Modeling solar modulation in cosmic rays

in light of new data from AMS-02 and PAMELA

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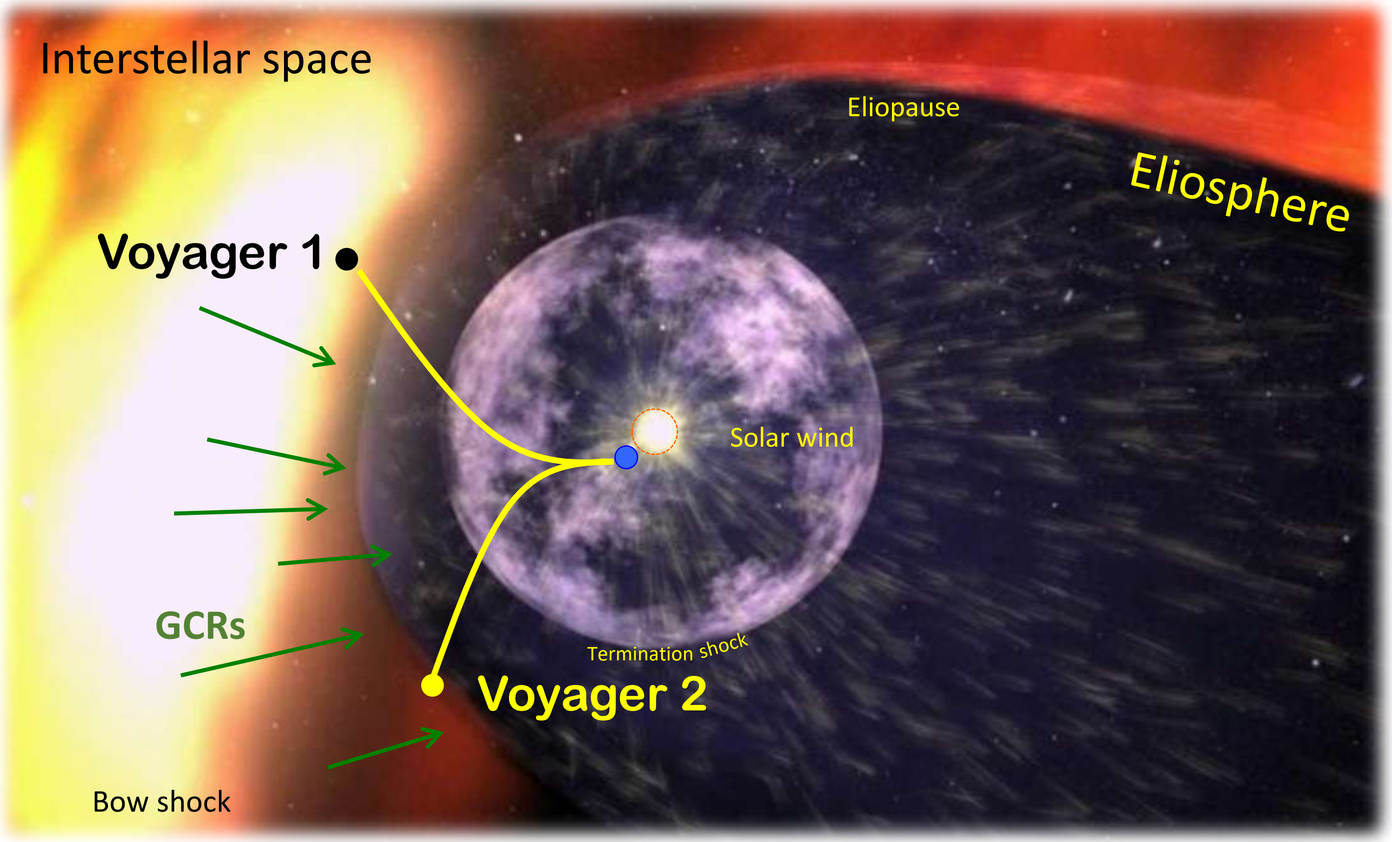
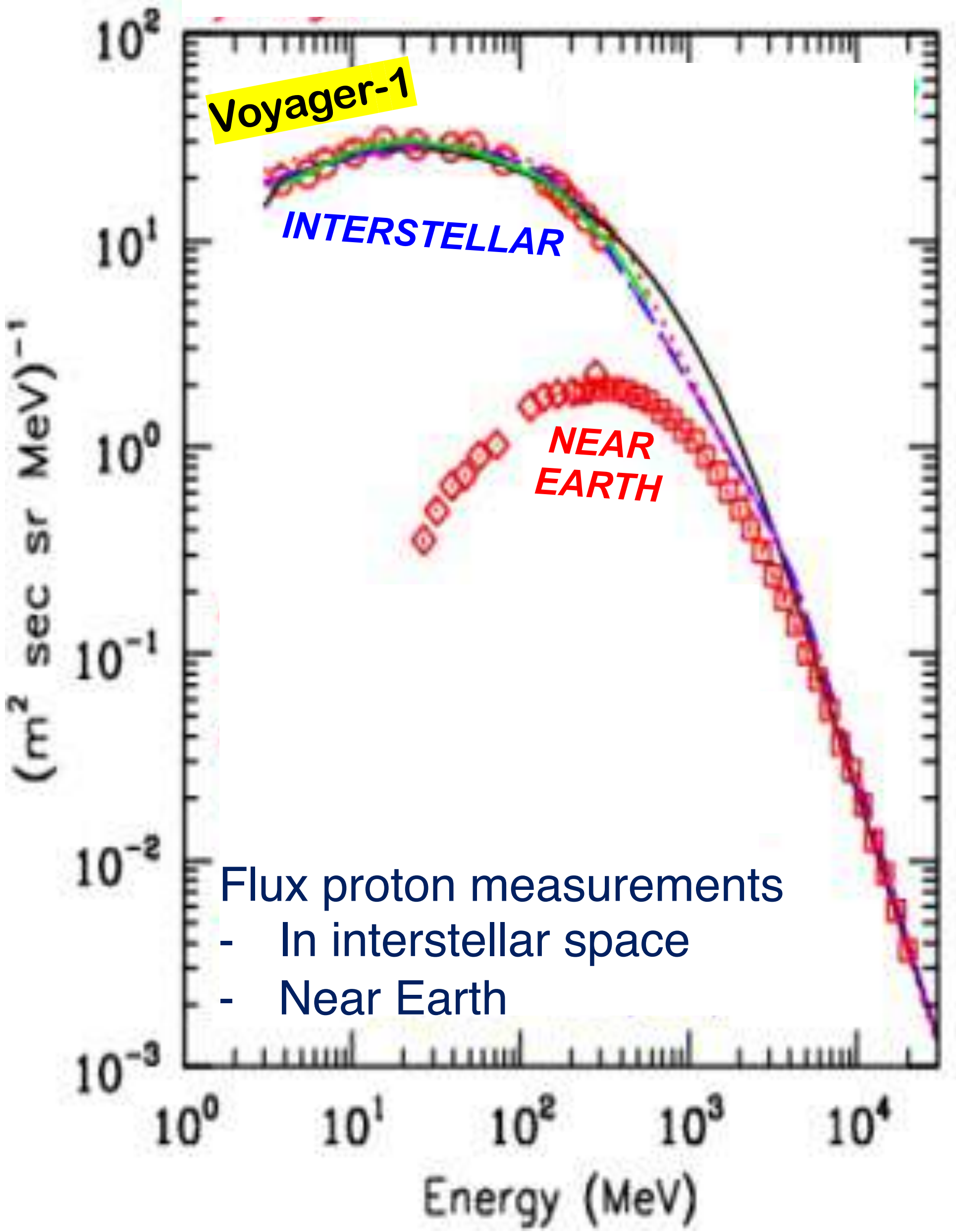
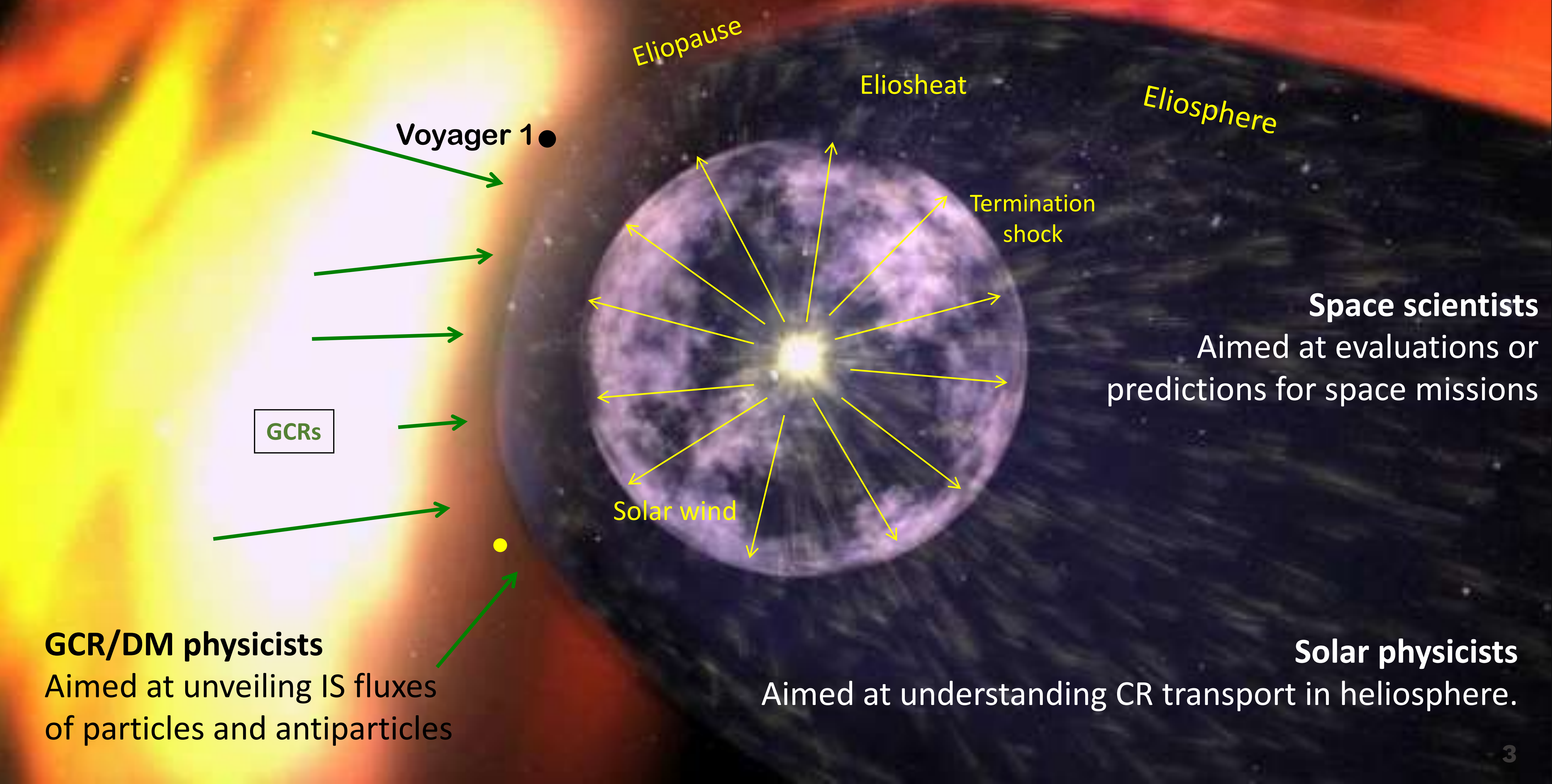
Solar modulation phenomenon

Voyager-1 in 2012, first data from interstellar space
Voyager-2 since 2018 in interstellar space





