Study of solar modulation effects on cosmic ray fluxes measured by the AMS experiment

Miguel Orcinha
IST/LIP Lisboa, Portugal

5th IDPASC/LIP Students Workshop

2 July 2019
Minho University - Braga, Portugal

Who am I?

Miguel Reis Orcinha

PhD Student in Physics
Instituto Superior Técnico

MSc in Technological Physics Engineering
Instituto Superior Técnico

Member of LIP – Lisboa
since 2013

Member of AMS Collaboration
since 2013

migorc@lip.pt

Scientific Interests:

- Solar Modulation of Galactic Cosmic Rays
- Cosmic Ray Physics
- Computational Physics and Numerical Methods
- Data Analysis and Statistics
- Experimental Particle Physics

ALPHA MAGNETIC SPECTROMETER

Image:NASA

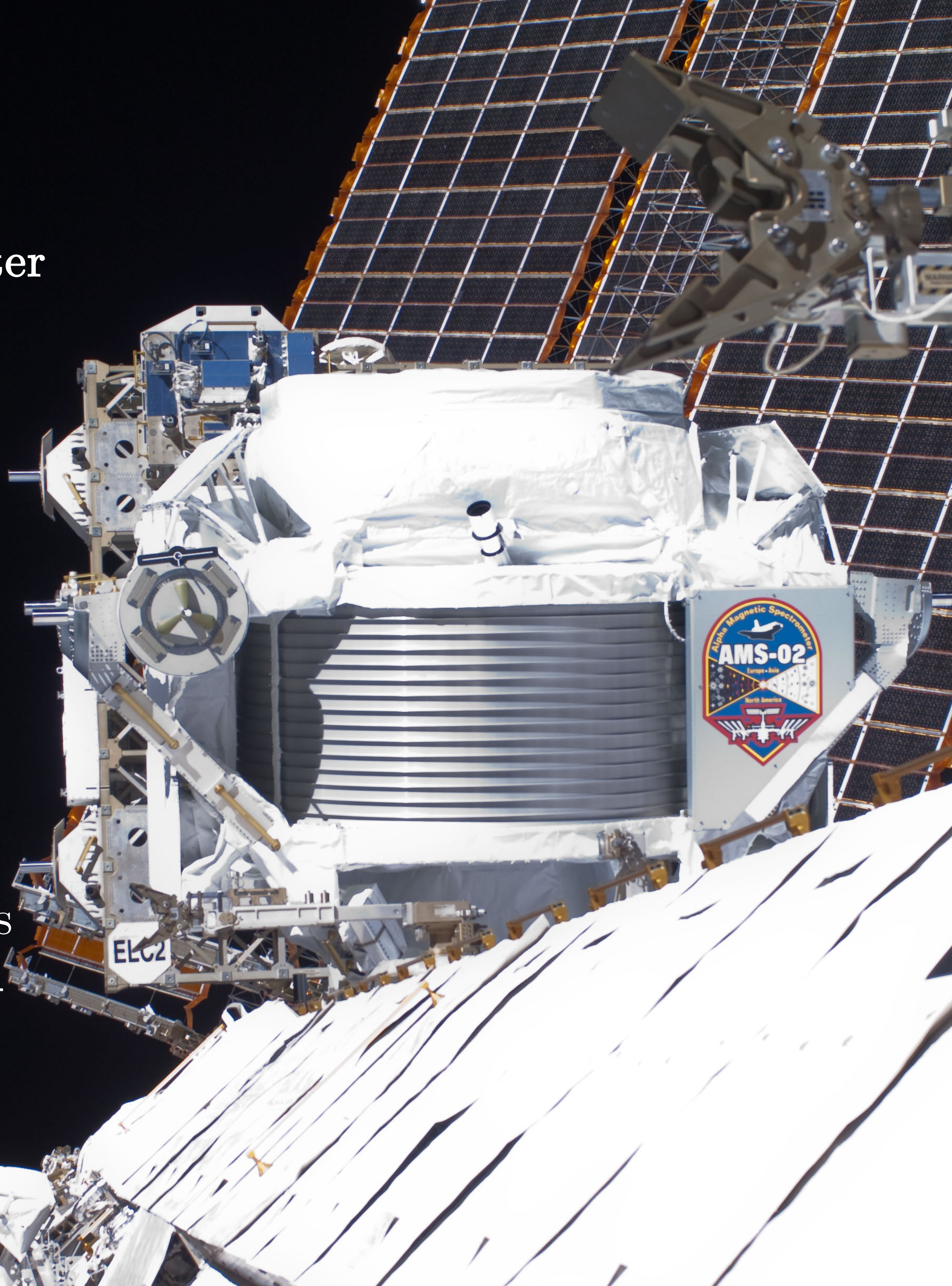
History of AMS

The **Alpha Magnetic Spectrometer** (AMS-02) is a state-of-the-art cosmic-ray detector designed to operate as an external module on the International Space Station (ISS).

Installed on the ISS in May of 2011, its main objective is the search for antimatter and dark matter.

AMS has collected more than **135,000,000,000 events** up to this day, at a rate of about **45 million events per day**.

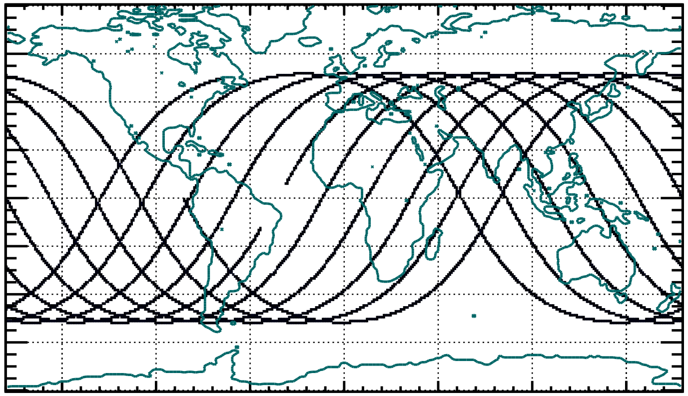
It will continue in space for the duration of ISS' lifetime.



INTERNATIONAL SPACE STATION

Image:NASA

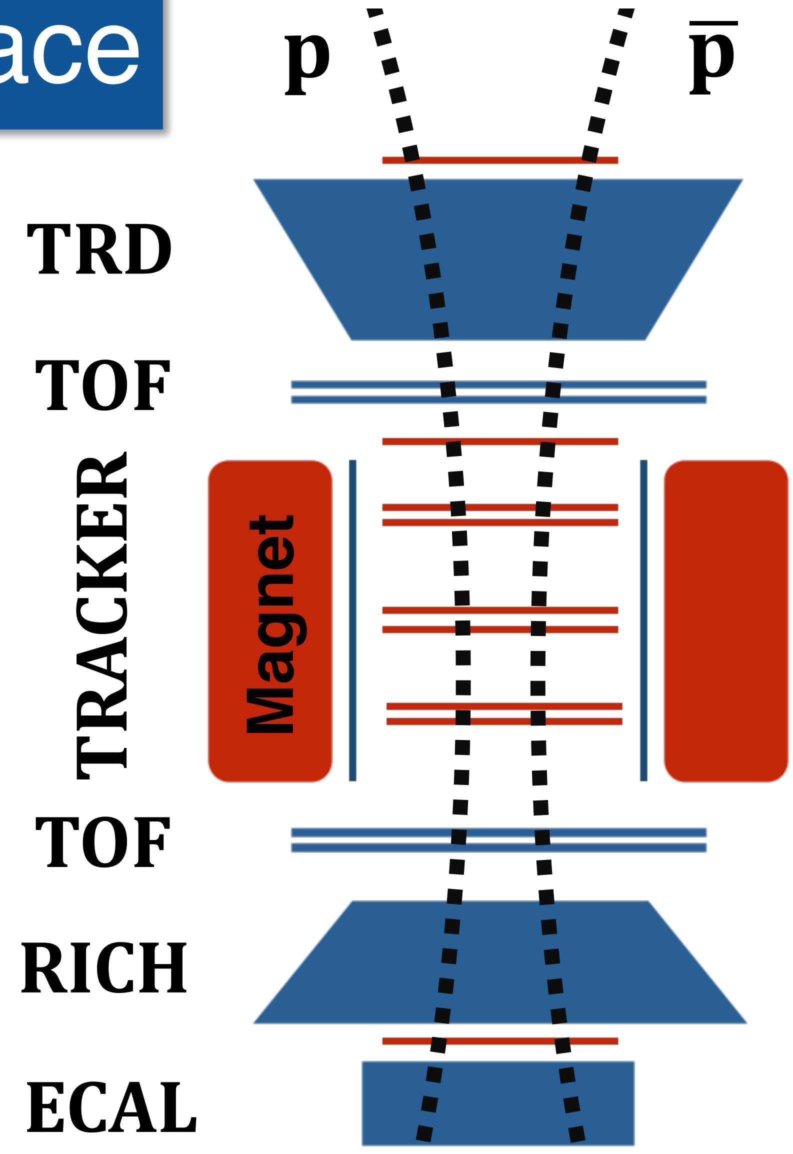
Image:Tested



ALTITUDE: 400 KM
ORBITAL PERIOD: 92.49 MIN
VELOCITY: 27600 KM/H
LAUNCH: 20 NOV 1998

AMS: A detector in space

Image:NASA

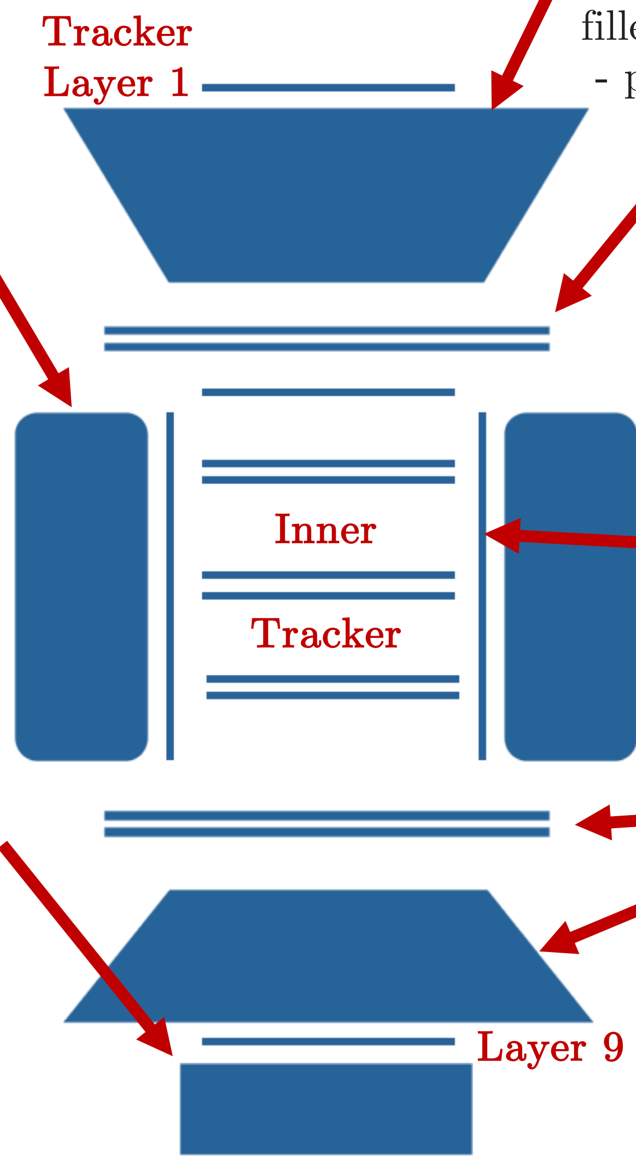


45 MILLION EVENTS PER DAY
135.000.000.000 EVENTS

Anatomy of a detector

Transition Radiation Detector (TRD)
- 20 layers of proportional chambers filled with a Xe/CO_2 gas mixture
- p/e rejection ~10^2-10^4

Permanent Magnet
6000 Ne-Fe-B magnets
Magnitude: 0.15 T



Time-of-Flight (ToF)
- 4 layers of scintillation counters
- AMS main trigger
- Measurement of β=v/c with ~1% uncertainty

Sillicon Tracker
- 9 layers of double-sided silicon sensors
- Spatial accuracy in bending direction: ~10μm
- Measurement of rigidity (p/q) up to ~2 TV for protons
- Measurement of charge-sign

Anti-Coincidence Counters (ACC)
- Veto for particles traversing from the side

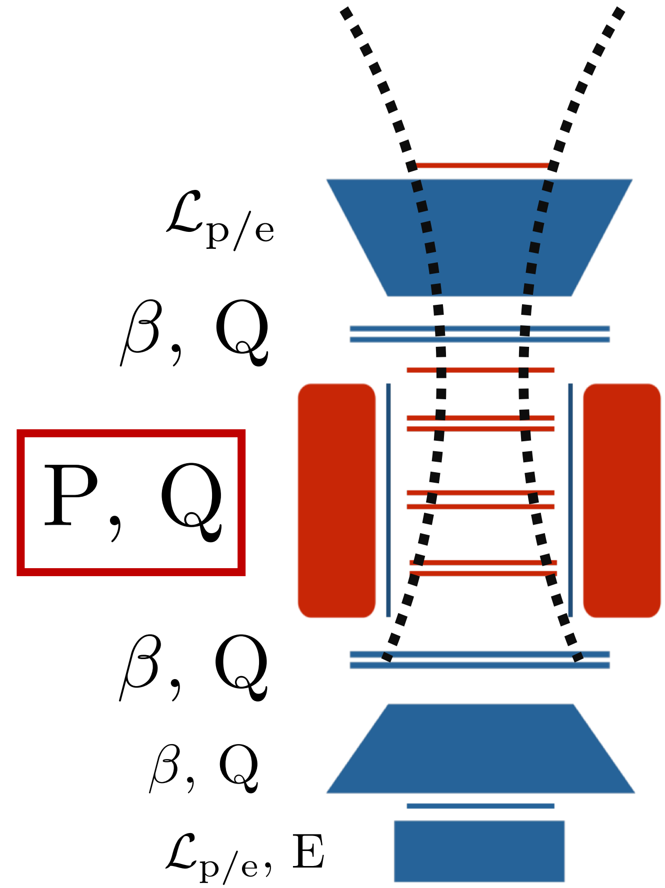
Electromagnetic Calorimeter
- 9 super-layers of lead and scintillating fiber (17 X_0)
- Measurements of e± and γ energy (ΔE/E~2% - 100GeV)
p/e rejection >10^4

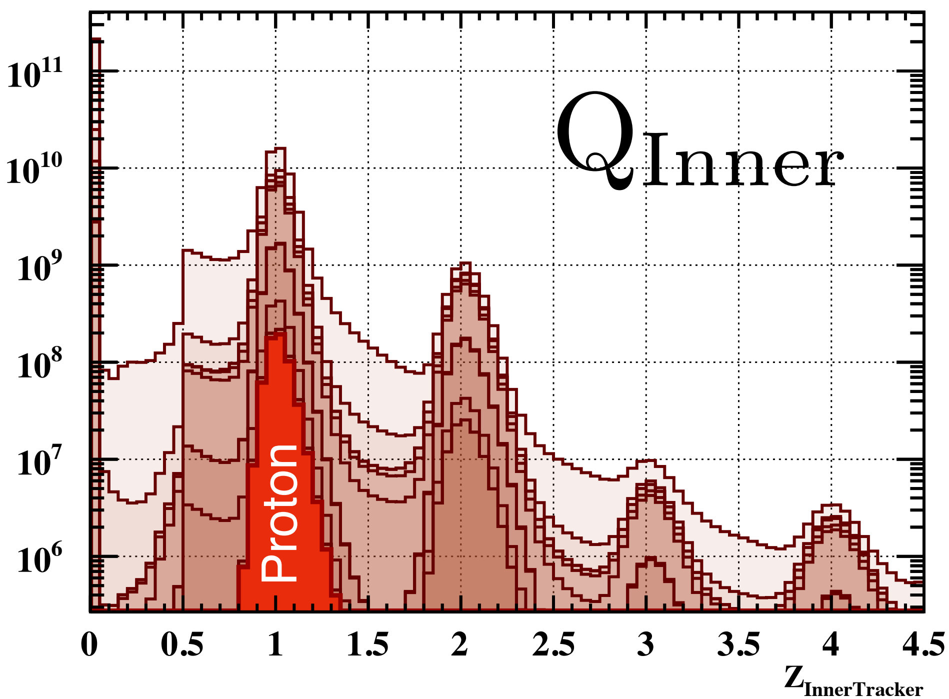
Time-of-Flight (ToF)

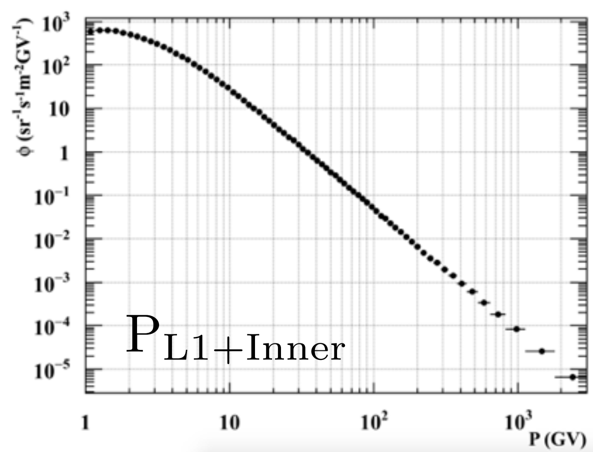
Ring Imaging Cherenkov (RICH)
- Aerogel and NaF radiators
- Precise measurement of β=v/c with ~0.1% uncertainty

Selecting CR data

$$\phi(P,t) = \frac{N_{\mathrm{part}}(P,t)}{\Delta t(P,t)\varepsilon_{\mathrm{trigg}}(P,t)Acc_{\mathrm{MC}}(P)C_{\mathrm{MC}}^{\mathrm{Data}}(P,t)\Delta P}$$





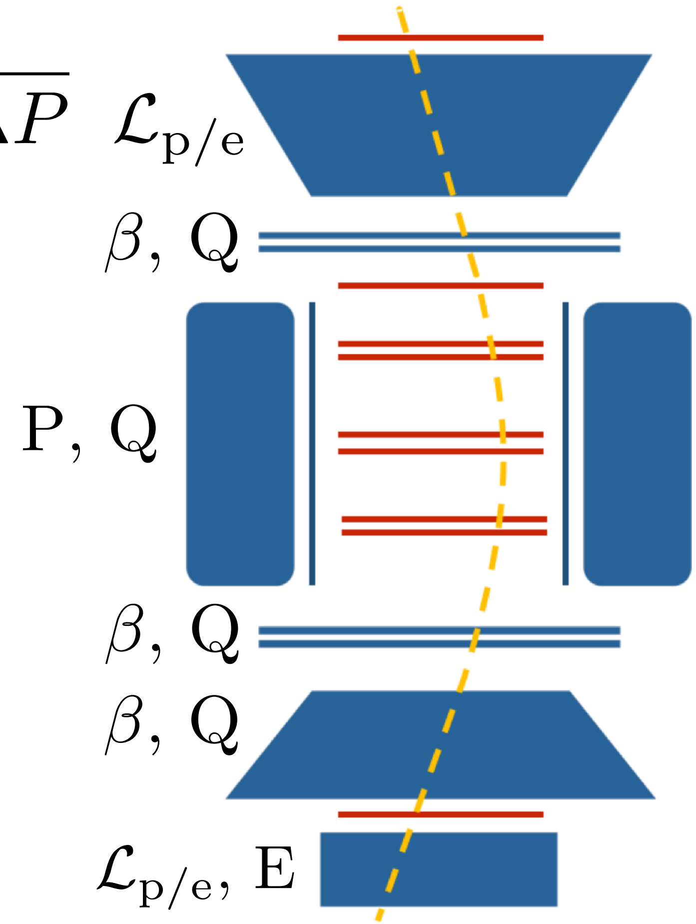


Proton flux estimation

$$\phi(P) = \frac{N_{\mathrm{part}}(P)}{\Delta t \, \varepsilon_{\mathrm{trigg}}(P) \, Acc_0 \, \varepsilon_{\mathrm{sel}}(P) \, \Delta P}$$

To estimate the proton flux some key ingredients are necessary:

- **Selection of Events**
- **Exposure Time**
- **Trigger Efficiency**
- **Detector Acceptance and Efficiency**

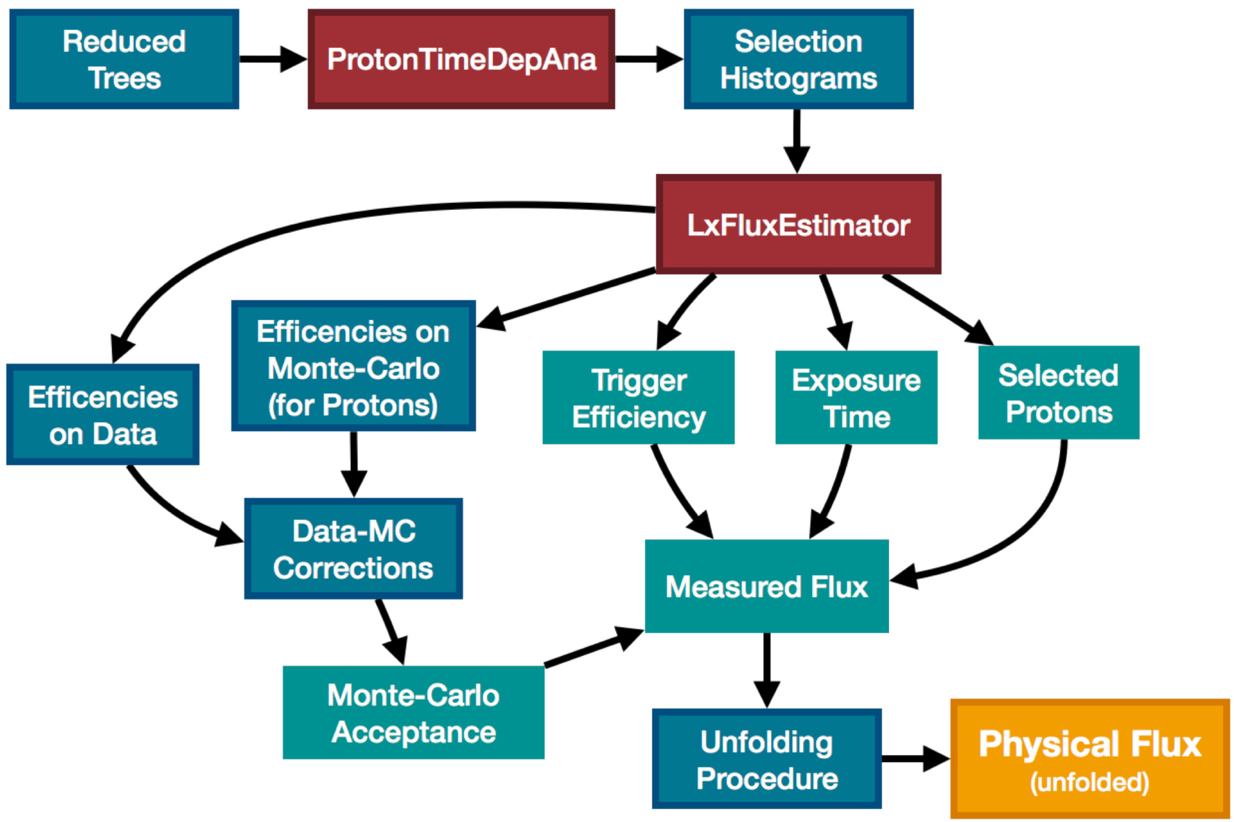


Proton flux estimation

The determination of the proton flux requires the study of the interaction of the cosmic-rays with the AMS detector as well as with earth's magnetic field.

