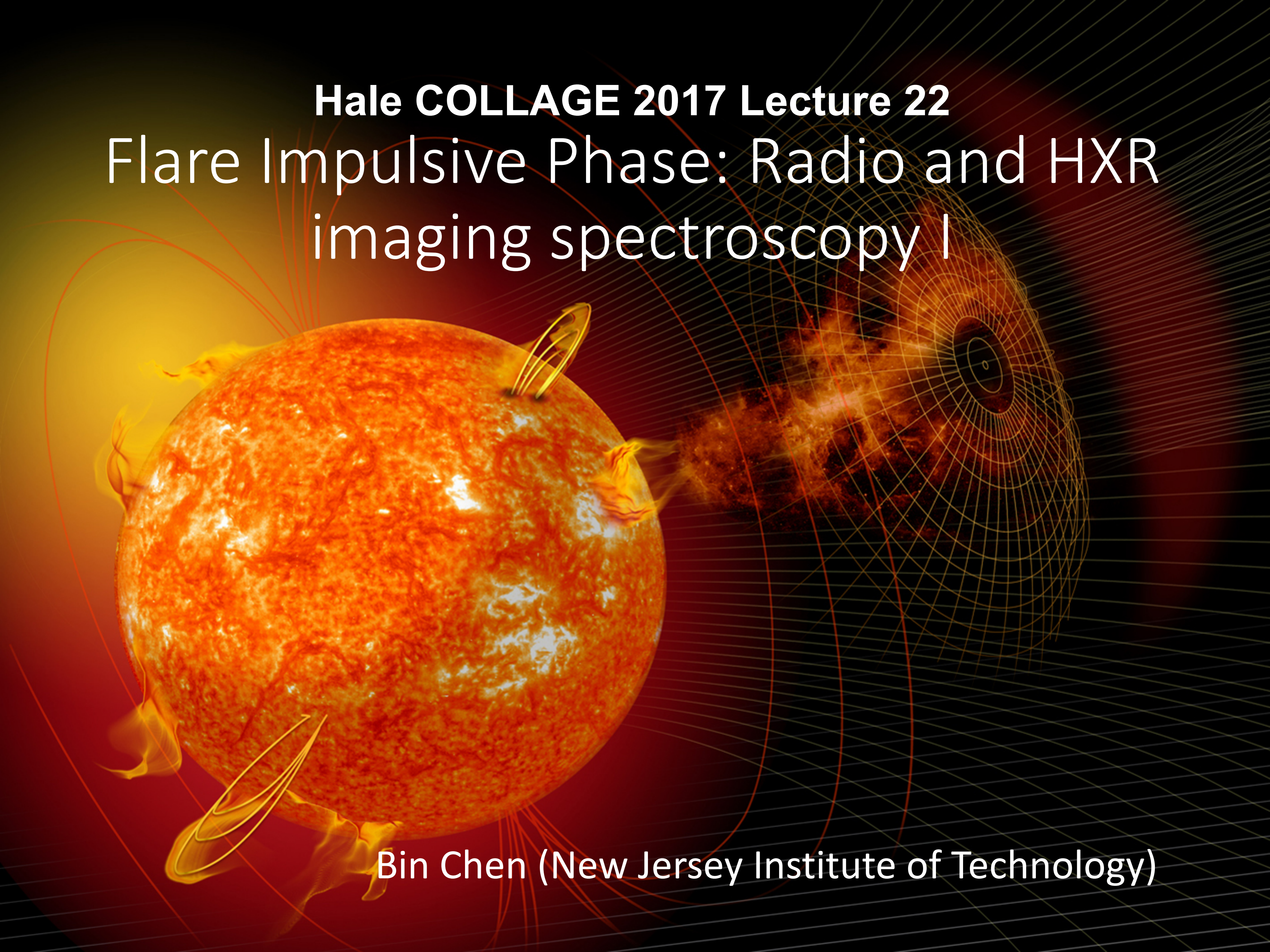


Hale COLLAGE 2017 Lecture 22

Flare Impulsive Phase: Radio and HXR imaging spectroscopy I

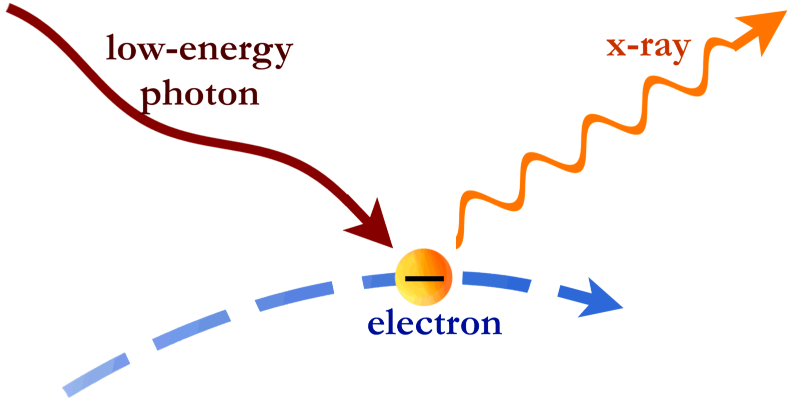
Bin Chen (New Jersey Institute of Technology)

Outline

- Radiation from energetic particles
  - Bremsstrahlung → lecture 20
  - Gyromagnetic radiation ("magnetobremsstrahlung") → Previous lecture
  - Other radiative processes → This lecture (briefly)
    - Inverse Compton, coherent radiation
- Diagnosing flare energetic particles using hard X-ray and radio spectroscopy and imaging → This and next lecture
- Suggested reading: Ch. 13 of Aschwanden's book for hard X-rays and Ch. 15 for radio

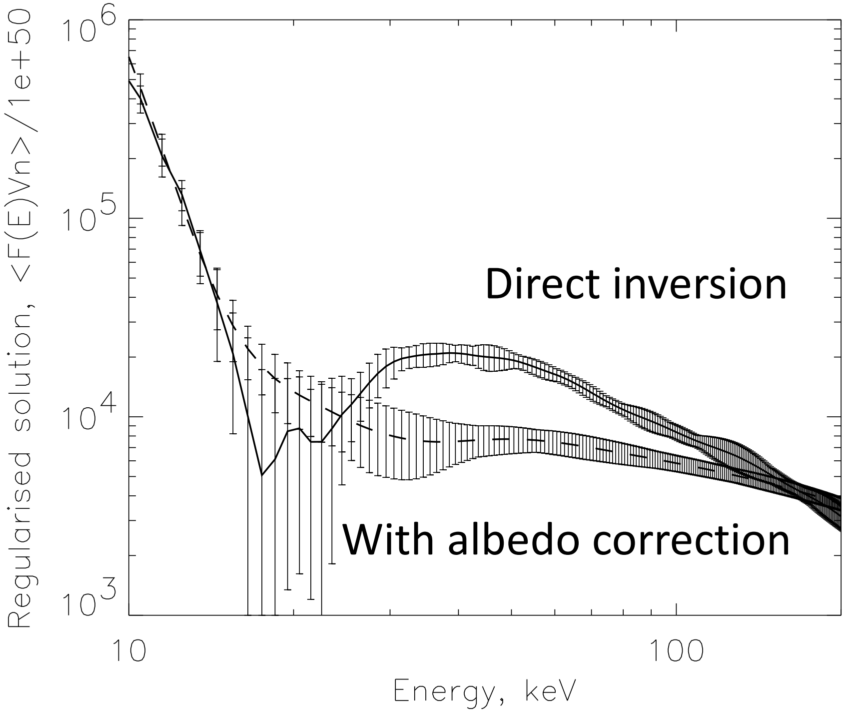
Inverse Compton Scattering

- Low-energy photon elastically scatter off low energy electrons → Thomson scattering
  - Responsible for white-light corona
- Low-energy photon scatter off a high energy electron and emit at higher energy → Inverse Compton



Inverse Compton and HXR spectrum

- HXR photons of 10-100 keV get Compton backscattered from the lower solar atmosphere
- It is therefore important to take into account these effects when interpreting HXR spectra



