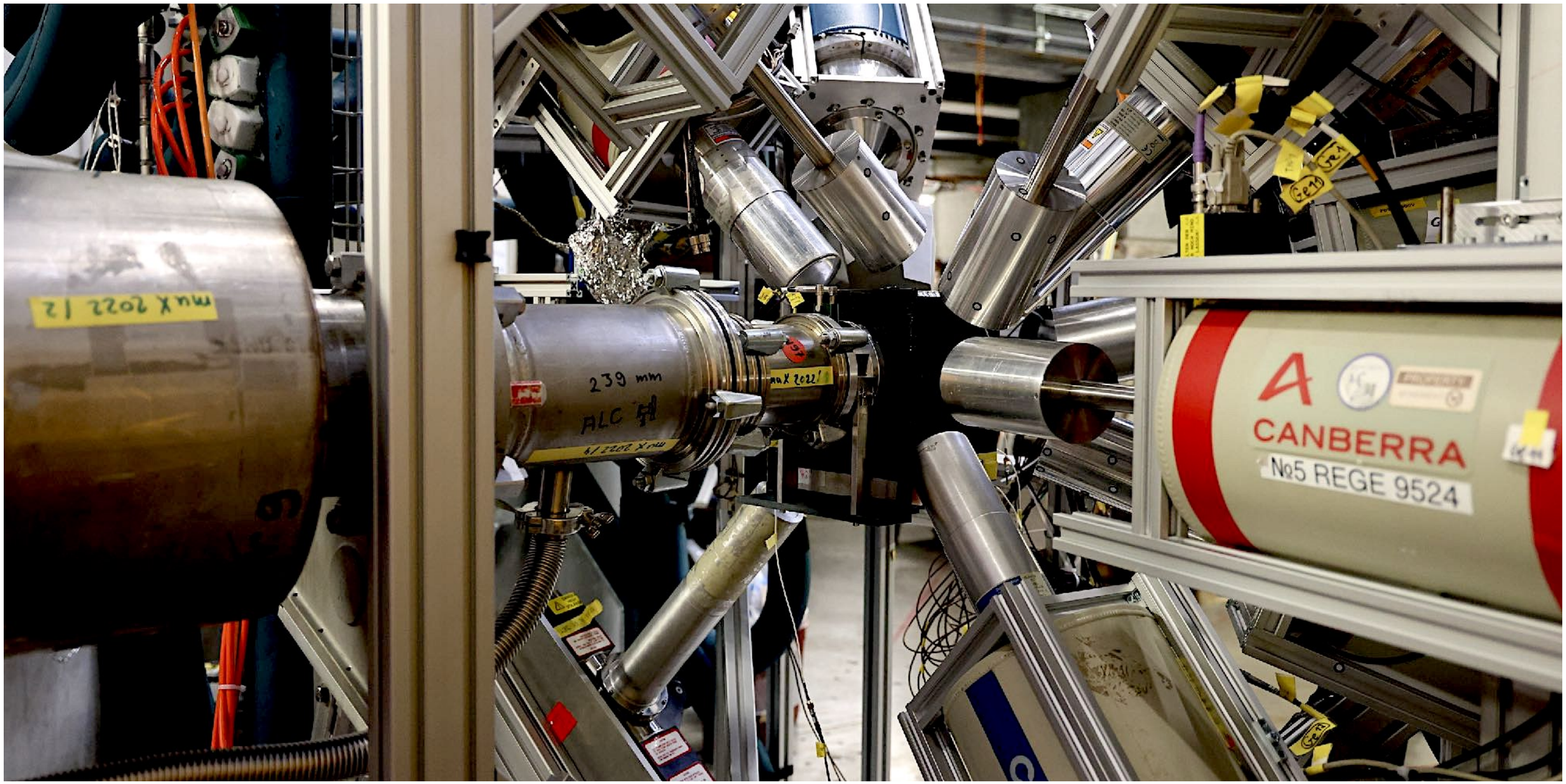
Muonic atom spectroscopy on ^{nat}La, ^{nat,enr}Lu, and ^{28,29,30}Si isotopes

2024 ReferenceRadii beamtime @PSI

11.10.2024



Muonic atom spectroscopy

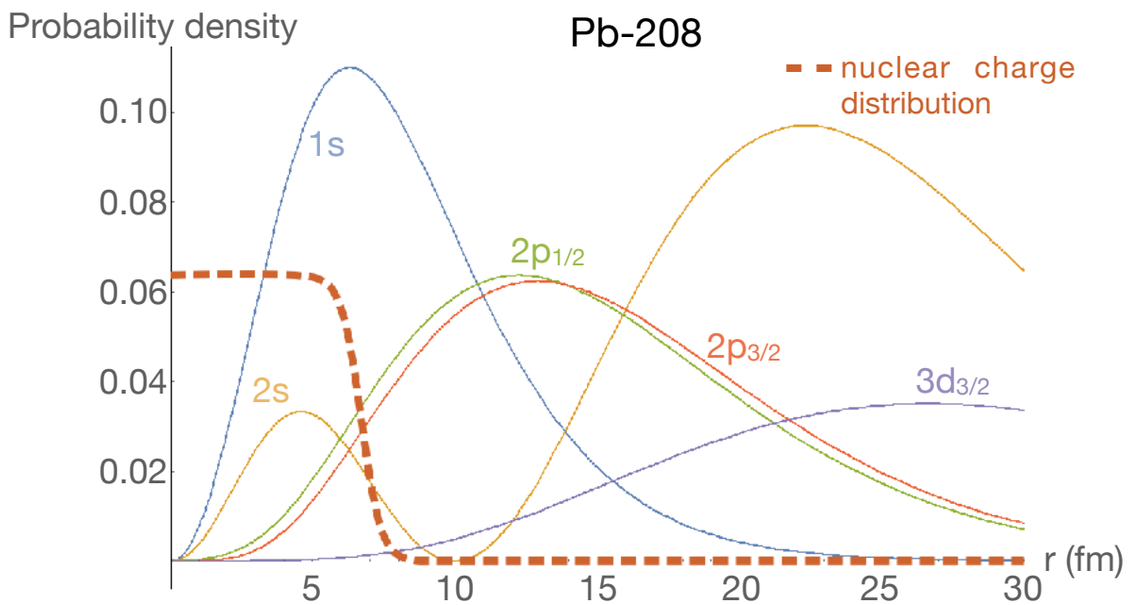
- Large overlap of the low-lying muonic states with the nuclear charge distribution.

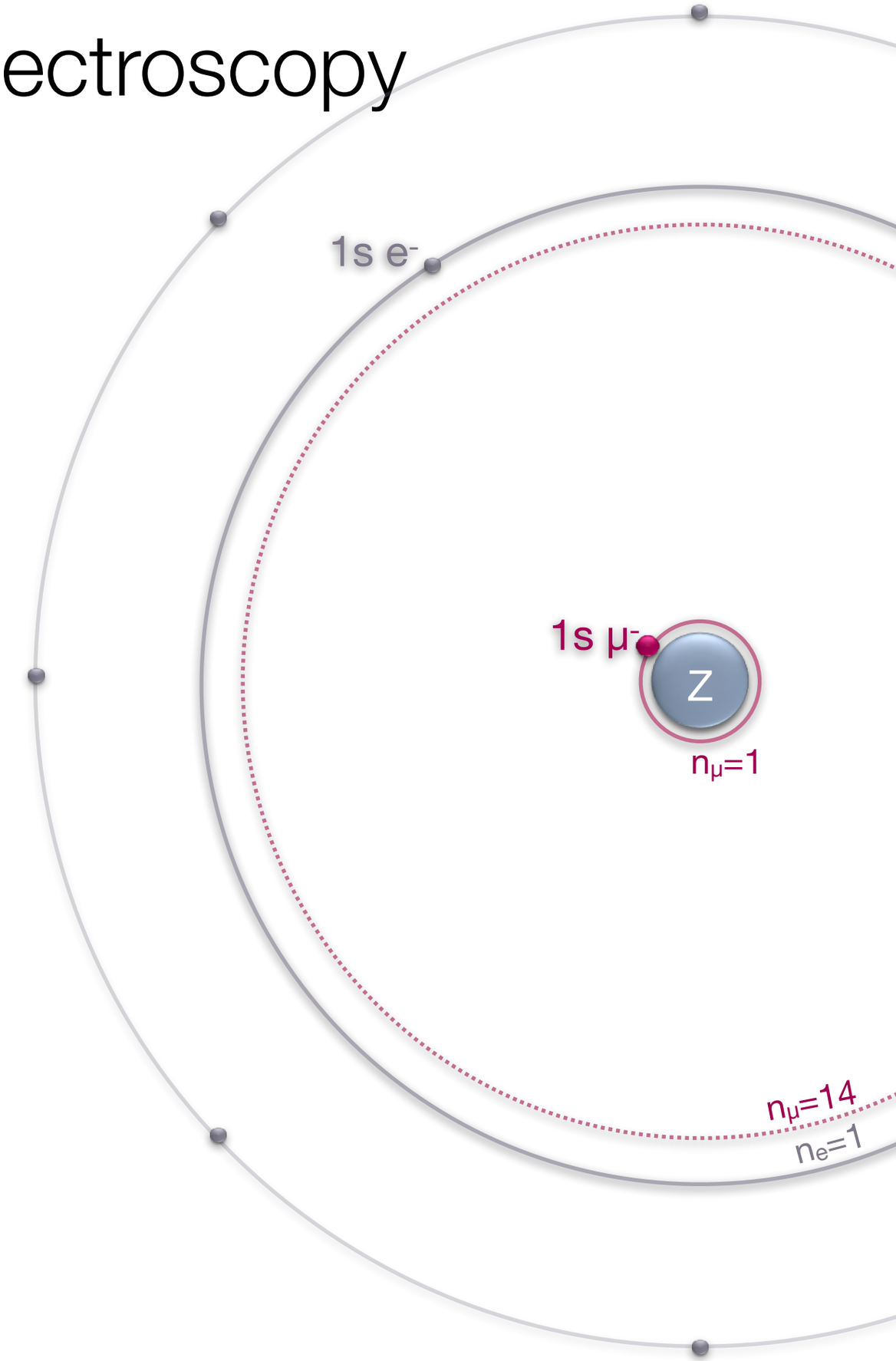
- The measurement of the muonic energy levels allows to extract properties of the nucleus such as the charge radius R_N:

