SAIP Annual Conference 2023

Investigating the Role of Turbulence in Solar Energetic Particle Transport

Jaclyn Stevens (NWU)
Supervised by Prof RD Strauss

NWU®

MEAN-FREE-PATH

λ

The average distance moved by a particle before its velocity is uncorrelated with its initial velocity.

Van den Berg (2019)

PARALLEL MEAN-FREE-PATH

$\lambda_{\parallel}$

The average distance a particle would move in a turbulent plasma,

being continuously subjected to small **pitch-angle** changes,

before the pitch-angle is changed significantly and the particle's

guiding centre reverses its **direction of motion** parallel to the background magnetic field.

Van den Berg (2019)

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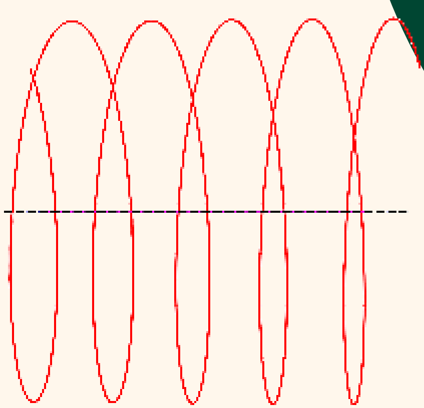

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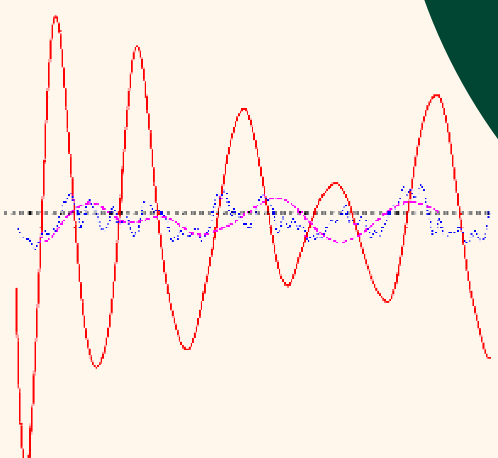


Van den Berg (2019)

CALCULATING PARALLEL MEAN-FREE-PATH?

Particle velocity

Pitch-angle

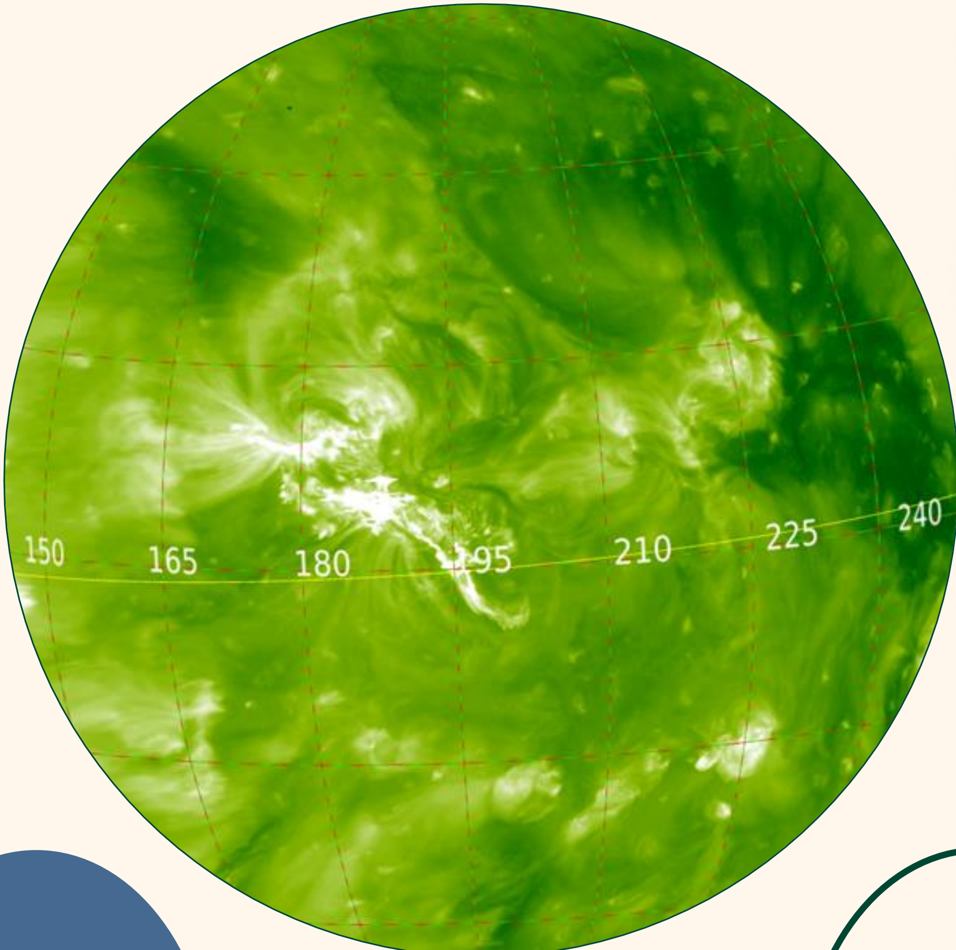
$$\lambda_{\parallel} = \frac{3}{8} v \int_{-1}^{+1} \frac{\left(1-\mu^{2}\right)^{2}}{D_{\mu\mu}} d\mu$$

Pitch-angle Diffusion Coefficient

FOCUSED TRANSPORT EQUATION

Strauss & Fichtner (2015)

$$\frac{\partial f}{\partial t} + \underbrace{\frac{\partial}{\partial z}(\mu v f)}_{\text{Convection}} + \underbrace{\frac{\partial}{\partial \mu}\left(\frac{1-\mu^2}{2L} v f\right)}_{\text{Focusing}} = \underbrace{\frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right)}_{\text{Collisions}}$$



A GLANCE AT SOME BEST FIT RESULTS

How to find and fit observations.

WHAT CRITERIA IS CONSIDERED WHEN FINDING OBSERVATIONS TO MODEL?

Model Restrictions

Finding flares and their details.
Checking instruments.

