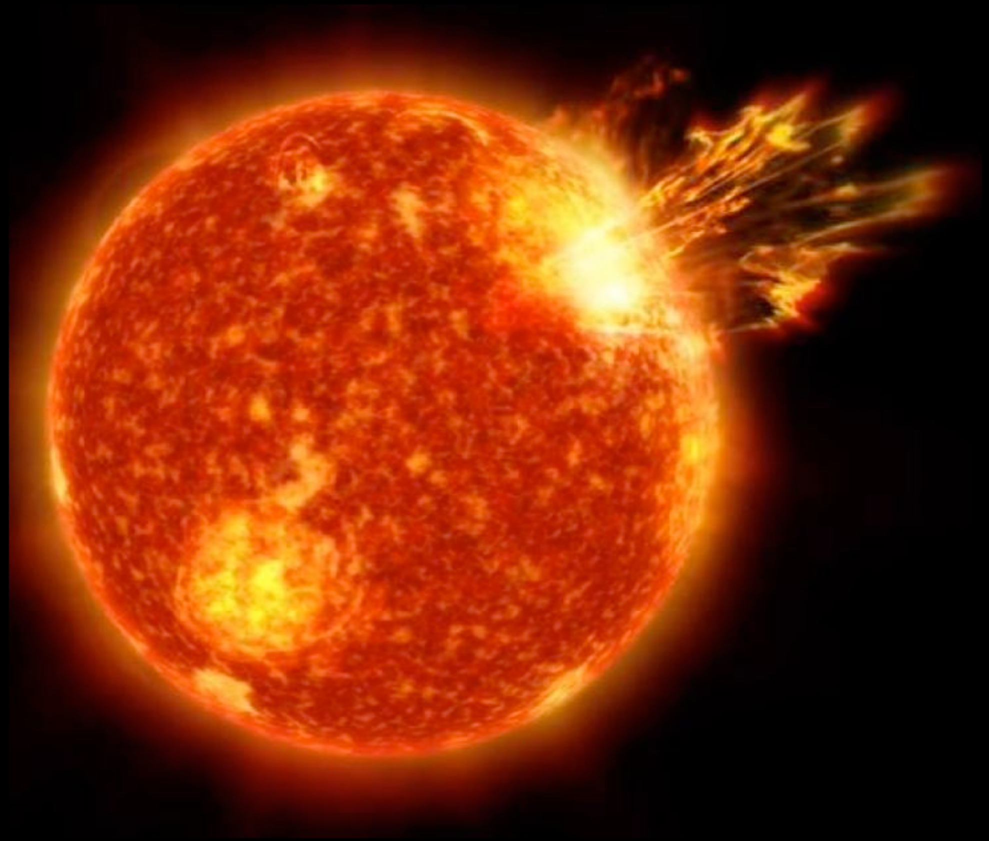
Models of cosmic ray modulation
in light of new data from AMS-02

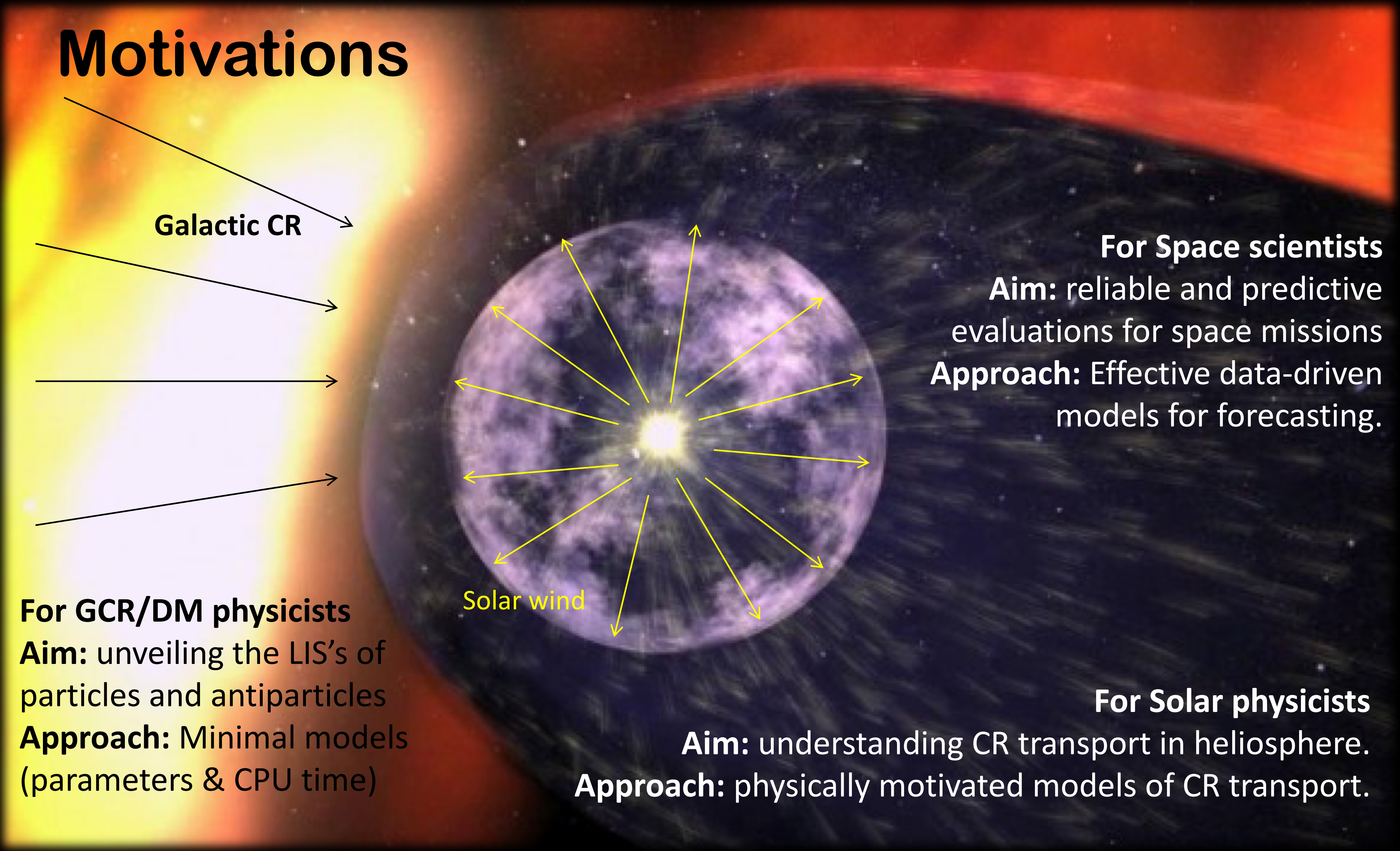


Nicola Tomassetti
with B. Bertucci, E. Fiadrini

Perugia University & INFN

Solar Energetic Particles, Solar Modulation and Space Radiation: new opportunities in the AMS Era #3
23-26 April 2018 – Washington DC, USA

Motivations



For Space scientists
Aim: reliable and predictive evaluations for space missions
Approach: Effective data-driven models for forecasting.

For GCR/DM physicists
Aim: unveiling the LIS's of particles and antiparticles
Approach: Minimal models (parameters & CPU time)

For Solar physicists
Aim: understanding CR transport in heliosphere.
Approach: physically motivated models of CR transport.

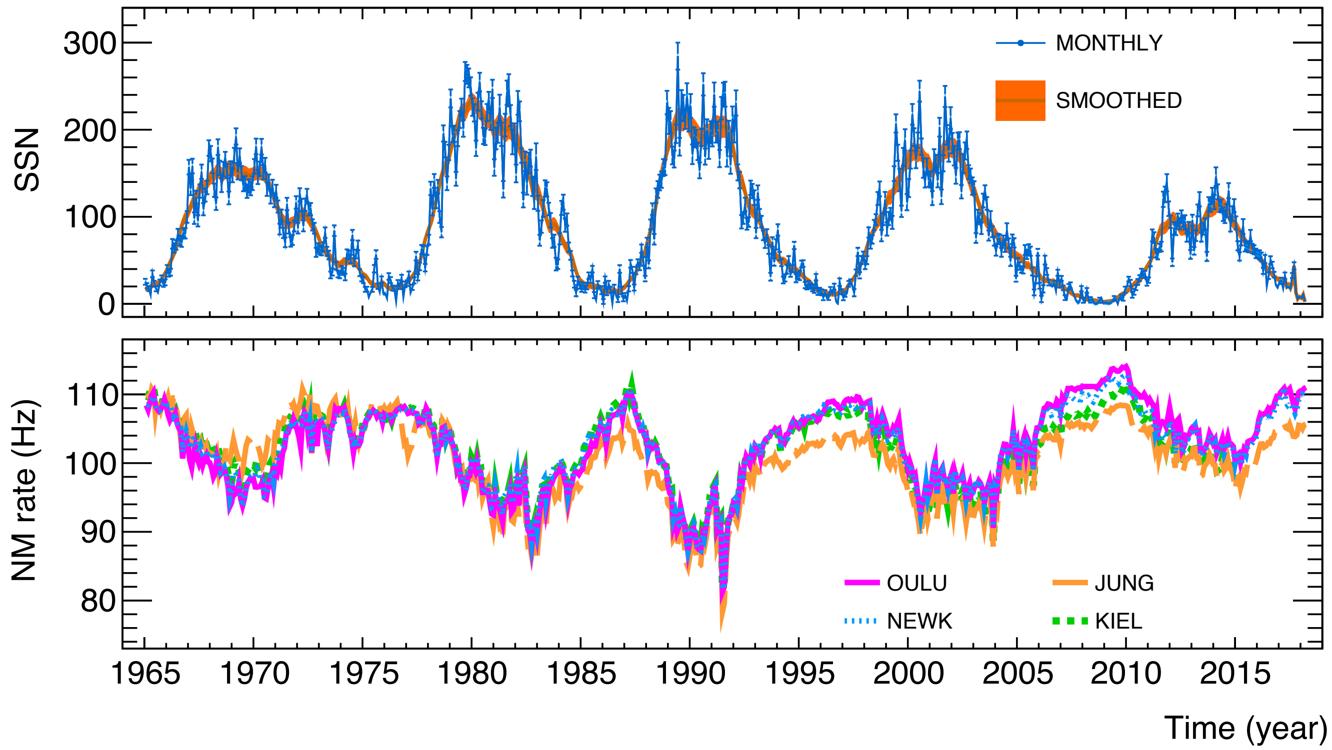
Basic phenomenology

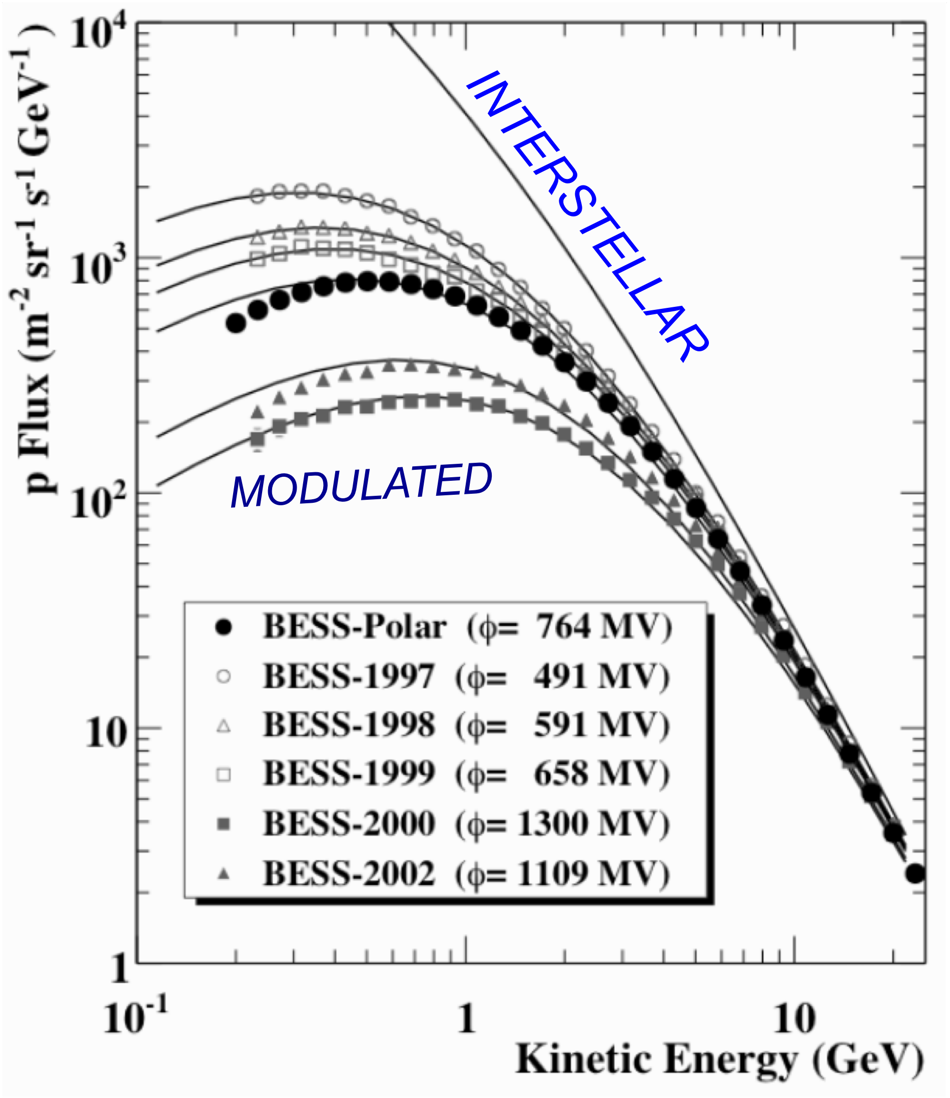
Time dependent **Space dependent**

Energy dependent **Particle dependent**

→ **Connection with Sun's magnetic activity**

→ **Need of multichannel & time-resolved data**

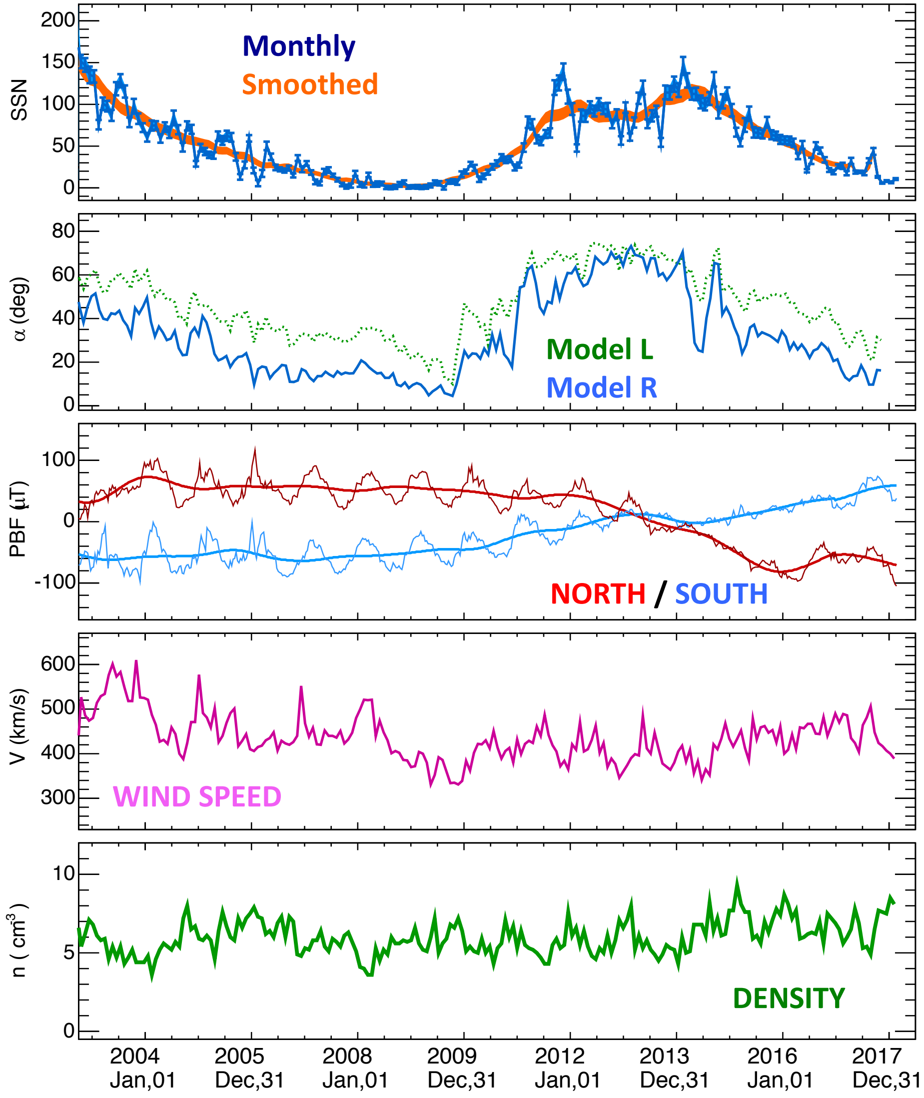




Solar-activity observations

- ✓ Real time
- ✓ In situ

- Sun's properties and how they evolve with time
- Properties of the interplanetary plasma



Monthly number of **sunspot** [#]

SIDC – Royal observatory of Belgium

Tilt-angle of the current sheet [deg]

WSO – Wilkox Solar Observatory - Stanford

Strength of the polar **magnetic field** [uT]

WSO – Wilkox Solar Observatory - Stanford

Solar **wind** plasma **speed** [km/s]

