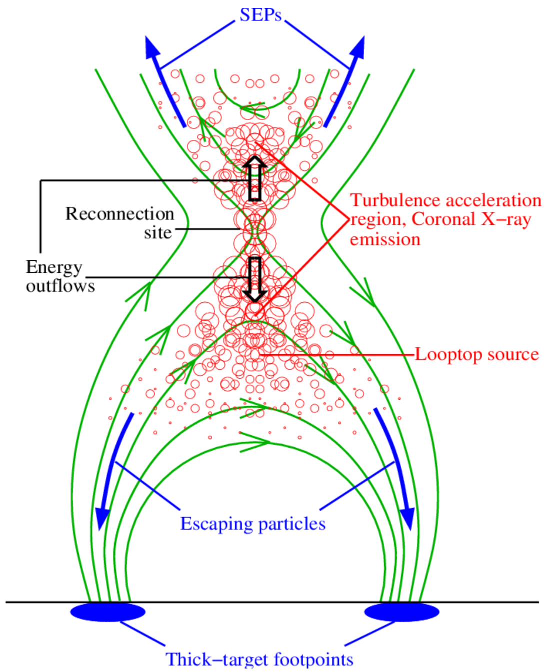
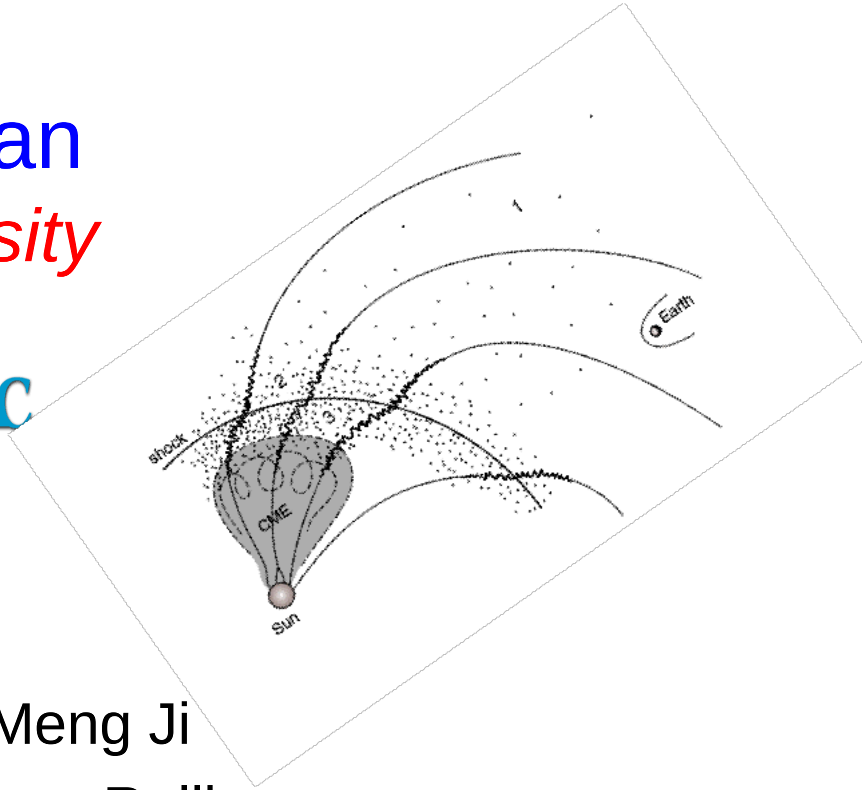
What Can We Learn From Fermi Observations of Solar Flares? About Acceleration and Transport of Particles in the *Flare-reconnection and CME-shock environments*



Vahe Petrosian

Stanford University



With

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AMS-2 2018

Outline

I. General remarks on acceleration sites and mechanisms

II. Nonthermal radiation and SEP connections

III. Combined SEP and radiating particle acceleration

Coronal acceleration and re-acceleration at the CME

IV. Detailed analysis of Fermi behind-the-limb Flares

I. General Remarks
Solar Eruptive Events

Flare Radiative Signatures and SEPs

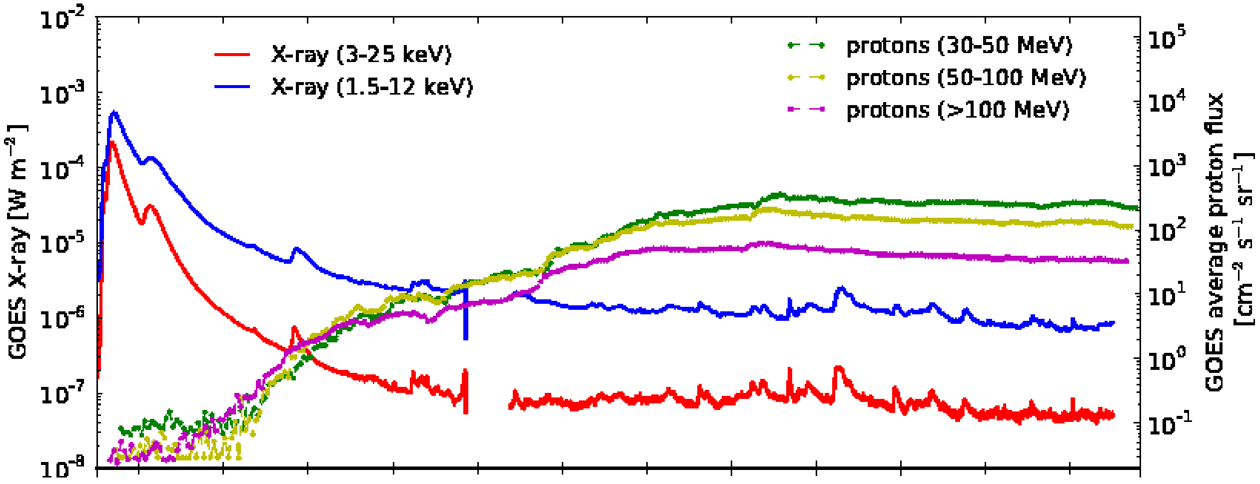
I. General Remarks

Two signatures of particle acceleration;

1. Nonthermal radiation producing particles (**RPPs**) *Focus of solar physics*
2. **SEPs** and CME-shock environment *Focus of heliophysics*

GOES X-rays

And SEP protons



I. General Remarks

Two signatures of particle acceleration;

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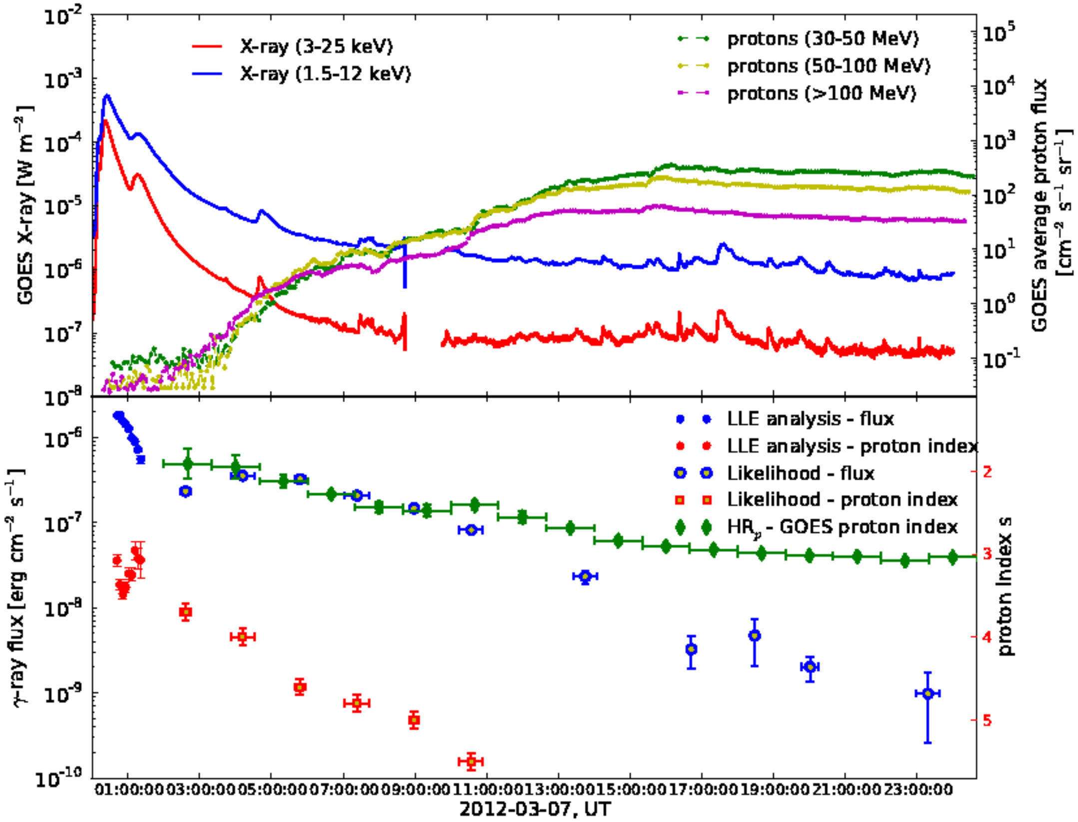
GOES X-rays

SEP protons

Fermi Gamma-rays

SEP proton HR



I. General Remarks

1. Important distinction: *Particles in the acceleration site and in radiating or observing sites* (Accelerated vs Escaping spectra)

A. Closed; no escape

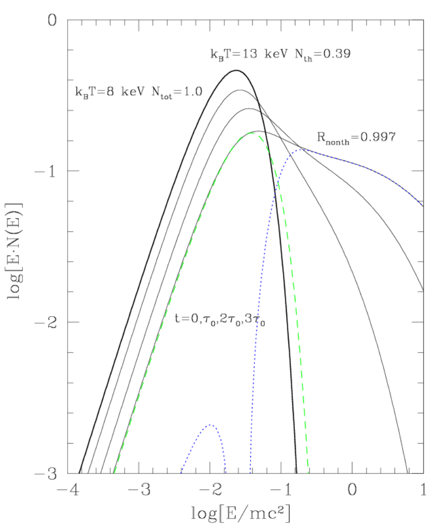
B. Open with escape

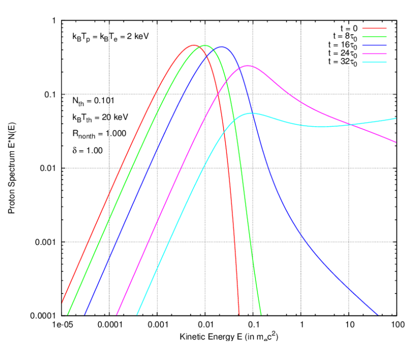
more heating than acceleration

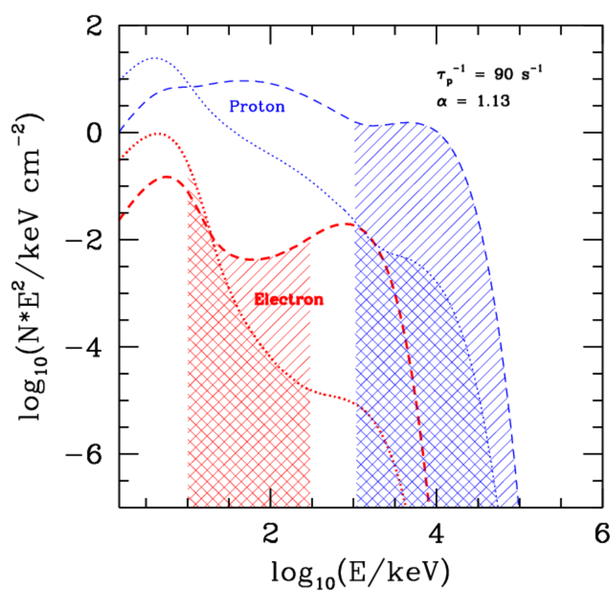
harder escaping spectra

VP, East, ApJ, 2008   Vp, Kang, ApJ, 2015

VP, Liu, ApJ, 2004







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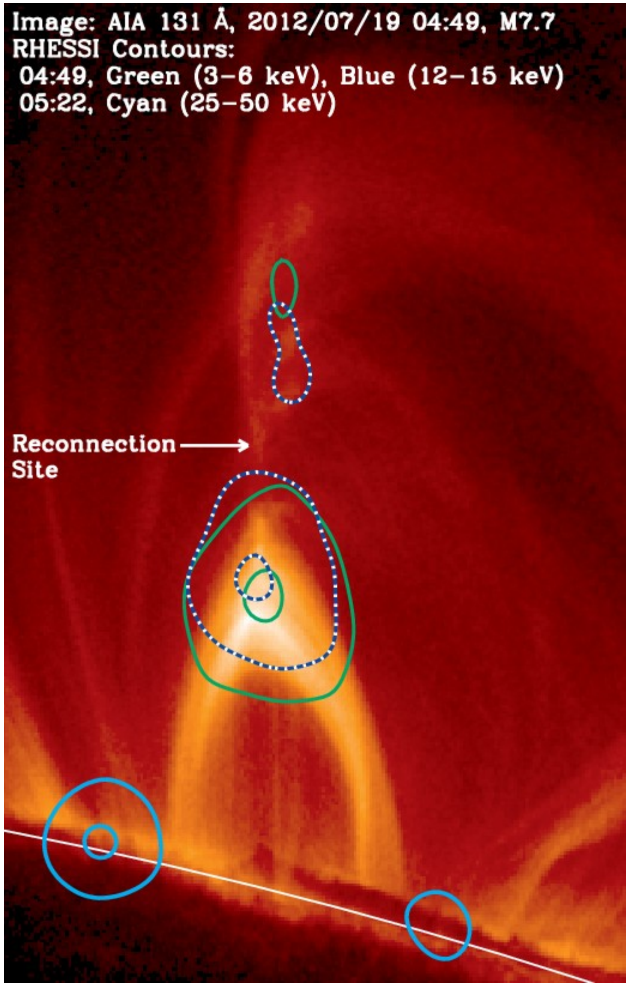
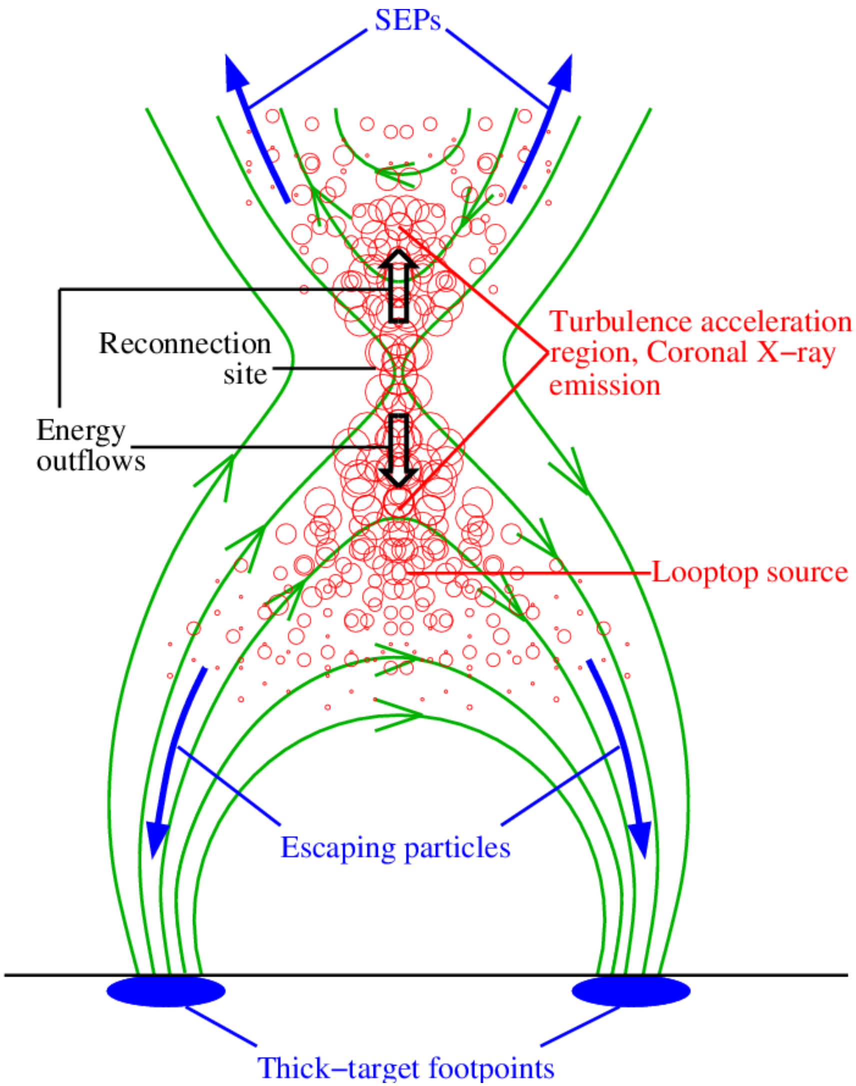
II. RPP and SEP connection

RPPs as seeds in CME acceleration of SEP

Acceleration at the reconnection site and RPPs





Acceleration at the CME-shock and SEPs
Question: Seed particles?

1. Solar wind particles

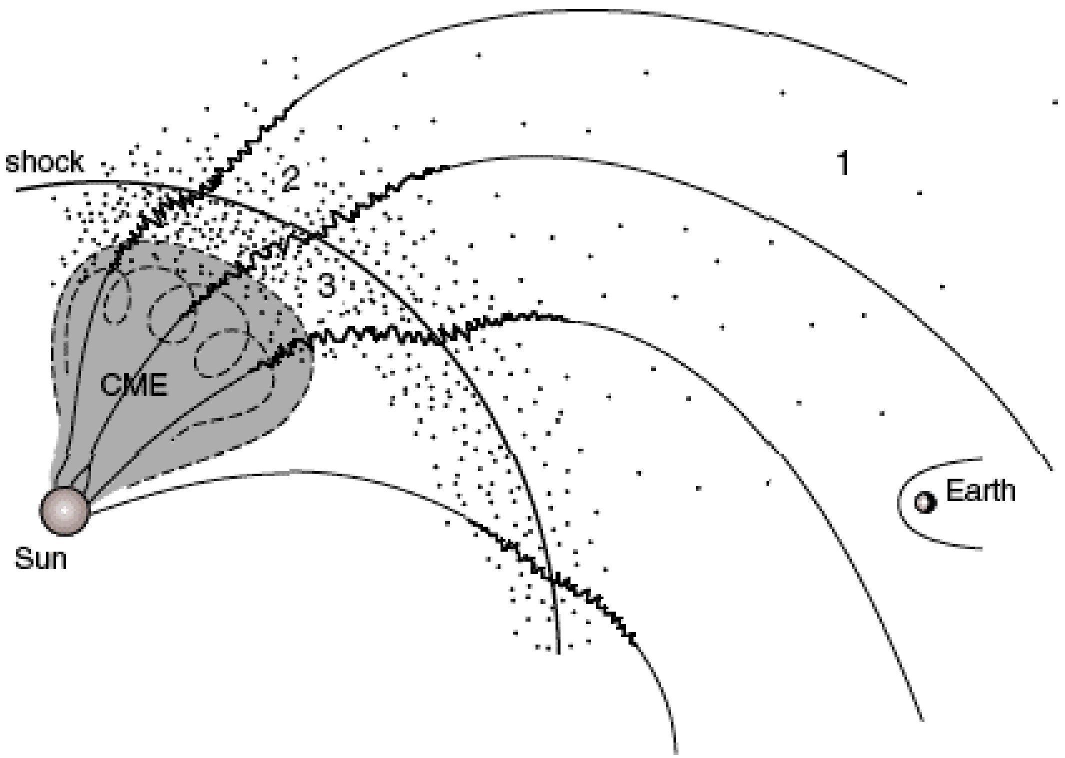
Need non-thermal

Kappa-distribution

2. Accelerated particles

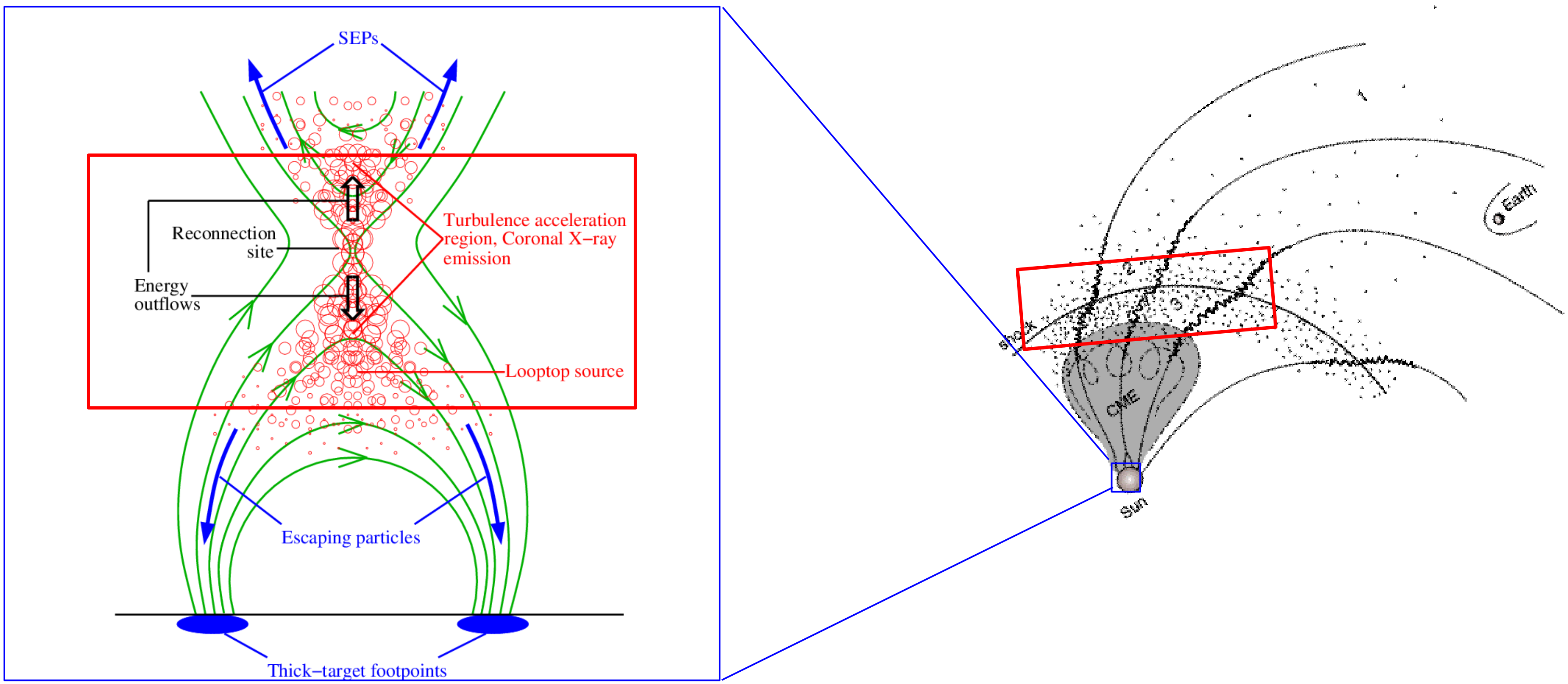
From downstream of

Previous CME



Fermi-LAT and other Observations

Re-acceleration of flare particles in the CME



Acceleration and Transport

Escape time

Leaky box model of the kinetic equation

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

Diffusion Accel. Loss Escape Source

The Escape Times

Up and down reconnection site

From Downstream and upstream of CME-shock

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

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 $T_{\rm esc} \propto \tau_{\rm sc}$

