NPA studies with direct methods using small accelerators A (*very* short and biased) overview

György Gyürky
Institute of Nuclear Research (ATOMKI)
Debrecen, Hungary

ChETEC-INFRA SNAQs
Schools on Nuclear Astrophysics Questions
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Outline

- Why direct methods?
  - Proton- and alpha-induced reactions in nuclear astrophysics
- Why small accelerators?
  - Relevant energy range
  - Beam requirements
- More about experimental needs
  - Targets
  - Detection
  - Background reduction

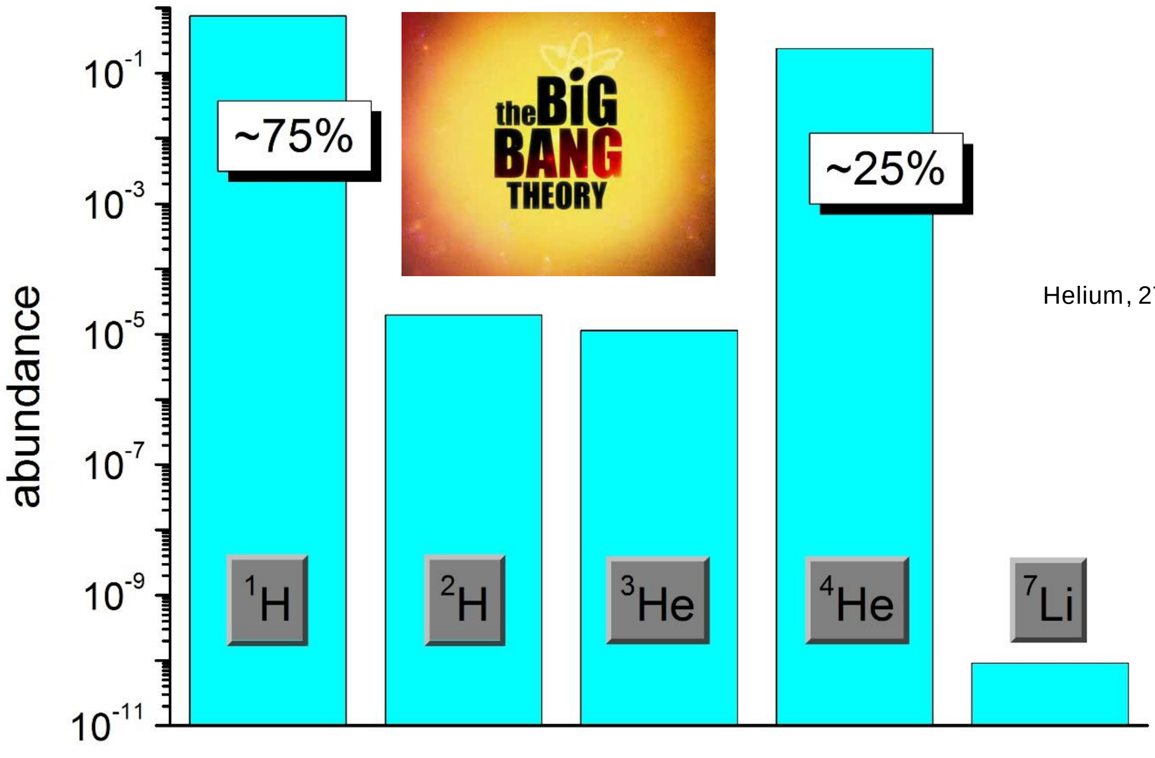
Why direct methods?
Key quantity: astrophysical reaction rate

To be determined by us

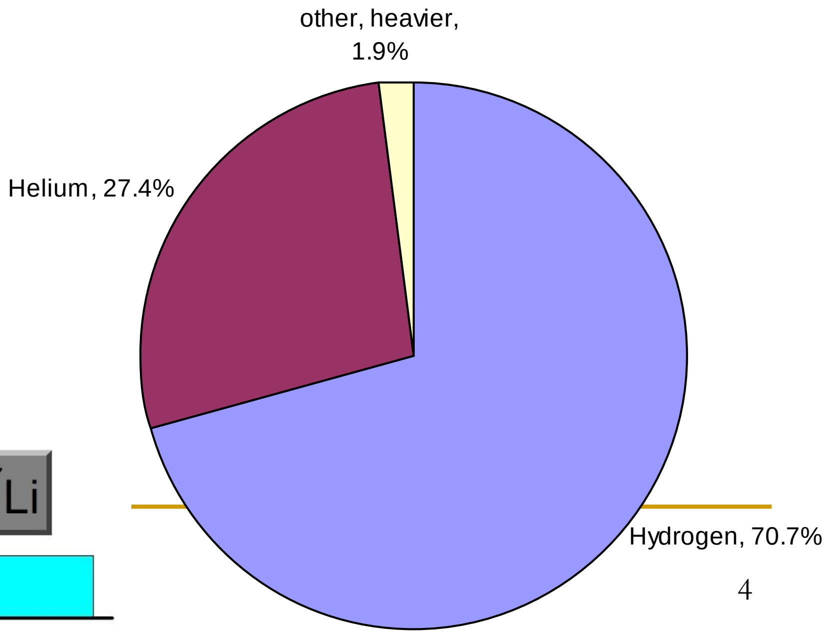
$$N_A\langle\sigma v\rangle = N_A\left(\frac{8}{\pi m}\right)^{1/2}\frac{1}{(kT)^{3/2}}\int_0^\infty E\sigma(E)e^{-E/kT}\,dE$$

Given by astrophysicists

Mainly proton and alpha-induced reactions



Still today...

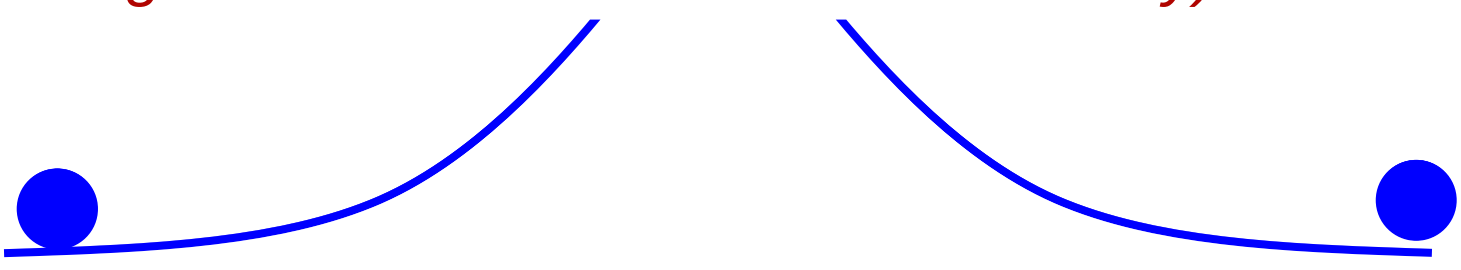


Moreover: the Coulomb barrier

- $^{1}H + ^{2}H$: ~ 0.4 MeV rate (10^{8} K): ~ 10^{1}
- $^{1}H + ^{12}C$: ~ 1.8 MeV rate (10^{8} K): ~ 10^{-5}
- $^{12}C + ^{12}C$: ~ 8 MeV rate (10^{8} K): ~ 10^{-50}

[cm^{3}/(mol·s)]

(Neutron and gamma-induced reactions are not discussed, see e.g. the talk of Adriana Banu later today)



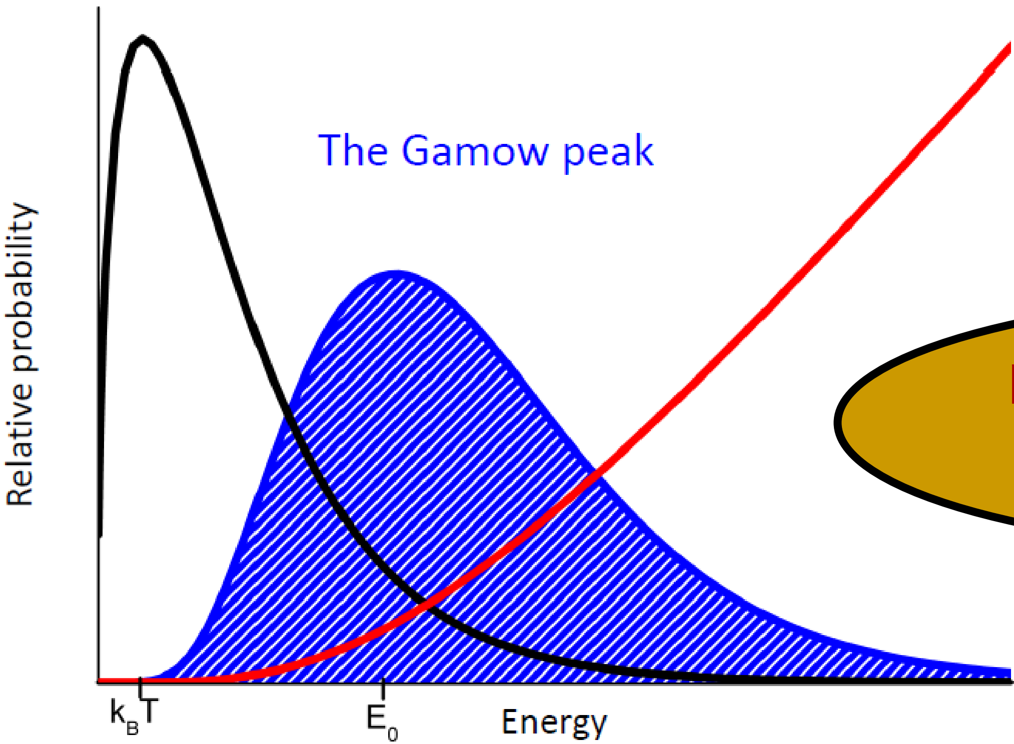
Why small accelerators?

CNO cycle of H-burning in the Sun

- $^{14}N + p$, ≈ 15 MK, 20 - 33 keV
- $^{12}C + {^4He}$, ≈ 200 MK 230 – 400 keV
- $^{144}Sm + {^4He}$, ≈ 3 GK 8 – 12 MeV

He-burning in red giants

p-process of heavy element nucleosynthesis in supernovae



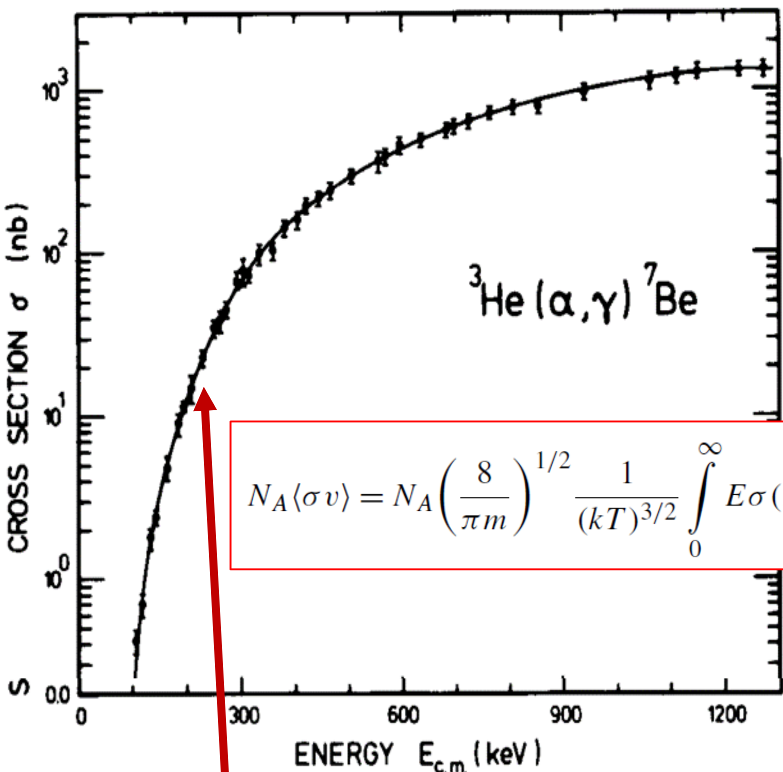
Accelerators: requirements

The original sin of stars: low cross sections (fbarn-μbarn)

- High beam intensity (~ 100 μA)
- Long term availability and stability (weeks – months)
- Automatic operation
- Precise energy calibration

Importance of accelerator energy calibration

Nonresonant reaction



$$N_A\langle\sigma v\rangle = N_A\left(\frac{8}{\pi m}\right)^{1/2}\frac{1}{(kT)^{3/2}}\int_0^\infty E\sigma(E)e^{-E/kT}\,dE$$

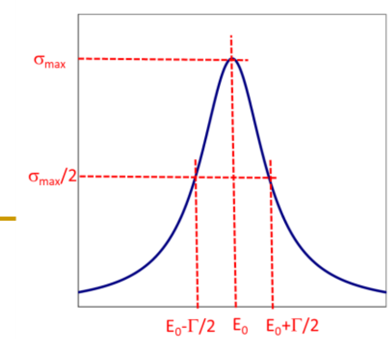
We have to know where we are

Resonant reaction

Resonance energy

$$<\sigma v> \sim \omega\gamma \cdot \exp\left(a\cdot\frac{E}{kT}\right)$$

Resonance strength



Cross section from an experiment

Number of projectiles
"beam current"

Cross section

$$N_r = N_p \cdot N_t \cdot \sigma$$

$[\frac{1}{s}]$ $[\frac{1}{s}]$ $[\frac{1}{cm^2}]$ $[cm^2]$

Number of
reactions

Target surface density
i.e. "target thickness"

