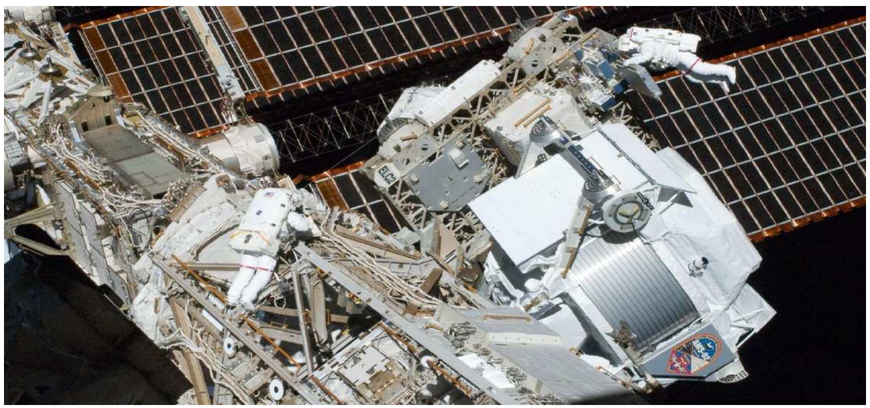
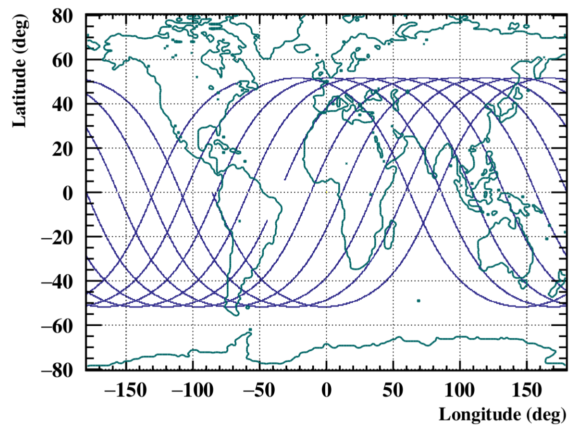
AMS
a cosmic ray experiment in the ISS

eight years operating in space near earth





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FCT Fundação para a Ciência e a Tecnologia

Research project: CERN/FIS-PAR/0013/2019

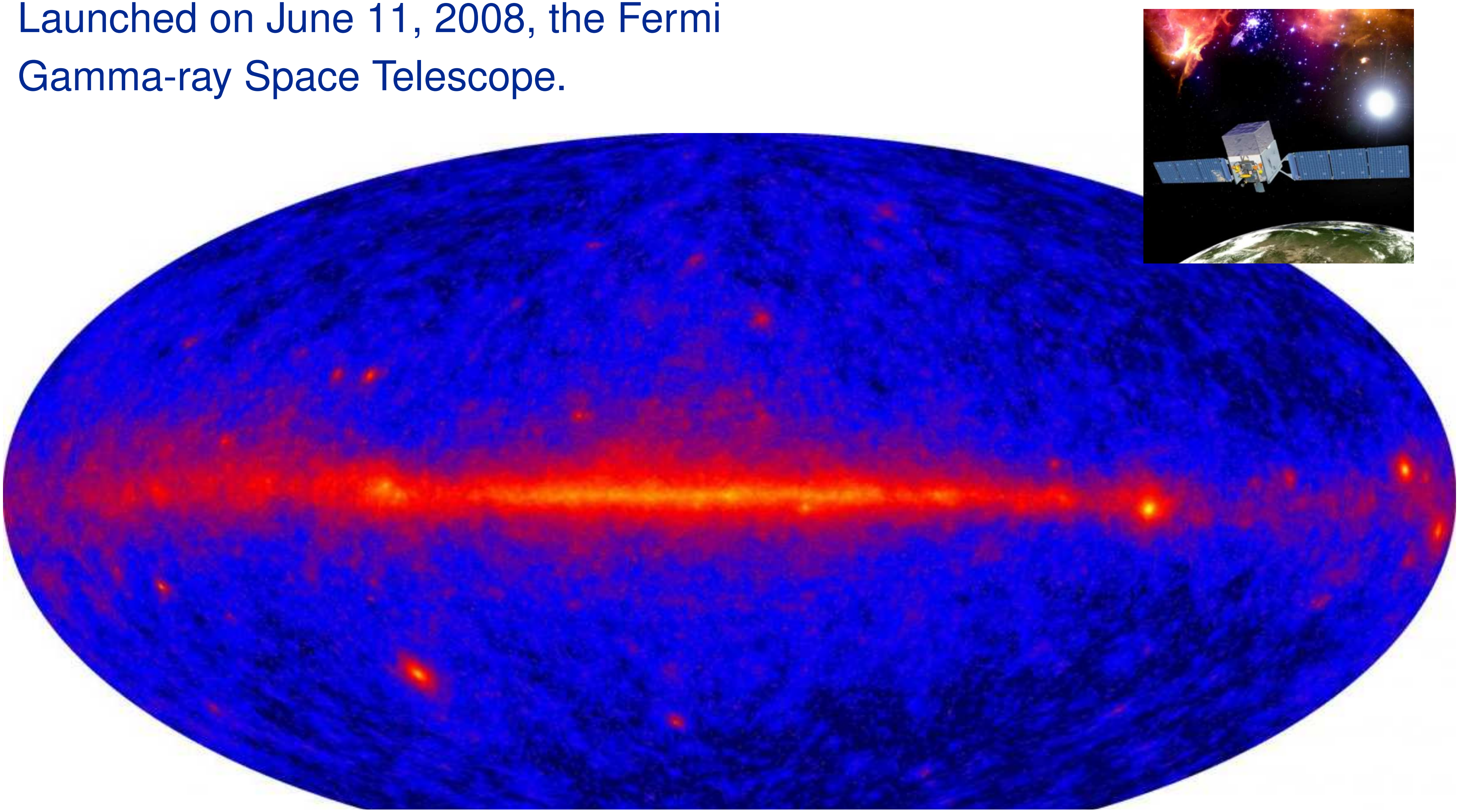
Cosmic rays

Sources

Propagation

Galaxy view with $\gamma > 100$ MeV ...

Launched on June 11, 2008, the Fermi Gamma-ray Space Telescope.

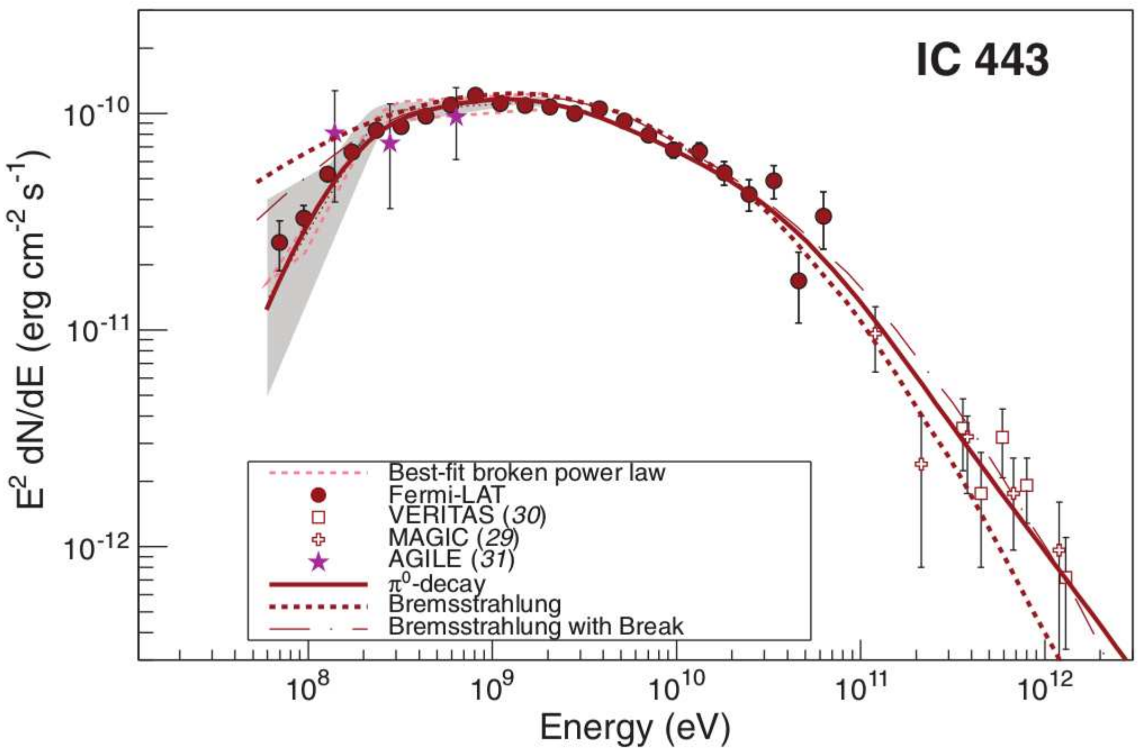


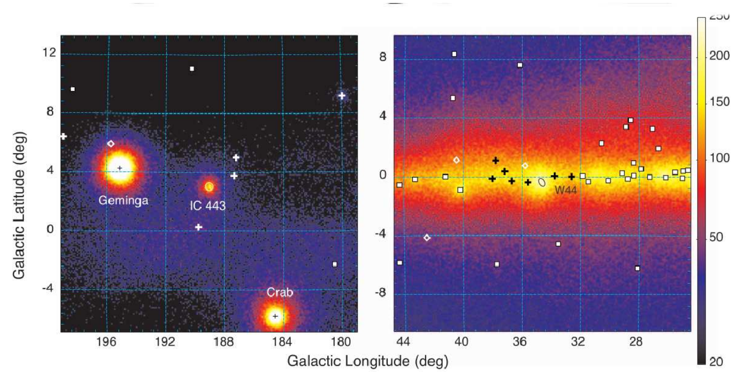
γ radiation is a tracer of high energy protons (and nuclei) and interstellar matter in the Galaxy

SNR: proton accelerators...

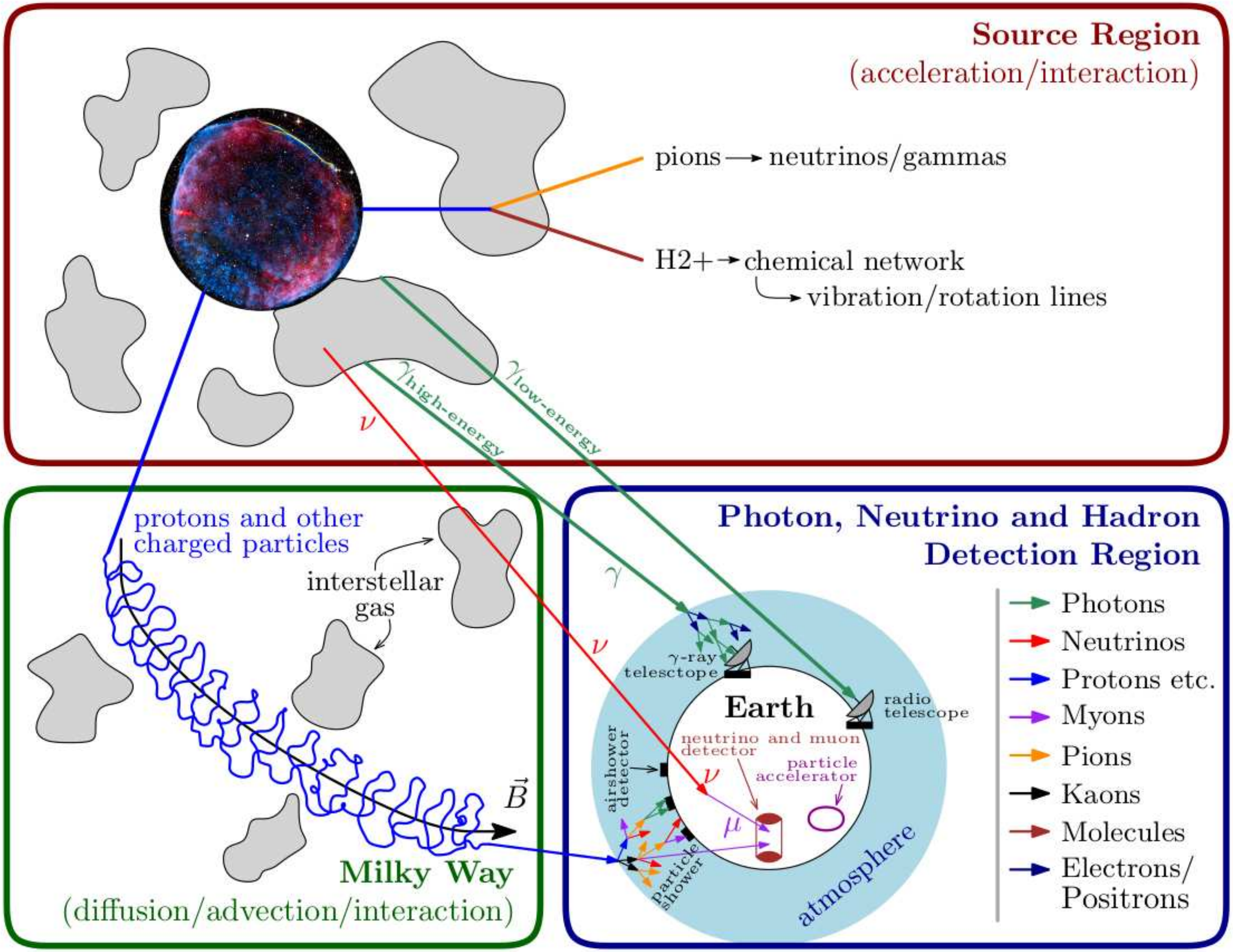
A direct signature of high-energy protons is provided by gamma rays generated in the decay of neutral pions

$$p + p \to \left(\pi^0 \to \gamma\gamma\right) + \cdots$$





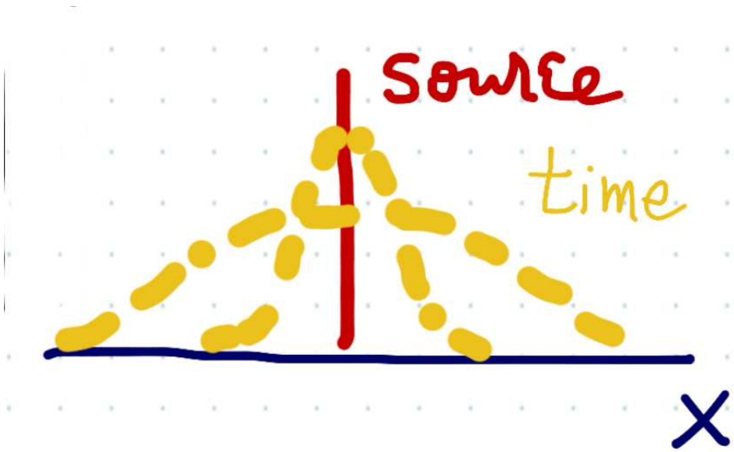
CRs: from sources to observation...

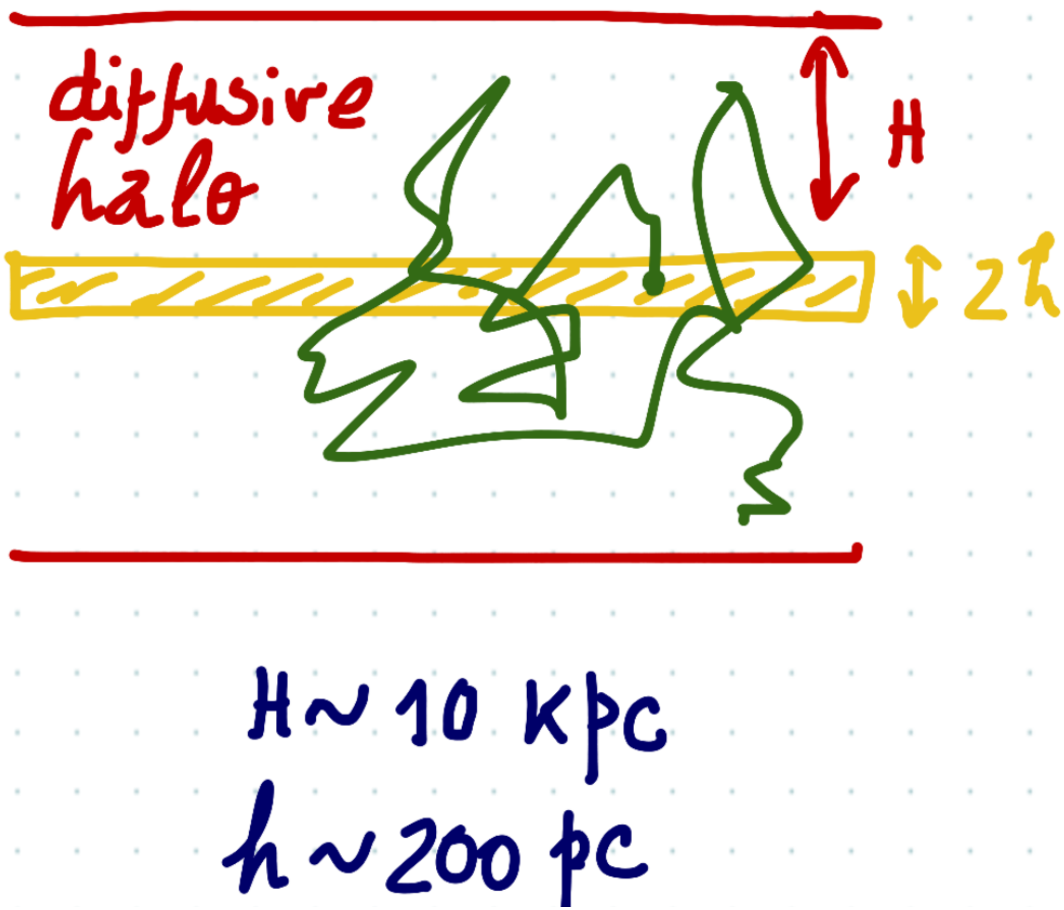


CRs: transport equation

cosmic-rays are accelerated to a power-law spectrum in local sources, $Q(E)$ and diffuse within the galaxy (magnetic field environment)

diffusion coefficient: D



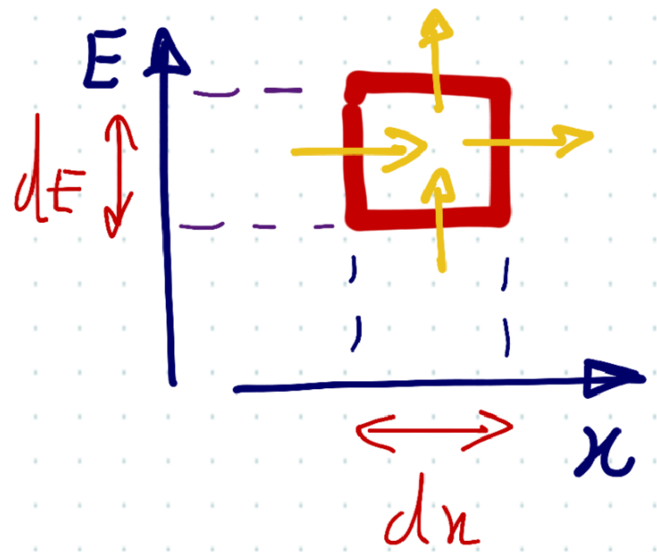


CRs: transport equation

let's evaluate the variation in time of the density of particles, N in an energy-space cell

