Precision laser spectroscopy and applications
--From atoms to radioactive isotopes

Using laser spectroscopy experiments at ISOLDE-CERN as examples

Xiaofei Yang
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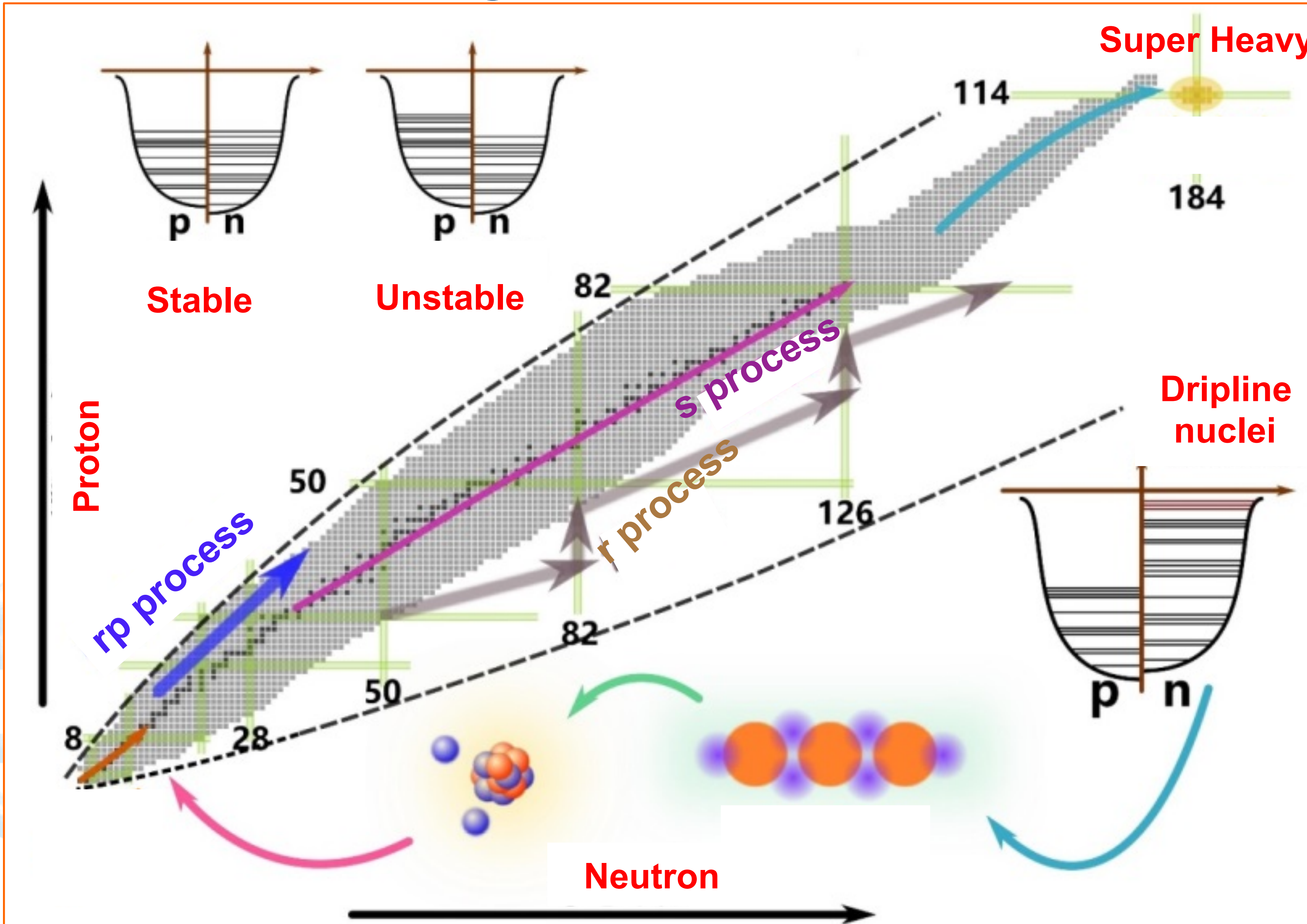
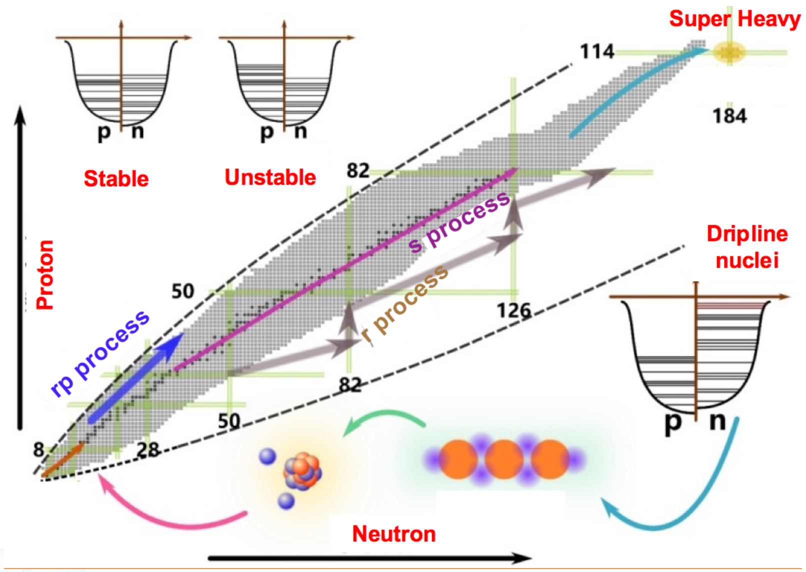
Exploring the nuclear landscape



Stable Nuclei: ~ 300 “Known Nuclei”:~3000 Theory predicting :~ 8000

To understanding ……

---from the view of nuclear structre



- How does the nuclear chart emerge from fundamental interactions?
- How does nuclear structure evolve across the nuclear landscape?
- What shape can nuclei adopt?
- How complex are nuclear excitations?
- *What are the limits of existence of nuclei?*
- ……….

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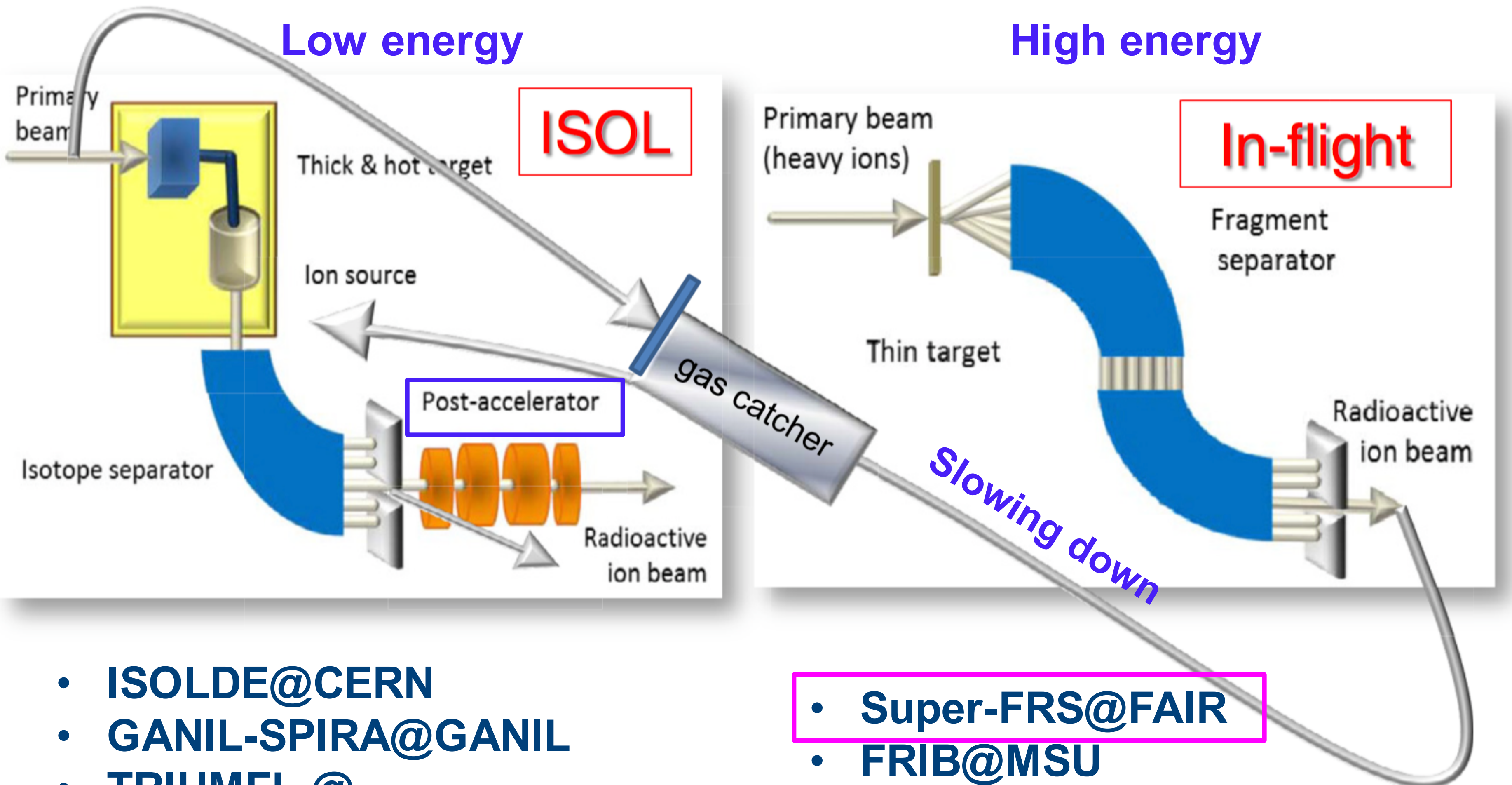
Two approaches to produce radioactive beams



- ISOLDE@CERN
- GANIL-SPIRA@GANIL
- TRIUMFL @
- EUROSOL (planned)

- Super-FRS@FAIR
- FRIB@MSU
- BigRIPS, RIPIS@RIKEN

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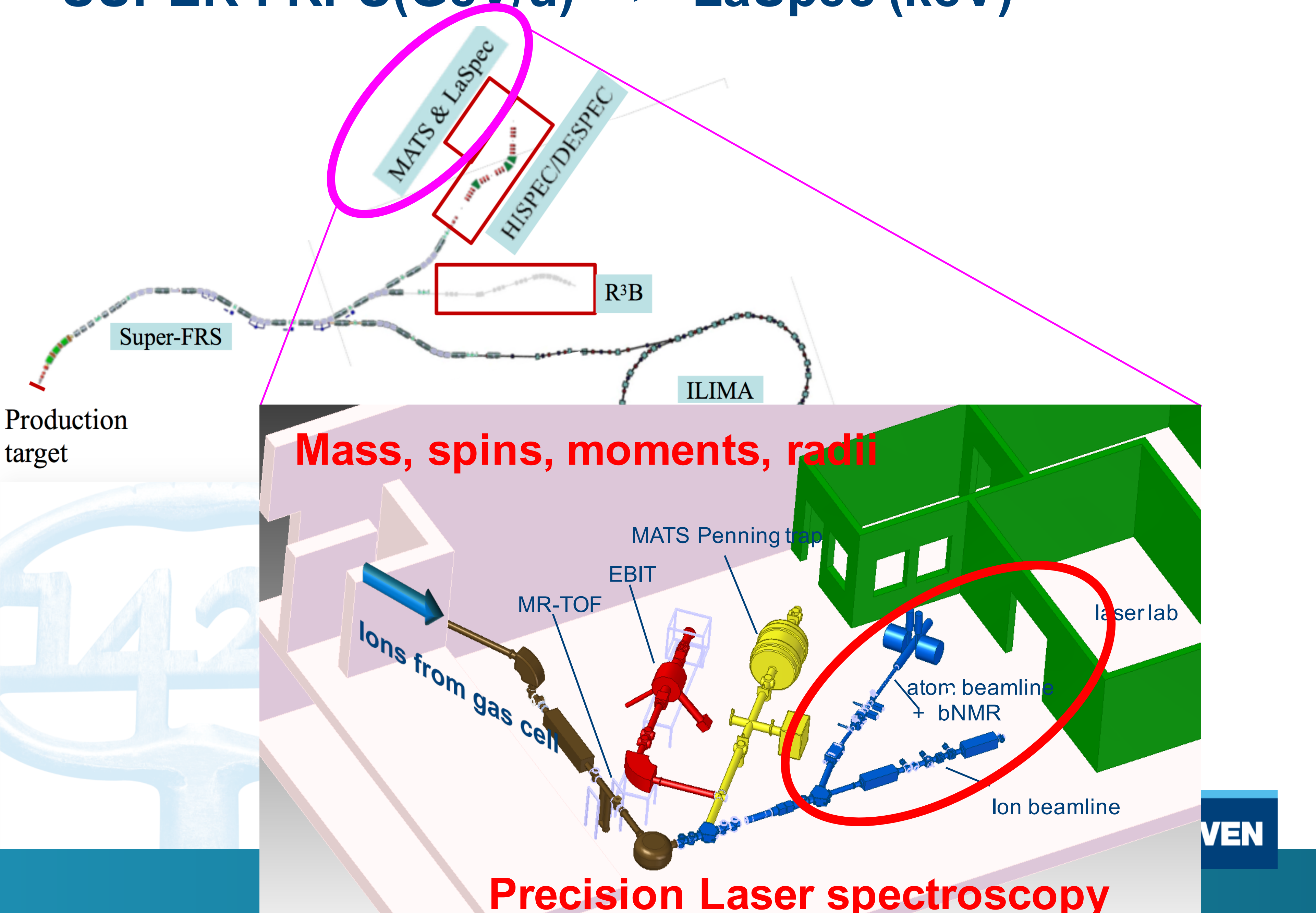
Phys. Scr. T152 (2013) 014023 (24pp)

SUPER-FRPS(GeV/u) -> LaSpec (keV)



Outline :

- **What & why laser spectroscopy**
  - ➢ Electronic energy level and Hyperfine structure (HFS)
  - ➢ Nuclear properties involved in the HFS

- **Laser spectroscopy for nuclear physics studies**
  -- probing the radioactive (RI) isotopes
  - ➢ Collinear laser spectroscopy (COLLAPS) @ISODLE
  - ➢ Collinear resonant ionization spectroscopy @ISOLDE
  - ➢ Few examples of nuclear structure studies via laser spectroscopy

- **Laser spectroscopy for applications**
  --Producing and manipulating radioactive isotopes
  - ➢ Producing & purification of RI beam with laser resonant ionization
  - ➢ Laser polarized RI (VITO) at ISOLDE
    -- applications to interdisciplinary researches

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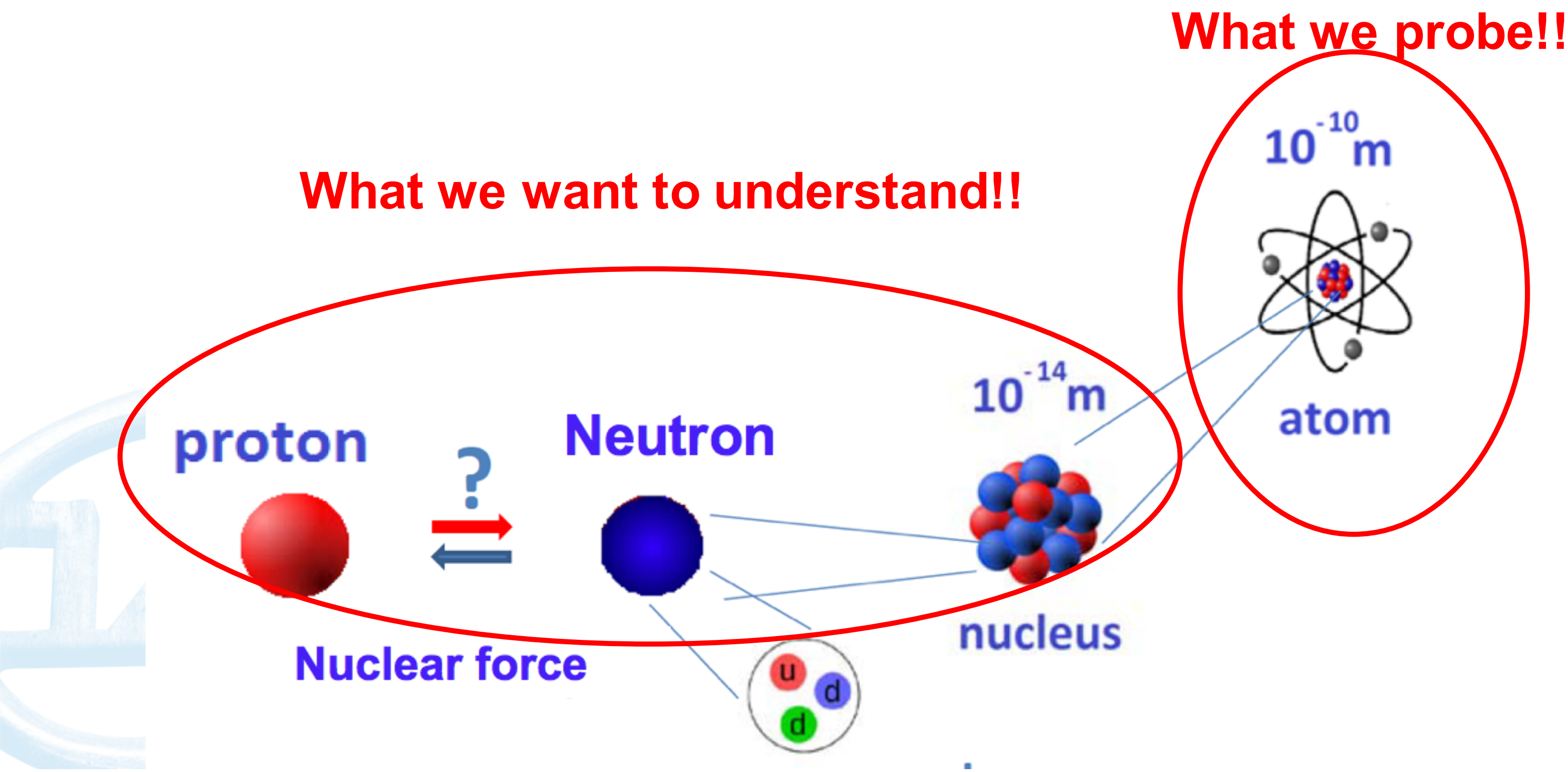
What is Laser spectroscopy

Using laser as a prober for all kinds of research?