2p-1s transition most sensitive to R_N

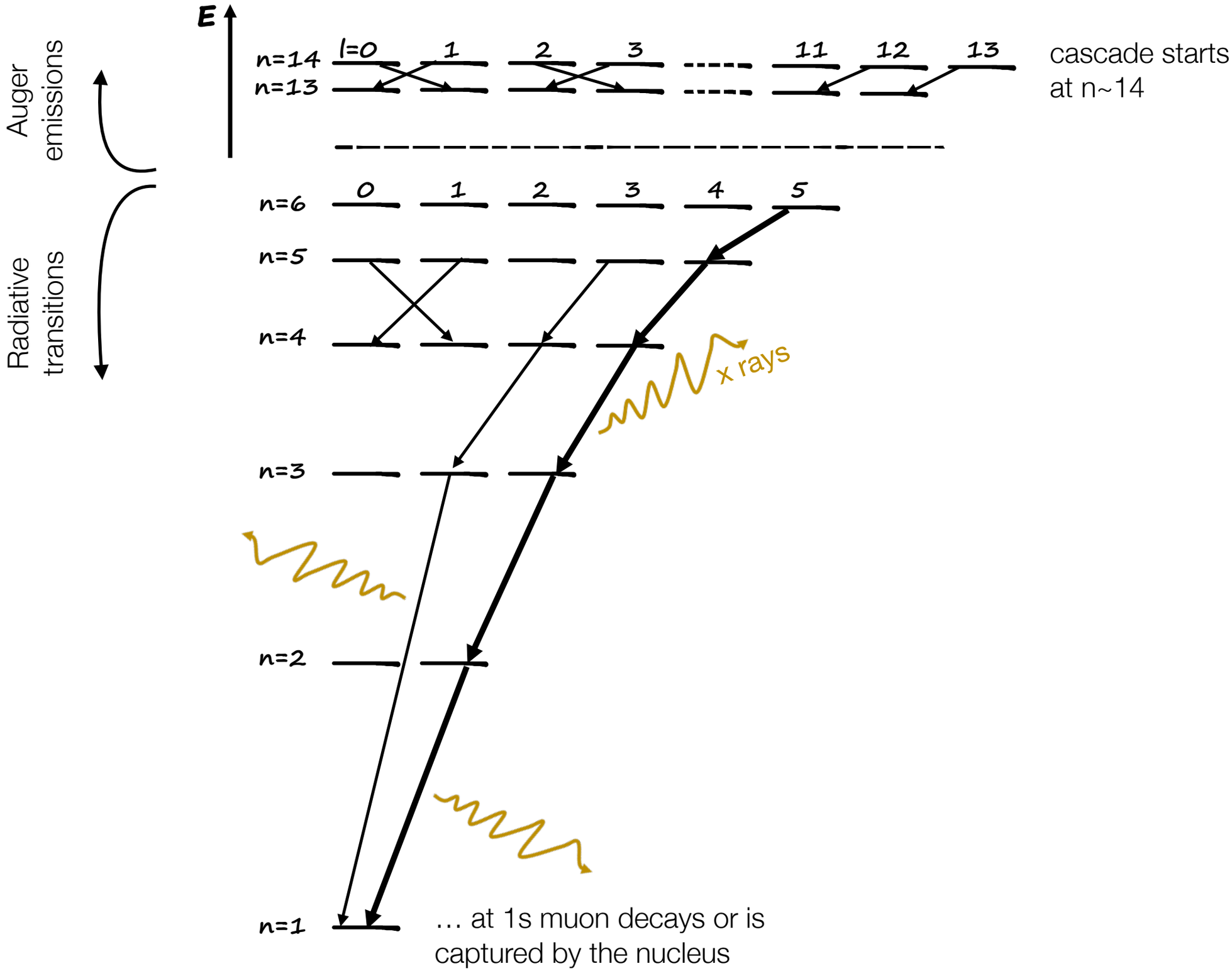
$$R_N^2 = \langle r^2 \rangle = \frac{1}{Ze} \int d^3\vec{r}\, \rho(\vec{r})\, r^2$$

nuclear charge distribution





Muonic cascade



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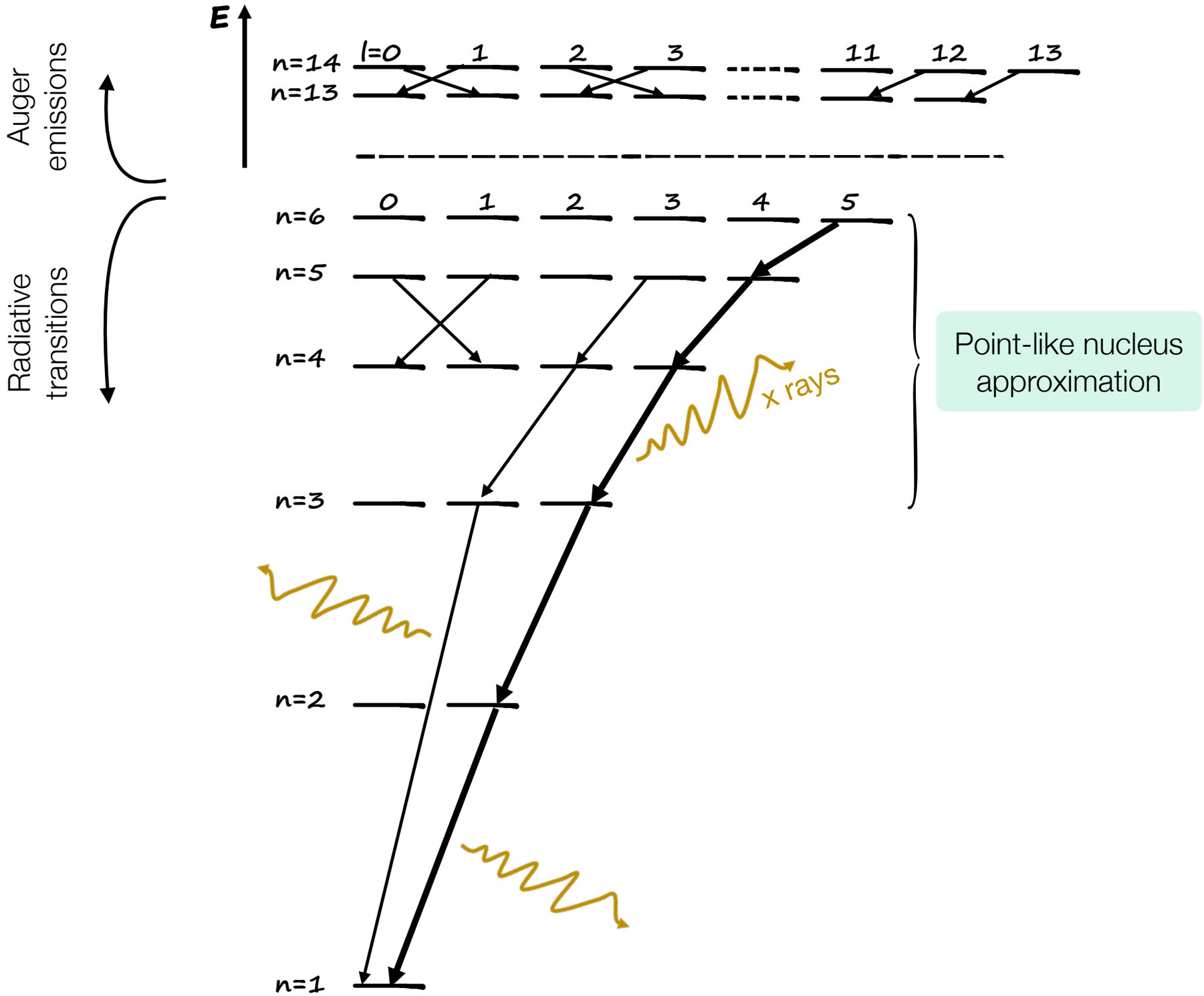

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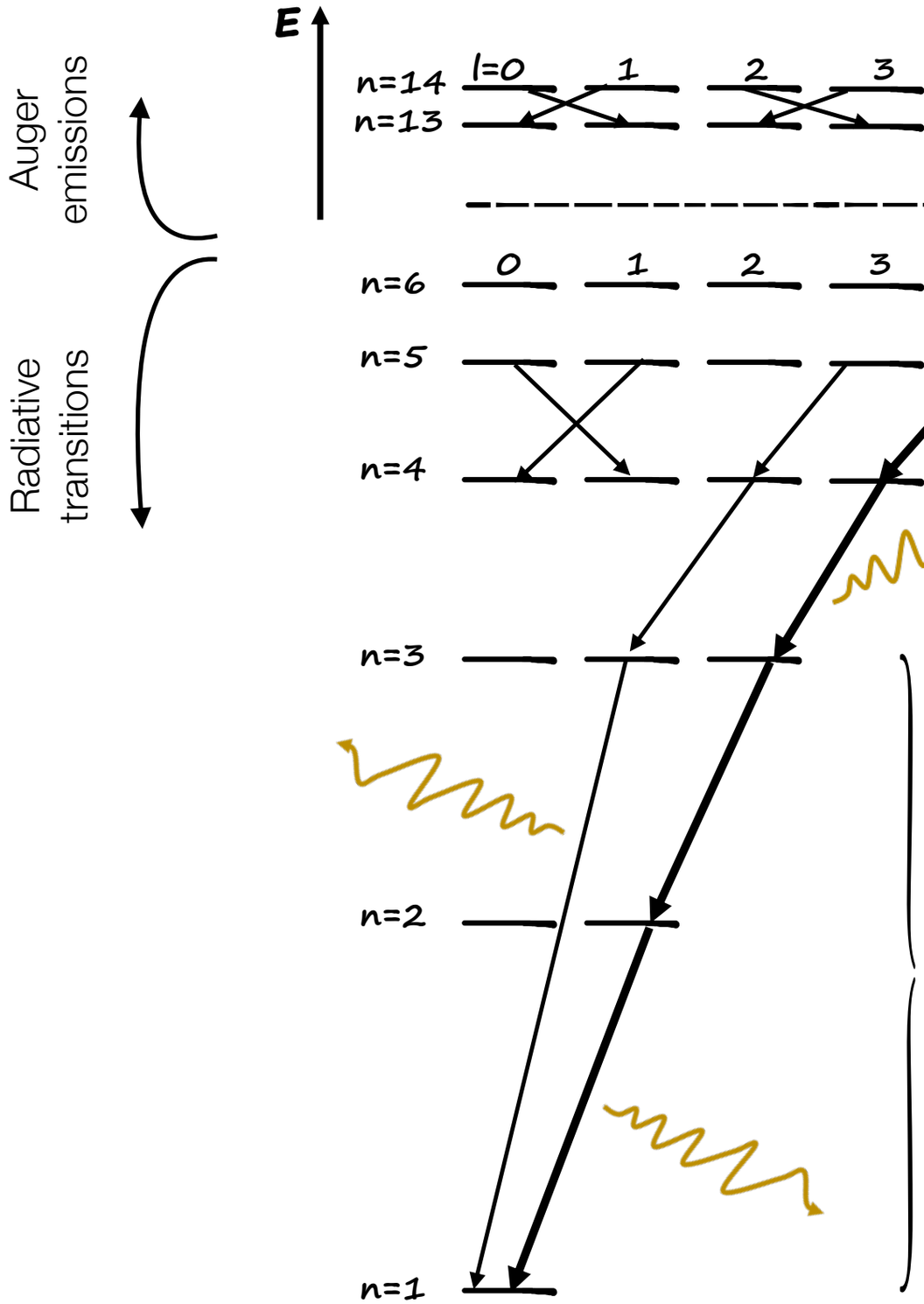
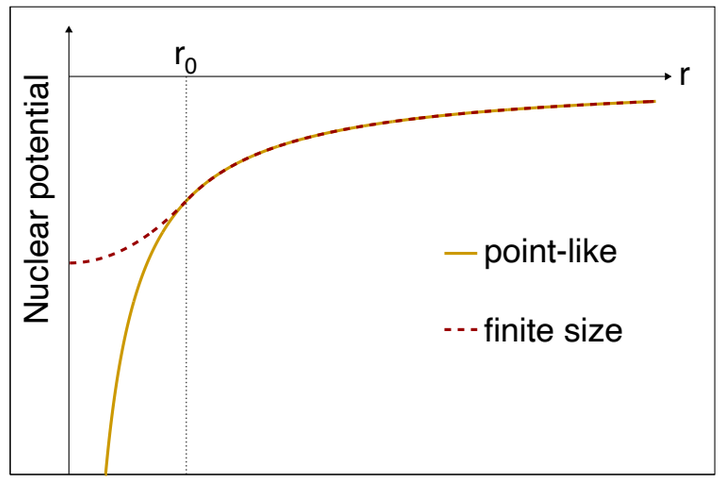


