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Estimating the energy in escaping electron beams

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1. UCL MSSL

Energetic electron beams

The energy content of accelerated electron beams must be constrained to refine particle acceleration models and understand the electron component of space weather.

Previous estimations have compared confined and escaping electron beams using in situ measurements at 1 AU.

- Krucker et al. (2007): 16 C-M flares: RHESSI and Wind, break energy 50 keV.
  10^{35}–10^{36} confined electrons
  10^{31}–10^{33} escaped electrons (~0.2% escaped).
- [Tomin] James et al. (2017): 6 weaker flares (<C1.0). RHESSI and ACE, break 74 keV.
  10^{30}–10^{33} confined electrons
  10^{30}–10^{32} escaped electrons (4.64–148.3% escaped, *i.e.* sometimes more escaped than were confined).
  Energy in escaped beams: 10^{23}–10^{25} erg (above break energy 74 keV).
- Dresing et al. (2021): 17 intermediate flares (B5.1–C9.1). RHESSI and STEREO, break energy 45 keV.
  10^{33}–10^{34} confined electrons
  10^{30}–10^{31} escaped electrons (0.18-0.24% escaping).

In situ measurements at 1 AU are subject to propagation effects.
We give the first estimate of energy density from remote sensing observations.

Confined electron beams

M5.0 flare 22 May 2013. RHESSI HXR intensity peaked at 13:12 UT in the 25–50 keV band.

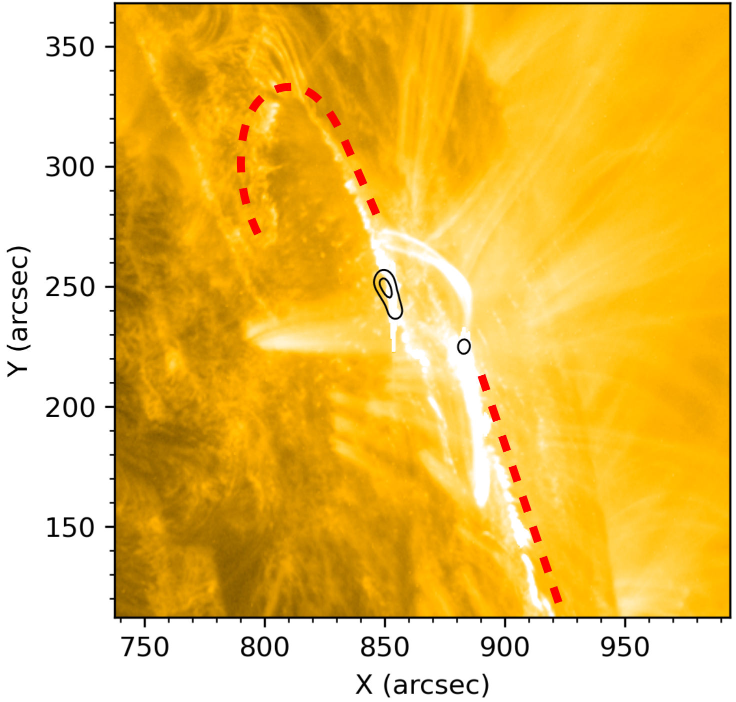
Two coherent HXR sources imaged along flare ribbons:

➡ Flare-accelerated electrons streaming down newly reconnected loops.

We fit the impulsive phase of the flare (thermal component for the low energy part):

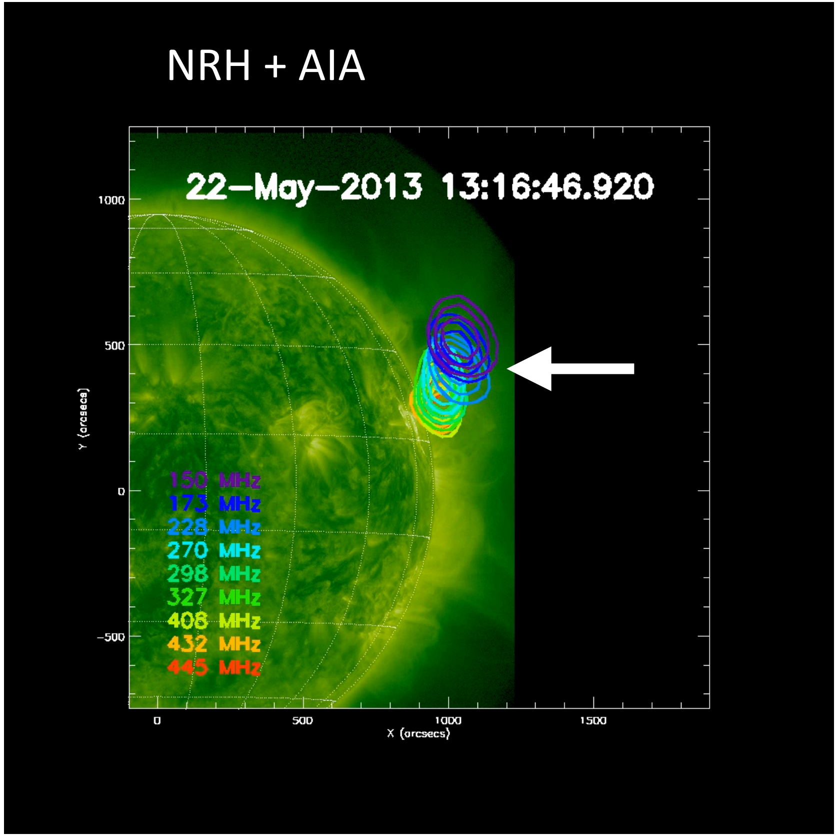
➡ Spectral index $\alpha_E = 5$ (energy space) or $\alpha_v = 10$ (velocity space).

