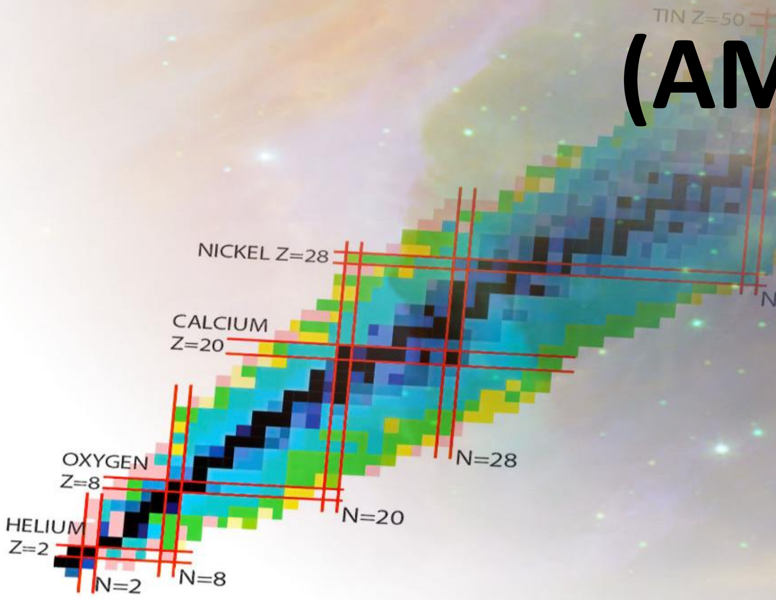
Accelerator Mass Spectrometry (AMS), recent new (positive) directions



Philippe Collon - ChETEC-INFRA 4th Gen Assembly Strasbourg May 27-28, 2024

AMS orders of magnitude

Isotopic ratios from 10^{-12} to 10^{-17}

Current volume of lake Michigan: ~ 4.9×10^{15} l

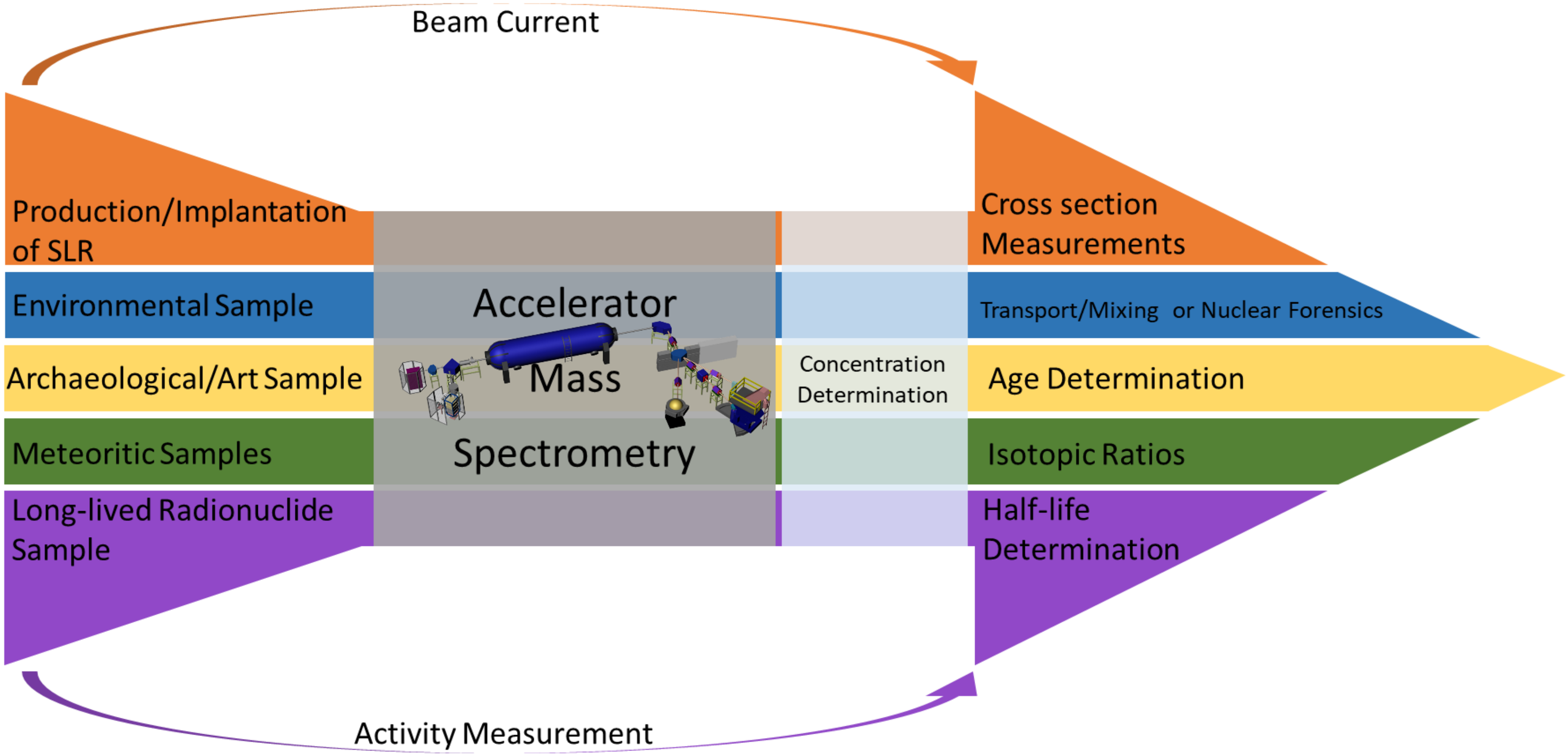
2.5×10^{6} liters of water (5.1×10^{-10})

Ratio of a bottle of vodka in lake Michigan: 1.5×10^{-16}

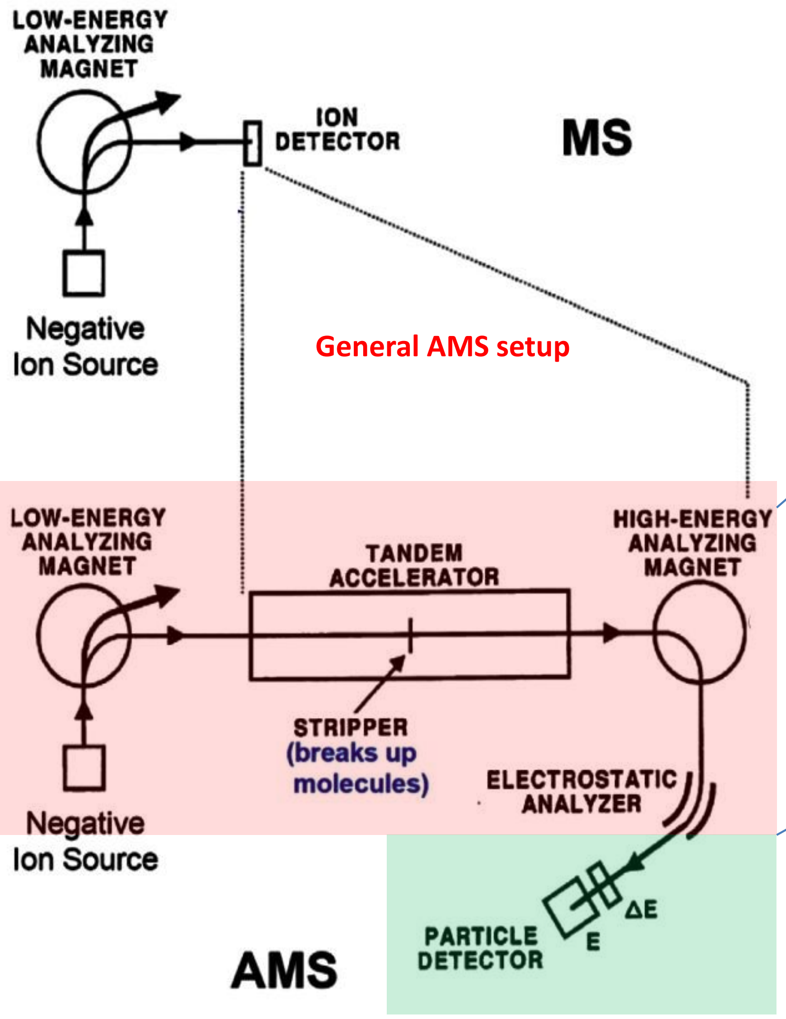
→ Very bad idea anyway

→ 4.2×10^{-17} corresponds to 0.2l

AMS provides isotopic ratio measurements resulting in:



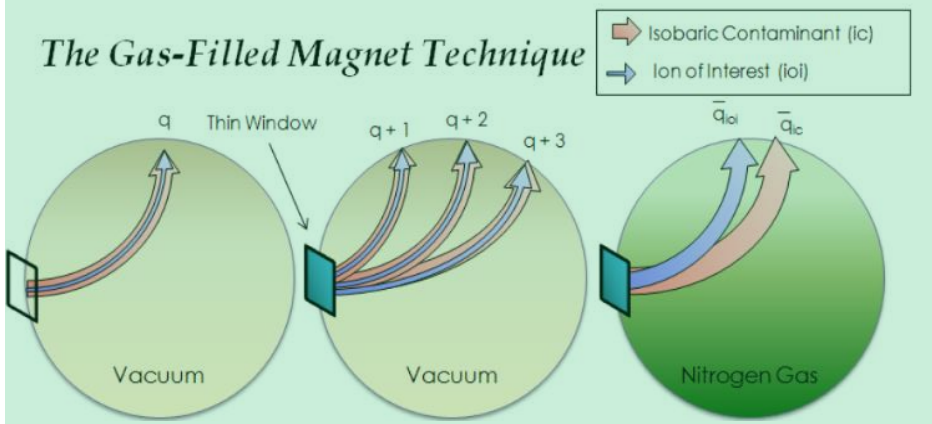
Principle of any AMS measurements



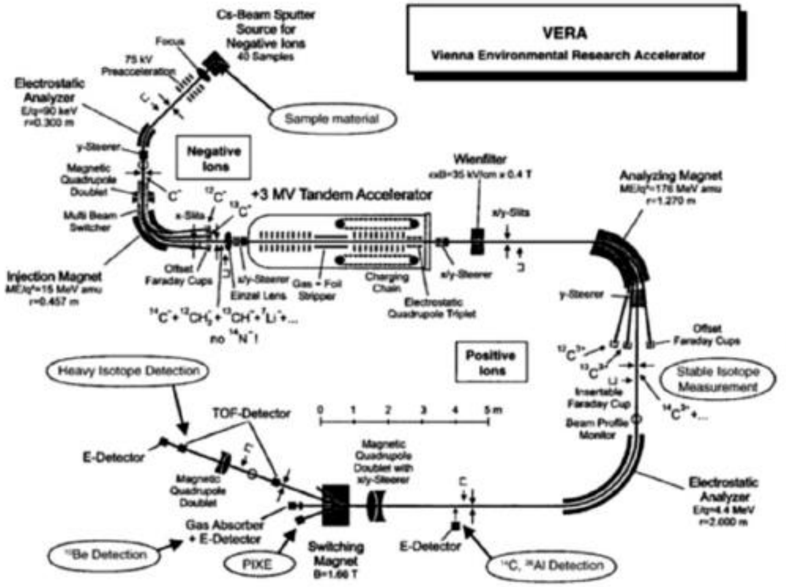
Isotopic separation

Magnetic separation
Wien Filter
Time-of-Flight
……….

Isobaric separation



Traditional AMS developments: From Large to small



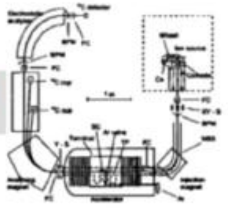
3 MV, 200 m²

Standard AMS, TV = 3 MV
16 m x 12 m = 192 m²
VIENNA

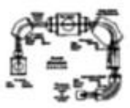
Most require negative ions from a source and are limited in Energy

Do not allow certain isobar separation techniques

500 kV, 30 m²

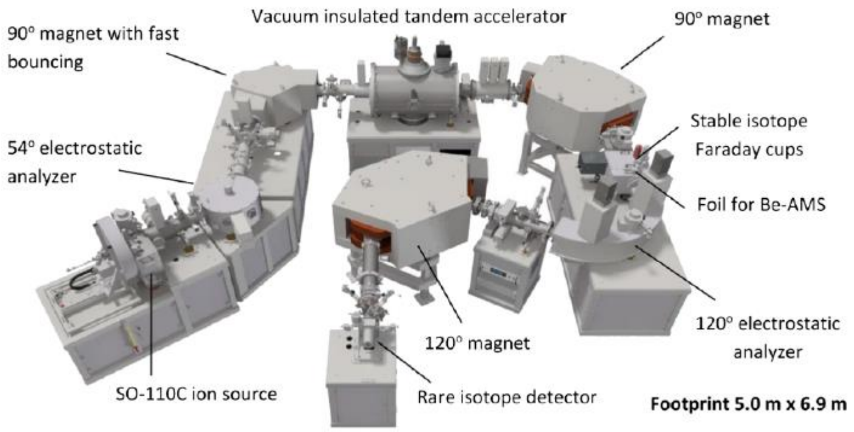


Compact AMS, TV = 0.5 MV
6 m x 5 m = 30 m²
POZNAN

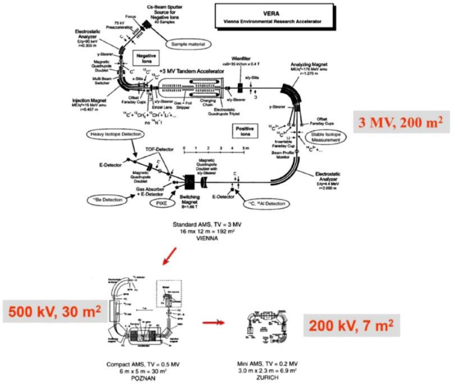


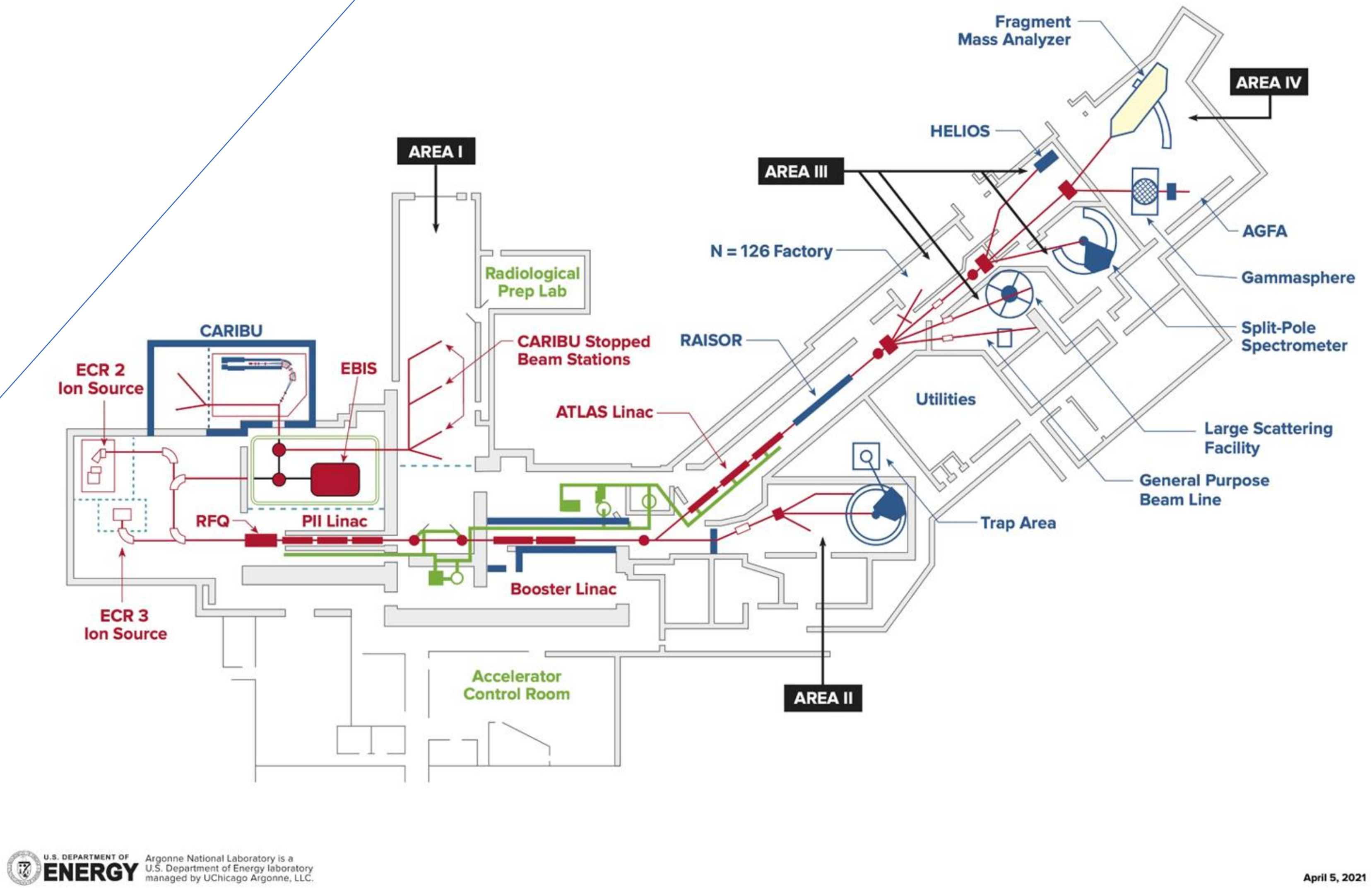
Mini AMS, TV = 0.2 MV
3.0 m x 2.3 m = 6.9 m²
ZURICH

