Assemblea di Sezione at INFN-Bologna (23/01/2026)

Measurement of Cosmic-Ray Fluxes with the Alpha Magnetic Spectrometer and Studies of Propagation in Galaxy

José Ocampo-Peleteiro / *1st-year postdoc of AMS experiment*

Who I am

- Born in Vigo, Spain (1996) 🌊☔
- Bachelor in Physics (2018) 🎓
  → Durham University 🇬🇧🥶
- Master in Theoretical Physics (2020) 🎓🎓
  → Universidad Complutense de Madrid 🇪🇸🏛️
- PhD in Astro-Particle Physics and AMS Experiment (2024) 🎓🎓🎓
  → CIEMAT 🇪🇸🤯
  → Research visits at CERN ⚛️
  → ***Measurement of the Cosmic-Ray Fluxes of Silicon, Phosphorus and Sulphur and Galactic-Propagation Studies with the Alpha Magnetic Spectrometer***
  → I will explain my thesis in more detail...
- Postdoc in the AMS Experiment (present)
  → Held since February 2025. Just extended! 🇮🇹🍝
  → **AMS group at INFN Bologna lead by Alberto Oliva**
  → Later, I will develop my current work in more detail...

4 anni dopo...

My PhD Research

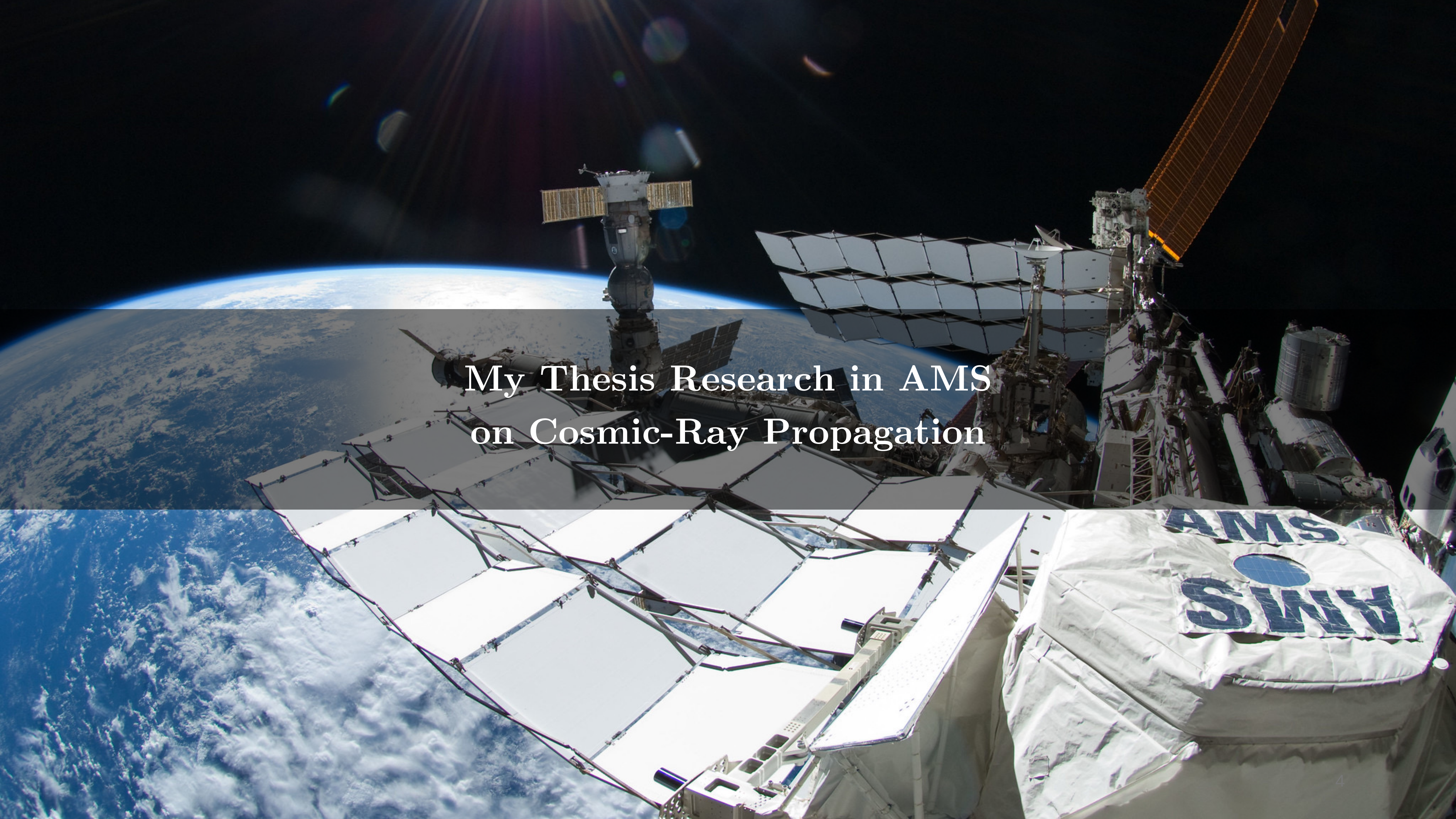
- 4-year research contract at CIEMAT.
  → Centre for research on fundamental physics, nuclear energy, environment and technological design in Madrid.
  → Large high-energy-physics group (CMS, DUNE, DESI...).
  → **Leading role in AMS design and data analysis.**
  → Supervised by Jorge Casaus and Francesca Giovacchini.

- AMS has measured the fluxes of nuclei in cosmic rays:
  → light nuclei (He, Li, Be, B, C, N, O),
  → heavy nuclei (F, Ne, Na, Al, Mg) and
  → ultra-heavy nuclei (Fe)

- **My research expanded the charge spectra of nuclei with silicon (Si, Z=14), phosphorus (P, Z=15) and sulphur (S, Z=16).**
  → M. Aguilar et al., Phys. Rev. Lett. **130**, 211002 (2023).
  → Talks at TeVPA 2023, ICHEP 2024 and ICRC 2025.

- In addition, I did some work on phenomenological studies of cosmic-ray propagation in the galaxy.

My Thesis Research in AMS on Cosmic-Ray Propagation



Spectrum, Origin and Composition of Cosmic Rays

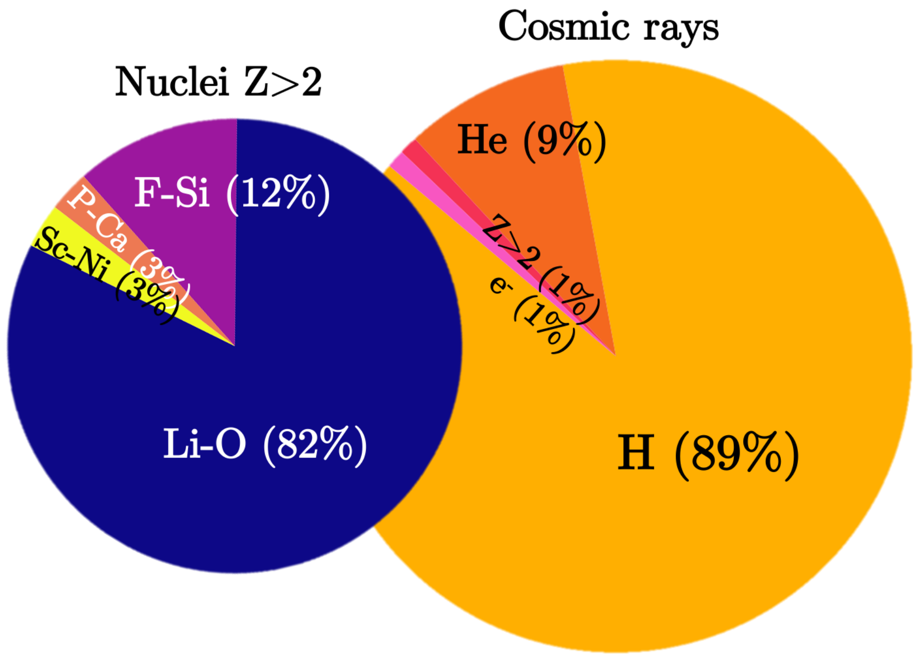
- **Cosmic rays are charged non-thermal particles from outer space.**
- The **flux** (energy distribution) of cosmic rays follows a **power-law,**