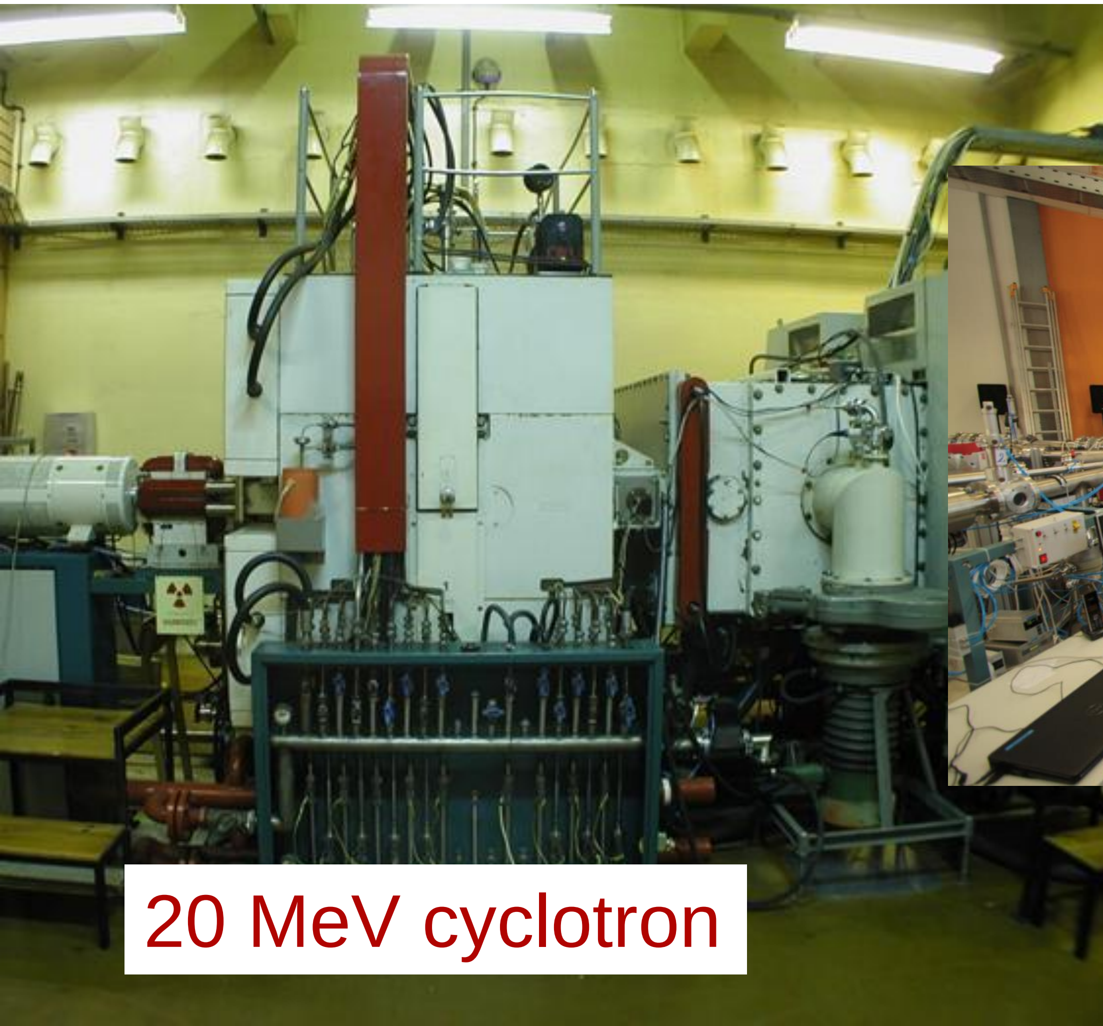
The LUNA collaboration

LUNA
Laboratory for Underground Nuclear Astrophysics

- Italian-German-British-Polish-Hungarian collaboration
- Operates the only underground accelerator of the world at LNGS, Gran Sasso, Italy
- Measurement of extremely low cross sections of astrophysical reactions

http://luna.lngs.infn.it/

Accelerator center of Atomki, Debrecen, Hungary



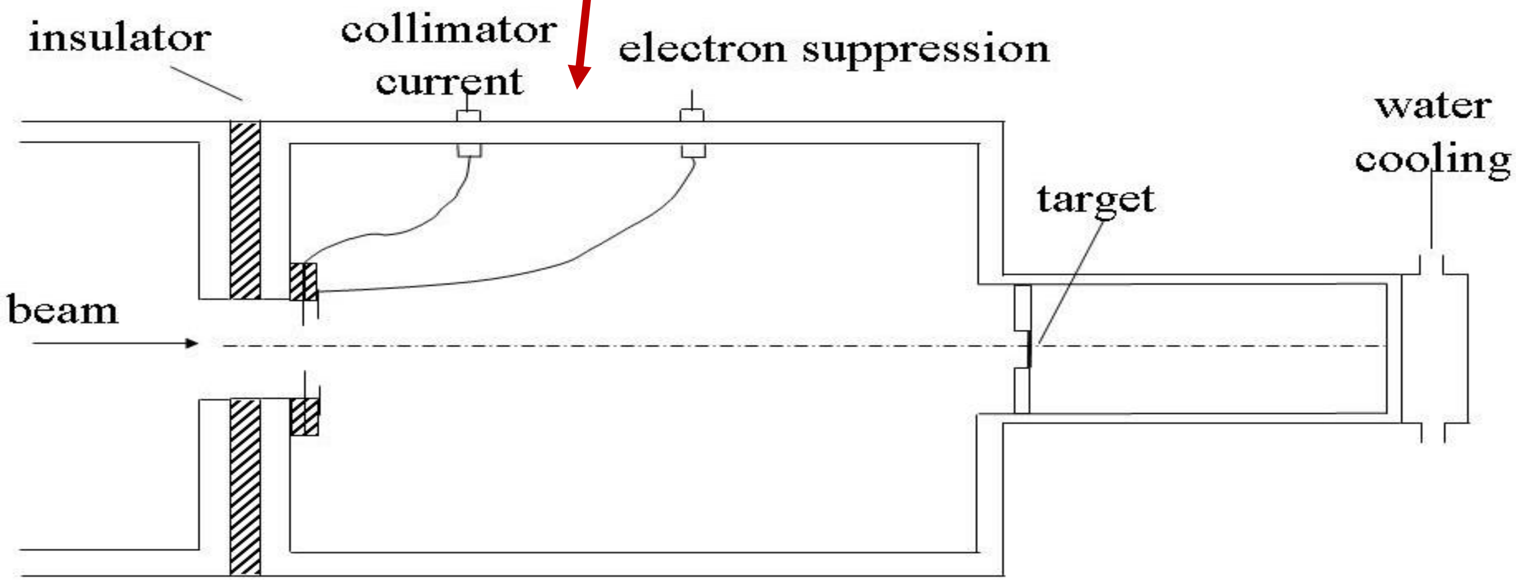
20 MeV cyclotron

2 MV Tandetron

Number of projectiles

$$N_r = N_p \cdot N_t \cdot \sigma$$

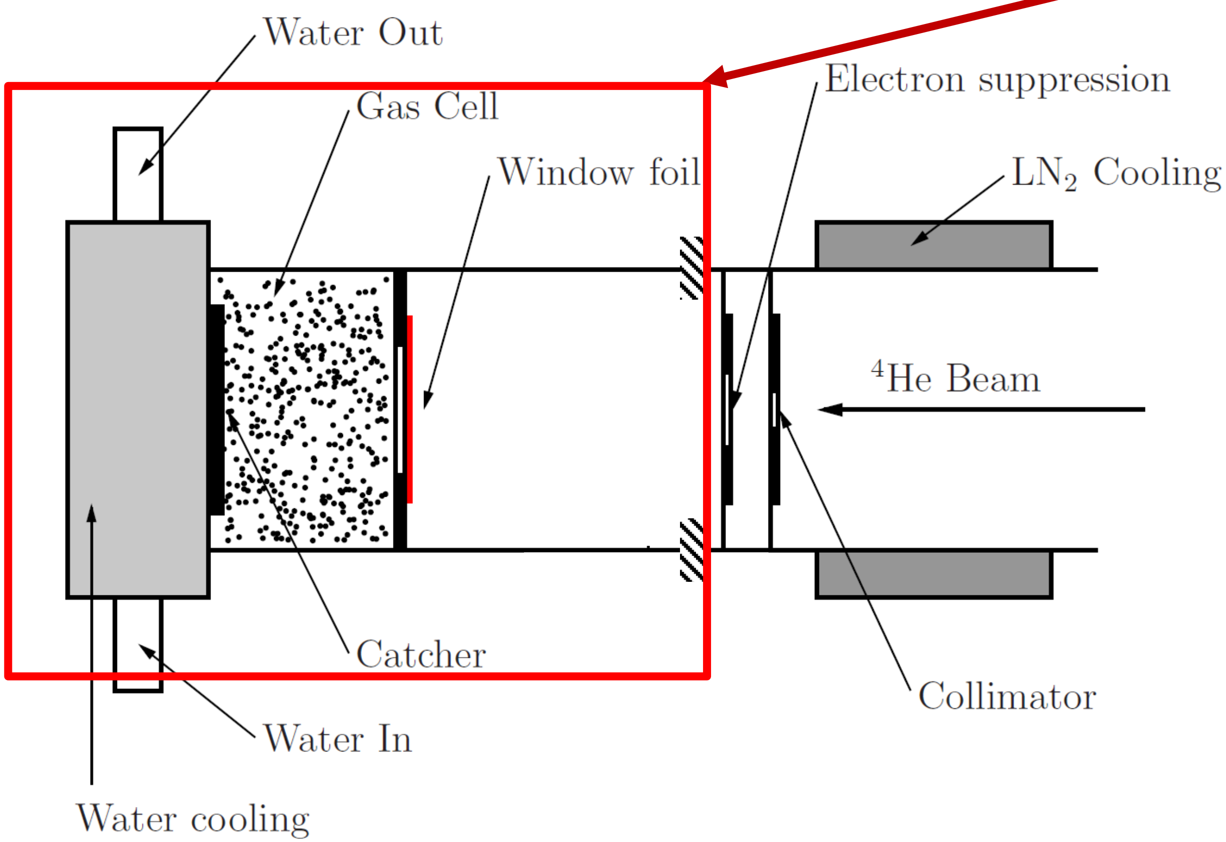
- Charged particle induced reaction: charge measurement
- Required: $\boxed{\text{good Faraday cup:}}$ complete charge collection, suppression of secondary electrons



Number of projectiles: gas target

$$N_r = N_p \cdot N_t \cdot \sigma$$

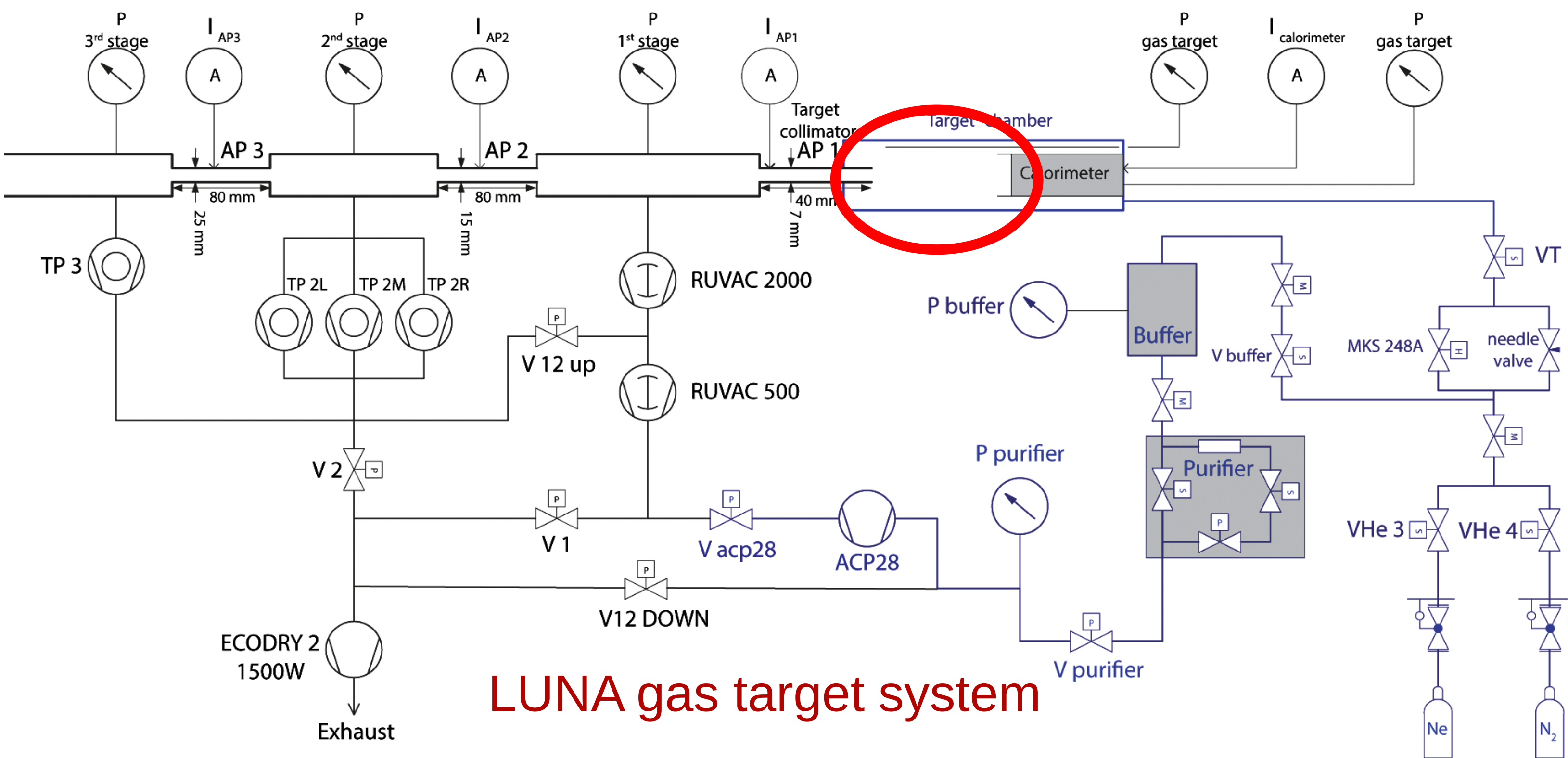
- thin window gas cell: charge measurement possible (the cell is part of the Faraday cup)