200 kV, 7 m²

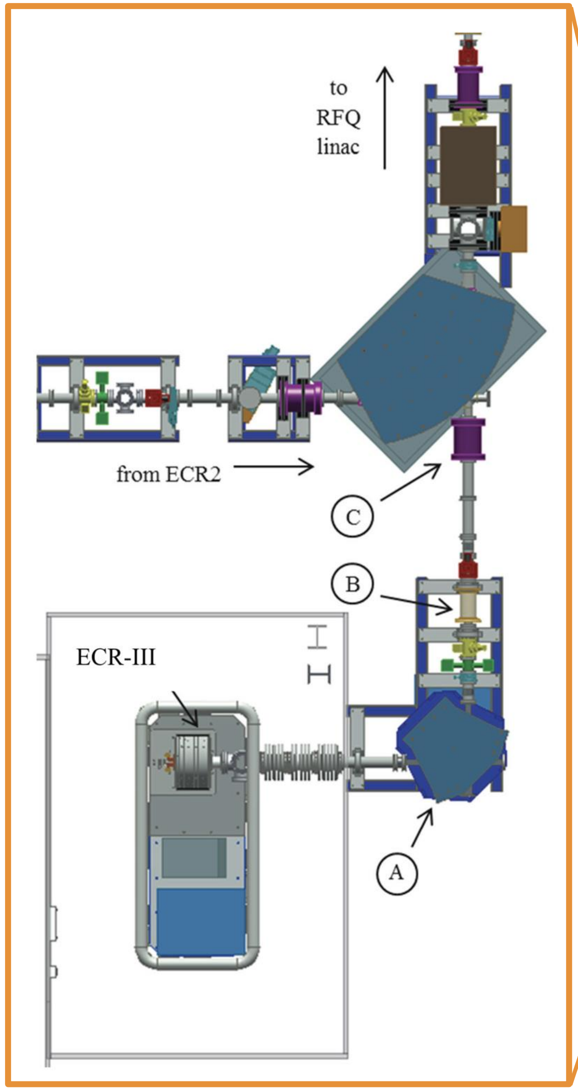


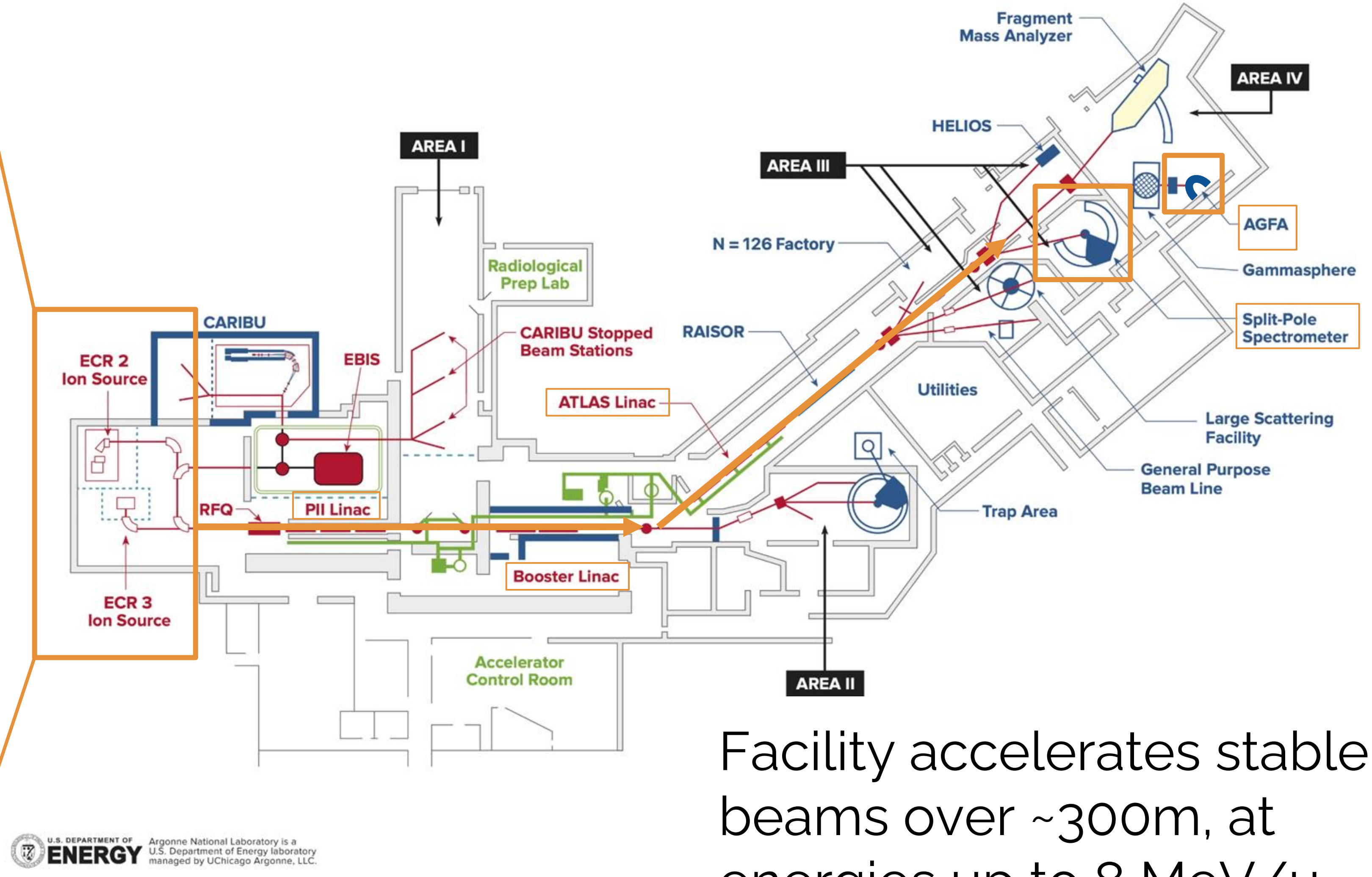
AMS developments: lets go bigger and more positive





Argonne Tandem Linear Accelerator System (ATLAS)





Facility accelerates stable ion beams over ~300m, at energies up to 8 MeV/u

Diagram courtesy of www.anl.gov

Recent ATLAS developments fueled by AMS

Capture and Restore: ALL electrical and magnetic elements (including ALL resonators) of ATLAS are digitally monitored and controlled. This allows to:

- Go from a manually tuned pilot beam (ex. $^{80}Kr^{12+}$ for $^{146}Sm^{22+}$) to the beam of interest automatically