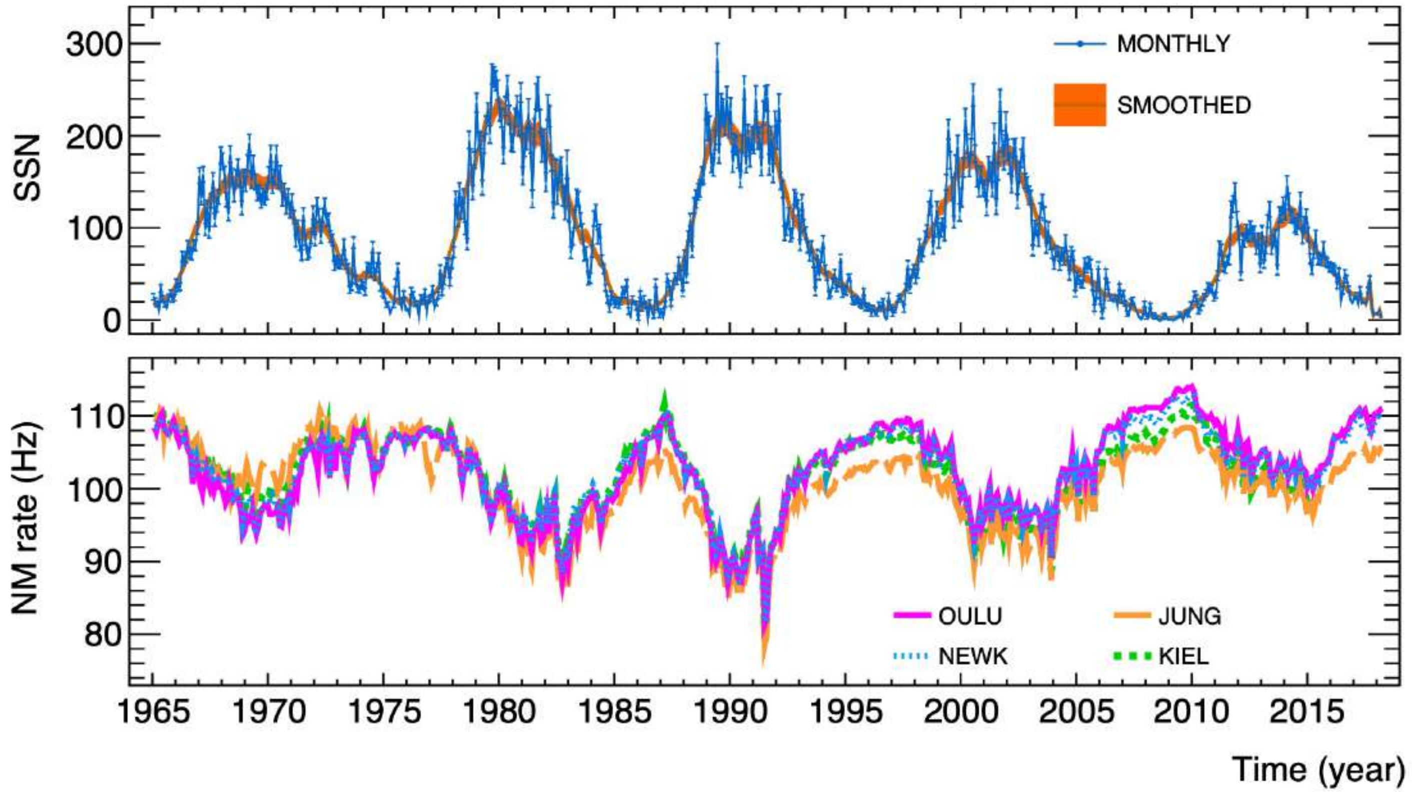
Galactic cosmic rays in the Heliosphere

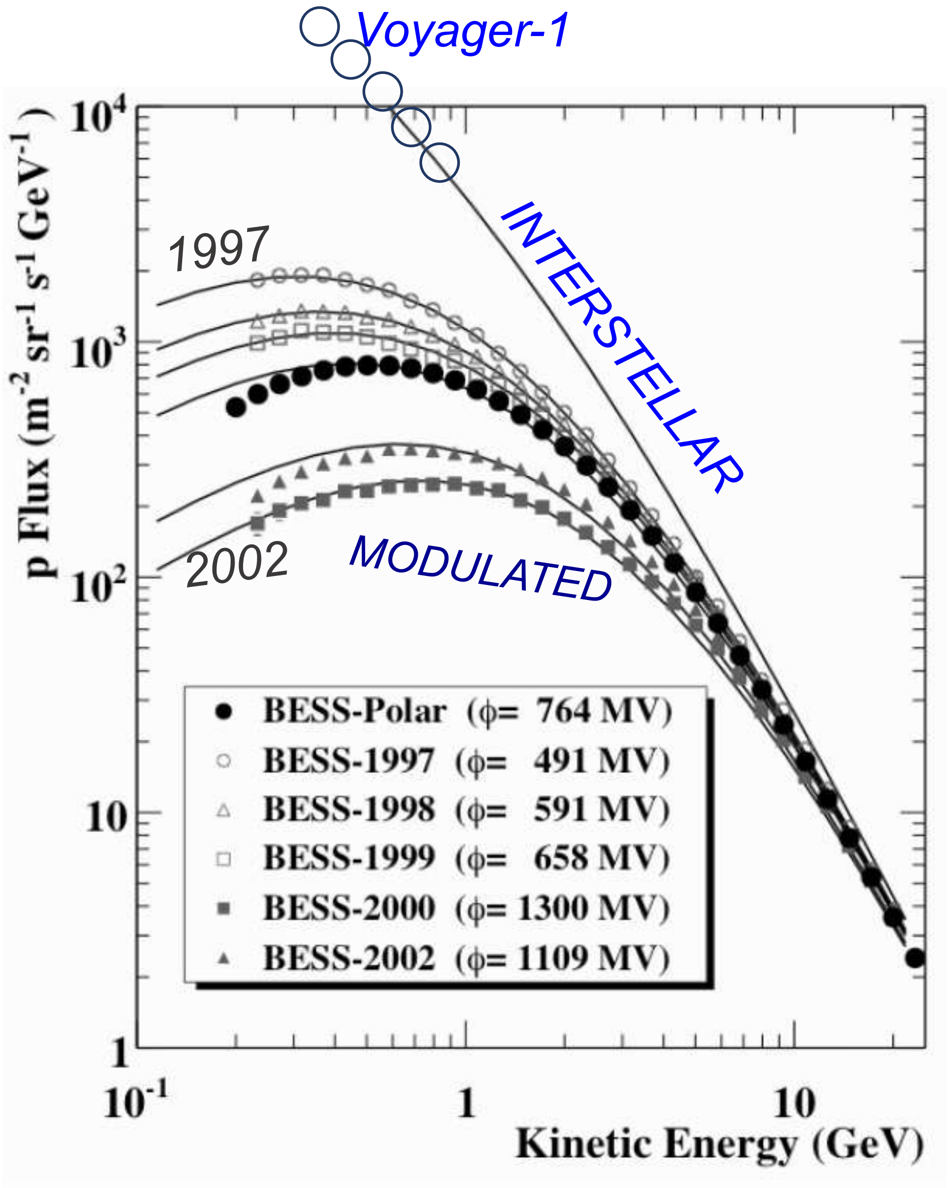


Basic phenomenology

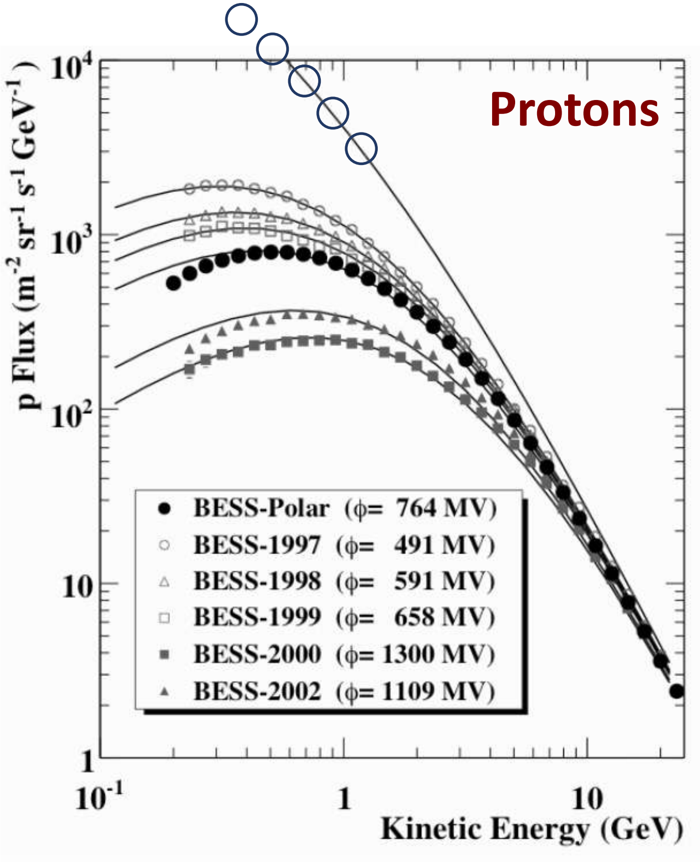
Time dependent | Space dependent
Energy dependent | Particle dependent

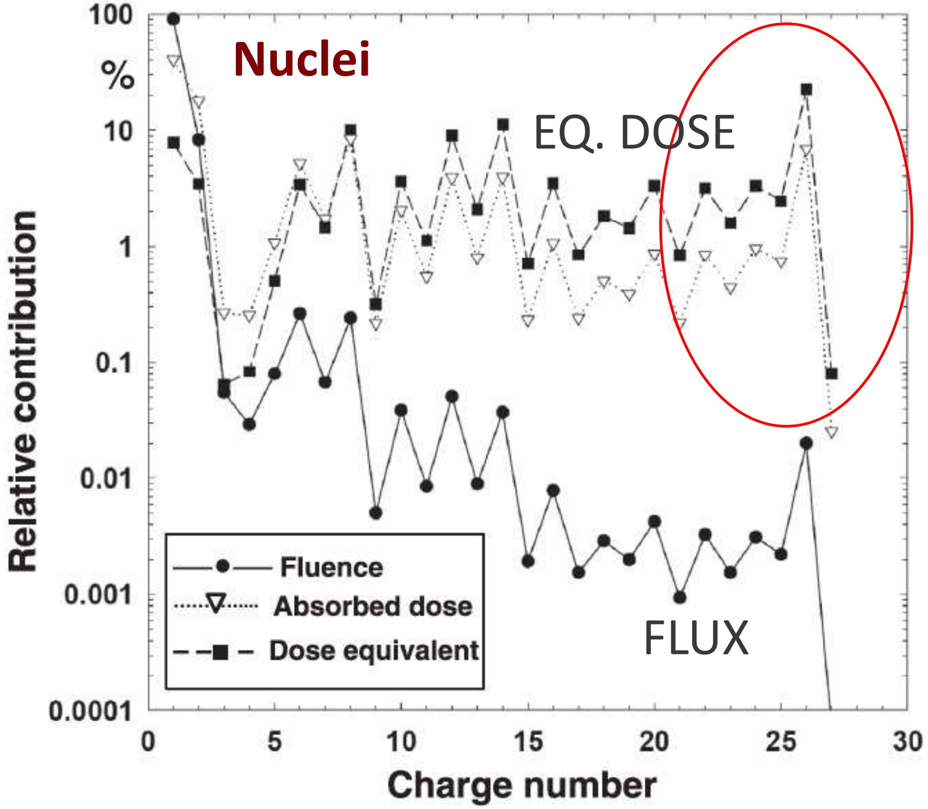
→ Connection with Sun's magnetic activity
→ Need of multichannel & time-resolved data

