Propagation of Galactic Cosmic Rays in the Heliosphere: A global View

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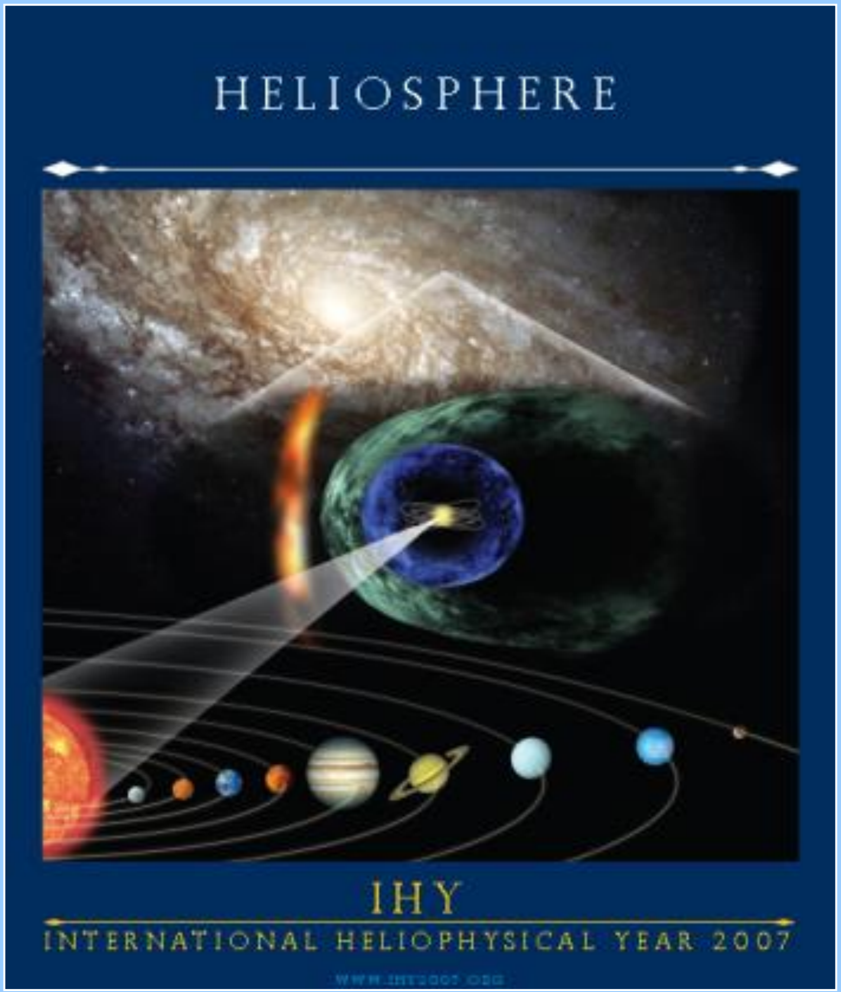
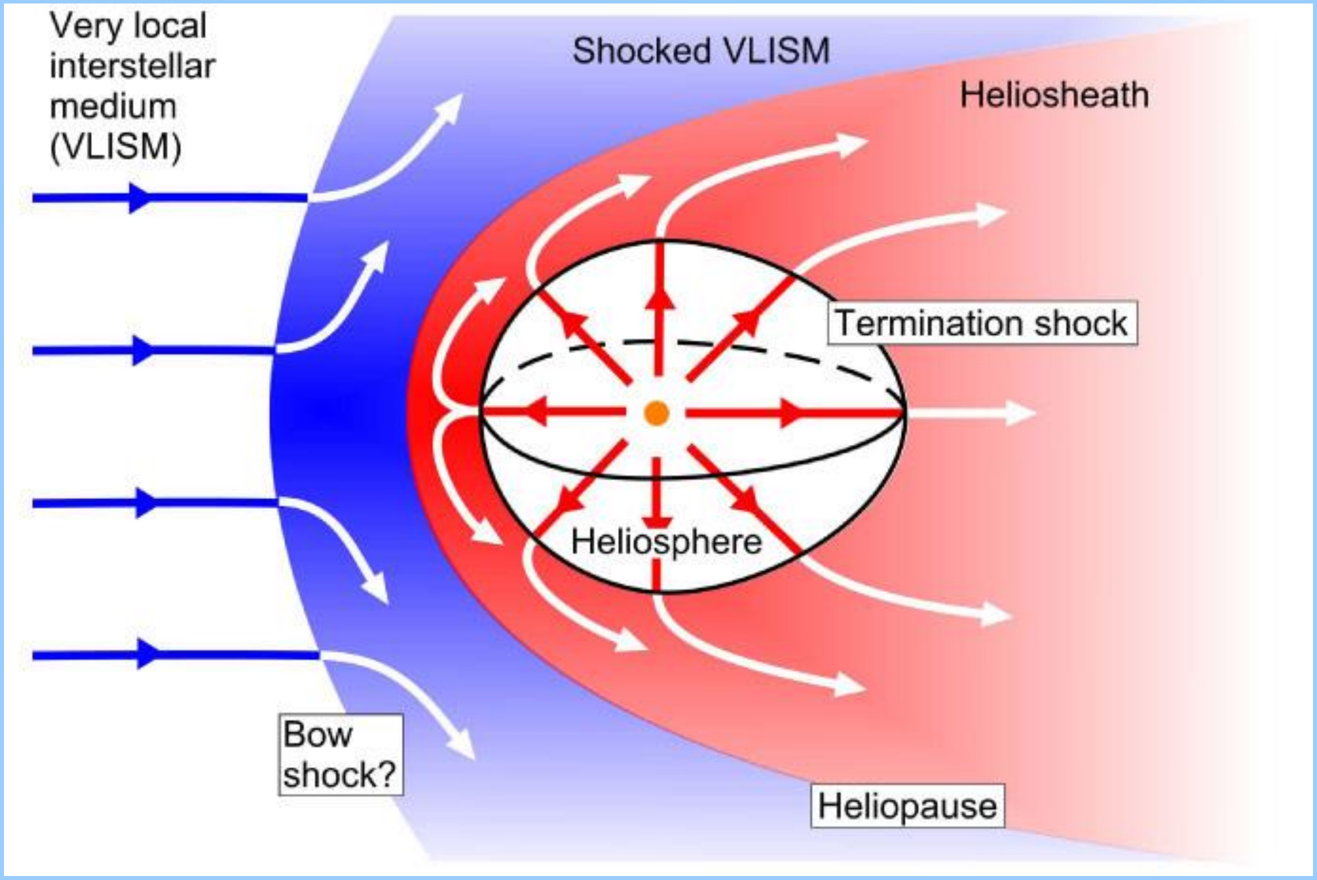
Cosmic Ray Physics in Space, June 2017

Outline of presentation



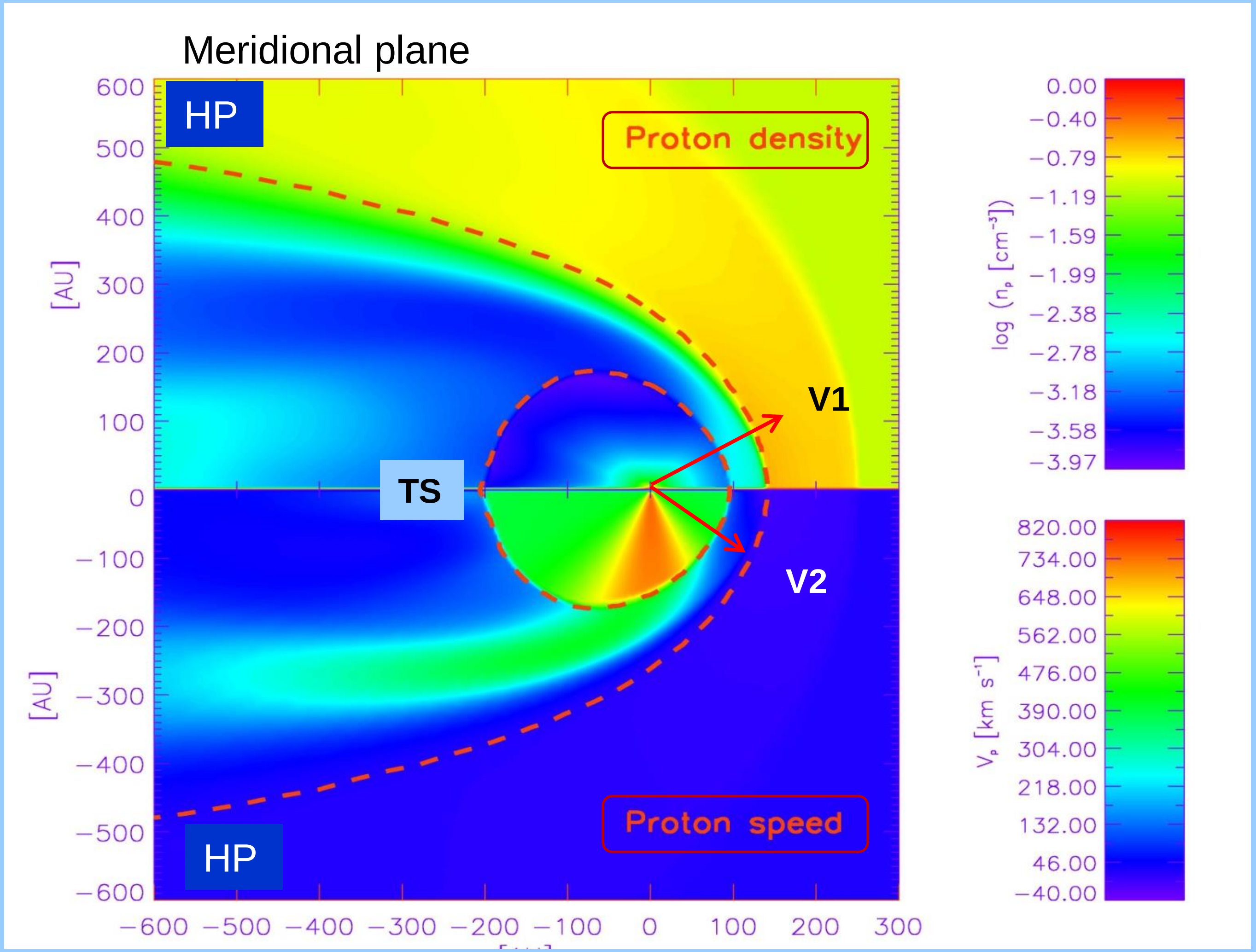
- The heliosphere
- Modulation boundaries
- New heliopause spectra (HPS)
- Observations of GCRs
- Transport and modulation theory
  - Diffusion theory
- Numerical models
  - Complexity
- Modeling results and implications

The schematic heliosphere



Owens and Forsyth. Living Rev. 2013

Major heliospheric structures (e.g. HD simulated)



Fact sheet:

Heliosphere is highly asymmetric

TS was observed by V1 at 94 AU, by V2 at 84 AU…

V1 crossed the HP at 121.5 AU

V1 now at ~138 AU from the Sun

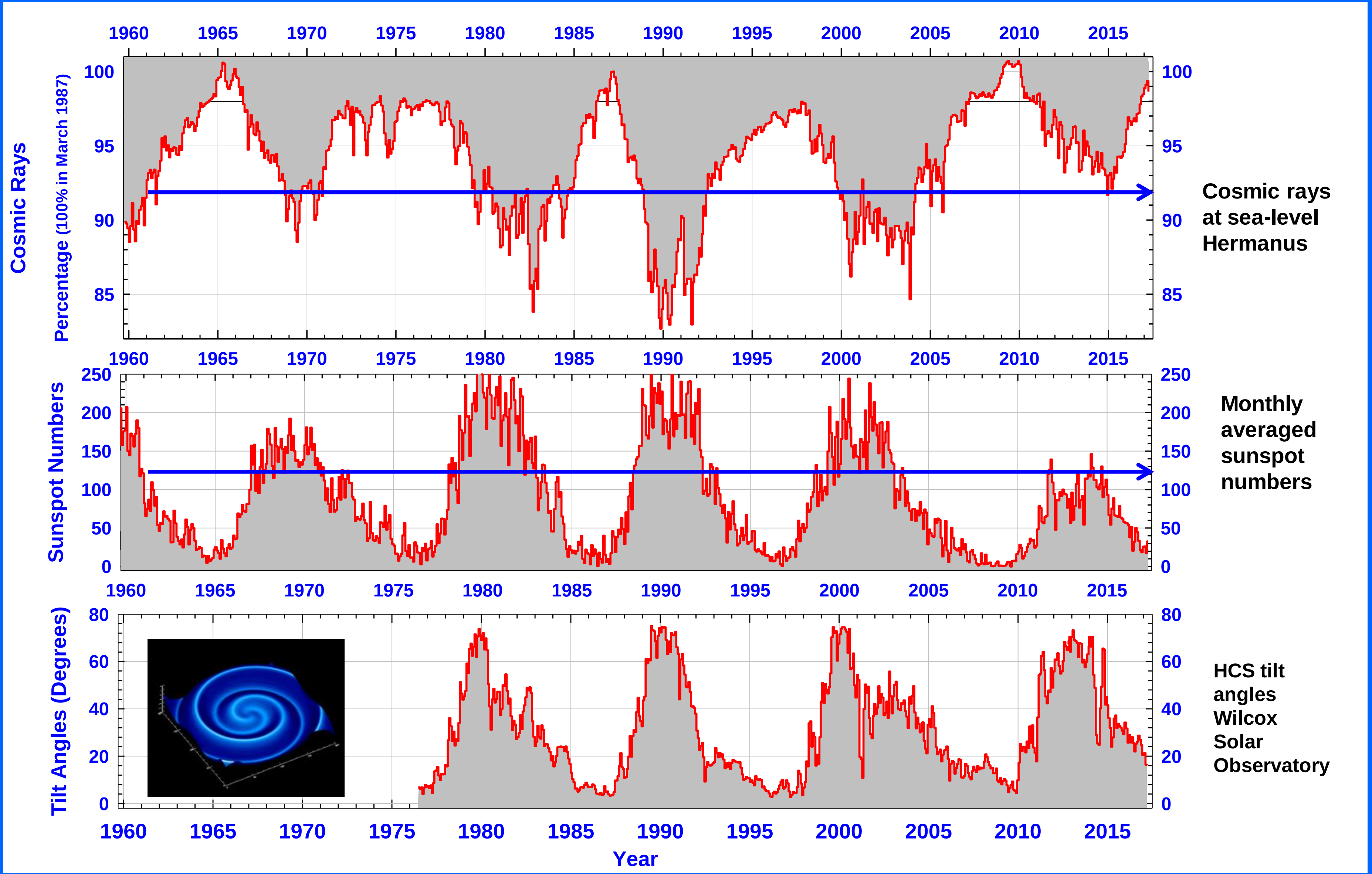
V2 still inside the inner heliosheath at ~114 AU

http://voyager.jpl.nasa.gov/

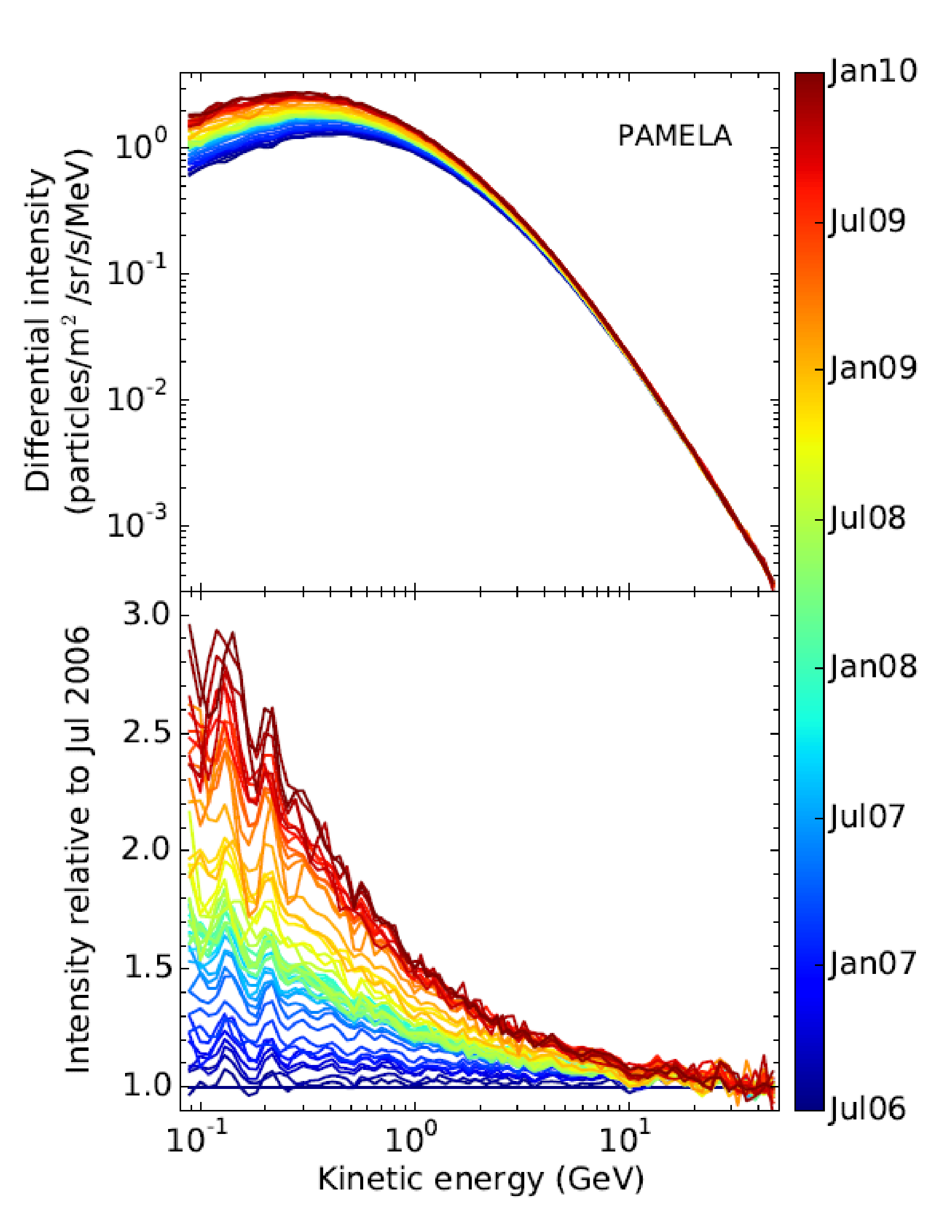
Ferreira, S. E. S., & Scherer, K. 2004, ApJ

Scherer, K., & Ferreira, S. E. S. 2005

Modulation of Galactic Cosmic Rays Observed at the Earth
with two solar activity proxies



Global modulation of cosmic ray protons: mid-2006 to end of 2009



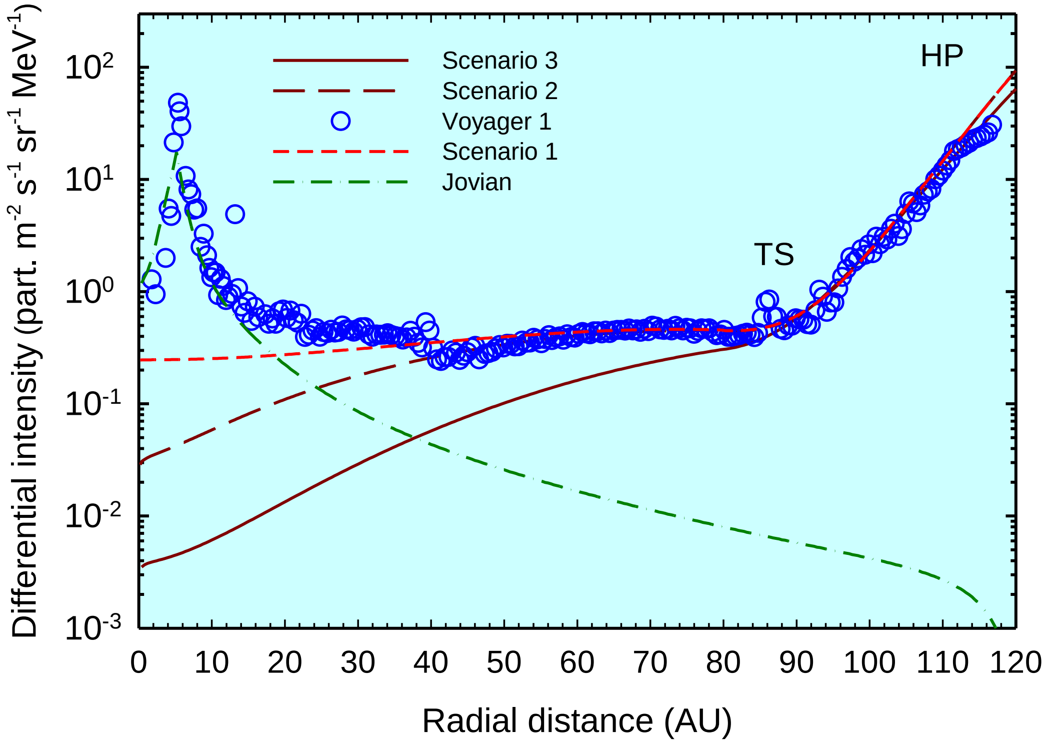
PAMELA proton observations at the Earth

PAMELA-SA bilateral cooperation:
Mirko Boezio & colleagues

Proton spectra published
Adriani et al. ApJ 2013
Potgieter et al. Solar Phys 2014

PhD's: Valeria Di Felice, Nico De Simone, Valerio Formato, Riccardo Munini, Etienne Vos, Jan-Louis Raath

Radial profile of galactic and Jovian electrons at 12 MeV



V1: 4-16 MeV; Webber (private comm.)

