Physics opportunities with atomic physics techniques

to probe nuclear ground-state properties

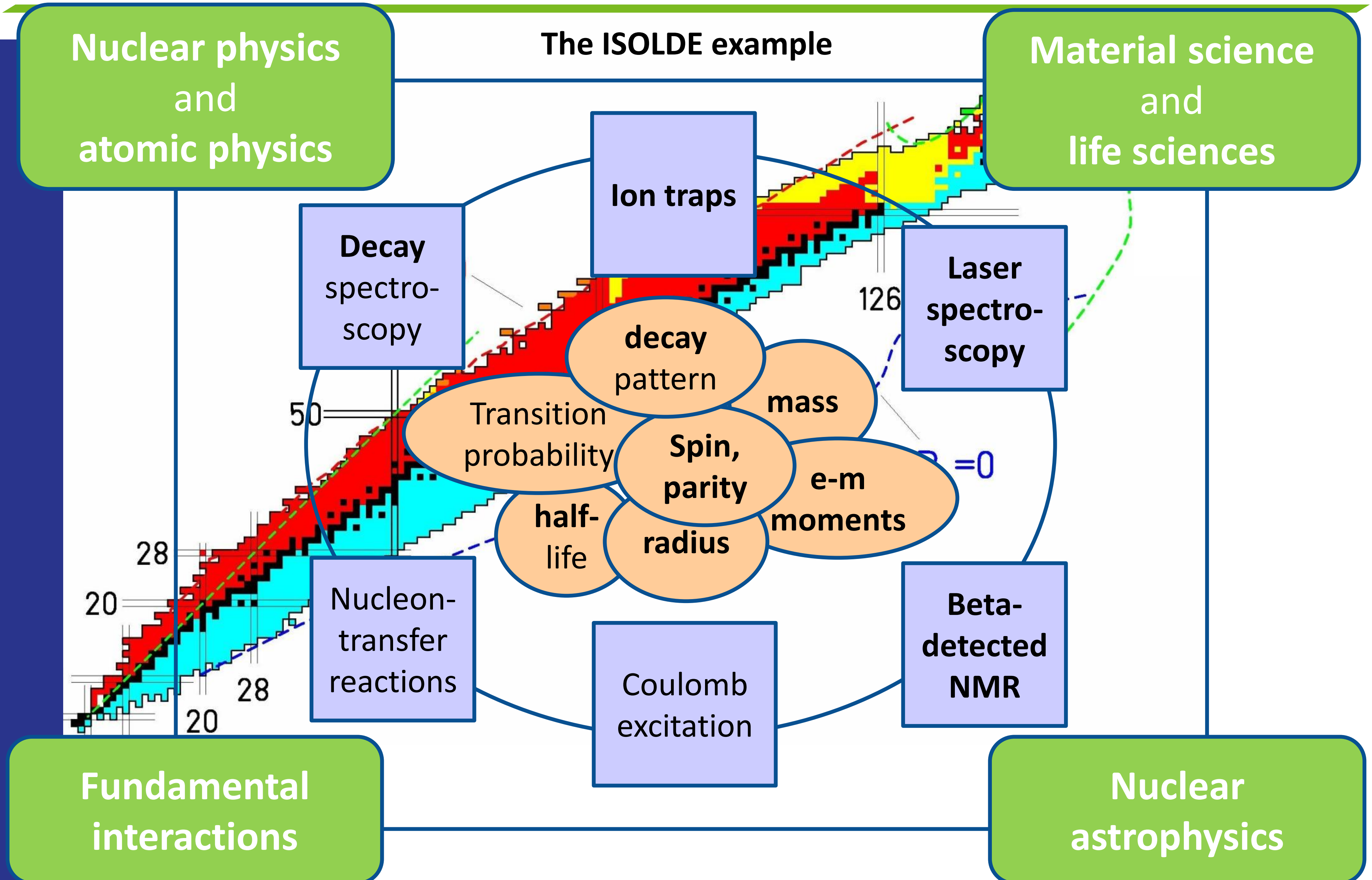
and not only …

Magdalena Kowalska
ISOLDE Physics Coordinator

Outline

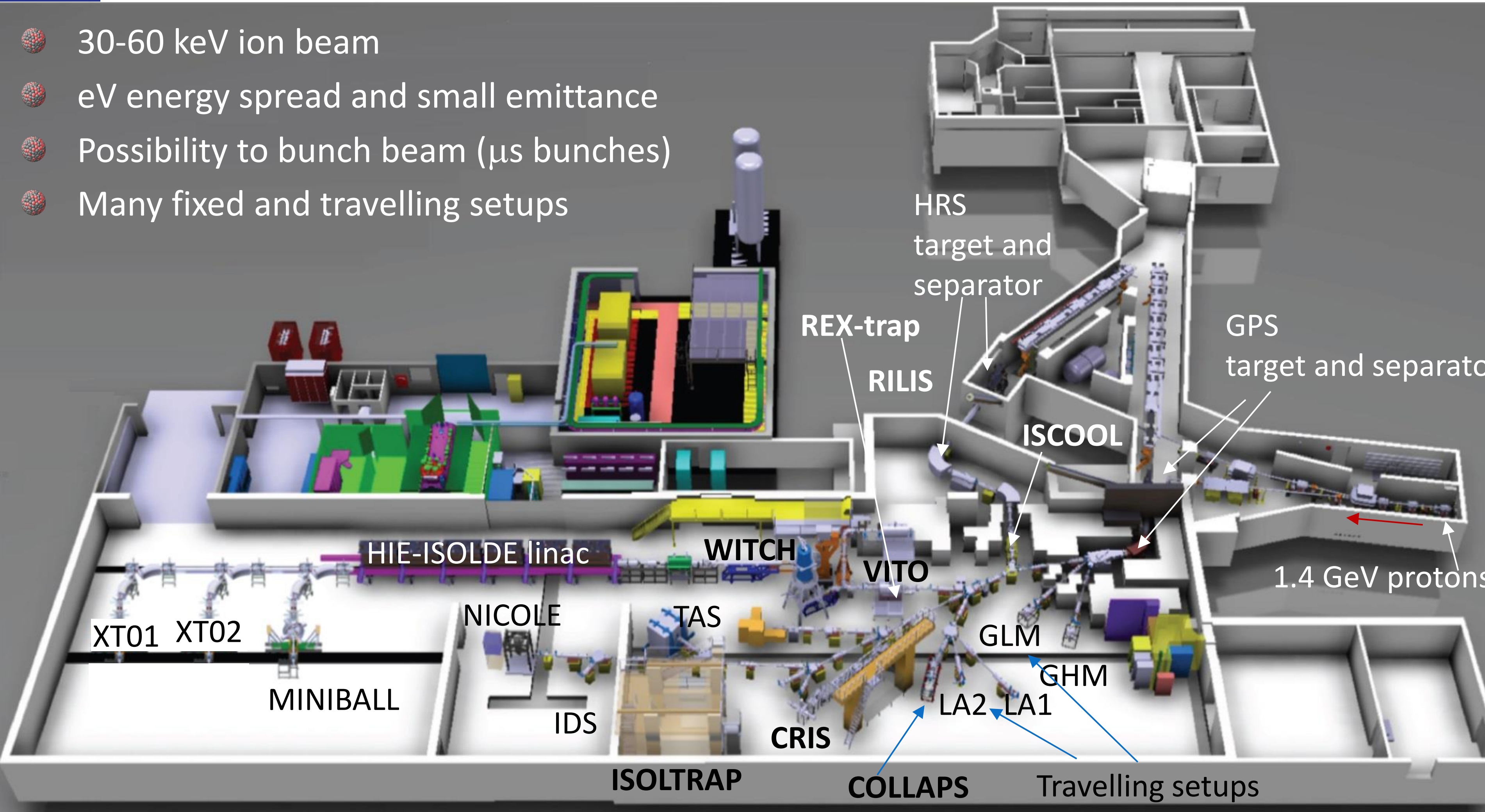
- Atomic physics techniques to study radionuclides (at ISOLDE and elsewhere)
- Laser spectroscopy, polarization and beta-NMR
- Ion traps
- New applications
- Summary and outlook

RIB physics and techniques



ISOLDE & atomic physics techniques

- 30-60 keV ion beam
- eV energy spread and small emittance
- Possibility to bunch beam (μs bunches)
- Many fixed and travelling setups

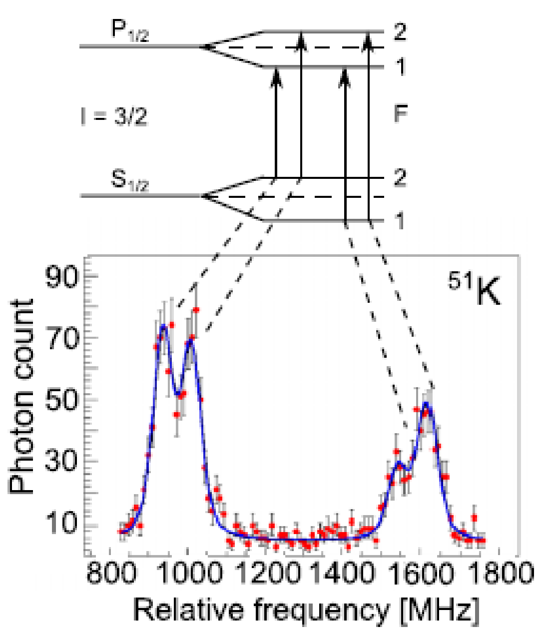


Laser spectroscopy

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

Atomic **hyperfine structure (HFS)**
(interaction of nuclear and atomic spins)

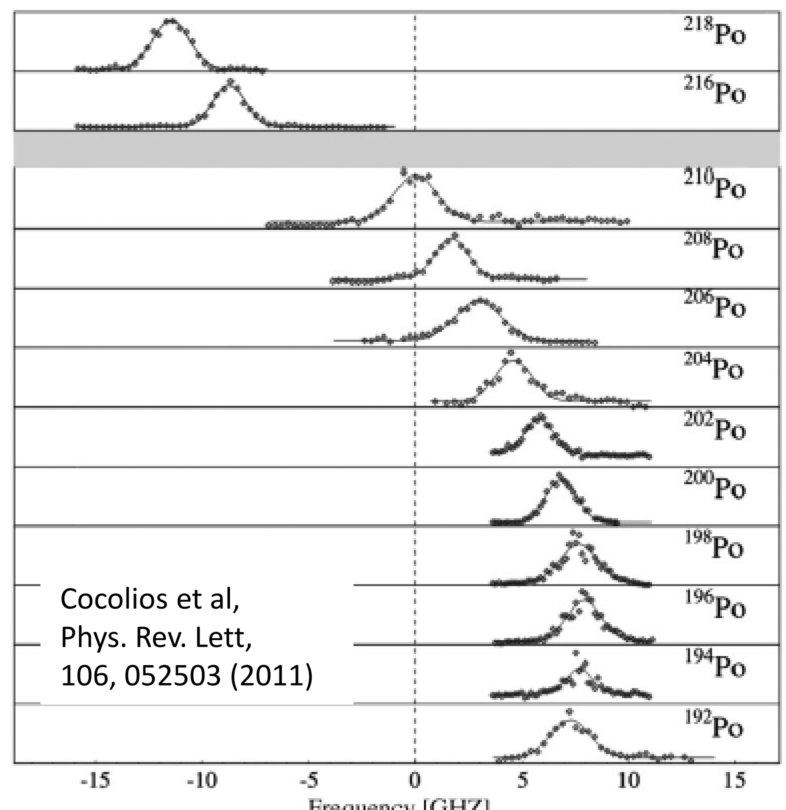
- HFS details depend on:
  - Spin -> orbit of last proton&neutron
  - Magnetic dipole moment -> orbits occupied by p&n
  - Electric quadrupole moment -> deformations



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

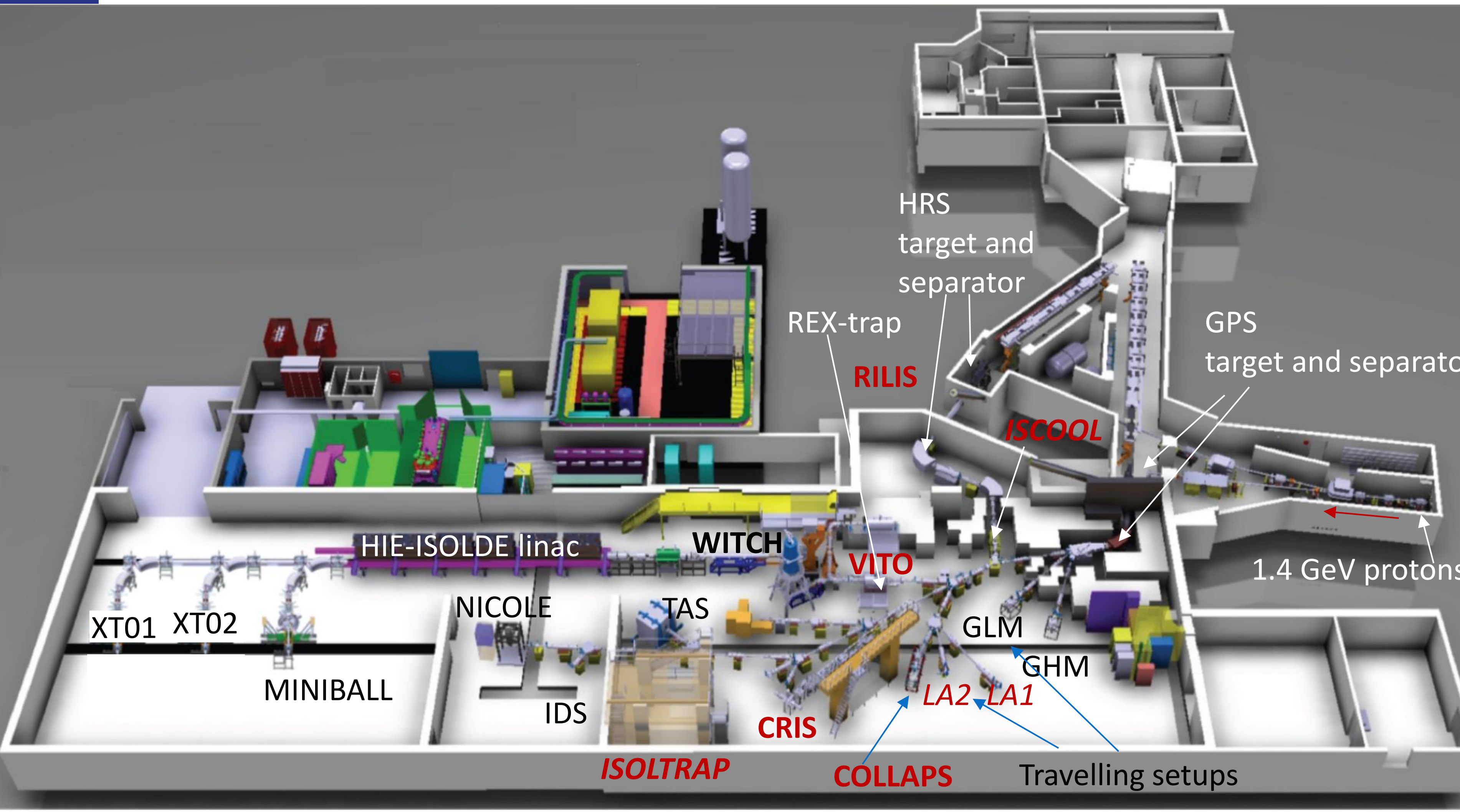
Isotope shifts (IS) in atomic transitions
(change in mass and size of different isotopes of the same chemical element)