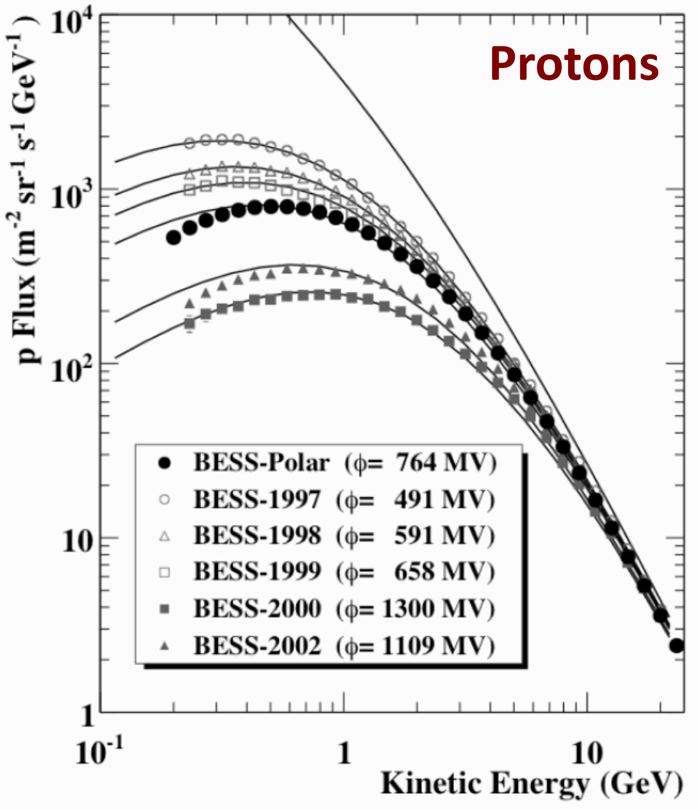
NASA OMNIWeb spacecraft data (ISEE3, ACE)

Solar **wind** plasma **density** [N/cm3]

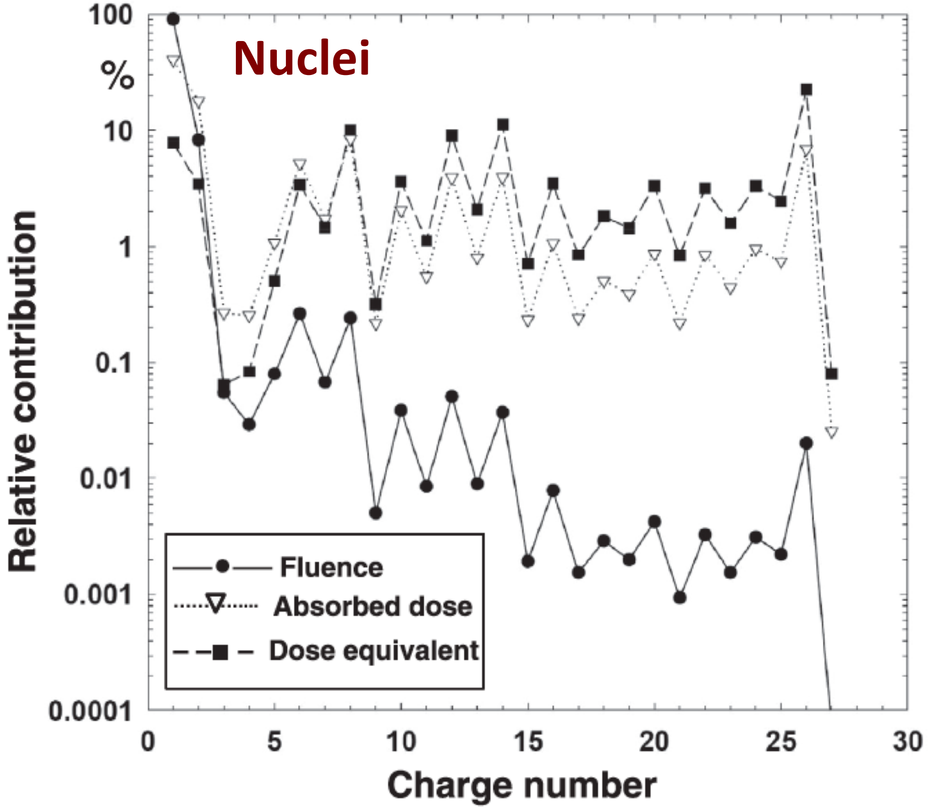
NASA OMNIWeb spacecraft data (ISEE3, ACE)

Cosmic ray data

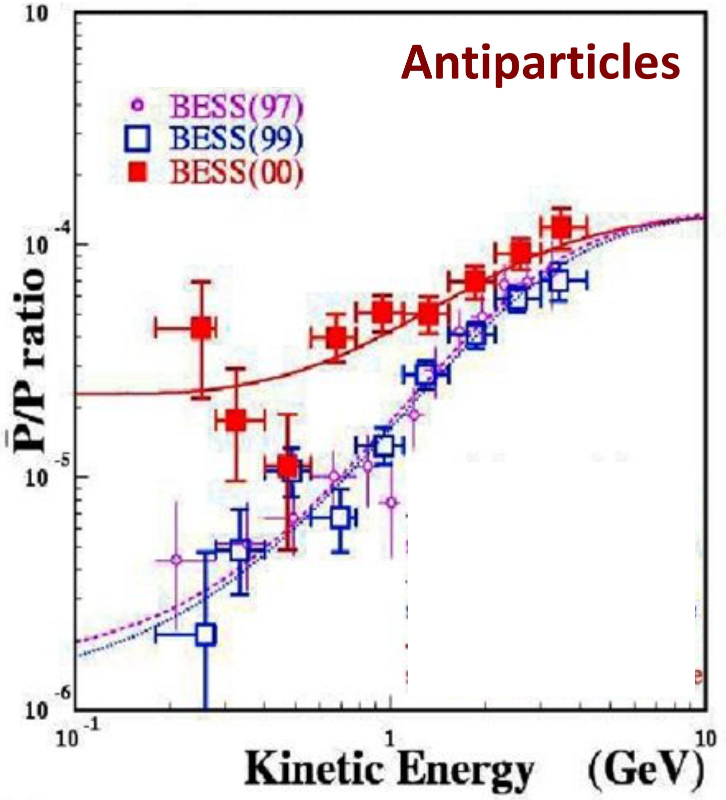
- ✓ NM ground data: good time-resolution. Unresolved in energy and particle.
- ✓ CR data from space: energy-, particle-, and time- resolved.



Dominant in GCRs. Best data.
To probe GCR transport



Important source of radiation
To assess radiation dose

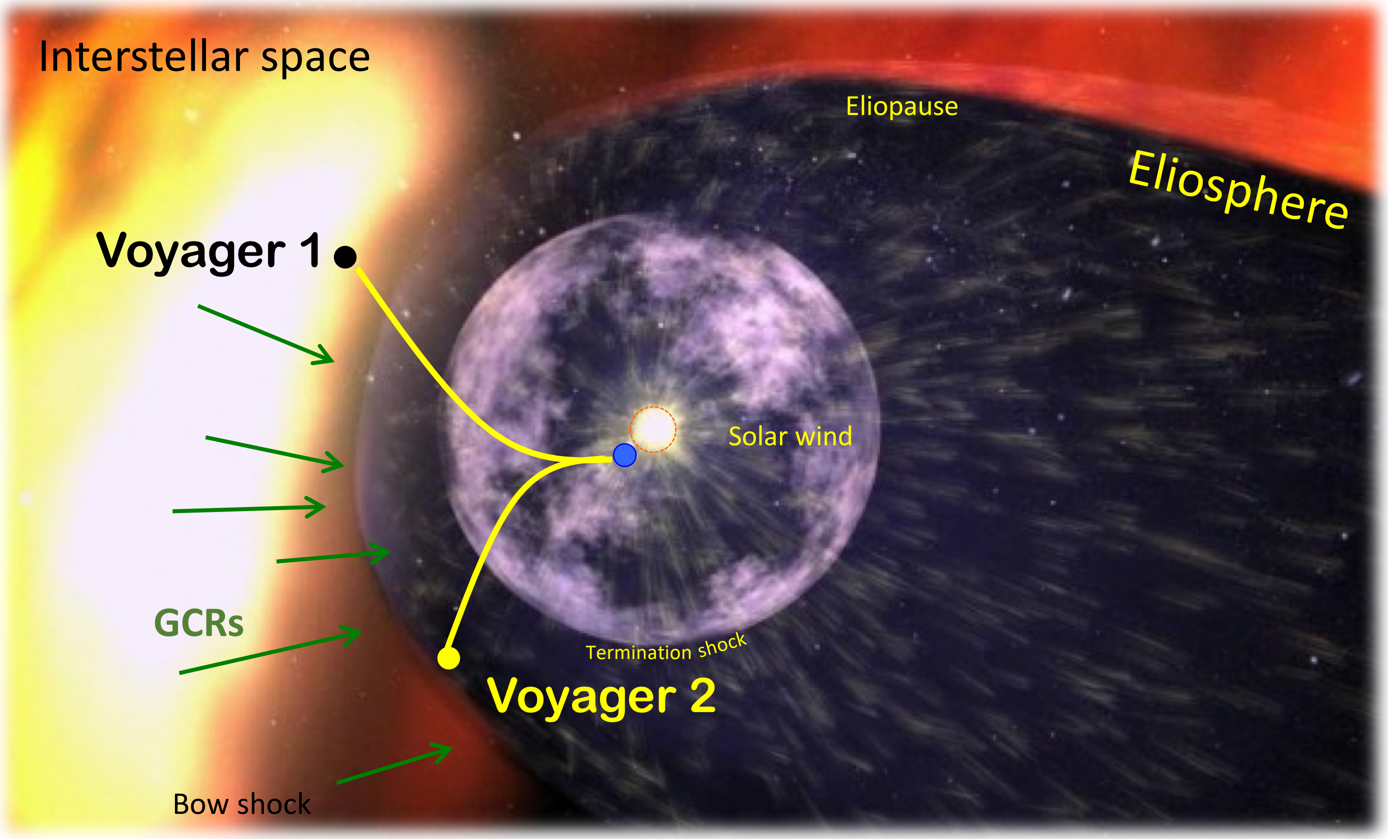


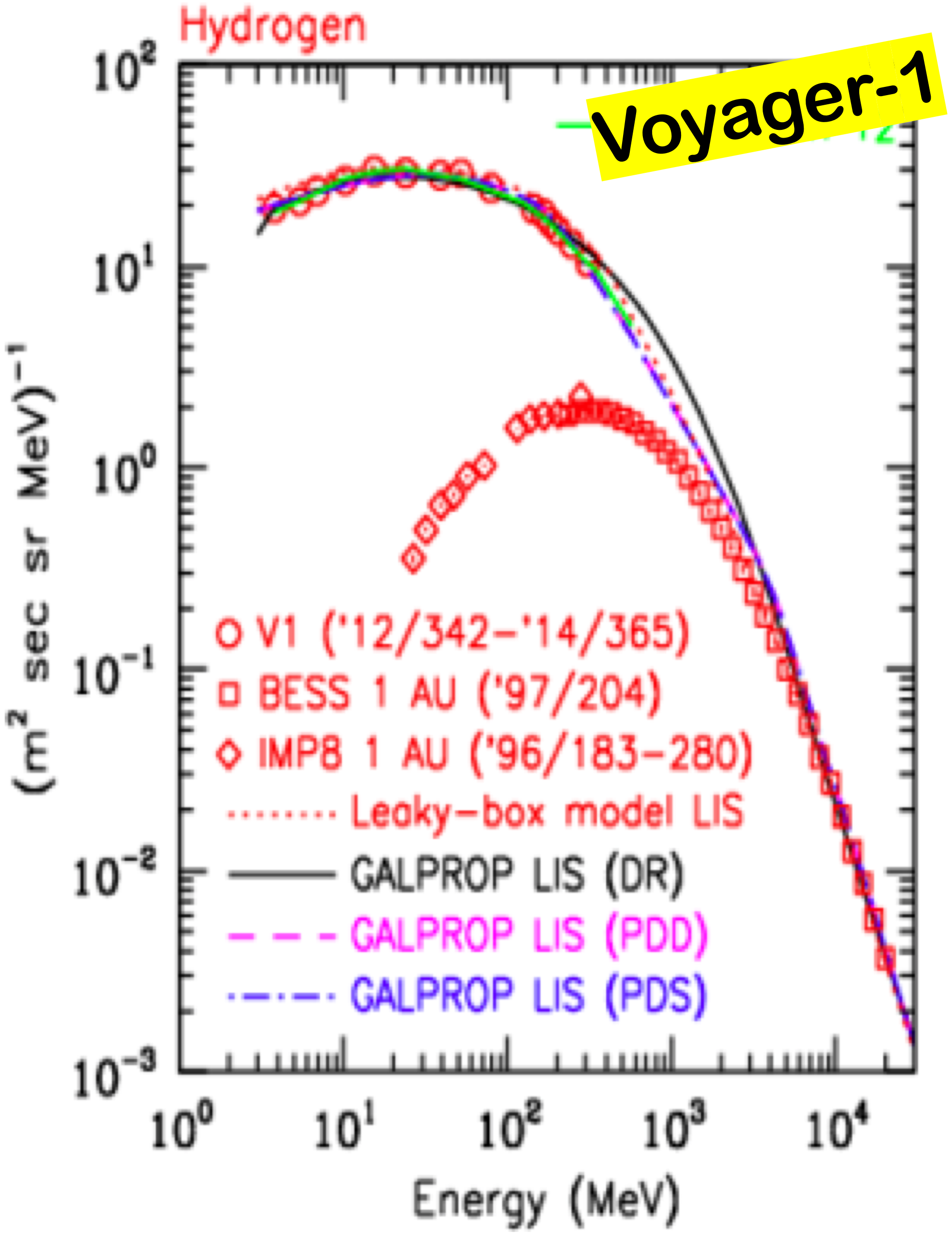
Messengers for new physics
Precious source of information

Observational milestones

1. Very first data from interstellar space

Cummings et al. ApJ 831, 18, 2016

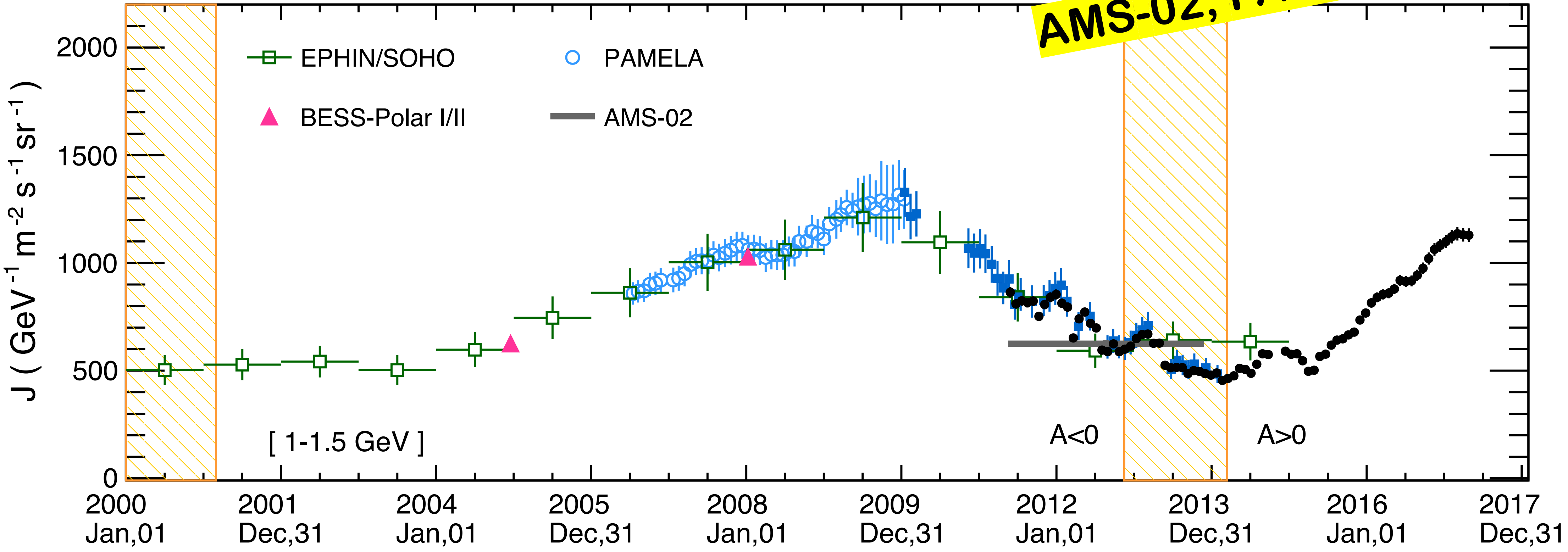




Observational milestones

2. Time-resolved proton data

AMS-02, PAMELA, SOHO



EPHIN / SOHO
Kuhl et al. Solar Phys. 291, 965, 2016
Yearly resolved, 1996 - 2015

PAMELA
Martucci et al. ApJ 854, L1, 2018
Monthly-resolved, 2006-2014
-> Munini talk

