High-Resolution Poisson Bracket Scheme Performance on Solar Energetic Particle and Galactic Cosmic Ray Simulations

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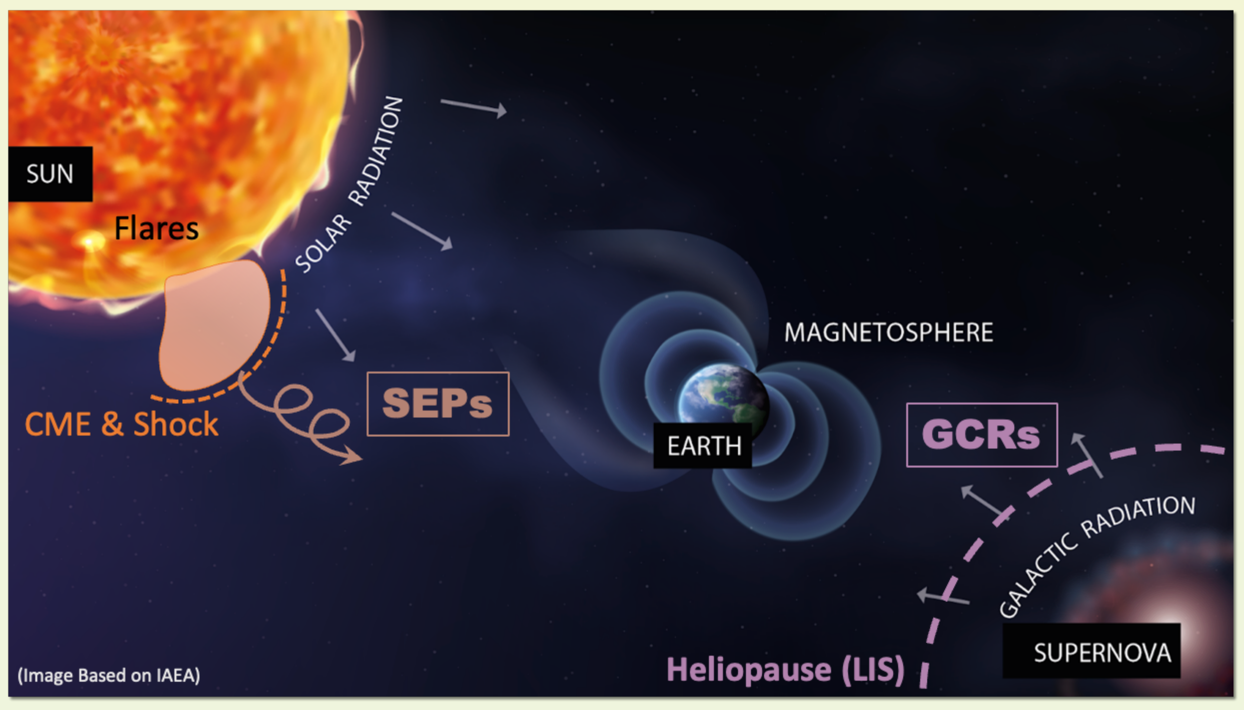
I. Introduction: SEPs & GCRs



Science Question: How can these energetic particles get accelerated and transported in space?

Operational Target: How can we accurately predict the SEP and GCR spectra considering their radiation risks?

