Status and prospect for AMS-02

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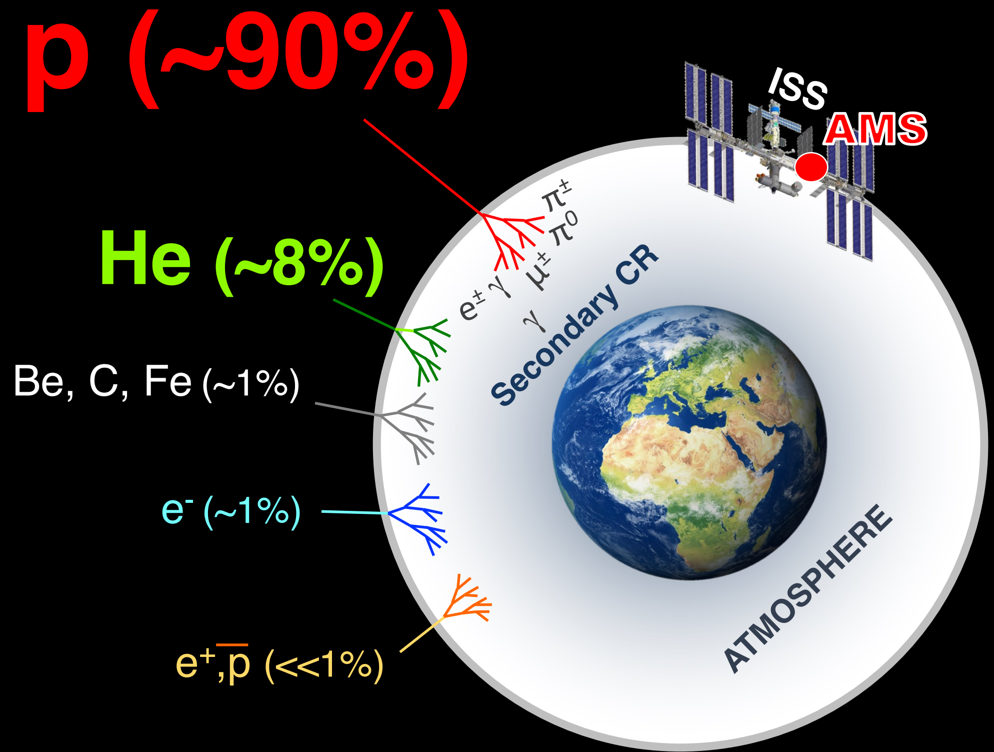
Interplay between Particle and Astroparticle Physics 2022

Technische Universität (TU) Wien,
September 05-09

AMS is observing charged comsic rays in the $\mathcal{O}$(GeV)-$\mathcal{O}$(TeV) energy range



AMS has collected

208,592,047,799

cosmic ray events

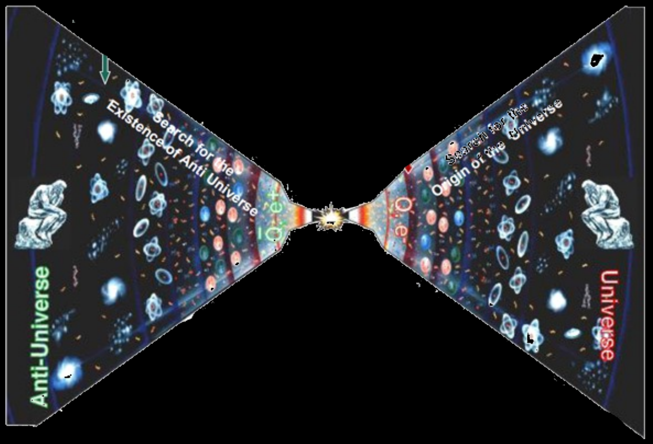
Last update: September 5, 2022, 8:35 AM

AMS-02: OBJECTIVES

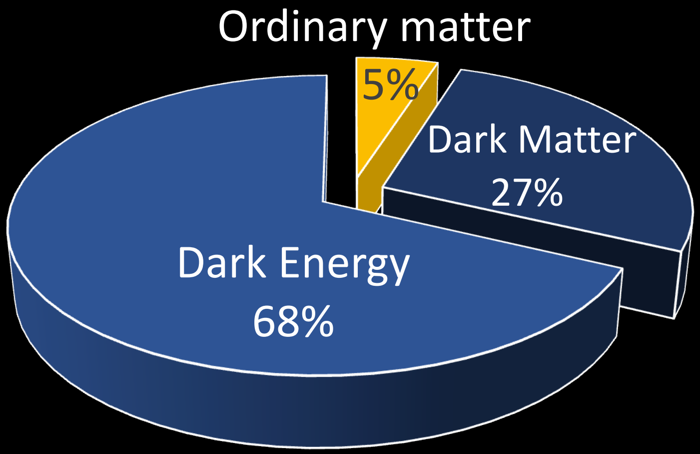
- Primordial antimatter search (anti-nuclei) with sensitivity of 10^{-9}

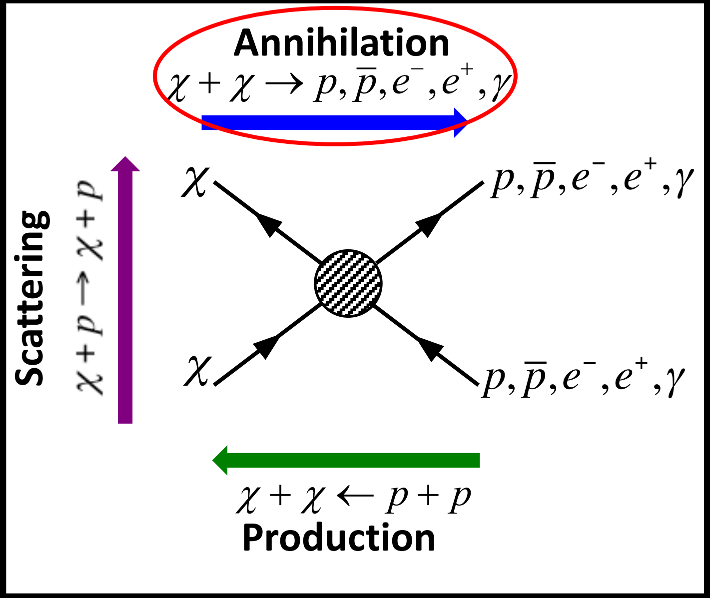
Dirac's Nobel Speech

"We must regard it rather as an accident that the Earth [...] contains a preponderance of negative electrons and positive protons. It is quite possible that for some stars it is the other way about."



- Indirect Dark Matter search (e^{+}, p, …)





- Improving the knowledge about CR source, acceleration and propagation in the Interstellar Medium

AMS-02: OBJECTIVES

PROTONS AND NUCLEI FLUXES

Protons → Chance of selecting a proton randomly: ~90%.

nuclei → "easily" selected by charge value

RARE COMPONENTS OF CRs (e^-, e^+, $\bar{p}$, …)

- 1 electron every 10^2-10^3 protons
- 1 positron every 10^3-10^4 protons
- 1 anti-proton every 10^4 protons

Major challenge: a correct measurement of the charge.

What is needed?

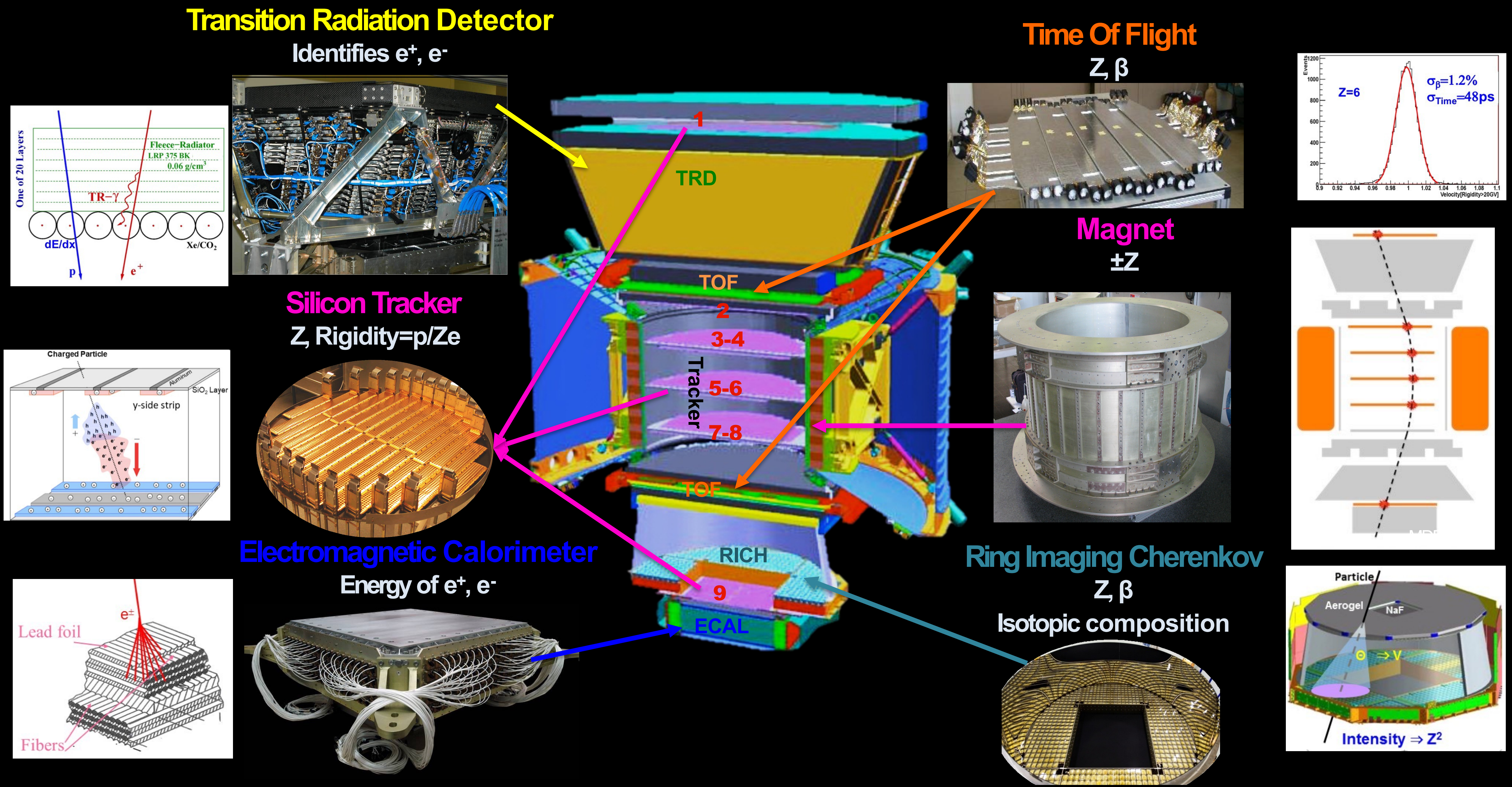
→ **Particle identification and E measurement up to TeV:**

- ▹ e/p separation at the 10^4 level by means of independent detectors
- ▹ Z: redundant measurements to evaluate fragmentation along the detector
- ▹ Charge sign: matter to anti-matter separation (magnetic field!)

→ **Statistics**

- ▹ Acceptance & efficiency: **size**
- ▹ Exposure time: **space**

AMS-02: A TeV precision magnetic spectrometer in space



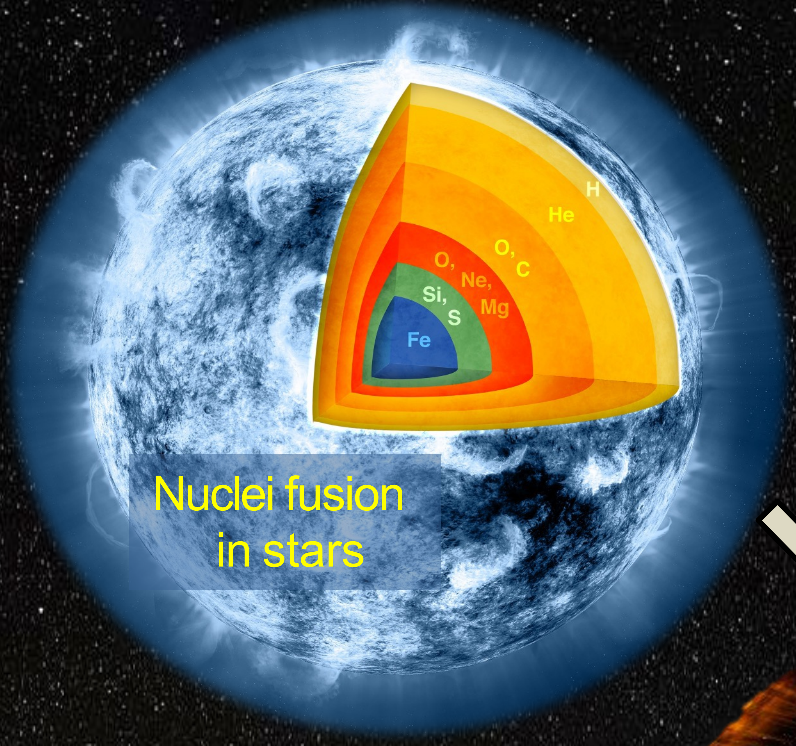
Results

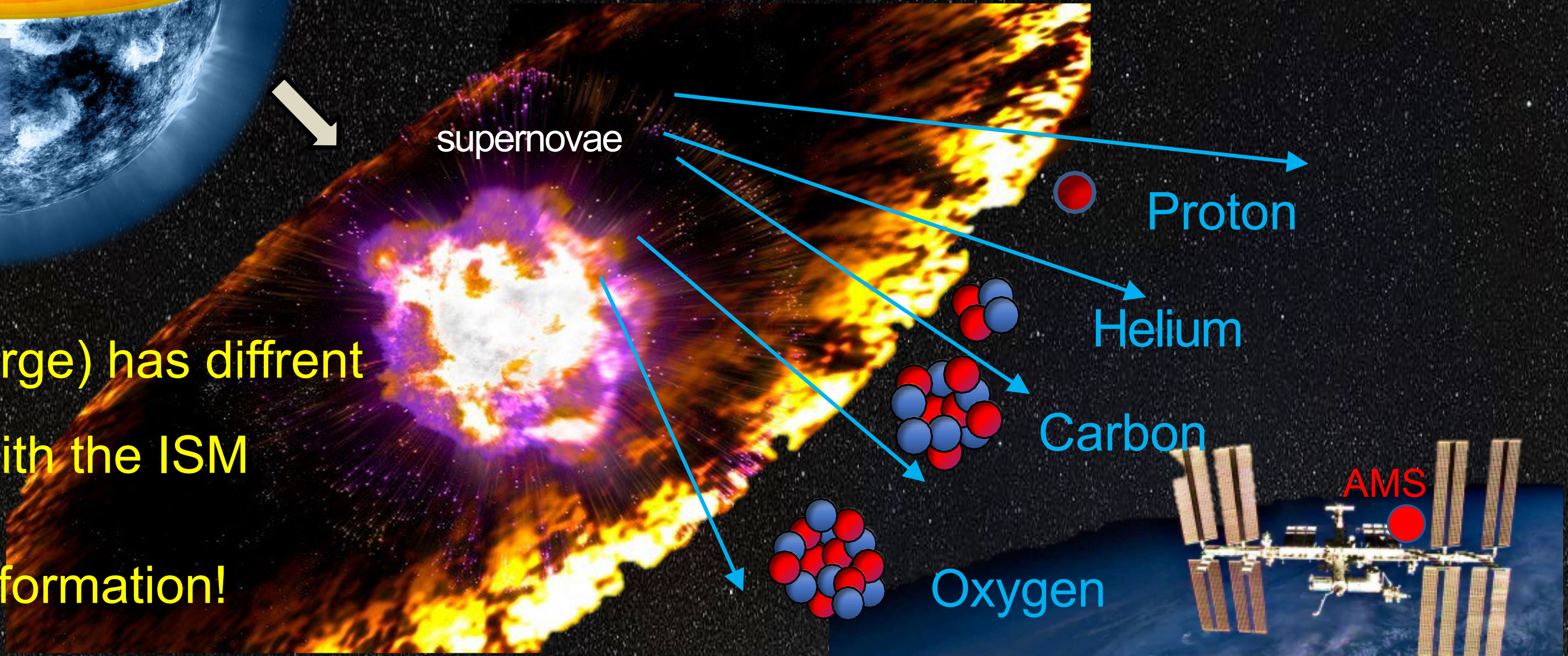
Alpha Magnetic Spectrometer
AMS-02
Europe • Asia
North America

PRIMARY COSMIC RAYS NUCLEI → Directly from their sources

Information about

- CR's **sources**
- CR's **acceleration** mechanism
- **Interstellar medium (ISM)**

