Modeling the 2017 September 10 Long Duration Gamma Ray Flare

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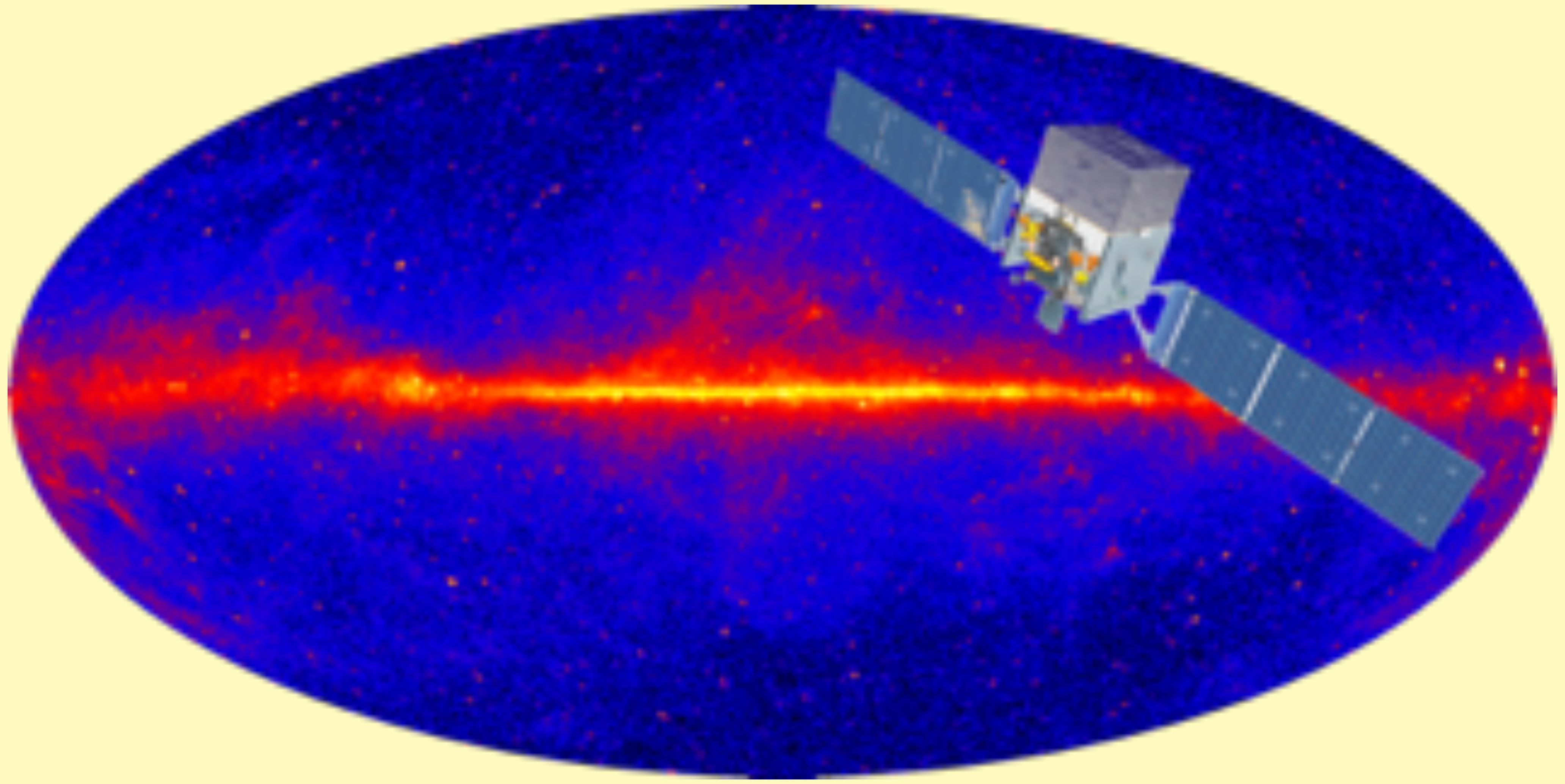
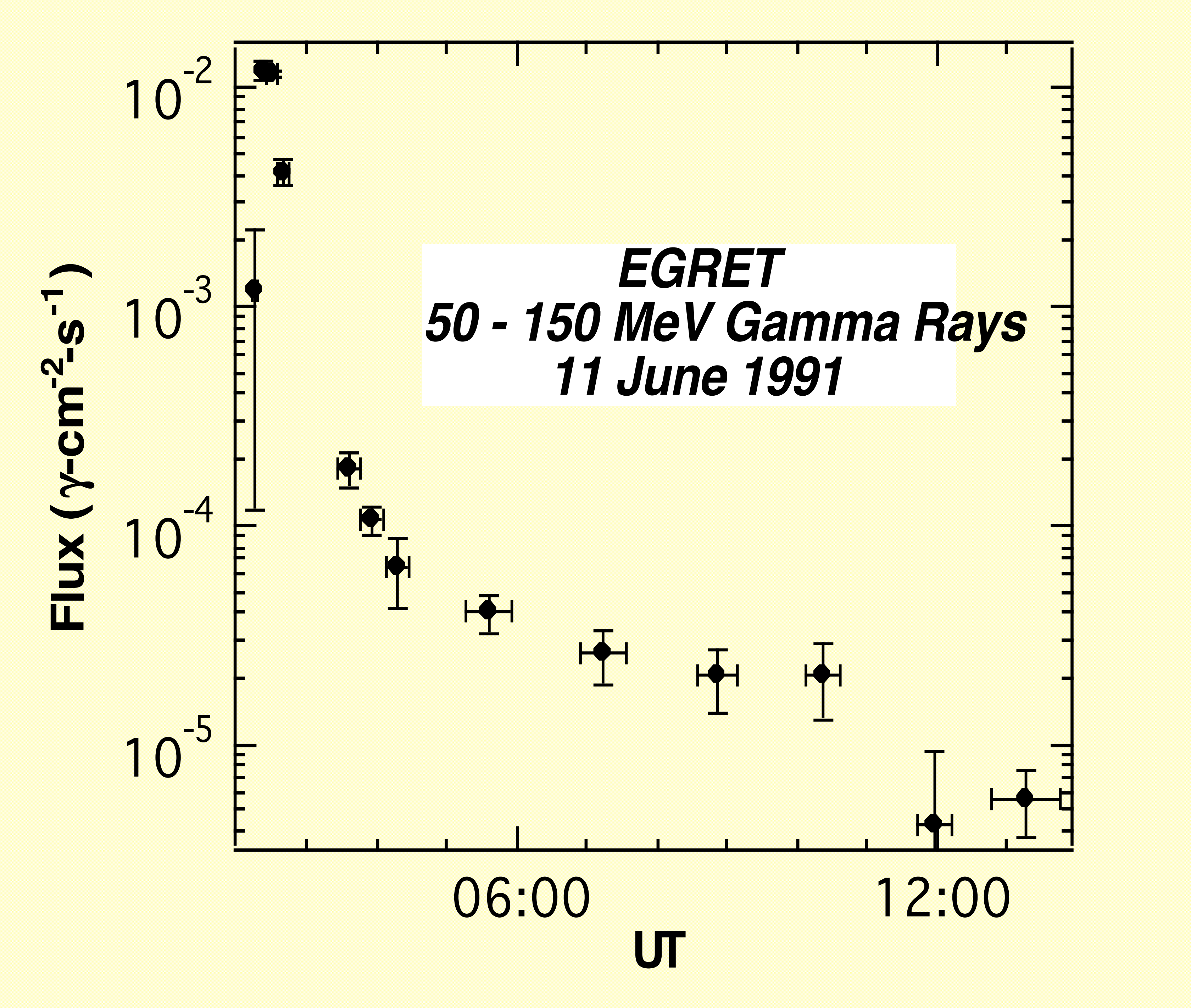
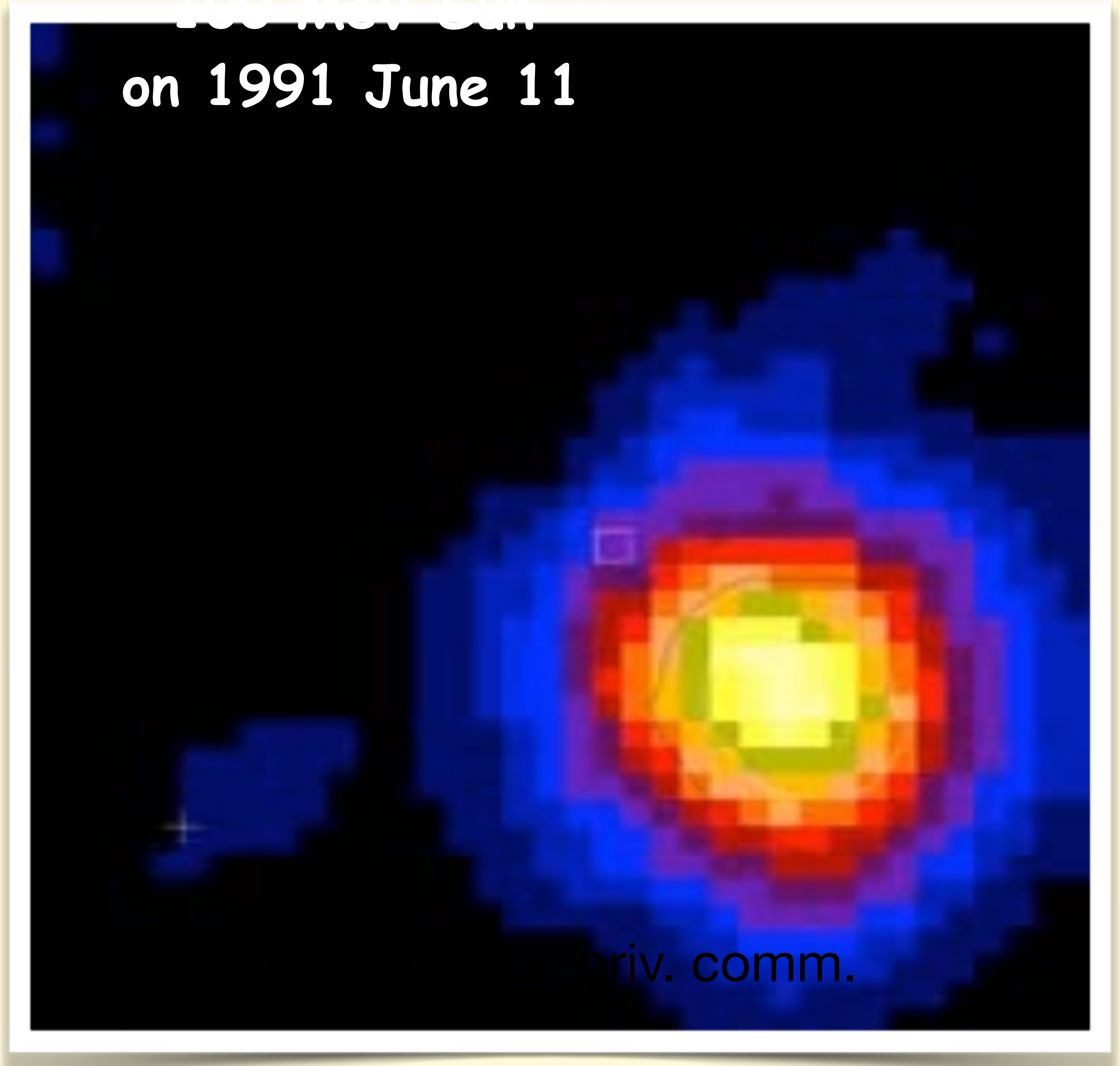


