Fission barrier measurements at ISS

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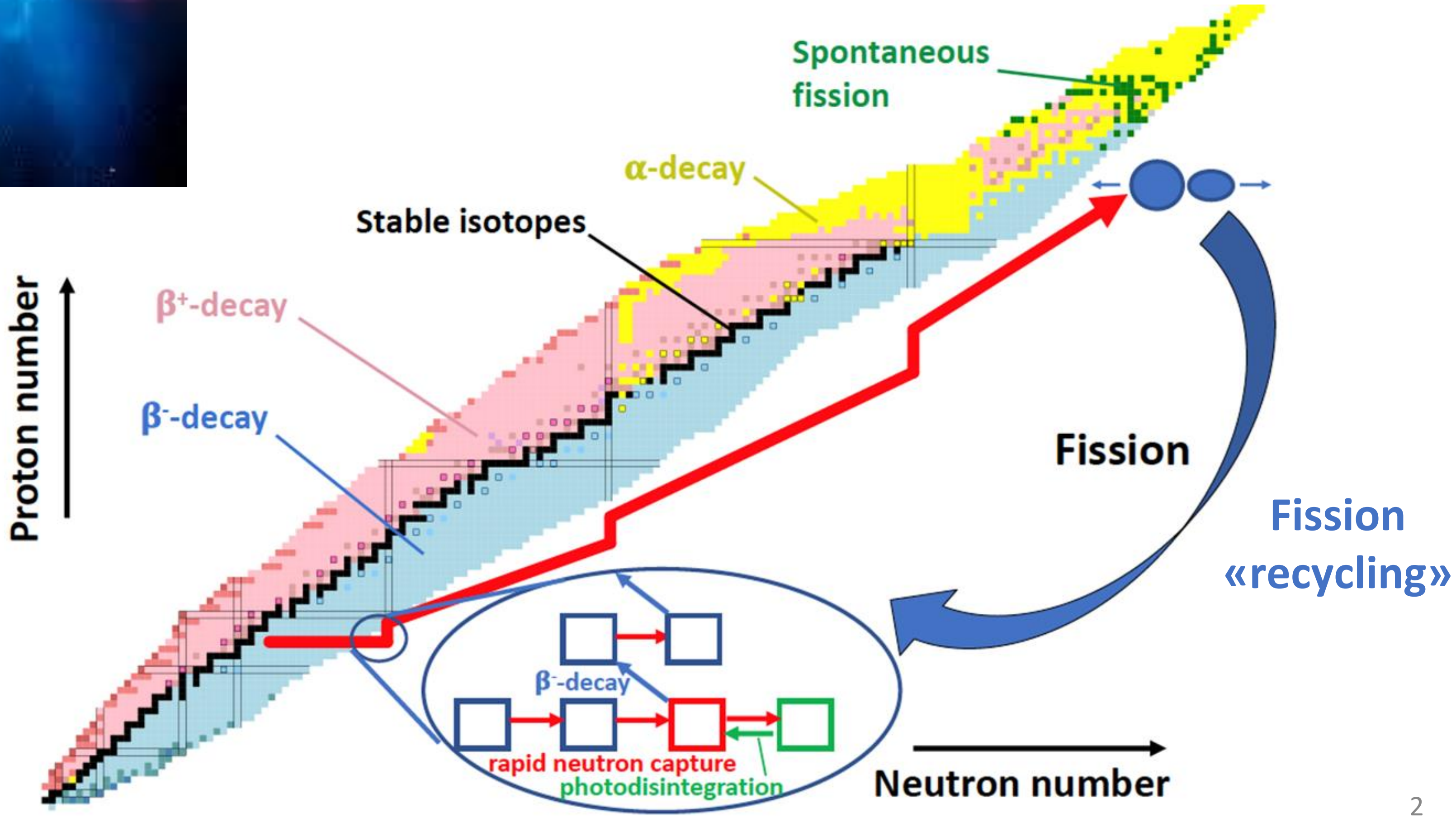
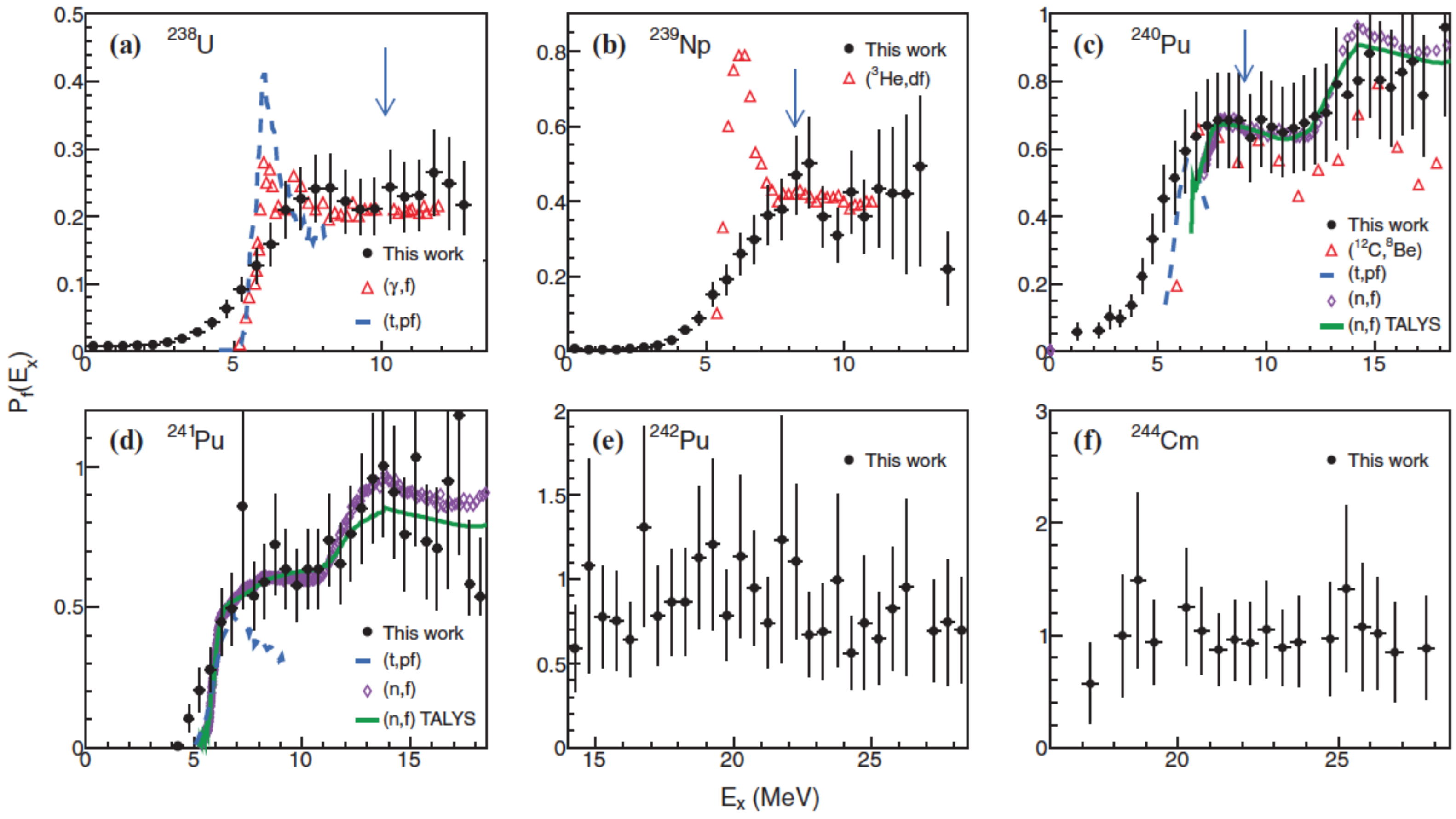
Why is fission so important?



Fission barrier ingredients

What is needed?

- Fission probability as a function of the excitation energy.
- Charge-mass distribution of FFs.
- Energy released in γ radiation during fission.

