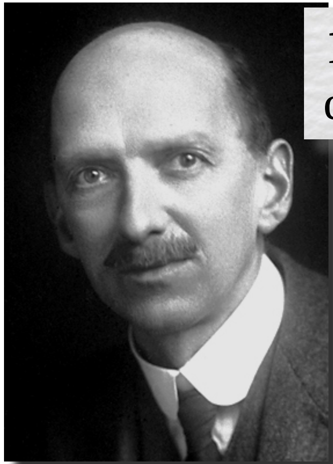
Cosmic Ray Interactions in the Milky Way

Neeraj Amin
Institute for Astroparticle Physics
01.08.2024

Where it all began...



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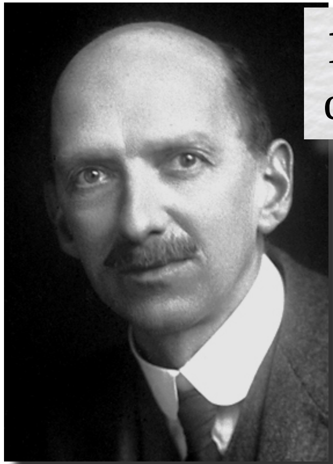

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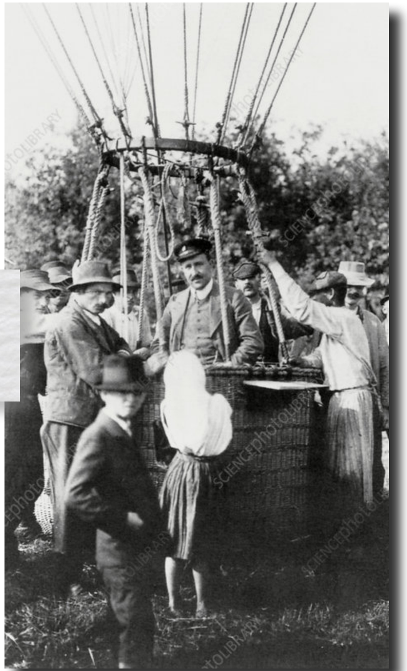

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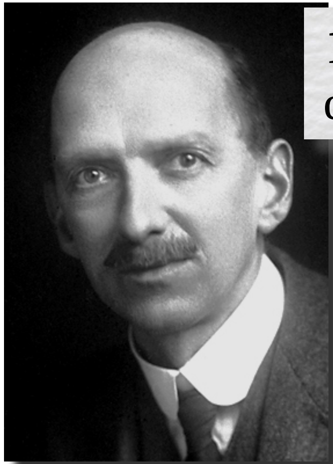

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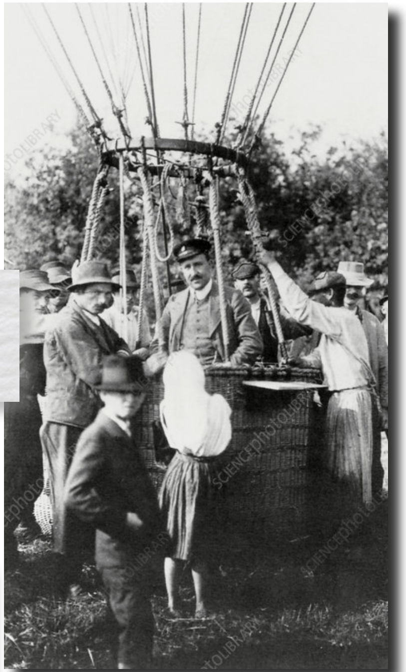

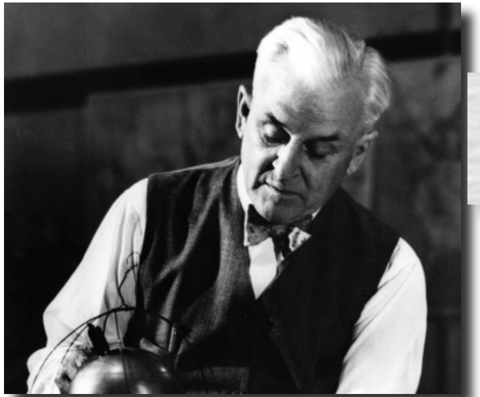

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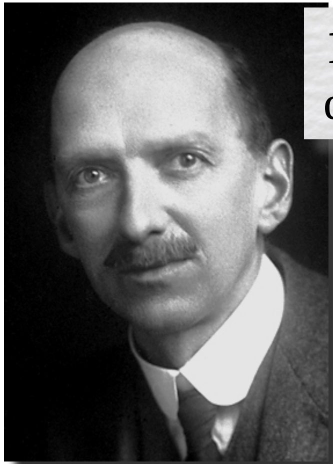

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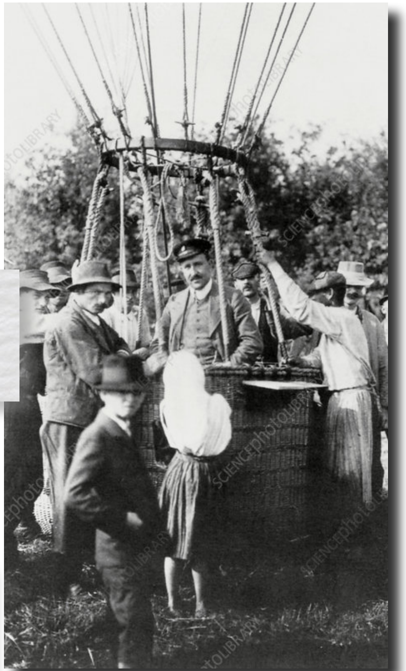

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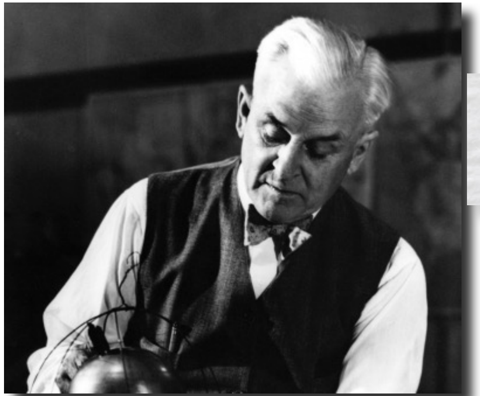
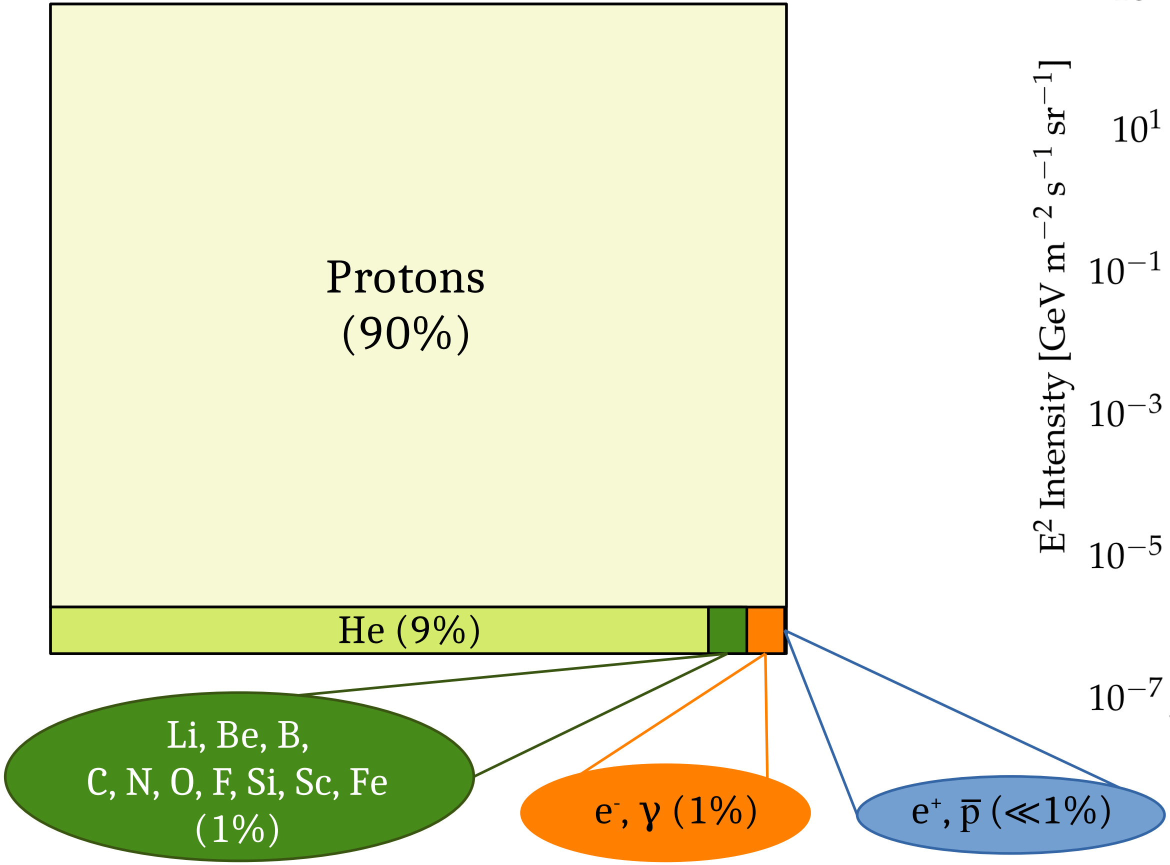


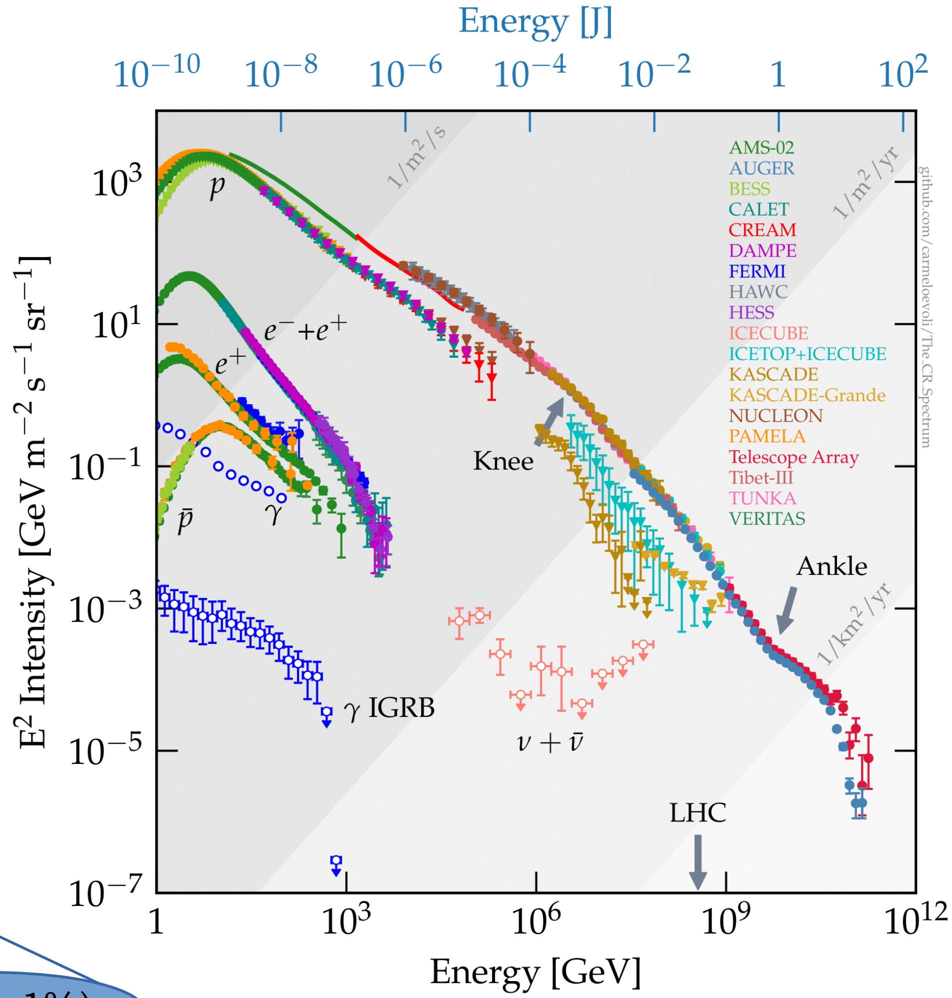
1928 – Robert Millikan concluded the cosmic origin of this radiation, and named them “Cosmic rays”!

1929 – Arthur Compton confirmed that cosmic rays are charged particles.

What are they?

- Relativistic, charged particles
- Energy: 10^9 eV - 10^{21} eV
- Origin: Galaxy and beyond





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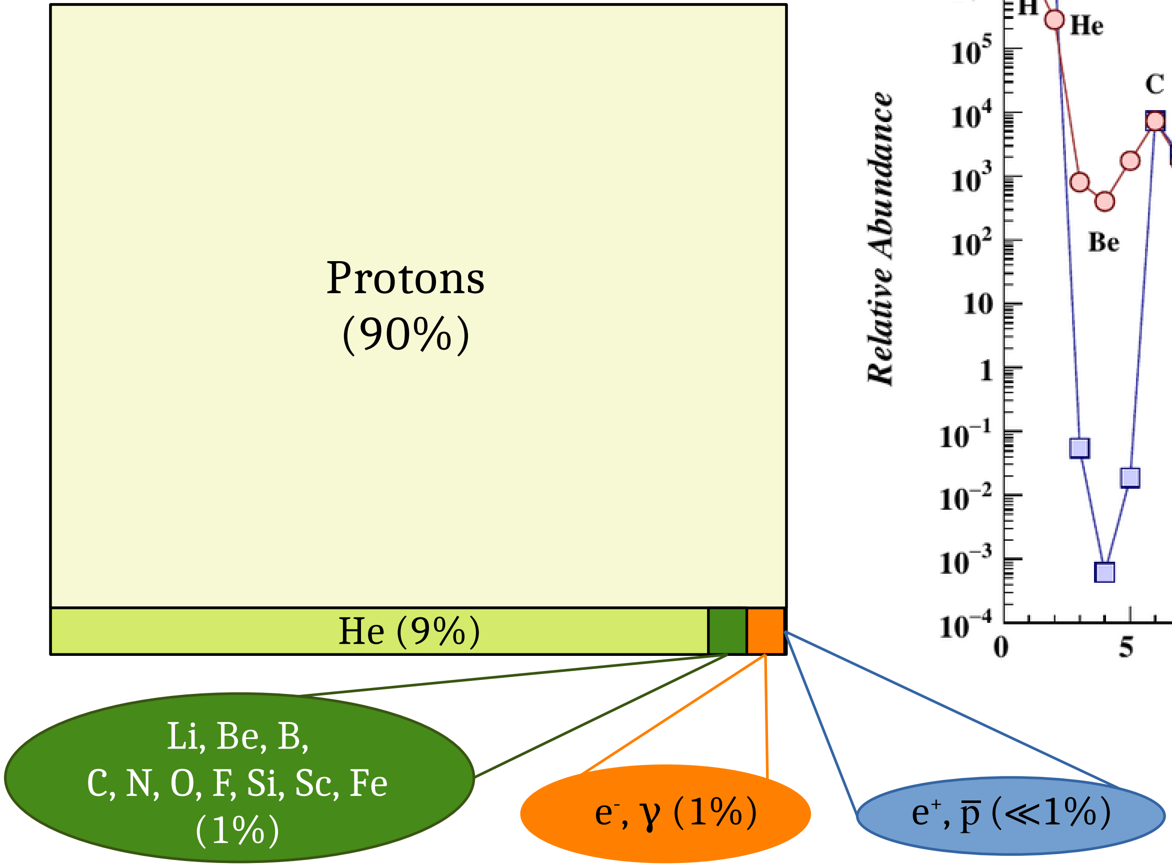