But here, I will talk of **laser spectroscopy of radioactive isotopes** for **nuclear physics studies and applications**

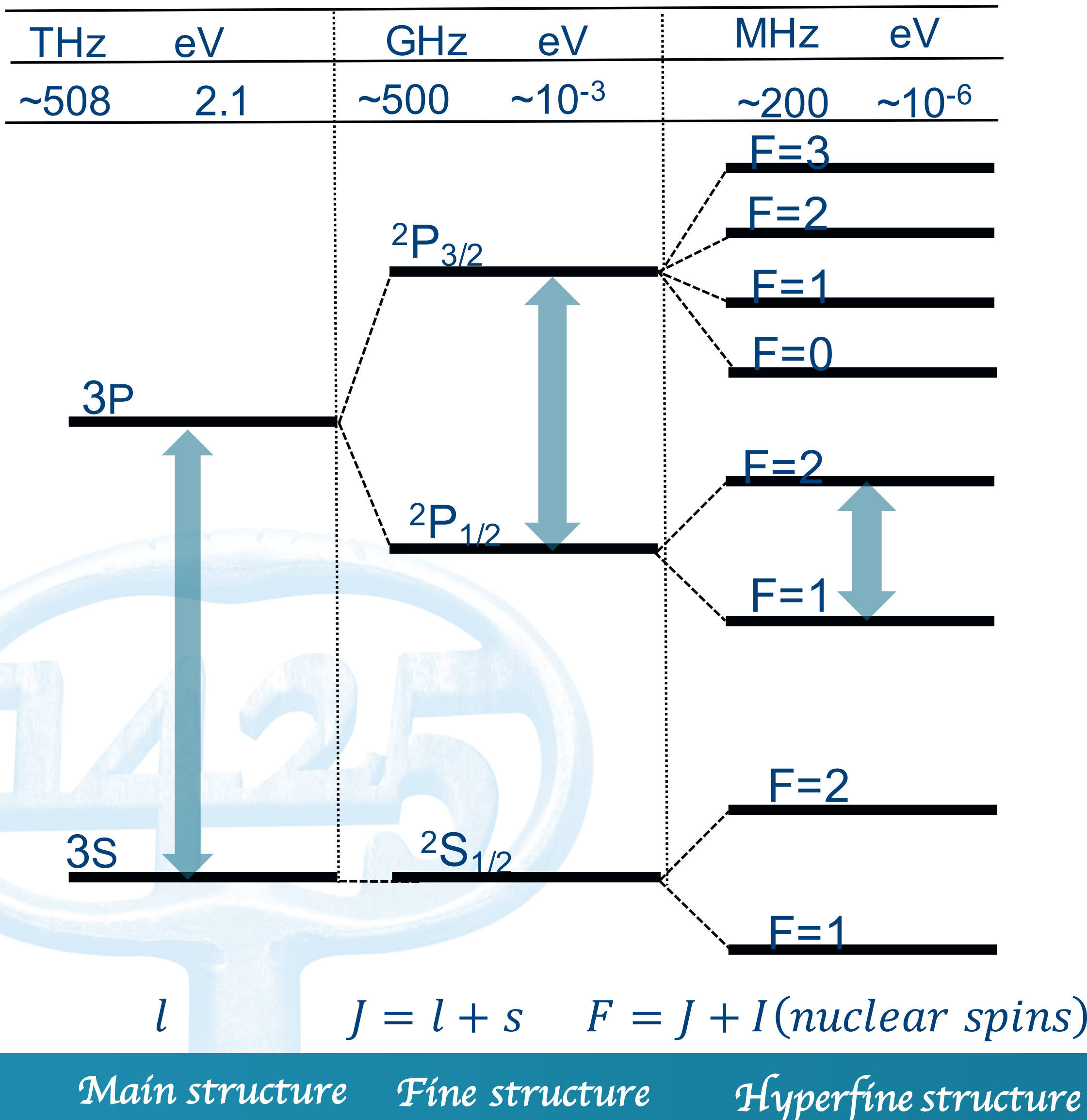


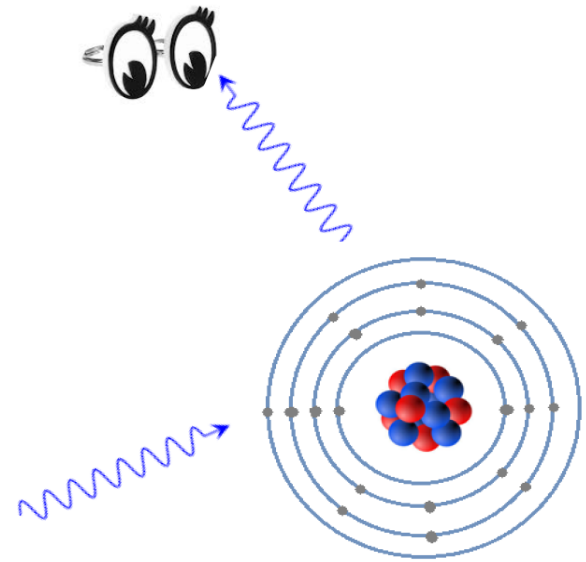
How to describe the interaction between nucleons: Nuclear force?
Limits of existence: How many nucleus can be attached in a nucleus?
What is the impact of nuclear structure at different time/energy/size scales?

What is Laser spectroscopy

--Spectroscopy of electronic transitions of atoms/ions

Electronic energy level structure





Only in **HFS** precision level, **nuclear information** are involved

How??

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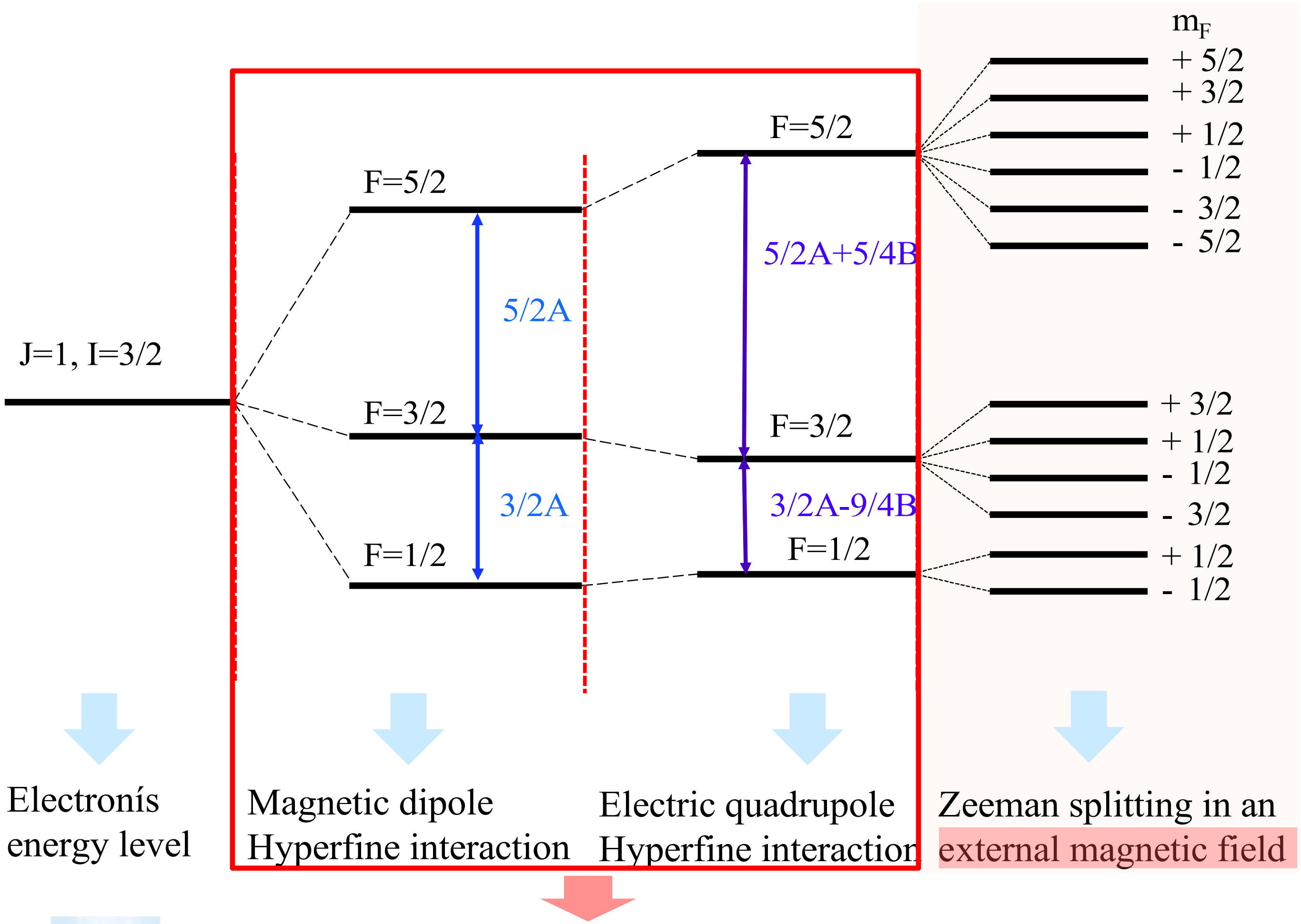
Probe the hyperfine structure

$$\Delta E = A \cdot K/2 + B \cdot \{3K(K+1)/4 - I(I+1)J(J+1)\}/\{2(2I-1)(2J-1)IJ\}$$

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



Usually, we probe this part!!

Probe the hyperfine structure

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

Atomic parameters

- Magnetic dipole HF parameter

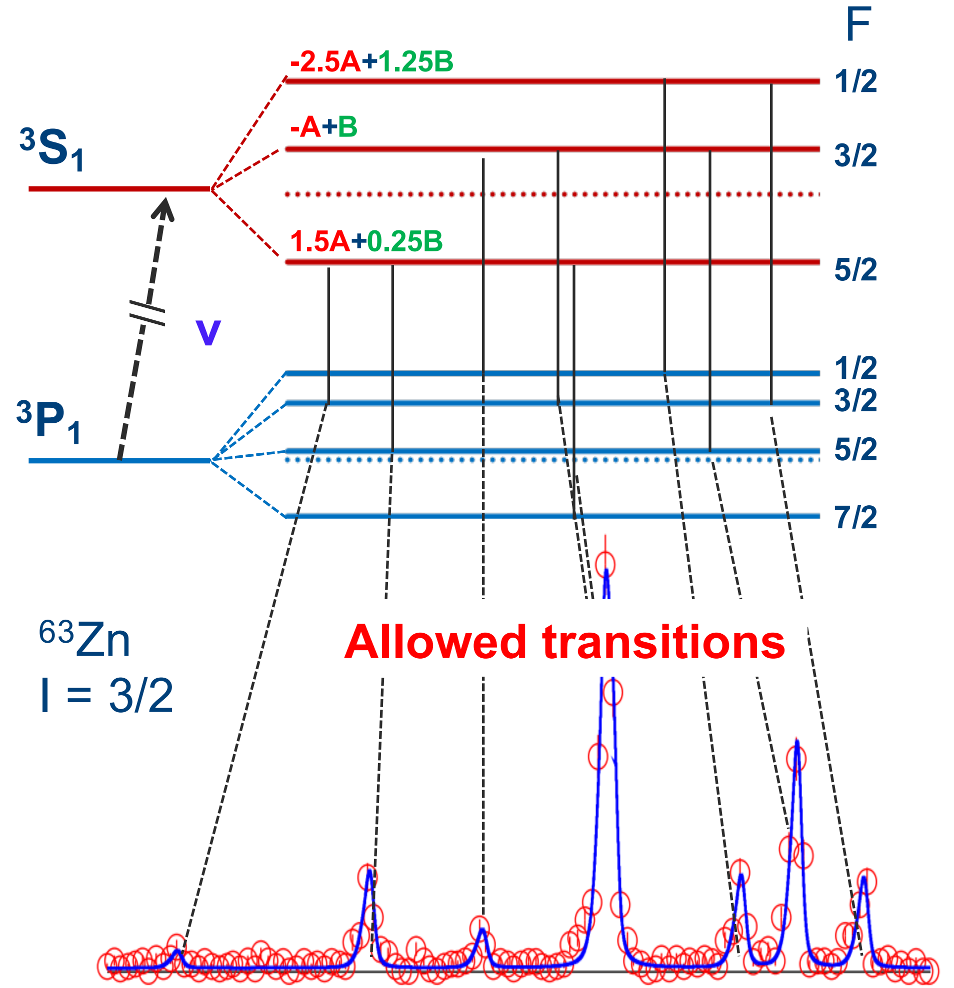
$$A = \frac{\mu_I B_J}{IJ}$$ **I, μ**

- Electric quadrupole HF parameter

$$B = eQV_{zz}$$ **Q**

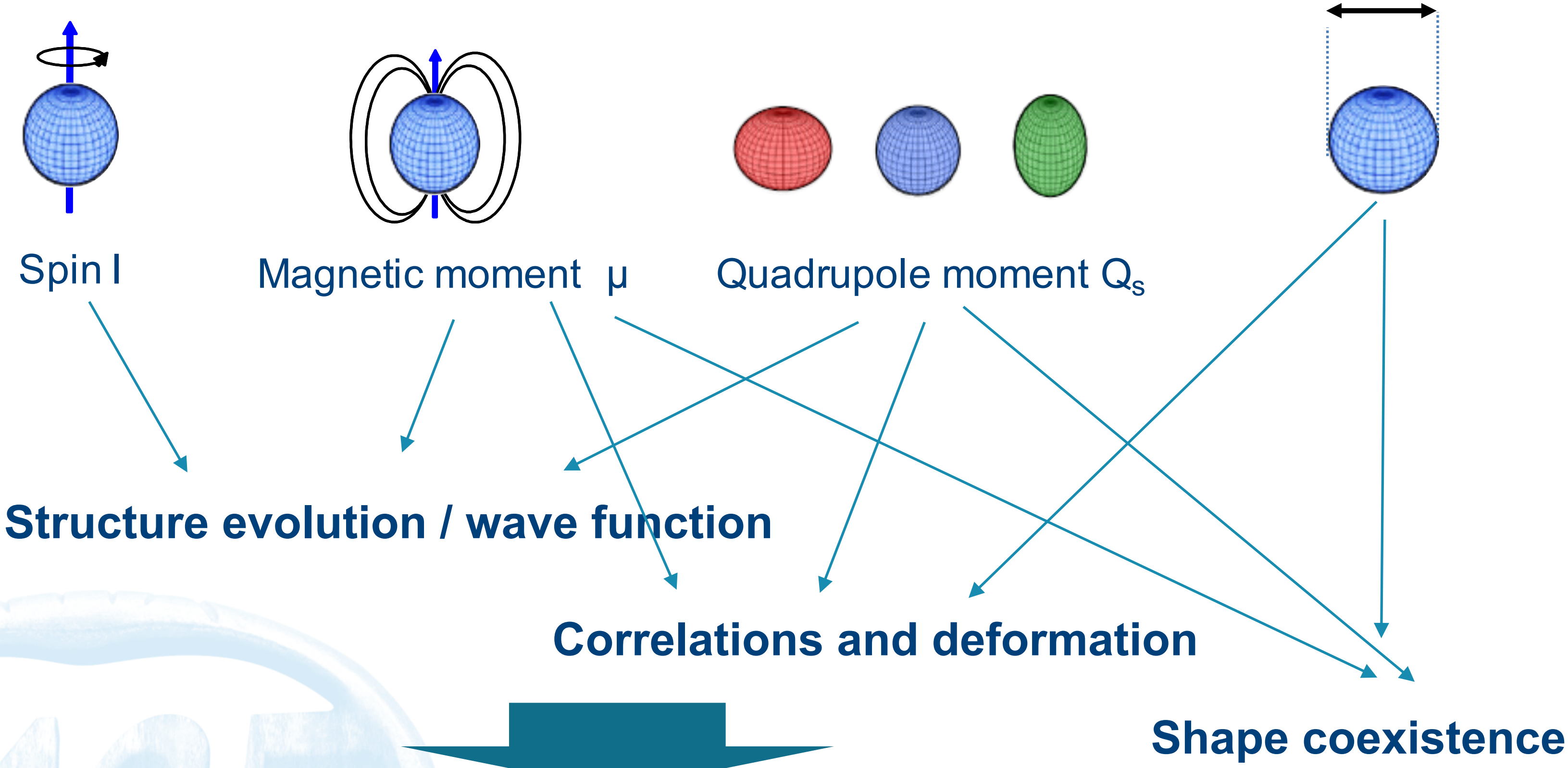
- Centroid ν_0
  Isotopes shift **$\langle r^2 \rangle^{1/2}$**

$$\delta\nu_{\mathrm{FS}} = \frac{2\pi Z}{3}\Delta|\psi(0)|^2 \, \delta\langle r^2\rangle^{A,A'}$$



$$\gamma = \nu_0 + (\alpha_u - \alpha_l R_A)A_u + (\beta_u - \beta_l R_B)B_u \qquad R_A = A_l/A_u \qquad R_B = B_l/B_u$$

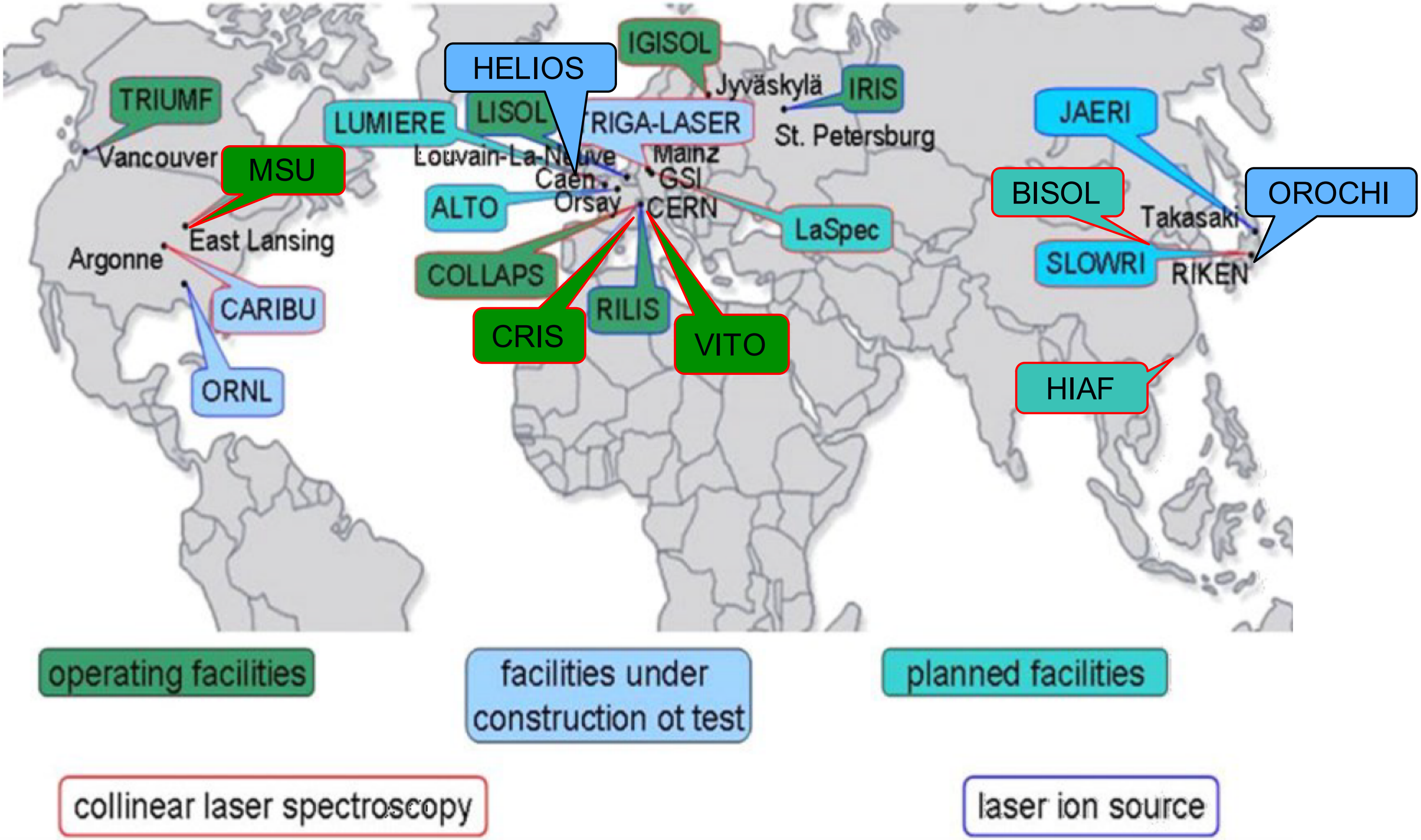
What we learn? Nuclear properties



Magicity and shell closure

Test state-of-the art nuclear theories

World-wide laser spectroscopy setups



- **Collinear laser spectroscopy**
- **Collinear resonance ionization spectroscopy**
- **In source spectroscopy**
- **Laser spectroscopy of trapped ions/atoms**