Windowless gas target

$$N_r = N_p \cdot N_t \cdot \sigma$$

- Low energy: entrance window must be avoided
- Charge exchange in gas: charge measurement does not work



LUNA gas target system

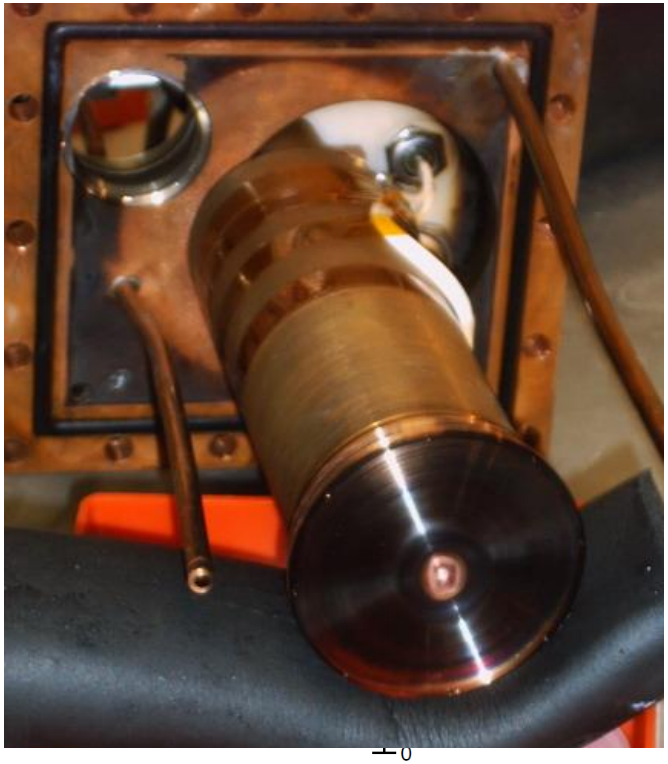
Windowless gas target

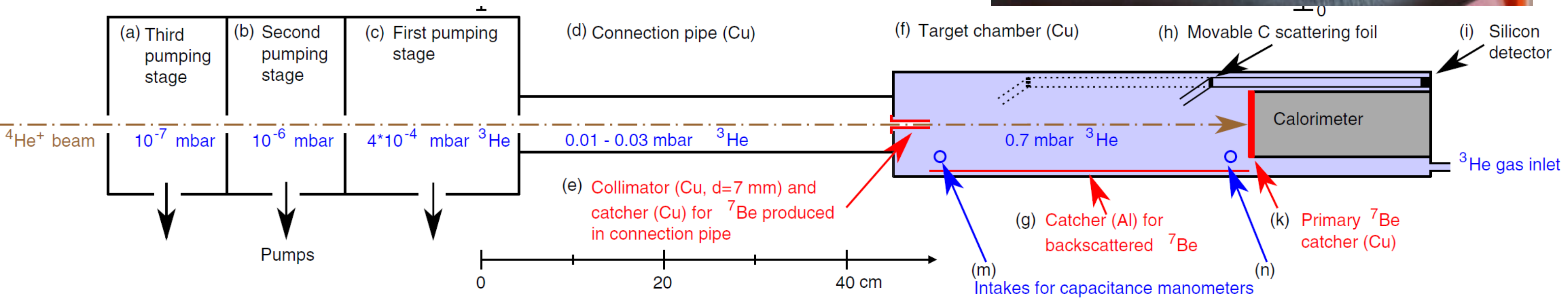
$$N_r = N_p \cdot N_t \cdot \sigma$$

- calorimetric technique: determination of current from beam power

$$i_{beam}[\mu A] = \frac{p_{beam}[watt]}{E_{beam}[MeV]}$$

- good for high beam intensities
- usually must be calibrated using charge measurement in empty target





Target thickness: requirements

- energy loss < typical cross section variation

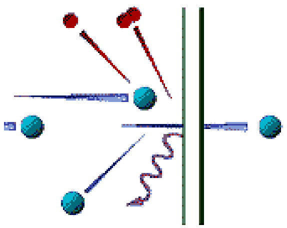
$\Rightarrow$ 10^{16}-10^{18} atom/cm^2 ~ $\Rightarrow$ ~ μg/cm^2

- homogeneity
- purity (background!)
- stability under bombardment

$$N_r = N_p \cdot N_t \cdot \sigma$$

Target thickness determination $N_r = N_p \cdot N_t \cdot \sigma$

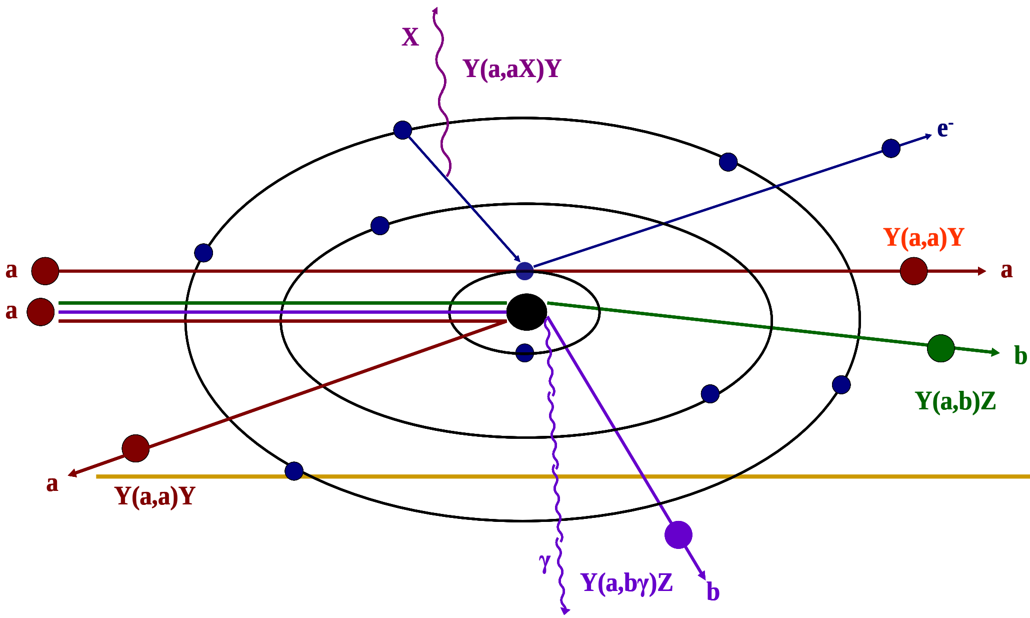
- Off line (before or after the c.s. meas.):
  - weighing
  - energy loss
  - active (accelerator based) techniques
    - PIXE, RBS, NRRA, ...

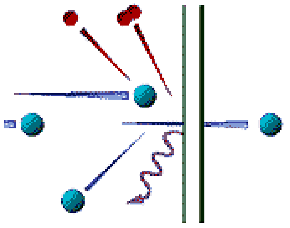


- On line (during cross section measurement):
  - scattering
  - atomic and nuclear reactions
  - etc...

Proton-induced X-ray emission (PIXE)

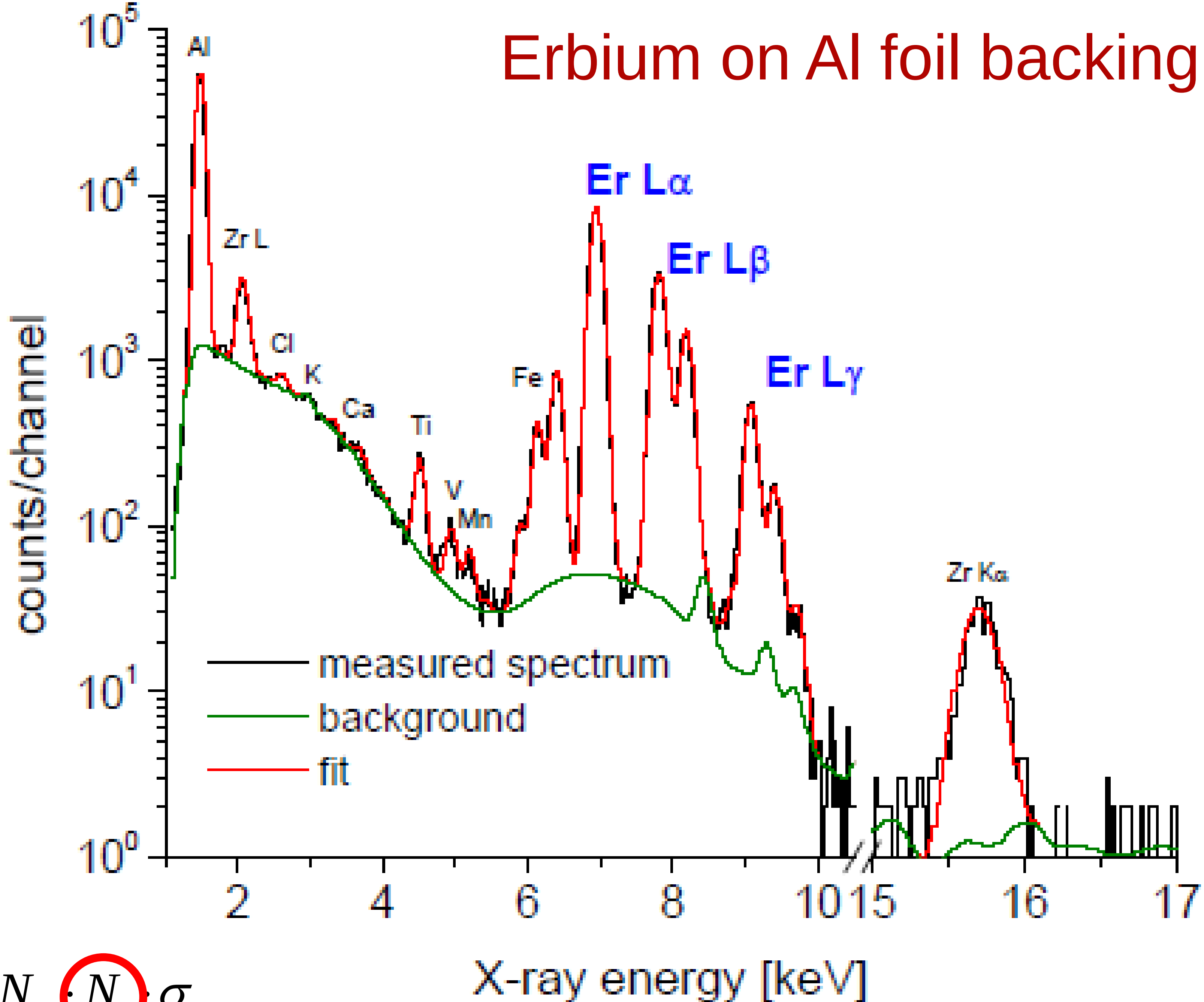
- Absolute number of target atoms
- Target composition (stoichiometry) can be revealed
- Only for heavy elements (above Carbon)





$$N_r = N_p \cdot N_t \cdot \sigma$$

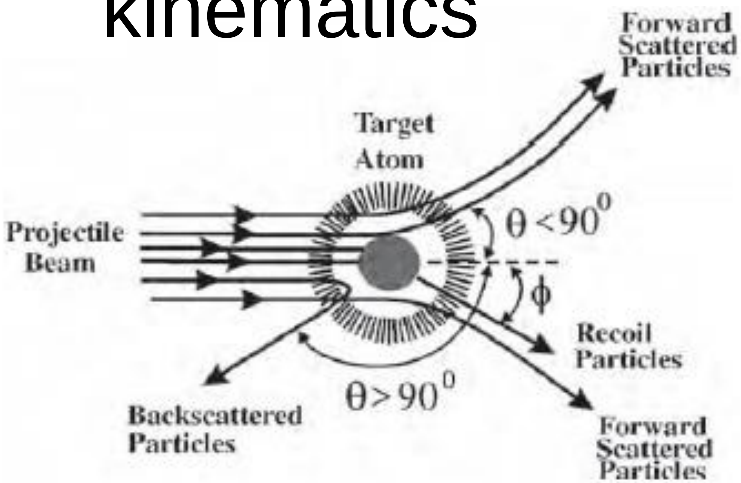
Erbium on Al foil backing



$$N_r = N_p \cdot N_t \cdot \sigma$$

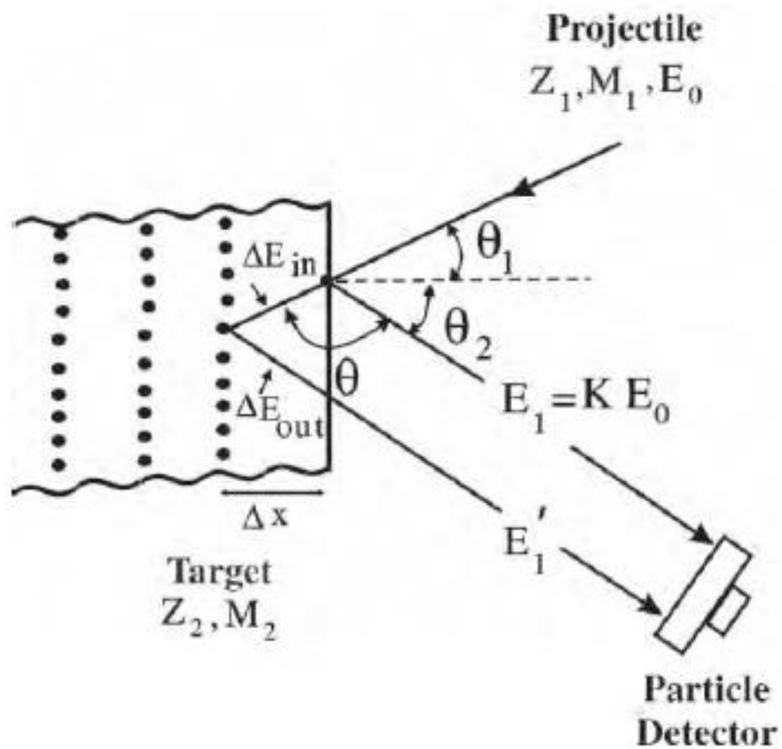
Rutherford backscattering (RBS)

