Ground-level enhancement pulse shape and solar wind stream interface

Olakunle Ogunjobi
Department of Physics and Astronomy, University of Calgary

DASP WORKSHOP

UNIVERSITY OF CALGARY

Cosmic Ray Ground Level Enhancement (GLE)

•Abrupt intensity increases in cosmic rays registered by ground-based detectors such as neutron monitors

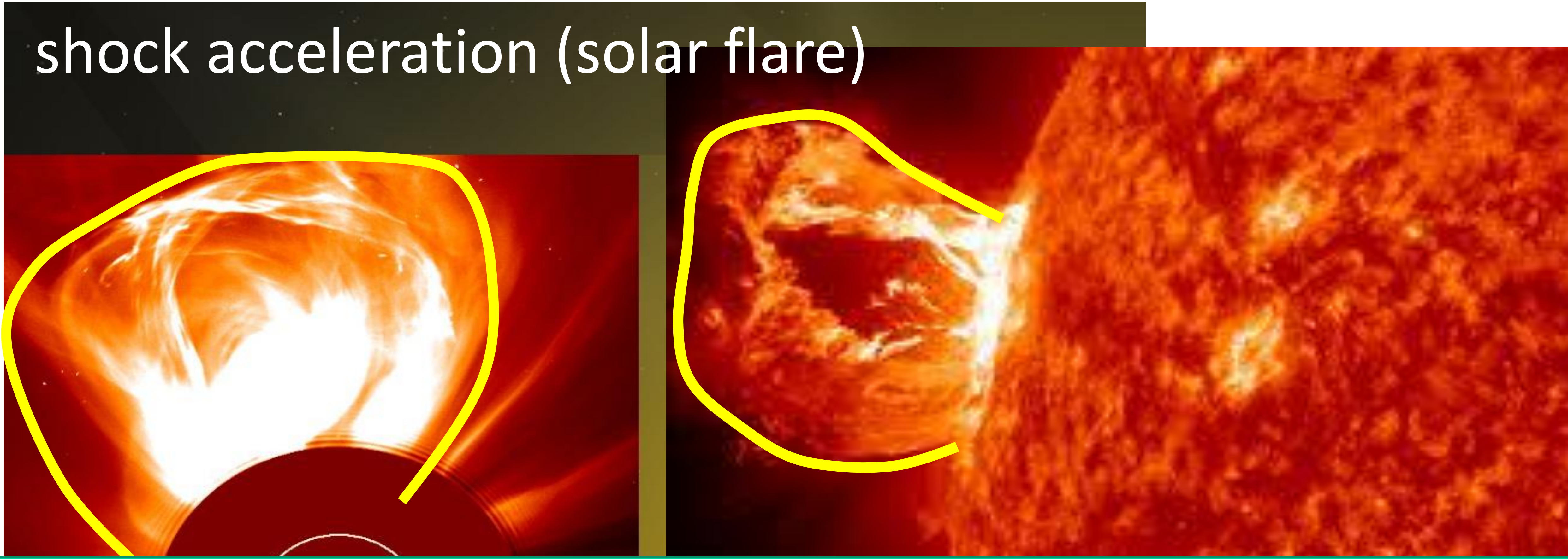
•Caused by relativistic solar energetic particles (SEPs) with energies ≥ 500 MeV impacting Earth's atmosphere

•Produce atmospheric shower of secondary particles, some reaching ground level

•Typically proton intensities elevated 10-100% above galactic background levels; 73 GLEs observed since 1942; useful measure of most intense SEP events and space weather

•**Associated with explosive solar eruptions like flares and coronal mass ejections; GLE intensity-time profiles ("pulse shape") used to study particle acceleration and transport**

Solar flare and coronal mass ejection - shocks

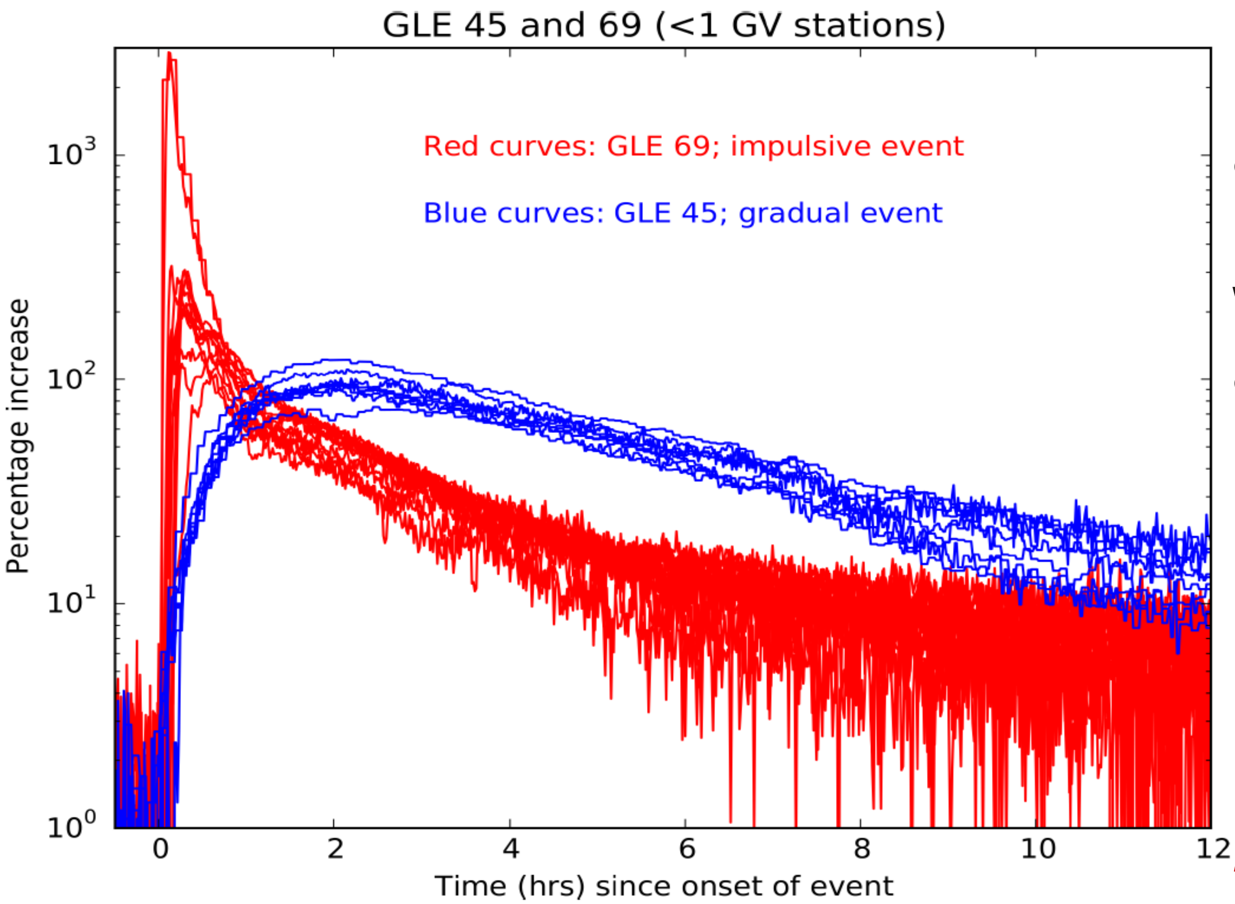


Classification:

impulsive (***with magnetic reconnection in solar flares***);

gradual (***diffusive shock acceleration in the shock front of large CMEs***) **events**

GLE Events: Gradual and Impulsive



Background:

Impulsive GLEs have faster rise times and are thought to originate from solar flares,

while gradual GLEs have slower rise times and originate from CME-driven shocks.