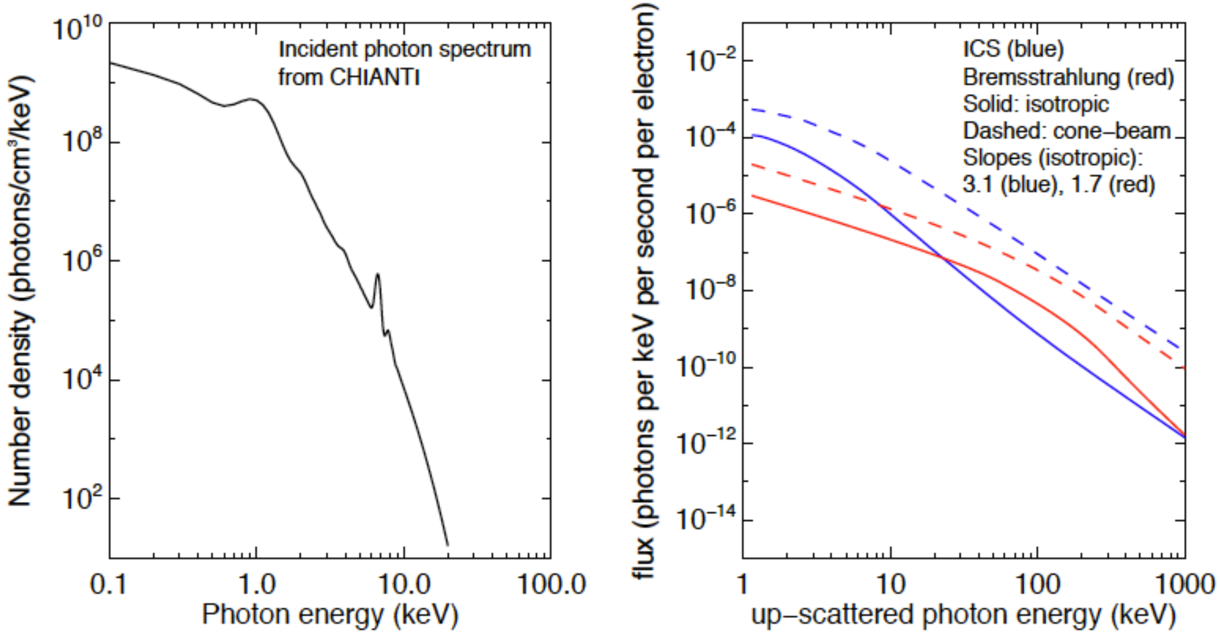
Direct inversion

With albedo correction

Kontar et al 2006

Inverse Compton and HXR spectrum

- EUV and SXR photons can be upscattered to HXR energies
- Significant esp. when electrons are directed toward the LOS



Chen & Bastian 2012

Coherent radiation

- All the previously discussed radiative processes - bremsstrahlung, gyromagnetic, inverse Compton - are incoherent, which means each electron radiates photons independently
- But if electrons somehow “know” each other and excite waves in phase, the radiation becomes “coherent”

Nonlinear wave growth

- From Lecture 19, we obtained a bunch of wave modes $\omega(k)$ using the Fokker-Planck equation. The imaginary part is the key for wave growth:

$$\mathbf{E}(\mathbf{x},t) = \hat{\mathbf{E}}^{(1)} e^{i\mathbf{k}\cdot\mathbf{x}-i\omega t}$$

$\mathrm{Im}(\omega) < 0$: damped

$\mathrm{Im}(\omega) > 0$: unstable → **Wave Growth**

- Plasma oscillation (Langmuir wave) is a natural wave mode of a plasma and can be excited by a variety of mechanisms.

Growth of Langmuir waves

- One can use the (collisionless) Vlasov Equations, with some approximations, to obtain the dispersion relation $\omega(k)$ of Langmuir waves:

$$\omega_L^2 = \omega_{pe}^2 + \frac{3k_B T_e}{m_e} k^2$$

where ω_{pe} and T_e are the electron plasma frequency and temperature. This is the real part of $\omega(k)$.

- The imaginary part of $\omega(k)$, often denoted Γ_k, is the growth (or damping, if <0) rate:

$$\Gamma_k \propto \frac{\omega_{pe}^2}{k^2} \frac{\omega_L}{n_e} \frac{\partial f(v_z)}{\partial v_z}$$

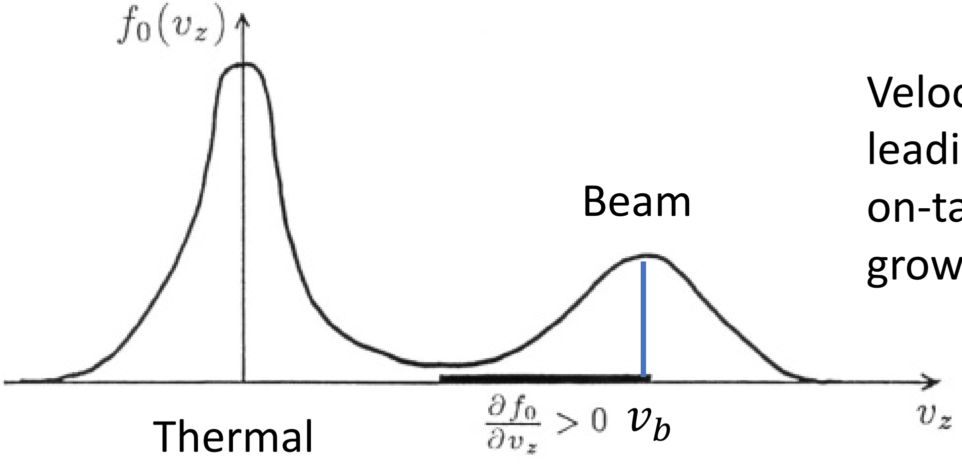
where $f(v_z)$ is the the electron distribution function along the B field direction

Growth of Langmuir waves

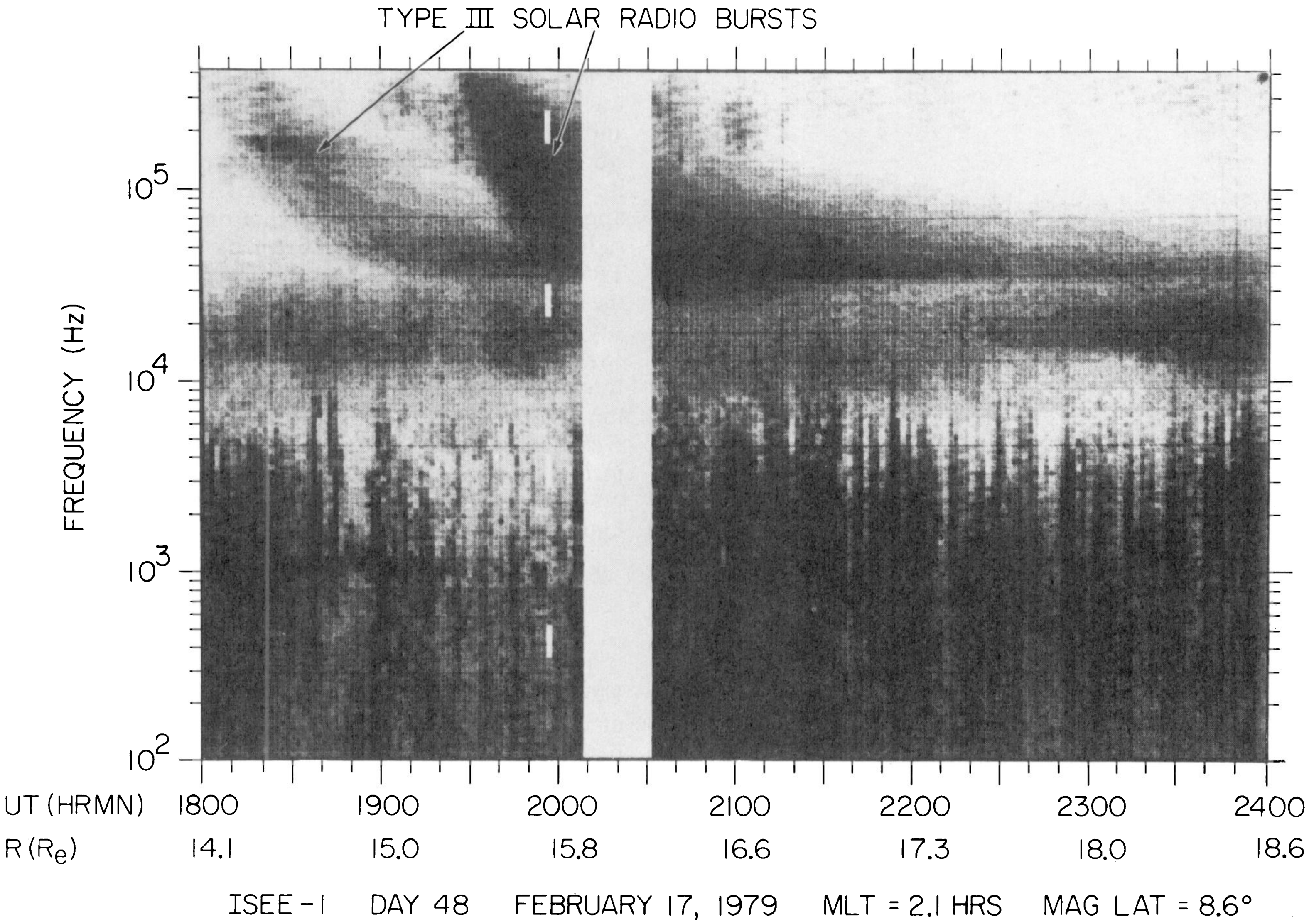
- Normally $\frac{\partial f(v_z)}{\partial v_z} < 0$ → negative γ_k → damped waves (Landau damping)
- Sometimes $\frac{\partial f(v_z)}{\partial v_z} > 0$ → positive γ_k → waves grow exponentially
- In the Sun's corona, propagating electron beams, trapped electrons, and/or shocks can excite plasma waves, which may result in observable radio bursts