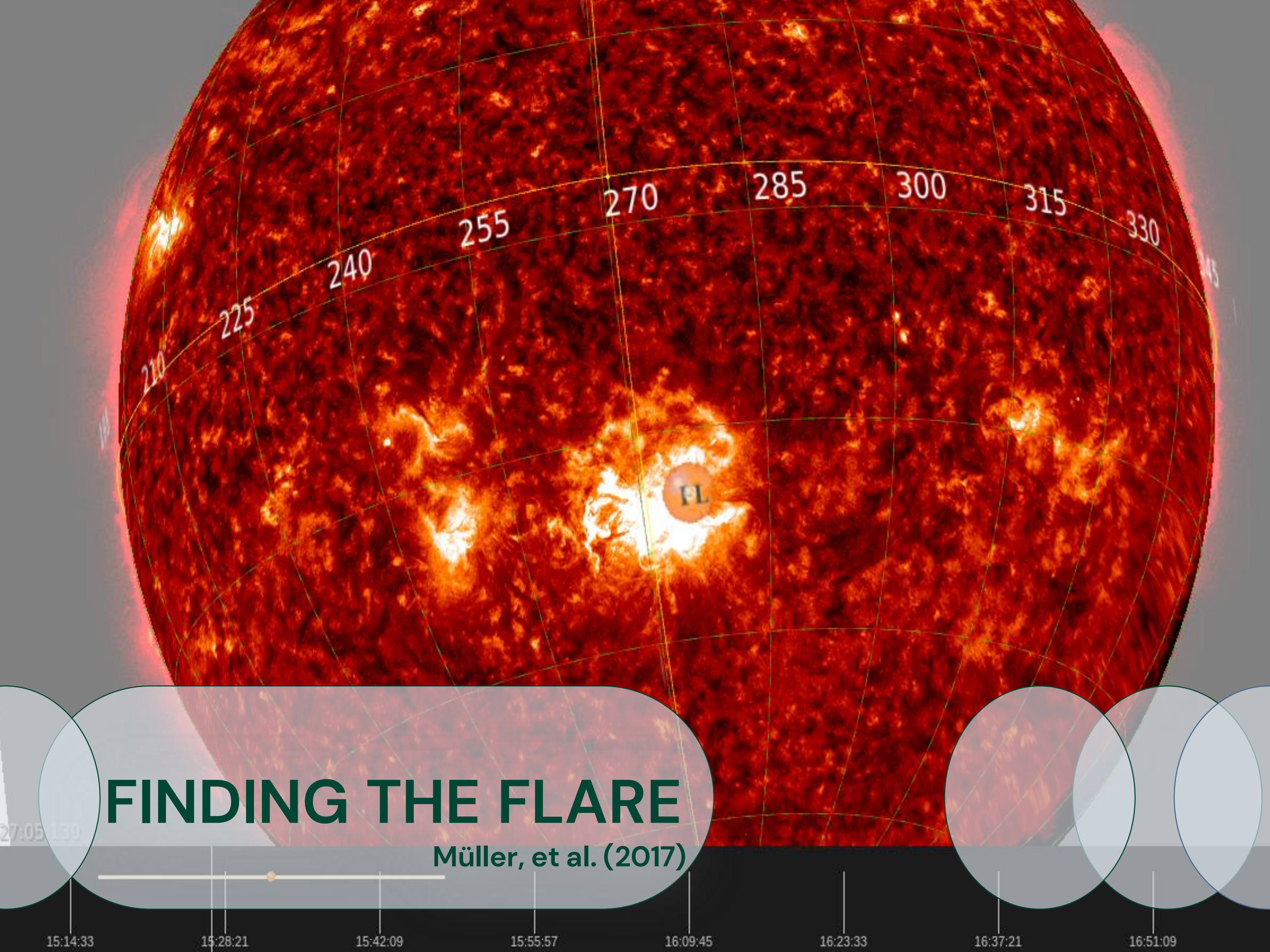
Data Restrictions

Making sure the data is usable.

GOOD MAGNETIC CONNECTION

FROM THE FLARE TO THE RECEIVING INSTRUMENT

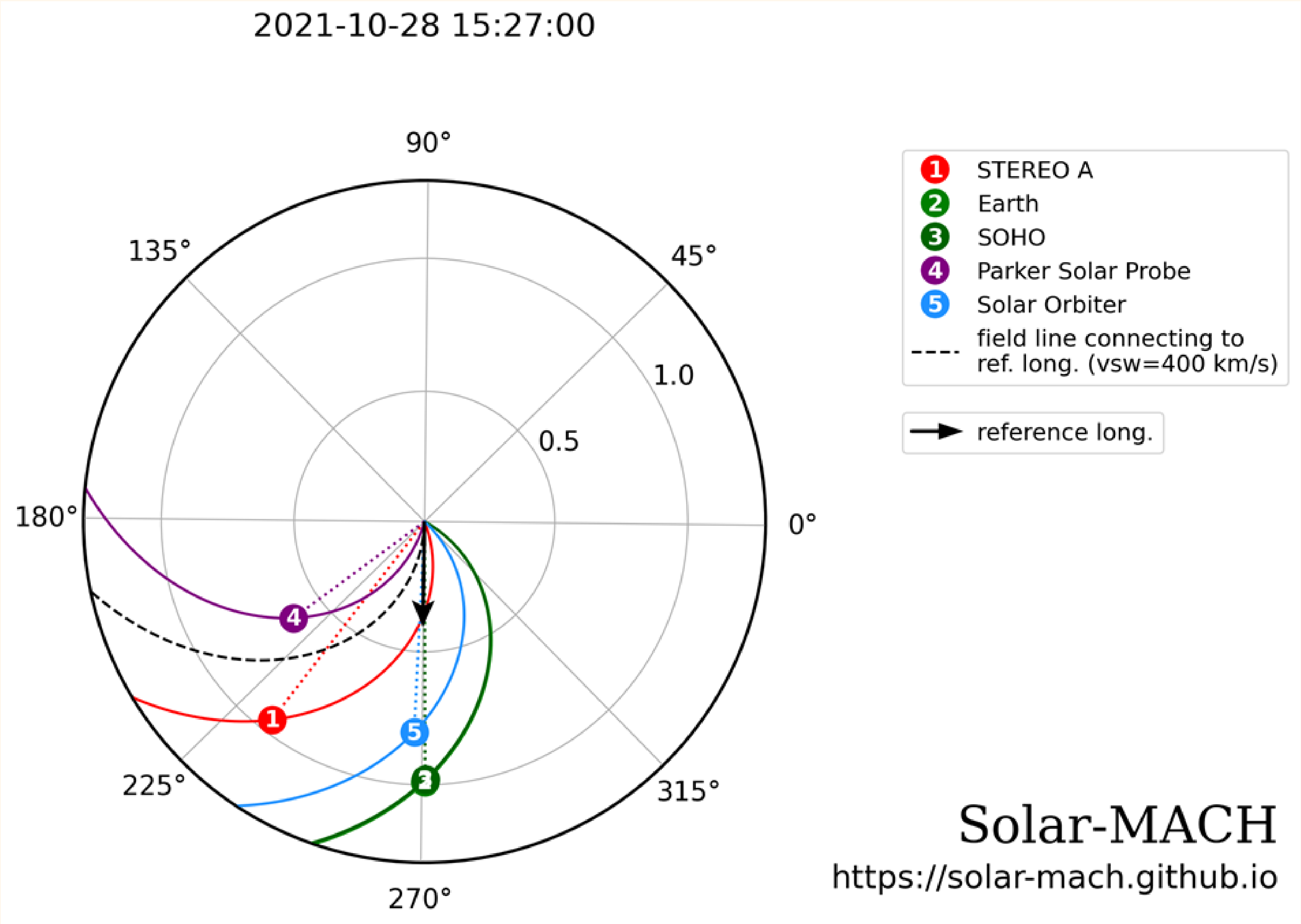
- 1D MODEL REQUIRES MAGNETICALLY WELL-CONNECTED EVENTS
- INSTRUMENT PARKER SPIRAL FOOTPRINT ON THE SUN'S SURFACE
- FOOTPRINT MUST BE 30 DEGREES FROM THE FLARE LOCATION (Roelof, 2015)



FINDING THE FLARE

Müller, et al. (2017)