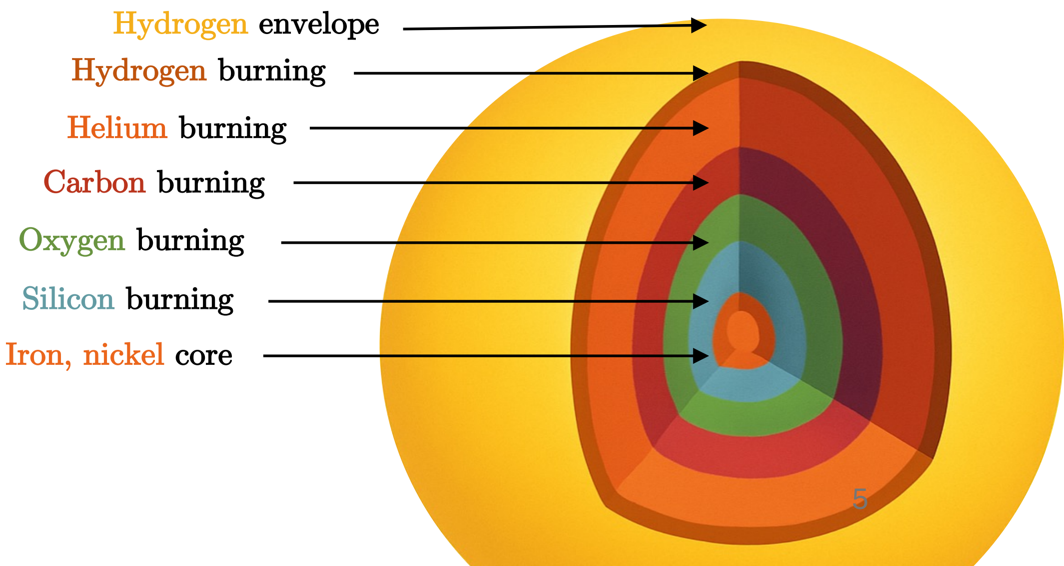
$$\phi \sim \frac{dN}{dE} \sim E^{-\gamma}$$

- Cosmic rays are made mostly of protons and ionised nuclei.
- **A very small fraction of heavy nuclei ($Z > 8$) is found (~ 0.1%).**

- **Heavy nuclei are fused in massive stars.**
  → α-process, ${}^{A}_{Z}X + {}^{4}_{2}He \rightarrow {}^{A+4}_{Z+2}Y$.
  → **Over-production of more stable even-Z nuclei.**

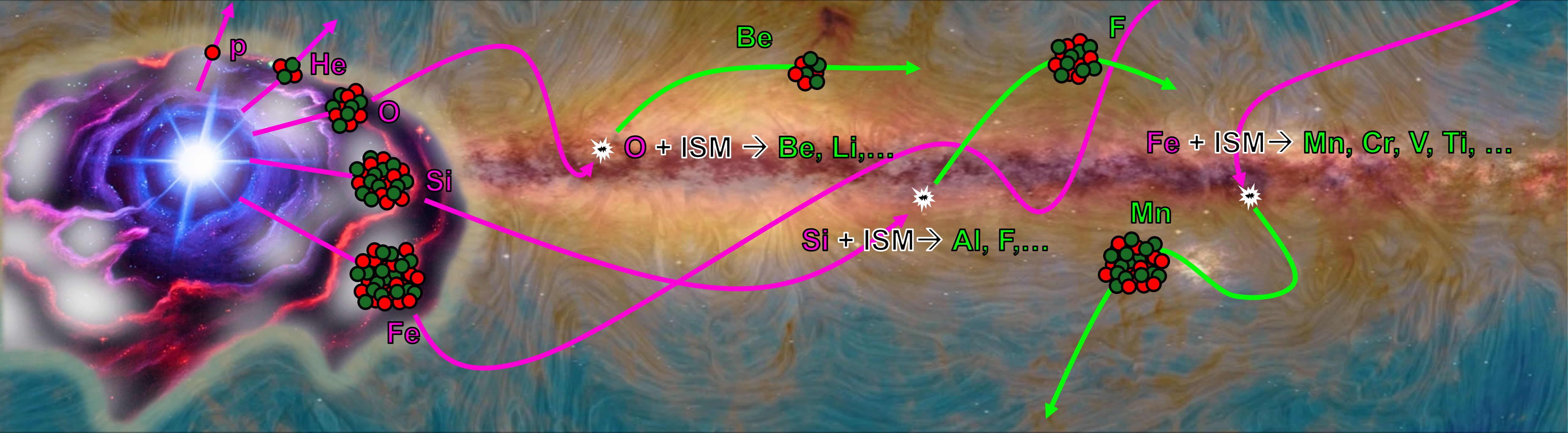
- Finally, the star collapses in a supernova.
  → The synthesised material is ejected.
  → Later, nuclei are accelerated in the remnant's shockwave.
  → Stochastically, few particles remain inside the accelerator to reach very high energies.
  → **Injection spectrum is a power law!** $dN/dE \sim E^{-\gamma}$.





Cosmic Rays in the Galaxy *(diffusion + spallation)*

- Nuclei are injected with spectrum $E^{-\gamma}$ **and repeatedly scatter in the** turbulent **magnetic fields of the galaxy.**
- Nuclei of high rigidity, $R = |\mathbf{p}|/Z$, escape the galaxy faster than lower rigidity nuclei.
  → **Propagation in the galaxy is characterized by a diffusion coefficient,** $D \sim R^{\delta}$.
  → The original spectrum of primary nuclei is *diffused* as $\phi_{\mathrm{pri}} \sim R^{-\gamma-\delta}$.



- Primary nuclei may fragment with interstellar gas producing secondary nuclei.
  → Secondary nuclei diffuse again. The spectrum of secondary nuclei is *doubly diffused*, $\phi_{\mathrm{sec}} \sim R^{-\gamma-2\delta}$.
- Therefore, **the rigidity dependence of the diffusion coefficient** is derived from secondary-to-primary **flux ratios**
  → $\phi_{\mathrm{sec}}/\phi_{\mathrm{pri}} \sim R^{-\gamma-2\delta}/R^{-\gamma-\delta} \sim R^{-\delta} \sim 1/D(R)$. Then, **the index at the source, γ, is also found!**

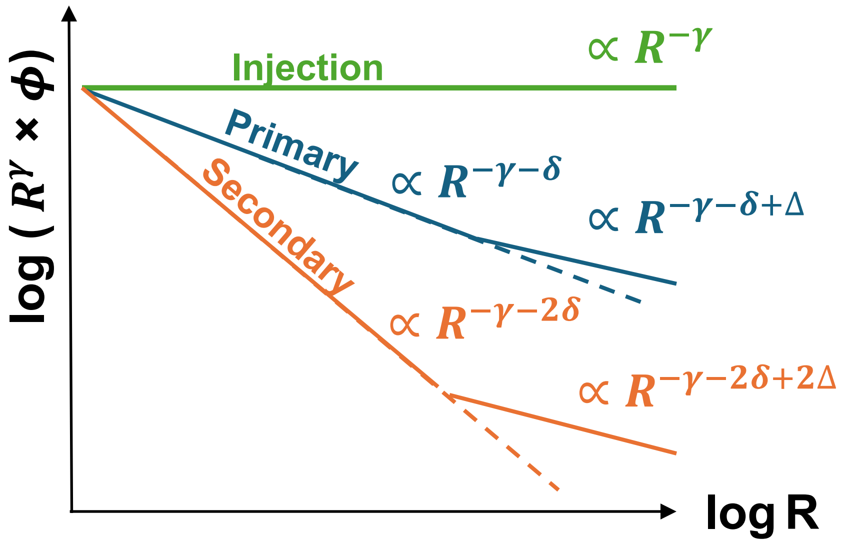
Cosmic Rays in the Galaxy *(the case for heavy nuclei)*

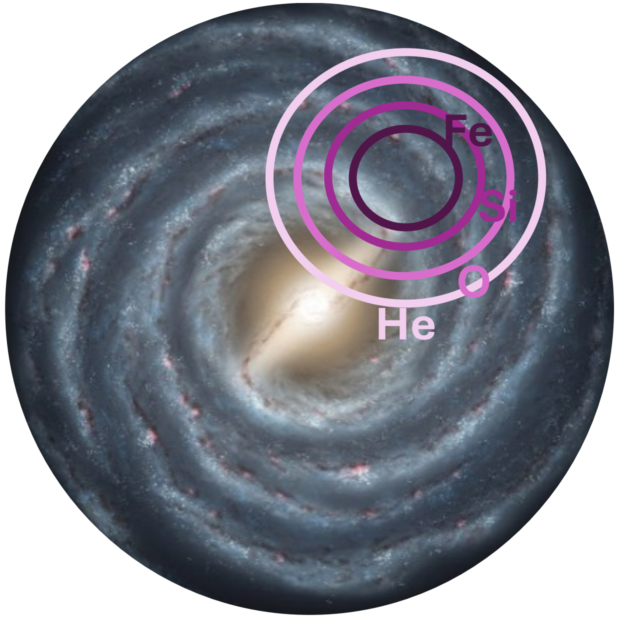
- Simple models of cosmic-ray propagation offer a consistent picture of AMS measurements of light nuclei (He to O).
  → ***Is that still the case for heavy nuclei?***

- AMS has observed the existence of a spectral break in the diffusion coefficient of light nuclei (B/C, Li/O, ..)
  → ***Is the break still present in heavy nuclei?***

- Heavy nuclei (short mean free path) effectively sample the diffusion coefficient at smaller galactic scales.
  → ***Is the diffusion coefficient unique for light and heavy?***