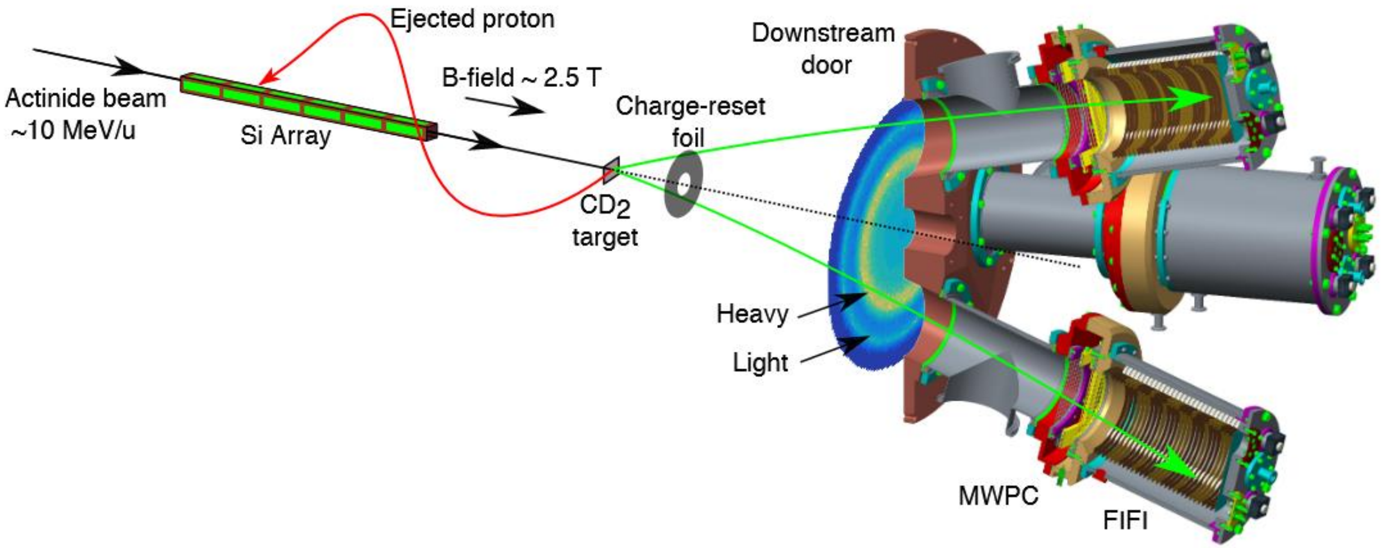


C. Rodríguez-Tajes et al., PRC 89, 024614 (2014).

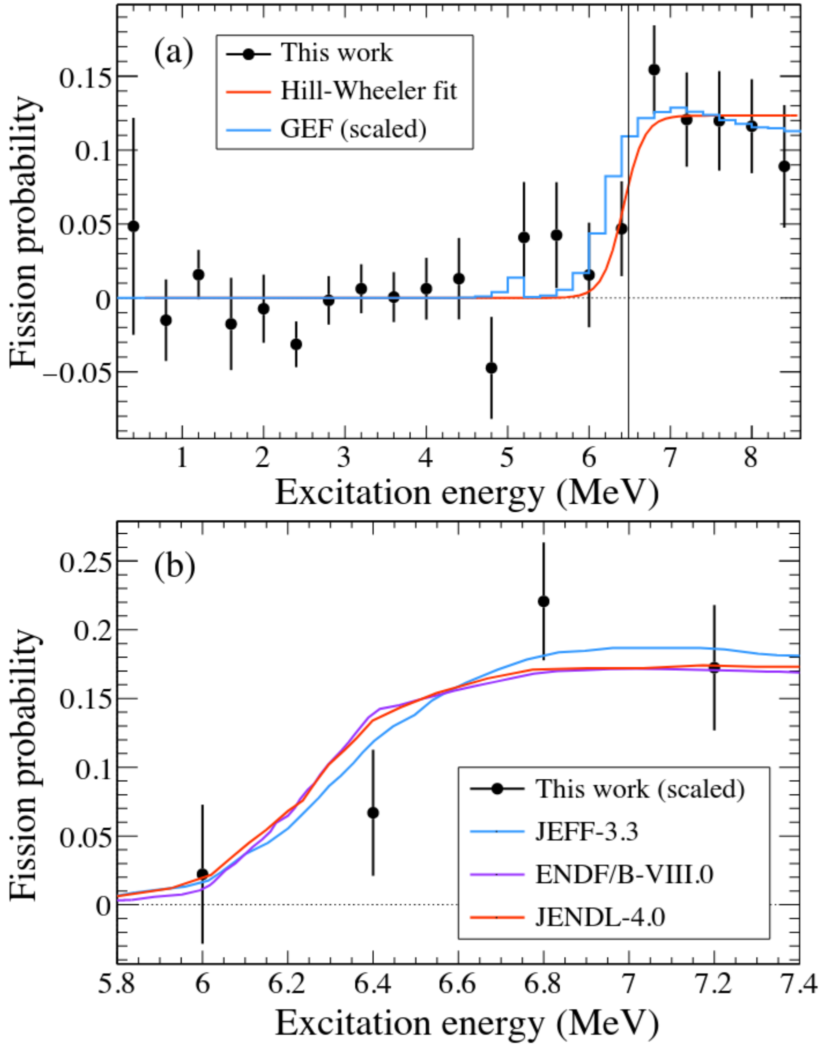
We need this info for n-rich nuclei –> n-rich actinides beams

Proof-of-principle experiment at ANL – HELIOS

^{238}U(d,pf) @8.6 MeV/u



(LoI, INTC-I-224)



S. A. Bennett et al., Phys. Rev. Lett. 130, 202501

Very promising for ISS, BUT.... Geometrical efficiency of the setup is limited:

(S. A. Bennett et al., Phys. Rev. Lett. **130**, 202501)

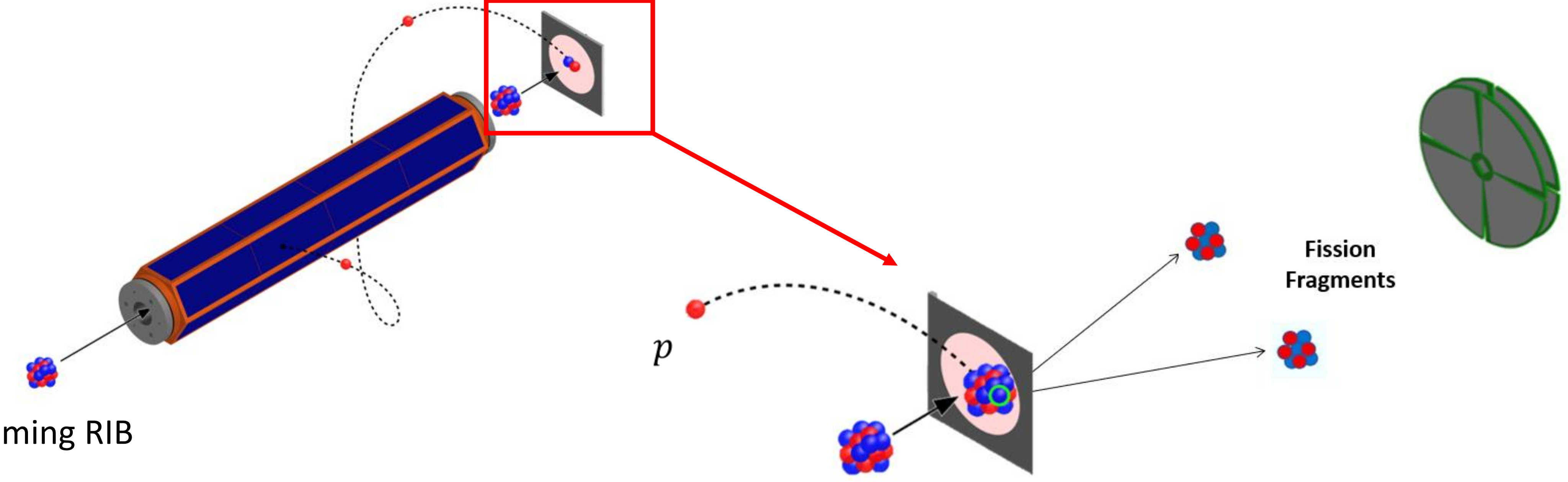
- ~10% for the detection of one or more FF,
- ~1% for the coincident detection of light and heavy fragments

Commissioning experiment for ISS is planned (IS224).

(d,pf) transfer reaction

Inverse kinematics approach

Idea: use a CD-shaped DSSSD to increase the efficiency

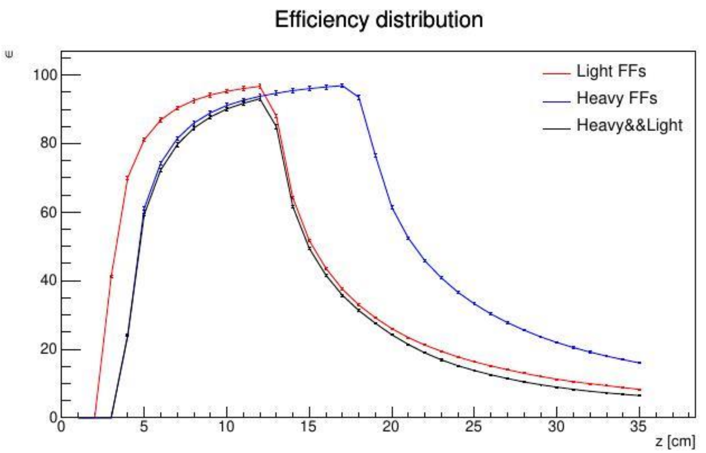


Background - reactions with carbon

$$E_X = -m_2 + \sqrt{M_C^2 + m_1^2 - 2\gamma M_C(E - \alpha\beta z_{hit})}$$

$$\cos\theta_{cm} = \frac{\gamma(E\beta - \alpha z_{hit})}{\sqrt{\gamma^2(E - \alpha\beta z_{hit})^2 - m_1^2}}$$

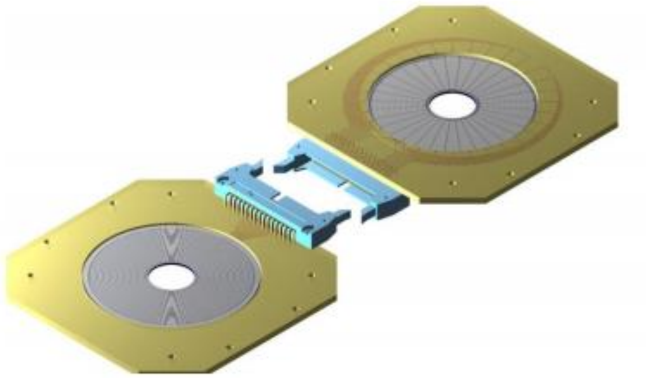
CD-shaped Si detector



Conceived for detecting **fission fragments**

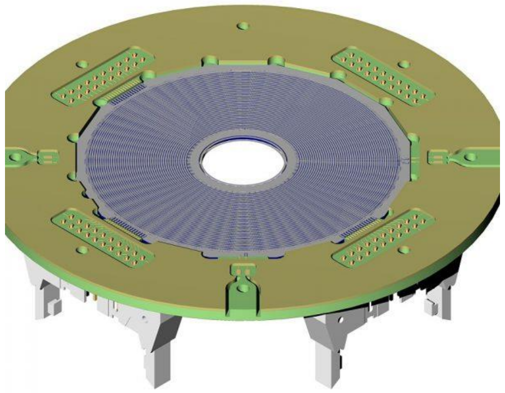
Different options by **Micron Semiconductor Ltd.**

