DIRECT CROSS-SECTION MEASUREMENTS

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WHAT IS A *DIRECT* MEASUREMENT, ANYWAY?

Any measurement of the quantity of interest (e.g. cross-section) that does not rely on a different reaction.

Advantages:

- Analysis is straightforward.
- No model-related uncertainties.
- No issues with interpretation.

Disadvantages:

- Really hard! (All the easy ones have been done already)
- In practice, some models are almost always required

WHAT IS A *DIRECT* MEASUREMENT, ANYWAY?

Example: If $^{18}F(p,\alpha)^{15}O$ cross-section is the aim, then the following are direct measurements

- Proton beam on ^{18}F target -> $^{15}O+\alpha$ (direct reaction, direct kinematics)
- ^{18}F beam on H target -> $^{15}O+\alpha$ (direct reaction, inverse kinematics)

- Alpha beam on ^{15}O target -> $^{18}F+p$ (time-reversed direct reaction, direct kinematics)
- ^{15}O beam on He target -> $^{18}F+p$ (time-reversed direct reaction, inverse kinematics)

STABLE BEAM EXPERIMENTS FOR QUIESCENT STELLAR SCENARIOS

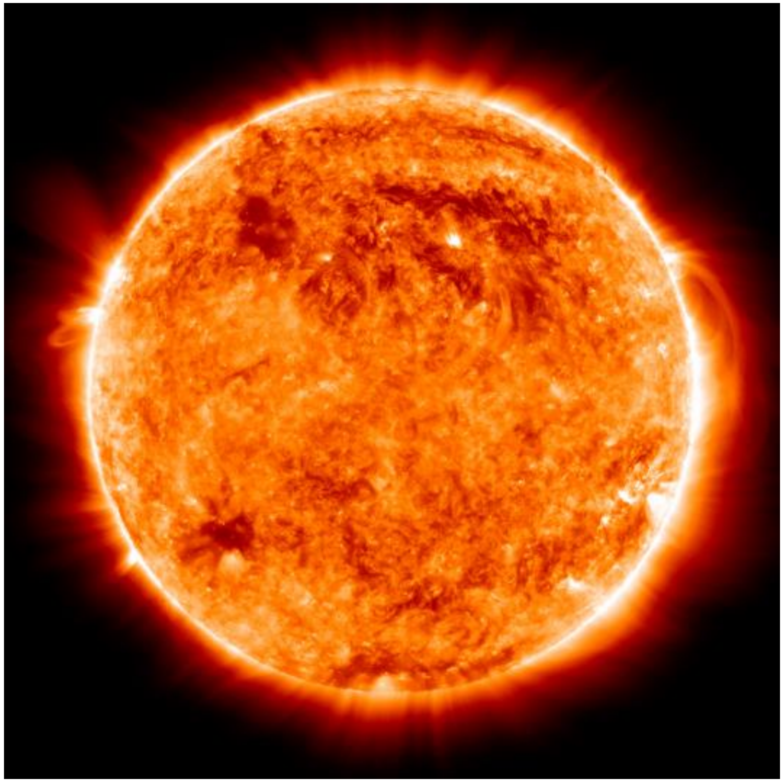
The Challenge

In a star

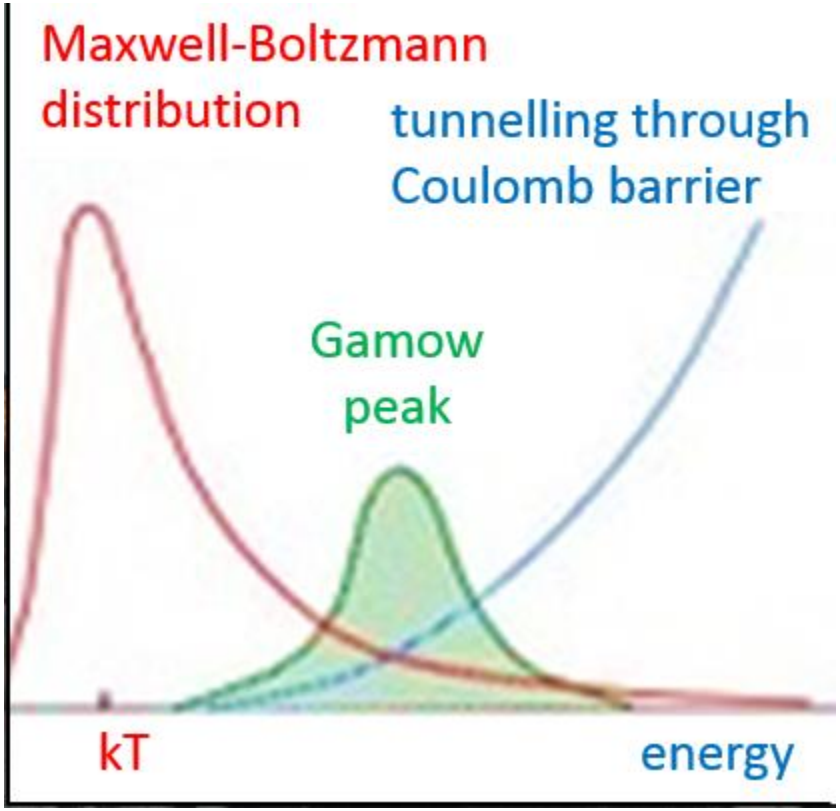
T = 15 x 10^6 K

Energy ≈ 1 keV

Coulomb barrier ≈ 600 keV



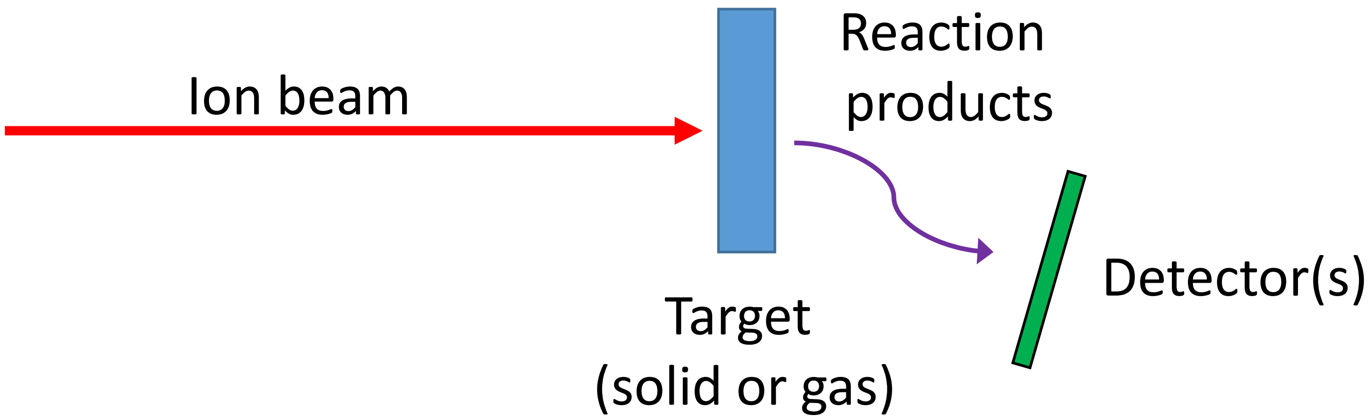
Gamow peak: most significant energy range



The Challenge

Some typical values

- Cross-section: as low as 10^{-15} barn
- Target thickness: 10^{18} atoms/cm^2
- Beam intensity: 100 μA (10^{15} particles per second)



Yield = $N_{projectiles}$ x N_{target} x Cross-section x Det. efficiency

= 10^{15} pps x 10^{18} cm^{-2} x 10^{-39} cm^2 x 100% (charged particles)

~1% (gamma rays)

= **0.3-30 counts/year**

How do we carry out a measurement?

- Improve signal
  Increase beam intensity, increase target enrichment, …
- Reduce background
  Active / passive shielding, background rejection via PSA, …
- Novel detection techniques
  Improve efficiency as much as possible

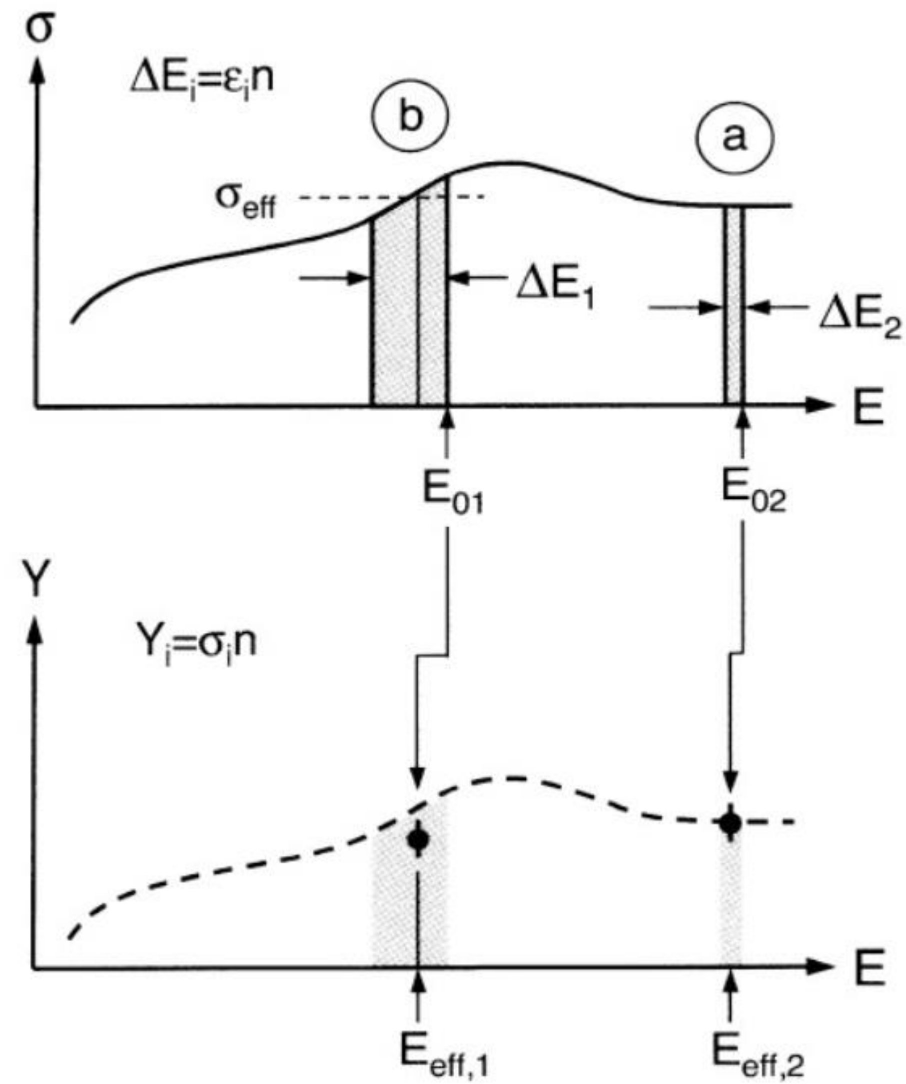
Why don't we increase the **target thickness**?

Thicker target = more counts. You can almost always just make a target thicker. What is stopping us?

As the target gets thicker, reactions will occur over a wider range of energies.

Frequently, there is no way to tell which events we detect correspond to which energy.

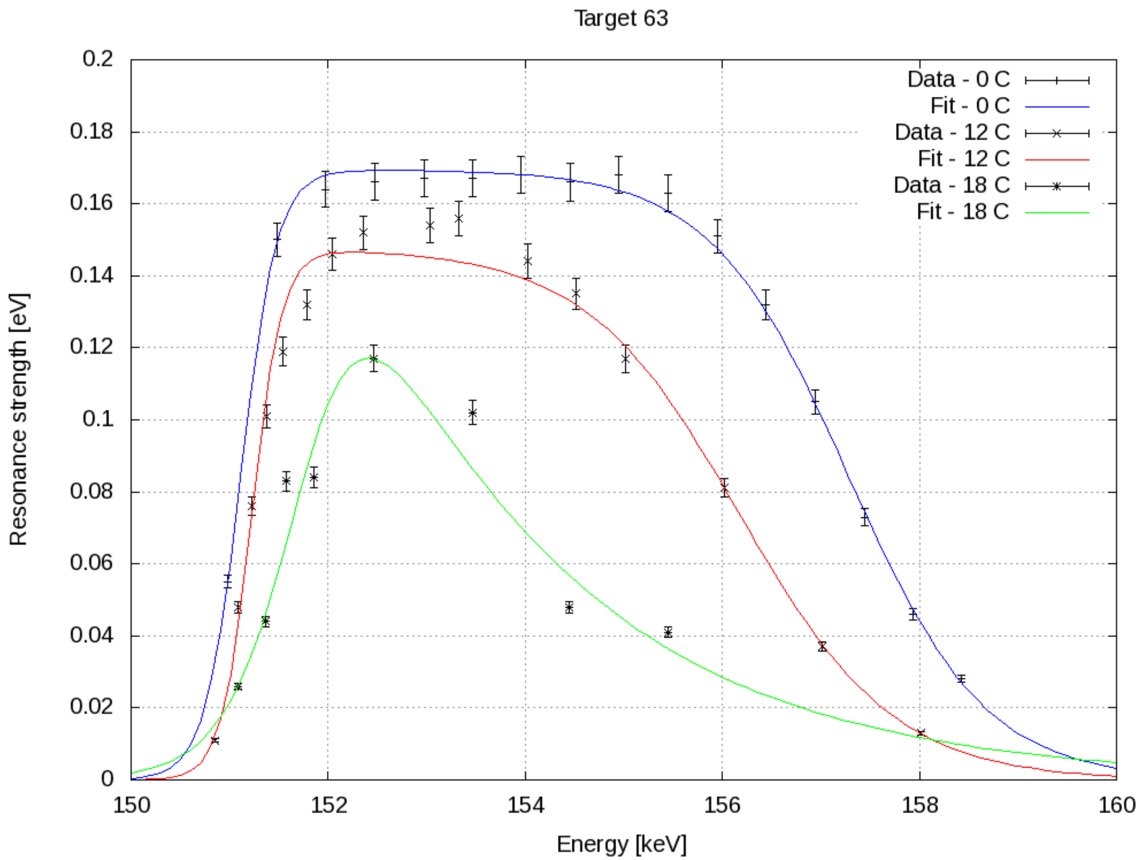
Even if we can, we are getting events for different energies. For a given energy we are not seeing more events!



Why don't we increase the **beam intensity**?

100 uA is not a technical limit. Accelerators capable of delivering ~1A proton beams existed for decades.
More beam intensity = more signal - what's stopping us?