Bump-on-tail instability

- A fast electron beam has two velocity components at a given location: a thermal component and a beam component



Velocity distribution leading to the “bump-on-tail” instability of growing plasma waves



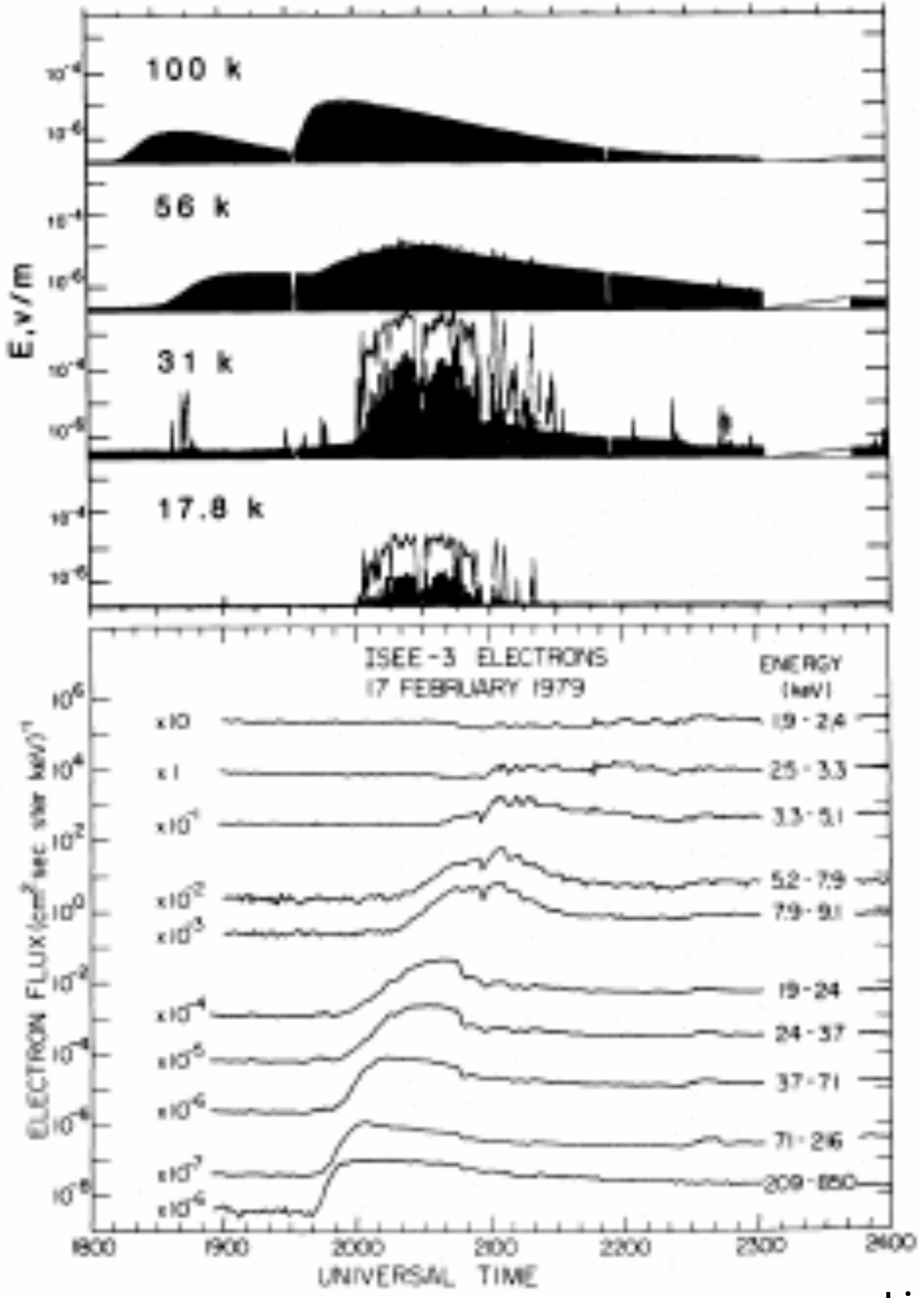
ISEE-3 type III

1979 Feb 17

Lin et al. 1981

ISEE-3 type III

1979 Feb 17



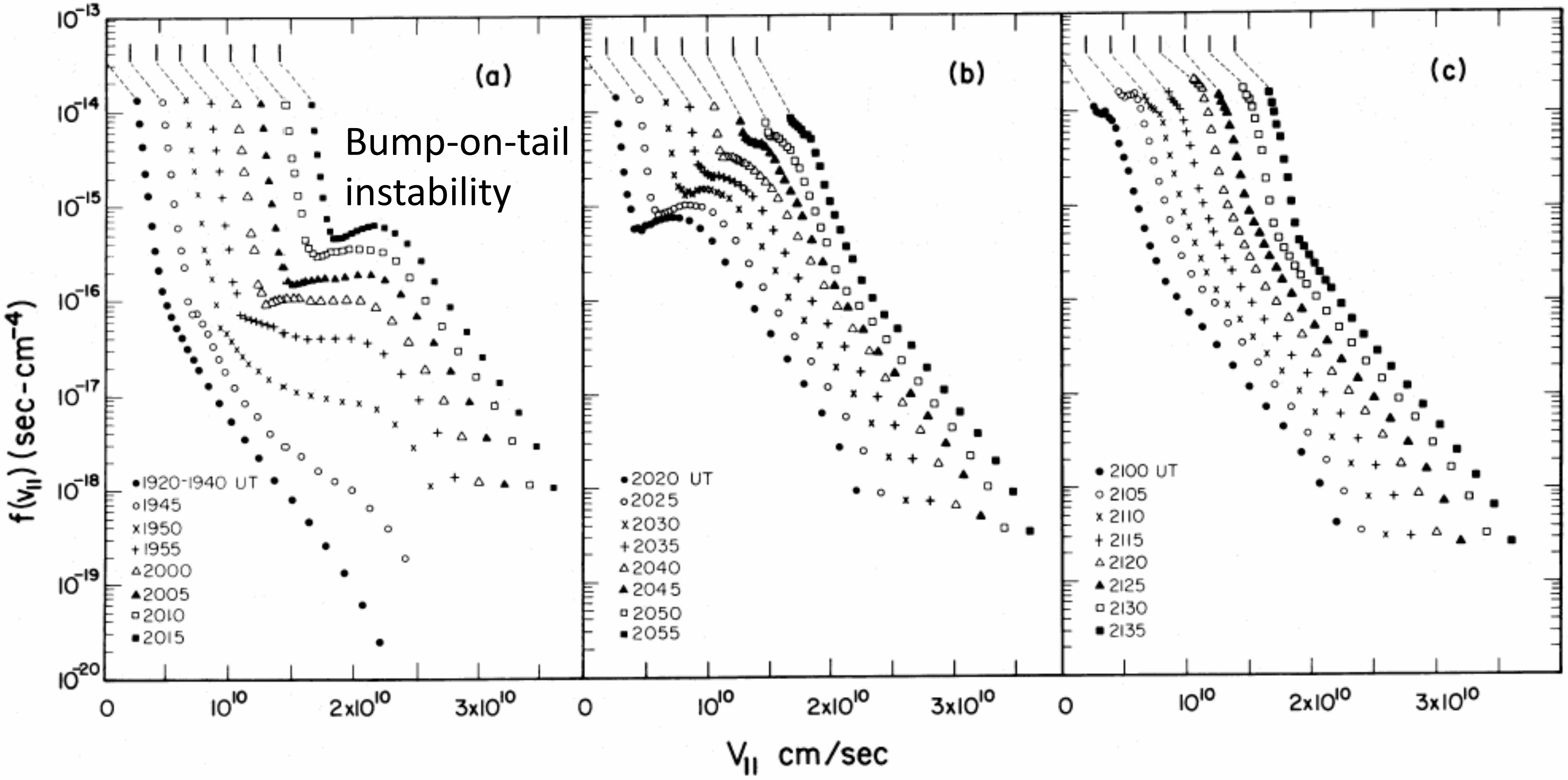
IP Type III bursts (harmonic plasma radiation)