- **S3**



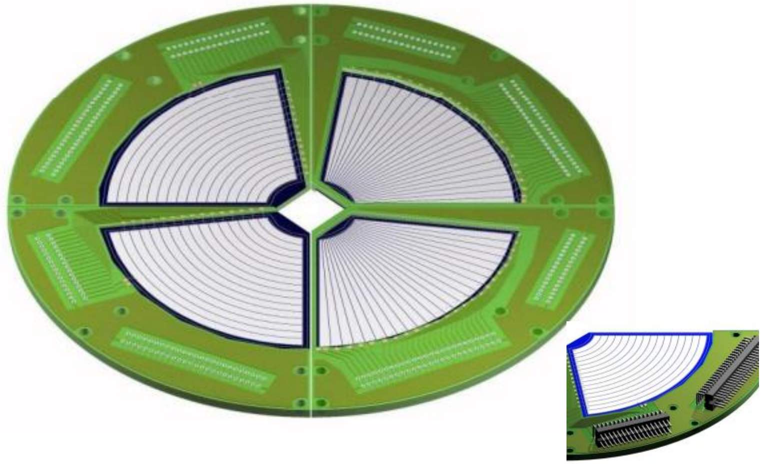
Junction number of elements	24 rings
Ohmic number of elements	32 sectors
Active area Ø - inner (mm)	22
Active area Ø - outer (mm)	70

- **S7**



Junction number of elements	45 rings
Ohmic number of elements	16 sectors
Active area Ø - inner (mm)	25.92
Active area Ø - outer (mm)	70.09

- **QQQ2**



Junction number of elements	16 rings
Ohmic number of elements	24 sectors
Active area Ø - inner (mm)	18.00
Active area Ø - outer (mm)	82.00

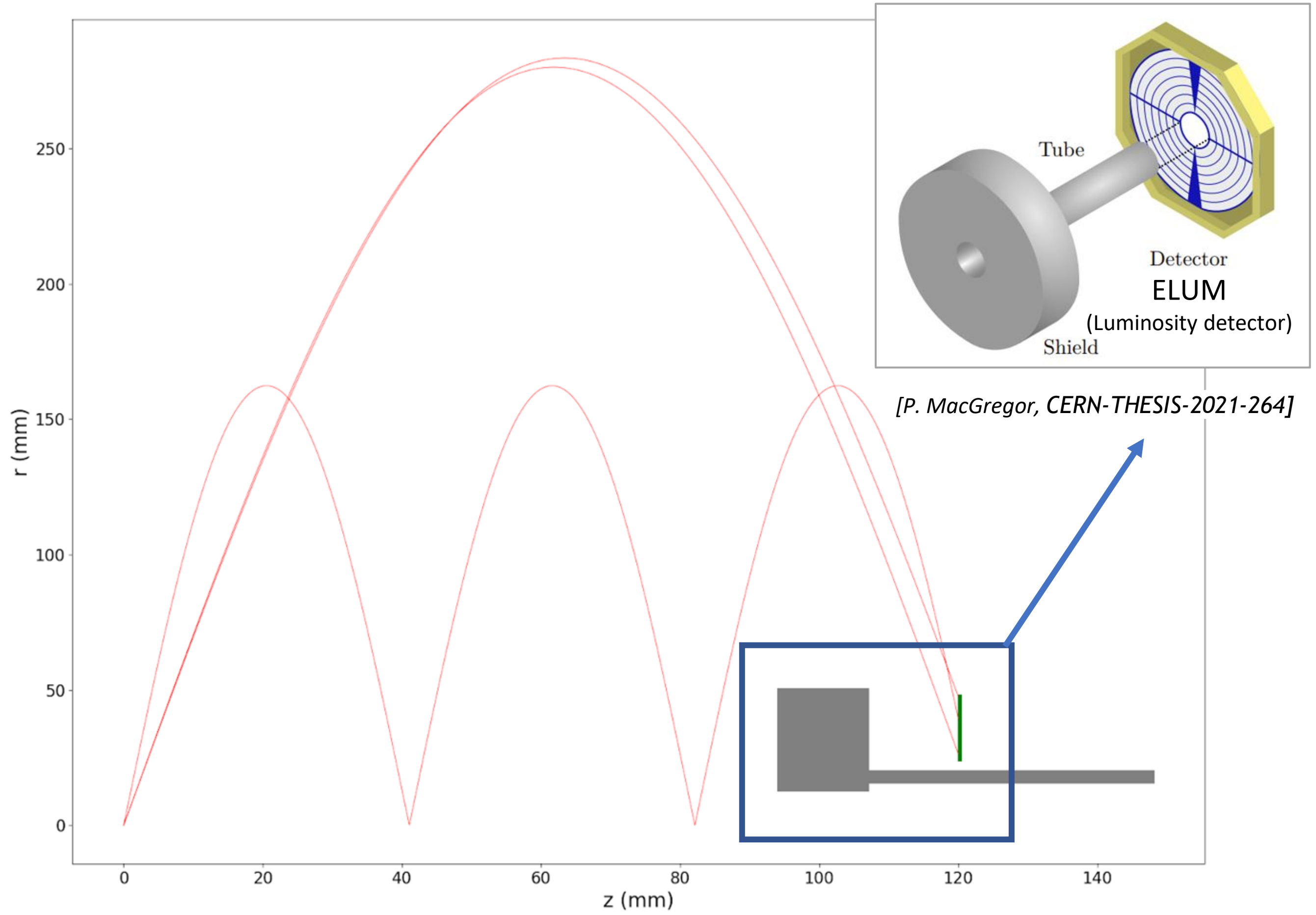
Normalisation

total number of **d** scattered **from the target** → number of beam particles impinging on the target → normalisation of fission probability

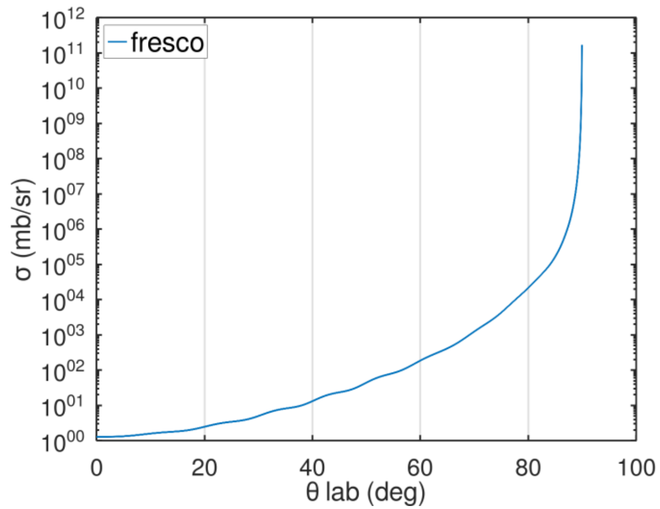
Problem deuteron breakup-input from theory is needed.

