Direct measurement of the $^{12}C(^{12}C,\alpha)^{20}Ne$ cross section at stellar energies

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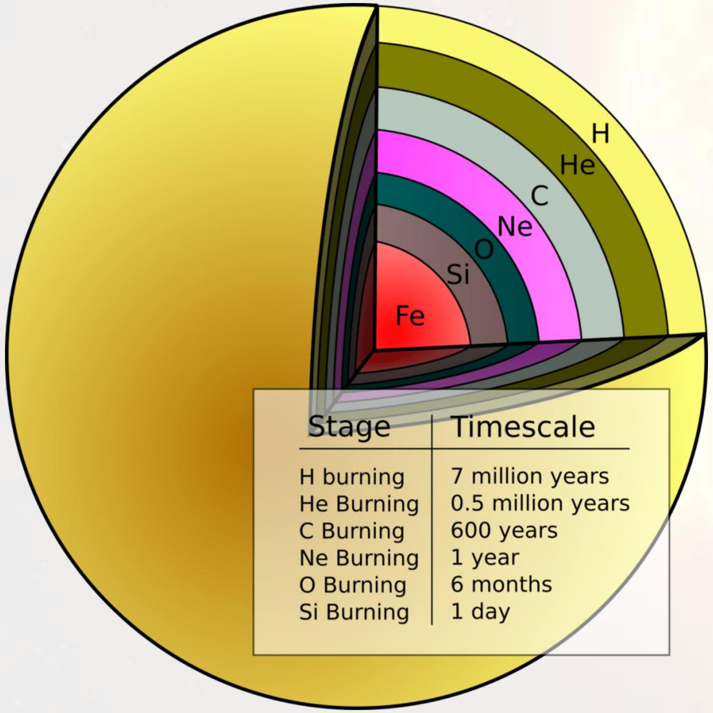
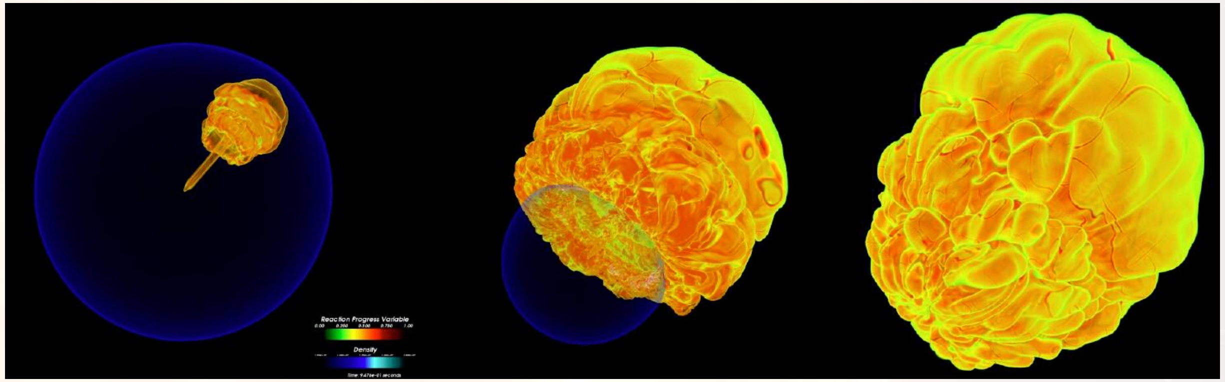
The carbon fusion reactions in the Universe

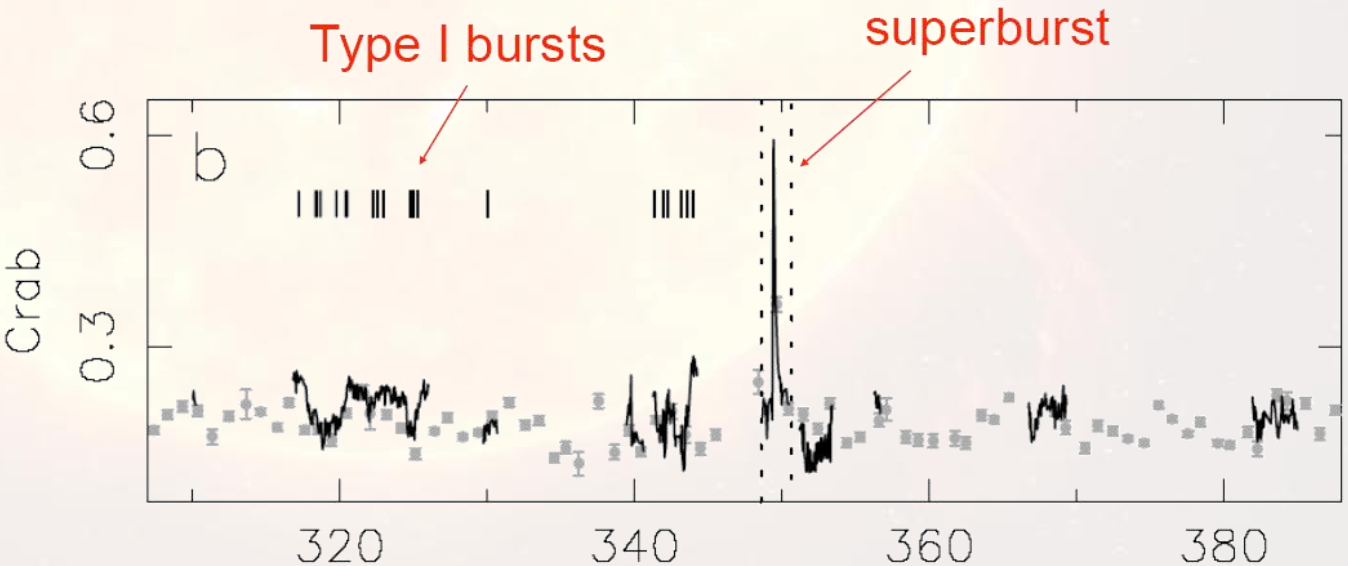
Nucleosynthesis in massive stars



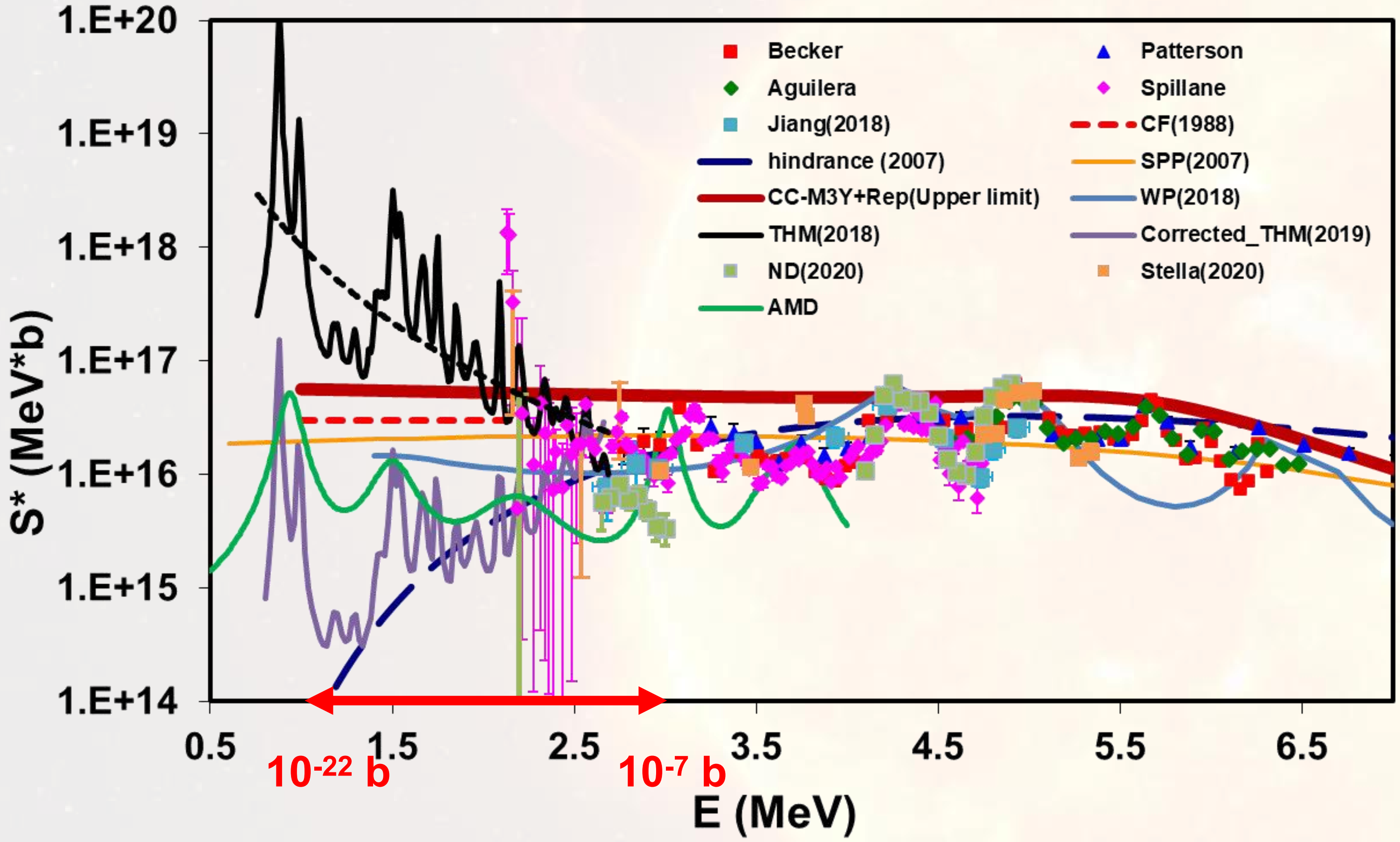
Ignition in type Ia supernovae



Candidate for Superburst ignition



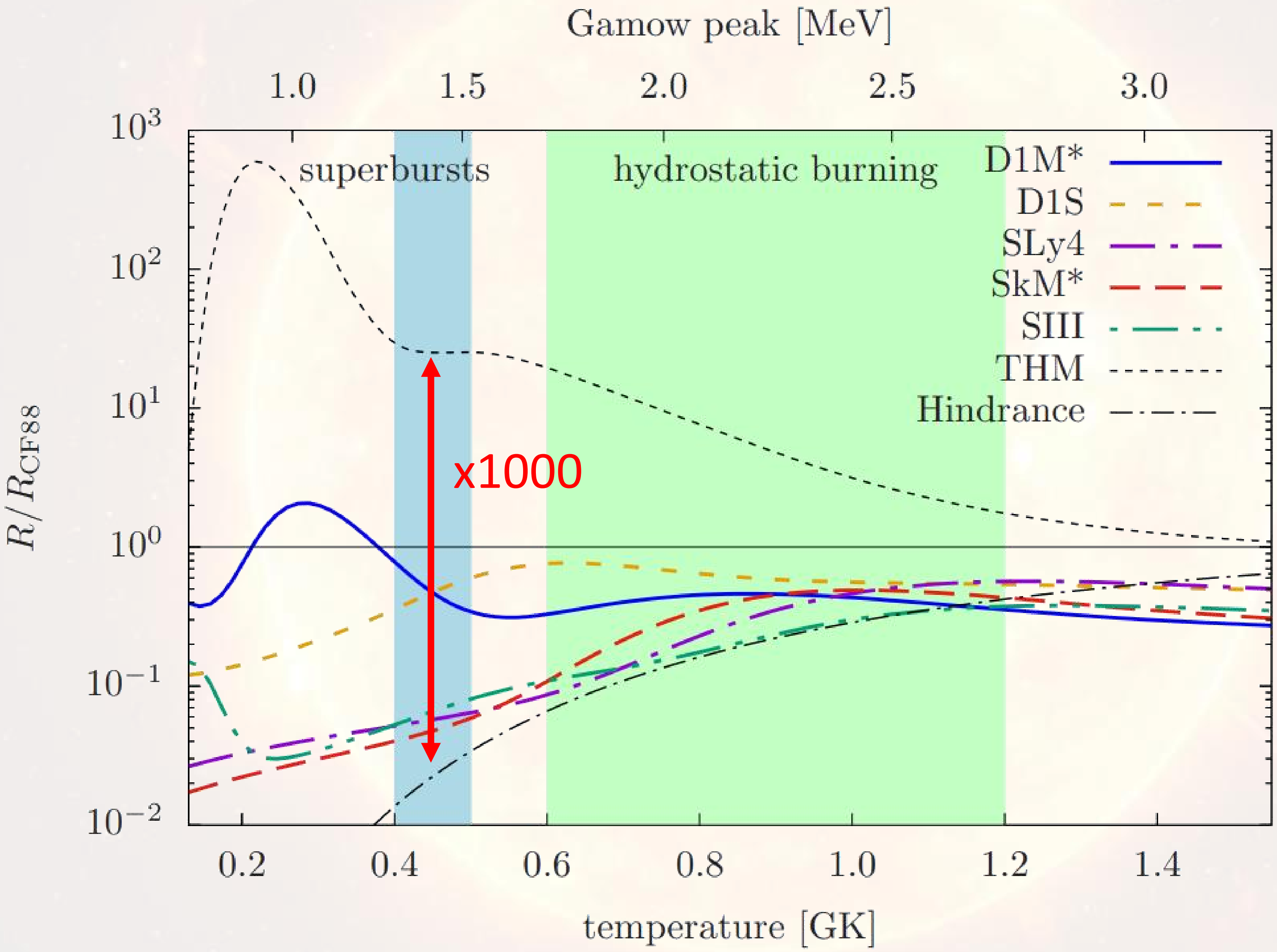
Uncertain cross section at stellar energies