Long Duration Gamma Ray Flares

- Multi-hour >100 MeV γ-ray emission.
- Spectrum often >1 GeV.
- Starts many minutes after the HXR and μ-waves.
- Continues while all other flare-related emissions have ceased.
- No detectable electronic component.

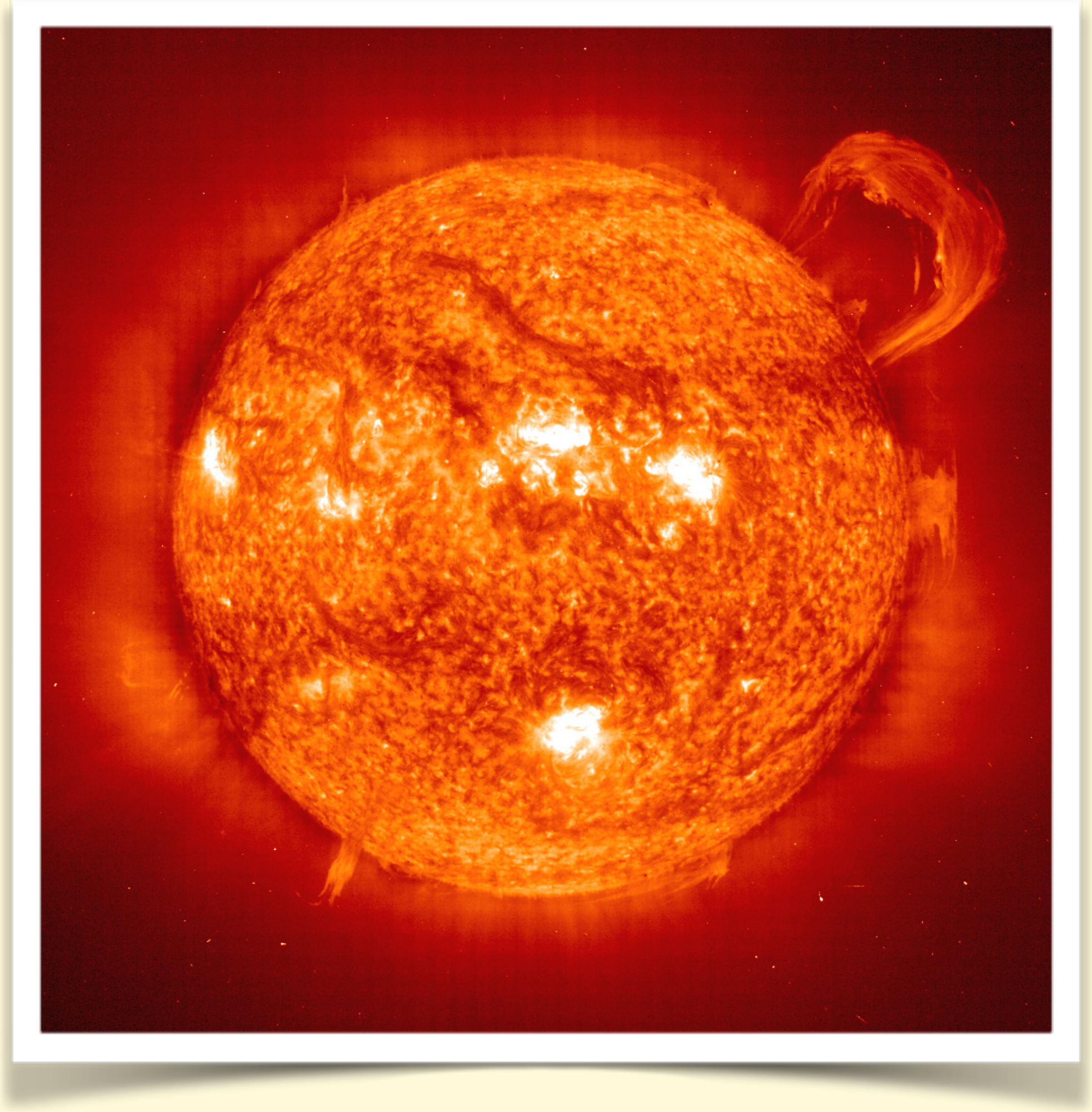


8 hour exposure starting 90 minutes after the flare

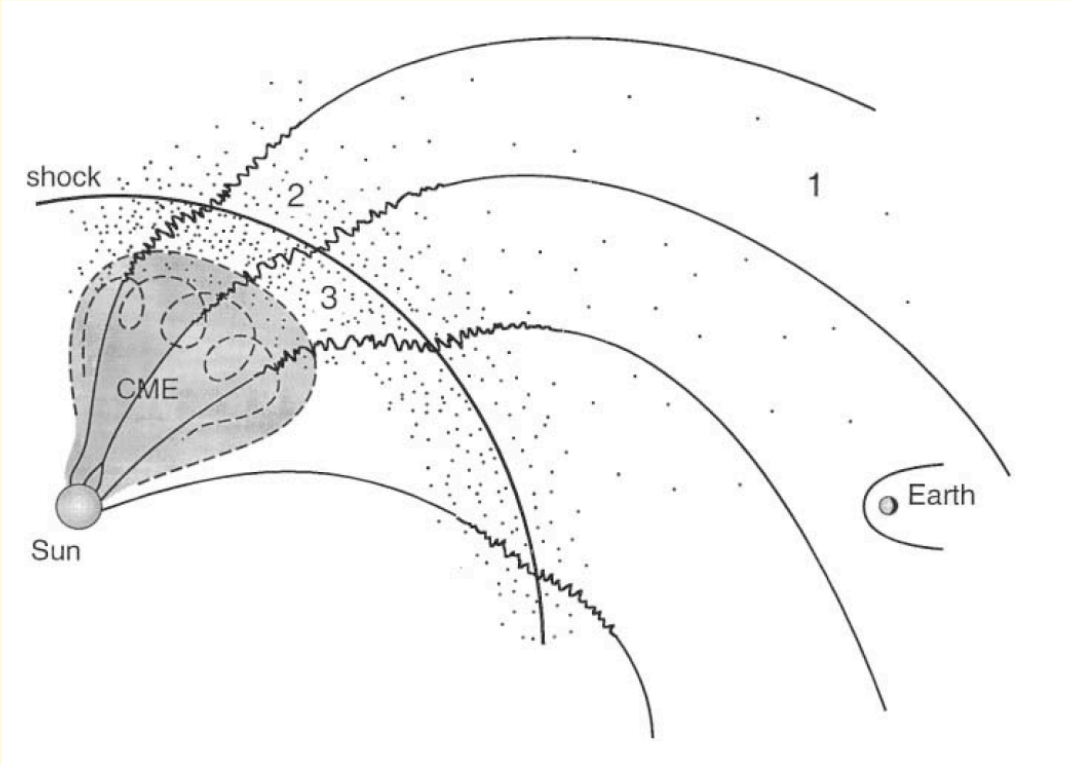


Two Competing Scenarios

Trapped and continuously accelerated in large coronal structure (local)