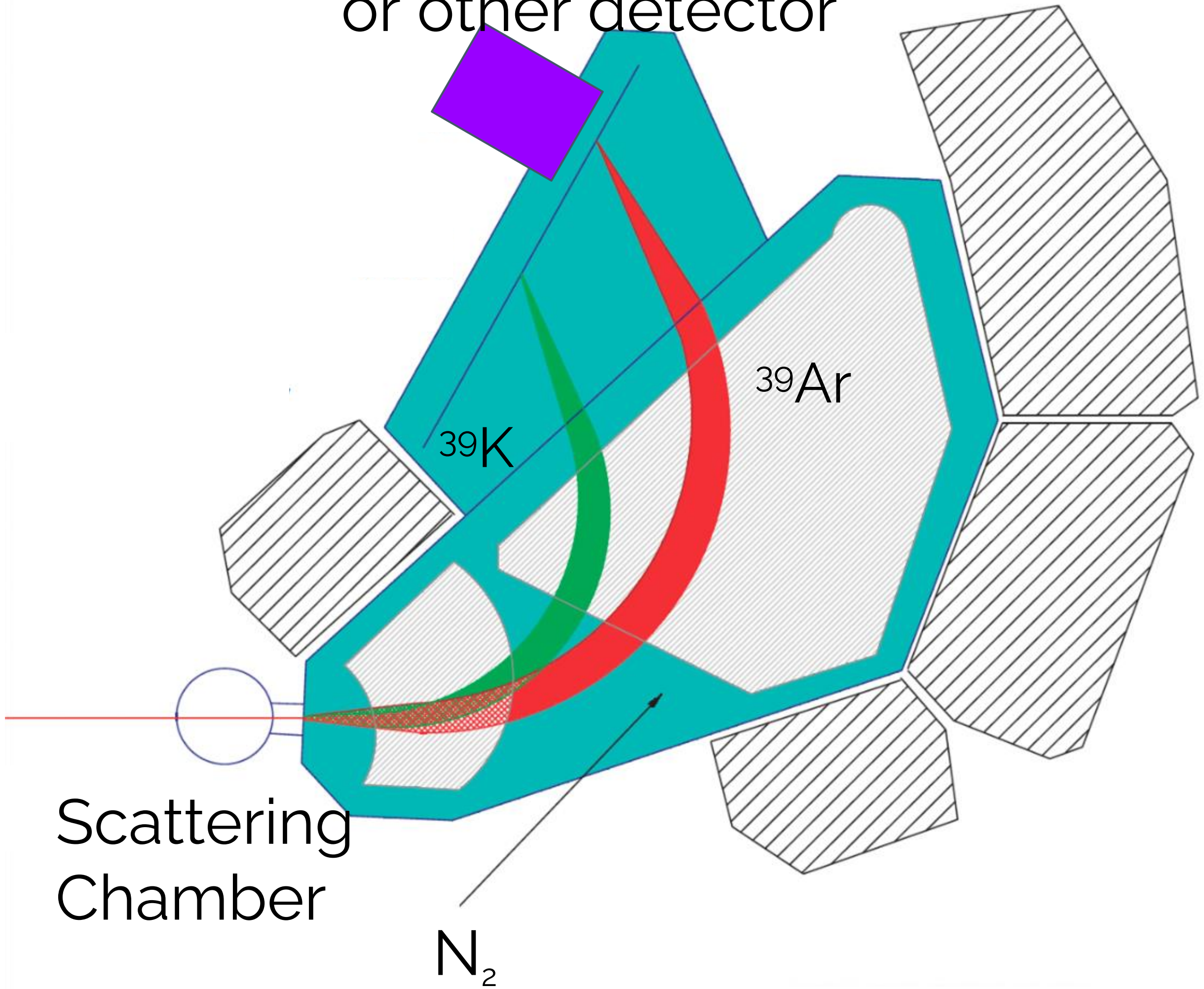
- Capture every tune and the restore it as we switch between stable beam and isotope of interest

Traditional AMS measurements rely on relative measurements using standard and blanks between unknown samples.

Capture and Restore allows **absolute measurements** using stable and radioactive beams (where stable beams are attenuated using **chopped beams** to allow repeateable attenuation over orders of magnitude) (Ex. ^{147}Sm, ^{146}Sm)

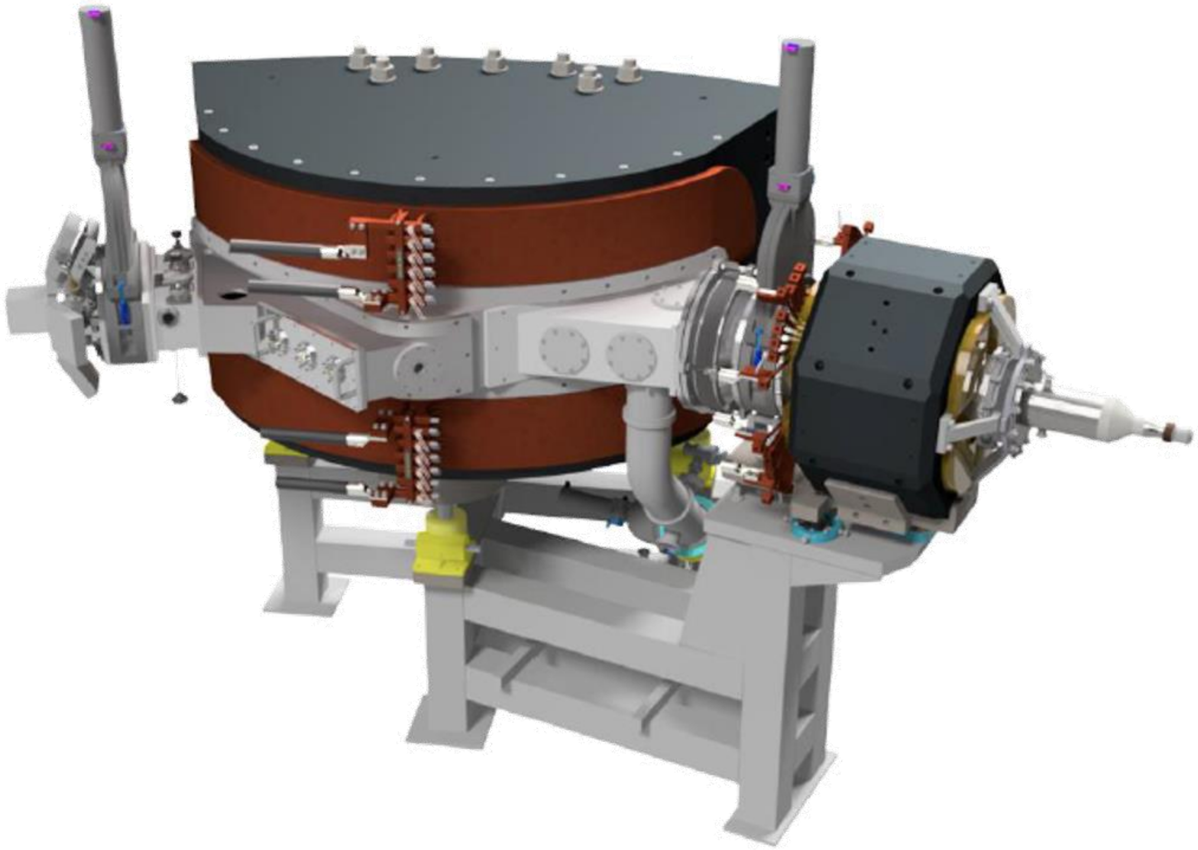
Enge Split-Pole Spectrograph

- Consists of two sets of magnetic dipoles enveloped by a single coil
- Traditionally used for AMS experiments at ATLAS
- In this work, used for exploration of $^{39,42}Ar$



Magnetic Rigidity of the Enge: 0.7 T-m

Argonne Gas-Filled Analyzer (AGFA)