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



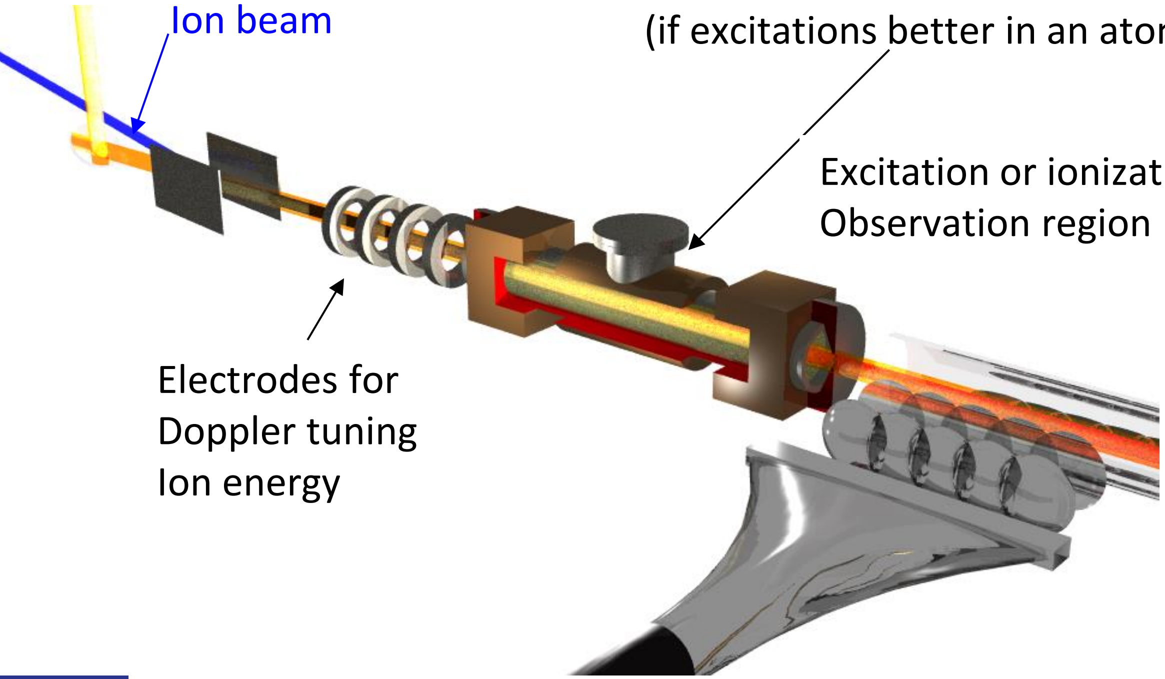
Cocolios et al,
Phys. Rev. Lett,
106, 052503 (2011)

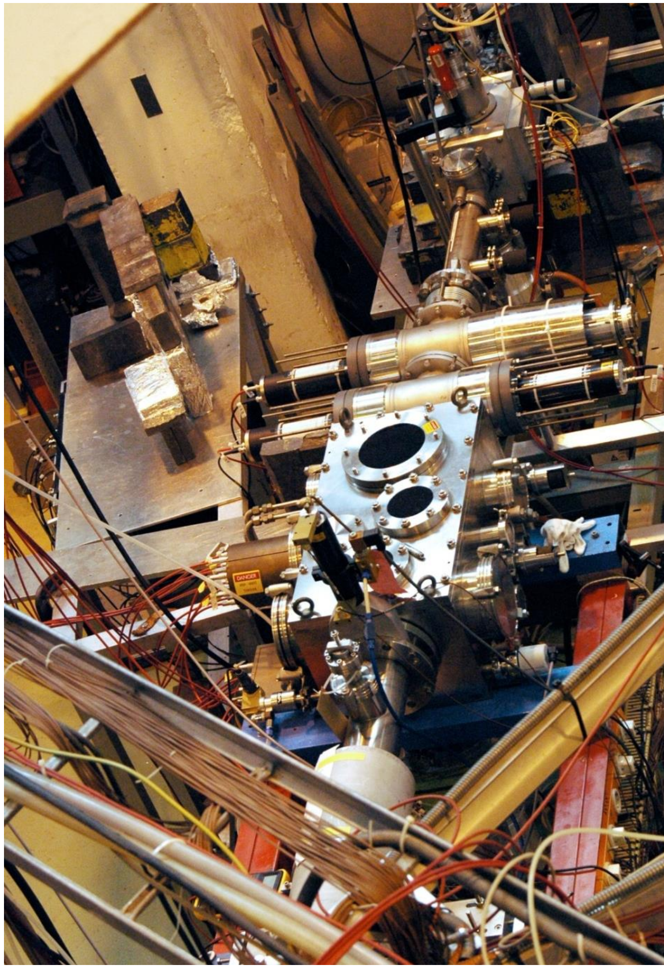
Laser spectroscopy and polarization



Collinear laser spectroscopy

COLLAPS, CRIS setups





Detection method depends on the case => optimised for best S/N ratio:

Fluorescence photons (1e6 ions/ s)

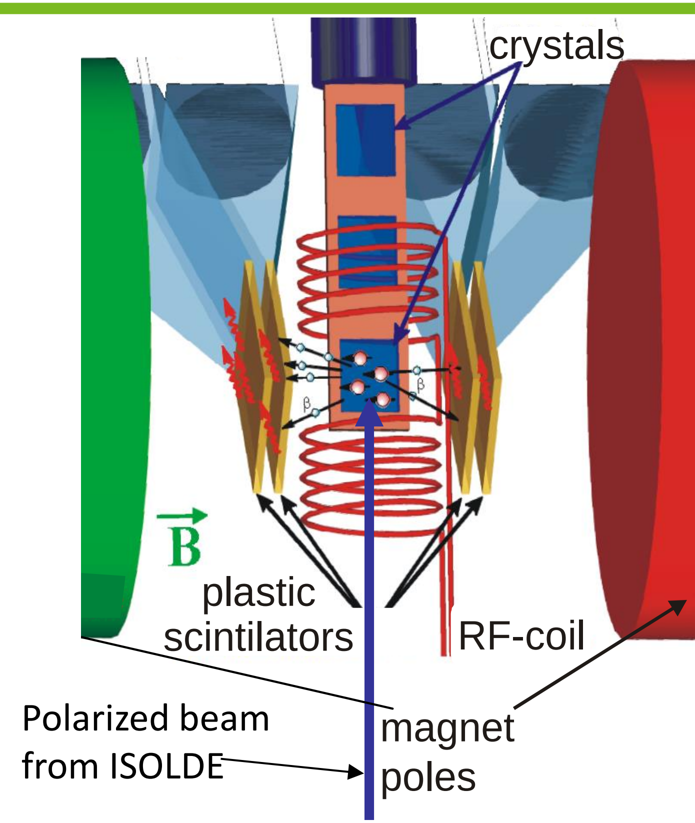
Ion-photon coincidence (1e3-1e4 ions/s)

Particles: betas, ions (1e2-1e4 ions/s)

Laser polarization and β-NMR

Spin polarization:
Circularly polarized laser light
Overlap with ion beam (collinear or traps – MR-TOF or Penning/Paul trap)
Polarizations of 10-90%

beta-detected NMR:
High polarization
High efficiency: beta-particles
=>Extreme sensitivity: 1e3 ions/s

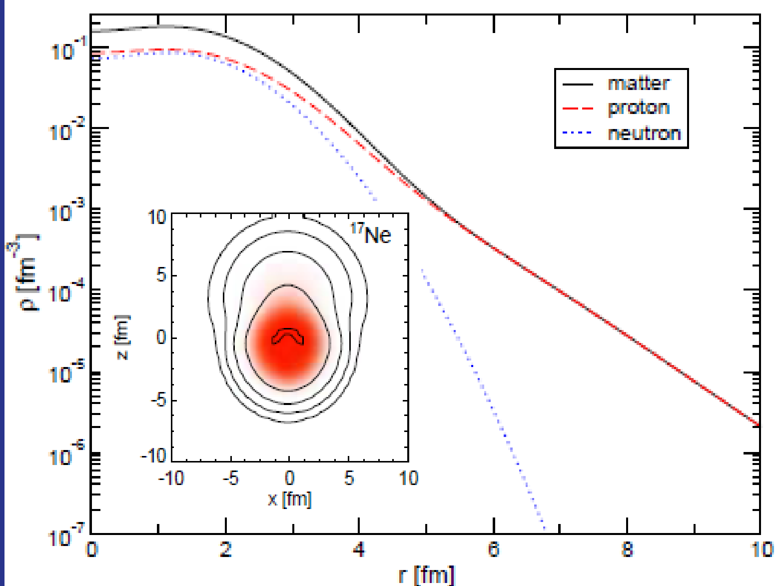


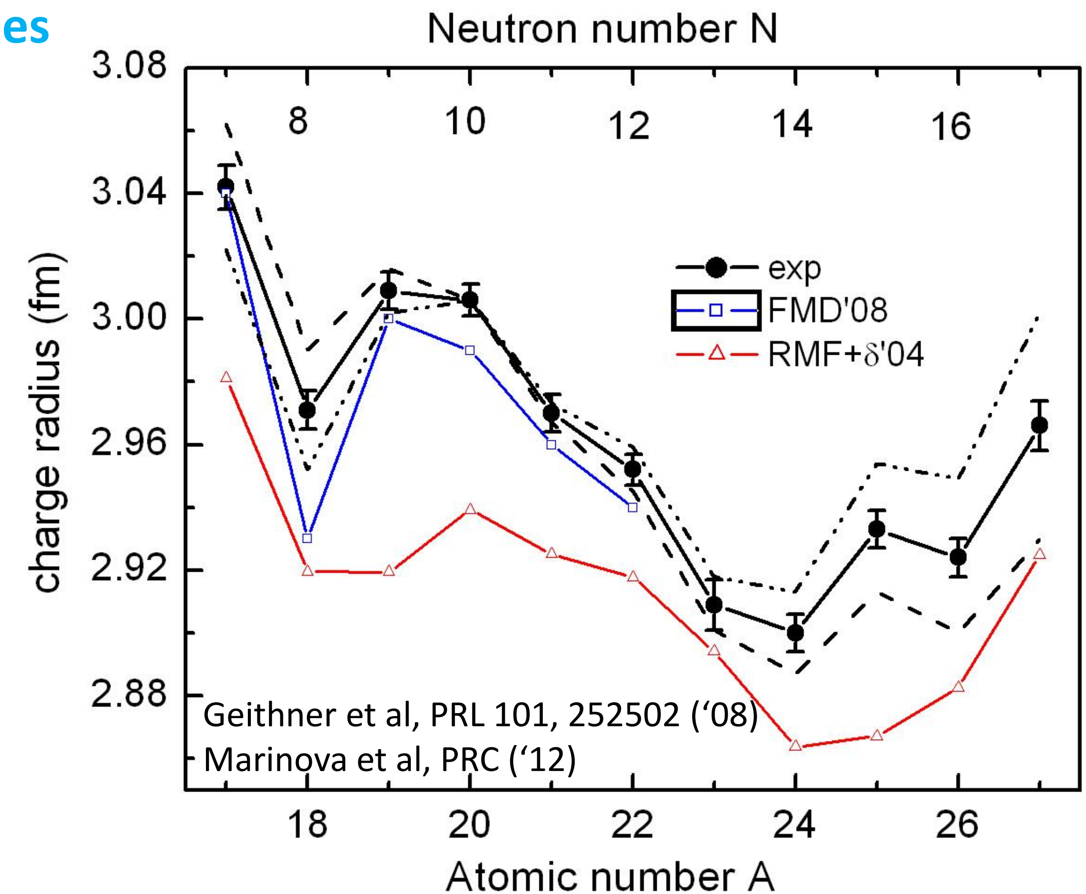
Applications:
-Measure precisely beta-asymmetry: probe Hamiltonian of Weak Interaction – fundamental studies (Measurement of the beta-asymmetry parameter in 35Ar with laser-polarized beam)
-Measure unknown e-m moments – nuclear structure
-Measure chemical shifts of resonances – material science and soon biology (e.g. my ERC grant starting in Oct15), Beta-NMR of Mg and Cu isotopes in ionic liquids

Collinear laser spectroscopy: nuclear structure

COLLAPS: Charge radii of Ne isotopes

Intrinsic density distributions of dominant proton FMD configurations





Open or data-analysis projects:

Ground-state properties of K-isotopes from laser and β-NMR spectroscopy

Laser Spectroscopy of Cadmium Isotopes: Probing the Nuclear Structure Between the Neutron 50 and 82

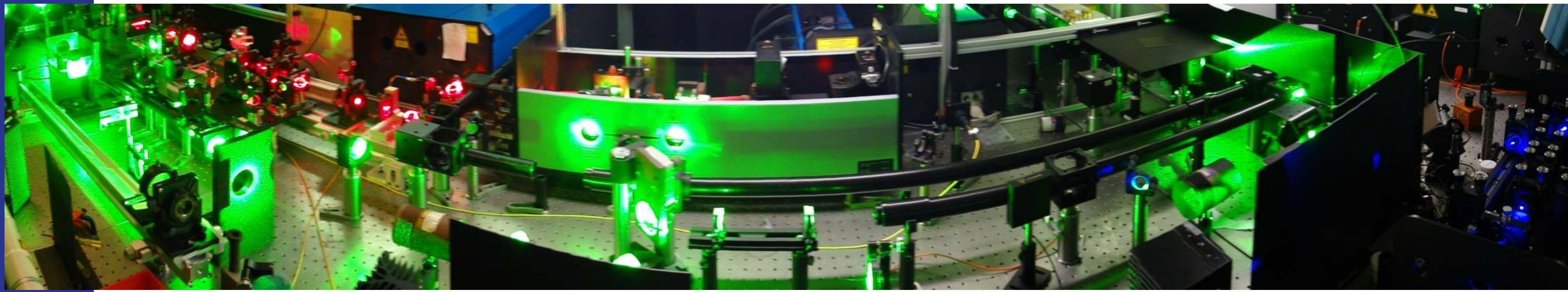
Shell Closures: **discovery of ms isomers in 127,129Cd**

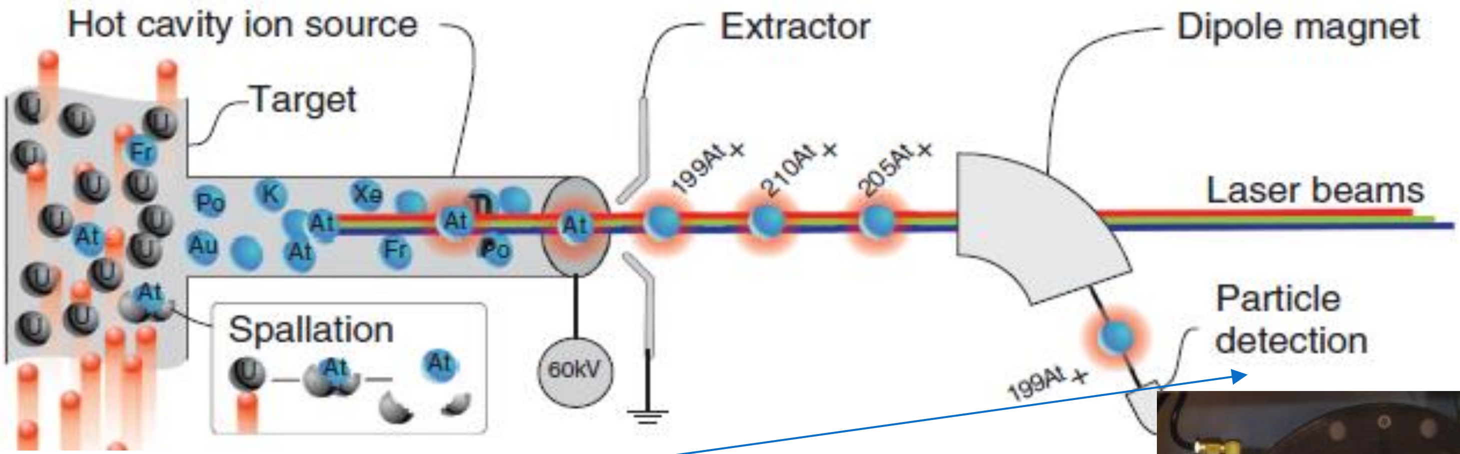
Shell structure and level migrations in zinc studied using collinear laser spectroscopy: **done up till 80Zn**