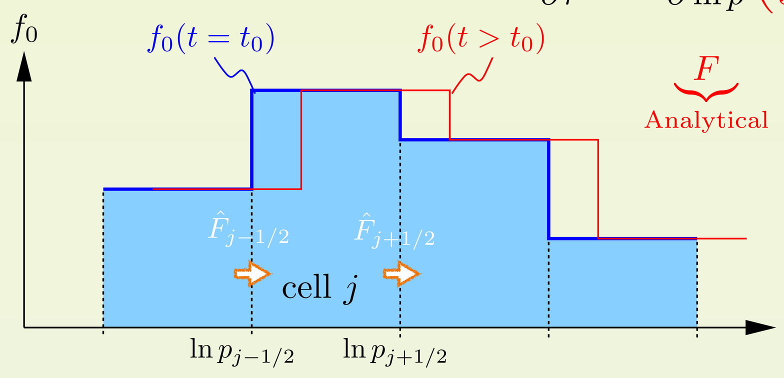
Simulations + Observations

II. Method: Poisson Bracket Scheme

Governing Equation: **Parker Transport Eqaution** *(Parker 1965)*

$$\frac{\partial f_0}{\partial \tau} = \underbrace{-\frac{1}{3}\frac{\partial \ln\rho}{\partial \tau}\frac{\partial f_0}{\partial \ln p}}_{\text{Adiabatic Term}} + \underbrace{\nabla\cdot\left(\overleftrightarrow{\kappa}\cdot\nabla f_0\right)}_{\text{Diffusion}} + \underbrace{Q}_{\text{Extra Source/Sink}}$$

- **Splitting Method:** Explicit in Time for Advection + Implicit for Diffusion
- **Finite Volume Method** $\frac{\partial f_0}{\partial \tau} = -\frac{\partial}{\partial \ln p}\left(\frac{1}{3}\frac{\partial \ln \rho}{\partial \tau} f_0\right) \equiv -\frac{\partial F}{\partial \ln p}$



$\underbrace{F}_{\text{Analytical}} \Longrightarrow \underbrace{\tilde{F}}_{\text{Numerical}}$

- **Poisson Bracket:** $\partial_t f + \sum_{l=1}^{L}\{f;H\}_{q_l,p_l} = \partial_t f + \sum_{l=1}^{L}\left(\frac{\partial f}{\partial q_l}\frac{\partial H}{\partial p_l} - \frac{\partial f}{\partial p_l}\frac{\partial H}{\partial q_l}\right) = 0$

Distribution function = Const along the Hamiltonian trajectory: $\left[\frac{\mathrm{d}f(t,\mathbf{x},\mathbf{p})}{\mathrm{d}t}\right]_{\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t}=\frac{\partial H}{\partial \mathbf{p}},\ \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t}=-\frac{\partial H}{\partial \mathbf{x}}} = 0$

- Particle number conserves
- Second-order in space
- Total variation diminishing (TVD)

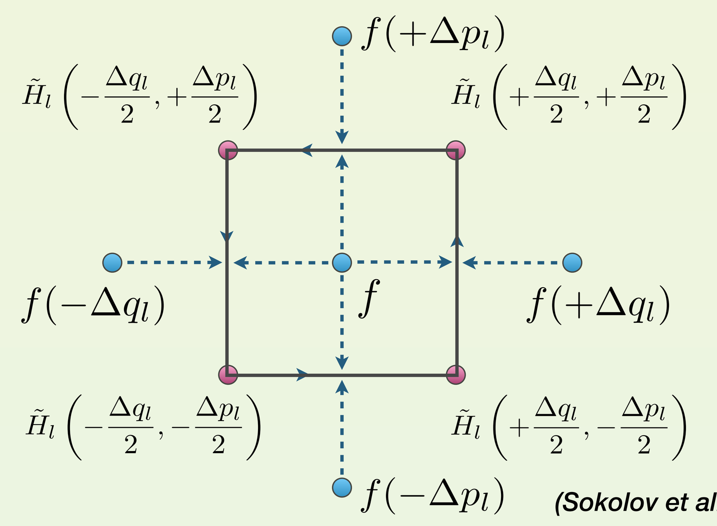
→ **Computationally Efficient**

Poisson Bracket Scheme
Lagrangian Coordinates

$$\frac{B}{\delta s}\left\{f_{j,k};\frac{\delta s}{B}\frac{p^3}{3}\right\}_{\tau,\,p^3/3} = \frac{B}{\delta s}\frac{\partial}{\partial s_L}\left(\frac{D_{xx}}{B\delta s}\frac{\partial f_{j,k}}{\partial s_L}\right)$$