The essential ingredients can be aggregated into the following quantities:

- Selection of Events
- Exposure Time
- Trigger Efficiency
- Detector Acceptance and Efficiency

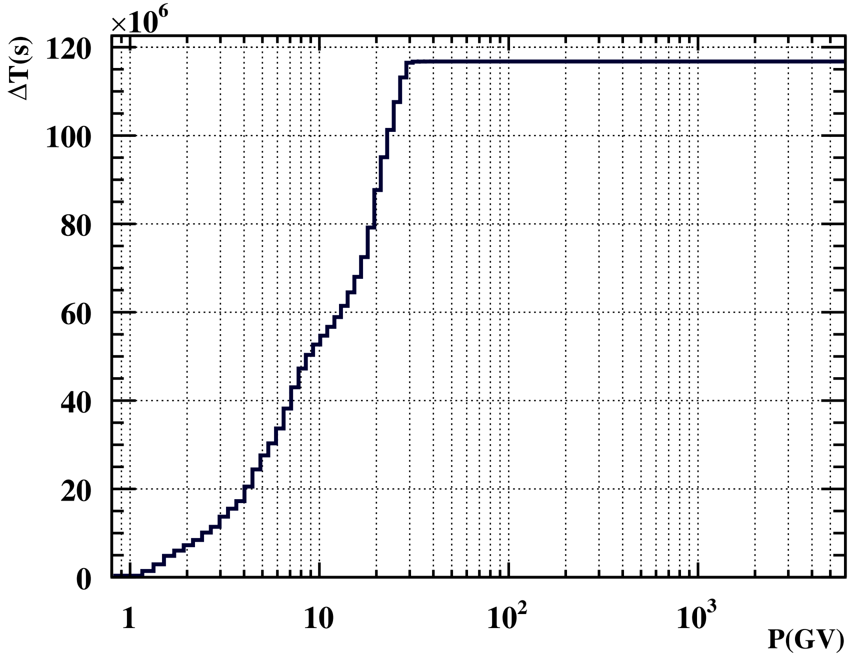


Geomagnetic cutoff and livetime

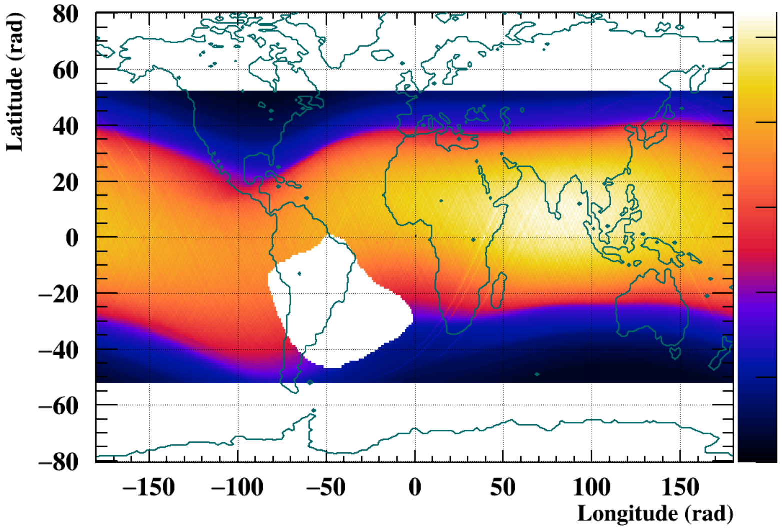
$$\phi(P) = \frac{N_{\text{part}}(P)}{\boldsymbol{\Delta t}\, \varepsilon_{\text{trigg}}(P) Acc_0 \varepsilon_{\text{sel}}(P) \Delta P}$$

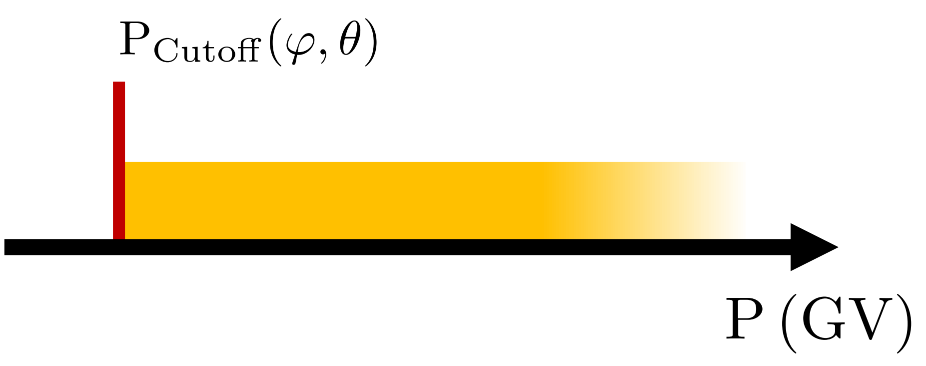
Rigidity Dependent!

$$\phi(P) = \frac{N_{\text{part}}(P)}{\boldsymbol{\Delta t(P)}\, \varepsilon_{\text{trigg}}(P) Acc_0 \varepsilon_{\text{sel}}(P) \Delta P}$$



Geomagnetic Cutoff (GV)



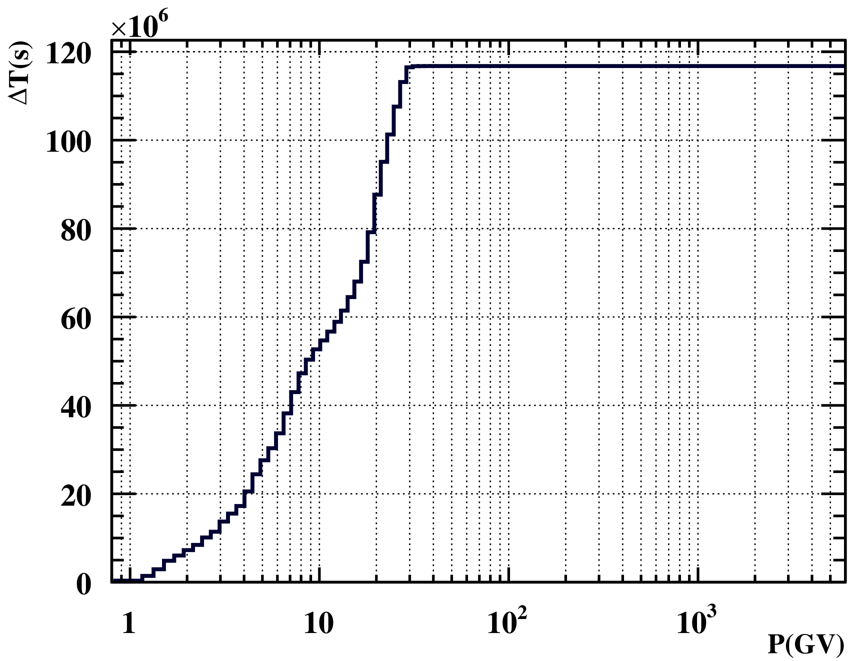


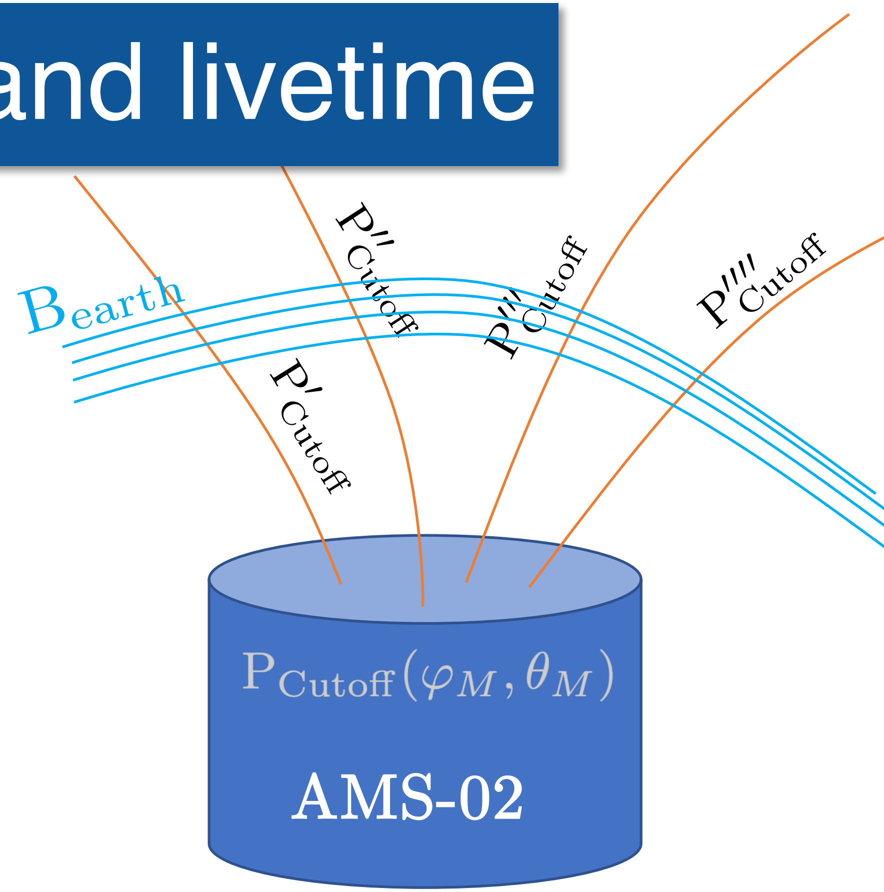
Geomagnetic cutoff and livetime

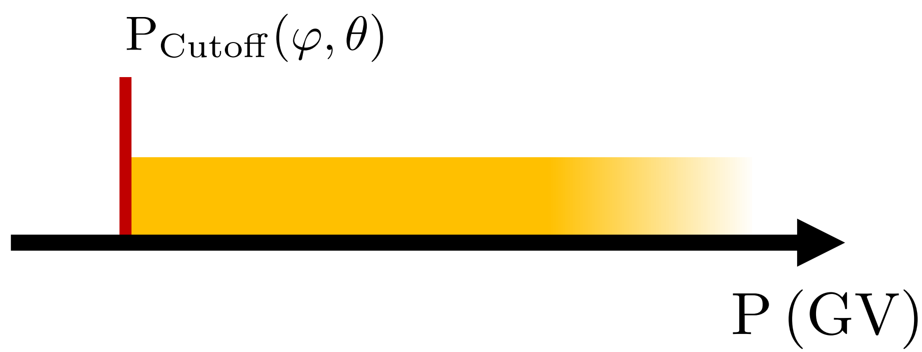
$$\phi(P) = \frac{N_{\rm part}(P)}{\boldsymbol{\Delta t}\,\varepsilon_{\rm trigg}(P)\,Acc_0\,\varepsilon_{\rm sel}(P)\,\Delta P}$$

Rigidity Dependent!

$$\phi(P) = \frac{N_{\rm part}(P)}{\boldsymbol{\Delta t(P)}\,\varepsilon_{\rm trigg}(P)\,Acc_0\,\varepsilon_{\rm sel}(P)\,\Delta P}$$







Unfolding a flux

$$N(P) = \int_0^\infty \underbrace{\phi_0(P_0)\,\Delta t(P_0)}_{\text{Physics}}\,\underbrace{Acc(P_0)\,K(P|P_0)}_{\text{Detector}}\,\mathrm{d}P_0$$

(... some calculations later ...)

$$\Delta N_j \simeq \sum_i \langle \Delta t_i \rangle\,\mathcal{P}(j|i)\,Acc^{\text{gen}}\,\Delta P_i\,\langle \Delta\phi_0 \rangle_i$$

$$\Delta N_j \simeq A^{ij}\,\langle \phi_0 \rangle_i$$

Ideal unfolding problem!

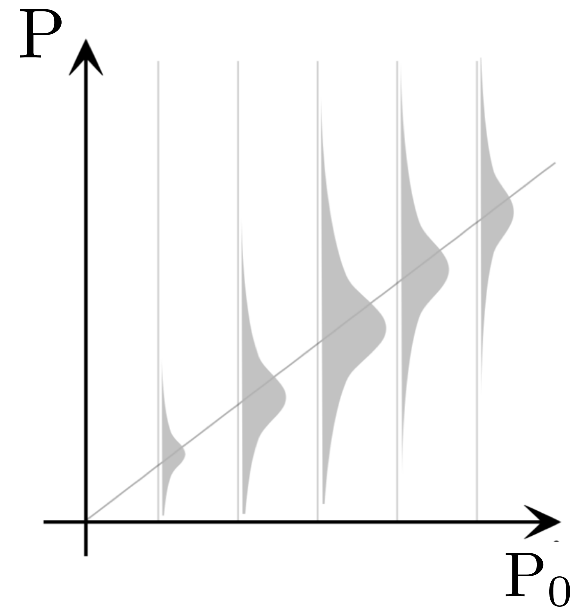
$$\Delta N_j \simeq A^{ij}(\phi_0)\,\langle \phi_0 \rangle_i$$

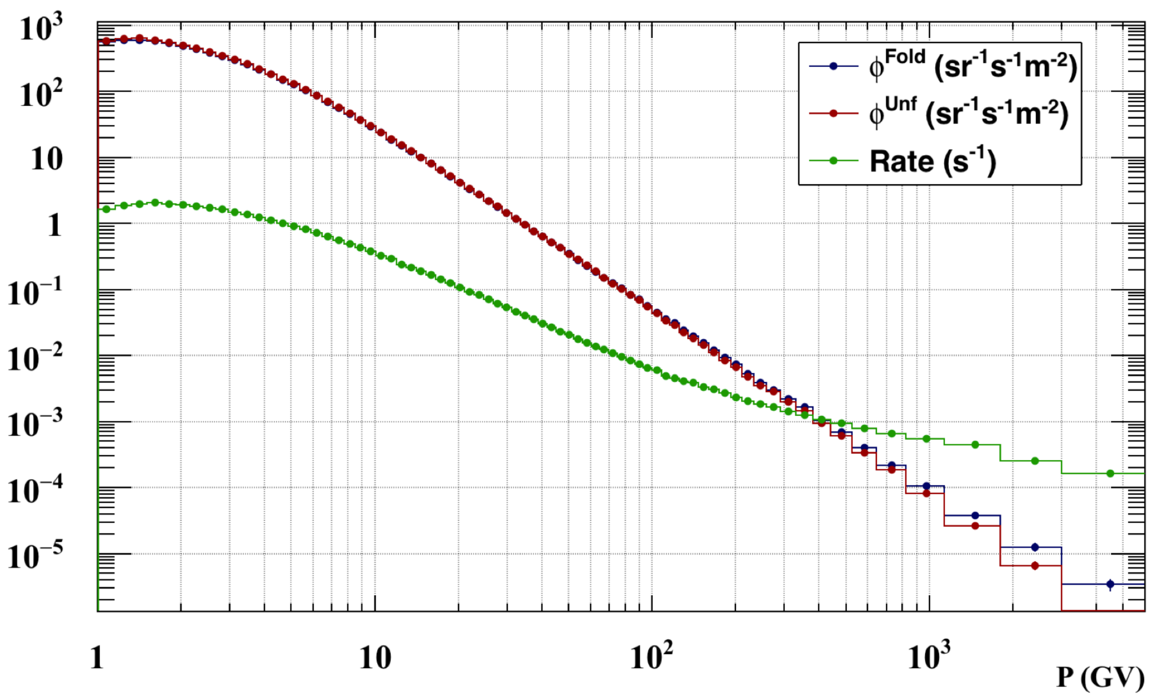
True and problematic unfolding problem!

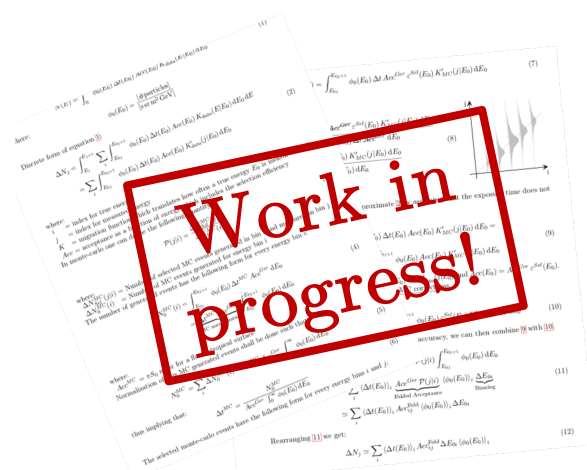
Unfolding a flux

$$\Delta N_j \simeq \sum_i \langle \Delta t_i \rangle \, \mathcal{P}(j|i) \, Acc^{\text{gen}} \, \Delta P_i \, \langle \Delta \phi_0$$

$$\Delta N_j \simeq A^{ij} \, \langle \phi_0 \rangle_i$$







Unfolding a flux – An iterative process

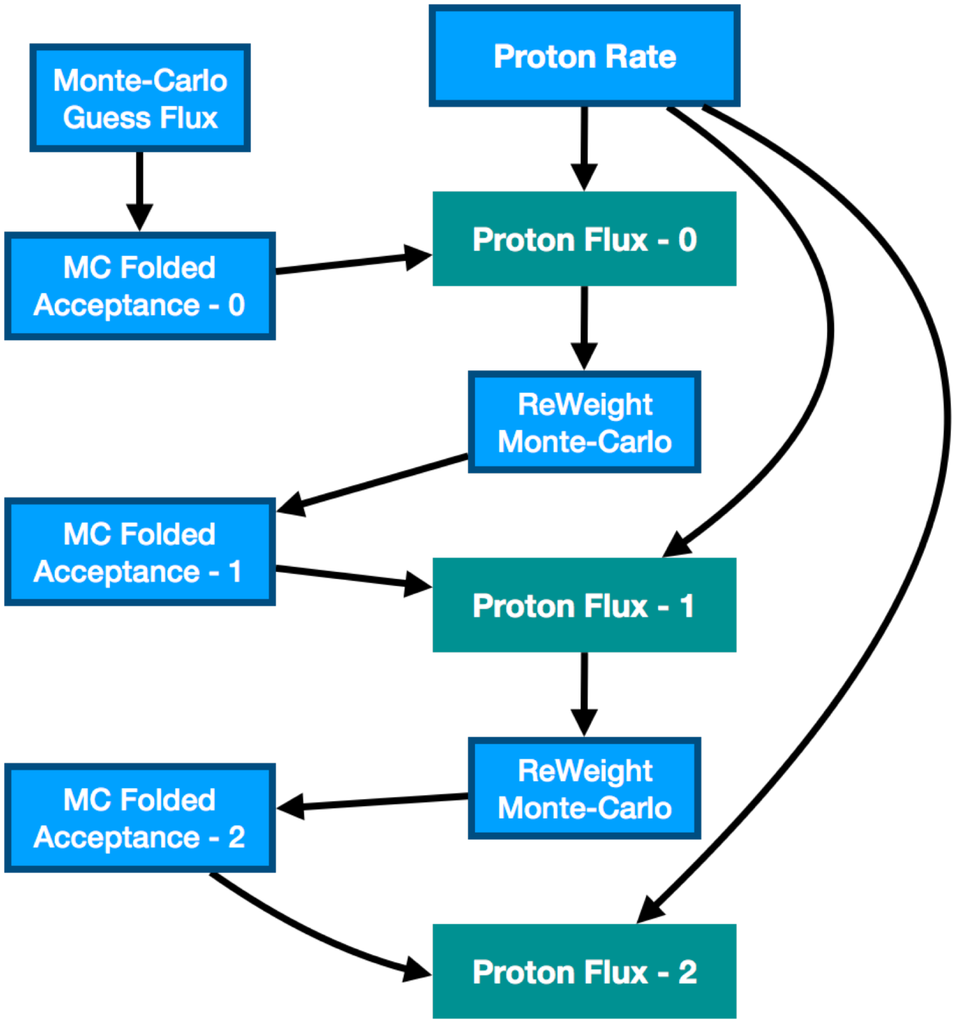
$$\text{Rate} = \frac{\text{Selected Events}}{\text{Exposure Time}}$$

$$\phi^{0}_{\text{Unf}} = \frac{\text{Rate}}{\text{Acc}^{0}_{\text{Fold}}\left(\phi^{\text{MC}}_{\text{Guess}}\right)}$$

$$\phi^{1}_{\text{Unf}} = \frac{\text{Rate}}{\text{Acc}^{1}_{\text{Fold}}\left(\phi^{0}_{\text{Unf}}\right)}$$

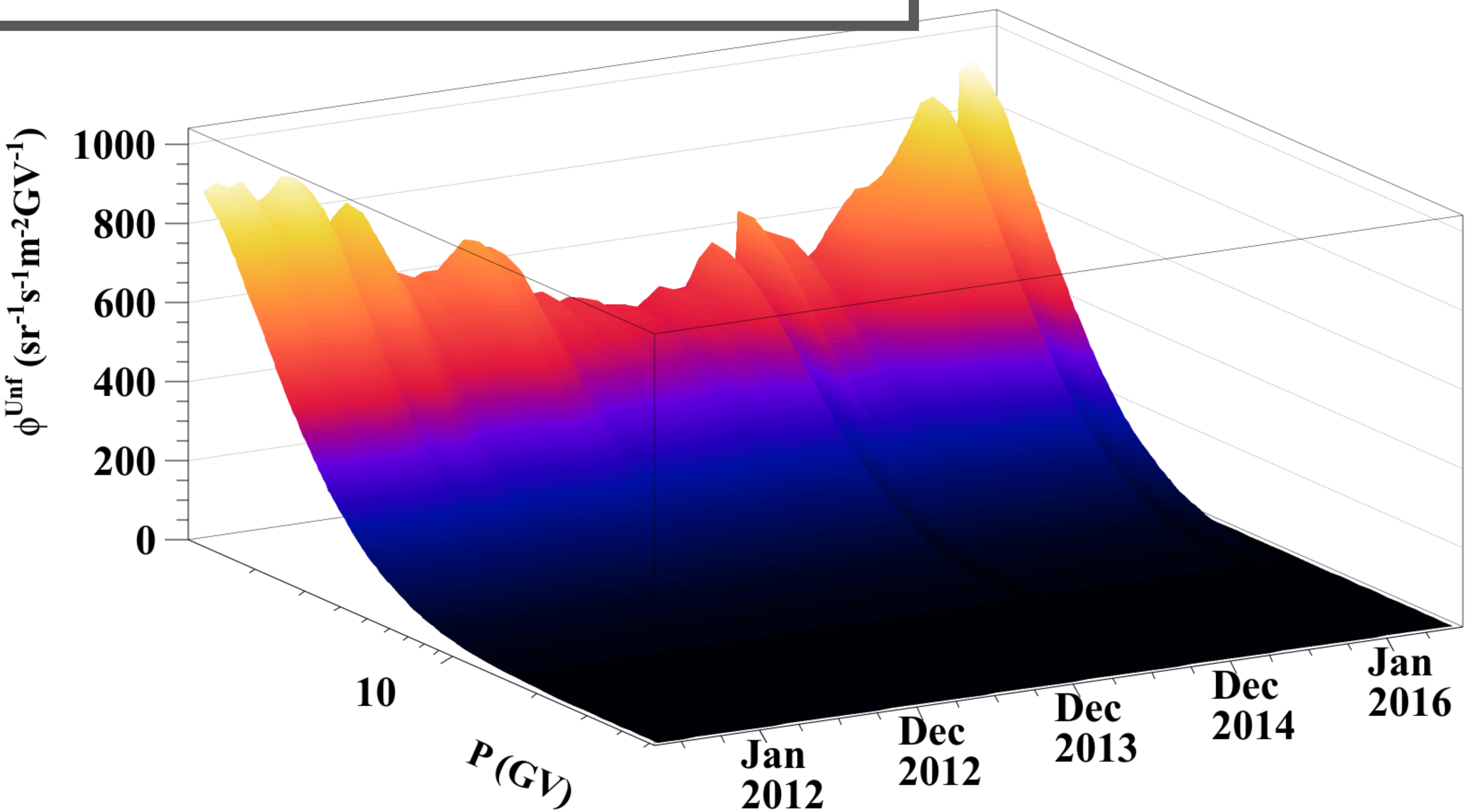
$$\phi^{2}_{\text{Unf}} = \frac{\text{Rate}}{\text{Acc}^{2}_{\text{Fold}}\left(\phi^{1}_{\text{Unf}}\right)}$$

$$\vdots$$



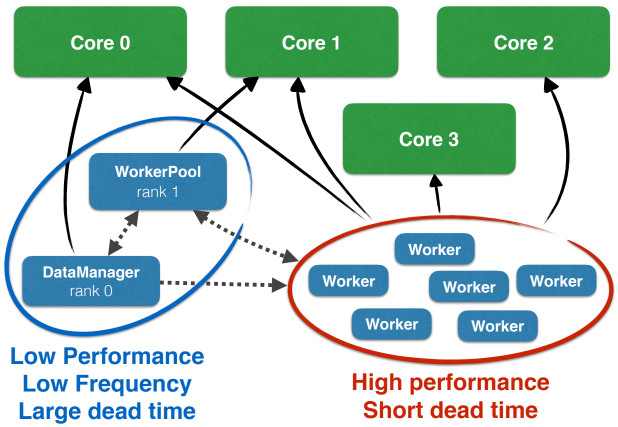
Proton Flux

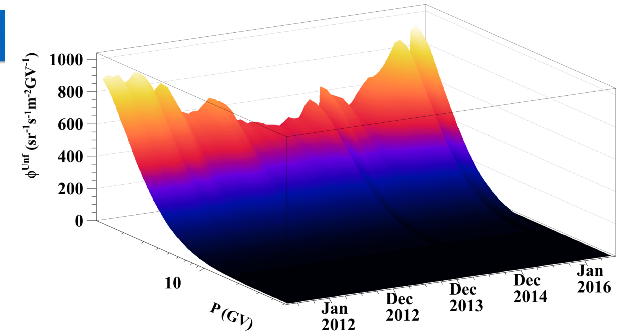
$$\phi(P,t) = \frac{N_{\mathrm{part}}(P,t)}{\Delta t(P,t)\varepsilon_{\mathrm{trigg}}(P,t)Acc_{\mathrm{MC}}(P)C_{\mathrm{MC}}^{\mathrm{Data}}(P,t)\Delta P}$$



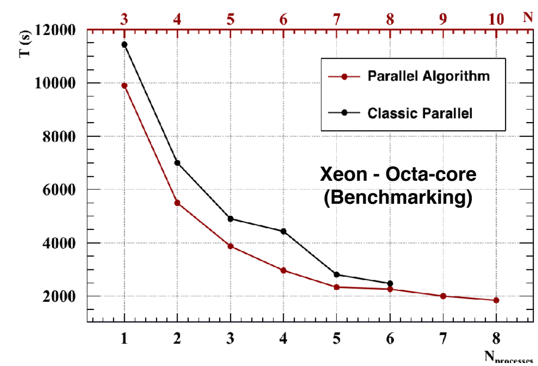
AMS Proton Parallel Selection

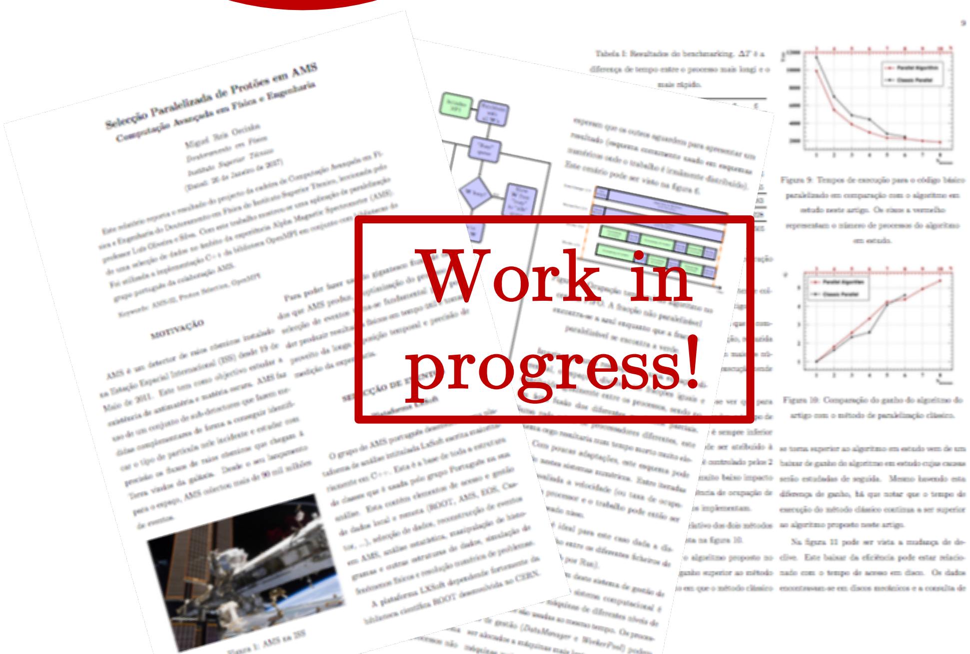
Program Topology - Quad-core

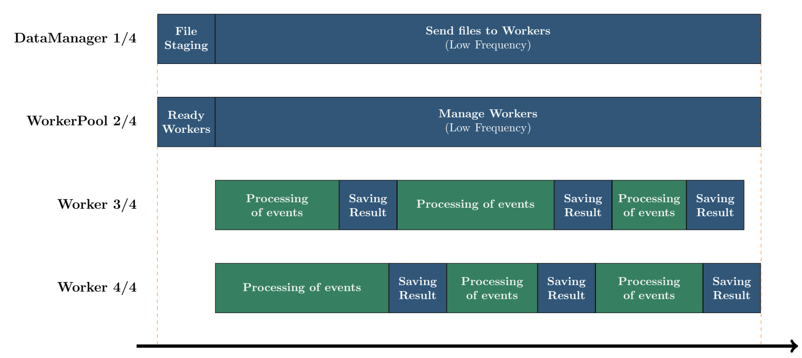




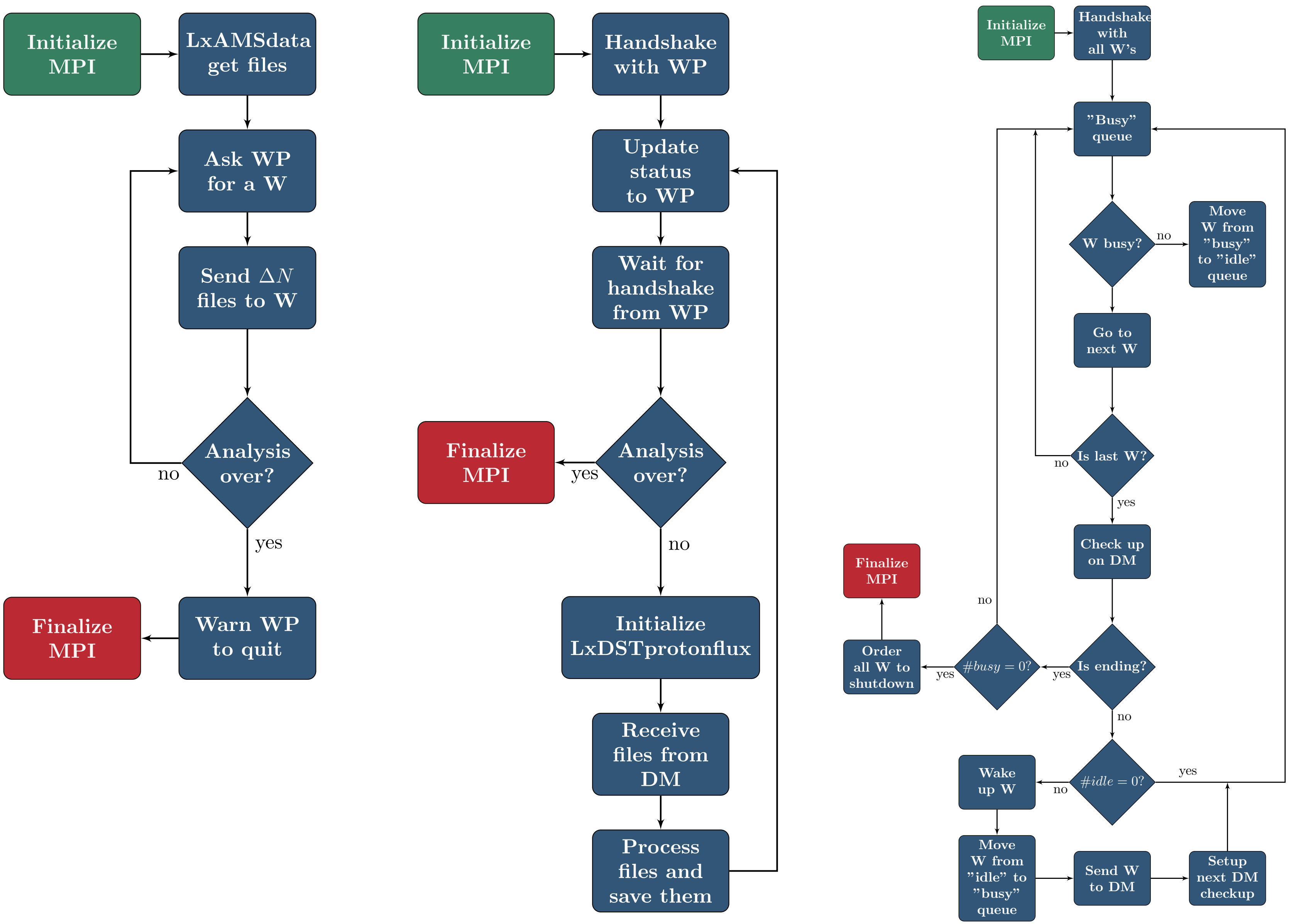
Results







AMS Proton Parallel Selection



SOLAR MODULATION OF COSMIC RAYS

INTERPRETATION OF TIME VARIABILITY UNDER TRANSPORT THEORY

Solar Modulation

Solar modulation is:

✓ Time dependent

Correlated to the 11-year solar activity cycle and to short-term events.

