Constraints on the acceleration region of type III radio bursts from radio and X-ray signatures

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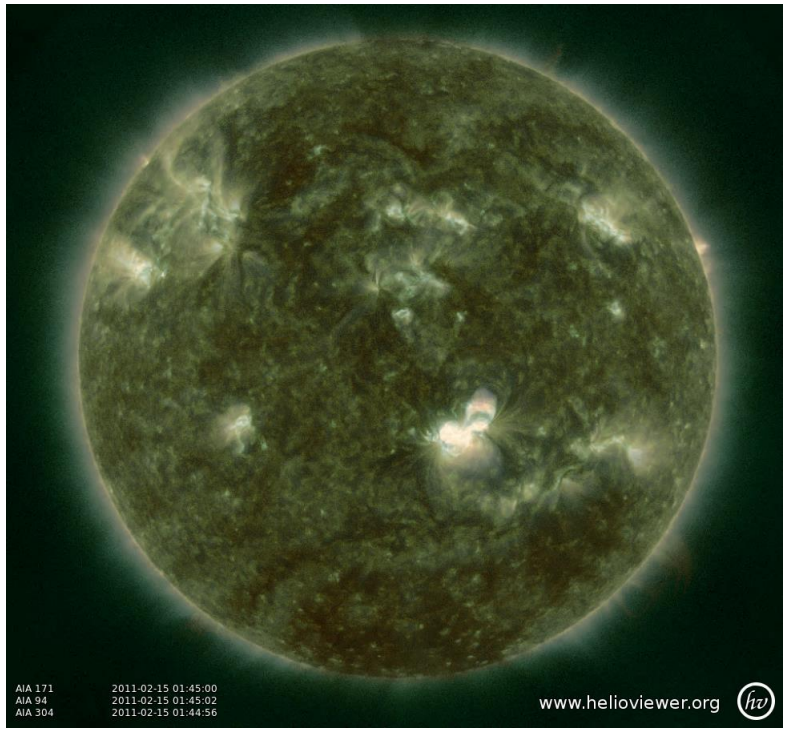
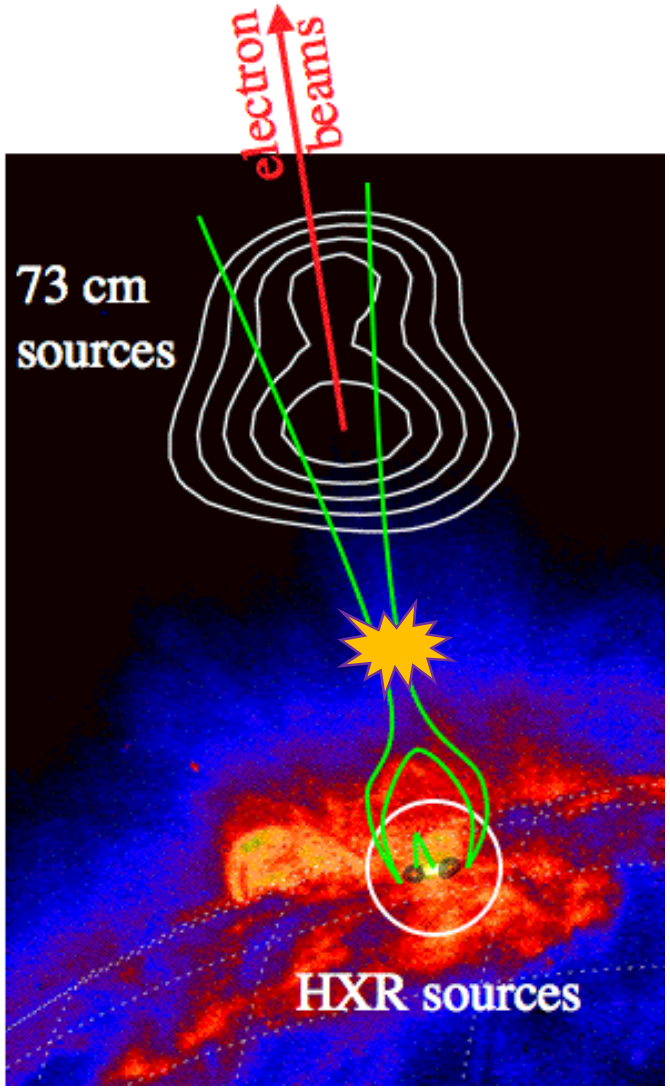
Diagnostics of solar energetic electrons

Solar flares = sudden energy release in the solar corona





Vilmer et al. (2002)

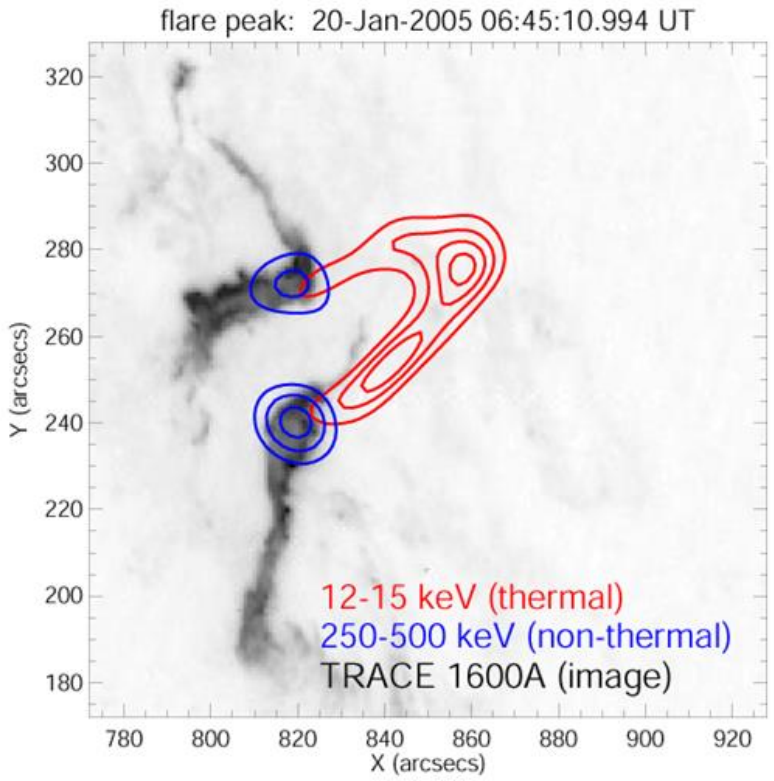
Particles propagating upward 'escaping the solar atmosphere'
→ **Coherent radio emission** with frequency ∝ plasma frequency