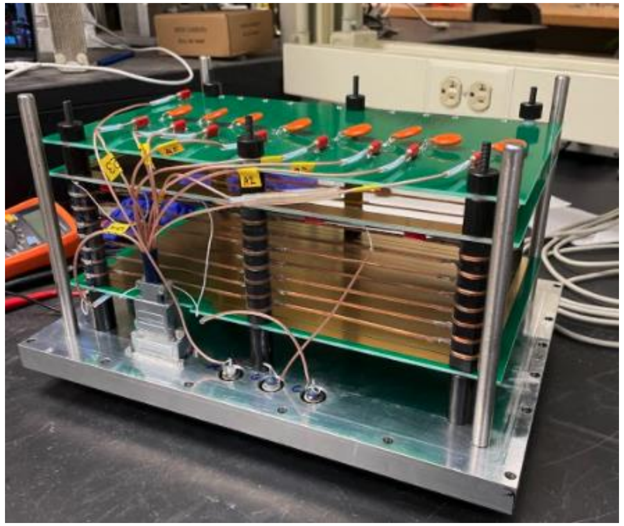
Magnetic Rigidity of AGFA: 2.5 T-m

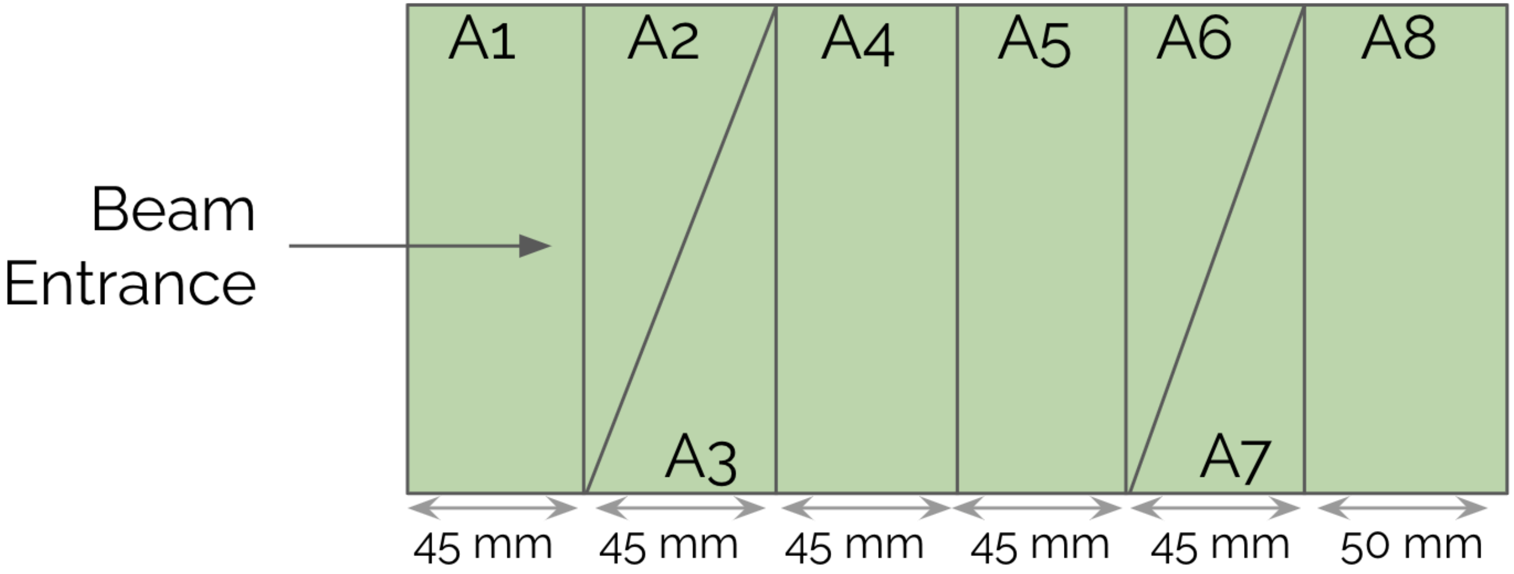
- Higher magnetic rigidity than the Enge Split-Pole allows the study of heavier isotopes using AMS
- Consists of a vertically-focusing quadrupole & horizontally-focusing dipole
- Created primarily for use in separating and studying the structure of transuranic nuclei produced in heavy-ion fusion reactions
- In this work, used for tests of AMS of medium-heavy ions

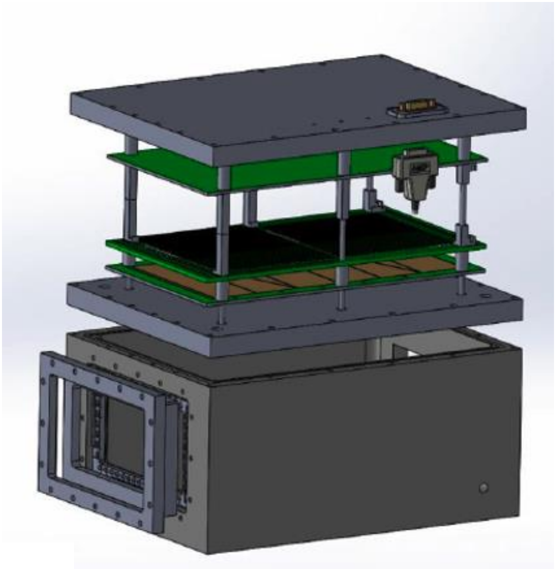
B. B. Back, *EPJ Web of Conferences*, 163 (2017)

The MONICA detector

- Ionization Chamber comprised of 8 anodes, including 2 sets of split anodes





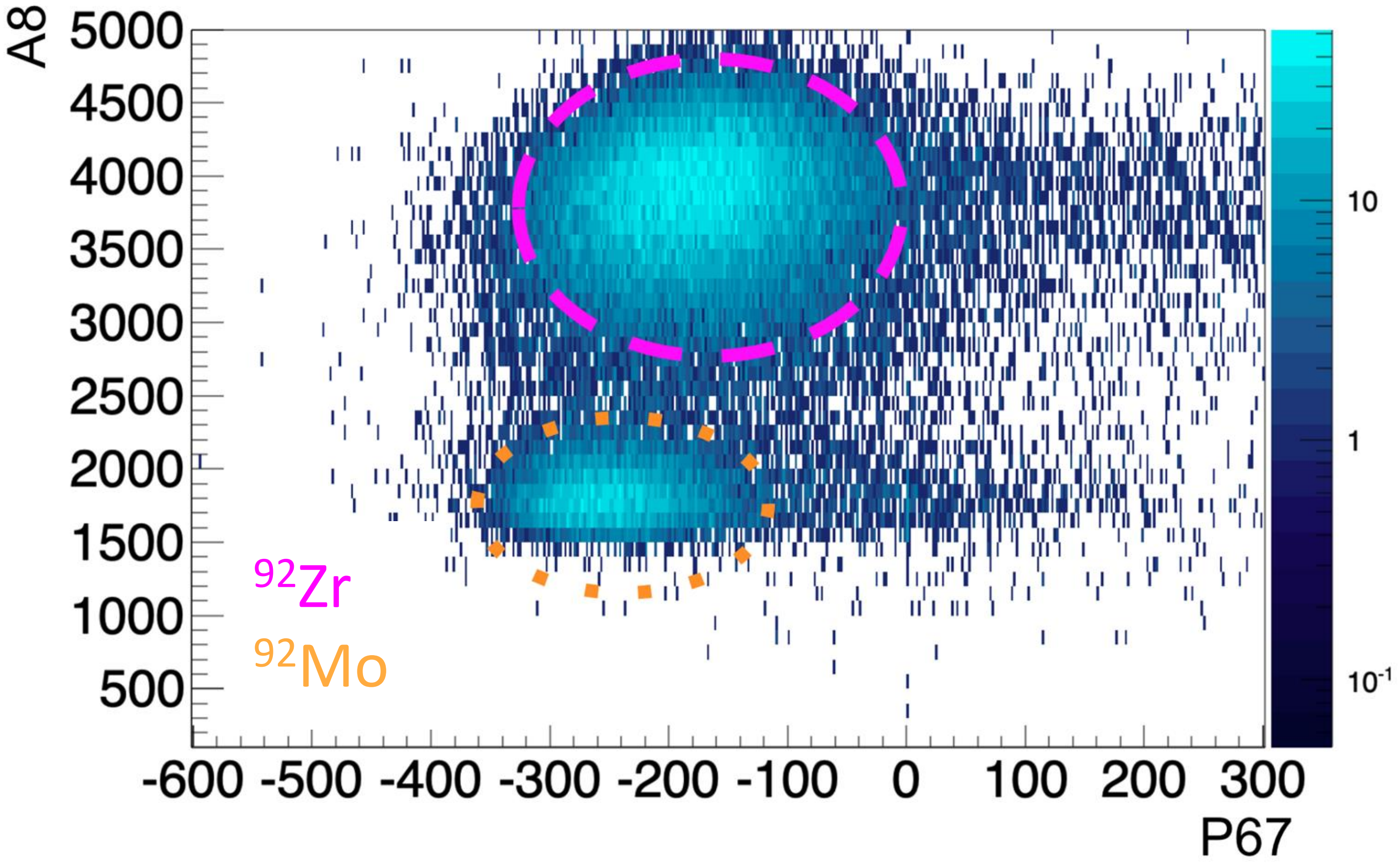


^{92}Nb

^{92}Tc 4.25 m	^{93}Tc 165 m	^{94}Tc 4.8833333 h	^{95}Tc 19.258 h	^{96}Tc 4.28 d
^{91}Mo 15.49 m	^{92}Mo	^{93}Mo 4 ky	^{94}Mo	^{95}Mo
^{90}Nb 14.6 h	^{91}Nb 680 y	^{92}Nb 34.7 My	^{93}Nb	^{94}Nb 20.4 ky
^{89}Zr 78.36 h	^{90}Zr	^{91}Zr	^{92}Zr	^{93}Zr 1.61 My
^{88}Y 106.629 d	^{89}Y	^{90}Y 64.05 h	^{91}Y 58.51 d	^{92}Y 212.4 m