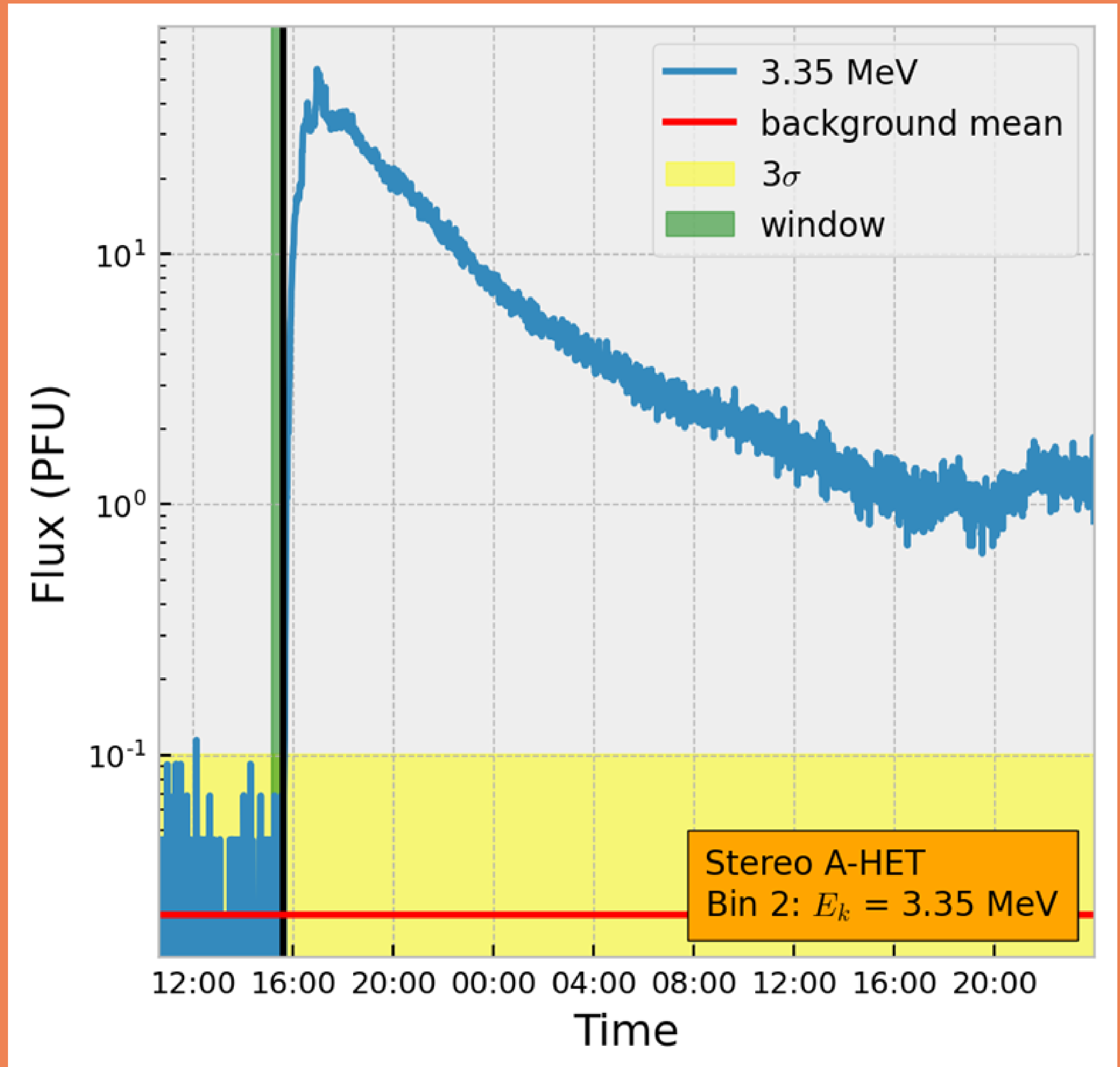
CONNECTING THE INSTRUMENTS TO THE FLARE



Gieseler, et al. (2023)

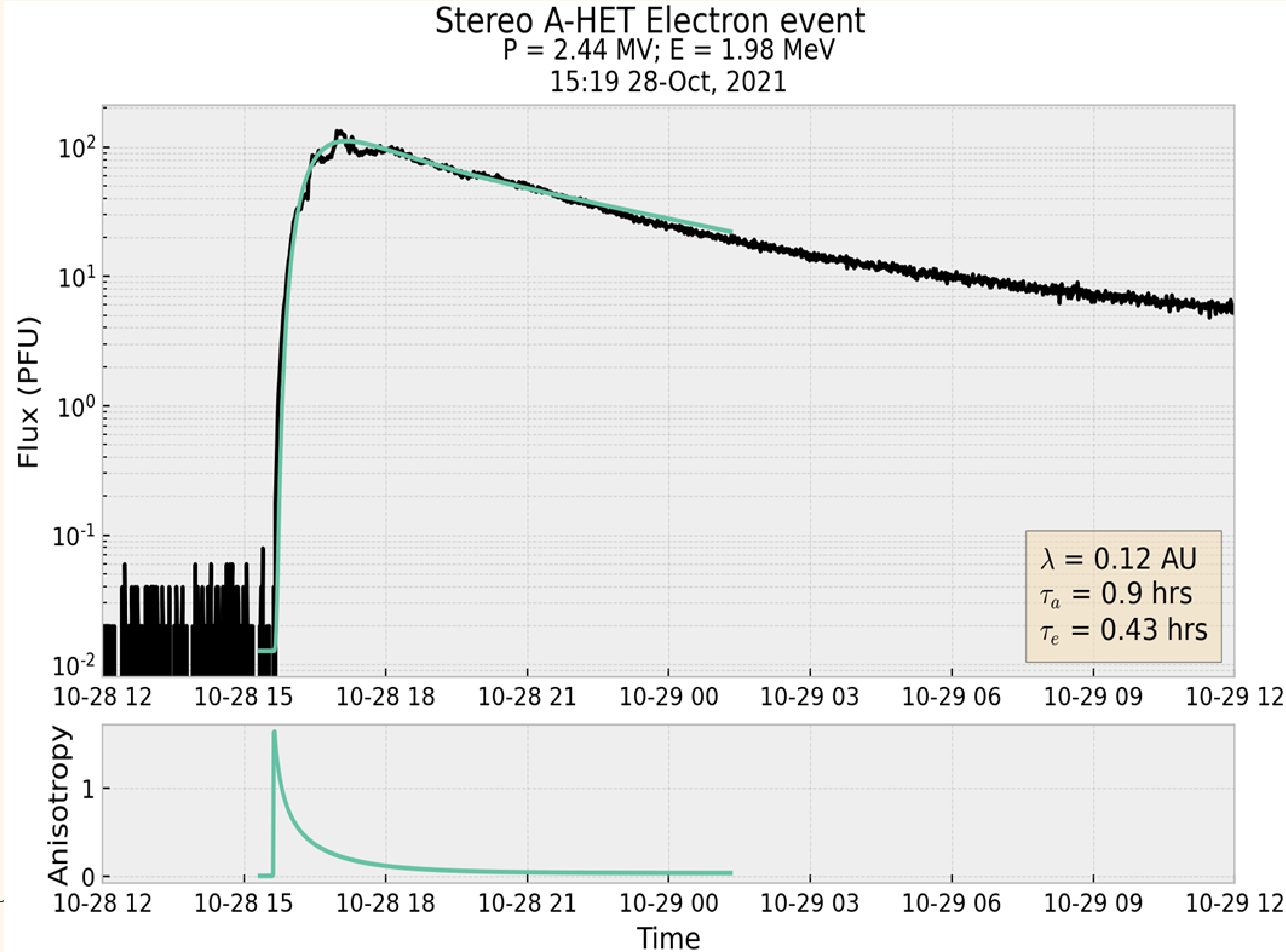
IS THE DATA GOOD ENOUGH?