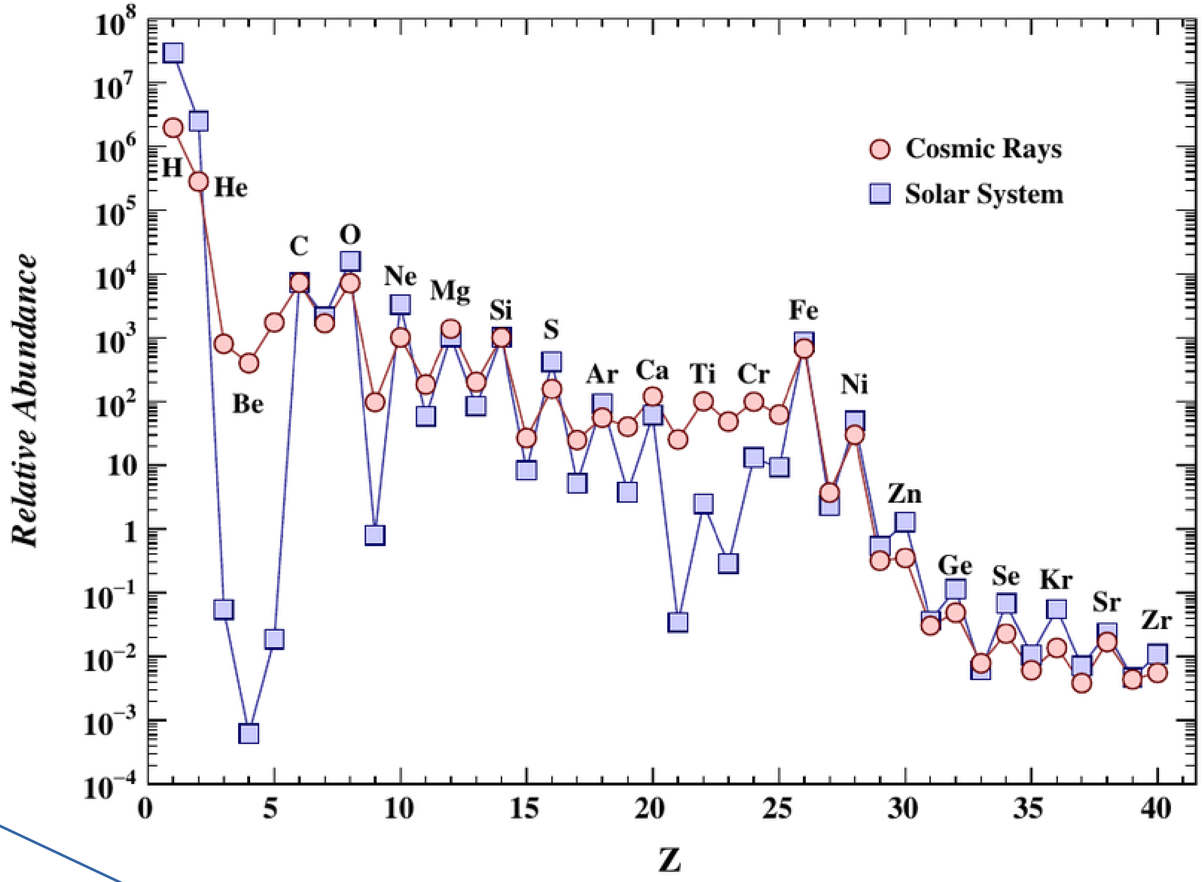

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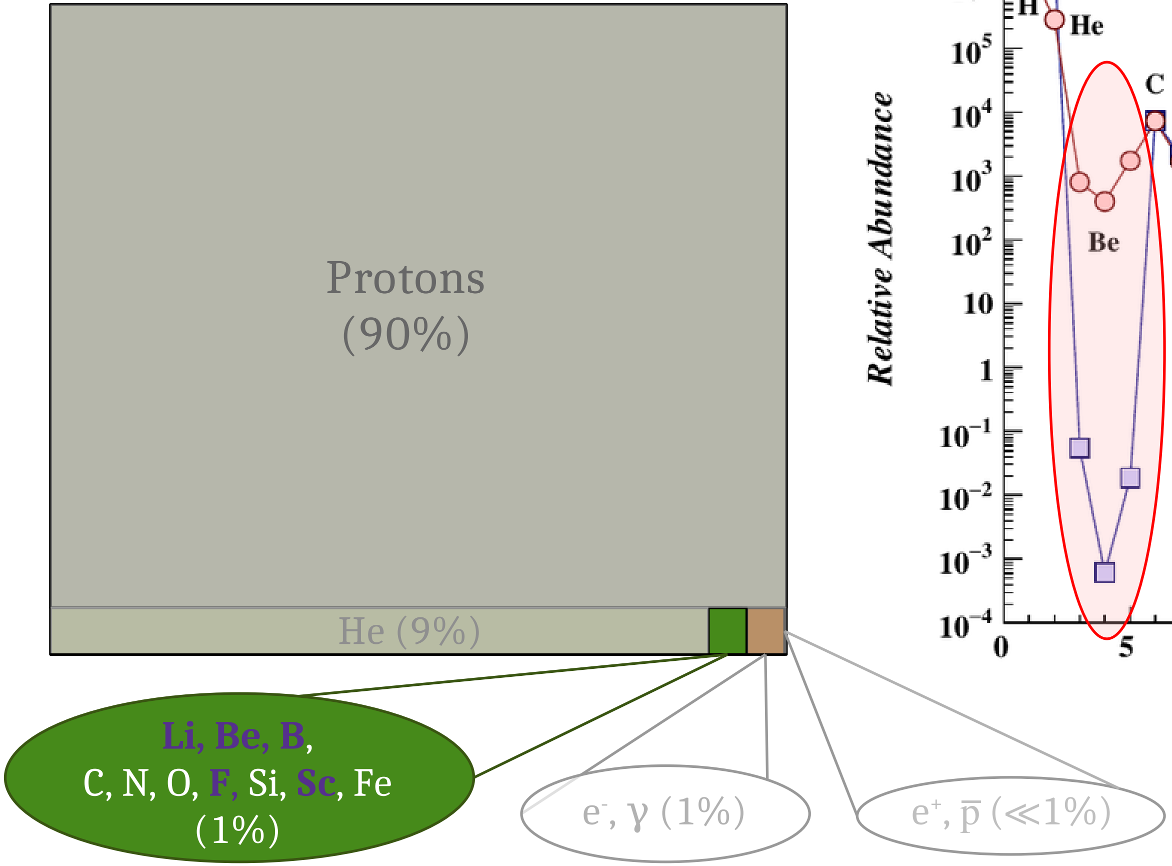

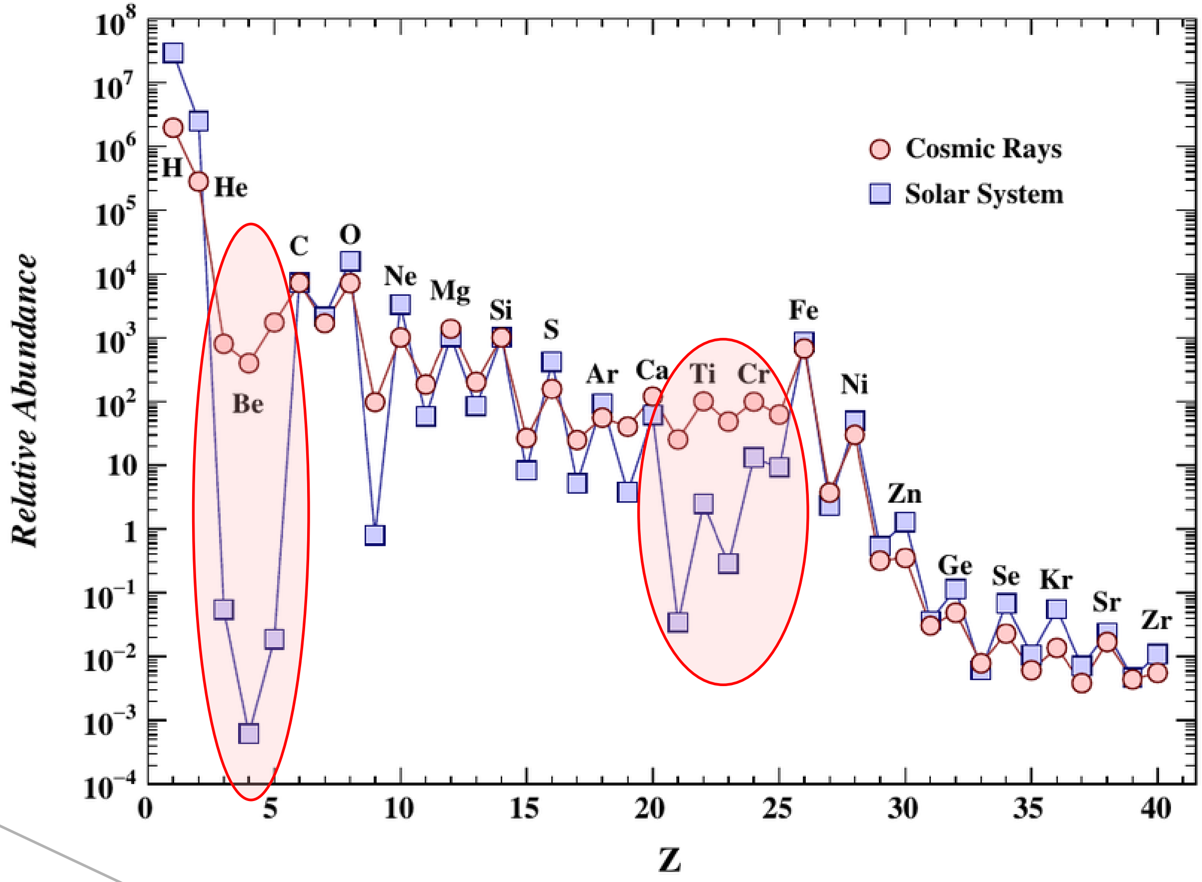

Cosmic Ray Nuclei in the Galaxy

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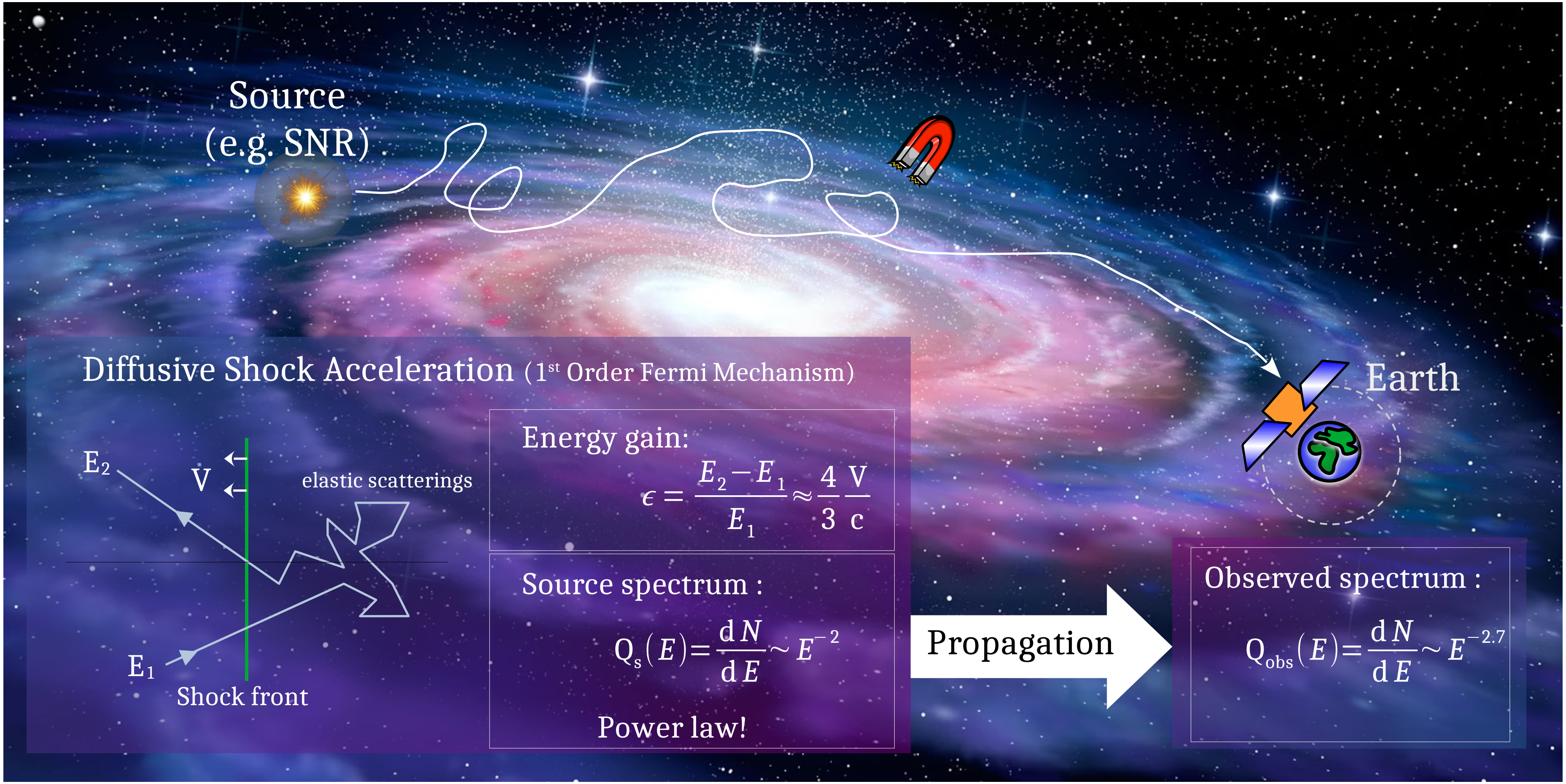

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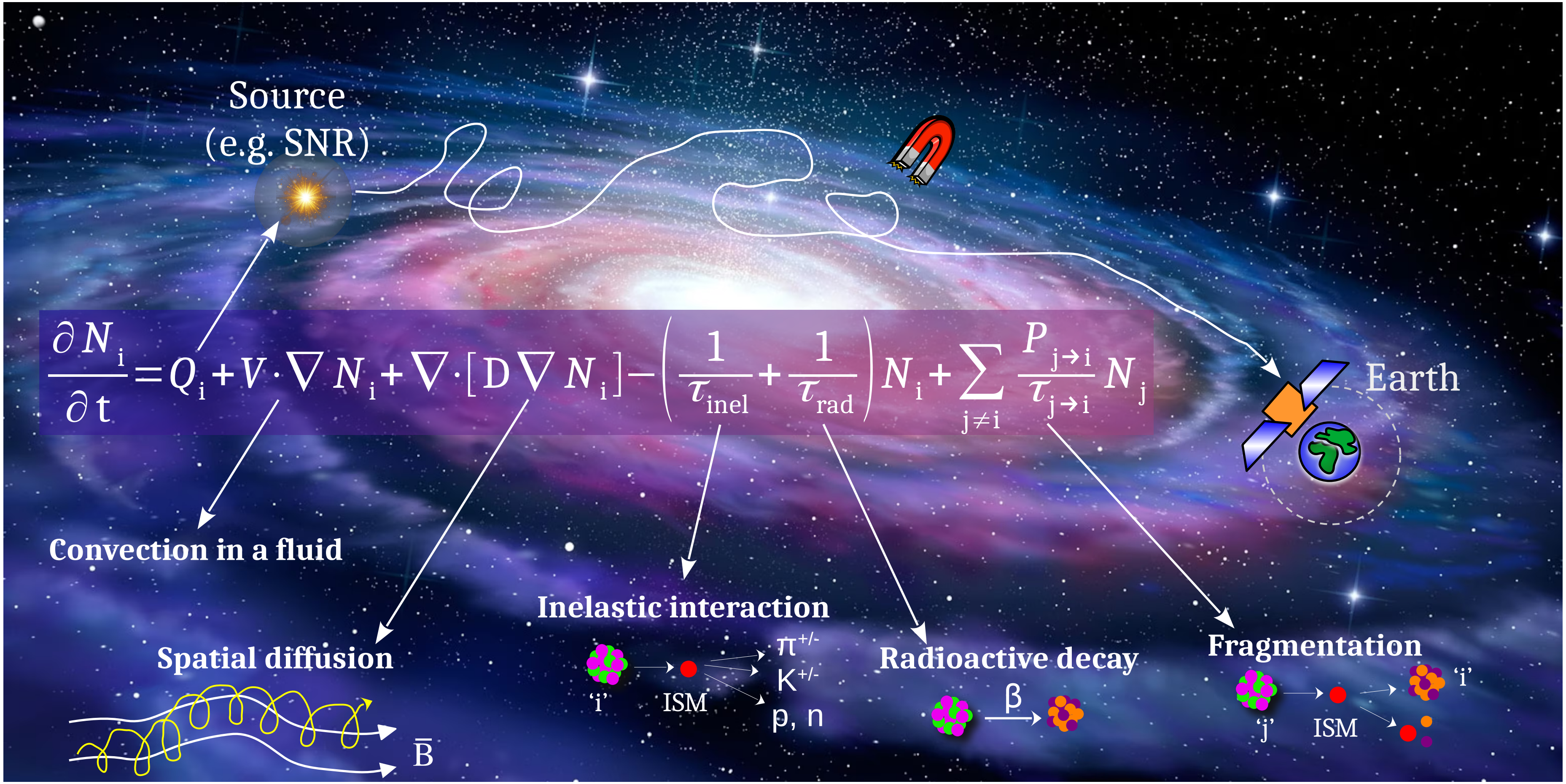

