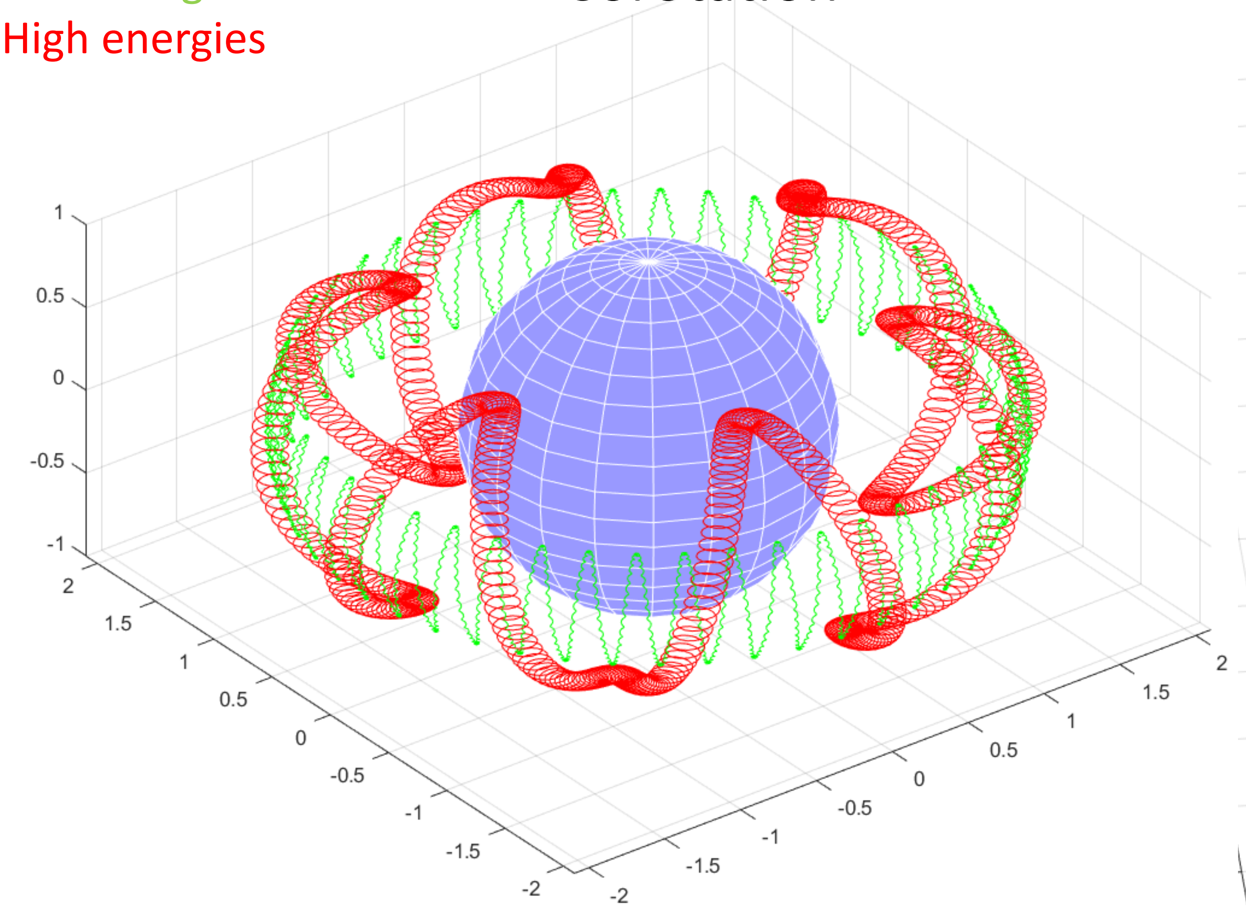
Deterministic propagation of suprathermal ions through the heliosphere

P. Kollmann, E.C. Roelof, M. Hill, R. Decker, and the New Horizons team

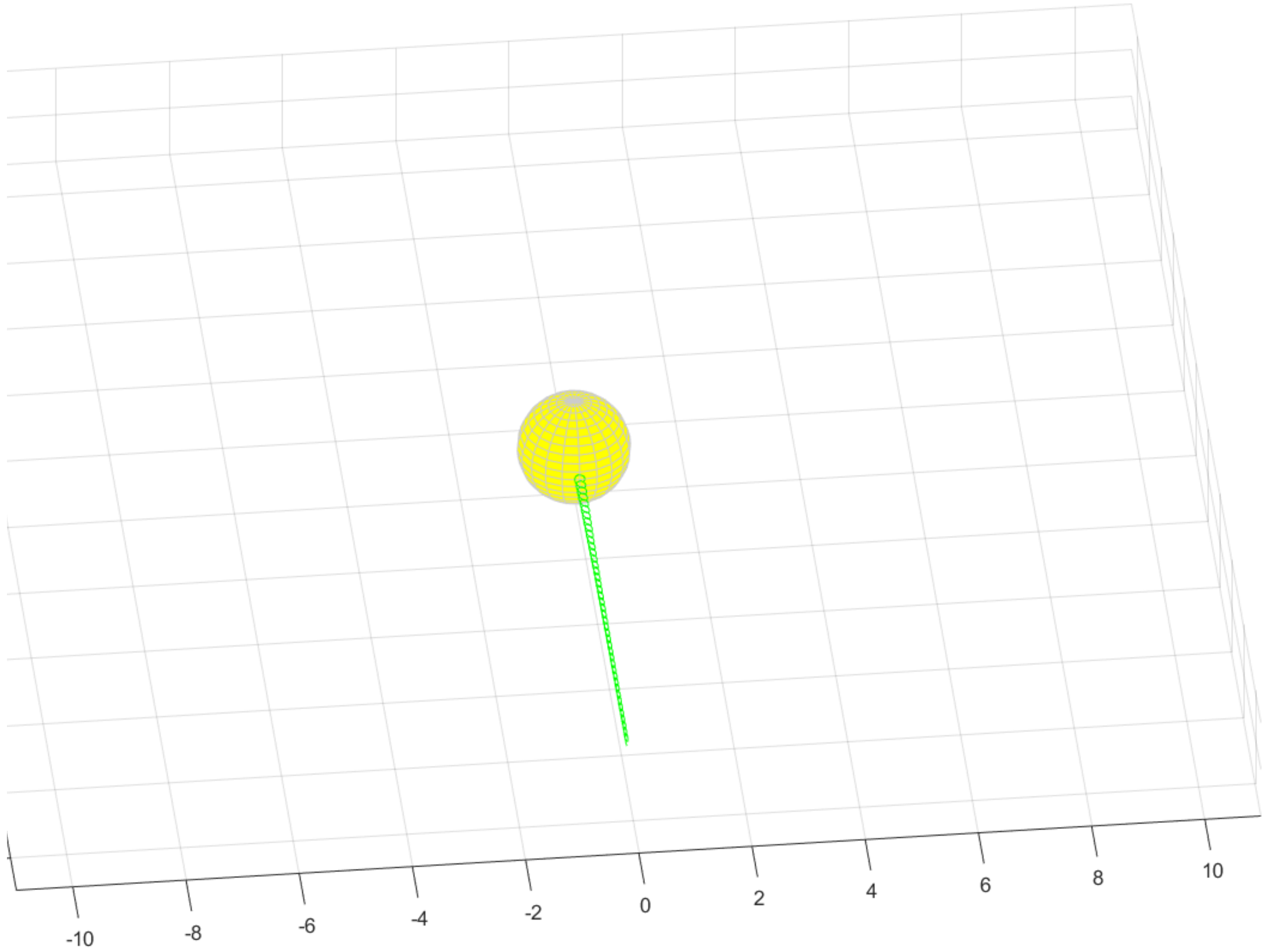
Charged particles in magnetic fields

Low energies
High energies

Dipole field
Corotation



Parker field
Outflow



Diffusion for energetic particles?

Convectional wisdom uses spatial diffusion to describe energy spectra (Fisk+ 80, Yu+ 17).

THE ASTROPHYSICAL JOURNAL, 237:620–626, 1980 April 15

SHOCK ACCELERATION OF ENERGETIC PARTICLES IN COROTATING INTERACTION REGIONS IN THE SOLAR WIND

The particle intensity increases upstream from the CIR are relatively steady in time, and thus their behavior should be described by the standard steady-state equation for propagation in the solar wind. In the corotating frame, the equation for f in a given magnetic flux tube, or equivalently along a given streamline in Figure 1, is (Parker 1965; Fisk, Forman, and Axford 1973; Ng 1972)

$$-\frac{1}{3r^2}\frac{\partial}{\partial r}(r^2 V)v\frac{\partial f}{\partial v} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\kappa\frac{\partial f}{\partial r}\right) - V\frac{\partial f}{\partial r}. \quad (1)$$

It is assumed here that the particles are nonrelativistic; i.e., equation (1) is written in terms of particle speed as opposed to particle momentum. The first term on the right-hand side describes the spatial diffusion of the particles. It is assumed that particles move only along, and not across, magnetic field lines, in which case $\kappa = \kappa_\parallel \cos^2\psi$, where $\kappa_\parallel$ is the diffusion coefficient for propagation along the mean magnetic field $\boldsymbol{B}$, and ψ is the angle between $\boldsymbol{r}$ and $\boldsymbol{B}$. The remaining two terms describe the effects of convection and adiabatic deceleration by the solar wind; V is the speed of the solar wind in the inertial frame fixed with respect to the Sun, i.e., it is the radial component of the solar wind in the corotating frame.

limit of large v. A more accurate approximate solution to equation (1) will also contain a power-law dependence on v, and other weaker dependencies on v and r. It can readily be shown that to the next highest orders the approximate solution to equation (1), for the case $\kappa = \kappa_0 v r$, which satisfies equation (2) and is finite as $r \to 0$, is

$$f = \left(\frac{r}{r_s}\right)^{2\beta/(1-\beta)+V/(\kappa_0 v)} v^{-3/(1-\beta)} \exp\left(-\frac{6\kappa_0\beta v}{V(1-\beta)^2}\right), \quad (6)$$

where the normalization constant has been ignored. This solution holds along a given magnetic flux tube in the solar wind, or equivalently along a given streamline in the corotating frame depicted in Figure 1; β is to be evaluated at r_s, the intersection of this streamline with the forward or reverse shock.

