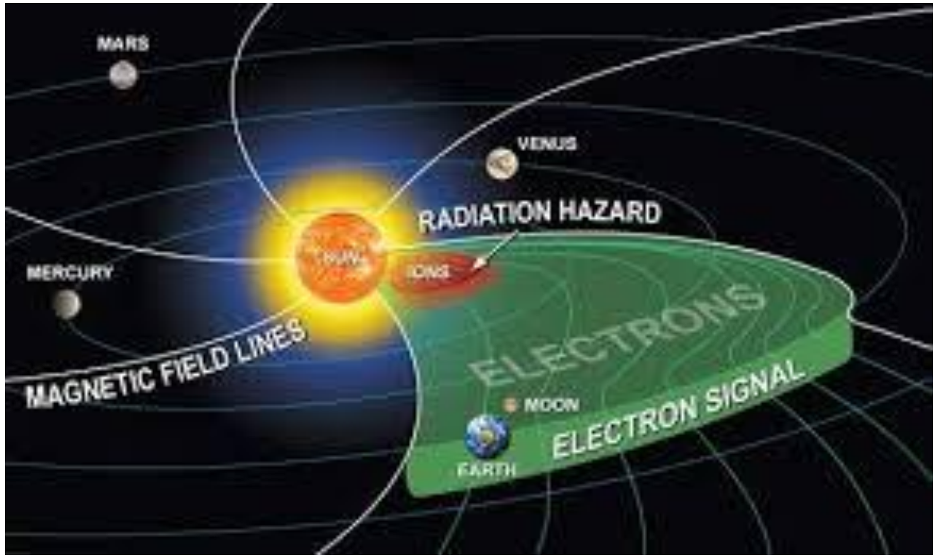
Solar Energetic Particle Transport in eruptive events: case study on GLE73

MHD school – HelAS – Sept 2024

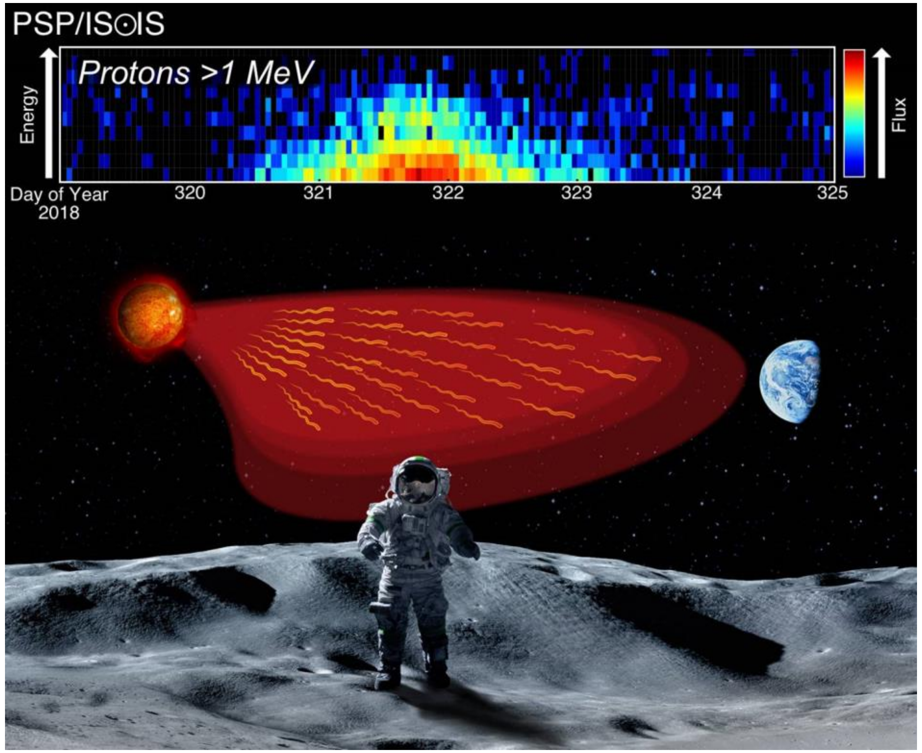
Eleni Lavasa | NKUA & IMSI-ATHENA RC

Supervisors:
Athanasios Papaioannou | IAASARS-NOA
Anastasios Anastasiadis | IAASARS-NOA
Ioannis A. Daglis | NKUA & HSC

Background & motivation



- **Solar Energetic Particle (SEP) events**: transient enhancements in p+, e- & ion fluxes, energies from ~10keV - ~1GeV/nuc
- **Drivers:** eruptive flare & Coronal Mass Ejection (CME) events (~3%)
- **Direct hazard** to humans and infrastructure in space



- We study the physics behind SEP acceleration – injection - **transport**
- **Aim:** contribute to SEP forecasting to shield human space flight from solar particle radiation

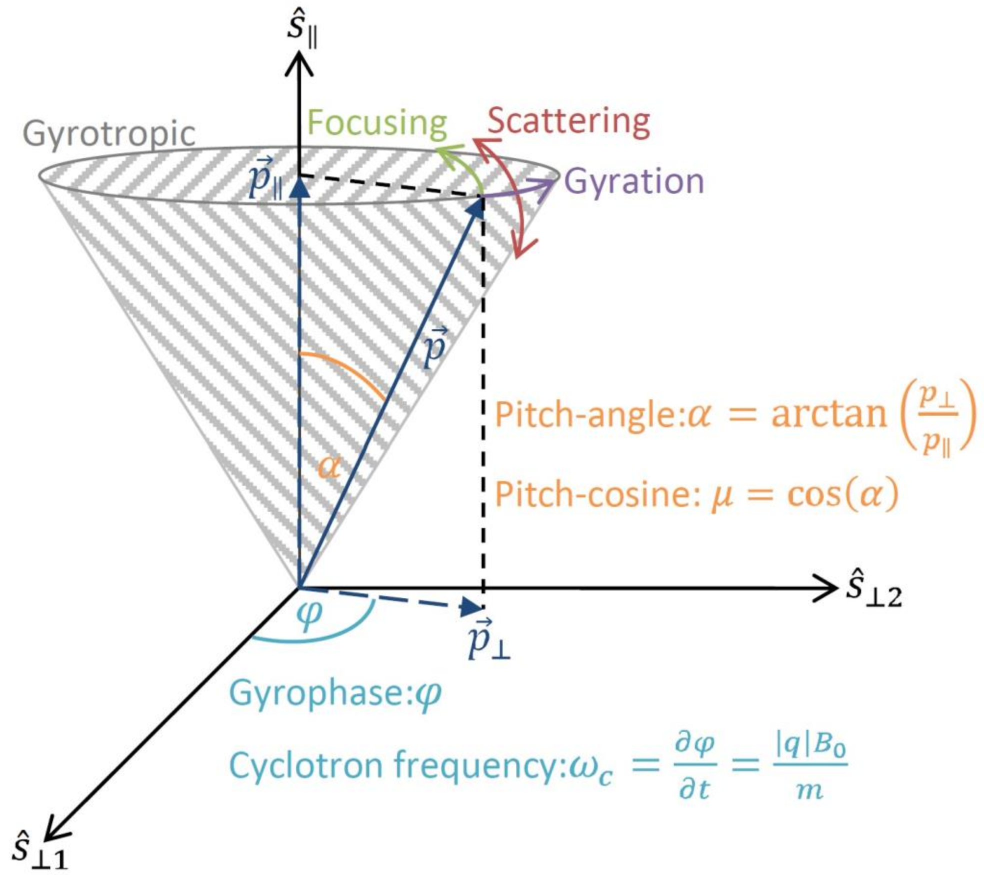
Focused transport of SEPs

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial s}[\mu v f] + \frac{\partial}{\partial \mu}\left[\frac{(1-\mu^2)v}{2L(s)} f\right] = \frac{\partial}{\partial \mu}\left[D_{\mu\mu}\frac{\partial f}{\partial \mu}\right]$$

(Roelof, 1968)

- *f(s; μ; t) : Distribution function in a given flux tube*
- v*: constant speed*
- *s: field-aligned coordinate*
- *L(s) : Focusing length of* $\vec{B}$ => $\frac{1}{L(s)} = -\frac{1}{B(s)}\frac{dB(s)}{ds}$
- $D_{\mu\mu}$*: Pitch-angle diffusion coefficient*

Magnetic focusing + particle scattering trade off



Van Den Berg et al, 2020

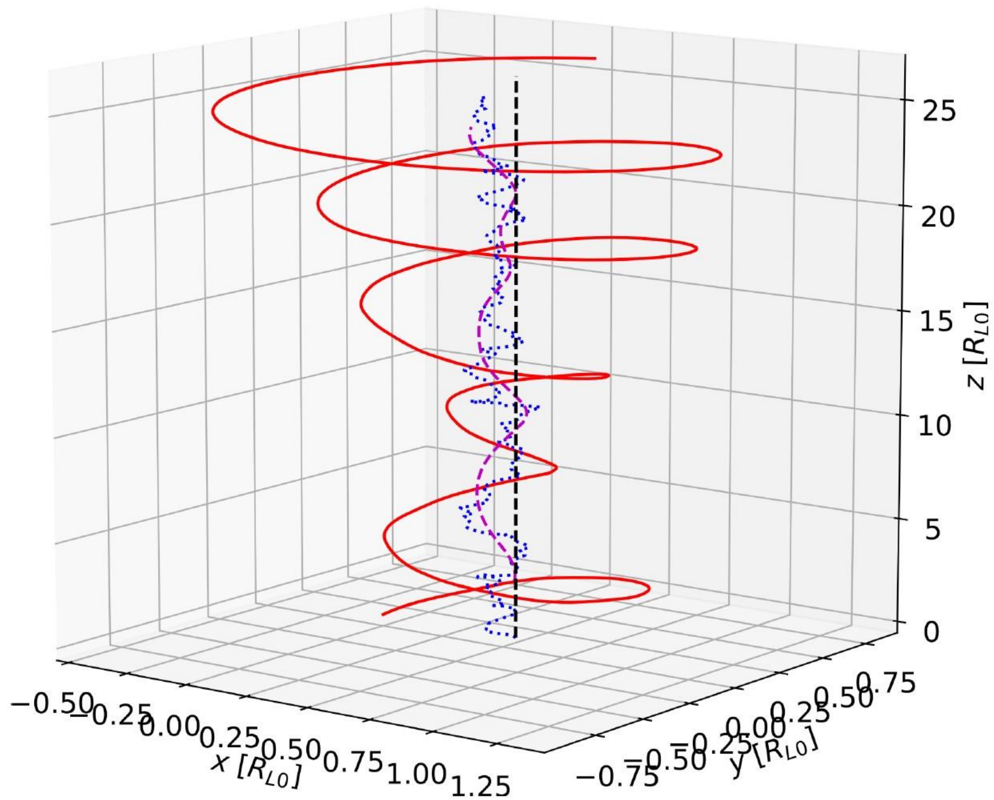
Focused transport of SEPs

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial s}[\mu v f] + \frac{\partial}{\partial \mu}\left[\frac{(1-\mu^2)v}{2L(s)} f\right] = \frac{\partial}{\partial \mu}\left[D_{\mu\mu}\frac{\partial f}{\partial \mu}\right]$$