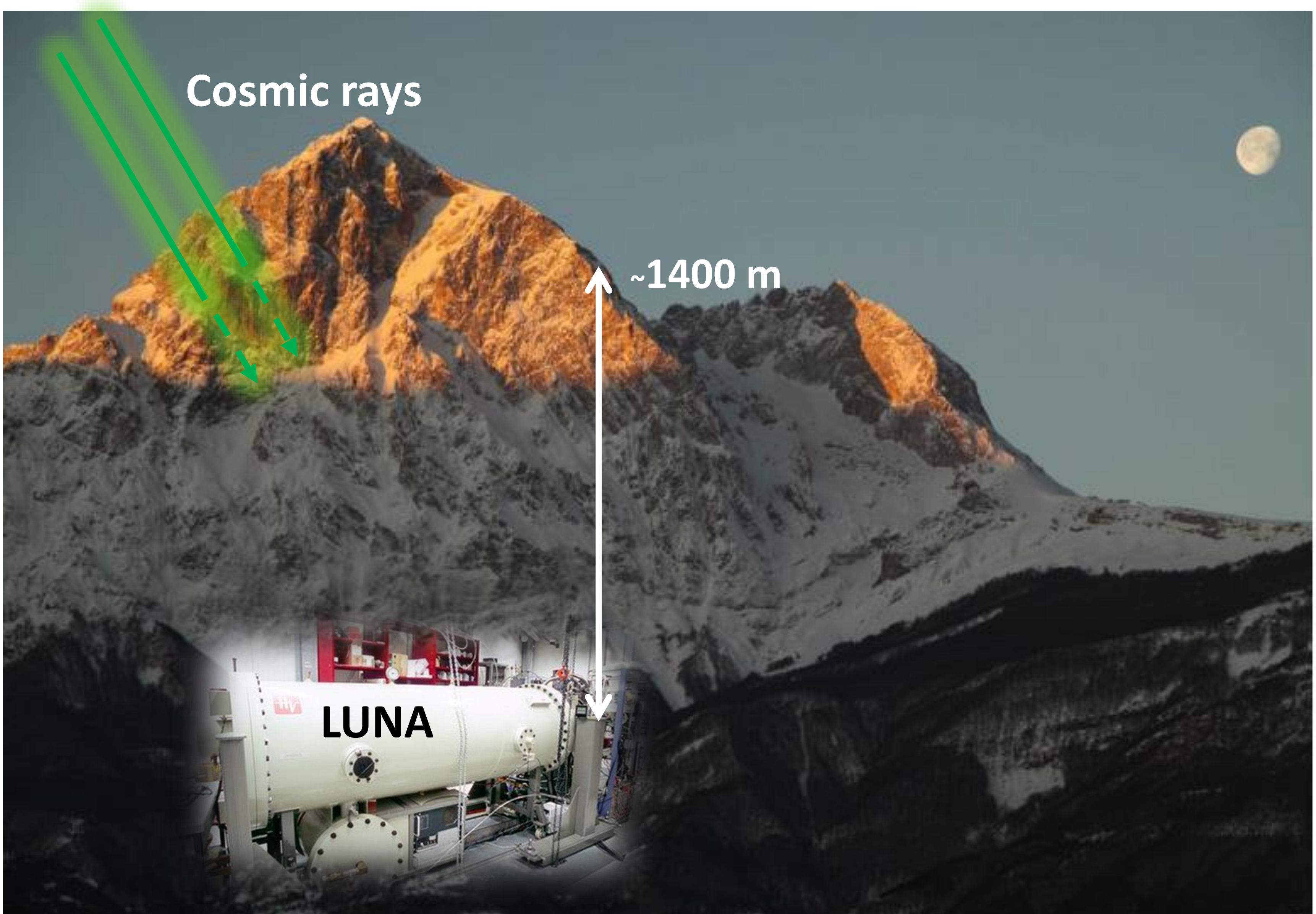
Target degradation



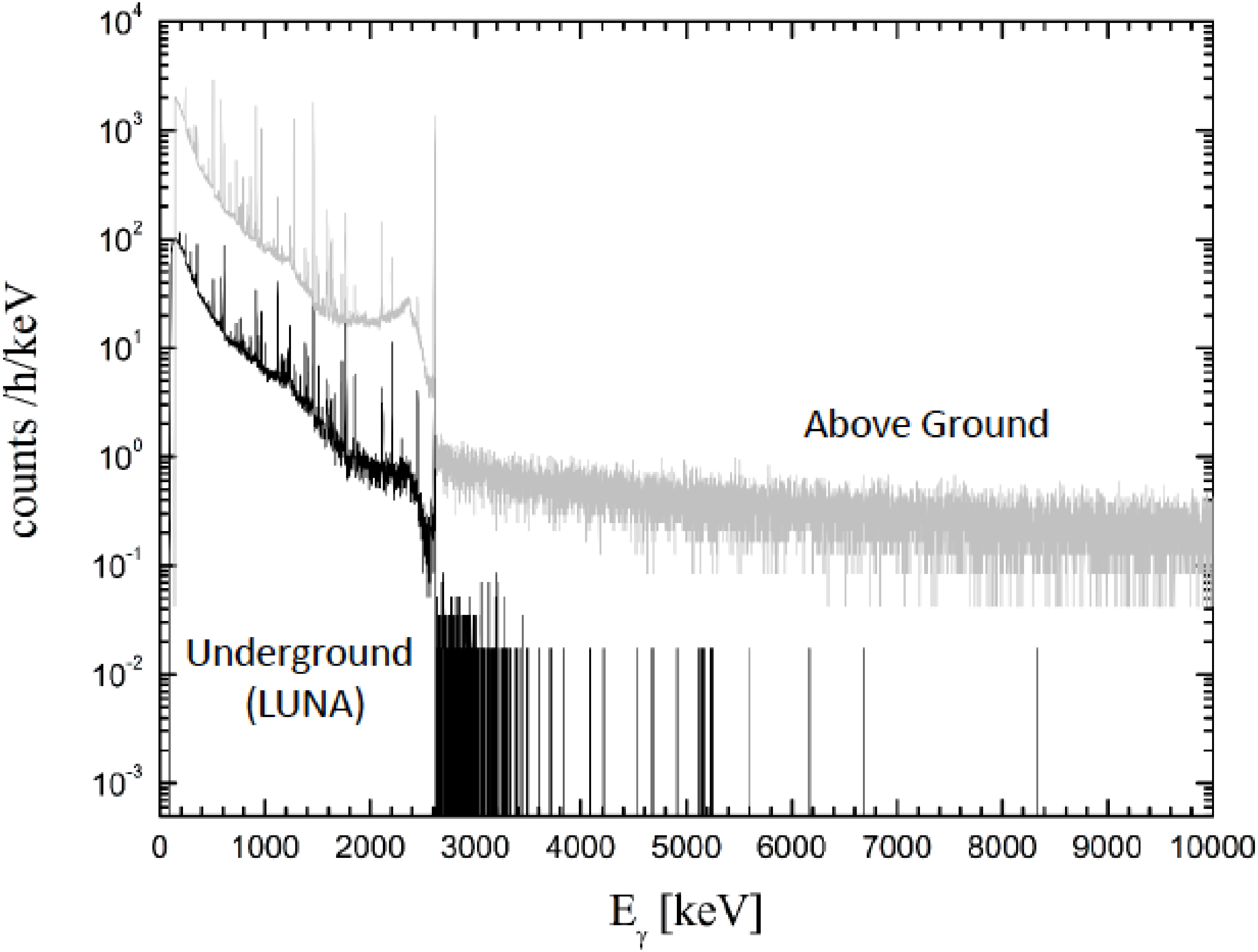
Solid target

LUNA

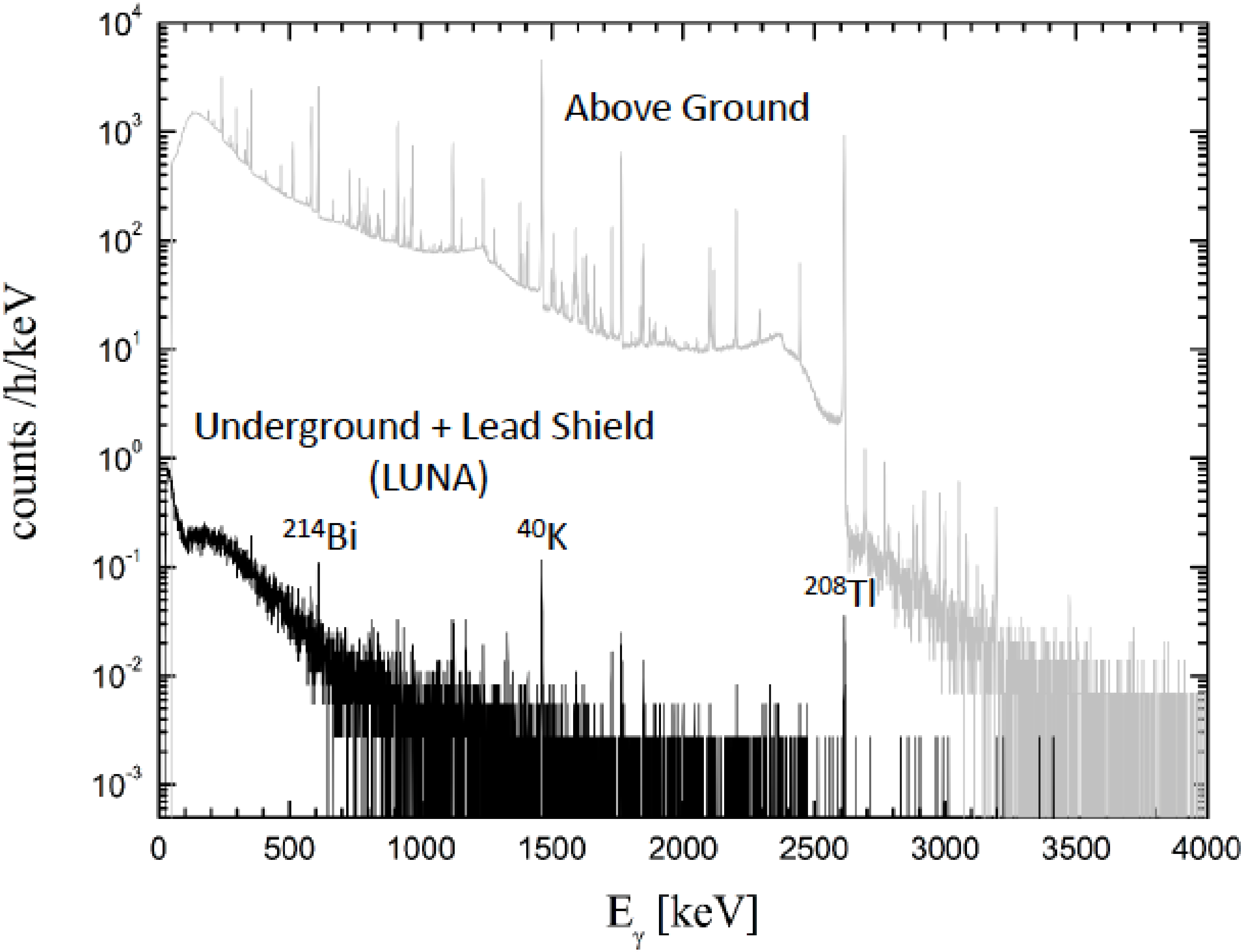
(Laboratory for Underground Nuclear Astrophysics)

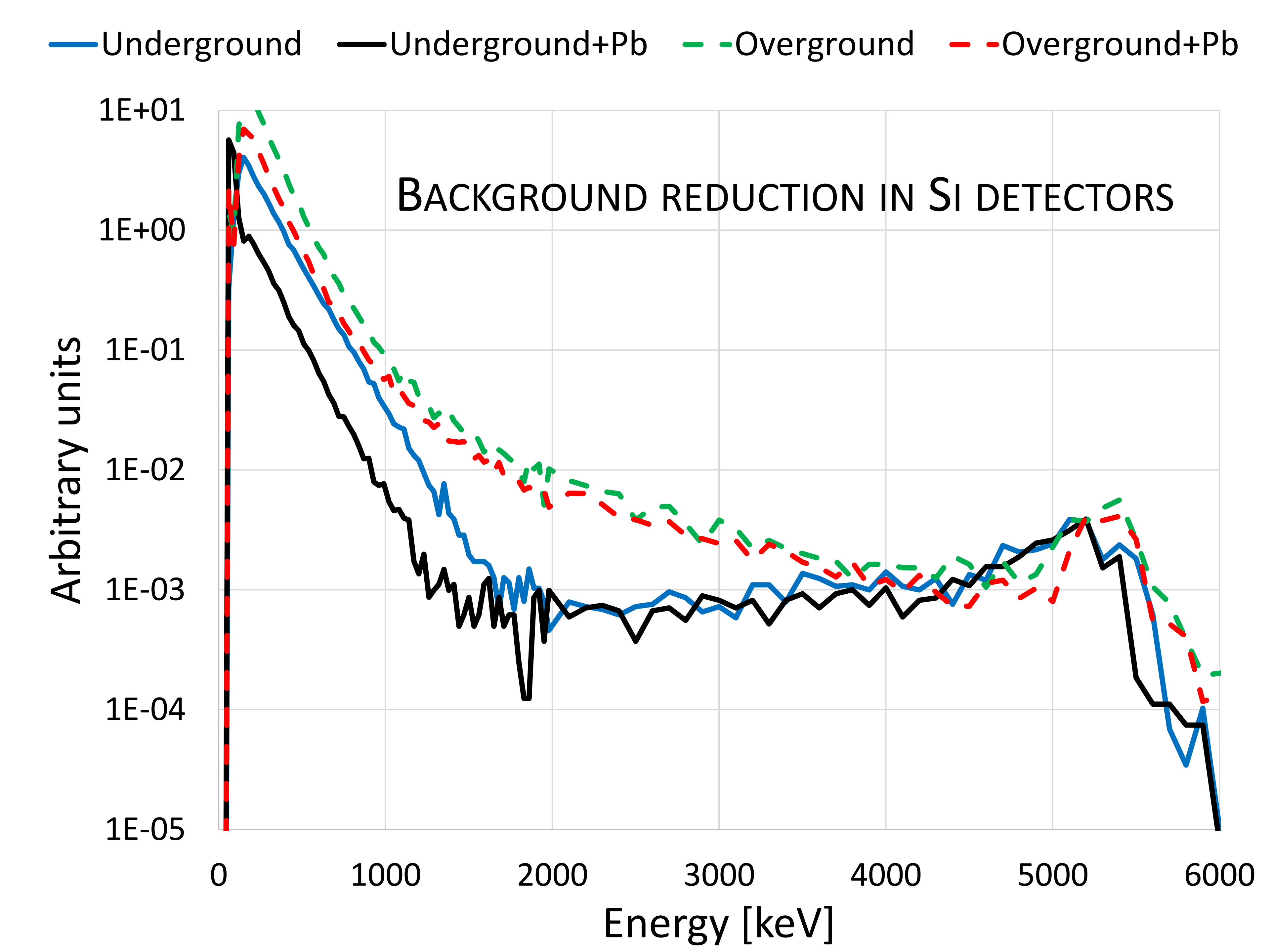


BACKGROUND REDUCTION IN HPGE



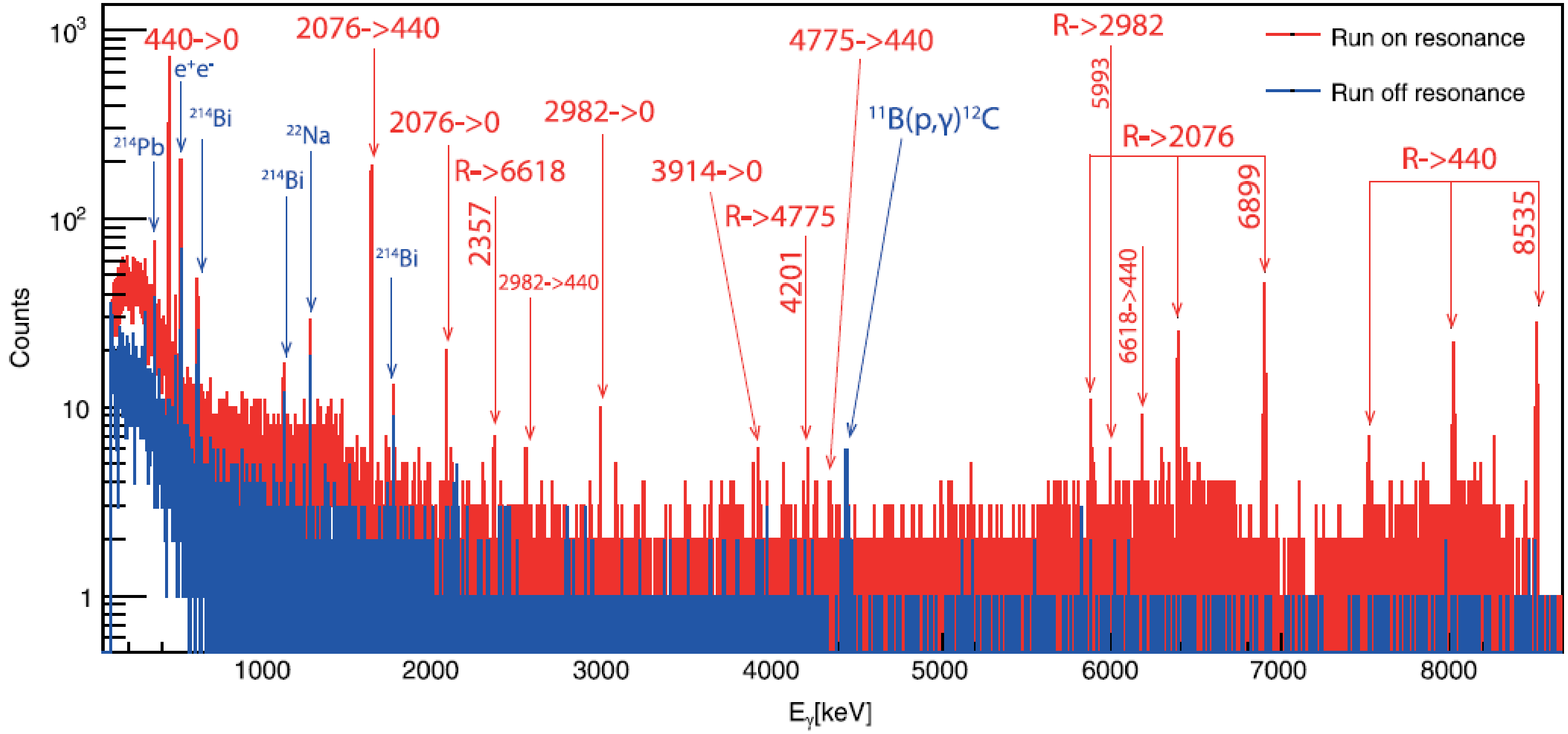
BACKGROUND REDUCTION IN HPGE



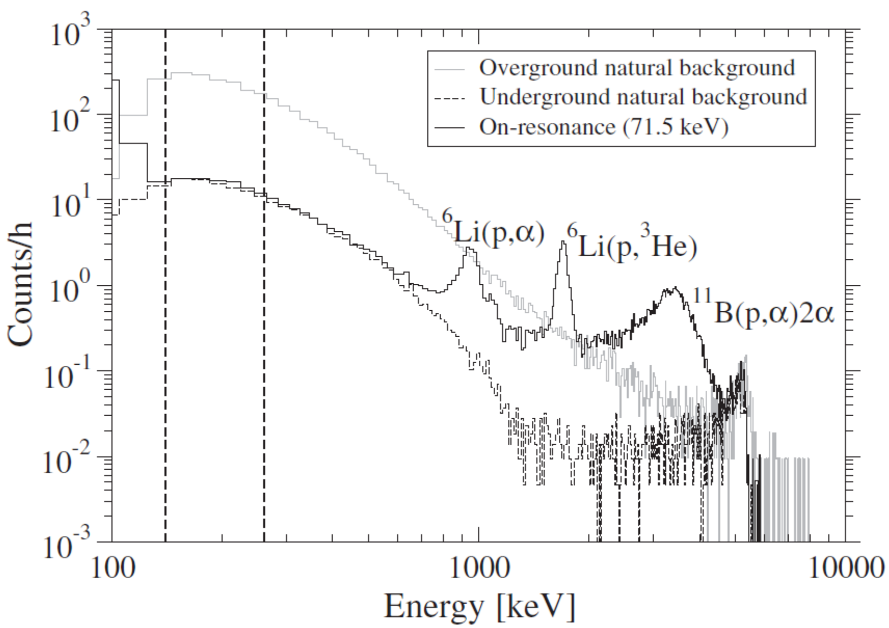


Underground
Underground+Pb
Overground
Overground+Pb
BACKGROUND REDUCTION IN SI DETECTORS
1E+01
1E+00
1E-01
1E-02
1E-03
1E-04
1E-05
Arbitrary units
0
1000
2000
3000
4000
5000
6000
Energy [keV]

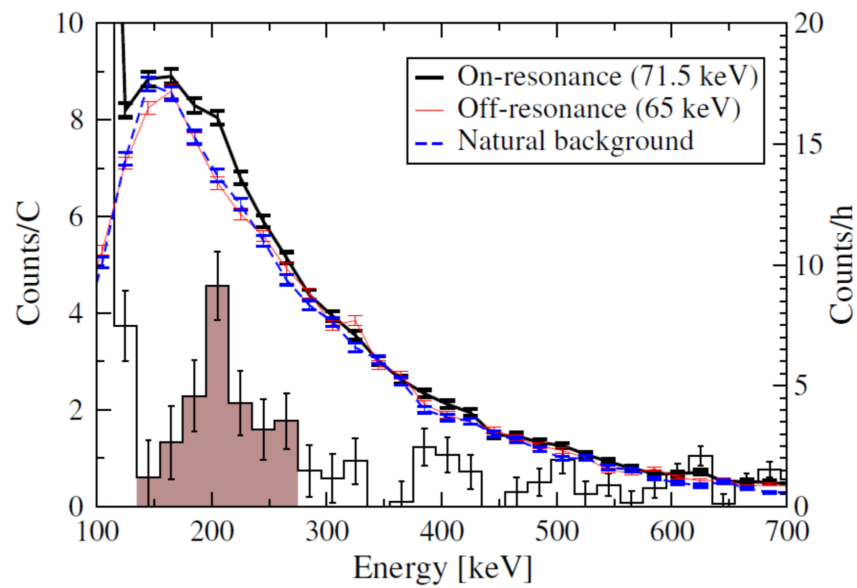
LUNA - 400



Run on resonance
Run off resonance
440->0
e⁺e⁻
2076->440
2076->0
2982->0
R->6618
3914->0
R->4775
4775->440
R->2982
R->2076
R->440
2357
2982->440
4201
5993
6618->440
6899
8535
²¹⁴Pb
²¹⁴Bi
²²Na
¹¹B(p,γ)¹²C
Counts
E$_\gamma$[keV]