✓ Space dependent

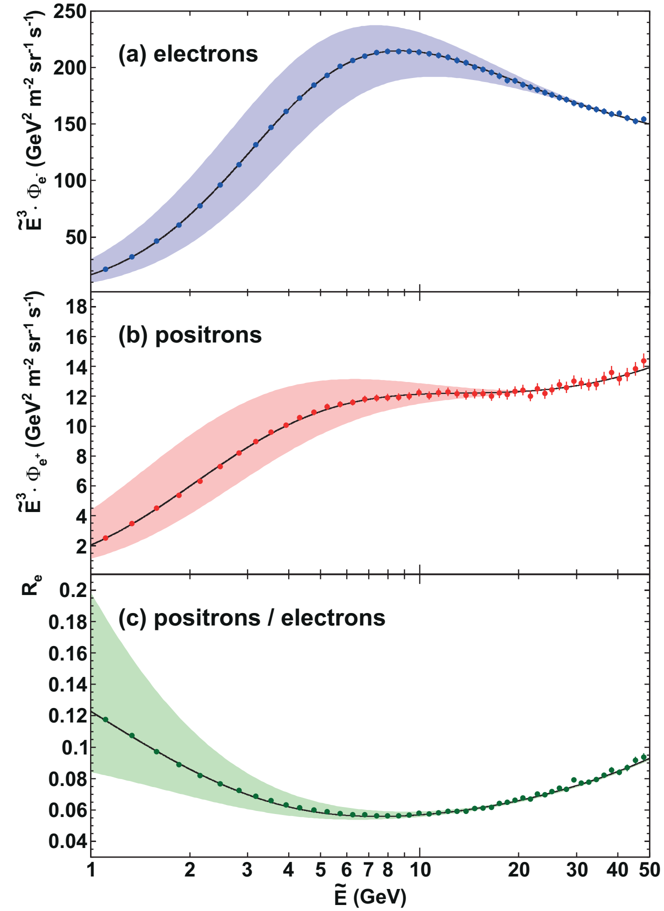
Modulation parameters vary as the spiral magnetic field spreads throughout the solar system.

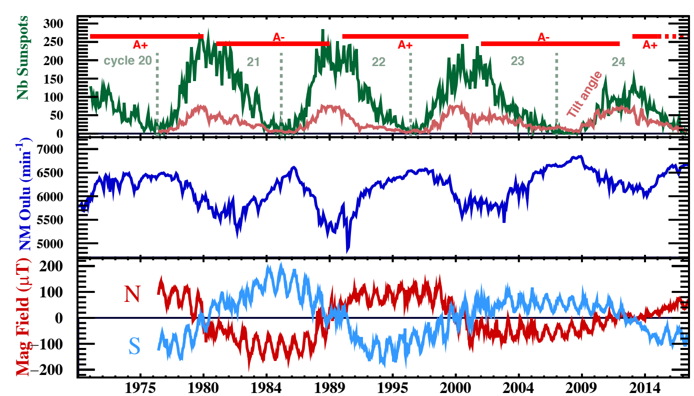
✓ Energy dependent

Effect **decreases** with CR **increasing** energy until it vanishes at the 20-50 GeV scale.

✓ Particle dependent

Depends on charge of the particle. Particles and antiparticles showcase this **charge-sign** effect.

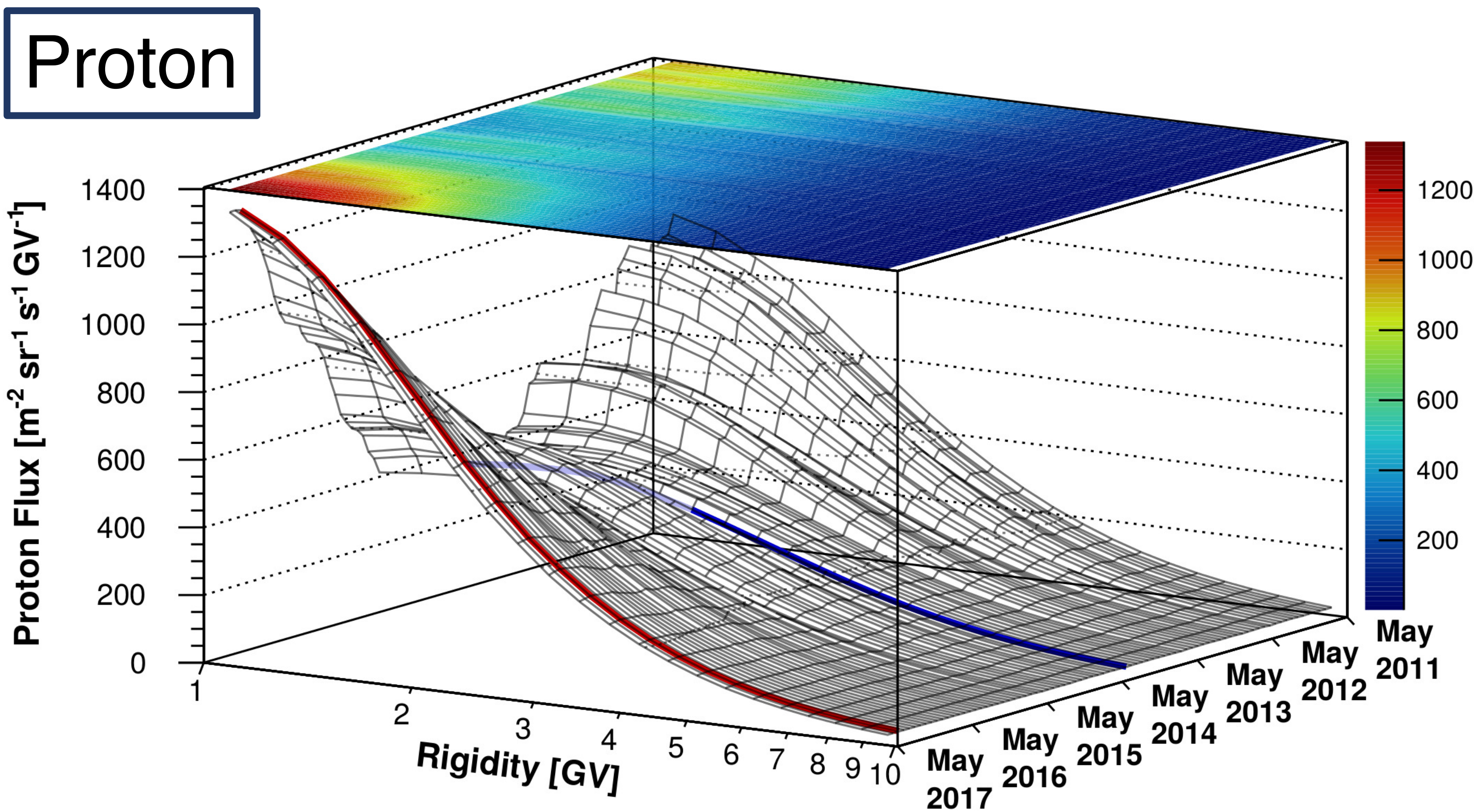




Proton Flux

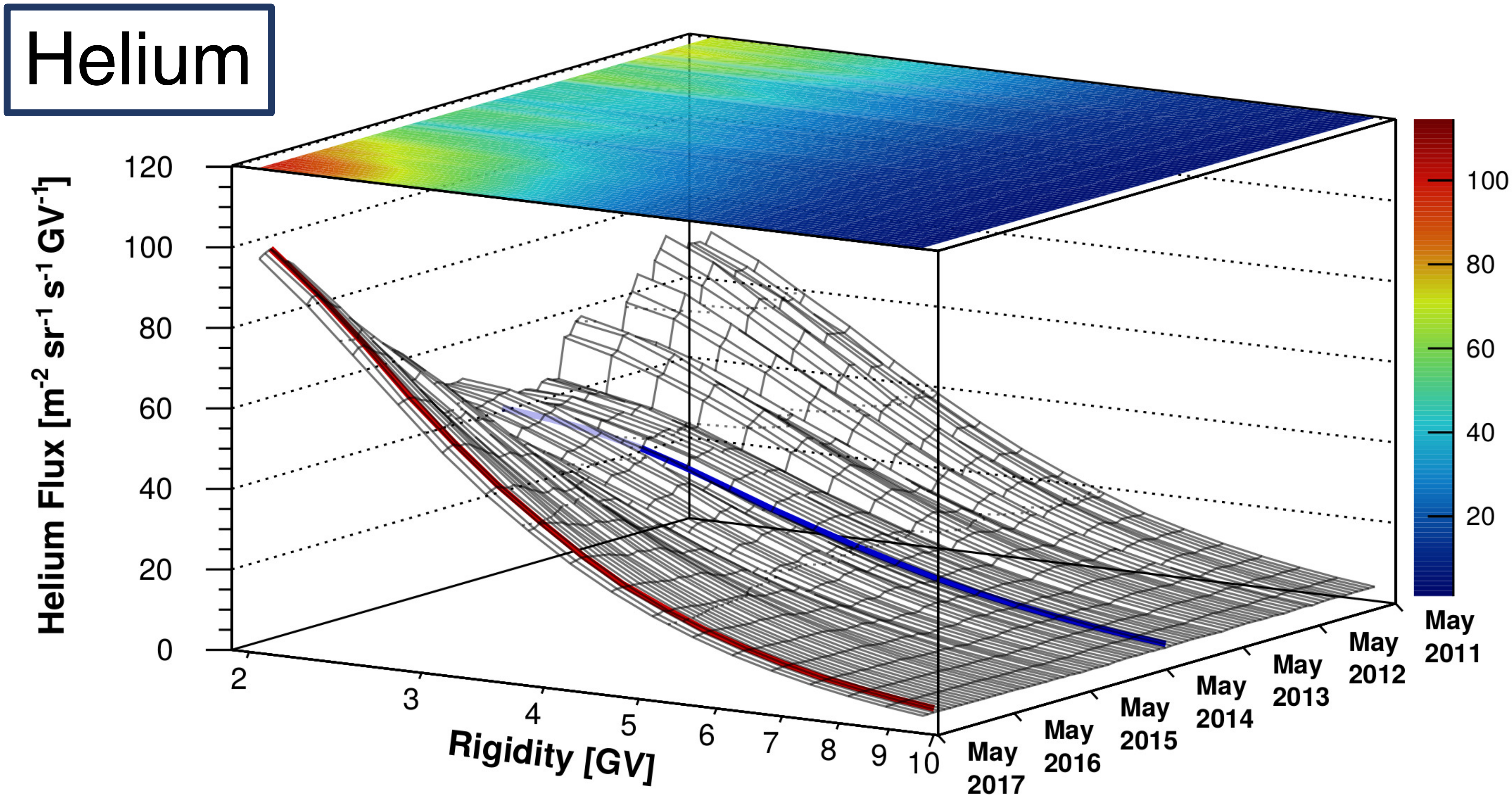
Observation of Fine Time Structures in the Cosmic Proton and Helium Fluxes with the Alpha Magnetic Spectrometer on the International Space Station

M. Aguilar *et al.* (AMS Collaboration)
Phys. Rev. Lett. **121**, 051101 – Published 31 July 2018

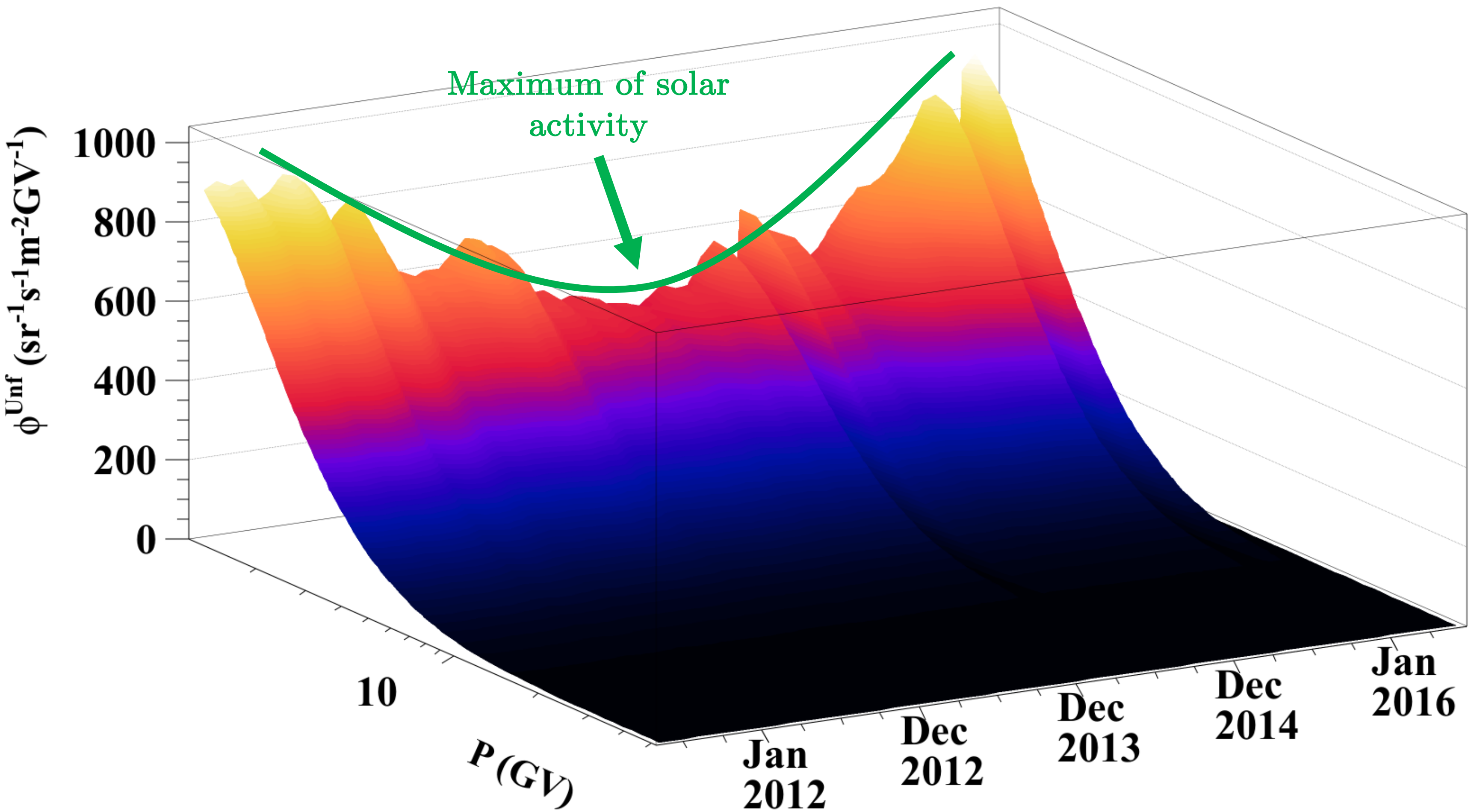


Helium Flux

Observation of Fine Time Structures in the Cosmic Proton and Helium Fluxes with the Alpha Magnetic Spectrometer on the International Space Station
M. Aguilar *et al.* (AMS Collaboration)
Phys. Rev. Lett. **121**, 051101 – Published 31 July 2018

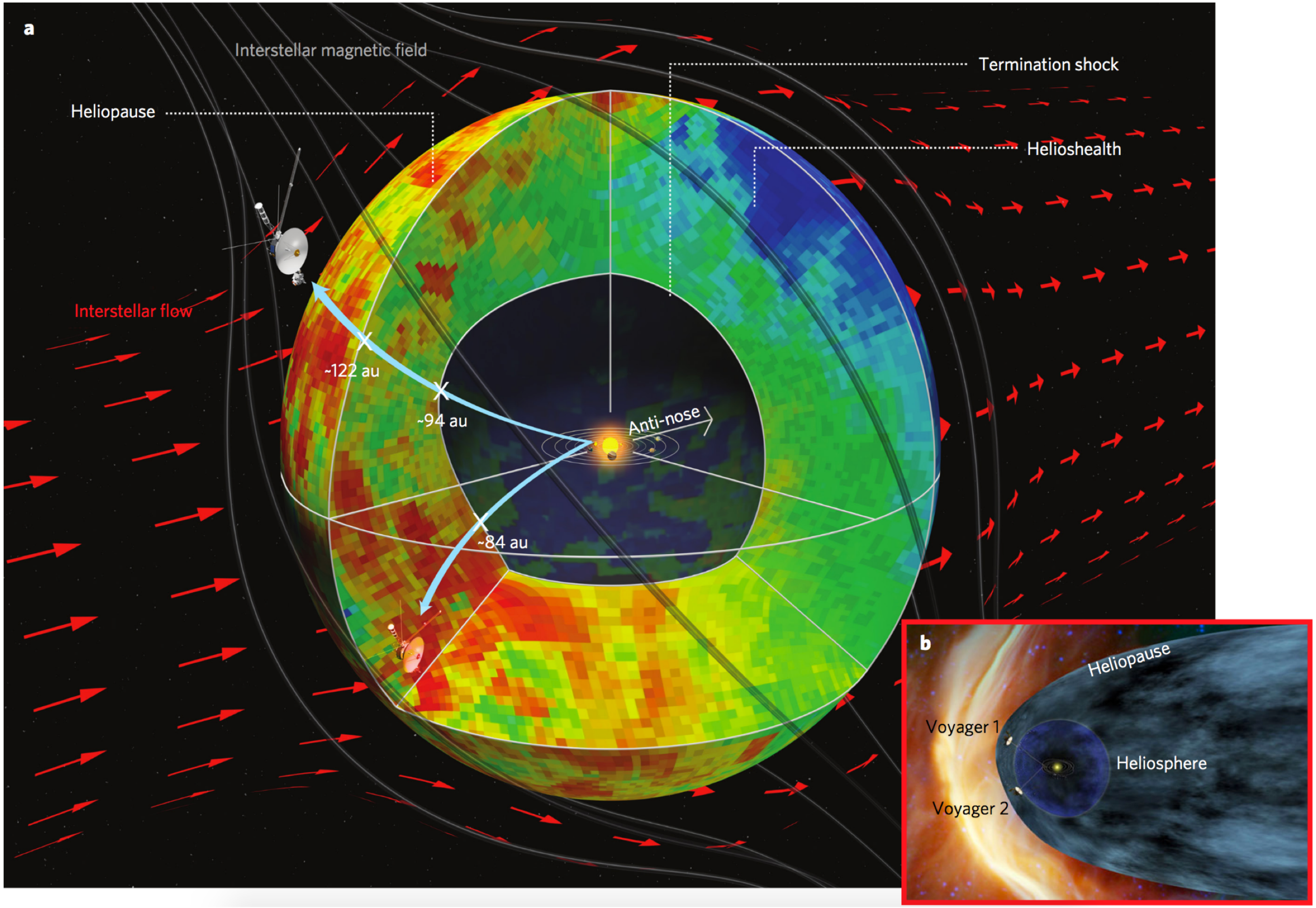


Proton Flux



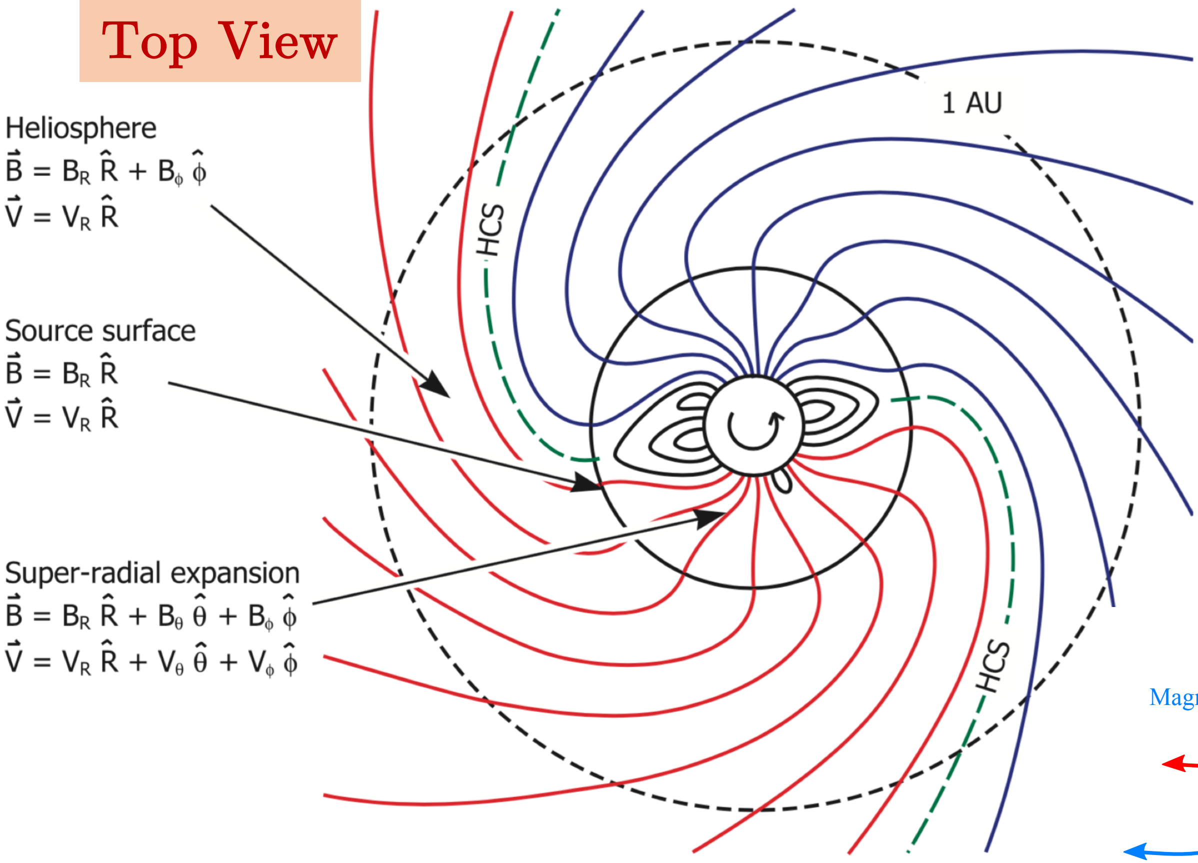
Maximum of solar activity
ϕ^{Unf} (sr^{-1}s^{-1}m^{-2}GV^{-1})
1000
800
600
400
200
0
10
P (GV)
Jan 2012
Dec 2012
Dec 2013
Dec 2014
Jan 2016

Heliosphere

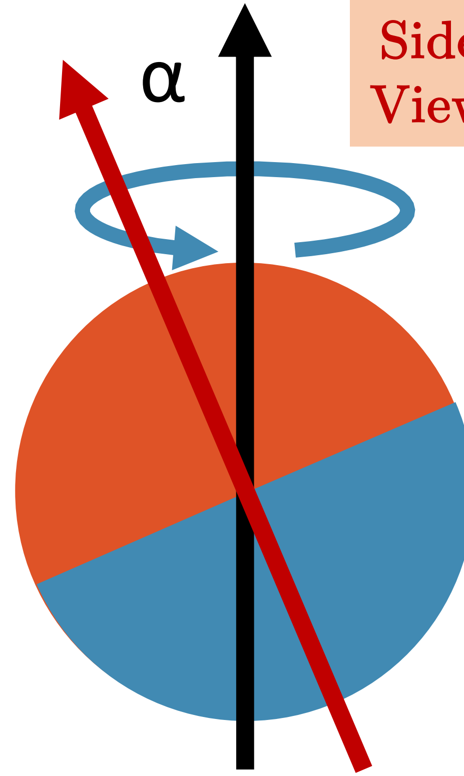


Magnetic Field

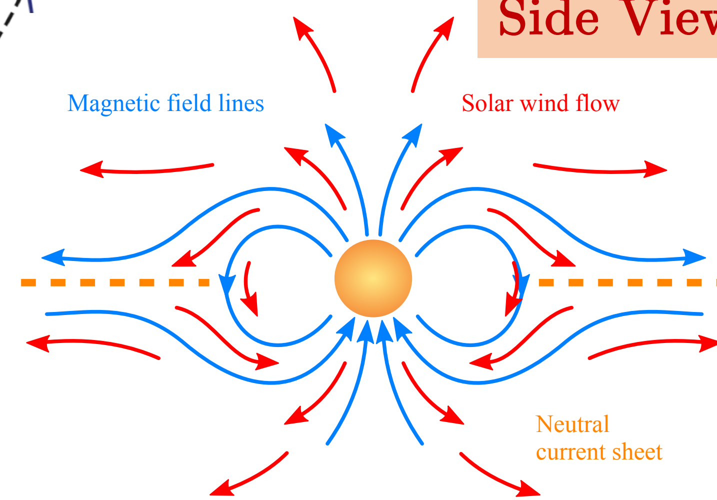
Top View



Side View



Side View



Parker's Equation

$$\frac{\partial f}{\partial t} = \underbrace{\nabla \cdot (\mathbf{K}_{\mathrm{s}} \cdot \nabla f)}_{\text{diffusion}} - \underbrace{(\mathbf{V} + \langle \mathbf{v}_{\mathrm{dr}} \rangle) \cdot \nabla f}_{\text{convection and drift}} + \underbrace{\frac{1}{3} (\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P}}_{\text{adiabatic energy loss}} + \underbrace{Q(\mathrm{r}, P, t)}_{\text{source/LIS}}$$