Conclusions:

Extraordinary type of modulation in heliosheath (HS) …

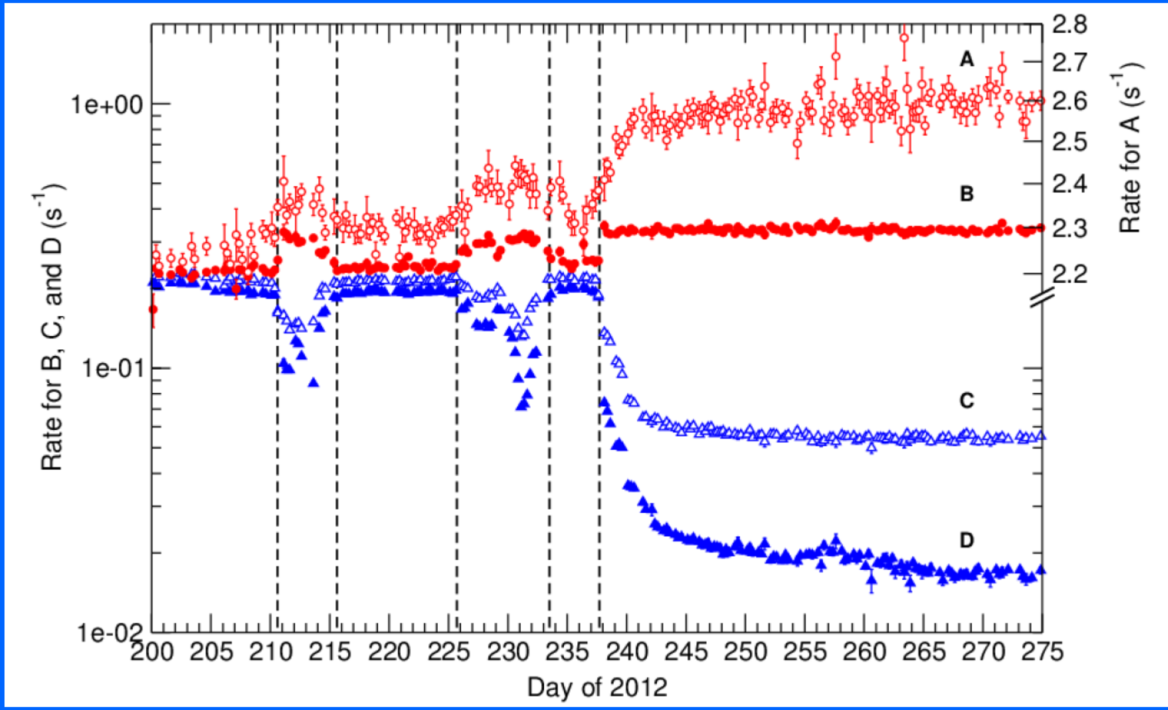
The HS indeed acts as a strong modulation 'barrier' for these low energy electrons …

With the HP position and LIS known, we can attempt to predict intensity of 12 MeV galactic electrons at the Earth …

Potgieter & Nndanganeni, Astrophys. Space Sci. 2013

PhD Rendani Nndanganeni 2015

What happened in August 2012?



GCR protons K.E. > 70 MeV

GCR electrons 7 to ~100 MeV

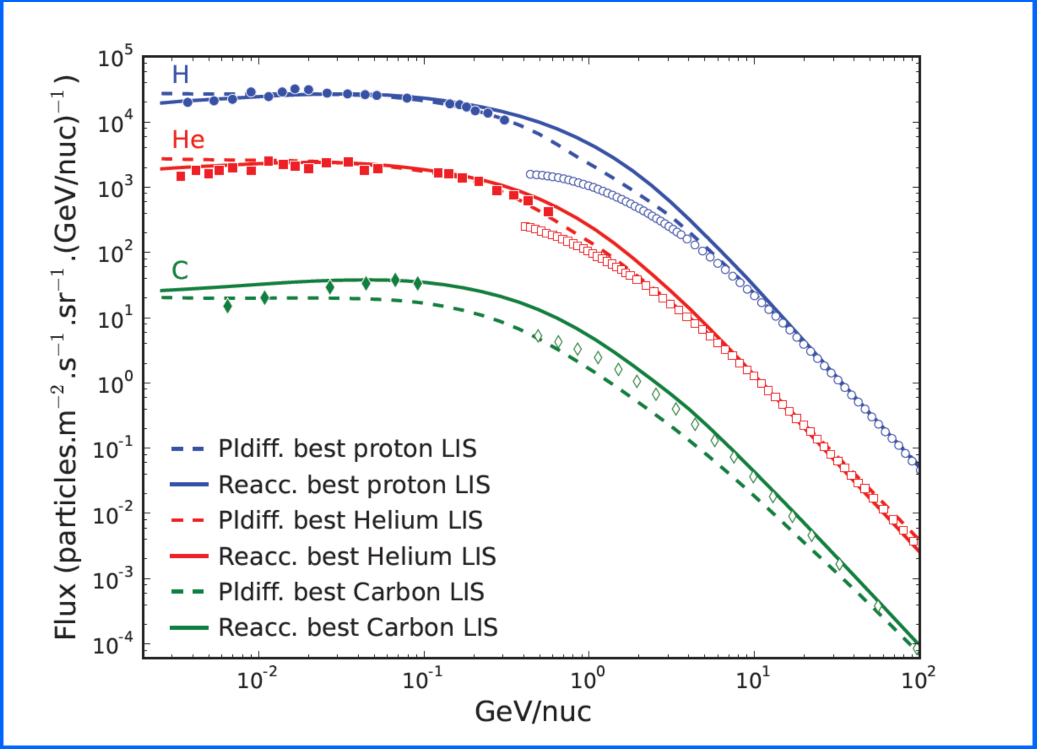
ACR protons 7 to 60 MeV

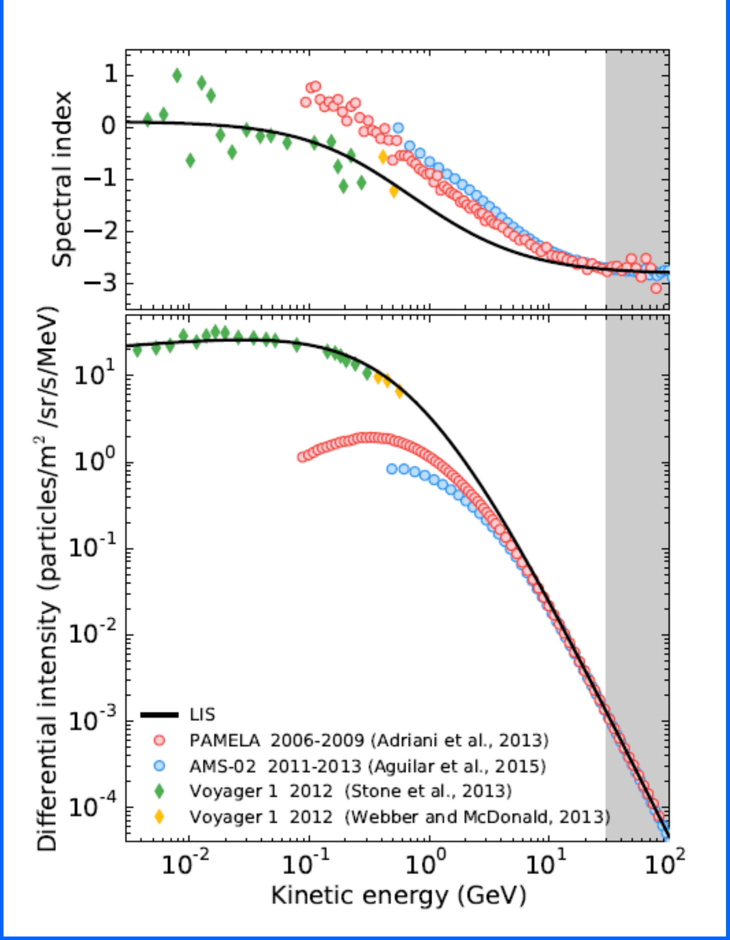
TSPs 0.5 to 30 MeV

Stone et al. 2013

The Heliopause Spectra: Voyager 1, PAMELA and AMS2 Observations and GALPROP computations

GALPROP; Plain Diffusion, and with re-acceleration

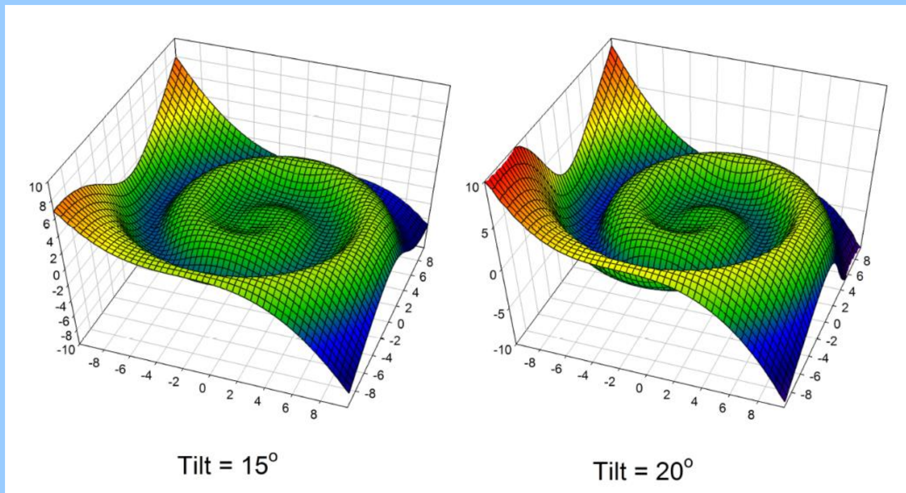


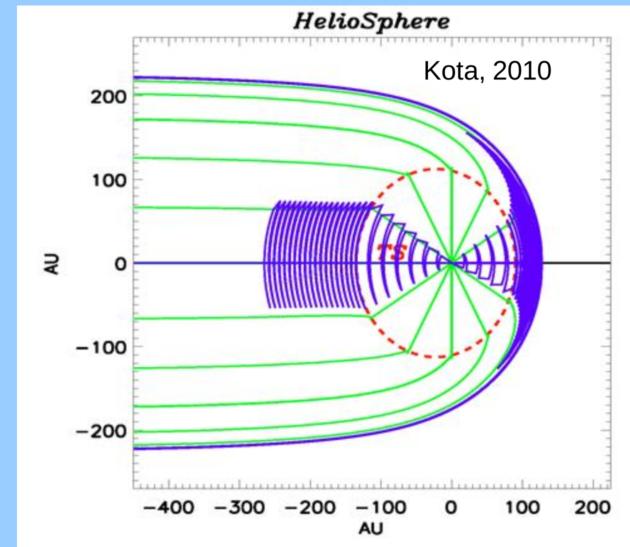


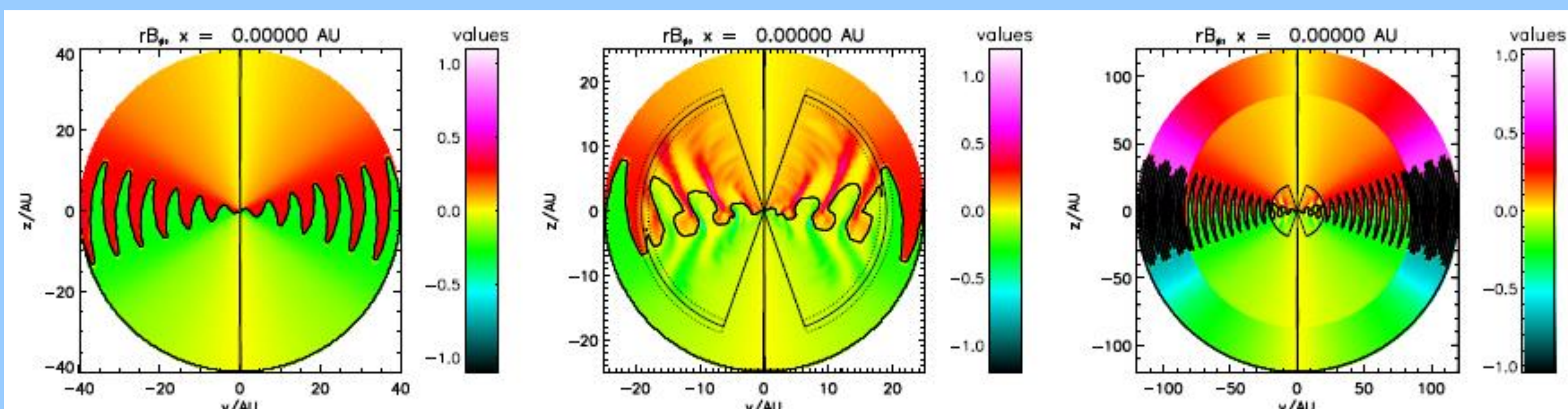
Bisschoff & Potgieter, 2015

Vos & Potgieter, 2015
Potgieter & Vos, 2017

The conceptual and simulated HCS (wavy current sheet)







Cosmic-Ray Transport in Heliospheric Magnetic Structures. II. Modeling Particle Transport through Corotating Interaction Regions

Andreas Kopp[1,2,6], Tobias Wiengarten[3], Horst Fichtner[3], Frederic Effenberger[4], Patrick Kühl[5], Bernd Heber[5], Jan-Louis Raath[2], and Marius S. Potgieter[2]

Transport equation for the transport, modulation and acceleration of cosmic rays in the heliosphere

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

Time-dependent, pitch-angle-averaged distribution function

Diffusion

Convection with solar wind

Particle Drifts

Adiabatic energy changes

Any local source

Parker (Planet. Space Science, 13, 9, 1965)

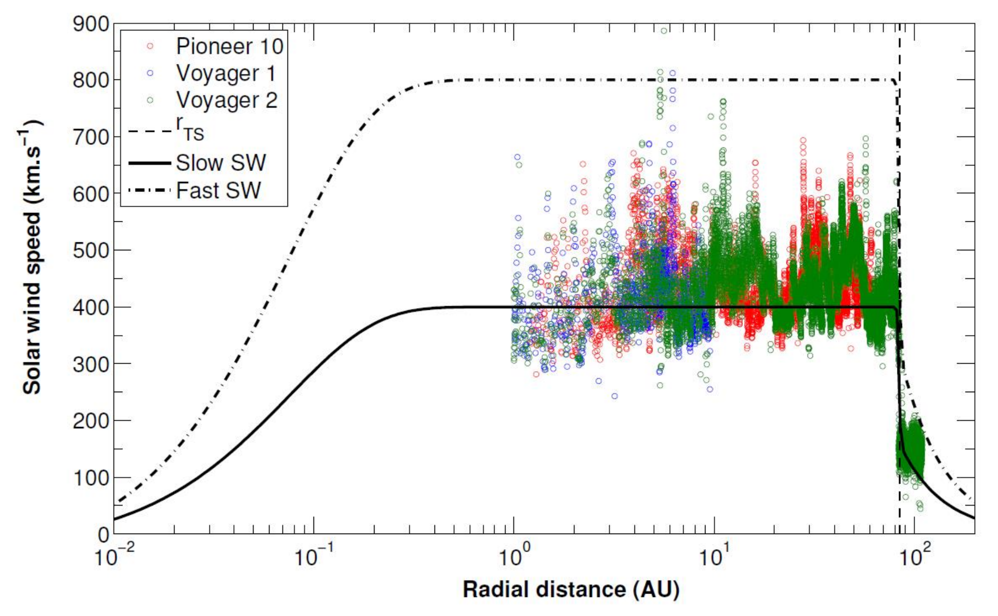
$$\ldots = \ldots + \frac{1}{p^2} \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial f}{\partial p} \right)$$