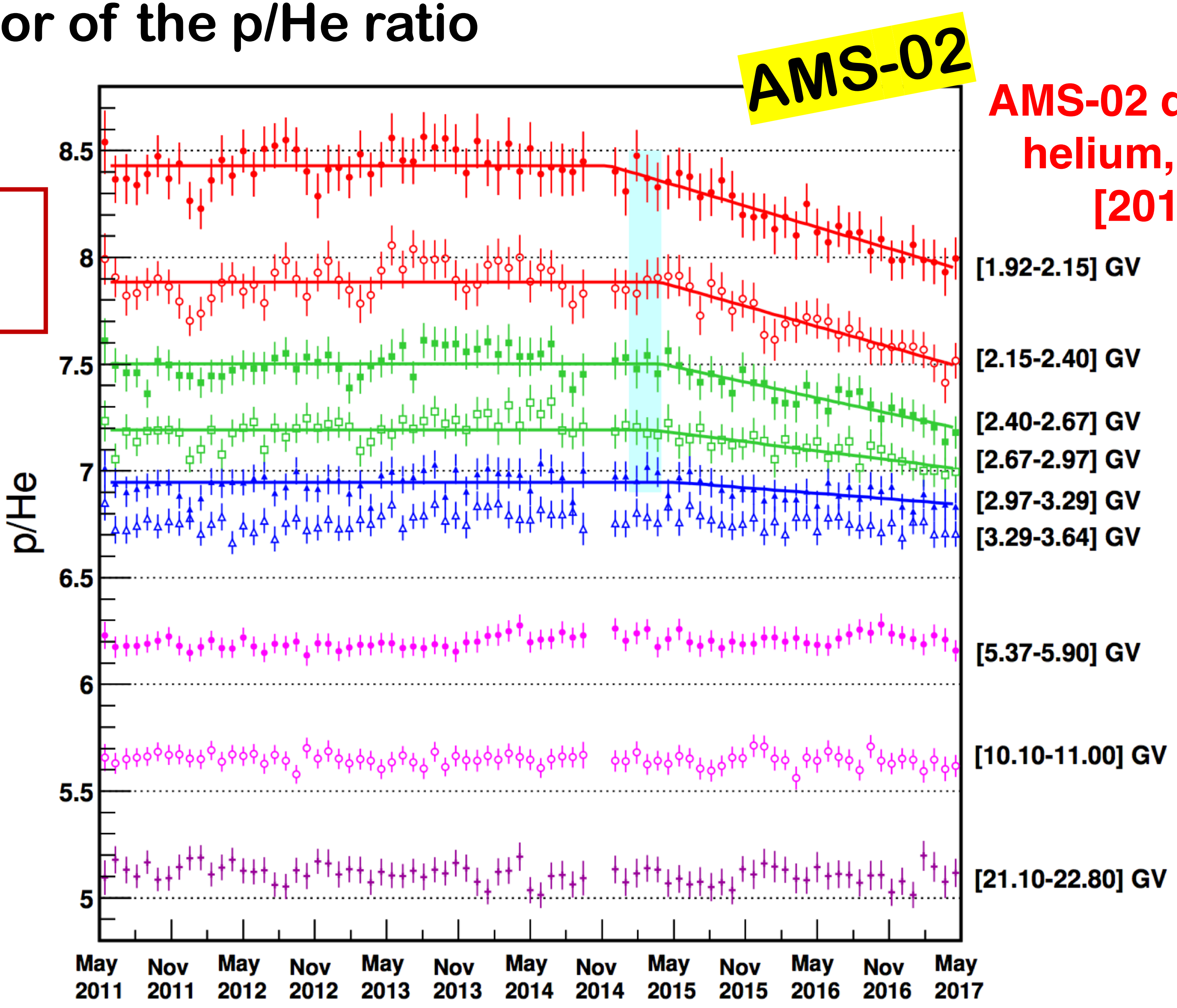
AMS-02
Aguilar et al. in progress, 2018
Monthly resolved, 2011-2017
-> Consolandi talk

2

Observational milestones

3. 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

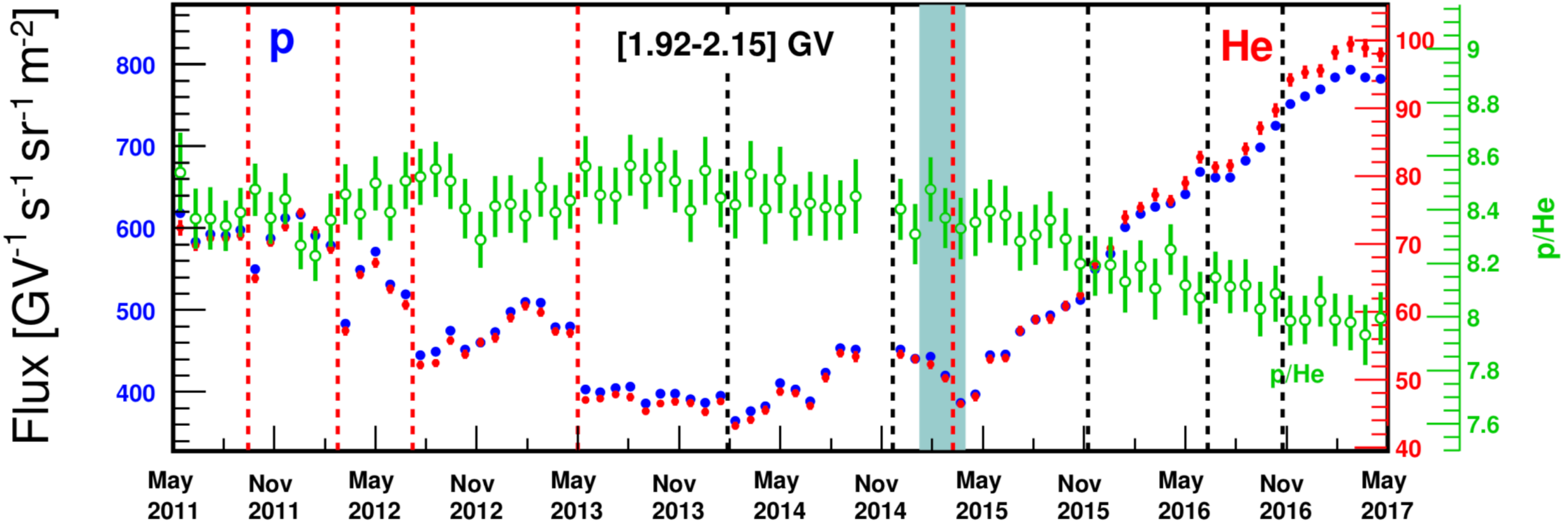


AMS-02 data on proton, helium, and p/He ratio [2018, preliminary]

Observational milestones

3. Long-term behavior of the p/He ratio

AMS-02

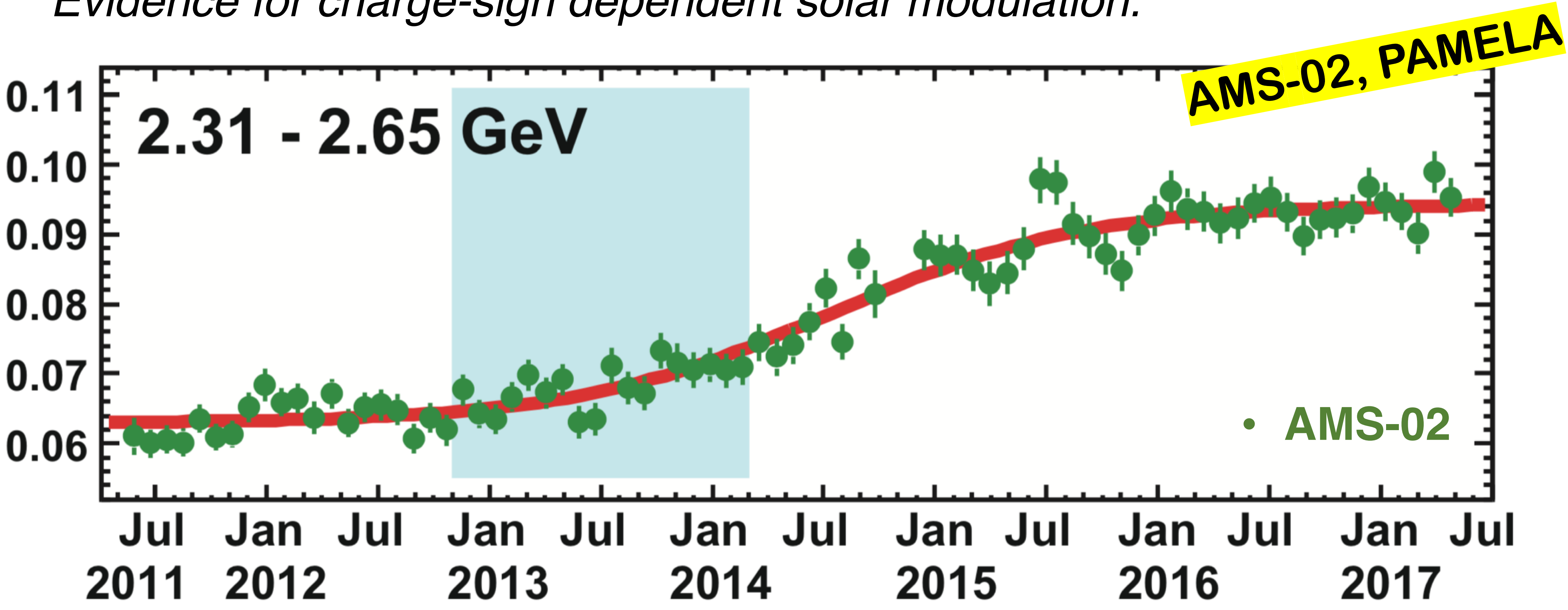


The decrease of the p/He ratio coincides with the flux *recovery* phase

Observational milestones

4. Antimatter/matter ratios

Gradual change of the e+/e- ratio after the solar polarity reversal.
Evidence for charge-sign dependent solar modulation.



PAMELA, e+/e-, Adriani et al. PRL 241105, 2016
AMS-02, electron and positron [2018, preliminary]

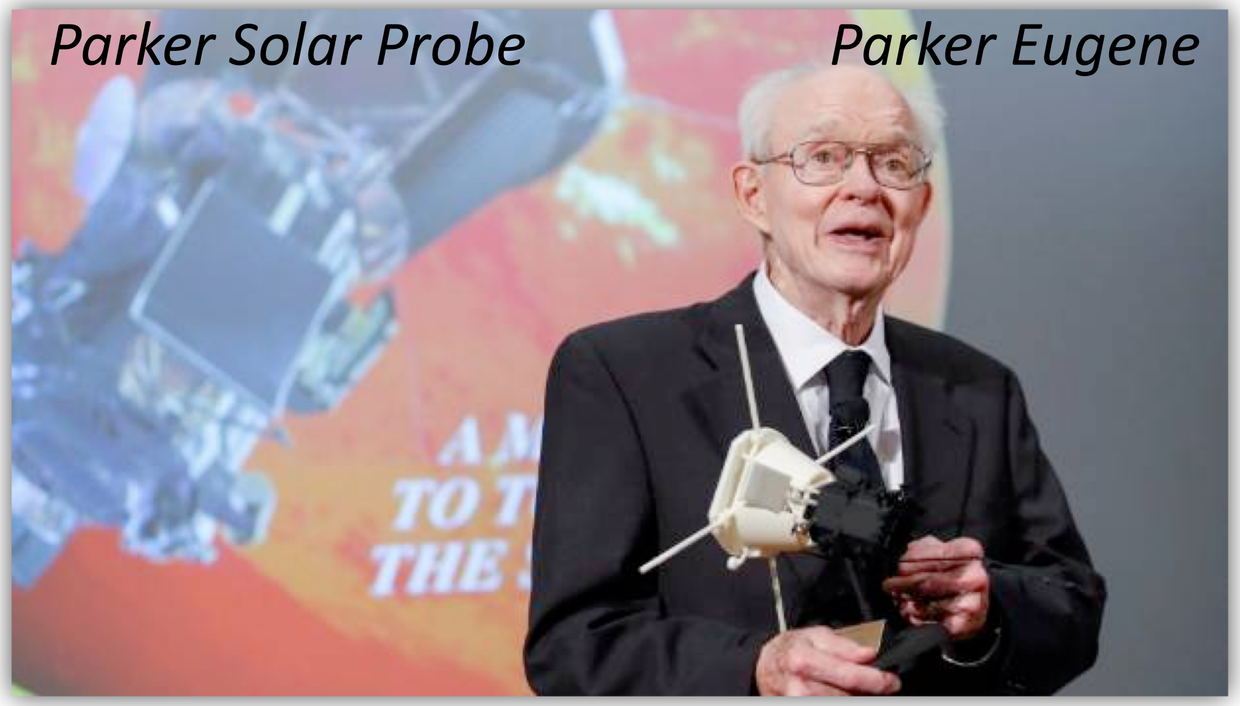
New insights on CR modulation models

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

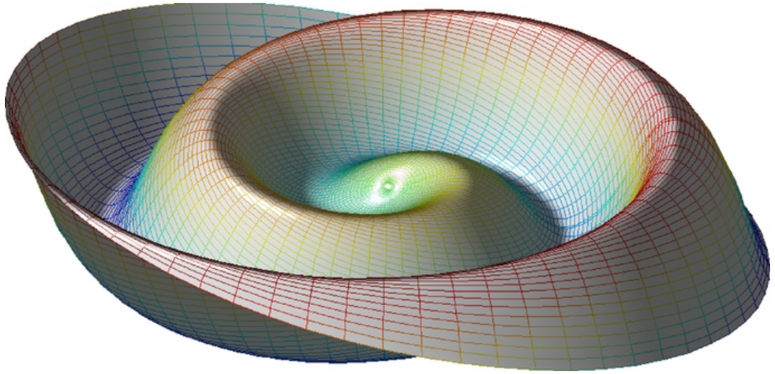
$$\frac{\partial f}{\partial t} = \nabla \cdot [\mathbf{K}\cdot\nabla f] - \mathbf{V} \cdot \nabla f - \langle \mathbf{v}_D \rangle \cdot \nabla f + \frac{1}{3}(\nabla \cdot \mathbf{V})\frac{\partial f}{\partial \ln p} + Q(r,p,t)$$

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

Parker Solar Probe *Parker Eugene*



Parker spiral



Insights from CR protons: time lag

Parker eq.

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

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

K-scaling parameter

Tilt-angle parameter

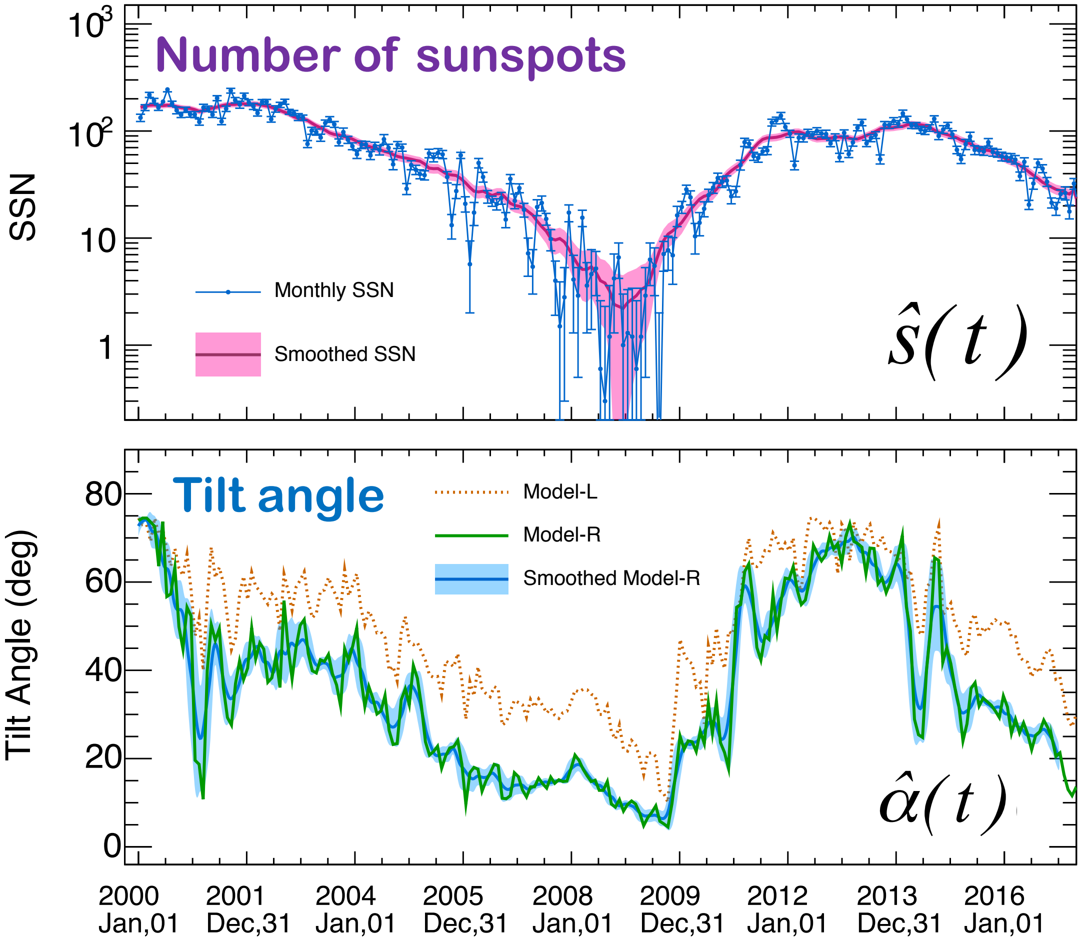
Connect model parameters to solar-activity data →