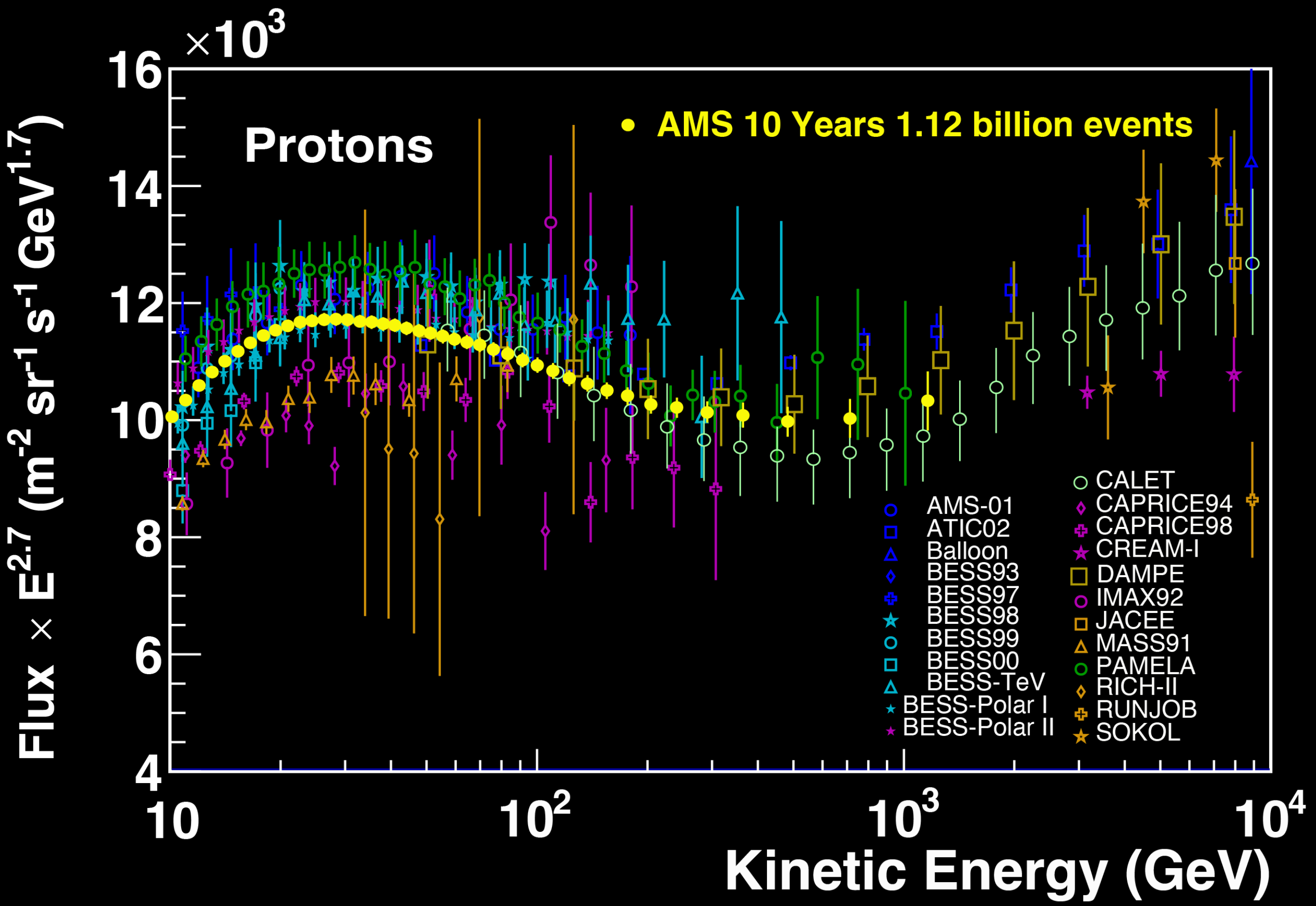


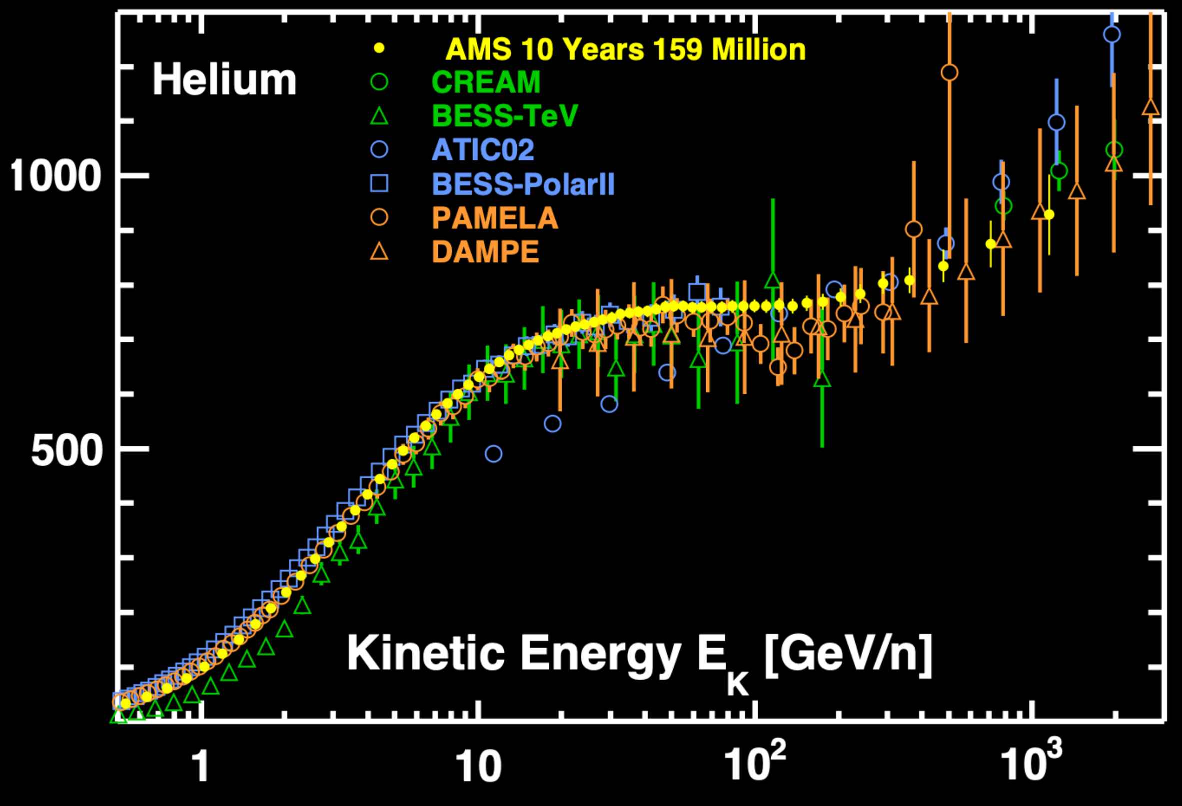


Each nuclei (i.e. charge) has diffrent cross section with the ISM

→ Different information!

PROTON AND HELIUM FLUXES





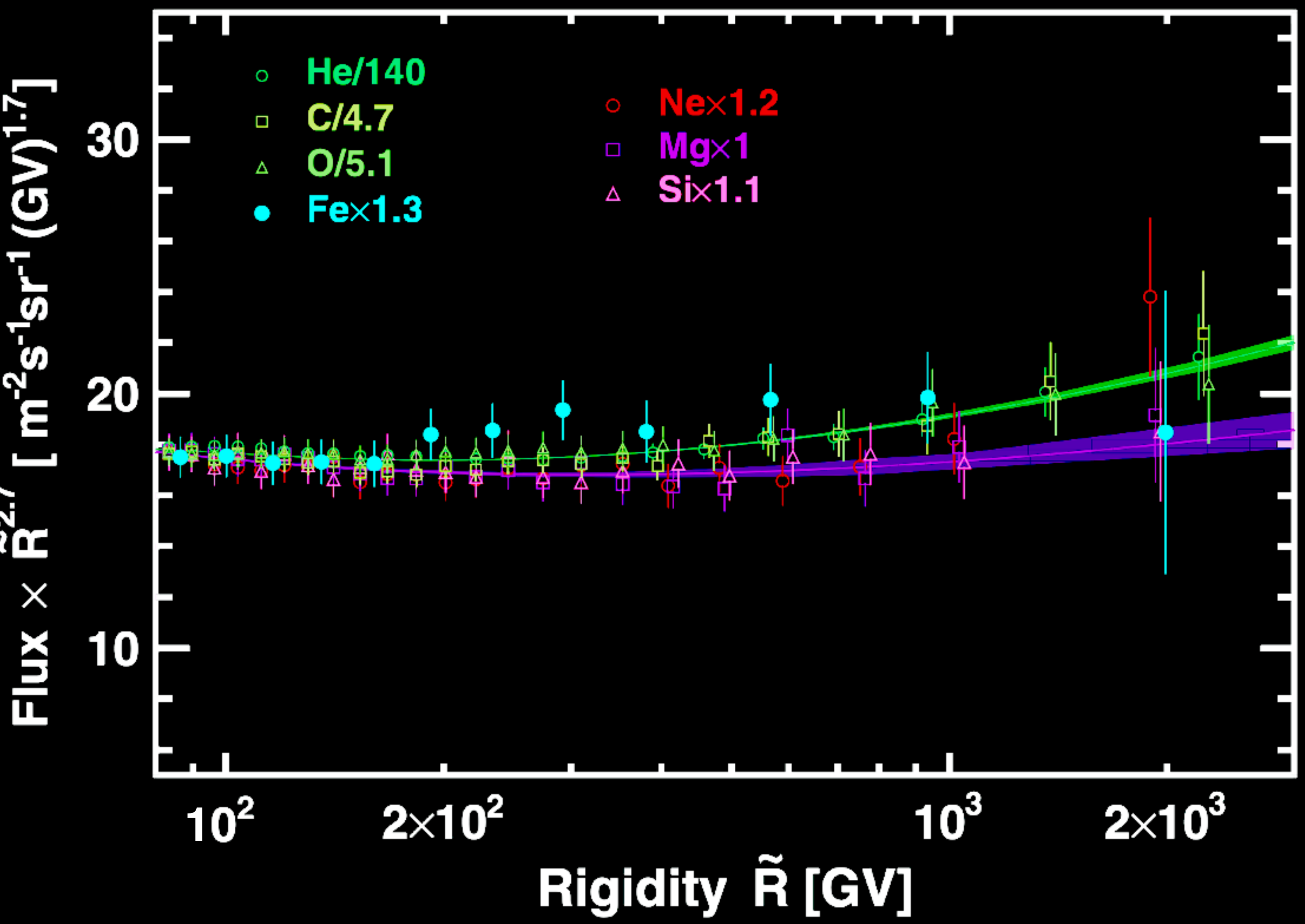
AMS provides the most accurate He measurement in the energy range 1 GeV to 1.6 TeV

Traditional Understanding of CR flux: Single power law $\Phi \sim R^{-\gamma}$

→ Both p and He fluxes show **a clear break** in the power law around ~ 300 GeV

He, C, O, Ne, Mg, Fe & Si FLUXES

All nuclei fluxes cannot be decrbed by a single power law



Ne, Mg, Si

≠ He, C, O, Fe

Ne, Mg, Si

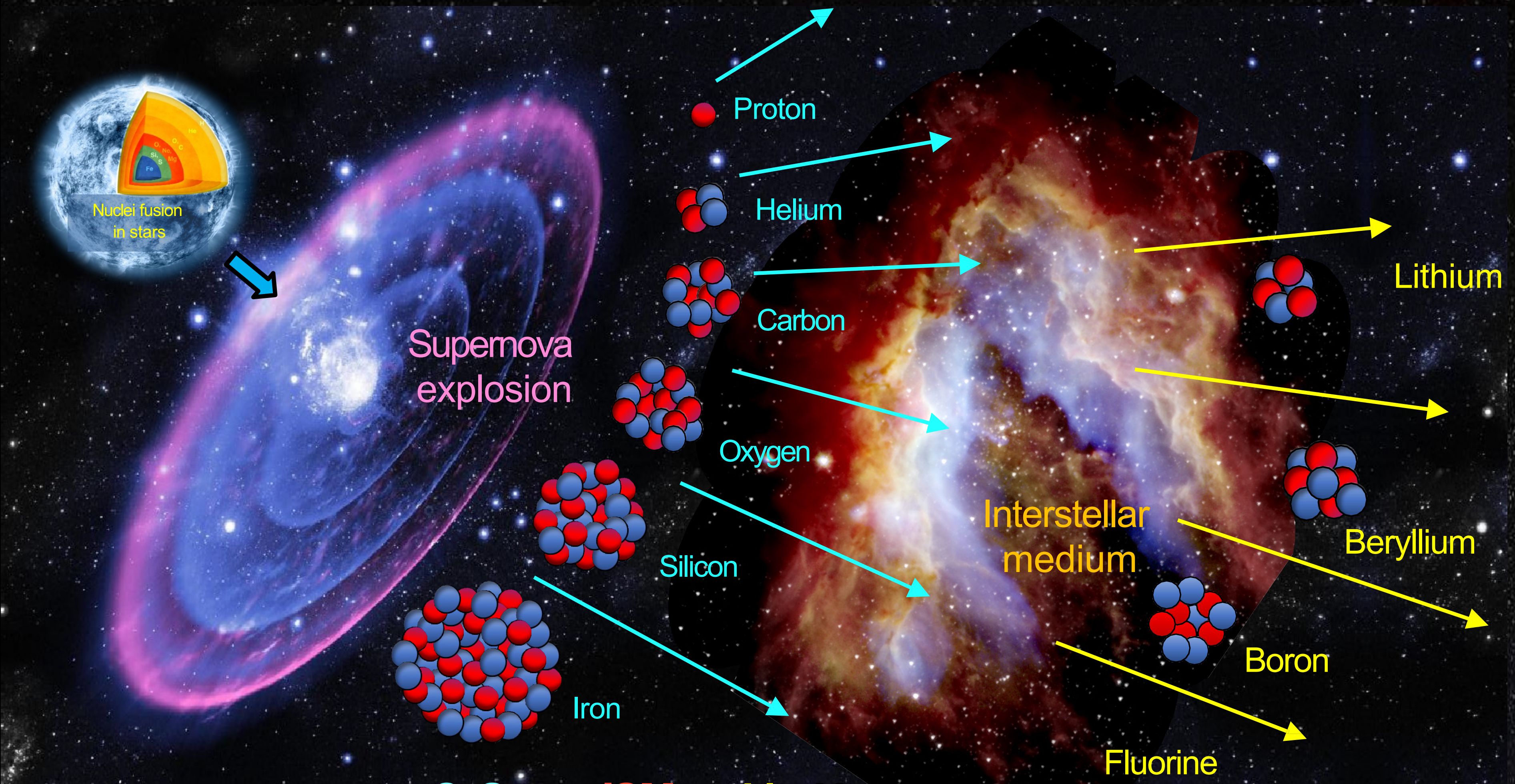
He, C, O, Fe

2 different classes of primary RC, caracterized by a different rigidity dependency

With AMS-02 is the first time that we observe this behaviour

Unexpectedly, Iron is in the He, C, O primary cosmic ray group

SECONDARY COSMIC RAYS NUCLEI → Produced by the collision of primary



provides information on Cosmic Ray interactions and propagation.