Combined equation (Malyshkin and Kulsrud 2001)

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

Agrees with simulations (points, from Effenberger and Petrosian)

The Escape Times

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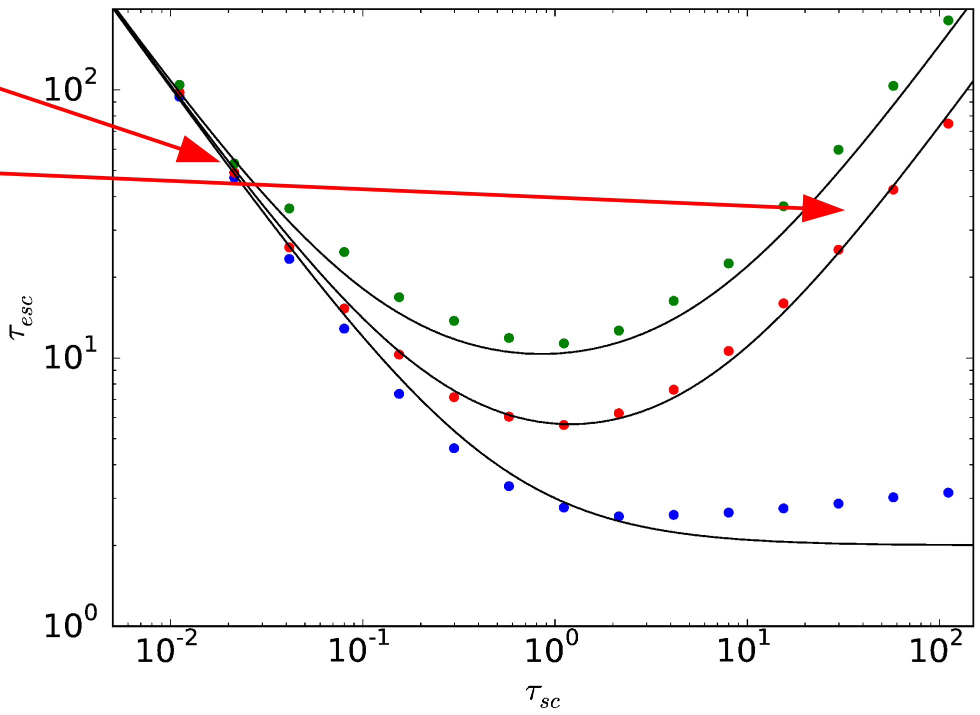
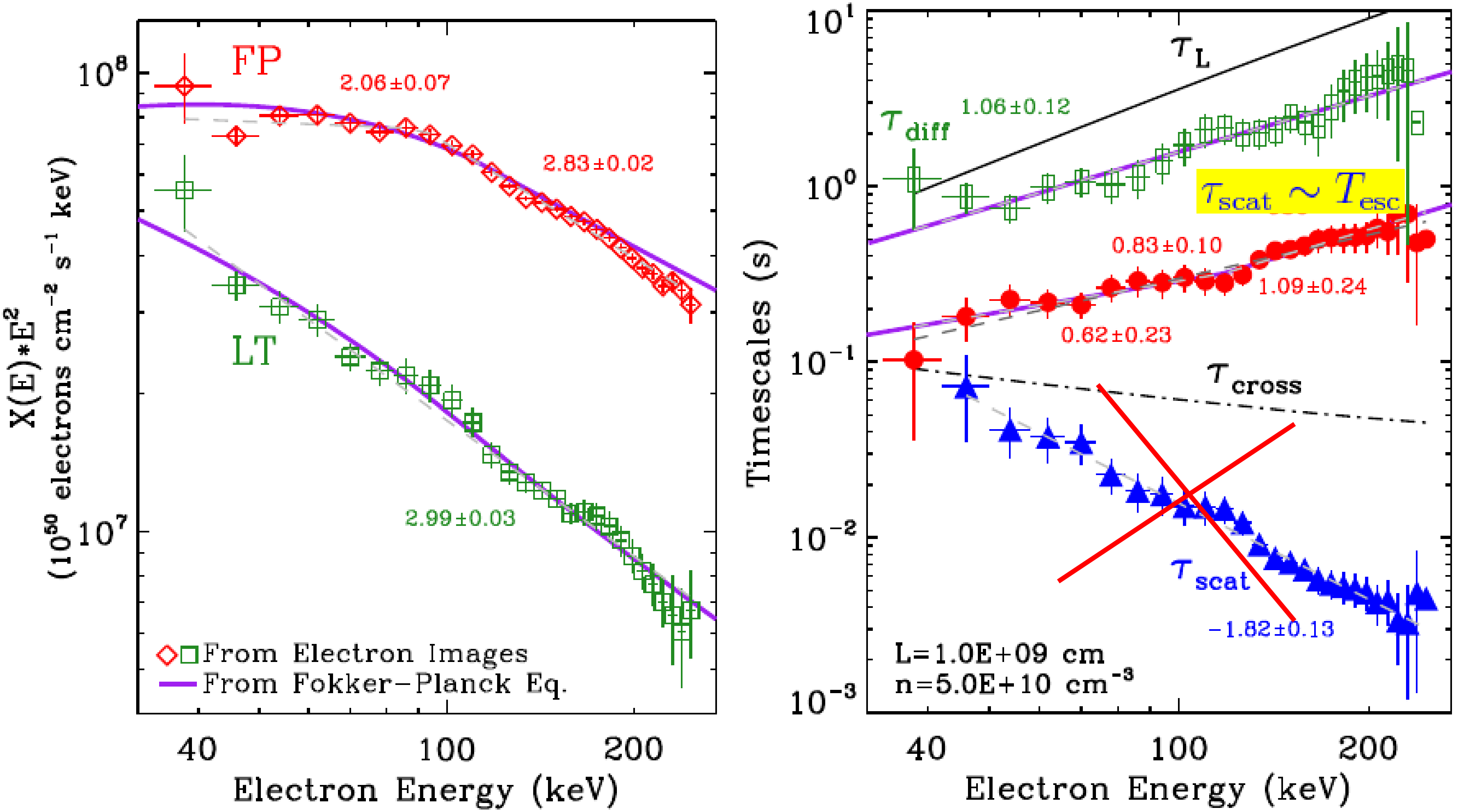
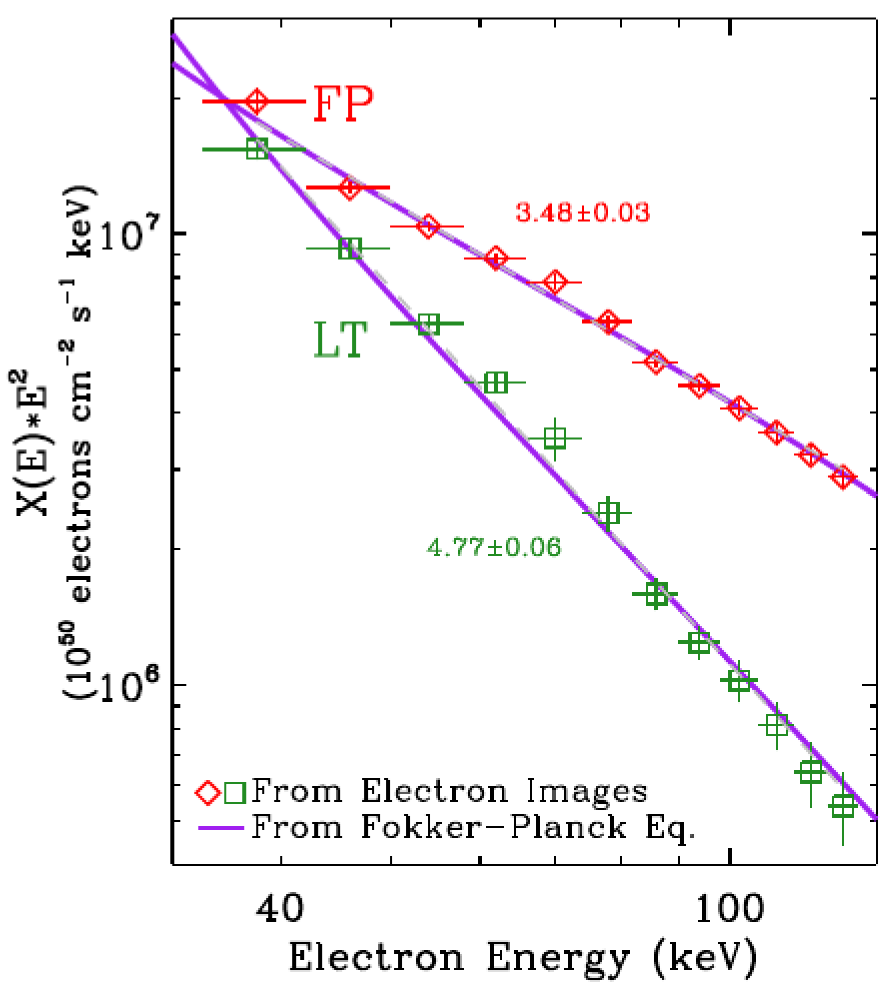


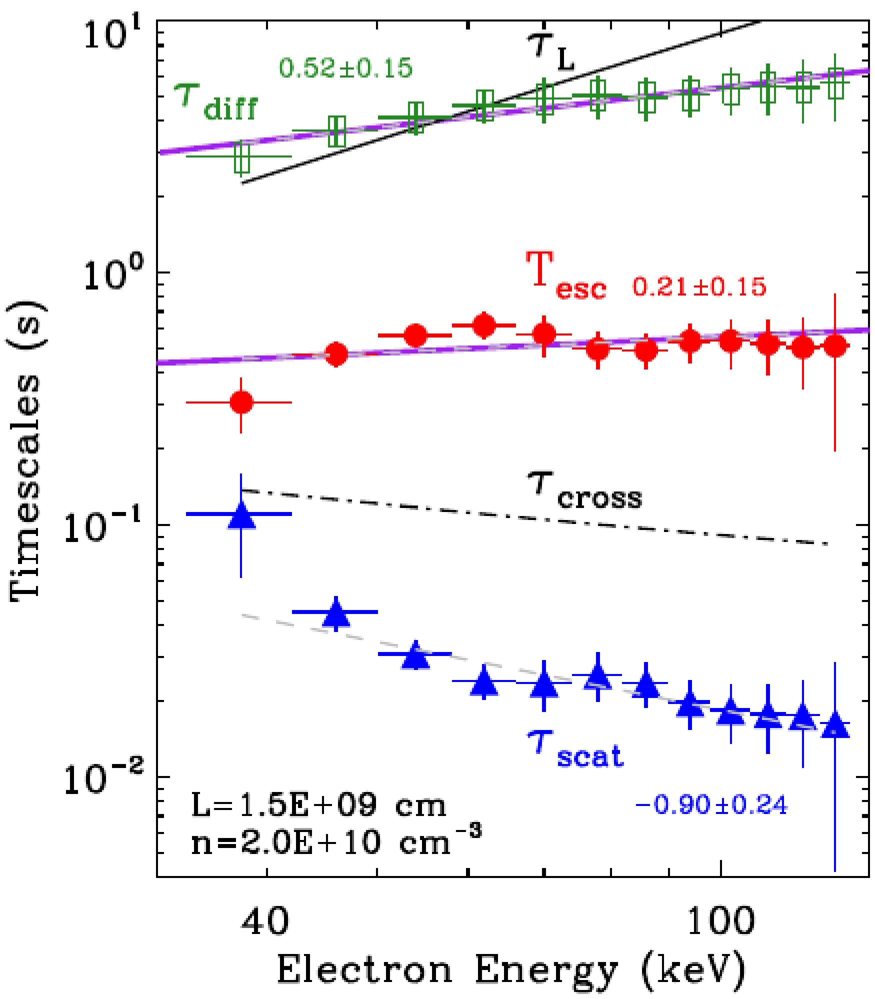
Inversion of RHESSI images

Chen and Petrosian 2013



2005 September 8 Flare M2.1



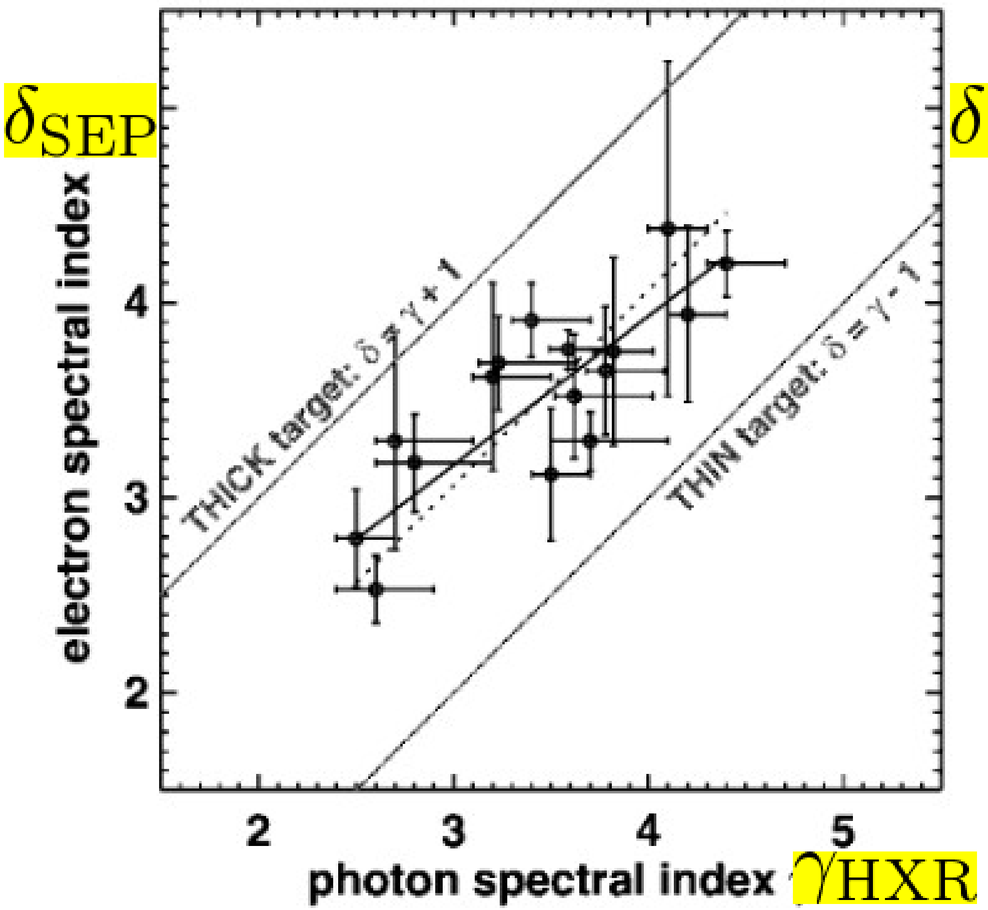


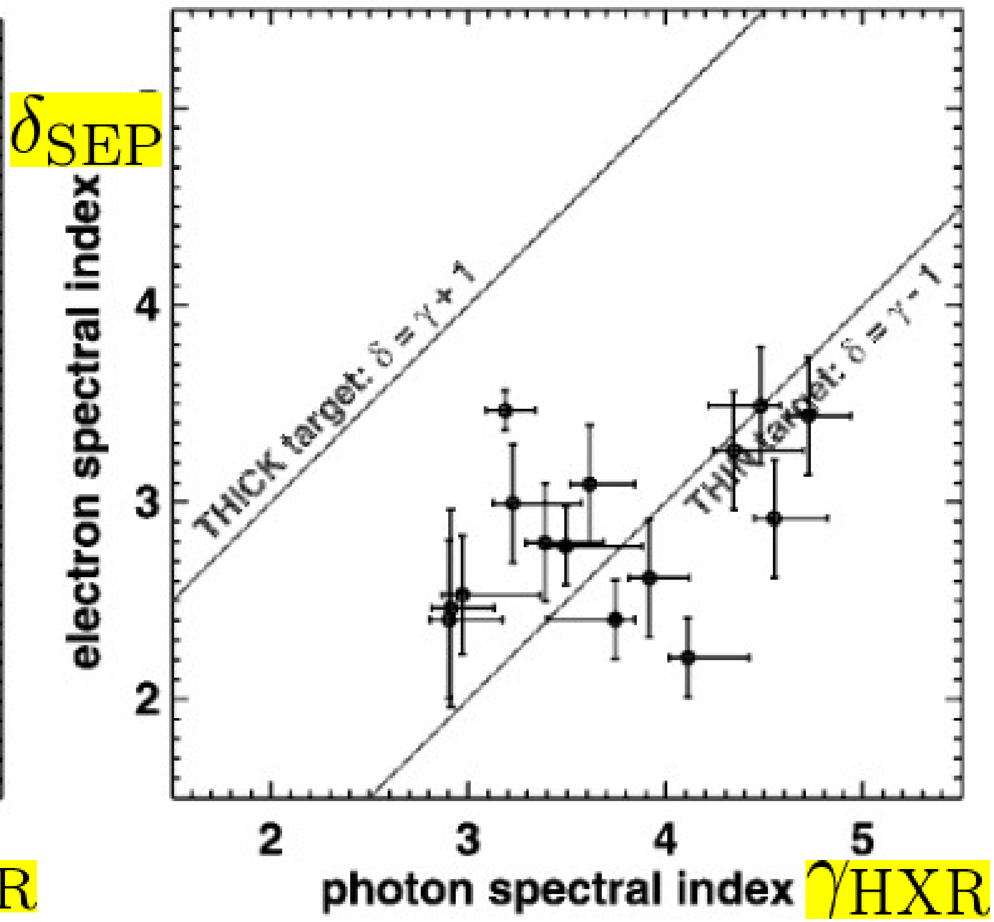
III. Combined Flare and CME Acceleration

RPPs as seeds in CME acceleration of SEP

1. SEP and HXR *Electron* Spectra

“Impulsive; Prompt” OR “Gradual; Delayed” Events





Krucker et al. 2007

Impulsive or Prompt Events

Acceleration by Turbulence at the Flare Site

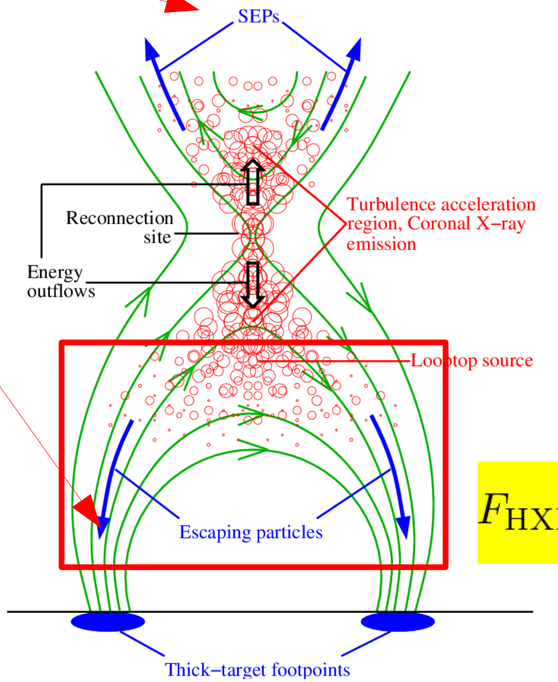
Escape up: SEPs

$$T^u_{\rm esc} \propto E^{\alpha_u}$$

$$F_{\rm SEP}(E) = N(E) E^{-\alpha_u}$$

Escape down: HXRs

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



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

Impulsive or Prompt Events

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

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

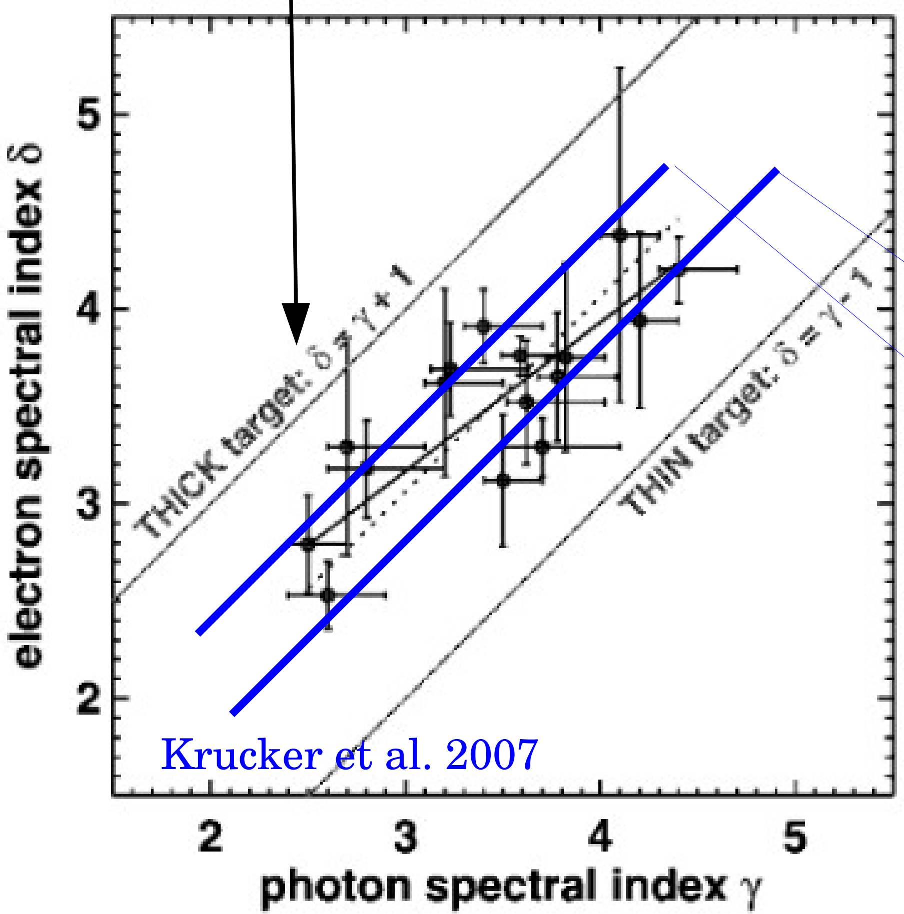
Strong diffusion

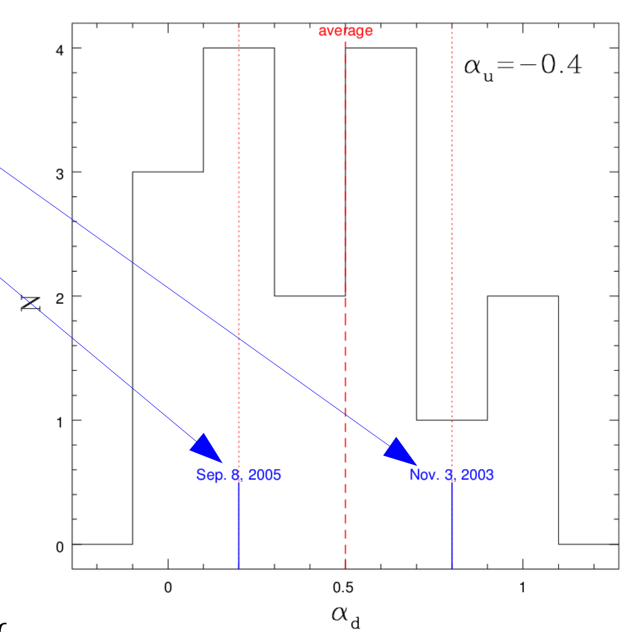
$\alpha_u = \alpha_d$

Weak diffusion

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

$\alpha_u \sim -0.5$, $\alpha_d \sim 0.6$; $\delta_{\mathrm{SEP}} \sim \gamma_{\mathrm{HXR}}$





