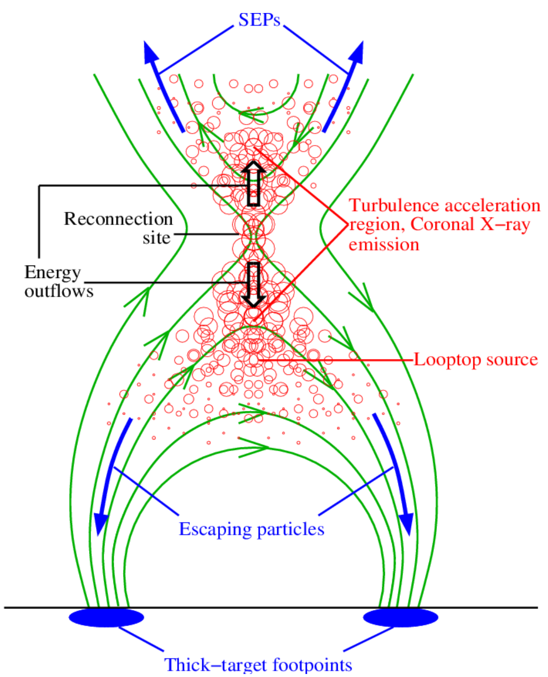
Particle Acceleration in Solar Flares and Associated CME Shocks:

What Have We Learned From FERMI Observations



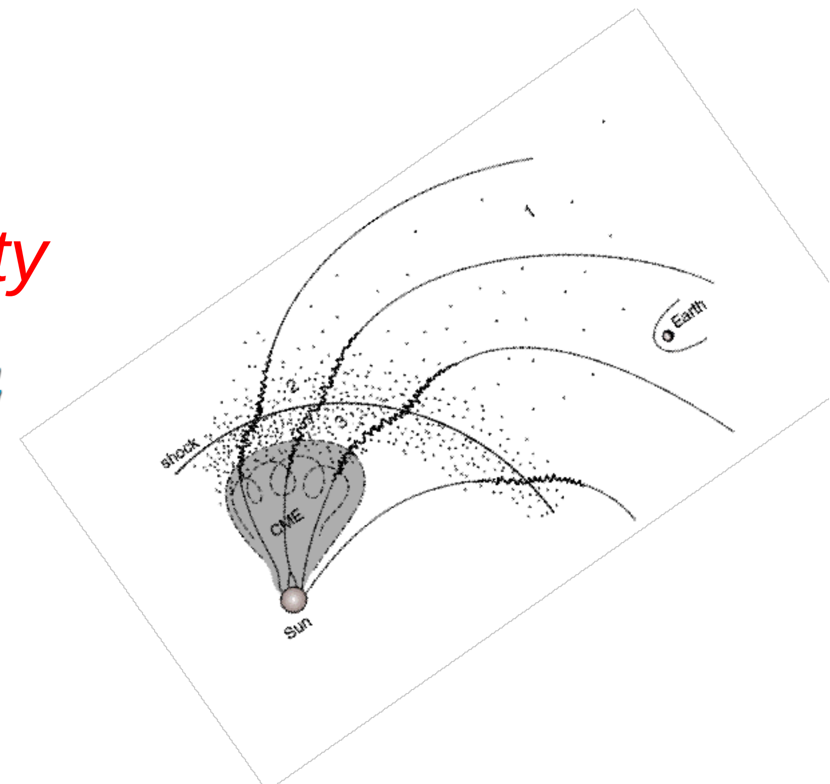
Vahe Petrosian

Stanford University

With

Meng Jin, Wei Liu,

Nicola Omodei and Melissa Pesce-Rollins



Konus-WIND at 25

The Connections Between Solar Energetic Particles *(SEPs)* and Radiation Producing Particles *(RPPs)* in Solar Eruptive Events

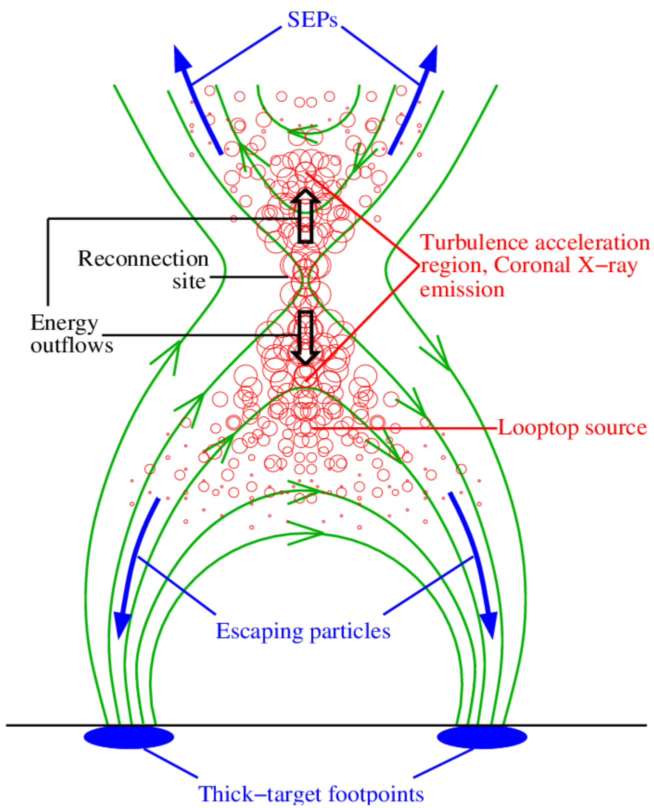
Vahe Petrosian
Stanford University

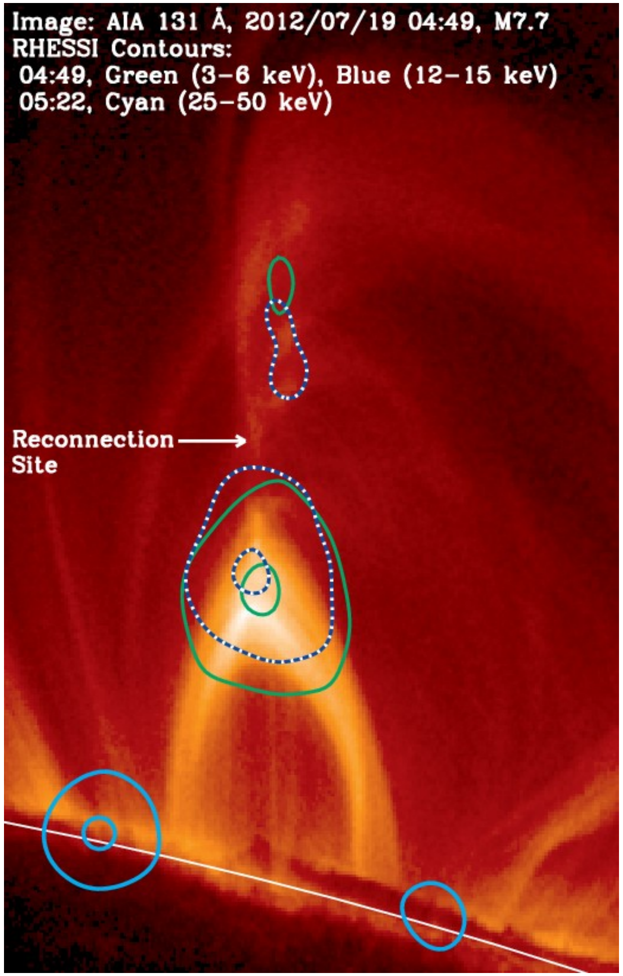
With
Meng Jin, Wei Liu,
Nicola Omodei and Melissa Pesce-Rollins

Konus-WIND at 25

Radiation Producing Particles: *RPPs*

Focus of solar physics



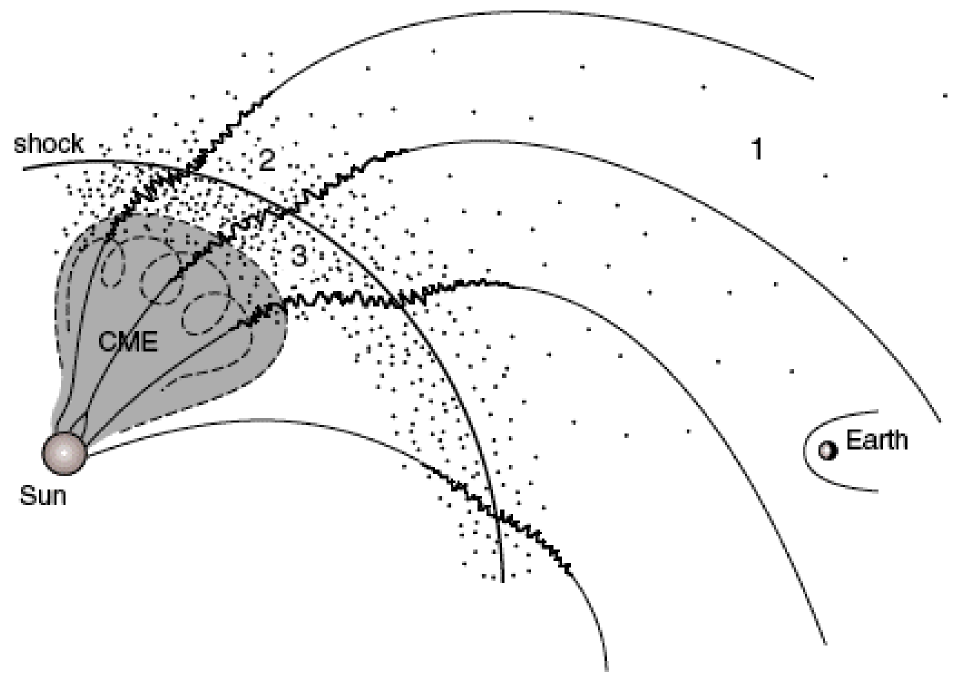


Solar Energetic Particles: *SEPs*

Focus of Heliophysics

Acceleration of Solar Wind Particles ?

In the CME-shock environment



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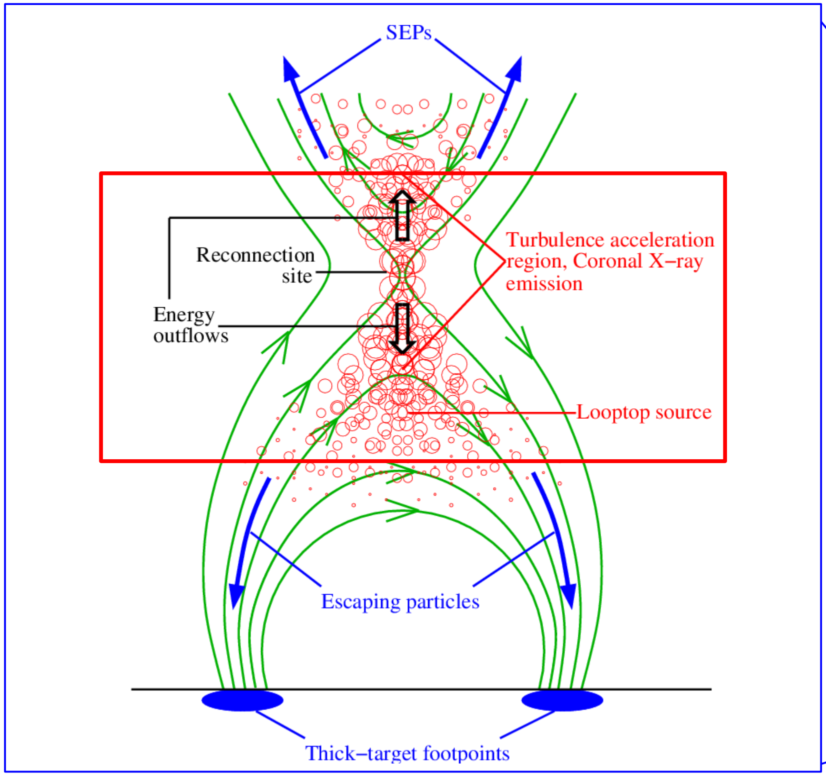
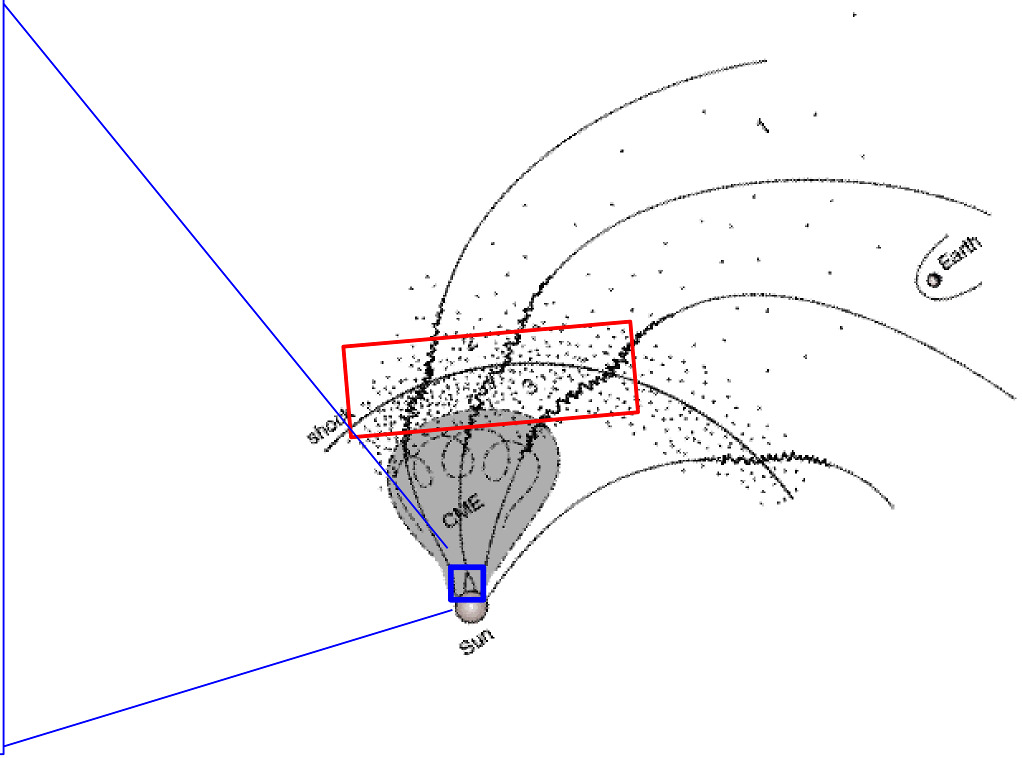
Connections between *SEPs and RPPs*

1. CME accelerated particles as RPPs: *Fermi Observations*

2. RPPs as seeds in CME-Acceleration of SEPs: *RHESSI Obs.*





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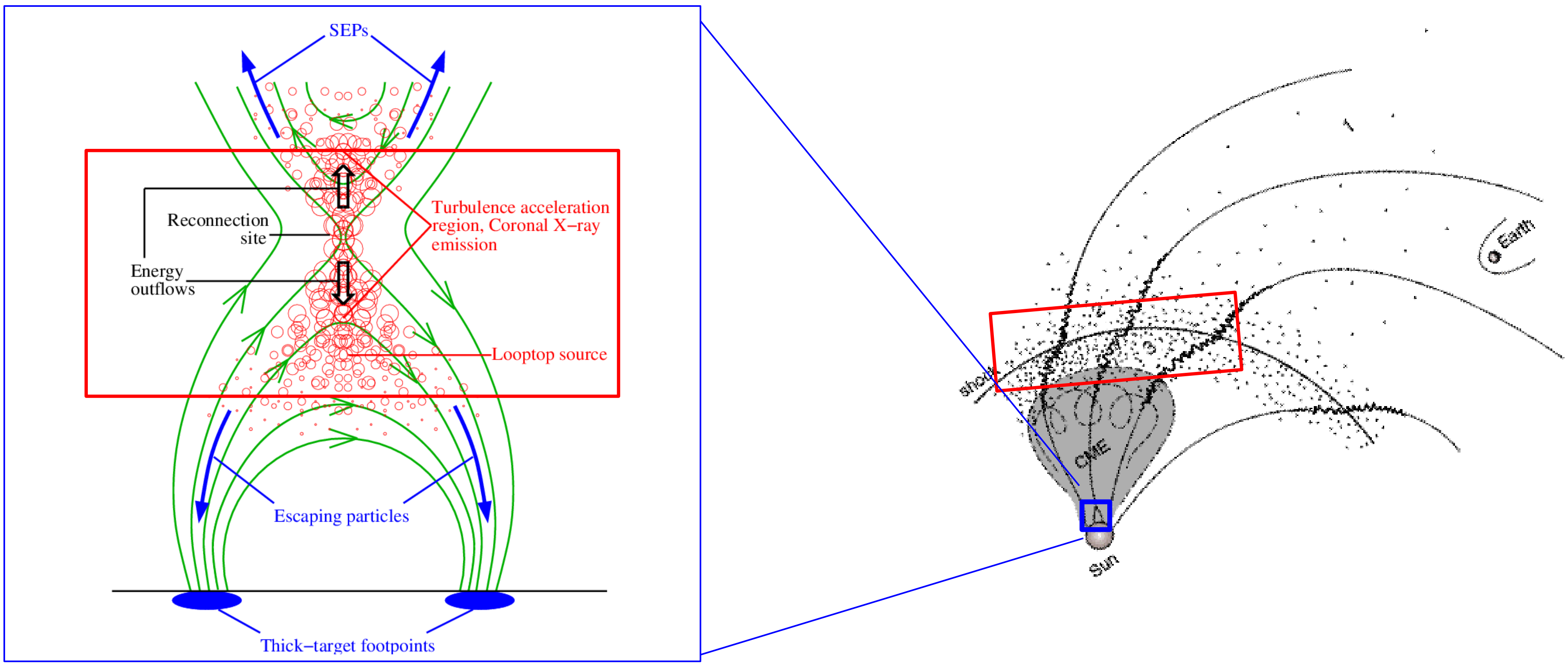

Konus-WIND at 25

Outline: Part 1

I. Motivation:

Fermi observations of extended >100 MeV *radiation from solar disk and behind the limb (BTL) flares*

II. Models of Gamma-ray Emission

Emission processes and acceleration sites

III. The Escape Time from acceleration site

Acceleration and Transport Processes

IV. Acceleration at CME and transport to the Sun

Simulations results and theoretical conjectures

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Example of a long duration gamma-ray emission

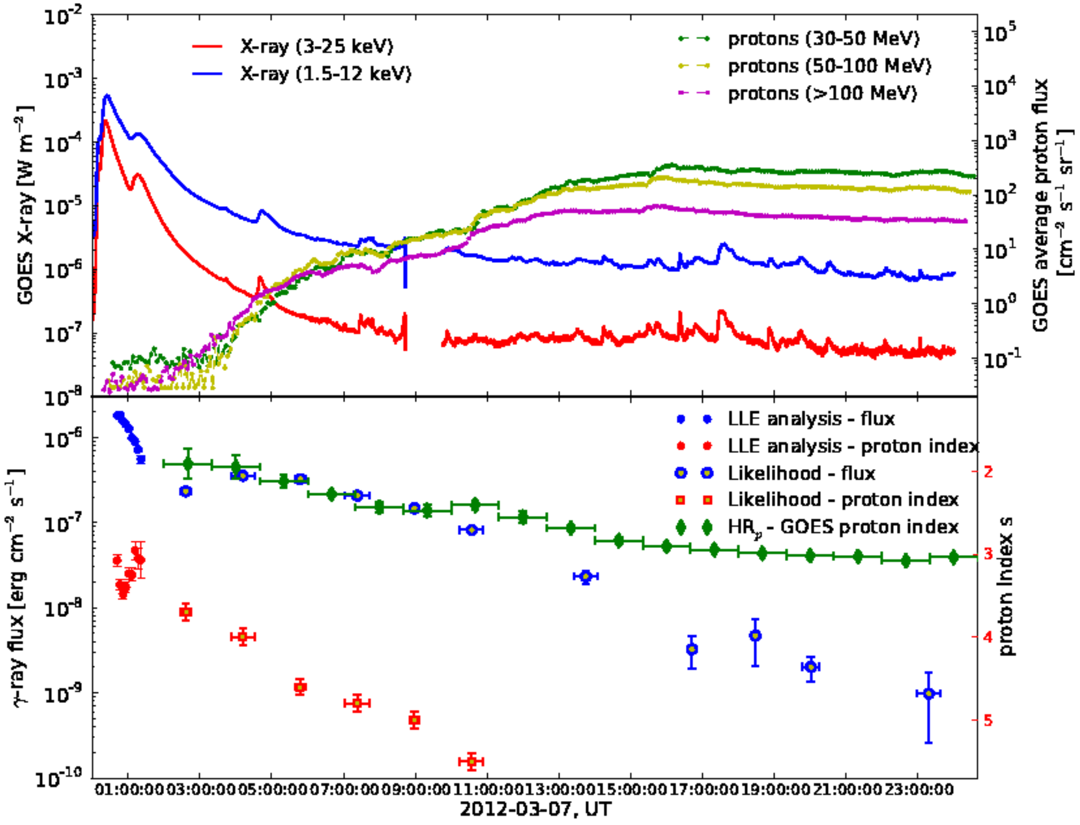
GOES X-rays

And SEP protons

Fermi Gamma-rays Flux

And spectral index

SEP proton Hardness Ratio



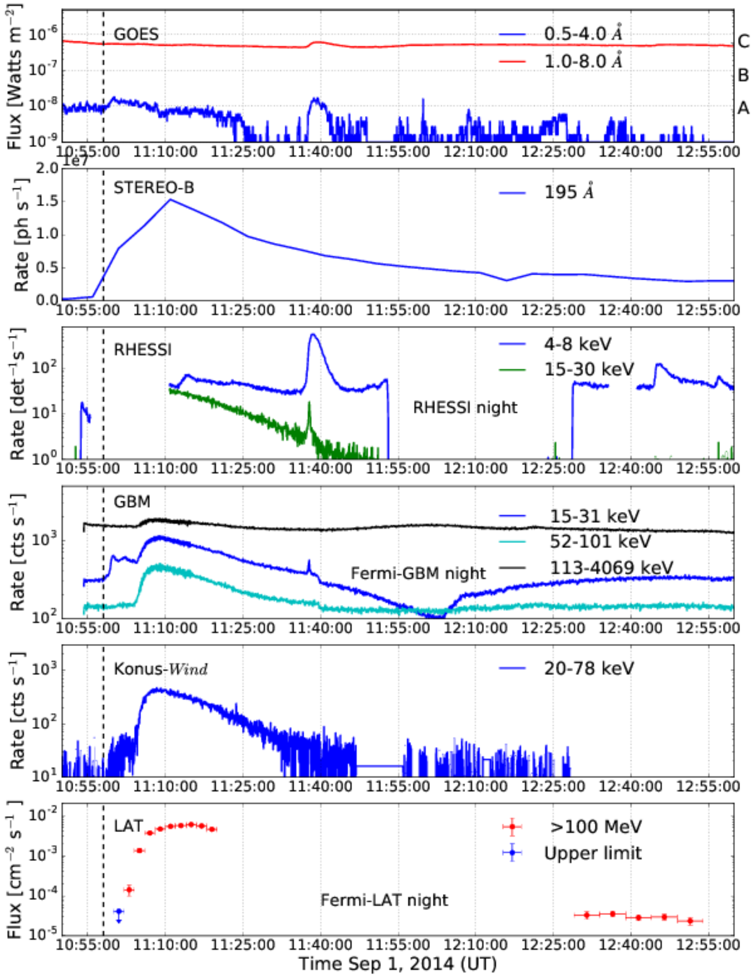
ALSO: the number of SEP protons much larger than those producing gamma-rays