Motivation:

Can interplanetary transport effects like scattering modify the time profile between the Sun and Earth, complicating this classification scheme?

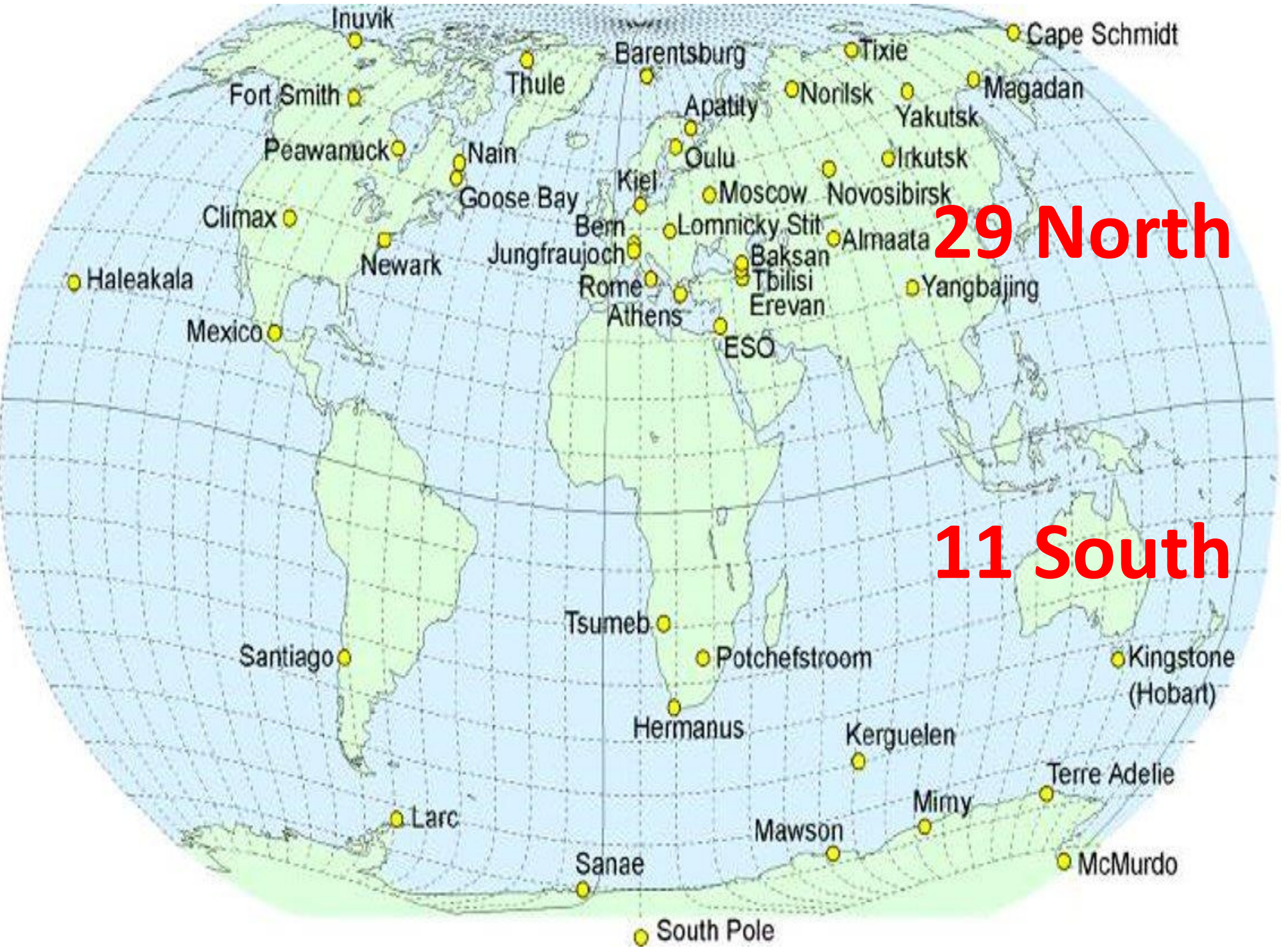
Methods:

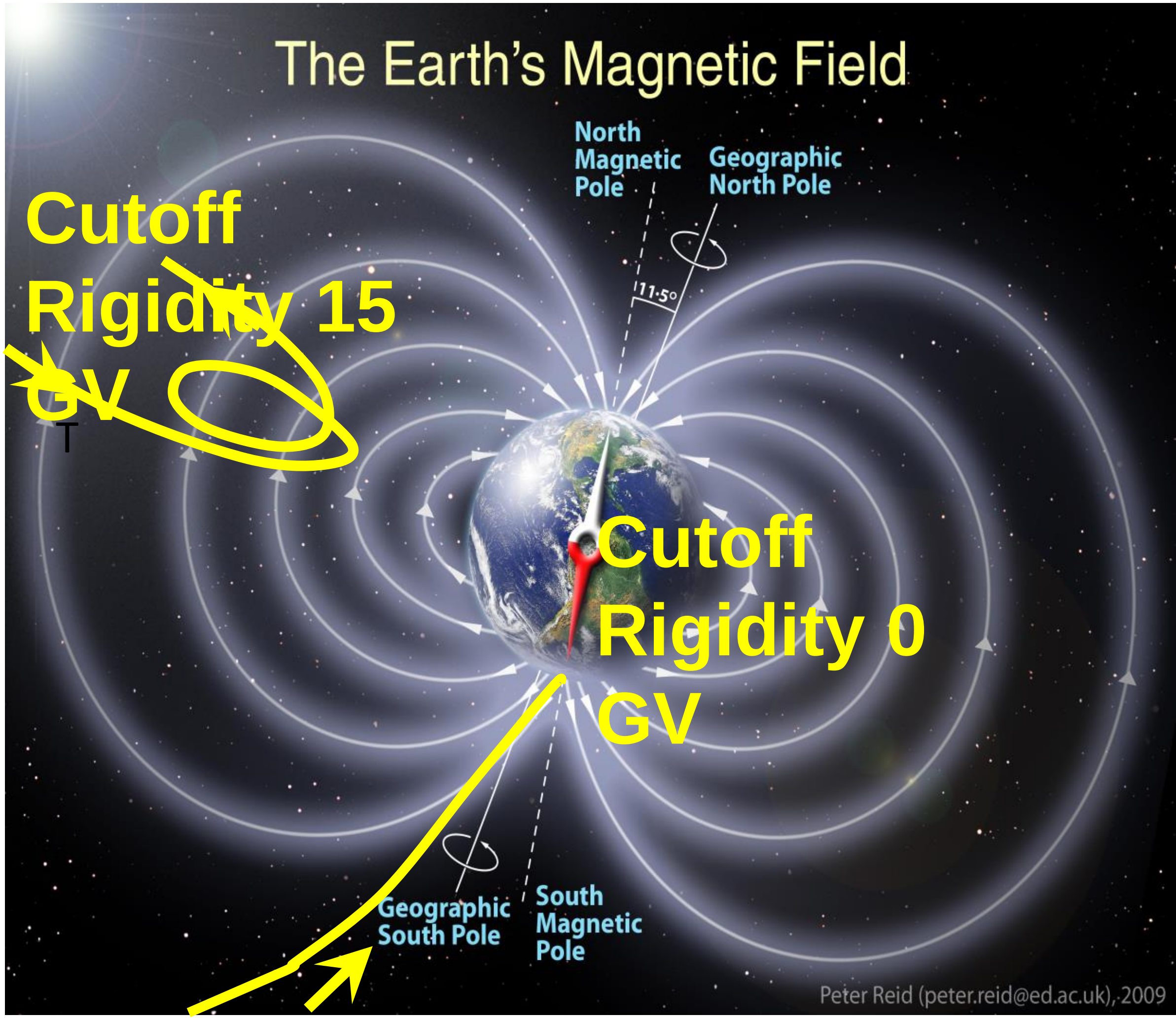
Analyzed the rise time and decay time of GLE events using multiple neutron monitor stations(> 1 cutt-off rigidities)

