# Solar Flares and $\gamma$-ray Measurements

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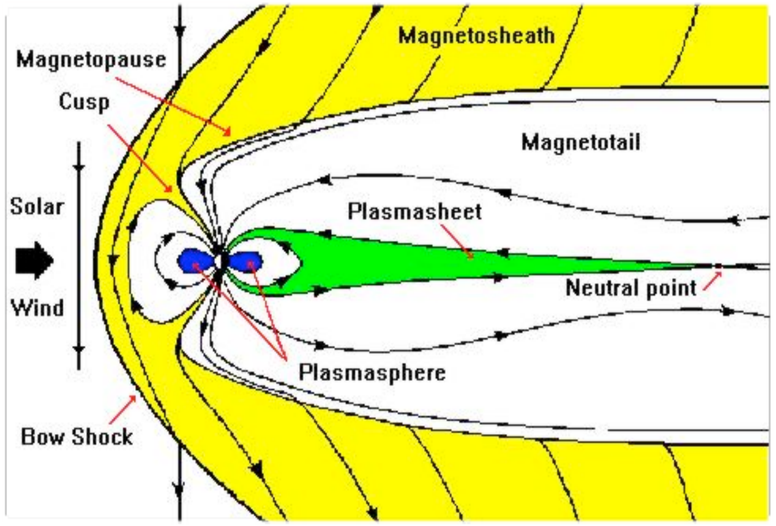
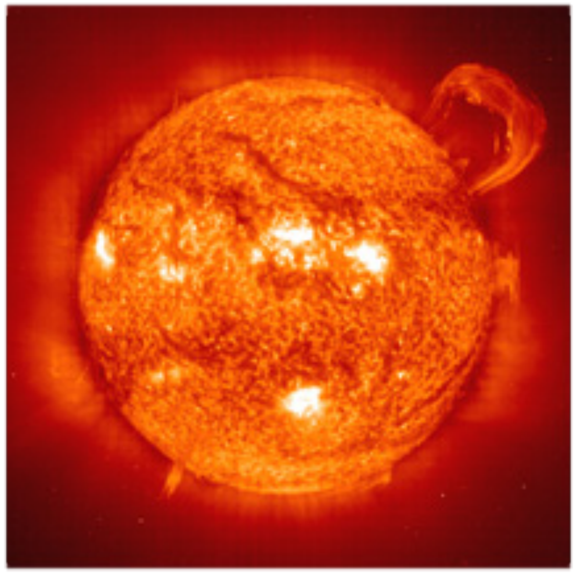
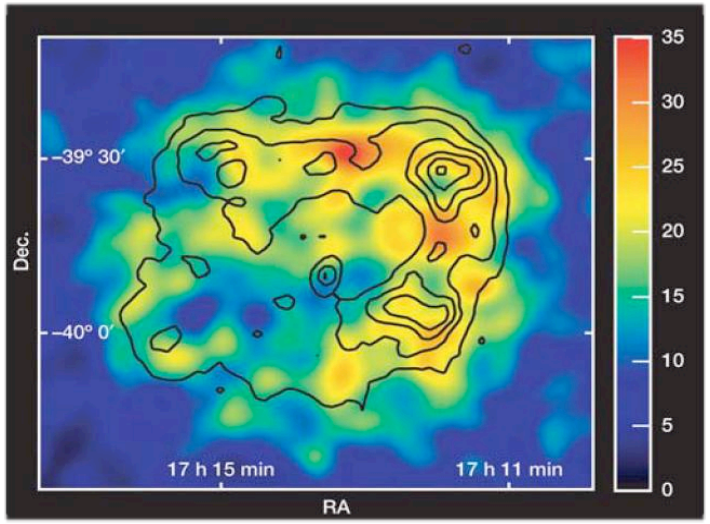





Aharonian et al. 2004

10 keV

1 GeV

$10^{15}$ eV

# The Situation and Questions

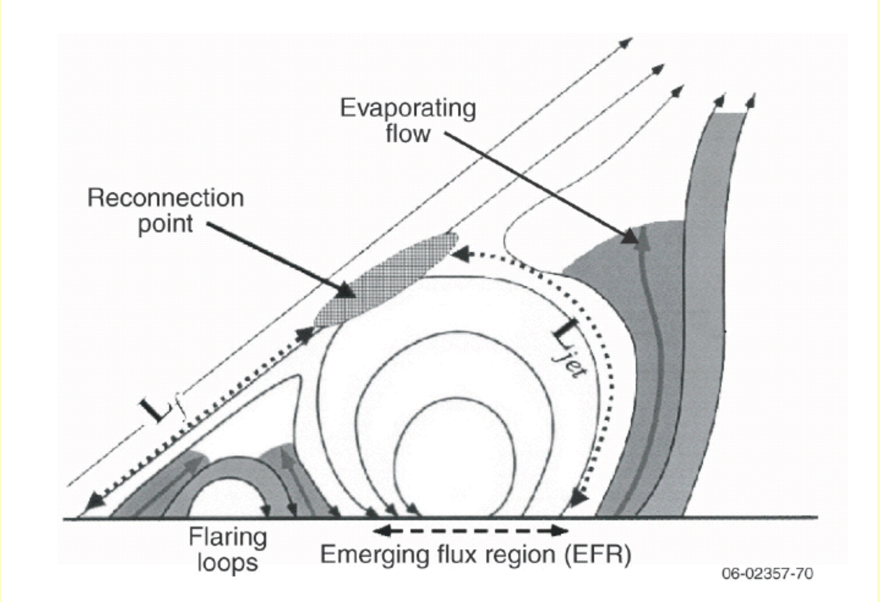
$10^9$ eV particles from a 100 eV spherical shell of hot magnetized gas (solar corona)!

Do the solar particles possess significant energy the way galactic cosmic rays do?

What dynamics are at work on different scales to make this happen?

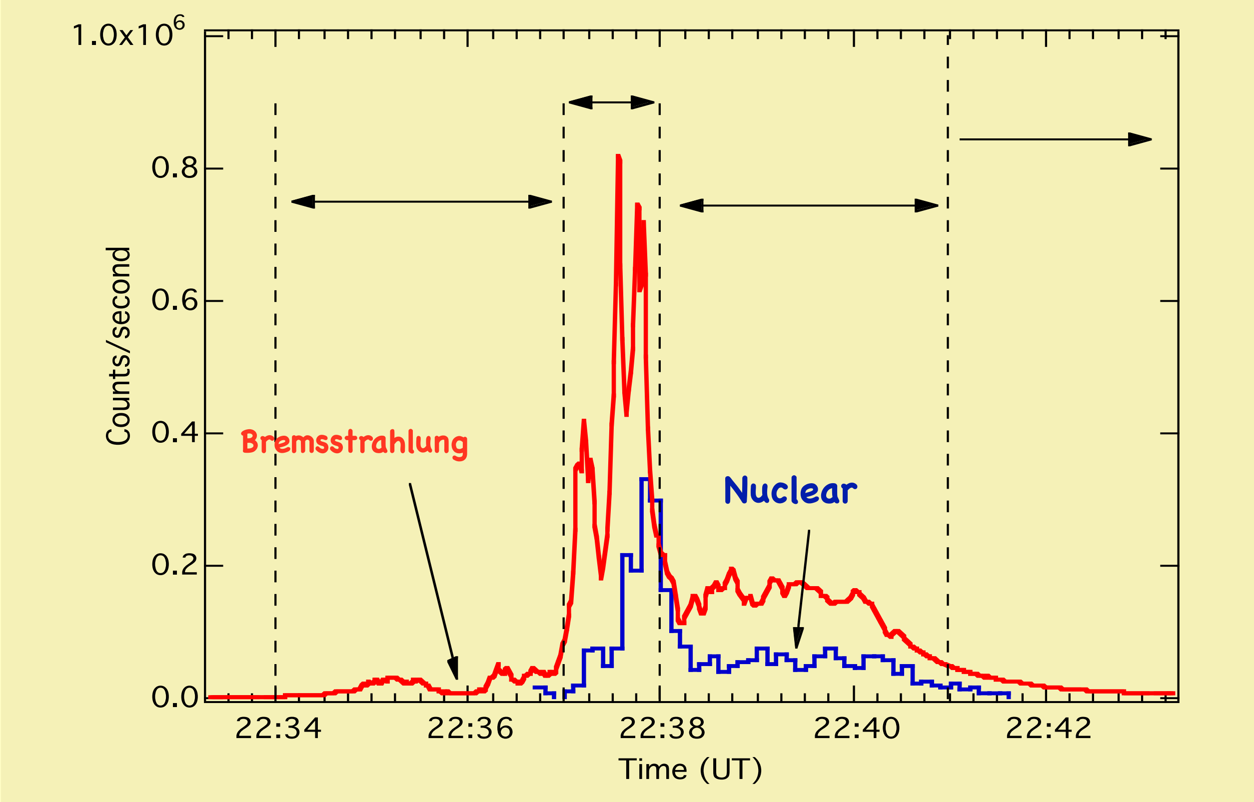
# What Typically Happens in a Flare?

- Stressed **B** reconnects releasing energy, **B** reconfigures itself
- Plasma heats to 30 MK
- 1 keV thermal X rays with lines
- Particles are accelerated
- UV emission (heats Earth's atmos.)




Shimojo and Shibata, 2000

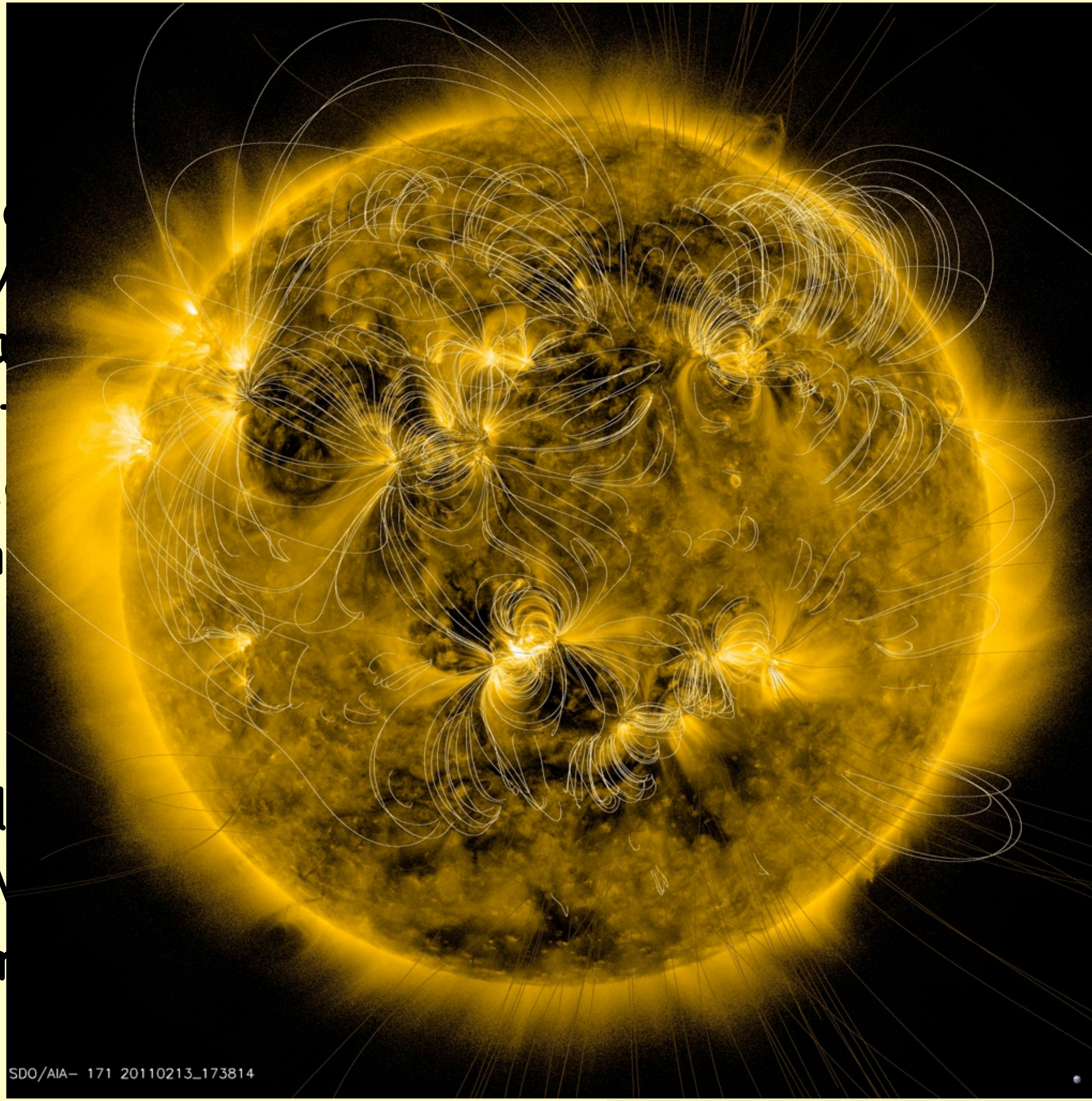
- MeV electrons accelerated
- 30 MeV ions accelerated
- Both precipitate and radiate