Gradual or Delayed Events

Re-acceleration at the CME shock

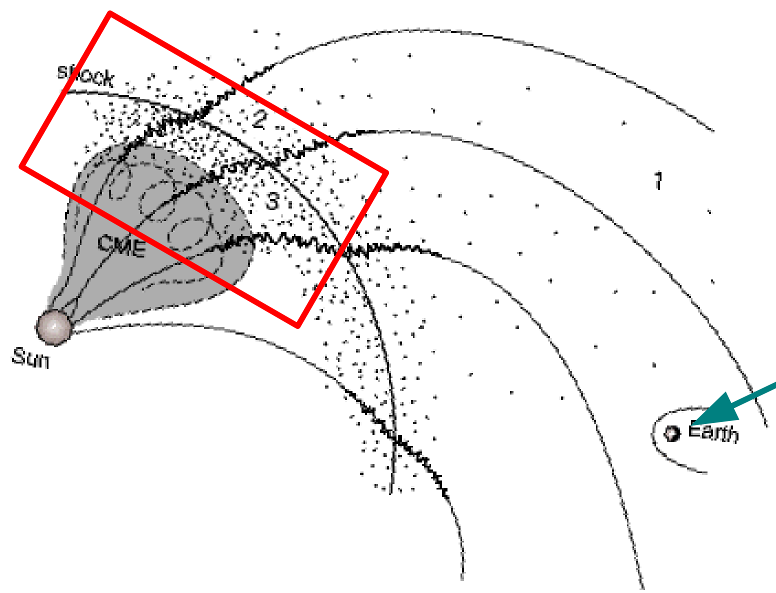
$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial E}\left(D_{EE}\frac{\partial N}{\partial E}\right) - \frac{\partial}{\partial E}[(A - \dot{E}_L)N] - \frac{N}{T_{\rm esc}} + \dot{Q}$$

Diffusion Accel. Loss Escape Source

by Turbulence *by Shock and Turbulence*

Flare Accelerated Particles

Observed SEPs



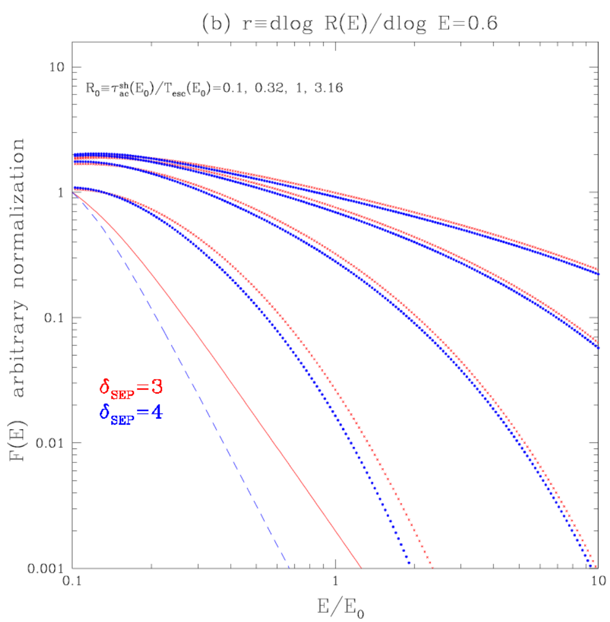
Gradual or Delayed Events

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

$$F(E) = N(E)/T_{\rm esc} = (\tau_{\rm ac}^{\rm sh}/T_{\rm esc}) \int_0^E \dot{Q}\, dE'/E \qquad R(E) \equiv \tau_{\rm ac}^{\rm sh}/T_{\rm esc} = R_0 E^r$$



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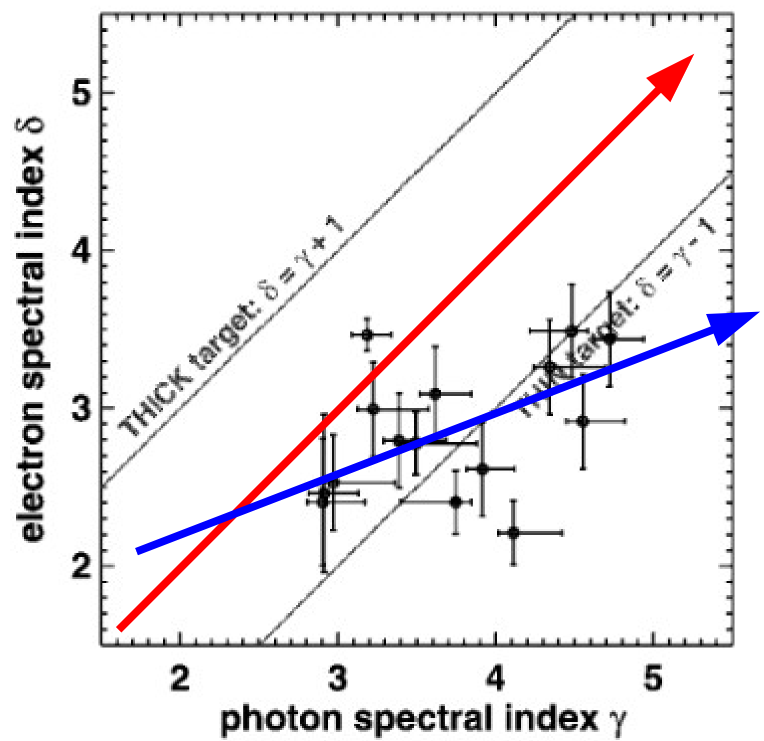
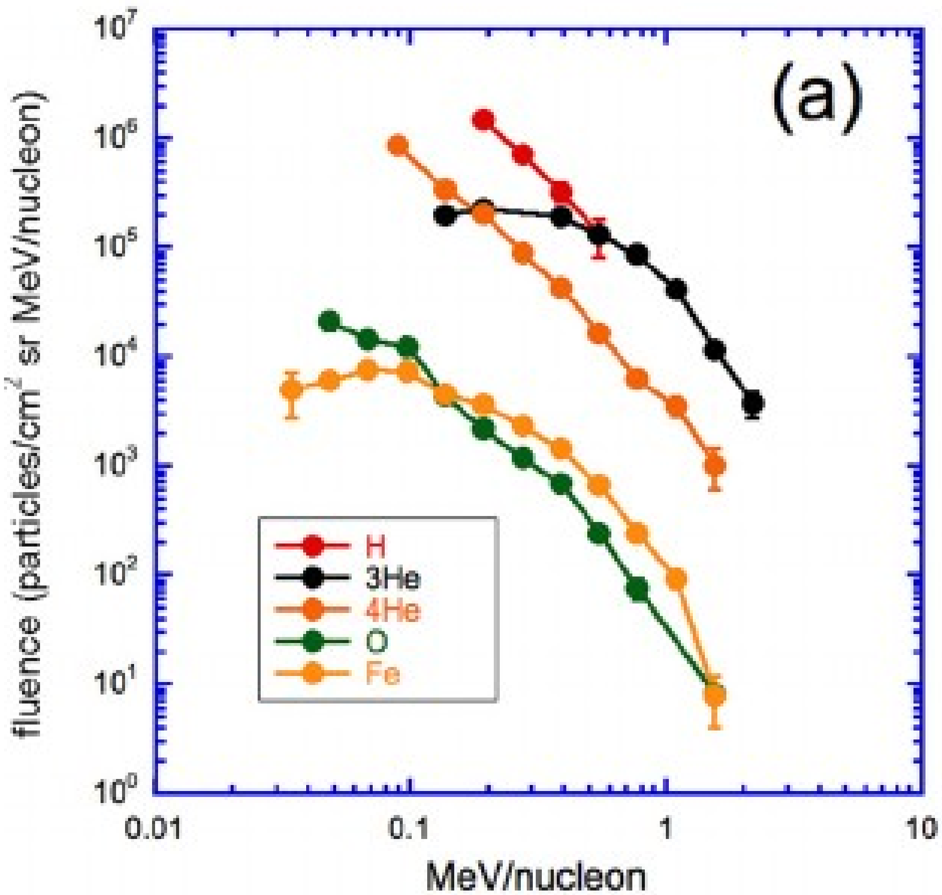
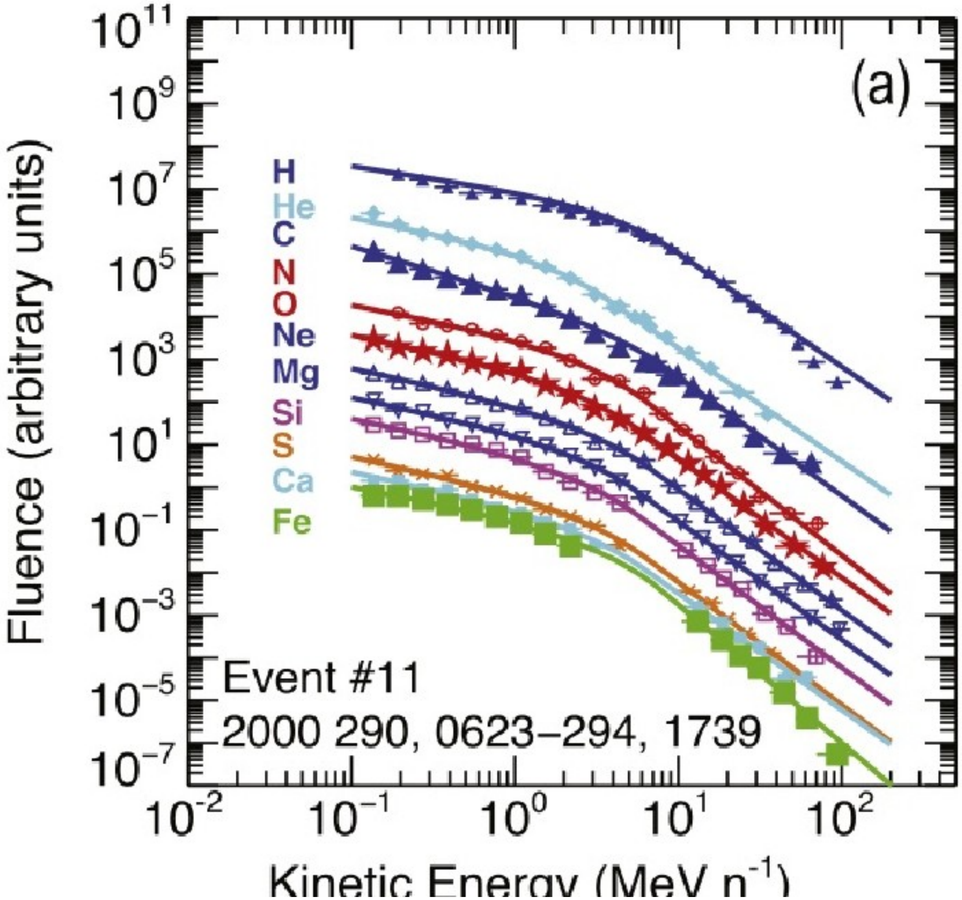


