Stellar Production and Destruction Rates of ^{60}Fe

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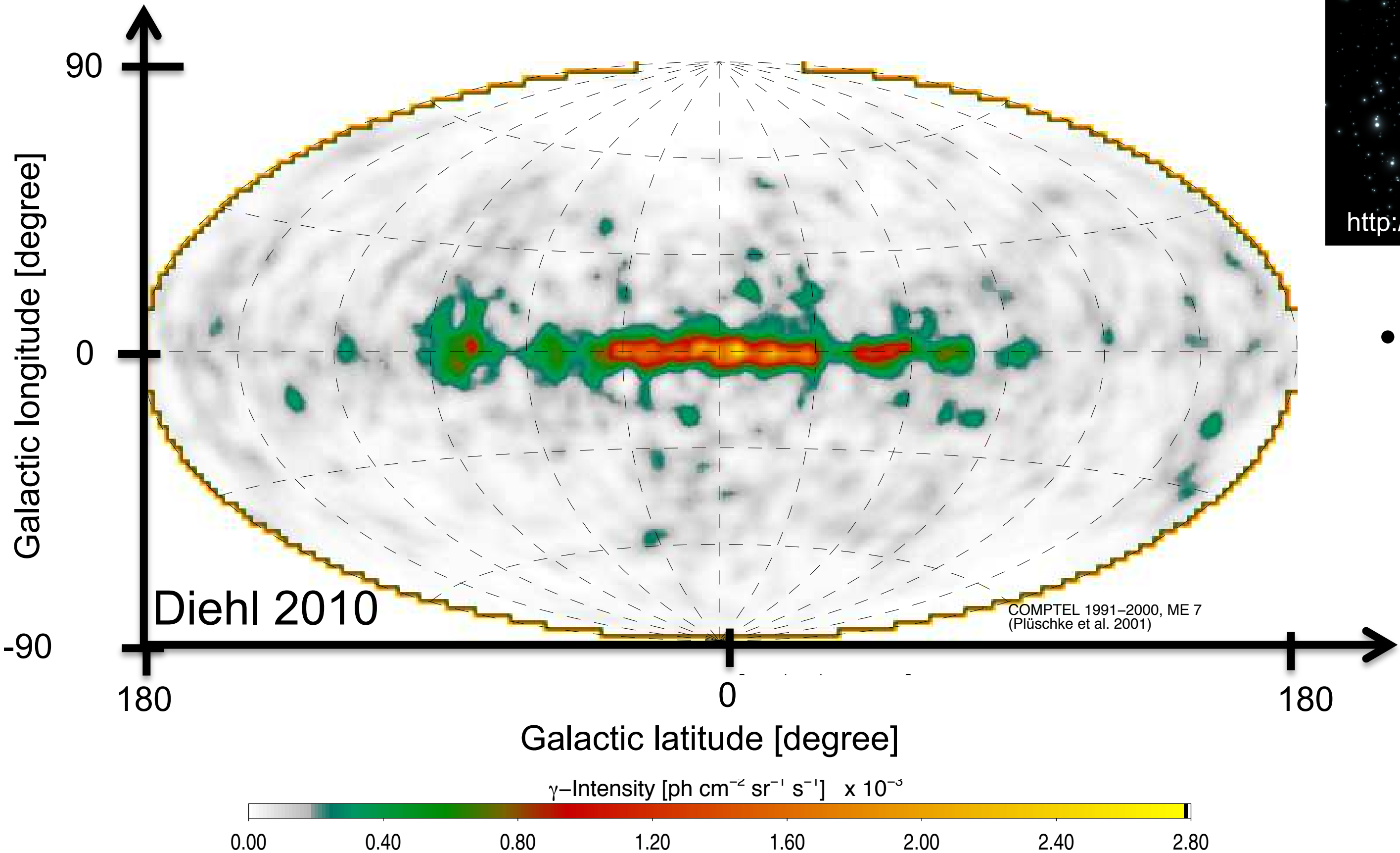
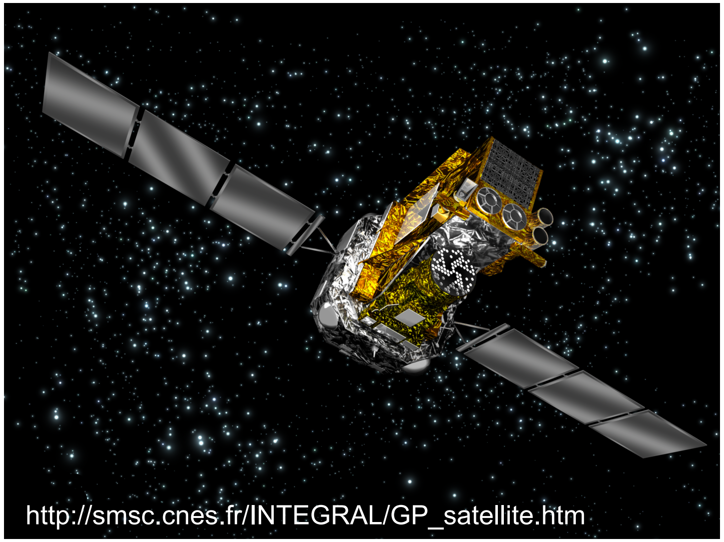
Outline

- Astrophysical Motivation
- Experimental Setup
- First Results
- Future Plans & Summary

Astrophysical Motivation

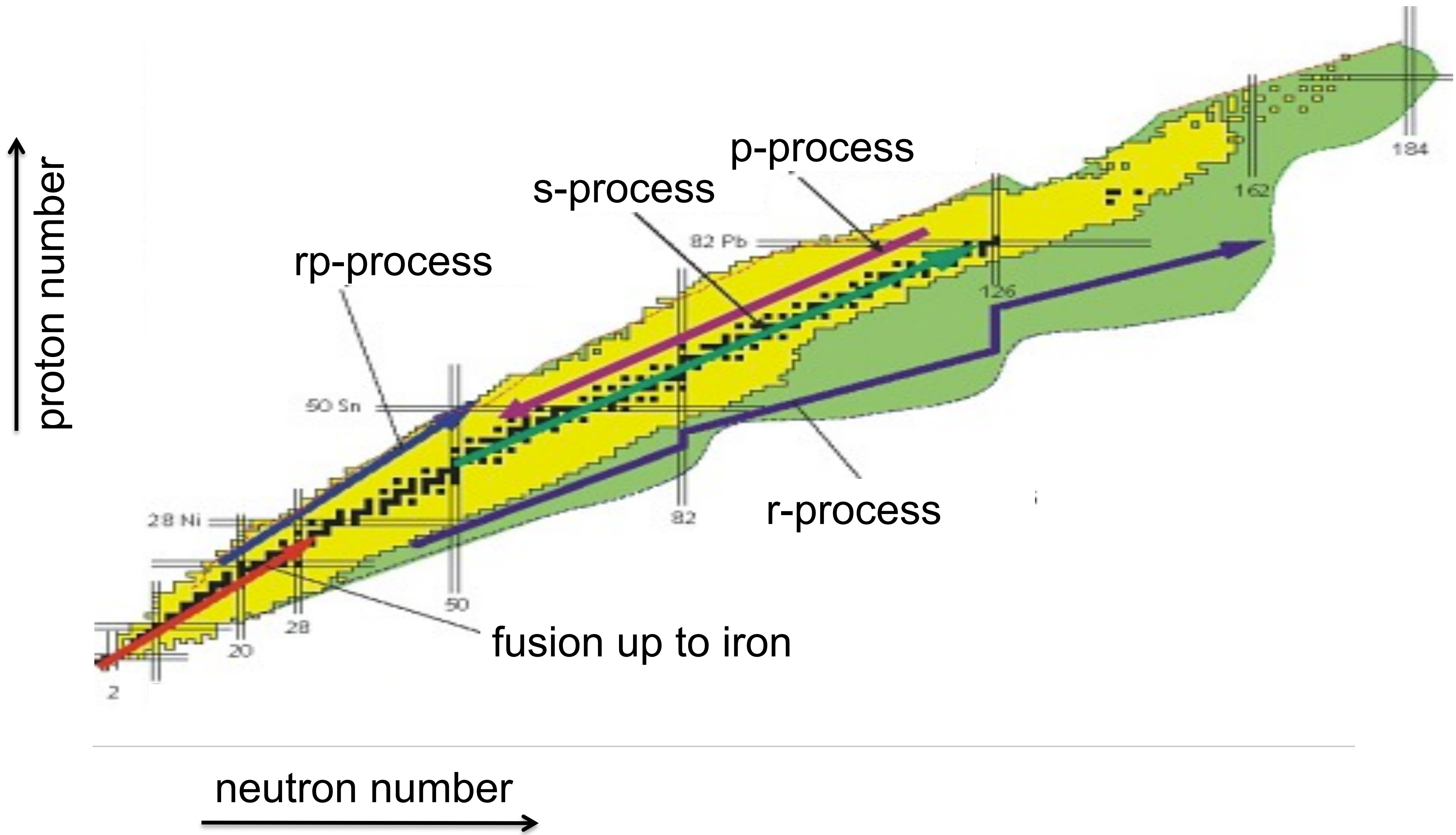
INTEGRAL (*INTE*rnational *G*amma *RA*y *L*aboratory) observed characteristic ^{60}Co decay lines at 1173 & 1332 keV produced by β-decay from ^{60}Fe





- scaled characteristic distribution of ^{60}Fe along the galactic plane based on **^{60}Fe**/^{26}Al measurements

