Solar Electron Acceleration and Propagation as revealed by X-ray and radio diagnostics

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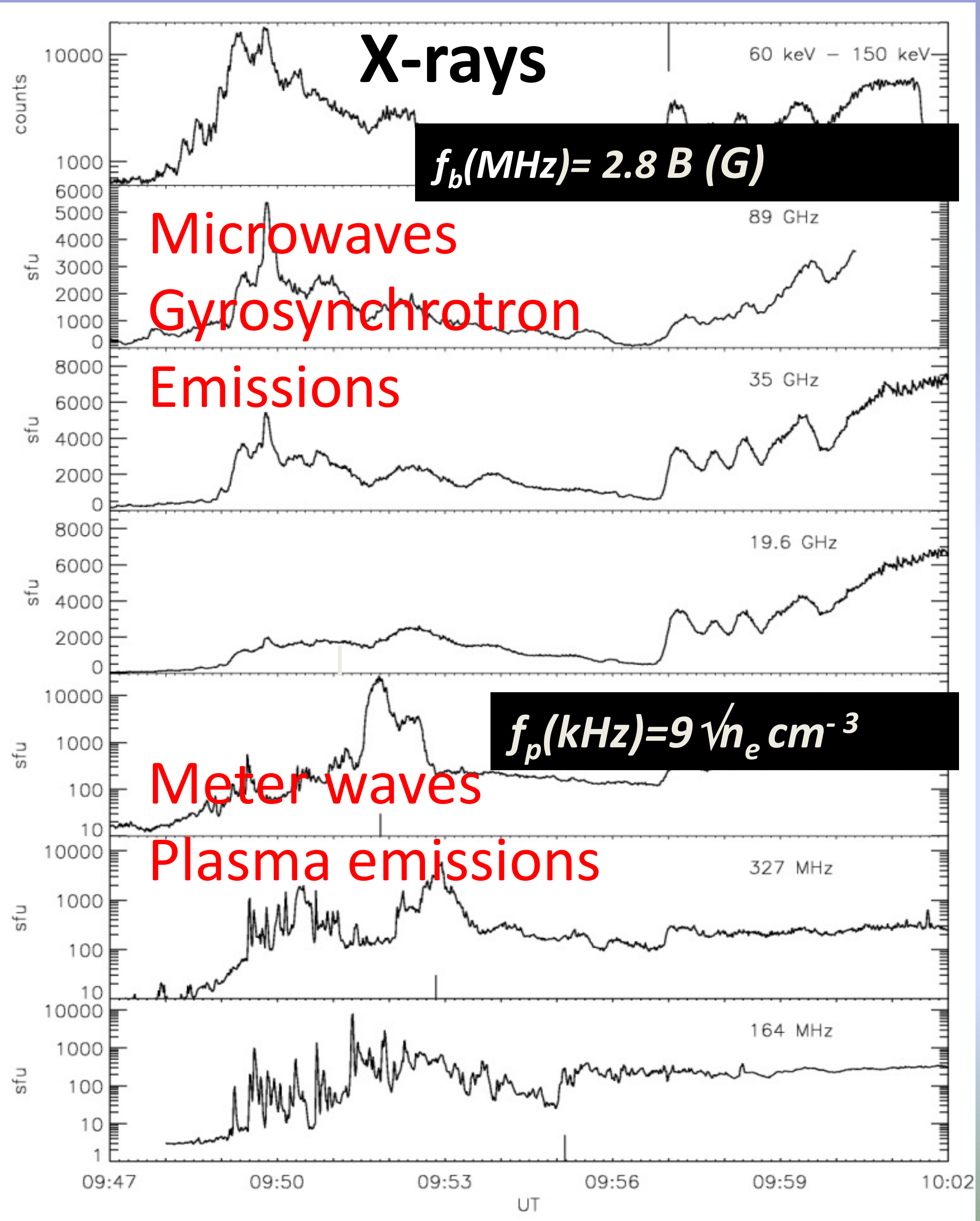
The sun: an efficient particle accelerator

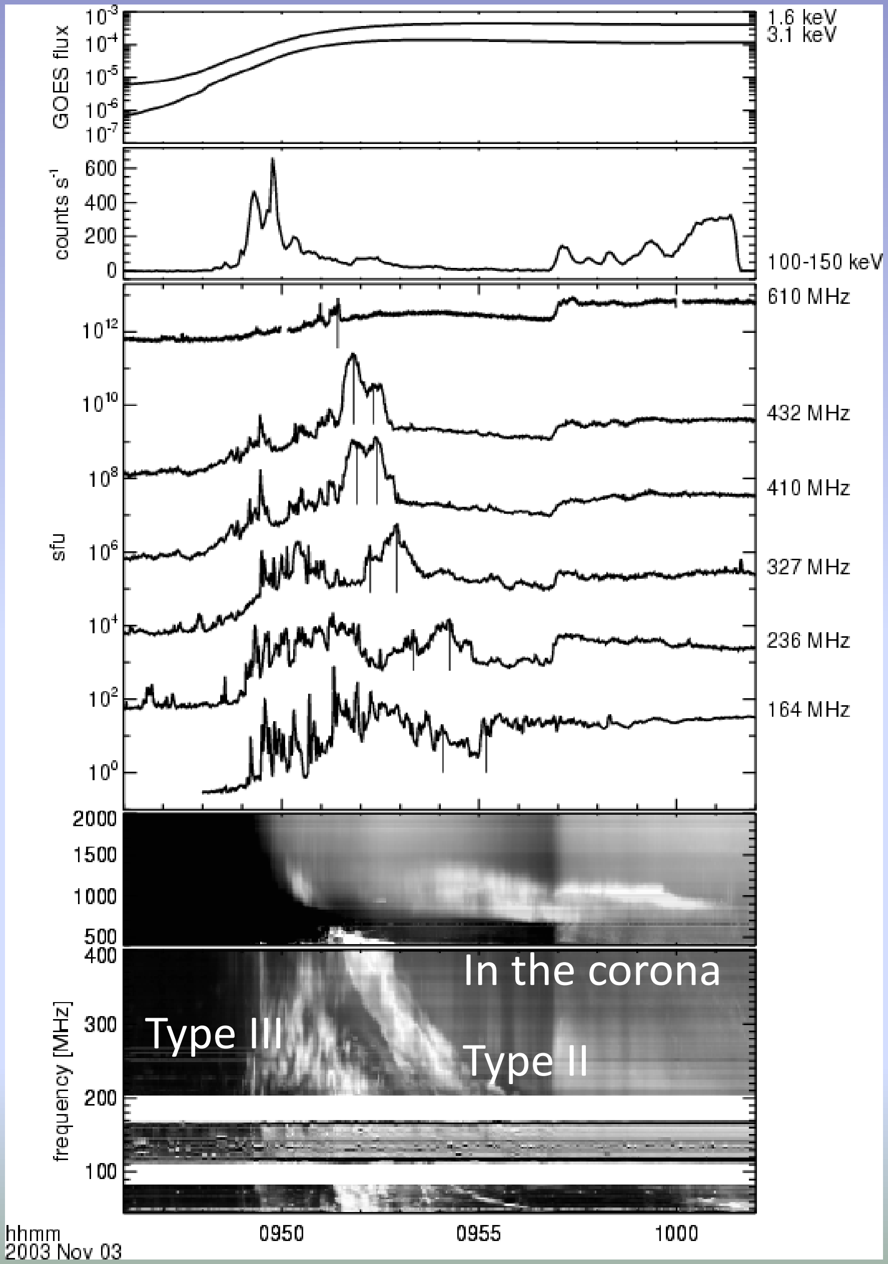


Energetic electrons from solar flares produce X-ray emissions in a wide energy band (~10^{36} e/s)and radio emissions in a large frequency band :

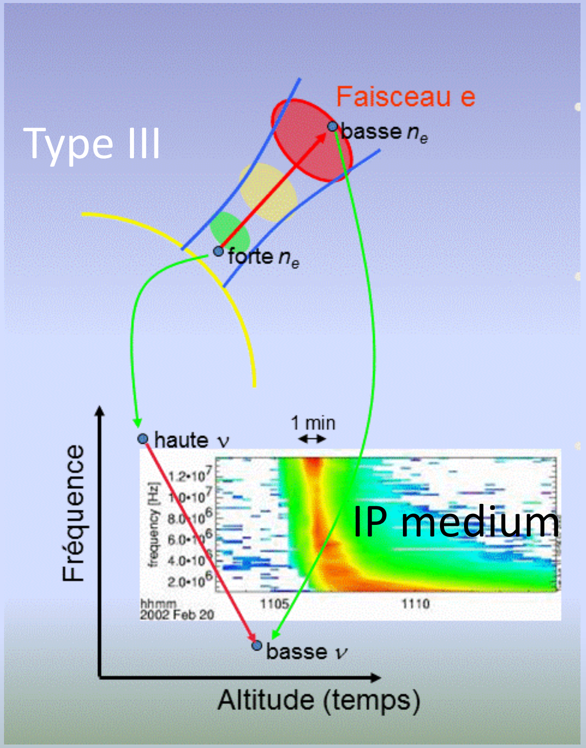
Radio emissions in the 90 GHz to 100 MHz domain

Dauphin, Vilmer et al., 2005

Electromagnetic radiation from energetic electrons



Energetic electrons from solar flares produce X-ray emissions in a wide energy band and Plasma radio emissions in a large frequency band : 600 MHz to 30 MHz