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Astronomy & Astrophysics

Suprathermal helium in corotating interaction regions: combined observations from SOHO/CELIAS/STOF and ACE/SWICS

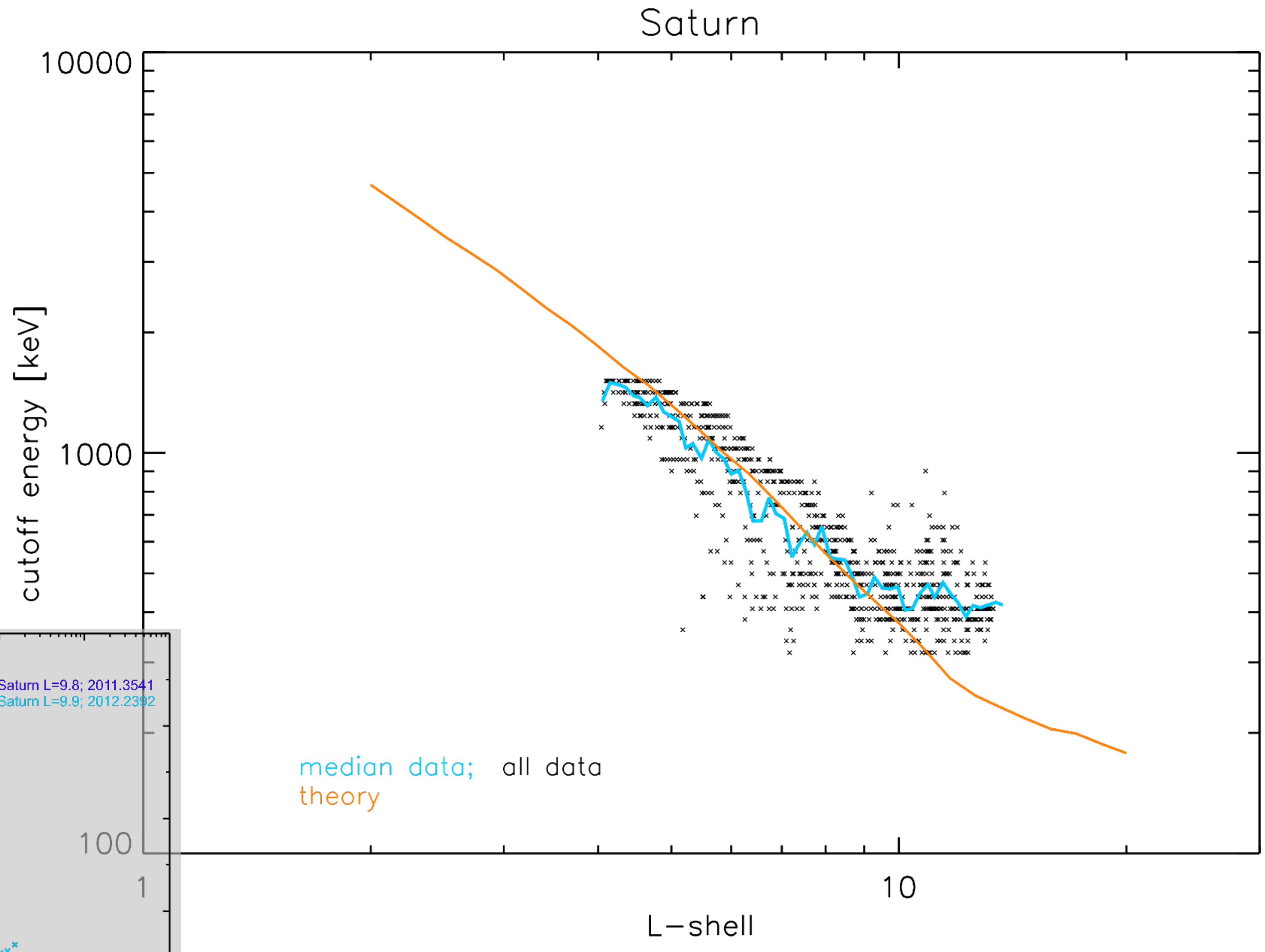
As we show in Fig. 6, we fitted the spectra of CIR 04 with the following theoretical expressions (2) (downstream of the shock) and (3) (upstream of the shock) given by Fisk & Lee (1980), as this event is associated with clear turnover spectra in the fast-wind region,

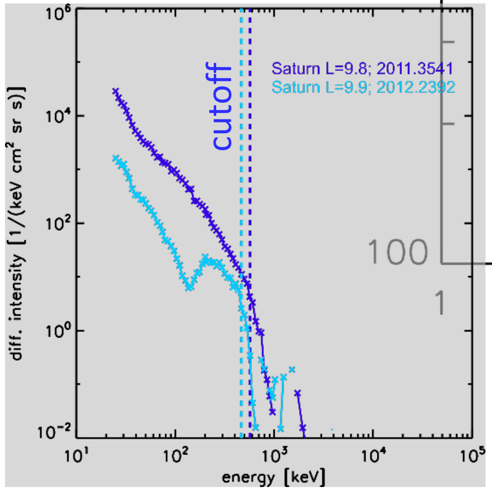
$$f = \left(\frac{r}{r_s}\right)^{-2/(1-\beta)} v^{-3/(1-\beta)} \exp\left[-\frac{6\kappa_0\beta v}{V(1-\beta)^2}\left(\frac{r}{r_s}\right)^{2/3}\right] \quad (2)$$

$$f = \left(\frac{r}{r_s}\right)^{2\beta/(1-\beta)+V/(\kappa_0 v)} v^{-3/(1-\beta)} \exp\left[-\frac{6\kappa_0\beta v}{V(1-\beta)^2}\right], \quad (3)$$

where f is the velocity distribution function, v is the ion speed, r is the heliocentric distance of the observer, r_s is the heliocentric distance of the reverse shock, V is the solar wind speed, κ_0 is a constant ($\kappa_0 = \kappa/vr$, where κ is the diffusion coefficient), and β is the inverse of compression ratio at the CIR-driven shock.

Diffusion works less often than thought...





- Conventional wisdom predicts that Saturn's electrons are accelerated by energy diffusion (Shprits+12, Woodfield +19, Yu+ 19).
- Yet data shows that adiabatic transport without any diffusion plays a major role (Kollmann+ 16B).

Kollmann+ 16B

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High energies

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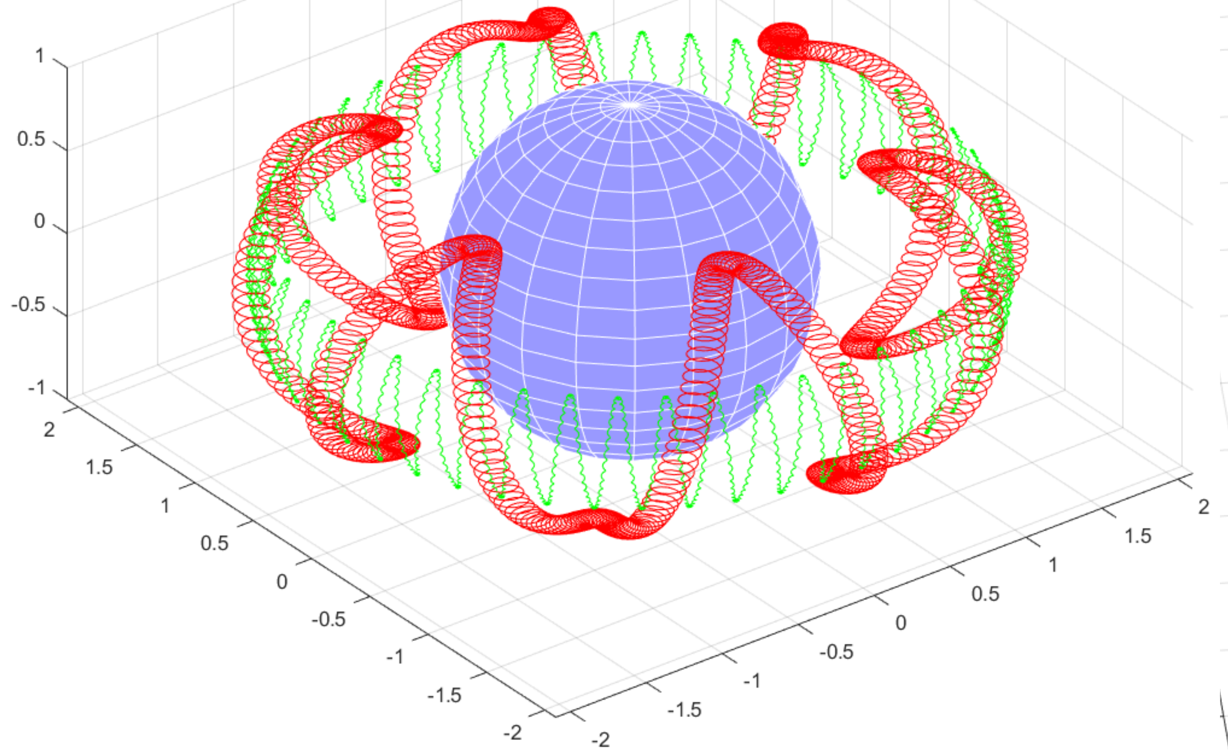
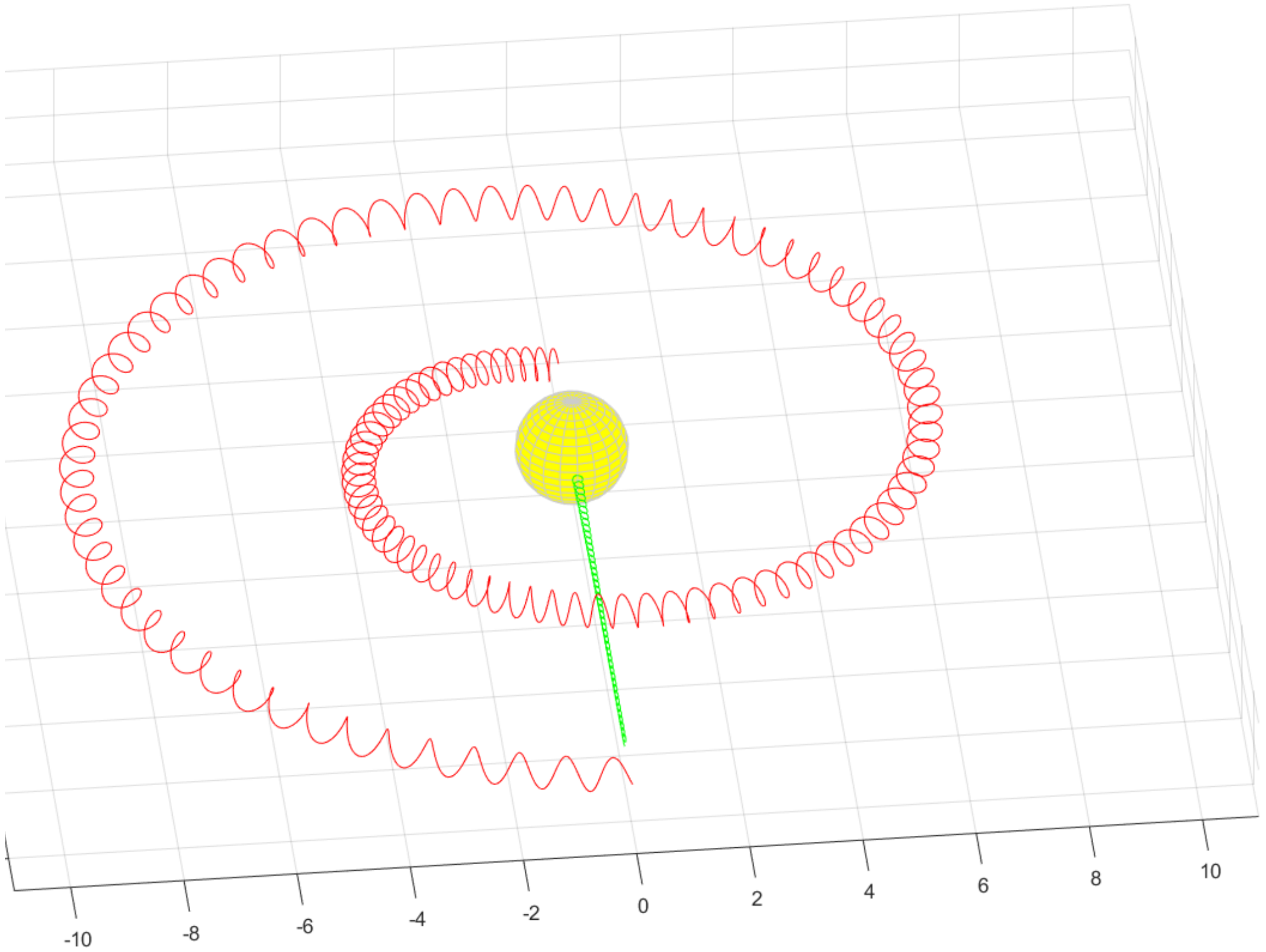
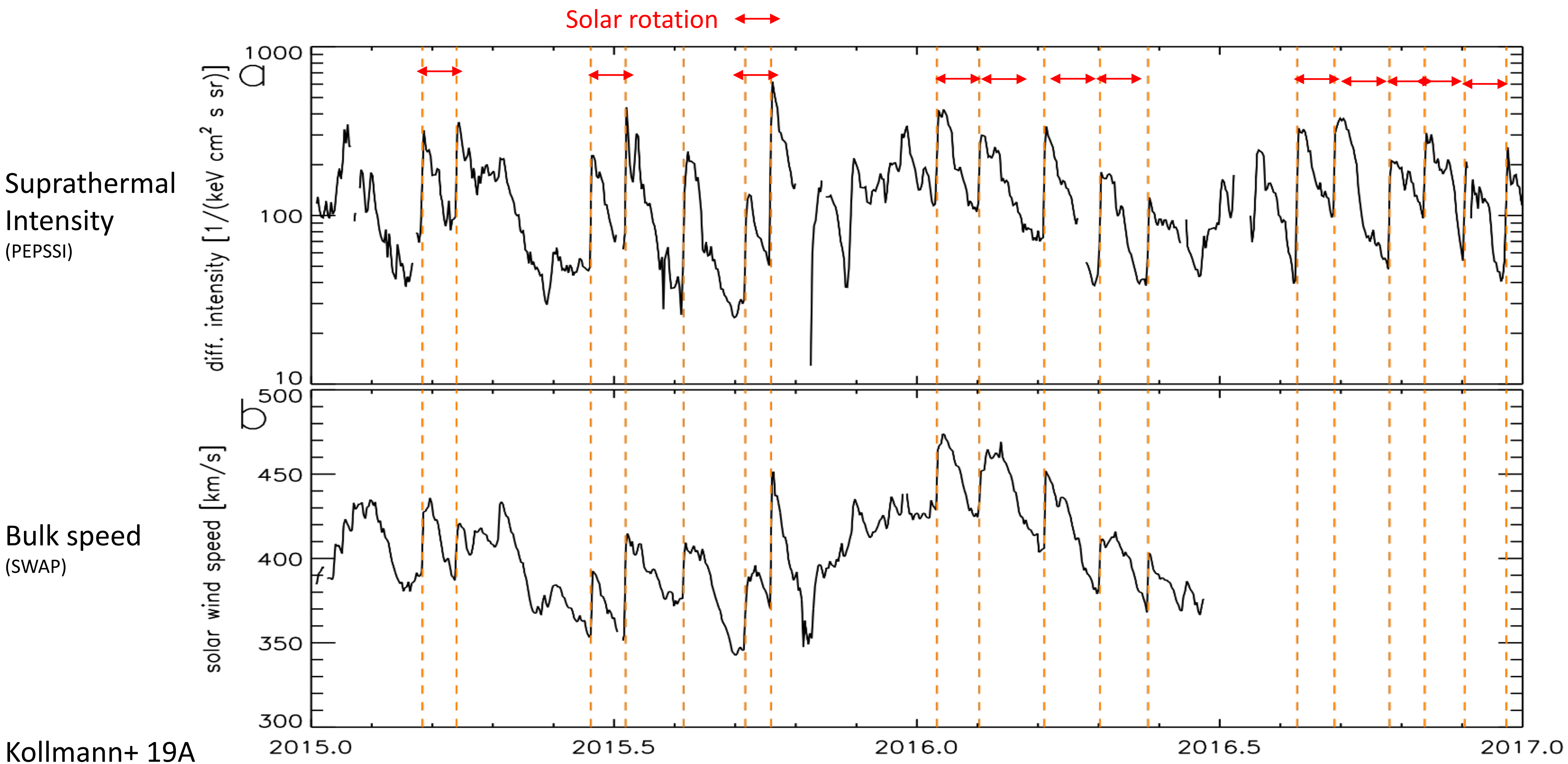
Corotation