Spins, Moments and Charge Radii Beyond 48Ca: **preparations for 54Ca run**

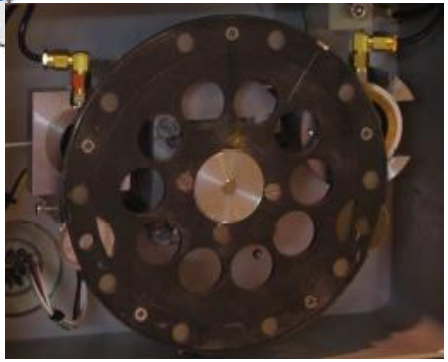
In-source laser spectroscopy

RILIS setup (ISOLDE Laser Ion Source):
pulsed lasers – high power, but large linewidth – best for heavy nuclei



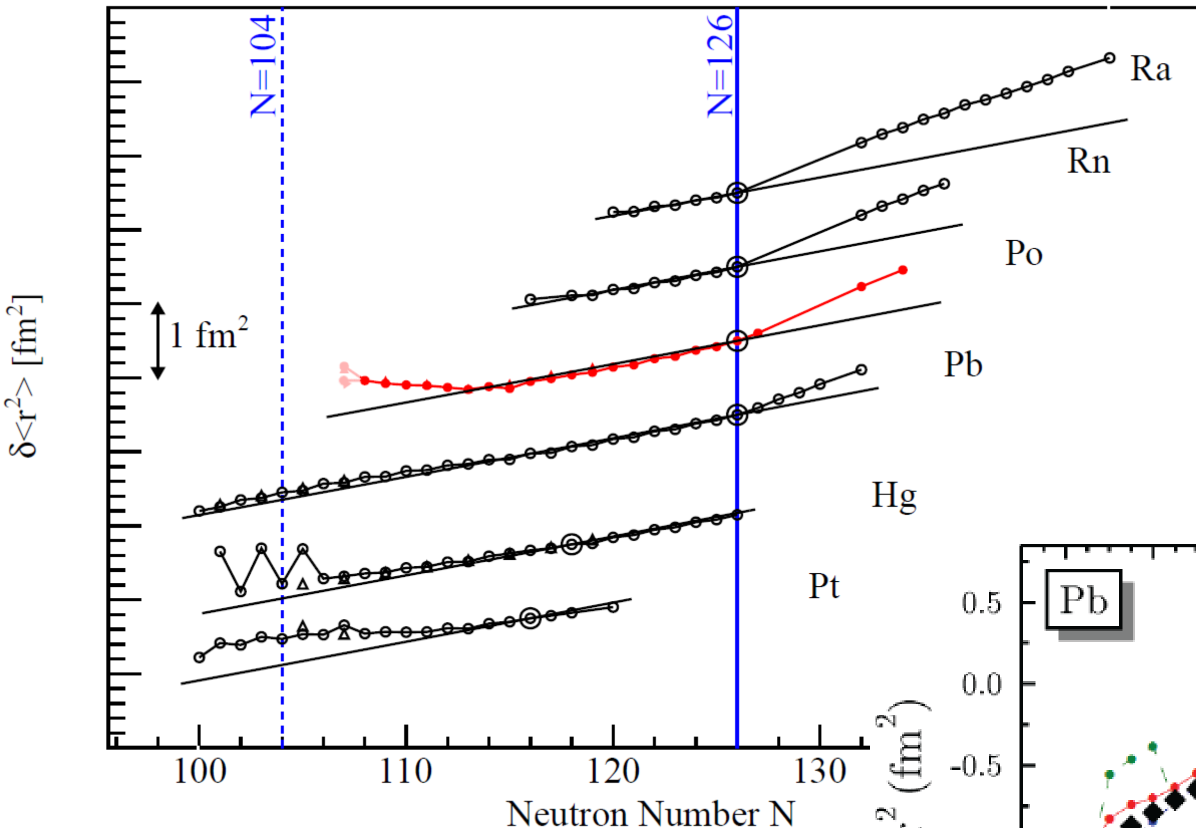


Detection method depends on the case => optimised for best S/N ratio:
Ions - ISOLDE Faraday Cups (>1 pA) or ISOLTRAPs MR-TOF (> 10 ions)
Alphas: WINDMILL setup at LA1 or LA2 beamlines



In-source spectroscopy: nuclear structure

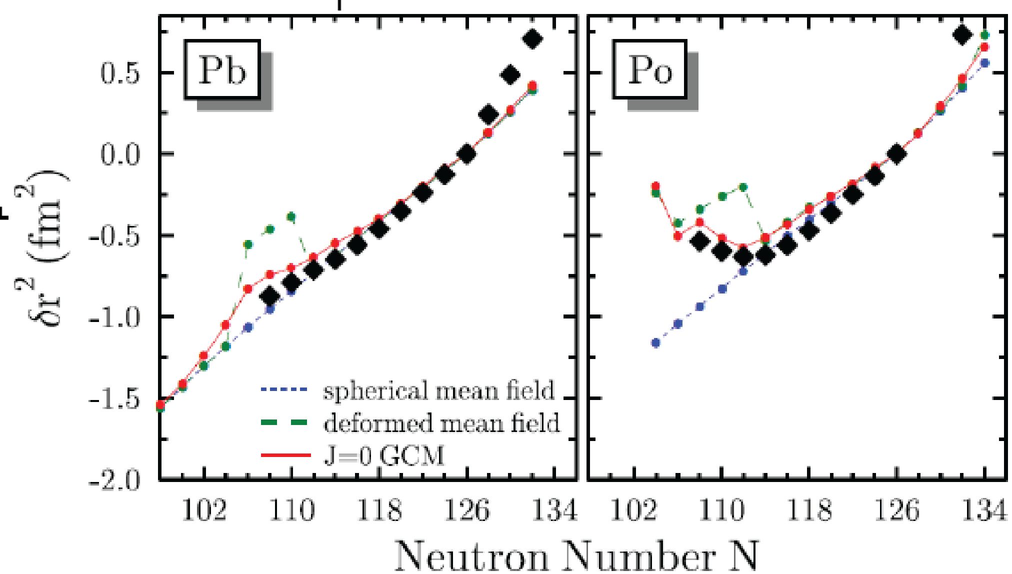
Changes in charge radii of heavy nuclei



Isotope shifts measured with RILIS setup (part of data shown):

Regions of deformation visible

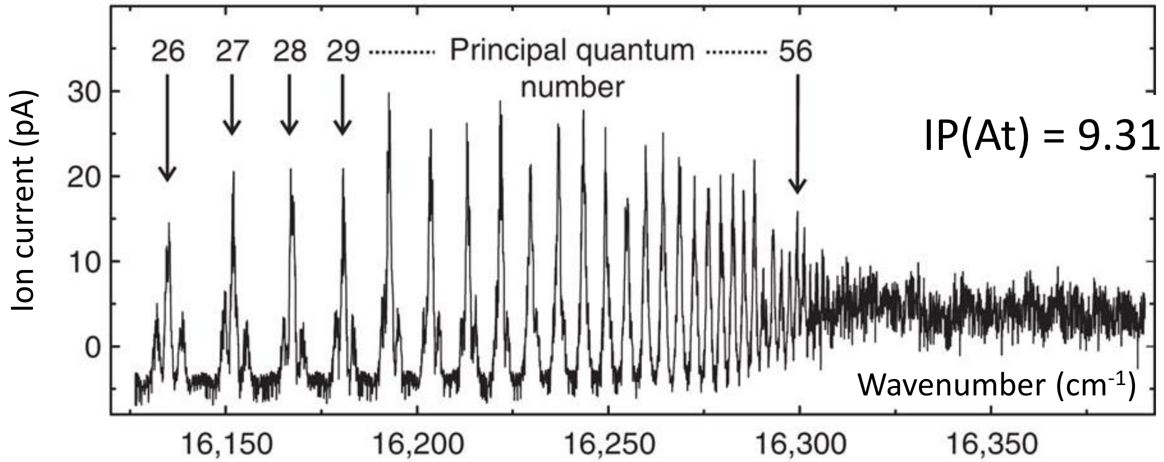
T.E. Cocolios et al., PRL 106 (2011) 052503
M. Seliverstov et al., EPJ A41(2009) 315
H. De Witte et al., PRL 98 (2007) 112502



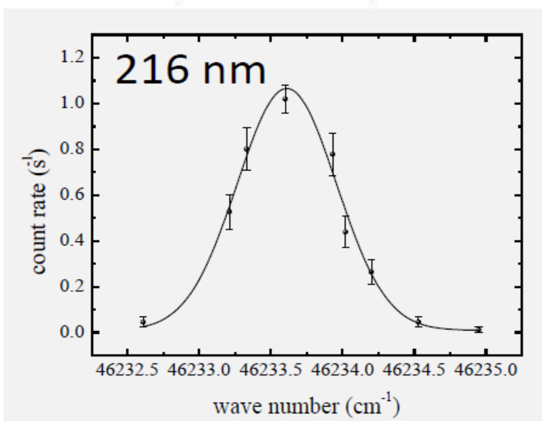
Radii described well with mean field models

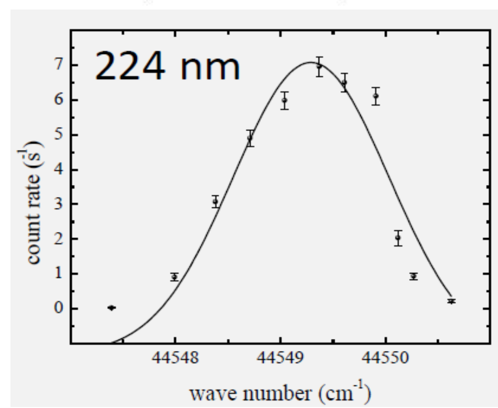
In-source spectroscopy: atomic properties

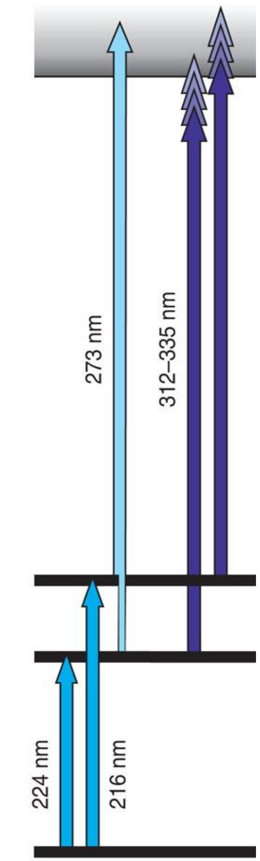
- Astatine: Last chemical element with unknown **ionization potential (IP)**
  - ➢ atomic fingerprint, determines chemical properties
- Ionization Potential determined with RILIS and detected in a Faraday cup



IP(At) = 9.31751(8) eV





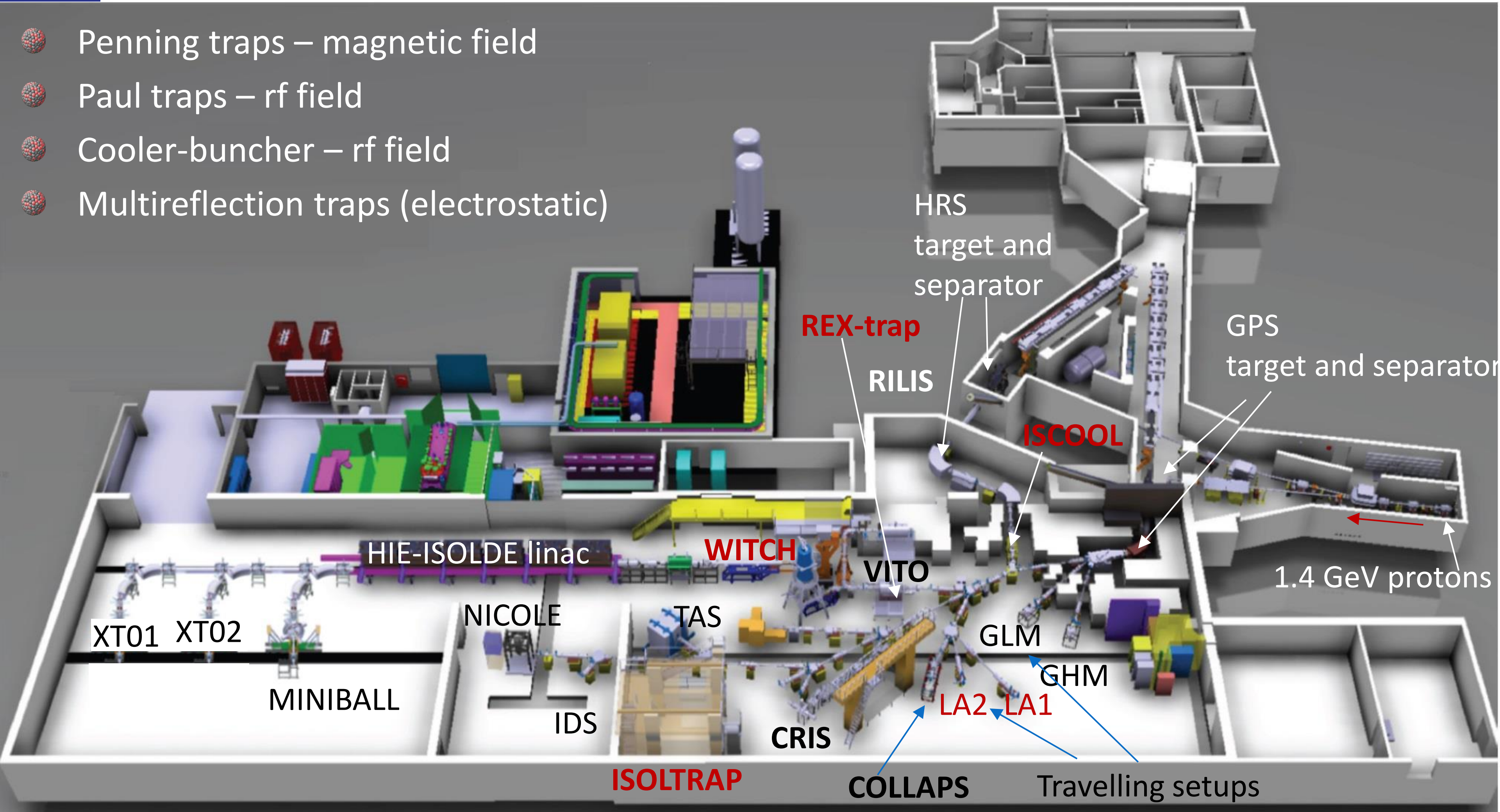


- Outlook: improved IP predictions for element 117

S. Rothe et al., Nature Communications 4, 1835 (2013)

Ion traps

- Penning traps – magnetic field
- Paul traps – rf field
- Cooler-buncher – rf field
- Multireflection traps (electrostatic)