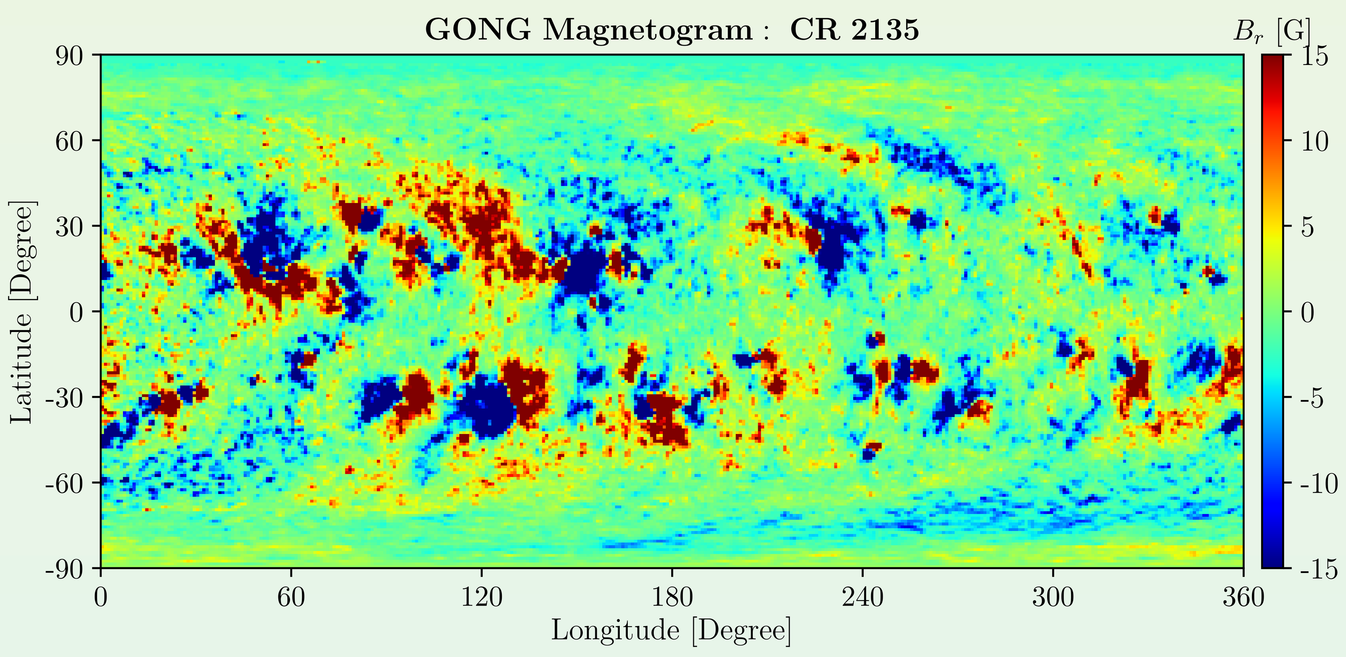
Splitting Method

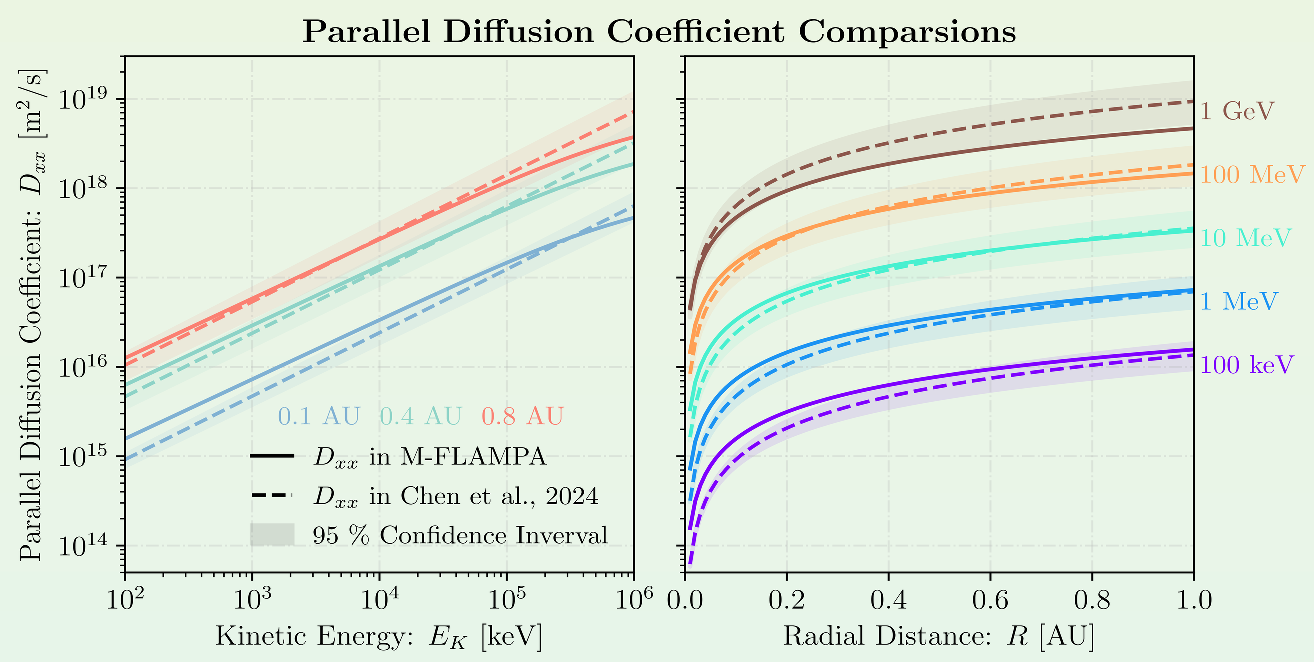
$$\left\{f_{j,k};\frac{\delta s}{B}\frac{p^3}{3}\right\}_{\tau,\frac{p^3}{3}} \equiv \{f_{j,k};H\}_{\tau,\frac{p^3}{3}} = 0,\quad \tilde{H}_l \equiv \int H\left(\tau, s_L, \frac{p^3}{3}\right)\mathrm{d}s_L$$

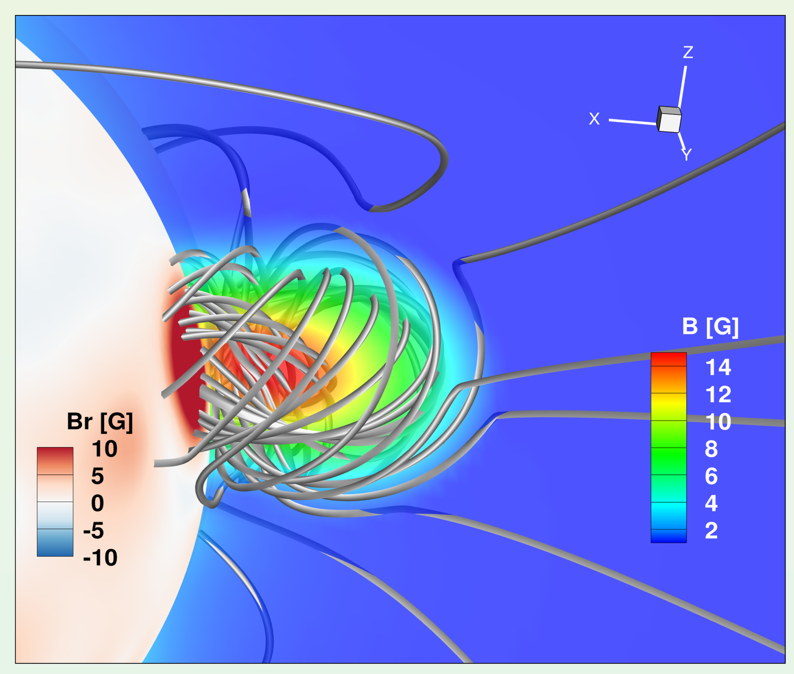


(Sokolov et al., 2023)