Parker field
Outflow

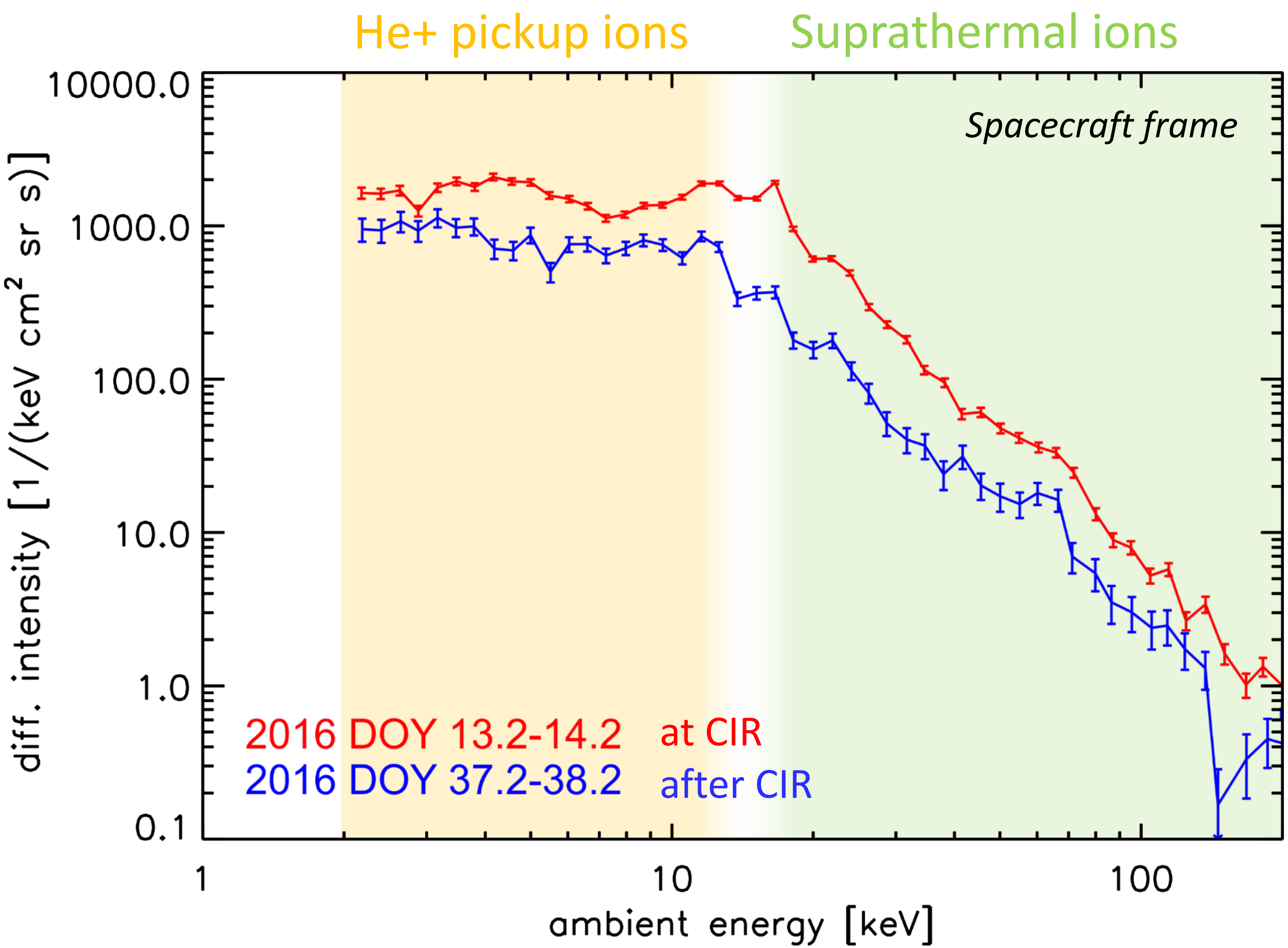


Particles released from CIRs



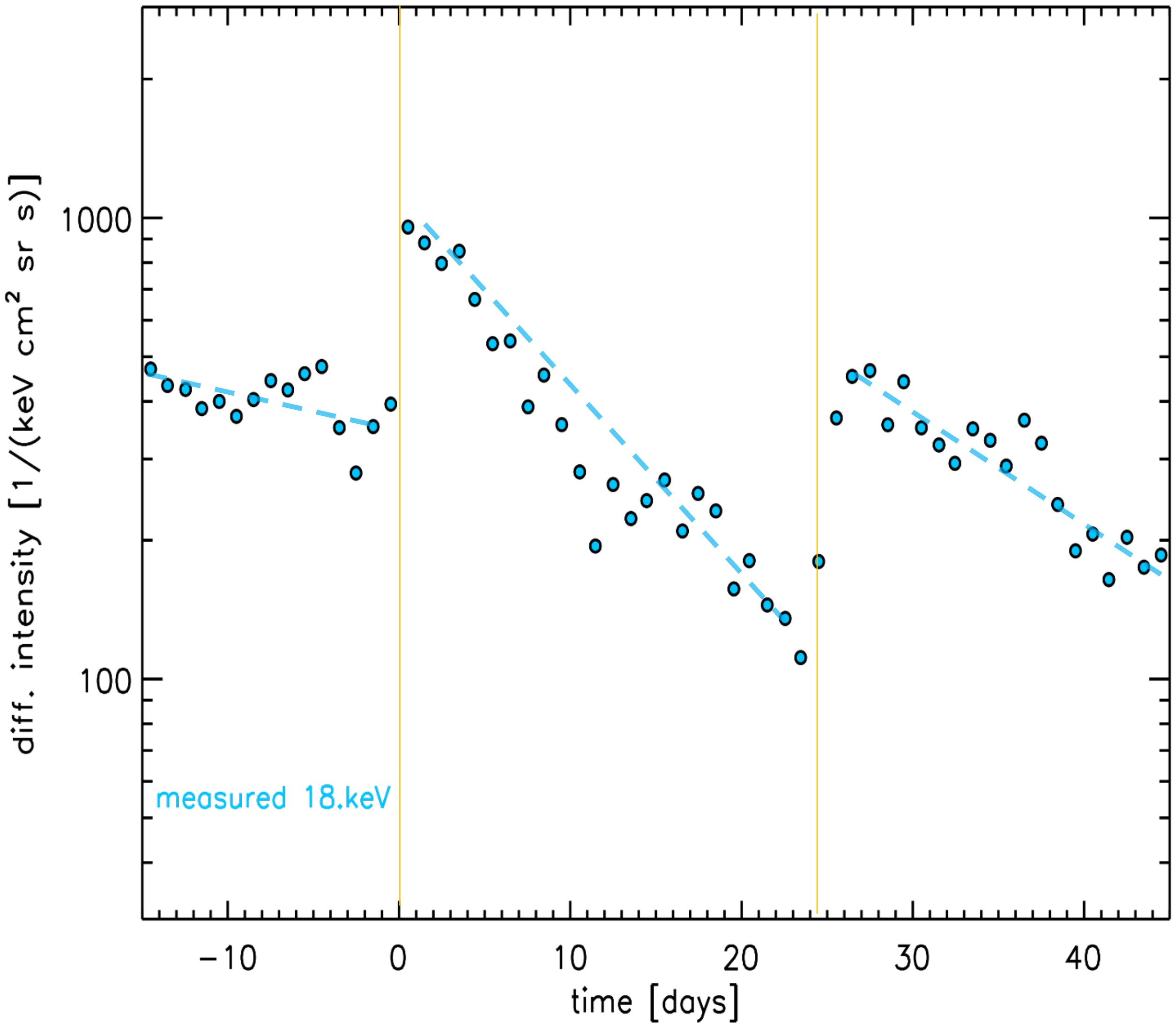
Kollmann+ 19A

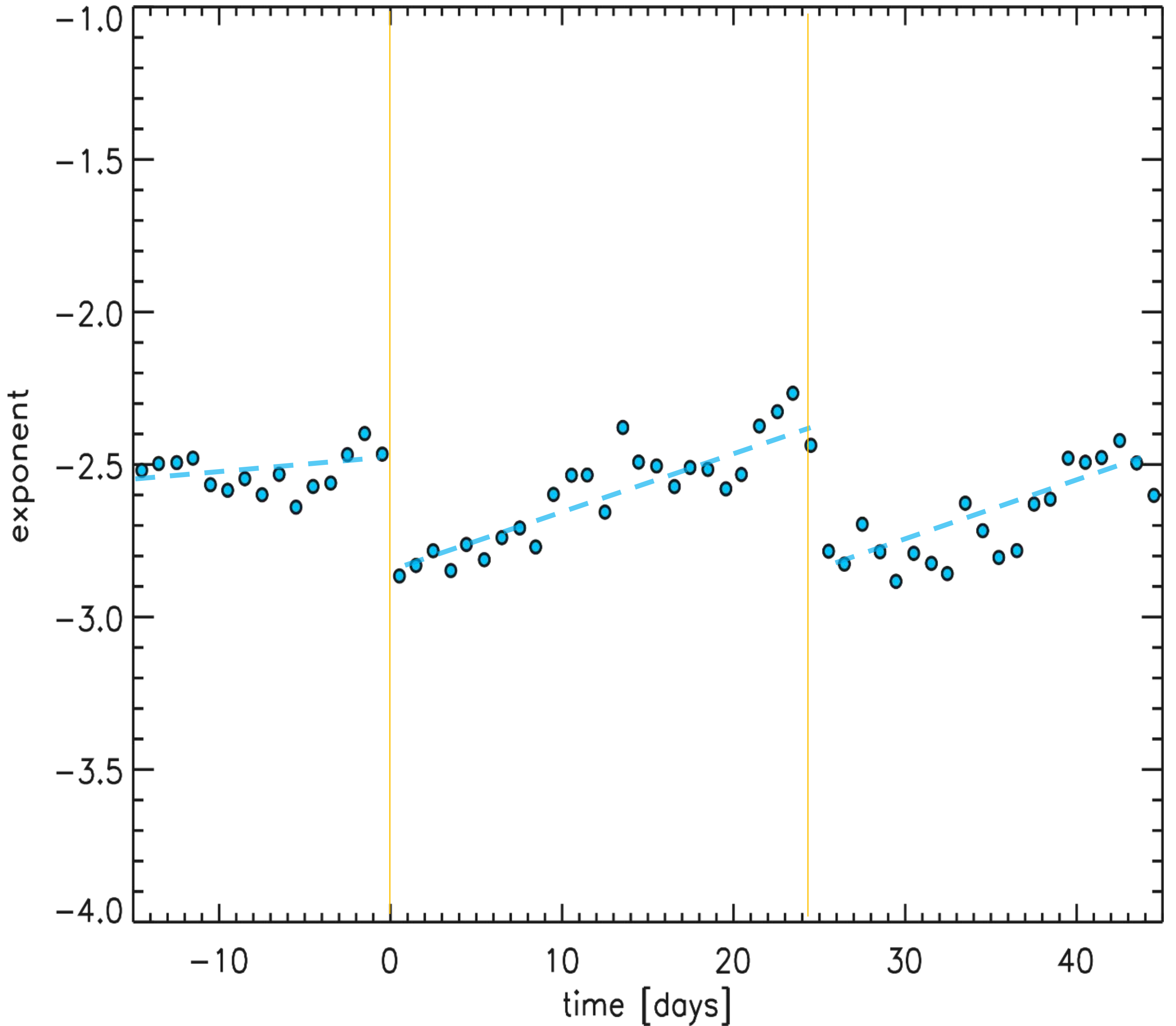
PEPSSI spectra



Kollmann+ 19A

Particles released from CIRs





Equations

Theory based on Northrop 63 & Roelof+ 15

$$\frac{d\vec{R}}{dt} = \vec{F} \times \frac{\vec{B}}{qB^2} + \vec{v}_{||}$$

- Guiding center drifts

$$\frac{dW}{dt} = q\vec{E}\frac{d\vec{R}}{dt} + M\frac{\partial B}{\partial t}$$

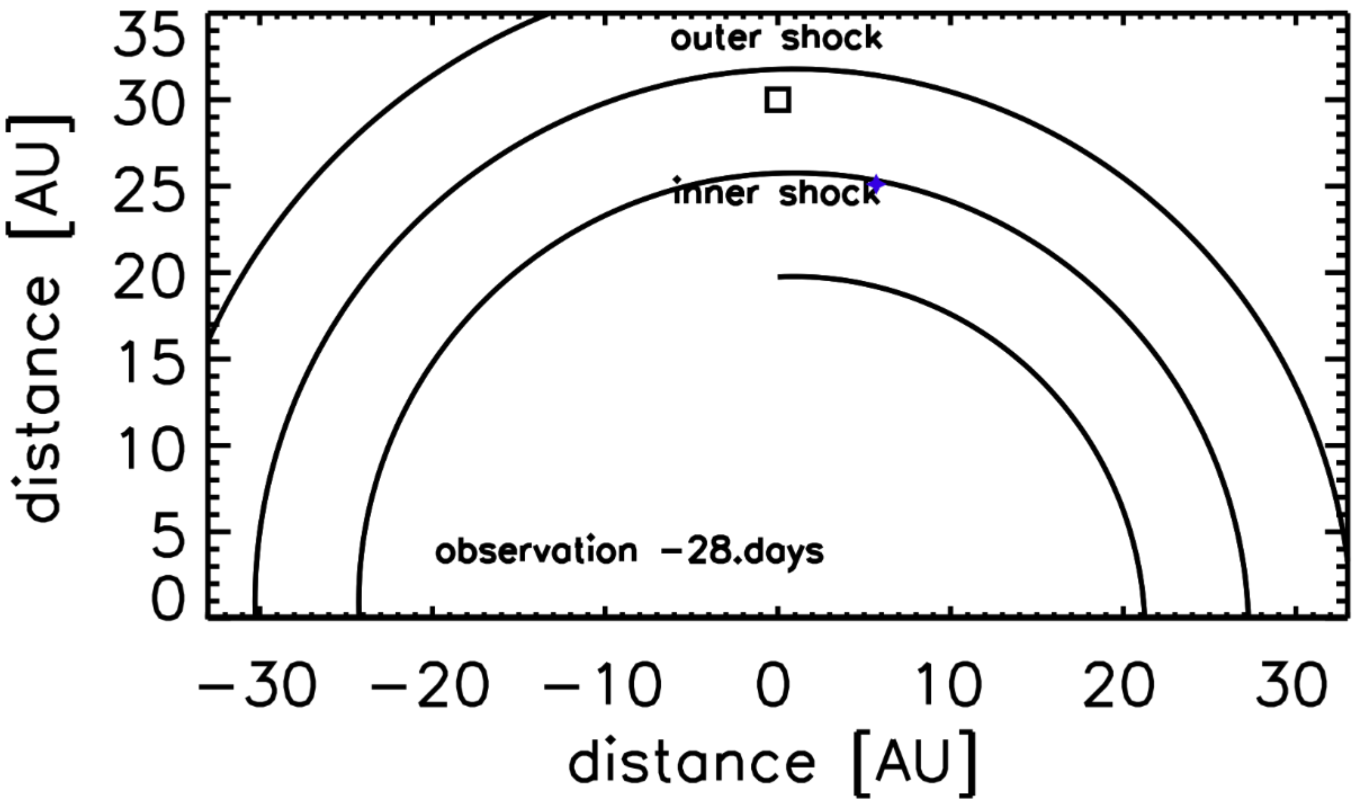
- Energy change within fields

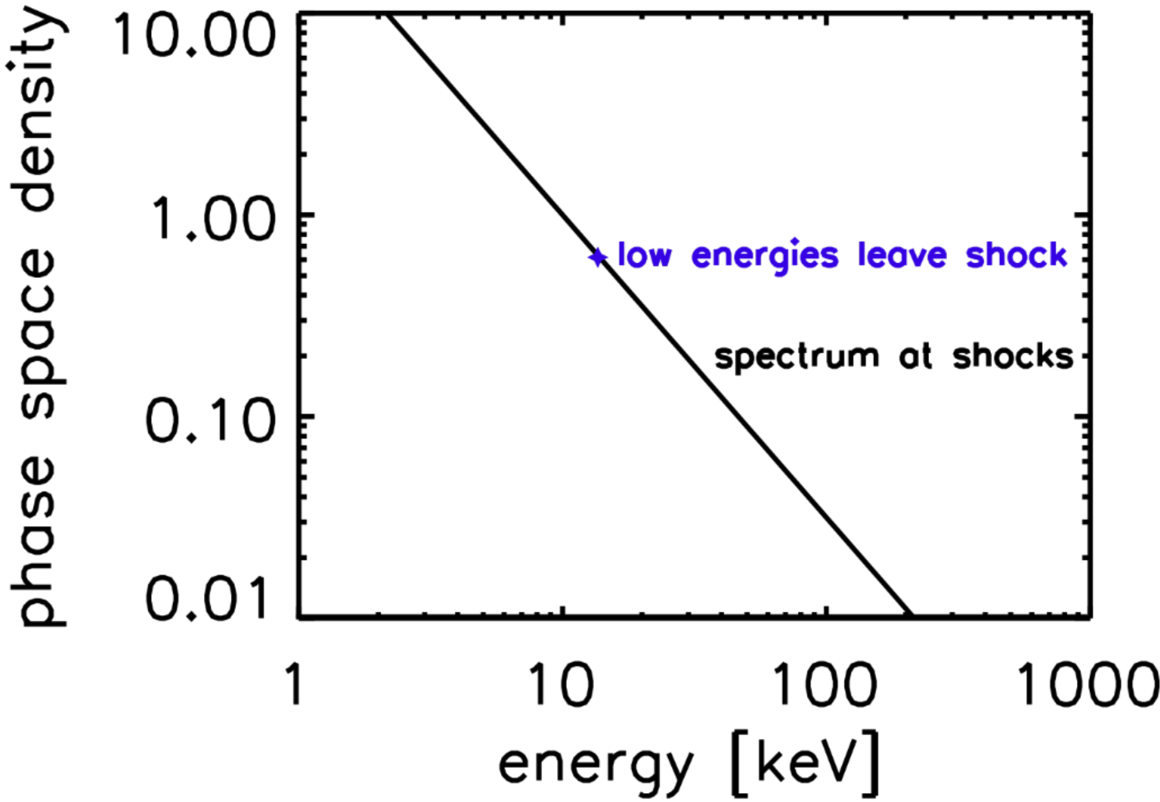
- Maxwell's equations
- Non-relativistic speeds
- Frozen-in plasma
- Radial solar wind
- B ~ 1/R

- No gradient & curvature drifts
- Near-azimuthal magnetic field
- Conservation of magnetic moment