Employed a numerical model solving the cosmic ray transport equation to simulate pulse shapes.

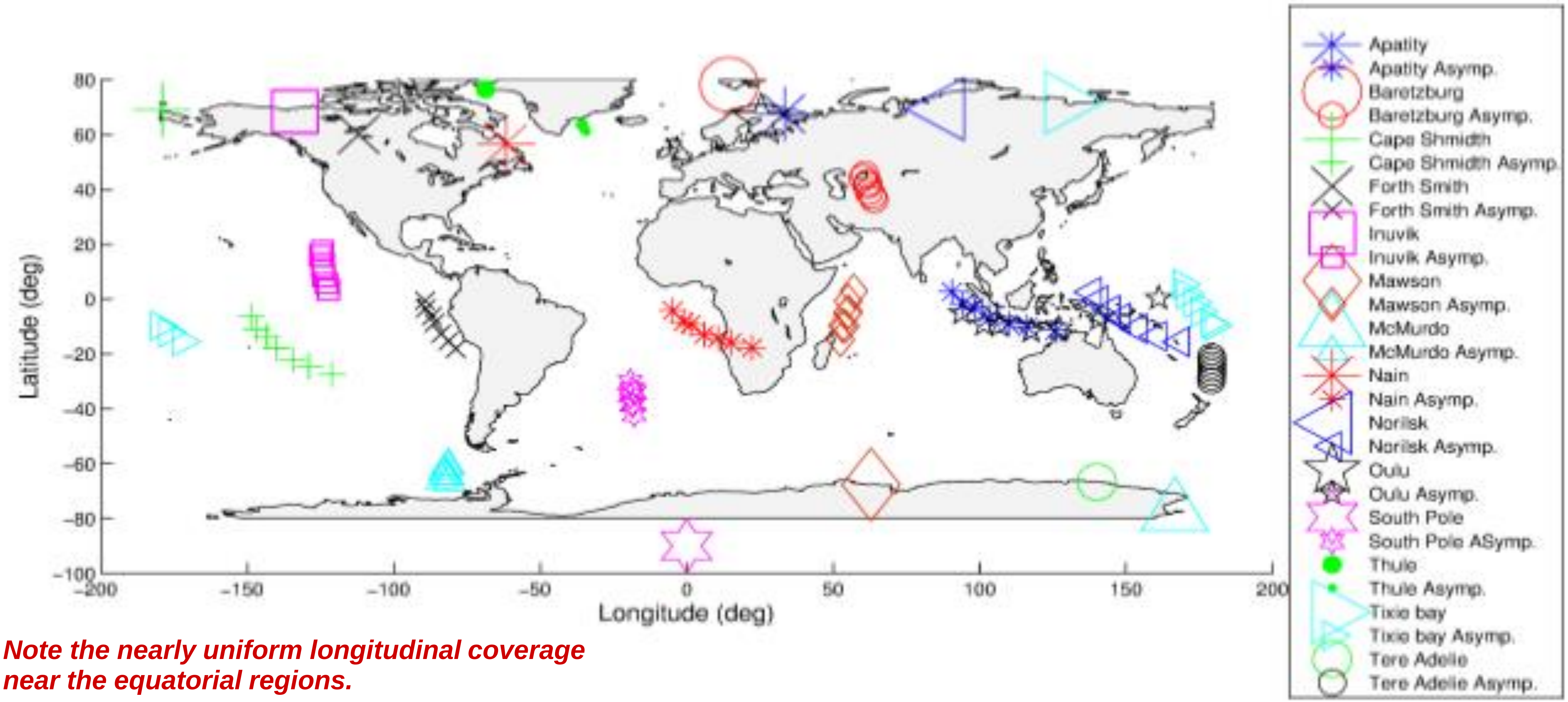
Compared numerical solutions to analytical transport approximations for an isotropic distribution.