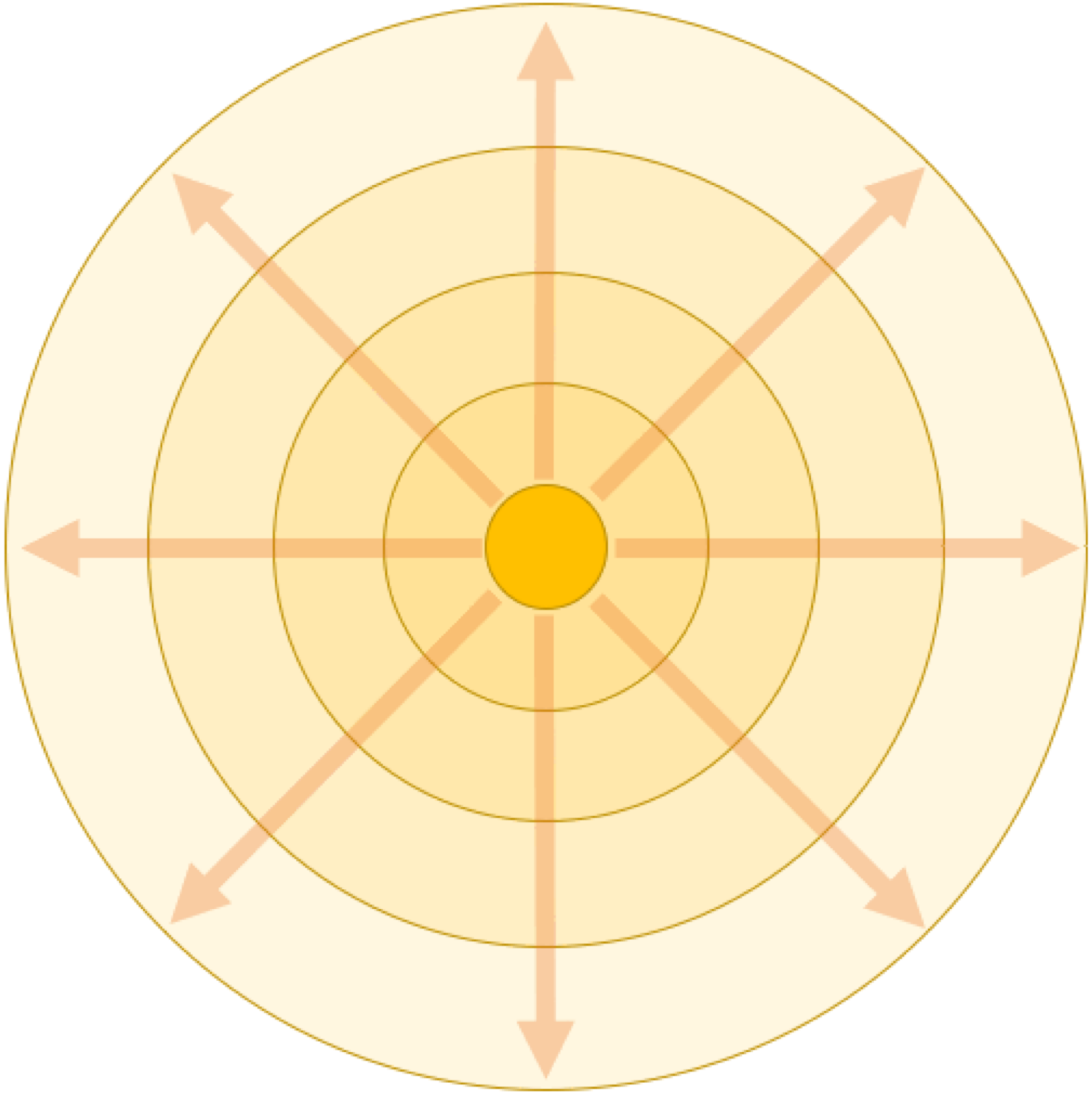
***Use "retarded"* physics inputs**

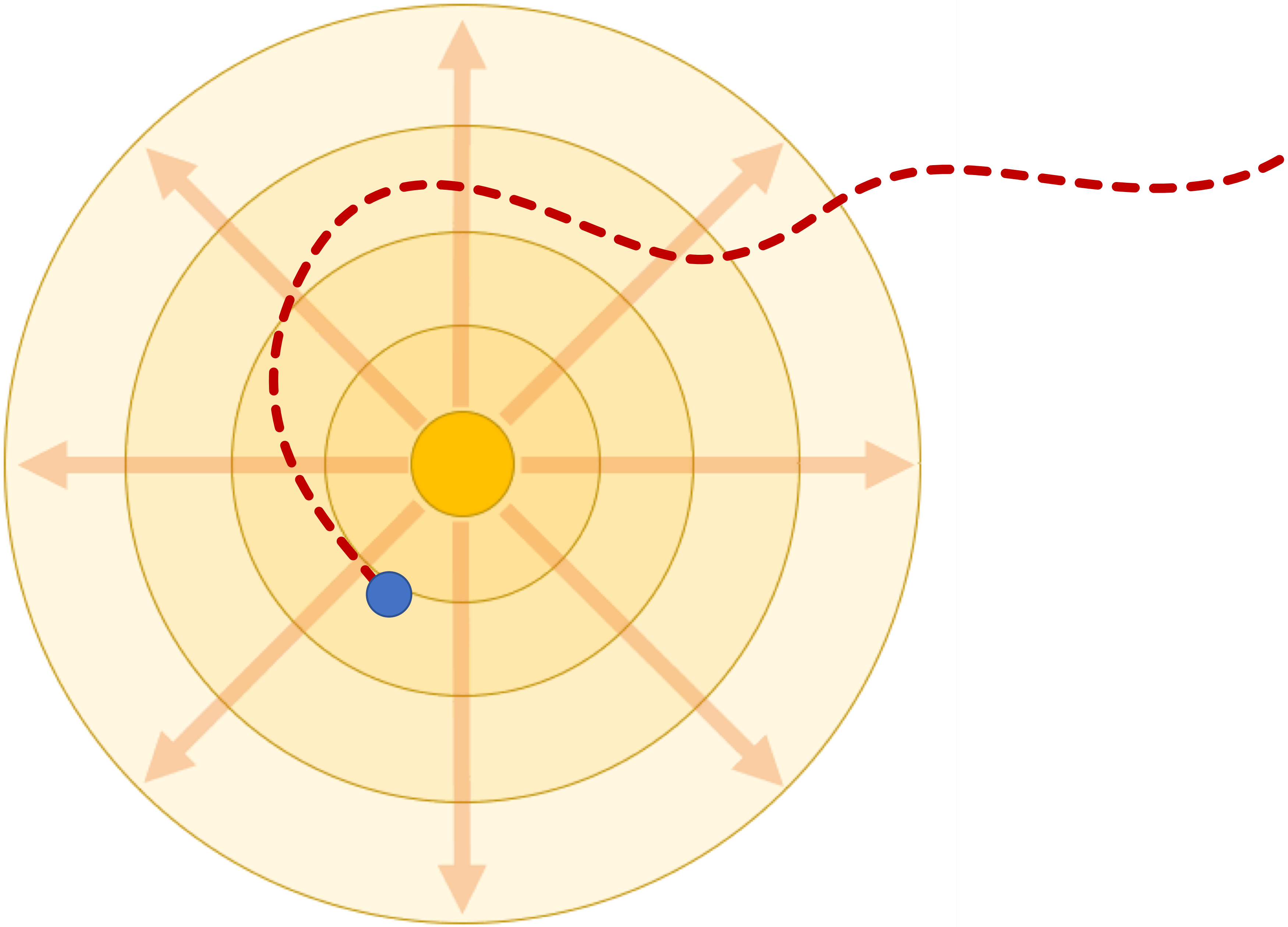
$$\kappa(t) = a \cdot log_{10}(\hat{s}(t - \Delta T)) + b$$
$$\alpha(t) = \hat{\alpha}(t - \Delta T)$$

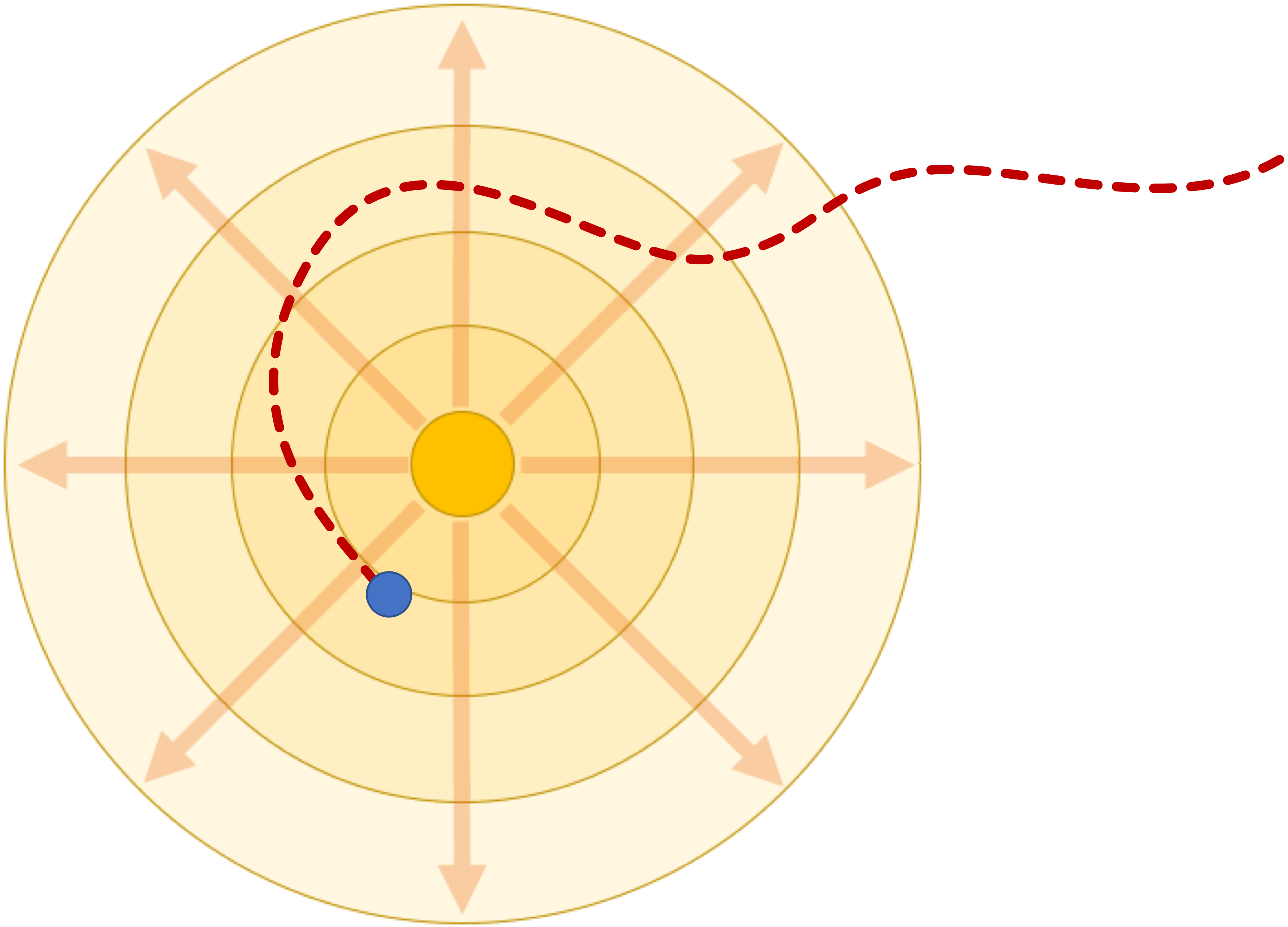
Global fitting using CR data from space

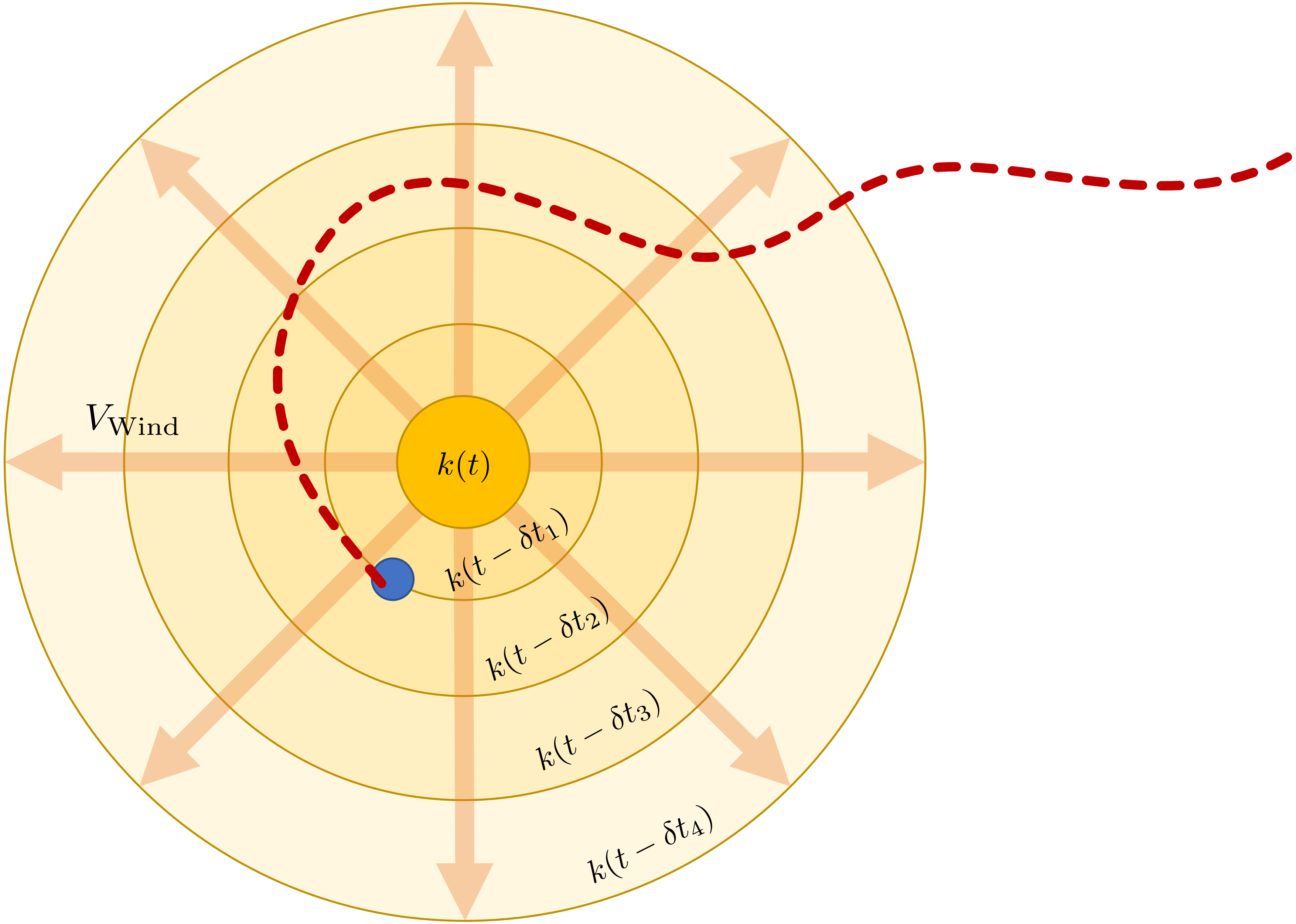
$$\chi^2 = \chi^2(a, b, \Delta t)$$







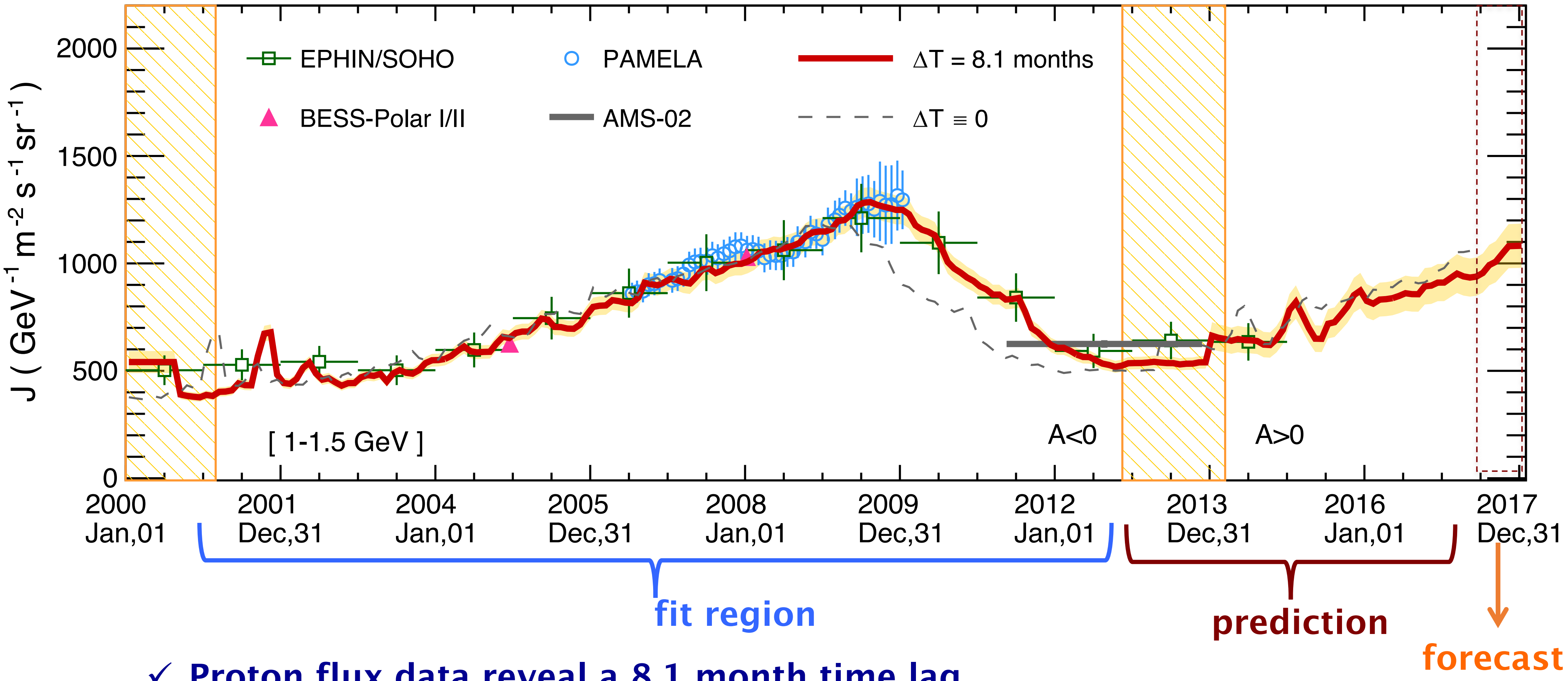




V_{Wind}
$k(t)$
$k(t-\delta t_1)$
$k(t-\delta t_2)$
$k(t-\delta t_3)$
$k(t-\delta t_4)$