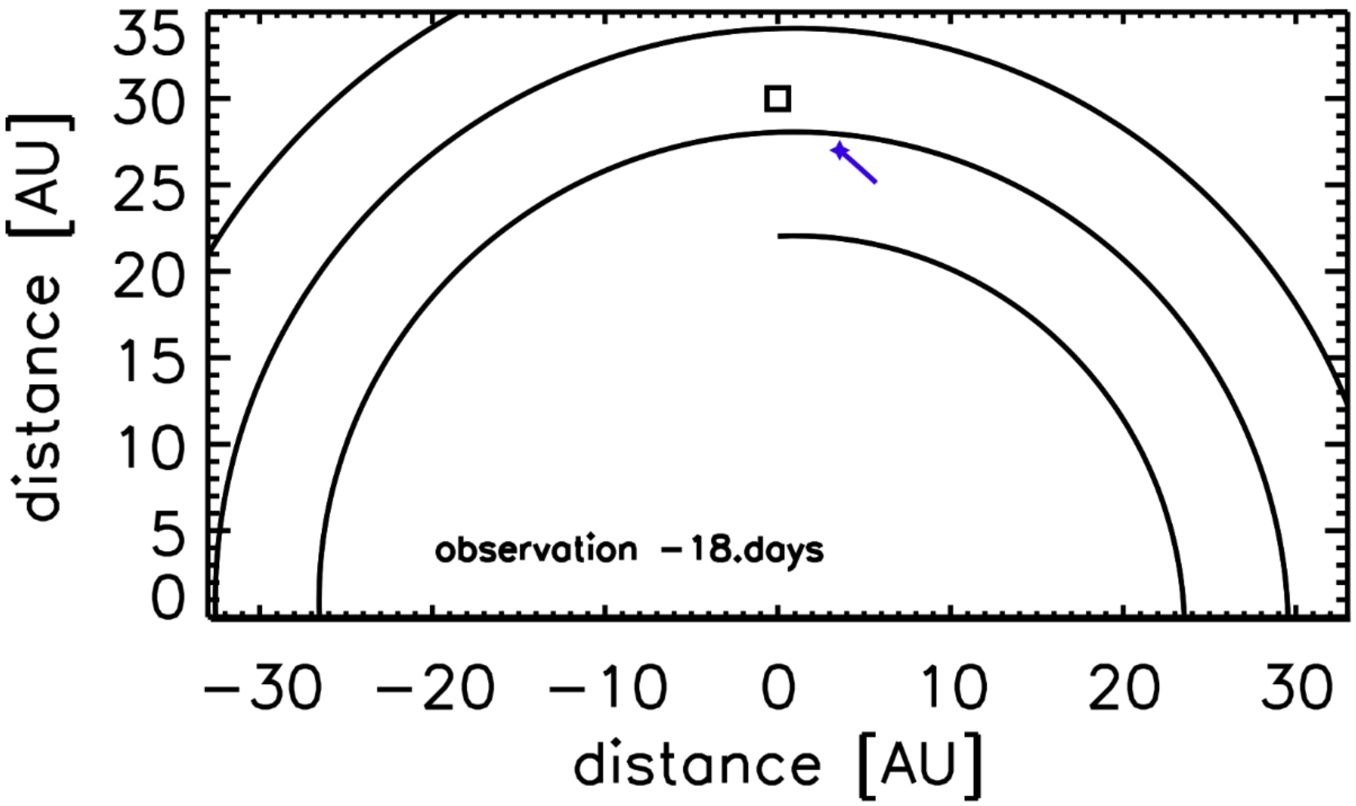
- Conservation of phase space density

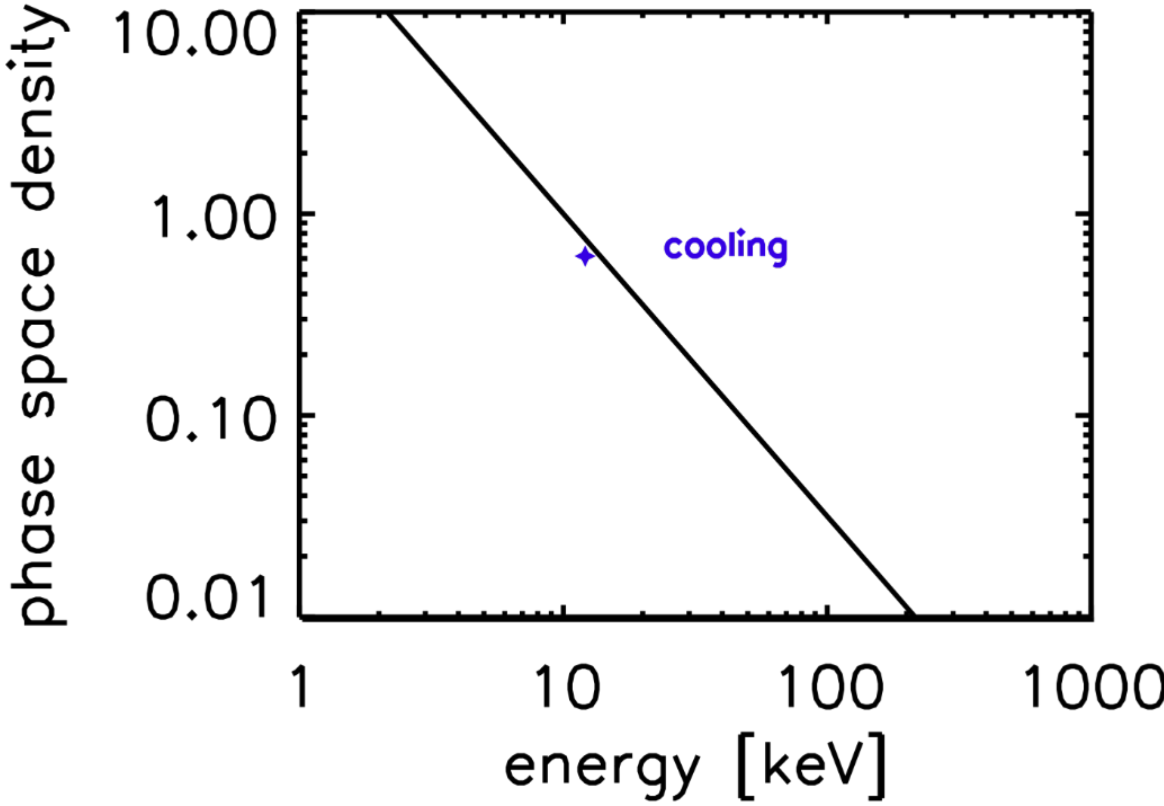
Deterministic propagation



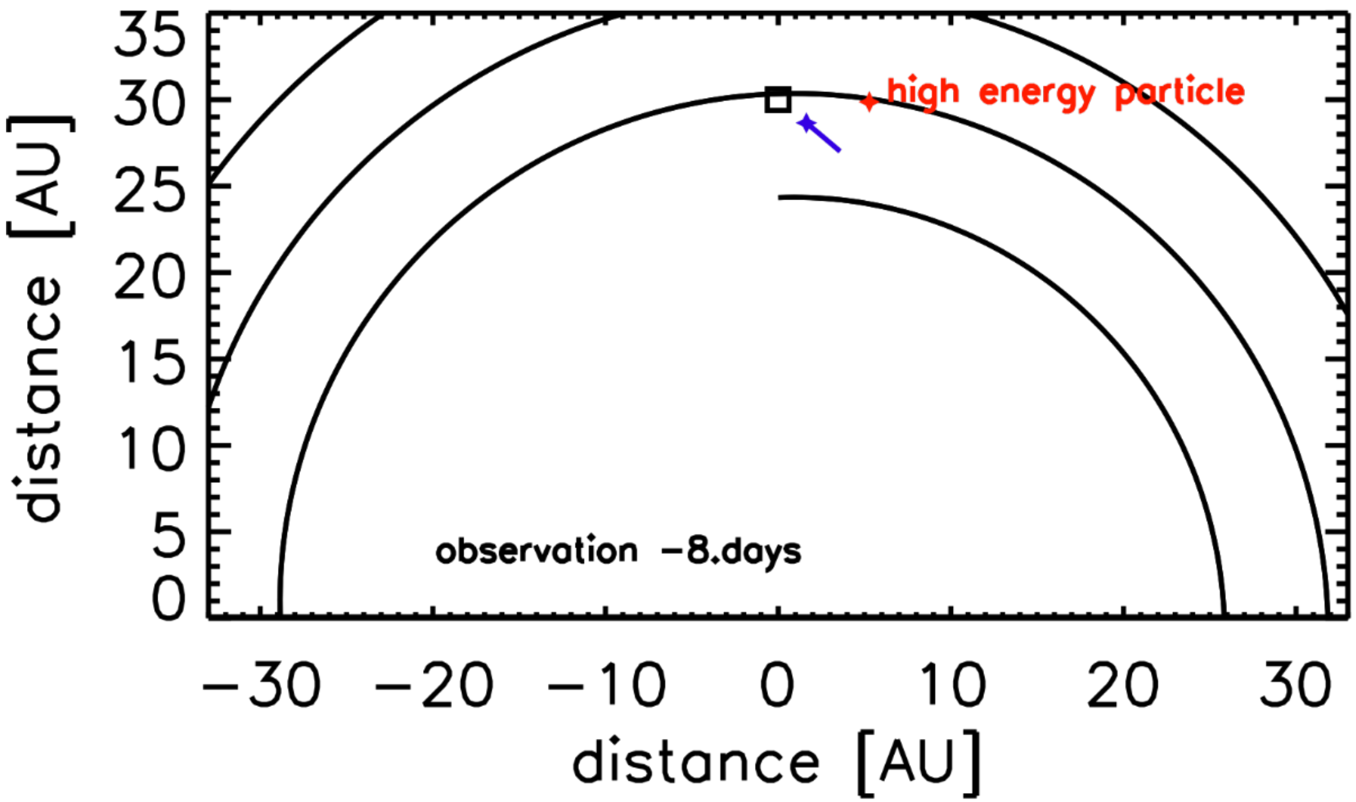


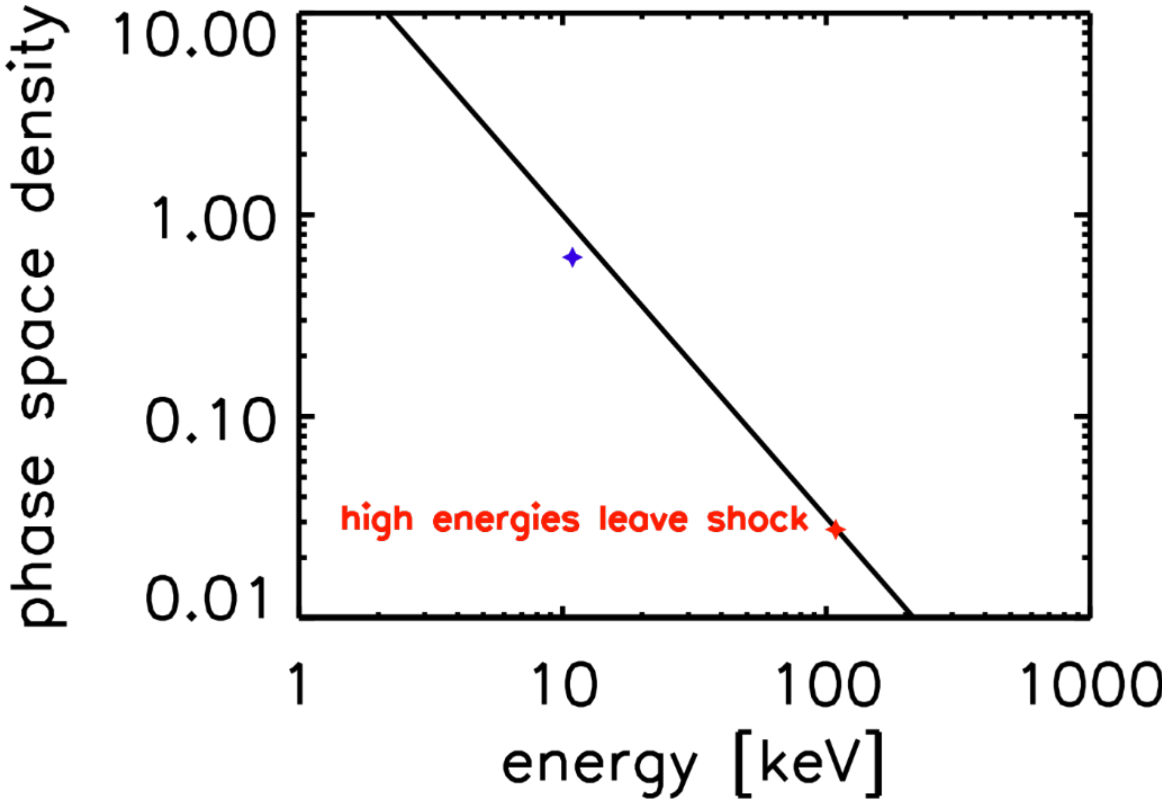
Deterministic propagation



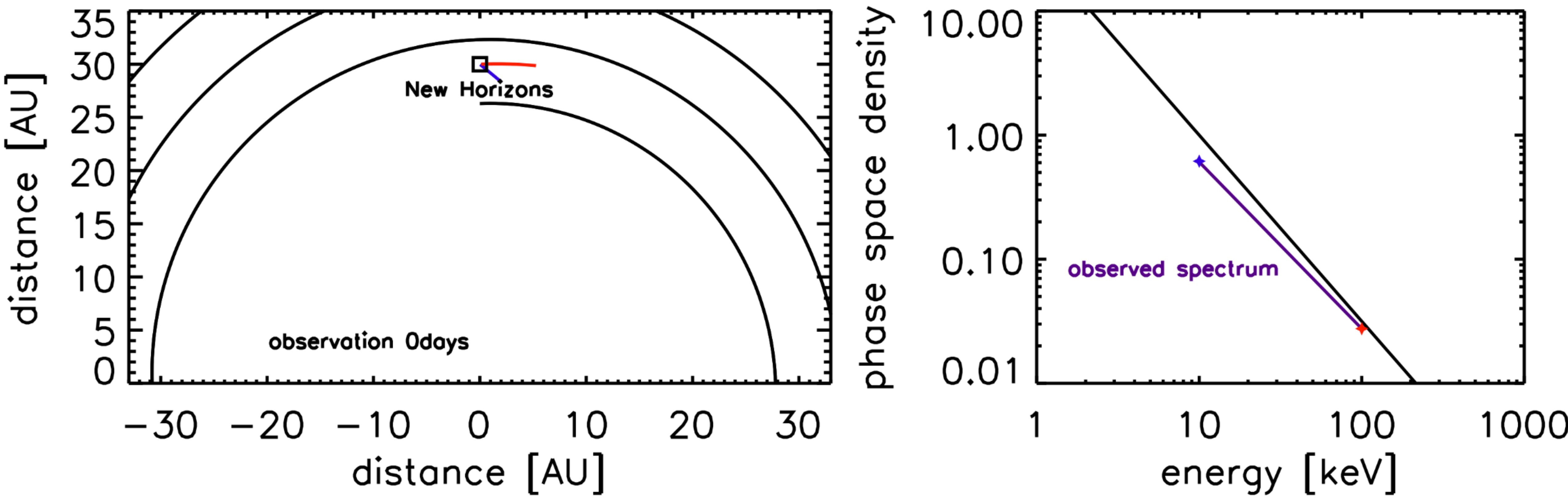


Deterministic propagation

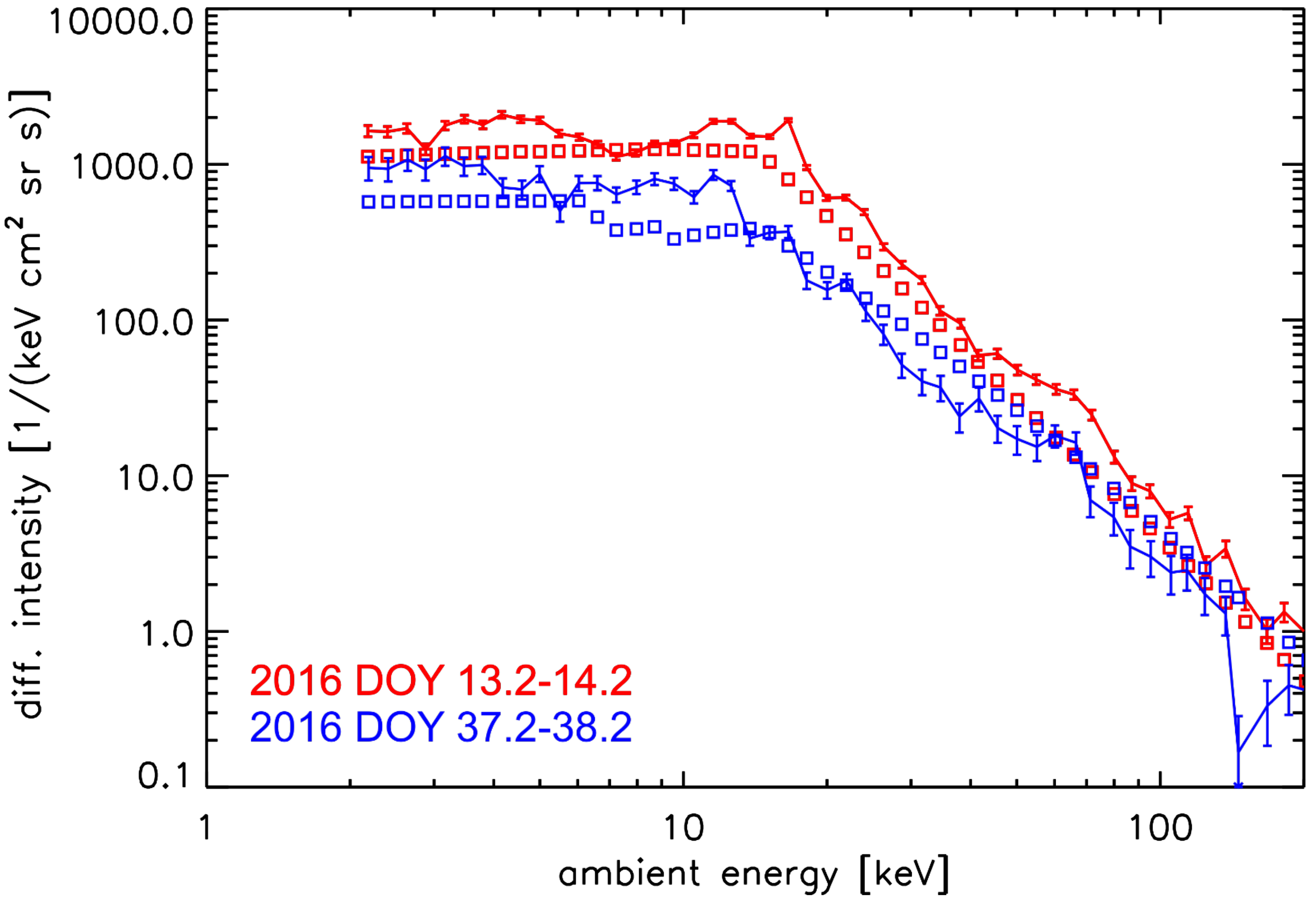




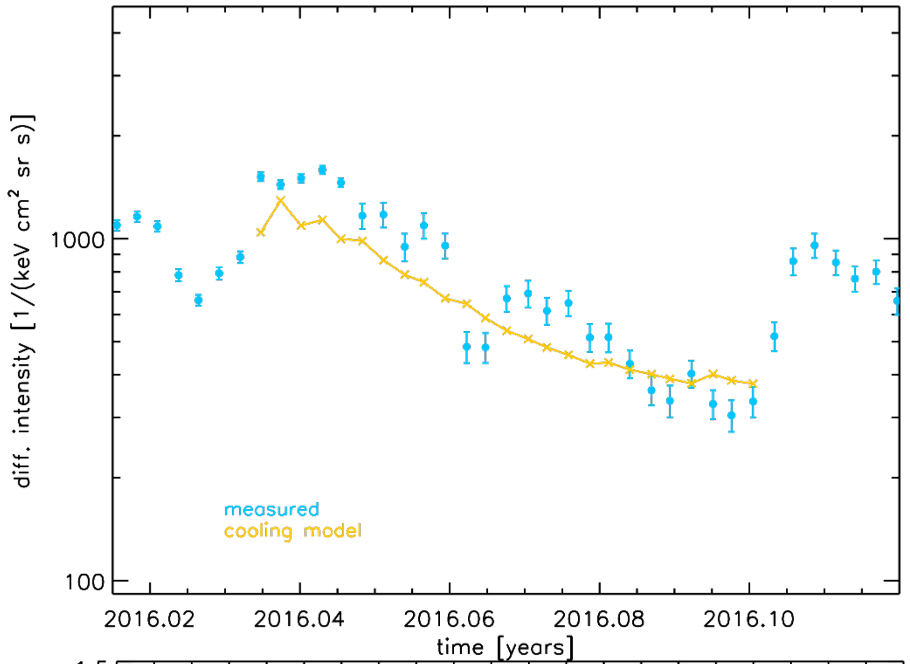
