Fermi and the Sun

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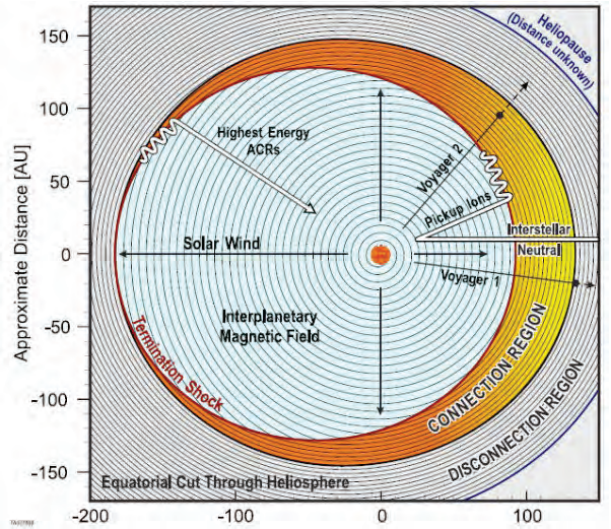
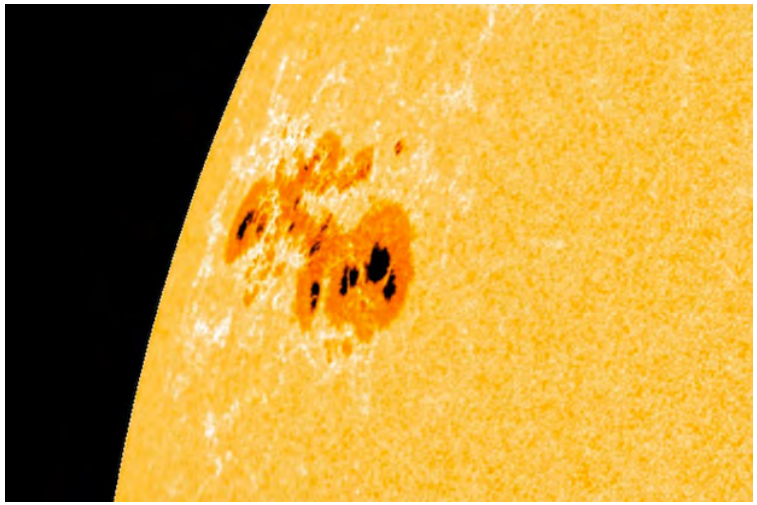
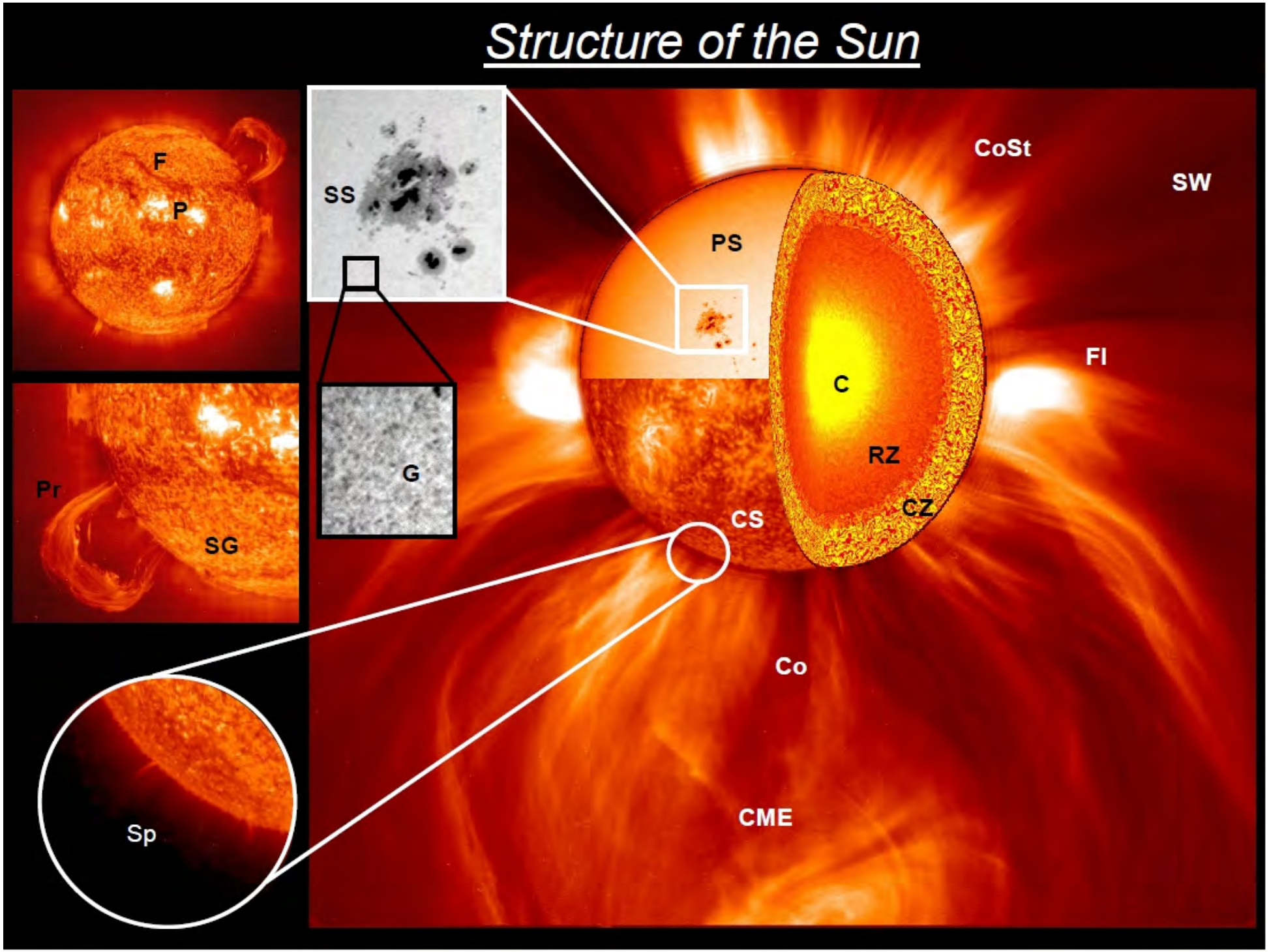
Scope