IP Langmuir waves

IP electrons

Lin et al. 1981

Velocity distribution



Bump-on-tail instability

Lin et al. 1981

Plasma radiation

- However, Langmuir waves are longitudinal plasma oscillations with very small group velocity, which have to convert to transverse waves in order to escape.

- How? Nonlinear wave-wave interactions. The resulting transverse waves have frequencies near the fundamental or harmonic of the local electron plasma frequency: i.e., ν_{pe} or $2\nu_{pe}$.

- Fundamental plasma radiation: Langmuir waves scatter off of thermal ions or, more likely, low-frequency waves (e.g., ion-acoustic waves)

$\omega_L + \omega_S = \omega_T$ and $k_L + k_S = k_T$ coalescence

or $\omega_L = \omega_S + \omega_T$ $k_L = k_S + k_T$ decay

Plasma radiation

Harmonic plasma radiation

- A process must occur that is unstable to the production of Langmuir waves
- A secondary spectrum of Langmuir waves must be generated
- Two Langmuir waves can then coalesce

$$\omega_L^1 + \omega_L^2 = \omega_T$$

and

$$k_L^1 + k_L^2 = k_T << k_L$$

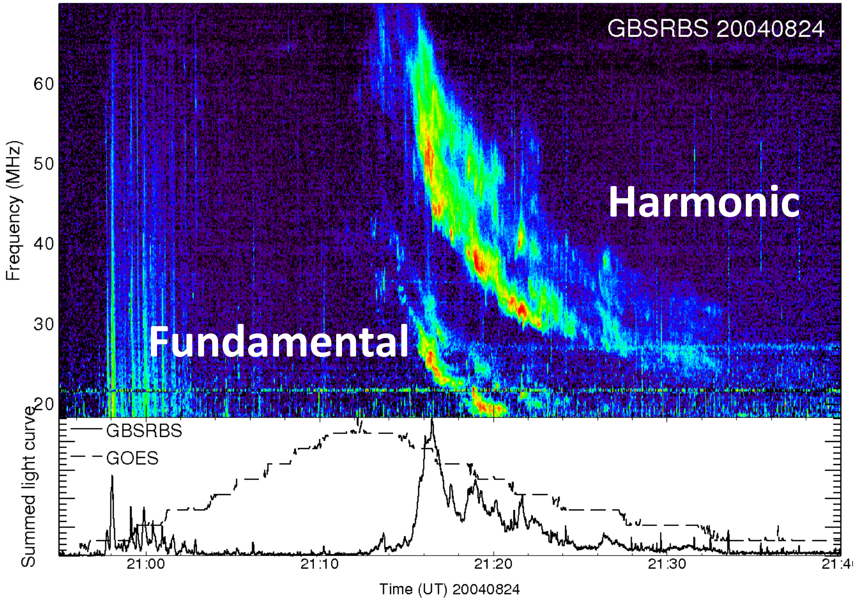
$$\omega_T \approx 2\omega_L$$

$$k_L^1 \approx -k_L^2$$

Plasma Radiation

- Type I, II, III, IV, V bursts discussed in Lecture 7
- Some of them show as fundamental-harmonic pairs

A type II radio burst (from a shock)



Loss-cone instability: resonance condition

- Resonance condition for strong wave-particle interaction:

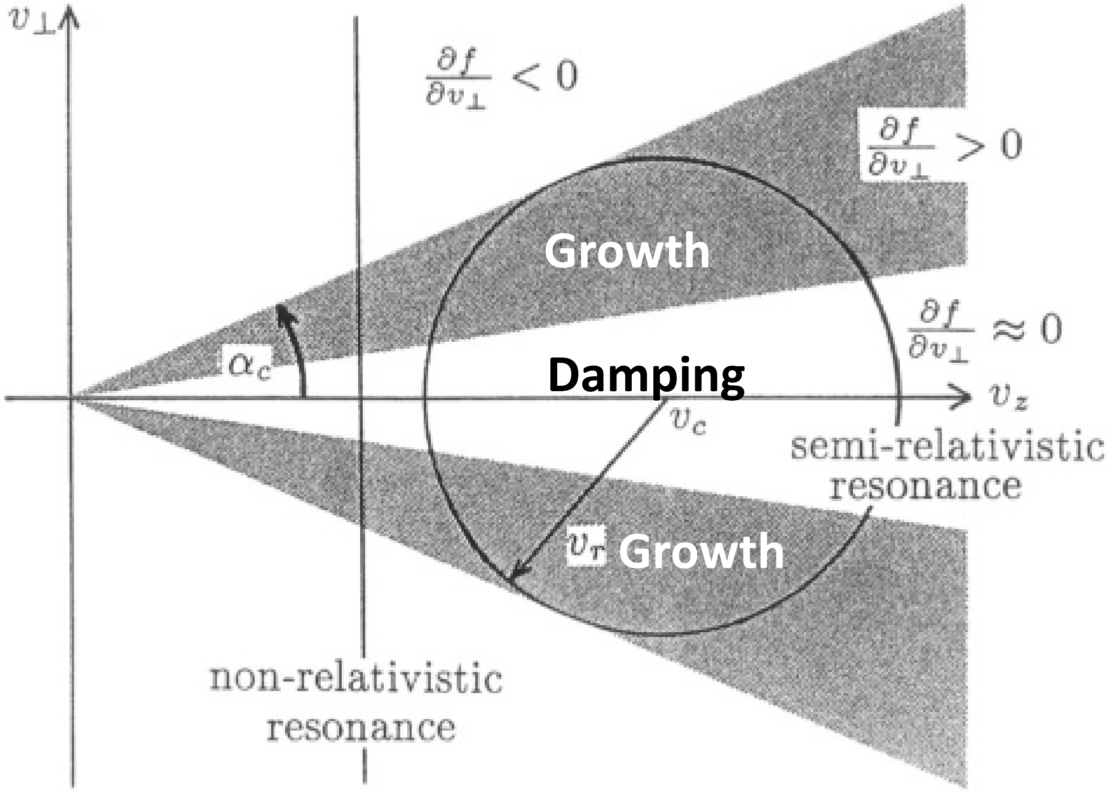
resonance: $$\boxed{\omega - k\mathrm{v}_z = \mp s\Omega_c}$$

electrons (s=-1)
resonate w/ **RH** wave

From Lecture 16 by Prof. Longcope

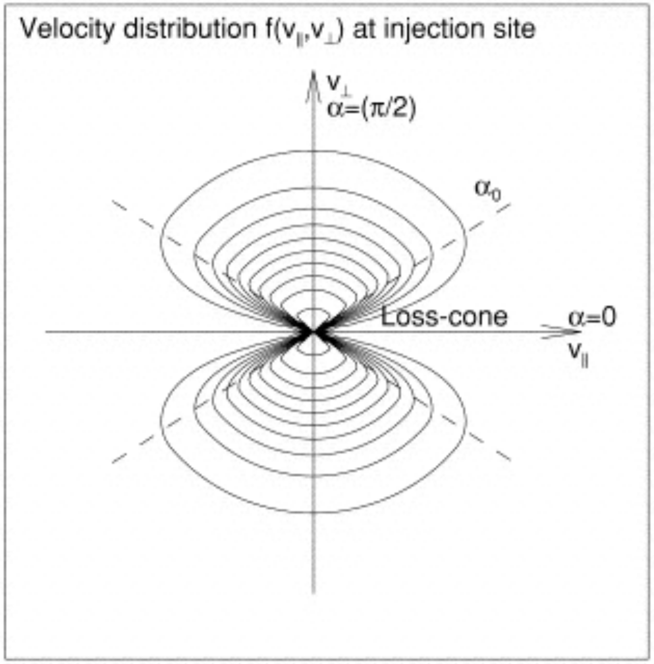
- S can be other integer numbers for different wave modes
- For energetic electrons, we need to apply relativistic correction to the gyrofrequency: $\omega_B = \omega_{ce}/\gamma$ (Ω_c in Dana’s notation)
- The condition defines a surface in the velocity space

Loss-cone instability: wave growth



$$\omega - k_z v_z = \frac{s\omega_{ce}}{\gamma}$$

Also known as “cyclotron maser radiation”



Relevant in e.g., some special types of solar radio bursts, Jupiter’s decametric radiation, aurora kilometric radiation, radio pulsars, etc.