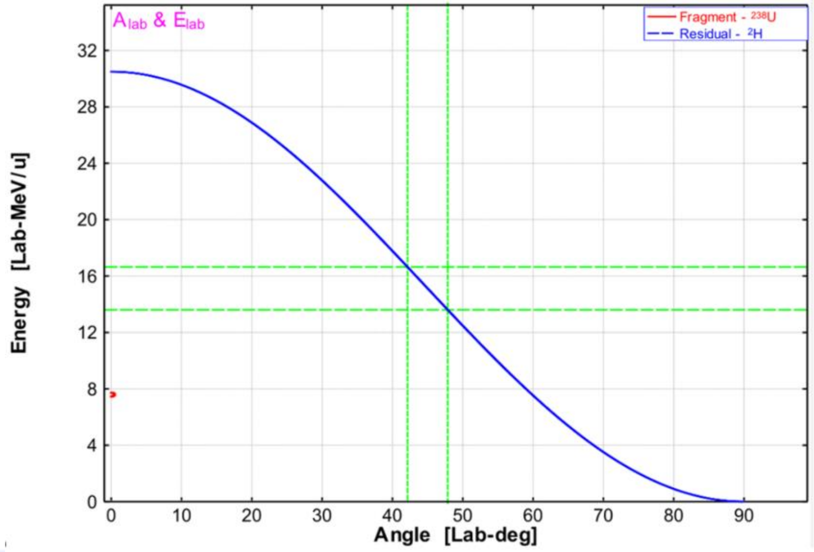
Elastically scattered deuterons

$^{2}H(^{238}U,^{238}U)^{2}H$ @10 MeV/u

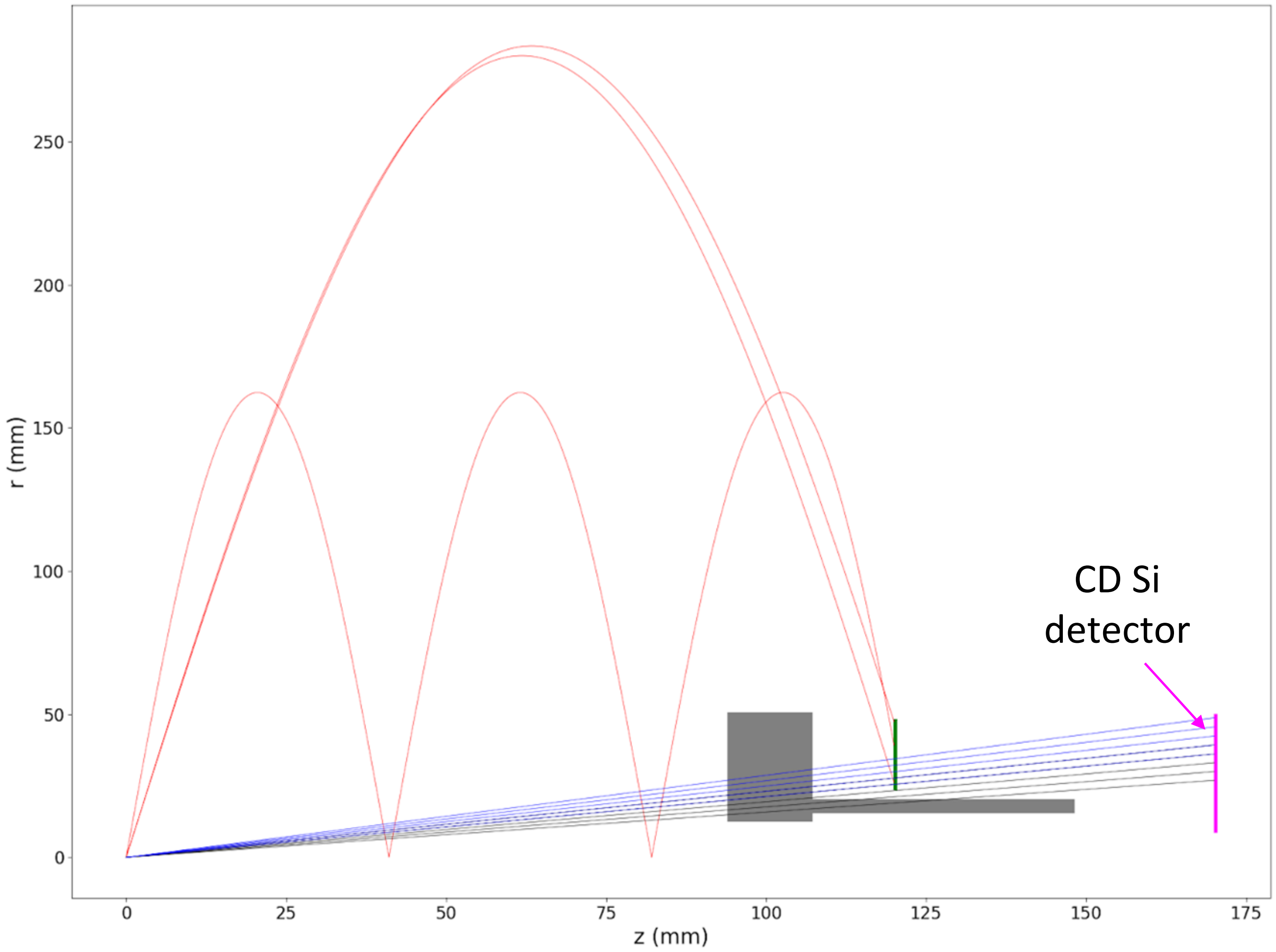


[P. MacGregor, CERN-THESIS-2021-264]



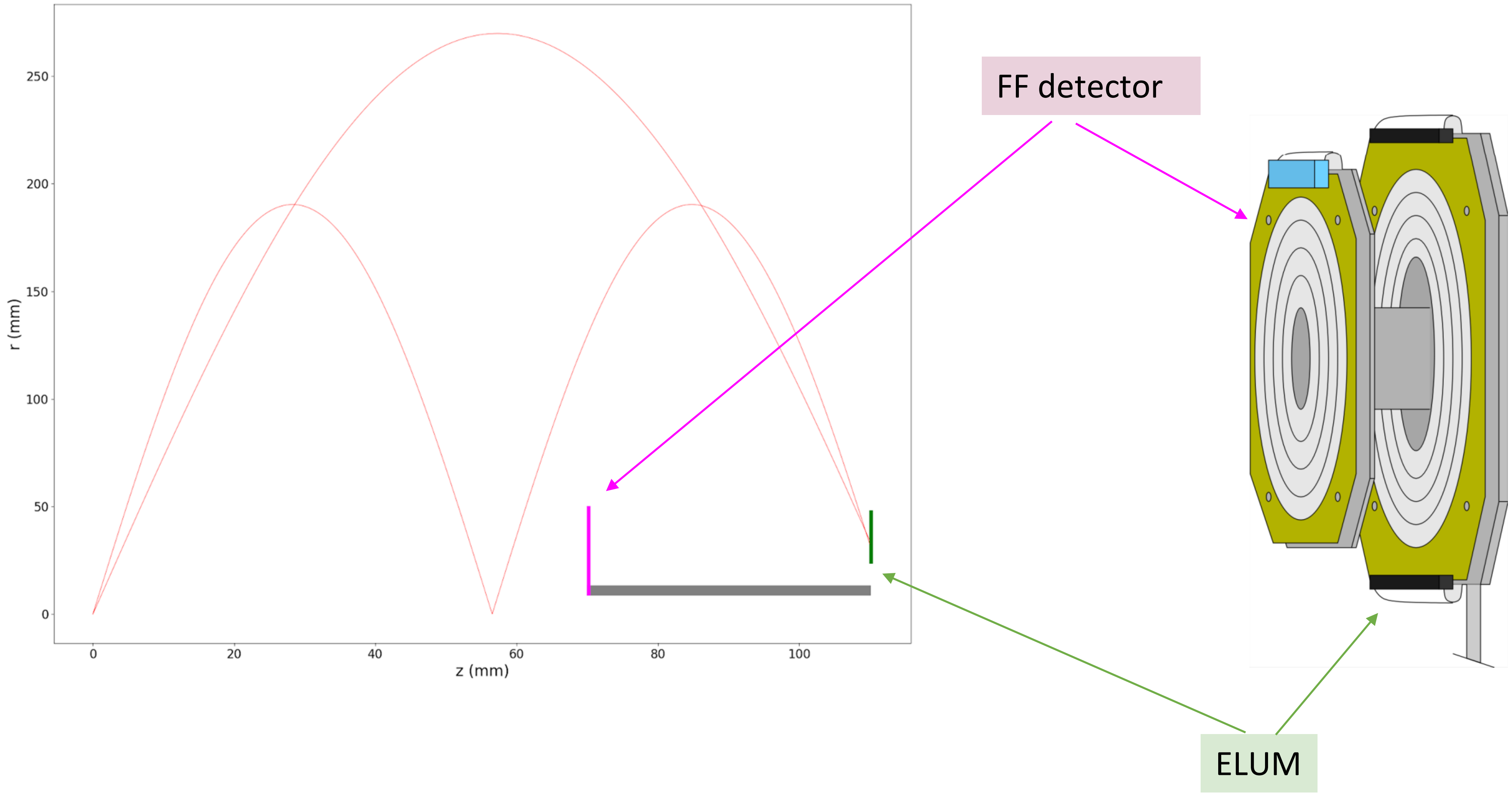


angular ranges of **d** hitting ELUM: ~82-84 degrees (depending on the distance)



ELUM is blocking the FFs trajectory. The traditional ELUM approach doesn't work.

Alternative ELUM configuration



Gamma detection

What we aim for?

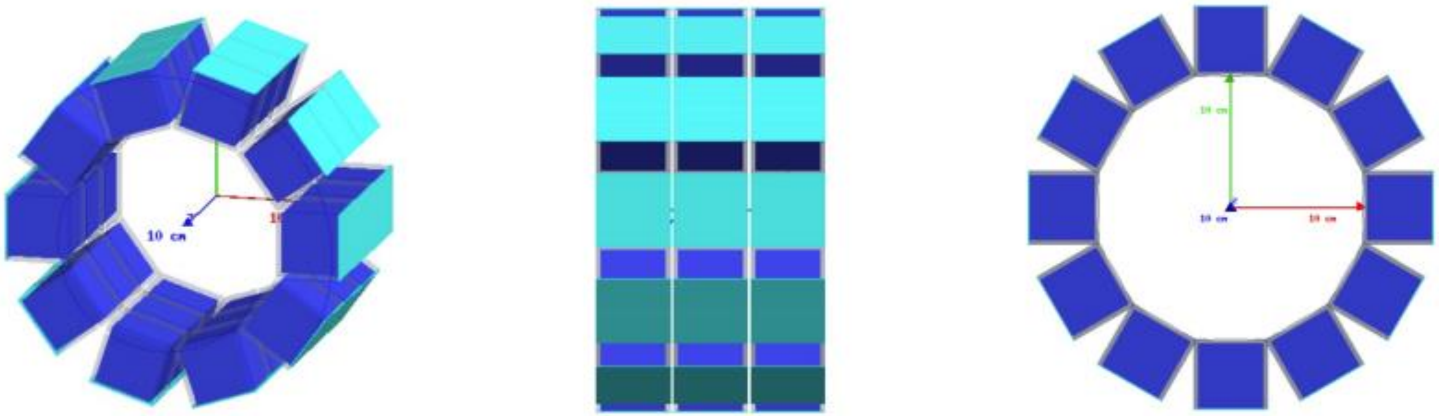
- Measure as much of the total γ-energy as possible.
- Accurate measurement and reconstruction of the γ-multiplicity per fissioning nucleus are nice to have.

Important for the energy balance in the r-process.

The highest statistics possible is desirable.

40 $CeBr_3$ scintillation detectors from SpecMAT.

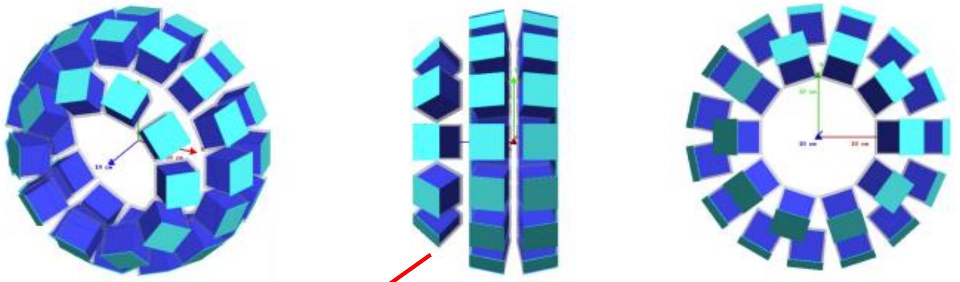
1. Cylinder configuration



Front side of $CeBr_3$ pointing towards the beam axis.

2. Rings facing beam target

Front side of $CeBr_3$ pointing towards the target.



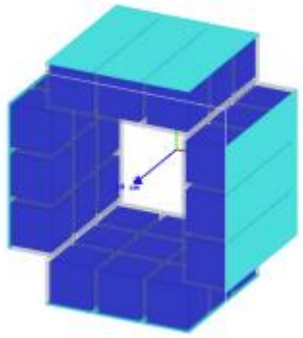
«outer» rings for a wider solid angle coverage with fewer detectors

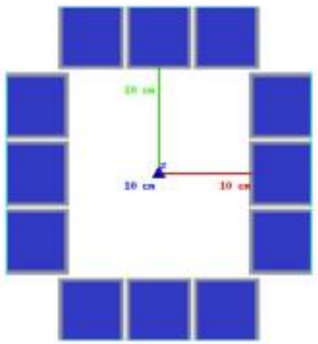
3. Box

Reduction of the gap between detectors.