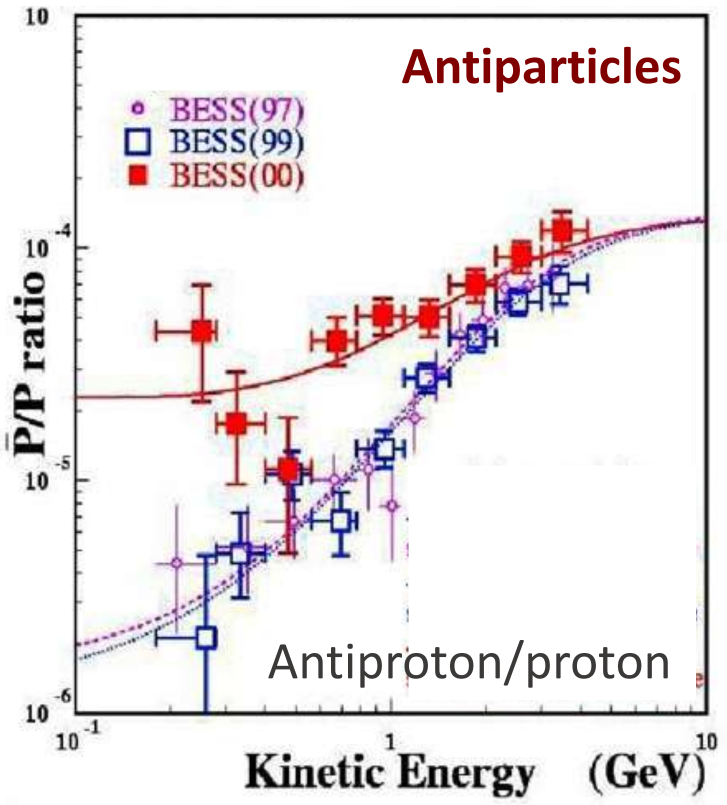




Basic phenomenology







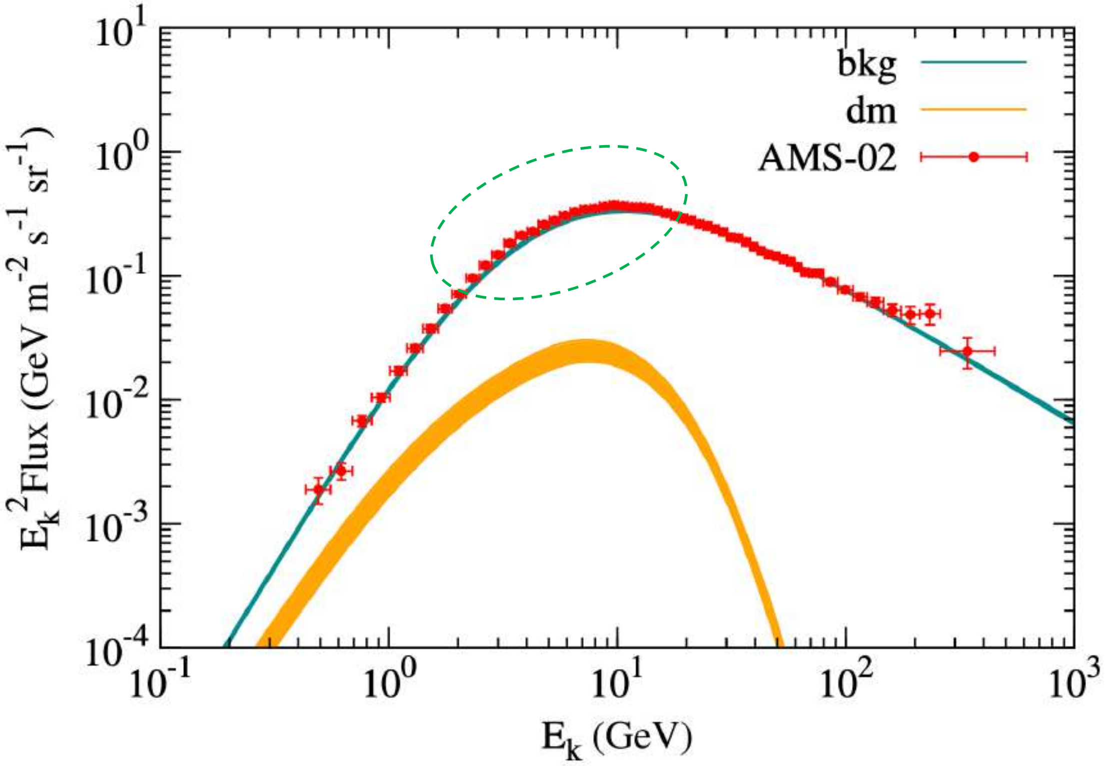
Dominant in GCRs. Best data.
To probe GCR transport

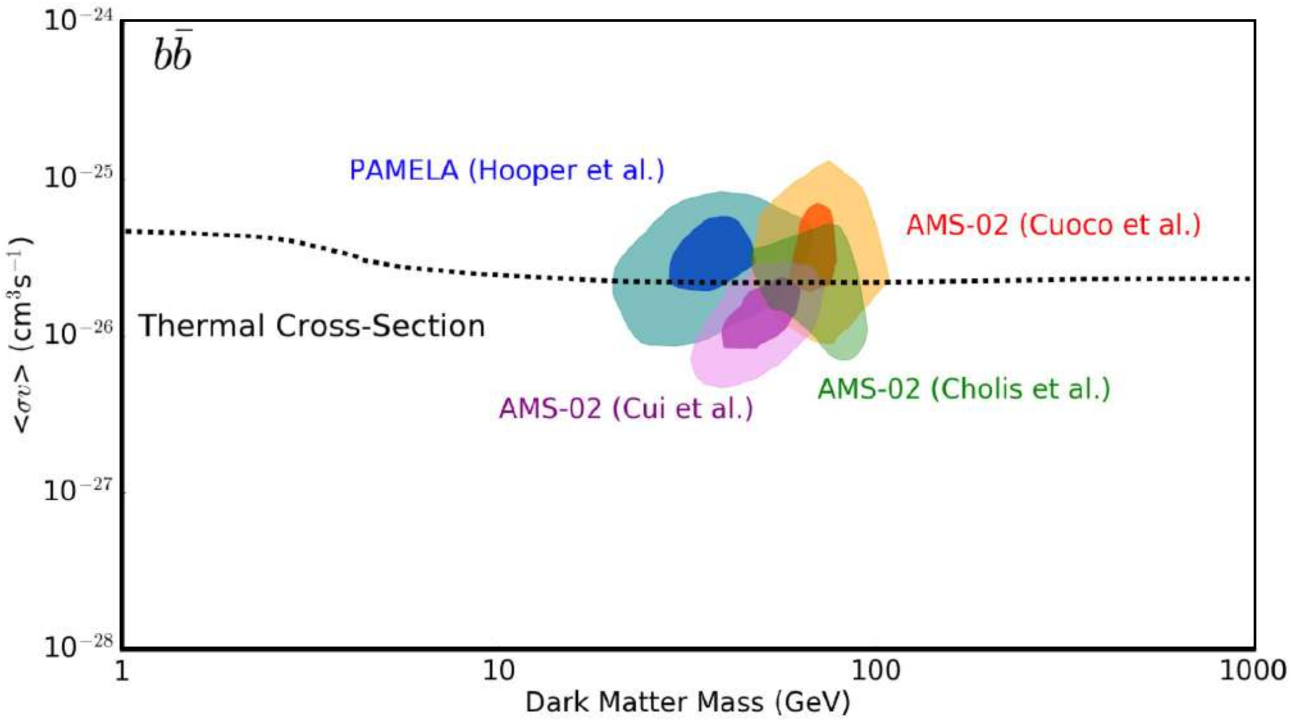
Important source of radiation
To assess radiation dose

Messengers for new physics
Precious source of information

Antiproton modulation

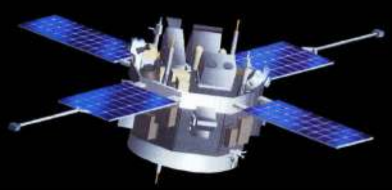
- Hint of a ~5 GeV excess. DM fit with $M_\chi \approx 50$ GeV and $\langle \sigma_A v \rangle \approx 10^{-26}\, cm^2/s$ in $\chi\chi \rightarrow b\bar{b}$.
- The DM fit is consistent with GeV excess, with the current limits, with the WIMP paradigm
- Uncertainties in the GeV region: production cross sections, propagation, **solar modulation**



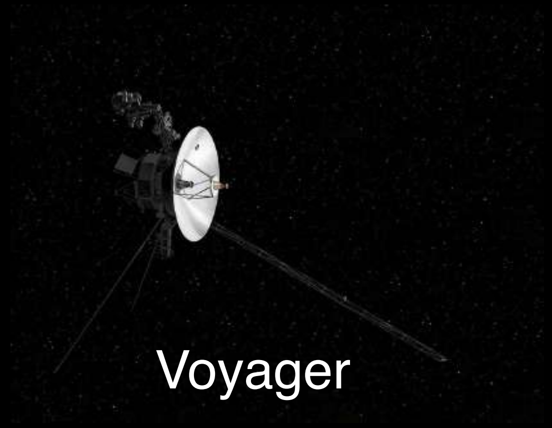


Observational milestones

- ☑ Particle-resolved
- ☑ Time-resolved
- ☑ Energy-resolved
- ☐ Space resolved

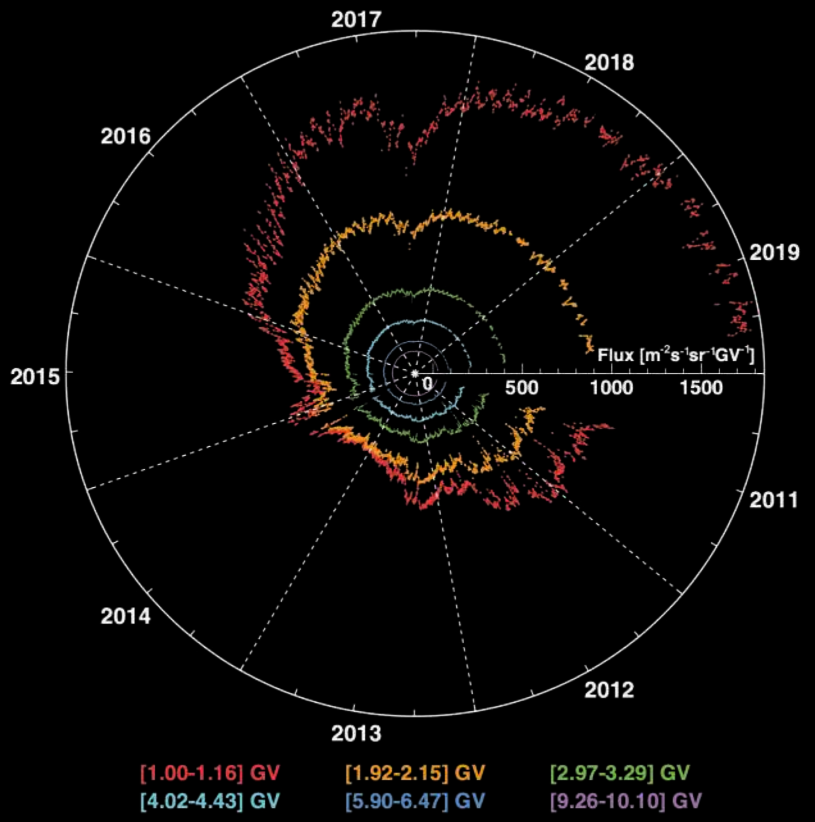


ACE, PIONEER, ULYSSES



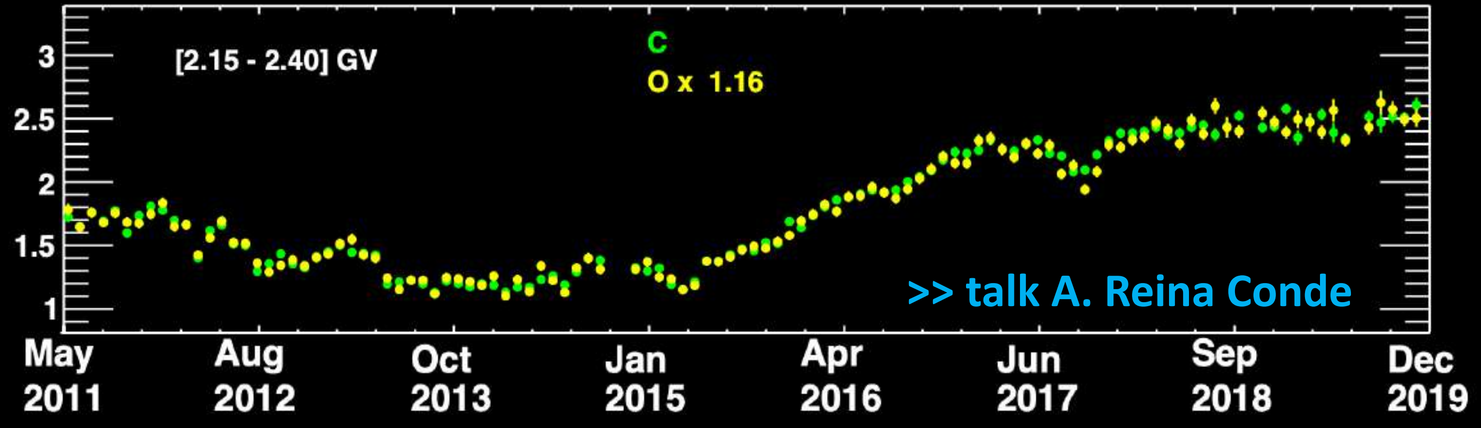
Observational milestones: AMS-02

Protons, Helium

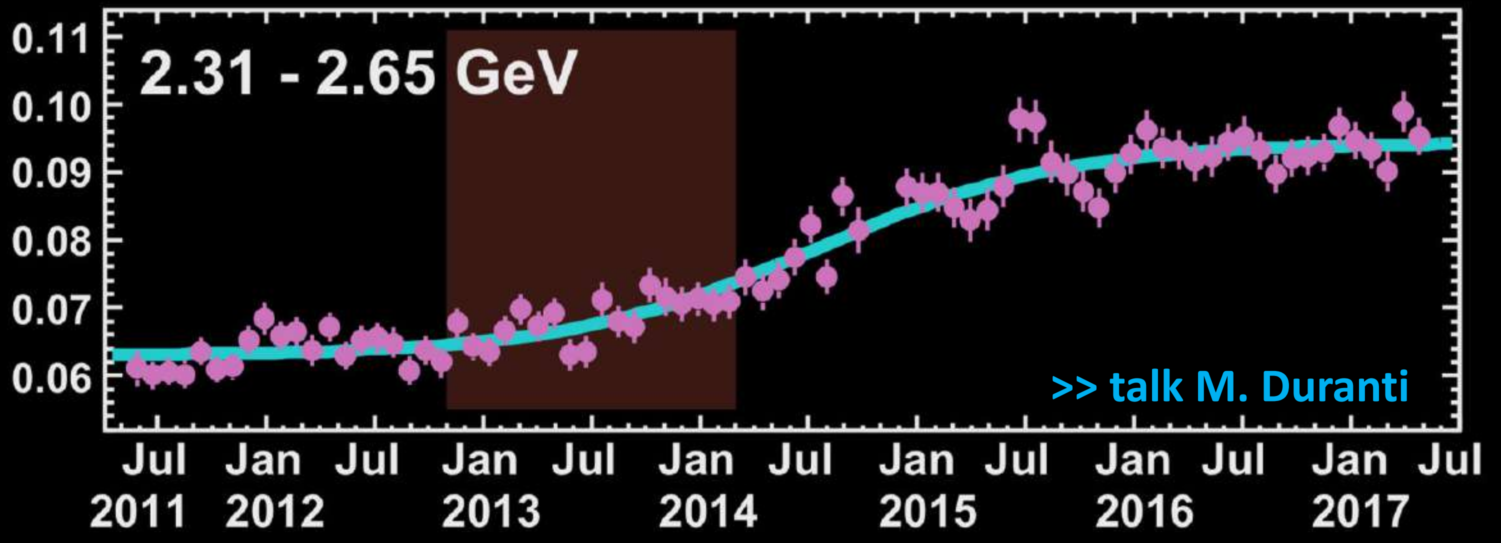


Daily proton and helium flux measurements from AMS-02 (PRL 2021 & PRL 2022)