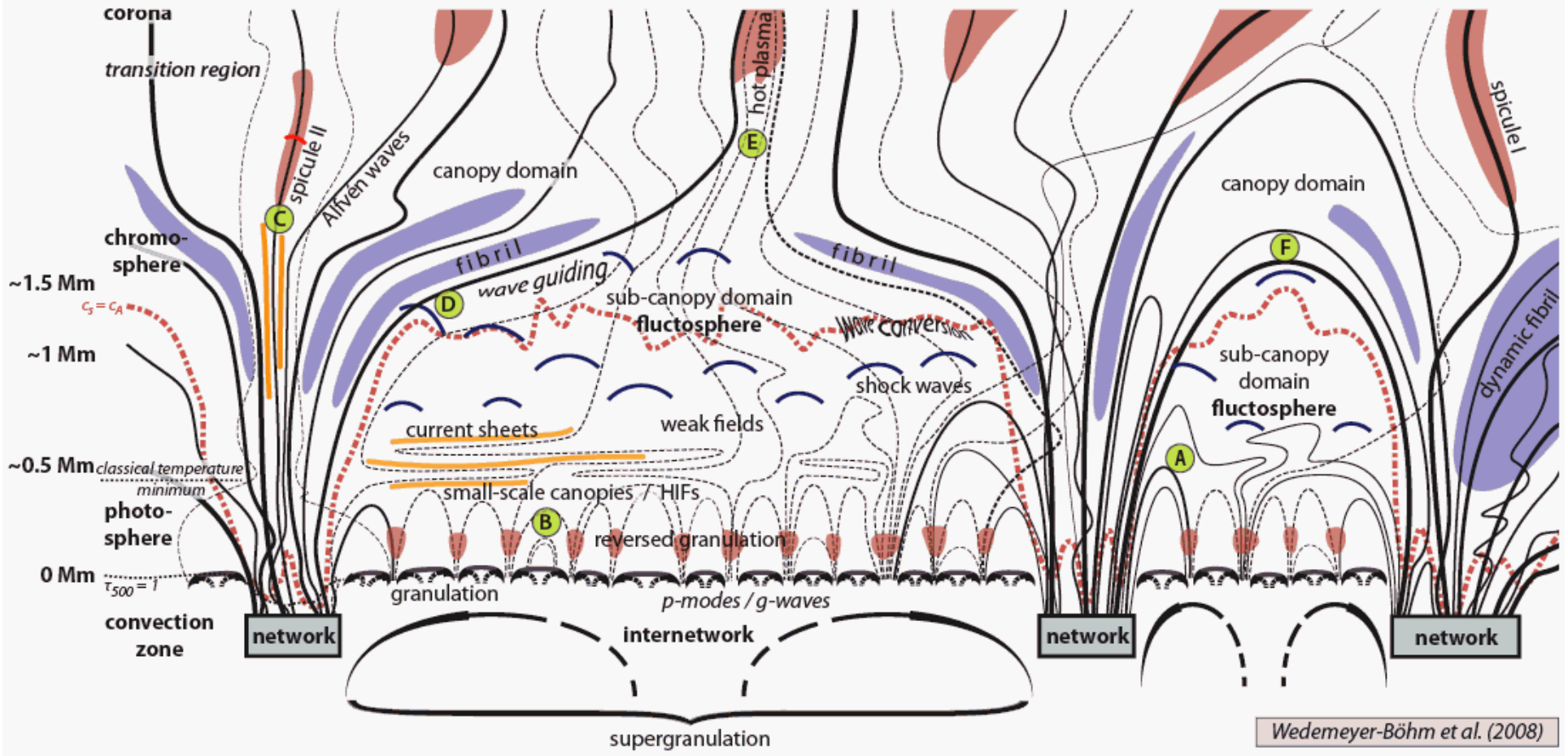
1) Where is research on the Sun now?
2) Cosmic rays
3) Flares at high energies
4) Conclusion






Structure of the Sun
F
P
SS
G
Pr
SG
Sp
PS
CoSt
SW
Fl
C
RZ
CZ
CS
Co
CME

Structure of the atmosphere



Corona

Transition region

Chromosphere

Photosphere

} Modeled in 1D “semi-empirical” style

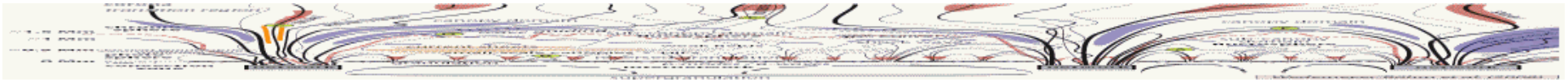
Wedemeyer-Bohm 2004

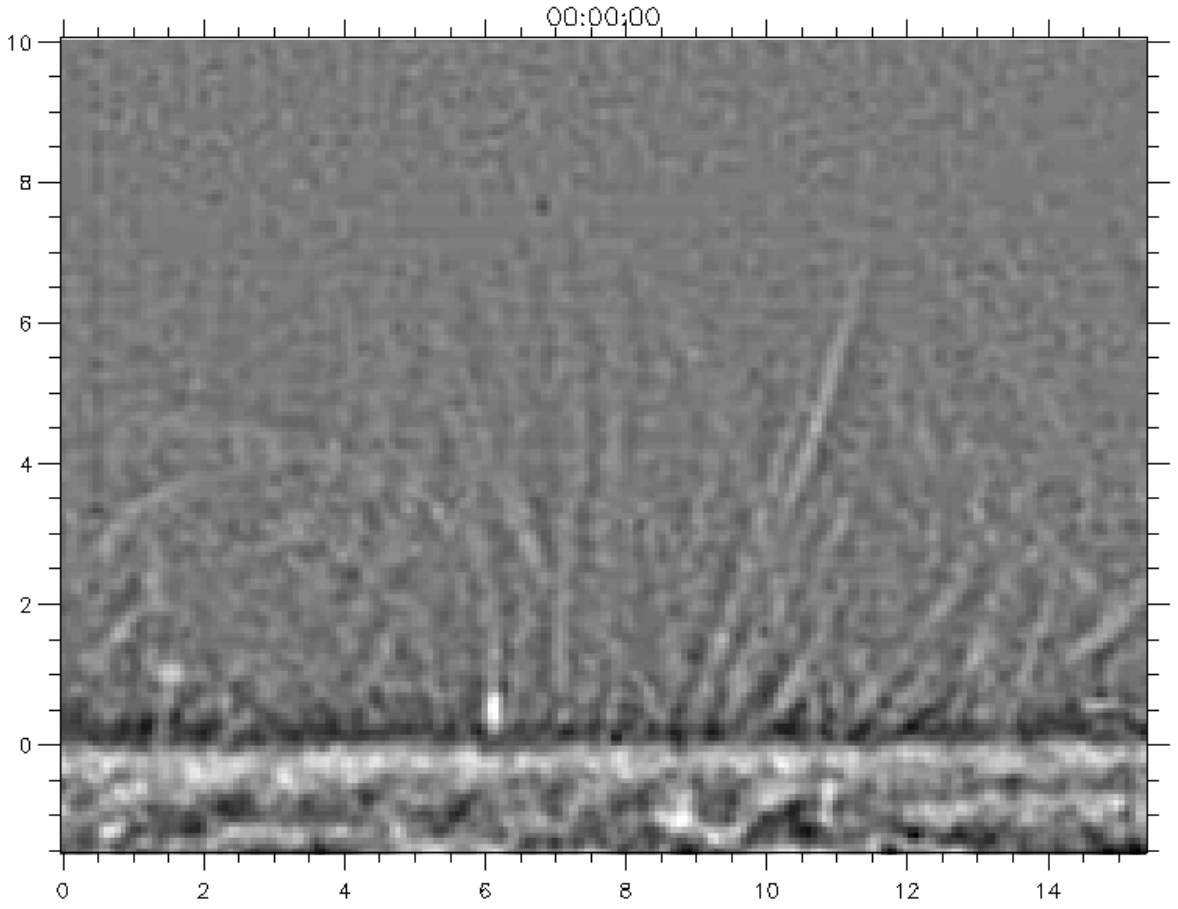
The interface region

- Comprising the upper photosphere, temperature minimum, chromosphere, and transition region: here
  - Collisionality ceases
  - Plasma beta drops from large to as low as 10^{-5}
  - “Temperature” jumps up by 2.5-3 decades
  - Electromagnetic radiation decouples
  - The magnetic field switches from fibril structure to space-filling, with unknown perpendicular currents
- For *Fermi*, the deep photosphere (the ~100 g/cm^2 just below $t_{5000Å}$ - a.k.a. the “super-adiabatic region”) is also important