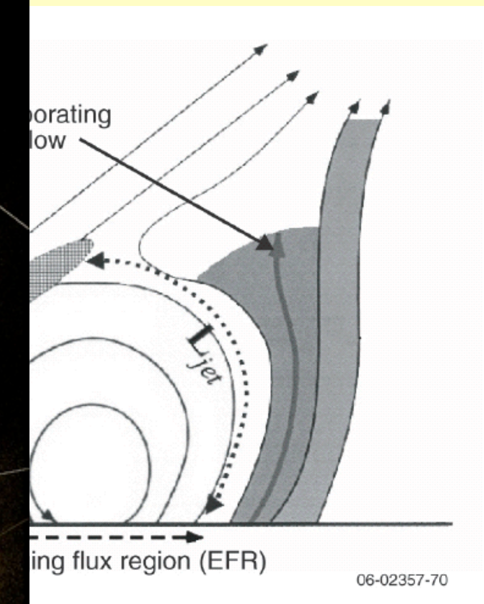



Arndt et al. 2002

# What ... are?

- Stress
  energy
- Plasma
- 1 keV
- Particl
- UV em

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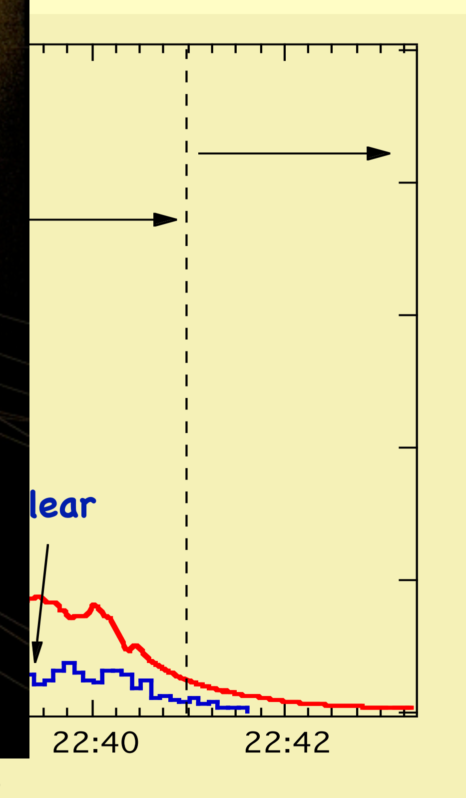


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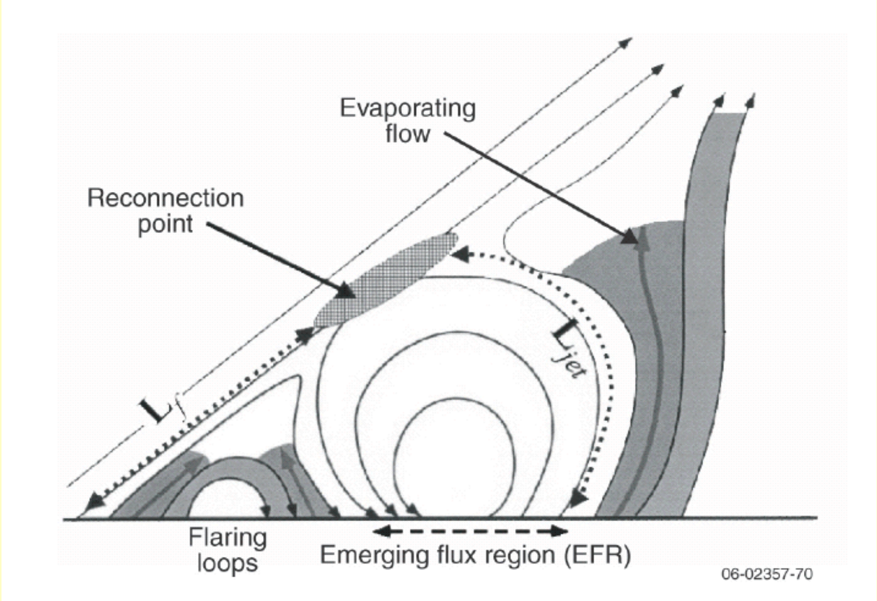


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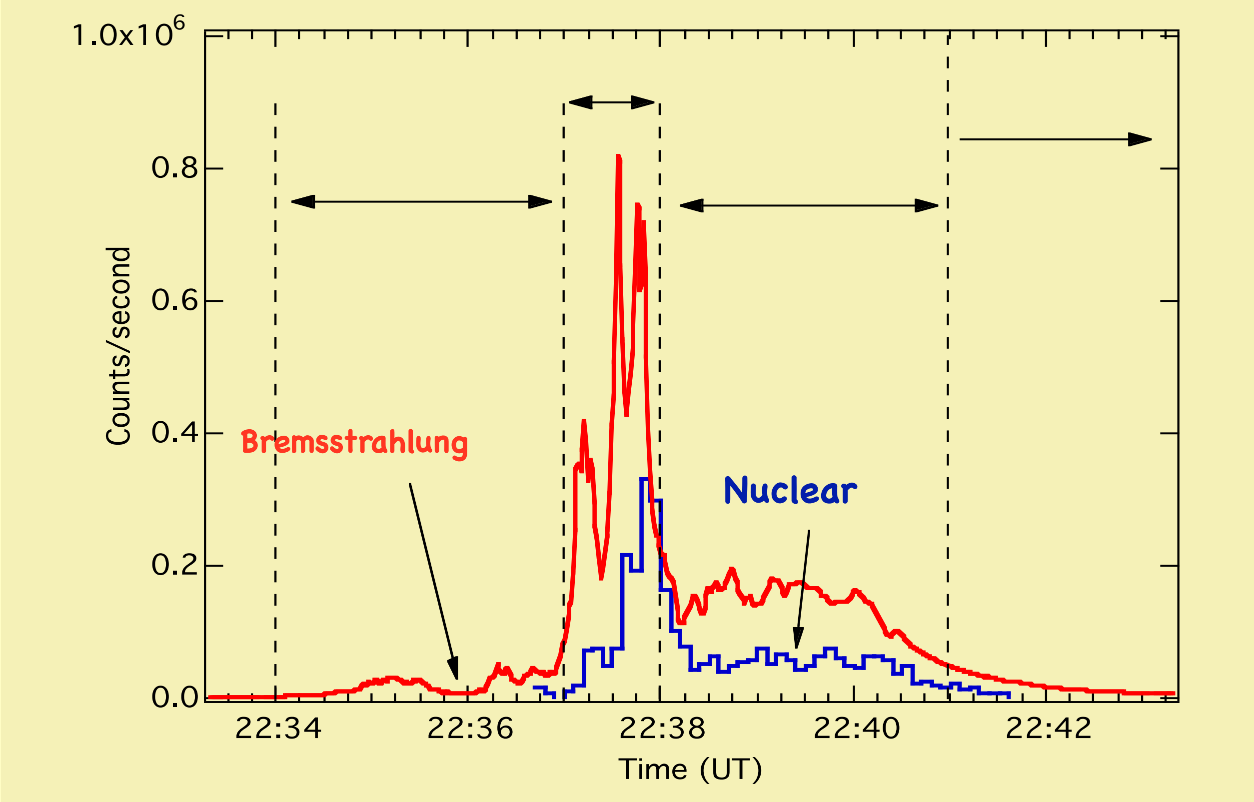
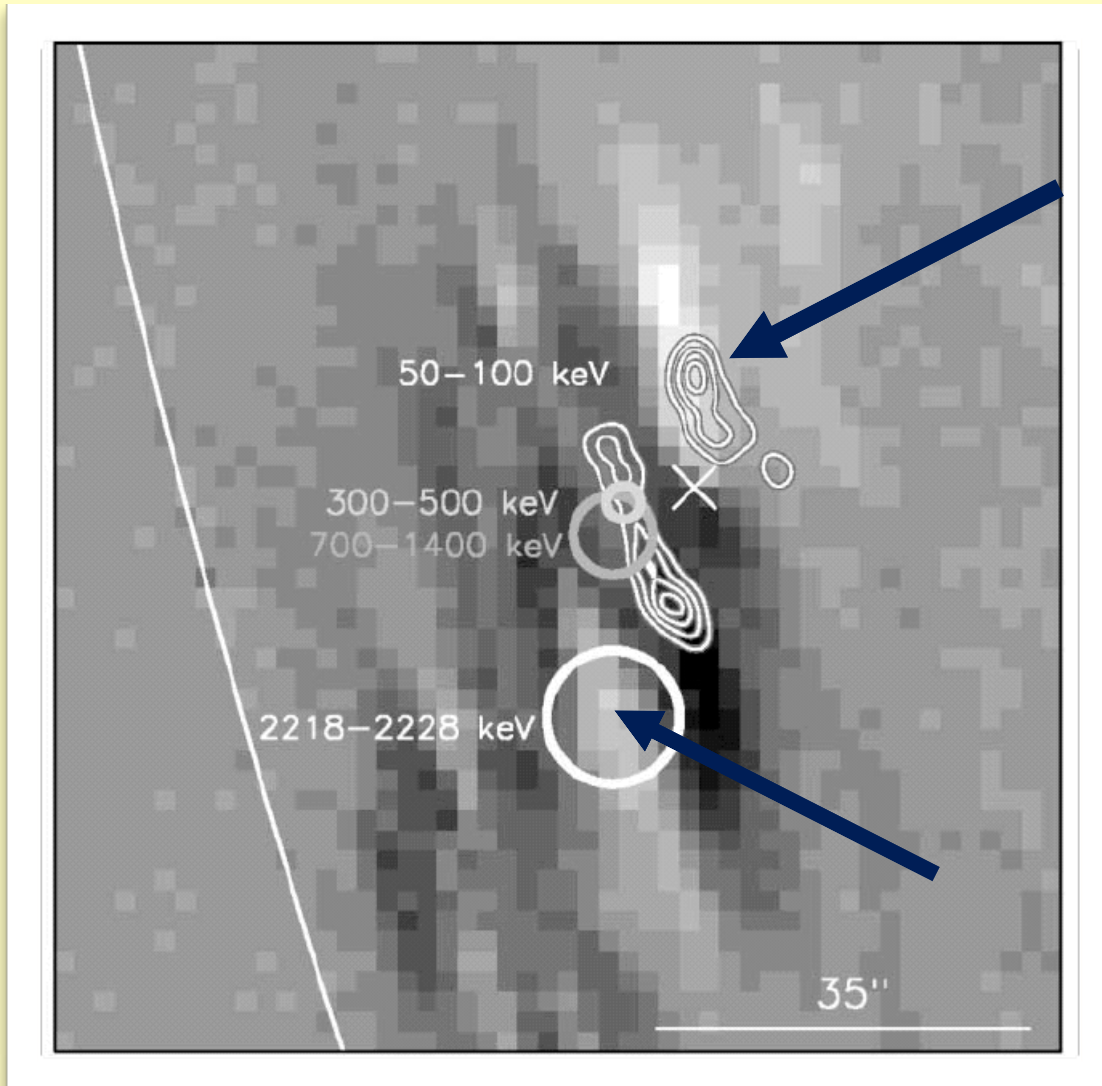