Point-like nucleus approximation

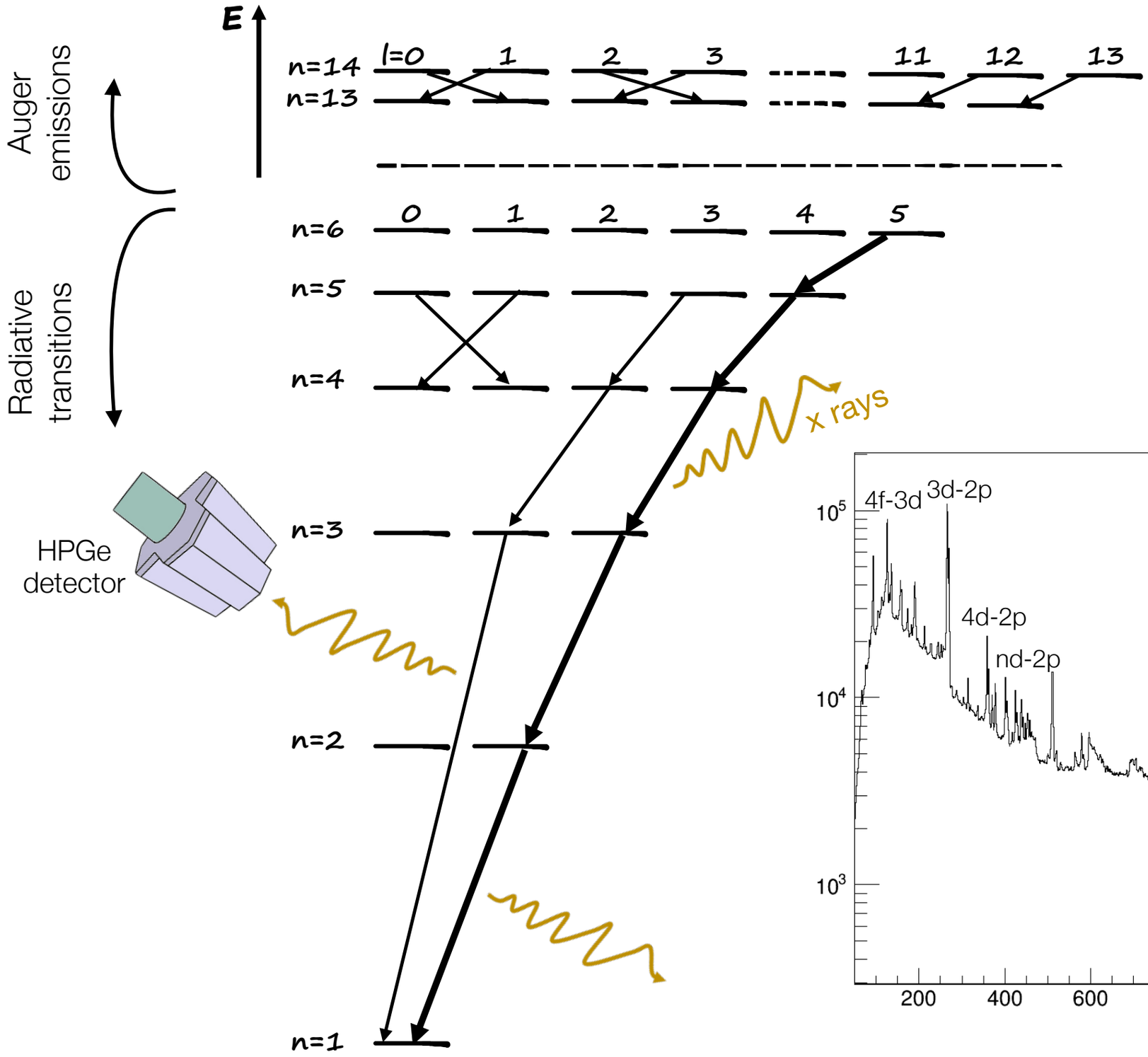
Finite size corrections of the nucleus become significant



$E_{1s}(Z = 82) \sim 19\,\mathrm{MeV}$ (point nucleus)

$\sim 10.6\,\mathrm{MeV}$ (finite size)