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Outline :

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Laser spectroscopy techniques at ISOLDE-CERN

- **Laser spectroscopy for nuclear physics studies**
  -- probing the radioactive (RI) isotopes

  - ➢ Laser spectroscopy experimental setups at ISOLDE
  - ➢ Few examples of nuclear structure studies via laser spectroscopy

- **Laser spectroscopy for applications**
  --Producing and manipulating radioactive isotopes

  - ➢ Producing & purification of RI beam with laser resonant ionization
  - ➢ Laser polarized RI (VITO) at ISOLDE
    -- applications to interdisciplinary researches

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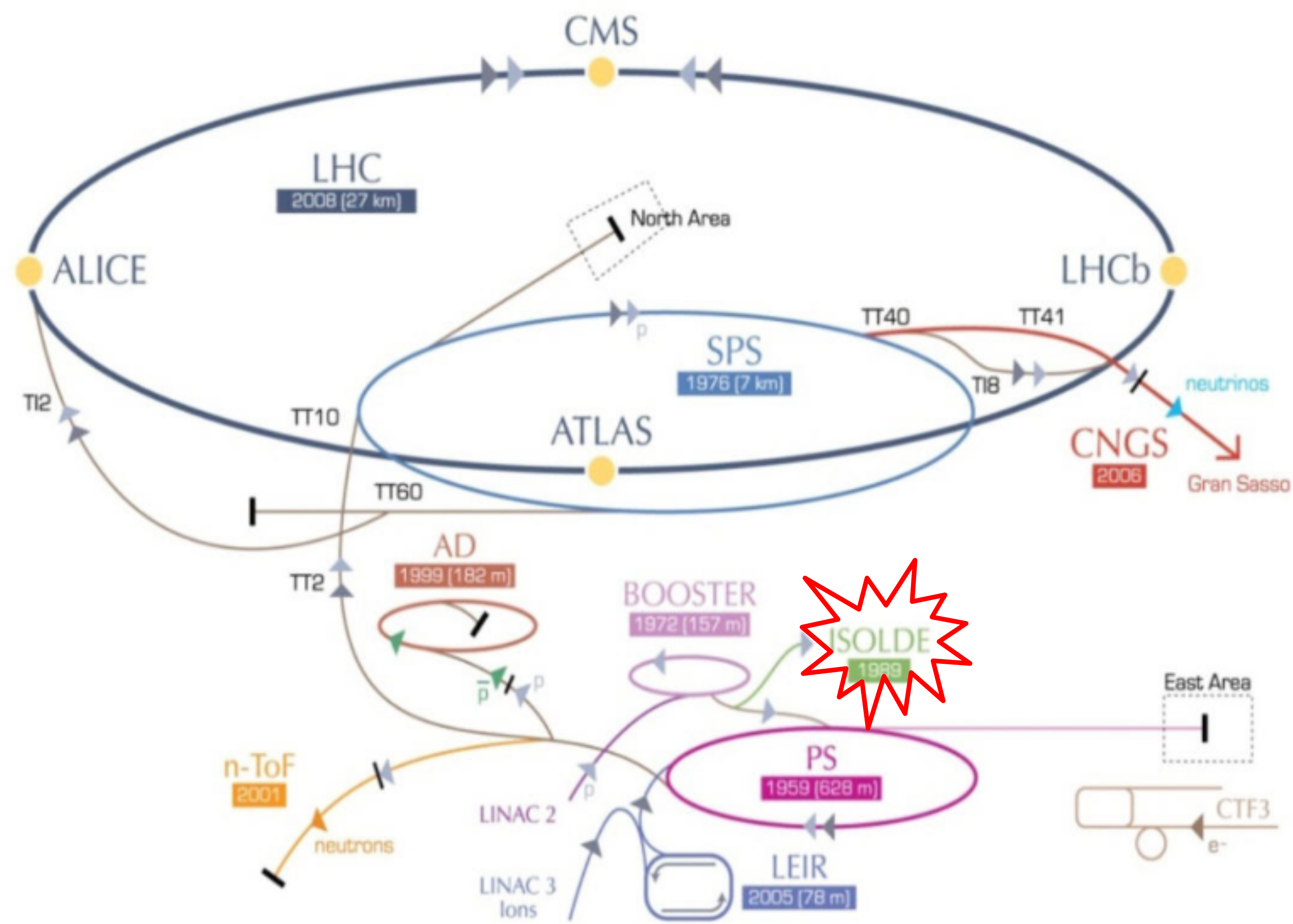
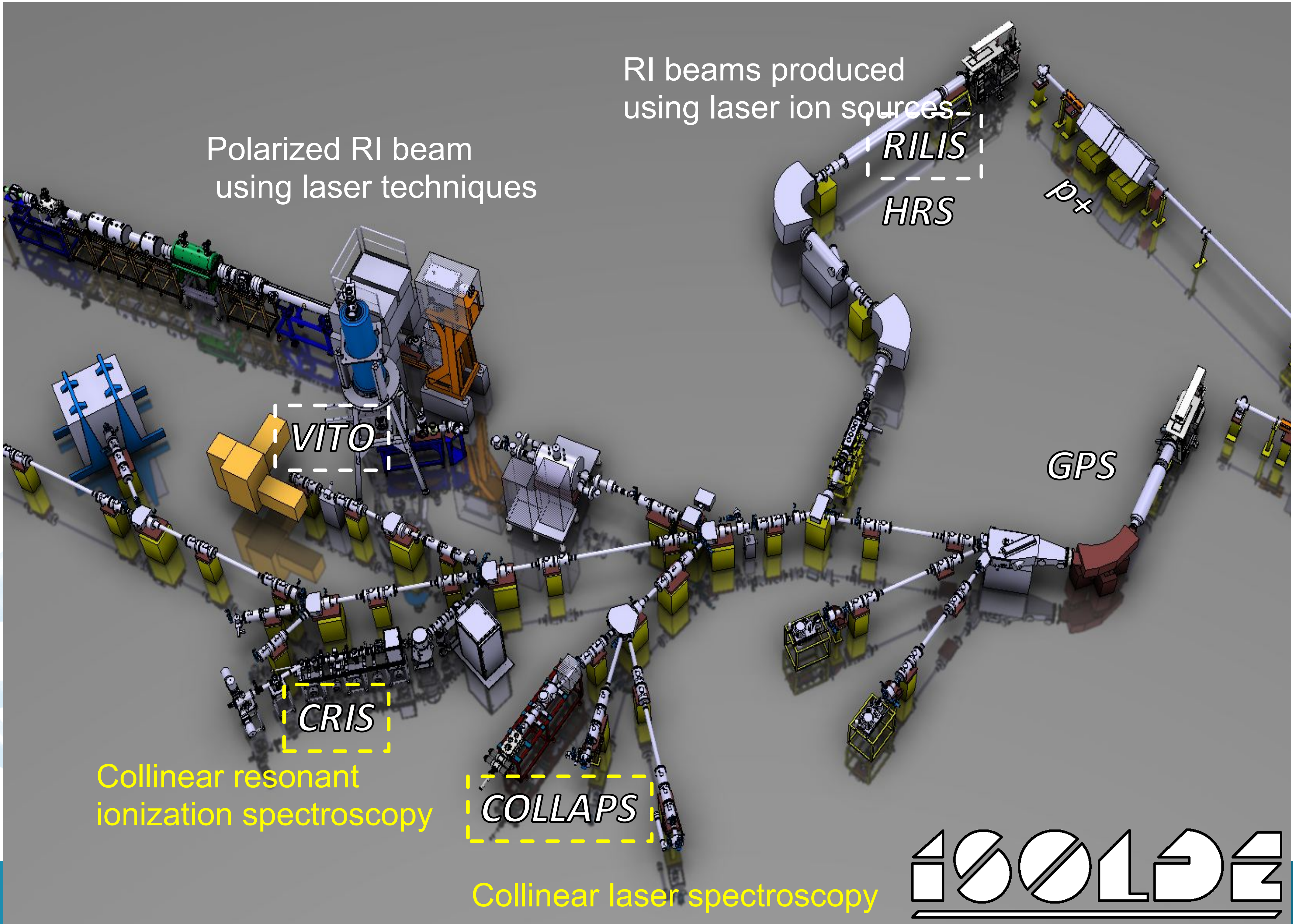
ISODLE at CERN



1.4GeV 2uA Proton beam + thick target => radioactive ion beams

The ISOLDE Radioactive Ion Beam facility

Laser spectroscopy setups at ISOLDE



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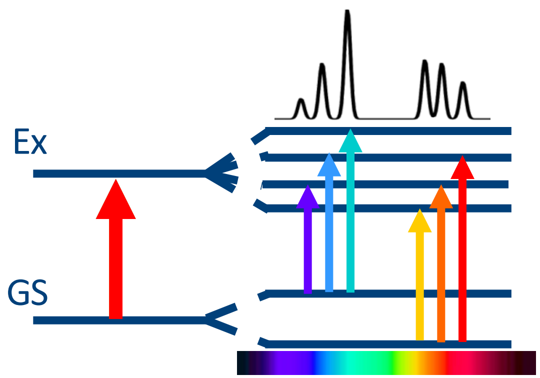
Two complementary high-resolution laser spectroscopy setups

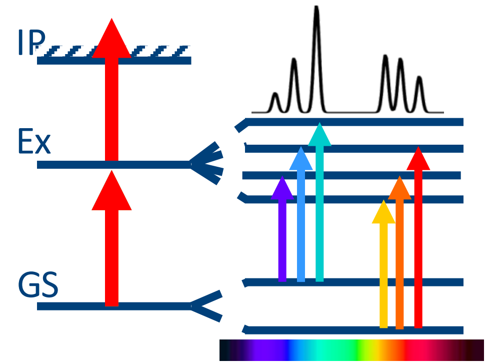
One laser beam



Photon detection

Collinear laser spectroscopy (COLLAPS)

Multiple laser beams



Ion detections

Collinear resonance ionization spectroscopy (CRIS)

High resolution <100MHz
Sensitivity : ~10^3 ions/s

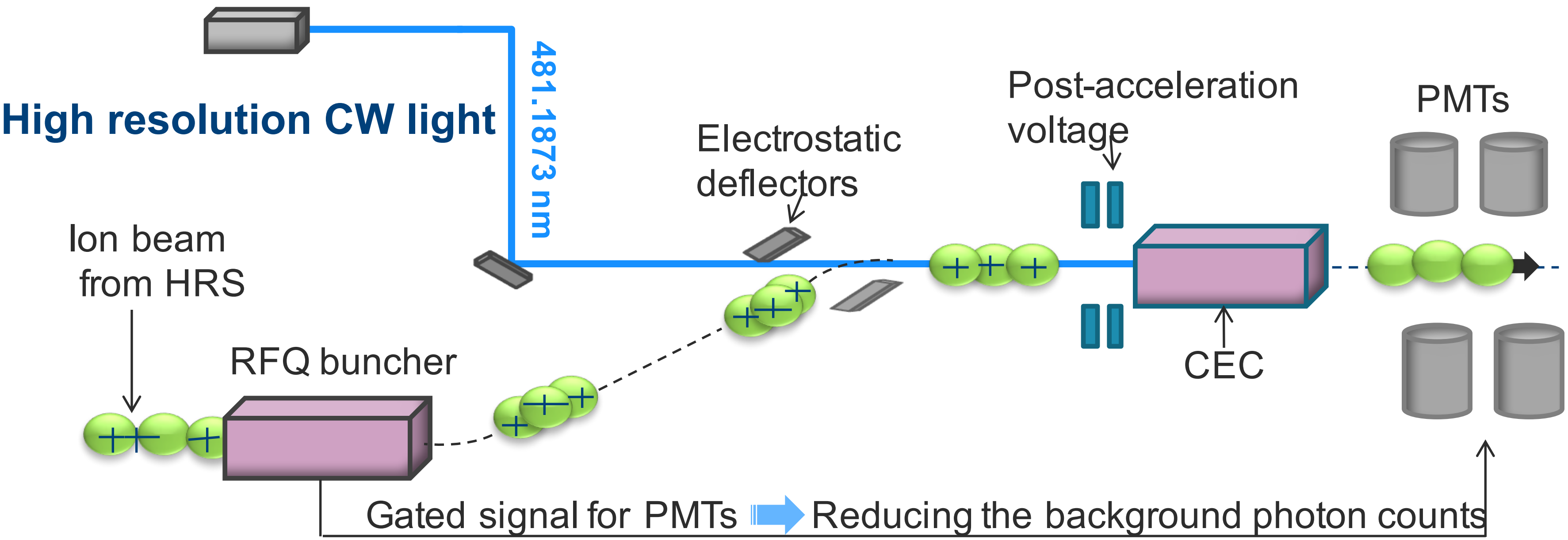
High resolution <100MHz
Sensitivity : down to 20 ions/s

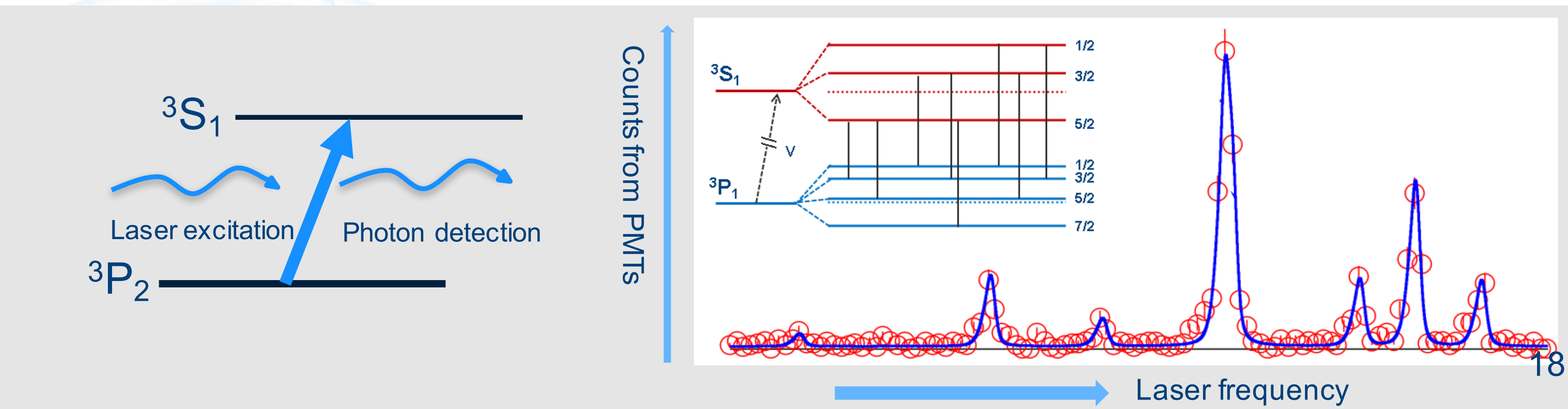
Versatile setups, can combine with beta-NMR and extended to high sensitivity measurements

Laser selected high-purity isomer beam
--- for decay spectroscopy studies

Journal of Physics G: Nuclear Physics, Vol. 44, No. 6, 2017   Physical Review X, Vol. 4, No. 1, 011055, 2014

COLLAPS@ISOLDE-CERN





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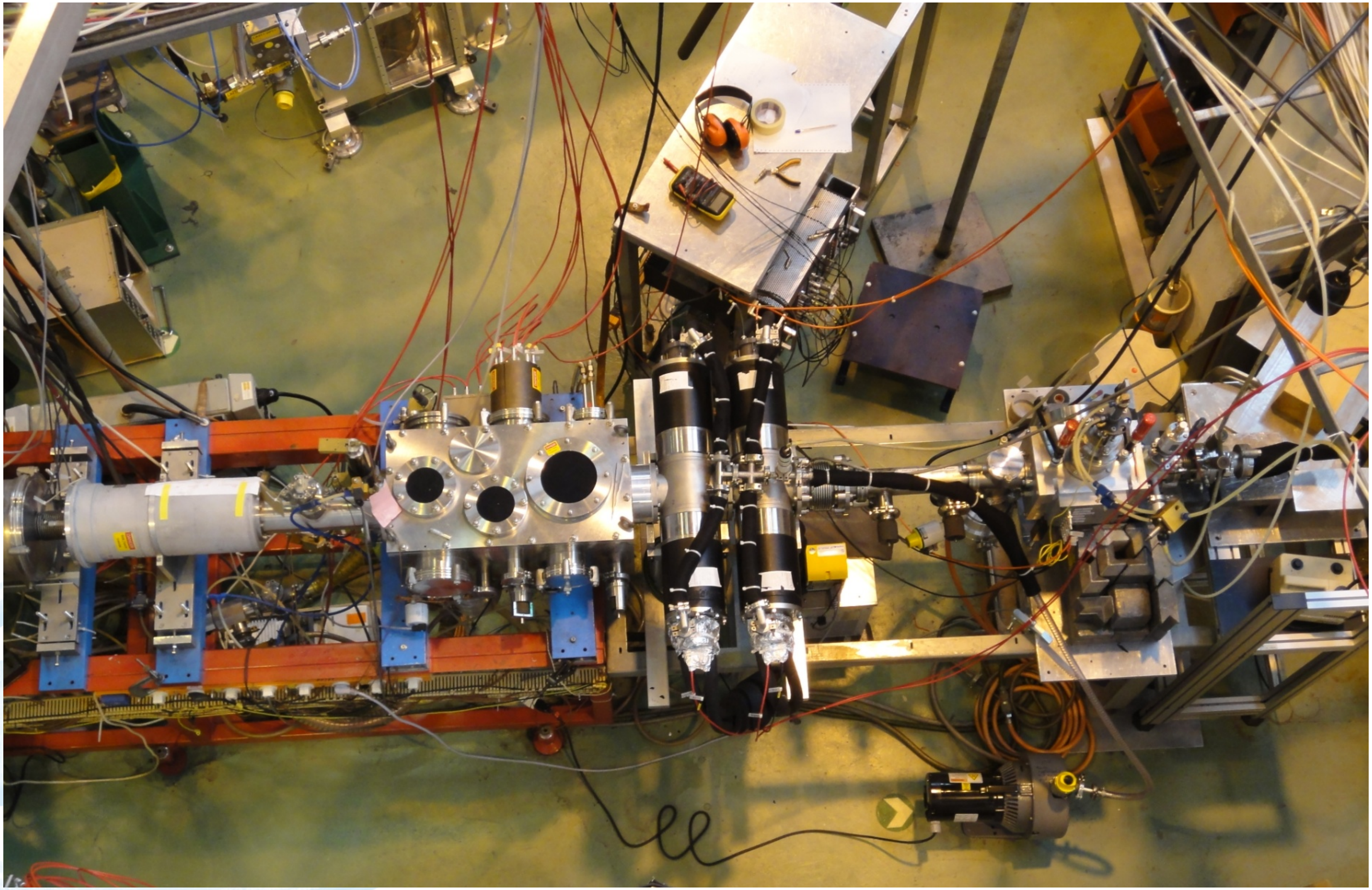
Well demonstrated technique for high resolution