Overground natural background
Underground natural background
On-resonance (71.5 keV)
⁶Li(p,α)
⁶Li(p,³He)
¹¹B(p,α)2α
Counts/h
Energy [keV]



On-resonance (71.5 keV)
Off-resonance (65 keV)
Natural background
Counts/C
Counts/h
Energy [keV]

LUNA-MV

- **LUNA-MV**: **new** accelerator to be installed underground
- Upgrade over current machine. Can reach higher energies.
- Fresh opportunities to study many quiescent scenarios

First reactions to be studied:

- $^{14}N(p,\gamma)^{15}O$ (cosmic chronometer)
- $^{13}C(\alpha,n)^{16}O$ (s-process nucleosynthesis)
- $^{12}C+^{12}C$ (final fate of a star, supernova luminosity, …)

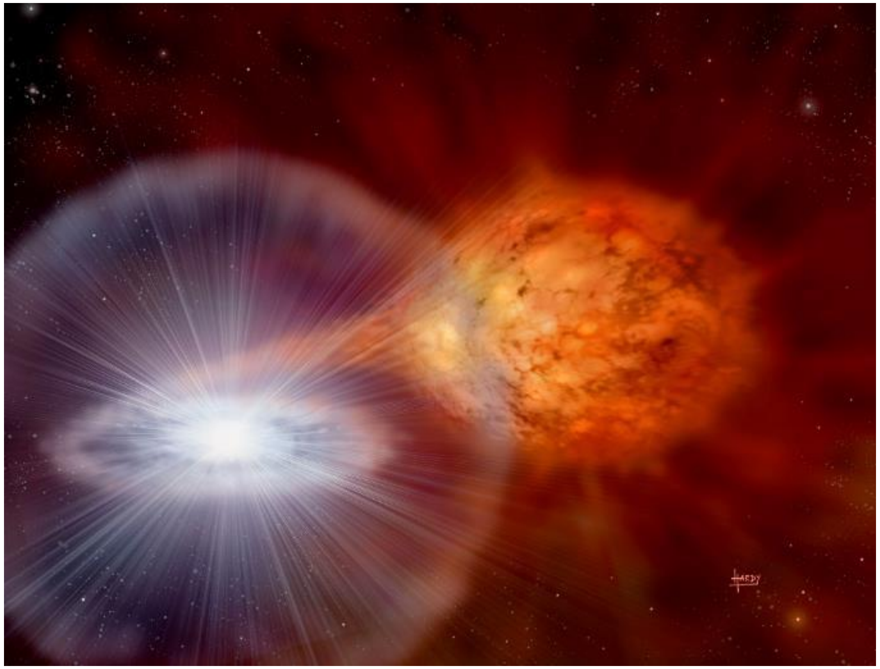
JUNA & CASPAR

- New underground accelerators in China and in the US
- JUNA is already producing science
- CASPAR is waiting to be allowed to start
- There are other shallow underground accelerator facilities, e.g. **Felsenkeller** in Germany

RADIOACTIVE BEAM EXPERIMENTS FOR EXPLOSIVE BURNING

The Challenge

In stellar explosions – reactions involve radioactive isotopes

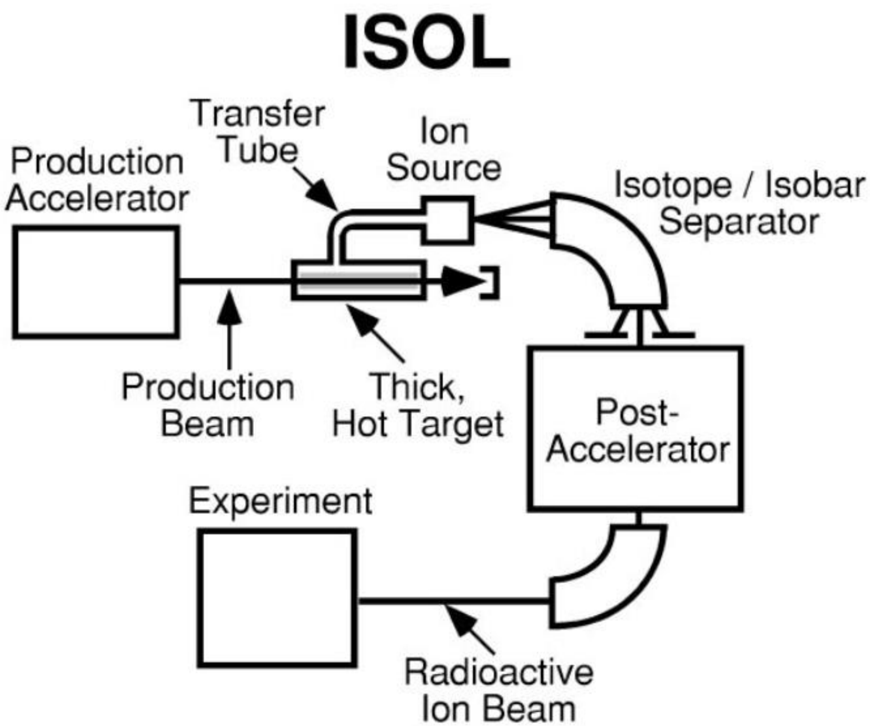


In a laboratory - challenges

- How to produce the radioisotopes of interest?
- Short lifetimes – cannot make radioactive target

ISOL (Isotope Separation On-Line)

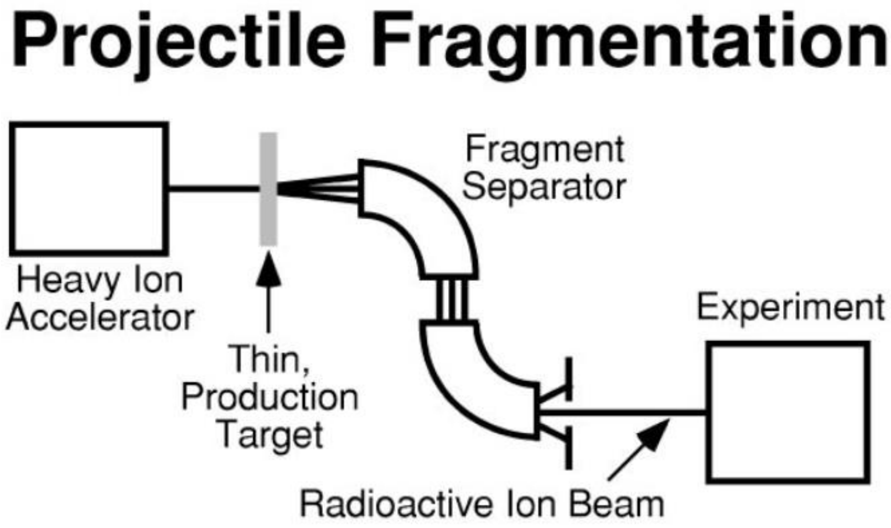
- Light beam on thick target (e.g. protons on SiC)
- Radioisotopes produced by nuclear reactions
- Isotopes diffuse out of target (hot chemistry)
- Separate, reaccelerate at energies of interest



- Good isotopic purity
- Good energy resolution
- Good intensity
- Available radioisotopes limited by chemistry

In-flight fragmentation

- Smash heavy beam on light, thin target (e.g. Pb on Be)
- Produce a cocktail of radioisotopes
- Select those of interest and direct on experiment target
- No re-acceleration! Produced at E >> MeV

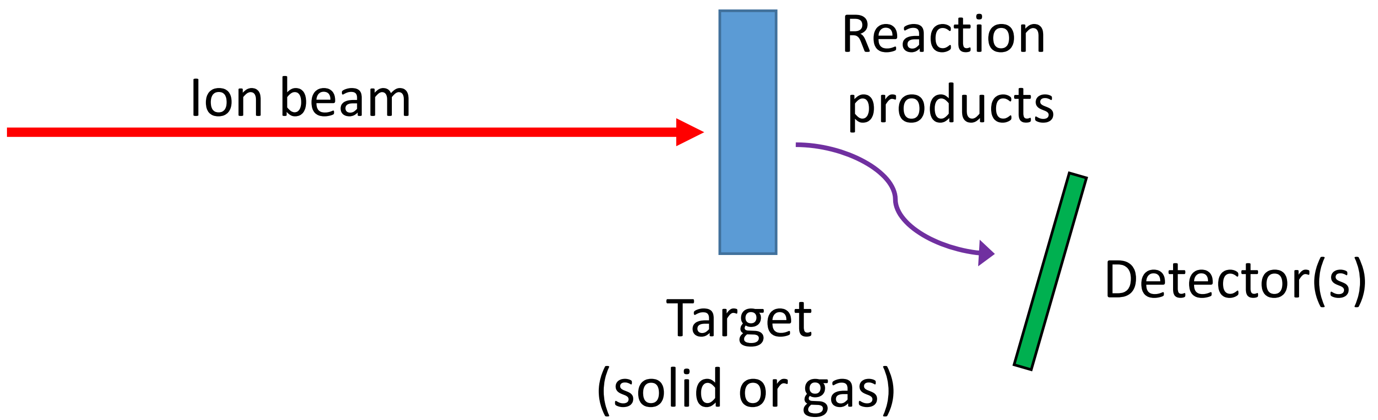


- Poor isotopic purity
- Poor energy resolution
- Poor intensity vs. ISOL
- No limitations on isotope production

RADIOACTIVE BEAMS

Some typical values

- Cross-section: ~10^{-6} barn
- Experiment target thickness: 10^{18} atoms/cm^2
- Beam intensity: 10^8 pps (ISOL), 10^6 pps (In-flight)



Yield = $N_{projectiles}$ x N_{target} x Cross-section x Det. efficiency

= 10^{6-8} pps x 10^{18} cm^{-2} x 10^{-30} cm^2 x 100% (charged particles)

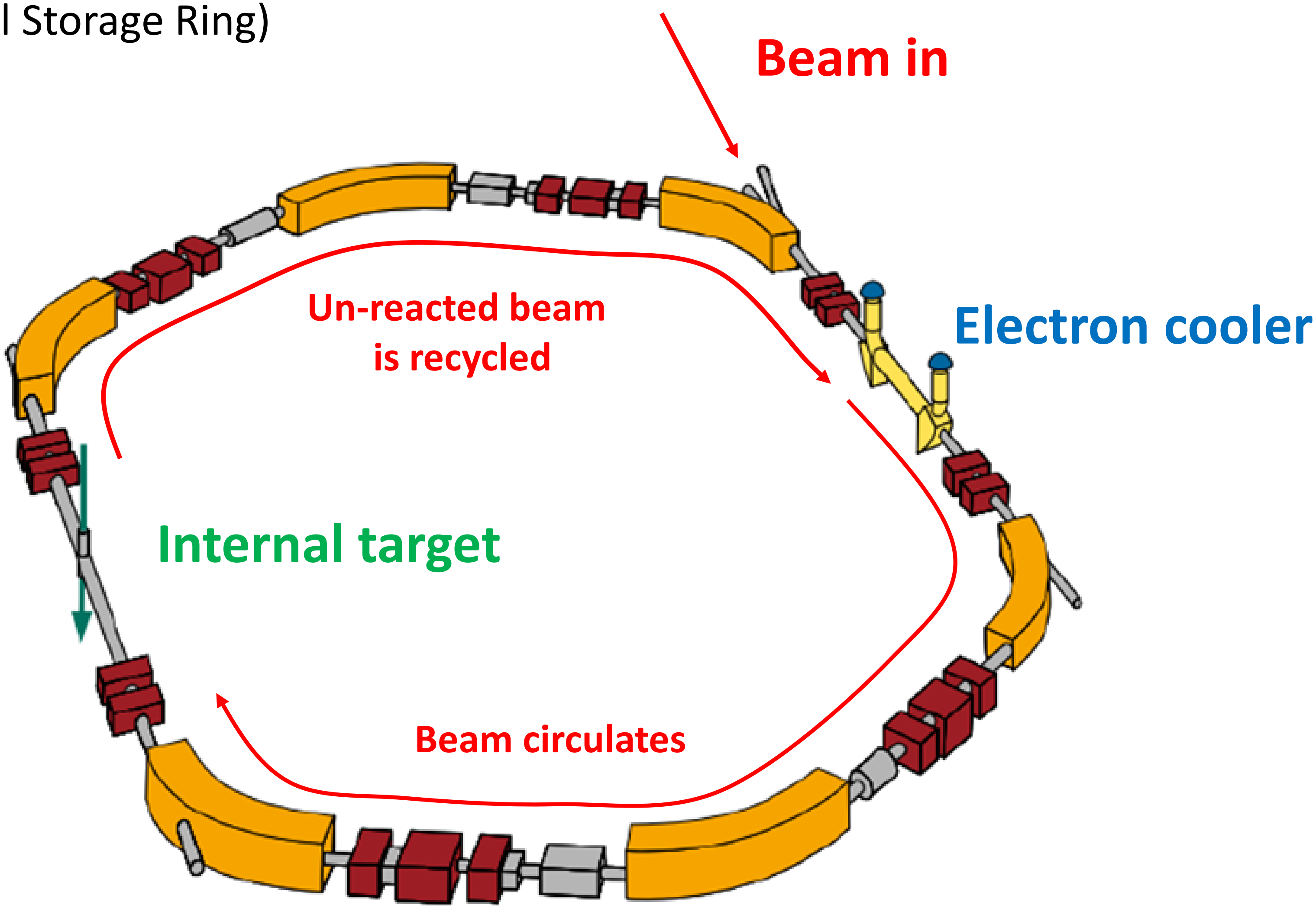
= **1-100 counts/week**

STORAGE RINGS

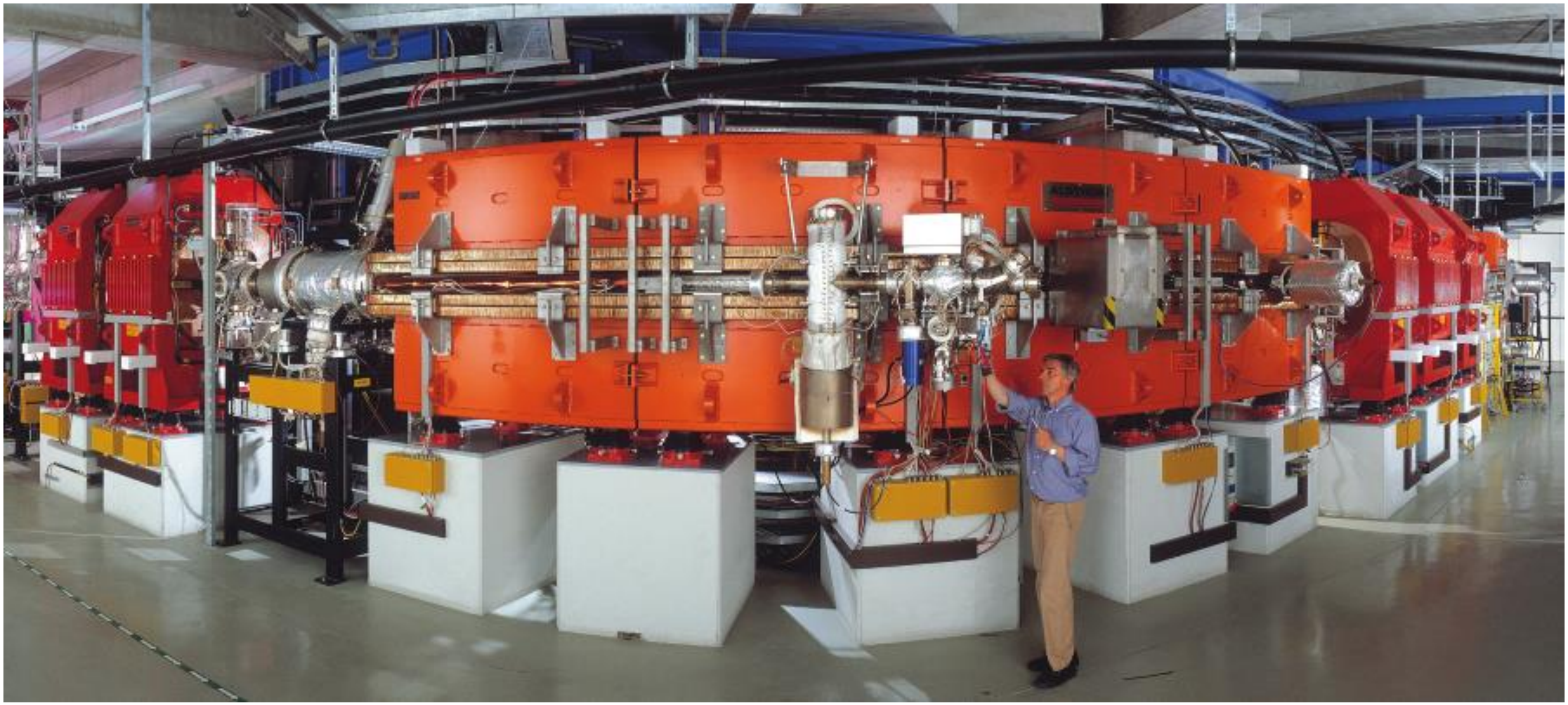
Storage Rings

ESR (GSI, Germany)

(Experimental Storage Ring)



Picture: Phys. Scr. T156 (2013) 014016



RINGS - ADVANTAGES

- Recirculation increases intensity

  Circumference = ~100 m
  For e.g. ^{30}P at E = 240 MeV => v = 3.9×10^7 m/s
  Revolution frequency = velocity / circumference = 390 000 Hz
  That is almost a one million increase in beam intensity!

- Recirculation improves isotopic purity
- Cooling improves beam emittance at every turn

Makes up for the three weakness of in-flight production!

One injection can last for seconds-minutes. Very efficient.
But wait! **Why is the beam lost?**

If stored ions interact with **obstacles** they may scatter off (Rutherford), or it may change its charge state (capture / lose electron). If either happens, ions are lost.