- Scattering kinematics



$$K(\theta, M_1, M_2) = \frac{E_1}{E_0} = \left(\frac{(M_2^2 - M_1^2 \sin^2\theta)^{1/2} + M_1 \cos\theta}{M_1 + M_2} \right)^2$$

- Energy loss



$$N_r = N_p \cdot N_t \cdot \sigma$$

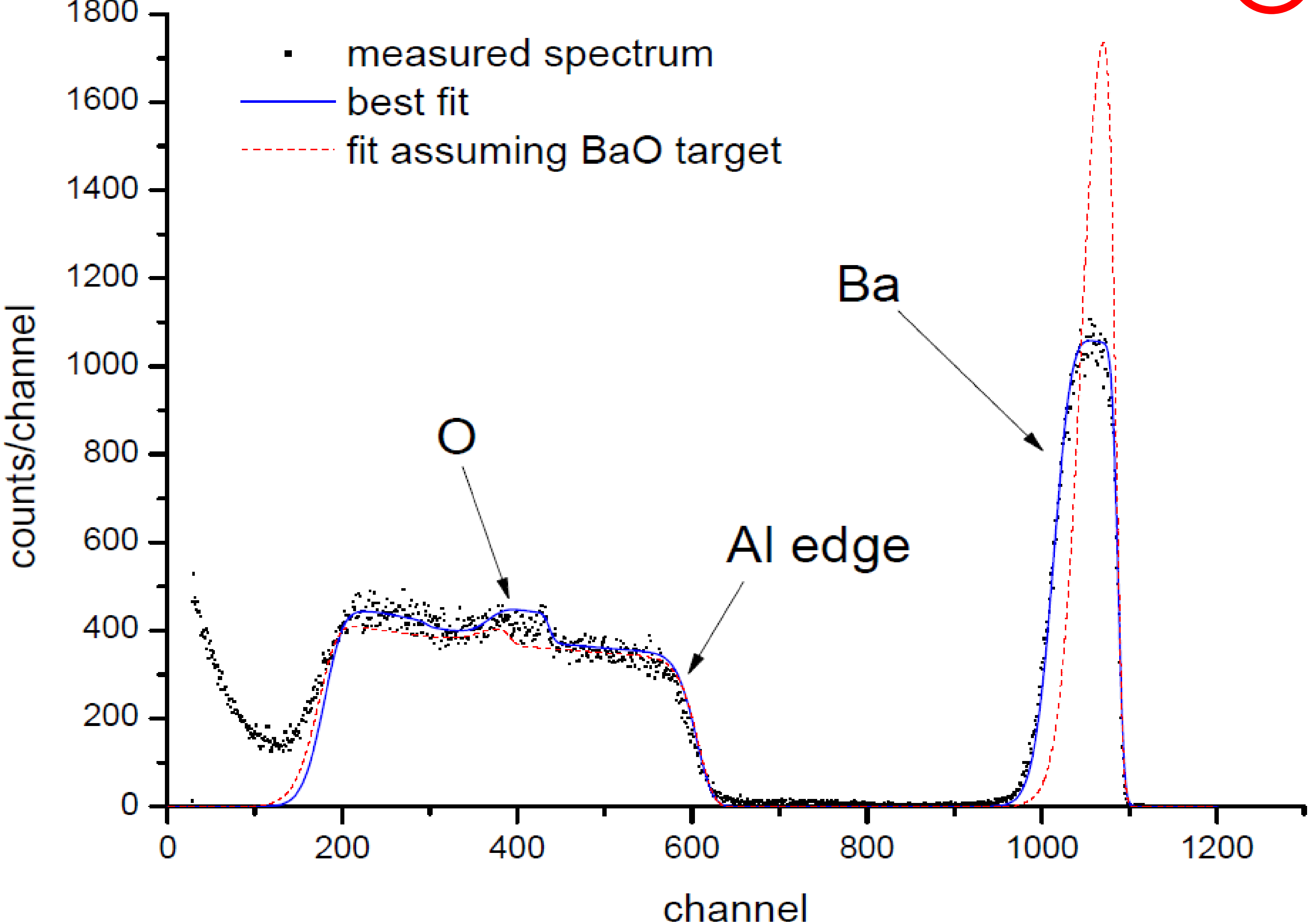
Rutherford backscattering (RBS)

- Absolute number of target atoms
- Target composition (stoichiometry) can be revealed
- Not ideal for light target on heavy backing

$$N_r = N_p \cdot N_t \cdot \sigma$$

$BaCO_3$ target on thin Al foil

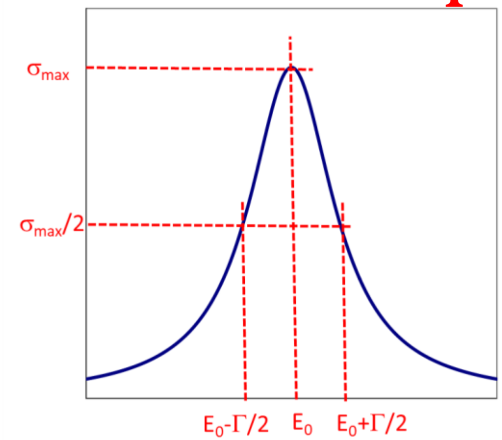
$$N_r = N_p \cdot N_t \cdot \sigma$$

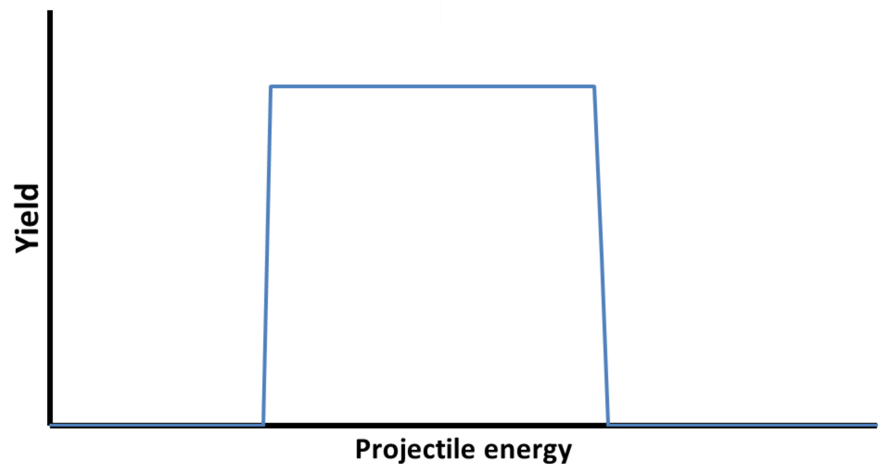


NRRA (Nuclear Resonant Reaction Analysis)

$$\sigma \sim \frac{\Gamma_1 \Gamma_2}{(E - E_0)^2 - \Gamma^2/4}$$

- Narrow, isolated resonance needed
- Ideal case:
  - Zero natural width
  - Infinitely good beam energy resolution
  - No energy straggling, homogenous target

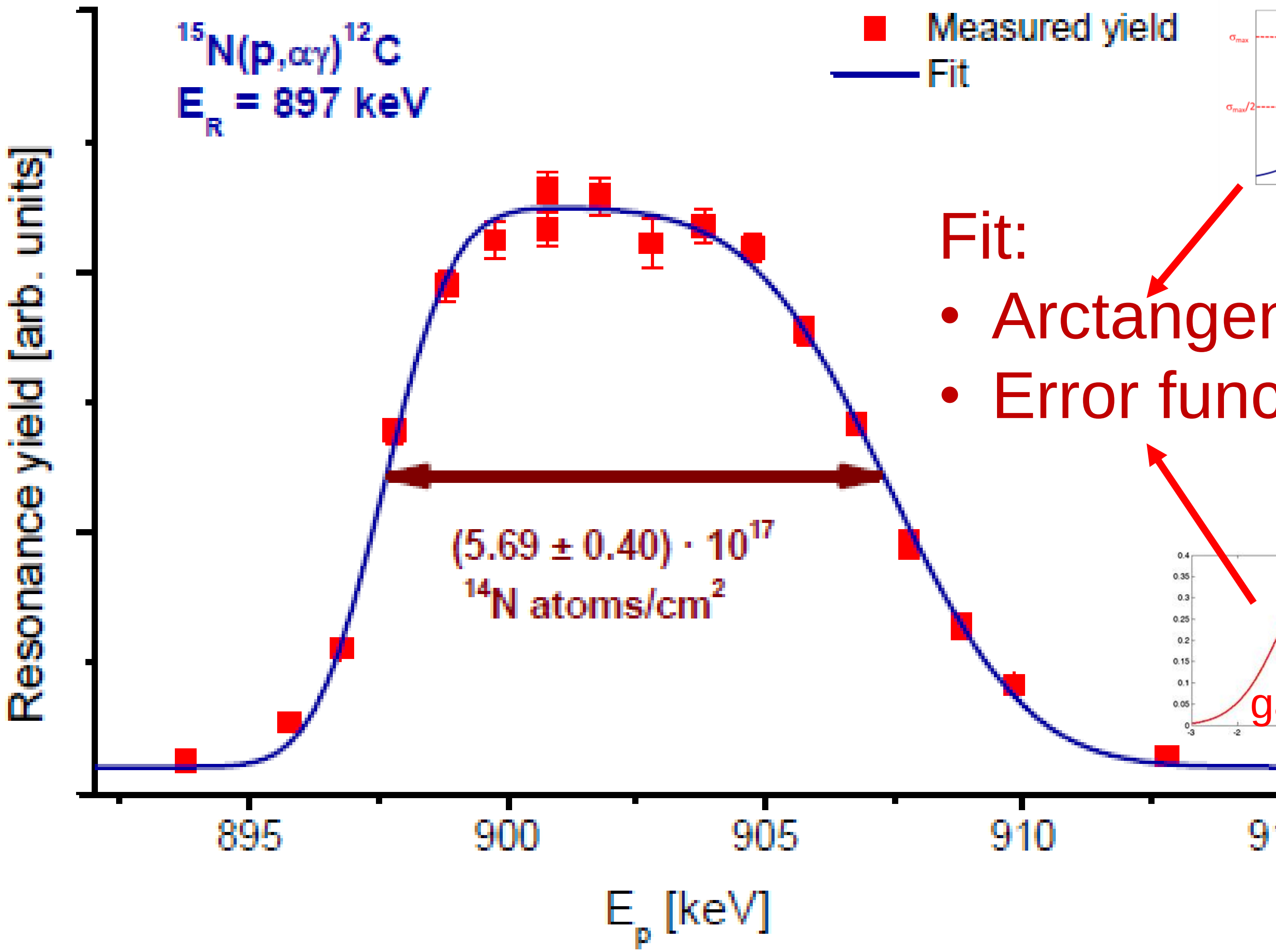


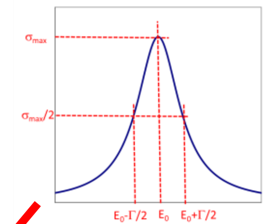


$$N_r = N_p \cdot N_t \cdot \sigma$$

NRRA An example

$$N_r = N_p \cdot N_t \cdot \sigma$$





Fit:

- Arctangent
- Error function

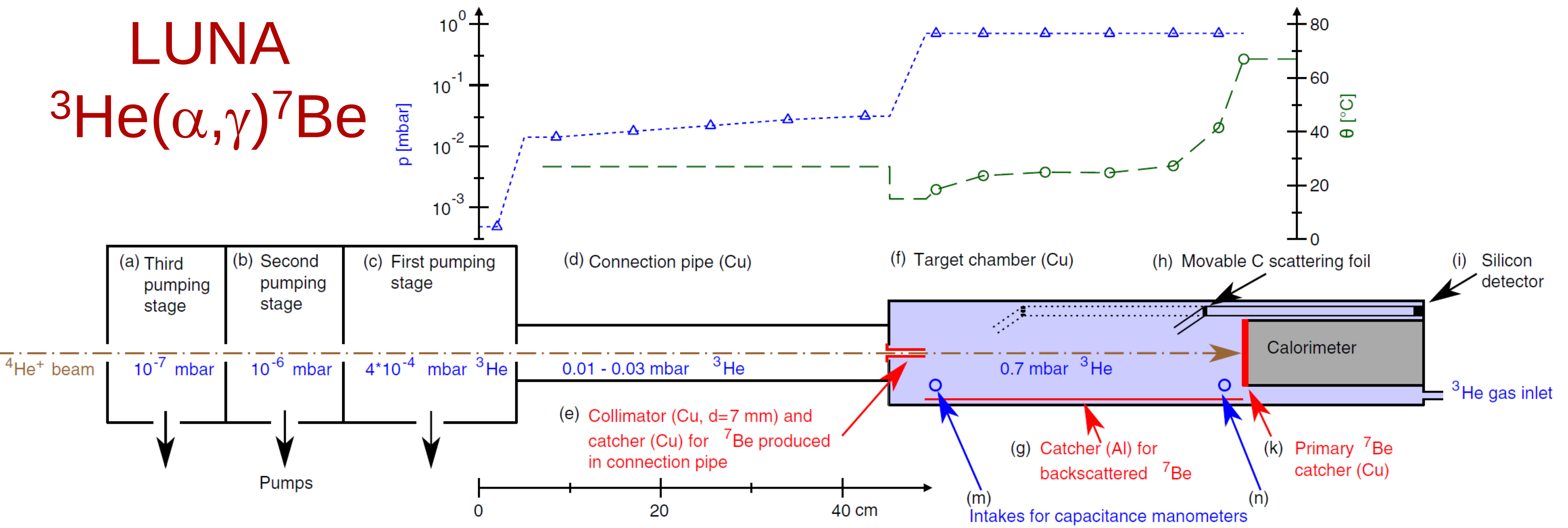
Target thickness: (extended) gas target

$$N_r = N_p \cdot N_t \cdot \sigma$$

- pressure and temperature measurement
- no problem with target stability
- beam heating effect!