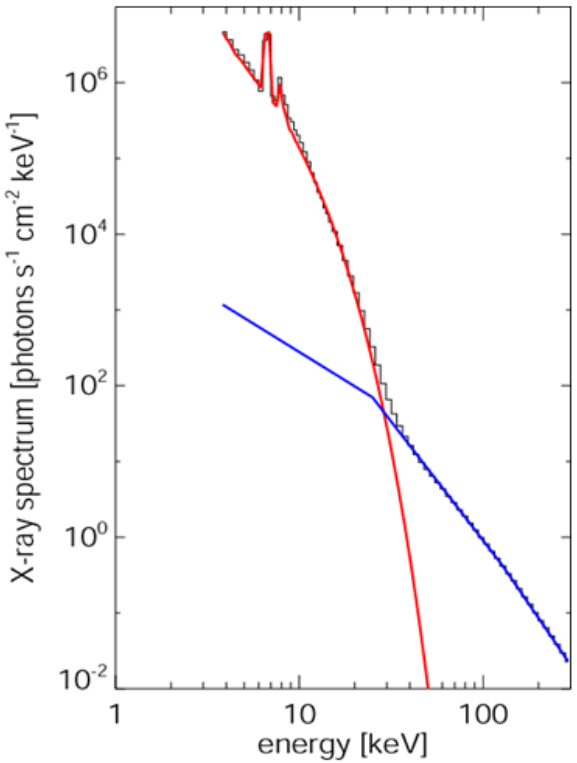
Magnetic reconnection
→plasma heating, particle acceleration…

Particles propagating downward
→ **Bremsstrahlung emission in X-ray**

X-ray diagnostics of energetic electrons

Typical X-ray observations of solar flares *(Krucker et al 2008)*





Thermal emission
- Plasma temperature
- Emission measure

Non-thermal emission
- Spectral index
- Non-thermal flux

X-ray diagnostics → plasma conditions + distribution of energetic electrons near the acceleration site (flare site)

Solar type III radio bursts

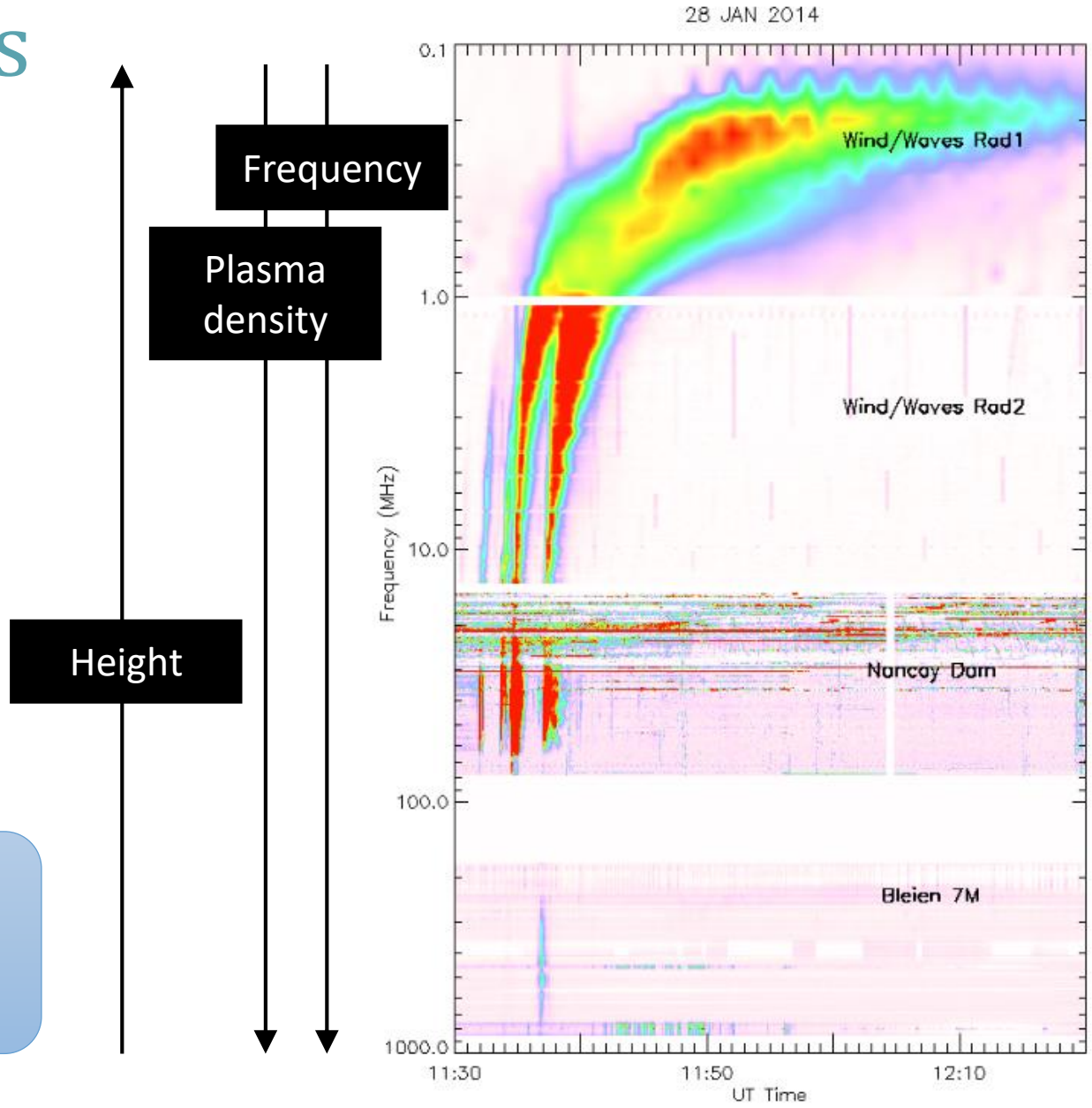
Typical type III burst observation
(Reid and Ratcliffe, 2014)

