Particle Acceleration at Coronal Shocks: the Effect of Large-scale Streamer-like Magnetic Field Structures

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Outline

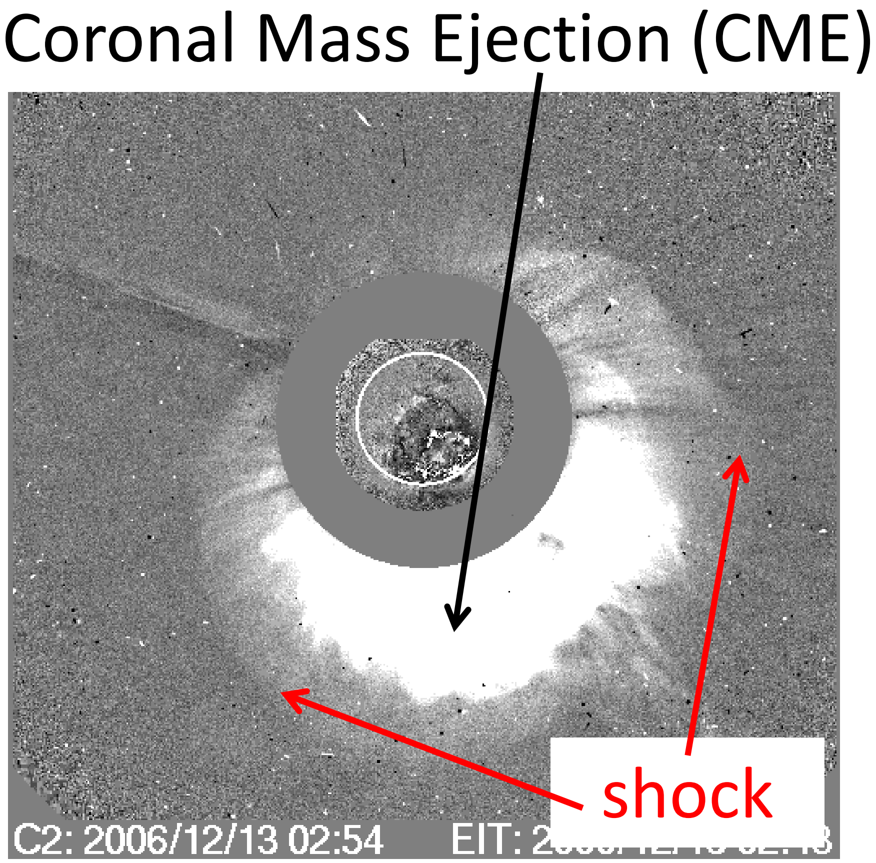
- Background & Motivation
  - Solar Energetic Particles (SEPs)
  - Evidences for closed field geometry, shocks and particle acceleration low in the corona
  - Basics of shock acceleration
- Numerical model & Results
  - A coronal shock + a streamer-like field
- Summary
  - Streamer-like magnetic field can be an important factor in producing large SEPs.

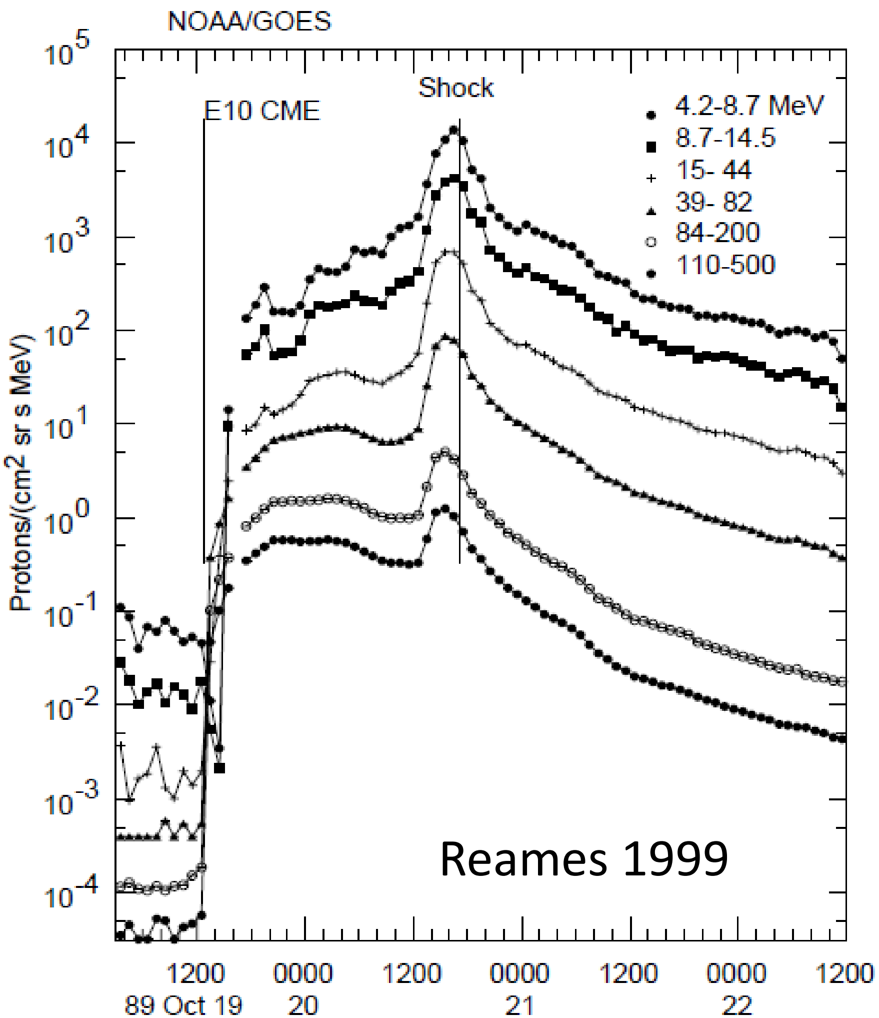
Solar Energetic Particles (SEPs)

- SEPs: energetic particles accelerated (from a few keV to up to ~GeV) near the Sun mainly during flares and coronal mass ejections.

- Large SEPs: proton intensity in >10 MeV *GOES* energy channel >10 pfu, 10 per year on average
- Ground Level Enhancements or GLEs: up to GeV, 16 in solar cycle 23, only 2 (3) in cycle 24, why?

- Large SEPs are usually associated with CMEs and are accelerated by CME-driven shocks.