Structure of the atmosphere

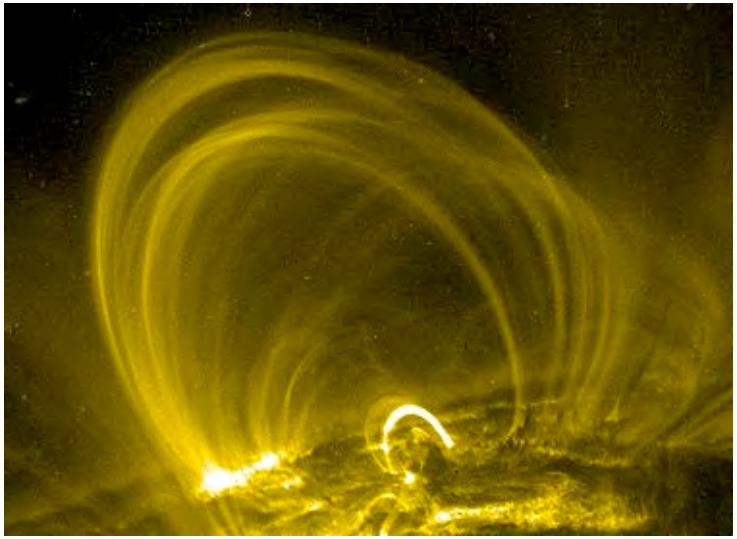
(on a roughly correct aspect ratio)



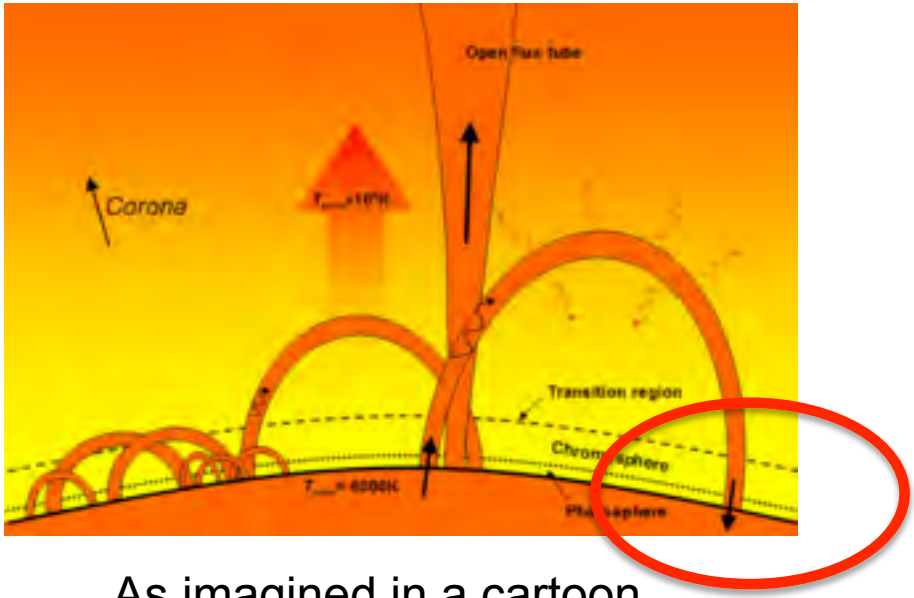


De Pontieu et al. 2007

Coronal loops



As observed by TRACE



As imagined in a cartoon

Note an oddity!

1) Are the things that look like loops are really magnetic flux tubes?
2) Theory tends to ignore the interface region

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What I've tried to say:

The exterior of the Sun (the *heliosphere*) and its interior are connected by a complicated interface, where all kinds of plasma physics happens. This physics dictates the structure of the heliosphere and supports flares.

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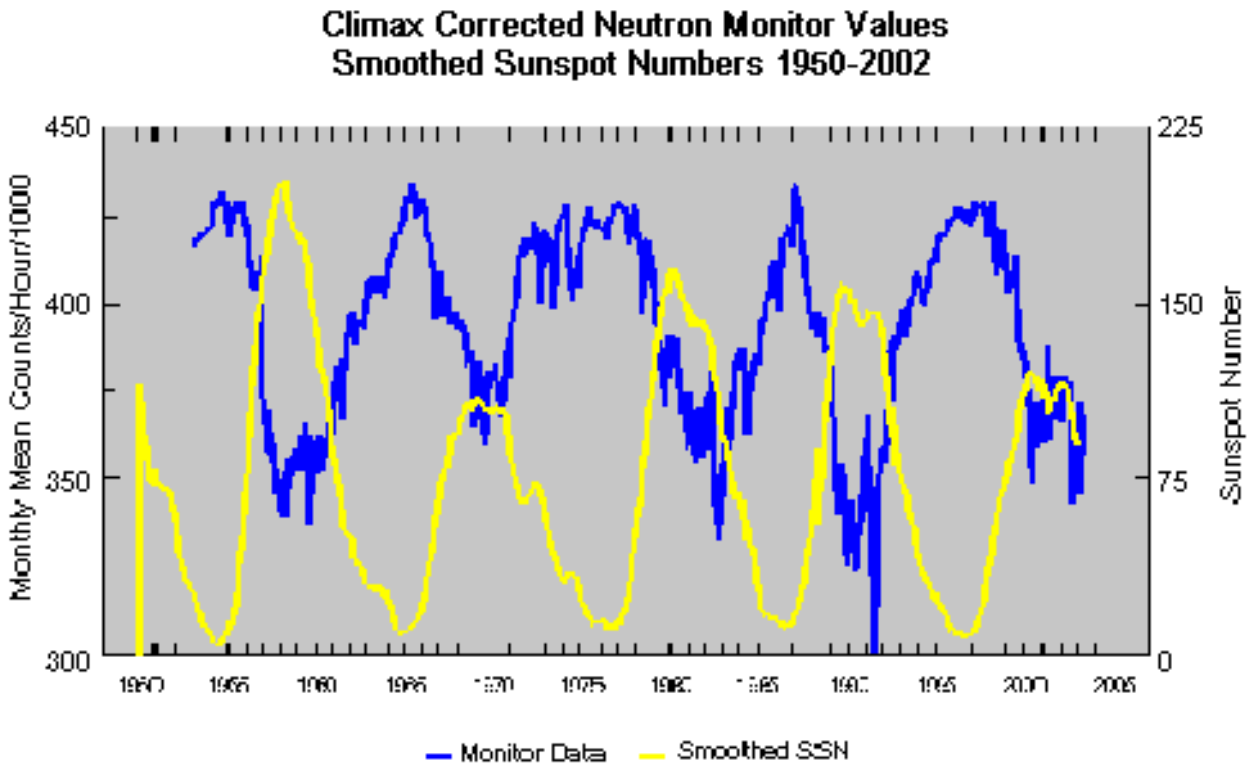
Carl Størmer