Tuning of the diffusion term in the CR propagation equation

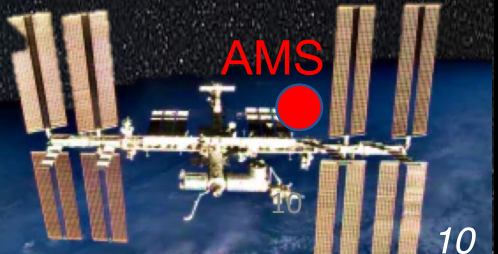
C, O, …+ ISM → Li + X

C, O, …+ ISM → Be

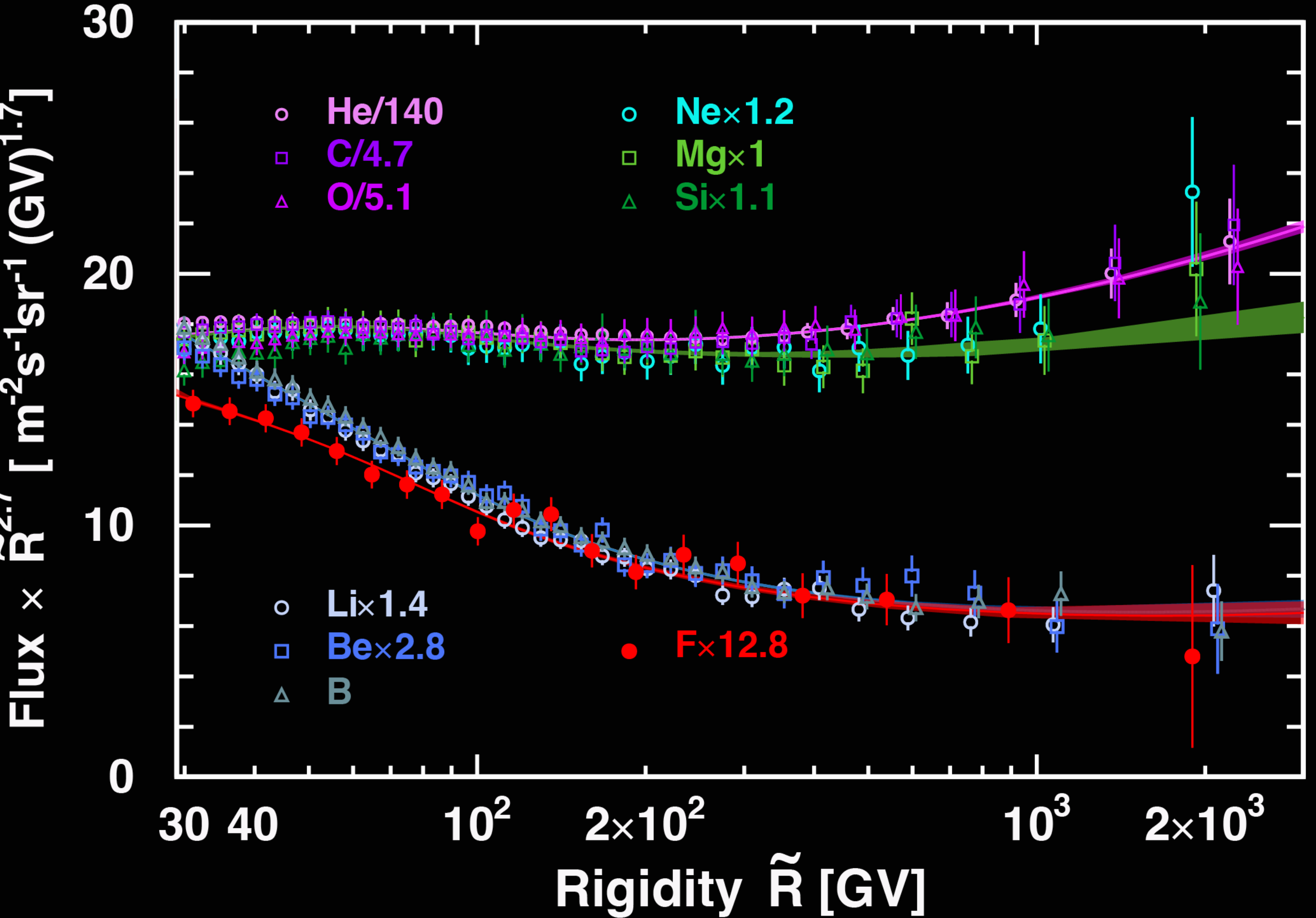
C, O, …+ ISM → B

Ne, Mg, Si, …+ ISM → F + X

Fe, …+ ISM → Sc, …,Mn



SECONDARY COSMIC RAYS LI, BE, B & F FLUXES

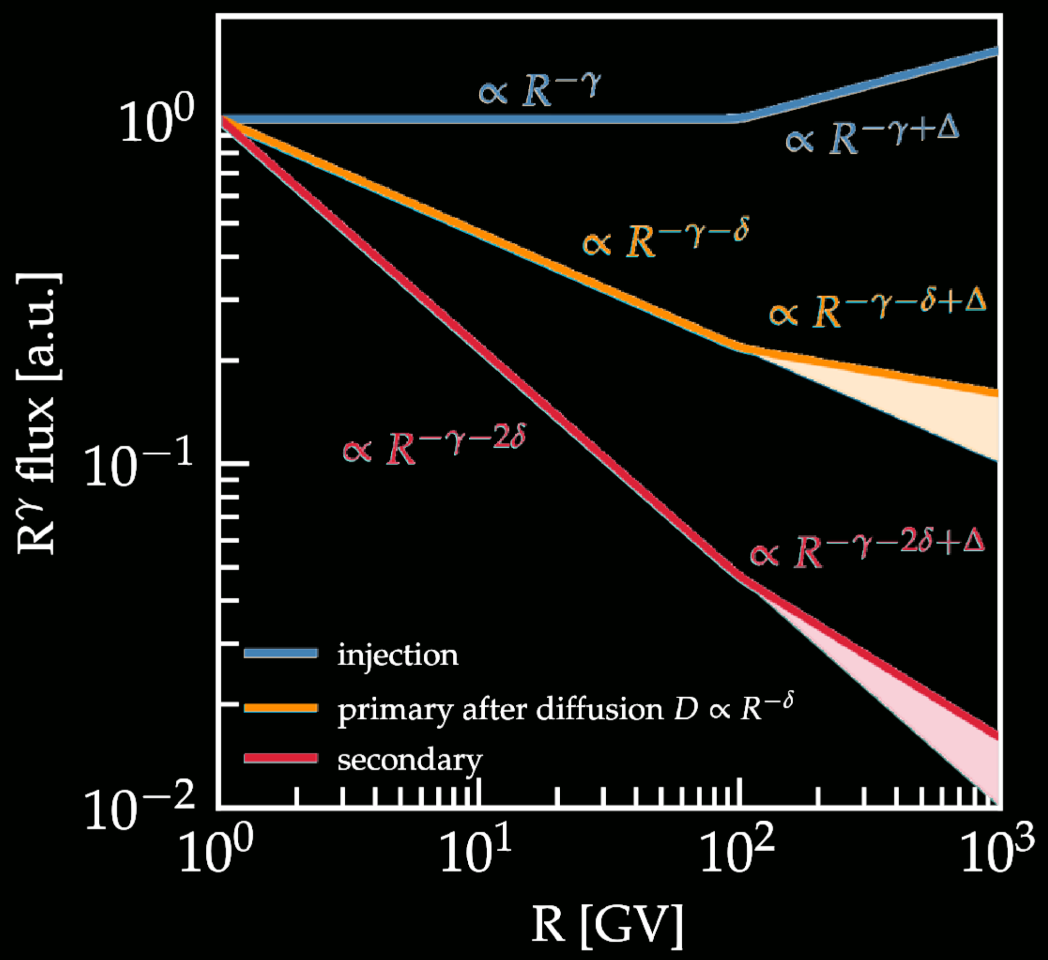


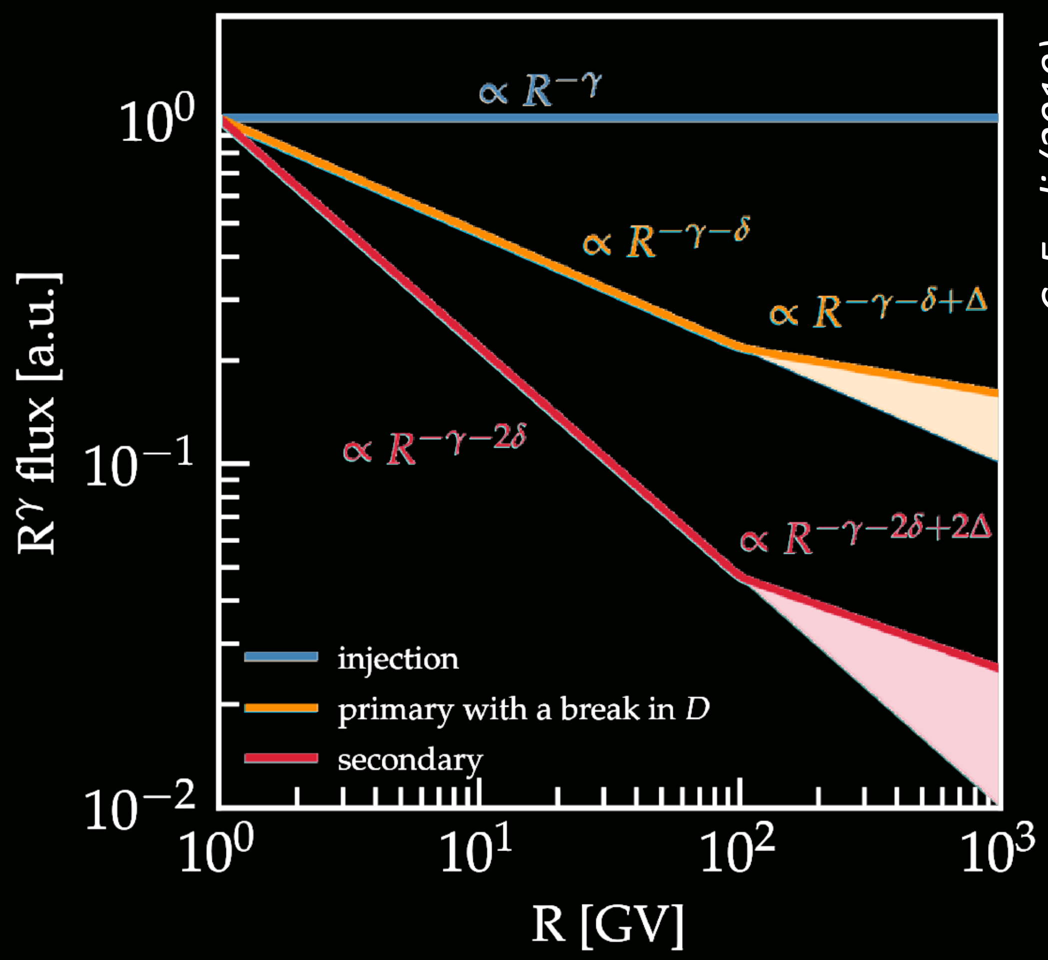
The secondary fluxes a exhibit a spectral hardening at 200 GV as do the primary cosmic rays

Secondary and primary Cosmic rays have distinctly different spectral shapes

Secondary Cosmic Rays also have two classes above 30 GV

SECONDARY NUCLEI AND THE SPECTRAL HARDENING ORIGIN





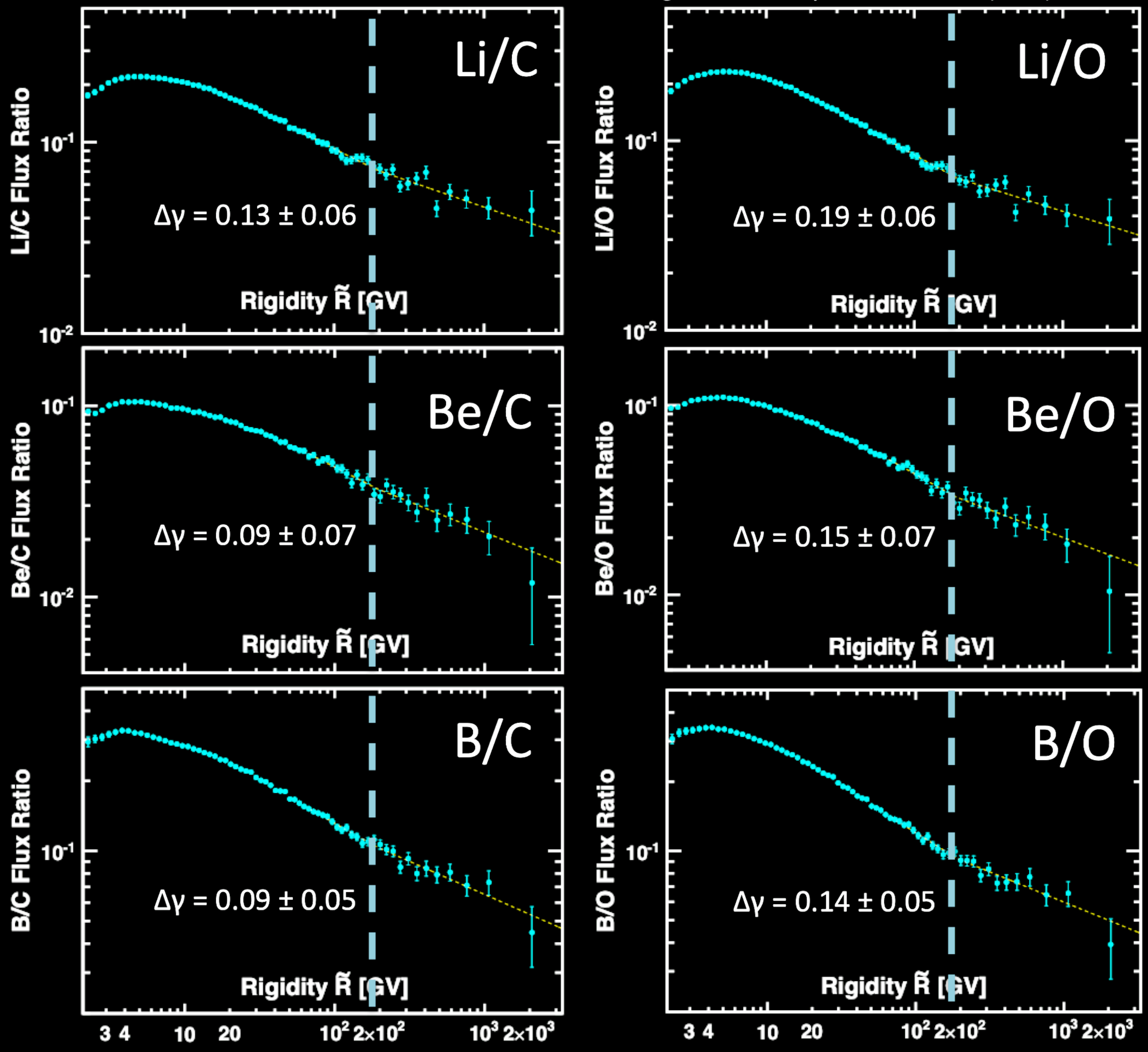
C. Evoli (2019)

If the hardening in CRs is related to the **injected spectra** at their source, then **similar hardening** is expected both for secondaries and primary cosmic rays.

If the hardening is related to **propagation properties** in the Galaxy then a **stronger hardening** is expected for the secondary with respect to the primary CRs.

SECONDARY TO PRIMARY RATIO

M. Aguilar et al., Phys. Rev. Lett. **120** (2018) 021101



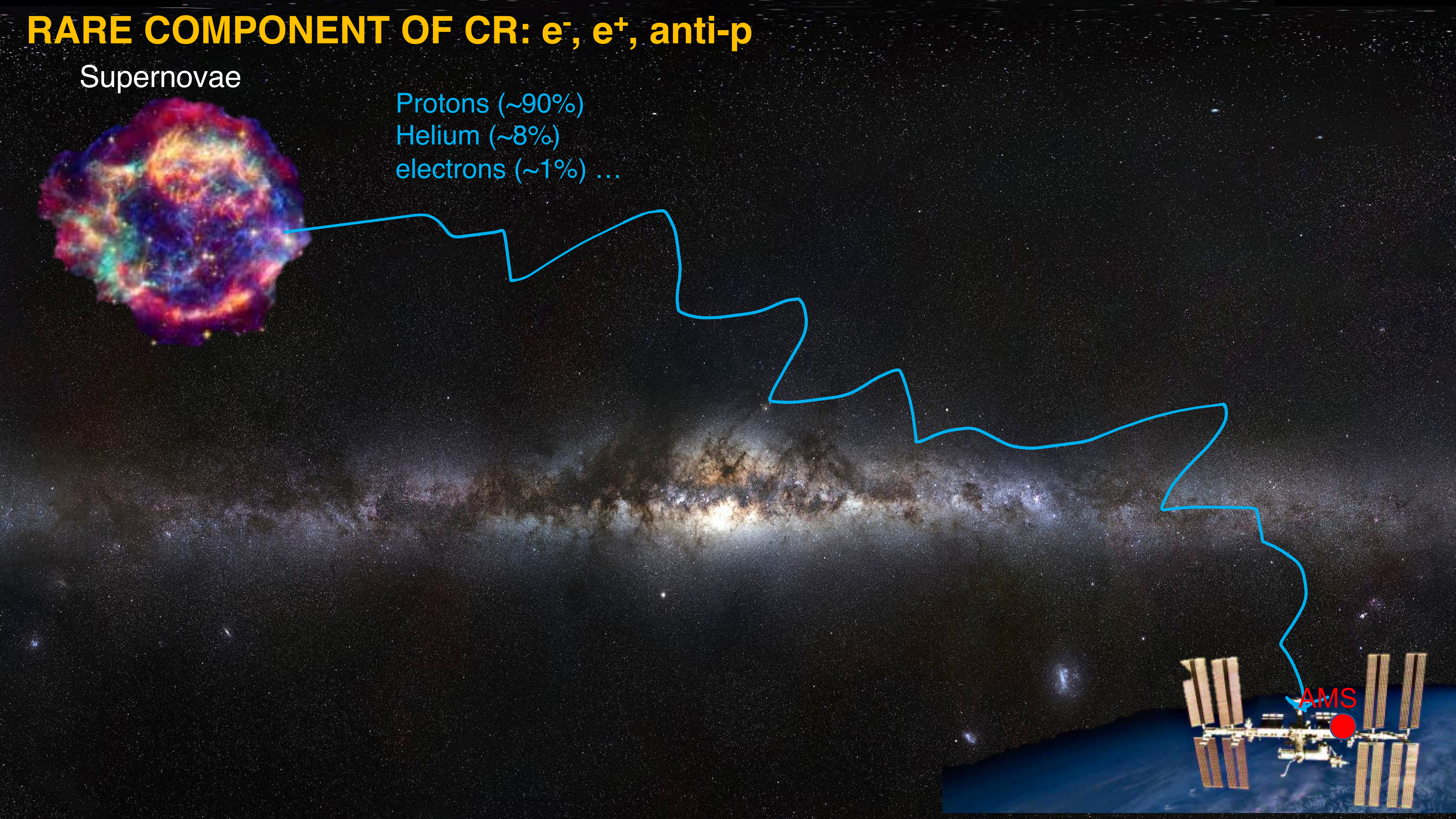
Which is the origin of the spectral index change ~200 GV?

Above 192 GV all six secondary-to-primary flux ratios harden.

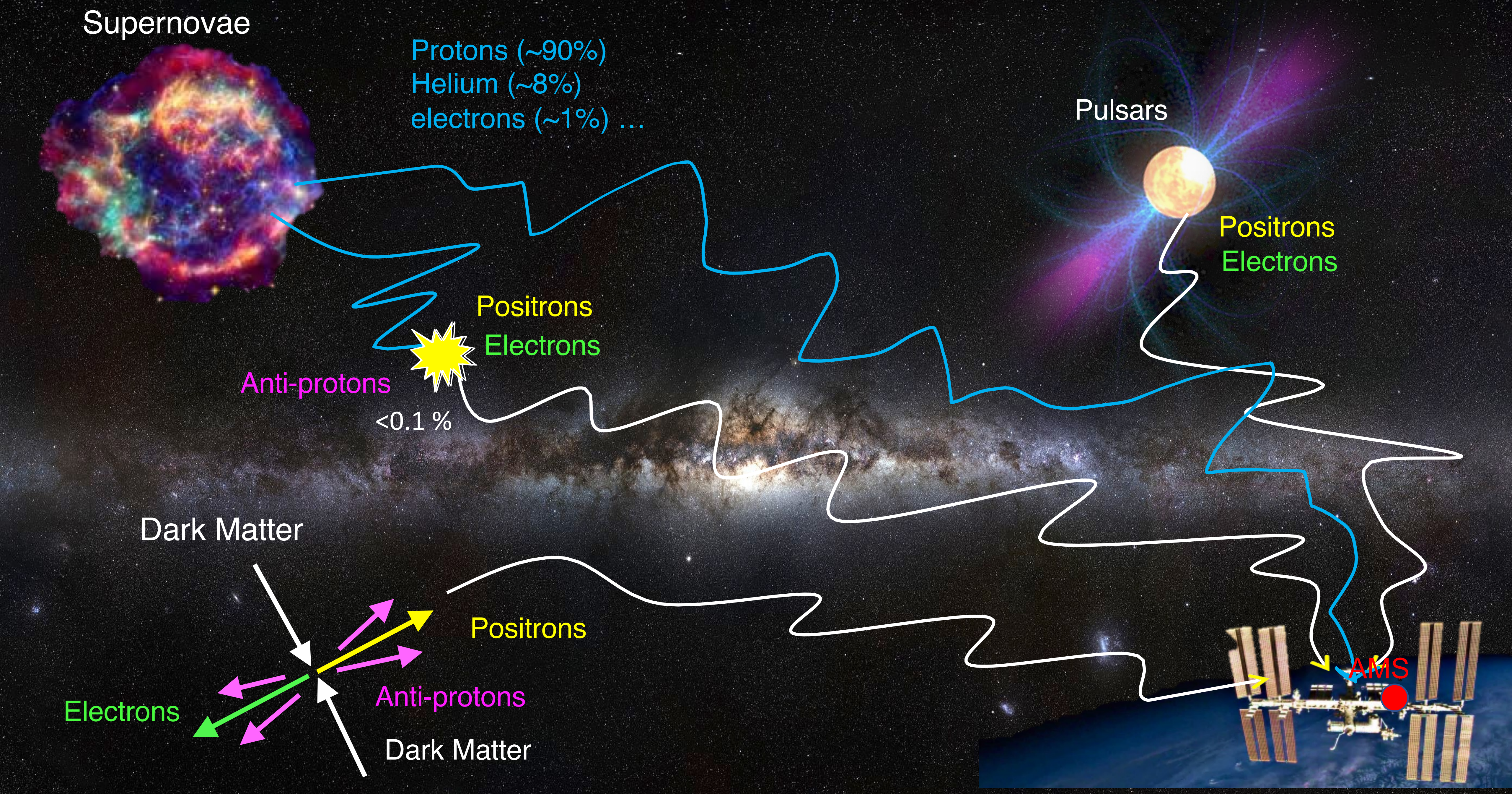
Average **hardening** of 0.145 ± 0.022 is observed, with a significance: $\mathbf{6.5\sigma}$

Secondary hardening is stronger respect to the primary one

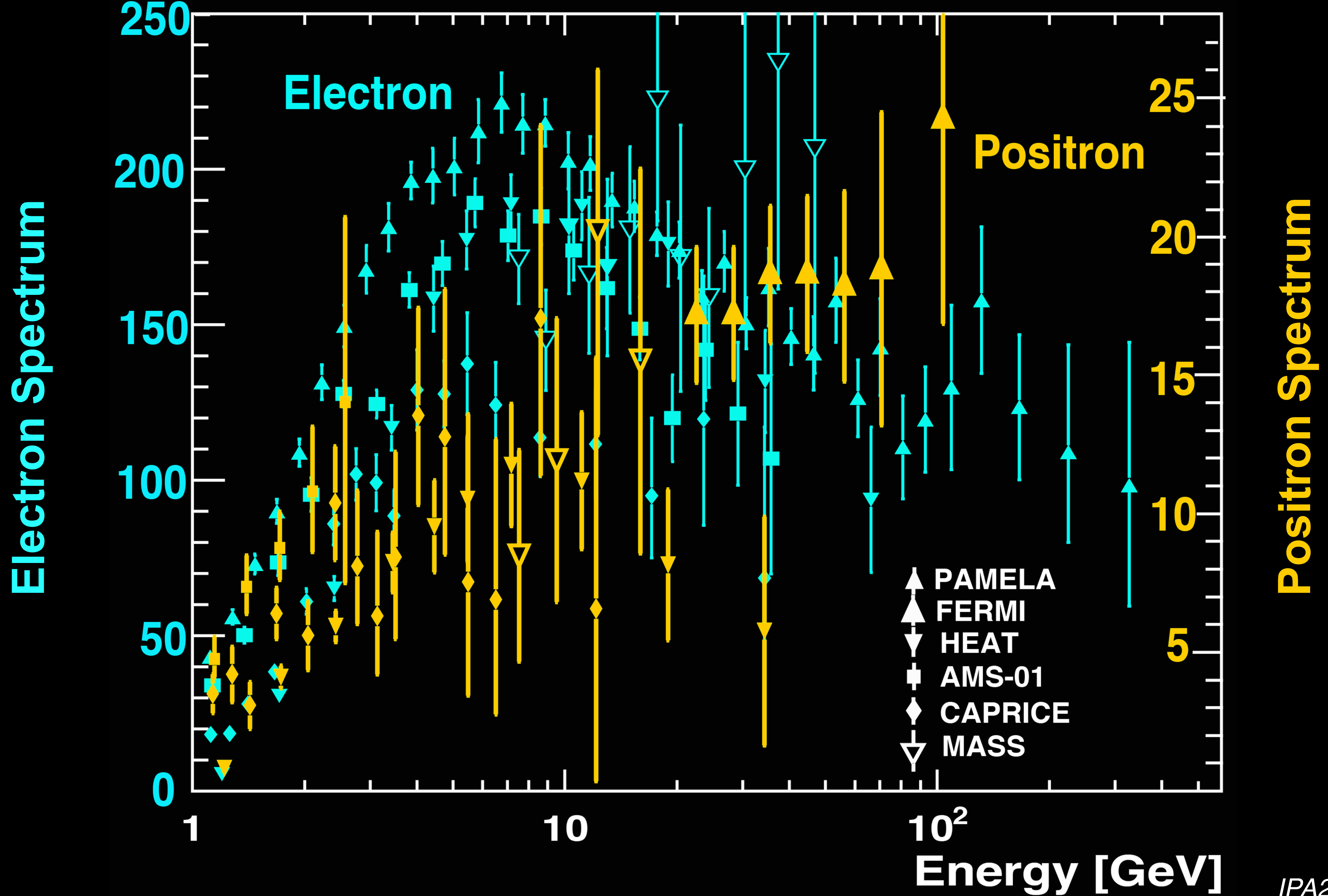
This favors the hypothesis that the flux hardening is an universal propagation effect.