Deterministic propagation



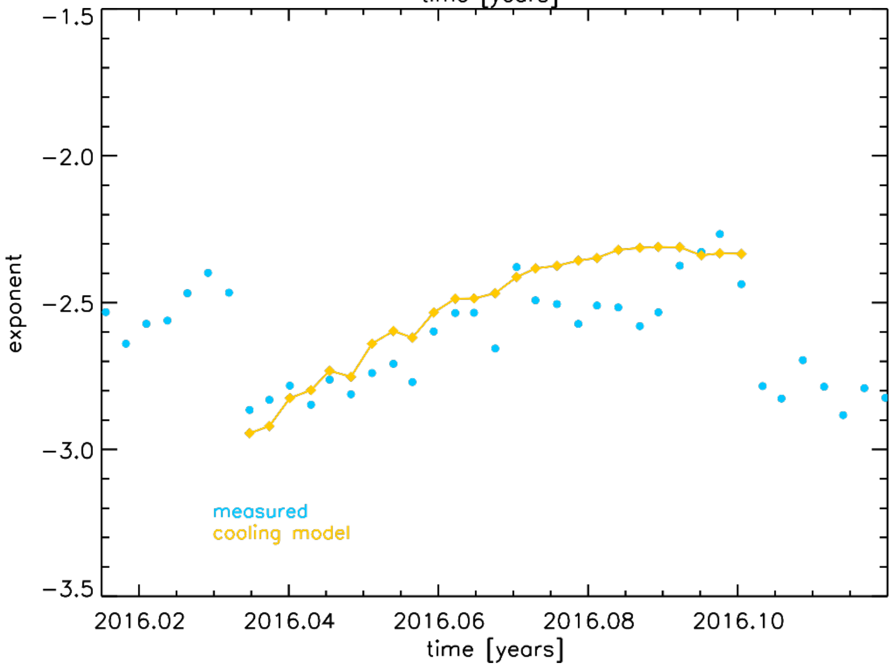
Solution



10000.0
1000.0
100.0
10.0
1.0
0.1
1
10
100
ambient energy [keV]
diff. intensity [1/(keV cm² sr s)]
2016 DOY 13.2-14.2
2016 DOY 37.2-38.2

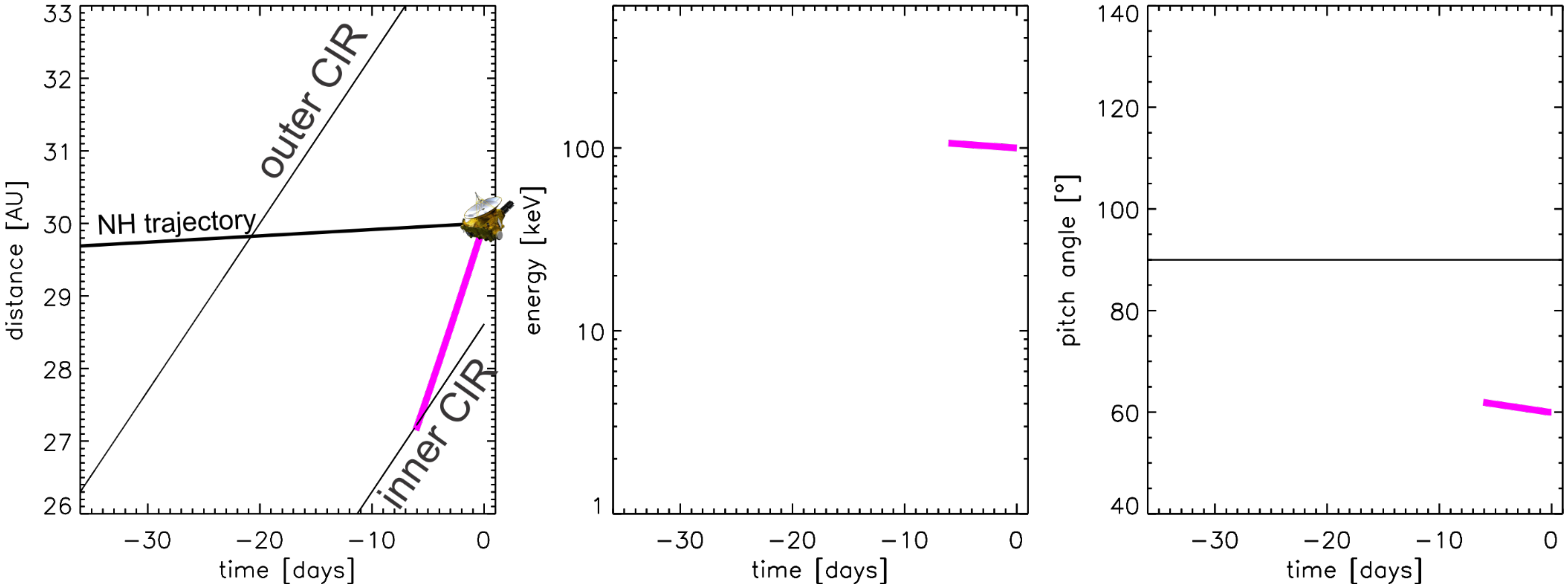


1000
100
diff. intensity [1/(keV cm² sr s)]
measured
cooling model
2016.02
2016.04
2016.06
2016.08
2016.10
time [years]