With Birkeland, observing the aurora (?) in 1910

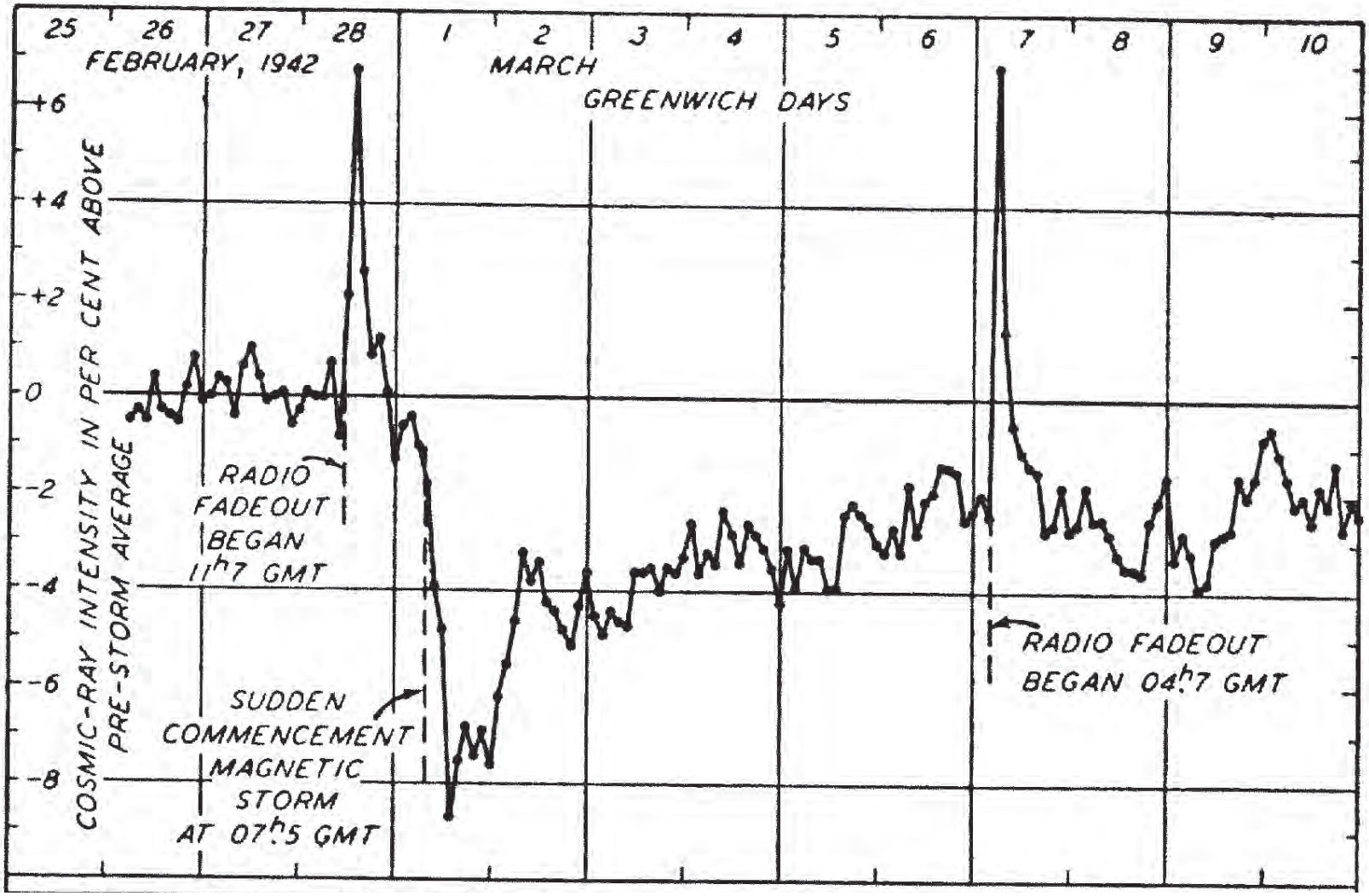
Things to have noticed

- It was only a century ago
- Størmer, the early theorist of particle motion in magnetic fields, is working with Birkeland, the early plasma experimentalist (the “terrella” experiment)
- They are finding, stereoscopically, that the aurora is in the upper atmosphere
- It looks like broad daylight in this Wikipedia picture

Cosmic-Ray Modulation



Forbush Decrease



Lange & Forbush, 1942; Forbush, 1946

What does *Fermi* bring?

- The *Fermi* solar observations have multiple cosmic-ray signatures: the Moon, the Sun, and the Compton-scattering source
- The solar ones enable remote sensing of the heliosphere via its effects on CR modulation, a wholly new capability
- The full Fermi time series will therefore be an important scientific asset
  - Calibration against neutron-monitor time series?
  - Differential modulation via Sun/Moon ratio
  - Differential modulation via Sun/Compton ratio?

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What I've tried to say:

The *Fermi* observations of solar-system γ-rays secondary to the cosmic rays can in principle allow us to study modulation by the heliospheric magnetic field in a wholly new manner.

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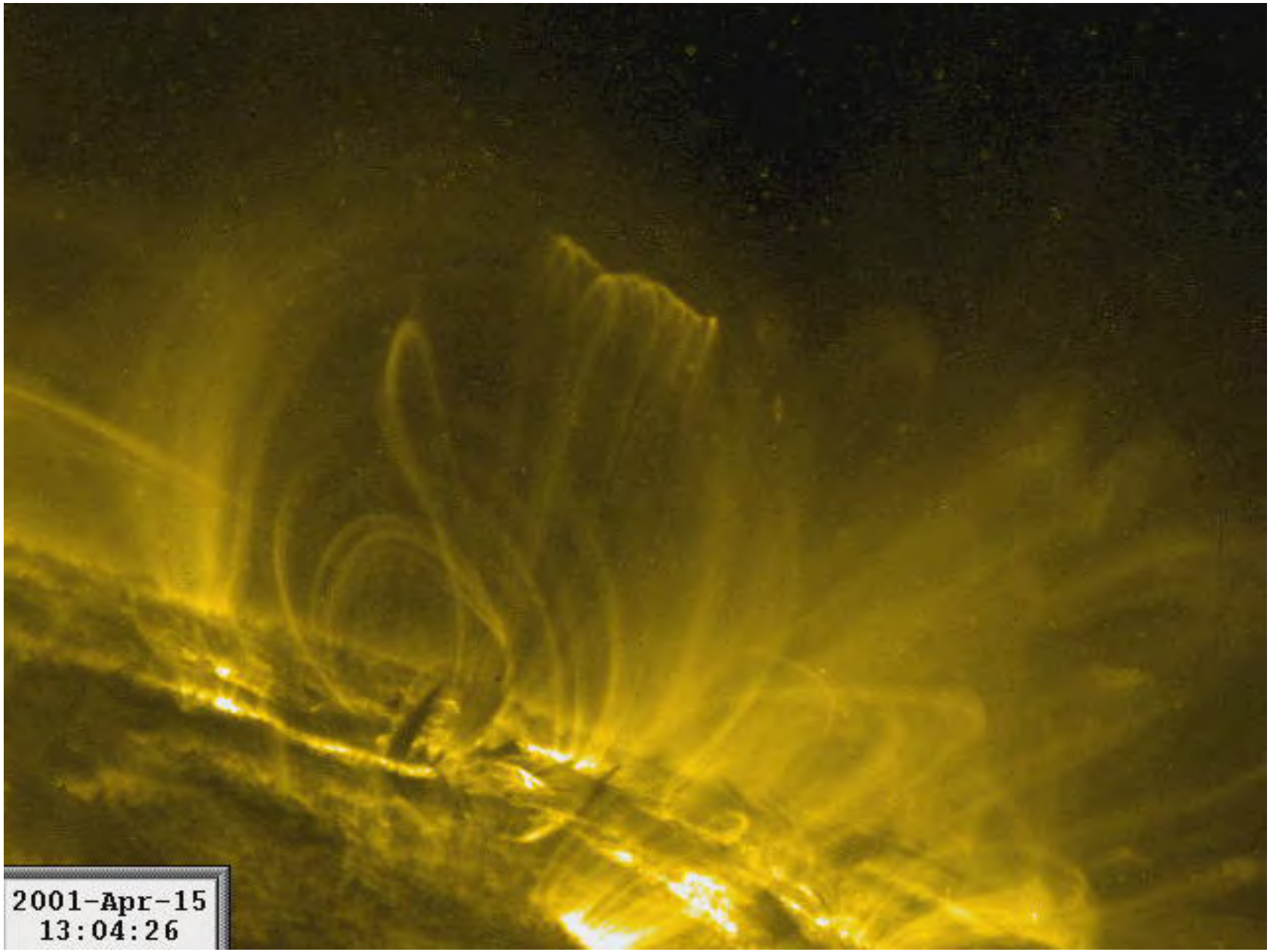
A flare movie (TRACE)