- Large Uncertainty in experimental results within the Gamow window
- Different predictions between models and indirect methods
- Unknow resonances: Need better selection T=0, $J^{\pi}=0^+,2^+$? lack of information of angular distribution

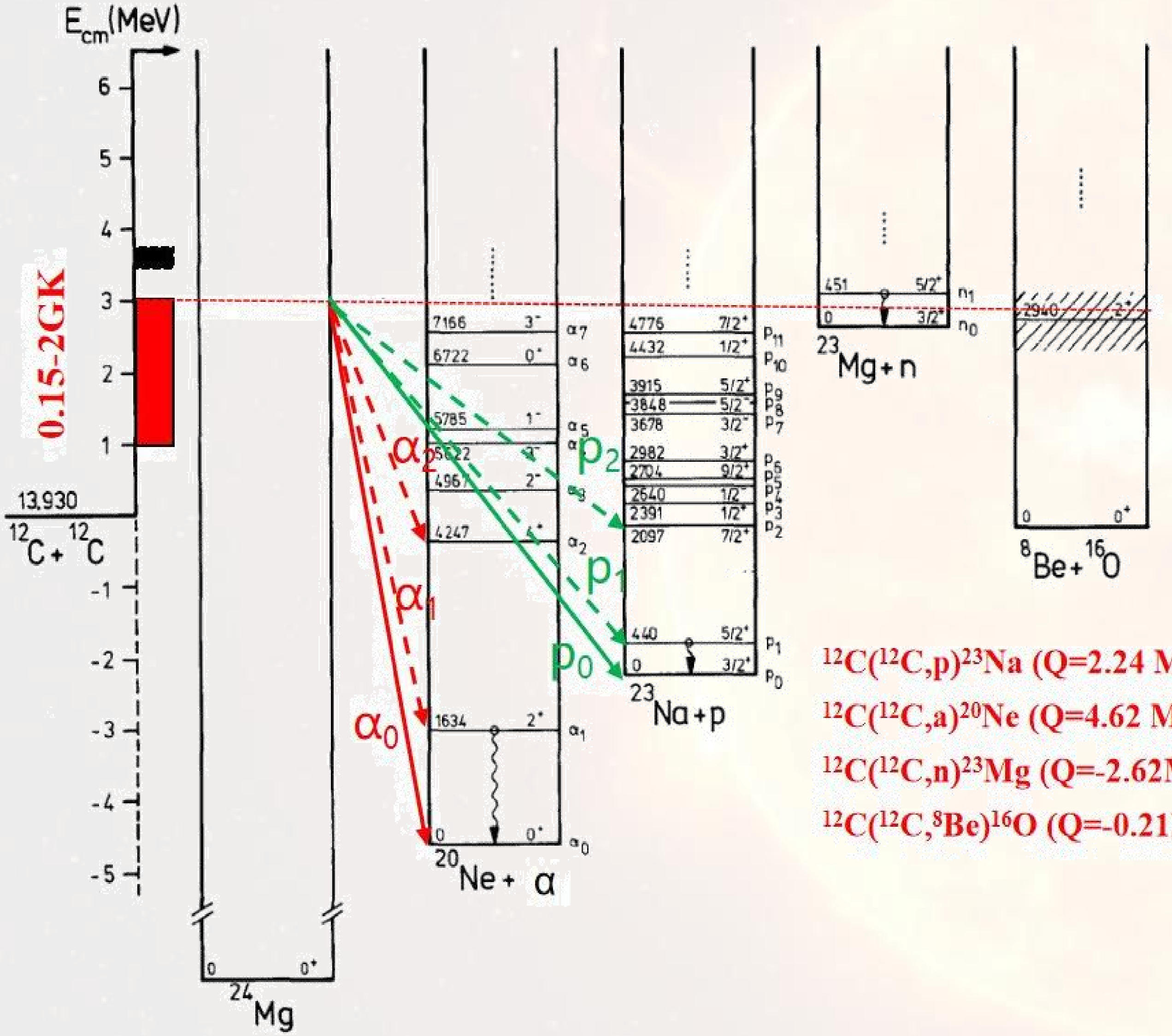
Beck, Mukhamedzhanov and Tang, Eur. Phys. J. A (2020) 56:87
Mukhamedzhanov, Eur. Phys. J. A (2022) 58:71
Tang & Ru, EPJ Web of Conferences 260, 01002 (2022)

Uncertain cross section at stellar energies



Taniguchi & Kimura, Phys. Lett. B 849 (2024)

Why we focus on the g.s. channels



$^{12}C(^{12}C,p)^{23}Na$ (Q=2.24 MeV)

$^{12}C(^{12}C,a)^{20}Ne$ (Q=4.62 MeV)

$^{12}C(^{12}C,n)^{23}Mg$ (Q=-2.62MeV)

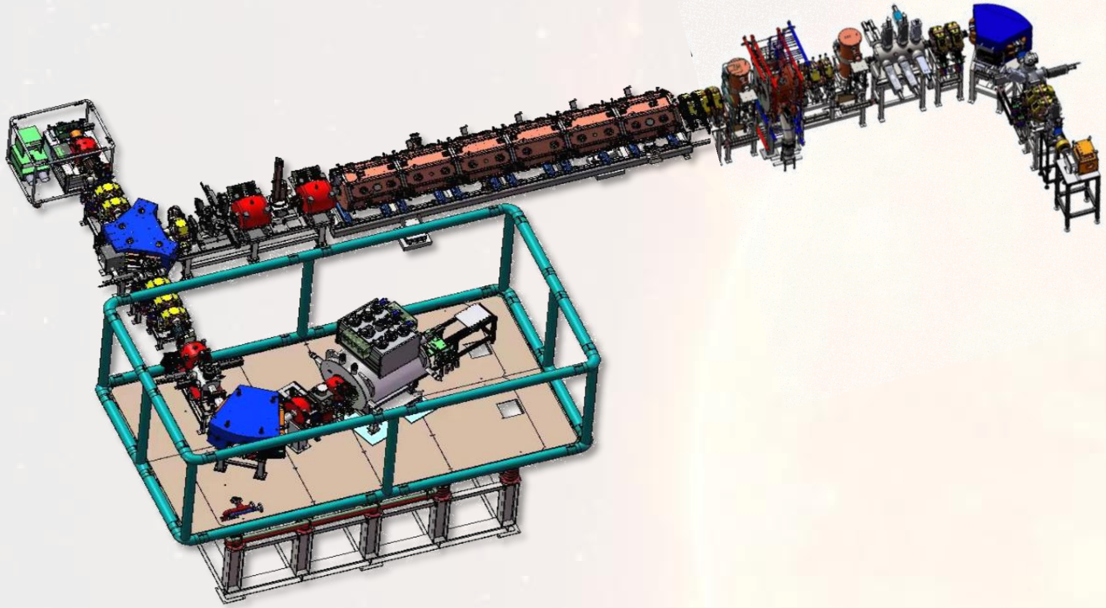
$^{12}C(^{12}C,^{8}Be)^{16}O$ (Q=-0.21MeV)

How to study this reaction?

- **Charged-particle measurement**
  - low statistics
  - huge backgrounds
- **γ-ray measurement**
  - sensitive probe
  - 1634keV, 440keV
  - cannot study the g.s. channels
- **Particle-γ coincidence**
  - suppress backgrounds
  - cannot study the g.s. channels

The accelerator and detectors

Low Energy Accelerator Facility (LEAF)

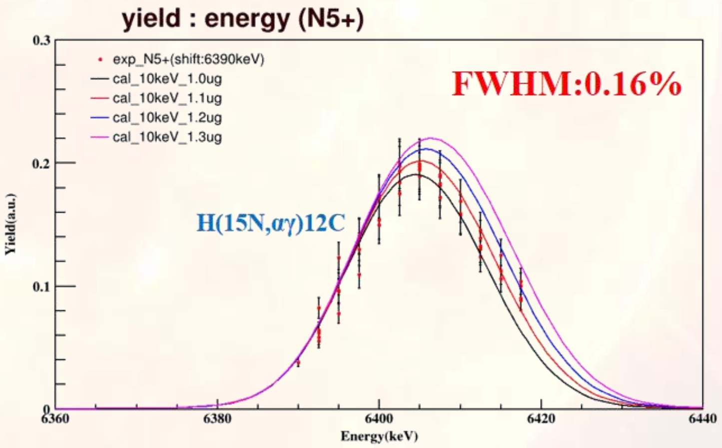


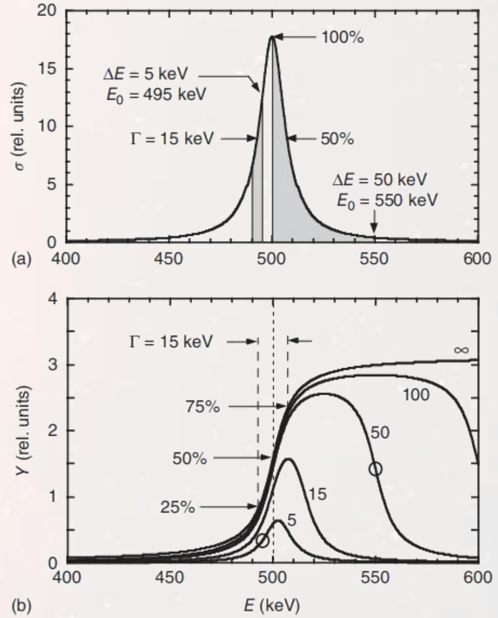
Accelerator platform：

- up to 100 puA(Spillane: 40puA) C^{2+}
- Energy spread < 0.2%
- Energy for ^{12}C beam: 4 - 8 MeV

Energy calibration by nuclear reaction resonances:

- $^{27}Al(p,\gamma)^{28}Si$： Er = 405.5 keV
- $H(^{15}N,\alpha\gamma)^{12}C$： Er = 6398 keV





Christain Iliadis,
Nuclear Pyhsics of Stars

The accelerator and detectors

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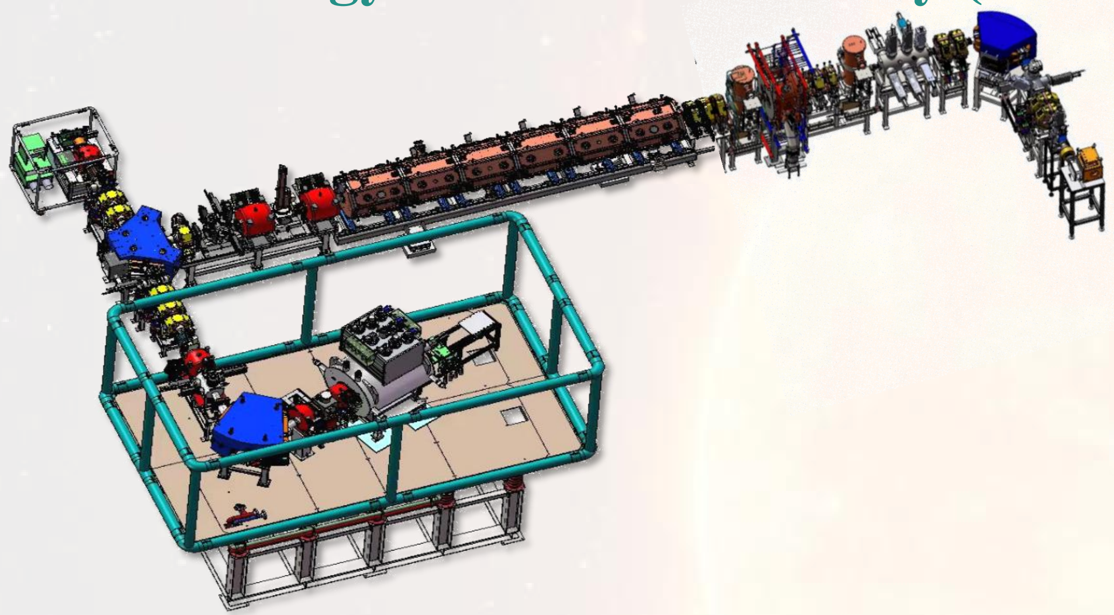

