Energetic Particles in the Solar Atmosphere (X-γ ray diagnostics)

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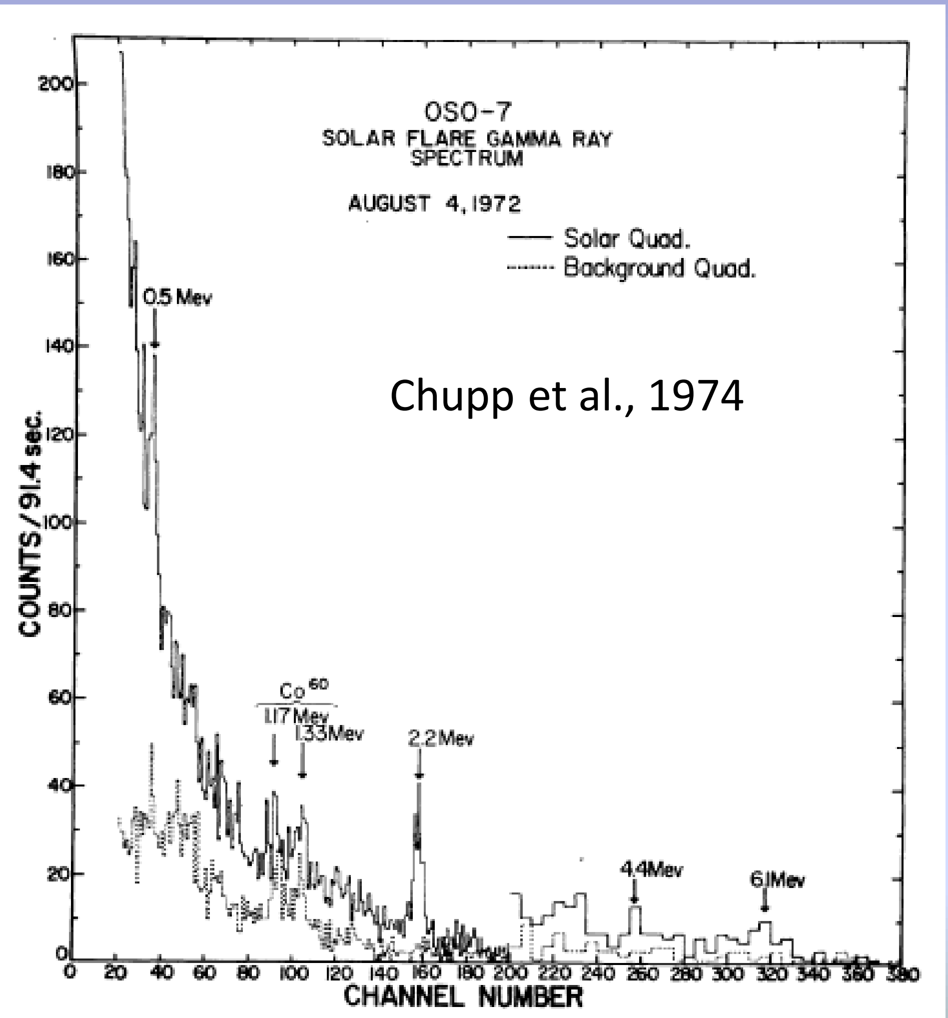
The Sun as a Particle Accelerator:



First detection of energetic protons from the Sun(1942) (related to a solar flare)

First X-ray observations of solar flares (1970)

First observations of γ-ray lines from solar flares (OSO7/Prognoz 1972)

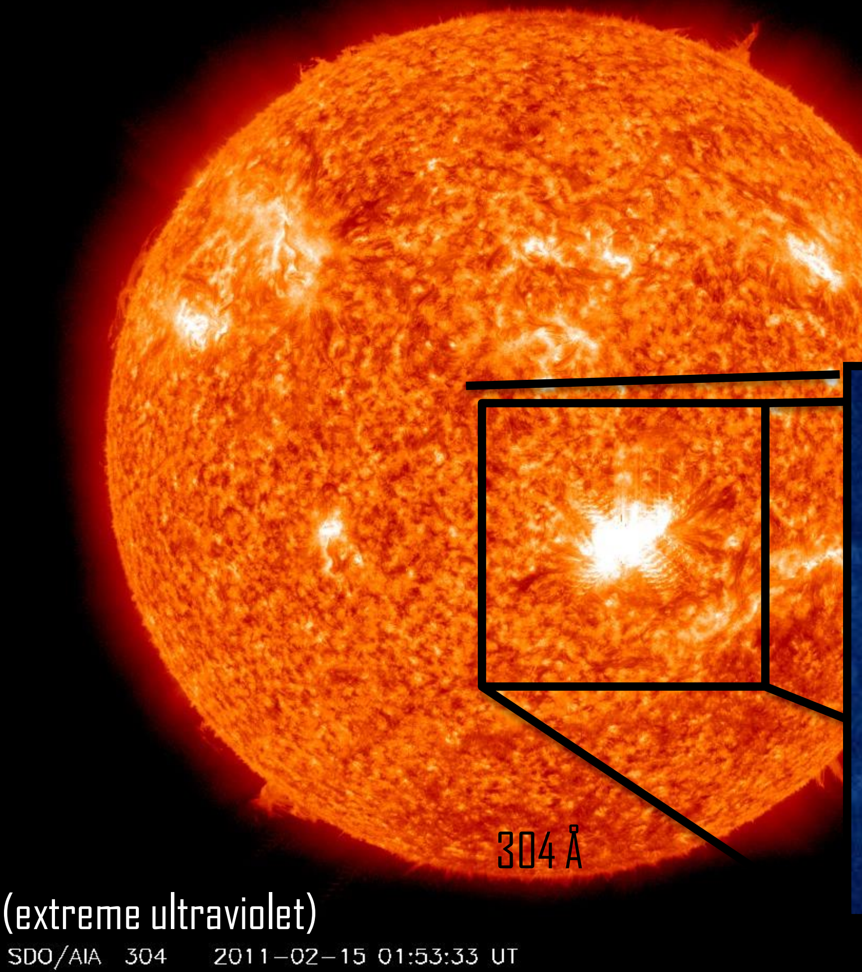
Since then many more observations With e.g. RHESSI (2002-2018) And also INTEGRAL, FERMI

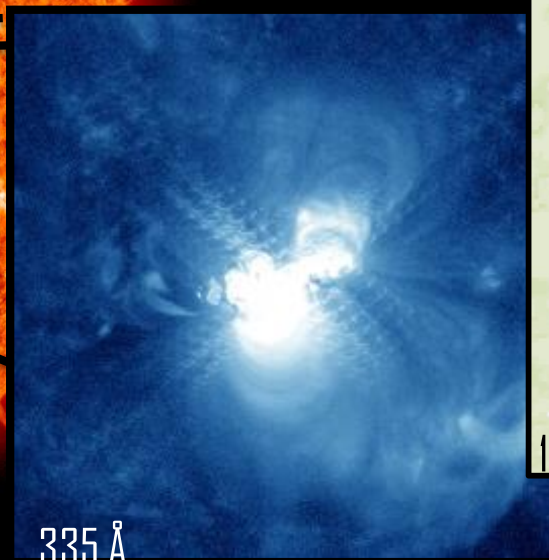
>120000 X-ray flares observed by RHESSI (NASA/SMEX; 2002-2018) But still a limited number of gamma-ray line flares ~30

Solar flare:

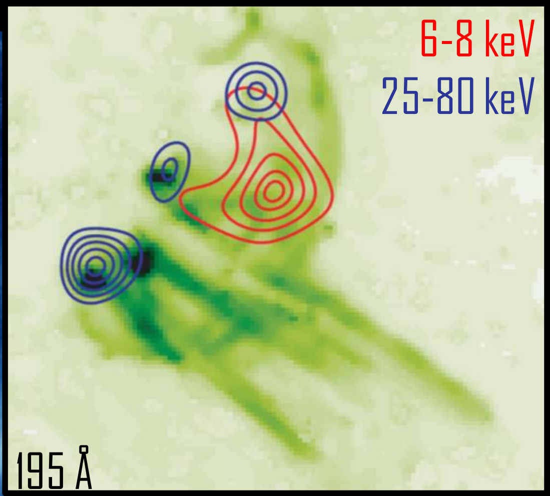
Sudden release of magnetic energy

Heating
Particle acceleration → X-rays



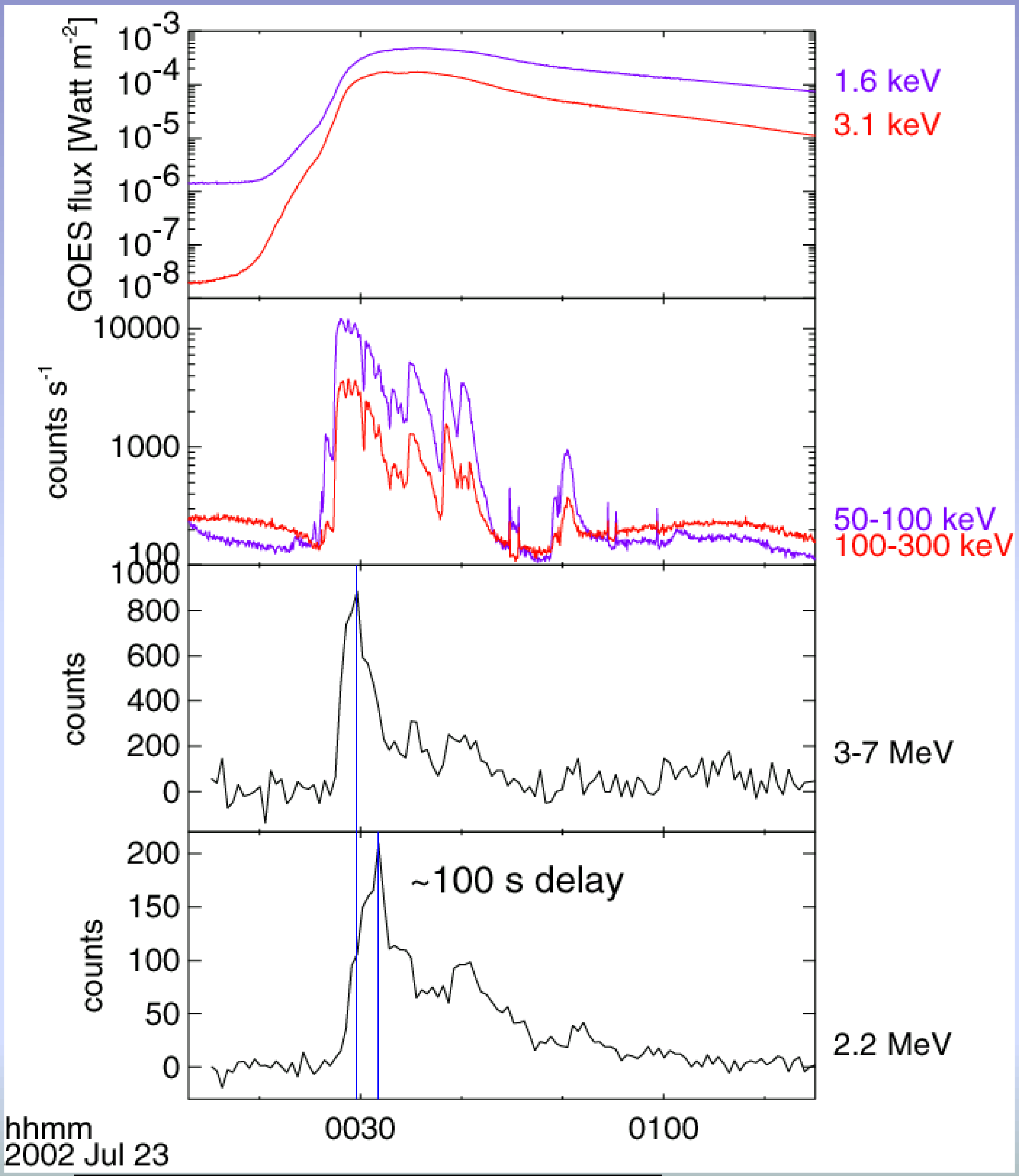


15 fev 2011



21 aug 2002

HXR/GR diagnostics of energetic electrons and ions



RHESSI Observations

SXR emission
Hot Plasma (7to 8 MK)