Coherent plasma emission:
frequency ∝ plasma frequency

Plasma frequency ∝ (plasma density)$^{1/2}$

Negative frequency drift over time
= electron beam propagating upwards / escaping the solar atmosphere

Type III radio bursts → trace the propagation of energetic electron beam in solar atmosphere and heliosphere



Radio spikes

Narrow-band, short-lived emissions, observed at high frequencies (0.8-8 GHz)

- Timescales ~ tens of milliseconds
- Bandwidth ~ a few % of the center frequency *(Benz et al, 1992; Paesold et al, 2001)*

Often **associated with type III radio bursts**

- With frequencies slightly > type III starting frequencies *(Benz et al, 1992)*

Radio spikes are the radio signatures with the **higher association rate with HXR**

(e.g. Aschwanden & Guedel 1992)

- No distinct temporal correlation between X-ray flux and radio spikes *(Benz, 1985; Benz et al, 2002)*
- Sources of spikes displaced from HXR souces *(Battaglia & Benz, 2009)*

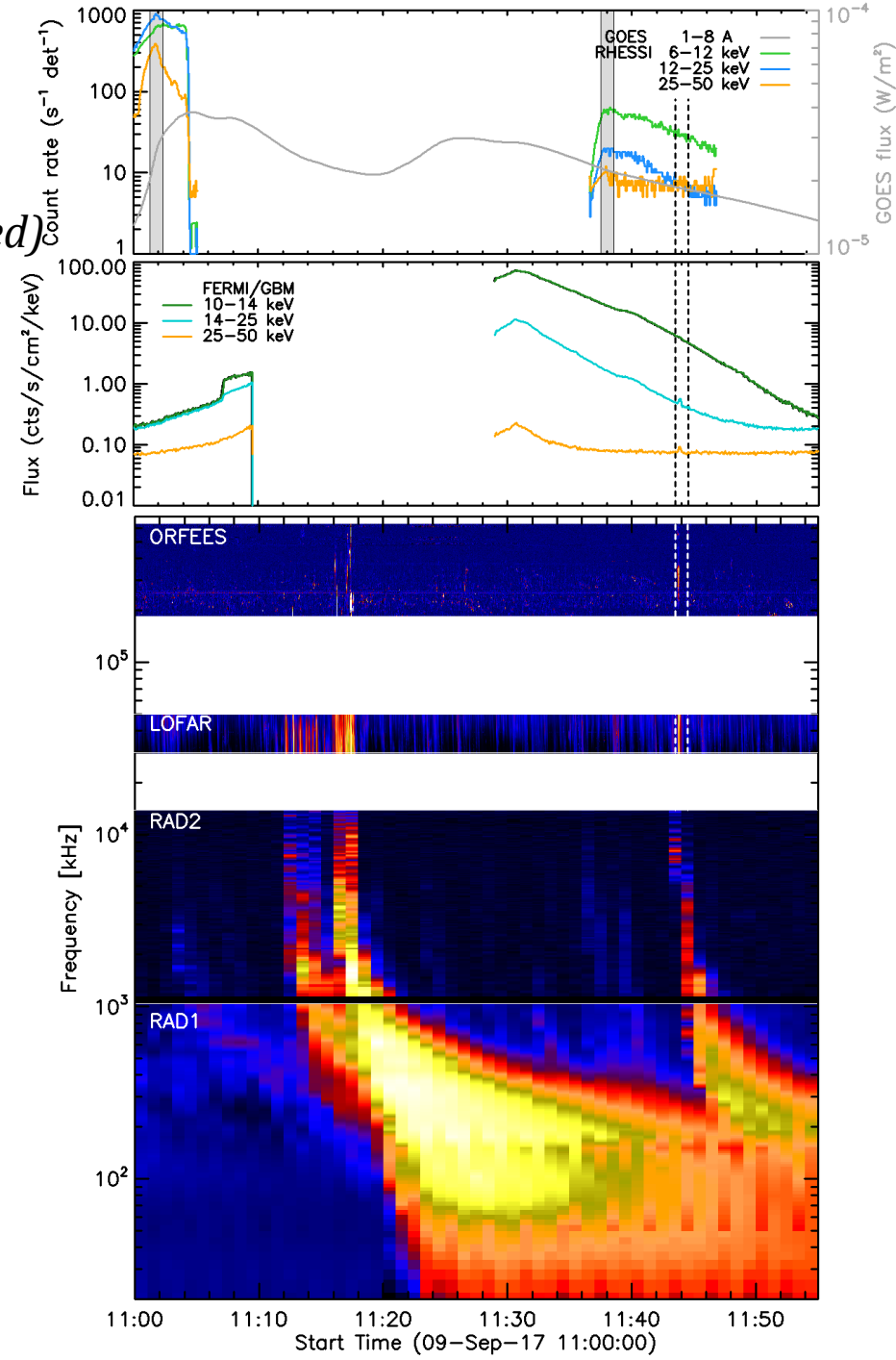
Close temporal relationship with HXR bursts + type III radio bursts

→ **Spikes closely related with the acceleration/injection region of energetic electrons**

Radio and X-ray timing

Example of the event on Sept. 9 2020

(Musset et al, submitted)