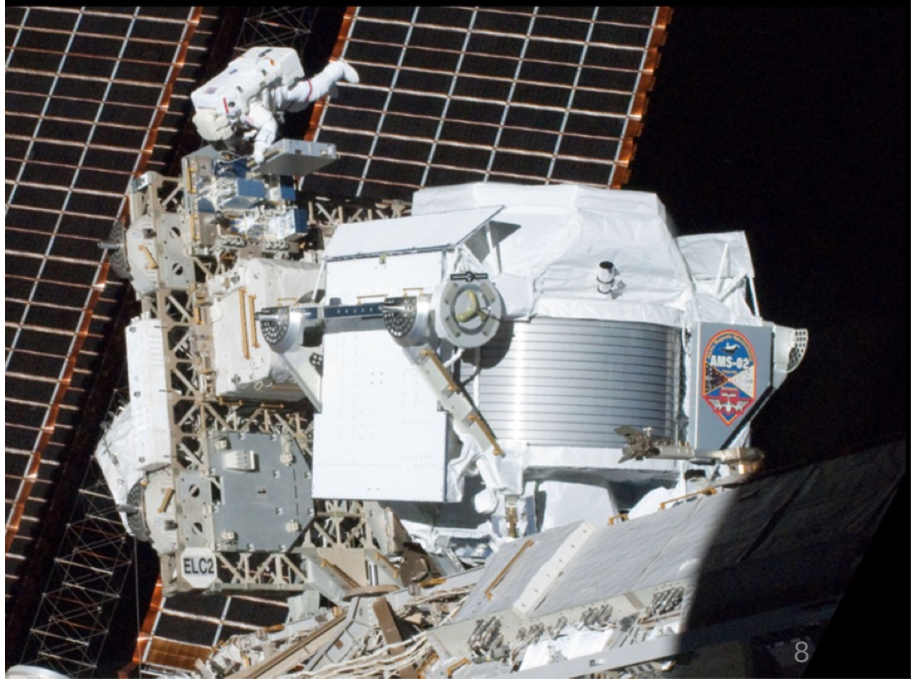
- Complete understanding of propagation in the galaxy is needed for the description of the antimatter background
  → ***Identification of an antimatter excess.***





Alpha Magnetic Spectrometer

- **AMS is a large-acceptance TeV-precision magnetic spectrometer installed on the ISS since May 2011.**
- Space environment involves technical challeges such as temperature control, radiation exposure, data transmission and mechanical integrity.
- Characteristics:
  - → 7.5 tons and size of 5 m × 4 m × 3 m
  - → 300k electronic channels with event rate ~1 kHz
  - → 2.5 kW of power cosumption
  - → 90 min orbit at an altitude of 400 km.
- AMS Collaboration has involved more 600 scientists from 16 countries and major scientific and space agencies, such as NASA, ESA, ASI, CERN, DOE and INFN (cost ~2 billion dollars).
- AMS targets several science cases, namely
  - → Dark-matter searches (e^{-}, e^{+}, $\bar{p}$, $\bar{D}$)
  - → Primordial antimatter detection ($\overline{He}$)
  - → **Cosmic-ray acceleration and propagation (nuclei).**



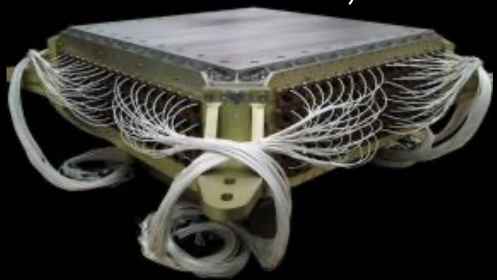
Alpha Magnetic Spectrometer *(sub-detectors)*

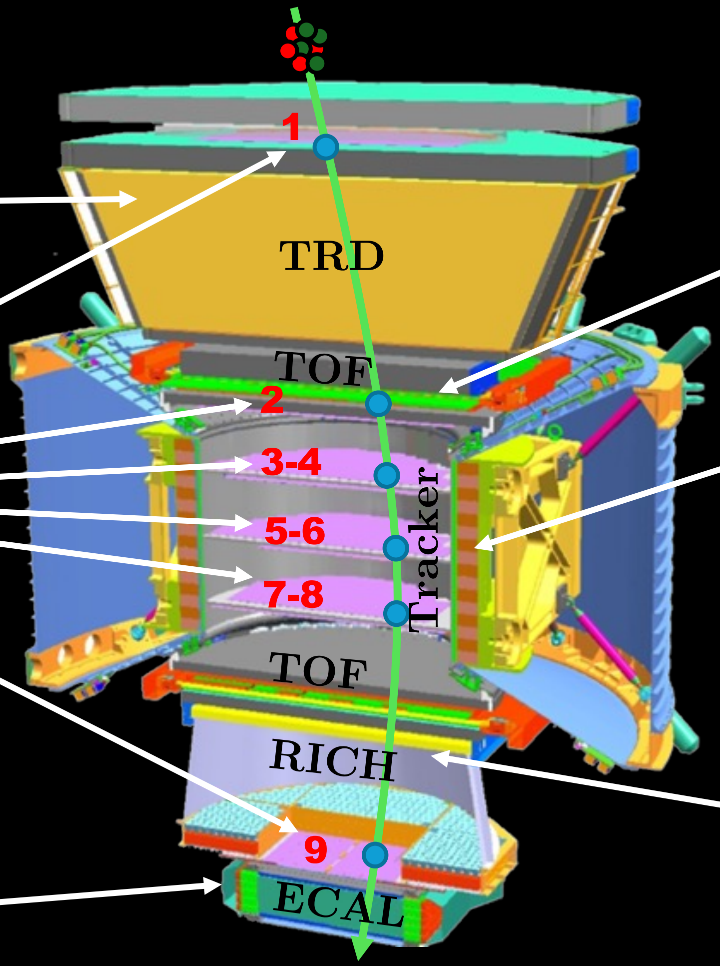
Particles and nuclei are defined by their charge (Z), rigidity ($R = |\mathrm{p}|/Z$) and velocity (β).

TRD: identification e^+, e^-, Z

Tracker: Z, R

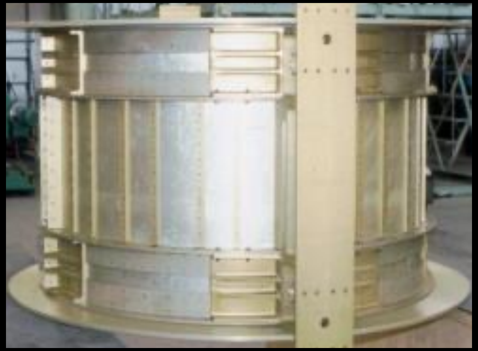
ECAL: $E \sim \gamma(\beta)$ and identification e^+, e^-



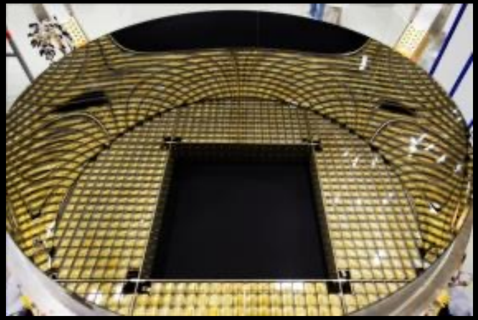


ToF: Z, β

Magnet: $\pm$ Z



RICH: Z, β



Z and R (or β)

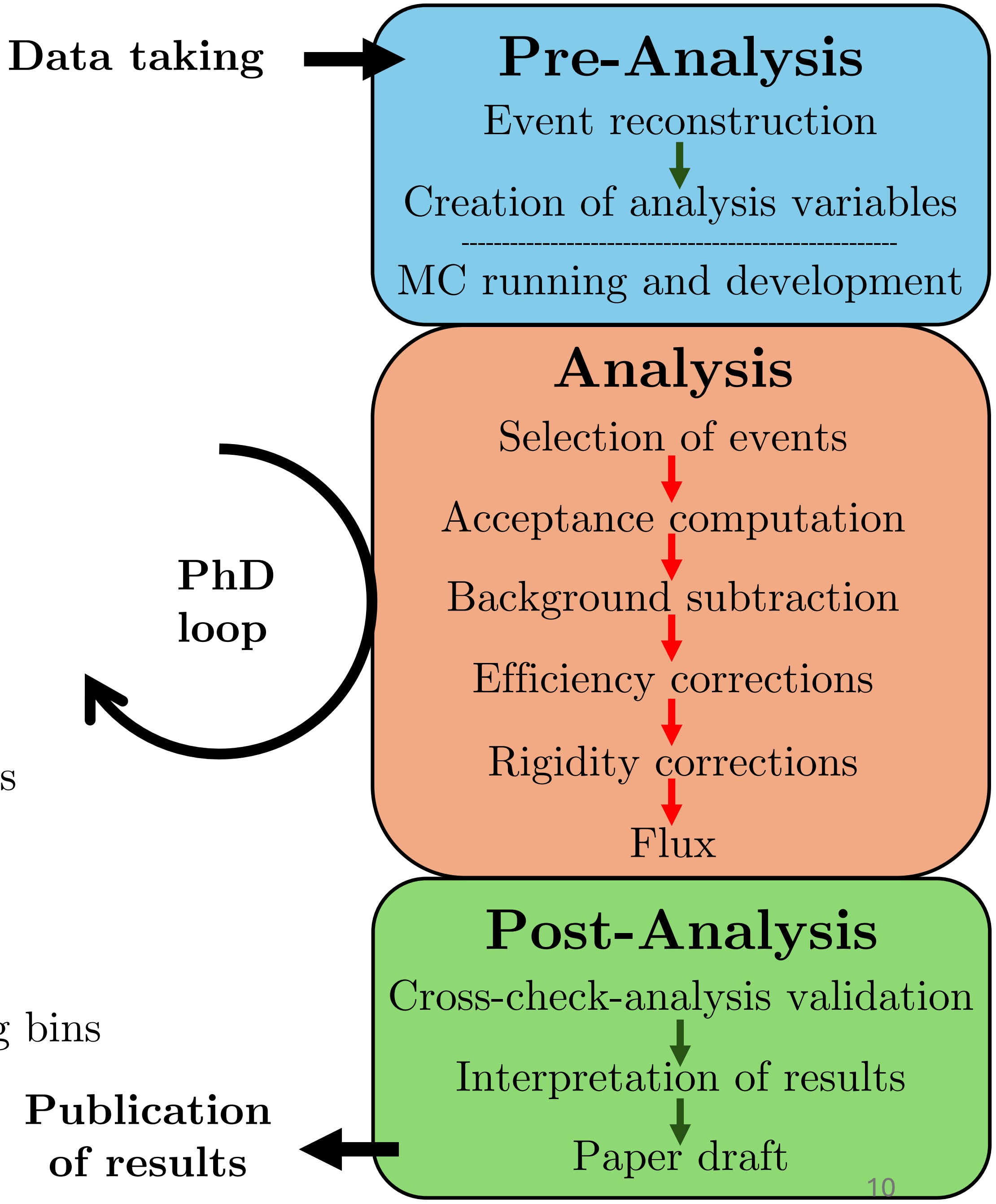
are measured ***redundantly*** by the Tracker, RICH, TOF and ECAL