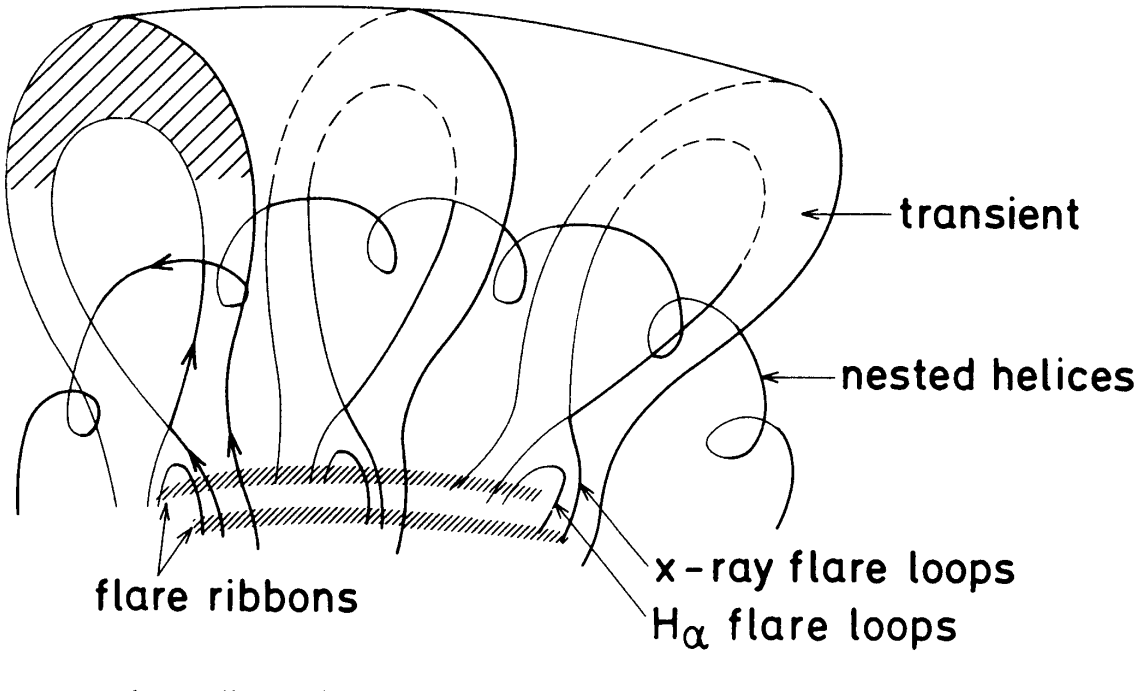


Things to have noticed in the movie

(from TRACE at 195 Å)

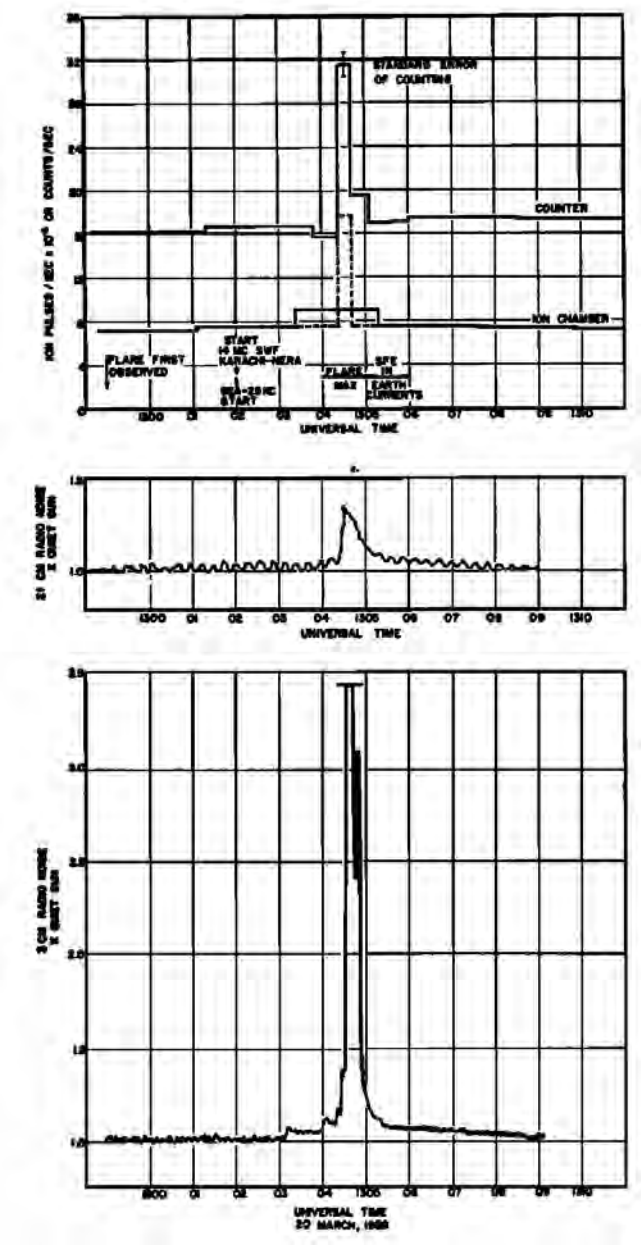
- Diffraction spikes (Lin et al. 2001; this Lin was a high-school research helper at Stanford)
- Dimming of the preflare corona (Hudson & Webb, 1997)
- The flare implosion (Hudson, 2000)
- Coupled oscillations in the Slinky-like magnetic arcade (Verwichte et al. 2004)
- This movie too, no matter how fine it is, does not show the non-thermal particles – which are energetically fundamental