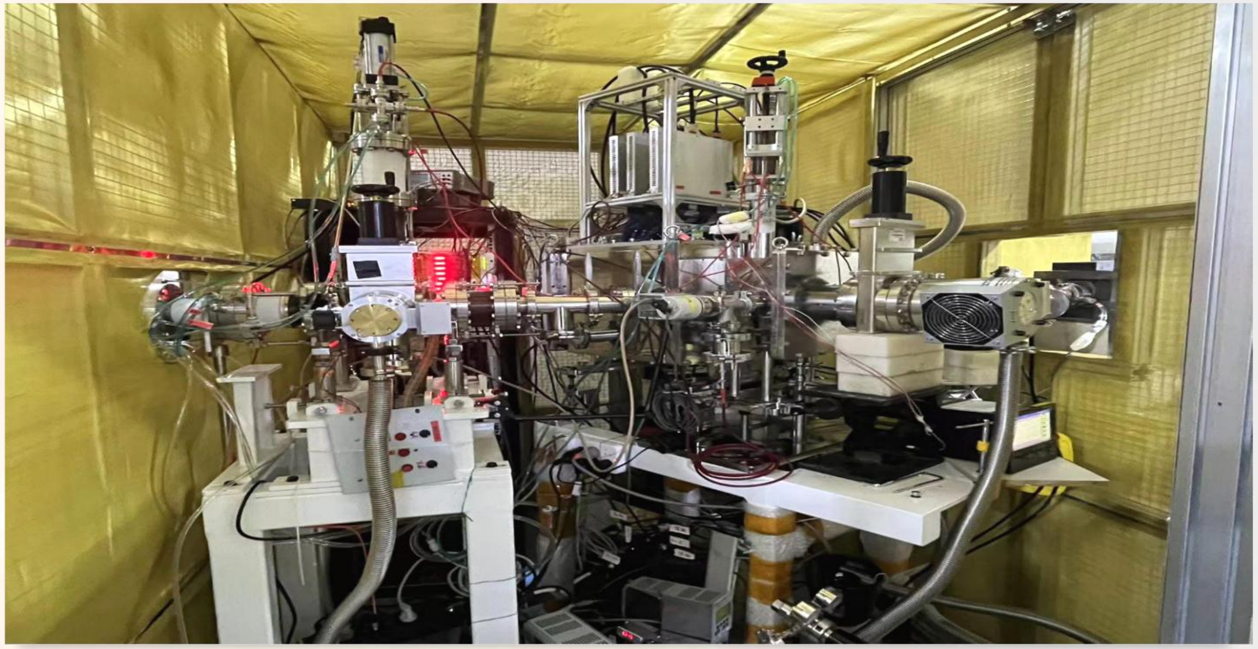

Accelerator platform：

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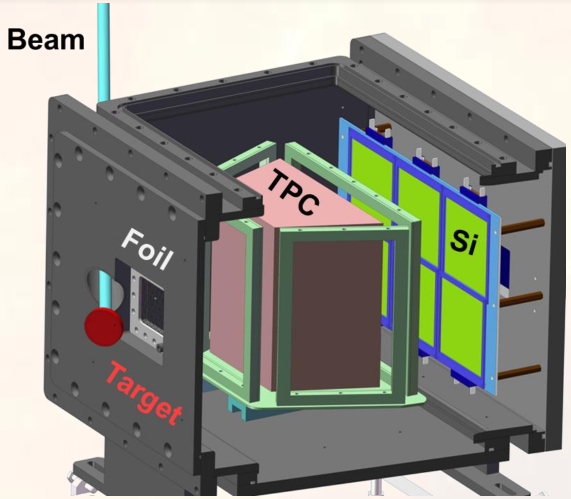
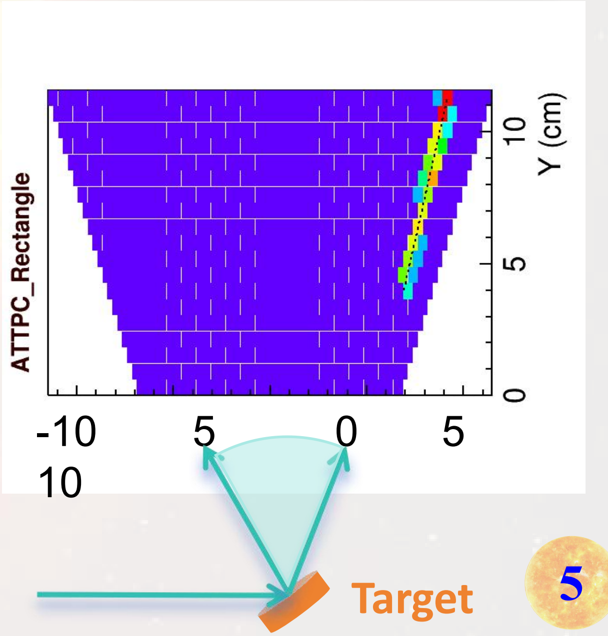
Detection system:

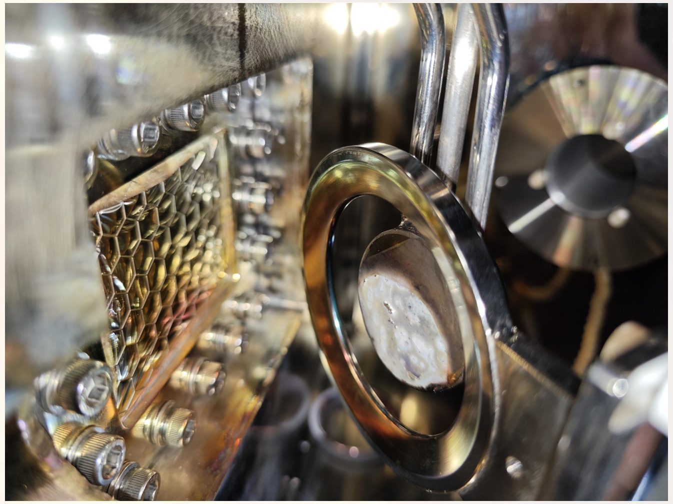
- **TPC:** Ultra sensitive tracking detector
- **Si:** record energy information



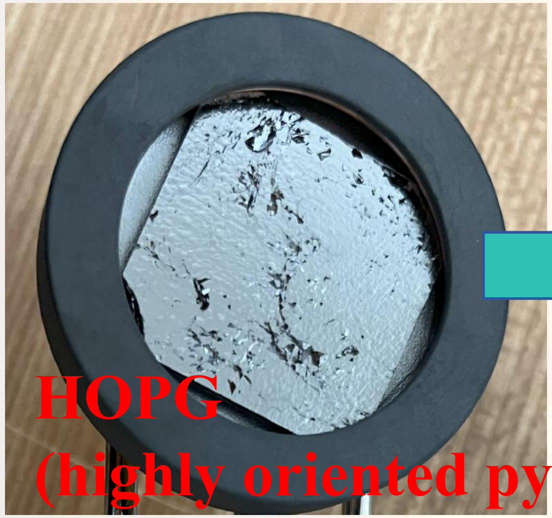


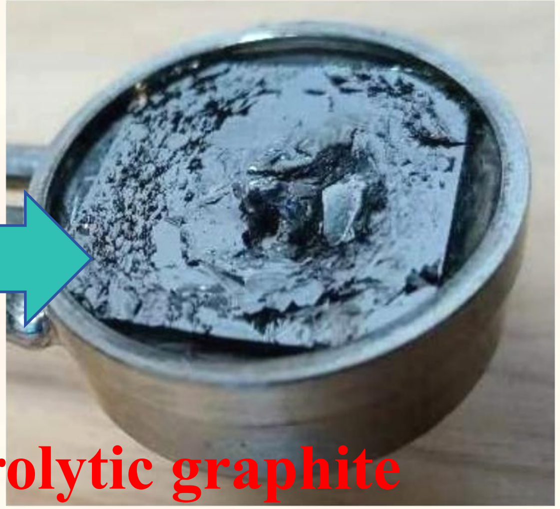
Carbon targets

- The selection of carbon target
  - high-purity: very little ^{13}C, Li, Be, B...
  - very thick target, unsensitive to target declination
  - stable, not easily destroyed by beam
  - good conduction for heat