Full arrangement

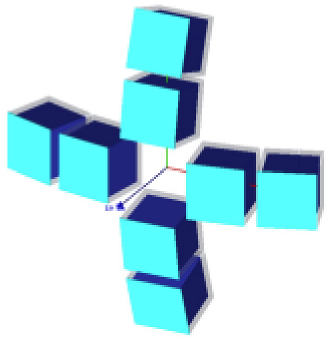
4. Box with overlap

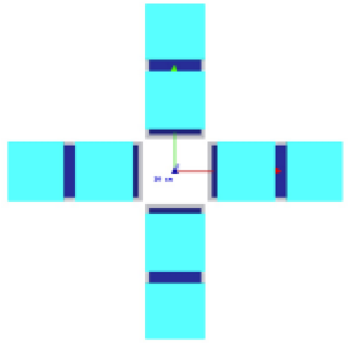




- Reduction of losses due to Compton scattered γ-rays.

5. Cross



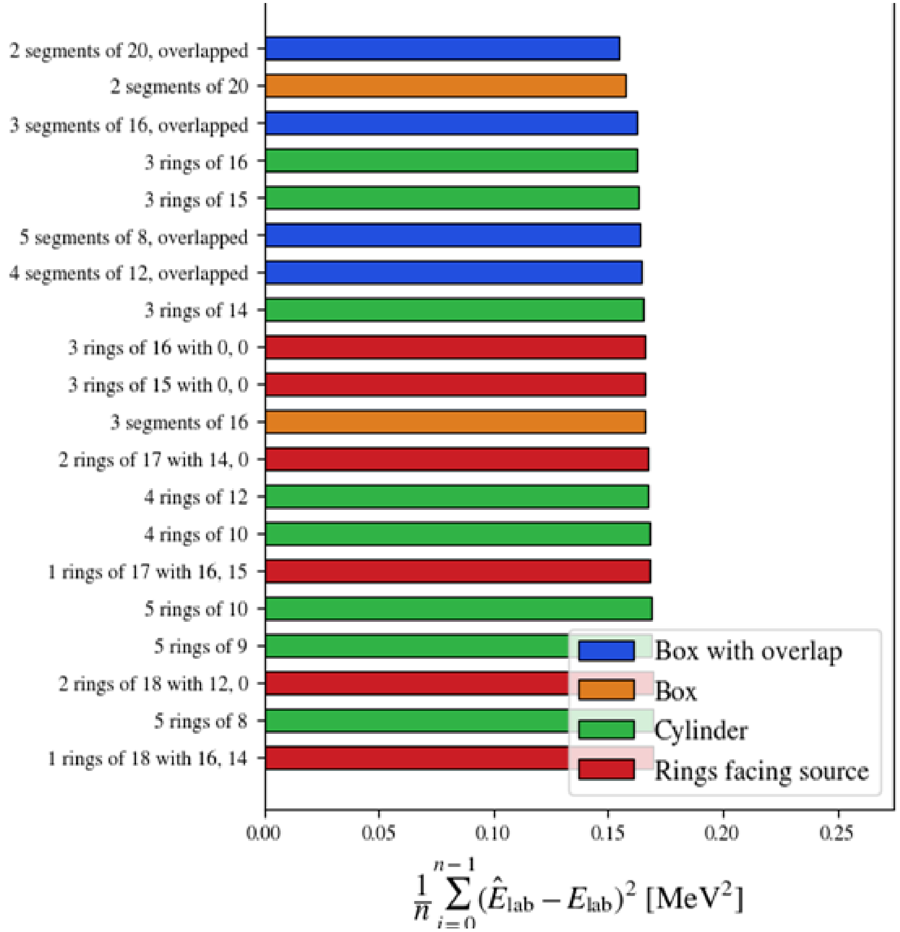


- To be eventually coupled to one of the other configurations.
- Detection of γ in the forward direction.

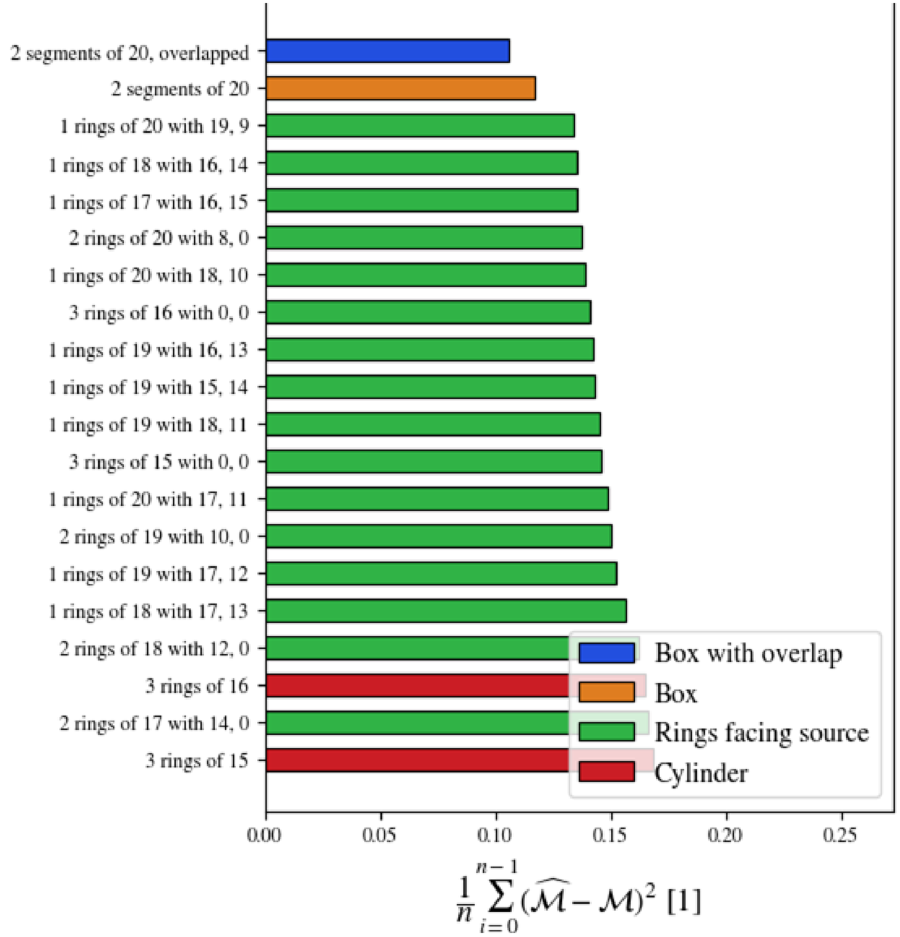
B. Johansson, A.J. Onbeck and G.S. Ahlgren *«Study of detector placement for gamma detection and reconstruction – simulations with ggland for ISS»,* internal report, August 2022

Example metrics for different configurations…

Mean squared error of deposited energy per event, excluding misses



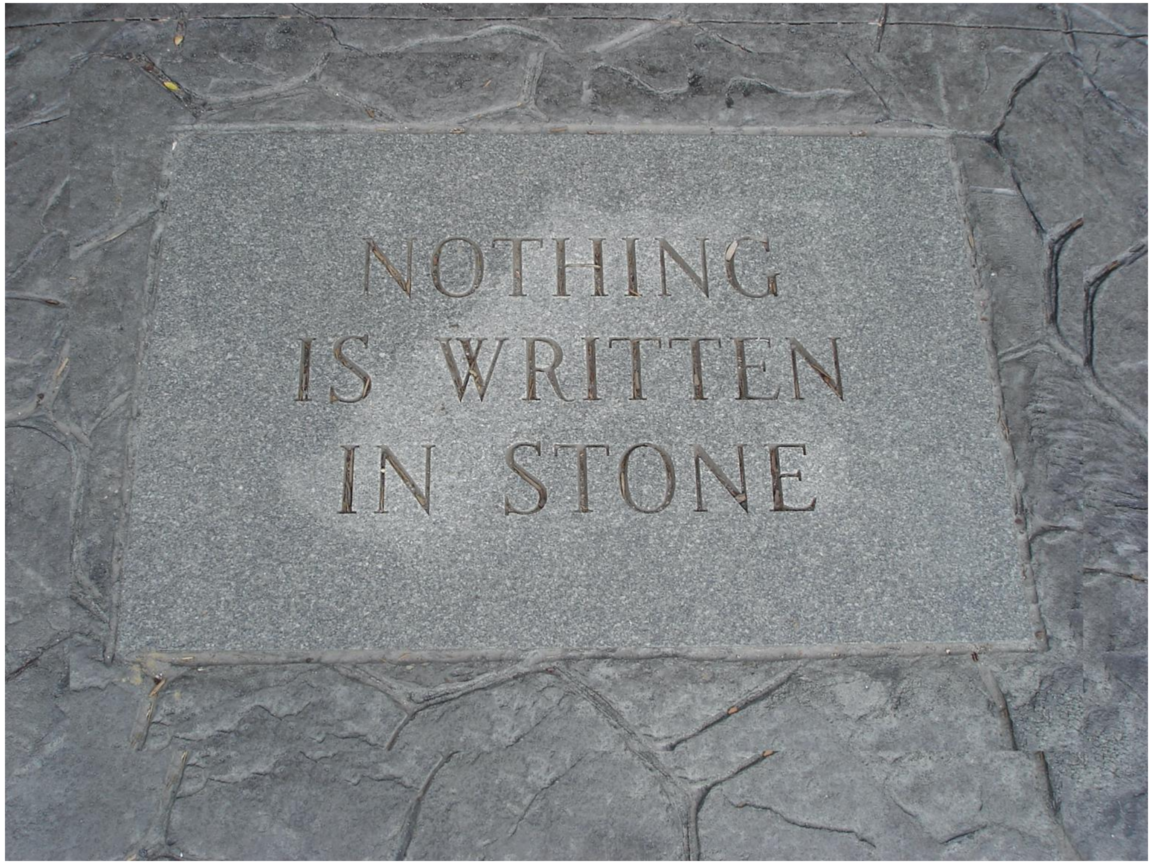
Mean squared multiplicity error per event, excluding misses