Analysis

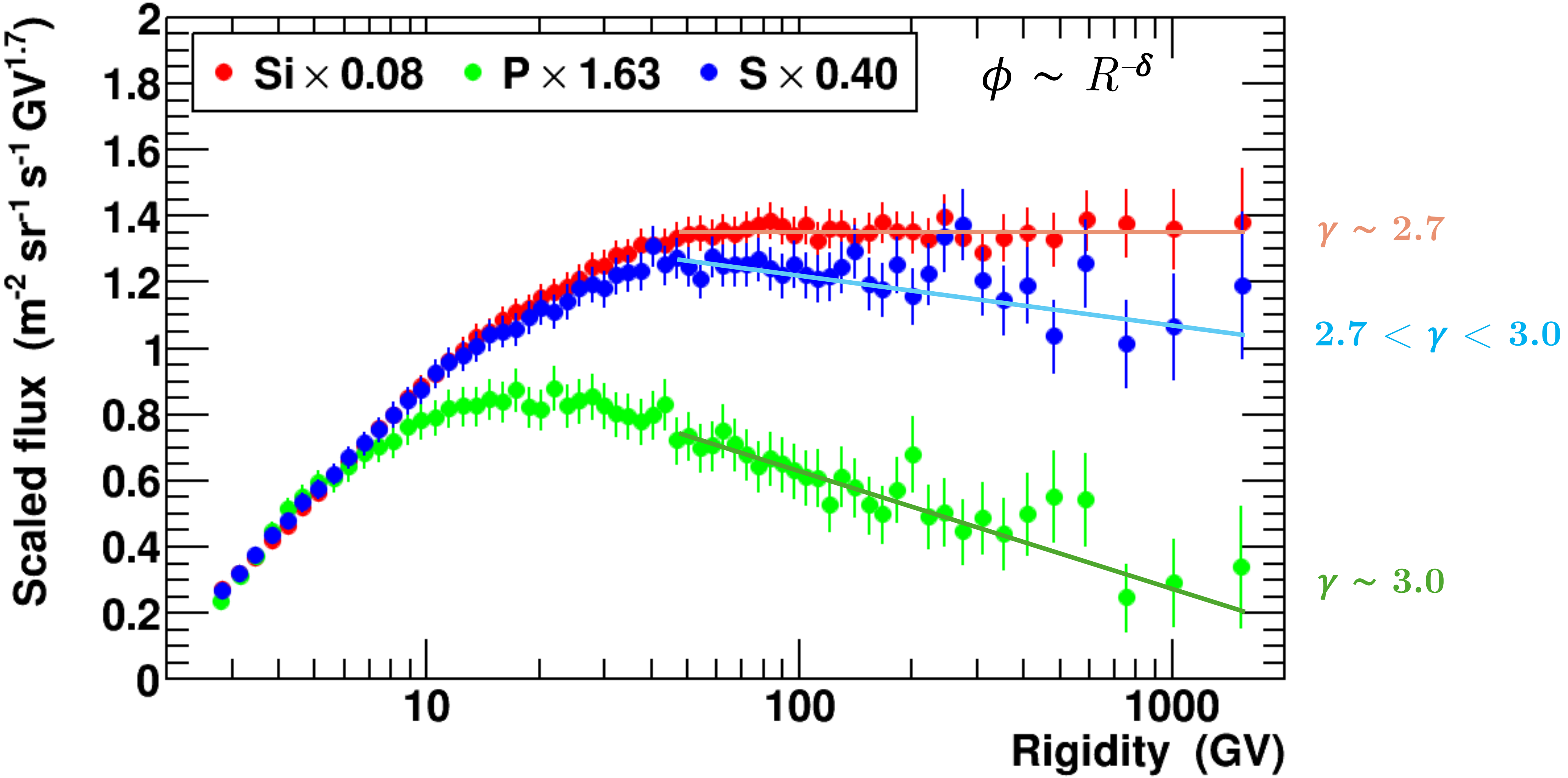
- AMS flux in the bin $[R_i\ ,\ R_i + \Delta R_i\ ]$ is computed as

$$\phi_i = \frac{N_i}{A_i T_i \Delta R_i} = \frac{N_{sel,i}\, c_{bkg,i}\, c_{unf,i}}{A_{MC,i} \prod_j \left(\varepsilon_{i,j}/\varepsilon_{i,j}^{MC}\right) T_i \Delta R_i}$$

- The the selection of good seconds of exposure and the selection of events give
  - → T_i exposure time
  - → $N_{sel,i}$ number of selected counts (signal + bkg.)
  - → $A_{MC,i}$ acceptance simulated with Monte Carlo
- The selected events include contamination of non-Z events
  - → $c_{bkg,i}$ correction for background subtraction
- The Monte-Carlo acceptance has a limited accuracy
  - → $\varepsilon_{i,j}/\varepsilon^{MC}{}_{i,j}$ data-to-Monte-Carlo efficiency corrections
- Due to rigidity resolution, some events go to neighbouring bins
  - → $c_{unf,i}$ correction for bin-to-bin migrations

