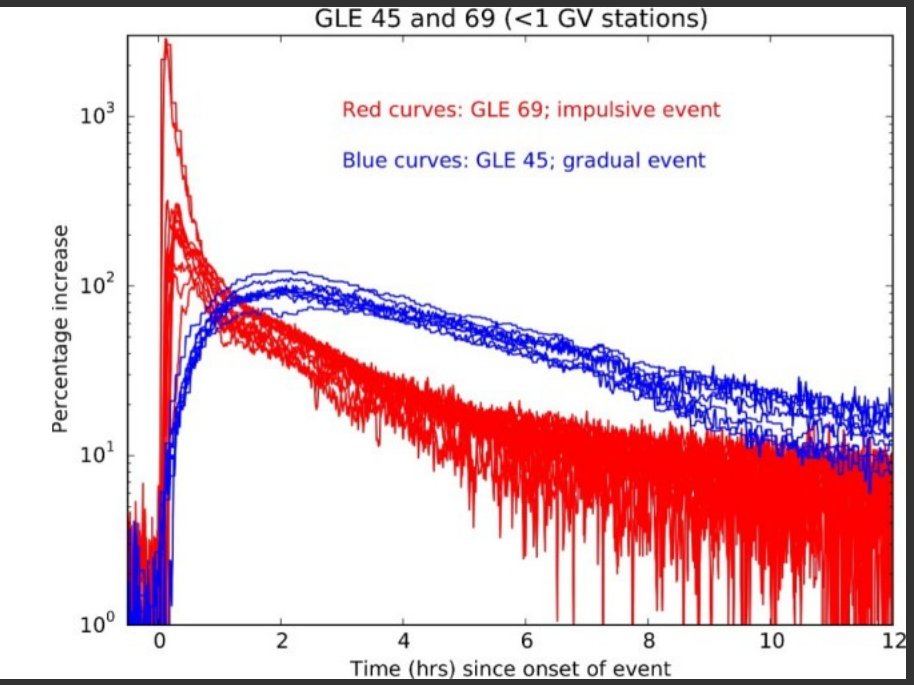
# Propagation of relativistic protons from solar eruptive events

S. Dalla[1], G. de Nolfo[2], J. Giacalone[3], A. Bruno[2], M. Battarbee[4], T. Laitinen[1] and S. Thomas[5]

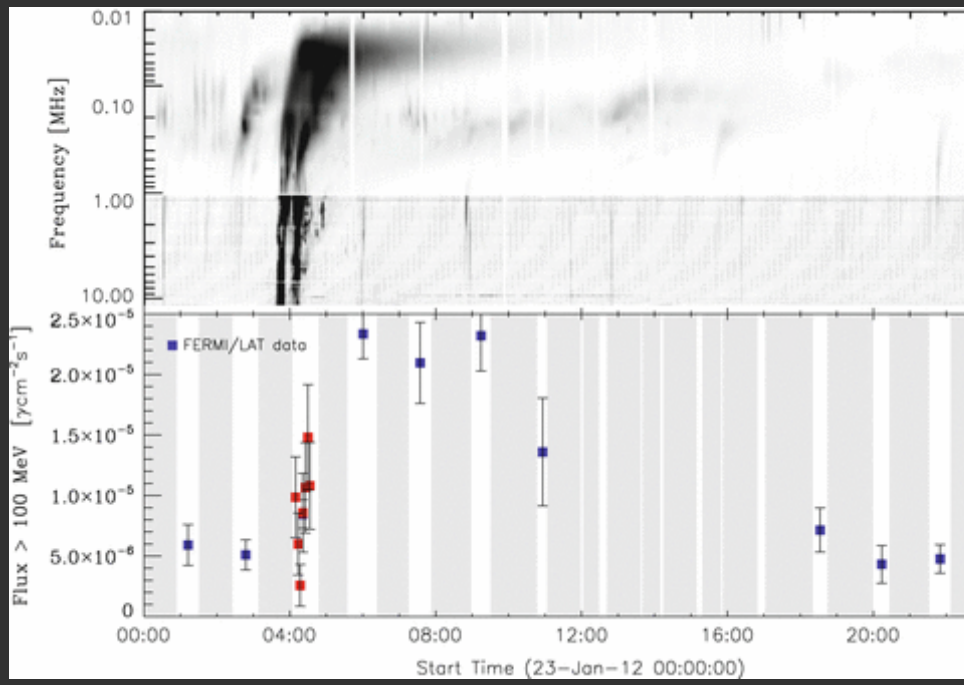
[1]Univ of Central Lancashire, Preston [2]NASA GSFC
[3]Univ of Arizona [4]Univ of Helsinki [5] Univ of Reading

