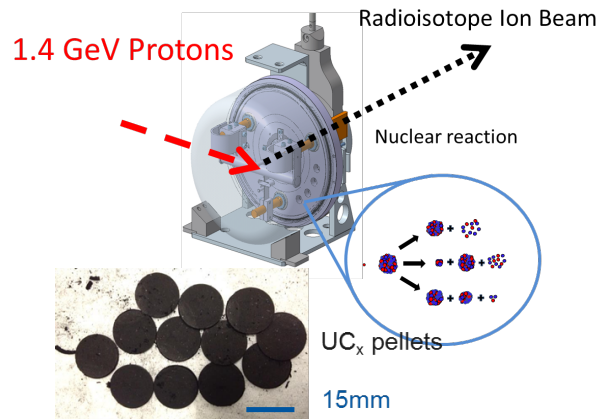
# 1. Medical Applications

# MEDICIS @ CERN



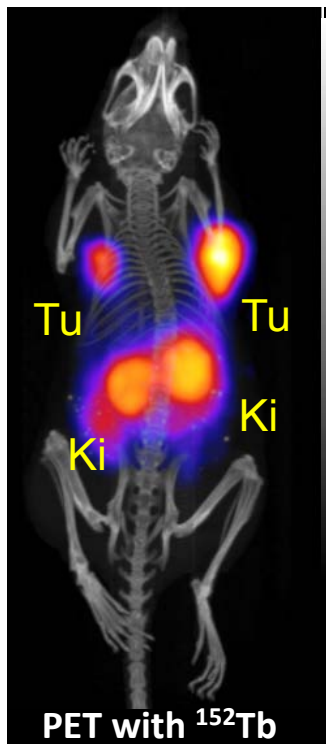
- MEDical Isotopes Collected from ISolde
- Production of non-conventional radioisotope for medical research
  - 80 – 90% of the proton beam goes through the ISOLDE target unaffected
  - Use these (free!) protons to create more radioisotopes
- Benefit from 50 years of ISOLDE experience

# MEDICIS process

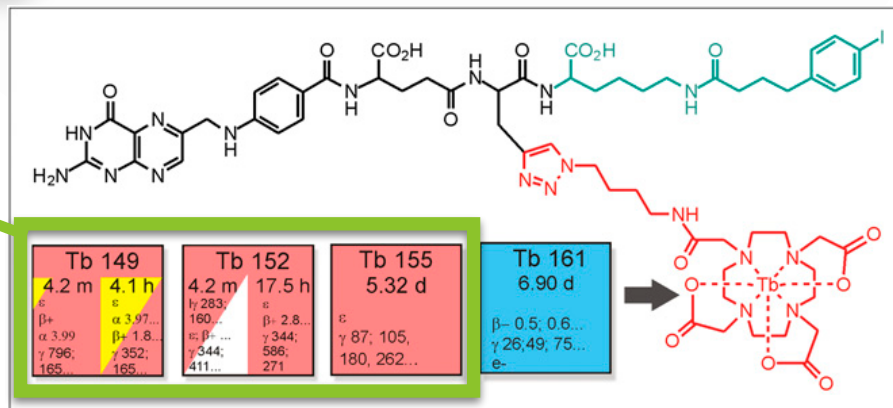




# Tb as innovative medical isotopes




- synthesised at ISOLDE / CERN  
 ➔ in fact: Dy, then  $\beta$  decay to Tb
- chemical separation
- In Vivo Studies



C. Müller et al., *J. Nucl. Med.* 53, 1951 (2012)  
 C. Müller et al., *EJNMMI Radiopharm. Chem.* 1, 5 (2016)

THERE ARE FOUR FUNDAMENTAL FORCES BETWEEN PARTICLES:  
(1) **GRAVITY**, WHICH OBEYS THIS INVERSE SQUARE LAW:


$$F_{\text{gravity}} = G \frac{m_1 m_2}{d^2}$$


OK...

(2) **ELECTROMAGNETISM**, WHICH OBEYS THIS INVERSE-SQUARE LAW:

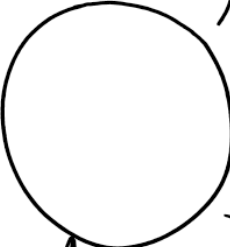
$$F_{\text{static}} = k_e \frac{q_1 q_2}{d^2}$$

AND ALSO MAXWELL'S EQUATIONS



ALSO WHAT?


(3) THE **STRONG NUCLEAR FORCE**, WHICH OBEYS, UH...  
...WELL, UMM...  
...IT HOLDS PROTONS AND NEUTRONS TOGETHER.



I SEE.

IT'S STRONG.

AND (4) THE **WEAK FORCE**. IT [MUMBLE MUMBLE] RADIOACTIVE DECAY [MUMBLE MUMBLE]  
THAT'S NOT A SENTENCE. YOU JUST SAID 'RADIO—  
—AND THOSE ARE THE **FOUR FUNDAMENTAL FORCES!**



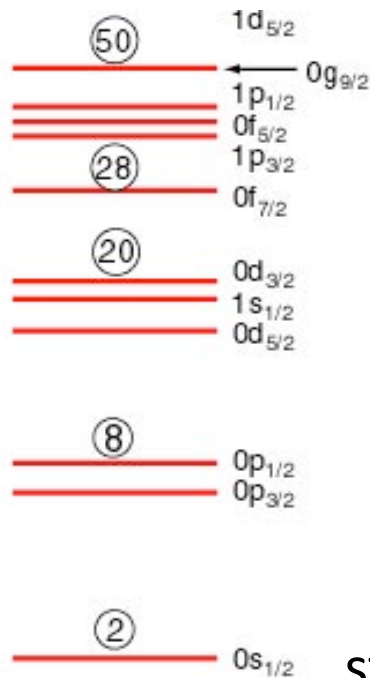
## 2. Nuclear physics

# nuclear shell structure

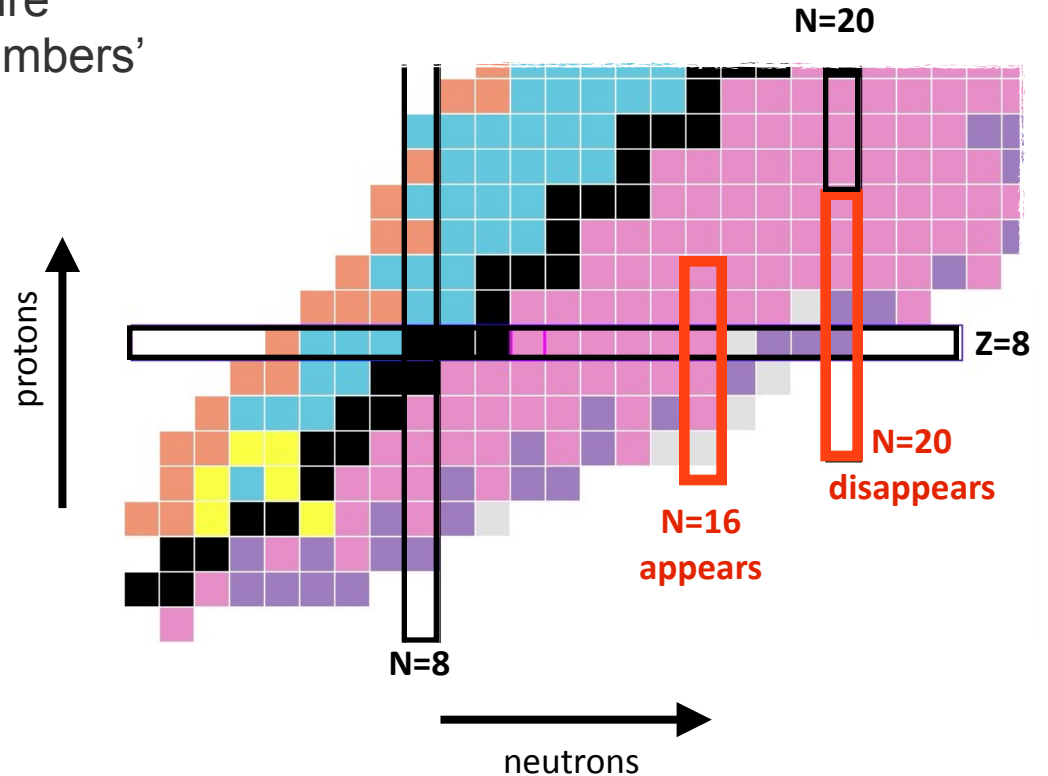


*Maria Goeppert  
Mayer  
J. Hans D. Jensen  
Nobel Prize 1963*

shell structure  
& 'magic numbers'



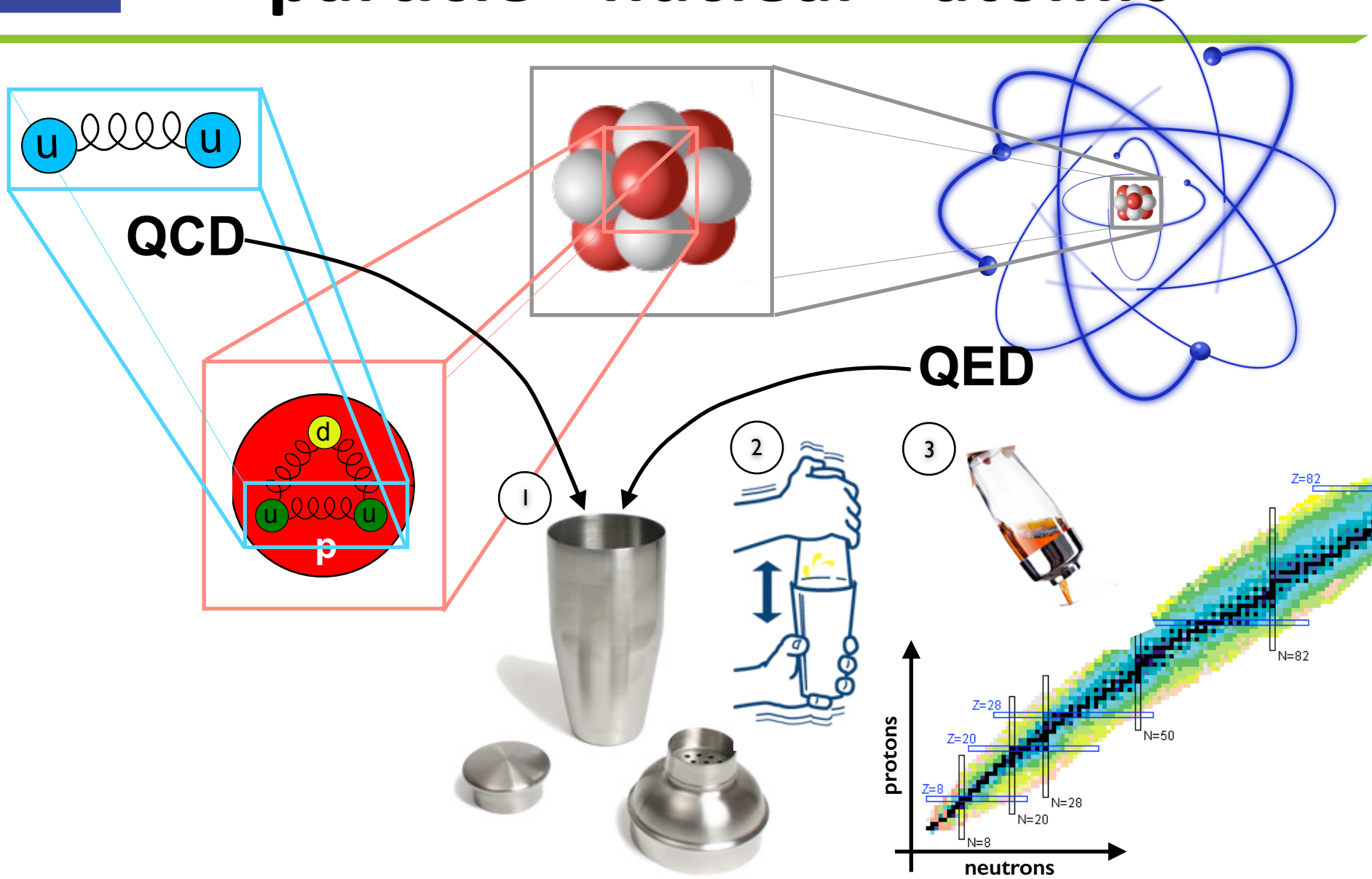
**Shell Model  
of Nuclei**



studies at modern radioactive ion beam (RIB) facilities  
 ➡ disappearance of established shell closures  
 ➡ emergence of new ones