99.999%
pure graphite



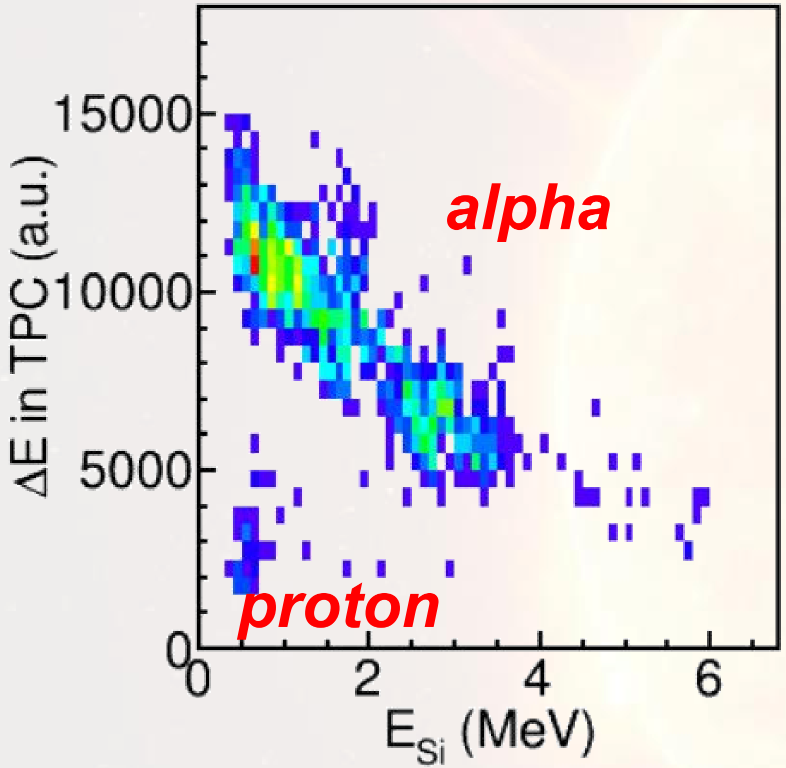


HOPG
(highly oriented pyrolytic graphite

DLC

Analysis: Ecm=2.75MeV with graphite

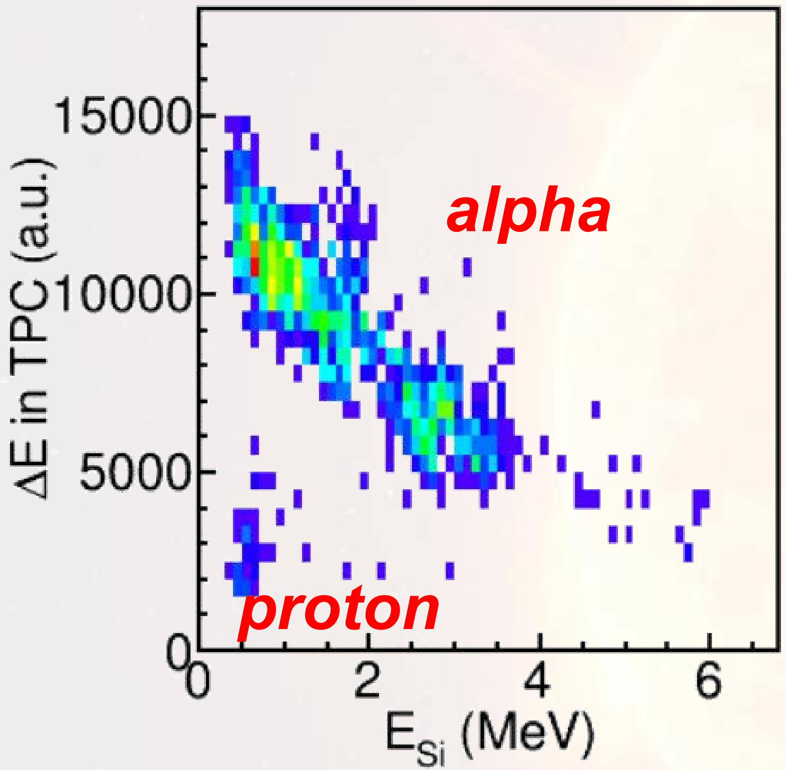
Particle identification



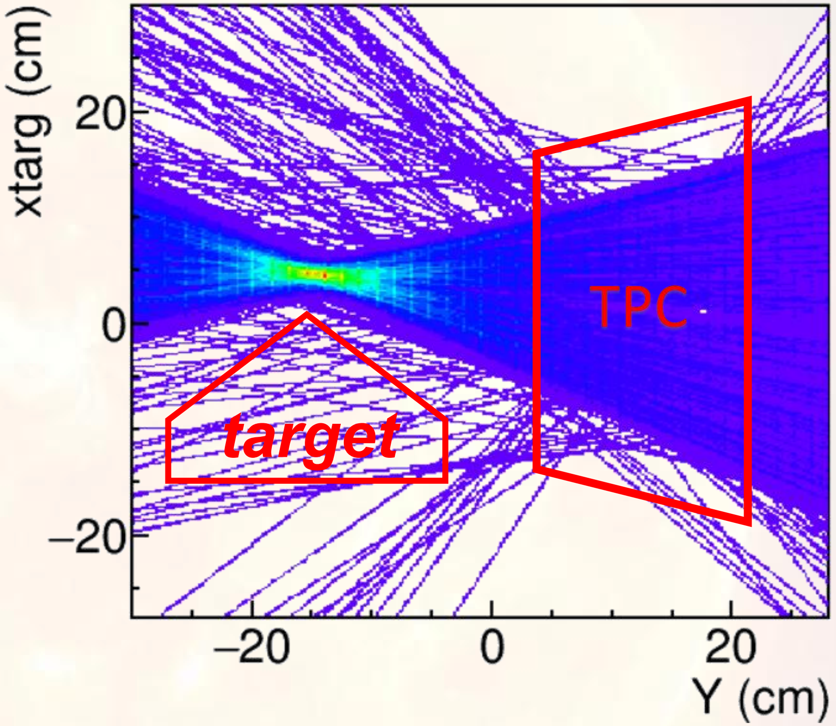
✓ Particle identification via energy-loss in TPC and energy in silicons

Analysis: Ecm=2.75MeV with graphite

Particle identification

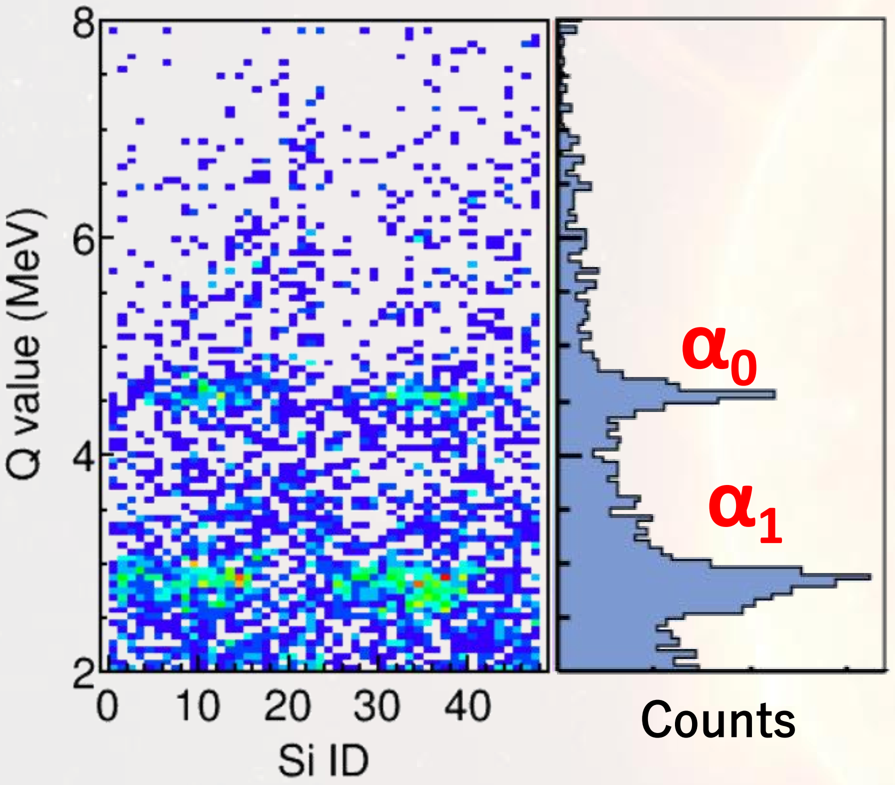


Track tracing



- ✓ Particle identification via energy-loss in TPC and energy in silicons
- ✓ Tracing the origin of tracks to suppress natural backgrounds

Analysis: Ecm=2.75MeV with highly pure graphite

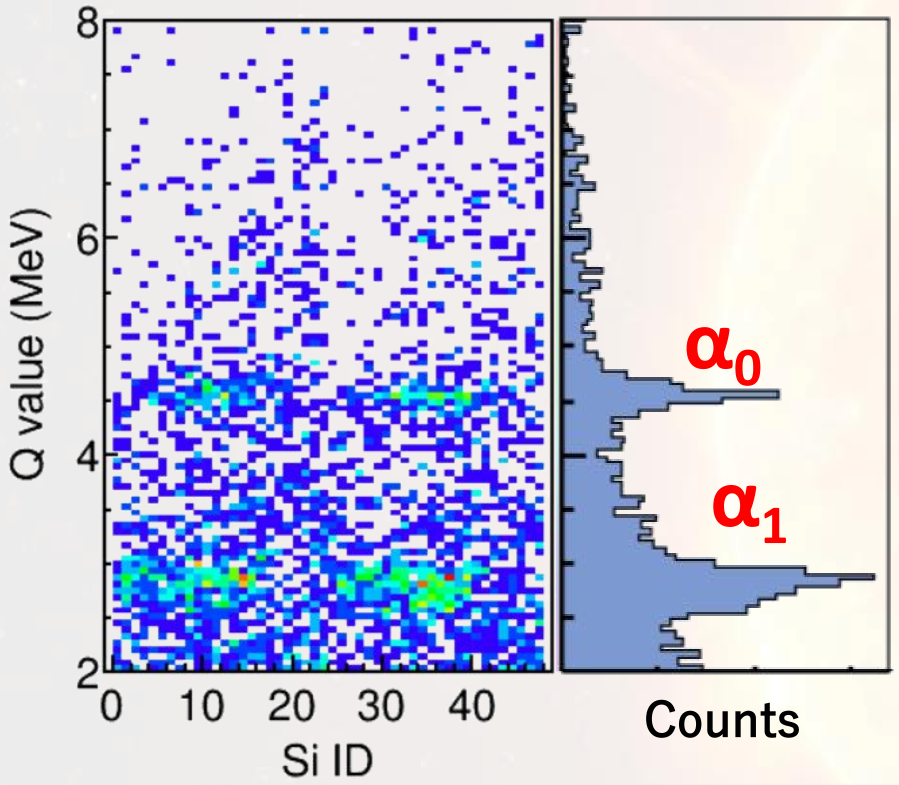


spectra w/o tracking

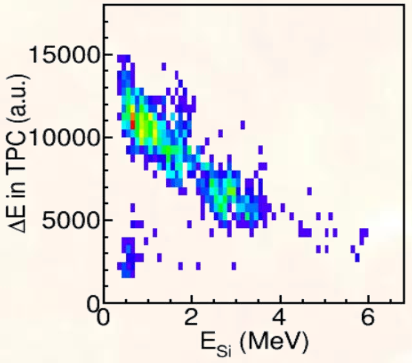
The Q-values for this reaction were calculated from the angles and energies of ejections

Alpha peaks can be found with backgrounds

Analysis: Ecm=2.75MeV with highly pure graphite

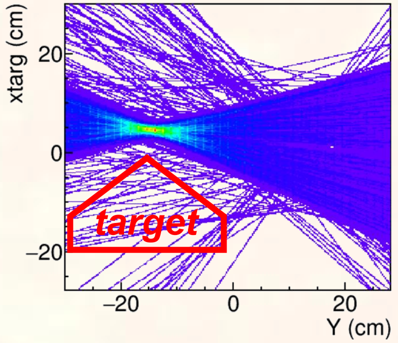


spectra w/o tracking



(1) Particle identification
to choose alpha events

(2) track selection
to choose events from target



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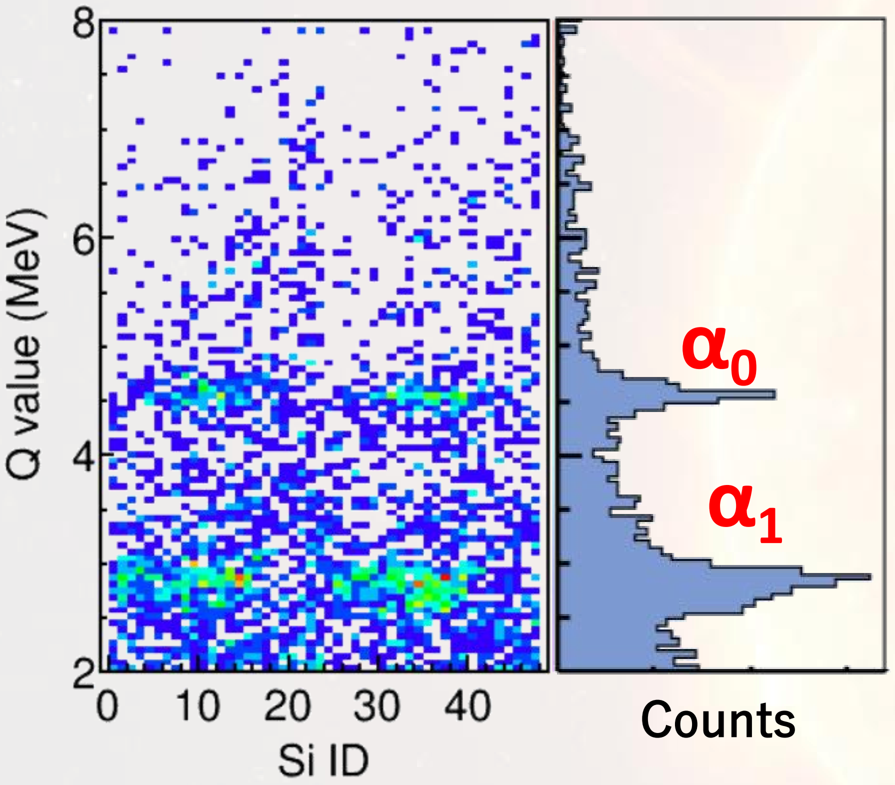

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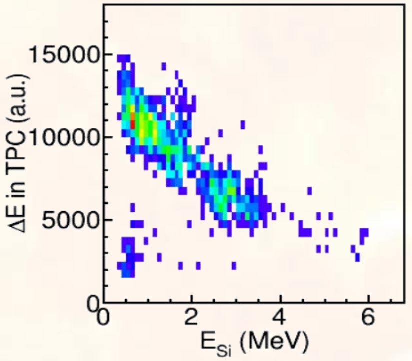