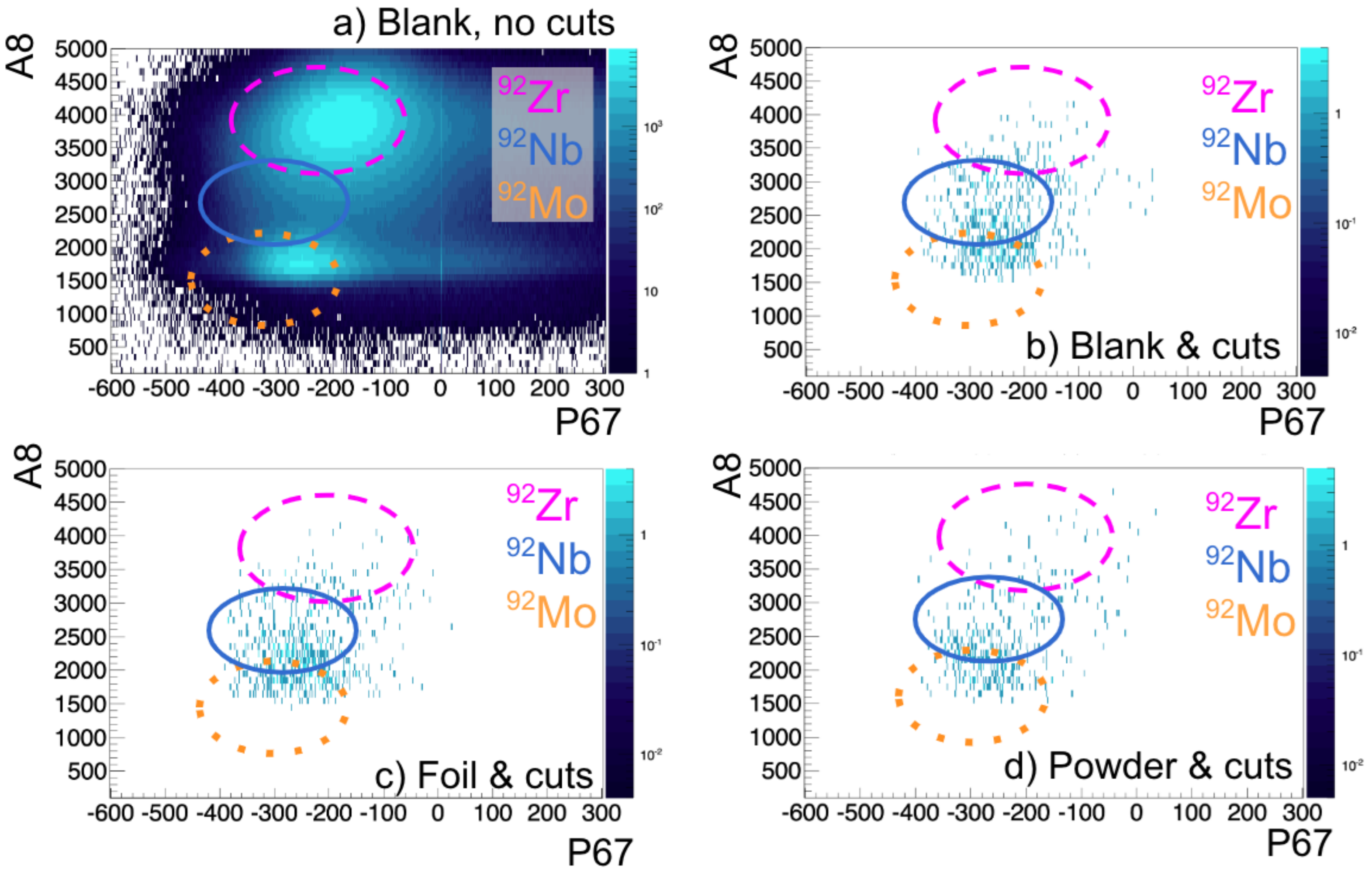
- *p*-process nuclei present in the Early Solar System (within a few hundred My after formation), but extinct in current solar material
- Medium-heavy isotope with two isobaric contaminants
- **Experimental Focus:** detection of ^{92}Nb & determination of the yield of reaction ^{93}Nb(γ,n)^{92}Nb
  - Sample created via bremsstrahlung-irradiation (HZDR, Germany)

Test of MONICA with AGFA



- **Source**: Blank
- ^{92}**Nb**$^{17+}$, 472.56 MeV beam
- **Pressure in MONICA**: 35.1 Torr CF_4
- **Pressure in AGFA**: 8.1 Torr N_2
- Very short run, slits open **55.5 mm**

Measurement of ^{92}Nb



- **Source**: Blank
- **^{92}Nb^{17+}**, 472.56 MeV beam
- **Pressure in MONICA**: 35.1 Torr CF_4
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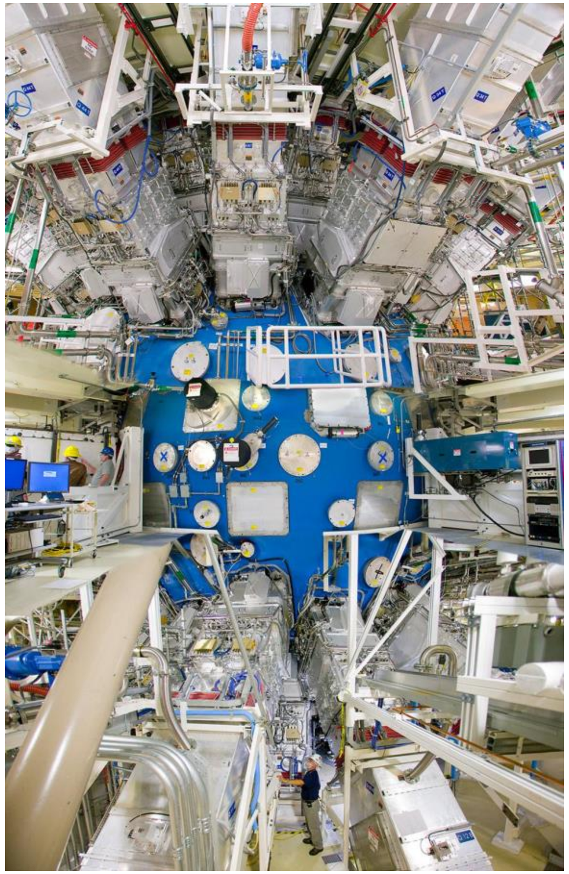
MEASUREMENT INCONCLUSIVE

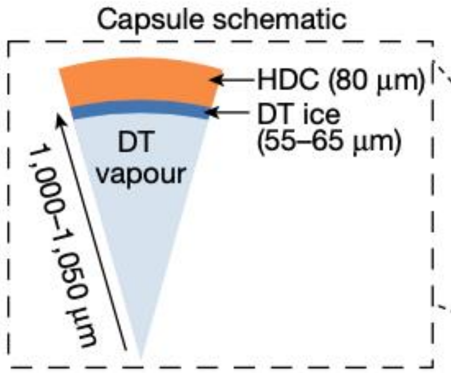
National Ignition Facility (NIF)