So far…

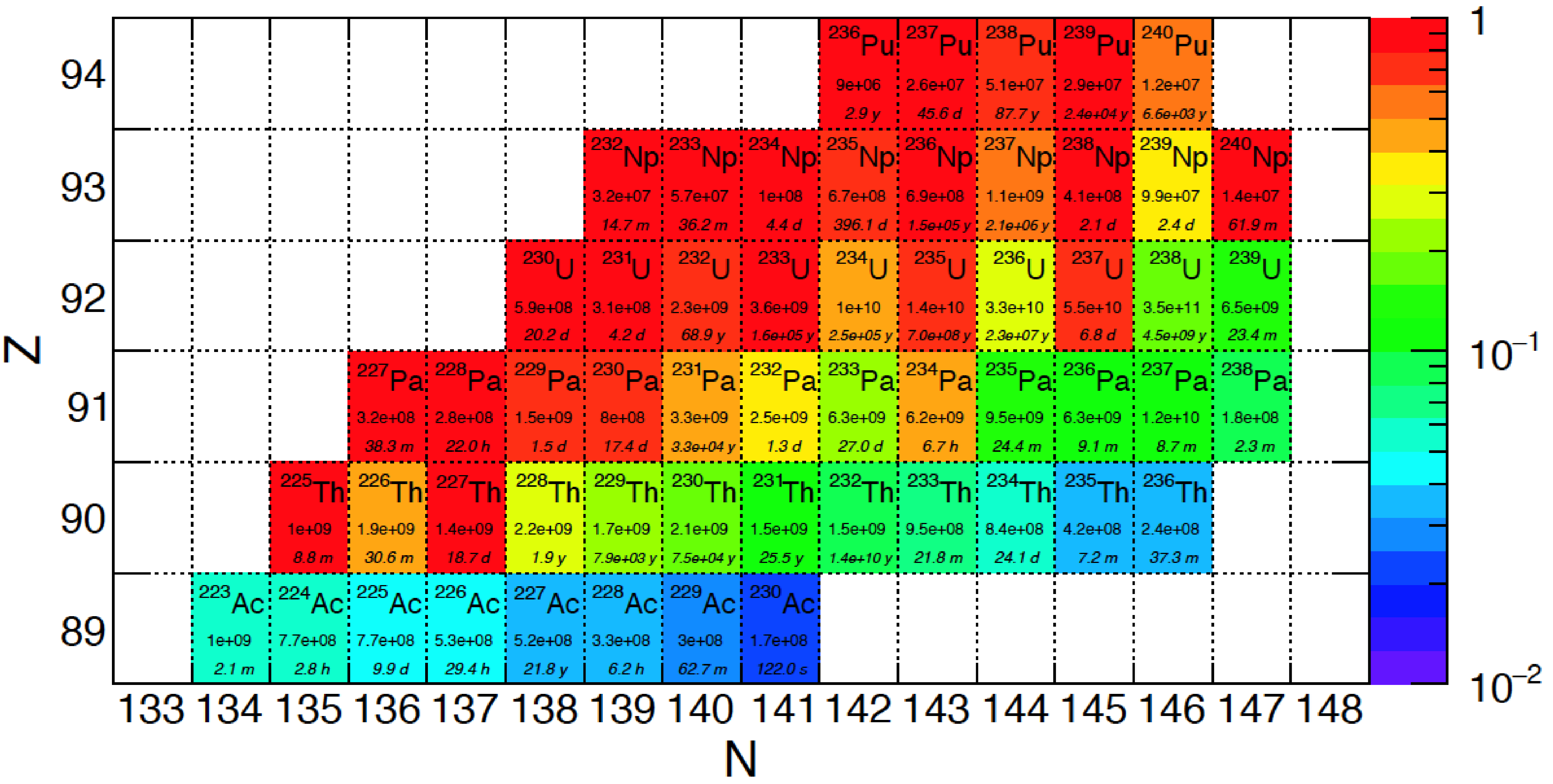
…those are our ideas. Comments and suggestions are very welcome!

Because



Thank you!

Thank you!

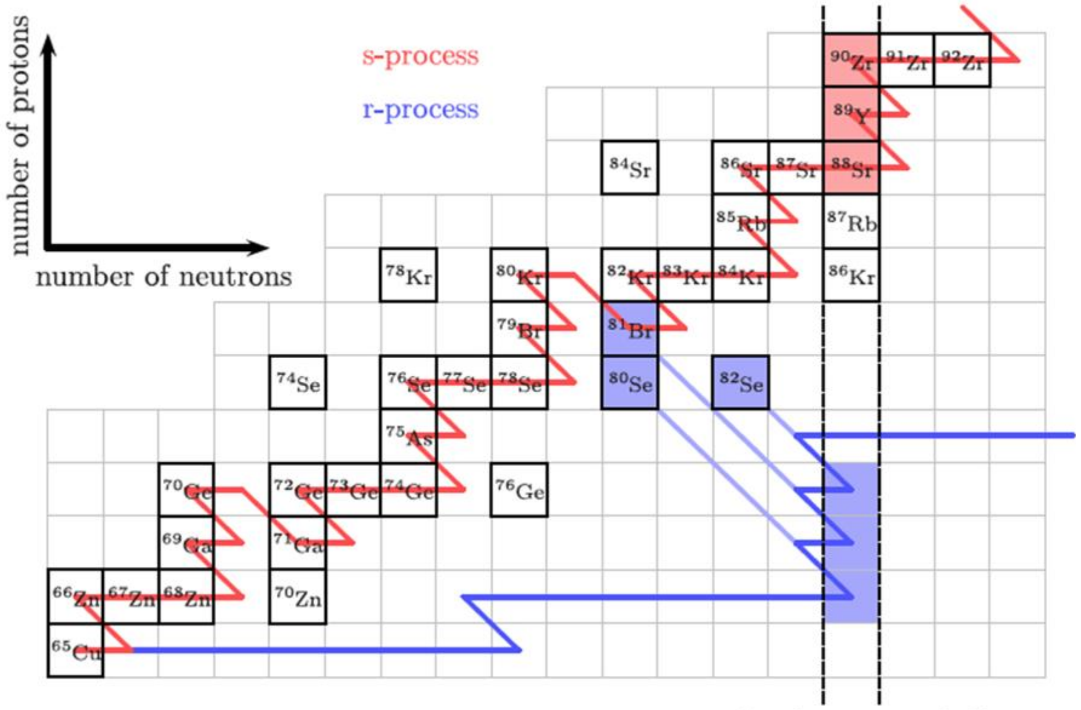


(LoI, INTC-I-224)

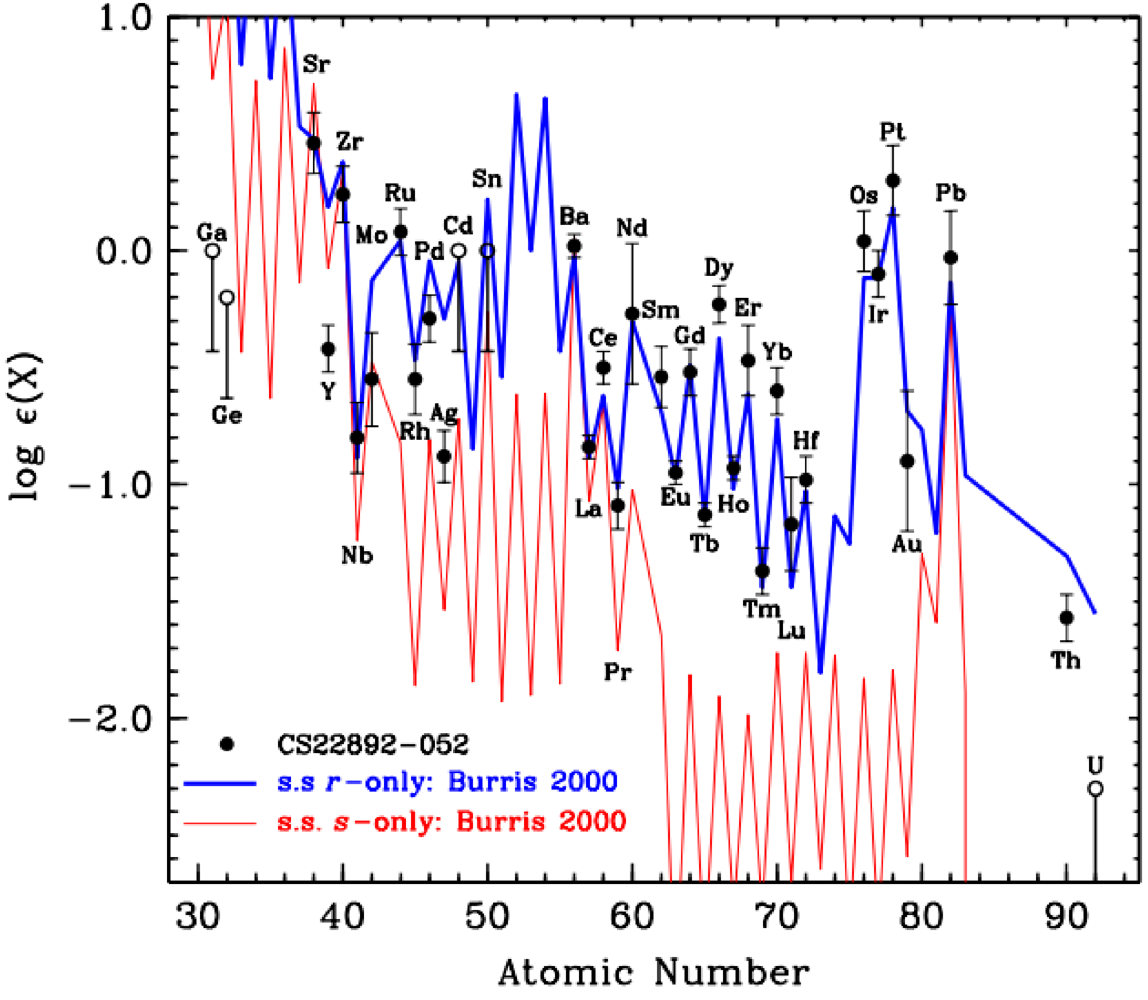
Solar system abundances of heavy elements