**explain this shell evolution from first principles**

# particle - nuclear - atomic

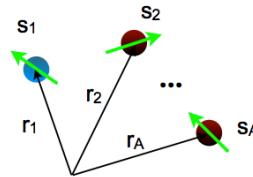




# nuclear theory: the big challenges

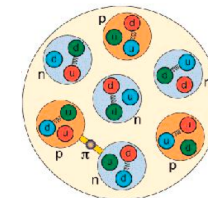
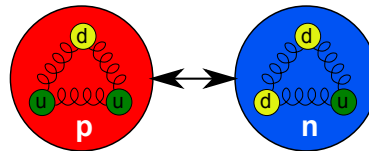
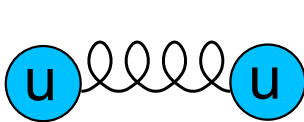
'ingredients' well understood, **BUT**

- neither a few nor a many body problem



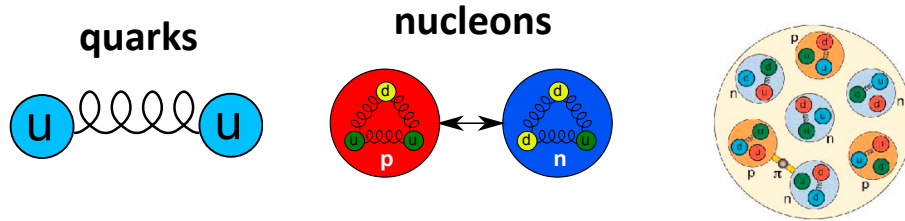
method

- nucleons composites of quarks: **force between nucleons?**

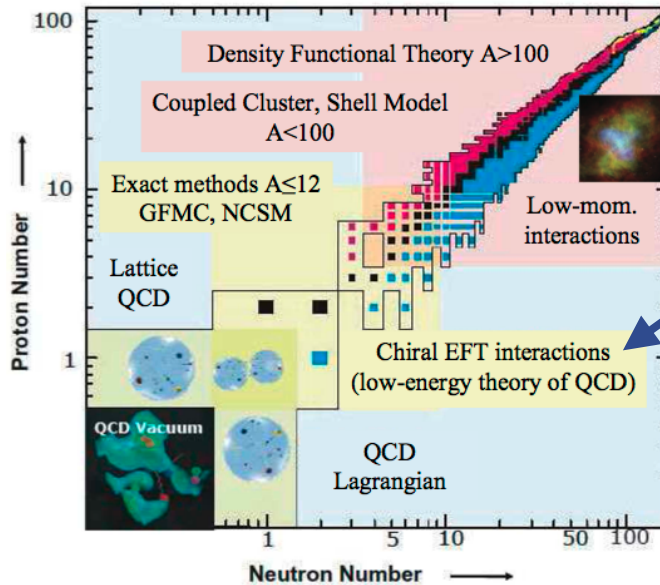


nuclear forces

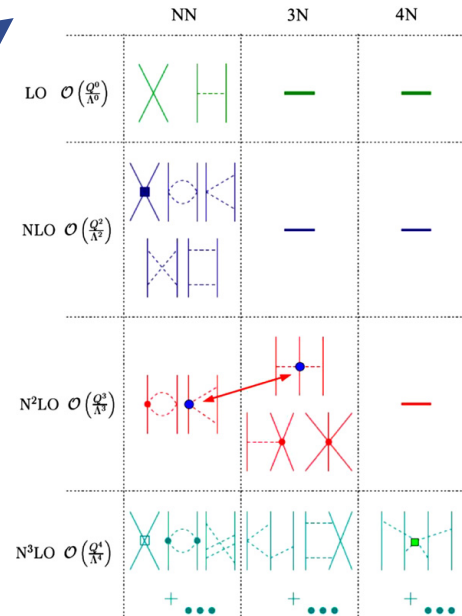
# modern nuclear forces



- bridge QCD to nuclear forces
- coupling constants fixed to (small) set of exp. data
- employ renormalisation methods
- ‘one’ nuclear potential used over whole nuclear chart
- potential employed in different few and many body methods

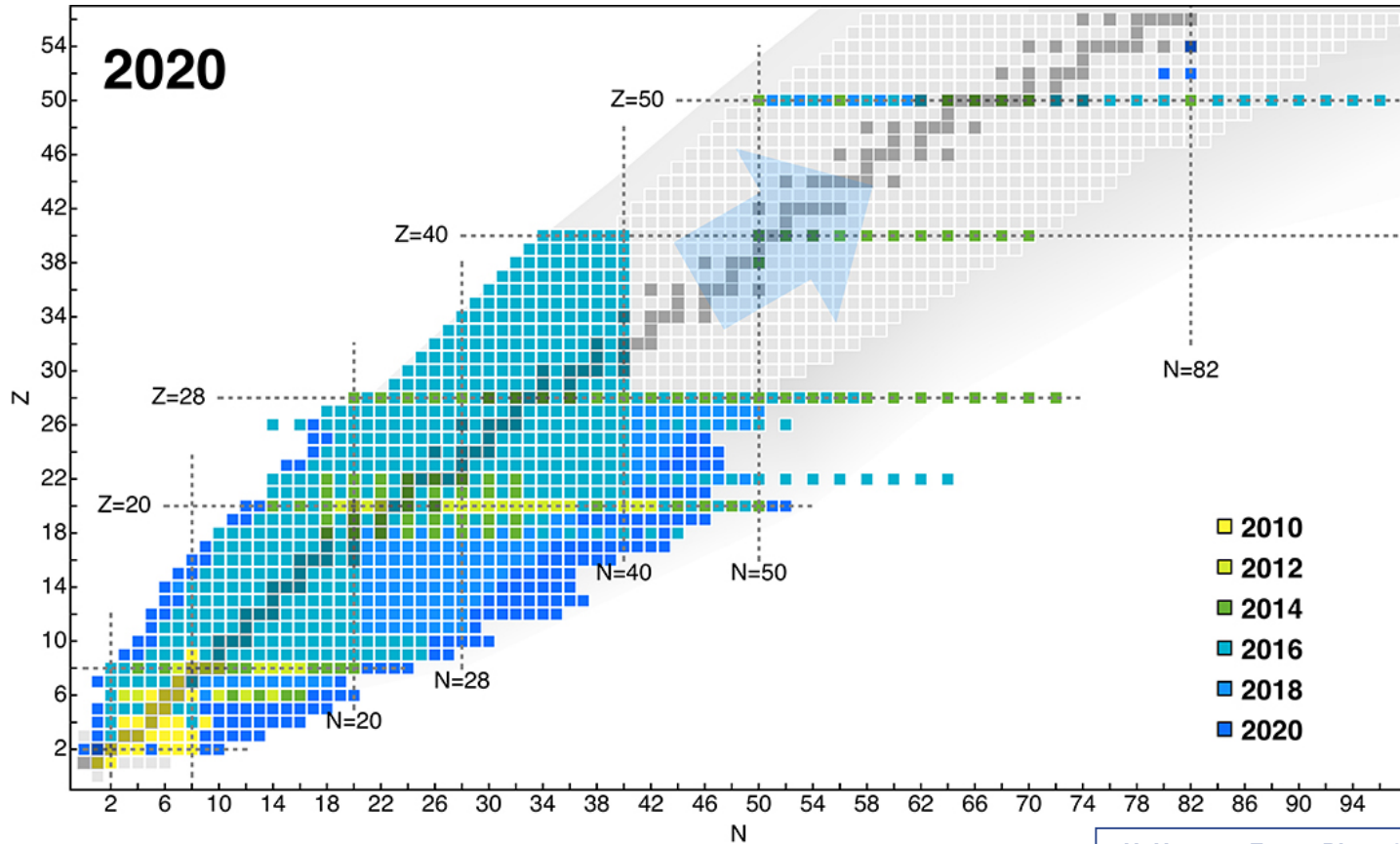


## Chiral EFT



E. Epelbaum et al., *Rev. Mod. Phys.*, 81, 1773 (2009)  
 S.K. Bogner et al., *Prog. Par. Nuc. Phys.*, 65,94, (2010)  
 R. Machleidt and D.R. Entem, *Phys. Rep.* 503, 1 (2011)

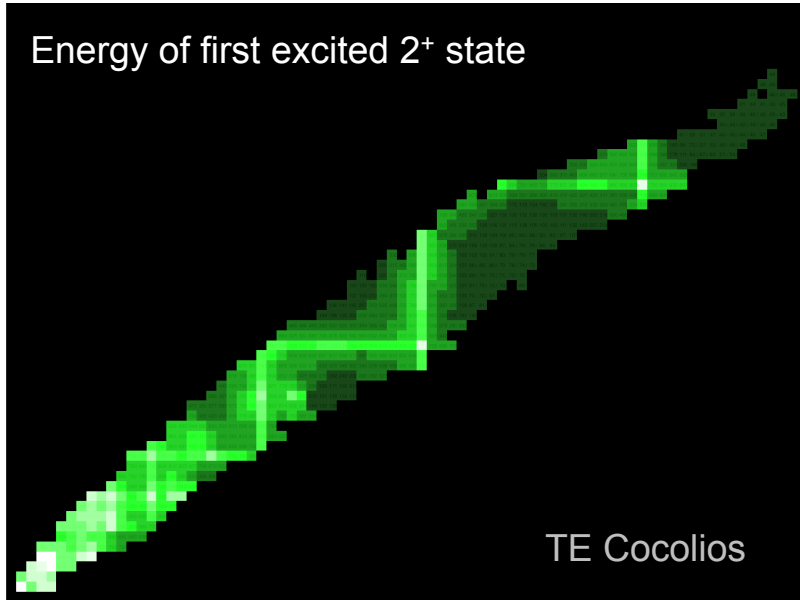
# reach of ab-initio methods



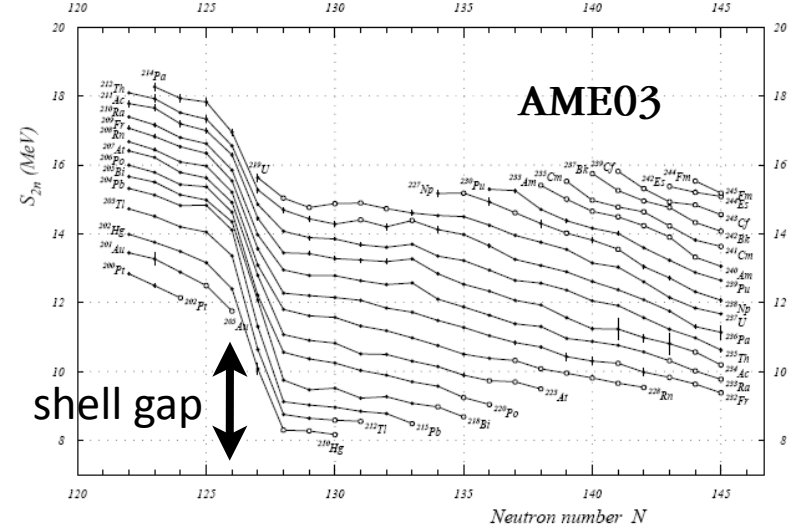
H. Hergert, *Front. Phys.* 8, 379 (2020)