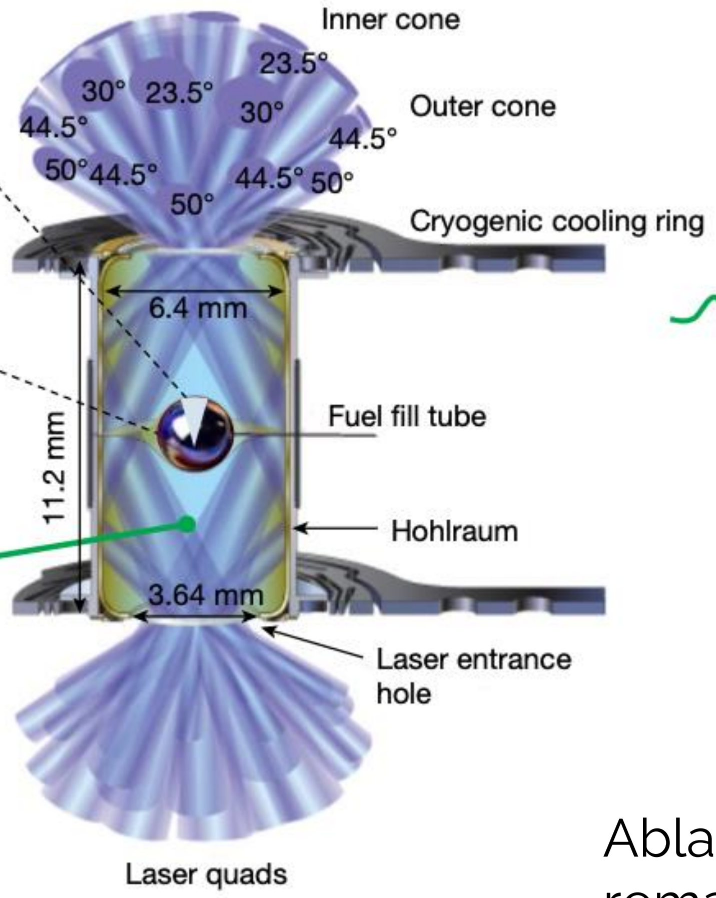
- One of the most powerful laser facilities in the world
- Fusion ignition achieved in December, 2022, with record yield of ~1 MJ
- 192 laser beams are amplified and guided to deliver 1.9 MJ onto a target inside a large vacuum sphere (seen right)

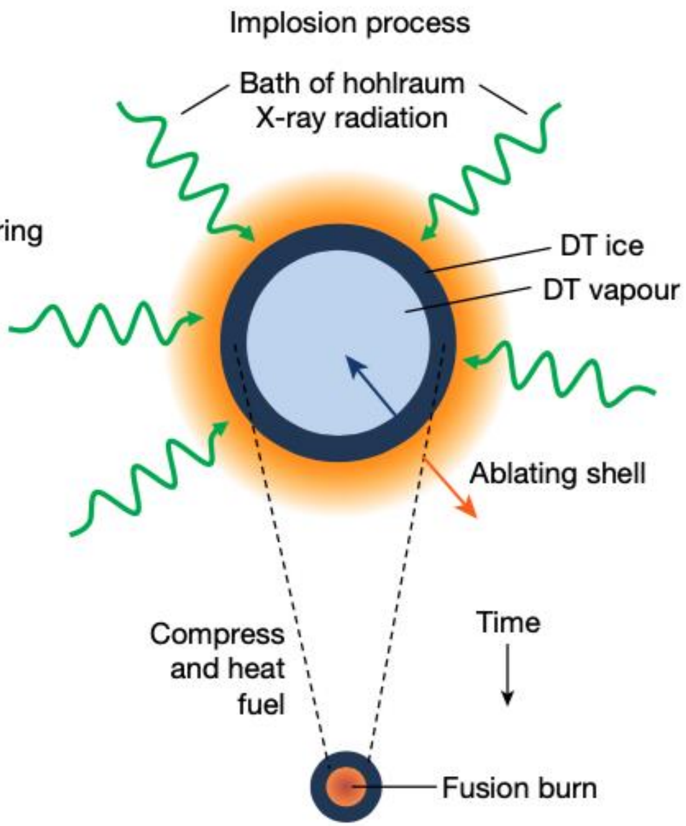


lasers.LLNL.gov

NIF Implosion Process ("Shots")







Lasers are focused into the 'Hohlraum', a high-Z, gold-lined, depleted uranium cavity that converts the lasers into X-rays

Closest analogue to a stellar explosive environment in the laboratory, which allows us to study nucleosynthesis explosive processes and theoretical models

Ablation of capsule causes the remaining mass and fuel to accelerate inward at about 10^{14} m s^{-2}, achieving velocities of 350-400 km s^{-1}

A. B. Zylstra, *Nature*. Vol. 601 (2021)

Neutron-Induced Reactions on ^{40}Ar Seeds, Specifically ^{39,42}Ar

^{40}Ar(n,2n)^{39}Ar (10.1 MeV Threshold), as a monitor of the integrated fast neutron flux produced at 14 MeV by the D(T,n)^{4}He fusion reaction

^{40}Ar(2n,γ)^{42}Ar, with a focus on observing a rapid two neutron capture ("mini *r*-process") for the first time in a laboratory setting

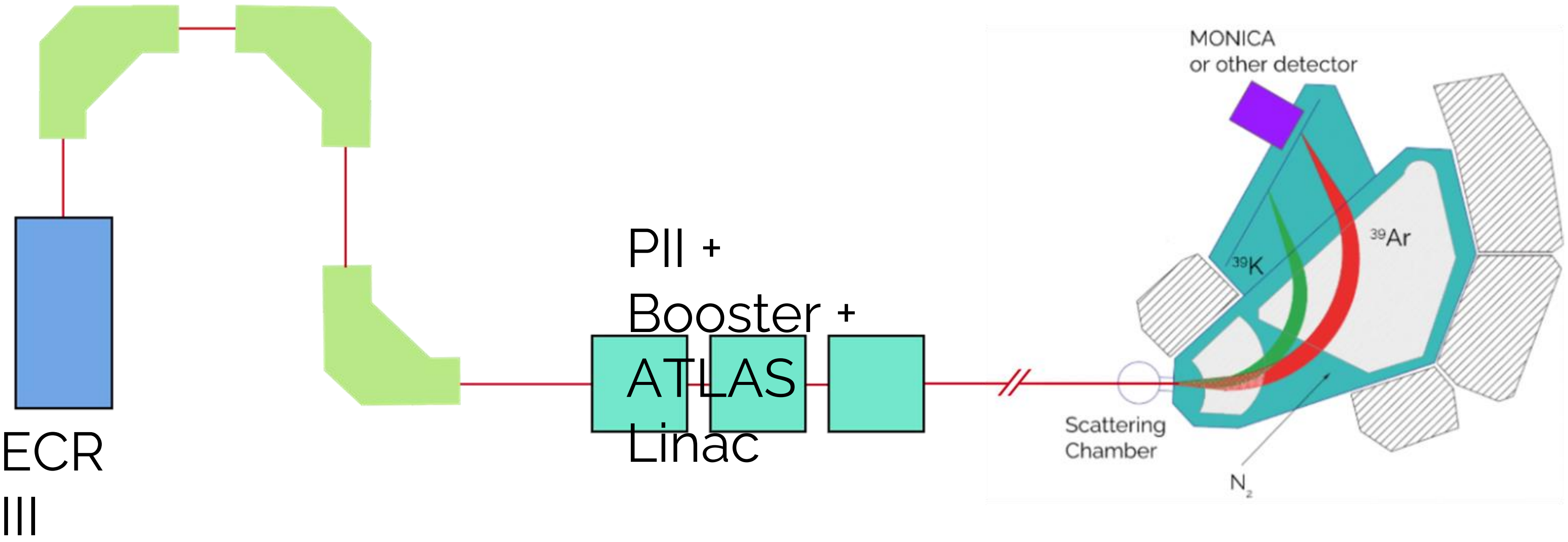
^{38}K 7.651 m	^{39}K	^{40}K 1.248 Gy	^{41}K	^{42}K 12.355 h	^{43}K 22.3 h	^{44}K 22.13 m
^{37}Ar 35.011 d	^{38}Ar	^{39}Ar 268 y	^{40}Ar	^{41}Ar 109.61 m	^{42}Ar 32.9 y	^{43}Ar 5.37 m
^{36}Cl 301.3 ky	^{37}Cl	^{38}Cl 37.23 m	^{39}Cl 56.2 m	^{40}Cl 81 s	^{41}Cl 38.4 s	^{42}Cl 6.8 s