- The internal target is an obstacle. Air in an obstacle.
- Electron Capture is *normally* the dominant loss

$$\sigma_{EC} = 1.1 \cdot 10^{8} \frac{q^{3.9} Z_{gas}^{4.2}}{E^{4.8}}$$

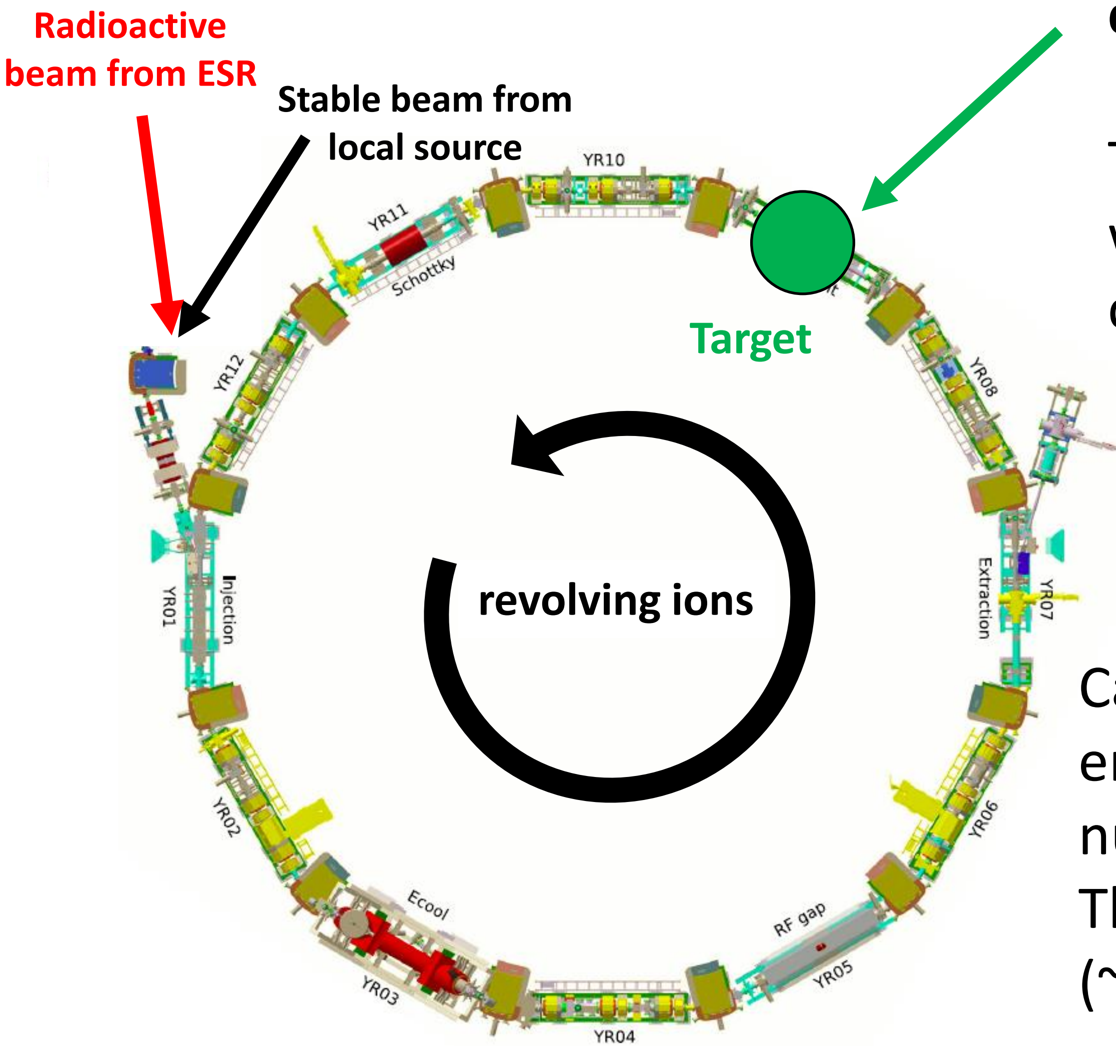
Where q and E are the charge and energy of the beam.

- Need **extremely good vacuum** in a ring ($<10^{-10}$ mbar)
- Can only use very thin target (max 10^{14} atoms/cm2)
- Low Z targets are best (H, He)
- High beam energies are best

CARME @ CRYRING

CRYRING @ FAIR/GSI

Beam injected via local ion source, or radioactive beam via the ESR

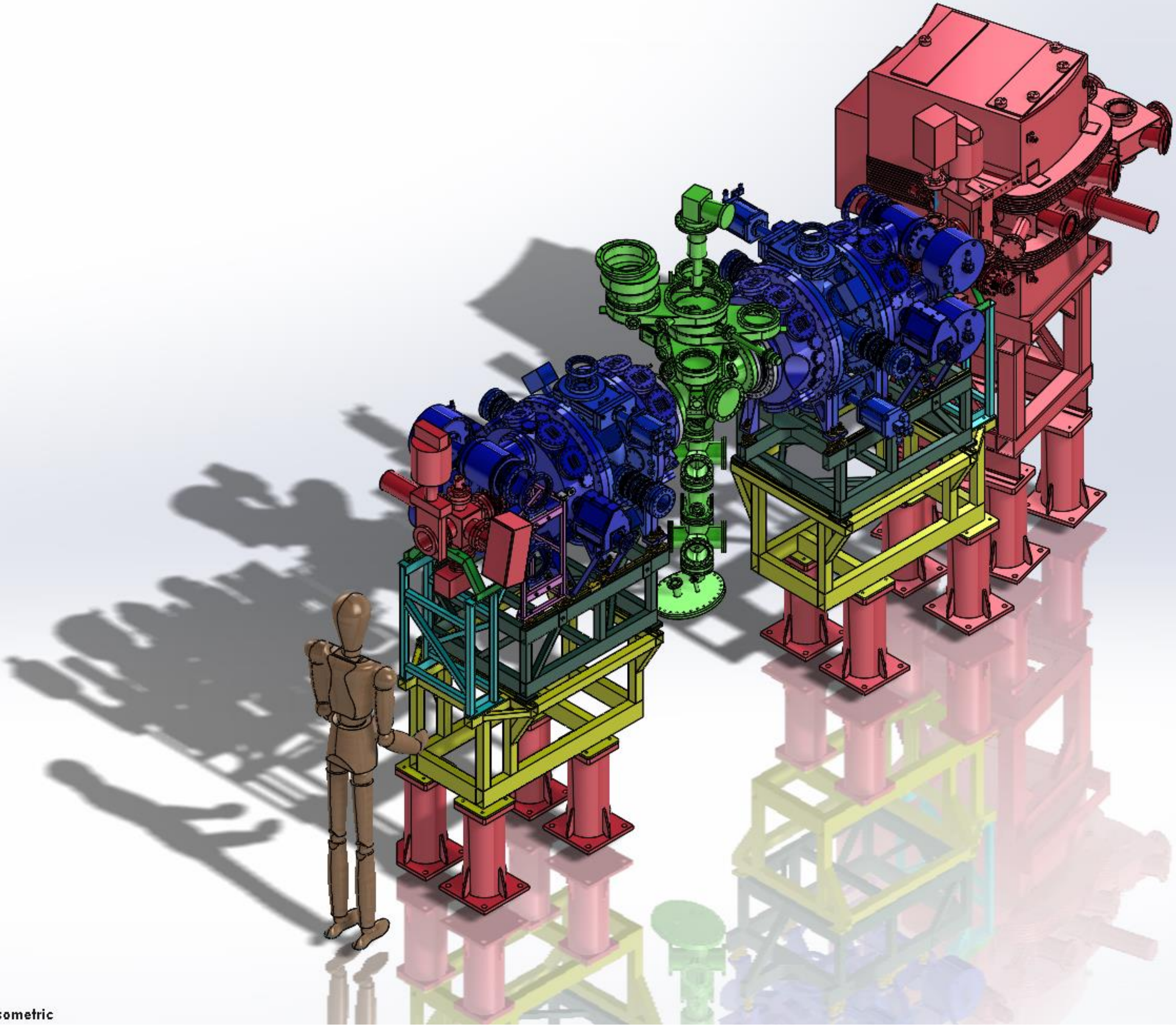


It has one straight section for experiments with an **internal cryogenic microdroplet target**.

To exploit this novel possibility, we built a new detection array called CARME, mounted here

Can store ions at uniquely low energy (E<10 MeV/u), ideal for nuclear astrophysics.

The ring operates in XHV ($\sim 2 \times 10^{-11}$ mbar)

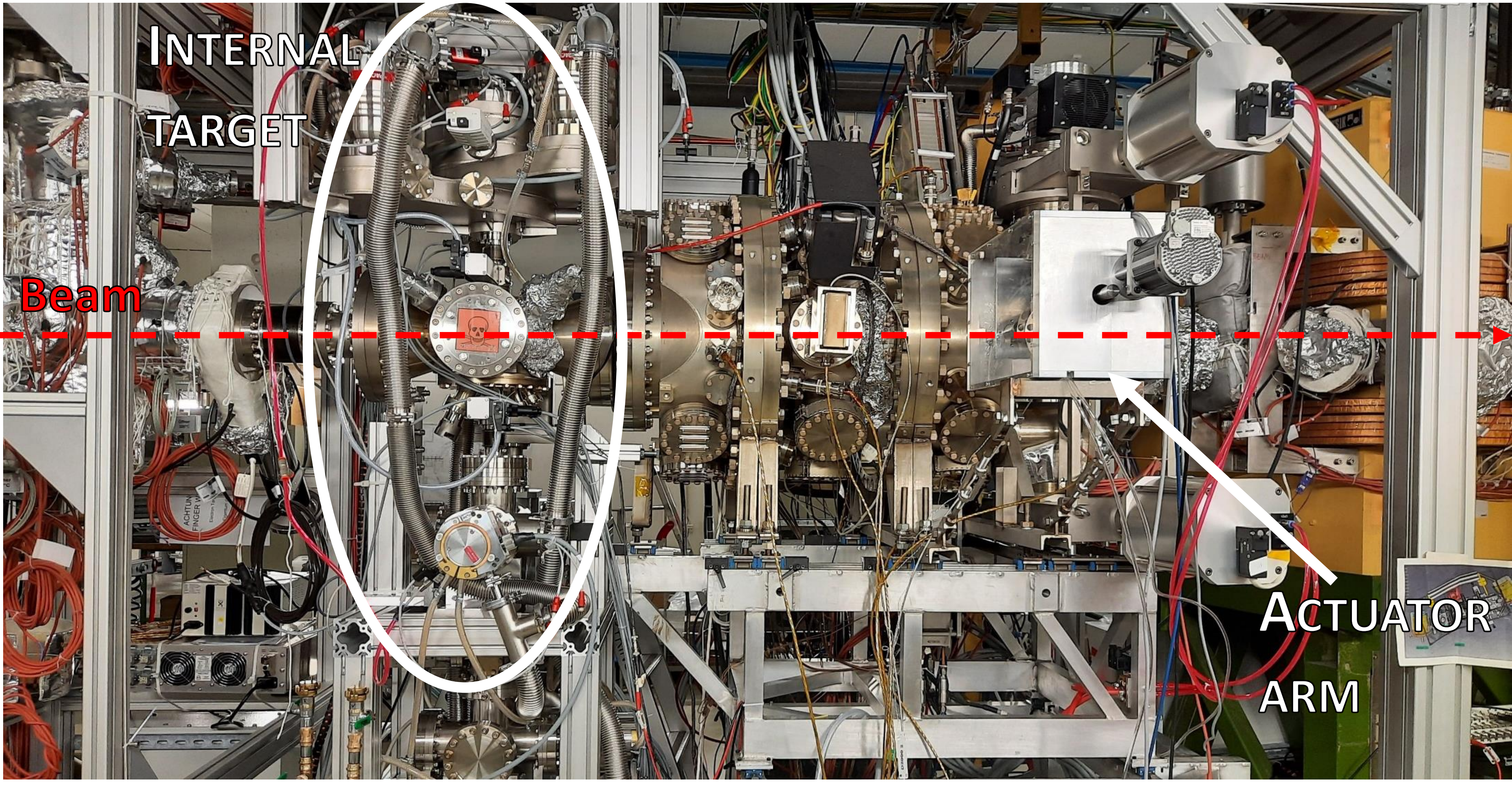


*Isometric

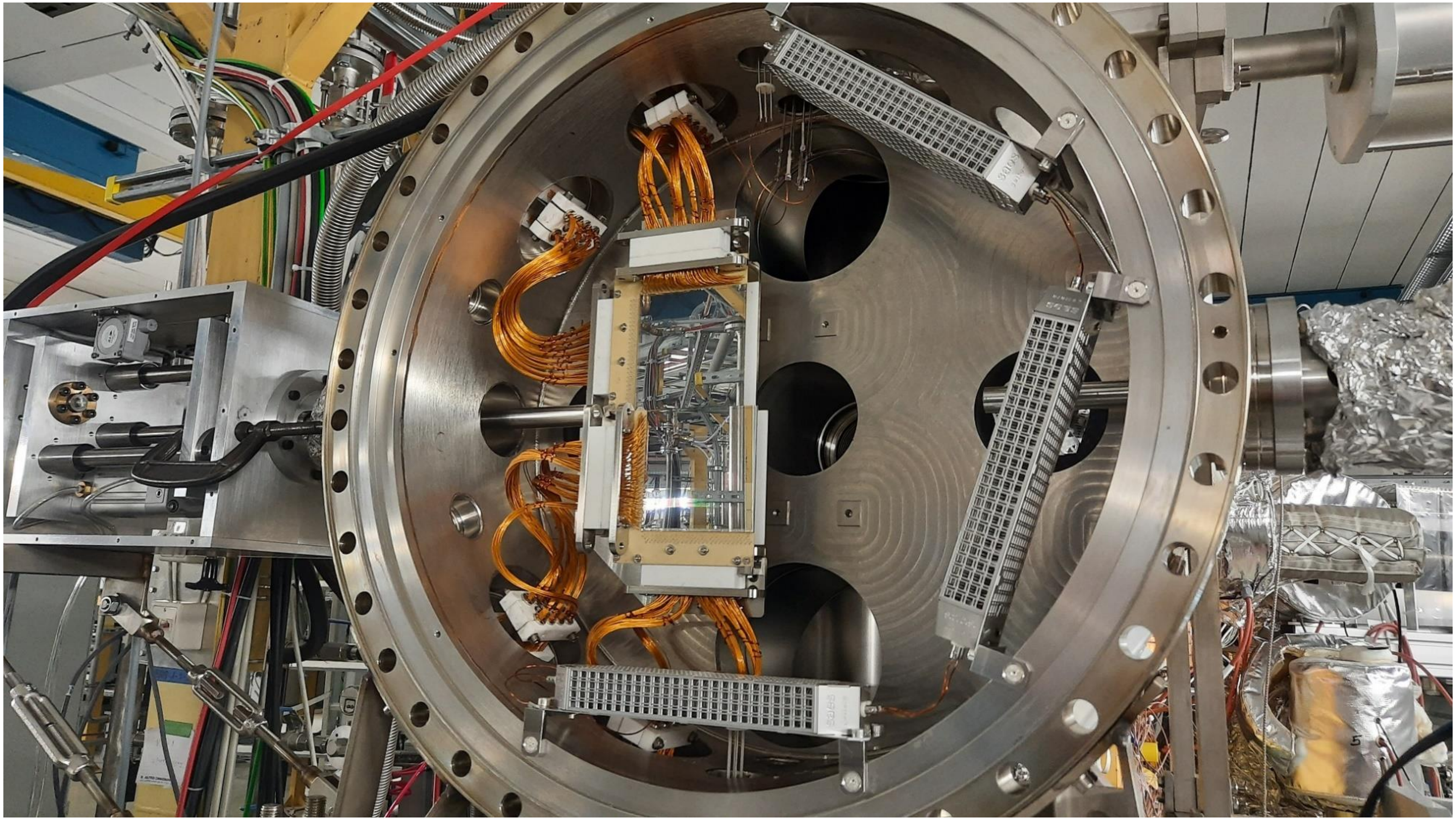
CARME

CRYRING ARRAY FOR REACTION MEASUREMENTS

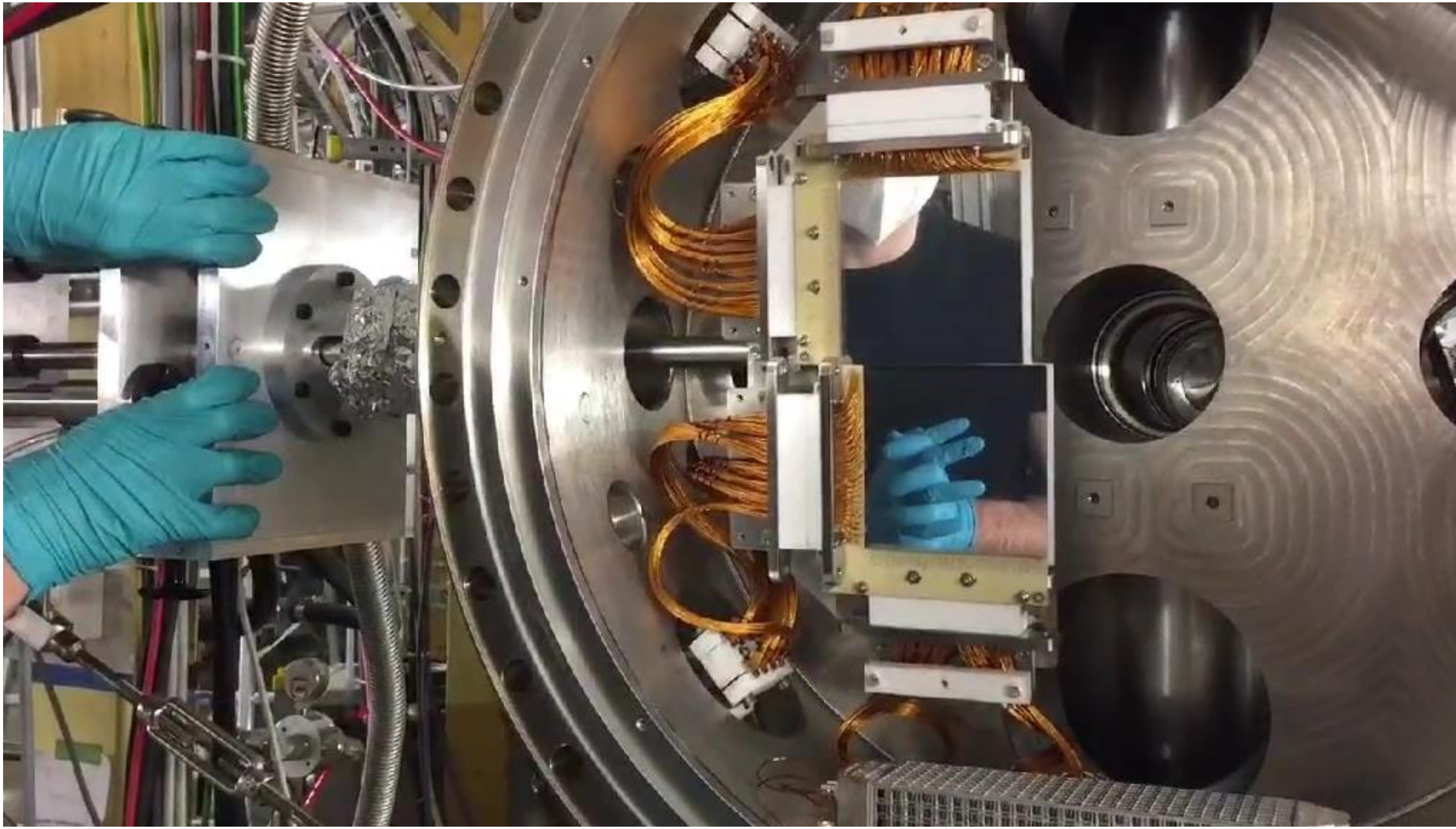
- Reaction chamber mounted **downstream** or upstream of target
- Mounts silicon detectors to detect charged-particles
- Mounted on the CRYRING in 2021, commissioned February 2022