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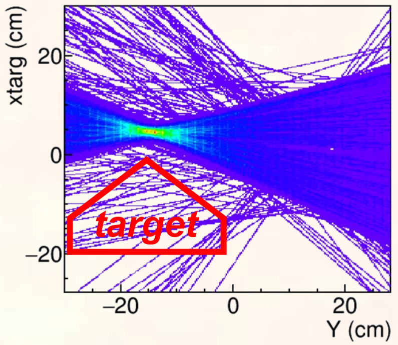
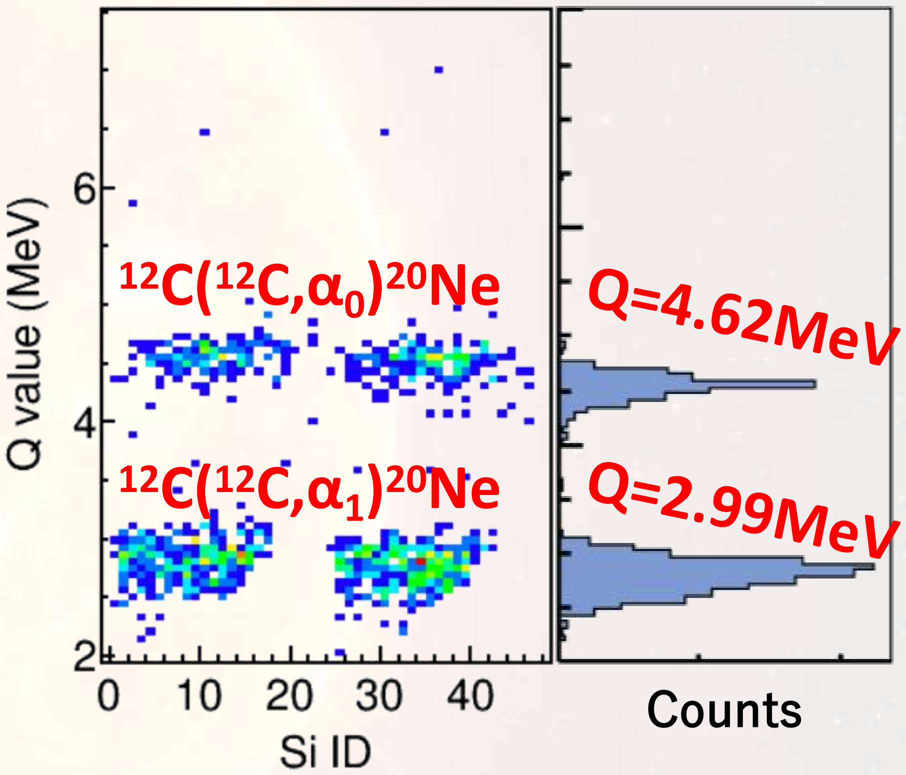
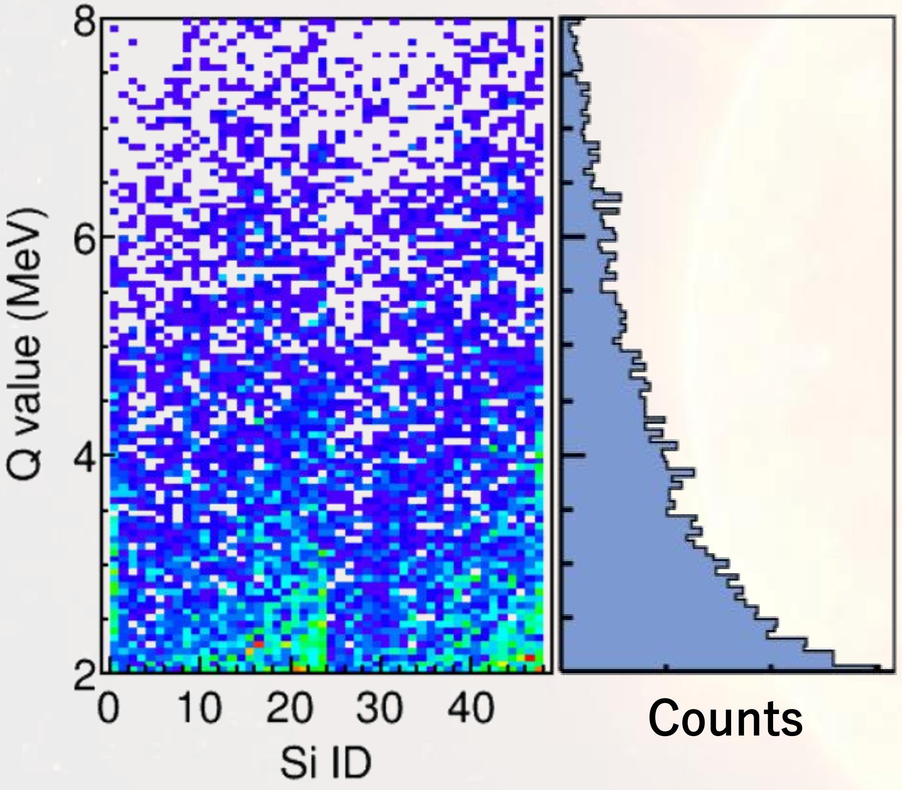




spectra w/ tracking

Analysis: Ecm=2.40MeV with HOPG

Very low energy : Long-time measurement brings **more backgrounds**
but **events of interests are even fewer**



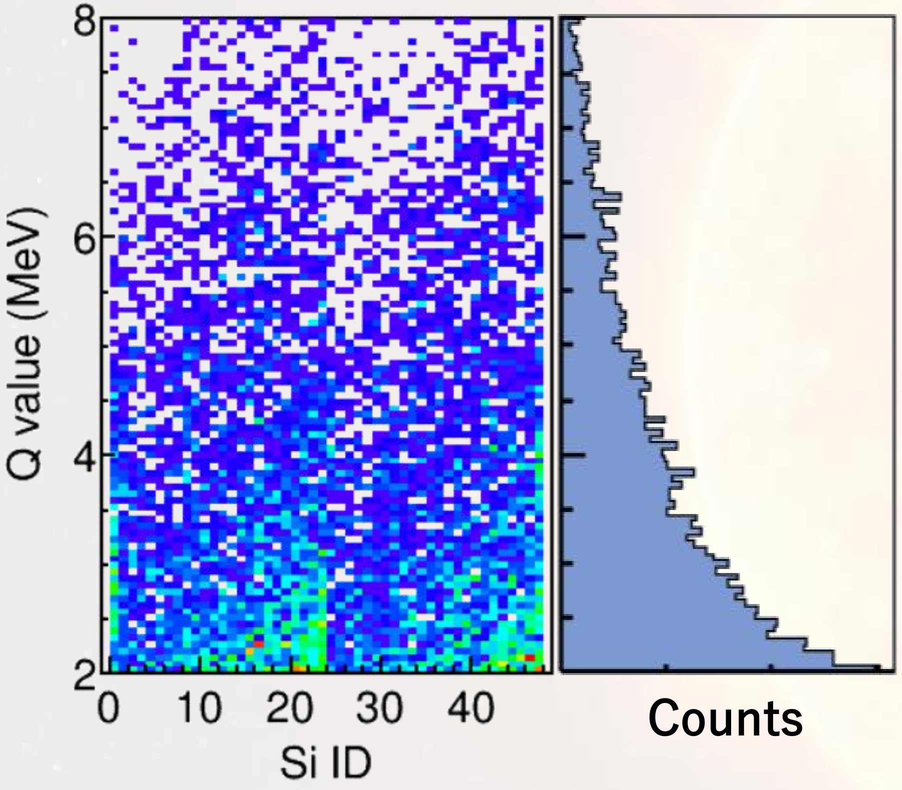
spectra w/o tracking

No signals in the natural alpha backgrounds

It`s difficult for direct measurements at such low energies

Analysis: Ecm=2.40MeV with HOPG

Very low energy : Long-time measurement brings **more backgrounds**
but **events of interests are even fewer**

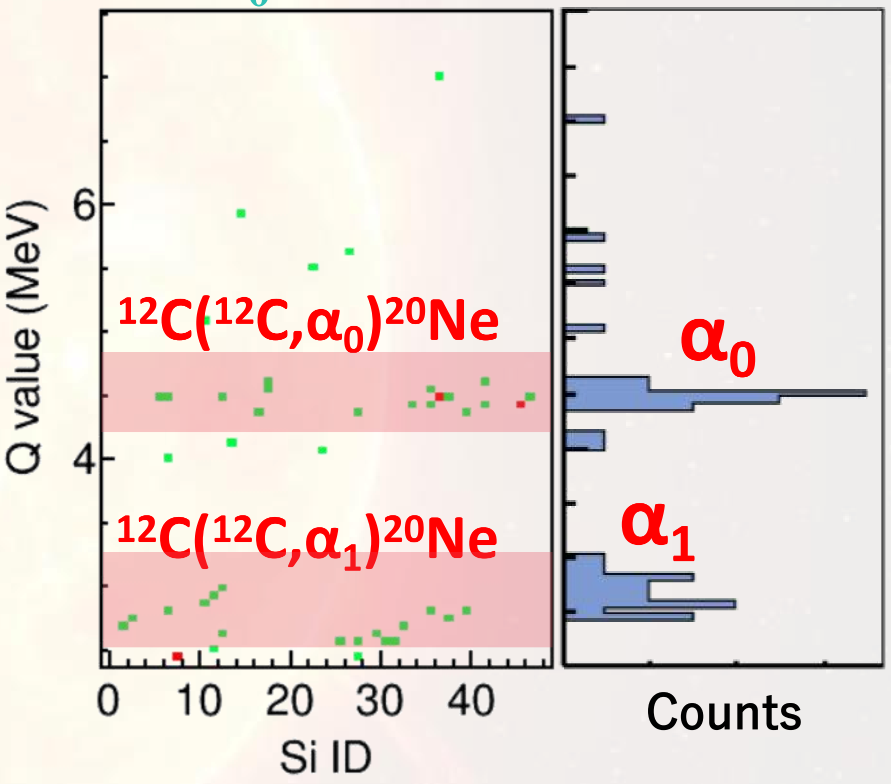


spectra w/o tracking

Particle identification

track selection

19 α_0 events in 16 hours



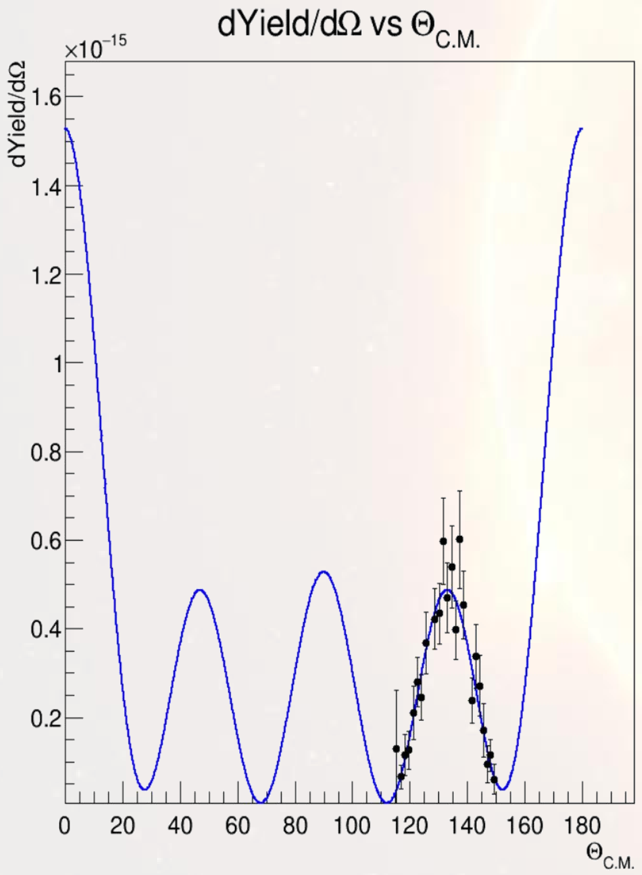
spectra w/ tracking

The TPC+Si systerm is still effective in very-low-energy measurement!

Angular Distribution Results

The detector solid angle coverage θ： 116°-151°(c.m.) / 100°-140° （lab.)

Differential thick target yield dYield/dΩ can be calculated



fitted by R-matrix using AZURE2

- Similar methods are applied to obtain the angular distribution from E_{cm} = 2.4MeV to E_{cm} = 3.5MeV
- First high-precision angular distribution measurement of $^{12}C(^{12}C,\alpha_0)^{20}Ne$ channel below E_{cm} = 3.0MeV
- The J^{π} of resonances can be determined with the information of angular distribution

Summary

❑Direct measurement of $^{12}C+^{12}C$ (charged particle measurement)

- First direct measurement of a_0 channel below 2.5 MeV indicates new resonances
- Analysis of angular distribution in large energy range
- Complementary to direct measurements (eg. gamma ray, particle-gamma) of other reaction channels
- New reaction rate ~ CF88/3

❑Indirect+Direct measurements +theoretical extrapolation are essential

- Direct measurements will help theories(eg. AMD) and indirect measurements (THM, ^{24}Mg(a,a'))to provide a more reliable prediction
- Experiments for lower energies and more channels are needed
- Collaboration will end up with better science!