Radio and X-ray timing

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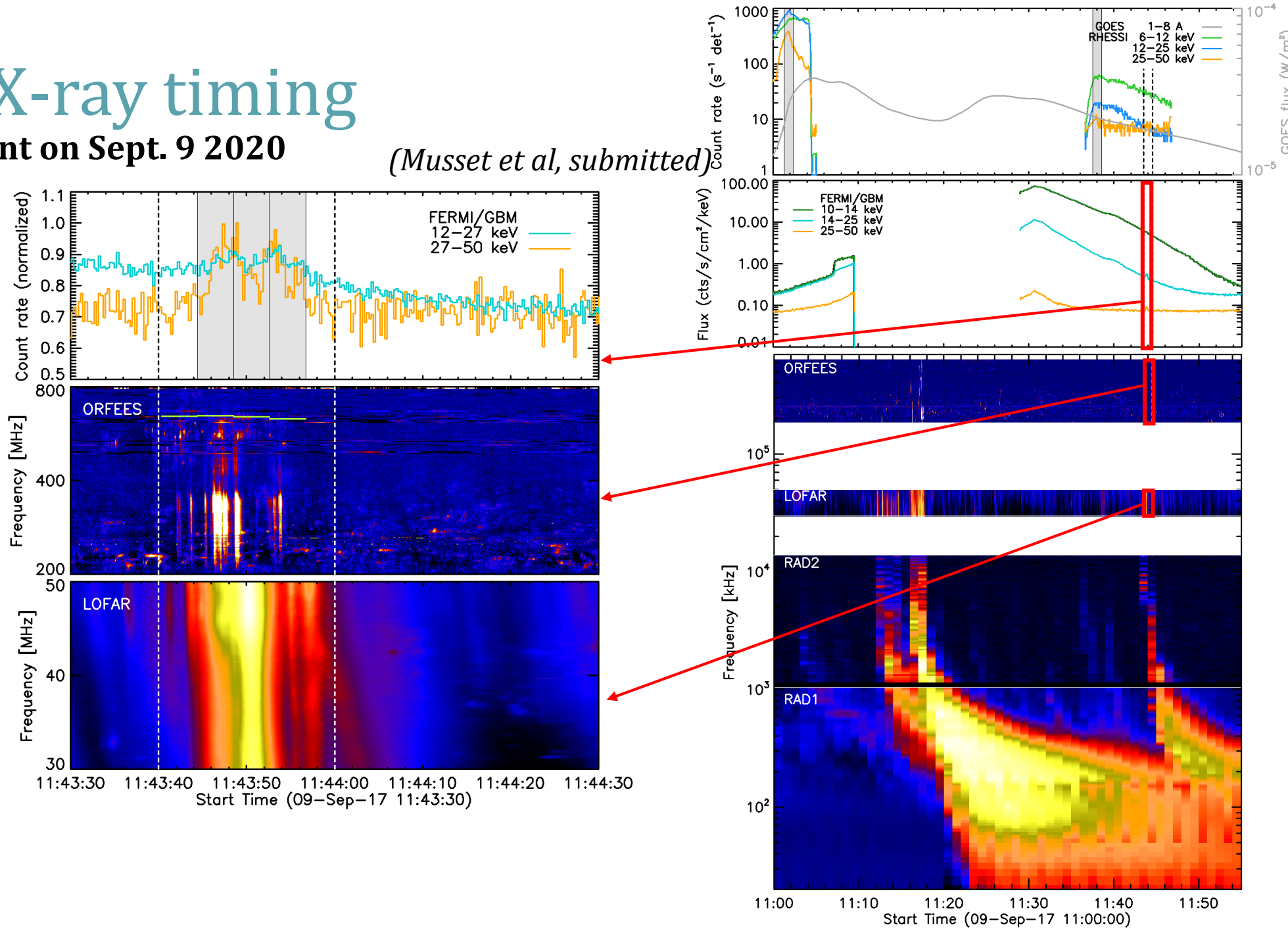
Excess in high-energy X-ray emission

