Unstable nuclei research

Meet ISOLDE trailer:
https://videos.cern.ch/record/2285037

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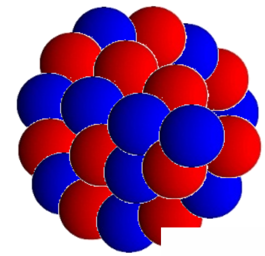
on behalf of the CERN ISOLDE team
www.cern.ch/isolde

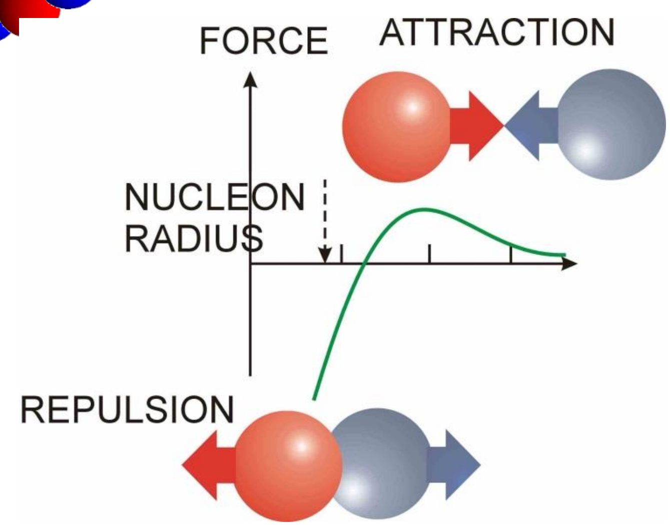
WHY:

All forces acting in (unstable) nuclei

- **Coulomb force** repels protons

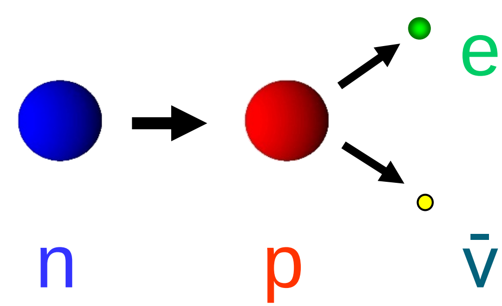


- **Strong interaction** ("nuclear force") causes binding which is stronger for proton-neutron (pn) systems than pp- or nn-systems



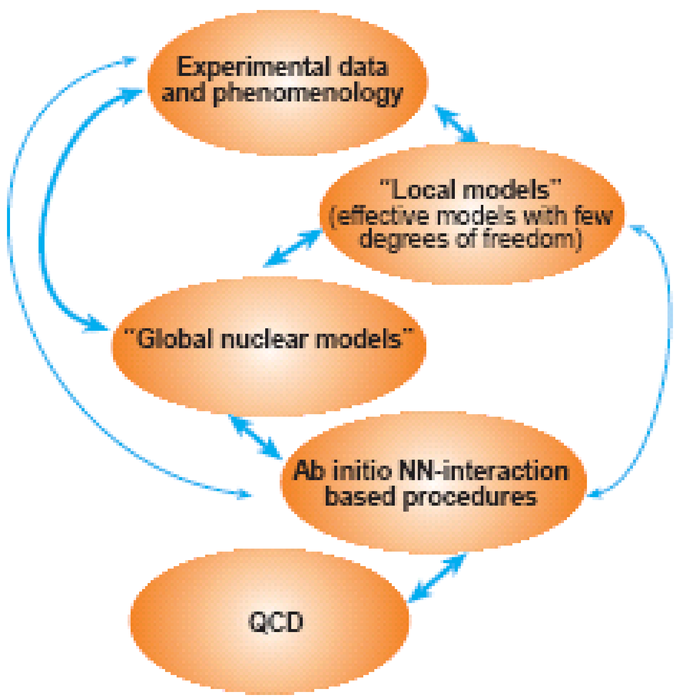
- Neutrons alone form no bound states (exception: neutron stars (**gravitation**!)

- **Weak interaction** causes β-decay



Nuclei and QCD

- Different energy scales
- In nuclei: non-perturbative QCD, so no easy way of calculating
- Have to rely on nuclear models (shell model, mean-field approaches)
- Recent progress: lattice QCD



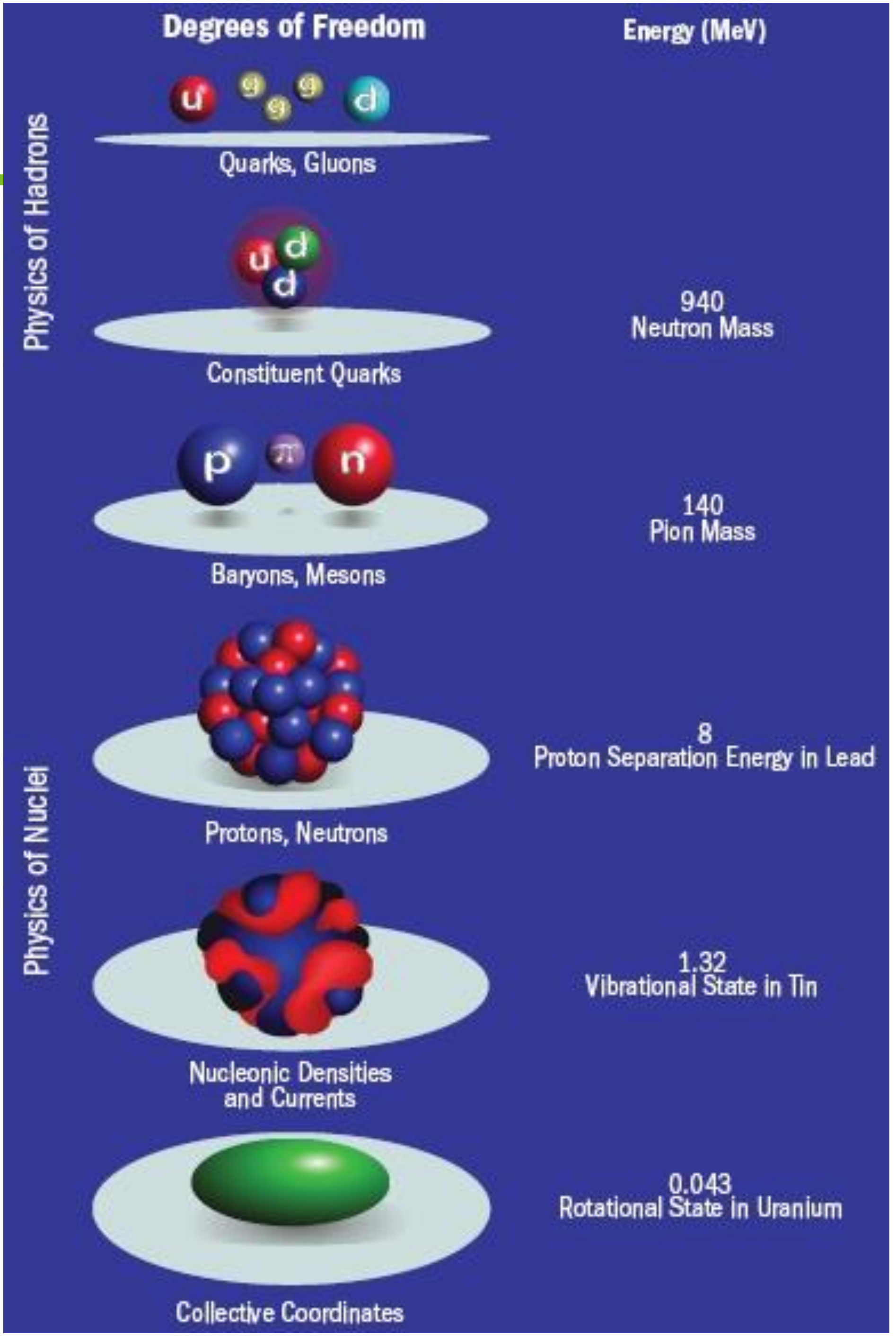
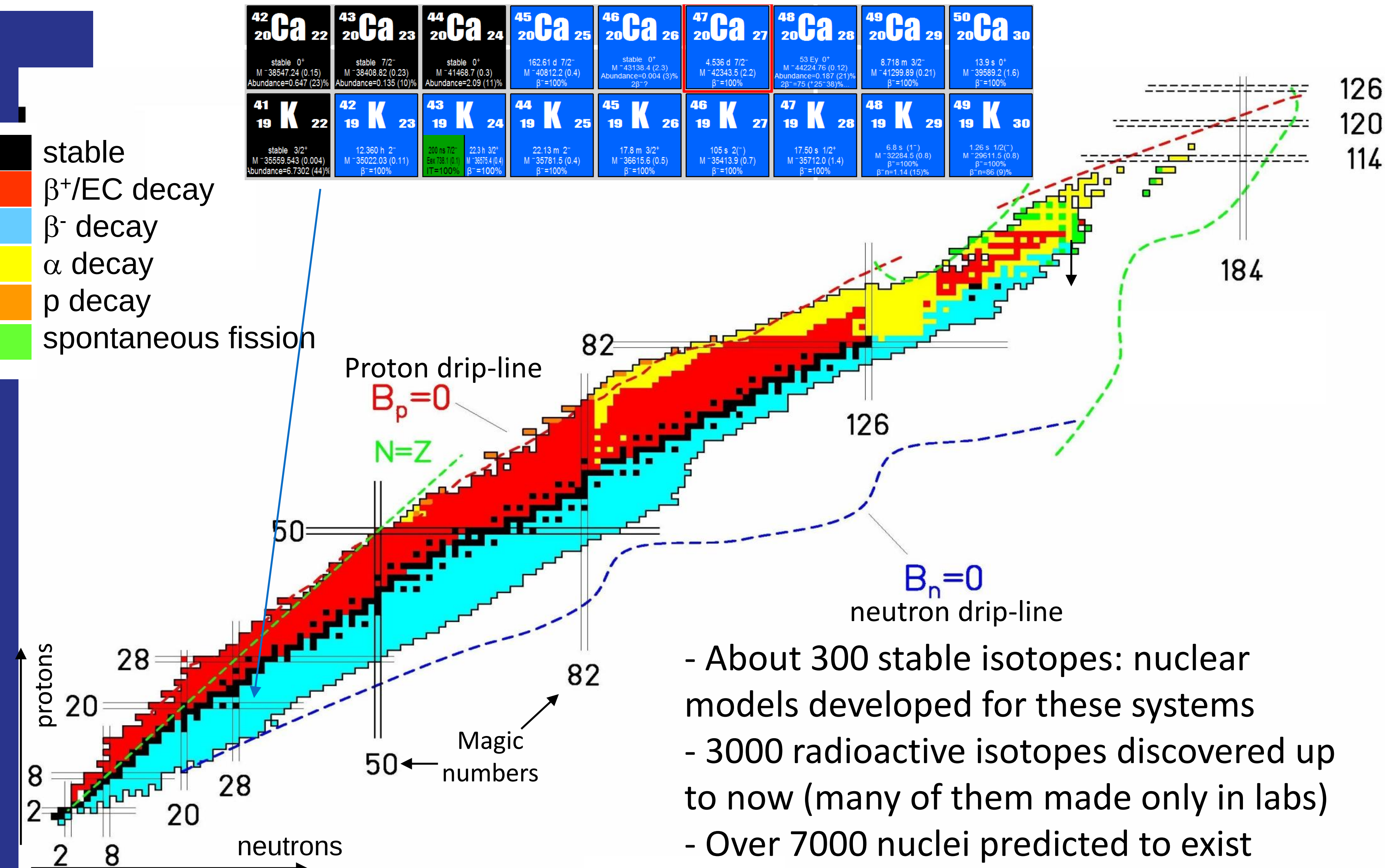