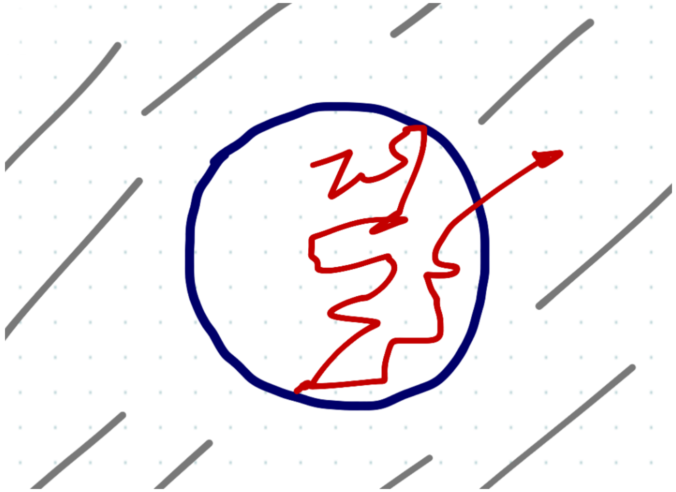
$$\frac{\partial N}{\partial t} = -\frac{\partial \varphi}{\partial x} - \frac{\partial \varphi}{\partial E} + Q(E)$$

$$\varphi = -D\,\frac{\partial N}{\partial x} \qquad \text{(Fick Law)}$$



$$\frac{\partial N_i}{\partial t} = D\nabla^2 N_i + \frac{\partial}{\partial E}\left[b(E)N_i\right] + Q_i(E) - \frac{N_i}{\tau_i} + \sum_{j\geq i} P_{ij}\frac{N_j}{\tau_j}$$

CRs: Leaky-Box model approximation



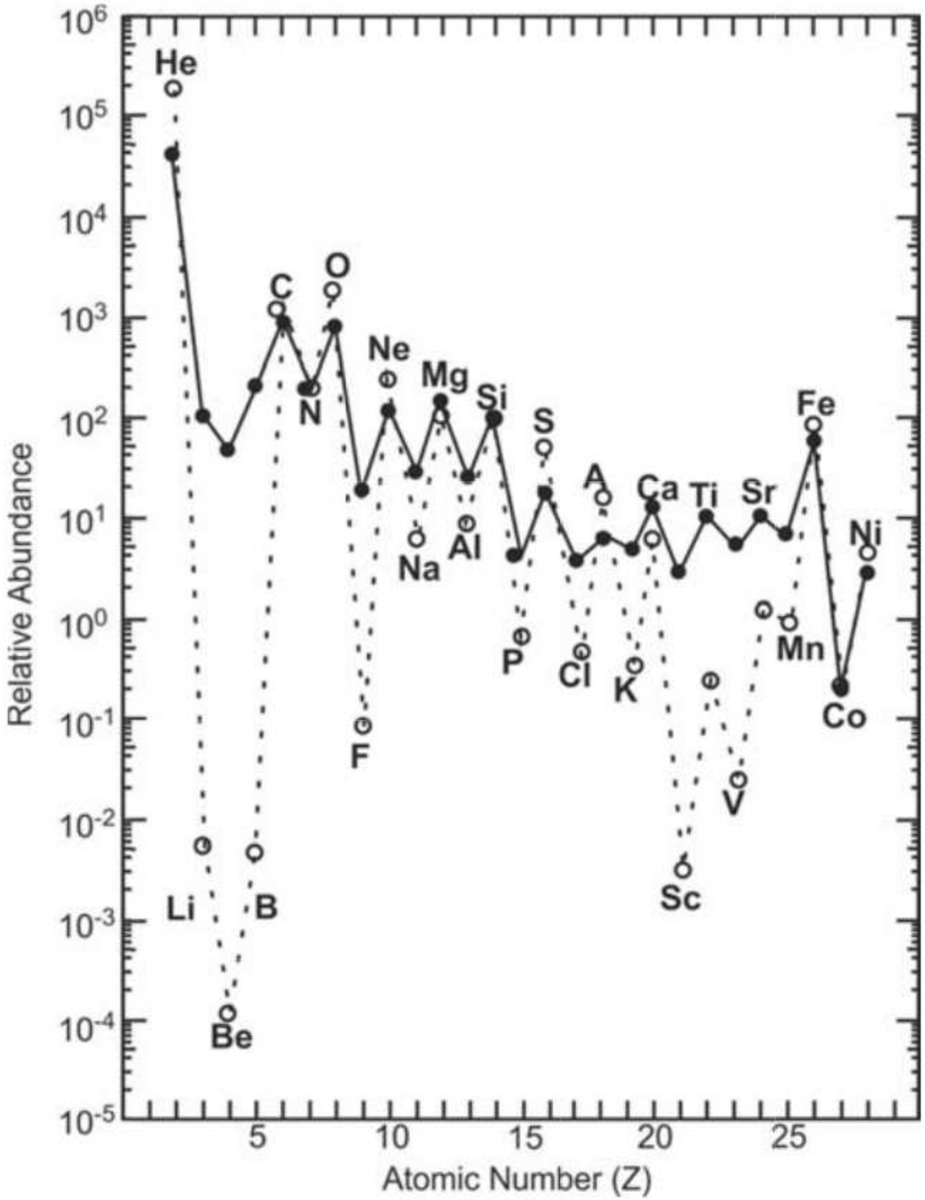
- particles will diffuse staying confined in the galactic volume before escaping into intergalactic space
- can be modeled as particles diffusing inside a boxed volume freely and being reflected at its boundaries with some probability
- escape time (τ_e), $D\nabla^2 N \to -\frac{N}{\tau_e}$ $\Rightarrow$ $\boxed{\frac{N_i}{\tau_e} + \frac{N_i}{\tau_i} \simeq Q_i + \sum_{j\geq i} P_{ij}\frac{N_j}{\tau_j}}$ (steady state)
- relating particle density and source spectrum,

$$\boxed{N(E) \sim Q(E) \cdot \tau_e(E) \propto E^{-(\alpha+\kappa)}}$$

source acceleration: $\alpha \sim 2.3$

diffusion: $\kappa \sim 0.4$ secondaries/primaries

CRs: elemental abundances



secondaries

- ✔ lithium (Li)
- ✔ berylium (Be)
- ✔ boron (B)
- ✔ fluor (F)
- ✔ sodium (Na)
- ✔ aluminium (Al)
- ✔ . . .
- ✔ sub-Fe

AMS LIP team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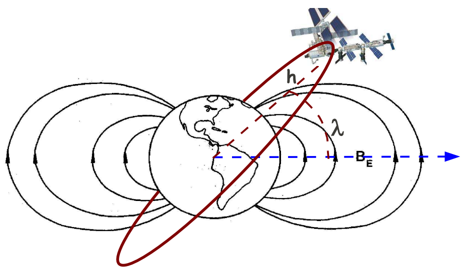
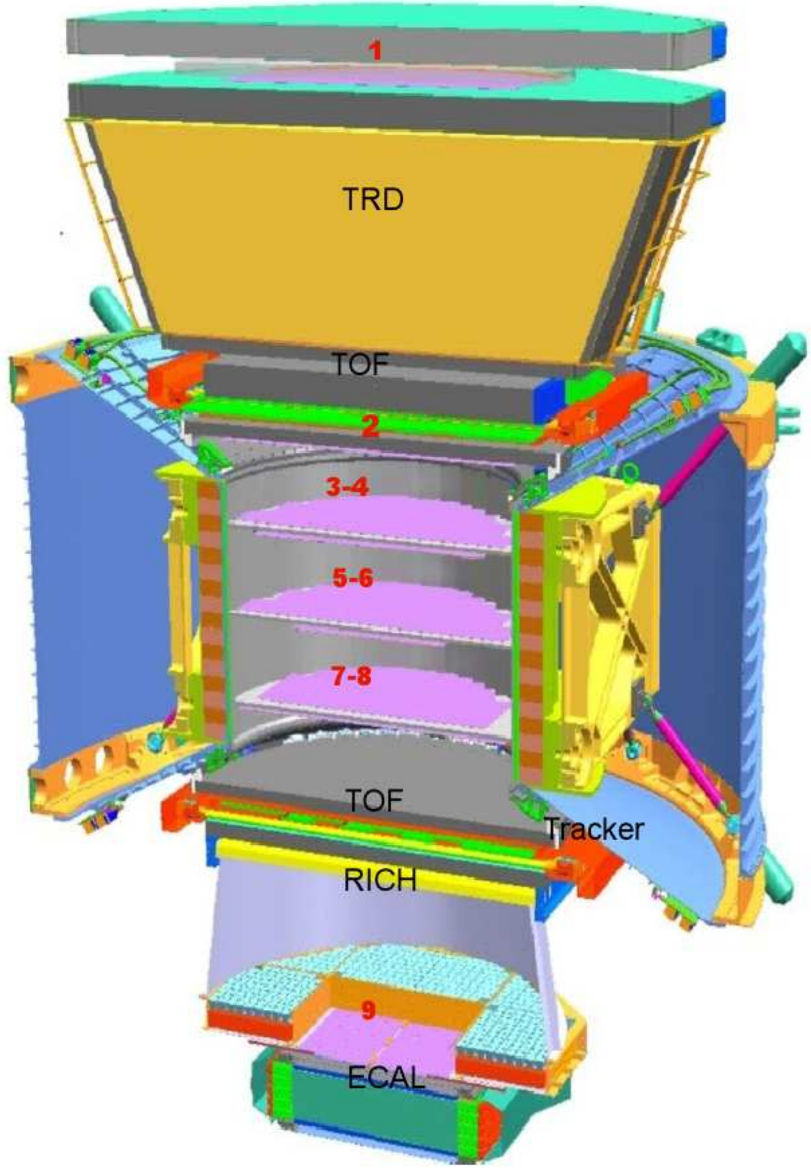
AMS02 detector and data colection

AMS is orbiting around earth at around 400 Km of altitude and taking data since May 2011





detector:

- ✔ high redundancy on measuring particle observables

on every day:

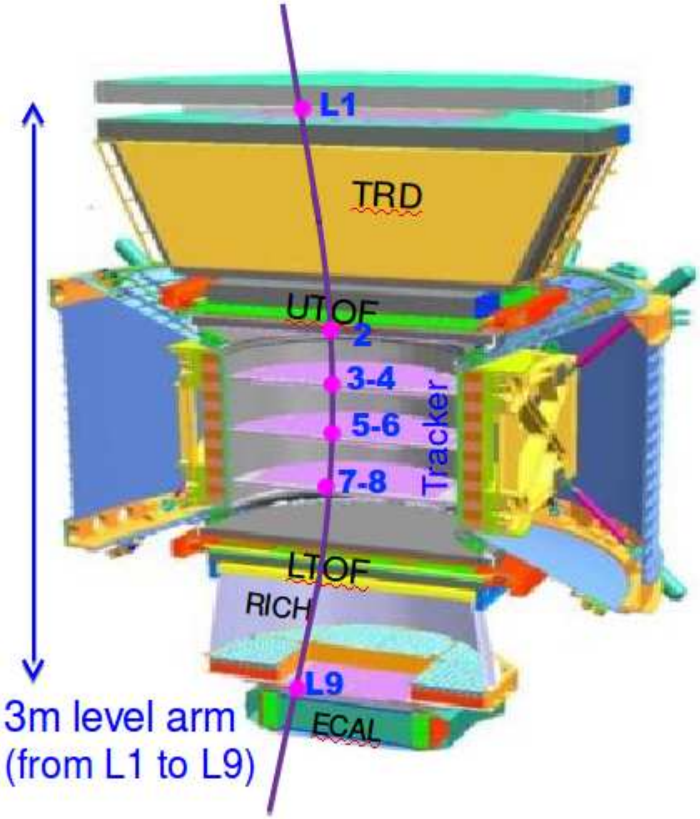
- ✔ around 40 million events gathered
- ✔ ~ 100 GBytes to transfer every day at 10 Mb/s through relay satellites (TDRS)

on every year:

- ✔ $16.5\ 10^9$ Triggers (Raw Data)

almost 150 billions of events gathered till now

AMS nuclei identification



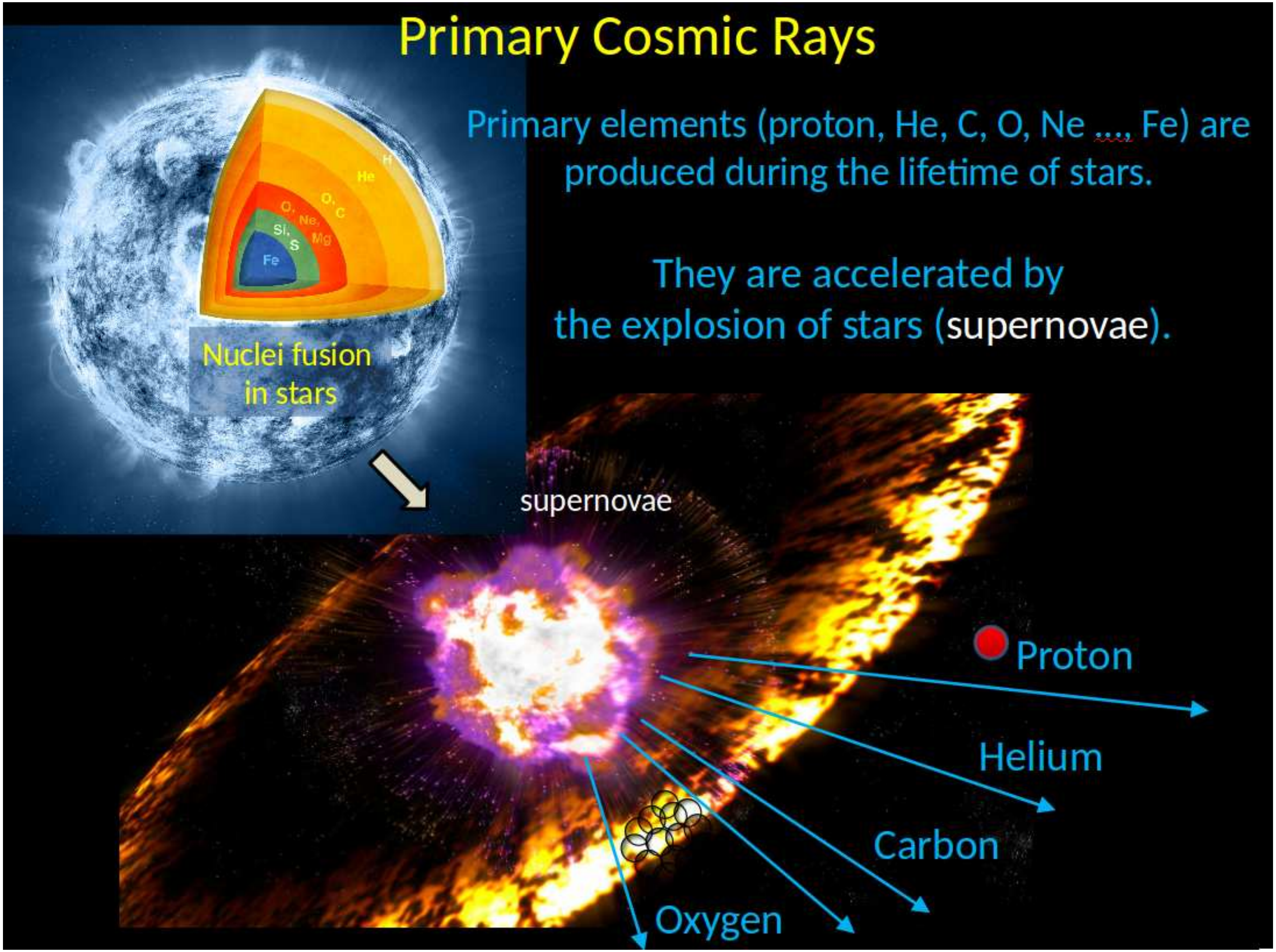
Tracker (9 Layers) + Magnet: Rigidity (Momentum/Charge)

Charge	Coordinate Resolution	MDR
Z=1	~10 μm	2 TV
2≤Z≤8	5-7 μm	3.2-3.7 TV
9≤Z≤16	6-8 μm	3-3.5 TV

L1, UToF, Inner Tracker (L2-L8), LToF and L9

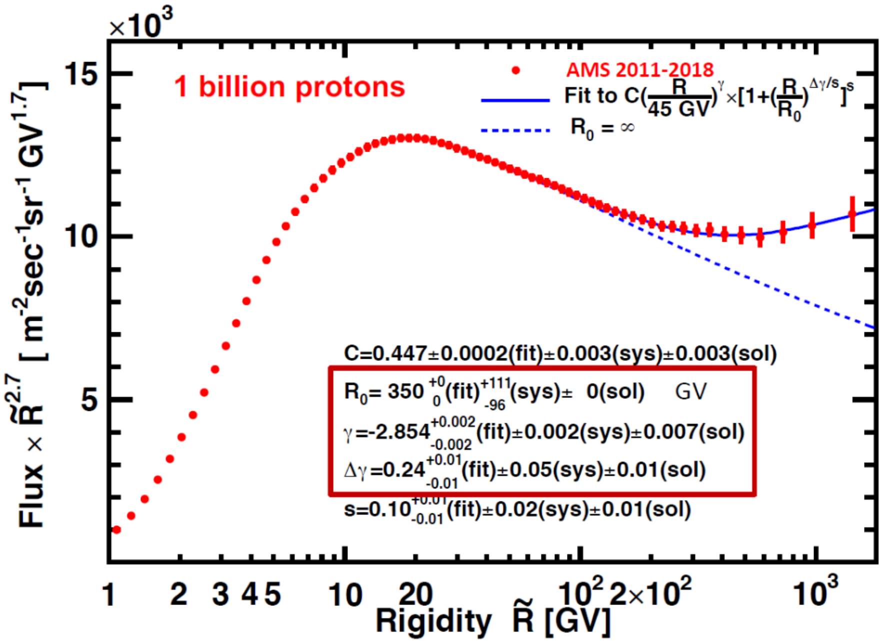
Consistent Charge along Particle Trajectory

Charge	Inner Tracker Charge Resolution (c.u.)
1≤Z≤8	0.05 - 0.12
9≤Z≤16	0.13 - 0.19