(Roelof, 1968)

- *f(s; μ; t) : Distribution function in a given flux tube*
- v*: constant speed*
- *s: field-aligned coordinate*
- *L(s) : Focusing length of* $\vec{B}$ => $\frac{1}{L(s)} = -\frac{1}{B(s)}\frac{dB(s)}{ds}$
- $D_{\mu\mu}$*: Pitch-angle diffusion coefficient*

Magnetic focusing + particle scattering trade off

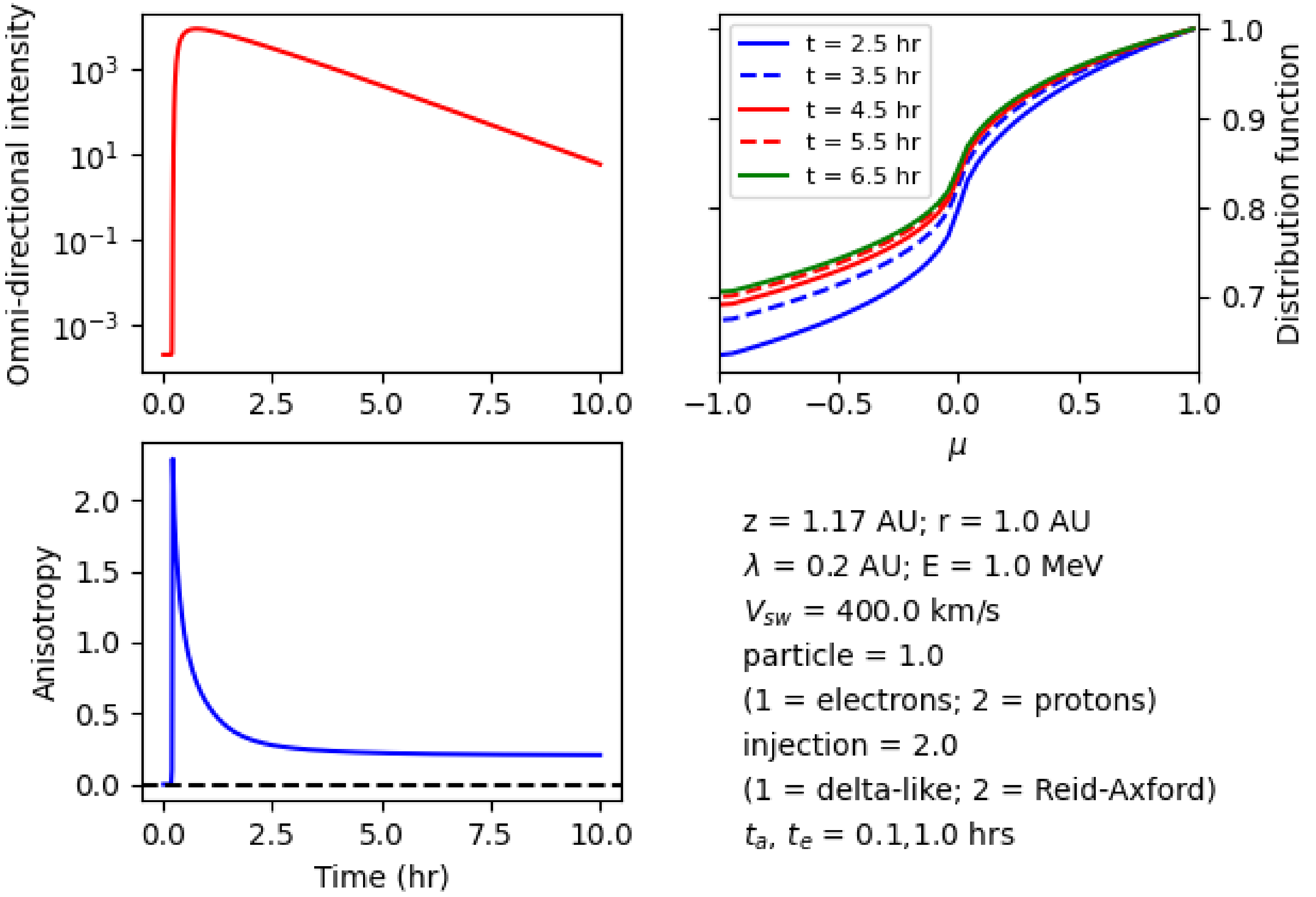


Van Den Berg et al, 2020

Focused transport of SEPs

1D SEP-propagator model

- ❑ Numerical solution based on a finite difference scheme
- ❑ Configurable parameters:
  - Distance to observer
  - Solar wind speed
  - Particle energy **E**
  - Parallel mean free path **λ//**
  - Acceleration time **ta**
  - Escape time **te**



https://github.com/RDStrauss/SEP_propagator

Focused transport of SEPs

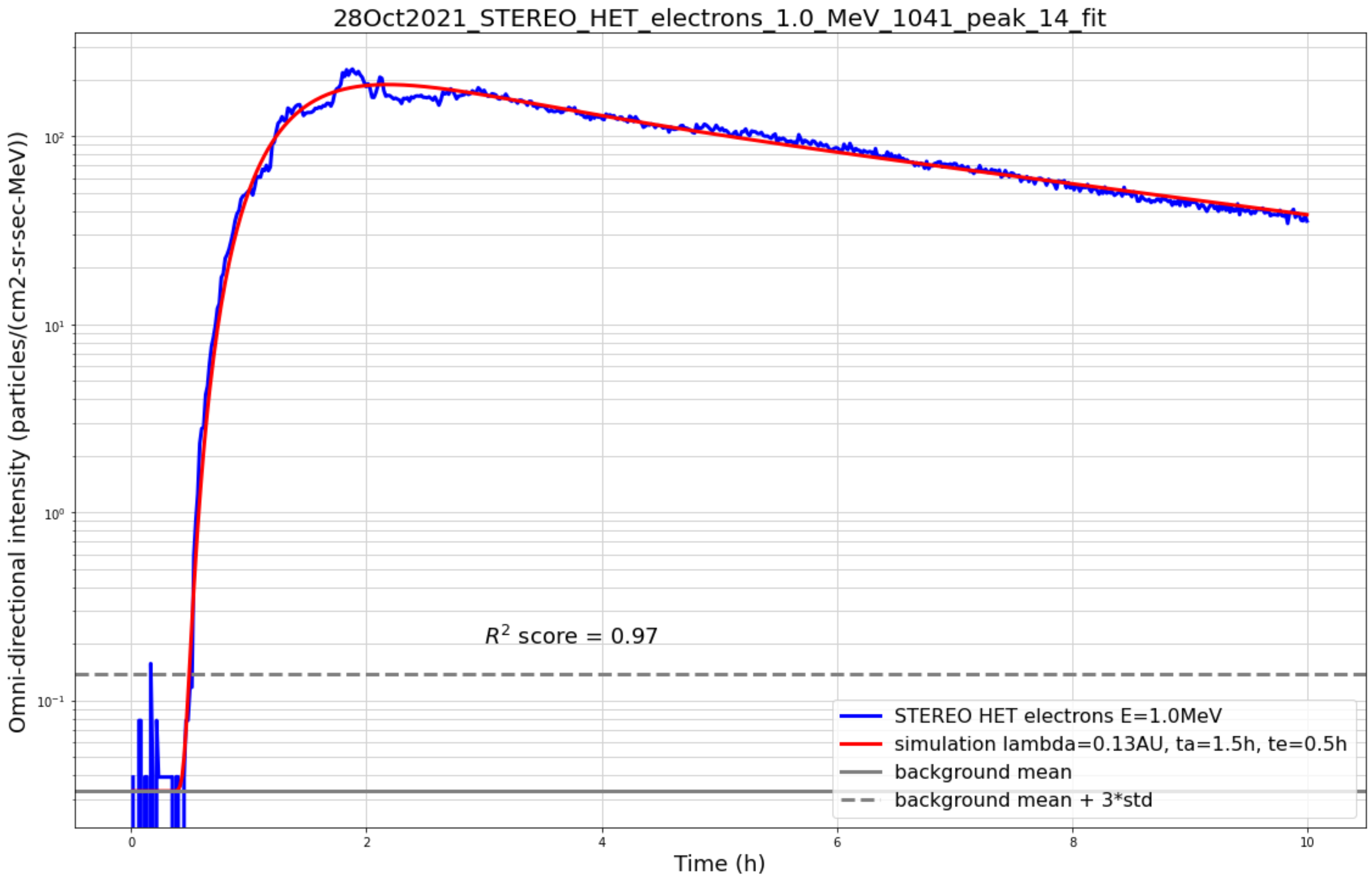
Inverse solution

❑ Fit simulations to real observed profiles

❑ Estimate free parameters:
- Particle energy **E**
- Parallel mean free path **λ//**
- Acceleration time **ta**
- Escape time **te**

e^- **1.0MeV**

λ// = 0.13 AU
ta = 1.5 h
te = 0.5 h



Perpendicular diffusion & turbulence

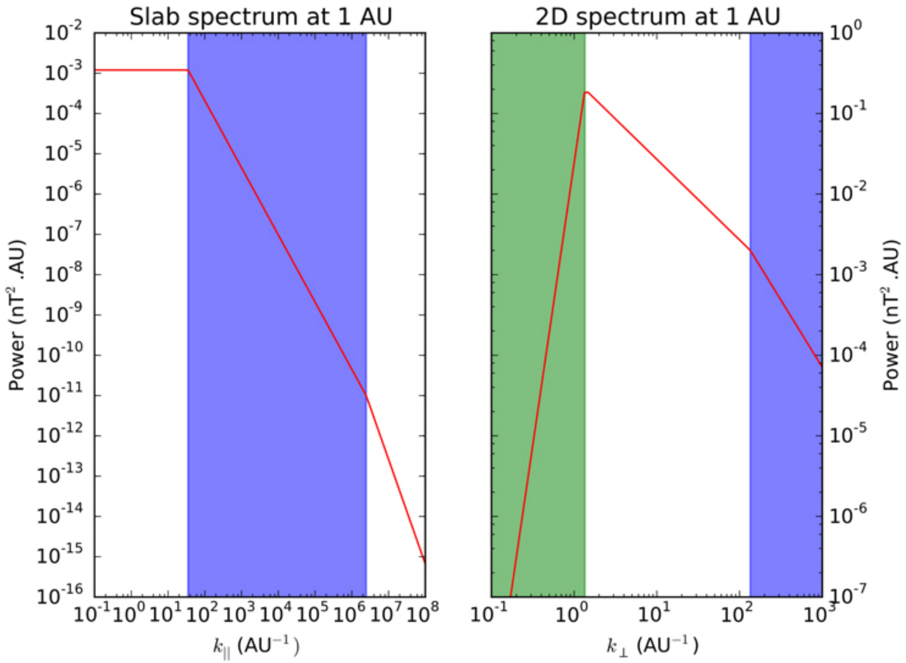
$$\frac{\partial f(\boldsymbol{x},\mu,t)}{\partial t} = -\nabla\cdot(\mu v\hat{b}f) - \frac{\partial}{\partial\mu}\left(\frac{1-\mu^2}{2L}vf\right) + \frac{\partial}{\partial\mu}\left(D_{\mu\mu}(\boldsymbol{x},\mu)\frac{\partial f}{\partial\mu}\right) + \nabla\cdot\left(\mathbf{D}_\perp^{(x)}(\boldsymbol{x},\mu)\cdot\nabla f\right)$$