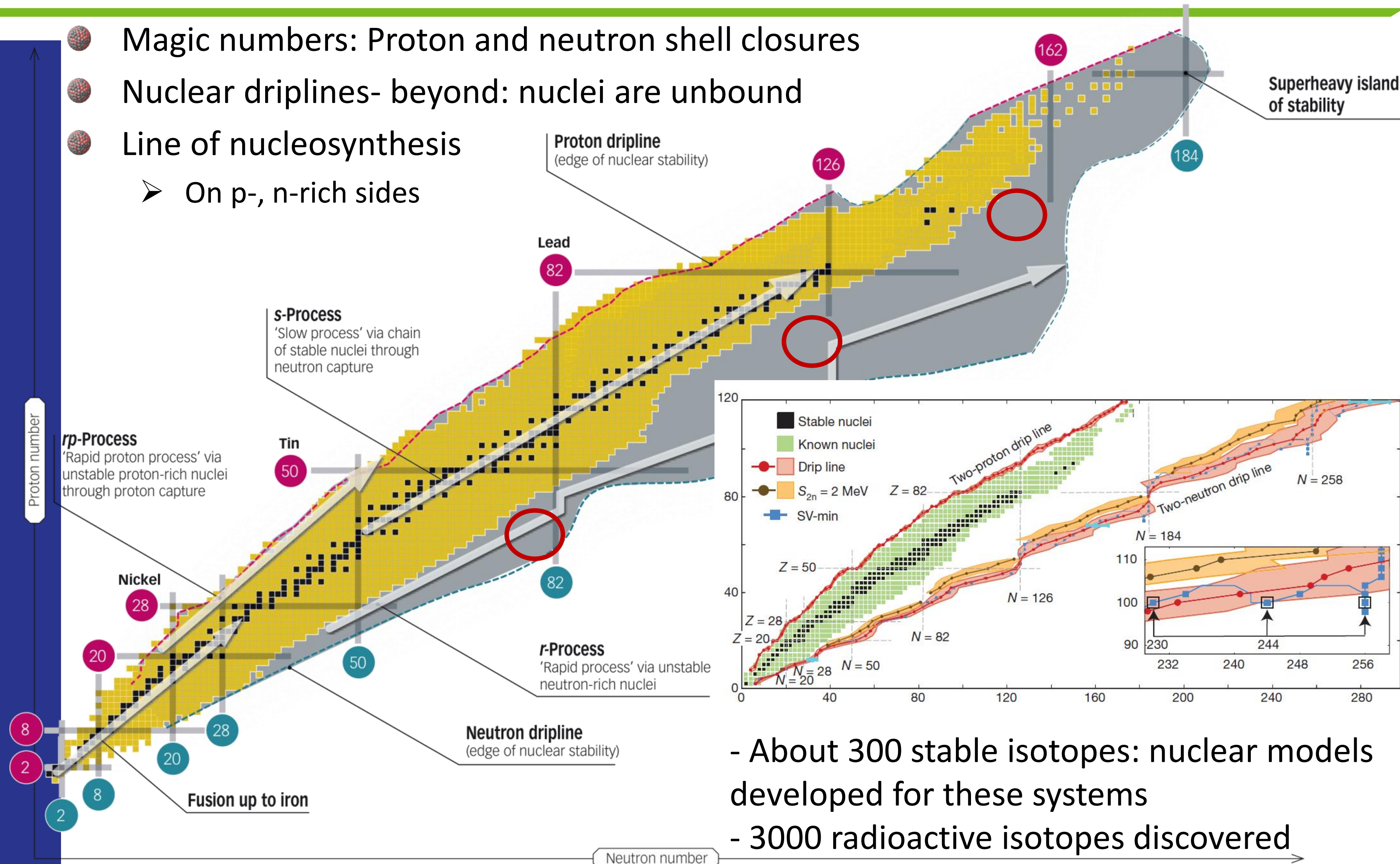
Chart of nuclei



- About 300 stable isotopes: nuclear models developed for these systems
- 3000 radioactive isotopes discovered up to now (many of them made only in labs)
- Over 7000 nuclei predicted to exist

Chart of nuclei

- Magic numbers: Proton and neutron shell closures
- Nuclear driplines- beyond: nuclei are unbound
- Line of nucleosynthesis
  - On p-, n-rich sides



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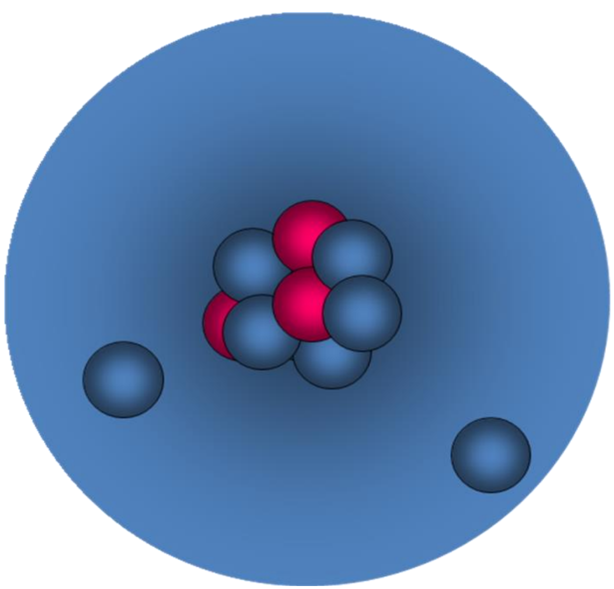
Nature **486**, 509 (2012)

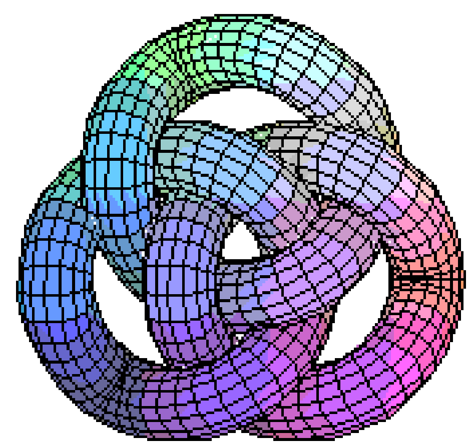
Properties of radio-nuclides

- Different neutron-to-proton ratio than stable nuclei leads to:
  - New structure properties
  - New decay modes

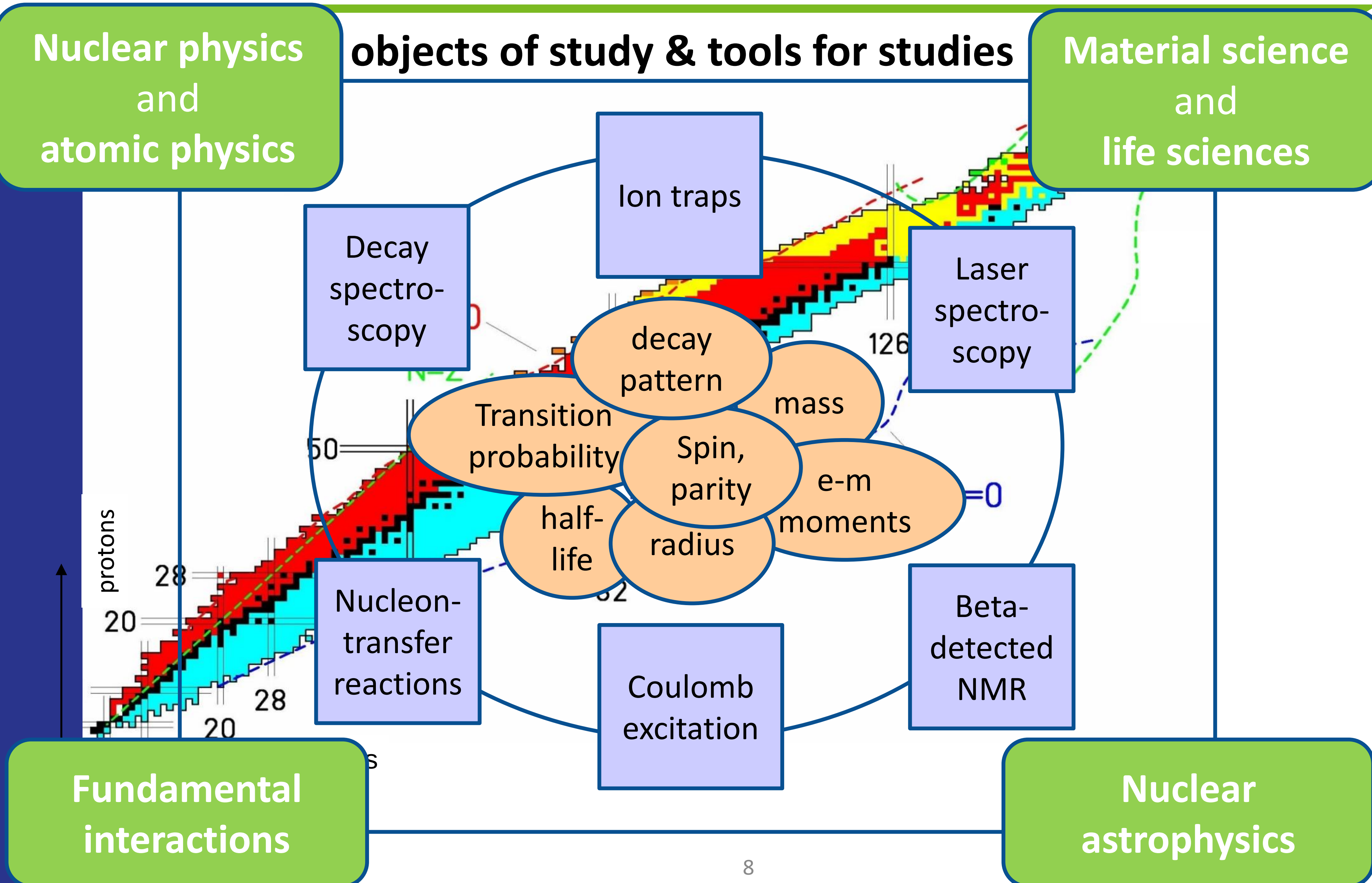
=> Nuclear models have problems predicting and even explaining the observations

- Example - halo nucleus ^{11}Li:
  - Extended neutron wave functions make ^{11}Li the size of ^{208}Pb
  - When taking away 1 neutron, the other is not bound any more (10Li is not bound)