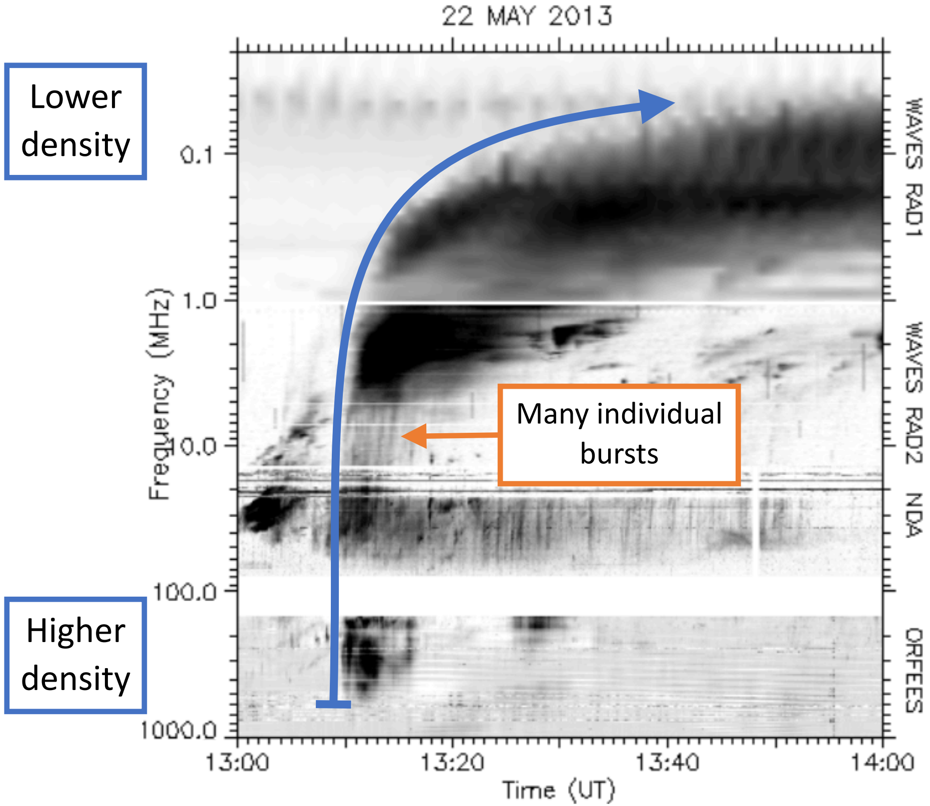
➡ Low energy cutoff around 30 keV.