(Skilling, 1971)

$\mathbf{D}_\perp^{(x)}$*(r, ϕ)* contains perpendicular diffusion coefficients

Include the effect of turbulence in transport coefficients:

- ❑ Decompose $\vec{B}$ into locally uniform & random turbulent components
- ❑ Assume decomposition of the fluctuating field into a slab & 2D component

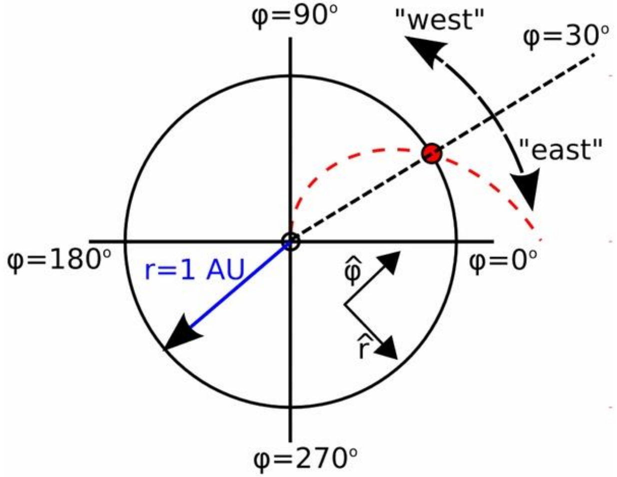


Strauss et al, 2017

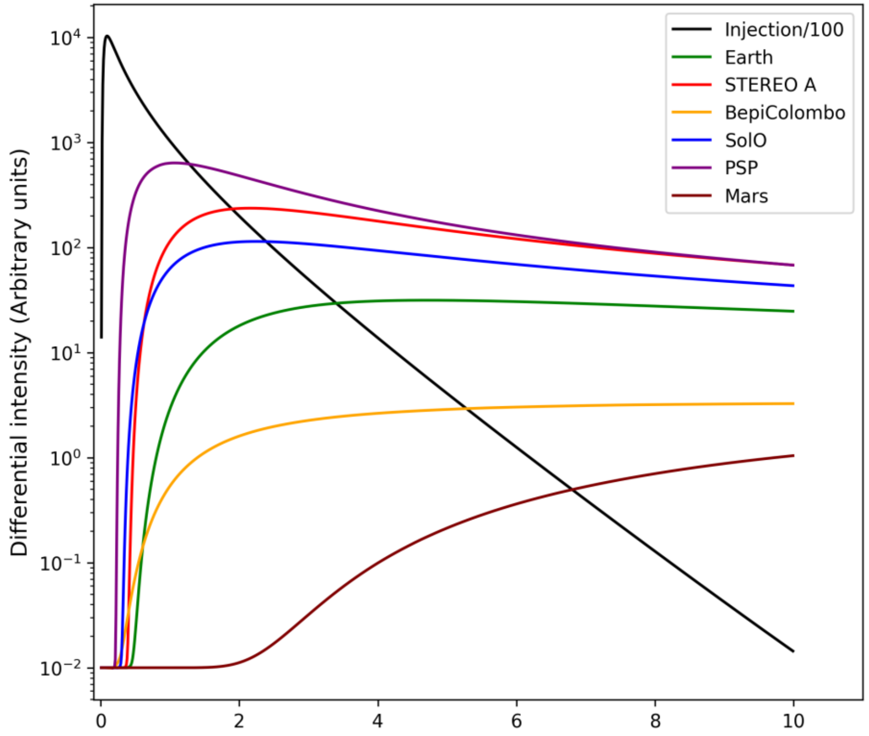
Perpendicular diffusion & turbulence

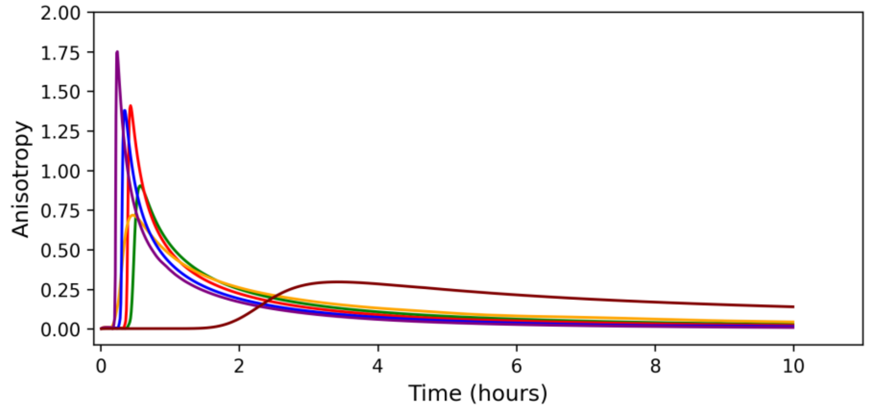
2D SEP-propagator model

- ❑ Numerical solution based on finite difference scheme
- ❑ Configurable parameters:
    - Solar wind speed
    - Particle energy **E**
    - Parallel mean free path $\boldsymbol{\lambda_{//}}$
    - Acceleration time **ta**
    - Escape time **te**
    - Perpendicular mean free path $\boldsymbol{\lambda_{perp}}$
    - **Helio-longitude** and **size of injection source**
    - **Radial distances** and **longitudes** for different observers

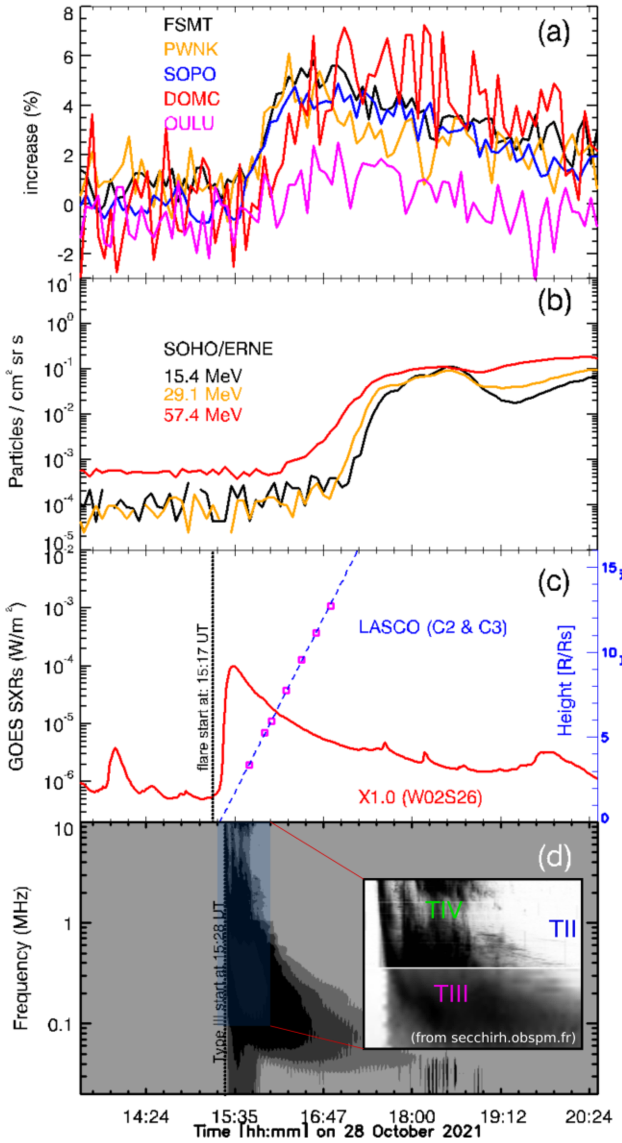


Strauss et al, 2017



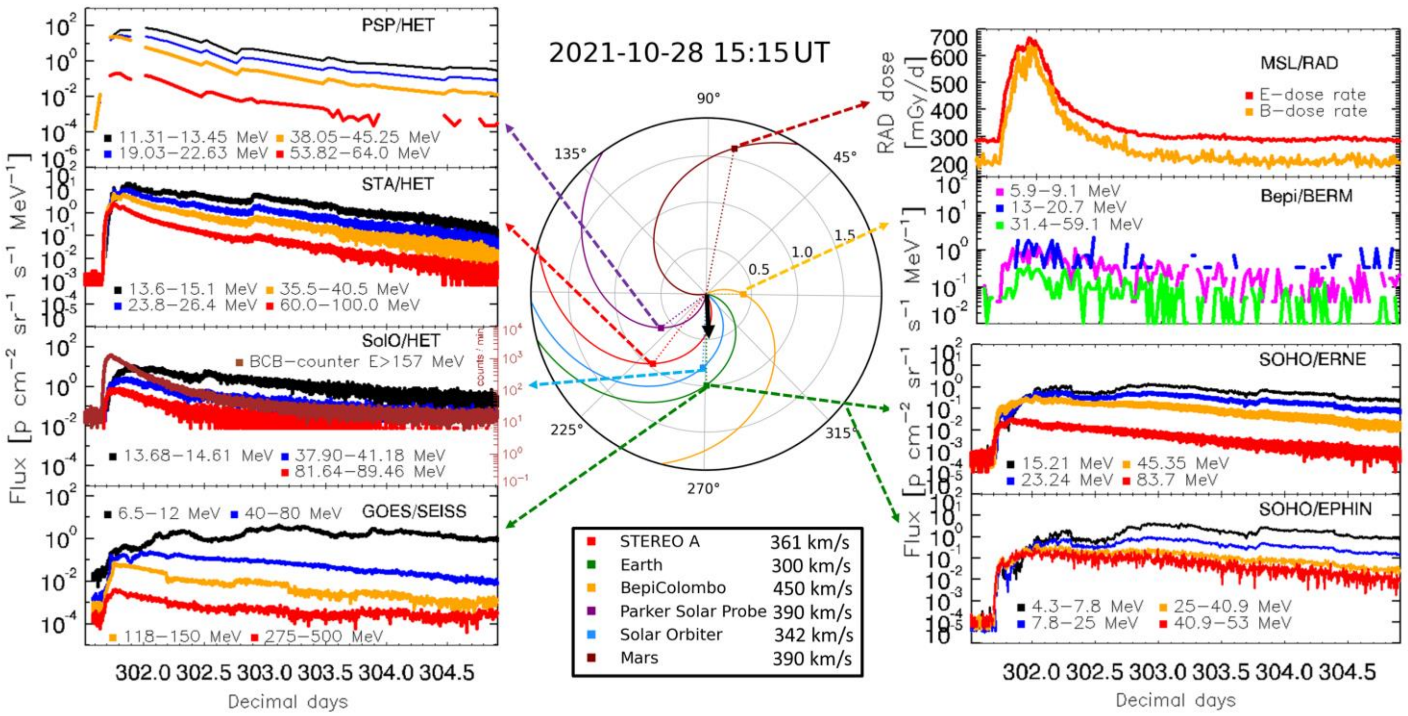


Case study: 28 Oct 2021 (GLE 73) event



Papaioannou et al, 2022

The first Ground-Level Enhancement of SC 25



Kouloumvakos et al, 2024

- ❑ Powerful X.1. class flare
- ❑ Type II, III, IV radio bursts
- ❑ Fast CME (~1640km/s)