III. Results: Simulations & Validations







Input: GONG Magnetogram

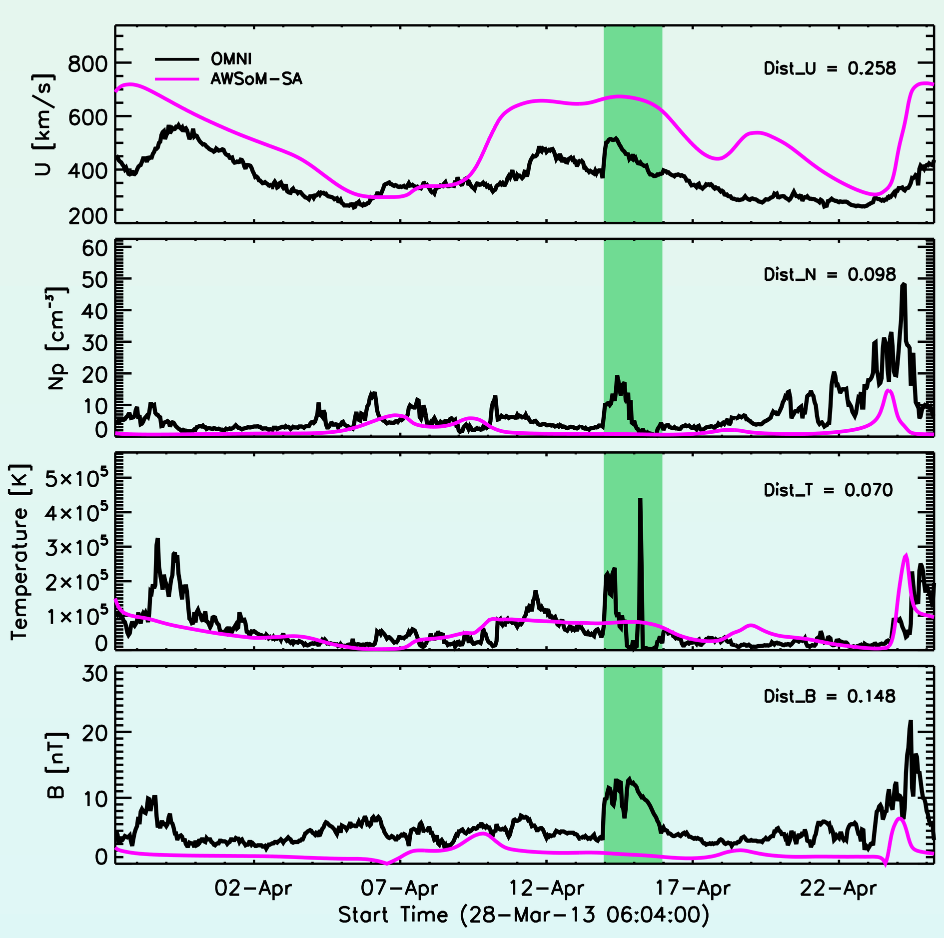
Poisson Bracket Scehme Implemented into M-FLAMPA in SWMF

Input: Diffusion Coefficient for Particle Scattering in IH (QLT-Based, Compared with the One Derived from *PSP* Obs.)