Radio spikes

High-frequency type III radio bursts

Low-frequency counterpart of the type III radio burst



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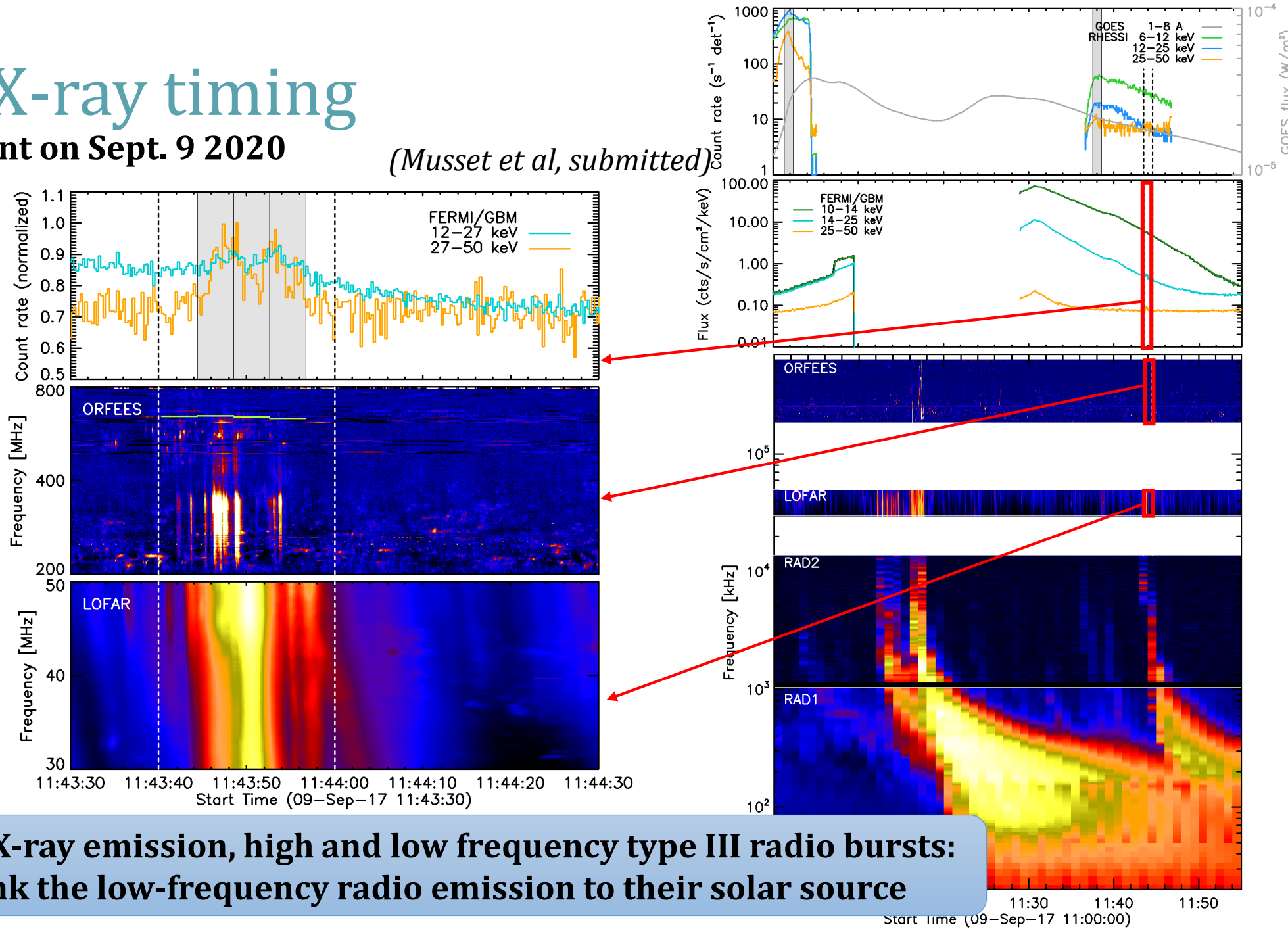
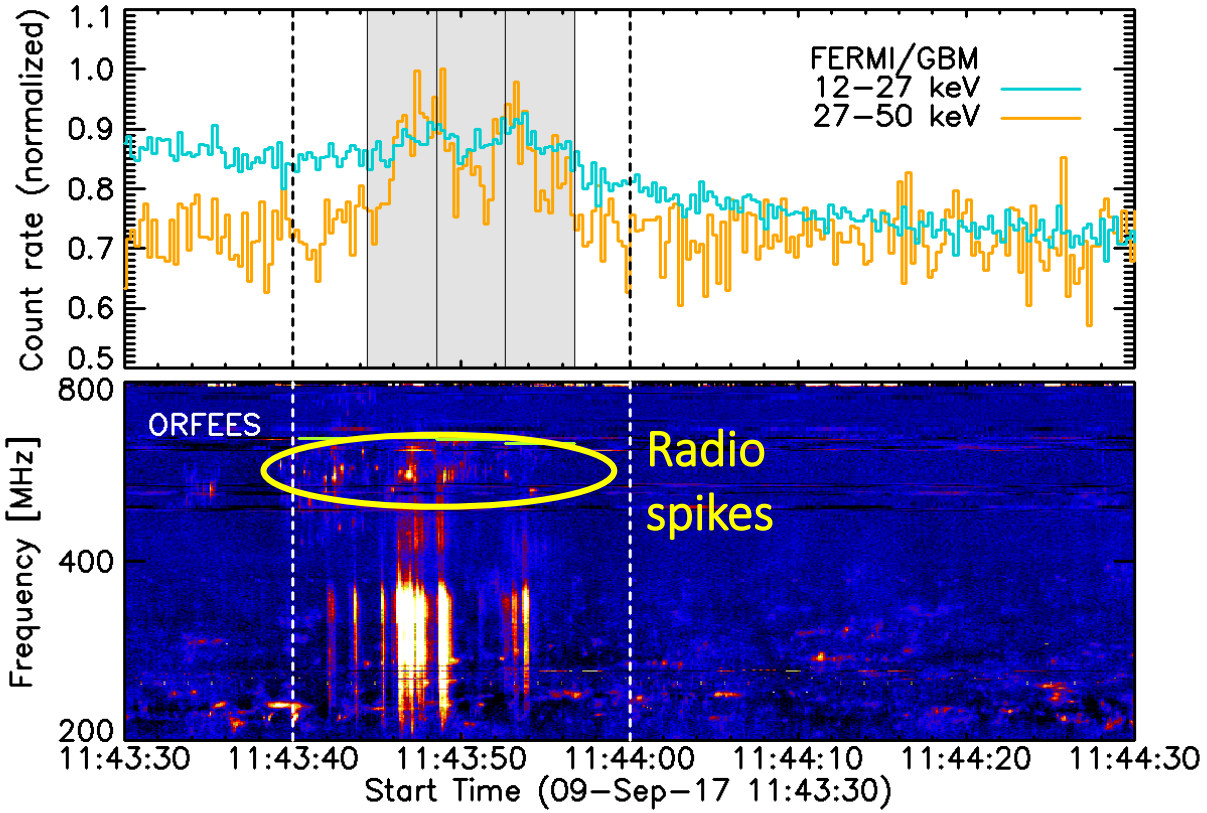
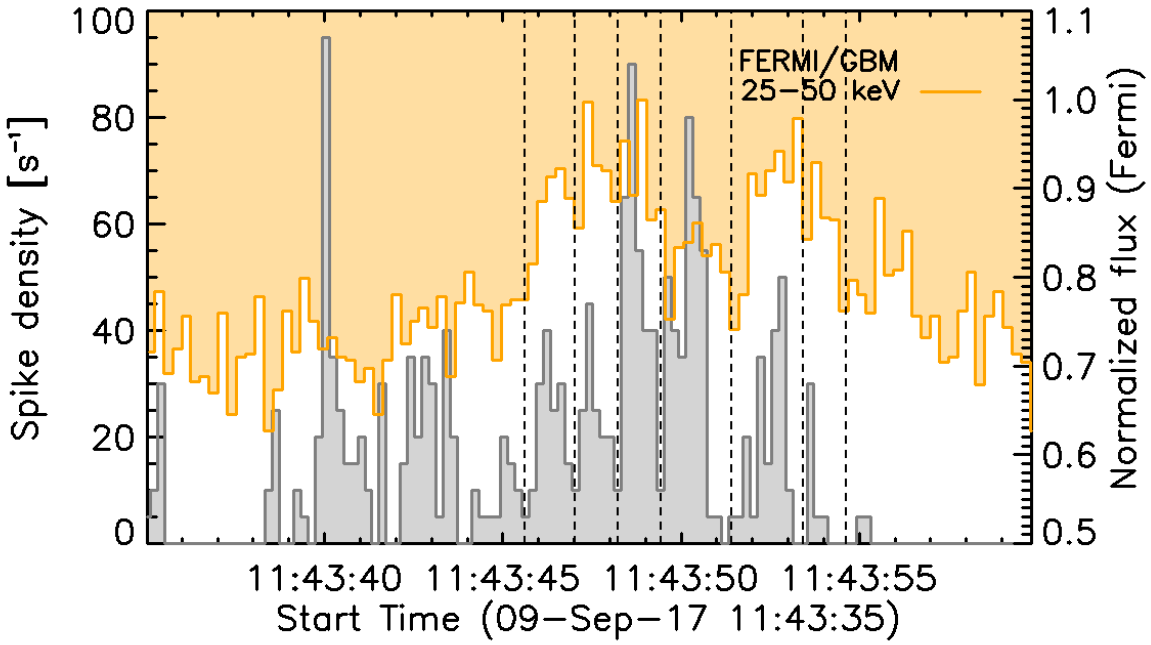