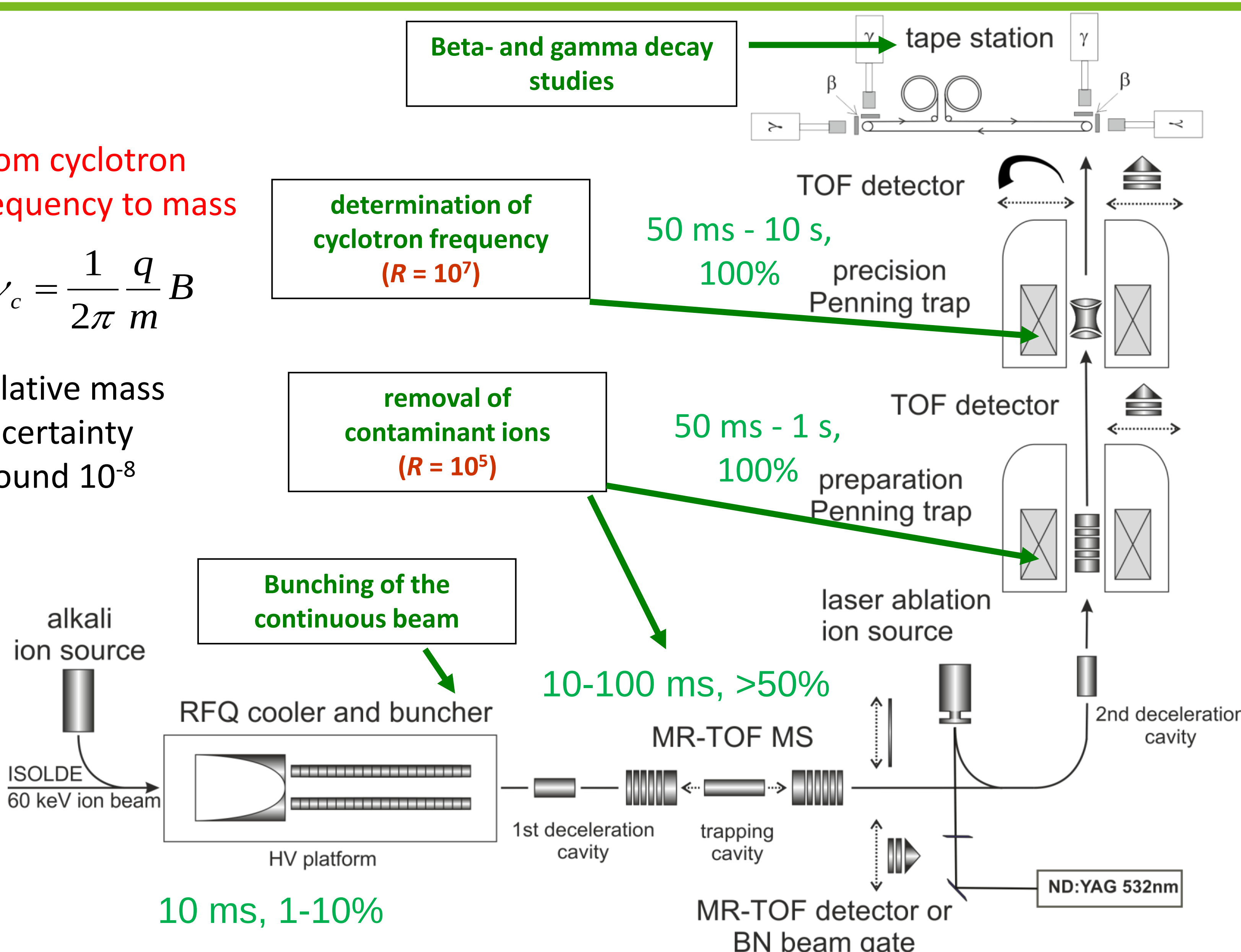
- Ion manipulation with rf in Penning traps
- Possibility of purifying the ion ensembles

ISOLTRAP: ISOLDE mass spectrometer

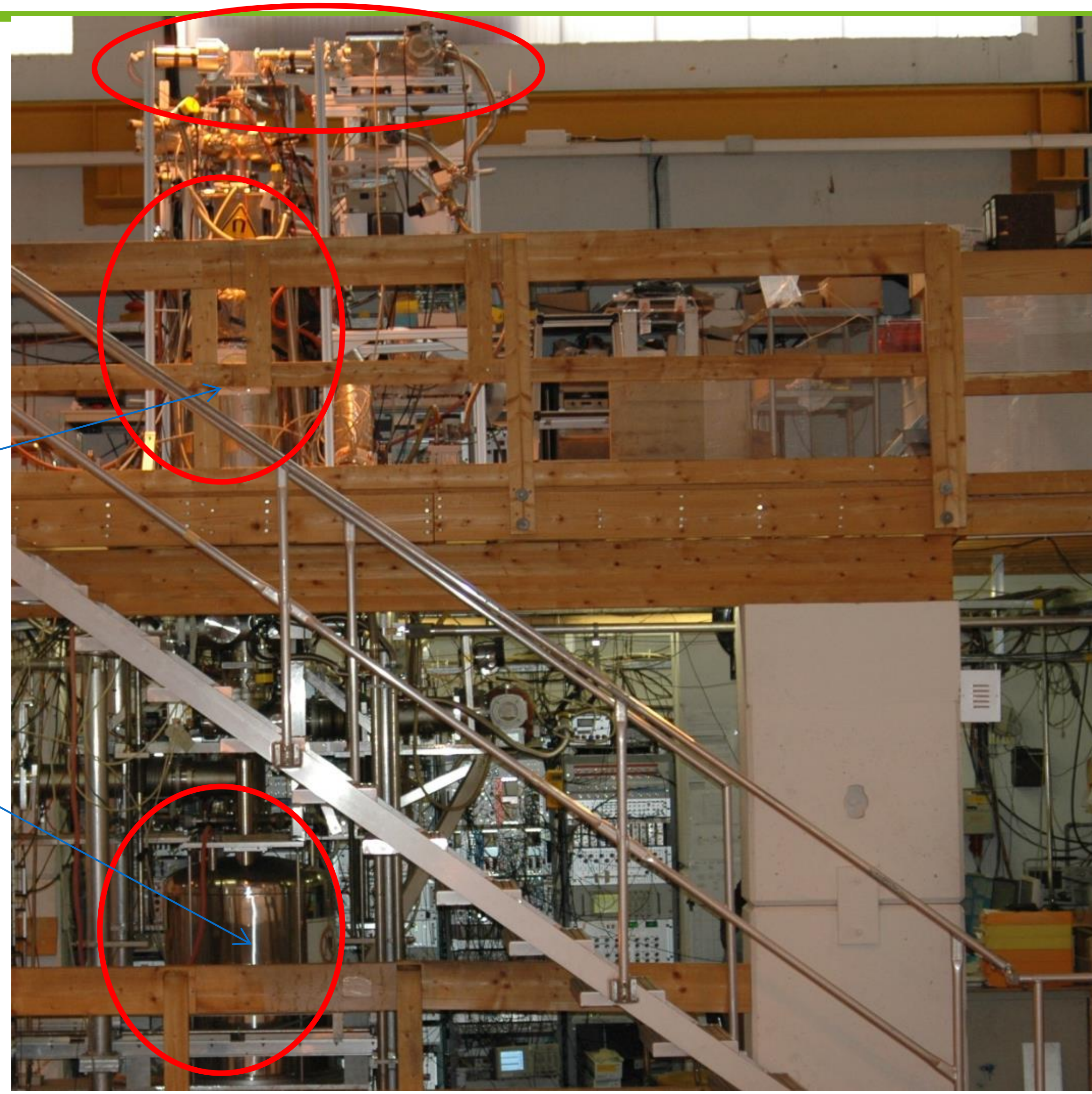
From cyclotron frequency to mass

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

Relative mass uncertainty around 10^{-8}

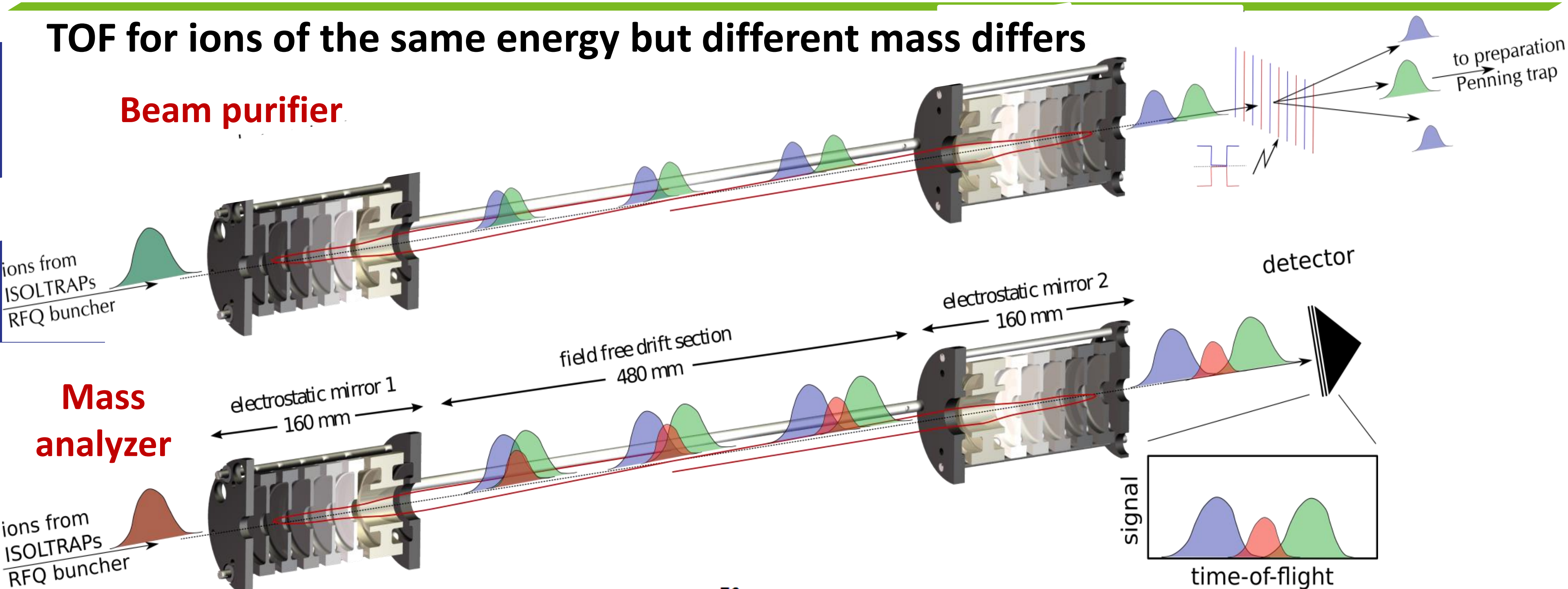


ISOLTRAP



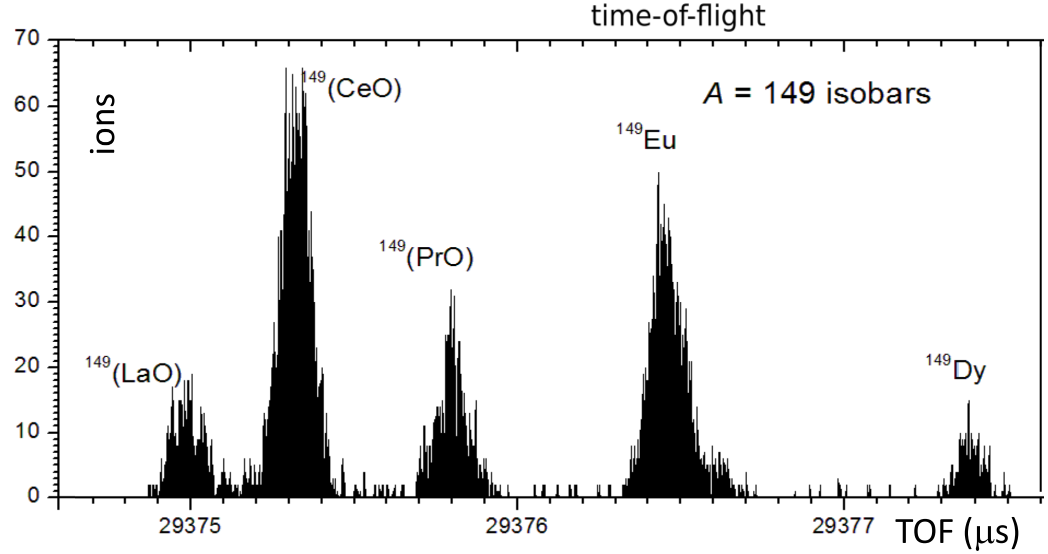
Multi-Reflection Time-of-Flight Mass Separator

TOF for ions of the same energy but different mass differs



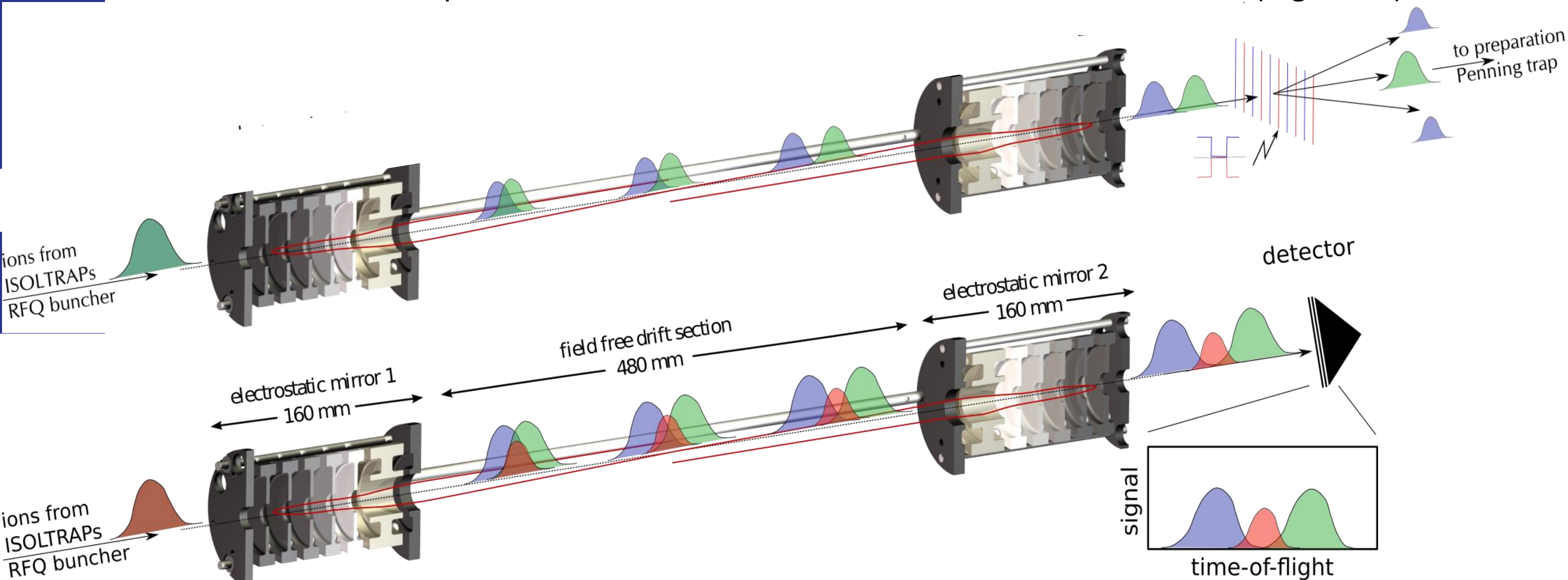
- Electrostatic potentials
- Typical trapping time: 25-75 ms
- Production: >10-100 ions/s
- m/Δm (FW) > 10^5
- Suppression factor 10^4
- Mass uncertainty < 50 keV

R.N. Wolf et al., Nucl. Instr. and Meth. A 686, 82-90 (2012)



Multi-Reflection Time-of-Flight Mass Separator

- Lifetime measurements:
  - Mass separation and observation of ion number vs trapping time (e.g. 82Zn)

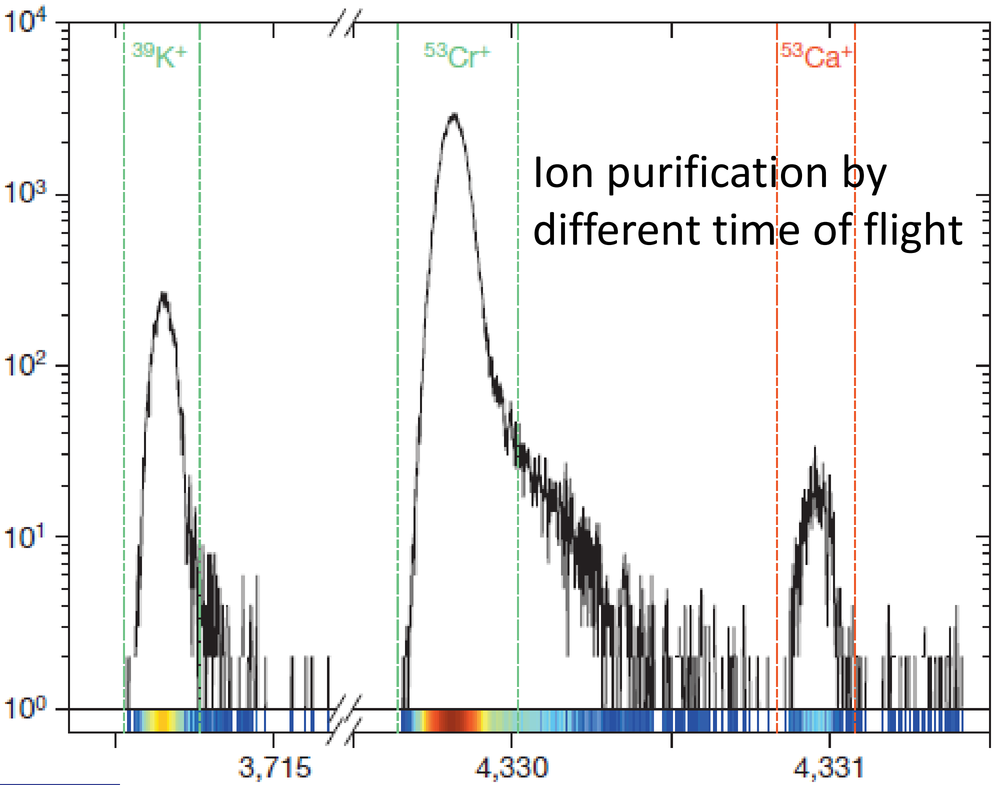


- Soon: laser spectroscopy on trapped ions
  - Long laser-ion overlap
  - Space for in-trap photon and particle detectors