CARbon FUSion Experiment (CARFUSE) @LEAF, IMP

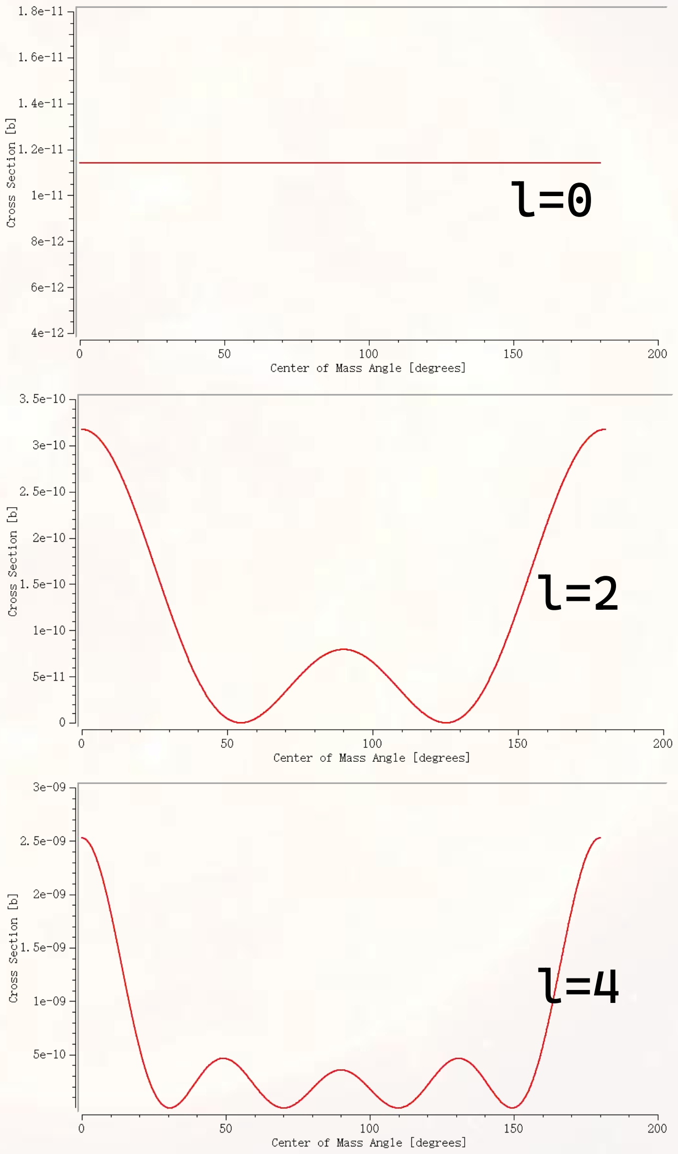
Backups

Backup

Legendre polynomials can be used to describe the variation of the differential cross section with respect to the angle.

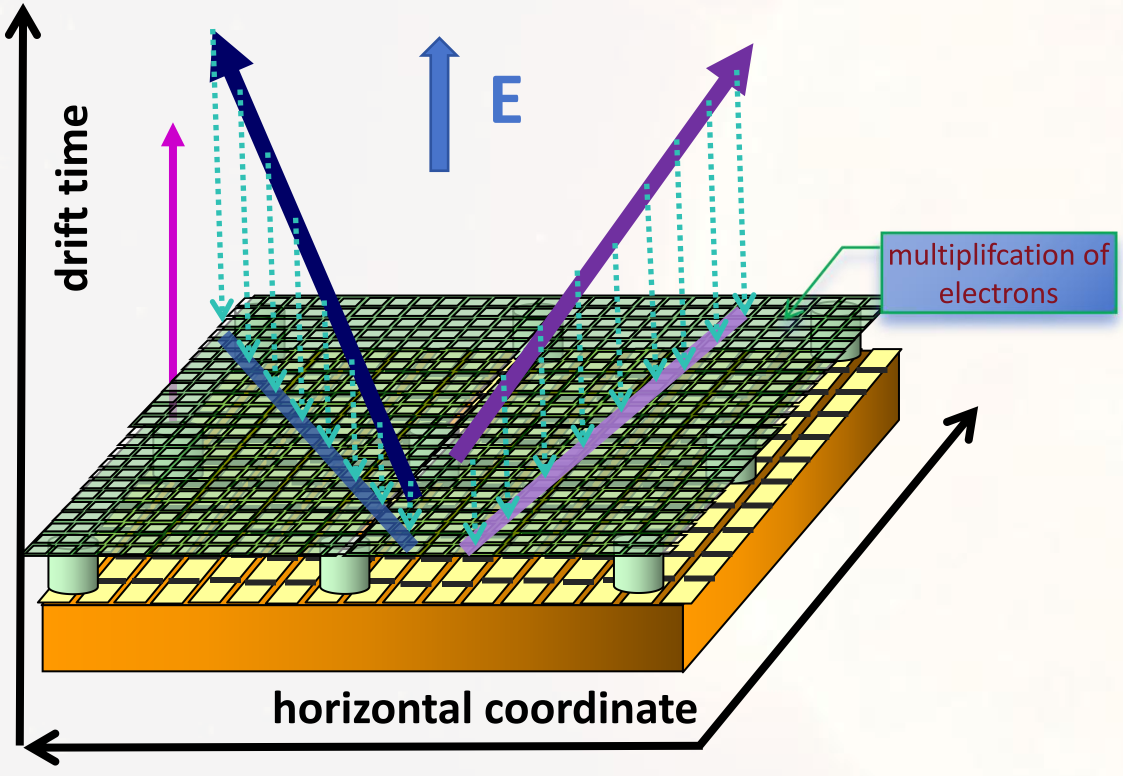
$$\frac{d\sigma}{d\Omega}(\theta_{c.m.}) = \sum(b_l P_l(cos\theta_{c.m.}))$$

n	$P_n(x)$
0	1
1	x
2	$\frac{1}{2}(3x^2 - 1)$
3	$\frac{1}{2}(5x^3 - 3x)$
4	$\frac{1}{8}(35x^4 - 30x^2 + 3)$
5	$\frac{1}{8}(63x^5 - 70x^3 + 15x)$
6	$\frac{1}{16}(231x^6 - 315x^4 + 105x^2 - 5)$
7	$\frac{1}{16}(429x^7 - 693x^5 + 315x^3 - 35x)$
8	$\frac{1}{128}(6435x^8 - 12012x^6 + 6930x^4 - 1260x^2 + 35)$

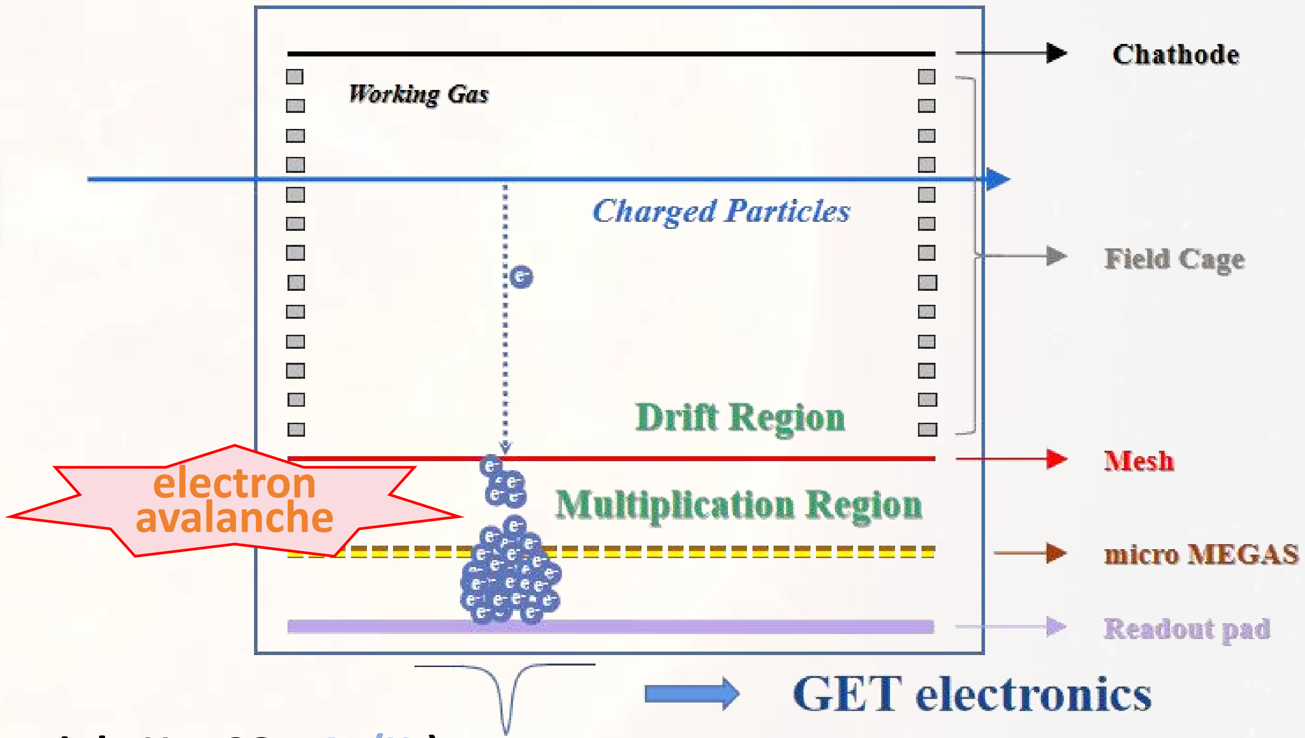


Time Projection Chamber(TPC)