Neutron monitor network





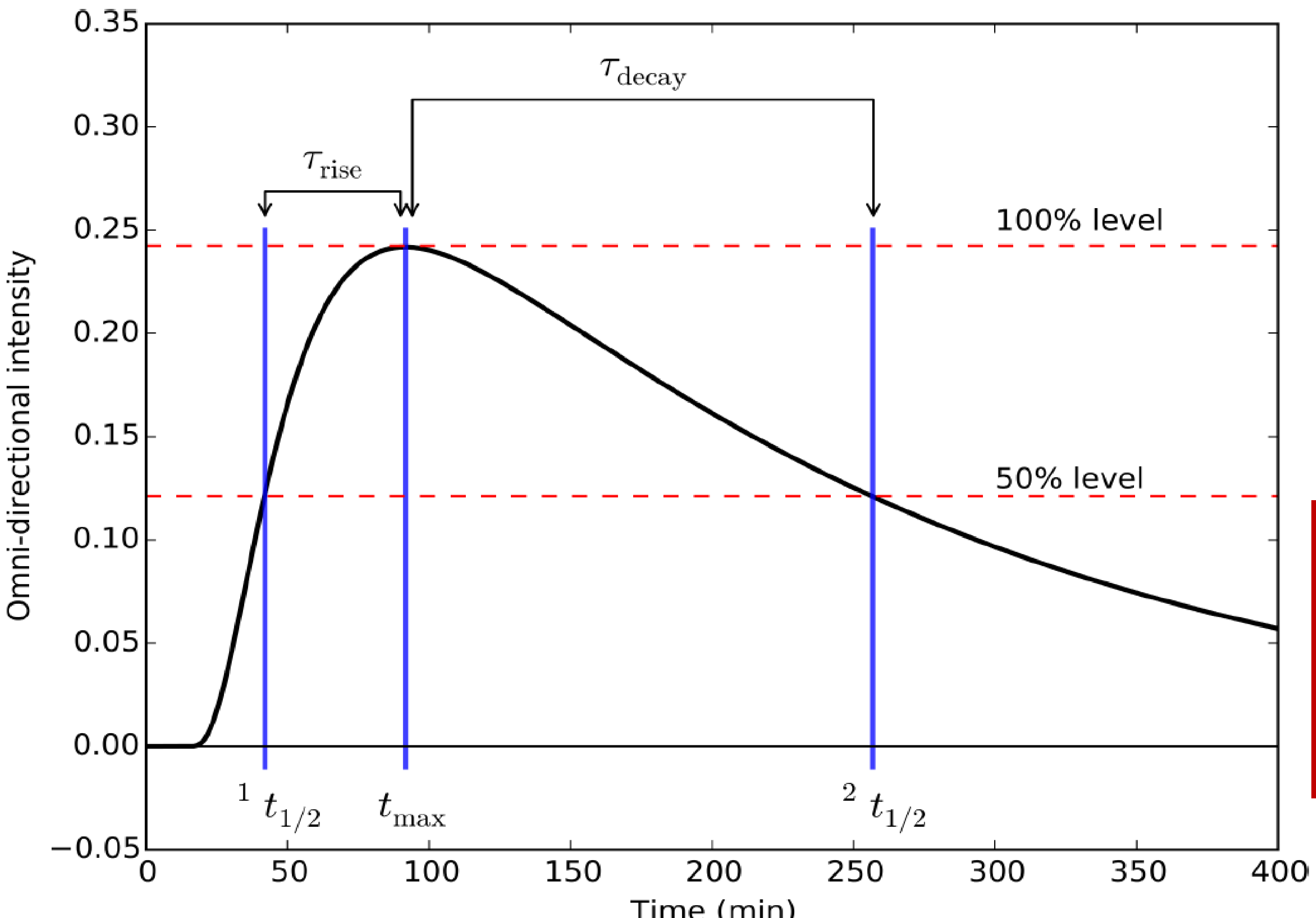
Asymptotic cone of acceptance



Note the nearly uniform longitudinal coverage near the equatorial regions.

- **Calculated asymptotic viewing directions of neutron monitors used;**
- **shows good longitudinal coverage to reduce directional bias;**
- **allows averaging over many stations.**

Rise time instead of time to the maximum

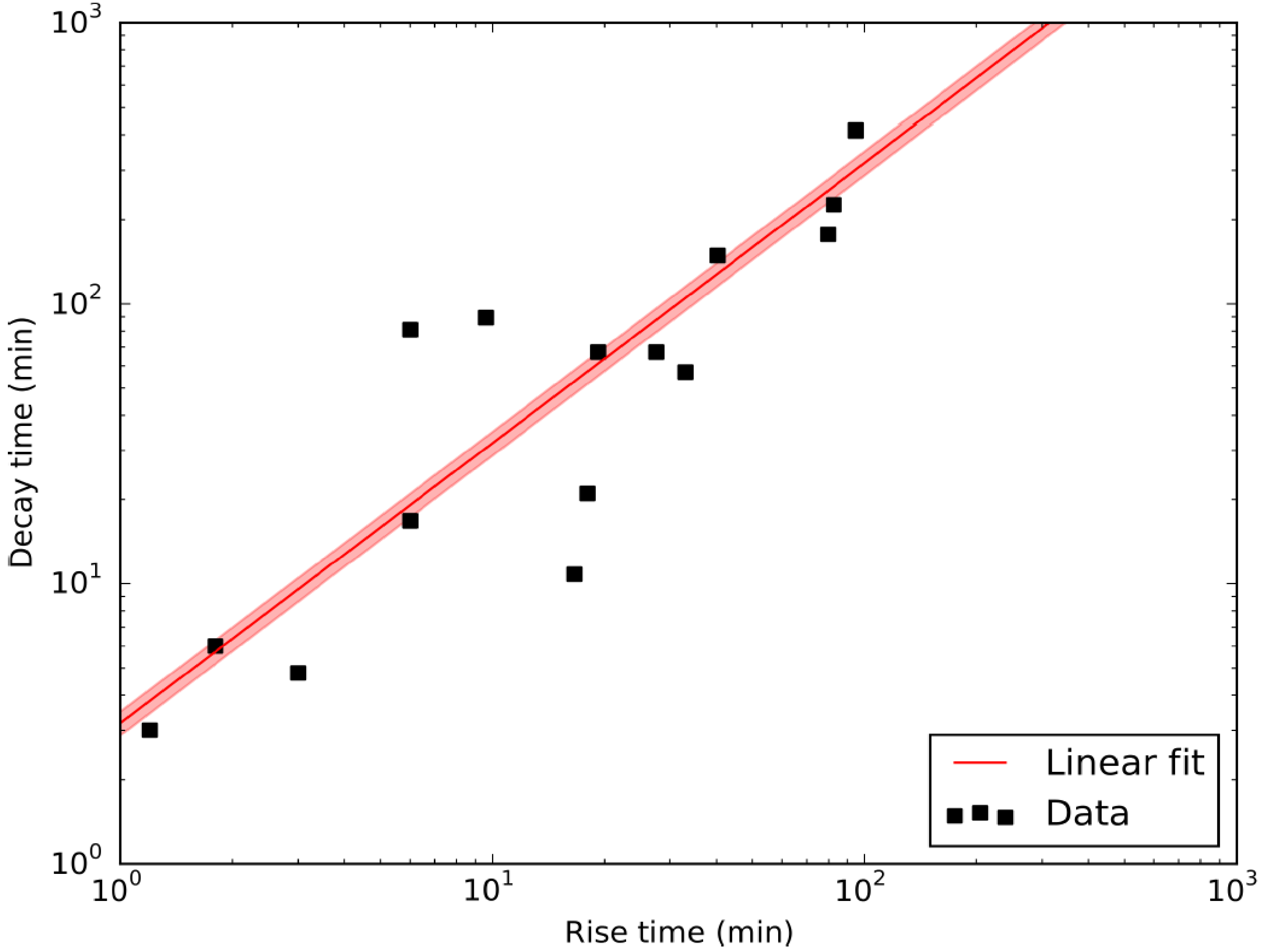


The time profile of the omni-directional intensity is calculated and the time of maximum intensity, t max, recorded.

We then search for times when the intensity is half of its maximum value and note the corresponding times $^1t_{1/2}$ and $^2t_{1/2}$.

- Definition of rise and decay times from intensity profile;
- quantifies pulse shape;
- allows systematic characterization across events.

Rise vs Decay times



The decay time is roughly 3 times longer than the rise time for a broad range of time-scales containing both impulsive and gradual events.

- **Rise and decay times for 15 GLEs;**
- **shows linear relation despite event variations;**
- **suggests common dependence on transport.**

Next, we interpret this seemingly universal dependence in terms of a particle transport model.

Comparison with Theory

Transport Equation for cosmic-ray intensity *f*

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

Convection Diffusion Energy changes

The propagation of a gyro-tropic distribution of SEPs can be described by the Roelof (1969) transport equation

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

Following **Dröge et al. (2010)**, we parametrize the pitch-angle diffusion coefficient as:

$$D_{\mu\mu}(z,\mu) = D(z)\left(1-\mu^2\right)\left\{ |\mu|^{q-1} + H \right\}$$

q = 5/3 is the spectral index of the inertial range of the turbulence power spectrum and;