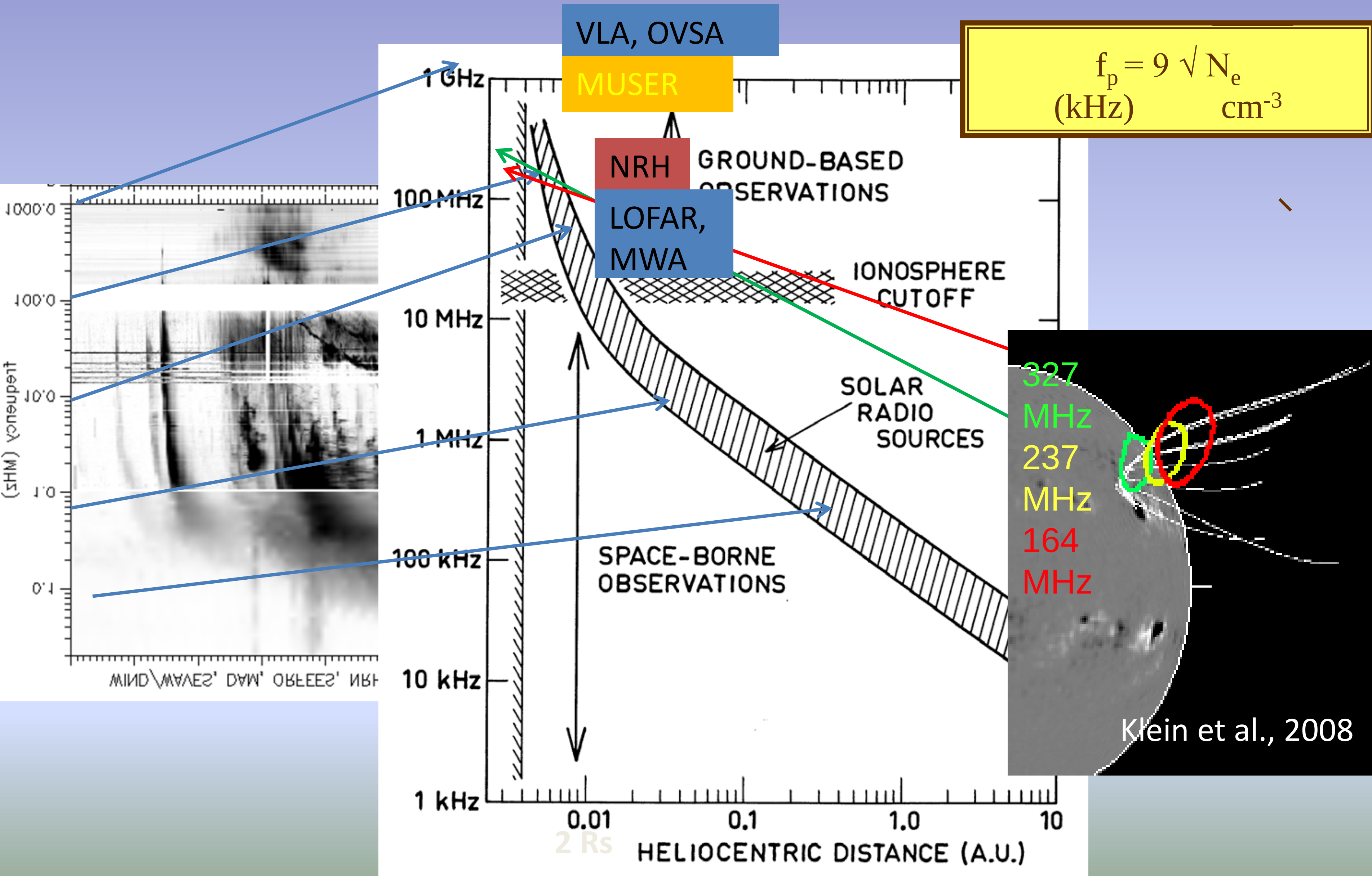


Dauphin, Vilmer, Krucker, 2006

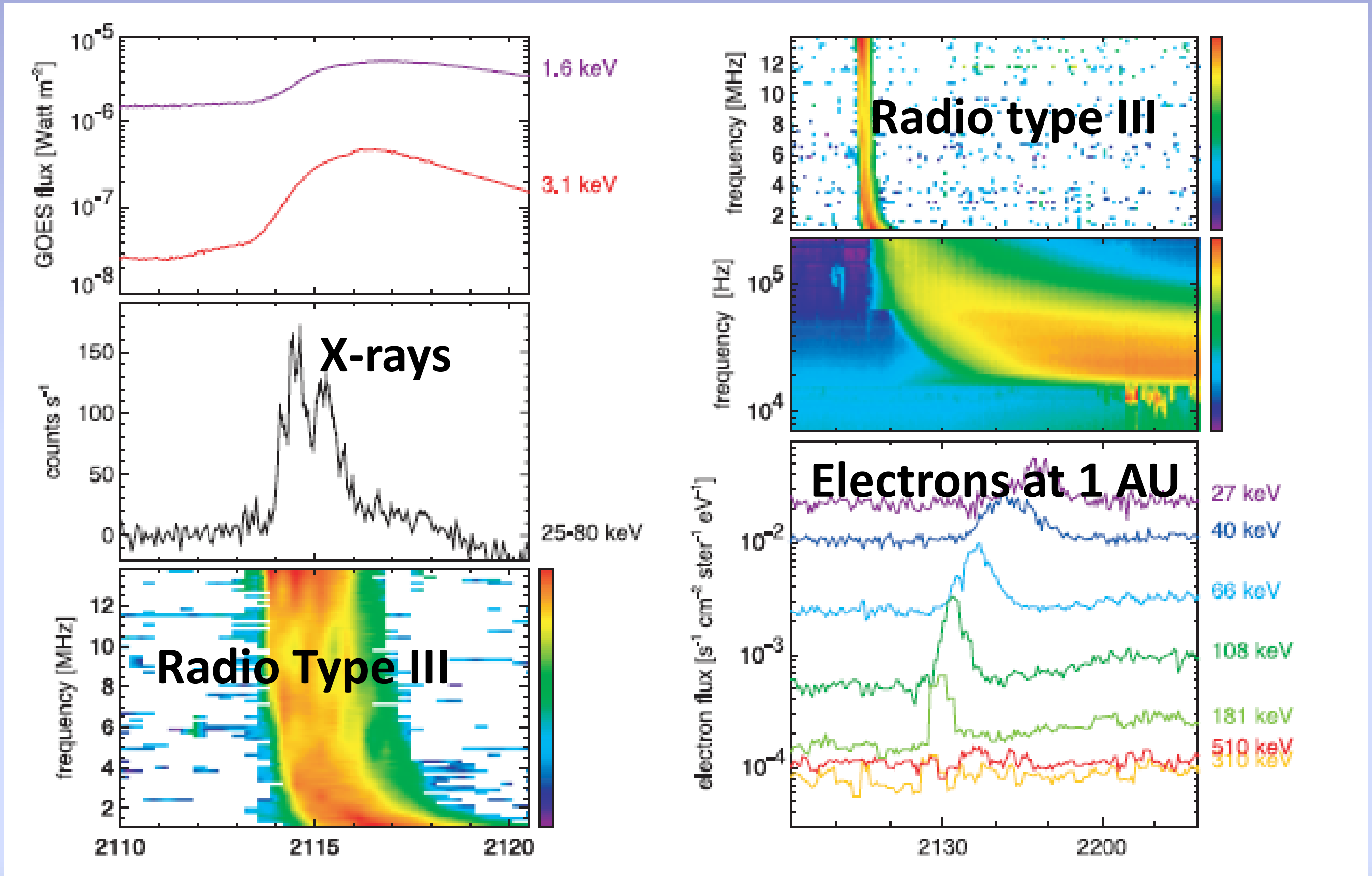
Radio emissions in the corona

$$f_p = 9\sqrt{N_e}$$

(kHz) $\quad$ cm^{-3}



Energetic electrons at the Sun and directly detected in the interplanetary medium



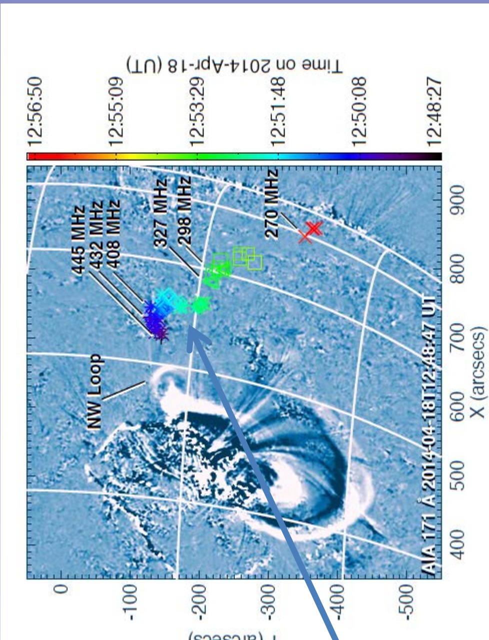
Krucker et al., 2007

Acceleration of particles in solar flares?

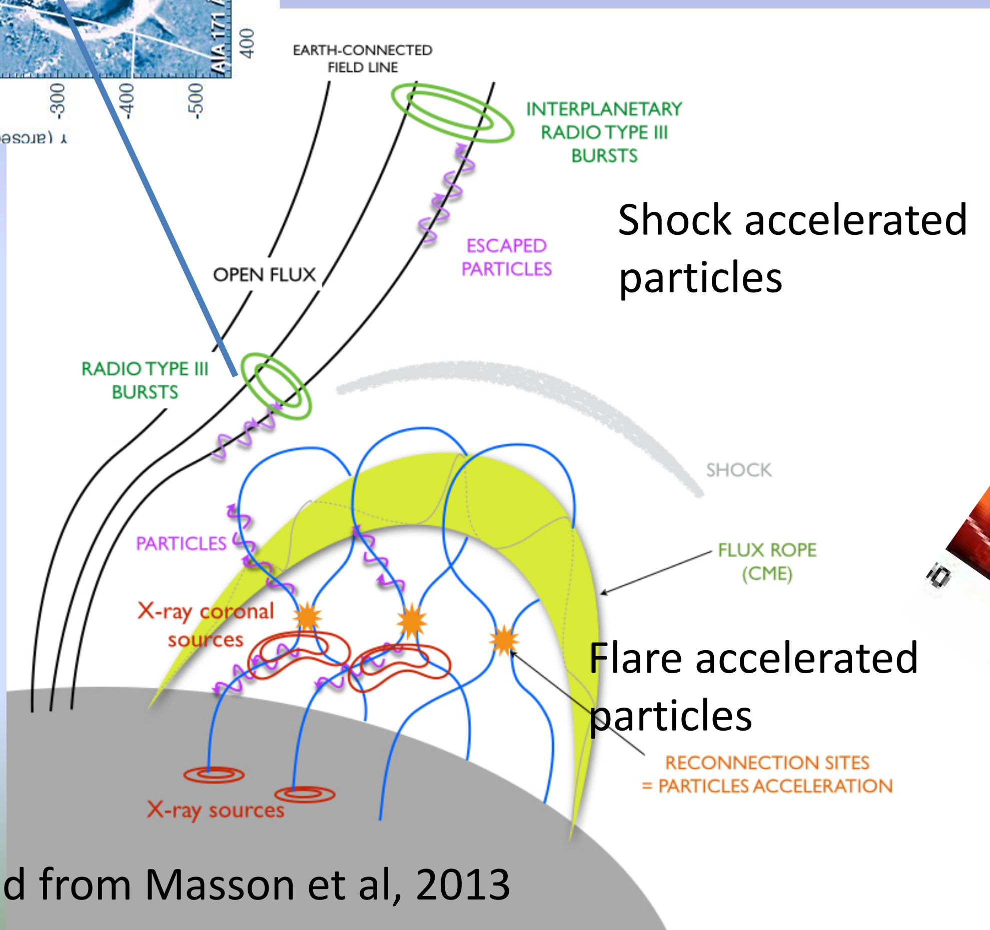
What are the acceleration mechanisms?