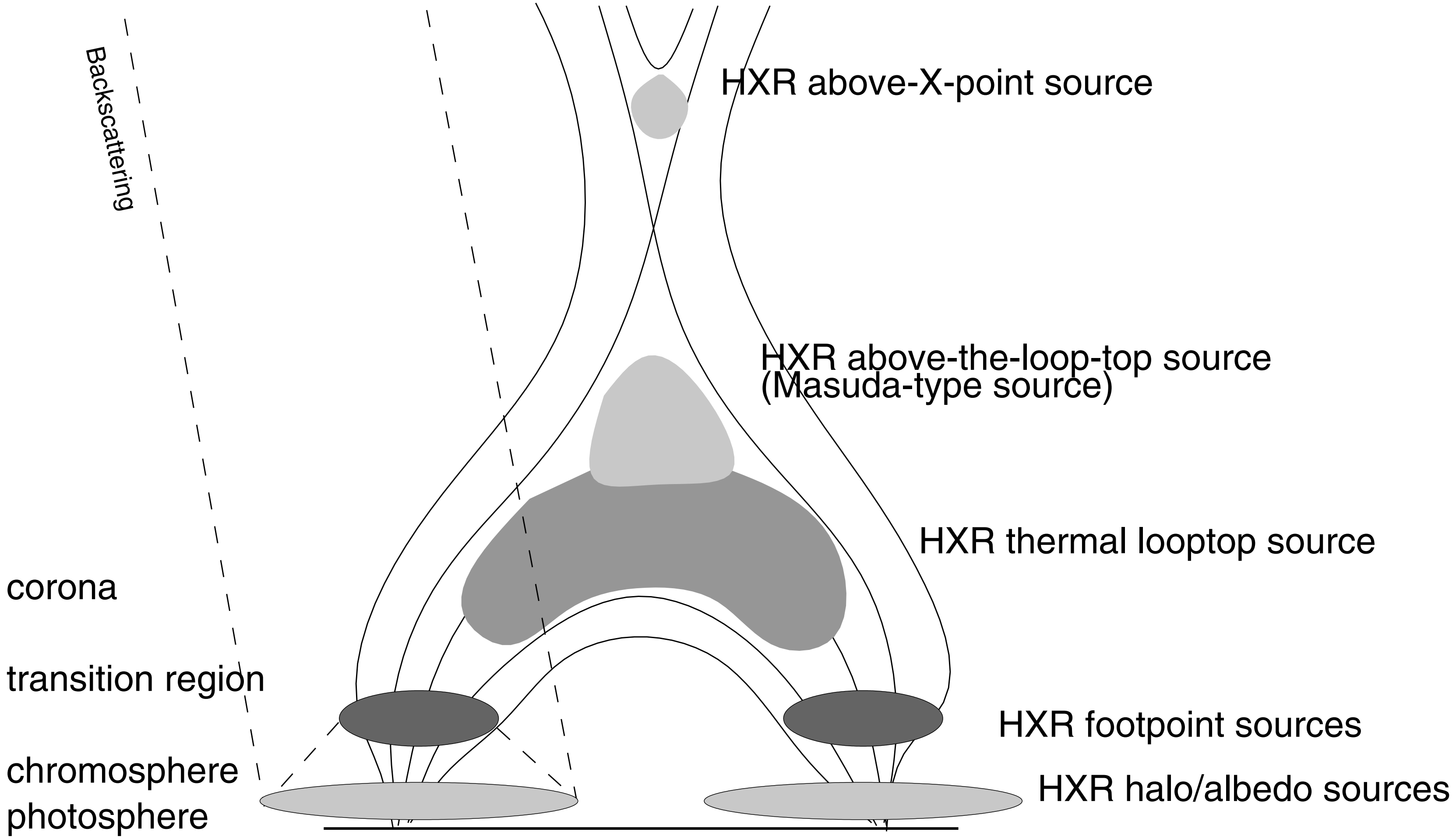
Diagnosing energetic electrons

- Each mechanism provides a method to probe the thermal plasma and/or energetic electrons

  → **Acceleration: Where? When? What?**

- HXR:
  - Thermal bremsstrahlung → n_e, T_e
  - Nonthermal thin-target and thick-target bremsstrahlung → $f(E)$
  - Inverse Compton → mostly corrections to $f(E)$
- Radio:
  - Thermal bremsstrahlung → n_e, T_e
  - Gyrosynchrotron → $f(E), n_e, T_e, B, \theta$
  - Coherent radiation → n_e (possibly $f(E)$, B, model dependent)

Overview of HXR sources in flares



HXR above-X-point source

HXR above-the-loop-top source
(Masuda-type source)

HXR thermal looptop source

corona

transition region

HXR footpoint sources

chromosphere

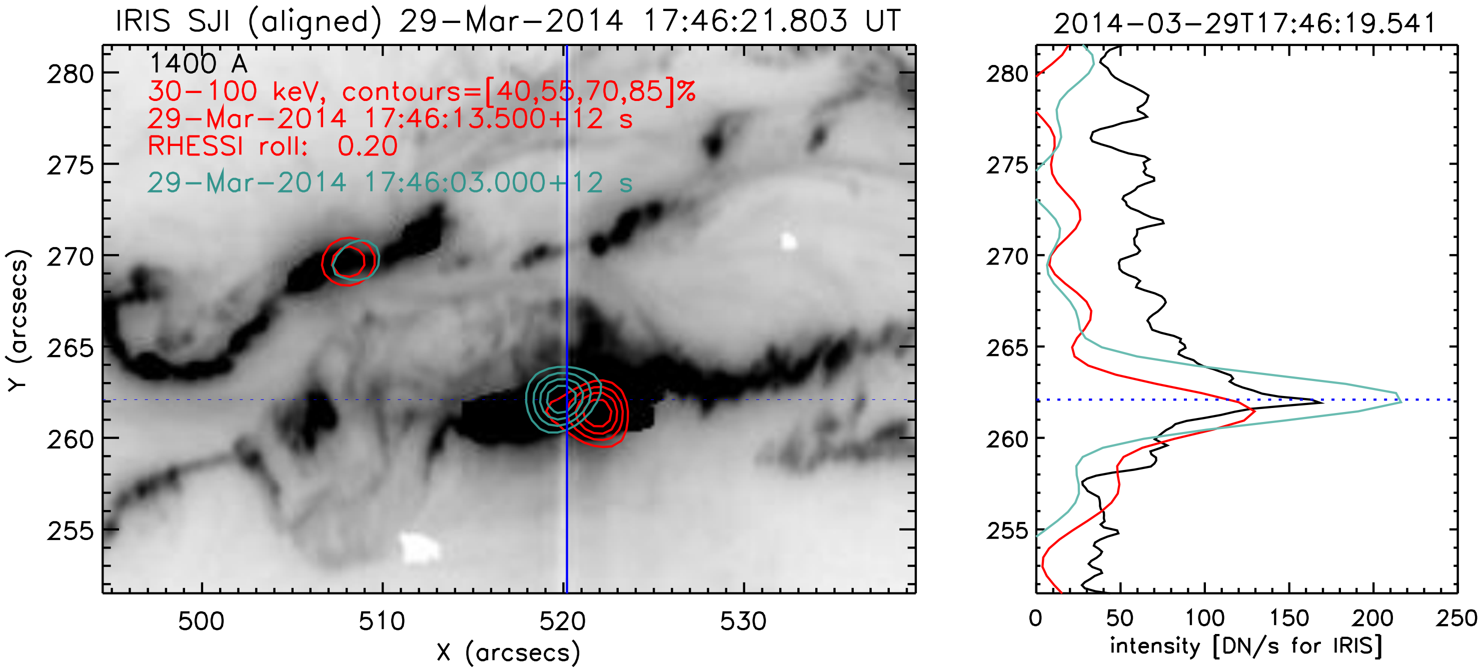
HXR halo/albedo sources

photosphere

From Aschwanden's book

HXR footpoint sources

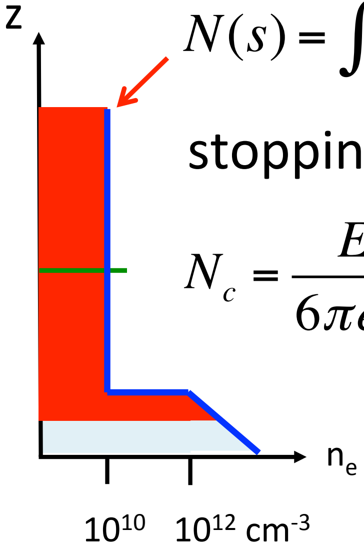
- HXR emission in flares is usually dominated by intense footpoint sources
- Nonthermal thick-target bremsstrahlung from precipitating electrons