Muonic cascade



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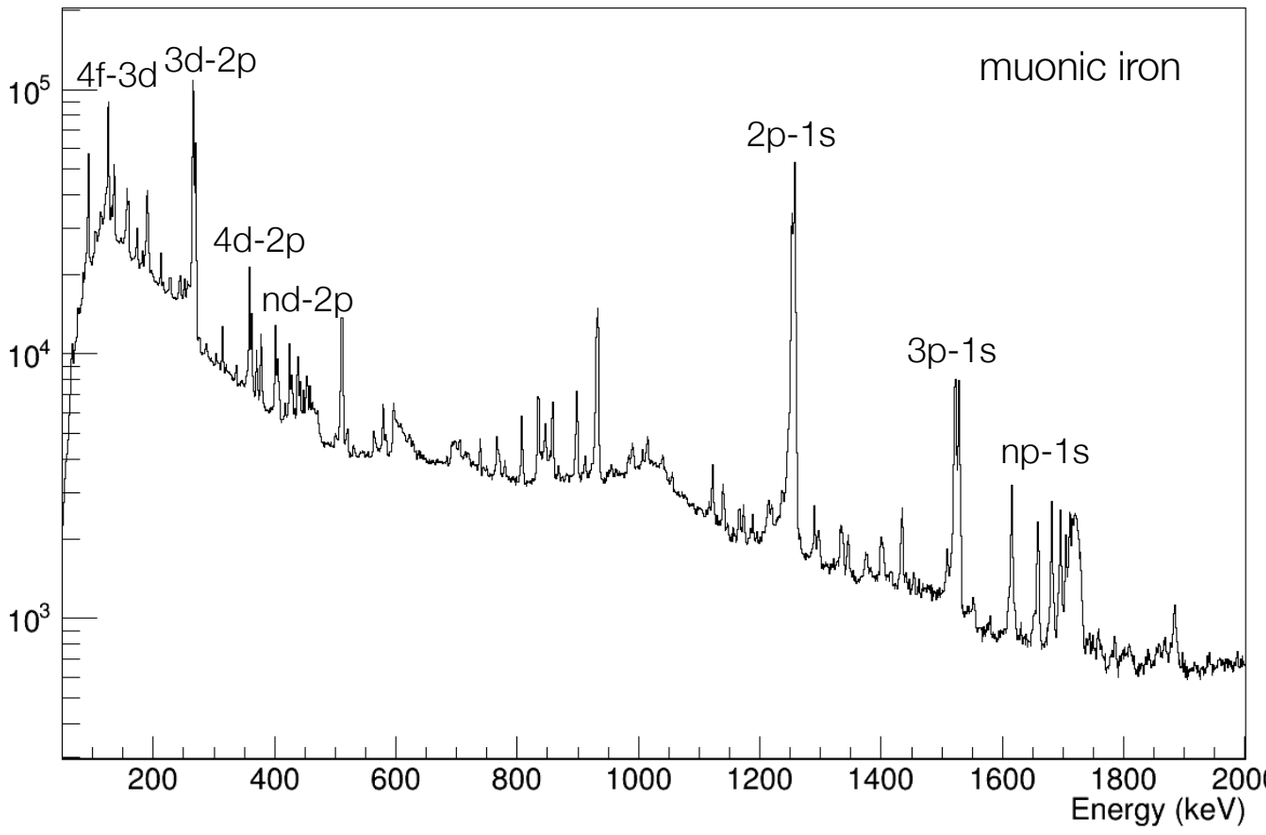
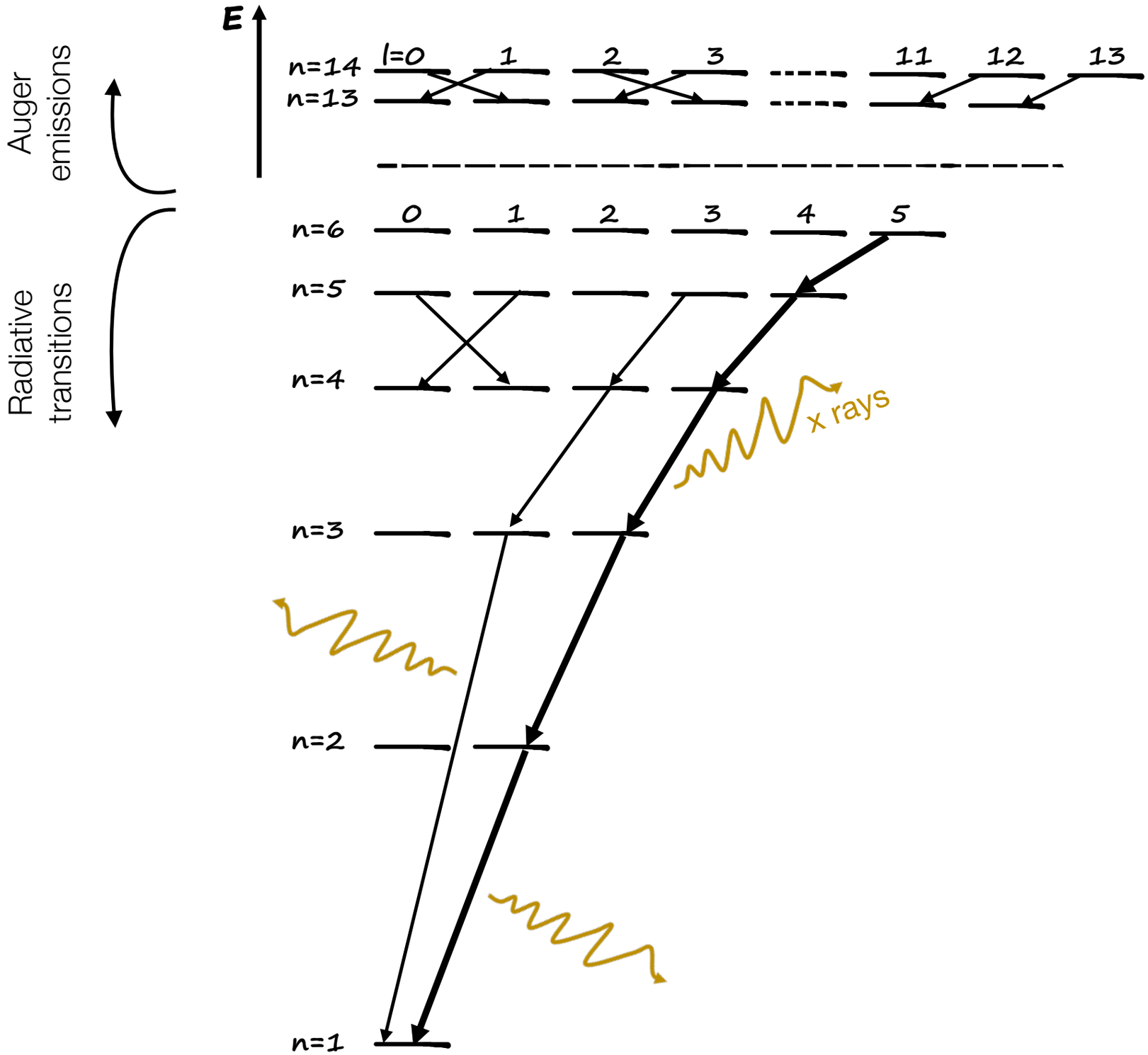
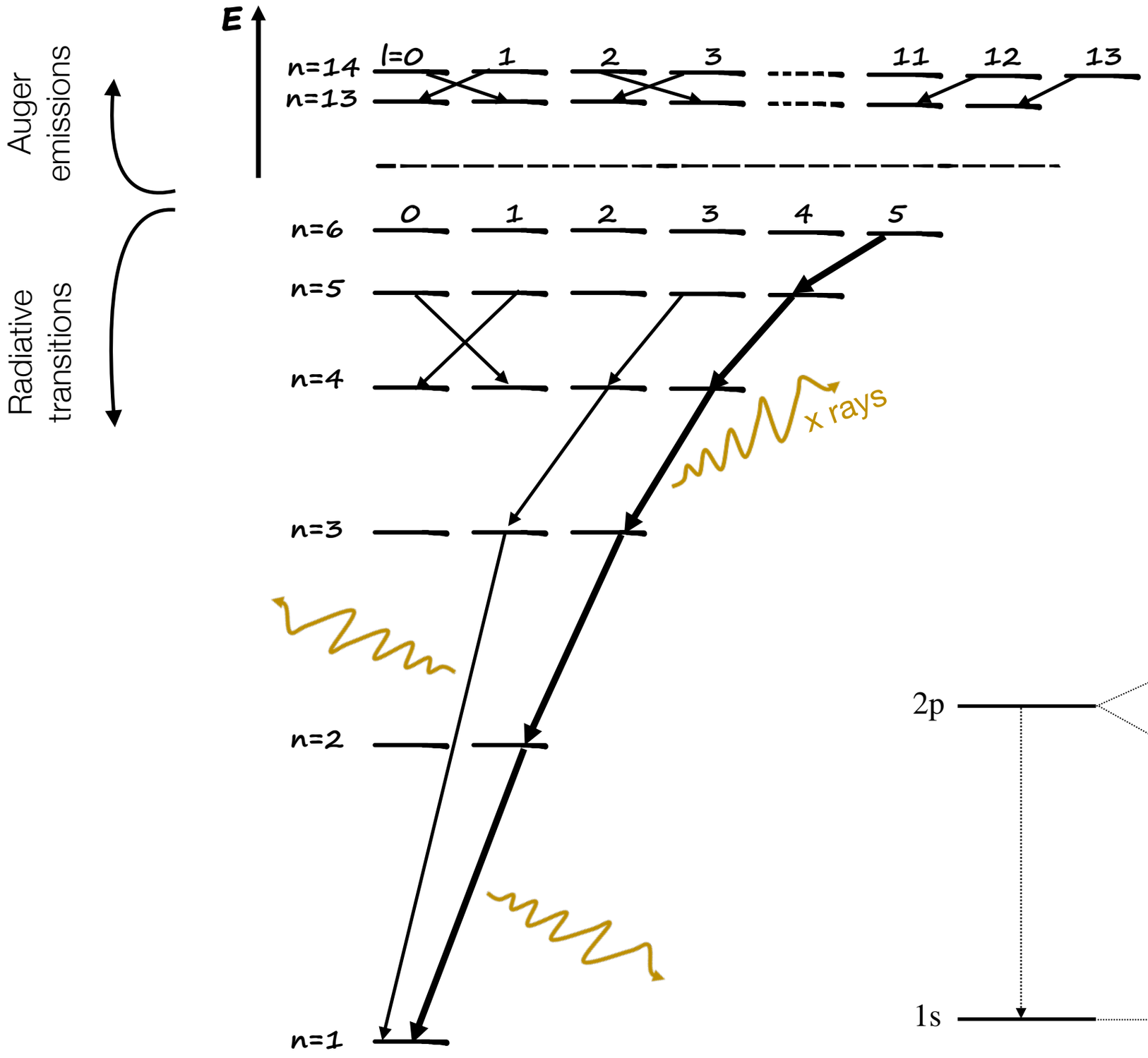


Muonic cascade

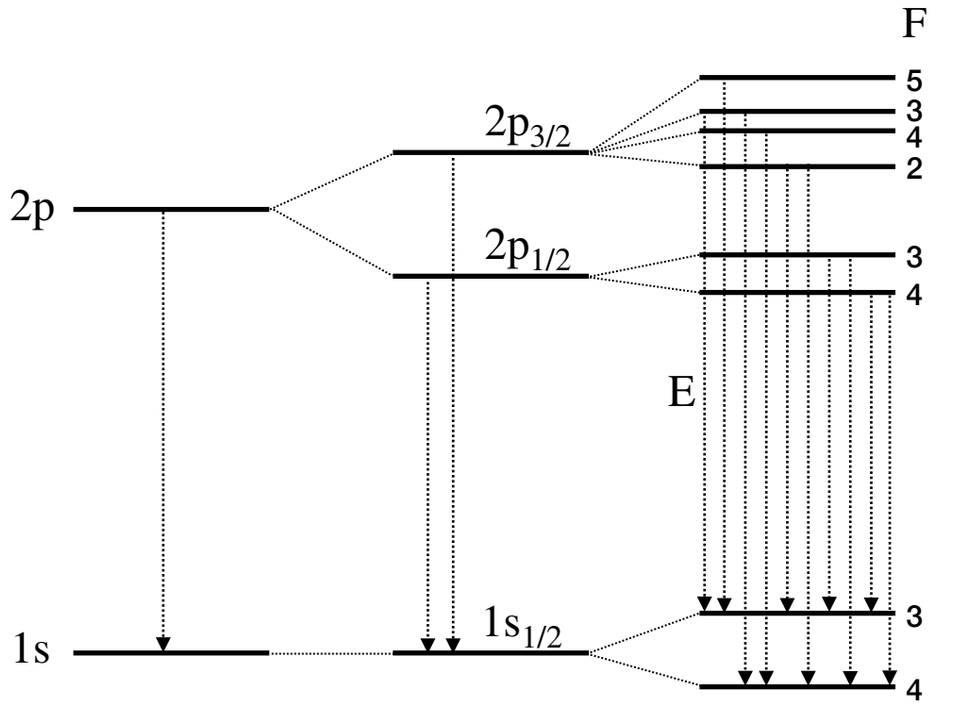


Muonic cascade



Fine splitting (FS): $\vec{J} = \vec{l} + \vec{s}$

Static hyperfine splitting (HFS): $\vec{F} = \vec{I} + \vec{J}$



$$I_{ground} = \frac{7^+}{2}$$

How to extract nuclear charge parameters from measured muonic energies

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Theoretical calculations of the Dirac equation

$$(\alpha \cdot \mathbf{p}_\mu + \beta\, \mathrm{m}_\mu)\, \psi = (\mathrm{E} - \mathrm{V}(\mathrm{r}))\, \psi$$

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Charge distribution parameters in $\mathrm{V}(\mathrm{r})$

How to extract nuclear charge parameters from measured muonic energies

Corrections of the muonic energy levels

Theoretical calculations of the Dirac equation

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Charge distribution parameters in $V(r)$

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Energies of the muonic levels