Where are the acceleration sites?

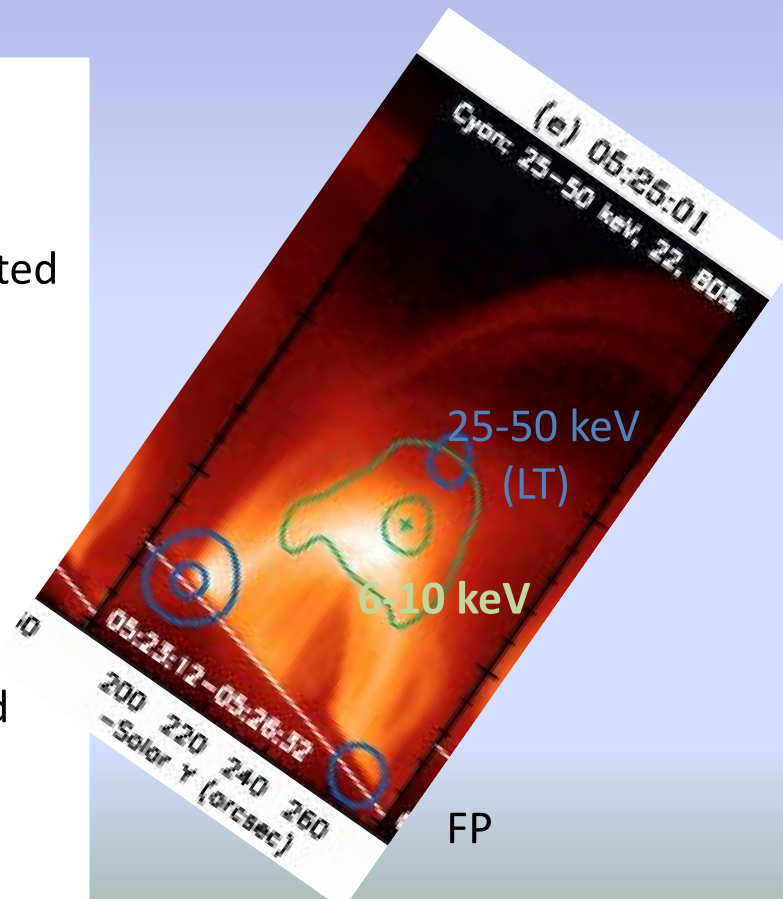
How are energetic particles affected by transport from the acceleration to the emitting sites (in X-rays?) How do they propagate from the corona in the interplanetary medium?



Carley et al., 2016



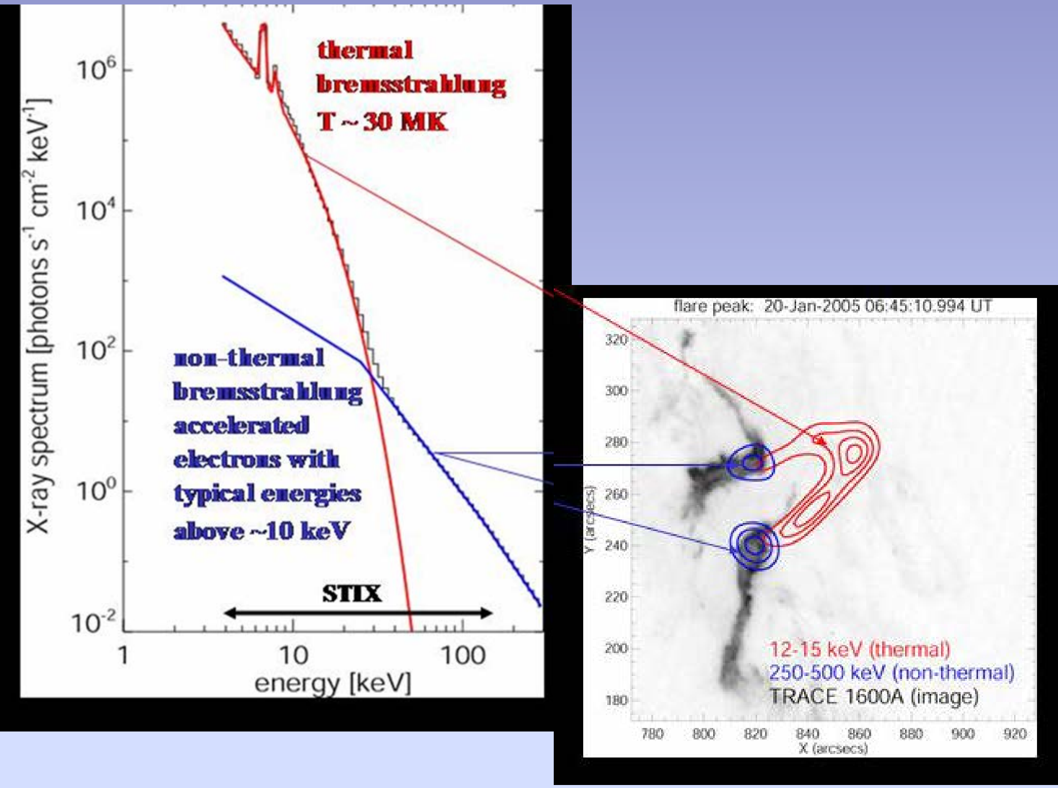
Adapted from Masson et al, 2013



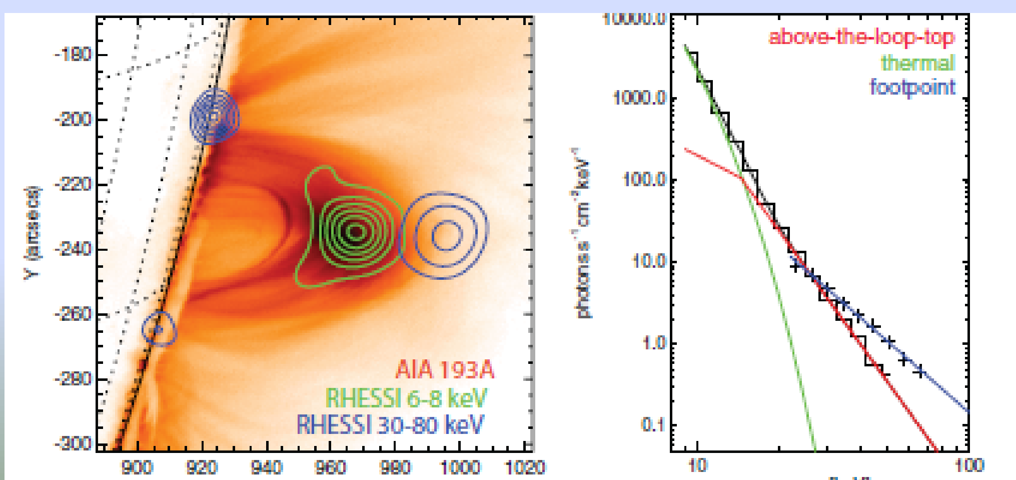
Liu W., et al., 2013

Transport of electrons in the corona: input of RHESSI imaging spectroscopy

X-ray diagnostics of energetic electrons



Krucker et al., 2008



Magnetic energy dissipation and particle acceleration in current sheet above flare loop

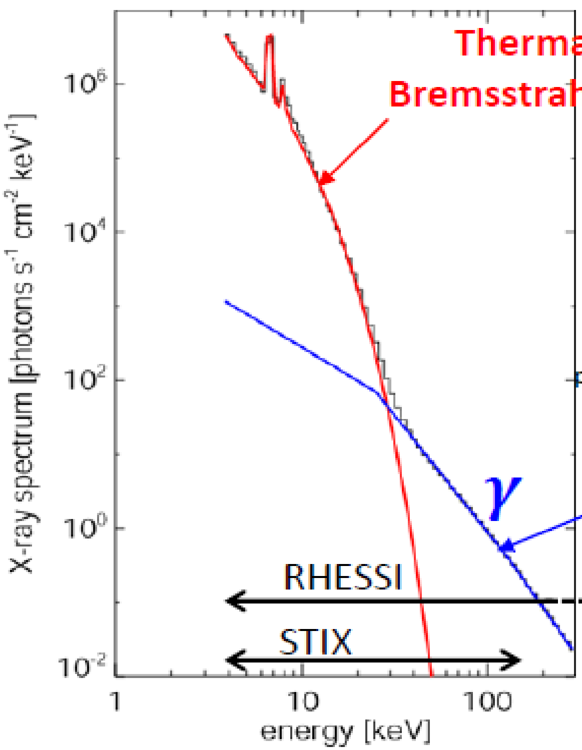
Detection of non thermal X-ray source in the 30-80 keV band

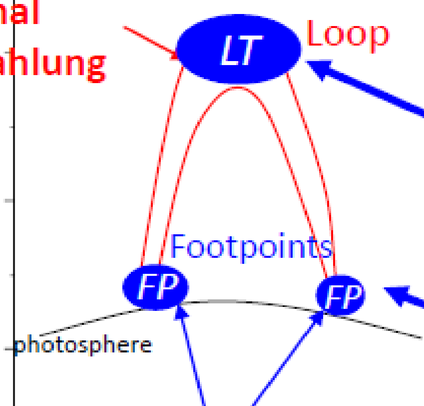
Above X-ray source X in the 6-8 keV band

Acceleration region?

