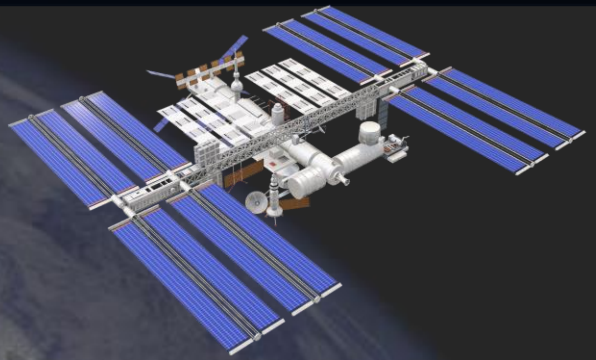
TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA
Dipartimento di Fisica

HSERLAB
Human Space Exploration Radiation LAB



LIDAL: exploiting the Bethe Bloch equation for single particle energy identification

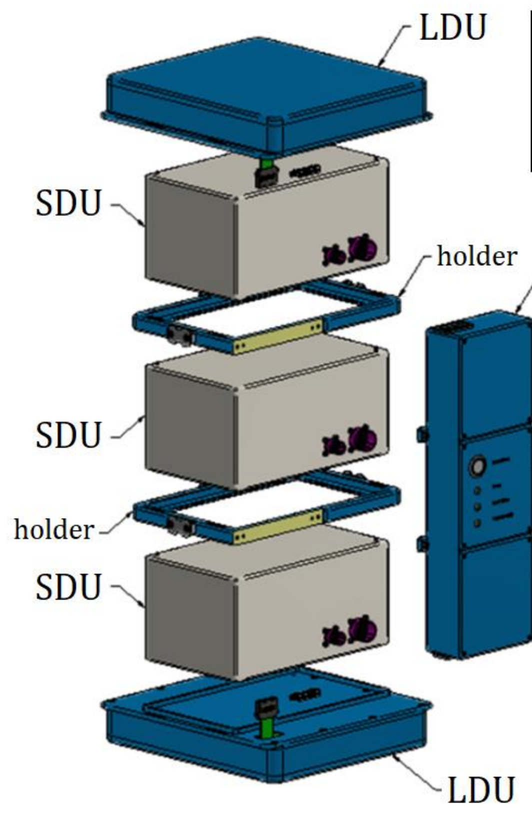
Romoli G.* on behalf of the LIDAL collaboration

* giulia.romoli@roma2.infn.it

Workshop on Radiation Monitoring on International Space Station
24th WRMISS
3 - 5 September 2019

INFN Istituto Nazionale di Fisica Nucleare
ASI
argotec SPACE FOR AMBITIONS
TELESPAZIO a LEONARDO and THALES company
UNIVERSITÀ DI PAVIA
KAYSER ITALIA

The LIDAL detector



LDU: LIDAL Detector Unit
LCU: LIDAL Control Unit
SDU: Silicon Detector Unit

REAL TIME
DATA DOWNLINK

on-board ISS

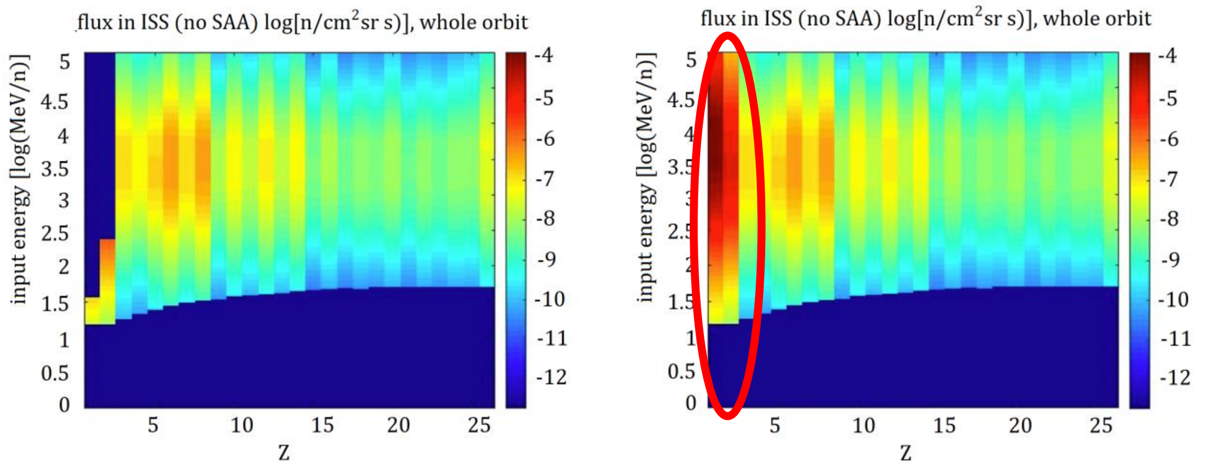
from Jan 2020 on
about 2 TB of data acquired
pos along X, Y, Z directions

LIDAL (Light Ion Detector for ALTEA):

- enhanced telescope capabilities (18 silicon planes + 2 scintillator planes)
- first measurement of TOF ($\rightarrow z^2/\beta^2$) in space
- expand acceptance window of ALTEA for light nuclei

ALTEA
1 % of the flux and 41 % of the Dose

ALTEA – LIDAL
≈100 % of the flux and ≈100 % of the Dose



SIMULATED GCR FLUX IN ISS

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The LIDAL detector

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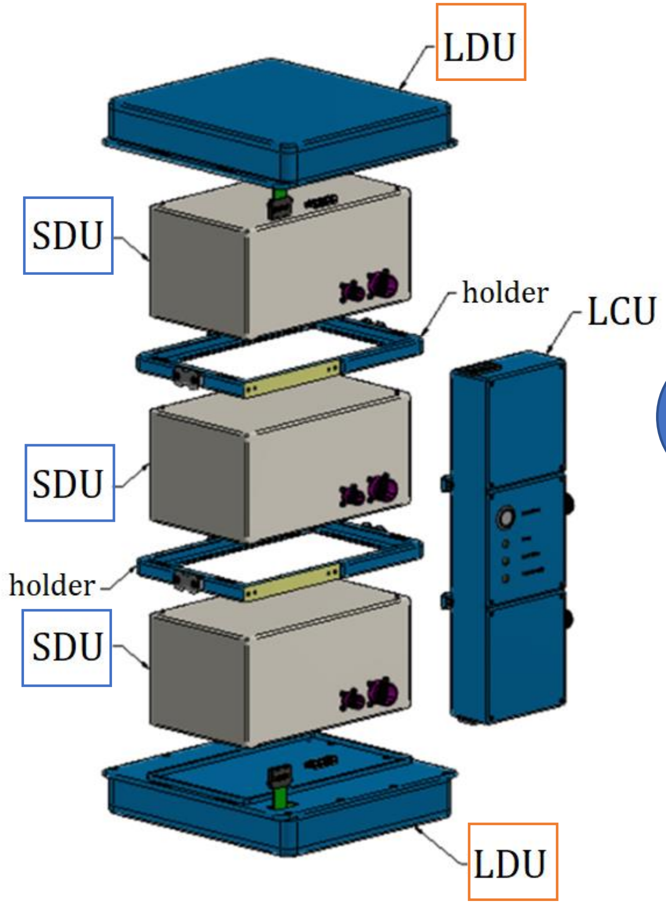
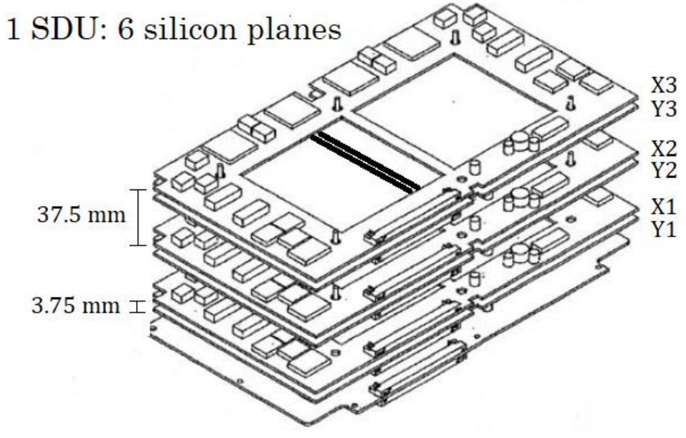
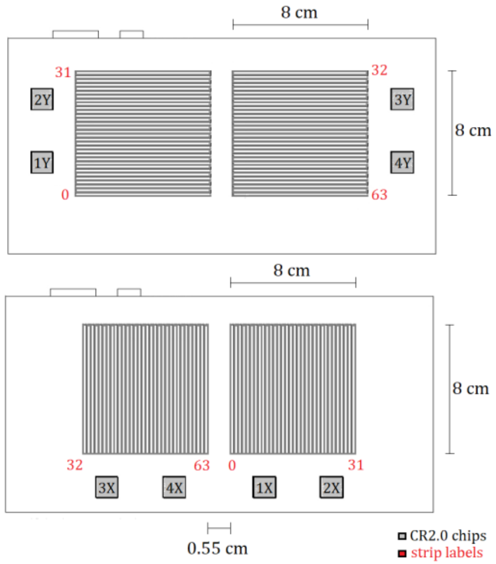
LID AL