- ❑ SEPs recorded at different observers
- ❑ Large longitudinal spread

Magnetically well-connected observer – 1D model

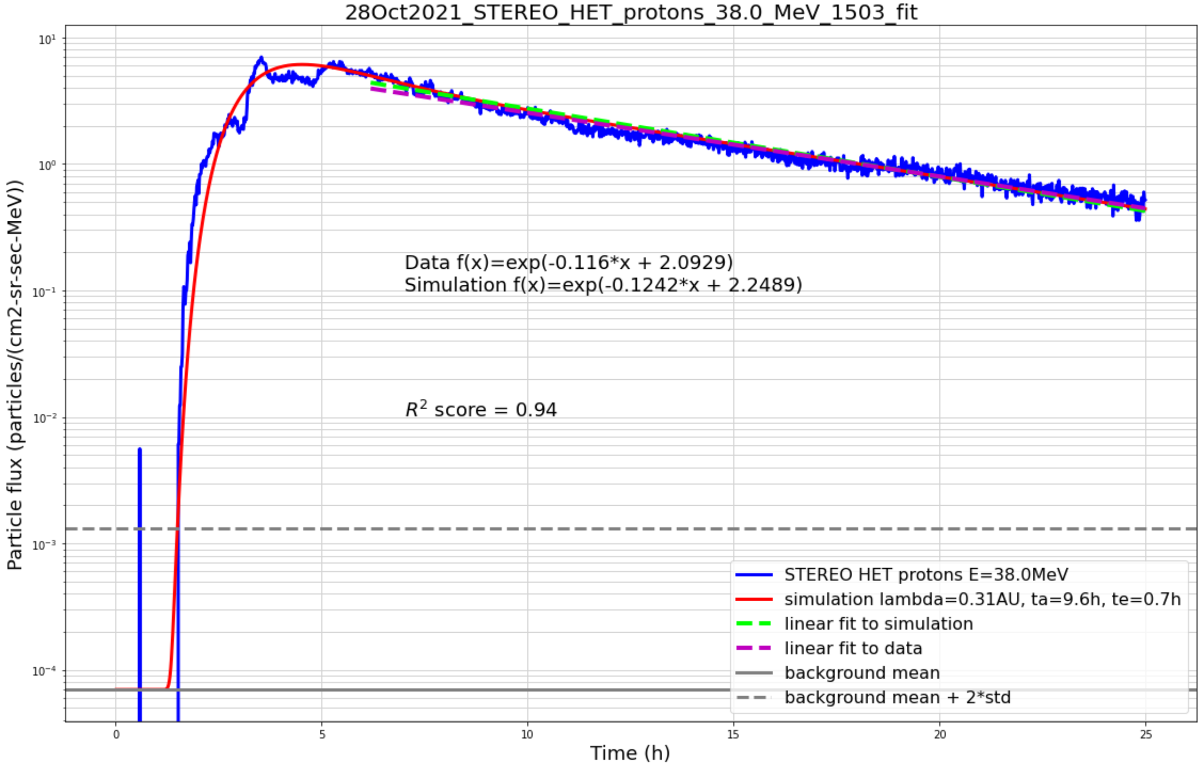
Fit simulations to well-connected observer: STEREO A

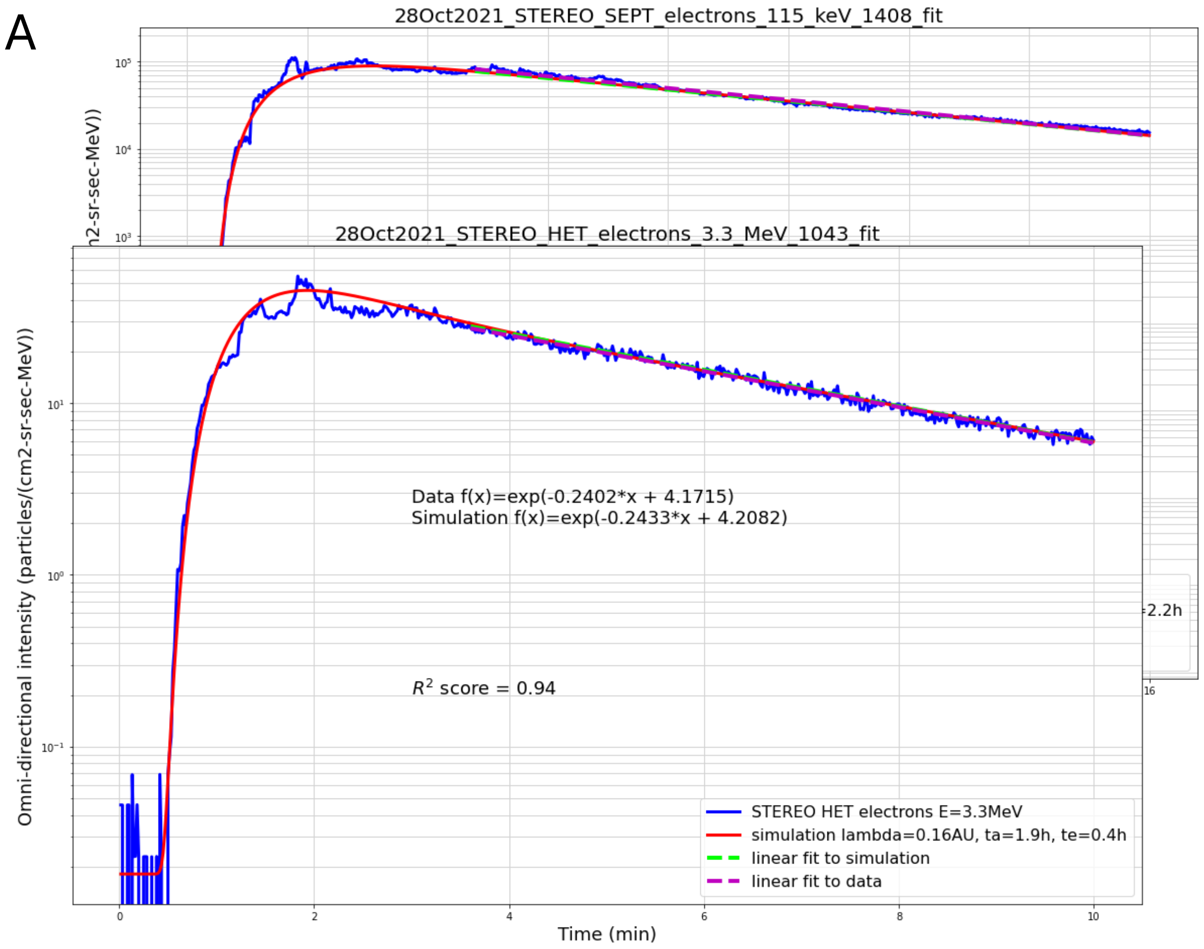
Constrain **λ// , ta, te**

STA – HET p+

Mean Energies 14.3 – 77.5 MeV

11 channels





STA – SEPT & HET e-

Mean Energies 0.07 – 3.3MeV

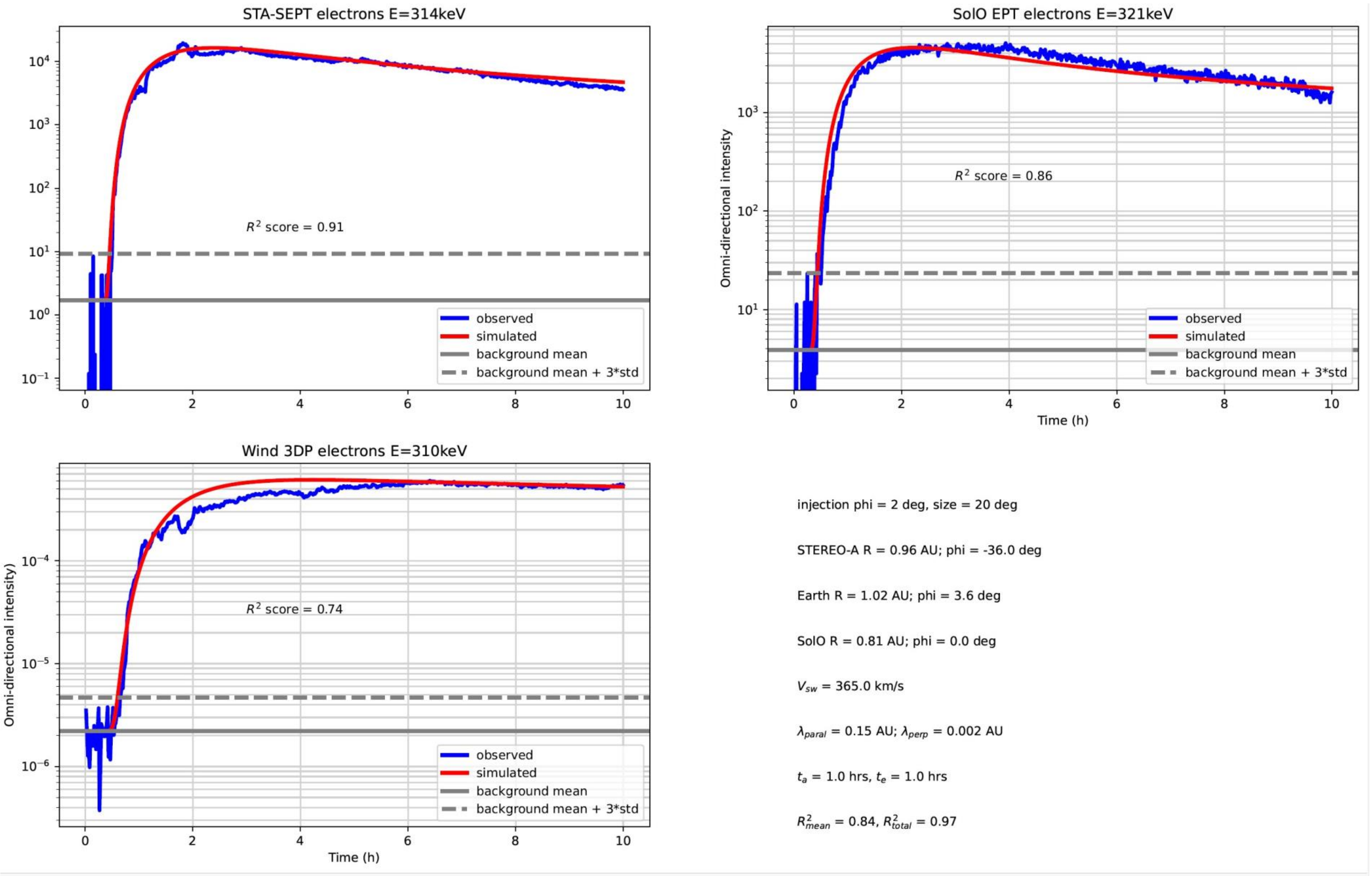
16 channels

Magnetically disconnected observers

2D model:

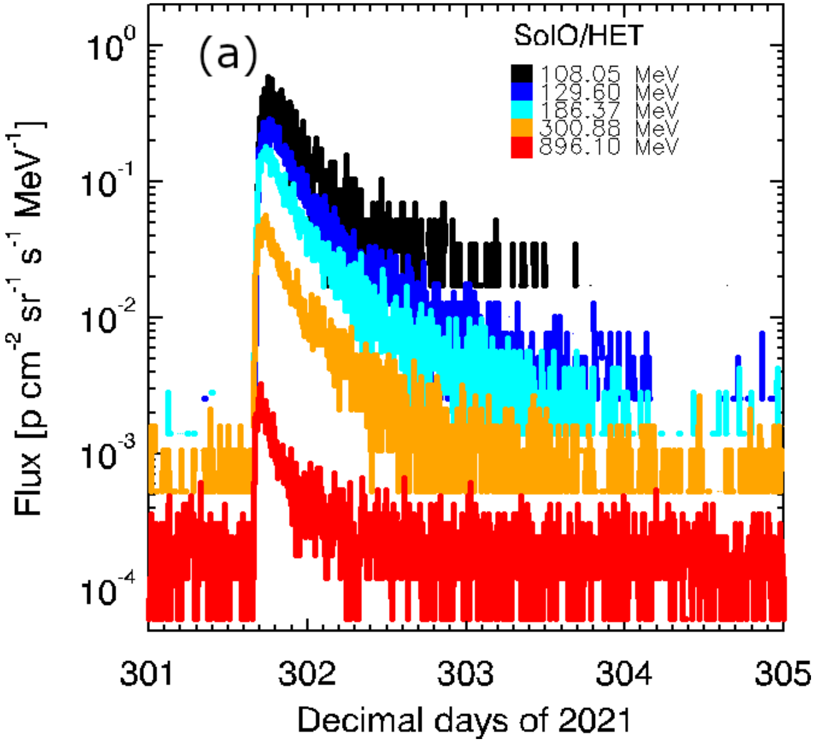
Use fitted **λ// , ta, te**

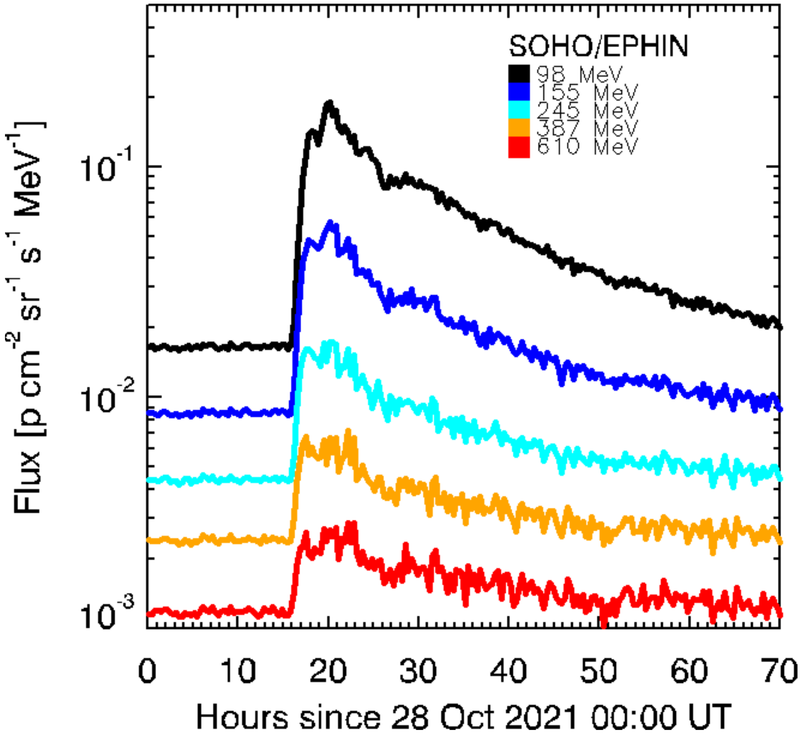
Fit for **perpendicular mfp, size of injection source**



Magnetically disconnected observers

- Very high energy novel datasets
- Penetrating p+ channels
- SolO/HET ~108 – 896 MeV (nominal L2 data upper limit: ~100 MeV)
- SOHO/EPHIN ~98 – 610 MeV (nominal L2 data upper limit: ~53 MeV)

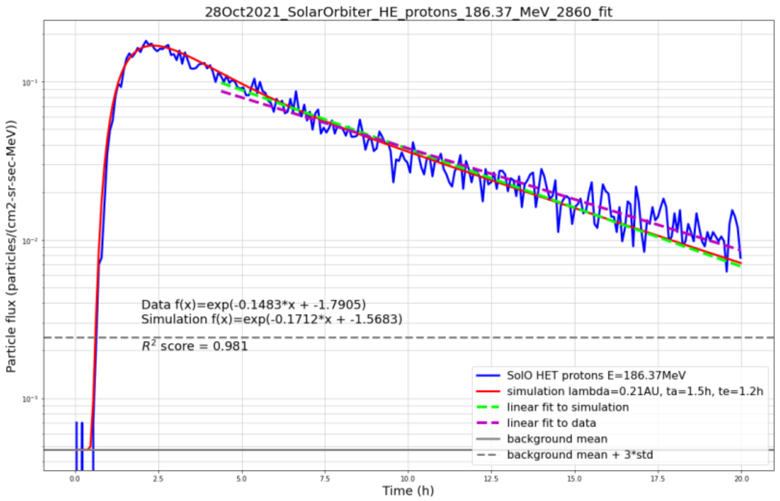


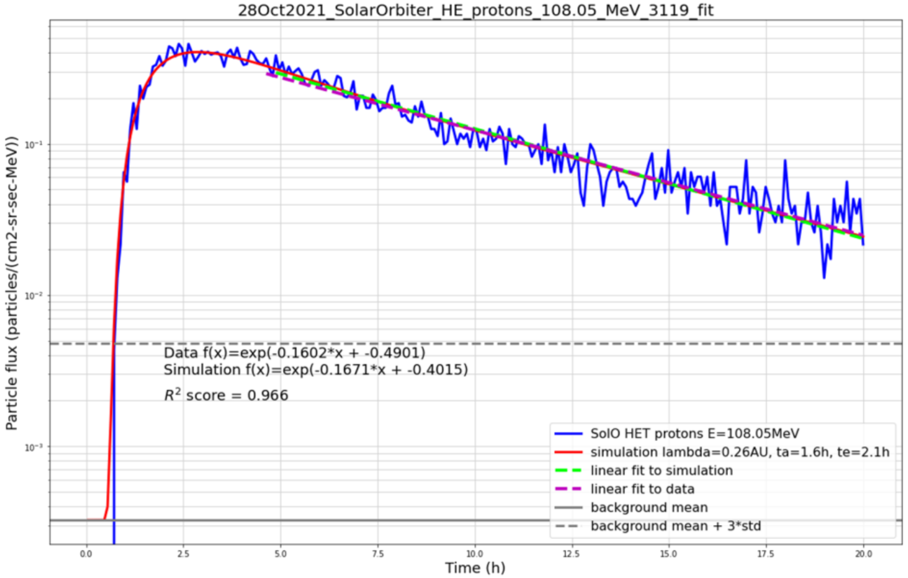


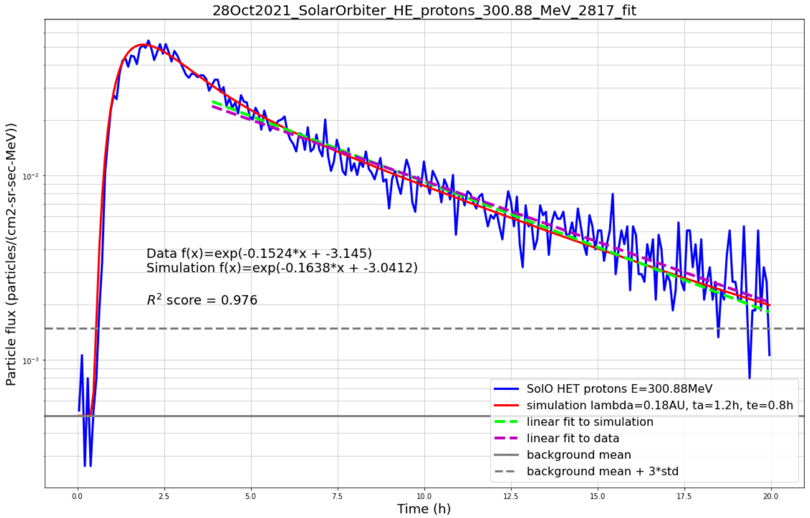
For details see
Kouloumvakos et al, 2024
Kuhl et al 2015, 2017