DETECTORS

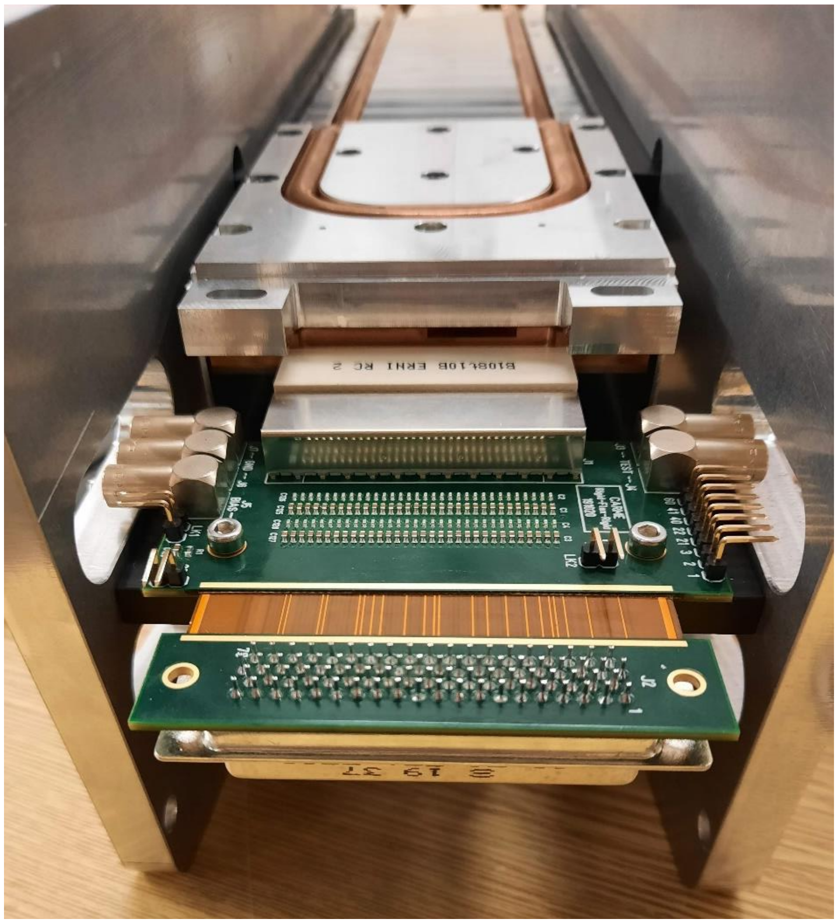


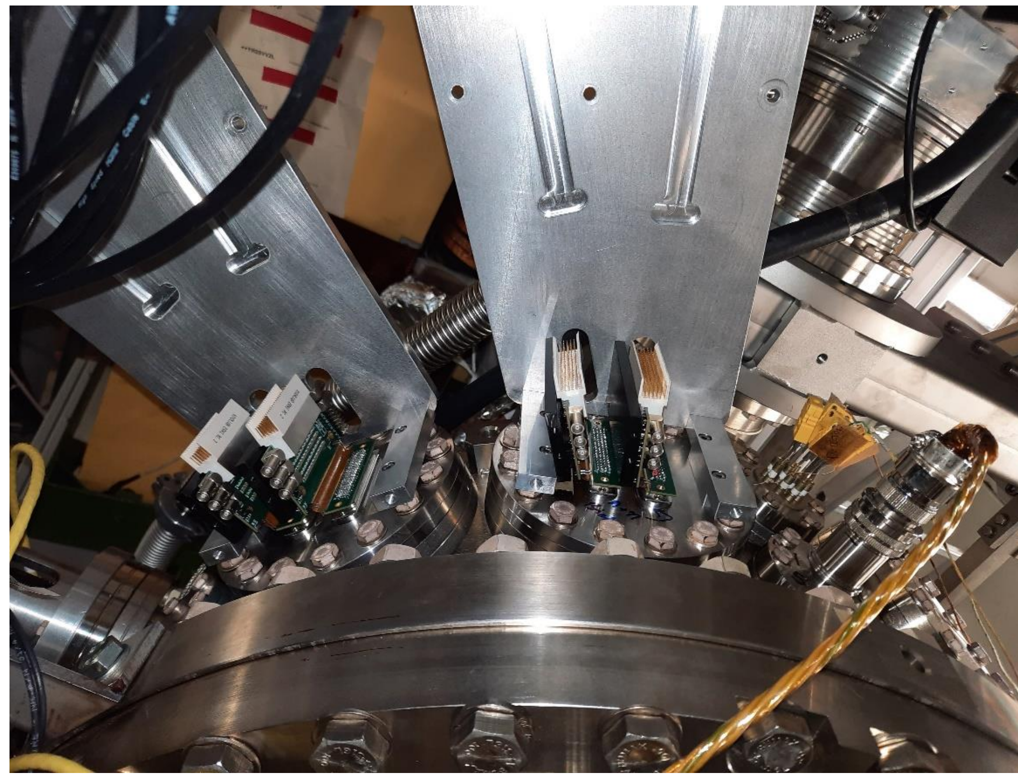
- Double-sided Silicon Strip Detectors (DSSD)
- Placed directly under XHV (no pockets)
- Can move under XHV – avoid uncooled beam



ELECTRONICS

- Highly segmented DSSDs – 128 x 128 strips = 256 channels each
- Custom FEE64 cards, 64 channels each + triggerless AIDA DAQ





Reaching XHV

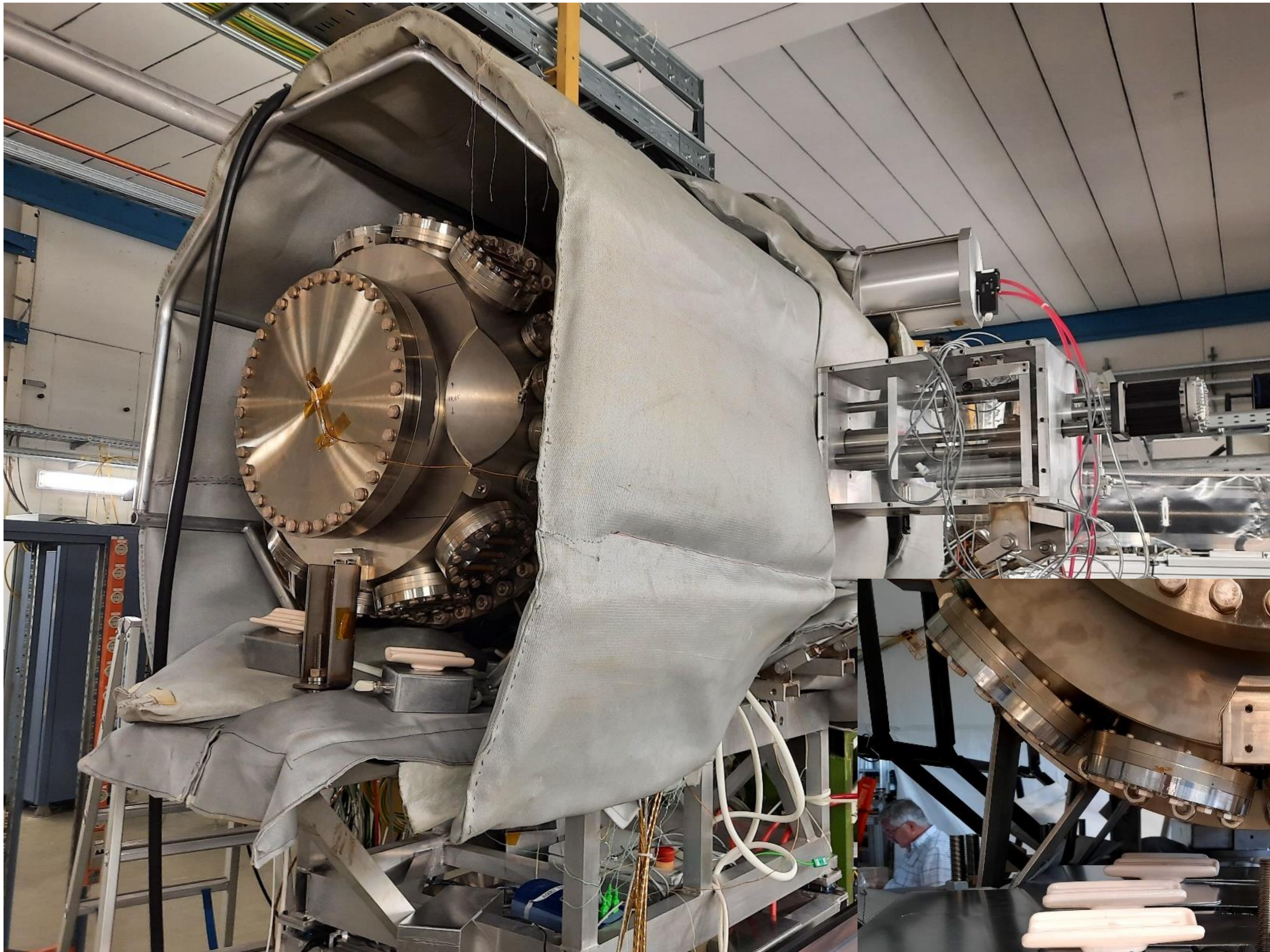
- CARME needs to reach XHV for beam to pass through – very challenging from a technical point of view

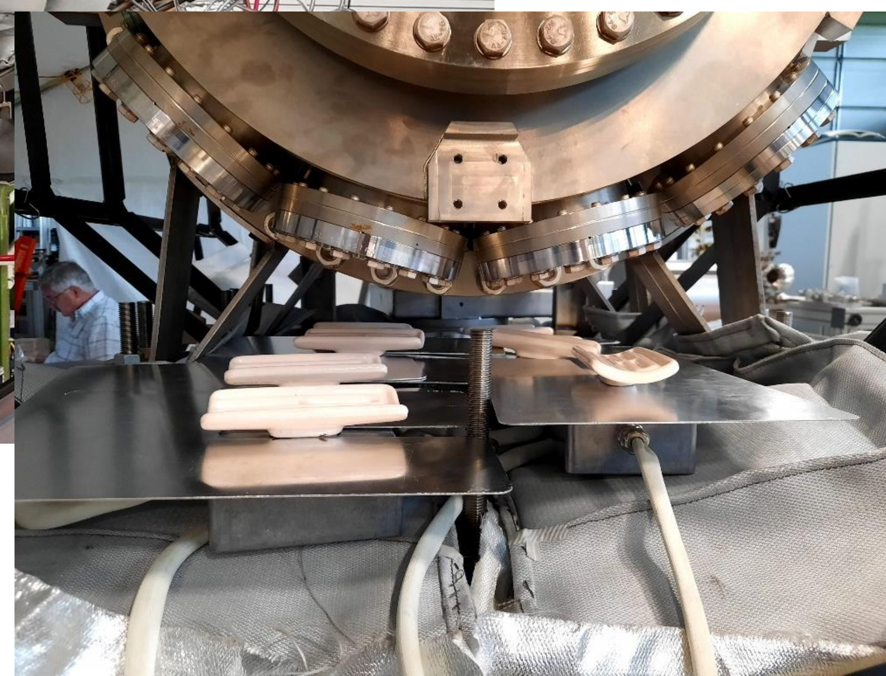
- From atmosphere (1E3 mbar) to 0.1 mbar: oil-free scroll pumps. Standard technology. Takes a few minutes.
- From 0.1 to 1E-7 mbar: mag-lev turbo-molecular pumps. Relatively standard technology. Takes a few hours

- Below 1E-7 mbar, outgassing becomes the primary challenge. Outgassing = release of trapped gases (mainly H) from materials under vacuum.

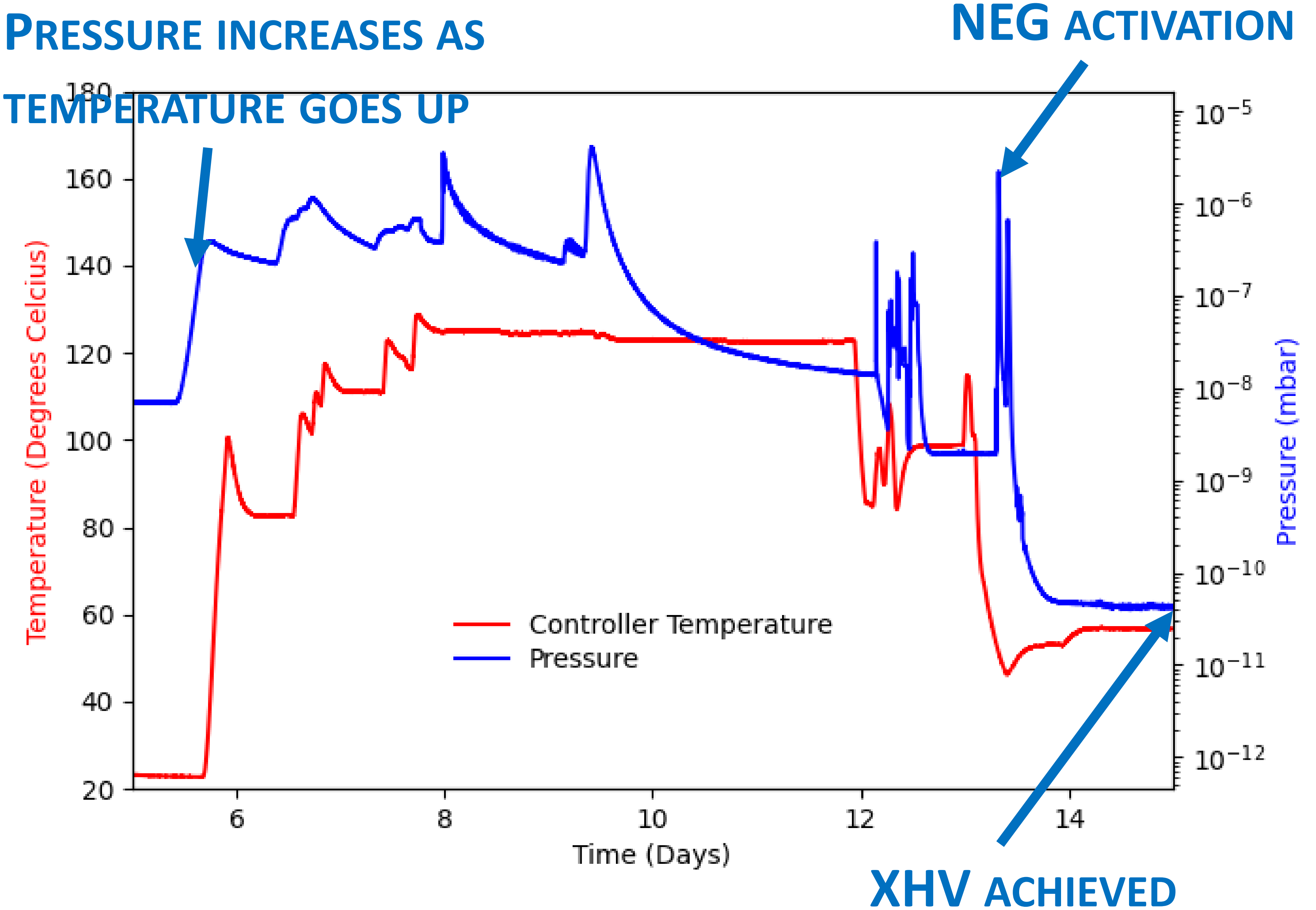
- Careful choice of materials is crucial, but not sufficient
- One needs to heat the chamber (bake) to 100-150C to force outgassing, then cool down and use NEG getters and Ion pumps