COLLAPS@ISOLDE-CERN



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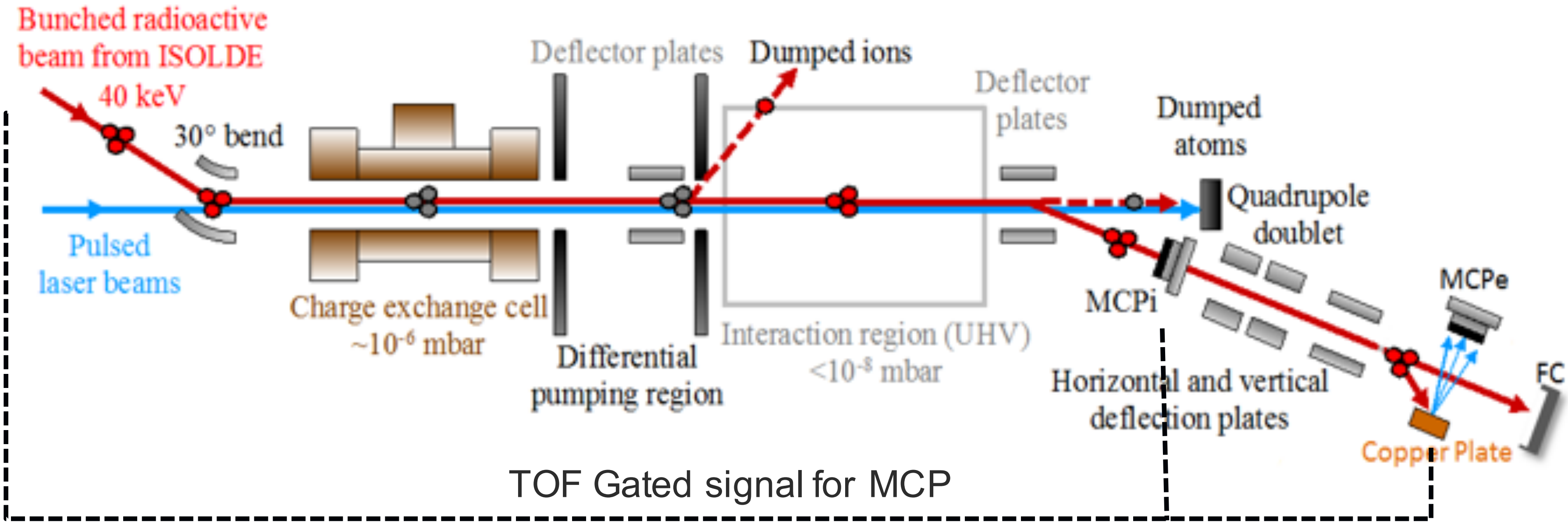
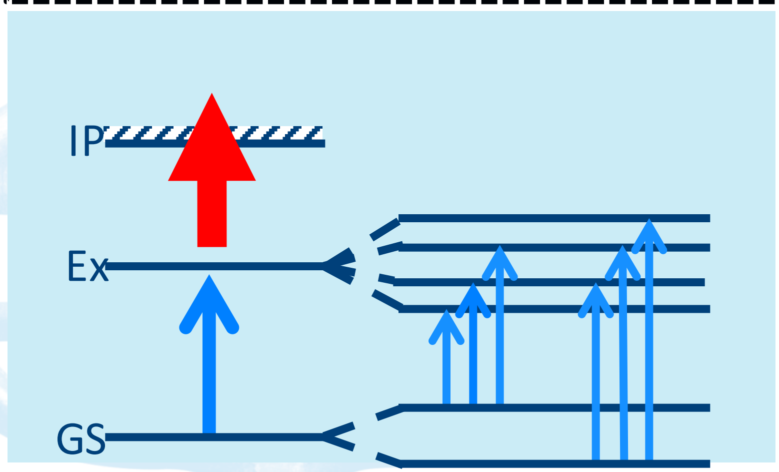
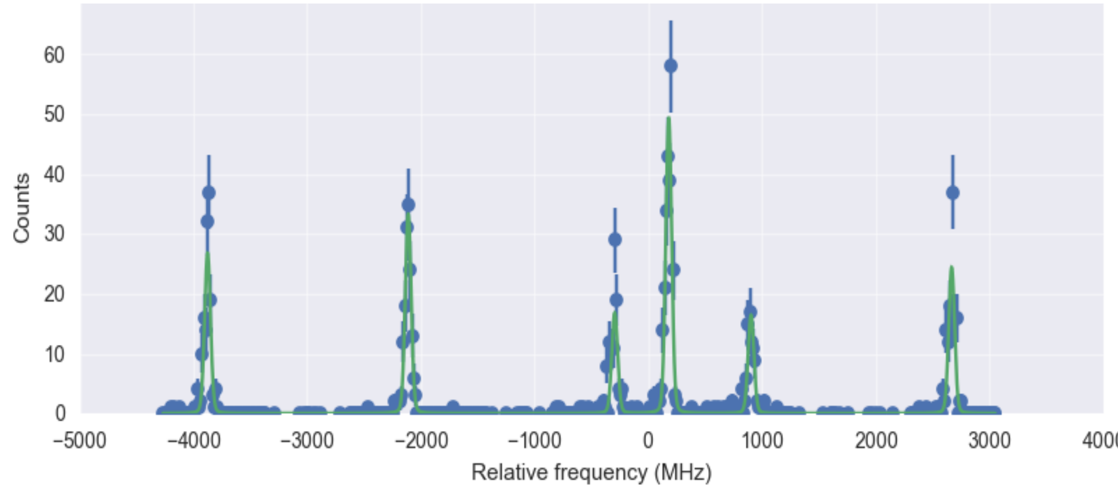
CRIS@ISOLDE - CERN







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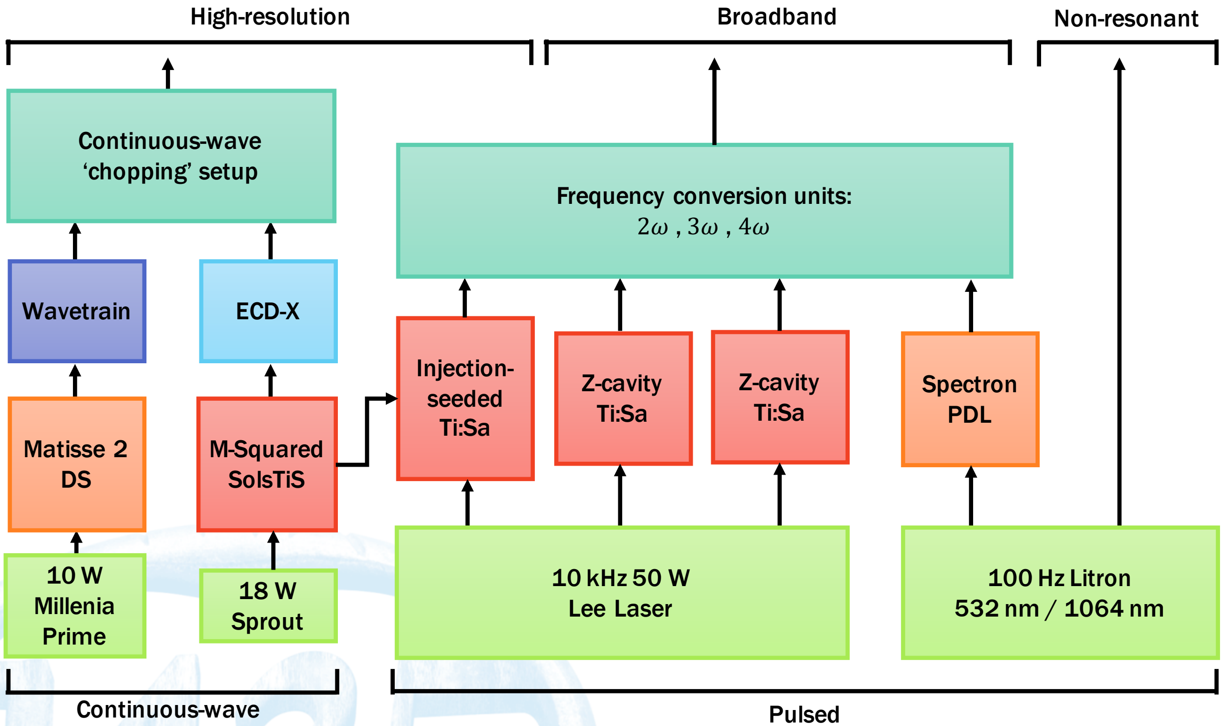
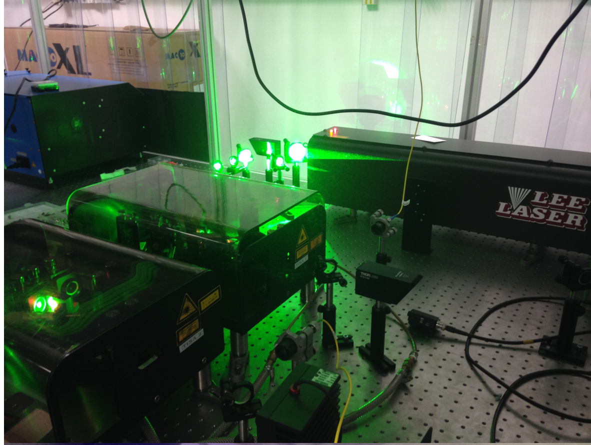
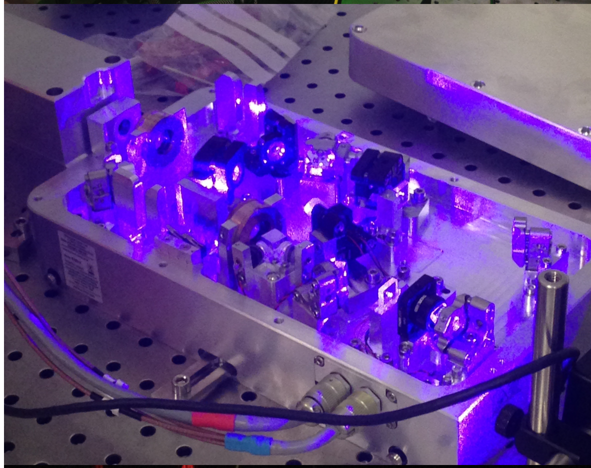
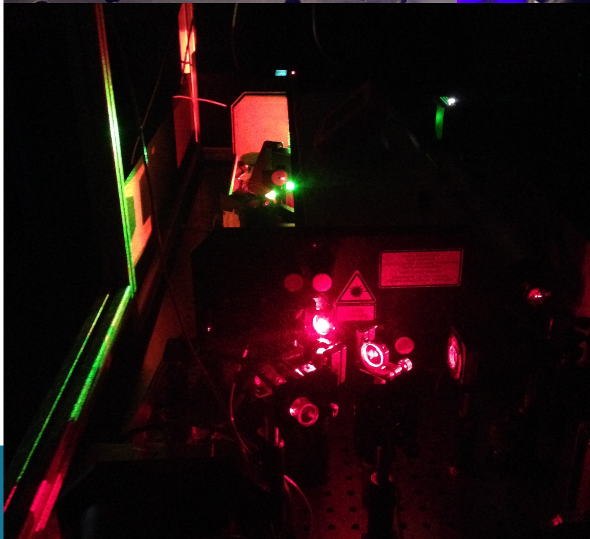
R.P. de Groote et al., data May 2016

CRIS laser SYSTEM







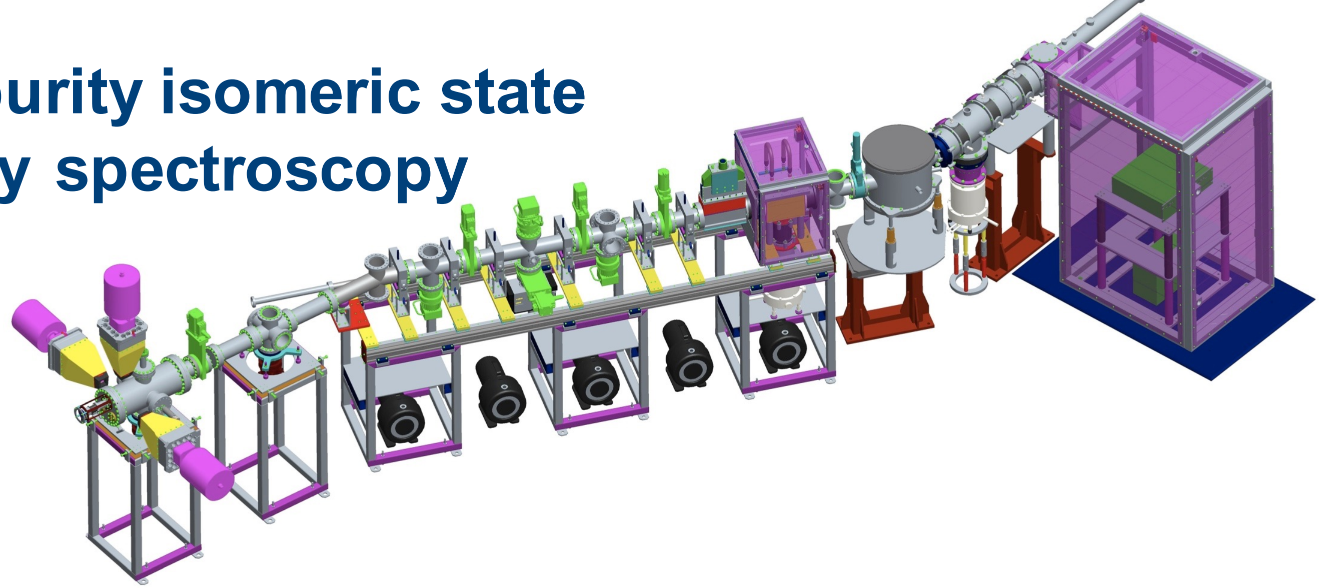


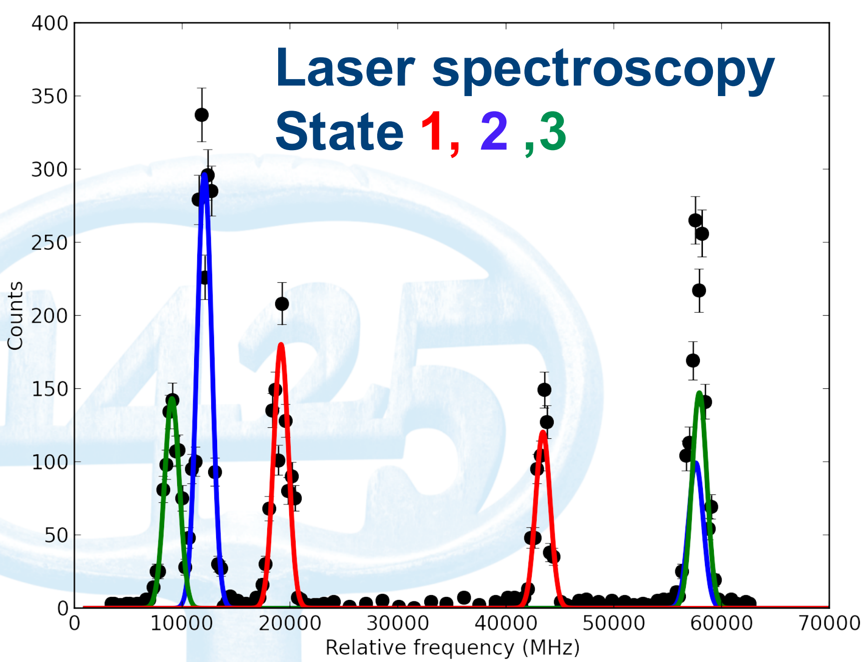
High resolution pulsed light (MHz)

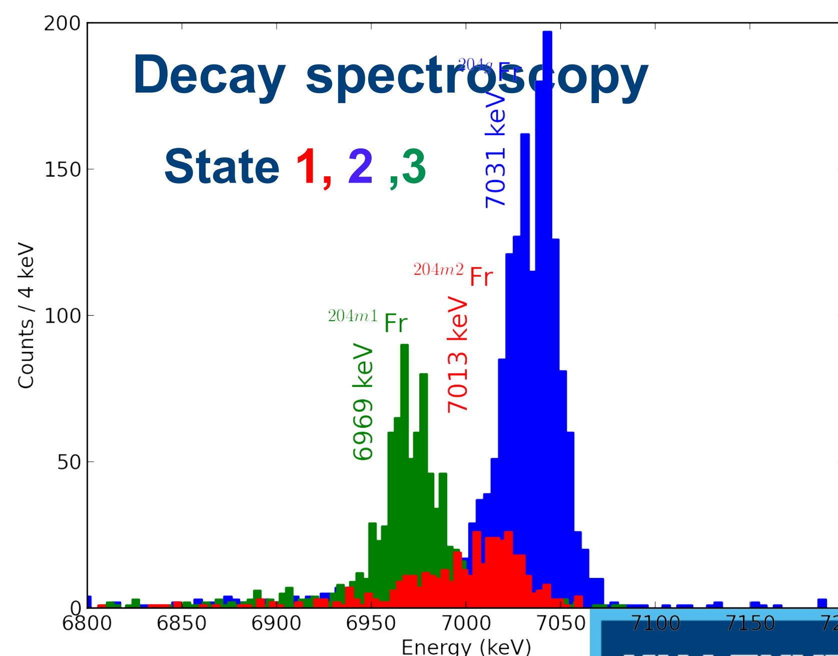
+

high power/low resolution pulsed laser (GHz)

Laser selected purity isomeric state
---Decay spectroscopy







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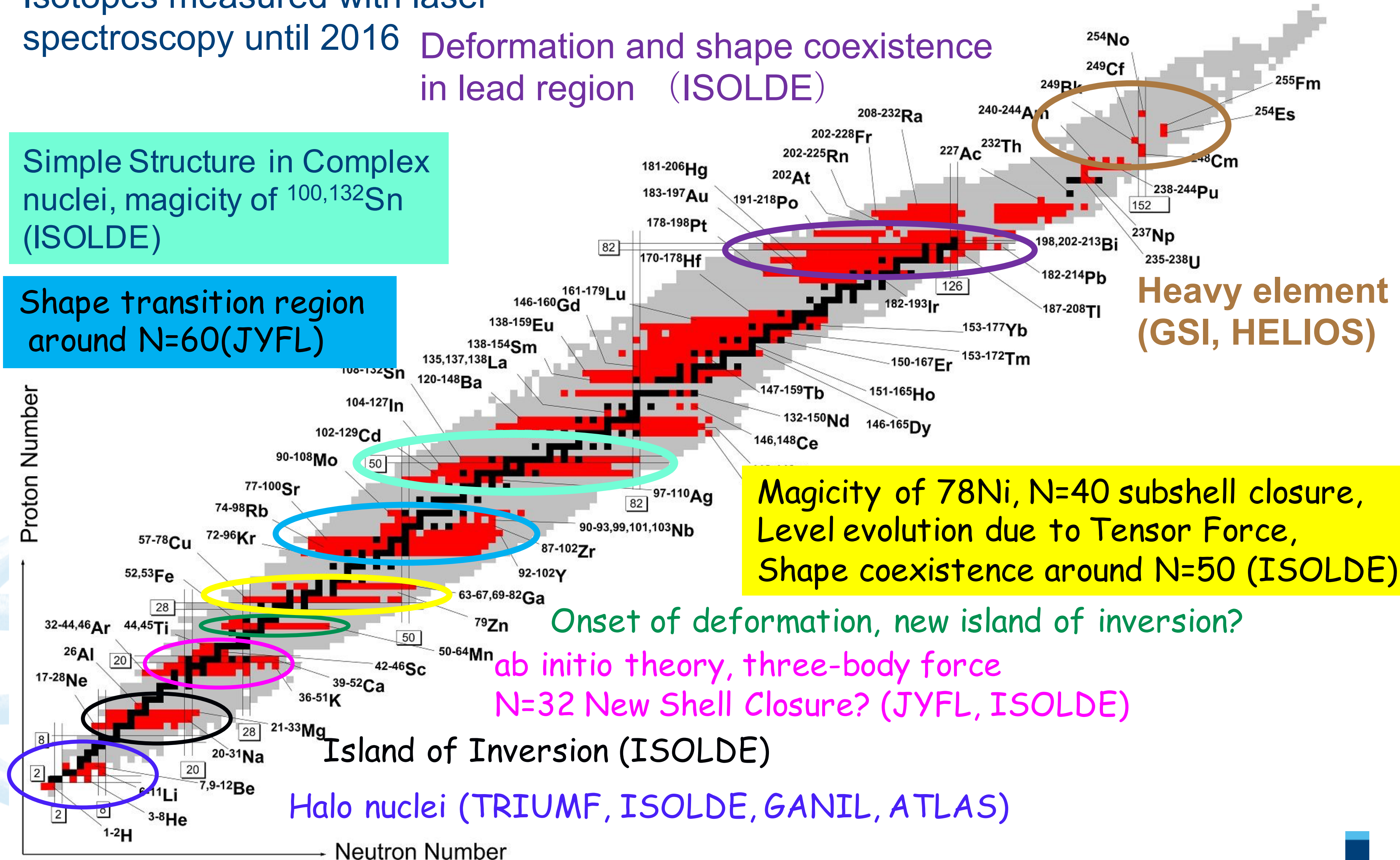
Contribution of laser spectroscopy to nuclear chart