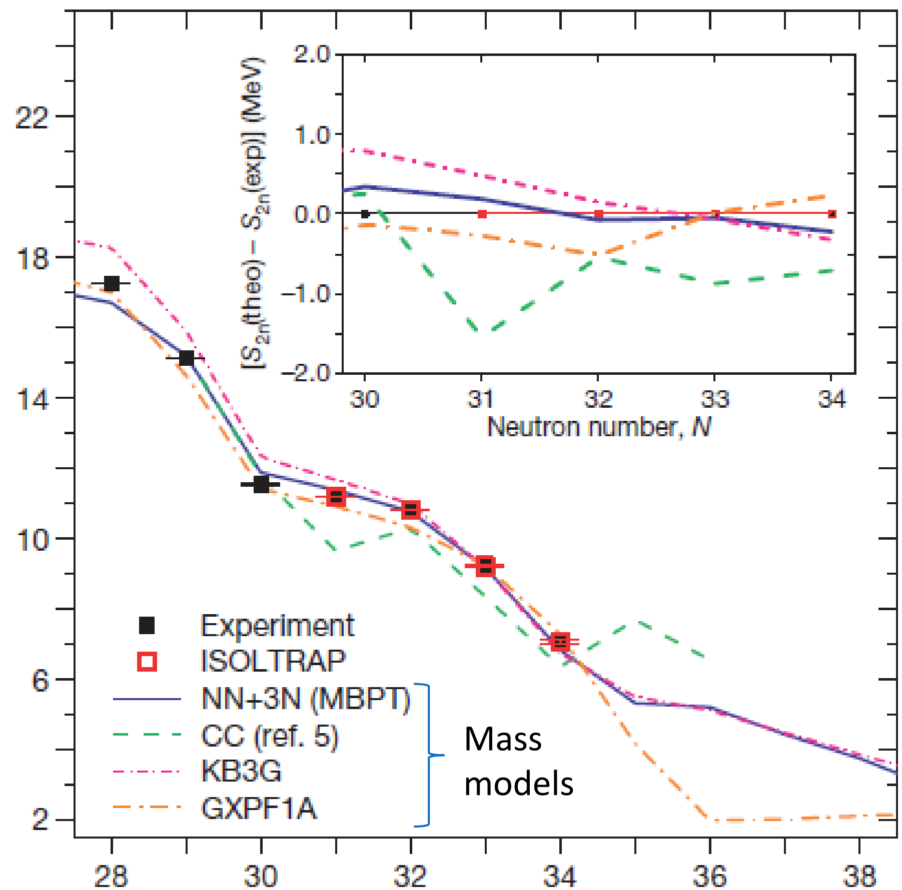
Masses: nuclear structure

Ion counts behind electrostatic trap

F. Wienholtz et al, Nature 498 (2013), 346



Two-neutron separation energy (MeV):
Sudden drop points to a shell closure

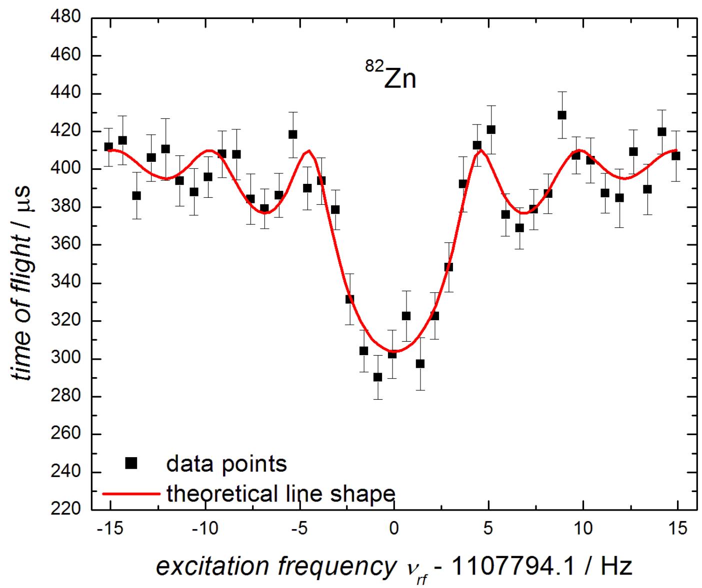


Masses: astrophysics

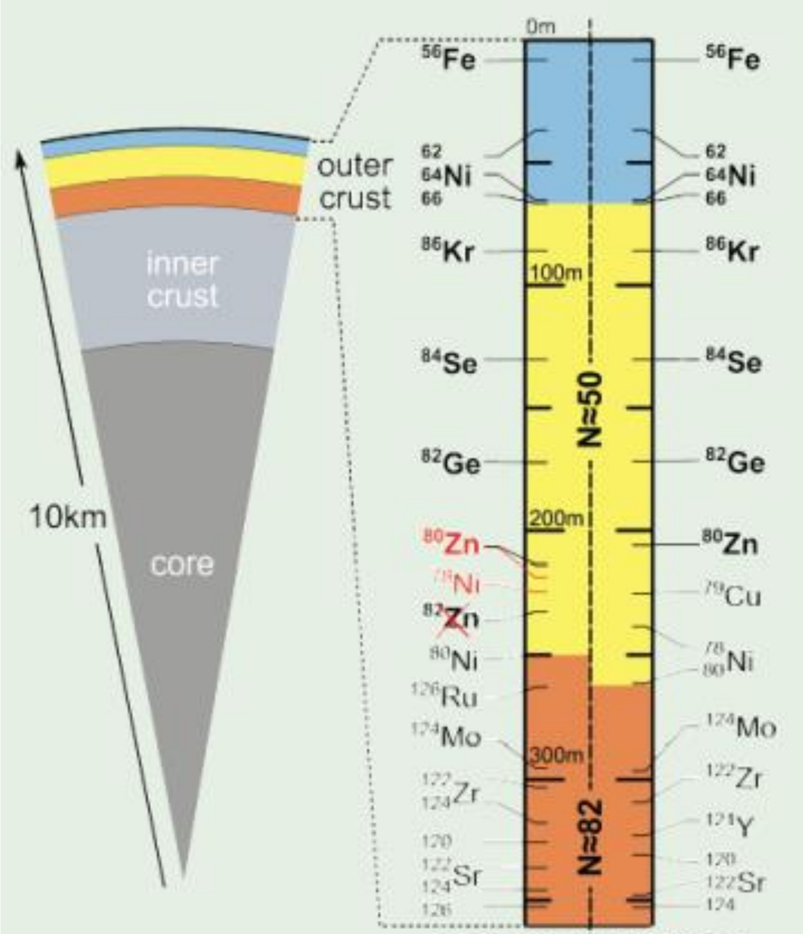
After several attempts at ISOLTRAP and elsewhere

Neutron-star composition:
- Test of models
- 82Zn is not in the crust

- Combined ISOLDE technical know-how:
  - neutron-converter and quartz transfer line (contaminant suppression)
  - laser ionisation (beam enhancement)



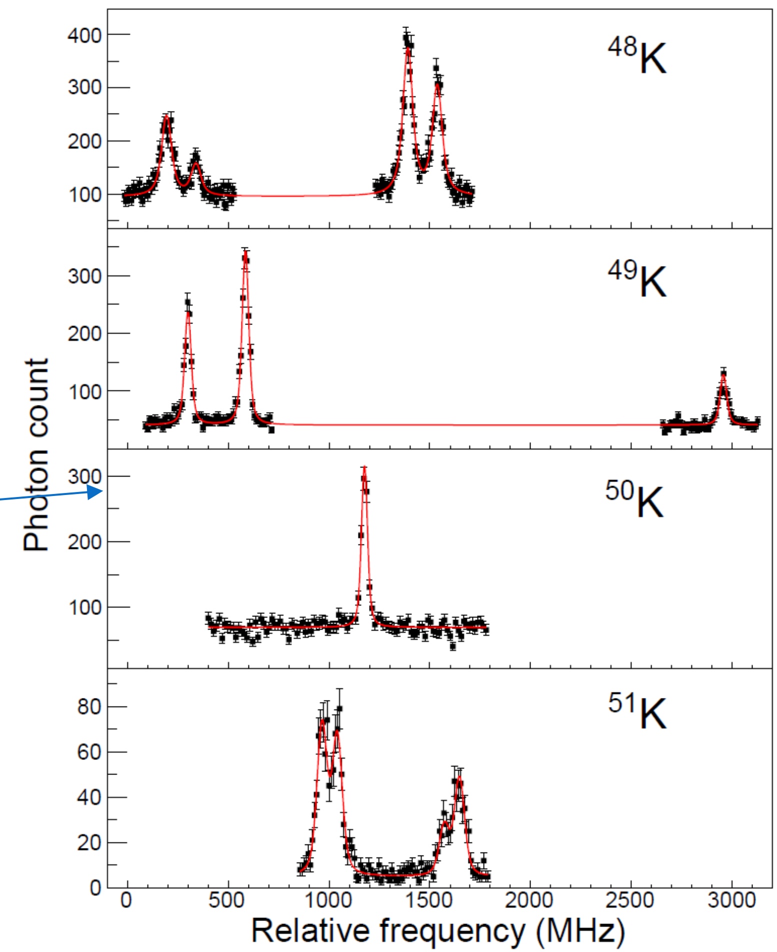
R.N. Wolf et al, Phys. Rev. Lett. 110, 041101 (2013)



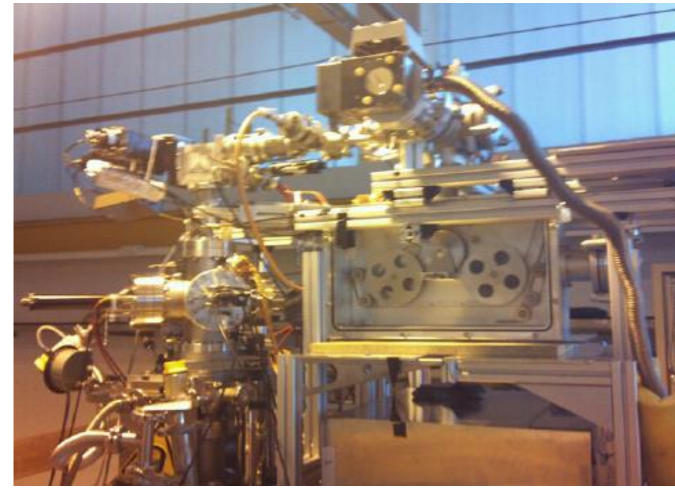
Mean-field models: HFB-19 | HFB-21

ISOLDE cooler-buncher ISCOOL

- Linear rf trap filled with He gas
  - Ion bunching
  - Lowering of ion emittance
- Increase in laser-spectroscopy sensitivity up to 1e4
  - Photon observation only when ion bunch arrives (e.g K)
- Optical pumping with lasers
  - Change in atomic-state occupation – used for laser spectroscopy (e.g. Mn)
  - Soon: preparation of spin-polarized beams?

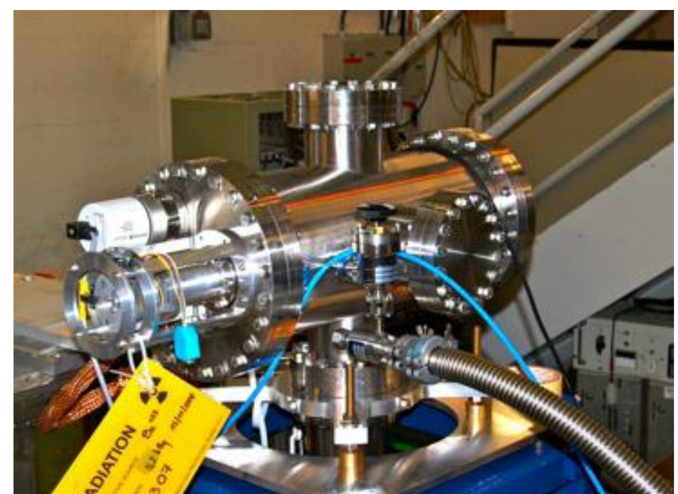


Trap- or laser-assisted decay studies



- Decay stations behind ISOLTRAP and CRIS
- Isobar and even isomer purification in an ion trap or by laser ionisation
- Studies of radionuclides suffering from contamination

Recent and open projects at ISOLTRAP:
Mass measurements and decay studies on isobarically pure neutron-rich Hg and Tl isotopes
Study of the odd-A, high-spin isomers in neutron-deficient trans-lead nuclei with ISOLTRAP
Trap-assisted studies of Po isotopes



Open projects at CRIS:
Purification and studies of Po isotopes

Summary and outlook

RIB (ISOLDE) atomic physics techniques

- Laser spectroscopy, polarization and beta-NMR:
  - Nuclear structure
  - Atomic properties
  - Material science and biology
- Ion traps
  - Masses – nuclear structure and astrophysics
- New (unexpected) techniques and applications:
  - Electrostatic traps
  - Beam purification and isomer-selectivity with lasers and traps
- More classical and new applications awaiting, e.g.
  - laser spectroscopy in electrostatic traps
  - beta-NMR in liquids for biological applications

Thank you for your attention

Laser and β-NMR Spectroscopy

Based on the hyperfine interaction between electromagnetic moments of the nucleus with internal or external electromagnetic fields

Atomic **hyperfine structure**

(interaction of nuclear and atomic spins)

$$\Delta E_{HFS} = \frac{A}{2}K + B\frac{\frac{3}{4}K(K+1) - I(I+1)J(J+1)}{2(2I-1)(2J-1)I \cdot J}$$

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

$$A = \frac{\mu_I B_0}{I\,J} \qquad B = eQV_{zz}(0)$$

Isotope shifts in atomic transitions

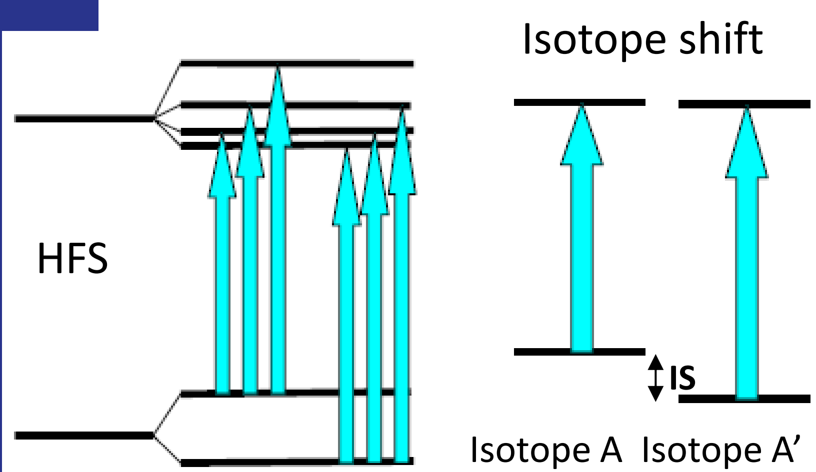
(change in mass and size of different isotopes of the same chemical element)