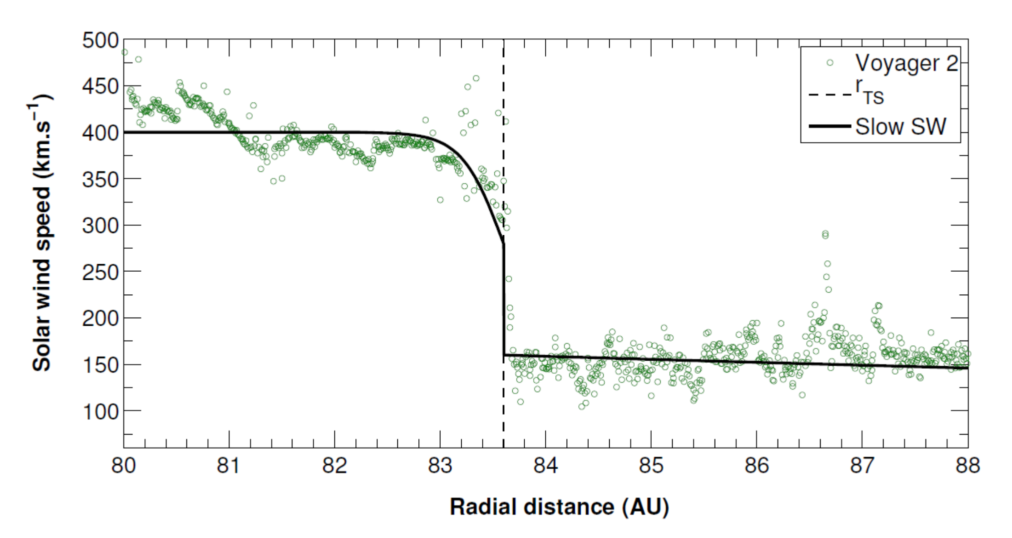
Second order Fermi acceleration

$$P = \frac{pc}{q} = \frac{mvc}{Ze},$$

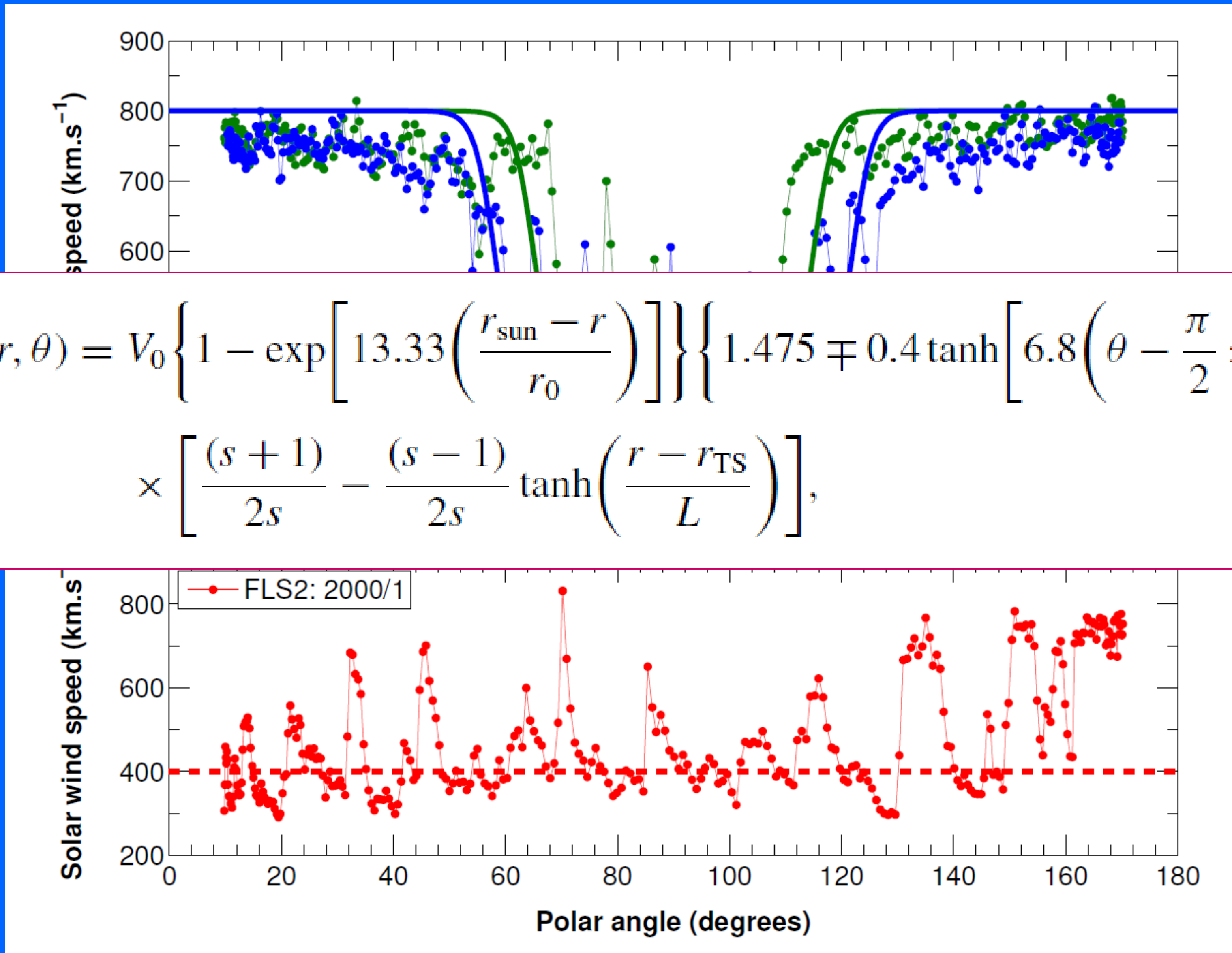
$$P = \frac{A}{Z} \sqrt{E(E + 2E_0)} = \left(\frac{A}{Z} \right) \beta (E + E_0).$$

Solar wind radial profile: Observations and Simplifications





Solar wind latitudinal profile: Observations and Simplifications



$$V(r,\theta) = V_0 \left\{1 - \exp\left[13.33\left(\frac{r_{\text{sun}} - r}{r_0}\right)\right]\right\}\left\{1.475 \mp 0.4\tanh\left[6.8\left(\theta - \frac{\pi}{2} \pm \theta_{\text{T}}\right)\right]\right\}$$
$$\times \left[\frac{(s+1)}{2s} - \frac{(s-1)}{2s}\tanh\left(\frac{r - r_{\text{TS}}}{L}\right)\right],$$

Theory and dimensional complexity (1D to 2D to 3D)

Eugene Parker published his solar wind, heliosphere and transport theory in several papers between 1958 and 1965.
His transport equation (TPE) is:

$$\frac{\partial f}{\partial t} + \nabla \bullet (\mathbf{V} f - \mathbf{K} \bullet \nabla f) - \frac{1}{3p^2}(\nabla \bullet \mathbf{V}) \frac{\partial}{\partial p}(p^3 f) = 0$$

$$\frac{\partial f}{\partial t} + \mathbf{V} \bullet \nabla f - \nabla \bullet (\mathbf{K} \bullet \nabla f) - \frac{1}{3}(\nabla \bullet \mathbf{V}) \frac{\partial f}{\partial \ln p} = 0$$

f is the distribution function with $I = p^2 f$, with p momentum
Assumption of small anisotropies
$\mathbf{V}$ is the solar wind velocity
$\mathbf{K}$ is the diffusion tensor

Theory and dimensional complexity (1D to 2D to 3D)

Analytical solution of Parker's basic TPE (1960's and 1970's)

- Convection-diffusion approach
- Force-Field approach

Steady-state numerical models

1D approach (early 1970's) One DC (diffusion coefficient)

2D approach (late 1970's) Two DC's

3D approach (early 1980's) Particle drifts and two DC's

3D approach (early 1990's) Particle drifts and three DC's

Time-dependent models

1D approach (early 1980's)

2D approach (early 1990's)

3D approach NOT DOABLE IN INFINITE-DIFFERENCES METHODS

Need approach of Stochastic Differential Equations

Simplified solutions of the TPE

$$\frac{\partial f}{\partial t} + \mathbf{V} \bullet \nabla f - \nabla \bullet (\mathbf{K} \bullet \nabla f) - \frac{1}{3}(\nabla \bullet \mathbf{V}) \frac{\partial f}{\partial \ln p} = 0$$

Convection-diffusion approach

$$\mathbf{S} = \mathbf{V} f - \mathbf{K} \bullet \nabla f$$
$$= V f - \kappa \frac{\partial f}{\partial r}$$
$$\approx 0$$

$$M = \int_{r_{Earth}}^{r_{Boundary}} \frac{V}{\kappa} dr = \frac{V}{\kappa}[r_{boundary} - r_{Earth}]$$

$$f_{Earth} = f_{LIS} \exp\left[-\int_{r_e}^{r_{HP}} \frac{V dr}{\kappa} \right]$$

Modulation parameter

Simplified solutions of the TPE

Force-Field approach

$$\mathrm{S} = CVf - \mathrm{K} \bullet \nabla f \quad = CVf - \kappa \frac{\partial f}{\partial r} = 0$$

$$f_{Earth} = f_{Boundary} \exp\left[-\int_{r_E}^{r_B} \frac{CVdr}{\kappa} \right], \quad \text{with } C = -\frac{1}{3} \frac{\partial \ln f}{\partial \ln p}$$

This resembles an energy loss without considering the adiabatic process

Approximated Force-Field approach

$$j(T) = j_{LIS}(T + \Phi) \frac{T(T + 2E_0)}{(T + \Phi)(T + \Phi + 2E_0)}$$

Valid if κ is separable : $\kappa = \kappa_1(r)\kappa_2(P)$ with $\kappa_2 = \beta P$ when $\beta \approx 1$

Complexity & Dimension issues

Force Field gives an indication of the modulation level (depth), nothing more, nothing about the physics responsible, always ‘forced’ approximated solutions in 1 D, so that your heliosphere looks like this:

1 D spherically symmetric, steady-state, numerical approach

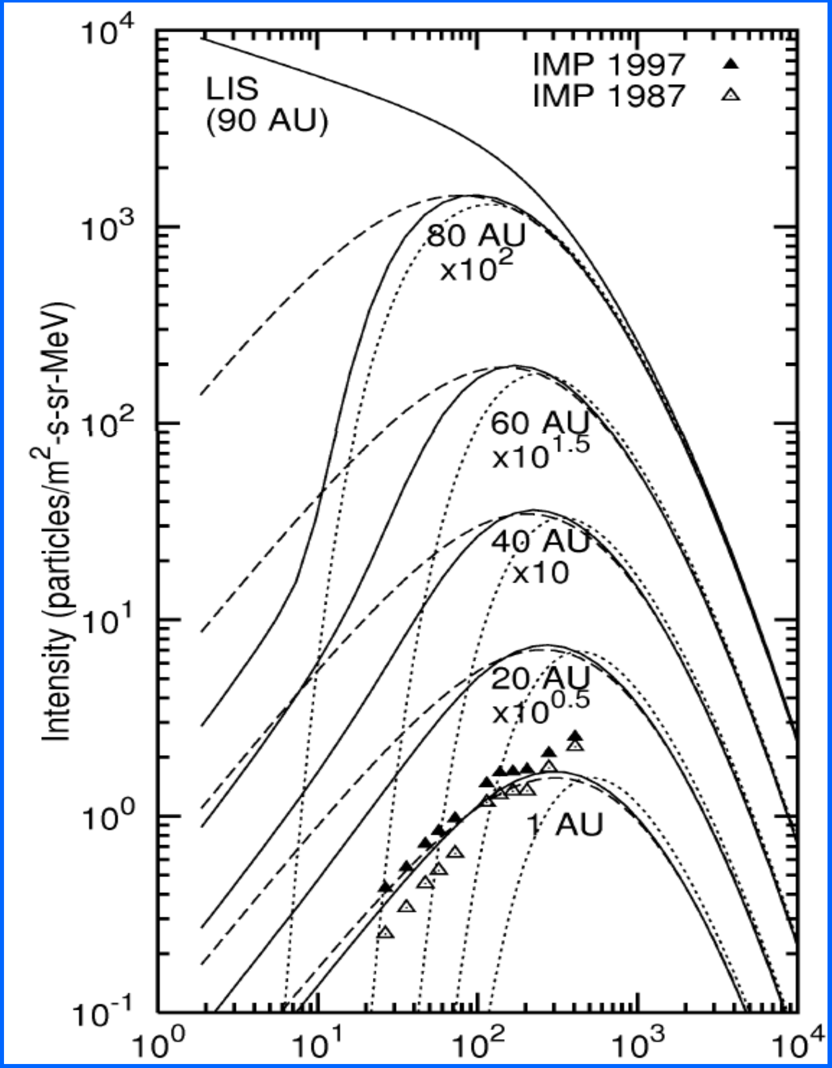
$$V\frac{\partial f}{\partial r}-\frac{1}{r^2}\left(r^2\kappa\frac{\partial f}{\partial r}\right)-\frac{1}{3r^2}\frac{\partial}{\partial r}\left(r^2V\right)\frac{\partial f}{\partial \ln p}=0$$

Input : V LIS, $r_{Boundary}$, $V(r)$ and $\kappa(r,P)$

Ouput : Adiabatic energy loss now taken care of...

Approximation : $\phi=\beta\kappa_2\int_{r_{Anywhere}}^{r_B}\frac{V}{\kappa}\,dr$

Comparison of 1 D modeling approaches



Kinetic energy (MeV)

Protons

Solid lines: 1D numerical

Dotted lines: Convection – Diffusion model

Dashed lines: FF model

Caballero et al. (2004)

TPE in heliocentric spherical coordinates

$$
\begin{aligned}
\frac{\partial f}{\partial t} &= \left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\kappa_{rr}\right) + \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}\left(\kappa_{\theta r}\sin\theta\right) + \frac{1}{r\sin\theta}\frac{\partial\kappa_{\phi r}}{\partial\phi} - V_{sw}\right]\frac{\partial f}{\partial r} \\
&+ \left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r\kappa_{r\theta}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\kappa_{\theta\theta}\sin\theta\right) + \frac{1}{r^2\sin\theta}\frac{\partial\kappa_{\phi\theta}}{\partial\phi}\right]\frac{\partial f}{\partial\theta} \\
&+ \left[\frac{1}{r^2\sin\theta}\frac{\partial}{\partial r}\left(r\kappa_{r\phi}\right) + \frac{1}{r^2\sin\theta}\frac{\partial\kappa_{\theta\phi}}{\partial\theta} + \frac{1}{r^2\sin^2\theta}\frac{\partial\kappa_{\phi\phi}}{\partial\phi}\right]\frac{\partial f}{\partial\phi} \\
&+ \kappa_{rr}\frac{\partial^2 f}{\partial r^2} + \frac{\kappa_{\theta\theta}}{r^2}\frac{\partial^2 f}{\partial\theta^2} + \frac{\kappa_{\phi\phi}}{r^2\sin^2\theta}\frac{\partial^2 f}{\partial\phi^2} + \frac{2\kappa_{r\phi}}{r\sin\theta}\frac{\partial^2 f}{\partial r\partial\phi} \\
&+ \frac{1}{3r^2}\frac{\partial}{\partial r}\left(r^2 V_{sw}\right)\frac{\partial f}{\partial\ln p} + Q,
\end{aligned}
$$

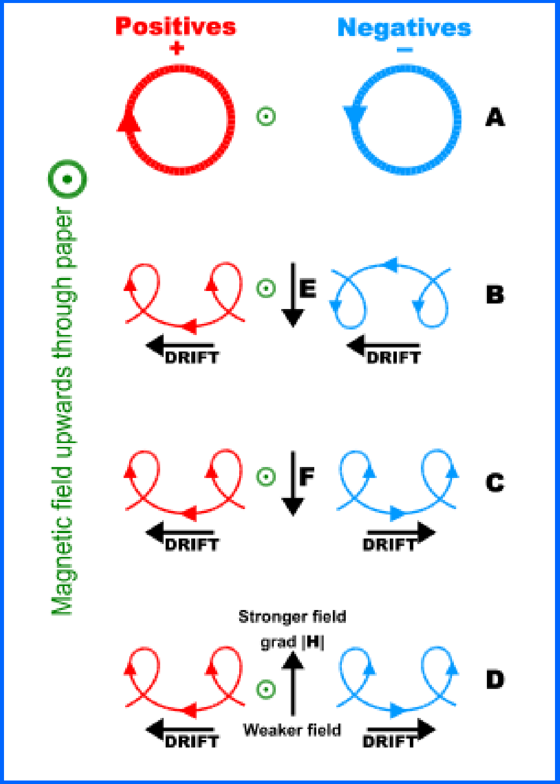
Diffusion tensor based on a simple HMF geometry

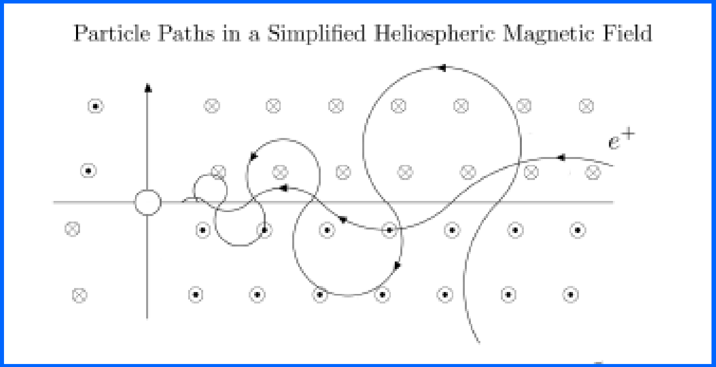
$$
\begin{bmatrix}
\kappa_{rr} & \kappa_{r\theta} & \kappa_{r\phi} \\
\kappa_{\theta r} & \kappa_{\theta\theta} & \kappa_{\theta\phi} \\
\kappa_{\phi r} & \kappa_{\phi\theta} & \kappa_{\phi\phi}
\end{bmatrix}
$$

$$
\begin{bmatrix}
\kappa_{||}\cos^2\psi + \kappa_{\perp r}\sin^2\psi & -\kappa_D\sin\psi & \left(\kappa_{\perp r} - \kappa_{||}\right)\cos\psi\sin\psi \\
\kappa_D\sin\psi & \kappa_{\perp\theta} & \kappa_D\cos\psi \\
\left(\kappa_{\perp r} - \kappa_{||}\right)\cos\psi\sin\psi & -\kappa_D\cos\psi & \kappa_{||}\sin^2\psi + \kappa_{\perp r}\cos^2\psi
\end{bmatrix}
$$

$$
\tan\psi = \frac{\Omega(r-b)\sin\theta}{V_{\mathrm{sw}}(r,\theta)}
$$

Gradient, curvature and current sheet drifts: Basic concepts





Gradient, curvature and current sheet drifts: Basic Drift Theory (and the trouble with it)

$$\langle \vec{v}_D \rangle = \frac{pv}{3Q} \frac{(\omega\tau_d)^2}{1+(\omega\tau_d)^2} \nabla \times \frac{\vec{B}}{B^2}$$