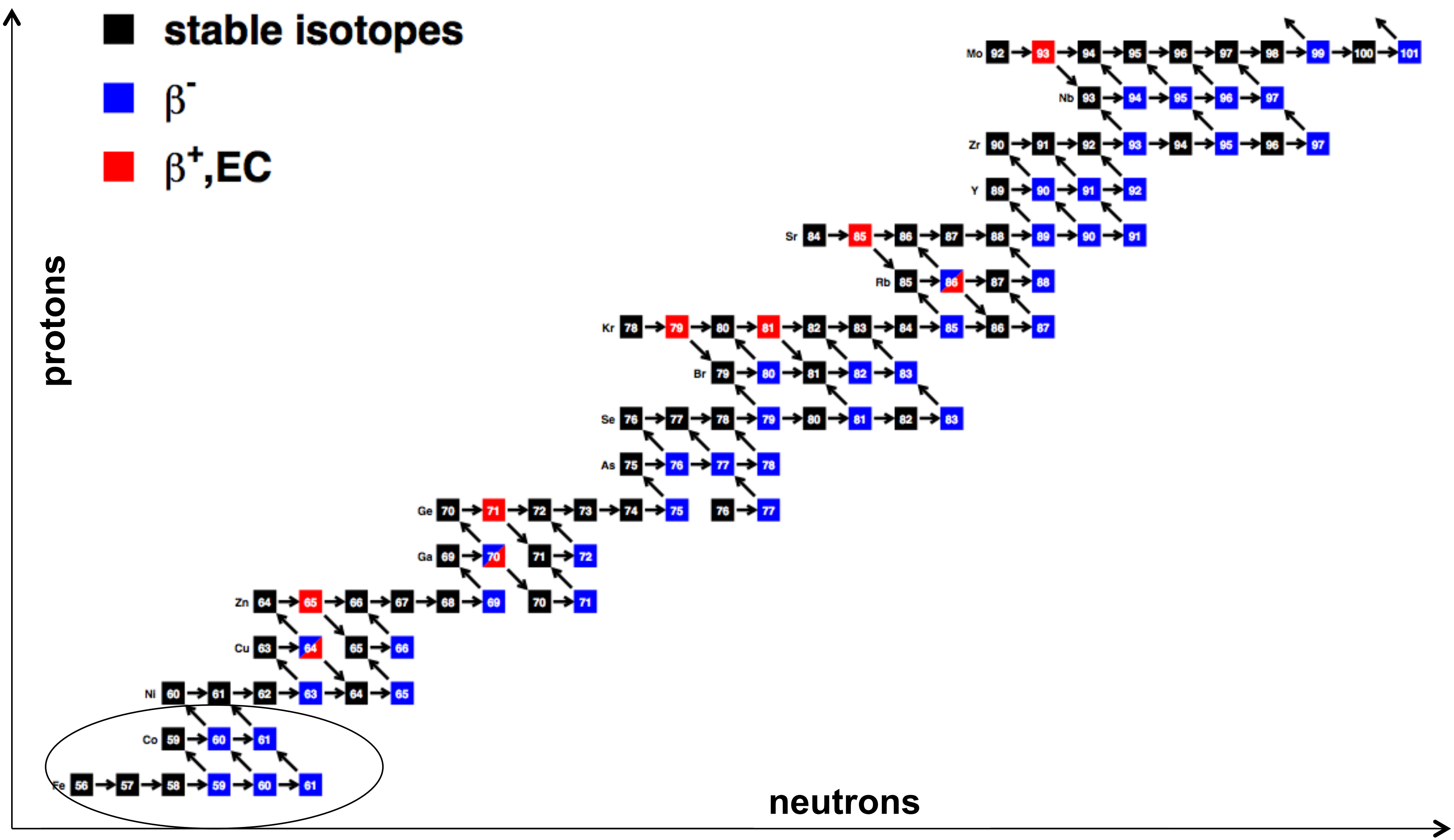
Nucleosynthesis of the Elements



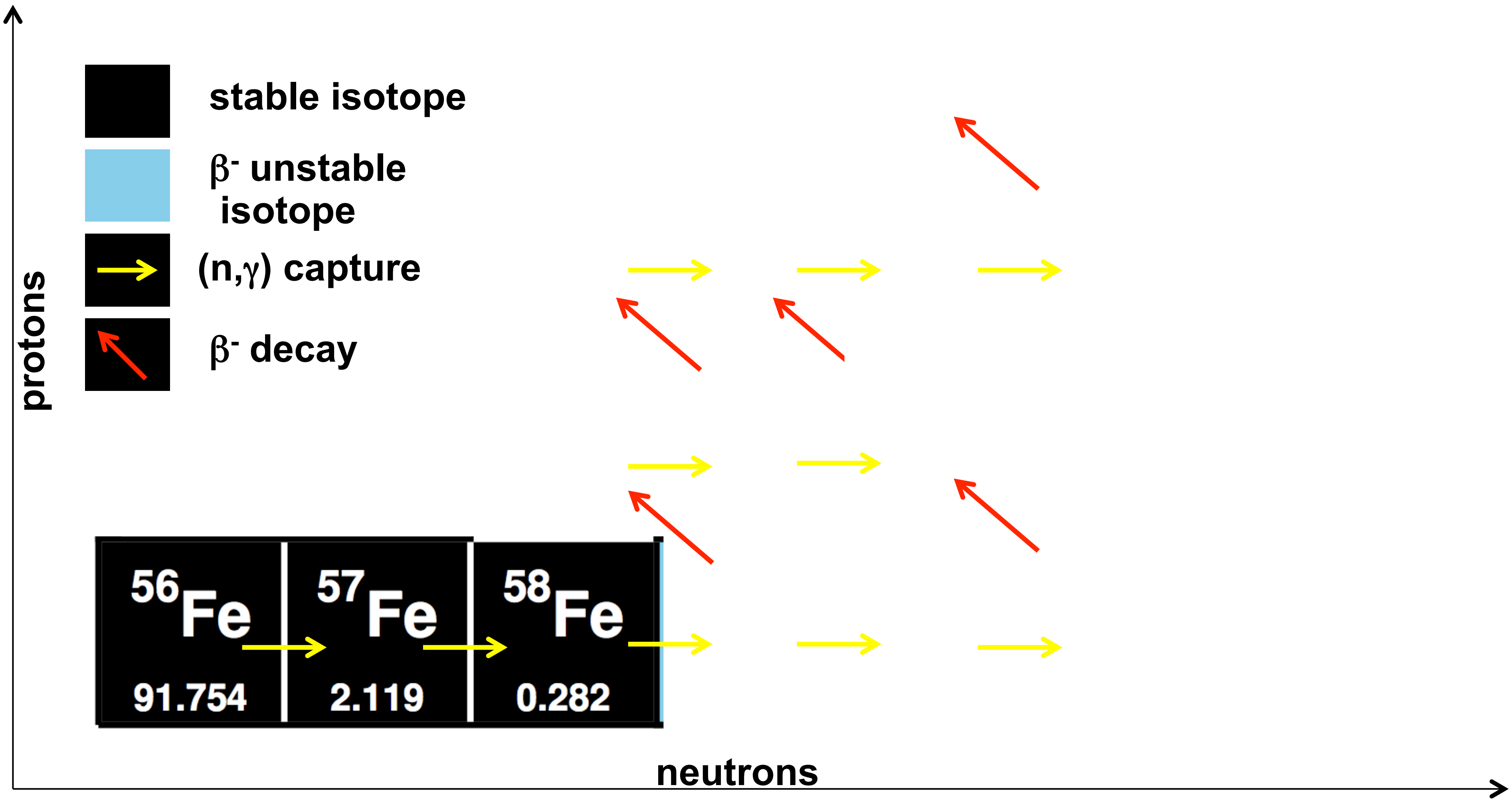
s-process

- slow neutron capture process
- seed isotopes: ^{56}Fe,^{57}Fe, ^{58}Fe
- neutron capture and β^- decay
- neutron capture rate is small relative to the beta decay rate
- about 50% of the element abundances beyond iron are produced via s-process
- synthesizing elements between iron & bismuth

s-process



s-process



Provided we know about the nuclear reaction rates for production and destruction we will get information on:

temperature & density

s-process

- s-process:
  - main component & weak component

- main component:
  - He shell burning phase in AGB stars
  - nuclei with A = 90 - 209 are mainly produced
  - $^{13}C(\alpha,n)$:

$\rho_n = 10^7\ cm^{-3}$ at kT= 5 keV ➡ $$\boxed{\frac{(n,\gamma)-ratio}{\beta^- -ratio} \approx 10^{-4}}$$ ➡ **no ^{60}Fe production**

  - $^{22}Ne(\alpha,n)$:

$\rho_n = 10^{11}\ cm^{-3}$ at kT= 30 keV ➡ $$\boxed{\frac{(n,\gamma)-ratio}{\beta^- -ratio} \approx 2}$$ ➡ **^{60}Fe production**

s-process

- weak component
  - massive stars (20-25 $M_\odot$)
  - mainly nuclei A = 56 - 90 are produced
  - there are two phases:
  - 1st phase: He core burning

$\rho_n = 10^6\,cm^{-3}$ at kT= 25 keV ➡ $\boxed{\frac{(n,\gamma)-ratio}{\beta^- - ratio} \approx 10^{-5}}$ ➡ **no ^{60}Fe production**

  - 2nd phase: C shell burning

$\rho_n = 10^{12}\,cm^{-3}$ at kT= 90 keV ➡ $\boxed{\frac{(n,\gamma)-ratio}{\beta^- - ratio} \approx 10}$ ➡ **^{60}Fe production**

Production and Destruction of ^{60}Fe

^{60}Fe(β^-) :
in progress, new measurements: e.g. **talks by**
G. Rugel
W. Kutschera et al.
R. Dressler et al.

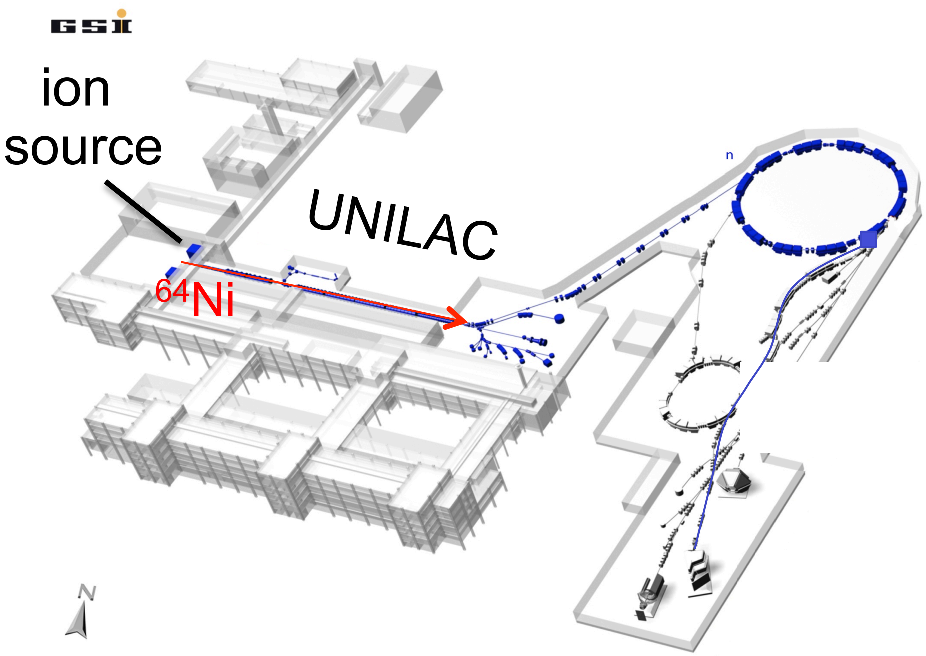
^{59}Fe(n,γ) :
extremely difficult

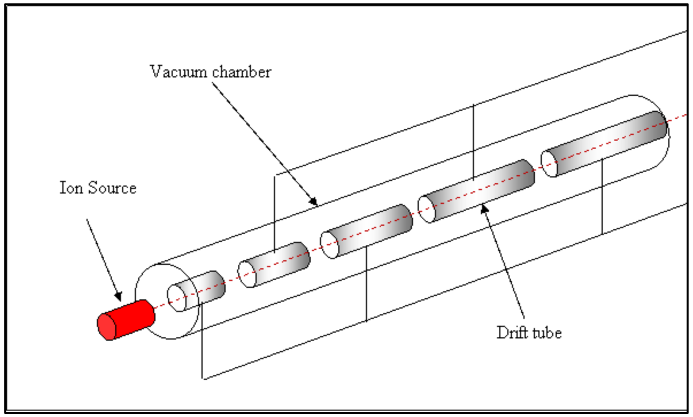
^{60}Fe

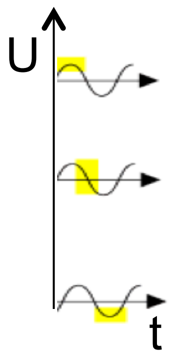
(n,γ)^{61}Fe :
activation experiments
kT = 25 meV
kT = 25 keV
kT = 90 keV
R. Reifarth et al.
next talk