LUNA

$^{3}He(\alpha,\gamma)^{7}Be$

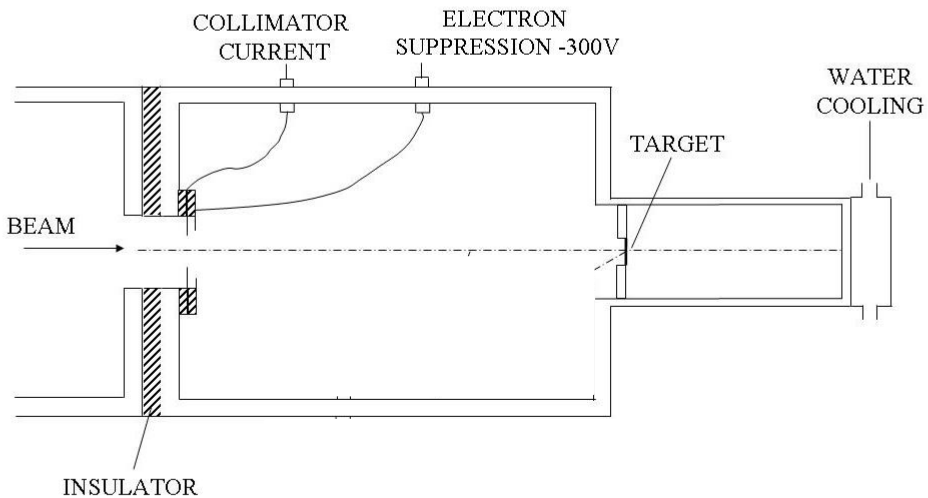


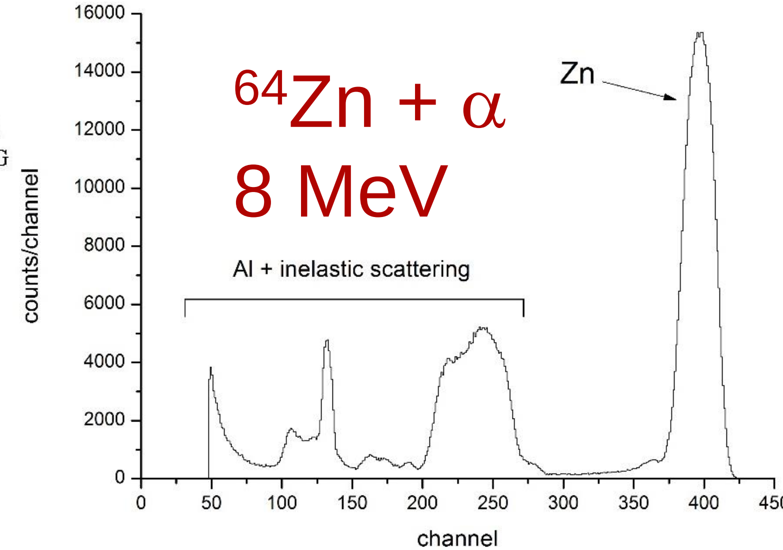
Controlling the target stability

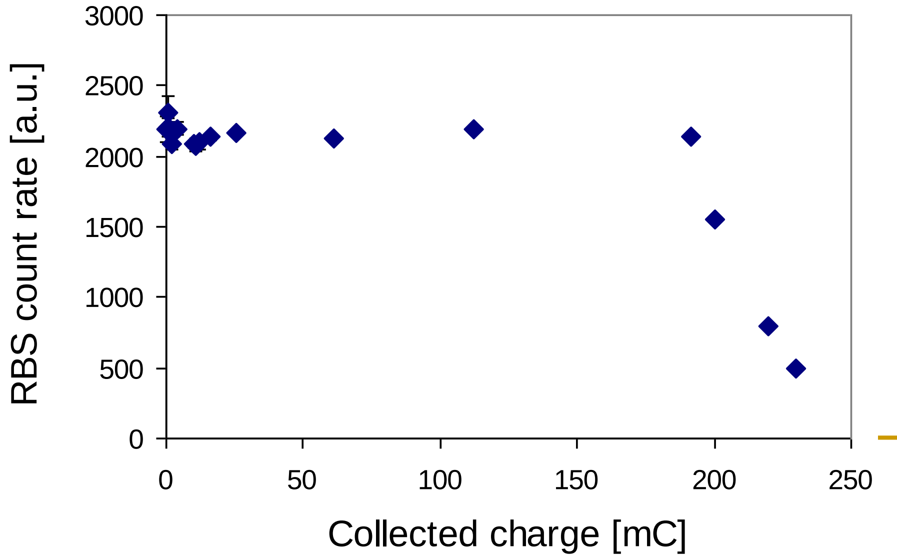
- High intensity beam: target degradation may occur
- Target properties must be continuously controlled
- Can be done with several different methods:
  - RBS
  - nuclear reaction with know cross section
  - Coulomb excitation
  - etc...

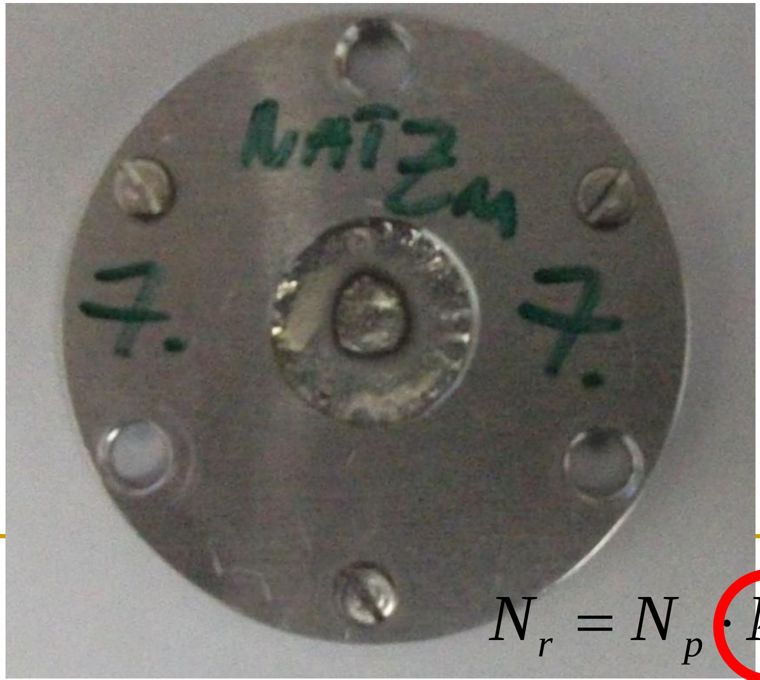
$$N_r = N_p \cdot N_t \cdot \sigma$$

Target thickness and stability through RBS



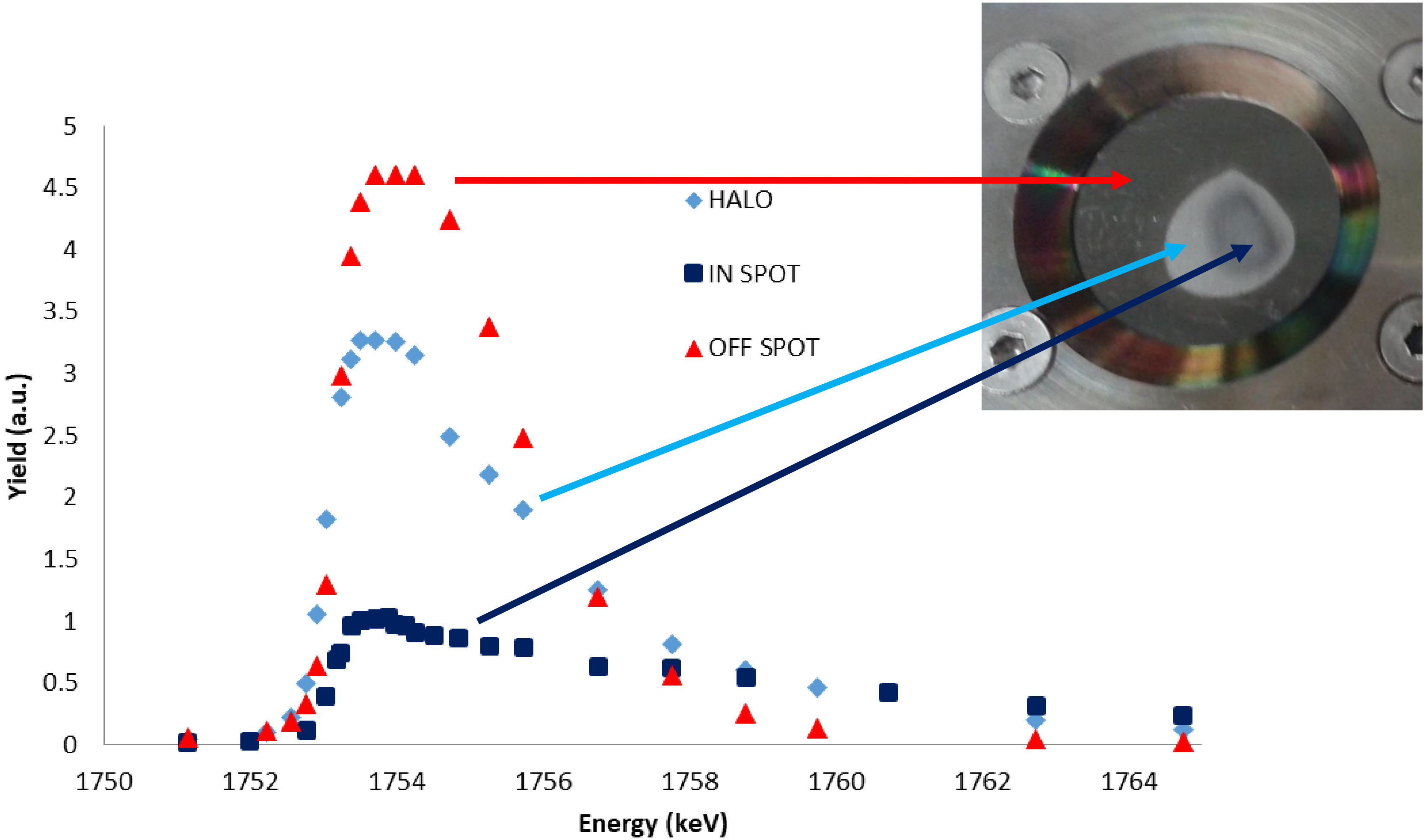






$$N_r = N_p \cdot N_t \cdot \sigma$$

Target thickness and stability with NRRA



$$N_r = N_p \cdot N_t \cdot \sigma$$

$^{13}C(p,\gamma)^{14}N$

Determination of the number of reactions

- Aim 1: high detection efficiency
- Aim 2: identification of reaction
- In-beam method
  - particle detection (alphas, protons, neutrons)
  - gamma detection
  - (recoil separator)
  - (storage ring)
- Off-line method: activation

$$N_r = N_p \cdot N_t \cdot \sigma$$

Charged particle detection (in beam)

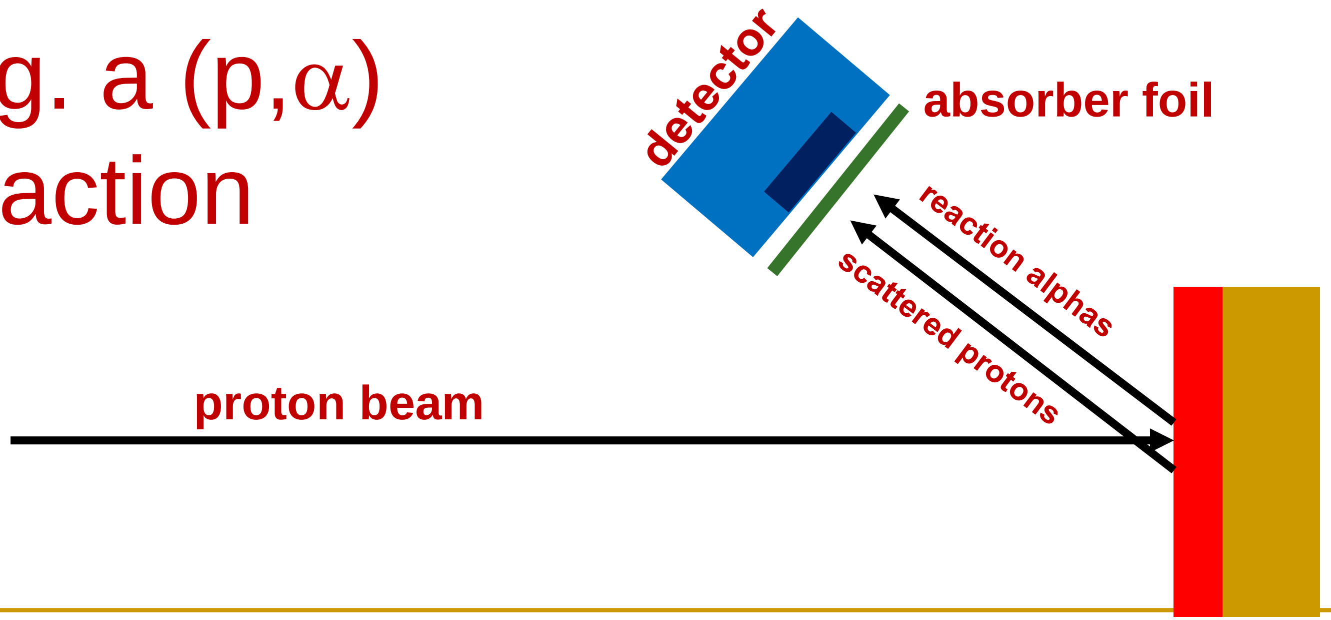
- 100% intrinsic efficiency
- Solid angle to be determined
- Angular distribution effect

$$N_r = N_p \cdot N_t \cdot \sigma$$

Charged particle detection (in beam)