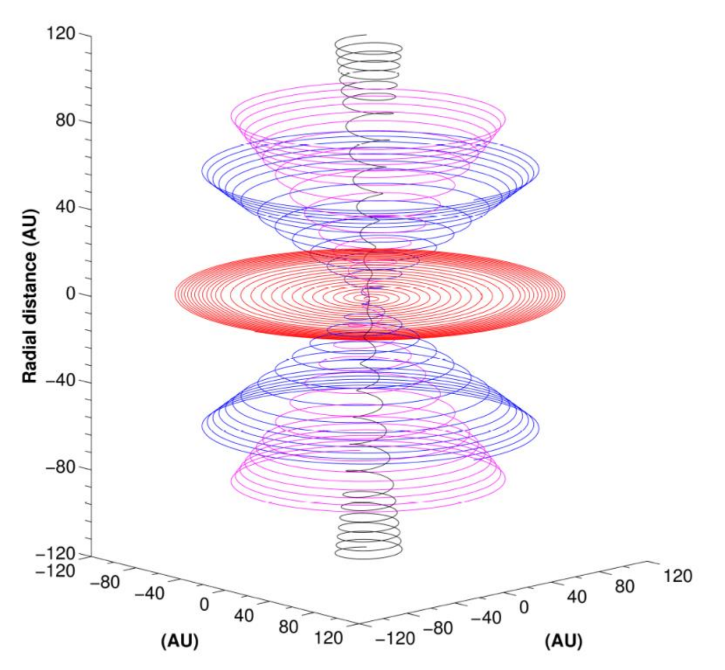
$$(\omega\tau_d)^{ws} \gg 1$$

$$\begin{aligned} \langle \vec{v}_D \rangle^{ws} &= \nabla \times \frac{v}{3} r_L \mathbf{e}_B \\ &= \nabla \times \kappa_D \mathbf{e}_B, \end{aligned}$$

$$K_D = \frac{\beta P}{3B_m} f_D = \frac{\beta P}{3B}\left[\frac{(\omega\tau)^2}{1+(\omega\tau)^2}\right],$$

$$\mathbf{K}_D \equiv \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & \kappa_D \\ 0 & -\kappa_D & 0 \end{bmatrix} \quad \mathbf{K}_s \equiv \begin{bmatrix} \kappa_{\|} & 0 & 0 \\ 0 & \kappa_{\perp\theta} & 0 \\ 0 & 0 & \kappa_{\perp r} \end{bmatrix}$$

$$\begin{bmatrix} \kappa_{rr} & \kappa_{r\theta} & \kappa_{r\phi} \\ \kappa_{\theta r} & \kappa_{\theta\theta} & \kappa_{\theta\phi} \\ \kappa_{\phi r} & \kappa_{\phi\theta} & \kappa_{\phi\phi} \end{bmatrix}$$



$$\langle v_A \rangle_r = -\frac{A}{r\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta K_{\theta r}\right),$$

$$\langle v_A \rangle_\theta = -\frac{A}{r}\left[\frac{1}{\sin\theta}\frac{\partial}{\partial\phi}\left(K_{\phi\theta}\right) + \frac{\partial}{\partial r}\left(rK_{r\theta}\right)\right],$$

$$\langle v_A \rangle_\phi = -\frac{A}{r}\frac{\partial}{\partial\theta}\left(K_{\theta\phi}\right),$$

A complex HMF geometry

$$B = B_0\left[\frac{r_0}{r}\right]^2\sqrt{1+\left[\frac{\Omega(r-r_\odot)\sin\theta}{V_{sw}}\right]^2+\left[\frac{r\delta(\theta)}{r_\odot}\right]^2},$$

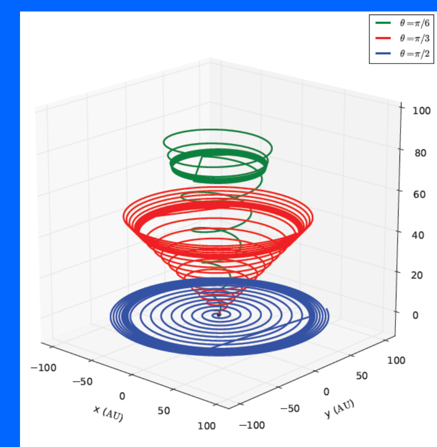
Modified Parker type HMF

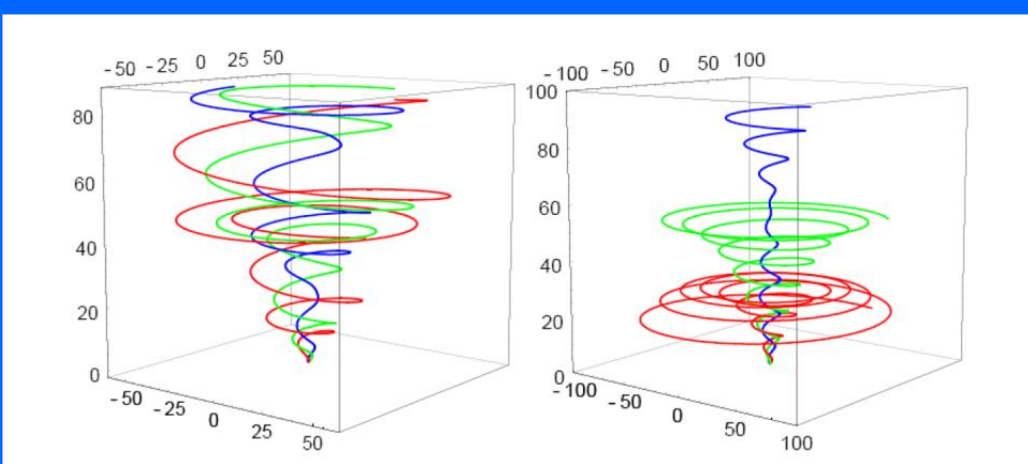
$$\tan\psi = \frac{\Omega(r-b)\sin\theta}{V_{\rm sw}(r,\theta)} - \frac{r}{b}\frac{V_{\rm sw}(b,\theta)}{V_{\rm sw}(r,\theta)}\left(\frac{B_{\rm T}(b)}{B_{\rm R}(b)}\right),$$

Smith & Bieber 1991

$$\begin{aligned}
B_r &= B_0\left[\frac{r_0}{r}\right]^2\\
B_\theta &= B_r\frac{(r-r_{ss})}{V_{sw}}\sin\beta\sin\left(\phi+\frac{\Omega(r-r_{ss})}{V_{sw}}\right)\\
B_\phi &= B_r\frac{(r-r_{ss})}{V_{sw}}\left[\omega\sin\beta\cos\theta\cos\left(\phi+\frac{\Omega(r-r_{ss})}{V_{sw}}\right)+\sin\theta(\omega\cos\beta-\Omega)\right]
\end{aligned}$$

Fisk (1996) type HMF

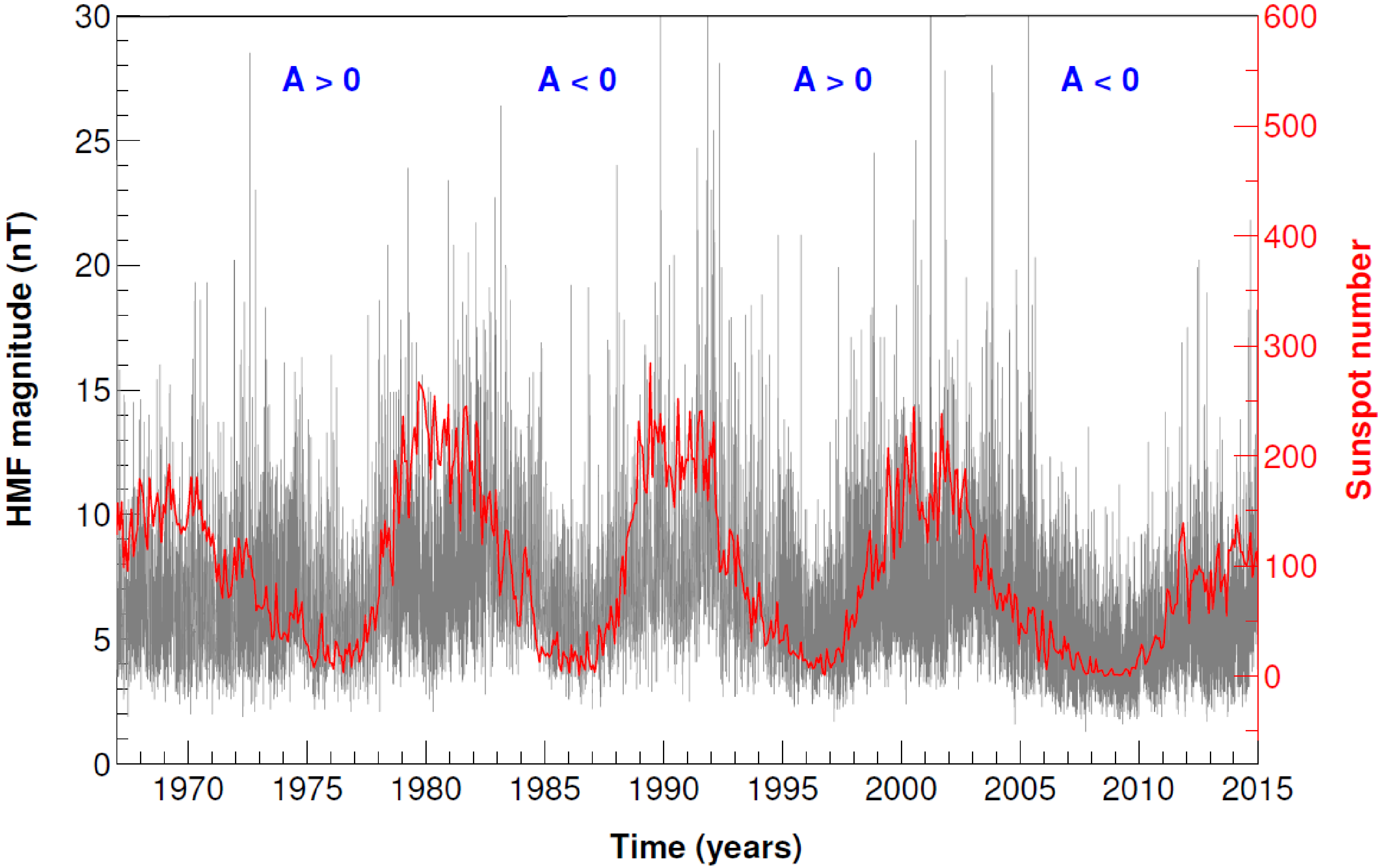




Possible Evidence for a Fisk-type Heliospheric Magnetic Field I: Analysing Ulysses/KET Electron Observations

O. Sternal, N.E. Engelbrecht[1], R.A. Burger[1], S.E.S. Ferreira[1], H. Fichtner[2], B. Heber, A. Kopp, M.S. Potgieter[1] and K. Scherer[2]

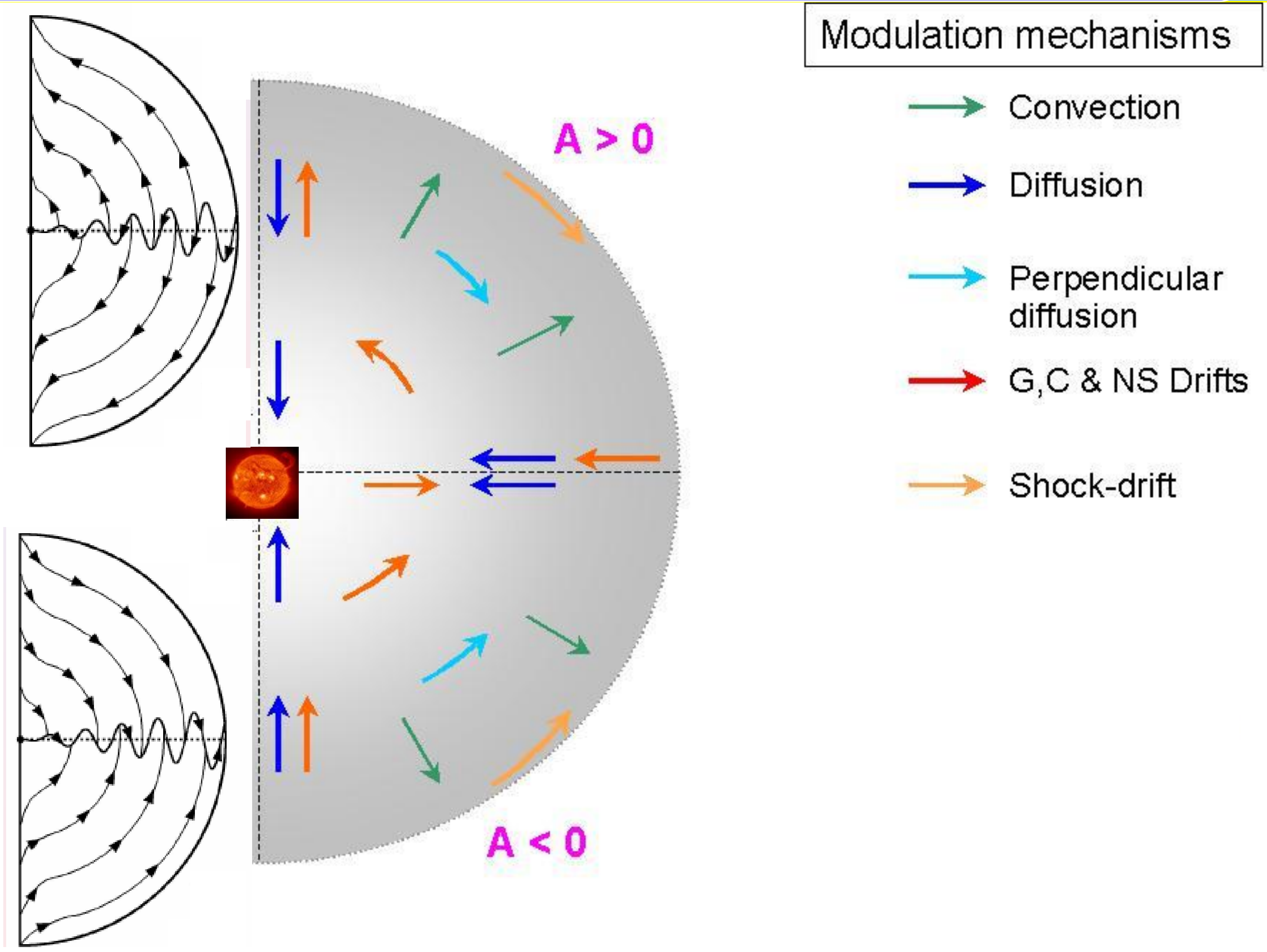
Observed HMF magnitude at the Earth



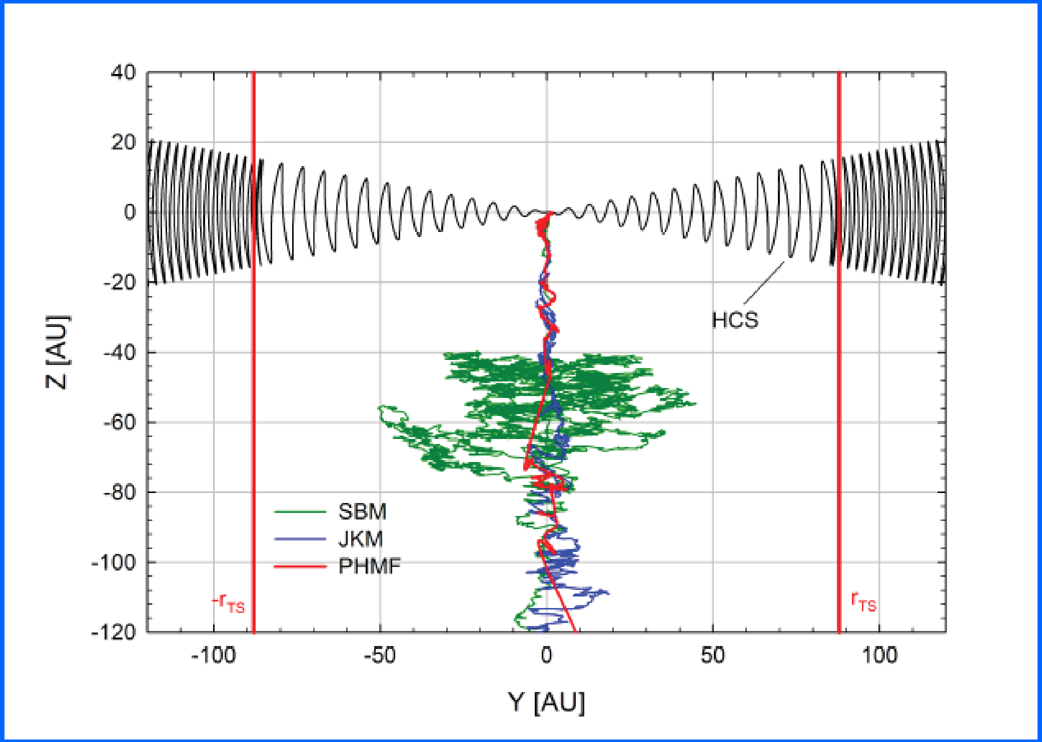
Charge-sign dependent modulation

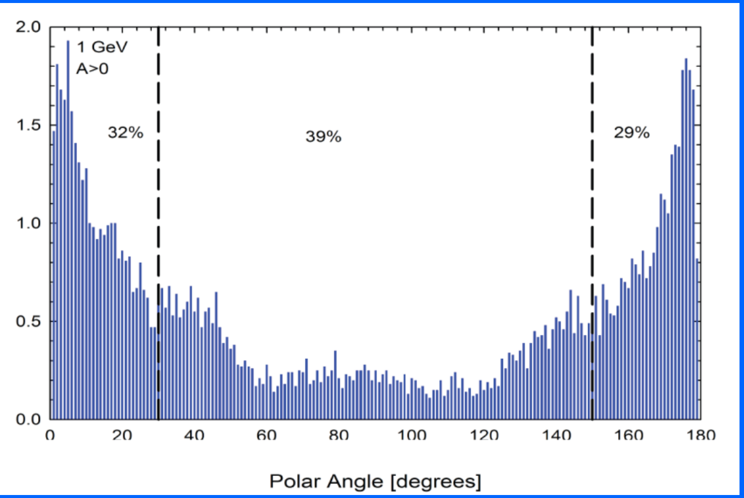
Drift direction of electrons in A > 0 cycle

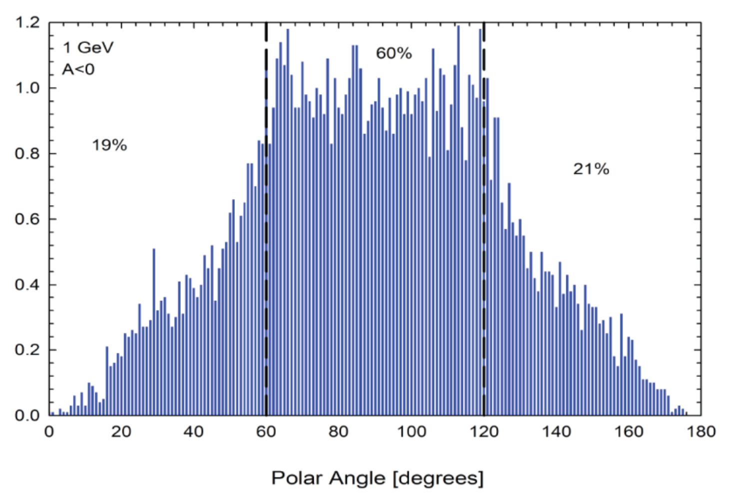
Drift direction of electrons in A < 0 cycle