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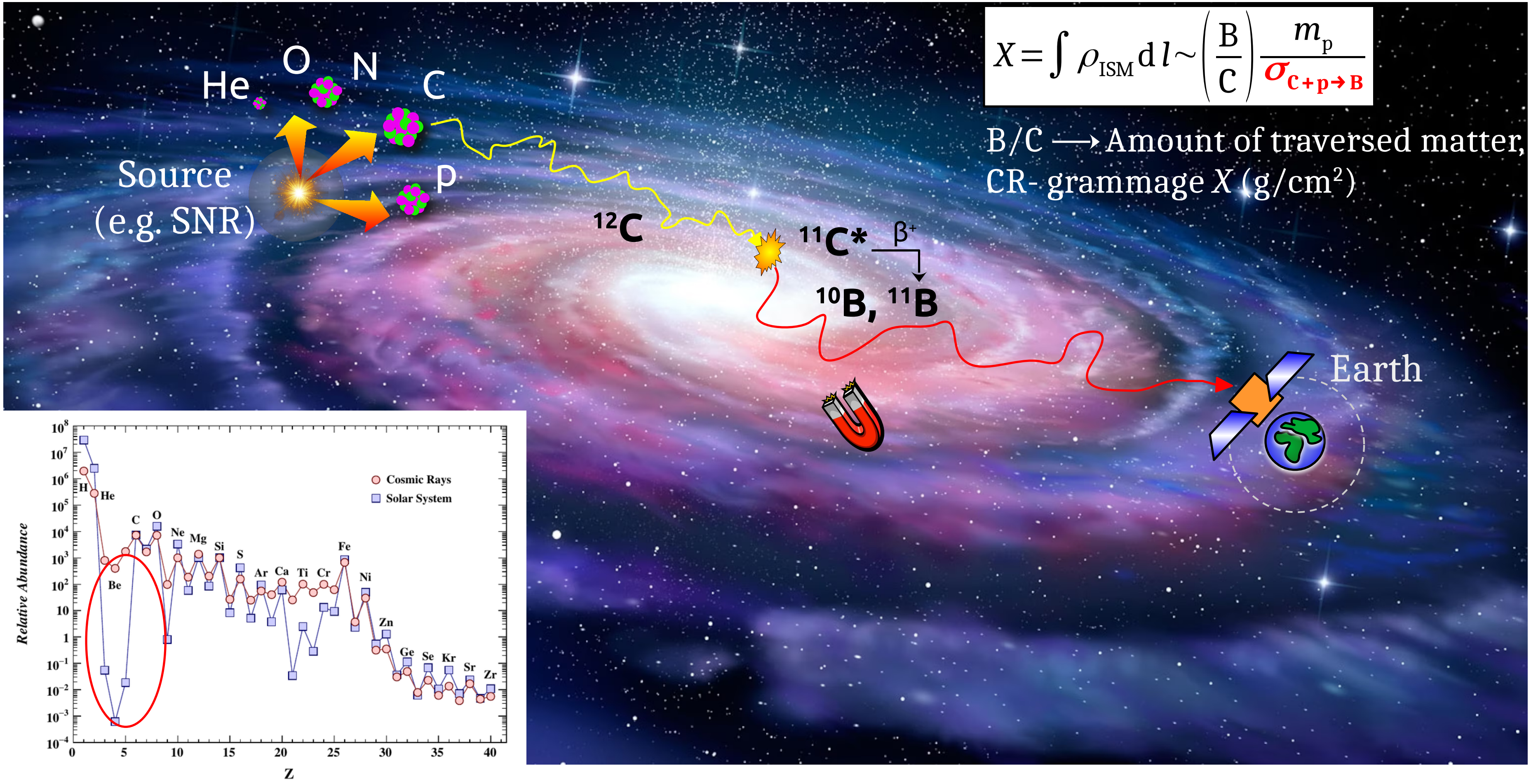
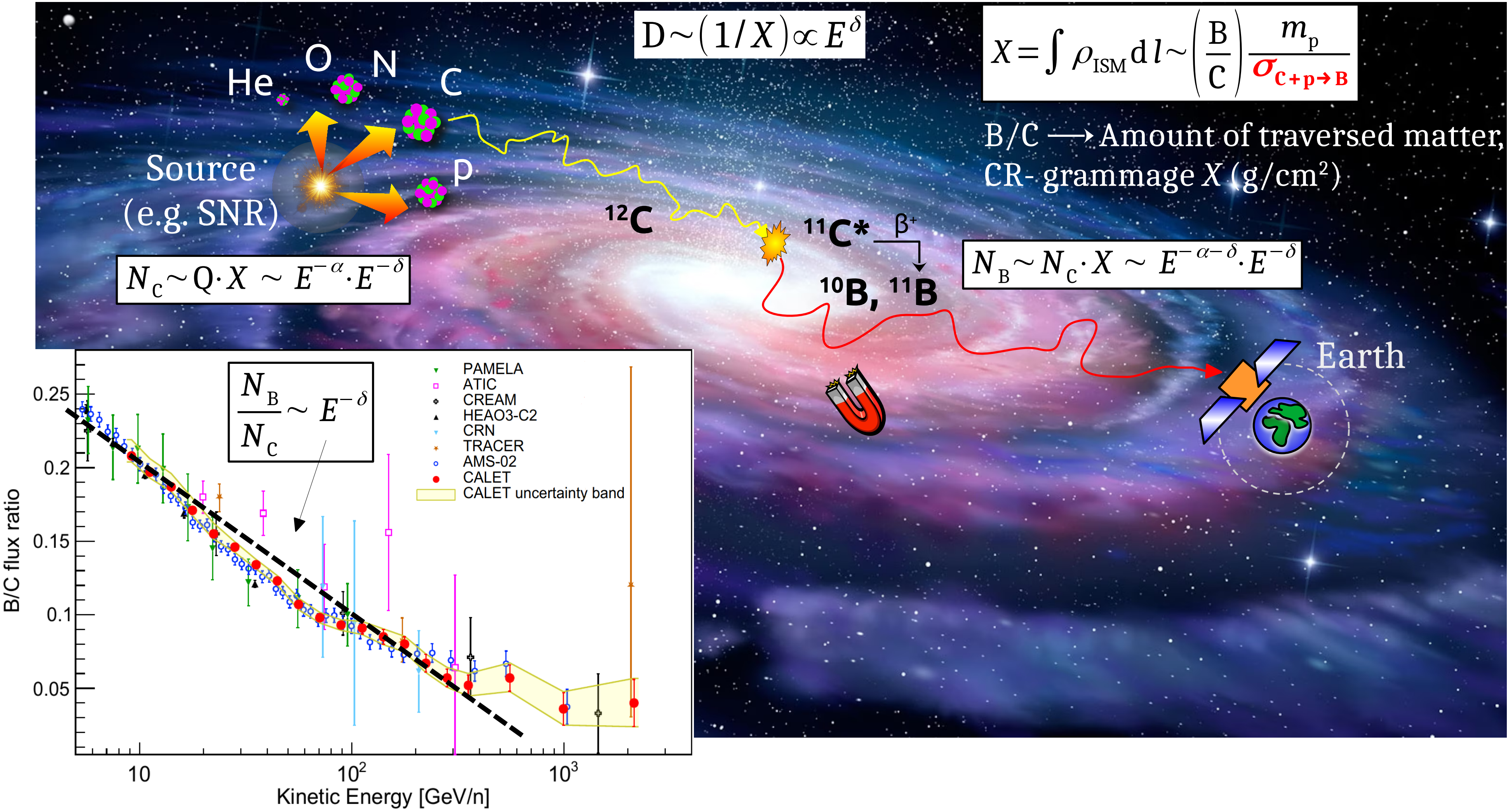


$$X = \int \rho_{ISM}\, dl \sim \left(\frac{B}{C}\right) \frac{m_p}{\sigma_{C+p \to B}}$$

B/C ⟶ Amount of traversed matter, CR- grammage X (g/cm^2)

Cosmic Ray Nuclei in the Galaxy



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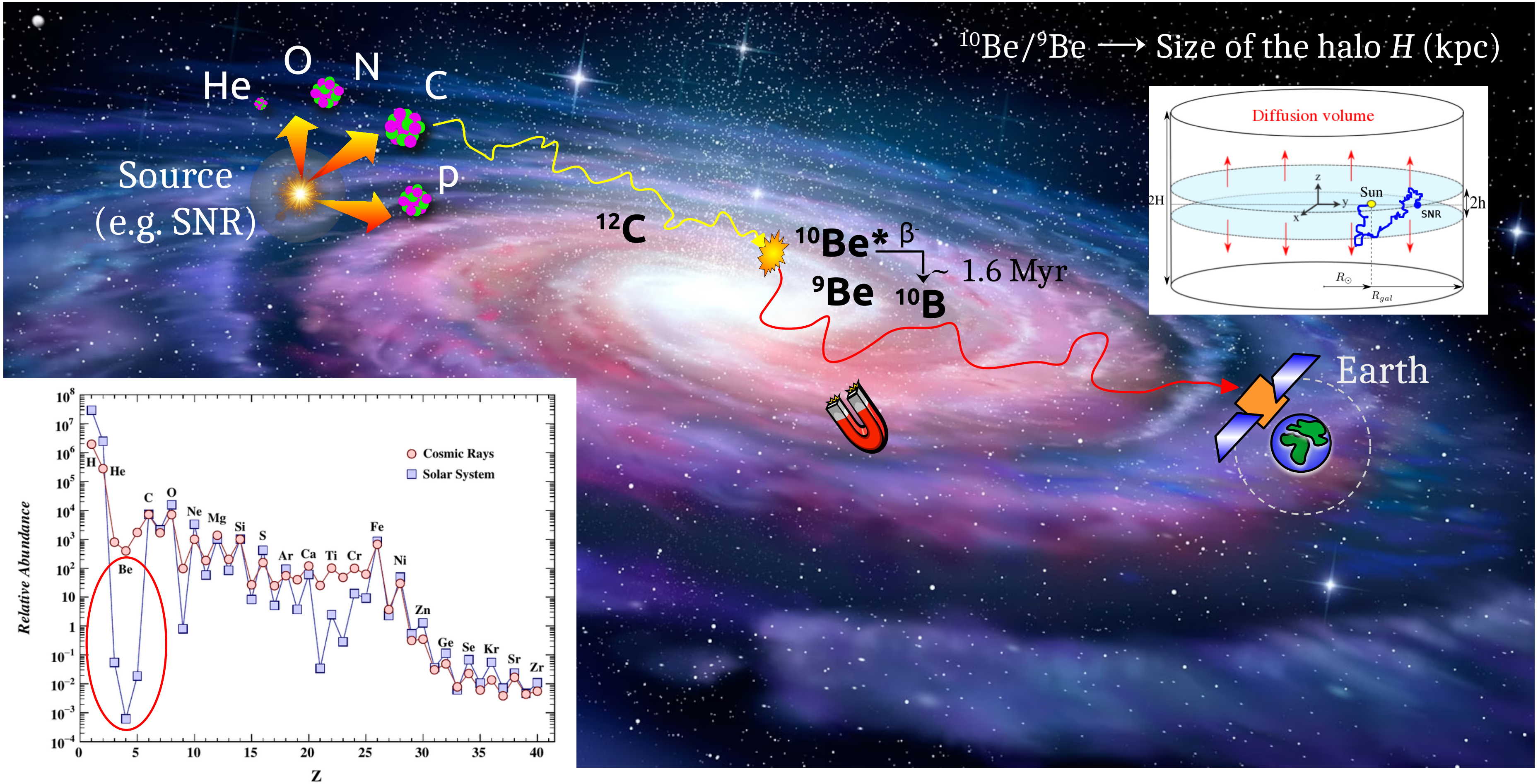

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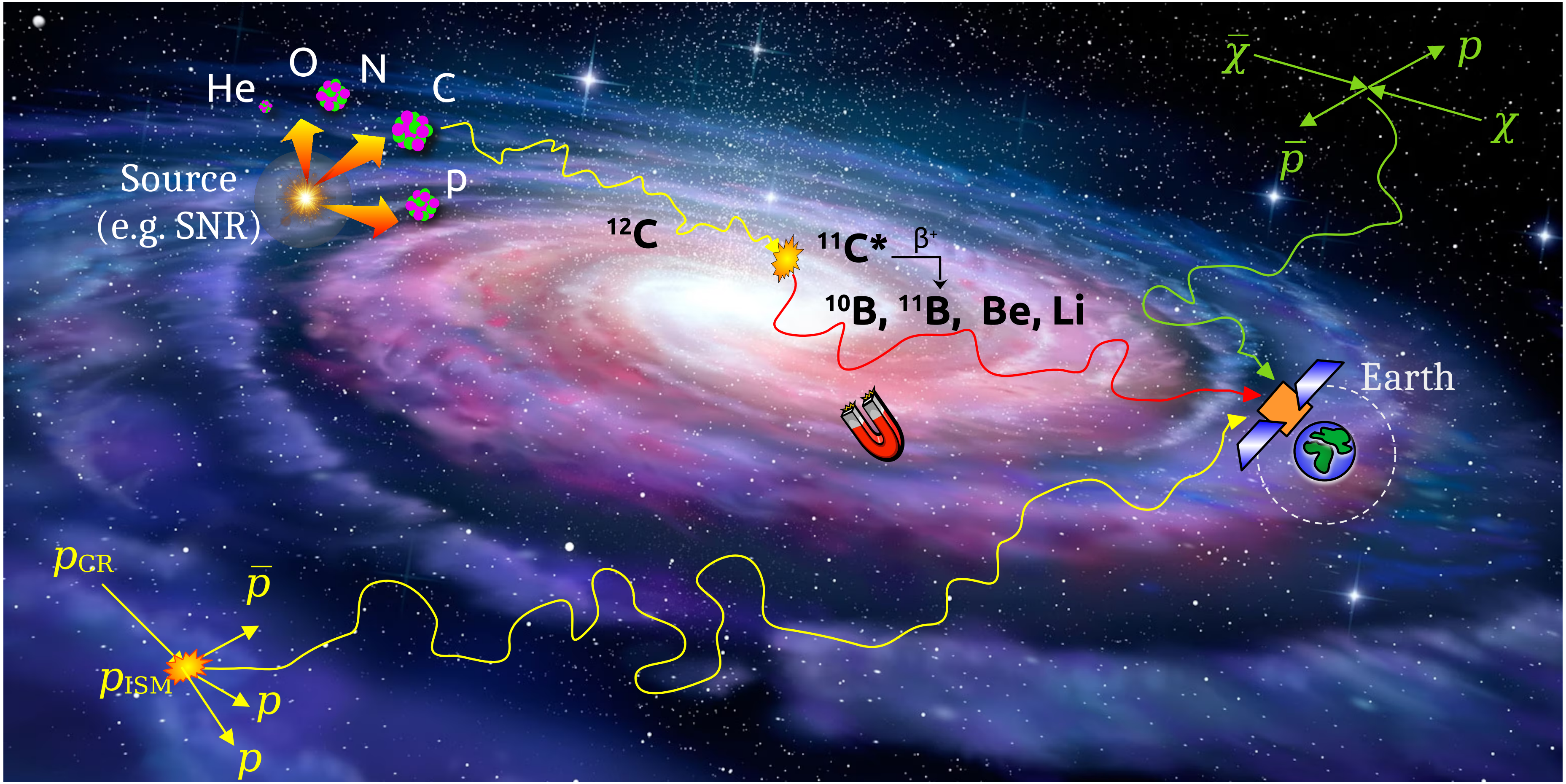

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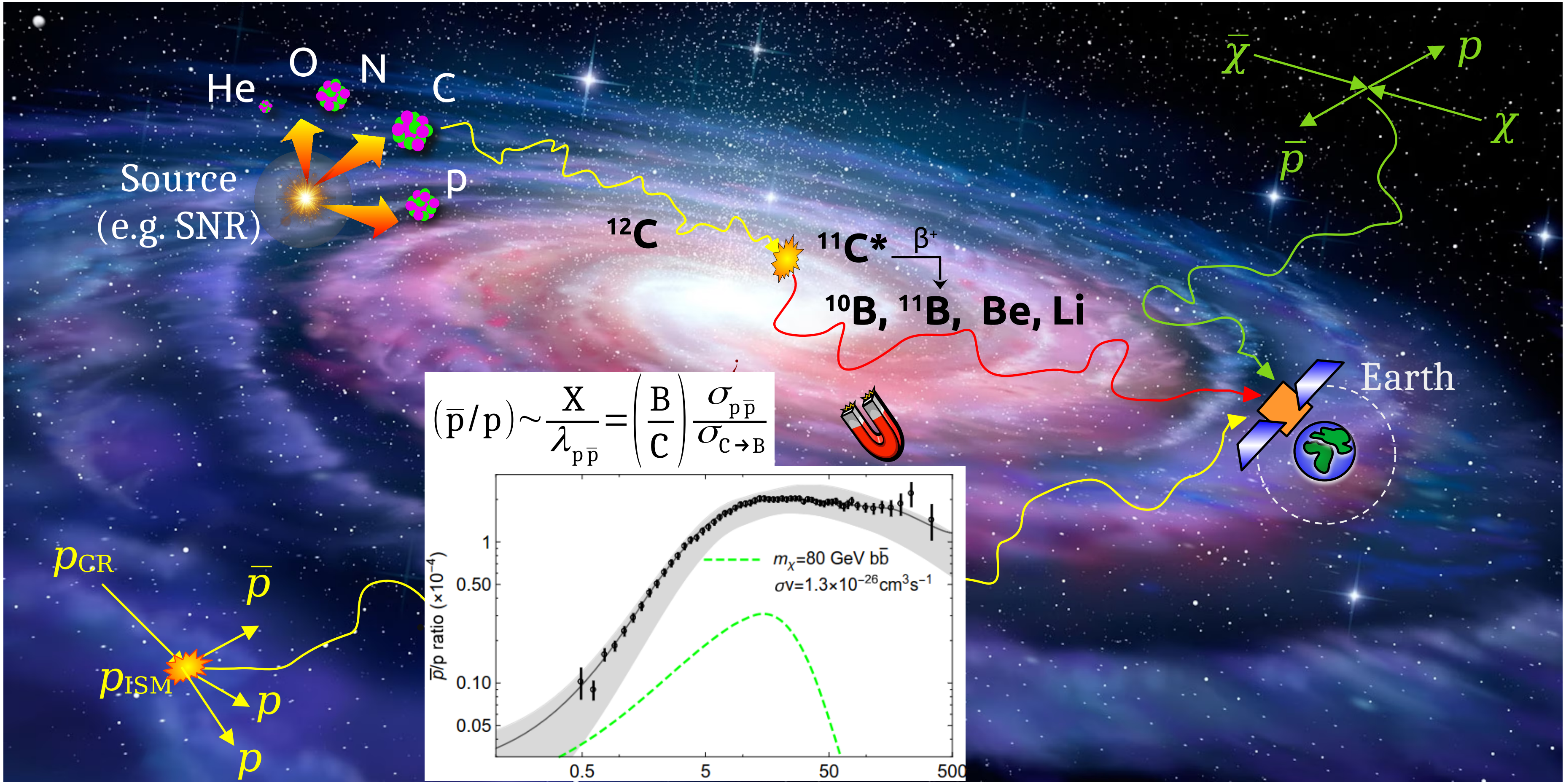
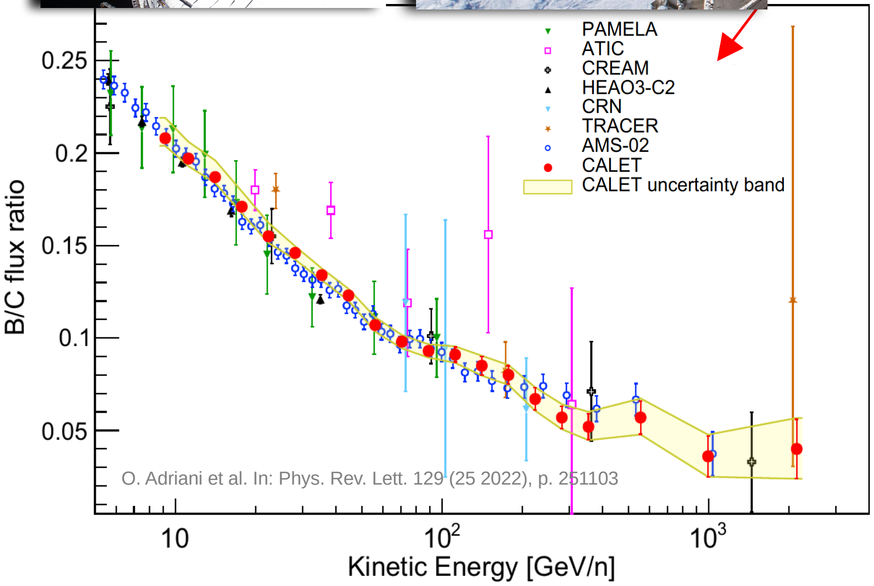