Arndt et al. 2002

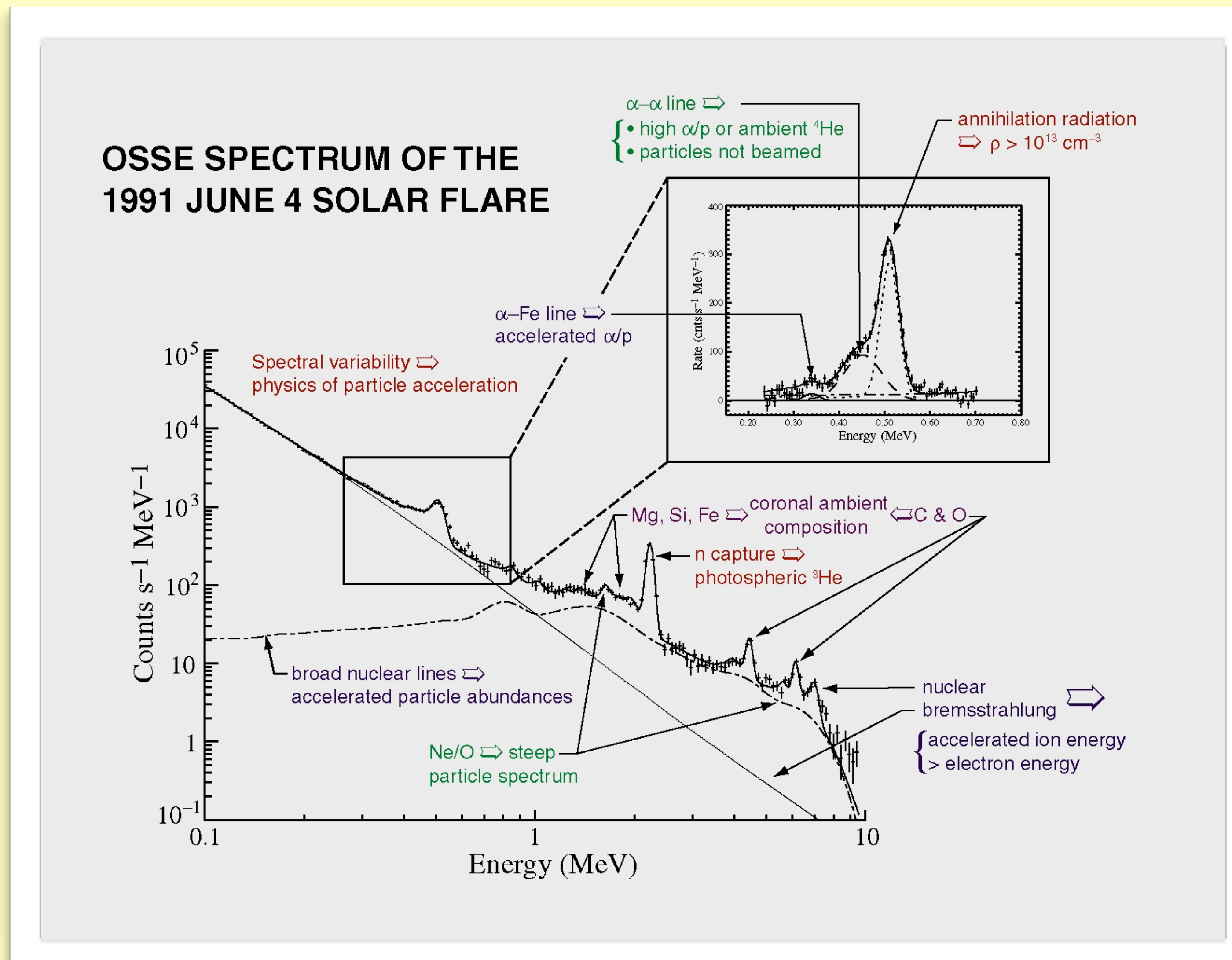
# Transport of ions differs from that of electrons!

Hurford et al. 2003

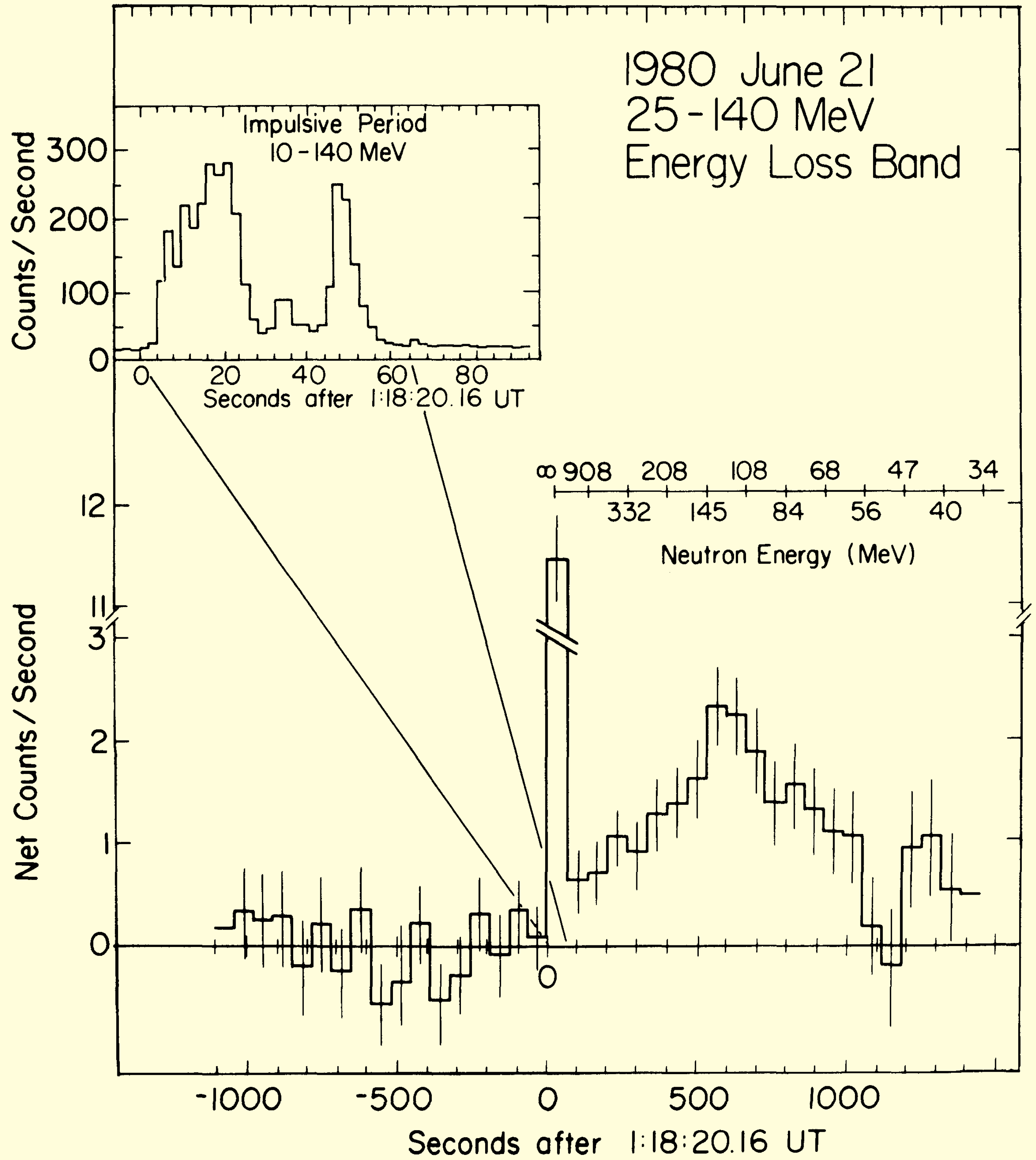



# Nuclear emission and Bremsstrahlung

Murphy, priv. comm.