Isotopes measured with laser spectroscopy until 2016



Selected results from laser spectroscopy

★ Halo nuclei (TRIUMF, ISOLDE, GANIL, ATLAS)

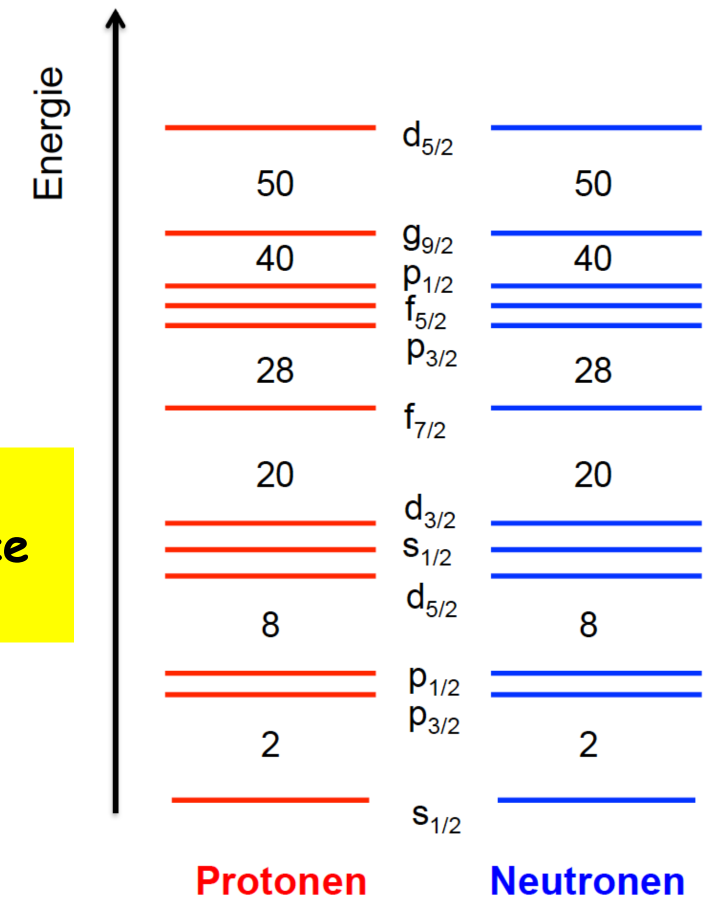
Light system

★ Magicity of 78Ni, N=40 subshell closure, Level evolution due to Tensor Force, Shape coexistence around N=50 (ISOLDE)

Middle mass region

★ Deformation and shape coexistence in lead region （ISOLDE）

Heavy mass region



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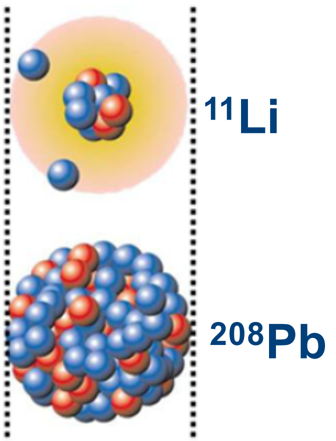
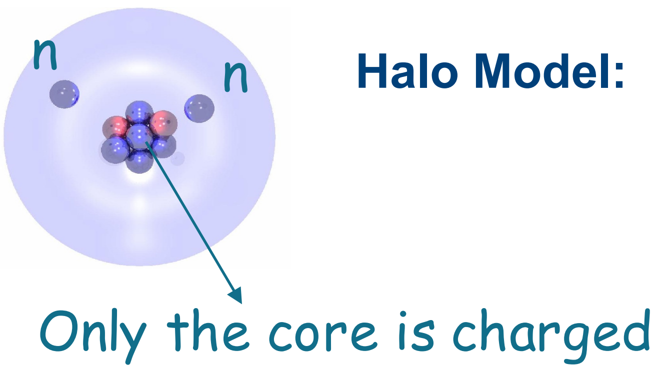
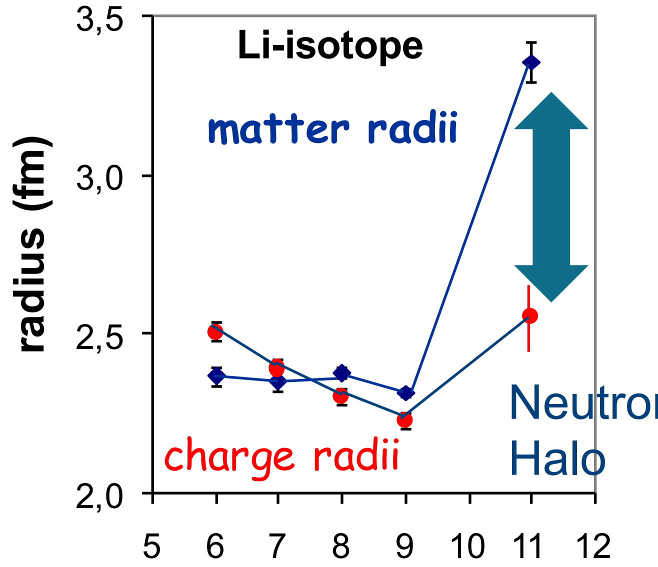
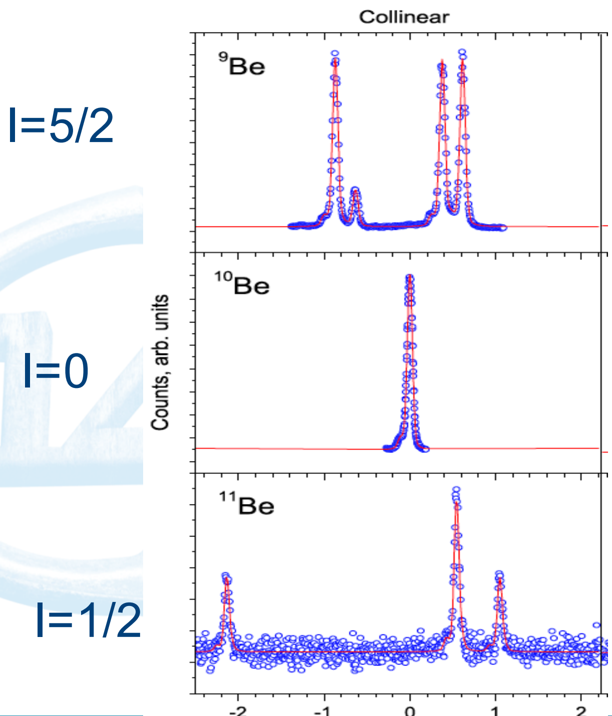
Halos and Clustering (TRIUMF, ISOLDE,GSI …)

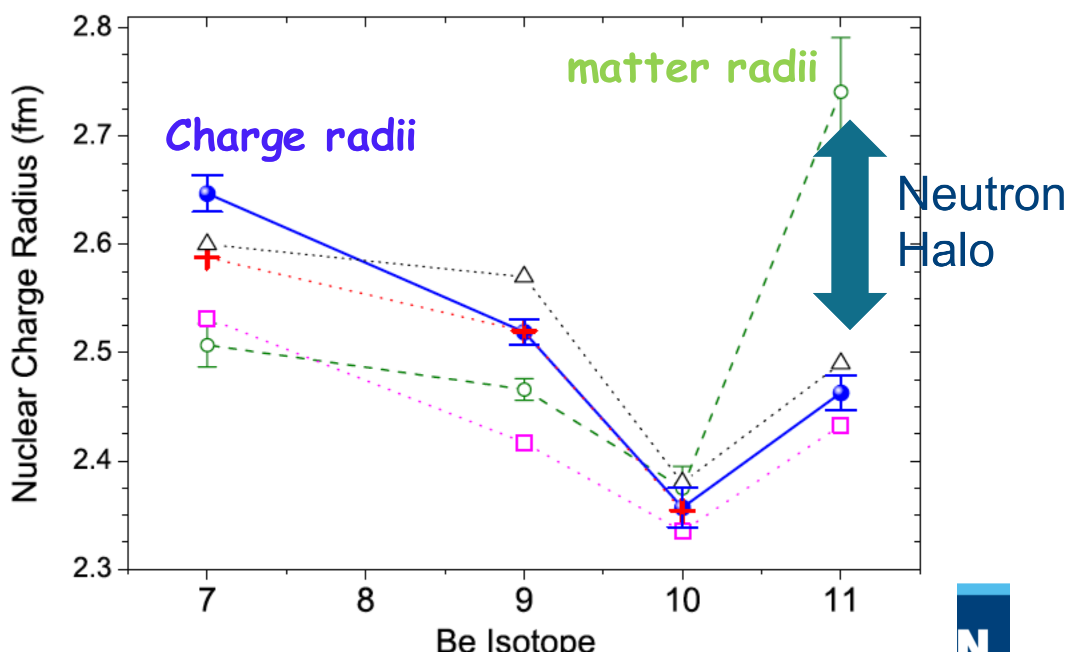




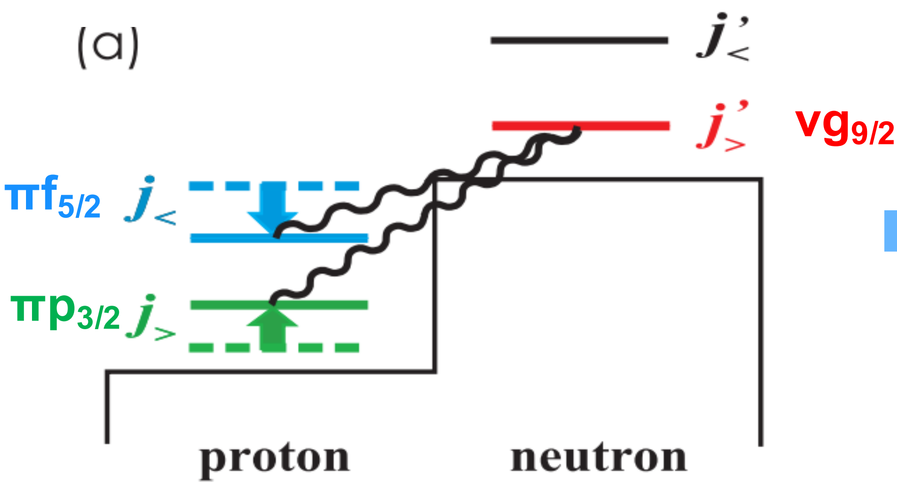
Halo Model:

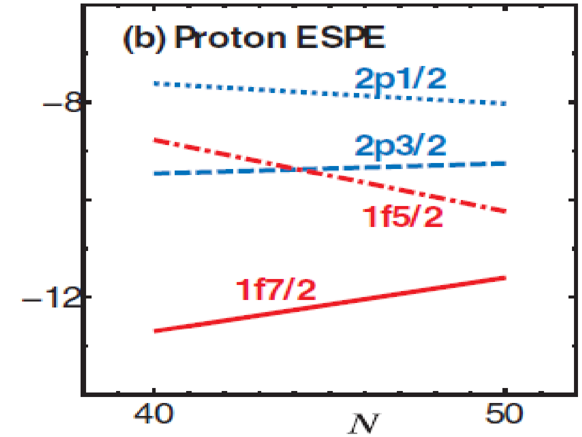




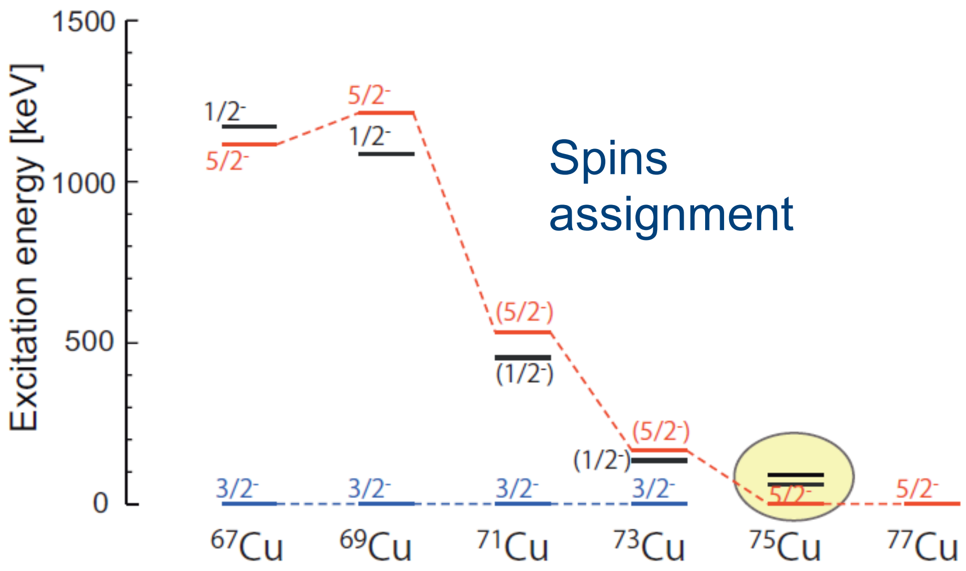


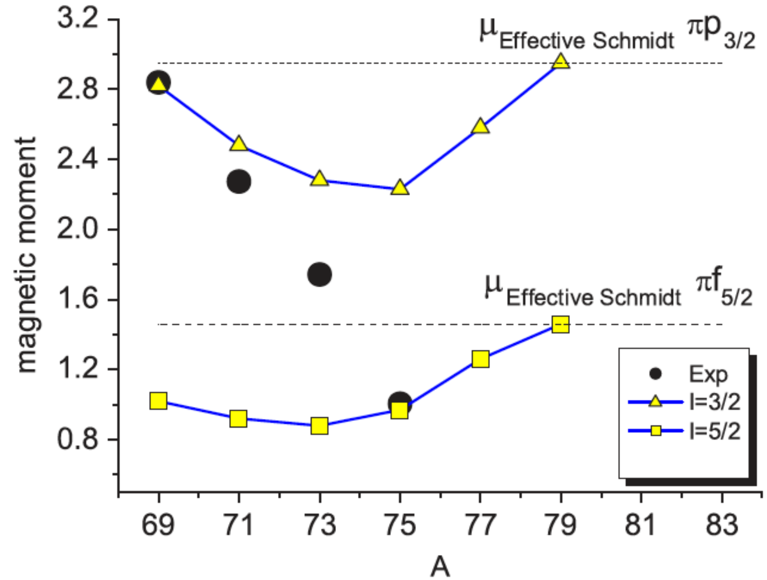
Magicity of 78Ni, N=40 subshell closure, Level evolution due to Tensor Force, Shape coexistence around N=50 (ISOLDE)