Insights from CR protons: time lag

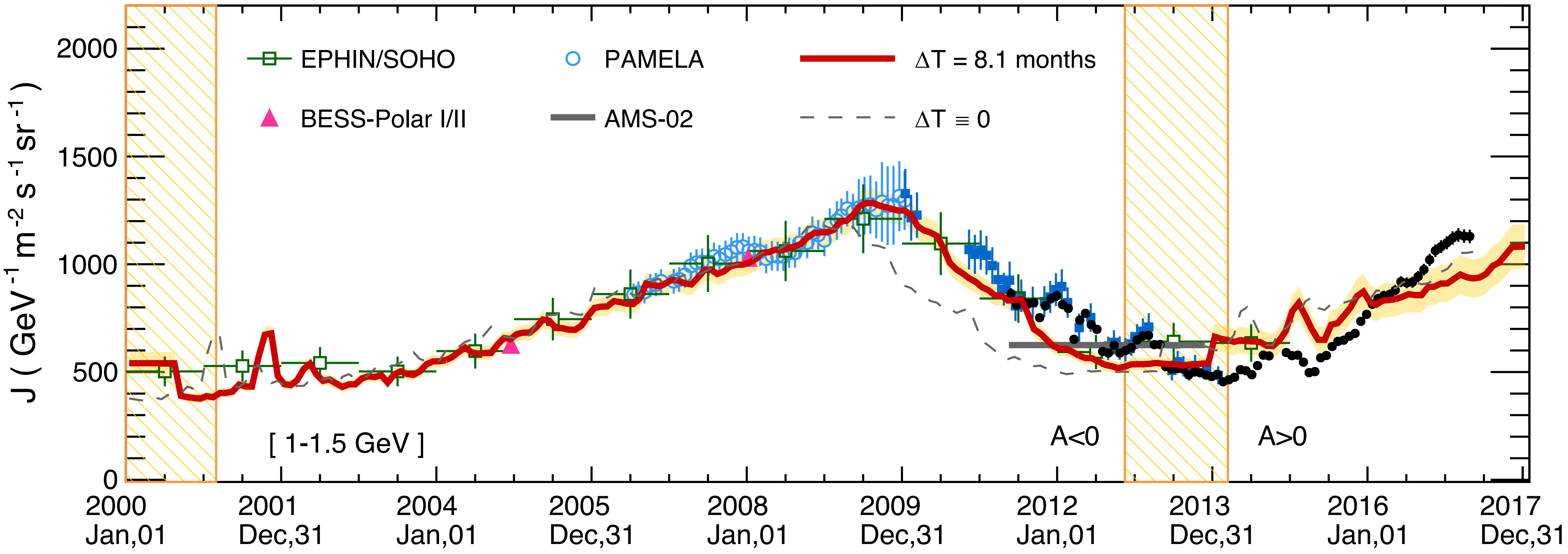
NT, Orcinha, F. Barao, B. Bertucci ApJ 849, L32 (2017)



- ✓ Proton flux data reveal a 8.1 month time lag
- ✓ Real-time solar data → ability to *forecast* 8 months in advance
- ✓ Predictions on antiparticle/particle ratios (test for AMS)

Insights from CR protons: time lag

NT, Orcinha, F. Barao, B. Bertucci ApJ 849, L32 (2017)

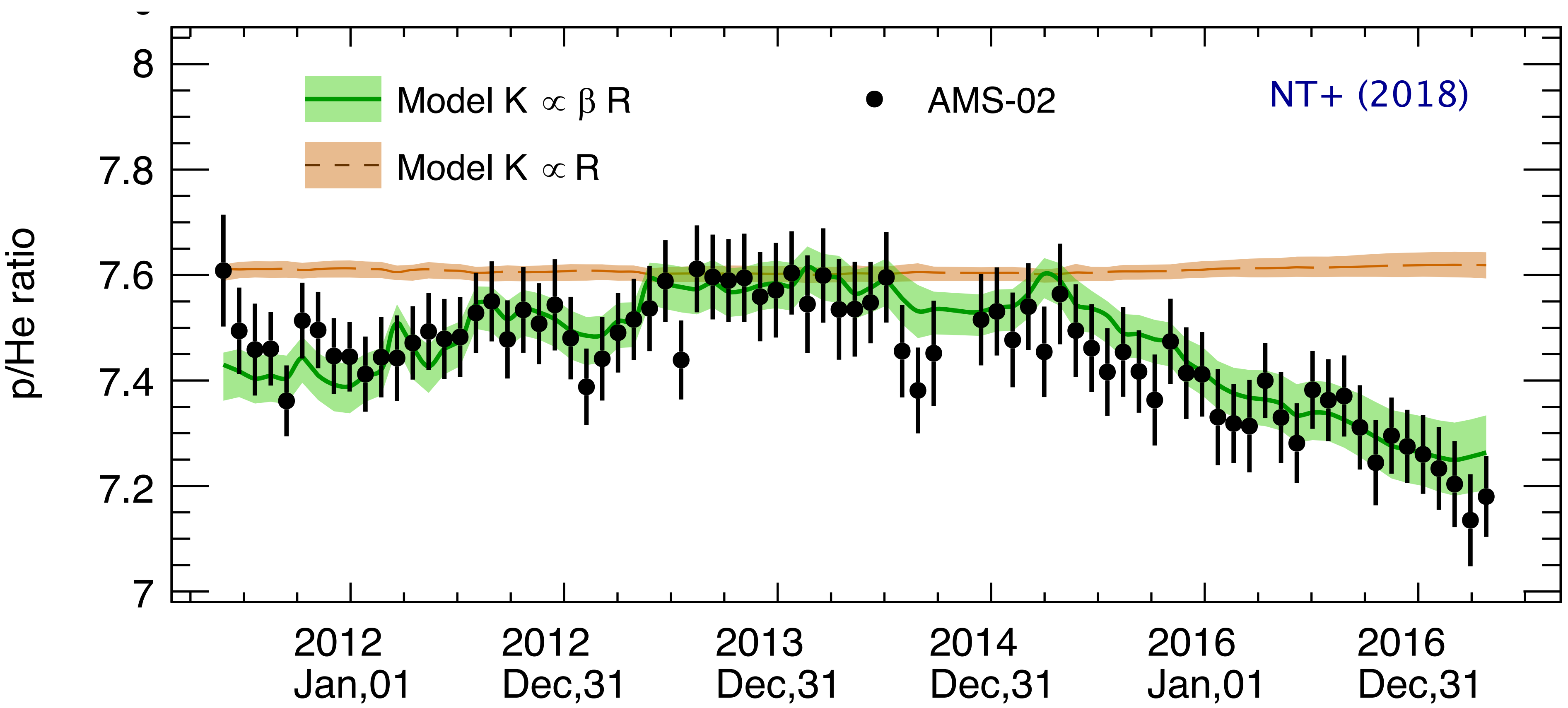


Insights from the p/He ratio: diffusion

K(R) = (v/3)λ(R) parallel diffusion coefficient

λ(R) = **universal** “composition-blind” mean free path

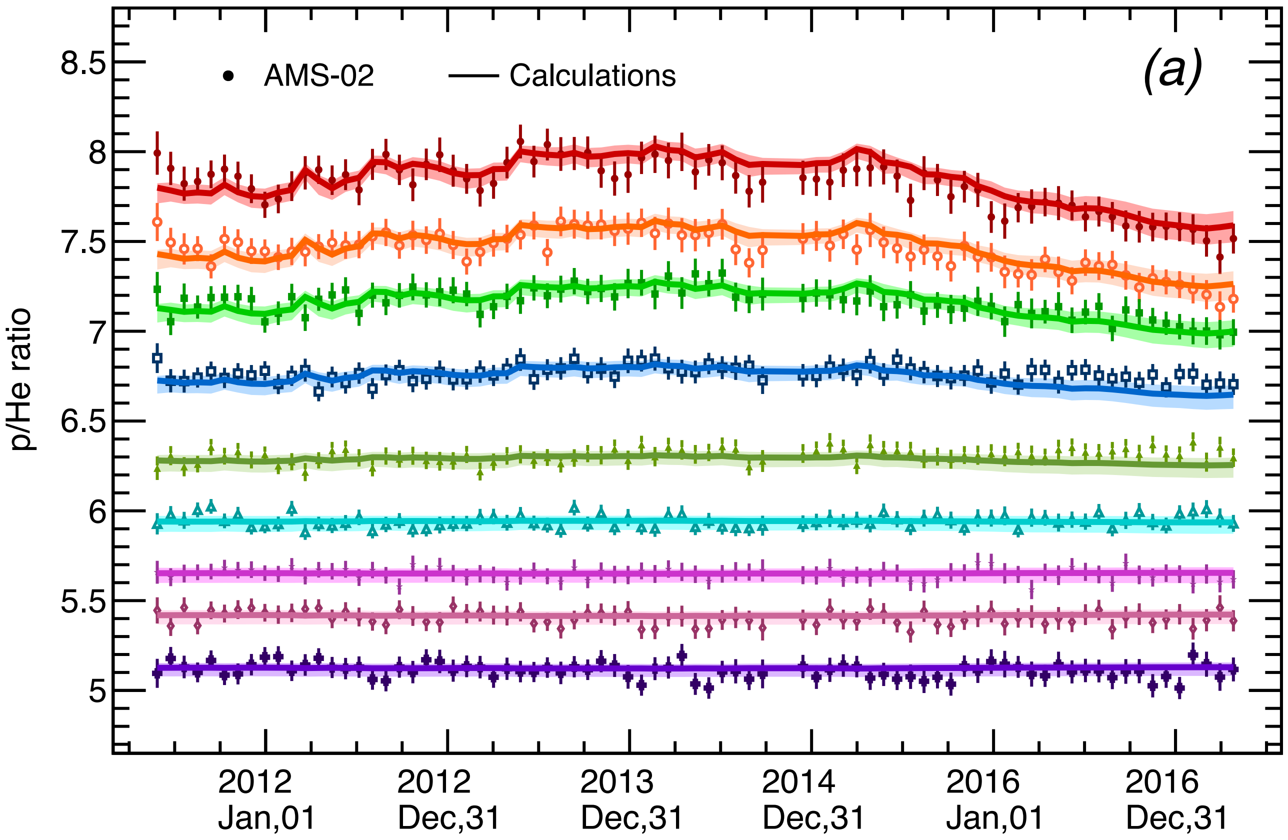
$$K(R,t) = \beta \times k_0(t) \times R$$

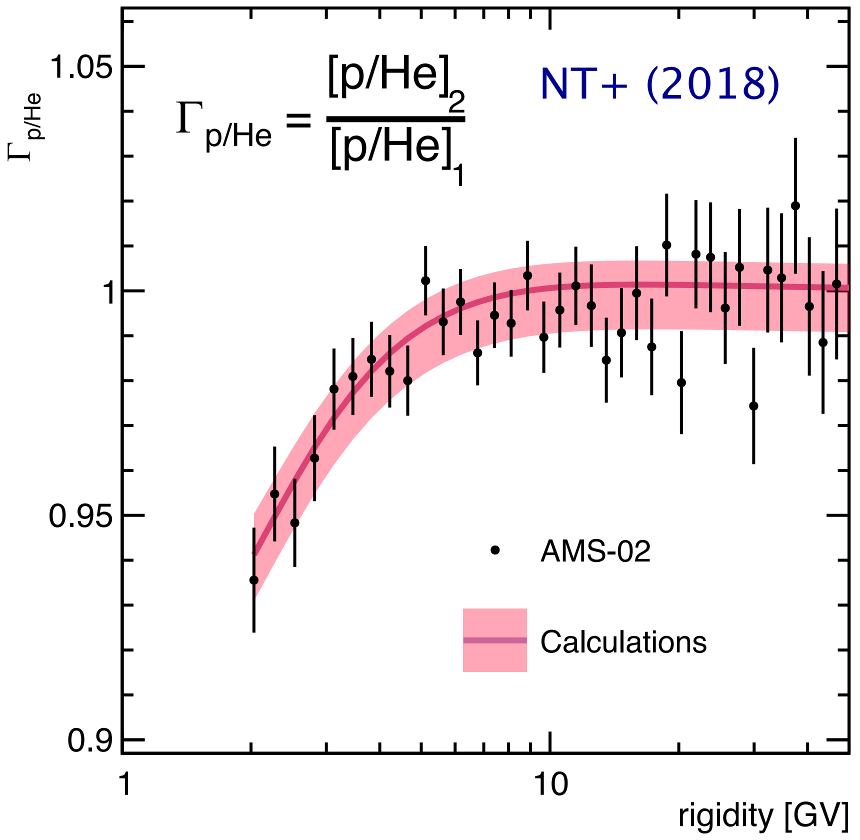


The p/He long-term behavior is a signature of *universality* of the CR mean free path λ(R)

Insights from the p/He ratio: diffusion

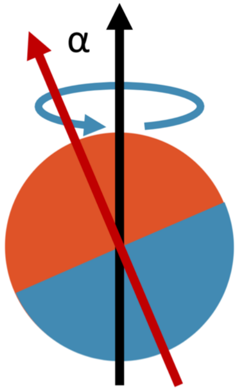
- ✓ The p/He time-dependence is *predicted* from a proton-driven model
- ✓ The p/He structure is expected to disappear at relativistic rigidities



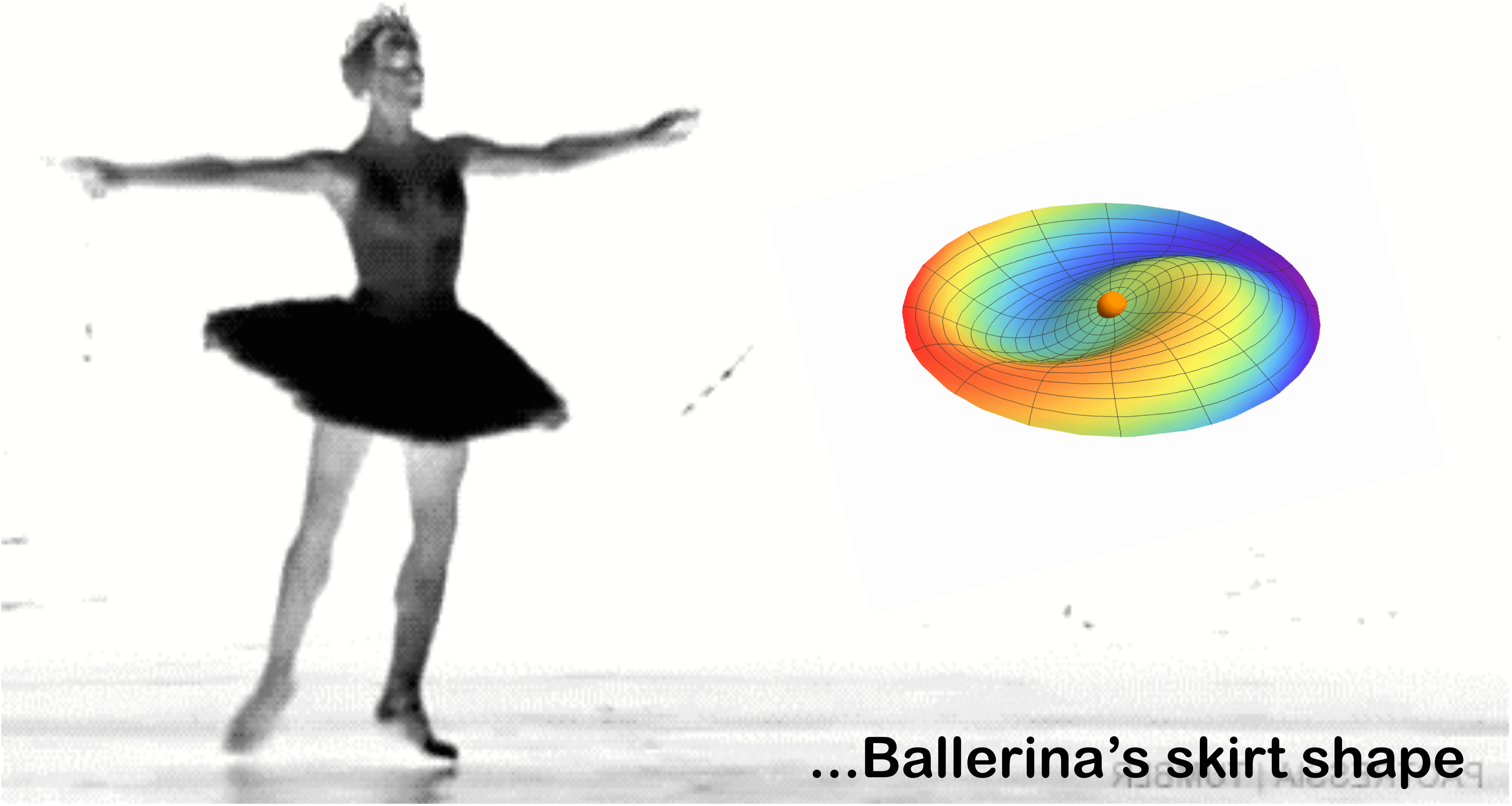


The p/He long-term behavior is a signature of *universality* of the CR mean free path λ(R)

Insights from antimatter/matter ratios: drift

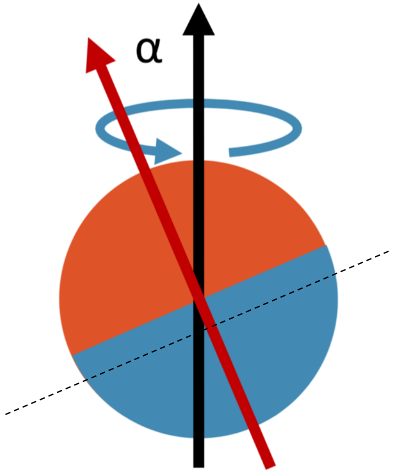


Dynamics of the Heliospheric current sheet...