# Impulsive Hi-E Gammas



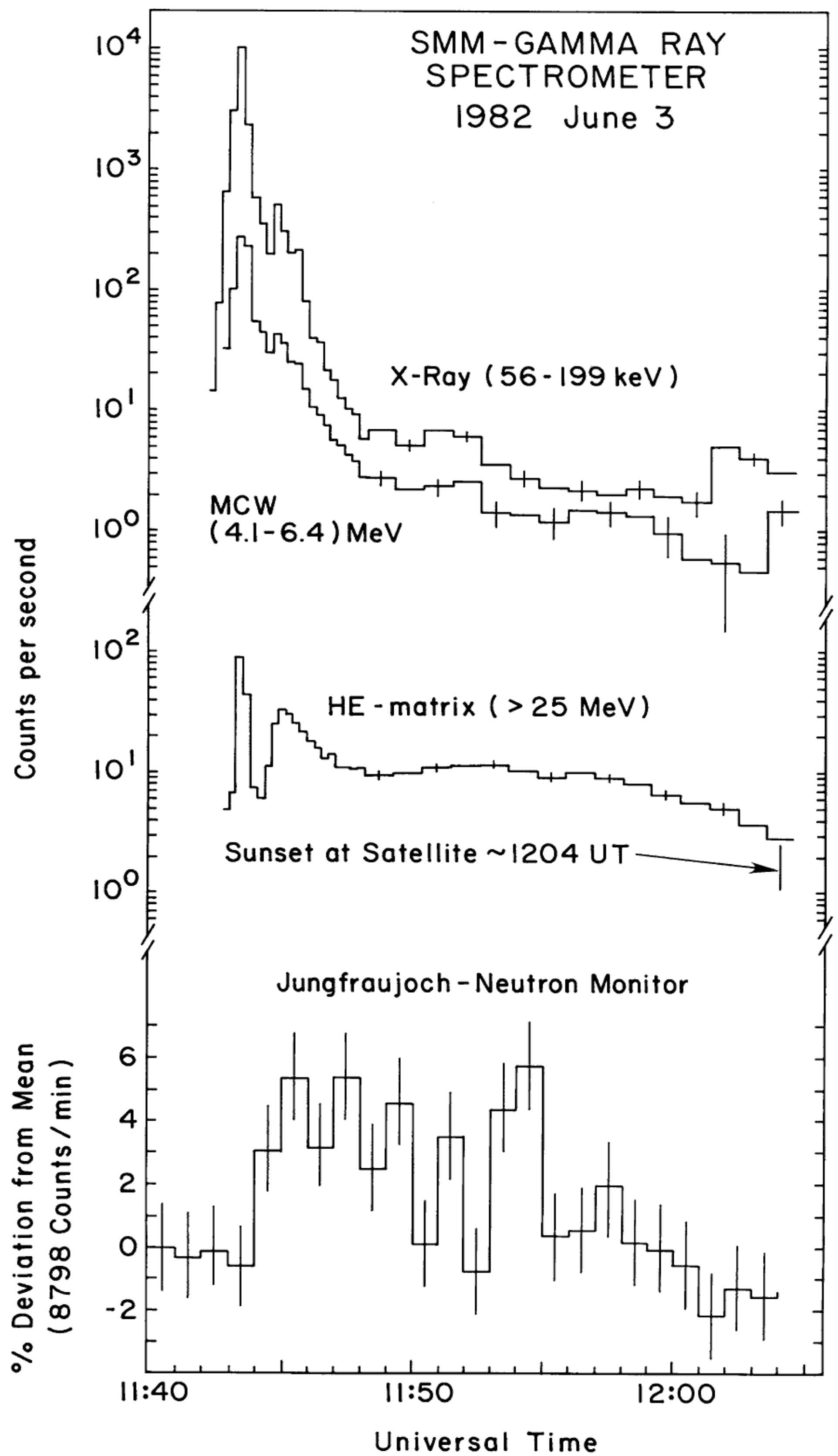

One-minute impulsive phase with late arrival of neutrons

**2-s delay or rise time**

**☞ $\ell$ = $10^4$ km**

# Long Duration γ-ray Flares

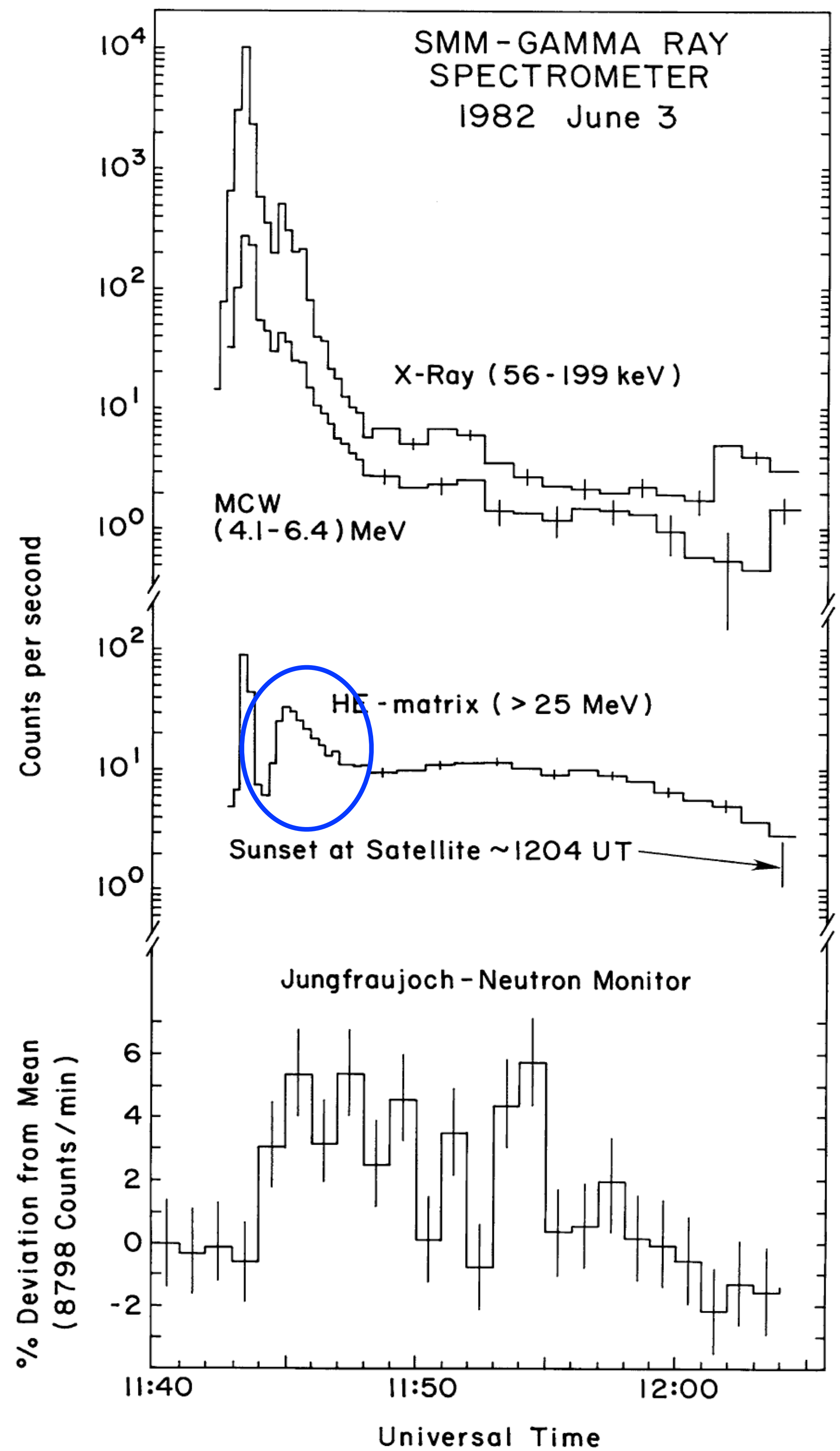
- Big Events
- Delayed onset of hi-E emission
- Long decay, much longer than impulsive phase x rays or anything else sometimes.
- Heavily proton/ion dominated.




# Earliest Evidence

- 1982 June 3 Solar $\gamma$–ray flare
- Delayed hi-E phase
- Harder spectrum than impulsive phase
- Slower development

Chupp et al. 1987

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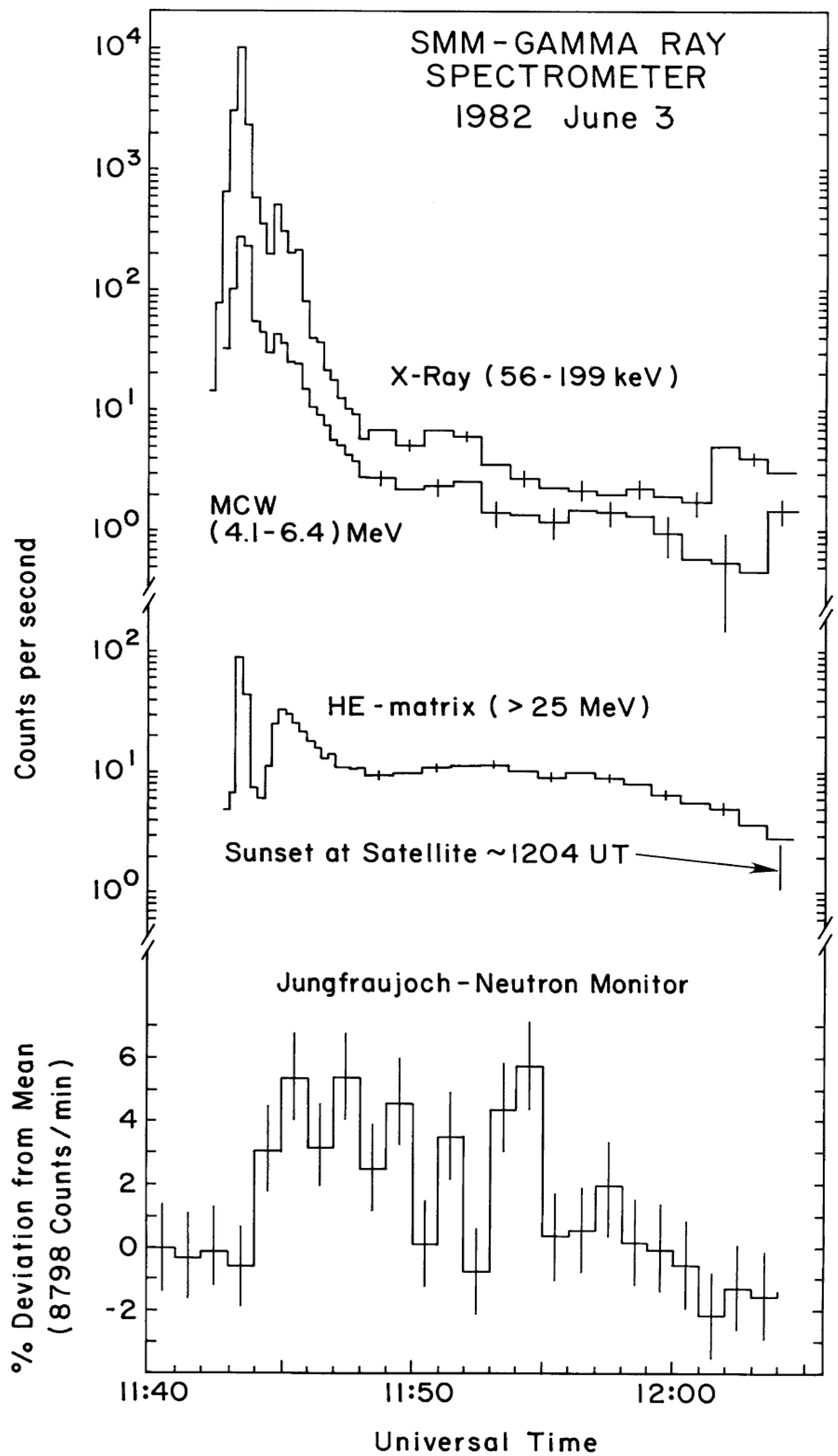


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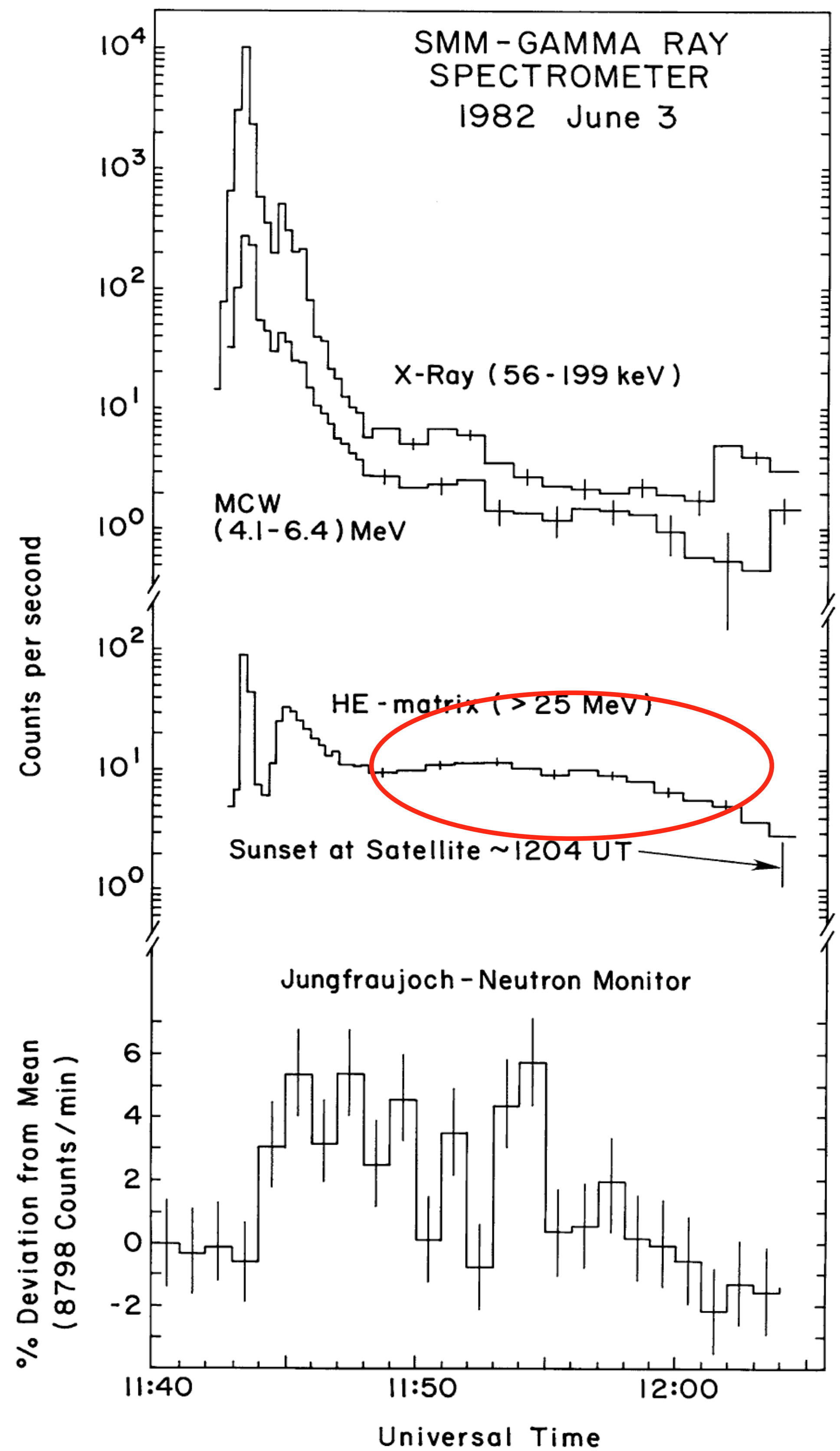