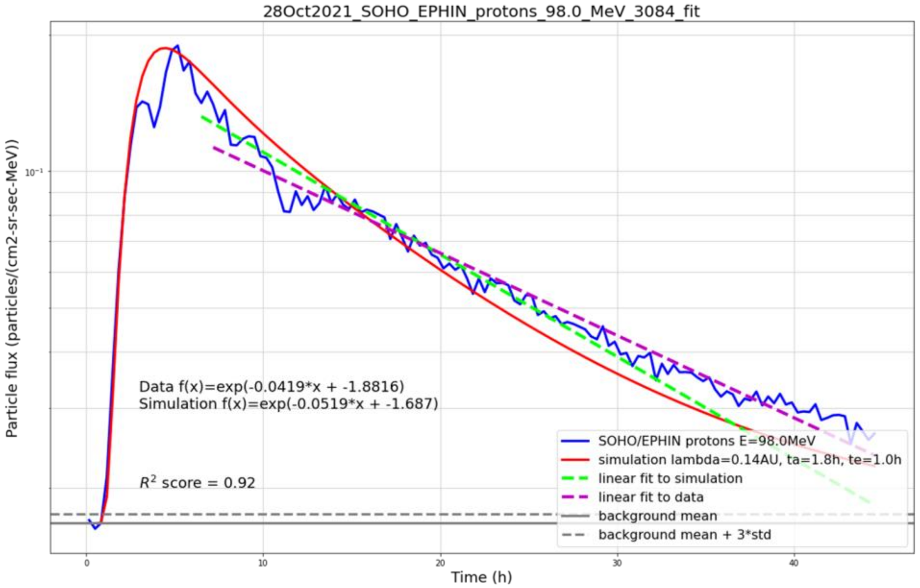
Magnetically disconnected observers

1D model: estimate **λ// , ta, te**



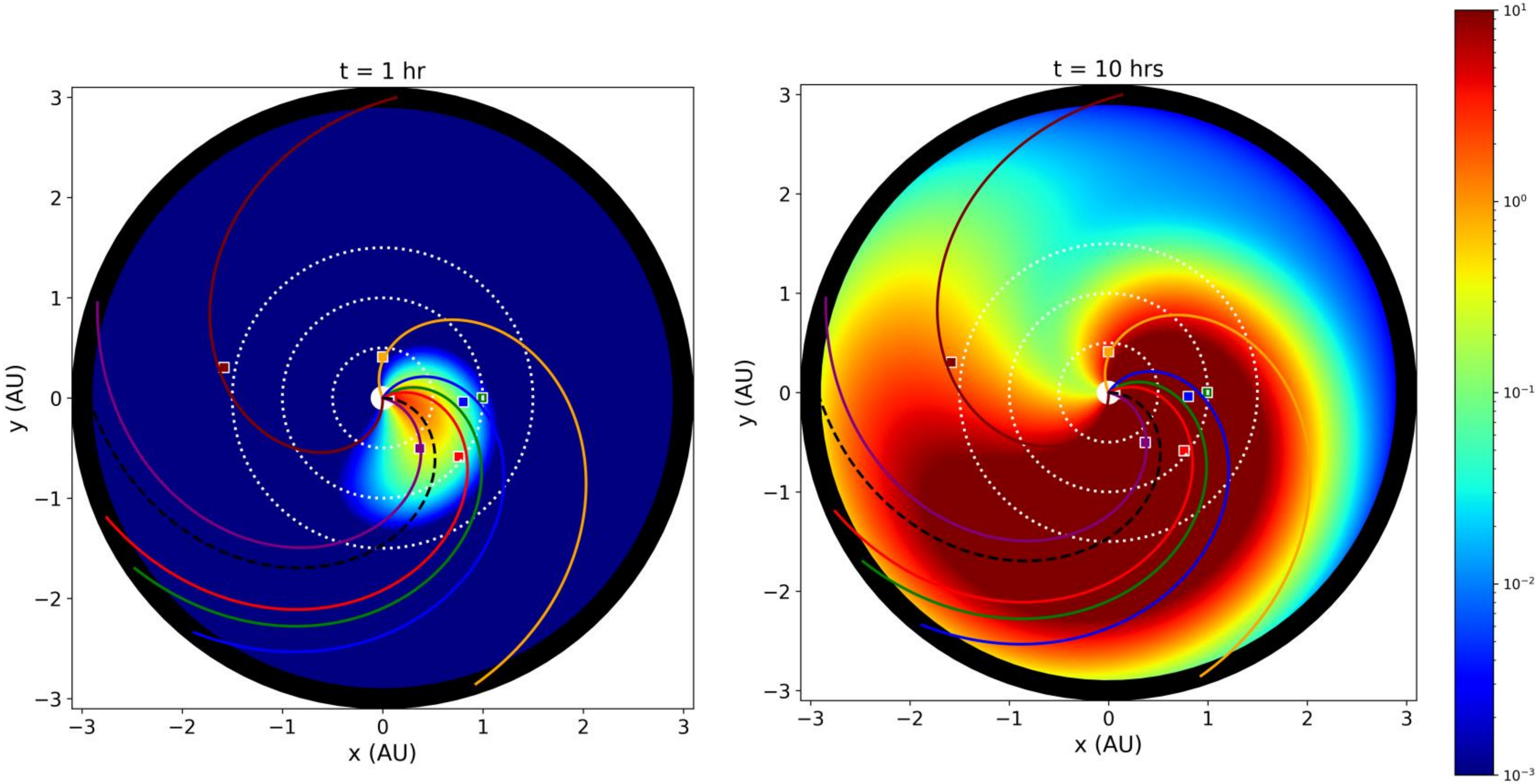


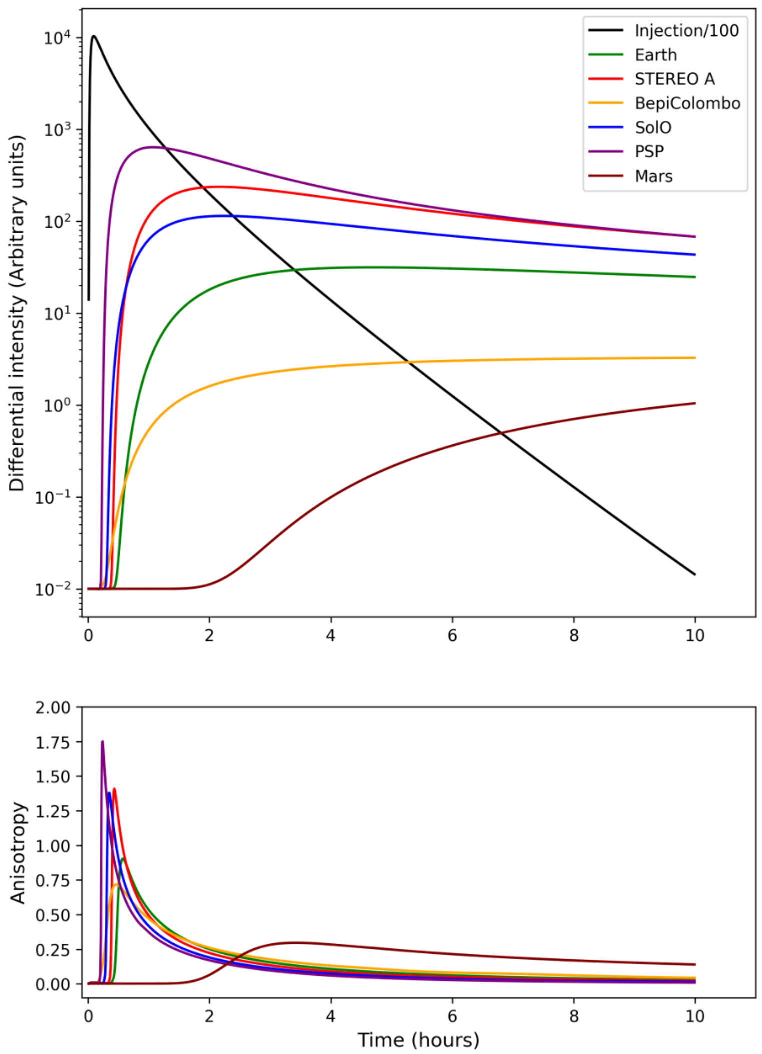




Magnetically disconnected observers

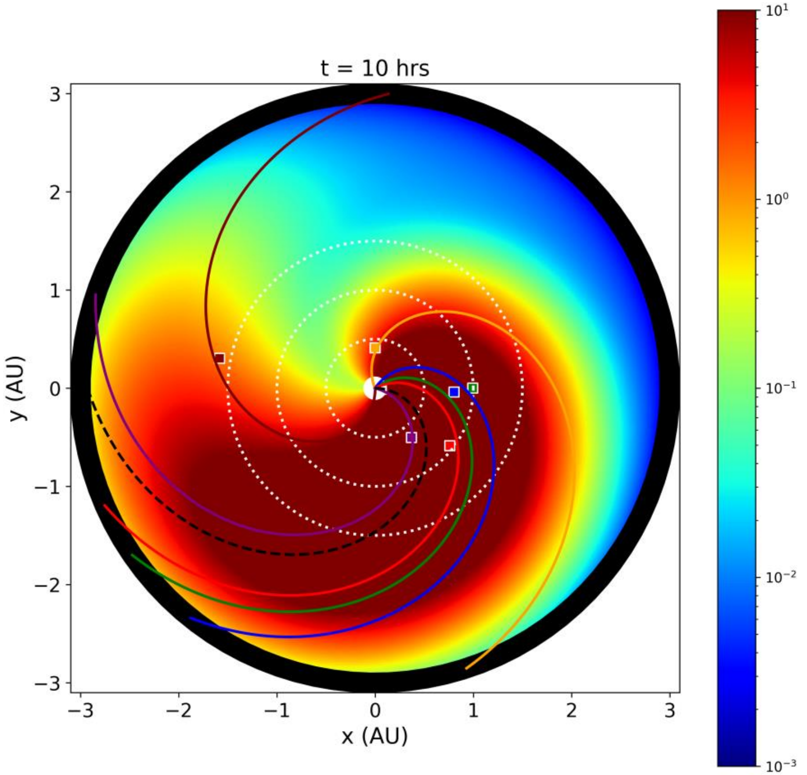
2D model:
Use fitted **λ//** , **ta, te**
Fit for **perpendicular mfp, size of injection source**