The data must display a tight enough result that we can calculate the onset.



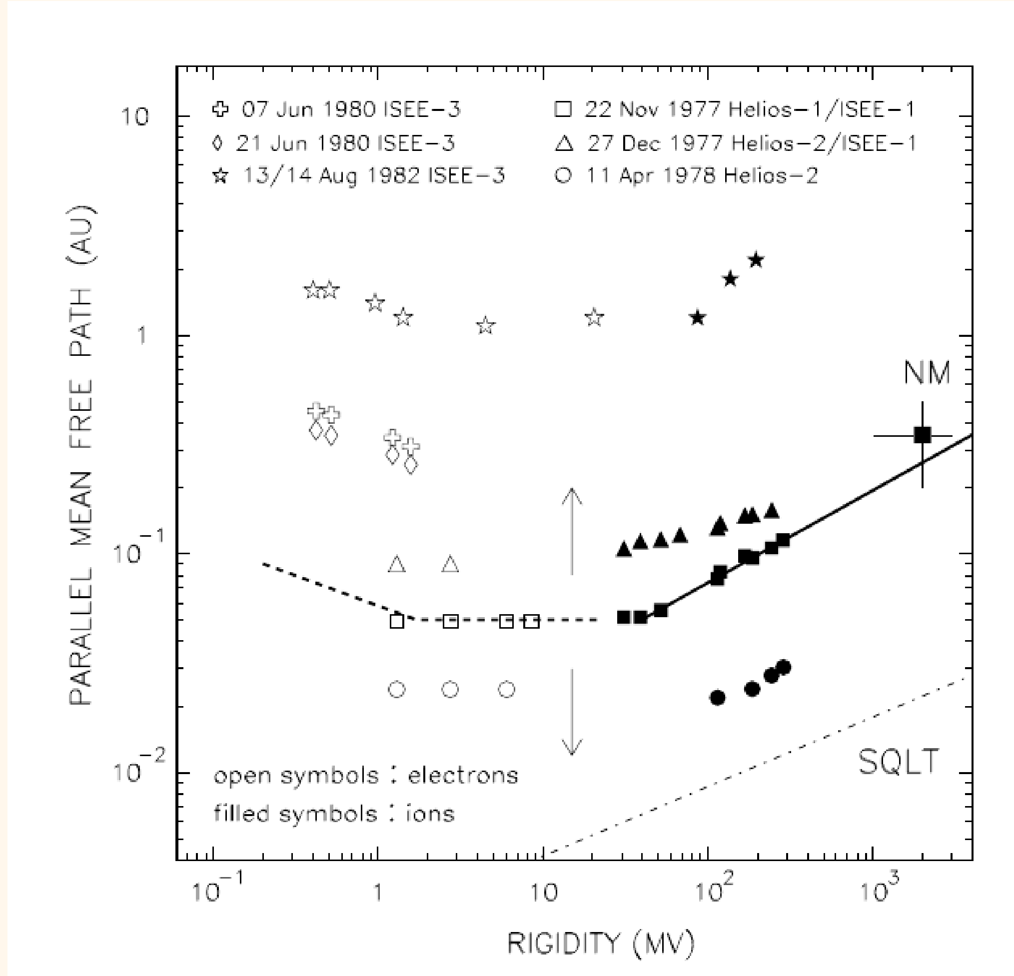
Stereo A (HET) Electron bin 2 for event on October 28th, 2021.