HXR emission
Bremsstrahlung from
non-thermal electrons

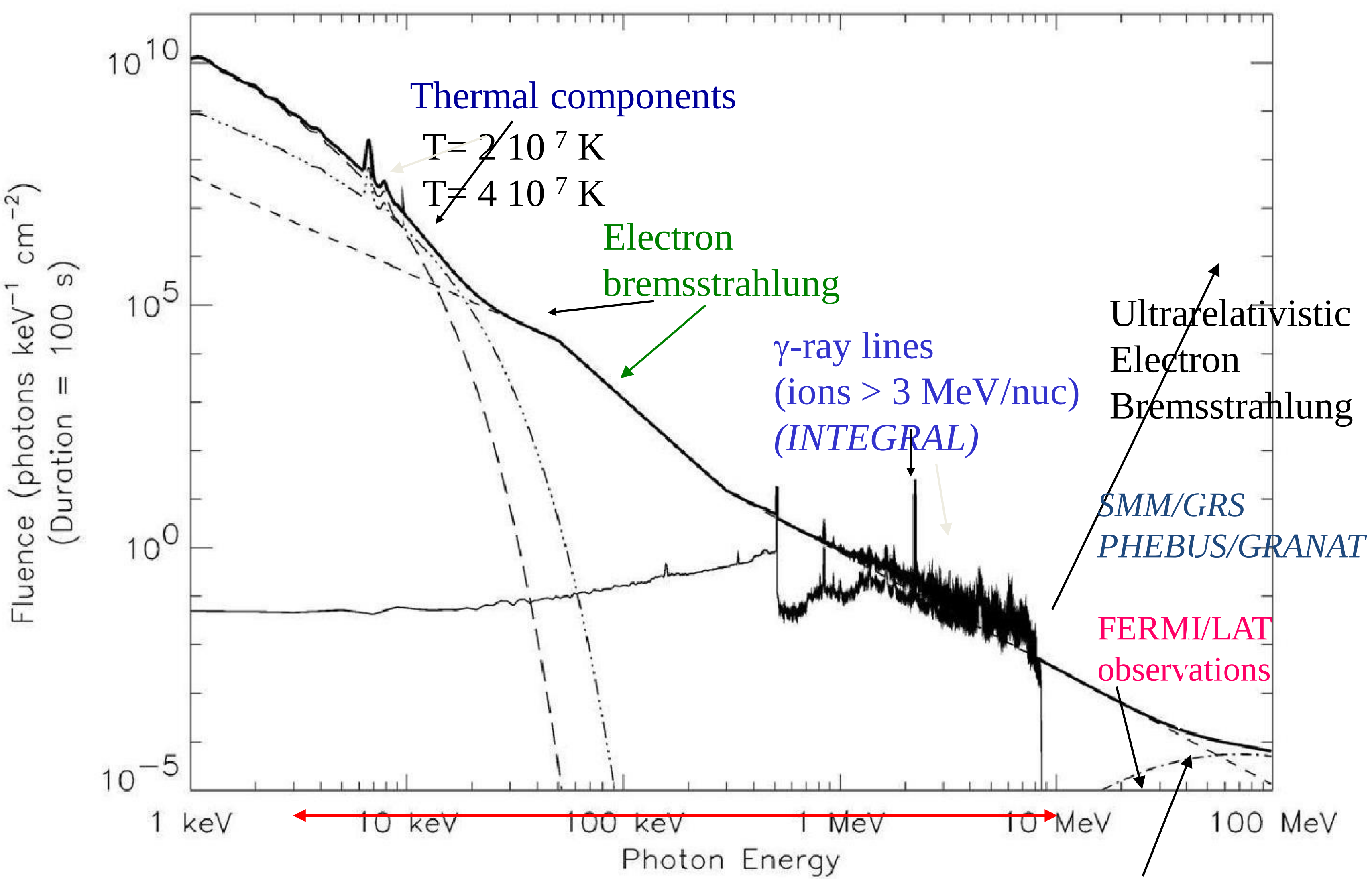
Prompt γ-ray lines :

Deexcitation lines(C and 0) (60%)
Signature of energetic ions (>2 MeV/nuc)

Neutron capture line:

p –p ; p-α and p-ions interactions
Production of neutrons
Collisional slowing down of neutrons
Radiative capture on ambient H
⇒ deuterium + 2.2 MeV. line

X/ γ spectrum



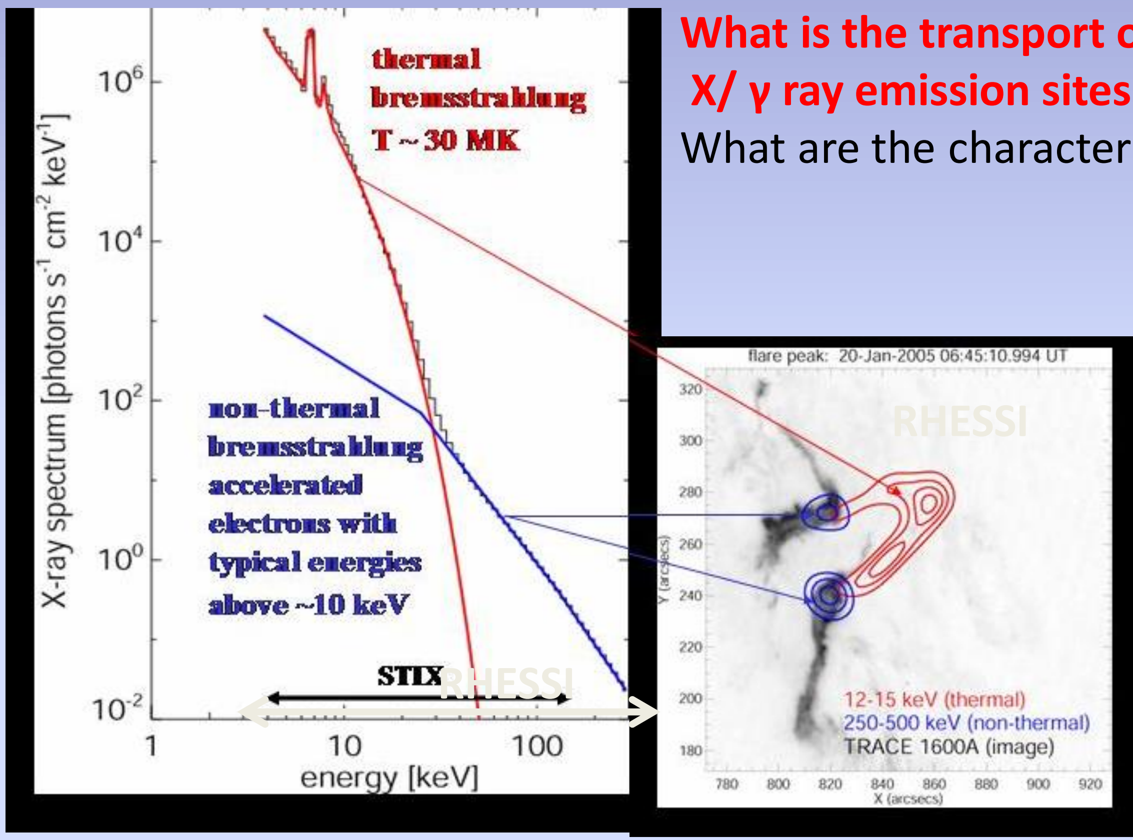
RHESSI

Pion decay radiation(ions > ~300MeV/nuc)

Particle acceleration in solar flares

What is the link between heating and particle acceleration?

Where are the acceleration sites?
What is the transport of particles from acceleration sites to X/ γ ray emission sites?
What are the characteristic acceleration times?

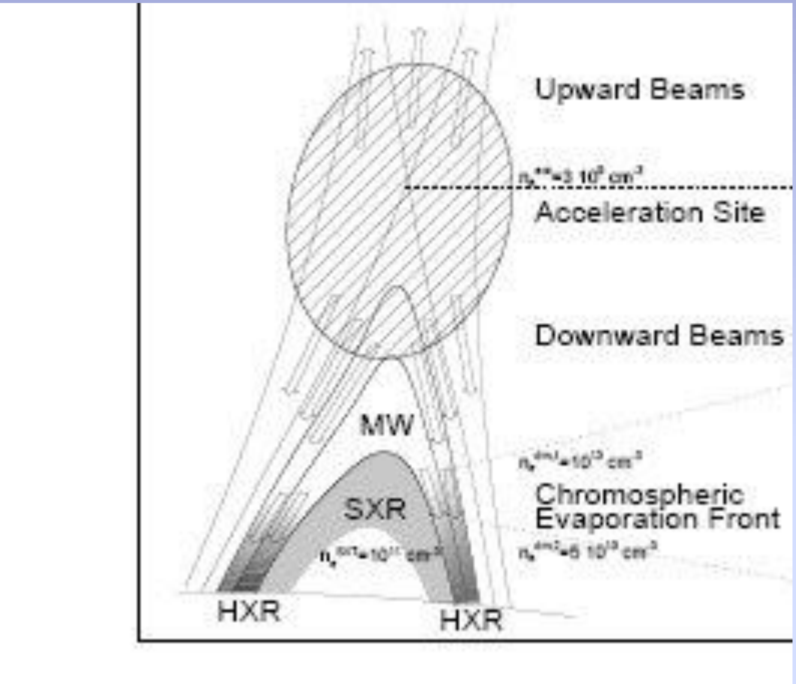


How many energetic particles?
Energy spectra?
Relative abundances of energetic ions?

Which acceleration mechanisms in solar flares?
Shock acceleration?
Stochastic acceleration?
(wave-particle interaction)
Direct Electric field acceleration.
(e.g. current sheets)

Krucker et al;, 2008

Where and how to accelerate flare particles?



Standard model ??