T. Otsuka et al, PRL **95**, 232502 (2005)
T. Otsuka et al, PRL **104**, 012501 (2010)

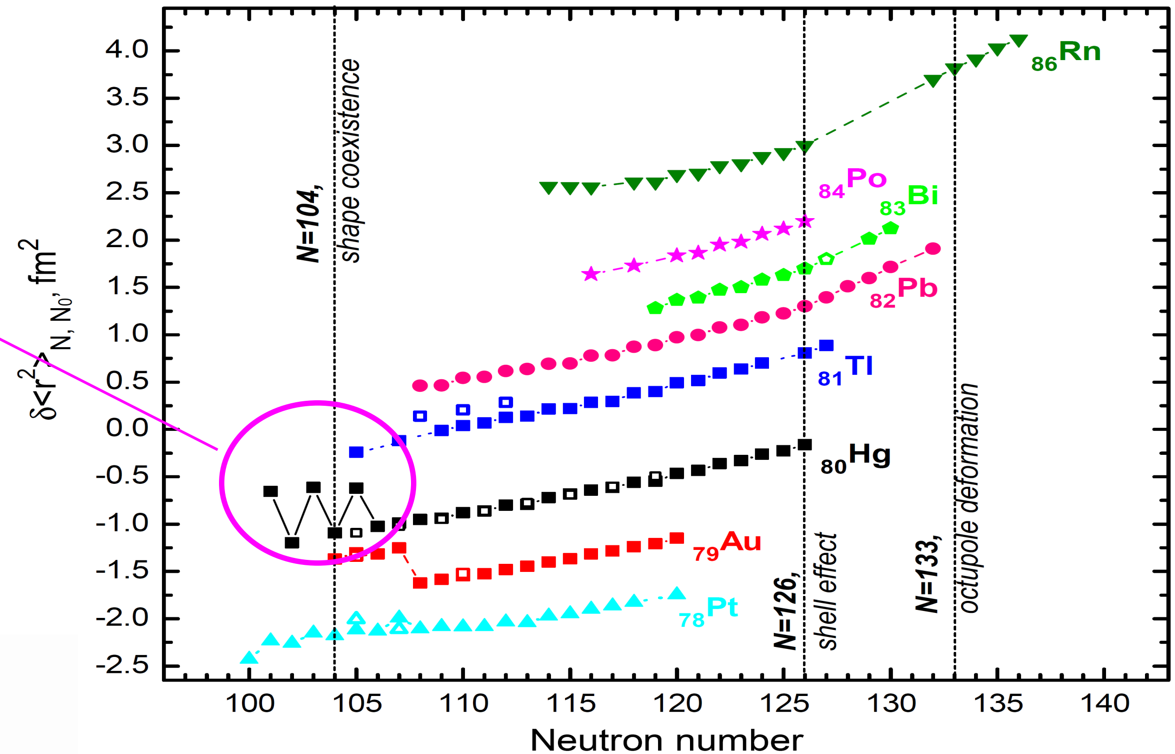


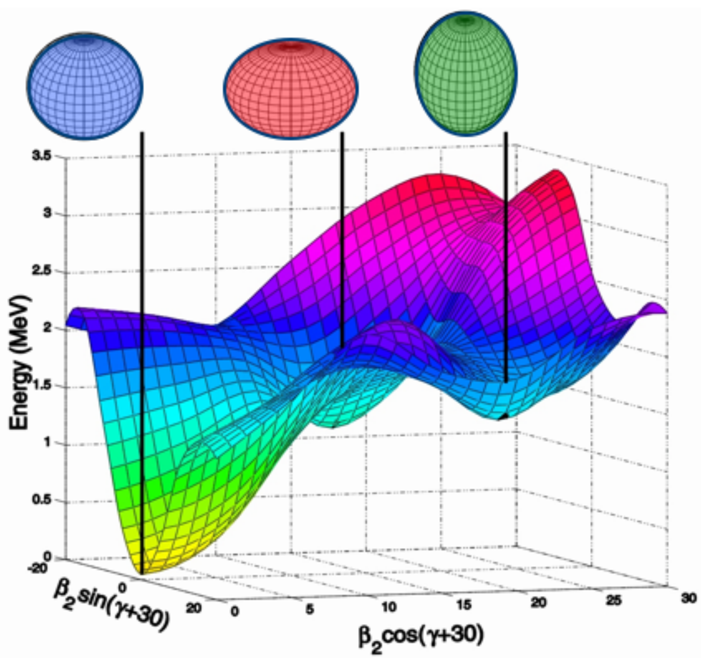


★Deformation and shape coexistence in lead region （ISOLDE）

First indication of Shape coexistent in this regions

Unexpected large isomer shift in Hg from laser spectroscopy

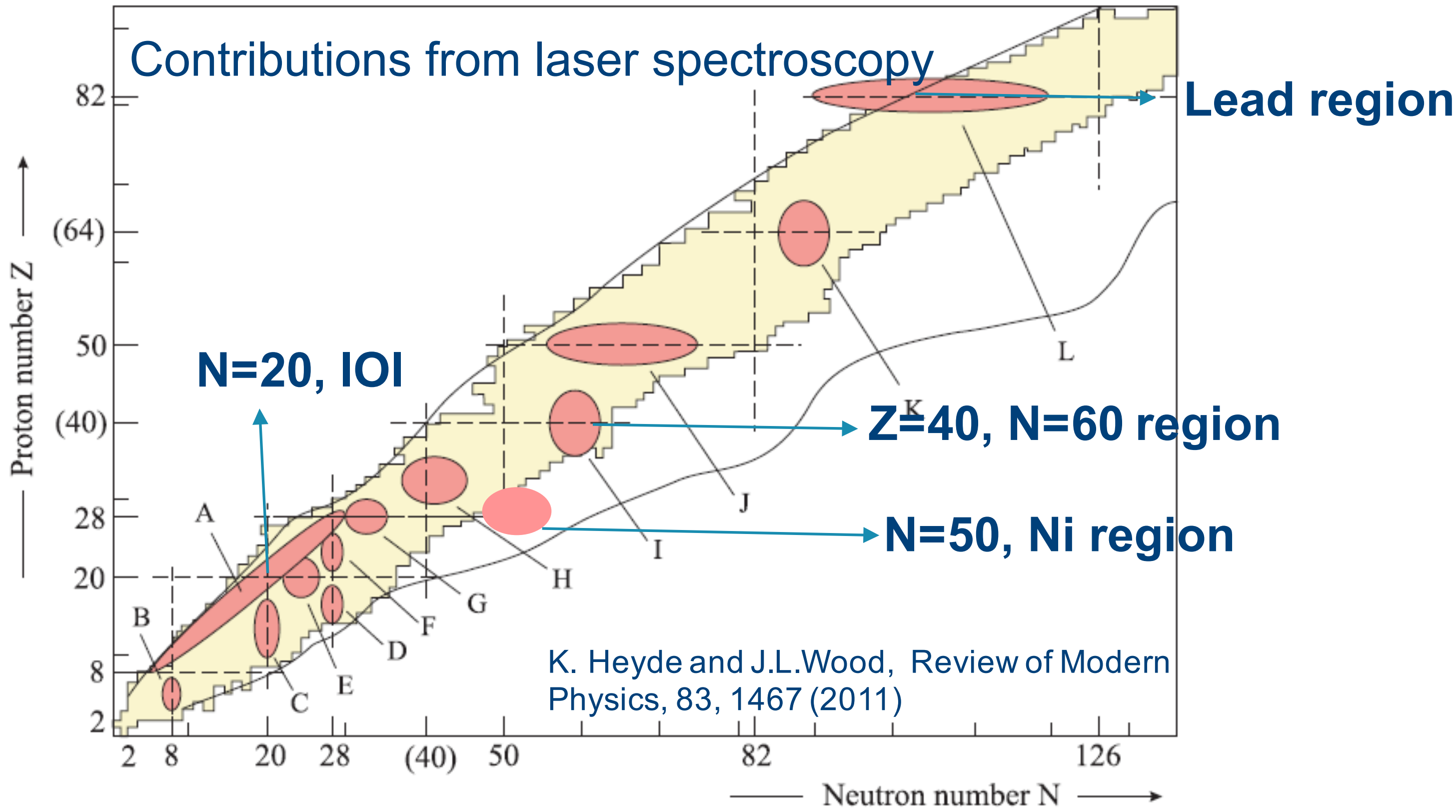




Potential energy surface 186Pb

A. Andreyev et al., Nature 405 (2000) 430

Shape coexistence in Nuclear chart



- Isomer shift and Q moments provides definitive evidence of shape coexistence
- Magnetic moment reveal essentially the SP nature of a state and thus fingerprint a shell-model intruder configuration

Three types of static moments are commonly measured for nuclear states: (i) the nuclear charge volume; (ii) the magnetic dipole moment; (iii) the electric quadrupole moment. The measurement, for a given excited state relative to the ground state, of the nuclear charge volume (isomer shift) provides definitive evidence of shape coexistence. Such evidence is similarly provided by electric quadrupole moment measurements. Magnetic dipole moment measurements reveal essentially the single-particle nature of a given nuclear state, and thus can fingerprint a shell-model intruder configuration.

Why?

Apectrochimica Acta B 58, 1031 (2003).

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  - Few examples of nuclear structure studies via laser spectroscopy

- **Laser spectroscopy for applications**
  --Producing and manipulating radioactive isotopes
  - Producing & purification of RI beams (RILIS)
  - Laser polarized RI beams (VITO)
    -- applications to interdisciplinary researches

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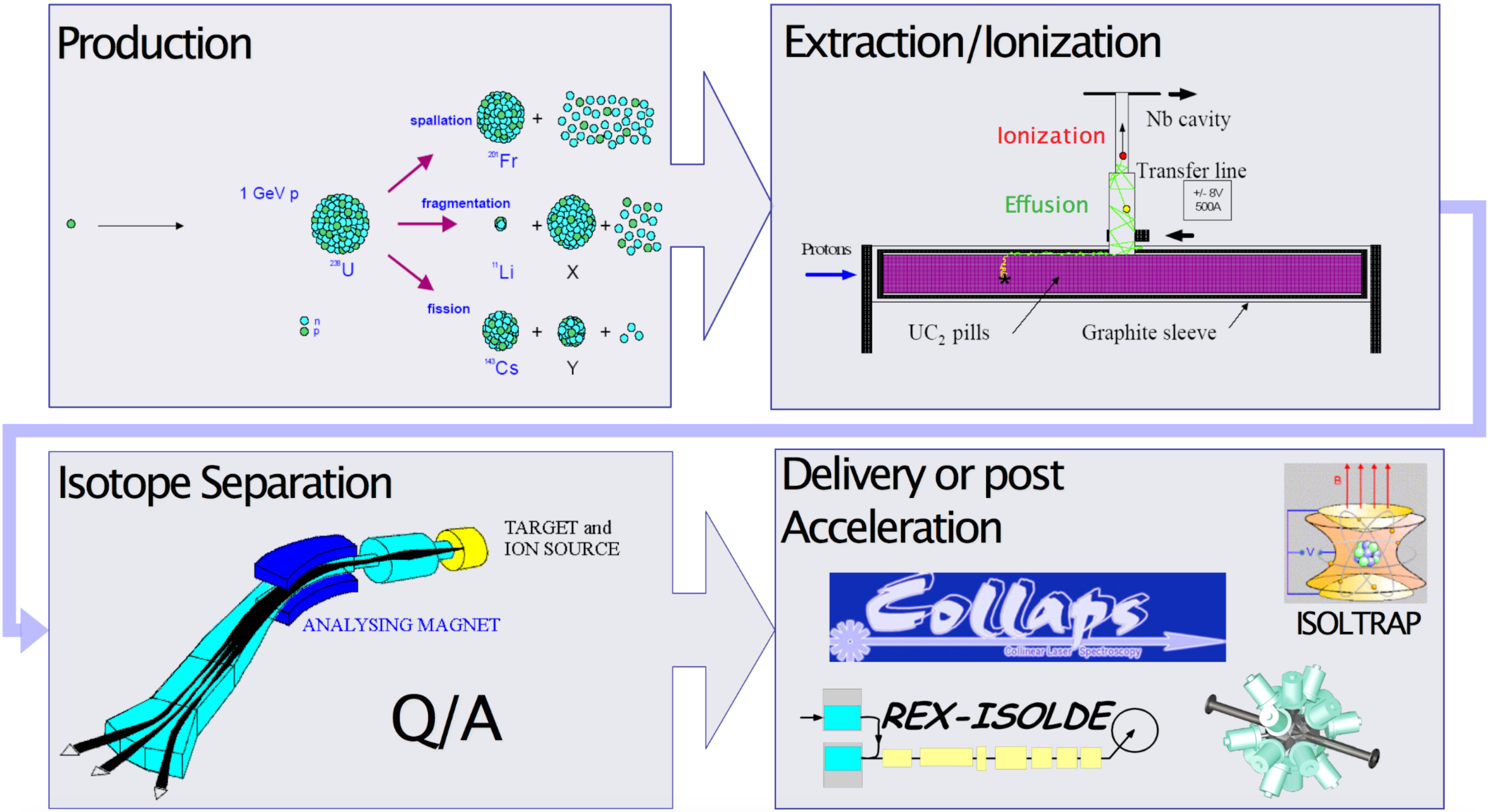
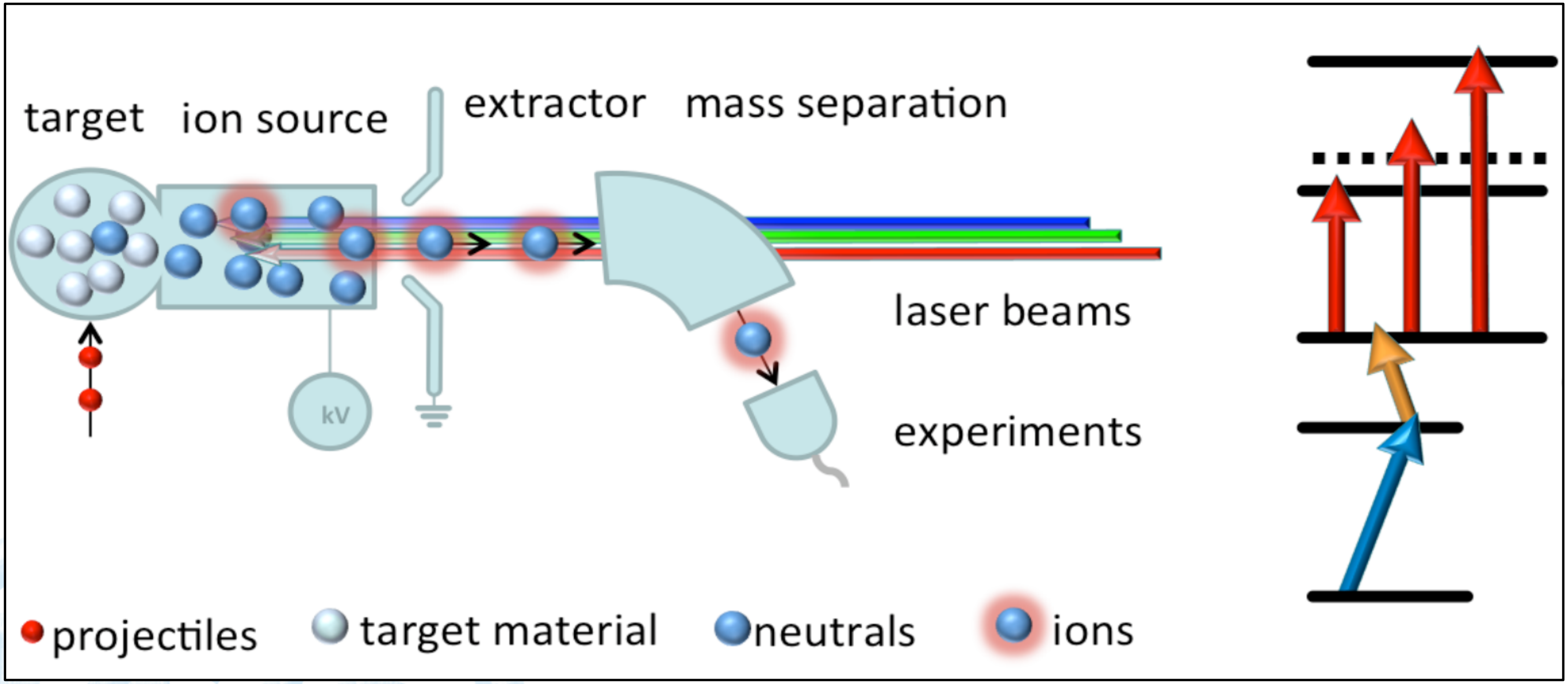
Producing & purification of RI beams (RILIS)

Common process to produce radioactive beams from ISOL facility



http://rilis.web.cern.ch/isol-process

Producing & purification of RI beams using laser ion source (RILIS)



Advantages:

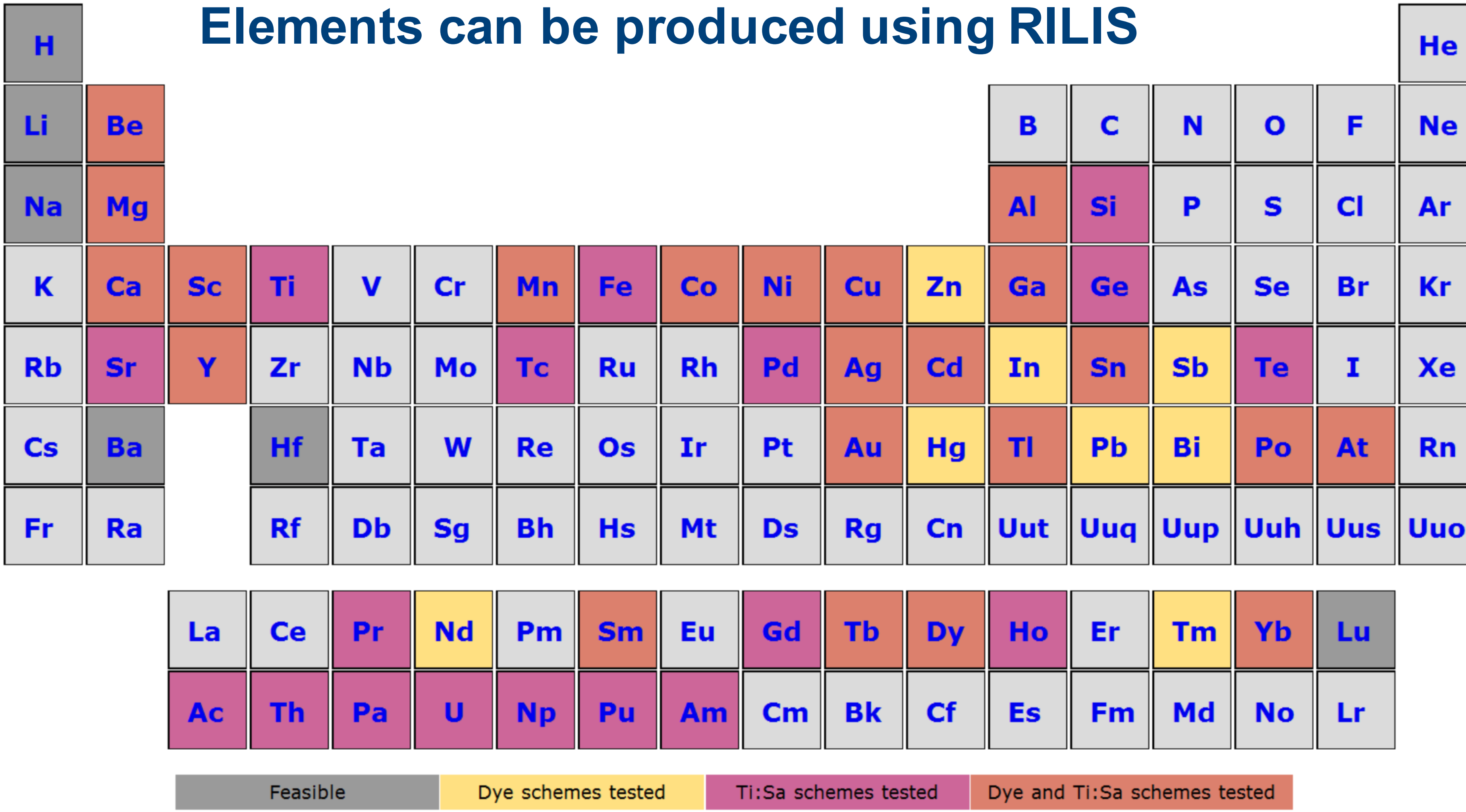
- **Usually enhance the producing yield**
- **With relative high purity RI beams**