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Charge distribution parameters in $V(r)$

Measured energies by HPGe detectors

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Corrections of the muonic energy levels

Theoretical calculations of the Dirac equation

$$(\alpha \cdot \mathbf{p}_\mu + \beta\, m_\mu)\,\psi = (E - V(r))\,\psi$$

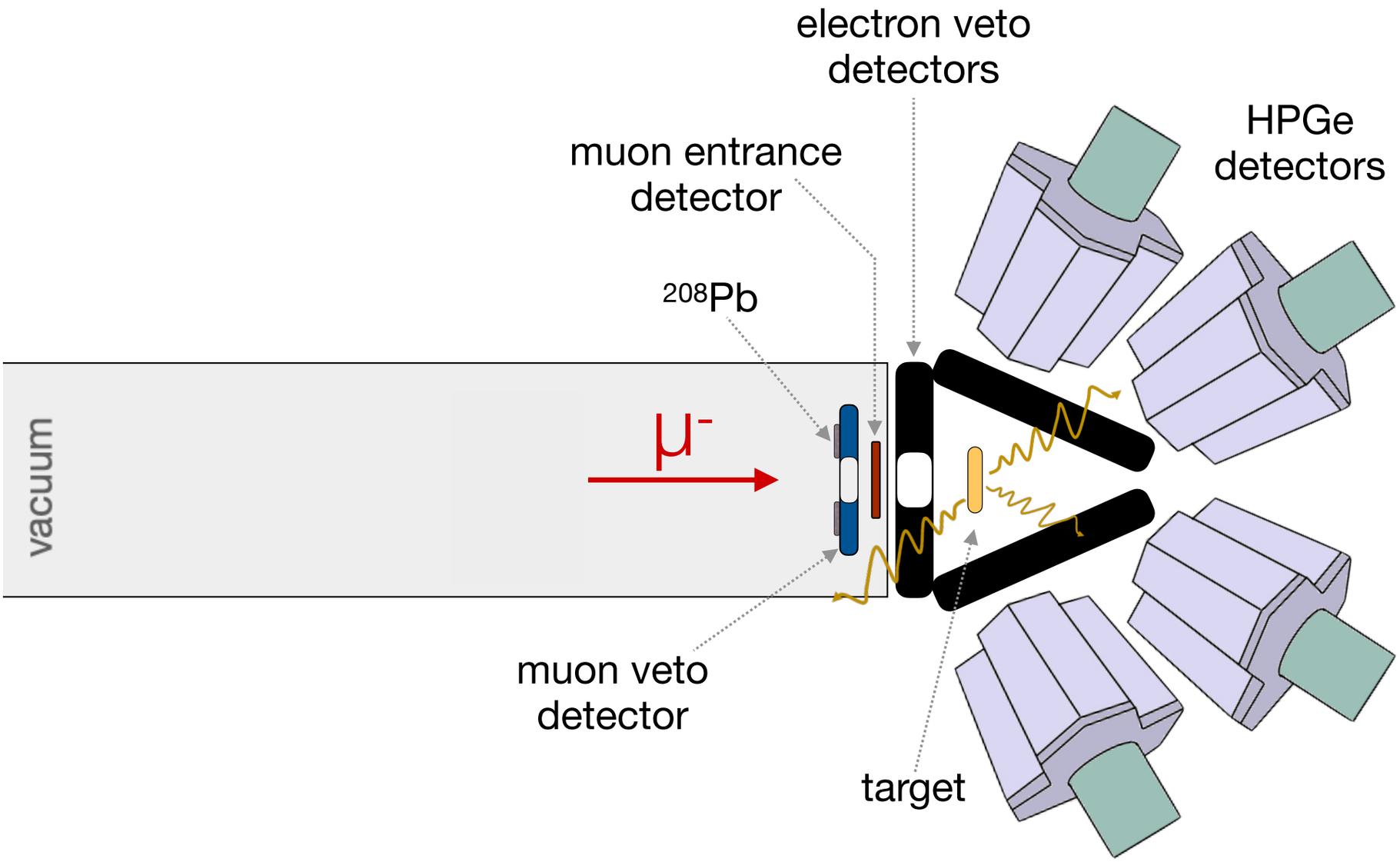
Extract the charge distribution parameters

Measured energies by HPGe detectors

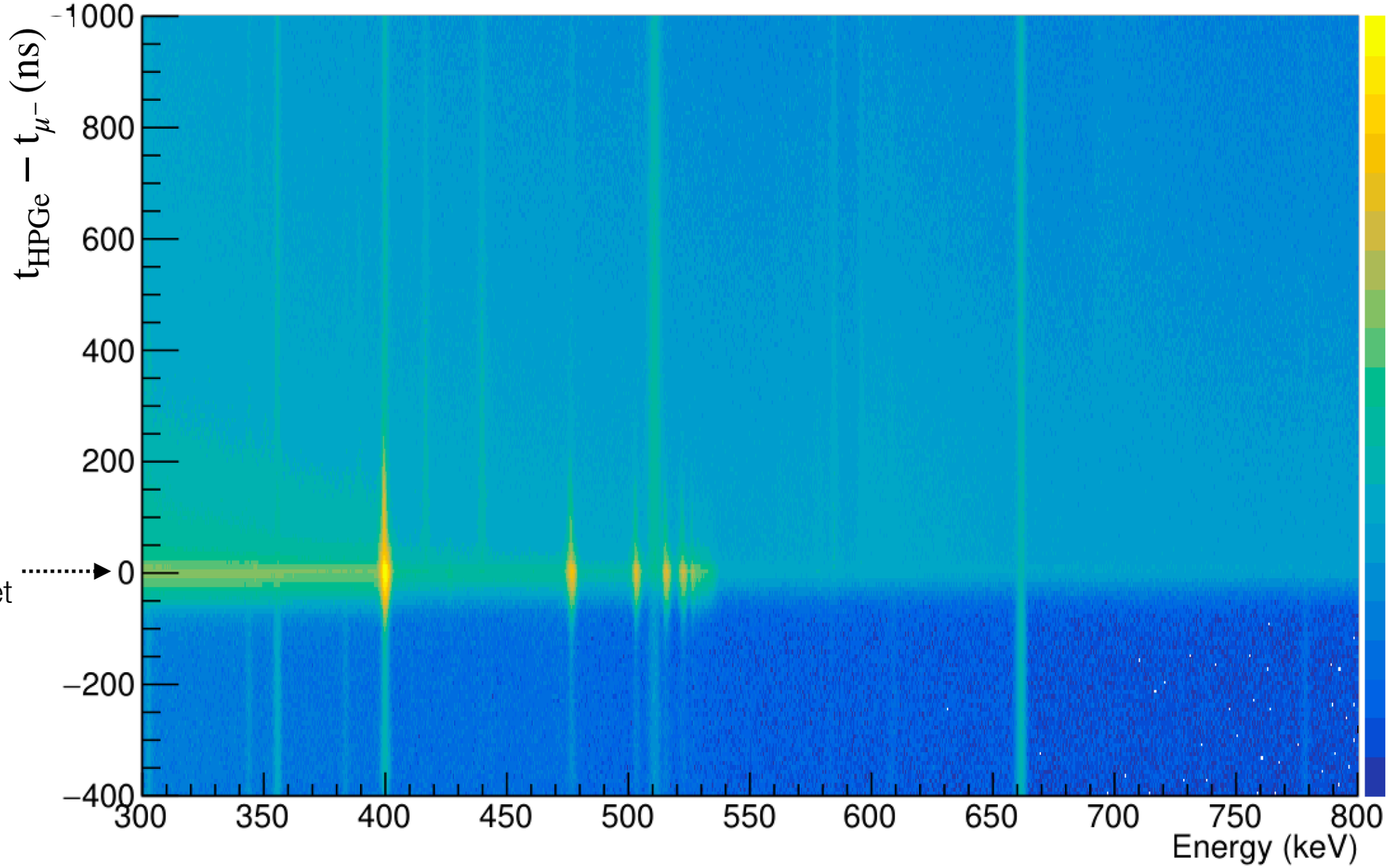
Paul Scherrer Institute (PSI)