Clear association of X-ray emission, high and low frequency type III radio bursts: Opportunity to link the low-frequency radio emission to their solar source

Radio spikes as a signature of the acceleration process



Density of spikes and X-ray non-thermal flux



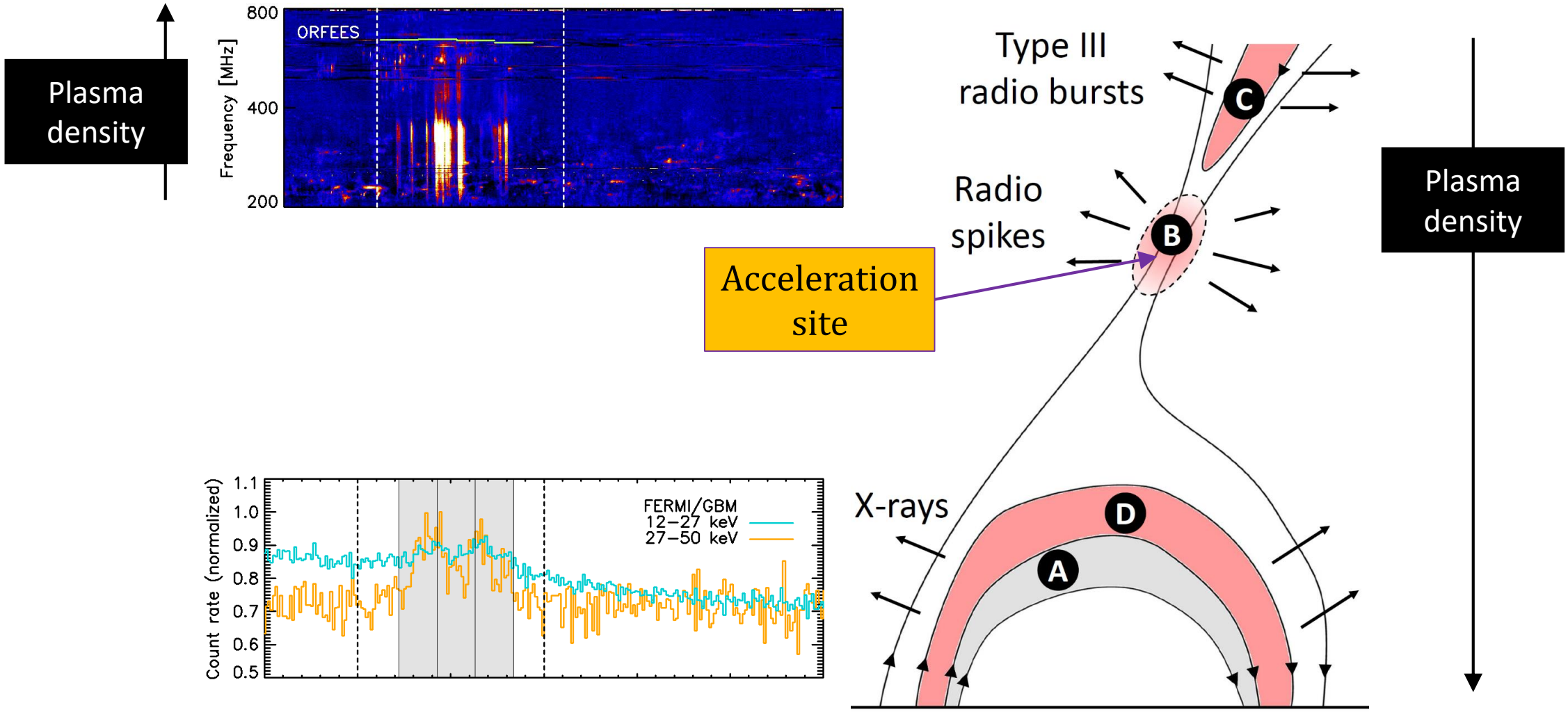
Radio spikes density correlate with X-ray non-thermal emission of energetic electrons

→ **Radio spike emission linked to the acceleration process**

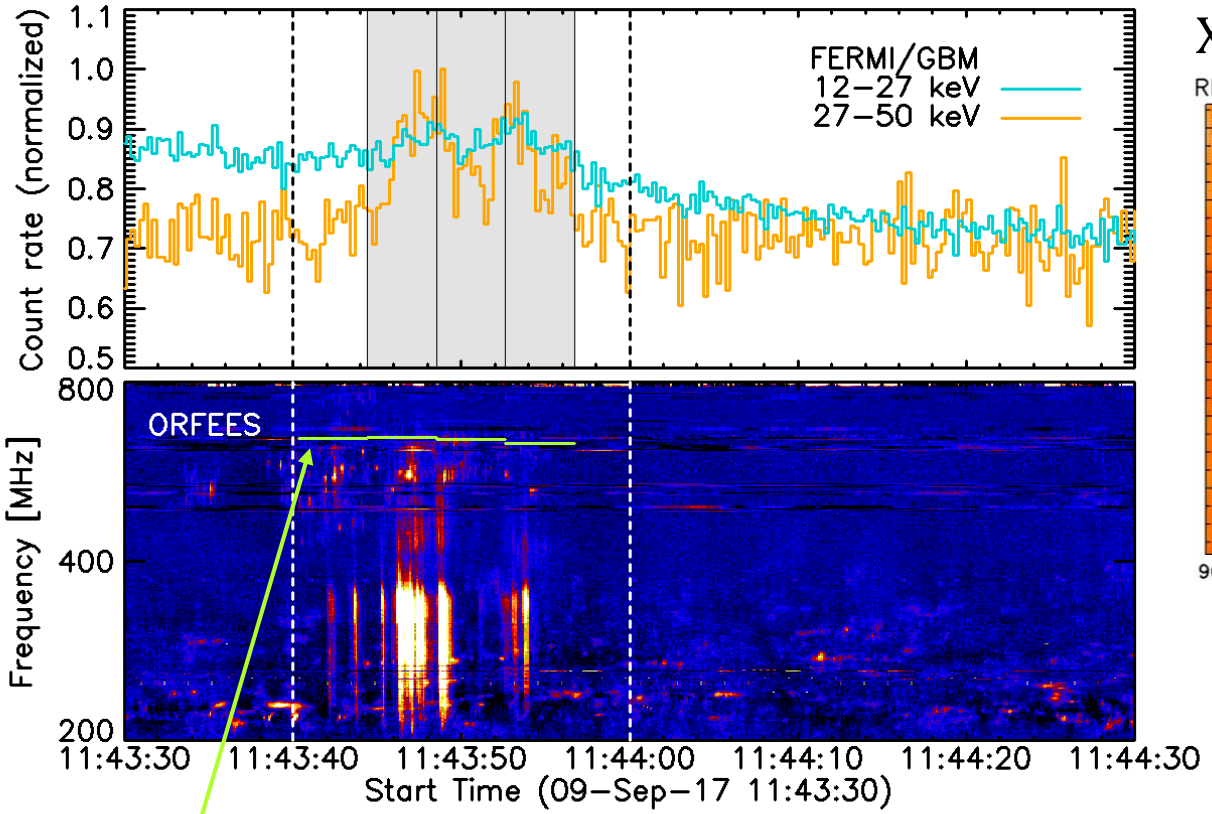
→ **Fragmentation of radio emission linked to the fragmented nature of particle acceleration**