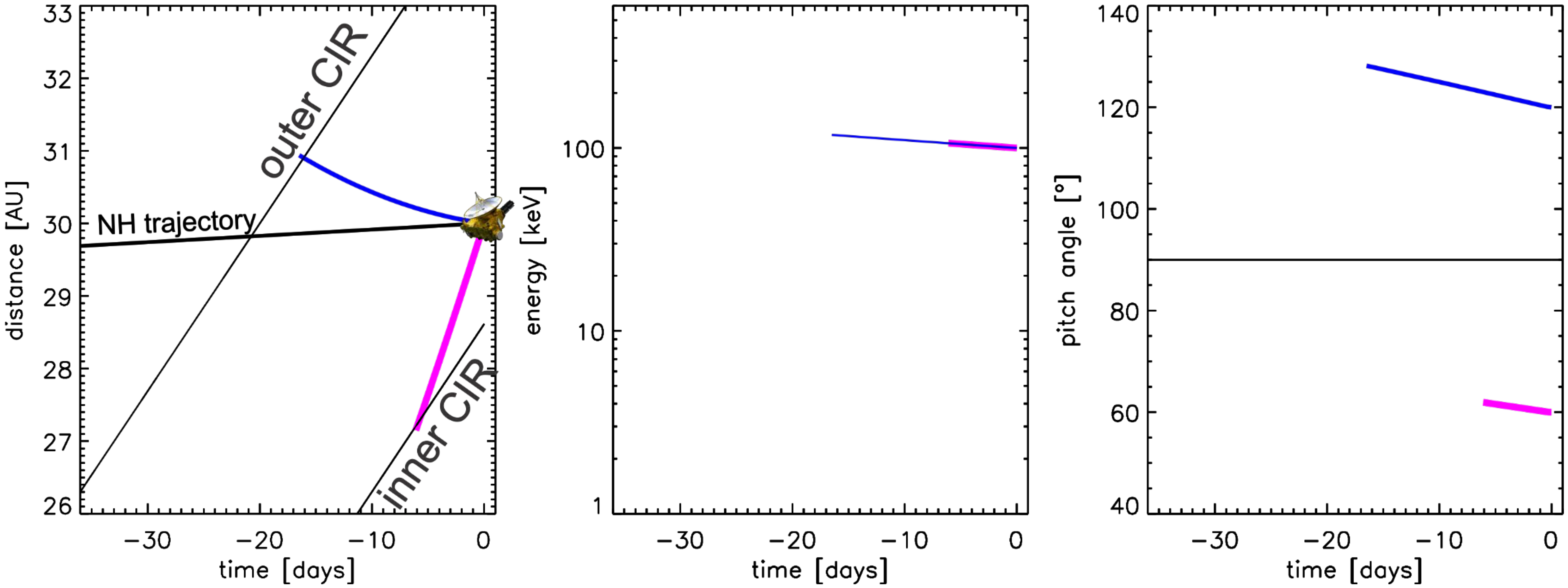


−1.5
−2.0
−2.5
−3.0
−3.5
exponent
measured
cooling model
2016.02
2016.04
2016.06
2016.08
2016.10
time [years]