REACHING XHV



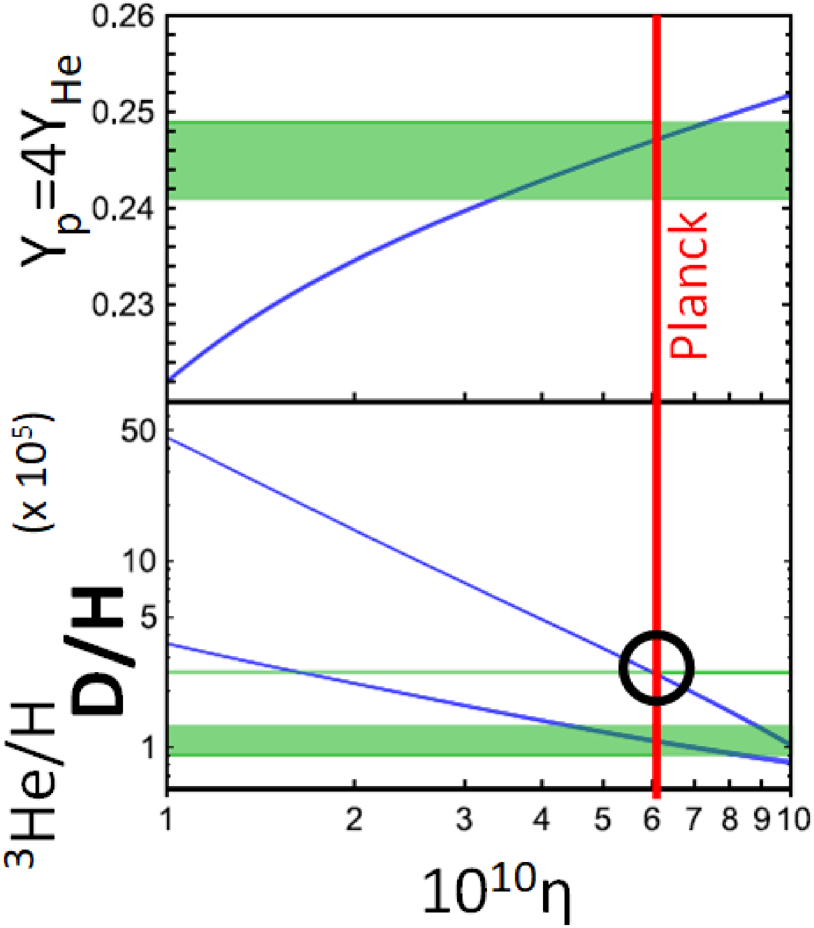


Reaching XHV



SCIENCE AIMS

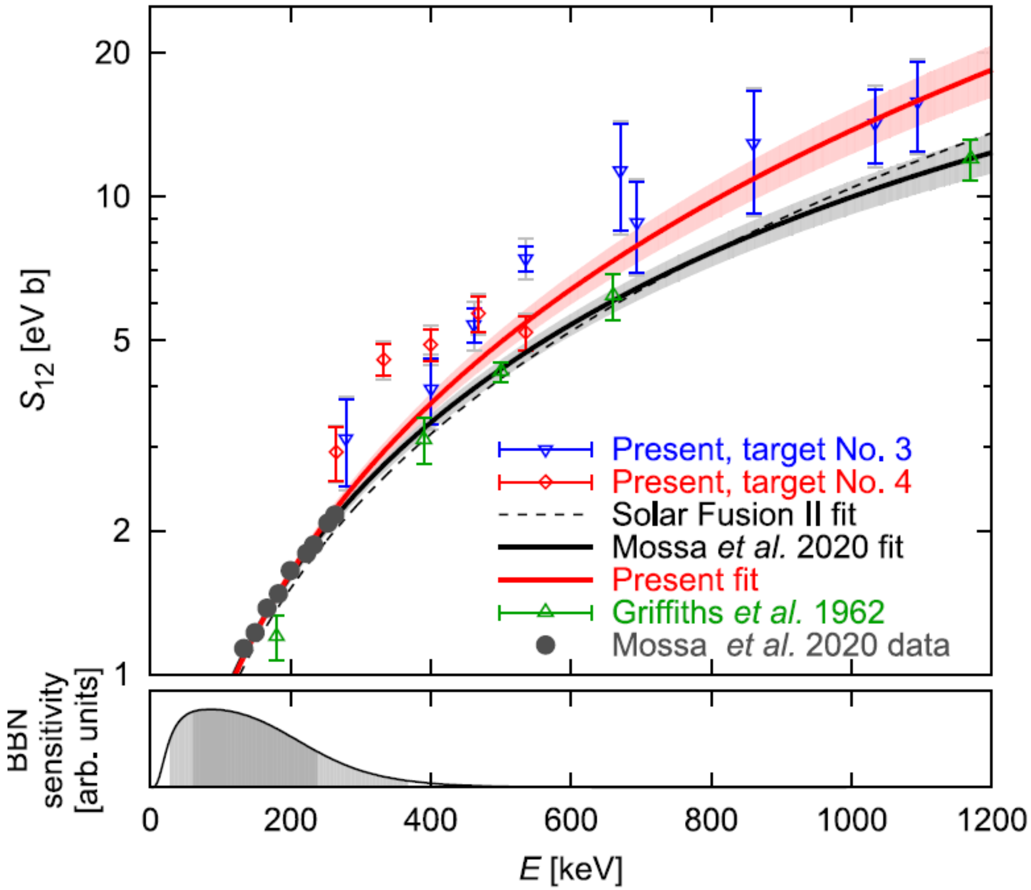
Big Bang Nucleosynthesis



- Elements up to lithium were synthesised during the Big Bang
- Compare astronomical observations in ancient stars vs. Standard Model predictions
- Predictions have a single free parameter

- Comparing results allows for test of the Standard Model
- **Deuterium** has lowest uncertainty

Deuterium burning via $^2H(p,\gamma)^3He$ is a key reaction for Big Bang prediction uncertainty



Turkat *et al.*, PRC, 2021

Some issues remain open: e.g. disagreement at high energies, angular distributions

Measure $^{2}H(p,\gamma)^{3}He$ directly at Big Bang energies at CRYRING using CARME

HOW DOES IT WORK?

- Deuterium is stable, but unwelcome (produces D and T). Injected into from local ion source. 10^8 ions per injection, once in 10 seconds or so, filling the ring.

- Beam is accelerated / decelerated as required, and cooled
- Hydrogen target turned on (10^{13} atoms/cm2)
- CARME detectors move in
- Measure – beam is lost due to interaction with target

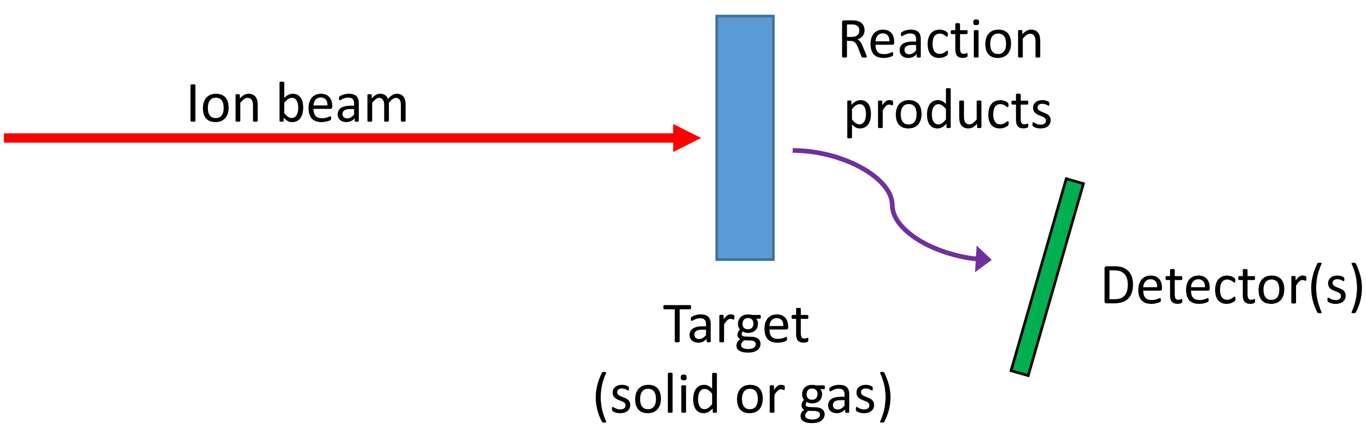
- After a few seconds-minutes (depends on energy!) not much beam left. Dump it.
- Refill, restart

What is different?

- Much less deuterium used. 10^8 ions once per e.g. 10 seconds is equivalent to 10^7 ions per second. That's less than some radioactive beams! No radiation safety risk.

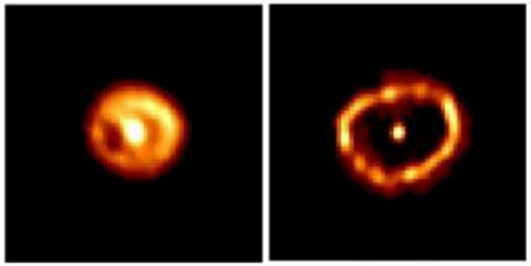
- Ultra-thin target (10^{13} atoms/cm2) means ^{3}He produced **lose no energy** and can be detected. Impossible with traditional targets ($10^{17\text{-}18}$ atoms/cm2)

- Luminosity loss due to thin target + low beam intensity is compensated by recirculation.

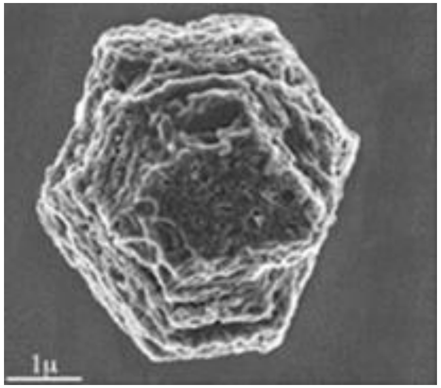


NOVA EXPLOSIONS

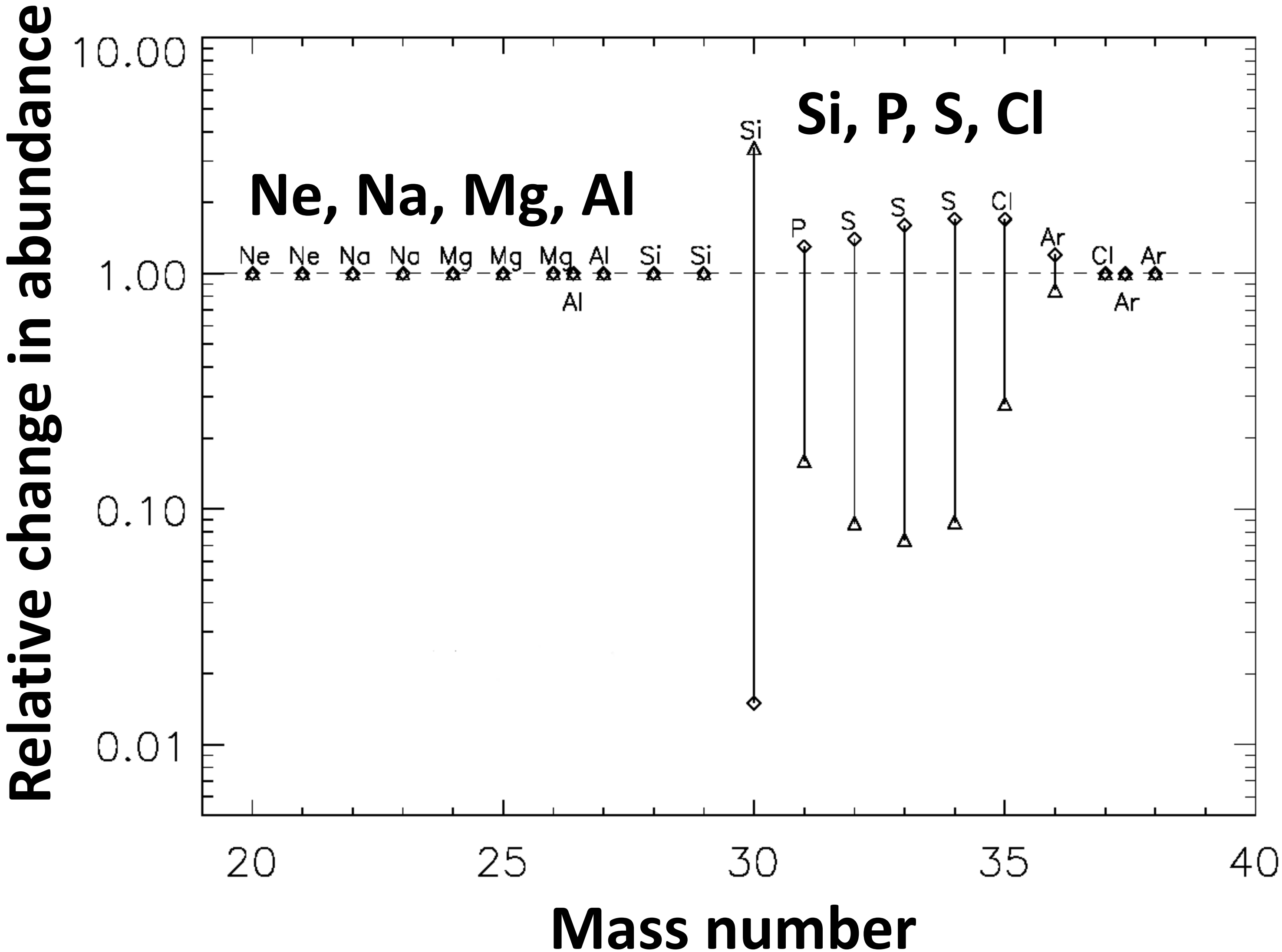
Gamma astronomy



Optical



Nova dust

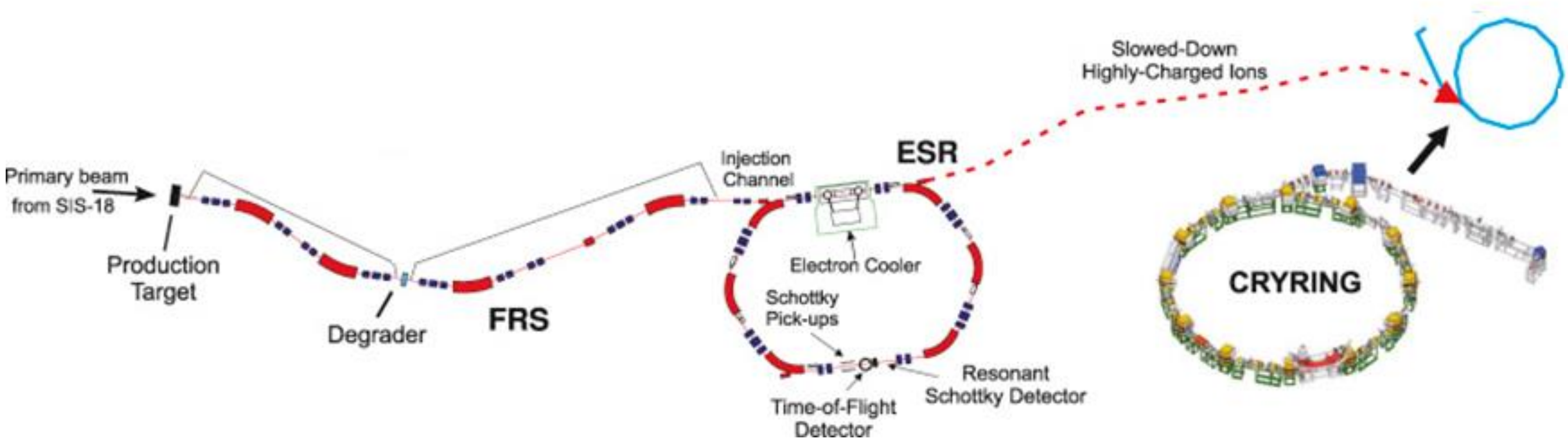


$^{30}P(p,\gamma)^{31}S$ is a bottleneck which controls abundance of elements from Si → Ca isotopes emitted in novae ejecta.

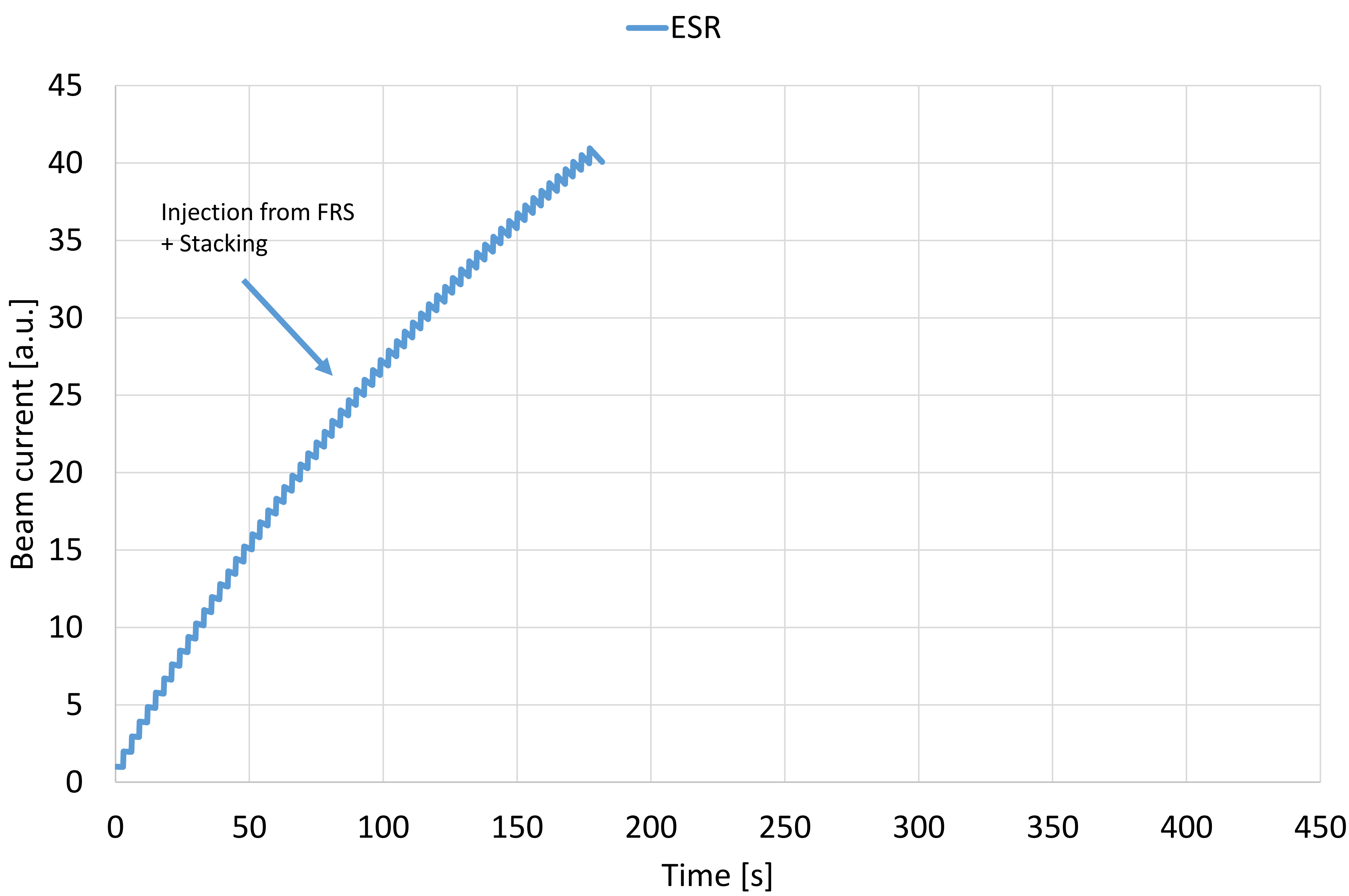
Experimental procedure

^{30}P beams are **very** difficult to obtain using conventional techniques, but can be obtained with good intensities at CRYRING