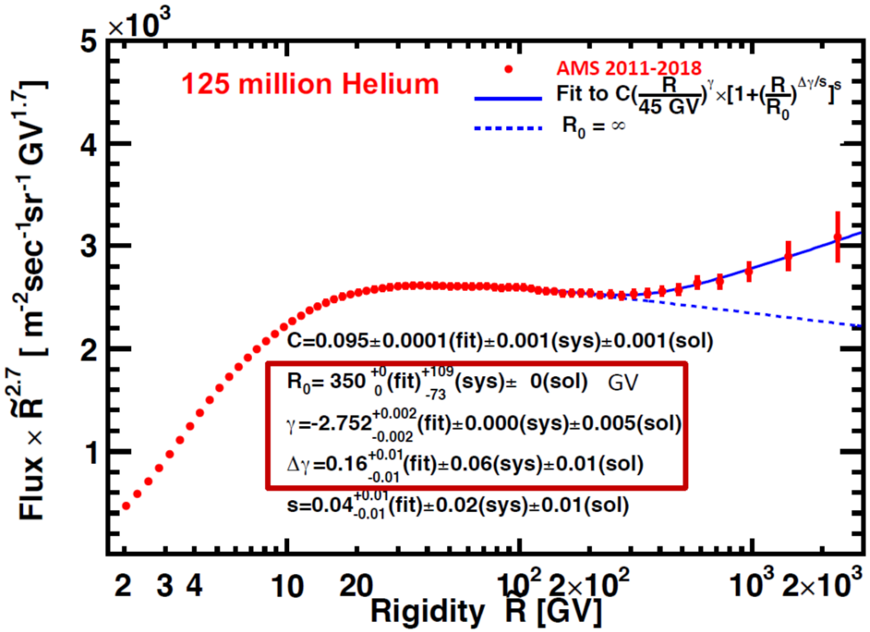

Primary Cosmic Rays
Primary elements (proton, He, C, O, Ne ..., Fe) are produced during the lifetime of stars.
They are accelerated by the explosion of stars (supernovae).
H
He
O, C
O, Ne, Mg
Si, S
Fe
Nuclei fusion in stars
supernovae
Proton
Helium
Carbon
Oxygen

CRs primaries: AMS protons, helium

AMS Proton Spectrum (2011 - 2018)

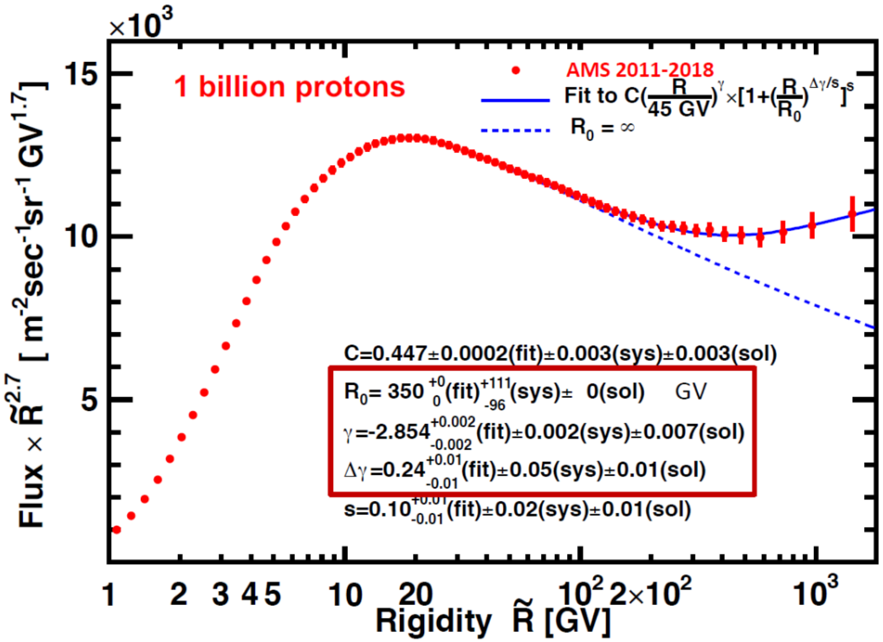


AMS Helium Spectrum (2011 - 2018)



CRs primaries: AMS protons, helium

AMS Proton Spectrum (2011 - 2018)



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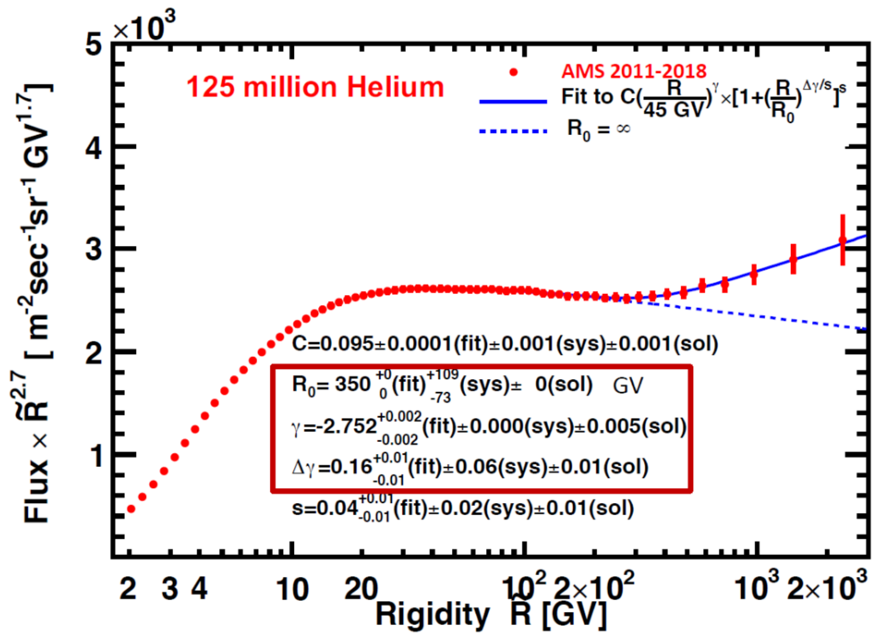
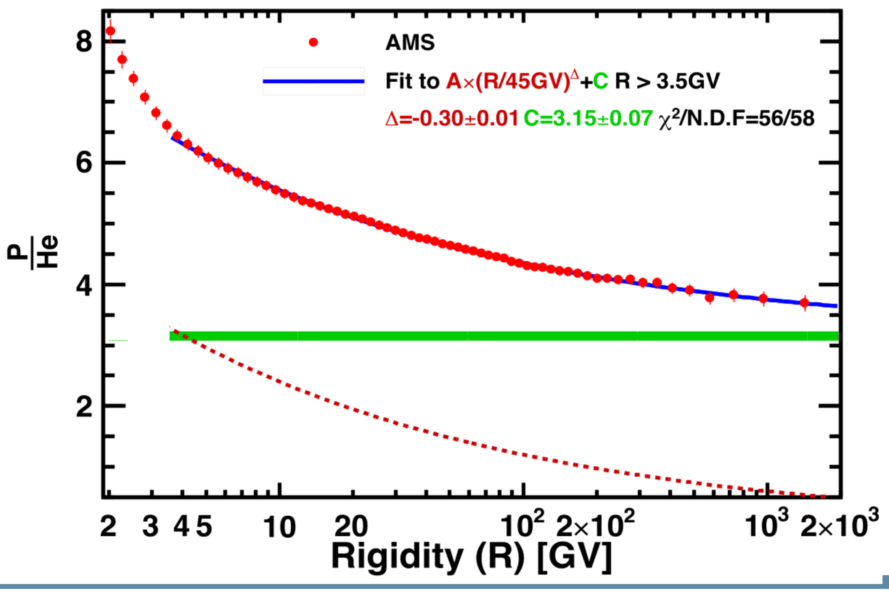
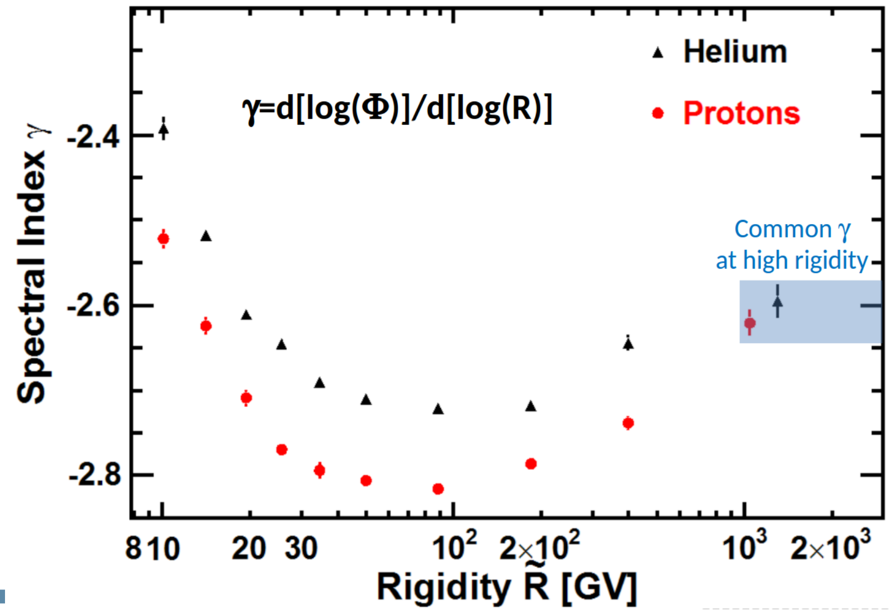
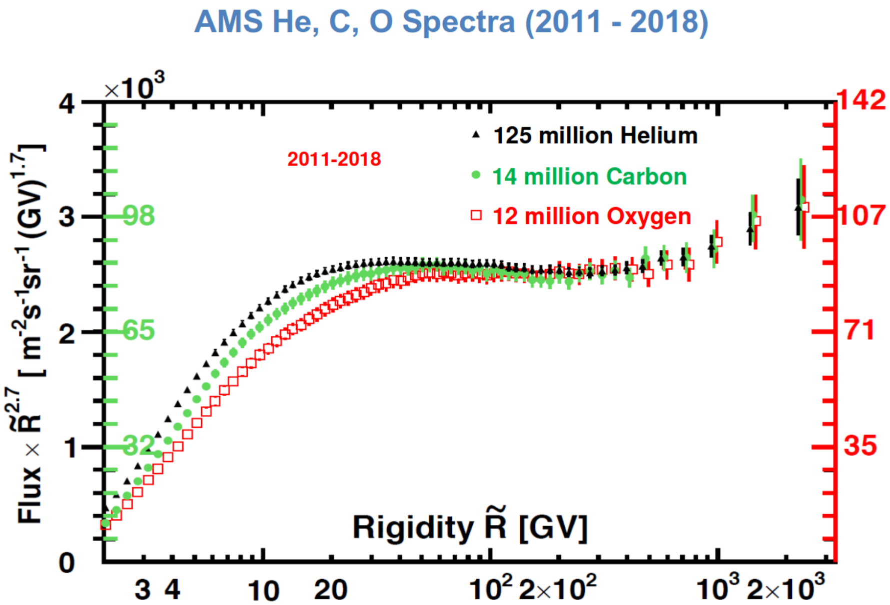
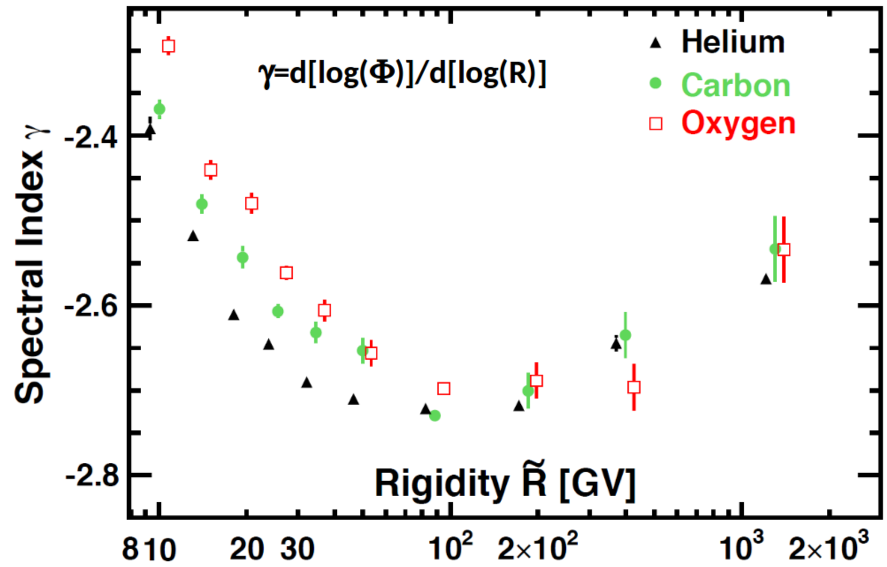


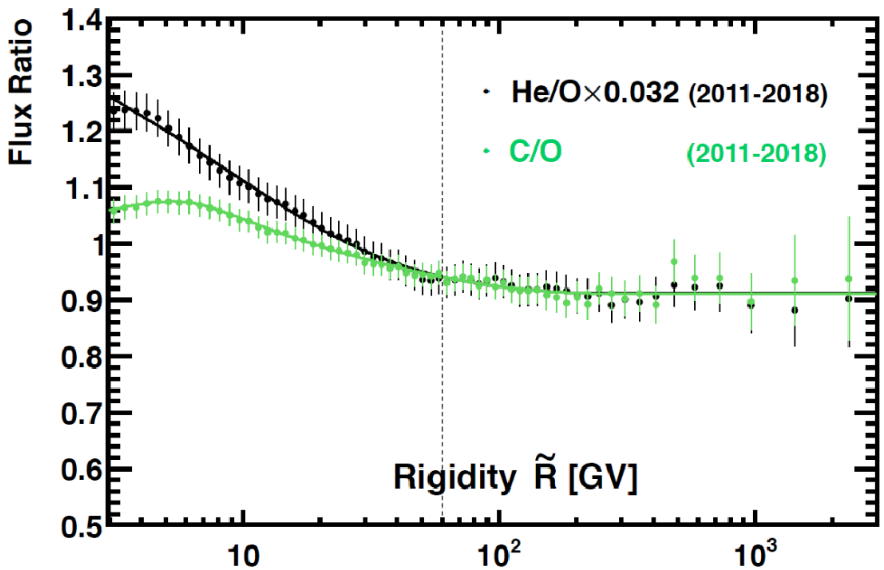




CRs primaries: He, C, O







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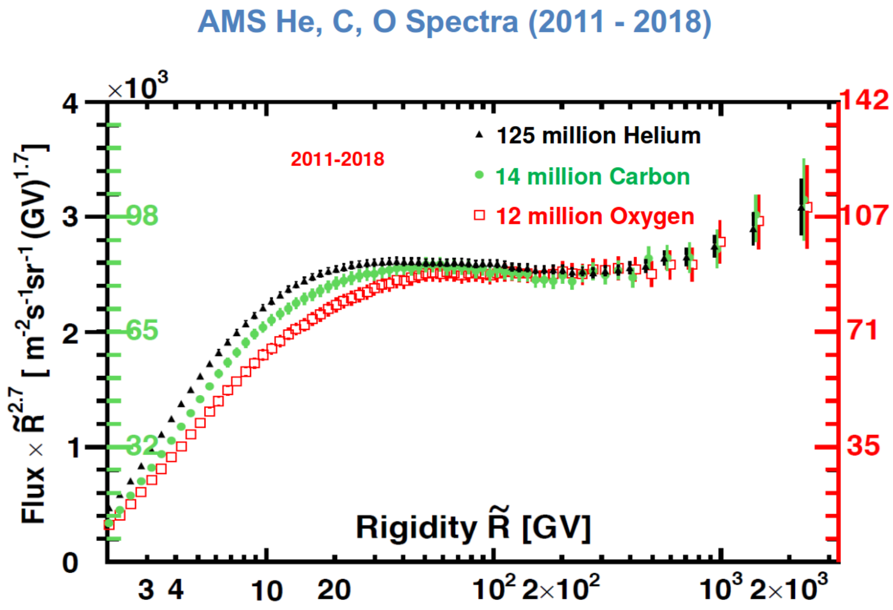
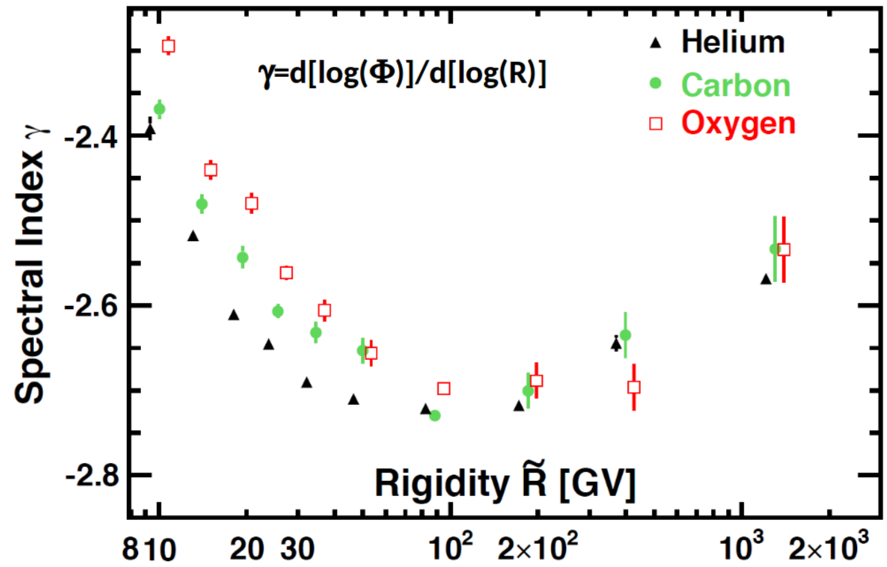
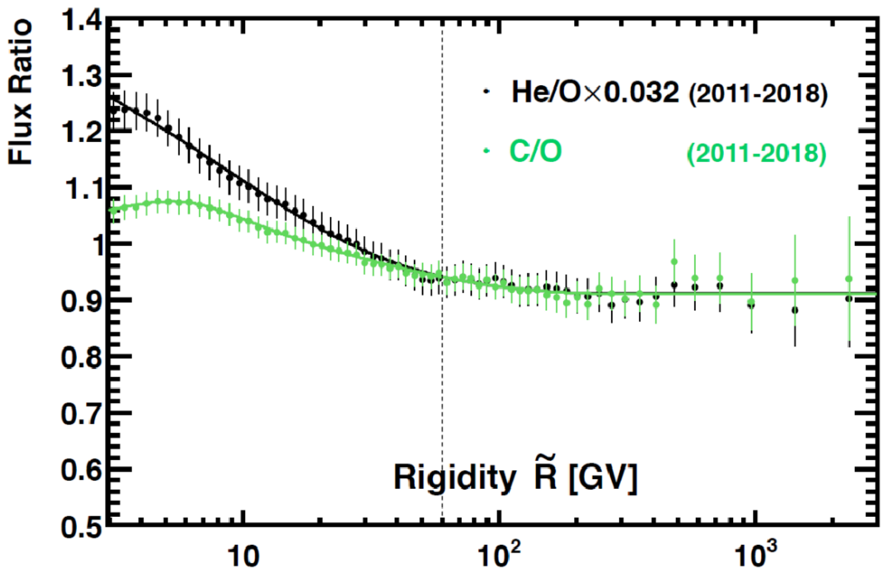
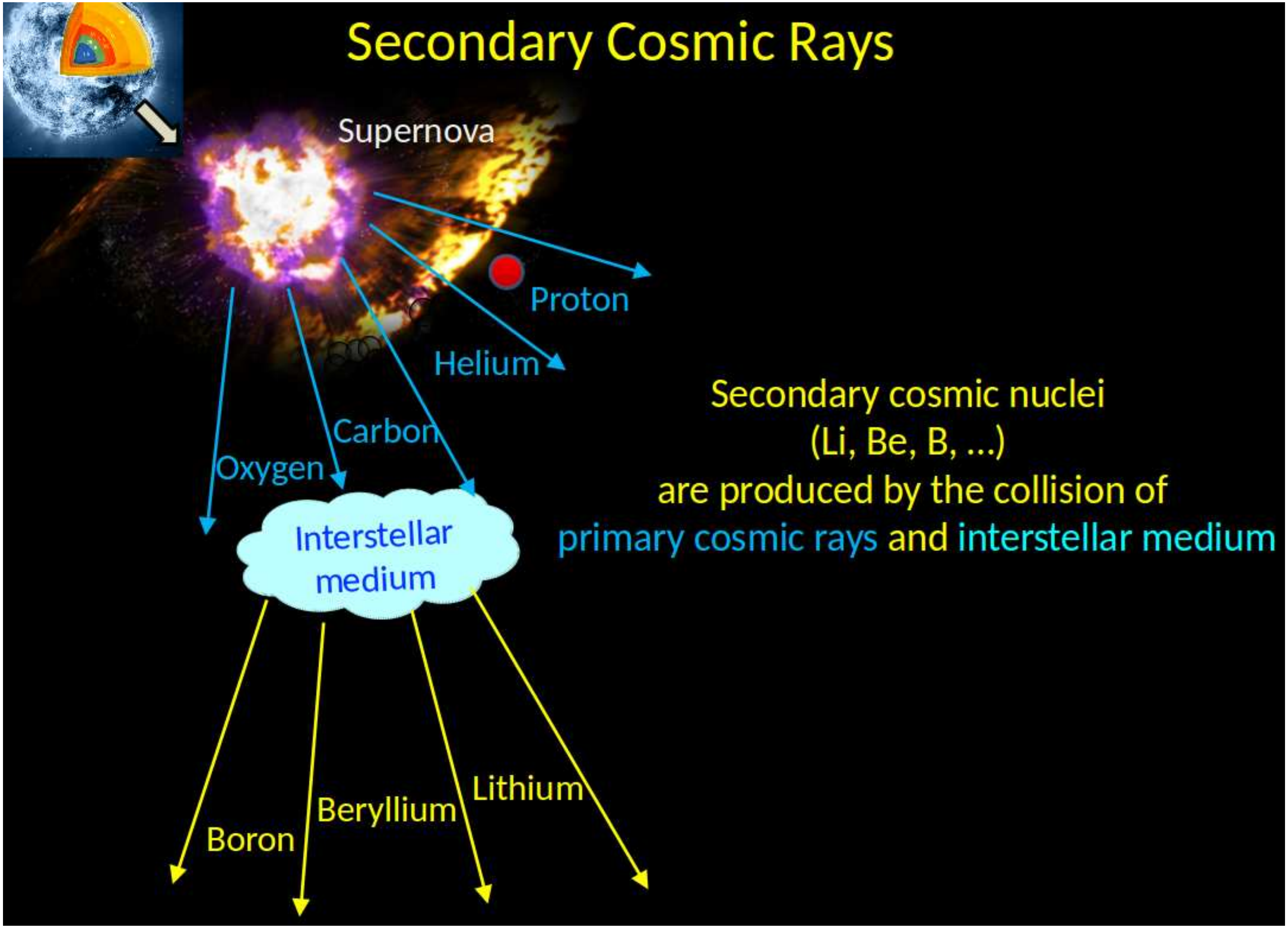