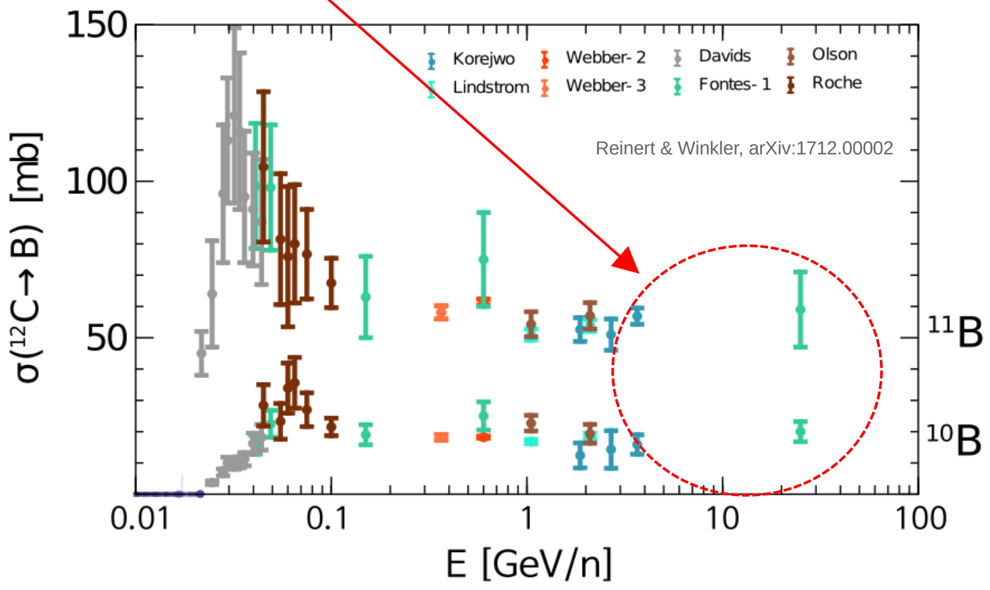
Need for Precise Cross section Measurements

The traversed CR-grammage, $X\,(\mathrm{g/cm^2})$

$$X \sim \left(\frac{\mathrm{B}}{\mathrm{C}}\right)\frac{m_{\mathrm{p}}}{\sigma_{\mathrm{C+p\to B}}}$$

- Predict CR contribution to galactic p-bar flux.
- Answer to the observed excess in Li/C and the F anomaly.
- Determine Galactic Halo height L.

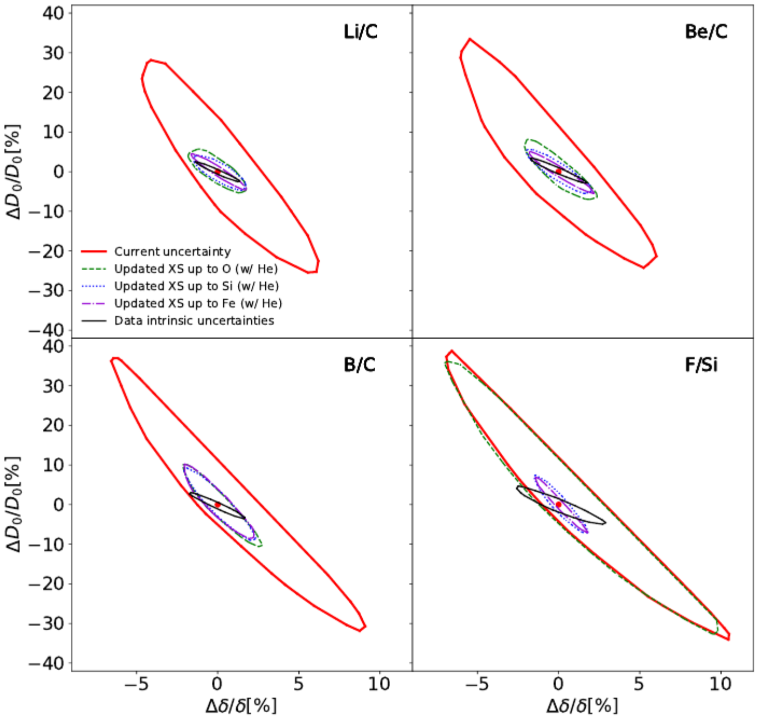




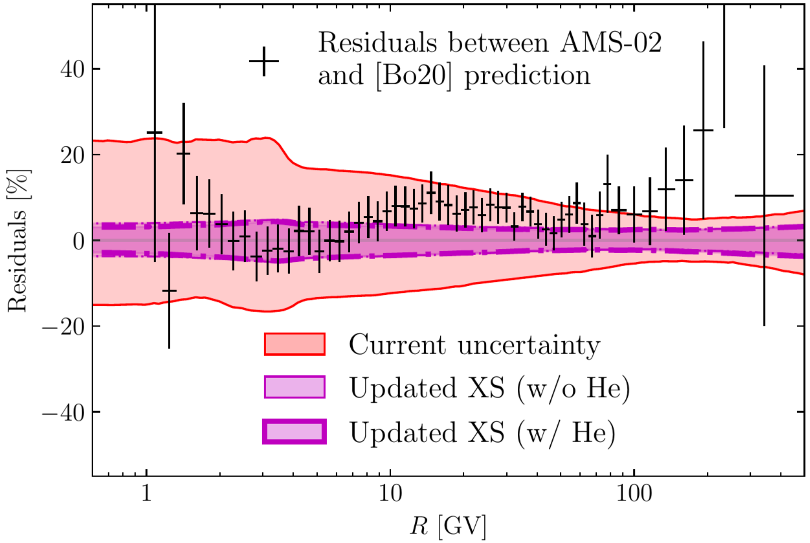
Includes contribution from β^+ decay of $^{11}\mathrm{C}\to{}^{11}\mathrm{B}$ and $^{10}\mathrm{C}\to{}^{10}\mathrm{B}$

Need for Precise Cross section Measurements

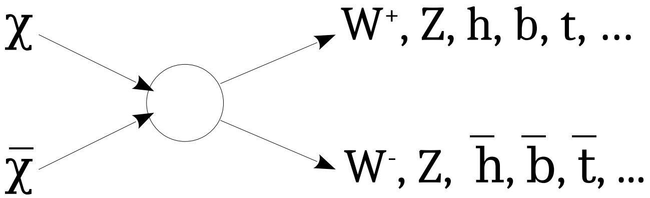
Stable Secondary-to-primary ratios → Propagation parameters D_0 and δ



Predicting the CR antiproton contribution



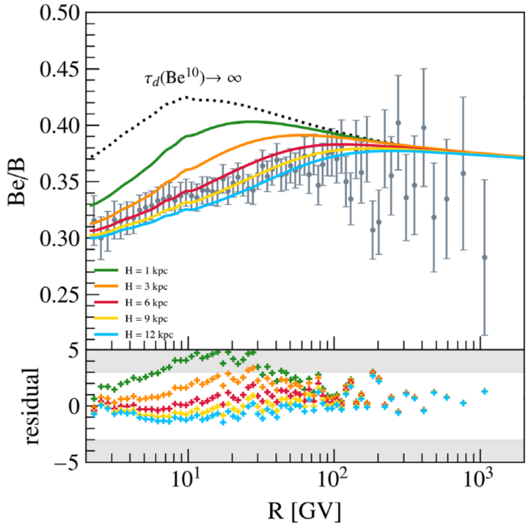
Estimate background for DM signal

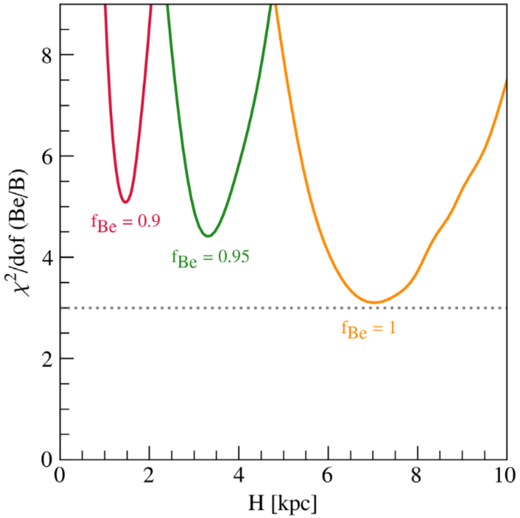


Y. Genolini, D. Maurin, I.V. Moskalenko, M. Unger (arXiv: 2307.06798)

Need for Precise Cross section Measurements

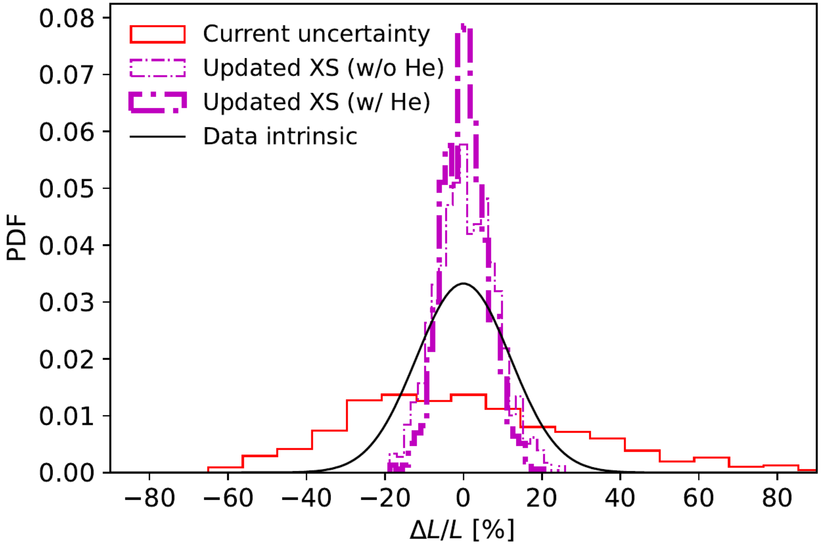
Current cross section uncertainties → determination of Halo size (L)





C. Evoli et. al PRD 101 (2020) 023013

Improved rel. uncertainty on Halo size L



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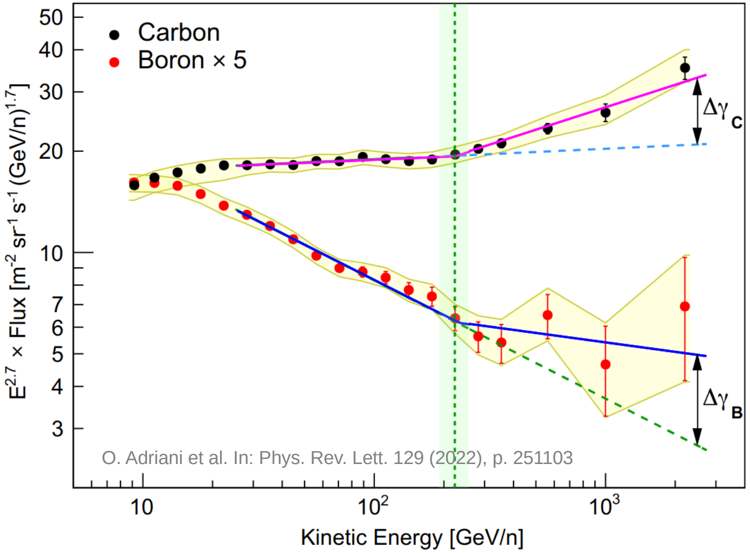
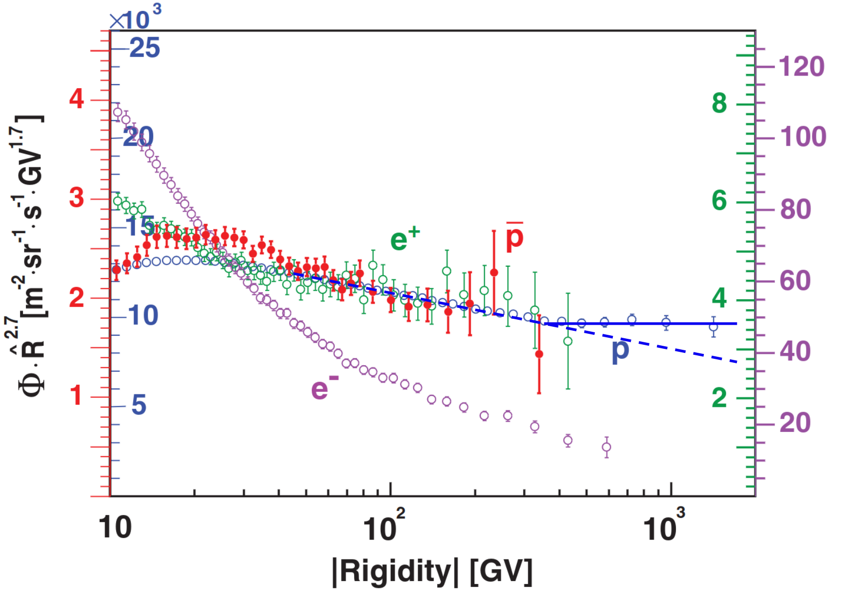
Cosmic Discoveries → New Physics?

Break in the spectrum, $E > 200$ GeV/n





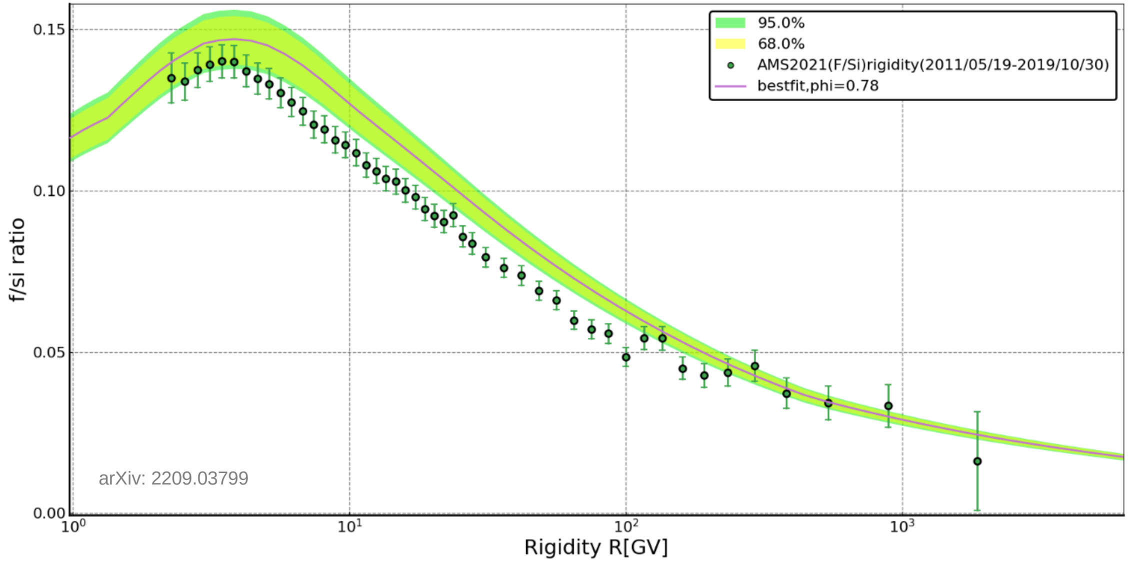
- break in source spectrum: break in secondaries similar

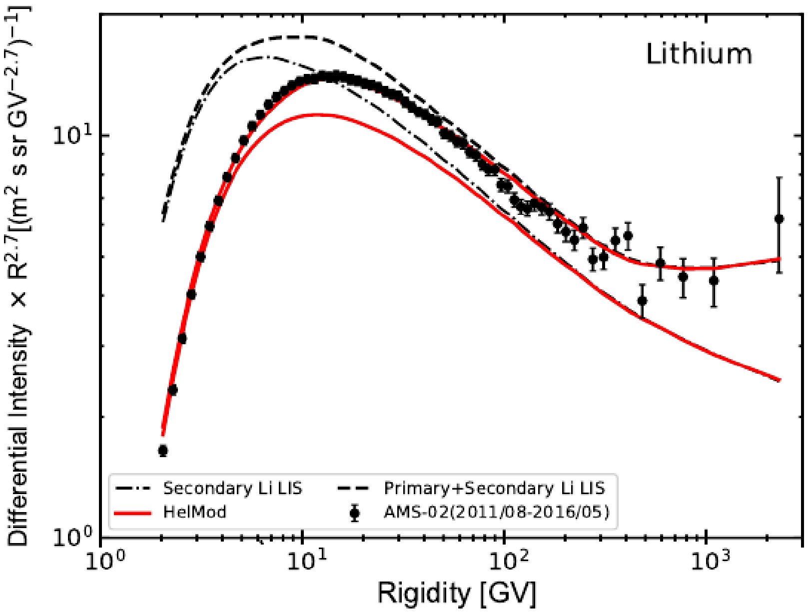
- break in diffusion coefficient: break in secondaries $\sim 2\times$ as strong

Cosmic Discoveries → New Physics?