requires experimental benchmark for nuclear theory

# Examples for signatures of Shell Closures



## Neutron separation energies & nuclear Masses



## Beta decay energies

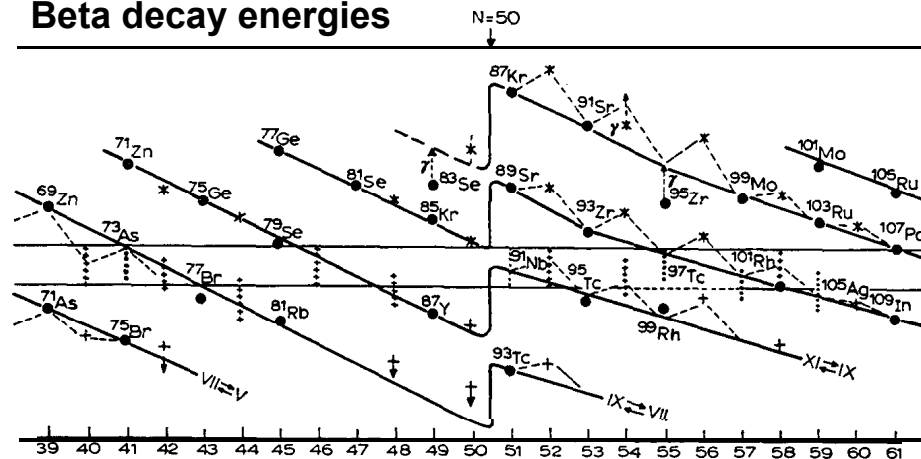
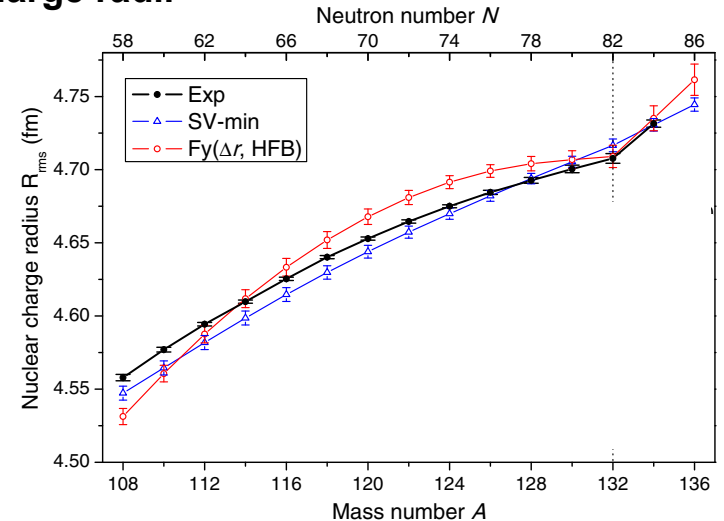


Fig. 3. Beta decay energies in the neighborhood of  $N=50$ .

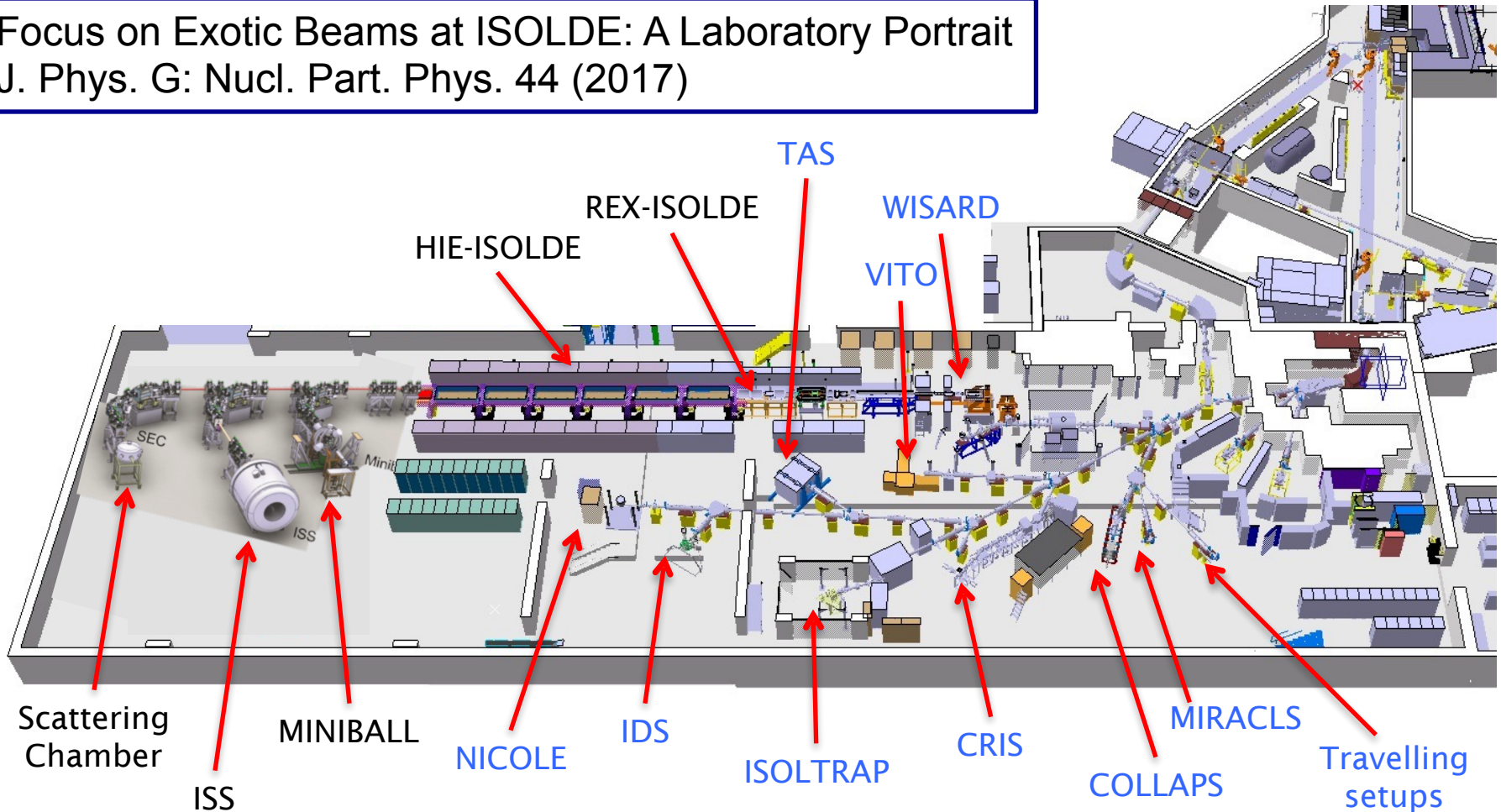
## Charge radii





# Experiments to probe nuclear structure

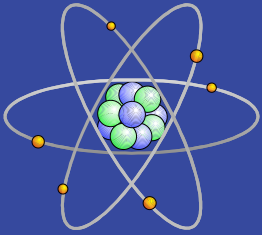
Focus on Exotic Beams at ISOLDE: A Laboratory Portrait  
J. Phys. G: Nucl. Part. Phys. 44 (2017)



- Low energy experiments
- High energy experiments

# masses

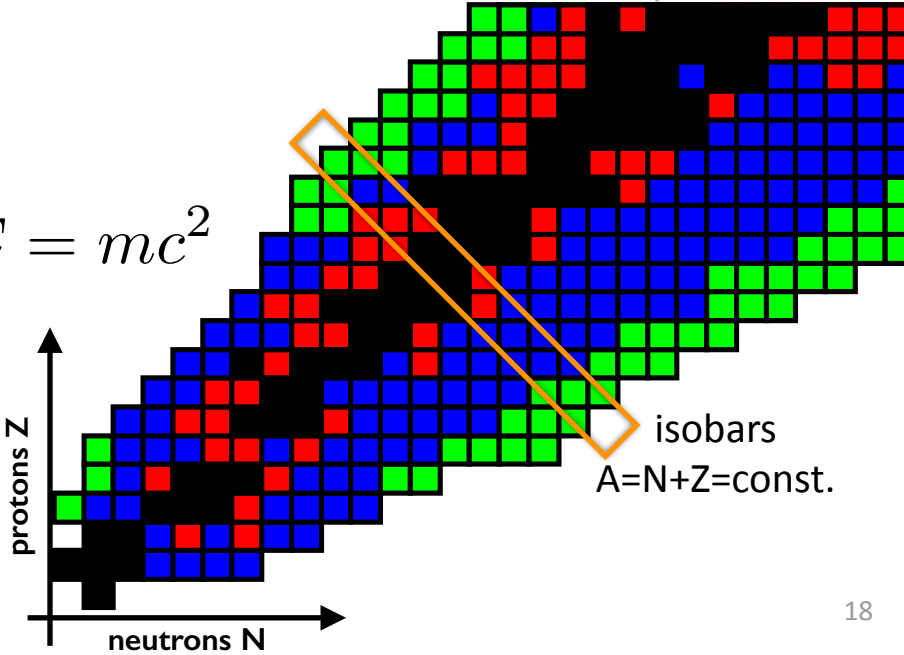
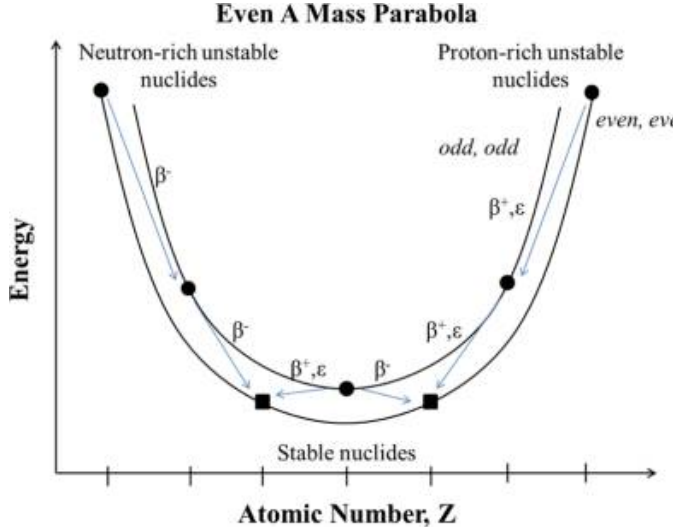
## Atomic Masses