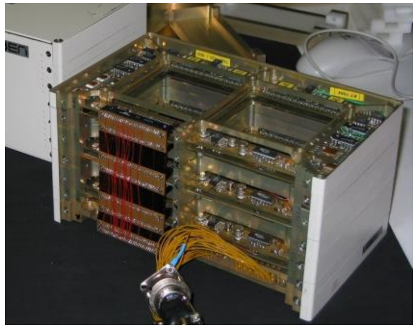
GF: $15.32\ cm^2\ sr$ (bi-directional)

THE ALTEA SUBSYSTEM (3 SDUs)

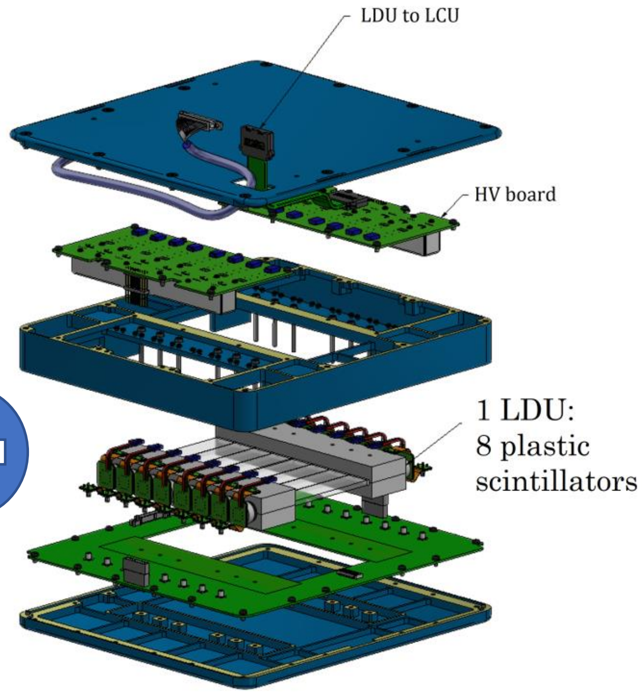




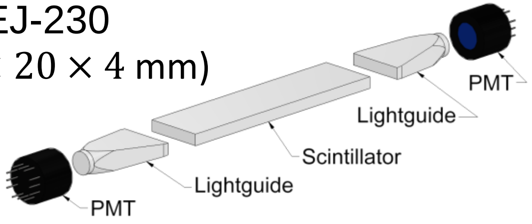
$8 \times 8\ cm^2$ **silicon chips**
380 µm thick
segmented in 32 strips
strips' pitch of 2.5 mm



THE LID SUBSYSTEM (2 LDUs)

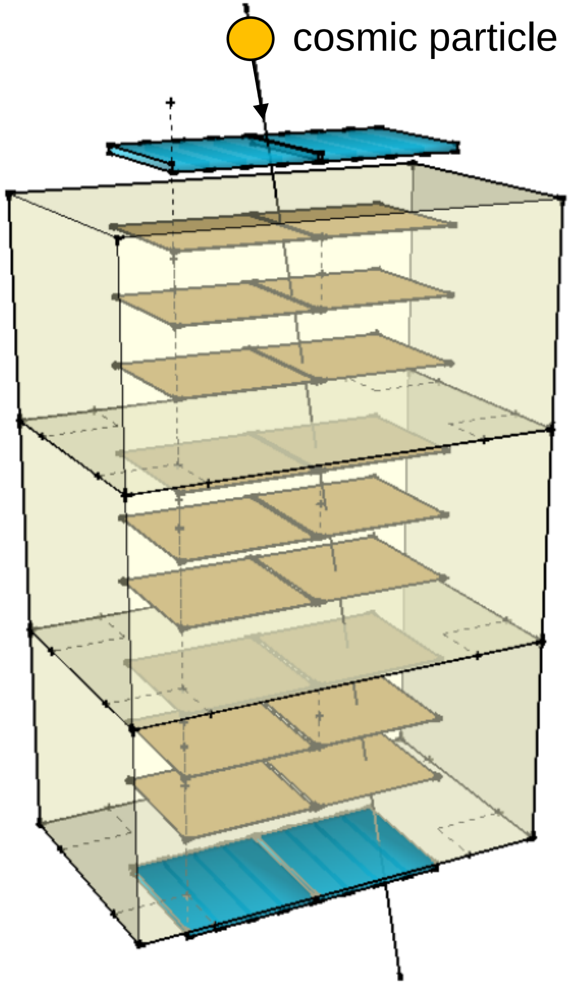


EJ-230
($80 \times 20 \times 4$ mm)



up to **100 ps** time resolution

Summary



INCIDENT PARTICLE PROPERTIES

ATOMIC NUMBER Z
INITIAL KINETIC ENERGY

↓

BETHE-BLOCH

↑

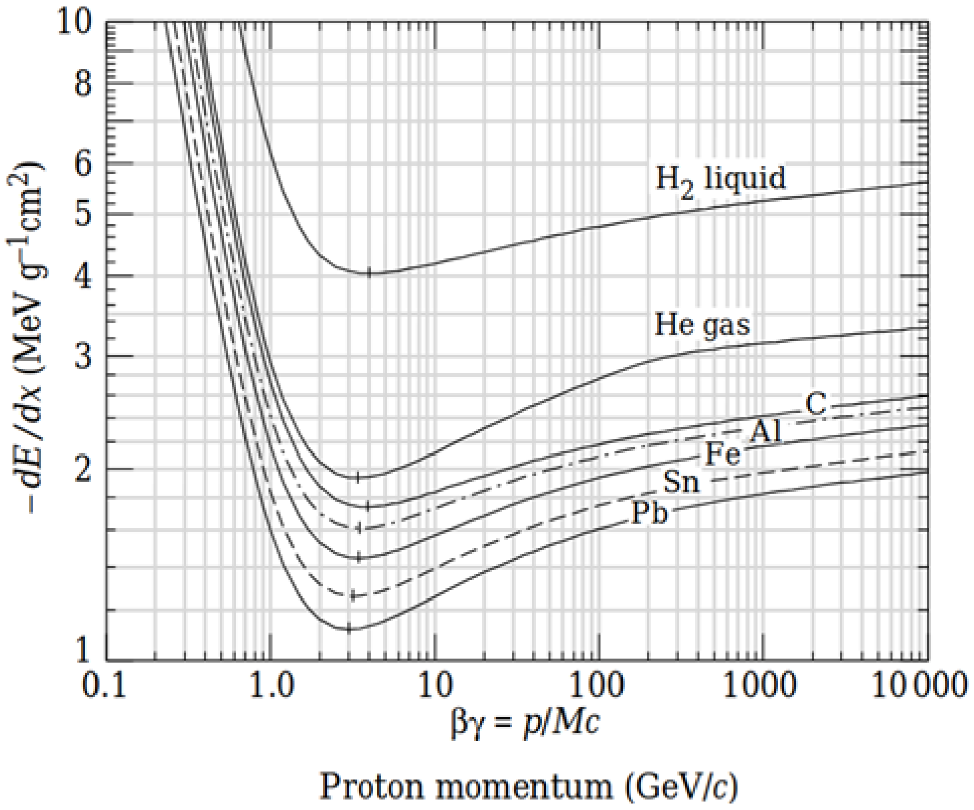
LAYERS PROPERTIES

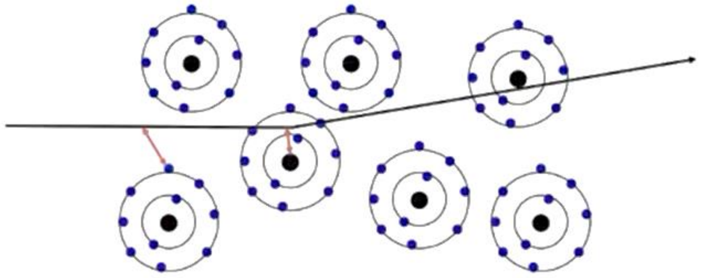
CHEMICAL COMPOSITION
THICKNESS

BETHE-BLOCH →

- ENERGY PROFILE $E(x)$
- VELOCITY PROFILE $\mathrm{v}(x)$
- TIME OF FLIGHT PROFILE $\mathrm{T}(x)$

The Bethe-Bloch equation





$$\left\langle -\frac{dE}{dx}\right\rangle = 2\kappa\rho\frac{Z}{A}\frac{z^2}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_e v^2\gamma^2 W_{max}}{\langle I\rangle^2}\right)-\beta^2\right]$$

stopping power for **HEAVY CHARGED PARTICLES**

$0.1 \leq \beta\gamma \leq 1000$

traversing a prior-defined **MEDIUM**

The Bethe-Bloch algorithm

INCIDENT PARTICLE PROPERTIES

ATOMIC NUMBER Z
INITIAL KINETIC ENERGY

BETHE-BLOCH

$$\left\langle -\frac{dE}{dx}\right\rangle = 2\kappa\rho\frac{Z}{A}\frac{z^2}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_e v^2\gamma^2 W_{max}}{\langle I\rangle^2}\right)-\beta^2\right]$$