^{60}Fe(γ,n) :
coulomb dissociation,
experiment performed

Beam Production





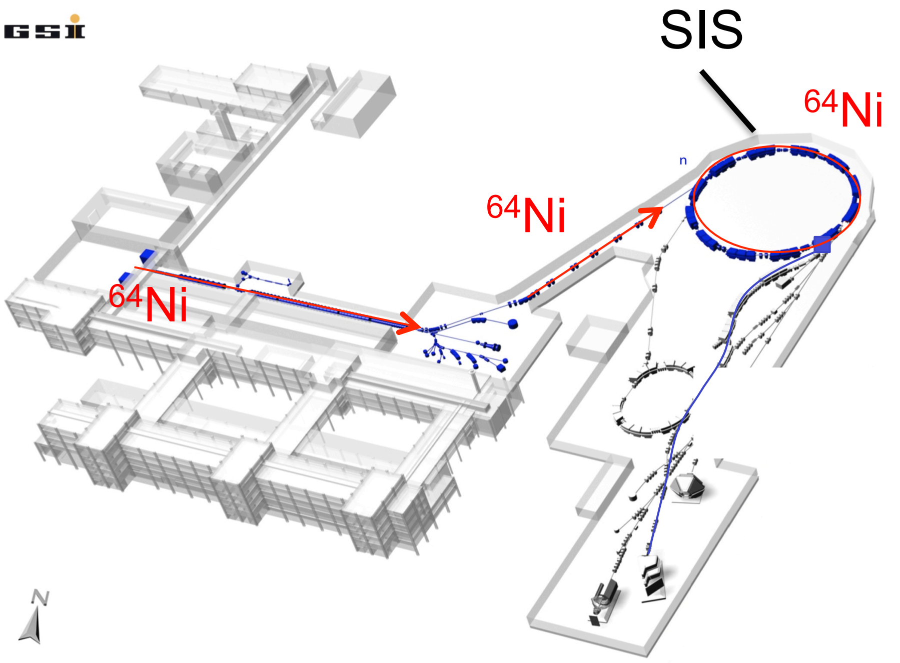


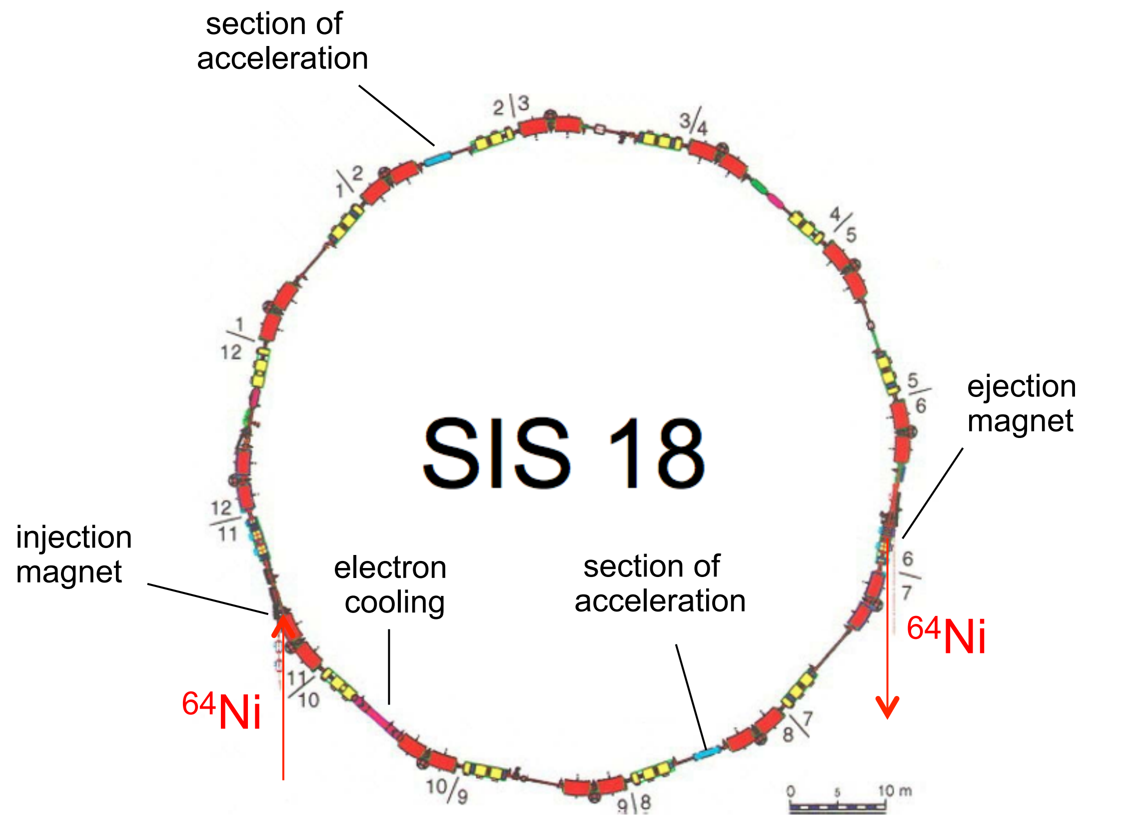
$U \approx U_{max}$: distance between tubes
=> acceleration
U=0: field-free distance
=> drift
$U \approx U_{max}$: distance between tube with reversed polarity
=> new acceleration

<u>UNIversaLACcelarator:</u>

- length: 120m
- energy of particles: 20% speed of light
  $\Rightarrow$ 11,4 AMeV

Beam Production

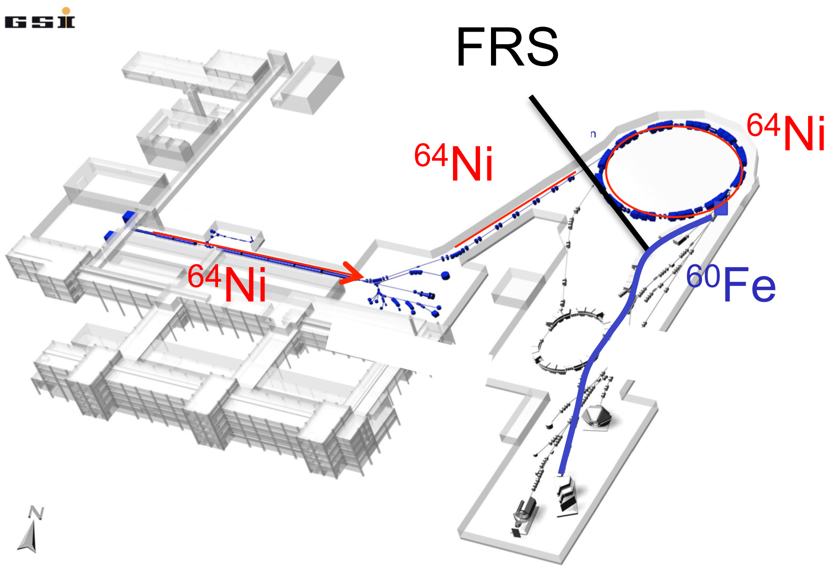




<u>“**S**chwer**I**onen“(heavy ion)-**S**ynchrotron</u>

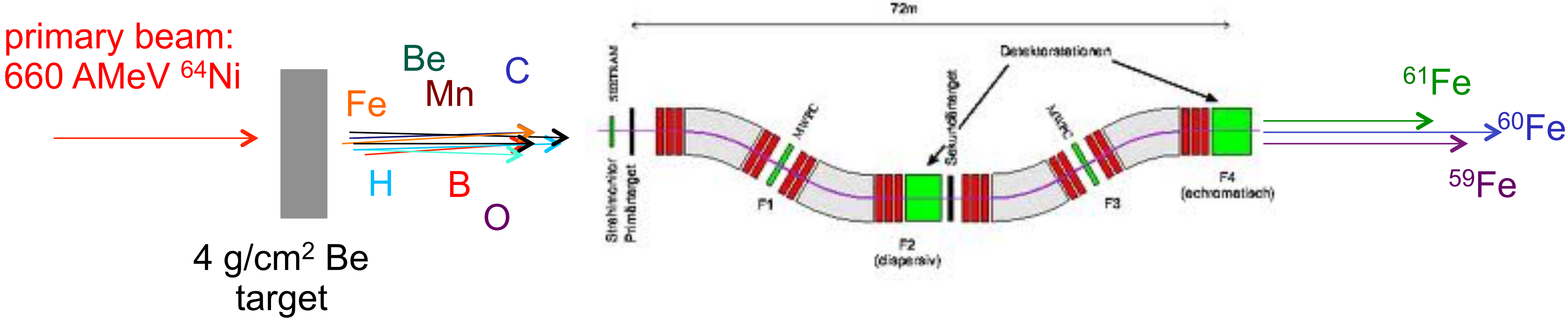
- pulse duration varies from 1 to 400 μs
- to get higher beam intensity several pulses are injected into SIS
- 90% speed of light ⇒ 1000 AMeV
- this energy can be reached for protons as well as for uranium

Beam Production

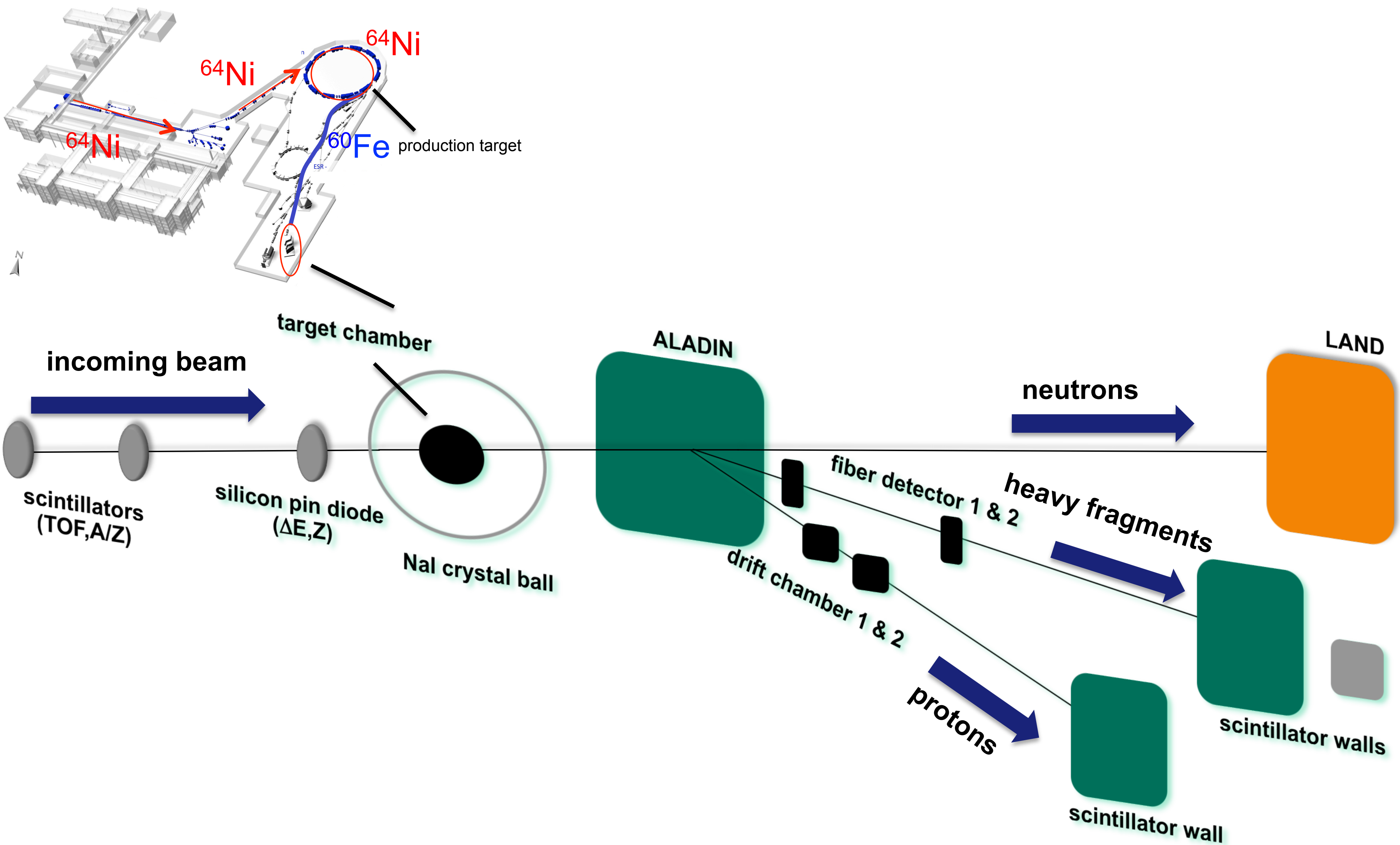


FRagment **S**eperator:

- seperates the isotopes of interest
- energy of particles: 535 AMeV
- intensities of 10^7 particles/s
- reduction after FRS:
  10^4-10^5 particles/s