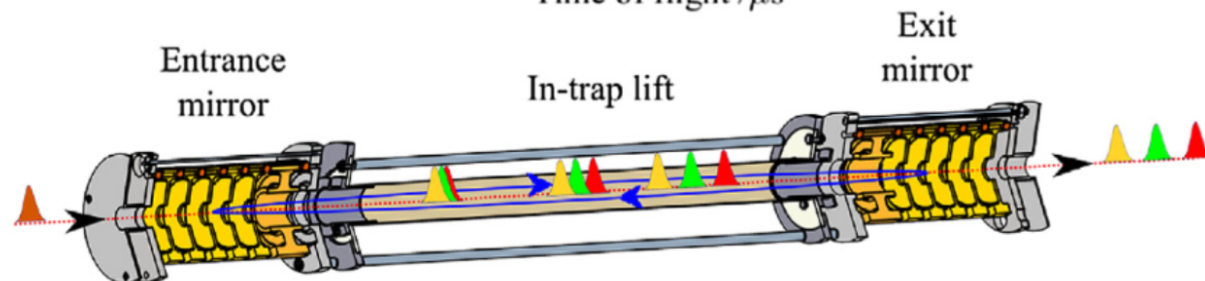
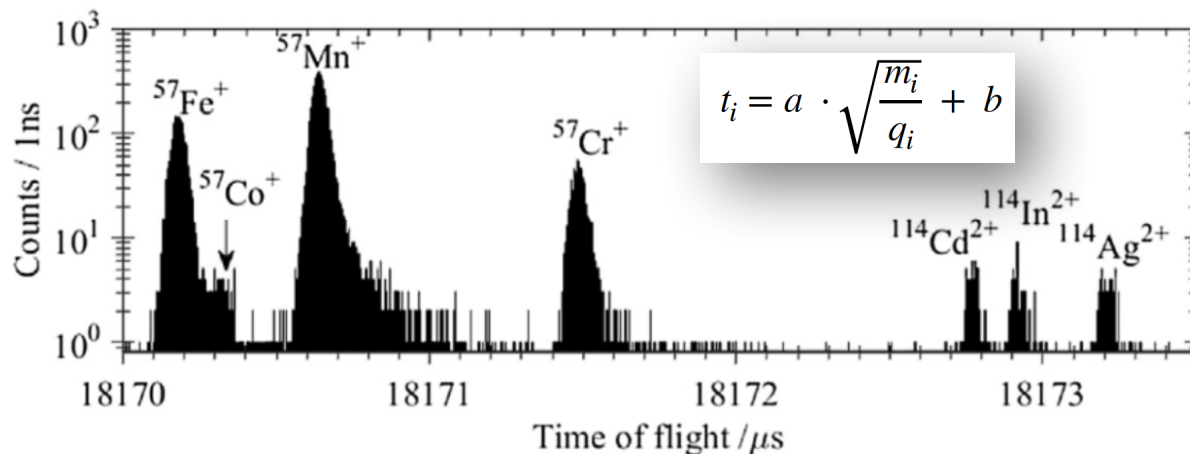
$$= N \cdot m_n + Z \cdot m_p + Z \cdot m_e - \text{binding energy}$$

	Mass [MeV/c <sup>2</sup> ]
neutron	939.565 420 52(54)
proton	938.272 088 16(29)
electron	0.510 99895000(15)
nuclear binding	≈8 per A
electron binding	0.000013 (Hydrogen) 0.115606 (inner e <sup>-</sup> in U)

$$E = mc^2$$



# ISOLTRAP MR-ToF mass spectrometer



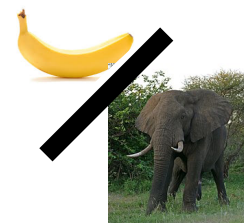
## Multi-reflection Time-of-Flight (MR-ToF)

- Fold 1000s m of flight-path in device of  $\sim 1\text{m}$
- Limitation
  - $< 1$  pps
  - 10 ms half-life
- Resolving power
  - $10^5$  in  $\sim 20$  ms

$\frac{\delta m}{m}$   
mass resolution

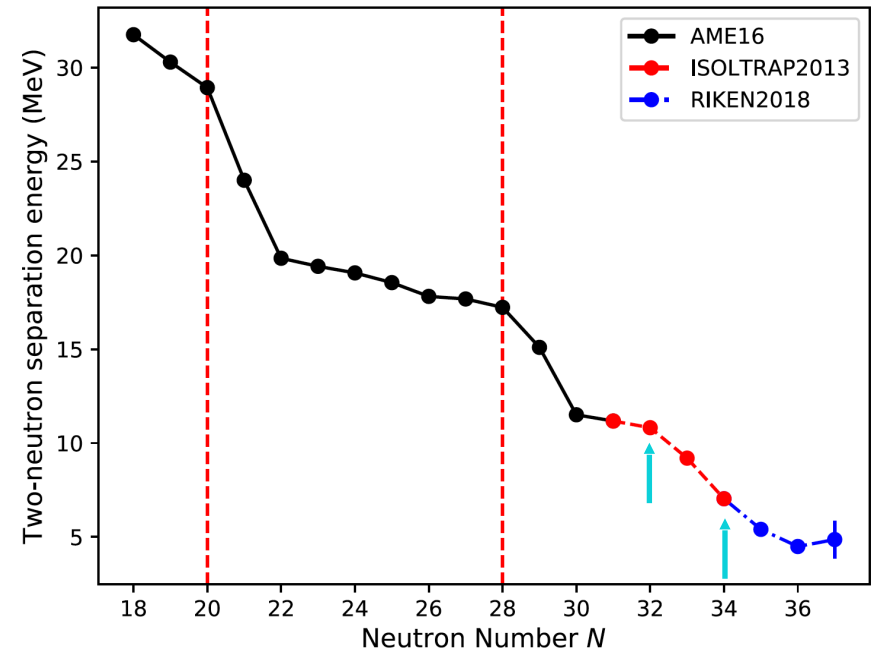
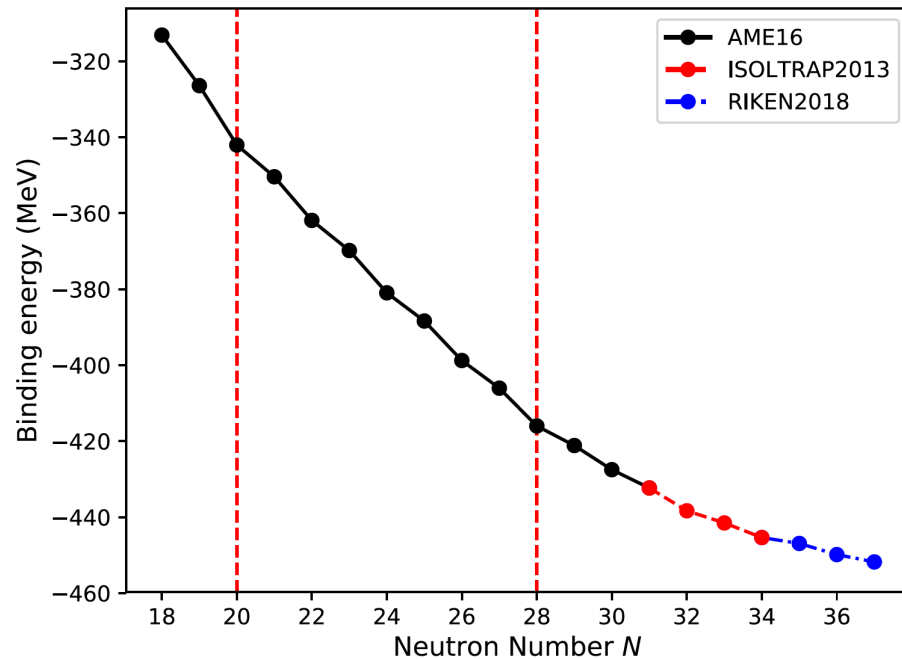
$\approx$

$\frac{m_{\text{banana}}}{m_{\text{elephant}}}$   
mass



# ISOLTRAP mass spectrometer

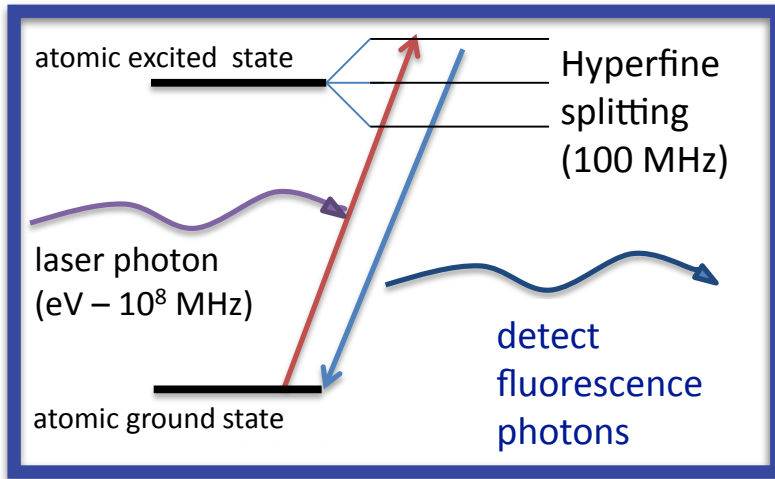
- Ca-isotopes
  - $Z = 20$  closed shell: benchmark for nuclear models
  - New magic numbers at  $N = 32$  and  $N = 34$ ?



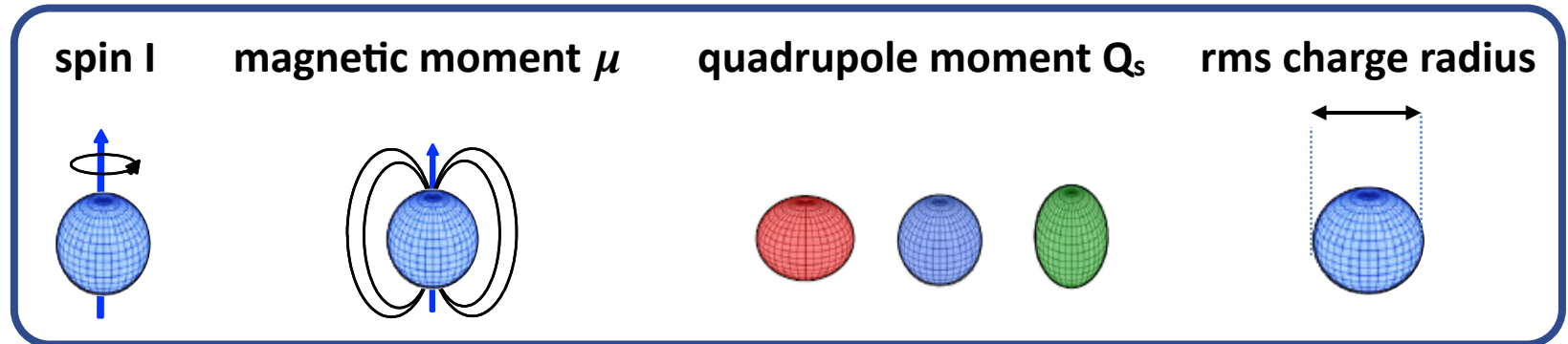
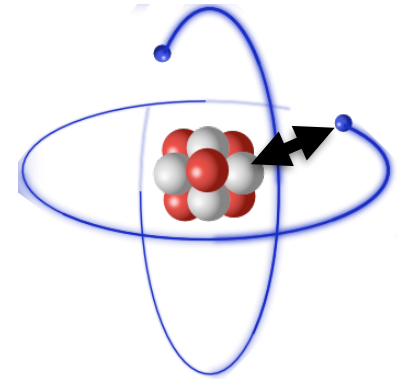
$$S_{2n}(Z, N) = E(Z, N-2) - E(Z, N)$$