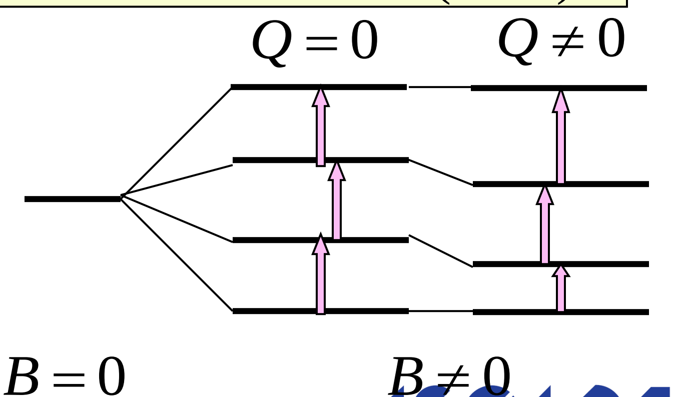
$$\delta\nu^{A,A'} = K_{MS} \times \frac{m_A - m_{A'}}{m_A m_{A'}} + F \times \delta\langle r^2 \rangle^{A,A'}$$

Nuclear Magnetic Resonance – NMR

(Zeeman splitting of nuclear levels)

$$\Delta E_{mag} = -m_I g_I \mu_N B_0 + eQV_{zz}\frac{3m_I^2 - I(I+1)}{4I(2I-1)}$$





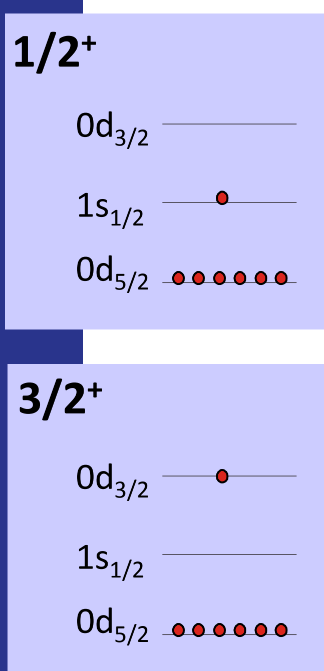
=> Probing single-particle and colective properties

Laser spectroscopy and nuclear physics

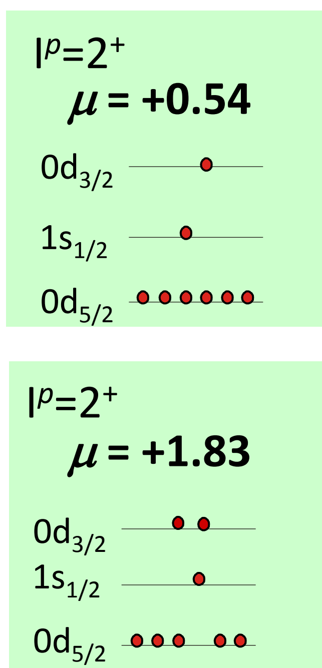
- **Spin** (orbital+intrinsic angular momentum), **parity** (I^π)
- Nuclear ***g*-factor** and **magnetic** dipole **moment** (g_I and μ_I)
- Electric quadrupole moment (Q)
-**Charge radius** ($\langle r^2 \rangle$)

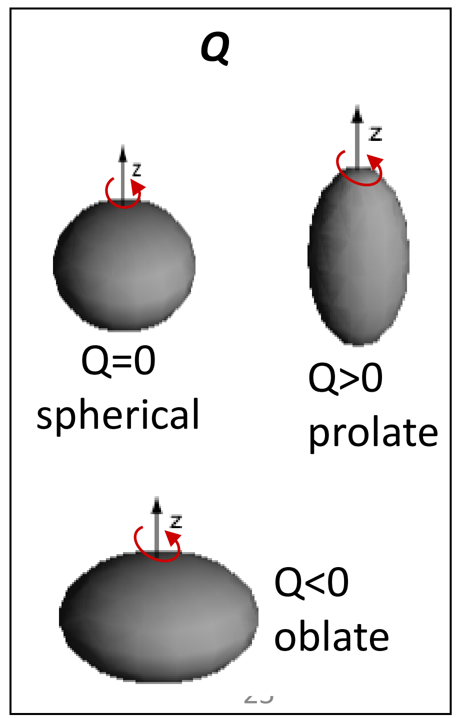
Give information on:
- Configuration of neutrons and protons
- Size and form of the nucleus

I^π

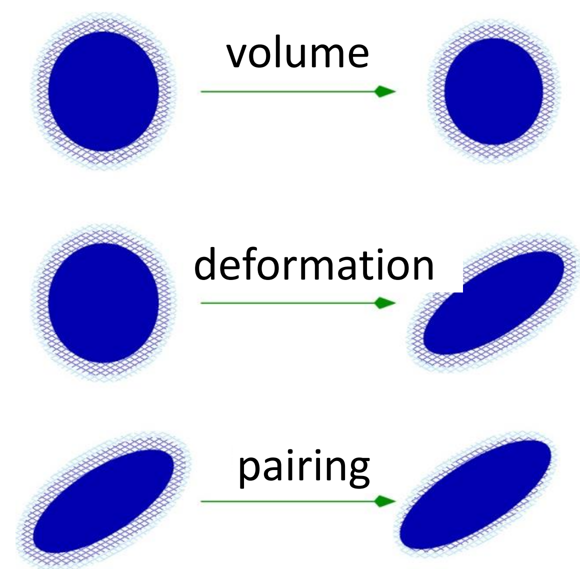


g_I and μ_I





$\langle r^2 \rangle$



CRIS

- Collinear Resonant Ionisation Spectroscopy
- High sensitivity, lower resolution -> perfect for heavy ions

1. Bunched ion beam of ~1 μs temporal width

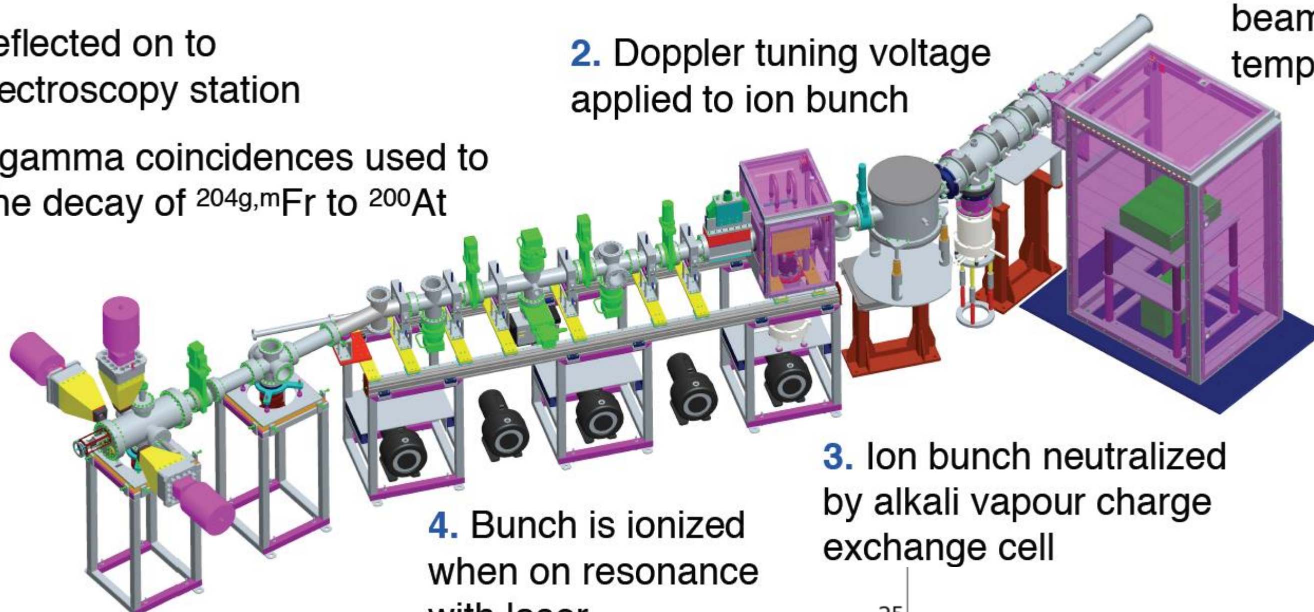
2. Doppler tuning voltage applied to ion bunch

3. Ion bunch neutralized by alkali vapour charge exchange cell

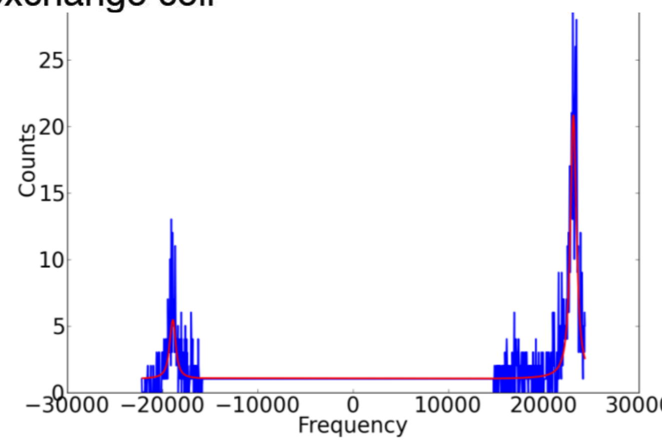
4. Bunch is ionized when on resonance with laser

5. Ions deflected on to decay spectroscopy station

6. Alpha-gamma coincidences used to identify the decay of $^{204g,m}Fr$ to ^{200}At



First physics experiment in 2011:
HFS and decay of 207Fr

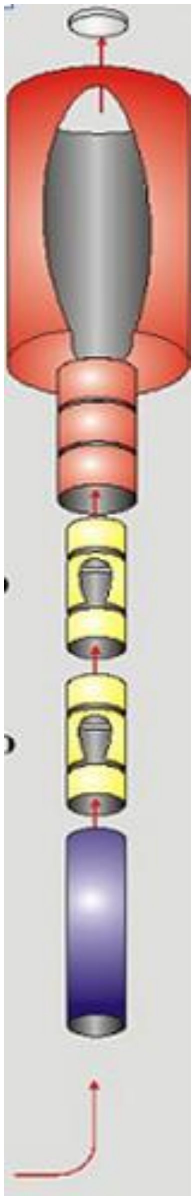


Open projects:

IS471: Collinear resonant ionization laser spectroscopy of rare francium isotopes

IS531: Collinear resonant ionization spectroscopy for neutron rich copper isotopes

WITCH



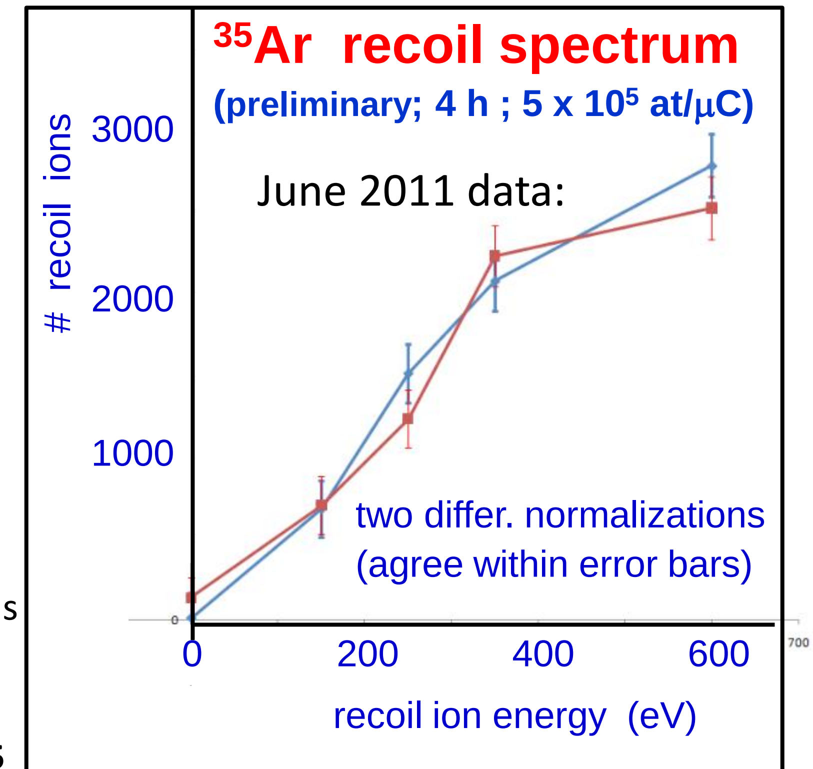
Weak Interation Trap for Charged particles -> fundamental studies

Goal: determine βν correlation for ^{35}Ar with $(\Delta a/a)_{stat} \leq 0.5$ %

-> energy spectrum of recoiling ions with a retardation spectrometer

Use a Penning trap to create a small, cold ion bunch

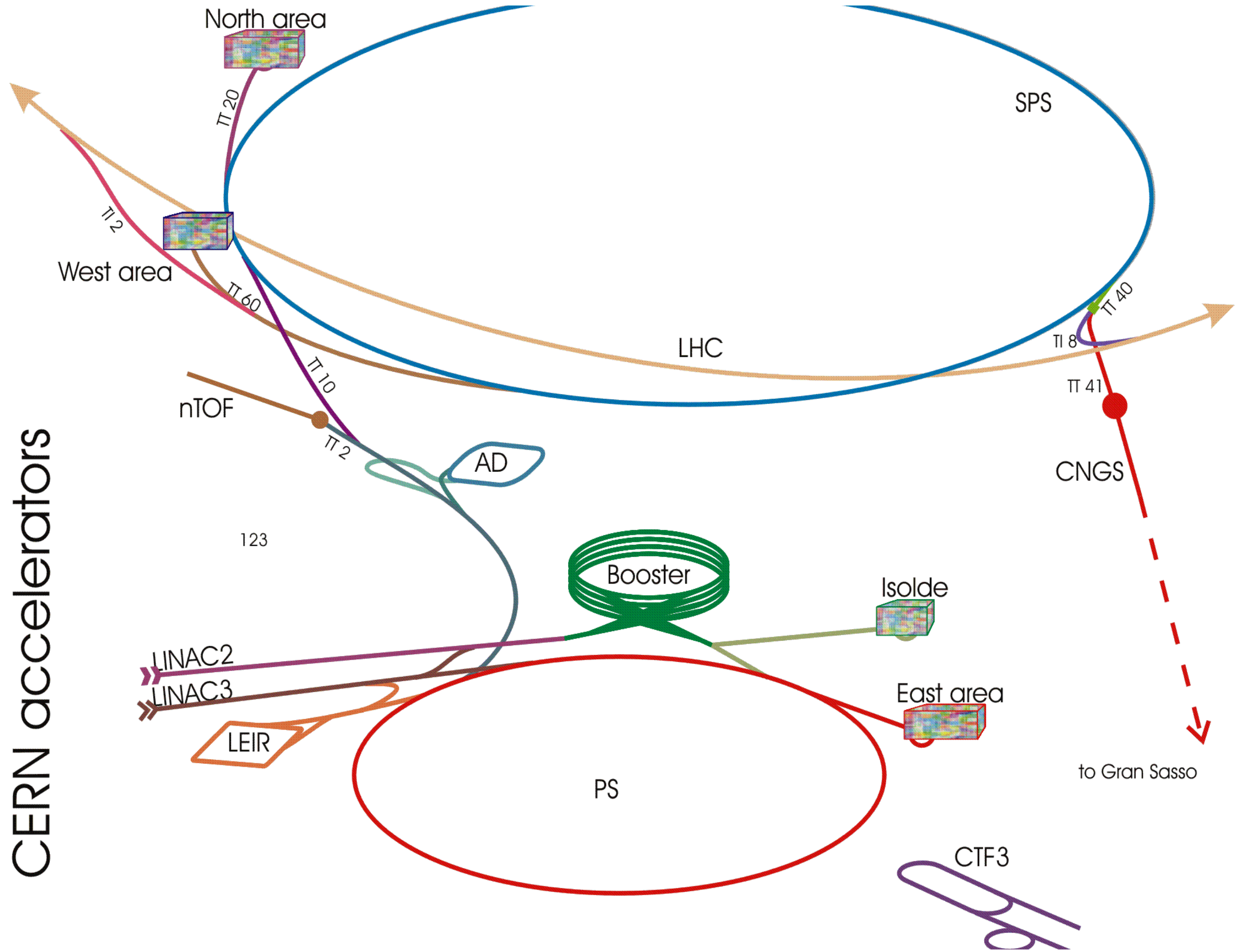
First high-statistics run in Nov 2011(data analysis ongoing)