Some important factors for large SEPs

- Very fast (1-2%) CMEs (Kahler 2001; Gopalswamy et al.; Mewaldt et al.; …)
- Magnetic connectivity to Earth (Gopalswamy et al.; Reames; …)
- Preceding CME or twin-CMEs (Gopalswamy et al. 2004; Li et al. 2012; Ding et al. 2013; …)
- Magnetic-field geometry (Tylka et al. 2005; Sandroos & Vainio 2009; Guo et al. 2010; this work; …)
- ……

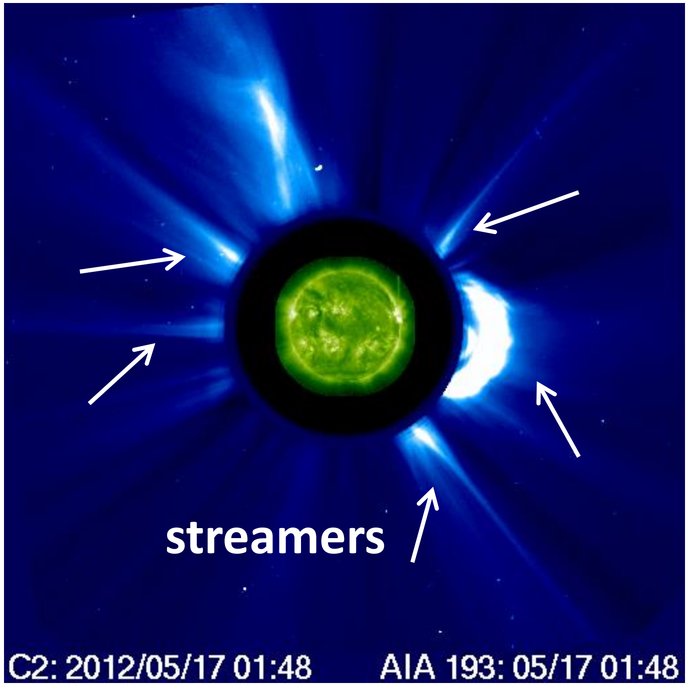
In this talk, I shall emphasize the importance of a streamer-like magnetic field to particle acceleration at coronal shocks.

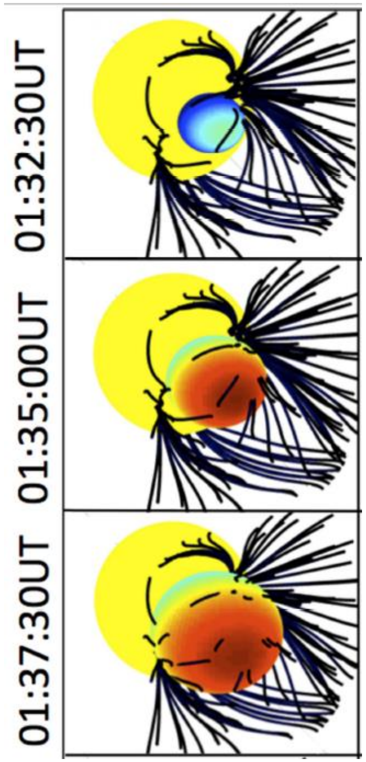
Why a steamer-like magnetic field?

- Streamers are the most obvious structures in the corona.
- Many CMEs originate below a streamer or interact with streamers as propagating outwards/expanding laterally.
- It will affect the shock properties, not considered here.

Rouillard et al. 2016

GLE 2012/05/17





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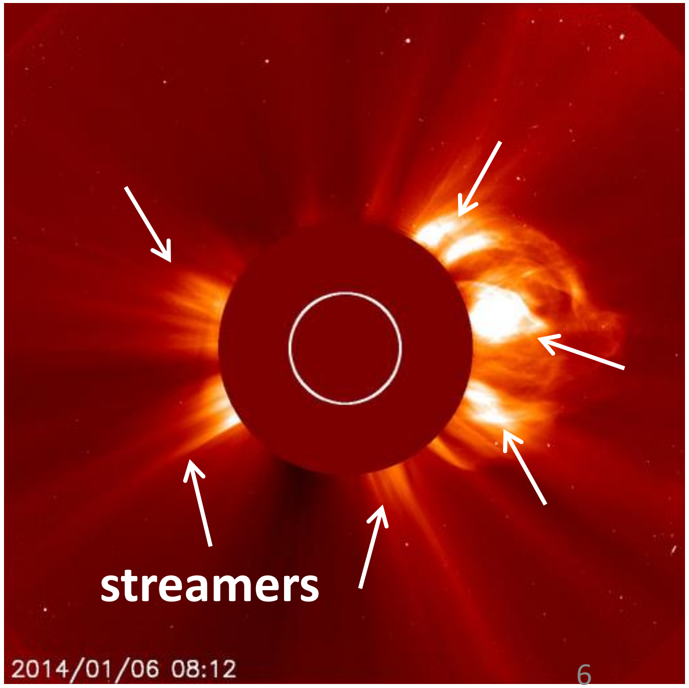
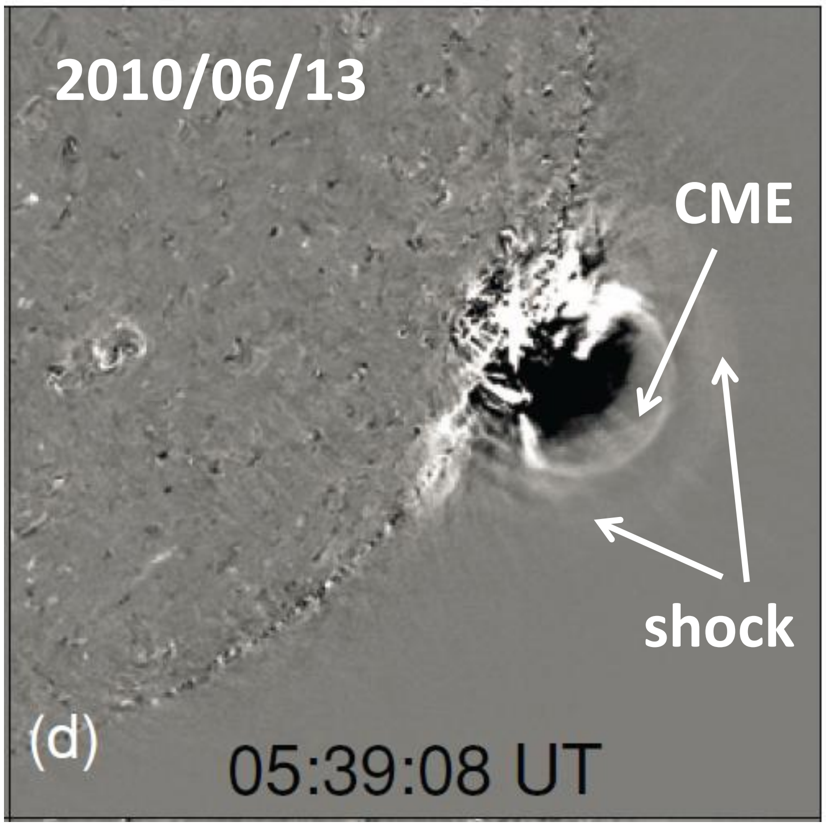
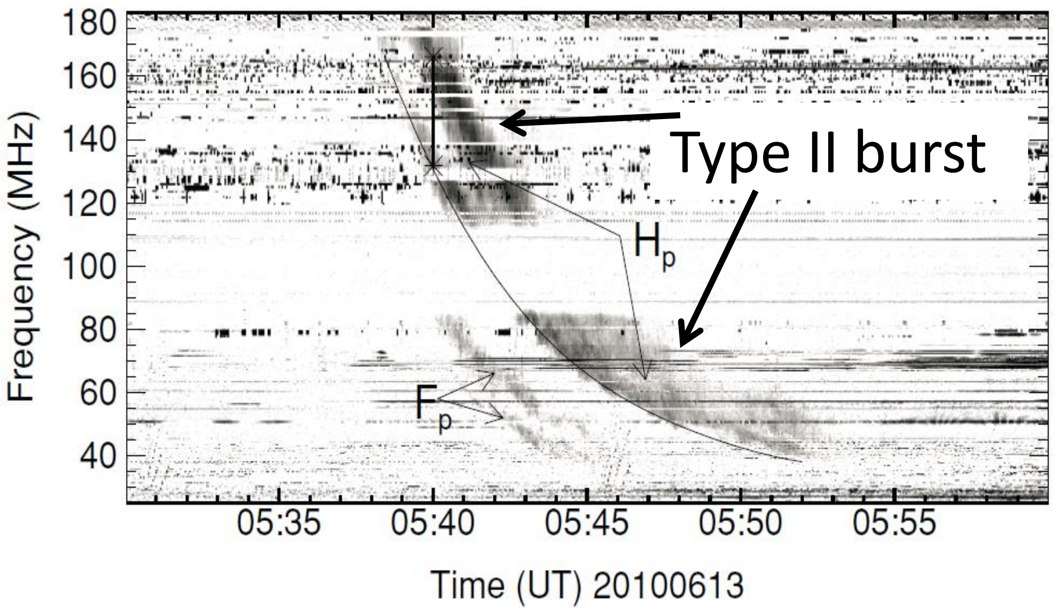