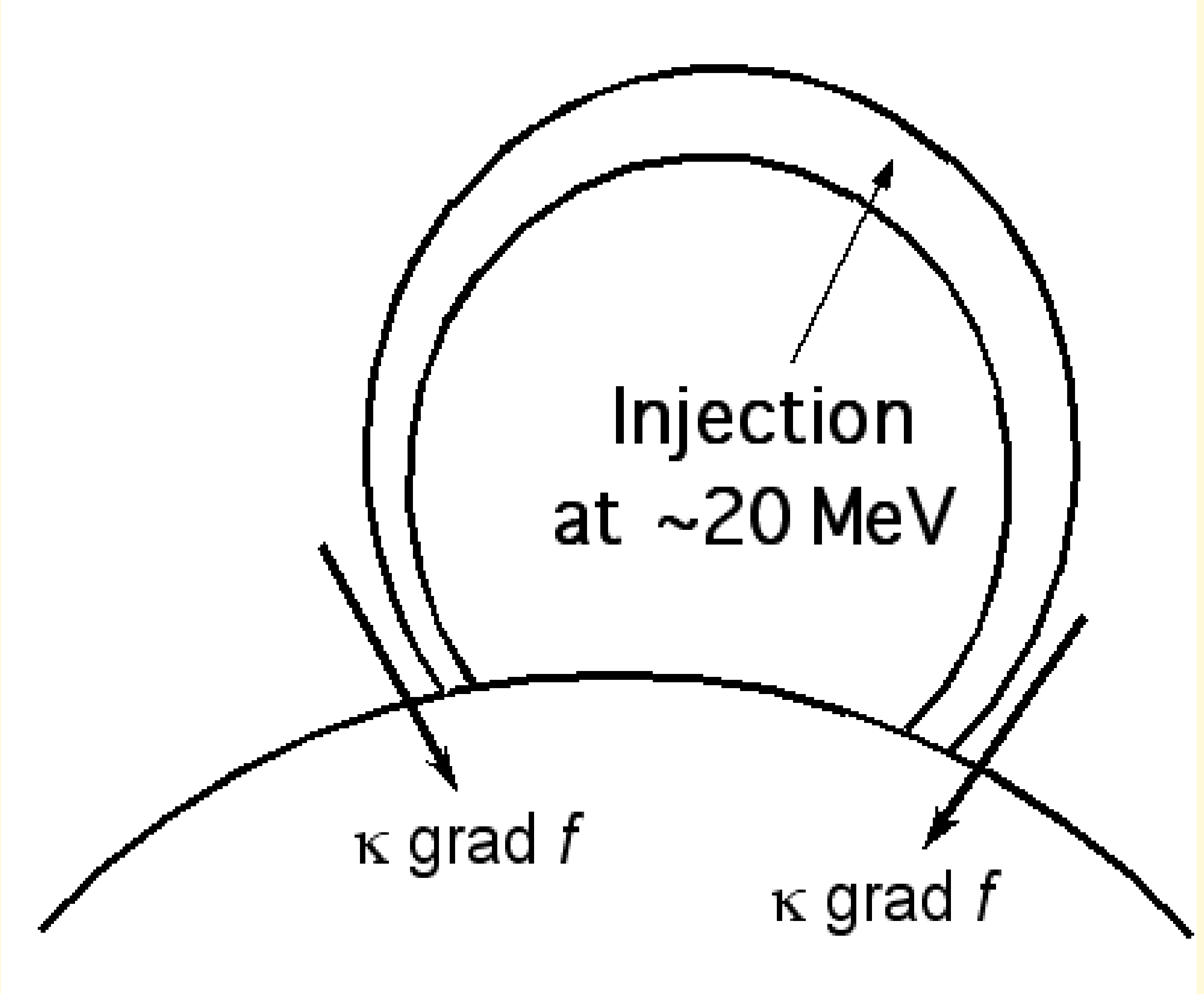


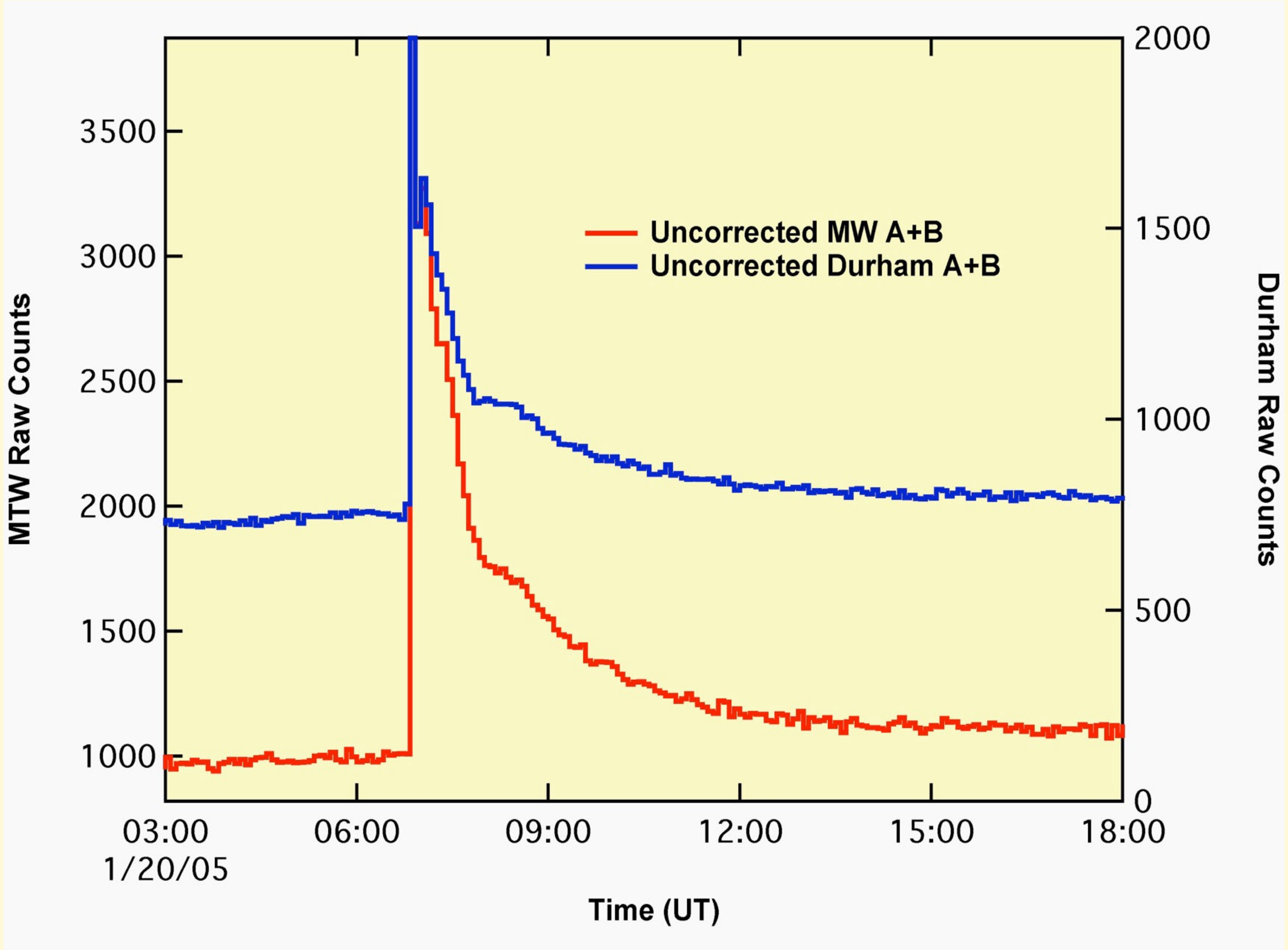
Accelerated at shock, then transported back to the Sun (remote)



Protons obey spatial and momentum diffusion (second order Fermi)

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





Unresolved Controversy

<u>Problems with Remote Acceleration</u>

- No robust model for transporting particles back to Sun.
- Wildly discrepant numbers of particles estimated in space and at Sun.
- Some events require ~100% of IP particles to precipitate back to Sun.
- "Flare" spectrum significantly harder than IP spectrum.