H = 0.05 a parameter to account for non-linear or dynamical processes

Analytical approximations

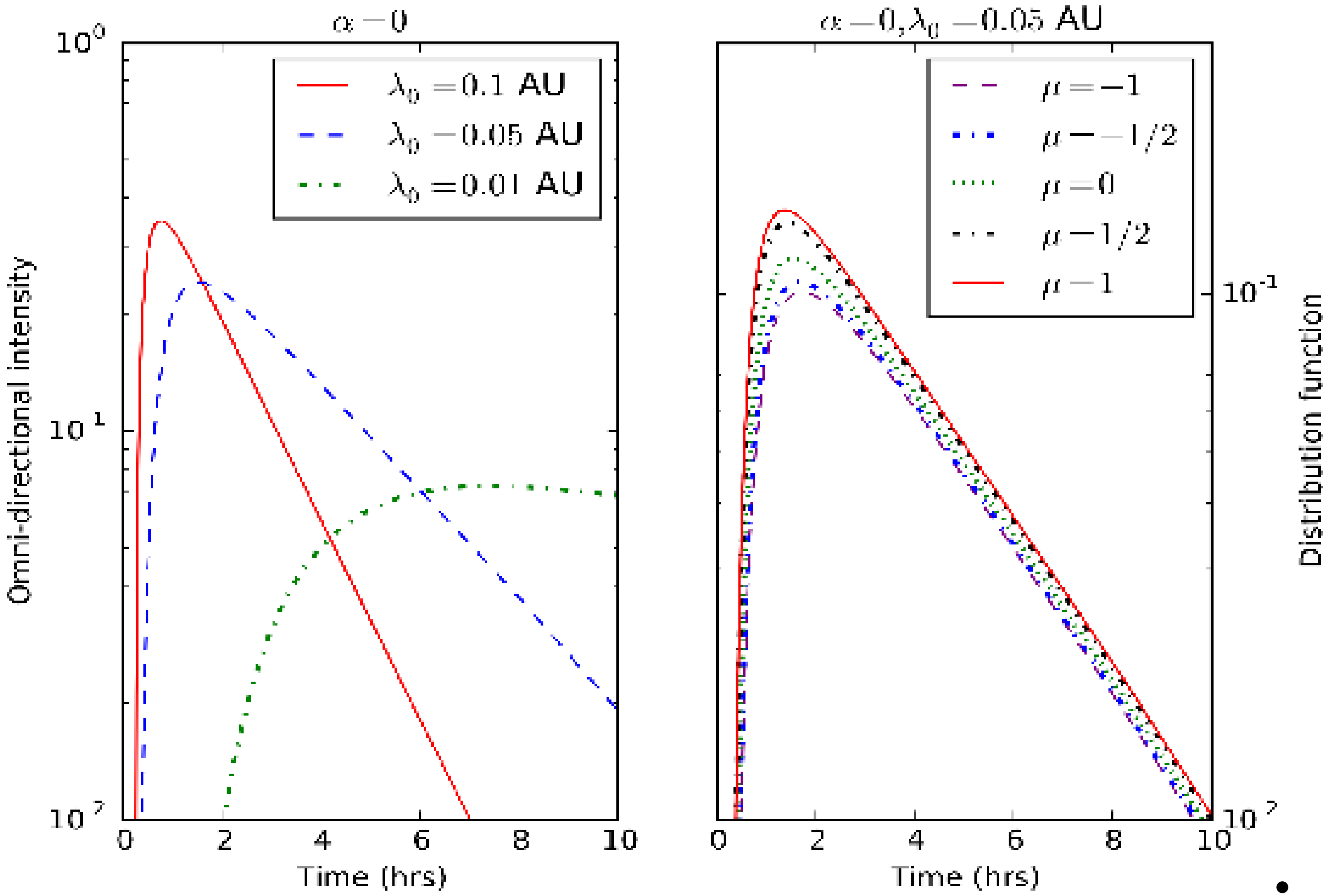
In order to compare our results to analytical approximations, and to get a more intuitive feeling for the level of particle scattering, we specify the parallel mean free path:

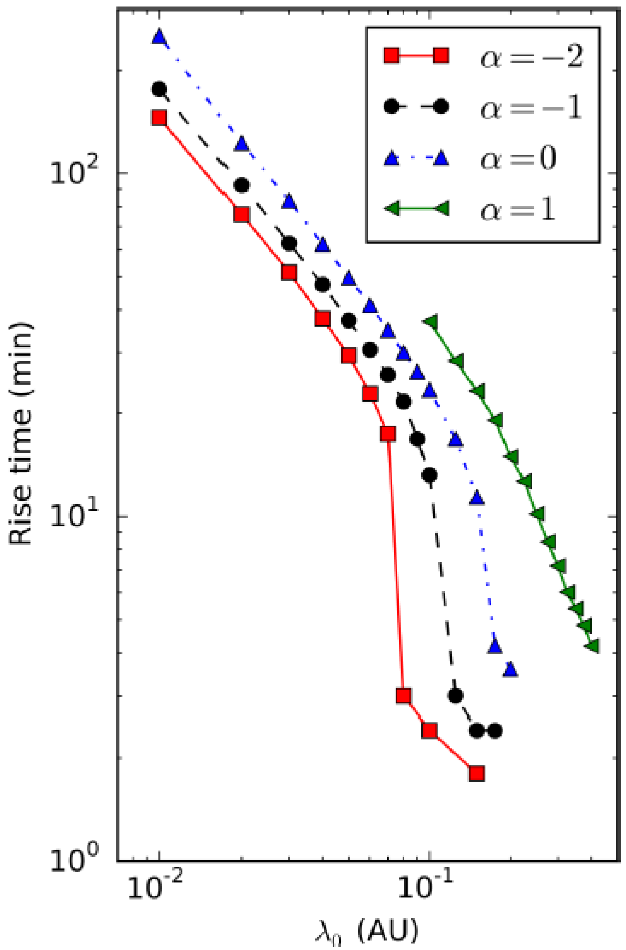
$$\lambda_{||}(z) = \frac{3v}{8} \int_{-1}^{+1} \frac{\left(1-\mu^2\right)^2}{D_{\mu\mu}(z,\mu)} d\mu,$$