RHESSI contours at 30% & 70% maximum

Escaping electron beams



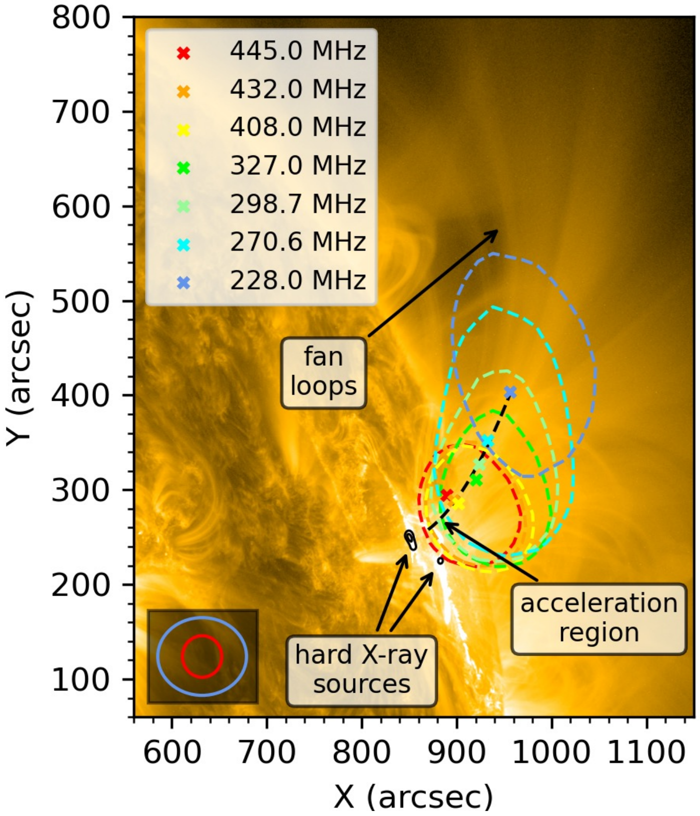


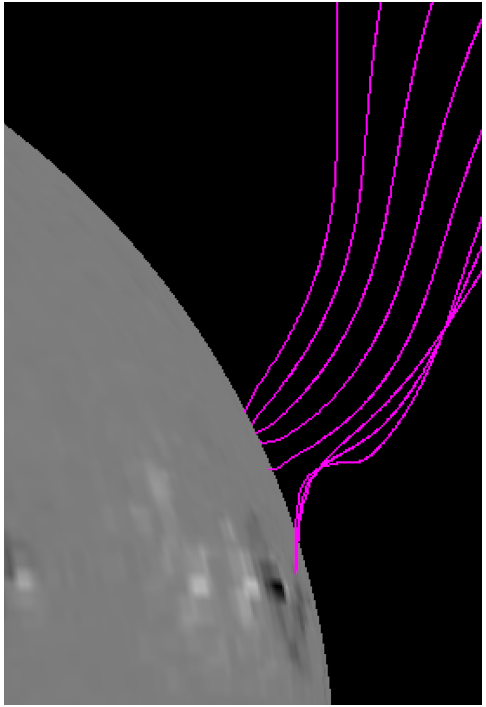
Escaping electron beams

The emitting electron beams appear to follow a set of fan loops observed in EUV. PFSS ⇒ open field.

Flare arcade and two ribbons. In the standard model, the reconnection (particle acceleration) site would occur somewhere above the flaring loops.

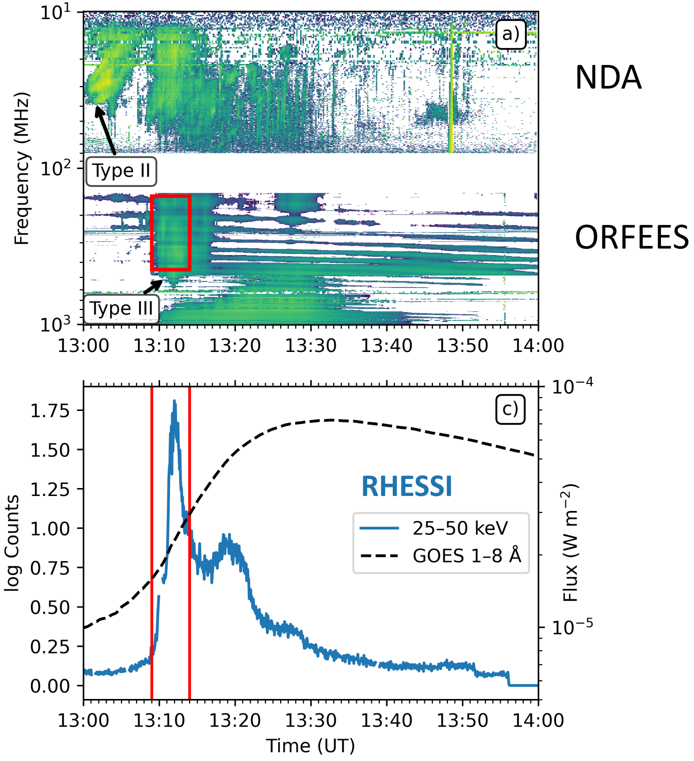
Very small region between flaring loops and 445 MHz source (~10 Mm).



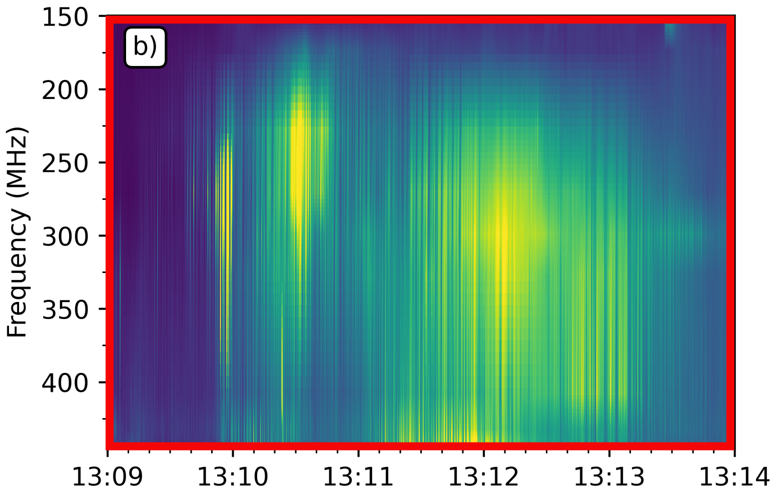


Radio observations

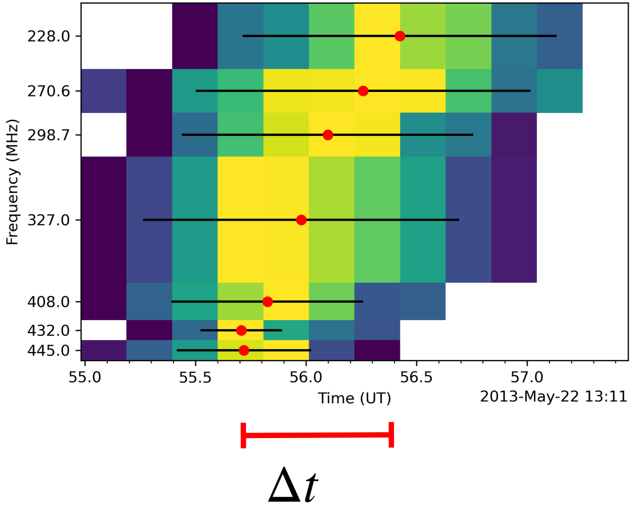
NRH: 150–445 MHz @ 0.225s. 4 solar radii @ 30''.