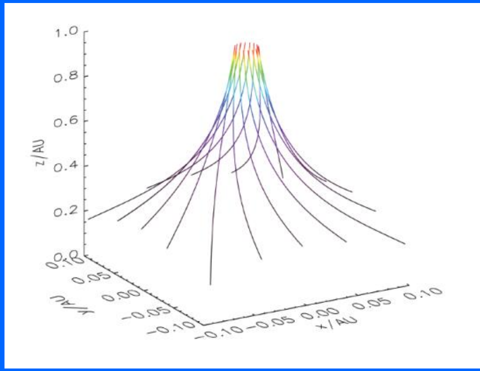


Particle drifts in the heliospheric polar regions; SDE approach





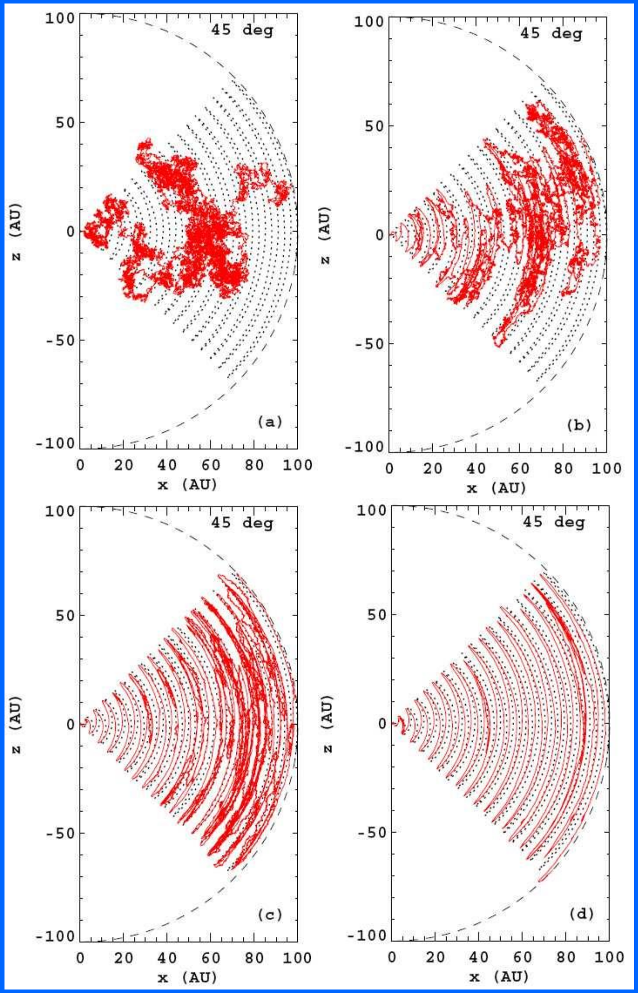




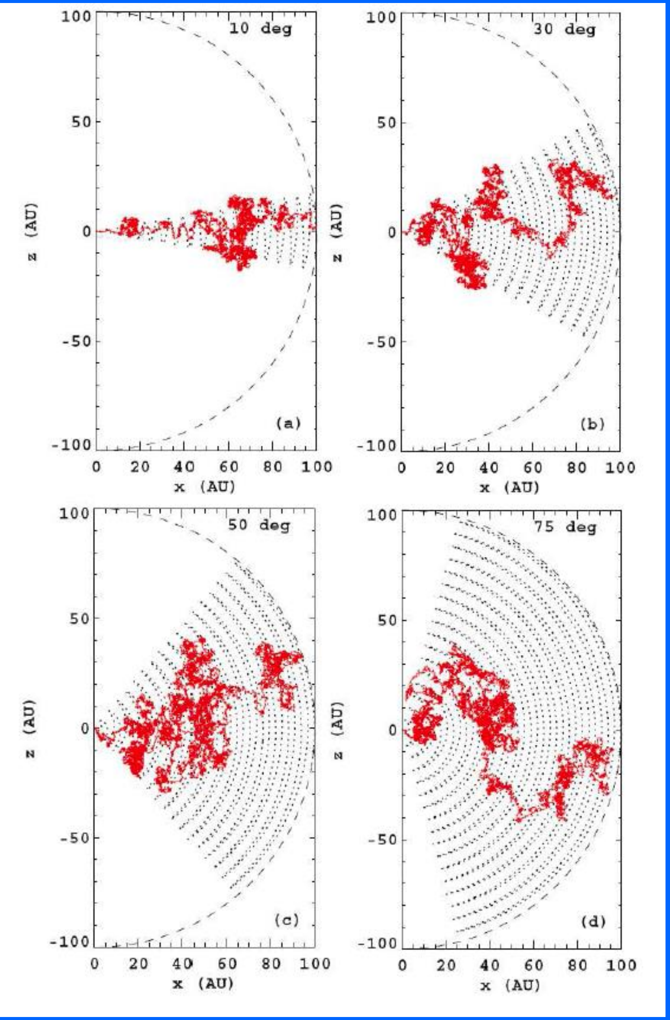
Jan-Louis Raath's MSc thesis, Nov. 2014

Proton trajectories in the heliosphere along the HCS
Impact of SDE models

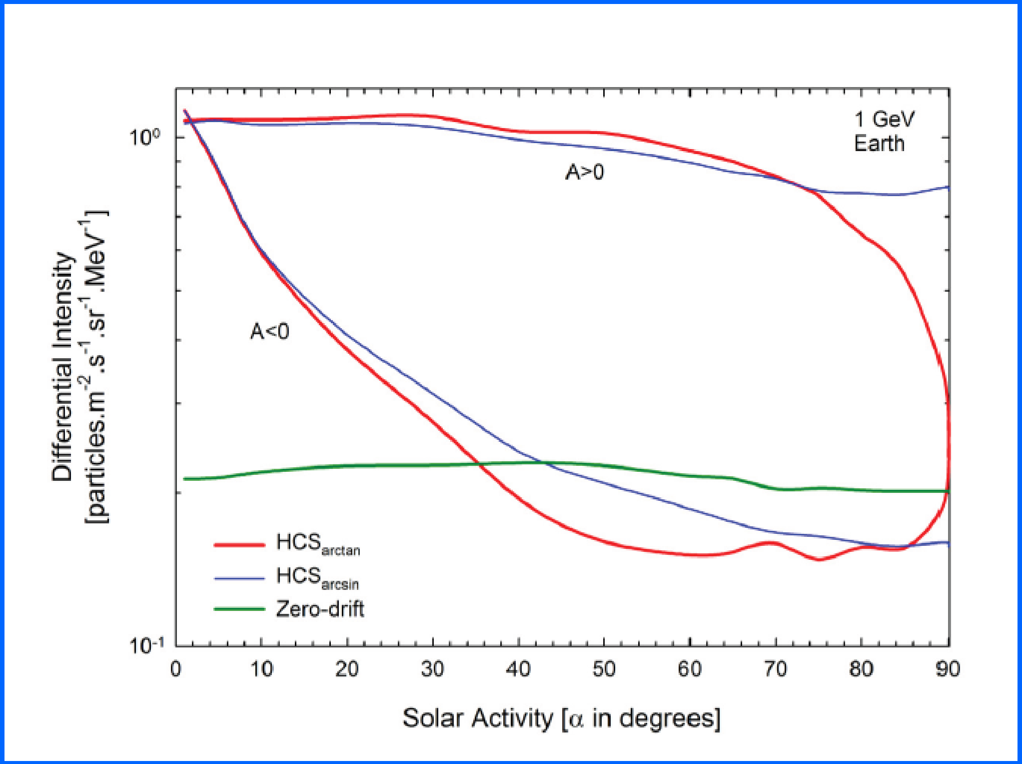
Decreasing diffusion causes increasing drift effects



Decreasing HCS tilt angle



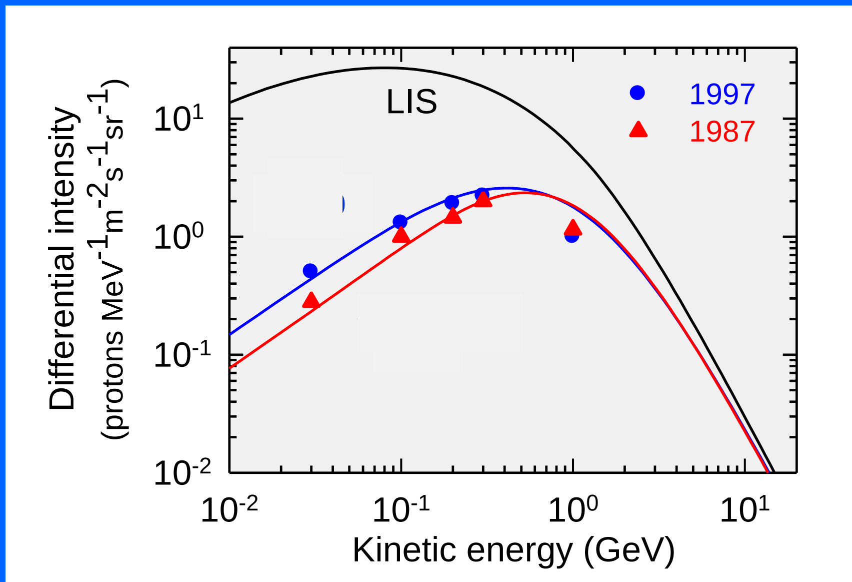
Effects of the wavy HCS on proton modulation

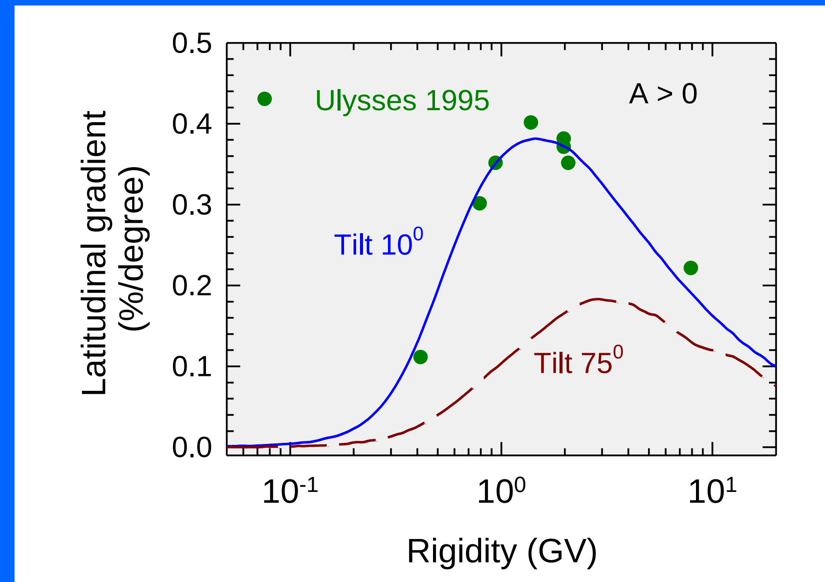


Raath, Potgieter, Strauss, ASS, 2015

Major features of observed modulated cosmic rays near Earth:

Required as validation for ALL numerical models



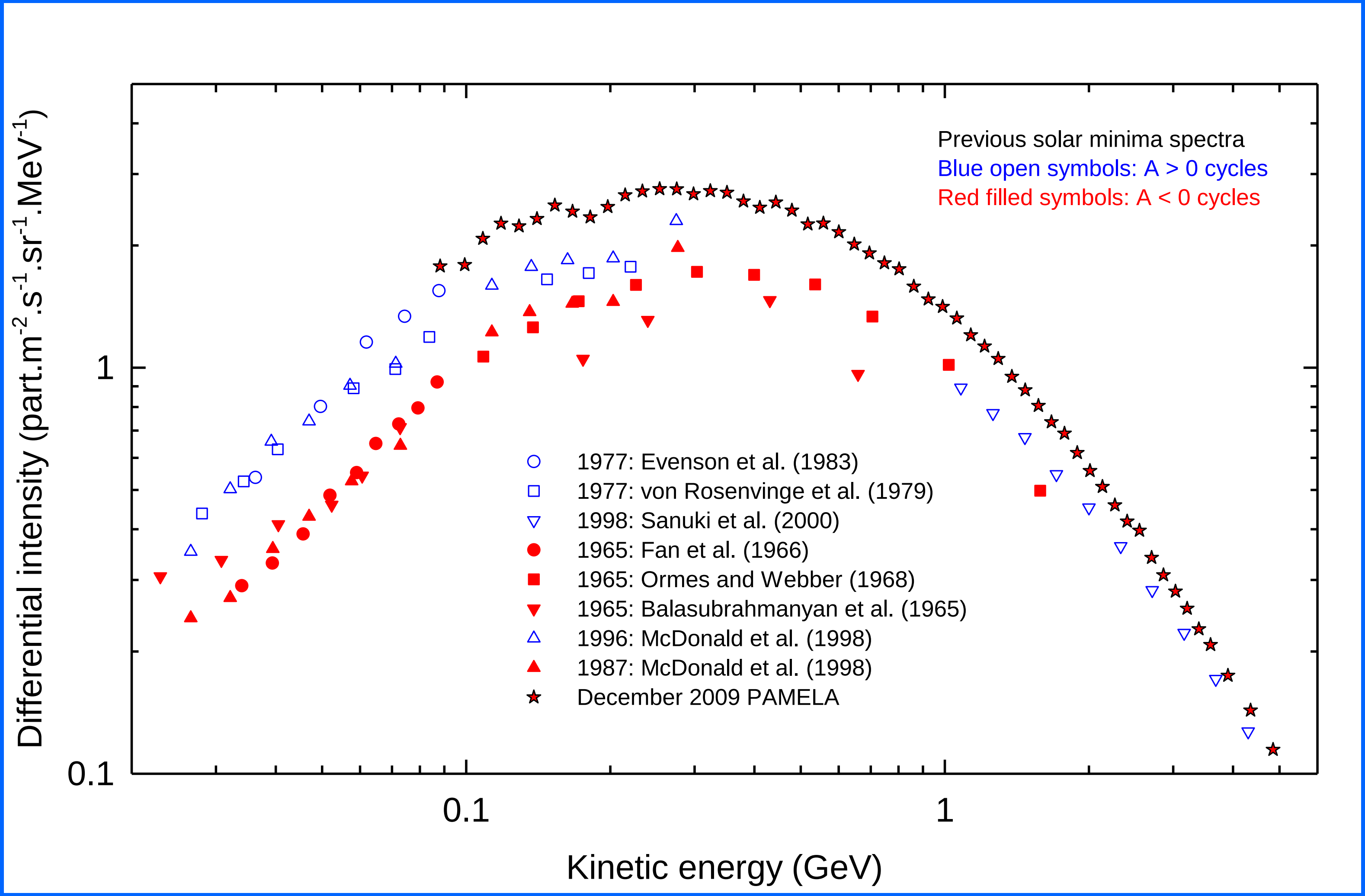


Observed and computed spectra crossings at Earth, for A > 0 and A < 0 solar minima polarity cycles…

Computed latitudinal gradients compared to Ulysses-KET observations, for A > 0, solar minimum to maximum…

Langner, Potgieter & Webber, JGR, 2003; ASR, 2004

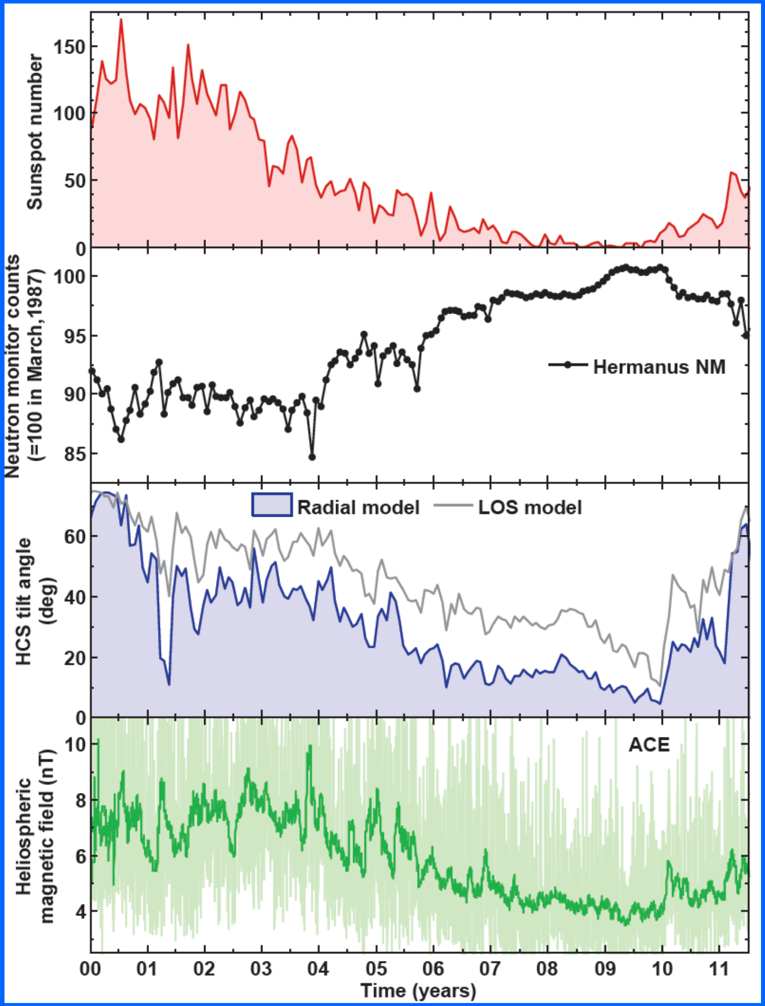
Highest every recorded cosmic ray protons in 2009