Parker's Equation

$$\frac{\partial f}{\partial t} = \underbrace{\nabla \cdot (\mathbf{K}_{\mathrm{s}} \cdot \nabla f)}_{\text{diffusion}} - \underbrace{(\mathbf{V} + \langle \mathbf{v}_{\mathrm{dr}} \rangle) \cdot \nabla f}_{\text{convection and drift}} + \underbrace{\frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P}}_{\text{adiabatic energy loss}} + \boxed{\underbrace{Q(\mathrm{r}, P, t)}_{\text{source/LIS}}}$$

Local Interstellar spectra

✓ Low energy: Strong constraints from Voyager-1

✓ High energy constraints from AMS-02

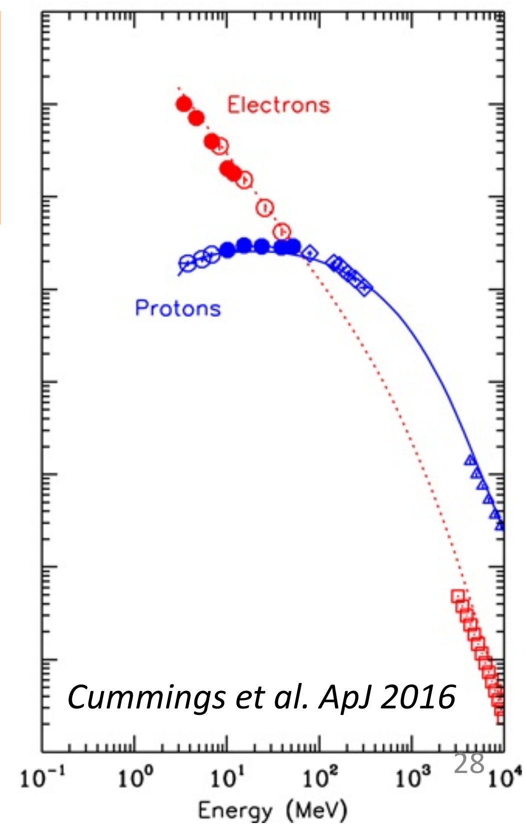
Protons and electrons

✓ Voyager-1 (Cummings et al. 2016)

✓ AMS-02 (Aguilar et al. 2014 & 2015)

Antiprotons and positrons

✓ from calculations of secondary CR production in the interstellar medium (NTomassetti PRD 2015)

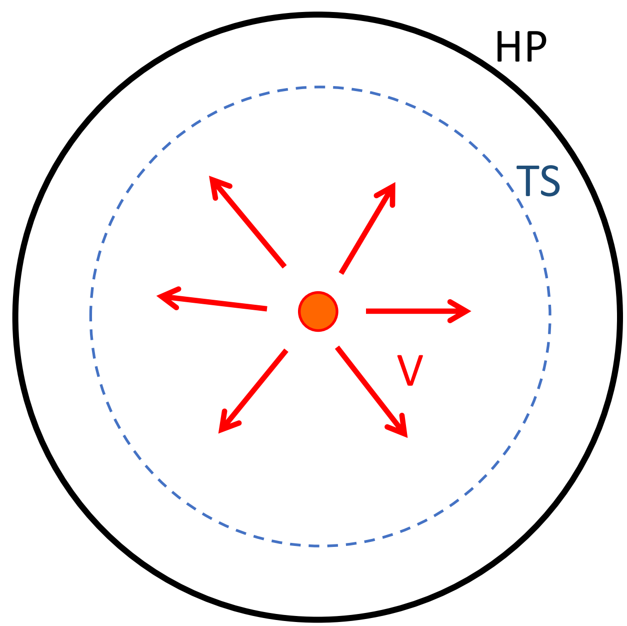


Parker's Equation

$$\frac{\partial f}{\partial t} = \underbrace{\nabla \cdot (\mathbf{K}_s \cdot \nabla f)}_{\text{diffusion}} - \underbrace{(\mathbf{V} + \langle \mathbf{v}_{dr} \rangle) \cdot \nabla f}_{\text{convection and drift}} + \boxed{\underbrace{\frac{1}{3} (\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P}}_{\text{adiabatic energy loss}}} + \underbrace{Q(\mathrm{r}, P, t)}_{\text{source/LIS}}$$

Convection and energy losses

- ✓ Radially outflowing from the sun
  - ✓ V=400km/s
- ✓ Changes to subsonic speed beyond termination shock (R=85AU)
- ✓ Vanishing at the Heliopause boundary (R=122AU)



Parker's Equation

$$\frac{\partial f}{\partial t} = \boxed{\underbrace{\nabla \cdot (\mathbf{K}_\mathrm{s} \cdot \nabla f)}_{\text{diffusion}}} - \underbrace{(\mathbf{V} + \langle \mathbf{v}_\mathrm{dr} \rangle) \cdot \nabla f}_{\text{convection and drift}} + \underbrace{\frac{1}{3} (\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P}}_{\text{adiabatic energy loss}} + \underbrace{Q(\mathrm{r}, P, t)}_{\text{source/LIS}}$$

Diffusion

- ✓ Parametrized through an adimensional normalization factor
- ✓ Time-dependent due to correlation to solar activity

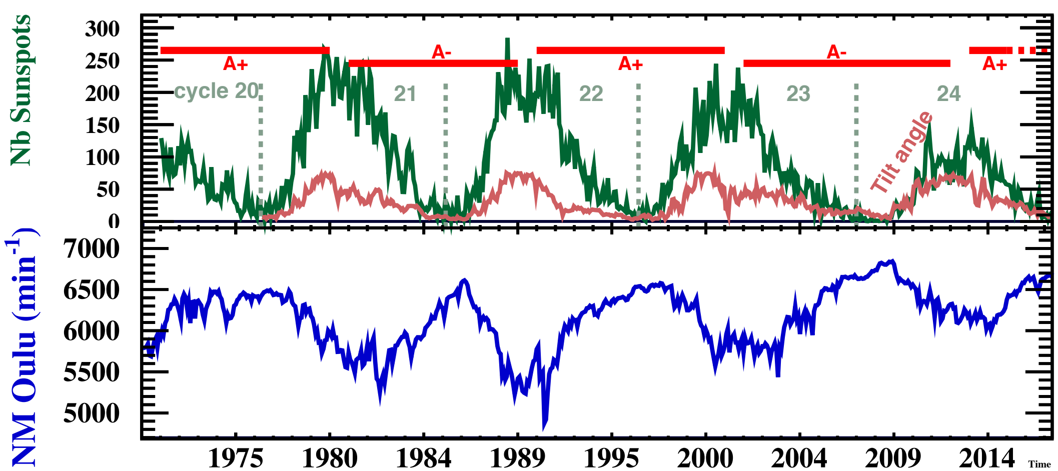
$$K_\perp = 0.02 K_\parallel$$

$$K_\parallel = k_0(t) \frac{A}{3B} \beta \, (P / 1\,\mathrm{GV})$$

$$\boxed{\mathrm{SSN} = \mathrm{SSN}(t)}$$

Parametrization of diffusion parameter

$$\boxed{k_0(\mathrm{SSN}) = a \, \log_{10}(\mathrm{SSN}) + b}$$



Parker's Equation

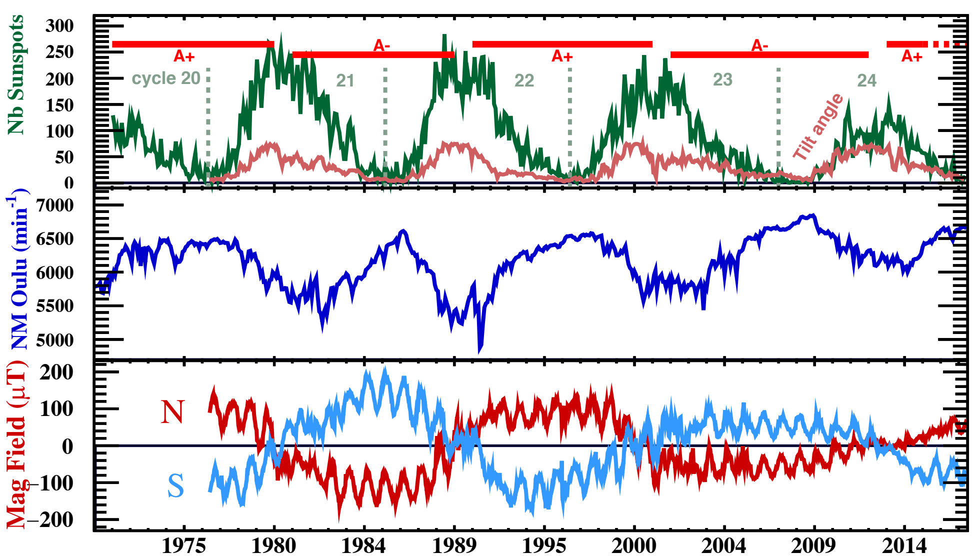
$$\frac{\partial f}{\partial t} = \underbrace{\nabla \cdot (\mathbf{K}_{\mathrm{s}} \cdot \nabla f)}_{\text{diffusion}} - \underbrace{(\mathbf{V} + \boxed{\langle \mathbf{v}_{\mathrm{dr}} \rangle}) \cdot \nabla f}_{\text{convection and drift}} + \underbrace{\frac{1}{3} (\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P}}_{\text{adiabatic energy loss}} + \underbrace{Q(\mathrm{r}, P, t)}_{\text{source/LIS}}$$

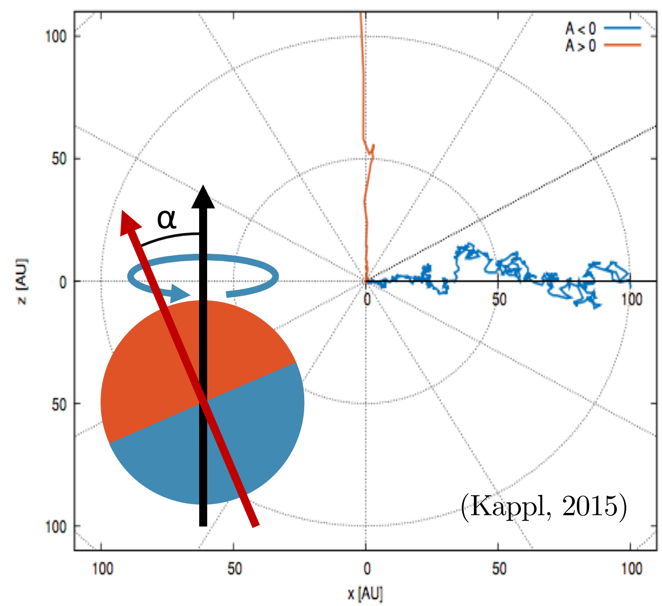
Drift motion along B-field

- ✓ Charge-sign effects
- ✓ Definition of heliospheric current sheet

$$\langle v_{\mathrm{dr}} \rangle = \frac{\beta \, (P/1\,\mathrm{GV})}{3} \nabla \times \frac{\boldsymbol{B}}{B^2}$$

$$B = B(r, \theta, \phi, \alpha(t))$$





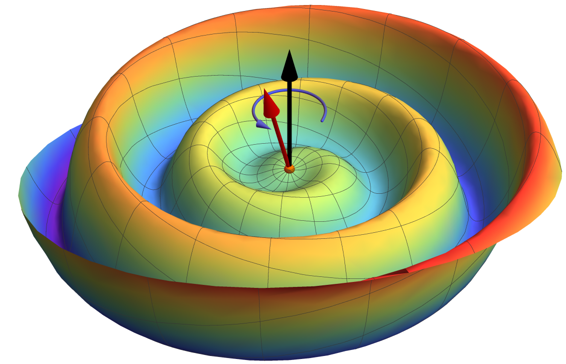
(Kappl, 2015)

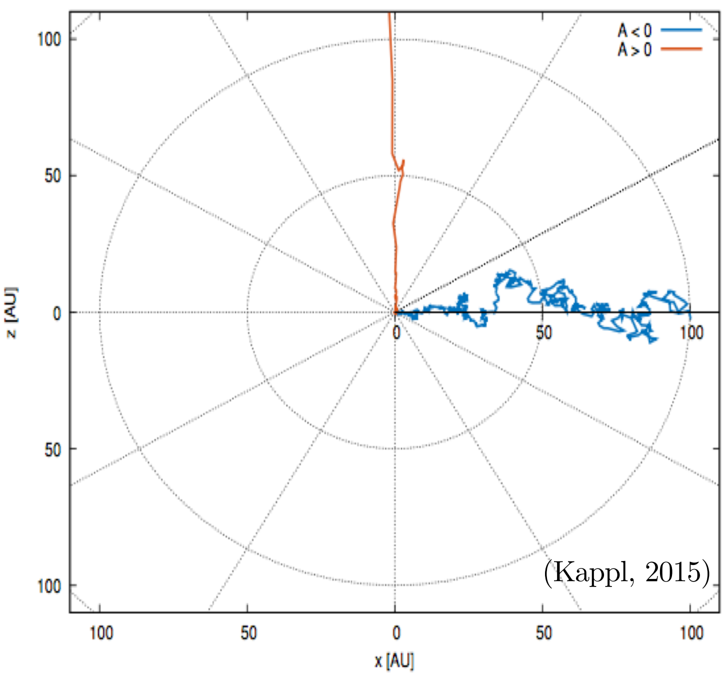
Parker's Equation

Drift motion along B-field

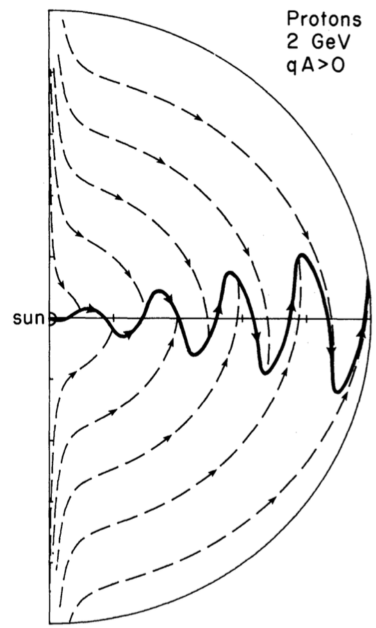
- ✓ Charge-sign effect
  - ✓ Different trajectories for particles and antiparticles
  - ✓ Role reversal with magnetic reversal
- ✓ Tilt angle defines heliospheric current sheet

Heliospheric current sheet



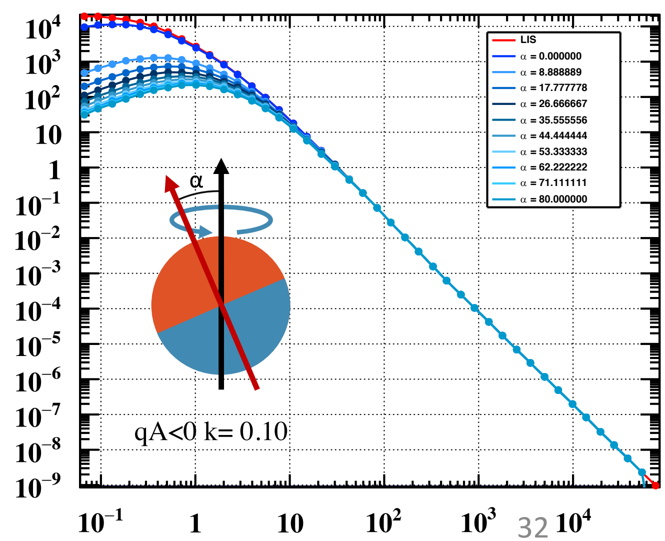


(Kappl, 2015)

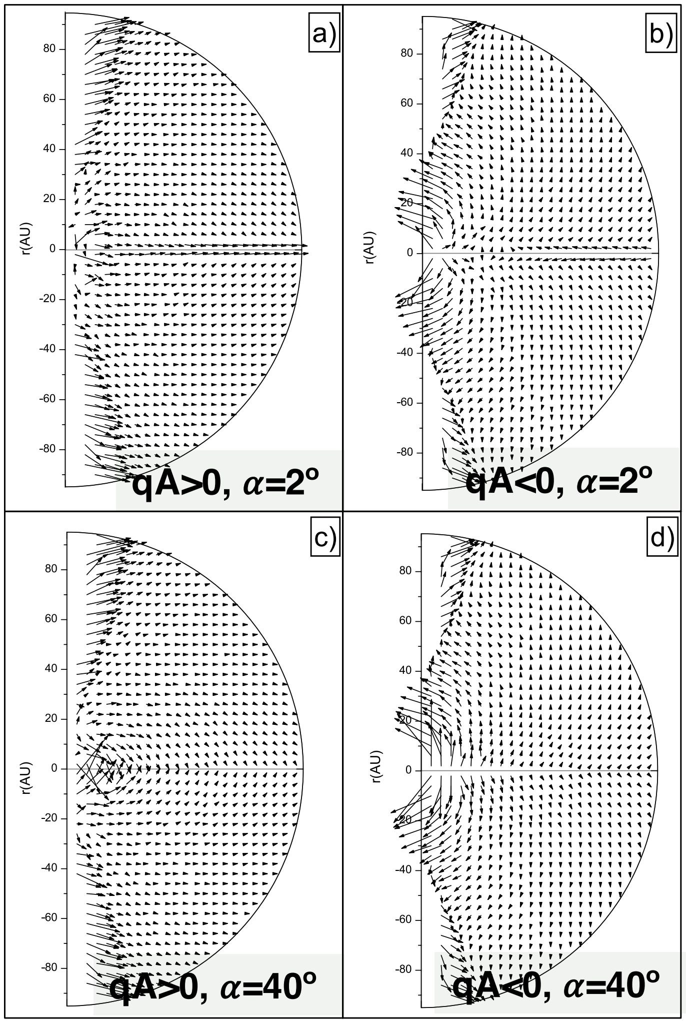


(Jokipii and Thomas, 1981)

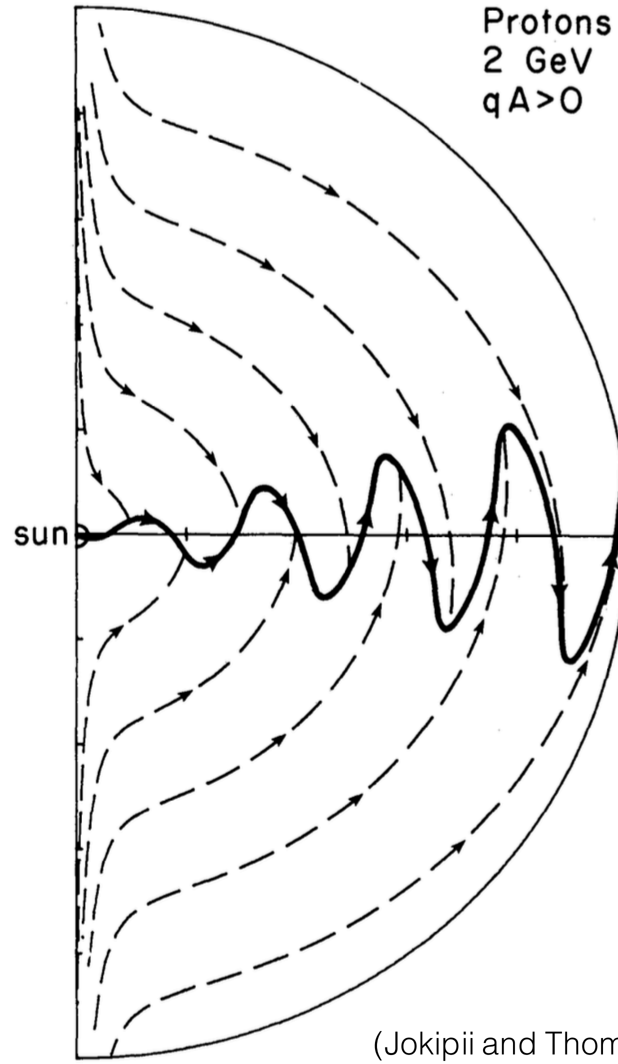
Simulated protons for varying tilt angle



Cosmic ray drifts

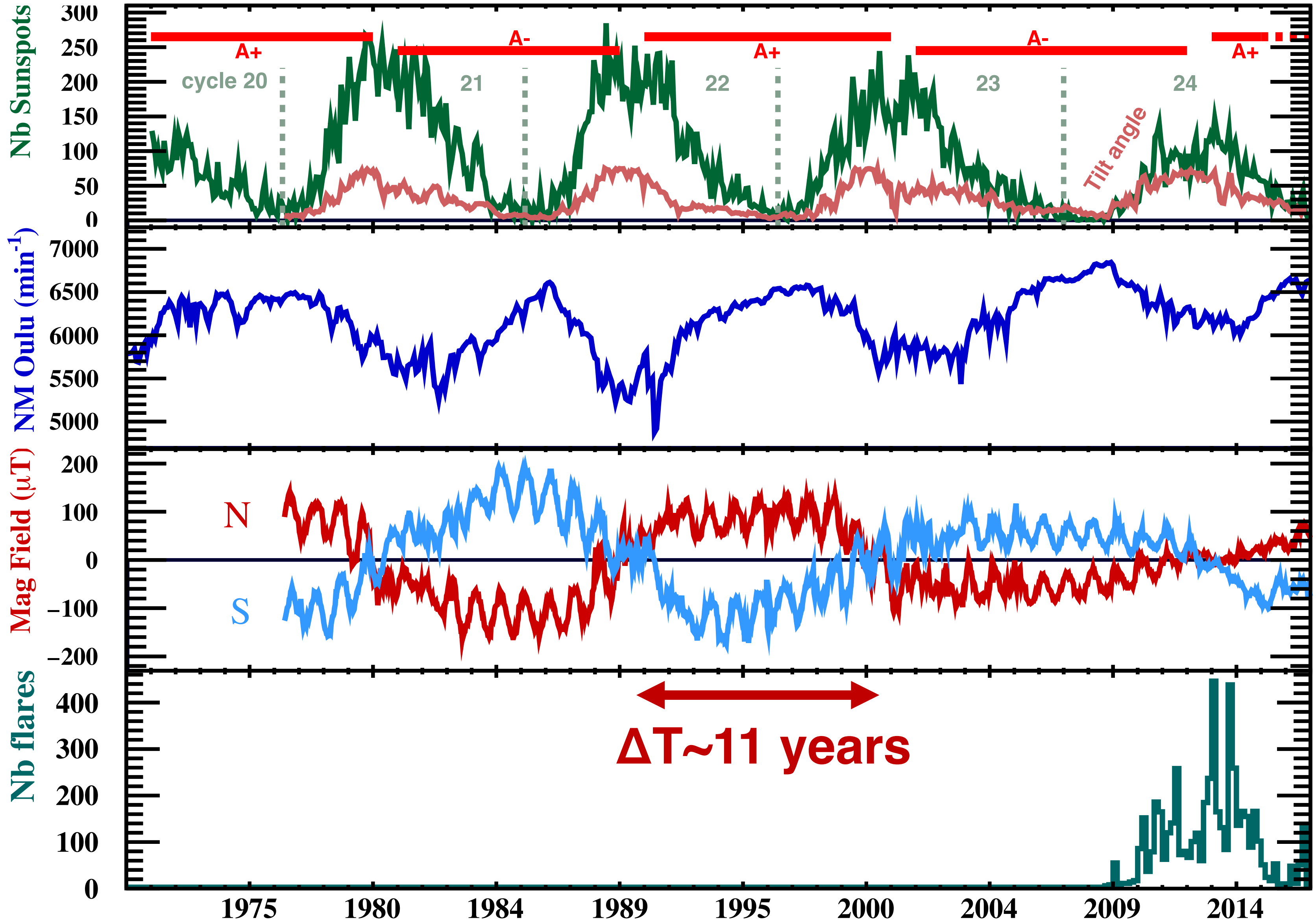


(Alanko-Huotari, 2007)



(Jokipii and Thomas, 1981)