(Krucker & Battaglia, 2014)

X-ray diagnostics of energetic electrons





Non-thermal Bremsstrahlung

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

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

[e-/s/cm²/keV]

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)

« Standard » propagation model

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

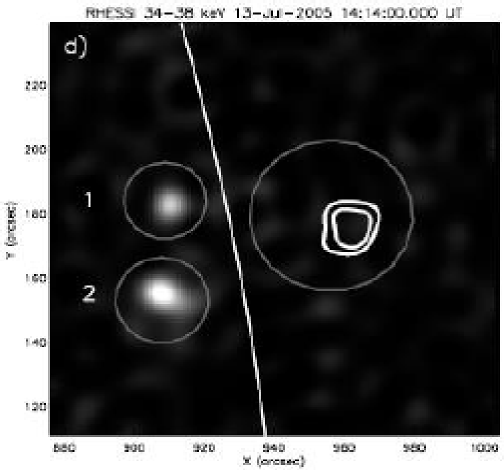
$$\dot{N}_{LT} = \dot{N}_{FP} \quad \text{[e-/s]}$$

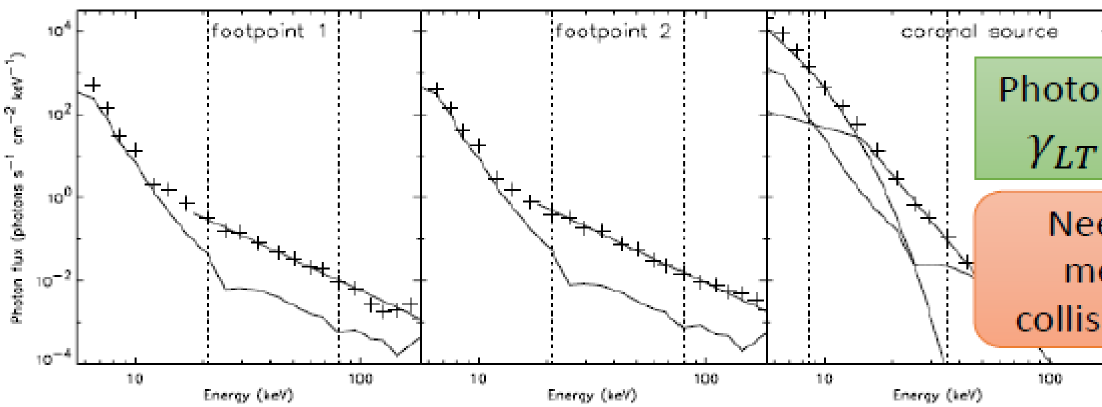
Thermal Bremsstrahlung: T ≈ 30 MK

Non-thermal Bremsstrahlung: electrons with energie > 30 keV

Acceleration ? Transport ?

RHESSI Imaging Spectroscopy: a new tool to study energetic electron transport during flares



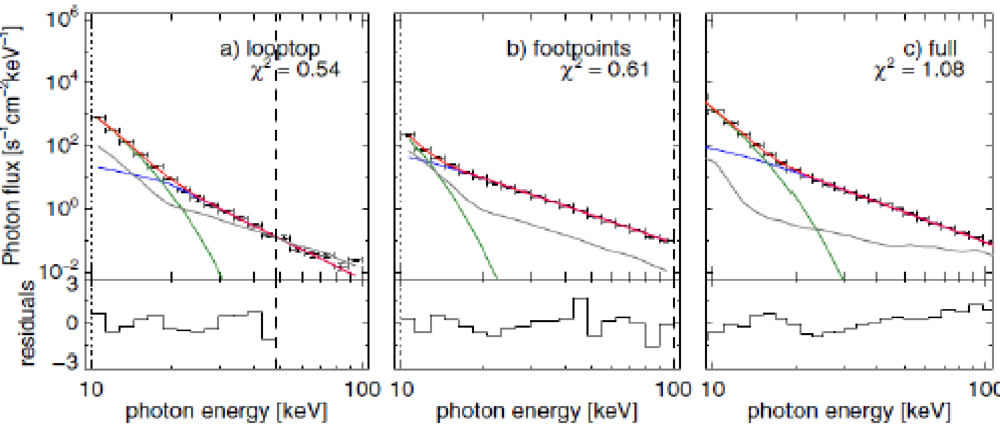


Battaglia & Benz (2006)

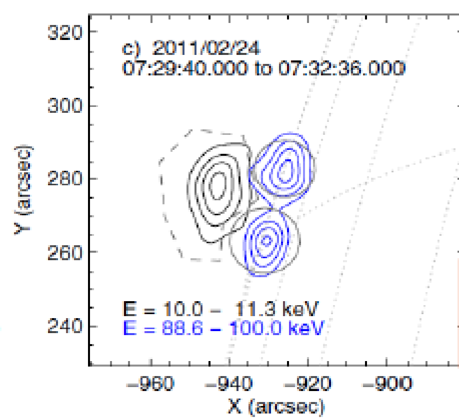
Photon spectral index

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

Need additional mechanism to collisional transport



Simoes & Kontar (2013)



Electron spectral index

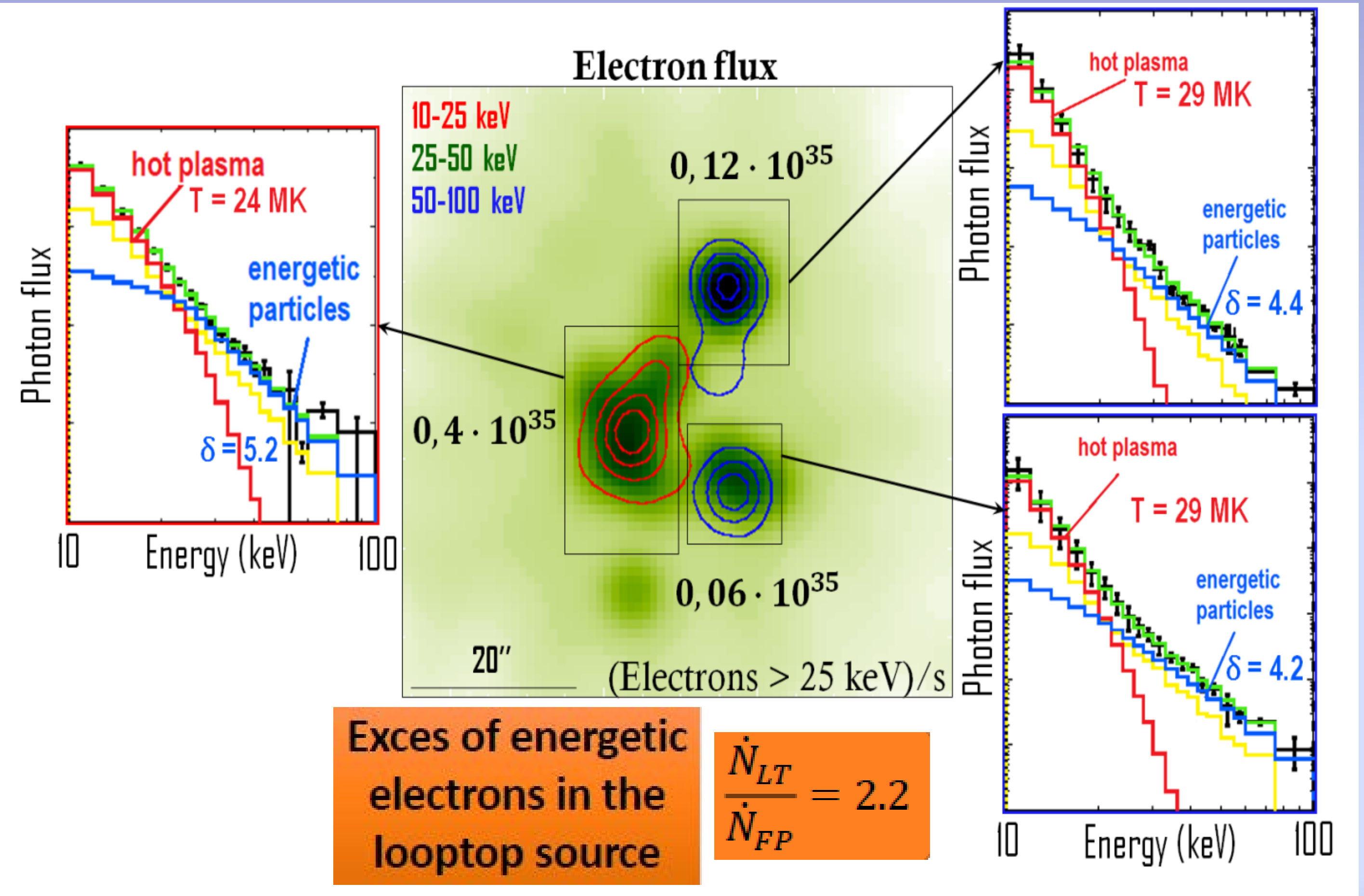
$$\delta_{LT} - \delta_{FP} < 0$$

Ratio of electron rate

$$\frac{\dot{N}_{LT}}{\dot{N}_{FP}} > 1$$

Need additional mechanism to collisional 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).