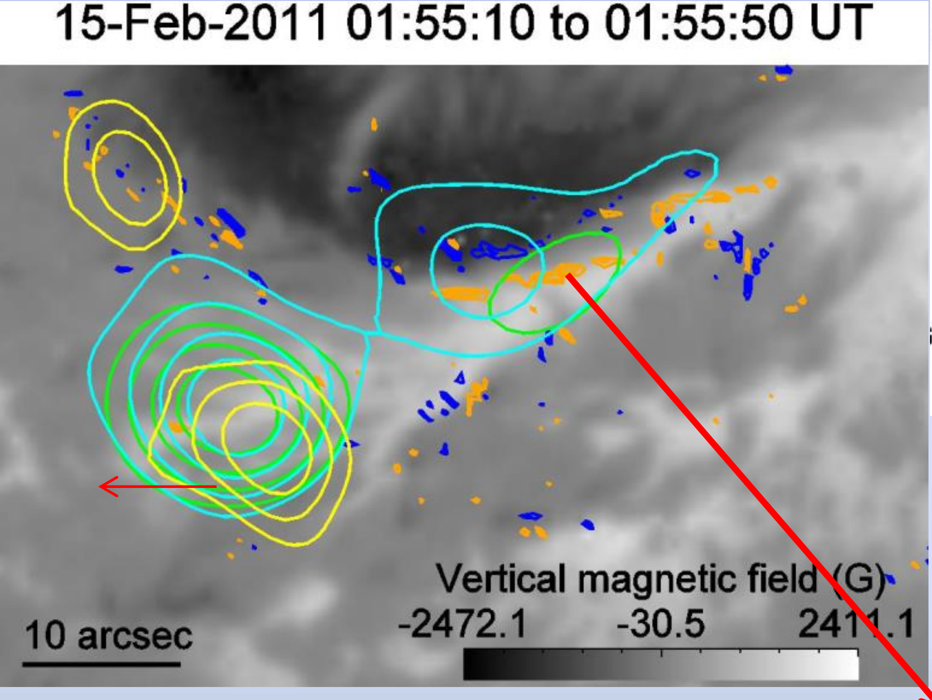
Acceleration site in the low corona

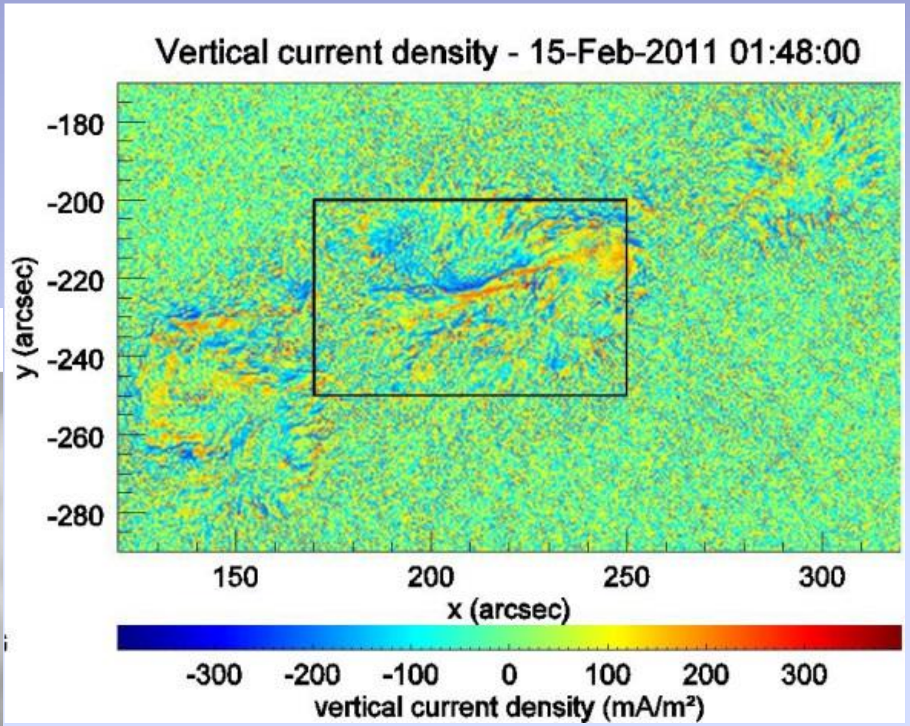
In the vicinity of reconnecting current sheets

Particle acceleration in solar flares

- **Is there a link between electric currents and energetic electron acceleration sites?**

Measurements of vertical current density from vector magnetic fields at the solar surface



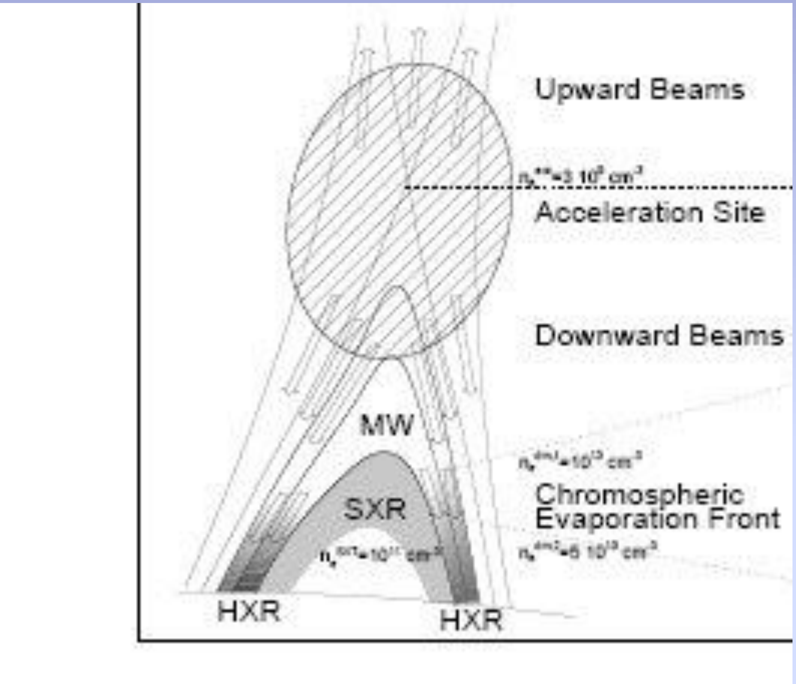


HXR contours from RHESSI and maps of electric currents

HXR sources in the vicinity (in projection) of strong electric currents

Musset, Vilmer, Bommier (2015)

Where and how to accelerate flare particles?



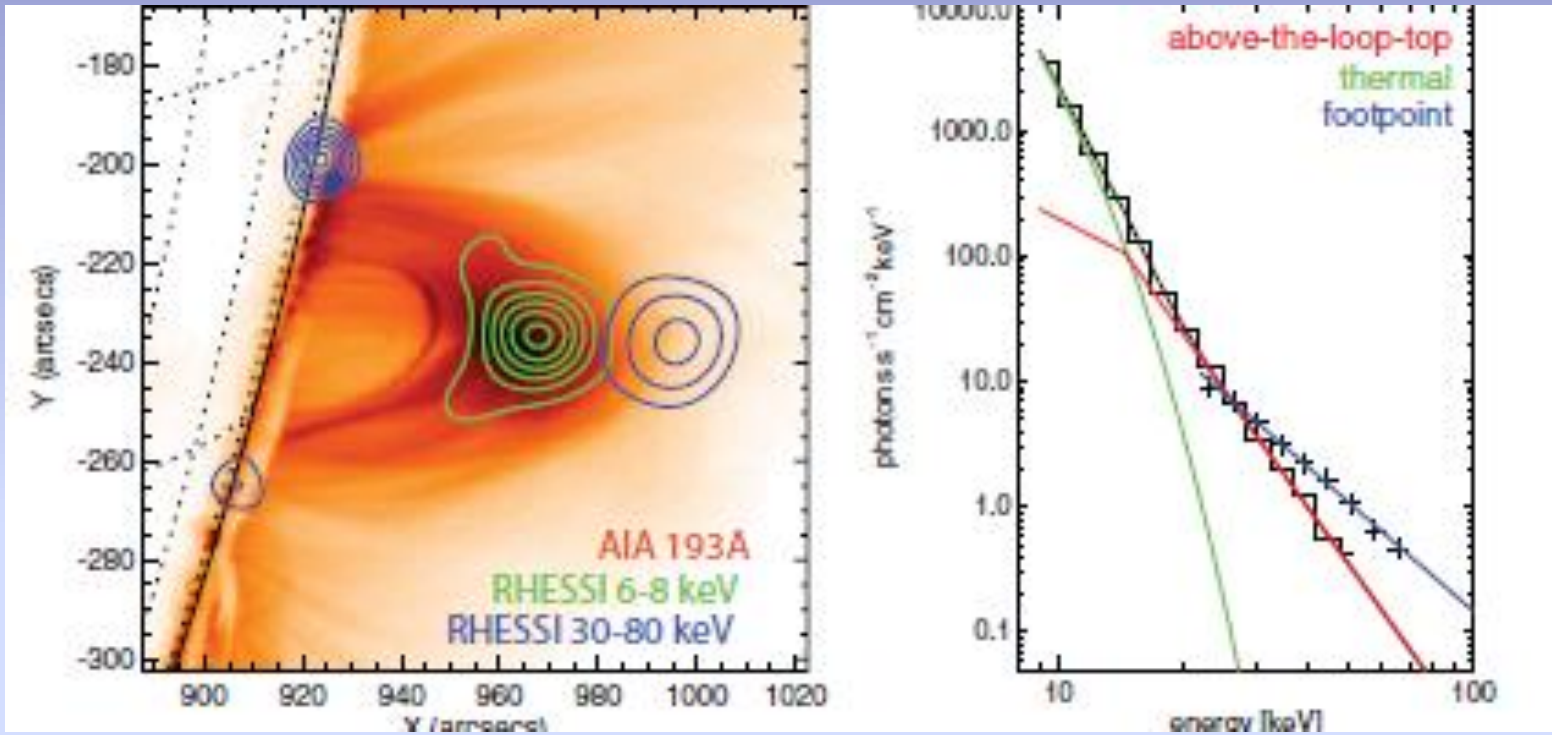
Standard model ??

Acceleration site in the low corona

In the vicinity of reconnecting current sheets

Acceleration/Transport of electrons in the corona: input of imaging spectroscopy with RHESSI

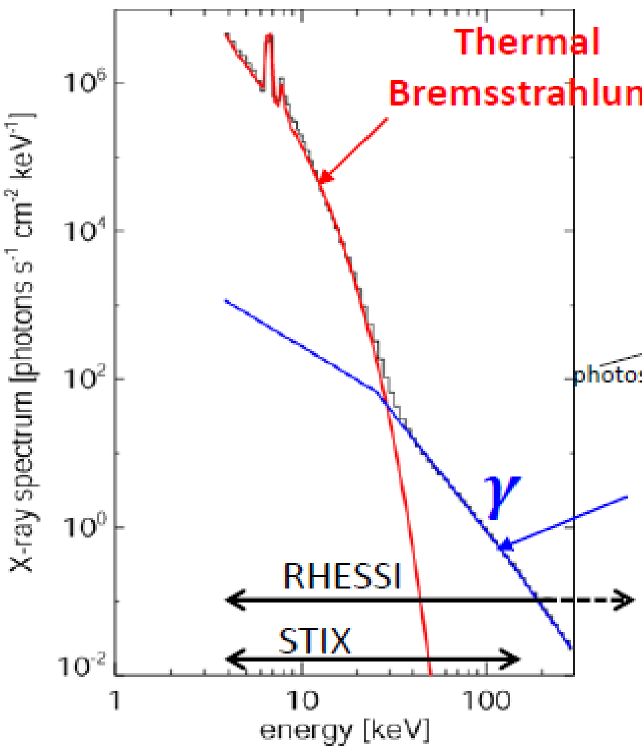
X-ray photon spectrum (electron spectrum) at different locations

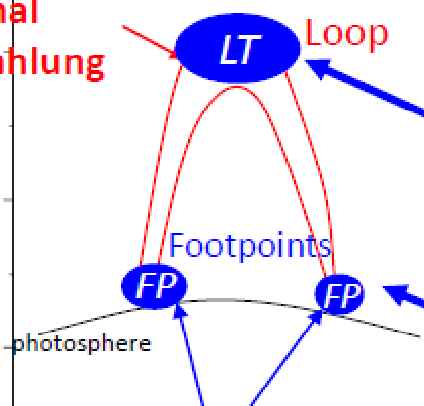


Magnetic energy dissipation and particle acceleration in current sheet above flare loop
Detection of non thermal X-ray source in the 30-80 keV band at the footpoints and above the EUV hot loop

Is it the acceleration region? (nnth ~10^9 cm^{-3})
(Krucker & Battaglia, 2014)

X-ray diagnostics of energetic electrons





Thermal emission $$I(\varepsilon) \propto \mathrm{EM}\,\frac{e^{-\varepsilon/kT}}{T^{1/2}}$$

With $\mathrm{EM} = n^2 V$

Thin target approximation

$$\gamma = \delta + 1$$

Thick target approximation

$$\gamma = \delta - 1$$

e.g. Holman et al. (2011)

Non-thermal Bremsstrahlung

$$I(\varepsilon) \propto \varepsilon^{-\gamma}$$

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

[e-/s/cm²/keV]