Solar Activity



Estimation of a delay

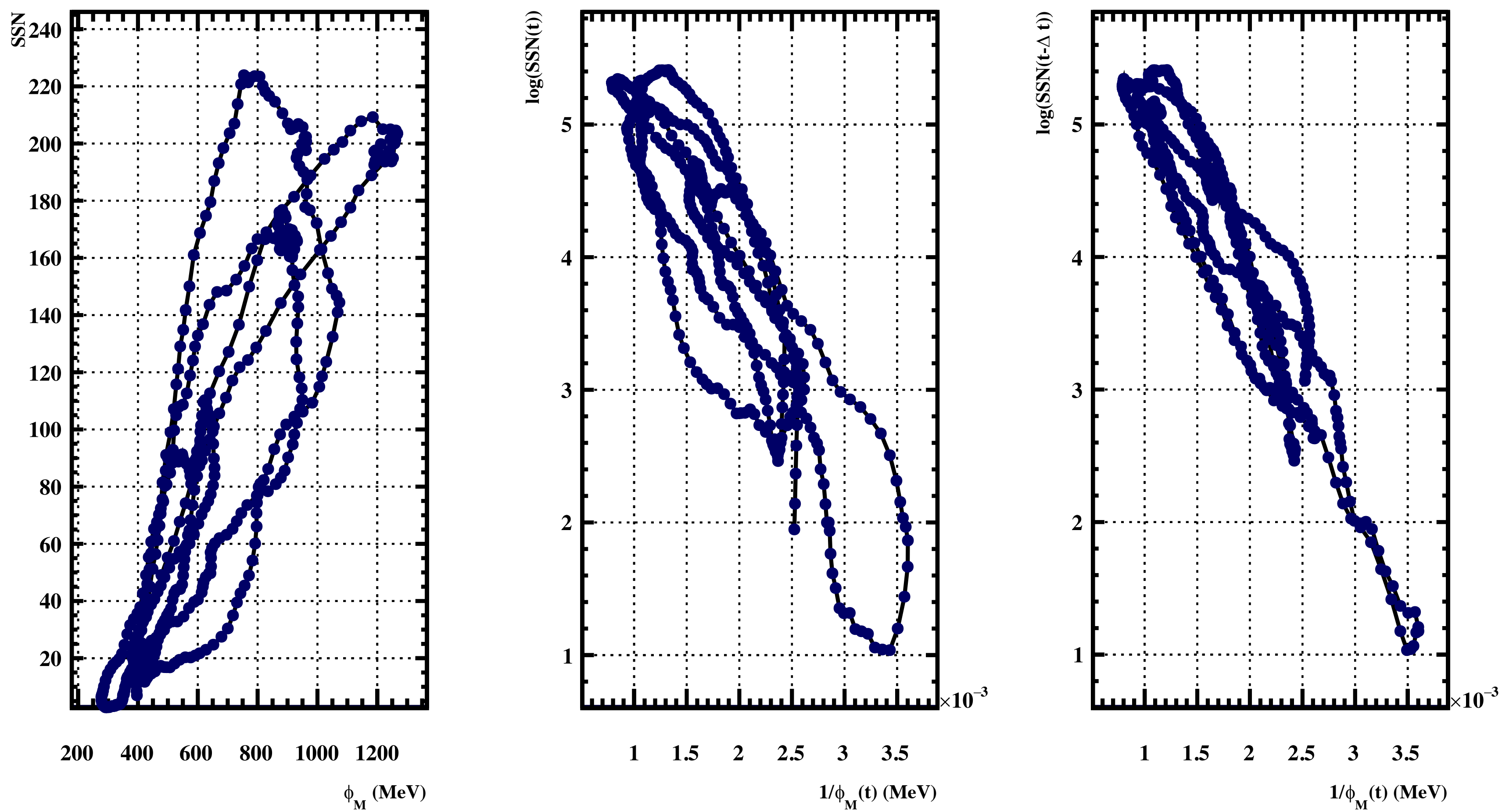
Force-Field

$$K \sim \frac{1}{\phi_{\rm SM}}$$

1977 - 2018

No delay

8 month delay



Estimation of a delay

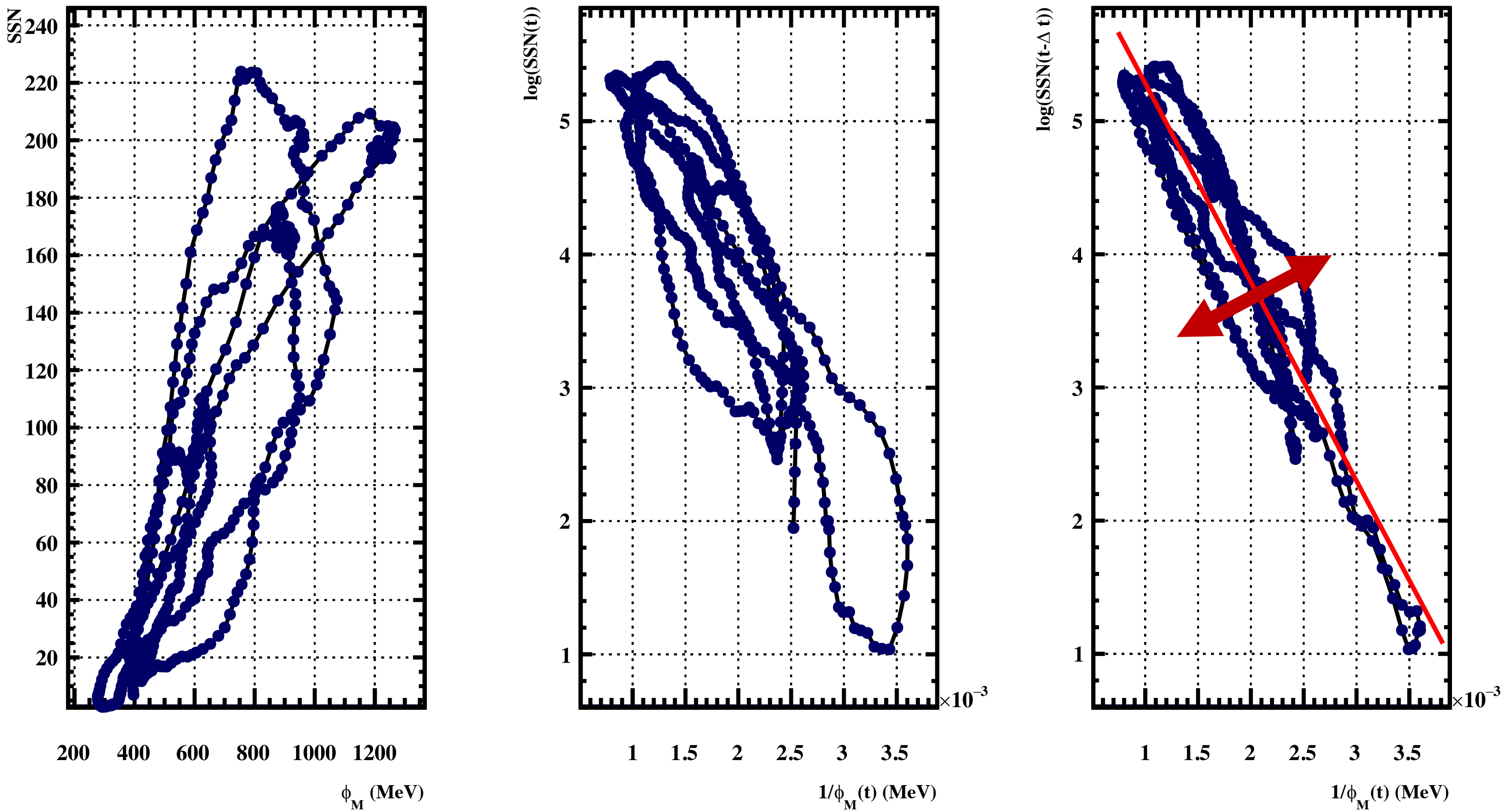
Force-Field

$$K \sim \frac{1}{\phi_{\rm SM}}$$

1977 - 2018

No delay

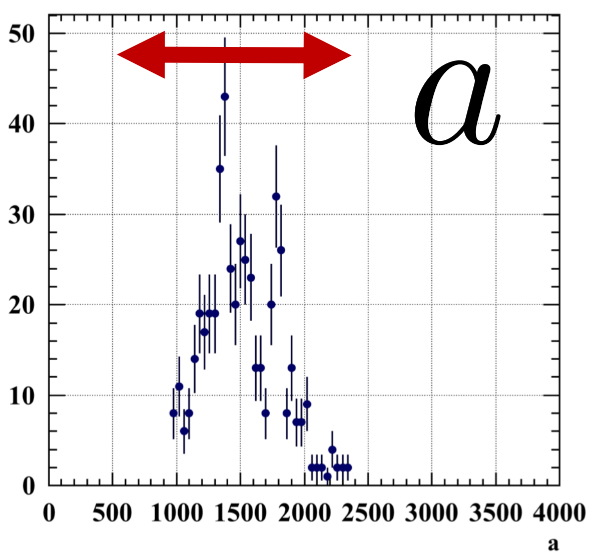
8 month delay



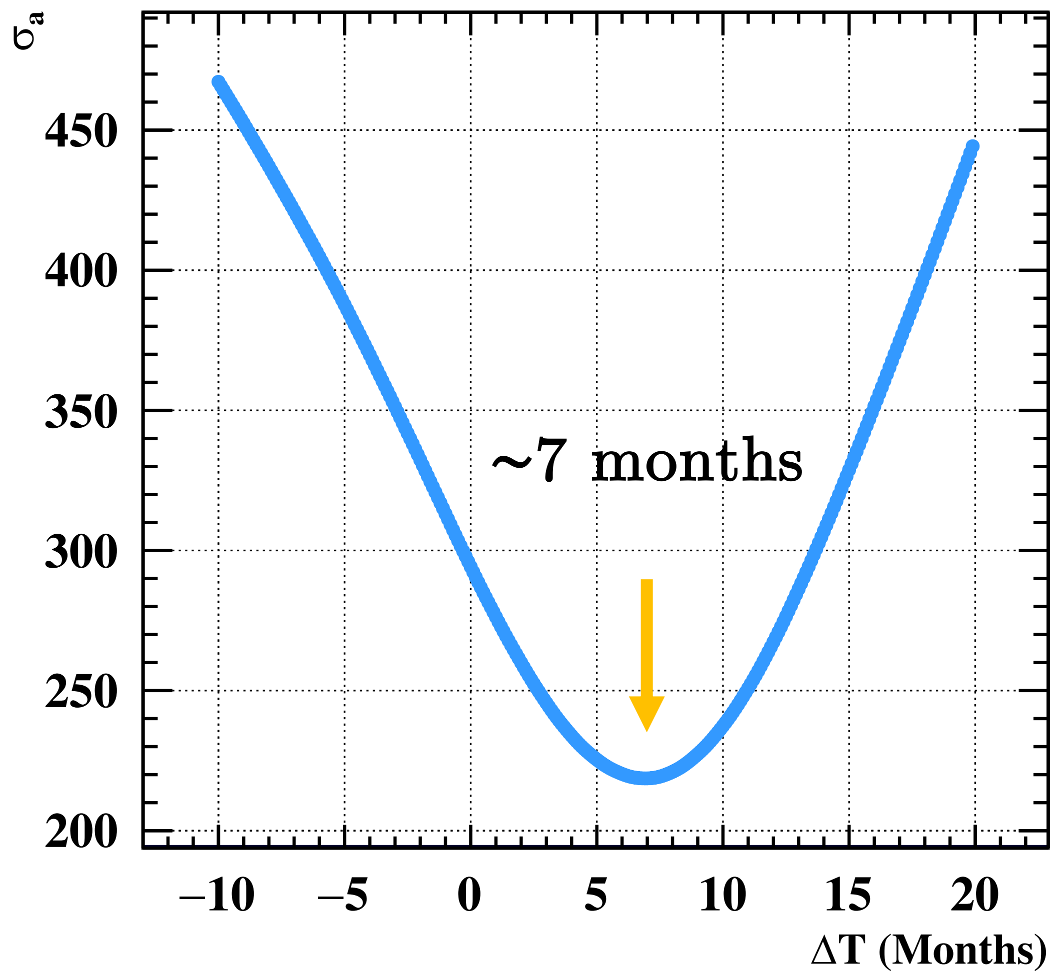
Estimation of a delay

NM Oulu ϕ_{SM}
1977 - 2018

$$x = \log(SSN(t - \Delta T))$$
$$y = 1/\phi_{\mathrm{SM}}(t)$$
$$y = a\,x + b$$
$$a = \frac{y-b}{x}$$



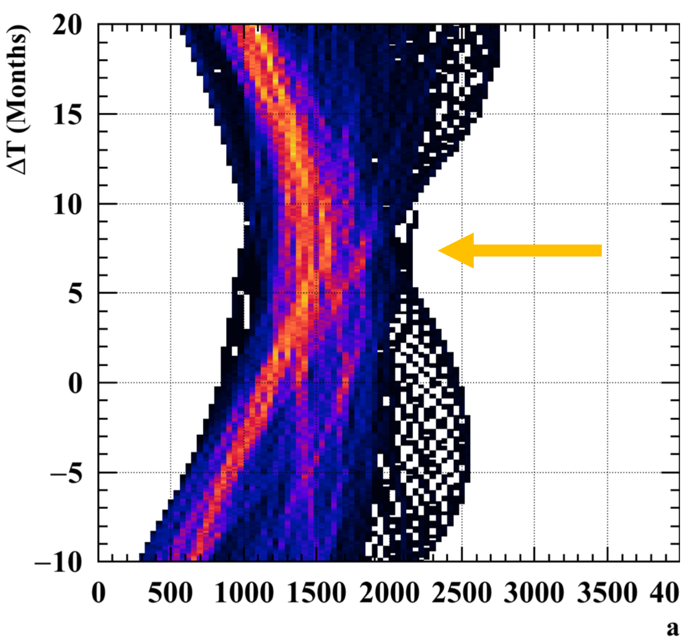
σ_a



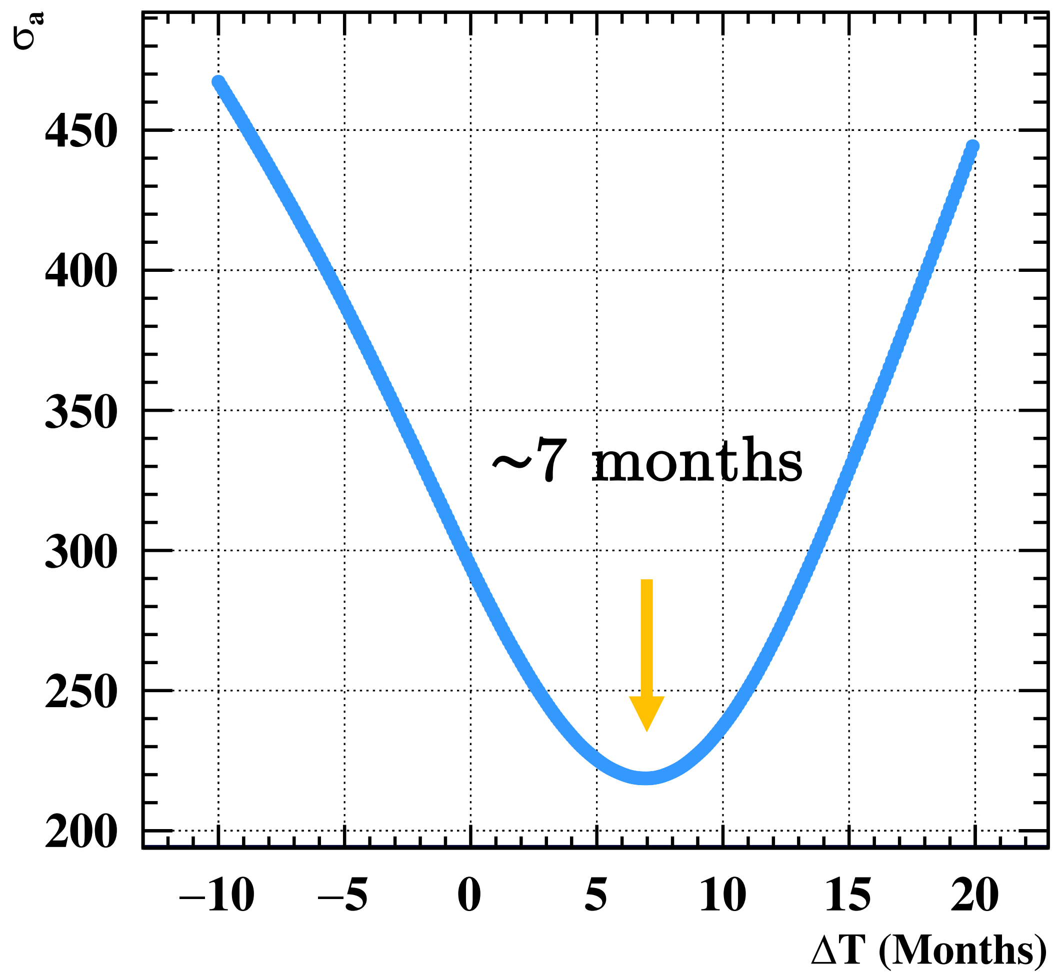
Estimation of a delay

NM Oulu ϕ_{SM}
1977 - 2018

$$x = \log(SSN(t - \Delta T))$$
$$y = 1/\phi_{SM}(t)$$
$$y = a\,x + b$$
$$a = \frac{y-b}{x}$$



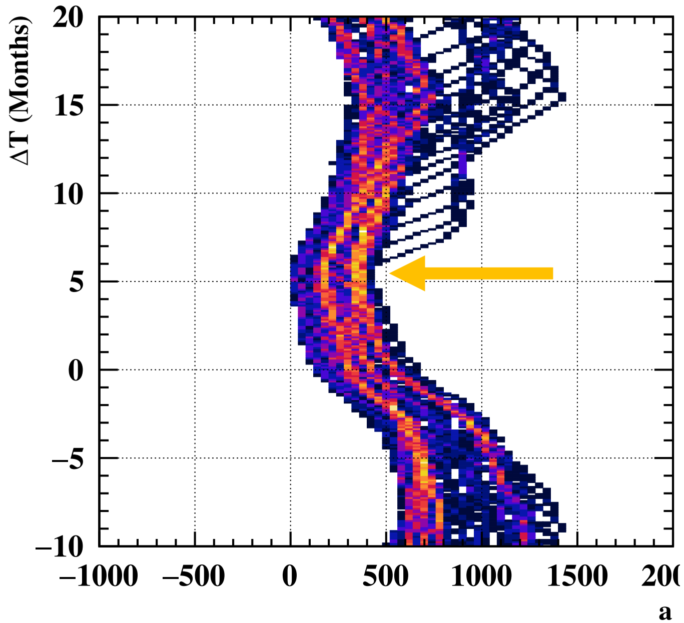
σ_a



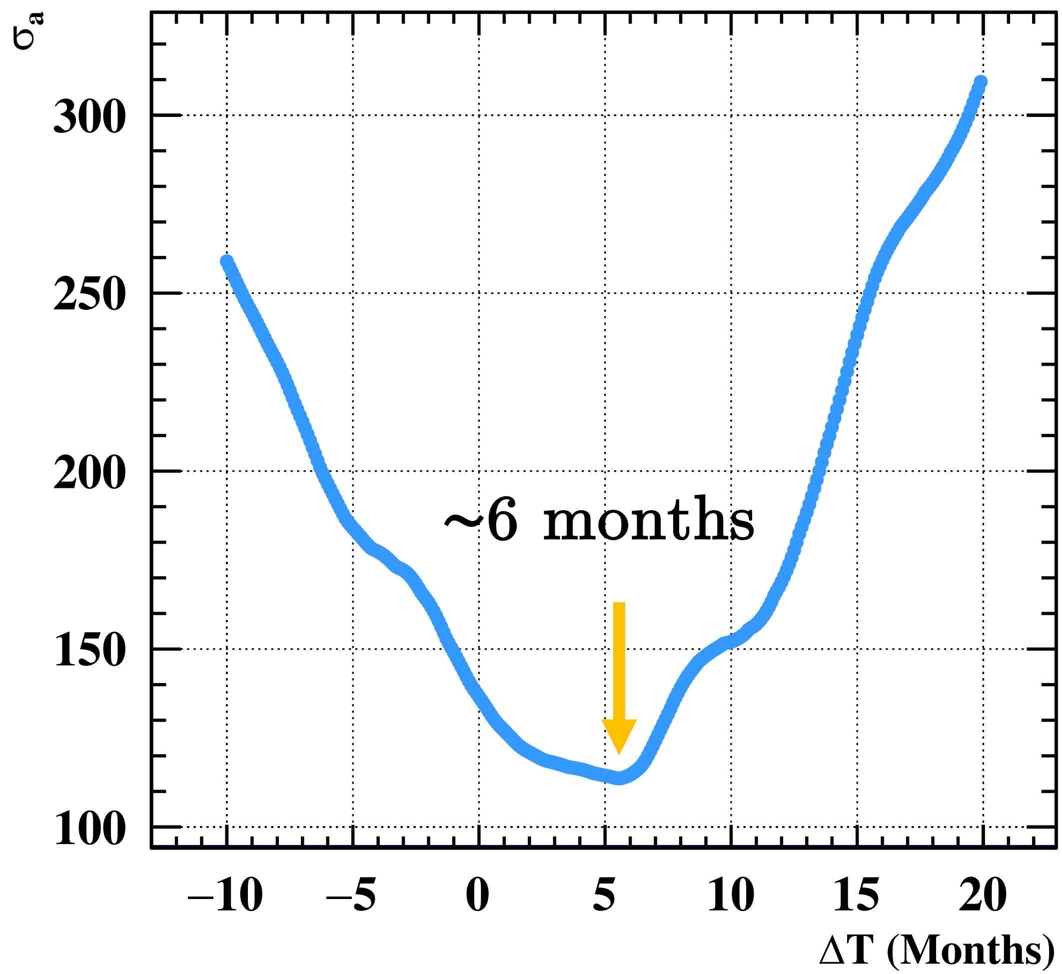
Estimation of a delay

AMS ϕ_{SM}
2011 - 2016

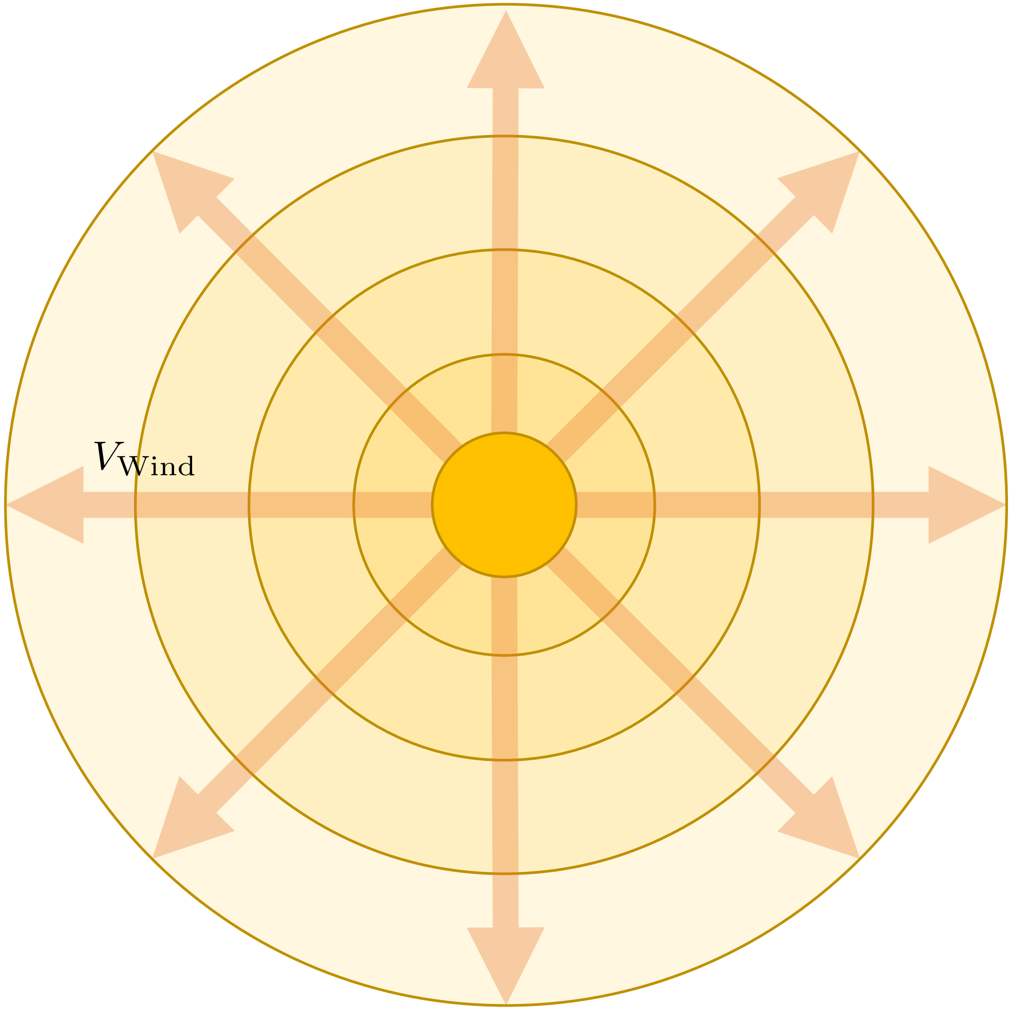
$$x = \log(SSN(t - \Delta T))$$
$$y = 1/\phi_{\mathrm{SM}}(t)$$
$$y = a\,x\, + \,b$$
$$a = \frac{y - b}{x}$$



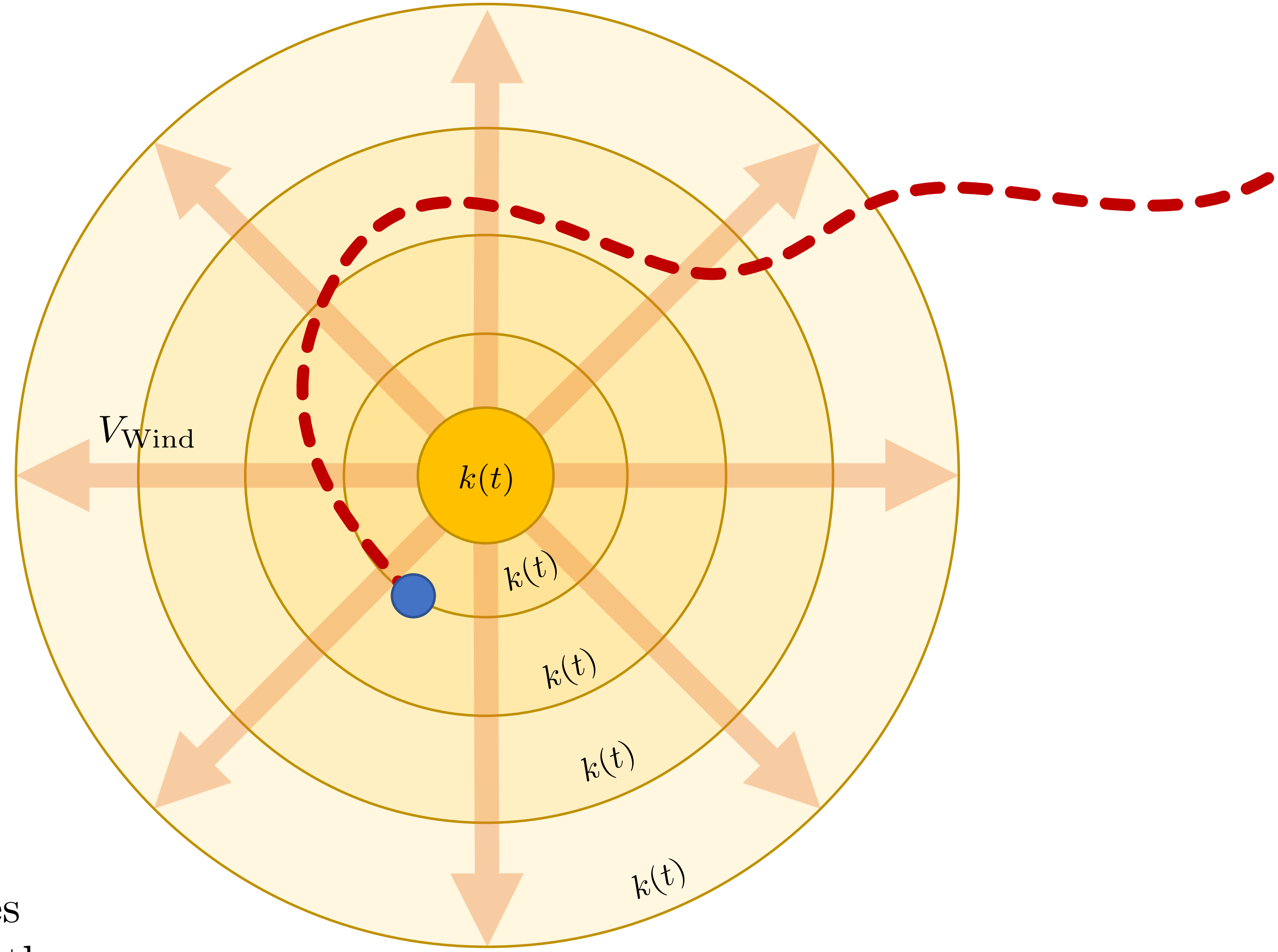
σ_a



Evidence of a delay



Evidence of a delay

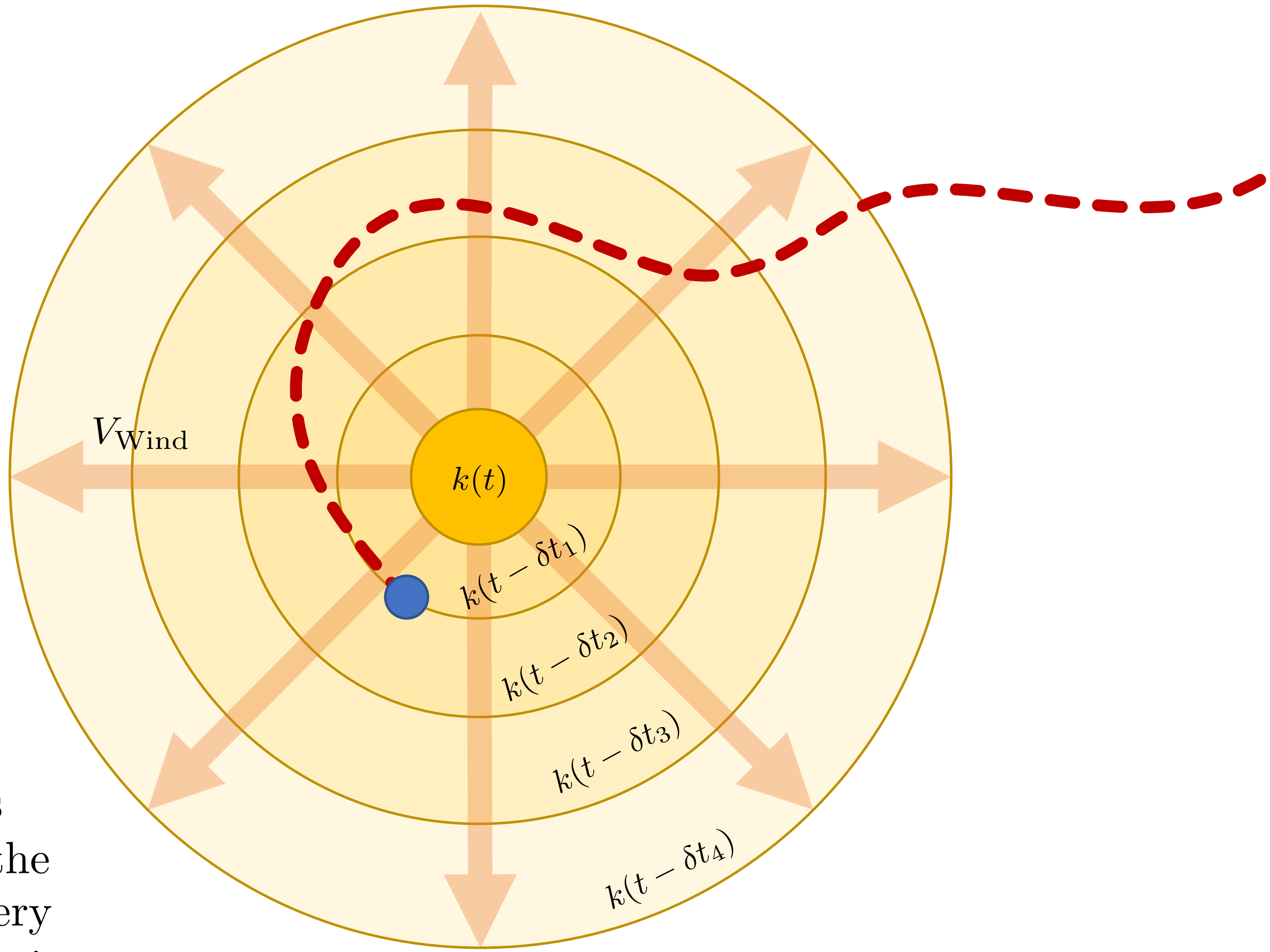


Static sun

The solar properties propagate through the solar system evenly, carried by the plasma.