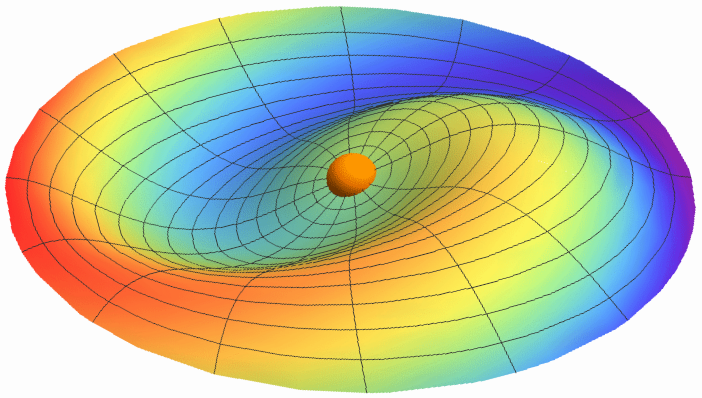
...Ballerina's skirt shape

Insights from antimatter/matter ratios: drift



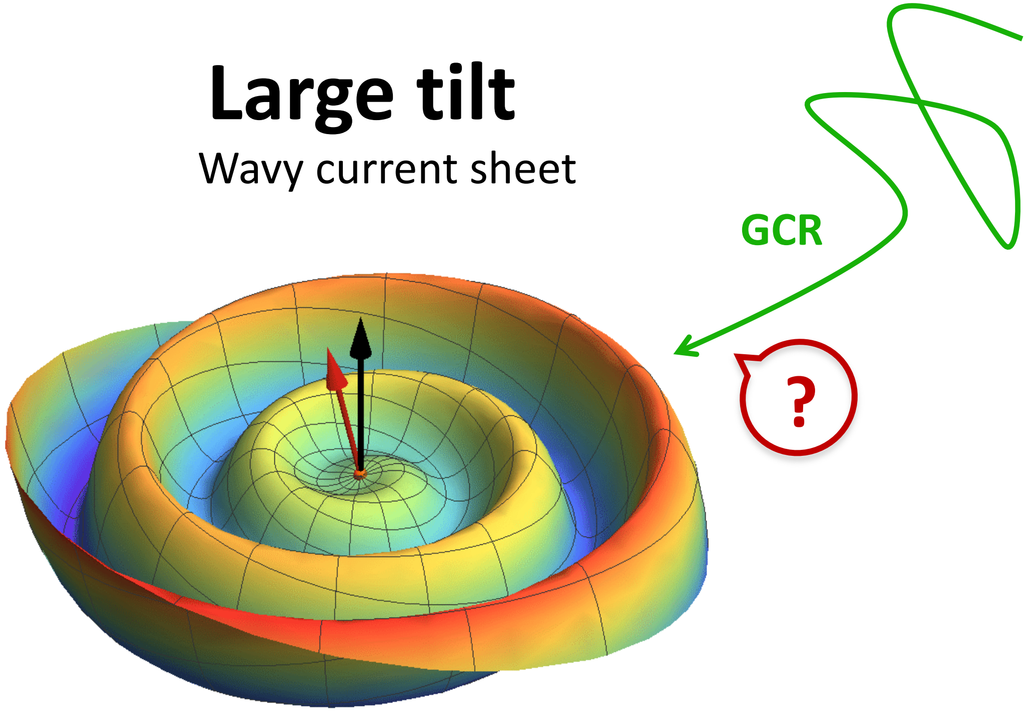
Small tilt

Flat current sheet

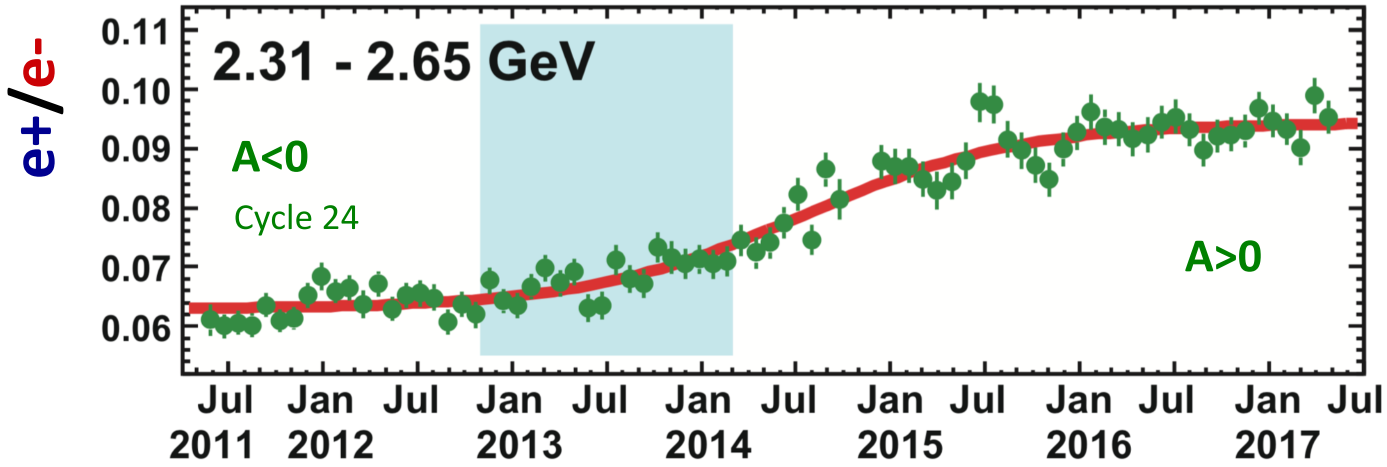


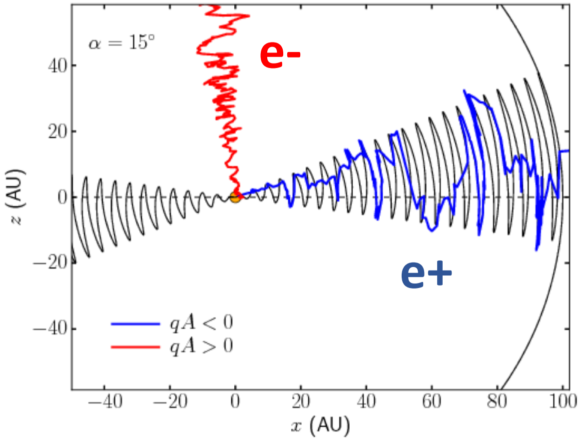
Large tilt

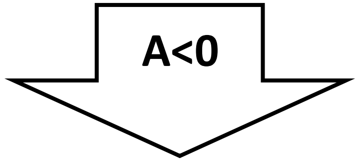
Wavy current sheet

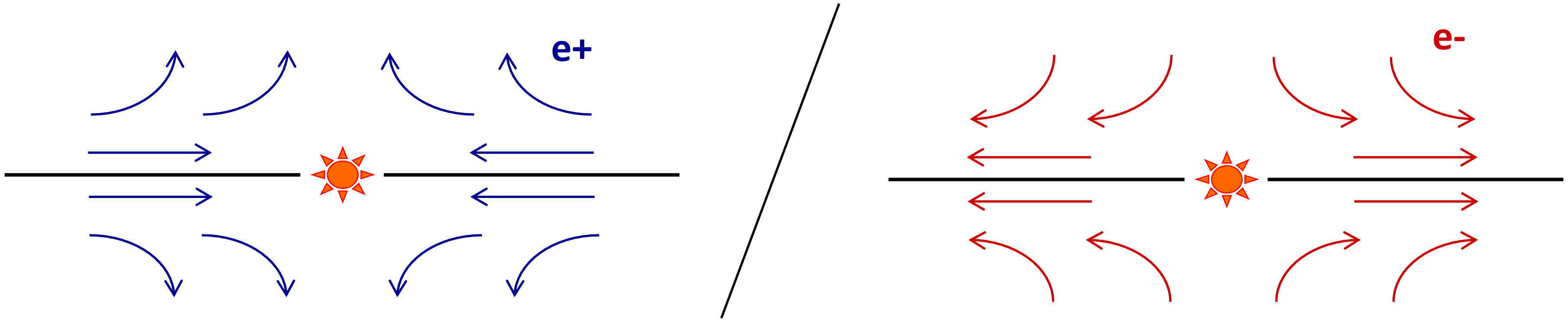


Insights from antimatter/matter ratios: drift

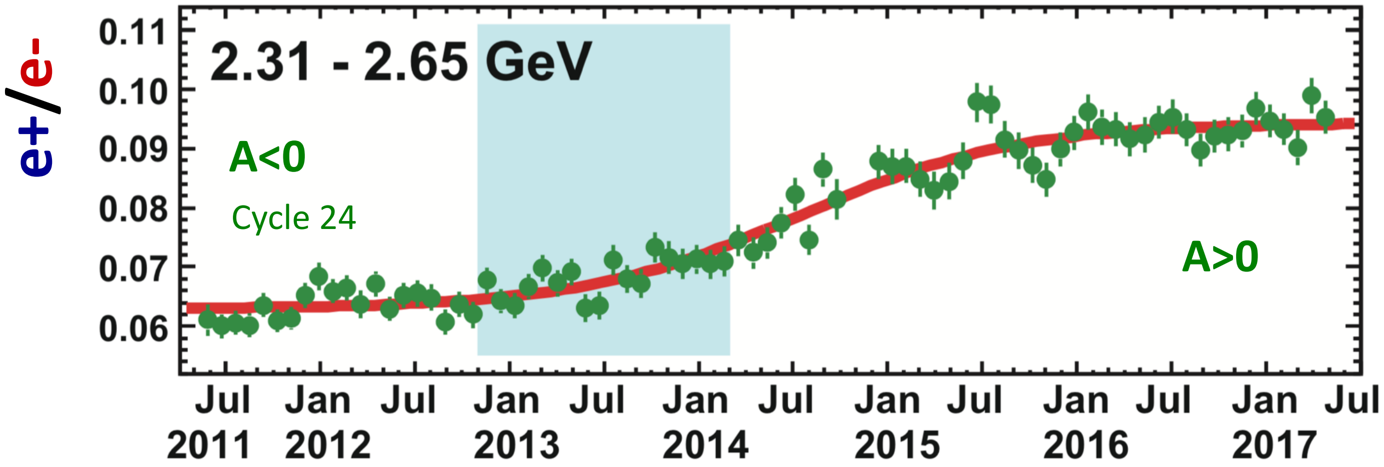


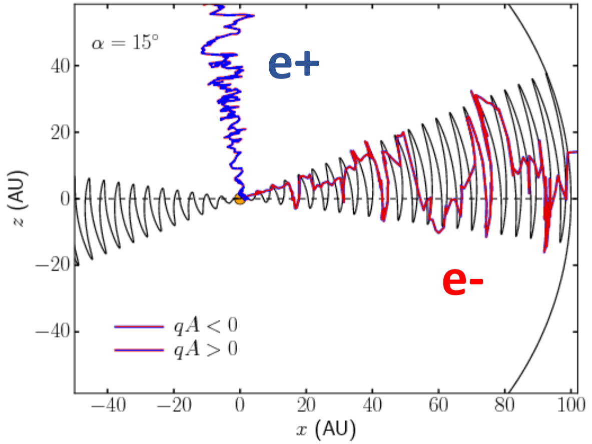


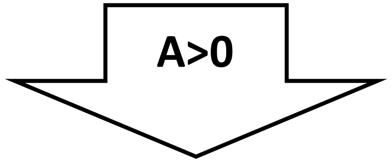


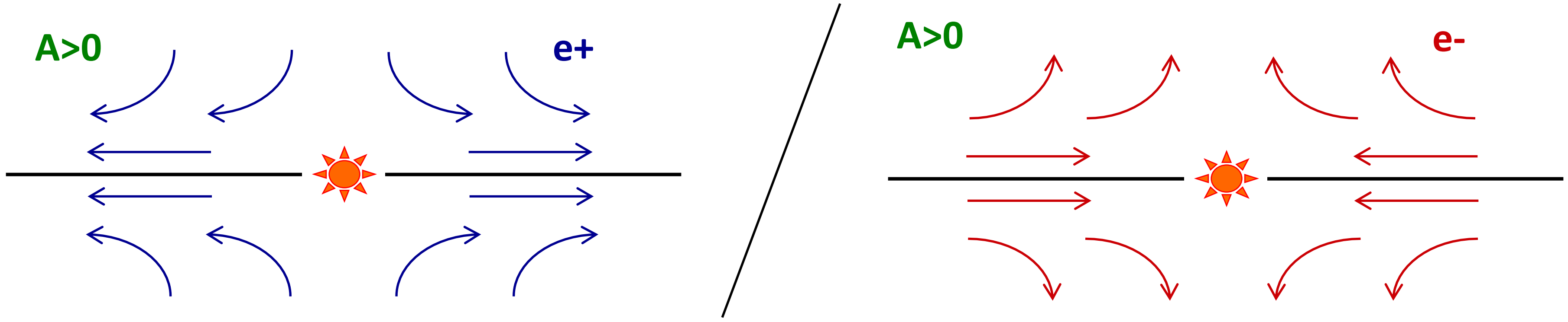


Insights from antimatter/matter ratios: drift

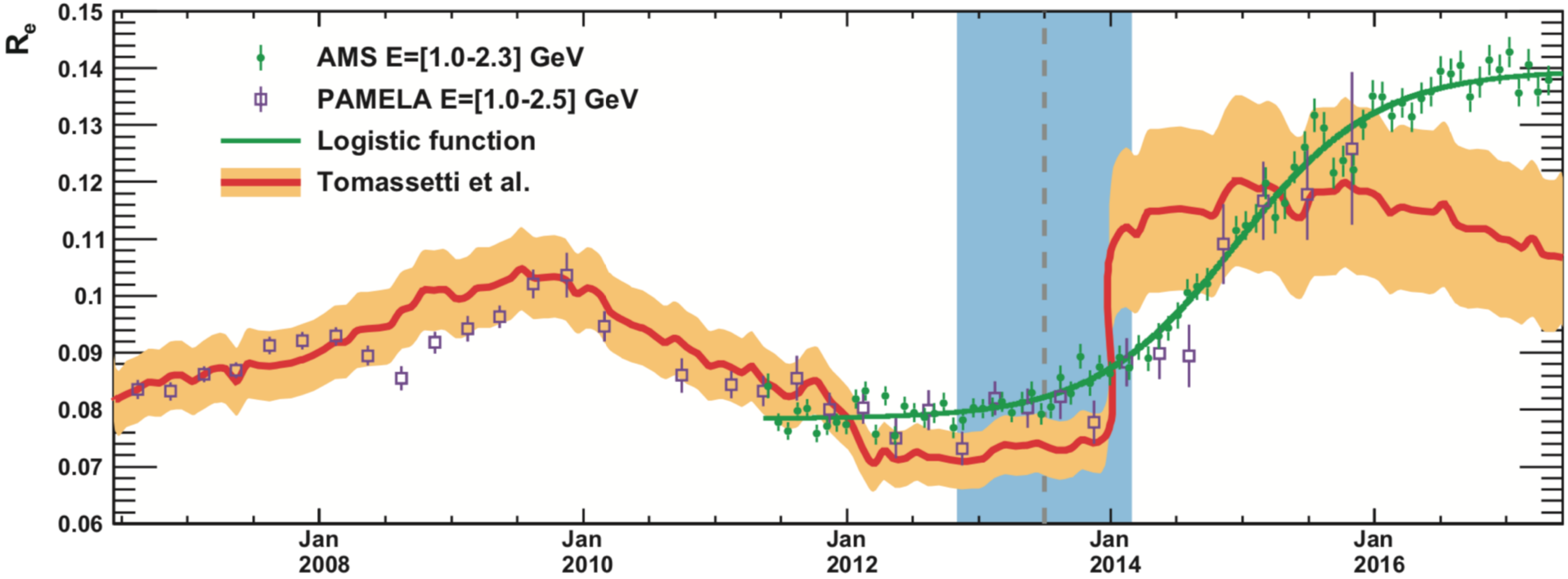






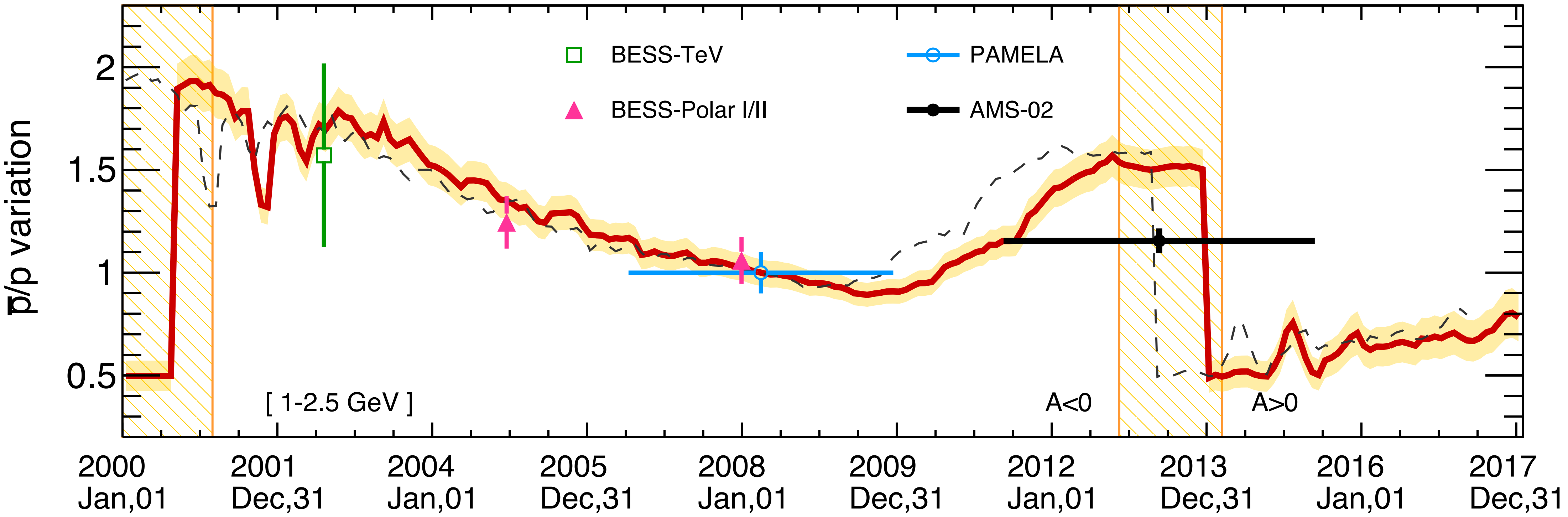


Insights from antimatter/matter ratios: drift



→CR proton-driven retuning using new AMS/PAMELA data
→Smooth transitrion across reversal.
→LIS, diffusion and drift parameters for GCR leptons.

Insights from antimatter/matter ratios: drift



Conclusions

Golden age for cosmic ray measurements

- News from space: Voyager-1, SOHO, PAMELA, AMS
- Multi-channel data protons, He, Nuclei, antiparticles

New insights to CR physics

- Proton data -> evidence for a time-lag -> timescale of CR modulation
- P/He data -> test for low-energy diffusion of CRs in heliosphere
- Antimatter/matter -> test for charge-sign dependent effects

From multi-channel & long-term data to space physics

- Establishment of predictive model with *forecast* capabilities
- Improve risk assessment in manned exploration missions

Models of cosmic ray modulation
in light of new data from AMS-02

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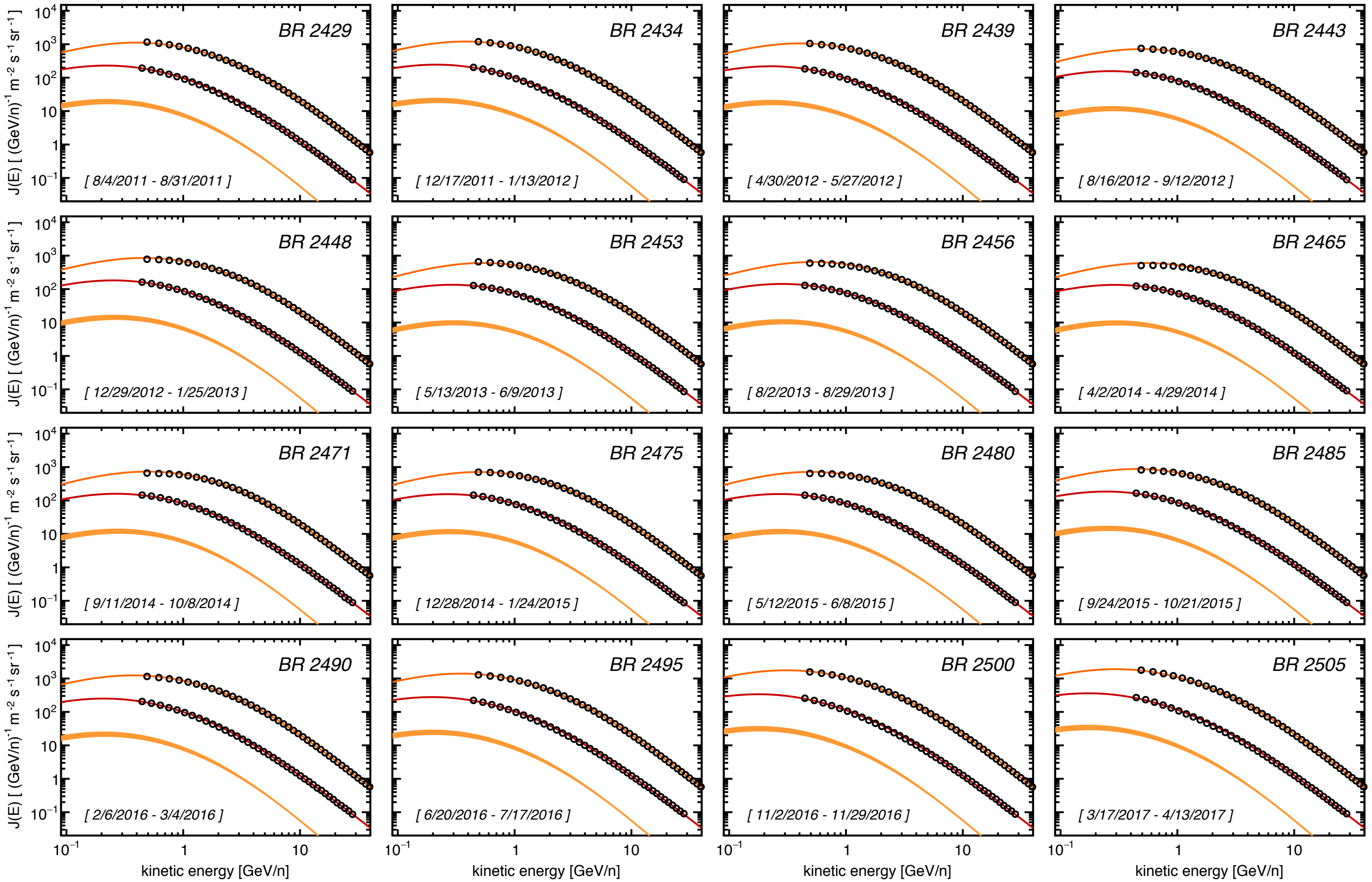
23-26 April 2018 – Washington DC, USA

Insights from the p/He ratio: diffusion

Fit on CR proton fluxes

$K(R,t) = \beta \times k_0(t) \times R$

Proton and helium energy spectra for 16 (out of 79) time periods



Proton are shown for the best-fit model. Total He and 3He (w/ uncertainty) are calculated.

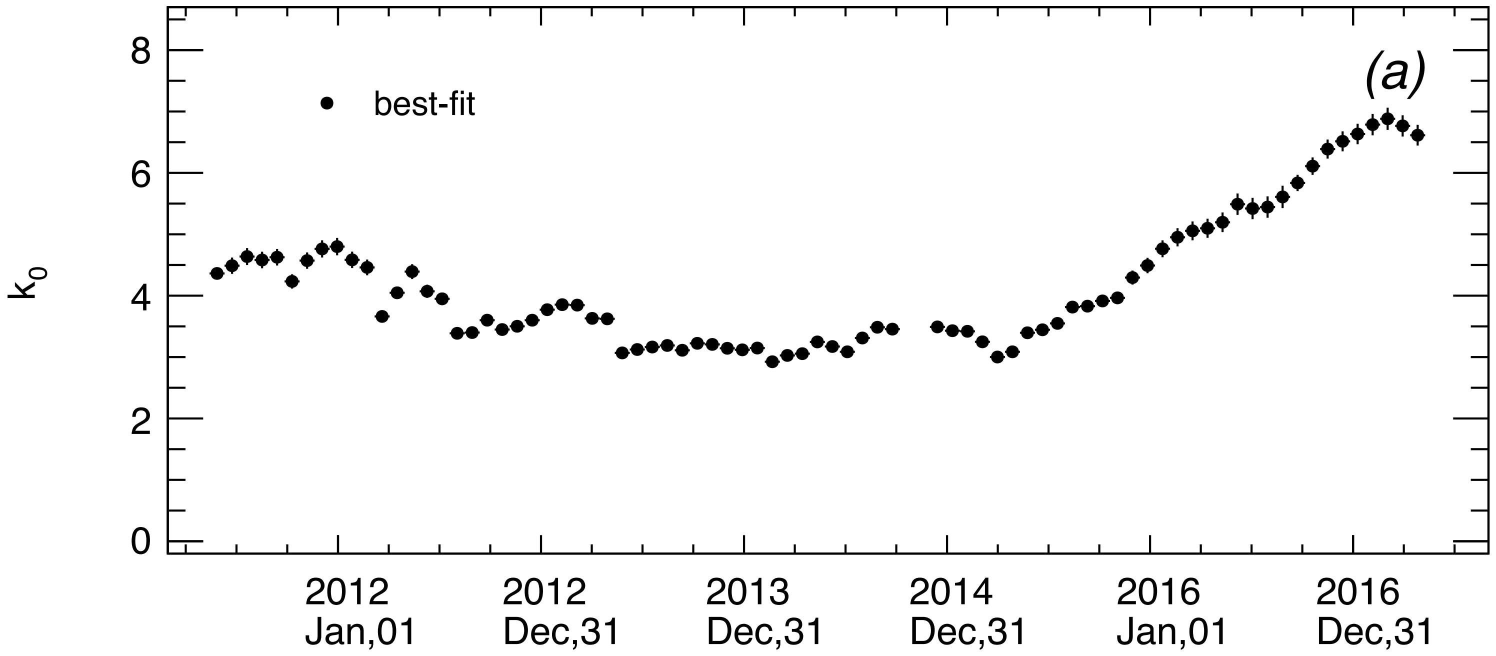
Insights from the p/He ratio: diffusion

- Different p-He LIS and their uncertainties accounted
- Isotopic composition accounted.
- Tested various diffusion coefficients with numerical models

$K(R,t) = \beta \times k_0(t) \times R$