R^3B/LAND Setup

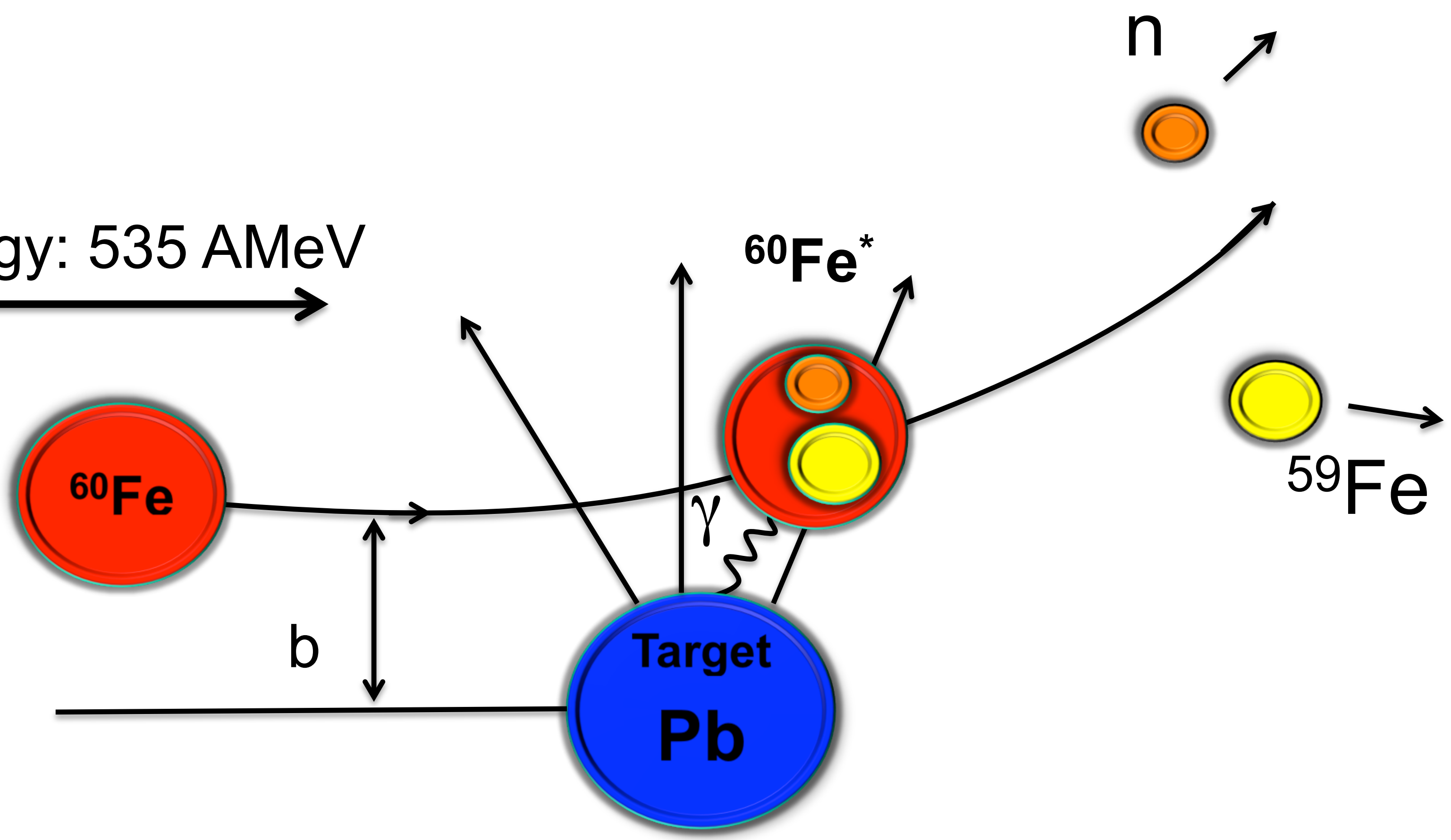


Coulomb Dissociation

reaction of interest: $^{59}Fe + n \longrightarrow {}^{60}Fe + \gamma$
idea: measure time-reversed process:

$$^{60}Fe + \gamma \longrightarrow {}^{59}Fe + n$$

Beam Energy: 535 AMeV



Coulomb Dissociation

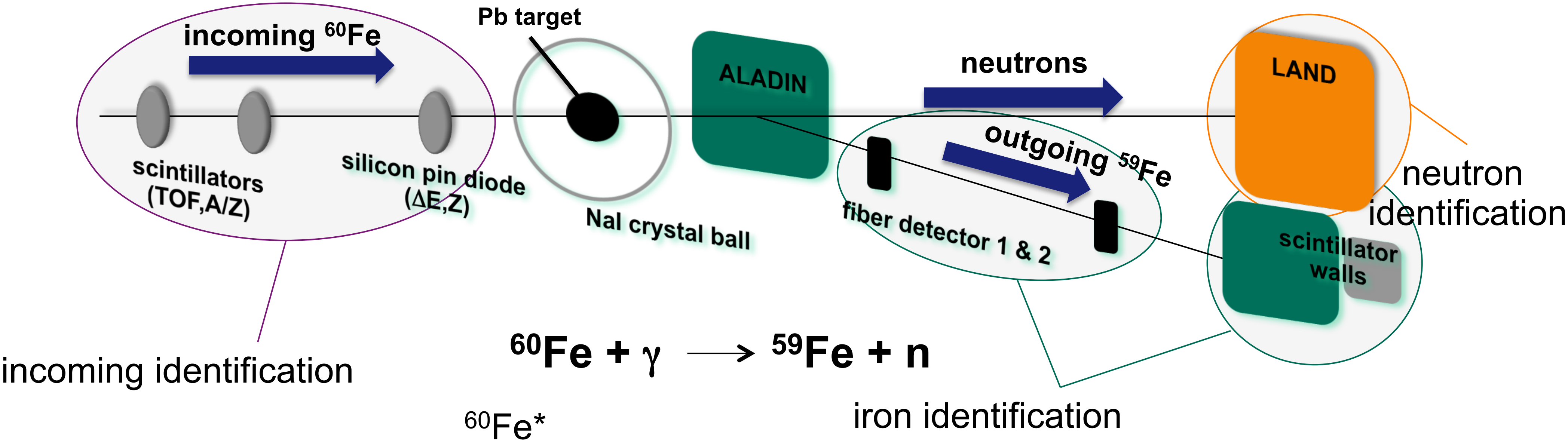
Advantages:

experiments with radioactive nuclei are possible

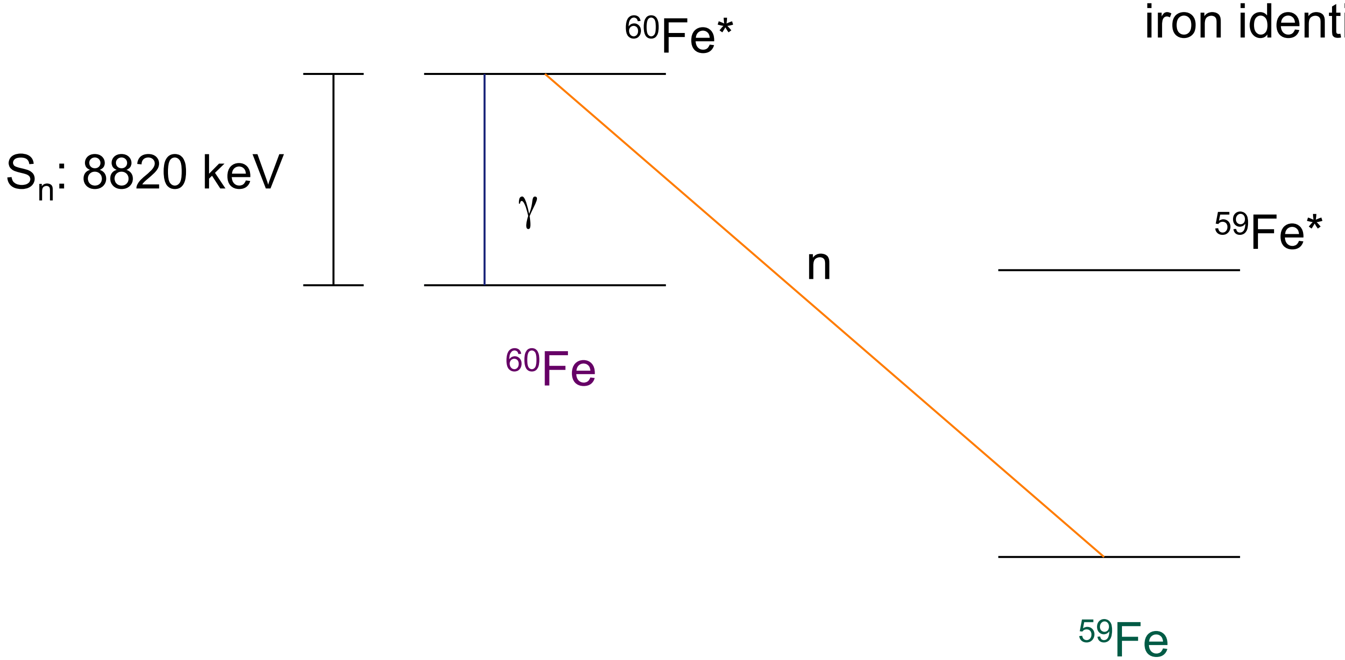
Disadvantages:

- indirect method
  - ⇒ needs theoretical input
  - ⇒ data for verification
- nuclear interaction must be subtracted
- bad energy resolution which is needed for the $(\gamma,n) \longleftrightarrow (n,\gamma)$
- multipole admixtures must be determined

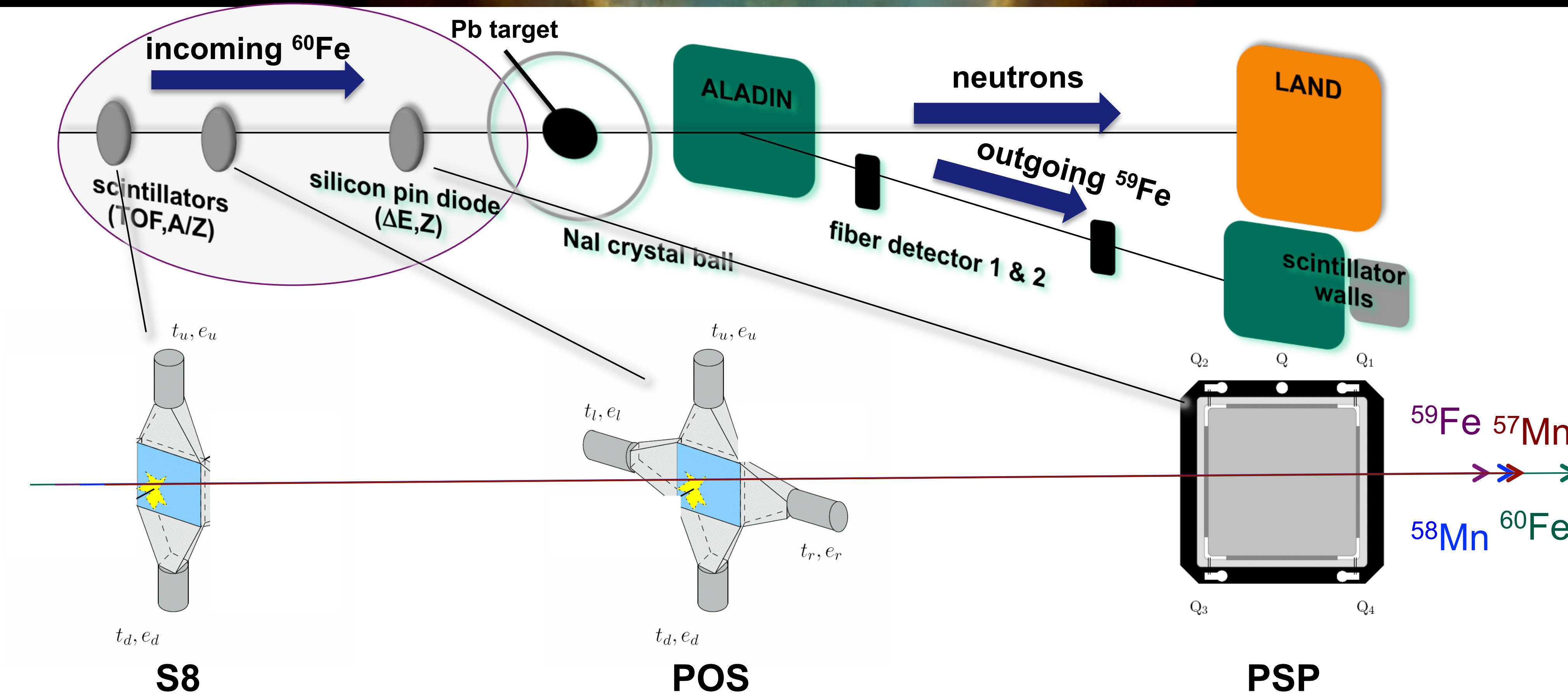
$^{60}Fe(\gamma,n)^{59}Fe$ at R^3B/LAND Setup