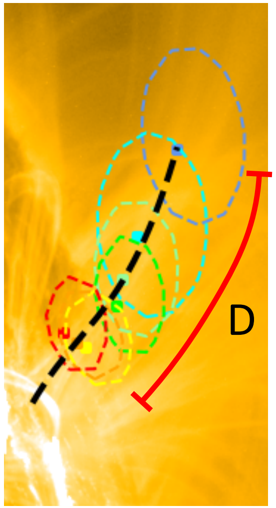
>100 electron beams in 3 minutes
(≈ every 2s)

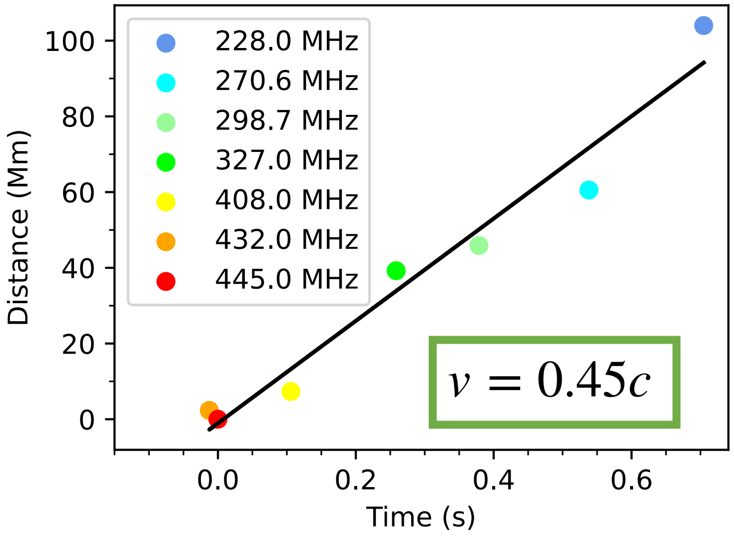


Beam speed



1. Fit peak flux times of a beam at each frequency.
2. Plane of sky distance between imaged sources.
3. Distance vs time ⇒ beam speed:



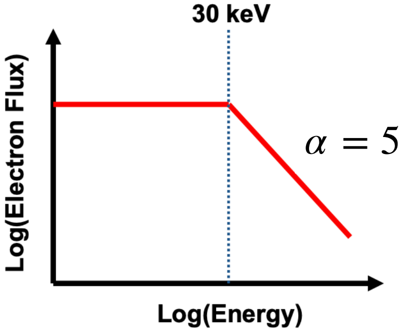


Electron density & energy

Estimate energy distribution in the escaping beams:

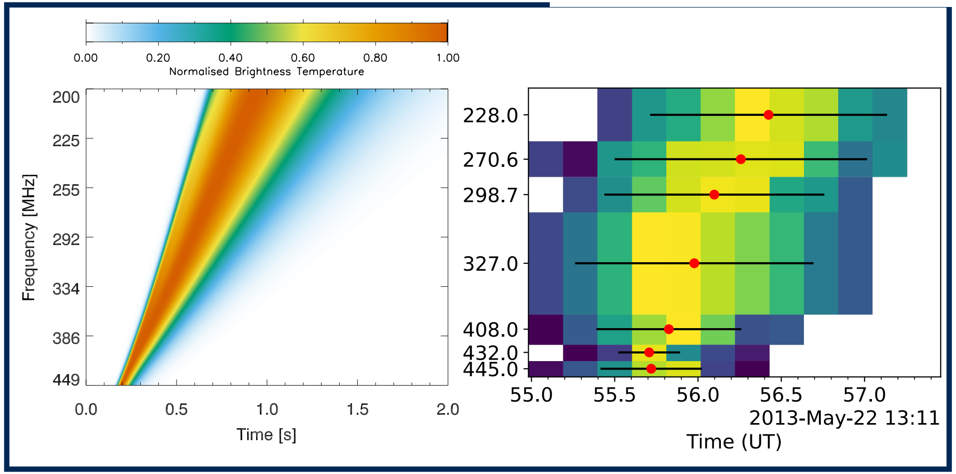
- ➡ Assume same energy distributions in upward and downward beams (Krucker et al. 2007; Dresing et al. 2021).

Broken power law with cutoff 30 keV (RHESSI fit). $\Rightarrow n_{e,beam} = 10^{2.5}\,\mathrm{cm}^{-3}$.



Simulate an electron beam starting 15 Mm above the surface (AIA) with a background frequency of 600 MHz (ORFEES), $\alpha = 10$ and $n_{e,beam} = 10^{2.5}\,\mathrm{cm}^{-3} \Rightarrow v = 0.45c$. ✅

From n_e and v, we can estimate the energy density $\Rightarrow \epsilon_{beam} = 2 \times 10^{-5}\,\mathrm{erg\,cm}^{-3}$.