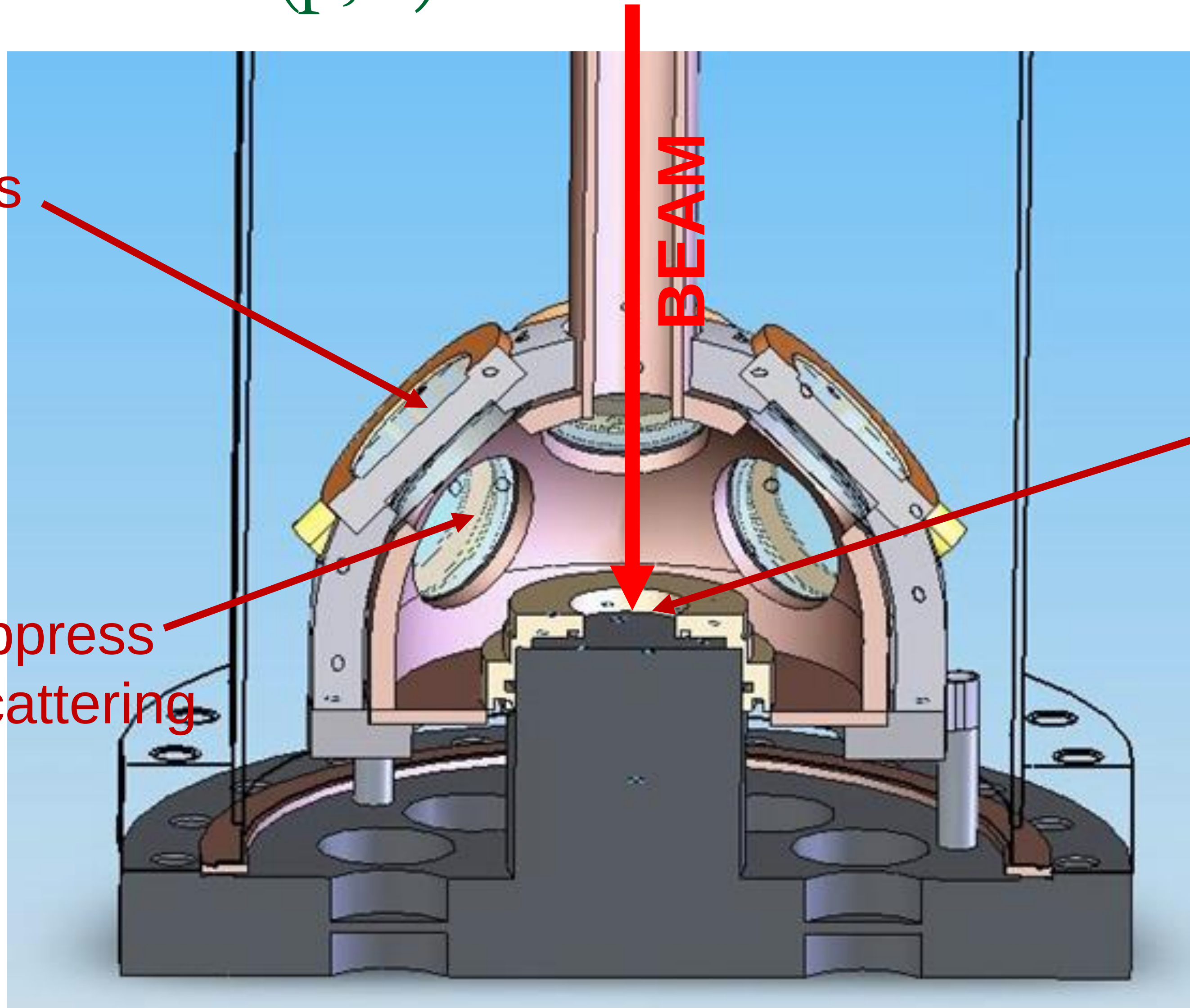
- Background (e.g. elastic scattering) must be avoided
  - foil in front of detector
  - particle identification (ΔE-E detector)

e.g. a (p,α) reaction



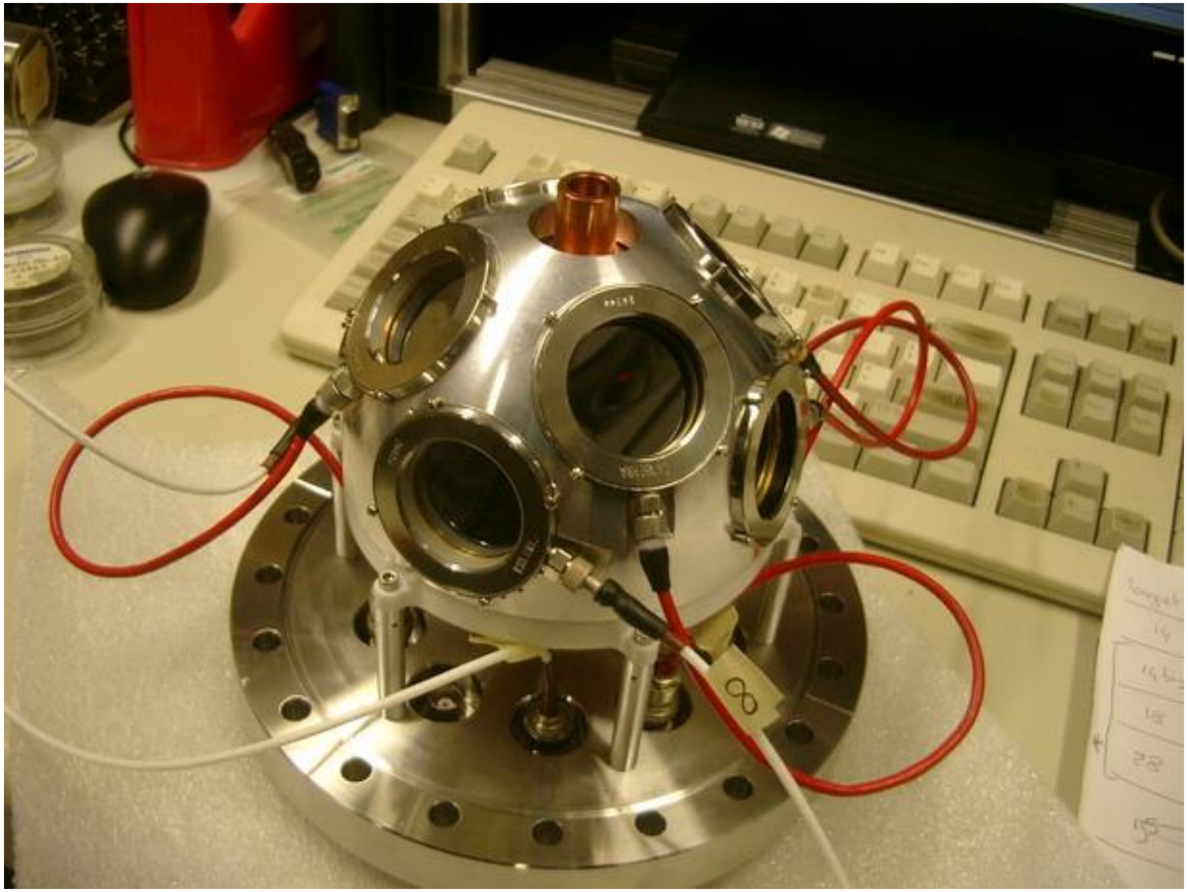
$$N_r = N_p \cdot N_t \cdot \sigma$$

LUNA $^{17}O(p,\alpha)^{14}N$ measurement



$$N_r = N_p \cdot N_t \cdot \sigma$$

LUNA $^{17}O(p,\alpha)^{14}N$ measurement

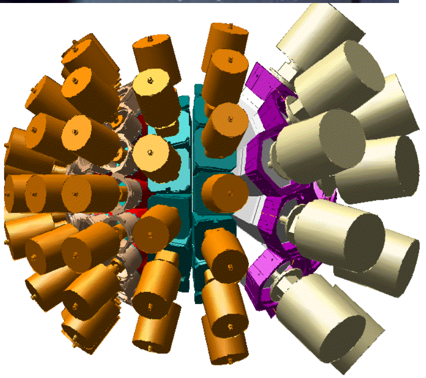


$$N_r = N_p \cdot N_t \cdot \sigma$$

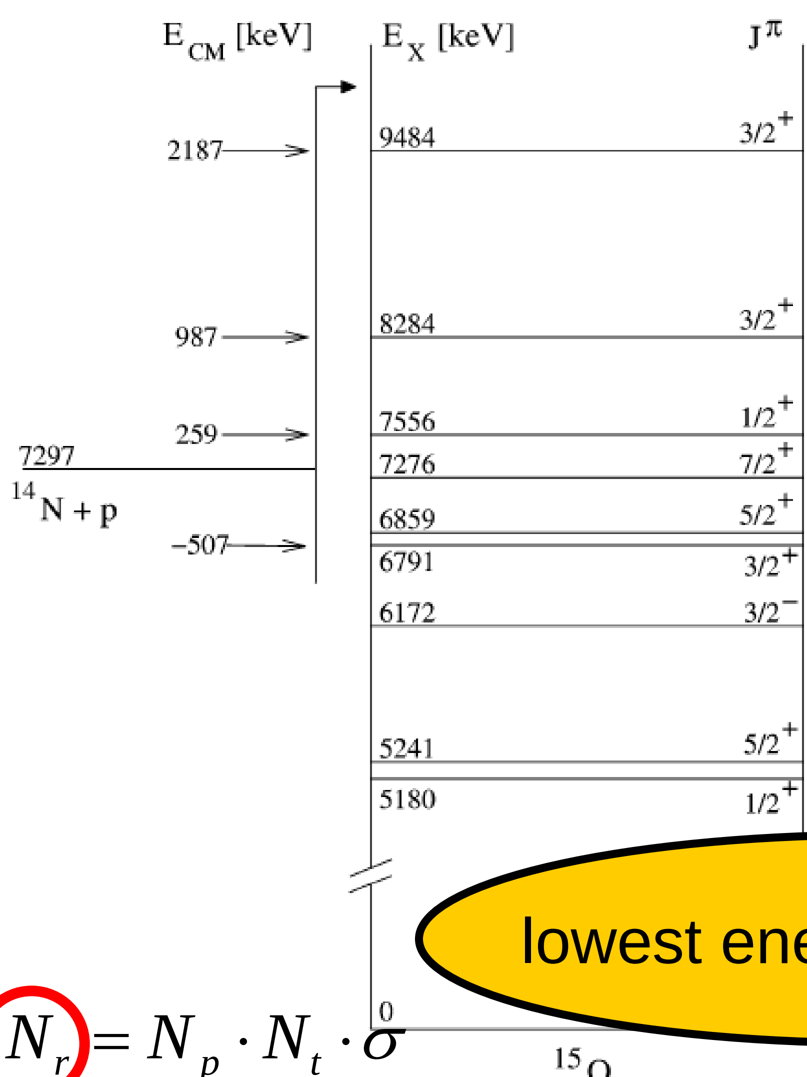
Gamma-detection (in-beam)