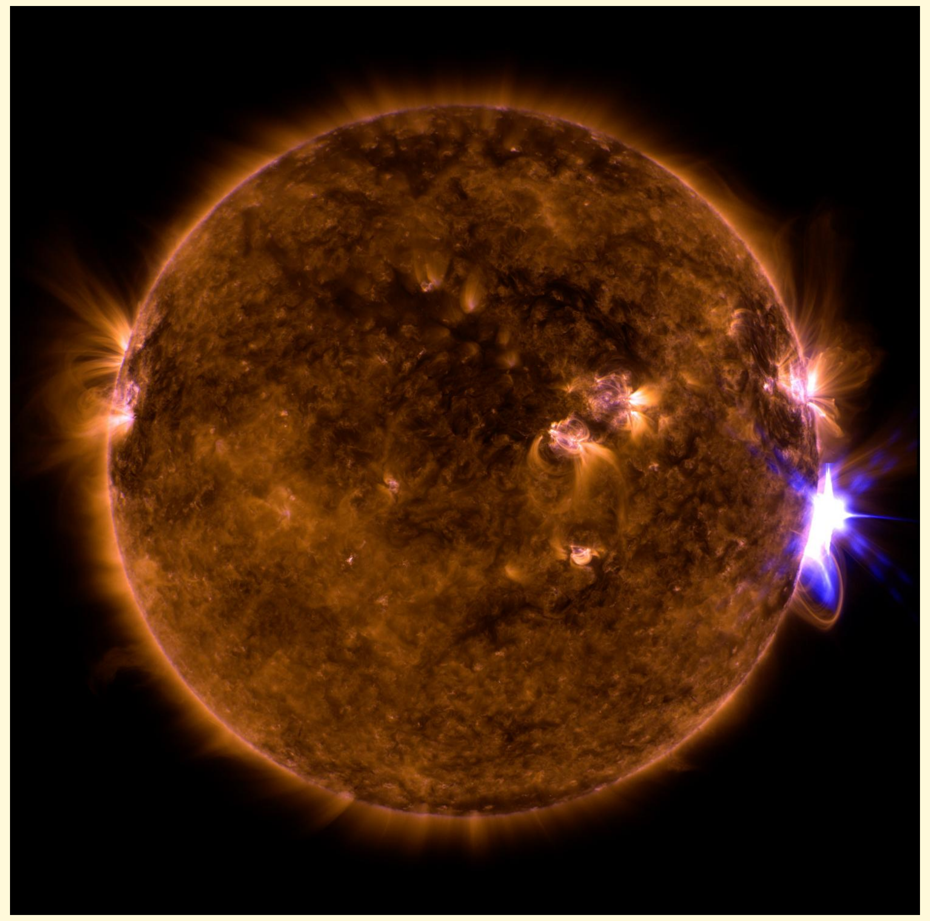
<u>Problems with Local Production</u>

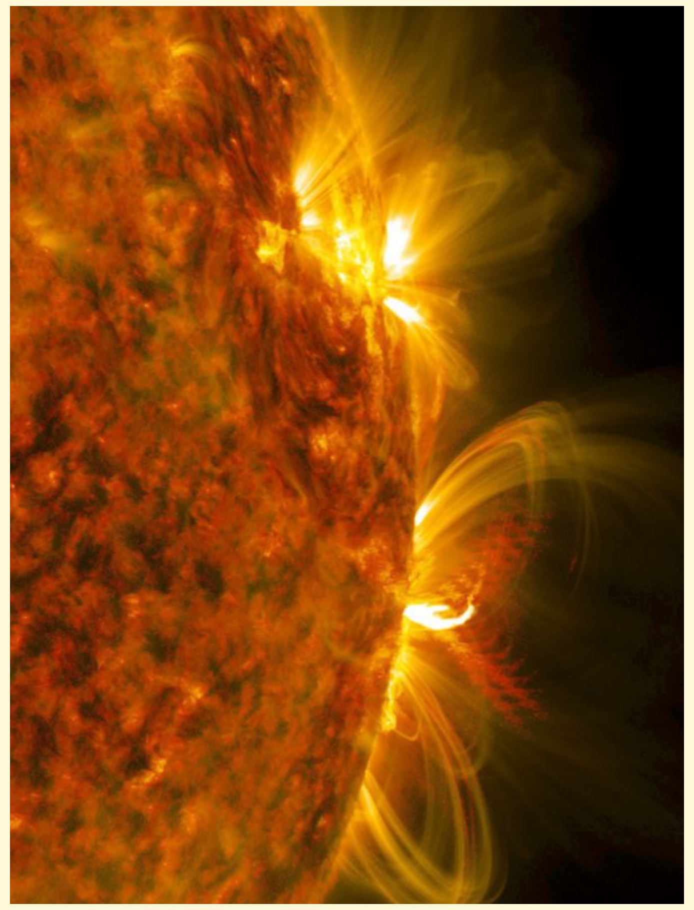
- Maintaining wave field for hours.
- Large loops quite common, but difficult to visualize.
  ✓ Little glowing gas (SXR).
- With no direct indicator of loop size, difficult to estimate κ from l.

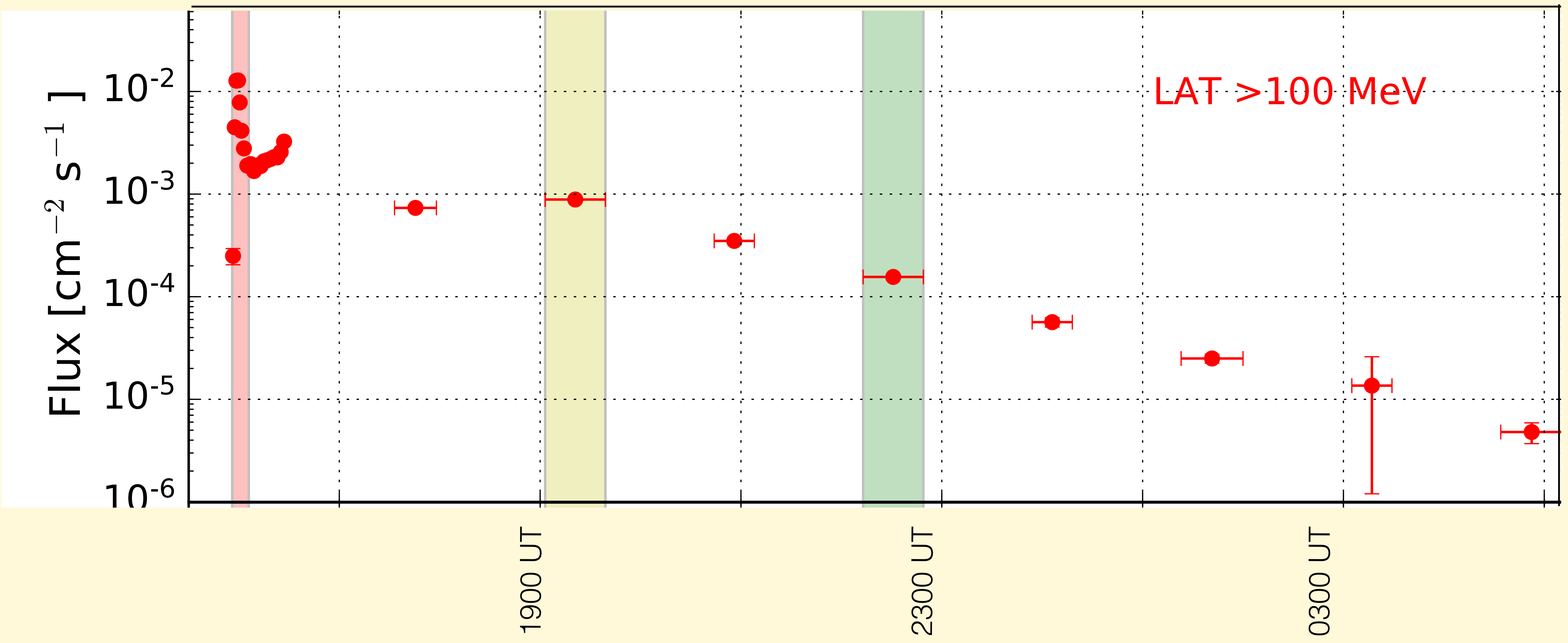
2017 September 10

This event is the best yet in terms of revealing the coronal environment.