LAYERS PROPERTIES

CHEMICAL COMPOSITION
THICKNESS

1

LOOK-UP TABLE

x	v	1/v
…	…	…
…	…	…

[Grimes, 2017], [Martinez, 2019]

ENERGY PROFILE $E(x)$

VELOCITY PROFILE $v(x)$

TIME OF FLIGHT PROFILE $\mathrm{T}(x)$

Bethe-Bloch approximate solution

1

$$\left\langle -\frac{dE}{dx}\right\rangle = 2\kappa z^2 \rho \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma}{\langle I\rangle}\right) - \beta^2\right]$$

$$E = (\gamma - 1)m_p c^2$$

$$\frac{dE}{dx} = \frac{dE}{dv}\frac{dv}{dx} = m_p v(x)\gamma^3\frac{dv}{dx}$$

$$dx' = \gamma^3 dx$$

$$\frac{dE}{dx'} = m_p v(x')\frac{dv}{dx'}$$

$$A = \frac{2}{m_p}\kappa z^2 \frac{Z}{A}\rho c^2 \quad [m^3/s^4]$$

$$\ln\left(\frac{2m_e c^2\beta^2\gamma}{\langle I\rangle}\right) - \beta^2 \approx \ln\left(\frac{2m_e c^2\beta^2}{\langle I\rangle}\right)$$

$$B = \frac{2m_e}{\langle I\rangle} \quad [s^2/m^2]$$

$$-v\frac{dv}{dx'} = \frac{A}{v^2}\ln(Bv^2)$$

$$l_c = v_0^4/A,\ \beta_0 = v_0/c,\ b = Bv_0^2$$

$$\boldsymbol{v} = \frac{v}{v_0},\ \boldsymbol{x} = \frac{x}{l_c}$$

$$\frac{d\boldsymbol{x}}{d\boldsymbol{v}} = -\frac{\boldsymbol{v}^3}{(1-(\beta_0\boldsymbol{v})^2)^{\frac{3}{2}}}\left(ln(b\boldsymbol{v}^2)\right)^{-1} \equiv F(\boldsymbol{v})$$

$F(\boldsymbol{v})$ can be approximated by a Taylor series about $\beta_0 = 0$

Bethe-Bloch approximate solution

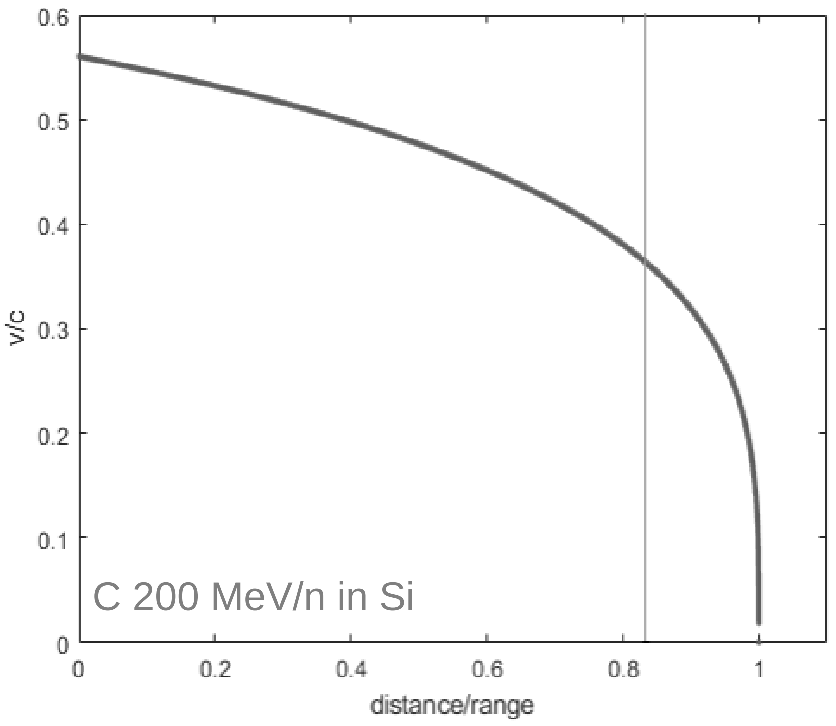
$$\frac{d\boldsymbol{x}}{d\boldsymbol{v}} = F(\boldsymbol{v}) = -\frac{\boldsymbol{v}^3}{\ln(b\boldsymbol{v}^2)} - \beta_0{}^2\frac{3\boldsymbol{v}^5}{2\ln(b\boldsymbol{v}^2)} - \beta_0{}^4\frac{\boldsymbol{v}^7}{\ln(b\boldsymbol{v}^2)}\left(\frac{15}{8} - \frac{1}{2\ln(b\boldsymbol{v}^2)}\right) - \beta_0{}^6\frac{\boldsymbol{v}^9}{\ln(b\boldsymbol{v}^2)}\left(\frac{35}{16} - \frac{13}{12\ln(b\boldsymbol{v}^2)}\right) + O(\beta_0{}^8)$$

Taylor series about $\beta_0 = 0$

... seeking a solution like: $\boldsymbol{x}(\boldsymbol{v}) = \boldsymbol{x}_0(\boldsymbol{v}) + \beta_0{}^2\boldsymbol{x}_1(\boldsymbol{v}) + \beta_0{}^4\boldsymbol{x}_2(\boldsymbol{v}) + \beta_0{}^6\boldsymbol{x}_3(\boldsymbol{v}) + O(\beta_0{}^8)$

$$\boldsymbol{x} - \boldsymbol{R} = -\boldsymbol{v}^4\left(\frac{2\ln^2 b\boldsymbol{v}^2 + \ln b\boldsymbol{v}^2 + 1}{8\ln^3 b\boldsymbol{v}^2}\right) - \beta_0{}^2\boldsymbol{v}^6\left(\frac{9\ln^2 b\boldsymbol{v}^2 + 3\ln b\boldsymbol{v}^2 + 2}{36\ln^3 b\boldsymbol{v}^2}\right) + $$
$$-\beta_0{}^4\boldsymbol{v}^8\left(\frac{120\ln^2 b\boldsymbol{v}^2 - 2\ln b\boldsymbol{v}^2 - 1}{512\ln^3 b\boldsymbol{v}^2}\right) + 31\,\beta_0{}^6\boldsymbol{v}^{10}\left(\frac{25\ln^2 b\boldsymbol{v}^2 + 5\ln b\boldsymbol{v}^2 + 2}{2400\ln^3 b\boldsymbol{v}^2}\right) + O(\beta_0{}^8)$$

[Grimes, 2017], [Martinez, 2019]



BETHE-BLOCH

$$\left\langle -\frac{dE}{dx}\right\rangle = 2\kappa\rho\frac{Z}{A}\frac{z^2}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_e v^2\gamma^2 W_{max}}{\langle I\rangle^2}\right) - \beta^2\right]$$