« Standard » propagation model

$$\gamma_{LT} - \gamma_{FP} = 2$$

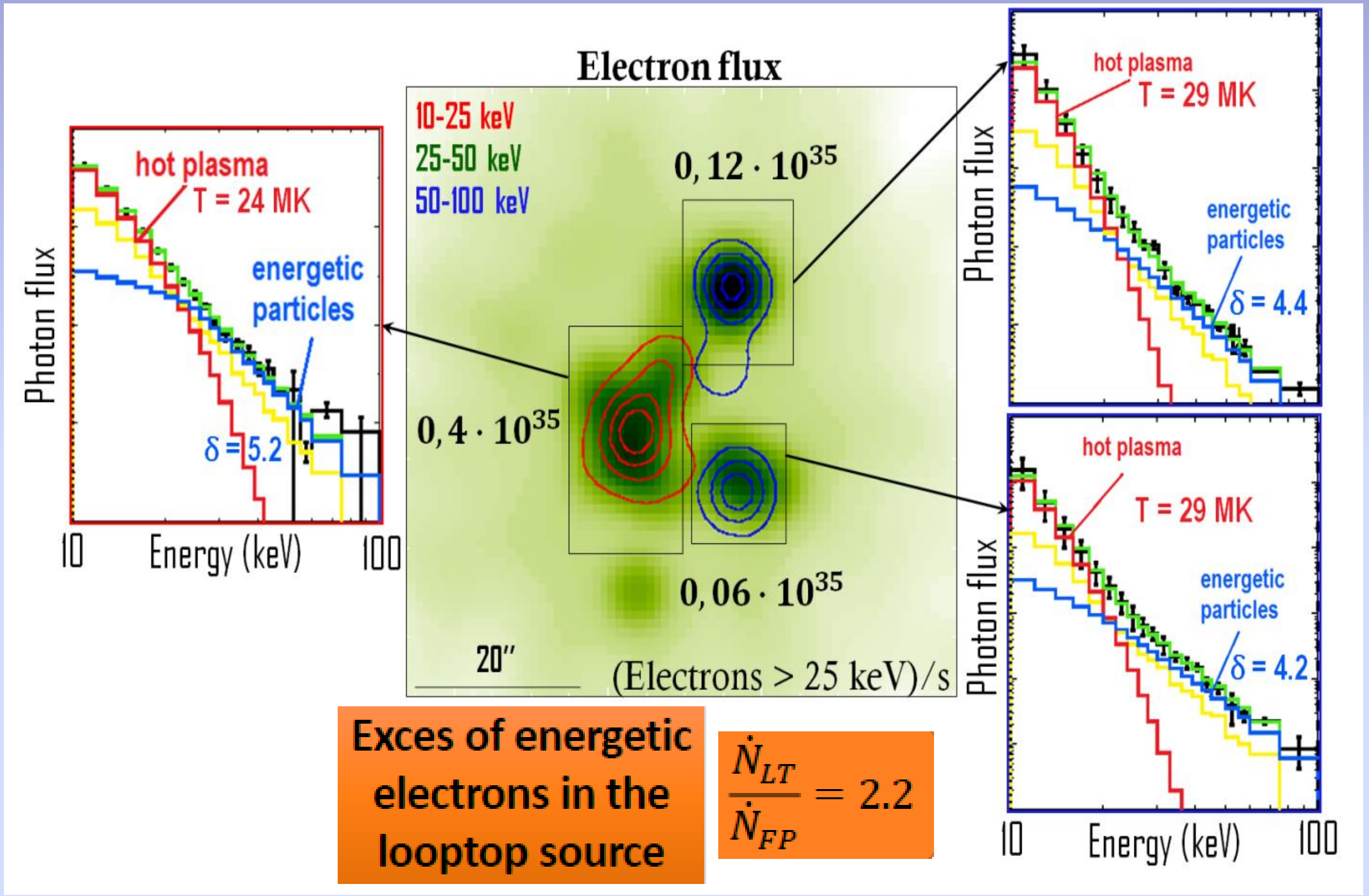
$$\dot{N}_{LT} = \dot{N}_{FP} \quad \text{[e-/s]}$$

Thermal Bremsstrahlung: T ≈ 30 MK

Non-thermal Bremsstrahlung: electrons with energie > 30 keV

Acceleration ? Transport ?

Acceleration and transport of energetic electrons in the low corona



Exces of energetic electrons in the looptop source

$$\frac{\dot{N}_{LT}}{\dot{N}_{FP}} = 2.2$$

+ different electron spectra
(deduced from the fit of the photon spectrum)

Musset, Kontar, Vilmer, A&A, 2018

How to confine electrons in the loop top sources?

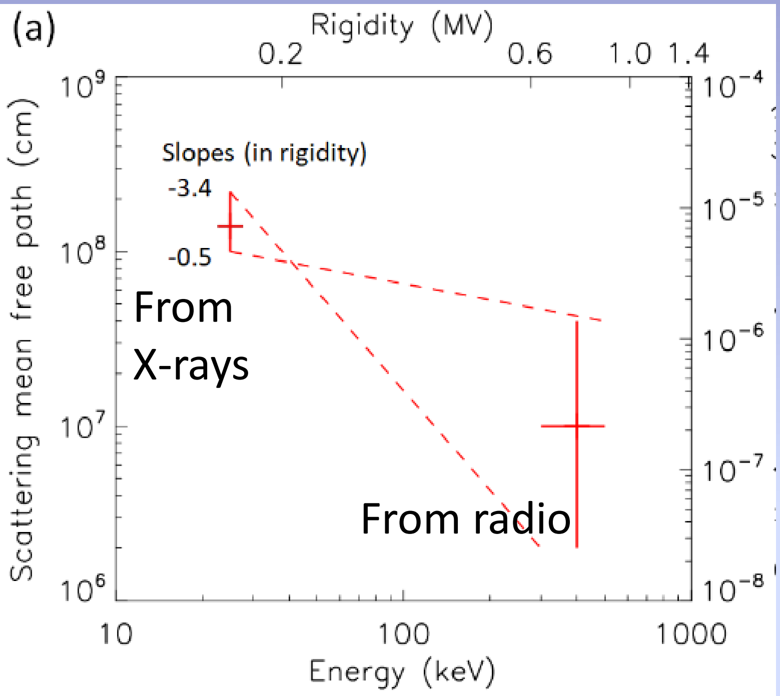
- Magnetic mirroring due to converging magnetic field (e.g. Kennel & Petchek, 1966; Leach&Petrosina, 1981; Melrose & Brown, 1976; Vilmer et al., 1986; Takakura, 1996,…with applications in e.g. Simoes & Kontar, 2013…)

- *Confinement by strong turbulent pitch-angle scattering due to small scale fluctuations of B leading to diffusive parallel transport*

(Bian et al., 2011; Kontar et al., 2014).

Energy dependance of the diffusive scattering mean free path of energetic electrons

In the Corona



Comparison with radio observations of the same flare
Gyrosynchrotron emission of > 100s keV electrons

Diffusive transport can describe the transport of energetic electrons in the corona for some events

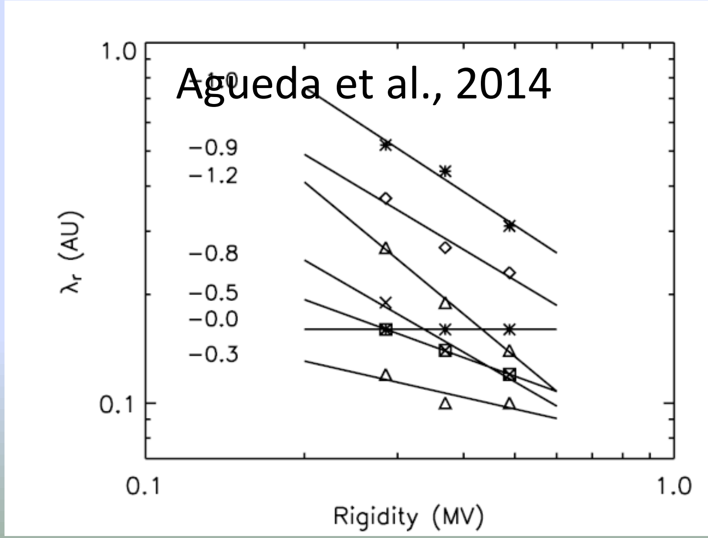
BUT

Decrease of the scattering mean free path with electron energy/rigidity necessary to explain X-ray and radio observations

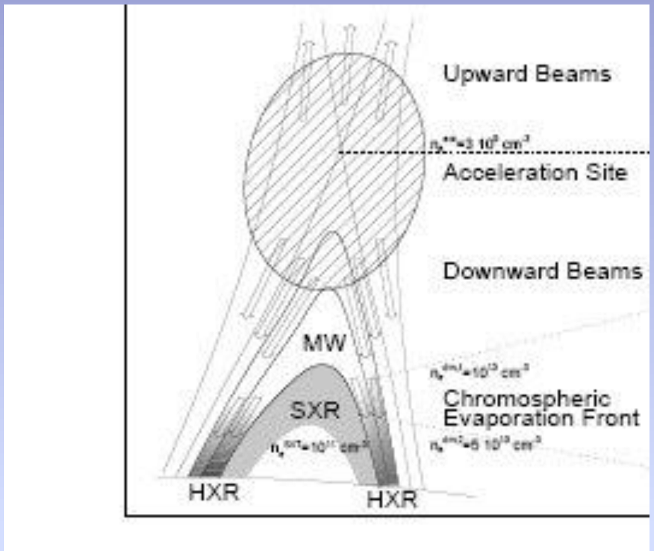
(First evaluation in the corona)

Musset, Kontar, Vilmer, A&A, 2018

This evolution of the scattering mean free path with rigidity is also derived for some electron events in the IP medium



Where and how to accelerate flare particles?



Standard model ??

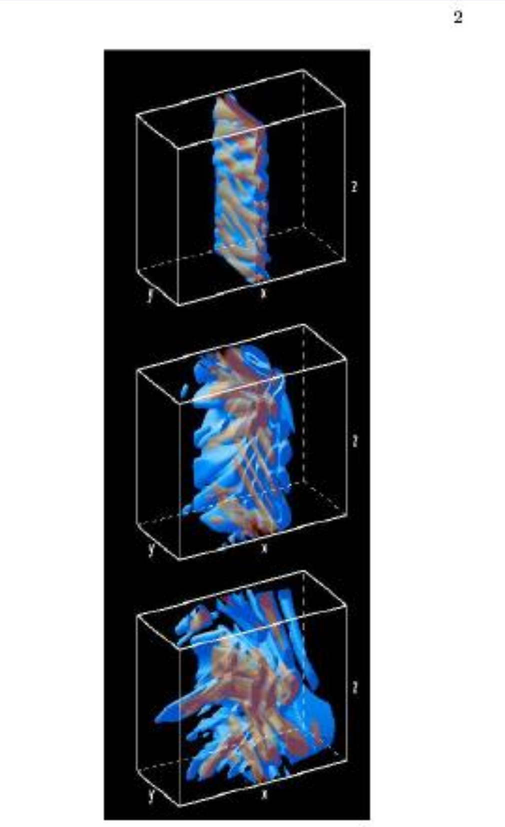


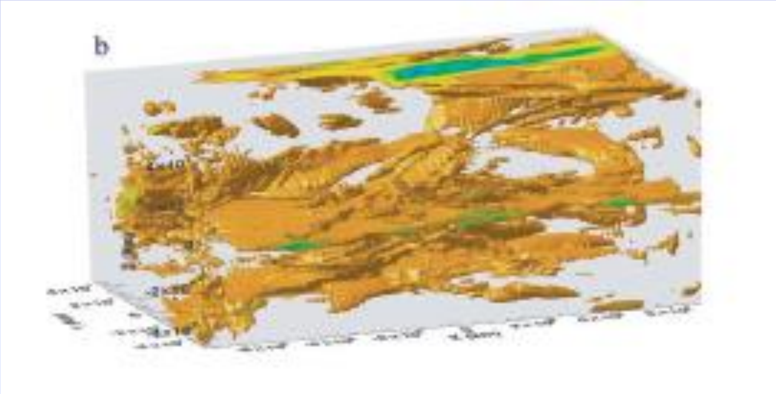
FIG. 1: Electric field isosurfaces at $t = 50\tau_A$, $t = 200\tau_A$ and $t = 400\tau_A$.