SDO/UV images
Full Sun and reduced FoV



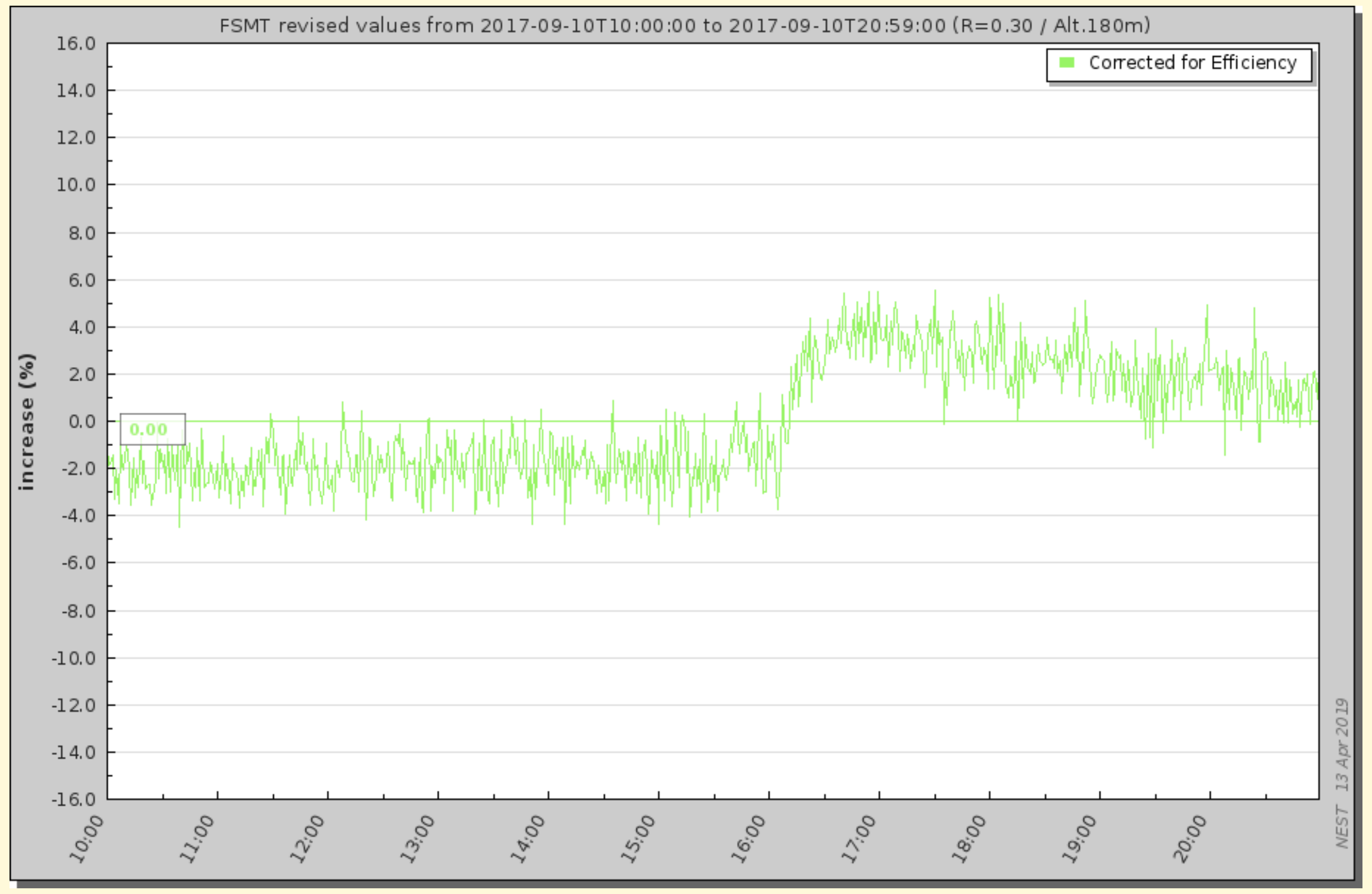




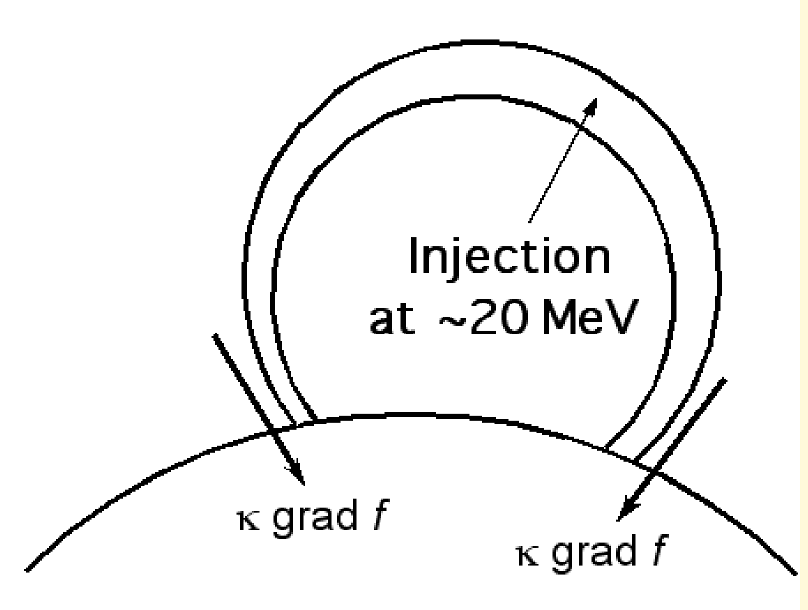
GeV Protons

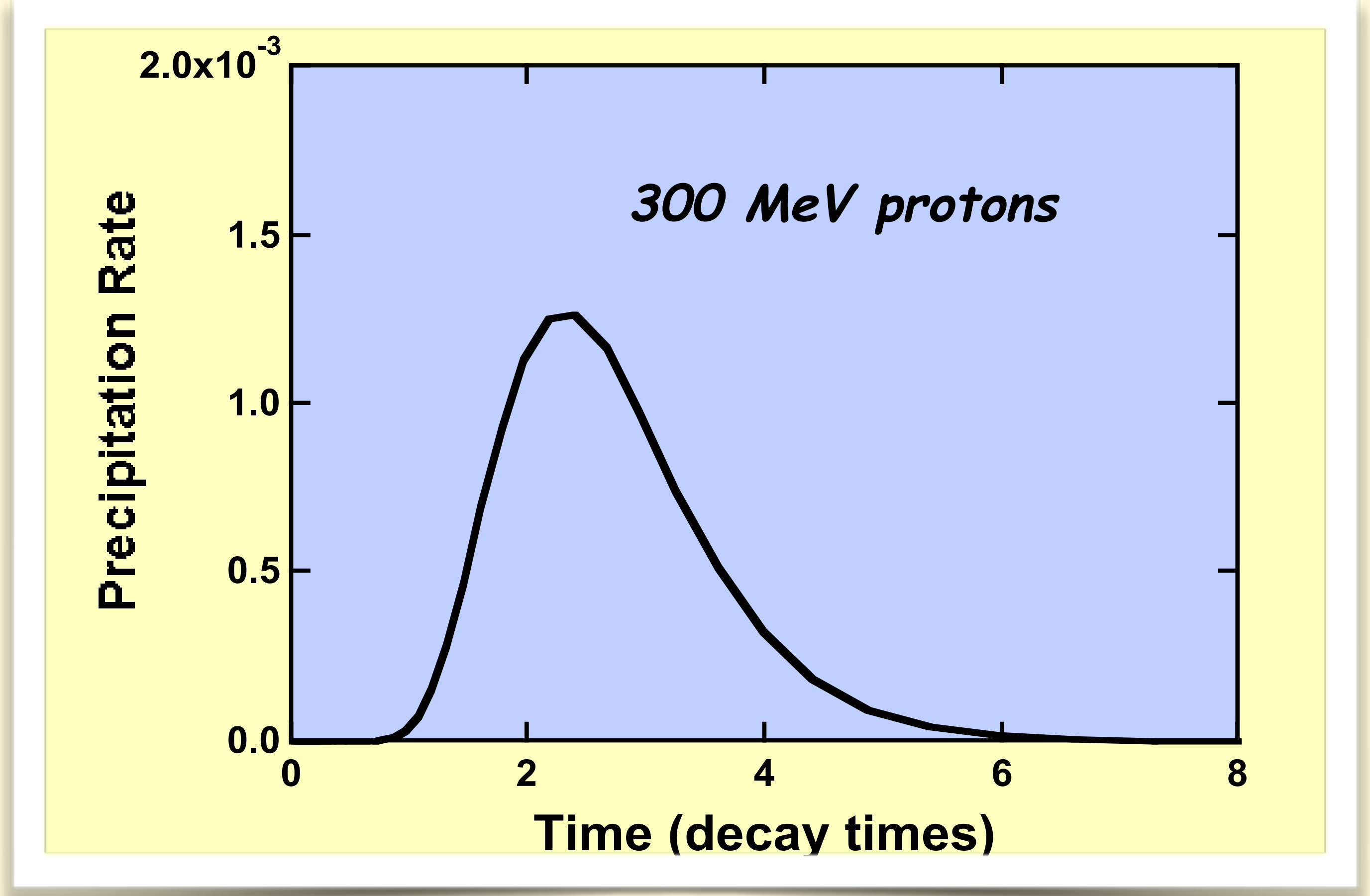
At Sun

At Earth



The Model





1. Ions from impulsive phase or shock injected into large (length *l*) magnetic bipolar structure.
2. MHD turbulent plasma traps particles ($\lambda \ll l$).
3. Particles diffuse to dense atmosphere.
4. Ions accelerated by Fermi process to high energies (>300 MeV)