2. SEP-Ion Spectra and 3He Enrichment

"Impulsive" Events Mason et al. 2016

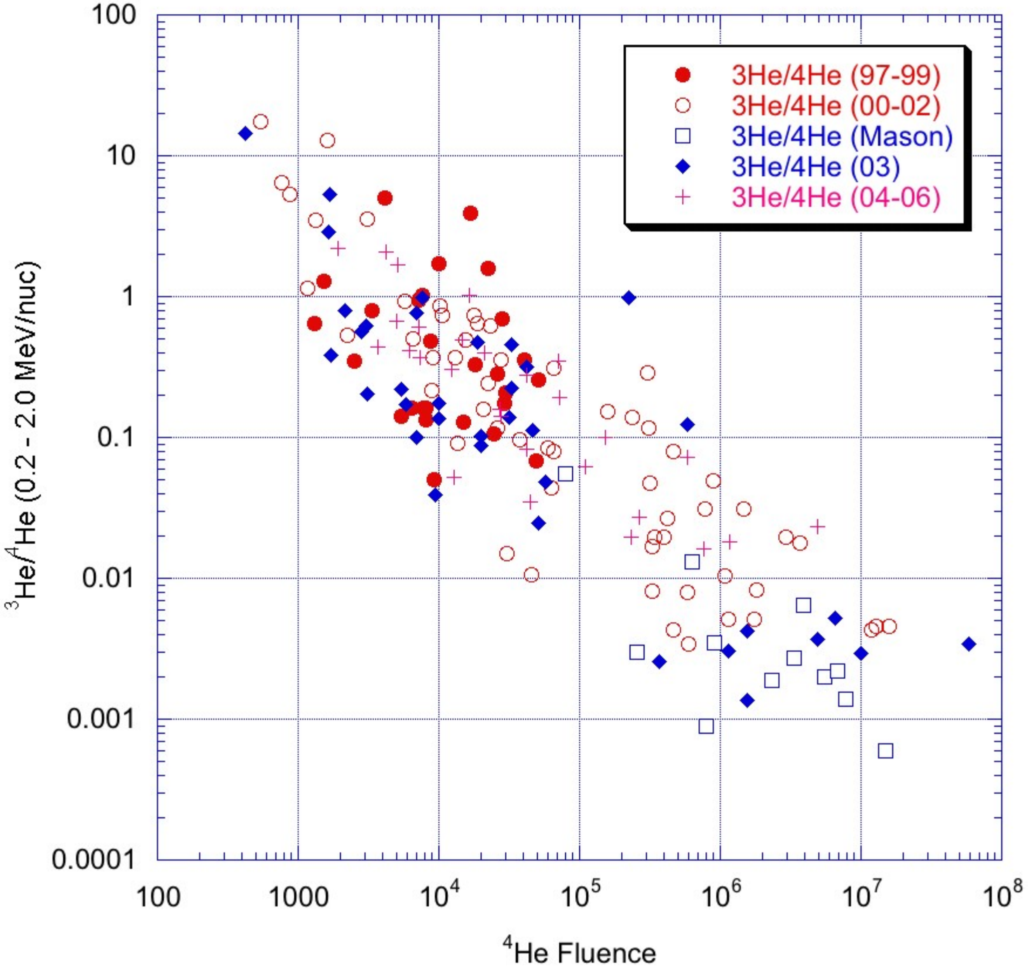


"Gradual" Events Desi t al. 2015

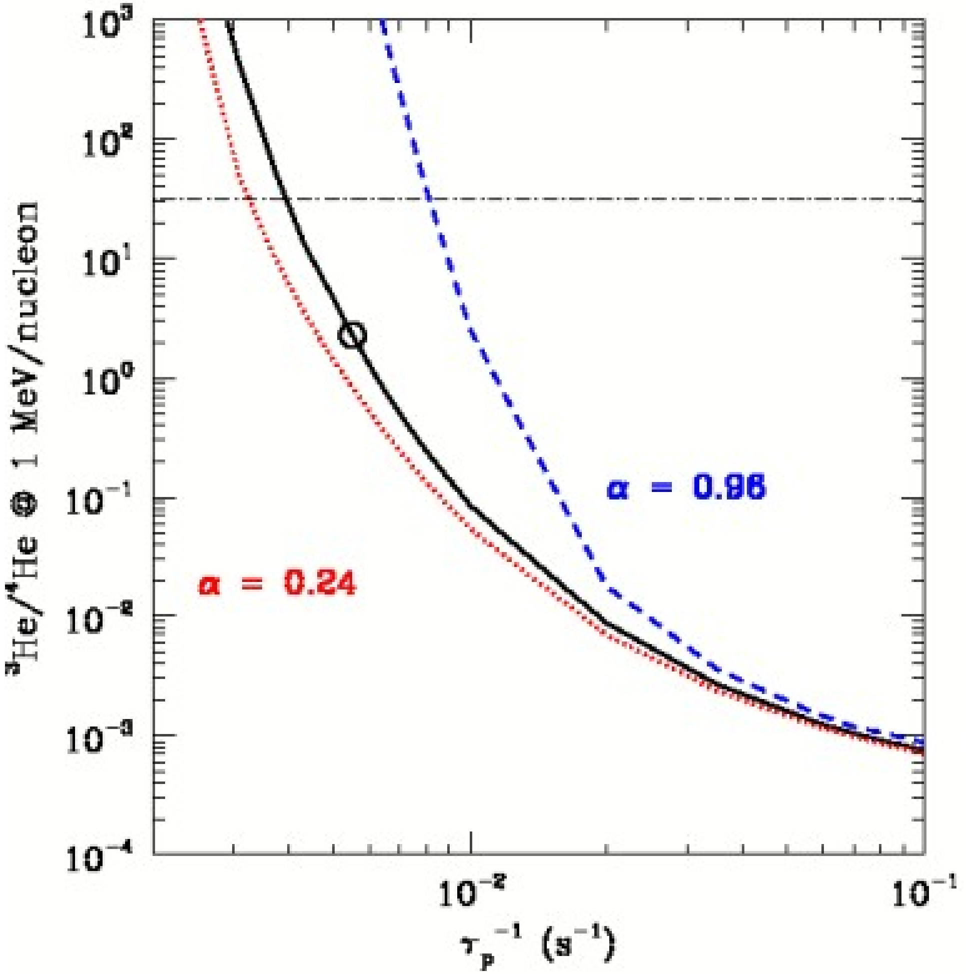


He3, He4 Fluence Ratios

Not bimodal: *gradual variation with acceleration rate*



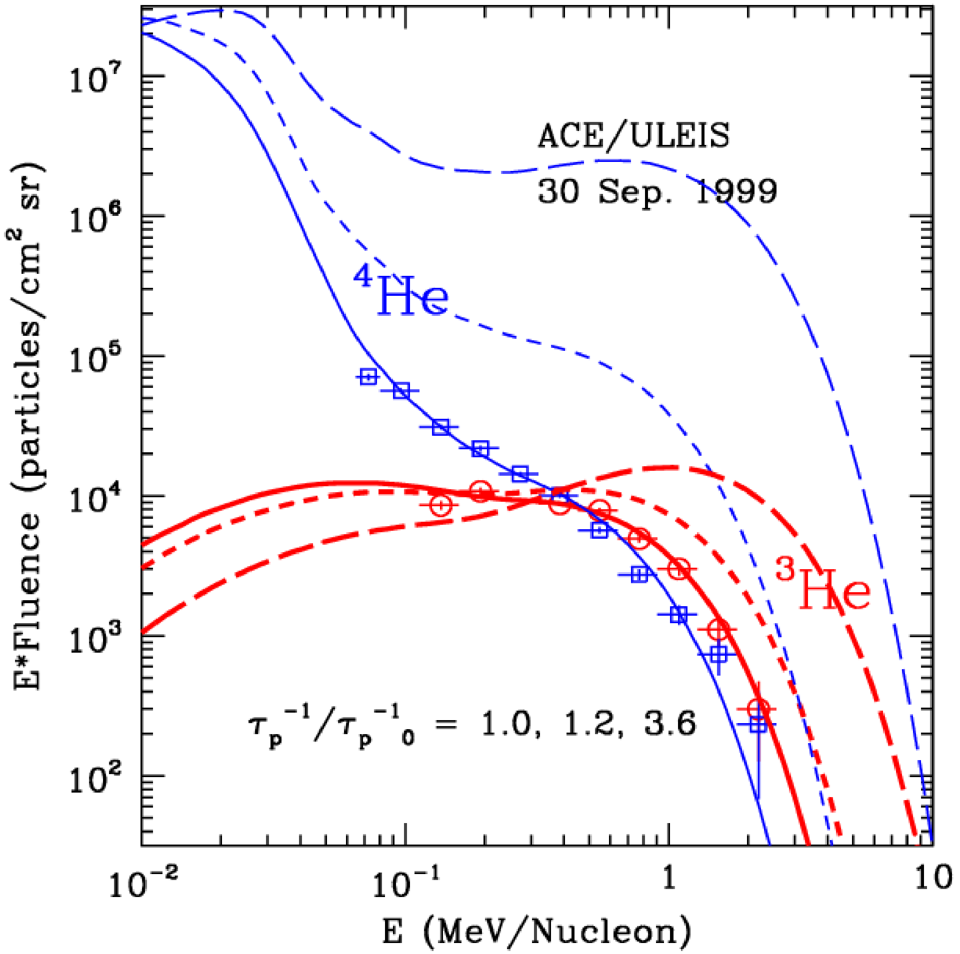
Observations

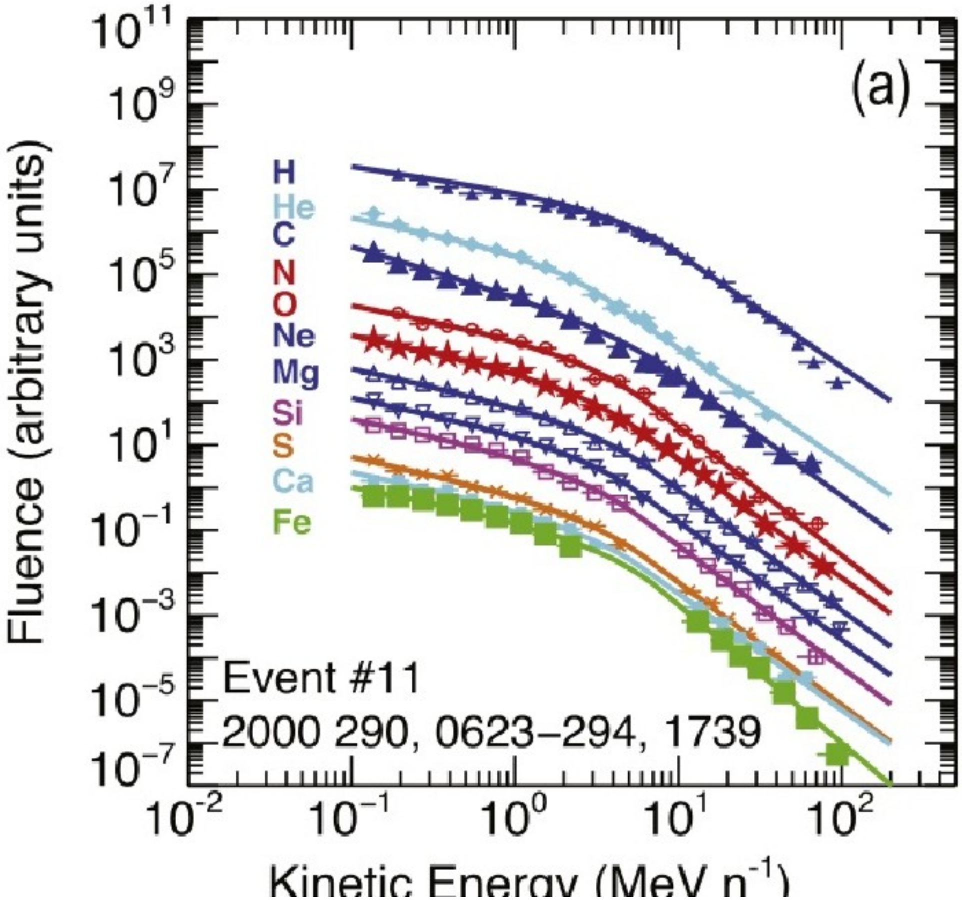


Model Results

Flare accelerated He4 Spectra

Do not agree with observed gradual events

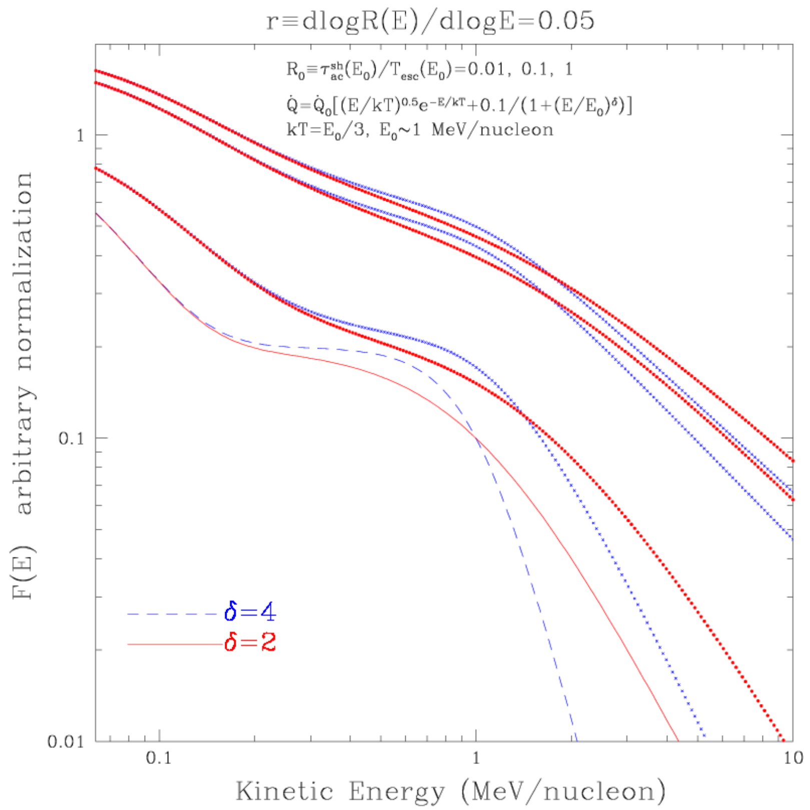


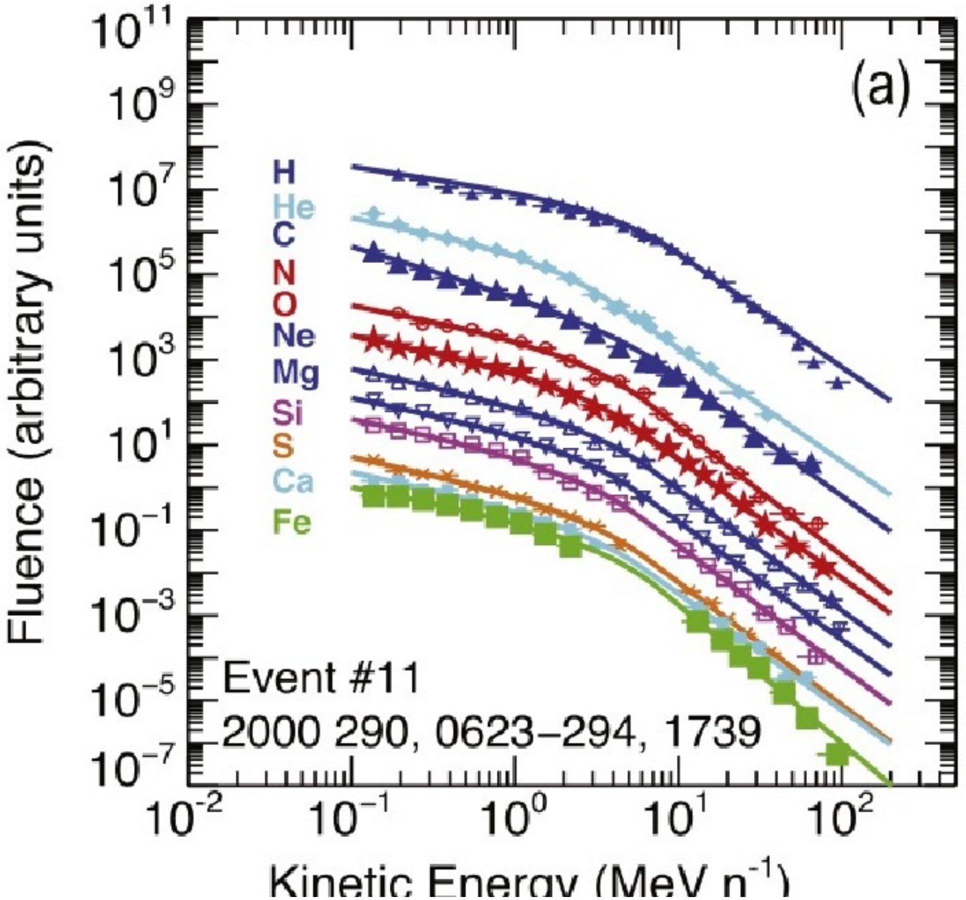


BUT Flare accelerated He4 Spectra

after re-acceleration at the CME-shock agree

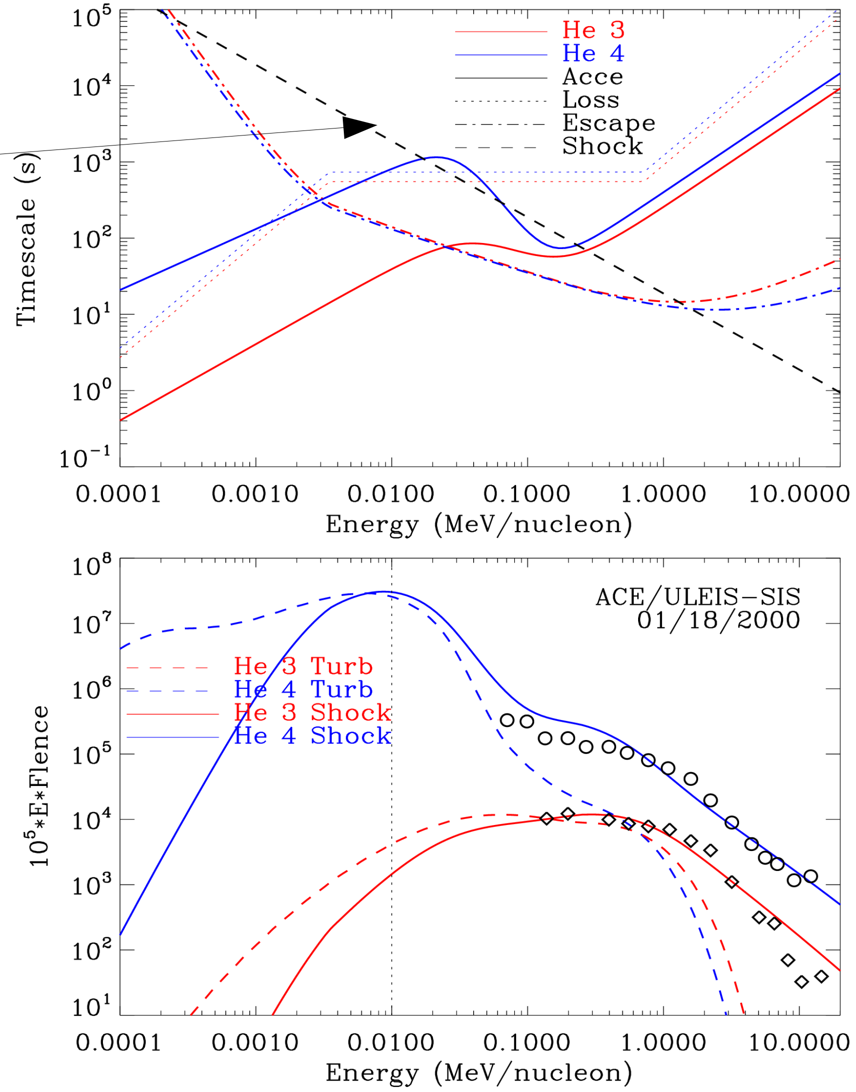
$$F(E) = N(E)/T_{\rm esc} = (\tau_{\rm ac}^{\rm sh}/T_{\rm esc}) \int_0^E \dot{Q} dE'/E$$





Numerical treatment of re-Acceleration

Re-acceleration time



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Summary I

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

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

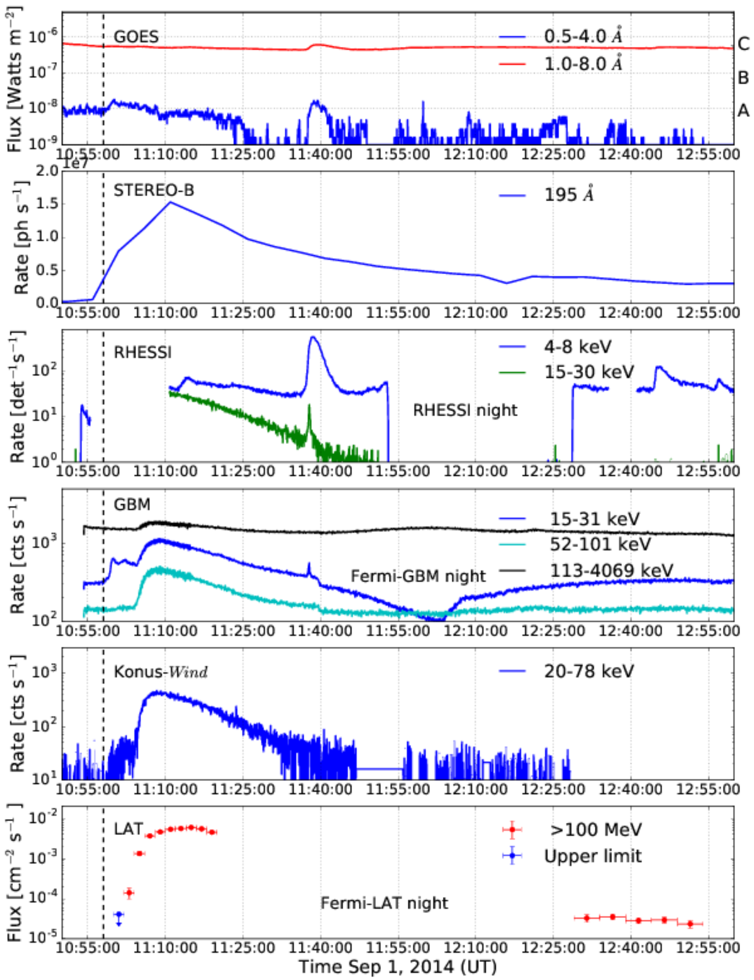
3. Abundances and spectra of 3He and 4He also agree with this scenario.

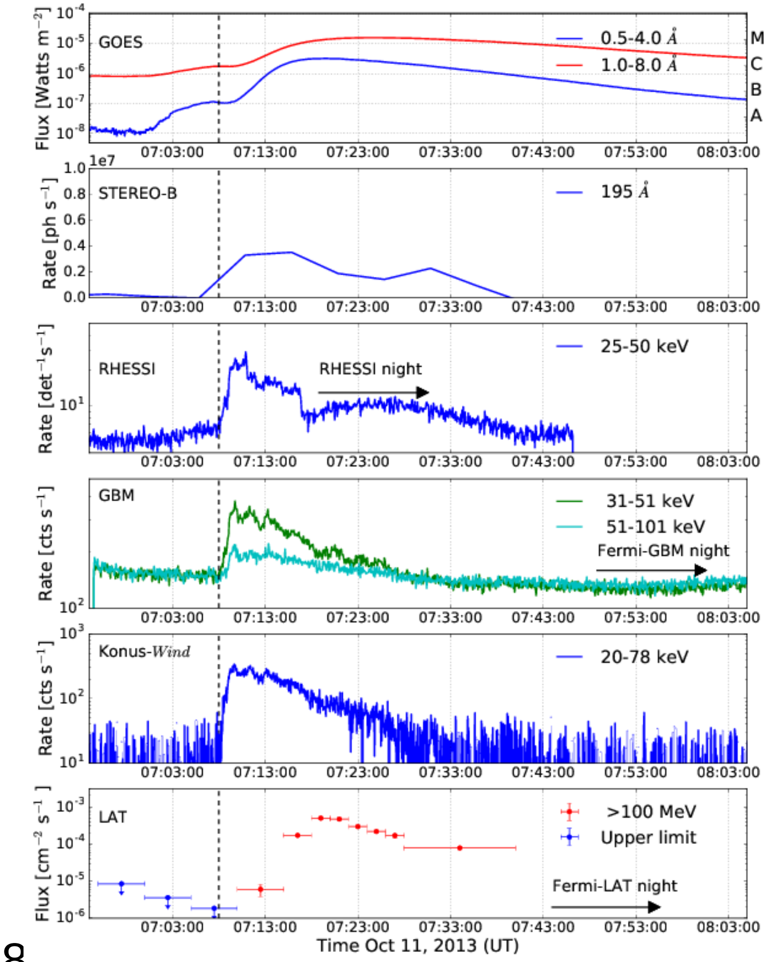
IV. Evidence From Fermi

Spectra, Images and Magnetic Connections

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

1. Light Curves





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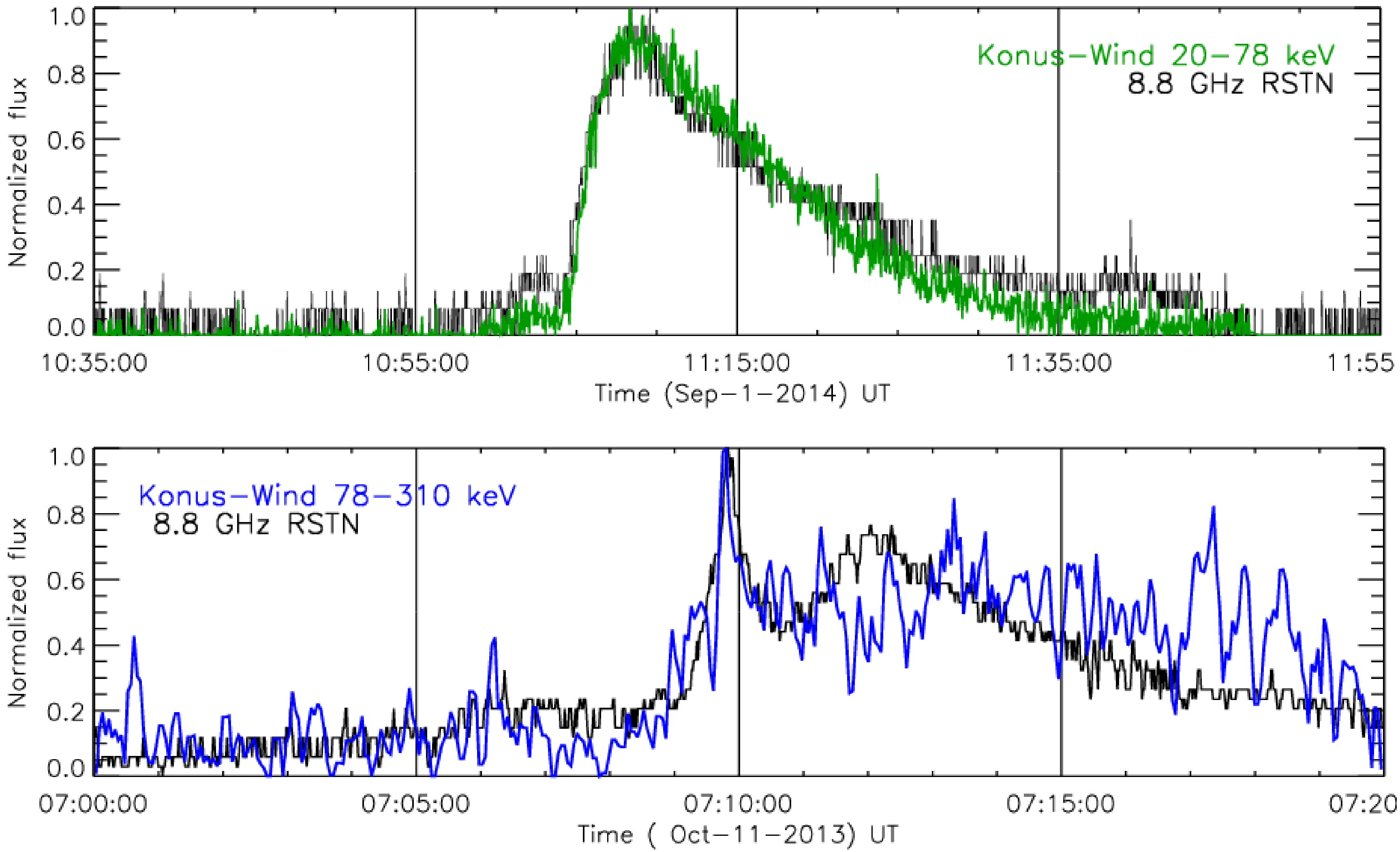
Relevant Observations of
*Sol:*2014-09-01 and *Sol:*2013-10-11