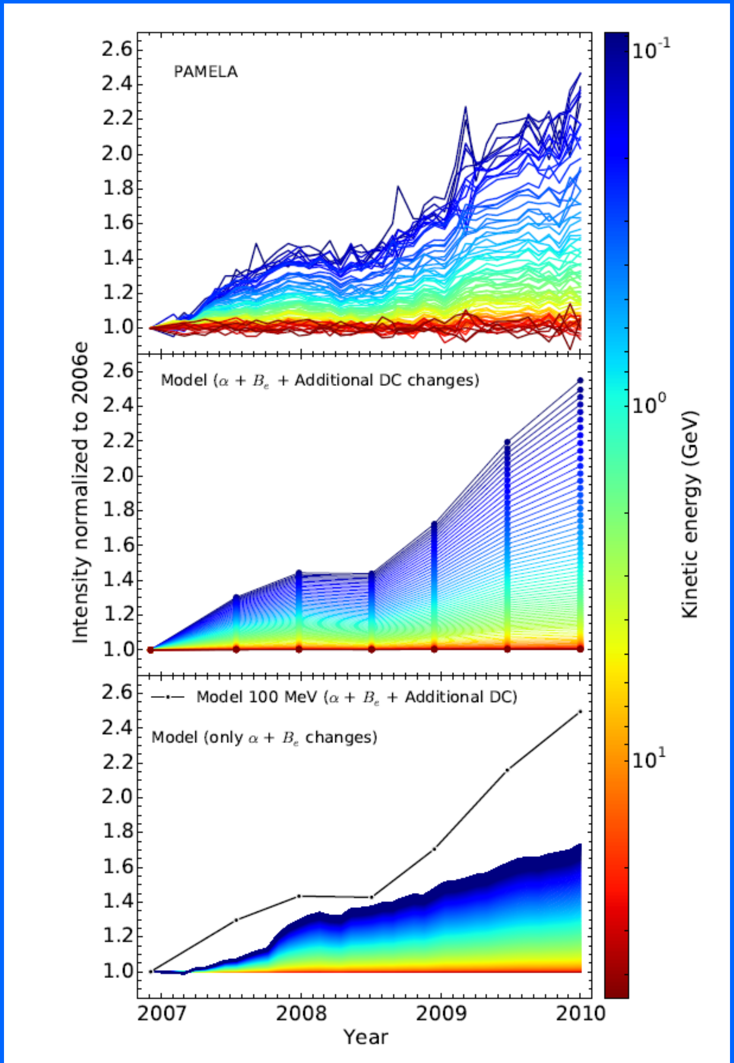


Red data points: A < 0 cycles **Blue data points: A > 0 cycles**

Strauss R.D., Potgieter M.S. Is the highest cosmic rays yet to come? Solar Physics, 289, 8, 3197-3205, 2014

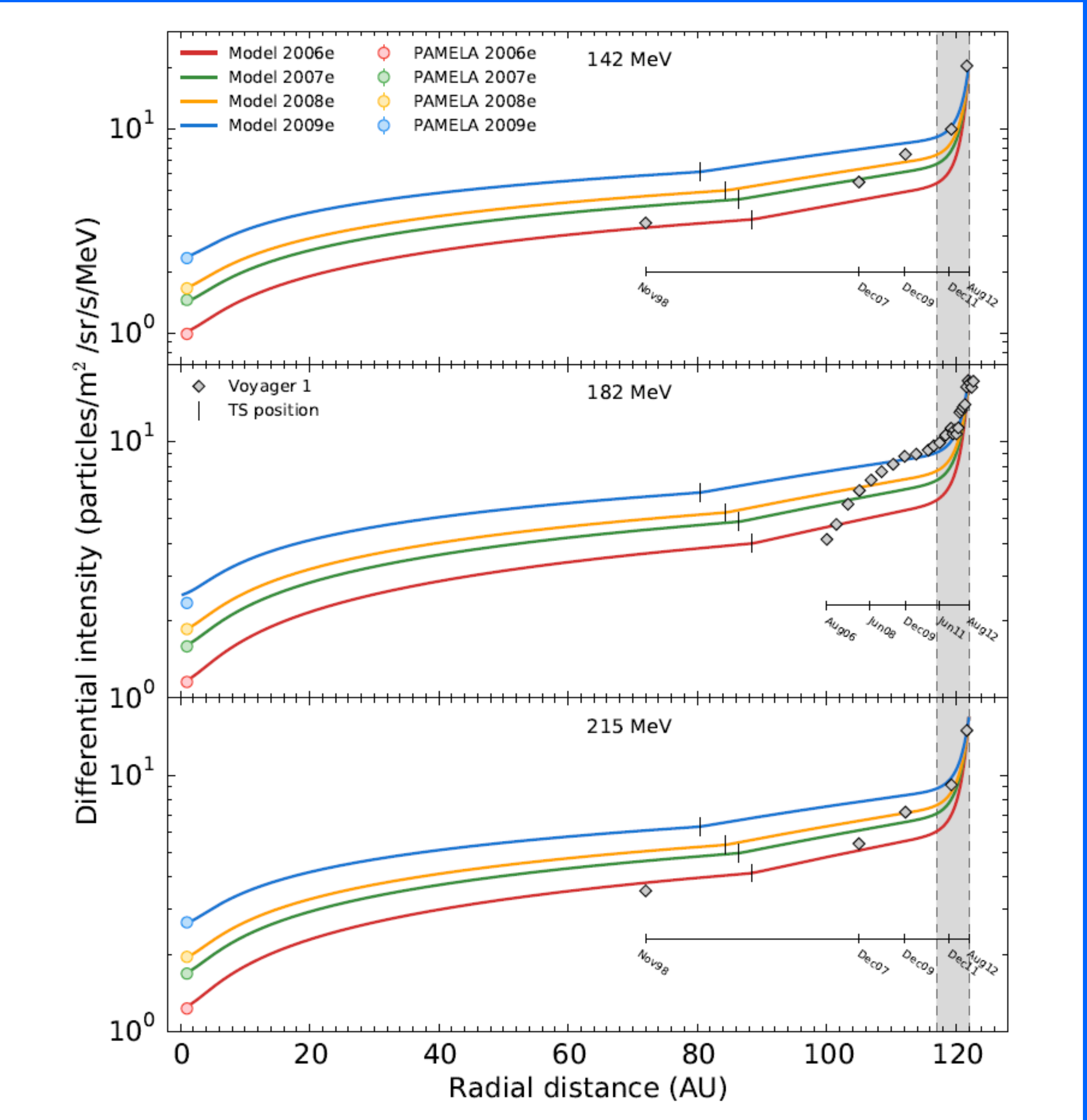
Proton modulation during the unusual 2009 minimum period



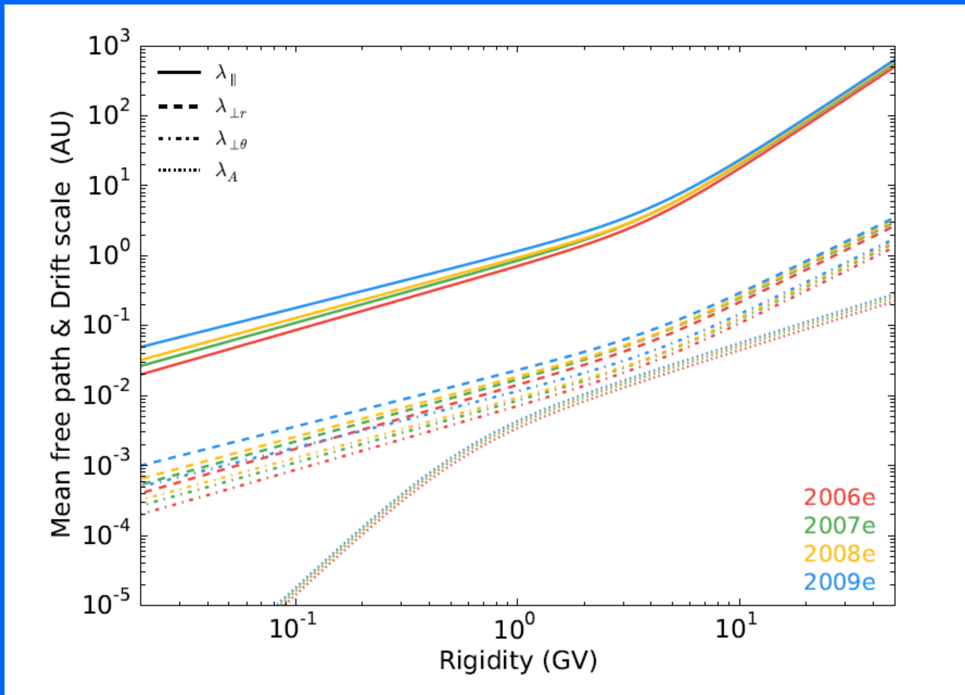


Potgieter, Vos, Boezio et al. 2014
Vos & Potgieter, 2015

Proton Radial and Latitudinal Modeling and Observations

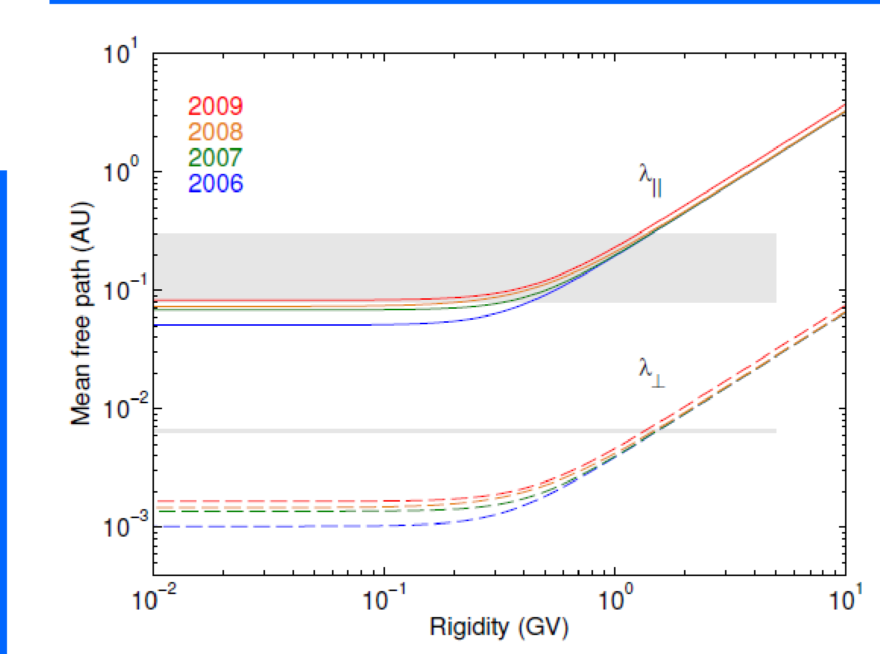


Consequences for Diffusion & Drift Theory



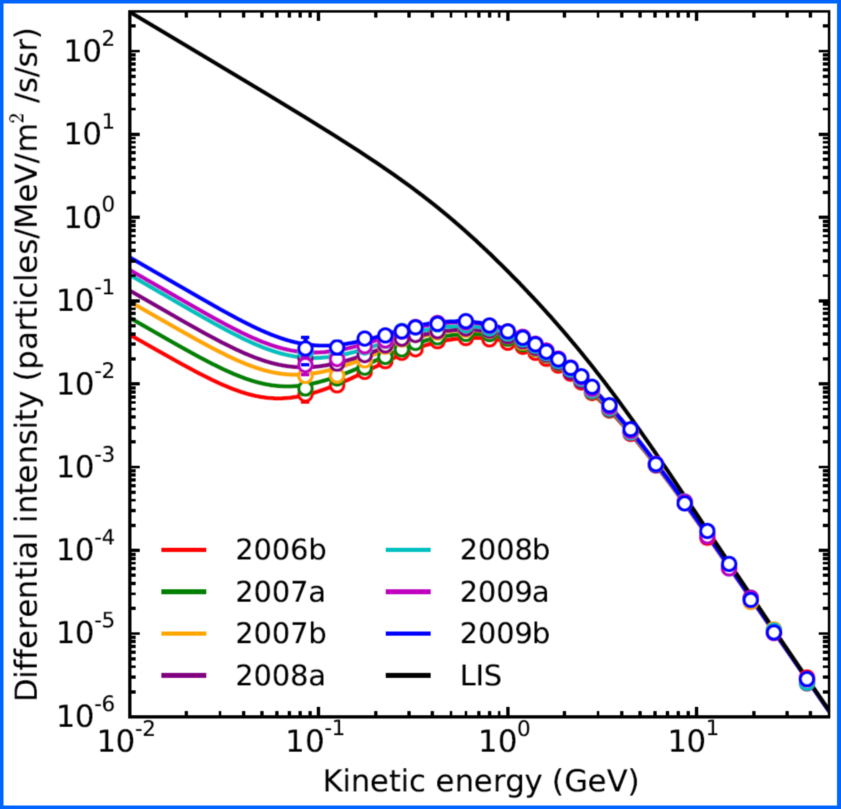
Protons

Electrons

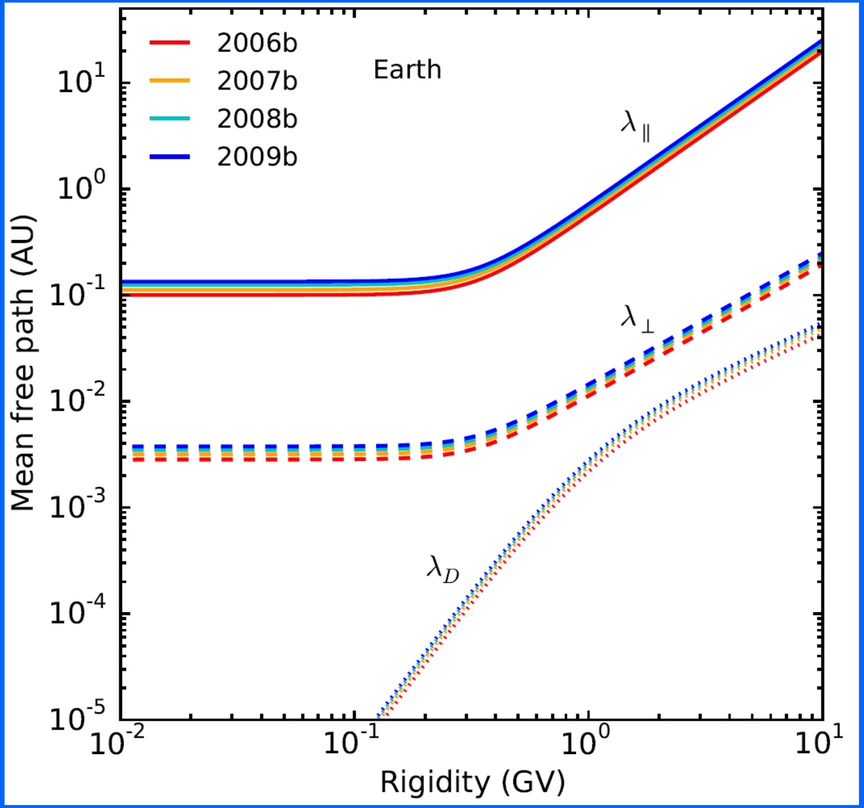


At Earth

PAMELA Electron Observations and Modeling



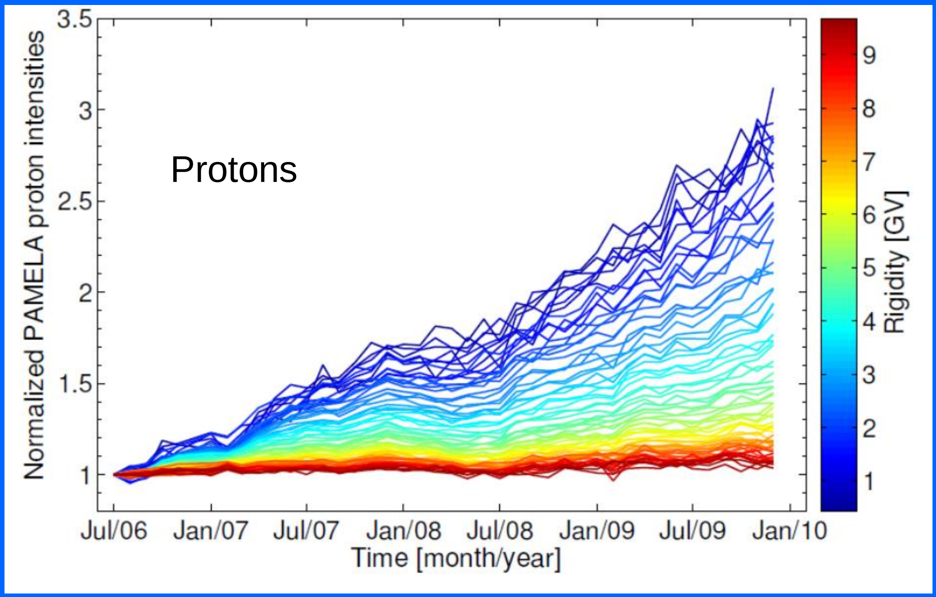
Consequences for electron diffusion theory

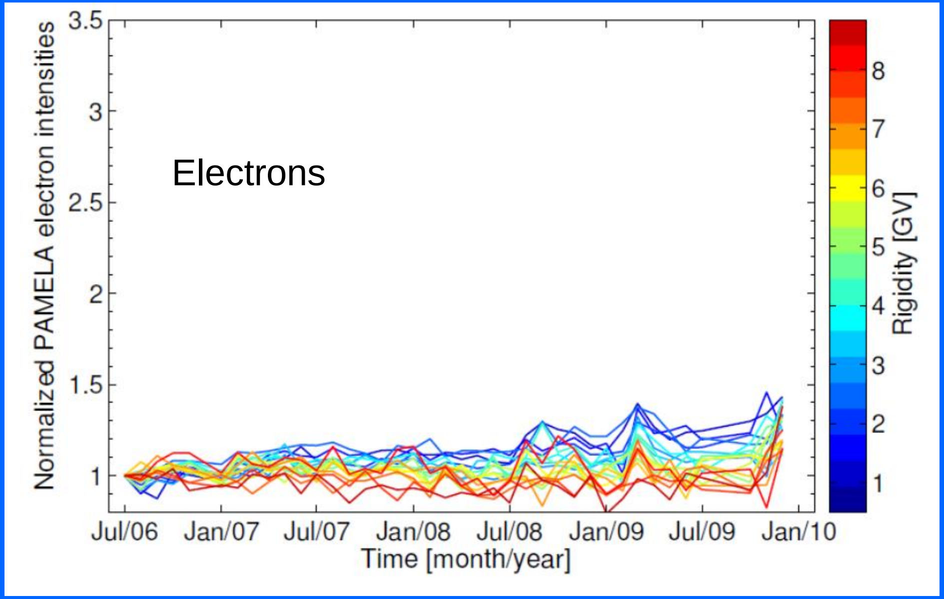


O. Adriani, et al. *Time dependence of the e⁻ flux measured by PAMELA during the July 2006- December 2009 solar minimum*, ApJ. 810, 142, 2015.

M.S. Potgieter, E.E. Vos, R. Munini, M. Boezio, V. Di Felice. *Modulation of galactic electrons in the heliosphere during the unusual solar minimum of 2006 to 2009: A modelling approach*. ApJ 810, 141 2015.