Evidences for shocks low in the corona

- Recent EUV imaging by SDO/AIA, enhancement ahead of the CME **(shock at ~1.2 Rs)**.
- Associated with a type II radio burst (excited by shock-accelerated electrons, a tracer for shocks).

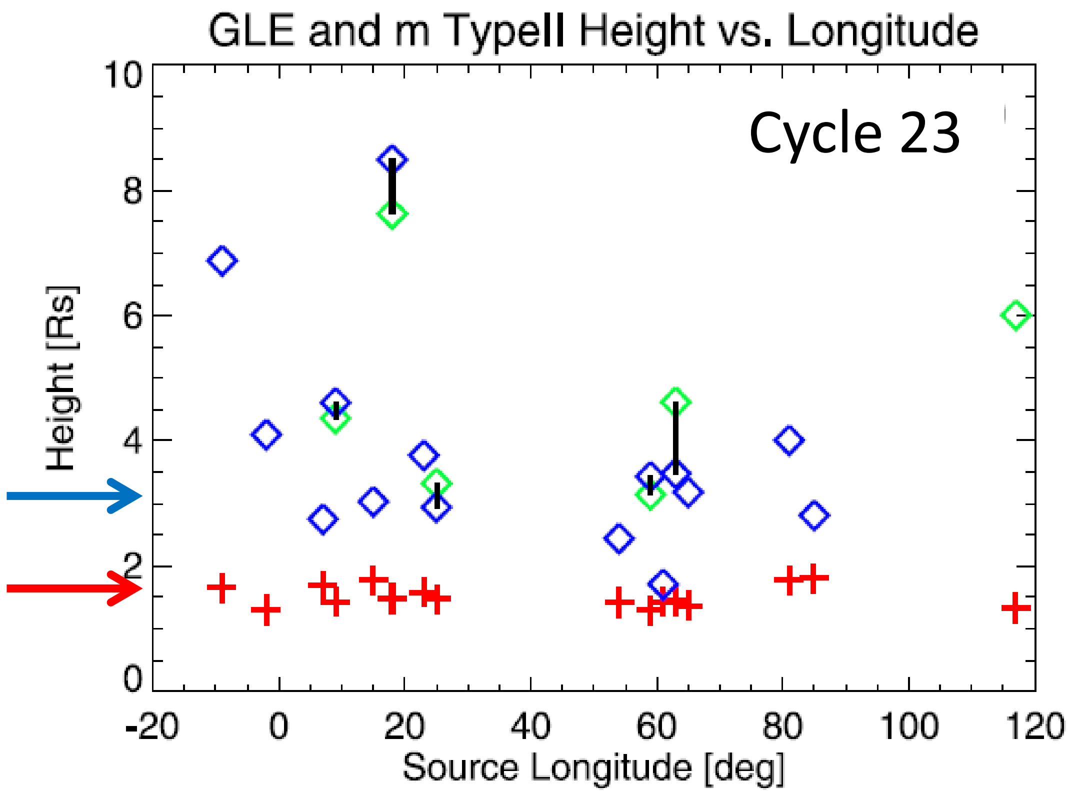




Ma et al. 2011

Evidence for particle acceleration low in the corona

- CME heights at GLE particle release time (diamond): at ~3 Rs on average for well-connected events
- CME heights at type II bursts onset (plus): at ~1.3-1.8 Rs



Gopalswamy et al. 2012

(also: Reames 2009)

A shock is very likely to form and start accelerating particles well below 2 Rs.