☞ **Prolonged high energy emission**

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

- No other losses
- Constant coefficients, but coupled diffusion in momentum/real space, i.e., $\tau_p \tau_x$=const.
- Free parameters: length, injection point, Alfvén speed

The Process

$p + {}^4He \rightarrow X + \pi^{\pm}$
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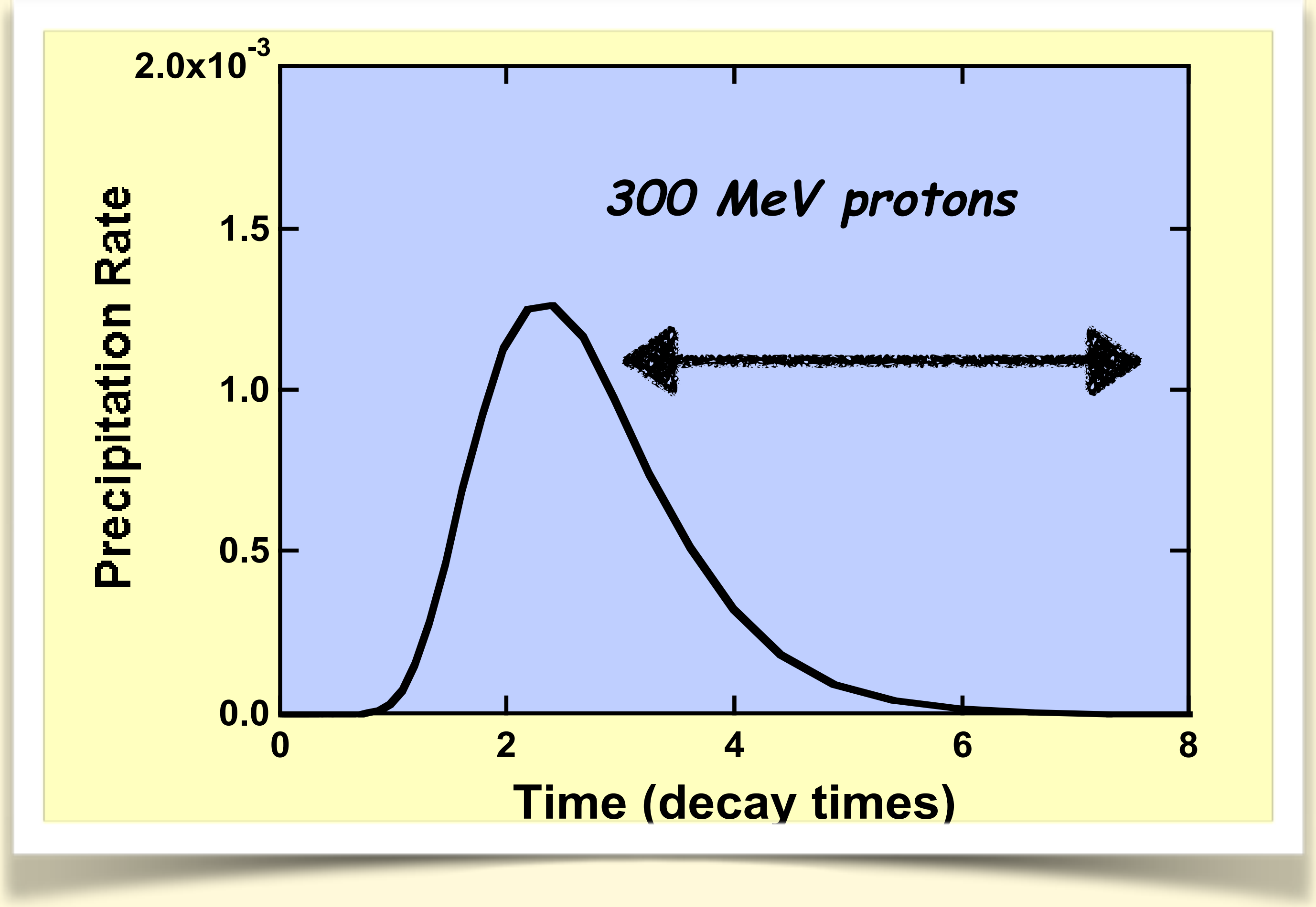
or π^0