Cartoon of eruptive flare



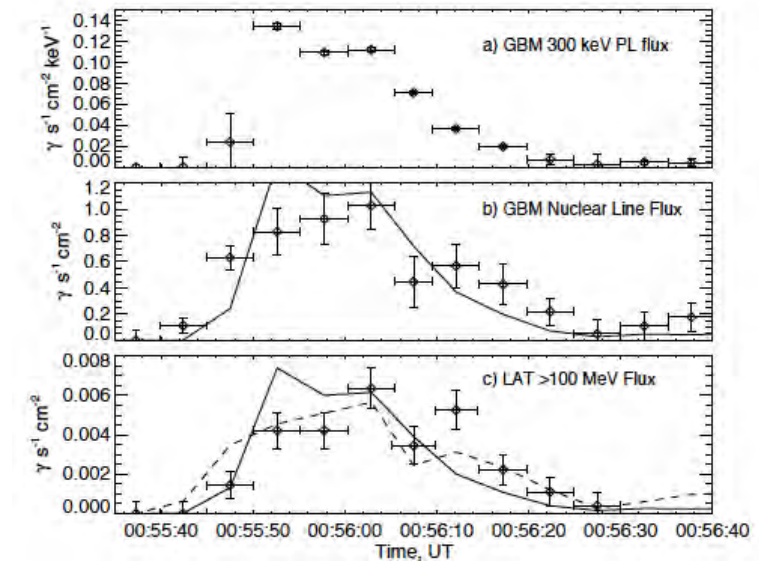
Anzer & Pneuman 1982. In this traditional picture, the flare ribbons result from magnetic reconnection in a current sheet separating the newly radial field polarities. The “transient” is now termed a Coronal Mass Ejection (CME).

Theory here tends to be “mired in MHD”!

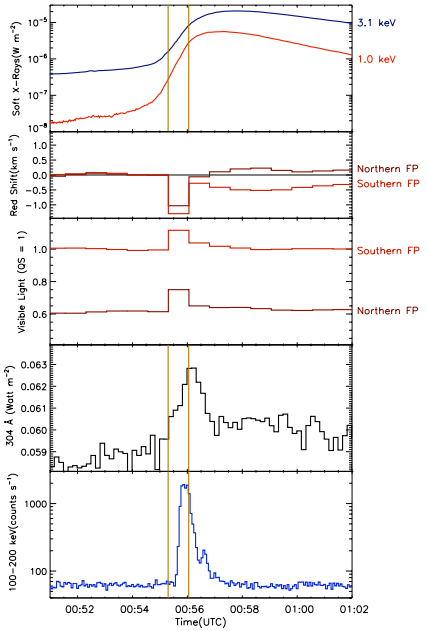


Peterson & Winckler 1959

Flare SOL1958-03-20 (balloon)