Beyond Fe, Ni → neutron-capture reactions

- **s-process** (slow neutron-capture process)
- **r-process** (rapid neutron-capture process)



C.J. Horowitz et al., JPG 46, 083001 (2019)



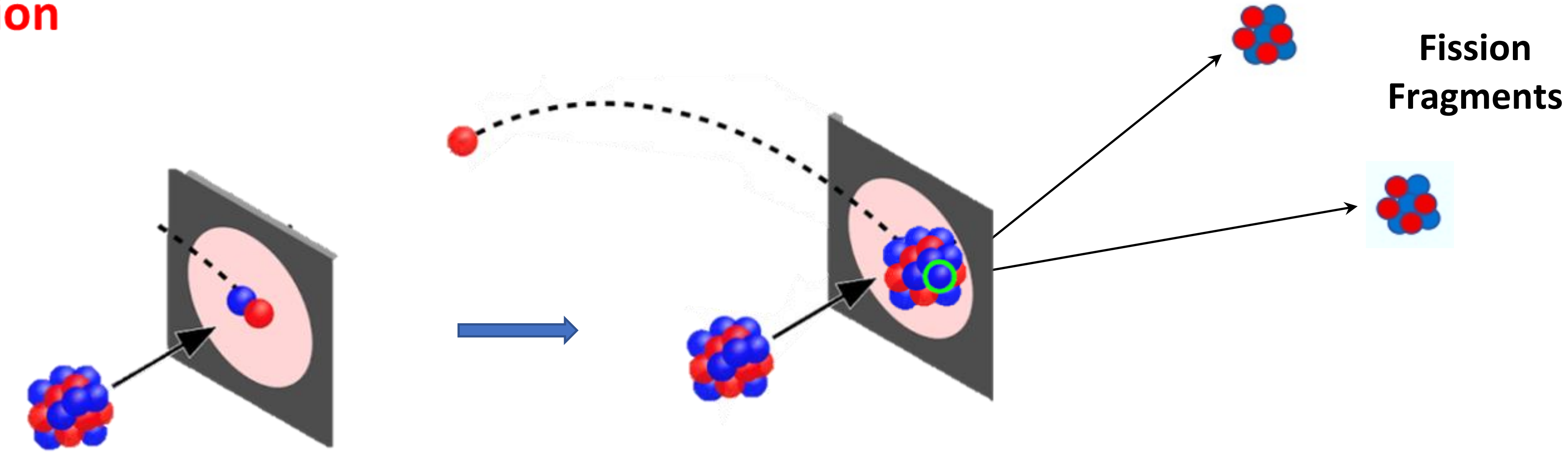
C. Sneden, *J.J. Cowan, Science 299, 70 (2003).*

Inverse kinematics using radioactive ion beams (RIBs)

The main focus is on the beam!

Projectile-like products ~ beam energy

(d, pf) **reaction**



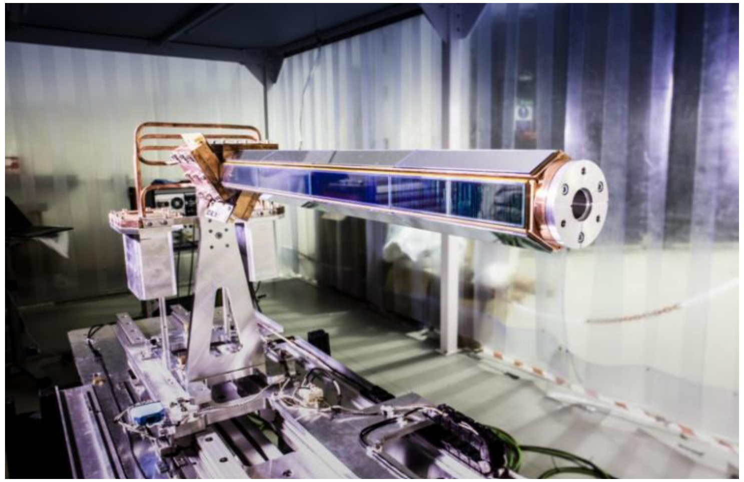
Advantages

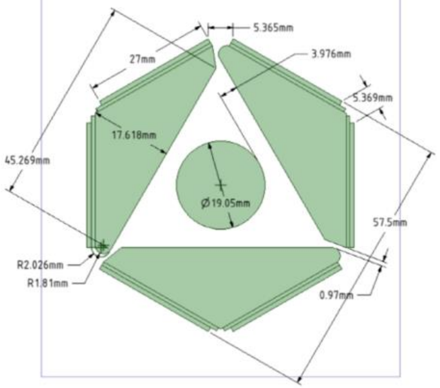
- Large kinematic **boost** in forward direction for fission fragments
- Study of fission barriers for very exotic nuclei.
- By measuring energy of the proton one can determine the excitation energy of the fissioning nucleus.

Studies on fission of neutron-rich nuclei

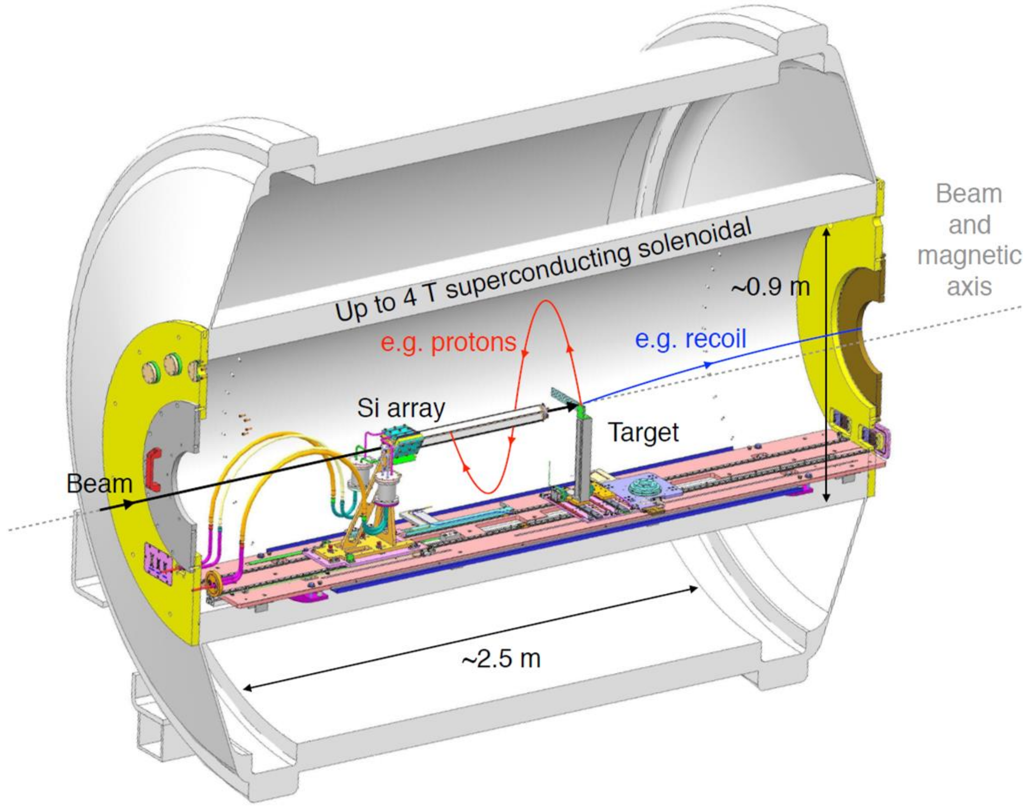
ISOLDE Solenoidal Spectrometer

https://ep-news.web.cern.ch/content/isoldes-solenoidal-spectrometer-iss-new-tool-studying-exotic-nuclei





Hexagonal-shaped Si array



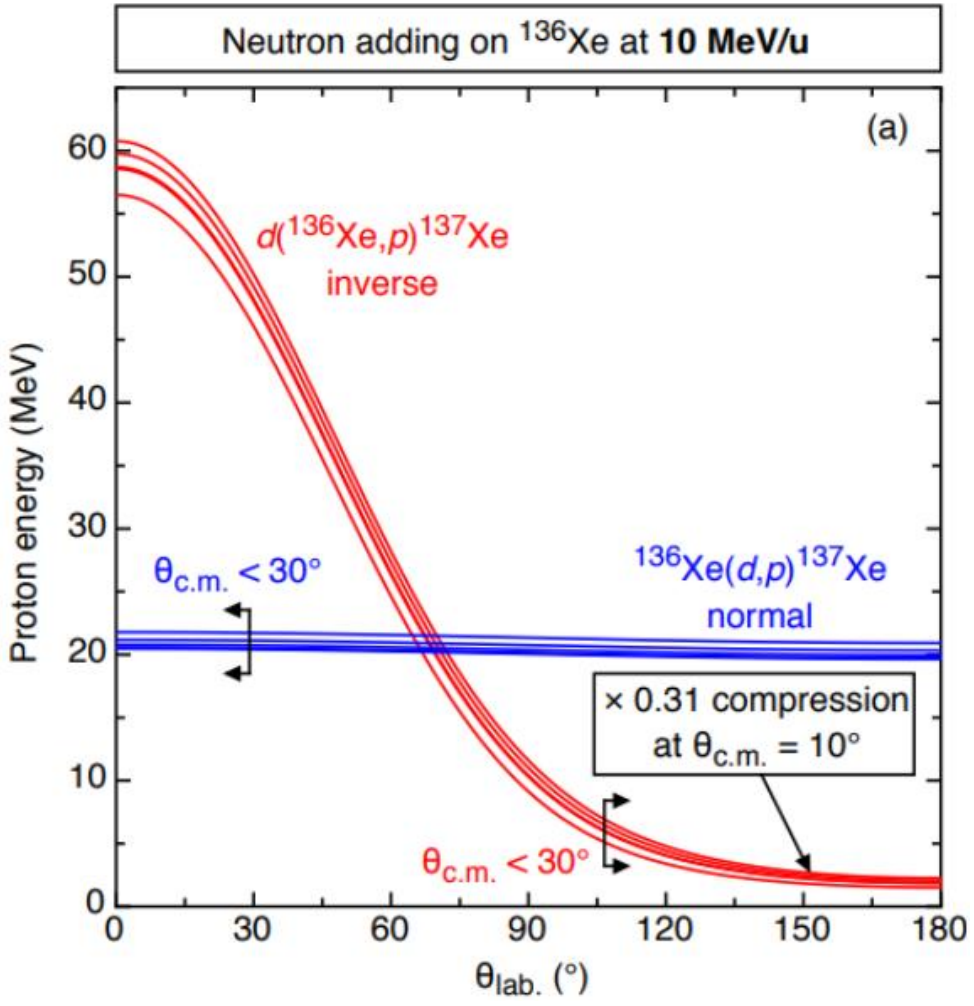
Investigate *(d,pf)* of radioactive beams in **inverse kinematics**.