^{60}Fe + γ $\longrightarrow$ ^{59}Fe + n



Incoming Identification

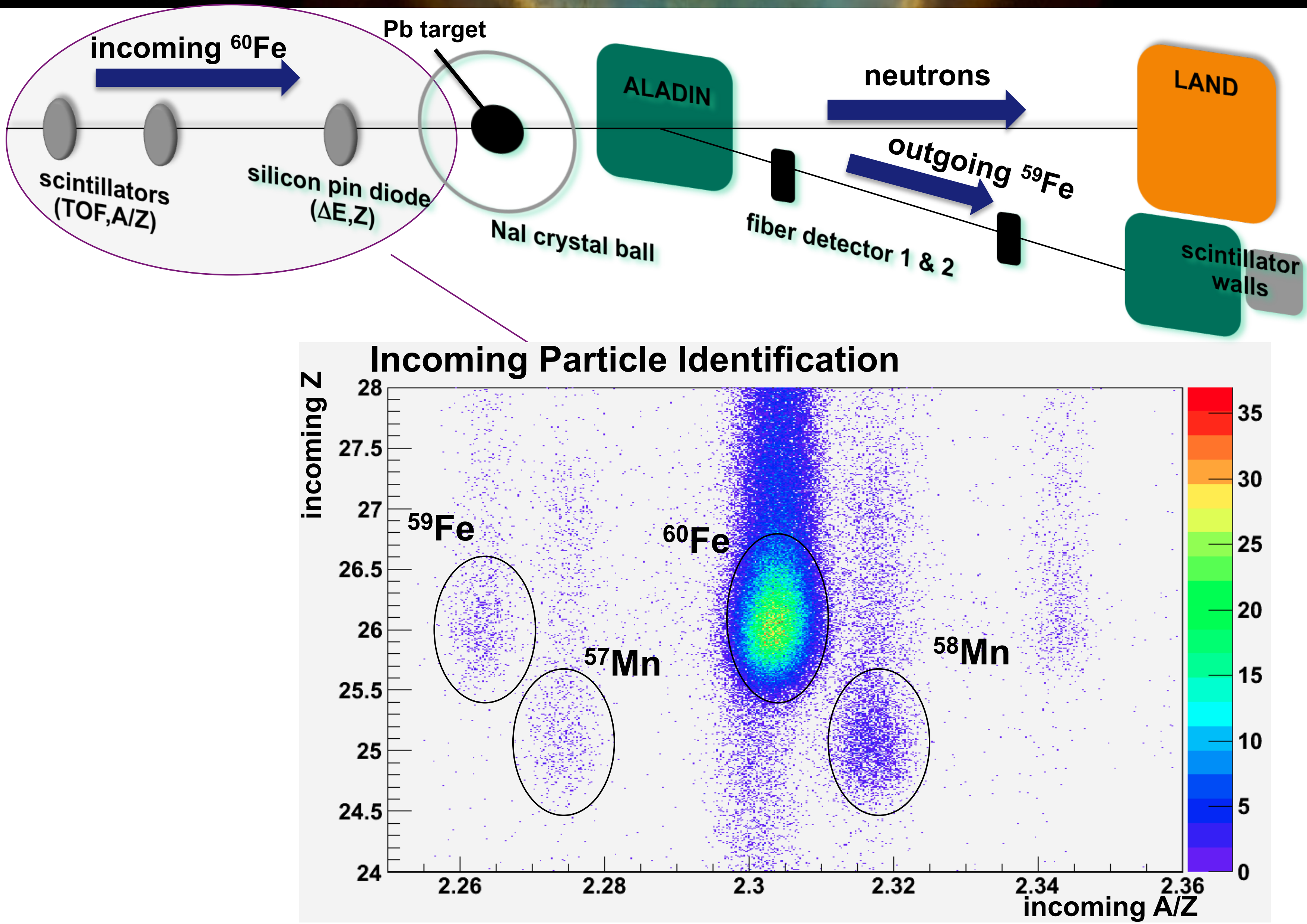


<u>**S**cintillator**8**</u>
- plastic scintillator
- 2 photomultipliers
- time measurement

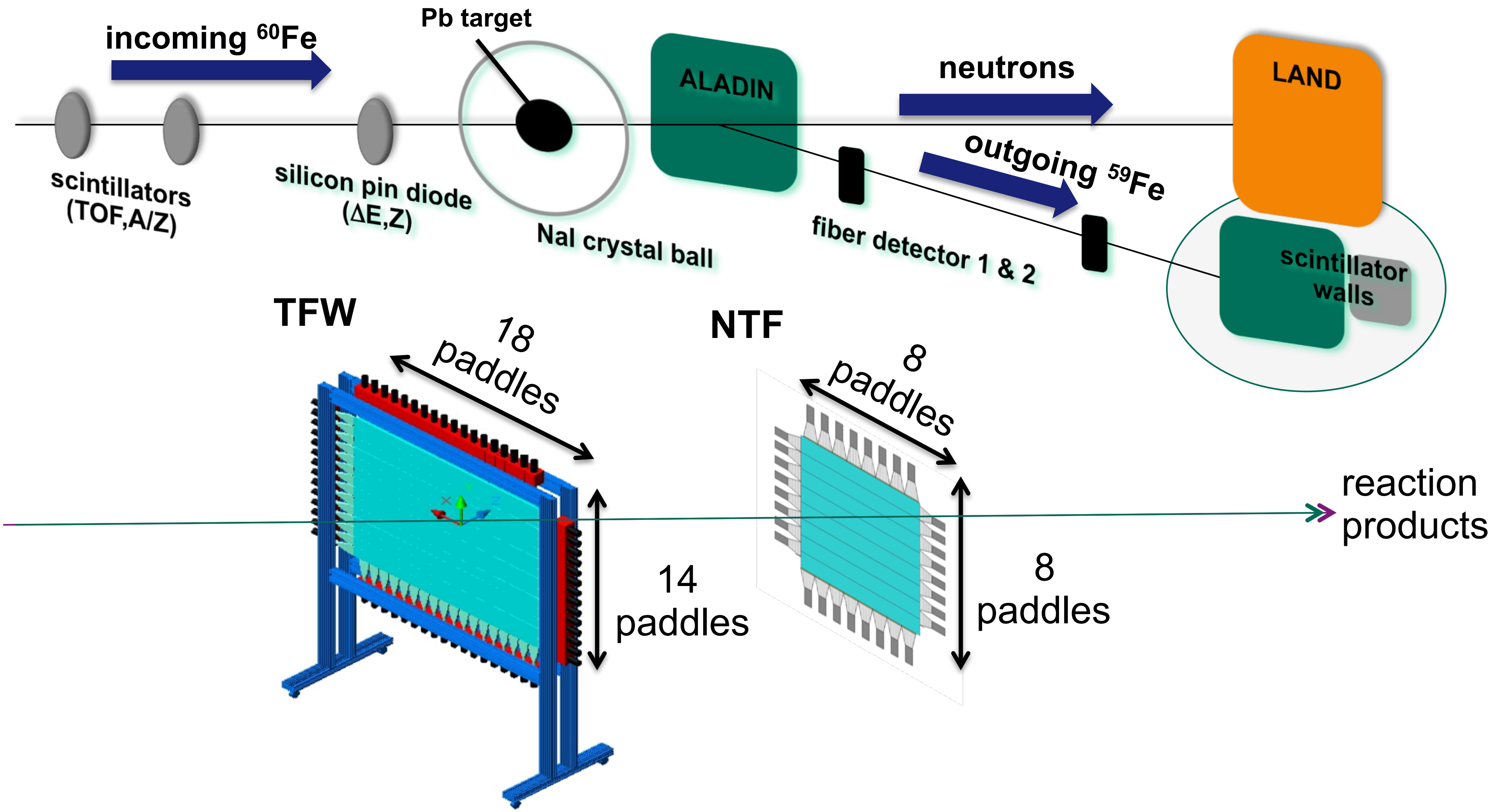
<u>**POS**ition detector</u>
- quadratic plastic scintillator
- 4 photomultipliers
- time measurement

<u>**P**osition **S**ensitive silicon **P**in diode</u>
- 2D position
- charge Z of a passing heavy ion can be obtained via ΔE (Bethe-Bloch formula)