Light Nuclei

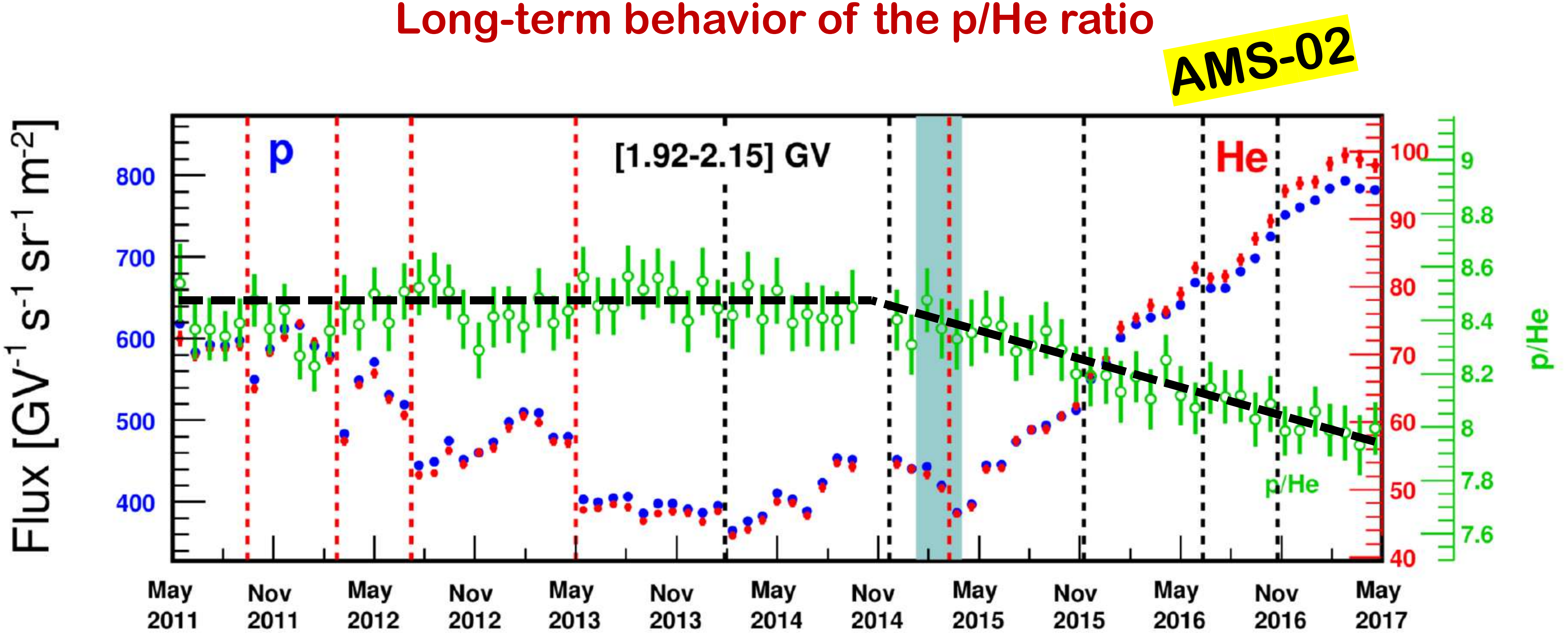


Positron



Observational milestones: protons & helium

Long-term behavior of the p/He ratio

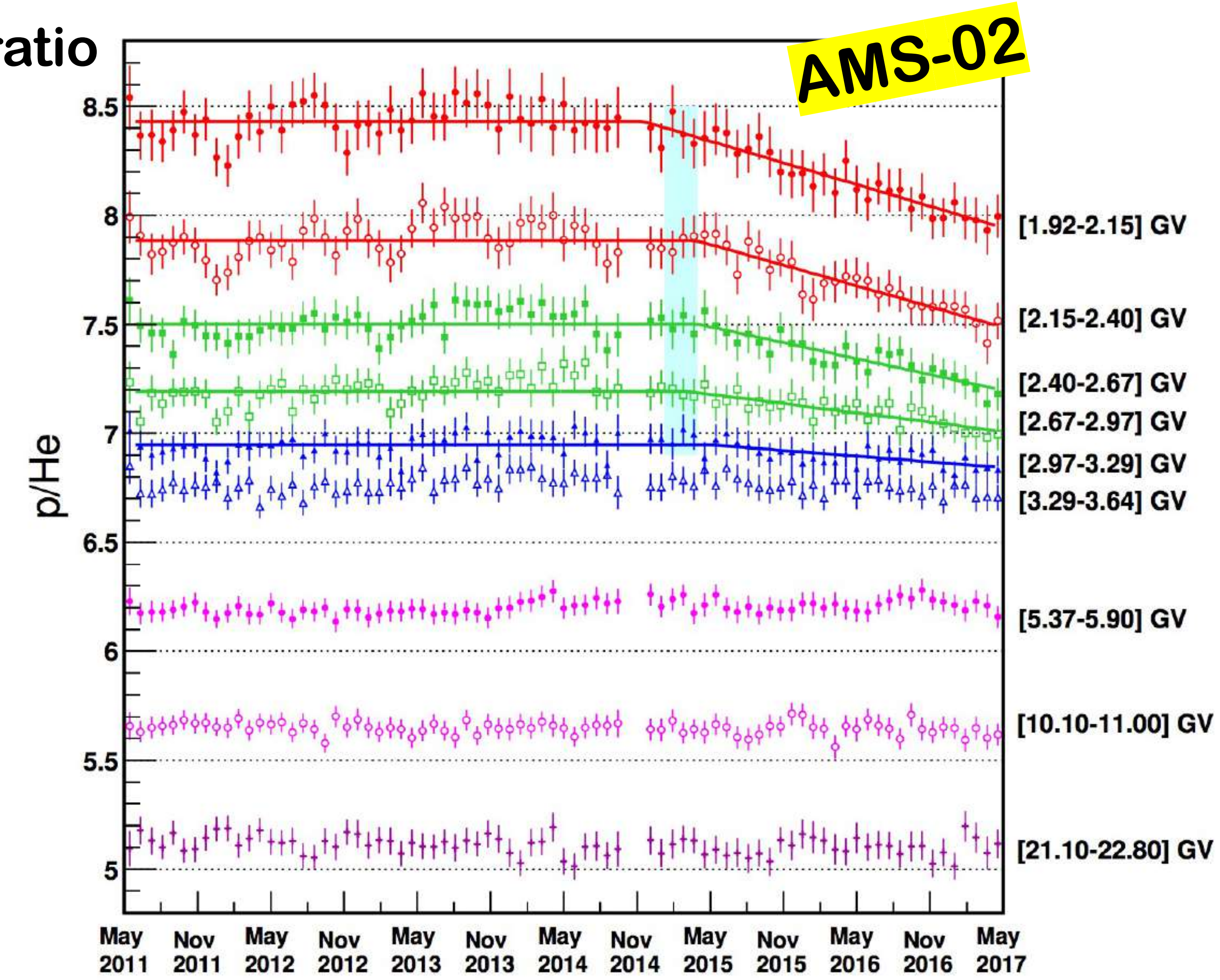


Aguilar et al. Phys. Rev. Lett. 120 (2018) 051101

Observational milestones

Long-term behavior of the p/He ratio

The ratio between proton and helium fluxes at the same rigidity value is not constant at rigidity below ~3 GV

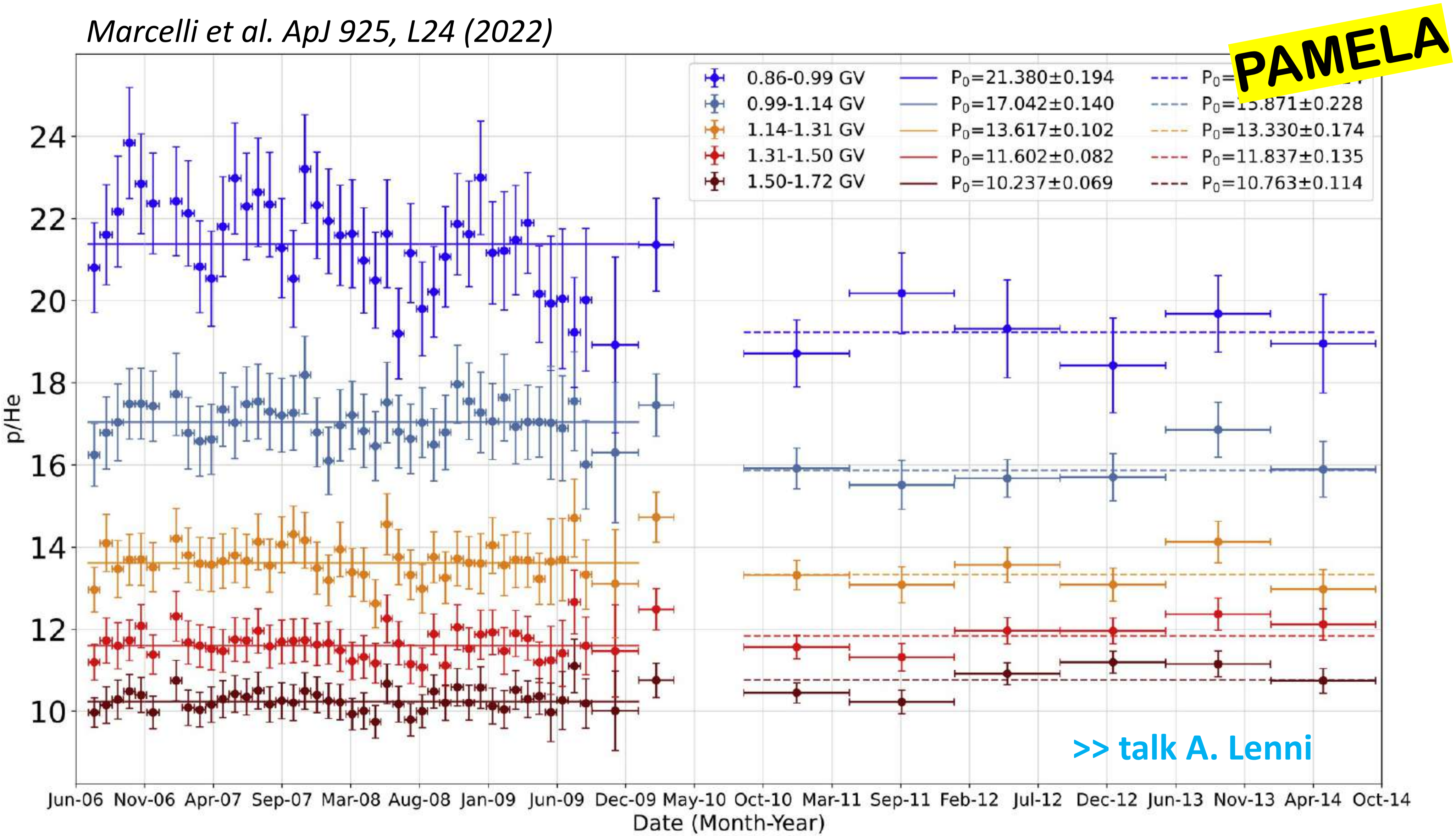


AMS-02 data on proton, helium, and p/He ratio

New measurements on daily basis:
Aguilar et al., PRL 128, 231102 (2022)