$K(R) = (\mathbf{v}/3)\lambda(R)$ parallel diffusion coefficient

$\lambda(R)$ = universal "composition-blind" mean free path



In collaboration with F. Barao, M. Orcinha

Basic phenomenology: Parker equation

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

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

- **Diffusion**: Small Scale Magnetic Field irregolarities
- **Convection**: Effects of the solar wind moving out from the Sun
- **Particle drift**: Large Scale structure of magnetic field (gradients & curvature)
- **Energy losses**: Adiabatic expansion of solar wind
- **Source**: GCR particles

Modeling cosmic-ray transport in Helisophere

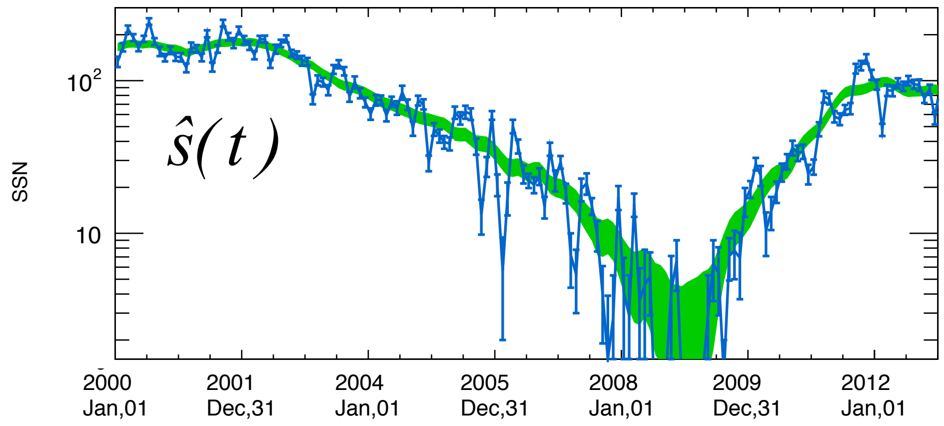
$$\underbrace{\frac{\partial f}{\partial t}}_{\text{Flux}} = \underbrace{\nabla\cdot[\mathbf{K}\cdot\nabla f]}_{\text{Diffusion}} - \underbrace{V\cdot\nabla f}_{\text{Convection}} - \underbrace{\langle v_D\rangle\cdot\nabla f}_{\text{Particle drift}} + \underbrace{\frac{1}{3}(\nabla\cdot V)\frac{\partial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

$$\begin{cases} K_{\perp} = 0.02\cdot K_{//} \\ K_{//} = k^0(t)\dfrac{10^{22}\cdot\beta p/GeV}{3B/B_0} \end{cases}$$

- ✓ Adimensional normalization factor
- ✓ Time-dependent & related to solar activity

$$\kappa^0(s) = a\cdot\log_{10}(s)+b$$

S = measured sunspot number



Modeling cosmic-ray transport in Helisophere

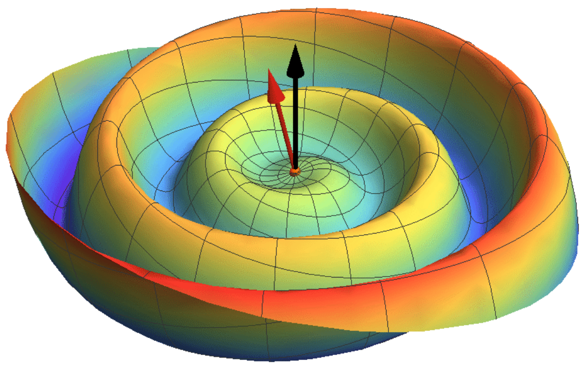
$$\frac{\partial f}{\partial t} = \nabla \cdot [\mathbf{K} \cdot \nabla f] - V \cdot \nabla f - \langle \boldsymbol{v}_D \rangle \cdot \nabla f + \frac{1}{3}(\nabla \cdot V)\frac{\partial f}{\partial \ln p} + Q(r,p,t)$$

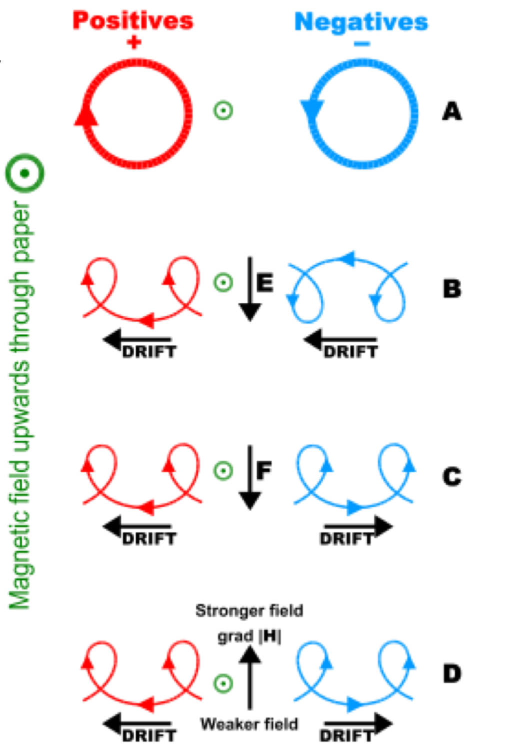
Flux — Diffusion — Convection — **Particle drift** — Adiabatic losses — Source / LIS

Drift motion along the B-field spiral

- ✓ Charge-sign dependent effect.
- ✓ Important in the Heliospheric Current Sheet

$$\langle \mathbf{v}_{\rm dr} \rangle = \frac{\beta P}{3} \nabla \times \frac{\mathbf{B}}{B^2}$$





- ✓ The HCS "*waviness*" depends on *tilt-angle* α

Modeling cosmic-ray transport in Helisophere

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

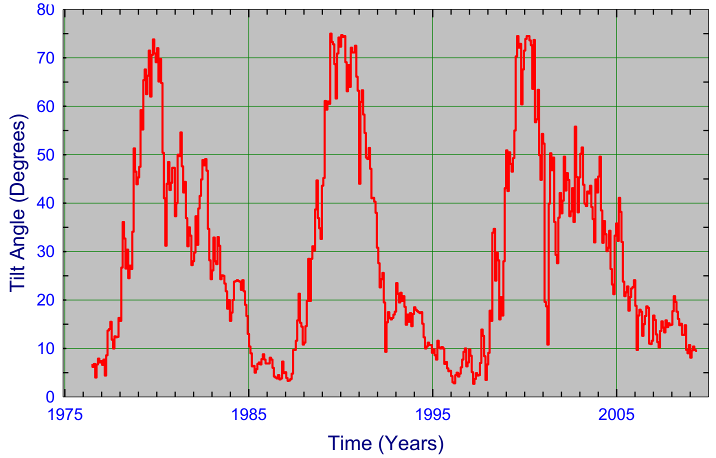
Flux — **Diffusion** — **Convection** — **Particle drift** — **Adiabatic losses** — **Source / LIS**