Incoming Identification



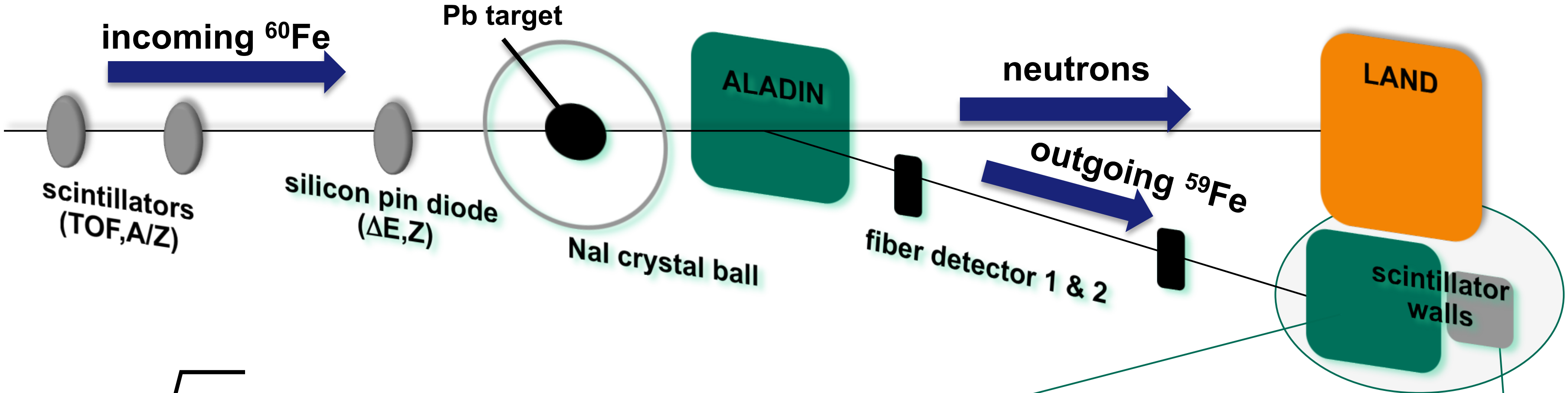
Outgoing Z Identification



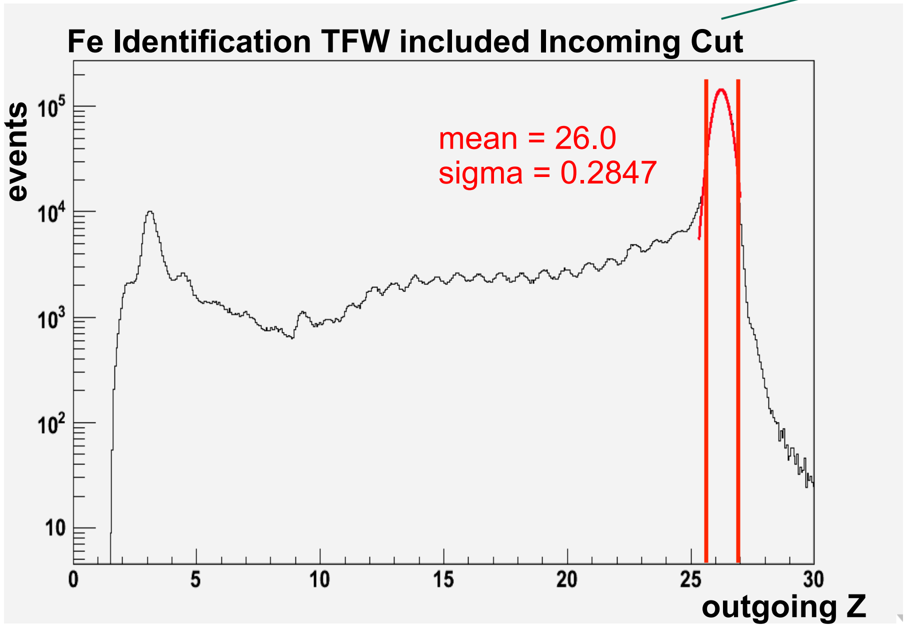
<u>**T**ime of **F**light **W**all & **N**ew **T**ime of **F**light Wall</u>

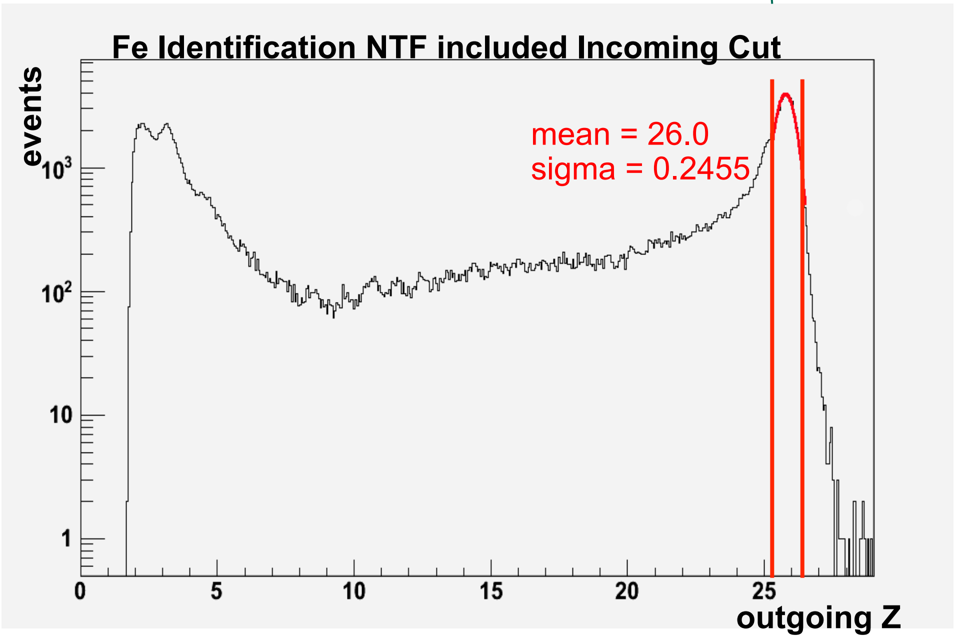
- ion detector with plastic scintillator and photo-multiplier tubes
- TFW & NTF identify the position, the outgoing Z and the TOF of reaction products

Outgoing Z Identification

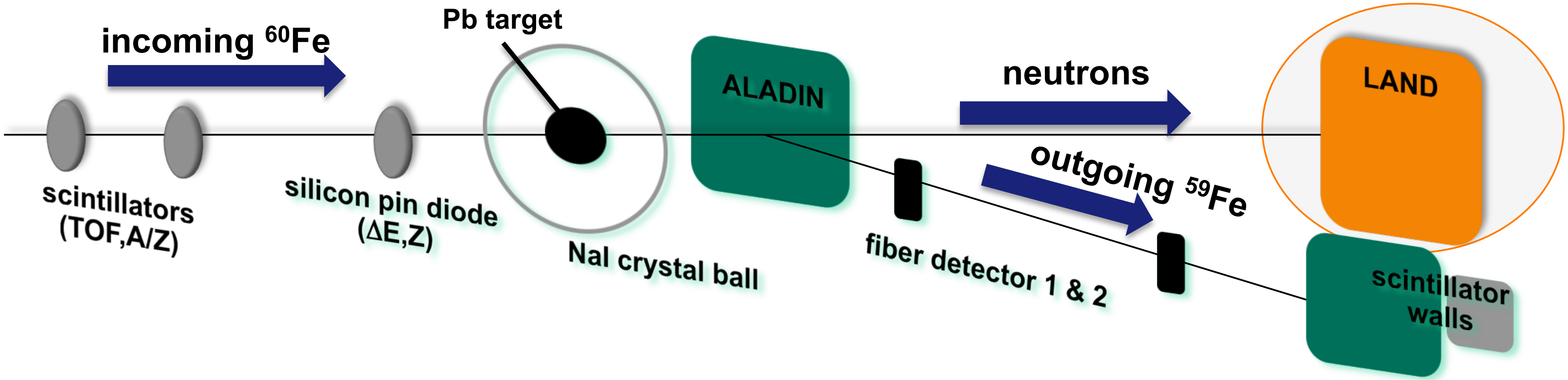


$$Z \propto \sqrt{E}$$



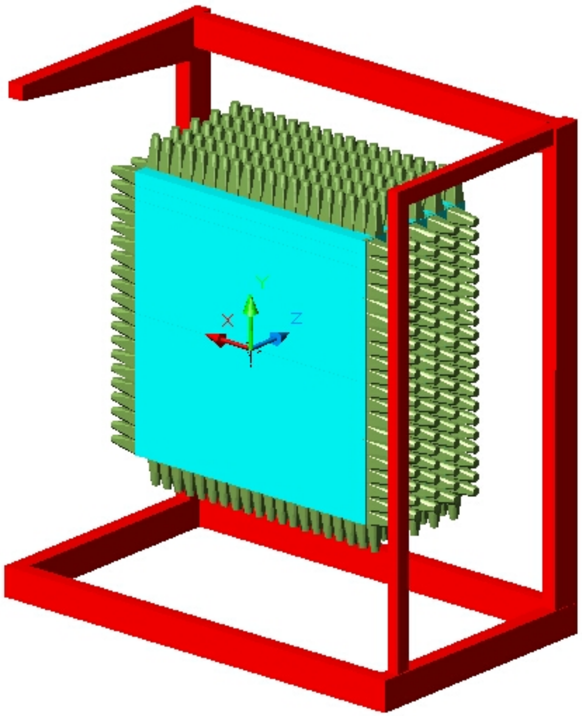


Neutron Identification

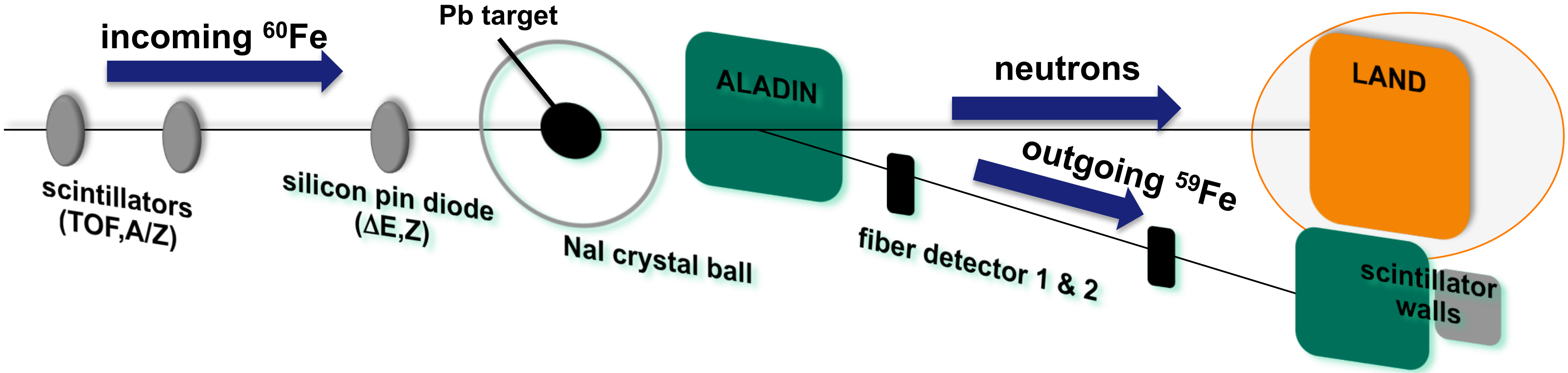


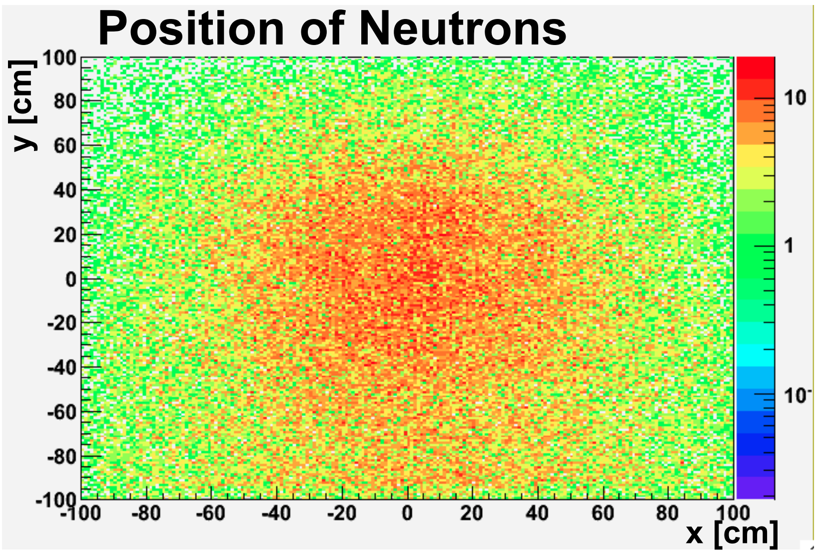
<u>Large **A**rea **N**eutron **D**etector</u>