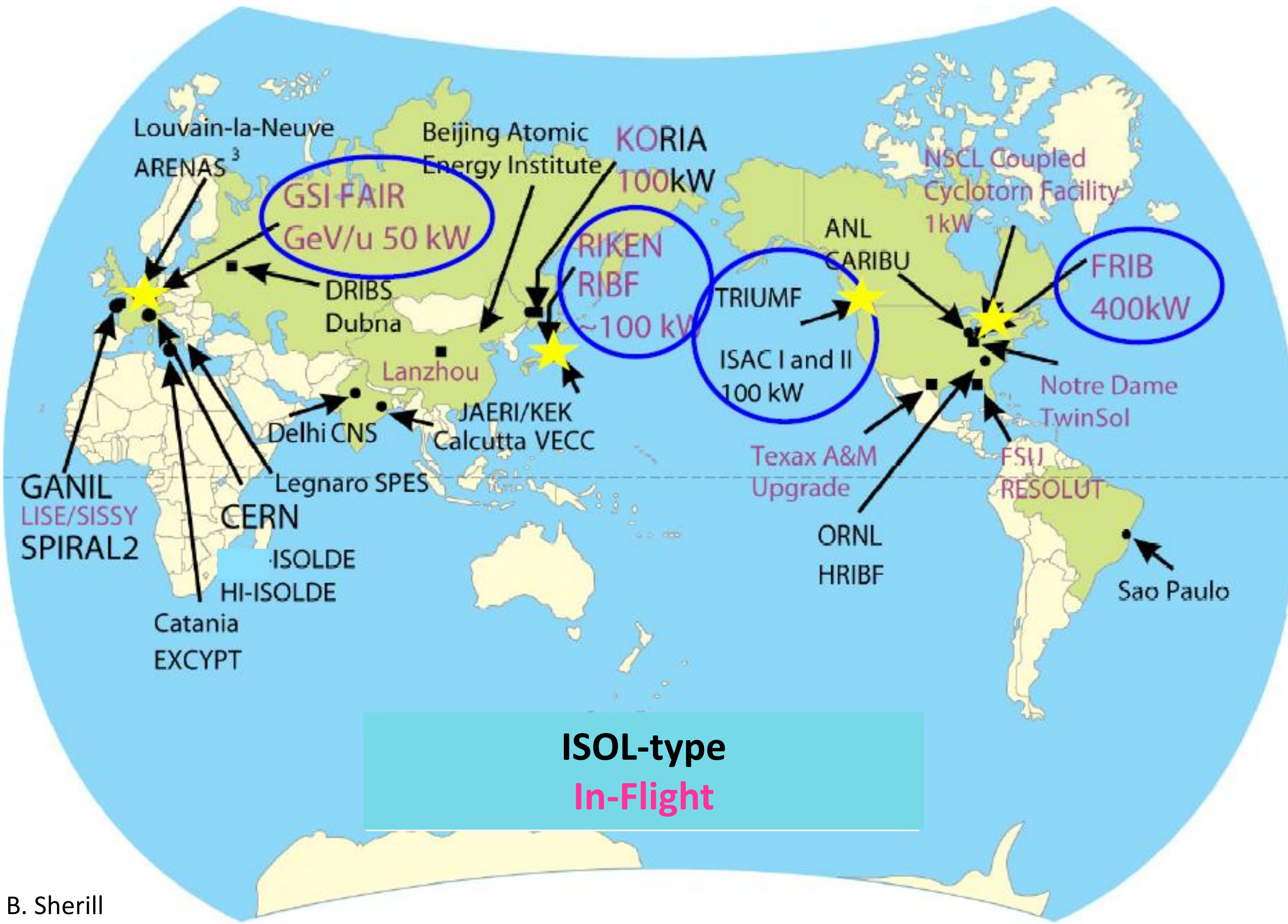
Research topics using unstable nuclei



WHERE

Radioactive Ion Beam facilities

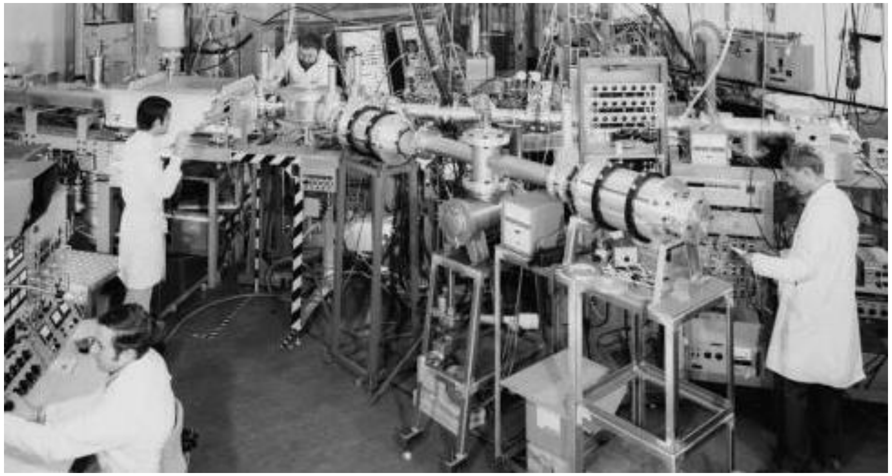
- Existing and in preparation



After B. Sherill

ISOLDE at CERN

- Isotope Separator OnLine DEvice
- First ISOL facility worldwide!
- Produces Radioactive Ion Beams (RIBs)
- Approved by the CERN council in 1964
  - 1st used 600 MeV protons from SC
  - Then used 1.0 GeV (later 1.4 GeV) protons from the PSB

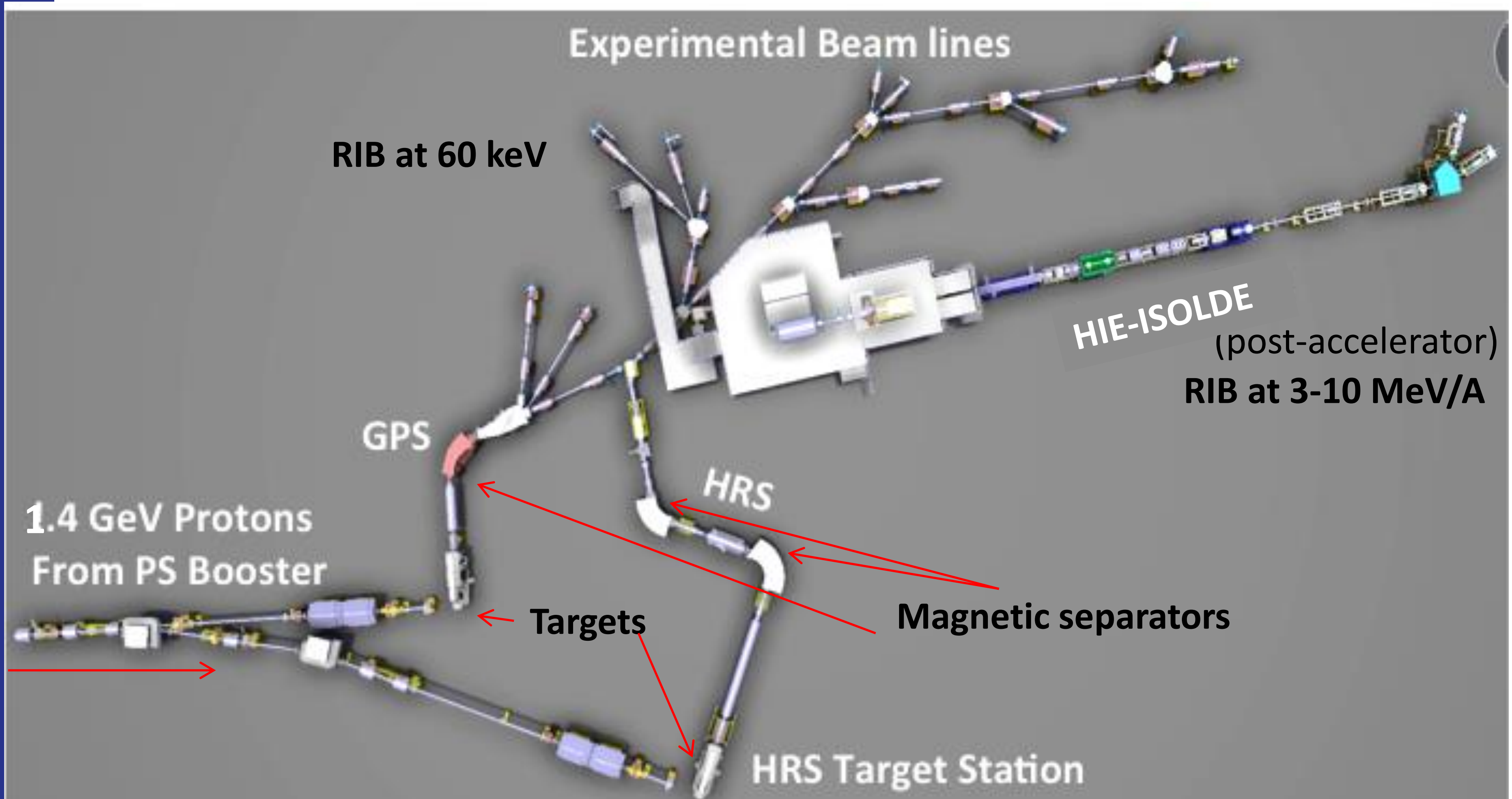


- A small facility with a big impact!
  - 0.1% of CERN budget
  - 7% of CERN scientists
  - 50% of CERN proton pulses
  - 80% of CERN protons