From Kleint et al. 2016

HXR footpoint sources

- Higher-energy electrons reach deeper in the chromosphere



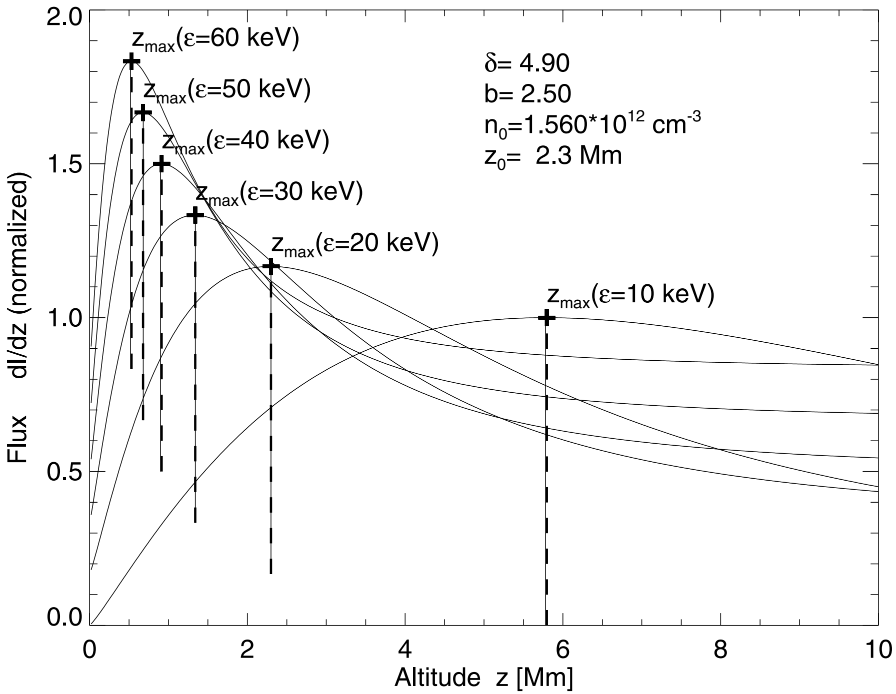
$$N(s) = \int n_e(s')\,ds' \quad [\mathrm{cm}^{-2}]$$

stopping column: N σ_e = 1

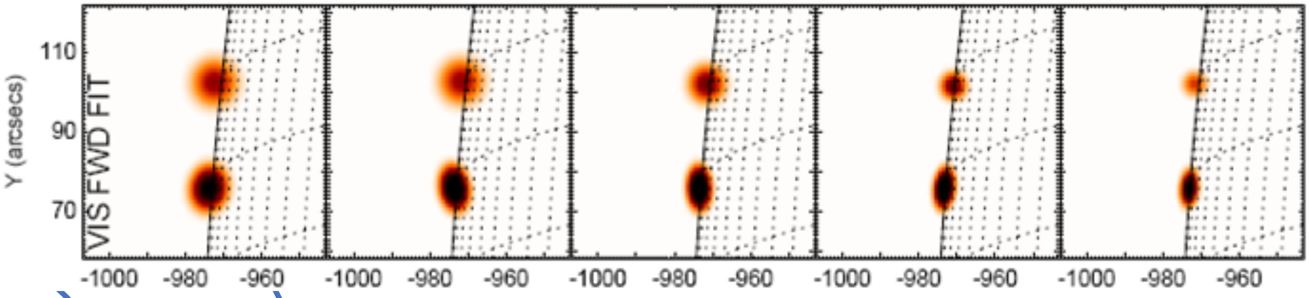
$$N_c = \frac{E_c^2}{6\pi e^4 \Lambda} = 1.4\times10^{17}\,\mathrm{cm}^{-2}\,E_{c,keV}^2$$