Can also be used for gs properties measurement,
but with low resolution (no quadrupole moment, low precision)

http://rilis.web.cern.ch/isol-process

Producing & purification of RI beams

Elements can be produced using RILIS



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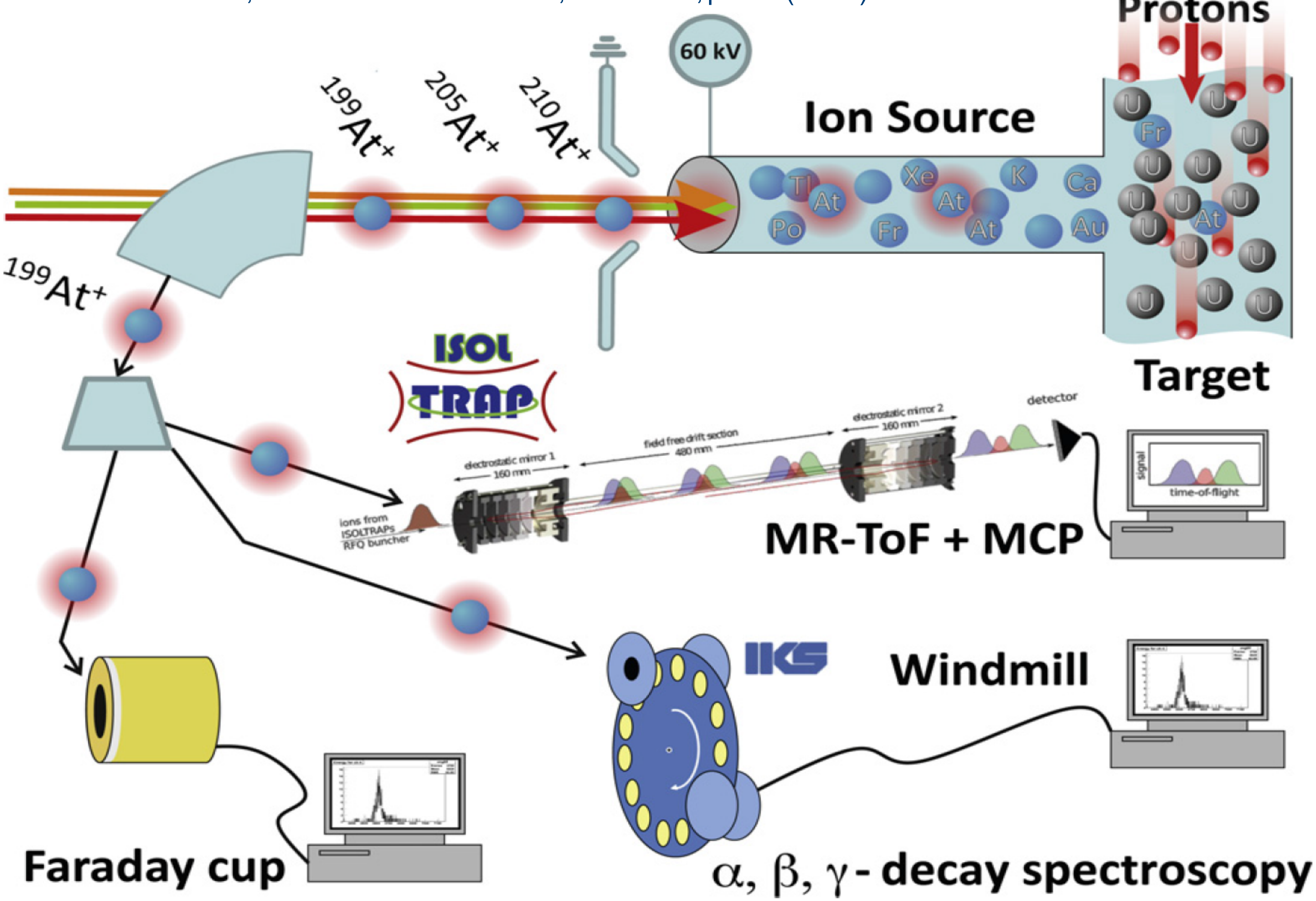
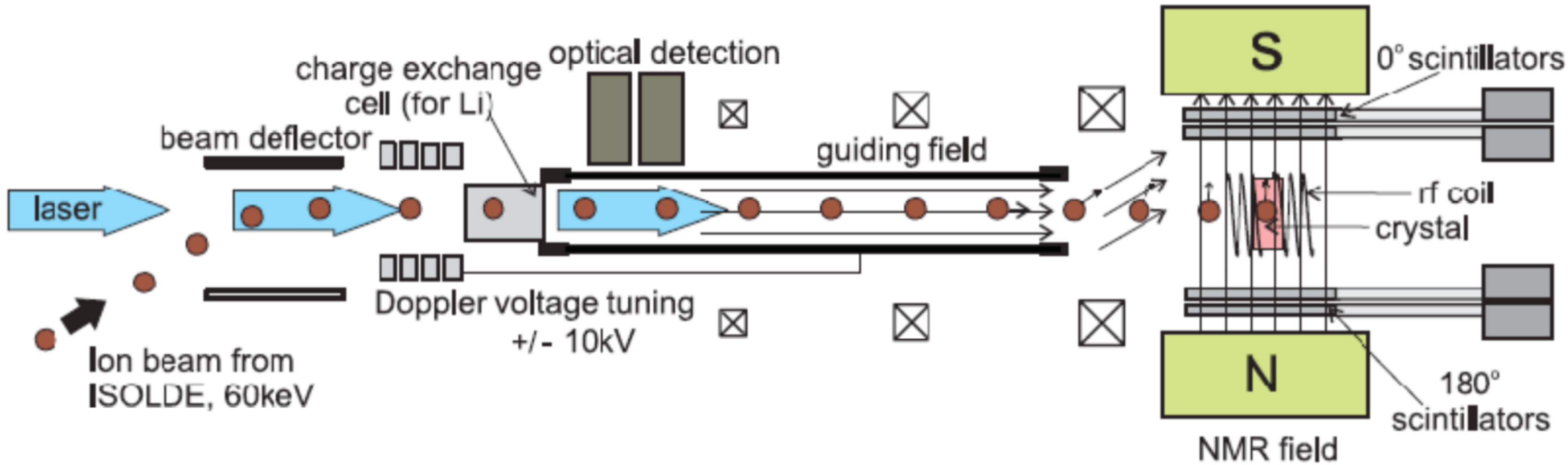
laser ion source (RILIS): in source spectroscopy

for gs properties measurement with high efficicency
but with low resolution (no quadrupole moment, low precision)

B. A. Marsh et al., 20013 EMIS conference, NIM B317, p.550 (2013)

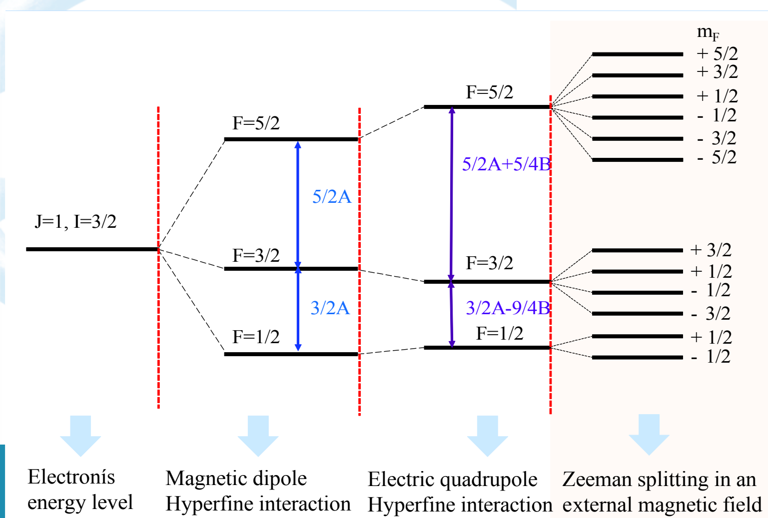


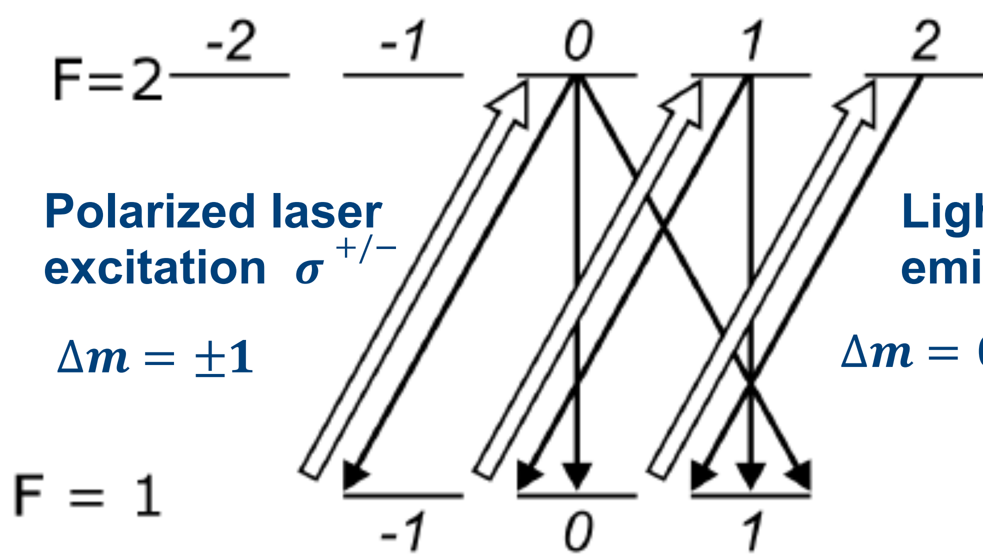
laser-polarization RI beams and ß-NMR setup



Optical pumping

External B





Polarized laser excitation $\sigma^{+/-}$

$\Delta m = \pm 1$

Light emission

$\Delta m = 0, \pm 1$

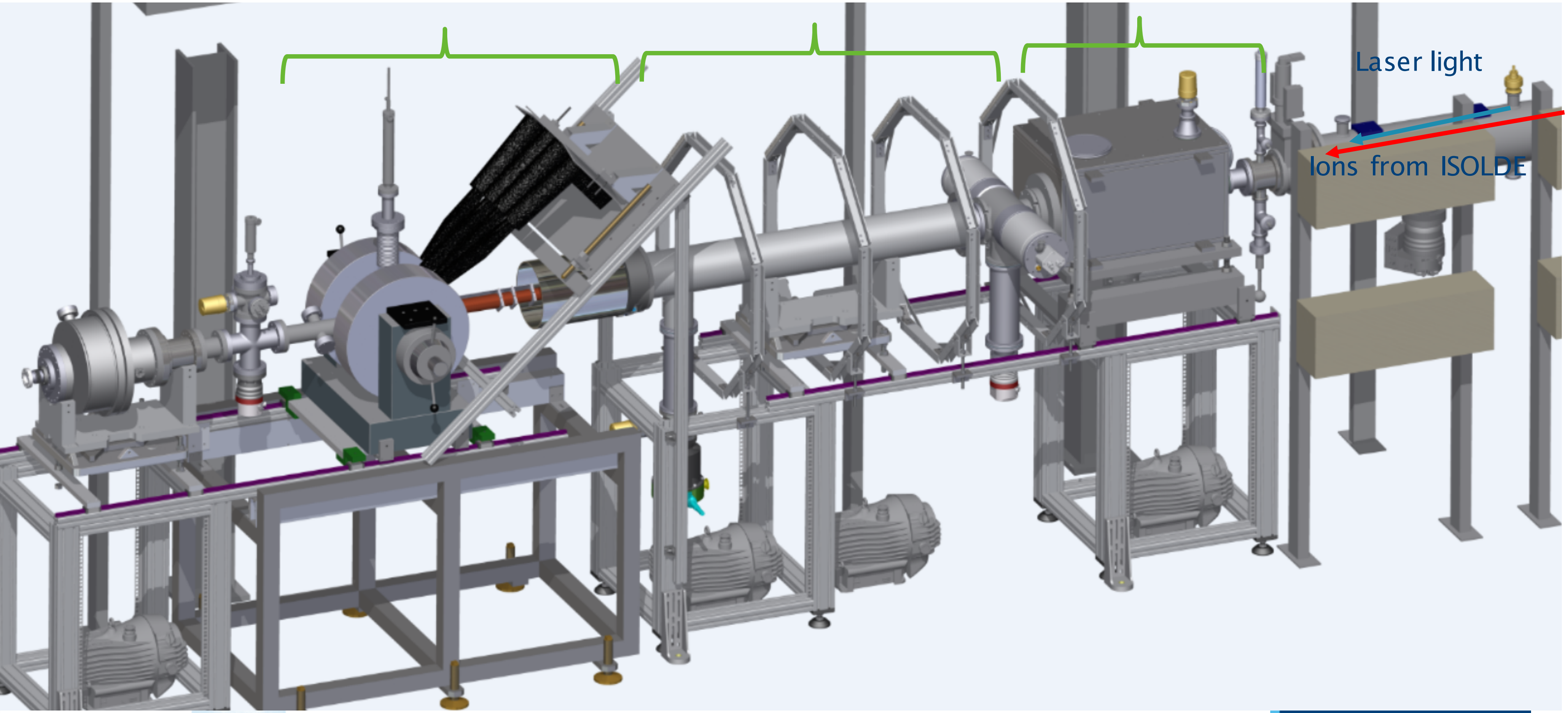
laser-polarization RI beams and ß-NMR setup

- atomic and nuclear spins
- Polarization observed in beta decay asymmetry in space

Observation of beta-decay asymmetry and beta-detected NMR

Laser spin polarization

Setting ions in resonance with laser and (optional) neutralization of ions



successfully commissioned at the end of 2016

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M. Kowalska et al, accepted to JPhysG

Laser polarized RI beams

Ingredients:

- Polarize nuclear ensemble: orient the nuclei in space
- Observe direction of radiation emission (beta particles, gamma rays) or apply radiofrequency signals and perform Nuclear Magnetic Resonance (NMR) studies

Interesting for:

- **Nuclear physics (even higher precision, e.g quadrupole moments of K)** :
  - Measure unknown electromagnetic moments of nuclei
  - Derive spins and parities of nuclear states
- **Fundamental interactions**:
  - Provide detailed information on beta-decay properties
  - Contribute to the determination of the Vud element of the quark mixing matrix
- **Chemistry and biology**:
  - Ultrahigh sensitivity NMR in liquids
  - Investigate interaction of metal ions with proteins, DNA, and RNA
- **Material science:**
  - Ultrahigh sensitivity NMR
  - Study interfaces, crystal lattices, or semiconductors

Summary… About radioactive isotopes

- Laser spectroscopy is a basic probe of the atomic structure of RI
- The HFDS of RI provides multiple nuclear parameters simultaneously in a model independent way.
- $I, \mu, Q, < r^2 >^{1/2}$ of exotic nuclei (gs, and isomer)provide complemental information of nuclear structure, shell evolution …..
- Complemantal experimental setups are avilable for laser spectroscopy of RI (Not all of them are included here)
- Laser spectroscopy can be applied for many Interdisciplinary Researches

↓

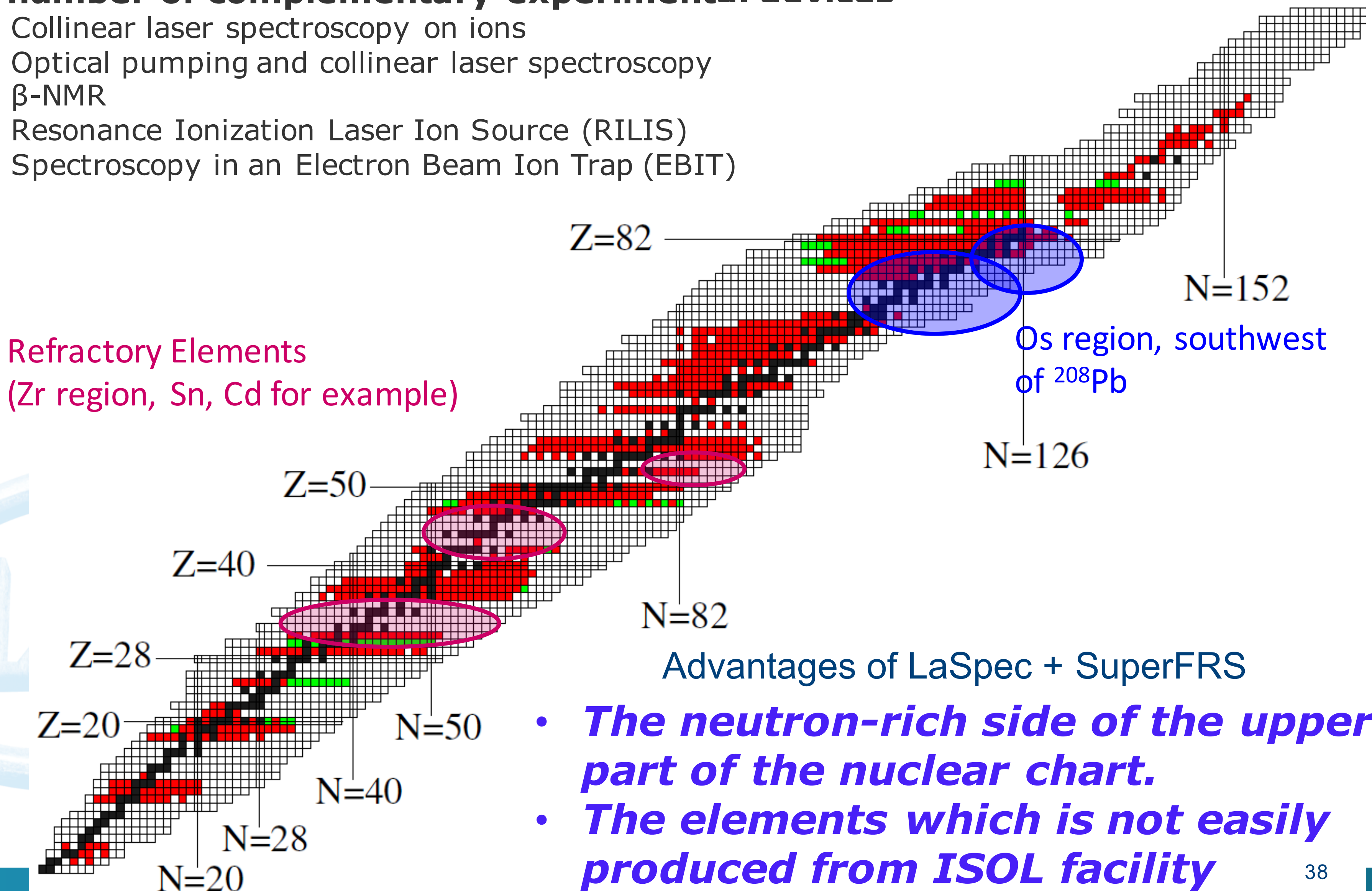
The motivation of LaSpec

KU LEUVEN

Status of laser spectroscopic landscape (2016)

The LaSpec collaboration intends to construct
a number of complementary experimental devices

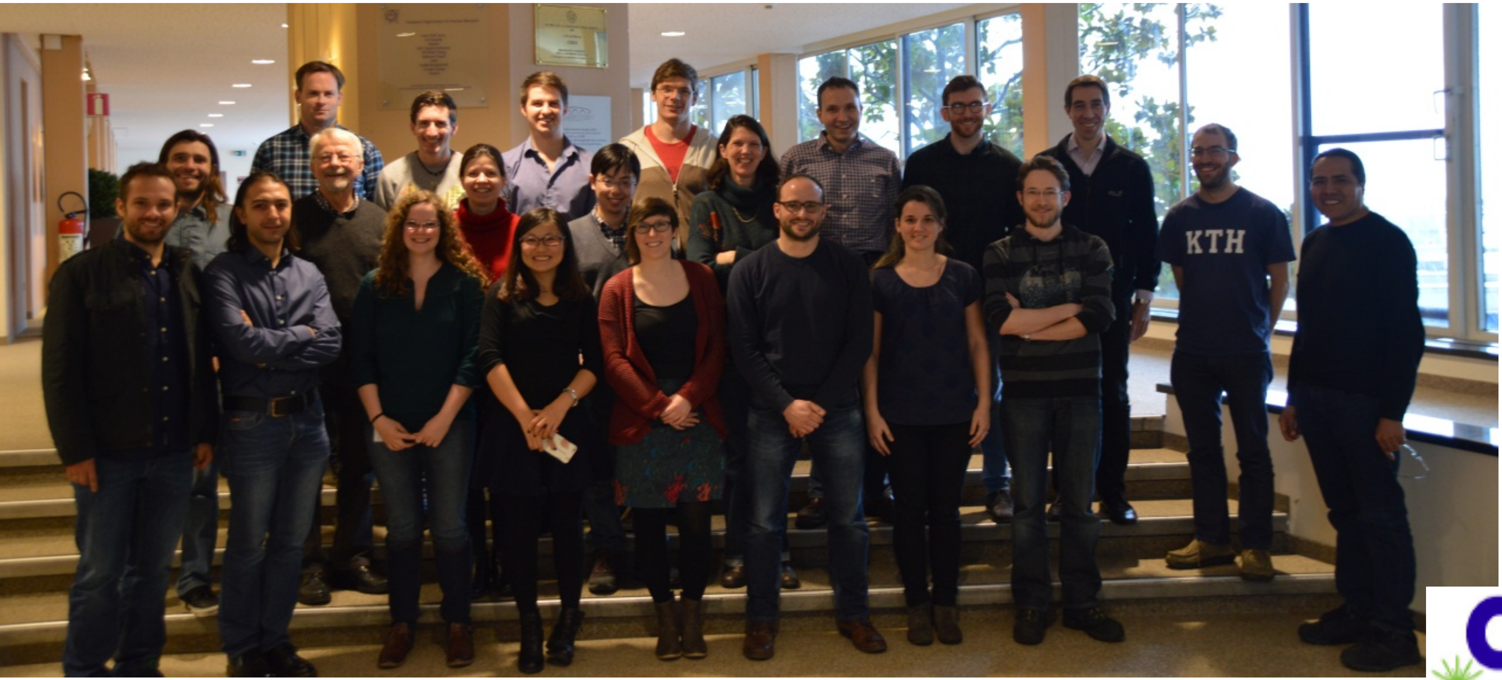
- Collinear laser spectroscopy on ions
- Optical pumping and collinear laser spectroscopy
- β-NMR
- Resonance Ionization Laser Ion Source (RILIS)
- Spectroscopy in an Electron Beam Ion Trap (EBIT)



Advantages of LaSpec + SuperFRS

- ***The neutron-rich side of the upper part of the nuclear chart.***
- ***The elements which is not easily produced from ISOL facility***

Thanks for your attention!