High Intensity Proton Accelerator (HIPA) facility at Paul Scherrer Institute

Schematics of detection system

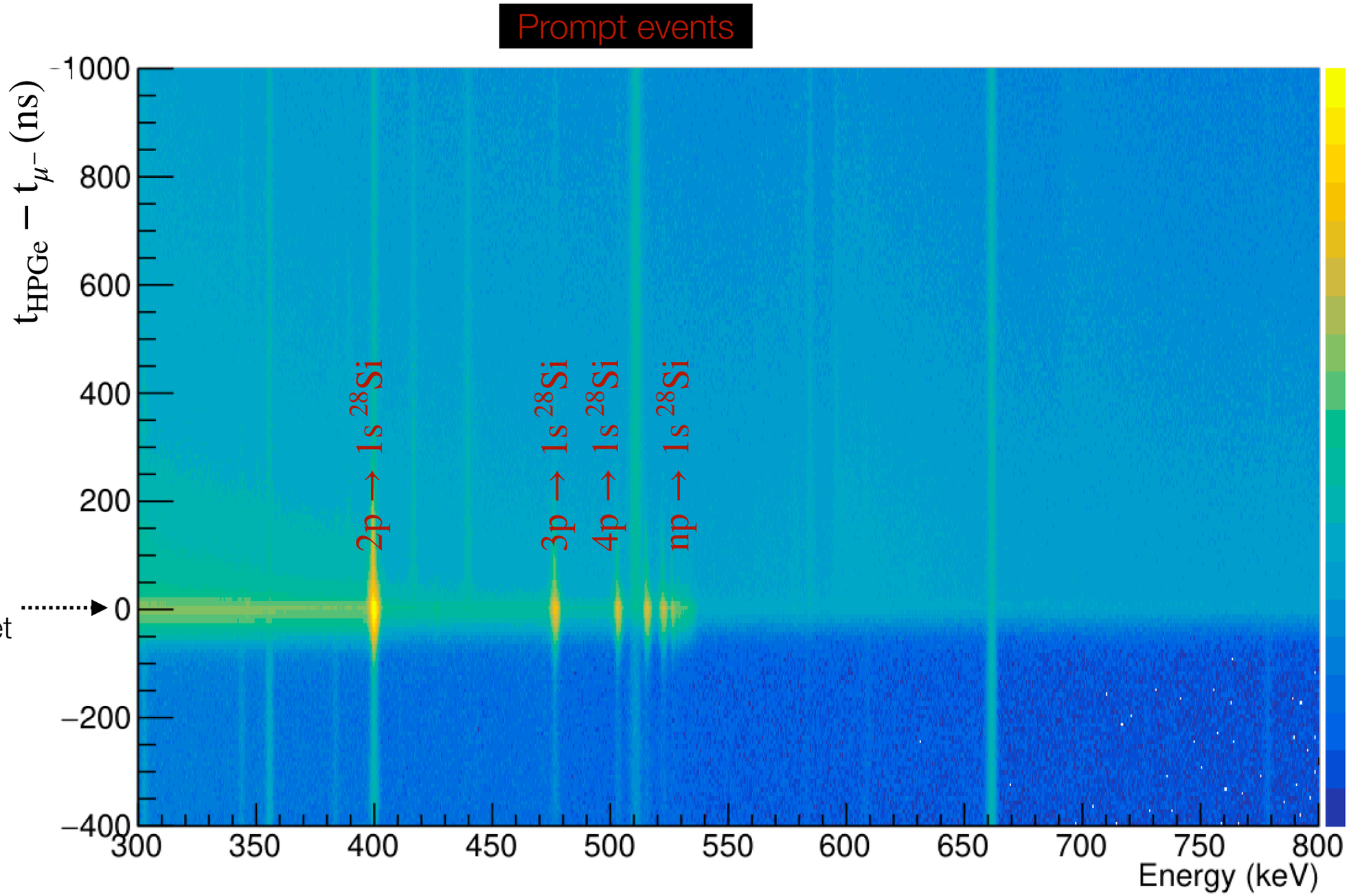


Muon-time correlated analysis



Time of the muon impinging on target

Muon-time correlated analysis



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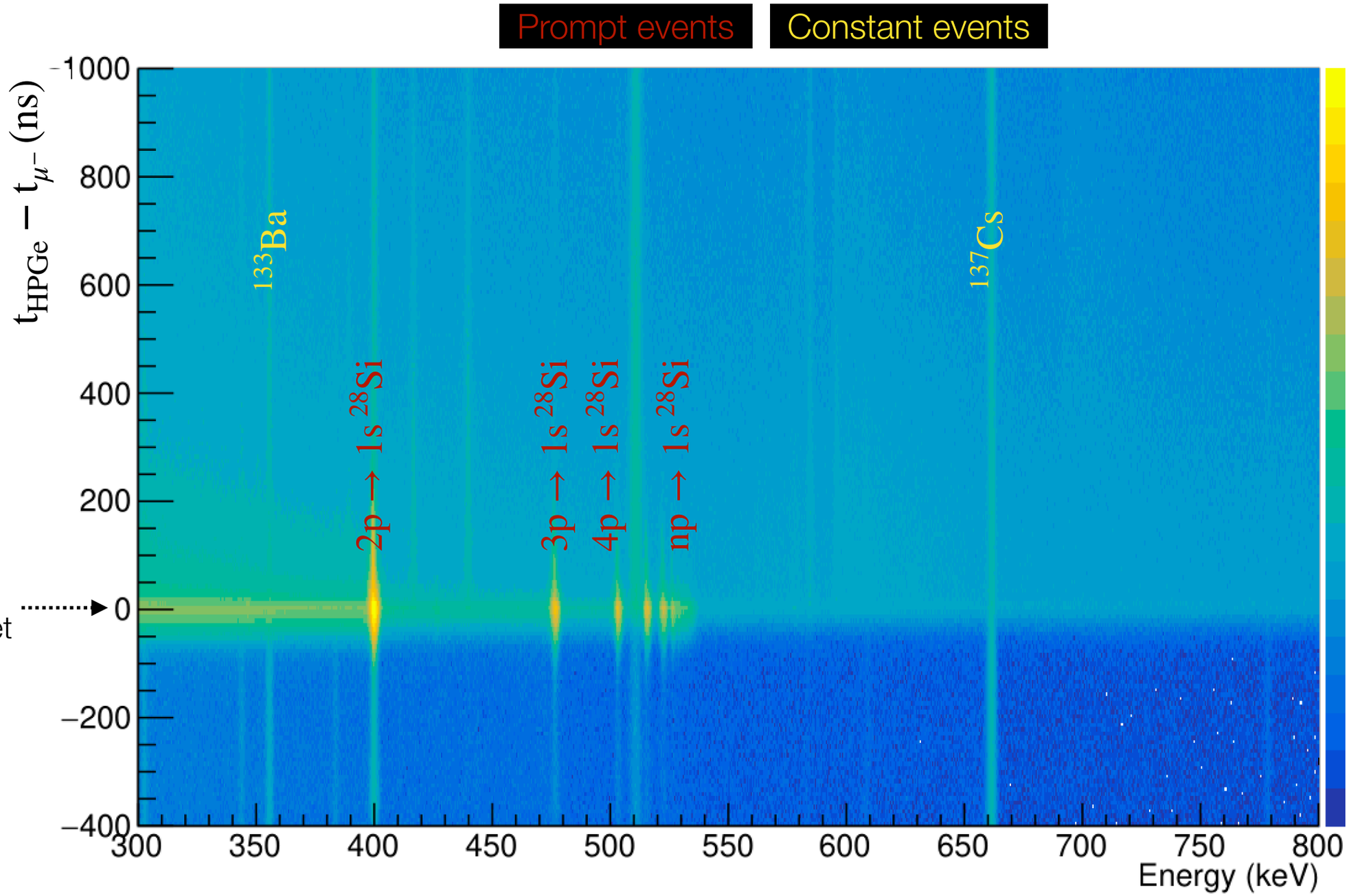

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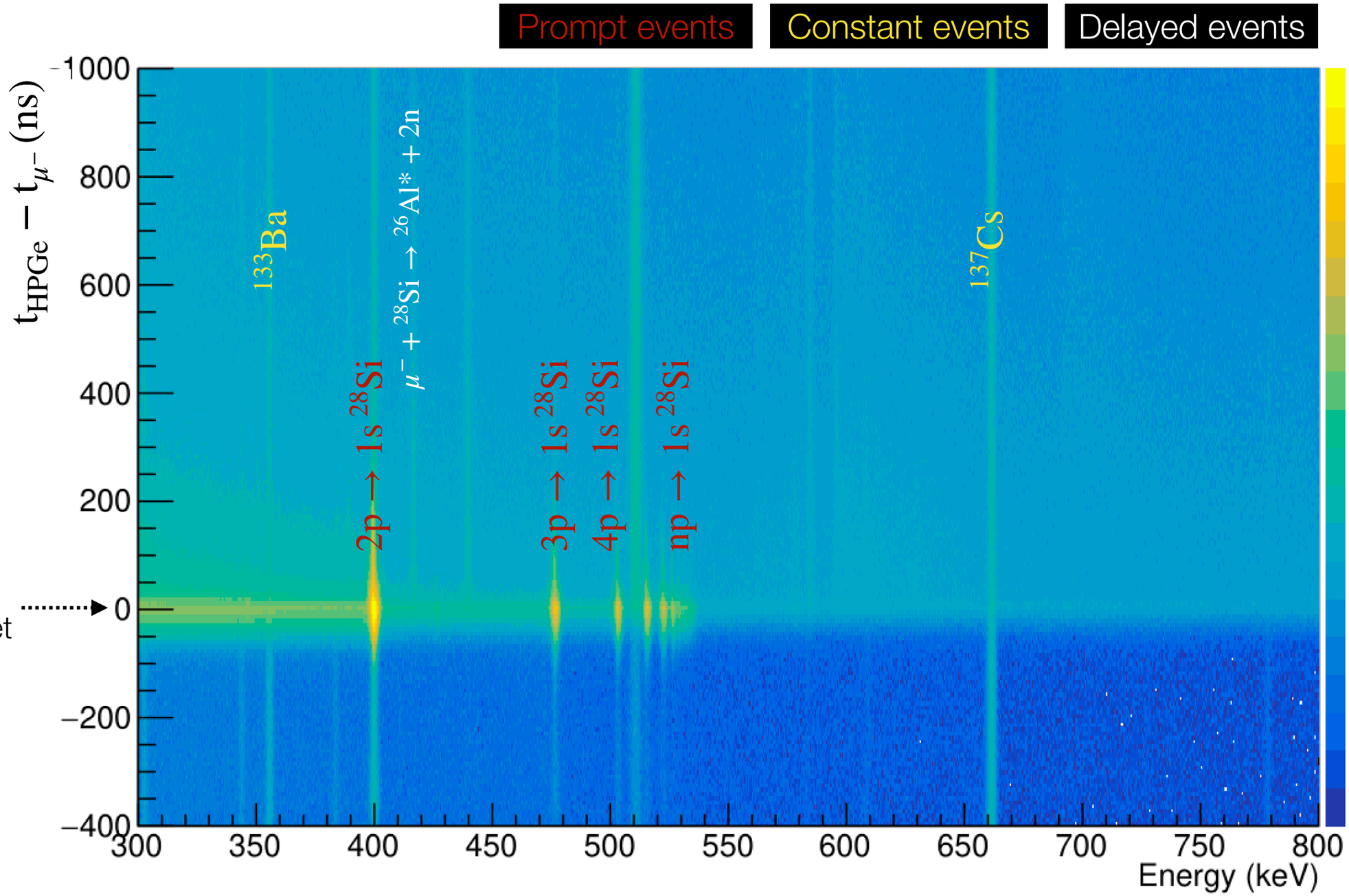
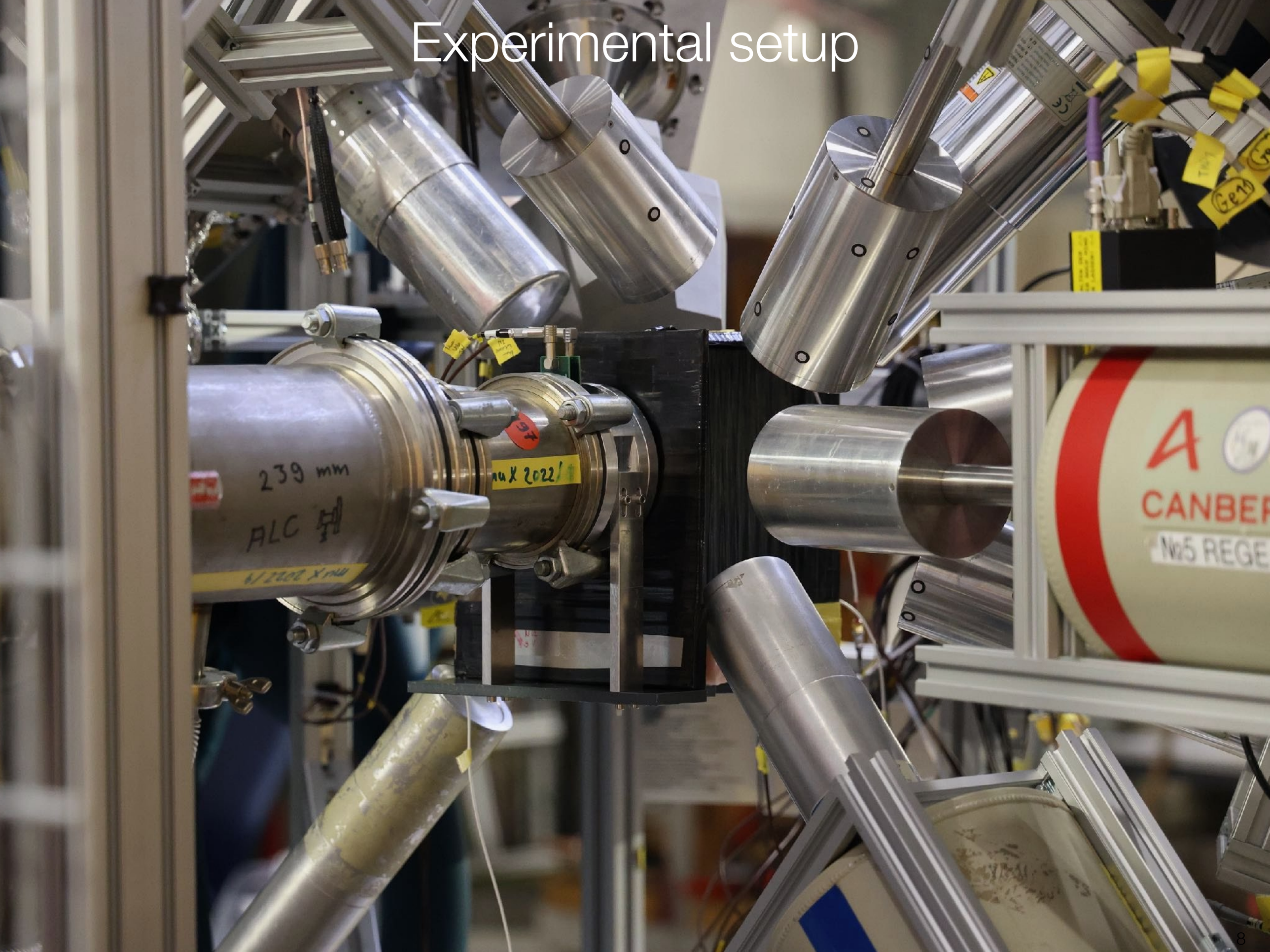