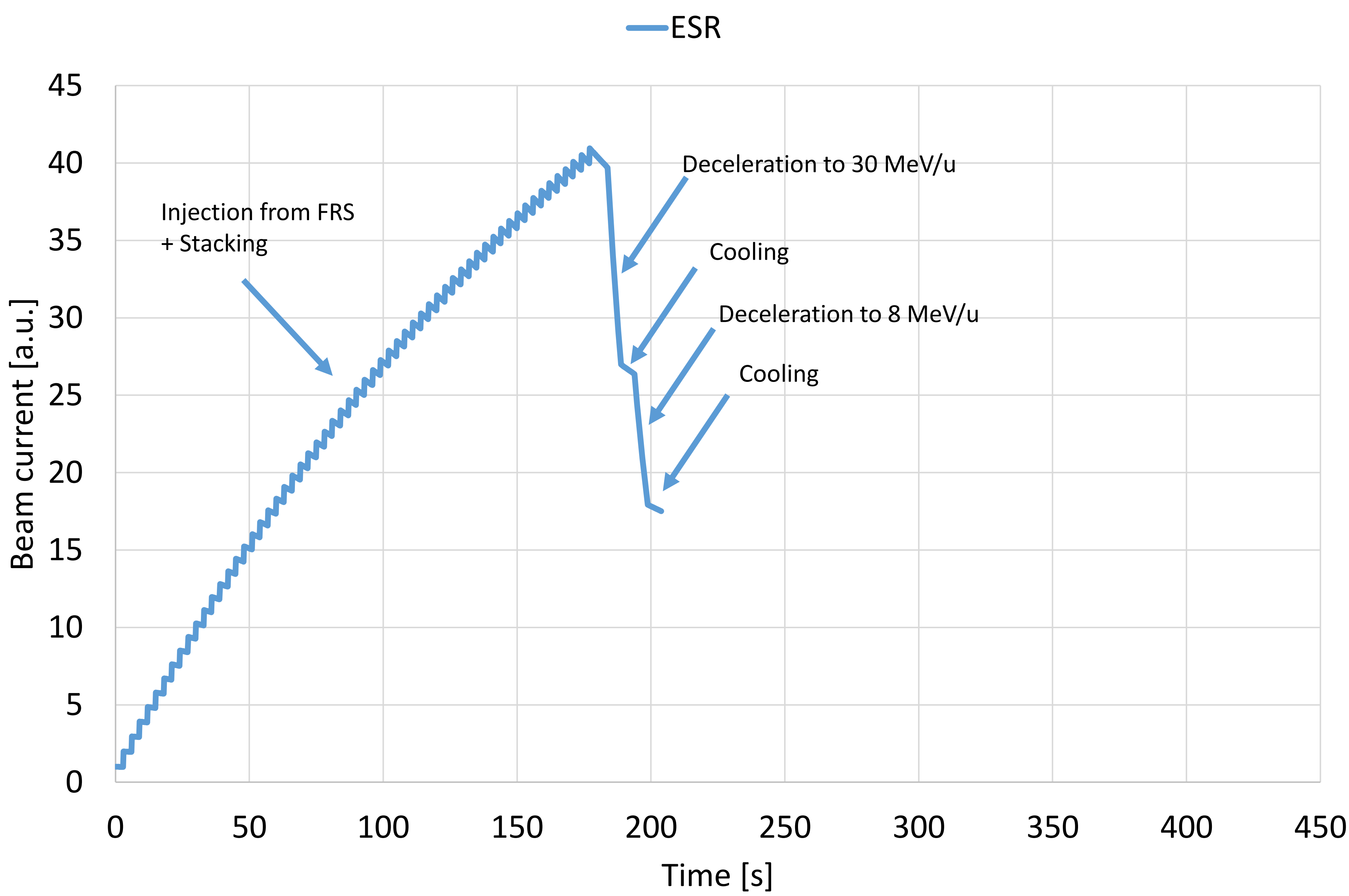
- Primary beam: ^{40}Ar (480 MeV/u) -> to FRS
- Secondary beam from FRS: ^{30}P -> to ESR
- Cool down & stack beam in ESR -> to CRYRING
- Measure in CRYRING & stack beam in ESR