http://timeline.web.cern.ch/timelines/ISOLDE

ISOLDE elements

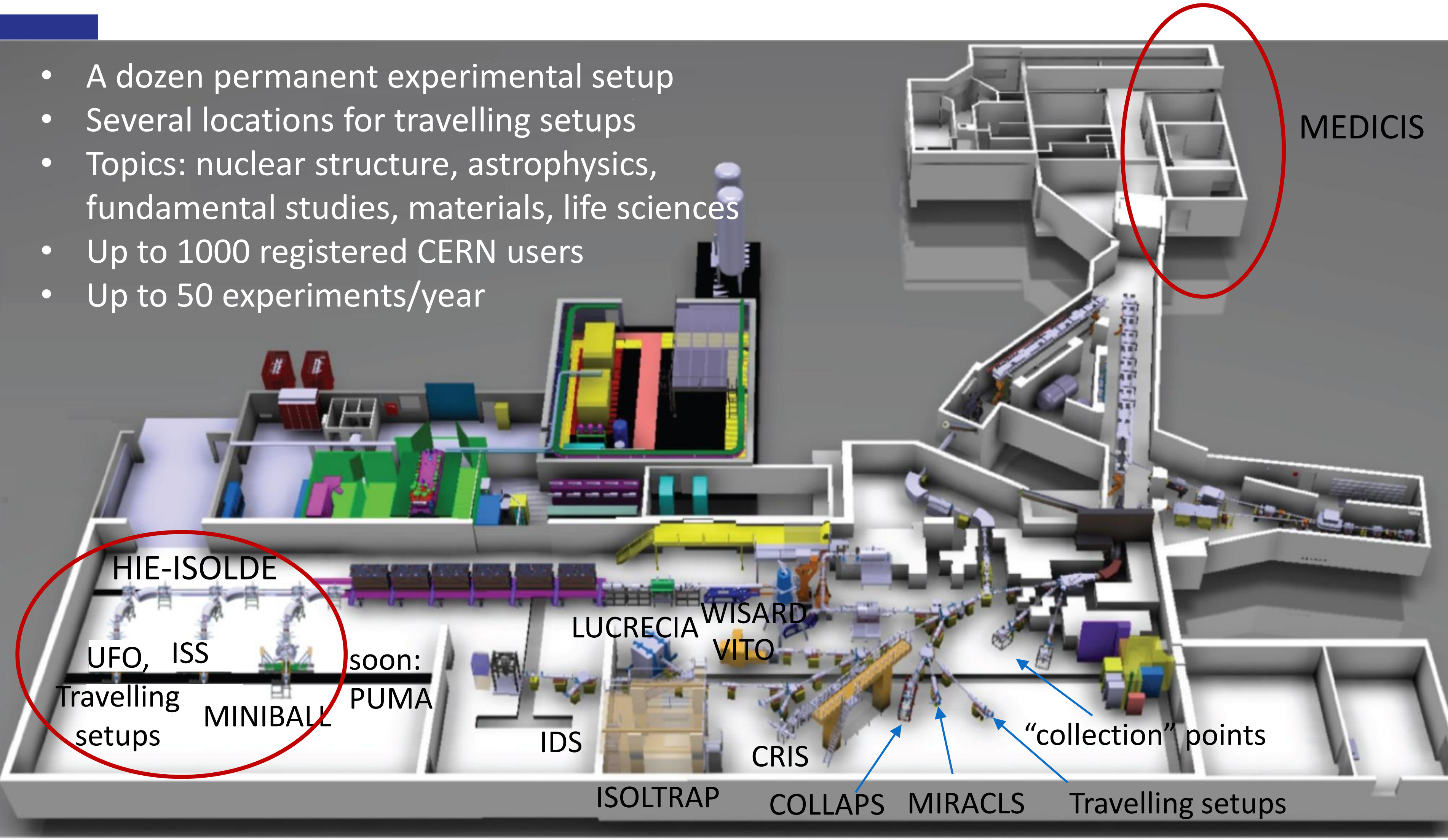
Isotope production via reactions of light beam with thick and heavy target



Production – ionization – separation

ISOLDE experimental setups

- A dozen permanent experimental setup
- Several locations for travelling setups
- Topics: nuclear structure, astrophysics, fundamental studies, materials, life sciences
- Up to 1000 registered CERN users
- Up to 50 experiments/year



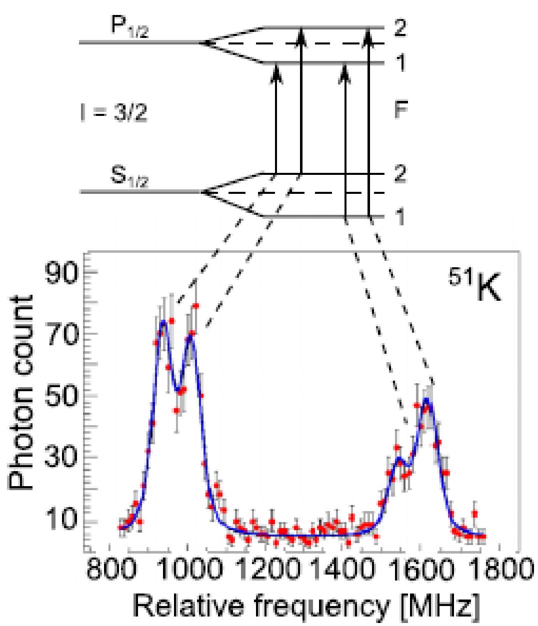
Laser spectroscopy and nuclear properties

Lasers allow studying **ground-state (and isomeric) properties of nuclei,** based on:

Atomic **hyperfine structure (HFS)**

(interaction of nuclear and atomic spins)

- HFS details depend on:
  - Spin -> orbit of last proton&neutron
  - Magnetic dipole moment -> orbits occupied by protons&neutrons
  - Electric quadrupole moment -> deformations



Yordanov et al, Phys. Rev. Lett., 110, 172503 (2013)

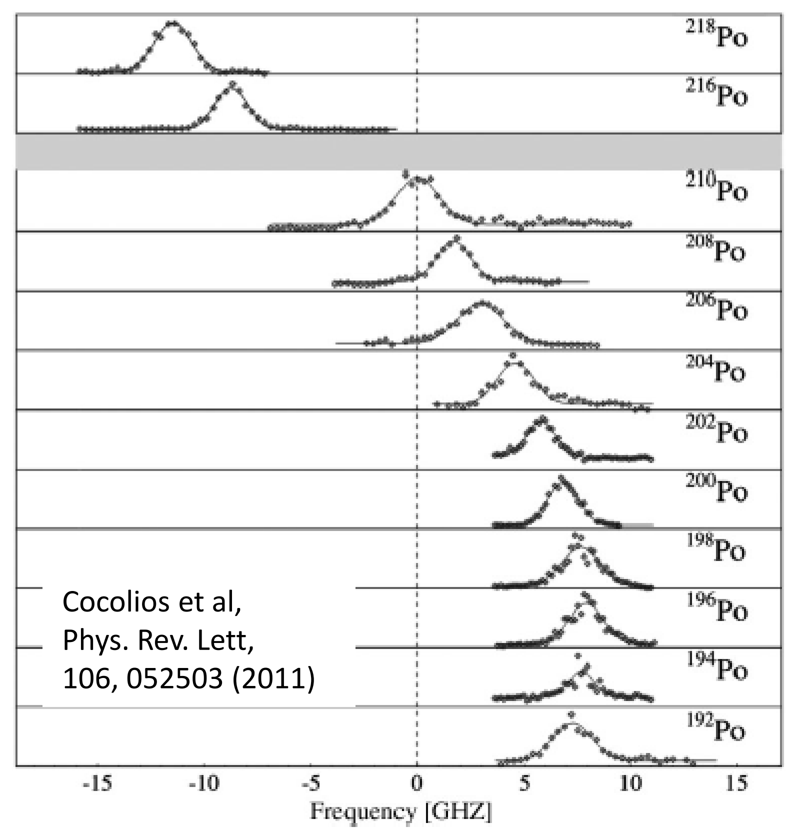
Setups:

COLLAPS
CRIS
MIRACLS
VITO

Isotope shifts (IS) in atomic transitions

(change in mass and size of different isotopes of the same chemical element)

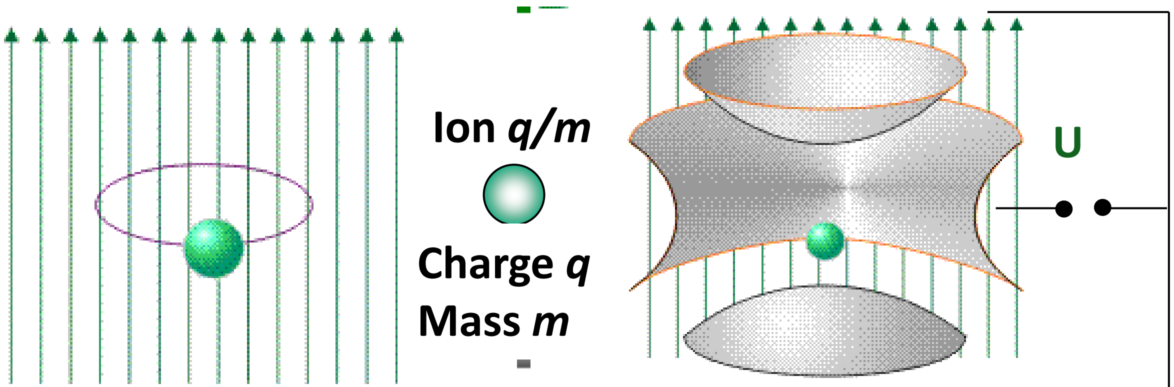
- IS between 2 isotopes depends on:
  - difference in their masses & charge radii



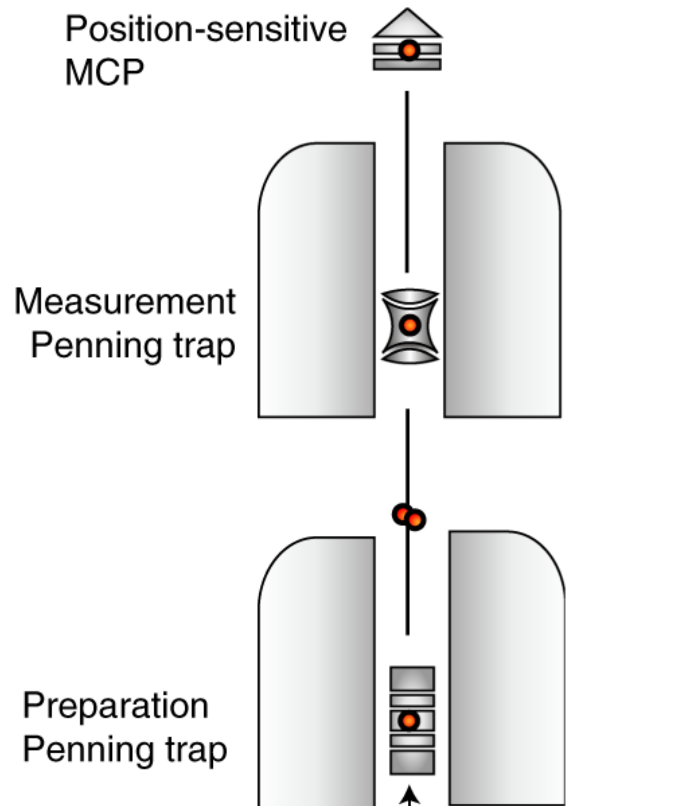
Cocolios et al, Phys. Rev. Lett, 106, 052503 (2011)

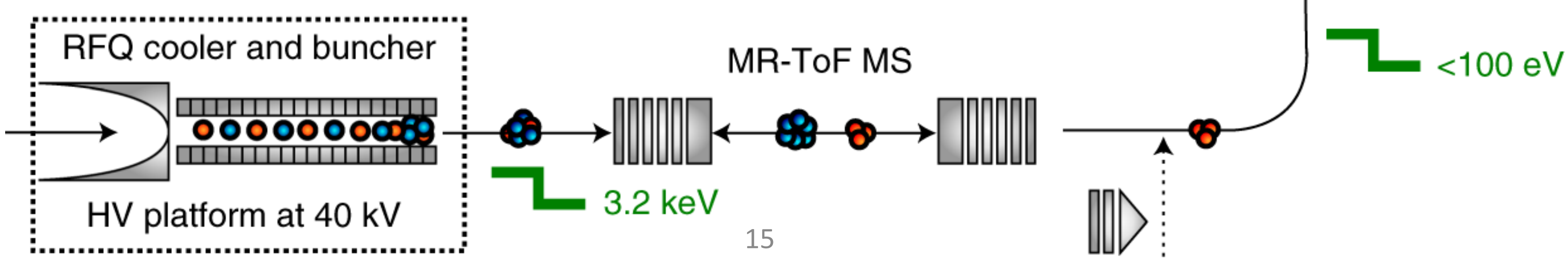
Penning-trap mass spectrometry

- Penning trap
  - superposition of static magnetic and electric field
  - Ion manipulation with radiofrequencies