The physics of the loop-top trapping

Diffusive transport of energetic electrons

Turbulent magnetic field

→ Pitch angle scattering

« Trapping » of energetic electrons in corona

+

Harder spectrum in footpoints

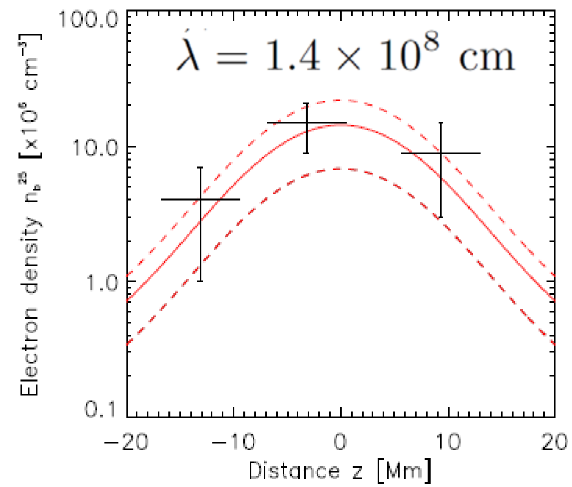
$$\frac{1}{v}\frac{\partial}{\partial z}\left(D_{zz}^{(T)}\frac{\partial F}{\partial z}\right) = \frac{\partial}{\partial E}\left(\frac{Kn}{E}F\right) + F_0 S(z)$$

Diffusion coefficient — Collisional energy losses — Source

Kontar et al. (2014)

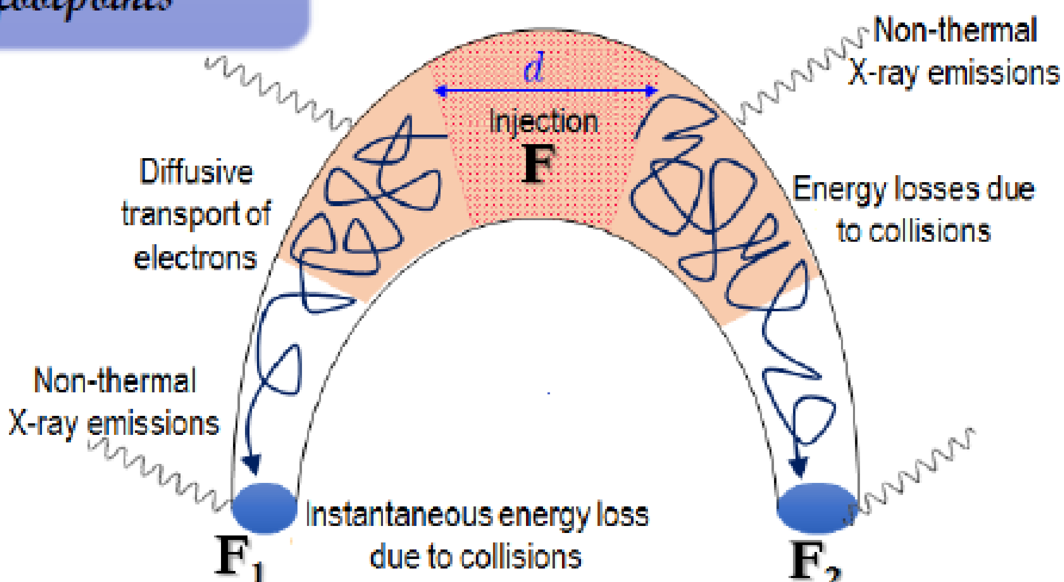
$$D_{zz}^{(T)} = \frac{\lambda v}{3} \quad F_0 = \dot{N}\frac{(\delta-1)}{E_0}\left(\frac{E}{E_0}\right)^{\delta} \quad S(z) = \frac{1}{\sqrt{2\pi d^2}}\exp\left(-\frac{z^2}{2d^2}\right)$$

Free parameters in the model:
Injected electron spectrum F_0,
Ambiant density n, scattering mean free path λ, size of the acceleration region d



$$F_D(E,z) = \frac{E}{Kn}\int_E^{\infty} dE' \frac{F_0(E')}{\sqrt{4a\pi(E'^2-E^2)+2d^2}} \times \exp\left(\frac{-z^2}{4a(E'^2-E^2)+2d^2}\right)$$

Kontar et al., 2014



Musset, Kontar, Vilmer, A&A, 2018

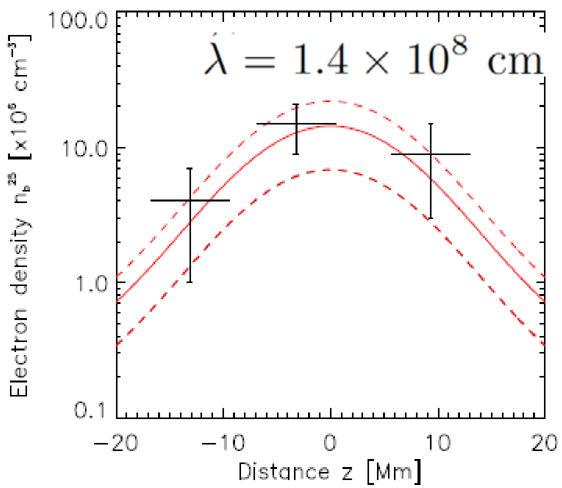
Energetic electron density

Maximum in the coronal part of the loop ➔ Energetic electrons are trapped in the coronal looptop

Ratio between energetic electron density in looptop and footpoints:

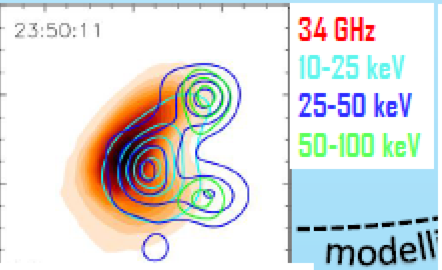
$$\frac{n_{b,LT}^{25}}{n_{b,FP}^{25}} = 1.6 \text{ et } 3.8$$

To be compared to



Spatial distribution of energetic electrons above 25 keV from X –rays

Energetic electron density deduced from radio observations (NoRH)

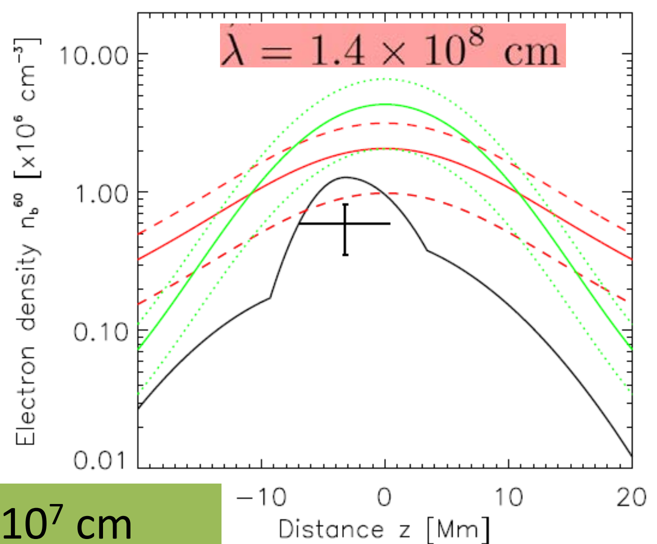


Kuznetsov & Kontar (2015)

$$\frac{n_{b,LT}^{60}}{n_{b,FP}^{60}} \geq 7.7 \text{ et } 9$$

$$\frac{n_{b,LT}^{60}}{n_{b,FP}^{60}} > \frac{n_{b,LT}^{25}}{n_{b,FP}^{25}}$$

modelling



$\lambda = 10^7$ cm

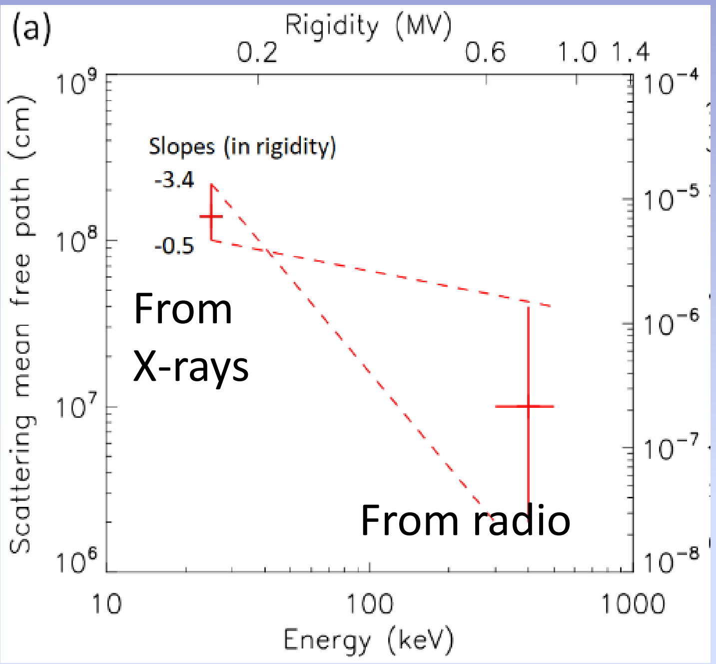
Spatial distribution of energetic electrons above 60 keV from radio (Nobeyama Radioheliograph observations)

(Kuznetsov & Kontar (2015))

Musset, Kontar, Vilmer, A&A, 2018

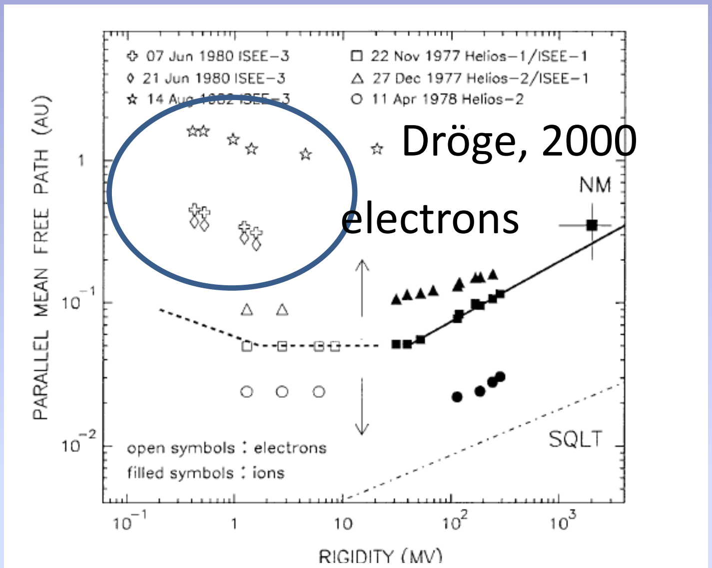
Energy dependance of the diffusive scattering mean free path