in the model rather than $D_{\mu\mu}$

These two quantities are related through **Hasselmann and Wibberenz (1968)**

Interpretation in terms of diffusive transport theorem

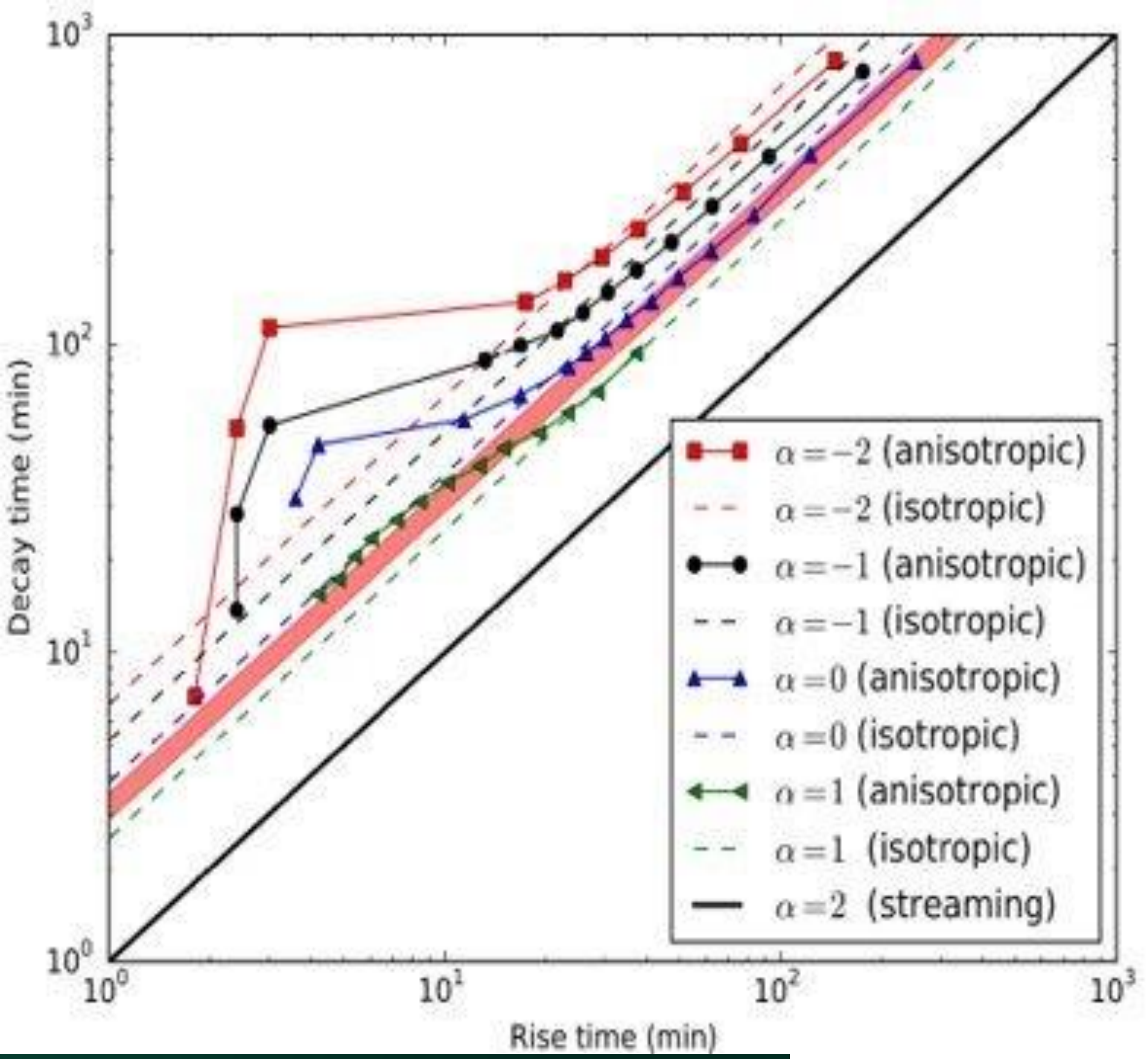




- Model intensity profiles and distributions;
- scattering controls pulse shape;
- even isotropic injection can produce gradual profiles.

- Modeled rise times vs scattering strength;
- linear relation in isotropic limit;
- slope depends on scattering spatial dependence.

Model vs observations



- Model vs observations show same linear trend;
- best fit for radially constant scattering;
- transport determines pulse shape.

IMPLICATION:

This suggests frequent strong pitch angle scattering leads to near-isotropic particle distributions, obscuring the original solar injection profile.

FURTHER EVIDENCE

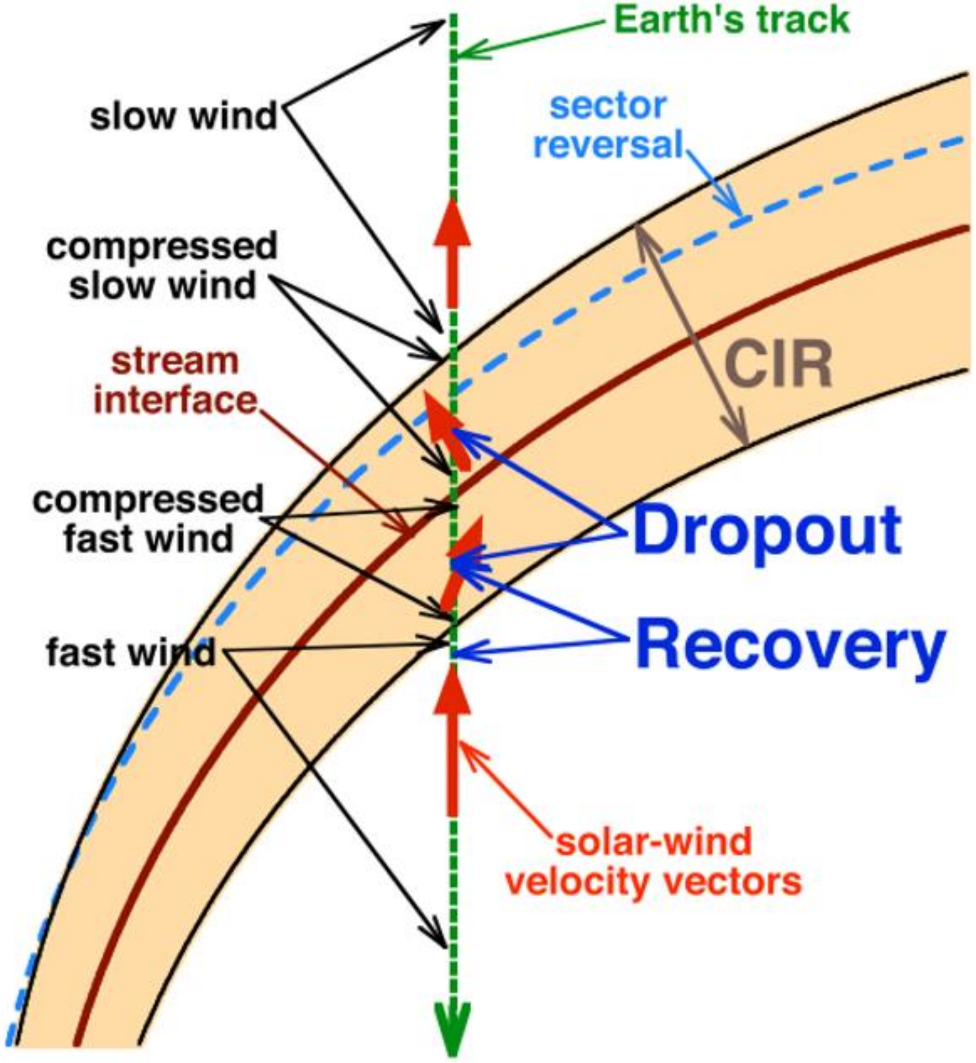
- Incorporates modeling constrained by upstream solar wind observations, including identification of a stream interaction region (SIR), to quantify scattering effects altering the pulse shape.

Further evidence: SI driven storms

We examined GLE 72 specifically, incorporating modeling constrained by upstream solar wind observations.