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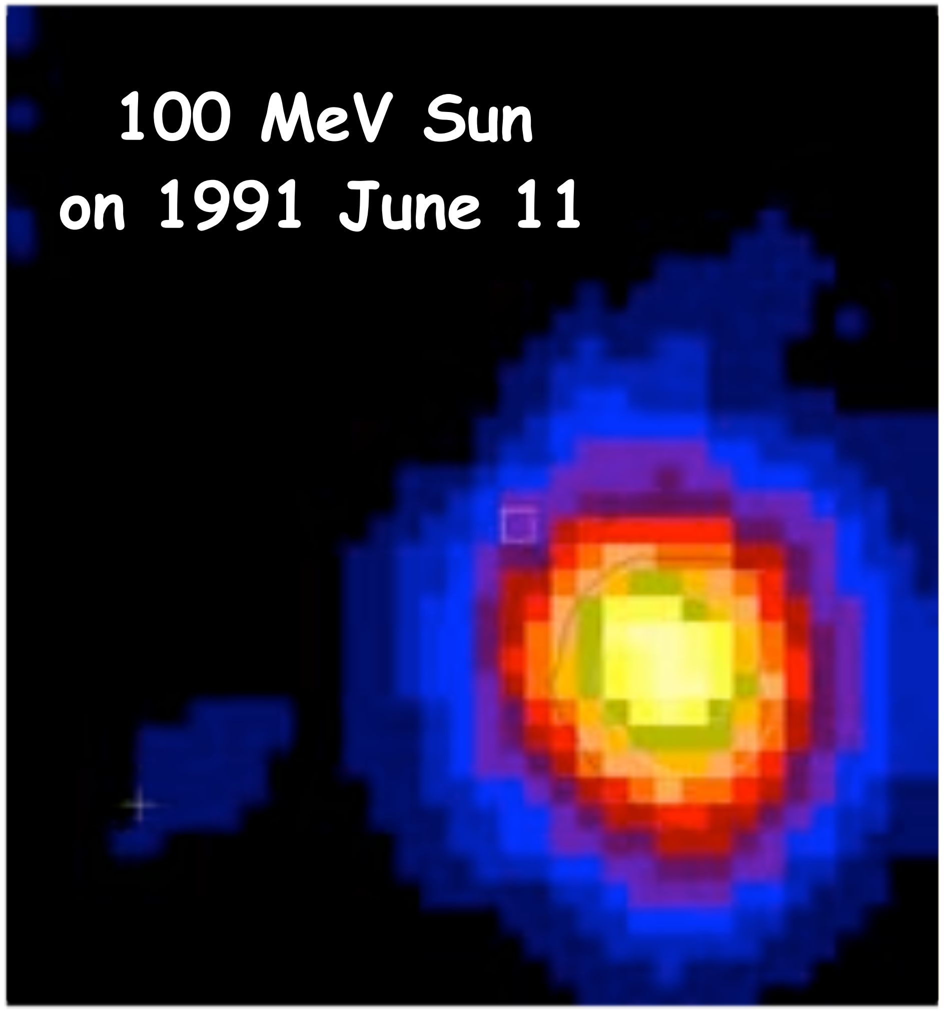
# Prolonged γ-ray Emission

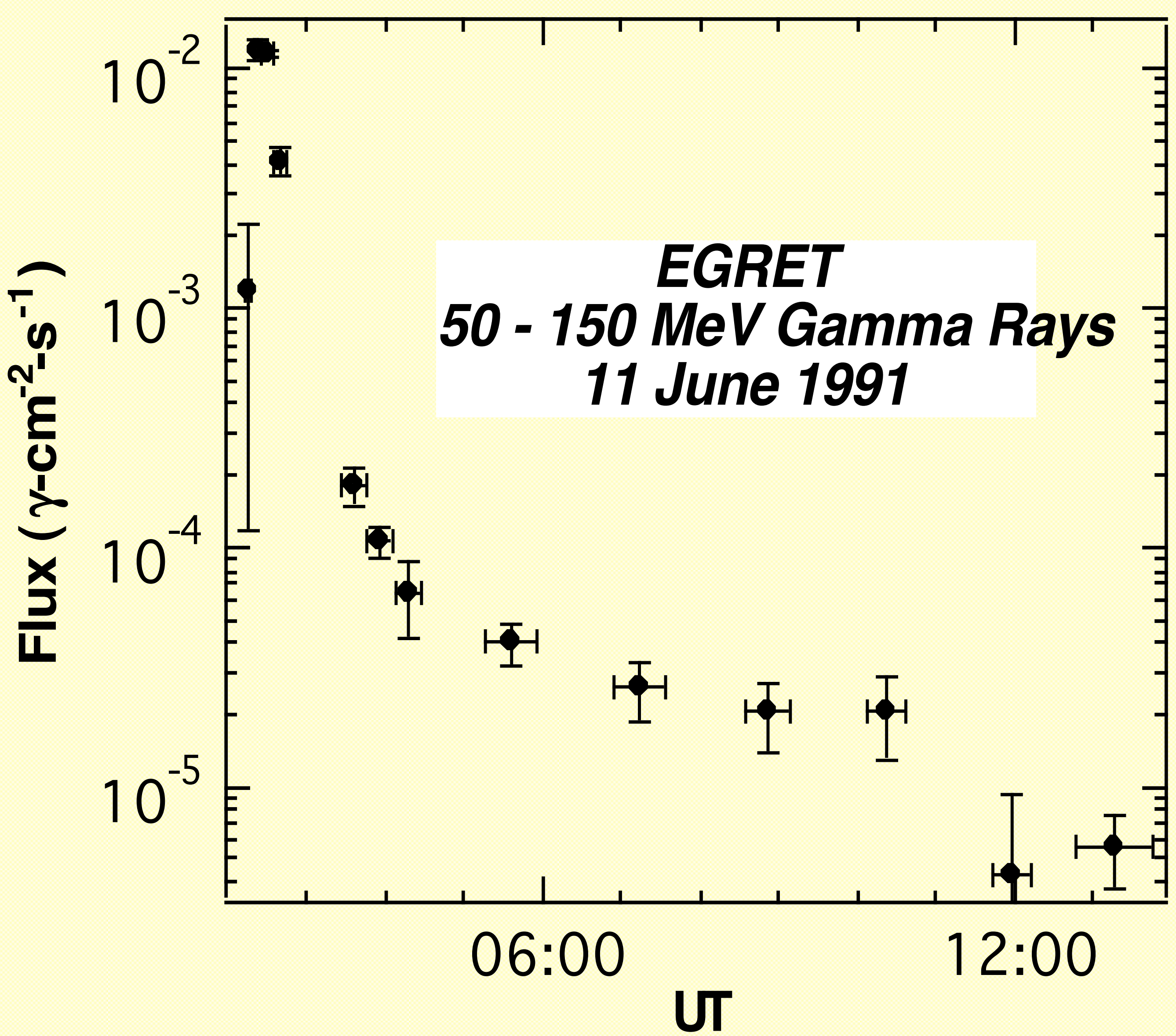



(Kanbach, priv. comm.)

- Steady >100 MeV emission, hours after impulsive phase
- Other examples:
- June 1, 4, 6, 9, 15

  (all from same region)

# Double exponential decay

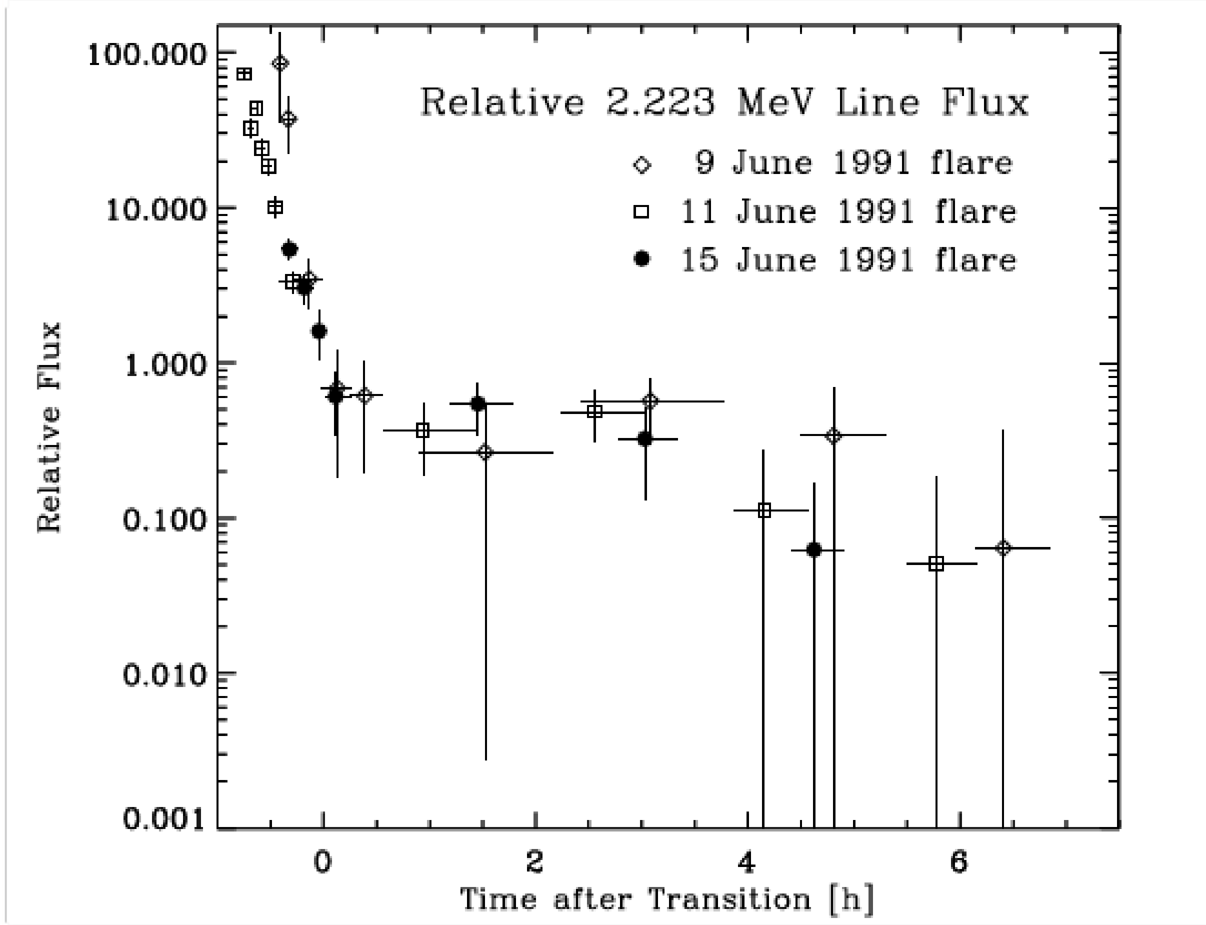



(Bertsch, priv. comm.)