# Solar relativistic protons

- Ground Level Enhancements (GLEs): protons ~1-30 GeV
- $\gamma$-ray flares: protons >300 MeV (Fermi/LAT)



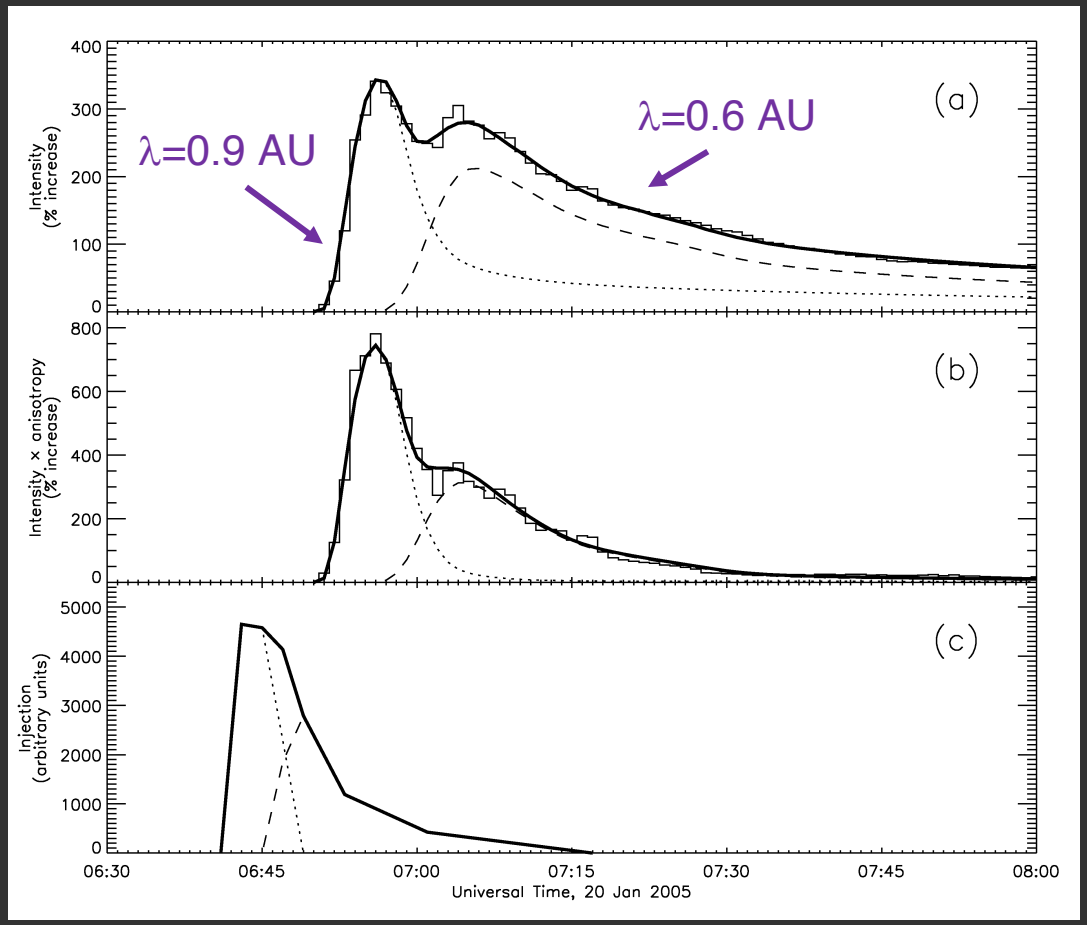

Strauss et al 2017




Klein et al 2018

# Interplanetary propagation models

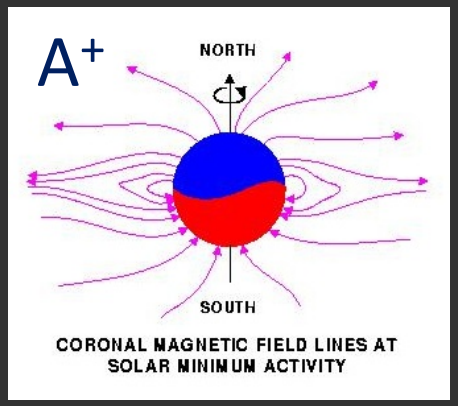
- 1D models, based on focussed transport equation
- single flux tube, i.e. no propagation across the field
- effects of magnetic field polarity and heliospheric current sheet not included