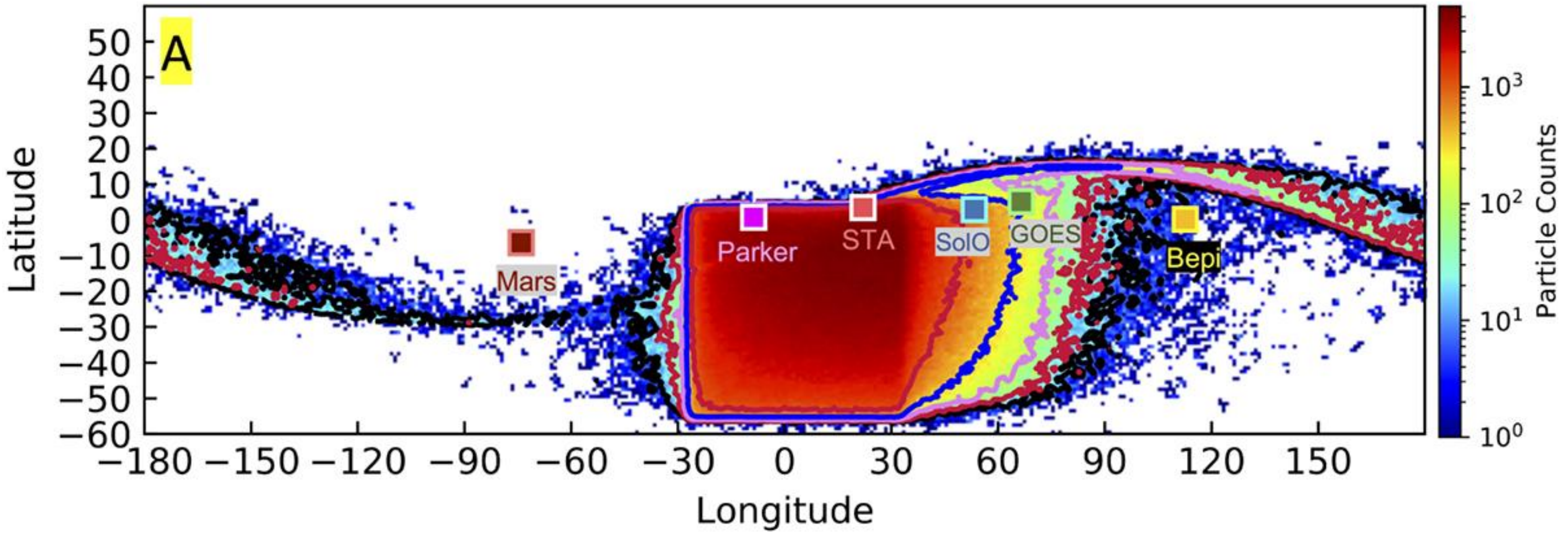


Magnetically disconnected observers

Injection source size: 5deg
Turbulent perpendicular diffusion



Extended source scenario: 30deg x 30deg
No perpendicular diffusion

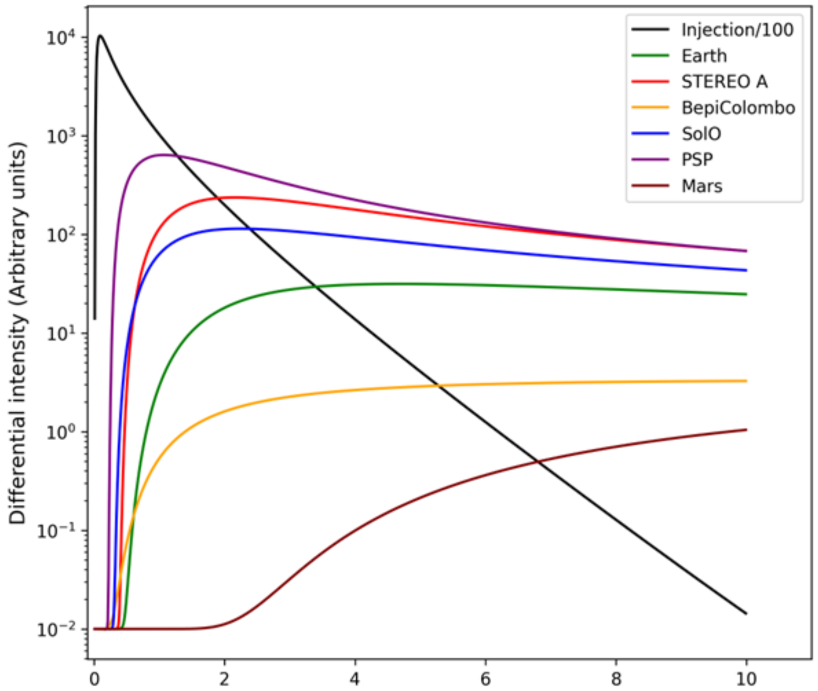


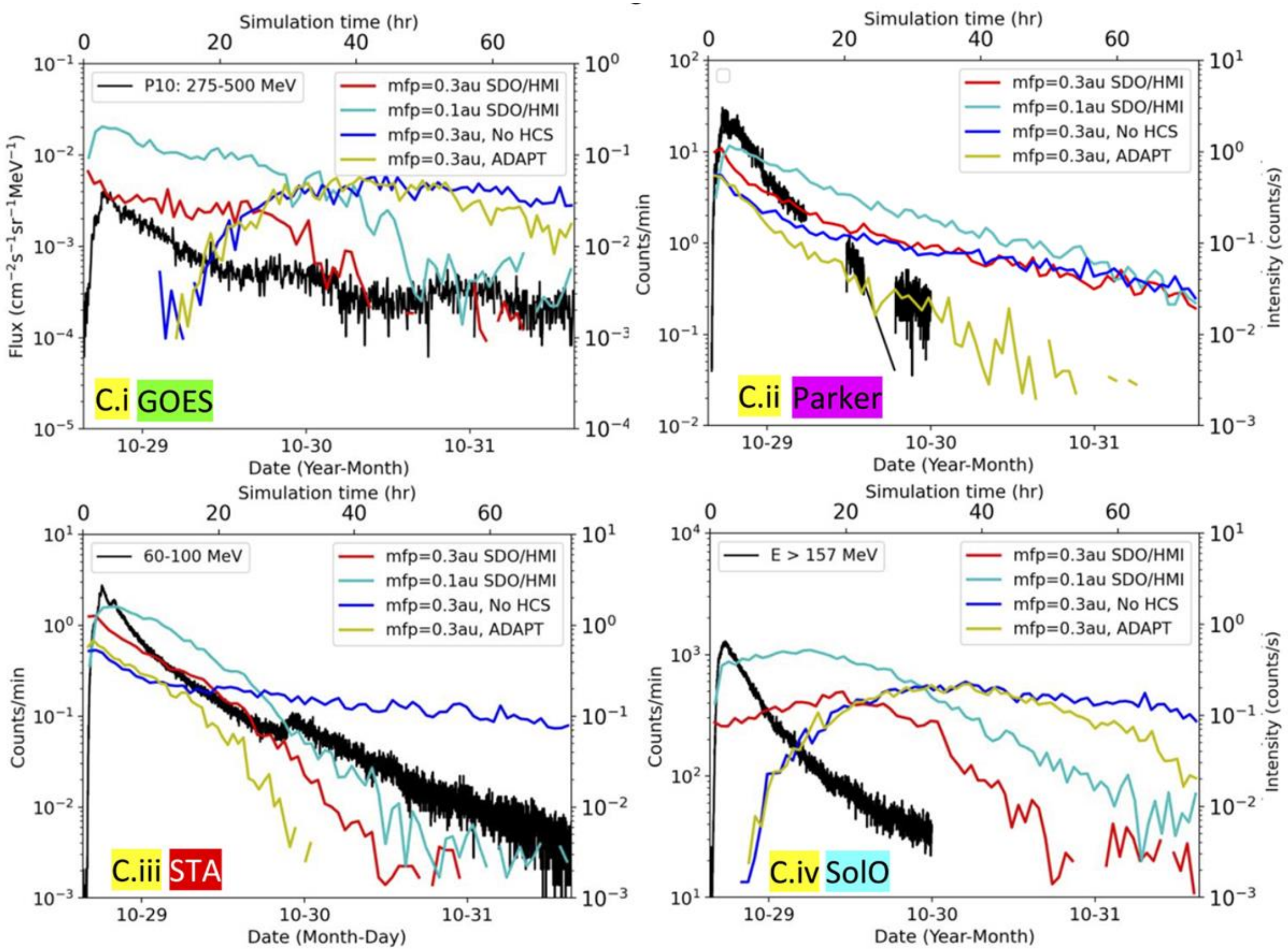
Kouloumvakos et al, 2024

Magnetically disconnected observers

Extended source scenario cannot fully account for the observed profiles

- No particles expected on Mars

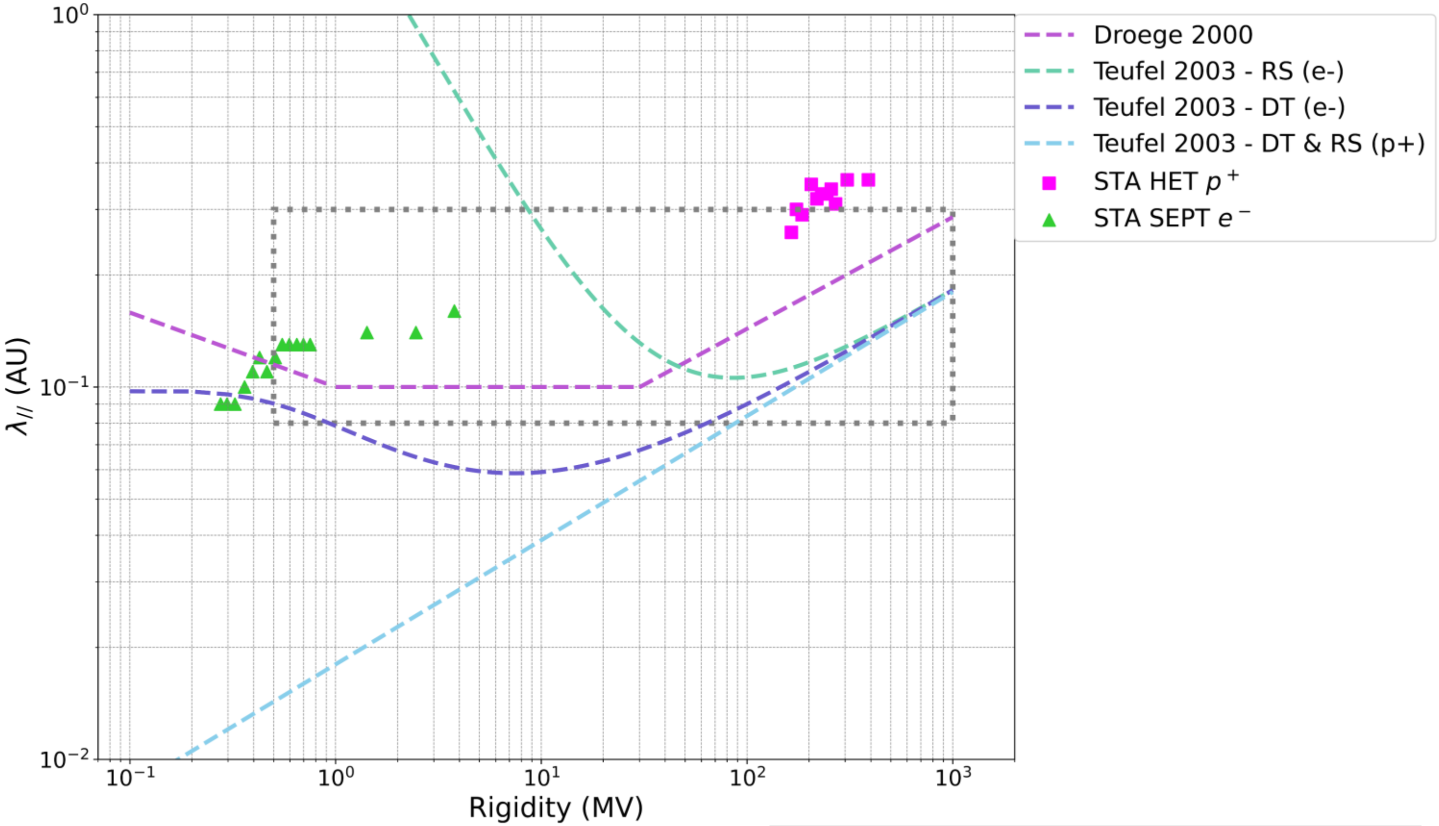


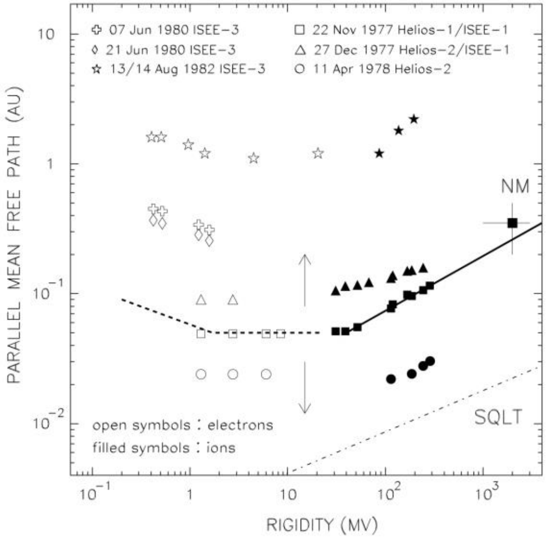


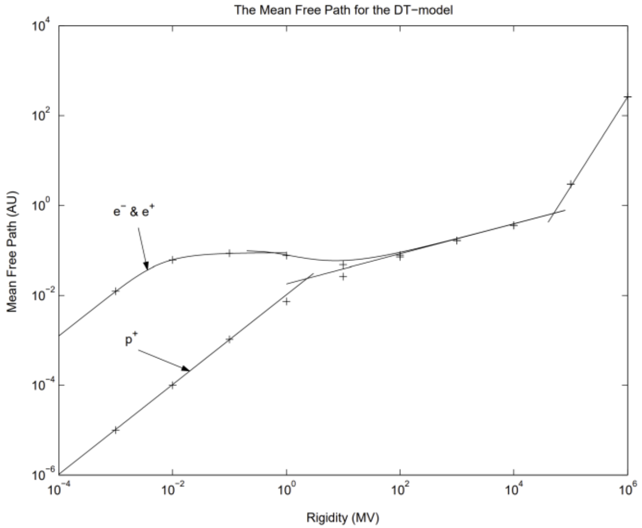
Kouloumvakos et al, 2024

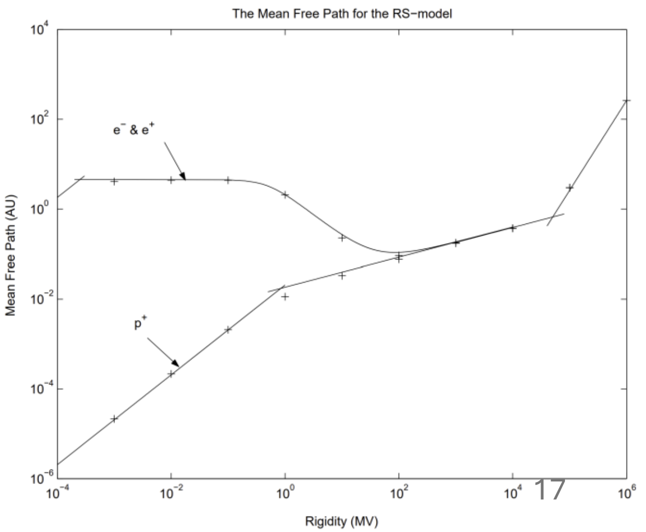