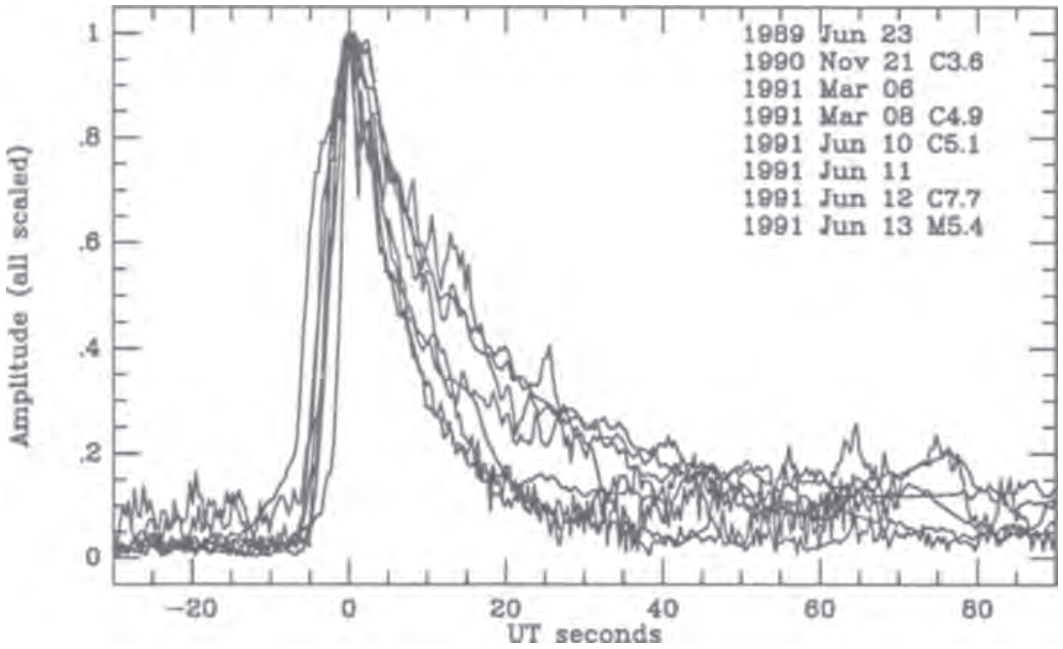
Ackermann et al, 2012



Fermi flare: SOL2010-06-12

Martinez Oliveros et al., 2012

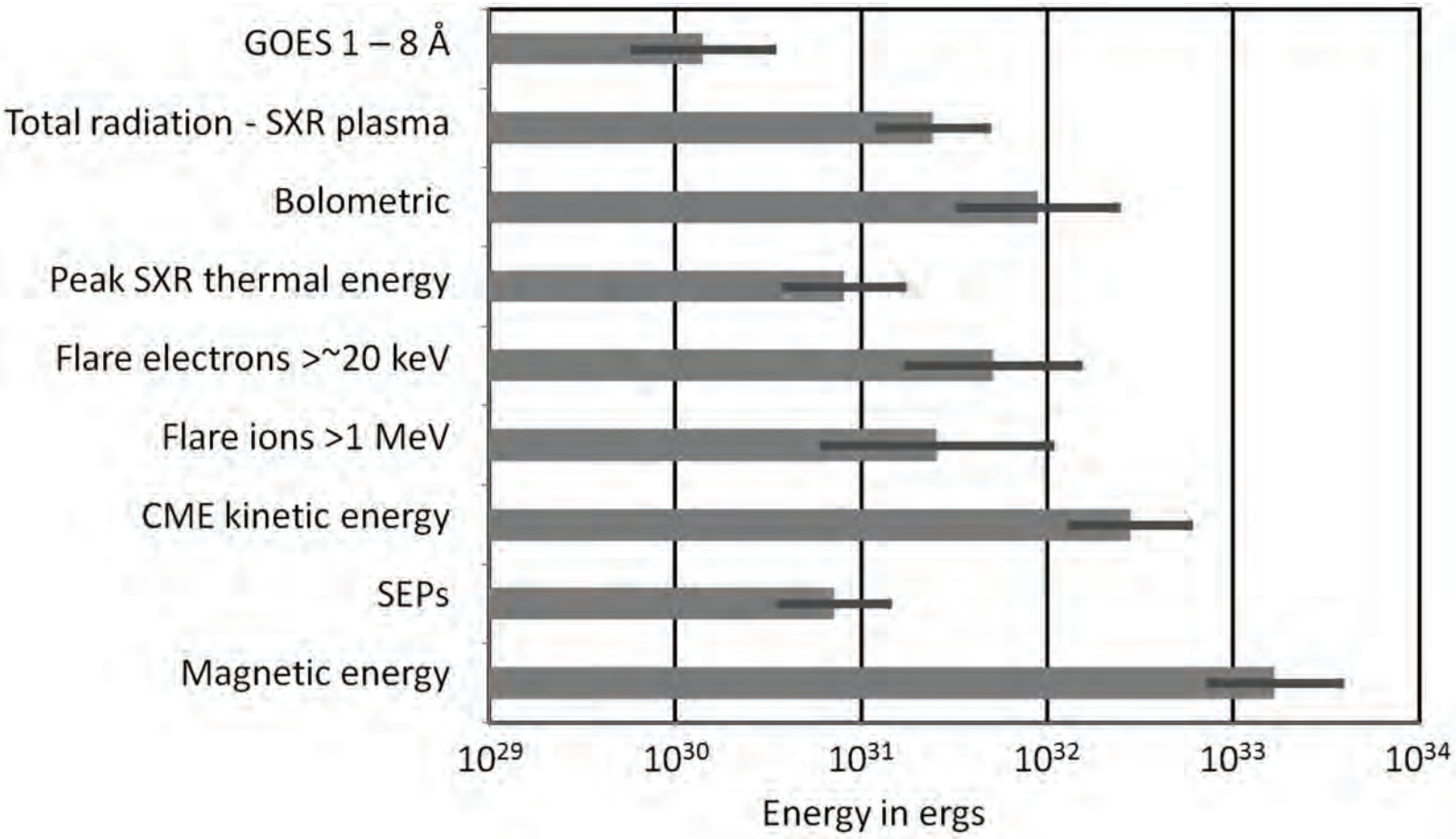
“Impulse-response” paradigm



Observations at 86 GHz (3 mm) (White, 1994)

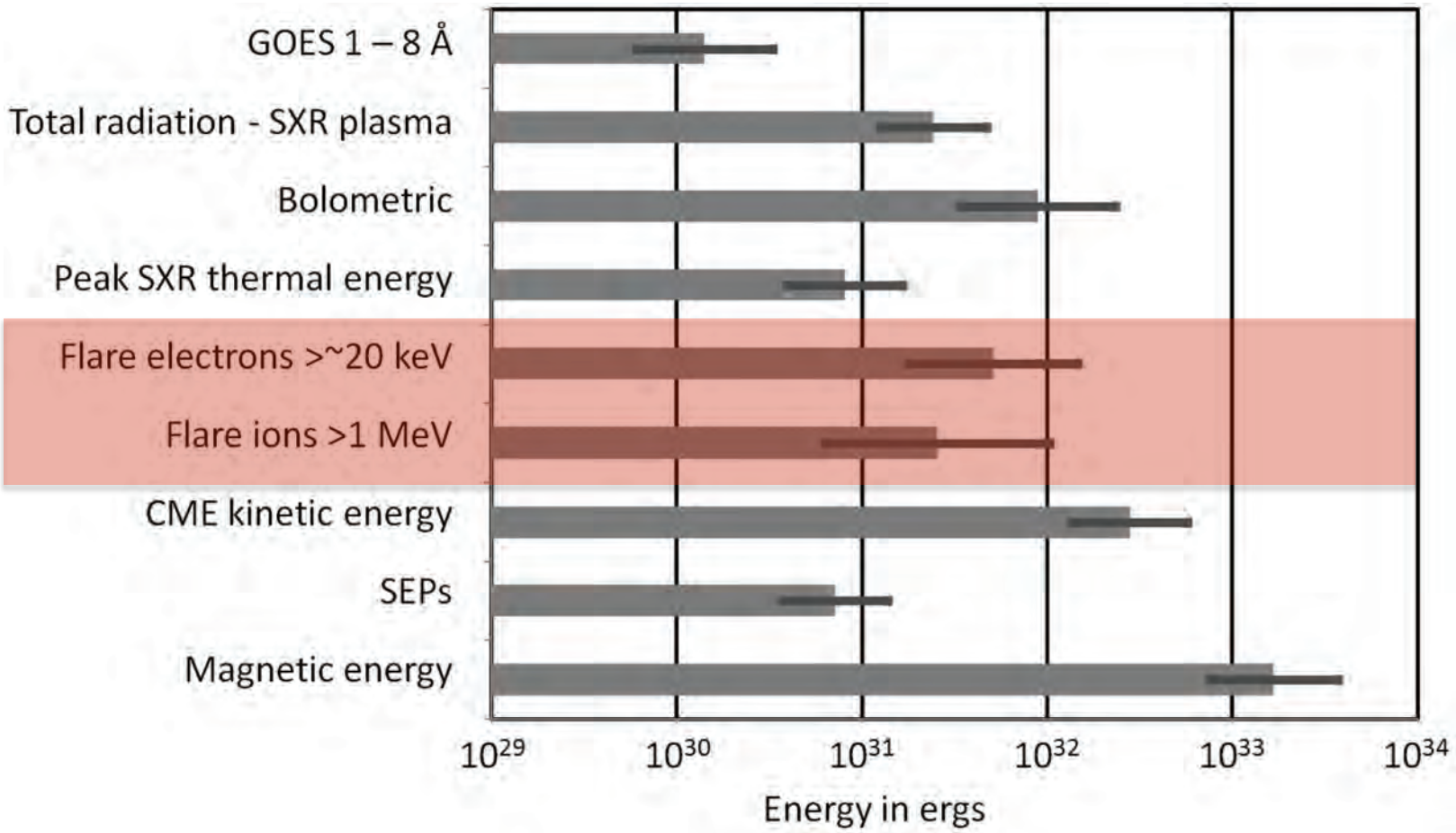
Note importance of ALMA and other mm/ submm/THz observations for *Fermi*

Flare energetics (6-event sample)

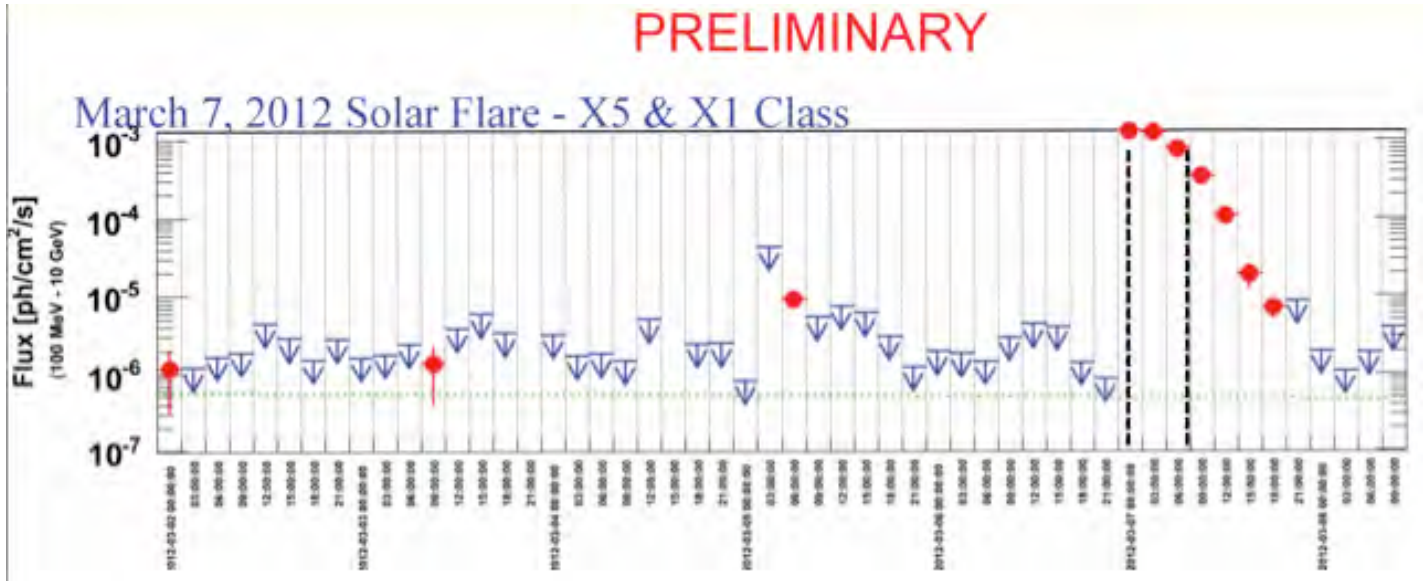


Emslie et al. (2012)