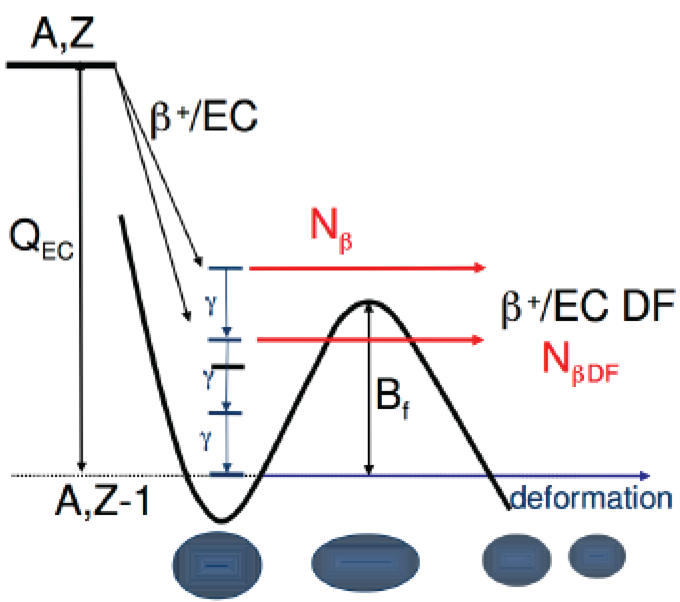
$$\omega_c = qB/m$$





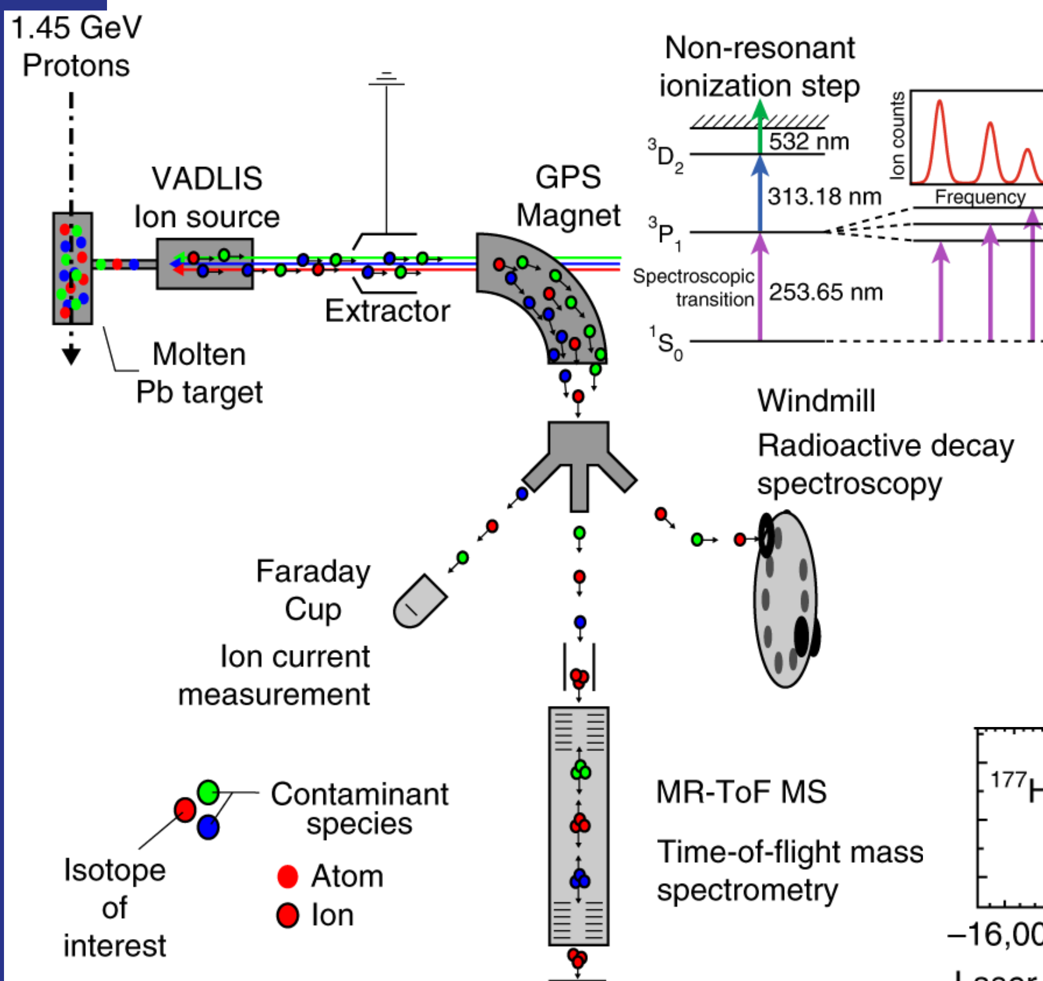
Decay spectroscopy

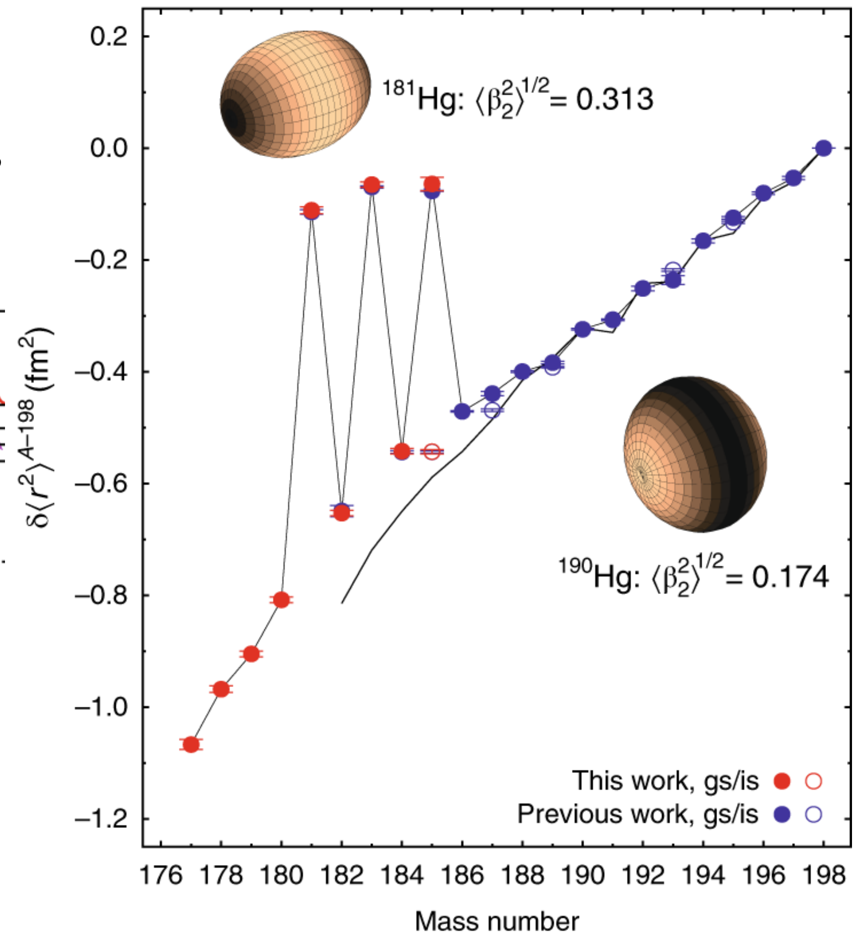
- Different detectors to sensitive to emitted:
  - Alpha particles
  - Beta particles
  - Gamma rays
  - Protons or neutrons
- Isolde Decay Station
- Polarised beams at VITO setup

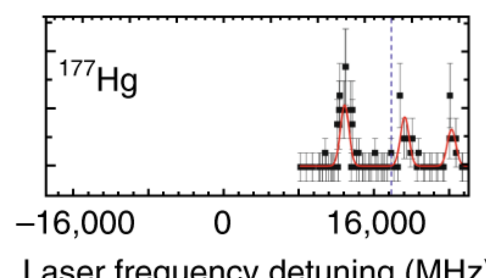


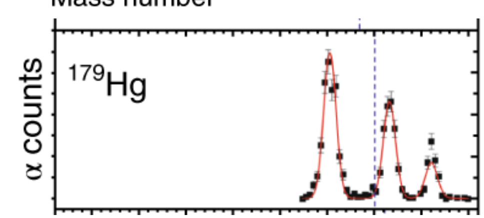
Synergies: lasers, traps, decays

- Laser spectroscopy, mass spectrometry, decay spectroscopy
- Extreme shape changes in mercury isotopes



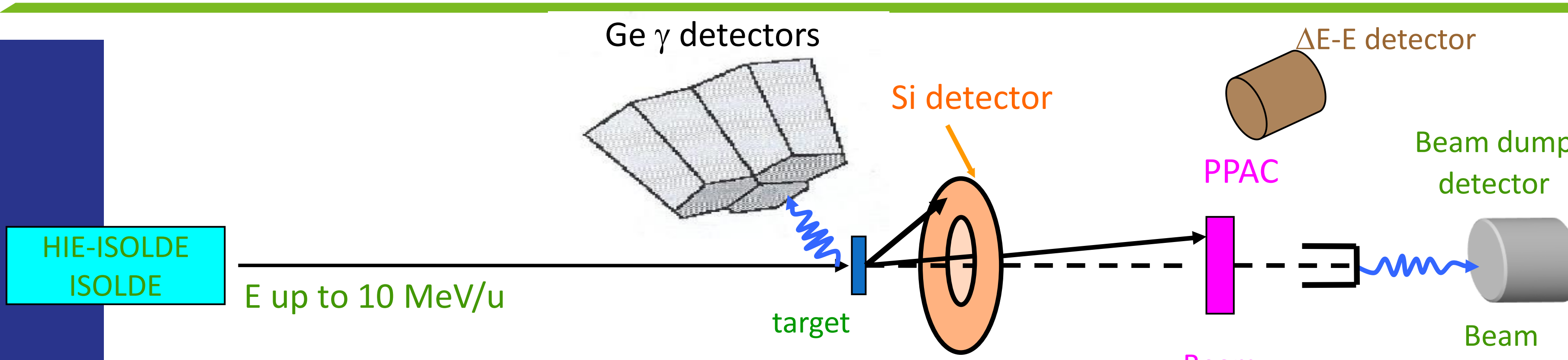




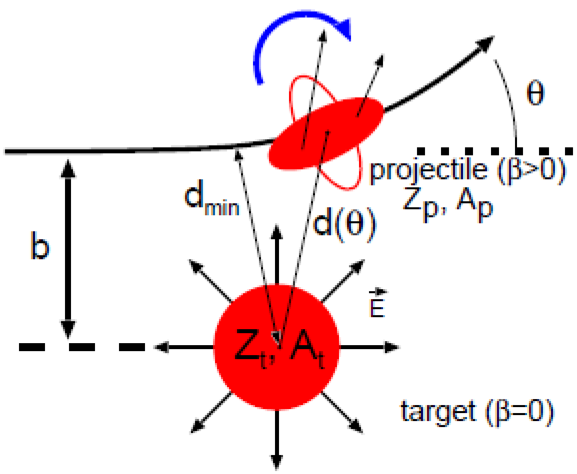


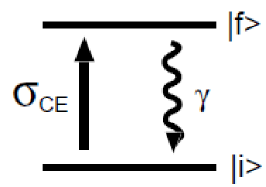
Nature Physics **14**, 1163 (2018)