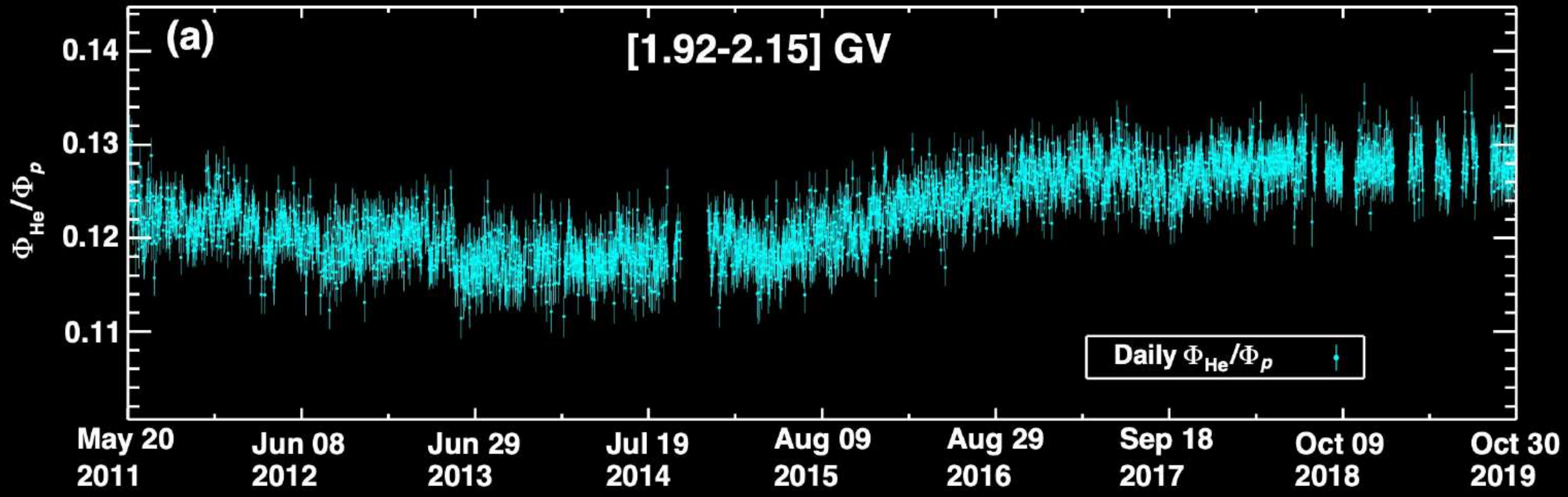
Observational milestones

Marcelli et al. ApJ 925, L24 (2022)



Observational milestones

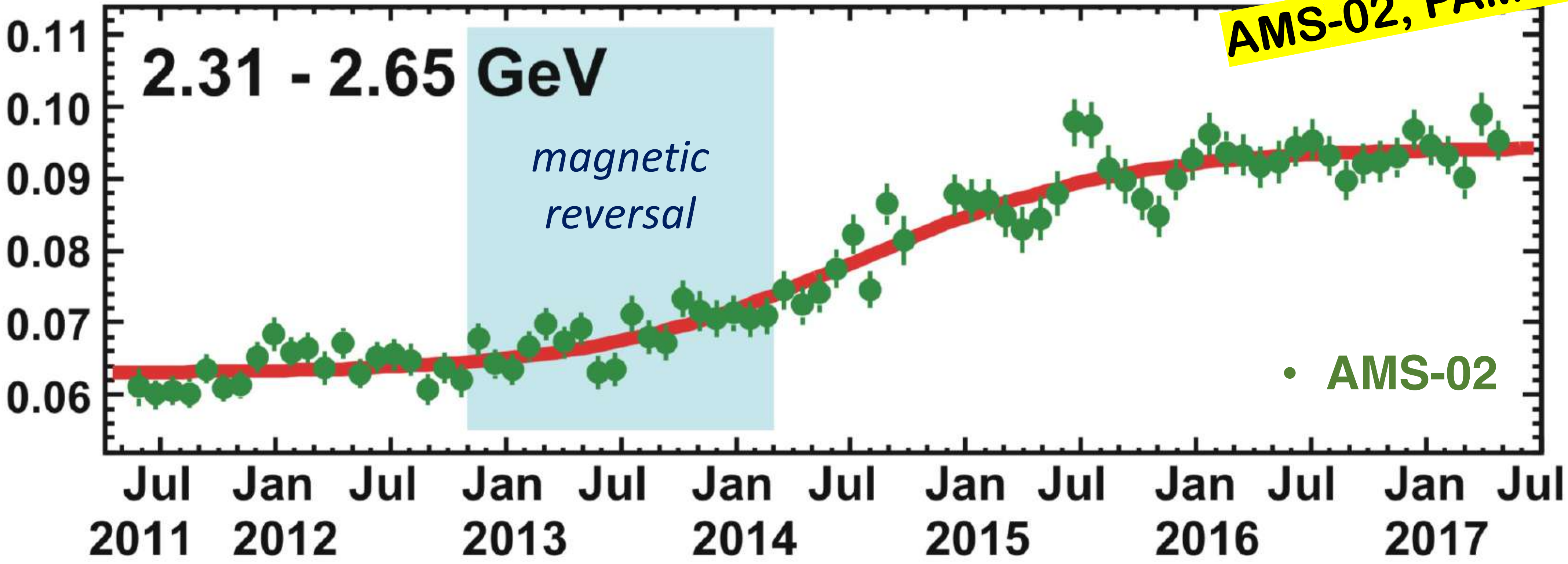
Aguilar et al., PRL 128, 231102 (2022)



Observational milestones

Evolution of e+/e- ratio through the solar magnetic reversal

AMS-02, PAMELA



AMS-02: Aguilar et al. PRL 120 051102 (2018)
PAMELA: Adriani et al. PRL 116 241105 (2016);

>> talk A. Lenni

Solar Modulation Calculations

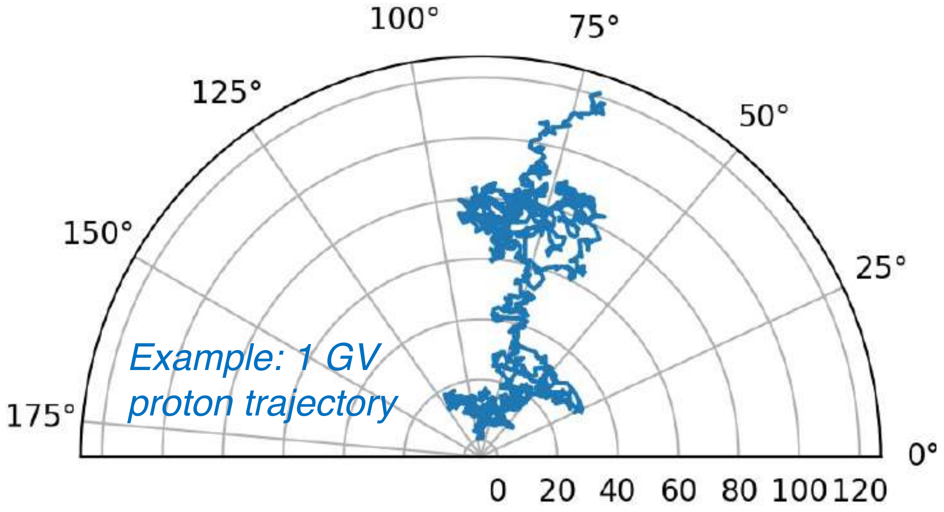
Parker equation *captures the whole phenomenology of CRs in the heliosphere*

$$\underbrace{\frac{\partial f}{\partial t}}_{\text{Flux}} = \underbrace{\nabla \cdot [\mathbf{K} \cdot \nabla f]}_{\text{Diffusion}} - \underbrace{\mathbf{V} \cdot \nabla f}_{\text{Convection}} - \underbrace{\langle \mathbf{v}_D \rangle \cdot \nabla f}_{\text{Particle drift}} + \underbrace{\frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln p}}_{\text{Energy losses}} + \underbrace{Q(r, p, t)}_{\text{Source}}$$

Stochastic method

The solution is obtained by MC sampling

Our setup: Fiandrini+ D 104, 023012 (2021)



CR transport parameters

Free parameters that regulate the processes of CR tranport in heliosphere, e.g. diffusion and drift.

connection

Heliospheric input parameters

Proxies for the average condition of the heliospheric plasma (the medium where CRs move throught) at a given epoch

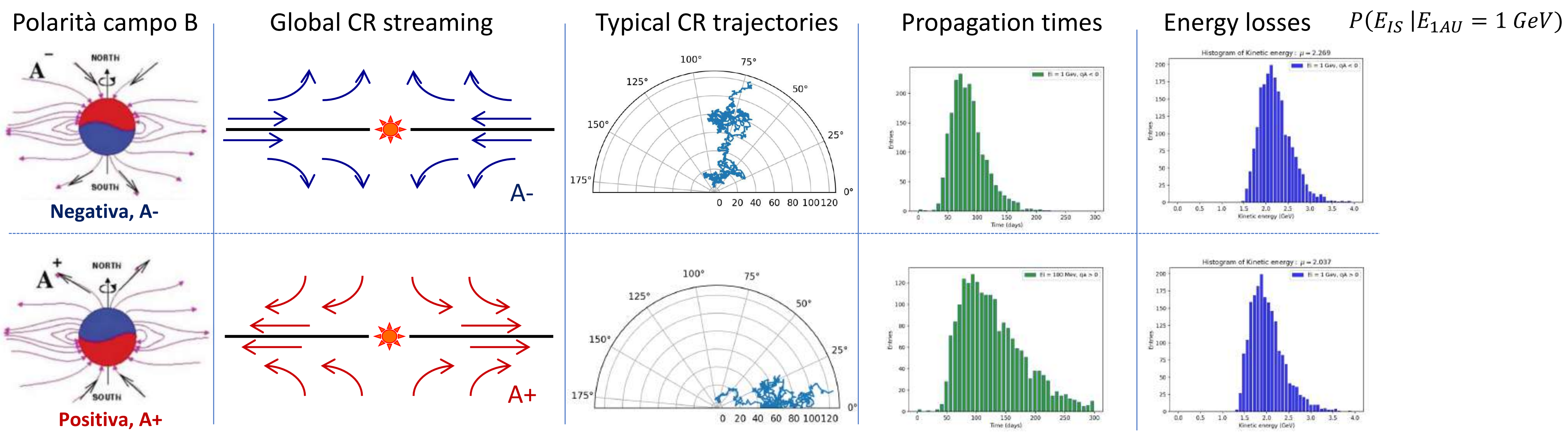
- *IMF intensity*
- *IMF polarity*
- *IMF Tilt Angle*

Solar Modulation Calculations

Parker equation *captures the whole phenomenology of CRs in the heliosphere*

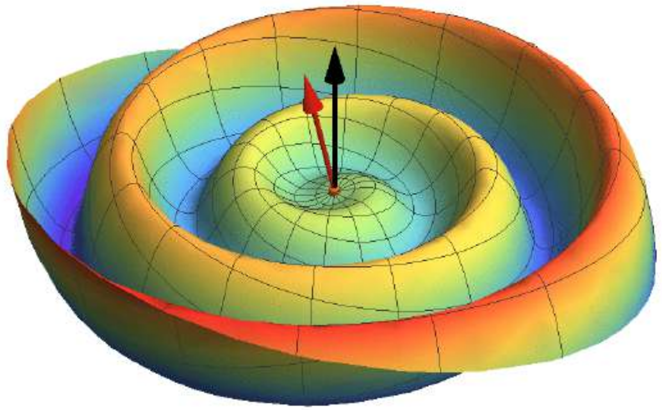
$$\frac{\partial f}{\partial t} = \nabla \cdot [\mathbf{K} \cdot \nabla f] - \mathbf{V} \cdot \nabla f - \langle \mathbf{v}_D \rangle \cdot \nabla f + \frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln p} + Q(r, p, t)$$

Flux — **Diffusion** — **Convection** — **Particle drift** — **Energy losses** — **Source**