FITTING THE OBSERVATIONS



HISTORICAL OBSERVATIONS

Mean-free-path as a function of Rigidity



Electrons

Protons

Dröge (2000) pattern

Convert Energy To Rigidity

Rigidity

$$P = \sqrt{E_k\,(E_k + 2\,E_0)}$$

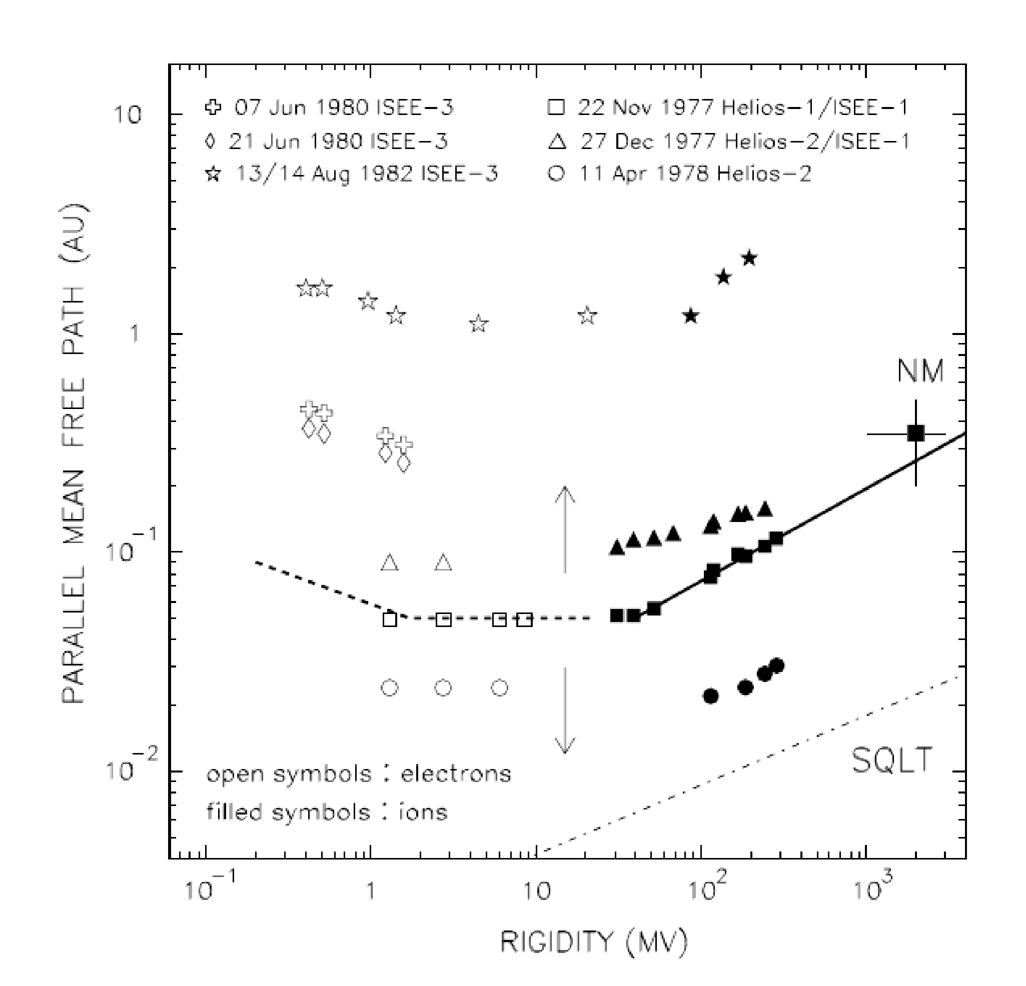
In units of MV

Rest Mass Energy

$$E_{0,e} = 0.511\,\mathrm{MeV}$$
$$E_{o,p} = 938.0\,\mathrm{MeV}$$

HISTORICAL OBSERVATIONS

Mean-free-path as a function of Rigidity

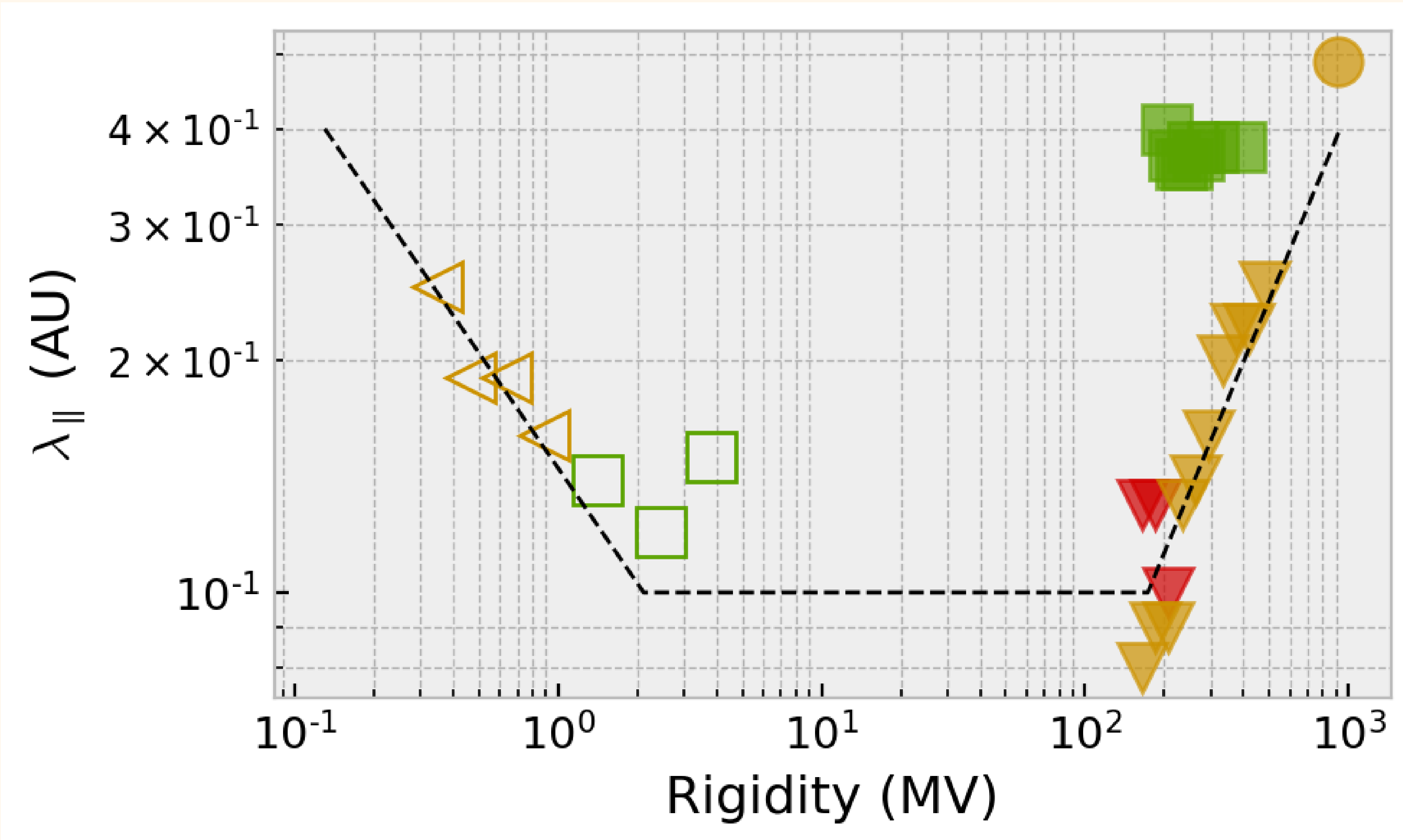


Electrons

Protons

Dröge (2000) pattern

MEAN-FREE-PATH vs RIGIDITY



DERIVING THE DIFFUSION COEFFICIENT

Teufel & Schlickeiser (2003)

$$e^{-\frac{t}{q_d}}$$

Random Sweeping (RS)

$$e^{-\left(\frac{t}{q_d}\right)^2}$$

Dynamical Turbulence (DT)

DERIVING THE DIFFUSION COEFFICIENT

Teufel & Schlickeiser (2003)

$e^{-\frac{t}{q_d}}$

Random Sweeping (RS)

$$\lambda_\parallel = \frac{3\,s}{\sqrt{\pi}\,(s-1)}\,\frac{R^2}{k_{min} b}\left(\frac{B_0}{\delta\,B_{slab}}\right)^2 \cdot\left[\frac{b}{4\sqrt{\pi}} + \left(\frac{1}{\Gamma(p/2)} + \frac{1}{\sqrt{\pi}(p-2)}\right)\frac{b^{p-1}}{Q^{p-s}\,R^s} + \frac{2}{\sqrt{\pi}\,(2-s)(4-s)}\,\frac{b}{R^s}\right]$$

$e^{-\left(\frac{t}{q_d}\right)^2}$

Dynamical Turbulence (DT)

$$\lambda_\parallel = \frac{3\,s}{(s-1)}\,\frac{R^2}{k_{min} a}\left(\frac{B_0}{\delta\,B_{slab}}\right)^2 \cdot\left[\frac{a}{4\,\pi} + {}_2F_1\left(1;\,\frac{1}{(p-1)};\,\frac{p}{(p-1)};\,\frac{\pi\,a}{f_1\,Q}\right)\frac{a^2}{f_1\,Q^{3-s}\,R^s} + \frac{2}{\sqrt{\pi}\,(2-s)(4-s)}\,\frac{a}{R^s}\right]$$

$$\text{where } f_1 = \frac{2}{p-2} + \frac{2}{2-s}$$

$$(\delta B_{slab})^2 = 13.2\, nT^2$$

DERIVING THE DIFFUSION COEFFICIENT

Teufel & Schlickeiser (2003)

$$k_D = 2\times 10^{-5}\ m^{-1}$$

$$e^{-\frac{t}{q_d}}$$

Random Sweeping (RS)

$$s = 5/3$$

$$\alpha_d = 1$$

$$\lambda_\parallel = \frac{3\,s}{\sqrt{\pi}\,(s-1)}\frac{R^2}{k_{min}b}\left(\frac{B_0}{\delta B_{slab}}\right)^2 \cdot\left[\frac{b}{4\sqrt{\pi}} + \left(\frac{1}{\Gamma(p/2)} + \frac{1}{\sqrt{\pi}(p-2)}\right)\frac{b^{p-1}}{Q^{p-s}\,R^s} + \frac{2}{\sqrt{\pi}\,(2-s)(4-s)}\frac{b}{R^s}\right]$$

$$V_A = 33.5\ km/s$$

$$e^{-\left(\frac{t}{q_d}\right)^2}$$

Dynamical Turbulence (DT)

$$p = 3.$$

$$k_{\min} = 10^{-10}\,\mathrm{m}^{-1}$$

$$\lambda_\parallel = \frac{3\,s}{(s-1)}\frac{R^2}{k_{min}a}\left(\frac{B_0}{\delta B_{slab}}\right)^2 \cdot\left[\frac{a}{4\pi} + {}_2F_1\left(1;\frac{1}{(p-1)};\frac{p}{(p-1)};\frac{\pi\,a}{f_1\,Q}\right)\frac{a^2}{f_1\,Q^{3-s}\,R^s} + \frac{2}{\sqrt{\pi}\,(2-s)(4-s)}\frac{a}{R^s}\right]$$