# laser spectroscopy of radionuclides

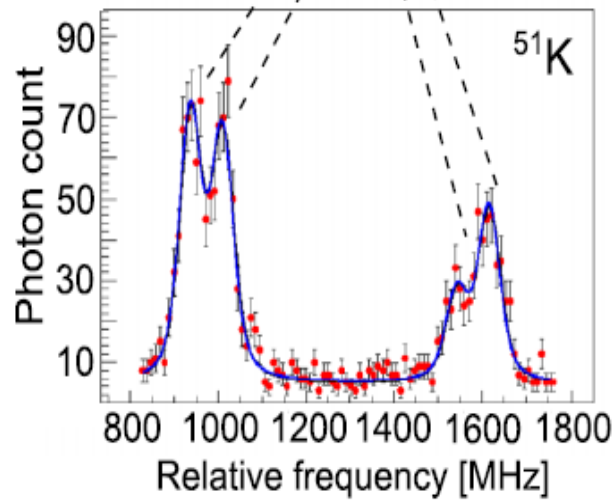
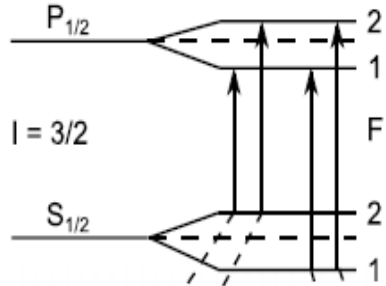


nucleus - electrons interaction  
 $\Rightarrow$  atomic hyperfine structure



**benchmark for modern nuclear structure theory**

# Collinear Laser Spectroscopy (CLS)

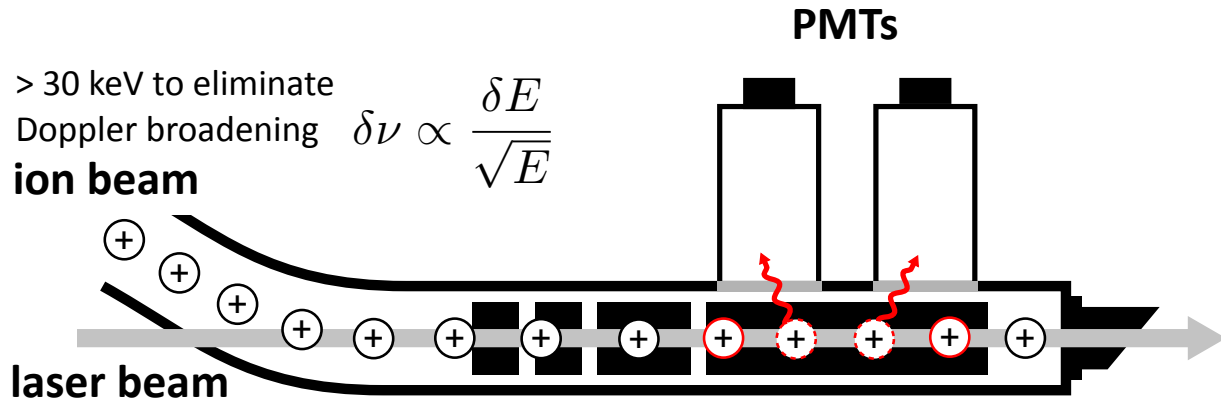


> 30 keV to eliminate  
Doppler broadening

$$\delta\nu \propto \frac{\delta E}{\sqrt{E}}$$

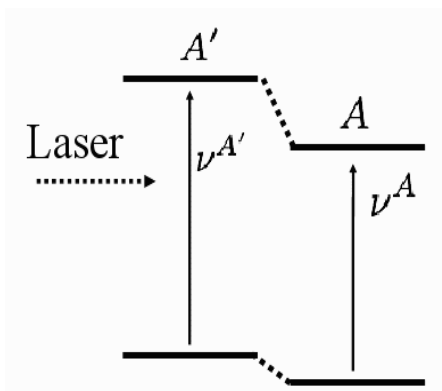
ion beam

laser beam



# CLS and nuclear charge radii

isotope shift

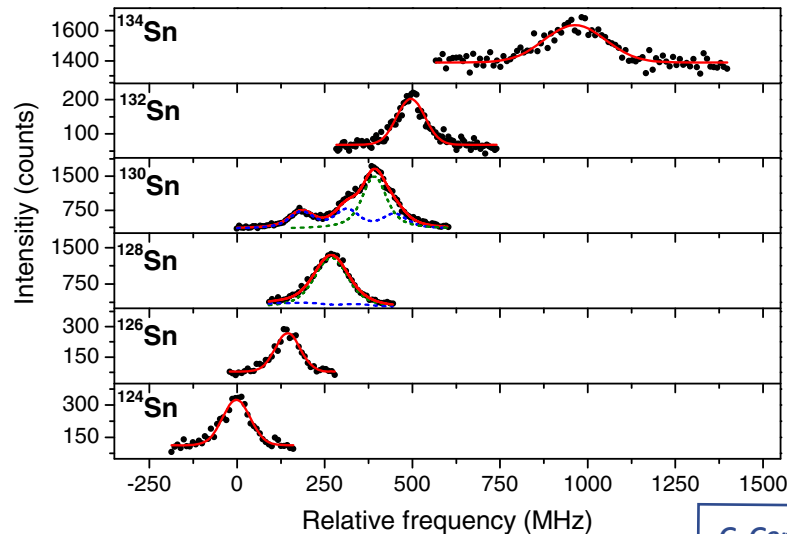


$$\delta\nu^{A,A'} = M \frac{A' - A}{A \cdot A'} + F \delta\langle r^2 \rangle_{A,A'}$$

difference in ms charge radii

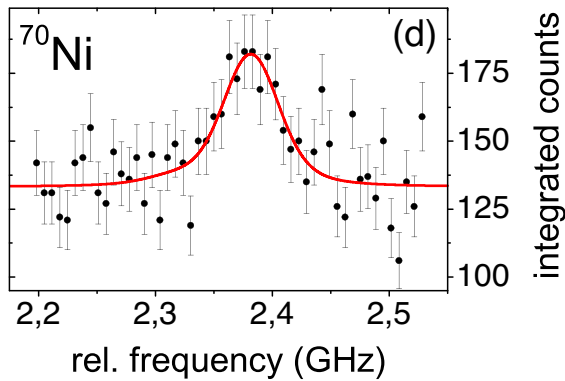
mass and field shift factors

- king-plot analysis of stable isotopes
- atomic theory



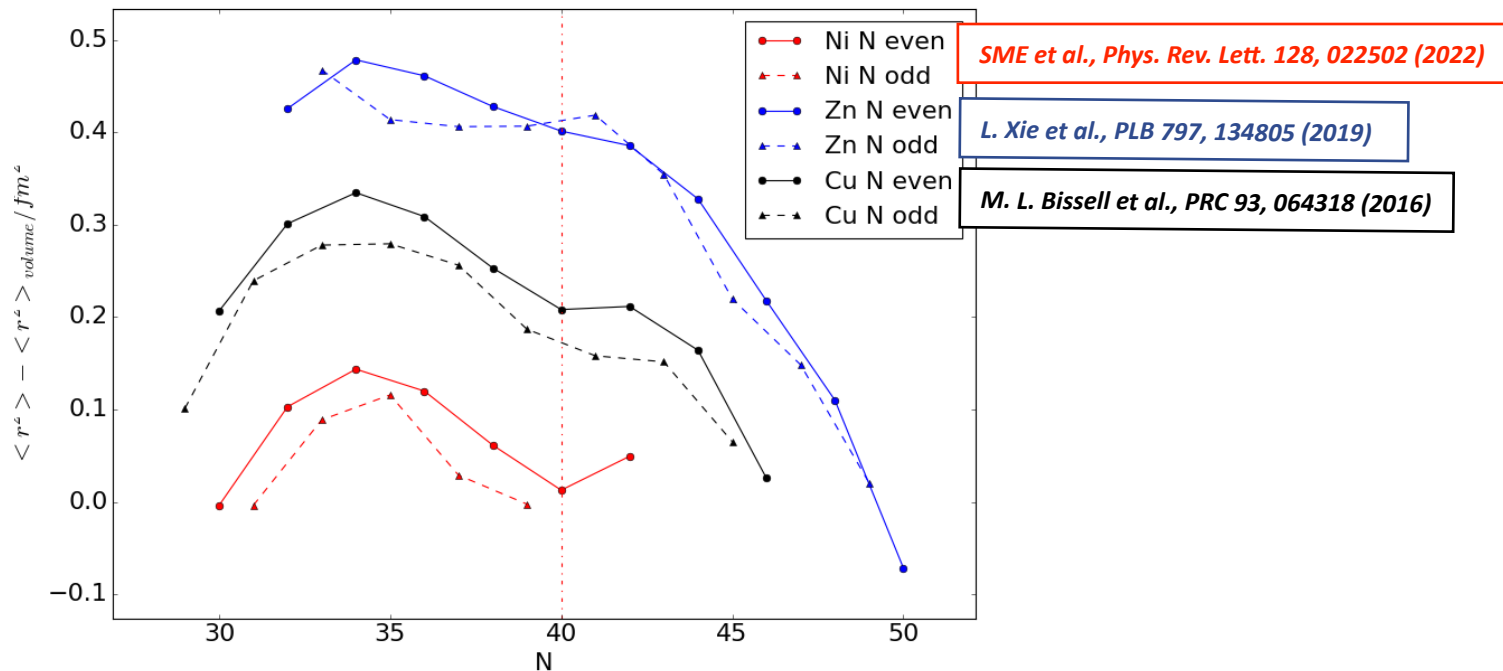
G. Gorges et al., *PRL* 122, 192502 (2019)

# CLS of exotic Ni isotopes

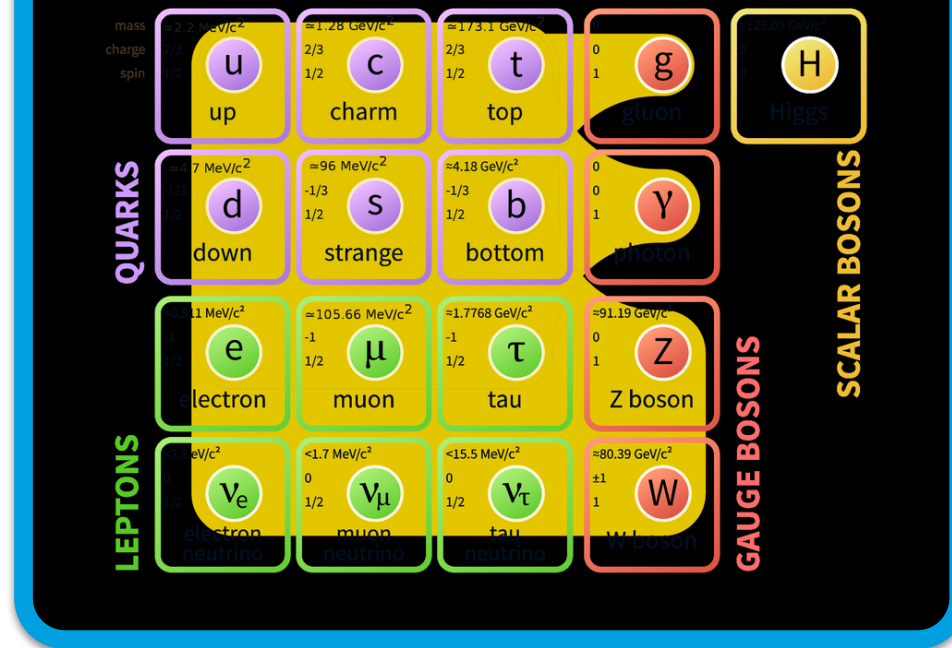


Most exotic, studied Ni isotope: <sup>70</sup>Ni

- $T_{1/2} = 6$  sec.
- typical ISOLDE yield  $10^4$  ions/sec
- <sup>70</sup>Ni : <sup>70</sup>Ga = 1 :  $10^4$