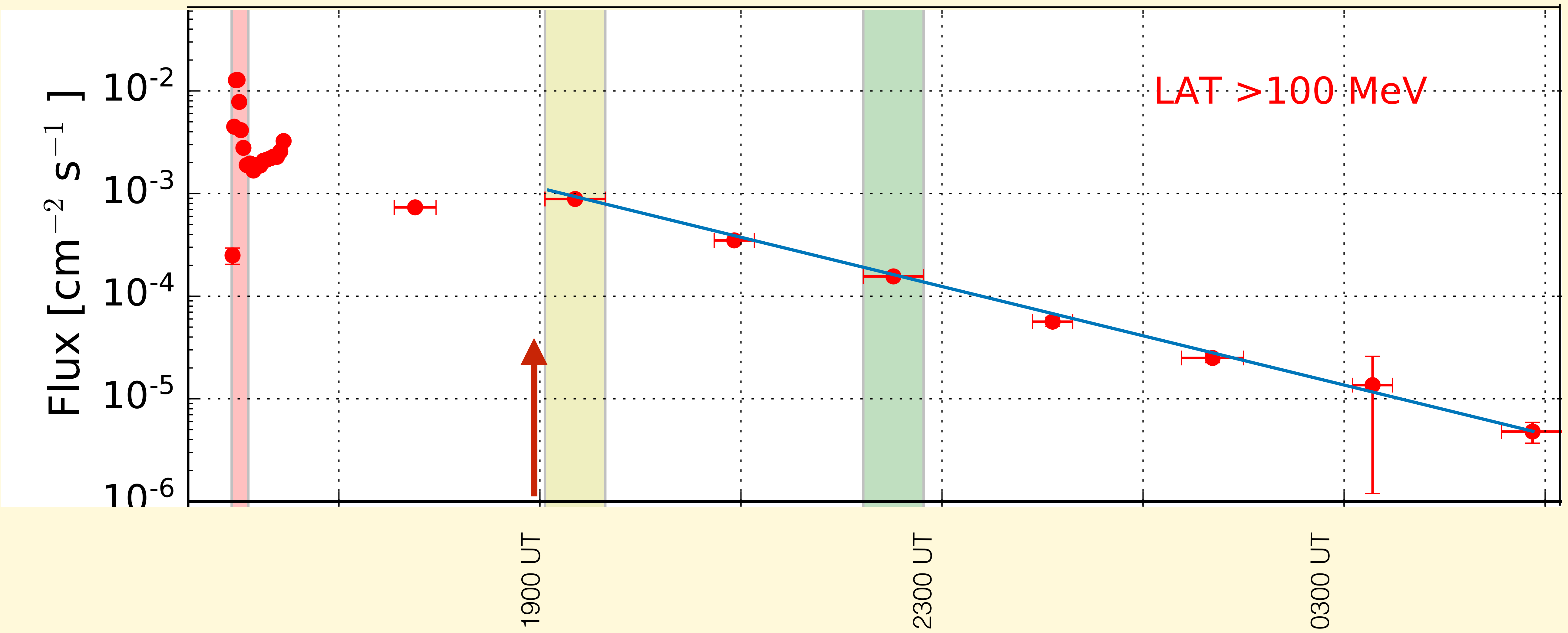
→ Doppler Broadened 69 MeV γ

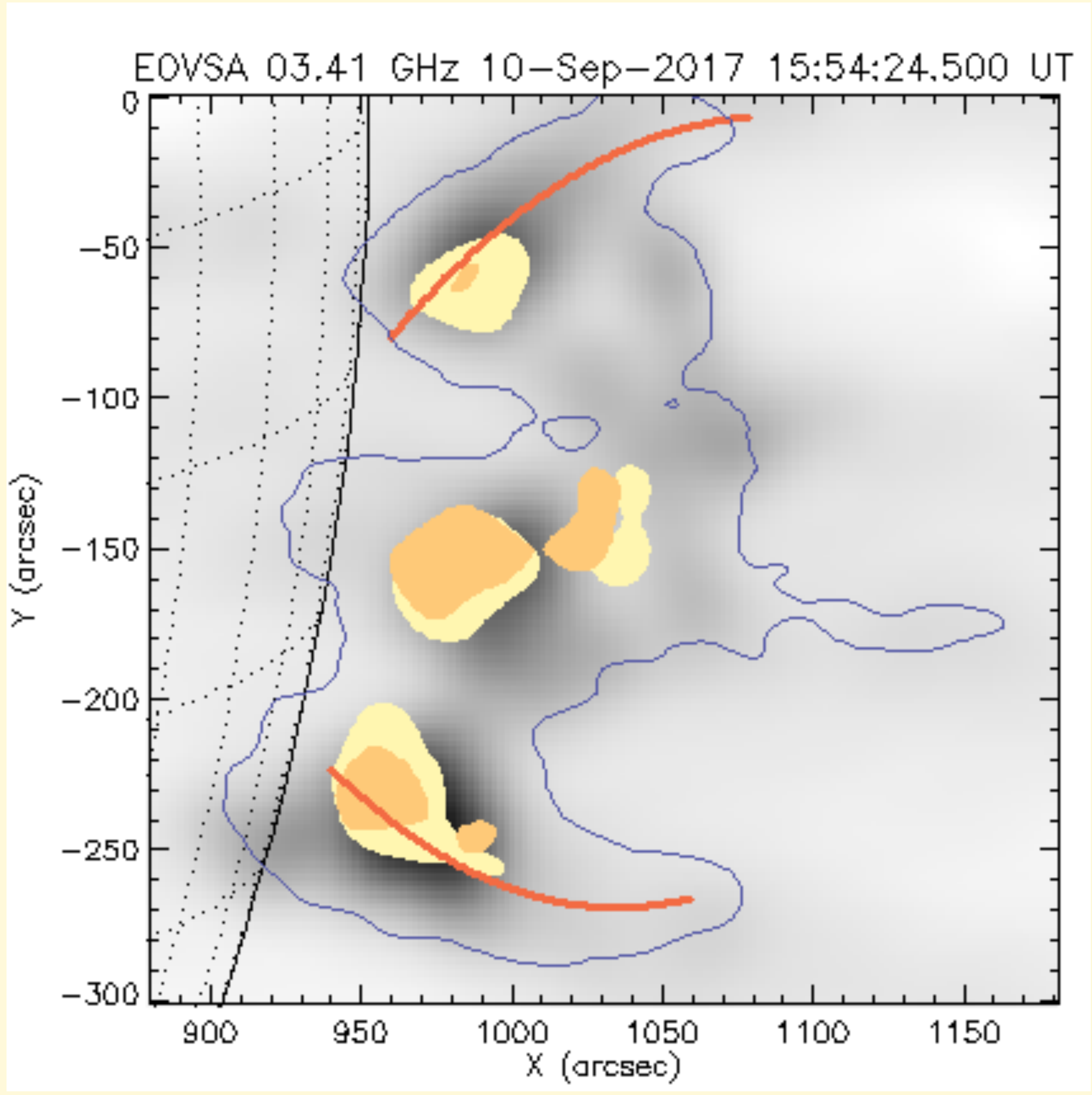


Simple model the precipitation of high energy protons (> 300-MeV) π threshold.

But first, we have see if we are in the ballpark:

- Focus on the exponential decay (drives the diffusion coefficient),
- Estimate structure dimensions from new EOVSA imaging data.





100 MeV γ Photometric Curve

- Smooth exponential decay after 1900 UT, 3 hours after CME liftoff.
- $J \propto \exp -(t/6500\ \mathrm{s}) \pm 20\%$
- 95% confidence γ "imaging" centroid location encompasses all features on the μ-wave image (on right) during this phase.
- Parent proton spectrum softens from –4.3 to –6.0.

Event Integrated Image at 3.4 GHz

- Reveals a complete inner region associated with the lower half of a reconnection event (beneath a CME).
- Reveals footpoints of a larger loop with height of 0.4 $R_\odot$ and length 1.4 $R_\odot$.

So how does this stack up?

- The 6500-s decay and $l = 1.4\ R_\odot$ ($\tau_x = l^2/\pi^2\kappa$) ➜ λ (= 3κ/υ) of 200 km (✓),
- 200 km λ implies a $k^{-5/3}$ integrated wave intensity of 0.7 ergs-cm^{-3} (Lee, 1983),
- 1 G B field of at loop top ➜ $\delta B/B$ of ~10 (✕) at top and 0.4 at base (✓),
- Acceleration time τ_a (= $9\kappa/V_A^2$) requires only V_A ∼140 km-s^{-1} (✓).

Things to note

- κ is a lower limit, because the spectrum softens, i.e., λ will be greater,
- Fewer demands on wave intensity ($\delta B/B$),
- Is B truly dipolar? Check against B-field calculation and
- More realistic model including other loss mechanisms, energy dependent κ, $\nabla_\parallel B$, and realistic wave dynamics.