PAMELA Observations and Charge-sign Dependence

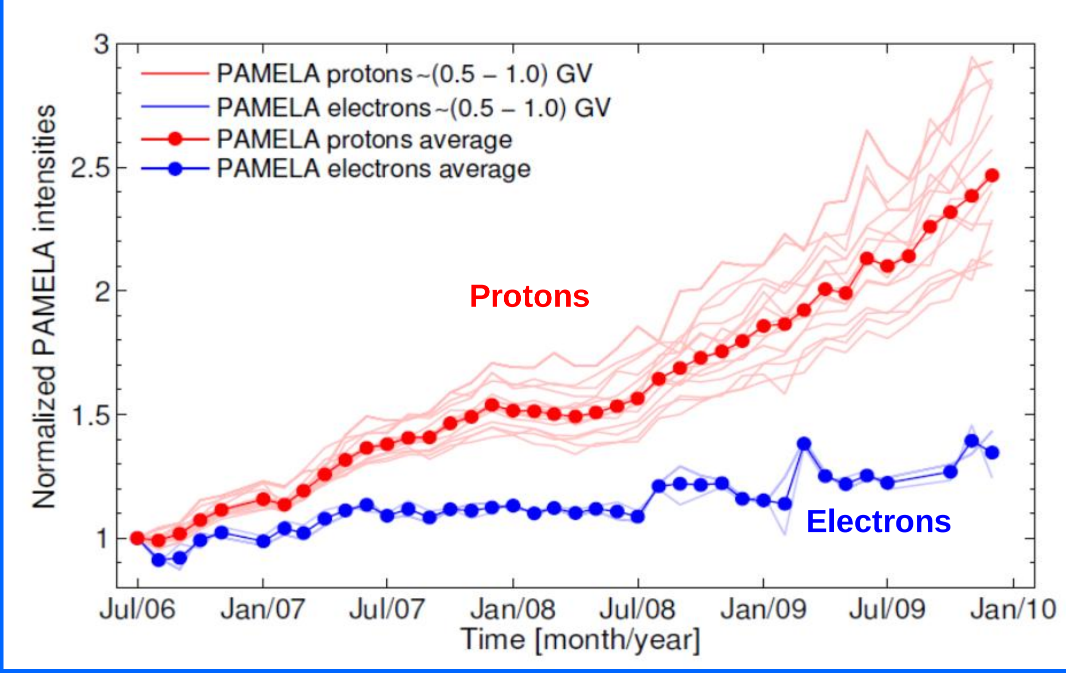




New evidence of charge-sign-dependent (drift) modulation for 2006-2009 from PAMELA…!

But, much smaller than anticipated from modelling of previous solar minimum activity periods….!

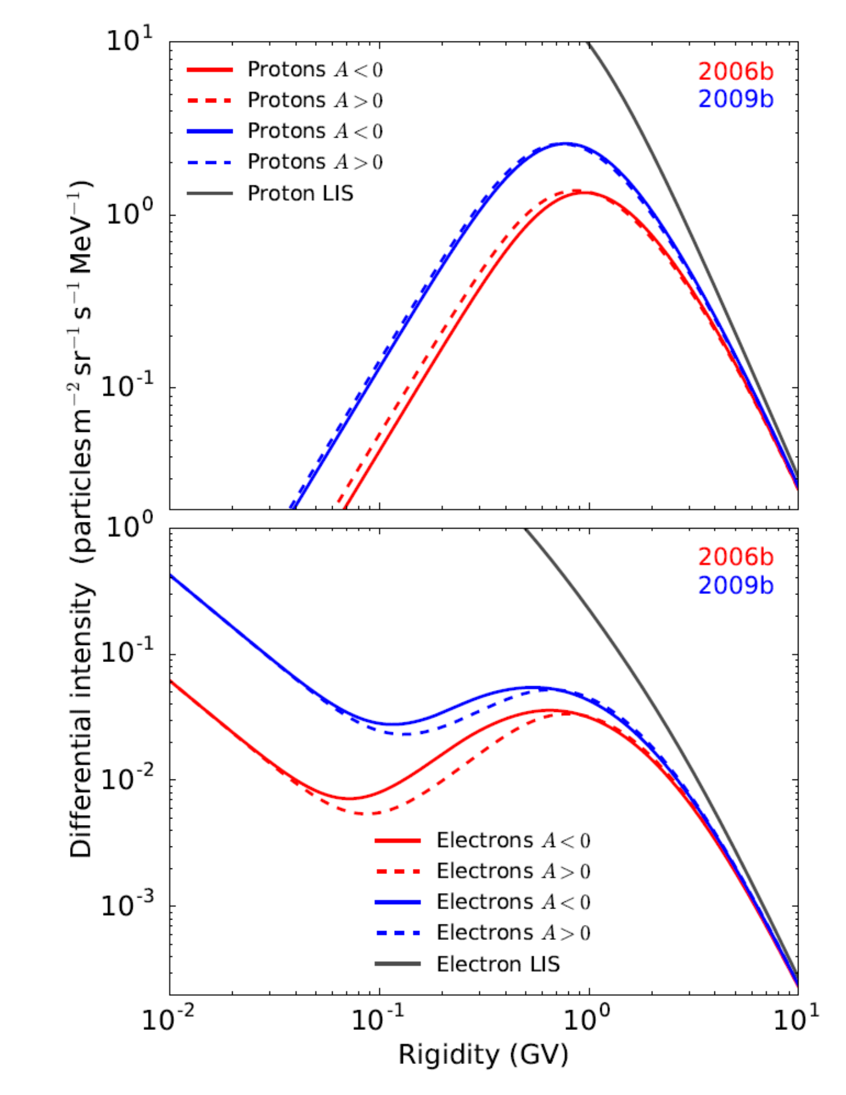
The 2009 minimum was different…

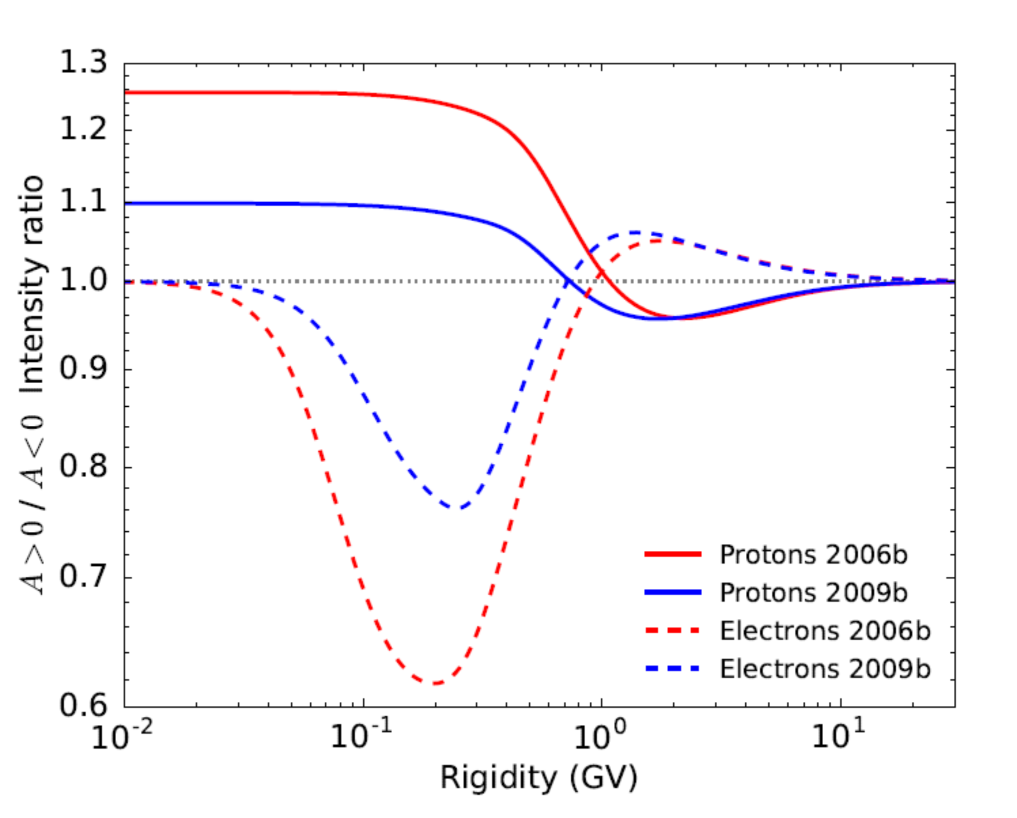


V. Di Felice, R. Munini, E.E. Vos, M.S. Potgieter. *New evidence for charge-sign dependent modulation during the solar minimum of 2006 to 2009*. ApJ. 834, 89, 2017.

Modeling of drift effects during a very quiet solar minimum

Prediction for next A > 0 solar minimum cycle

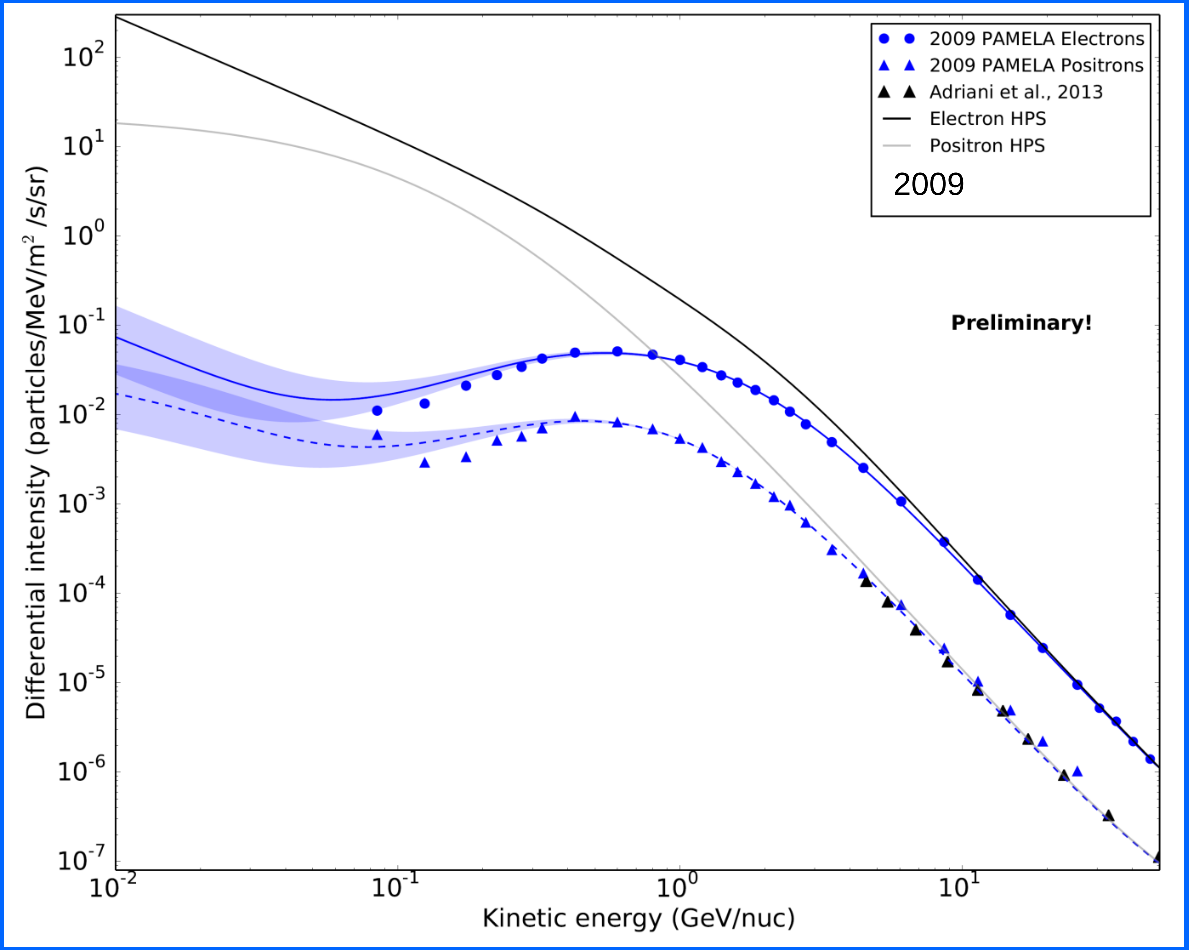




Potgieter & Vos, A&A, 2016

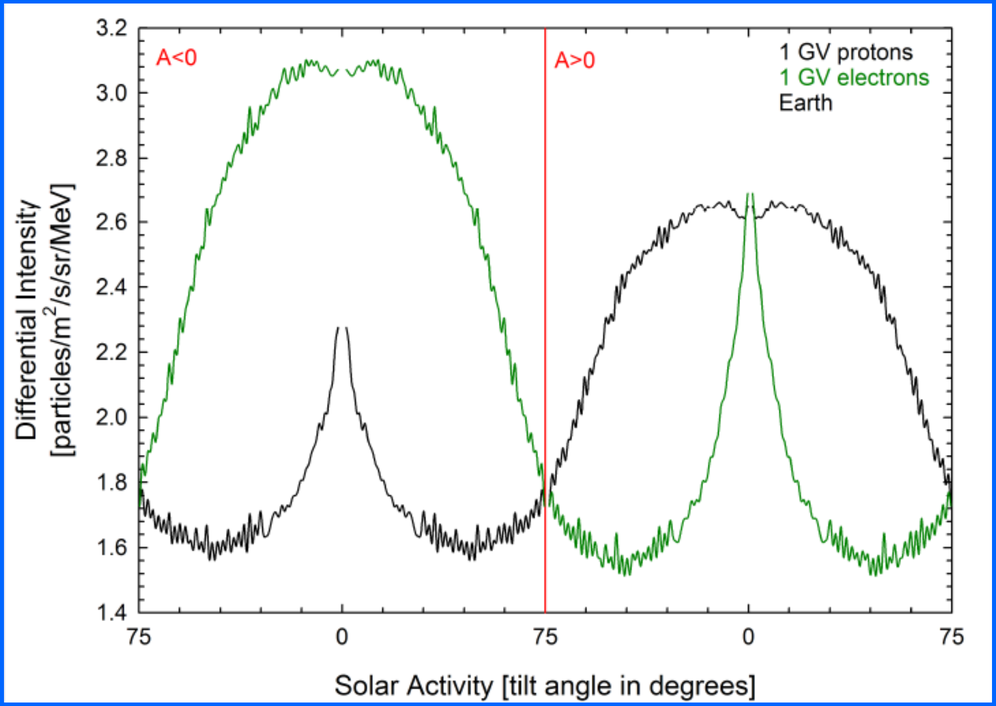
PAMELA Electrons and Positrons for 2009

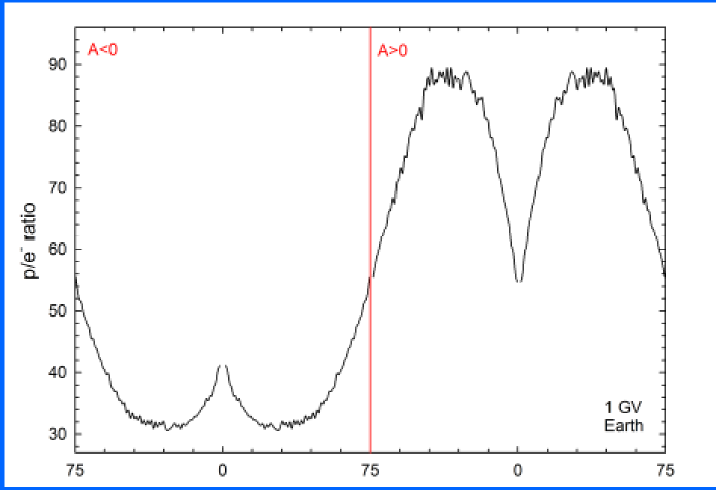
Numerical modeling with particle drifts

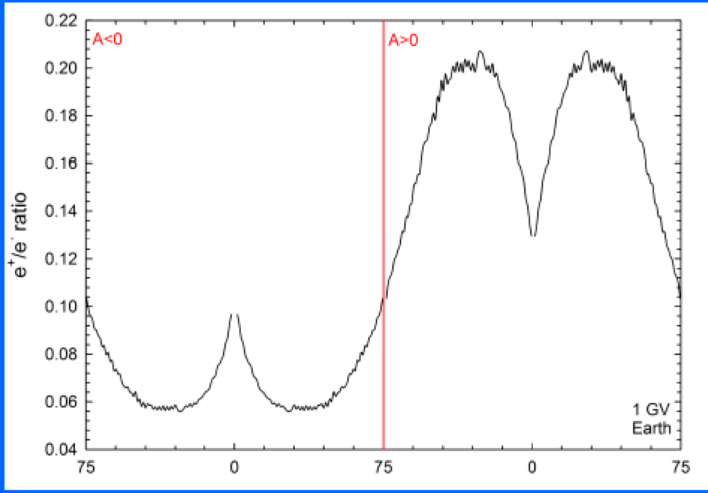


See PhDs of Riccardo Munini (2016) and Etienne Vos (2016)

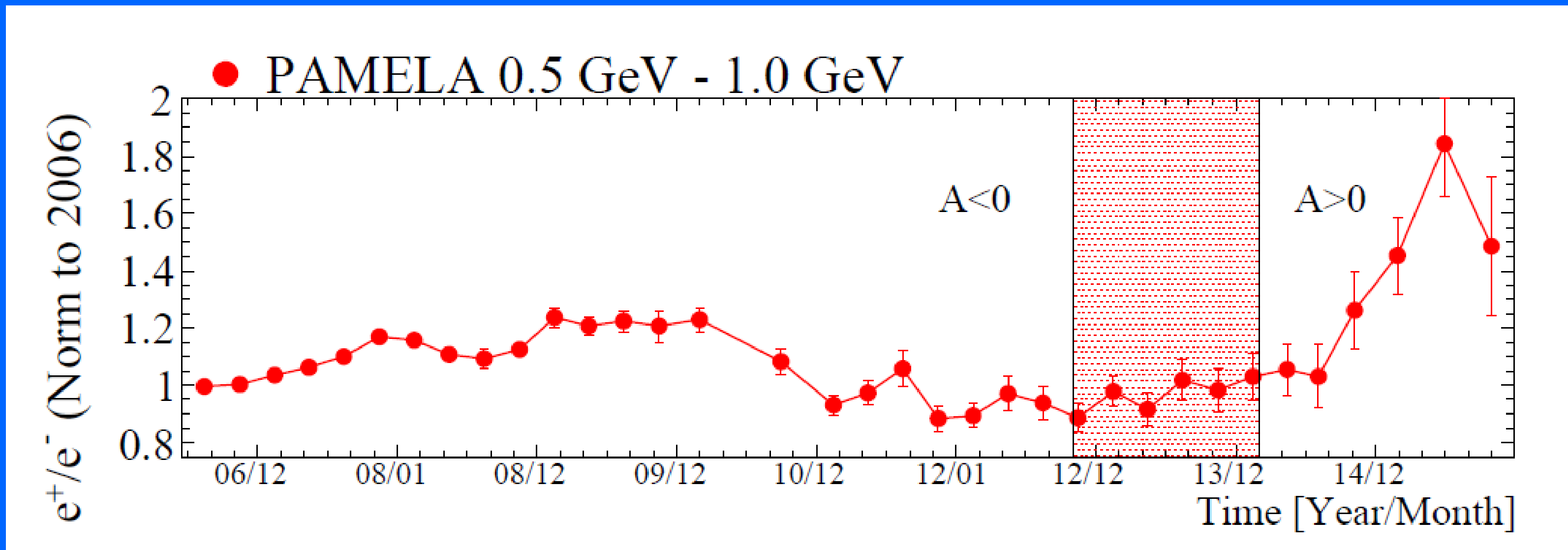
Drift & HCS effects in electron, proton and positron modulation