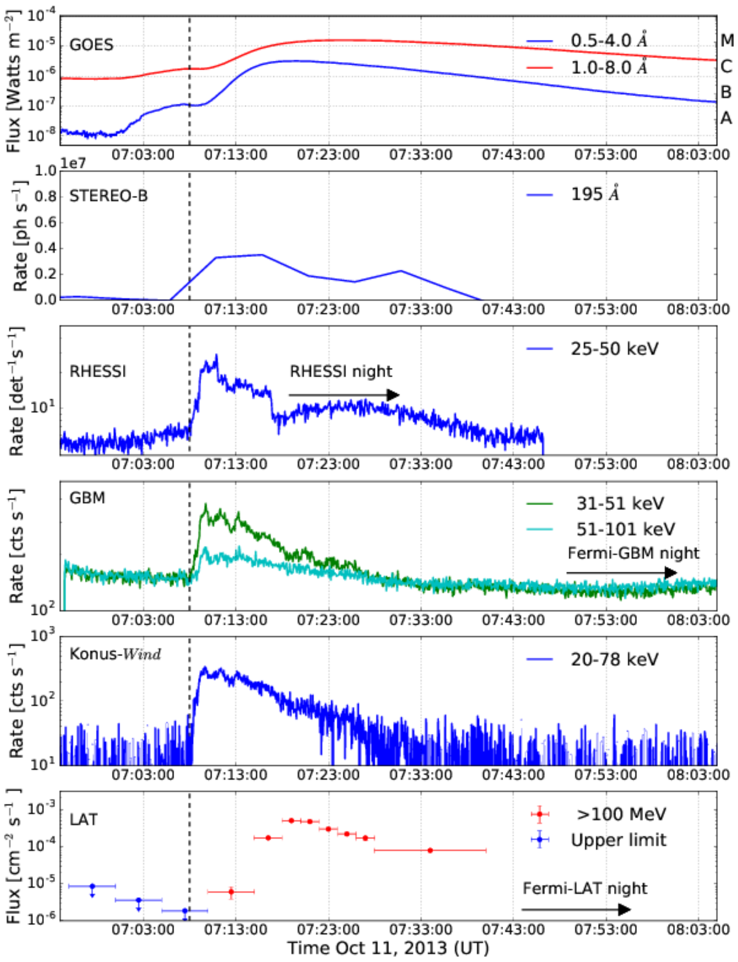
Konus-WIND at 25

Behind the limb flares

*Sol:*2014-09-01 and *Sol:*2013-10-11

1. Light Curves





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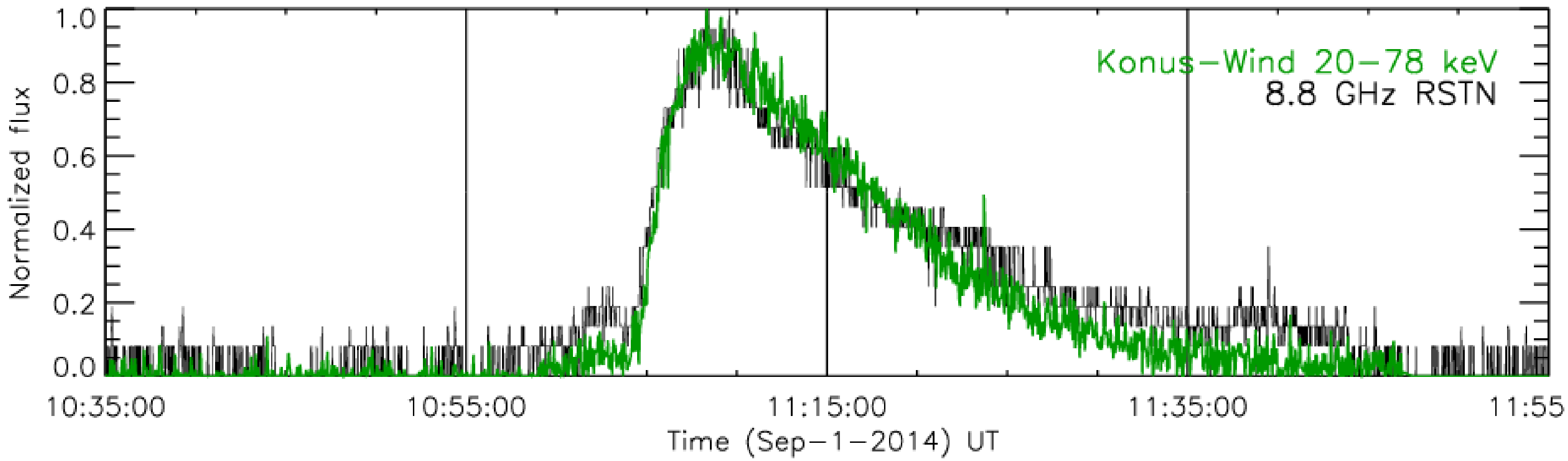
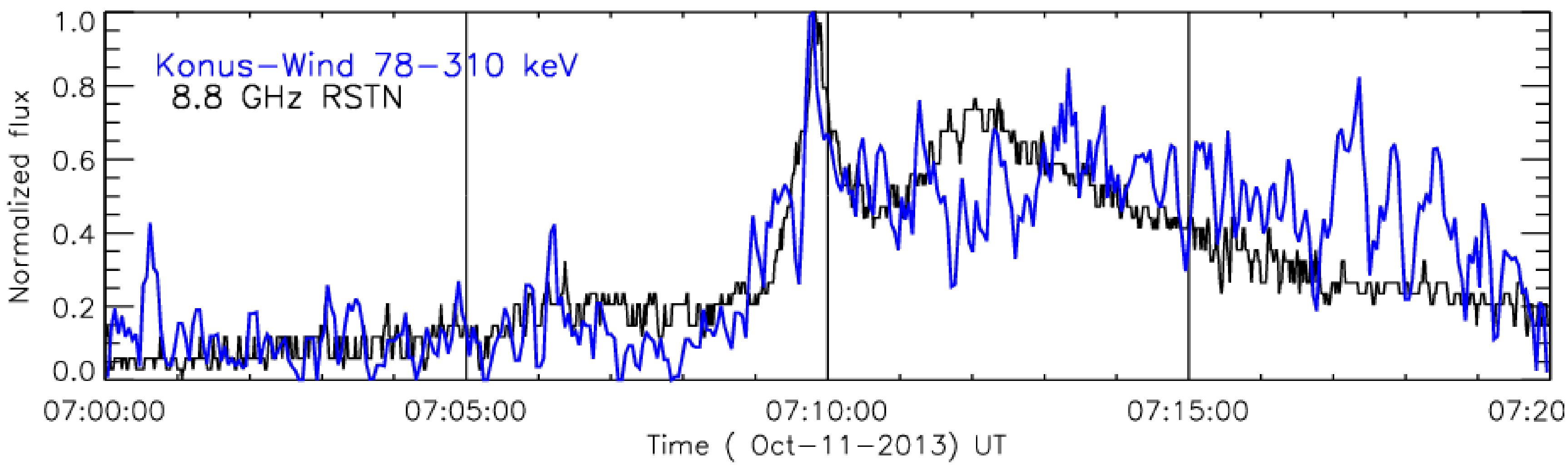
Relevant Observations of *Sol:*2014-09-01 and *Sol:*2013-10-11

1. Radio-Xray Light Curves

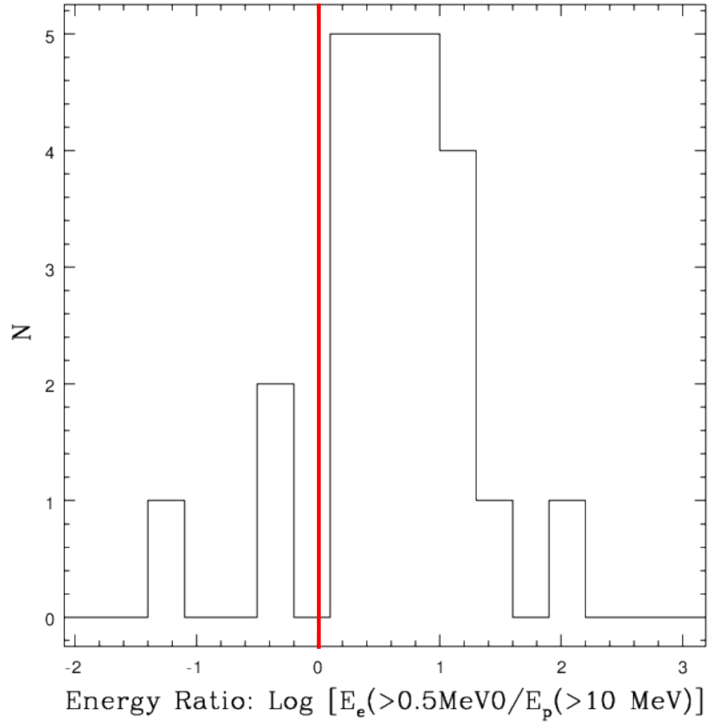


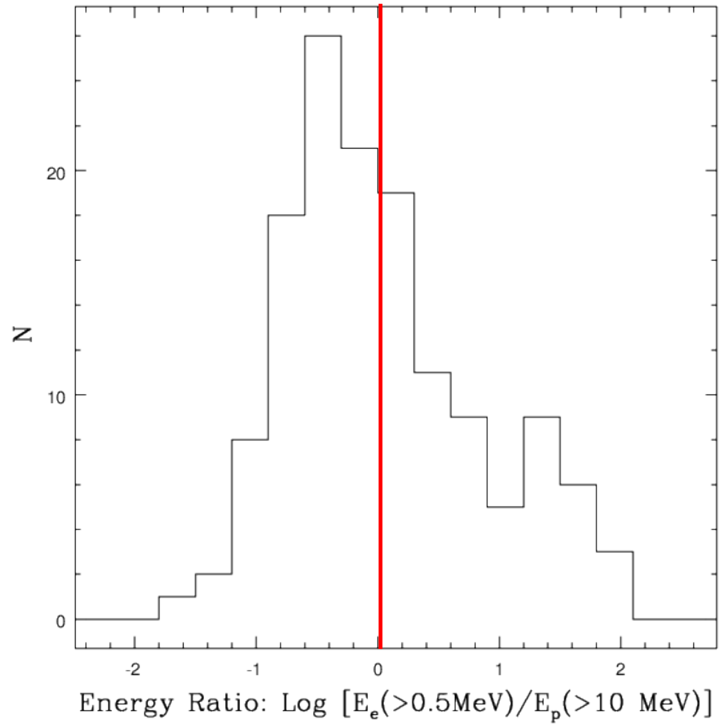


Accelerated electron to proton ratio

In general flare impulsive RPPs are electron dominate but Long duration RPPs are mainly protons, more akin to SEPs which are proton dominated

Flare E_e/E_p SEP E_e/E_p





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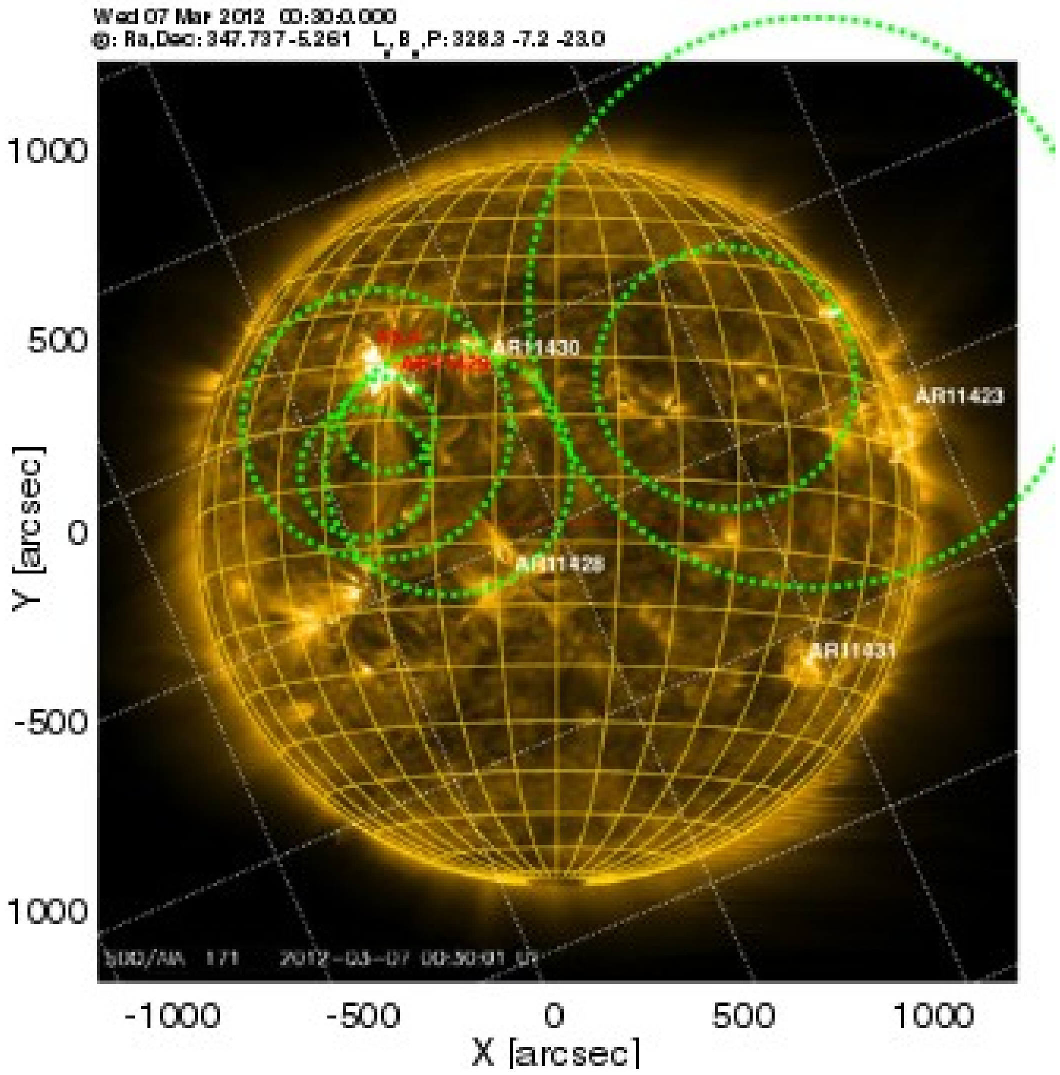
LAT centroids of a long duration 3-7-2012 flare



Konus-WIND at 25

Relevant Observations of *Sol:*2014-09-01 and *Sol:*2013-10-11

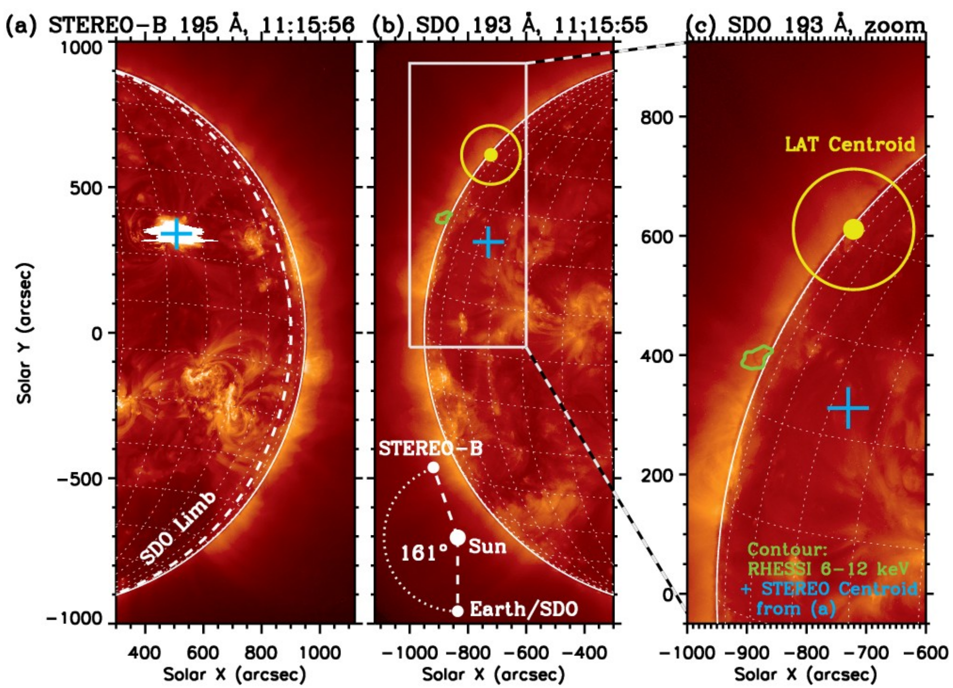
2. Images

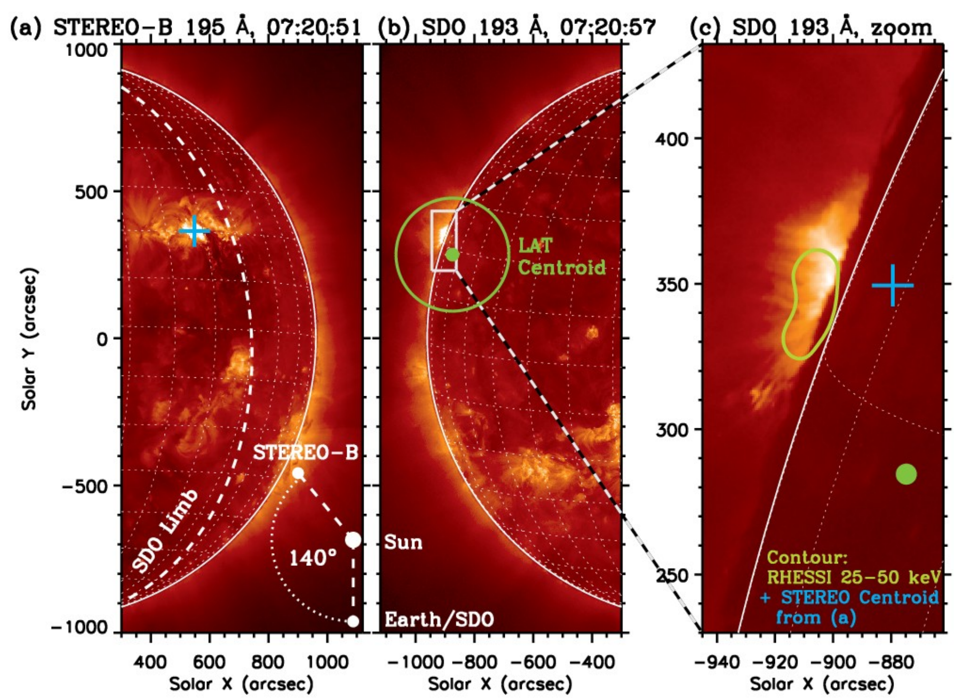
Size 56”x30”; Sep. 270”

Height 200 Mm

Size 38”x16”; Sep. 65”

Height 15 Mm





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Models for Loop top Emissions

Hard X-rays and Microwaves

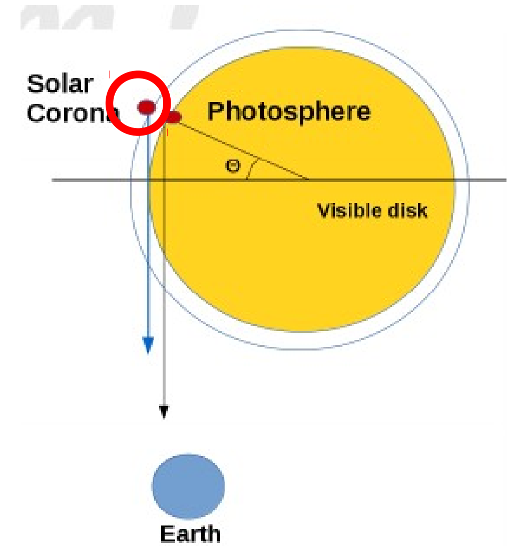
High Corona Emission: $h > R_\odot(1-\cos\theta)/\cos\theta$

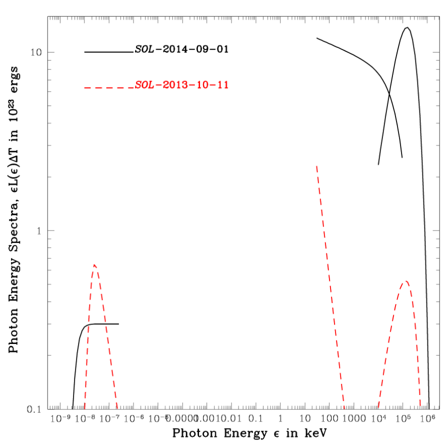
Sep14 $h = 2\times 10^{10}\mathrm{cm}$; Oct13 $h = 2\times 10^{9}\mathrm{cm}$

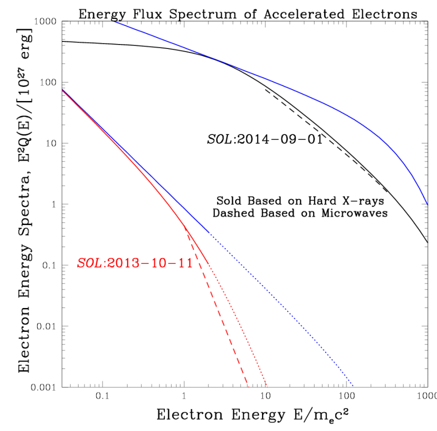
Continuous Acceleration $N(E,t)$

Flux escaping to occulted foot points

$$\dot{Q}(E,t) = N(E,t)/T_{\rm esc}(E,t)$$





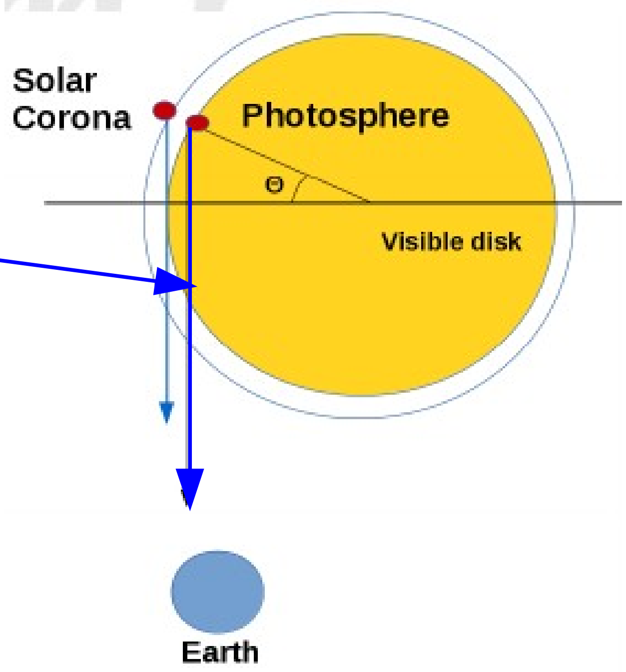


Konus-WIND at 25

Models for gamma-rays emission

Acceleration and emission at flare active region

1. Continuous acceleration and escape through the photosphere



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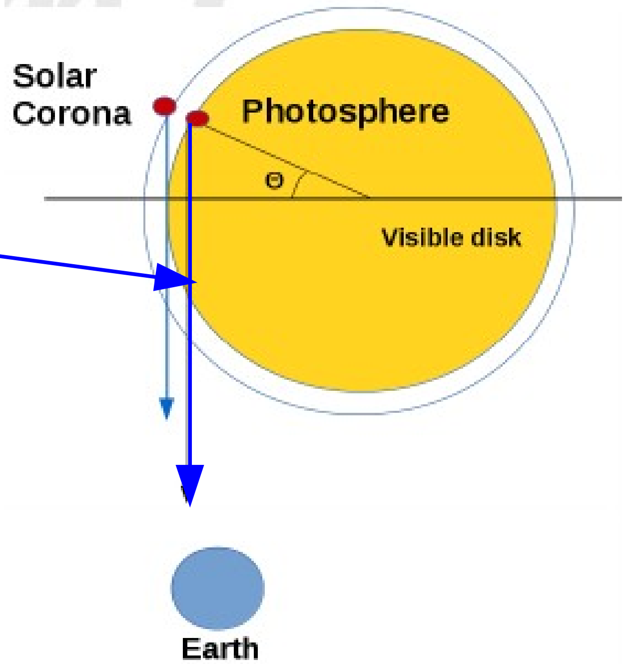
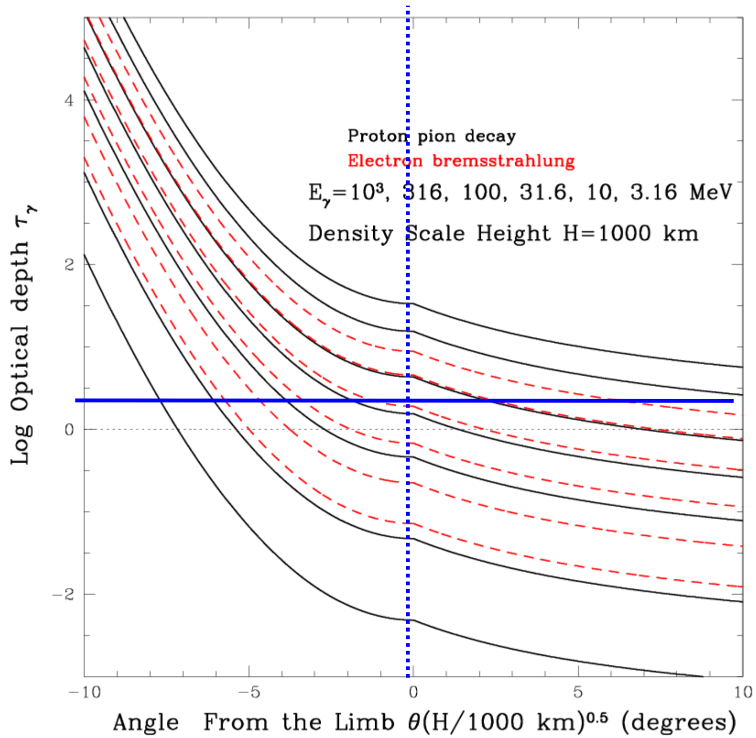