$$k(t) = cte$$

Evidence of a delay

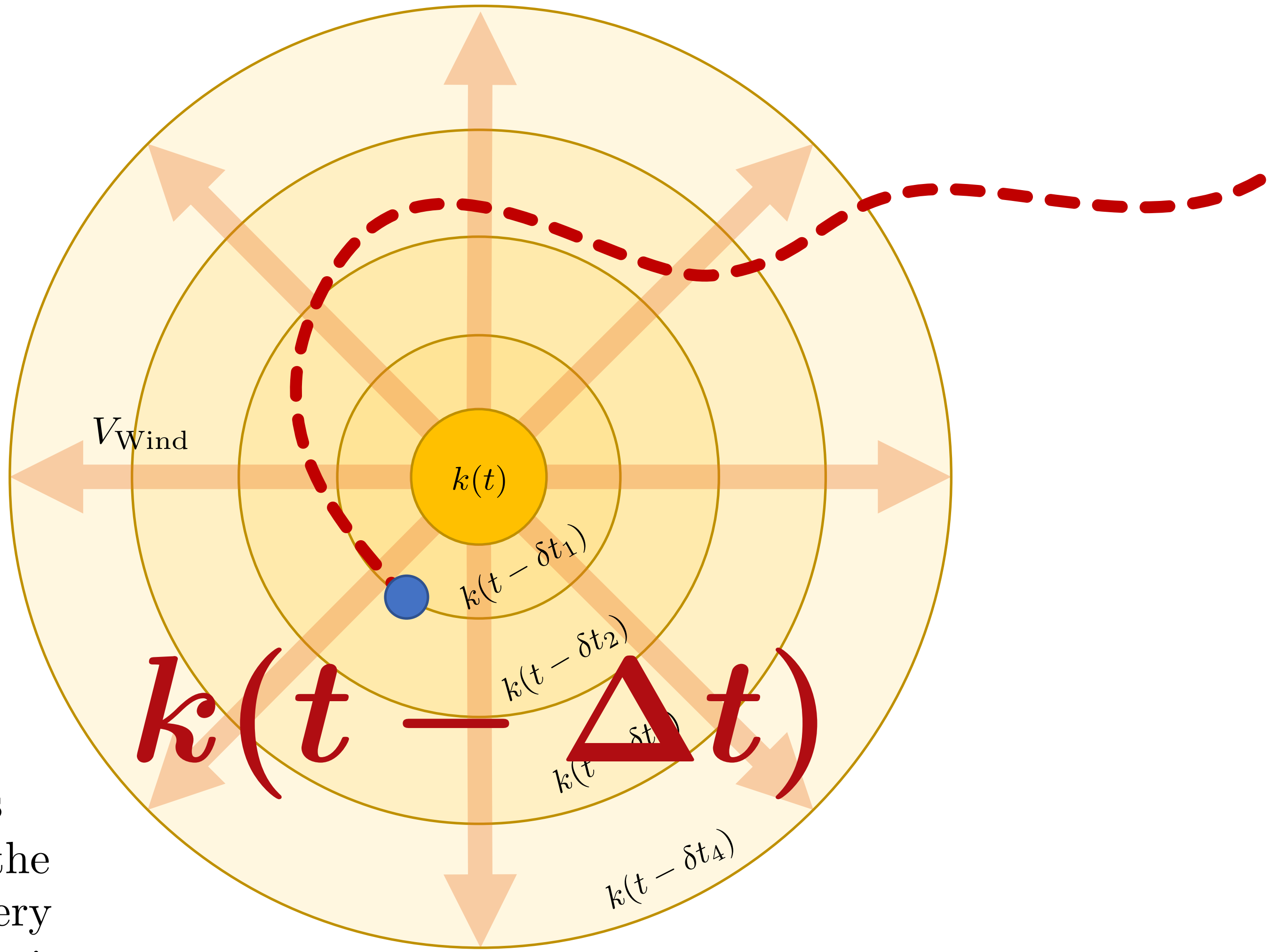


Evolving sun

The solar properties propagate through the solar system but every layer of plasma contains the solar parameters from a previous period.

$$k(t) \neq cte$$

Evidence of a delay



Evolving sun

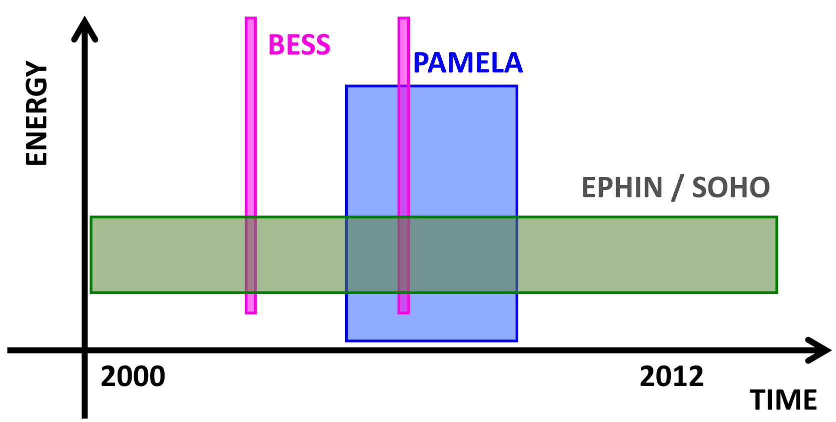
The solar properties propagate through the solar system but every layer of plasma contains the solar parameters from a previous period.

$$k(t) \neq cte$$

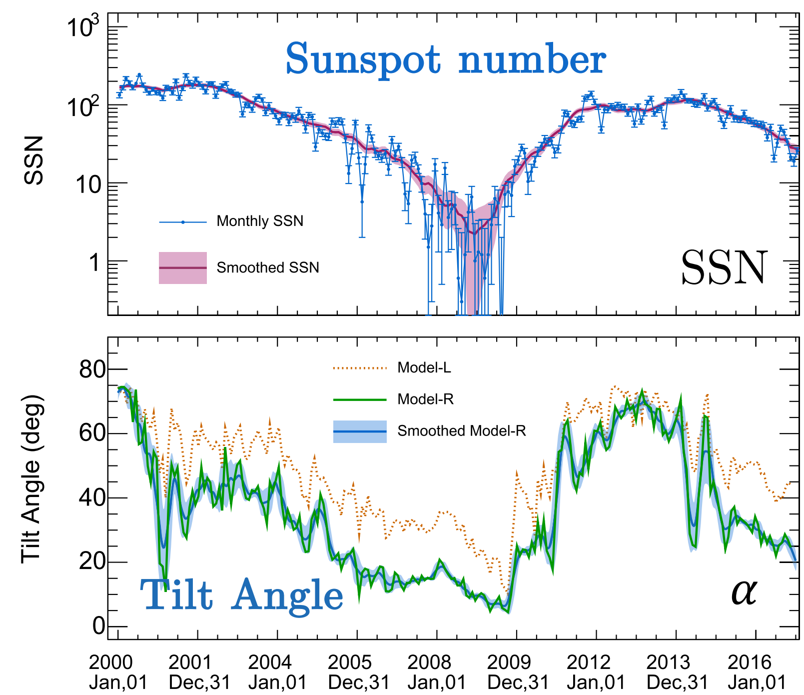
Cosmic Ray Data

Proton data collected during negative polarity between 2000 and 2012
PAMELA: E=0.08-50 GeV, 2006-2010 (3.5 y, Δt=1m)
EPHIN/SOHO: E=0.5-2 GeV, 2000-2013 (Δt=1y)
BESS-Polar I-II: E=0.1-50 GeV, 15 day flights in 2004 and 2008

Data coverage



Solar data
(Wilcox Solar Observatory)



The propagation model

$$\cancel{\frac{\partial f}{\partial t}} = \underbrace{\nabla \cdot (\mathbf{K}_{\mathrm{s}} \cdot \nabla f)}_{\text{diffusion}} - \underbrace{(\mathbf{V} + \langle \mathbf{v}_{\mathrm{dr}} \rangle) \cdot \nabla f}_{\text{convection and drift}} + \underbrace{\frac{1}{3} (\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P}}_{\text{adiabatic energy loss}} + \underbrace{Q(\mathrm{r}, P, t)}_{\text{source/LIS}}$$

Quasi-stationary conditions

$$\frac{\partial f}{\partial t} = 0 \quad \text{(Stochastic differential integration method)}$$

Model Parameters

$\alpha(t)$, $\mathrm{SSN}(t)$ Direct observation

$k_0(t) = a \log_{10}(\mathrm{SSN(t)}) + b$

$\phi^{\mathrm{sim}}(E, t) = \phi^{\mathrm{sim}}(E; k_0(t), \alpha(t))$

Three free parameters

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

Global Fitting procedure

Delayed input parameters

$$\chi^2 = \sum_t \sum_E \left[\frac{\phi^{\mathrm{sim}}(E, t - \Delta t) - \phi^{\mathrm{data}}(E, t)}{\sigma(E, t)} \right]$$

The propagation model

$$\cancel{\frac{\partial f}{\partial t}} = \underbrace{\nabla \cdot (\mathbf{K}_\mathrm{s} \cdot \nabla f)}_{\text{diffusion}} - \underbrace{(\mathbf{V} + \langle \mathbf{v}_\mathrm{dr} \rangle) \cdot \nabla f}_{\text{convection and drift}} + \underbrace{\frac{1}{3} (\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P}}_{\text{adiabatic energy loss}} + \underbrace{Q(\mathrm{r}, P, t)}_{\text{source/LIS}}$$

Quasi-stationary conditions

$$\frac{\partial f}{\partial t} = 0 \quad \text{(Stochastic differential integration method)}$$

Model Parameters

$\alpha(t)$, $\mathrm{SSN}(t)$ Direct observation

$k_0(t) = a \log_{10}(\mathrm{SSN(t)}) + b$

$\phi^{\mathrm{sim}}(E, t) = \phi^{\mathrm{sim}}(E; k_0(t), \alpha(t))$

Three free parameters

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

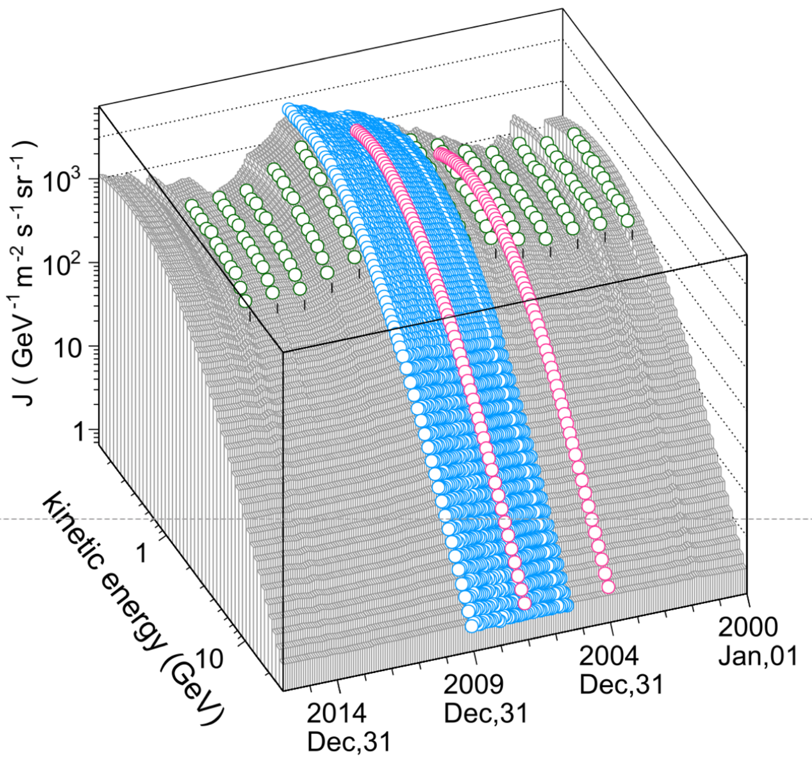
Delayed input parameters

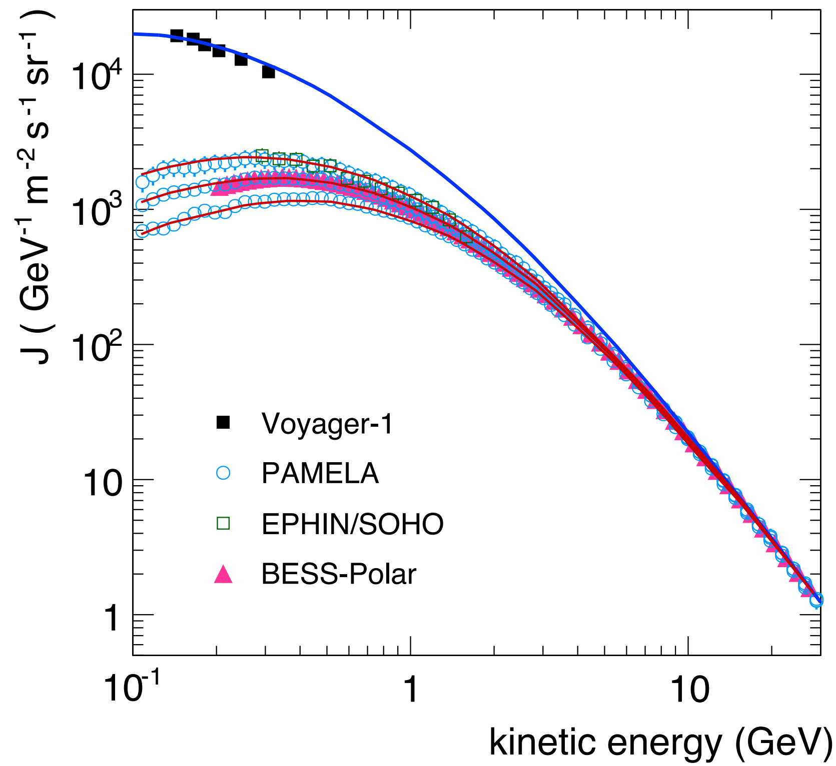
Global Fitting procedure

$$\chi^2 = \sum_t \sum_E \left[\frac{\phi^{\mathrm{sim}}(E, t - \Delta t) - \phi^{\mathrm{data}}(E, t)}{\sigma(E, t)} \right]$$

Parker's Equation

$$\Delta t = 8.1 \pm 1.2\,\mathrm{months}$$
$$a = -1.30 \pm 0.29$$
$$b = 4.07 \pm 0.95$$





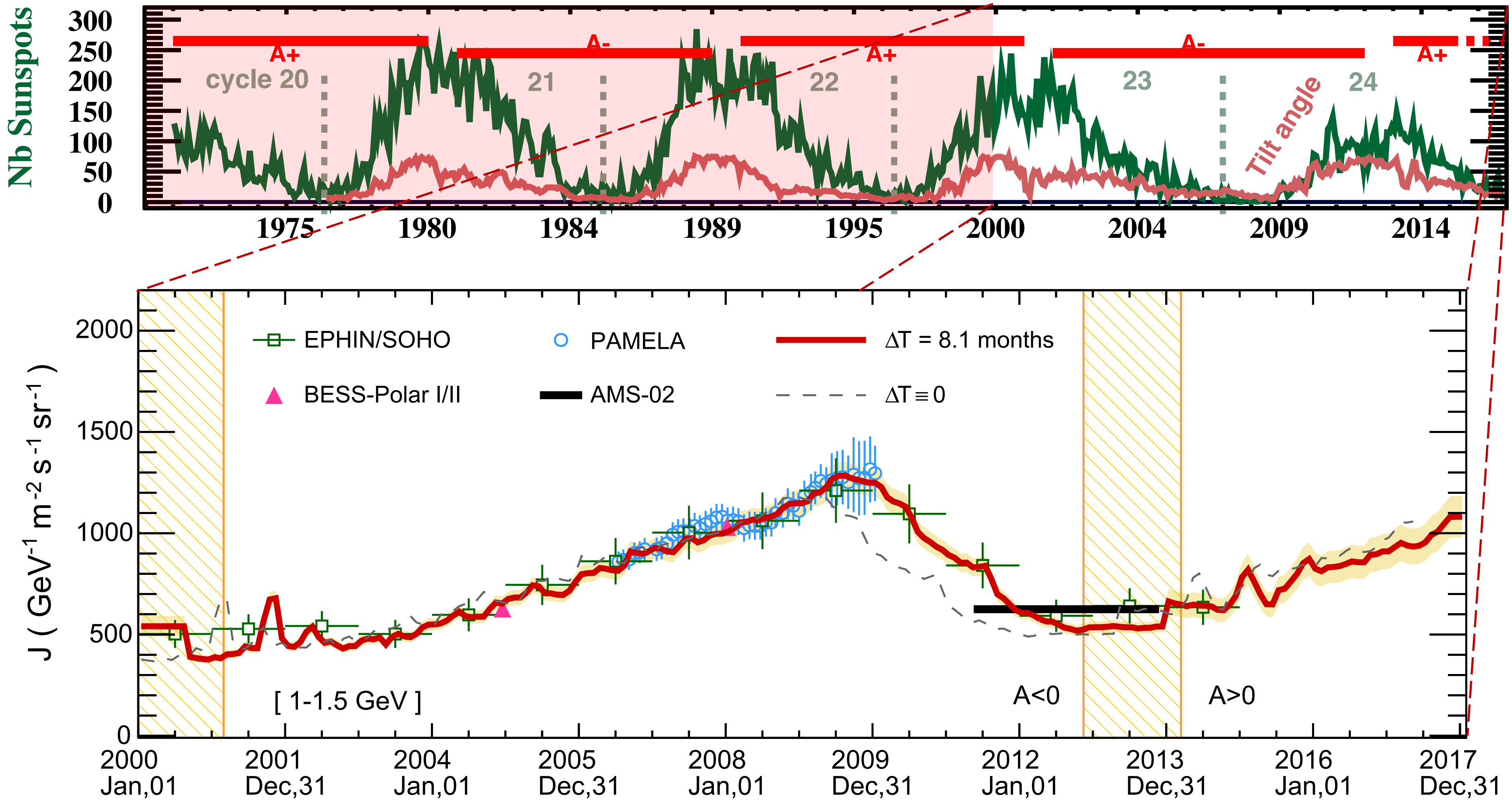
Model Parameters

$$k_0(t) = a\,\log_{10}(\mathrm{SSN(t)}) + b$$
$$\phi^{\mathrm{sim}}(E,t) = \phi^{\mathrm{sim}}(E;\,k_0(t),\alpha(t))$$

Global Fitting procedure

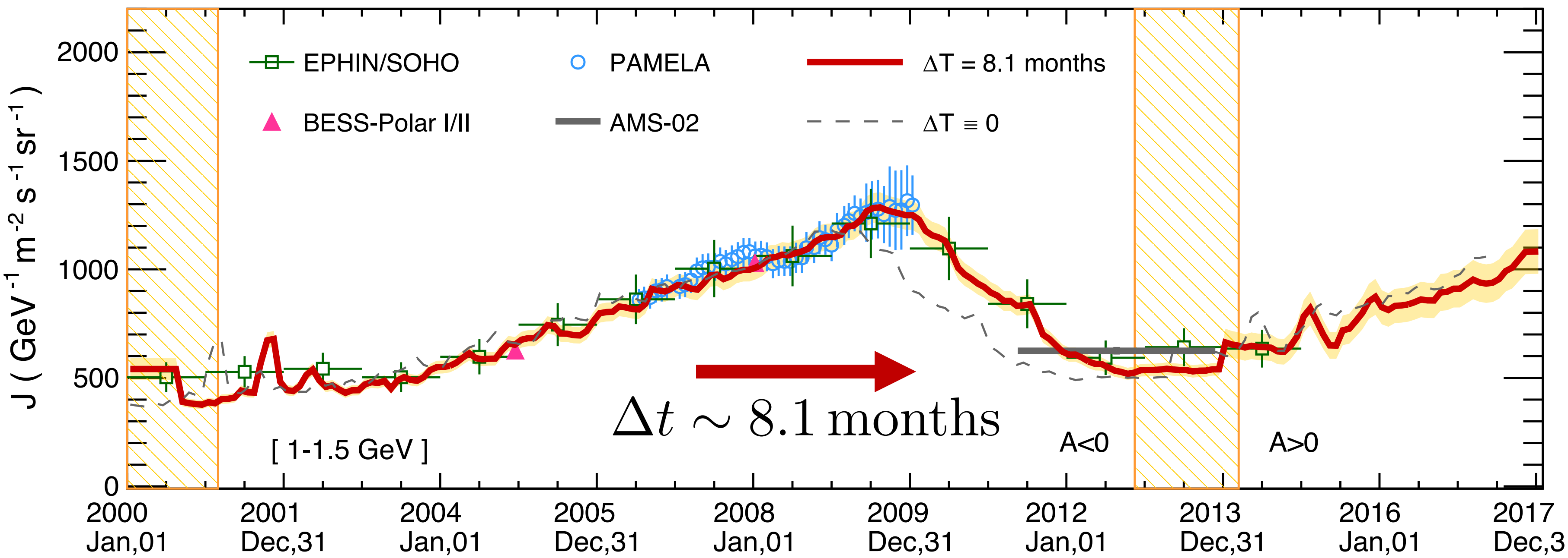
$$\chi^2 = \sum_t \sum_E \left[\frac{\phi^{\mathrm{sim}}\,(E, t-\Delta t) - \phi^{\mathrm{data}}(E,t)}{\sigma(E,t)}\right]$$

A time delay in the protons



$$\Delta t \sim 8.1\,\mathrm{months}$$

A time delay in the protons



$$\phi^{\mathrm{data}}(t) \sim \phi^{\mathrm{sim}}(\alpha(t-\Delta t),\, k_0(t-\Delta t))$$

Directly observable solar parameters are delayed, only affecting the cosmic ray flux 8.1 months later.

Observation of a time lag in solar modulation of cosmic rays in the heliosphere

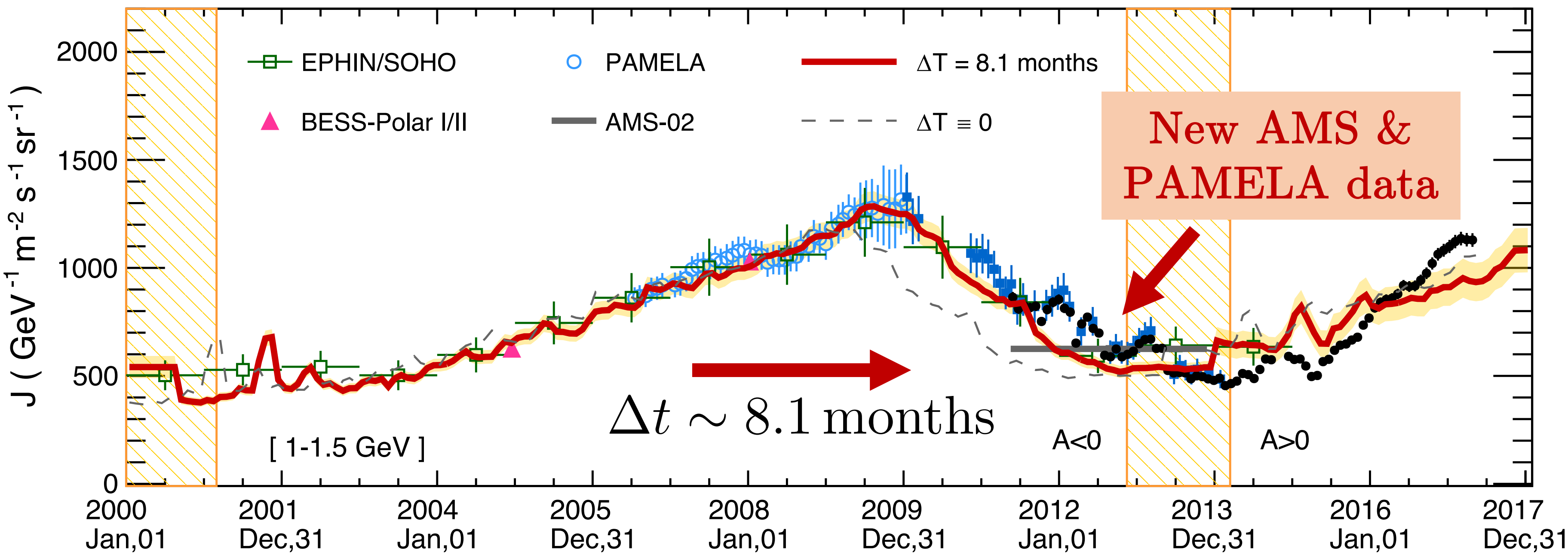
Miguel Orcinha[1], Nicola Tomassetti[2], Fernando Barão[1] and Bruna Bertucci[2]

Evidence for a Time Lag in Solar Modulation of Galactic Cosmic Rays

Nicola Tomassetti[1], Miguel Orcinha[2], Fernando Barão[2], and Bruna Bertucci[1]
[1] Università degli Studi di Perugia and INFN-Perugia, I-06100 Perugia, Italy; nicola.tomassetti@cern.ch
[2] Laboratório de Instrumentação e Física Experimental de Partículas, P-1000 Lisboa, Portugal

Received 2017 June 28; revised 2017 October 11; accepted 2017 October 12; published 2017 November 8

A time delay in the protons



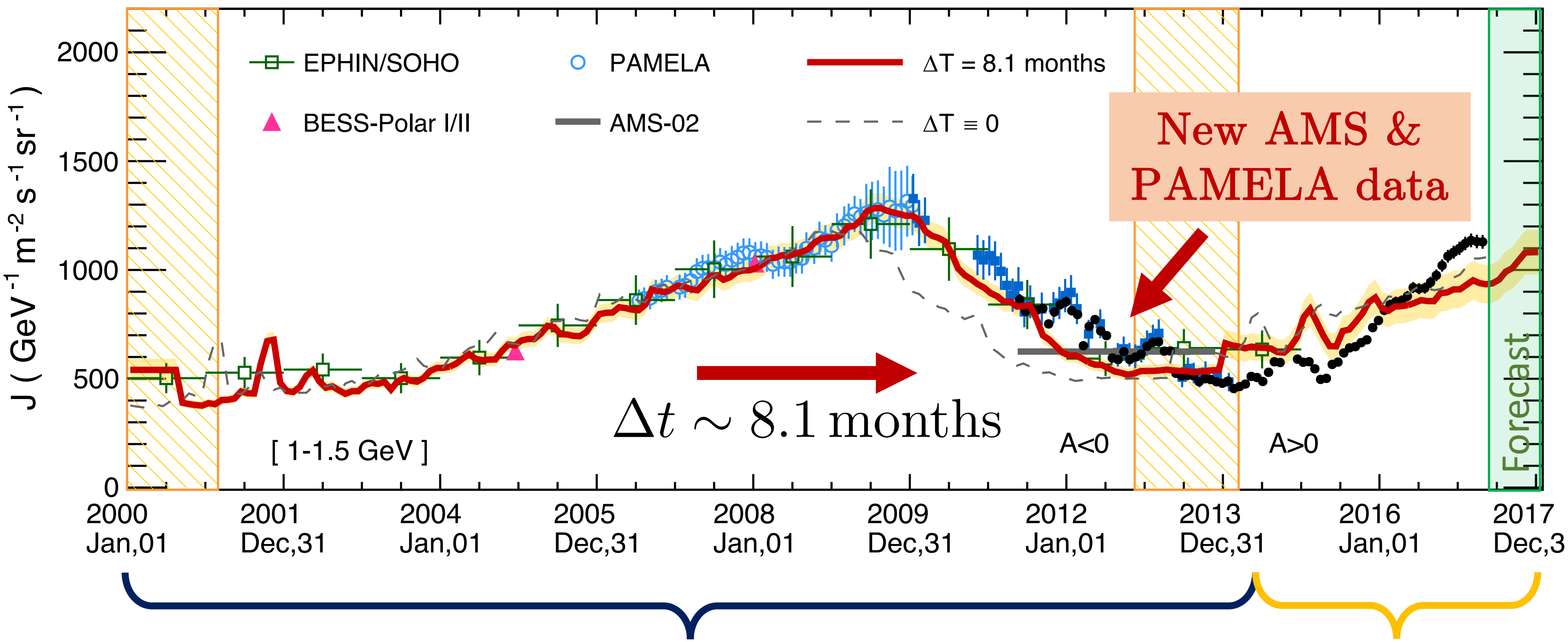
Good agreement between prediction and new AMS & PAMELA data.