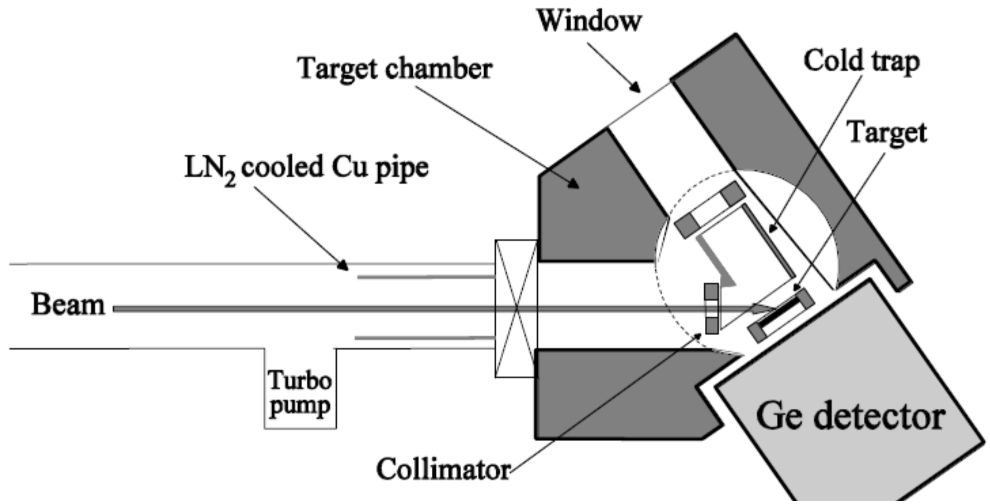
$$N_r = N_p \cdot N_t \cdot \sigma$$

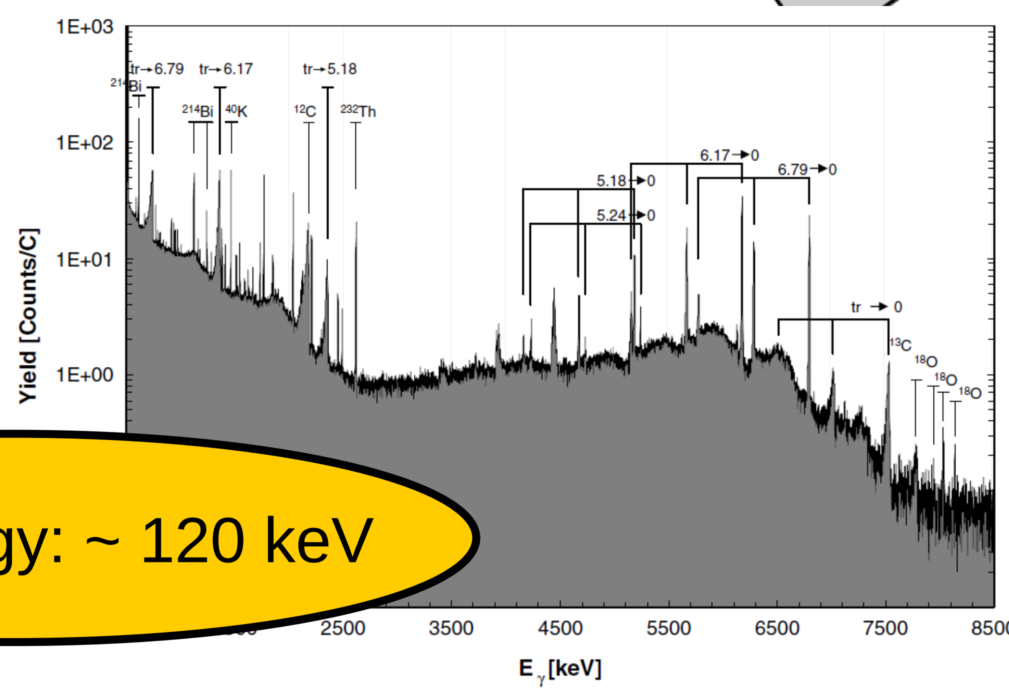
- HPGe detectors
  - low efficiency
  - high resolution: detailed decay scheme
- Scintillator summing crystals
  - high efficiency
  - low resolution
  - only total cross section
- HPGe detector array
  - high efficiency, high resolution, coincidences
  - expensive, complicated



Example: LUNA $^{14}N(p,\gamma)^{15}O$, HPGe



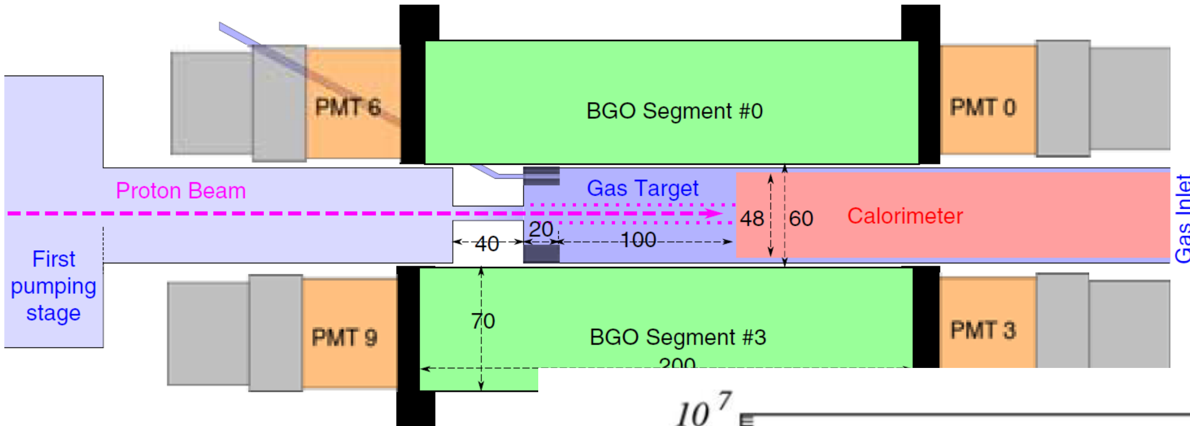


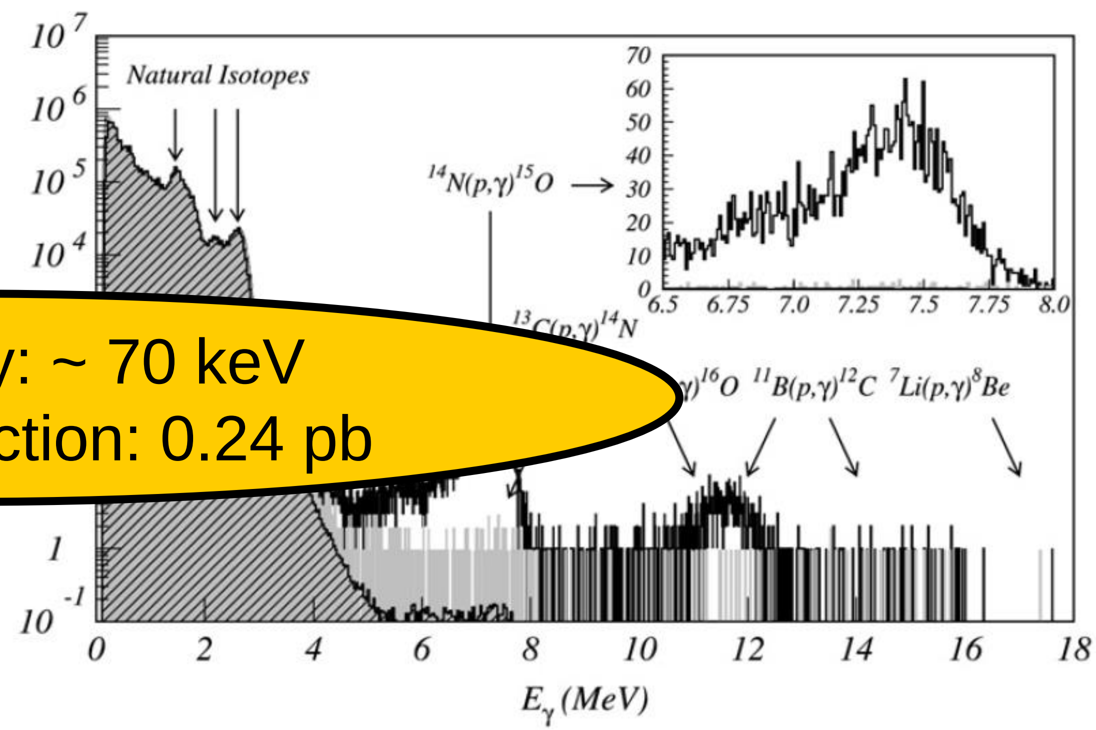


lowest energy: ~ 120 keV

$$N_r = N_p \cdot N_t \cdot \sigma$$

Example: LUNA $^{14}N(p,\gamma)^{15}O$, BGO





lowest energy: ~ 70 keV
lowest cross section: 0.24 pb

$$N_r = N_p \cdot N_t \cdot \sigma$$

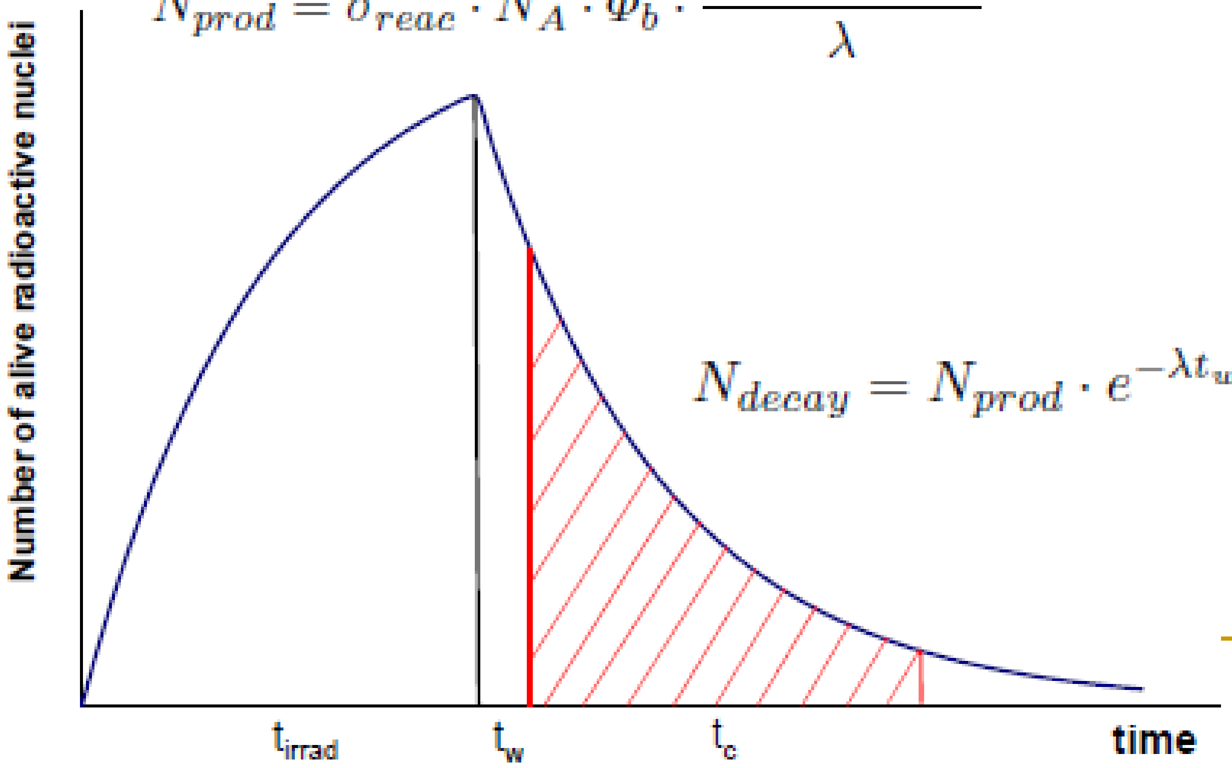
Off-line method: activation

$$N_r = N_p \cdot N_t \cdot \sigma$$

- Only if the reaction product is radioactive
- Its half-life must be suitable
- The decay must be measurable (gamma-radiation)

$$N_{prod} = \sigma_{reac} \cdot N_A \cdot \Phi_b \cdot \frac{1 - e^{-\lambda t_{irrad}}}{\lambda}$$