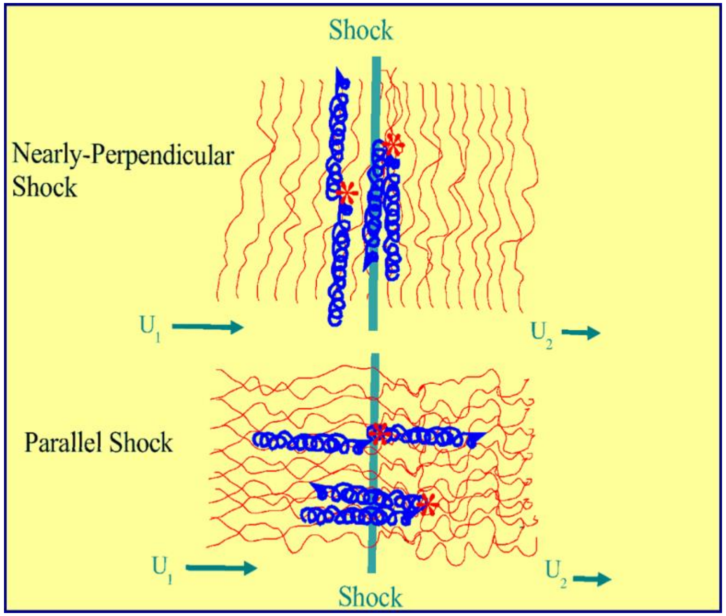
Modeling of particle acceleration at shocks

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}\frac{\partial f}{\partial x_j}\right] - U_i\frac{\partial f}{\partial x_i} + \frac{p}{3}\frac{\partial U_i}{\partial x_i}\frac{\partial f}{\partial p} + Q$$

diffusion ***advection*** ***energy change*** ***sources***

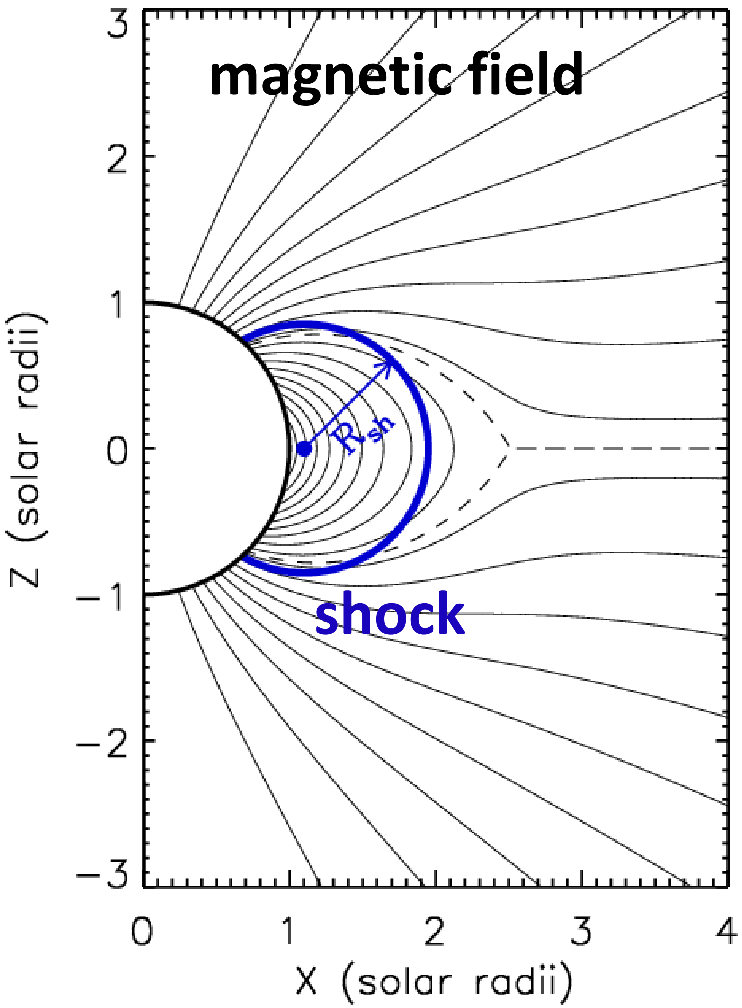
Steady-state solution of the Parker equation for a 1D planar shock, downstream distribution: $f(p) \sim (p/p_0)^{-\alpha}$ with $\alpha = 3X/(X-1)$

- Numerous SEP modeling works have been performed (Lee 1983; Ng et al. 1999; Zank et al. 2000; Li et al. 2003; Giacalone 2015; ...)
- Magnetic turbulence near the shock: enable particle scattering
- Shock geometry: acceleration rate is faster at a perp. shock than at a parallel shock (if not consider self-excited waves at parallel shocks)



J. Giacalone

Particle acceleration at coronal shocks



B.C. Low 1986

- A circular shock moves with constant speed (2000 km/s) and compression ratio (X = 3).
- Shock center fixed at 0.1 Rs above solar surface, initial shock radius 0.2 Rs (outermost shock front at 1.3 Rs).
- An analytical streamer-like coronal field (shock upstream).
- For comparison, also consider a radial magnetic field.

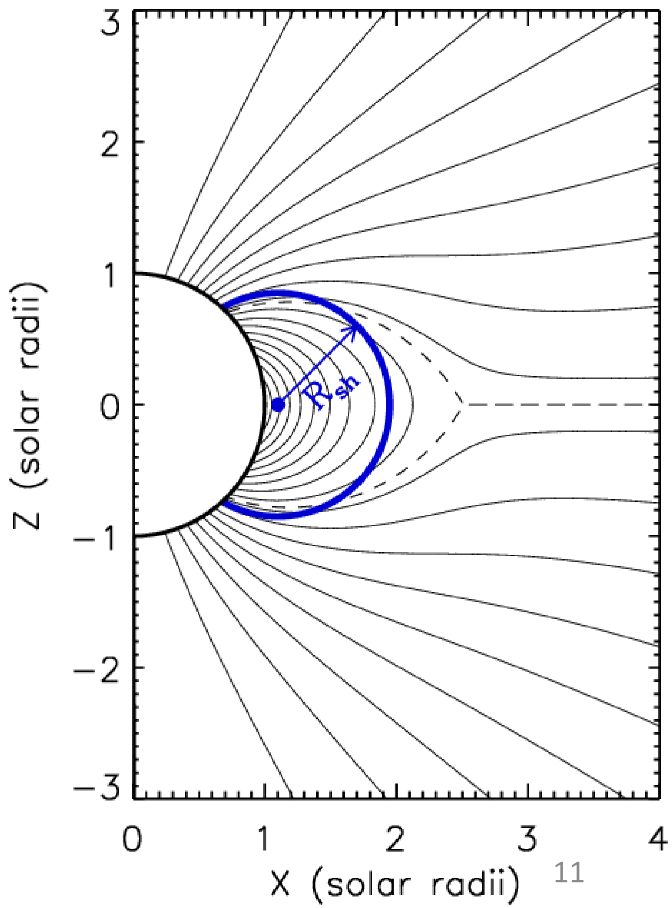
- Consider spatial diffusion both along (parallel) and across (perp.) the magnetic field, momentum-dependent.