AMS-02
Aguilar et al. PRL 121, 051101, 2018
Monthly resolved, 2011-2017

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

Predictability



Fit region

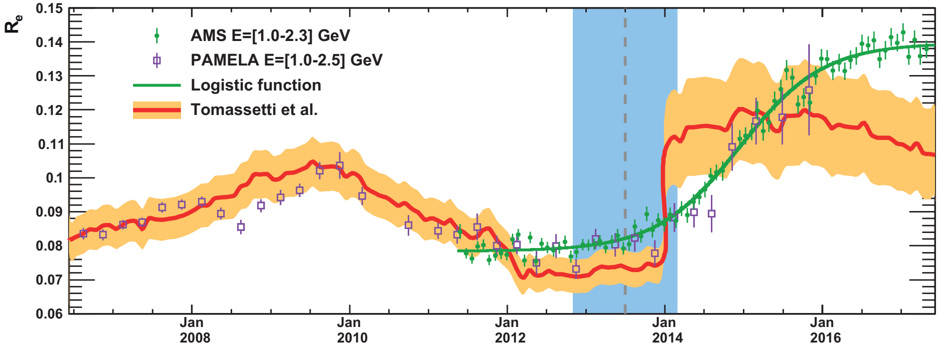
Prediction based on solar data

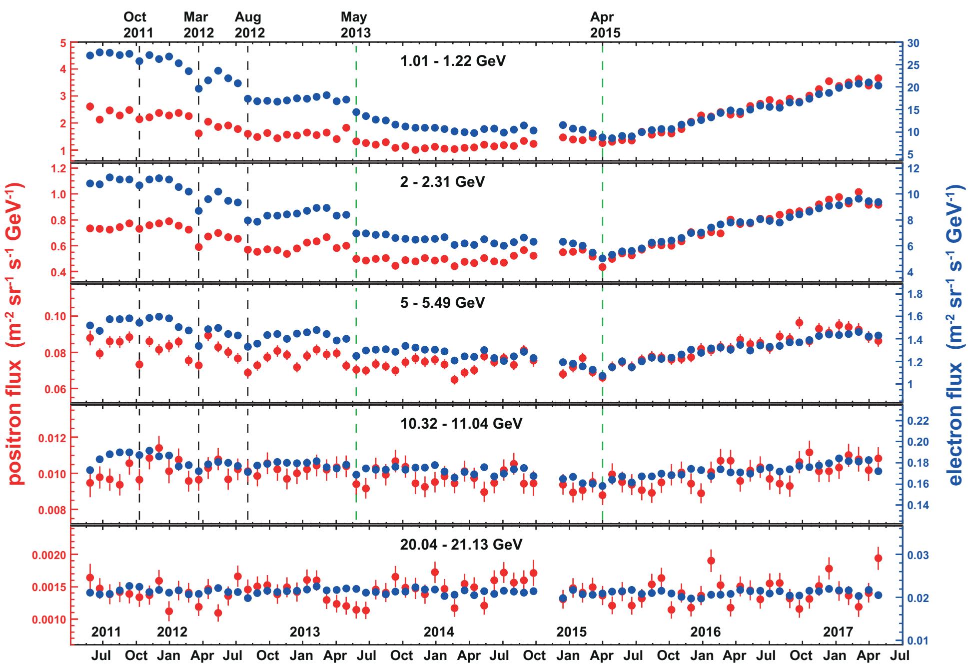
- ✓ Data is well described by the model
- ✓ Ability to forecast fluxes 8 months in advance
- ✓ Requires retuning using new AMS/PAMELA data

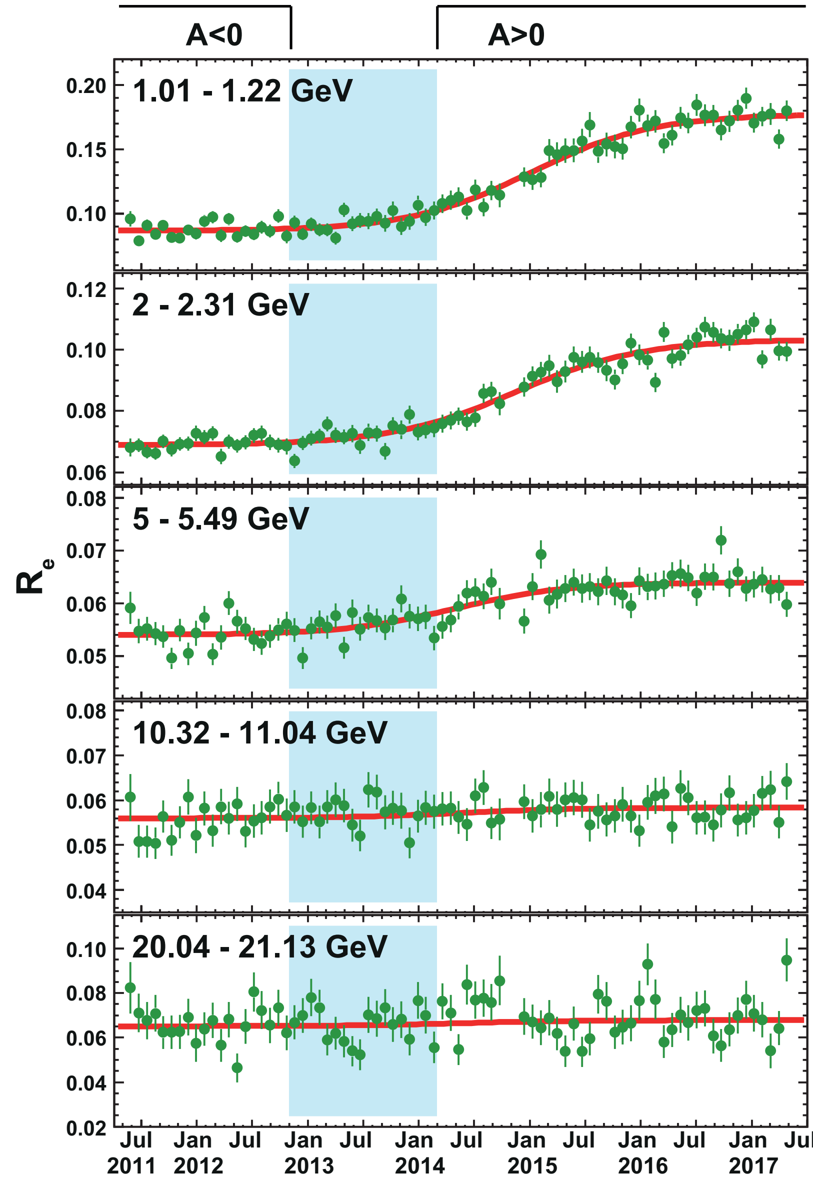
Electrons & Positrons

Observation of Complex Time Structures in the Cosmic-Ray Electron and Positron Fluxes with the Alpha Magnetic Spectrometer on the International Space Station

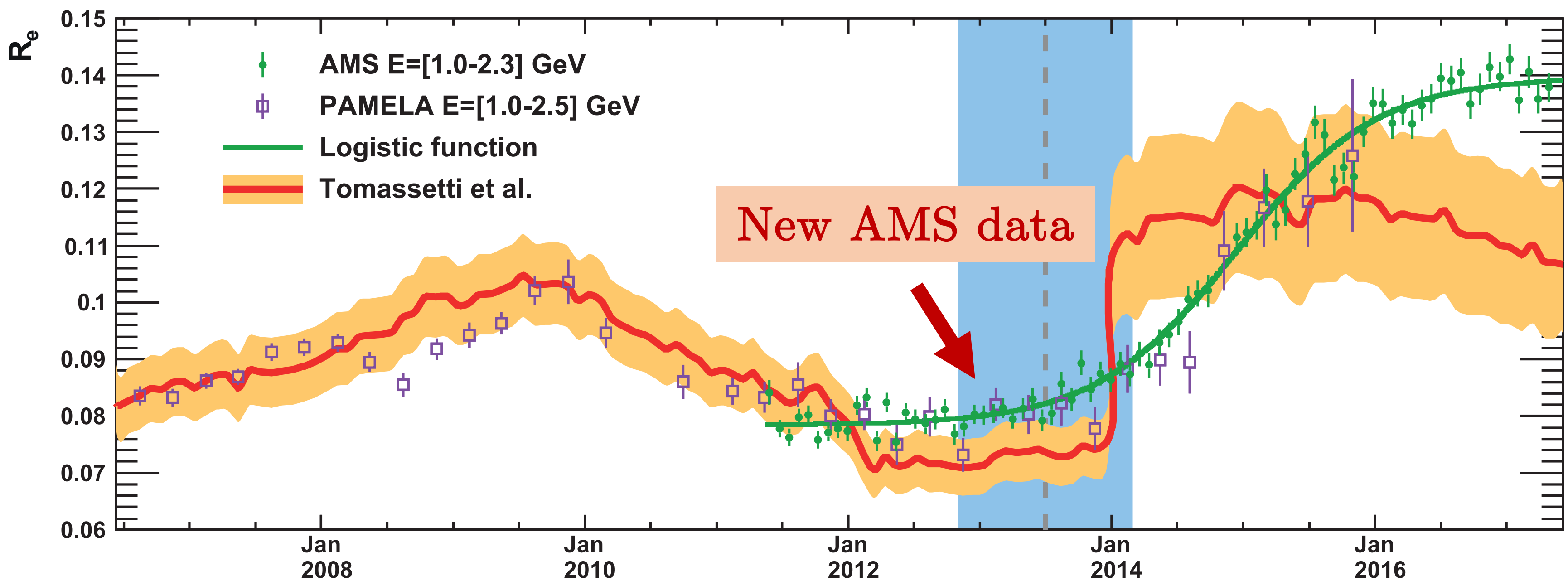
M. Aguilar *et al.* (AMS Collaboration)
Phys. Rev. Lett. **121**, 051102 – Published 31 July 2018







Charge Sign Effect



- ✓ CR proton-driven retuning using new AMS/PAMELA data
- ✓ Requires a smooth transition across reversal
- ✓ LIS, diffusion and drift parameters for GCR leptons.

Observation of Complex Time Structures in the Cosmic-Ray Electron and Positron Fluxes with the Alpha Magnetic Spectrometer on the International Space Station

M. Aguilar *et al.* (AMS Collaboration)
Phys. Rev. Lett. **121**, 051102 – Published 31 July 2018

Parker's Equation

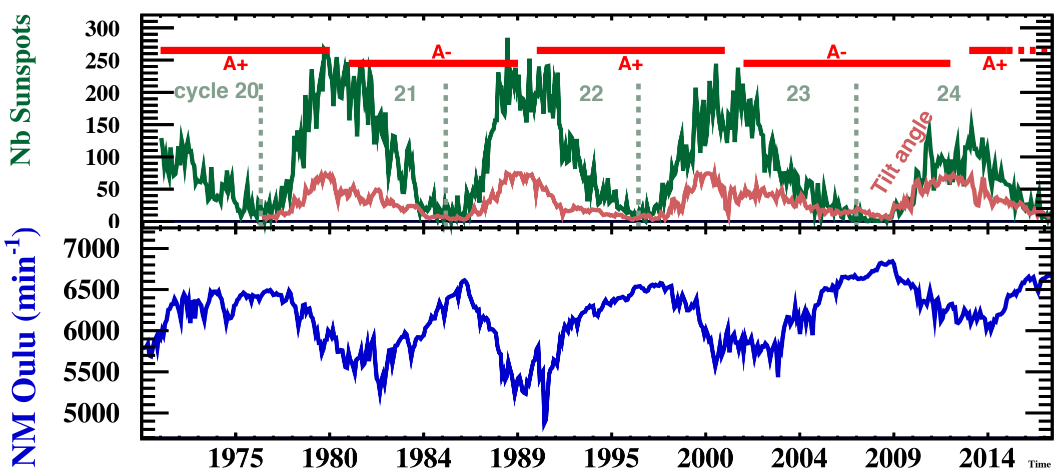
$$\frac{\partial f}{\partial t} = \boxed{\underbrace{\nabla \cdot (\mathbf{K}_{\rm s} \cdot \nabla f)}_{\text{diffusion}}} - \underbrace{(\mathbf{V} + \langle \mathbf{v}_{\rm dr} \rangle) \cdot \nabla f}_{\text{convection and drift}} + \underbrace{\frac{1}{3} (\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P}}_{\text{adiabatic energy loss}} + \underbrace{Q(\mathrm{r}, P, t)}_{\text{source/LIS}}$$

Diffusion

- ✓ Parametrized through an adimensional normalization factor
- ✓ Time-dependent due to correlation to solar activity

$$K_\perp = 0.02 K_\parallel$$

$$K_\parallel = k_0(t) \frac{A}{3B} \beta \, (P/1\,\mathrm{GV})$$

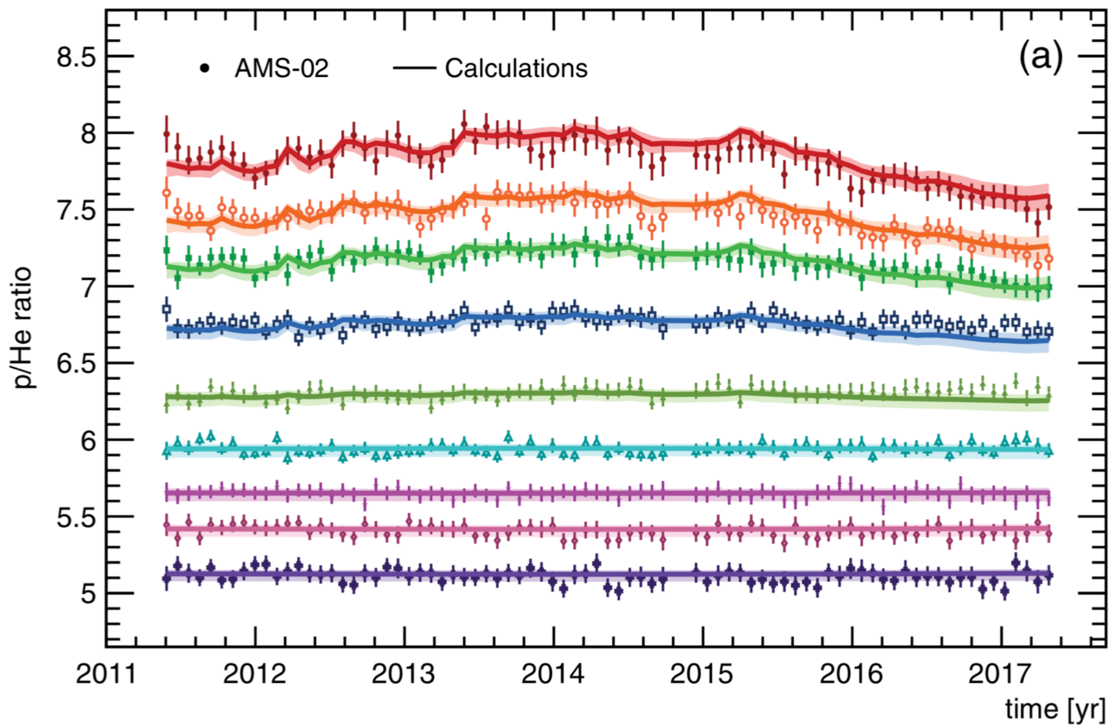


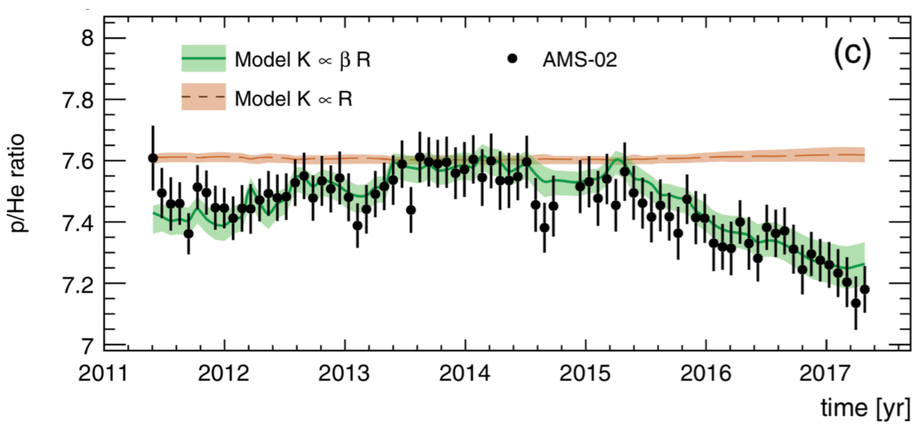
$$\boxed{\mathrm{SSN} = \mathrm{SSN}(t)}$$

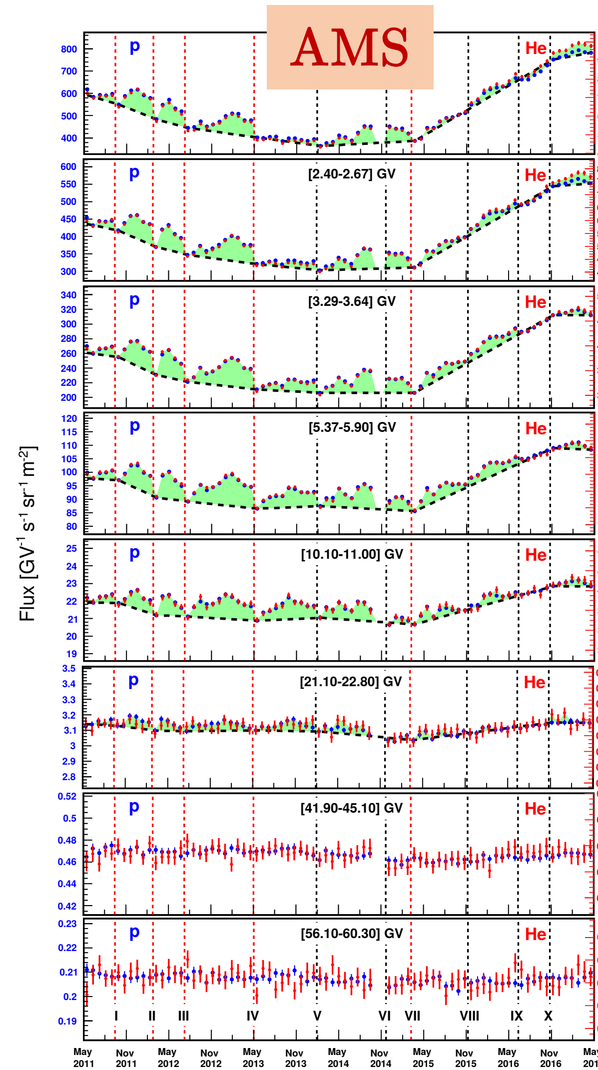
Parametrization of diffusion parameter

$$\boxed{k_0(\mathrm{SSN}) = a \, \log_{10}(\mathrm{SSN}) + b}$$

Proton & Helium Fluxes







Testing Diffusion of Cosmic Rays in the Heliosphere with Proton and Helium Data from AMS

N. Tomassetti, F. Barão, B. Bertucci, E. Fiandrini, J. L. Figueiredo, J. B. Lousada, and M. Orcinha
Phys. Rev. Lett. **121**, 251104 – Published 18 December 2018

Numerical modeling of cosmic-ray transport in the heliosphere and interpretation of the proton-to-helium ratio in Solar Cycle 24

Nicola Tomassetti [a], Fernando Barão [b], Bruna Bertucci [a], Emanuele Fiandrini [a], Miguel Orcinha [b]

QUESTIONS?

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

TÉCNICO LISBOA

FCT Fundação para a Ciência e a Tecnologia

POCH

PORTUGAL 2020

UNIÃO EUROPEIA
Fundo Social Europeu

BACKUP SLIDES

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

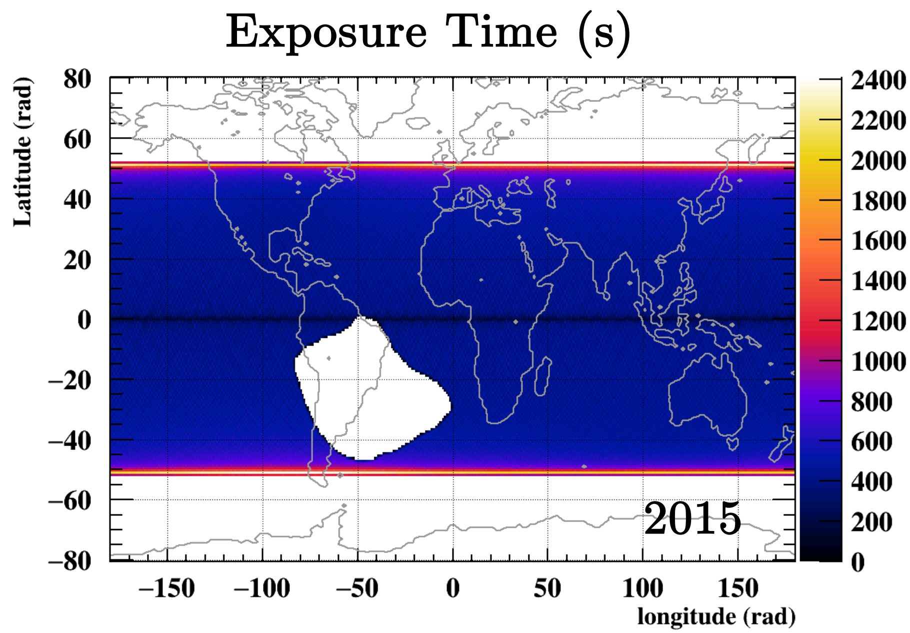
TÉCNICO LISBOA

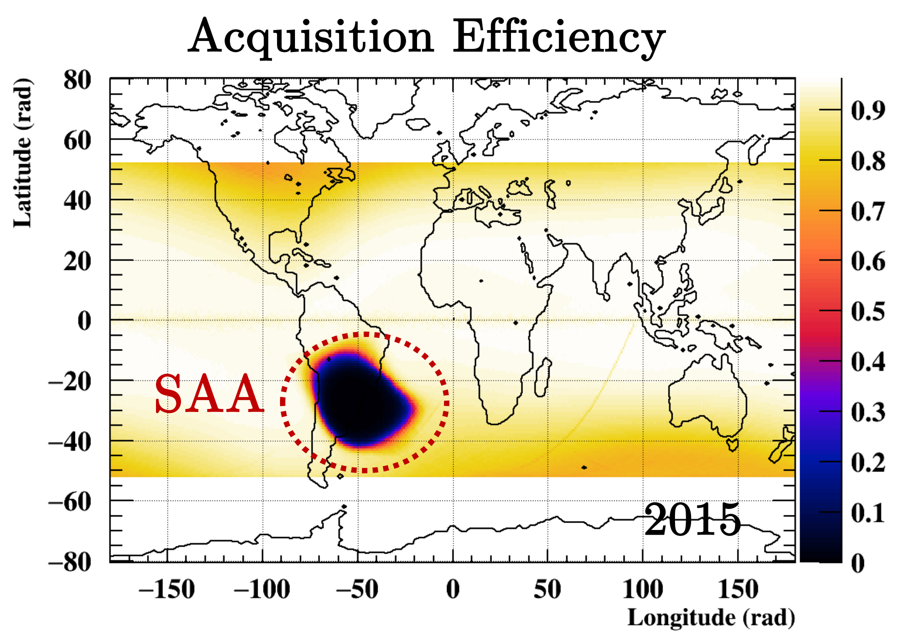
FCT Fundação para a Ciência e a Tecnologia

POCH PORTUGAL 2020 UNIÃO EUROPEIA Fundo Social Europeu

Exposure Time

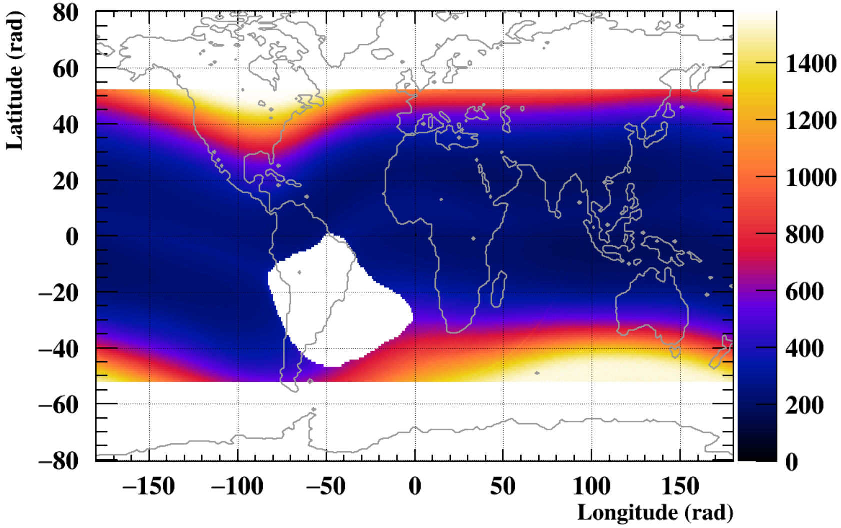
$$\phi(P) = \frac{N_{\text{part}}(P)}{\boldsymbol{\Delta t}\,\varepsilon_{\text{trigg}}(P) Acc_0 \varepsilon_{\text{sel}}(P) \Delta P}$$



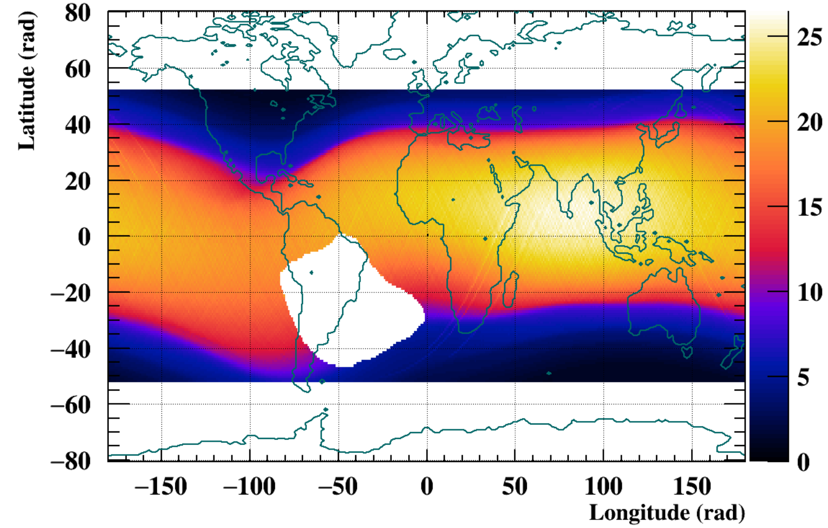


Geomagnetic cutoff and livetime

Event Rate (Hz)



Geomagnetic Cutoff (GV)



Event rate is correlated with Earth's magnetic field

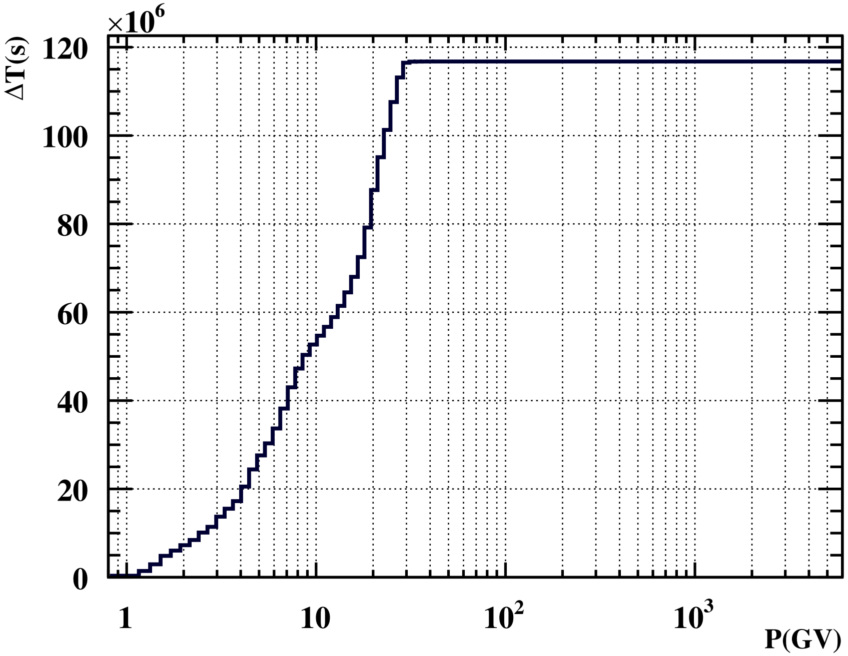
Highest cutoff rigidity for positive particles with a maximum 40° inclination to detector.
It uses the International Geomagnetic Reference Field (IGRF).