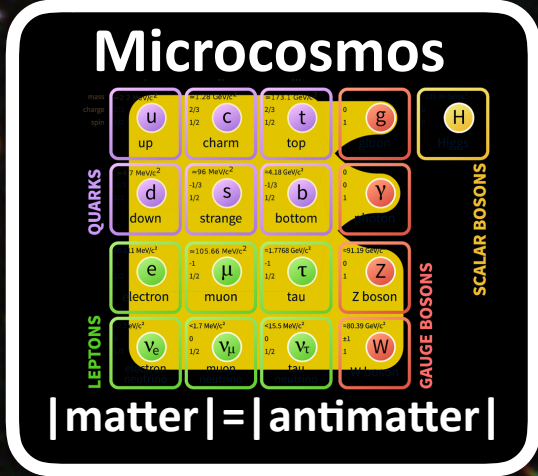
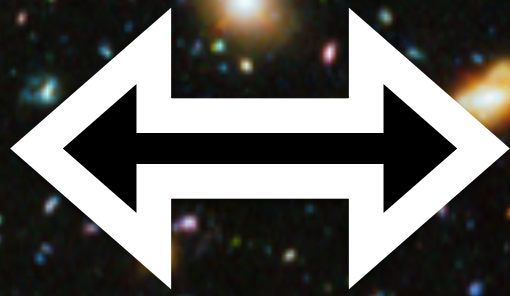
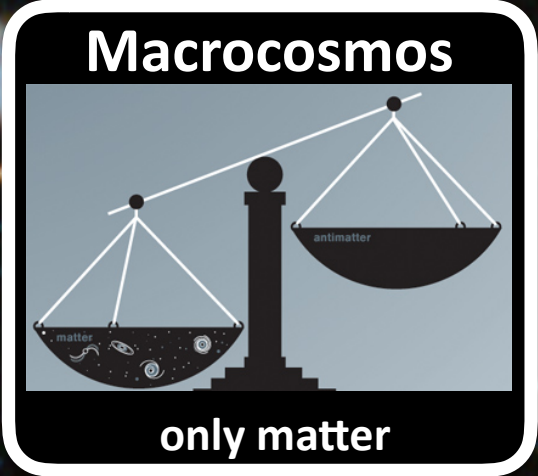
# Standard Model



## 3. Radionuclides & Fundamental Symmetries of Nature

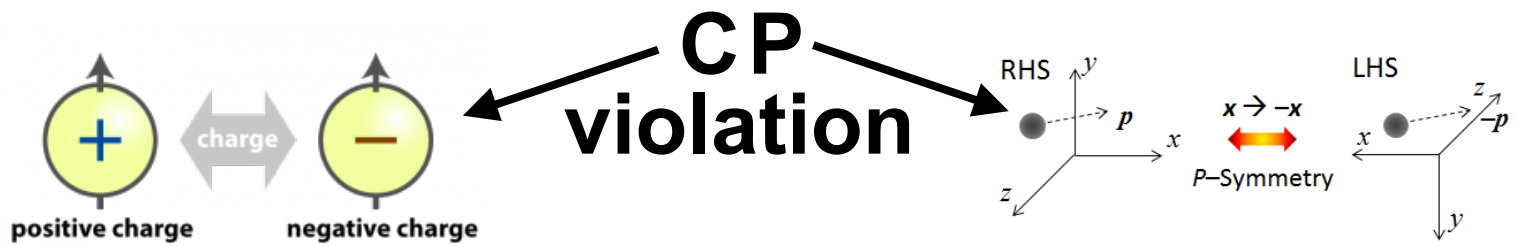


# where is all the antimatter?



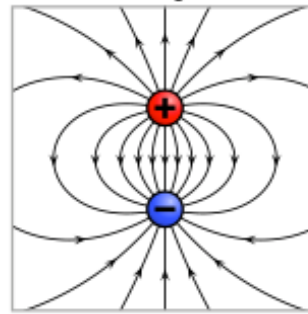
Sakharov, 1967

ingredient to resolve universe's matter-antimatter asymmetry:

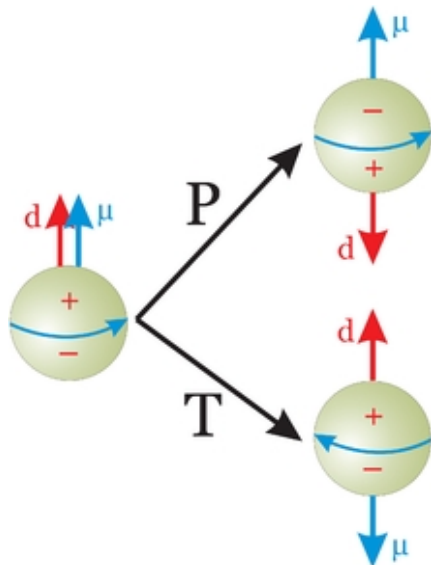


# Permanent electric dipole moment

- local separation of the electric charge along a particle's spin axis

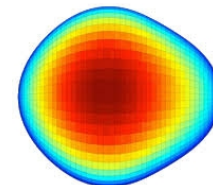


- implies time-reversal (T) violation  $\Rightarrow$  violation of CP symmetry (assuming CPT)



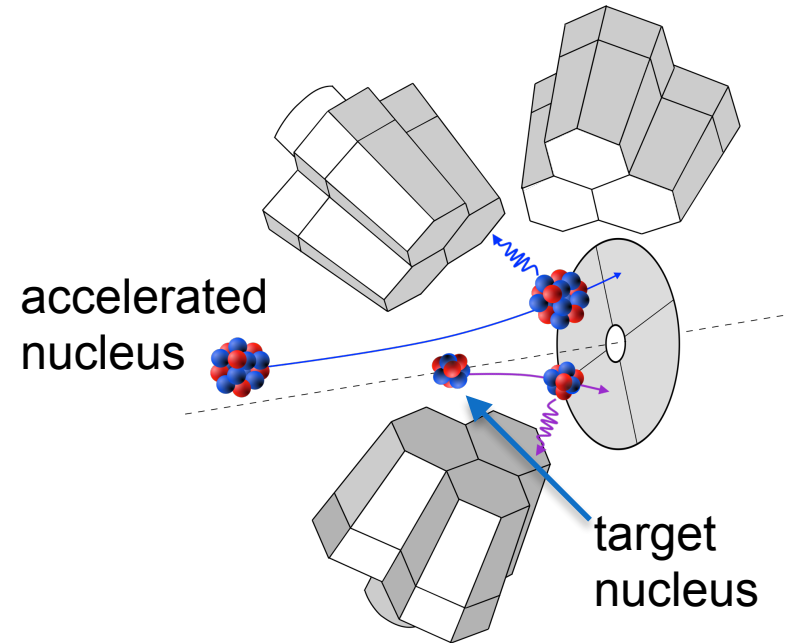
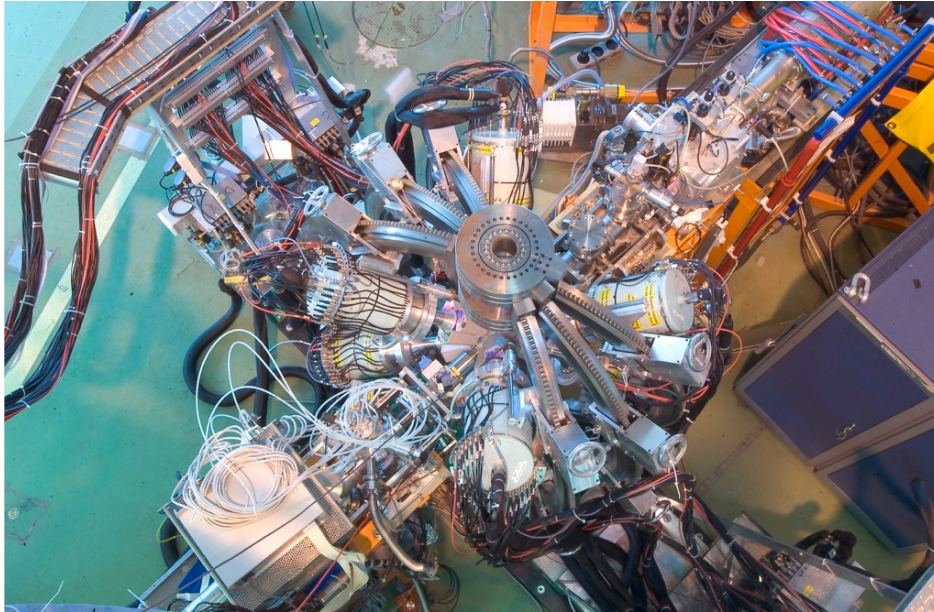
matter-antimatter asymmetry in the universe

pear-shaped nuclei & 'nuclear EDM'

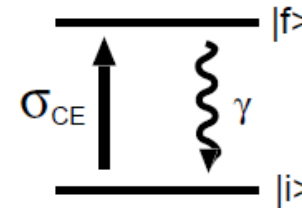


Schiff moment

# Miniball: Coulomb excitation



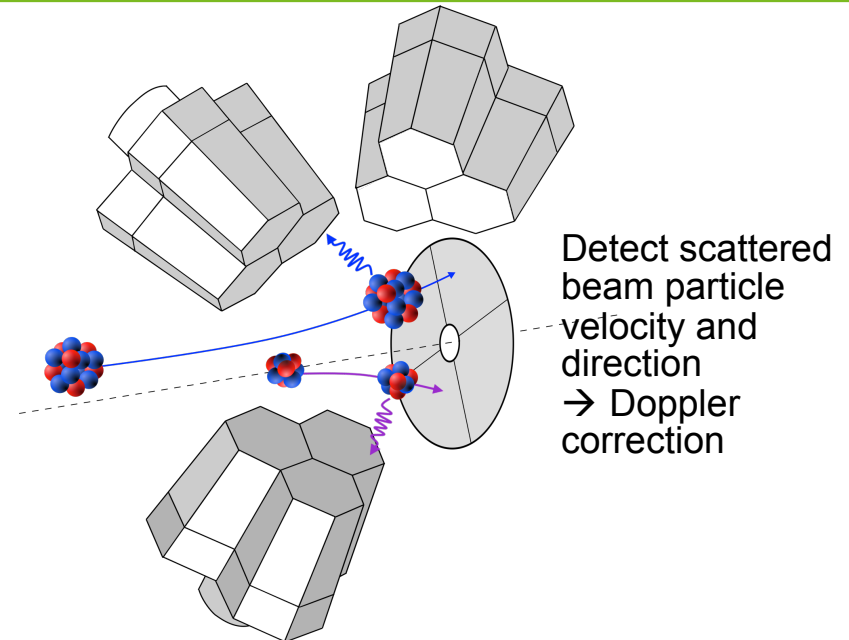
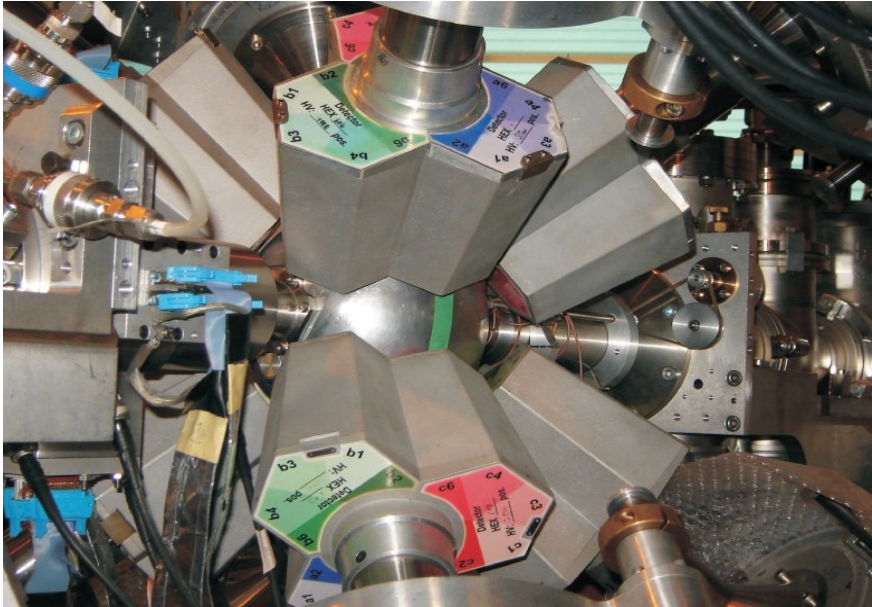
- Coulomb excitation
  - Inelastic scattering of nuclei with electromagnetic force only
  - Nuclei never collide
- Observables
  - Gamma-decay energies
  - Probability to excite to final state