Acceleration region length

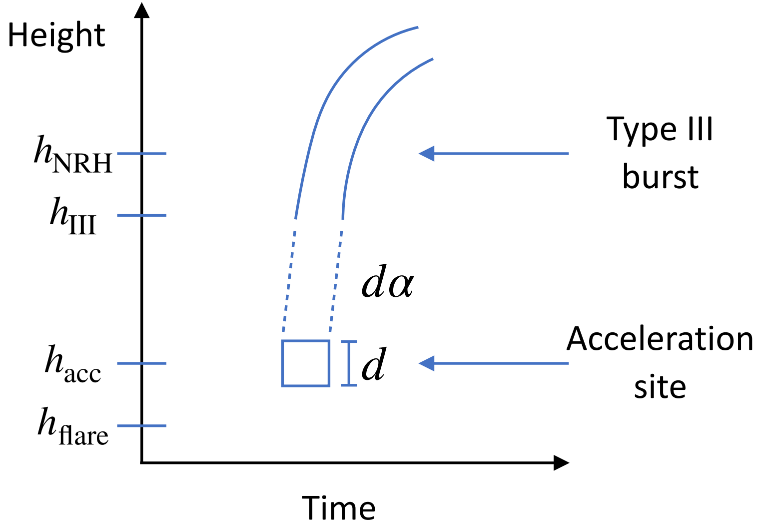
There will be an instability distance, $d\alpha$, between h_{acc} and h_{III} (Reid et al. 2011).

$$h_{\mathrm{III}} - h_{\mathrm{acc}} = d\alpha$$

NRH sources begin shortly above the flaring loops, suggesting a very short instability distance $d\alpha \sim 10$ Mm.

The spectral index $\alpha_v = 10$, so

the acceleration region must be very short: $d \sim 1$ Mm.



Shorter injection time = shorter $d\alpha$ (Reid et al. 2013).

Width of Acceleration Region

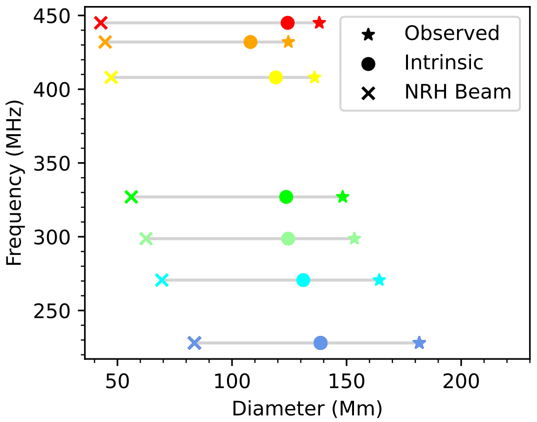
Beam expansion along path, assuming constant expansion. Account for scattering.

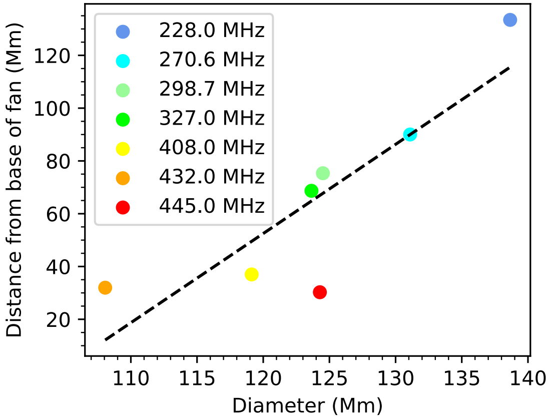
➡ Suggests 100 Mm acceleration region width. Similar to width of flaring loops.

However, possible early, rapid, nonlinear expansion.

Acceleration volume = $1\,\mathrm{Mm} \times (70 - 100\,\mathrm{Mm})^2$
$= 10^{26} - 10^{28}\,\mathrm{cm}^3$. Cross section may not be square.

- Chen et al. (2018): compact source region $\approx 600\ \mathrm{km}^2$.
- Guo et al. (2012): 10-15 Mm width = half flare loops.
- Gordovskyy et al. (2020): Cylinder length 20-25 Mm, diameter 5 Mm $\Rightarrow$ V=10^{26} cm^3.
- Fleishman et al. (2022): loop top region of interest $\Rightarrow$ V=10^{27} cm^3.





Acceleration region properties

- Radially thin but tangentially wide acceleration region.
  QSL atop flaring loops? Quasi-periodic reconnection accelerates many beams?

- Acceleration region volume = 1 Mm × (70–100 Mm)^2 = $\mathbf{10^{26} - 10^{28}}$ cm^3.
  Gordovskyy et al. (2020): cylinder length 20–25 Mm, diameter 5 Mm, $V = 10^{26}\,\mathrm{cm}^3$.
  Fleishman et al. (2022): loop top region of interest $V = 10^{27}\,\mathrm{cm}^3$.

- 10^2 beams @ $n_{e,beam} = 10^{2.5}\,\mathrm{cm}^{-3}$ in $V = 10^{26} - 10^{28}\,\mathrm{cm}^3$ ⇒ $\mathbf{10^{31} - 10^{33}}\,e^-$.
  Same as Krucker et al. (2007; $10^{31} - 10^{33}$). M-flares.
  Higher ends of James et al. (2017; $10^{30} - 10^{32}$) and Dresing et al. (2021; $10^{30} - 10^{31}$).

- $\epsilon = 2 \times 10^{-5}$ erg cm^{-3} beam^{-1} in this V for 10^2 beams ⇒ **E = $\mathbf{10^{23} - 10^{25}}$ erg**.
  [Tomin] James et al. (2017) found $10^{23} - 10^{25}$ erg in escaping beams.