Input: Flux Rope for CME Eruption *(Gibson & Low, 1998)*

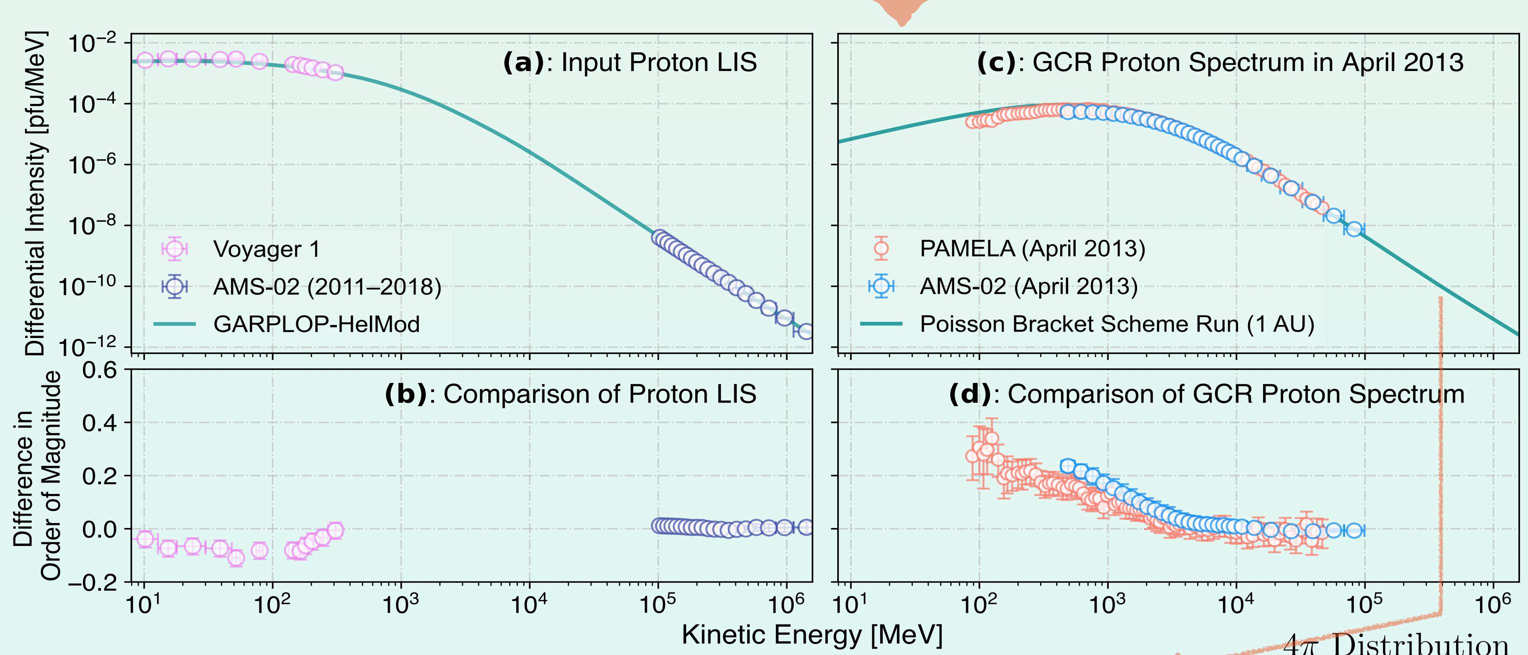
Stream-Aligned AWSoM-R → **Steady-State Poisson Bracket Scheme** → **Time-Accurate Poisson Bracket Scheme**