Ar is an inert gas that allows absolute collection efficiency without further reactions, making it an ideal diagnostic tool

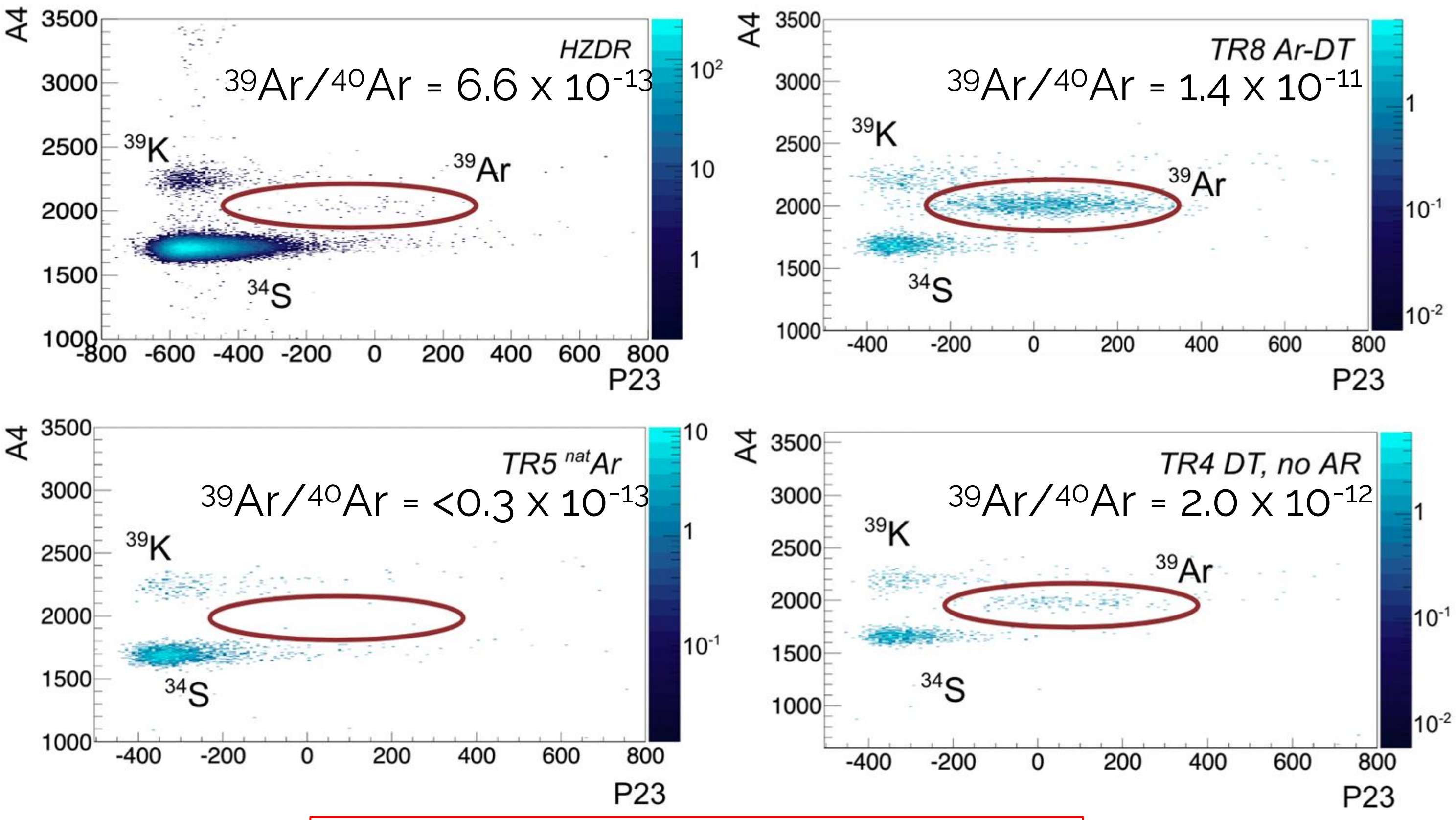
Neither dedicated shot for the study of neutron-induced reactions on ^{40}Ar seeds have been analyzed at this time

Recall the Enge Split-Pole Spectrograph

- After the NIF shot, gas is collected from the vacuum sphere and is used in the ECR source at ATLAS
- NOGAMS analysis occurs using the Enge Split-Pole Spectrograph with MONICA



Preliminary Experiments for ^{39}Ar



All results are preliminary!

214 MeV, $^{39}Ar^{8+}$ beam

Samples:

- **HZDR** : ^{40}Ar enriched gas at a pressure of ~55 bar activated during 4 hours in the 14 MeV neutron flux of the DT generator at TU Dresden at HZDR.
- **TR5** : blank (tank ^{nat}Ar)
- **TR2 / TR4** : background of ^{39}Ar in a shot without Ar in the capsule
- **TR8** : ^{39}Ar produced by $^{40}Ar(n,2n)^{39}Ar$ in NIF shot on DT-Ar (0.05%) filled capsule

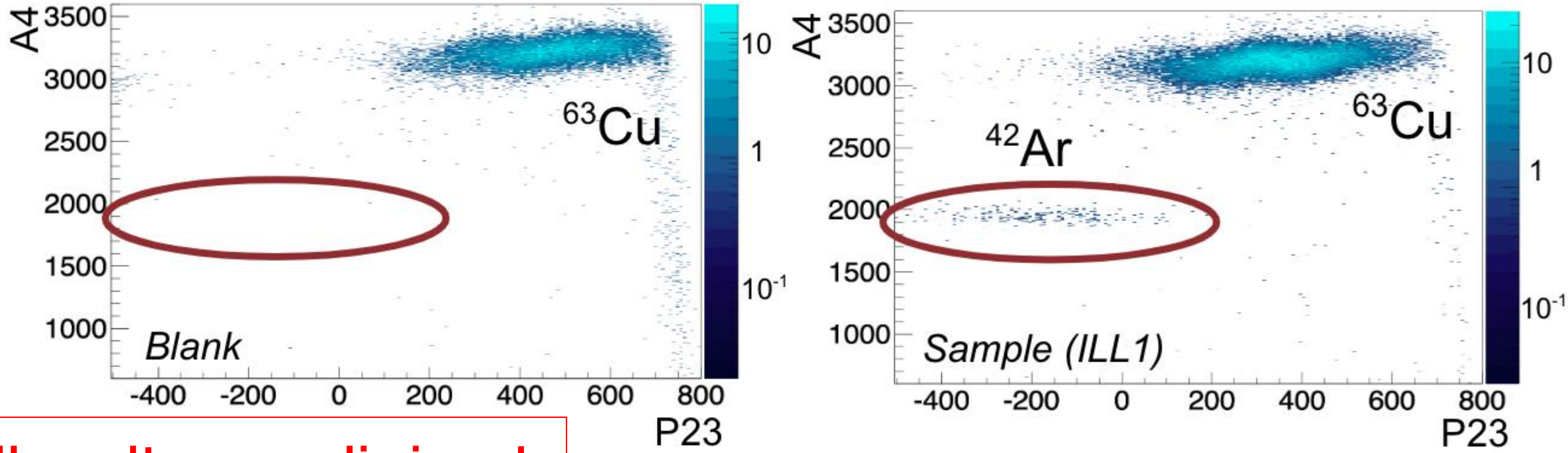
Preliminary Experiments for ^{42}Ar

231 MeV, $^{42}Ar^{8+}$ beam

Sample ILL1 produced by slow, double neutron capture on ^{40}Ar at the high-flux nuclear reactor at Institut Laue-Langevin (ILL) in 8.17 day irradiation under neutron fluence of 6.0(9) x 10^{20} cm^{-2}. Diluted at HUJ to reach ratio of $^{42}Ar/^{40}Ar \approx 10^{-12}$.

Preliminary isotopic abundance $^{42}Ar/^{40}Ar = 2.5(3) \times 10^{-12}$

Preliminary isotopic abundance sensitivity in the 10^{-15} range



All results are preliminary!

Many thanks to Lauren Callahan for some of her defense slides

Collaborators: M. Paul, R. Vondrasek, R. Scott, R. Pardo, D. Robertson, T. Bailey, L. Callahan, A. Clark, A. Nelson

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