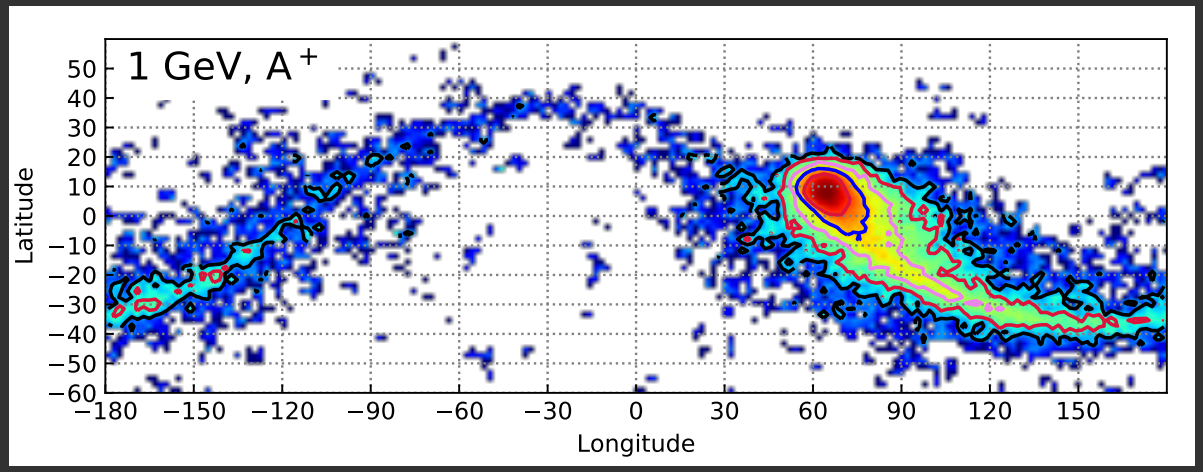


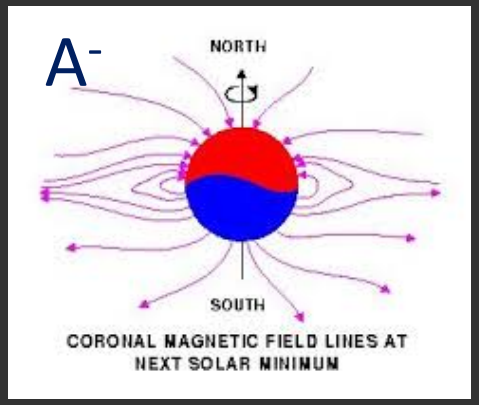

Saiz et al 2005

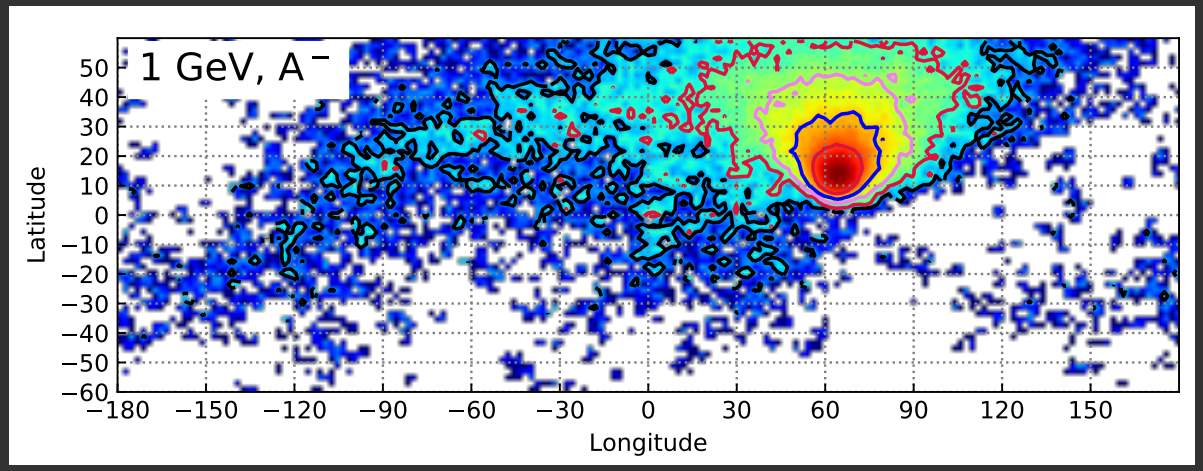
# 3D test particle propagation

Maps of crossings of 1 AU sphere