Heliospheric input Parameters: IMF

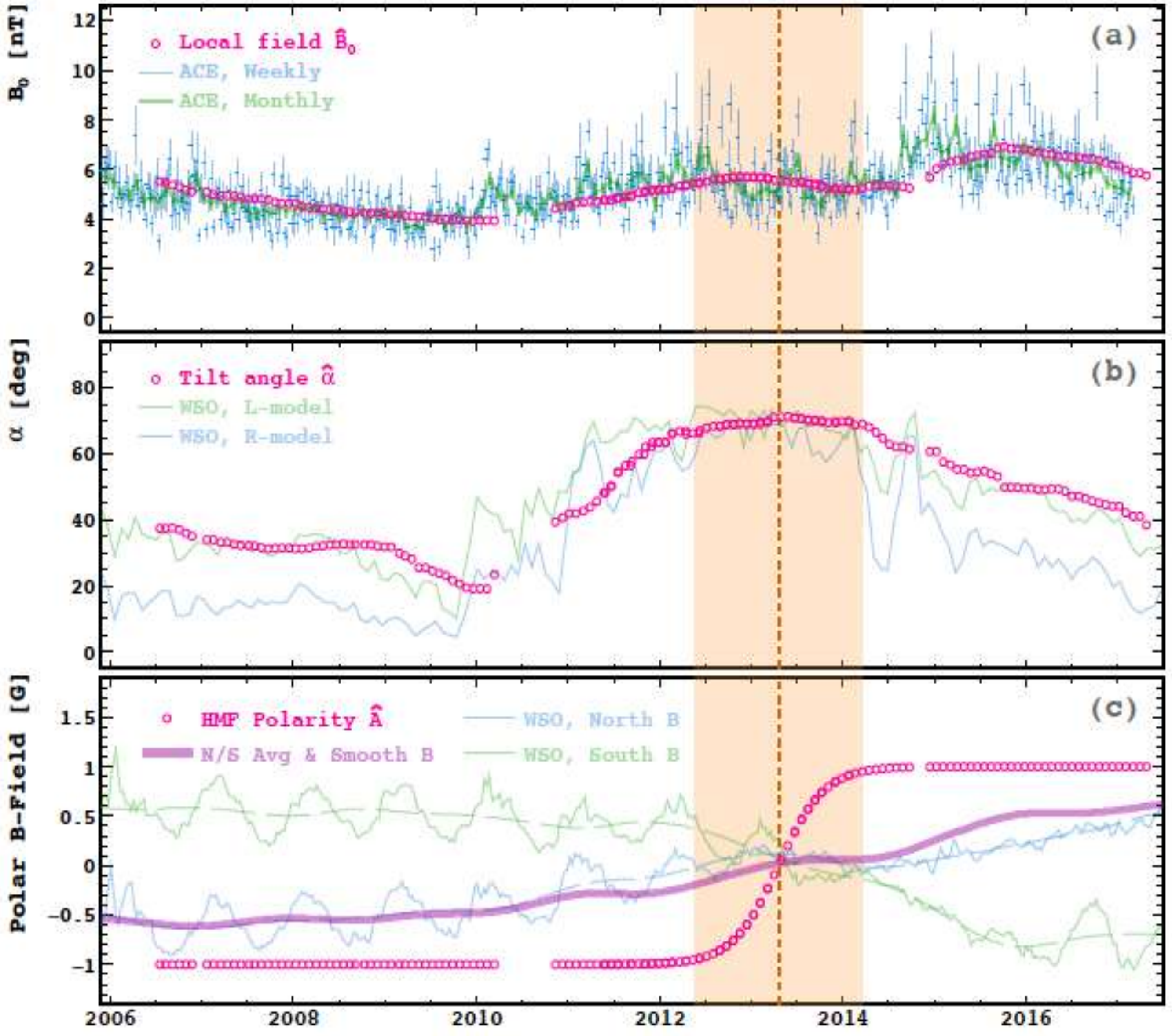
Fiandrini et al. Phys. Rev. D 104, 023012 (2021)



intensity

tilt angle

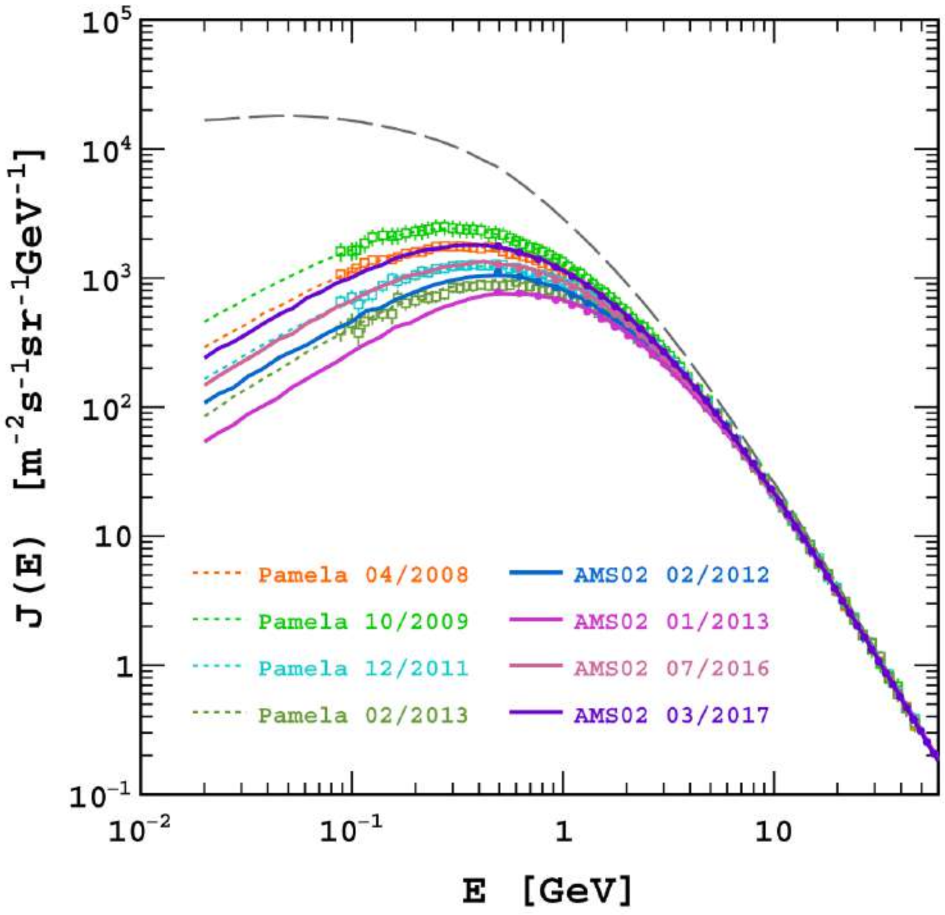
polarity



Solar Modulation Calculations

Parameters of CR diffusion determined over one solar cycle and across reversal

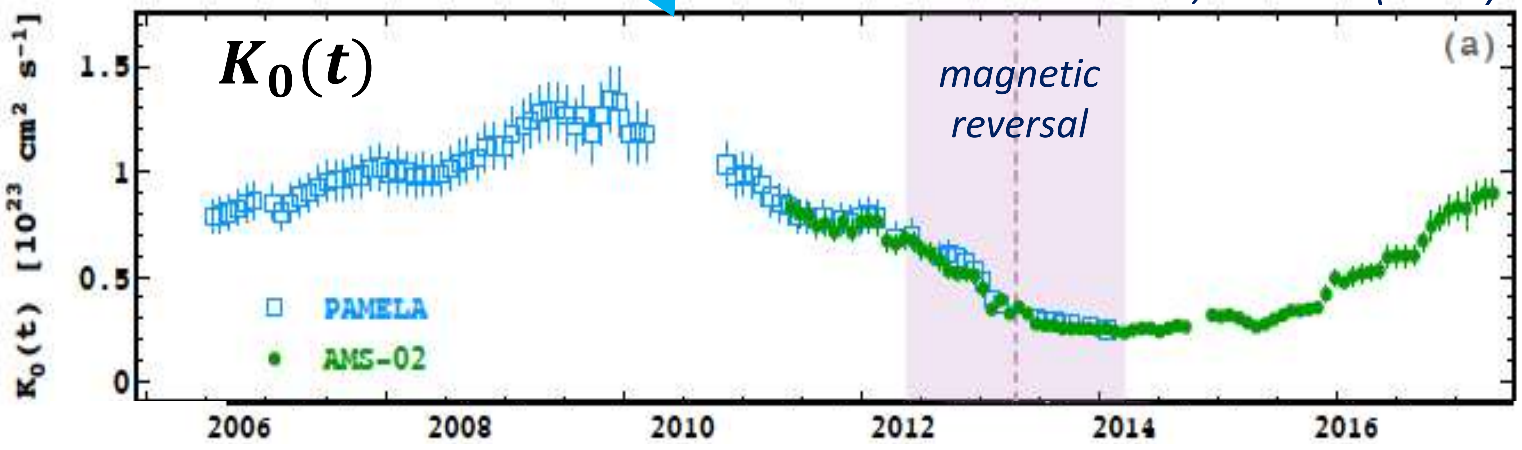
Modelled GCR spectra



Parallel component of the diffusion tensor

$$K_{\parallel}(R,t) = \begin{cases} K_0(t) R^{a(t)} & (R < R_0) \\ K_0(t) R^{b(t)} & (R > R_0) \end{cases}$$

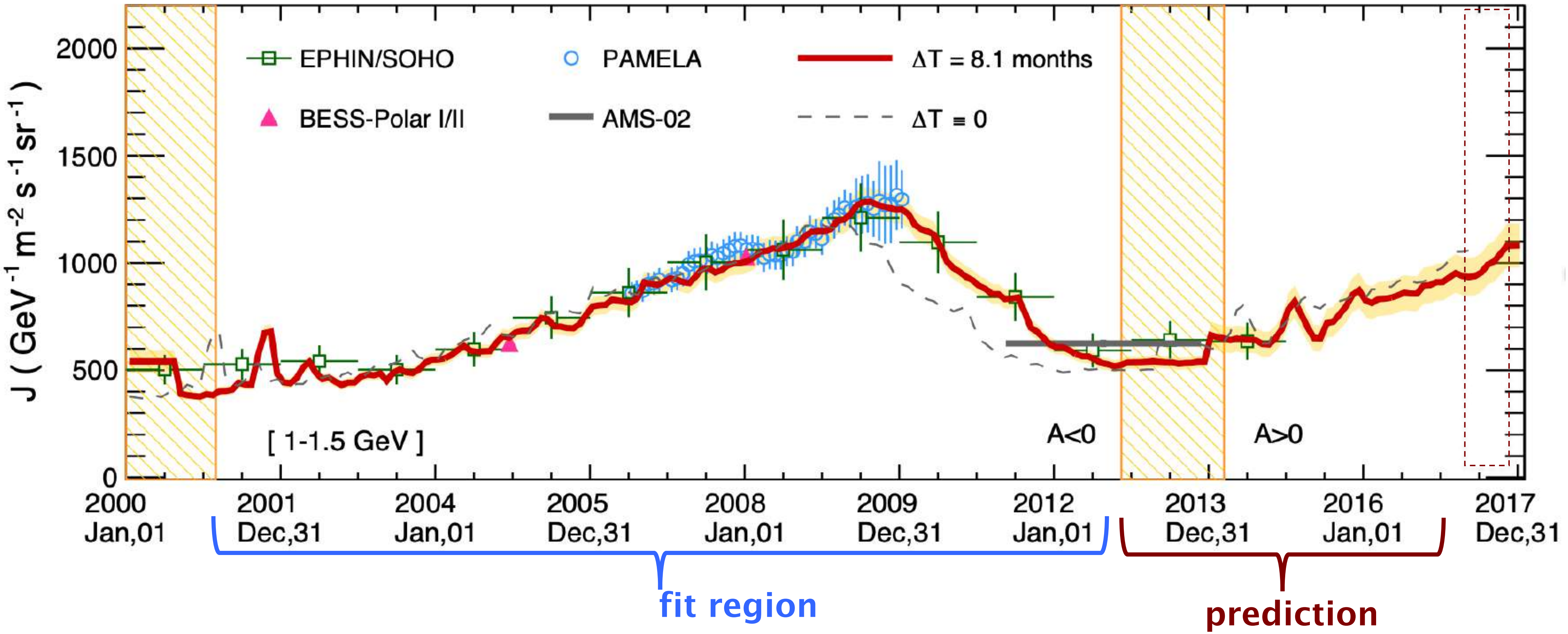
Fiandrini+ PRD 104, 023012 (2021)



Insights from protons: time lag beween CR and SSN

Connection between CR diffusion (K_0) and solar activity (SSN): delayed correlation