But...

Inverse kinematics challenges

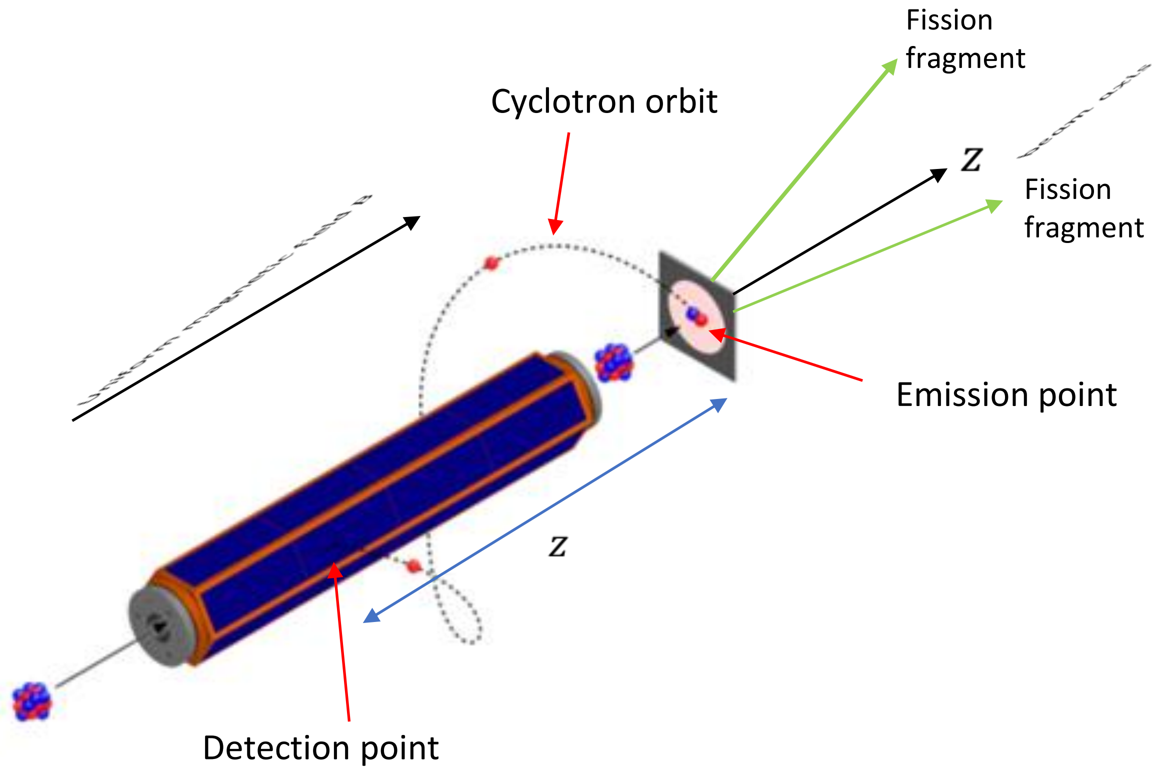
Typical experimental problems

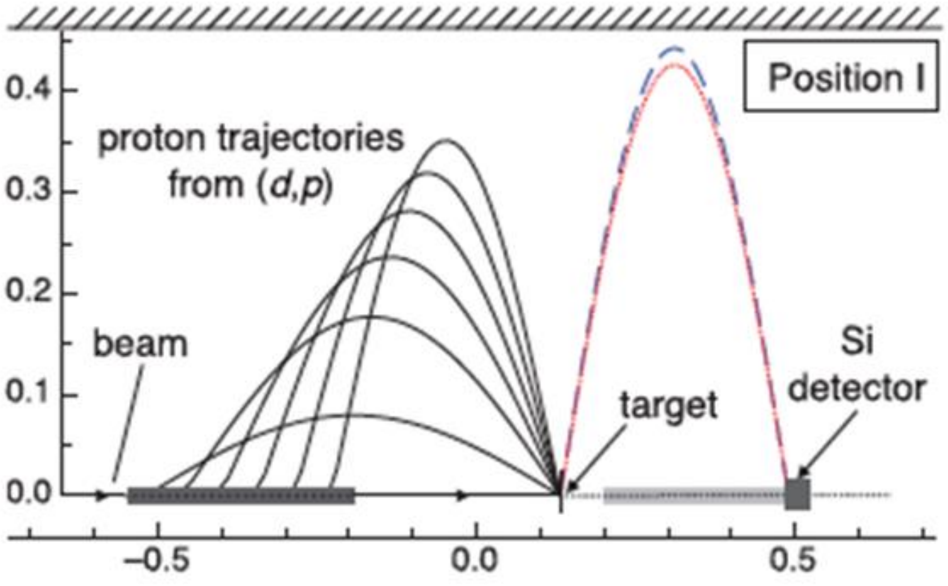
- Strong angular dependence of proton energy on the LAB angle.
- Kinematic compression → much worse resolution in backward angles.
- Low intensity beams (detection efficiency).



J.S. Winfield. Neutron transfer reactions with radioactive beams. NIM A, 396(1-2):147–164, 1997

Why ISS?





What do we measure?

- Position along the magnetic axis **z**,
- cyclotron period T_{cyc},
- energy of the proton in the laboratory frame E_{LAB}

- Target inside the solenoid
- Fission fragments
- Proton follows helical trajectory and then is detected in a position-sensitive silicon array

→ **Energy** of a proton is related to its **z** position along the beam axis.

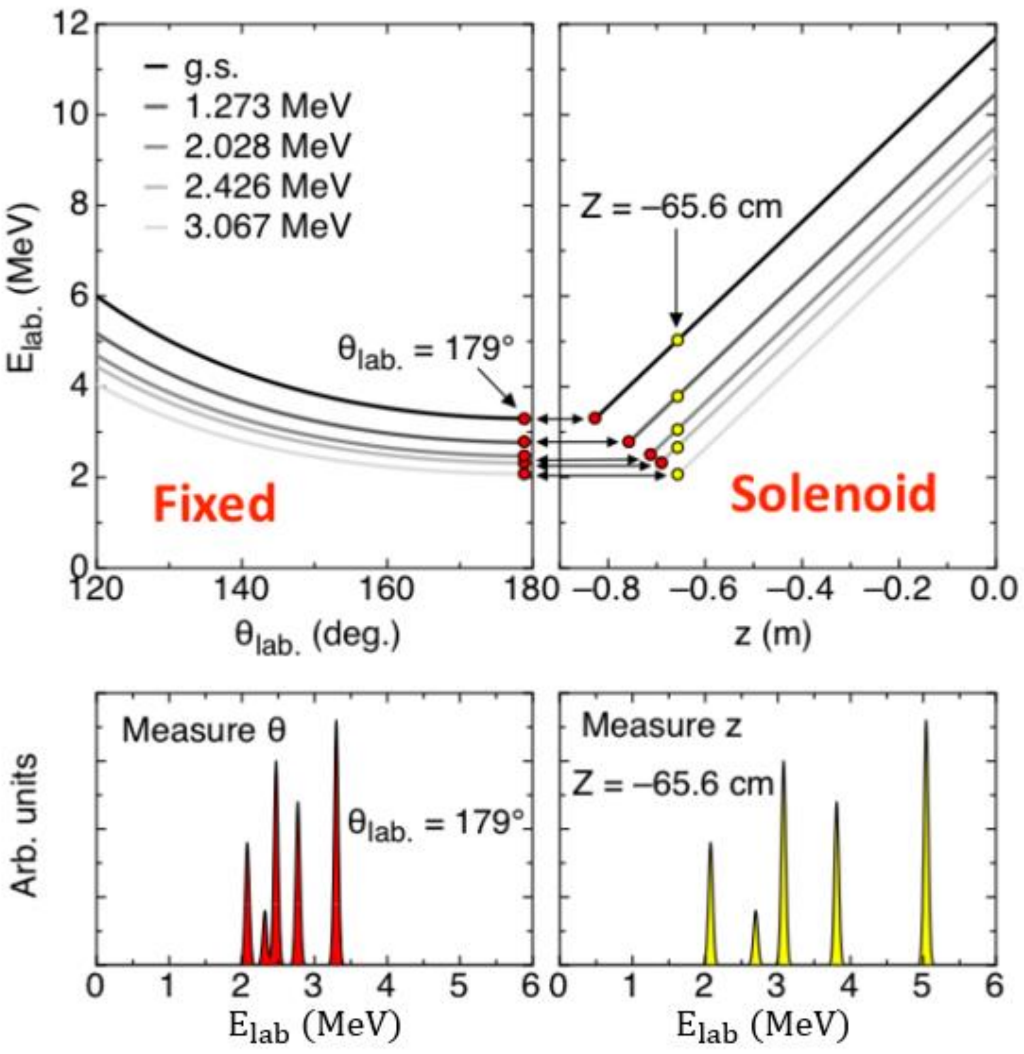
An important difference

- Particles are **NOT** detected at a fixed laboratory angle (conventional approach), but rather at a fixed distance from the target.

- The effective resolution with the solenoid can be **considerably better** than with a conventional detector array.

$$E_{\mathrm{cm}} = E_{\mathrm{lab}} + \frac{mV_{\mathrm{cm}}^2}{2} - \frac{mzV_{\mathrm{cm}}}{T_{\mathrm{cyc}}}$$

- Large background reduction



A. Wuosmaa *et al.* NIMA **580** (2007) 1290