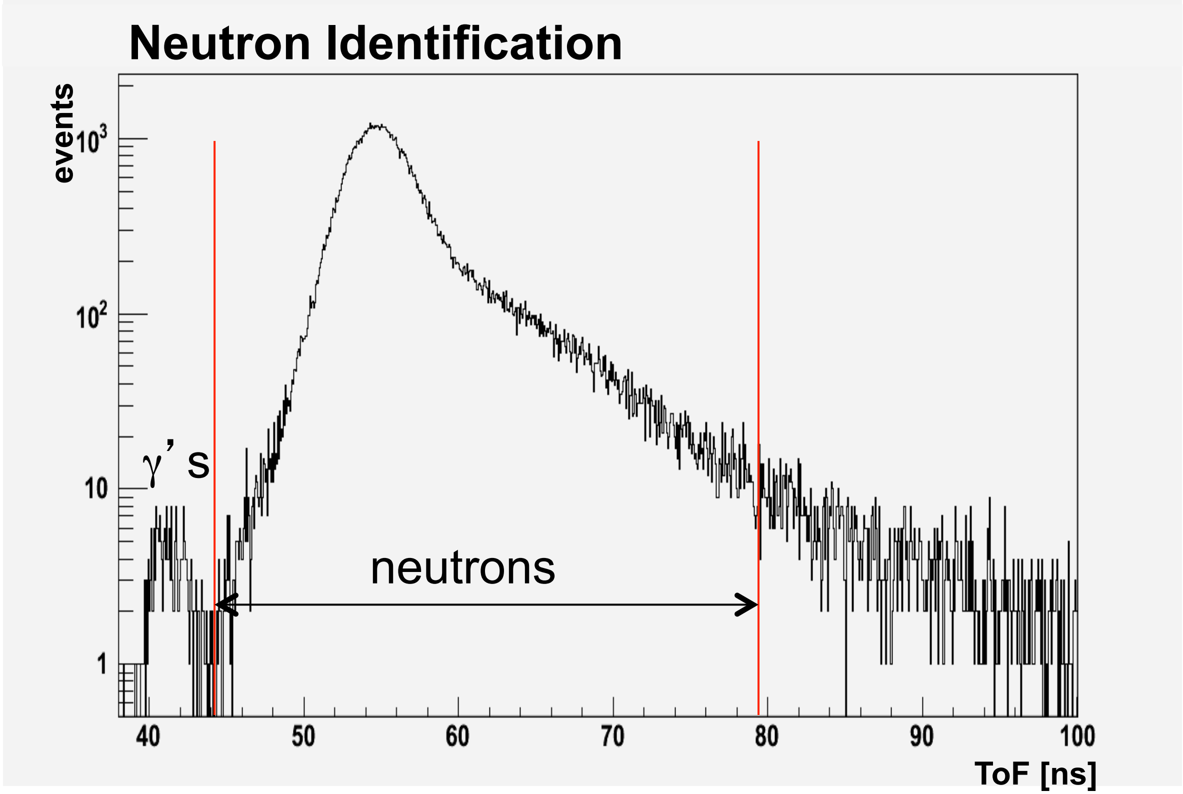
- sandwich detector of active & passive material
- 10 planes and every plane contains 20 modules
- 2 x 2 m with a depth of 1 m
- conversion of neutrons into protons via reactions in iron and the secondary protons are detected with plastic scintillators
- good position & time resolution and high efficiency



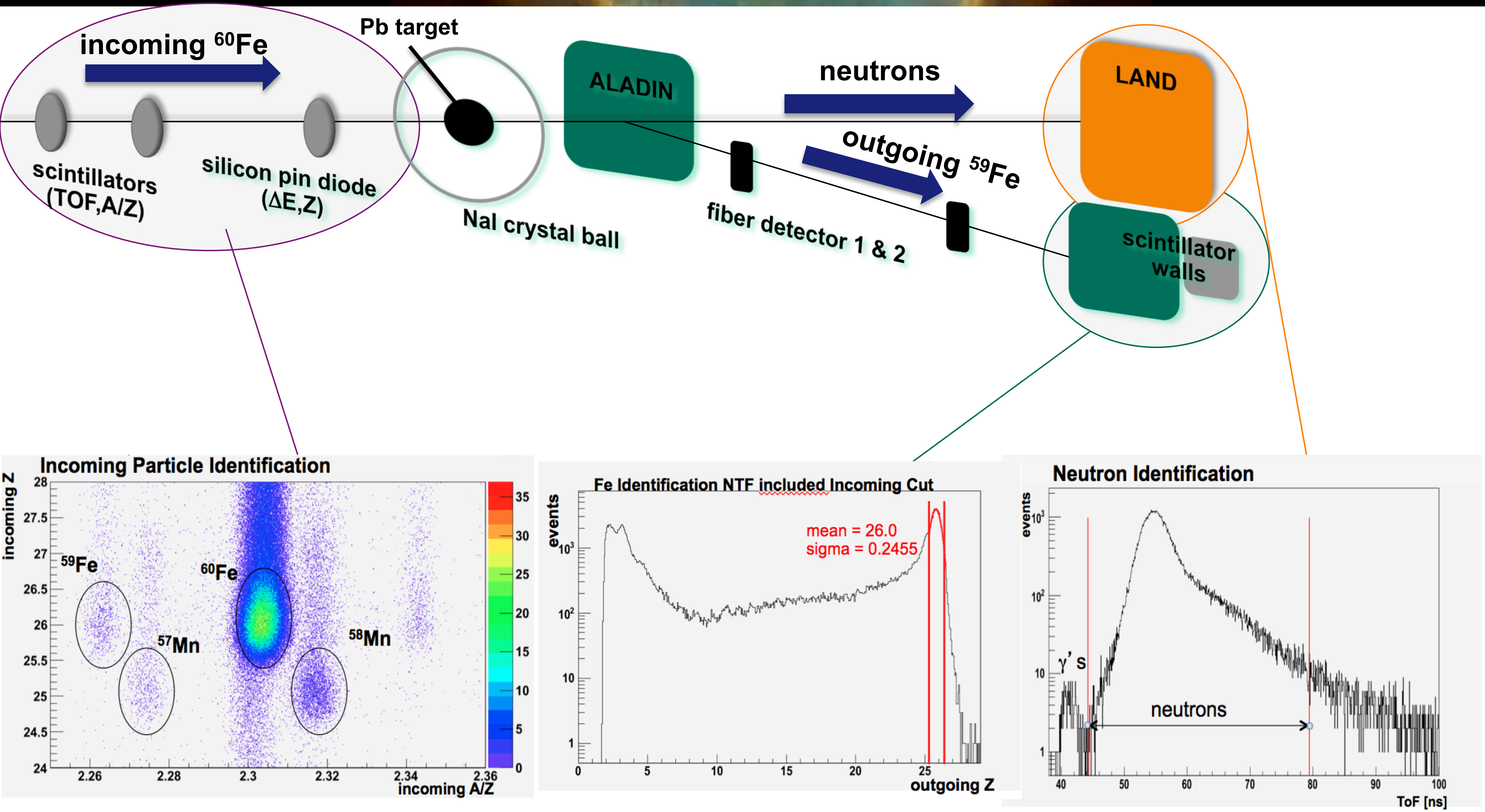
Neutron Identification







First Results



number of breakup events ≈ 70

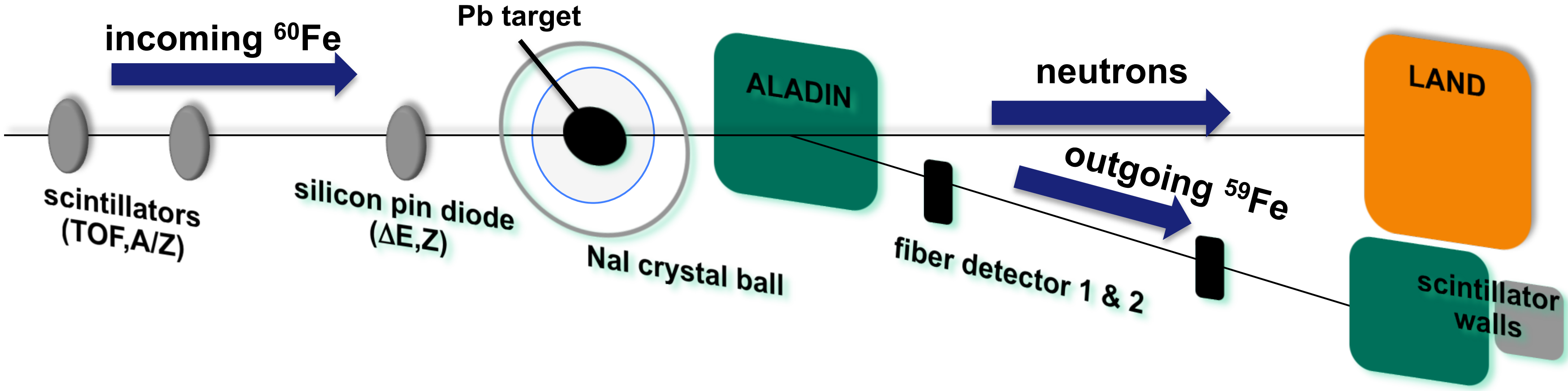
Tracking

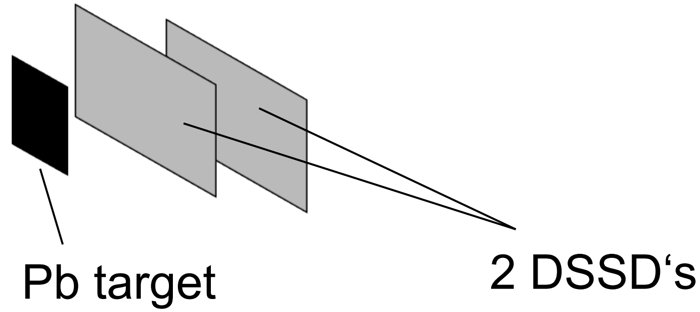
a complete measurement is ensured by the determination of:

- mass determination of outgoing particle
  $\Rightarrow$ distinguish $\frac{A}{Z}$ values: ^{59}Fe & ^{60}Fe
- identification and momentum vector of each ion before reaction
- identification and momentum vector of each ion after reaction
- for energy dependent cross section, the excitation energy needs to be precisely known