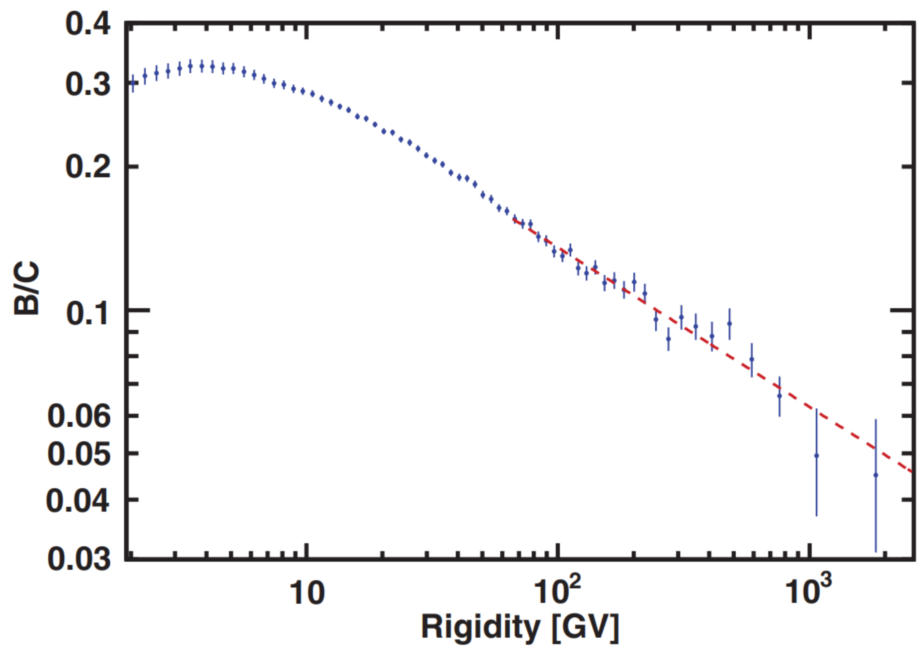
- ✔ All spectra show deviation from single power law (break) and hardening at high rigidity
  power break related to source of transport?
- ✔ proton/helium anomaly: helium energy spectrum is harder than the proton spectrum
  it follows a power law $p/he \sim \left(\frac{R}{45GV}\right)^{-0.30}$
- ✔ He, C, O show an identical rigidity dependence above 60 GV hardening above 200 GV

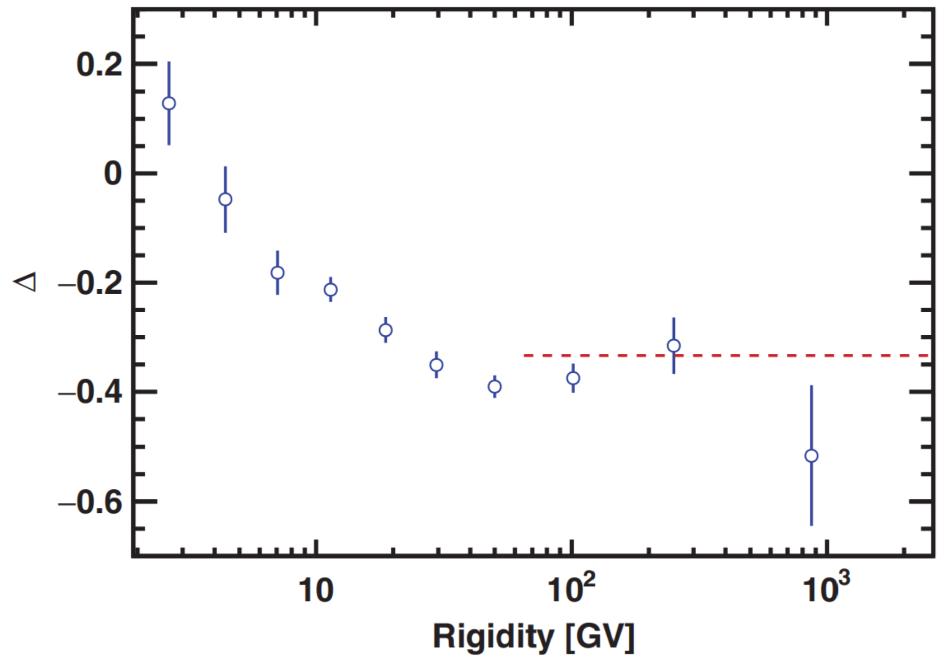

Secondary Cosmic Rays
Supernova
Proton
Helium
Carbon
Oxygen
Interstellar medium
Secondary cosmic nuclei
(Li, Be, B, ...)
are produced by the collision of
primary cosmic rays and interstellar medium
Lithium
Beryllium
Boron

CRs secondaries/primaries: B/C

- Boron equation: $\frac{N_B}{\tau_e} + \frac{N_B}{\tau_B} \simeq P_{C\rightarrow B}\frac{N_C}{\tau_C}$
- boron to carbon ratio: $\frac{N_B}{N_C} \simeq \frac{P_{C\rightarrow B}}{\tau_C}\left(\frac{1}{\tau_e} - \frac{1}{\tau_B}\right)^{-1} \quad \Rightarrow \quad \boxed{\frac{N_B}{N_C} \propto \tau_e}$

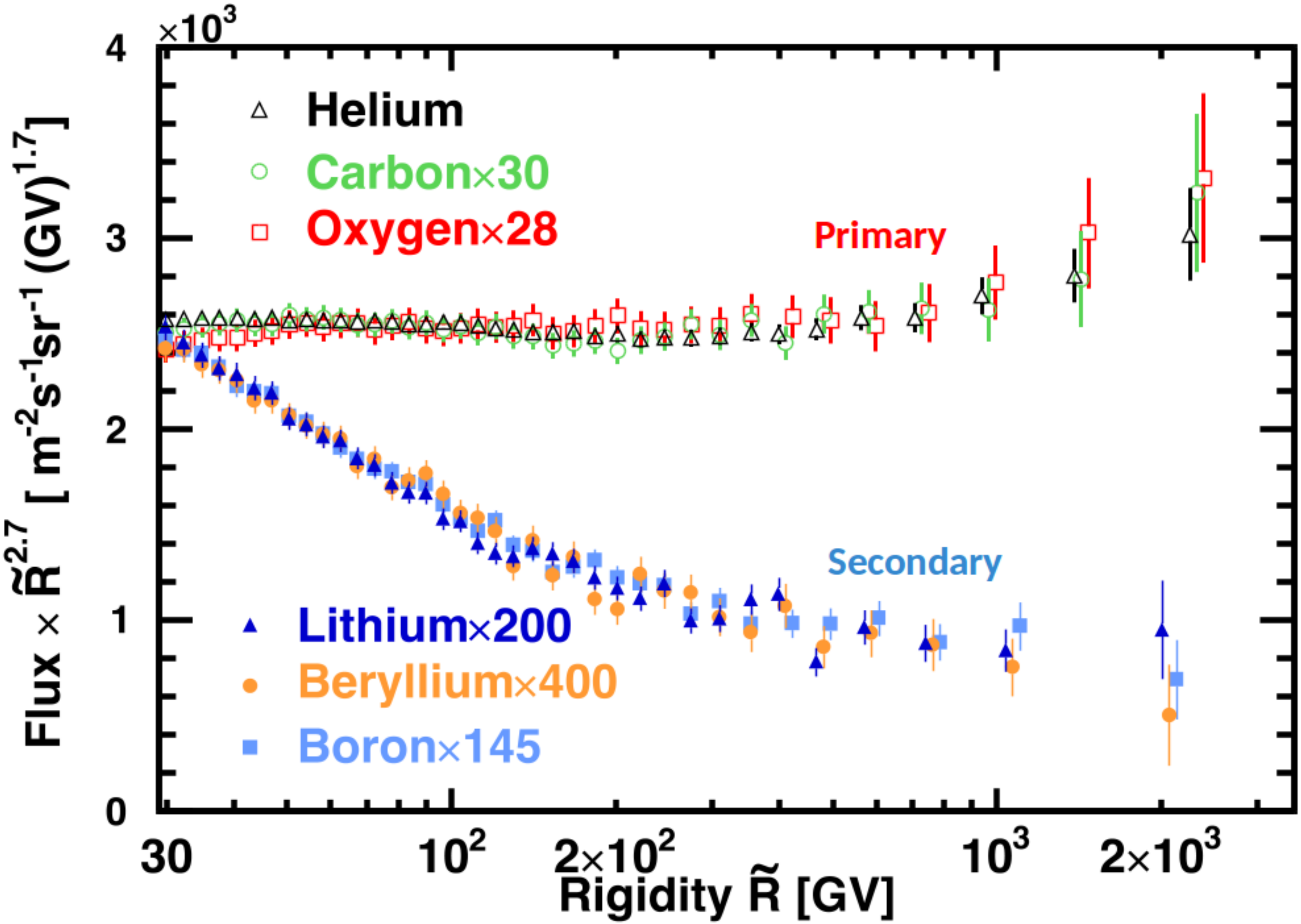
  as $\tau_e \sim 10^6 y << \tau_B = \frac{1}{n\, v\, \sigma_{pp}} \sim 10^{18} y$



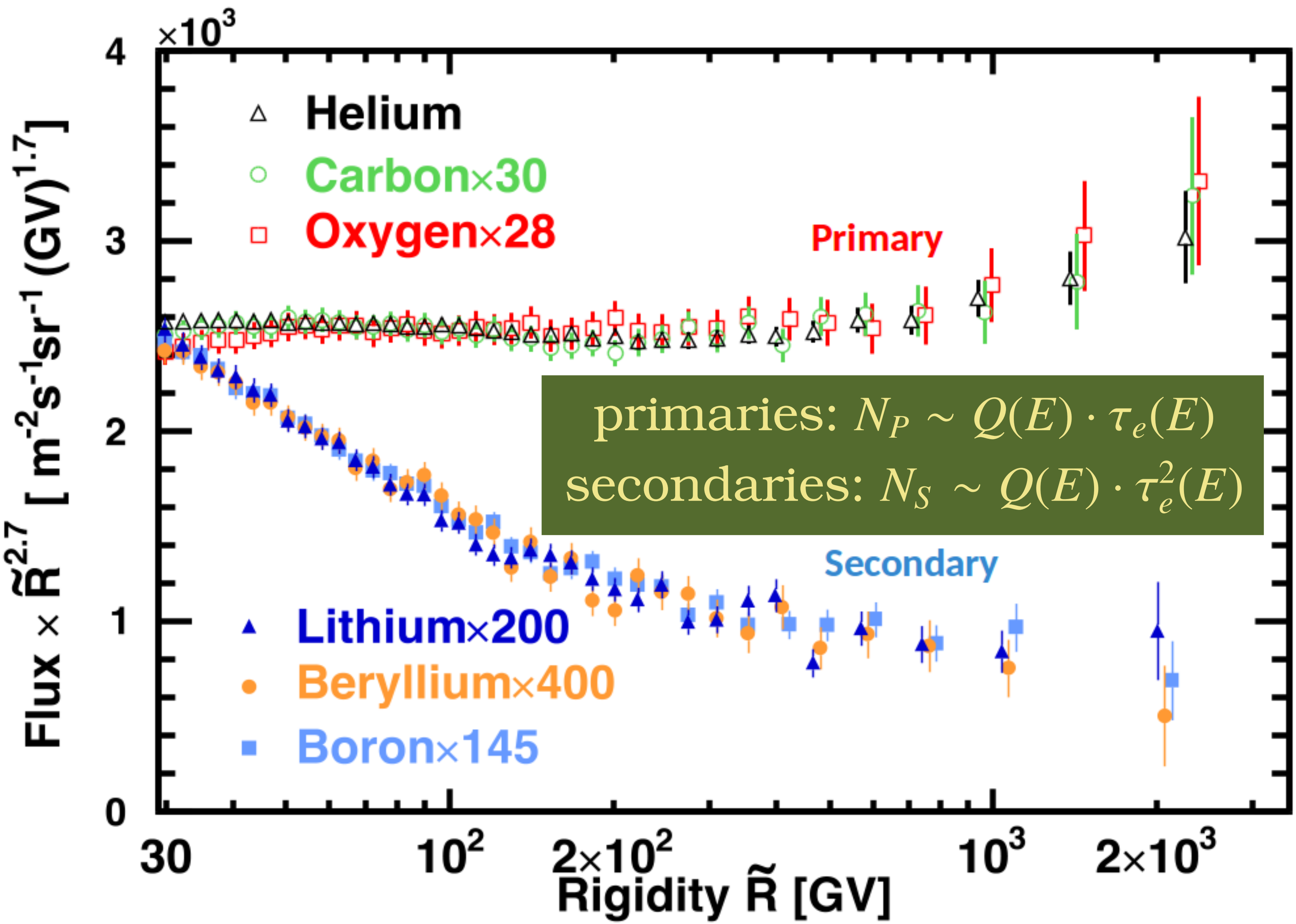


$$\tau_e \propto D^{-1} \sim E^{-0.3}$$

CRs secondaries/primaries: LiBeB



CRs secondaries/primaries: LiBeB



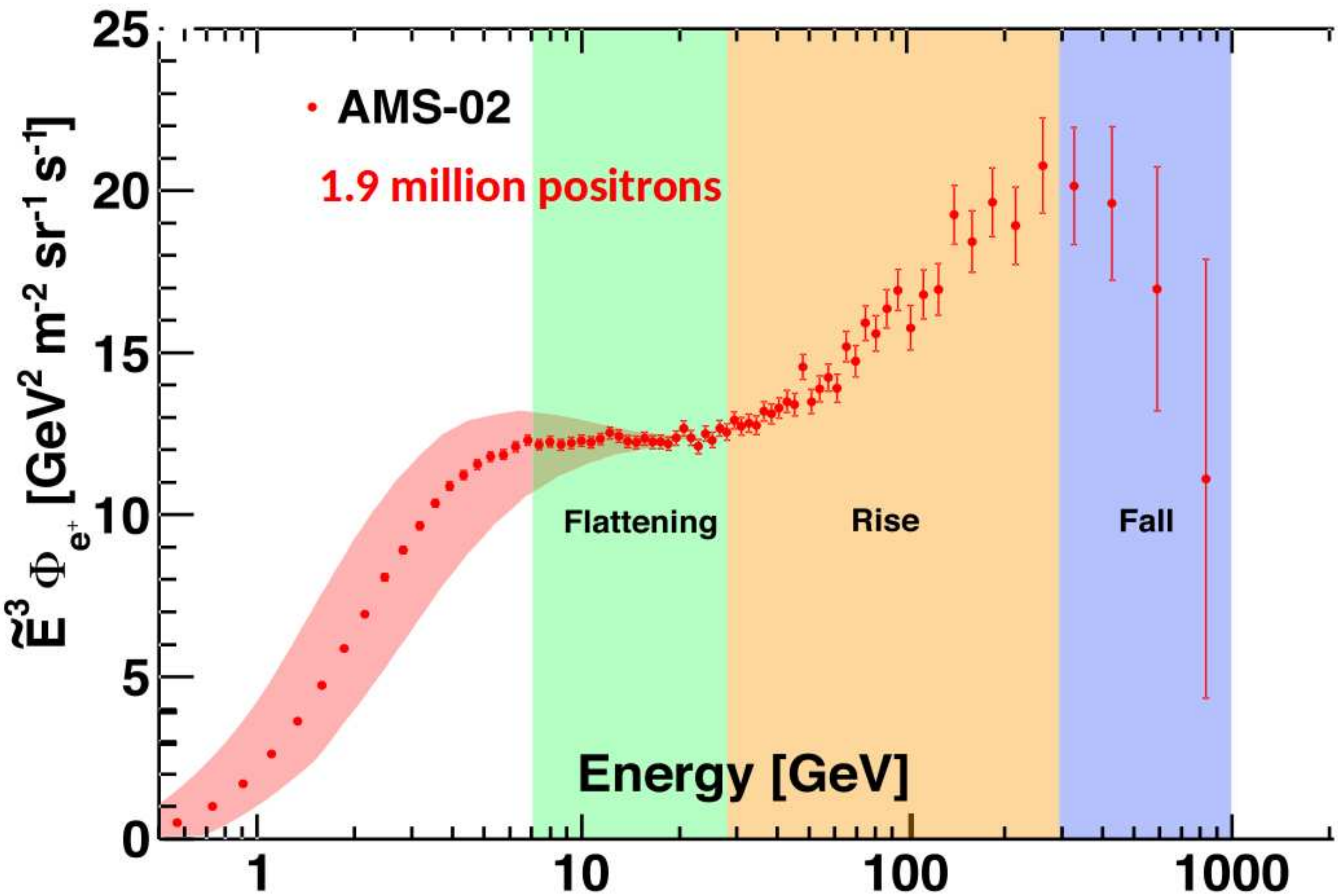
primaries: $N_P \sim Q(E) \cdot \tau_e(E)$