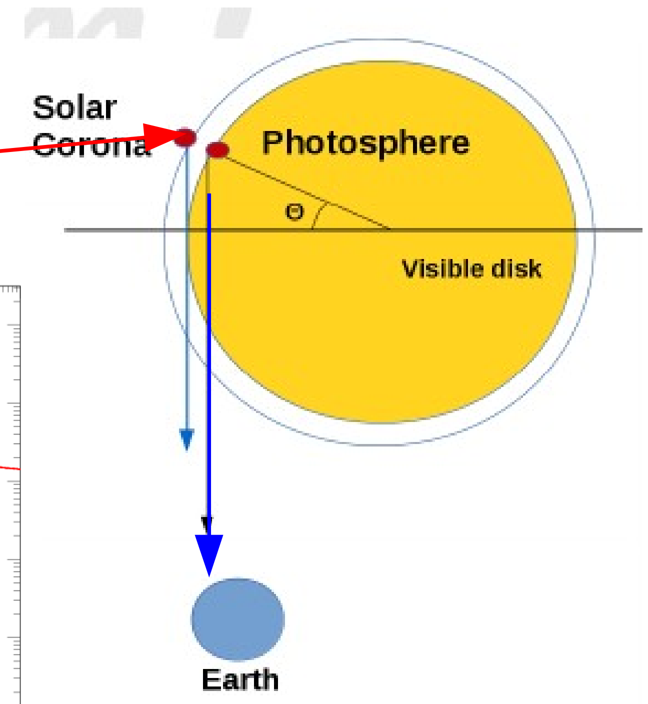
Konus-WIND at 25

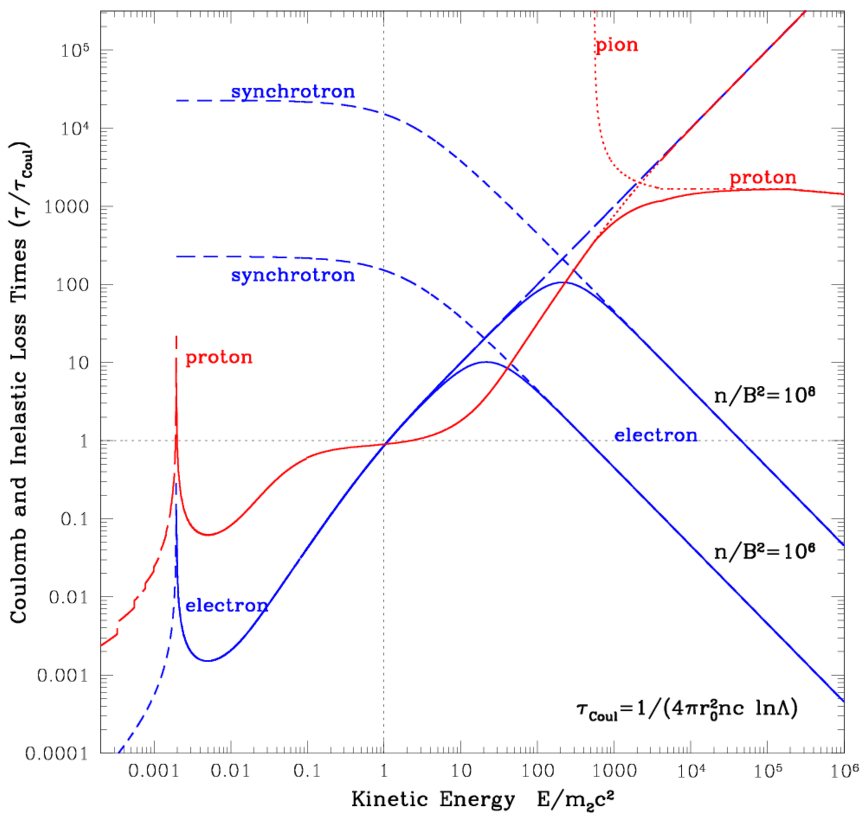
Models for gamma-ray emission

Flare site acceleration

2a. Prompt-Trap model emission

at loop top





Konus-WIND at 25

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Flare site acceleration

2a. Prompt-Trap model emission

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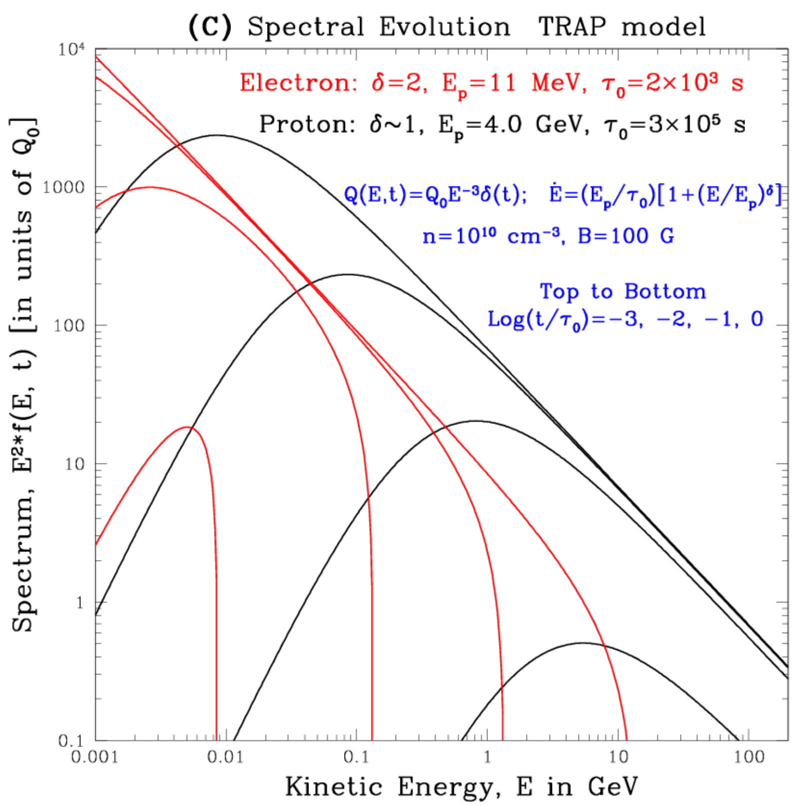

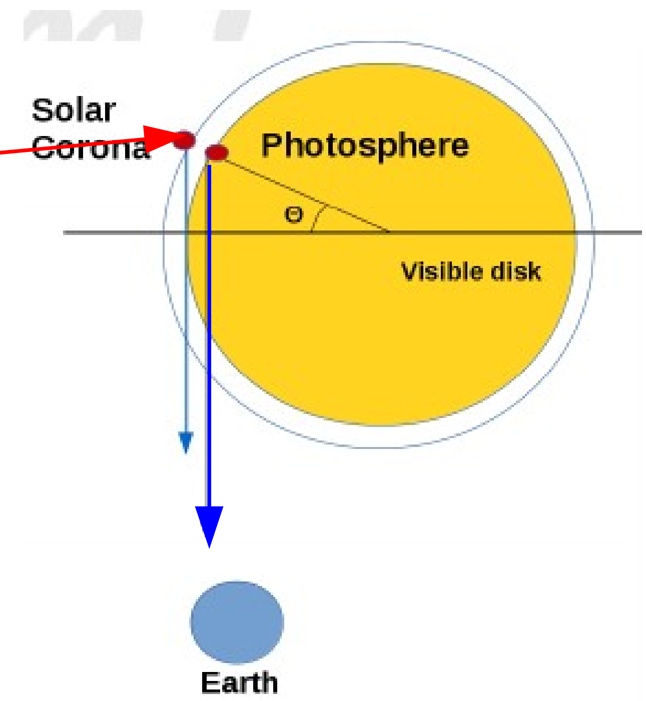

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Models for gamma-ray emission

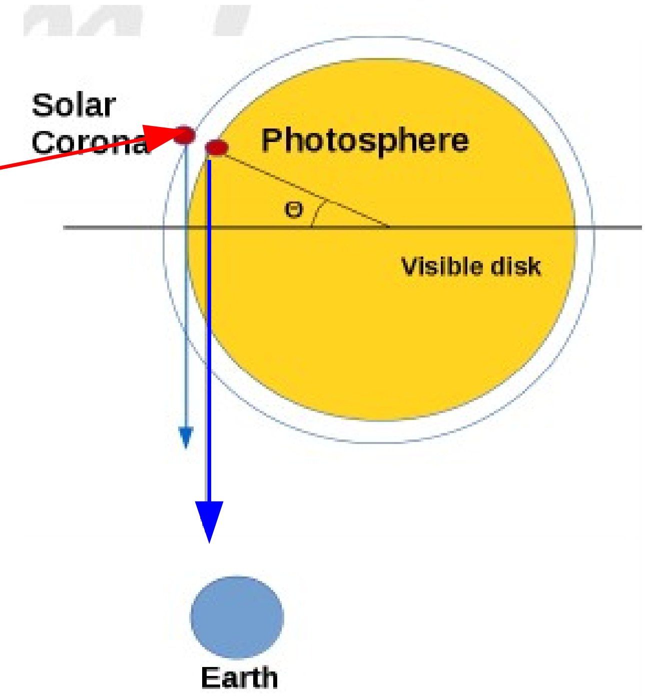
Flare site acceleration

2b. Continuous acceleration model

at loop top *(Thin target emission)*

Will require:

1. Higher number of protons
2. Why no electrons?



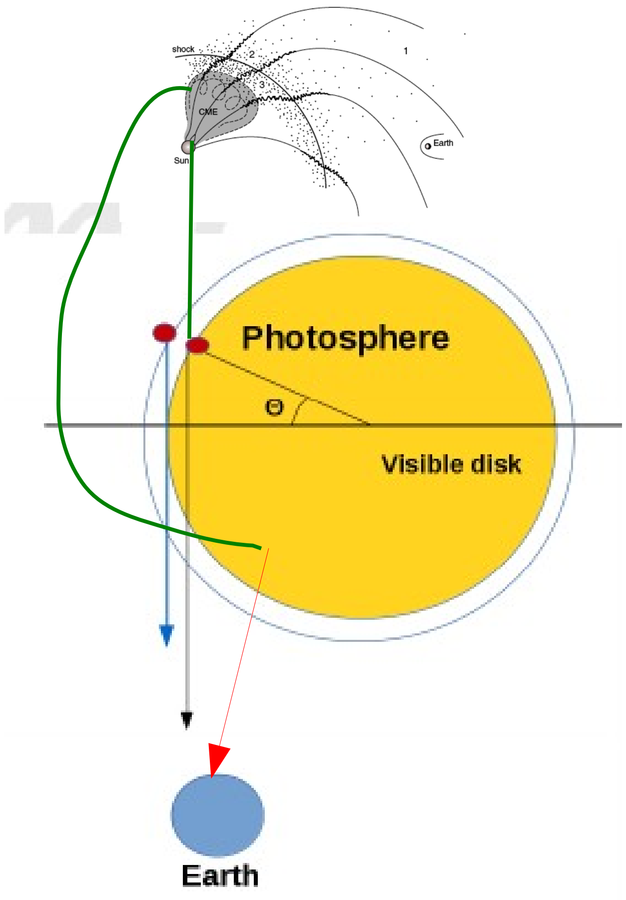
Models of gamma-ray emission

3. Acceleration at CME-shock and escape from downstream to the Sun

Objections

1. Need to transport particles to region far away from the Active region
To the visible side of the Sun for BTL flares
This requires diffusion across the magnetic field lines
Scattering by Turbulence Behind the Shock
Or presence of B field lines connecting CME to far regions
As we will see reconstruction of B field show this to be true

2. Field lines stretched by CME highly converging
A small fraction in the loss cone (H.Hudson; L. Klein)
As shown below proper treatment of escape from CME and Transport to the Sun show a significant fraction of particles can reach the Sun



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The Escape Time

In most models of particle acceleration a crucial question is:

How much time the particles spend in the acceleration site?

What determines the escape time of particles from the acceleration site?

The escape time is related to the flux of escaping particles as:

$$\dot{Q}(E,t) = N(E,t)/T_{\rm esc}(E,t)$$

The Escape Time is Important For Both Parts of This Talk

The Escape Time

1. Escape from Upstream of CME to 1 A.U. and from Downstream to the Sun

2. Escape time from reconnection site up to 1 A.U. And down to the Sun

General Fokker-Planck Acceleration and Transport Equation

$$\frac{\partial f}{\partial t} + v\mu\frac{\partial f}{\partial s} = -\frac{v\partial \ln B}{2\partial s}\frac{\partial}{\partial \mu}\left[(1-\mu^2)f\right] + \left(\frac{\partial u}{\partial s}\right)\frac{p}{3}\left(\frac{\partial f}{\partial p}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}[p^2\dot{p}_{\rm L}f]$$
$$+\left(\frac{1}{p^2}\right)\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial f}{\partial p} + p^2 D_{p\mu}\frac{\partial f}{\partial \mu}\right] + \frac{\partial}{\partial \mu}\left[D_{\mu\mu}\frac{\partial f}{\partial \mu} + D_{\mu p}\frac{\partial f}{\partial p}\right] + \dot{\mathcal{S}}$$

Isotropic or pitch angle averaged $F(p,s,t) \equiv \frac{1}{2}\int_{-1}^{1} d\mu f(p,\mu,s,t), \quad \dot{S}(p,s,t) \equiv \frac{1}{2}\int_{-1}^{1} d\mu \dot{\mathcal{S}}(p,\mu,s,t)$

$$\frac{\partial F}{\partial t} = \frac{\partial}{\partial s}\kappa_{ss}\frac{\partial F}{\partial s} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^4\kappa_{pp}\frac{\partial F}{\partial p} + p^2\langle\dot{p}_L\rangle F\right) + \frac{p}{3}\left(\frac{\partial u}{\partial s} + 3\frac{\partial \kappa_{sp}}{\partial s}\right)\frac{\partial F}{\partial p} - \frac{1}{p^2}\frac{\partial F}{\partial s}\frac{\partial}{\partial p}(p^3\kappa_{sp}) + \dot{S}$$

$$\kappa_{ss} = \frac{v^2}{8}\int_{-1}^{1} d\mu \frac{(1-\mu^2)^2}{D_{\mu\mu}}, \quad \kappa_{sp} = \frac{v}{4p}\int_{-1}^{1} d\mu \frac{(1-\mu^2)D_{\mu p}}{D_{\mu\mu}}, \quad \kappa_{pp} = \frac{1}{2p^2}\int_{-1}^{1} d\mu D_{pp}\left(1 - \frac{D_{\mu p}^2}{D_{\mu\mu}}\right)$$

Homogeneous $\partial/\partial s \to 0$ or Spatially integrated $N(t,E)dE = \int \mathcal{A}(s)ds[4\pi p^2 F(t,s,p)dp], \quad \dot{Q}(t,E)dE = \int \mathcal{A}(s)\,ds\,[4\pi\,p^2\,\dot{S}(t,s,p)dp]$

If We Define Escape Time as $\frac{N(t,E)}{T_{\rm esc}(E)} = -4\pi p^2 \int \mathcal{A}(s)ds\frac{\partial}{\partial s}\left(\kappa_{ss}\frac{\partial F}{\partial s} - 3\kappa_{sp}F\right)$

Acceleration at Transport Equation

Pitch angle averaged; Spatially integrated

The Leaky Box Model

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial E}\left(D_{EE}\frac{\partial N}{\partial E}\right) - \frac{\partial}{\partial E}[(A - \dot{E}_L)N] - \frac{N}{T_{\rm esc}} + \dot{Q}$$

Diffusion Accel. Loss Escape Source

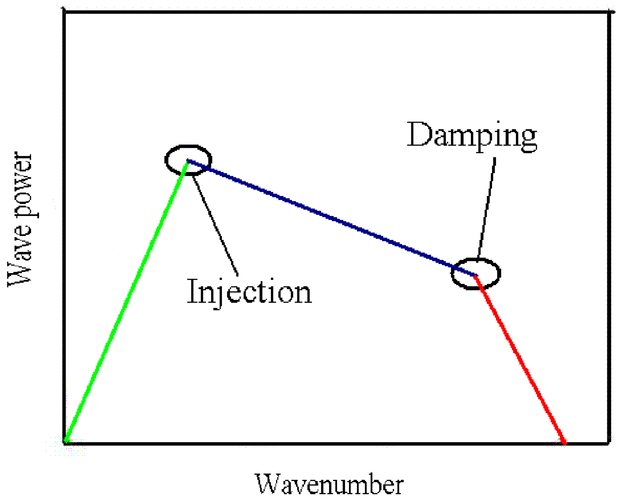
$D_{EE} = v^2 p^2 \bar{\kappa}_{pp}$ $A = A_{\rm SA} + A_{\rm sh}$ $\dot{E}_{\rm L} = v\dot{\bar{p}}_{\rm L}$

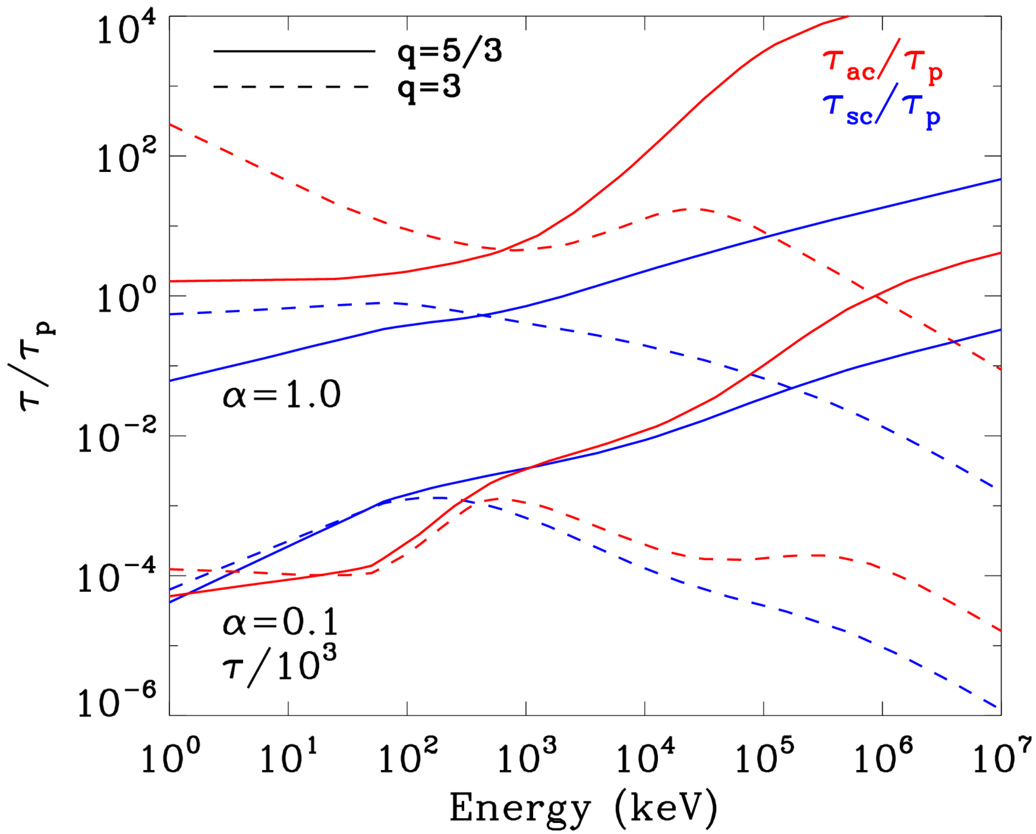
$$A_{\rm SA} = \frac{2\gamma^2 - 1}{\gamma^2 + \gamma}\left(\frac{D_{EE}}{E}\right), \quad A_{\rm sh} = \zeta E\left(\frac{u_{\rm sh}^2}{\kappa_{ss}}\right) = 8\zeta E\left(\frac{u_{\rm sh}}{v}\right)^2\left(\langle\frac{(1-\mu^2)^2}{\bar{D}_{\mu\mu}}\rangle\right)^{-1}$$

$$\tau_{\rm diff} = \frac{D_{EE}}{E^2}, \ \tau_{\rm ac,SA}(E) = \frac{1}{\bar{\kappa}_{pp}} = \frac{p^2}{\langle \bar{D}_{pp} - \bar{D}_{p\mu}^2/\bar{D}_{\mu\mu}\rangle}, \ \tau_{\rm ac,sh} = \left(\frac{v}{u_{\rm sh}}\right)^2\left(\frac{3}{\zeta}\right)\tau_{\rm sc}, \ \tau_{\rm sc}(E) = 3\frac{\bar{\kappa}_{ss}}{v^2} = \frac{3}{4}\langle\frac{(1-\mu^2)^2}{\bar{D}_{\mu\mu}}\rangle, \ \tau_L = \frac{E}{\dot{E}_L}$$

Model Scattering and Acceleration Times

Pryadko and Petrosian 1997, 98, 99





$$\tau_p^{-1} = \left(\frac{\pi}{2}\right)\Omega_e\left(\frac{u_{\rm turb}}{B^2/8\pi}\right)(q-1)\left(\frac{ck_{\rm min}}{\Omega_e}\right)^{q-1}$$

$$\alpha = \left(\frac{\omega_{\rm pe}}{\Omega_e}\right) \propto \left(\frac{\sqrt{n}}{B}\right) \text{ and } u_{\rm turb} \sim 8\pi\delta B^2 \sim \rho v_{\rm turb}^2$$

The Escape Times

Up and down reconnection site

From Downstream and upstream of CME-shock

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial E}\left(D_{EE}\frac{\partial N}{\partial E}\right) - \frac{\partial}{\partial E}[(A - \dot{E}_L)N] - \frac{N}{T_{\rm esc}} + \dot{Q}$$

$$\frac{N(t,E)}{T_{\rm esc}(E)} = -4\pi p^2 \int \mathcal{A}(s)ds \frac{\partial}{\partial s}\left(\kappa_{ss}\frac{\partial F}{\partial s} - 3\kappa_{sp}F\right) \sim N\left(\frac{\kappa_{ss}}{L^2}\right) \sim N\left(\frac{\tau_{\rm sc}}{\tau_{\rm cross}^2}\right)$$

Strong diffusion $T_{\rm esc} \sim \tau_{\rm cross}^2/\tau_{\rm sc}$

Weak diffusion $T_{\rm esc} \sim \tau_{\rm cross}$

Converging B-field $T_{\rm esc} \propto \tau_{\rm sc}$

The Escape Times

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Converging B-field $T_{\rm esc} \propto \tau_{\rm sc}$

Combined equation (For isotropic injection)

$$T_{\rm esc} = \tau_{\rm cross}\left(\eta + \frac{\tau_{\rm cross}}{\tau_{\rm sc}} + \ln\eta\,\frac{\tau_{\rm sc}}{\tau_{\rm cross}}\right)$$

(Malyshkin and Kulsrud 2001)

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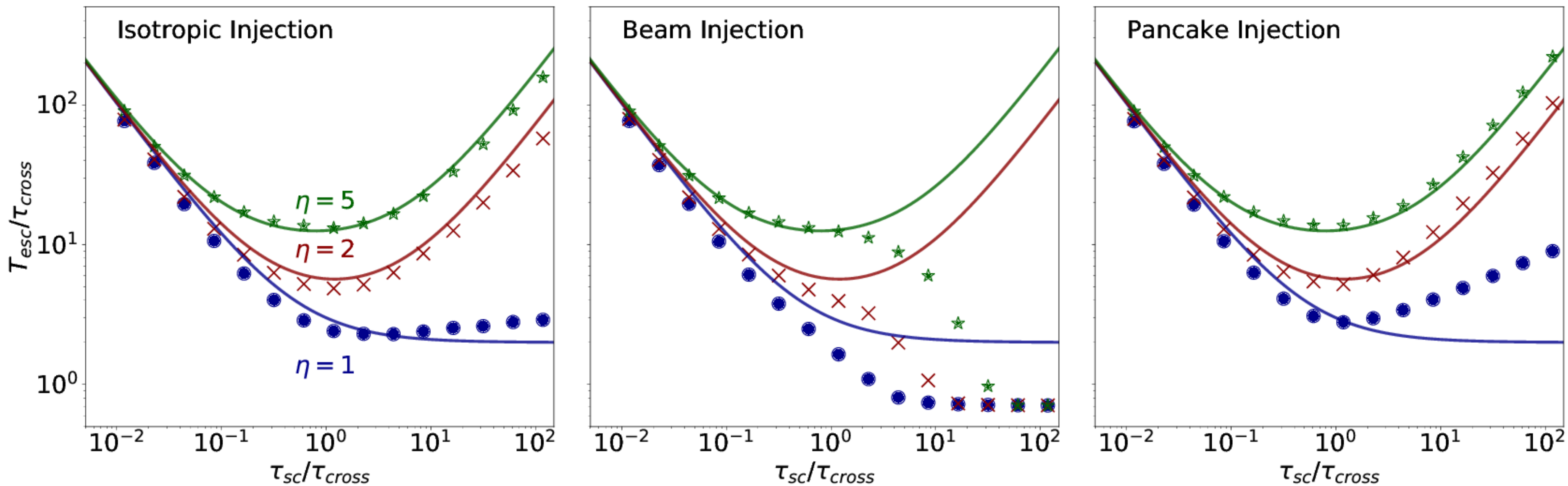
Simulation Results (F. Effenberger & VP, 2018, ApJ, 868, L28)