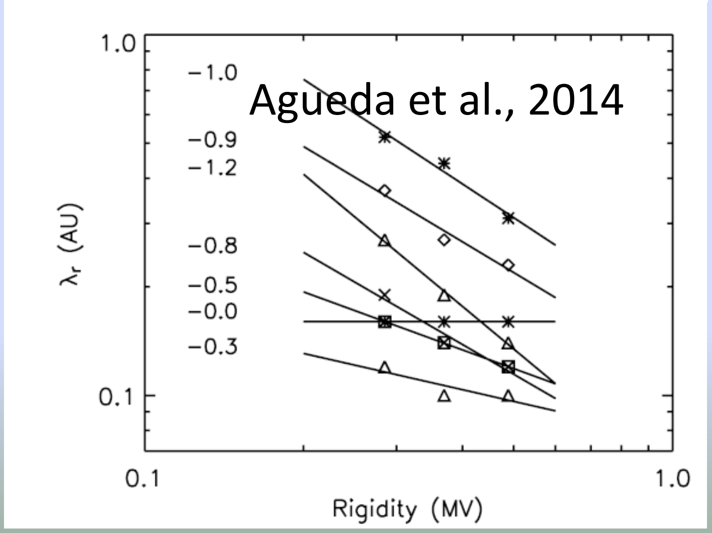
In the Corona



(Musset, Kontar, Vilmer, A&A, 2018)

In the Interplanetary medium





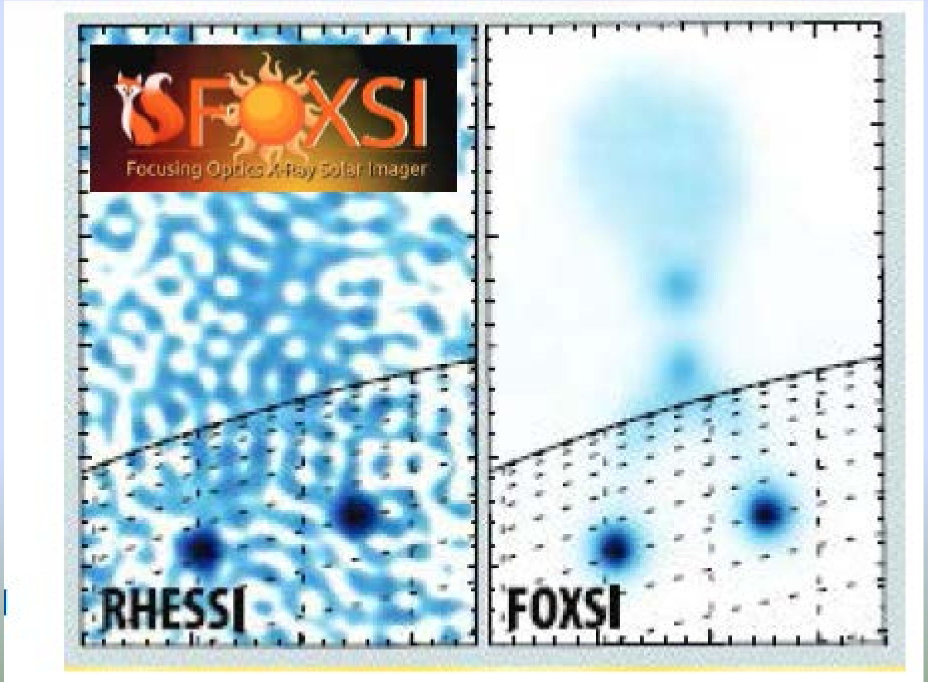
Conclusions: **Diffusive transport can describe the transport of energetic electrons in the corona for some events BUT Decrease of the scattering mean free path with electron energy/rigidity necessary to explain X-ray and radio observations**

(First evaluation in the corona)

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

Conclusions (I)

- *Diffusive transport of energetic electrons can explain some of the observations of X-ray emissions from energetic electrons in the corona obtained from imaging spectroscopy*
- **Some evidence of decrease of scattering mean free path with energy/rigidity in the corona (also in the IP medium) (low energy electrons 30-100 keV)**
- More to be learnt in the future with direct imaging in X-rays (e.g. FOXSI NASA/SMEX observations) in combination with new radio observations (EOVSA)



- Transport of energetic electrons associated with solar X-ray and radio bursts at the Sun and electrons escaping in the Interplanetary medium

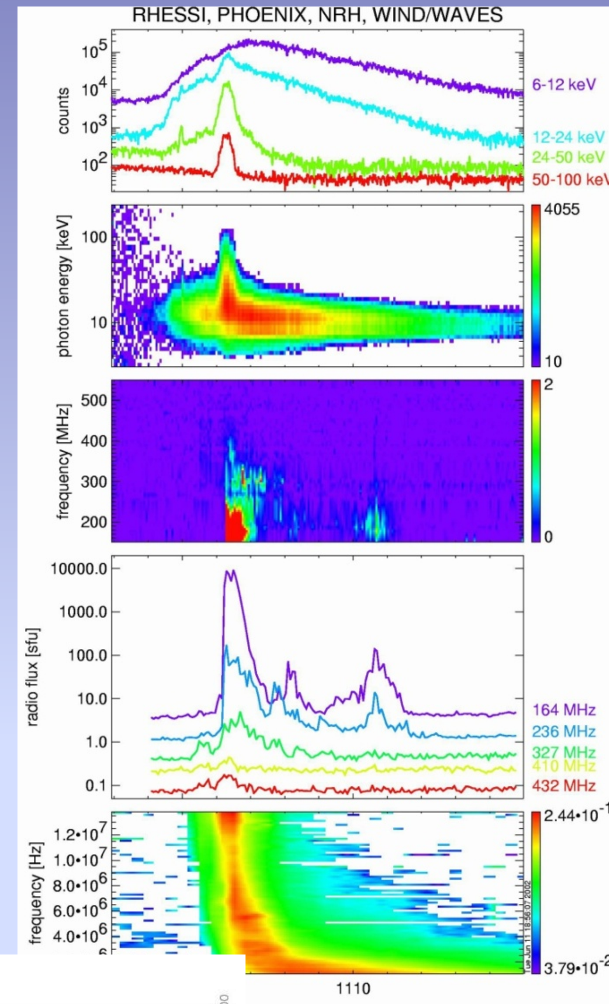
RADIO and X-RAY EMITTING ELECTRONS

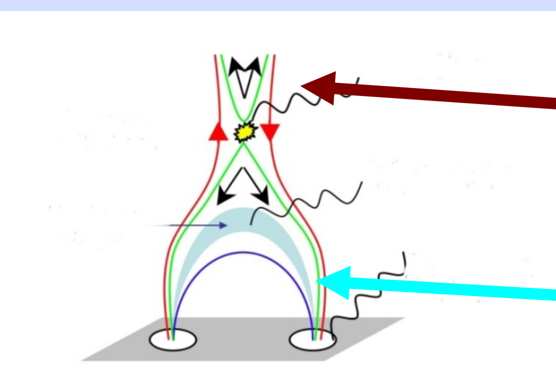
One of the cartoon

Electrons travelling downwards into the chromosphere radiate X-rays in dense ($n_e=10^{12}$ cm^{-3}) plasma via Bremsstrahlung.
Detected X-rays are usually in the 6-100 keV energy range
Electrons travelling upwards can induce Langmuir waves which in turn produce coherent radio emission (type III) in the rarefied ($n_e<10^9$ cm^{-3}) coronal and interplanetary plasma. Detected radio frequencies are from around 400 MHz down to 2 MHZ

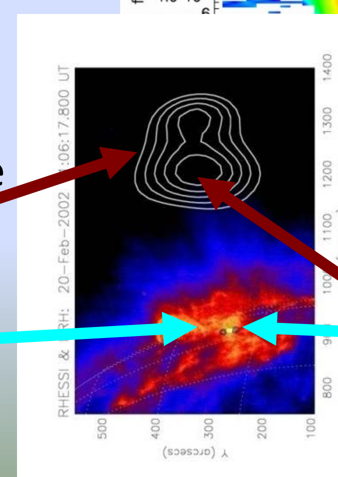
X-RAYS

RADIO





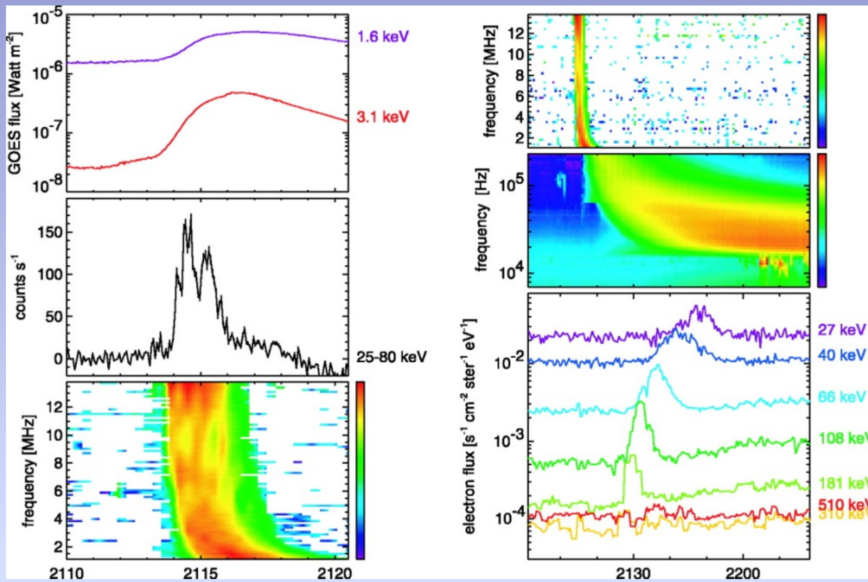
Standard picture ?
Electron acceleration in the corona
Propagation both upwards and downwards.