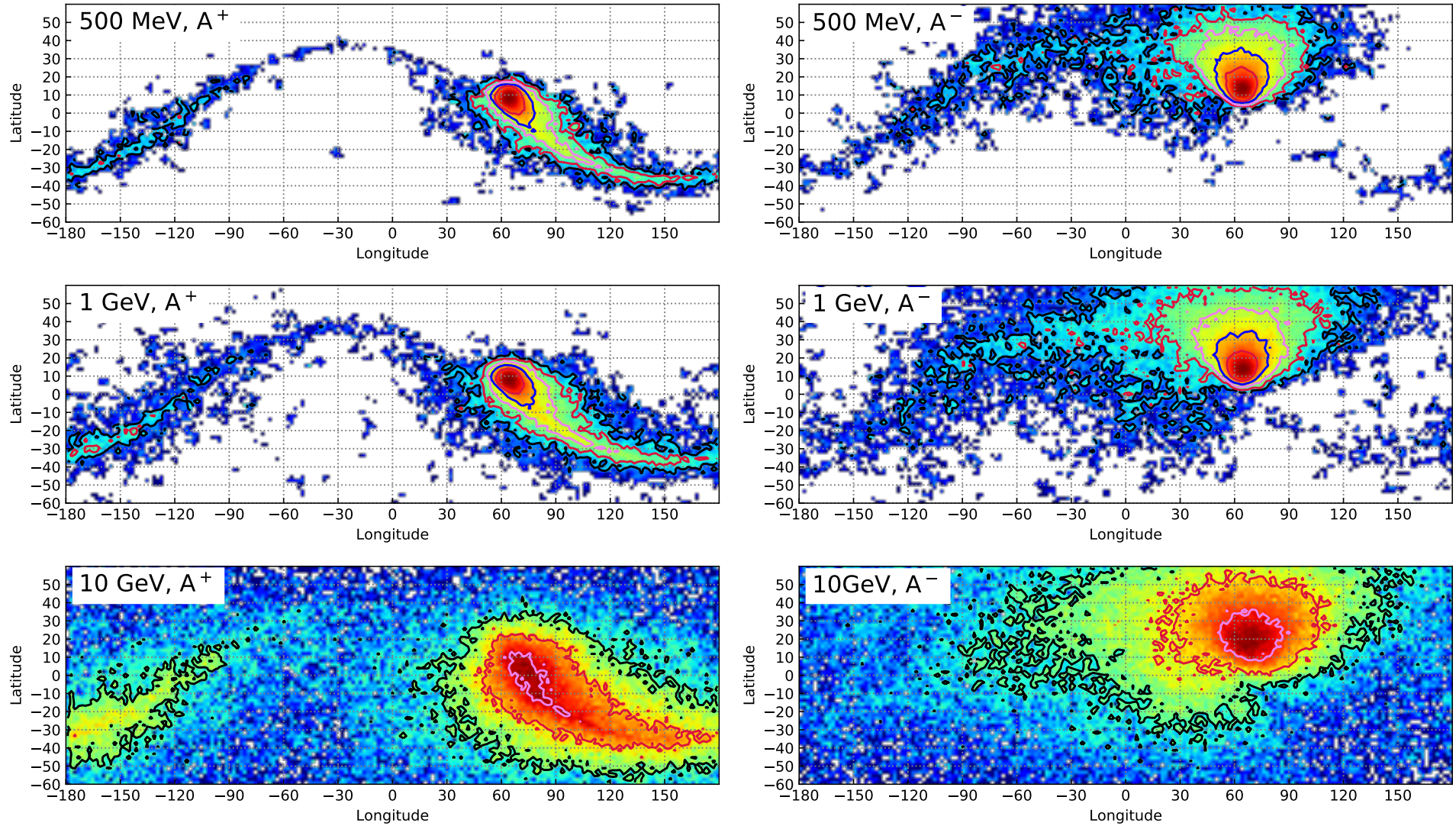



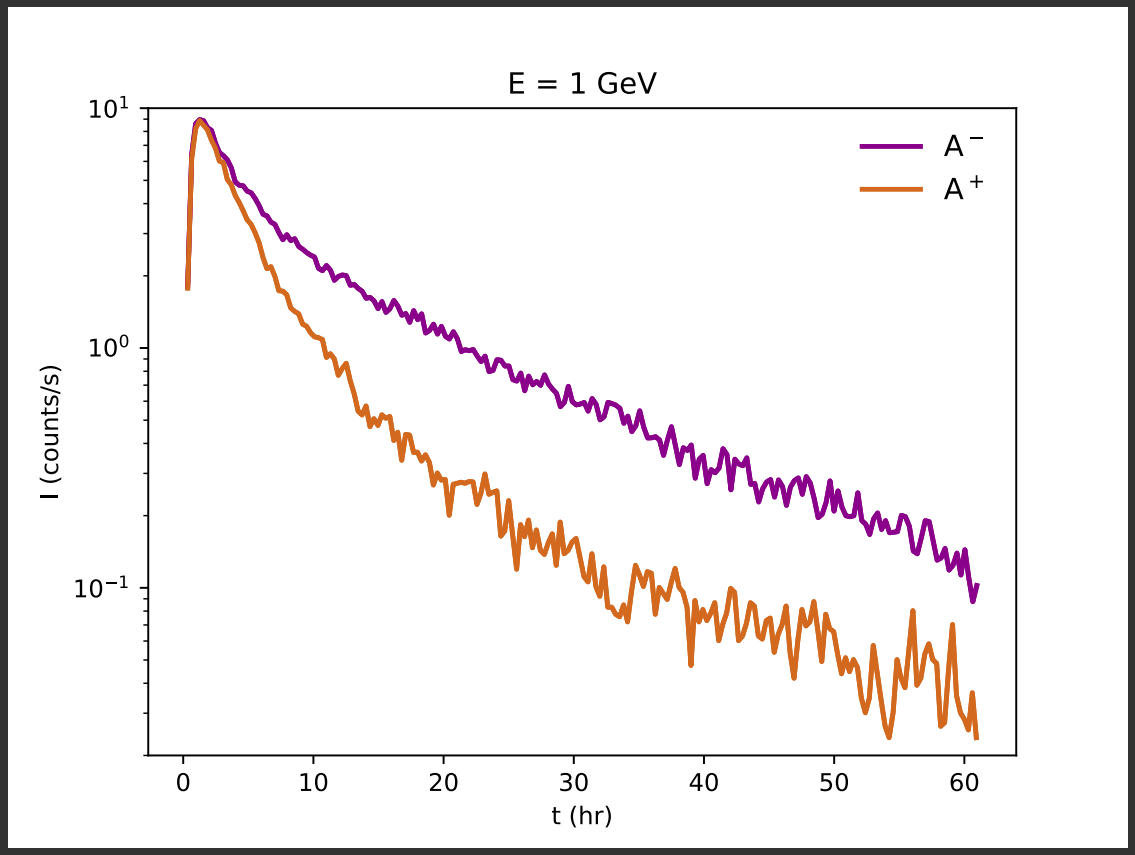




Battarbee et al 2018

# Dependence on particle energy



# Number of crossings of 1 AU sphere



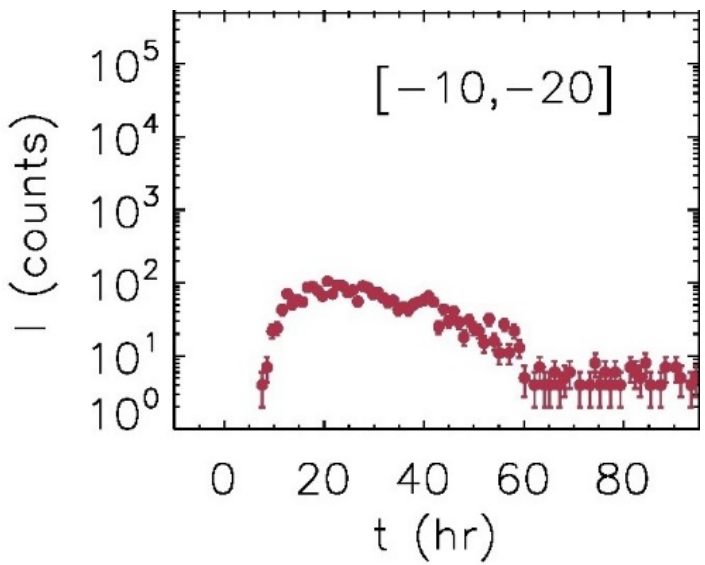