1. Radio-Xray Light Curves

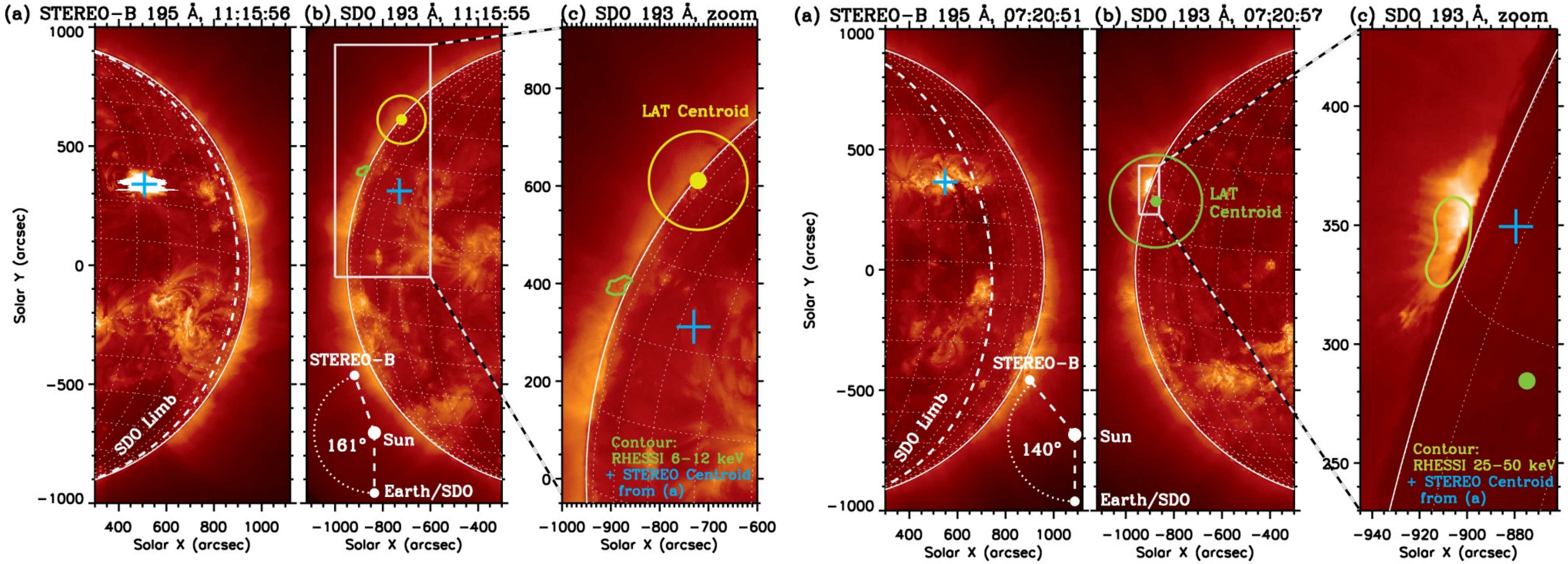


Relevant Observations of
*Sol:*2014-09-01 and *Sol:*2013-10-11

2. Images

Size 56”x30”; Sep. 270” — Height 200 Mm

Size 38”x16”; Sep. 65” — Height 15 Mm



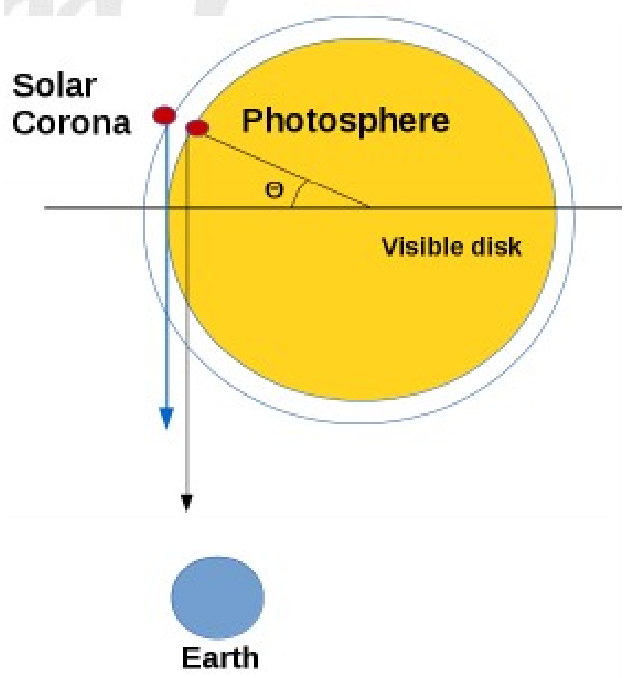
Behind The Limb Flares

Trap-pompt vs continuous accelertaion

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

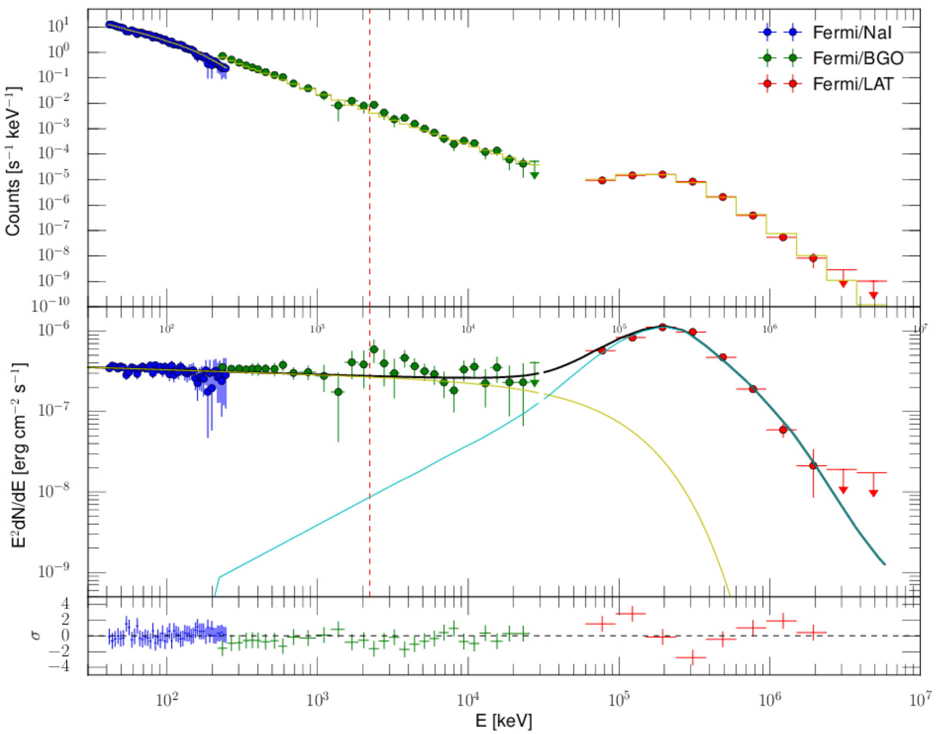
Need Prompt injection $\dot{Q}(E,t) = Q_o(E/Ep)^{-p_0}\delta(t - t_0)$

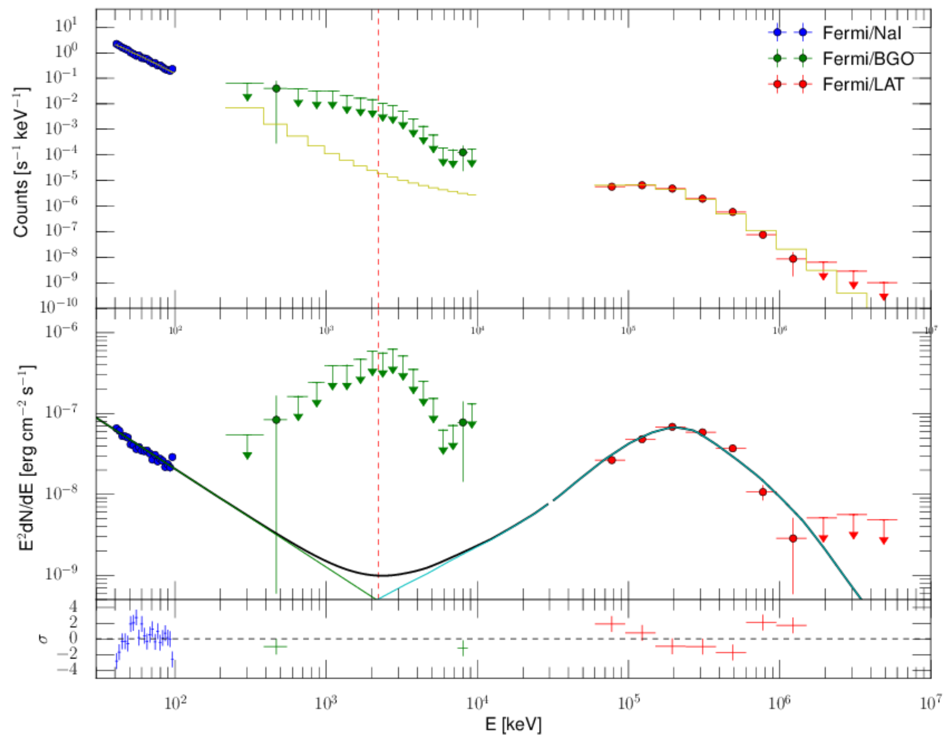
Energy loss rate $\dot{E} = -(E_p/\tau_0)[(1 + (E/E_n)^{\delta}]$



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

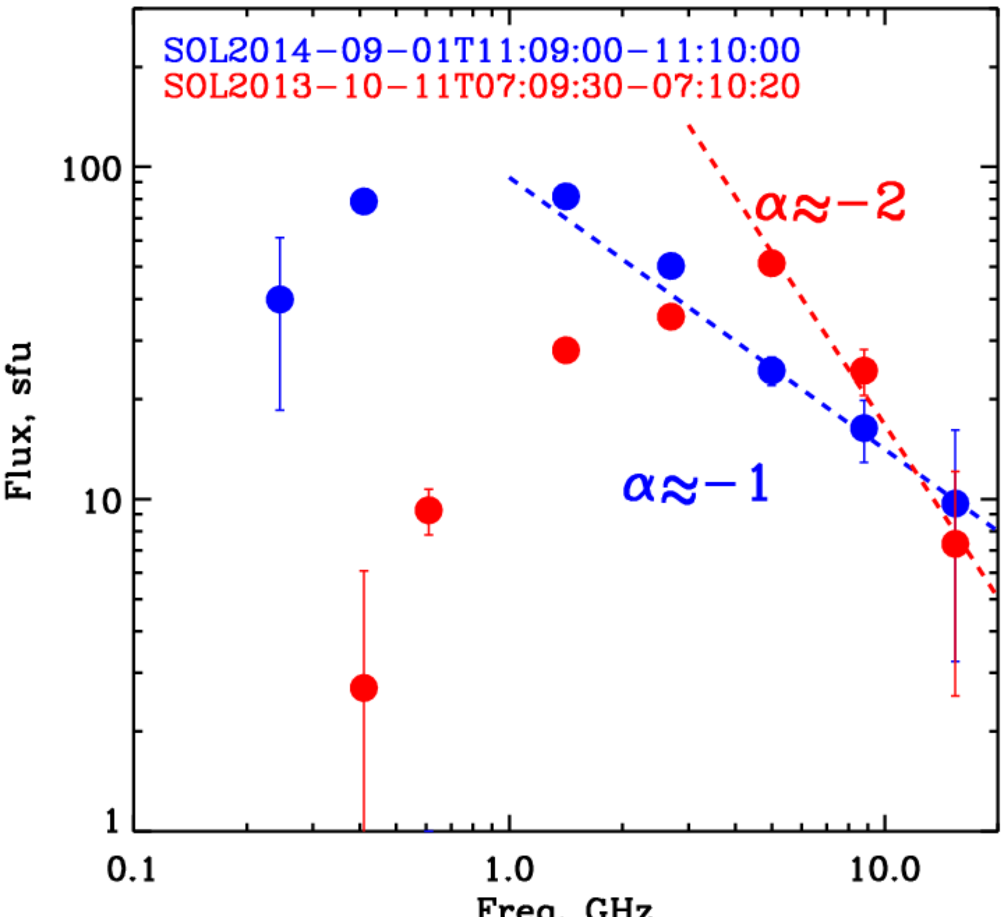
3. X- and Gamma-ray Spectra



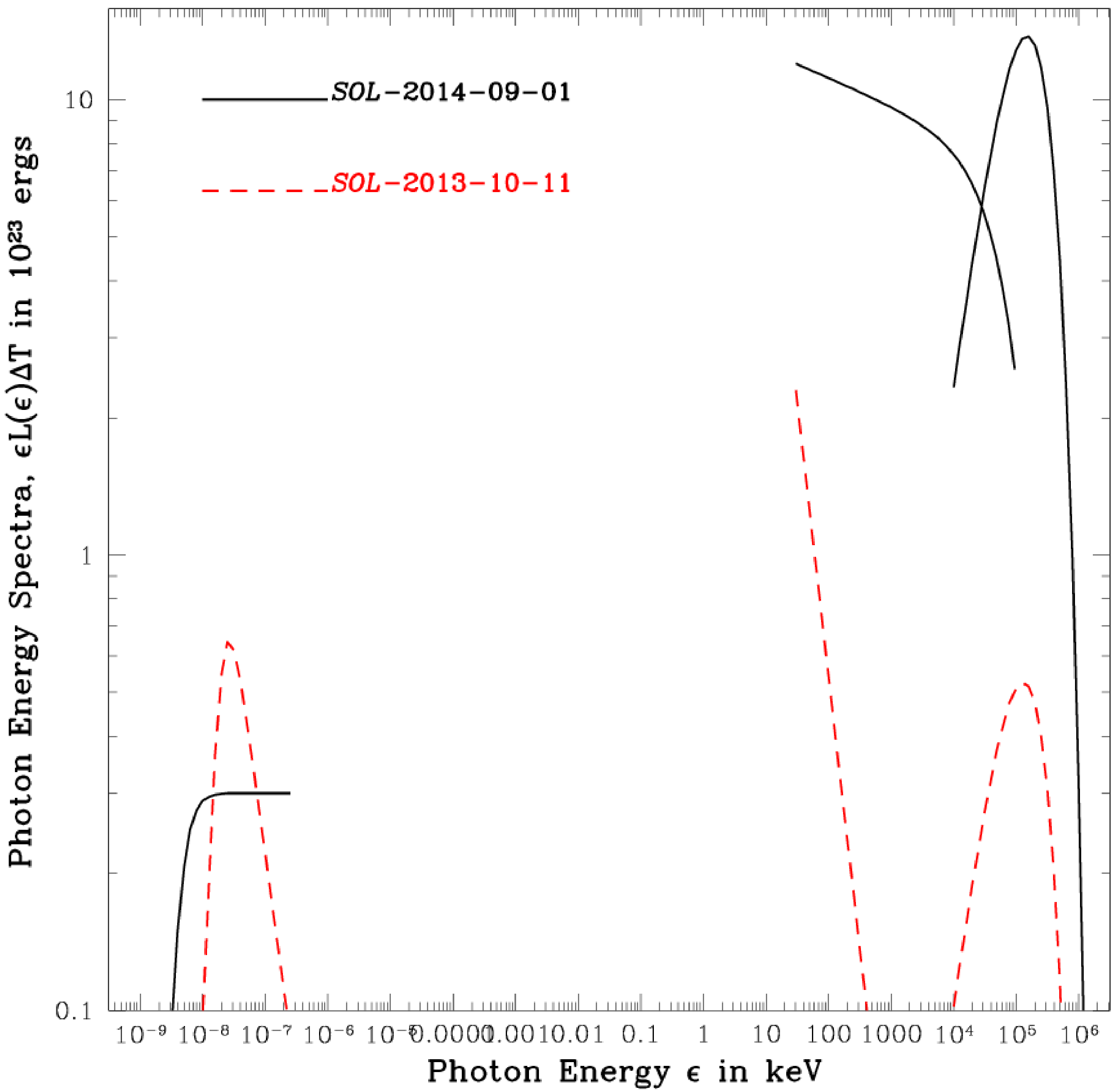


Relevant Observations of
*Sol:*2014-09-01 and *Sol:*2013-10-11

4. Radio: Self absorbed(?) synchrotron spectra?



Composite Energy Luminosities



II. Some Details

Two interpretation:

a. Acceleration in situ in the source; spectrum *N(E,t)*

Then the flux out of the loop top to footpoints is

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

b. Accelerated particles injected into the source. Then

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

Time integrated relation

$$N(E) = Q(E)T_{\rm esc}(E); \quad Q(E) = \int_{\Delta T} \dot{Q}(E,t)dt$$

II. Two Important Considerations

1. Trans-relativistic Effects

Changes in the relation between Velocity, Momentum, Kinetic Energy

$$E = \sqrt{p^2 + 1} - 1; \quad \beta = v/c = p/(E+1)$$

e. g. Power-law Spectra $N(E) \propto E^{-\delta} \quad \rightarrow \quad N(p) \propto [E(p)]^{-\delta} dp/dE$

Broken Power-law $N_{\rm nr}(p) \propto p^{-2\delta+1}, \quad N_{\rm er}(p) \propto p^{-\delta}$

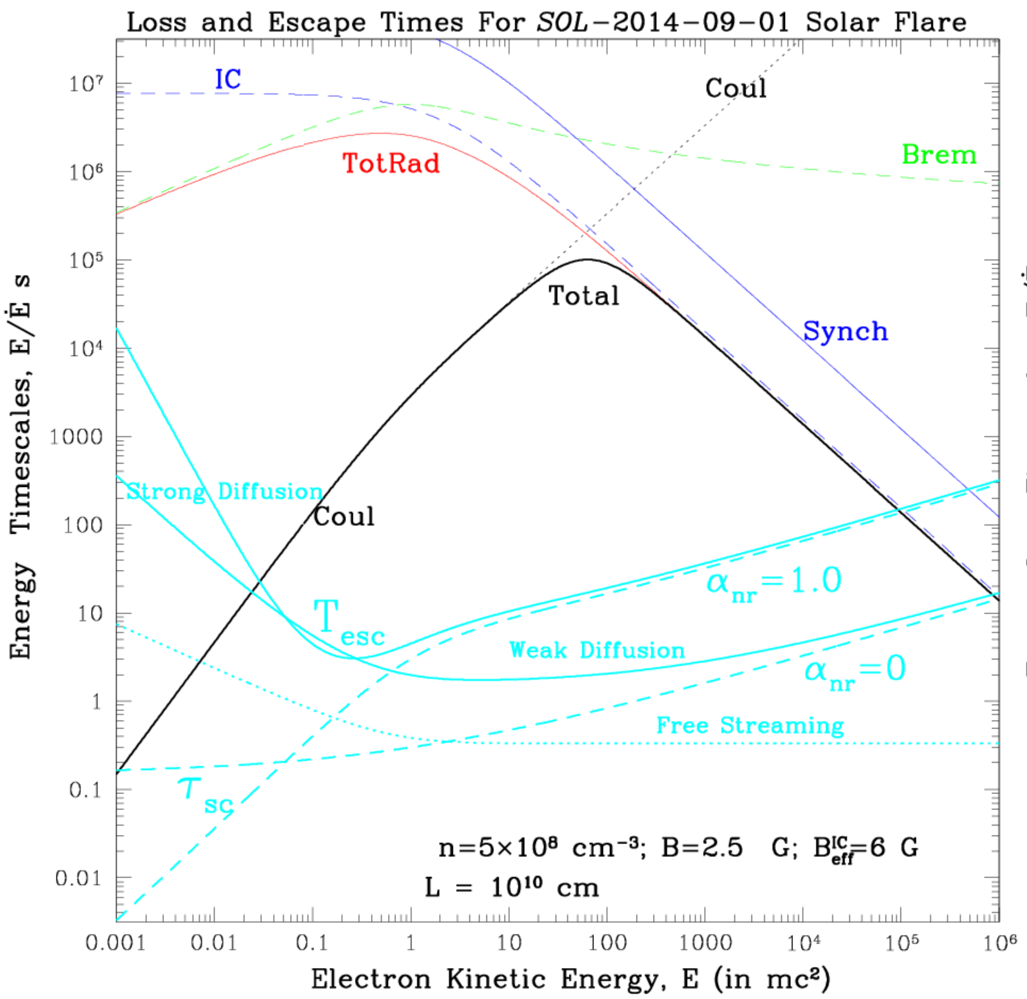
2. "Escape time" and its energy dependence

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

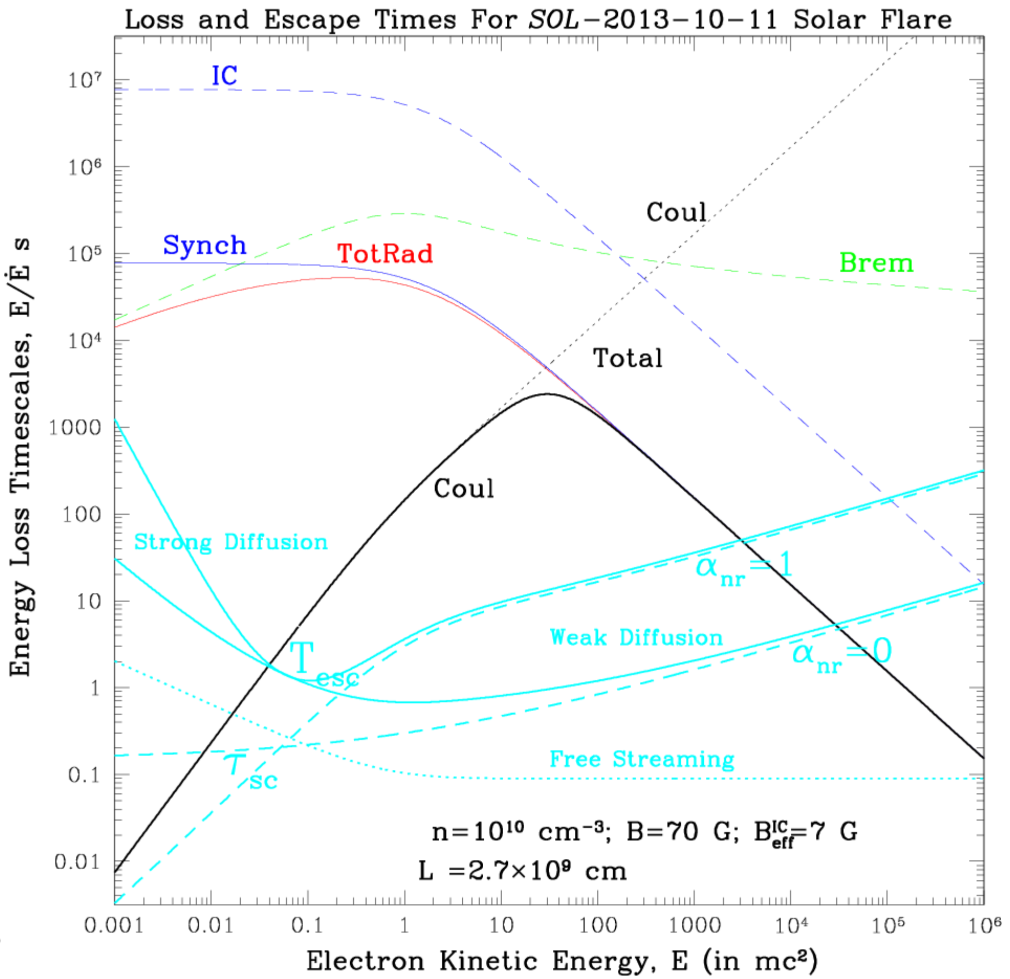
Loss vs Escape Time

Are the emissions Thin Target?

Sept. 2014



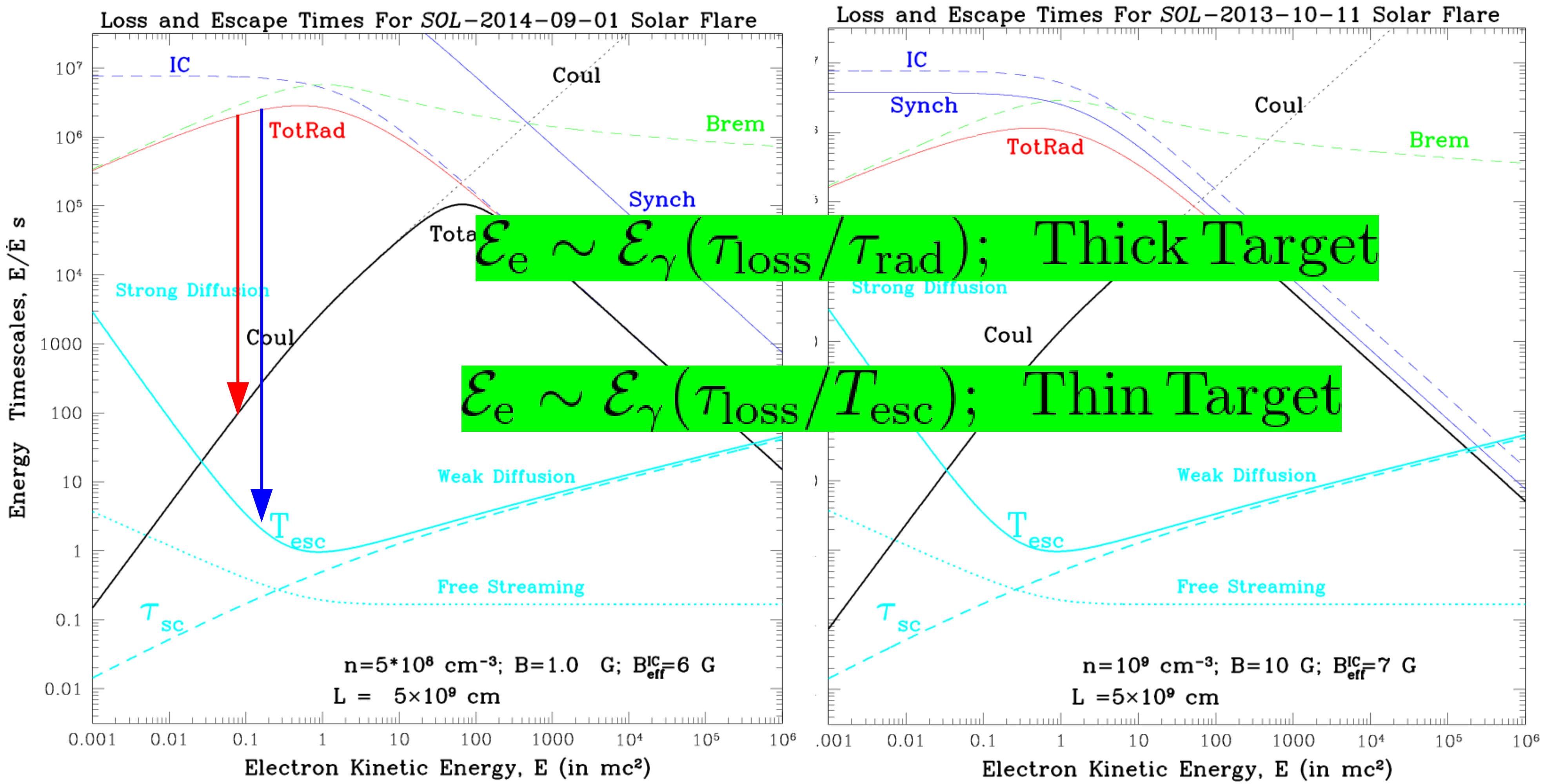
Oct. 2013



Loss vs Escape Time

Are the emissions Thin Target?