Fluorine Anomaly:
- Predicted F/Si from B/C ratio.
- Observed F/Si < Predicted F/Si!

Lithium Excess:
- Predicted Li/C from B/C ratio.
- Observed Li/C > Predicted Li/C!



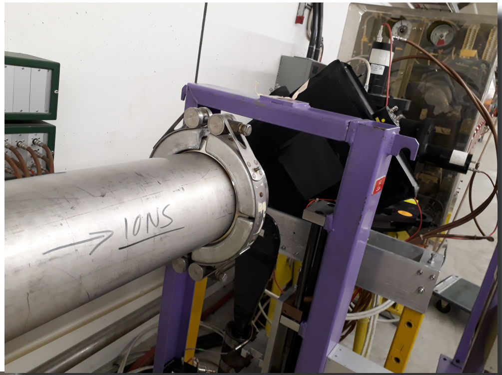


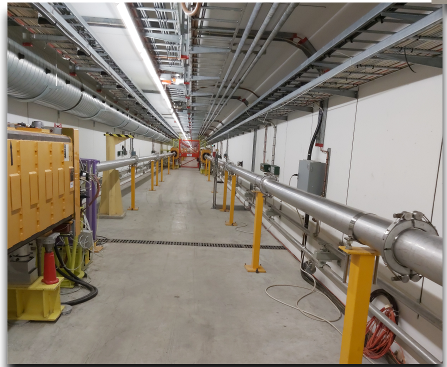
Fragmentation cross section uncertainties (?)

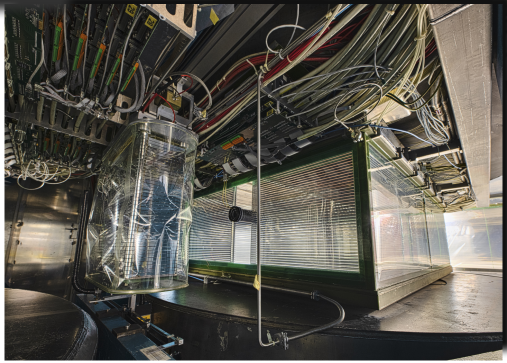
NA61/SHINE

NA61/**S**PS **H**eavy **I**on and **N**eutrino **E**xperiment

- Fixed target experiment on the H2 beamline at CERN
- SPS range : 13*A* GeV/*c* – 160*A* GeV/*c*.



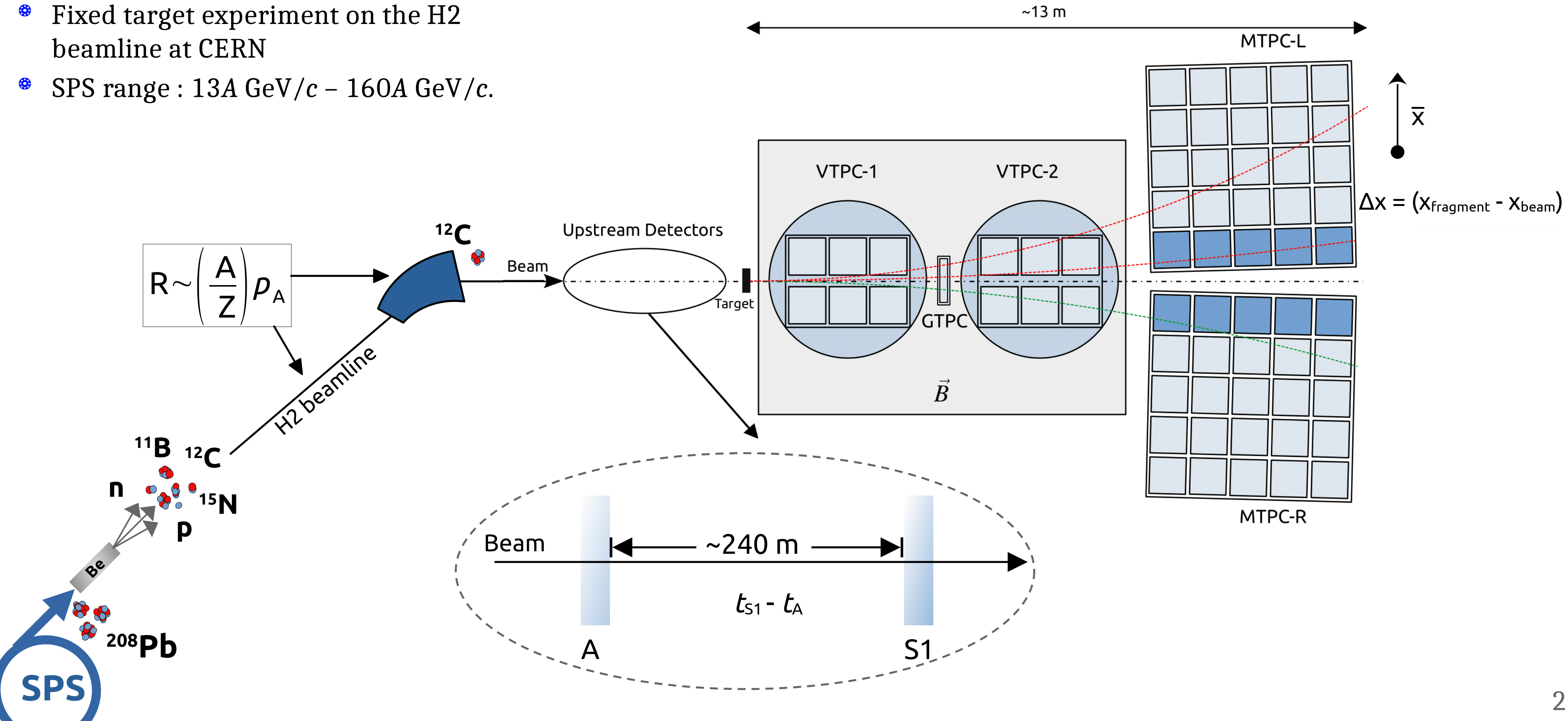




NA61/SHINE

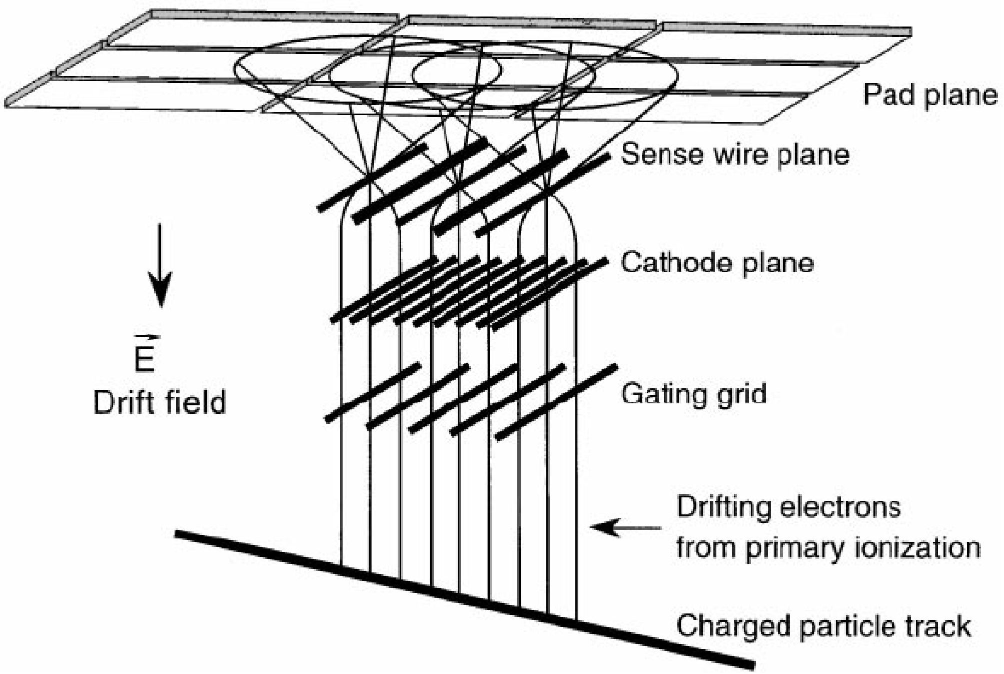
NA61/SPS Heavy Ion and Neutrino Experiment

- Fixed target experiment on the H2 beamline at CERN
- SPS range : 13A GeV/c – 160A GeV/c.

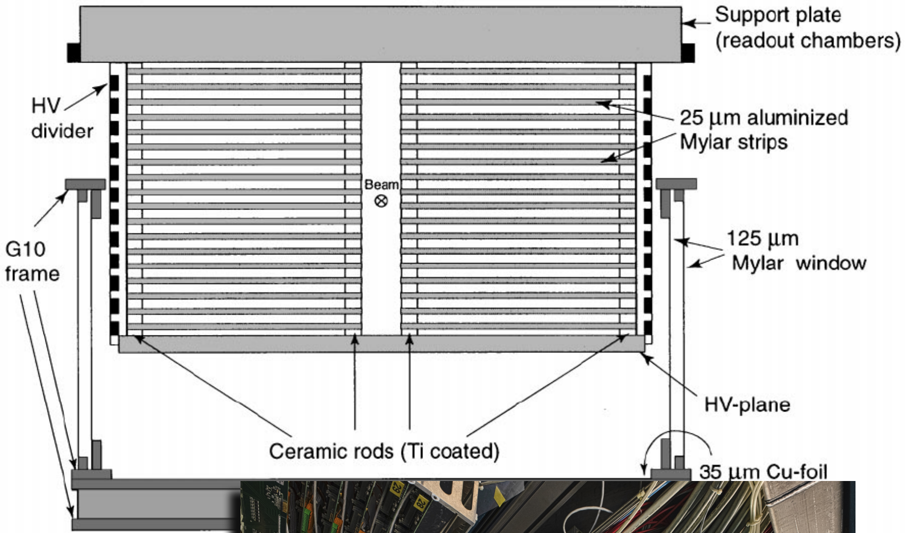


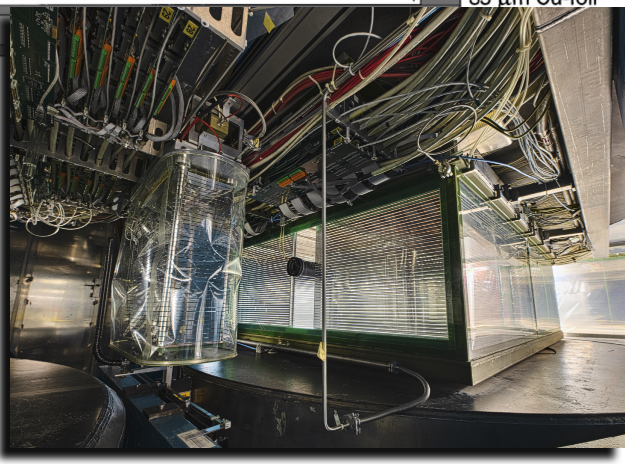
Time Projection Chamber (TPC)