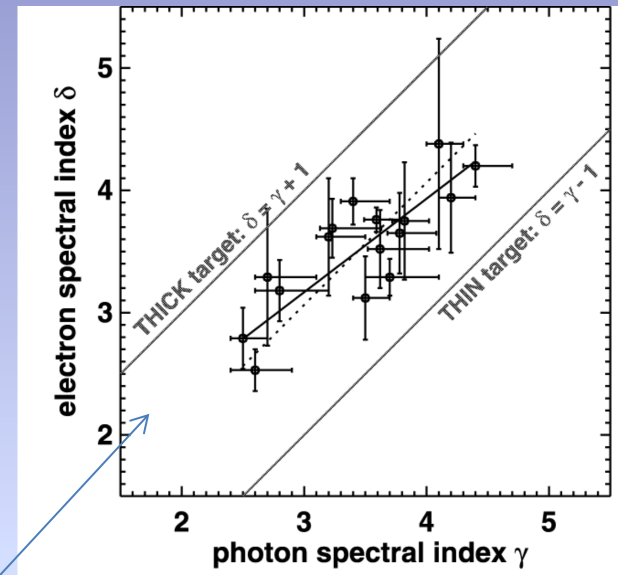


Vilmer et al. 2002

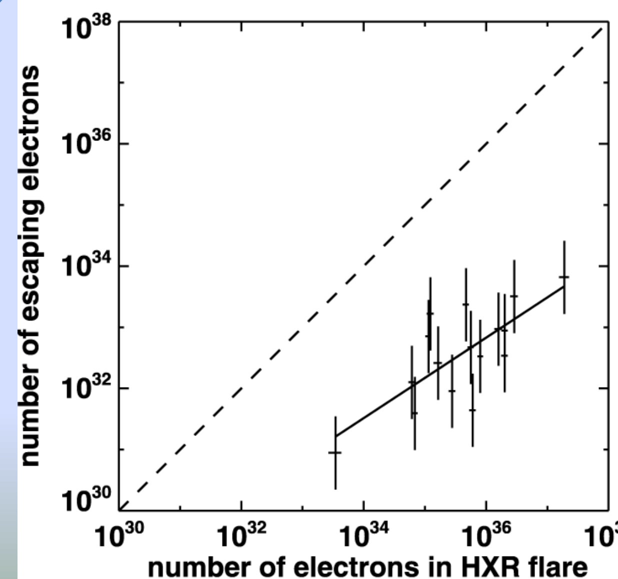
NRH and RHESSI observations

WHAT IS THE LINK BETWEEN X-RAY ENERGETIC ELECTRONS AT THE SUN AND ESCAPING ELECTRONS?





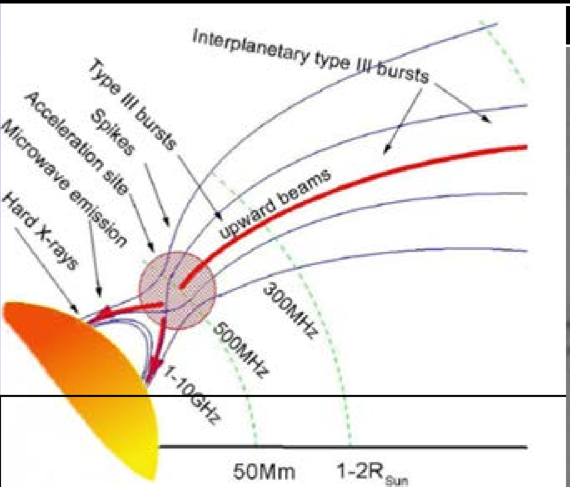
Impulsive electron events (WIND/3DP) measurements associated with HXR emissions (RHESSI observations) and radio type III emissions (WIND/WAVES)
Comparison of properties of electrons measured in situ (for prompt events) and deduced from HXR emissions

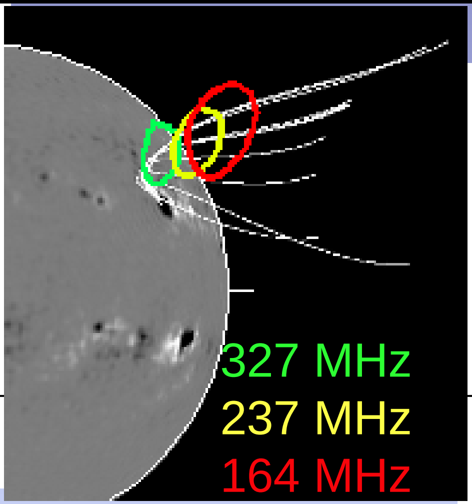


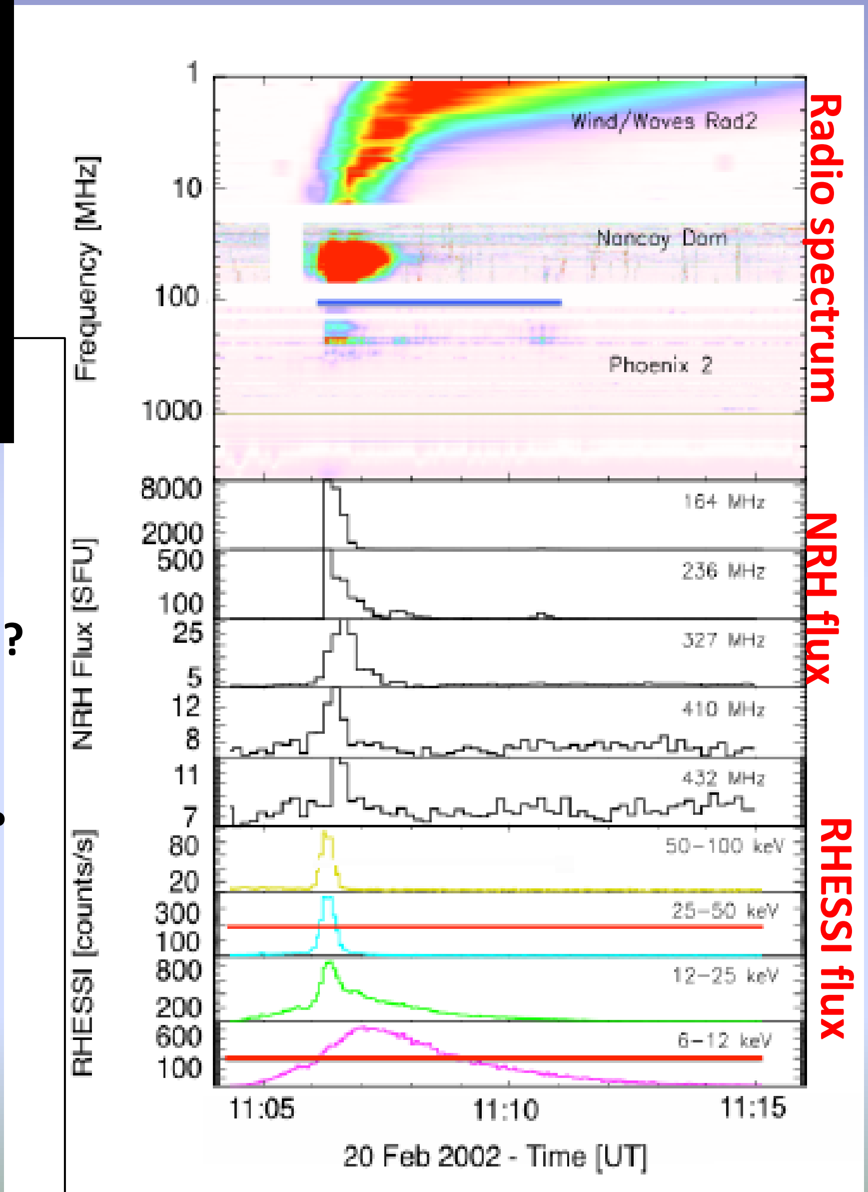
Total number of escaping electrons (type III associated) 0.2% of the number of HXR producing electrons (assuming thick target production)
To be reexamined with Parker Solar Probe/Solar Orbiter

Krucker et al., 2007

Transport of electron beams in the corona to the IP medium







What is the relationship between electrons at the Sun and in the interplanetary medium?

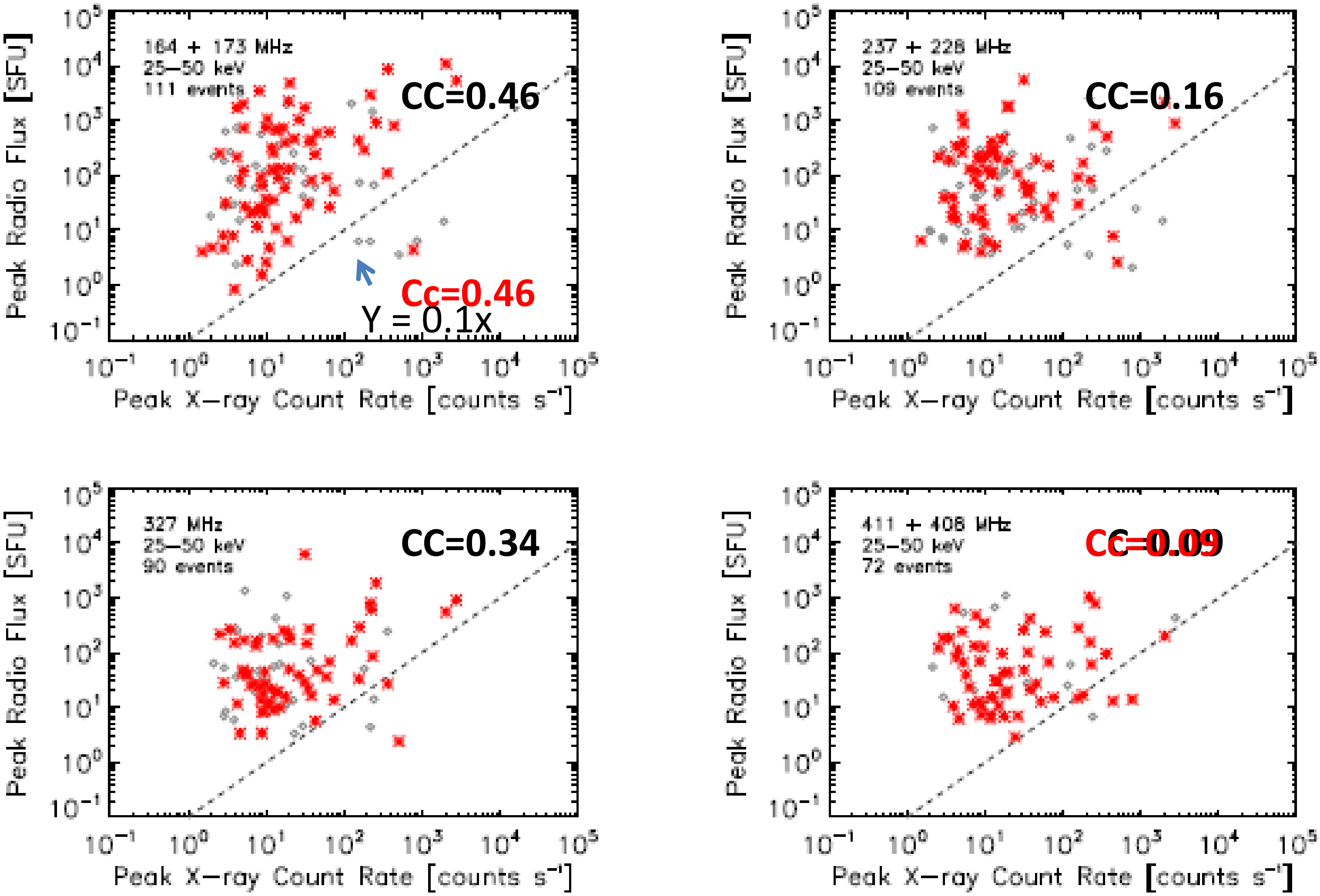
How far do electron beams propagate and radiate ?