secondaries: $N_S \sim Q(E) \cdot \tau_e^2(E)$

Cosmic rays

Leptons and antiprotons

AMS: positrons and antiprotons



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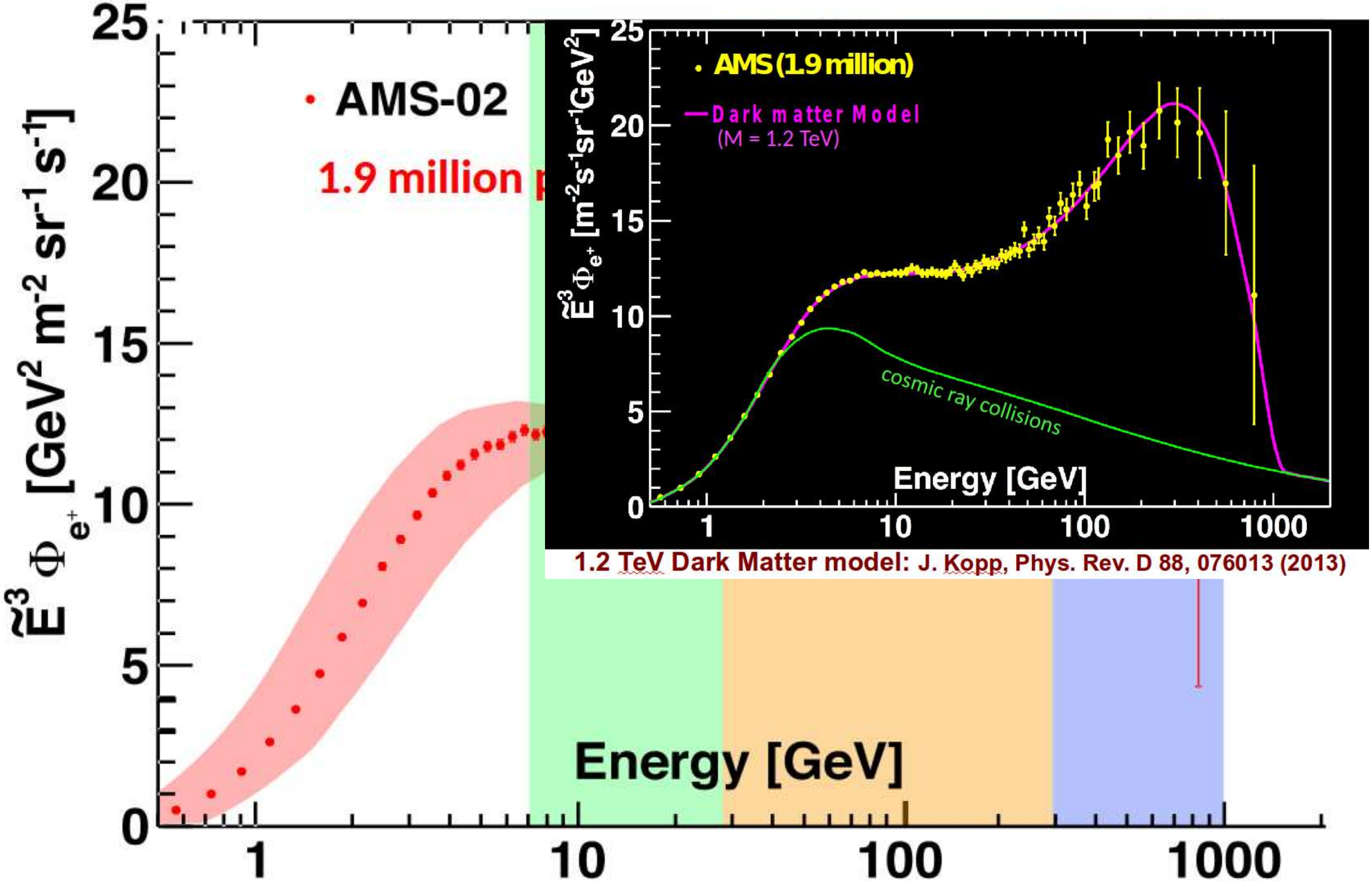

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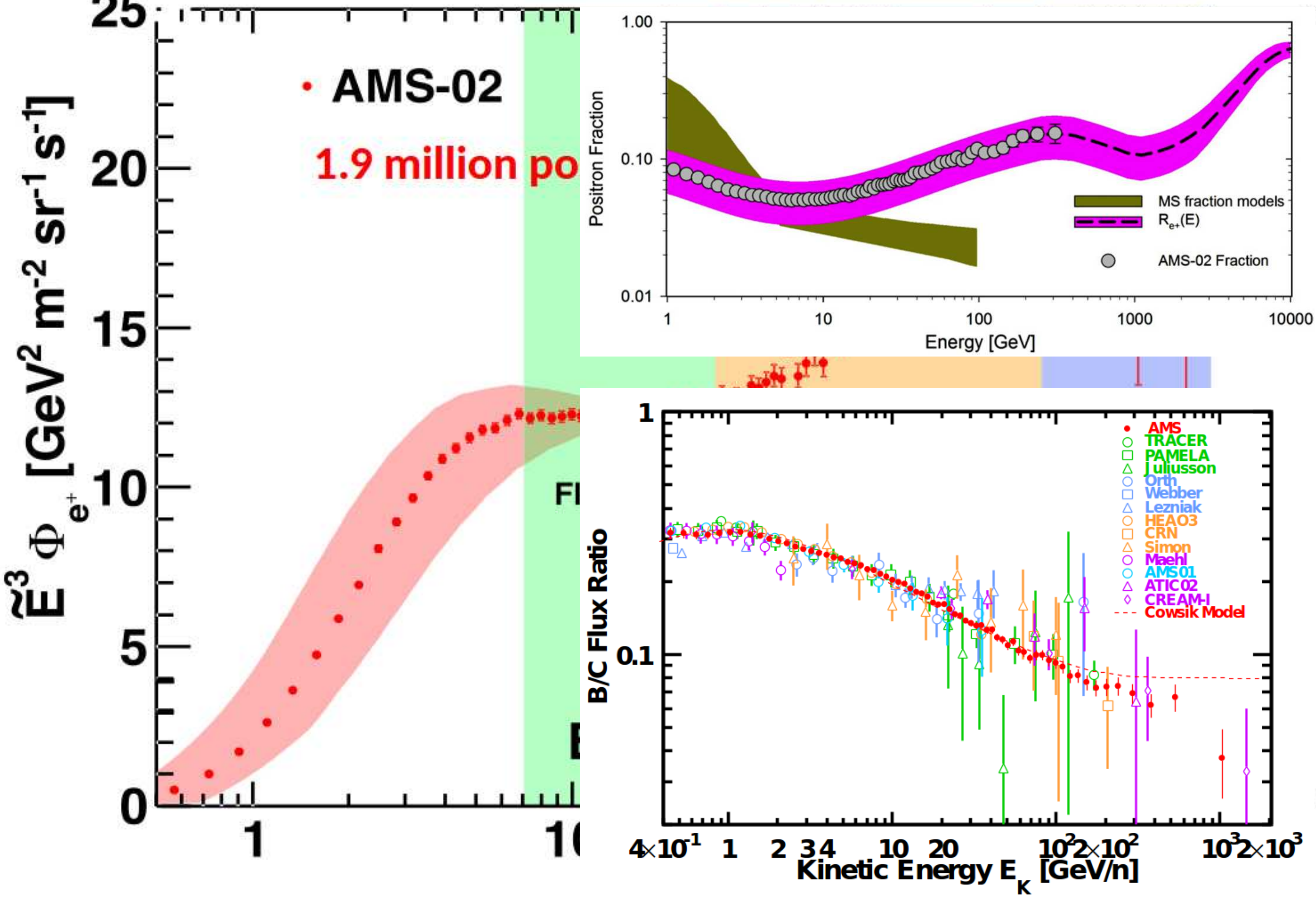

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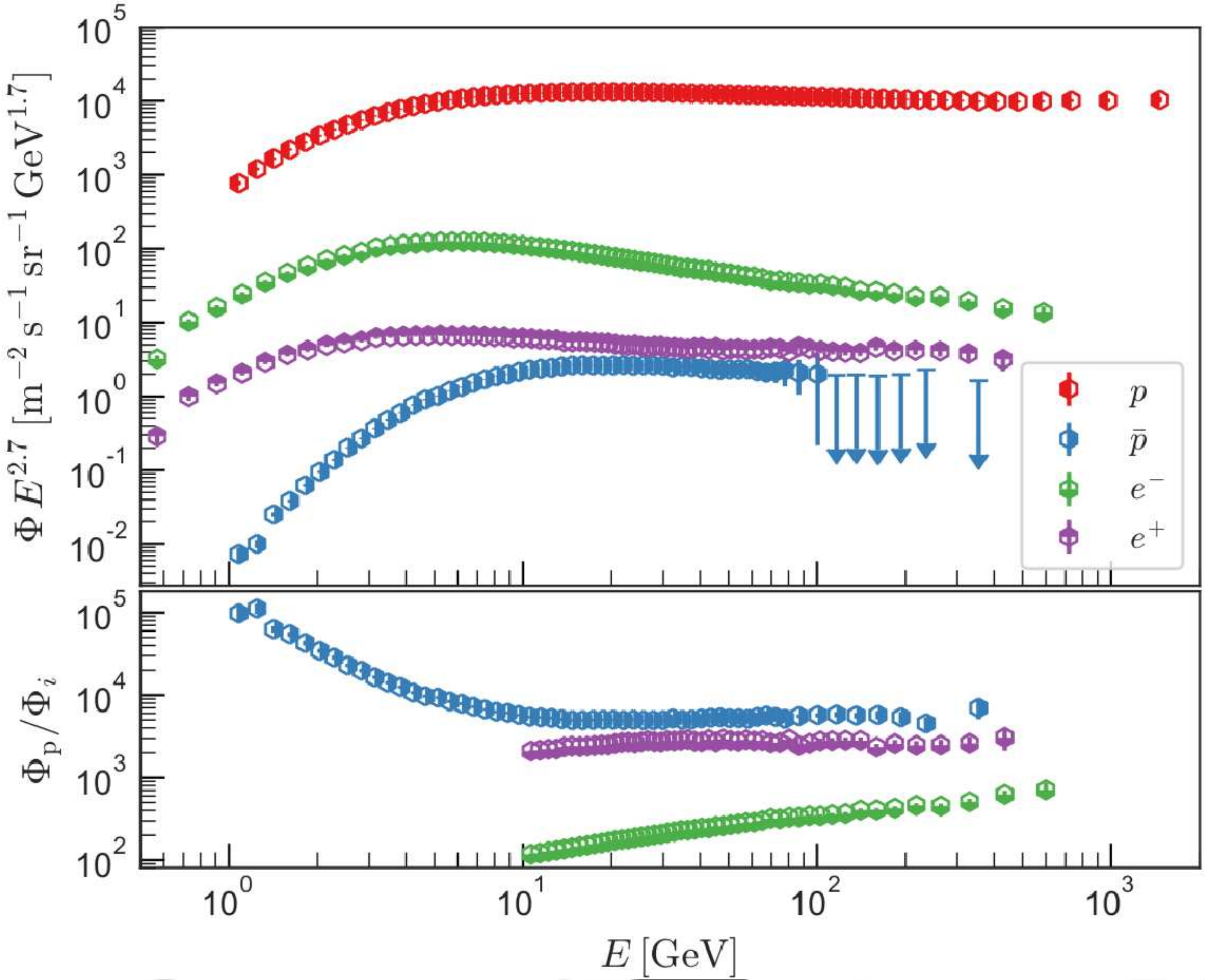
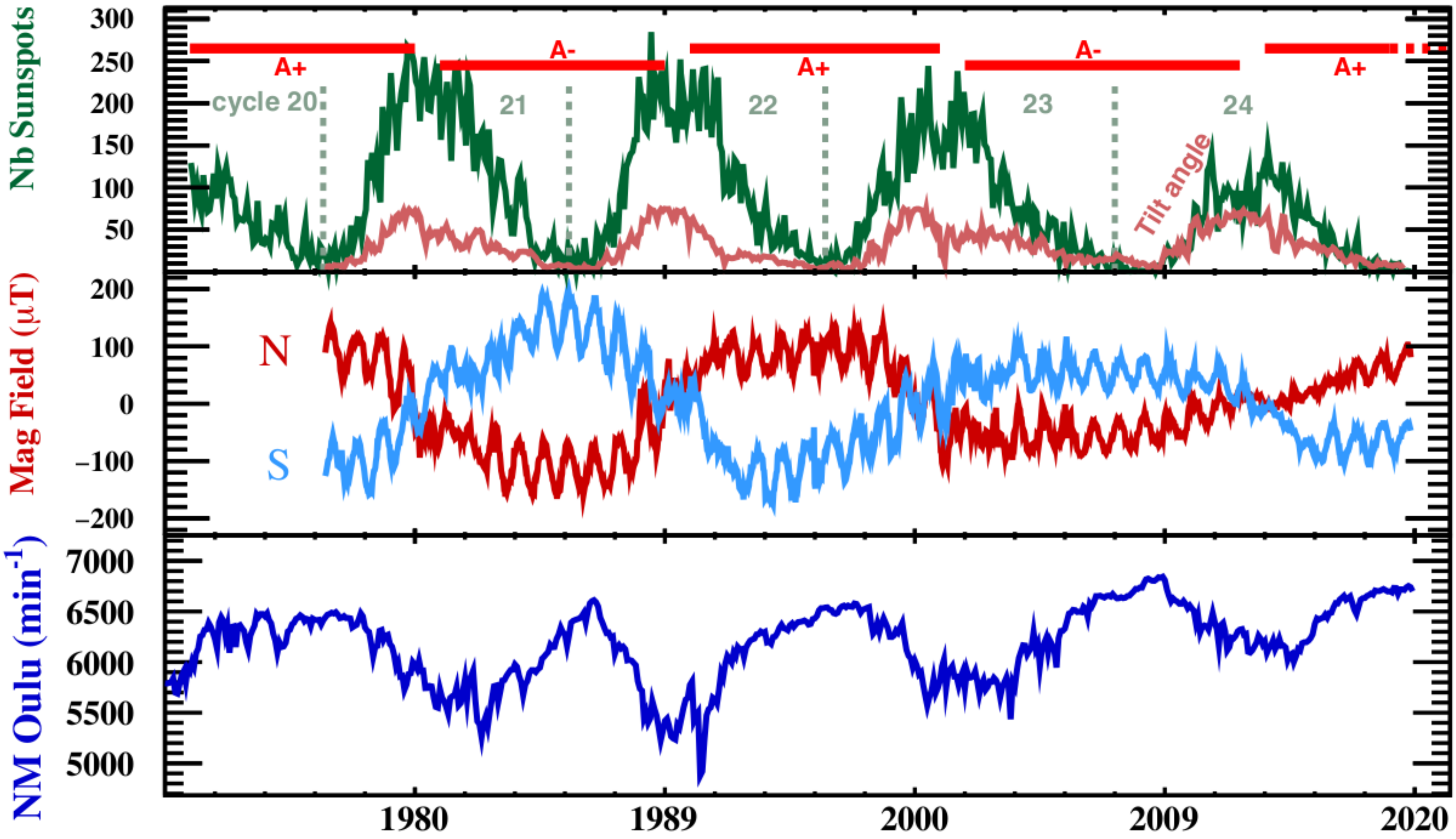