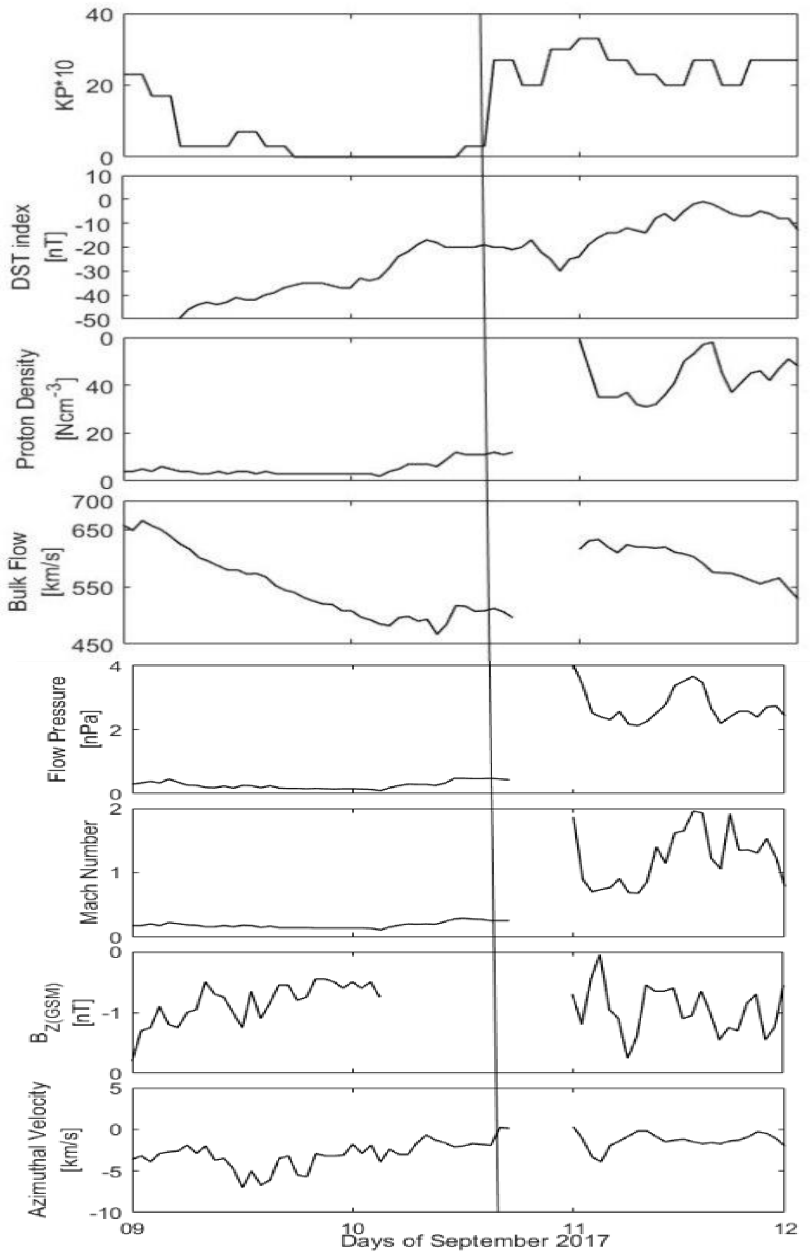
A stream interaction region (SIR) was identified prior to the event.

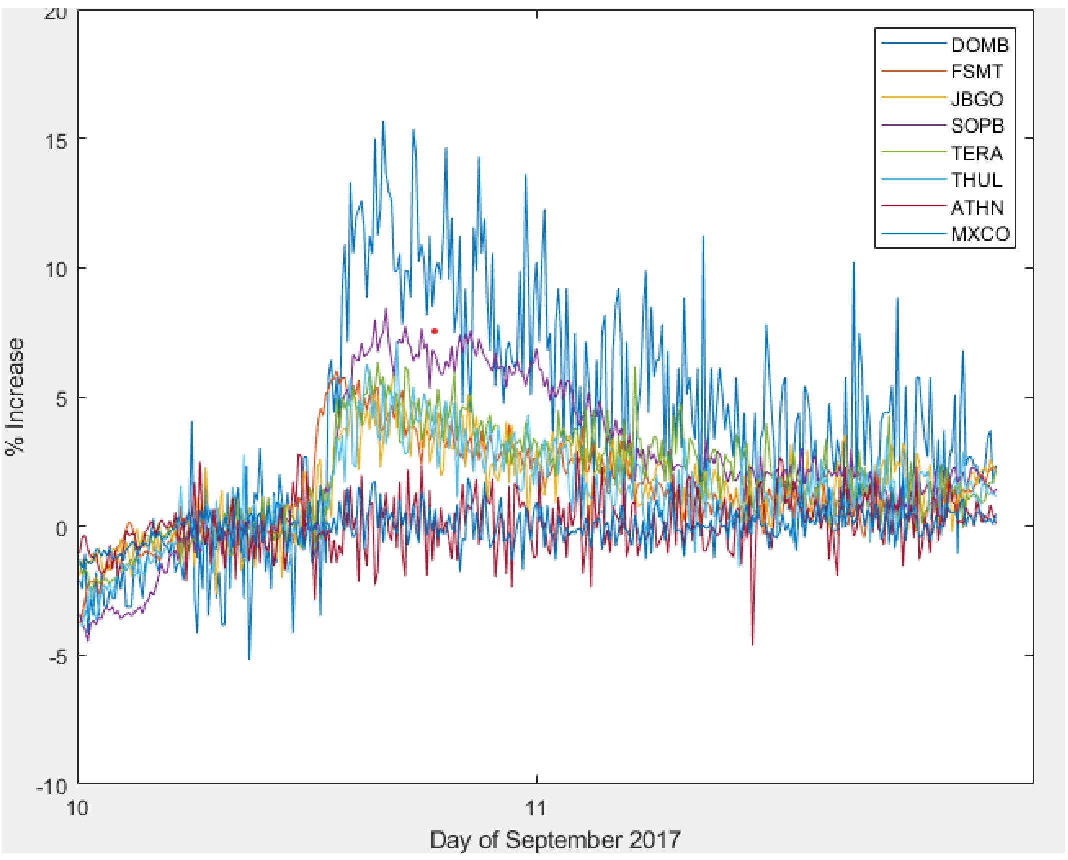
Modeling including enhanced scattering across the SIR matched the gradual intensity profile measured by neutron monitors during GLE 72.



Borovsky and Denton (2010)