RARE COMPONENT OF CR: e^-, e^+, anti-p
Supernovae
Protons (~90%)
Helium (~8%)
electrons (~1%) …
AMS

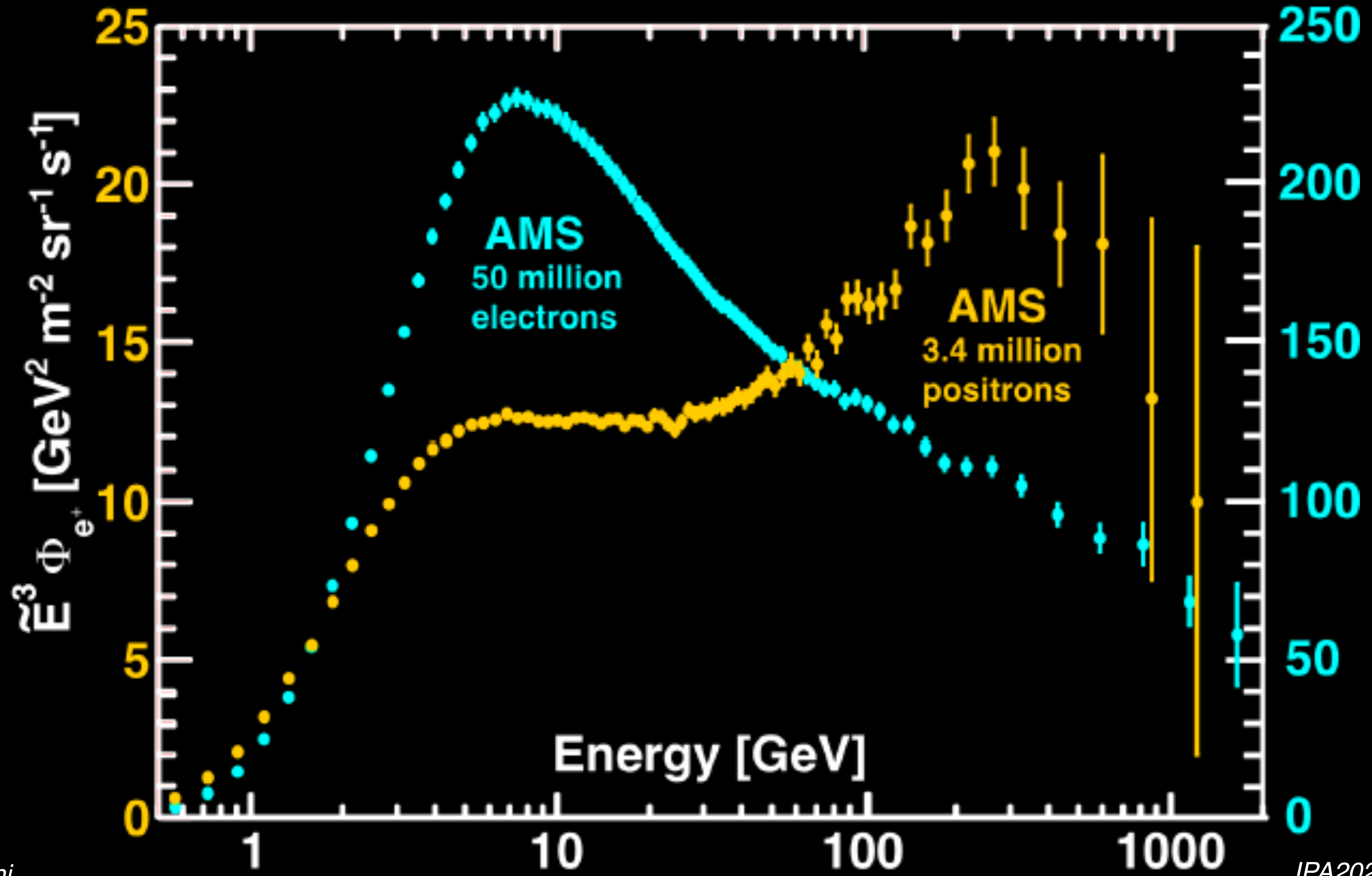
RARE COMPONENT OF CR: e^-, e^+, anti-p



ELECTRON AND POSITRON SPECTRA BEFORE AMS



LATEST ELECTRONS AND POSITRONS RESULTS

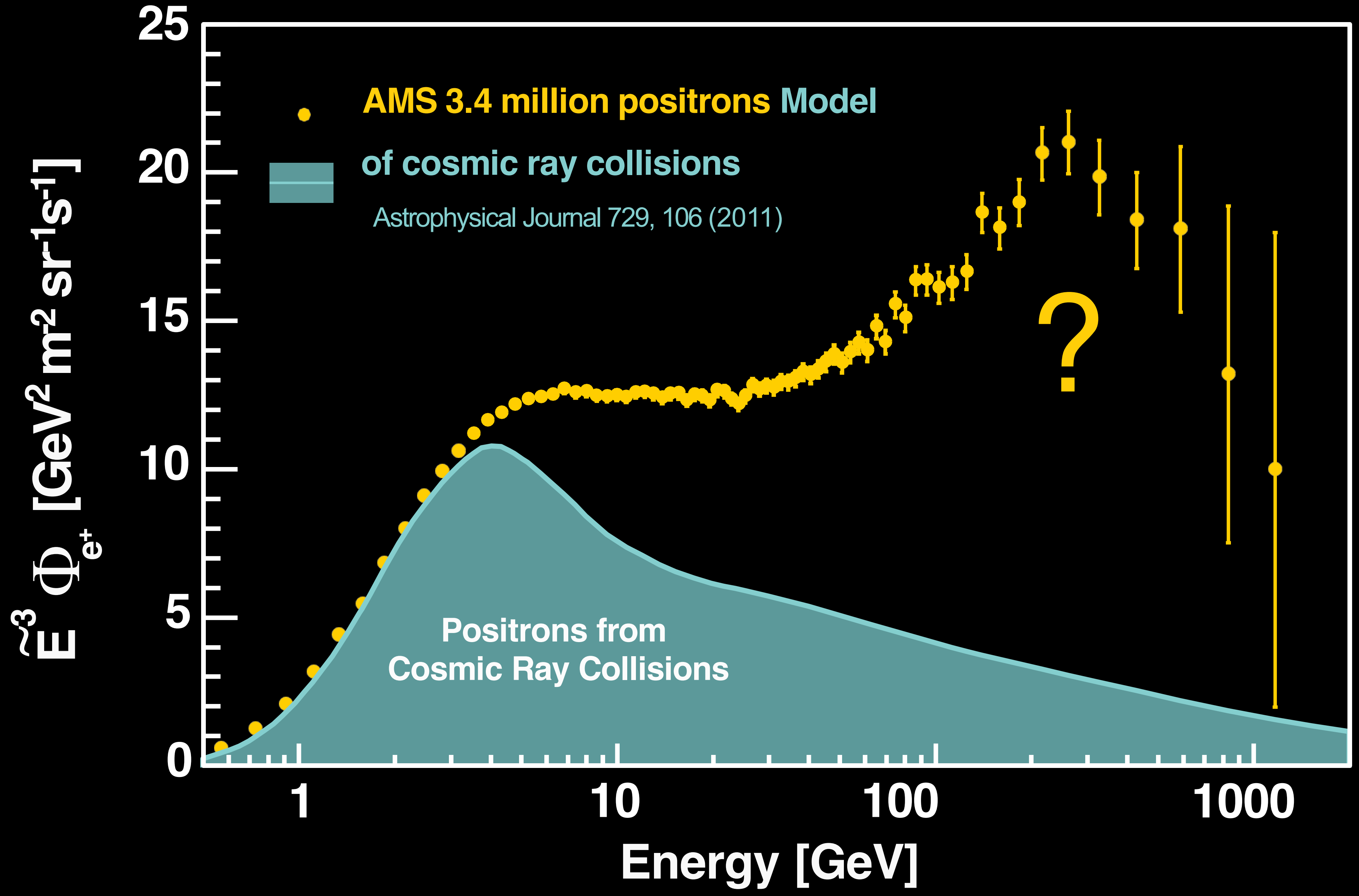


ORIGIN OF COSMIC POSITRONS

Positron flux cannot be described by a single power law…

Low energy positrons mostly come from cosmic ray collisions

High energy positrons?

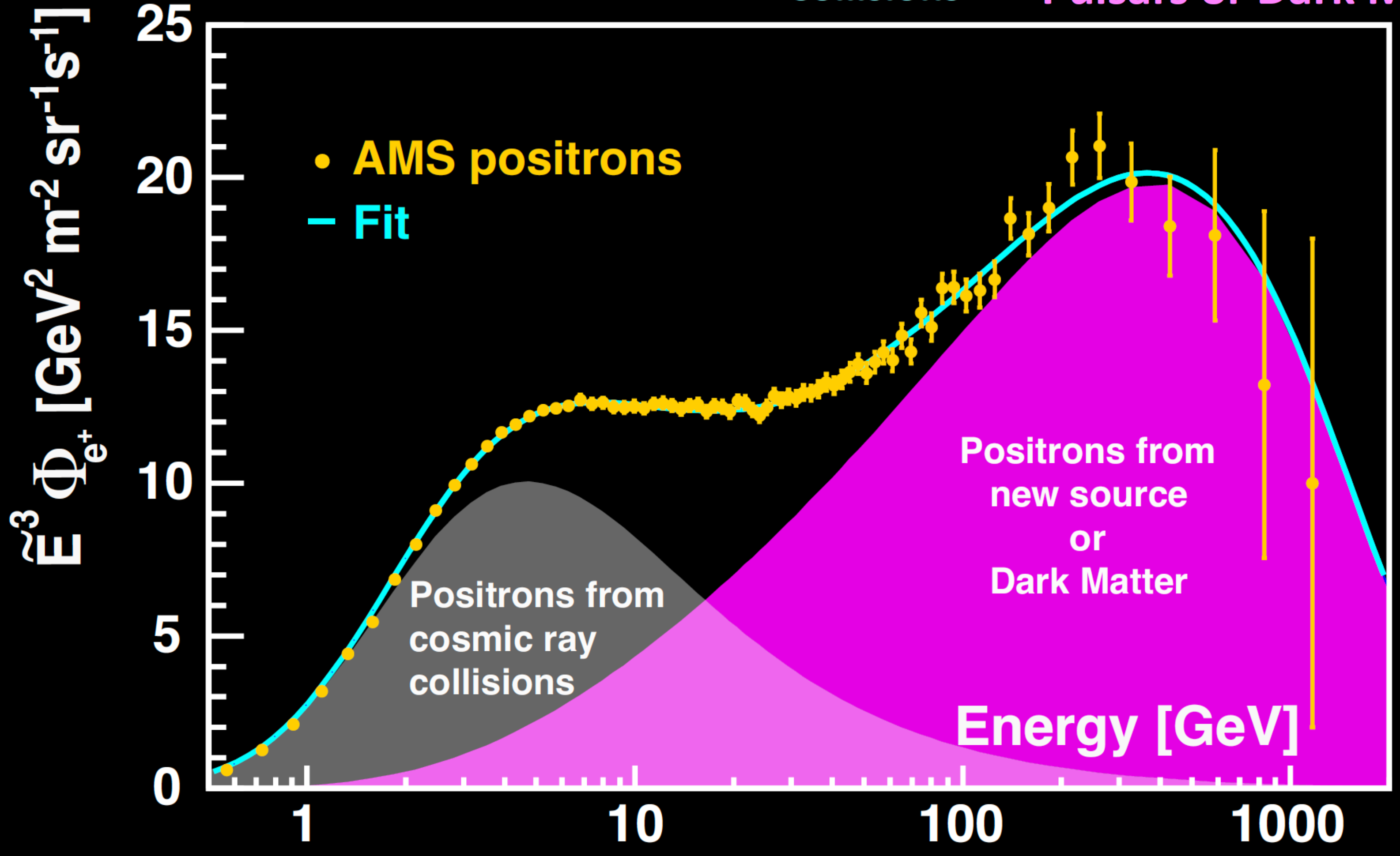


ORIGIN OF COSMIC POSITRONS

Positron flux is well described by sum of low-energy part from cosmic ray collisions plus a high-energy part from pulsars or dark matter., which dominates at high energies

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

Collisions Pulsars or Dark Matter



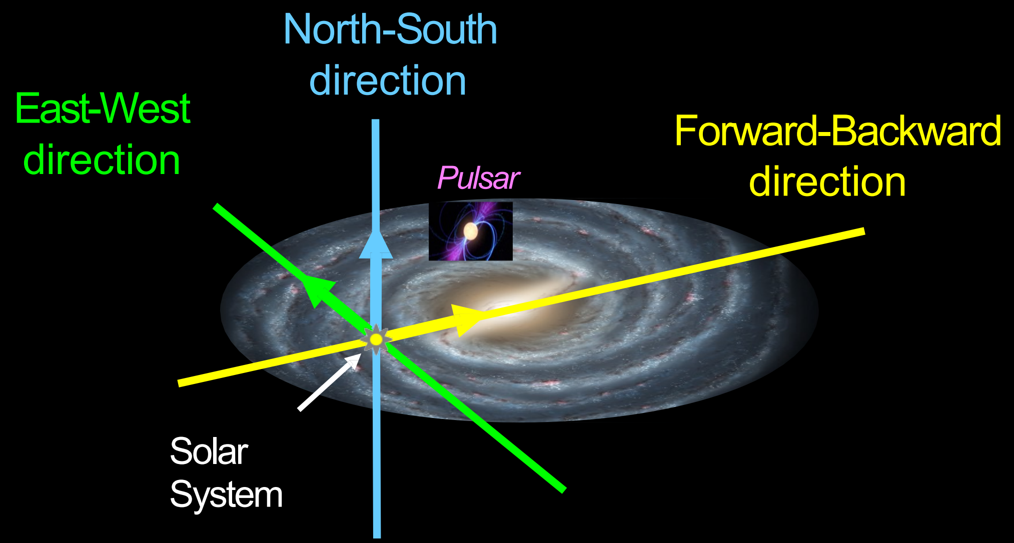
More information about this source?

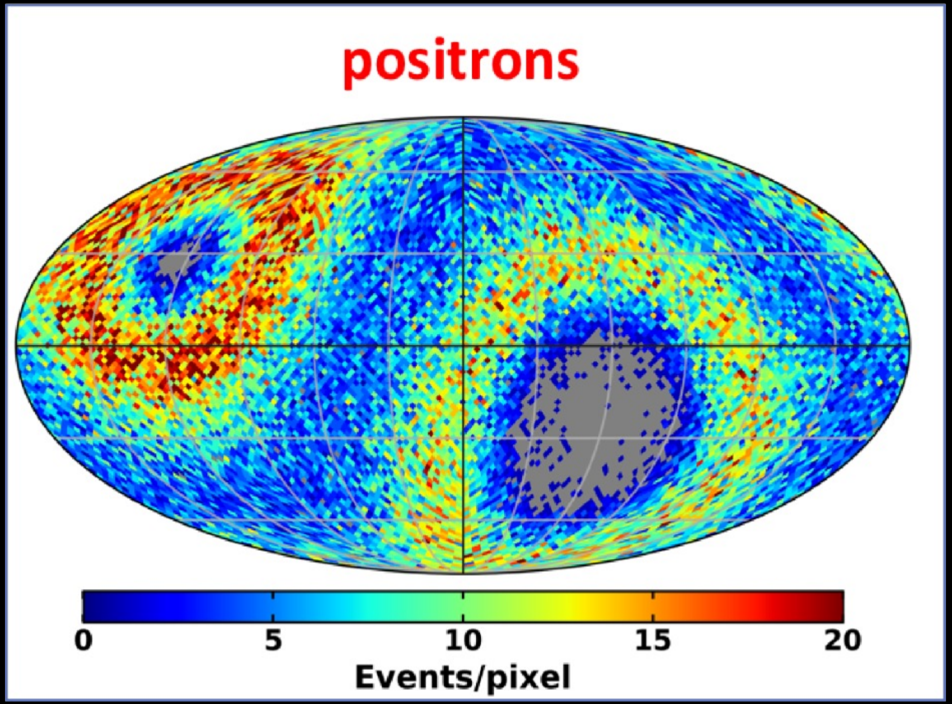
- Anisotropies
- antiprotons
- Electron flux
- Higher energies

POSITRON ANISOTROPIES

Astrophysical point sources will imprint a higher anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo.

Dipole anisotropy: $$\delta = 3\sqrt{C_1/4\pi}$$ C_1 is the dipole moment



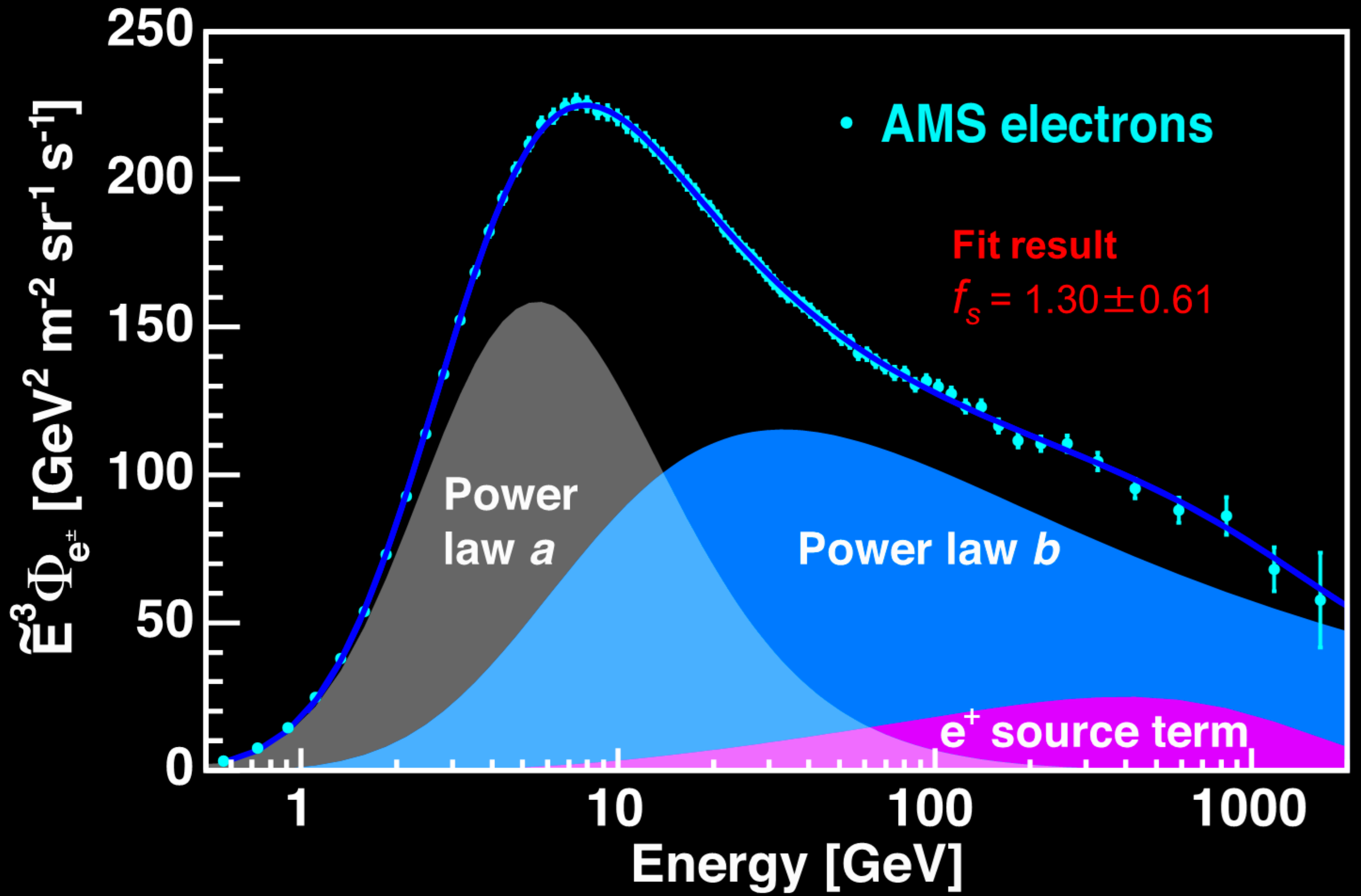


For 16 < E < 500 GeV currently at 95% C.L.: **δ < 0.0150**

ELECTRON FLUX

$$\Phi_{e^-}(E) = S(E)\left[C_a(\hat{E}/E_a)^{\gamma_a} + C_b(\hat{E}/E_b)^{\gamma_b} + f_s C_s^{e^+}(\hat{E}/E_2)^{\gamma_s^{e^+}} \exp(-E/E_s^{e^+})\right]$$