Quasi-linear theory (Giacalone & Jokipii 1999):

$$\kappa_{\|0} = 1.4 \times 10^{17}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$$ (for p = p_0, 100 keV protons)

$$\kappa_{\|} = \kappa_{\|0}(p/p_0)^{4/3} \qquad \kappa_{\perp} = 0.04\ \kappa_{\|}$$

- Background solar wind is at rest.
- Downstream magnetic field is compressed, analytically given by solving the induction equation.
- 100 keV protons are continuously injected upstream of the shock at a constant rate.
- The Parker equation is solved by a stochastic integration method.



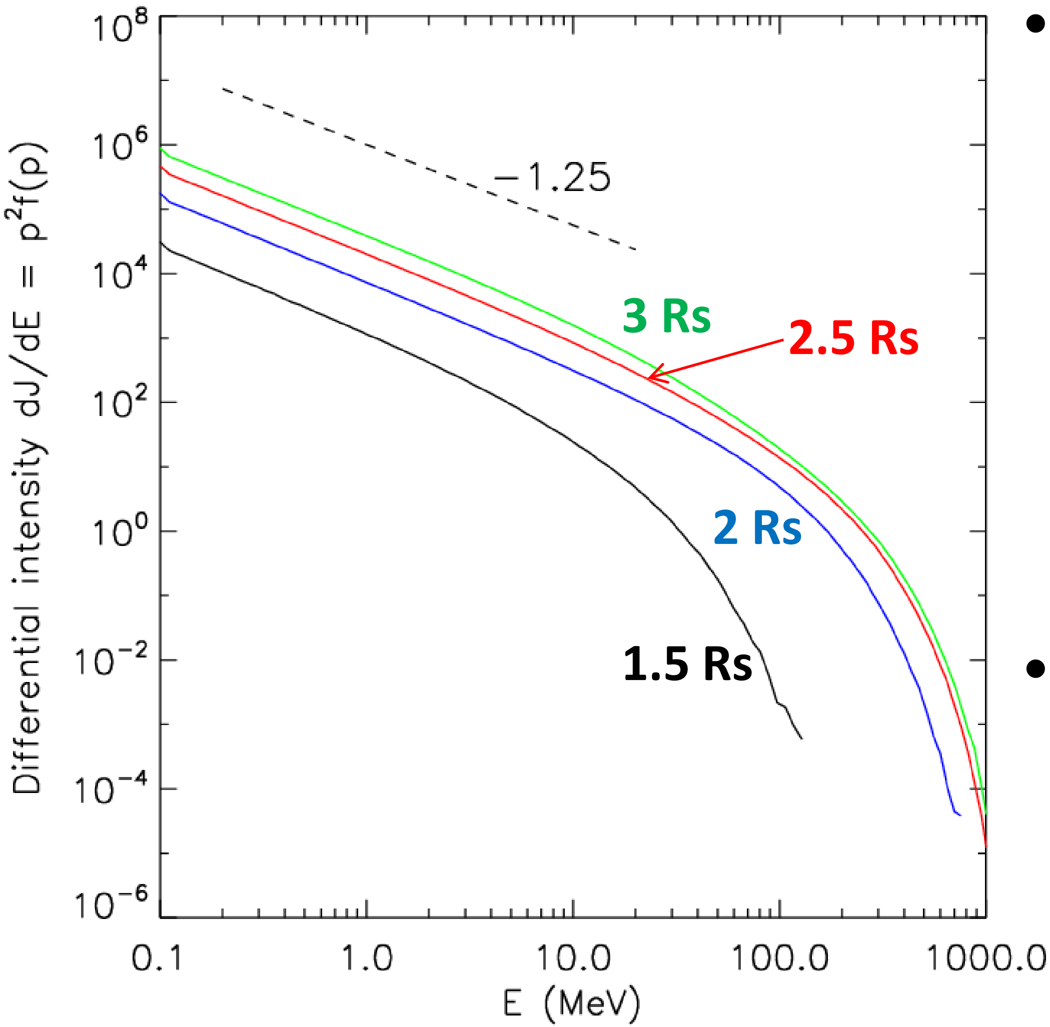
Advantages of the model:

- Varying shock geometry.
- Consider perpendicular diffusion, important to particle acceleration at a perpendicular shock.
- The shock can be well resolved, necessary to get correct results.

Main issues to be addressed:

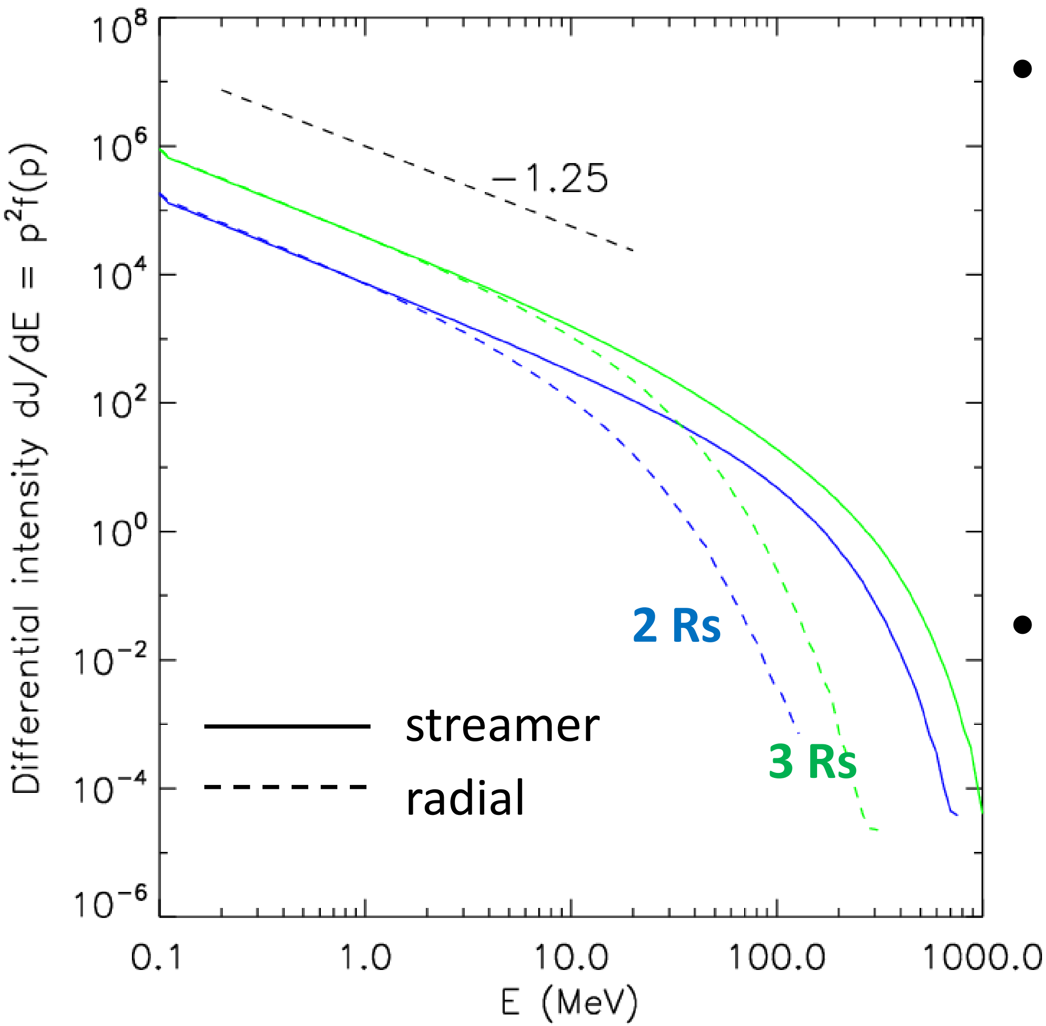
- Can a coronal shock accelerate particles efficiently within a few solar radii? To what energies?
- What is the effect of a streamer-like magnetic field?