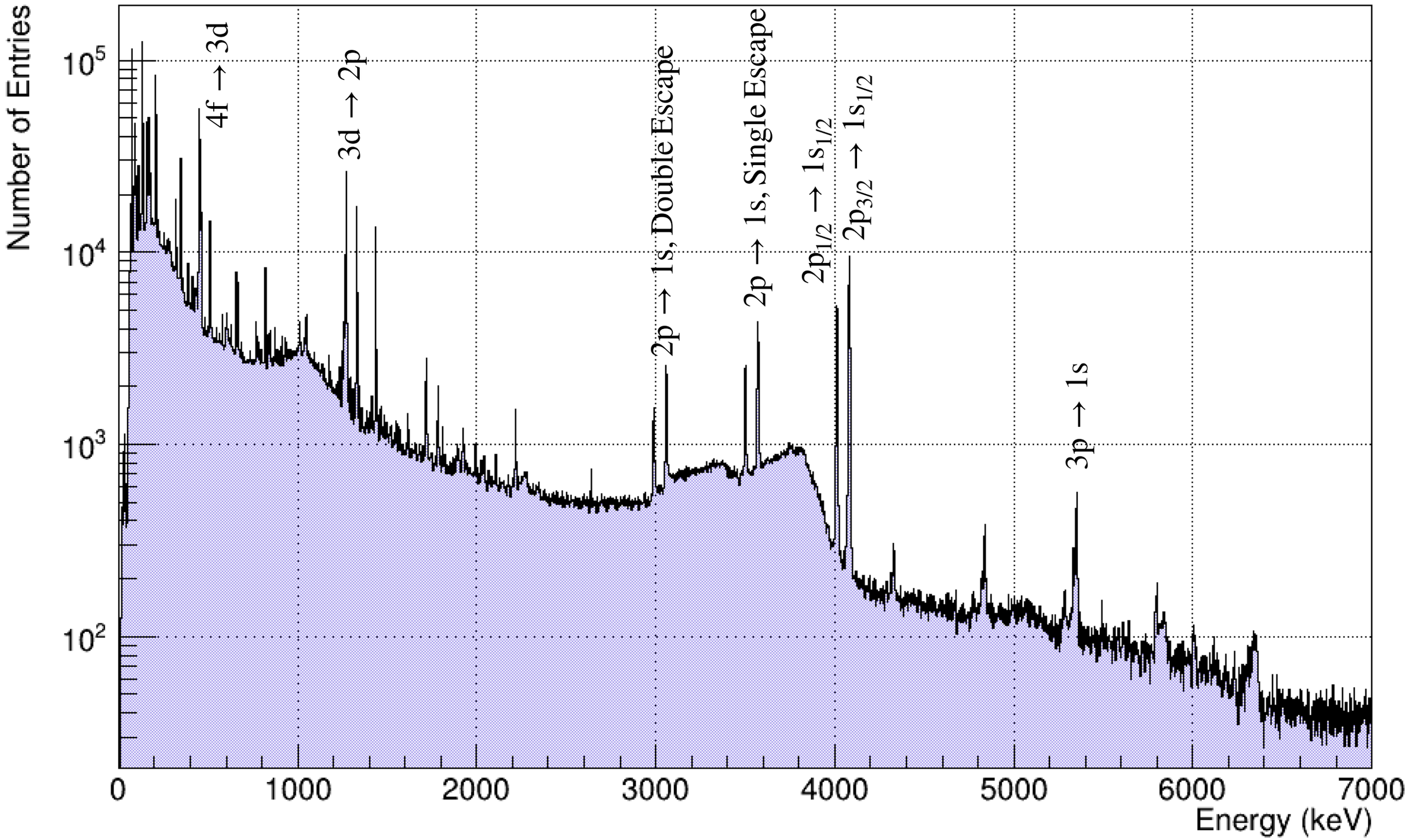
Time of the muon impinging on target

Experimental setup



- 13 HPGe detectors in total
- 6 electron veto detectors
- LN2 system to cool down the detectors