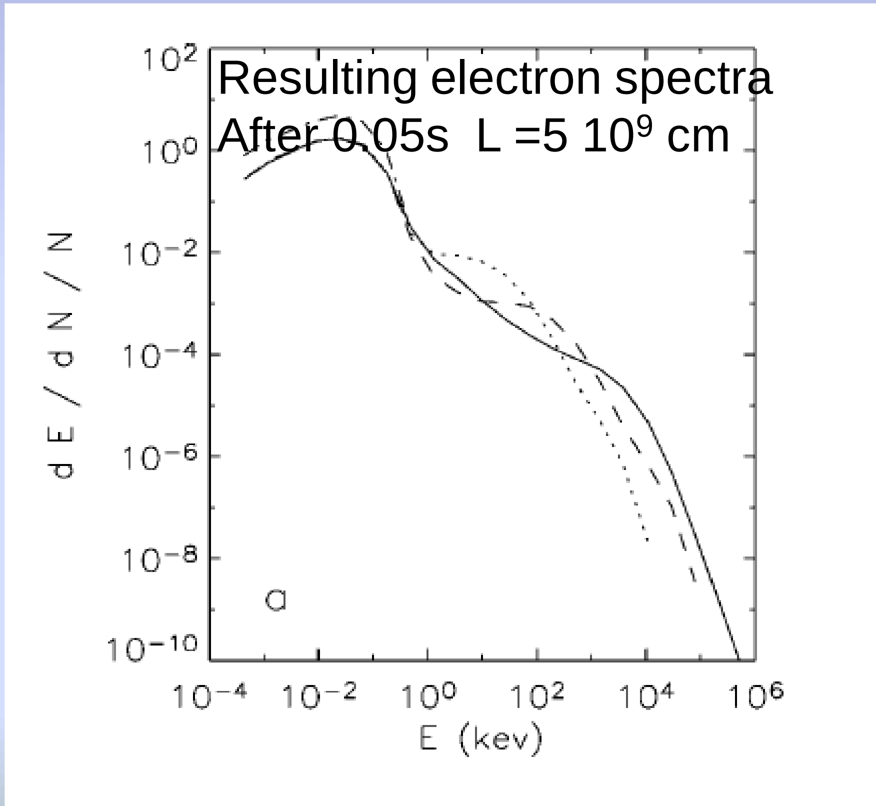
Or acceleration in many spatially distributed sites??

dynamical evolution of large scale current sheets towards small scale structures
(see e.g. MHD simulations Onofri et al., 2006)

Electron acceleration in distributed current sheets

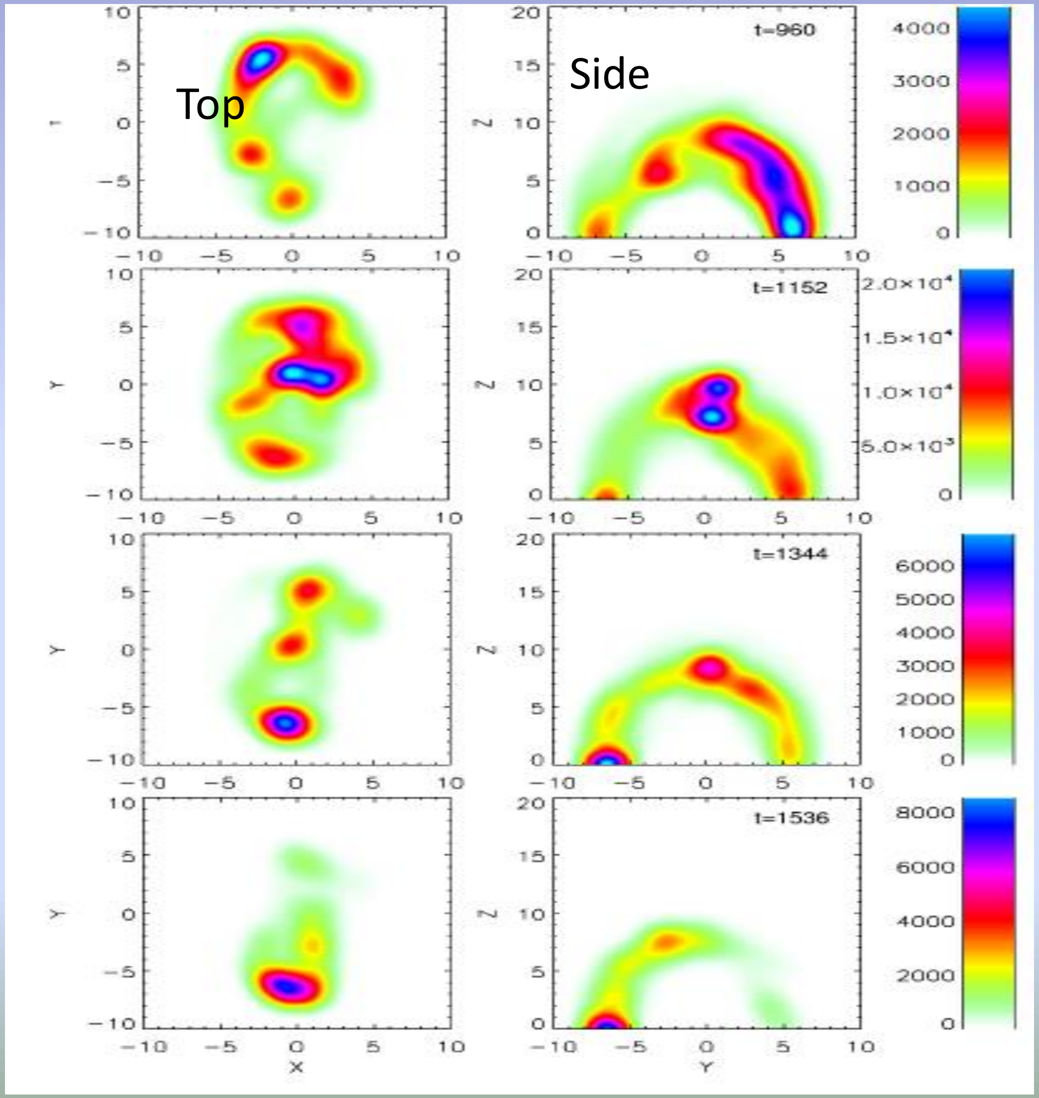
Development in the last fifteen years of many models with « spatially distributed acceleration sites »: e.g. in current sheets resulting from stressed magnetic fields (Turkmani et 2005, 2006) (Gordovskyy et al., 2012, 2013, 2014),…





Turkmani et al., 2005

Particle acceleration,transport and radiation in twisted coronal loops



Test particle coupled to
MHD loop simulations

- Relativistic guiding-centre equations

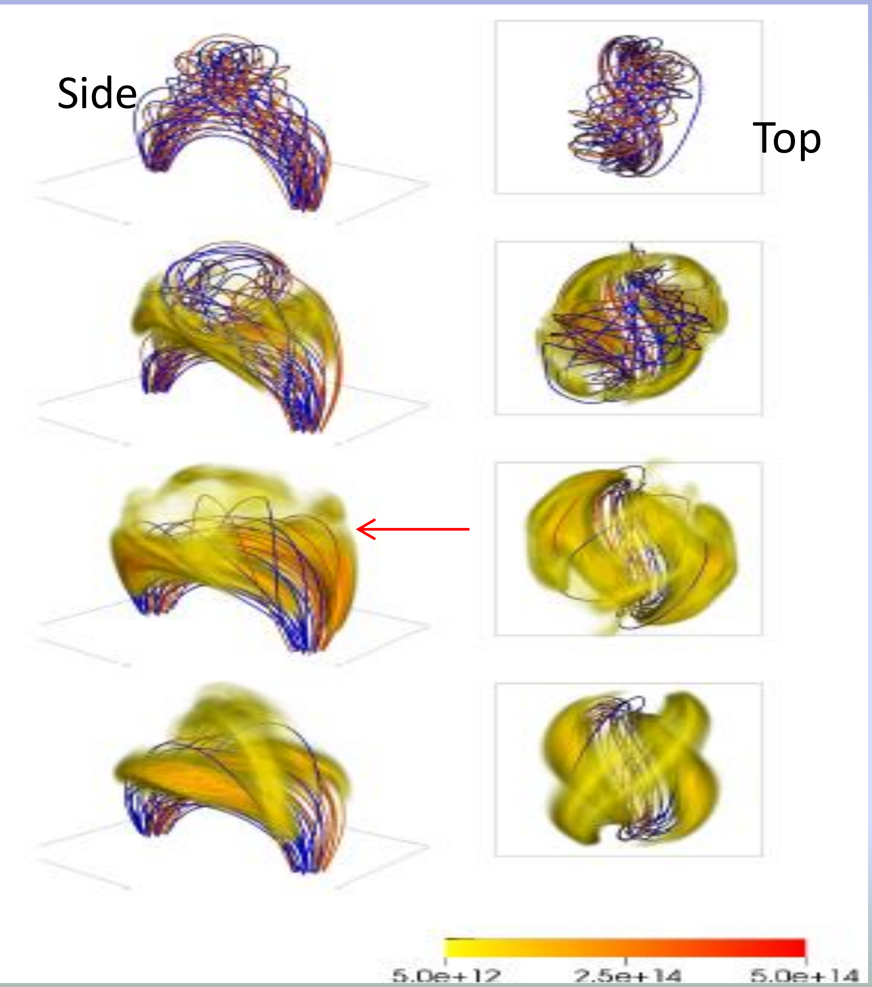
- Initial thermal particles uniformly distributed in volume
- Incorporate Coulomb collisions of test particles with background plasma

Hard X-ray emission at 10 keV
Produced in a dense coronal loop
(10^{11} cm^{-3})

Gordovskyy et al., 2014

Particle acceleration,transport, radiation, heating in twisted coronal loops

What is the link between plasma heating, particle acceleratio between thermal SXR and non thermal HXR radiations?