What Do Observations Say about *The Escape Time*

Escape time relates the accelerated particle spectra to the flux of escaping particles

$$T_{\rm esc}(E) = N(E)/\dot{Q}(E)$$

Thus from observed spectra of these two components we can obtain the escape time

Examples

1. Solar Flare Loop top and Foot point spectra
2. Supernova remnant and CR spectra (VP & Chen 2014 PR)

Regularized Inversion of Photon Images to Electron Images

$$I(x,y;\epsilon) = \frac{a^2}{4\pi R^2}\int_{E=\epsilon}^{\infty} N(x,y)\overline{F}(x,y;E)Q(\epsilon,E)\,dE \qquad J(x,y;q)\,dq = \int_x\int_y\int_{\epsilon=q}^{\infty} D(q,\epsilon)I(x,y;\epsilon)\,d\epsilon\,dx\,dy$$

RHESSI produces count visibility, Fourier component of the source

$$V(u,v;q) = \mathcal{F}^2(J(x,y;q)) \equiv \int_x\int_y J(x,y;q)e^{2\pi i(ux+vy)}\,dx\,dy$$

Defining electron flux visibility spectrum and count cross section

$$W(u,v;E) = a^2\int_x\int_y N(x,y)\overline{F}(x,y;E)e^{2\pi i(ux+vy)}\,dx\,dy \qquad K(q,E)\,dq = \int_{\epsilon=q}^{\infty} D(q,\epsilon)Q(\epsilon,E)\,d\epsilon$$

We get $V(u,v;q) = \frac{1}{4\pi R^2}\int_q^{\infty} W(u,v;E)K(q,E)\,dE$

Regularized inversion produced *smoothed* electron flux visibility spectrum

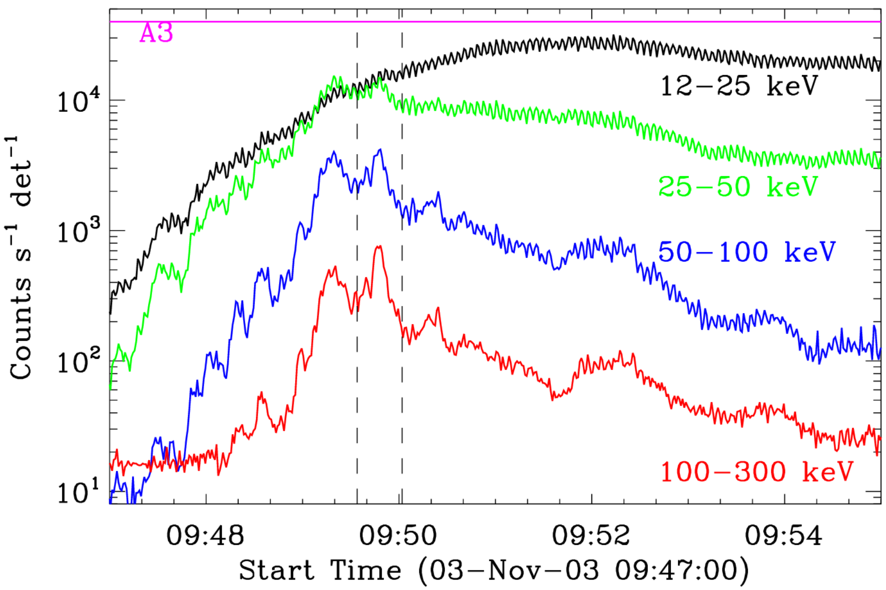
$$\left\|\boldsymbol{V}_{[u,v]} - \boldsymbol{K}\cdot\boldsymbol{W}_{[u,v]}\right\|^2 + \lambda_{[u,v]}\left\|\boldsymbol{W}_{[u,v]}\right\|^2 = \text{minimum}$$

Fourier Transform Gives $N(x,y)\overline{F}(x,y;E) = \frac{1}{a^2}\int_u\int_v W(u,v;E)e^{-2\pi i(ux+vy)}\,du\,dv$

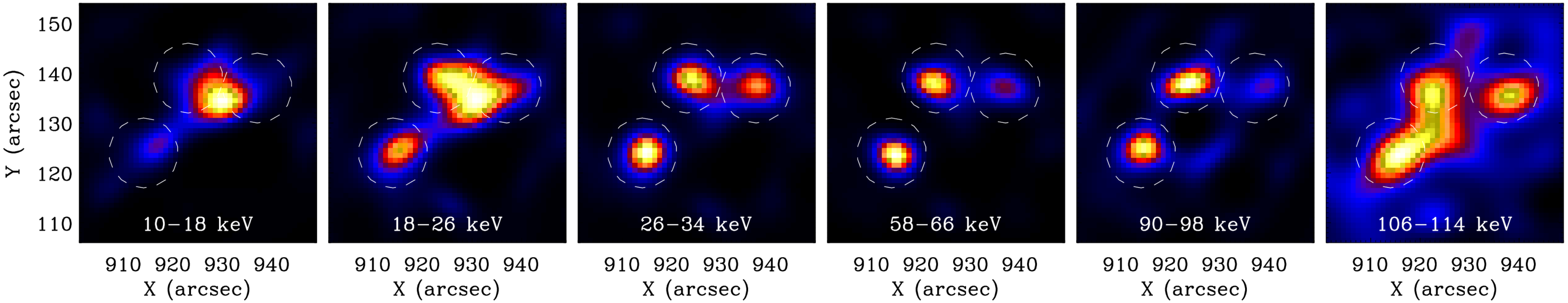
Piana et al. 2007

Inversion of (X3.9 class) 2003 Nov 3 Flare

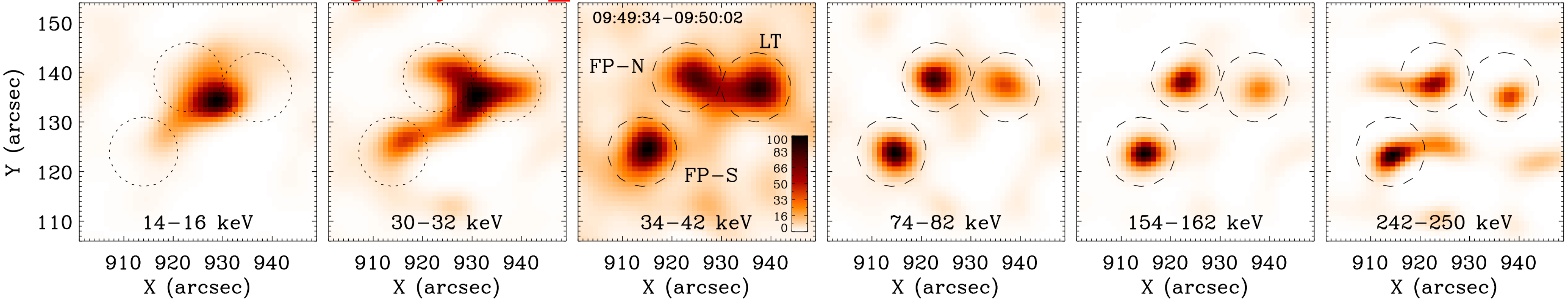
Petrosian & Chen 2010



HXR images by MEM_NJIT

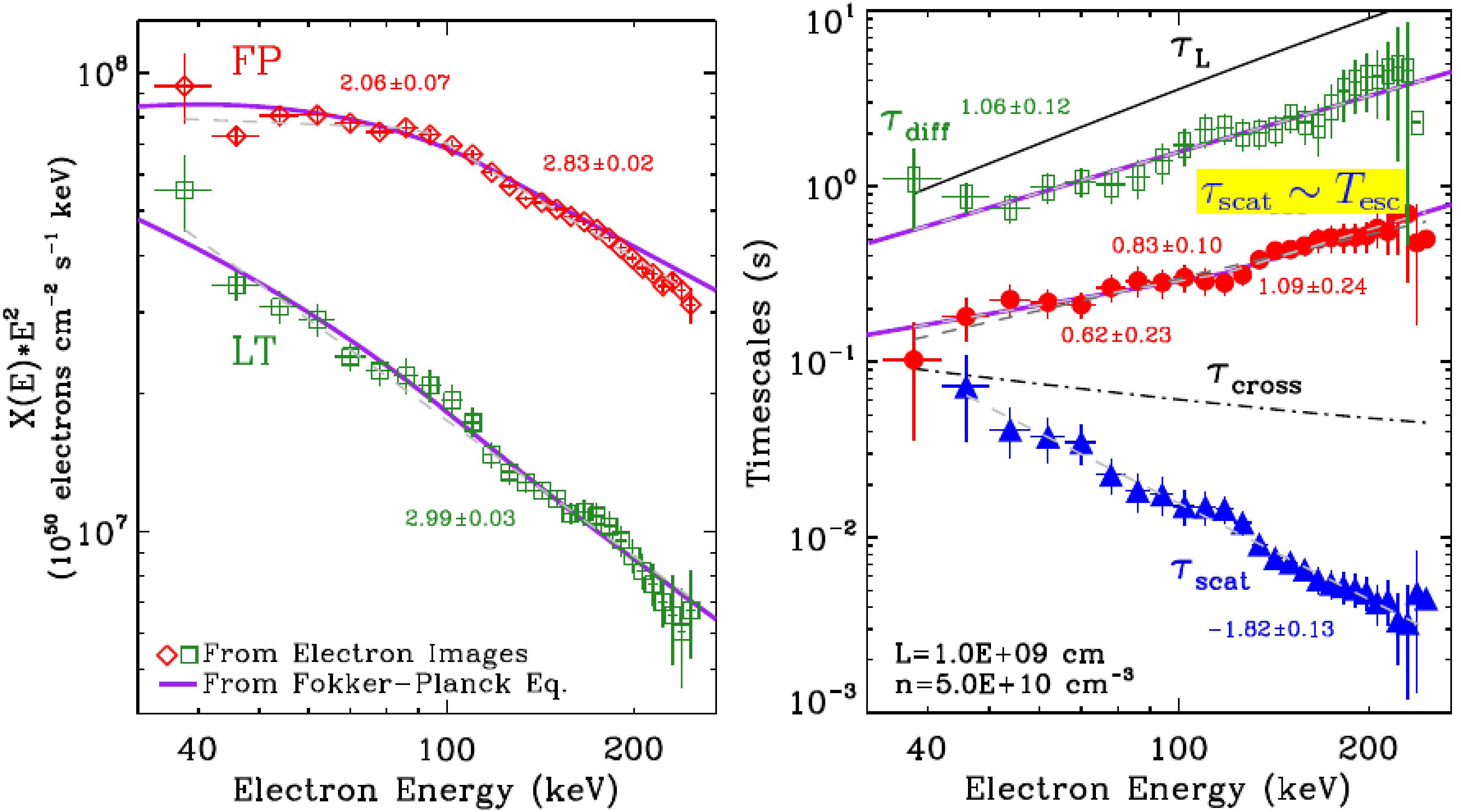


Electron flux images by MEM_NJIT



Inversion of RHESSI images

Chen and Petrosian 2013

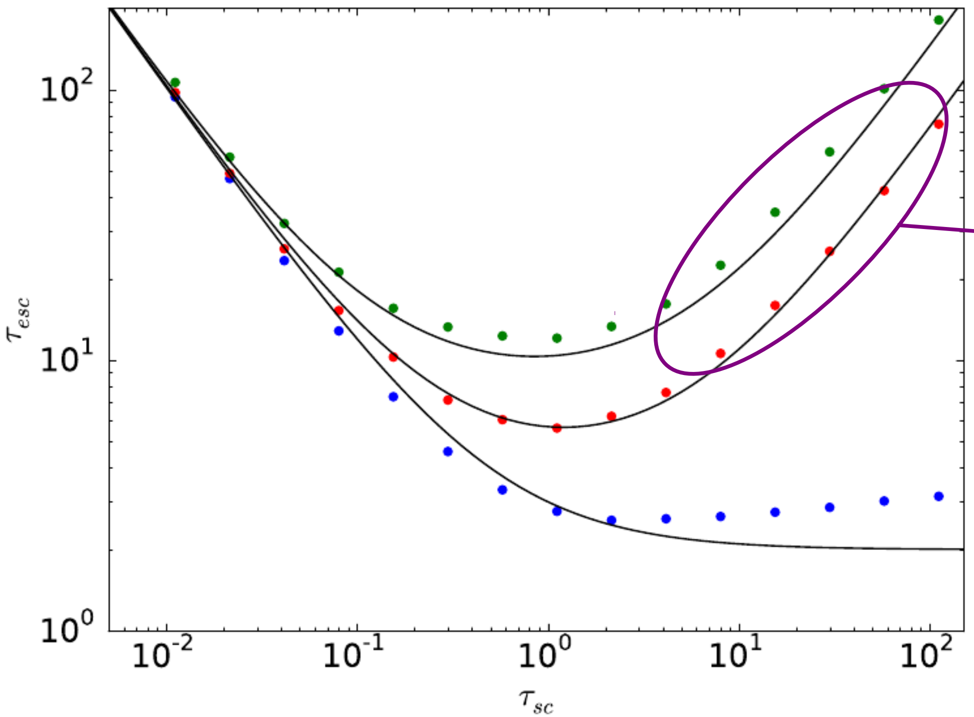


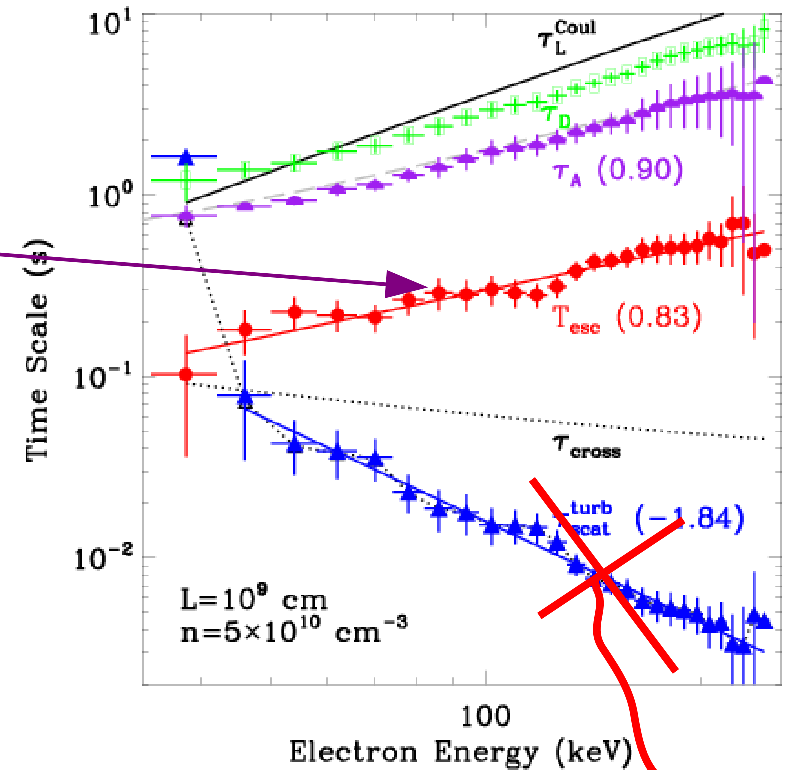
Konus-WIND at 25

Escape and Scattering Times

Theory and Empirical Determinations

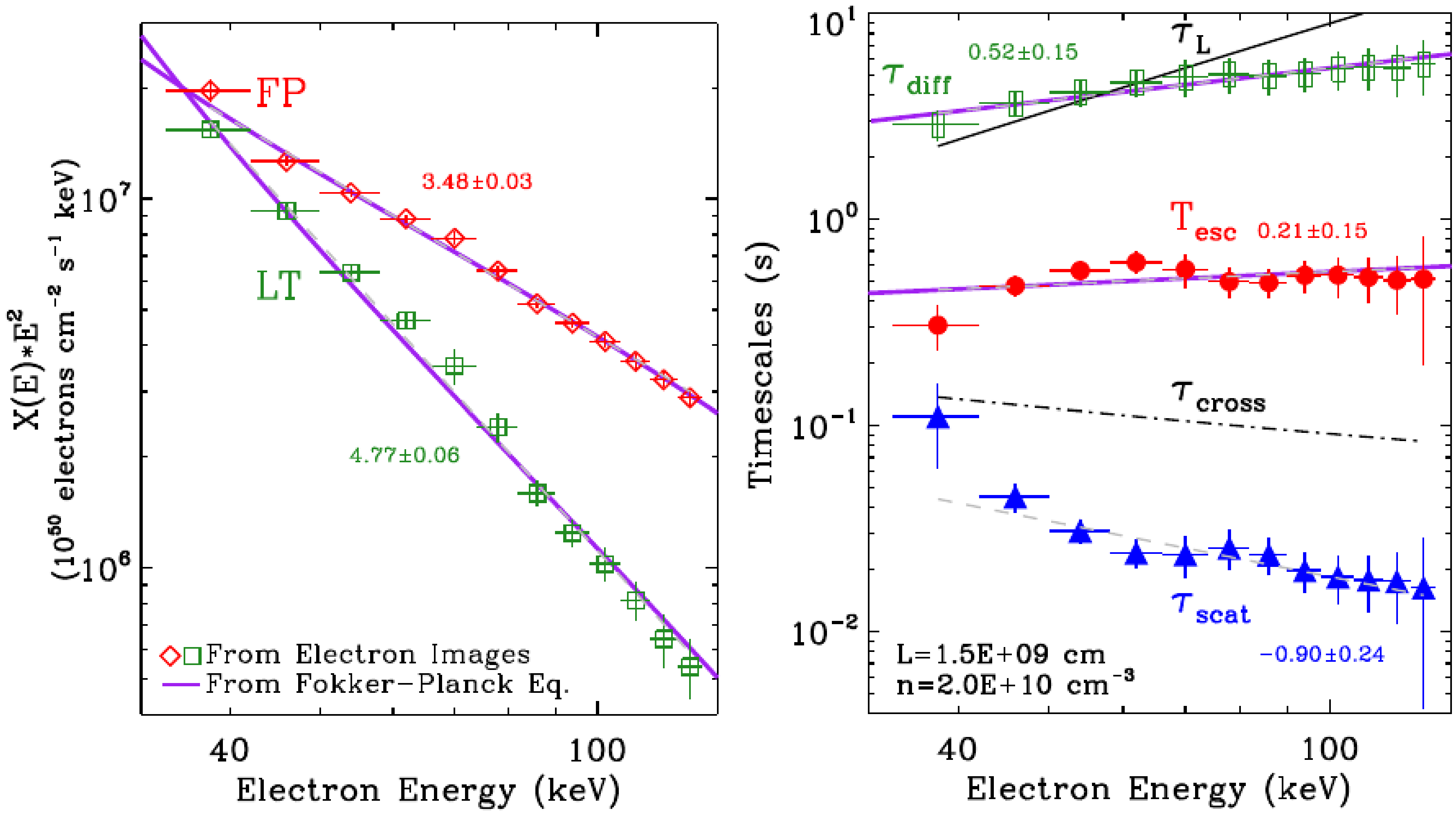
Effenberger and VP 2017 Chen & VP 2013





$$T_{\rm esc} = \tau_{\rm cross} \begin{cases} 1 & \text{if } \tau_{\rm sc} \gg \tau_{\rm cross}, \text{ Free stream} \\ \propto \tau_{\rm sc}/\tau_{\rm cross} & \text{if } \tau_{\rm sc} \gg \tau_{\rm cross}, \text{ Converging field} \\ \tau_{\rm cross}/\tau_{\rm sc} & \text{if } \tau_{\rm sc} \ll \tau_{\rm cross}, \text{ Strong diffusion} \end{cases}$$

2005 September 8 Flare M2.1



Konus-WIND at 25

Outline: Part 1

I. Motivation:

Fermi observations of extended >100 MeV *radiation from solar disk and behind the limb (BTL) flares*

II. Models of Gamma-ray Emission

Emission processes and acceleration sites

III. The Escape Time from acceleration site

Acceleration and Transport Processes

IV. Acceleration at CME and transport to the Sun

Simulations results and theoretical conjectures

Models of gamma-ray emission

Acceleration at CME-shock and escape from downstream to the Sun

Objections 1. Need to transport of particles to region far away from the AR

This requires either/both transport across field lines, field meandering or field lines connecting the acceleration site to regions far from the AR

Recent simulation of CME B field for Sep. 01, 2014 (~40 degree) BTL flare

(*Meng Ji, VP, Wei Liu et al. 2018, 867, 122*)

Shows B fields connecting both the shock and the CME to the visible Sun regions near the Fermi-LAT centroid

Konus-WIND at 25

Models of gamma-ray emission

Simulation Results

CME Simulation and Observations

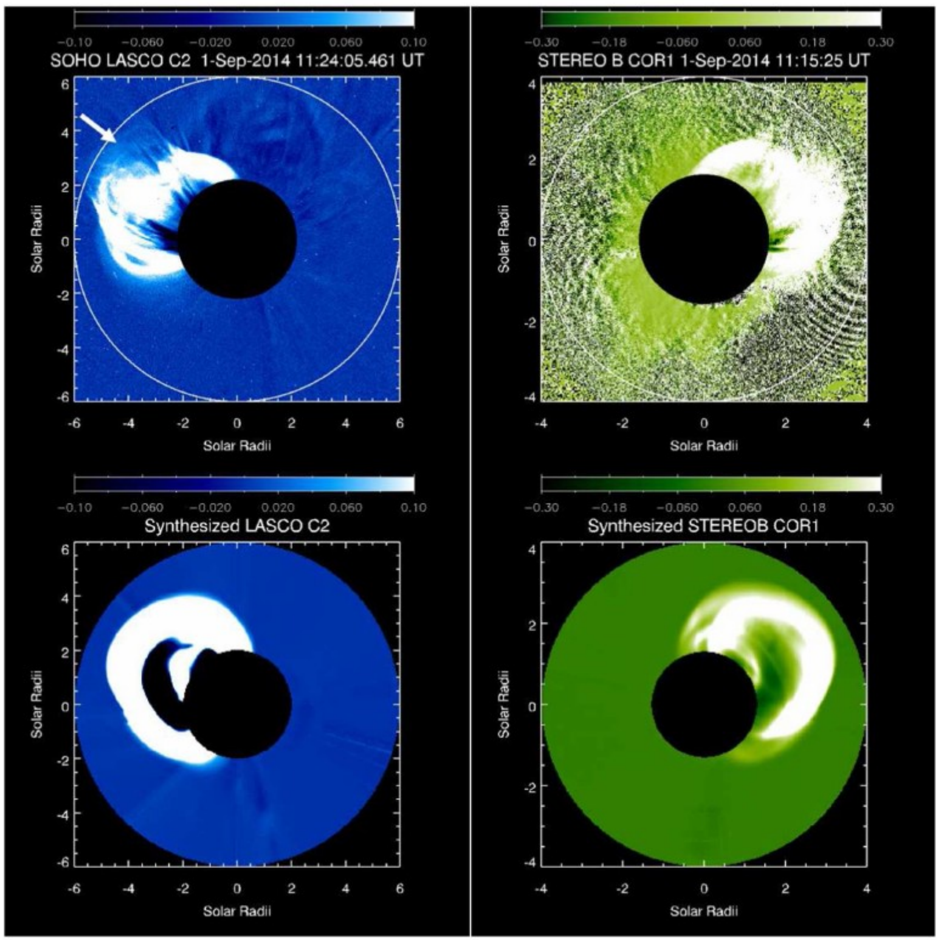


Figure 3. Comparison showing a general agreement between the white-light observations from *SOHO* LASCO C2 (top left) and *STEREO-B* COR1 (top right) and the respective synthesized white-light images from the simulation (bottom). The color scale shows the relative total brightness changes compared to the pre-event background level.