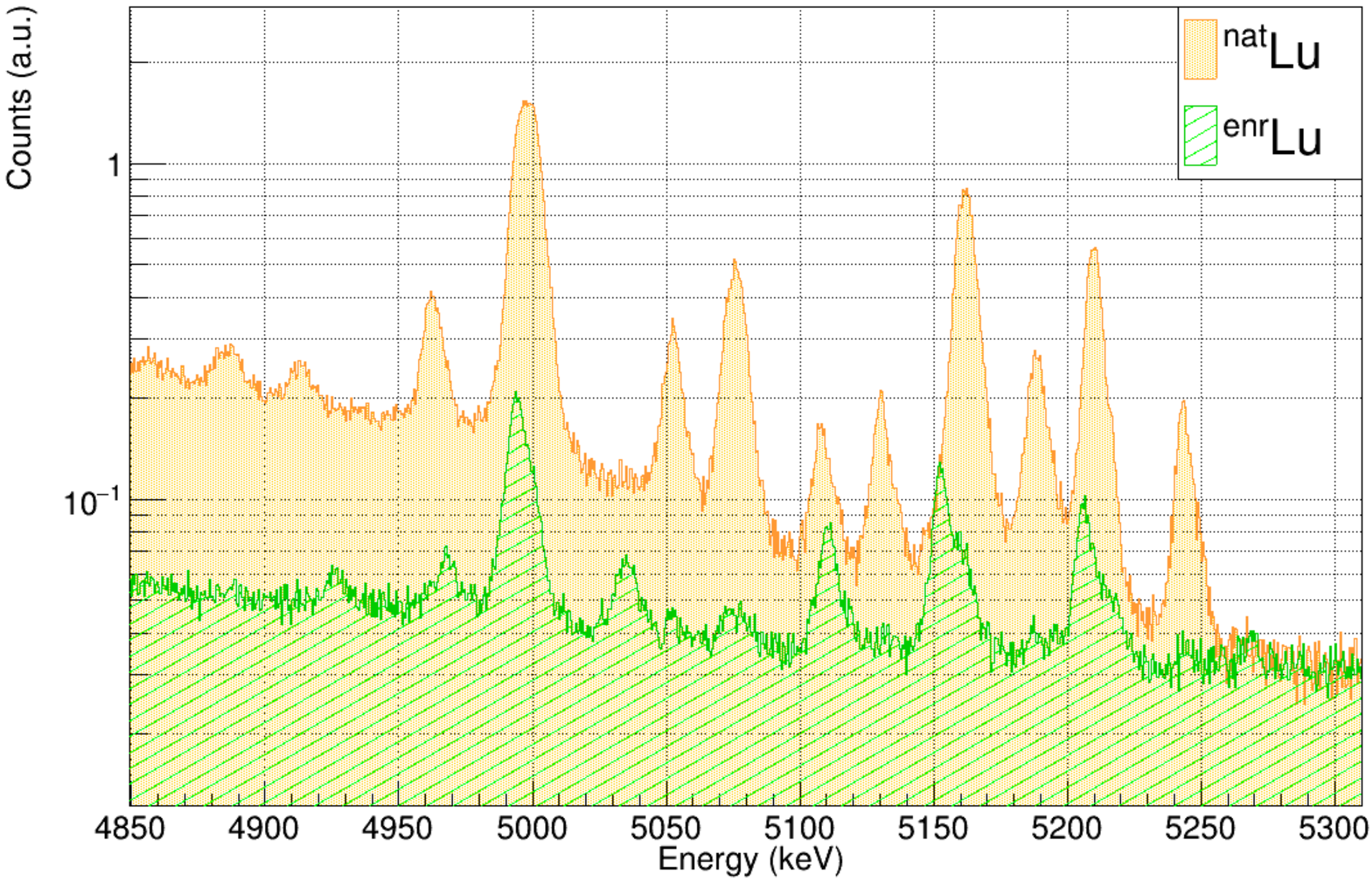
Muonic spectrum in ^{nat}La



2p→1s in natural vs enriched Lu

Natural sample 97.5 % /2.5 % ^{175}Lu/^{176}Lu

Enriched sample 25 % /75 % ^{175}Lu/^{176}Lu



Dynamic splitting in heavy & deformed isotopes

Fine splitting (FS): $\vec{J} = \vec{l} + \vec{s}$

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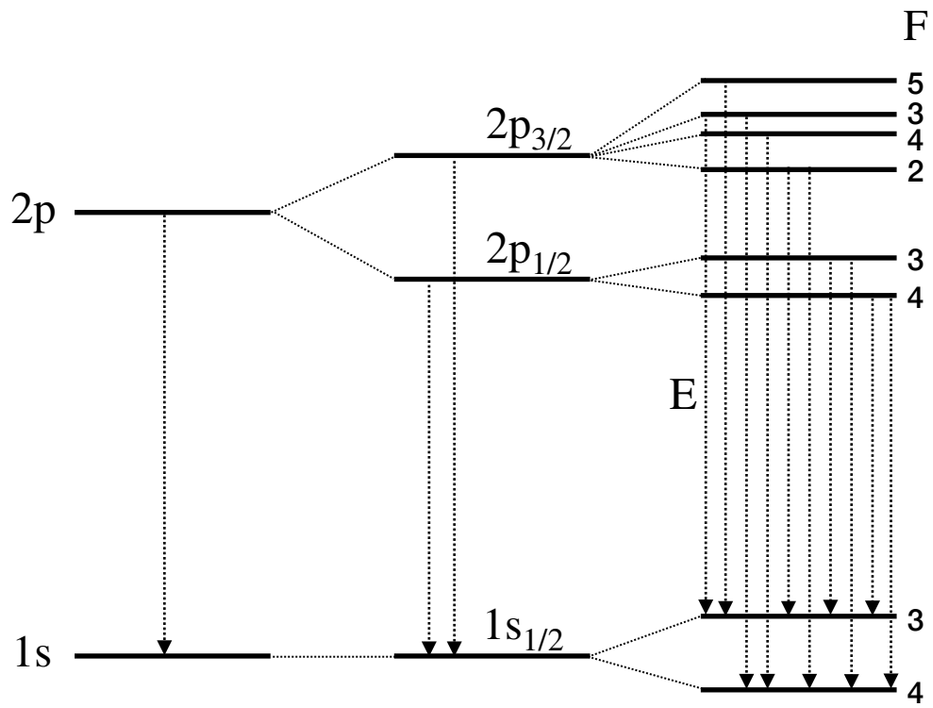

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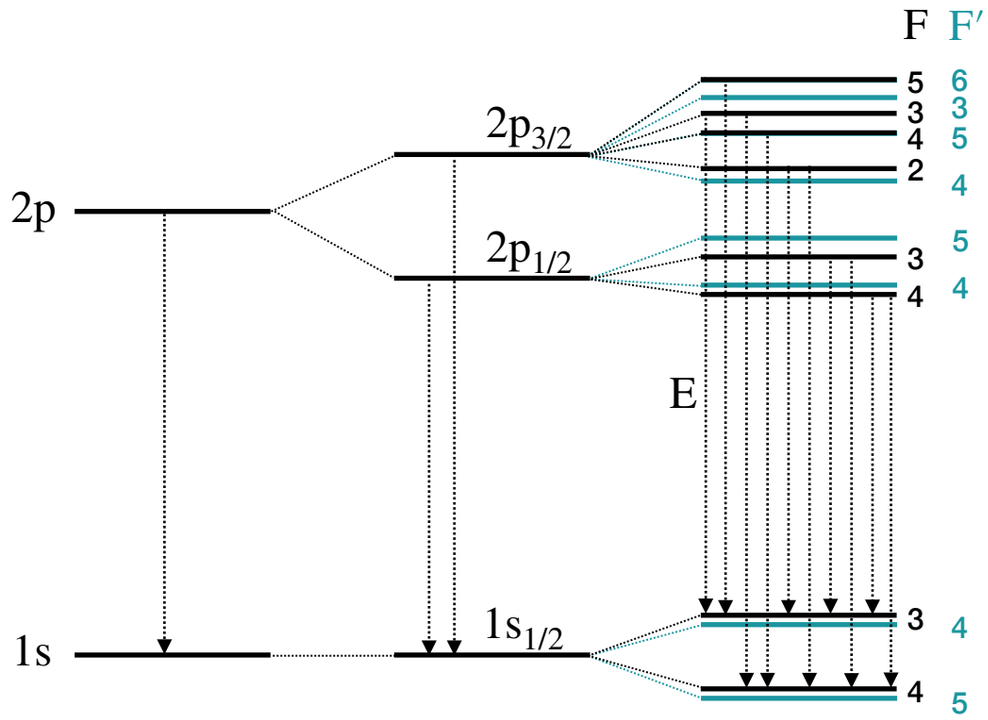
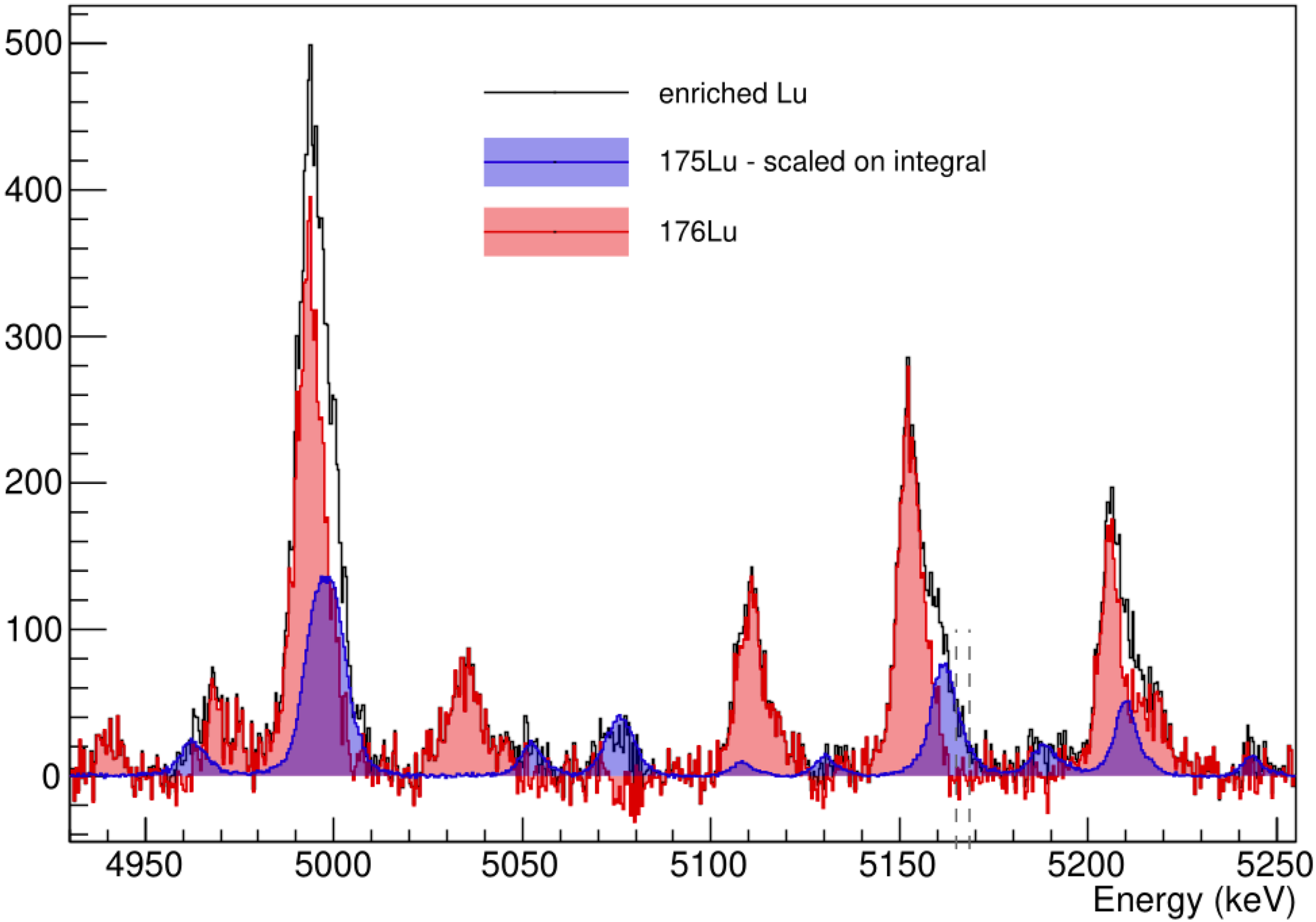
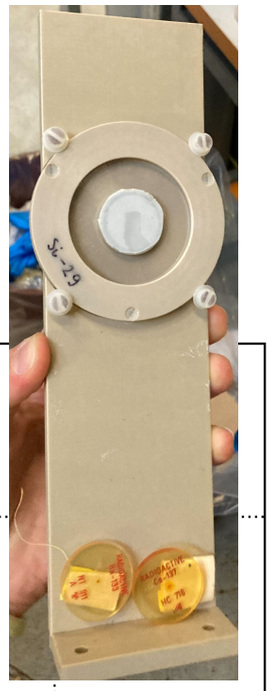


$I_{ground} = \frac{7^+}{2}$ $I_{excited} = \frac{9^+}{2}$

2p→1s in ^{176}Lu vs ^{175}Lu



np→1s in ^{28}Si



Number of Entries
10^6
10^5
10^4
10^3
$2p \rightarrow 1s\ ^{28}Si$
^{133}Ba
$\mu^- + {}^{28}Si \rightarrow {}^{26}Al^* + 2n$
$3p \rightarrow 1s\ ^{28}Si$
$4p \rightarrow 1s\ ^{28}Si$
$np \rightarrow 1s\ ^{28}Si$
^{137}Cs
300
350
400
450
500
550
600
650
700
750
800
Energy (keV)

It takes a team

and a beautiful sky