Power law a — Power law b — positron-like source term



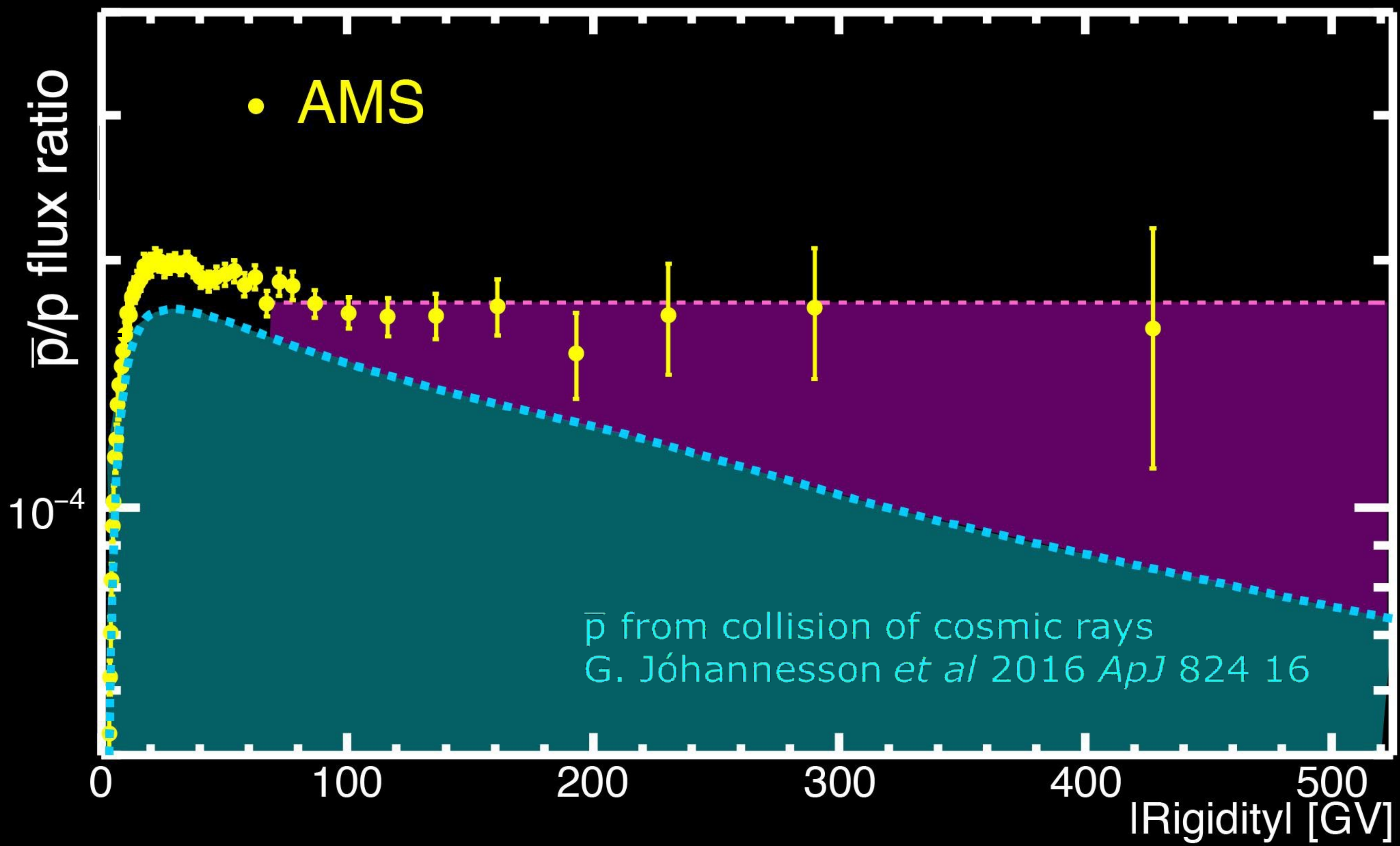
Electron spectrum favors the contribution of the **positron-like source term (@95%C.L.)**

↓

charge-symmetric nature of the high energy positron source term

ANTIPROTON–TO–PROTON RATIO

The antiproton-to-proton flux ratio shows unexpected energy dependence distinctly different from antiprotons from collision of cosmic rays



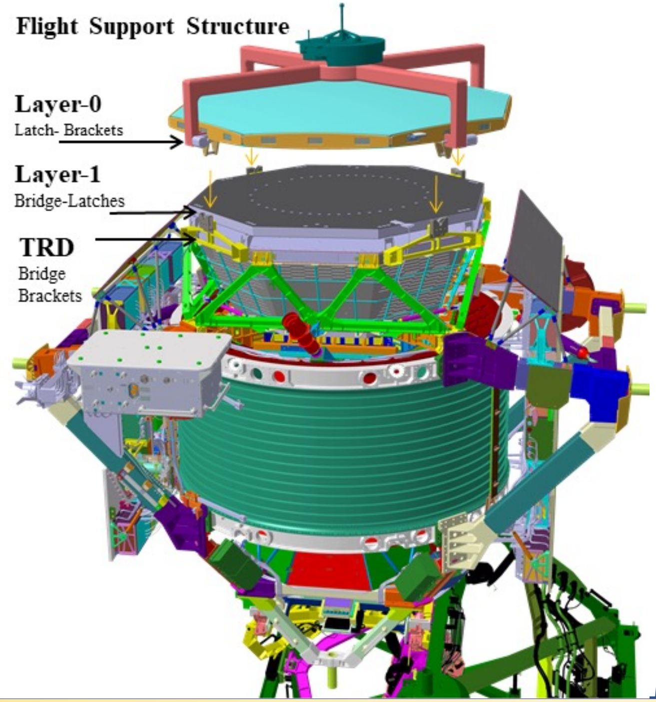
A SAMPLE OF RECENT THEORETICAL MODELS EXPLEINING AMS DATA

	Positrons	ANTI-p
DARK MATTER	1) H. Motz, H. Okada, Y. Asaoka, and K. Kohri, Phys.Rev. D102 (2020) 8, 083019 2) Z.Q. Huang, R.Y. Liu, J.C. Joshi, X.Y. Wang, Astrophys.J. 895 (2020) 1, 53 3) R. Diesing and D. Caprioli, Phys.Rev. D101 (2020) 10 4) A. Das, B. Dasgupta, and A. Ray, Phys.Rev. D101 (2020) 6 5) F. S. Queiroz and C. Siqueira, Phys.Rev. D101 (2020) 7, 075007 6) Z.L. Han, R. Ding, S.J. Lin, and B. Zhu, Eur.Phys.J. C79 (2019) 12, 1007 7) C.Q. Geng, D. Huang, and L. Yin, Nucl.Phys. B959 (2020) 115153 8) S. Profumo, F. Queiroz, C. Siqueira, J.Phys.G 48 (2020) 1, 015006 9) D. Kim, J.C. Park, S. Shin, JHEP 04 (2018) 093 and many other excellent papers …	1. J. Heisig, Modern Physics Letters A, (2021), 36, 05 2. Y. Genolini et al., arXiv:2103.04108 (2021) 3. I. Cholis et al., Phys. Rev. D, 99 (2019), 103026 4. A. Cuoco et al., Phys. Rev. D, 99 (2019), 103014 5. M. Carena et al., Phys. Rev. D, 100 (2019), 055002 6. A. Reinert et al., JCAP, 01 (2018), p. 055 7. A. Cuoco et al., Phys. Rev. Lett., 118 (2017), 191102 8. M. Cui et al., Phys. Rev. Lett., 118 (2017), 191101 9. Y. Chen et al., Phys. Rev. D, 93 (2016), p. 015015 10. ……
ASTROPHYSICAL SOURCES	1) P. Mertsch, A. Vittino, and S. Sarkar, Phys.Rev. D 104 (2021) 103029 2) P. Zhang et al., JCAP 05 (2021) 012 3) C. Evoli, E. Amato, P. Blasi, and R. Aloisio, Phys.Rev. D103 (2021) 8, 083010 4) K. Fang, X.J. Bi, S.J. Lin, and Q. Yuan, Chin.Phys.Lett. 38 (2021) 3, 039801 5) C. Evoli, P. Blasi, E. Amato, and R. Aloisio, Phys.Rev.Lett. 125 (2020) 5, 051101 6) O. Fornieri, D. Gaggero, and D. Grasso, JCAP 02 (2020) 009 7) P. Cristofari and P. Blasi, Mon.Not.Roy.Astron.Soc. 489 (2019) 1, 108 8) K. Fang, X.J. Bi, and P.F Yin, Astrophys.J. 884 (2019) 124 9) S. Recchia, S. Gabici, F.A. Aharonian, and J. Vink, Phys.Rev. D99 (2019) 10, 103022 and many other excellent papers …	NONE
PROPAGATION	1) E. Amato and S. Casanova, J.Plasma Phys. 87 (2021) 1, 845870101 2) Z. Tian et al., Chin.Phys. C44 (2020) 8, 085102 3) W. Zhu, P. Liu, J. Ruan, and F. Wang, Astrophys.J. 889 (2020) 127 4) P. Liu and J. Ruan, Int.J.Mod.Phys. E28 (2019) 09, 1950073 5) R. Diesing and D. Caprioli, Phys.Rev.Lett. 123 (2019) 7, 071101 6) W. Zhu, J. S. Lan and J. H. Ruan, Int. J. Mod. Phys. E27 (2018) 1850073 and many other excellent papers …	1. P. Mertsch et al., Phys. Rev. D 104 (2021) 103029 2. M. Boudaud et al., Phys. Rev. Research 2, 023022 (2020) 3. V. Bresci et al., Mon. Not. R. Astron. Soc., 488 (2019), p. 2068 4. M. Korsmeier et al., Phys. Rev. D 97 (2018), 103019 5. P. Lipari, Phys. Rev. D, 95 (2017), 063009 6. I. Cholis et al., Phys. Rev. D 95(2017), 123007 7. M. Winkler, JCAP, 2017(02), 048 8. ……


Alpha Magnetic Spectrometer
AMS-02
Europe • Asia
North America

What's next?

- Installation of one additional sylicon tracker layer (~7 m^2): **layer 0 (L0)**
  - **Acceptance** X3



2011 AMS-02 InstalledOnISS

2020 AMS-02.01 1°Upgrade:UTTPS

2024 AMS-02.02 2°Upgrade:L0

CONCLUSIONS

- AMS is providing simultaneous measurements of different cosmic ray species with O(%) accuracy in an extended energy range
- new phenomena are being highlighted by these measurements whose nature will be further clarified as more data will be collected by the experiment.

AMS-02 will continue to take data until the end of ISS mission (currently set to 2030)…

- Positron flux up to 2 TeV and electron flux up 3 TeV:

  → the positron-like source in the electron flux will be established at 4σ level
- Improving the measurment of **antiproton-to-proton ratio**
- Positron anisotropy: pulsar exclusion **@99.93% C.L.**

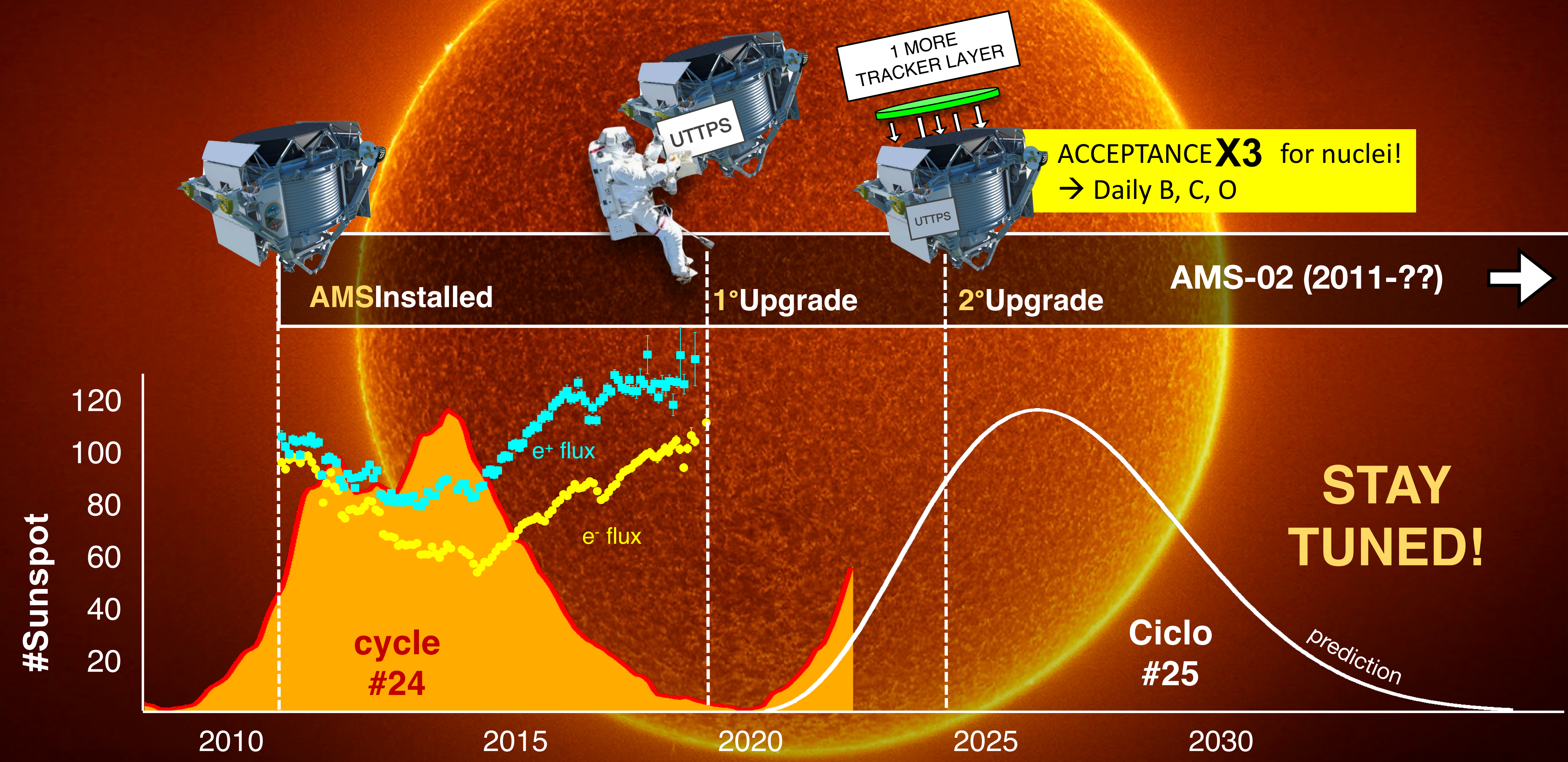
Indirect Dark Matter search

- **First measurment of nuclei with high Z (≥15) for R≥35GV**

Understanding of the Interstellar Medium

…AND SOLAR PHYSICS!

By 2030, AMS will explore ~2 complete solar cycle providing the flux time variation of ~all CR species



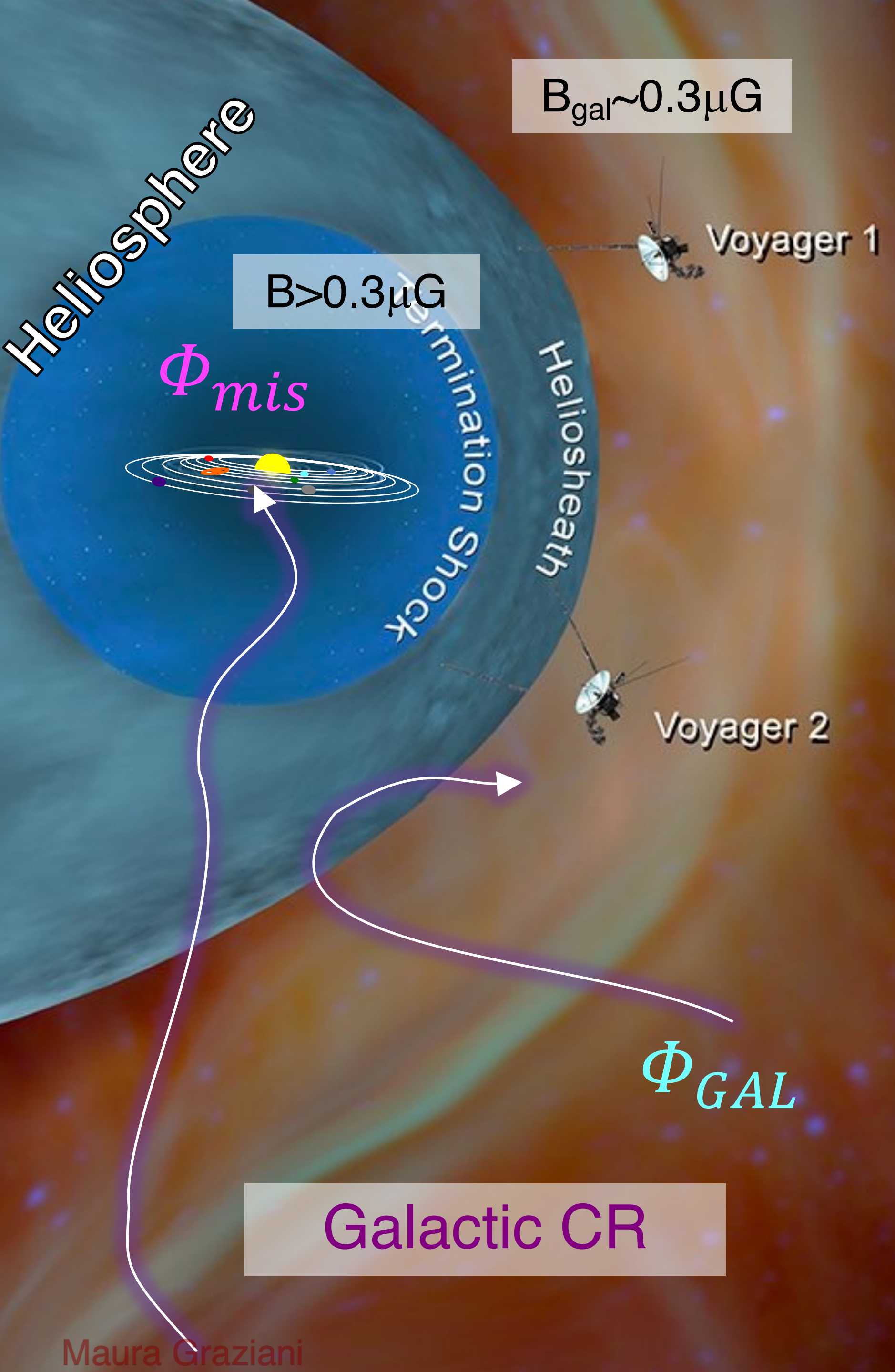
Thanks for the attention and Stay Tuned!