Rigidity dependence

- ❑ Use only well-connected observer
- ❑ p+ in par with expected trend
- ❑ e- follow an opposite trend



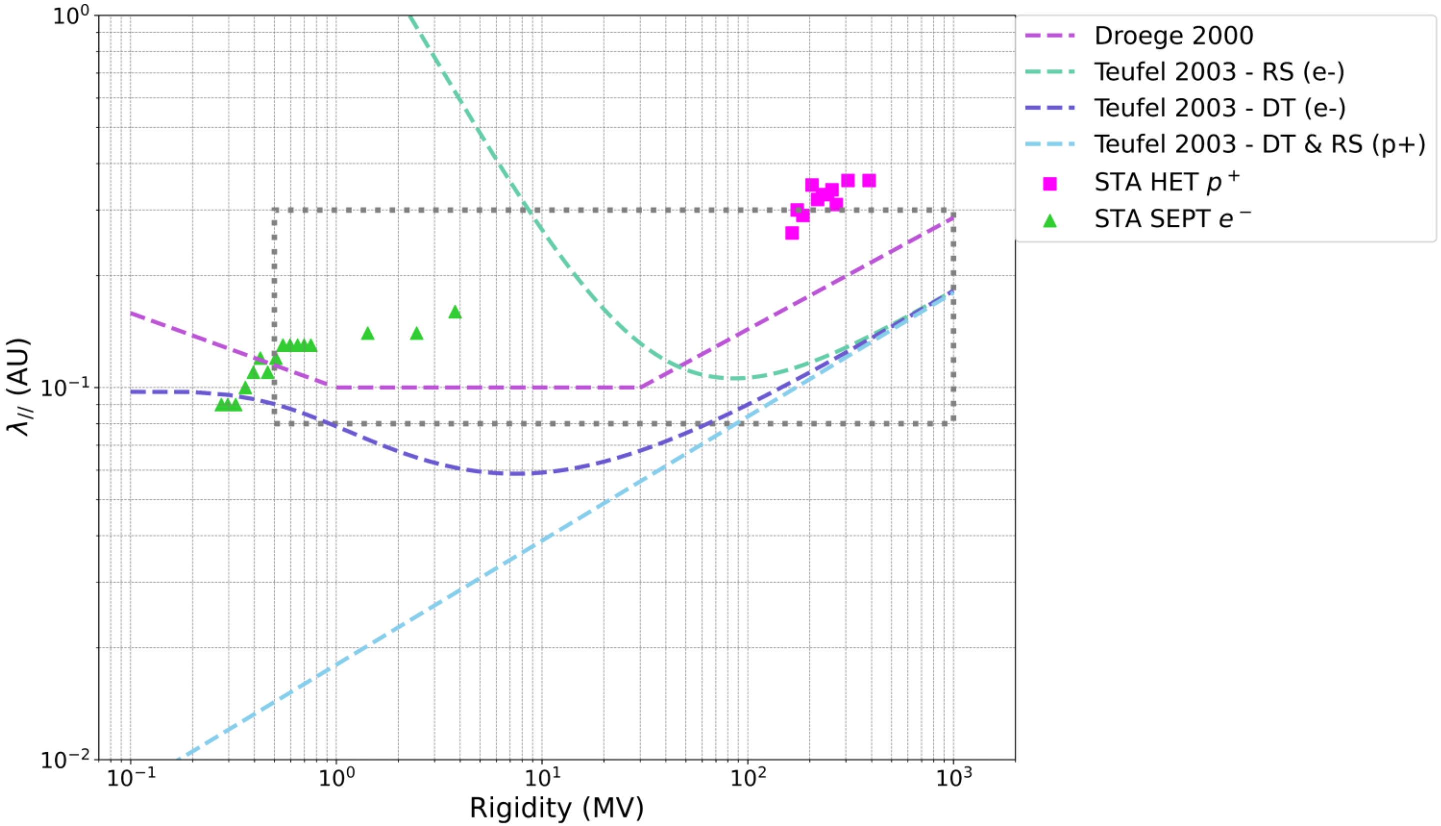


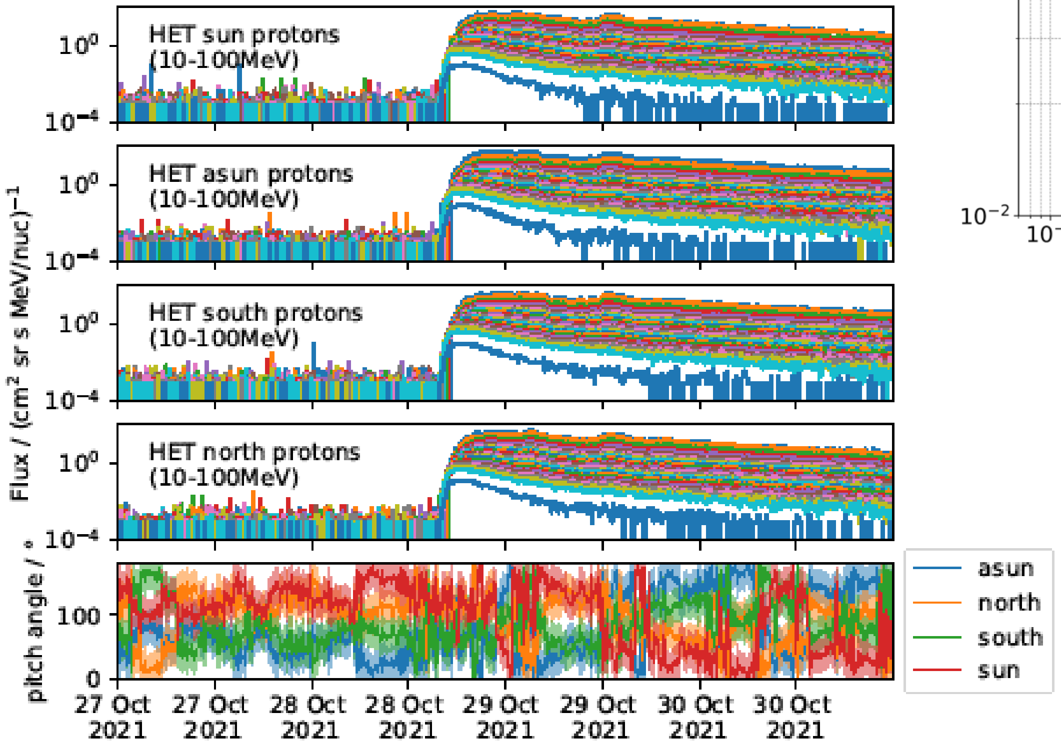




Rigidity dependence

- ❑ Use only well-connected observer
- ❑ p+ in par with expected trend
- ❑ e- follow an opposite trend





Ongoing work: Investigate anisotropy

$$A_1 = 3\,\frac{\sum_{i=1}^{N} \delta\mu_i \cdot \mu_i \cdot I(\mu_i)}{\sum_{i=1}^{N} \delta\mu_i \cdot I(\mu_i)}$$

$\delta\mu_i \rightarrow$ Pitch-angle ranges

$\mu_i = \cos(\alpha) \rightarrow$ Pitch-angle (or pitch-cosine)

$I(\mu_i) \rightarrow$ Intensity at that pitch-angle