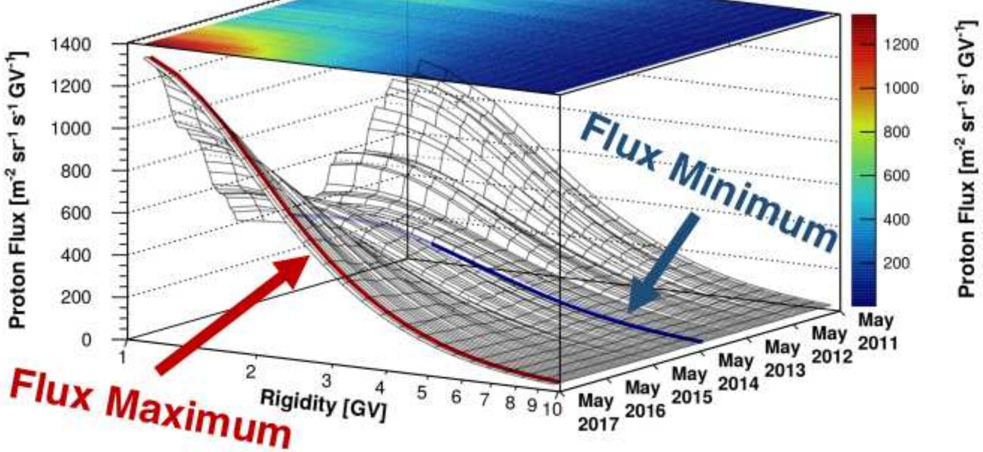
Cosmic rays

Solar activity indicators

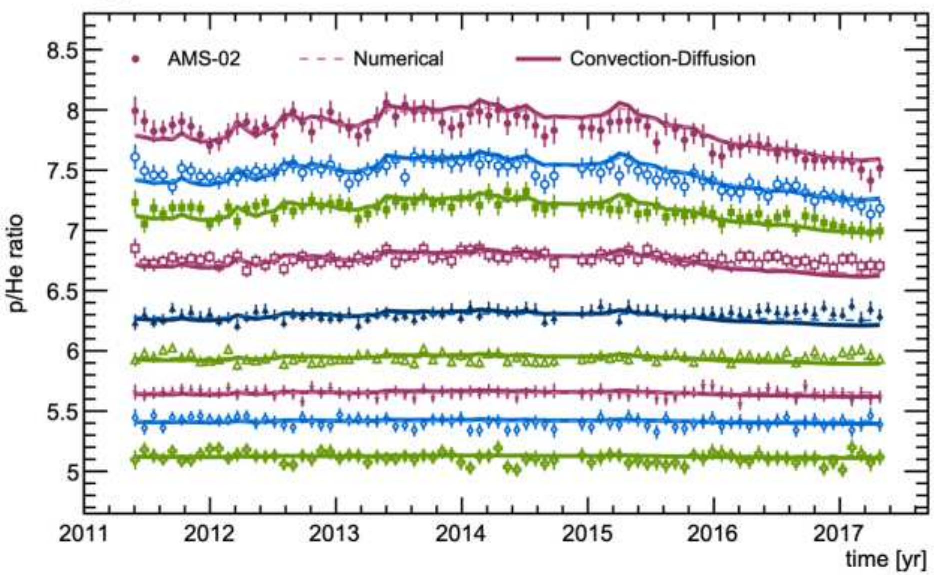


Time variability

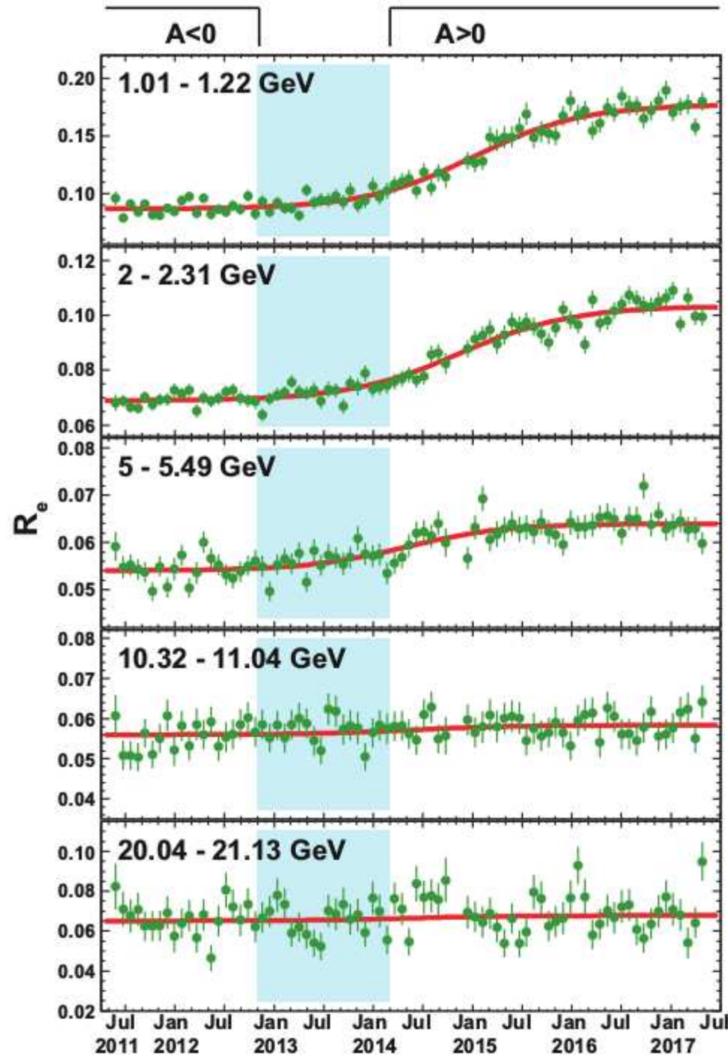
Protons



p/He ratio



Positron-electron ratio



Cosmic rays

Isotopes

Isotopes identification with AMS02

mass determination

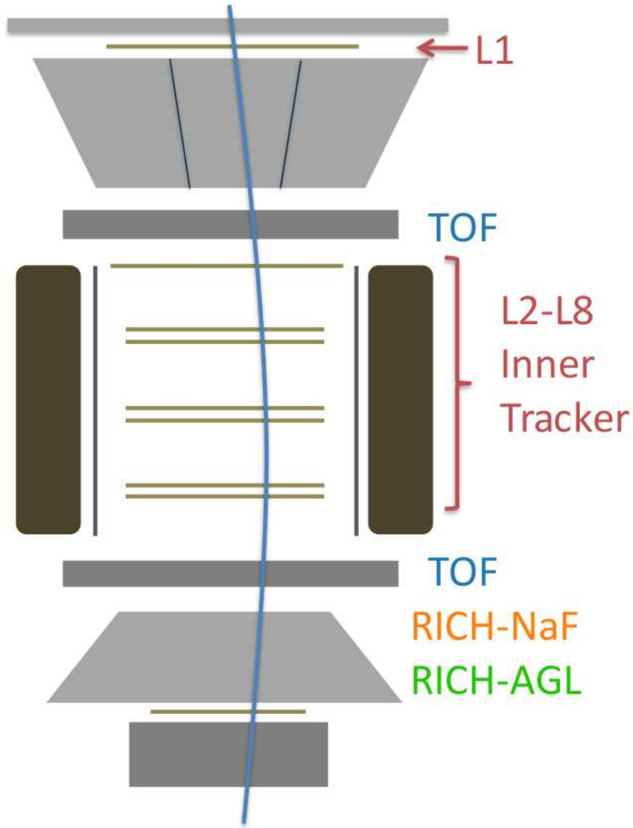
✔ It relies on **rigidity** ($R = \frac{pc}{Ze}$) and **velocity measurements** ($\beta = v/c$)

$$m = \mathbf{R}\,Z\,\sqrt{\frac{1}{\beta^2} - 1}$$

✔ mass separation: what mass resolution is required?

depends on abundance balance but assuming 3σ separation....

Z	elements	$\frac{\sigma_m}{m}$	amount
1	**2H, H**	30%	2/100
2	**4He, 3He**	15%	80/20
3	**7Li, 6Li**	10%	50/50
4	**10Be, 9Be, 7Be**	3%	20/80
5	**11B, 10B**	3%	70/30
6	**14C, 12C**	2%	?/100



✔ **Charge (Z) measurement in many detectors**

tracker L1, UTOF, tracker L2-L8, LTOF, RICH

ensures good charge separation

✔ **Velocity** (β)

TOF, RICH

complementar (overlapping) kinetic ranges

Isotopes identification with AMS02

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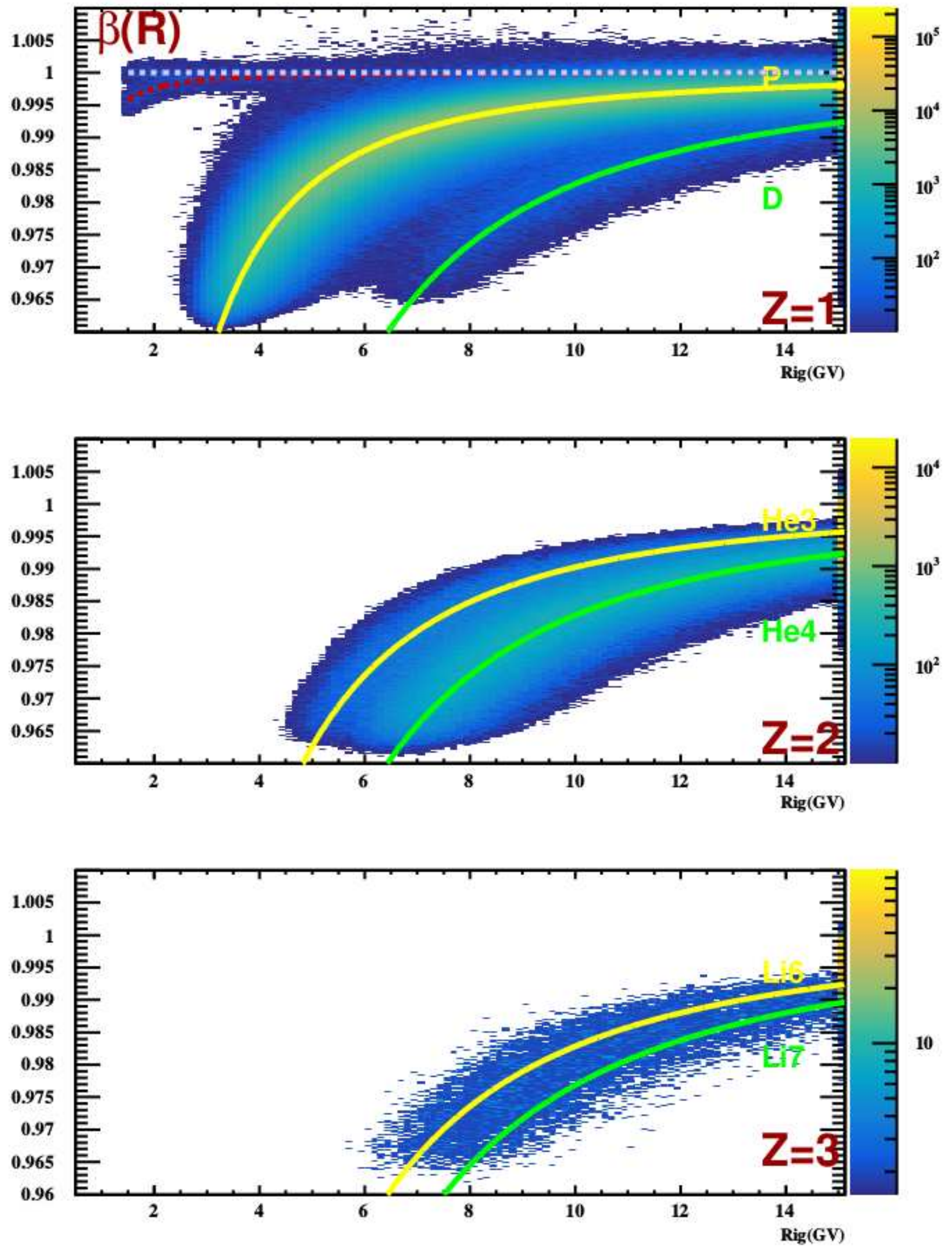
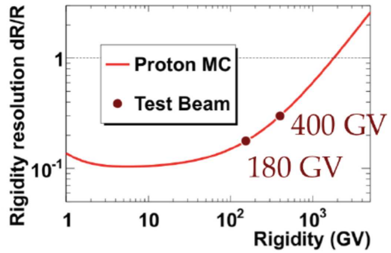


Mass resolution

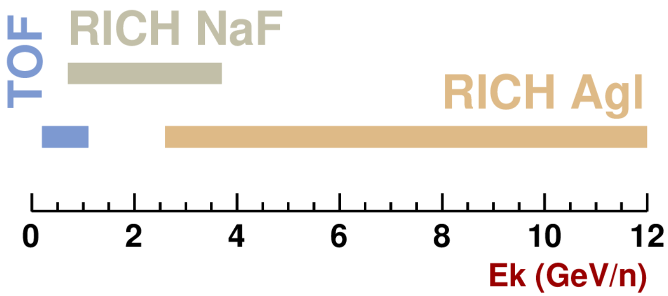
✔ tracker resolution

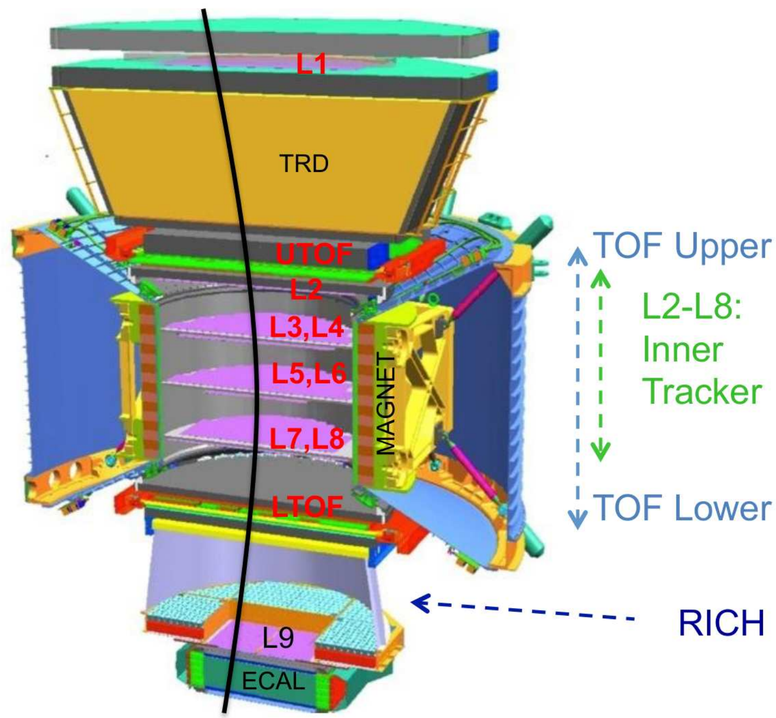
inner Tracker	$\sigma_R/R \sim 10\%$ (R< 20 GV)



✔ different detector regions of β measurement

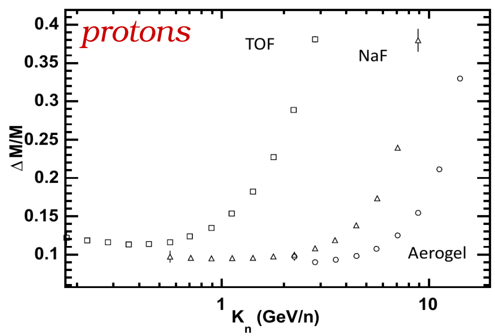
		$(\sigma_\beta/\beta)_{Z=1,2,3}$		
TOF	$E_k < 1.1$ GeV/n	$\sim 4\ \%$	$\sim 2\ \%$	$\sim 1.5\ \%$
RIGH NAF	$0.7 < E_k < 3.7$ GeV/n	$\sim 0.35\ \%$	$\sim 0.25\ \%$	$\sim 0.15\ \%$
RIGH AGL	$2.6 < E_k < 12$ GeV/n	$\sim 0.12\ \%$	$\sim 0.07\ \%$	$\sim 0.05\ \%$

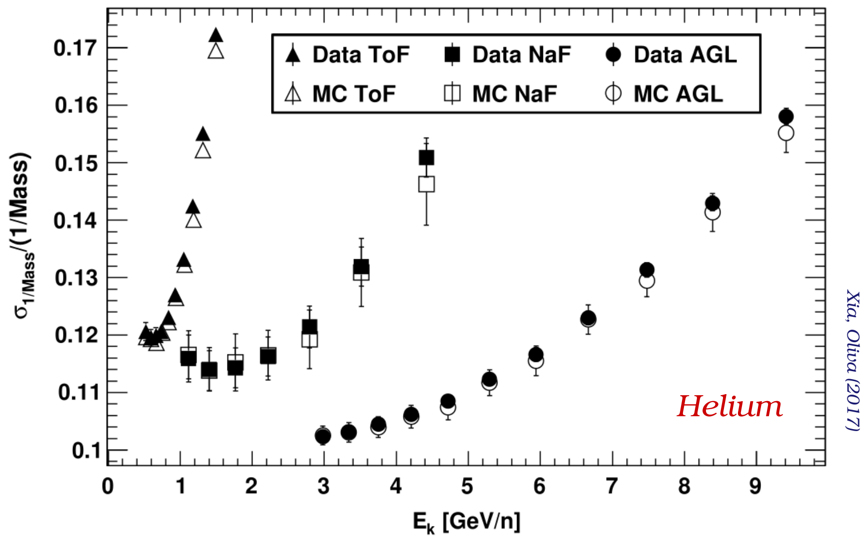




mass resolution

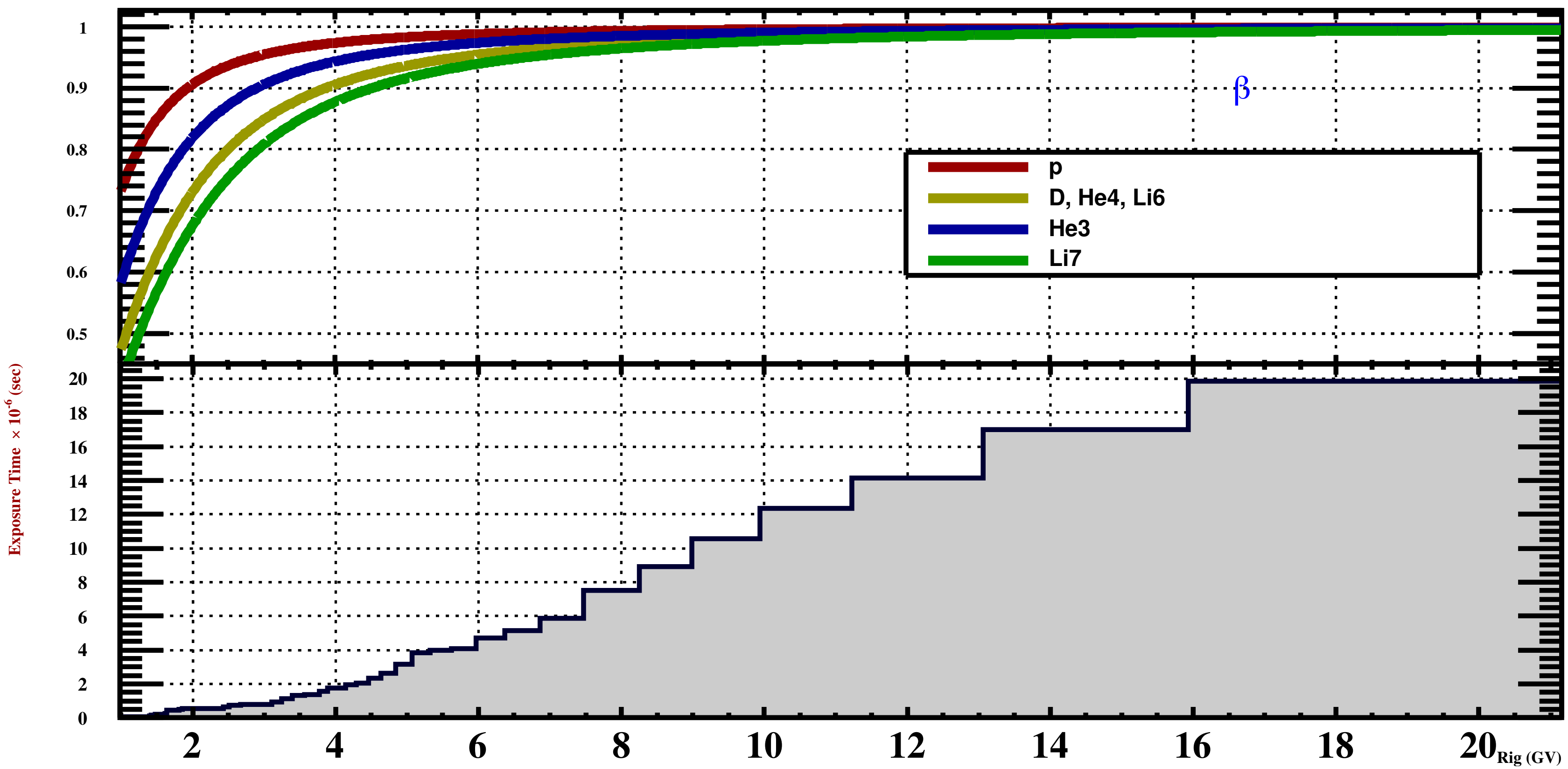
$$\frac{\sigma_m}{m} = \left(\frac{\sigma_R}{R}\right) \oplus \gamma^2 \left(\frac{\sigma_\beta}{\beta}\right)$$