B Field Construction

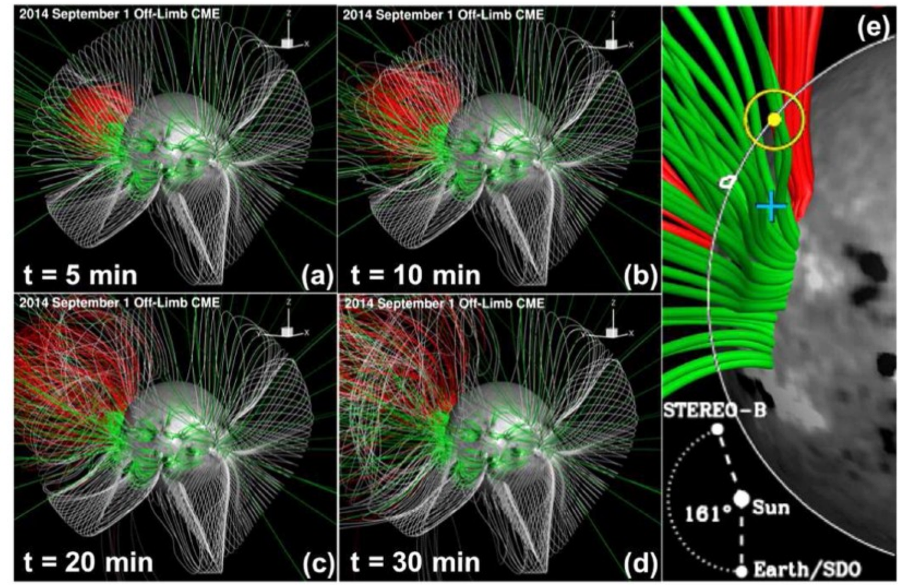
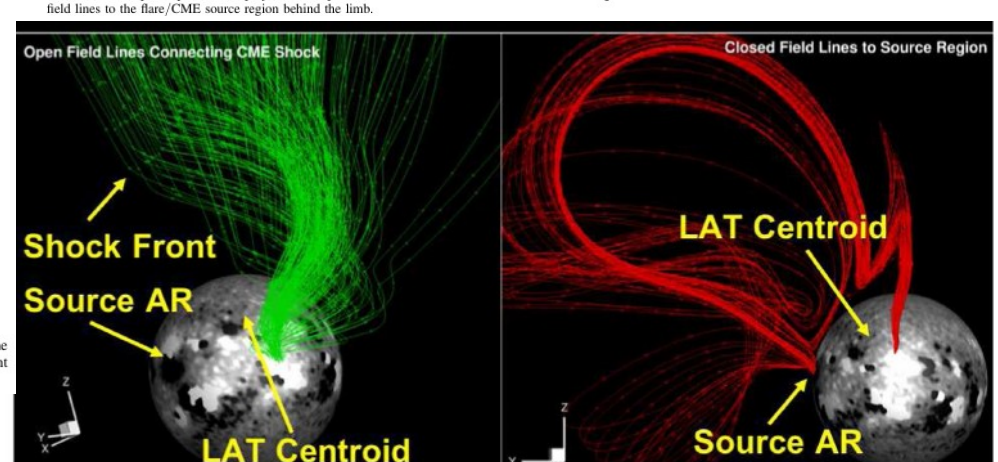


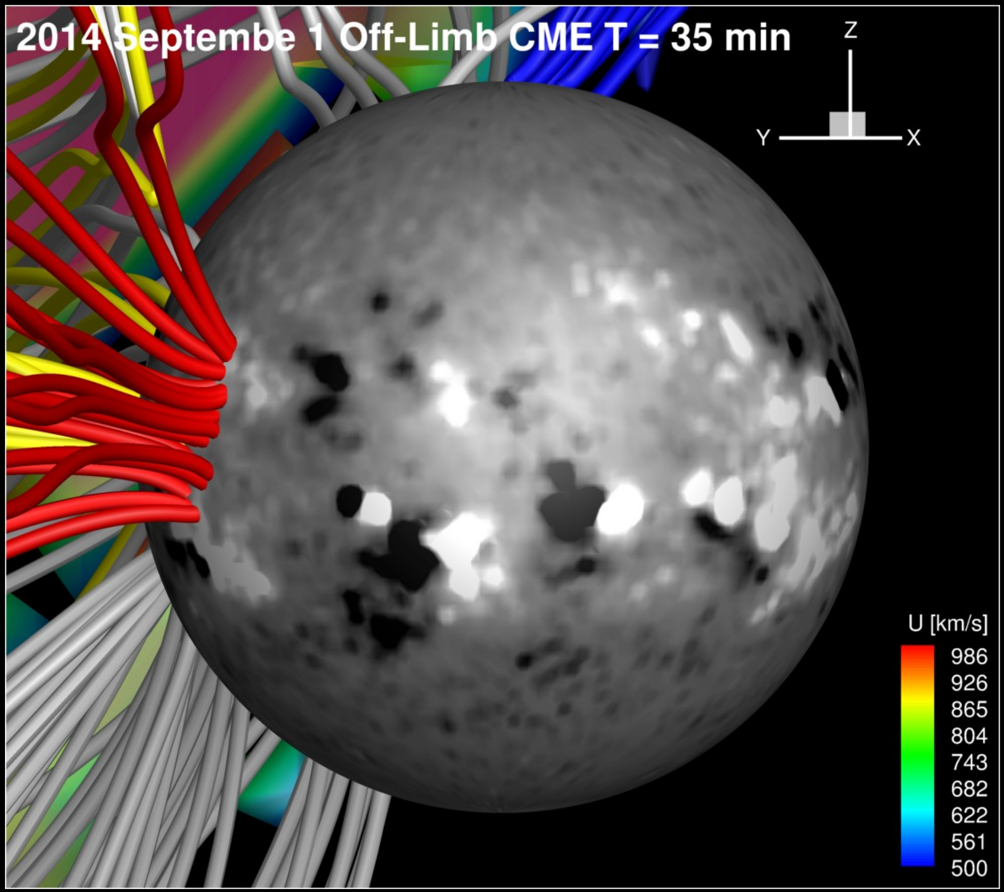
Figure 5. Magnetic field evolution in the first 30 minutes after the flux rope eruption. (a)–(d) show the 3D field configuration (viewed from the Earth) at $t = 5$, 10, 20, and 30 minutes. The red field lines represent the flux rope. The white field lines represent the large-scale helmet streamers. The green field lines are selected surrounding active region as well as open field lines. (e) Selected field lines near the *Fermi*-LAT γ-ray emission region from the simulation at $t = 30$ minutes. The yellow dot and circle indicate the LAT >100 MeV emission centroid and 68% error radius of 100″, respectively. The white contour shows the 6–12 keV *RHESSI* source. The blue plus represents the projected BTL position of the *STEREO* flare ribbon centroid. The green field lines connect to the CME-driven shock and the red field lines to the flare/CME source region behind the limb.



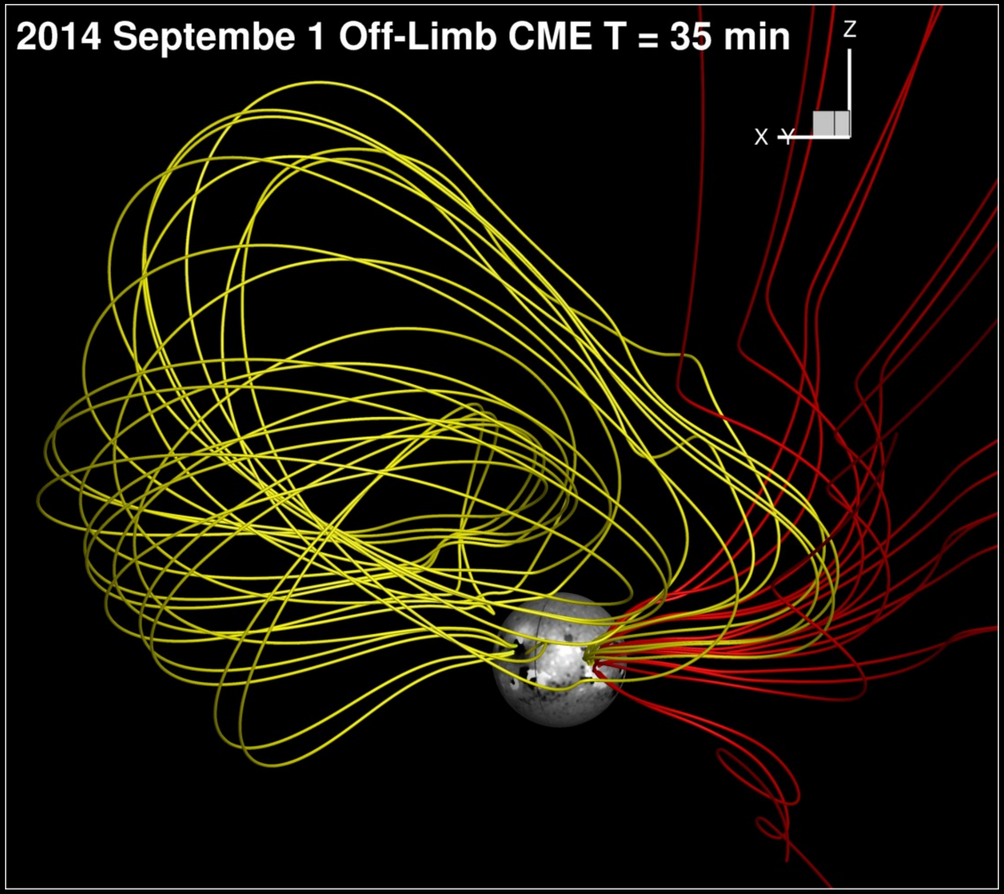
Konus

Meng Ji, VP, Wei Liu et al. ApJ 2018, 867, 122

Earth View



Overview



- **Red**: Field lines connected to the CME shock.
- **Yellow**: Field line connected to the CME source

Models of gamma-ray emission

Simulation Results

More simulation results

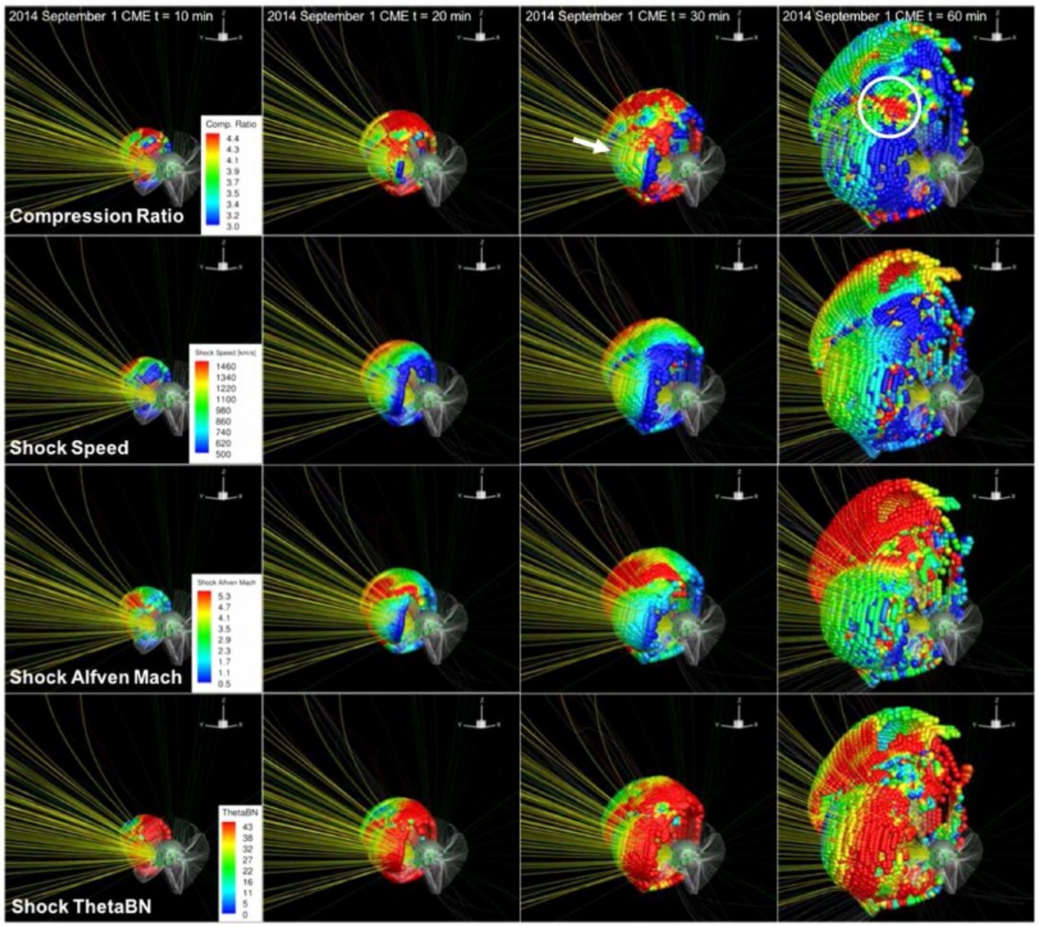
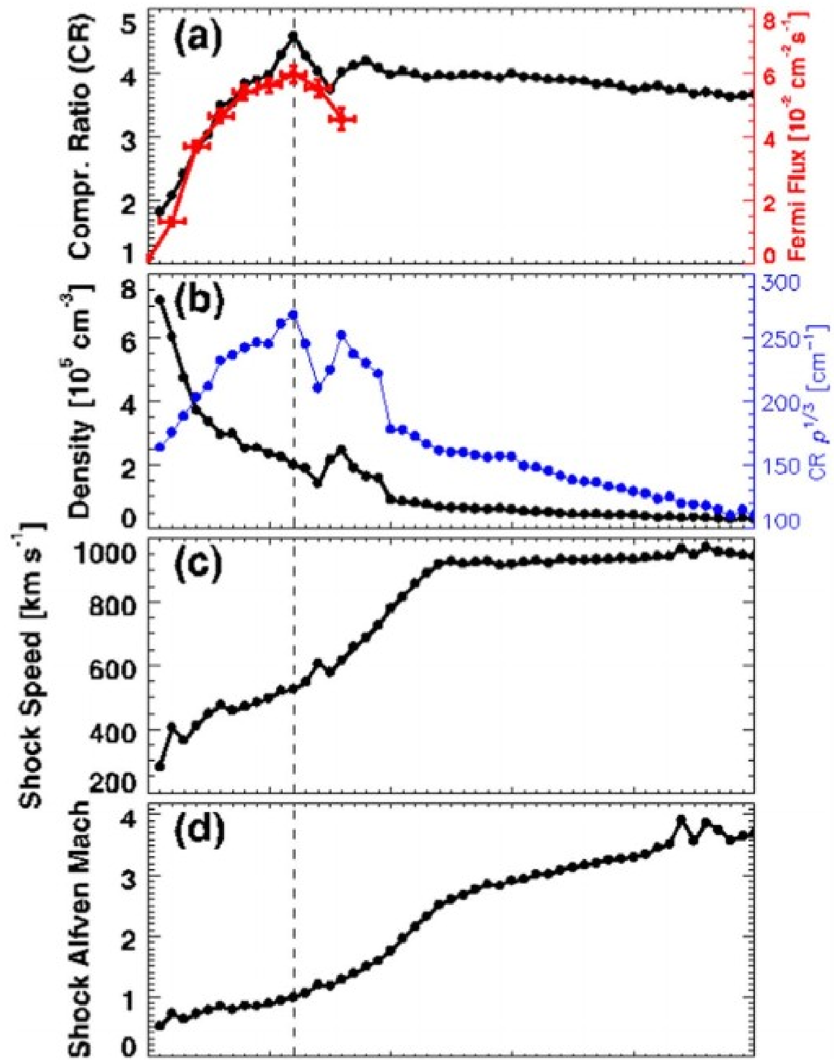


Figure 7. Evolution of shock parameters at t = 10, 20, 30, and 60 minutes from left to right. The top to bottom panels represent the compression ratio, shock speed, shock Alfvén Mach number, and shock θ_{Bn}. The yellow field lines represent the open field near the *Fermi*-LAT γ-ray emission region connected to the CME-driven shock. The white arrow points to the shock surface connected back to the visible side of the Sun. The white circle in the upper right panel marks the possible shock–shock interaction region (see the text).



Konus-WIND at 25

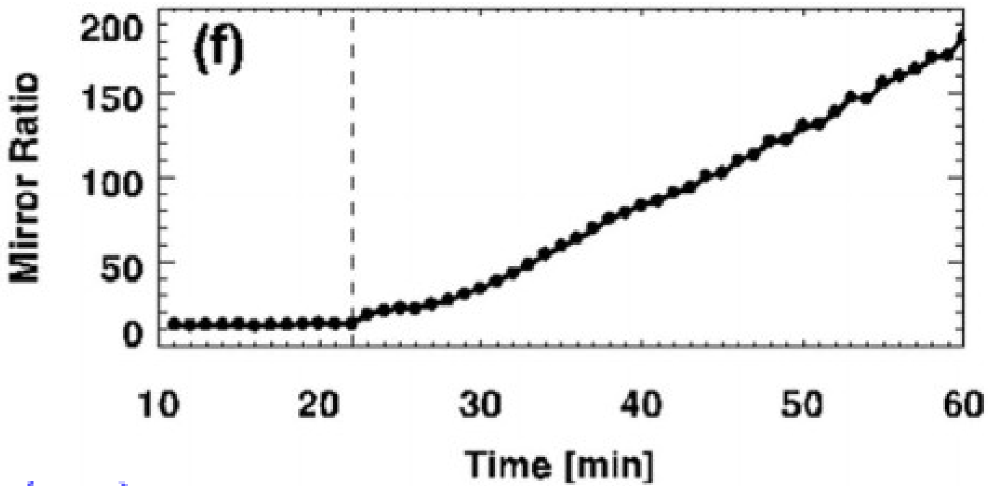
Models of gamma-ray emission

3. Acceleration at CME-shock and escape from downstream to the Sun

Objections 2. Large B convergence $(\eta \gg 1)$ *small loss cone*

Few particles escape if there is no scattering

However, collisions or turbulence can scatter particles into the loss cone and allow particles to escape on a timescale comparable to the duration time



$$T_{\rm esc} \le \eta \times \tau_{\rm cross} \sim \eta (u_{\rm CME}/v_p) t$$

$$T_{\rm esc} < t \quad {\rm for} \;\; u_{\rm CME} = 10^3, v_p = 2 \times 10^5, \;\; \eta \sim 170$$

Konus-WIND at 25

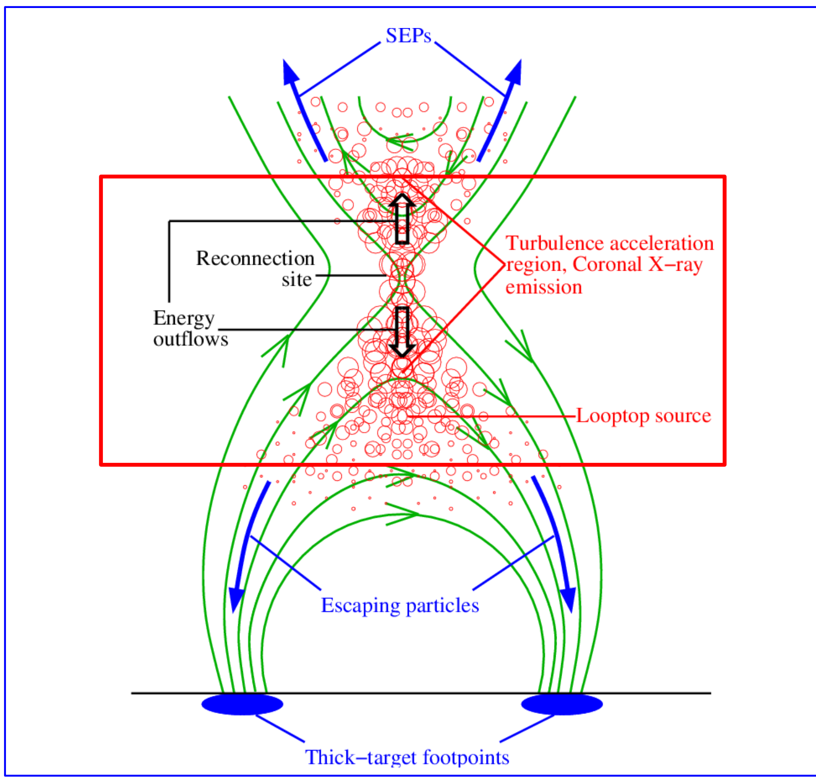
Summary Part 1

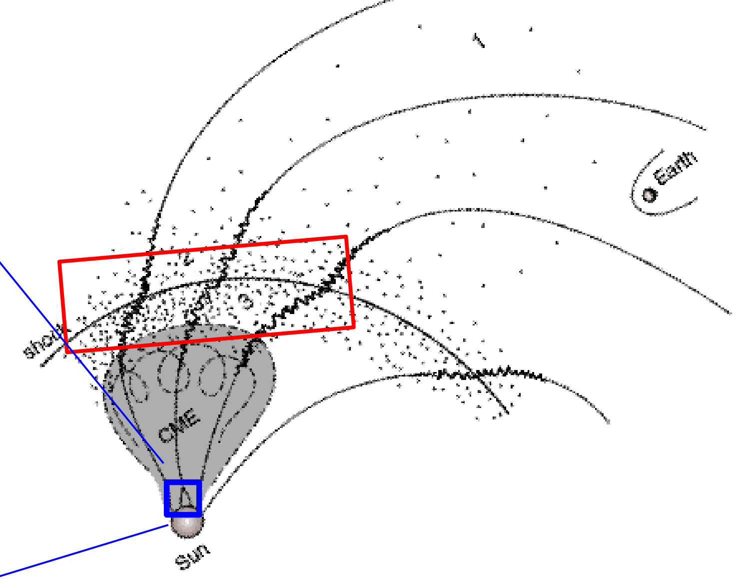
1. Acceleration of RPPs in flare reconnection site and SEPs at CME-shock environments are interconnected
2. Fermi-LAT gamma-ray flares have temporal evolution similar to CMEs and SEPs than the impulsive emissions
3. Gamma-ray centroid migrates far away its AR; a necessary behavior for BTL flares
4. Most likely scenario is that CME accelerated protons from downstream are transported to the photosphere
5. Simulations of the CME, shock and B fields are consistent with this scenario