LOOK-UP TABLE

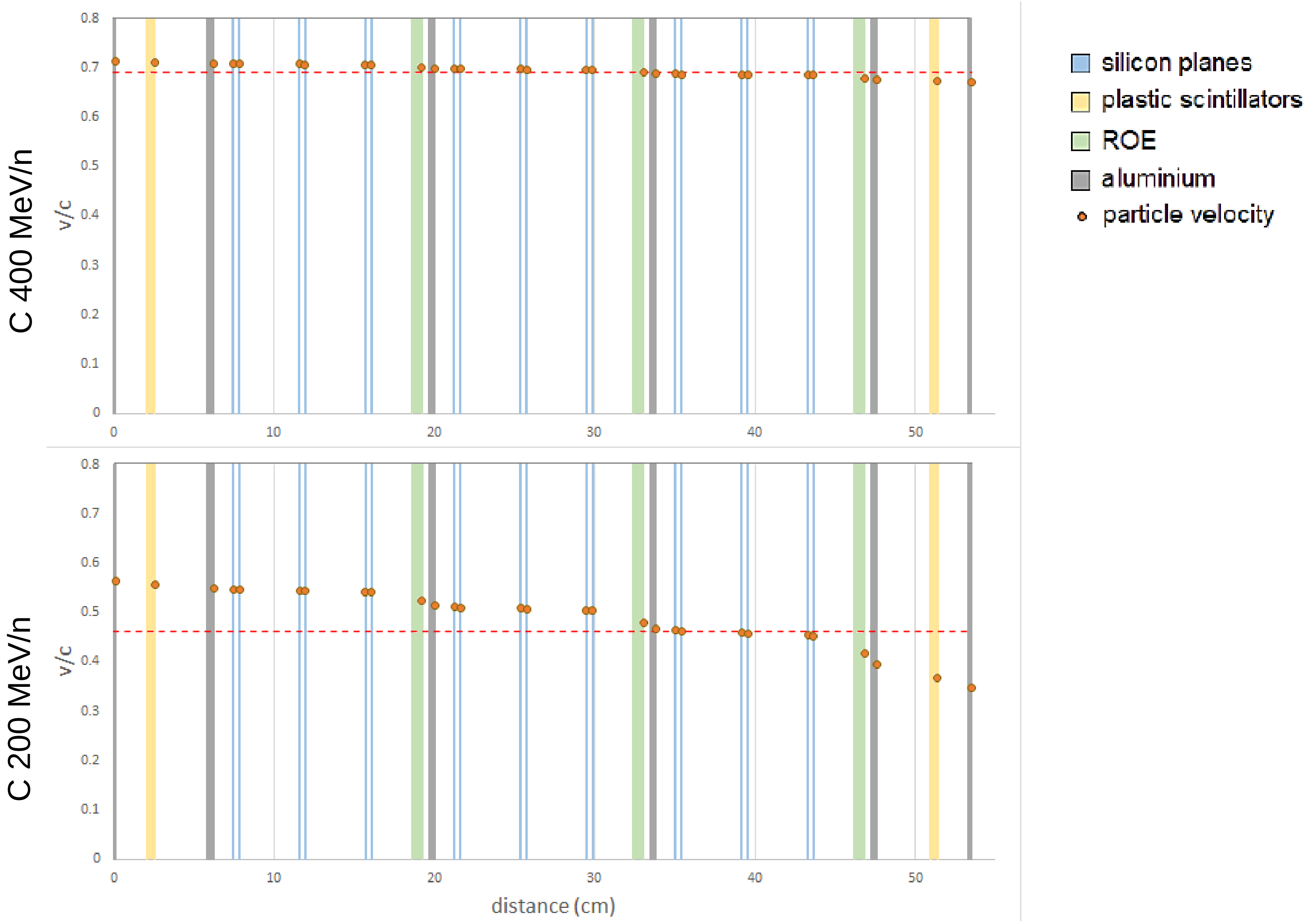
x	v	1/v
...	...	...
...	...	...

Velocity profile $v(x)$

mean velocity:

$$v_m = \frac{v_{in} + v_{fin}}{2} = \frac{\Delta s}{TOF}$$

VELOCITY PROFILE $v(x)$



The Bethe-Bloch algorithm

INCIDENT PARTICLE PROPERTIES

ATOMIC NUMBER Z
INITIAL KINETIC ENERGY

BETHE-BLOCH

$$\left\langle -\frac{dE}{dx}\right\rangle = 2\kappa\rho\frac{Z}{A}\frac{z^2}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_e v^2\gamma^2 W_{max}}{\langle I\rangle^2}\right)-\beta^2\right]$$

LAYERS PROPERTIES

CHEMICAL COMPOSITION
THICKNESS

LOOK-UP TABLE

x	v	1/v
…	…	…
…	…	…

2

ENERGY PROFILE $E(x)$

VELOCITY PROFILE $v(x)$

TIME OF FLIGHT PROFILE $T(x)$

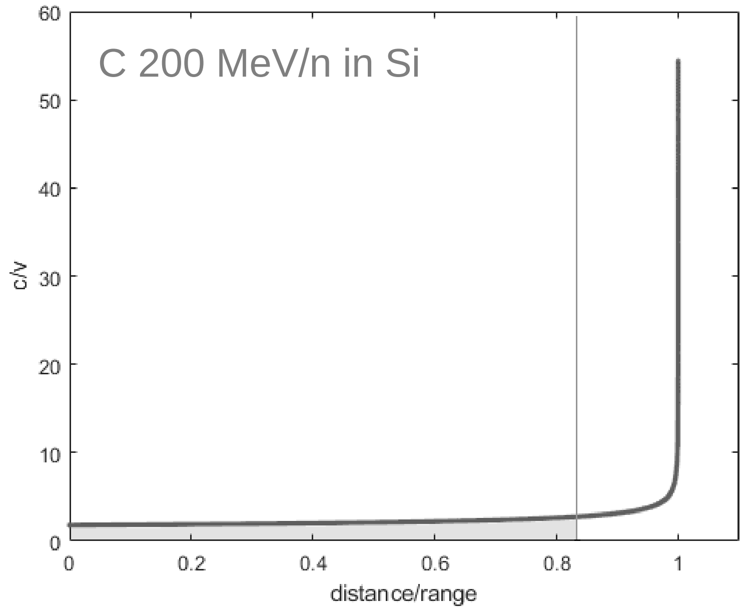
Energy and time profiles $E(x)$ and $T(x)$

2

$$\Delta T = \int_0^{\Delta x} \frac{1}{v(x)} dx$$

$$E = \int_0^{\Delta x} \langle -\frac{dE}{dx} \rangle dx = \kappa z^2 \rho \frac{Z}{A} \frac{c^2}{2} \int_0^{\Delta x} \frac{f(v(x)/c)}{v(x)^2} dx$$

$$f(\beta) = \ln\left(\frac{2 m_e c^2 \beta^2}{\langle I \rangle}\right)$$



$$TOF = \sum_{i=1}^{m} \Delta T_m = \sum_{i=1}^{m} \int_0^{\Delta x_m} \frac{1}{v_m(x)} dx = \sum_{i=1}^{m} \sum_{i=0}^{n_m - 1} \frac{(x_{i+1} - x_i)}{2} \left(\frac{1}{v_m(x_{i+1})} + \frac{1}{v_m(x_i)} \right)$$

$$E = \sum_{i=1}^{m} \Delta E_m = \sum_{i=1}^{m} \kappa z^2 \rho \frac{Z}{A} \frac{c^2}{2} \int_0^{\Delta x_m} \frac{f(v(x)/c)}{v_m(x)^2} dx = \kappa z^2 \rho \frac{Z}{A} \frac{c^2}{2} \sum_{i=1}^{m} \sum_{i=0}^{n_m - 1} \frac{(x_{i+1} - x_i)}{2} \left(\frac{f(v(x_{i+1})/c)}{v_m(x_{i+1})^2} + \frac{f(v(x_i)/c)}{v_m(x_i)^2} \right)$$

Straggling

STRAGGLING FUNCTION GIVEN BY LANDAU:

$$f(t,\Delta,\delta_2) = \frac{1}{\pi E_M} e^{k(1+\beta^2\Gamma)} \int_0^\infty e^{kf_1(y)-\frac{k\delta_2 y^2}{2\mathrm{K}E_M}} \cos(\lambda_1 y + kf_2(y))\, dy$$

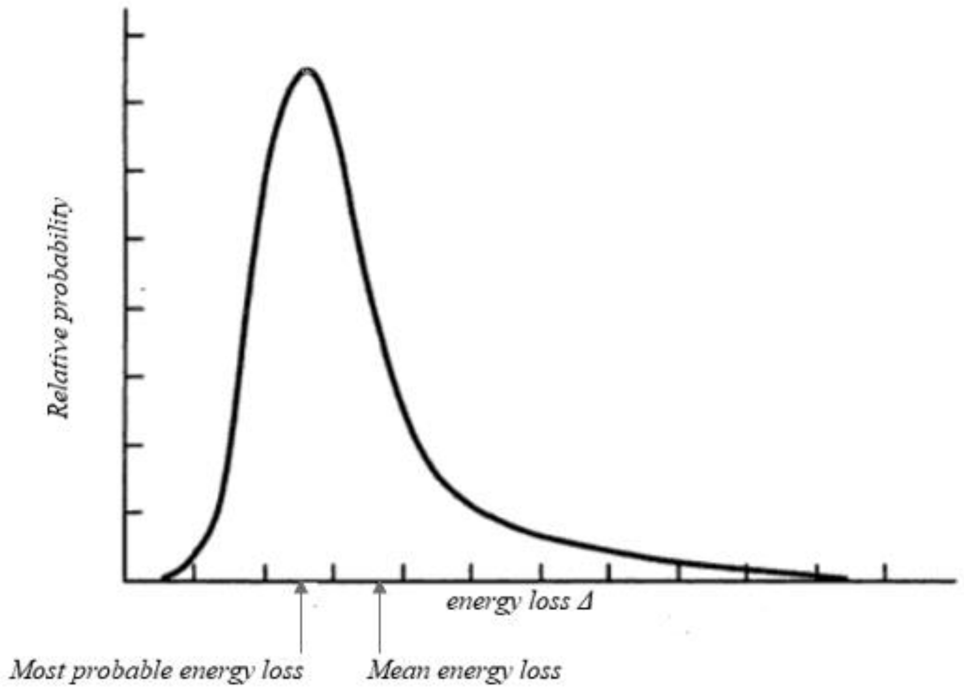
$k = \dfrac{\xi}{E_M}$ for thin absorbers, $k < 10$

for $k \geq 10$, the Landau distribution approaches the Gaussian limit

$\xi = 2.55 \times 10^{-19} N_0\, Zt \dfrac{z^2}{\beta^2}$ Landau parameter [KeV]