Geomagnetic cutoff and livetime

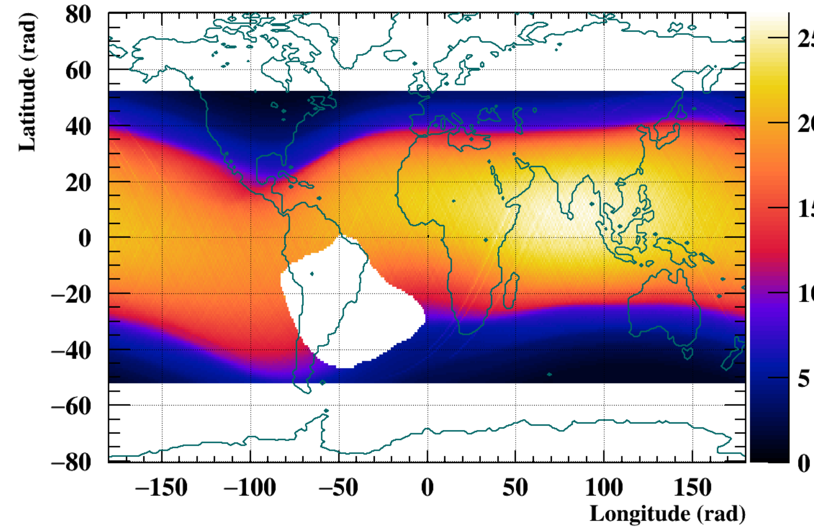
$$\phi(P) = \frac{N_{\text{part}}(P)}{\boldsymbol{\Delta t}\, \varepsilon_{\text{trigg}}(P) Acc_0 \varepsilon_{\text{sel}}(P) \Delta P}$$

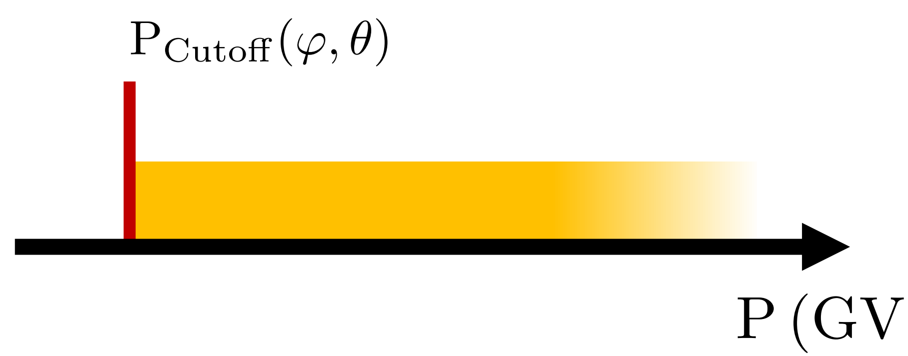
Rigidity Dependent!

$$\phi(P) = \frac{N_{\text{part}}(P)}{\boldsymbol{\Delta t(P)}\, \varepsilon_{\text{trigg}}(P) Acc_0 \varepsilon_{\text{sel}}(P) \Delta P}$$



Geomagnetic Cutoff (GV)



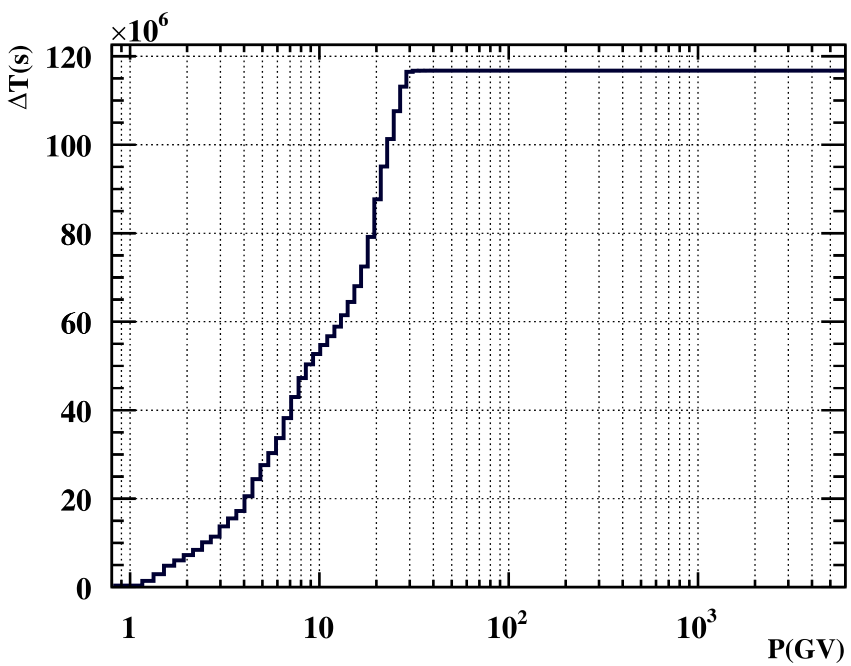


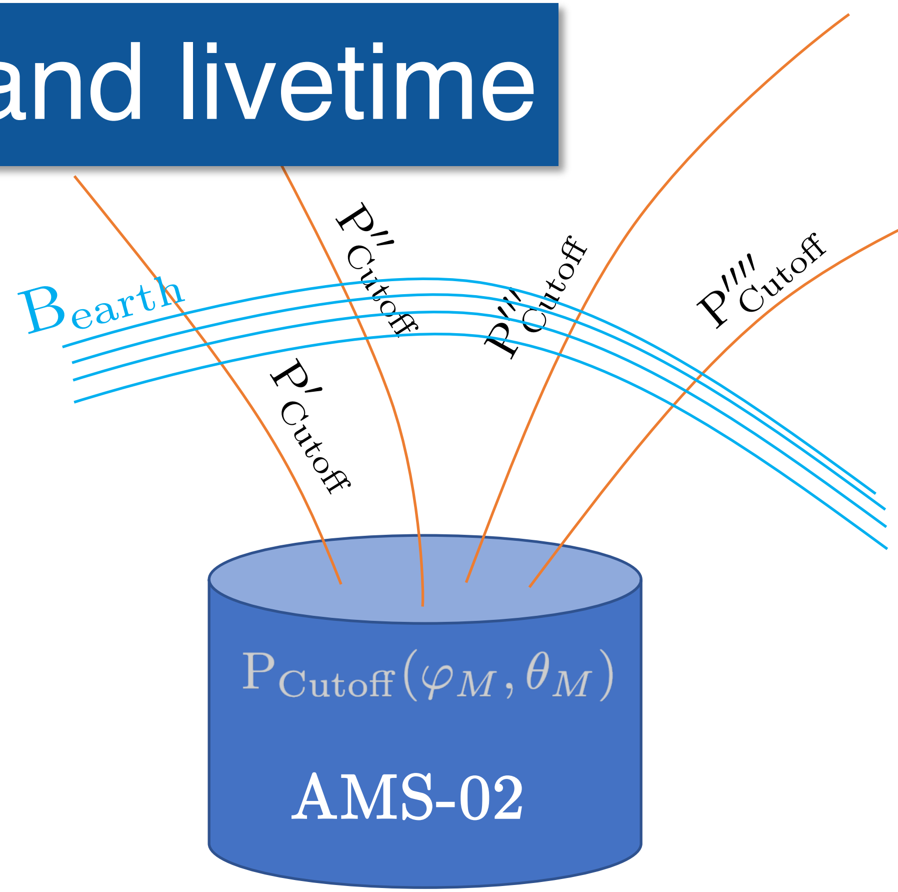
Geomagnetic cutoff and livetime

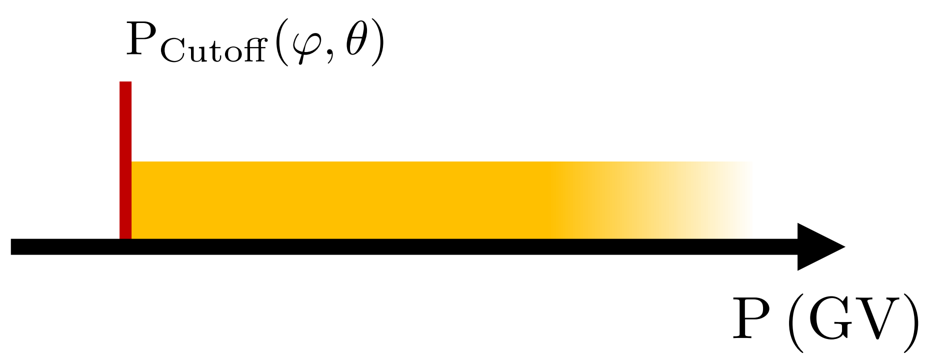
$$\phi(P) = \frac{N_{\text{part}}(P)}{\boldsymbol{\Delta t}\,\varepsilon_{\text{trigg}}(P) Acc_0 \varepsilon_{\text{sel}}(P) \Delta P}$$

Rigidity Dependent!

$$\phi(P) = \frac{N_{\text{part}}(P)}{\boldsymbol{\Delta t(P)}\,\varepsilon_{\text{trigg}}(P) Acc_0 \varepsilon_{\text{sel}}(P) \Delta P}$$

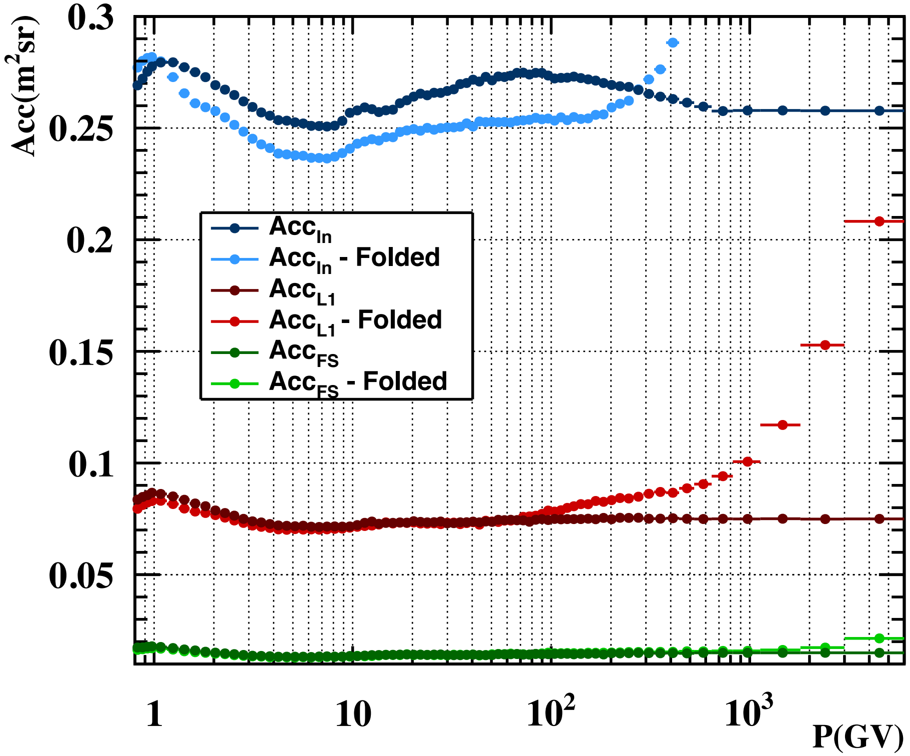


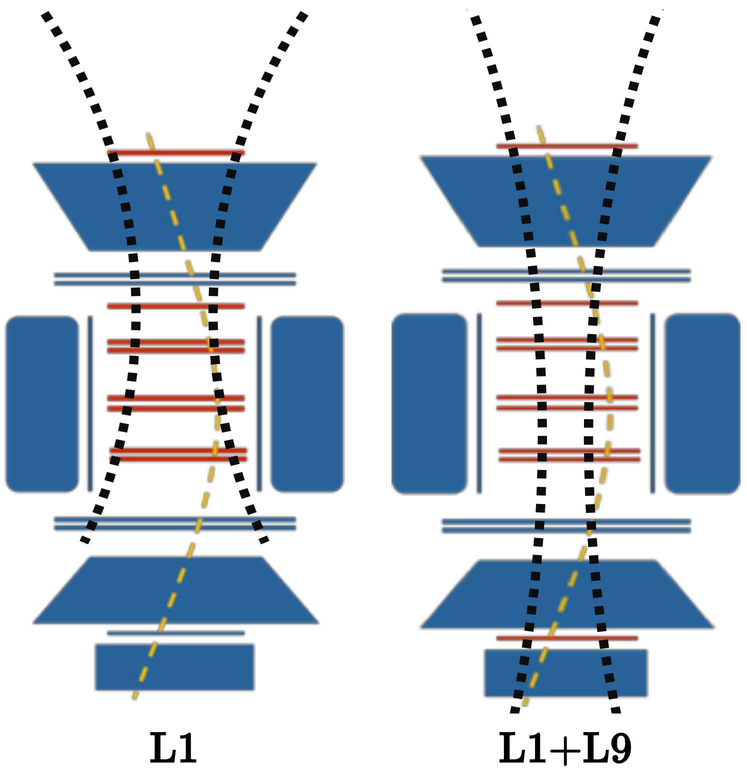




MC Acceptance & Data-MC corrections

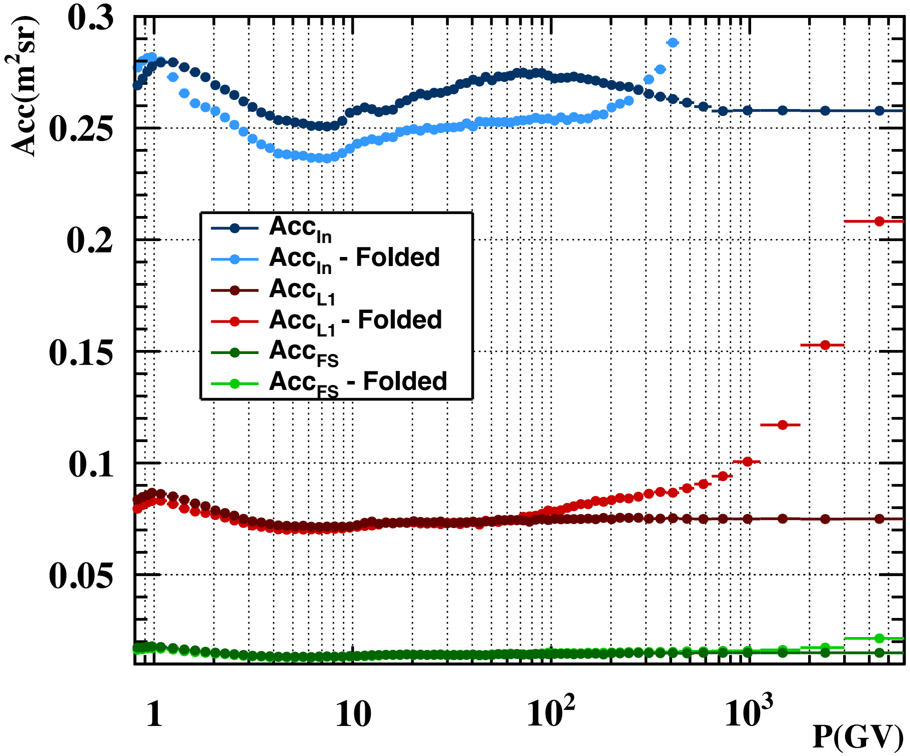
$$\phi(P) = \frac{N_{\text{part}}(P)}{\Delta t(P)\,\varepsilon_{\text{trigg}}(P)\,\boldsymbol{Acc_0}\,\varepsilon_{\text{sel}}(P)\,\Delta P}$$

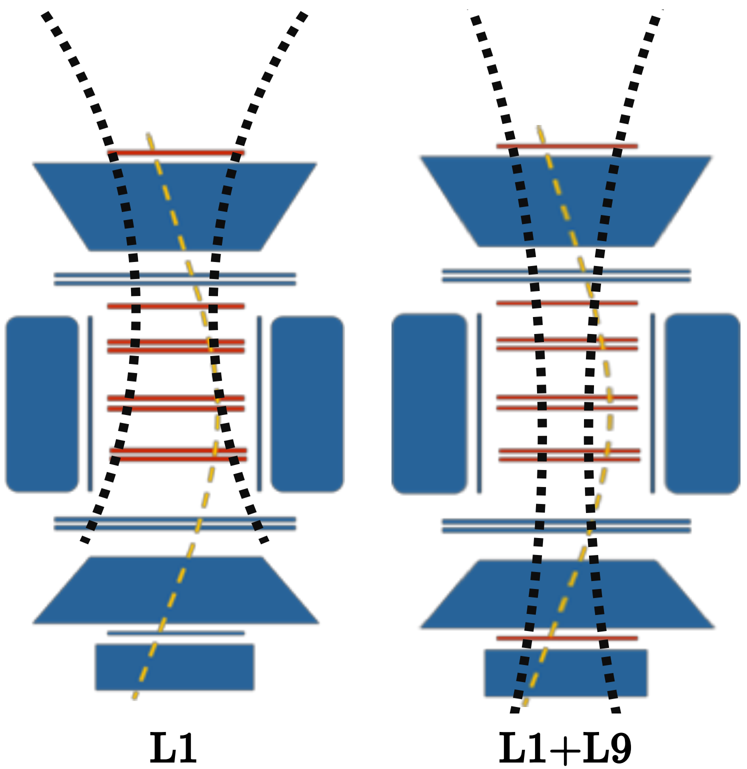




MC Acceptance & Data-MC corrections

$$\phi(P) = \frac{N_{\text{part}}(P)}{\Delta t(P)\,\varepsilon_{\text{trigg}}(P)\,\boldsymbol{Acc_{\mathrm{MC}}(P)}\;\boldsymbol{C_{\mathrm{MC}}^{\mathrm{Data}}(P)}\,\varepsilon_{\text{sel}}(P)\Delta P}$$





Unfolding a flux

$$N(P) = \int_0^\infty \underbrace{\phi_0(P_0)\,\Delta t(P_0)}_{\text{Physics}}\ \underbrace{Acc(P_0)\,K(P|P_0)}_{\text{Detector}}\,\mathrm{d}P_0$$

(... some calculations later ...)

$$\Delta N_j \simeq \sum_i \langle \Delta t_i \rangle\, \mathcal{P}(j|i)\, Acc^{\text{gen}}\, \Delta P_i\, \langle \Delta\phi_0 \rangle_i$$

$$\Delta N_j \simeq A^{ij}\, \langle \phi_0 \rangle_i$$

Ideal unfolding problem!

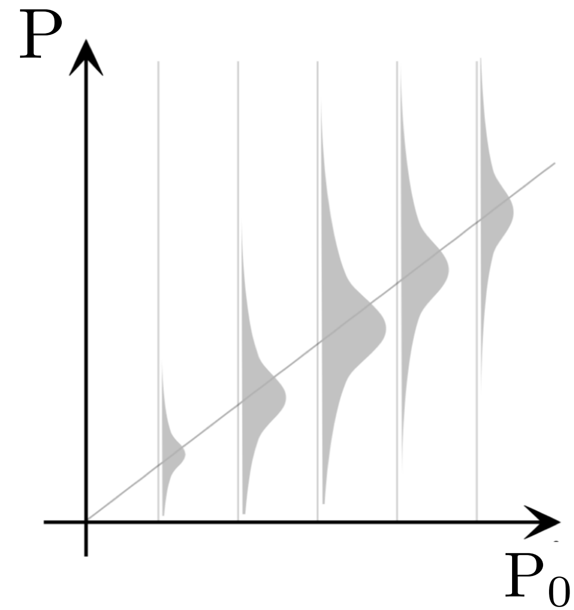
$$\Delta N_j \simeq A^{ij}(\phi_0)\, \langle \phi_0 \rangle_i$$

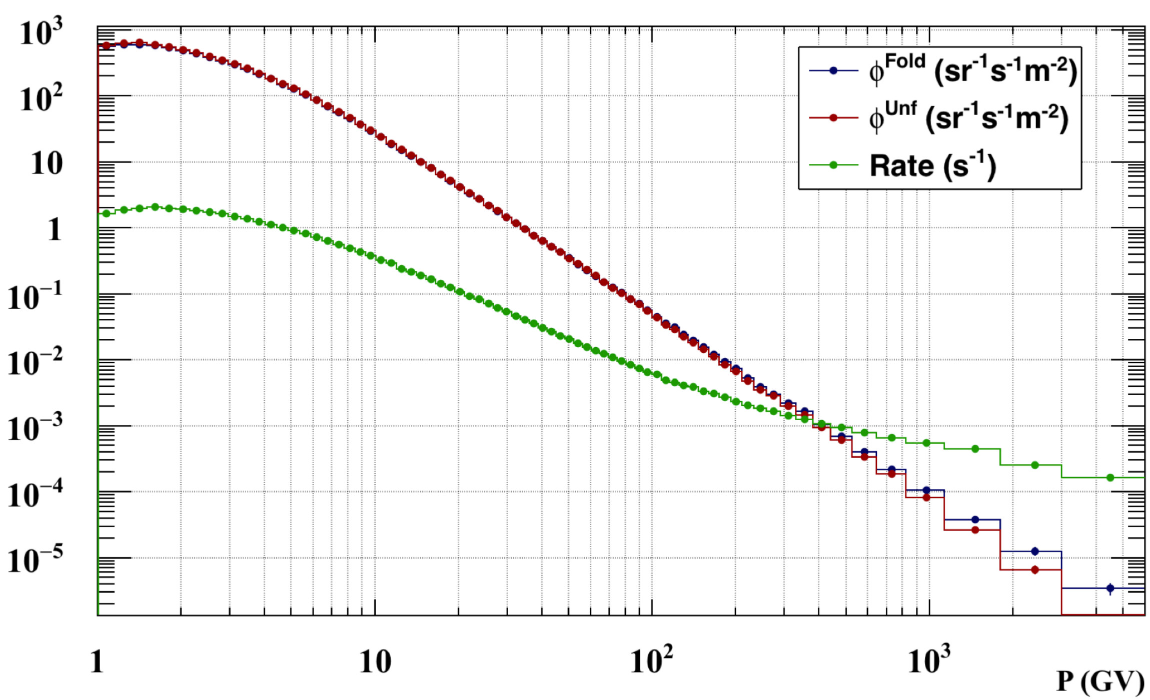
True and problematic unfolding problem!

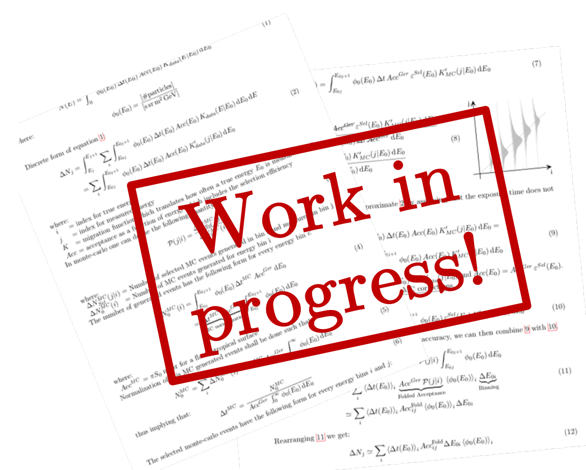
Unfolding a flux

$$\Delta N_j \simeq \sum_i \langle \Delta t_i \rangle \, \mathcal{P}(j|i) \, Acc^{\text{gen}} \, \Delta P_i \, \langle \Delta\phi_0$$

$$\Delta N_j \simeq A^{ij} \, \langle \phi_0 \rangle_i$$







Unfolding a flux – An iterative process

$$\text{Rate} = \frac{\text{Selected Events}}{\text{Exposure Time}}$$

$$\phi^{0}_{\text{Unf}} = \frac{\text{Rate}}{\text{Acc}^{0}_{\text{Fold}}\left(\phi^{\text{MC}}_{\text{Guess}}\right)}$$

$$\phi^{1}_{\text{Unf}} = \frac{\text{Rate}}{\text{Acc}^{1}_{\text{Fold}}\left(\phi^{0}_{\text{Unf}}\right)}$$

$$\phi^{2}_{\text{Unf}} = \frac{\text{Rate}}{\text{Acc}^{2}_{\text{Fold}}\left(\phi^{1}_{\text{Unf}}\right)}$$

$$\vdots$$