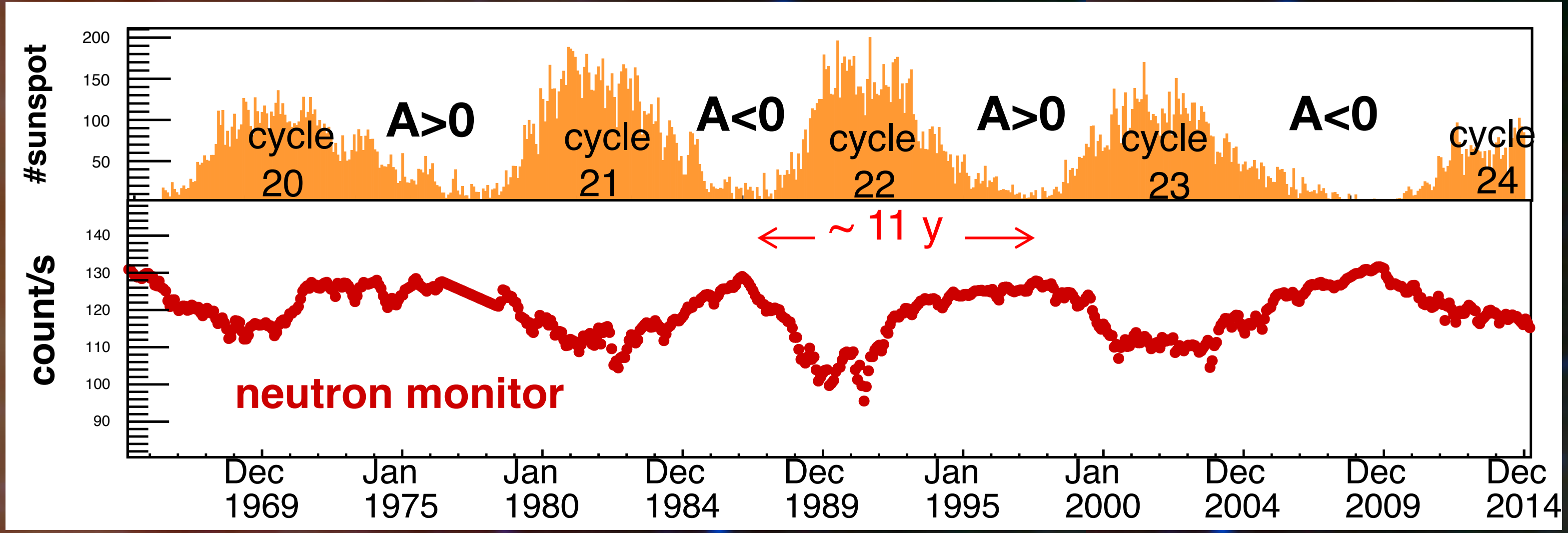
Back up

Solar physics

Low energies (E<30 GeV)

→ Solar Modulation of Cosmic Rays (CR)





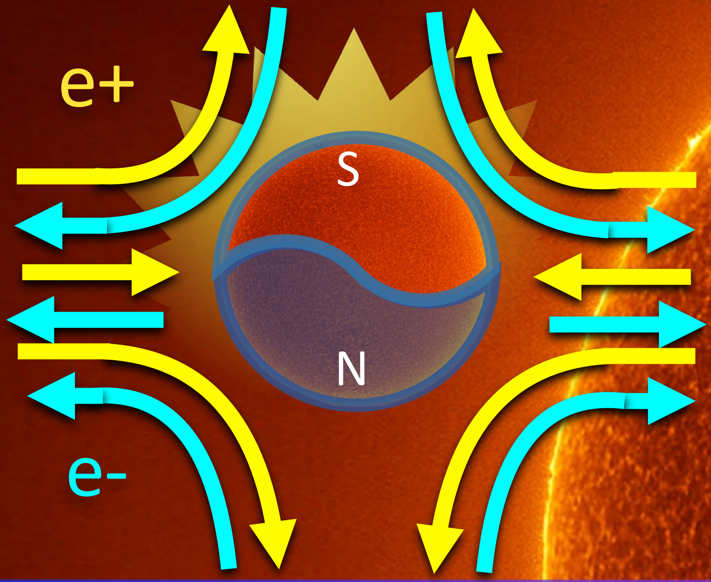
- Large time scale effect (~11 years);
- Small time scale effects (~days);
- Depends on CR mass, charge and energy;

Knowing the solar modulation of CR:

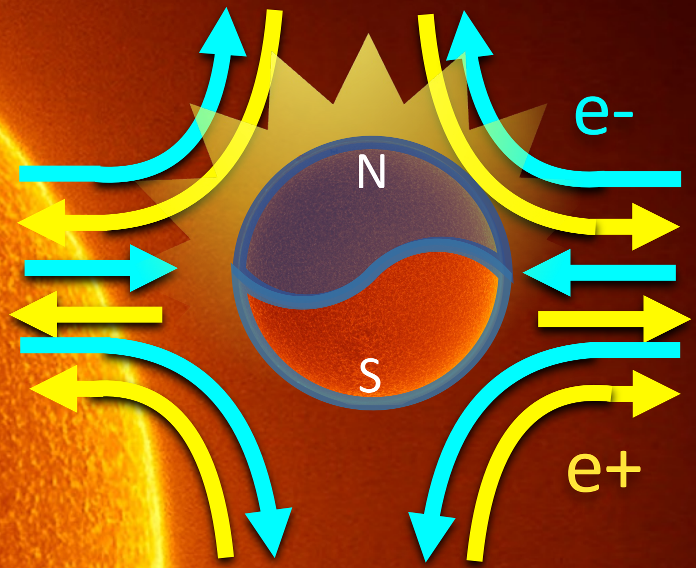
→ correct undesrtanding of galactic CR

→ Space weather

Why electrons and positrons?



DIFFUSION motion + MAGNETIC drift



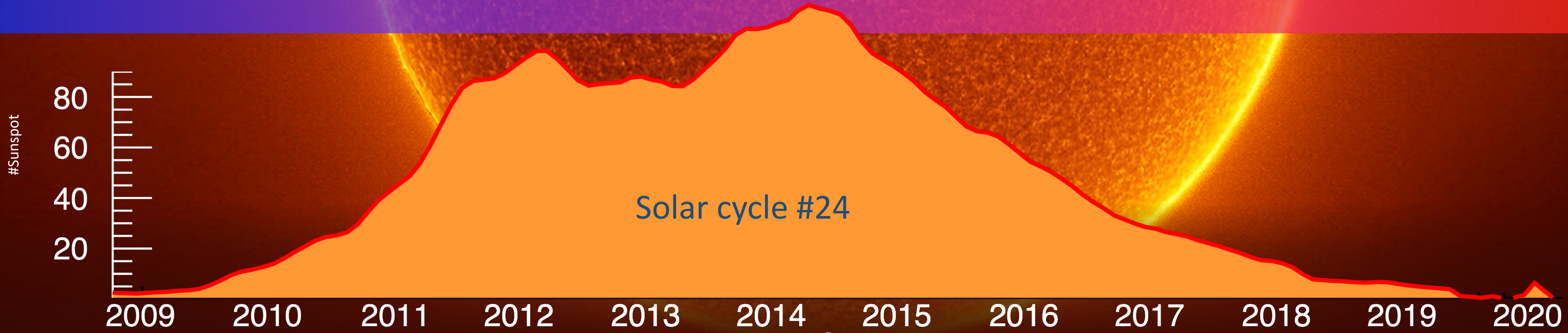
Studing of the charge-sign dependent effects

A<0

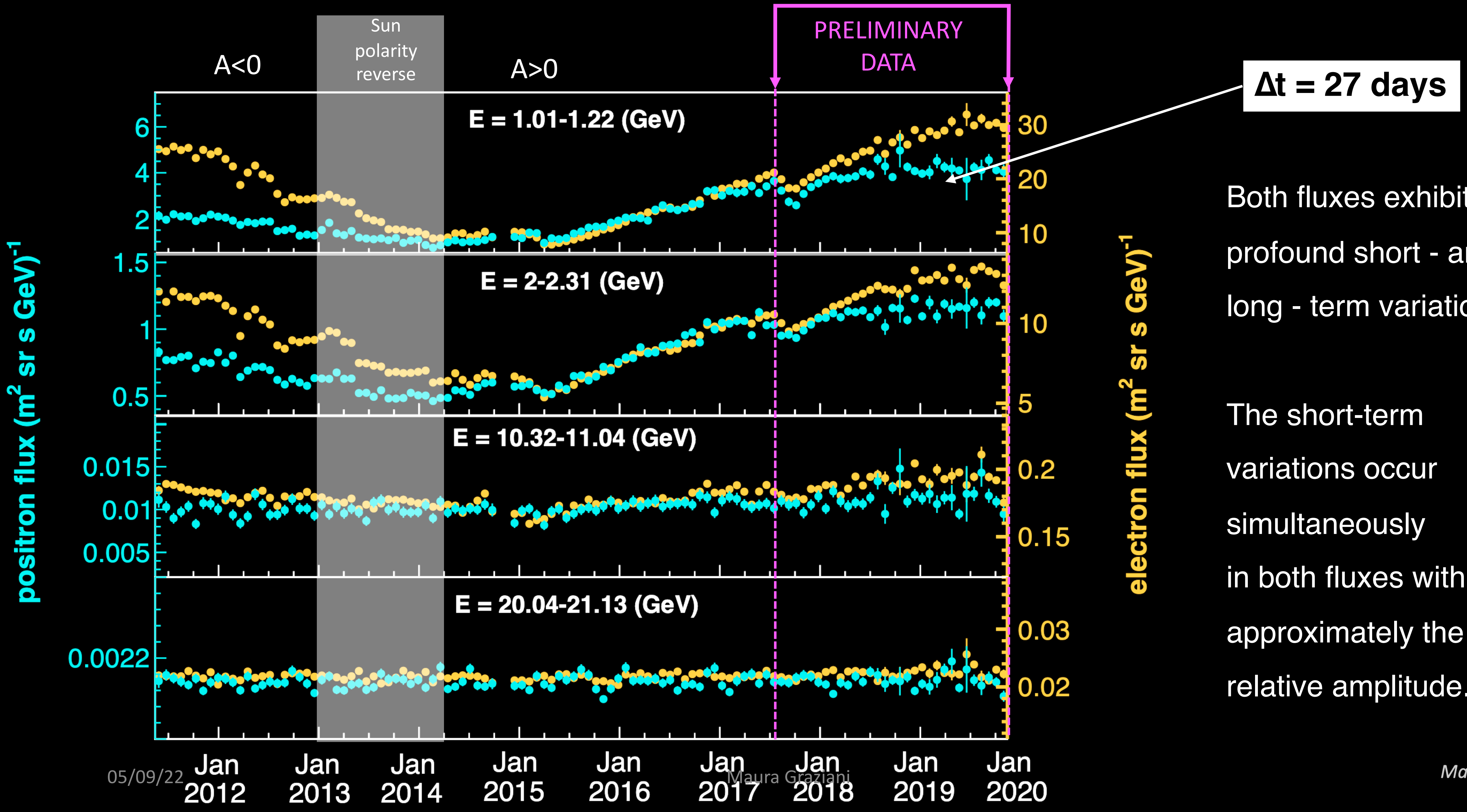
A??

Polarity reverse

A>0



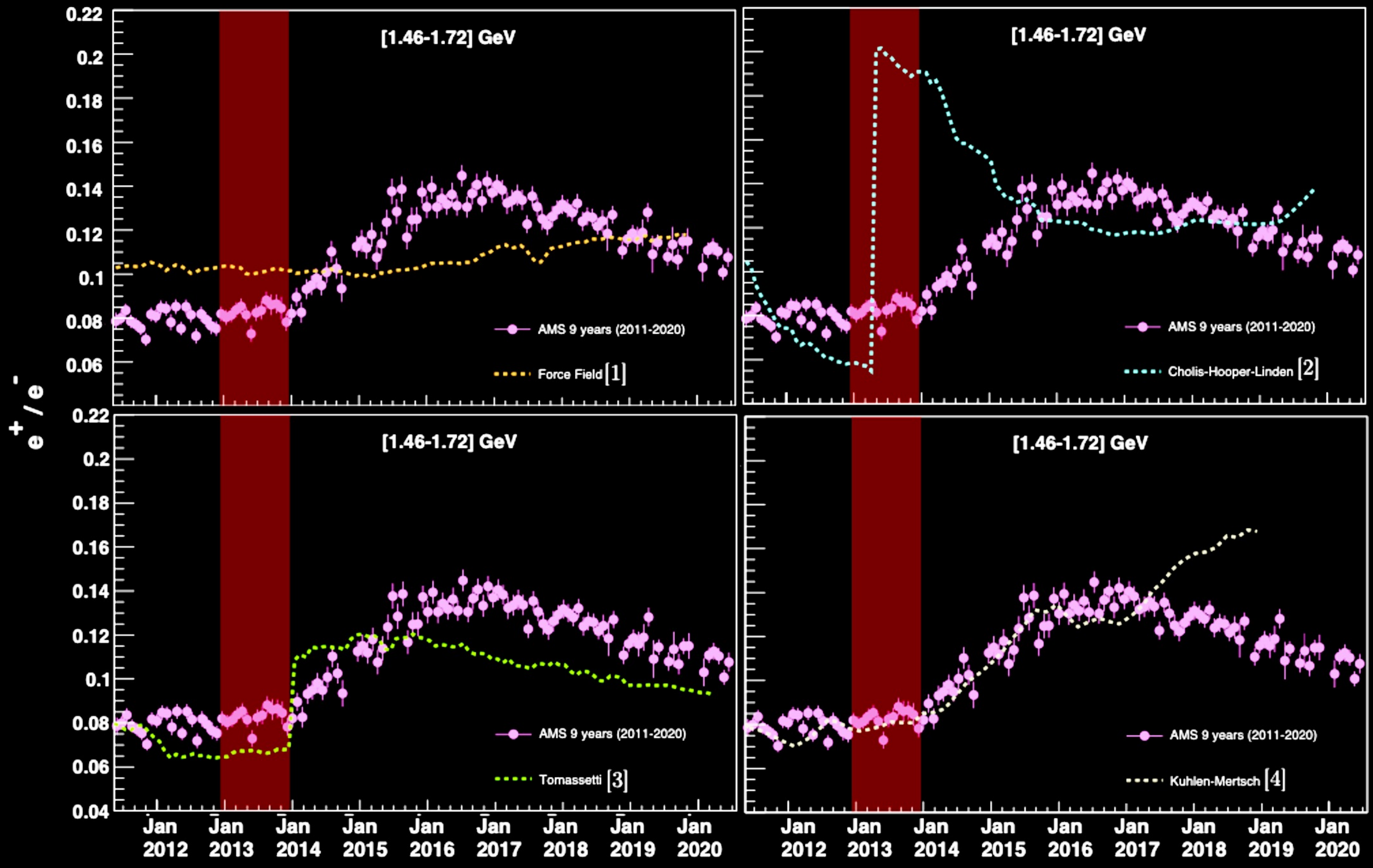
Electron and Positron fluxes in time



Both fluxes exhibit profound short - and long - term variations.

The short-term variations occur simultaneously in both fluxes with approximately the same relative amplitude.

Charge sign-dependent effects



Δt = 27 days

All four models fail to reproduce the long term dependence of AMS positron ratio.

AMS-02 data provide novel information on the e^+ and e^- flux time dependences.

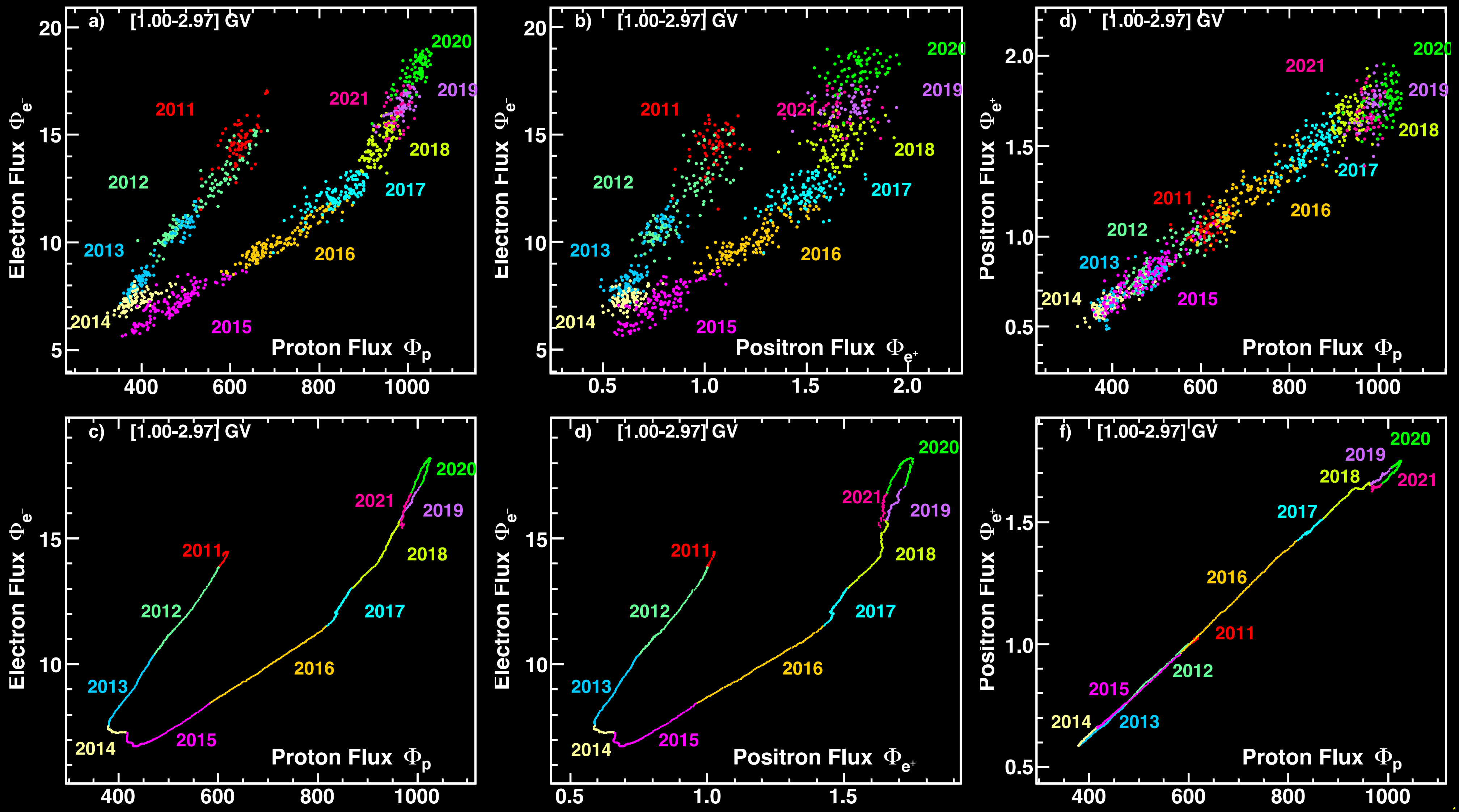
[1]: analytical model by Gleeson & Axford 1968. Modulation potential Φ from NM; e+/e- LIS from Bisschoff et al. Apj 2019
[2]: FF with charge sign dependent effect. e+/e- LIS from Bisschoff et al. Apj 2019. Solar Parameters constrained with AMS-02 p and antip
[3]: Solar Prop based 2D model from Tomassetti PRD 2015. e+/e- LIS from Bisschoff et al. Apj 2019. Solar Parameters constrained with p data
[4]: Semianalitical charge sign dependent 2D model from Kuhlen & Mertsh PRL 2019. Model constrained with AMS-02 data on e+/e- between 2011 and 2017