Connections between *SEPs and RPPs*

1. CME accelerated particles as RPPs: *Fermi Observations*

2. RPPs as seeds in CME-Acceleration of SEPs: *RHESSI and SEP Observ.*

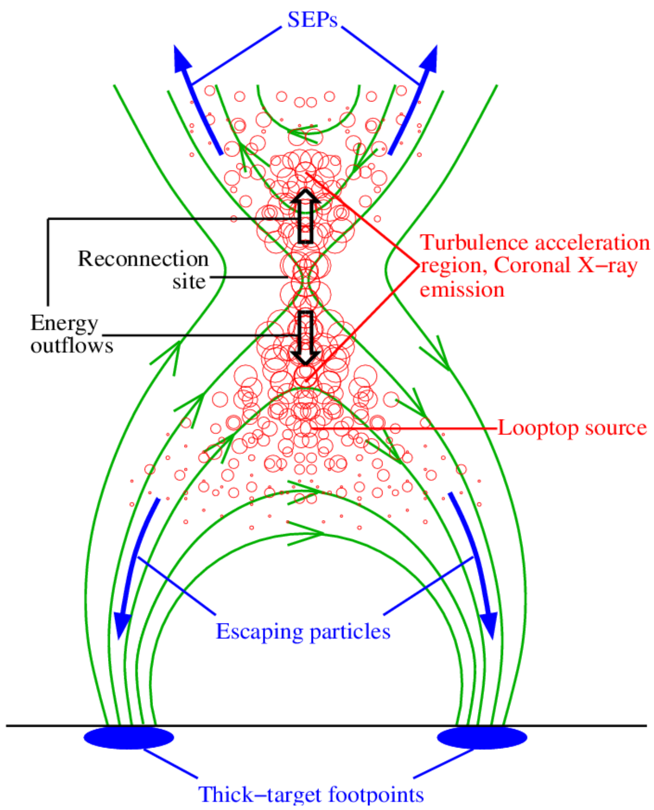


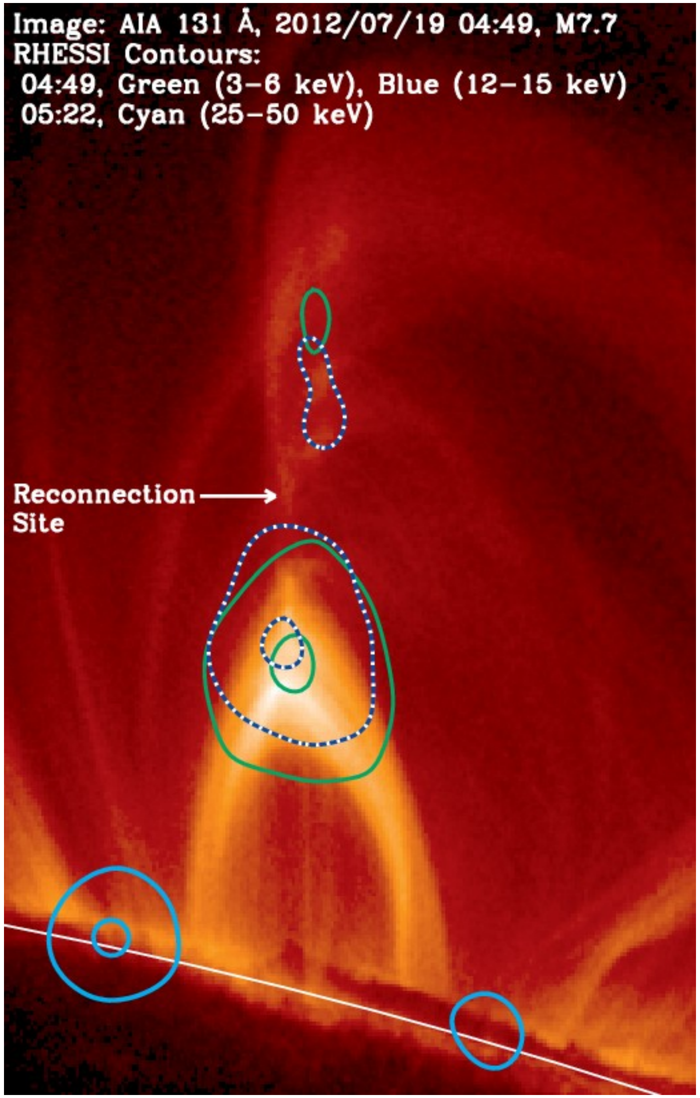


Konus-WIND at 25

Radiation Producing Particles: *RPPs*

Focus of solar physics





Outline: Part 2

I. Motivations:

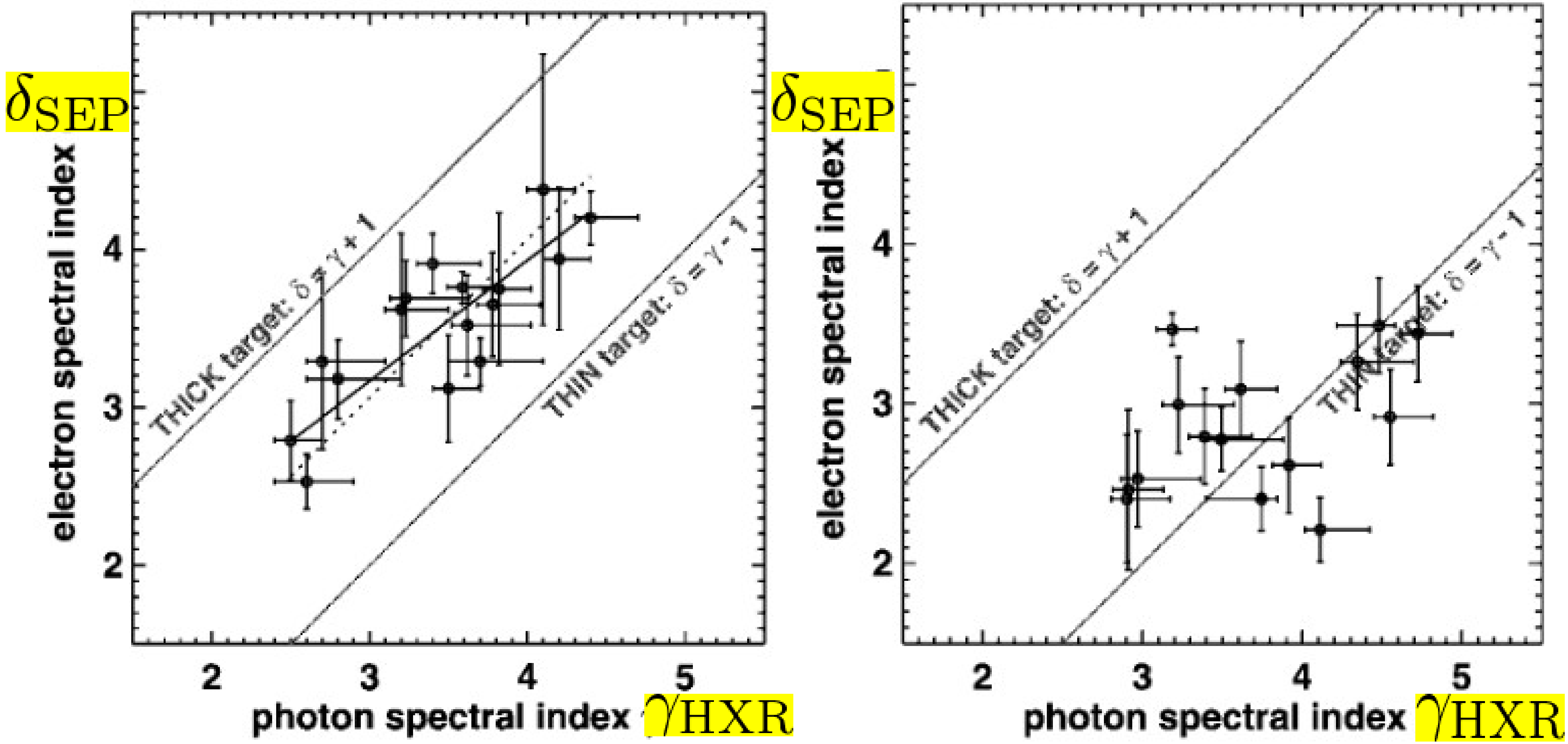
Observations and Seed particles for CME-shock

II. The Role of RPPs in Production of SEPs

Coronal acceleration and re-acceleration at the CME

1. SEP and HXR *Electron* Spectra

"Impulsive; Prompt" — *"Gradual; Delayed" Events*

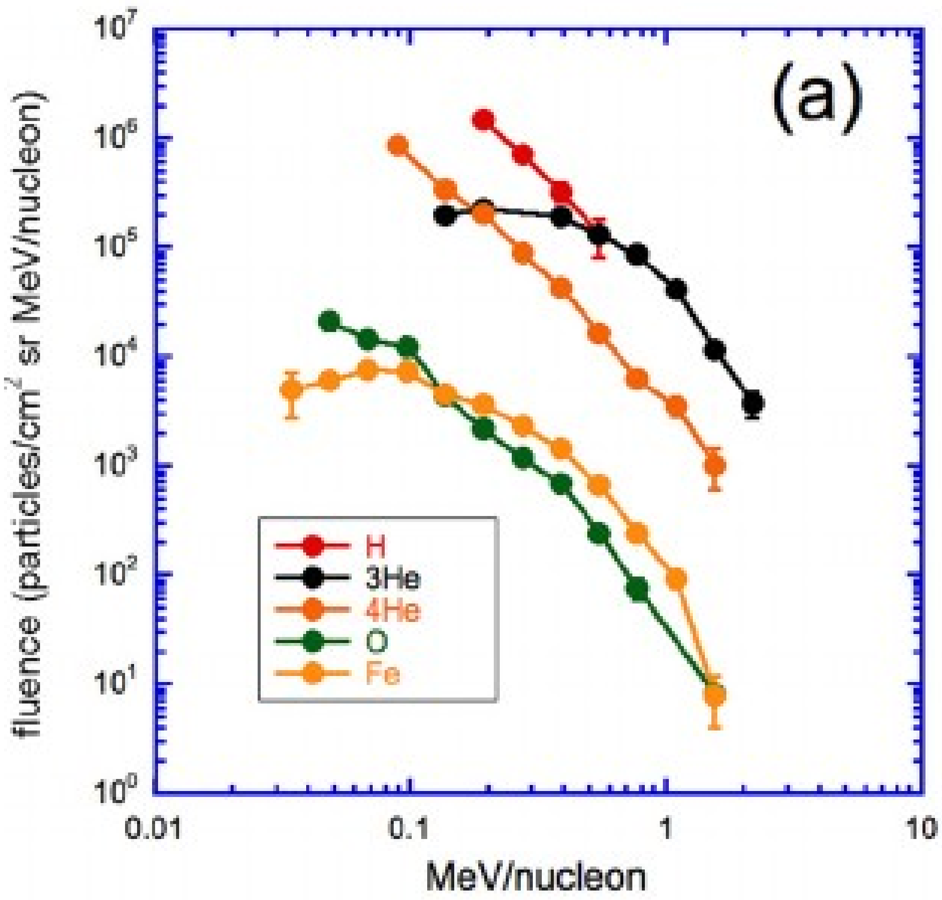


Konus-WIND at 25

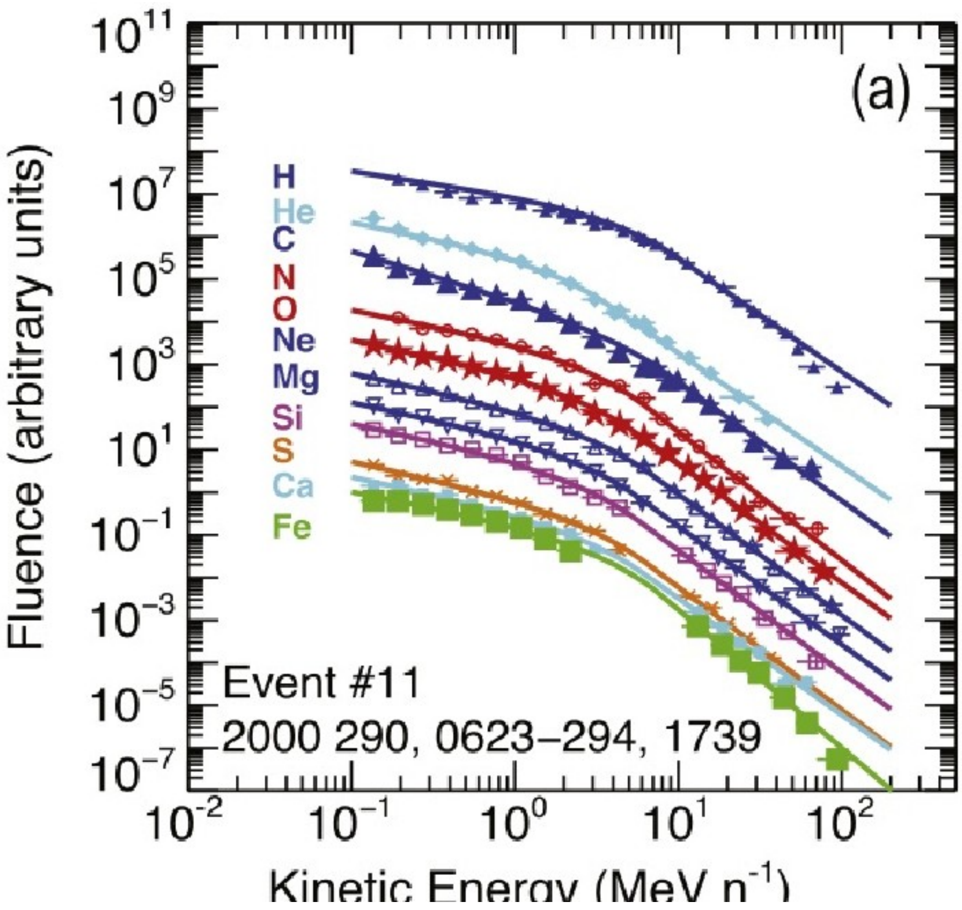
Krucker et al. 2007

2. SEP *ION* Spectra

"Impulsive" Events Mason et al. 2016



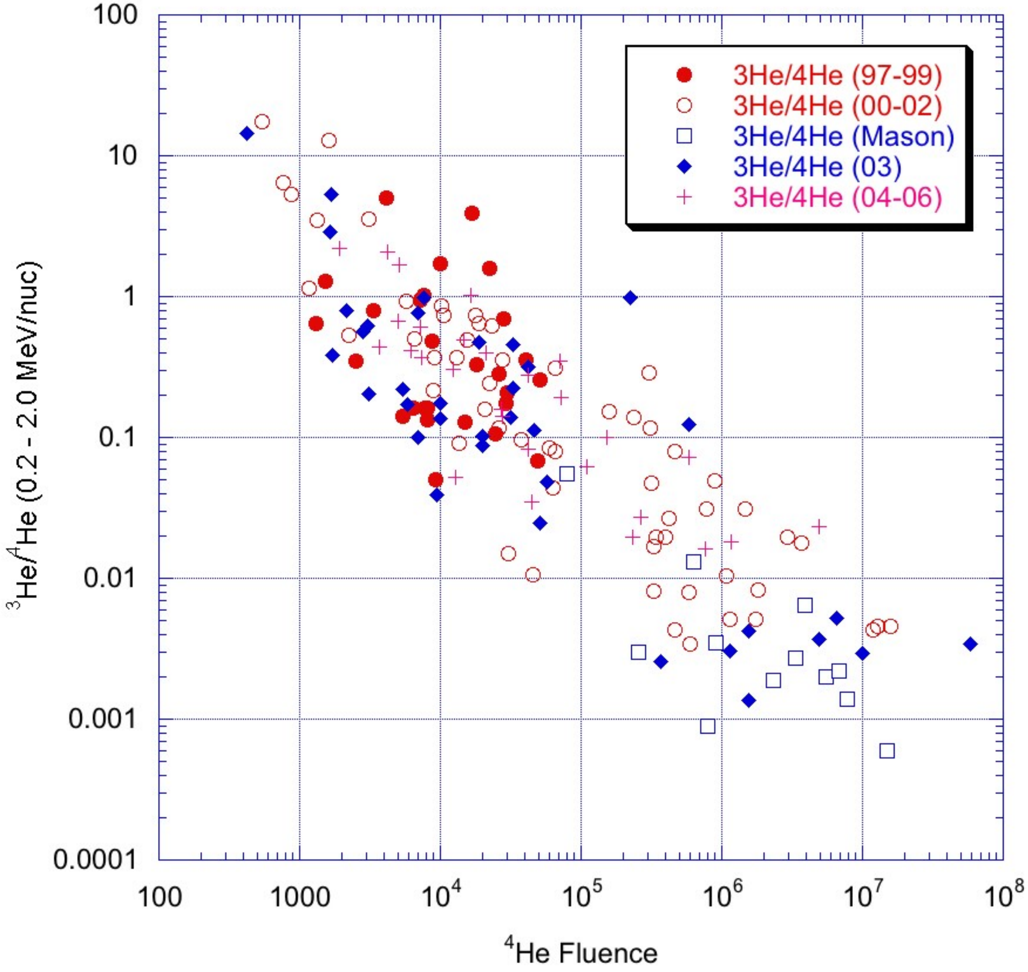
"Gradual" Events Desi t al. 2015



Konus-WIND at 25

He3, He4 Fluence Ratios

Not bimodal: *gradual variation with acceleration rate*



Observations

Impulsive or Prompt Events

Acceleration by Turbulence at the Flare Site

$$N(E) \propto E^{-\delta}$$

Escape up: SEPs

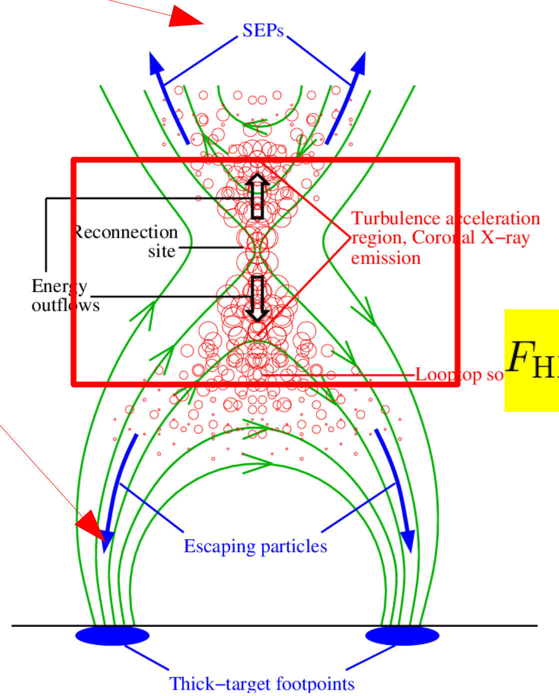
$$T^u_{\rm esc} \sim L/v \propto E^{\alpha_u}, \; \alpha_u = -d\ln v/d\ln E$$

$$F_{\rm SEP}(E) \propto E^{-\delta-\alpha_u}$$

$$\delta_{\rm SEP} = \delta + \alpha_u$$

Escape down: HXRs

$$T^d_{\rm esc} \propto E^{\alpha_d}$$



$$F_d(E) \propto E^{-\delta-\alpha_d}$$

$$F_{\rm HXR}(E) = vN_{\rm eff}(E) \propto \frac{v}{\dot{E}_L}\int_E^\infty N(E)E^{-\alpha_d}dE$$

$$\delta_{F_{\rm HXR}} = \delta + \alpha_d - 1 - 2\alpha_u$$

$$\gamma_{\rm HXR} = \delta + \alpha_d - 1$$

$$\delta_{\rm SEP} = \gamma_{\rm HXR} + 1 + \alpha_u - \alpha_d$$

Konus-WIND at 25

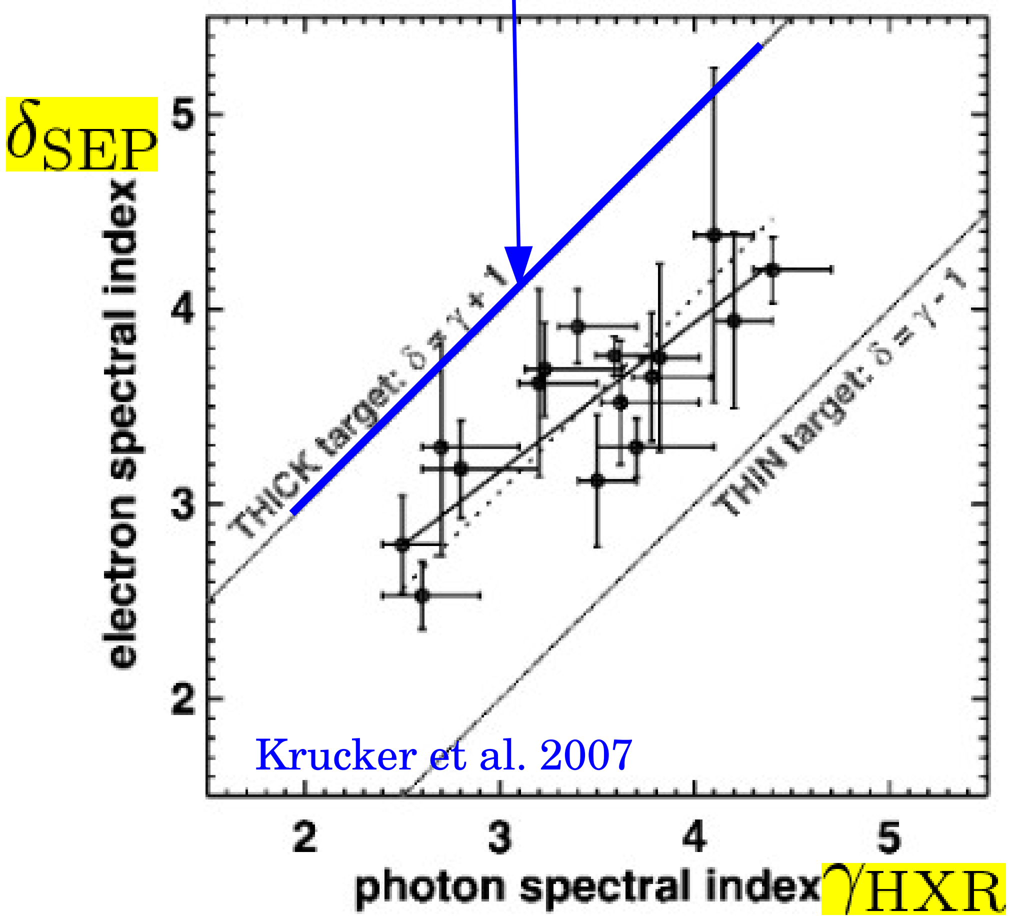
Impulsive or Prompt Events

*Acceleration by Turbulence **only** at the Flare Site*

$$\delta_{\mathrm{SEP}} = \gamma_{\mathrm{HXR}} + 1 + \alpha_u - \alpha_d$$

Strong diffusion

$\alpha_u = \alpha_d$



WIND at 25

Impulsive or Prompt Events

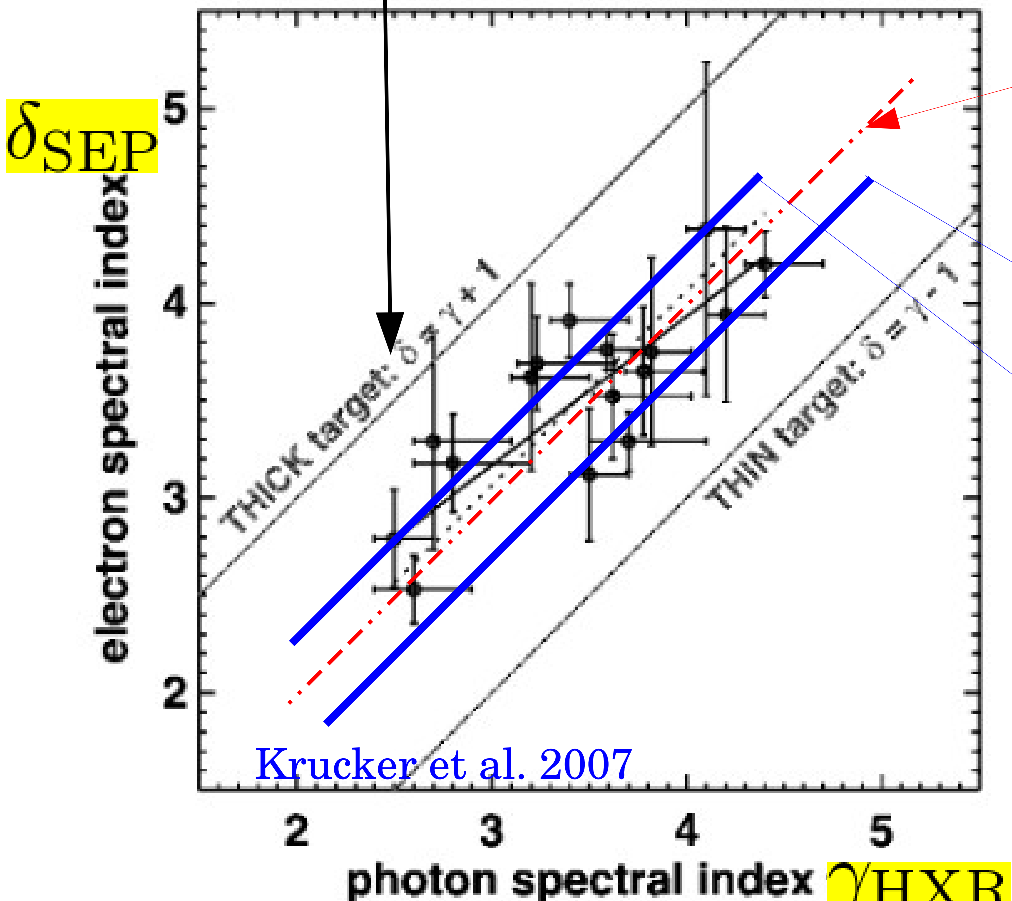
*Acceleration by Turbulence **only** at the Flare Site*

$$\alpha_d = \gamma_{\rm HXR} - \delta_{\rm SEP} + \alpha_u + 1$$

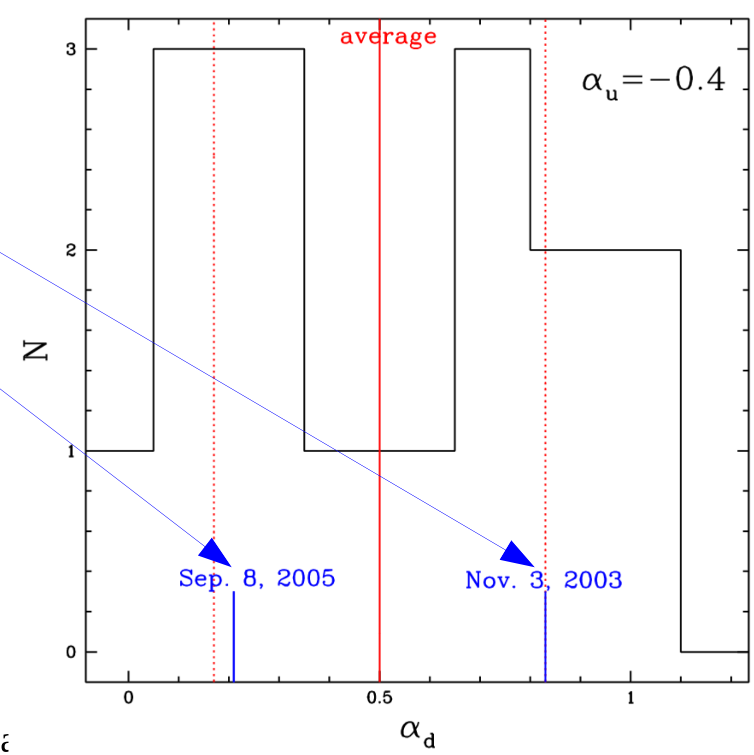
Weak diffusion

$T_{\rm esc,u} \sim L/v \propto E^{-0.5}$ and $T_{\rm esc,d} \propto \tau_{sc}$

$\alpha_u \sim -0.4,$ $\alpha_d \sim 0.6;$ $\delta_{\rm SEP} \sim \gamma_{\rm HXR}$



WIND



Impulsive or Prompt Events

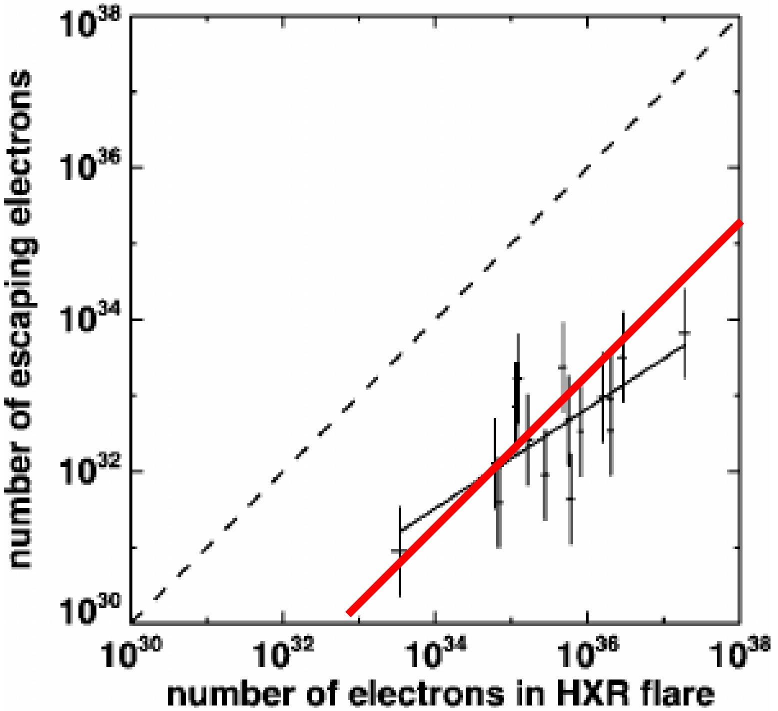
Acceleration by Turbulence ***only*** *at the Flare Site*