- Slow, smooth decay of hi-E emission.
- 1/2 day afterglow

What is the nature of the emission?

# 2.2 MeV follows hi-E emission



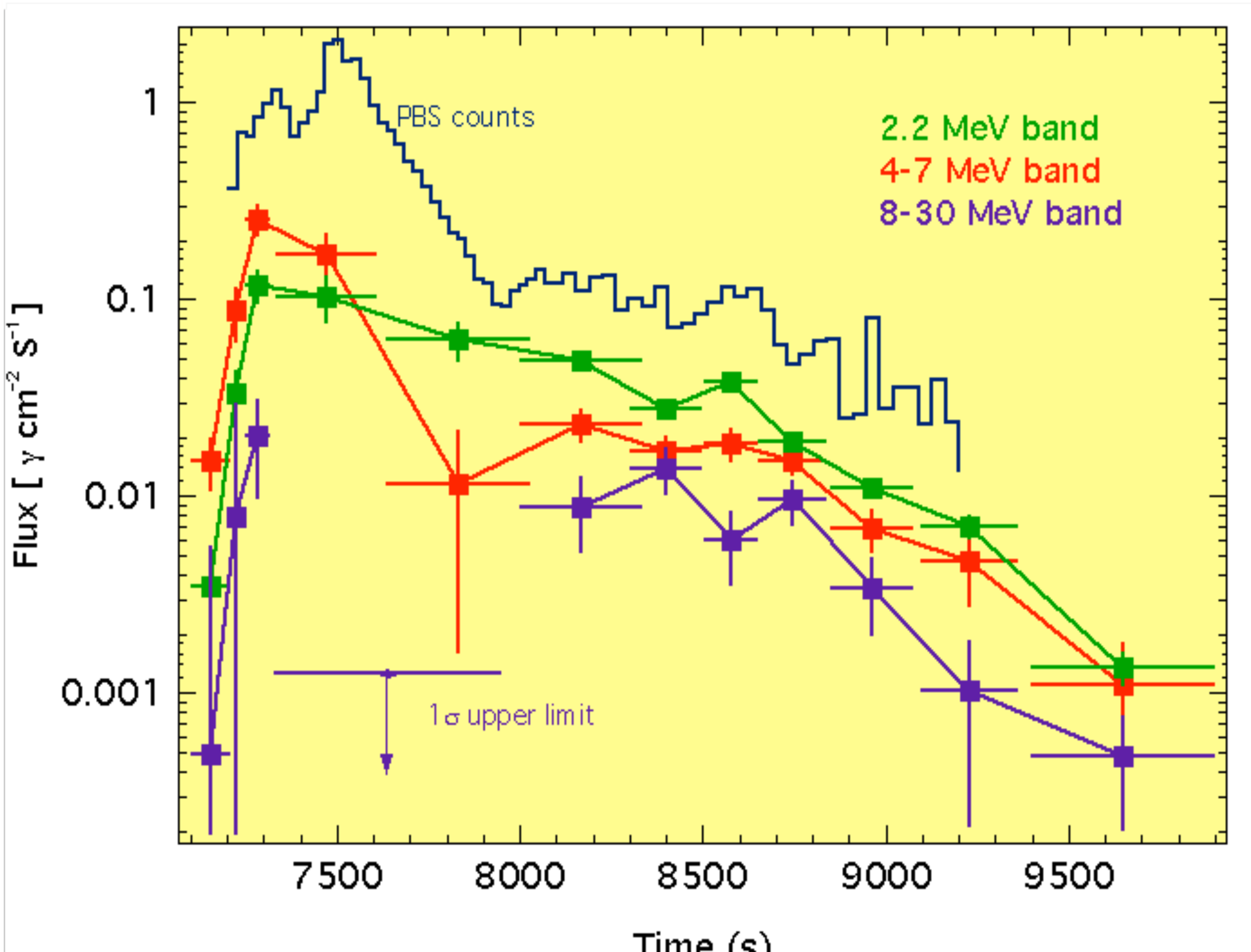

Rank et al. 2001

The widely different cross sections imply an invariant spectrum lasting for hours—balance between acceleration and losses. Also primary electrons are not significant here.

Three flares from same region with same time behavior!

# Two phases of June 11 hi-E event

- Hi-E emission shuts off for 10 minutes!



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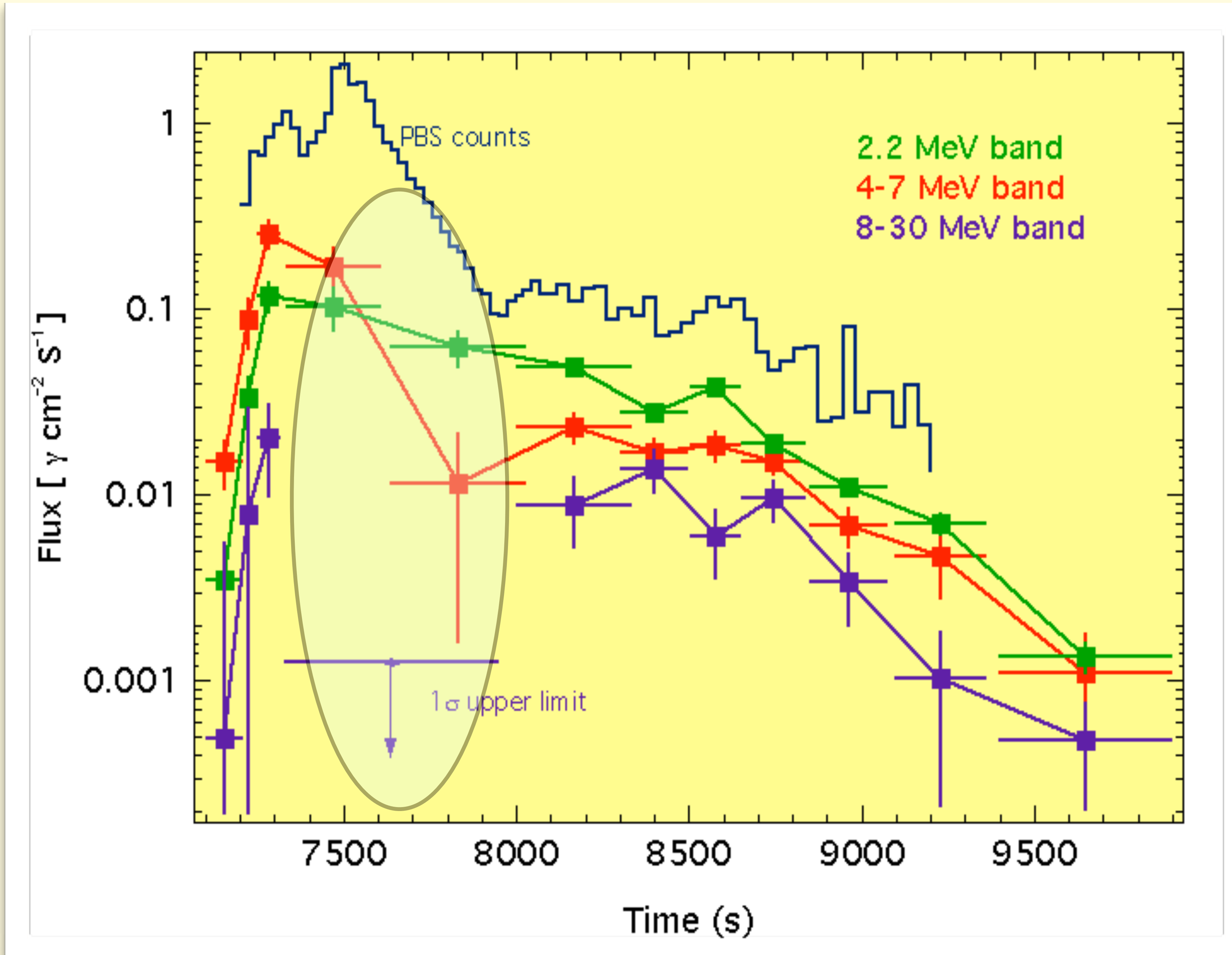