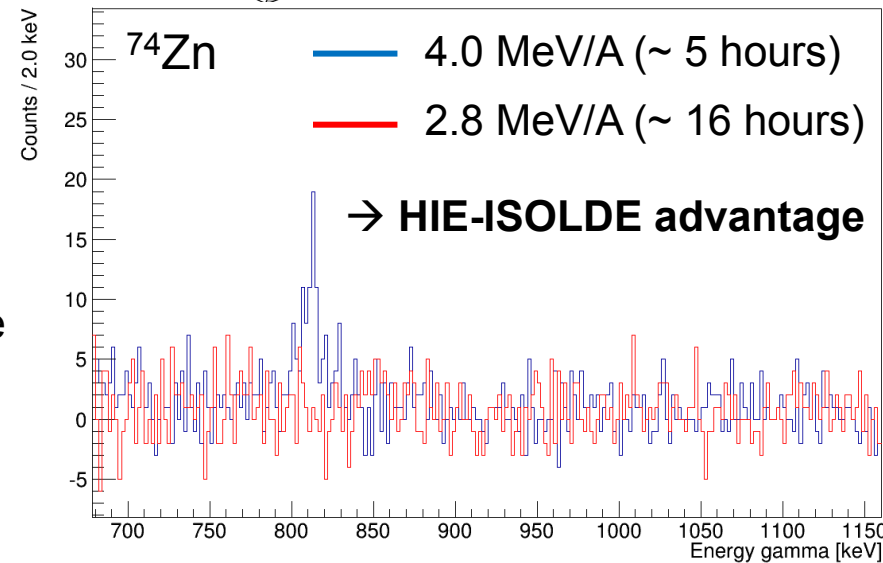


# Miniball: Coulomb excitation

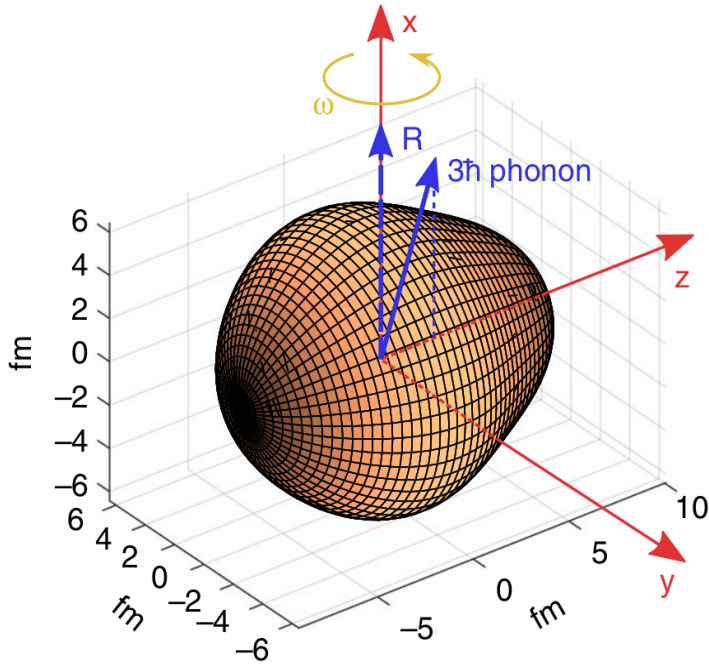
Joonas.konki@cern.ch



- Miniball set-up
  - Si detectors for particle identification
  - Ge detectors for efficient  $\gamma$ -ray detection
    - Compact and high-solid angle coverage
    - Segmented: position sensitive