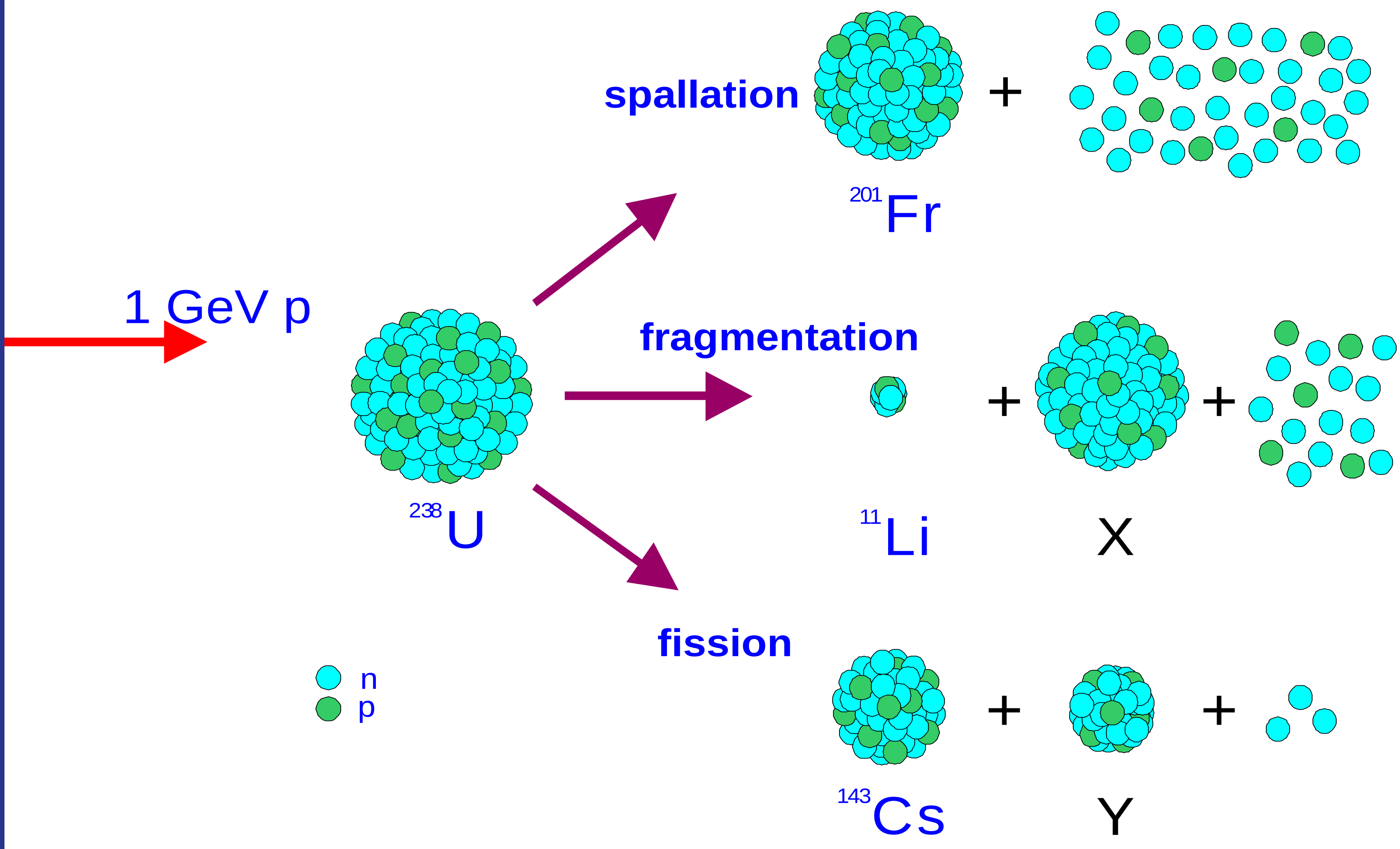
Recent experiment:
IS433: Search for new physics in beta-neutrino correlations using trapped ions and a retardation spectrometer

M. Beck et al., Eur. Phys. J. A47 (2011) 45
M. Tandecki et al., NIM A629 (2011) 396
S. Van Gorp et al., NIM A638 (2011) 192