$$\text{where } f_1 = \frac{2}{p-2} + \frac{2}{2-s}$$

$$B_0 = 4.12\, nT$$

$$(\delta B_{slab})^2 = 13.2\,\mathrm{nT}^2$$

$$R = R_L \cdot k_{min}$$

$$P = \sqrt{E_k(E_k + 2E_0)}$$

$$a = \frac{v}{\alpha_d V_A} = 2b$$

DERIVING THE DIFFUSION COEFFICIENT

$$Q = R_L \cdot k_D$$

Teufel & Schlickeiser (2003)

$$R_L = \frac{m_e v}{q\,B_0} = \frac{P}{B_0 c}$$

$$k_D = 2\times 10^{-5}\ \mathrm{m}^{-1}$$

$$e^{-\frac{t}{q_d}}$$

Random Sweeping (RS)

$$s = 5/3$$

$$\alpha_d = 1$$

$$\lambda_\parallel = \frac{3\,s}{\sqrt{\pi}\,(s-1)}\frac{R^2}{k_{min}b}\left(\frac{B_0}{\delta\,B_{slab}}\right)^2 \cdot \left[\frac{b}{4\sqrt{\pi}} + \left(\frac{1}{\Gamma(p/2)} + \frac{1}{\sqrt{\pi}(p-2)}\right)\frac{b^{p-1}}{Q^{p-s}\,R^s} + \frac{2}{\sqrt{\pi}\,(2-s)(4-s)}\frac{b}{R^s}\right]$$

$$V_A = 33.5\ \mathrm{km/s}$$

$$e^{-\left(\frac{t}{q_d}\right)^2}$$

Dynamical Turbulence (DT)

$$v = \frac{P\,c}{E_k + E_0}$$

$$p = 3.$$

$$k_{\min} = 10^{-10}\ \mathrm{m}^{-1}$$

$$\lambda_\parallel = \frac{3\,s}{(s-1)}\frac{R^2}{k_{min}a}\left(\frac{B_0}{\delta\,B_{slab}}\right)^2 \cdot \left[\frac{a}{4\,\pi} + {}_2F_1\left(1;\frac{1}{(p-1)};\frac{p}{(p-1)};\frac{\pi\,a}{f_1\,Q}\right)\frac{a^2}{f_1\,Q^{3-s}\,R^s} + \frac{2}{\sqrt{\pi}\,(2-s)(4-s)}\frac{a}{R^s}\right]$$

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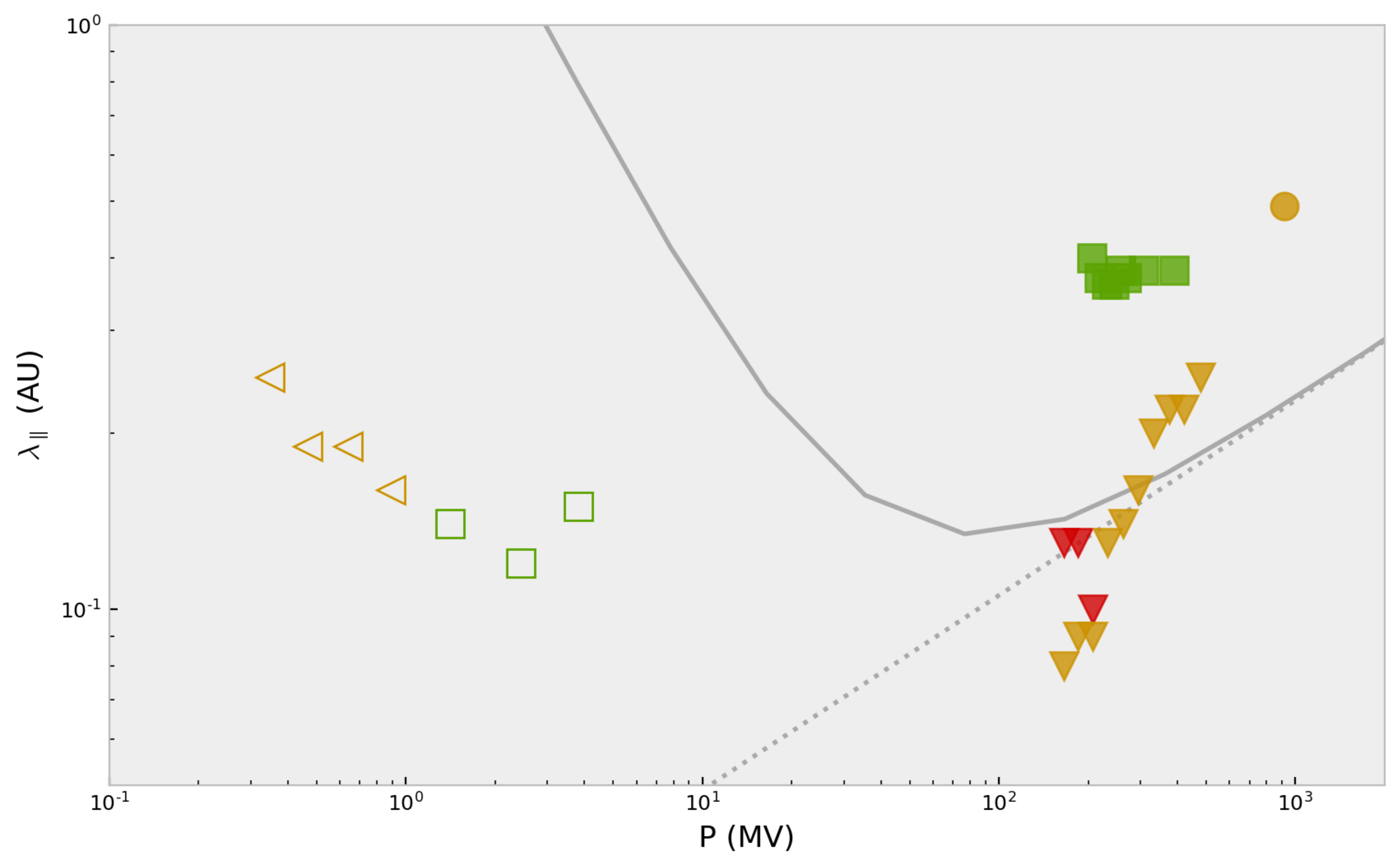
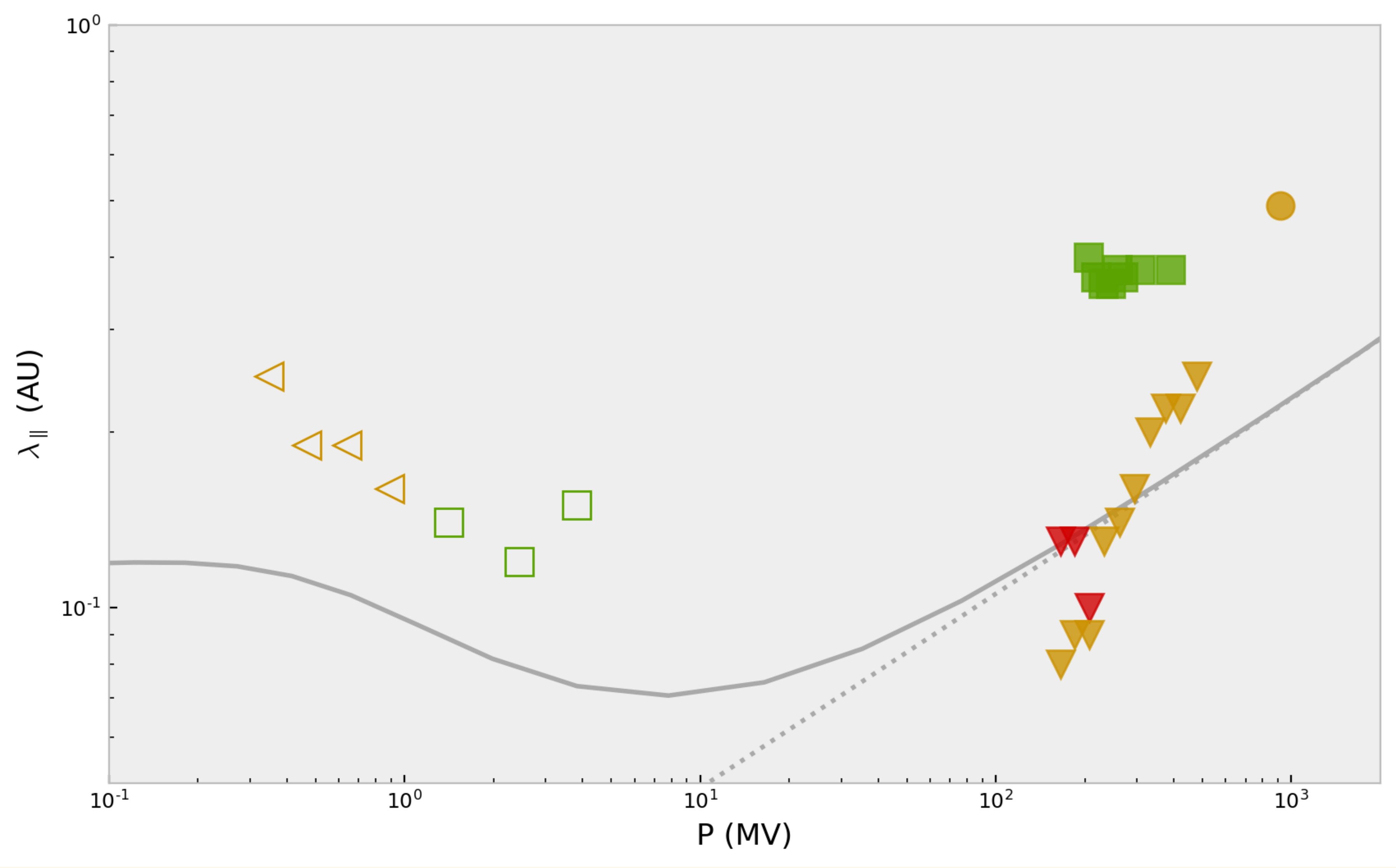
RANDOM SWEEPING