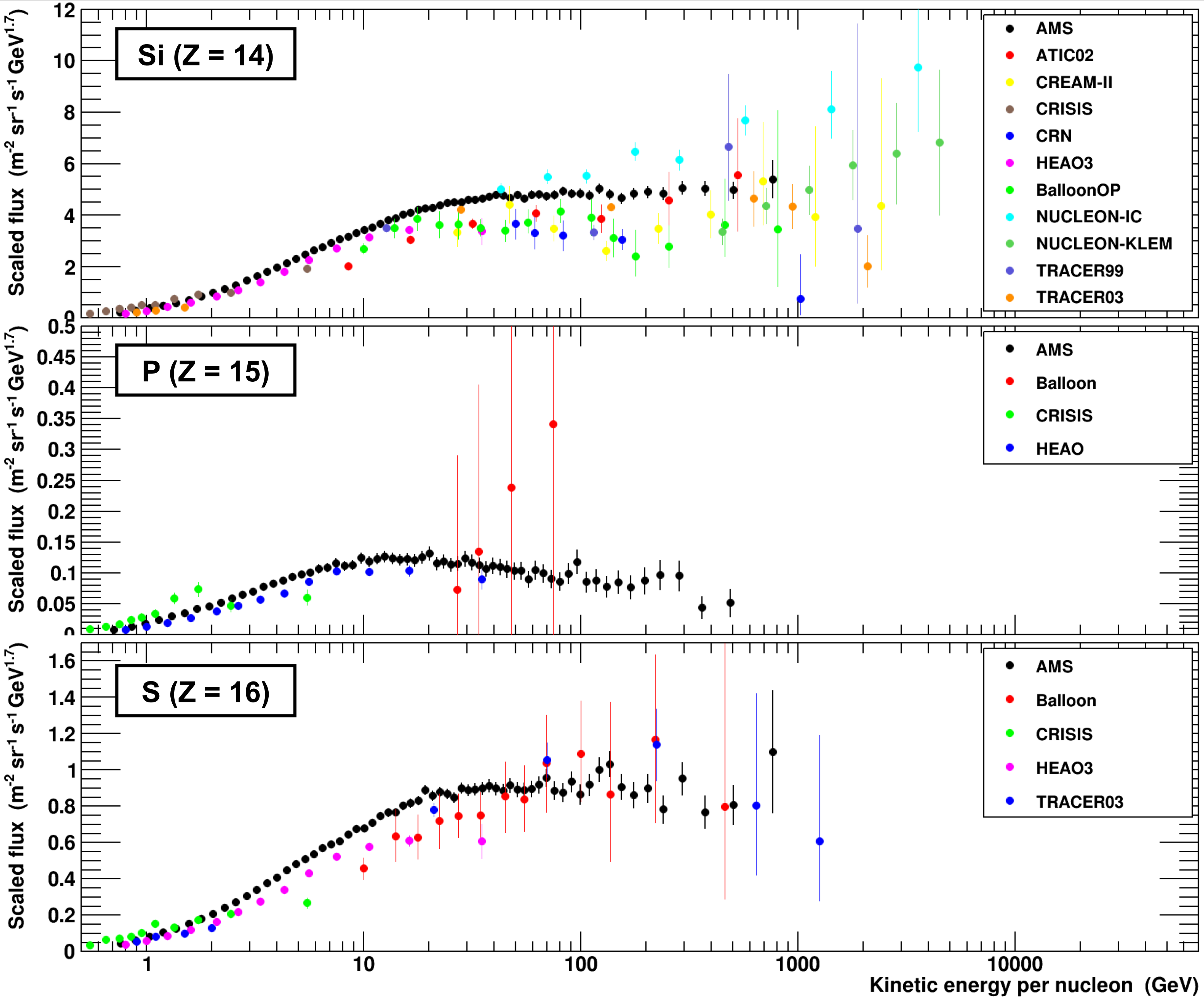


Results: Fluxes of Silicon, Phosphorus and Sulphur

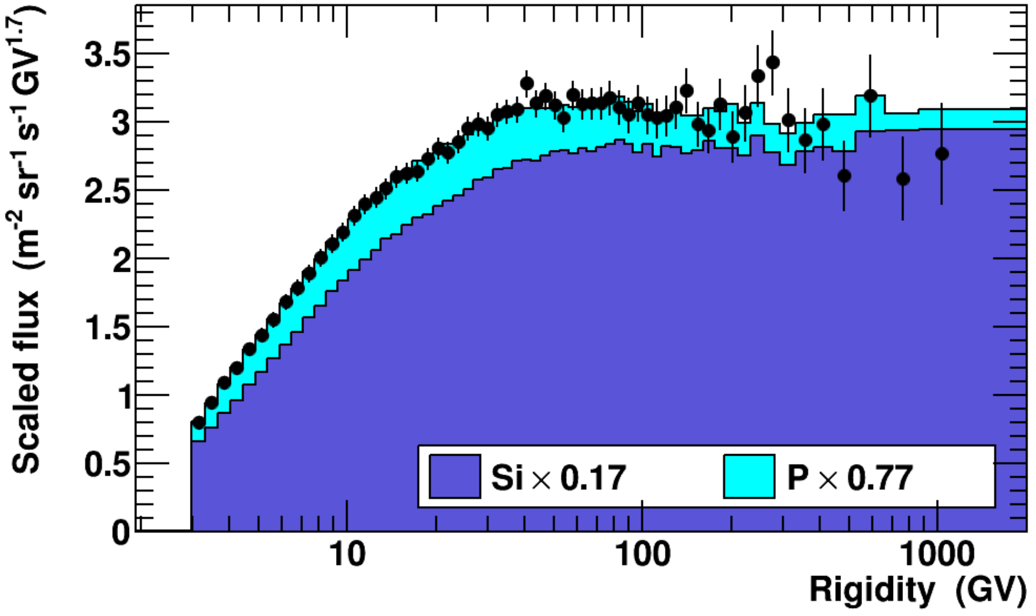


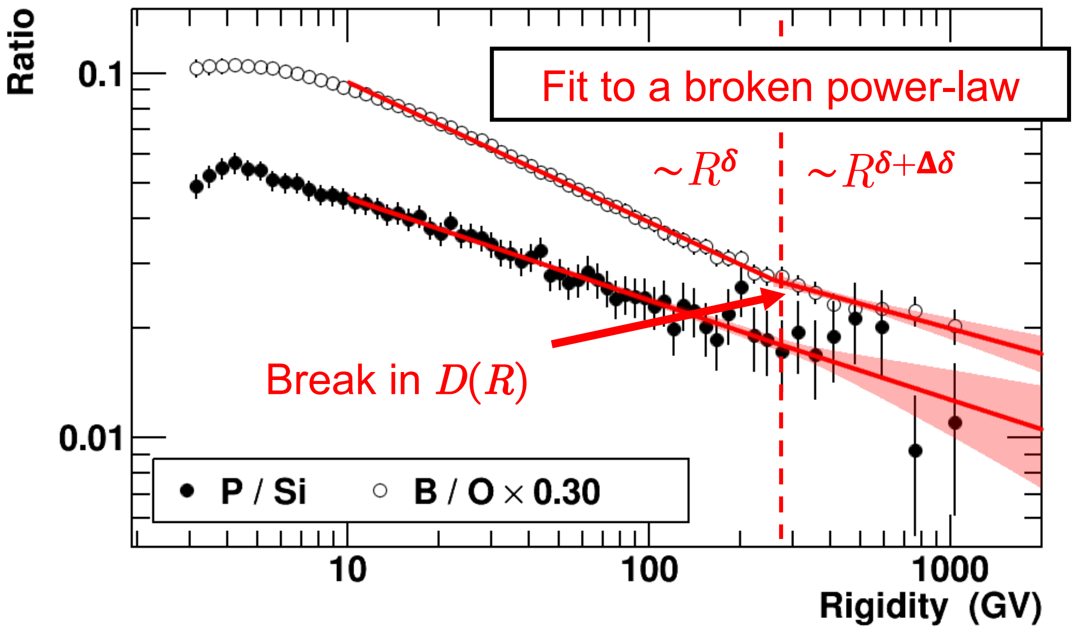
Silicon has a primary spectrum (injection + diffusion). Phosphorus has a secondary spectrum (injection + 'double' diffusion). Sulphur is primary-like, but not as pure as silicon.

Comparison of Results with Previous Measurements



Insights on Cosmic-Ray Propagation





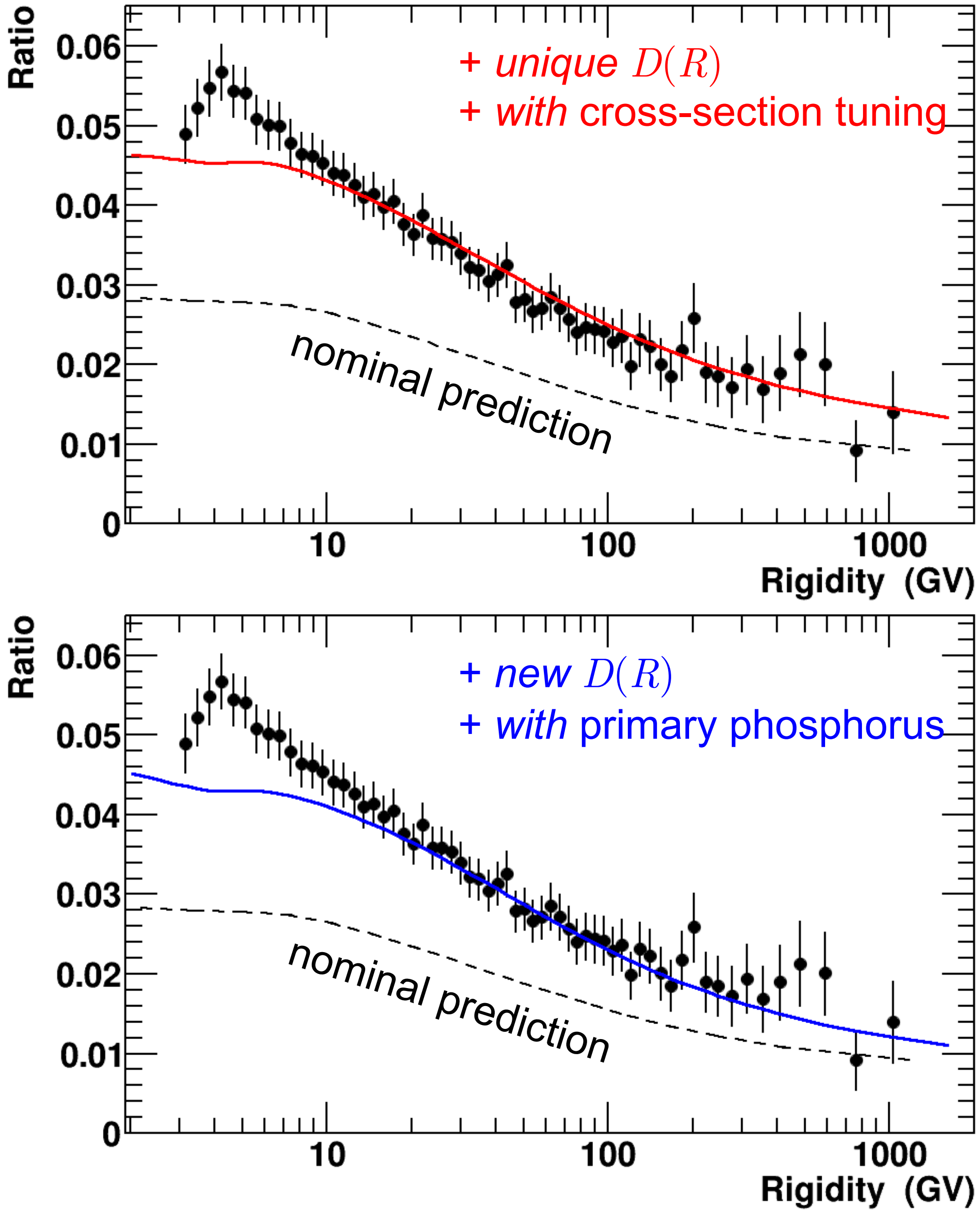
- The sulphur flux can be fitted to a linear combination of
  → **a primary flux** (silicon-like) and
  → **a secondary flux** (phosphorus-like).
- The sulphur flux has a mixed primary & secondary origin.
- The **production ratio at the source** of sulphur-to-silicon is thus inferred as 0.173 ± 0.004.