| | A- | A+ |
|---|---|---|
| λ=0.1 AU | 29 | 17 |
| λ=0.5 AU | 11 | 7 |

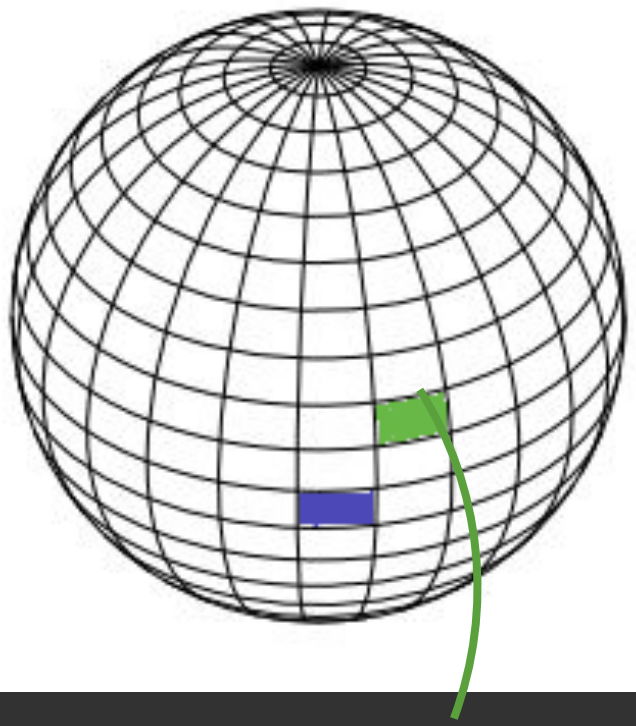
de Nolfo
et al 2019

# Intensity profiles at 1 AU

- Power law population injected ($\gamma$=2)