(Musset et al, submitted)

Geometry of the event

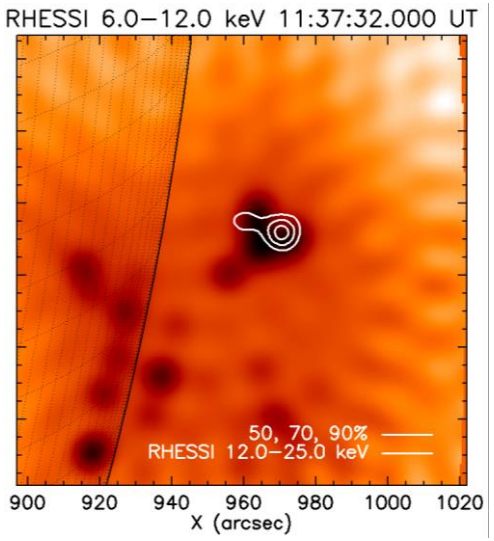


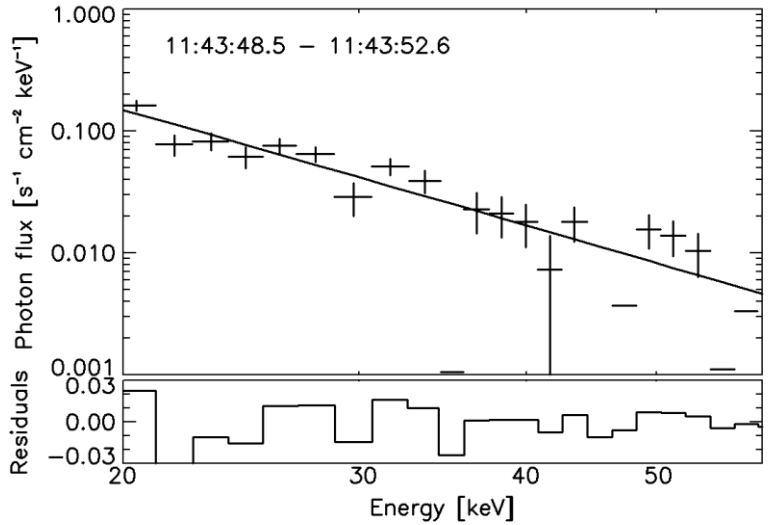
Electron beam size at its source



Lower limit on the plasma density from X-rays: just above the starting frequency of radio spikes and type III radio bursts