  => require precise momentum vectors and angles

Tracking

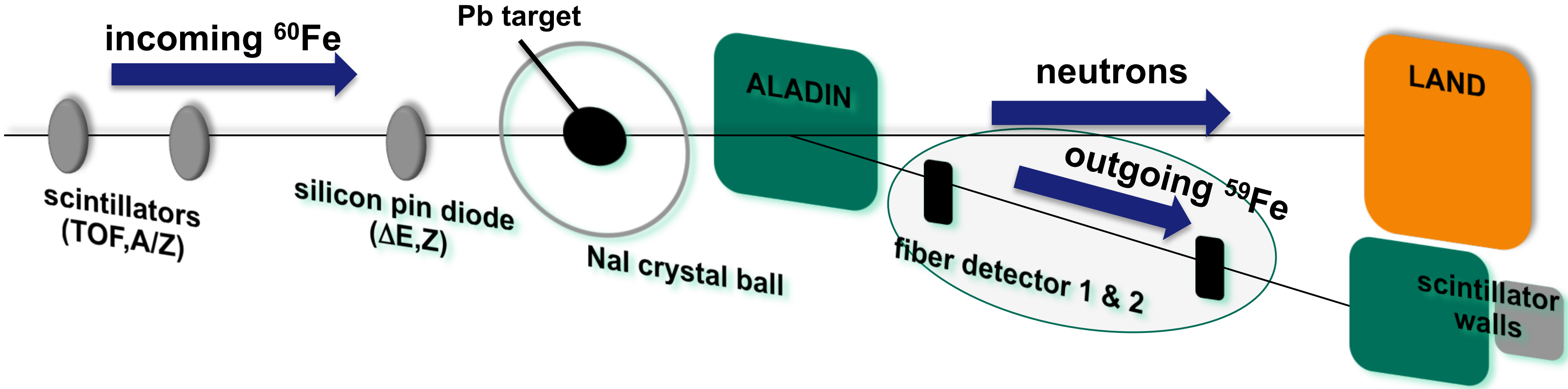


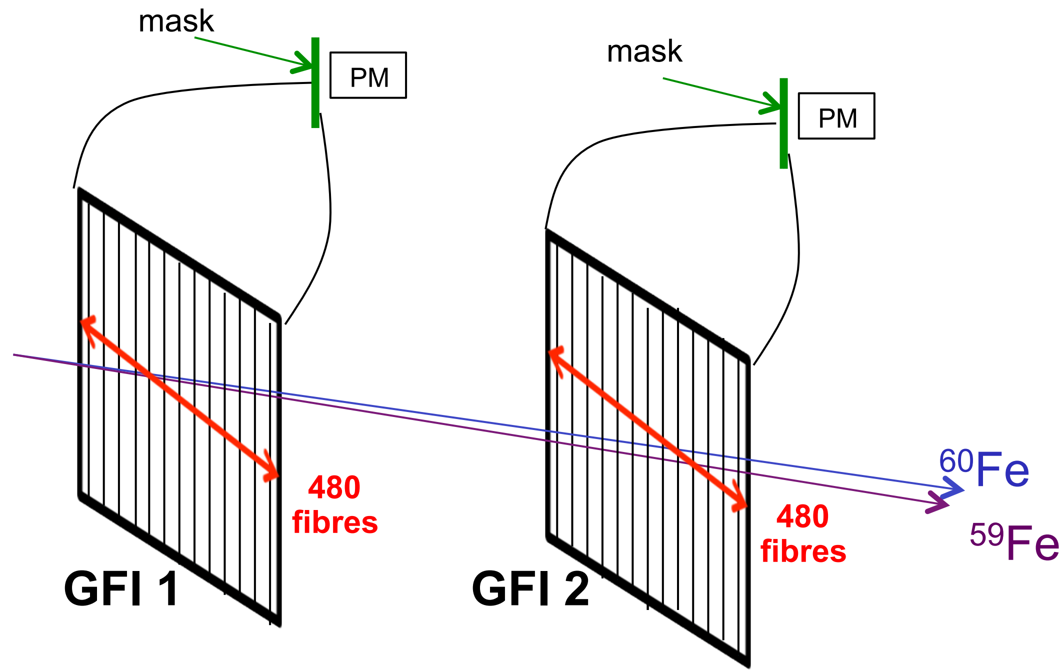


<u>**D**oubled **S**ilicon **S**trip **D**etector:</u>

- Si sensor size: 72 mm x 40 mm
- thickness: 0.3 mm
- x-plane: 640 strips & y-plane: 384 strips
- measures position of fragments with a resolution of ≈ 110 μm

Tracking





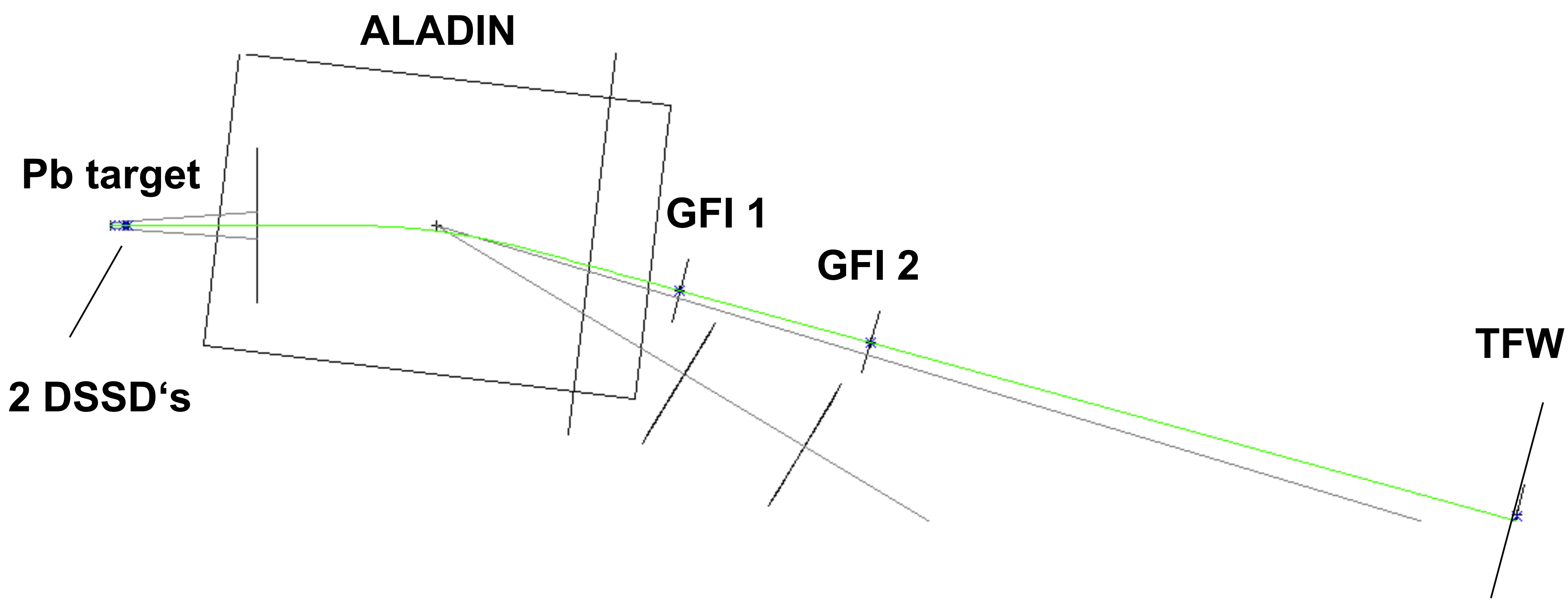
<u>Grand FIbre detector:</u>

- 480 fibres
- read out by a mask and PSPM
- position resolution ~ 1mm
- used for the reconstruction of the particle trajectory

Tracking

event 4

$$\text{deflection angle}_{\text{ALADIN}} \propto \frac{A}{Z}$$



Excitation Energy

- R³B/LAND setup:

  ⇒ many observables can be measured e.g.: TOF, position and ΔE

  ⇒ other quantities like the excitation energy are only accessible via an event-by-event reconstruction

- the invariant masses of the excited incoming and outgoing systems are given by the following expressions:

$$M_{inv}^{incoming} = m_{projectile} + E^*$$

$$M_{inv}^{outgoing} = \sqrt{\begin{pmatrix} \sum_i E_i \\ \sum_i \vec{p}_i \end{pmatrix}^2}$$

i:= fragments in the outgoing channel

Excitation Energy

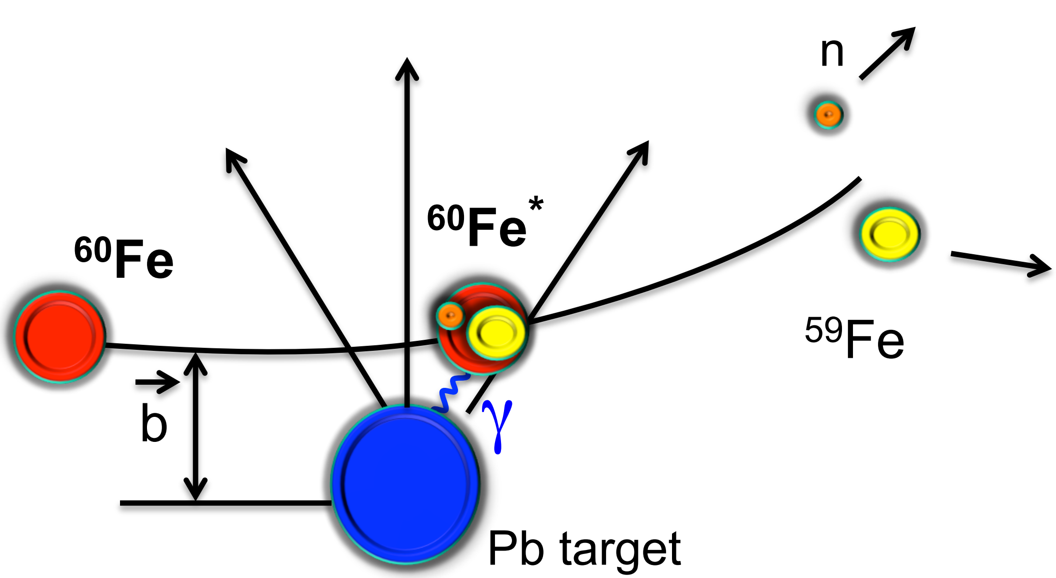
Due to the conservation of the invariant mass, the excitation energy is expressed by:

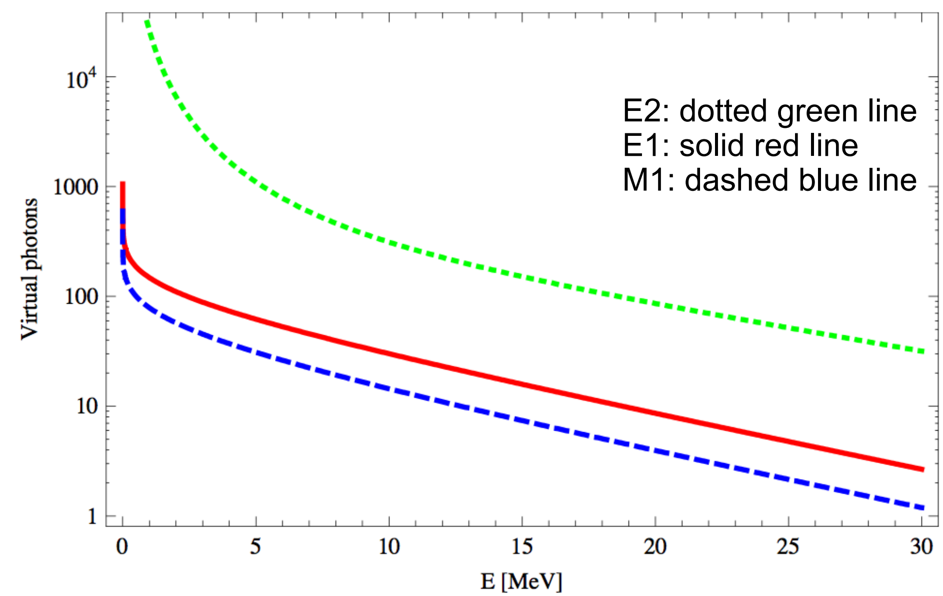
$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j (1 - \beta_i \beta_j \cos \vartheta_{ij})} + E_\gamma - m_{proj}$$

$\Rightarrow$ the reconstruction of the excitation energy relies on the identification and tracking of all outgoing species and on the rest mass of the incoming ion

Excitation Energy

Beam Energy: 535 AMeV





Total virtual photon numbers produced by a 500 AMeV beam impinging on a Pb (Z=82) target

$(\gamma,n) \longleftrightarrow (n,\gamma)$ Cross Section

^{60}Fe Excitation energy spectrum

virtual photon theory ↓

$$\frac{d\sigma_{CD}}{dE_\gamma} = \frac{1}{E_\gamma} n\sigma(\gamma,n)$$

detailed balance ↓

$$\sigma_{(\gamma,n)} = \frac{m_{^{60}Fe} m_\gamma E_{^{60}Fe,n}}{m_{^{59}Fe} m_n E_{^{59}Fe,n}} \frac{(2J_{^{60}Fe}+1)(2J_\gamma+1)}{(2J_{^{59}Fe}+1)(2J_n+1)} \sigma_{(n,\gamma)}$$

Future Plans & Summary

- steps of the analysis:
  - energy-dependent information about the dissociation cross section $^{60}Fe(\gamma,n)^{59}Fe$
  - determination of $^{59}Fe(n,\gamma)^{60}Fe$ cross section by the principle of detailed balance

- nucleosynthesis simulations of the late stages of massive stars

- experiment $^{60}Fe(\gamma,n)^{59}Fe$ at GSI succesfully performed
- analysis in progress

Production and Destruction of ^{60}Fe

$^{60}Fe(\beta^-)$:
in progress, new measurements: e.g.
S. Söllradl
G. Rugel
W. Kutschera et al.
R. Dressler et al.

$^{59}Fe(n,\gamma)$:
extremely difficult

^{60}Fe

$(n,\gamma)^{61}Fe$:
activation experiment
kT = 25 meV
kT = 25 keV
kT = 90 keV
R. Reifarth et al.
next talk

this talk

$^{60}Fe(\gamma,n)$:
coulomb dissociation,
experiment performed

Thank you for your attention!