Geomagnetic cutoff impact

- primary particles arrive to AMS with a minimum varying rigidity that depends on its location within the earth magnetic field
- Exposure time of the experiment is dependent on rigidity
- To notice that a rigidity cutoff corresponds to different thresholds on velocity for different isotopes (depends on A/Z)



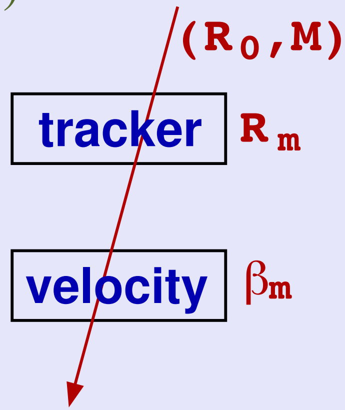
Isotopic separation methods

mass template method

- After applying Z selection: isotopes identification relies on the (β, Rig) measurement

  The number of particles crossing the detector having measured observables R_m, β_m and true rigidity R_0,

$$dN \propto P(R_m)\ P(R_0|R_m)\ P\left[\beta_m|\beta_0\ (R_0, m)\right]$$
$$= \Phi(R_0)\ dR_0\ \ell(R_m; R_0)\ dR_m\ \ell(\beta_m; \beta_0)\ d\beta_m$$



- Data can be sampled in one of the variables and look how is distributed the other one

  ⇒ splitting data in β bins and distribute data in terms of mass $M = f(R_m, \beta_m)$,

$$\frac{dN}{dM} \propto \int_0^{\infty} \Phi(R_0)\ dR_0 \int_{\beta}^{\beta+\Delta\beta} \ell(R_m|R_0, \sigma_{R_0})\ \ell(\beta_m|\beta_0, \sigma_{\beta_0})\ \frac{\gamma\beta}{z}\ d\beta_m$$

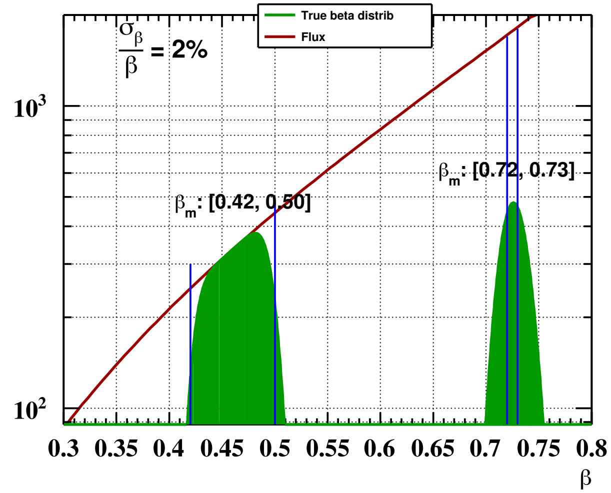
Isotopic separation methods

folded rigidity template

- Choosing a very thin sampling of β (bin $\Delta\beta_m \sim \sigma_\beta/10$)

$$P(\beta_0|\beta_m) = P(\beta_0)\; P(\beta_m|\beta_0)$$

$$\frac{dN}{d\beta_0} \propto \Phi(\beta_0) \int_{\beta_m}^{\beta_m+\delta} \mathcal{L}(\beta_m|\beta_0)\, d\beta_m \;\simeq \Phi(\beta_0)\; \mathcal{L}(\beta_0|\beta_m)$$



F Barao

- the selected events reflect the detector velocity resolution

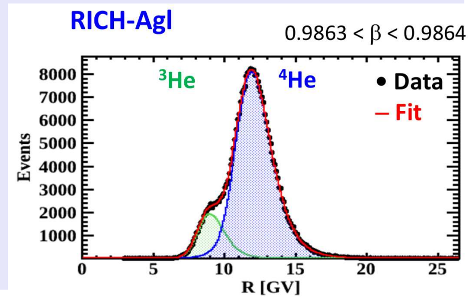
Therefore, their distribution in terms of the true rigidity dN/dR_0 will show clearly separated

$\Rightarrow$ rigidity peaking at: $R_0(\beta_0, m_i)$ (β_0 energy loss corrections needed)

$\Rightarrow$ The rigidity spread reflects the velocity resolution: $\frac{\sigma_{R_0}}{R_0} \simeq \gamma^2 \frac{\sigma_{\beta_0}}{\beta_0}$

- Build a folded rigidity template from true rigidity distributions

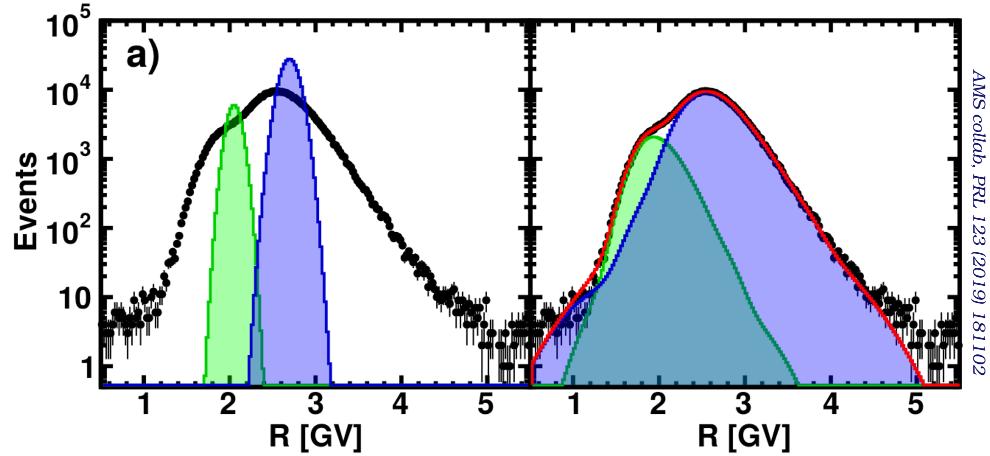
$$P(R_m, \beta_0) = P\left(R_0|\beta_0, \sigma_{\beta_0}\right)\; P\left(R_m|R_0(\beta_0, M)\right)$$



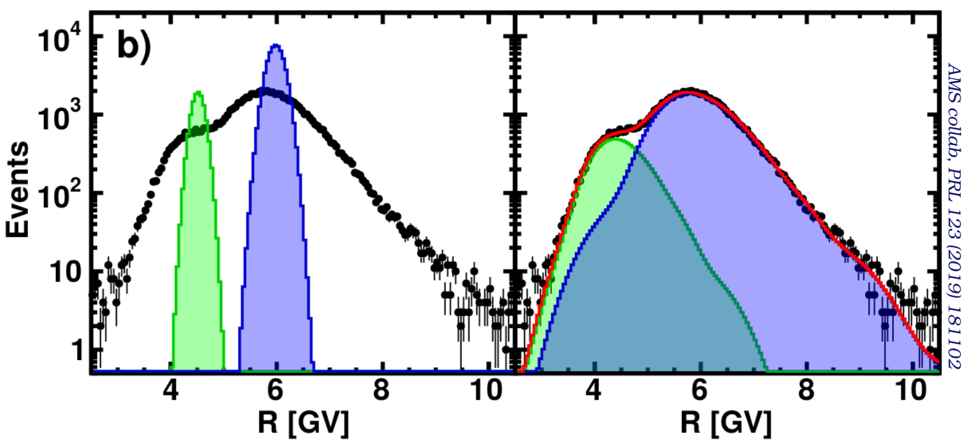
Helium isotopes: rigidity distributions

- **time period**
  May 2011 - Nov 2017 (6.5 years)
- **data sample**
  100 million events He4
  18 million events He3
- **selection**
  $\beta > 0.3$
  $Z = 2$ (Layer 1 crossed)
  same exposure time for both isotopes
- isotope population derived from unfolded rigidity

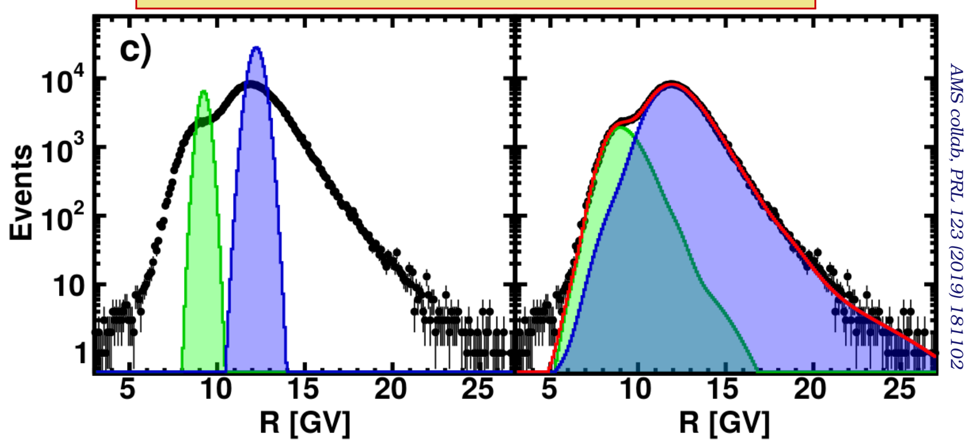
TOF region: $0.8149 < \beta_m < 0.8160$



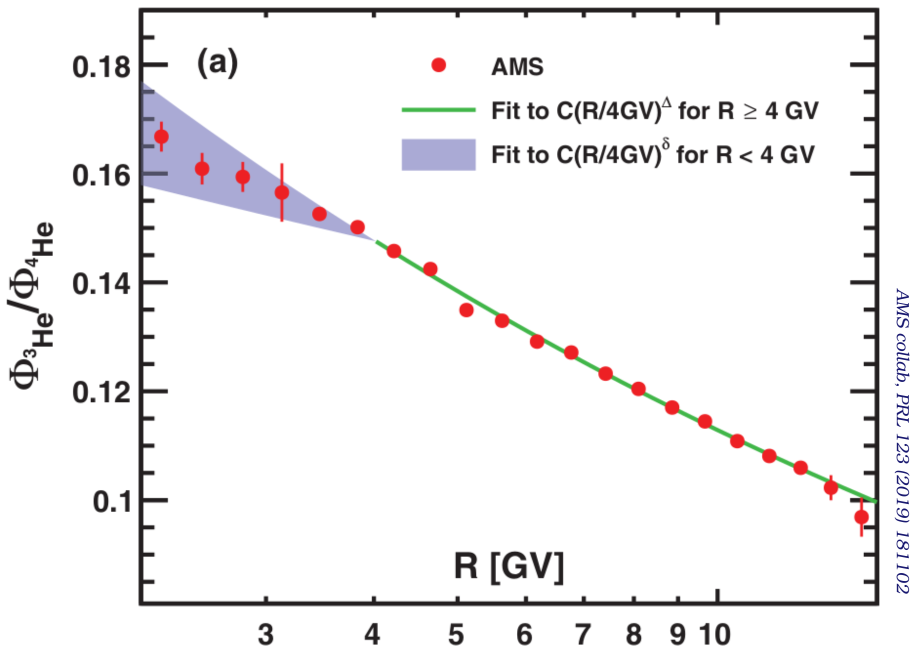
RICH-NaF region: $0.9532 < \beta_m < 0.9537$

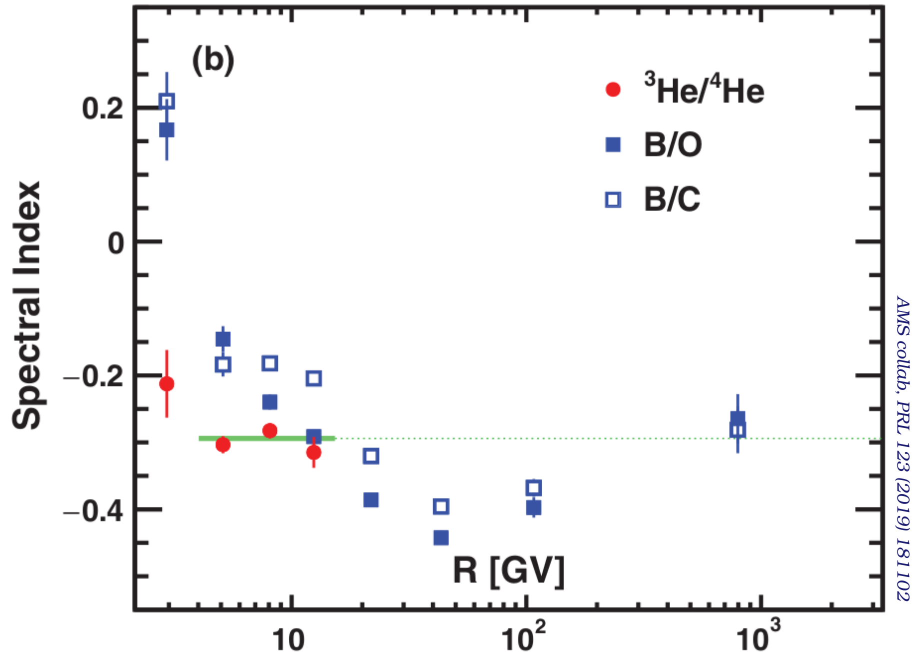


RICH-Agl region: $0.9863 < \beta_m < 0.9864$



Helium isotopes: flux ratio



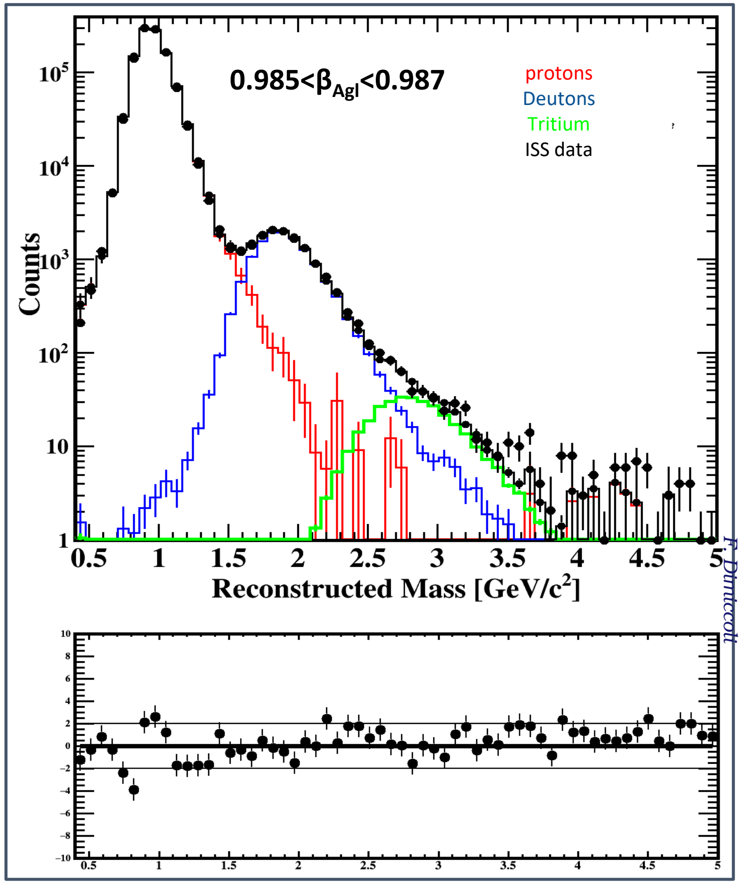


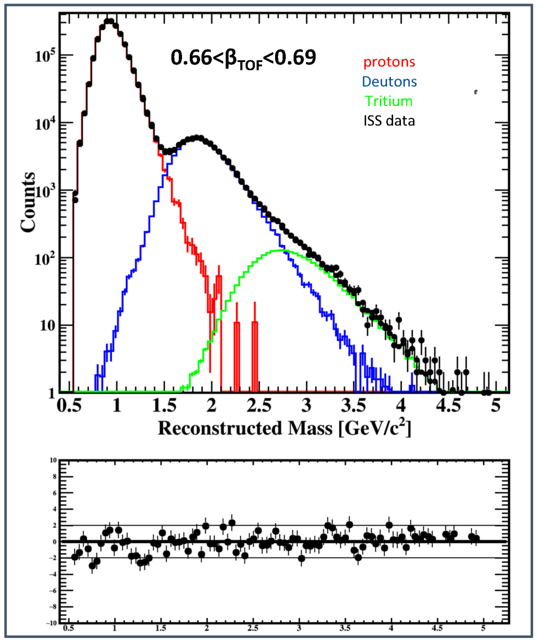
- ✔ Above rigidities of 4 GV, $He3/He4$ flux ratio shows no dependency with time and is well described by power law,
  $\Phi \propto \left(\frac{R}{4\ GV}\right)^{\alpha}$
- ✔ ratio spectral index (α) shows no dependence with rigidity above 4 GV
  $\alpha = -0.29$
  comparison with other sec/primaries measurements: B/C, B/O

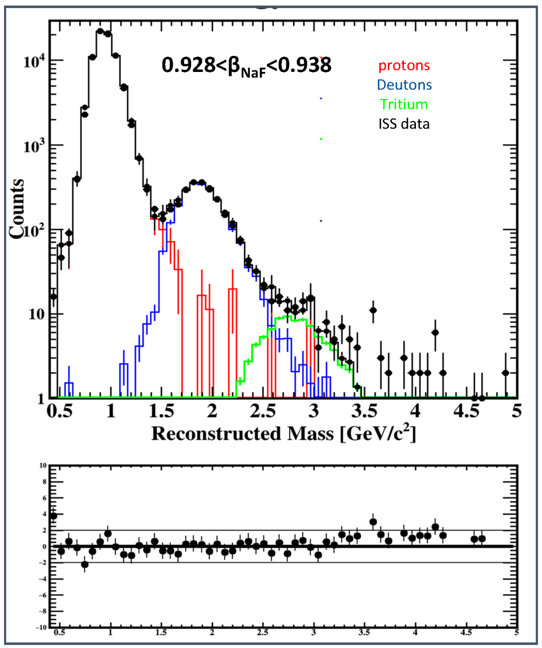
Deuterons

- ✔ deuterons are secondaries essentially created by helium fragmentation
- ✔ although a large mass gap to protons (compared to heavier isotopes), its very low abundance rends difficult its separation from protons