How to get tracks



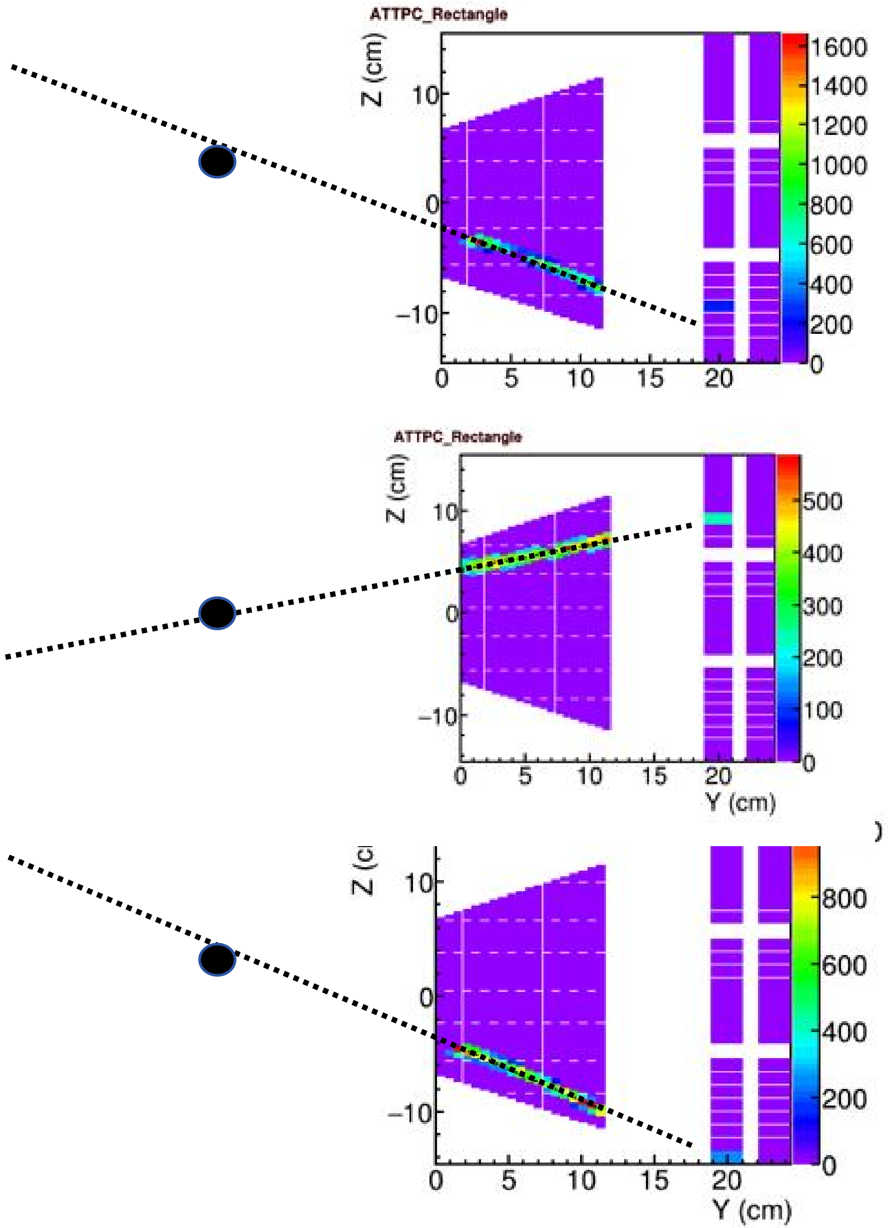
How to get the loss energy

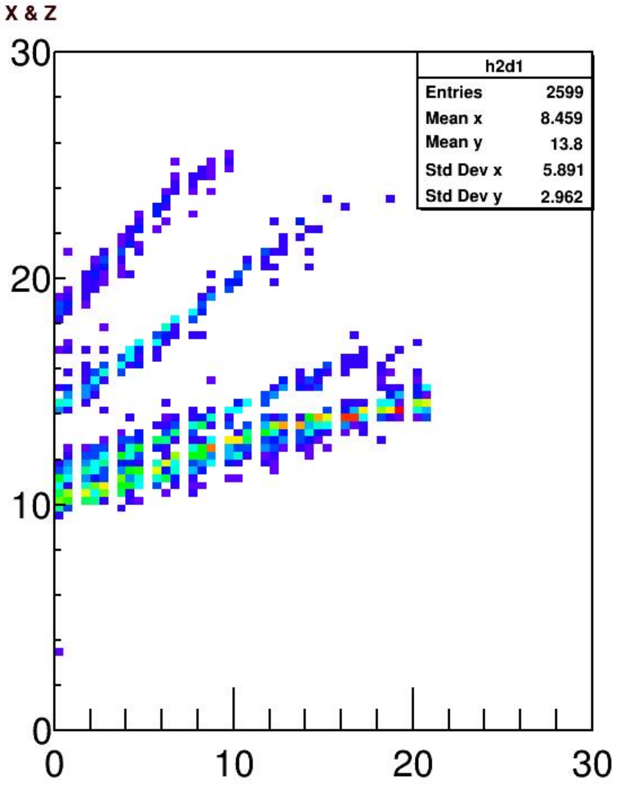


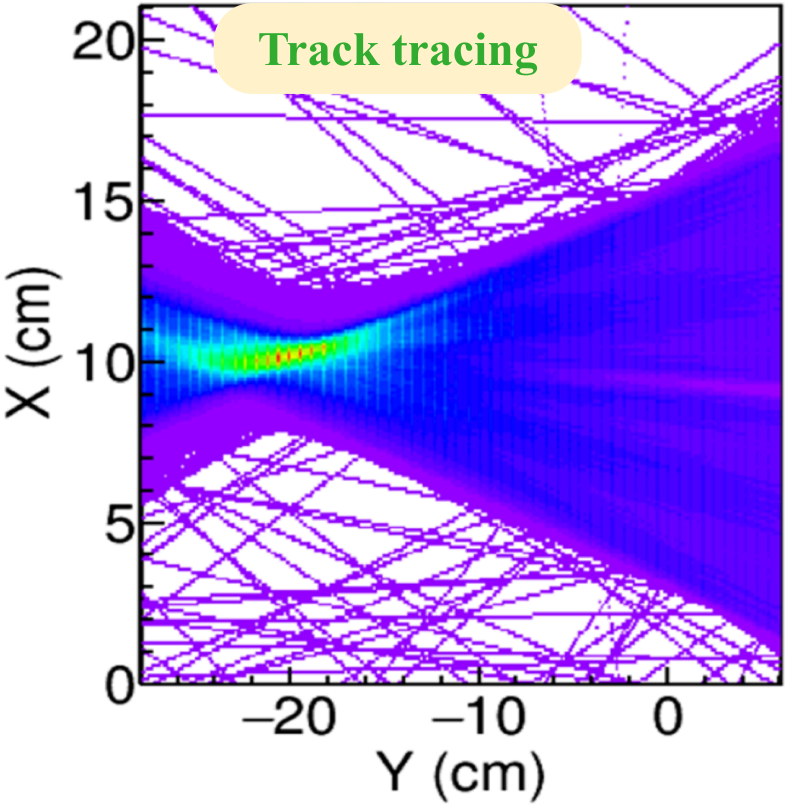
- Charged particles ionize electrons from working gas(mainly He+CO_2+Ar/Kr)
- Electrons drift to the *micro MEGAS* and are multiplied, the position and signal amplitude are recorded

Data analysis

Event selection

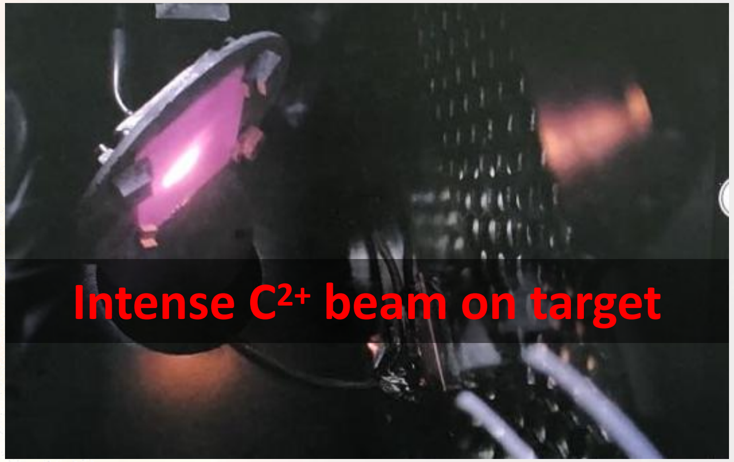




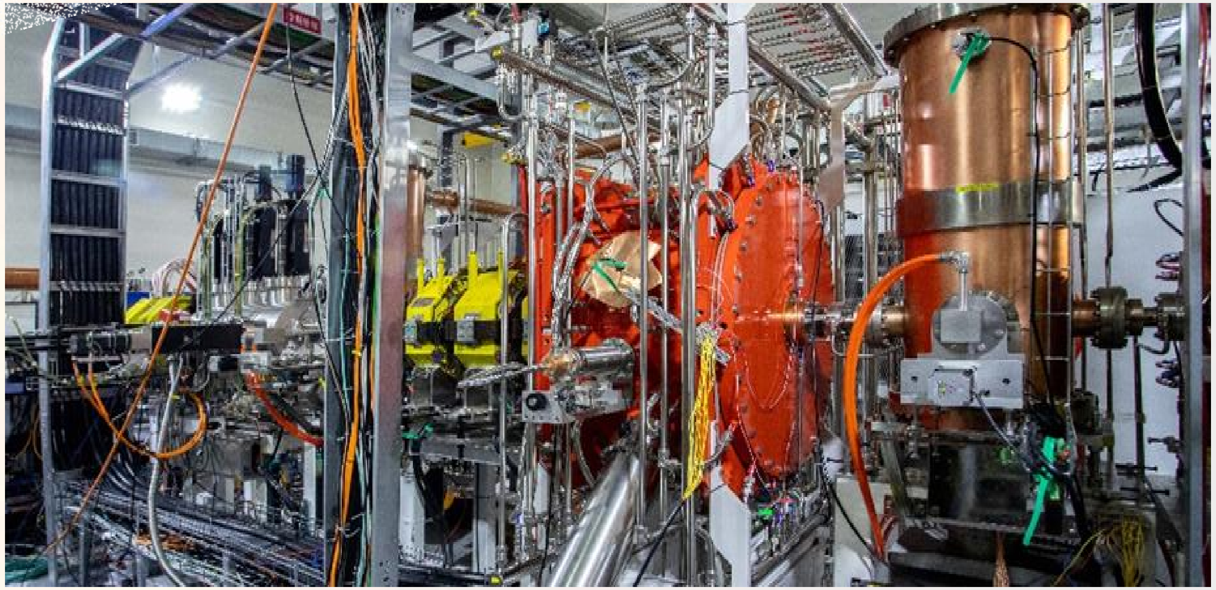


- By track tracing, we know where this track comes from
- Cosmos rays and natural background are thrown

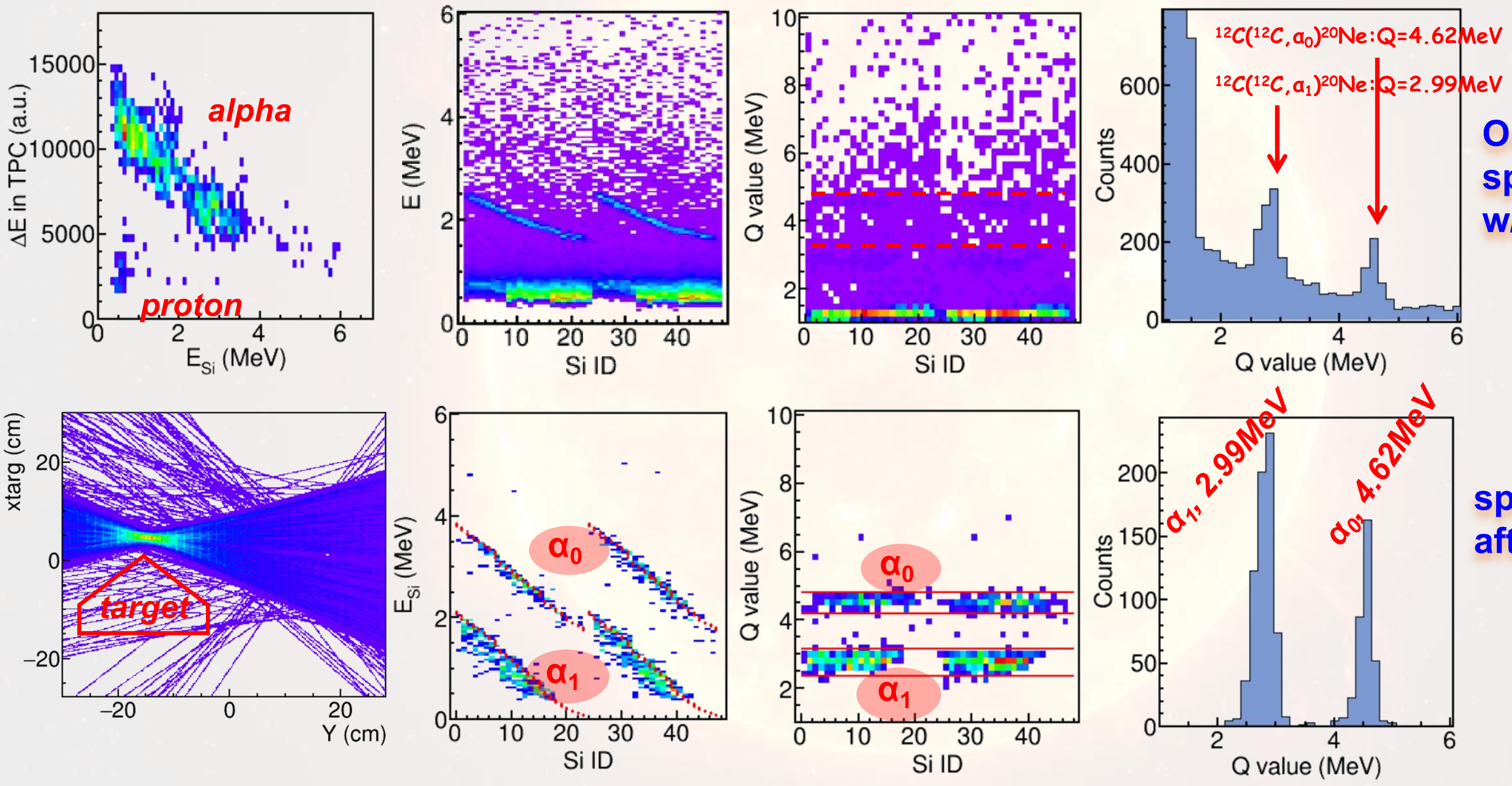
Low Energy Accelerator Facility (LEAF)



- Beam intensity up to **100 puA** on target(Spillane: 40puA)
- Energy spread < 0.2%
- Energy for ^{12}C beam: 4 - 8 MeV