1. Energy spectrum of accelerated particles



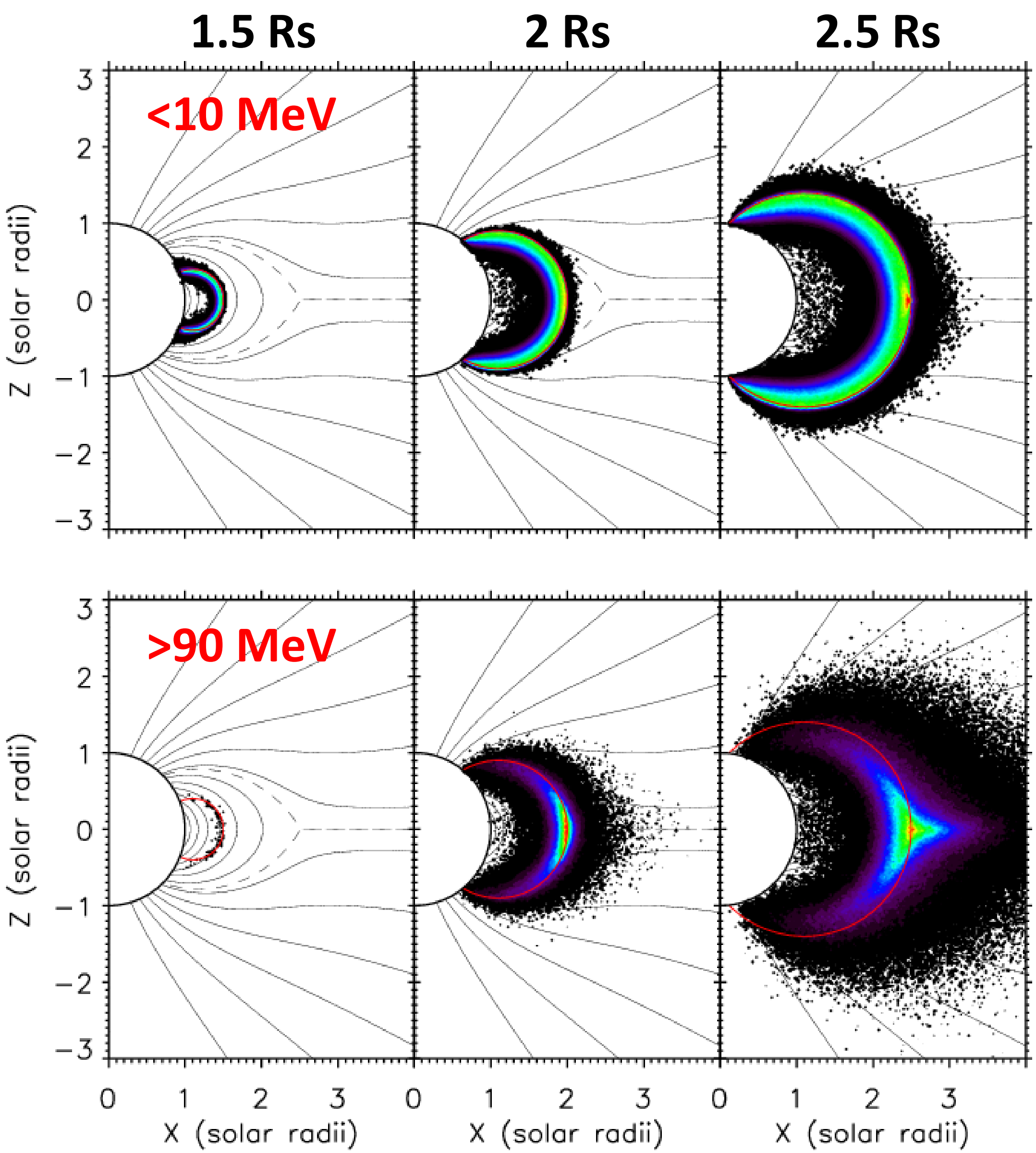
- Particles can be sufficiently accelerated to >100 MeV within 2 Rs, consistent with observations (Reames 2009; Gopalswamy et al. 2012).
- Power-law breaks at ~100 MeV, maximum energy several hundred MeV.

Comparison with a radial magnetic field:



- Particle acceleration in the streamer-like field is much more efficient compared to a simple radial field (breaks at ~10 MeV).
- At 2 Rs, the intensity at 100 MeV is enhanced by 10^3.