COLLAPS

CRIS

$$V_{pn} = \frac{\sum_J (2J+1) \times v_{pn}^J (j_p, j_n)}{\sum_J (2J+1)}$$

Monopole interaction

Central

Node dependent

General characteristics:

- Energy shift ~ occupation of the orbit
- Bigger overlap of the radial wave functions

&

higher j_p and j_n

↓

more drastic changes

Vector

Change of the SO splitting

Tensor

$j_> = l + \frac{1}{2}$ $j_< = l - \frac{1}{2}$

Spin dependent

$V_{j_> j'_<} < 0$ attractive

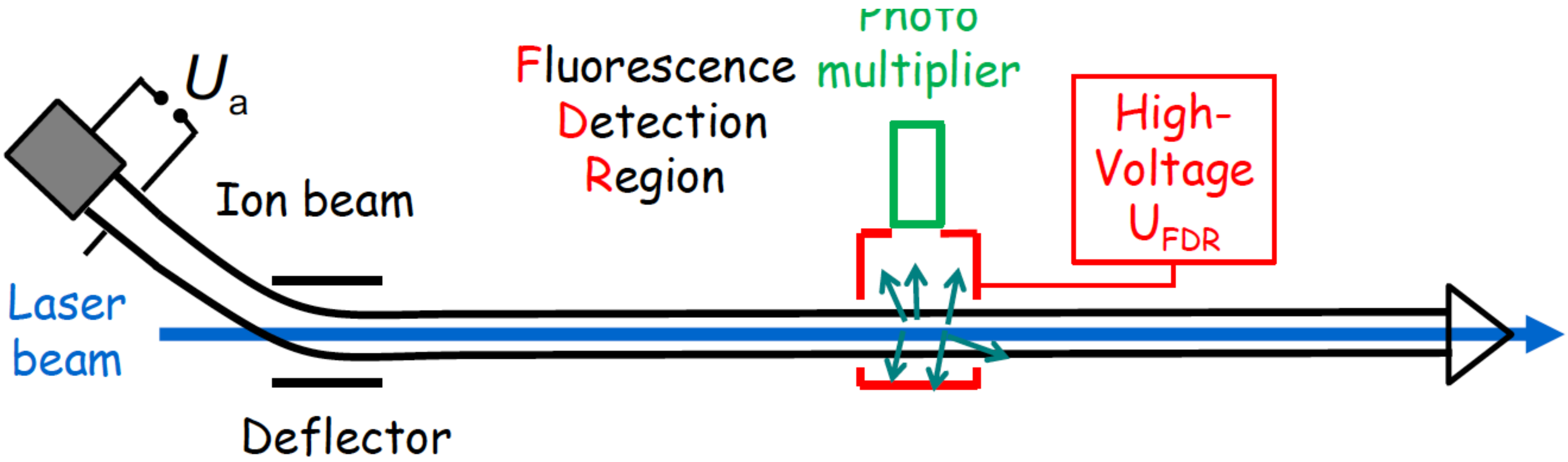
$V_{j_> j'_>}$, $V_{j_< j'_<} > 0$ repulsive

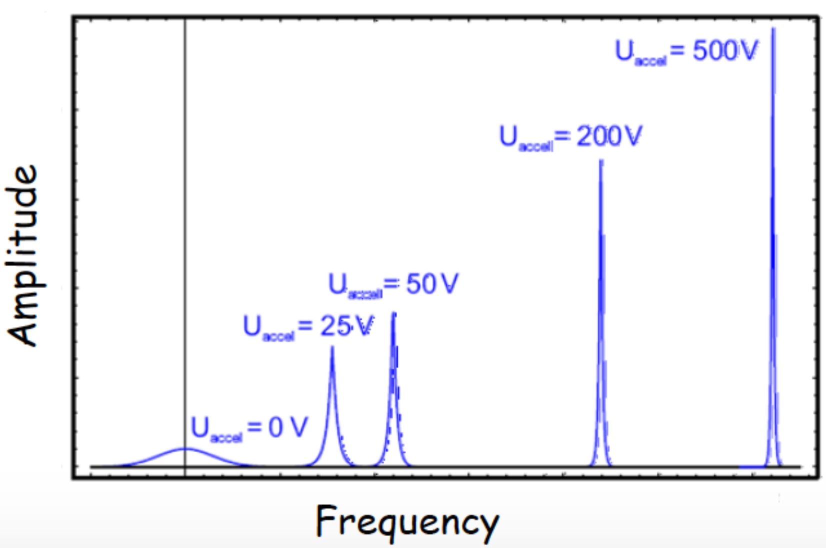
Node dependent

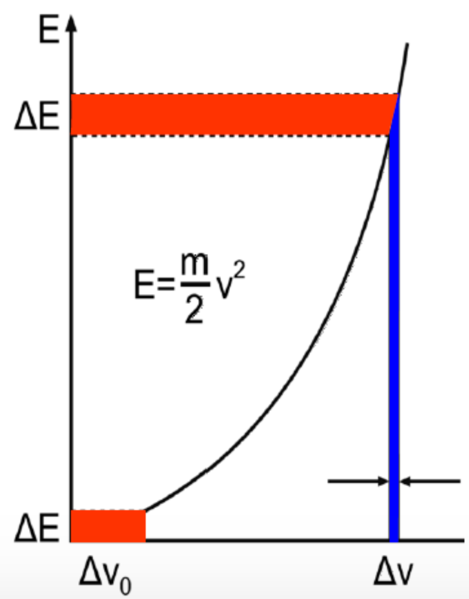
$\Delta l = 0, \Delta n = 0$ > $\Delta l = 1, \Delta n = 0$ > $\Delta l = 1, \Delta n = 1$

l is the orbital angular momentum

n is the principal quantum number







$$E = eU_a = 1/2\, m\upsilon^2$$

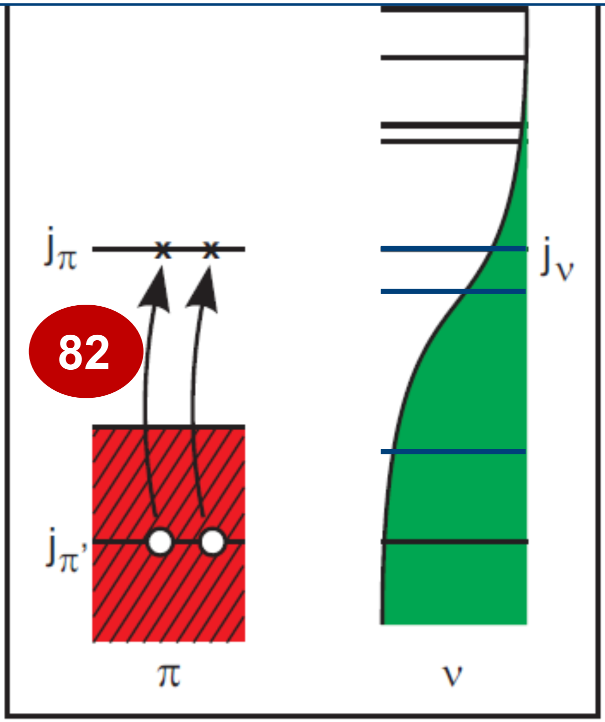
$$\delta E = m\upsilon\, \delta\upsilon$$

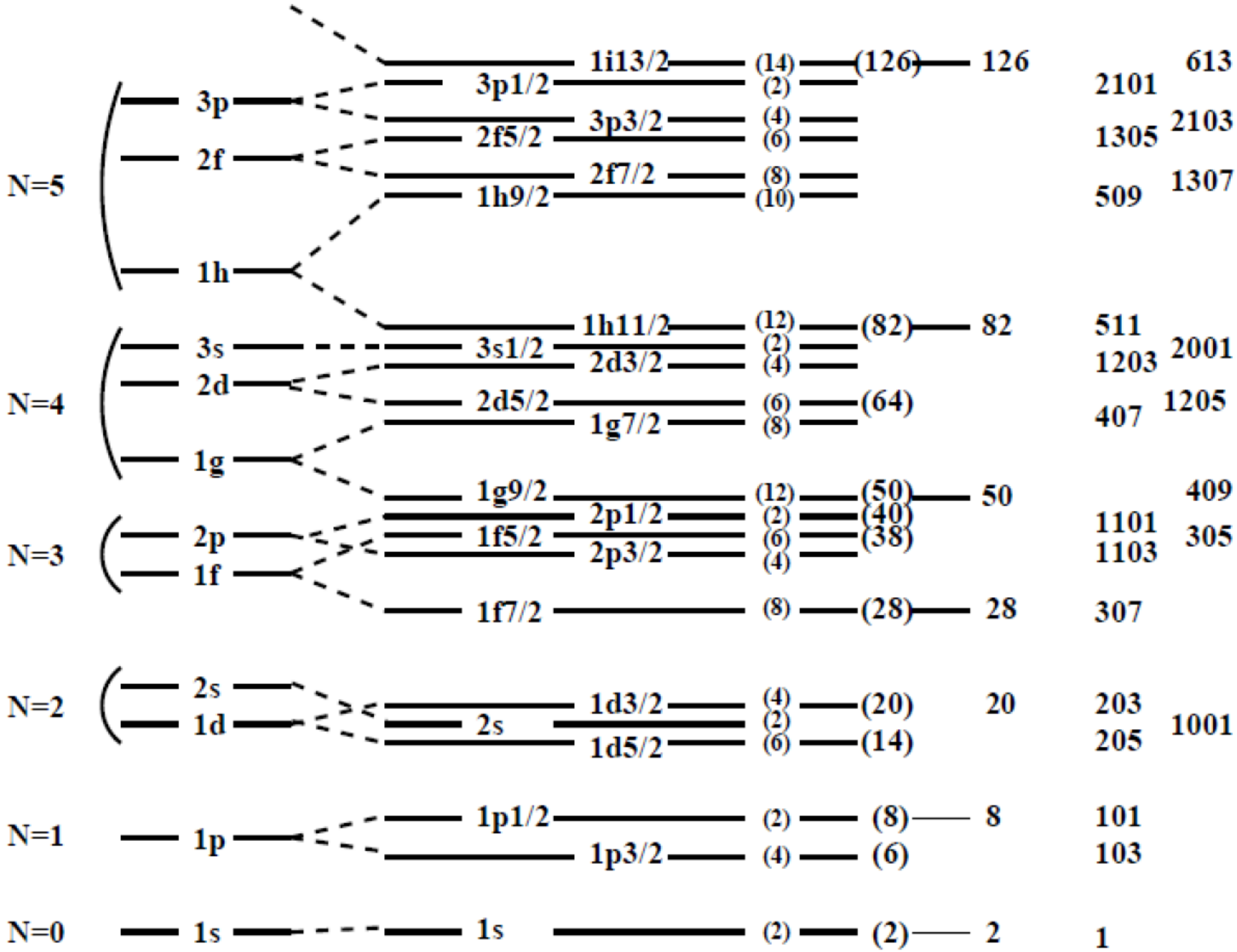
$$\delta\nu_{\text{Doppler}} = \nu_0\, \delta\upsilon / c$$

$$= \nu_0 \frac{\delta E}{\sqrt{2eU_a mc^2}}$$

- Shape coexistence: (Heyde and Wood, Review of Modern Physics (2011))
  - stabilizing effect of closed shells (and subshells):
    - spherical nucleus
    - cost of energy to redistribute protons and neutrons over different shells
  - residual proton-neutron interaction: correlation energy

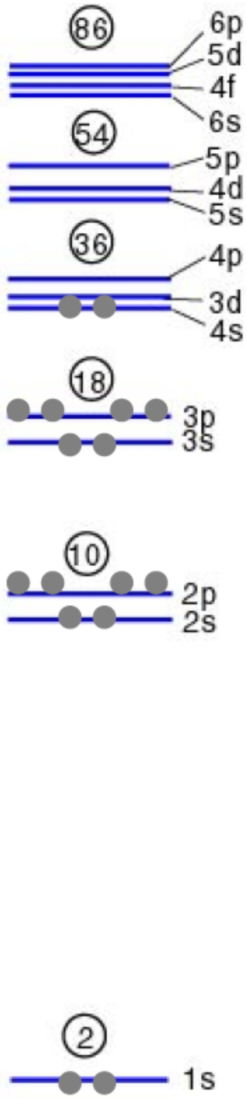
$$E_x(0^+(\pi 2p-2h)) = 2\left(\varepsilon_{j\pi} - \varepsilon'_{j'\pi}\right) - \Delta_{pairing} + \langle V_{\pi\nu} \rangle$$

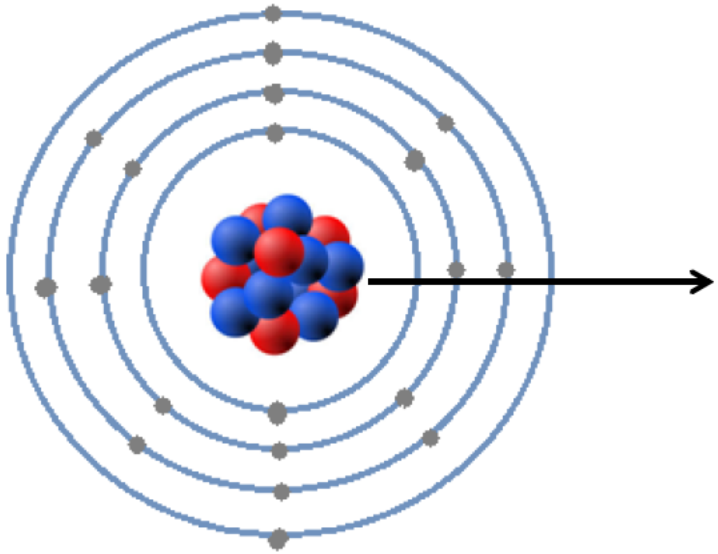




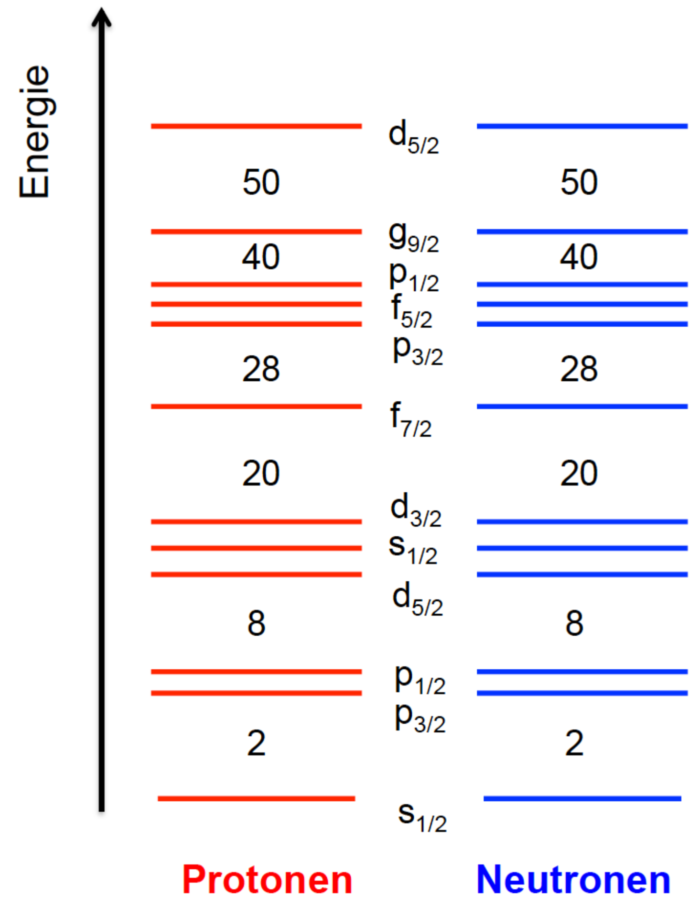
N=5
N=4
N=3
N=2
N=1
N=0
3p
2f
1h
3s
2d
1g
2p
1f
2s
1d
1p
1s
1i13/2 (14) (126) 126 613
3p1/2 (2) 2101
3p3/2 (4) 2103
2f5/2 (6) 1305
2f7/2 (8) 1307
1h9/2 (10) 509
1h11/2 (12) (82) 82 511
3s1/2 (2) 2001
2d3/2 (4) 1203
2d5/2 (6) (64) 1205
1g7/2 (8) 407
1g9/2 (12) (50) 50 409
2p1/2 (2) (40) 1101
1f5/2 (6) (38) 305
2p3/2 (4) 1103
1f7/2 (8) (28) 28 307
1d3/2 (4) (20) 20 203
2s (2) 1001
1d5/2 (6) (14) 205
1p1/2 (2) (8) 8 101
1p3/2 (4) (6) 103
1s (2) (2) 2 1

Atom


86
6p
5d
4f
6s
54
5p
4d
5s
36
4p
3d
4s
18
3p
3s
10
2p
2s
2
1s



Nuclei


Energie
$d_{5/2}$
50
$g_{9/2}$
40
$p_{1/2}$
$f_{5/2}$
$p_{3/2}$
28
$f_{7/2}$
20
$d_{3/2}$
$s_{1/2}$
$d_{5/2}$
8
$p_{1/2}$
$p_{3/2}$
2
$s_{1/2}$
Protonen
Neutronen

NMR in (chemistry and) biology

Most versatile method to study structure and dynamics of molecules in solution

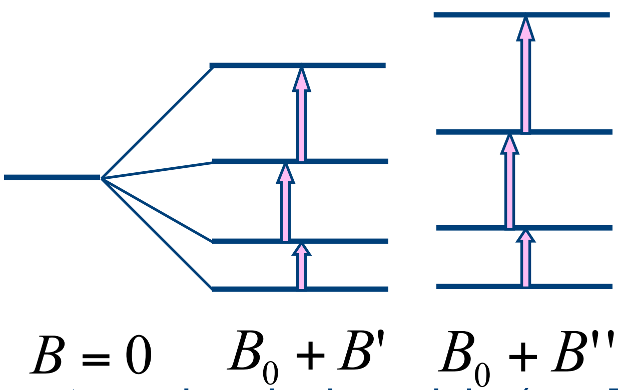
- **Observables**: chemical shift (Larmor frequency) and relaxation times in different hosts
- **Determined properties**
  - local electronic environment (i.e. **number and type of coordinating groups**)

Depends on environment

$$\Delta E_{mag} = |g_I| \cdot \mu_N \cdot B + \frac{1}{2} Q \cdot V_{zz}$$

known

Same B, different shielding by host



- **Derived information**: comparison to quantum-chemical models (e.g DFT)
  - kinetics and dynamics and ligand binding of the **metal ions and biomolecules**
  - 3D structure of proteins and **protein-metal complexes**