- ***Recall***: The ratio of a primary flux, $\phi_{\rm pri} \sim R^{-\gamma-\delta}$ and secondary flux, $\phi_{\rm sec} \sim R^{-\gamma-2\delta}$, shows the dependence of the diffusion coeff. with rigidity, $\phi_{\rm sec}/\phi_{\rm pri} \sim R^{-\delta} \sim 1/D(R)$.
- ***Recall***: *Heavy* cosmic rays (larger spallation rate) sample the diffusion properties at *smaller* galactic scales.

- *Light* secondary-to-primary ratio (B/O) shows a break at ~300 GV. **No sensitivity to the break** for *heavy* **P/Si.**

- **The diffusion index found for B/O [δ = 0.384 ± 0.007] and P/Si [δ = 0.28 ± 0.02] are different.**
  → Is the diffusion of heavy and light nuclei different?
  → Evidence of a galactic-scale effect?

Insights on Cosmic-Ray Propagation



- Better understanding is achieved with simple modelling.
- Predict phosphorus-to-silicon ratio (secondary-to-primary) with the same diffusion coefficient, $D(R)$, as light nuclei.
- **'Nominal' prediction fails to describe the data!**

- Two 'extreme' scenarios are observed.

1. ***Uniqueness* of diffusion coefficient + cross-section tuning.**

   → Avaliable cross-section measurements are quite poor.
   → Increase phosphorus-production cross section by 40%.

2. ***Different* diffusion coefficient for heavy nuclei.**

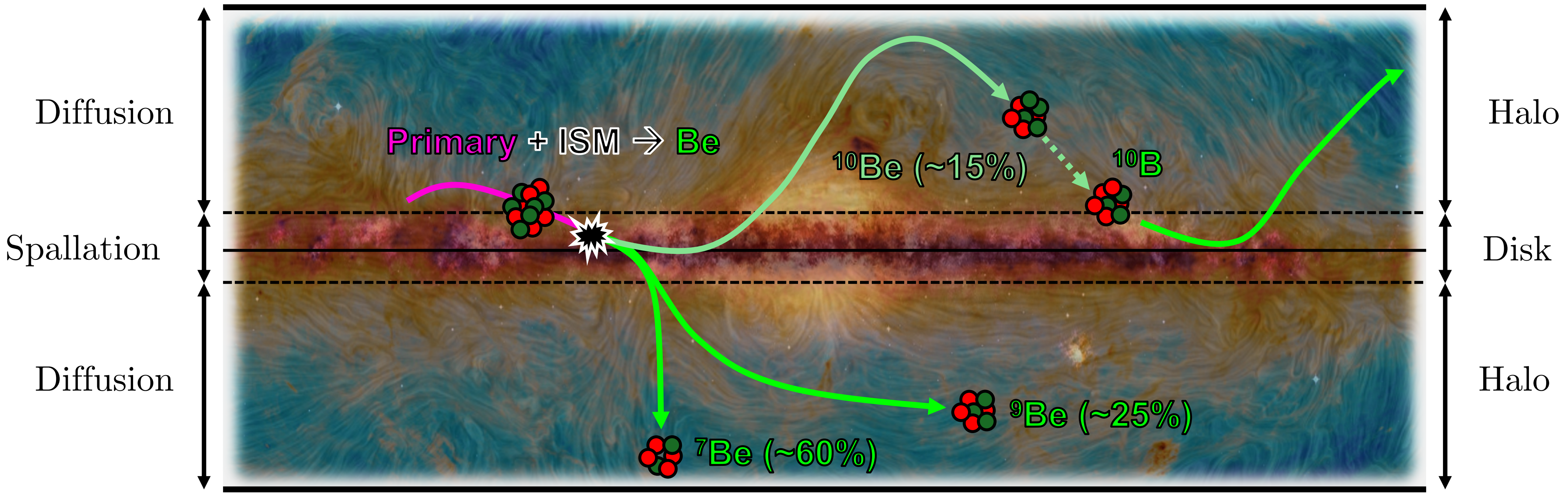
   → Fit $D(R)$ to heavier nuclei.
   → Add a primary phosphorus contribution!
   → Different diffusion than for light nuclei is found.

- **Accurate measurement of the phosphorus production cross section shall determine**
  → the amount of primary phosphorus and
  → the uniqueness of the diffusion coefficient.

My Current Research in AMS at INFN-Bologna

Further Studies on Cosmic-Ray Propagation

- Primary-to-secondary ratios constrain the rigidity dependence of the diff. coeff., **but not its normalisation!**
- The more material traversed, the more secondary production… **but is *any* amount of material traversed because diffusion is *slow* (low diff. coeff.) or because the confinement volume (halo size) is *small*?**



- The halo size is found from the energy dependence of unstable-to-stable beryllium-isotope ratio, ^{10}Be/^{9}Be.
  → At low energy, *all* ^{10}Be decays to ^{10}B (mean life ~2 million years), so ^{10}Be/^{9}Be $\rightarrow$ 0%.
  → At high energy, due to Lorentz time dilation, ^{10}Be does *not* decay, so ^{10}Be/^{9}Be $\rightarrow$ 60% (branching ratio).
  → **A low-/high-energy transition between the total- and no-decay regimes gives a smaller/larger halo size.**

Isotope Separation in AMS

- In AMS, for a nucleus of atomic number Z, mass separation is achieved with a simulataneous measurement of
  → (inverse) rigidity, R^{-1},
  → velocity, $\beta = v/c$,
  → $m^{-1} = R^{-1}\beta/Z\sqrt{1-\beta^2}$

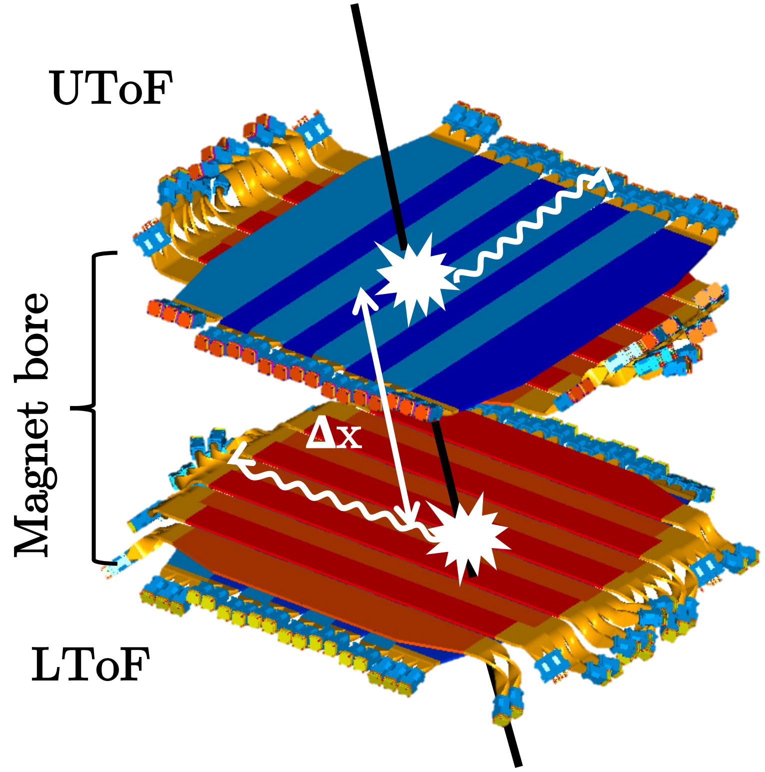
- **Rigidity** is measured by the tracker from the track curvaure
  → Limited by dynamic aligment of the tracker layers, multiple scattering and time-dependent magnetisation.

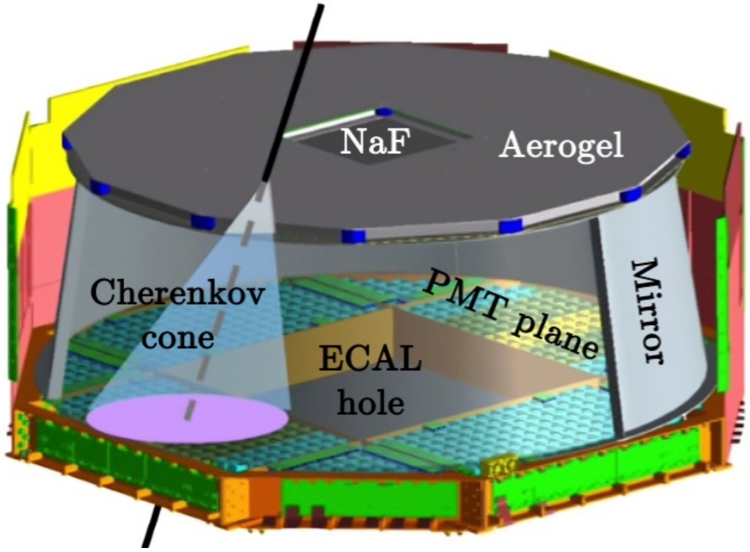
- **Beta** is measured by two detectors in three kinetic ranges

  → **Time interval between scintillator signals. [ToF]**
  → **Opening angle of Cherenkov light $\cos(\theta) \sim \beta^{-1}$. [RICH]**

  → 0.5 GeV/n — 1.2 GeV/n [ToF]
  → 1.2 GeV/n — 3.5 GeV/n (ref. index ~ 1.33) [RICH-NaF]
  → 3.5 GeV/n — 15 GeV/n (ref. index ~ 1.05) [RICH-Agl]

  → Limited by photon counts, granularity of photodetetction plane and directionality of track [RICH].