Relative numbers of RPP and SEP *(electrons)*

$$N_{\rm SEP} = \left(\frac{4\pi}{\Omega}\right)\left(\frac{c\Delta T}{L_u}\right)\int_{E_0}^{\infty}\beta(E)N(E)dE$$

$$N_{\rm HXR} = \frac{\Delta T c}{L_d}\frac{(E_0)}{T_{\rm esc}^d(E_0)}\frac{E_0^{\alpha_d-1}}{\beta(E_0)}\int_{E_0}^{\infty}\frac{N(E')}{E'^{,\alpha_d}}dE'\int_{E_0}^{E'}\beta^2 dE$$

$$R_N = \frac{N_{\rm HXR}}{N_{\rm SEP}} \sim \left(\frac{\Omega}{4\pi}\right)\left(\frac{\tau_{\rm coul}}{T_{\rm esc}^d}\right)g(\delta) \sim 100(10^{10}\,{\rm cm}^{-3}/n)$$



Krucker et al. 2007

Gradual or Delayed Events

Re-acceleration at the CME shock

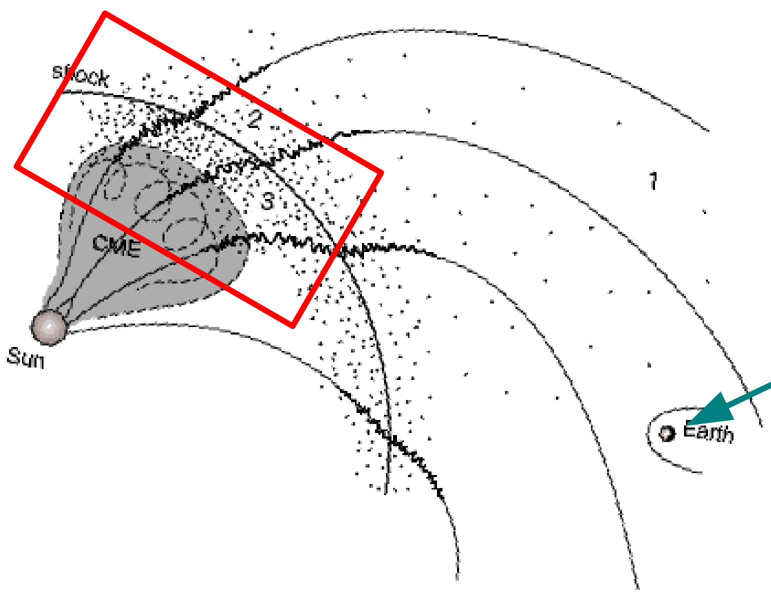
$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial E}\left(D_{EE}\frac{\partial N}{\partial E}\right) - \frac{\partial}{\partial E}[(A - \dot{E}_L)N] - \frac{N}{T_{\rm esc}} + \dot{Q}$$

Diffusion — Accel. — Loss — Escape — Source

by Turbulence — *by Shock and Turbulence*

Flare Accelerated Particles

Observed SEPs



Konus-WIND at 25

Gradual or Delayed Events

Re-acceleration at the CME

Shock: $\partial N/\partial t = -\partial(A_{\rm sh}N)/\partial E - N/T_{\rm esc} + \dot{Q} = 0$

Stochastic: $\frac{d}{dE}\left[D_{\rm EE}\left(\frac{dN}{dE} - \frac{N}{E}\xi\right)\right] - \frac{N}{T_{\rm esc}} = \dot{Q}$

$$A_{\rm eff} = \left(\xi - \frac{d\log N}{d\log E}\right)\frac{D_{EE}}{E},$$

$$\partial N/\partial t = -\partial(A_{\rm eff}N)/\partial E - N/T_{\rm esc} + \dot{Q}$$

Solution with Source term flare accelerated electrons

$$F(E) = \frac{R(E)}{E}e^{-\eta}\int_0^E e^{\eta'}\dot{Q}(E')dE'; \quad \frac{d\eta}{dE} = \frac{R(E)}{E}$$

$$R(E) \equiv \tau_{\rm ac}^{\rm sh}/T_{\rm esc} = R_0 E^r$$

Gradual or Delayed Events

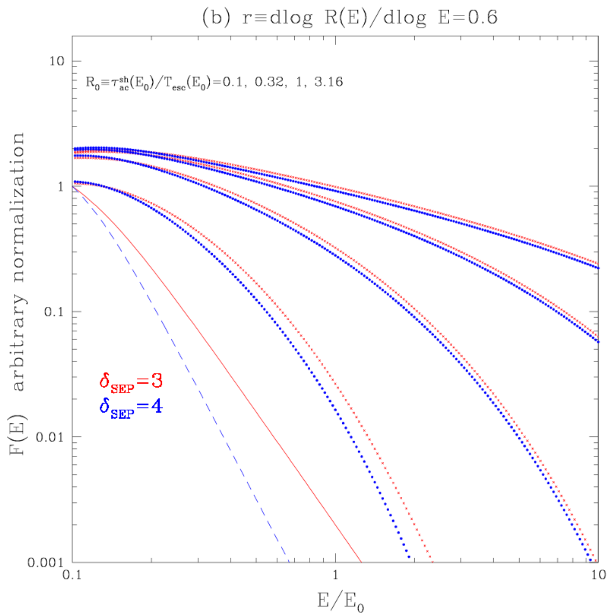
Re-acceleration at the CME shock

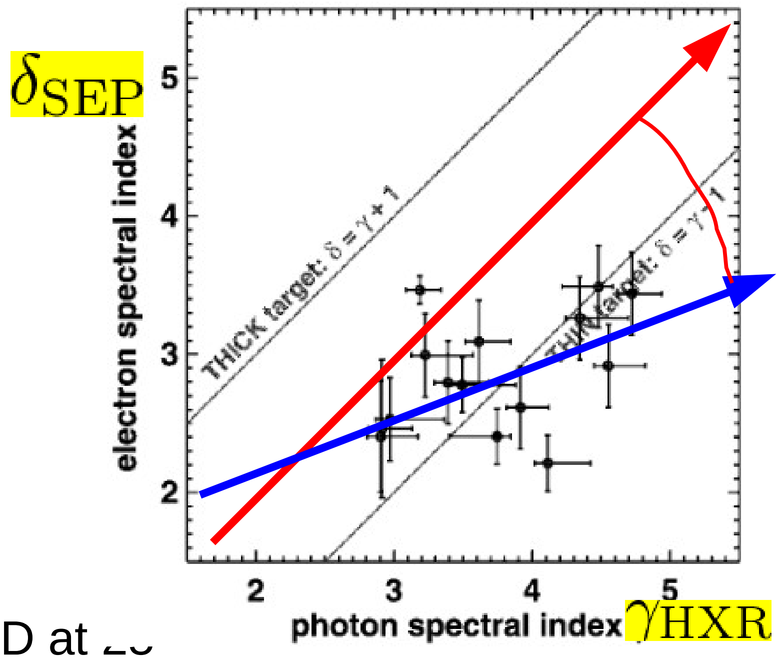
$$\partial N/\partial t = -\partial(A_{\rm sh}N)/\partial E - N/T_{\rm esc} + \dot{Q} = 0$$

Solution with Source term flare accelerated electrons

$$F(E) = \frac{R(E)}{E} e^{-\eta} \int_0^E e^{\eta'} \dot{Q}(E') dE'; \quad \frac{d\eta}{dE} = \frac{R(E)}{E}$$

$$R(E) \equiv \tau_{\rm ac}^{\rm sh}/T_{\rm esc} = R_0 E^r$$



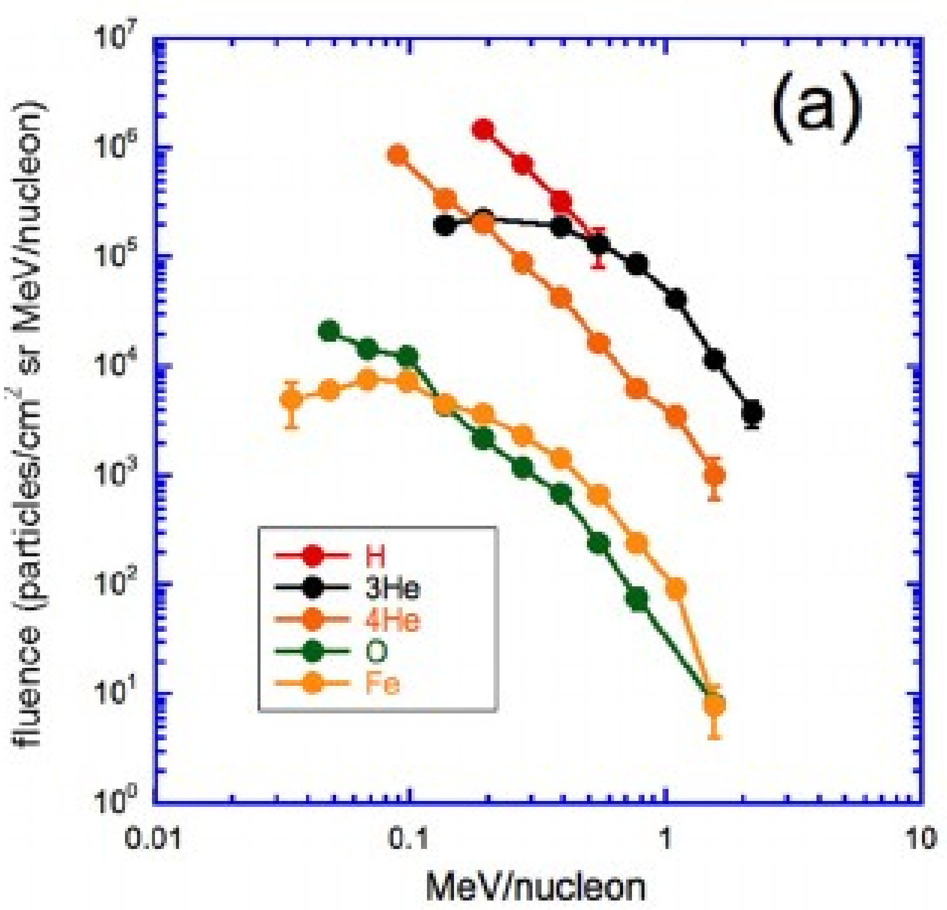


Konus-WIND at 25

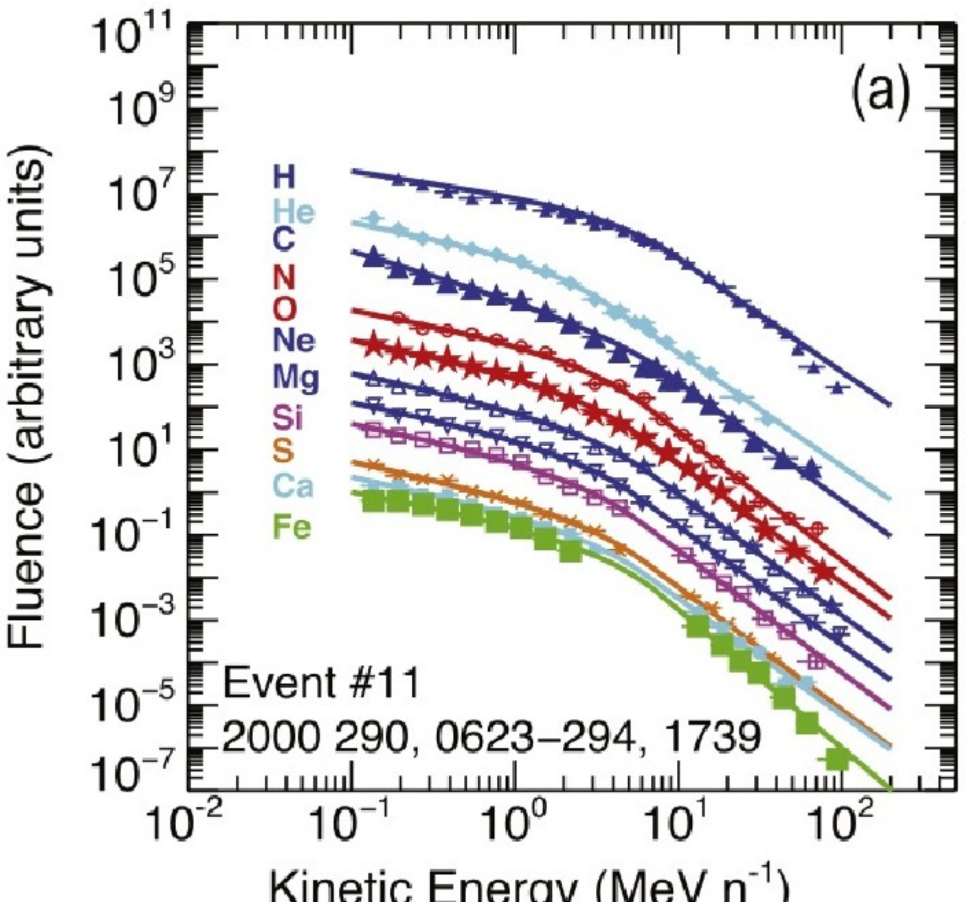
B. Ion ***(He)*** *spectra and abundances*

2. SEP-Ion Spectra and 3He Enrichment

"Impulsive" Events Mason et al. 2016



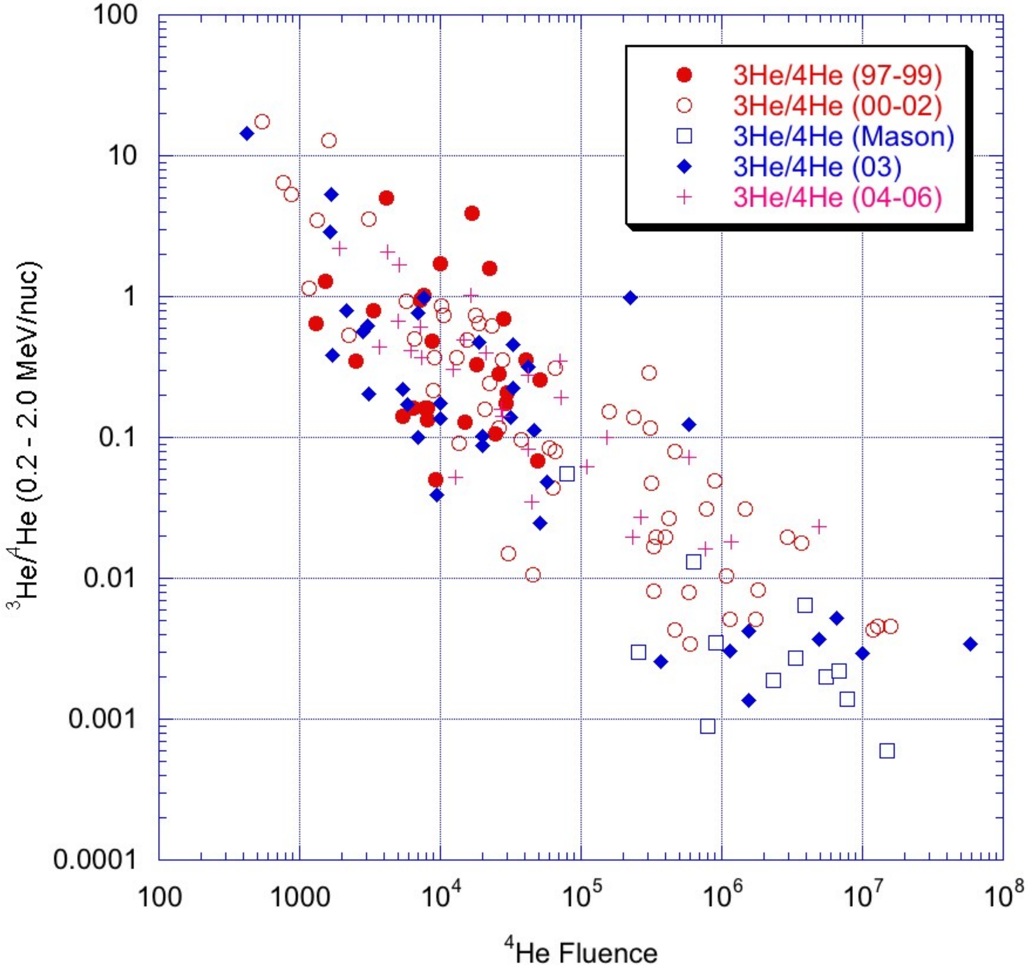
"Gradual" Events Desi t al. 2015



Konus-WIND at 25

He3, He4 Fluence Ratios

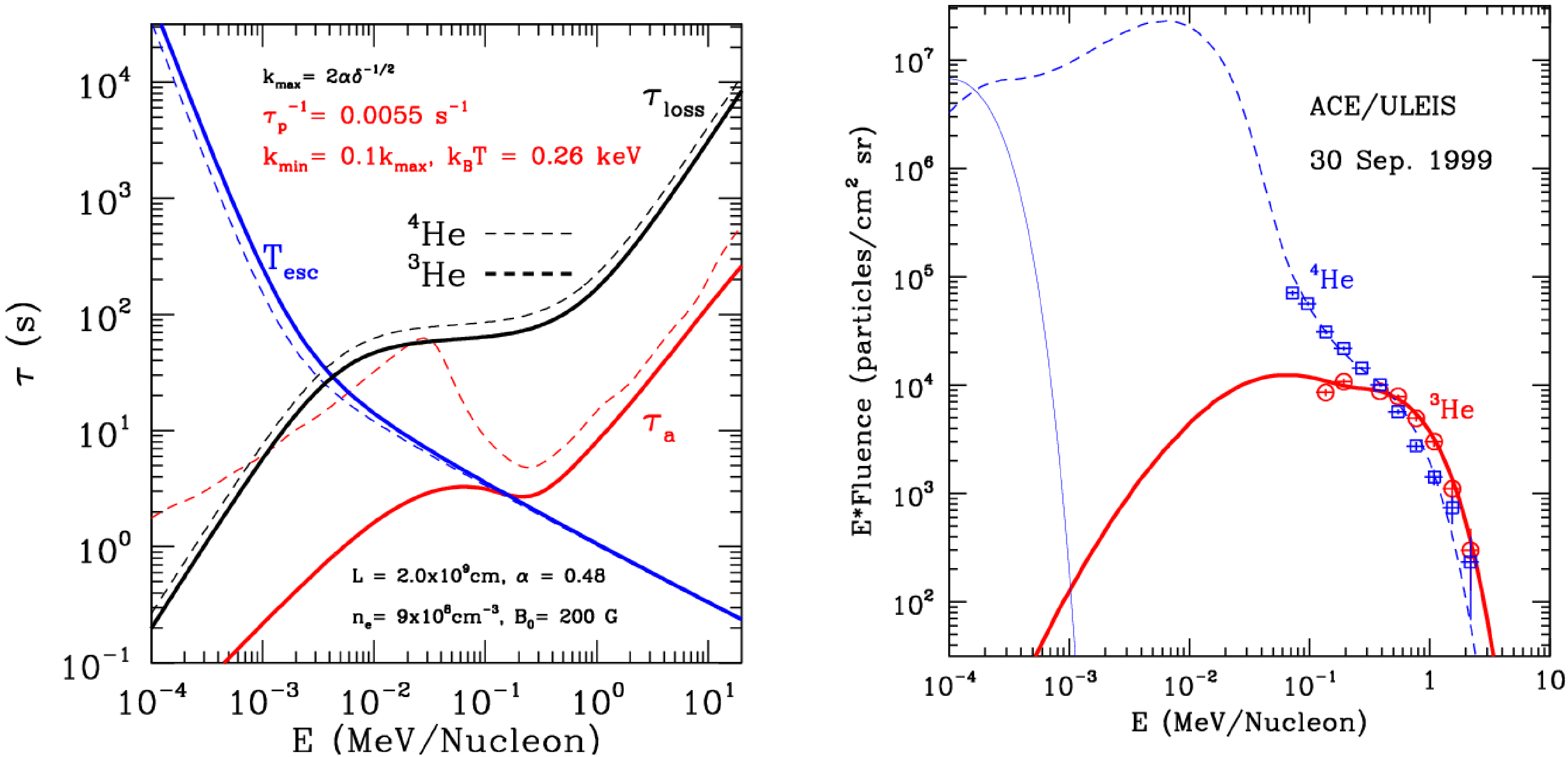
Not bimodal: *gradual variation with acceleration rate*



Observations

Konus-WIND at 25

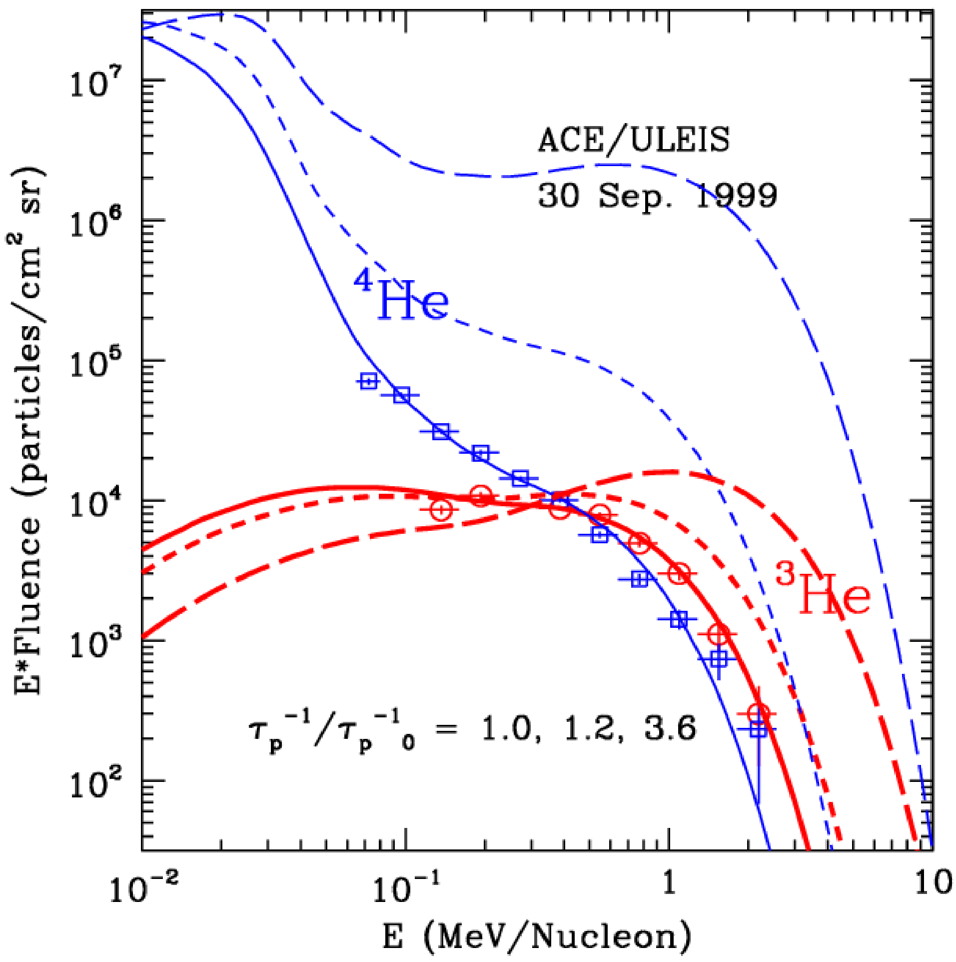
B. He3, He4 Abundances and Spectra



(Liu, Petrosian and Mason, 2004 ApJ)