DAMPING TURBULENCE



WHAT'S TO COME?

INCLUSIONS
More events to build on the patterns.

COMPARISONS
Any other patterns from the other parameters?

IMPROVEMENTS
Recreating Dröges results.

ADDITIONS
Finding the 0,3 AU parameters.

CONFIRMATIONS
Confirming the 1 AU parameters are correct.

THANK YOU!

Thanks to the people in the Center for Space Research for their support in getting this project where it is today.

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Software/Code

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Theory

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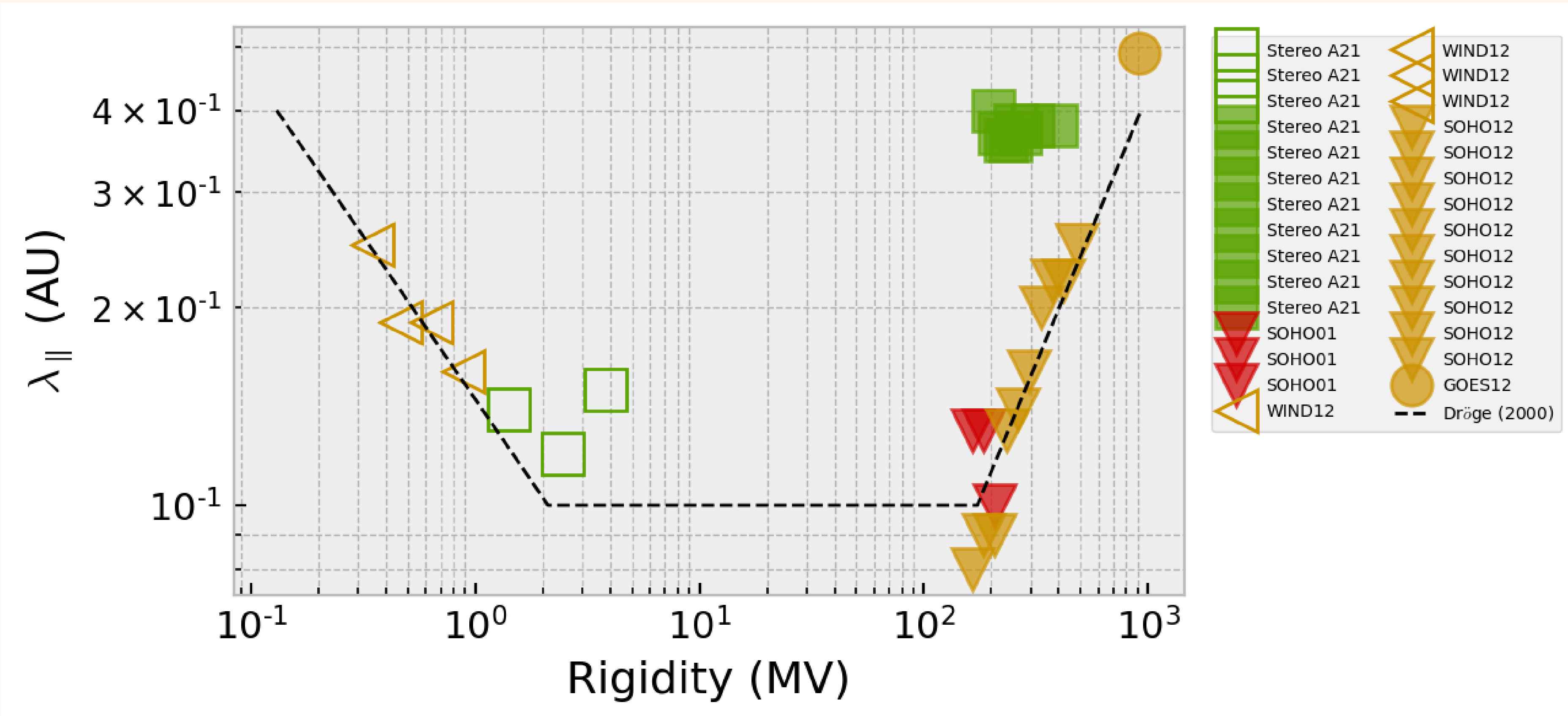
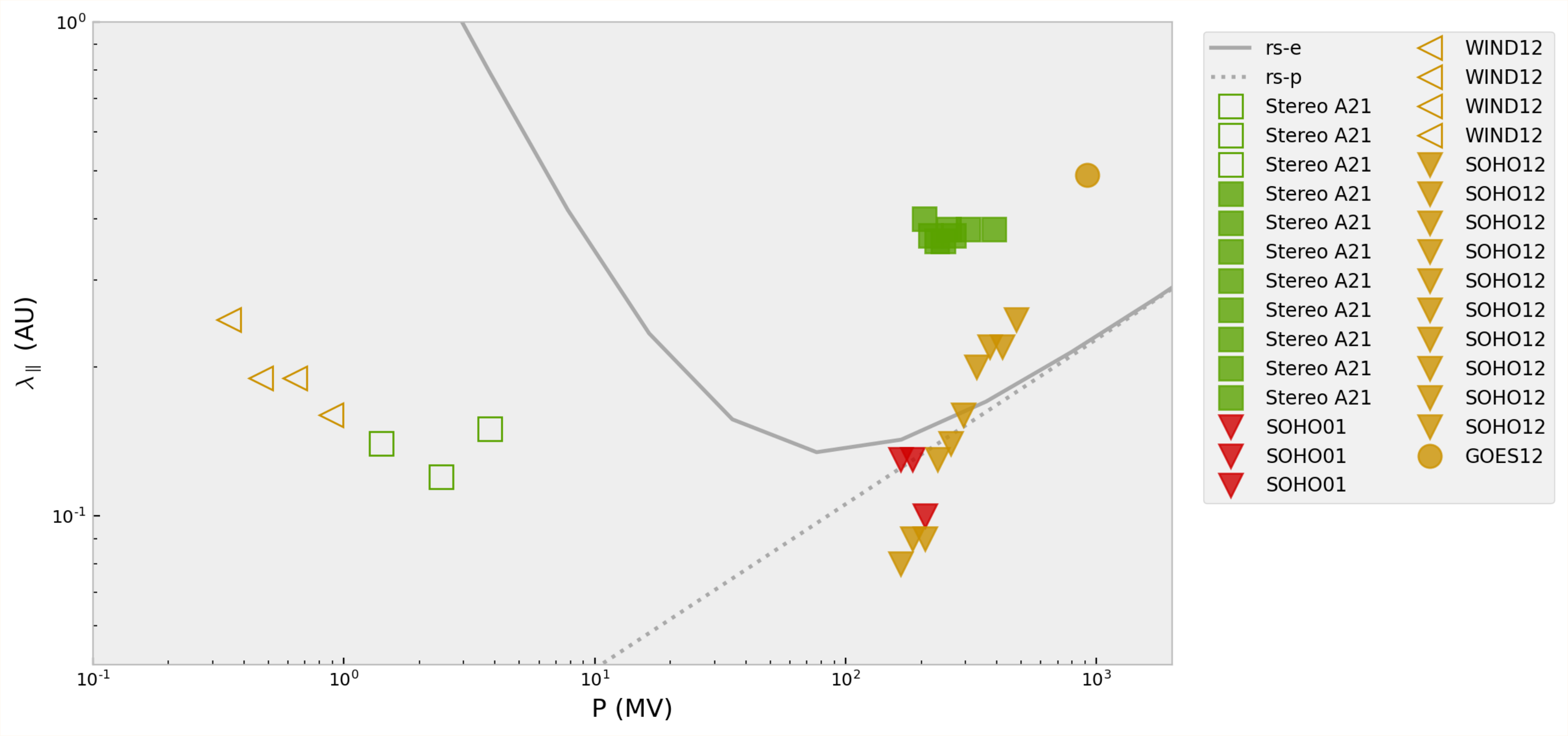
Additional Information