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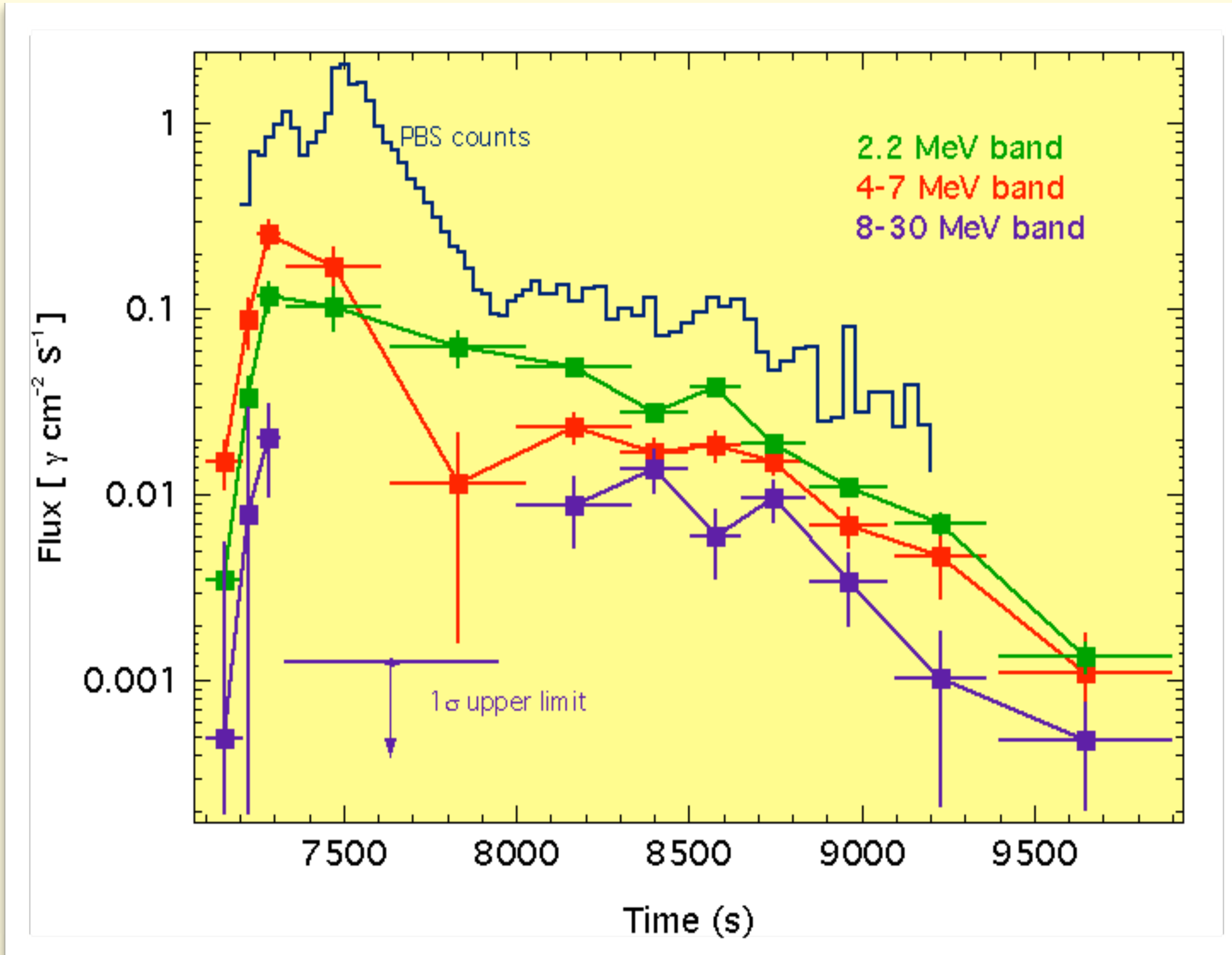
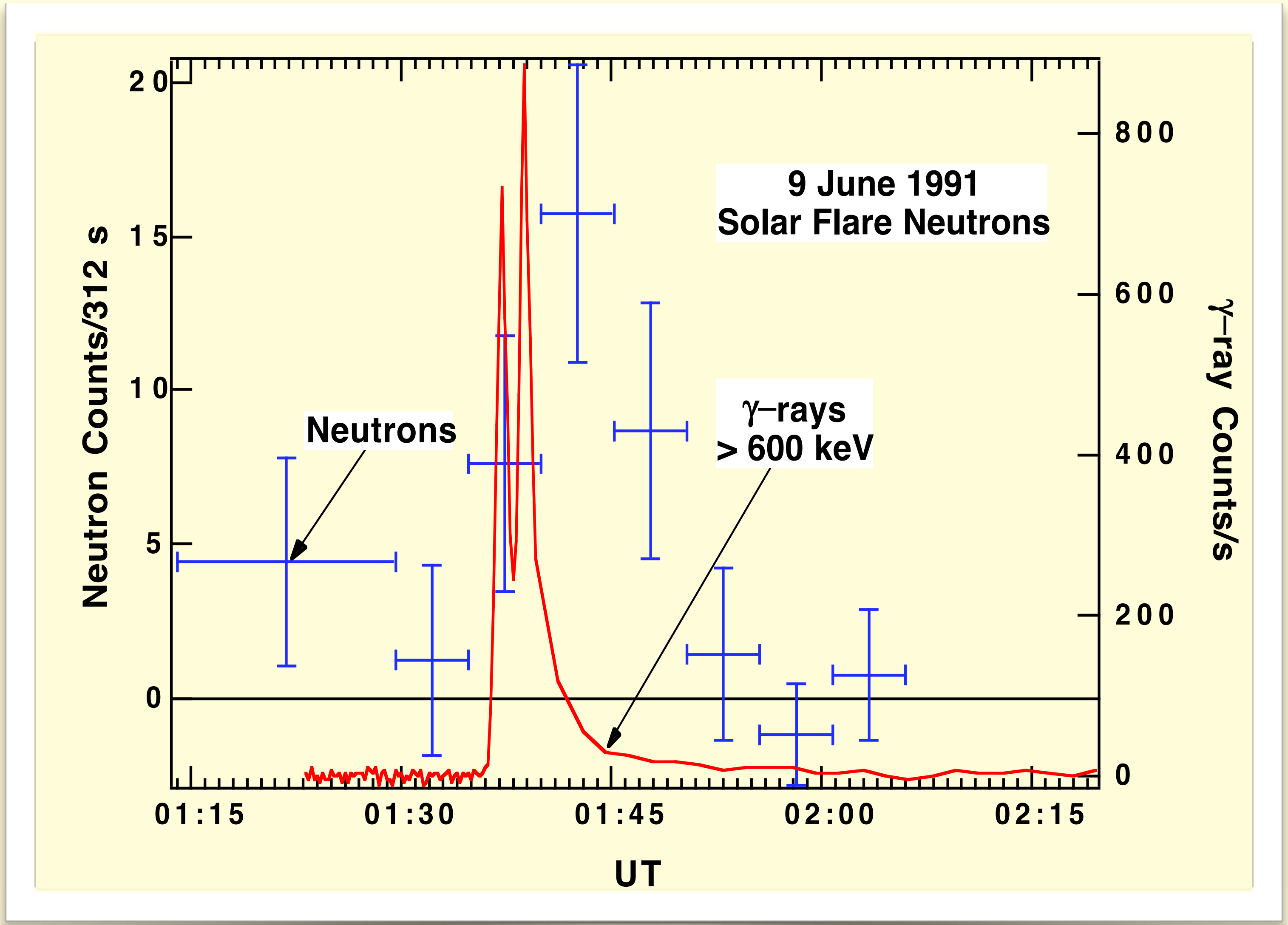


# Short-term spectral evolution




- Neutrons (higher E than nuclear γ rays) delayed
- 100 MeV γ rays delayed even further (not shown).

**The process is a continuous one. Middle energies can be sensed. The phase separation is due to the particle physics threshold.**

# Long Duration $\gamma$-ray Flares

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- Interactions of well known interplanetary GeV particles with ambient IP medium.
- Slow buildup of static **E** field in the restructuring high altitude corona.
- Trapping in turbulent static coronal structure.
- Cosmic-ray rain from shock-accelerated IP particles.

# Shock Accelerated Particles and Ground Level Enhancements

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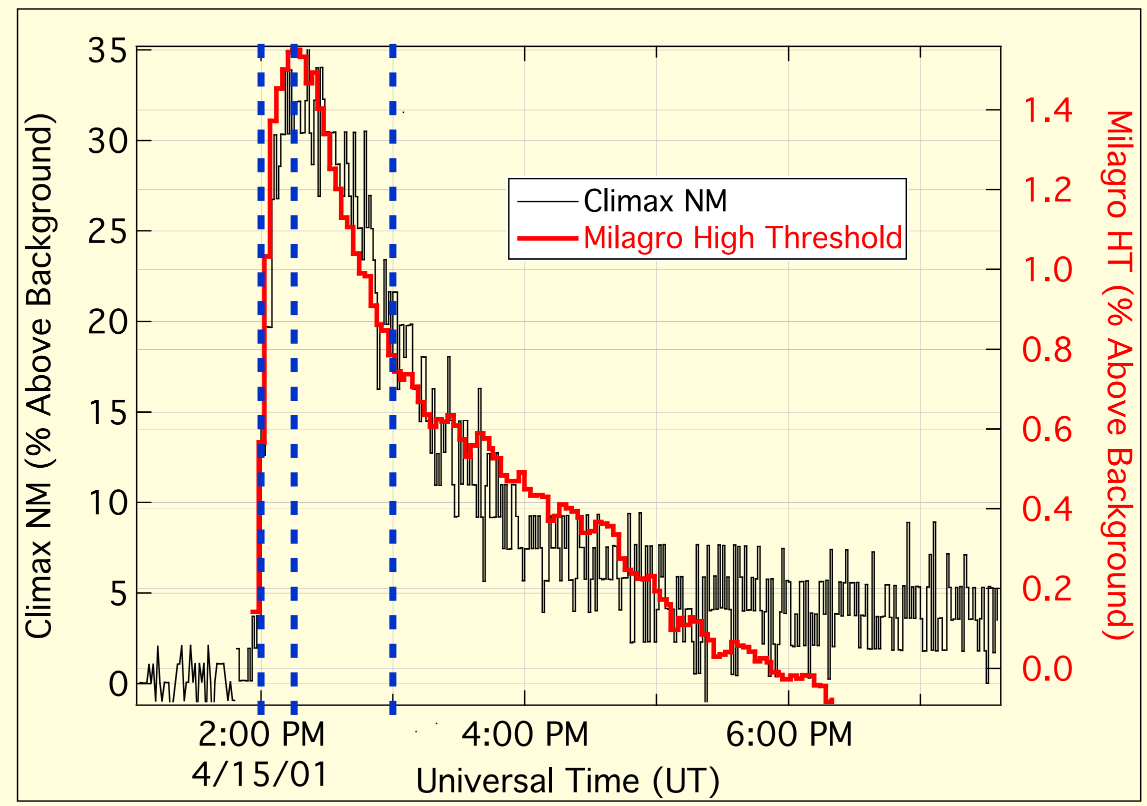
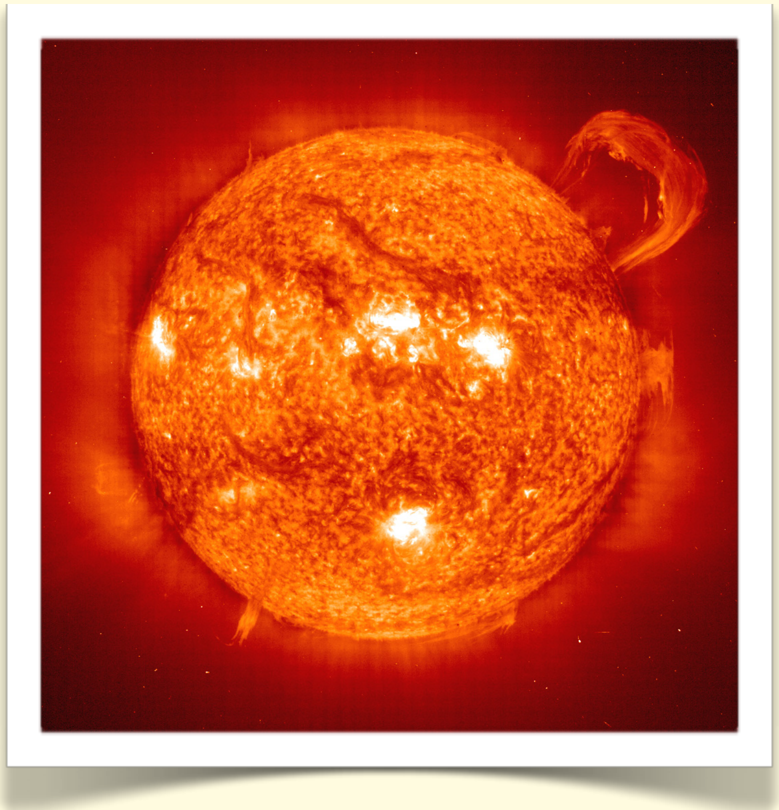


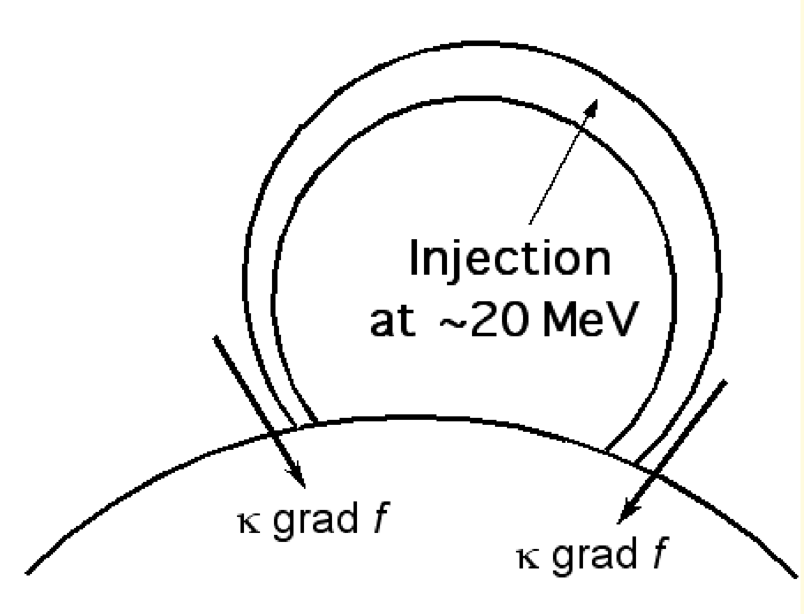

GLE particles at Earth

# The Model

1. Ions from impulsive phase injected into large (length $L$) magnetic bipolar structure
2. MHD turbulent plasma contains particles ($\lambda \ll L$)
3. Particle diffuse to ends of loop and precipitate onto dense atmosphere
4. Ions are accelerated by Fermi process along the way attaining high energies (100 MeV-1 GeV)

☞ **Prolonged high energy emission**





$$\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D \frac{\partial f}{\partial p}\right) + \frac{\partial}{\partial x}\left(\kappa \frac{\partial f}{\partial x}\right) + Q$$

- Spatial transport coupled to momentum transport ($\tau_p \tau_x$=const.) and threshold effects (300 MeV for pion creation) produces delayed hi-E onset.
- While particles are being transported to footpoints, they are being accelerated and once above $\pi$ threshold they begin to emit $\gamma$ rays (lower threshold for 50 MeV neutrons).