$$N_{decay} = N_{prod} \cdot e^{-\lambda t_w} \cdot (1 - e^{-\lambda t_c})$$



$$N_r = N_p \cdot N_t \cdot \sigma$$

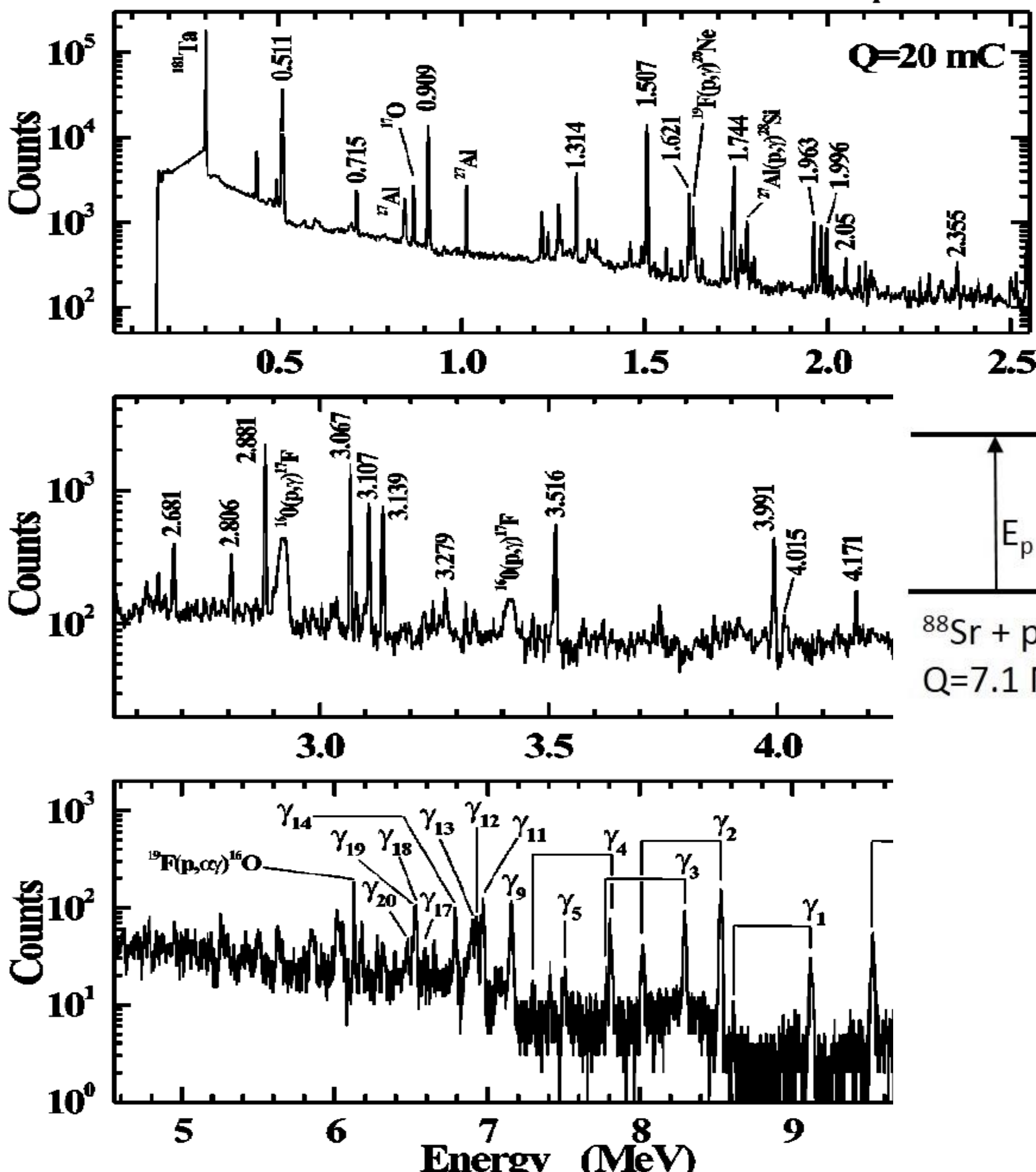
Detection

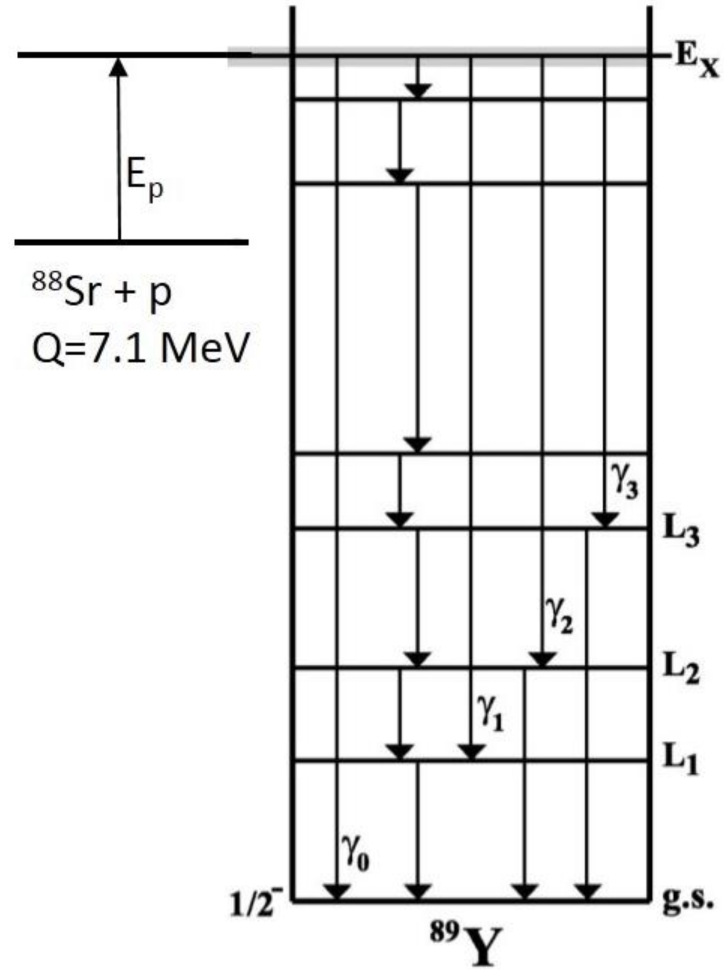
Activation: advantages

- Clean gamma-spectra
- Reduced beam-induced background
- No angular distribution effect
- More isotopes can be studied simultaneously
- Yields total cross section

$$N_r = N_p \cdot N_t \cdot \sigma$$

^{88}Sr(p,γ)^{89}Y in-beam

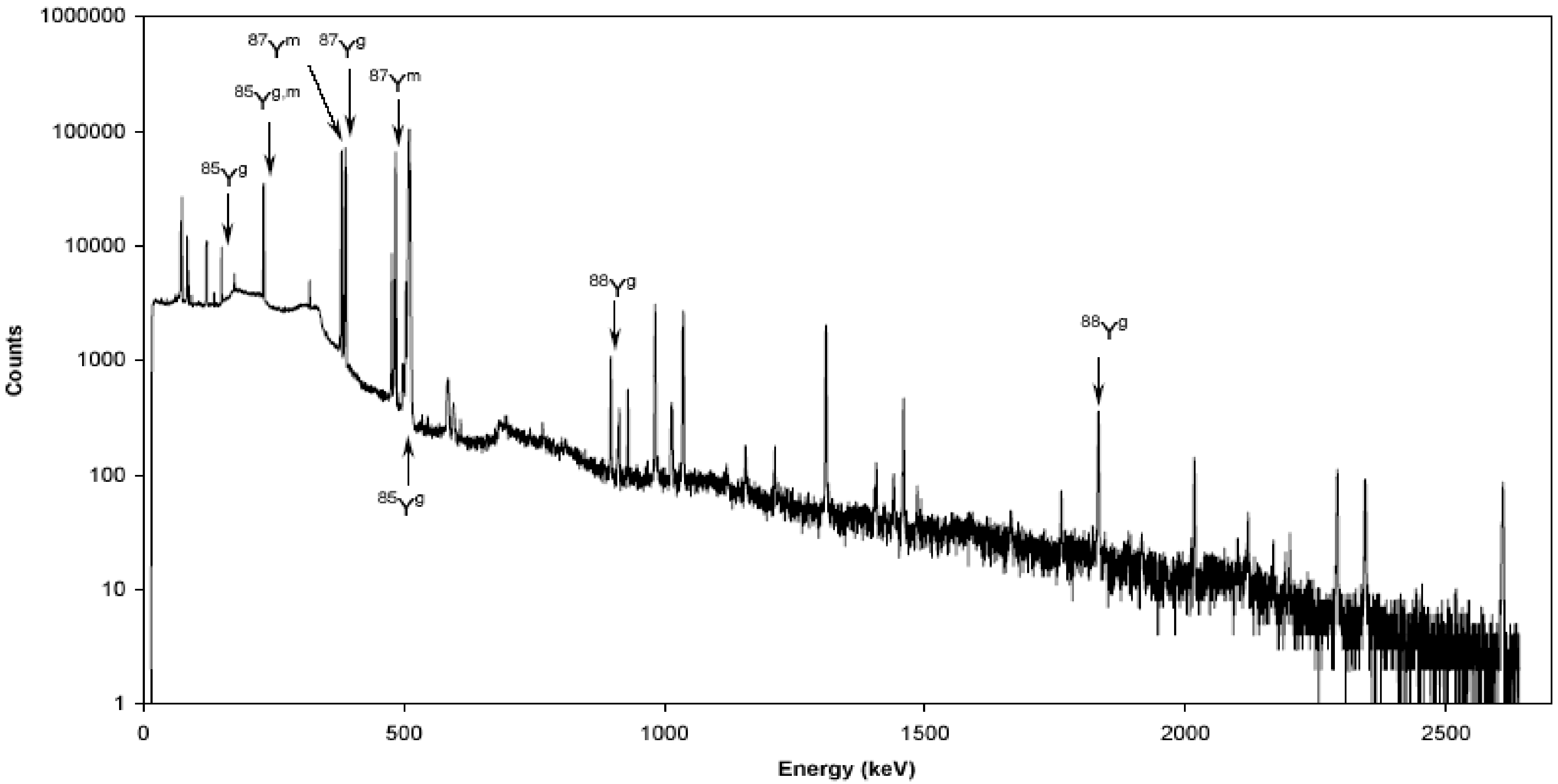




With activation

$$N_r = N_p \cdot N_t \cdot \sigma$$

$^{84}Sr(p,\gamma)^{85}Y$ $^{86}Sr(p,\gamma)^{87}Y$ $^{87}Sr(p,\gamma)^{88}Y$



Importance of background reduction

small

small

$$N_r = N_p \cdot N_t \cdot \sigma$$

limited

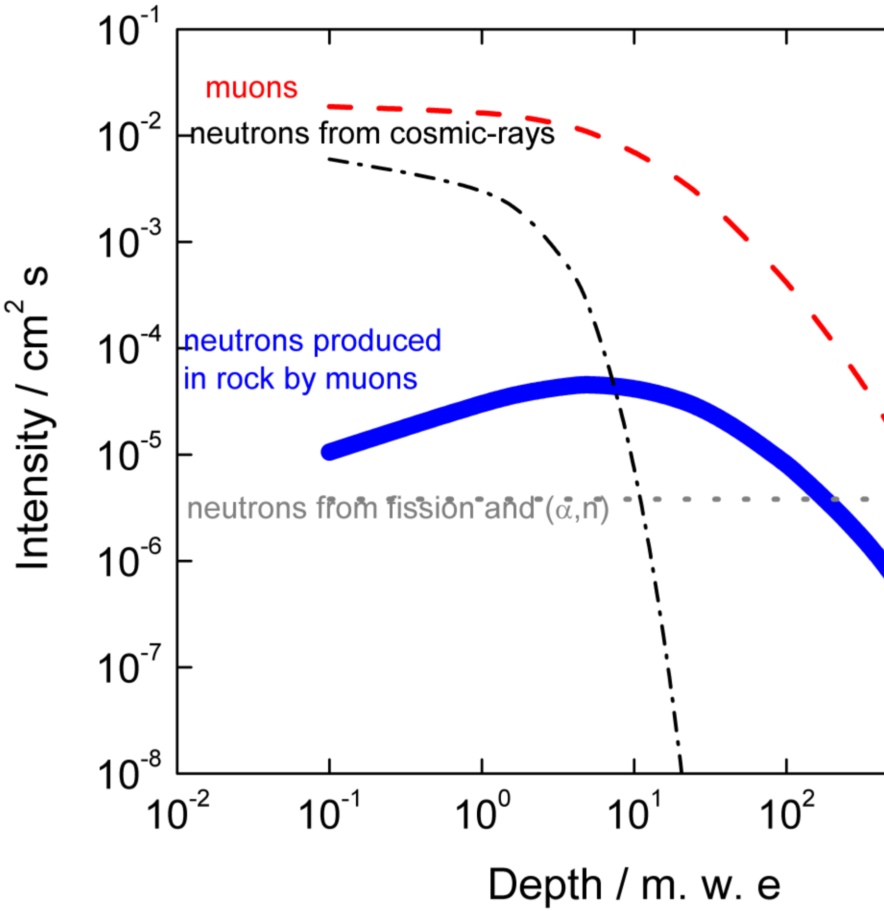
How to reduce background? Shielding!

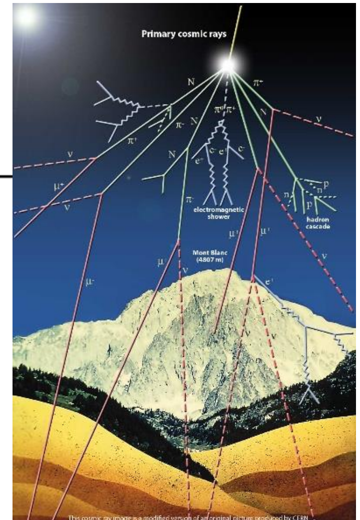
- Passive shielding

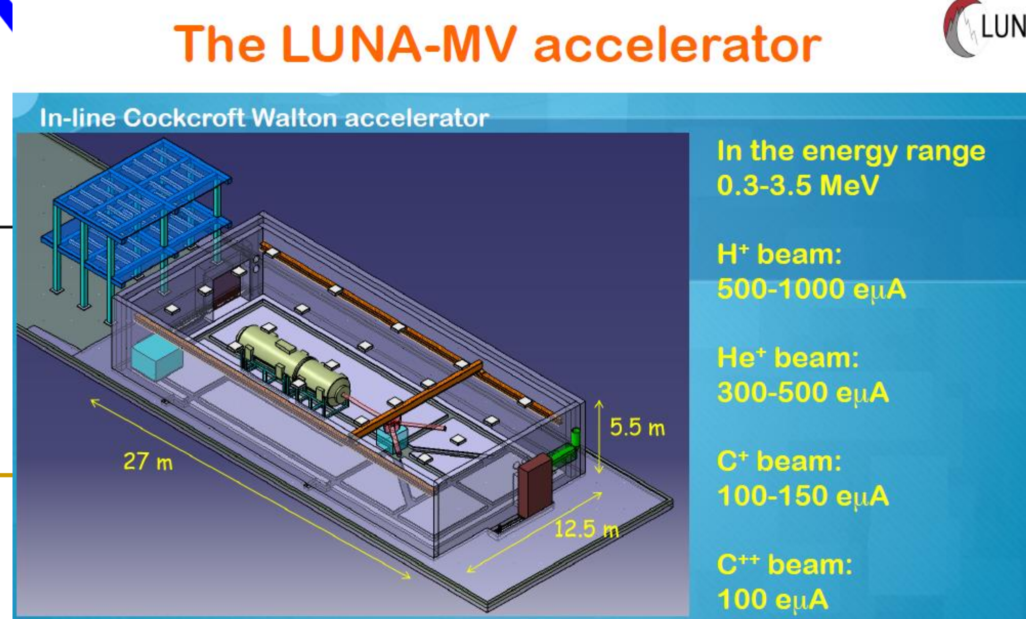
- Active shielding

- Underground facility

Let's go underground!







Summary

- Direct methods are the best to obtain cross sections
- Stars are cool: small accelerators are enough
- Cross sections are low: special experimental techinque is needed
  - good beam
  - good targets
  - good detectors
  - low background


Thank you for your attention!