Working principle

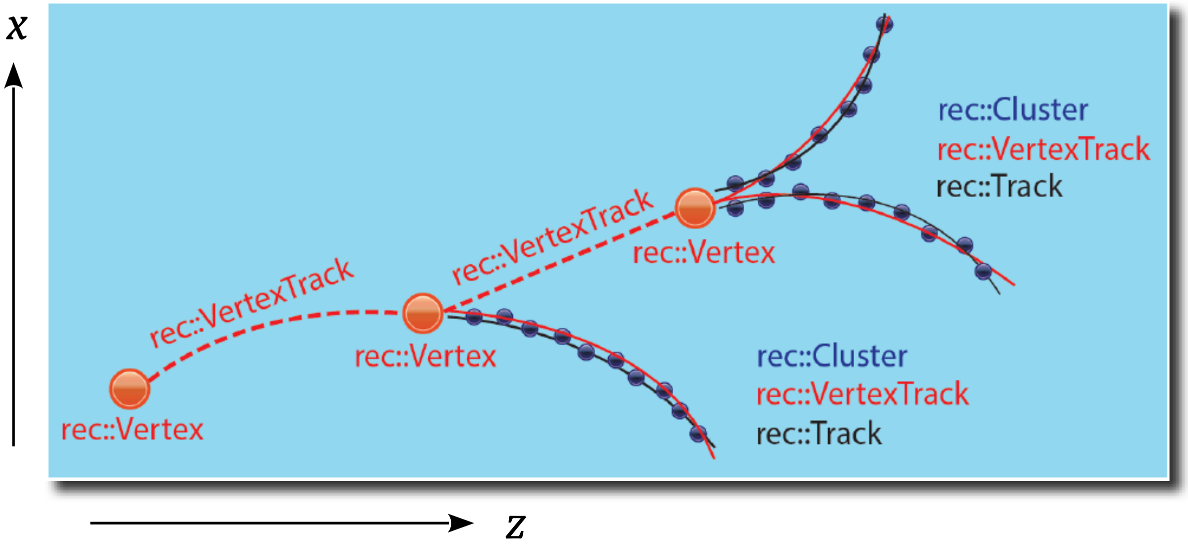


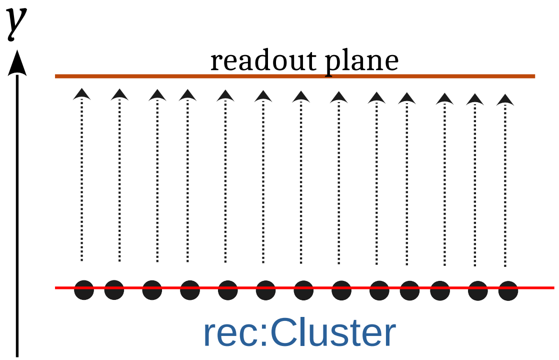
Schematic front view of the Vertex TPC





TPC Track Reconstruction

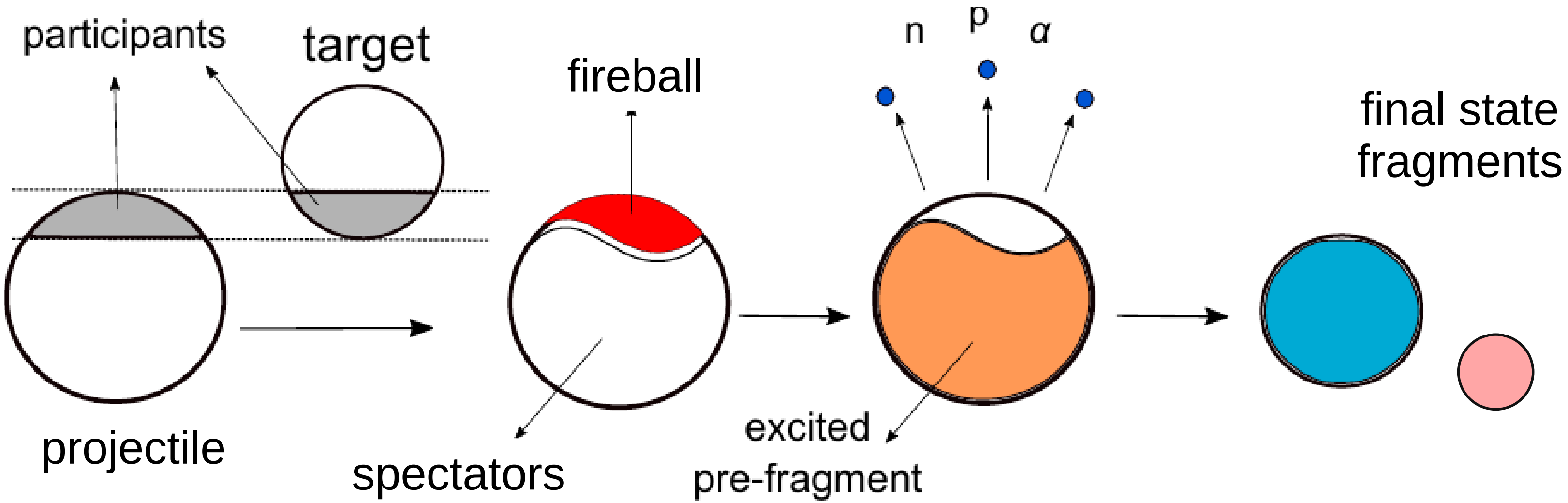




$$y = t_d v_d$$

Nuclear Fragmentation

Inelastic interaction leading to production of lighter fragments

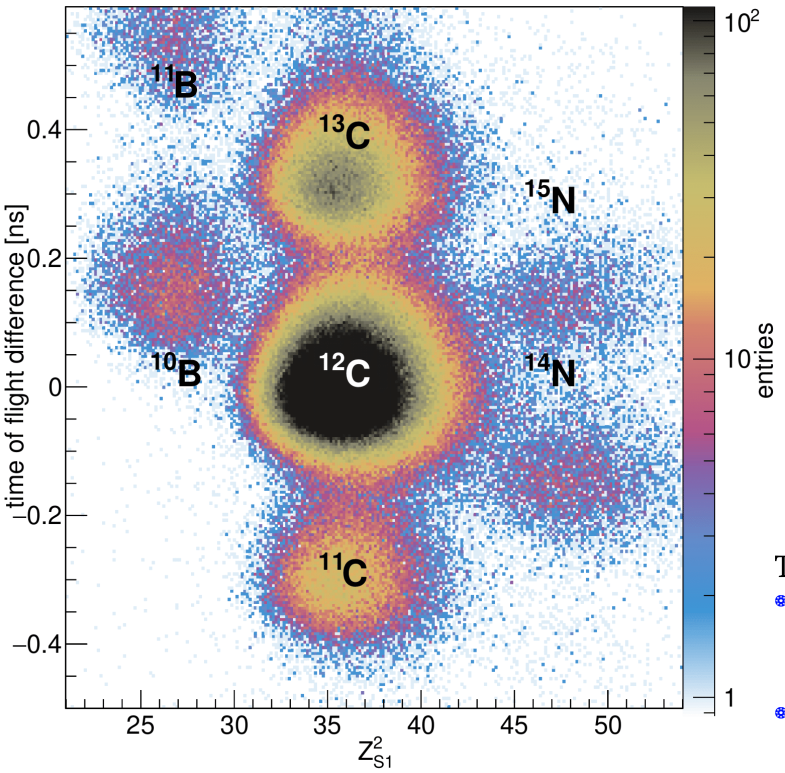


Abrasion: interaction of spectator nucleons

Ablation: disintegration of excited pre-fragment

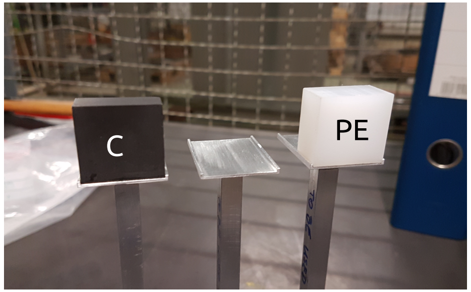
Pilot Run on Fragmentation Studies

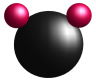
<u>Beam ID:</u>
- Z^2 from $(dE/dx)_{S1}$
- (A/Z) from *t.o.f.* difference = $t_{S1} - t_A$



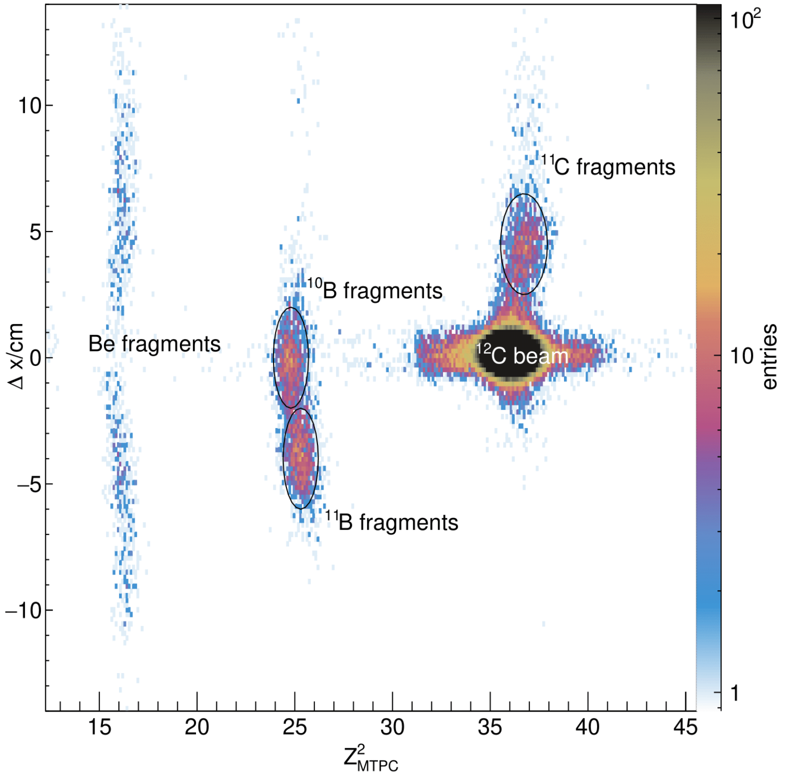
Triggered beam particles.

^{12}C+p at 13.5A GeV/c



Targets used:
- Polyethylene (PE) 
- Graphite (C) 

<u>Fragment ID :</u>
- Z^2 from $(dE/dx)_{MTPC}$
- (A/Z) from $\Delta x \propto R(A,Z)$



Fragments as measured in the MTPC.

Pilot Run on Fragmentation Studies

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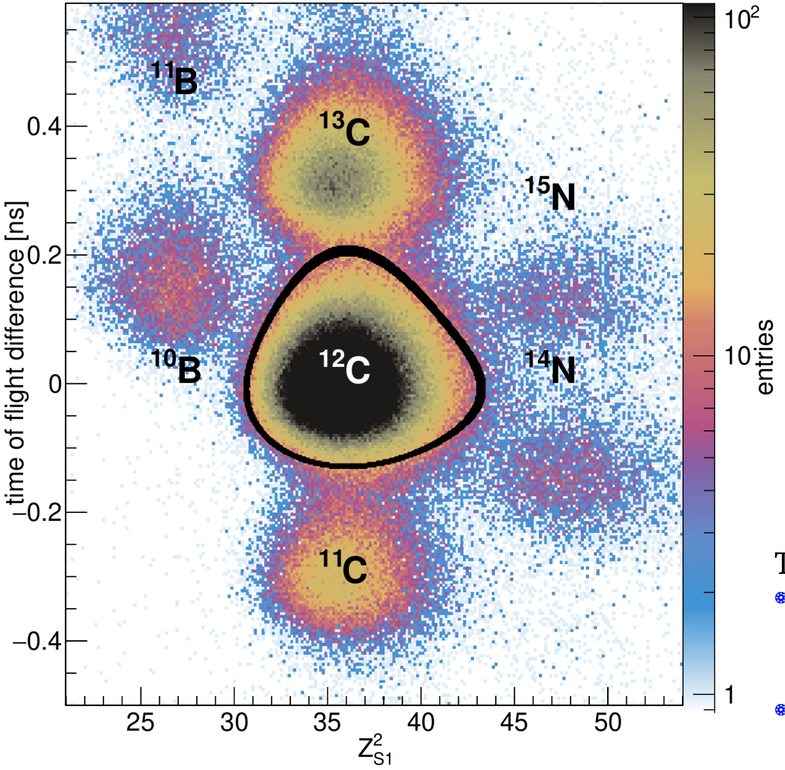

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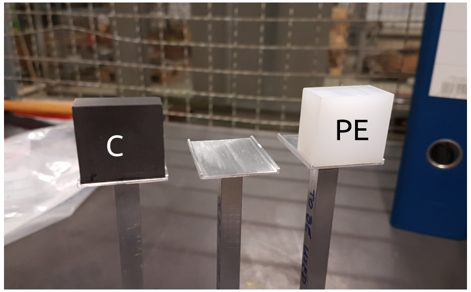

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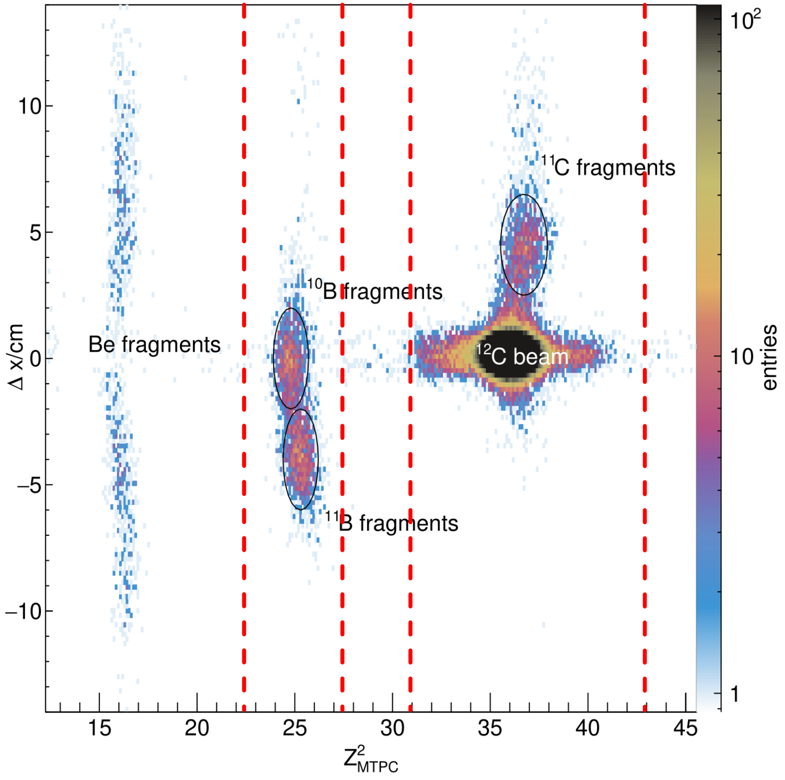
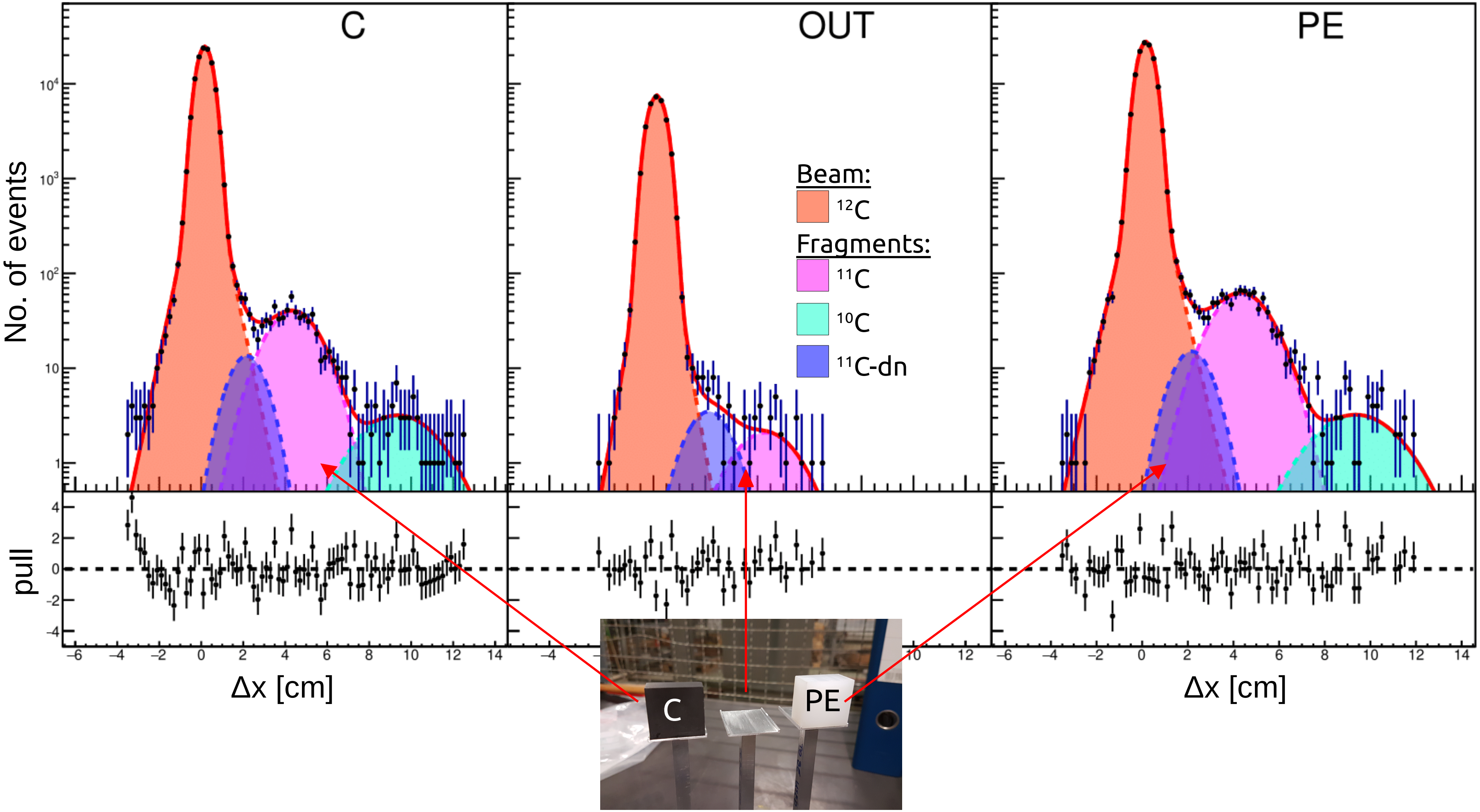


Fragments as measured in the MTPC.