Fragmentation Studies

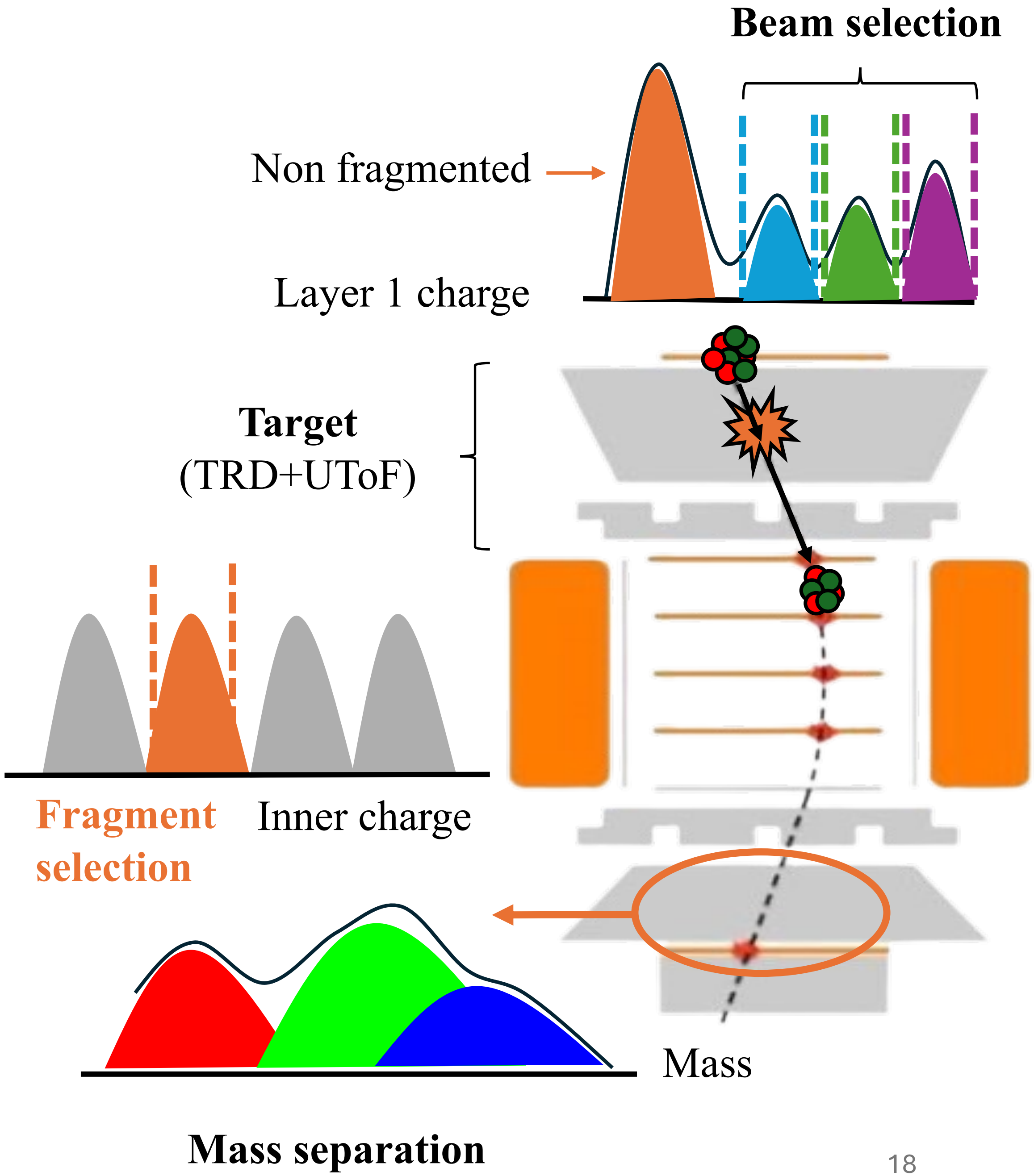
- **There is contamination in the beryllium mass sample**
  → fragmentations in the material at the top of the instrument, e.g. O, N, C, B → ^{7}Be, ^{9}Be, ^{10}Be.
  → **this contamination is irreducible**

- Contamination is Monte-Carlo simulated and subtracted from data.

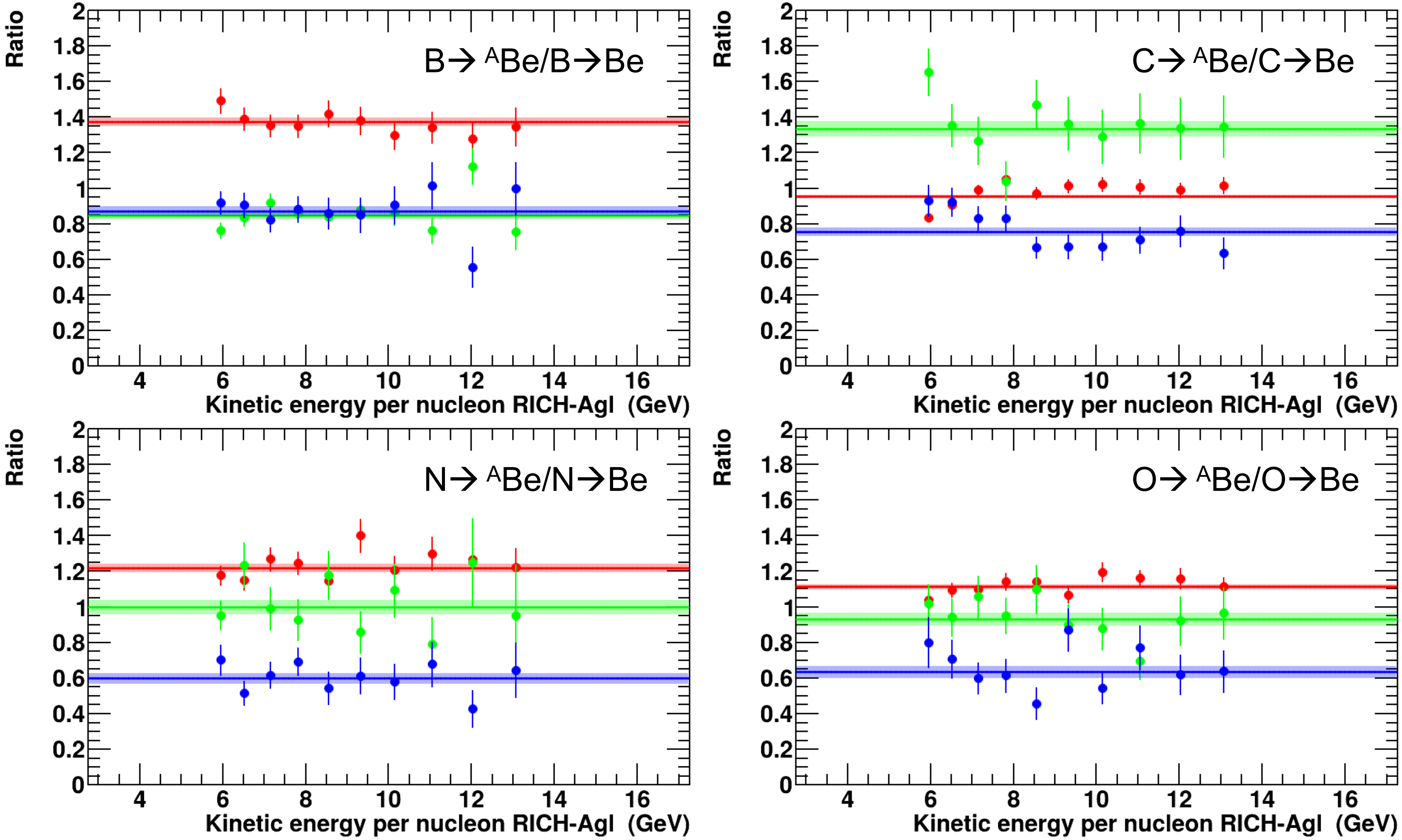
- The accuracy of the simulation is severly limited by the poorly known isotopic production cross sections above 1 GeV/n.