Sept. 2014 Oct. 2013



$$\mathcal{E}_e \sim \mathcal{E}_\gamma(\tau_{loss}/\tau_{rad}); \quad \text{Thick Target}$$

$$\mathcal{E}_e \sim \mathcal{E}_\gamma(\tau_{loss}/T_{esc}); \quad \text{Thin Target}$$

III. Analysis of Radio Data

Assume Self-absorption?!

Synchrotron emissivity, absorption and surface brightness

$$J(\nu) = N_0 \alpha a(\delta) \left(\frac{h\nu_B}{m_e c^2}\right) \left(\frac{\nu}{\nu_B}\right)^{(1-\delta)/2}$$

$$\kappa_\nu = \frac{d\tau_\nu}{dl} = N_0 \alpha b(\delta) \left(\frac{h\nu_B}{m_e c^2}\right) \left(\frac{c}{\nu}\right)^2 \left(\frac{\nu}{\nu_B}\right)^{-\delta/2}$$

$$S(\nu) = J(\nu)/\kappa_\nu = c(\delta)(\nu_B/c)^2(\nu/\nu_B)^{5/2} = F_0(\nu/\nu_B)^{5/2}$$

$$F(\nu) = S(\nu) g(\tau_\nu) \Delta\Omega$$

$$g(\tau_\nu) = \tau_0(1 - e^{-\tau_\nu})$$

$$\tau(\nu) = \tau_0 \times (\nu/\nu_b)^{-(p+4)/2}$$

$$g(\tau_\nu) = \tau_0(1 - 2/\tau_\nu + 2(1 - e^{-\tau_\nu})/\tau_\nu^2$$

$$B \propto F_p^{-2} \nu_p^5 (\Delta\Omega/4\pi)^2 (c(\delta) f(\tau_p))^2$$

III. Analysis of Radio Data
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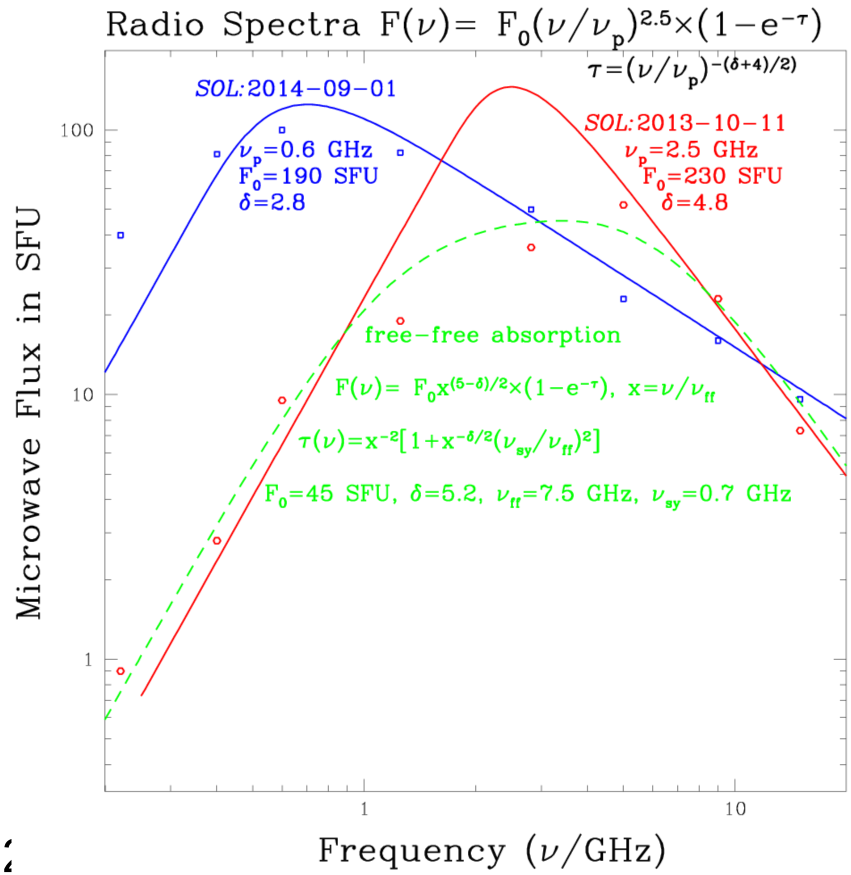
Synchrotron emissivity, absorption and surface brightness

$$F(\nu) = S(\nu) g(\tau_\nu) \Delta\Omega$$

$$B \propto F_p^{-2} \nu_p^5 (\Delta\Omega/4\pi)^2 (c(\delta) f(\tau_p))^2$$

Sept14 B~2.5 G

Oct13 B~100 G



Analysis of Hard X-ray Data

Bremsstrahlung emissivity $\epsilon^2\eta_(\epsilon) = \tau_{\rm brem}^{-1}\epsilon\int_{\epsilon}^{\infty}\beta(E)Q(E)T_{\rm esc}(E)f(\epsilon,E)dE$

Formula 3BN—Differential in photon energy.
Approximations (H), (B). Reference formulas: (15) in reference (a), (16) in reference (c), (17) in reference (d), (37) in reference (e).

$$d\sigma_k=\frac{Z^2r_0^2}{137}\frac{dk}{k}\frac{p}{p_0}\left\{\frac{4}{3}-2E_0E\left(\frac{p^2+p_0^2}{p^2p_0^2}\right)+\frac{\epsilon_0E}{p_0^3}+\frac{\epsilon E_0}{p^3}-\frac{\epsilon\epsilon_0}{p_0p}+L\left[\frac{8E_0E}{3p_0p}+\frac{k^2(E_0^2E^2+p_0^2p^2)}{p_0^3p^3}+\frac{k}{2p_0p}\left(\left(\frac{E_0E+p_0^2}{p_0^3}\right)\epsilon_0-\left(\frac{E_0E+p^2}{p^3}\right)\epsilon+\frac{2kE_0E}{p^2p_0^2}\right)\right]\right\},$$

where

$$L=2\ln\left[\frac{E_0E+p_0p-1}{k}\right];\quad \epsilon_0=\ln\left(\frac{E_0+p_0}{E_0-p_0}\right);\quad \epsilon=\ln\left(\frac{E+p}{E-p}\right).$$

Formula 3BN(a)—Differential in photon energy.
Approximations (H), (B), (I). Reference formula (18) in reference (c).

$$d\sigma_k=\frac{Z^2r_0^2}{137}\frac{16}{3}\frac{dk}{k}\frac{1}{p_0^2}\ln\left(\frac{p_0+p}{p_0-p}\right).$$

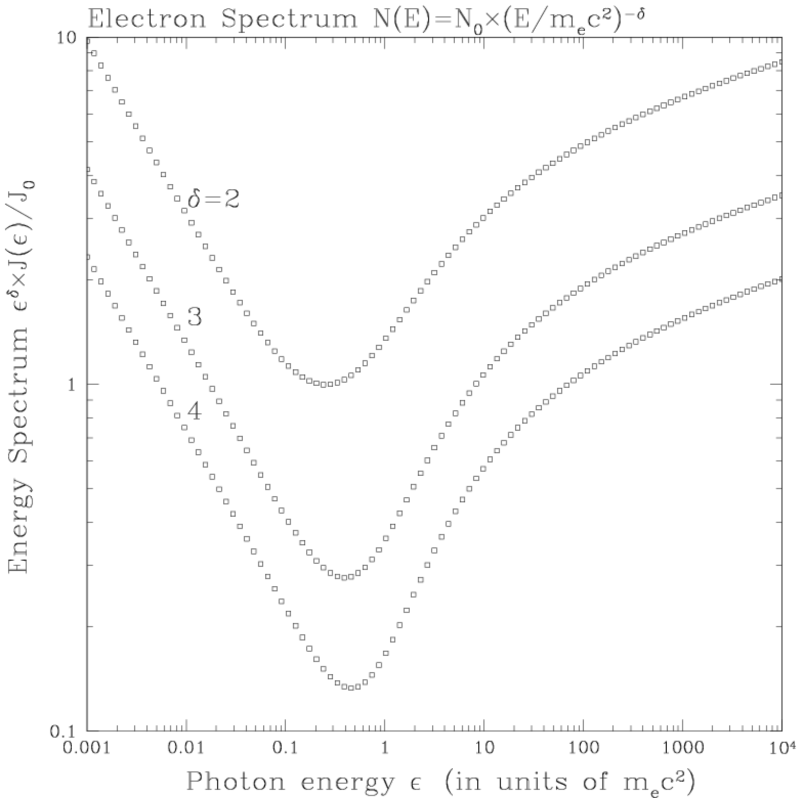
Formula 3BN(b)—Differential in photon energy.
Approximations (H), (B), (J). Reference formulas: (16) in reference (a), (21) in reference (c), (56) in reference (j).

$$d\sigma_k=\frac{4Z^2r_0^2}{137}\frac{dk}{k}\left[1+\left(\frac{E}{E_0}\right)^2-\frac{2}{3}\frac{E}{E_0}\right]\left[\ln\left(\frac{2E_0E}{k}\right)-\frac{1}{2}\right].$$