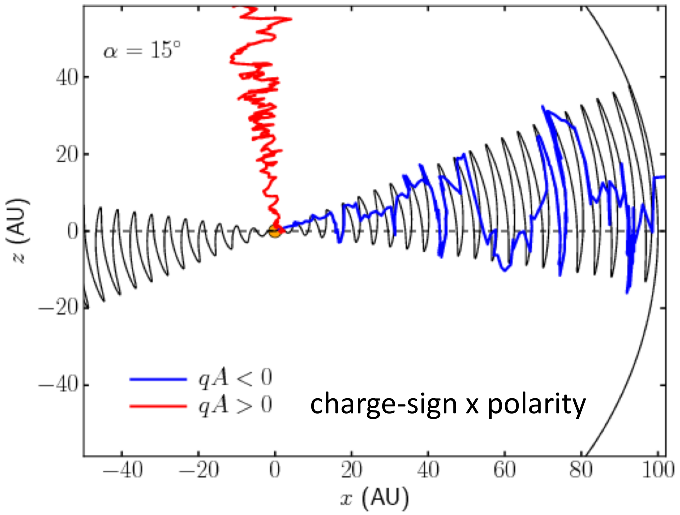
$$\langle \mathbf{v}_{\mathrm{dr}} \rangle = \frac{\beta P}{3} \nabla \times \frac{\mathbf{B}}{B^2}$$

Drift motion along the B-field spiral

- ✓ **Charge-sign dependent effect.**
- ✓ **Important in the Heliospheric Current Sheet**
- ✓ **Different trajectories for particles & antiparticles**
- ✓ **Interchanged role with B-field reversal (T=11-yrs)**

Tilt angle reconstruction from WSO





To investigate the effects, time-resolved flux data on particles and antiparticles are needed

Modeling cosmic-ray transport in Helisophere

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

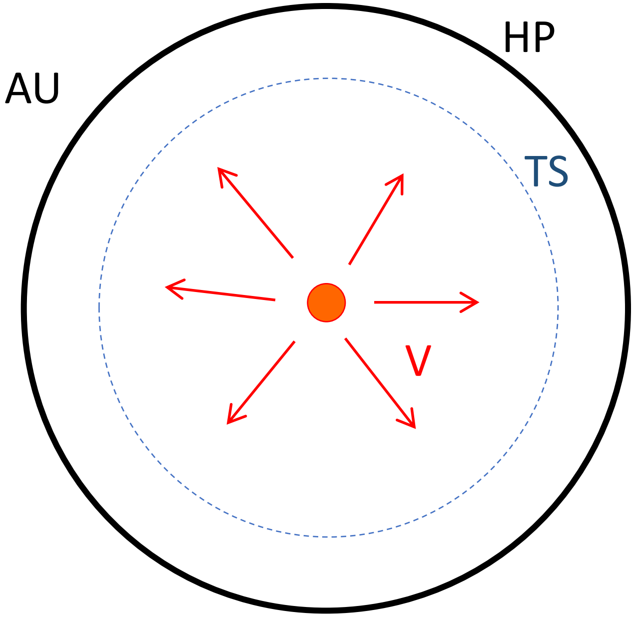
Flux — **Diffusion** — **Convection** — **Particle drift** — **Adiabatic losses** — **Source / LIS**

Convection and energy losses due to Solar Wind

Radially outflowing from the Sun with speed V= 400 km/s

Change to subsonic speed beyond termination shock @ r=85 AU

Vanishing at the Heliopause boundary @ r=122 AU



Model setting with time-lag ΔT accounted

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

We use "retarded" physics inputs

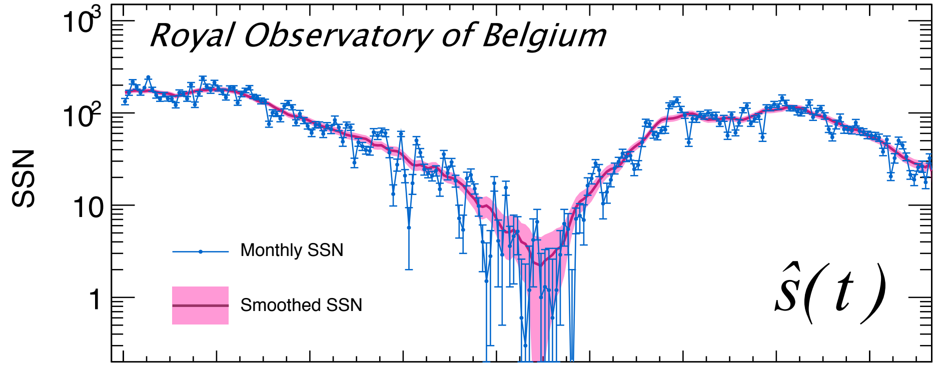
$$\kappa(t) = a \cdot log_{10}(\hat{s}(t - \Delta T)) + b$$
$$\alpha(t) = \hat{\alpha}(t - \Delta T)$$

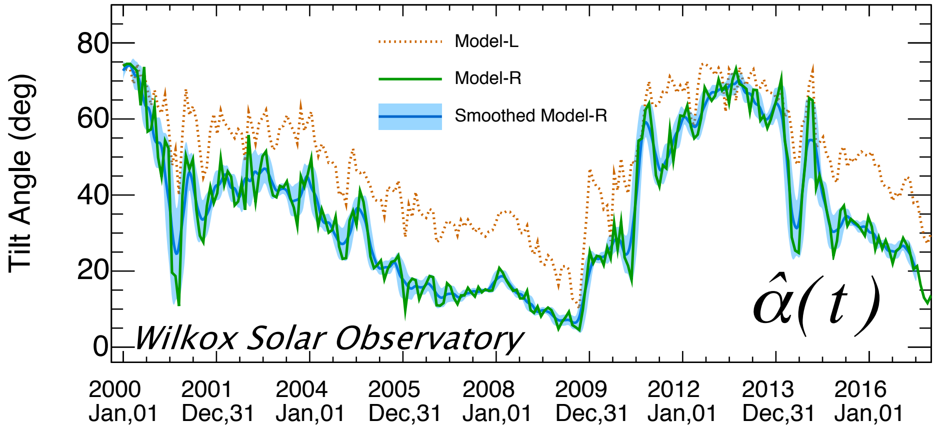
Quasi steady-state approach

$\partial f / \partial t = 0$ *Stochastic differential Integration method*

Free parameters TBD by data

$$\chi^2 = \chi^2(a, b, \Delta t)$$





Global fitting to cosmic-ray data

Proton flux data at negative polarity (A<0) beteen 2000 and 2012

- **PAMELA**: at E= 0.08 – 50 GeV, from 2006 to 2010 (3.5yrs) monthly resolved
- **EPHIN/SOHO**: at E=0.5-2 GeV, from 2000 to 2013, yearly resolved
- **BESS-Polar I-II**: at E=0.1-50 GeV, from two 15-day flights in 2004 and 2008

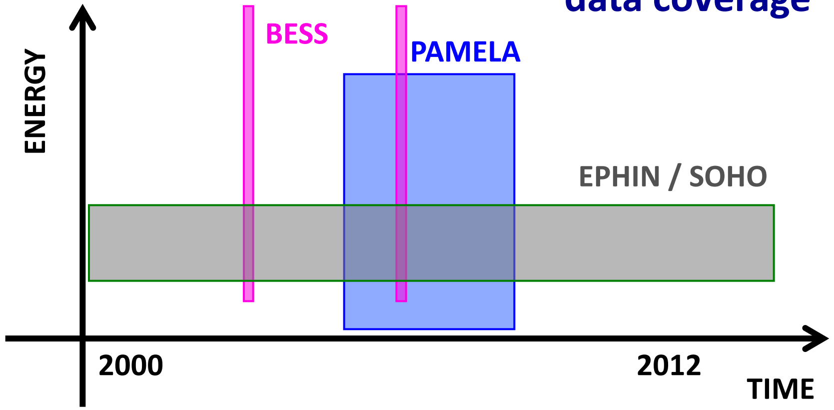
Global χ^2 estimator:

$$\chi^2 = \sum_t \sum_E \left[\frac{J(E,\alpha(t),\kappa(t)) - \hat{J}(E,t)}{\sigma_{tot}(E,t)} \right]^2$$

Three free parameters

$$\chi^2 = \chi^2(a,b,\Delta t)$$

nearly 4000 data points

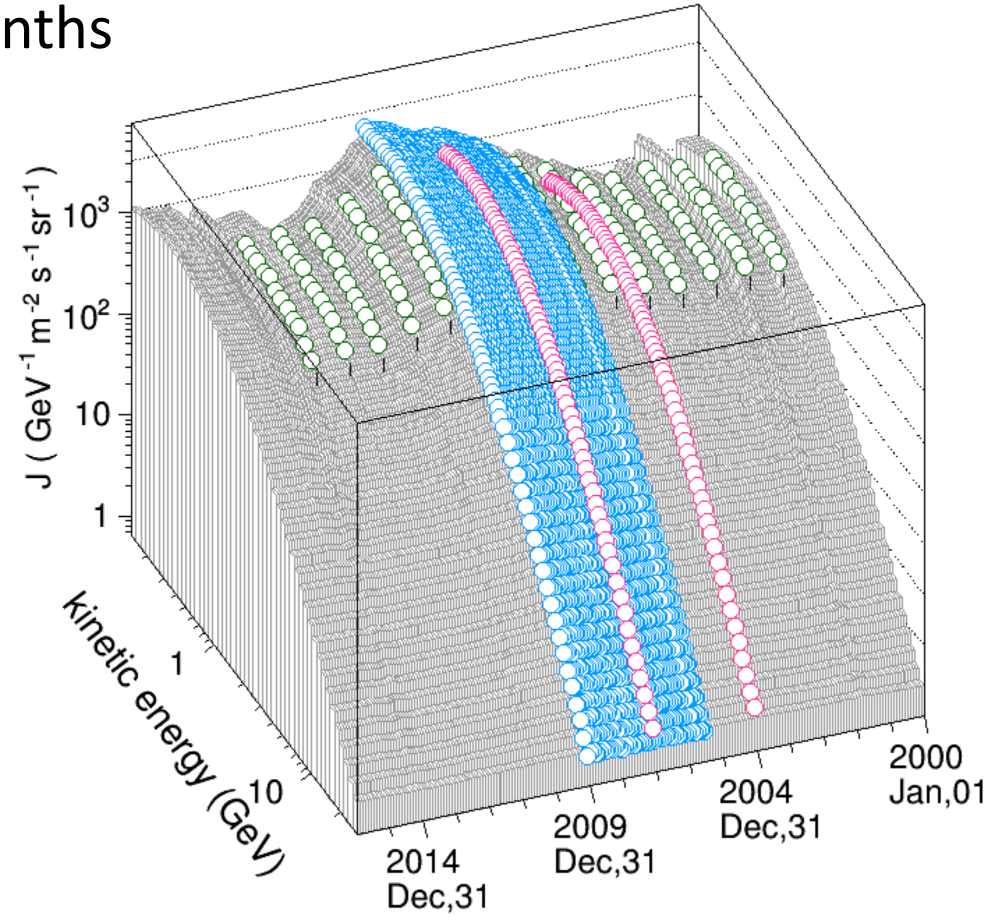


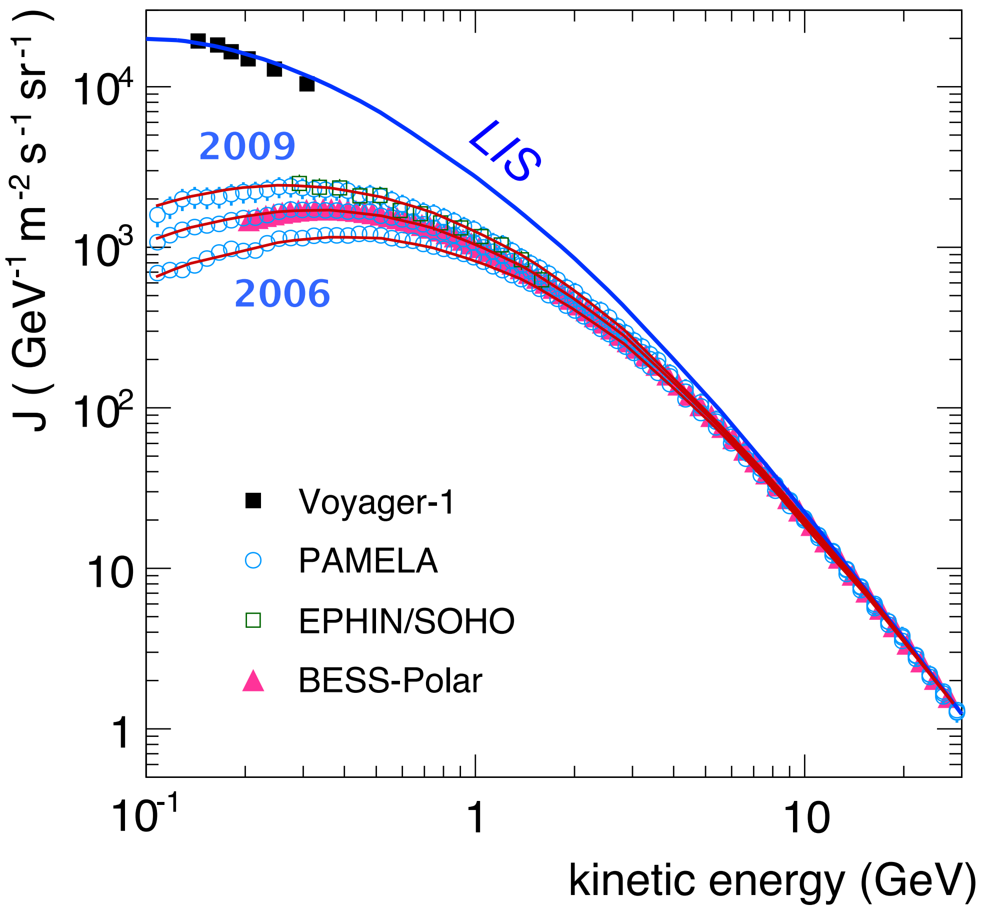
Fit results: protons vs time vs energy

$\Delta T = 8.1 \pm 1.2$ months

$a = 4.07 \pm 0.95$

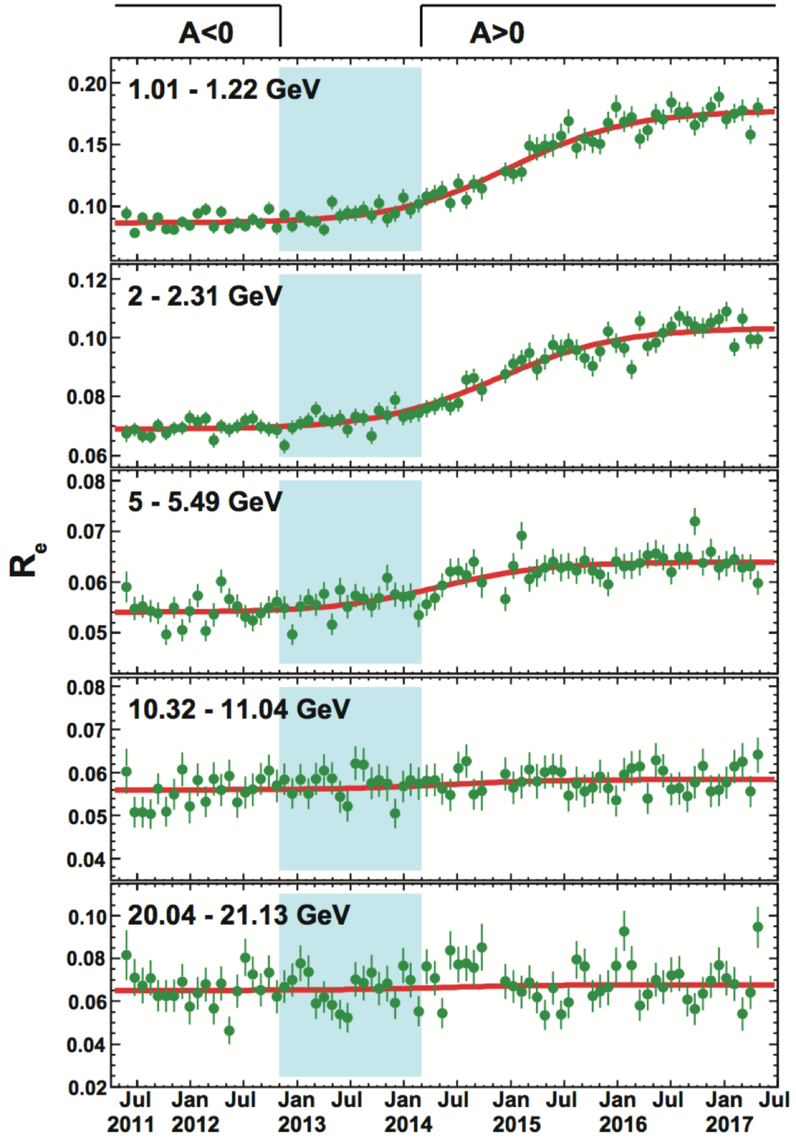
$b = -1.39 \pm 0.34$





e+/e- ratio vs time vs rigidity

3. Antimatter/matter ratios



AMS-02 data on electrons and positrons [2018, preliminary]

Observed a gradual change of the ratio e+/e- after the solar polarity reversal. Evidence for charge-sign dependent solar modulation.

The heliospheric magnetic field