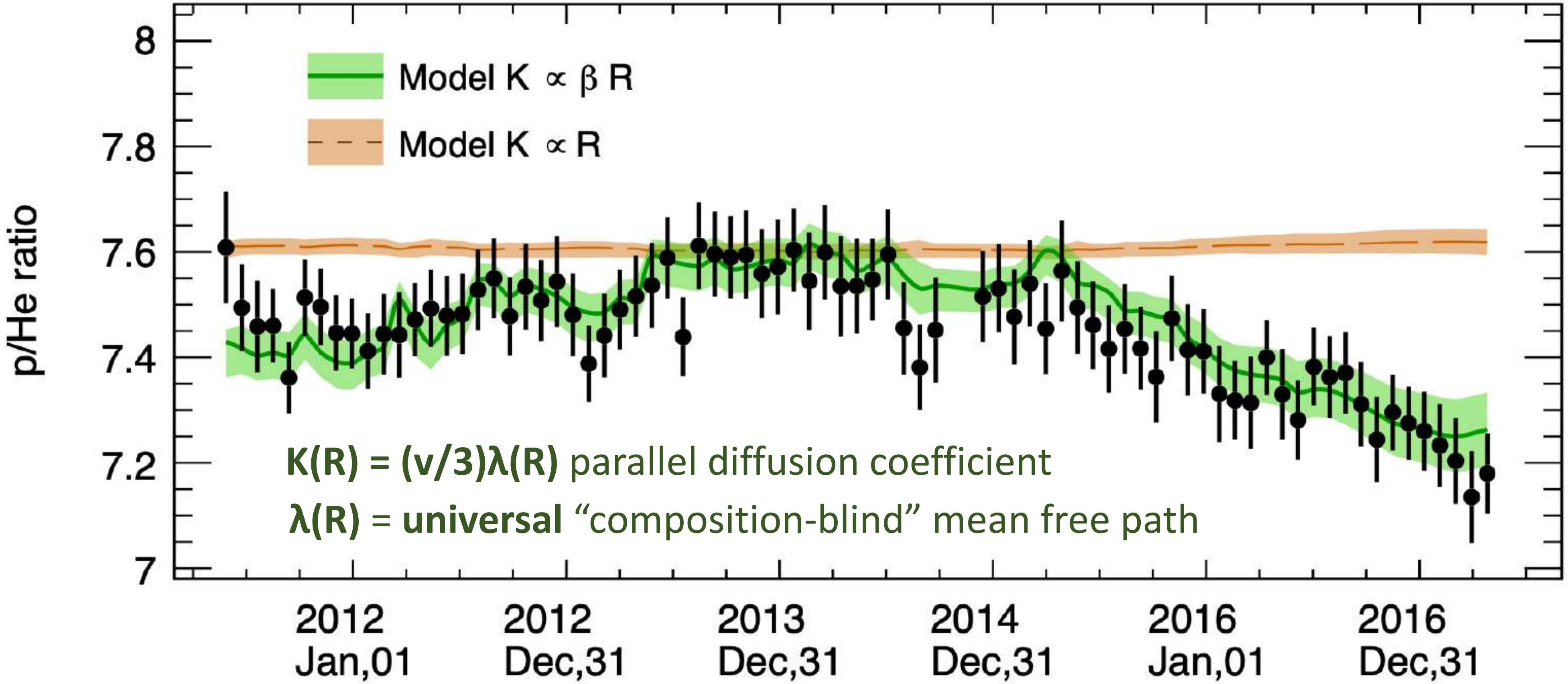
NT+ ApJ 849, L32 (2017) *Fiandrini+ PRD 104, 023012(2021)*



Insights from the p/He ratio: diffusion

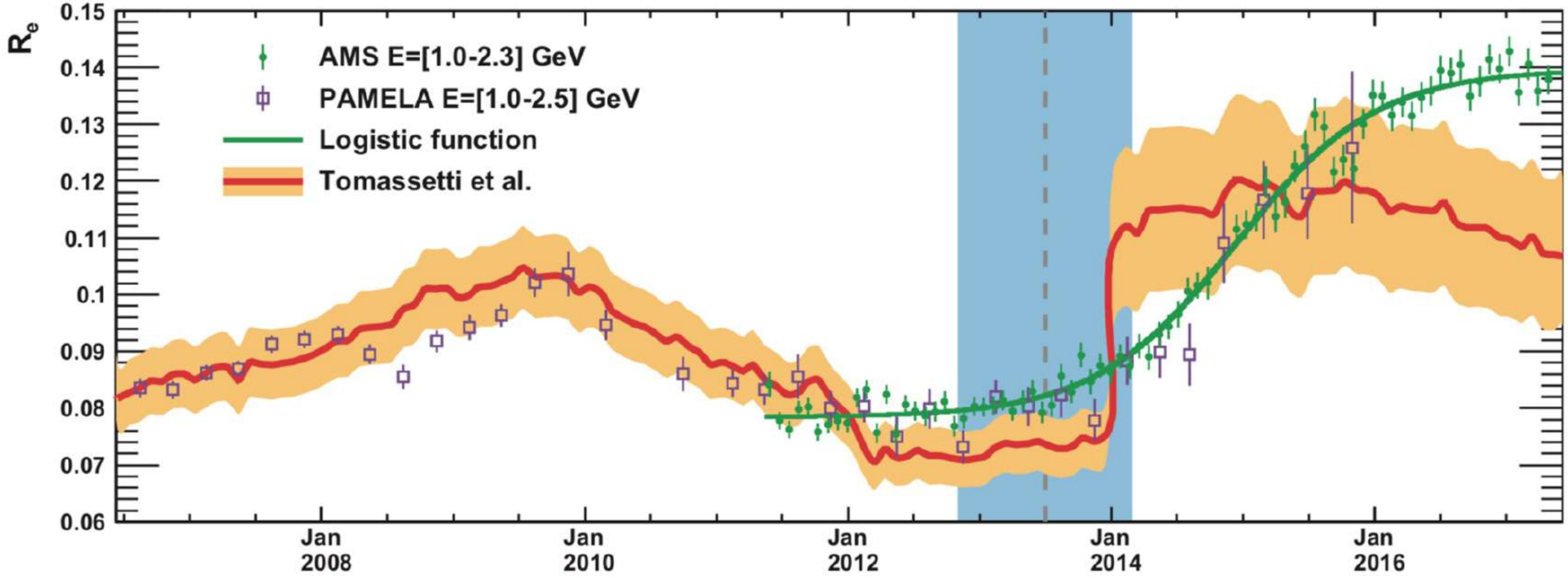
The p/He long-term behavior is a signature of *universality* of the CR mean free path λ(R)

NT+ PRL 121 251104 (2018) [arXiv:1811.08909] *NT+ ASR 64 2477 (2019) [arXiv:1906.11477]*



Insights from antimatter/matter ratios: drift

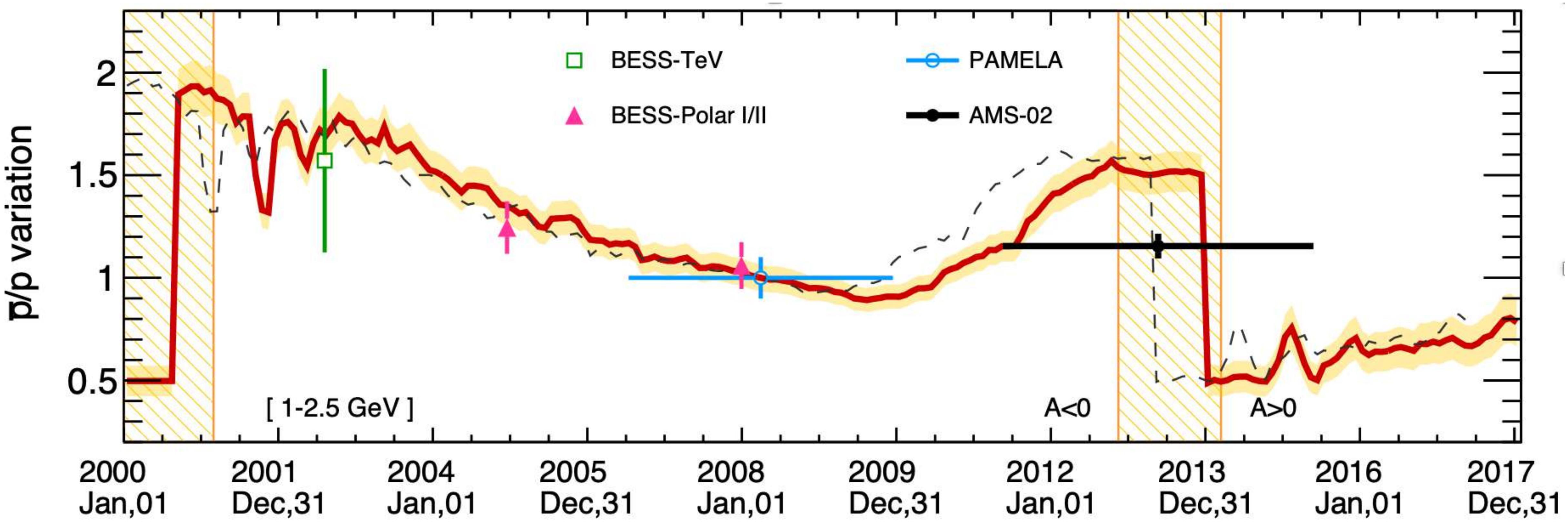
The e+/e- ratio is a signature of *charge-sign dependent drif* of CRs in the IMF



From: Aguilar et al. PRL 120 (2018) 051102

Insights from antimatter/matter ratios: drift

Predictions for the antiproton/proton ratio



Insights from antimatter/matter ratios: drift

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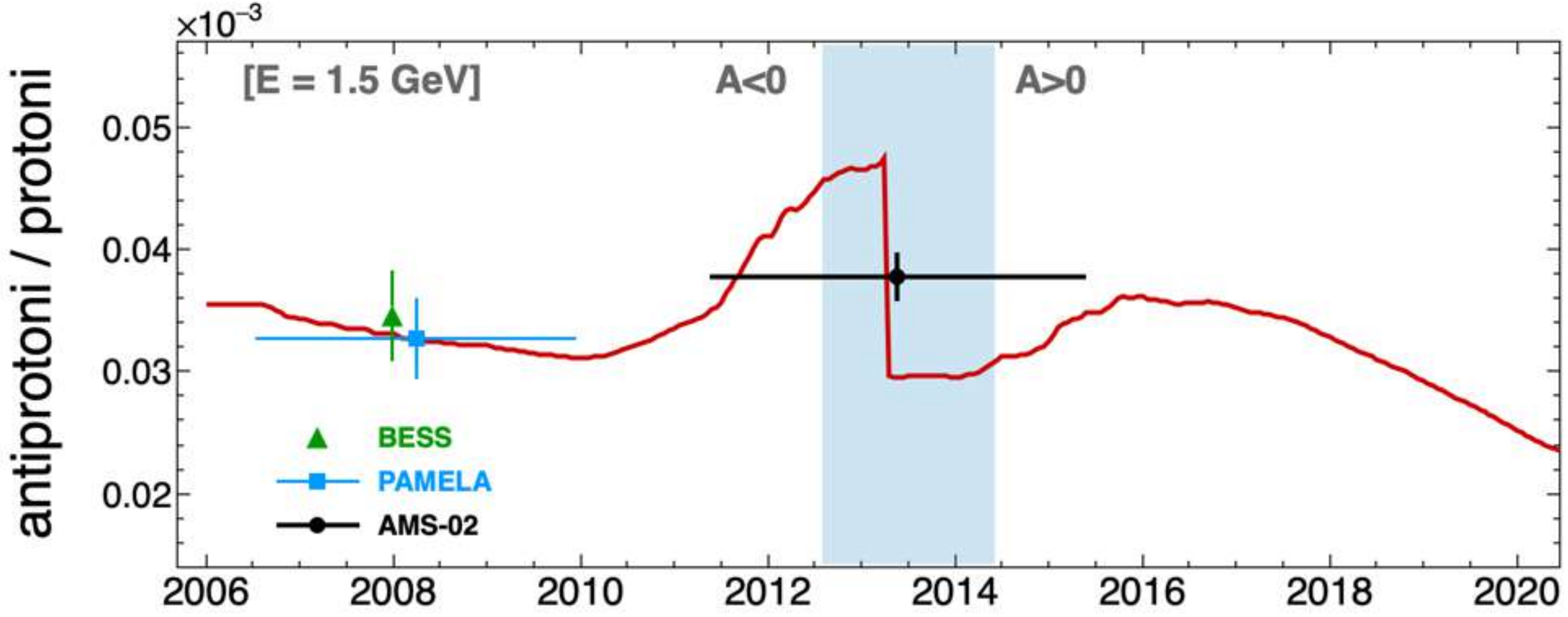
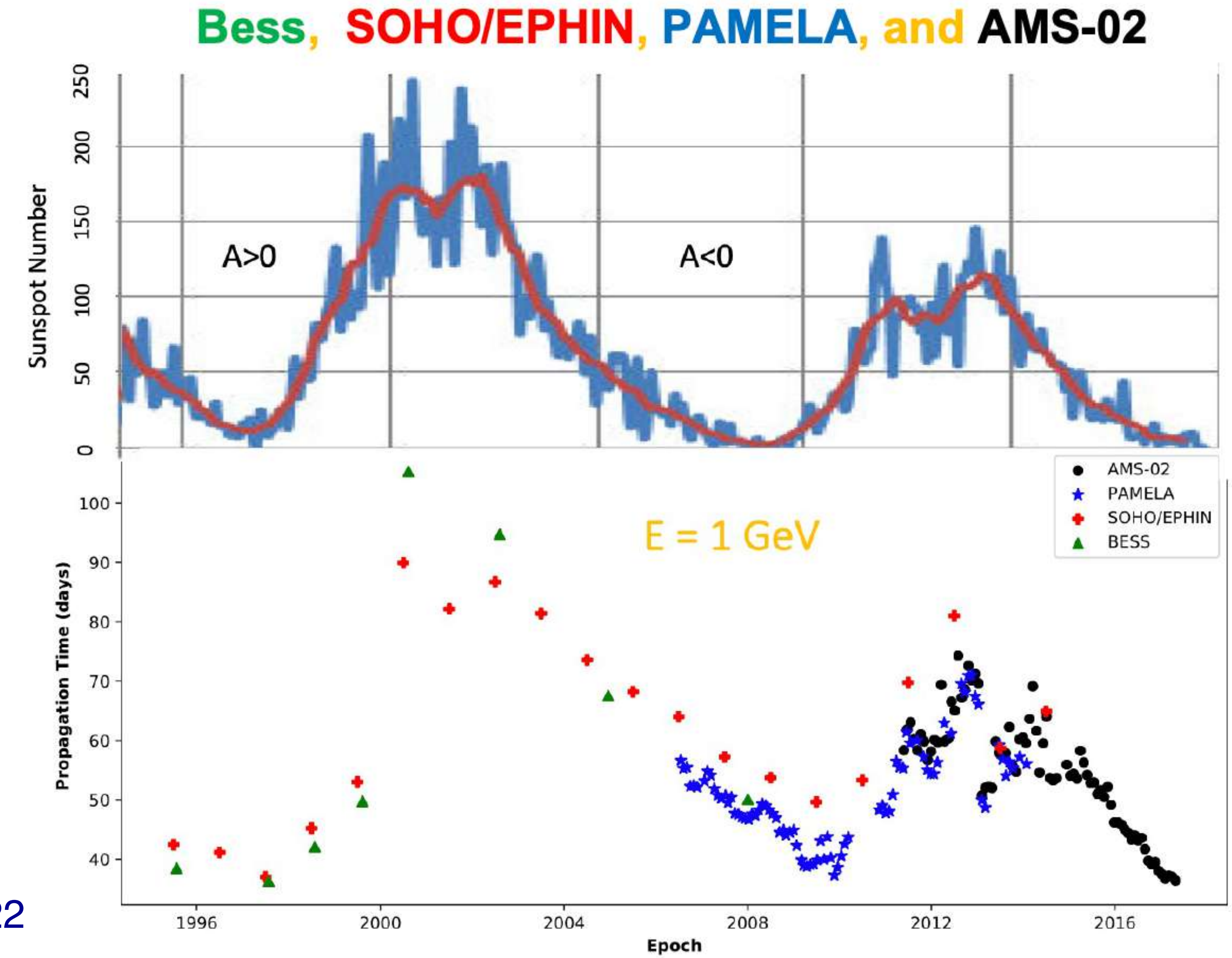