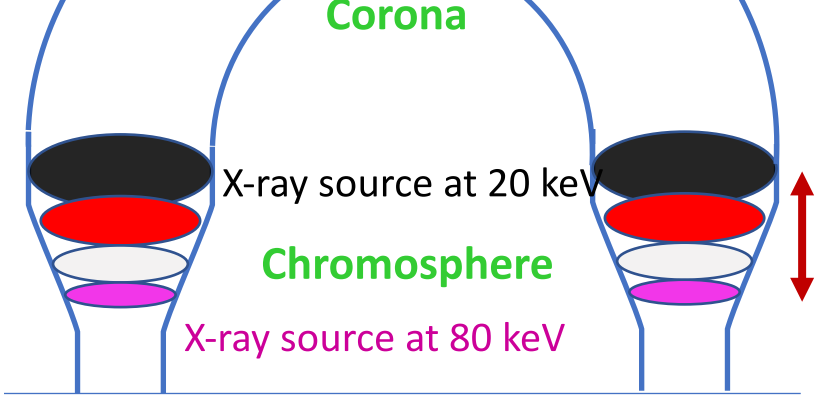
stop cut-off

From Lecture 10 by Prof. Longcope



HXR footpoint sources



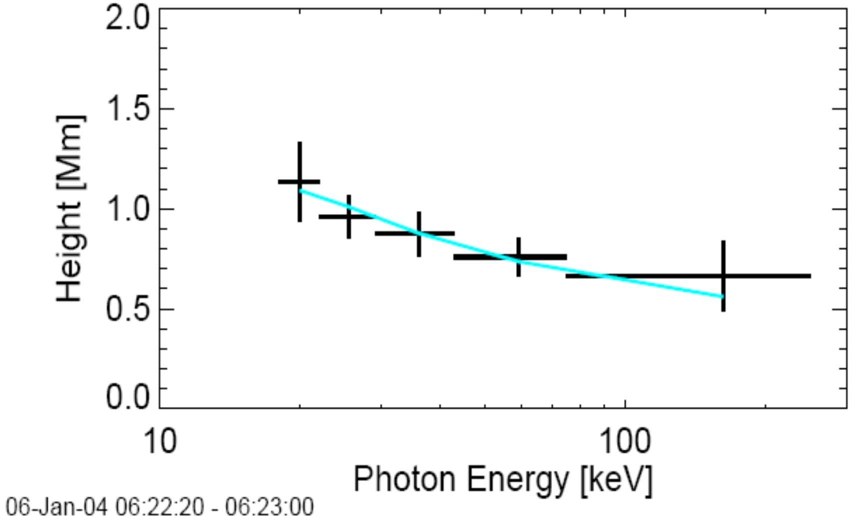


Corona

X-ray source at 20 keV

Chromosphere

X-ray source at 80 keV



HXR energy vs. height → chromospheric density vs. height

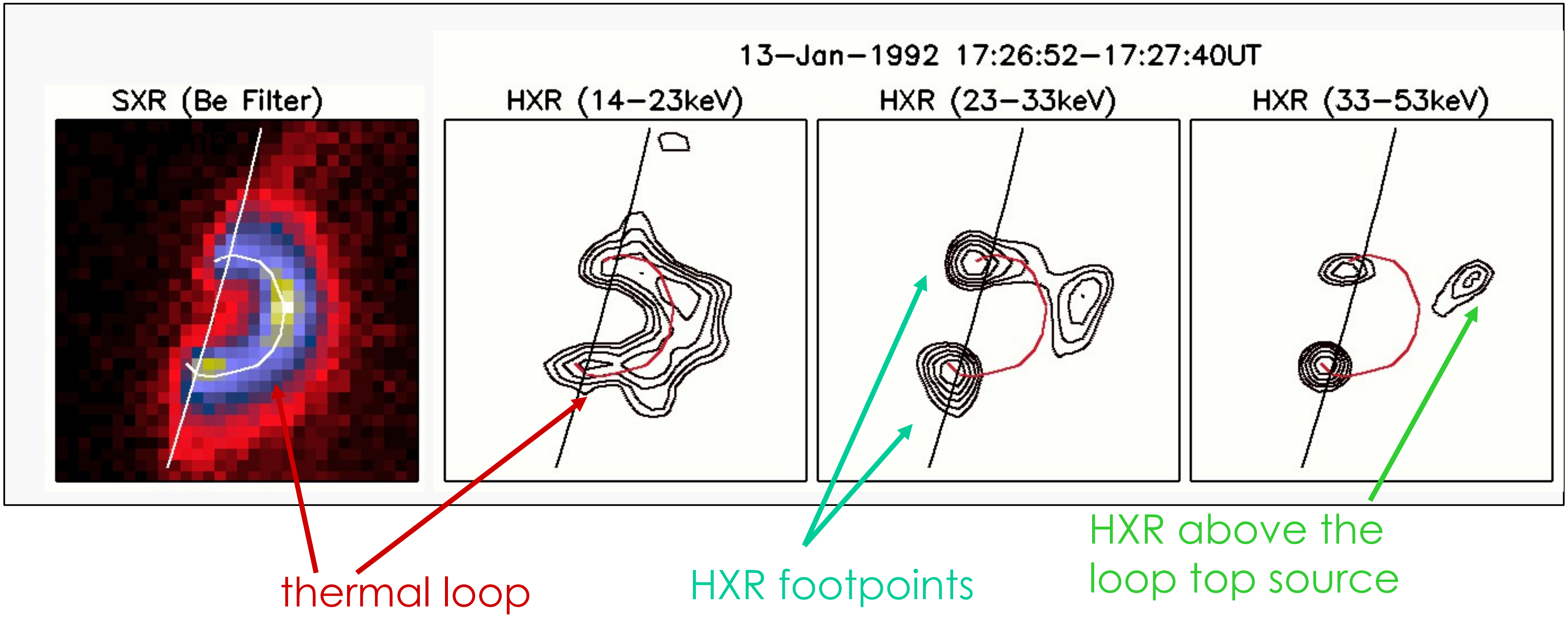
Kontar et al. 2008, 2009

Dominating footpoint HXR emission
→ Are particles accelerated near the footpoints?

There are debates, but probably not the primary site

Above-the-loop-top HXR source

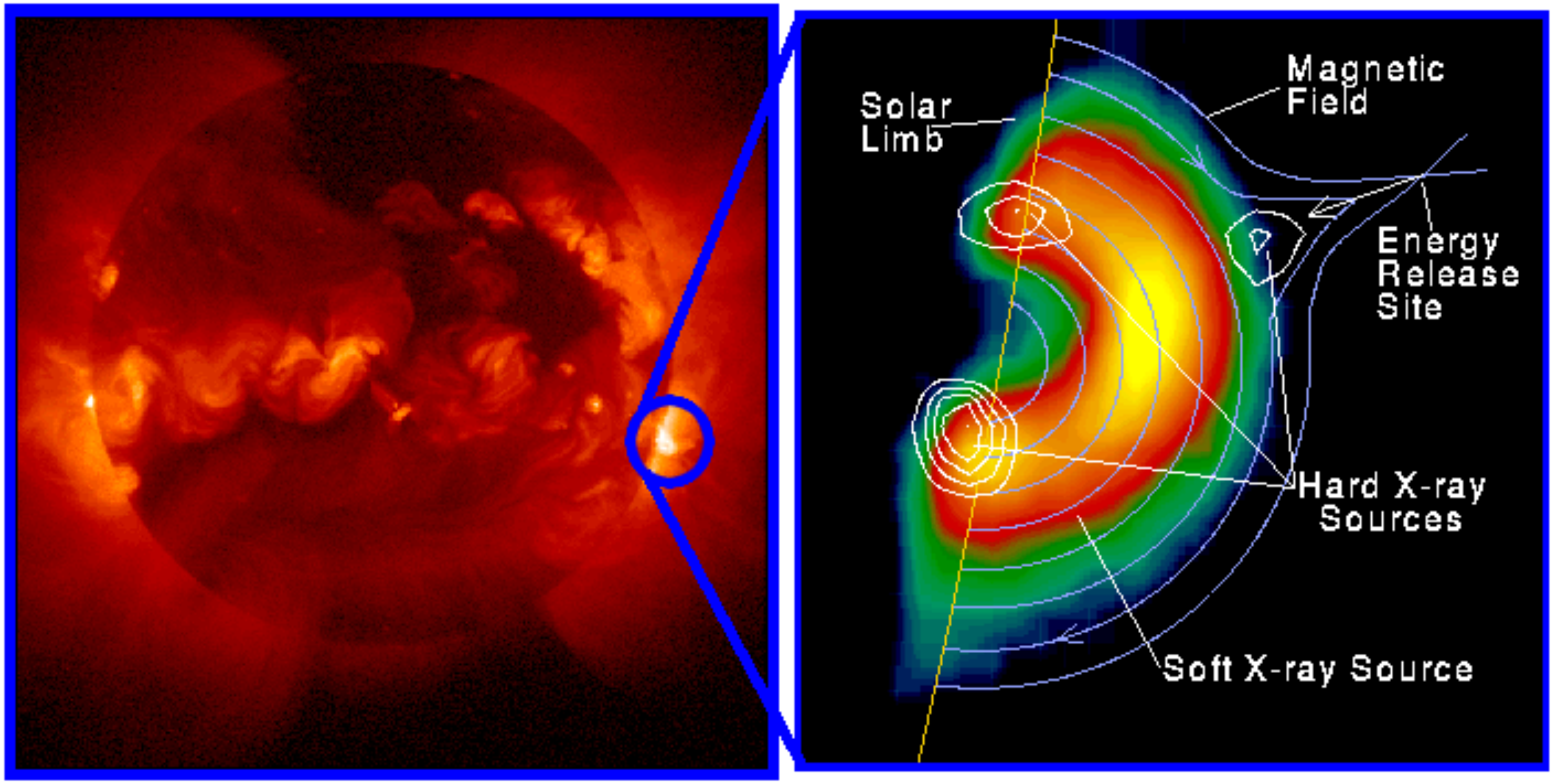
- The celebrated “Masuda” flare (Masuda et al. 1994): A HXR source is located **above** the soft X-ray flare loop



thermal loop

HXR footpoints

HXR above the loop top source



Nonthermal electrons are present above the looptop.

Are they accelerated there?

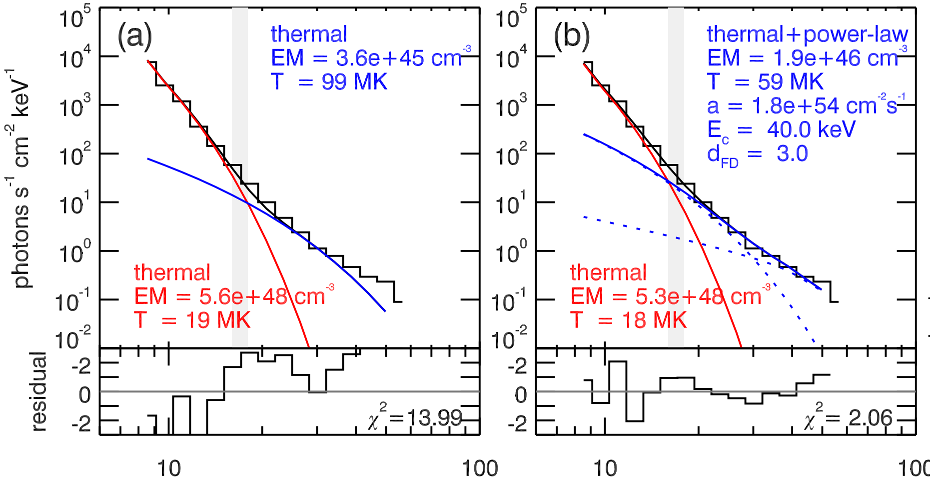
- If so, which acceleration mechanism(s)?
- If not, transport effects?