Observer at [$\Delta\phi$, $\Delta\theta$]



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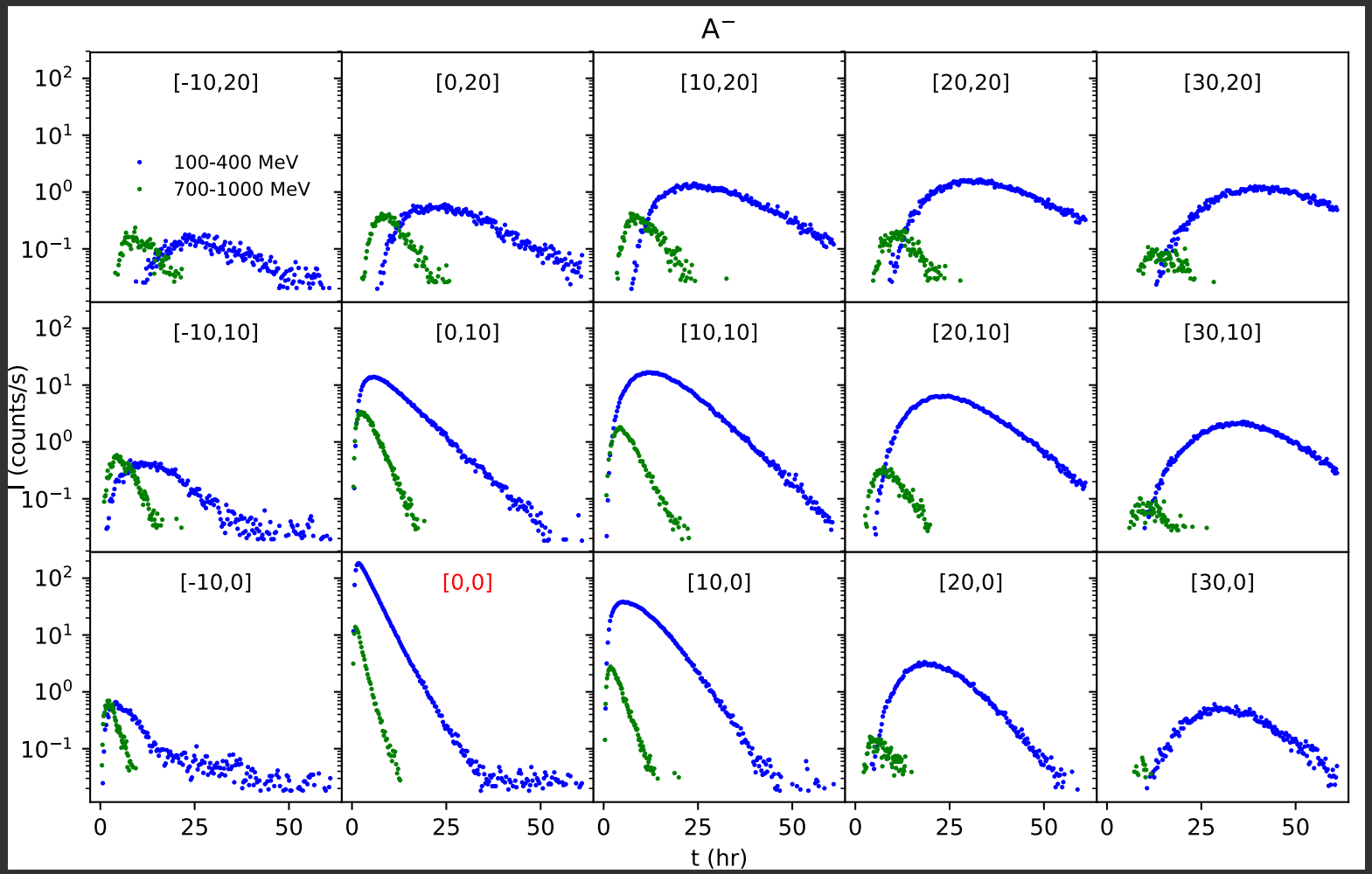
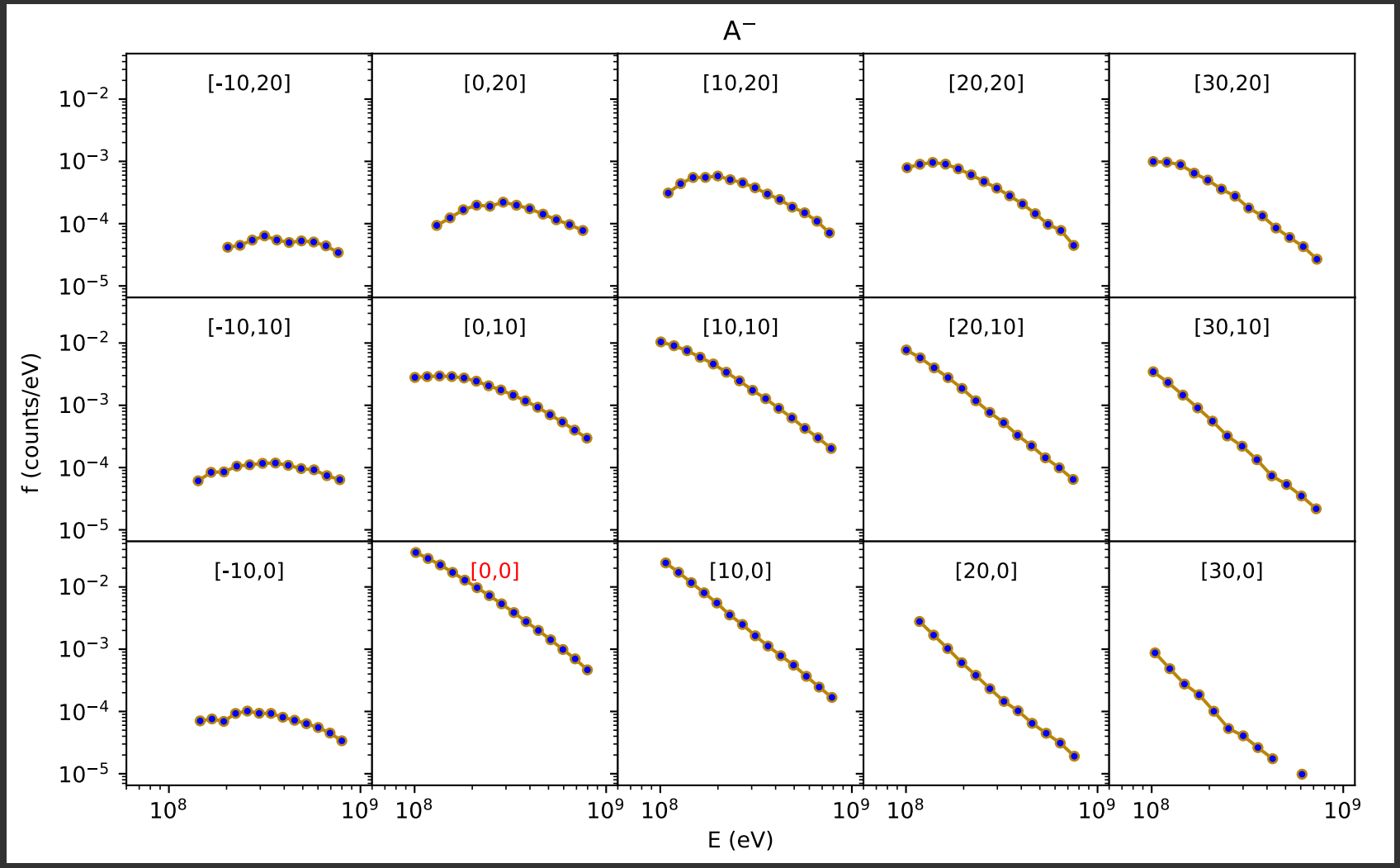
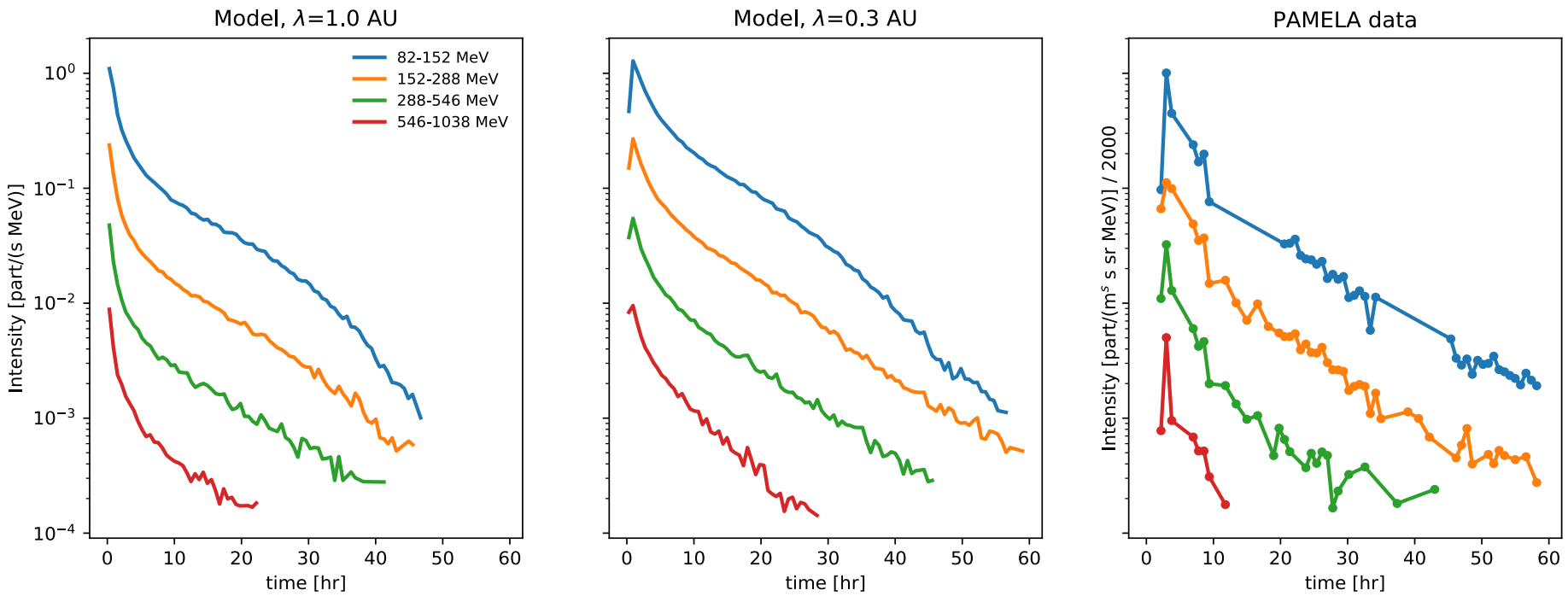