Summary

electron v.s. proton
Different mass, opposite charge

electron v.s. positron
Same mass, opposite charge

positron v.s. proton
Different mass, same charge



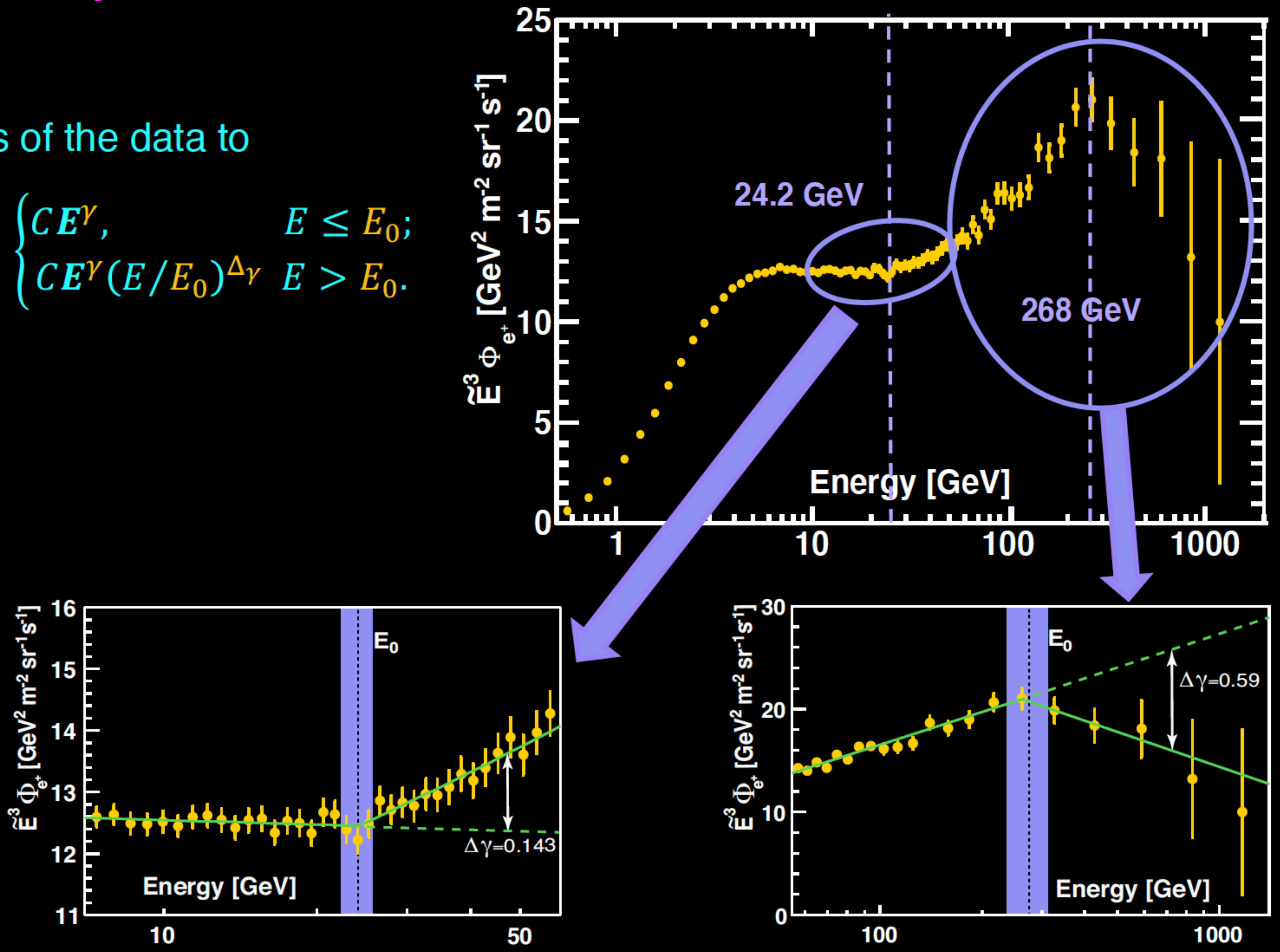
Comprehensive dataset to study propagation in the heliosphere of cosmic ray with **Z=1 ...**

Electron and positron

Transition energy for positrons

Fits of the data to

$$\Phi_{e^+}(E) = \begin{cases} C E^{\gamma}, & E \leq E_0; \\ C E^{\gamma}(E/E_0)^{\Delta\gamma} & E > E_0. \end{cases}$$



7.8σ excess above $E_0 = 24.2 \pm 1.1$ **GeV**

4.8σ sharp drop-off at $E_0 = 268^{+35}_{-33}$ **GeV**

Origin of Cosmic Electrons

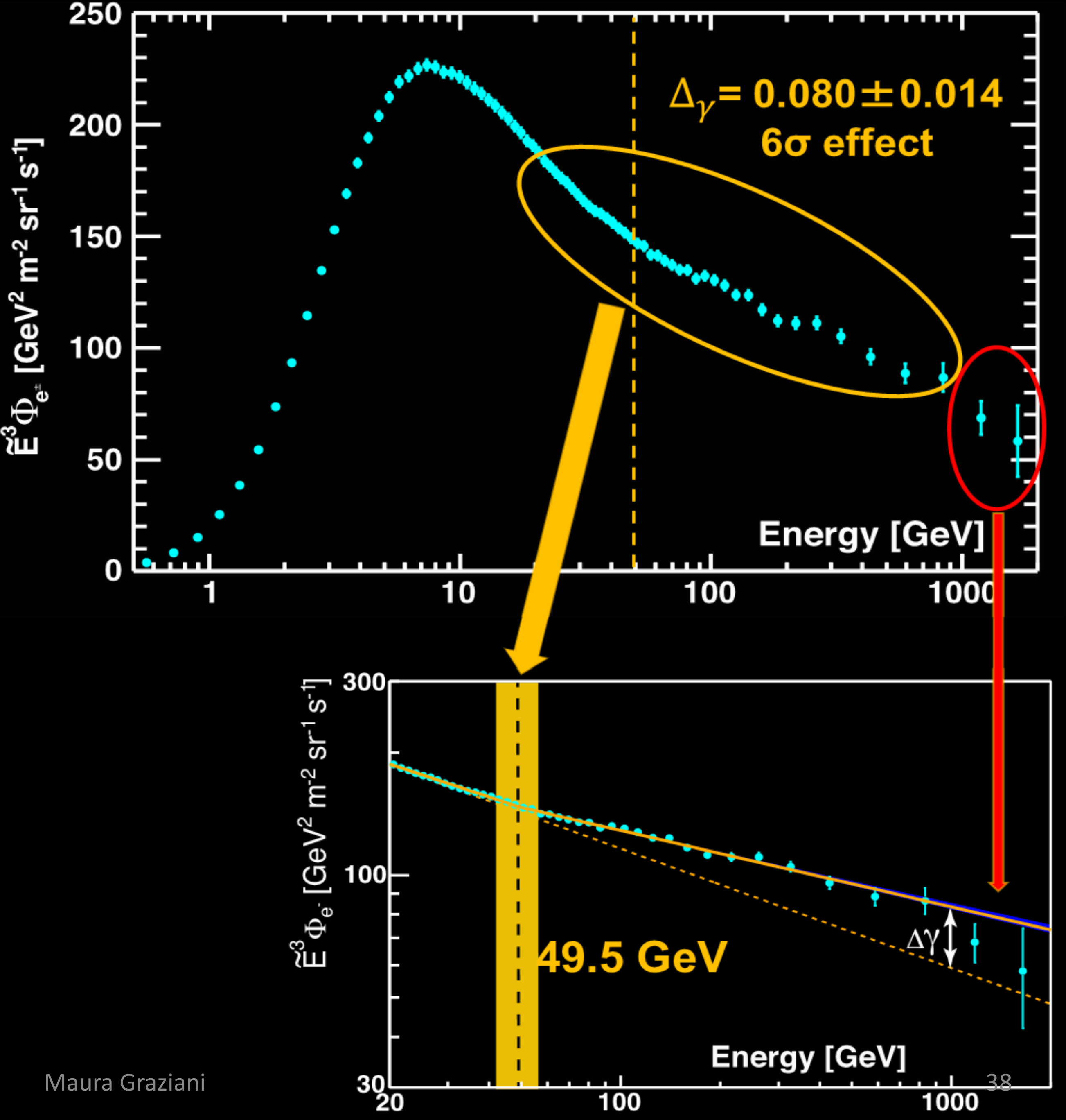
Traditionally, Cosmic Ray spectrum is described **by a power law function.**

Change of the behavior at **~50 GeV** and **at ~1 TeV**

Fit to data

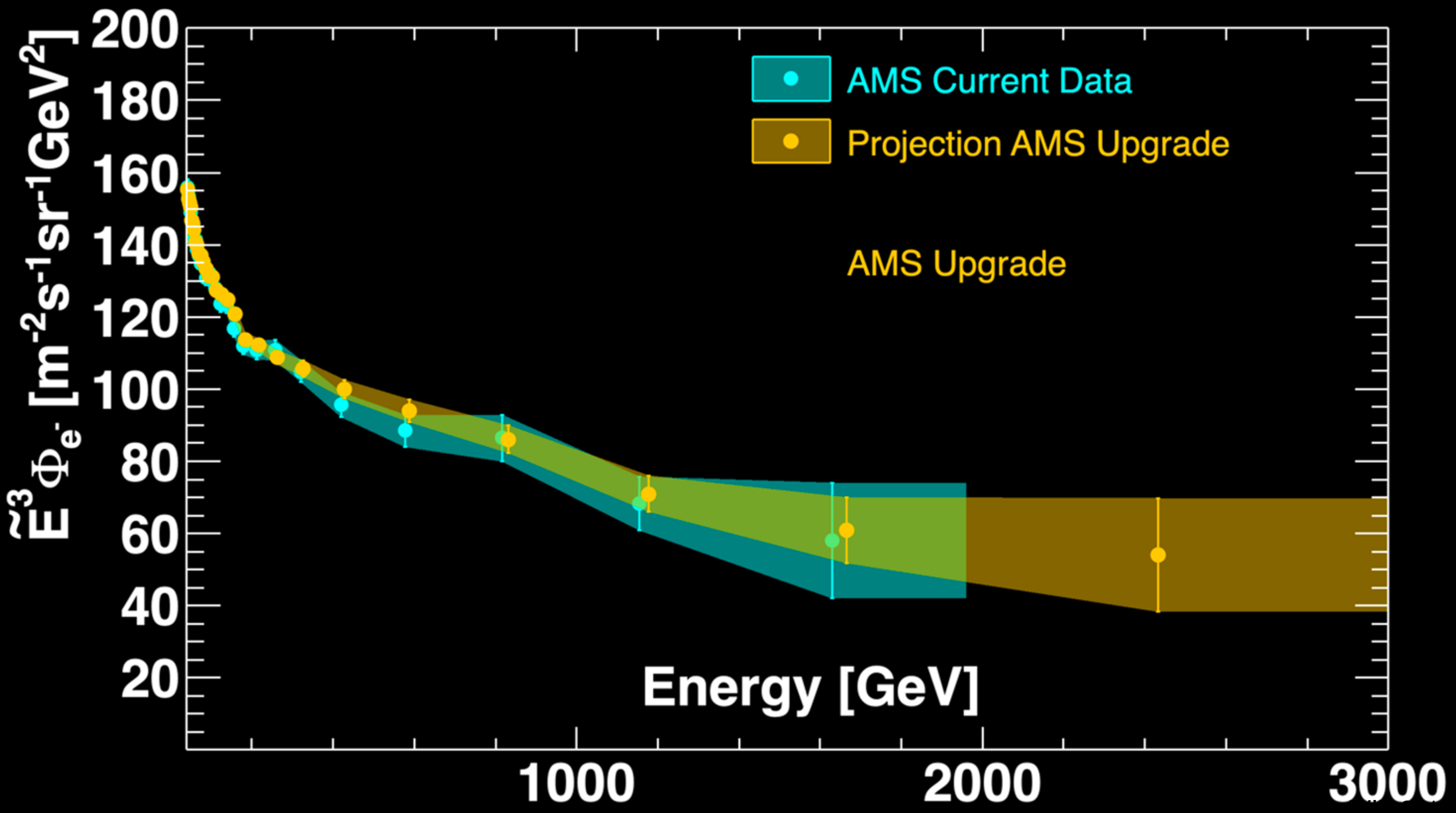
$$\Phi_{e^-}(E) = \begin{cases} CE^{\gamma}, & E \leq E_0; \\ CE^{\gamma}(E/E_0)^{\Delta\gamma}, & E > E_0. \end{cases}$$

A significant excess at E_0 = 49.5±5.6 GeV



AMS.02.02 – The Upgrade effect on electron measurement

The upgrade will extend the energy range of the electron flux measurement from **2 TeV to 3 TeV and reduce the error by a factor of two.**



AMS.02.02 – The Upgrade effect on electron measurement

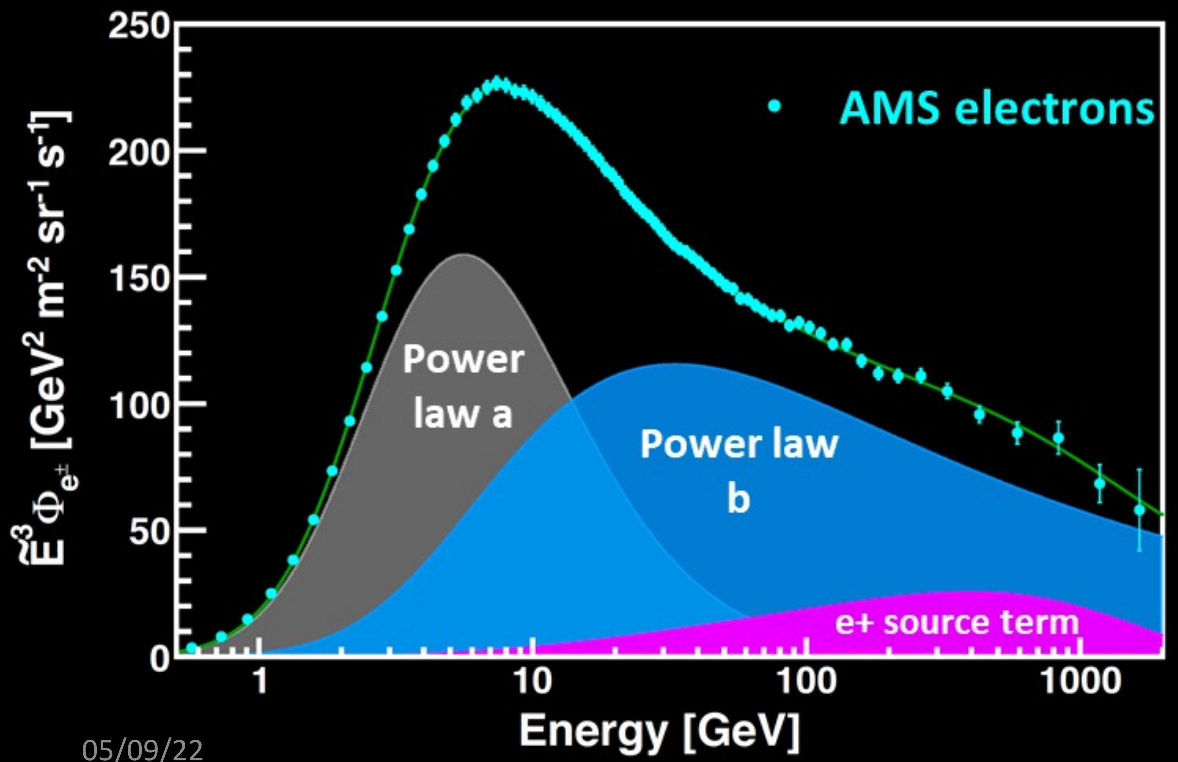
The upgrade will establish the charge-symmetric nature of the high energy positron source term

@99.994% C.L.

$$\Phi_{e^-}(E) = S(E)\left[C_a\left(\hat{E}/E_a\right)^{\gamma_a} + C_b\left(\hat{E}/E_b\right)^{\gamma_b} + f_s C_s^{e^+}\left(\hat{E}/E_2\right)^{\gamma_s^{e^+}} \exp\left(-E/E_s^{e^+}\right)\right]$$