“Impulsive” He Spectra: SA at Flare

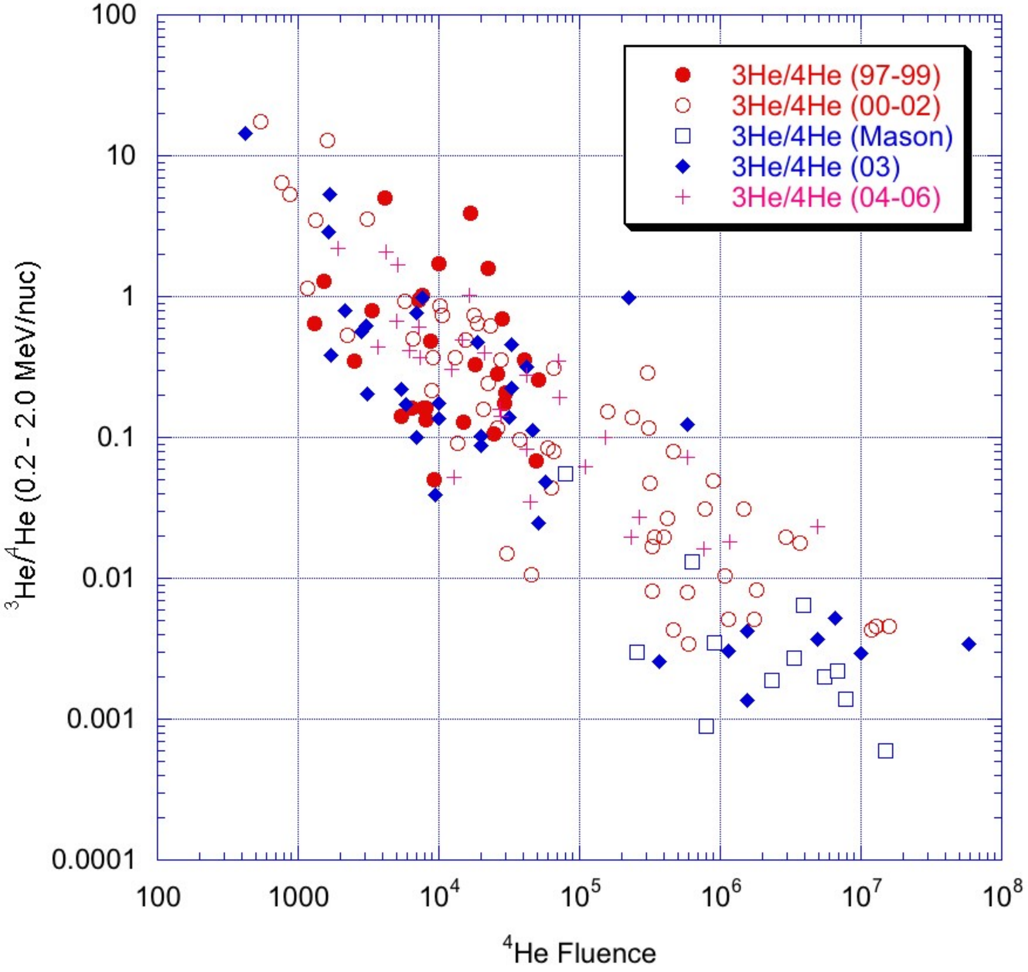
Excellent agreement with many events

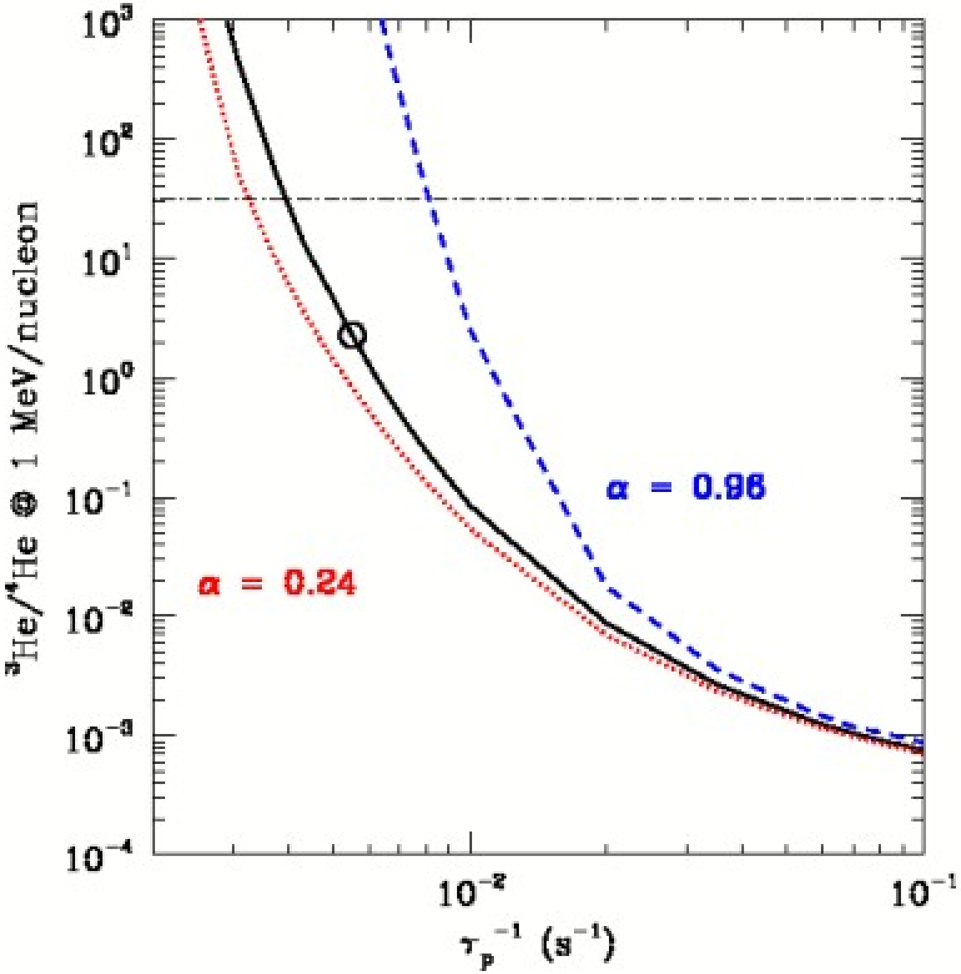


Konus-WIND at 25

He3, He4 Fluence Ratios

Not bimodal: *gradual variation with acceleration rate*

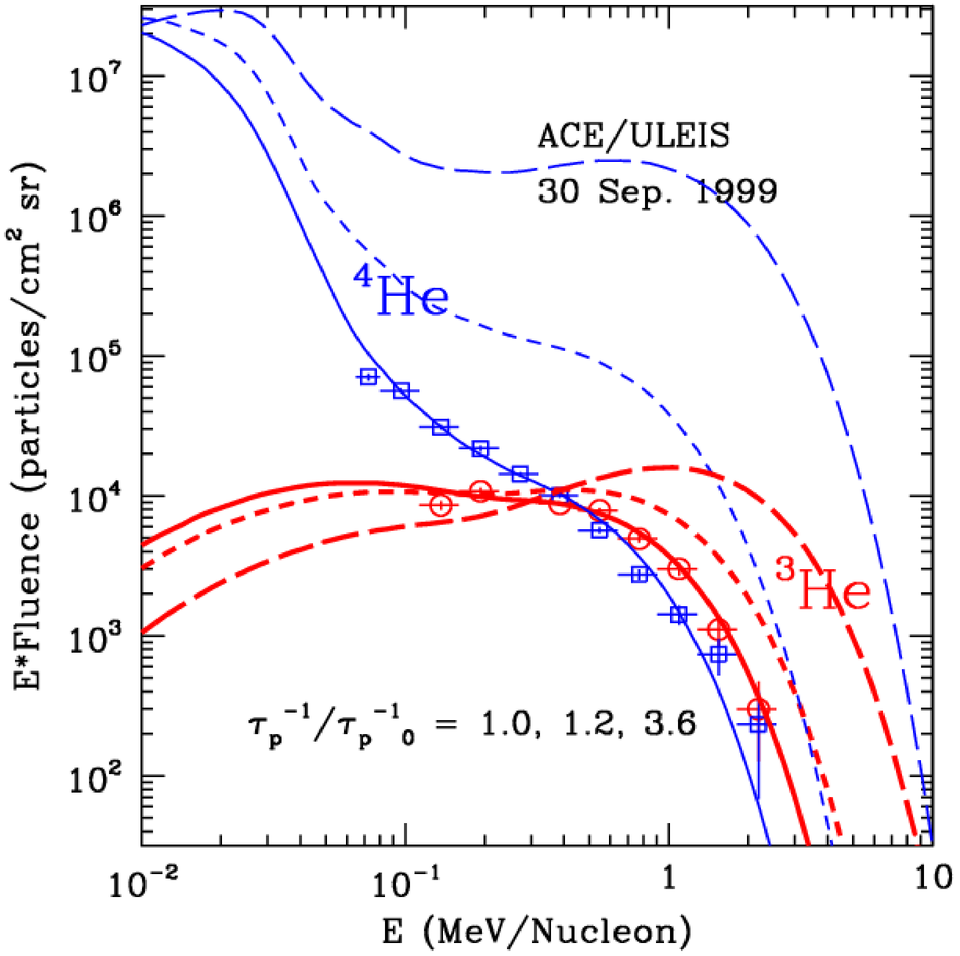


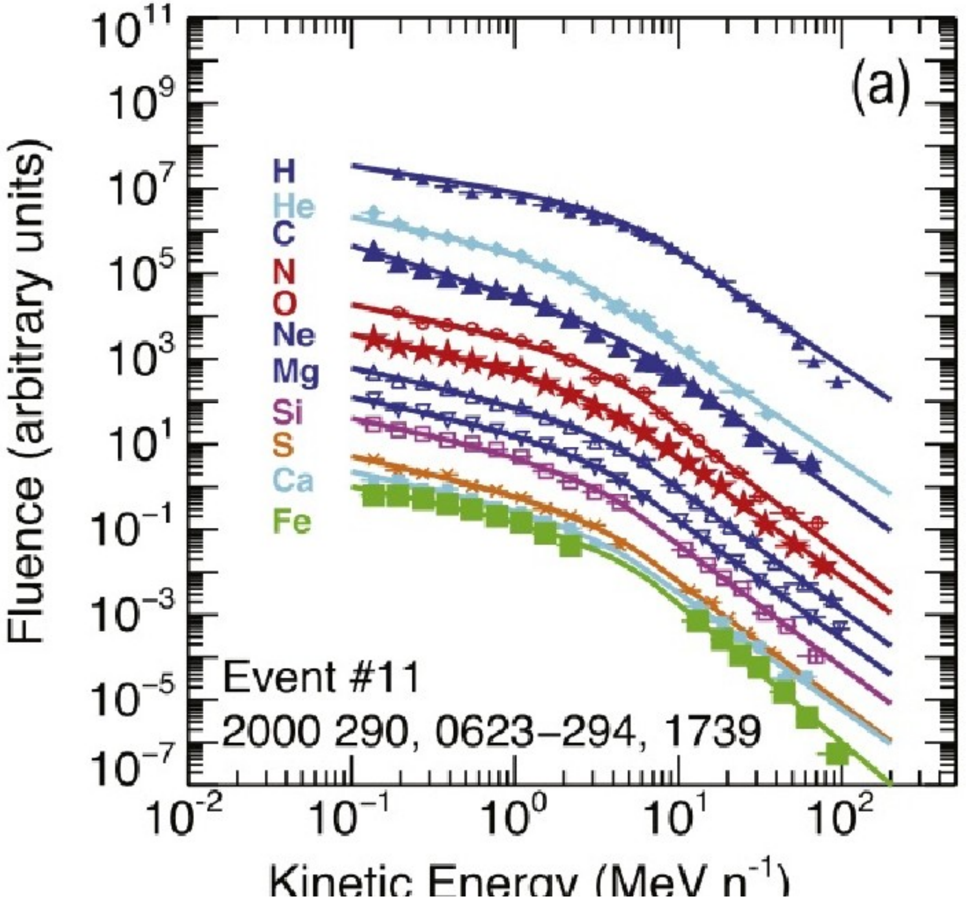


Observations *Model Results*

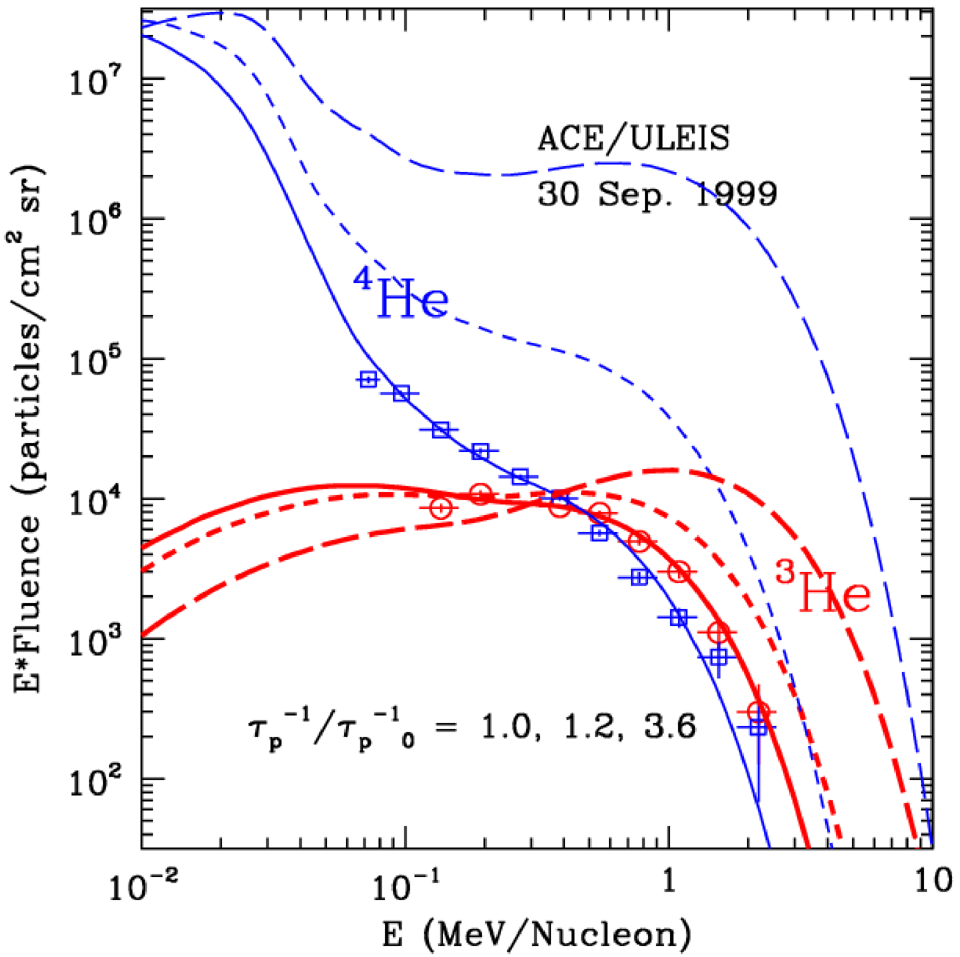
Flare accelerated He4 Spectra

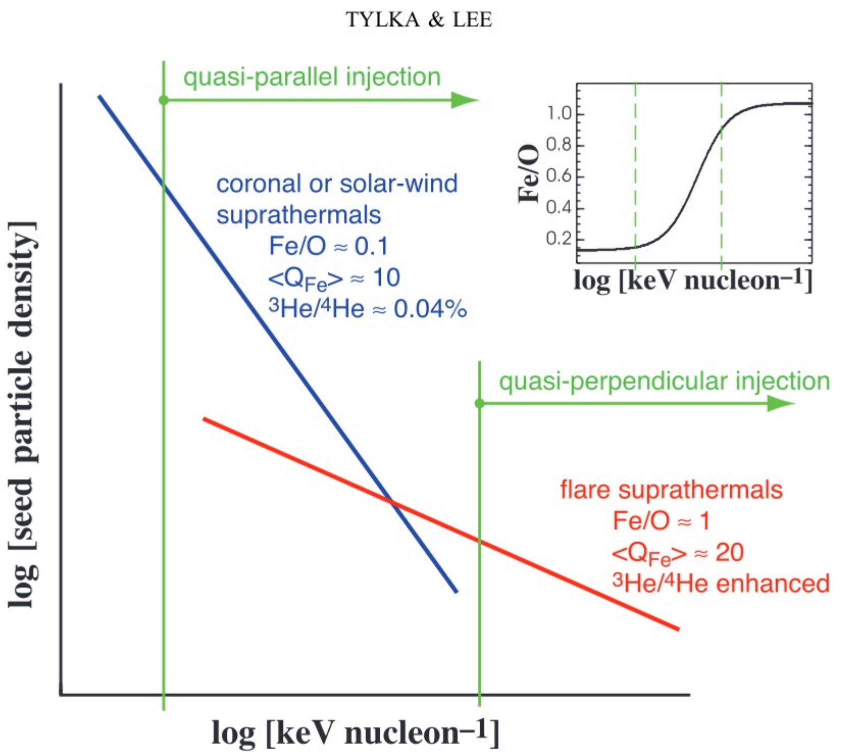
Do not agree with observed gradual events





He3, He4 Spectral Variations

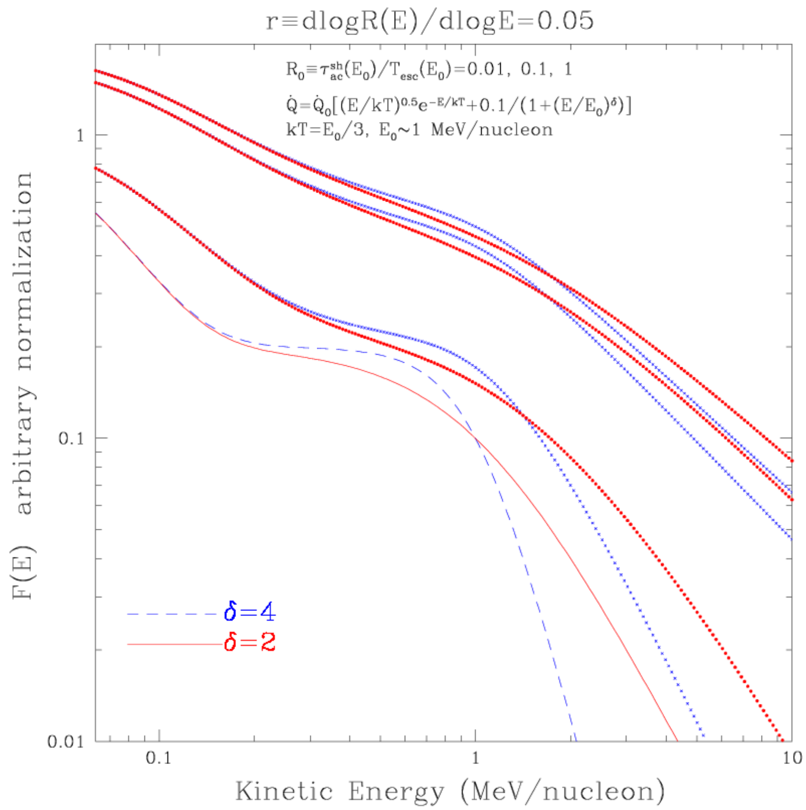


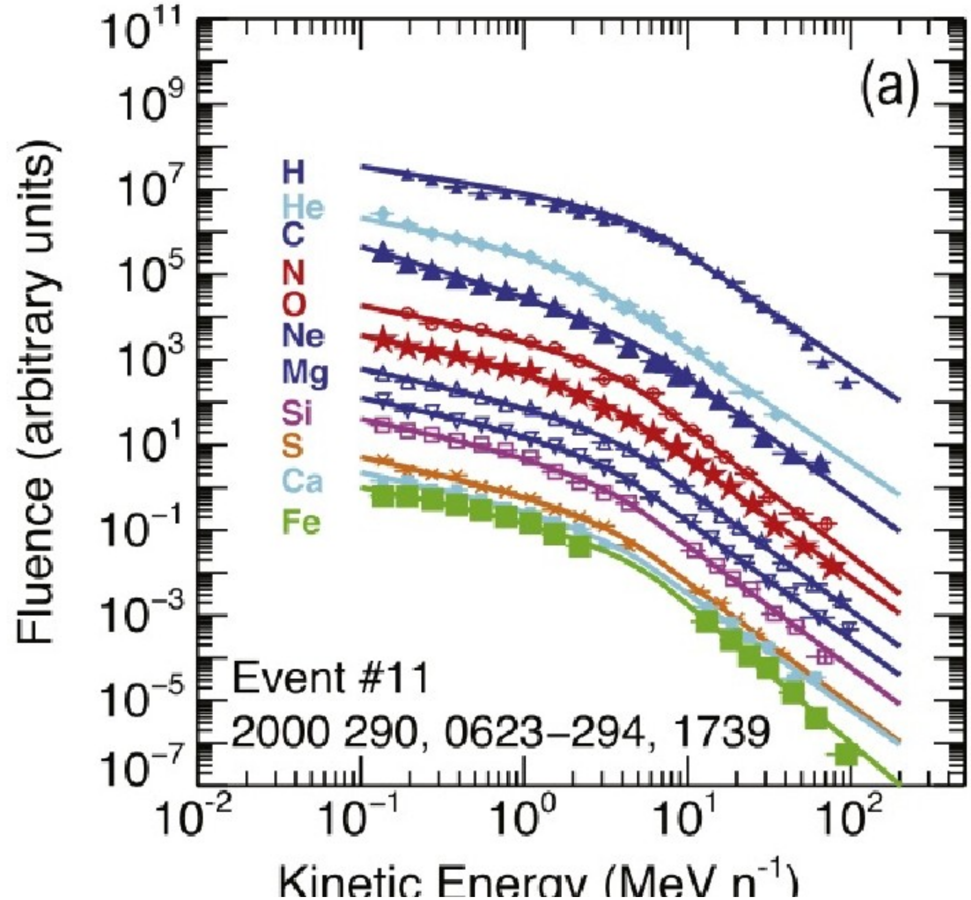


BUT Flare accelerated He4 Spectra

after re-acceleration at the CME-shock agree

$$F(E)=\frac{R(E)}{E}e^{-\eta}\int_0^E e^{\eta'}\dot{Q}(E')dE';\quad \frac{d\eta}{dE}=\frac{R(E)}{E}$$

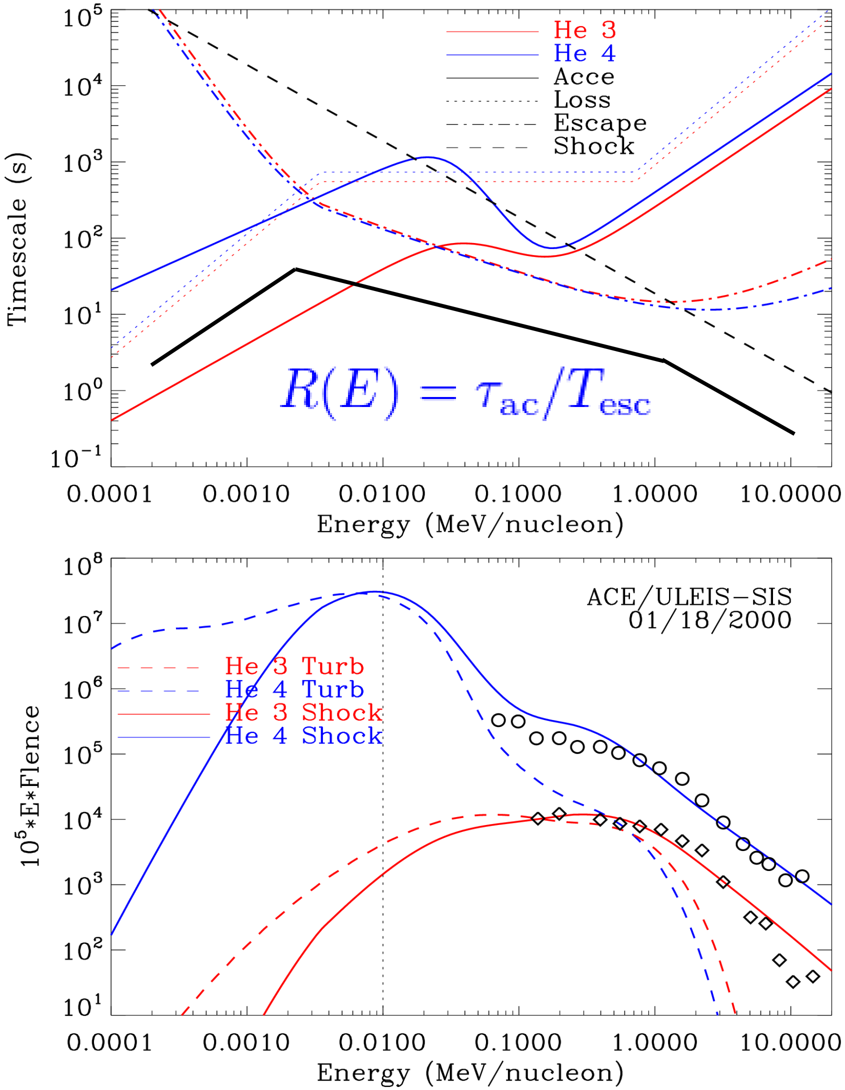




Numerical treatment of re-Acceleration

Re-acceleration timescales

$\tau_{\rm ac}^{\rm sh};\ \tau_{\rm diff};\ T_{\rm esc};\ \tau_{\rm loss}$



Konus-WIND at 25

Summary: Part 2

1. Acceleration in flare reconnection and CME-shock environments are interconnected

2. SEP electron and HXR producing electron number and spectral comparisons support the weak diffusion scenario and re-acceleration of flare particles at the CME-shock.

3. Abundances and spectra of 3He and 4He also agree with this scenario.