Coulomb excitation



Excitation of a projectile nucleus (radioactive) by the electromagnetic field of the target (made of stable nuclei)



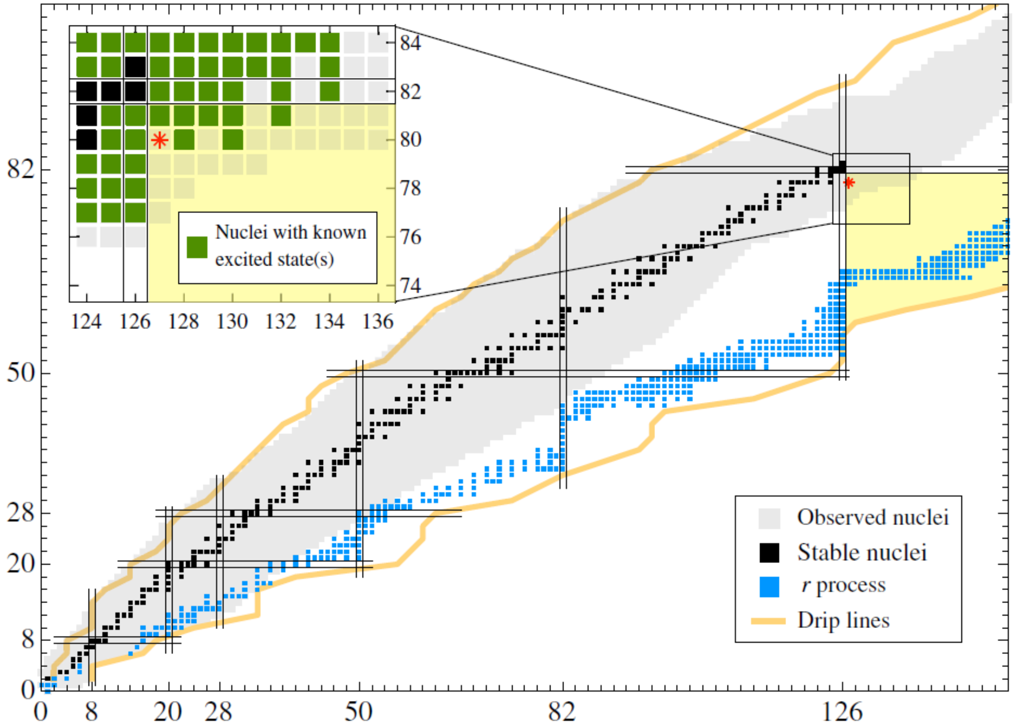


MINIBALL setup

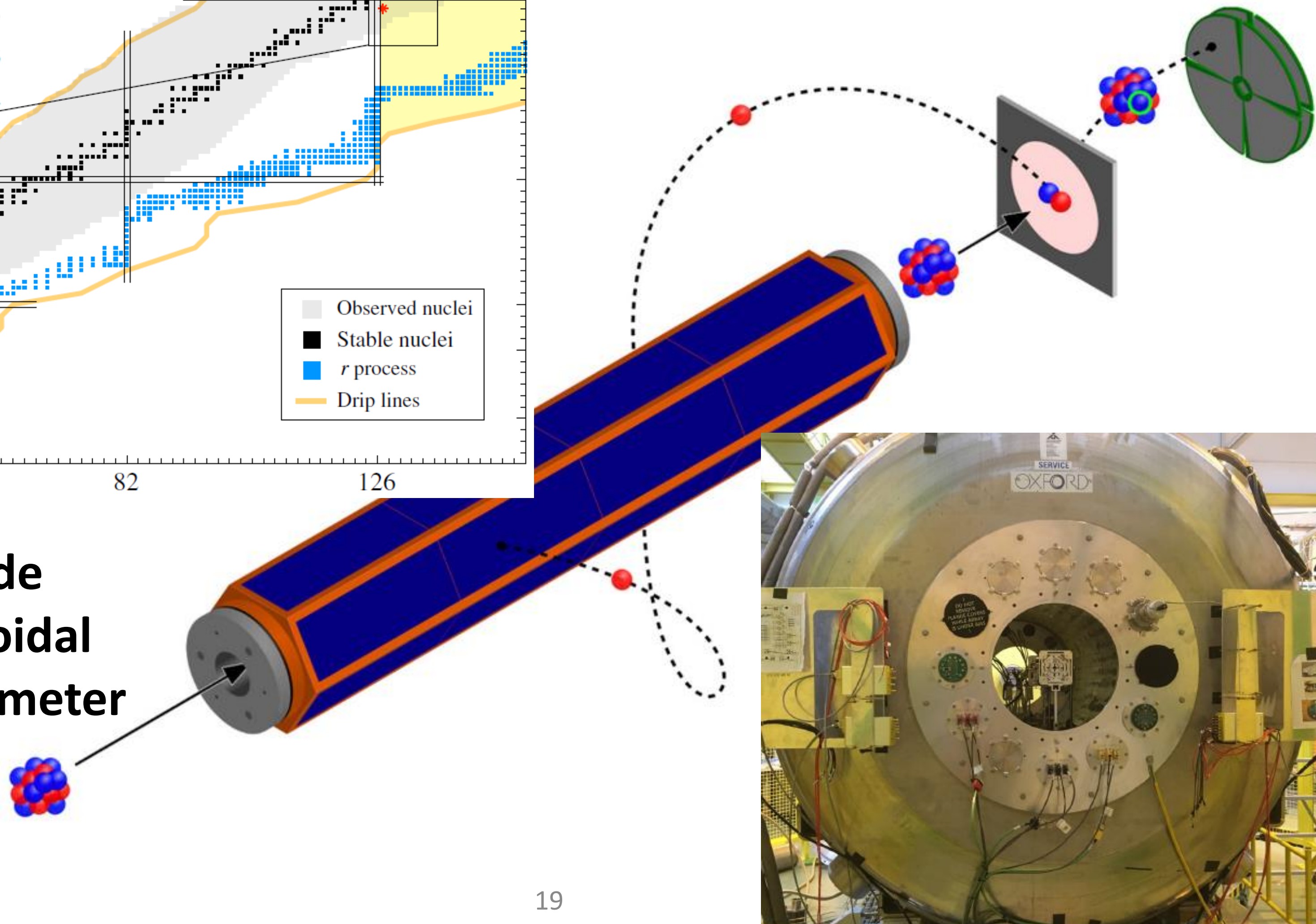
Observables: Transition energies and intensities

=> Find new excited levels and study deformations

Nuclear astrophysics at HIE-ISOLDE



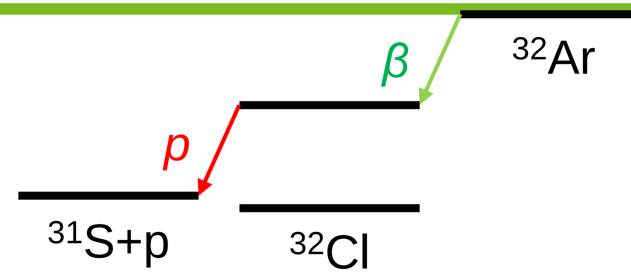
neutron excitations in ^{207}Hg by neutron-adding (d,p) reaction in inverse kinematics

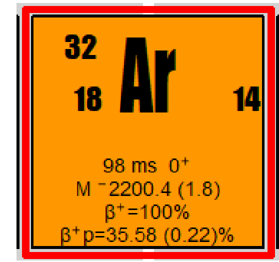


Isolde Solenoidal Spectrometer

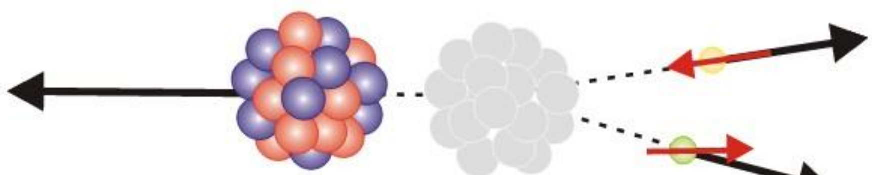
Scalar currents with ^{32}Ar

- Aim: search for scalar current contribution in predominantly vector current of β decay via β–ν correlation



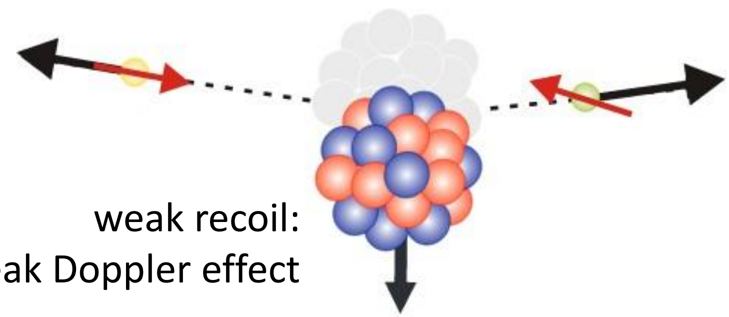


Vector current



strong recoil:
strong Doppler effect

Scalar current

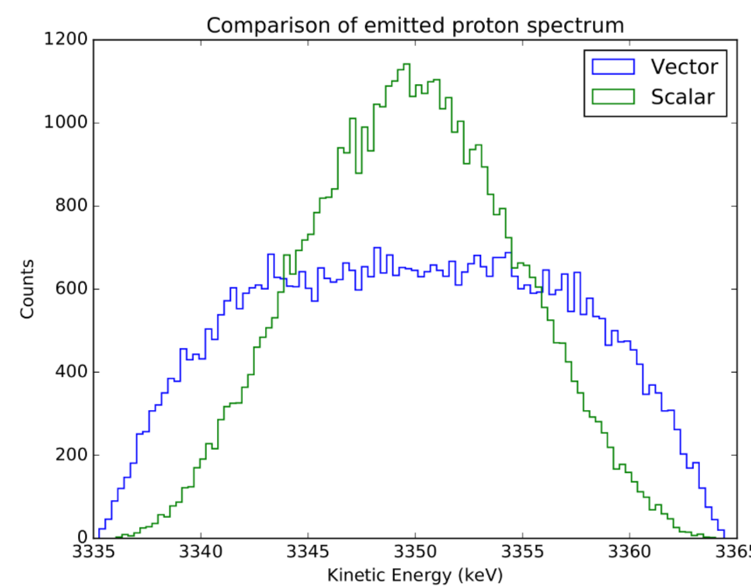


weak recoil:
weak Doppler effect

WISARD experiment

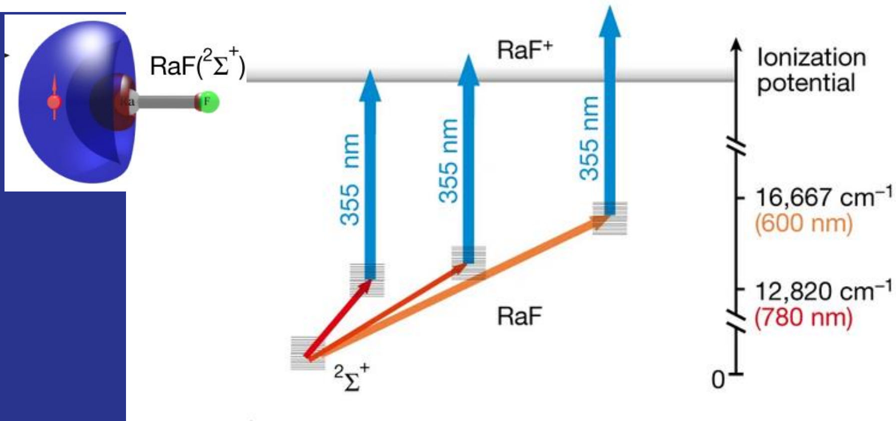
- Tool: β-delayed p decay of ^{32}Ar, Doppler effect on proton energy