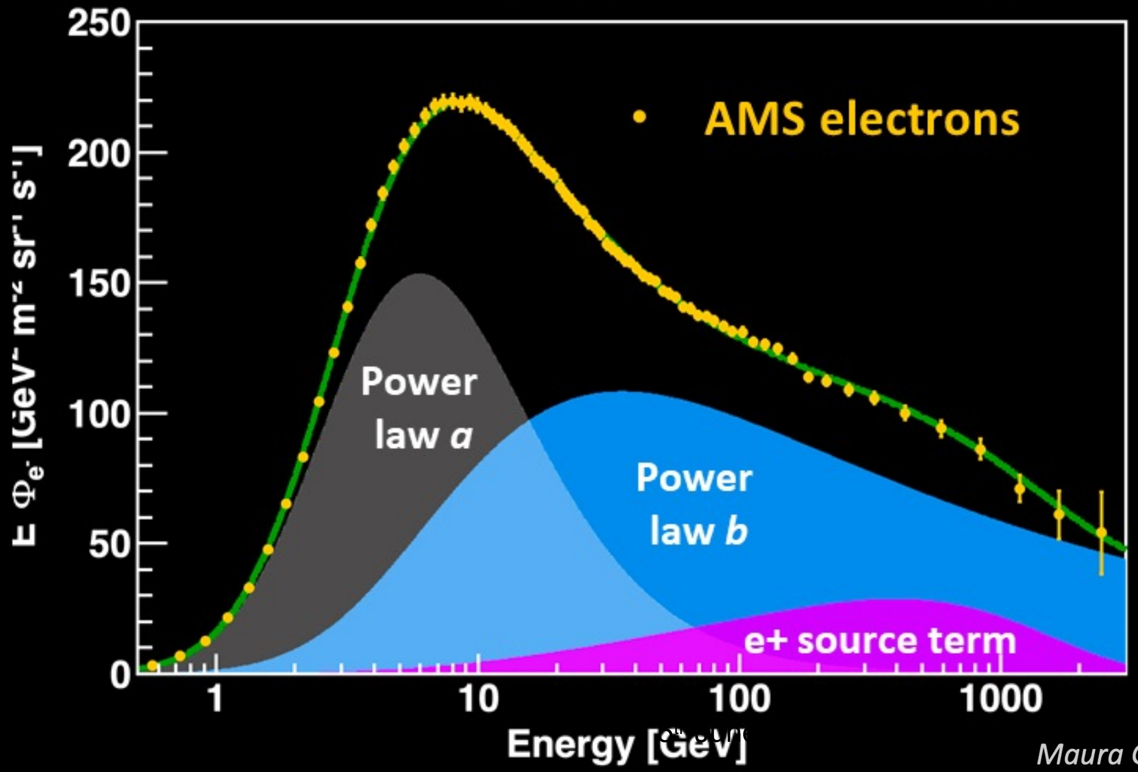
Current Data

95% C.L. detection of source term



With Upgrade

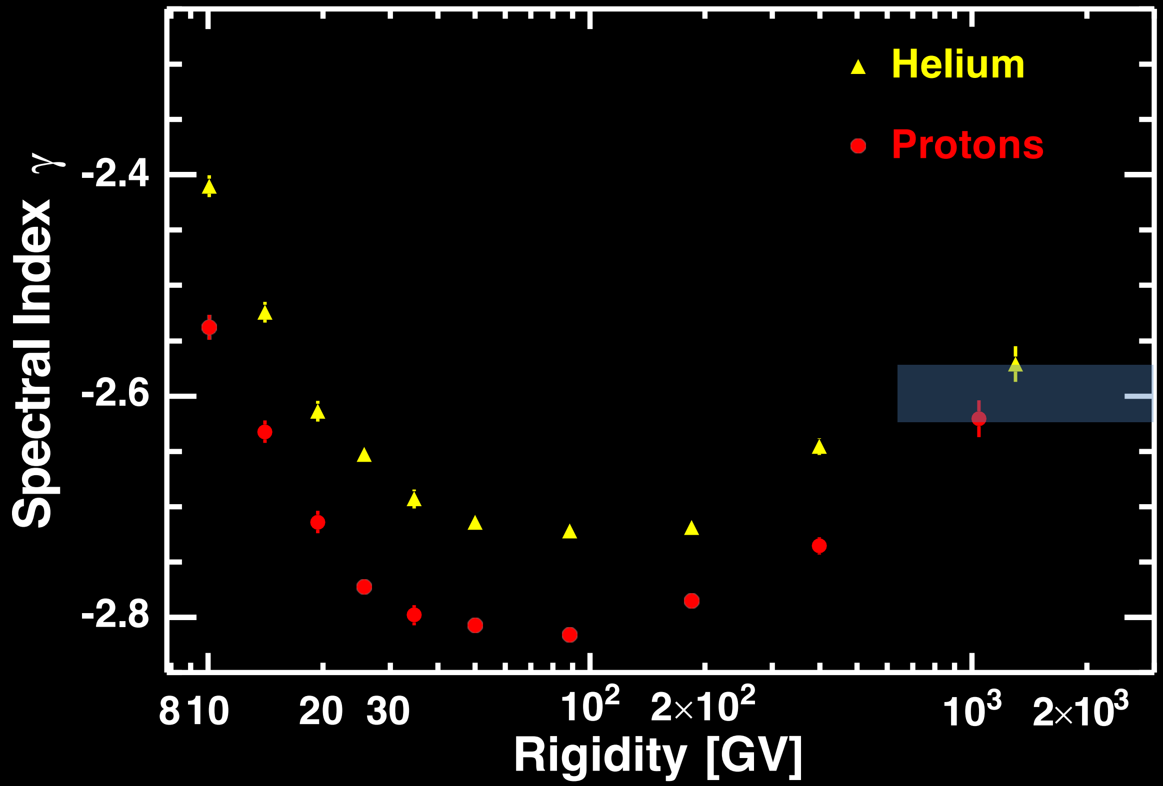
99.994% C.L. detection of source term

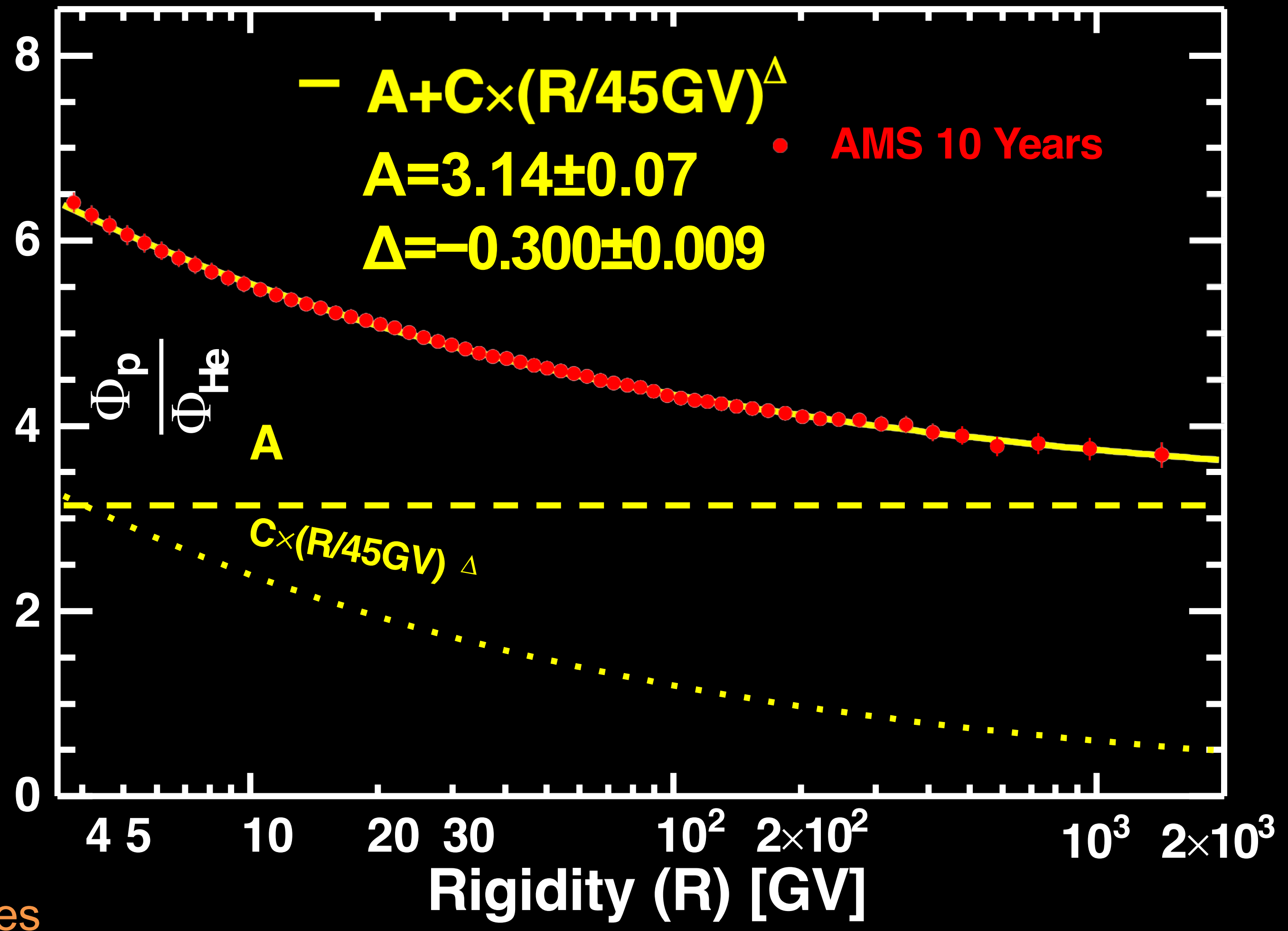


nuclei

Proton/Helium Flux Ratio

$\gamma = d\log\Phi / d\log R$

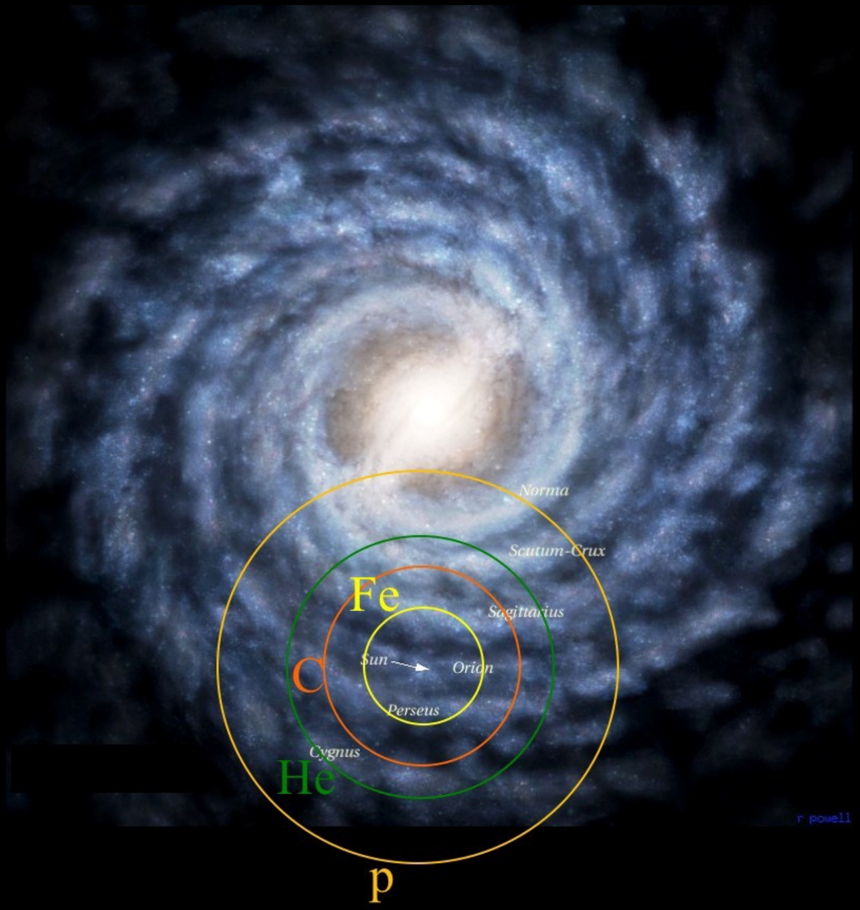




P and He may have same spectral index at highest rigidites

Physics Reports, 894, 1 (2021) :

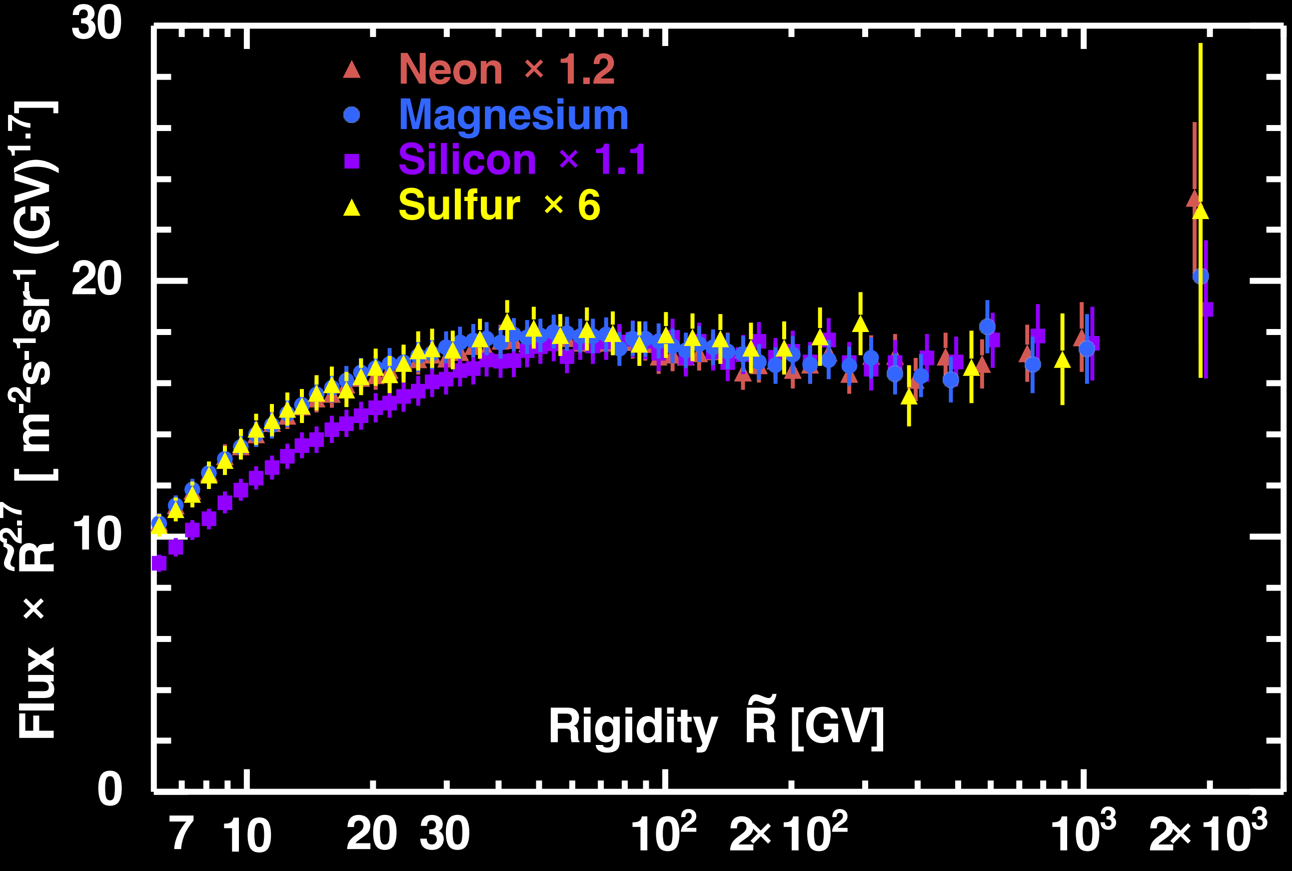
AMS found that proton flux have two components, one is like Helium and another is unique to proton flux.

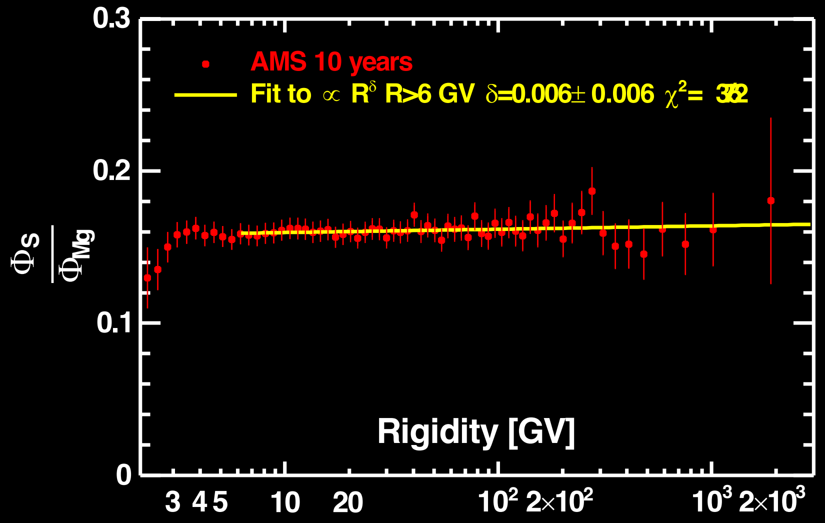


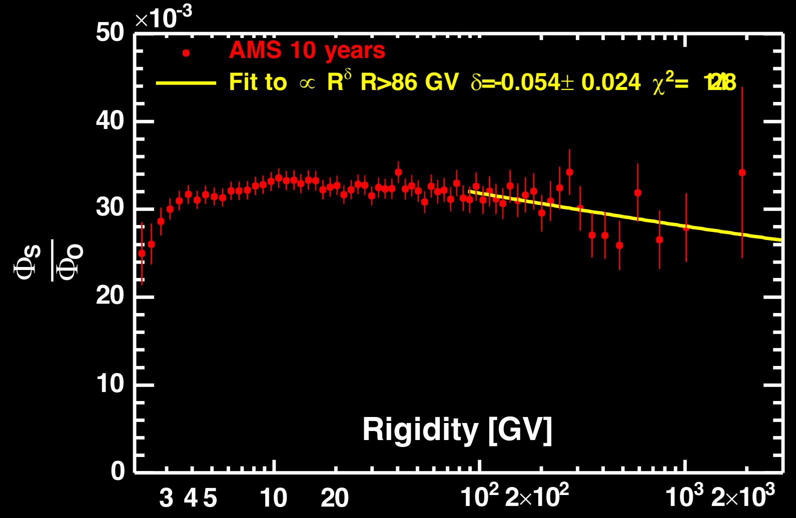
The effective propagation distances for p, He, C, and Fe for 1 GV rigidity.

Measurements of the heavy secondary cosmic ray nuclei with Z>14 will allow AMS to study propagation properties in the Galaxy at different distances. The precision
AMS data will provide the most comprehensive information on the cosmic ray propagation model.

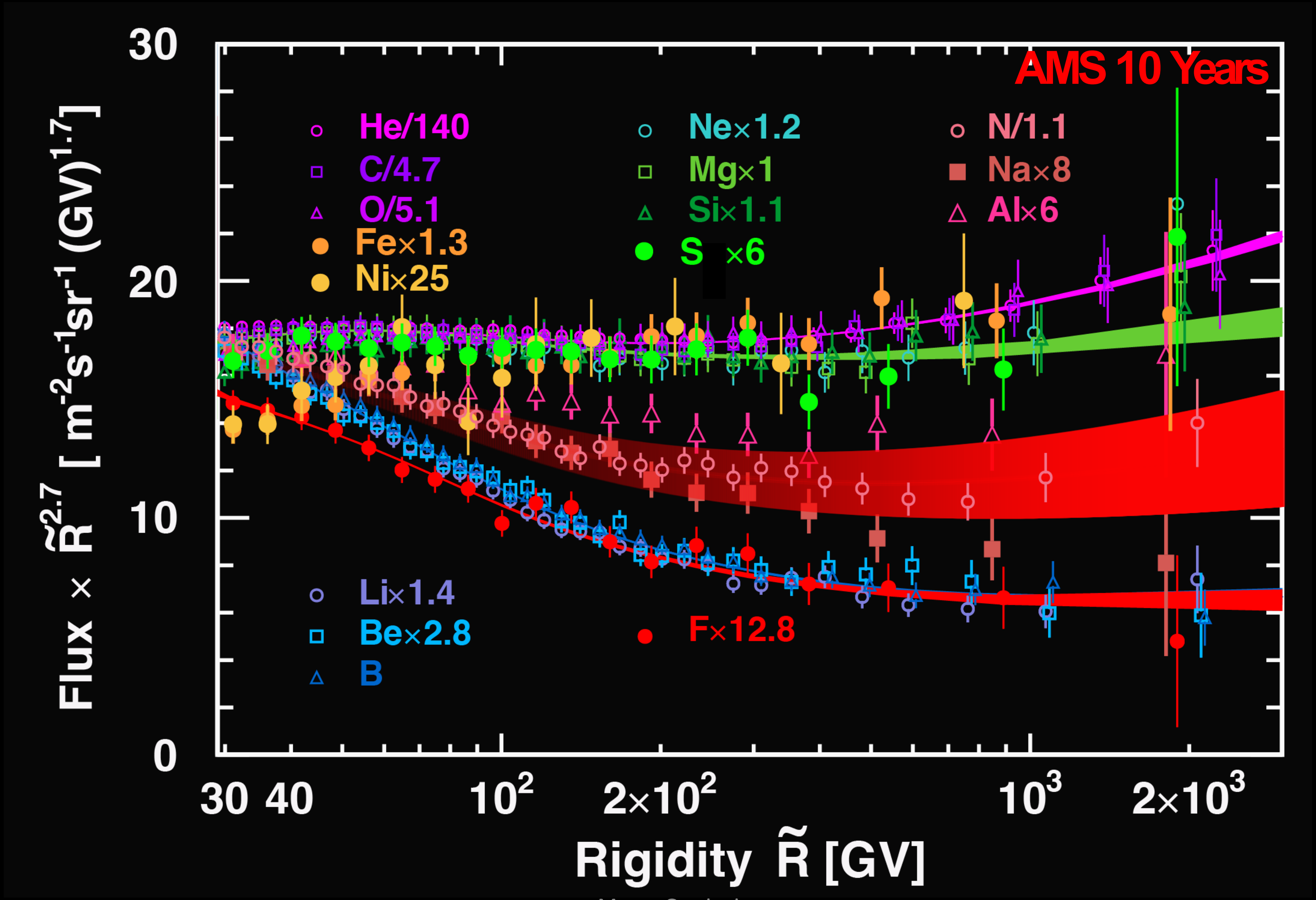
Latest AMS Results: Sulfur Rigidity Dependence







Sulfur belongs to the same class as Ne, Mg, and Si.



AMS 10 Years
He/140
C/4.7
O/5.1
Fe×1.3
Ni×25
Ne×1.2
Mg×1
Si×1.1
S [redacted] ×6
N/1.1
Na×8
Al×6
Li×1.4
Be×2.8
B
F×12.8
30
20
10
0
$\text{Flux} \times \tilde{R}^{2.7}$ [$m^{-2}s^{-1}sr^{-1}$ $(GV)^{1.7}$]
30 40
10^2
2×10^2
10^3
2×10^3
Rigidity $\tilde{R}$ [GV]