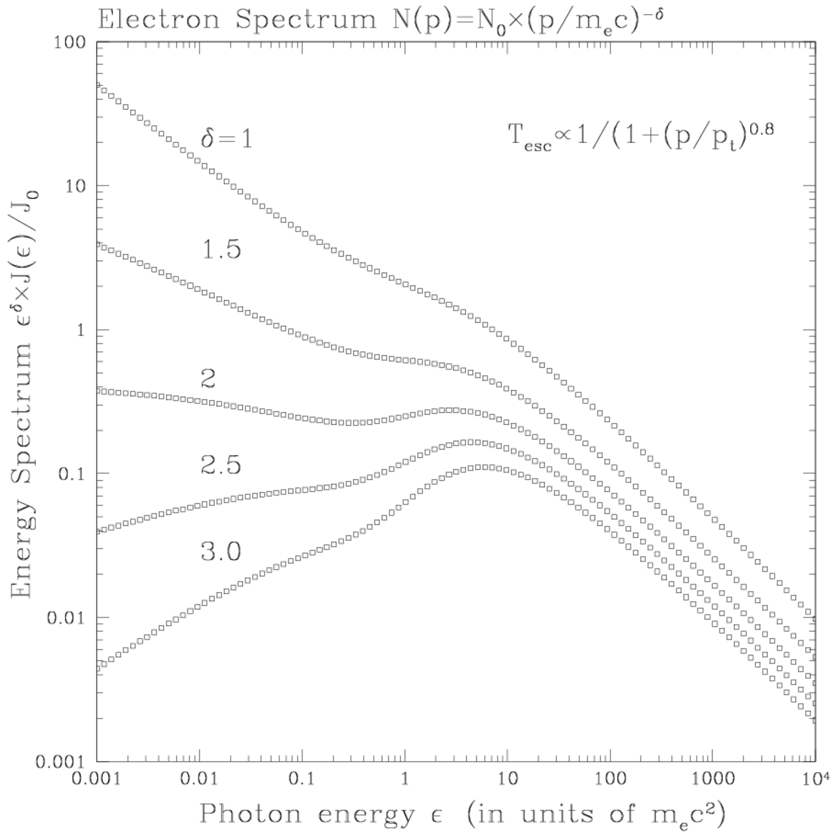
Analysis of Hard X-ray Data

Bremsstrahlung emissivity of power-law electrons

Power-law in energy



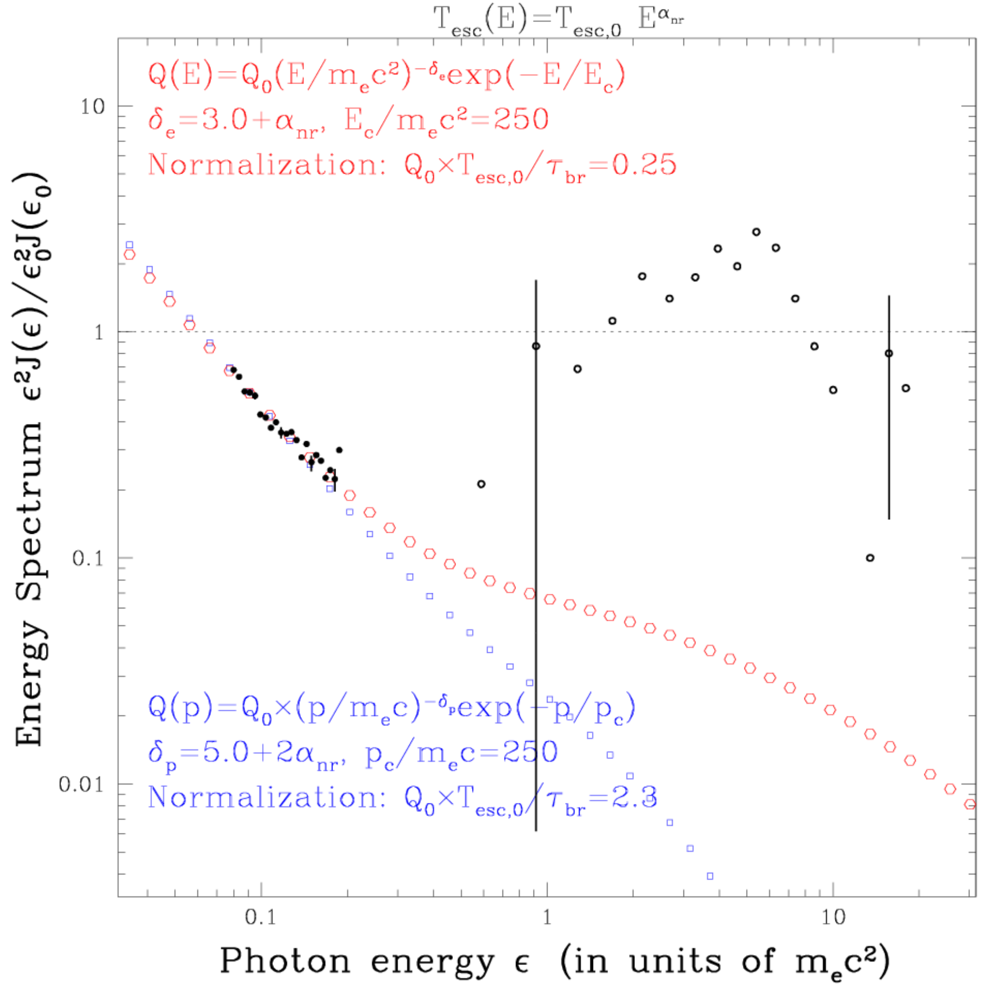
Power-law in momentum



Analysis of Hard X-ray Data

Bremsstrahlung emissivity of power-law electrons

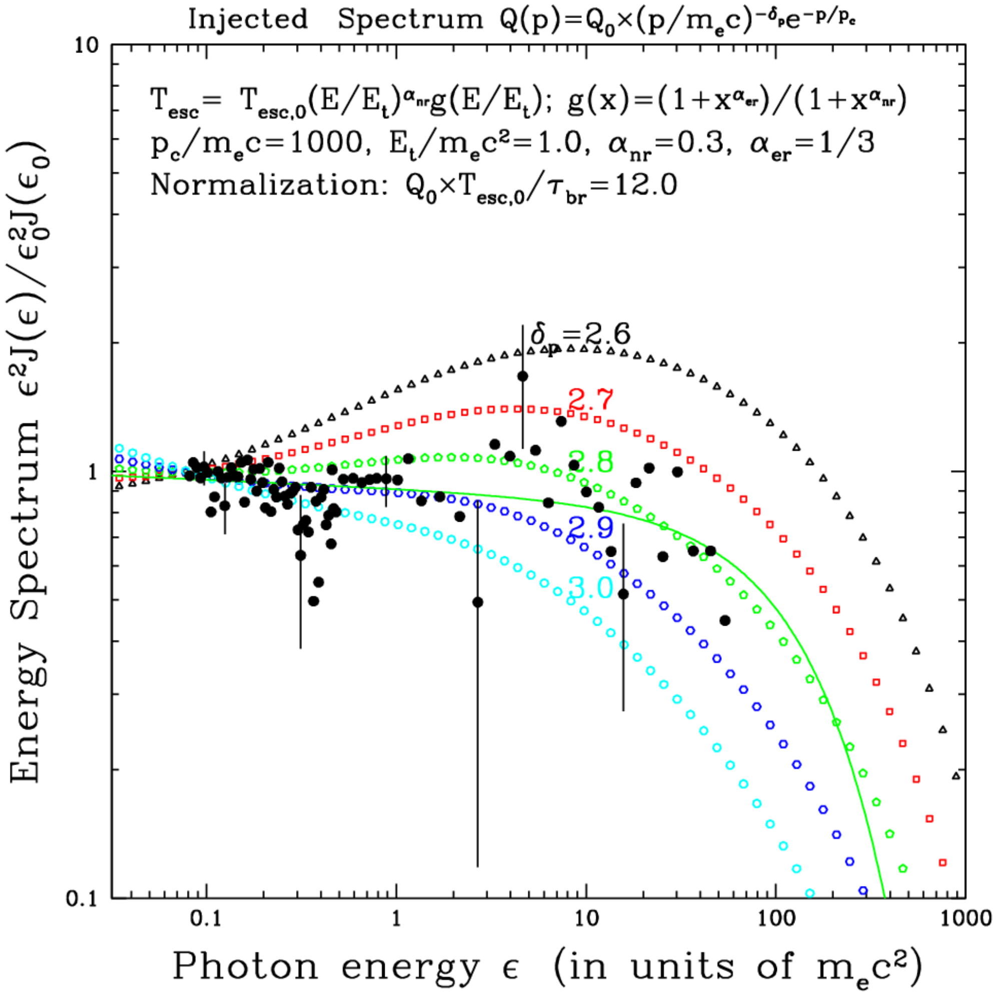
Sol: 2013-10-11

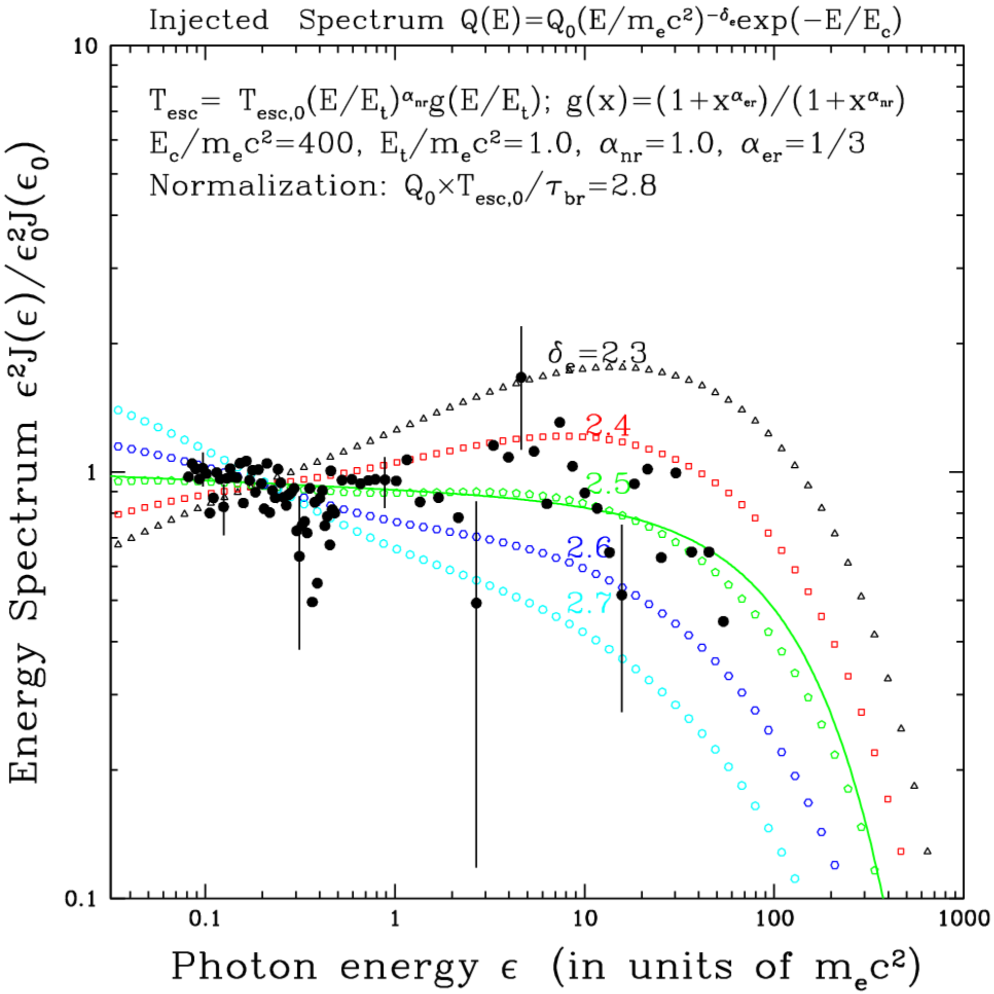


Analysis of Hard X-ray Data

Bremsstrahlung emissivity of power-law electrons

Sol: 2014-09-01





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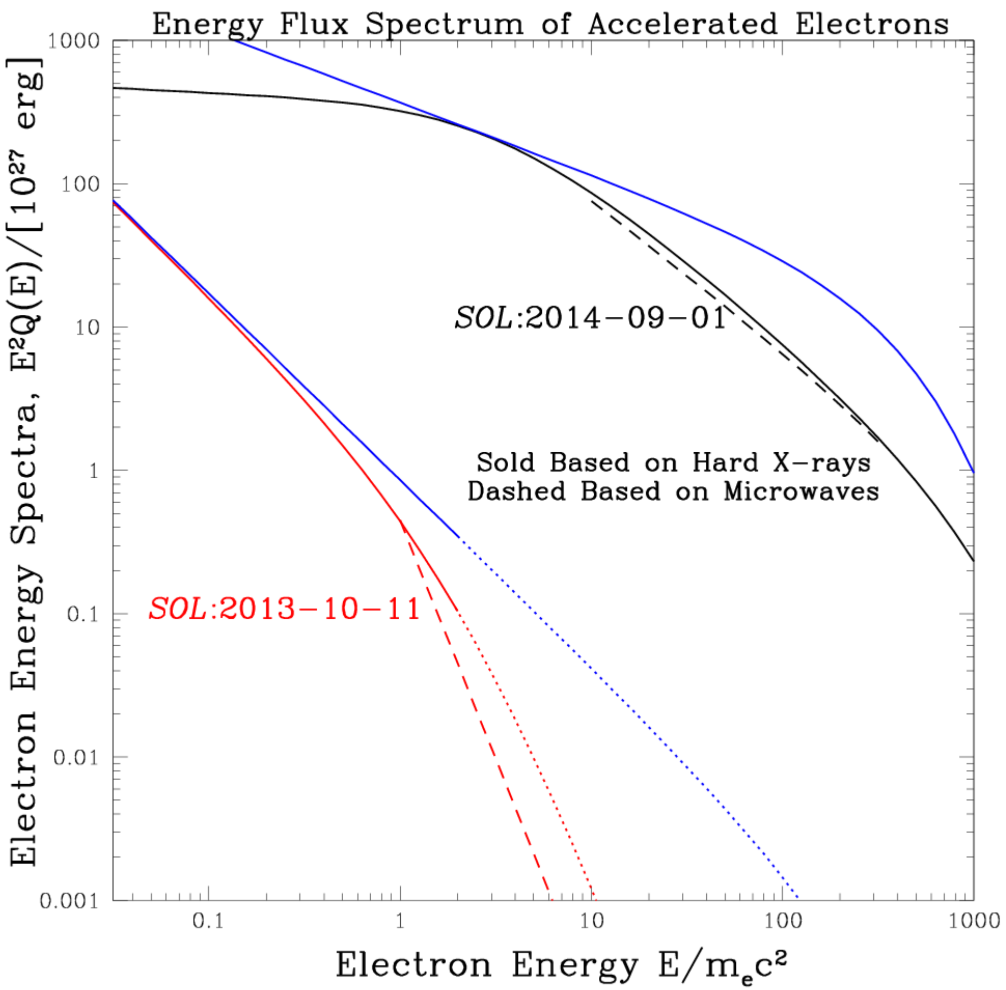
Injected Spectra of Accelerated Electrons



Solid lines: Based on X-rays

Dashed lines: Microwaves

$$E^2 N(E) \propto B^{-1.5}$$

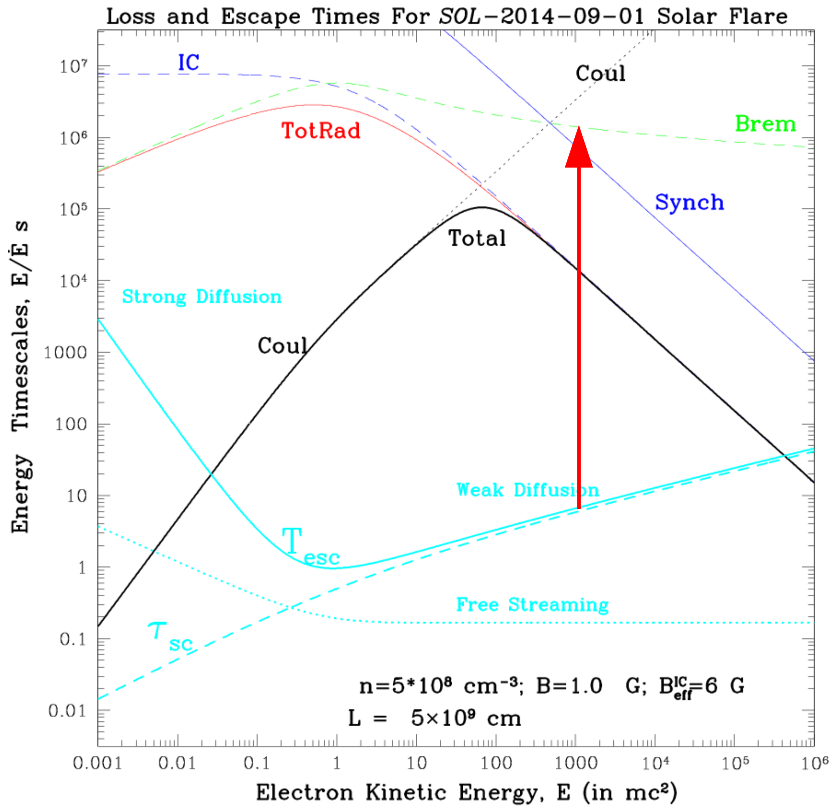
Analysis of Gamma-ray Data

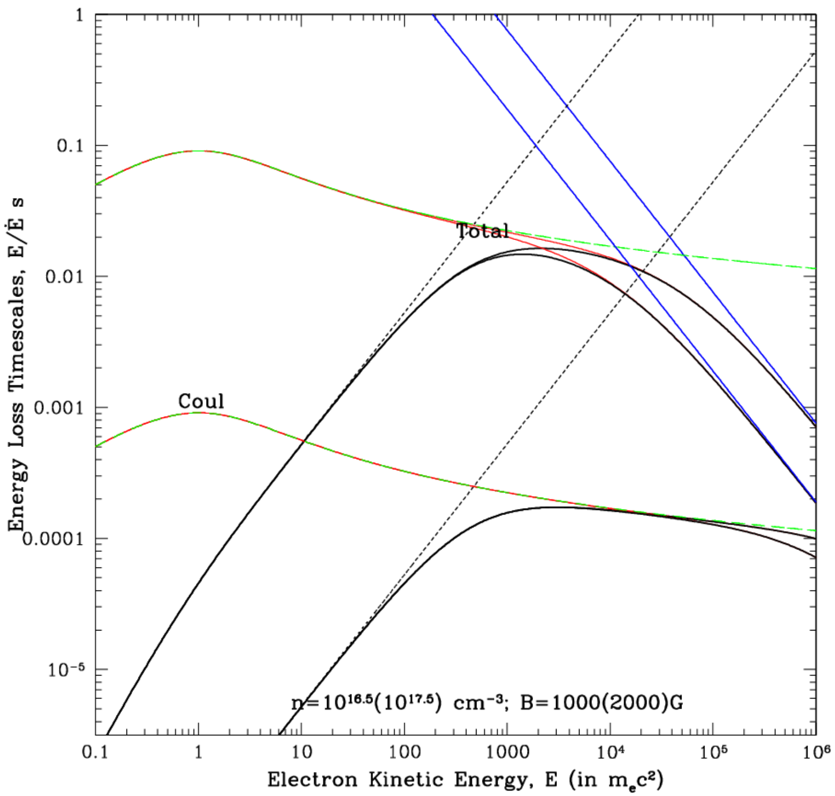
Electrons vs Protons and Thin vs Thick Target

1. Thin vs Thick Target   *(for electrons)*

$$\mathcal{E}_{\rm e,thin} \sim \mathcal{E}_\gamma(\tau_{\rm loss}/T_{\rm esc})$$

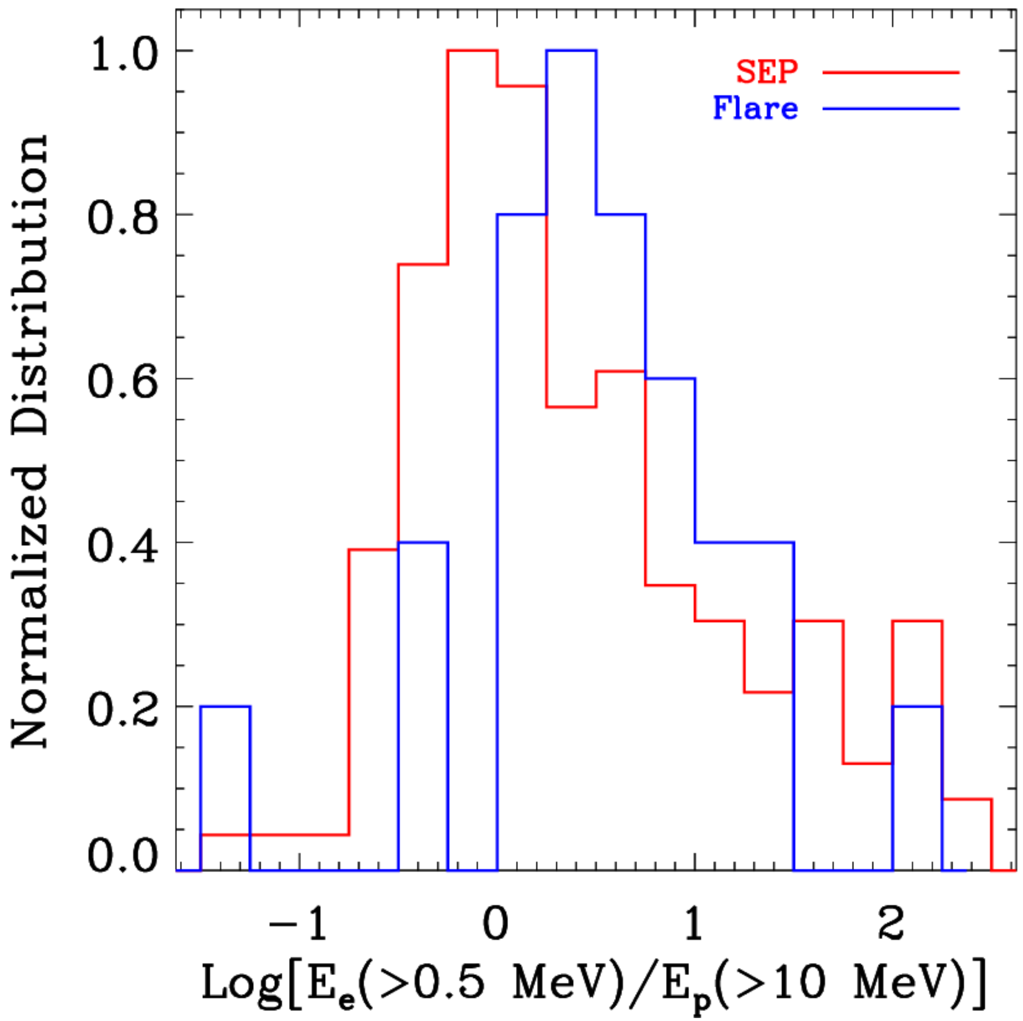
$$\mathcal{E}_{\rm e,thick} \sim \mathcal{E}_\gamma(\tau_{\rm loss}/\tau_{\rm rad}$$





3. Electron to Proton Ratio

SEPs vs Flares



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Questions Raised by Fermi-LAT Observations

II. Transport Related Processes

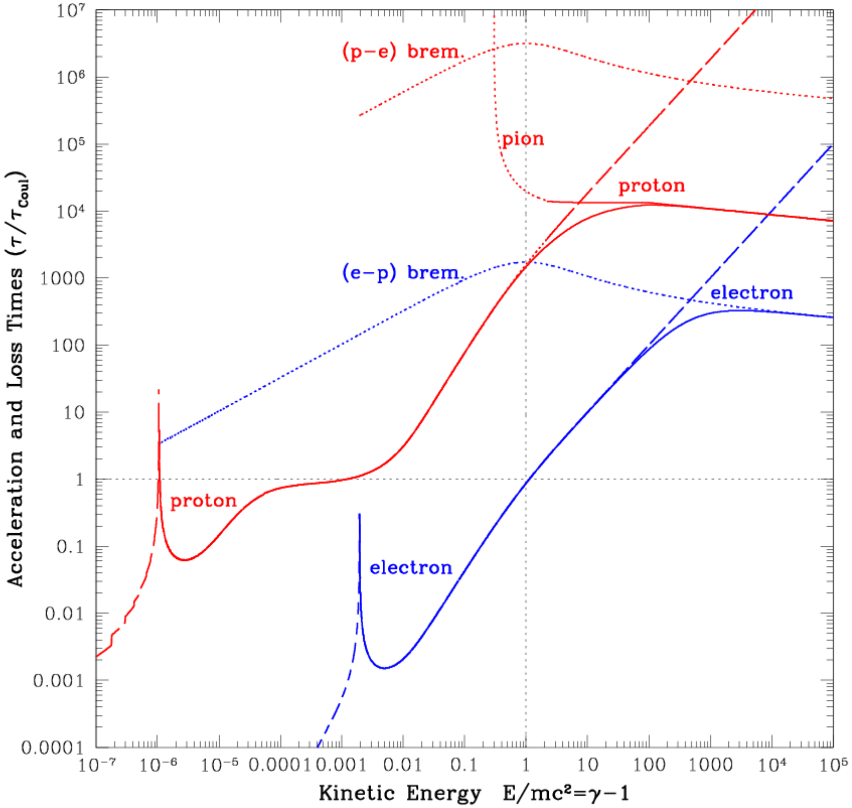
Energy loss, Scattering, Magnetic Field Geometry

Electrons:

Coulomb, Synchrotron-IC, Bremsstrahlung

Protons (ions):

Coulomb, p-p interactions



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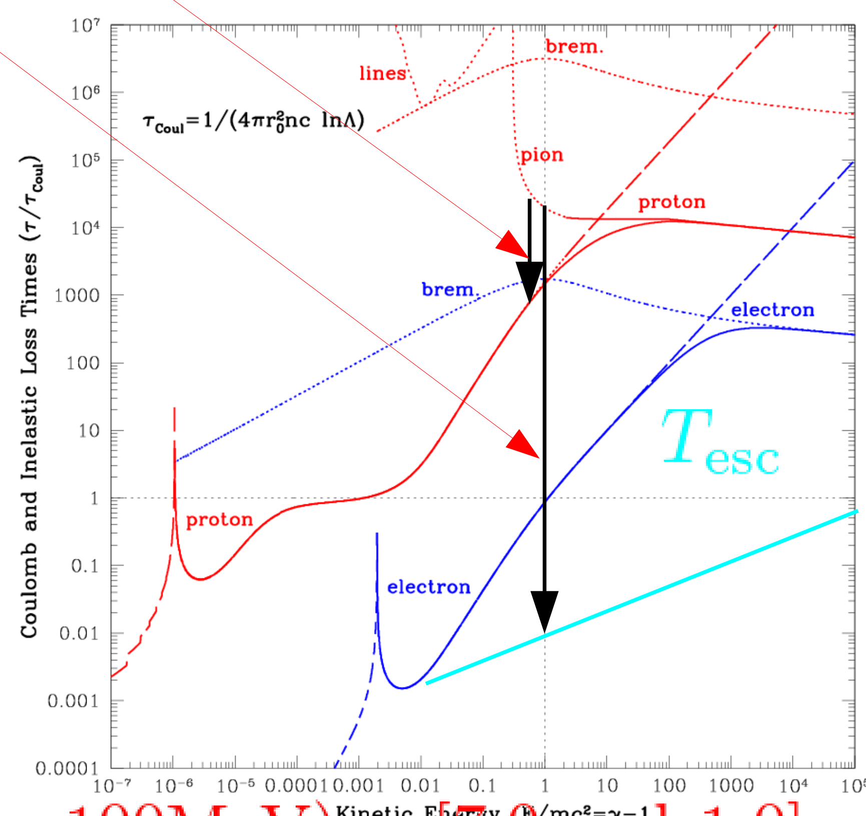
Analysis of Gamma-ray Data

Electrons vs Protons and Thin vs Thick Target

1. Thin vs Thick Target *(for protons)*



$$\mathcal{E}_p^{\rm thick}(>100{\rm MeV}) = [7.0 \text{ and } 1.0] \times 10^{25} \text{ ergs}$$

$$\mathcal{E}_p^{\rm thin}(>100{\rm MeV}) = [2.0 \text{ and } 0.30] \times 10^{29} \text{ ergs}$$

Behind The Limb Flares

3. Acceleration in the CME Shock

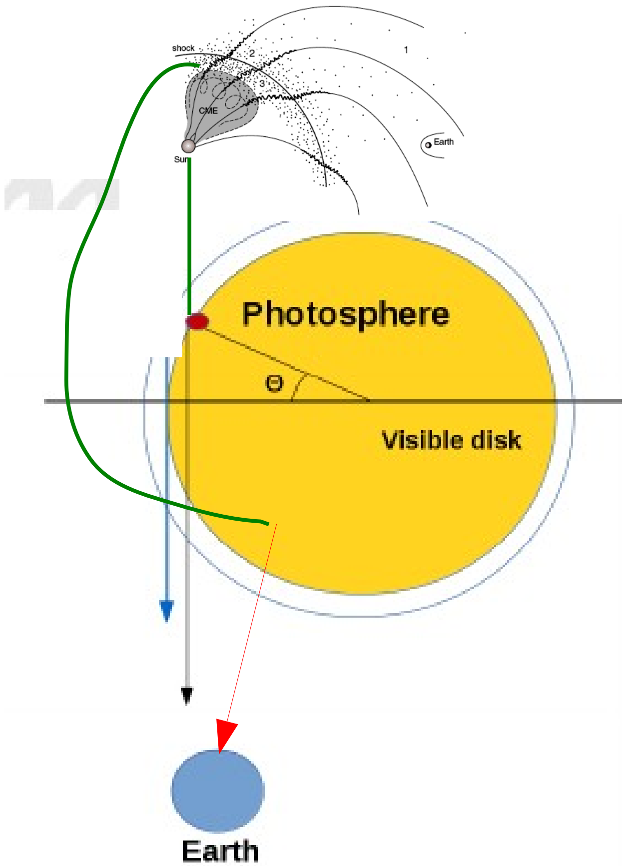
Need to transport particles from downstream of shock to the visible side of the Sun:

This requires diffusion

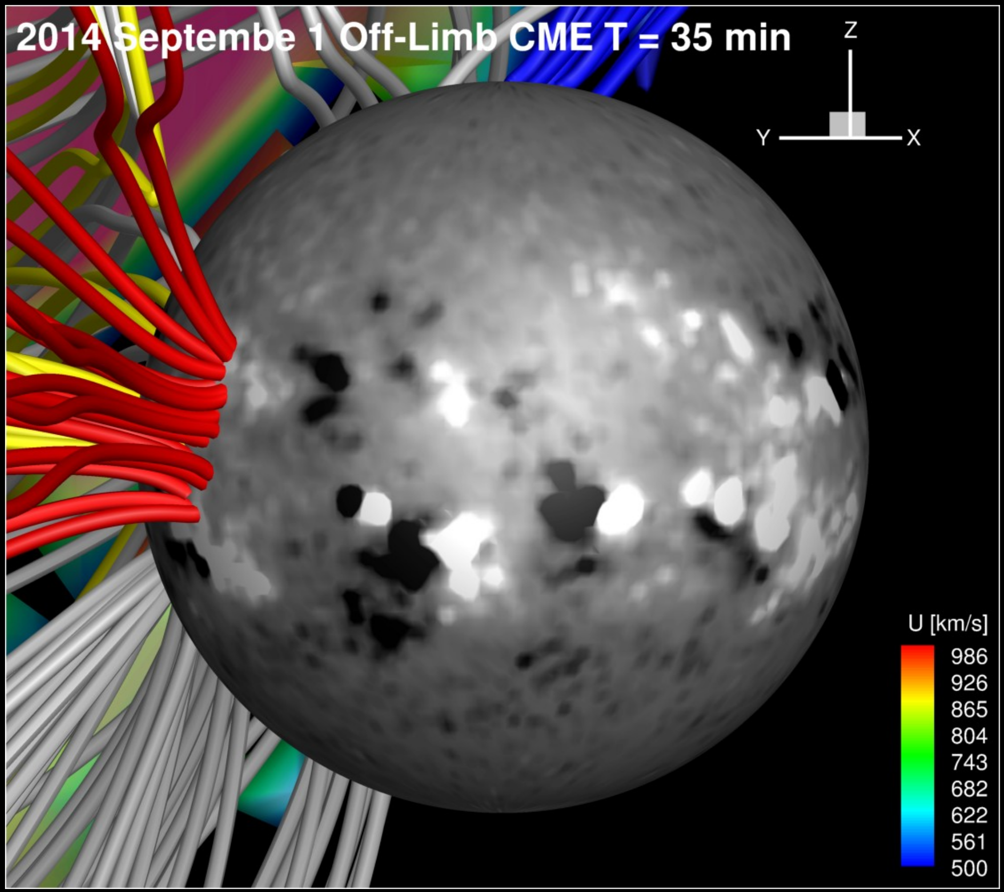
across the magnetic field lines

Scattering by Turbulence

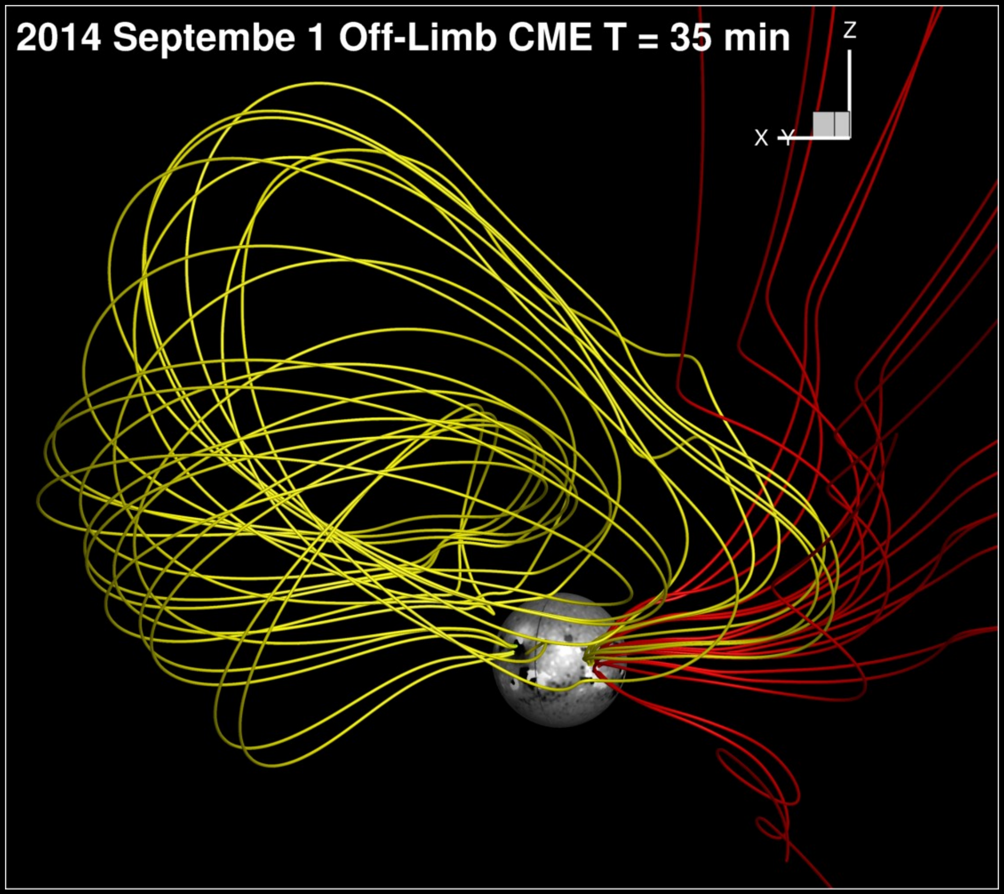
Behind the Shock



Earth View



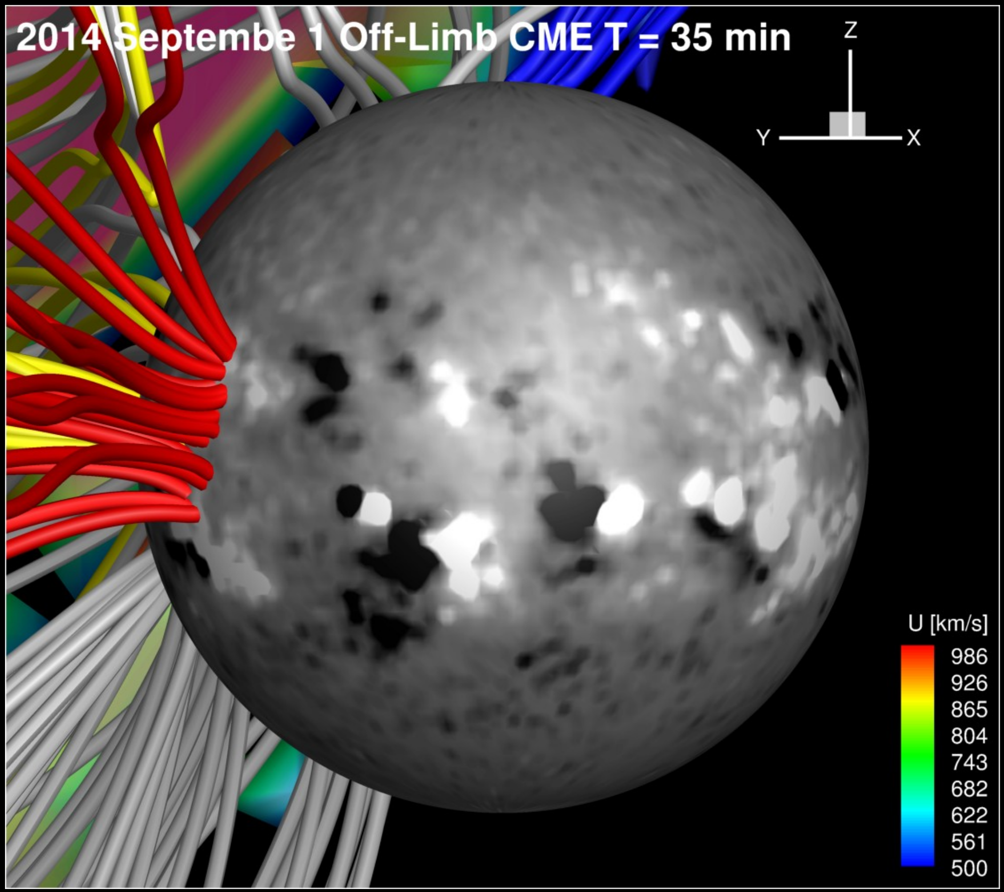
Overview



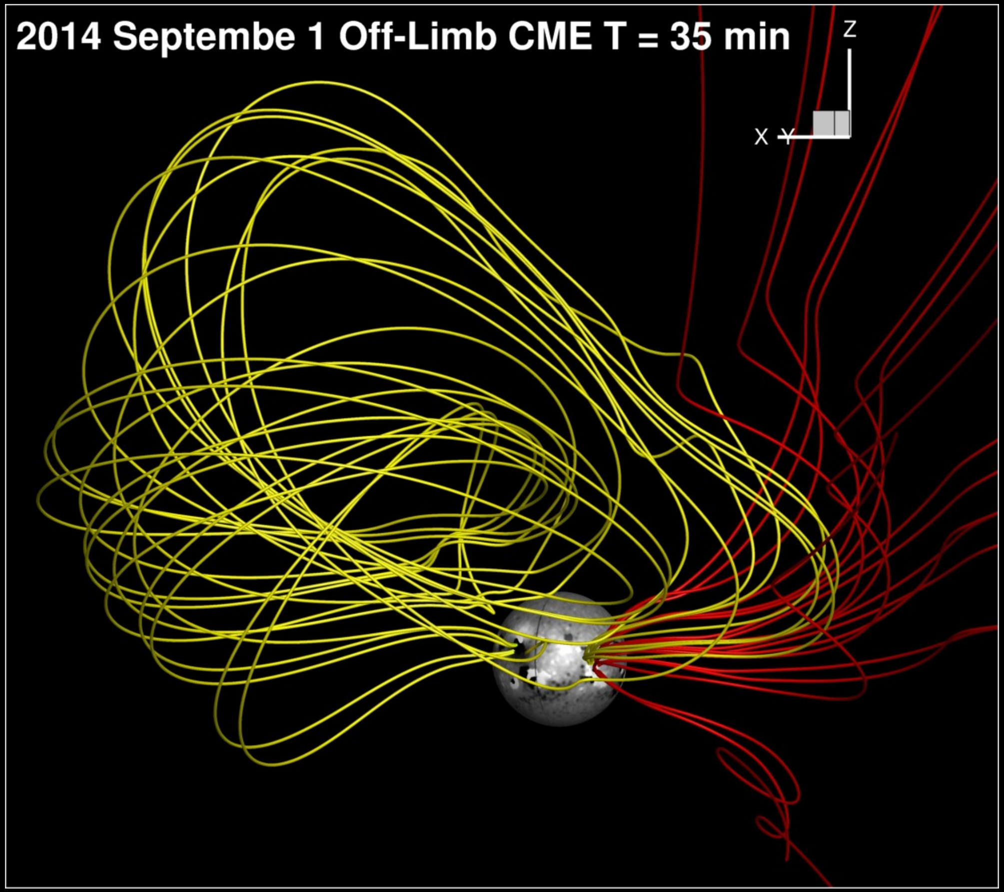
- **Red**: Field lines connected to the CME shock
- **Yellow**: Field line connected to the CME source

See POSTER 108.13. Data-driven Simulations of Magnetic Connectivity......BTL flare ...CME

Earth View



Overview



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

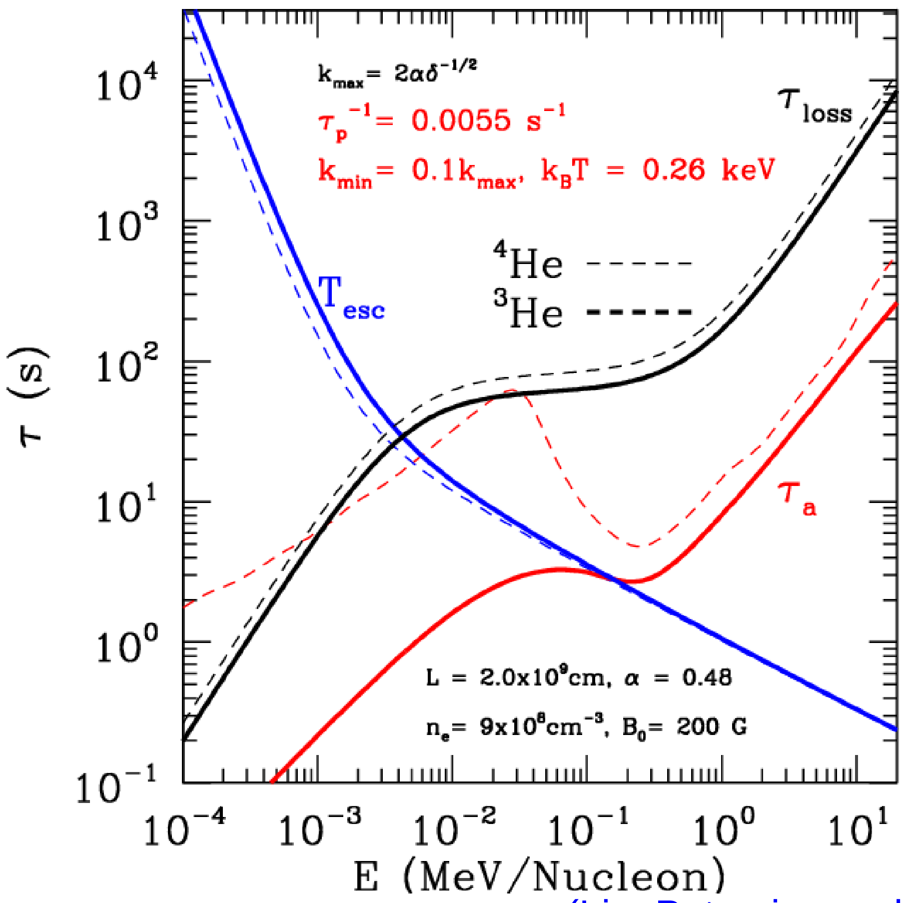
Summary II

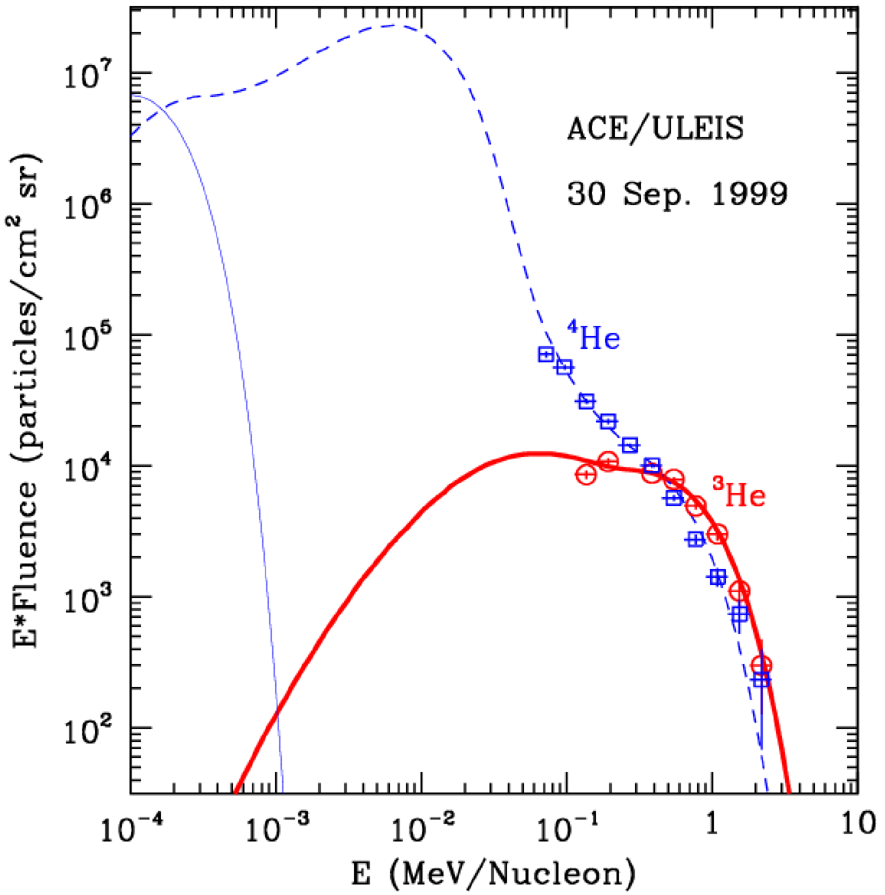
1. Fermi Behind the Limb (in general partially occulted) flares provide direct view of acceleration and thin target emissions.

2. Combined Microwave and HXR observations gives us Magnetic field and electron spectra over a broad (trans-relativistic) regime.

3. *Fermi*-LAT observations provide further connection between flare and CME processes.

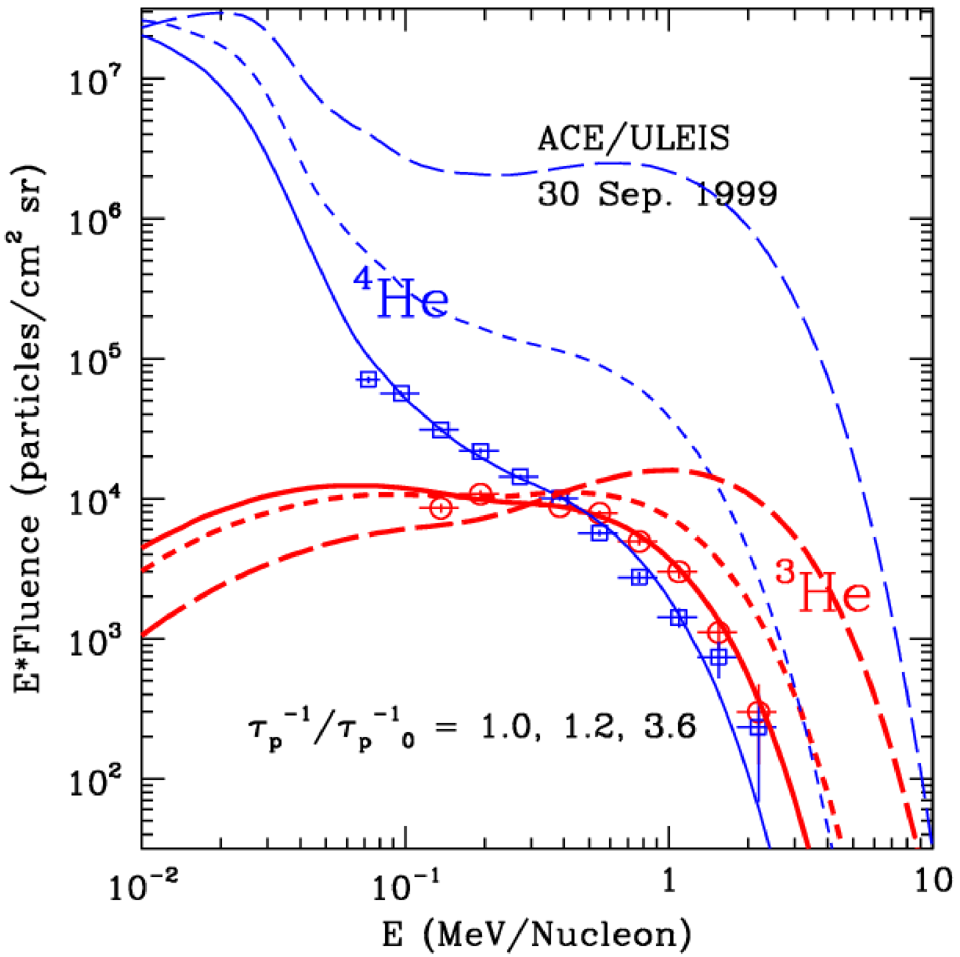
B. He3, He4 Abundances and Spectra

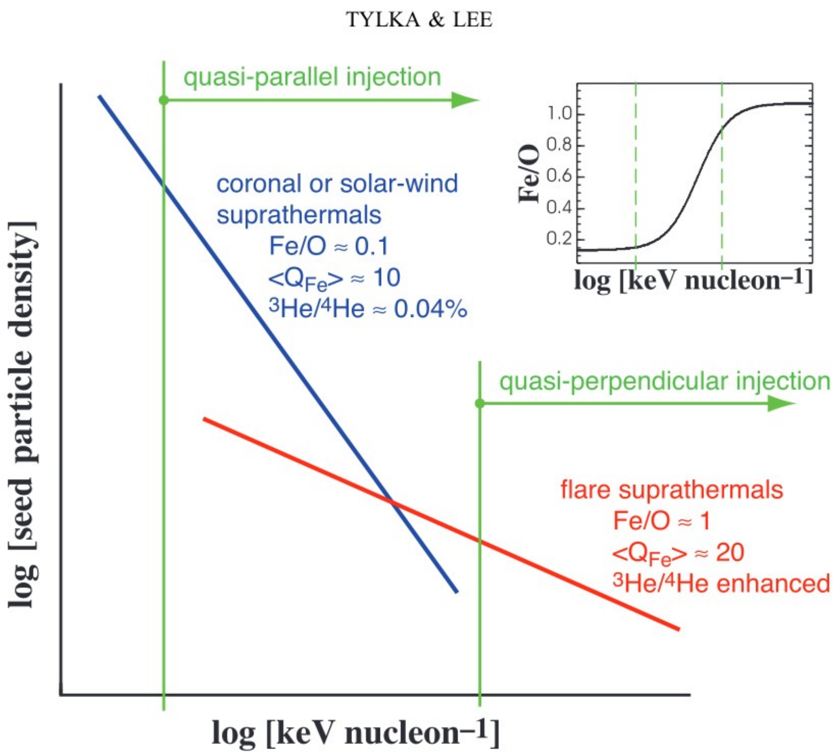




(Liu, Petrosian and Mason, 2004 ApJ)

He3, He4 Spectral Variations

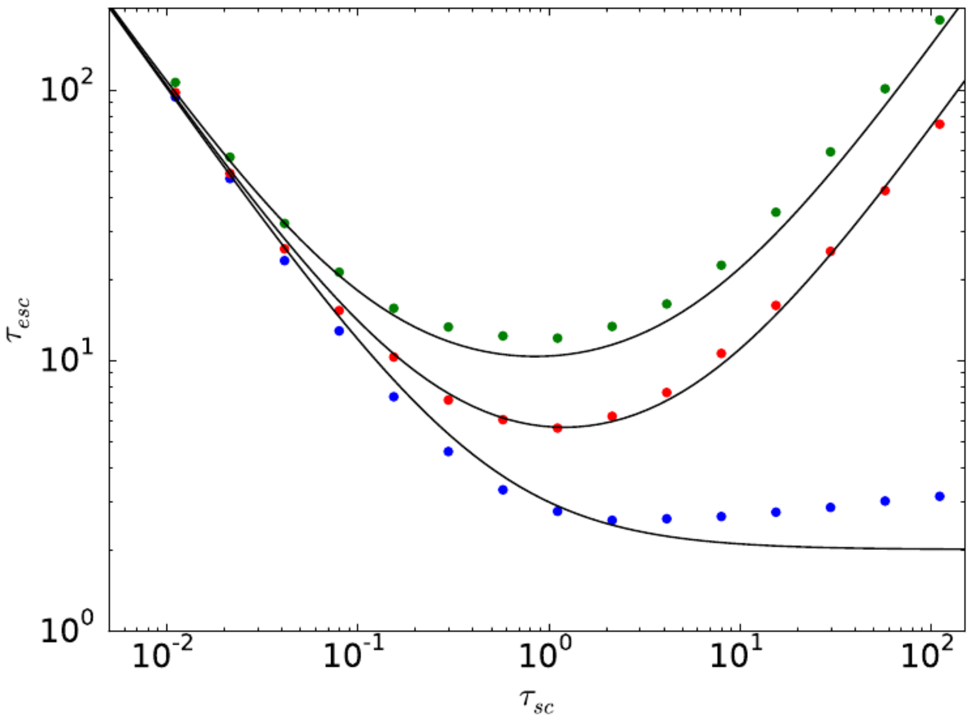




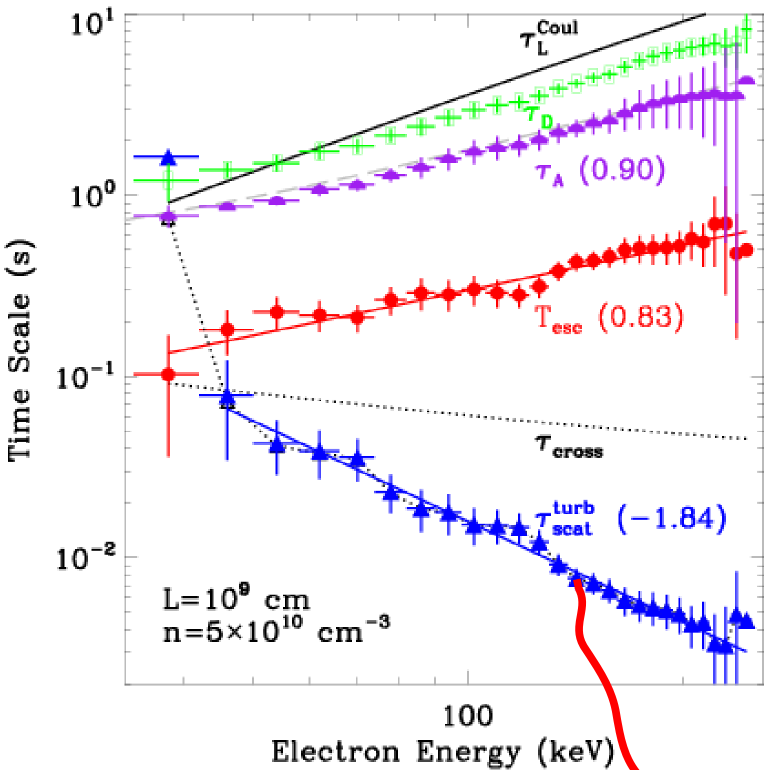
Escape and Scattering Times

Theory and Empirical Determinations

Effenberger and VP 2017



Chen & VP 2013



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