Primary forms of energy release

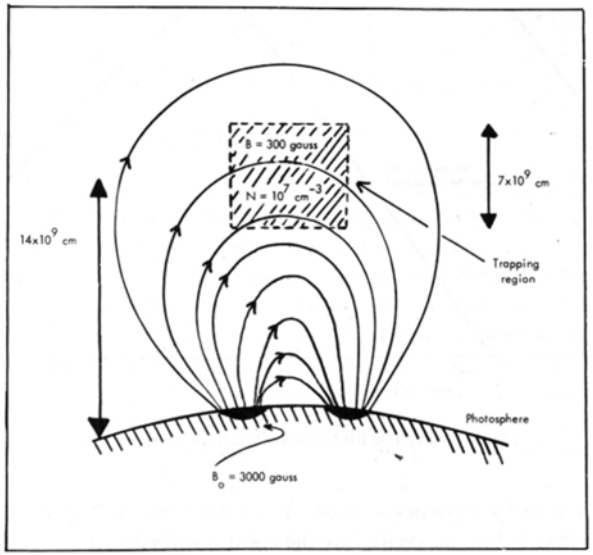


The Fermi “sustained” γ-ray events

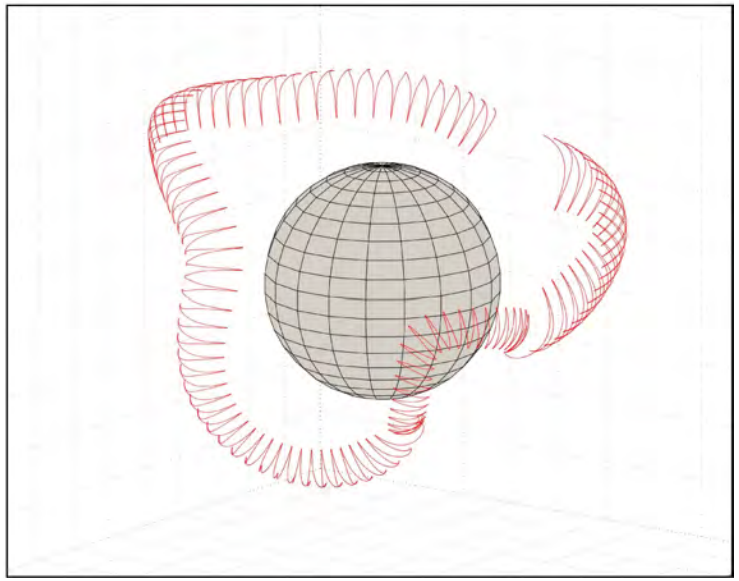


These hours-long events, observed in only two cases prior to *Fermi*, come from (p,p)=>Π_0=>2γ interactions and reflect either the trapping of primary subcosmic rays, or their continued acceleration

Particles can stress fields



Elliot, 1973



Hudson et al., 2009

- In a low-beta plasma, there is no obvious limit on the tail population, as long as $nkT < B^2/8p$ (roughly).
- The right-hand figure shows a proton trapped permanently (all 3 invariants) in a model solar coronal field

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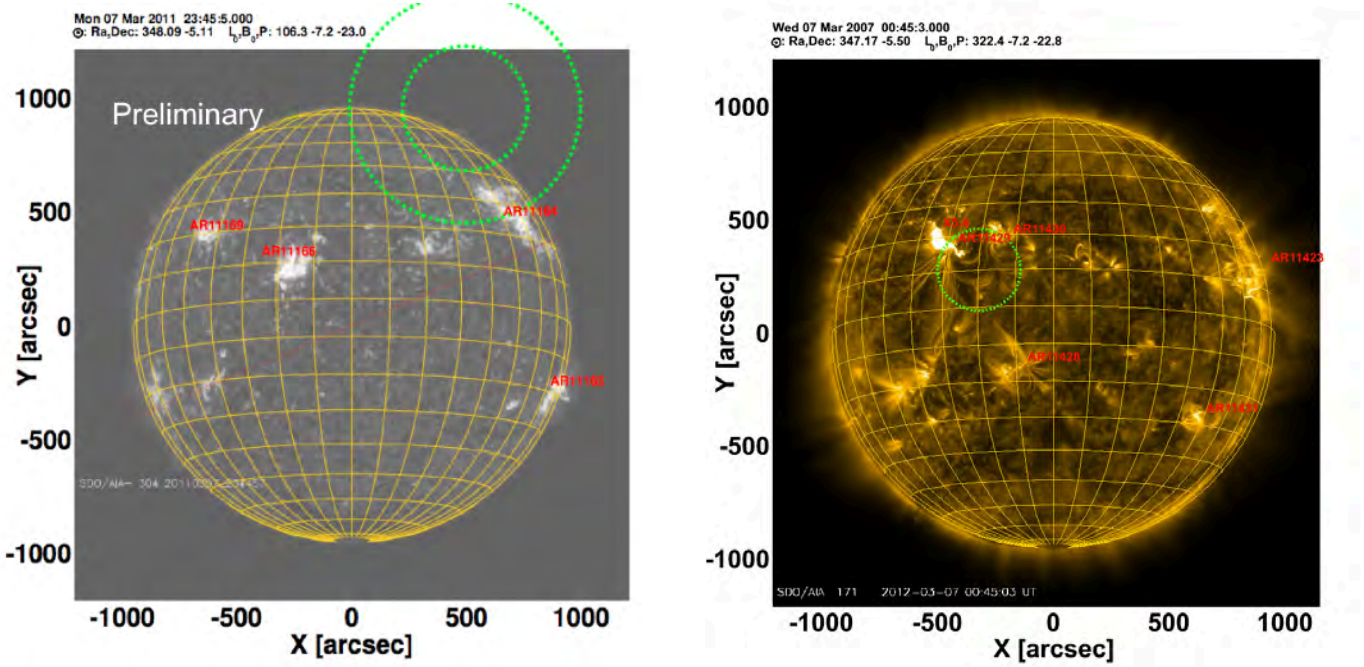
What I've tried to say:

The *Fermi* observations follow, amply confirm, and greatly extend the idea that particle acceleration dominates flare physics. *Fermi* contributes in unique ways to several aspects of flare observations:

- impulsive-phase chaotic HXRs
- impulsive-phase γ's (GBM and LAT)
- impulse-response paradigm
- sustained events

Final speculation



- In both of these cases, neither published yet, the Fermi sources seem not to be centered on the flare location.
- Could flare-induced shock acceleration have deposited the high-energy particles in nearby large-scale static loops? See Hudson (1985), for example. See also Vainio & Khan (2004)

Thank you, *Fermi!* Keep up the good solar observations and publish faster please!