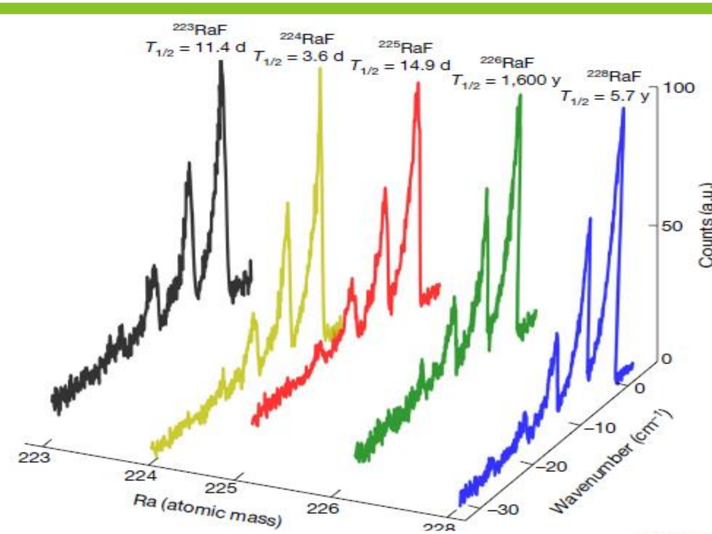
- Present limits on scalar current from βν correlation $a_F = 0.65\%$

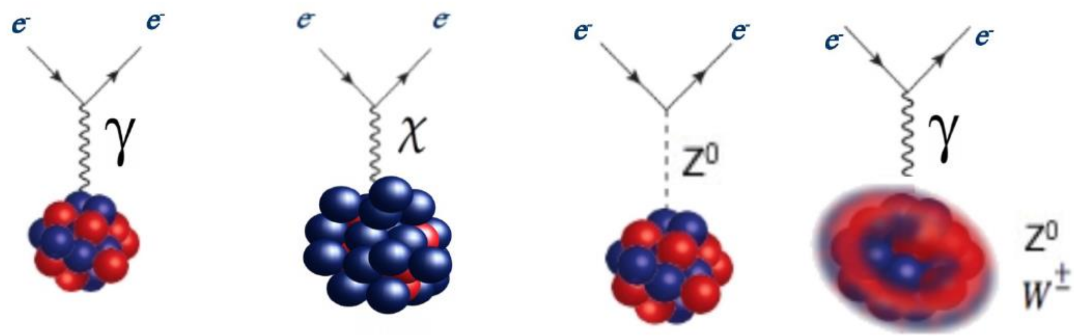


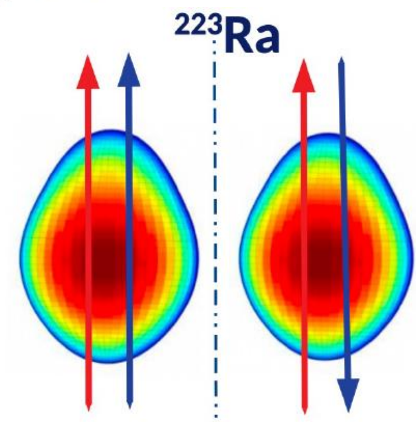
L. Hayen CRADLE++ (https://github.com/leenderthayen/CRADLE)

Radioactive molecules & Beyond SM









Low-energy SM tests New e-N interactions? P-violation T-violation

- Nuclear matter
- Nuclear structure
- BSM searches

- Dark Matter properties?
- New forces?

- Baryogenesis

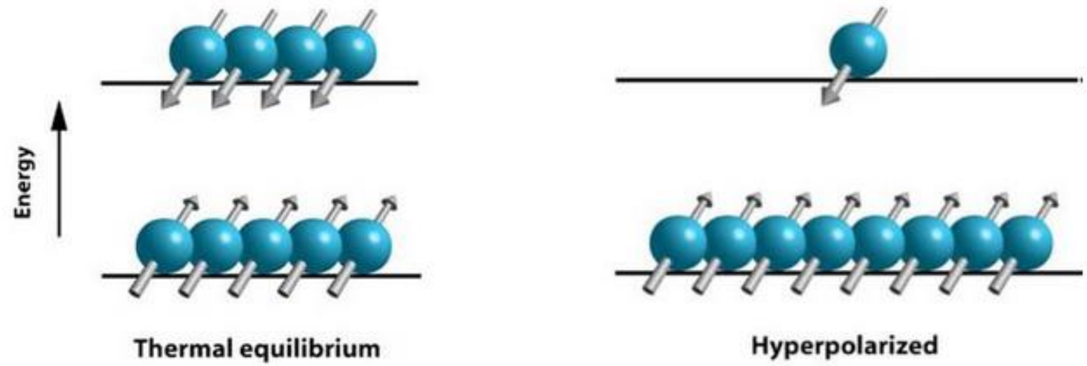
***Nature* 581, 396 (2020)**

From M. Udrescu

Beta-NMR in organic samples

Unstable probe nuclei with spin > 0 in magnetic field

Spin hyperpolarisation

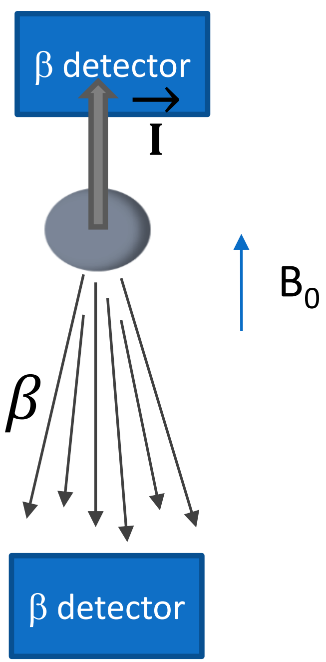


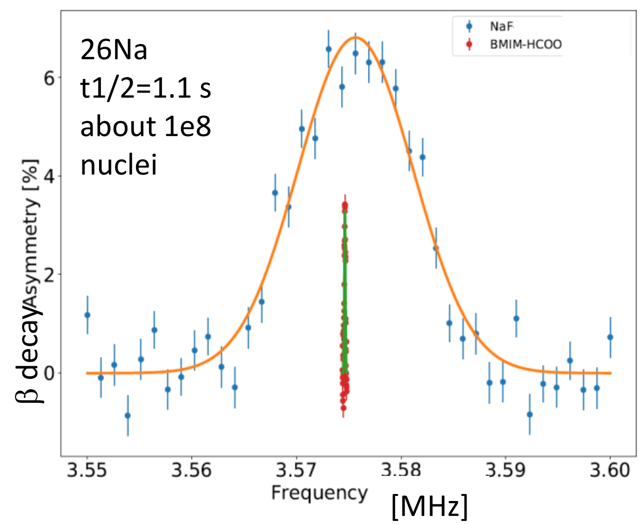
$P \approx 10^{-5} = \frac{1}{100{,}000}$ at 3T