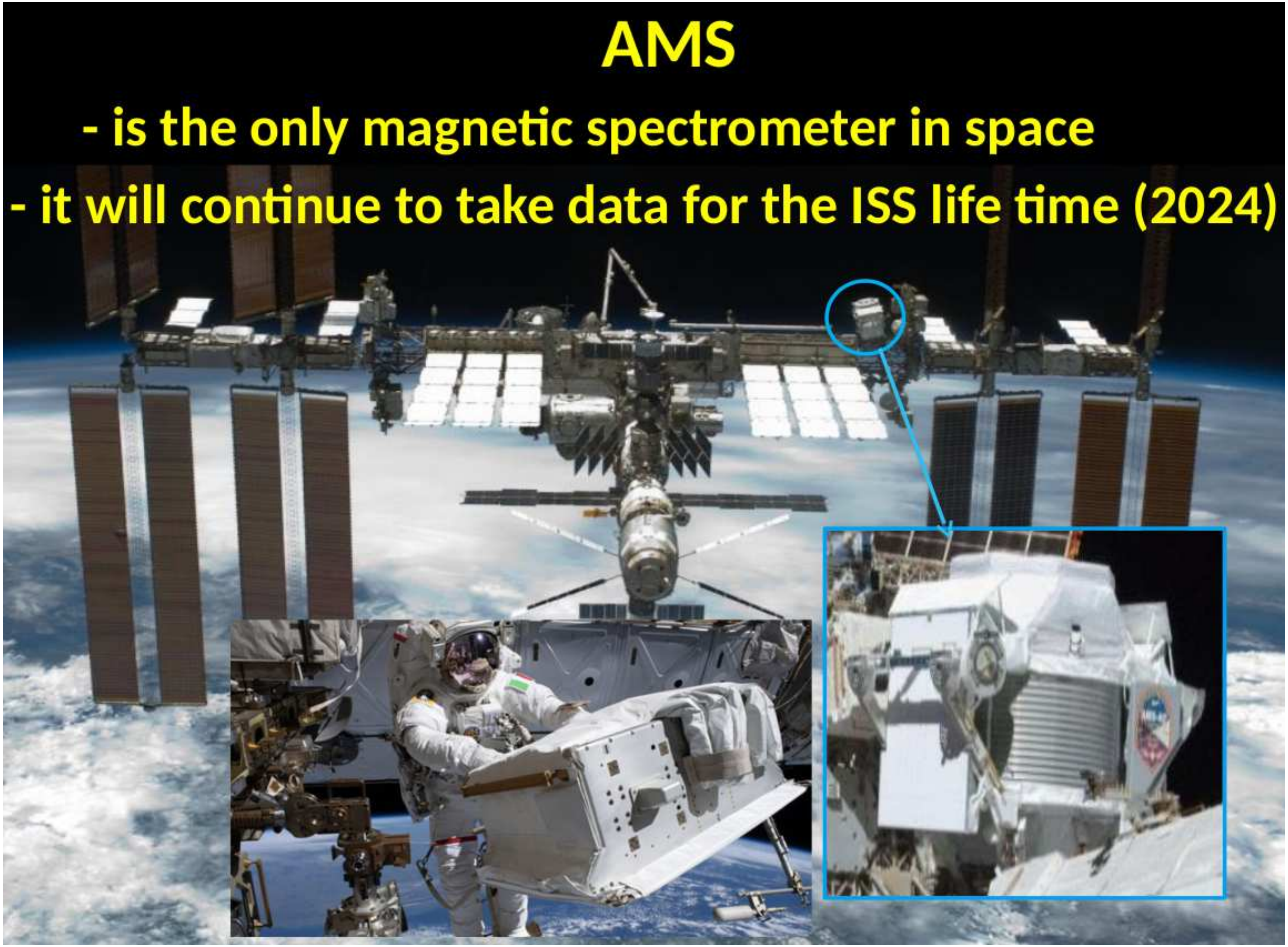
  mass templates have to include tail effects







Conclusions

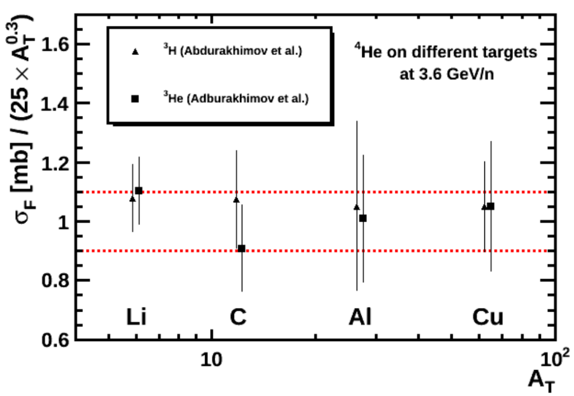


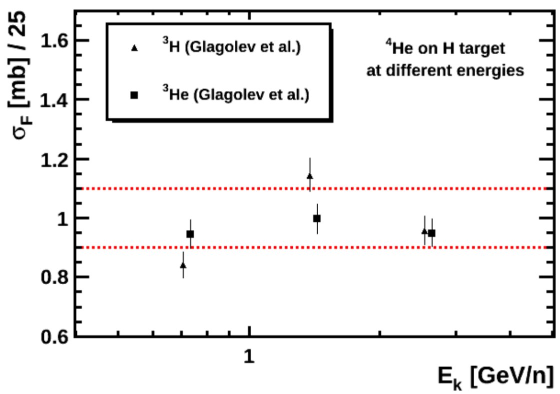

Backup slides
AMS-02
Fernando Barao
LIP/IST
LIP jornadas (Braga) Feb 2020

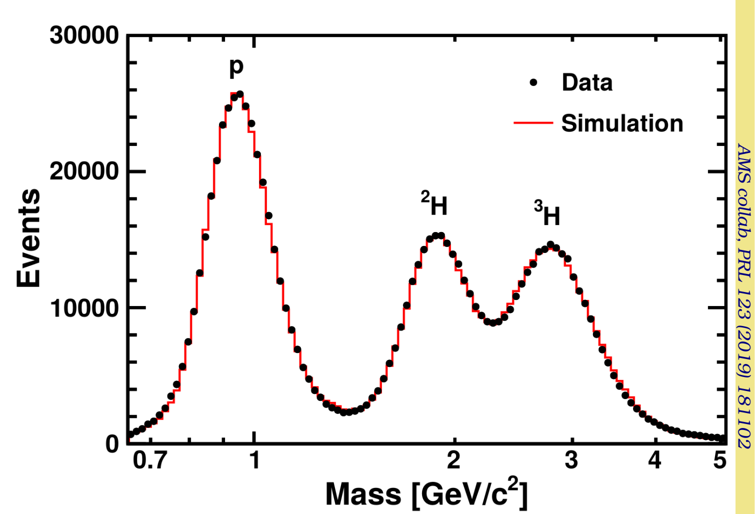
Helium: detector induced background

- ✔ **Z** selection based on independent detector measurements imply that helium sample contains negligible background from higher Z particles ($Z > 2, < 10^{-3}$)
- ✔ **He4** fragments in the detector (mostly carbon and aluminum) into **He3, H3, H2, H**
  He3 contamination can be estimated using the Tritium produced which is purely background, as their production cross-section is very similar
- ✔ To estimate the amount of **He3** detector induced in AMS, we charge select helium (Z=2) at the entrance of the detector (Tracker layer 1) and singly charged particles (Z=1) in the inner Tracker (layers 2 to 8)
  Mass distribution of events interacting between both charge measurements (Tracker layer 1 and inner Tracker)
  He3 contamination estimated as less than 10% for full analysis rigidity range

Helium fragmented events with velocity $0.9721 < \beta < 0.9954$ measured by the RICH detector (AgI radiator)

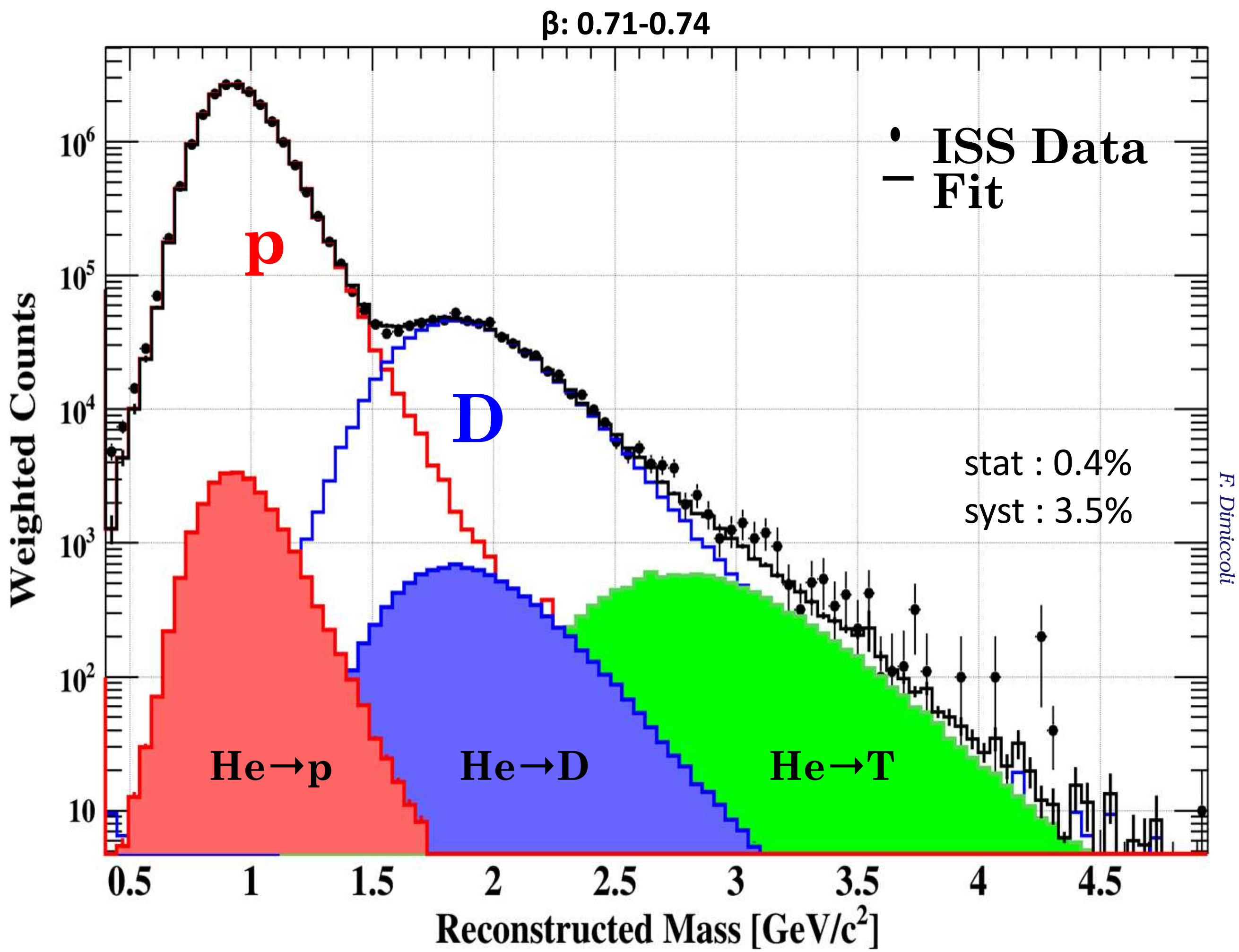




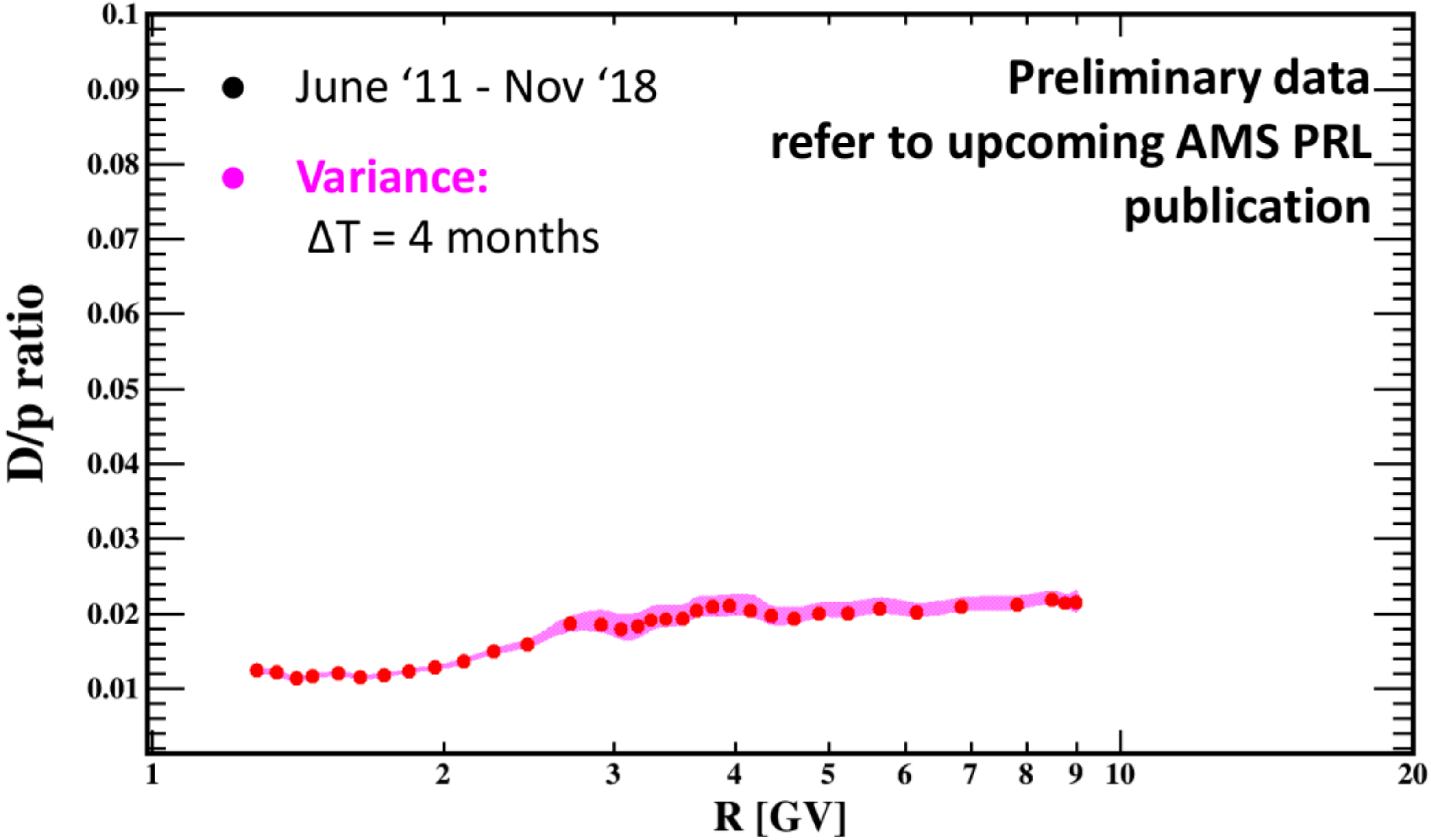


Deuterons: background

- Contributions to protons and deuterons abundances from helium fragmentation in the detector have to be evaluated and subtracted



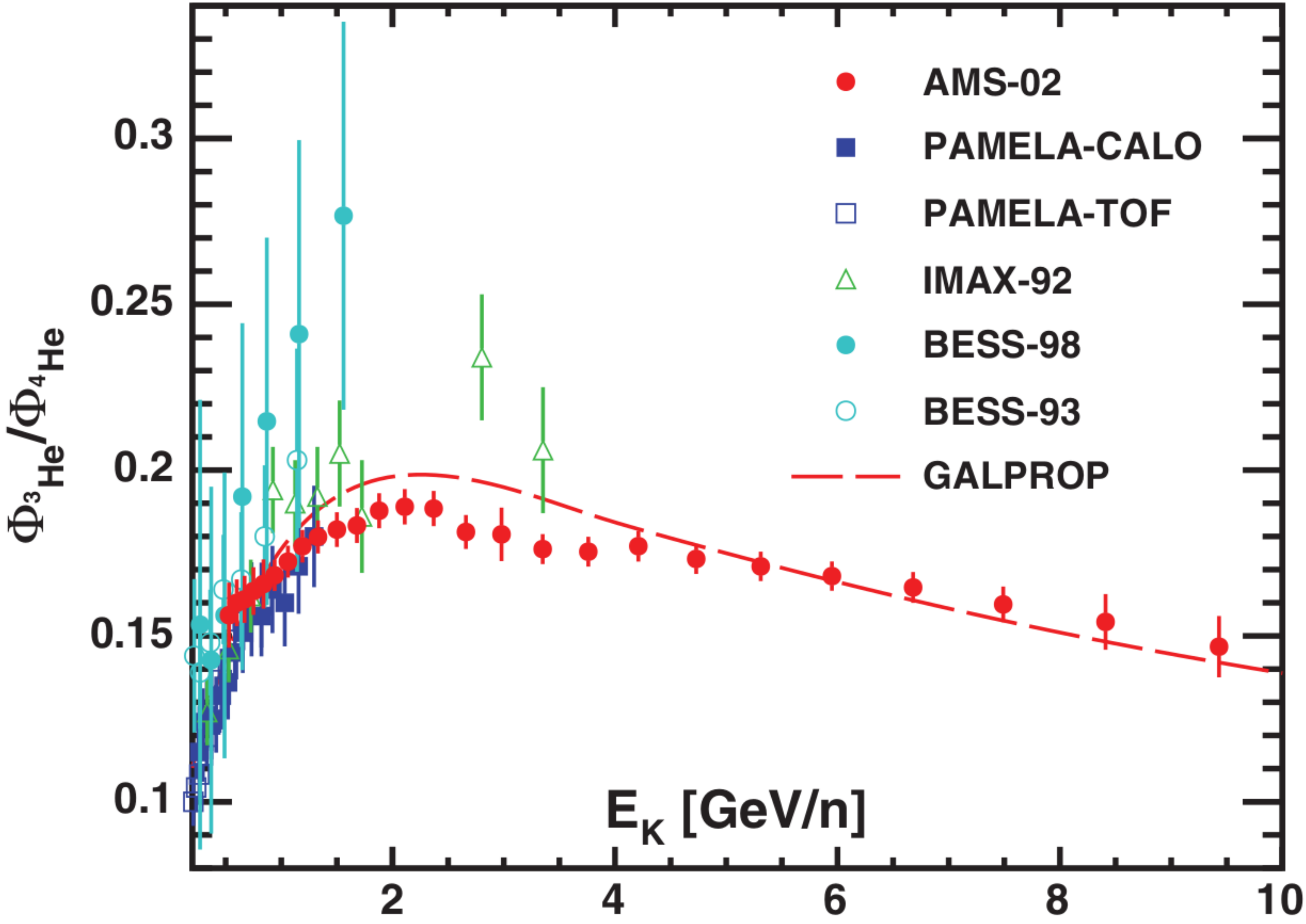
deuteron/proton



d/p ratio in terms of rigidity

- ◻ tends to stabilize above 3 GV
- ◻ do not show time variability

Helium isotopes: flux ratio



AMS collab, PRL 123 (2019) 181102