James & Reid
(Under Review)

Extra slides

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Two CMEs on 22 May 2013

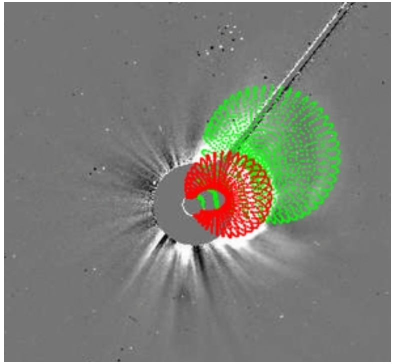
CME 1

- LASCO C2 @ 08:48 UT
- Origin in/around NOAA ARs 11748 & 11745
- $\approx 500\ \mathrm{km\,s^{-1}}$ (Ding et al. 2014, Palmerio et al. 2019)

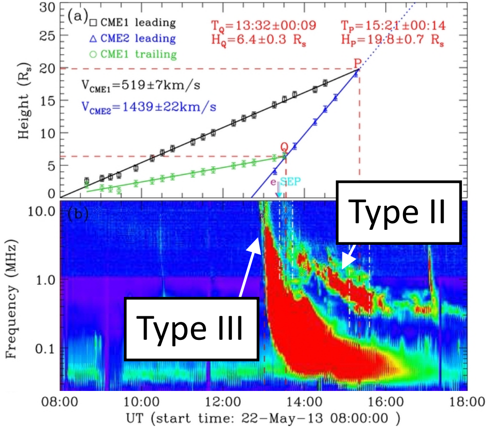
CME 2

- LASCO C2 @ 13:25 UT
- Origin in NOAA AR 11745
- $\approx 1500\ \mathrm{km\,s^{-1}}$ (Ding et al. 2014, Palmerio et al. 2019)

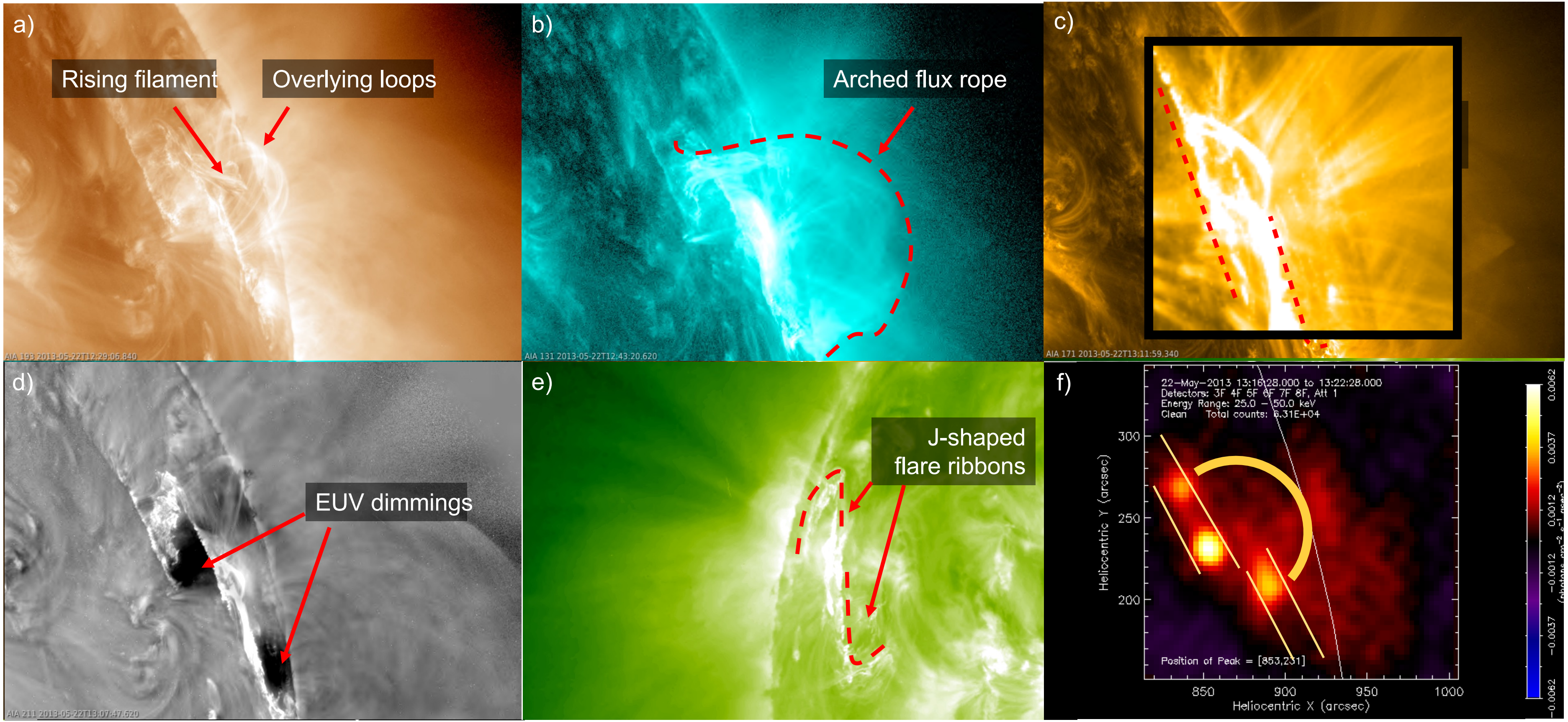
Interaction. CME 2 shock accelerates SEPs. Type II radio burst.