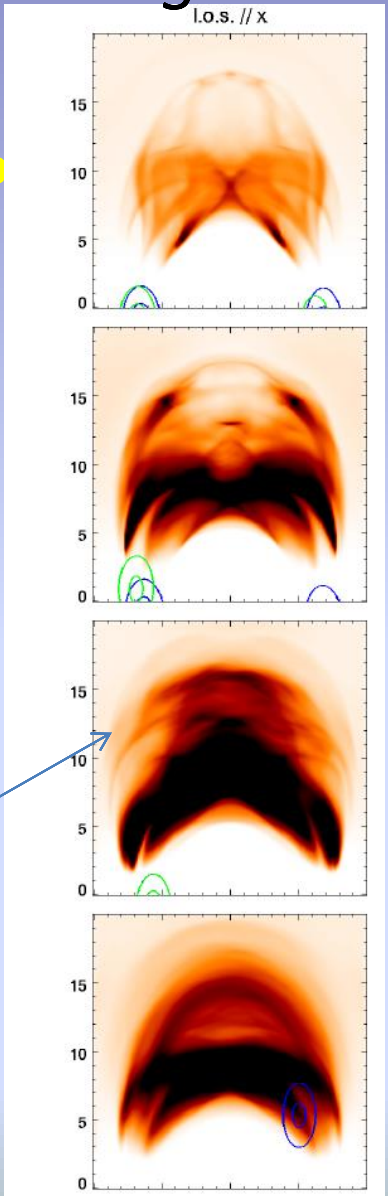
Pinto, Gordovskyy, Browning,,Vilmer 2016

MHD model from Gordovskyy et al., (2014) (stratified atmosphere)

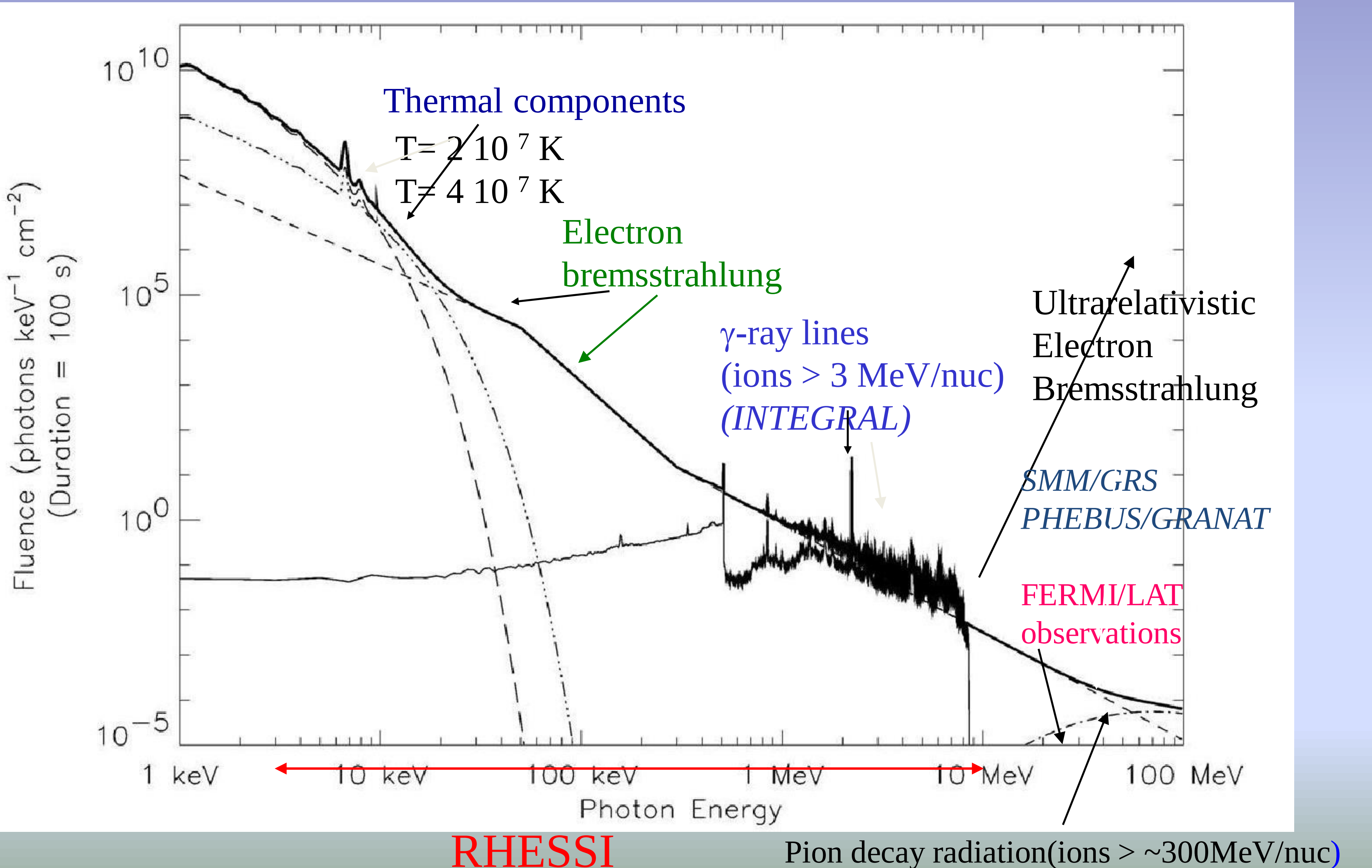
SXR emissivity (yellow) Resulting from plasma heating
(see Pinto et al. 2015)

Non thermal X-ray emissions Comparison with Observations?

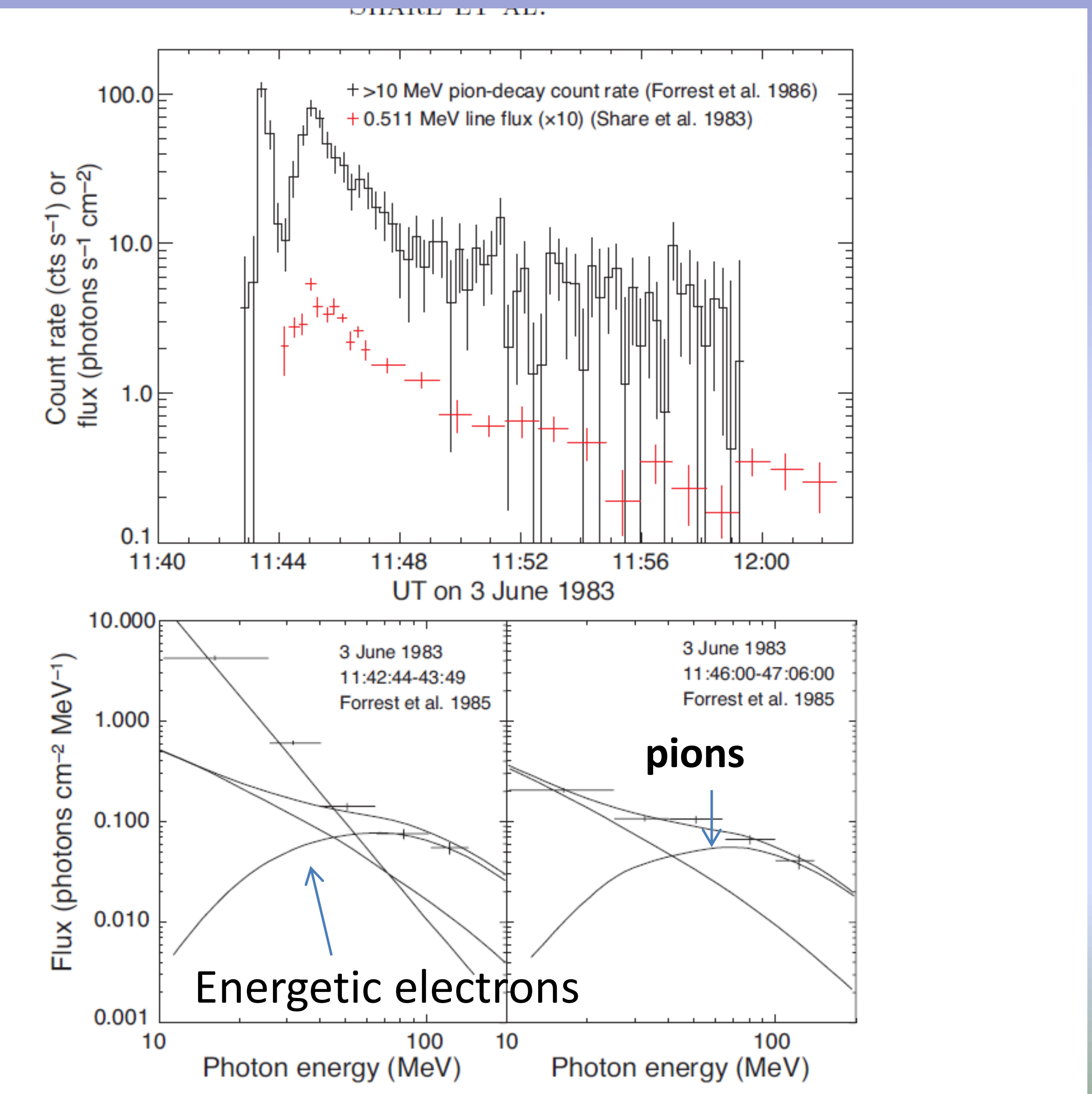
Need of more dynamic range in images (*FOXSI NASA/SMEX*)



Gamma-ray emission above >100 MeV from >300 MeV ions



High-energy emission above 60 MeV



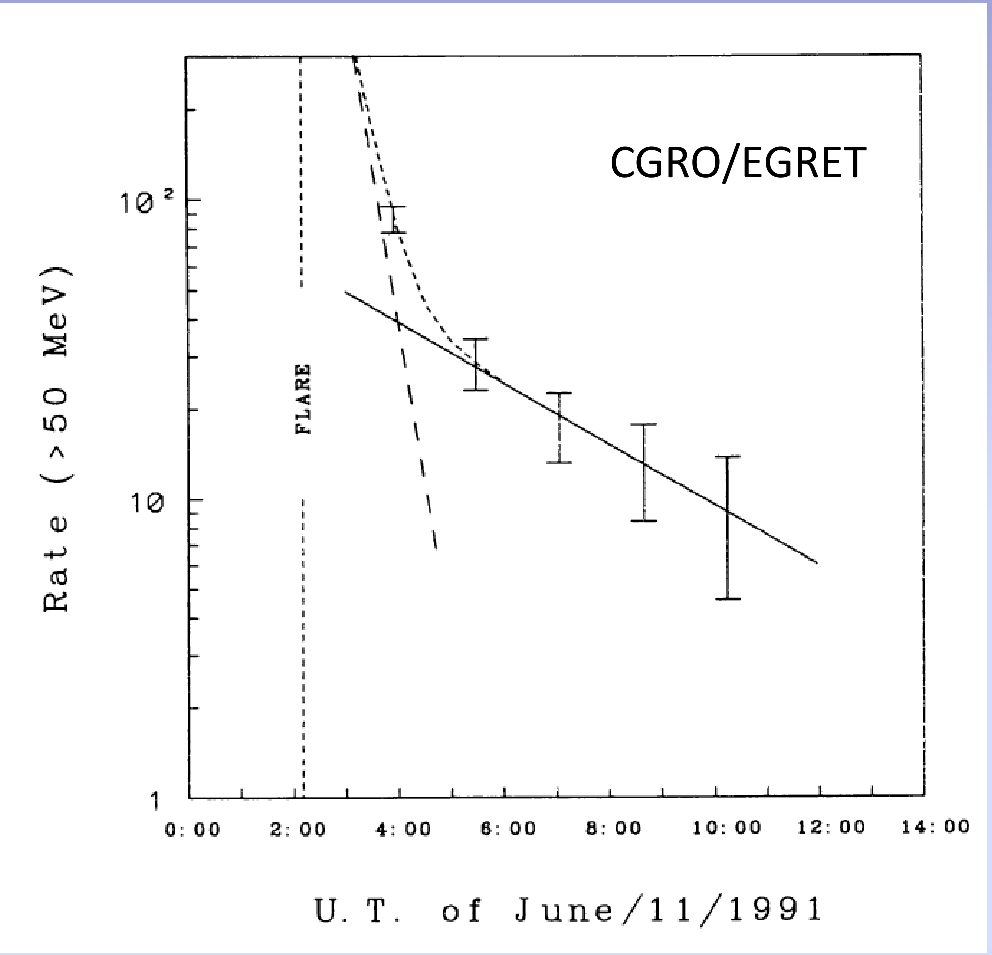
First observations of γ ray emissions from the Sun at photon energies > 10 MeV

(Solar Maximum Mission)

(Forrest et al., 1985; 1986)

(around 20 events)
(before FERMI era)
(see Chupp & Ryan, 2009; Vilmer et al., 2011)

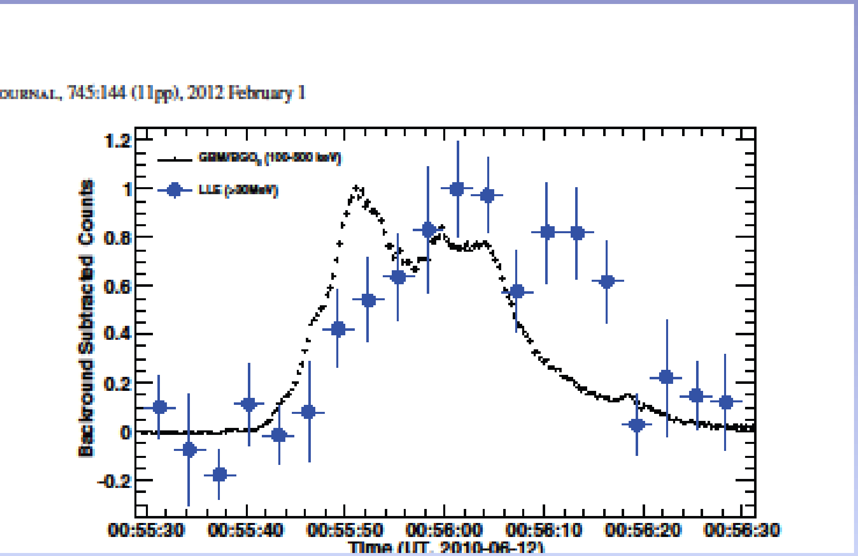
Long duration high-energy events



High energy radiation from pion-decay radiation may last for several hours after the flare impulsive flare!!