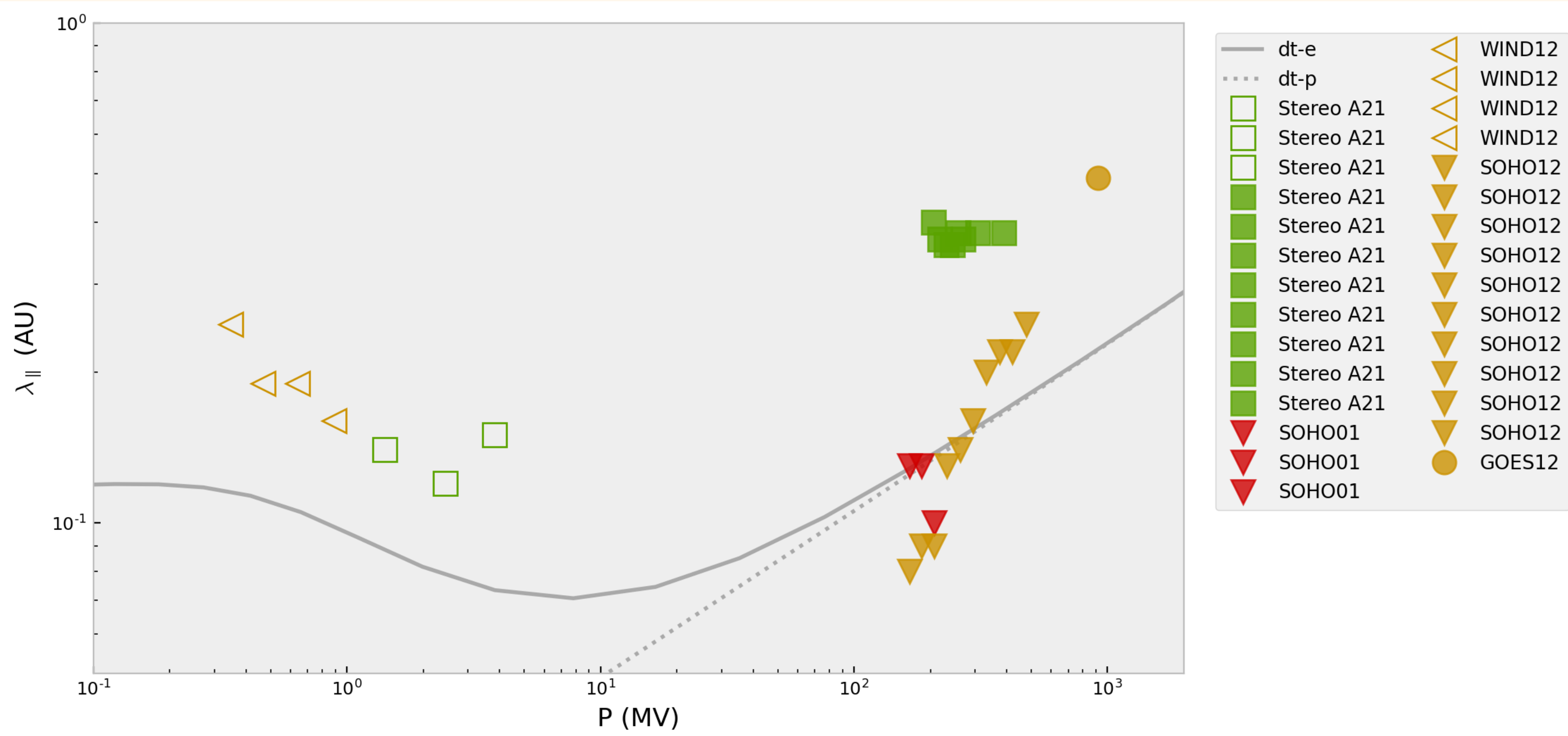
Mean-free-path as a function of rigidity with Dröge's pattern included.

Additional Information



Mean-free-path as a function of rigidity with the random sweeping function included for electrons (solid line) and protons (dashed line).

Additional Information



Mean-free-path as a function of rigidity with the damping turbulence function included for electrons (solid line) and protons (dashed line).