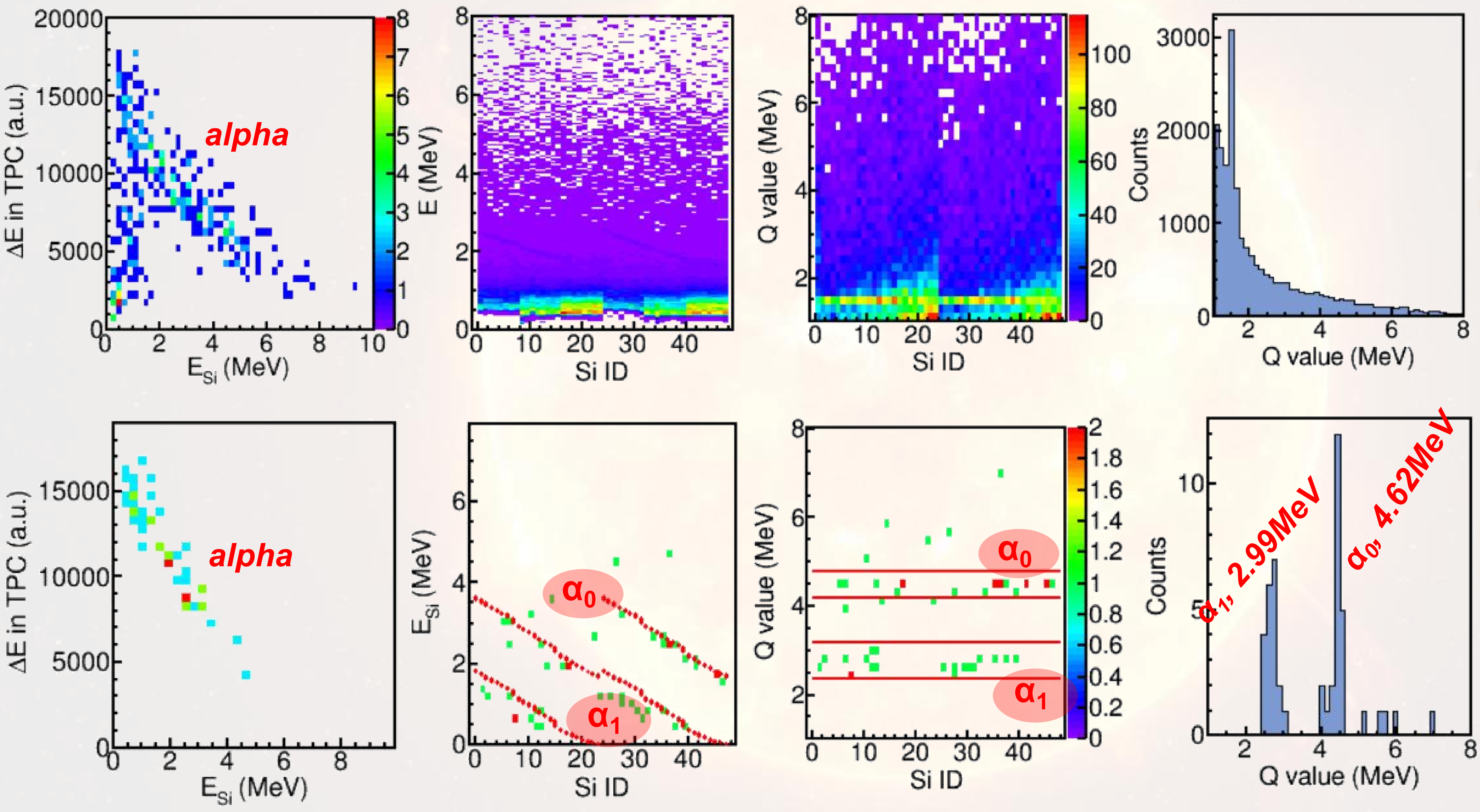
Analysis: Ecm=2.75MeV with highly pure graphite



Original spectra w/o tracking

spectra after tracking

Analysis: Ecm=2.40MeV with HOPG



spectra
w/o tracking

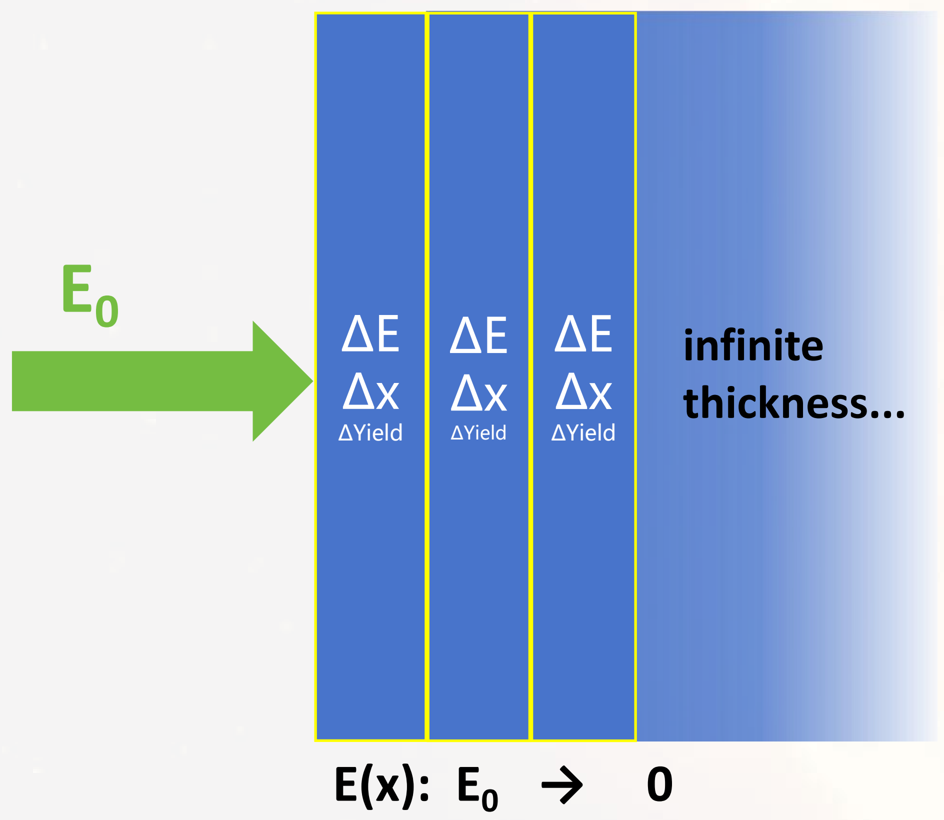
spectra
w/ tracking

Preliminary results

Angular distribution

Thick-target yield

Thick target can be seen as an accumulation of an infinite number of very thin targets



yield of thin layer of target with thickness of D:

$$Y = N_V \sigma D = N_s \sigma$$

(Nv: nucleus number density)

total yield for target of thickness D:

$$Y = N_V \int_0^D \sigma(E)\mathrm{d}x = N_V \int_0^{R(E_0)} \sigma(E)\mathrm{d}x$$

$$= N_V \int_{E_0}^0 \sigma(E) \frac{\mathrm{d}E}{(\mathrm{d}E/\mathrm{d}x)}$$

So

$$Y(E_0) = N_V \int_0^{E_0} \left[\sigma(E) \Big/ - \left(\frac{\mathrm{d}E}{\mathrm{d}x} \right) \right] \mathrm{d}E$$

Stopping power

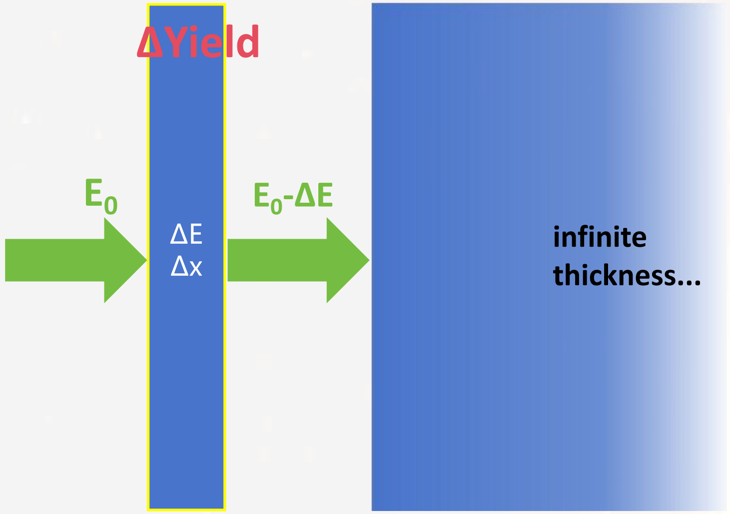
For this experiment, we used infinite thick target with so high beam intensity

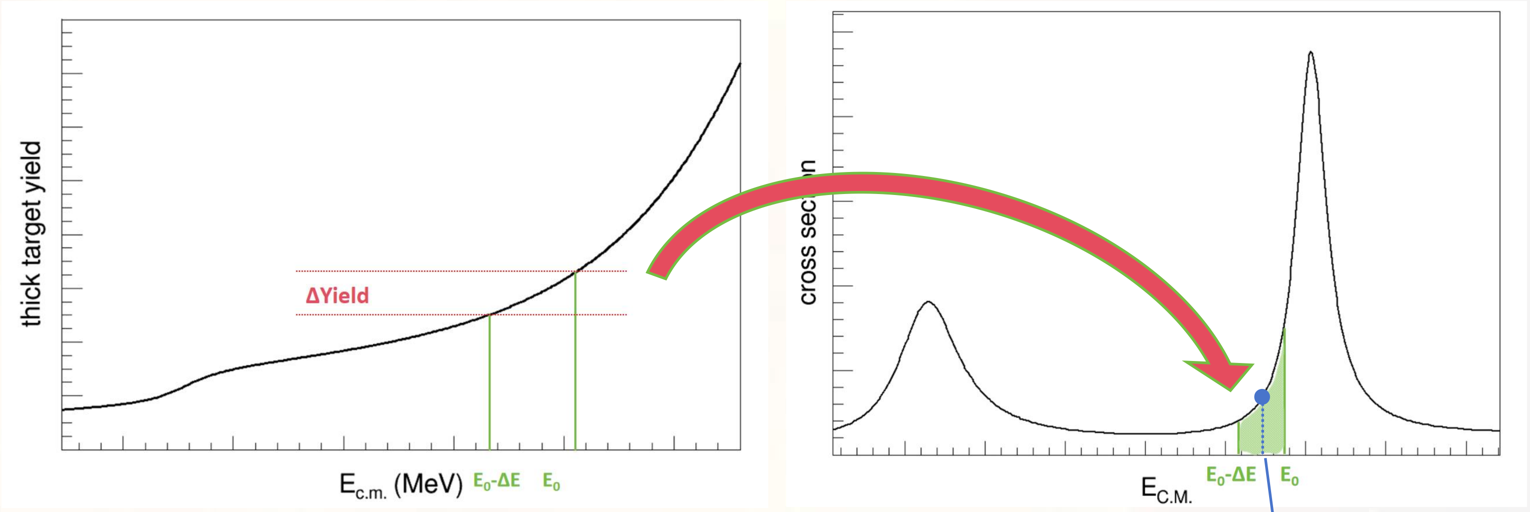
Preliminary results

Angular distribution

Thick-target yield

Cross section of reactions can be obtained by differentiating the yield of thick target





$$\Delta\mathrm{Yield} = \mathrm{N_V}\int_0^{\Delta x}\sigma(\mathrm{E})\mathrm{dx} = \mathrm{N_V}\frac{1}{-(\mathrm{dE/dx})}\int_{\mathrm{E_0}}^{\mathrm{E_0}-\Delta\mathrm{E}}\sigma(\mathrm{E})\mathrm{dE} \propto \int_{\mathrm{E_0}-\Delta\mathrm{E}}^{\mathrm{E_0}}\sigma(\mathrm{E})\mathrm{dE}$$

Based on
Lagrange's Mean Value Theorem

$$\sigma(\mathrm{Eeff}) \propto \frac{\Delta\mathrm{Yield}}{\Delta\mathrm{E}}$$

When $\Delta E \rightarrow 0$ ($\Delta x \rightarrow 0$), $E_{eff} \rightarrow E_0$, So:

$$\sigma(\mathrm{E}) = \left(-\frac{1}{N_v}\frac{dE}{dx}\right)\frac{\partial\mathrm{Yield}}{\partial\mathrm{E}}$$

This is how we calculated the cross section from the fit-curve of thick target yield