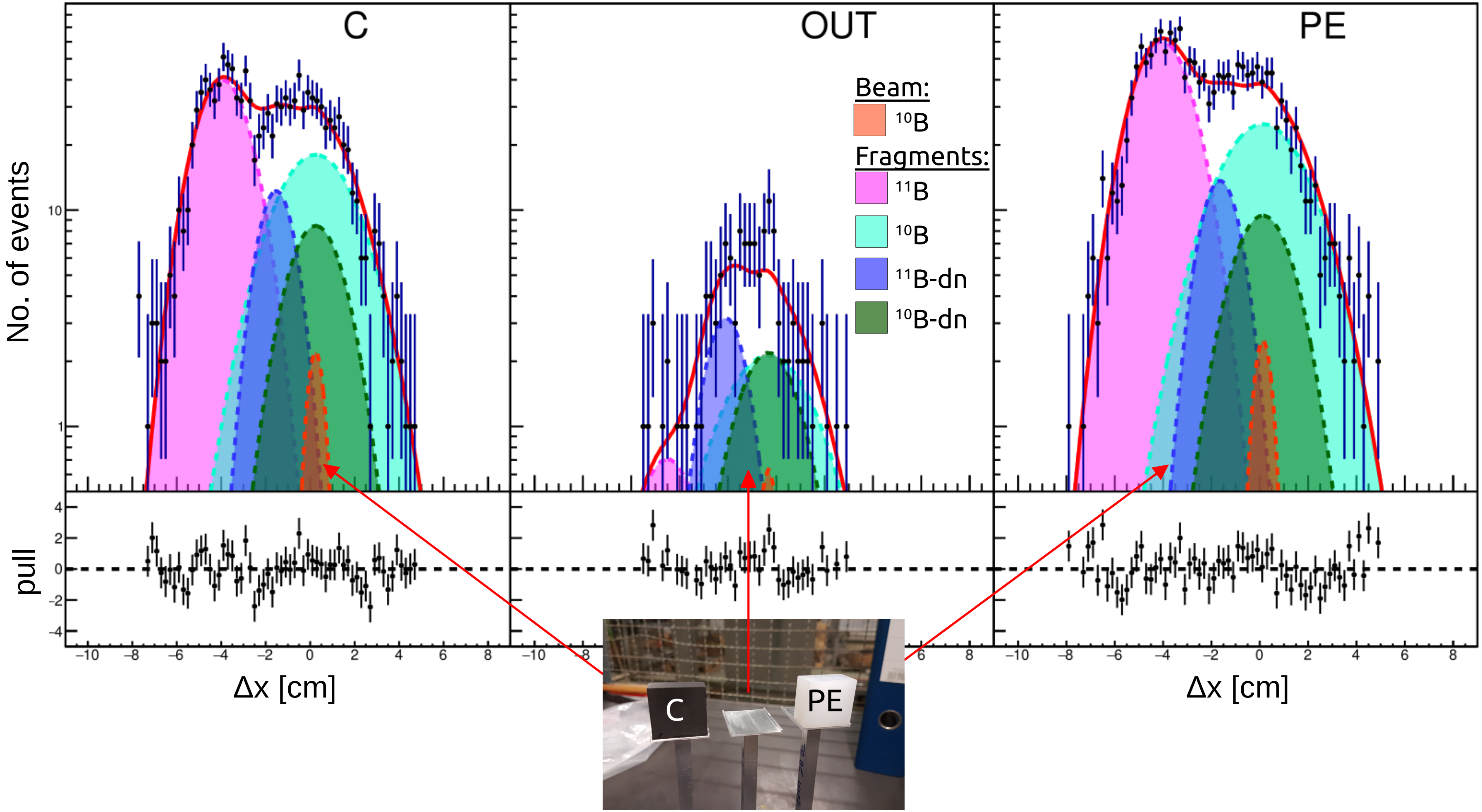
Fit to the Carbon Fragments in the MTPC

Fit Function $f(\Delta x)$ = Detector Model ⊗ Width due to Fermi Motion



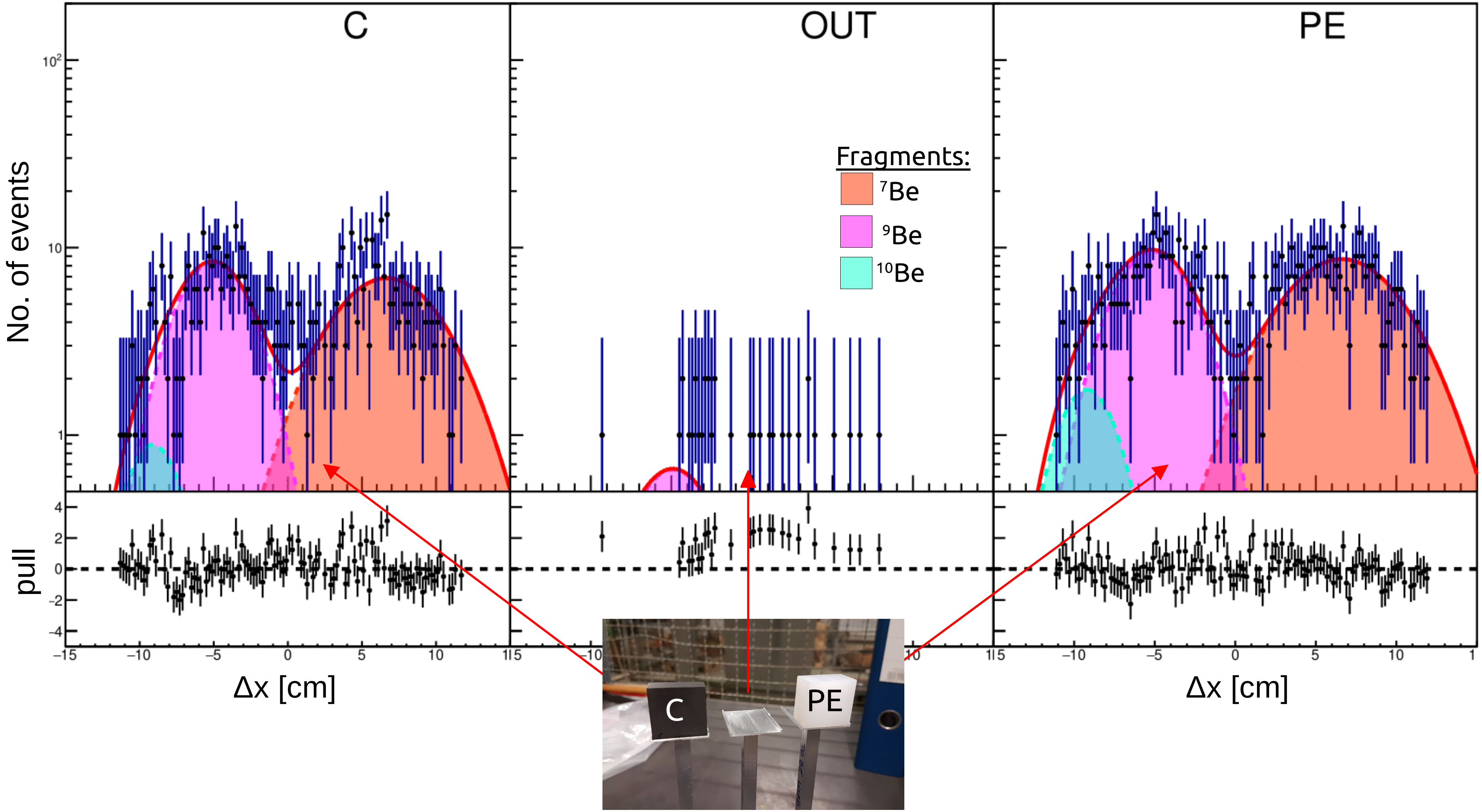
Fit to the Boron Fragments in the MTPC

Fit Function $f(\Delta x)$ = Detector Model ⊗ Width due to Fermi Motion



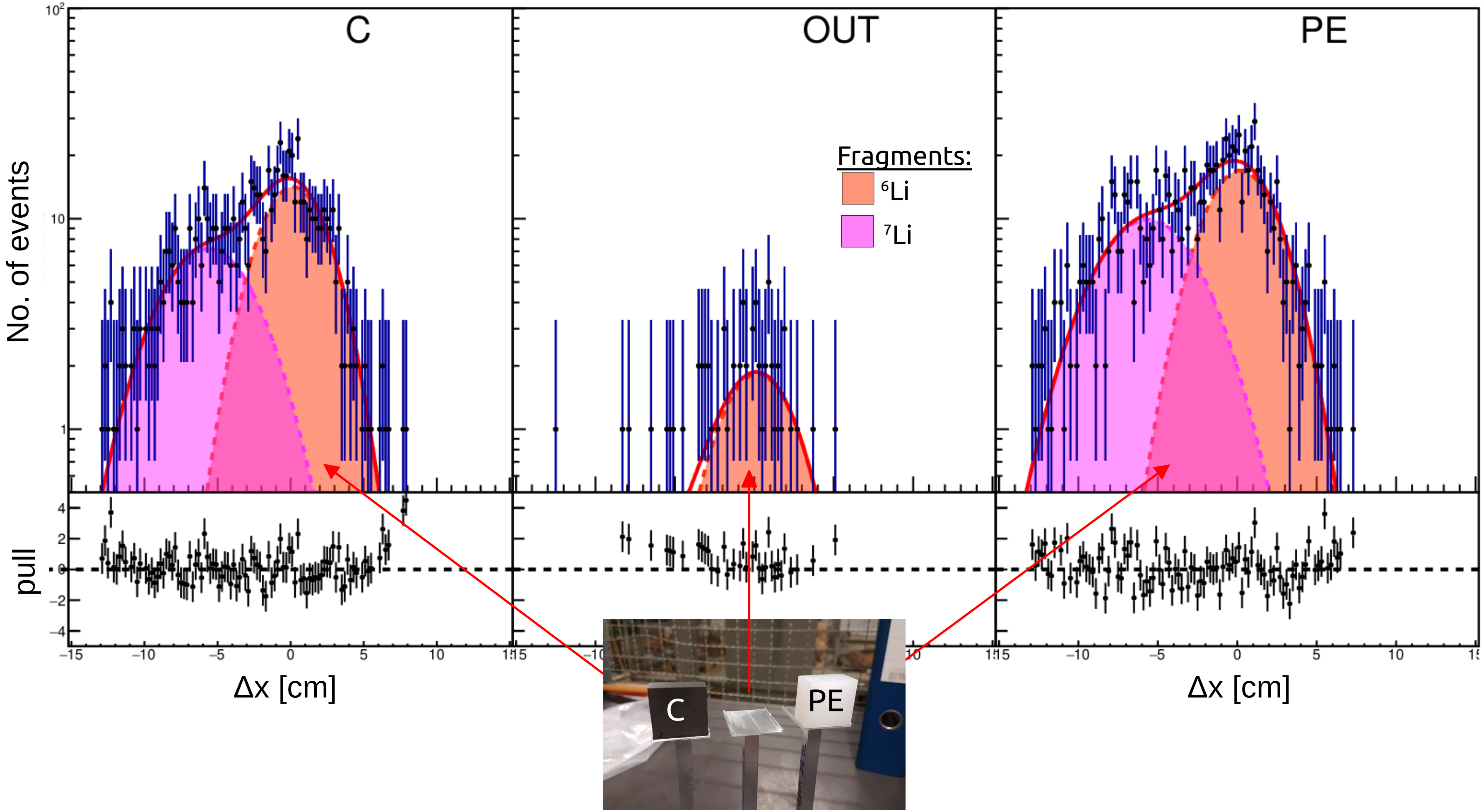
Fit to the Beryllium Fragments in the MTPC

Fit Function $f(\Delta x)$ = Detector Model ⊗ Width due to Fermi Motion



Fit to the Lithium Fragments in the MTPC

Fit Function $f(\Delta x)$ = Detector Model ⊗ Width due to Fermi Motion



Analysis

For each target setting,

$N_{\text{fragments}} \rightarrow P_{\text{total}} \rightarrow P_{\text{T}} \rightarrow$ $$\sigma_{\text{T}} = -\frac{\ln(1 - P_{\text{T}})}{n_{\text{T}}\, d_{\text{T}}}$$

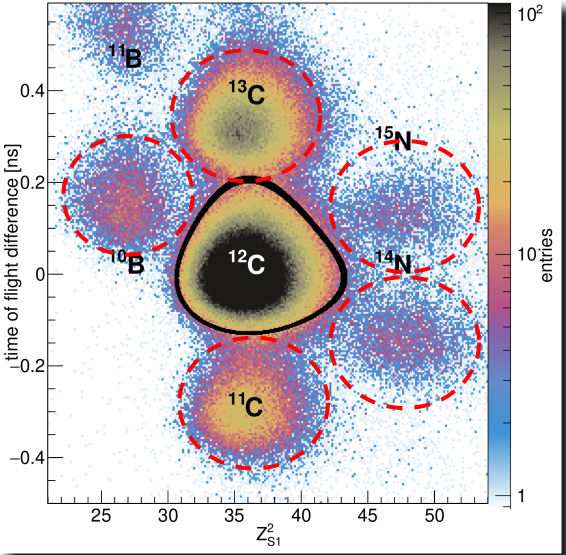
where, n_{T} is the number density,
d_{T} is the target thickness

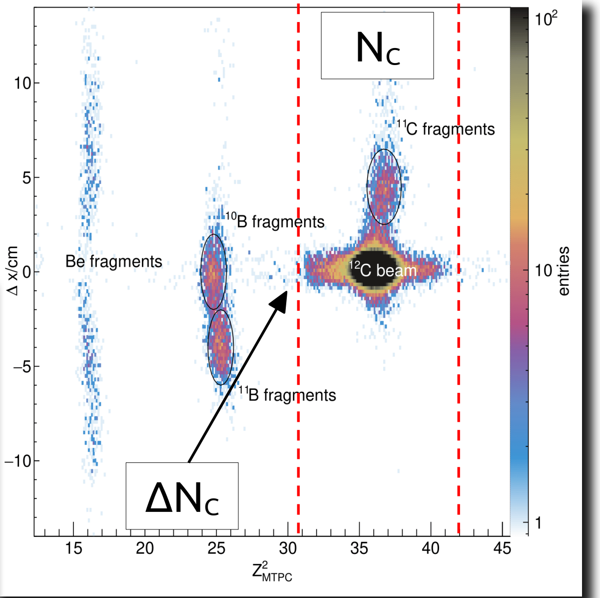
Data-driven corrections to the cross section:

- Fragment selection in the MTPC
- Beam selection
- Absorption inside the target

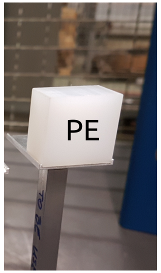
Nucleus (i)	Target	N_b	N_i	$P^{\text{IN/OUT}}_{i\rightarrow X} = \left(1 - \frac{N_i}{N_b}\right)$	$P^{T} = \left(\frac{P^{\text{IN}} - P^{\text{OUT}}}{1 - P^{\text{OUT}}}\right)$
^{13}C	PE	35810	30347	0.152 ± 0.002	0.084 ± 0.003
	C	31501	26887	0.146 ± 0.002	0.077 ± 0.004
	OUT	7953	7357	0.075 ± 0.003	-
^{11}C	PE	12300	10595	0.139 ± 0.003	0.068 ± 0.006
	C	10490	9144	0.128 ± 0.003	0.057 ± 0.006
	OUT	2669	2466	0.076 ± 0.005	-
^{15}N	PE	1692	1191	0.296 ± 0.011	0.098 ± 0.030
	C	1292	949	0.265 ± 0.012	0.059 ± 0.030
	OUT	315	246	0.219 ± 0.023	-
^{14}N	PE	1607	1302	0.190 ± 0.010	0.102 ± 0.019
	C	1383	1151	0.168 ± 0.010	0.078 ± 0.020
	OUT	349	315	0.097 ± 0.016	-
^{11}B	PE	1929	1379	0.285 ± 0.010	0.061 ± 0.028
	C	1743	1261	0.276 ± 0.011	0.049 ± 0.028
	OUT	473	360	0.239 ± 0.020	-
^{10}B	PE	3561	2872	0.193 ± 0.007	0.109 ± 0.012
	C	3100	2581	0.167 ± 0.007	0.081 ± 0.013
	OUT	785	711	0.094 ± 0.010	-