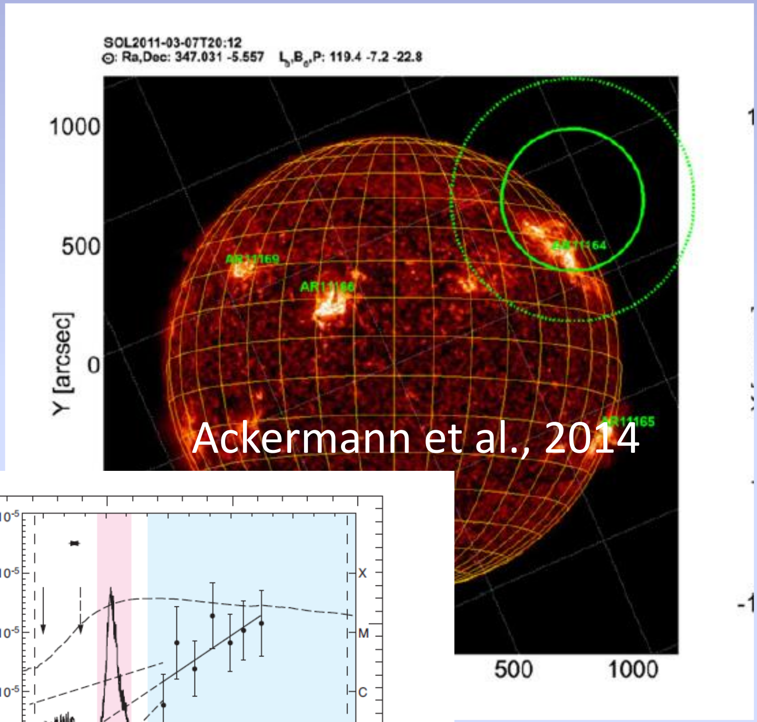
Kanbach et al., 1993

New observations from FERMI



High energy emission from a moderate flare (M2 flare)

Ackermann et al., 2012

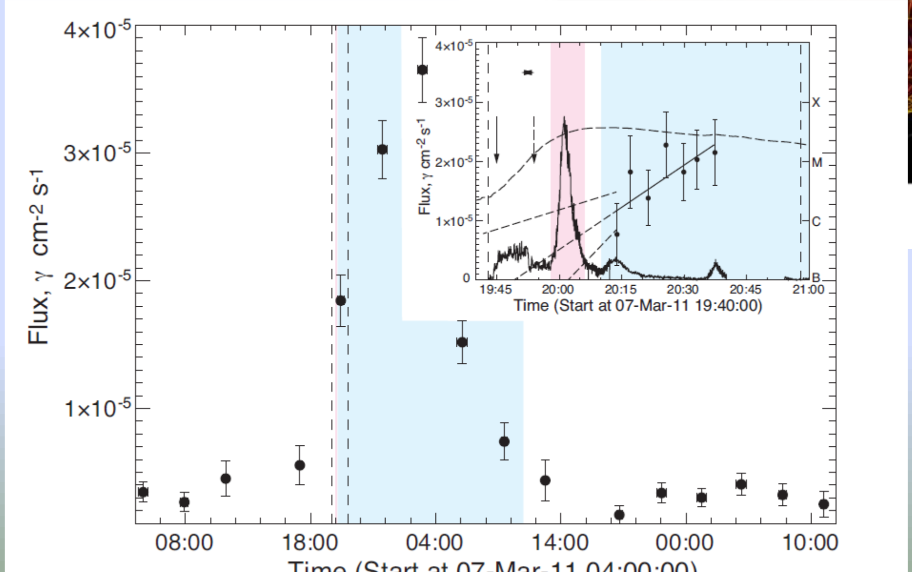


Ackermann et al., 2014

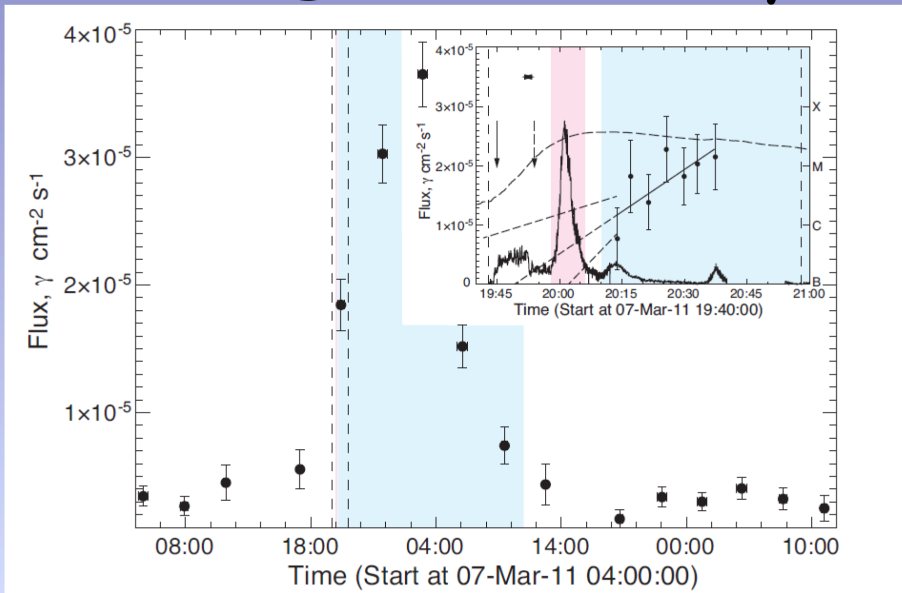
More long duration flares

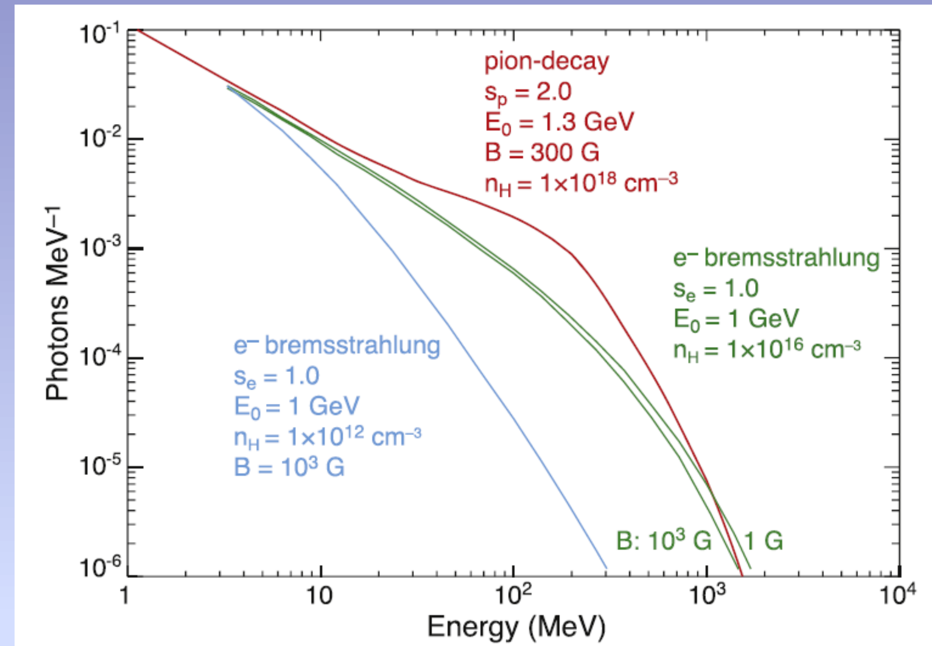
~30 events with sustained long duration emissions above 100 MeV
(see e.g. Share et al., 2018)

Localization of> 100 MeV emissions with FERMI/LATT



Long duration γ-ray flares from FERMI





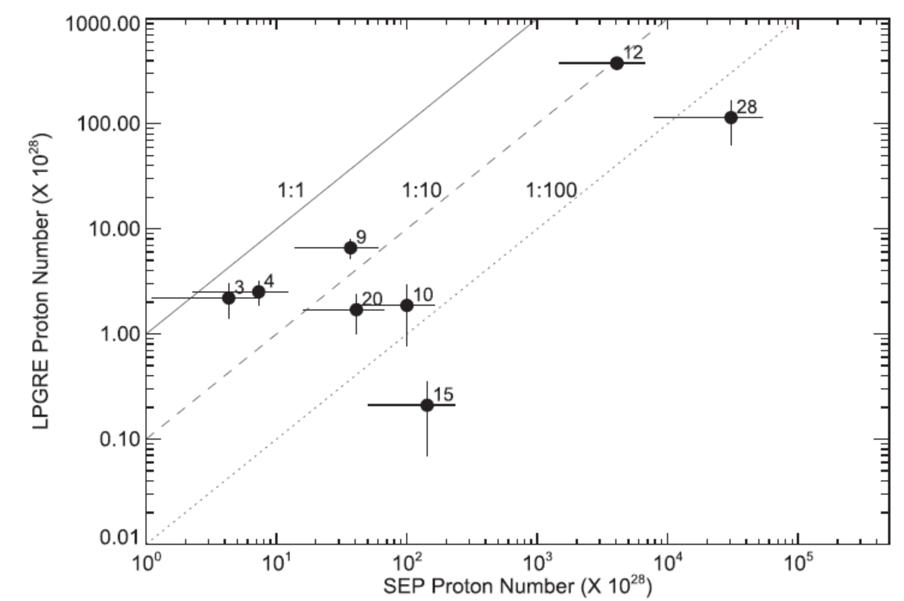
Systematic study of 30 late phase γ-ray emissions (LPGRE emissions

Number of LPGRE protons>500 MeV~10^{27}-10^{30}

Typically 10 times the number of protons in the flare impulsive phase when observed

0.01 to 0.5 the number of accompaniyng SEP Events (9 events)