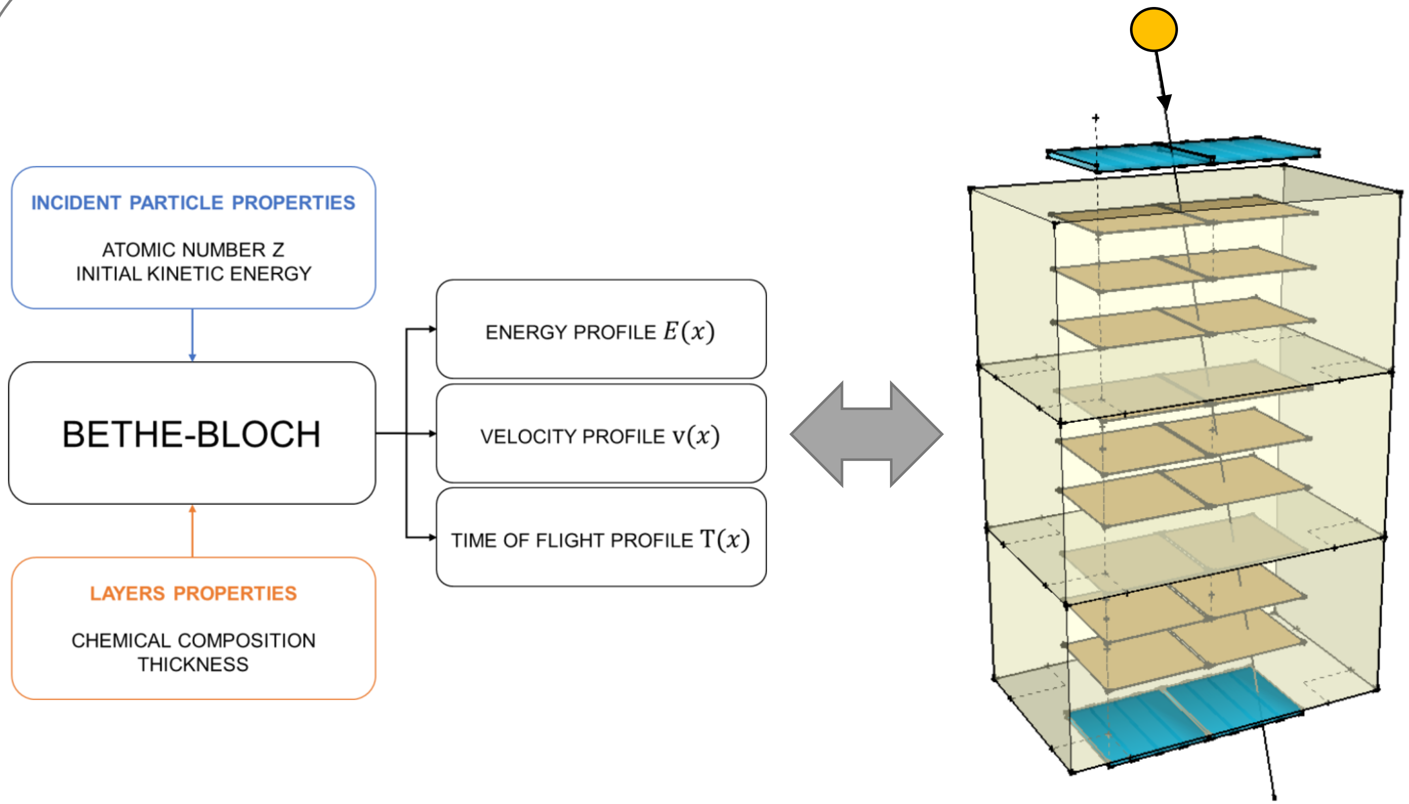
$\langle\Delta\rangle = 2B\xi$ mean energy loss

$\omega_L = 4.018\, \xi$ FWHM for Landau function



[Bichsel, 1988]

Results from LIDAL

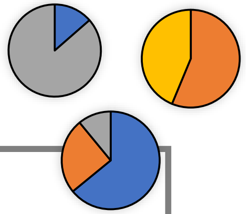


➡ IMPROVED PARTICLE IDENTIFICATION

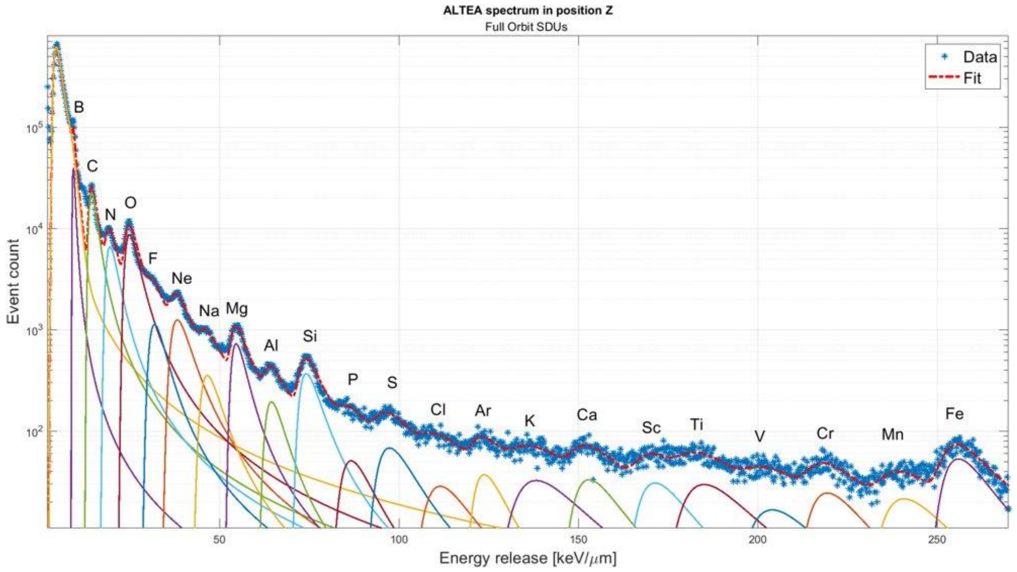
➡ UNDER-THRESHOLD ENERGY RELEASES FOR PARTICLES TRIGGERING THE SCINTILLATOR PLANES