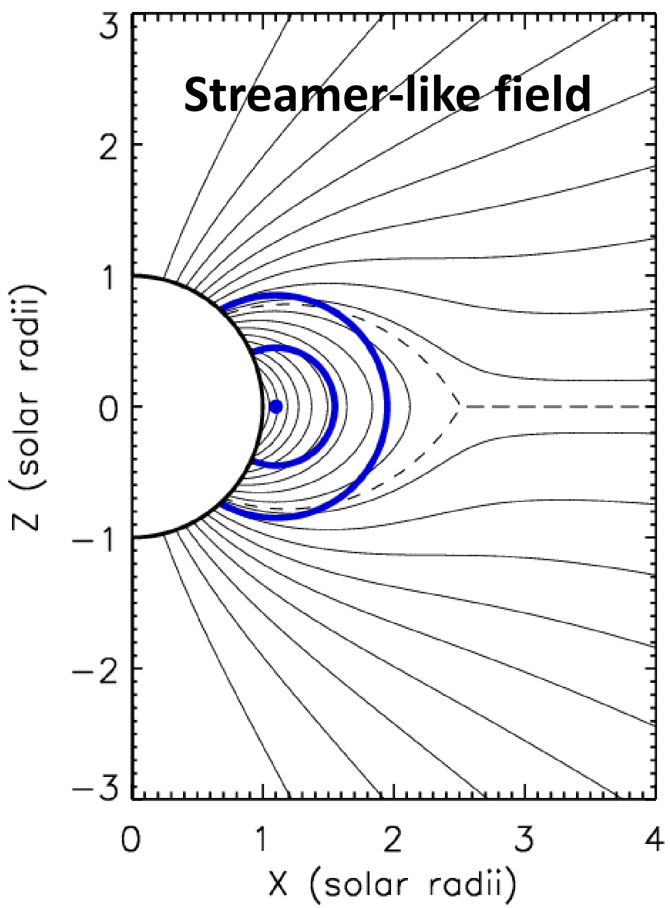
2. Distribution of accelerated particles

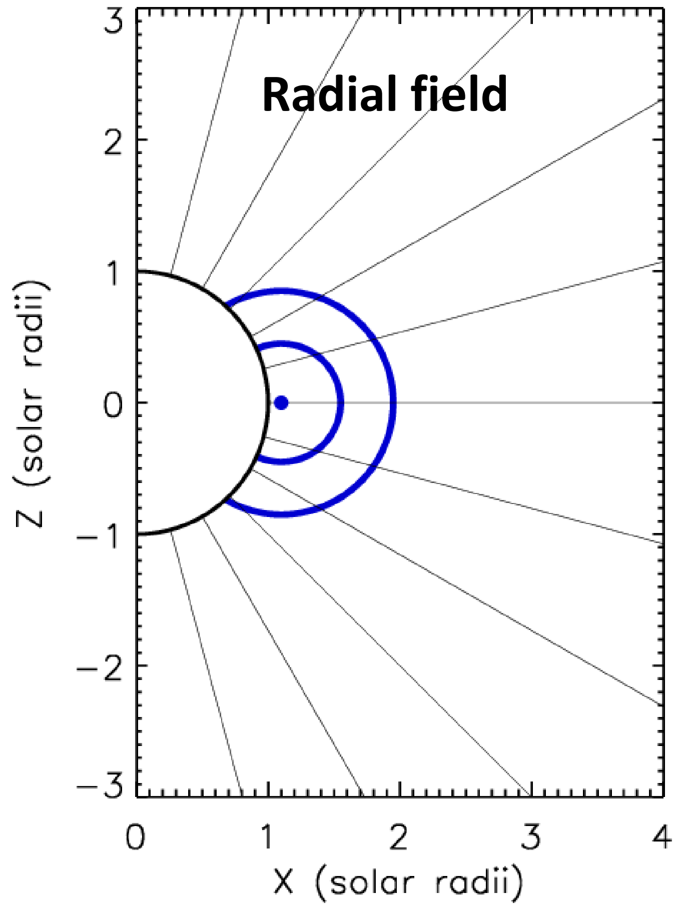


- Distribution of <10 MeV particles is generally uniform along the shock, while >90 MeV particles are concentrated at shock nose.
- Particles can be accelerated to ~100 MeV below 2 Rs.

What causes the difference?

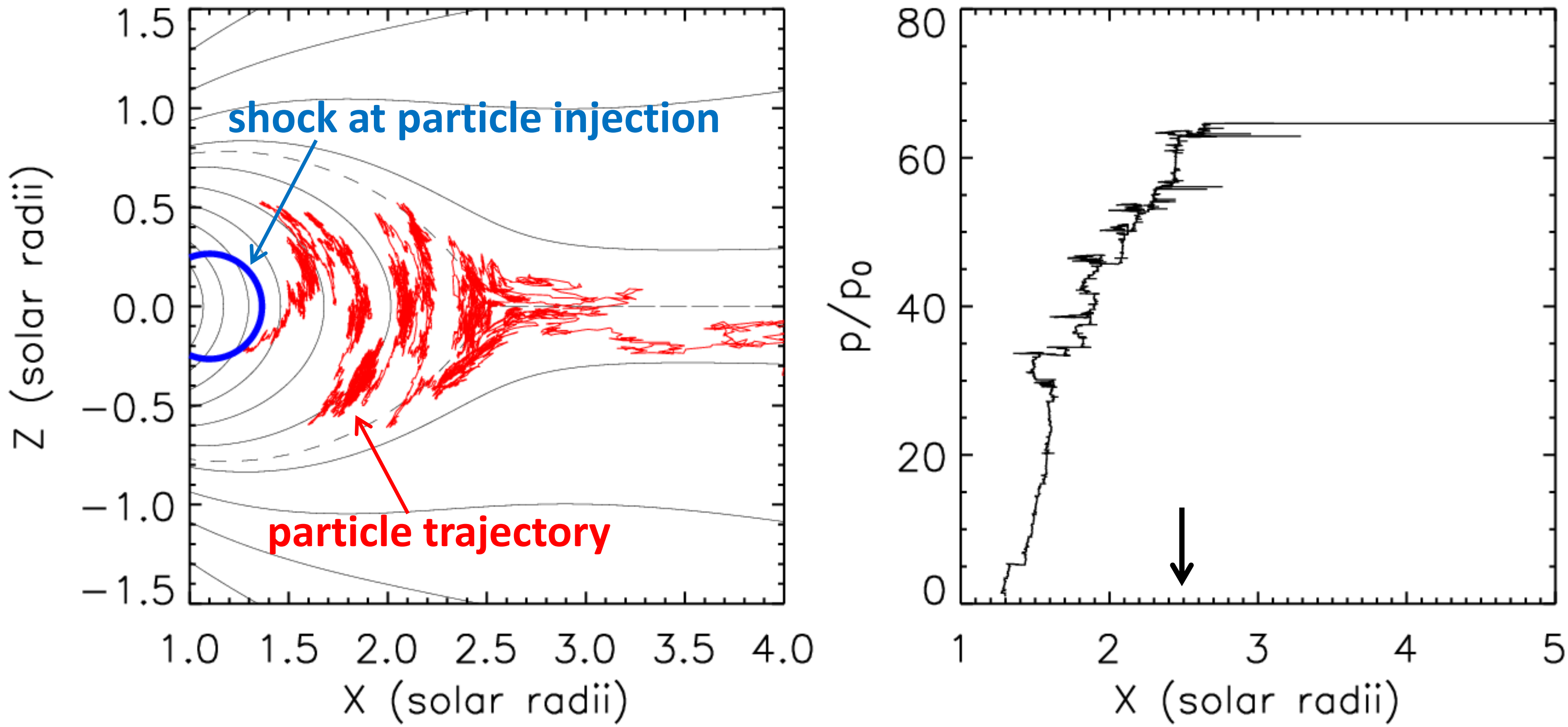
- Perpendicular shock geometry: in a streamer-like field, first at shock nose, later at shock flanks