Share et al., 2018



Origin of the long duration high energy radiation

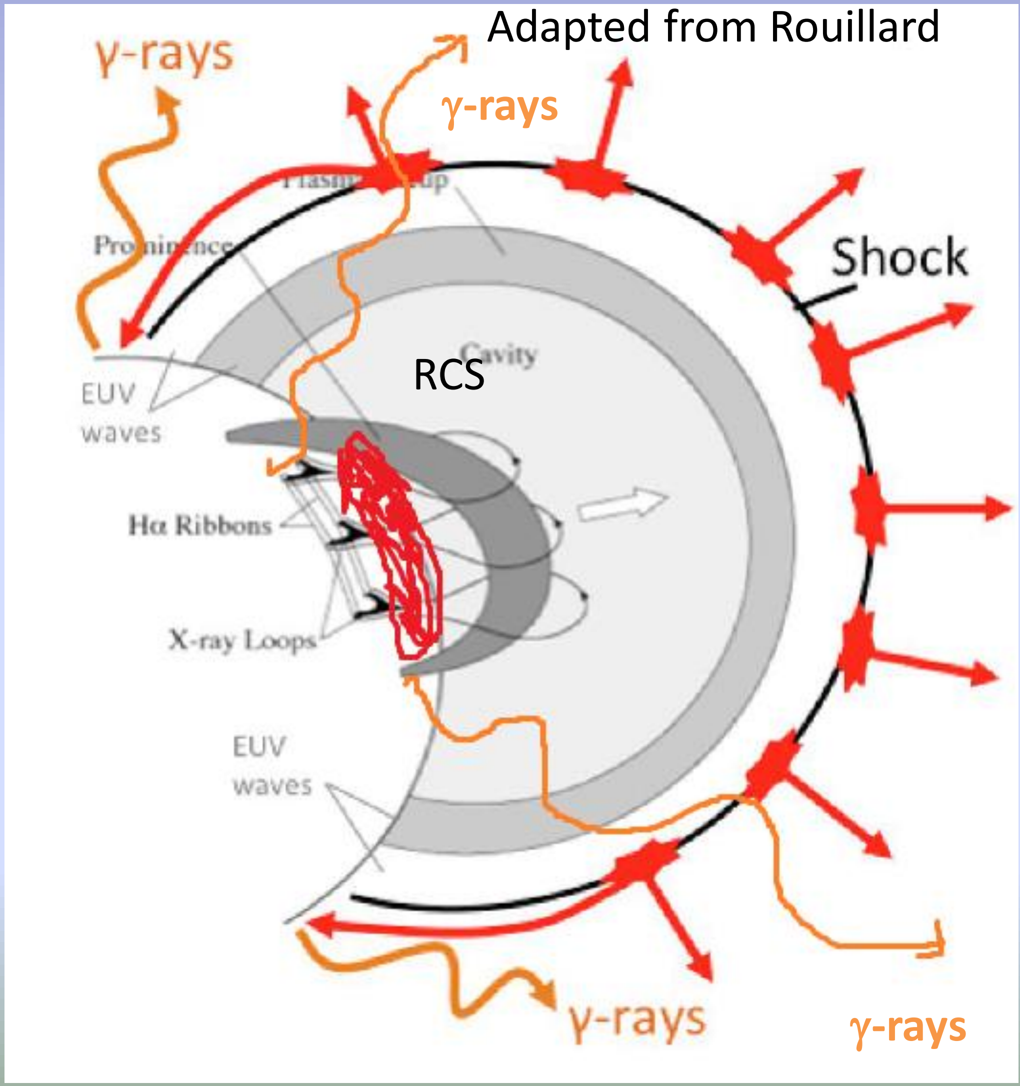
Already discussed at the CGRO time
(see e.g., Ryan, 2000)
(see also Klein et al., 2018, HESPERIA)

Continuous particle acceleration or long duration trapping?

- delayed precipitation of high-energy particles accelerated in the impulsive phase and trapped high in the corona;

- **acceleration by an expanding shock far from the flare site of particles that make their way back to the chromosphere (see e;g; Plotnikov et al;.2017 for the study of connectivity)**

- particles accelerated in the reconnection current sheet behind a Coronal Mass Ejection (CME);



Challenges of particle acceleration at the Sun:

	Electrons	Ions
Number	10^{39} _ 10^{41} (>20 keV)	310 ^{35} (>30MeV)
Acc. times	~ 100 ms @100 keV-1 MeV	< 1s @10 MeV
Duration (s)	10 → hour	60 → hour
Total energy (ergs)	10^{34} (> 20 keV)	10^{32}- 10^{33} (> 1 MeV)

From e.g.
Chupp 1996
Vilmer and MacKinnon 2003

The Sun is a very efficient particle accelerator:

Flares (but also CMEs) constitute large energy releases from coronal magnetic storage
(~ 50 % of the energy goes to energetic particles)
Number problem

The Sun can accelerate particles to very high energies

Up to a few GeV for electrons, to tens of GeV for ions

Like astrophysical objects But major challenges: time scales for acceleration
Fast acceleration **but also long duration acceleration in some events…**

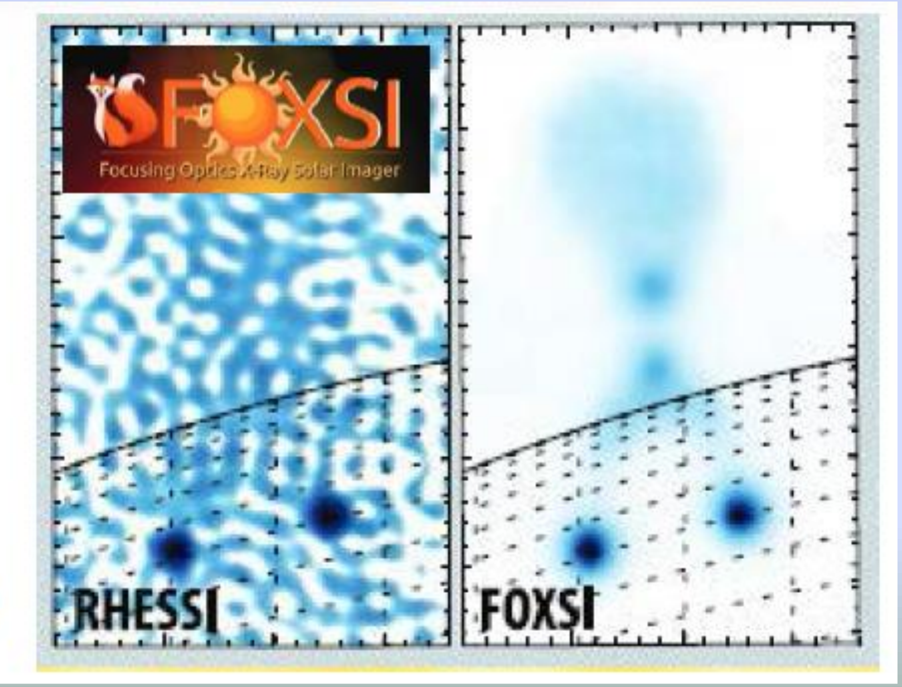
Energetic particles in the solar atmosphere? (I)

What are the acceleration mechanisms?
Where are the acceleration sites?

How are energetic particles affected by transport from the acceleration to the emitting sites (in X-rays?)

Still a lot of open questions

More to be learnt in the future with direct imaging in X-rays (FOXSI NASA/SMEX)



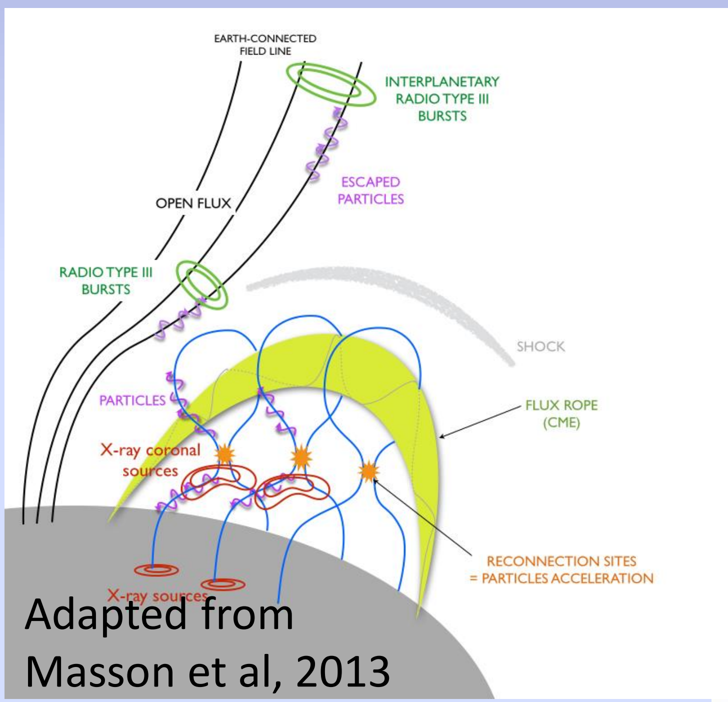
Energetic particles in the solar atmosphere? (II)

What are the acceleration mechanisms?

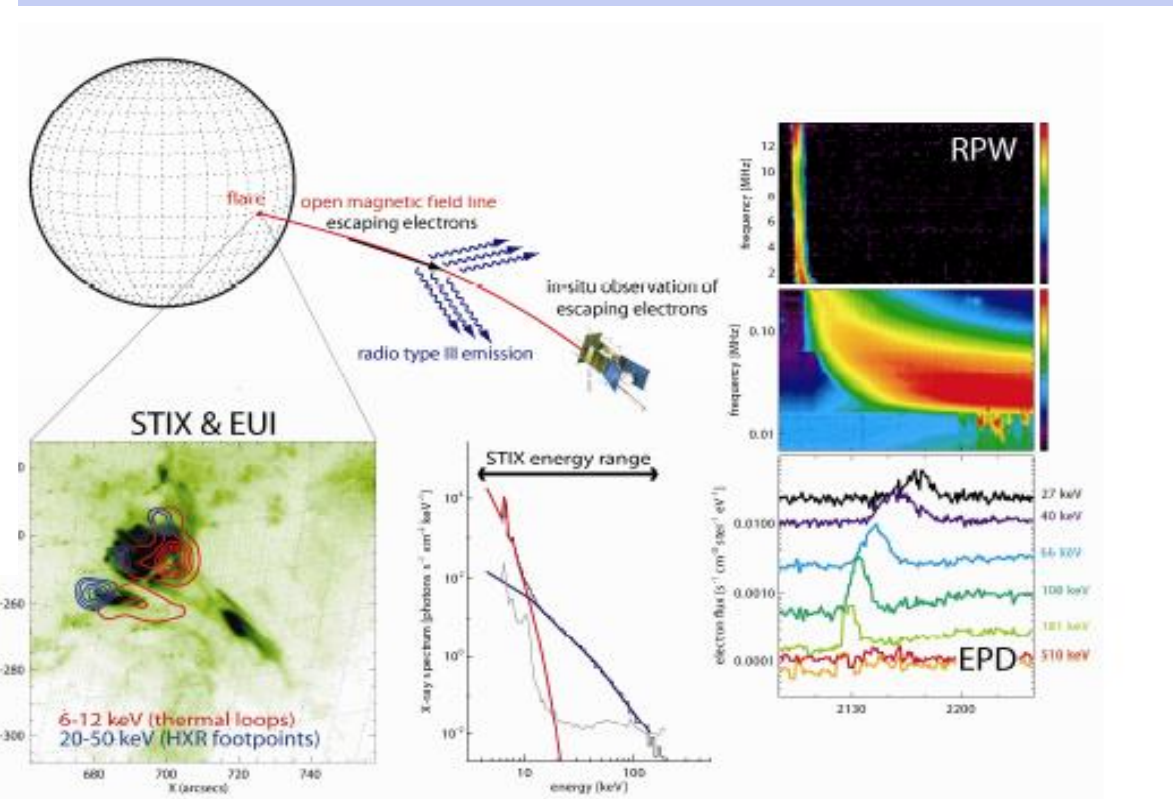
Where are the acceleration sites?

How do they propagate from the corona in the interplanetary medium?

What is the link between energetic particles at the Sun and in the interplanetary medium??



Adapted from Masson et al, 2013



one of the key questions for Solar Orbiter and of Parker Solar Probe