Ding et al. (2014)

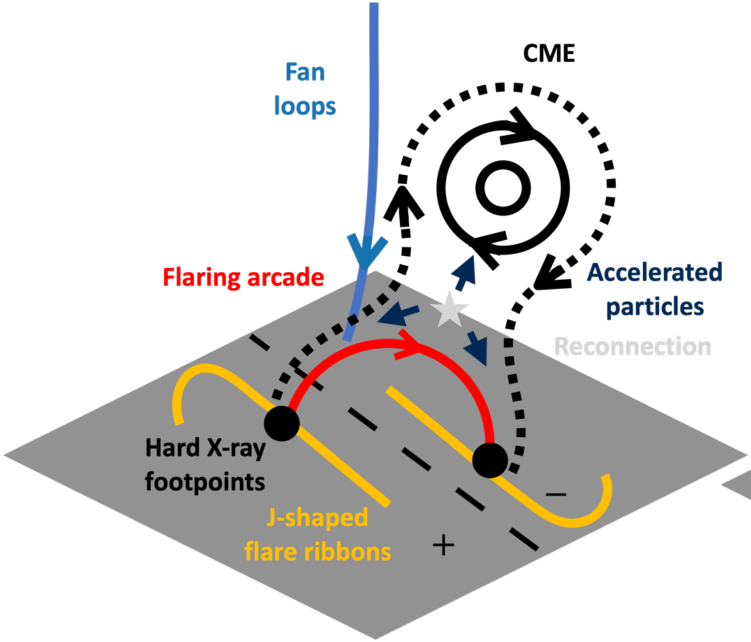


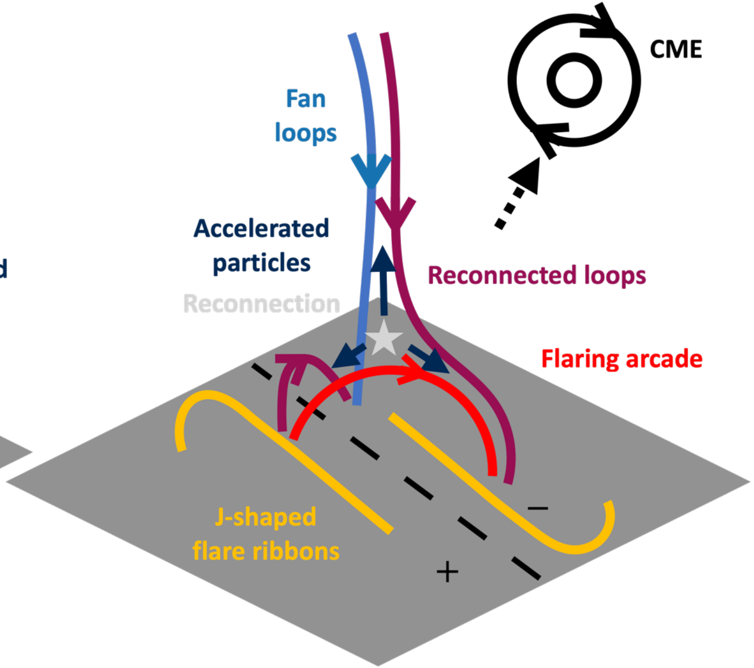
Observations



Electron escape

How do the electrons that produce the Type III emission get from the acceleration site on to the quasi-open fan loops?