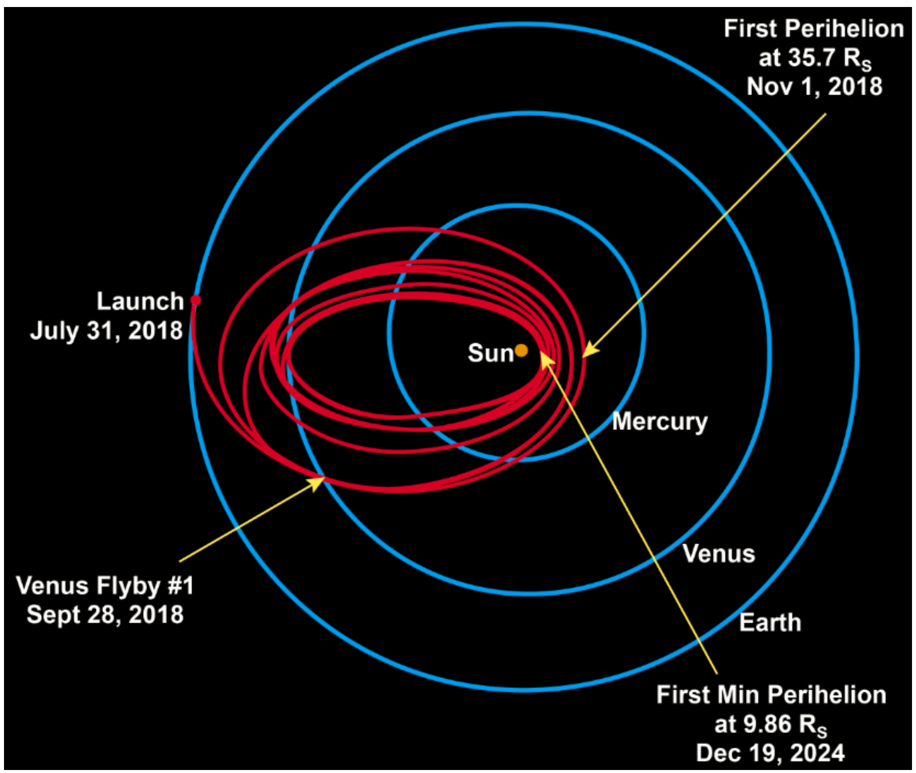
- Natural trapping effect of closed magnetic field: trap particles and help particle acceleration

Mainly accelerated in close field (<2.5 Rs), to 65 p0 (~400 MeV)

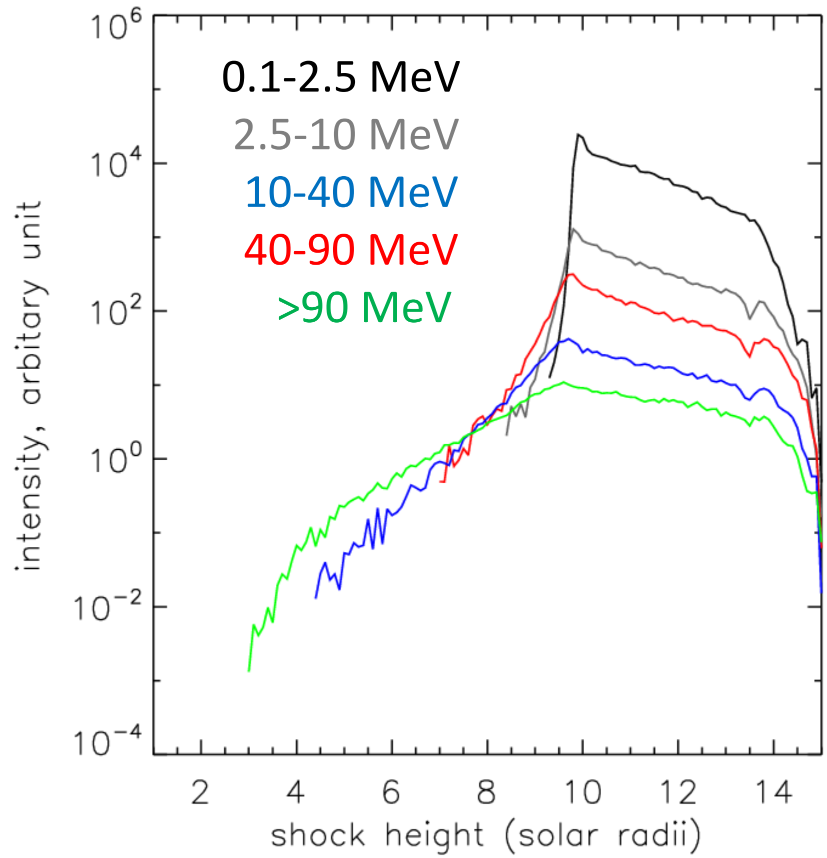


3. Provide predictions for *Solar Probe Plus*

- Energy spectrum
- Intensity-time profiles



Intensity profiles at 10 Rs at the equator:



Summary

- We present a numerical model to study particle acceleration at coronal shocks.
- A coronal shock can sufficiently accelerate particles to >100 MeV within a few solar radii.
- Streamer-like magnetic field (or more generally, closed loops) can be an important factor in producing large SEP events.
- Kong et al. *Particle Acceleration at Coronal Shocks: The Effect of Large-Scale Streamer-like Magnetic Field Structures*, Astrophysical Journal, in preparation