Do all coronal type III bursts have X-ray counterparts?
What kind of correlation between X-ray and radio intensities?
Do all coronal type III bursts have an interplanetary counterpart?
Study based on >1000 coronal type III bursts over 10 years of data (2002-2011)

28% association rate between the groups of type III bursts and X-ray flares.
54¨% of the coronal type III bursts have IP counterparts

Reid & Vilmer, 2017

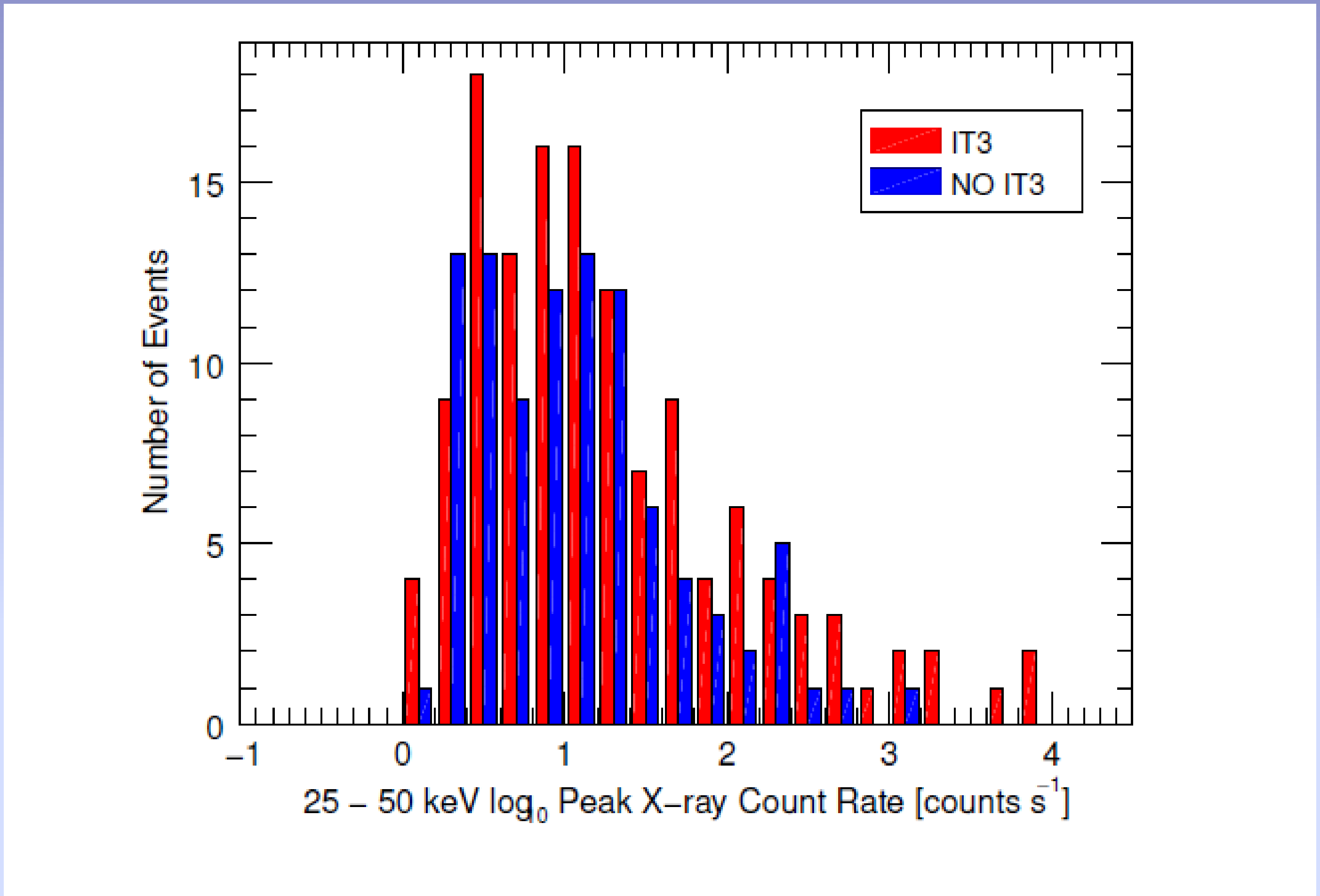
Peaks of X-ray and Radio events



Peak radio flux vs peak X-ray 25-50 keV count rate for events with NRH measurements of radio flux   Red: time difference between X-ray and radio peaks < 40s

Increase of the relationship between type III flux at low frequencies!

Interplanetary type IIIs and X-ray count rates

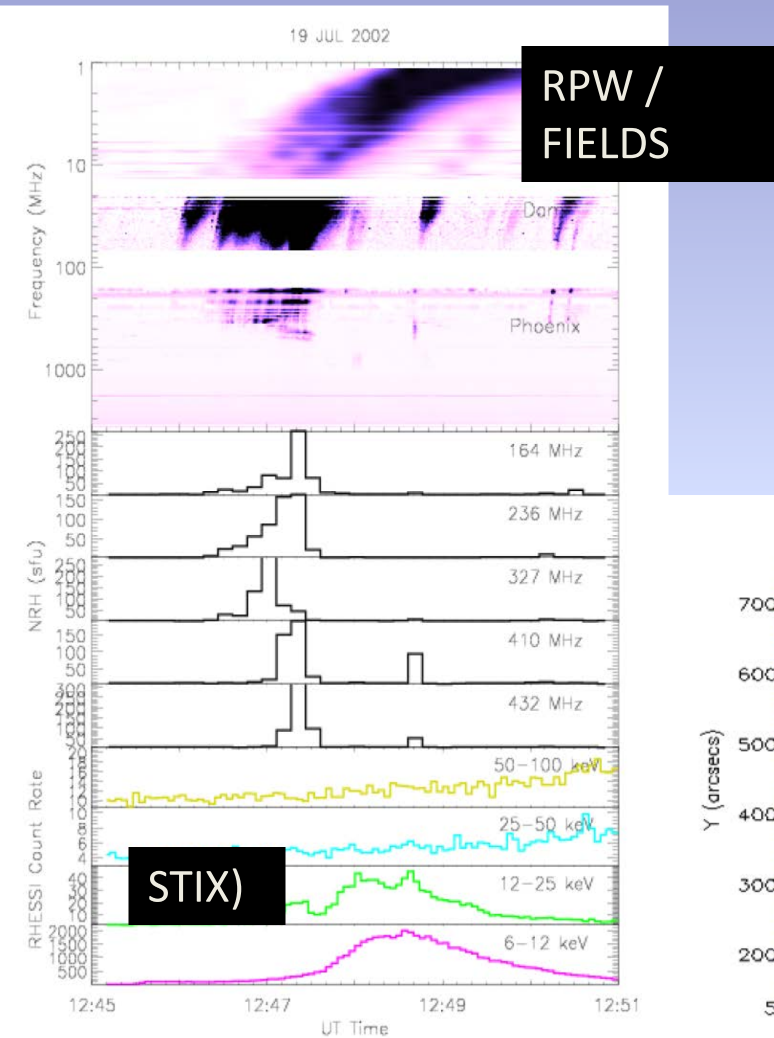


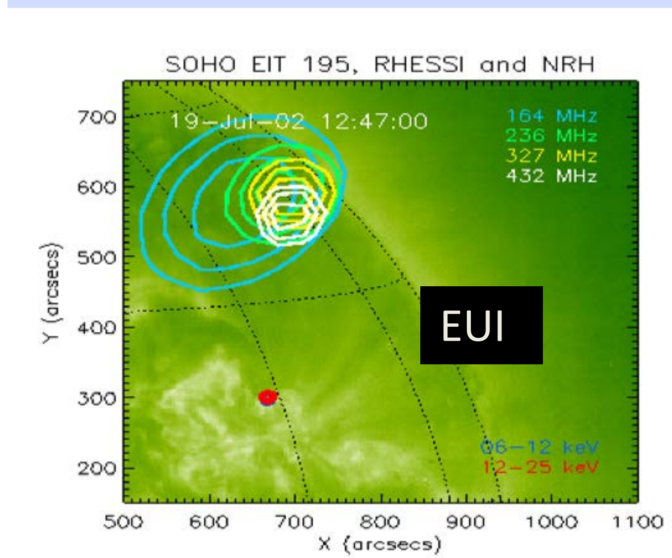
Is the X-ray count rate related to the likelihood of having an associated IP type III radio burst?
No strong link BUT events with high count rates tend to be associated with IP typeIII bursts
(Stronger electron beam 'number/energy) propagate and radiate further
(see Reid and Kontar (2015) on type III stopping frequencies)

Conclusion II: Electron beams in the corona to the IP medium in the Solar Orbiter-Parker Solar Probe era

More to be learnt in the future using
radio/X-ray instruments aboard Solar Orbiter
or radio instruments aboard Parker Solar Probe
in combination with ground-based NRH, LOFAR,
MUSER images of radio bursts
and ground-based radio spectrographs
and ground based radio imaging spectroscopy (SKA?)

Comparison with electron measurements of escaping electrons (measured closer to the sun)





LOFAR
Reid & Kontar 2017