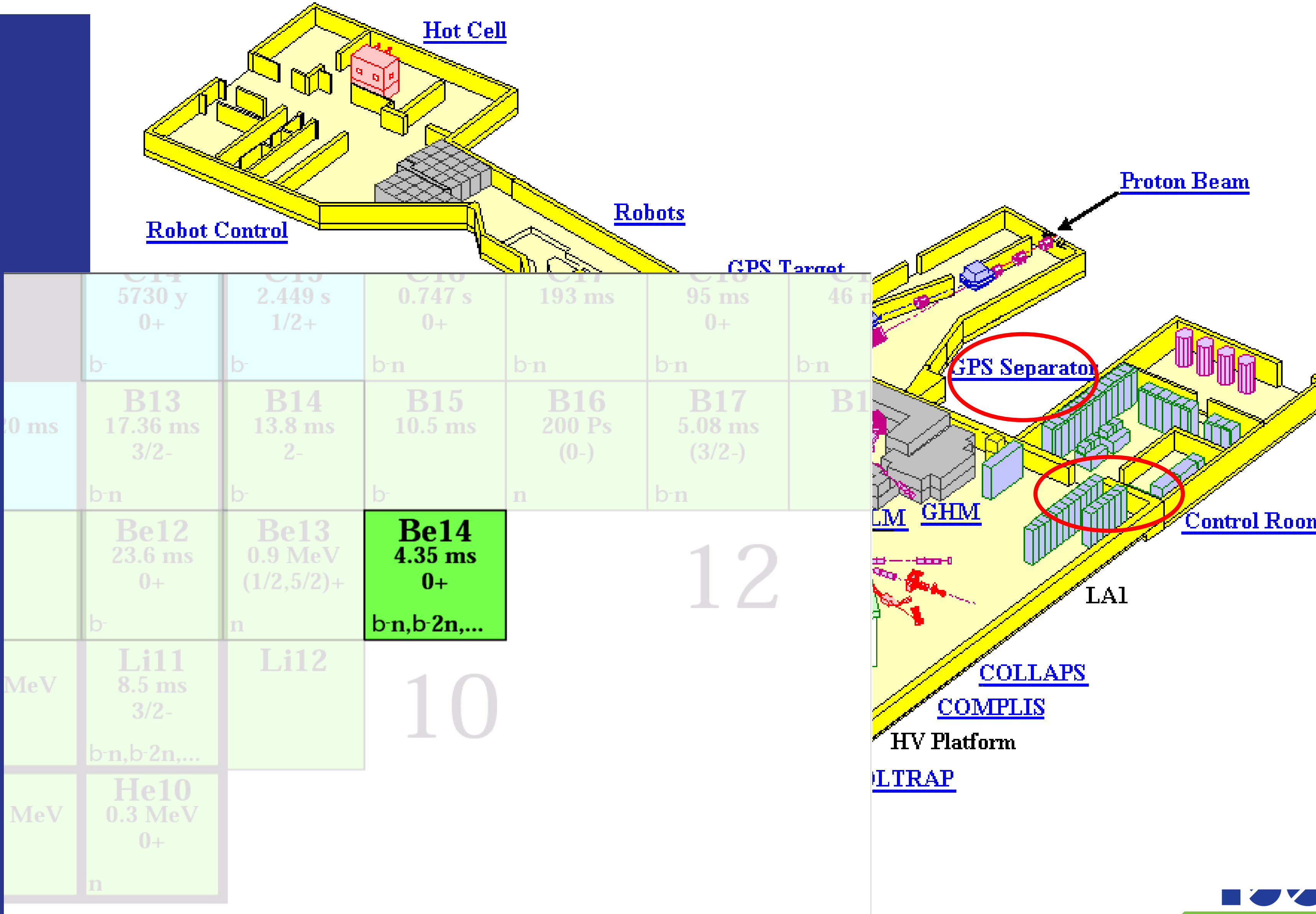
ISOLDE at CERN



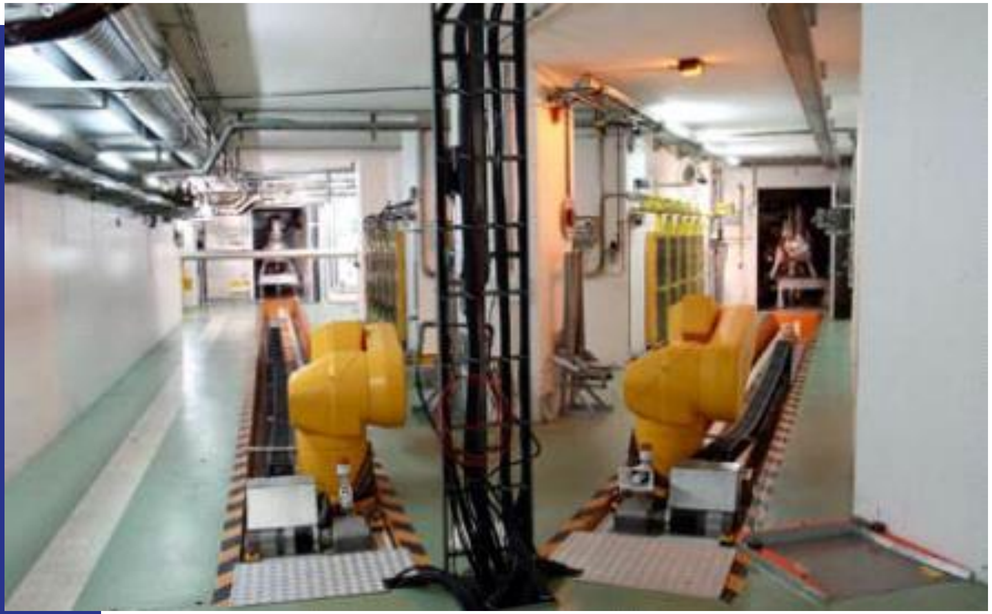
Nuclei production at ISOLDE

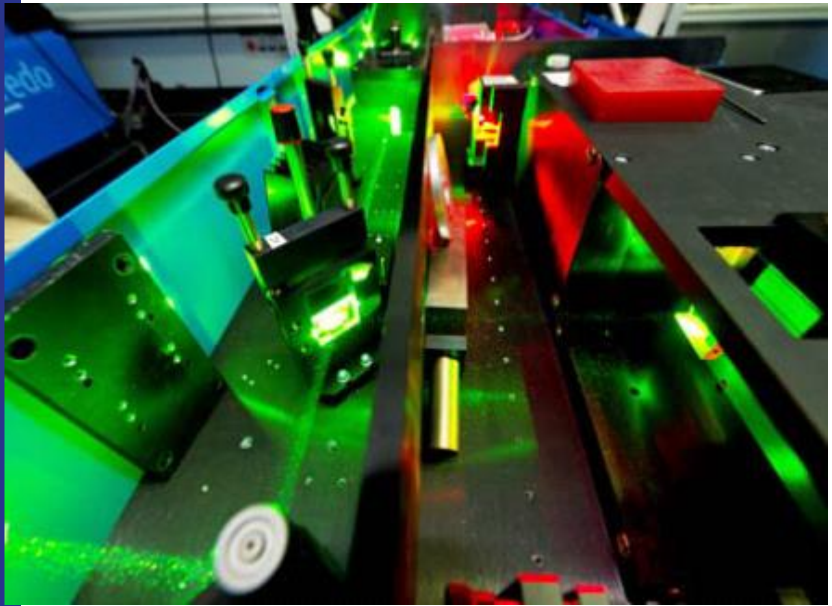


Production process

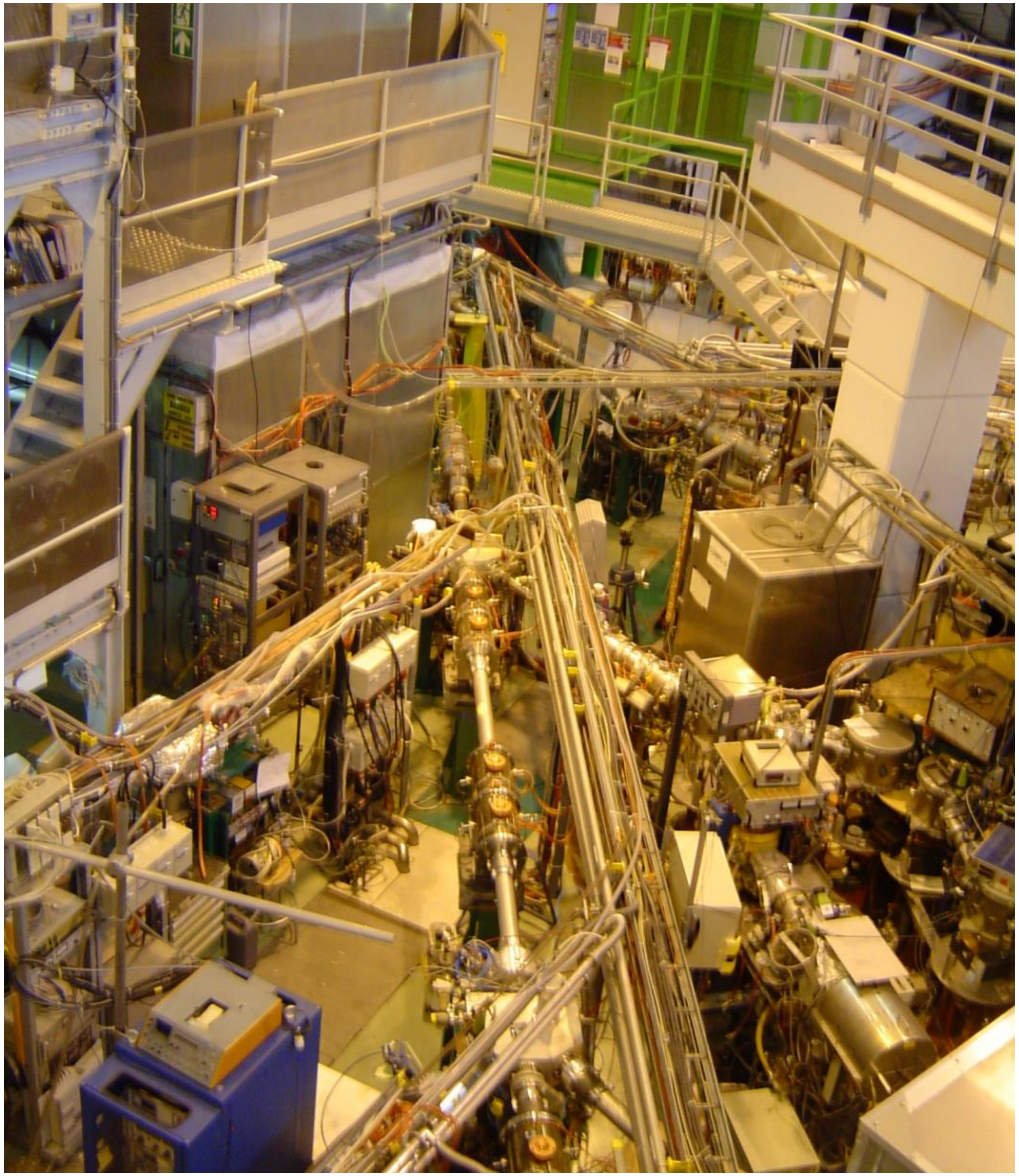


Facility photos

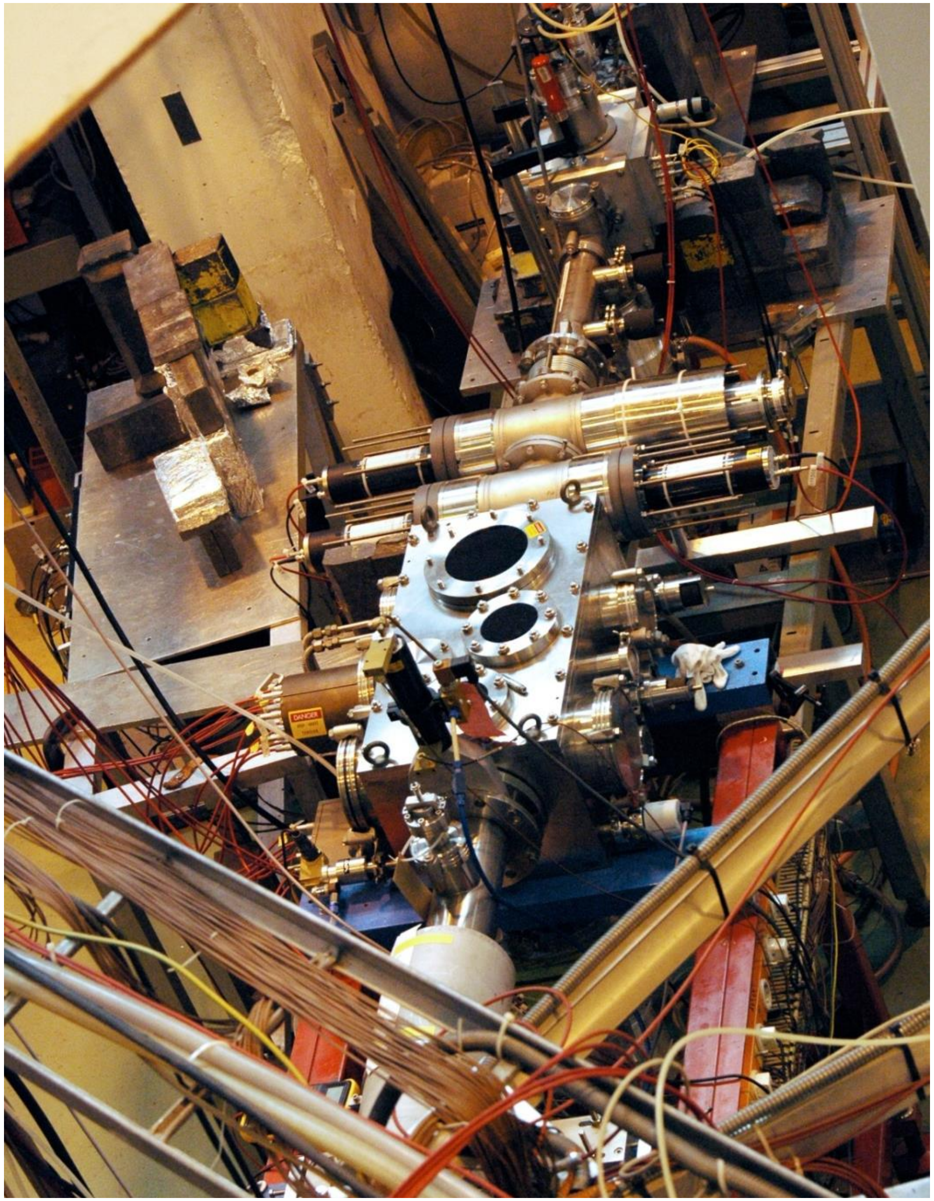


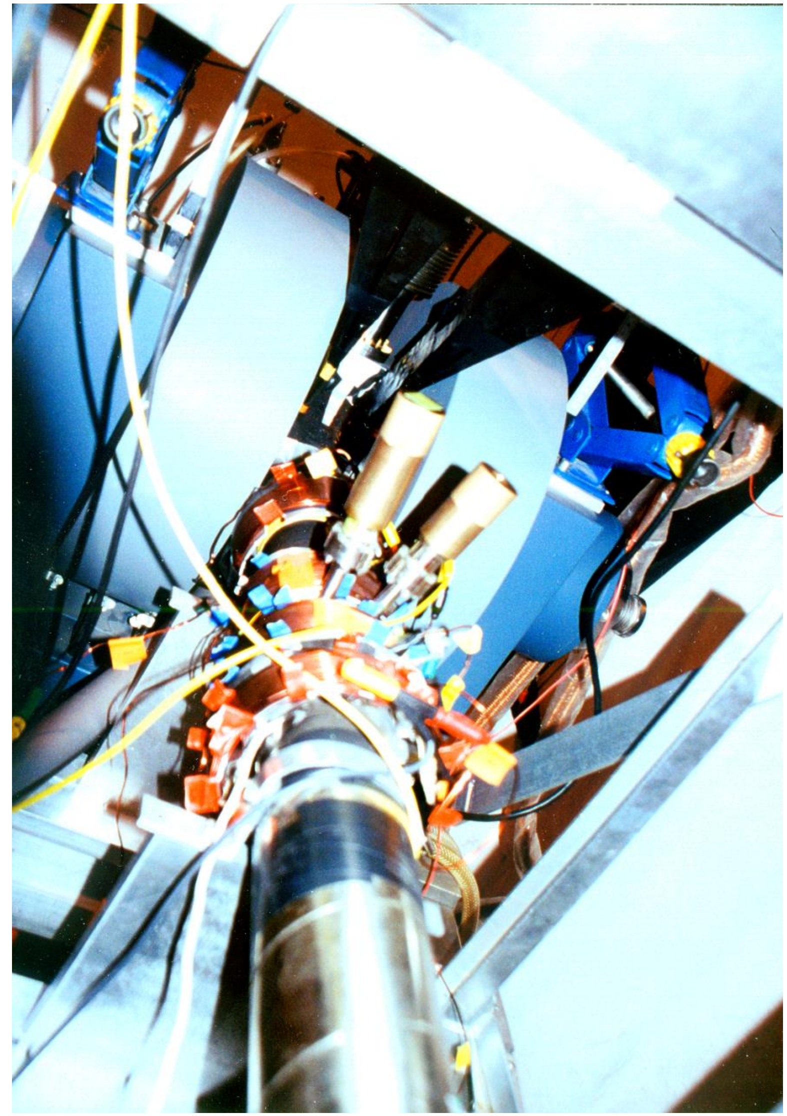


ISOLDE experimental setups



COLLAPS – laser spectroscopy

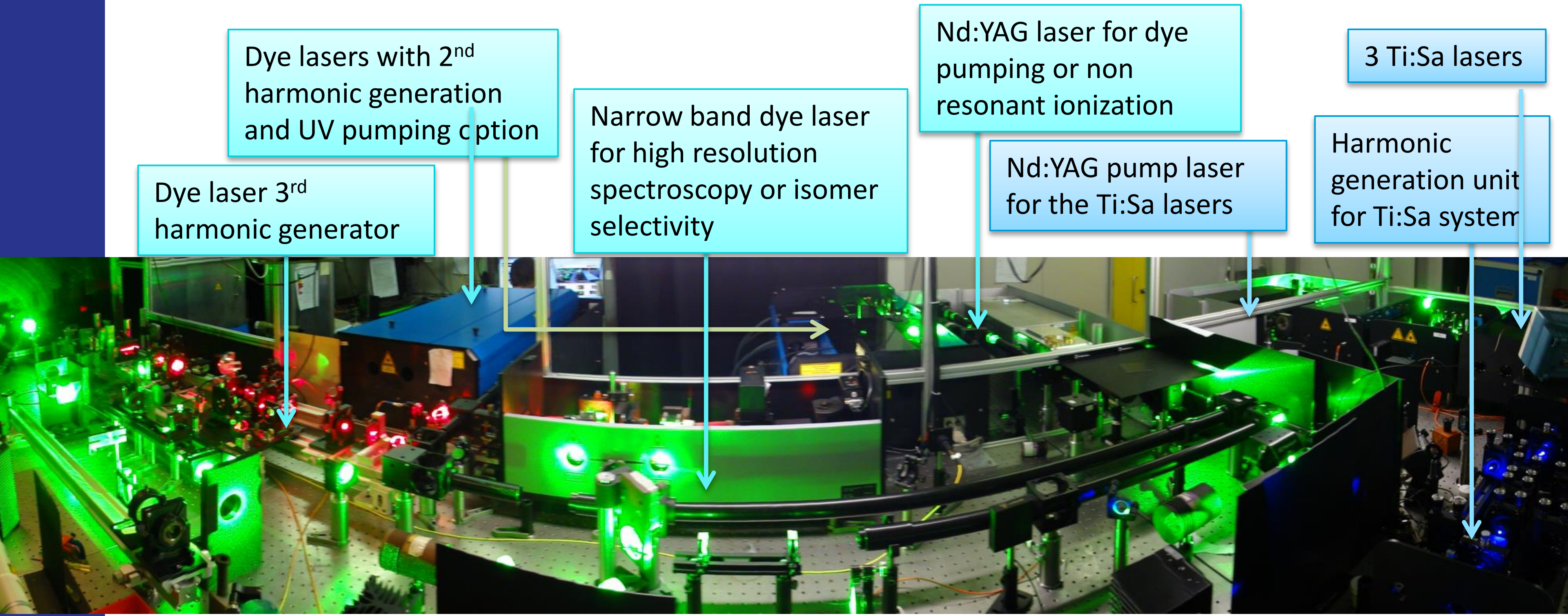




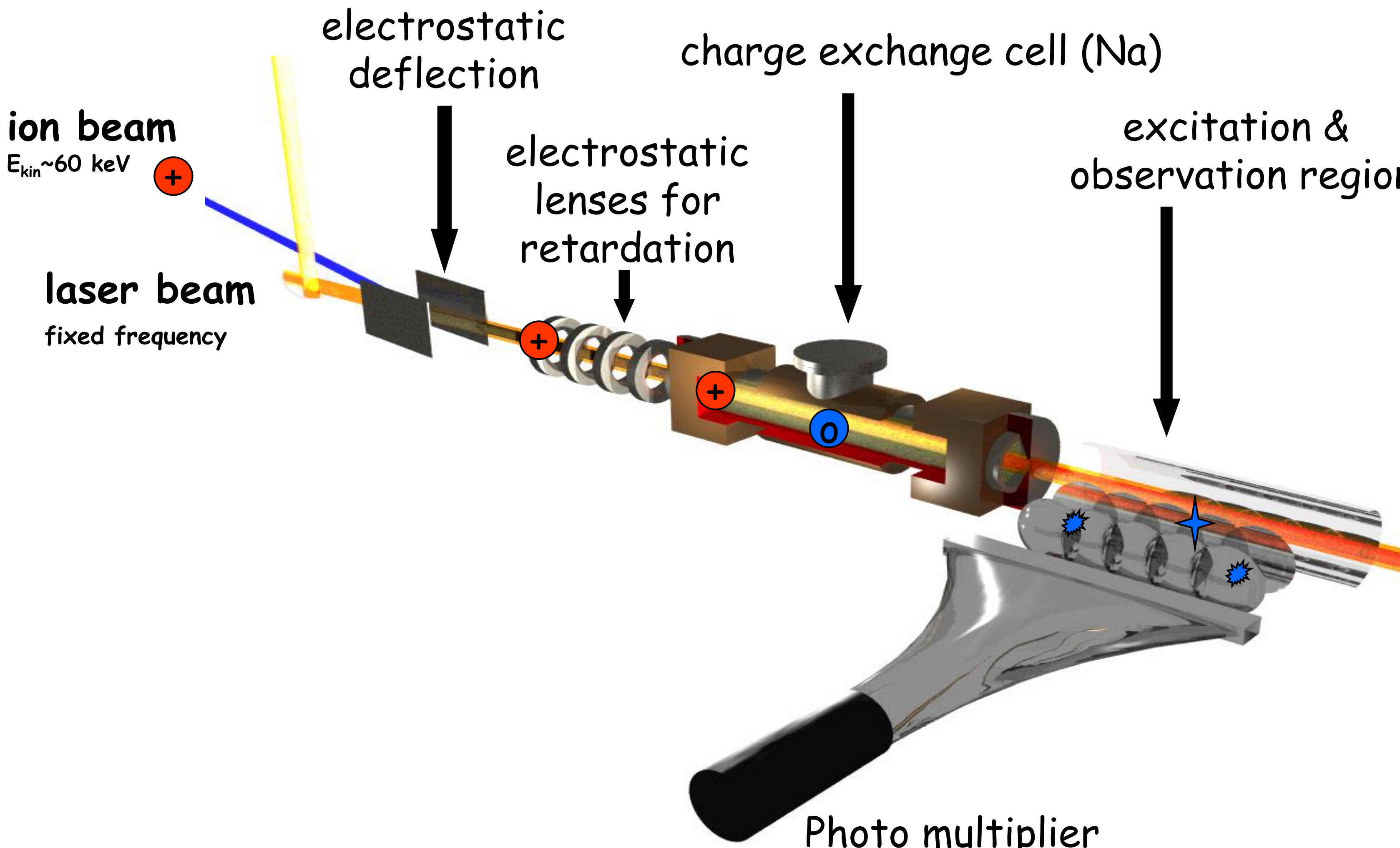
ISOLDE

RILIS

- **Resonant Ionisation Laser Ion Source**; one way to ionise produced atoms
- Nd: YAG pumping dye or Ti:Sa lasers, with possibility of doubling to quadrupling
- Atomic physics: Used to determine ionisation schemes and ionising potential of chemical elements with no stable isotopes (e.g. polonium, astatine)
- Nuclear physics: laser spectroscopy -> electromagnetic ground state properties

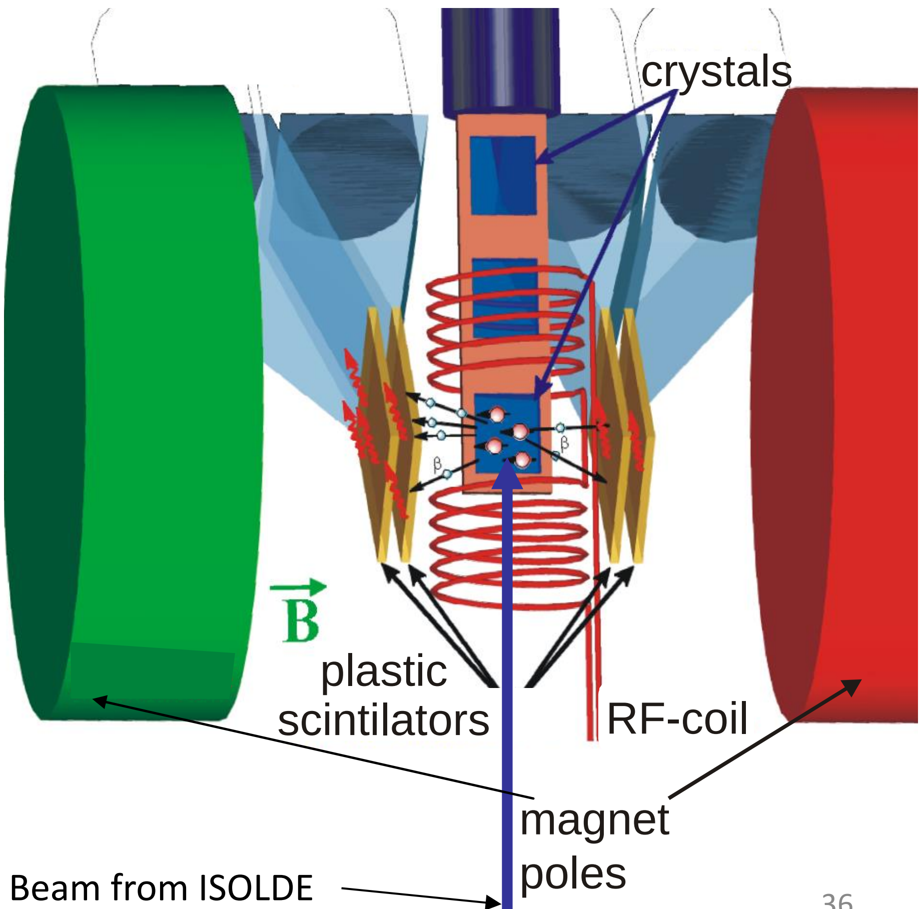


COLLAPS – laser spectroscopy



COLLAPS – beta-NMR

Beta particles (e-,e+) can be used as a detection tool, instead of rf absorption
(beams down to 1000 ions/s can be studied)



Beam from ISOLDE

Measured asymmetry:

$$A = \frac{N(0°) - N(180°)}{N(0°) + N(180°)}$$

Results:
Magnetic and electric moments of nuclei
(position of last nucleons, shapes)