Output: Background Solar Wind Parameters, Validated at 1 AU

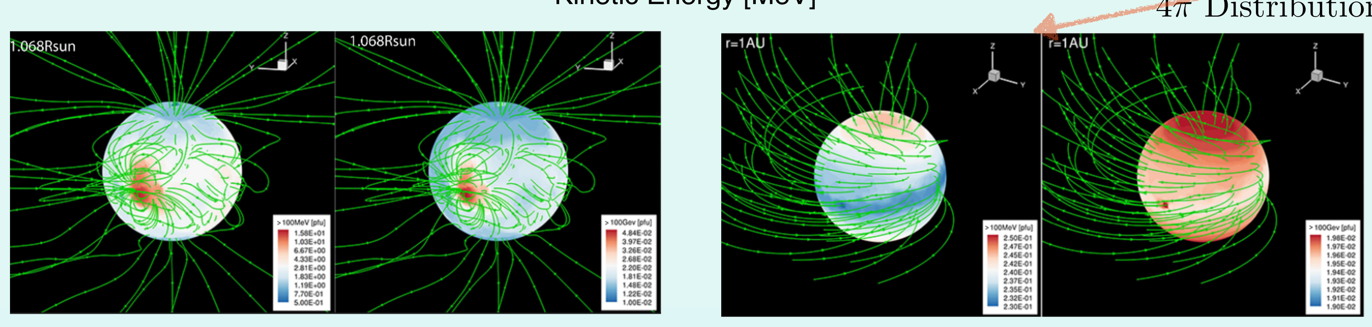


Input: LIS & Modulation Potential *(Usoskin et al., 2005)*

Output: **GCR** Spectrum at 1 AU

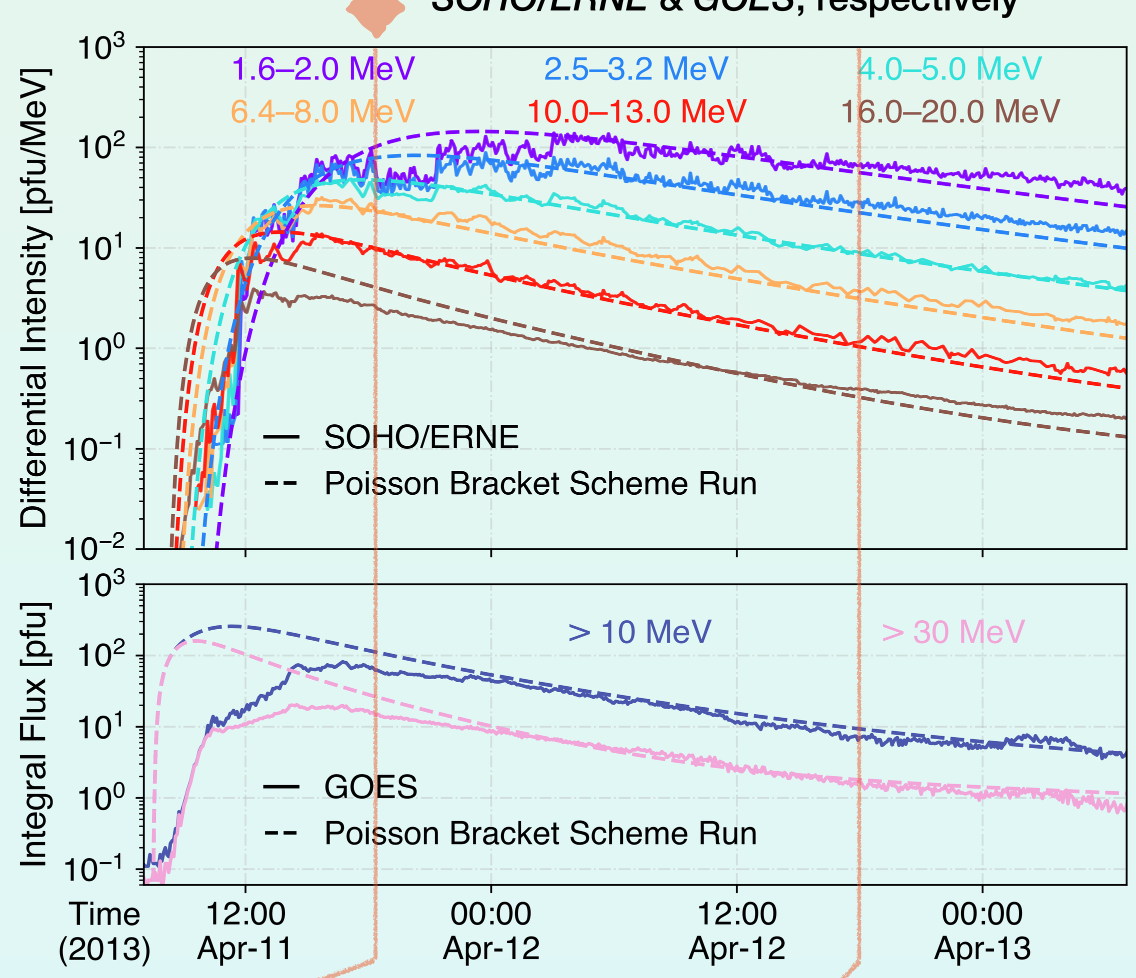


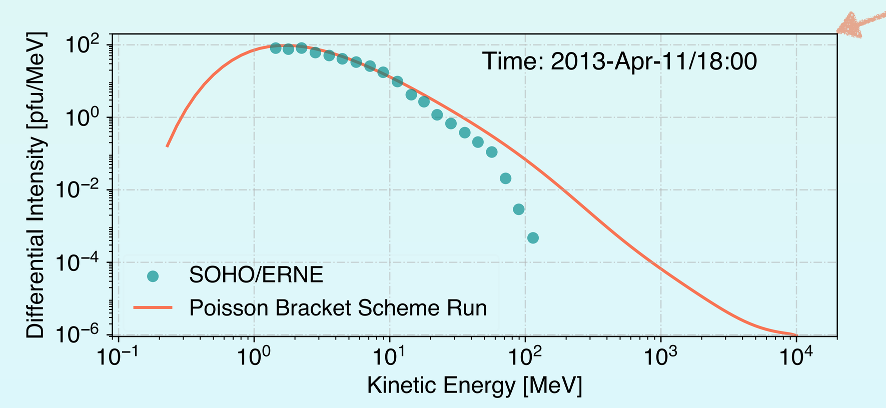
4π Distribution

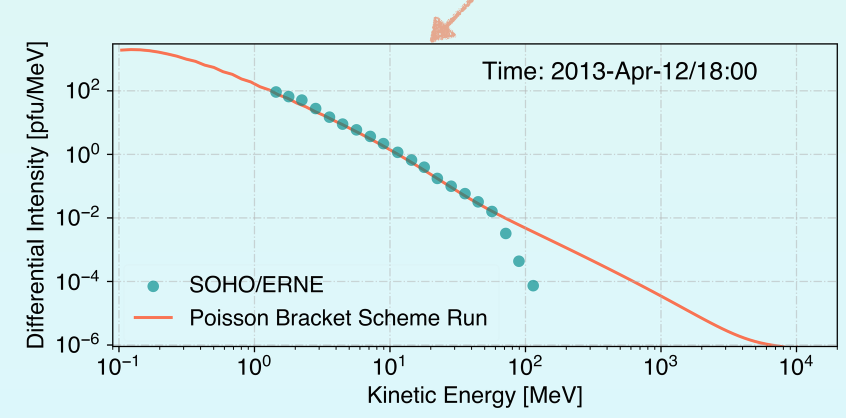


Close to Solar Corona

Output: **SEP** Spectra & Integral Flux at Earth (1 AU), Compared with *SOHO/ERNE* & *GOES*, respectively







IV. Future Work

- Investigate the compression ratio at shock surface and its evolution, and compare the energetic particles measurements by *STEREO-A/B*
- We will take the pitch angle into account, formulate the **Focused Transport Equation** *(Kóta & Jokipii 1997)* with Poisson brackets, and implement it into M-FLAMPA in SWMF:

$$\underbrace{\left\{f_{j,k};\left(3\mu^2\right)\frac{p^3}{3}\frac{\delta s}{B}\right\}_{\tau,\,p^3/3}}_{\text{Adiabatic Cooling or Acceleration}} + \underbrace{\left\{f_{j,k};\mu\left(1-\mu^2\right)\frac{\delta s}{B}\right\}_{\tau,\,\mu}}_{\text{Adiabatic Cooling or Acceleration \& Focusing}} + \underbrace{\left\{f_{j,k};\frac{\left(\mu^2-1\right)p}{2\gamma m_i B}\right\}_{s_L,\,\mu}}_{\text{Adiabatic Focusing}} +$$

$$\underbrace{\left\{f_{j,k};\frac{-\mu\left(1-\mu^2\right)p^3}{2}\delta s\partial_\tau\left(\frac{1}{B}\right)\right\}_{p^3/3,\,\mu}}_{\text{Betatron Acceleration}} + \underbrace{\left\{f_{j,k};\frac{\left(1-\mu^2\right)p^2}{2}\frac{\delta s}{B}\gamma m_i \partial_\tau\left(\mathbf{b}\cdot\mathbf{u}\right)\right\}_{p^3/3,\,\mu}}_{\text{Inertial Force}} = \frac{\delta s}{B}\underbrace{I^{(s)}}_{\text{Scattering}}$$

- We will test this new solver, run for SEPs and GCRs, and study the Forbush decrease.

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