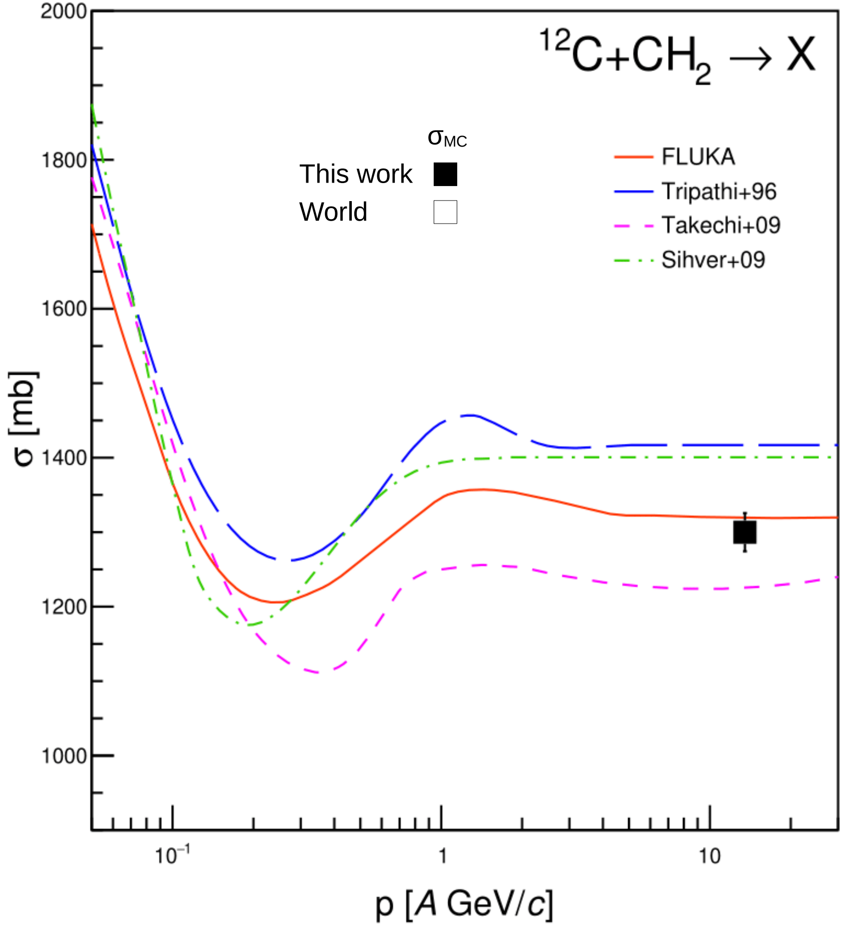
$\Sigma f_{\text{imp}} \sim 0.5\%$

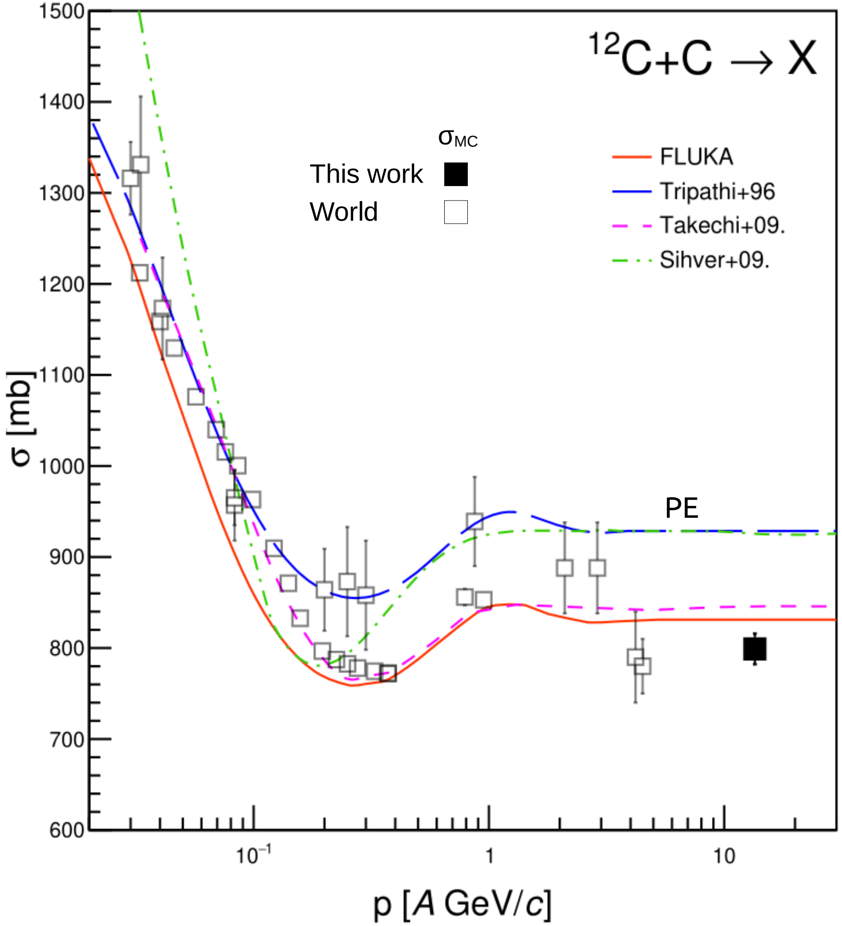


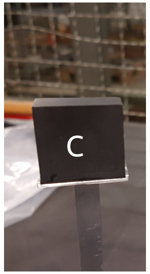


Results: Mass-changing Cross sections

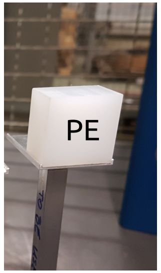


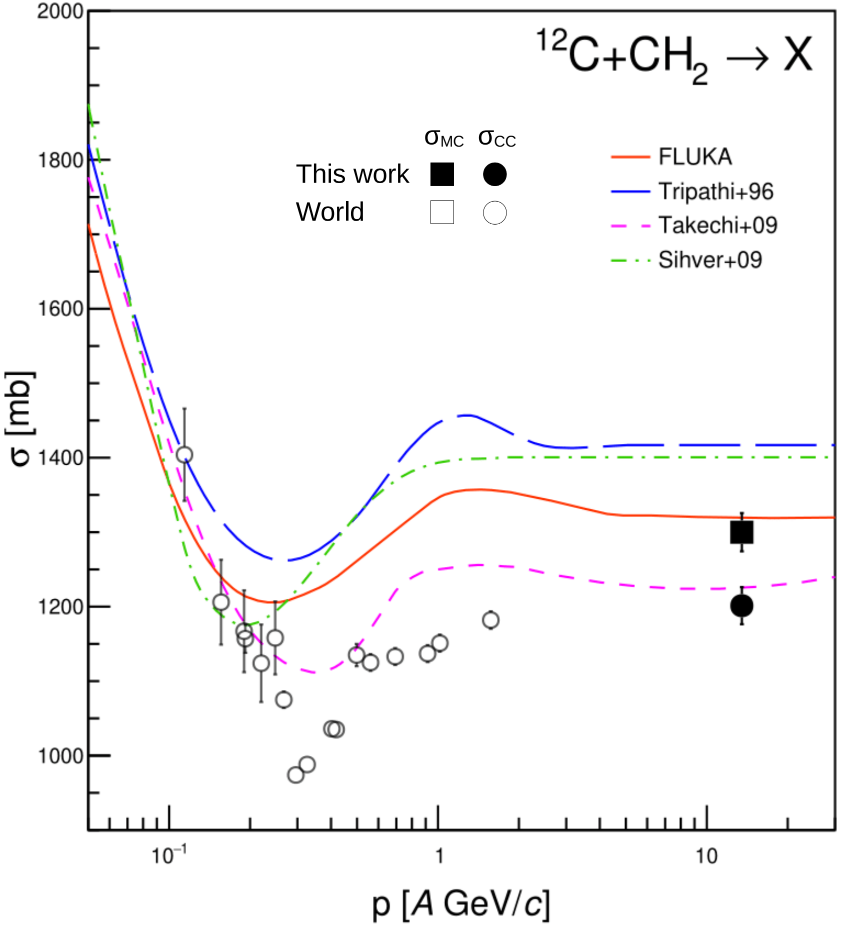


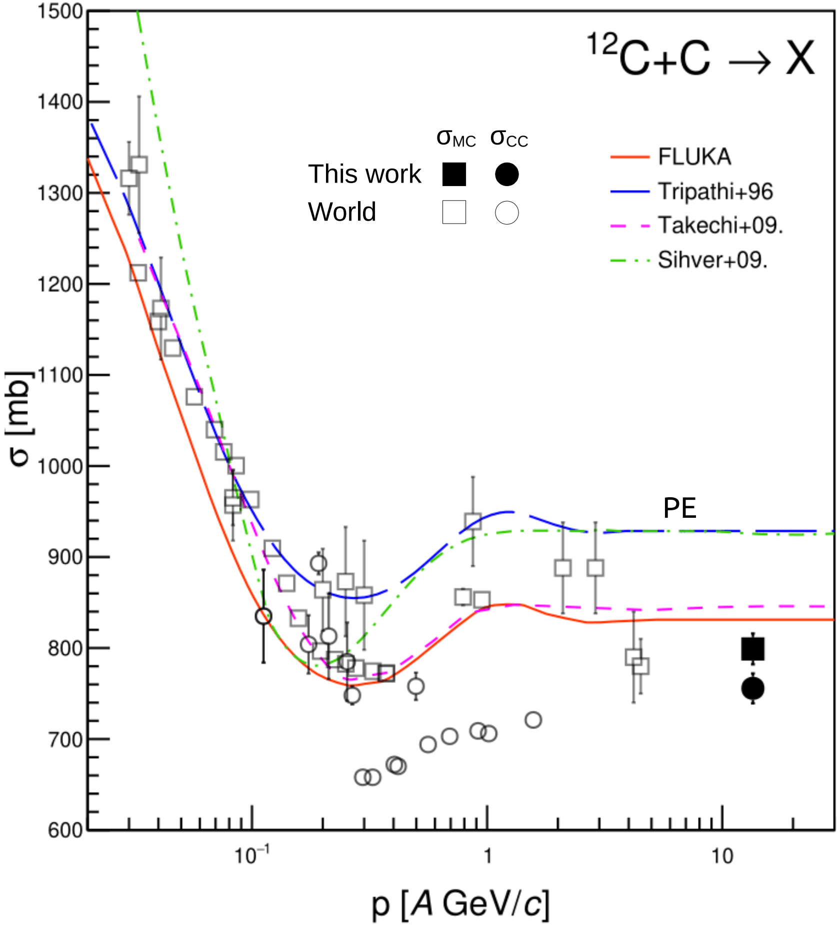


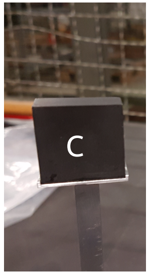


Results: Mass- and Charge-changing Cross sections

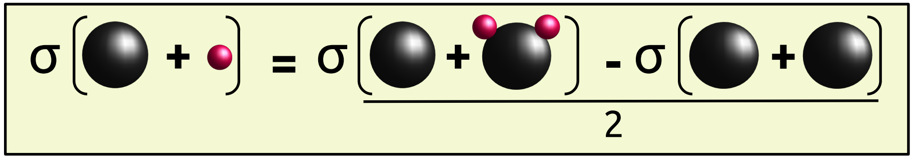


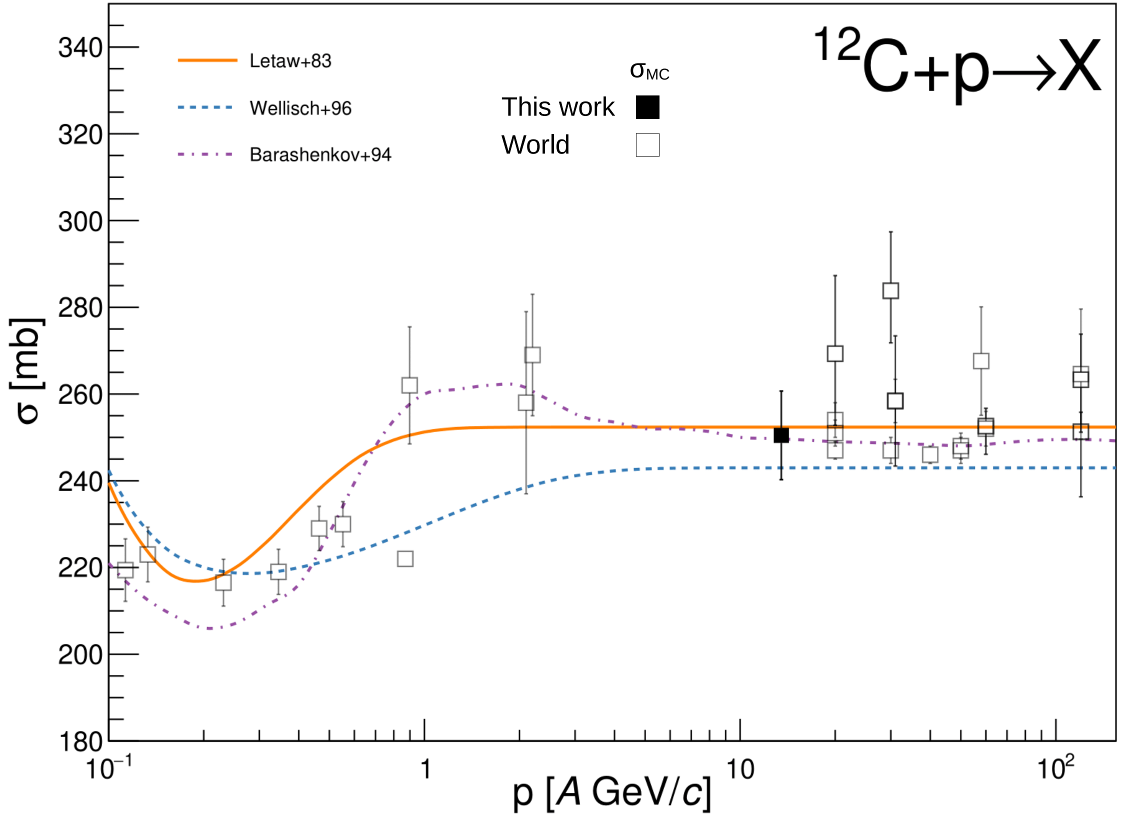




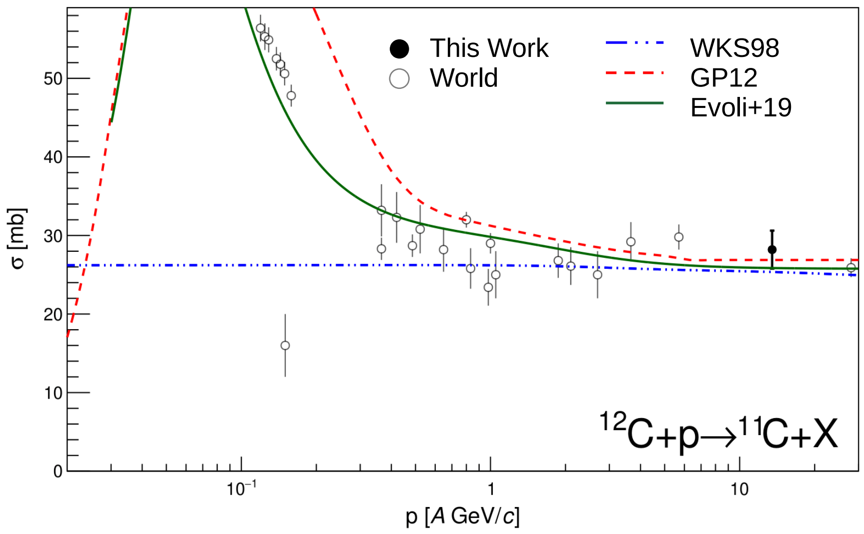


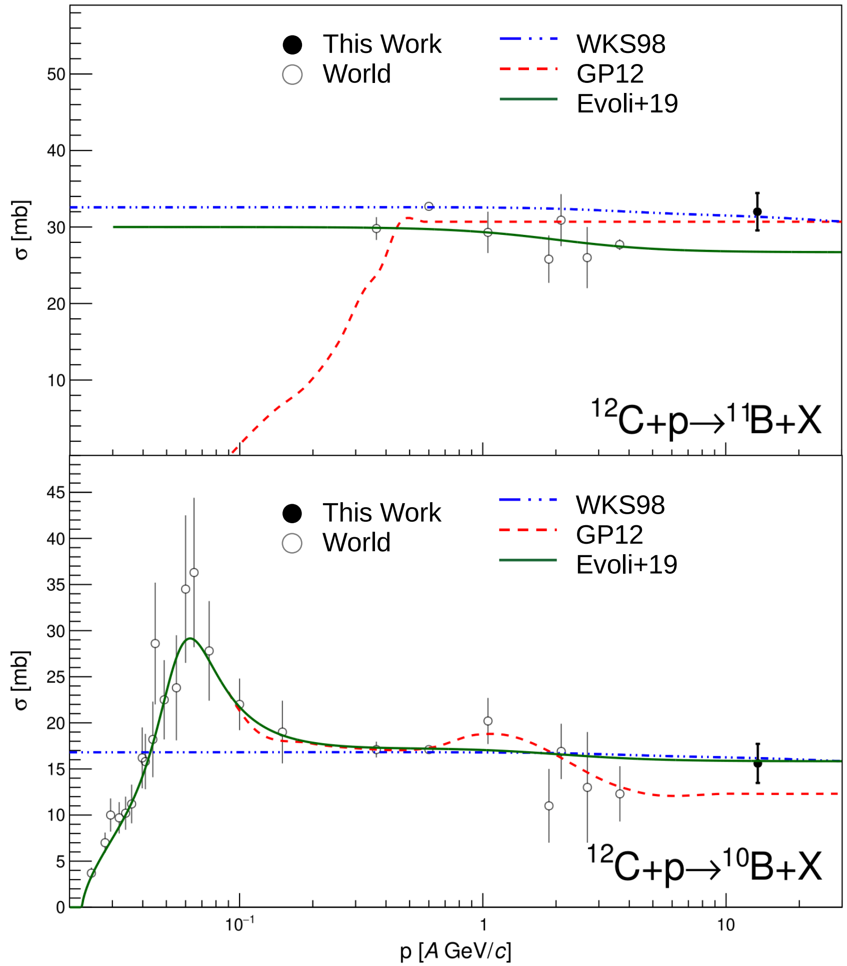
Results: Mass-changing Cross section with a Proton Target





Results: Boron Production Cross sections with a Proton Target





Total boron production cross section,

$$\sigma_{12C+p\rightarrow B} = (\sigma_{12C+p\rightarrow 11C} + \sigma_{12C+p\rightarrow 11B} + \sigma_{12C+p\rightarrow 10B})$$

$$= \mathbf{77 \pm 5}\ (\text{stat.})\ \mathbf{\pm 1}\ (\text{syst.})\ \mathbf{mb}$$

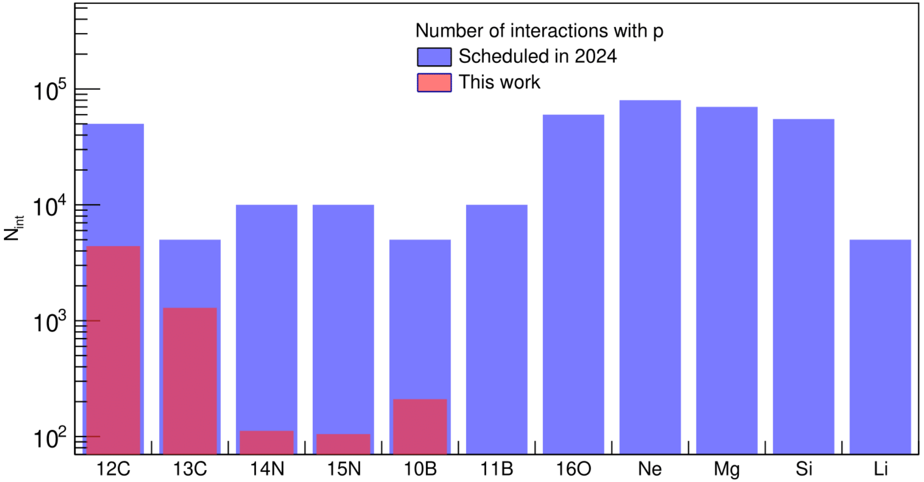
Measurement dominated by statistical uncertainty!

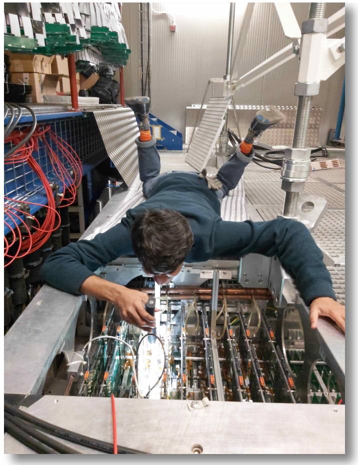
Summary and Outlook

- Cosmic ray interaction in the Galaxy → a window into CR propagation.
- Propagation parameters dominated by cross section uncertainties.
- Precise cross sections may answer recent discoveries – hinting at new physics.
- Mass-, charge-changing, and boron production cross sections are measured,

$$\sigma^{\text{total, B}} = (77 \pm 5\ (\text{stat.}) \pm 1\ (\text{syst.})\ )\ \text{mb}$$

  - Most precise measurement at $p_A > 10A$ GeV/c.
  - Fragmentation studies feasible with NA61/SHINE.
  - Publication under collaboration review.
- Data-driven results, corrections and systematic uncertainties!





Upgrade of MTPC readout electronics (2021)

- Faster readout, ~100Hz → ~1kHz
- ~10× more interactions
- $N_{int.} \geq N_{desired}$