$P \approx 50\% = \frac{50{,}000}{100{,}000}$

+ beta decay anisotropy

Beta decay, I>0





Up to 10 orders of magnitude more sensitive than conventional NMR,

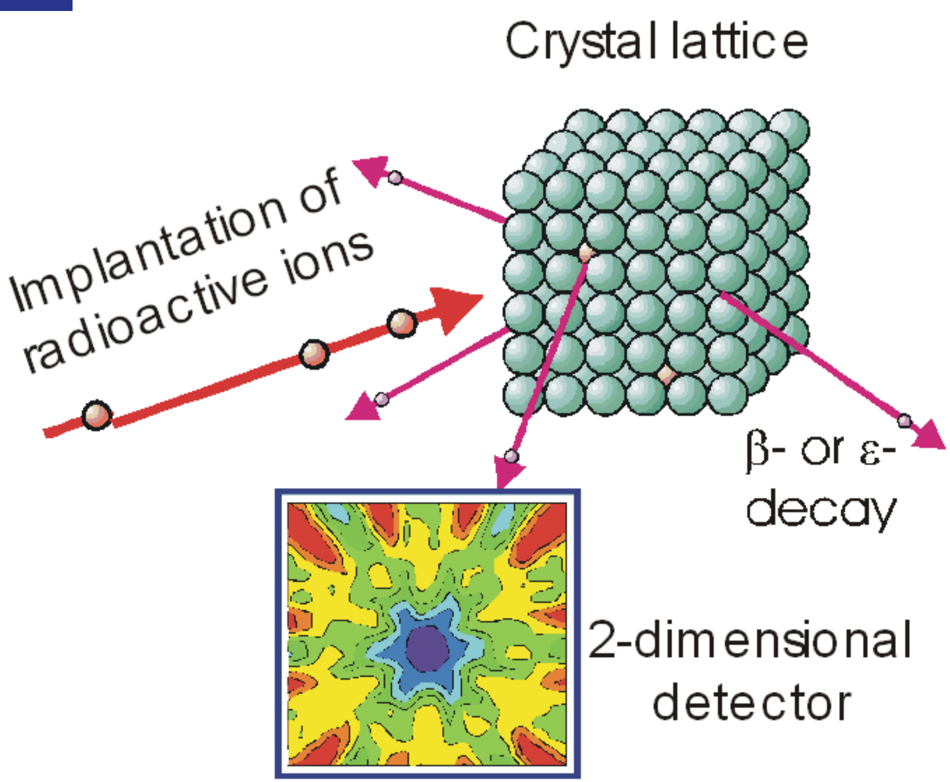
100 x more precise than solid state NMR

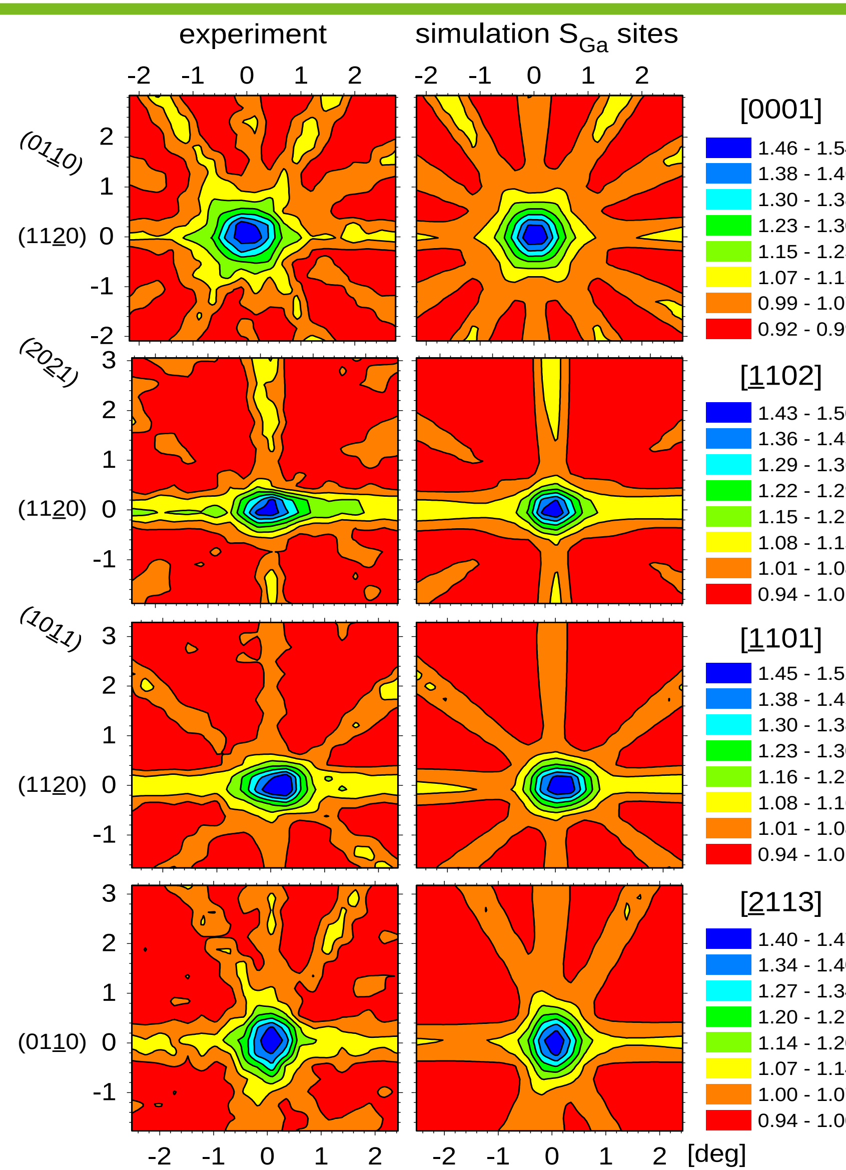
Phys. Rev. X 10, 041061 (2020)

Applications in biology (metal ion interactions)
And nuclear physics: distribution of magnetisation

Material science

- Emission channeling
  - Position of implanted ions

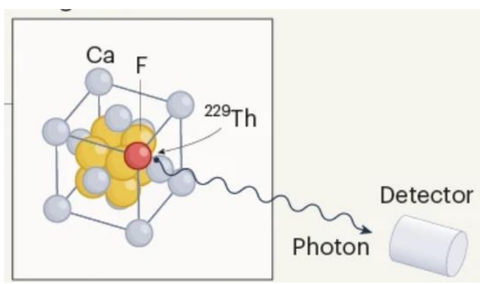


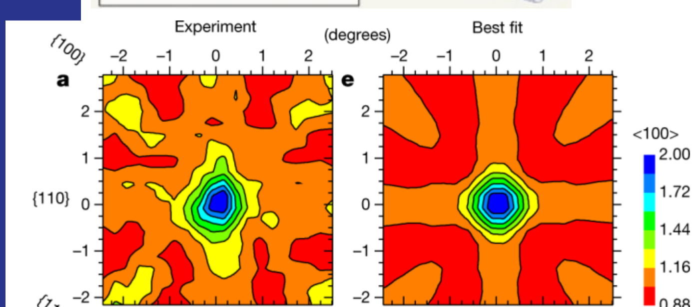


Emission channelling pattern

^{229m}Th: towards a nuclear clock

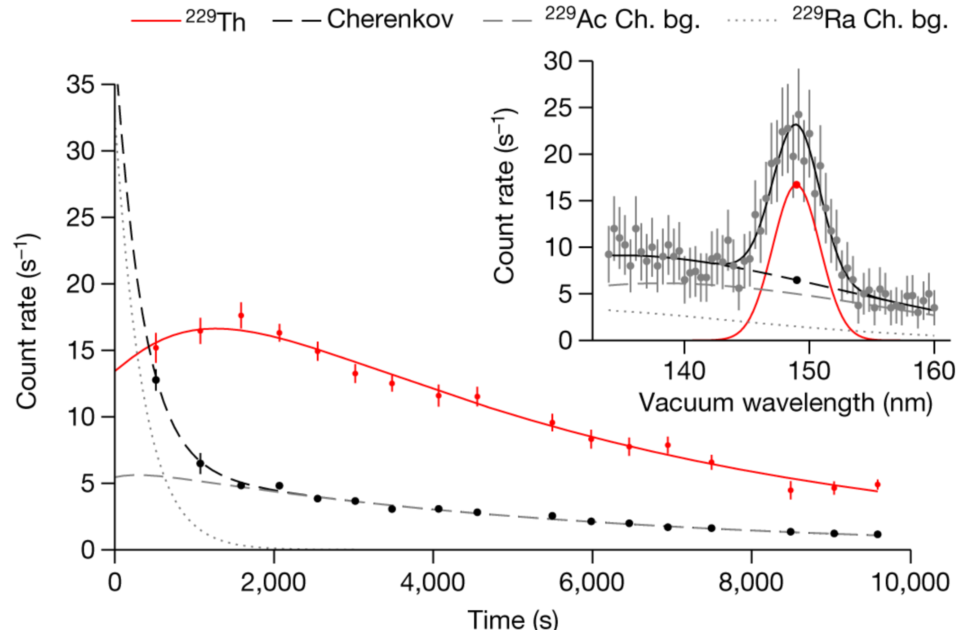
- Determination of isomer energy with vacuum UV spectroscopy:
  - 229Ac decay to 229mTh
  - Internal conversion decay branch removed via study in a crystal
  - CaF as host (wide band gap material)
- Implantation site verified with emission channeling

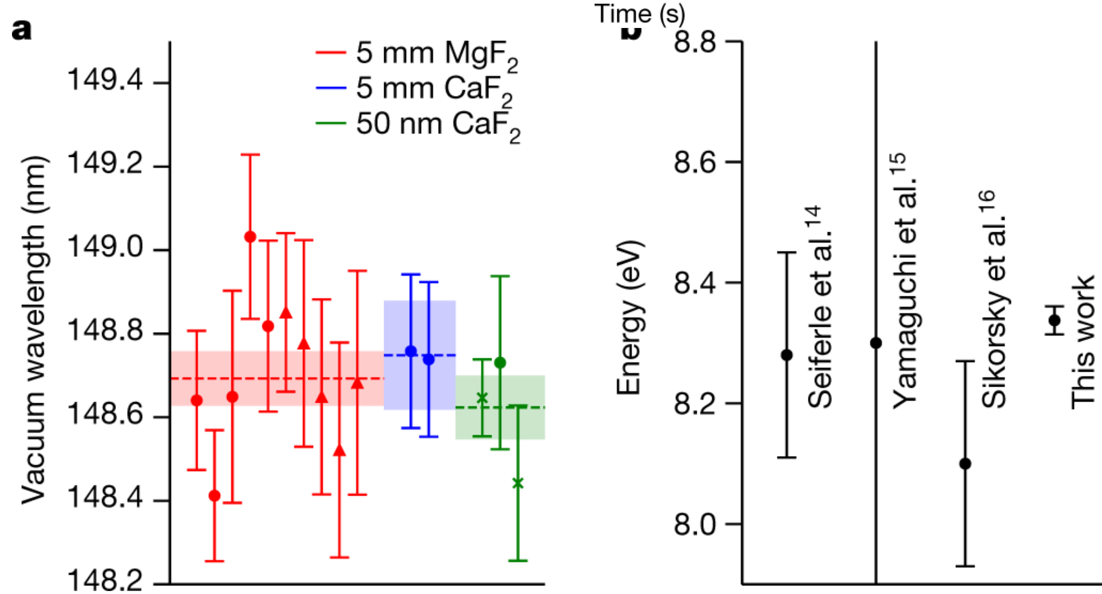




S Kraemer et al, *Nature* **617**, 706 (2023)

Video: https://videos.cern.ch/record/2297990





New medical isotopes

Collection at ISOLDE

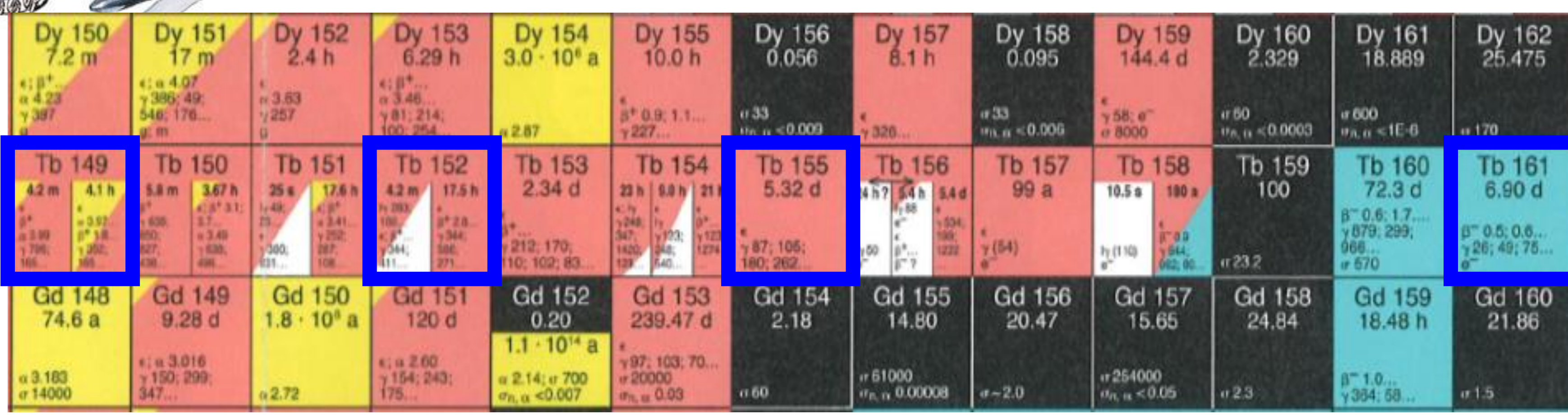
Radiochemical purification and labeling

Injection into mouse

PET/SPECT imaging and tumor treatment

- Theranostics = therapy and diagnostics together
  - Production of isotopes at ISOLDE
  - Chemical selection and mice treatment in PSI

- Also at ISOLDE-Medicis



After U. Koster, C Müller et al. 2012 J. Nucl. Med. 53, 1951

Summary

- Research topics with radionuclides:
  - Nuclear and atomic physics
  - Astrophysics
  - Fundamental studies
  - Applications

- Studied properties:
  - mass, radius, spin, moments, half-life, decay pattern, transition probabilities

- Examples of ISOLDE experimental techniques
  - Laser spectroscopy
  - Ion traps
  - Decay spectroscopy
  - Coulomb excitation
  - Nucleon-transfer reactions

- Applications
  - Material science
  - Life sciences: bio- and medical