Observed electron to positron ratios over time

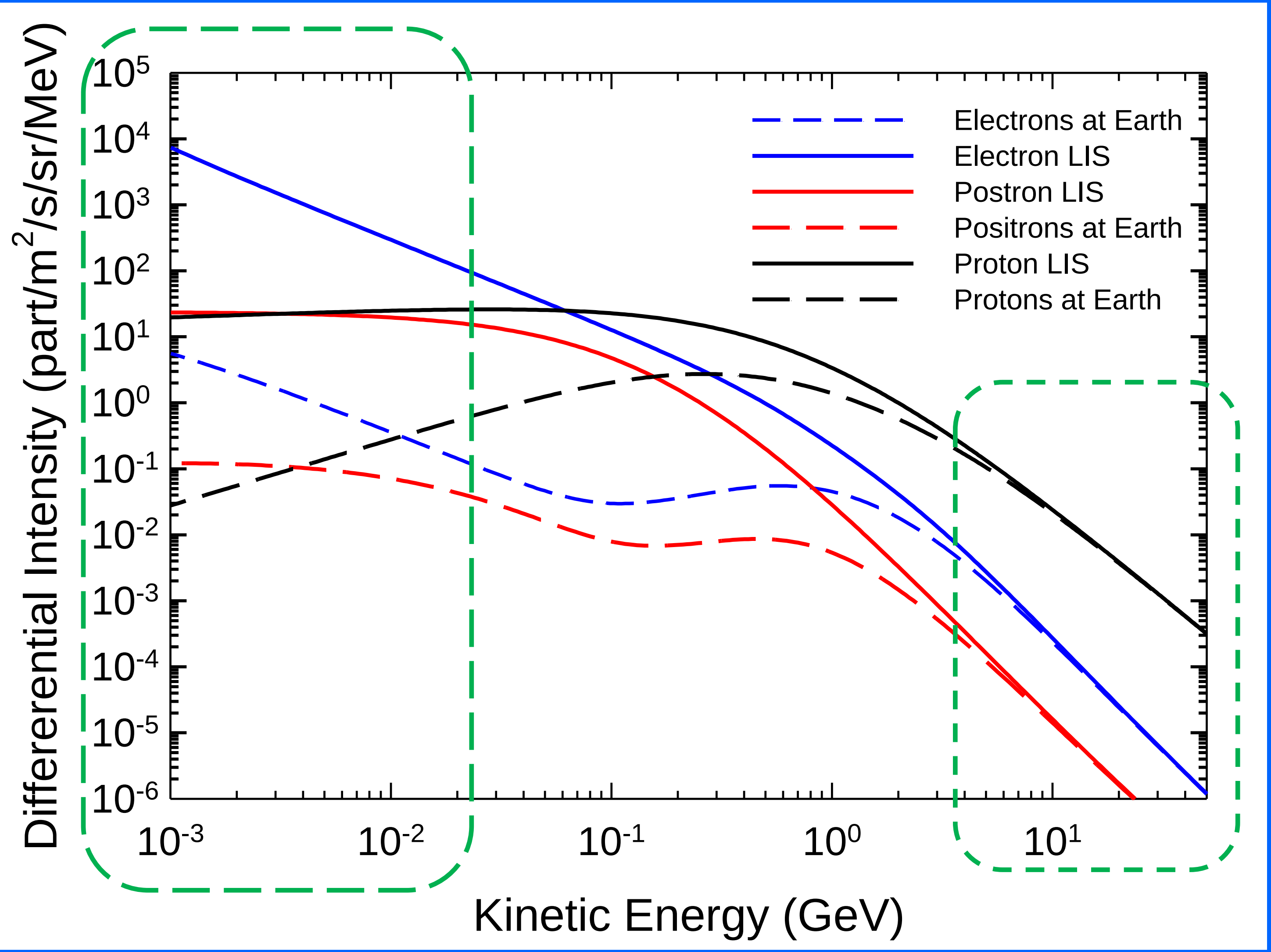


Time dependence of the electron and positron components of the cosmic radiation measured by the PAMELA experiment between July 2006 and December 2015.

O. Adriani,[1,2] G. C. Barbarino,[3,4] G. A. Bazilevskaya,[5] R. Bellotti,[6,7] M. Boezio,[8] E. A. Bogomolov,[9] M. Bongi,[1,2] V. Bonvicini,[8] S. Bottai,[2] A. Bruno,[6,7] F. Cafagna,[7] D. Campana,[4] P. Carlson,[10] M. Casolino,[11] G. Castellini,[12] C. De Santis,[11,13] V. Di Felice,[11,14] A. M. Galper,[15] A. V. Karelin,[15] S. V. Koldashov,[15] S. A. Koldobskiy,[15] S. Y. Krutkov,[9] A. N. Kvashnin,[5] A. Leonov,[15] V. Malakhov,[15] L. Marcelli,[13] M. Martucci,[13,16] A. G. Mayorov,[15] W. Menn,[17] M. Mergé,[11,13] V. V. Mikhailov,[15] E. Mocchiutti,[8] A. Monaco,[6,7] N. Mori,[2] R. Munini,[8,18,*] G. Osteria,[4] B. Panico,[4] P. Papini,[2] M. Pearce,[10] P. Picozza,[11,13] M. Ricci,[16] S. B. Ricciarini,[2] M. Simon,[17] R. Sparvoli,[11,13] P. Spillantini,[15] Y. I. Stozhkov,[5] A. Vacchi,[8,19] E. Vannuccini,[2] G. I. Vasilyev,[9] S. A. Voronov,[15] Y. T. Yurkin,[15] G. Zampa,[8] N. Zampa,[8] M. S. Potgieter,[20] and E. E. Vos[20]

Difference between computed spectra for protons, electrons and positrons

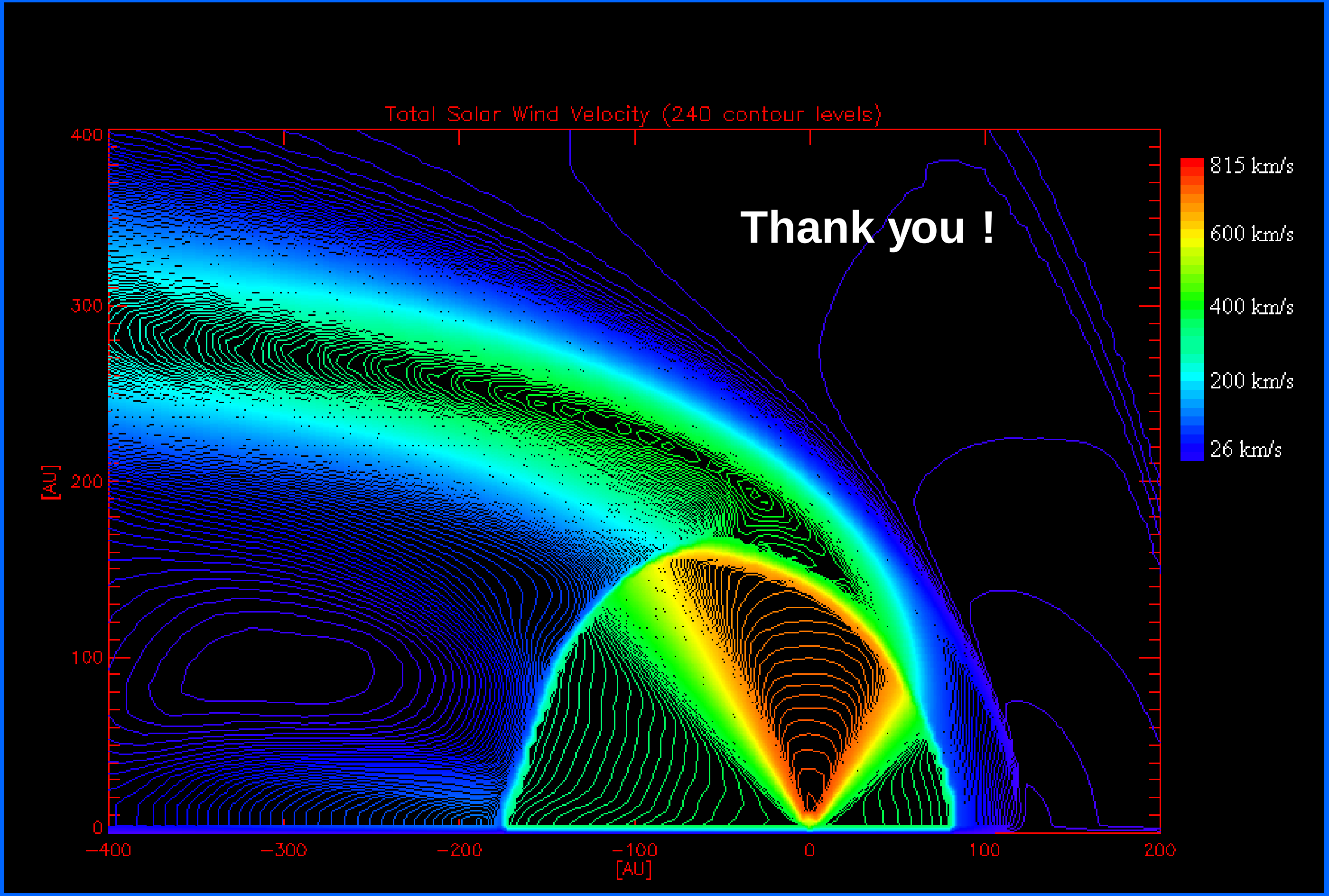
At the Earth for solar minimum



Concluding Remarks

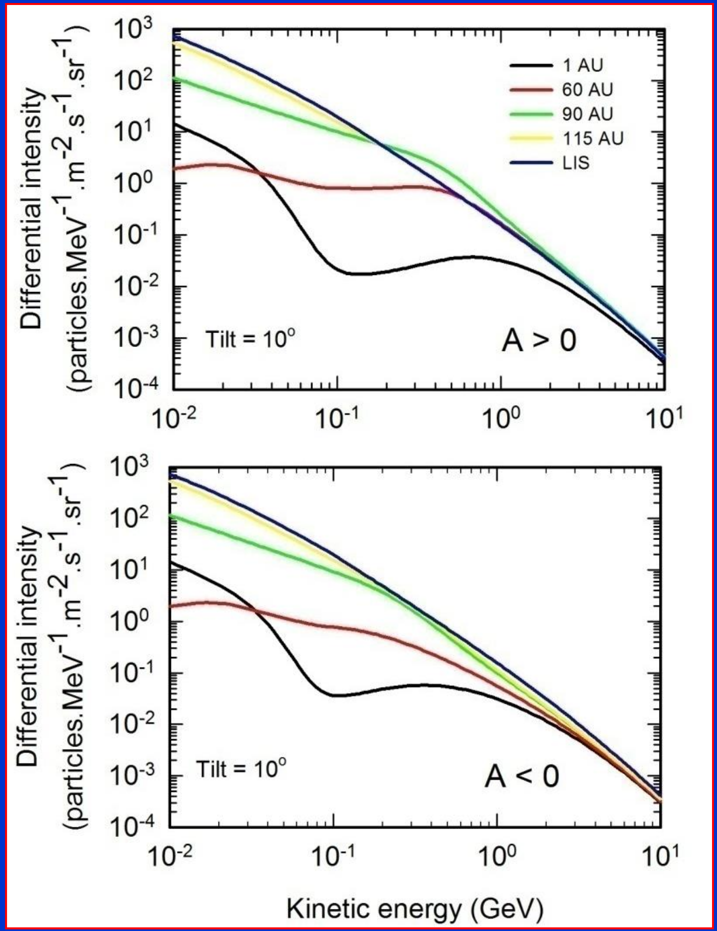
- Electron, proton, helium and carbon HPS (very LIS) are established…
- Finally, we can study and determine the total modulation of GCRs…
- Comprehensive modeling gives significantly useful insights…
- In particular concerning drift effects
- Combined with observations we have made good progress
- Towards a general diffusion and drift theory… but
- We need to address the complications introduced by the heliosheath.
- Need more good observational data…

Solar wind velocity profiles in the heliosphere

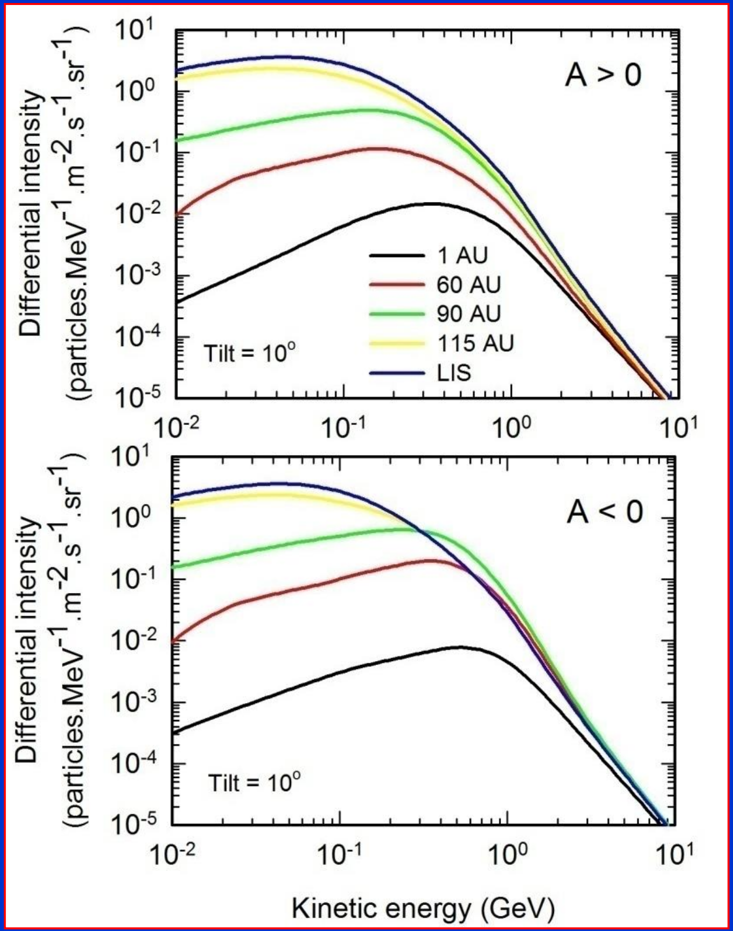


Computed modulation of galactic electrons and positrons at solar minimum for two polarity cycles

Electrons



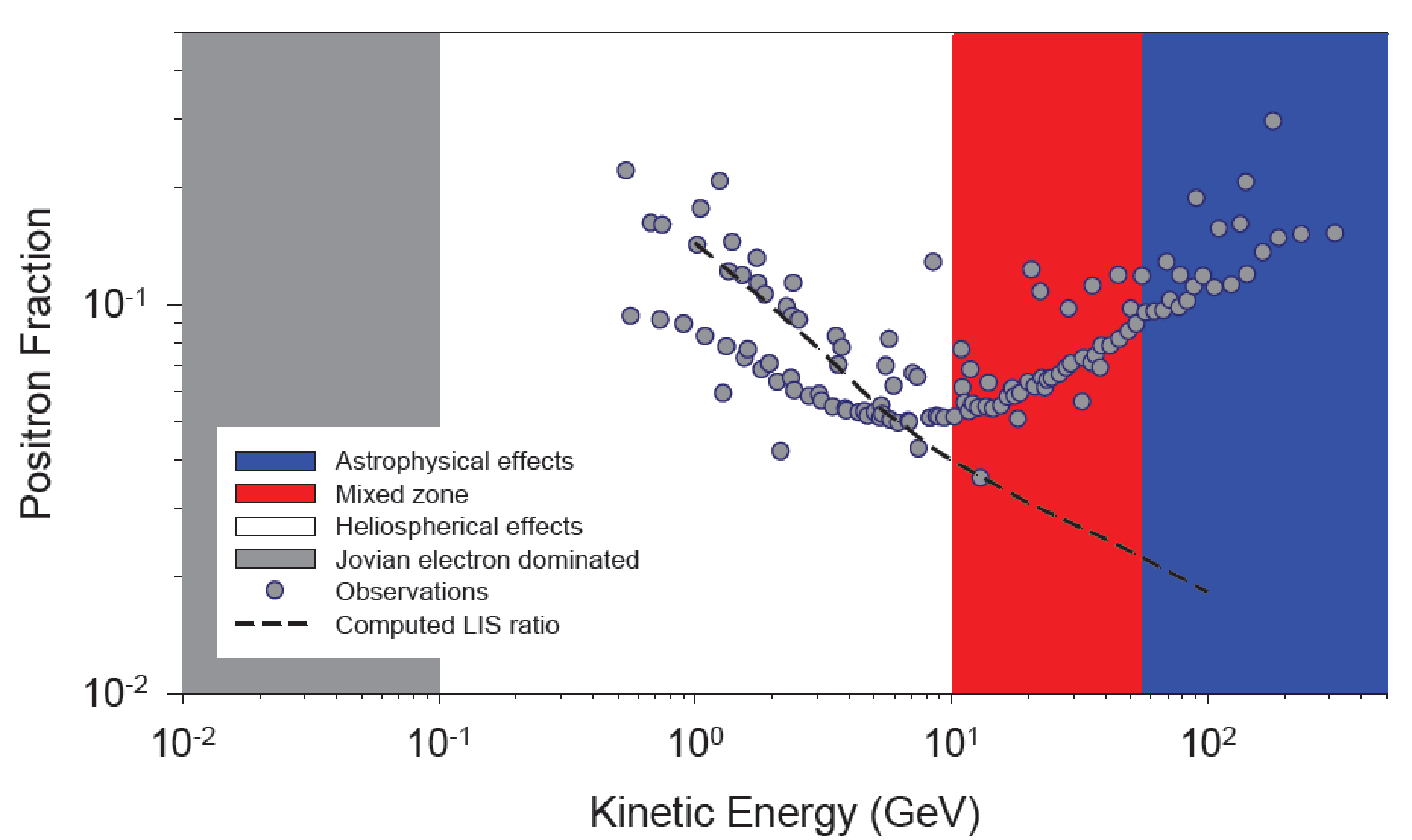
Positrons



Langner & Potgieter, Solar wind termination shock and heliosheath effects on charge-sign dependent modulation for protons and anti-protons, JGR, 109, 2004; Potgieter & Langner, Heliospheric modulation of cosmic ray positrons and electrons: Effects of the heliosheath and solar wind termination shock, ApJ, 602, 2004.

Positron fraction at the Earth

Effects of solar modulation with particle drifts



Strauss & Potgieter, Adv. Space Res., 2014