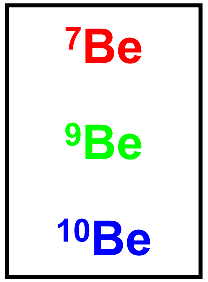
- **The mass-changing cross sections in the simulation are corrected with data derived from real fragmentation events.**

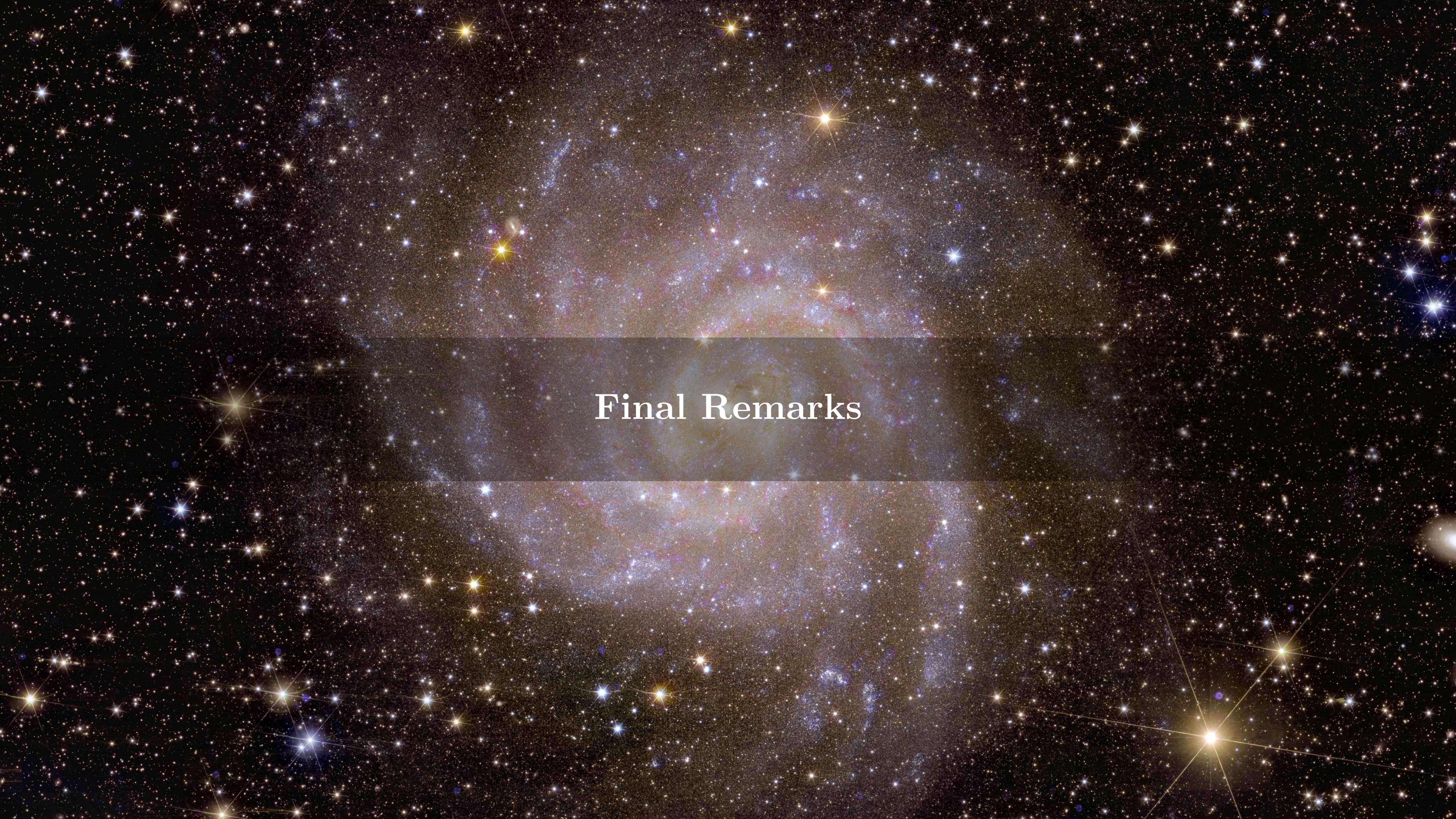
  → **Test beam through AMS material.**
  → Select parent at layer 1 (O, N, C, B).
  → Select beryllium (Z=4) in the inner tracker.
  → Mass separation of beryllium framents at RICH.



Fragmentation Studies






Final Remarks

Recap & Research Interests

- PhD in measurement of silicon, phosphphorus and sulphur fluxes with AMS.

- Results allow for a determination of the effective diffusion coeffient of hevy nuclei in the galaxy
  → diffusion-scale effects
  → injection at supernovae
  → measurement of nuclear cross sections required!

- Currenly working on beryllium isotopic separation with AMS.
  → fragmentation studies in detector material for accurate backrground reduction

- I am interested
  → measurement of cosmic-ray fluxes and data analysis/statistics methods
  → elemental propagation models of cosmic rays in the galaxy
  → measurement of nuclear cross sections with hydrogen target (propagation)
  → measurmenet of nuclear cross section with detector materials (instrument design)

- Please, approach me anytime if you are interested in measurement/theory of cosmic rays and/or physics of nuclear interactions.
  → jose.ocampopeleteiro@bo.infn.it / jose.ocampo.peleteiro@cern.ch

Back-Up

Isotope Separation in AMS

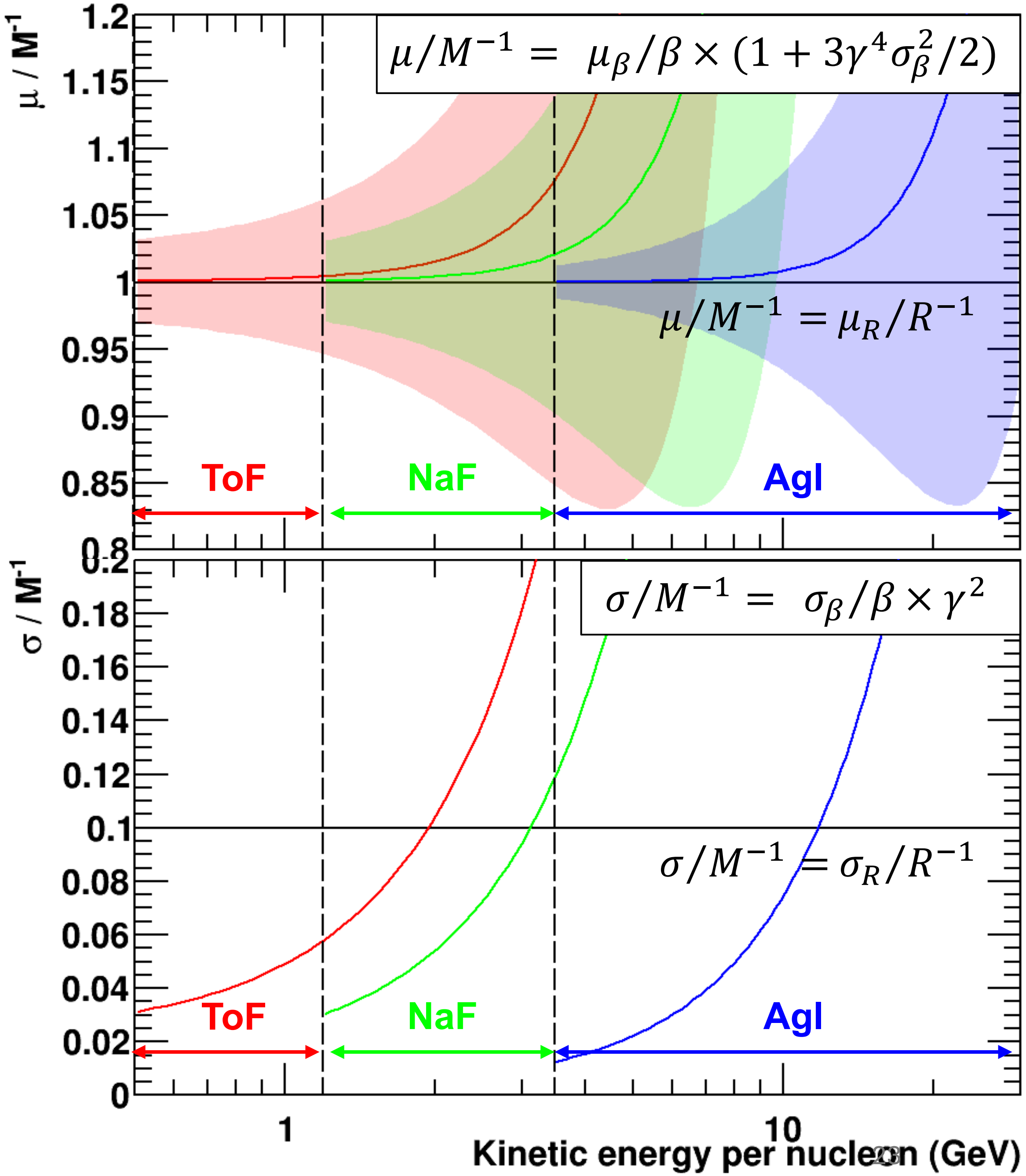
- Isotopic separation is conducted with template fits to the mass distribution of Be.

- Monte-Carlo templates must be verified with data!
- **Mass templates can be tuned to have**
  → the same mean, μ, as in data
  → the same standard deviation, σ, as in data.

- Dominant systematic errors arise from this data-driven 'calibration' of velocity (ToF or RICH) and rigidity (tracker).

- Monte-Carlo mass templates are tuned for a variation in the mean, $\delta\mu$, and the standard deviation, $\delta\sigma$.

- A characteristic enery dependence of $\delta\mu/M^{-1}$ ($\sim\gamma^4$) and $\delta\sigma/M^{-1}$ ($\sim\gamma^2$) arises for a *unique tuning* of beta.
- No energy dependence asirses with a single tuning of rigidity.



Rigidity and Velocity Calibration