GLE 72 observation and fortuitous SIR event

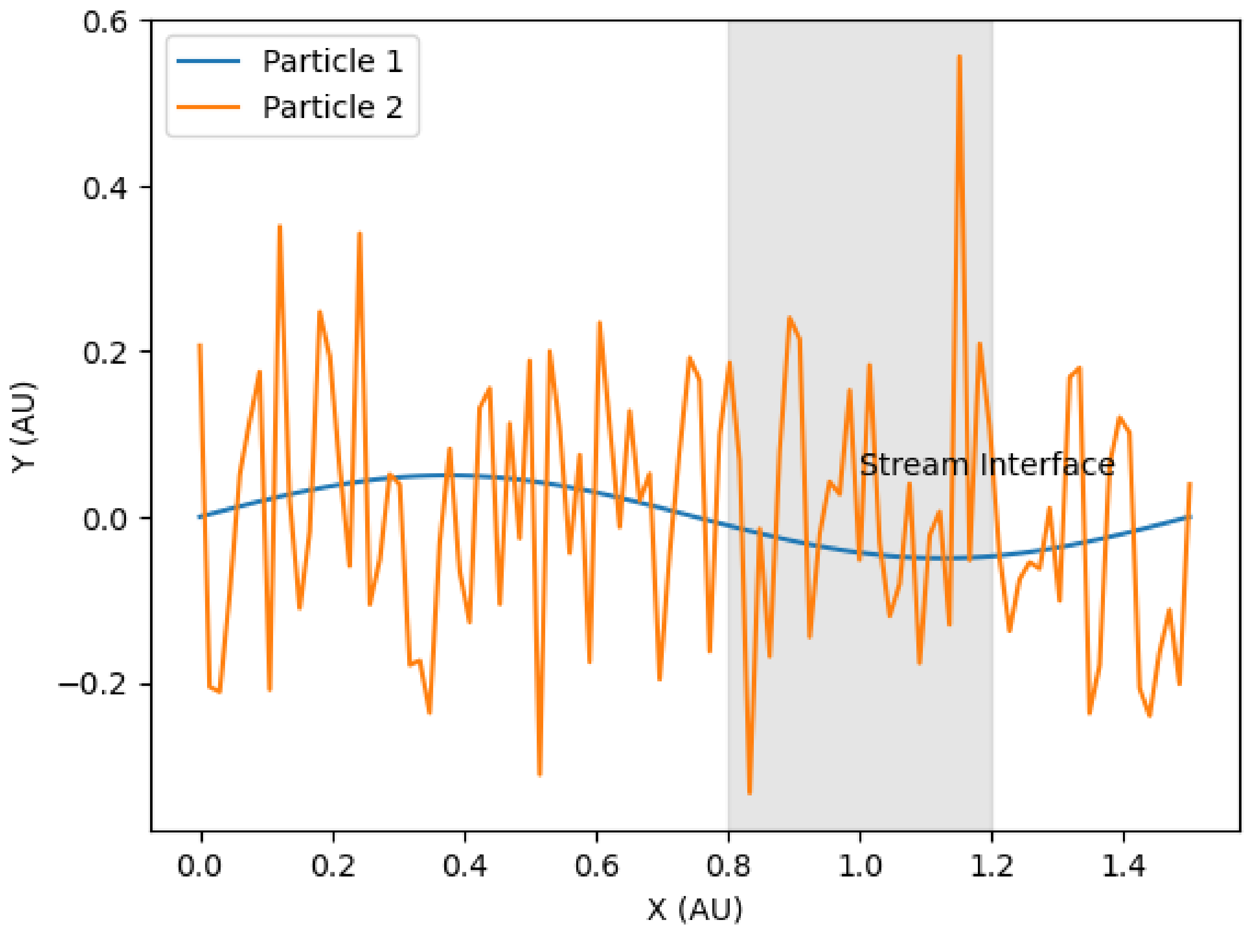




- Solar wind plasma measurements including compressed slow wind in a stream interaction region prior to GLE 72;
- illustrates transient interplanetary conditions particles propagate through.

Neutron monitor intensity profiles for GLE 72 from multiple stations; demonstrates moderate 25-30% intensity, gradual 8+ hour rise inconsistent with impulsive flare acceleration.

Testing the pitch angle diffusion at SIR

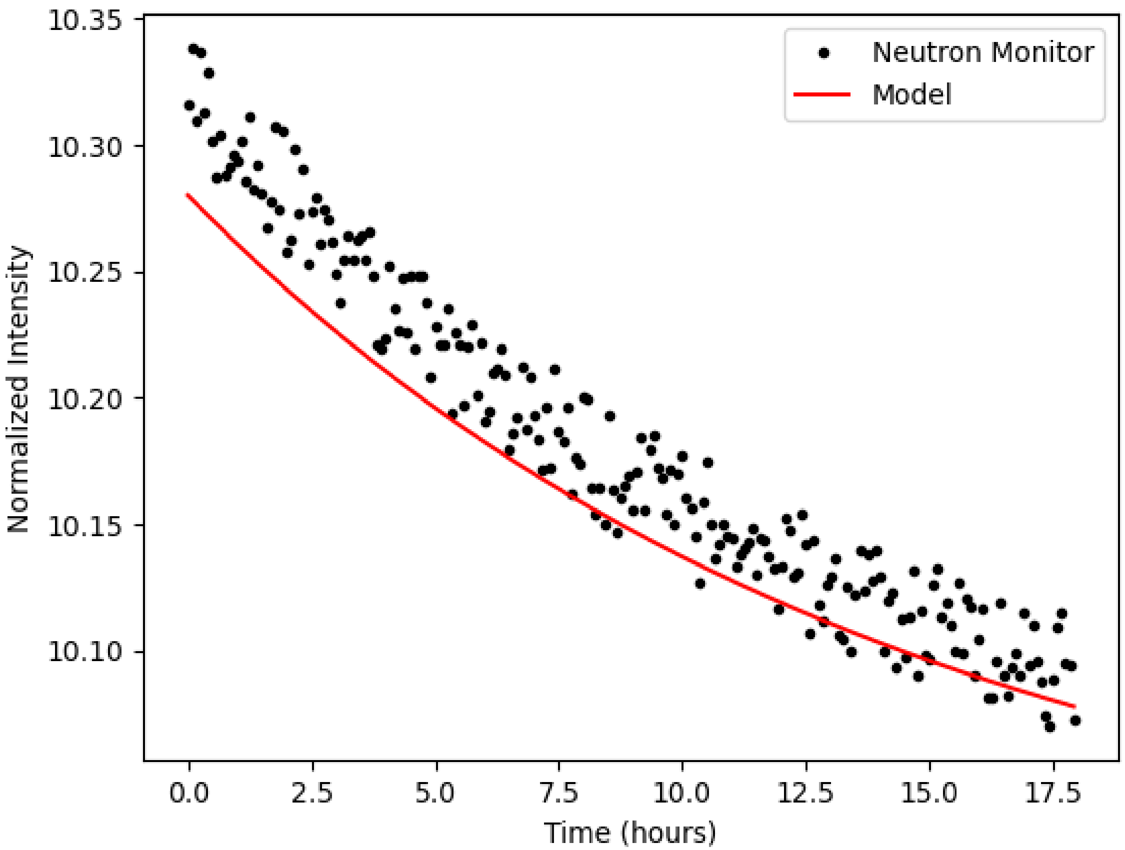


Particle 1 undergoes little scattering and advects directly through the stream interface region from 0.8 to 1.2 AU.

In contrast, Particle 2 has a randomized trajectory demonstrating increased pitch angle diffusion across the interface.

Individual particle trajectories contrast weak and strong scattering cases across the SIR, directly demonstrating increased pitch angle diffusion.

Modeled intensity profile comparison with NM



- **Mean free paths decreased by 33% and;**
- **decay constants increased by 35% within the SIR due to compressed flows and fields driving turbulence.**

We validates the modeled intensity profile against a neutron monitor observation:

- **exhibiting a 30% peak enhancement and**
- **12-hour decay timescale typical of small GLE events.**

The Monte Carlo approach including turbulence effects across the stream interface reproduces critical features like:

- **the 28% intensity maximum and**
- **14-hour decay constant, supporting its ability to constrain the interplanetary transport processes influencing ground detections.**

SUMMARY

- In summary, this work demonstrate interplanetary transport effects substantially modifying observed GLE intensity-time profiles.

- **The concept of classifying GLE events as intrinsically impulsive or gradual based solely on pulse shape becomes superfluous.**

- Instead, modeling constrained by solar wind data is required to disentangle acceleration and propagation contributions. Even minor solar wind structures can prolong SEP event signatures through increased particle scattering.

NEXT:

- **Pitch angle diffusion coefficient (How it varies through stream interface.**

Acknowledgements

Prof. David Knudsen,
Prof. Du Toit Strauss,
Dr. Helena Krüger,
Dr. Anne Mans,
Gert Benadé + Students + cosmic-ray and astrophysics working group
+ Antarctic expedition members of North-West University, Potchefstroom, South Africa
+ Department of Physics and Astronomy, University of Calgary.

In sweet memory of:

Prof. Ham Moraal and Prof. Pieter Stoker