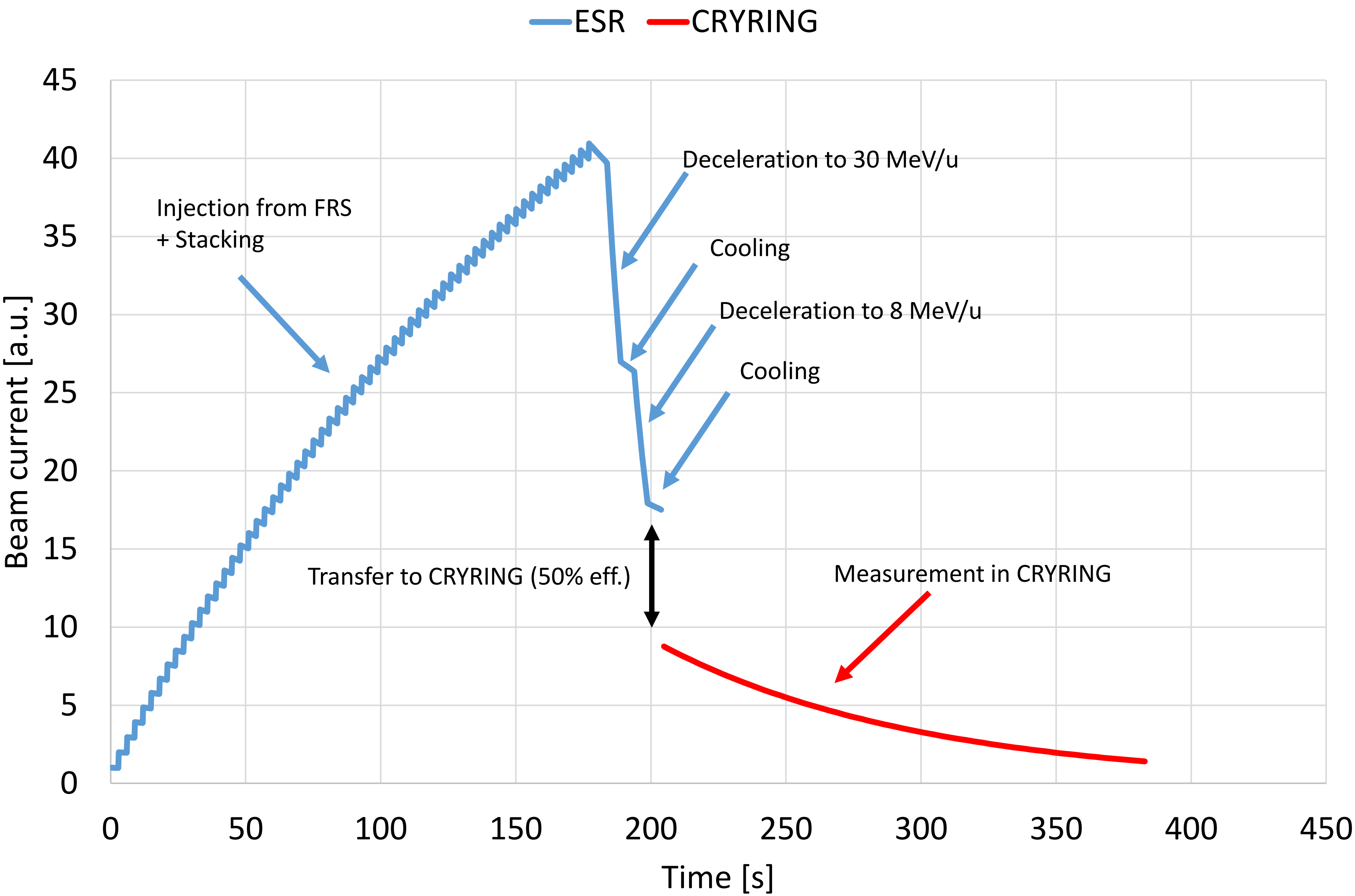
Experimental procedure



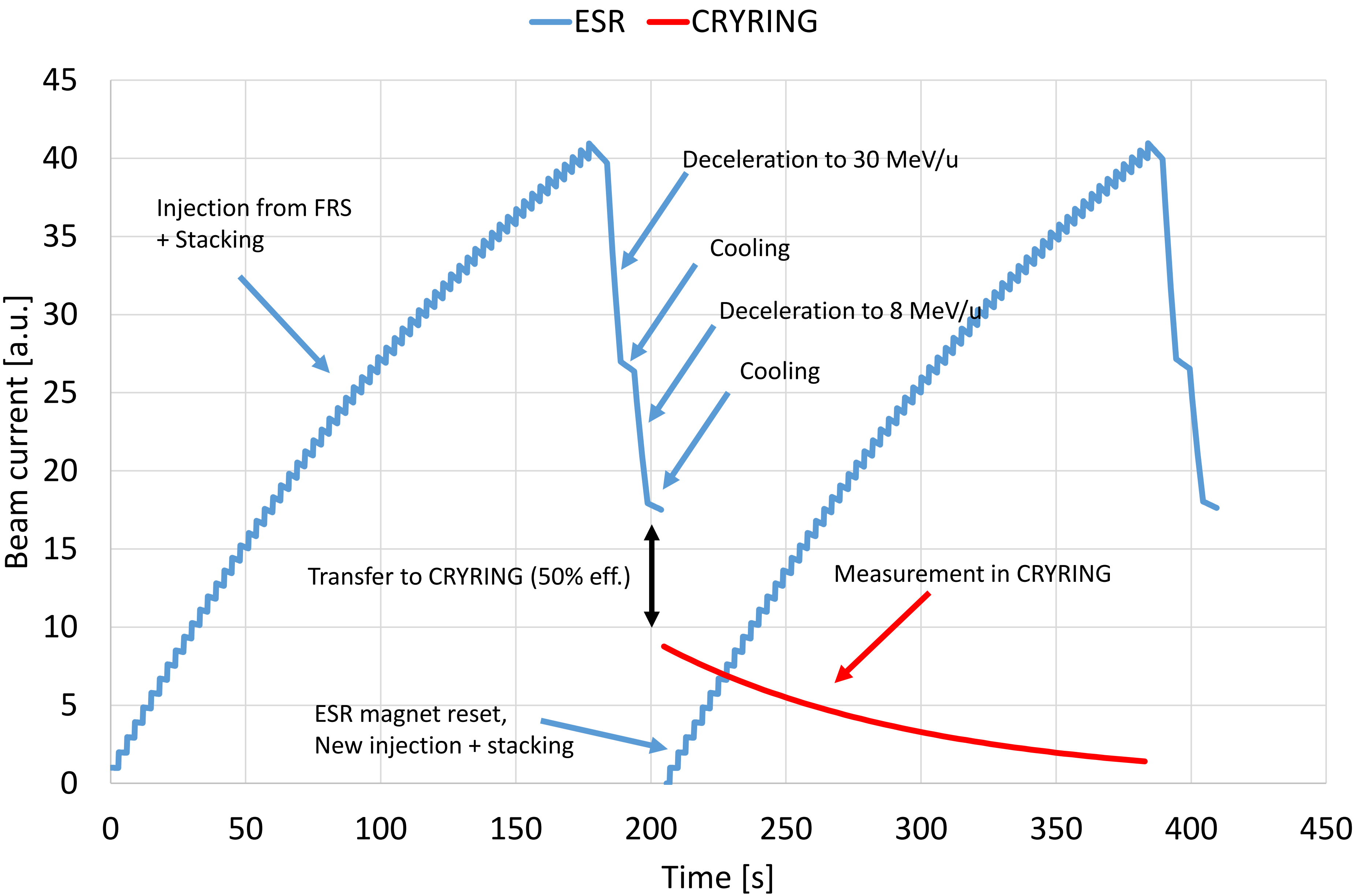
EXPERIMENTAL PROCEDURE



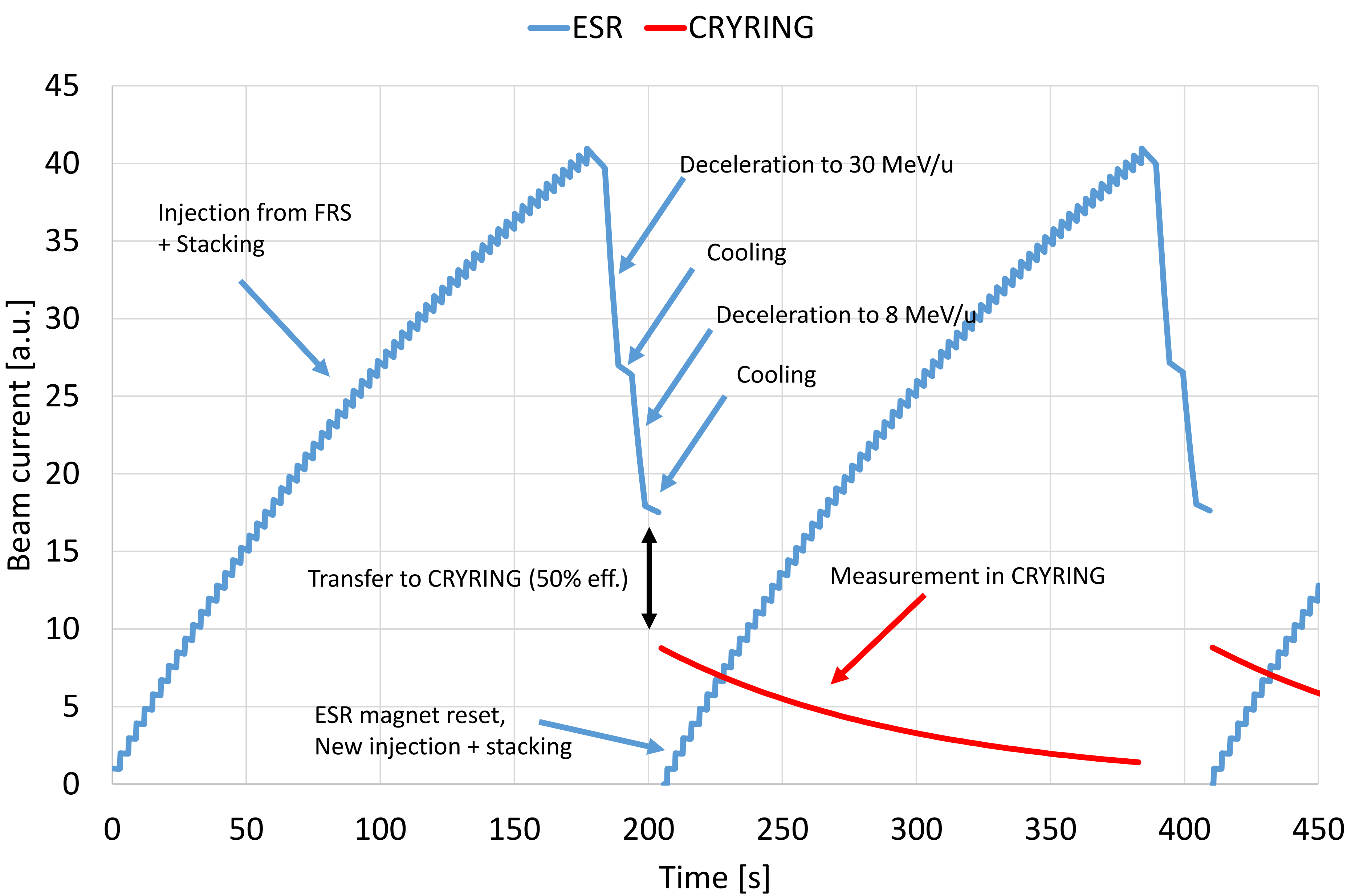
EXPERIMENTAL PROCEDURE



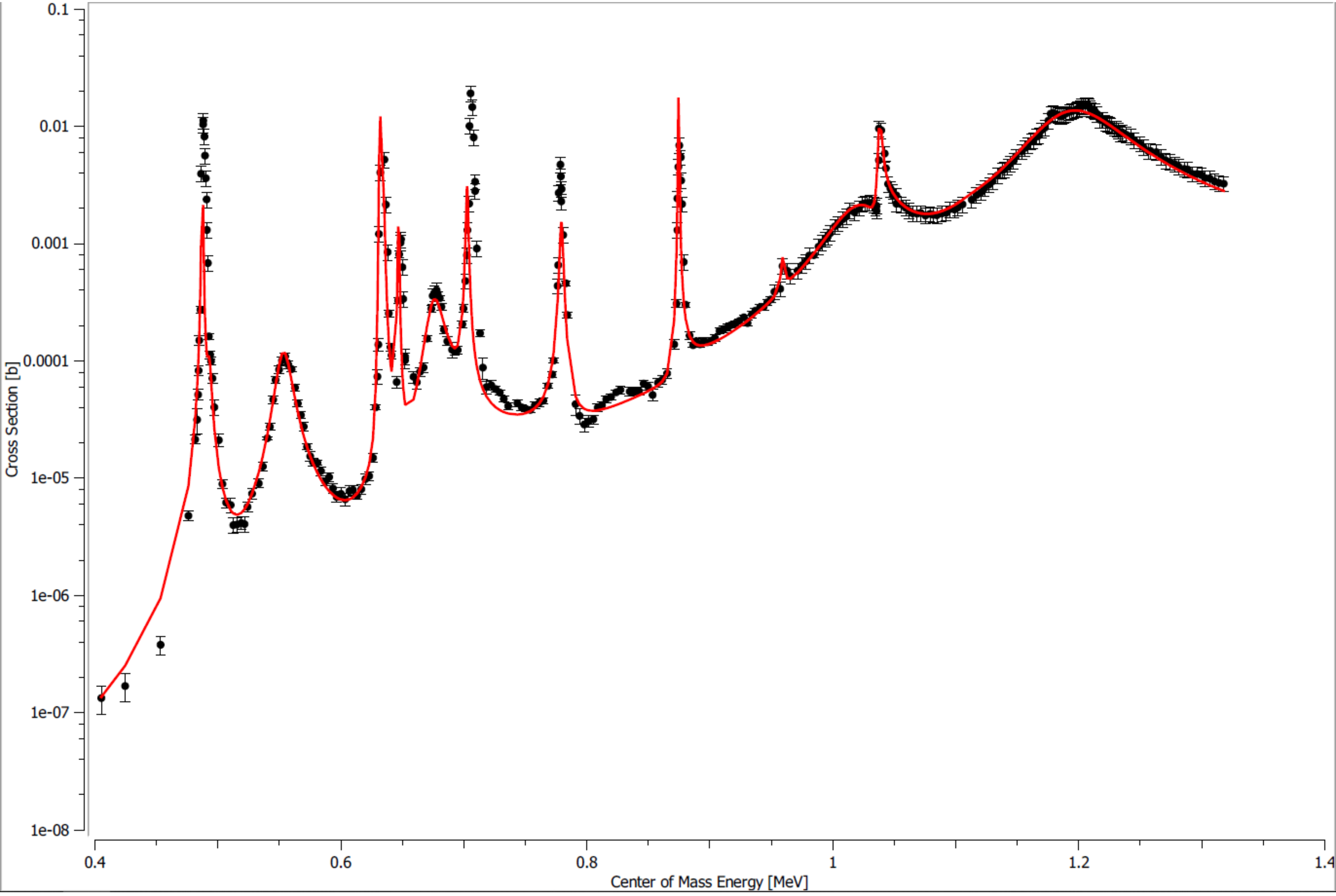
Experimental procedure



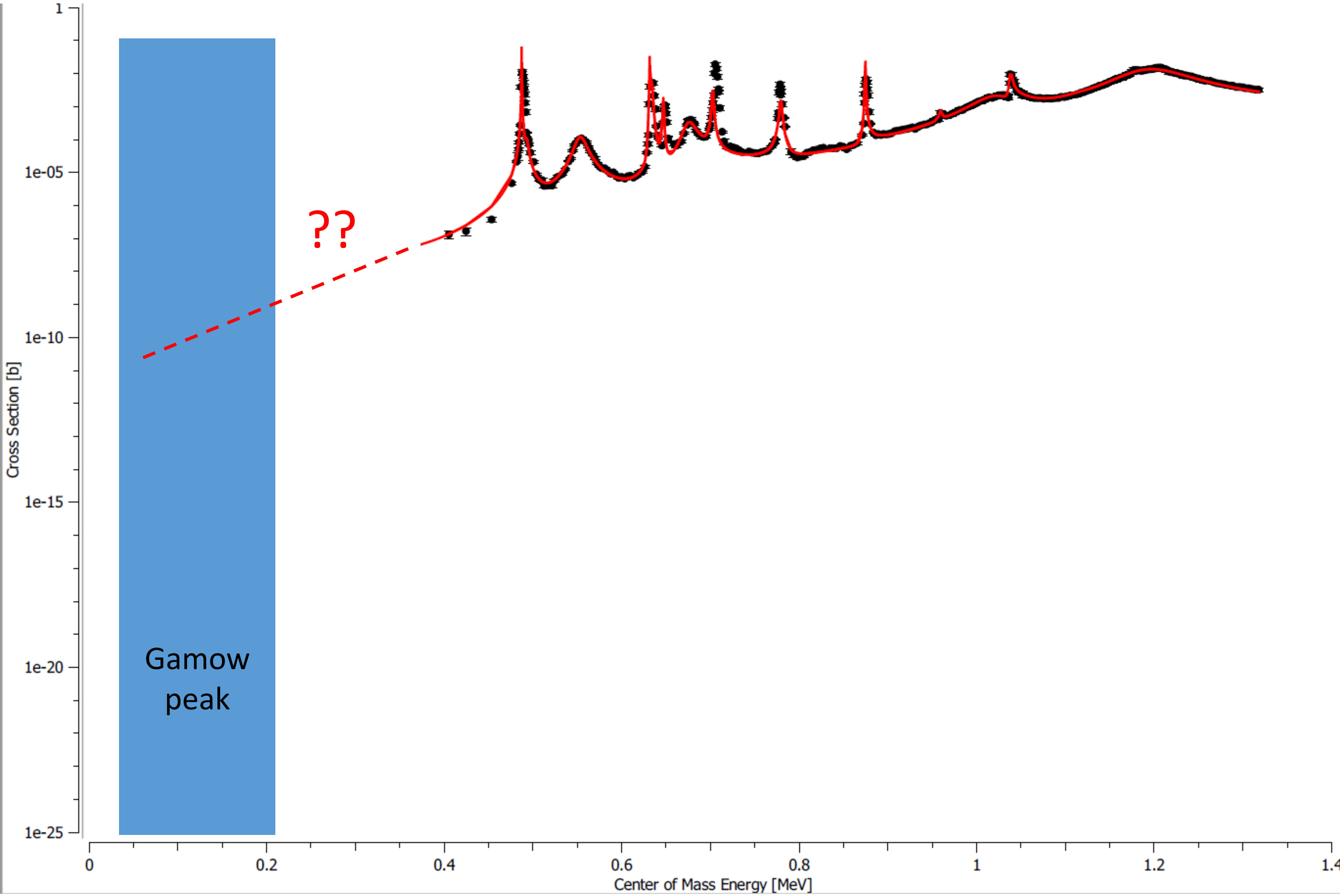
Experimental procedure



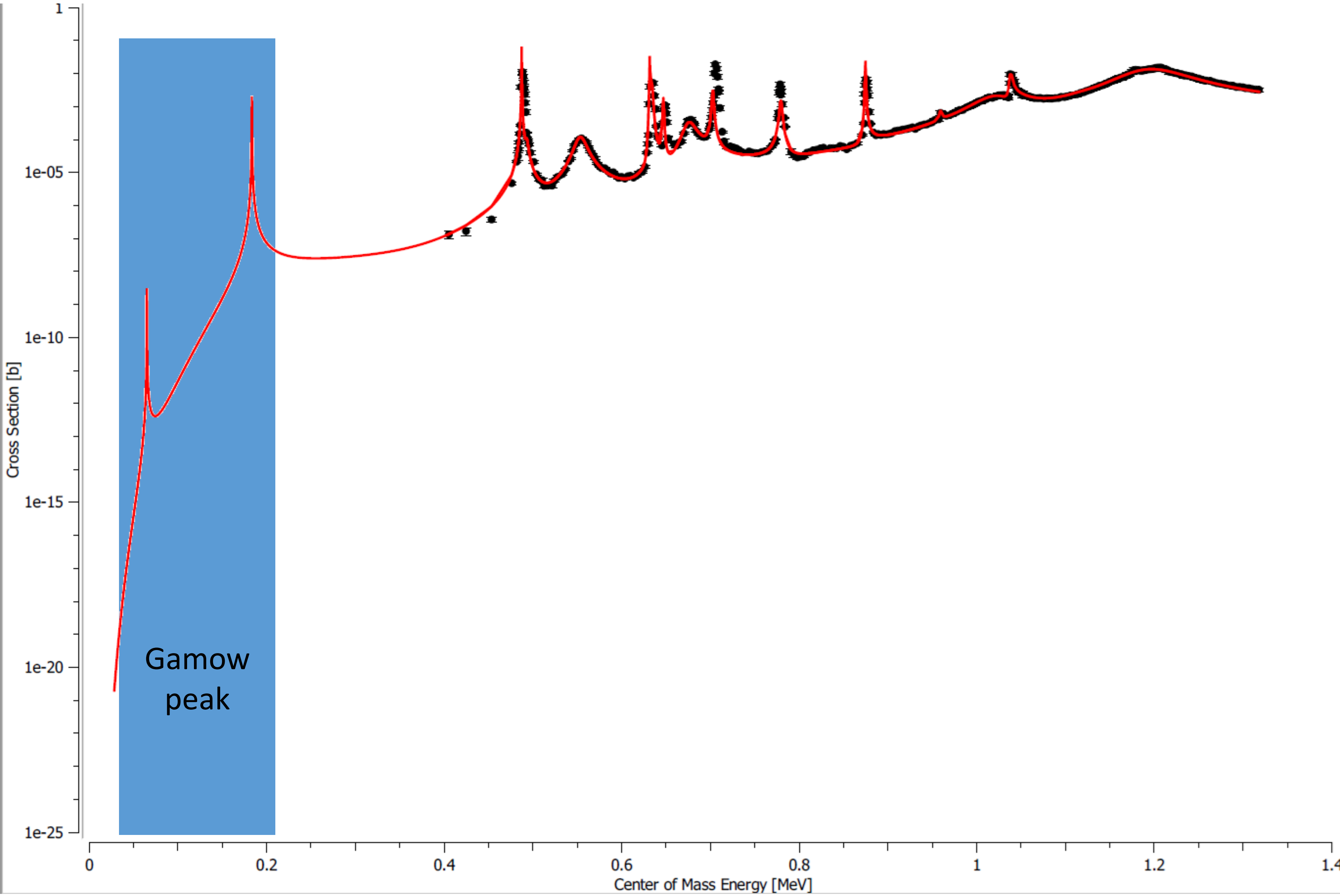
How do we get to the astrophysics?



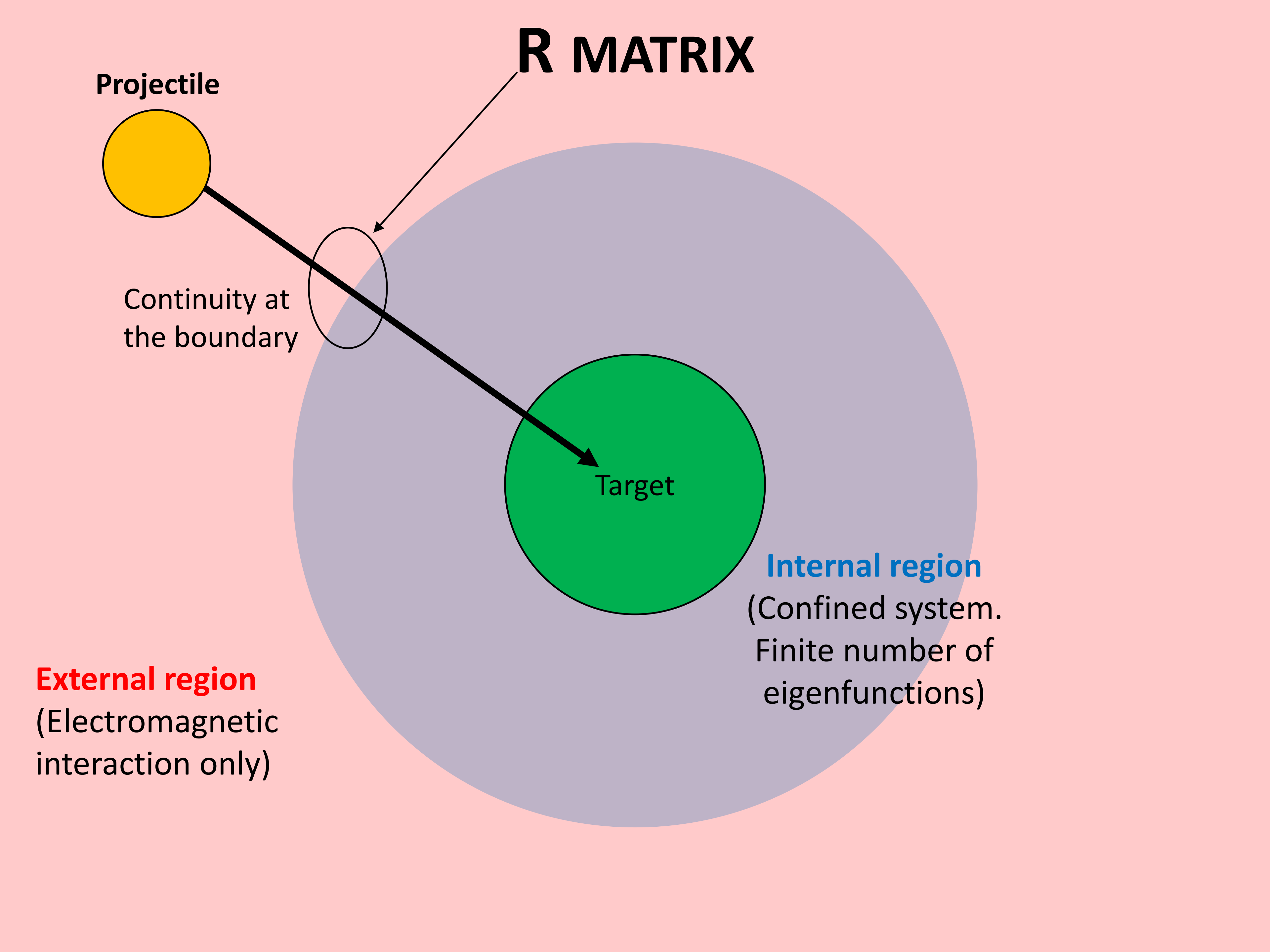
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
1e-08
Cross Section [b]
0.4
0.6
0.8
1
1.2
1.4
Center of Mass Energy [MeV]



Cross Section [b]
1
1e-05
1e-10
1e-15
1e-20
1e-25
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Center of Mass Energy [MeV]
Gamow peak
??



Gamow peak
Cross Section [b]
1
1e-05
1e-10
1e-15
1e-20
1e-25
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Center of Mass Energy [MeV]


R MATRIX
Projectile
Continuity at the boundary
Target
Internal region
(Confined system. Finite number of eigenfunctions)
External region
(Electromagnetic interaction only)

R MATRIX PARAMETERS

Schroedinger's equation for the system can be solved if one knows all the parameters of the R matrix

$$\boldsymbol{R_l \approx \frac{\gamma_i^2}{E_i - E}}$$

- Energies of the resonances ~ E_i
- Widths of the resonances ~ γ_i^2
- Spin-parity of the resonances J^π ~ related to l
- Interference sign ~ sign of some of the matrix elements

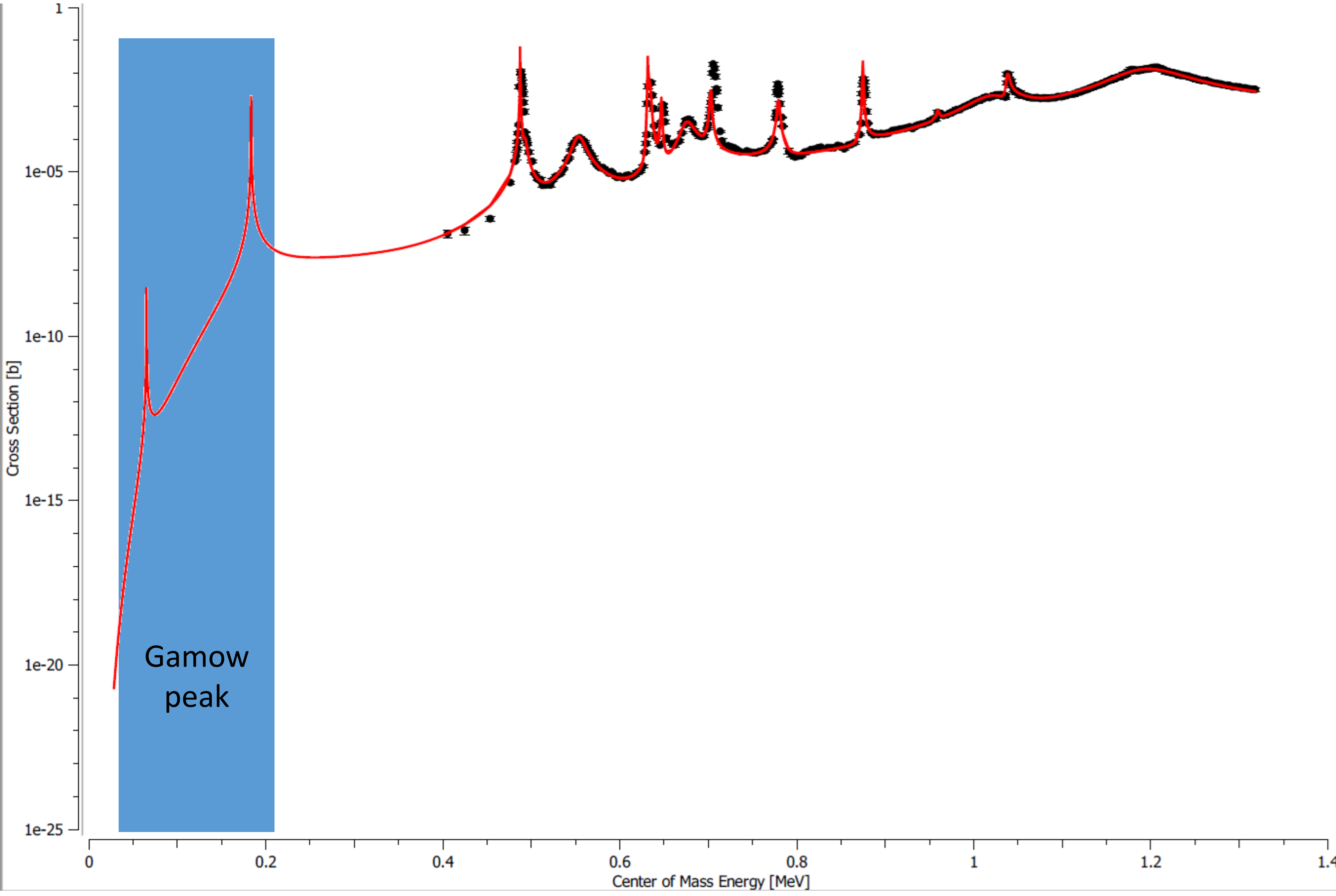
Once Shroedinger's equation is solved, any quantity of interest including the cross-section can be calculated

R MATRIX – HOW TO

1. Measure experimentally the cross-section and/or the energies and widths of the resonances (where they can be accessed)

2. Fit available data with R matrix parameters

3. Use *approximate* solution to Schroedinger's equation to estimate parameters and observables that could not be measured experimentally



Gamow peak
Cross Section [b]
Center of Mass Energy [MeV]
1
1e-05
1e-10
1e-15
1e-20
1e-25
0
0.2
0.4
0.6
0.8
1
1.2
1.4

DIRECT MEASUREMENTS

1. Very hard due to low cross-section / limited beam & target thickness
2. Usually carry lower systematic uncertainties than indirect measurements. No model-dependent issues.
3. Need novel approaches to make them work: underground measurements, new radio-isotopes production techniques, new measurement approaches
4. A combination of direct and indirect measurement is very often mandatory to solve a scientific issue