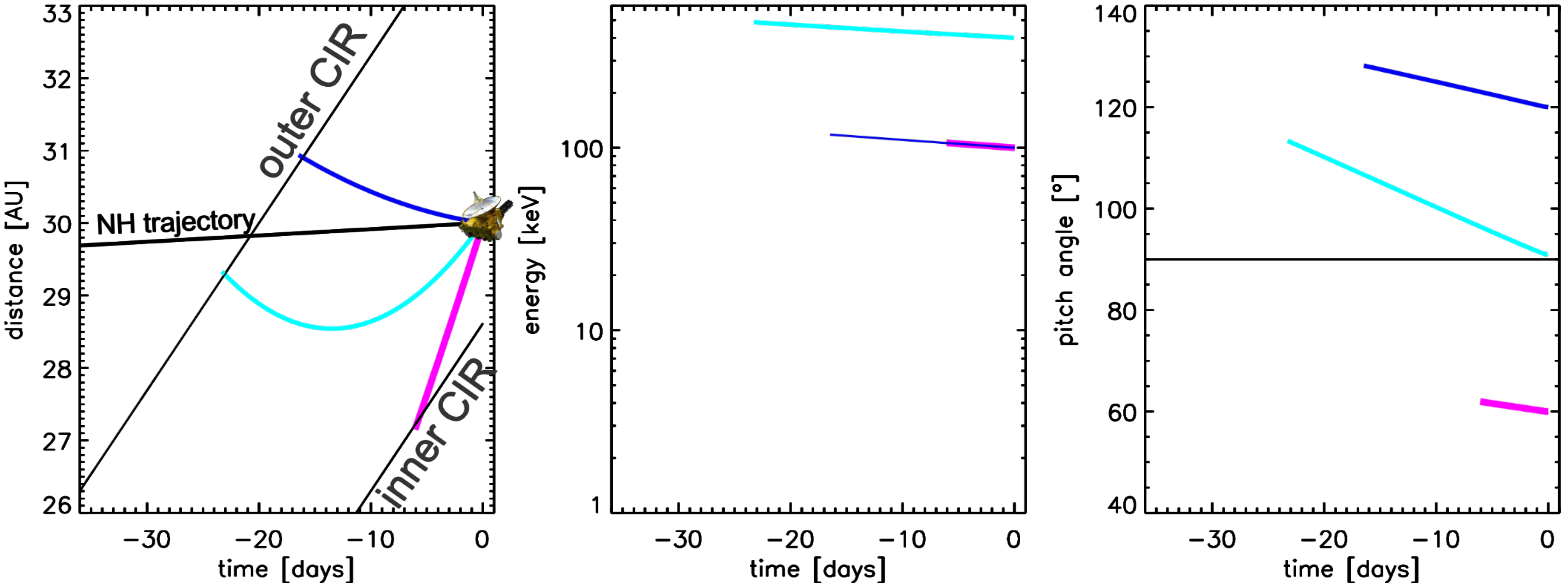
Propagation branches



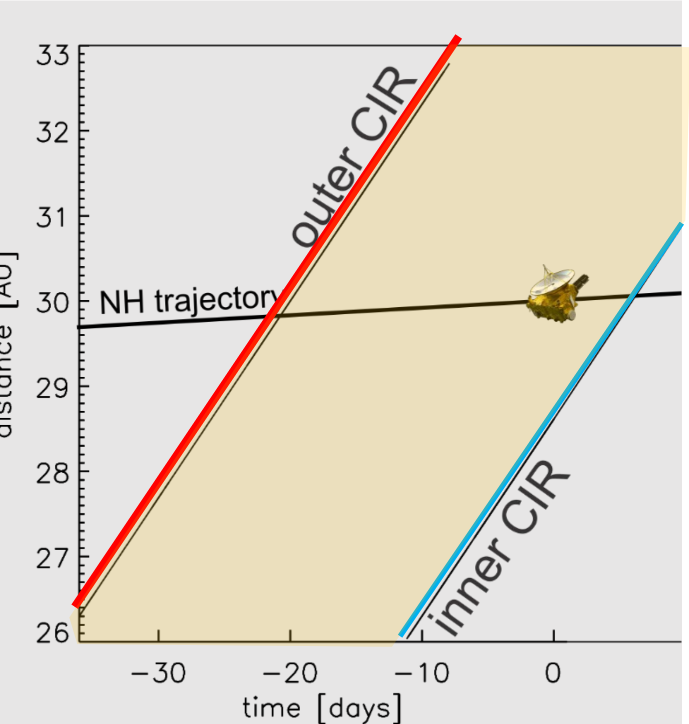
Propagation branches

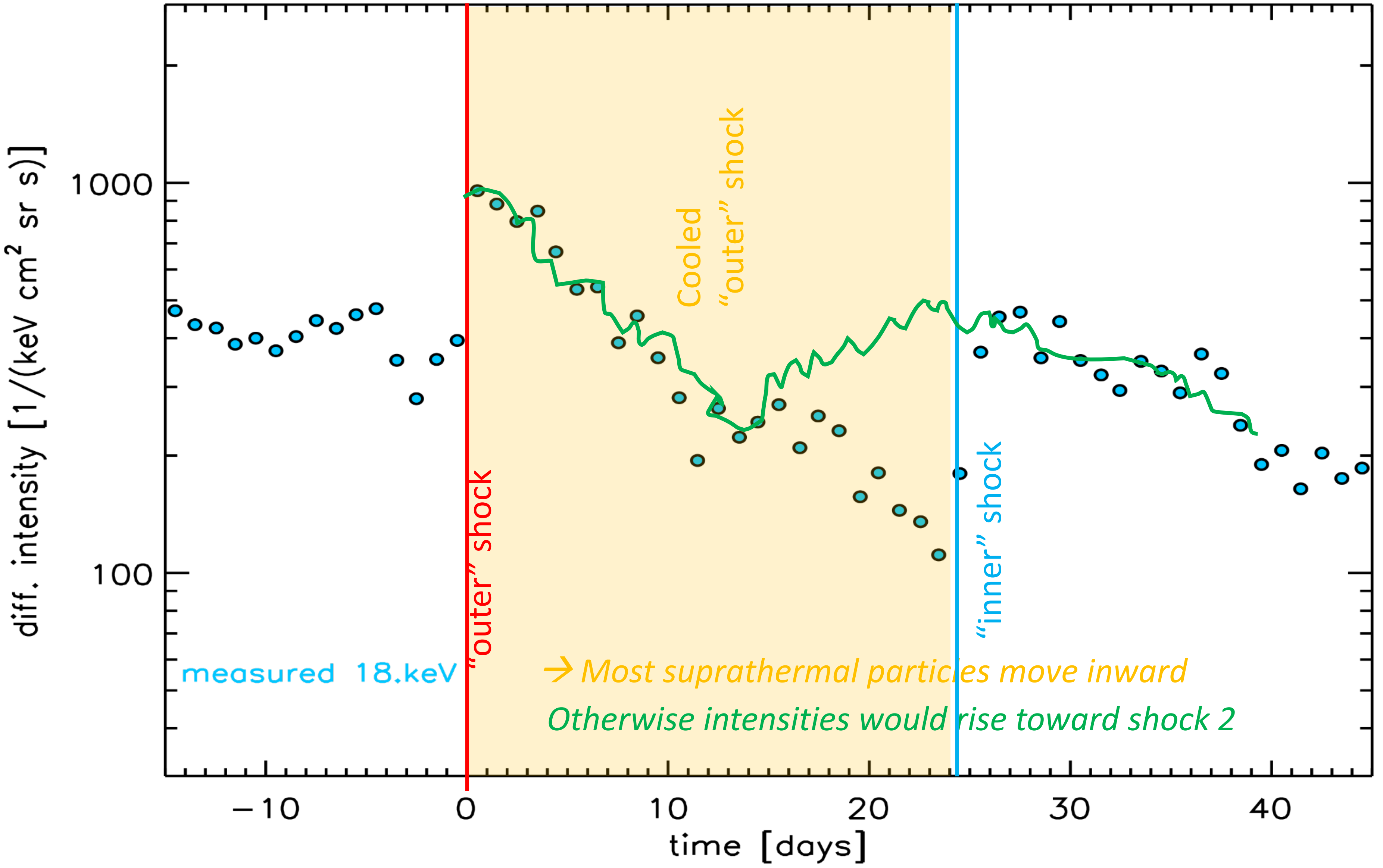


Propagation branches



Most particles released from outer CIR



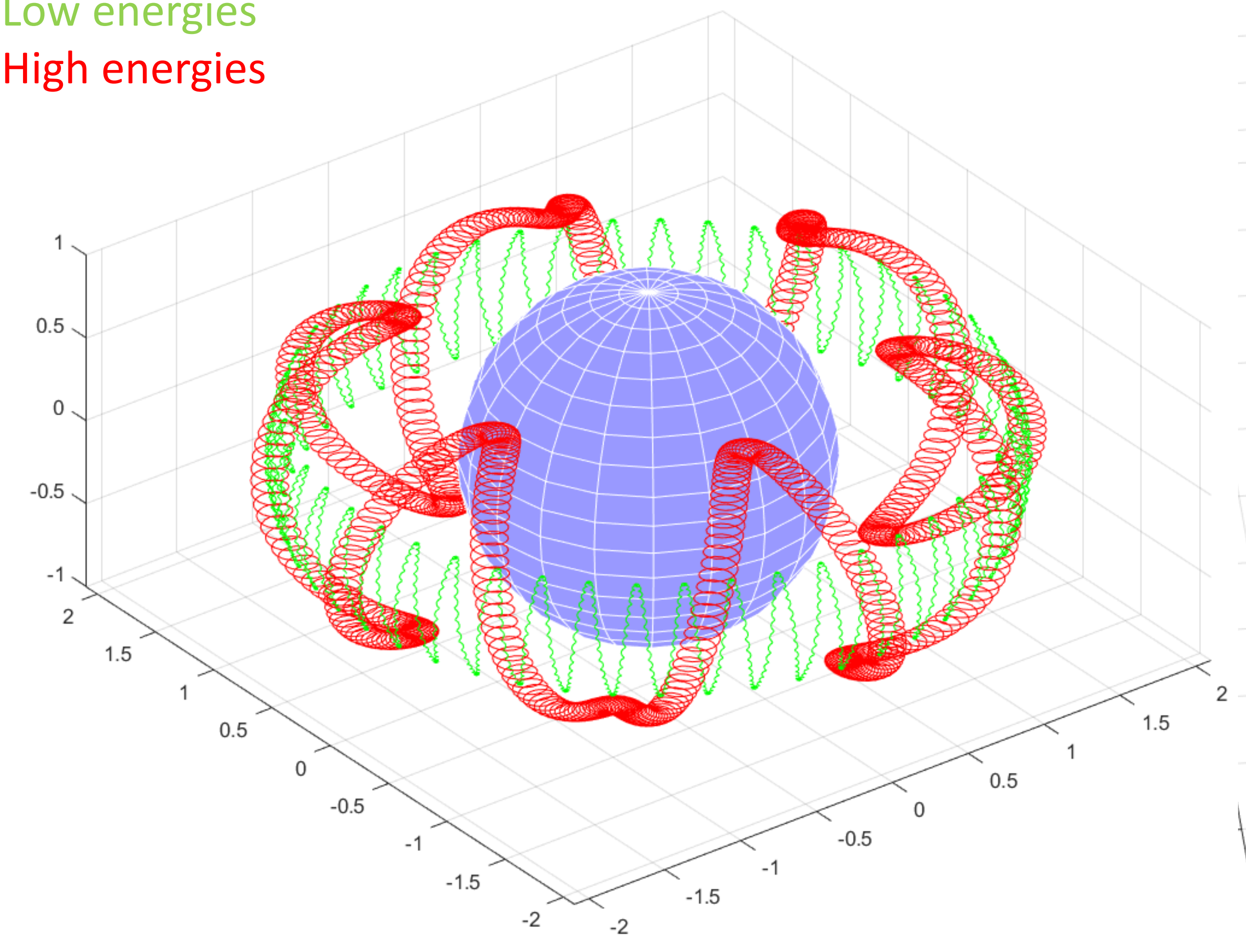


Summary

Dipole field