# Time Scales

Diffusion losses at ends of a 1-d trap (Newton's heat eqn.)

$$\tau = L^2/(\pi^2\kappa)$$

Acceleration time

$$D_0^{-1}$$

Collisional loss time in $10^9$ cm$^{-3}$ medium

2 weeks

Gradient and Curvature drift loss in

$(10^5$ km$)^3$ volume (B = 10 G)

$$10^4 \text{ s}$$

# Interpreting the June 1991 Events

The two disparate decay times imply two distinct trapping volumes of different dimensions.

With $\tau_1$ = 500 and $\tau_2$ = 13,000 s and assuming drifts do not contribute to the loss (especially initial decay), what is required to achieve acceleration to relativistic energies with these loss times?

Because ion spectrum shape is stationary,

☞ acceleration more efficient than diffusion, i.e.,

$\tau \gg D_0^{-1}$, so $\lambda \ll L$ ($\kappa$ small) and $L$ large.

We know the diffusion loss times for the two traps—560 and 13,000 s, but we also see that the rise of the hi-E emission after the impulsive phase is of order 100 s. We can combine these to arrive at typical length scales for the system.

$$\tau = L^2/(\pi^2\kappa) \text{ and } D_0 = {V_A}^2/(9\kappa)$$

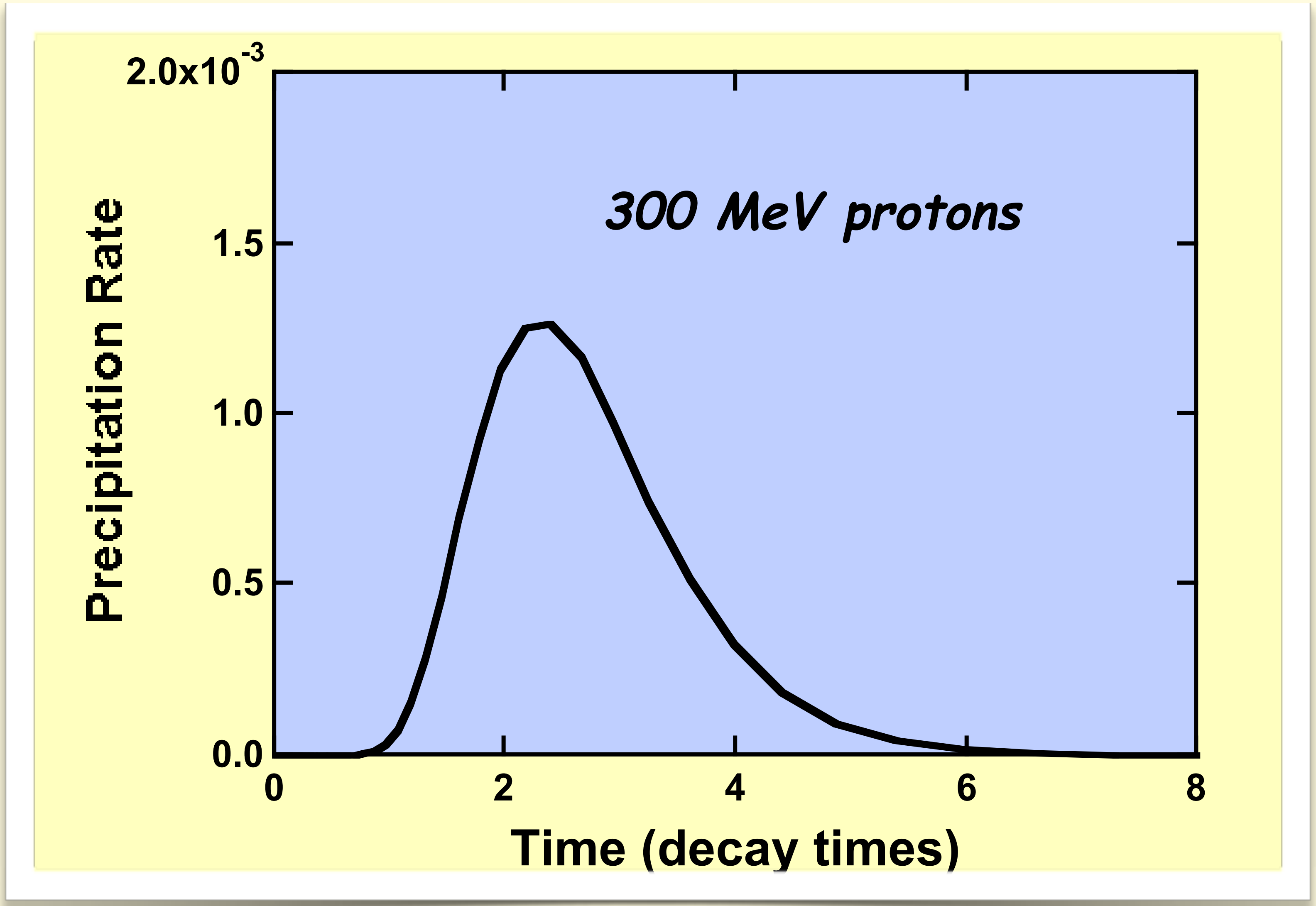
Schlickeiser (1986)

☞ $$D_0 = \tau\,({V_A}^2/L^2)$$

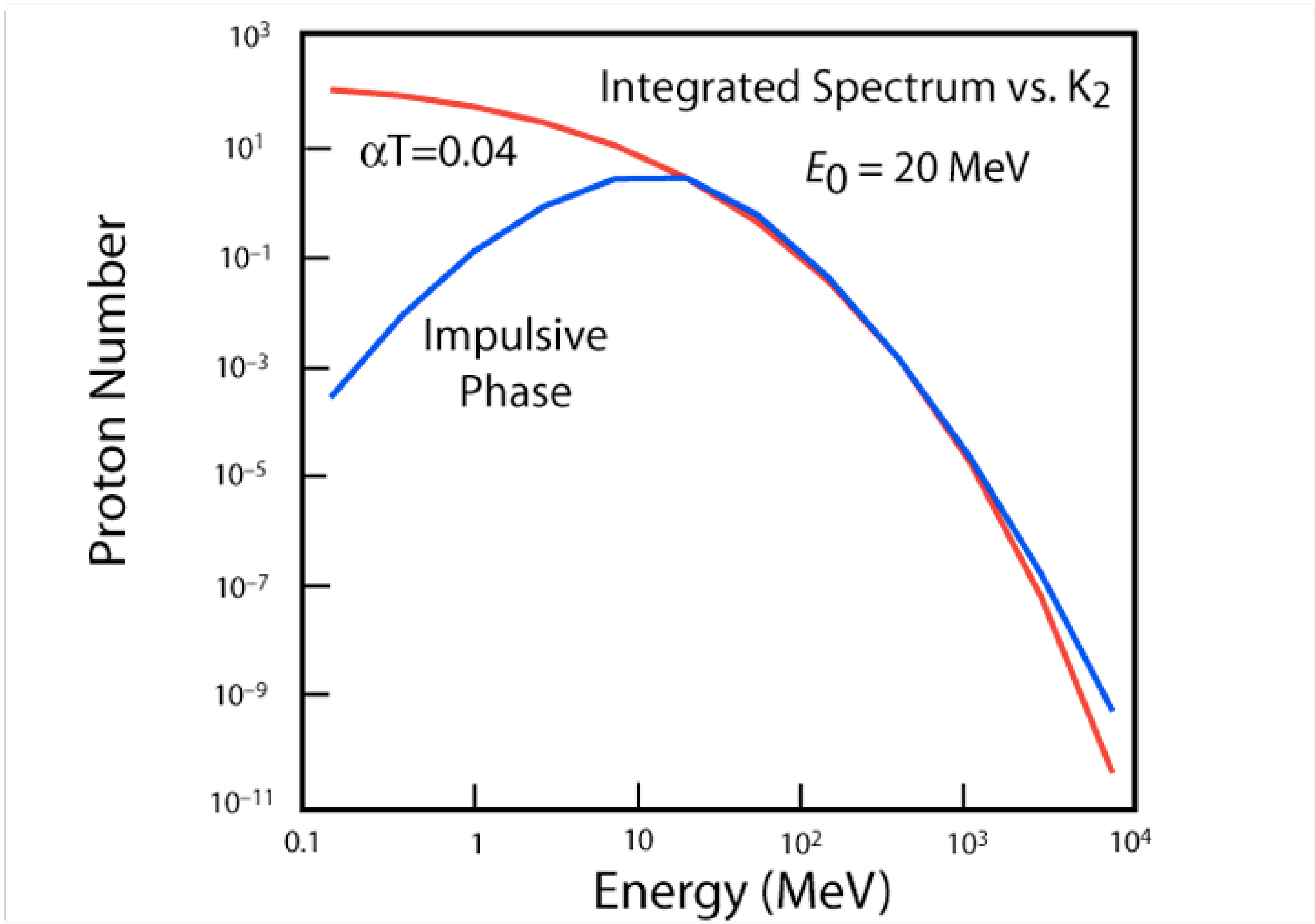
We get reasonable values of $D_0$ that have a fast enough rise time with measured decays for the two phases when $L$ = $2\times10^5$ and $10^6$ km, respectively. (Assuming $V_A$ = 1000 km-s$^{-1}$)

# Impulsive Response

- Combined threshold and transport effects delay peak time
- $D \propto p^2$ and $\kappa$ indep. of E



# Particle Spectrum




- Impulsive input produces a "standard" Bessel proton spectrum.
- Power law for entire flare.

# What conditions do we need?

- Large loops (big event) $>10^{10}$ cm for large $\tau_x$.
- Reasonable turbulence level in Alfvén waves ($\delta B/B \sim 10\%$) for large $\tau_p$.
- Maintenance of turbulence within loop through prolonged excitation or trapping in resonant cavity.
  - Transit time of waves too short.

# Other Possibilities

- Precipitating hi-E ions from GLE-producing CME. Protons swim upstream to reach photosphere where they radiate. Time scales not unreasonable. No attempt at theoretical description yet. Homologous hi-E flares and stationary spectrum could be a problem (Kahler and Ragot).

- Long duration reconnection produces large scale standing current sheet with huge electric potential (Litvinenko)