Evolution of the CR propagation times

New result: Data-driven calculation of the CR propagation times and energy losses and how they *evolve* over the solar cycle.

Example: 1 GeV CR protons spend 40 to 100 days in the heliosphere, on average



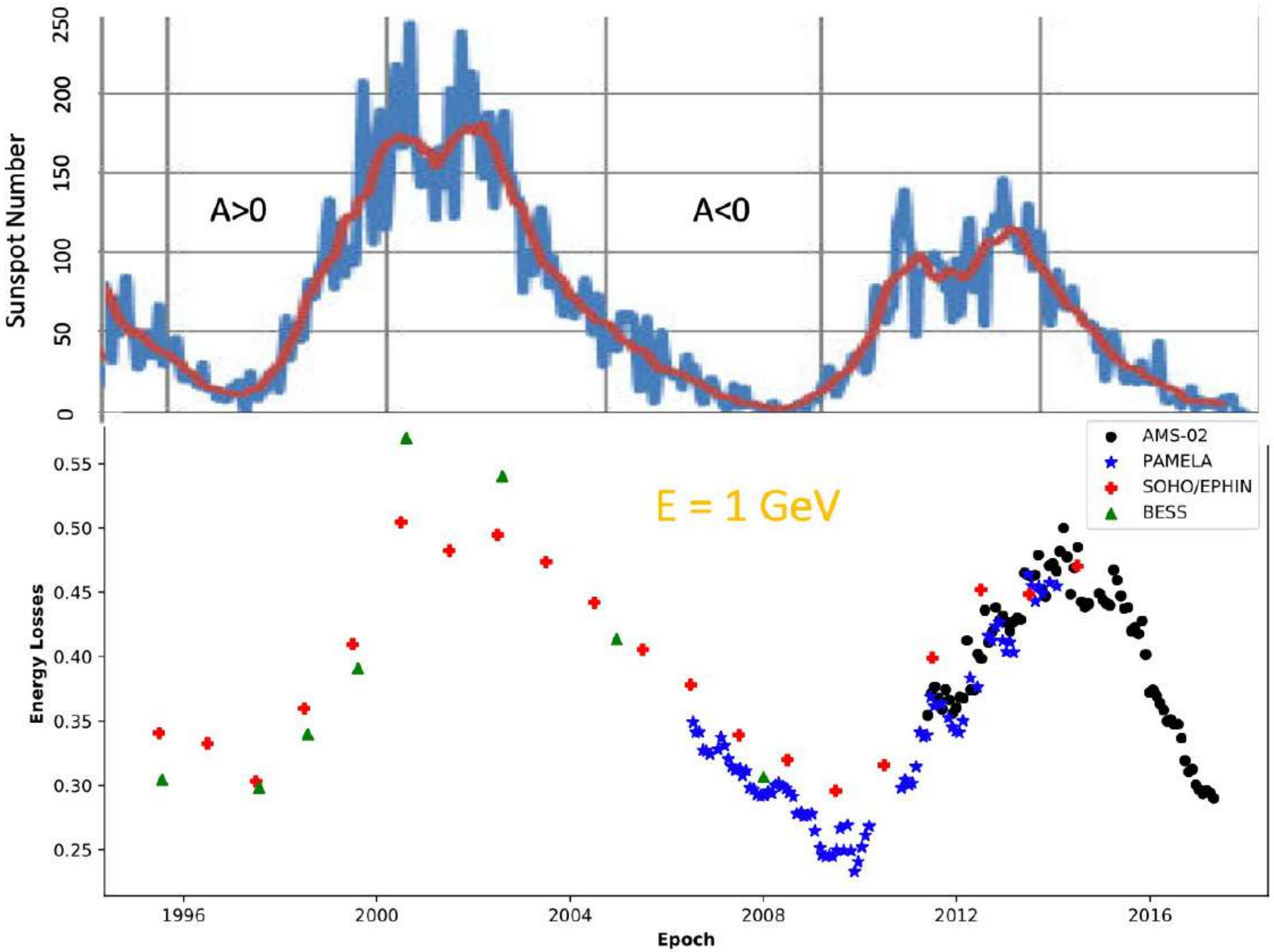
B. Khiali+ ECRS-2022

Evolution of the CR energy losses

New result: Data-driven calculation of the CR propagation times and energy losses and how they *evolve* over the solar cycle.

Example: 1 GeV CR protons have lost 30% to 60% of their energy in their travel to Earth.

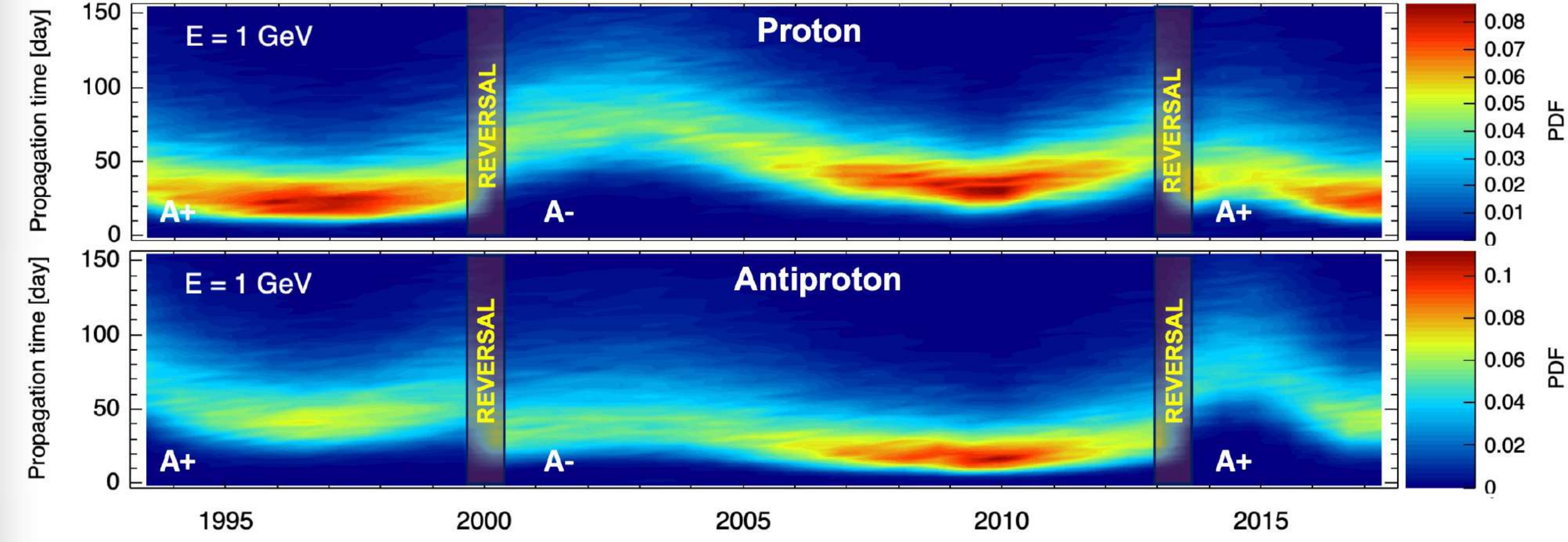
Bess, SOHO/EPHIN, PAMELA, and AMS-02



B. Khiali+ ECRS-2022

Comparing particles and antiparticles

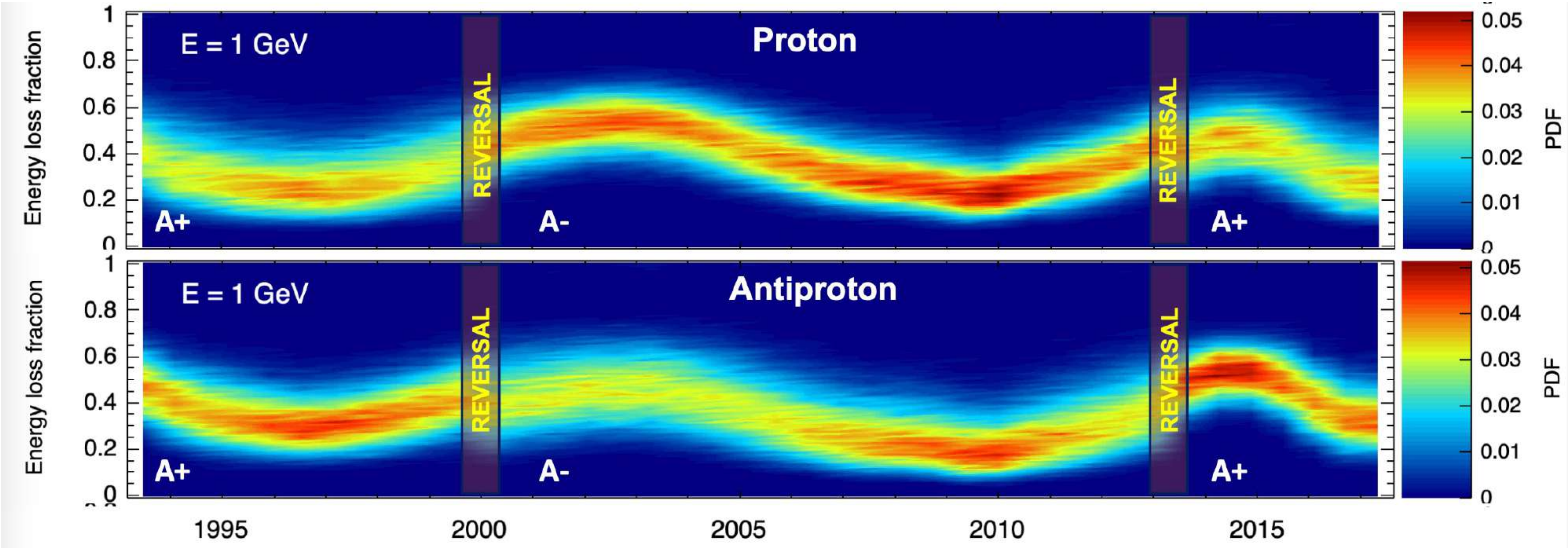
Propagation times of CR protons (reconstructed) and antiprotons (predicted)



B. Khiali+ ECRS-2022

Charge-sign dependence

Energy losses of CR protons (reconstructed) and antiprotons (predicted)



Conclusions

Golden age for cosmic ray measurements

- Data from space: Voyager-1, CRIS/ACE, PAMELA, AMS-02
- Multi-channel approach: protons, nuclei, antiparticles

New insights to CR physics

- Proton data -> determination of time lag in CR modulation.
- Proton data -> determination of propagation times & energy losses
- p/He & nuclei data -> test for low-energy diffusion of CRs in heliosphere
- Antimatter/matter -> test for charge-sign dependent effects