X-ray imaging and spectroscopy



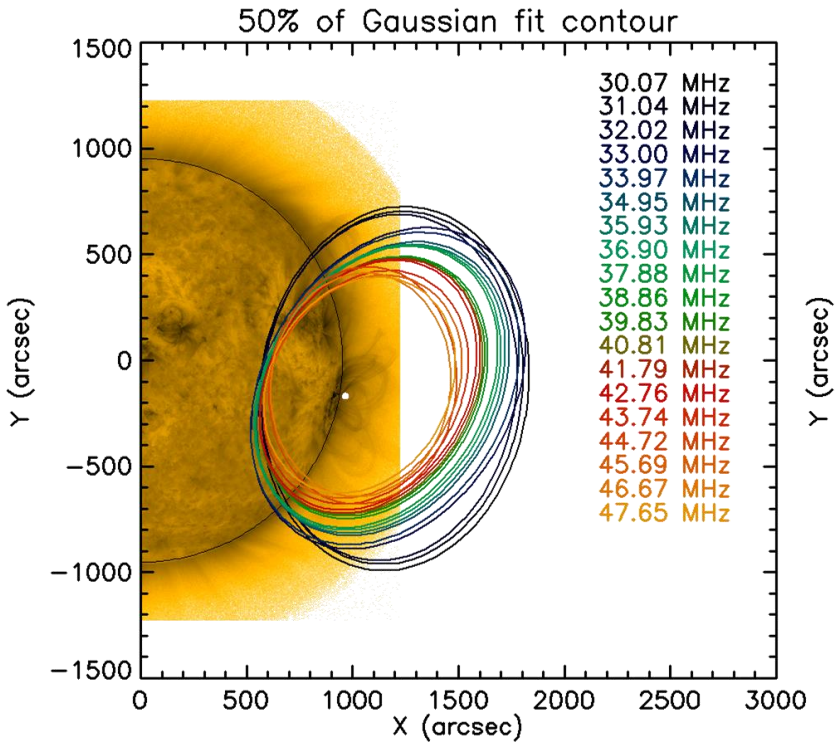


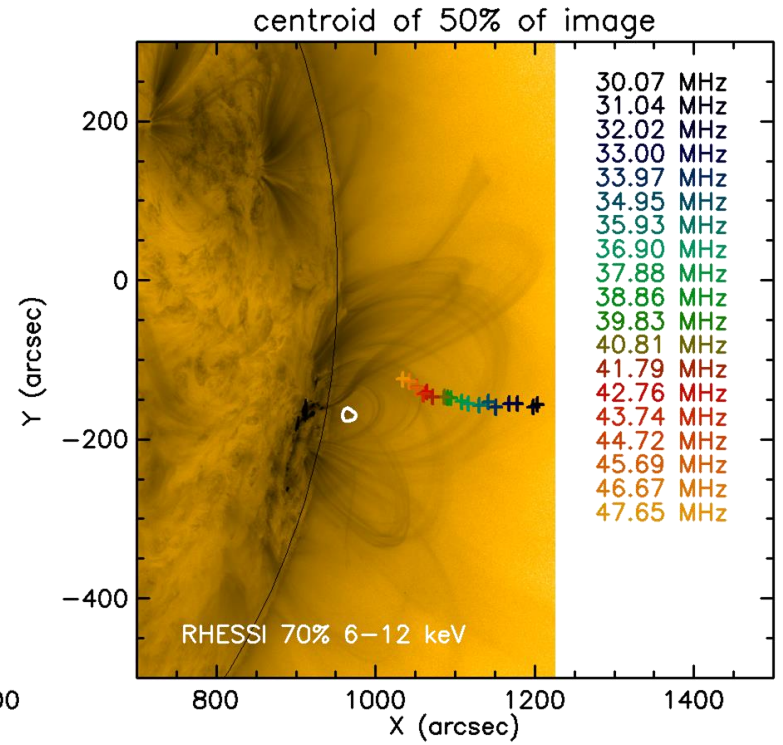
X-ray emitting source size: 0.12 arcmin^2
Plasma EM = 5.3x10^{47} cm^{-3}
→ Density of 5-13x10^9 cm^{-3} in the volume

Spectral index of the non-thermal electrons: 4.0
Number of accelerated electrons: 2x10^{33} e/s

(Musset et al, submitted)

Radio source sizes in the higher corona





LOFAR imaging of the type III radio burst emission at lower frequencies (30-48 MHz)

Frequency evolution is consistent with the propagation of a beam of energetic electrons

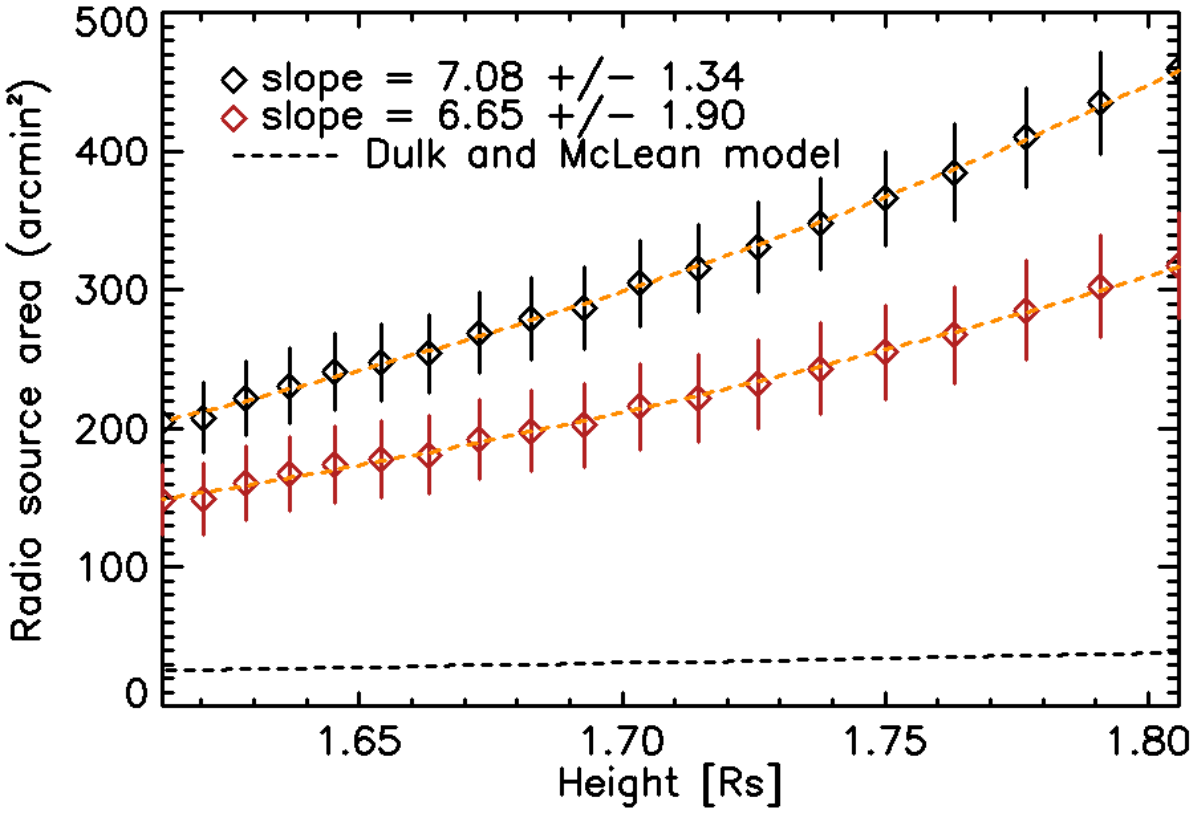
→ Evolution of the radio source sizes with frequency + Density model

$$n(r) = 4.8 \times 10^9 \left(\frac{R_\odot}{r}\right)^{14} + 3 \times 10^8 \left(\frac{R_\odot}{r}\right)^{6} + 1.4 \times 10^6 \left(\frac{R_\odot}{r}\right)^{2.3},$$

(Alcock 2018)

Evolution of the radio source sizes with height

Radio source areas



Radio source size

Radio source size – beam size

Expected size due to expansion of the magnetic field tube:
Empirical model for magnetic field evolution with height (Dulk & McLean, 1978):

$$B = 0.5 \left(\frac{R}{R_s} - 1 \right)^{-1.5}$$

Radio sources are larger and increase in size faster than expected from only the expansion of magnetic flux tubes

➔ Importance of radio-wave scattering on density fluctuations

Conclusion & perspectives

In this event, non-thermal X-ray emission and type III radio bursts are particularly well correlated

→ Enable to characterize the solar source of escaping beams of electrons responsible for low-frequency type III radio bursts

Decimetric radio spikes correlate with X-ray non-thermal flux on fine time scales

→ Indicates that their emission process is linked to the acceleration region

→ Fragmentation of radio spike emission could be a signature of the fragmentation of the acceleration process itself

The combination of X-ray and radio diagnostics of energetic particles in solar events is a powerful tool to investigate particle acceleration and transport in the corona.