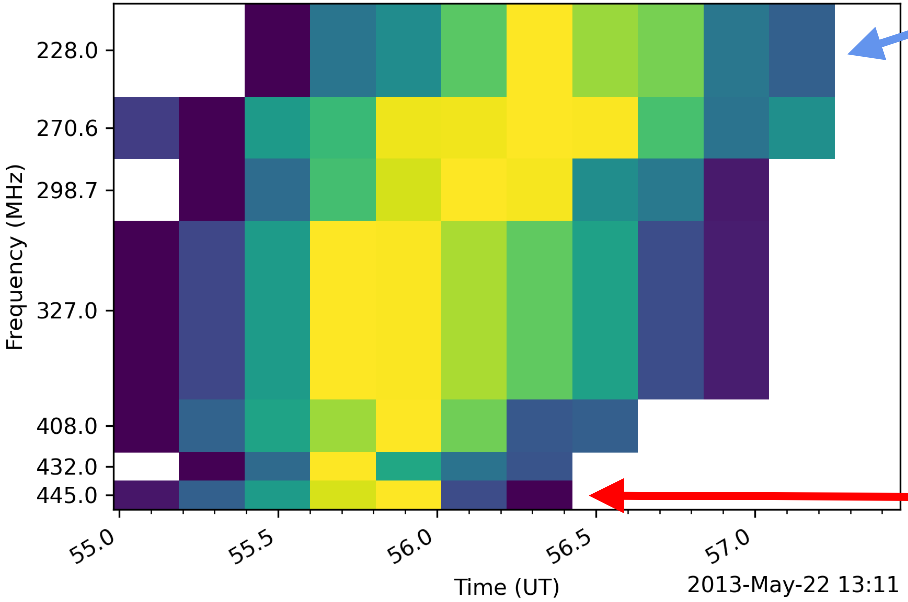


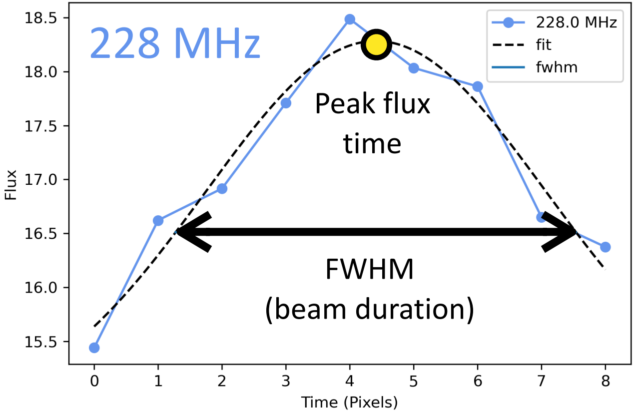


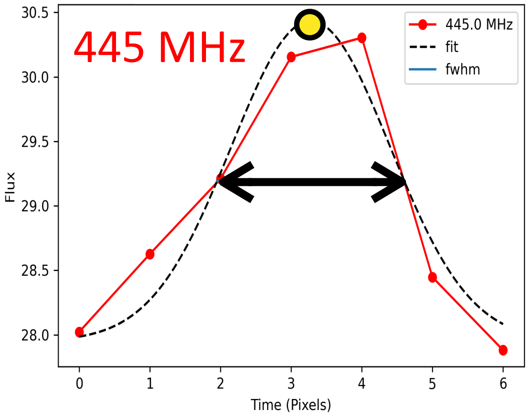
Take an individual electron beam

The electron beams travel outward through the corona, from high plasma density (high frequency) to low density (low frequency). Therefore, the time we observe the peak flux at each frequency will be different.

NRH data from around the RHESSI peak time:



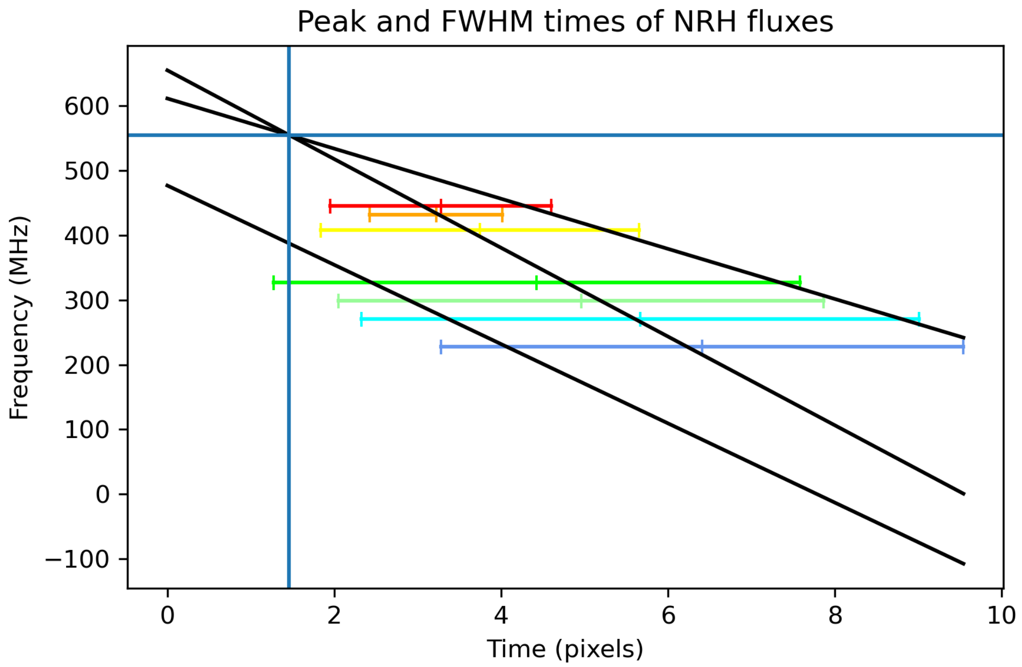




The source of the beam

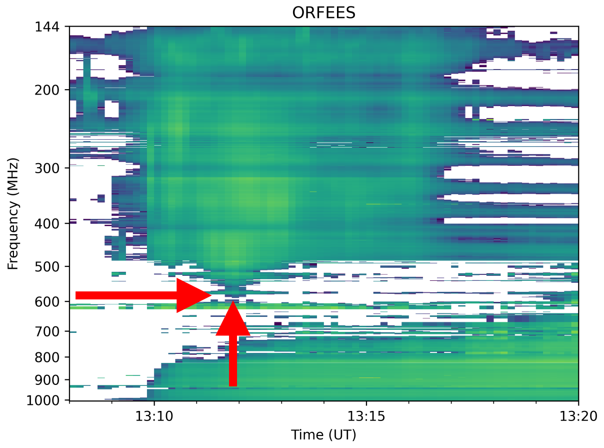
The front and back of an electron beam travel at different speeds. Beam expands.

Look at the expansion of the beam (FWHM) and extrapolate back to find the source.



[1 pixel = 0.225 seconds]

554 MHz @ 13:11:55 UT



$h_{typeIII} \lesssim 590\,\mathrm{MHz}$ (ORFEES)

Density Profile