Particle identification

hybrid candidates
for detected particles



ALTEA SPECTRUM + FIT WITH LANDAU FUNCTIONS

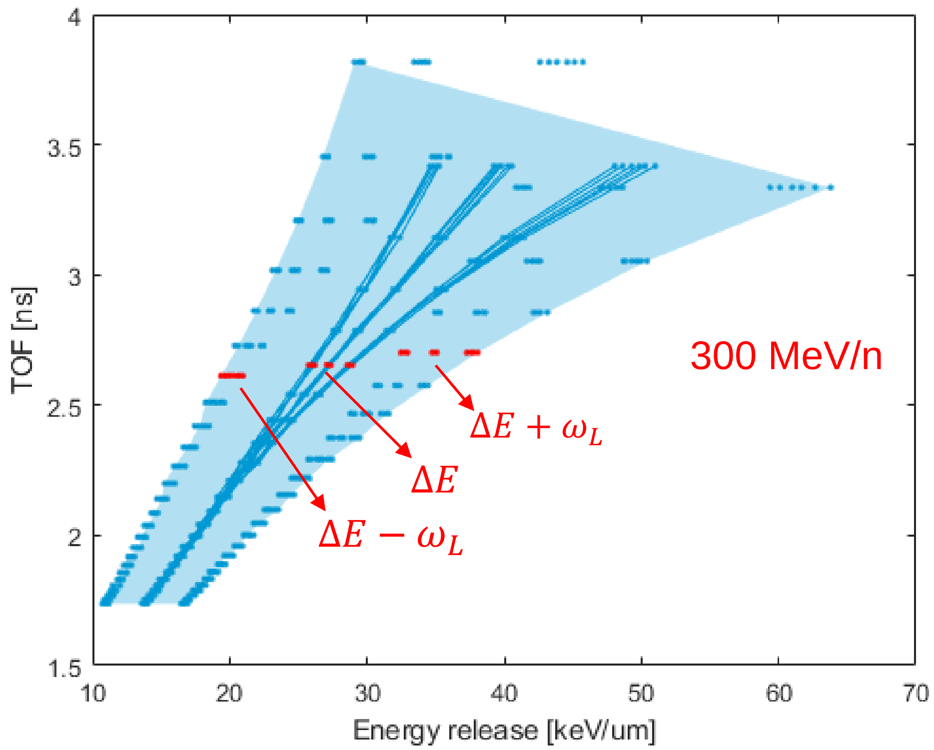


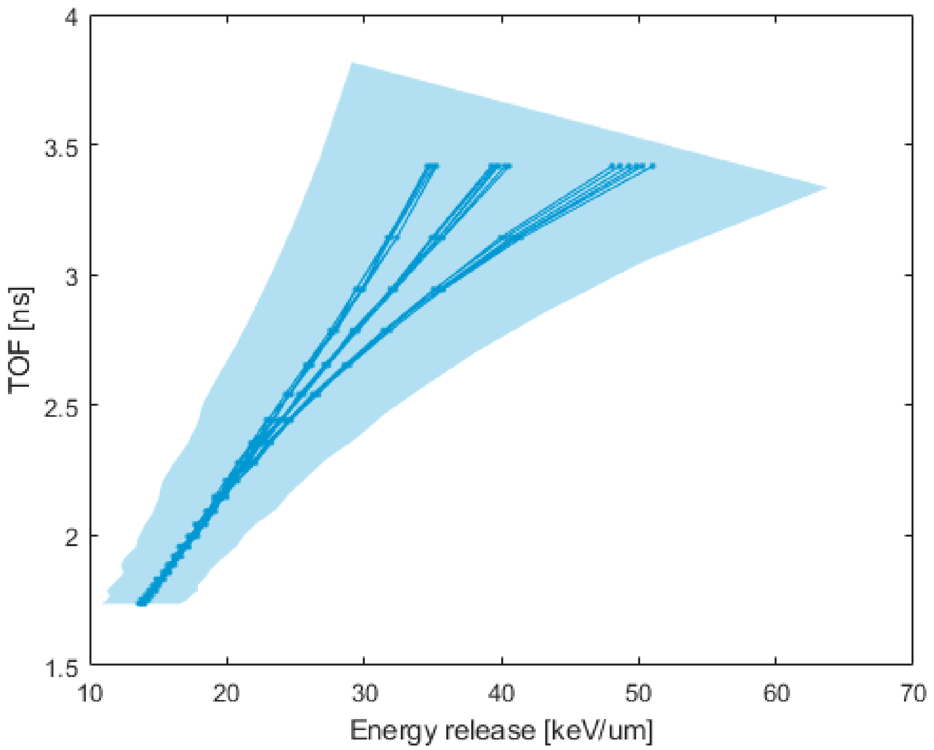
SINGLE PARTICLE IDENTIFICATION FROM REFERENCE SPECTRUM

for more details: talk by G. Santi Amantini

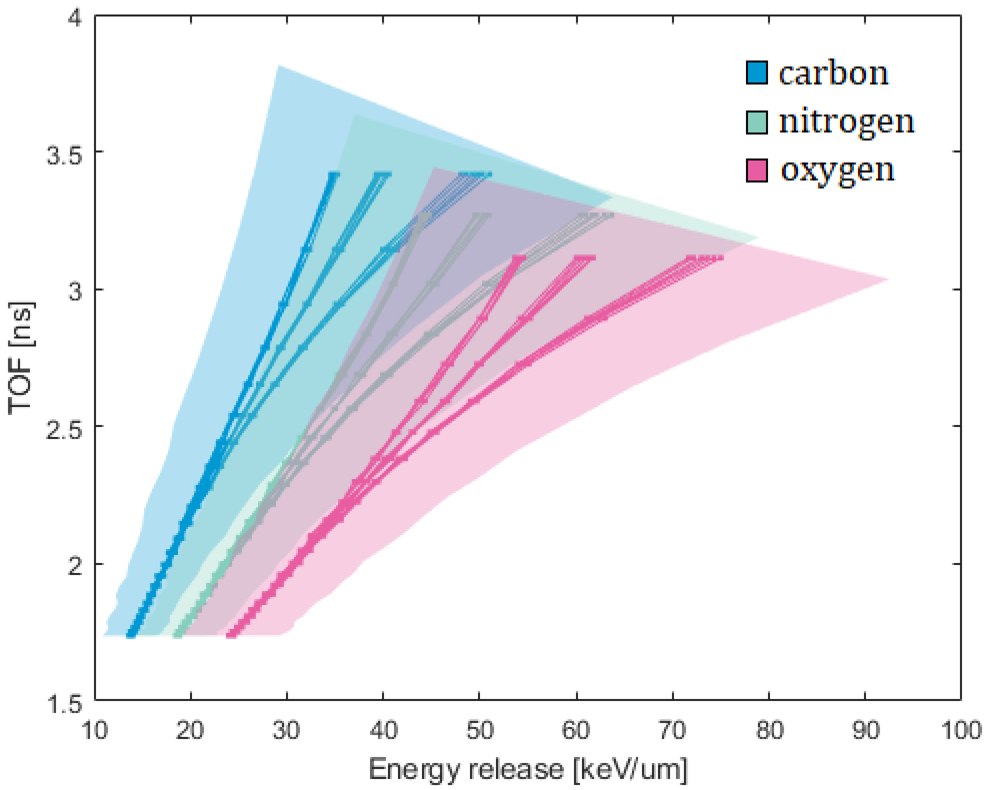