# Coulomb excitation

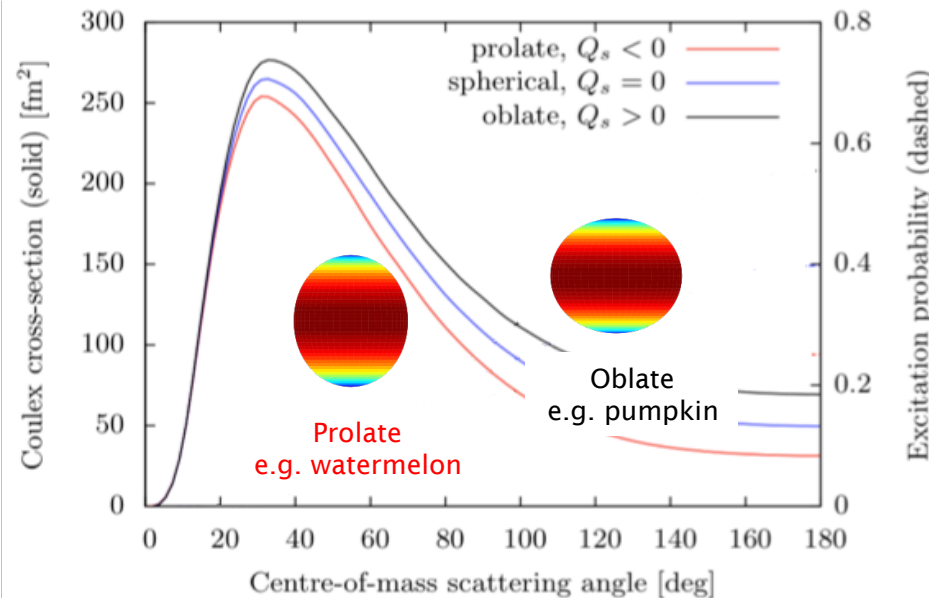


## Observation of vibrating pear-shapes in radon nuclei

P.A. Butler *et al.*, Nature Comm. 10 (2019) 2473

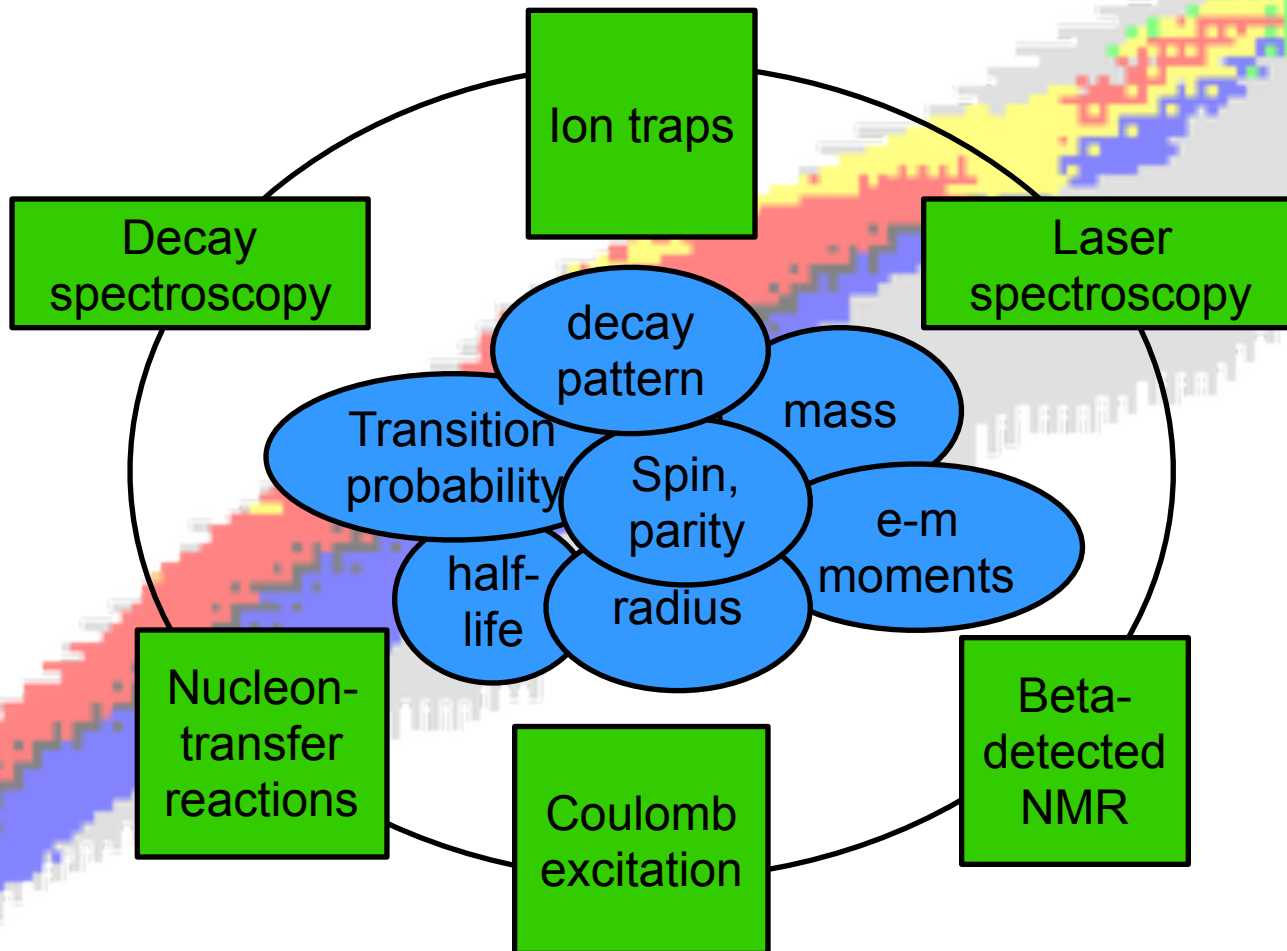
- Information

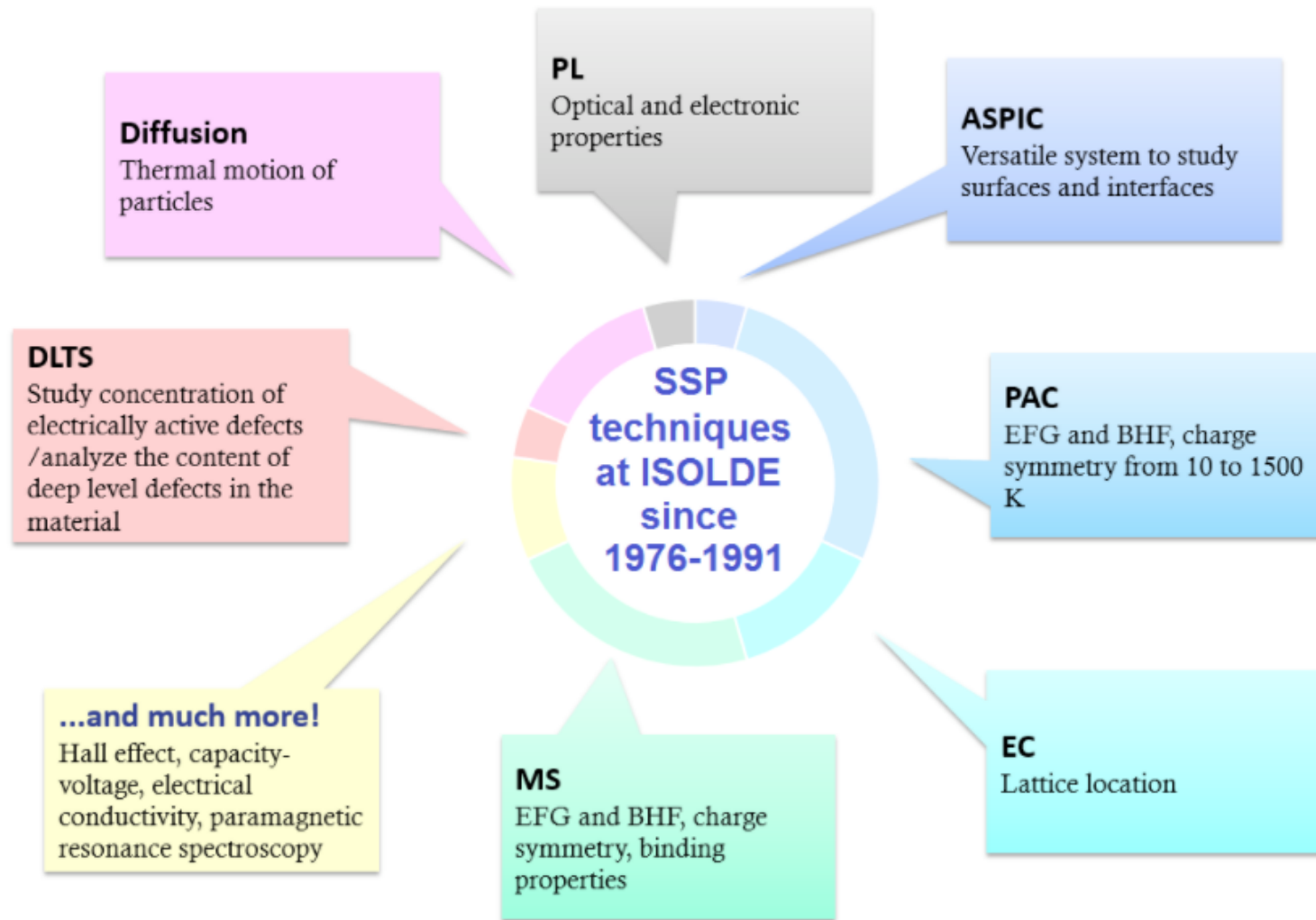
- Level scheme
- Nuclear shape of excited states





# Summary

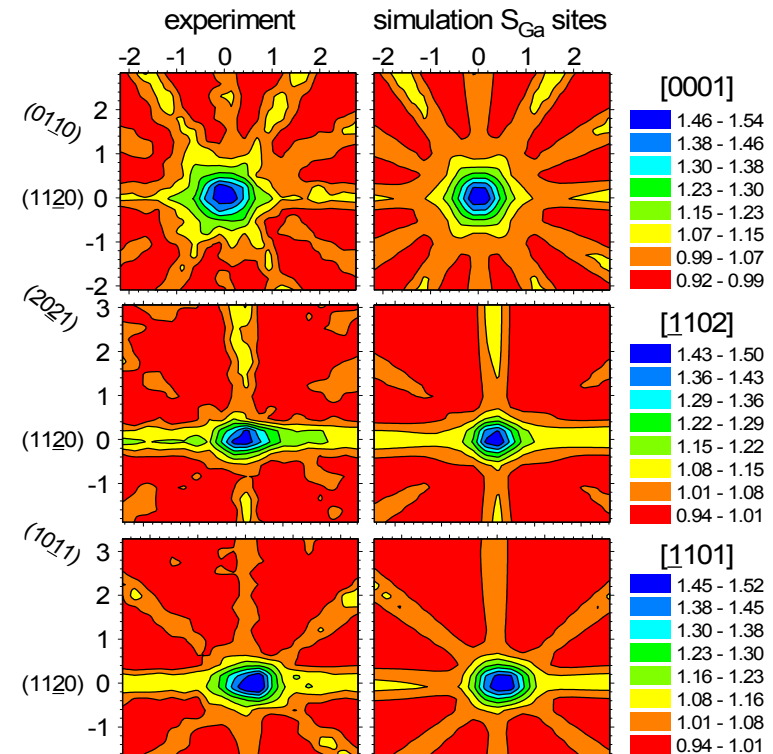
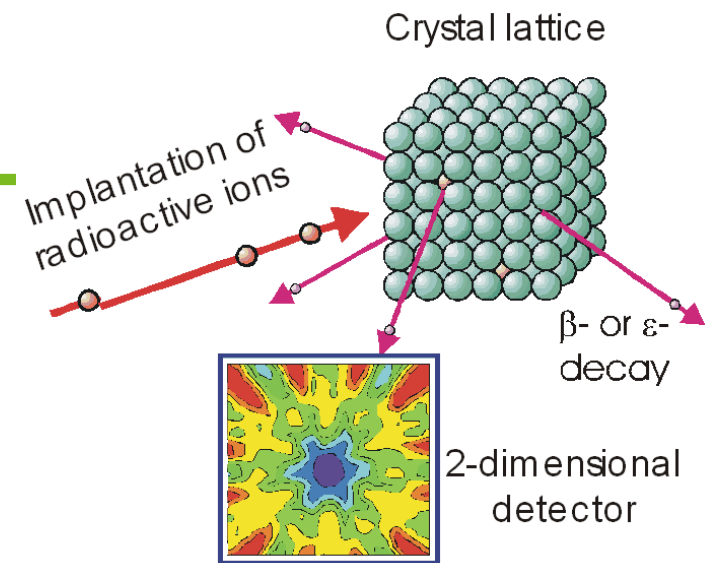




## 4. Research with radioactive isotopes

# Emission channeling

- Information on:
  - Probe atom lattice site location as function of implantation/annealing temperature
  - Diffusion of probe atom
  - Annealing of implantation defects





# Materials research with RIBs

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- Use radioactive ion as **probe** to characterise different materials
  - Solid state physics
  - Biophysics
- Advantages from radionuclides
  - Wide variety of isotopes with different half-lives and decay properties
  - High detection efficiency for radiation
  - Low quantities need to be implanted (no interference with host)

# Beta-NMR at ISOLDE



Metal ions in living organisms (Na, Mg, Cu, Zn ...)

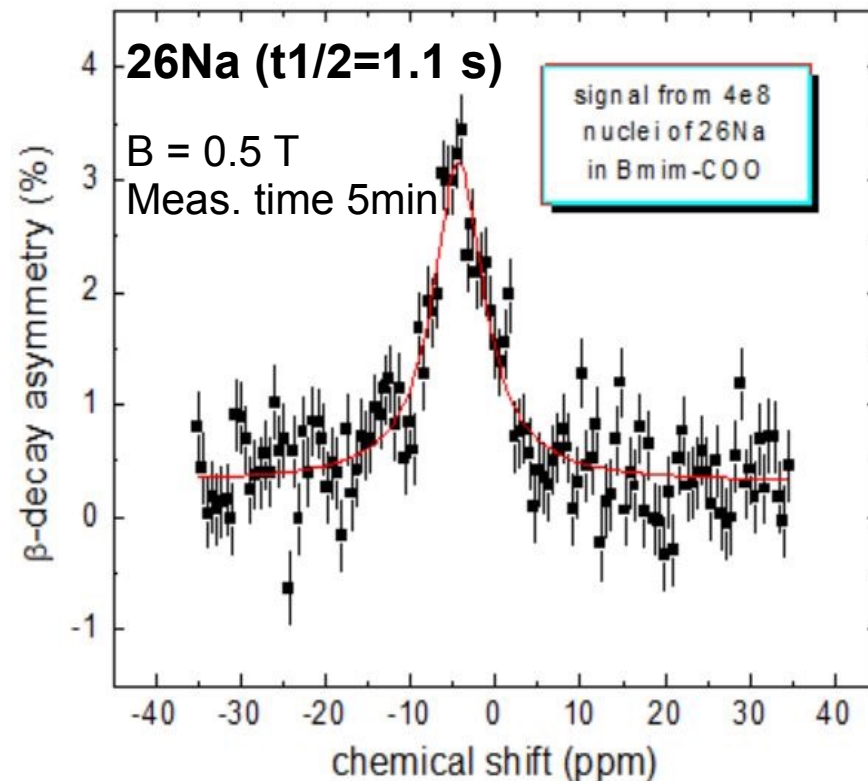
- Right concentration crucial for correct functioning of cells
- **Very important** but **not very abundant**
- Difficult to study with techniques on stable isotopes (e.g. NMR)



beta-NMR

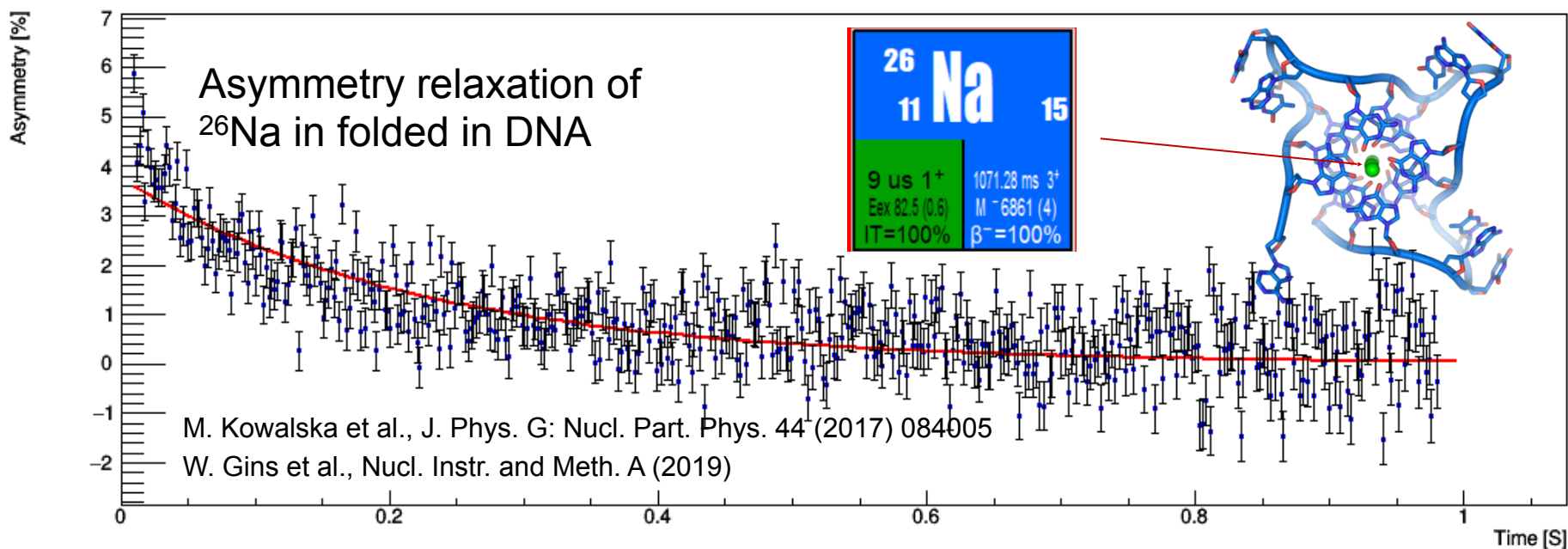
- Asymmetry in beta decay in space (due to parity non-conservation by weak interaction)
- **Up to  $10^{10}$  more sensitive than conventional NMR**
- Structure and dynamic of the interaction of metal ions with biomolecules

1<sup>st</sup> Na beta-NMR signal in a liquid





# Beta-NMR at ISOLDE





# Summary

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- ISOLDE is the world's first ISOL-type facility and is still a reference for radioactive ion beam production over 50 years later
- The upgrade of HIE-ISOLDE provides high-energy beams of up to 10 MeV/u
- ISOLDE is host to a dozen permanent experiments (and many travelling setups) studying:
  - Nuclear physics
  - Nuclear astrophysics
  - Solid state physics
  - Bio-physics
  - Fundamental physics
- The new facility MEDICIS produces radioactive isotopes dedicated to medical applications



Questions?