Corotation

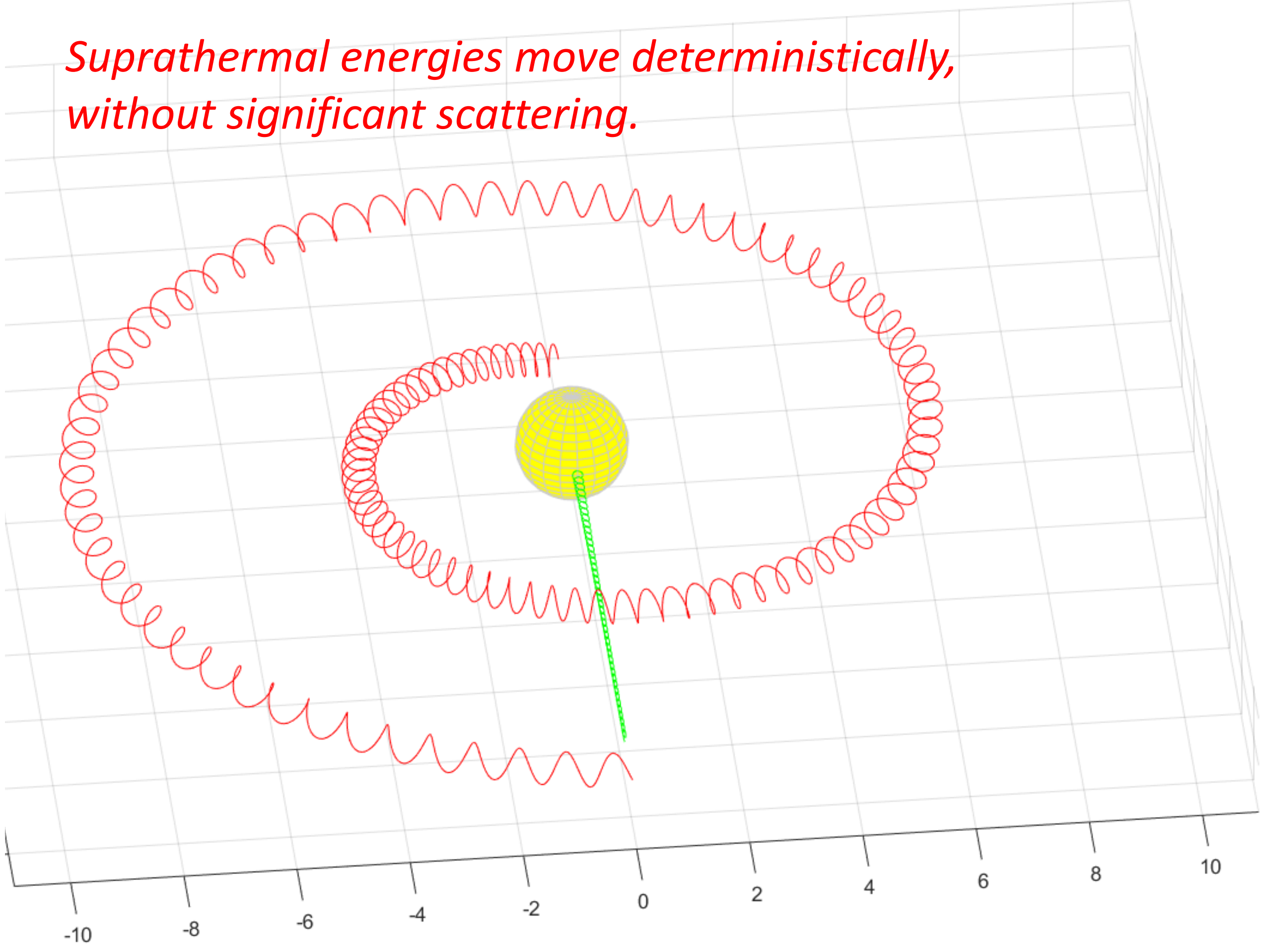
Low energies

High energies



Parker field
Outflow

Suprathermal energies move deterministically, without significant scattering.



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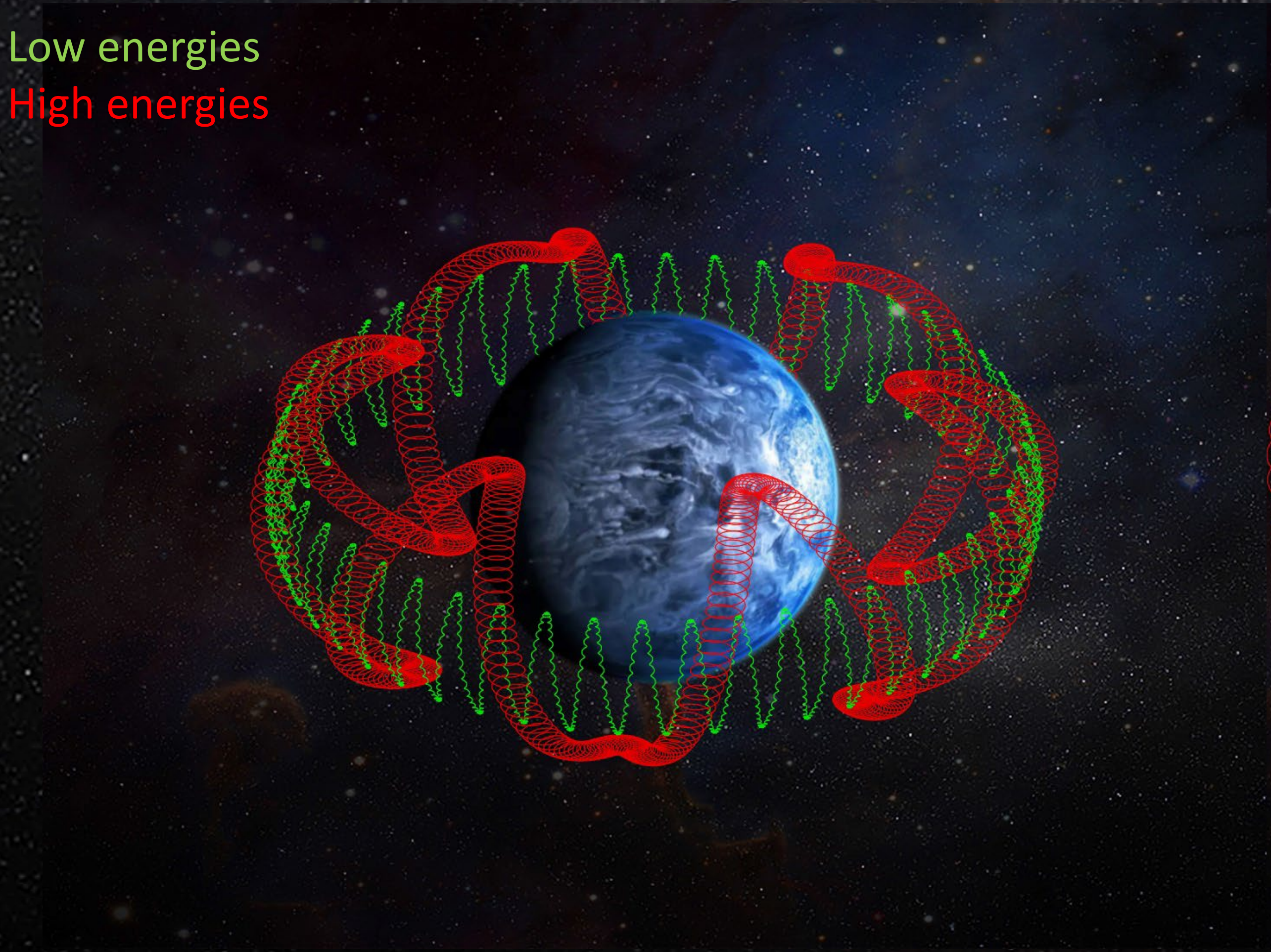

Parker field
Outflow