Particle identification

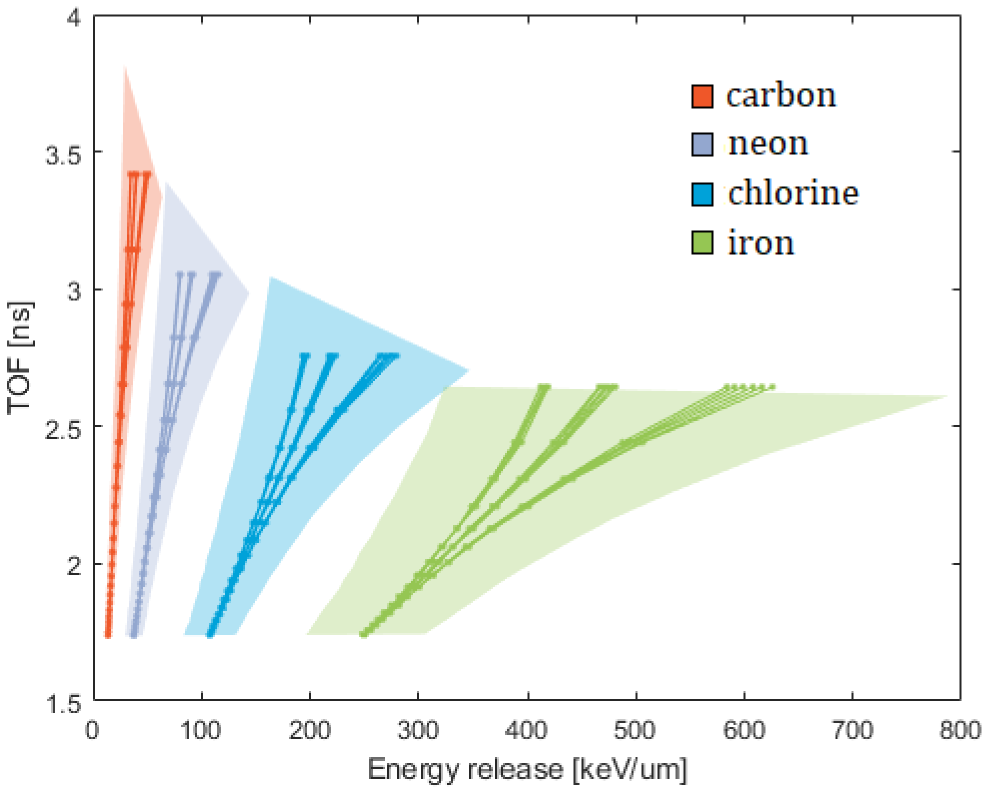
CARBON IONS



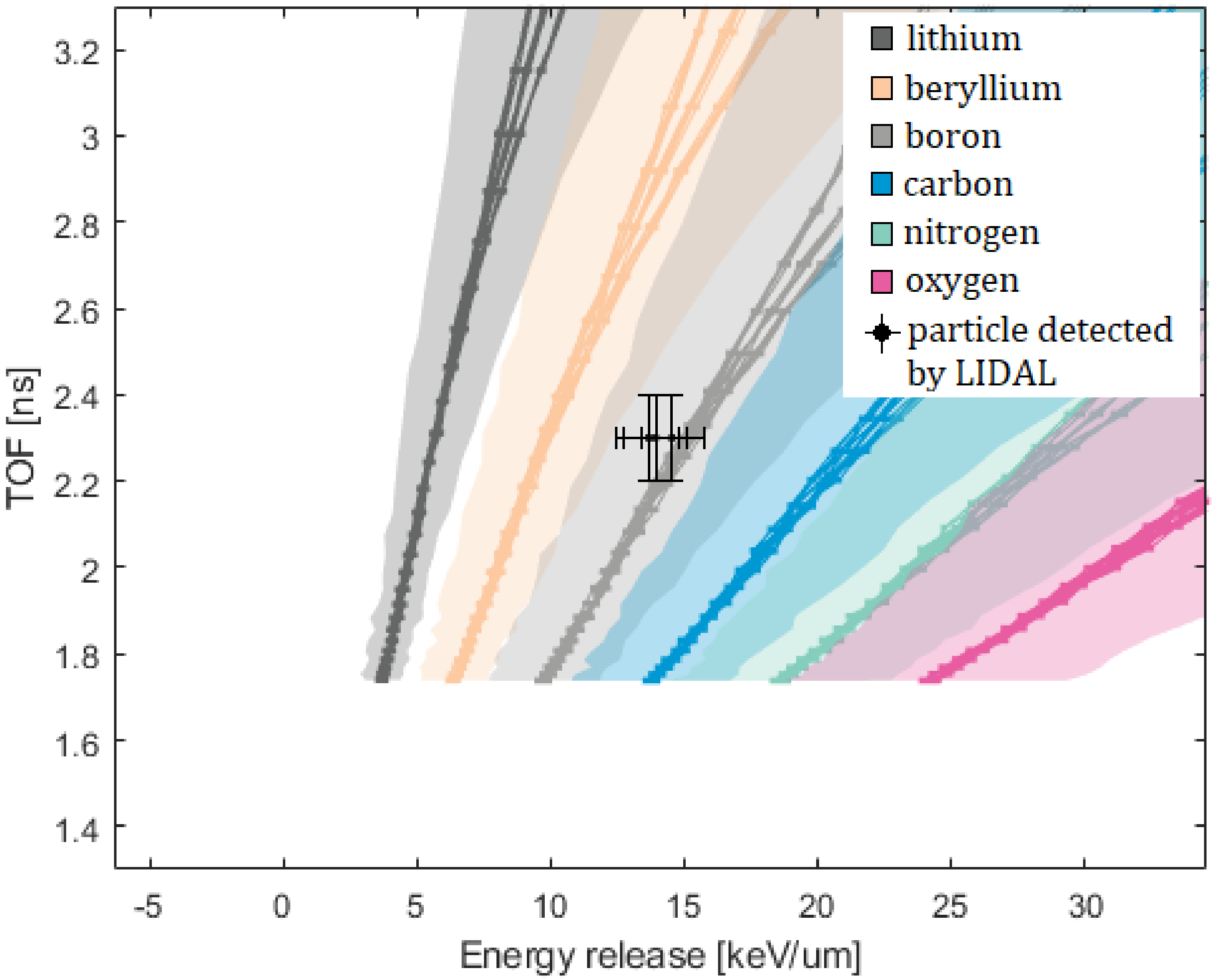


Particle identification



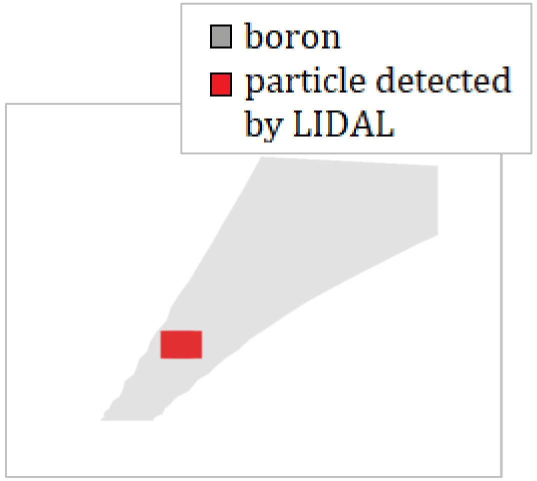


Particle identification

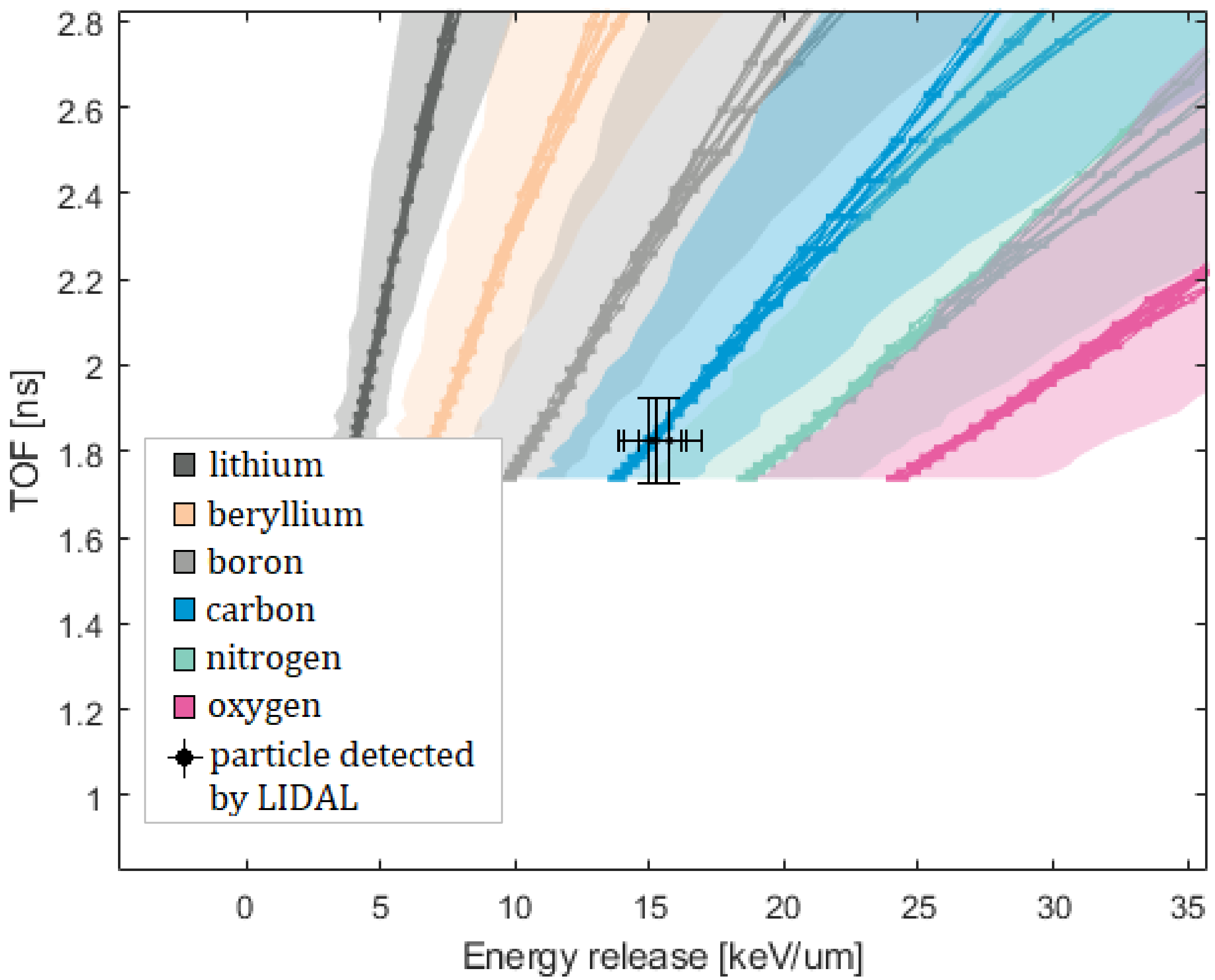


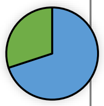
from Bethe-Bloch algorithm:

100% boron ion at 500 MeV/n



Particle identification

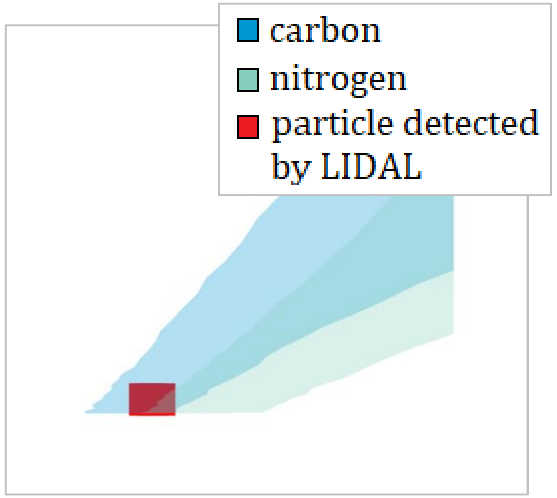




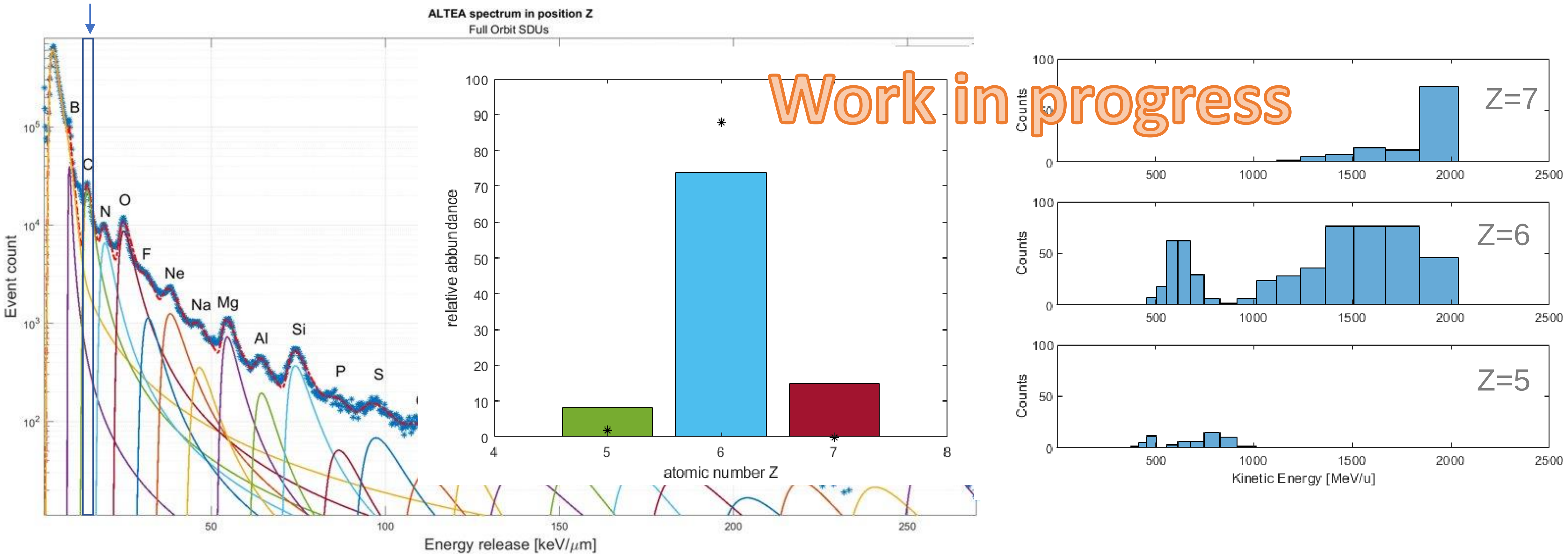
from Bethe-Bloch algorithm:

70% carbon ion at 1.2 GeV/n

30% nitrogen ion at 1.7 GeV/n



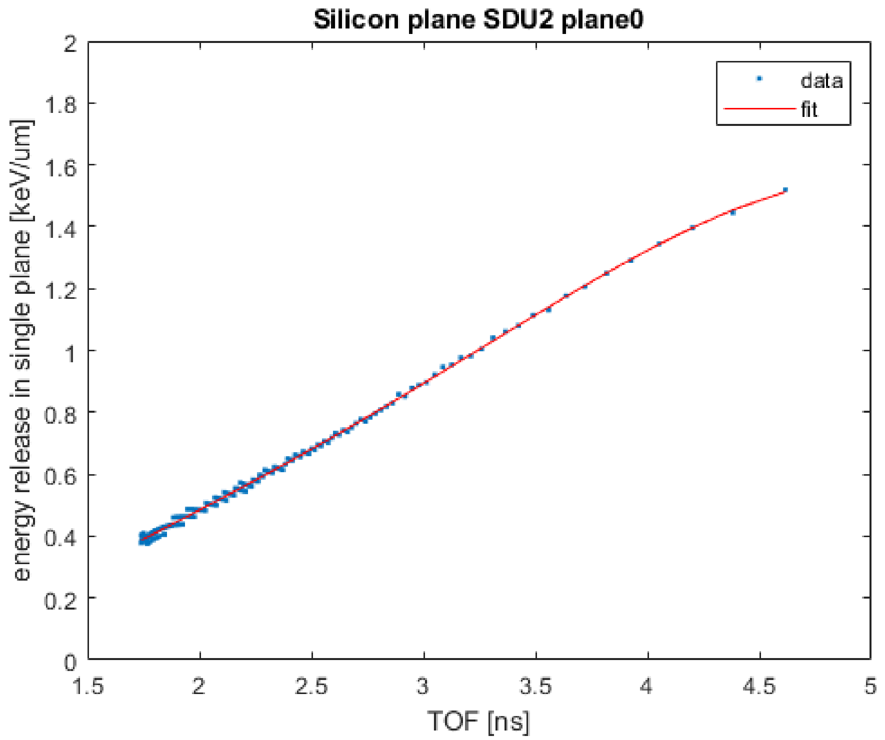
Particle identification



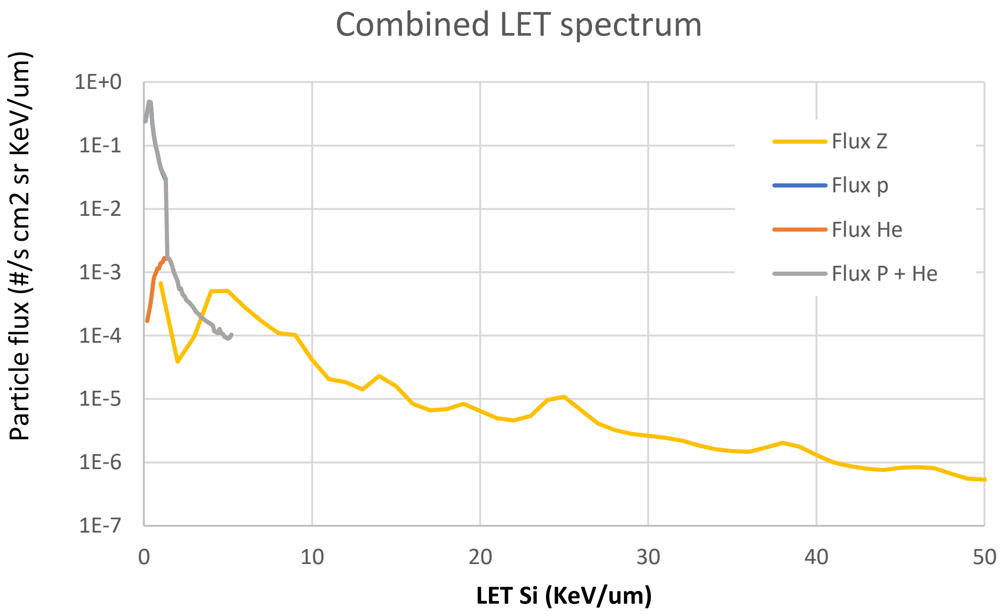
analysis from 750 particles detected by LIDAL

Under-threshold energy releases

$$E = p_1 TOF^4 + p_2 TOF^3 + p_3 TOF^2 + p_4 TOF + p_5$$



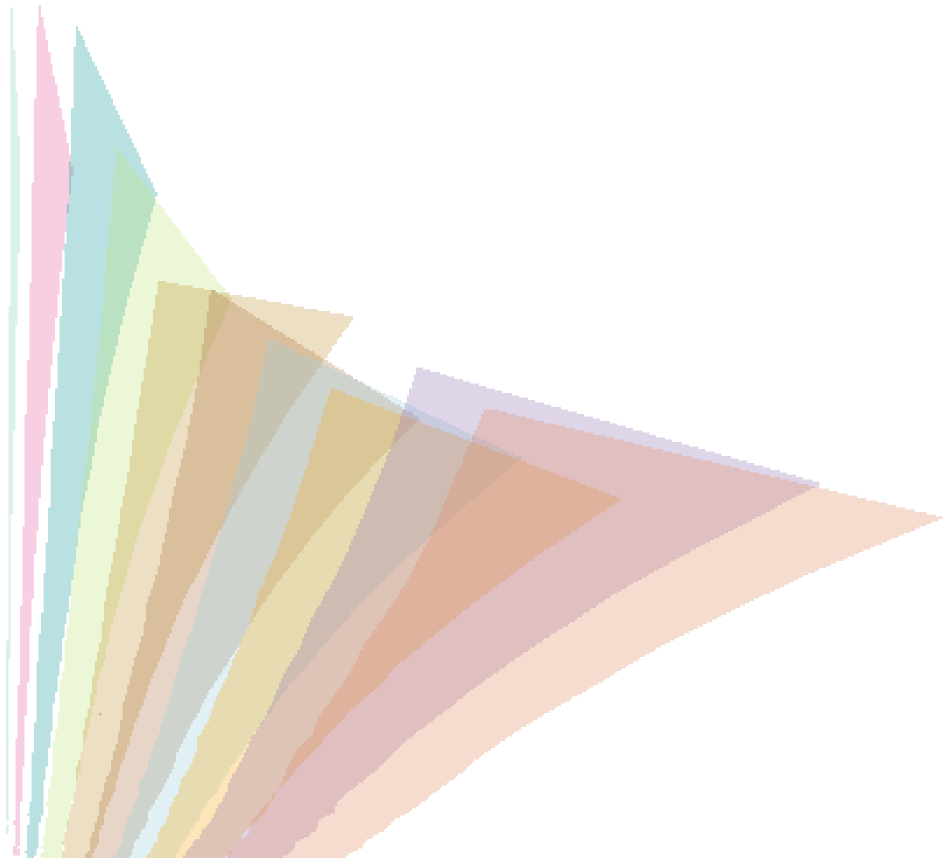
Work in progress



for more details: talk by L. Di Fino

Future perspectives

- improve the outlined method with MonteCarlo simulations
- extend the analysis to all particles detected by LIDAL so far



The LIDAL team

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V. Boretti