Dalla et al 2019 in prep

# Spectra at 1 AU



# Comparison with PAMELA for GLE 71




- Instantaneous power law ($\gamma$=2.8) injection from a 40x40° region, HCS tilt angle=57 °
- $\lambda$=0.3 gives better fit

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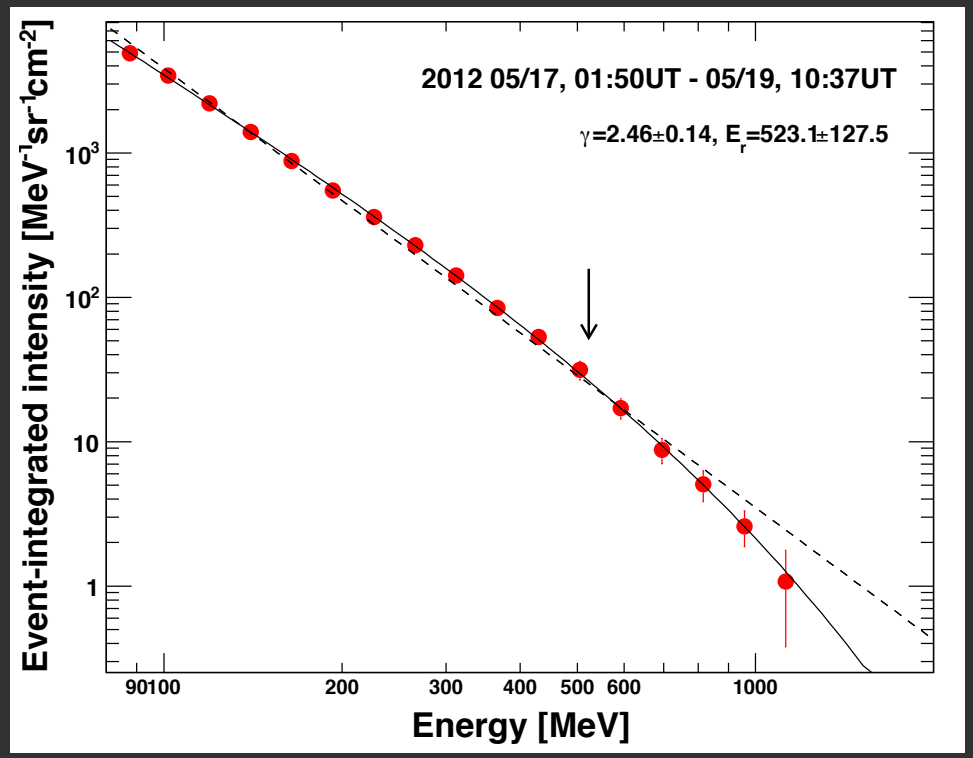

# Conclusions

- 3D test particle simulations show that IMF polarity and HCS strongly influence propagation of relativistic solar protons
- Dependence of 1 AU crossings on A+ vs A- (number and spatial patterns)
- In 3D, source properties are processed by transport, with features eg of spectra being observer-dependent