Nevertheless, the “Masuda-type” flares made a significant contribution to the suggestion of the current “standard” flare scenario

Well, let's back off a little... Are we sure that the ALT HXR source is nonthermal?

Thermal + Superhot

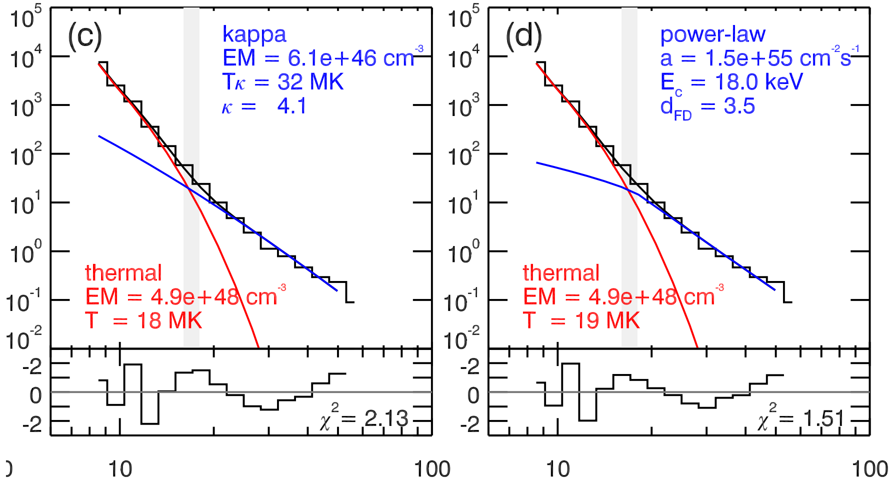
Thermal + Superhot + Power-law

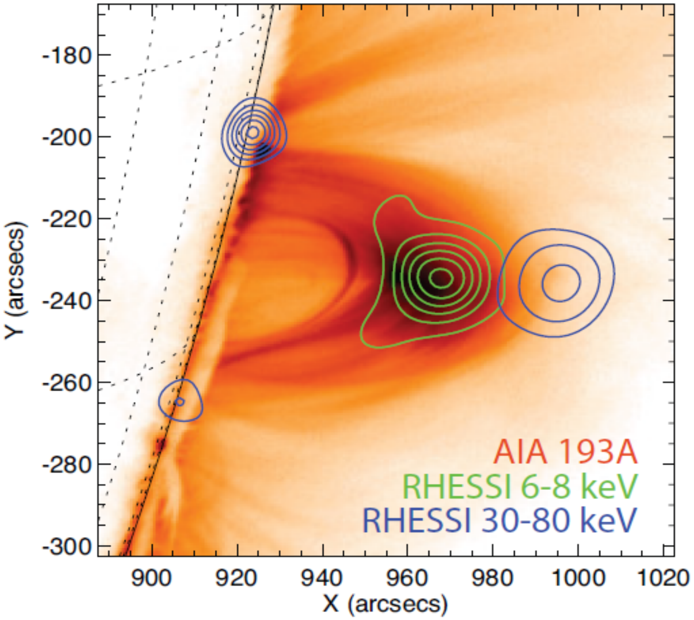


Fitting choices of the observed HXR spectrum is **not** unique!

Thermal + Kappa

Thermal + Power-law

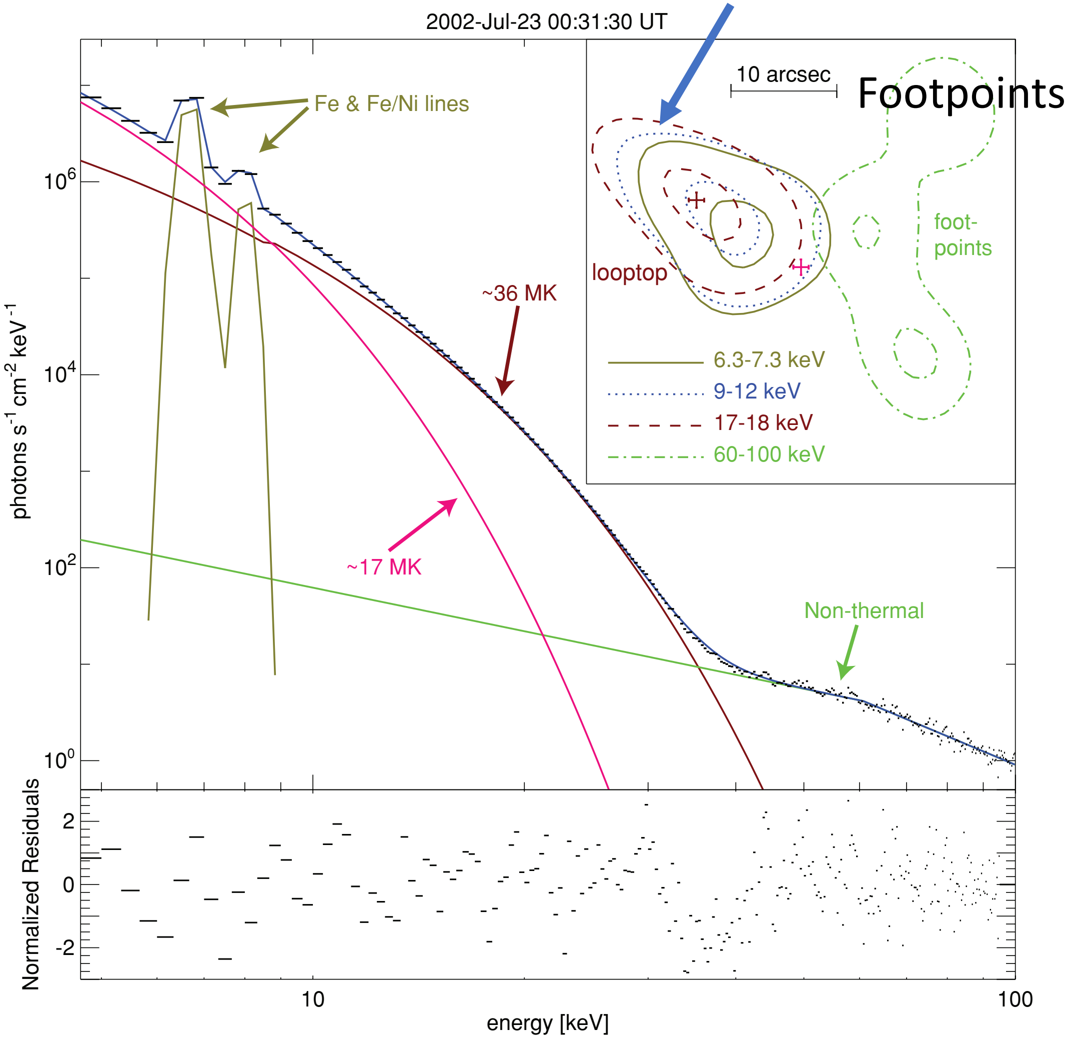




Oka et al. 2015

“Superhot” coronal HXR source

Superhot source: ~36 MK

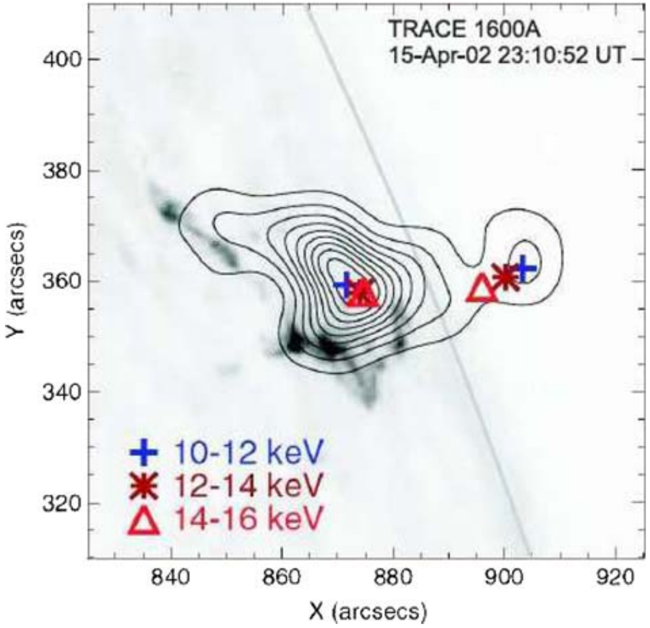


Caspi & Lin 2010

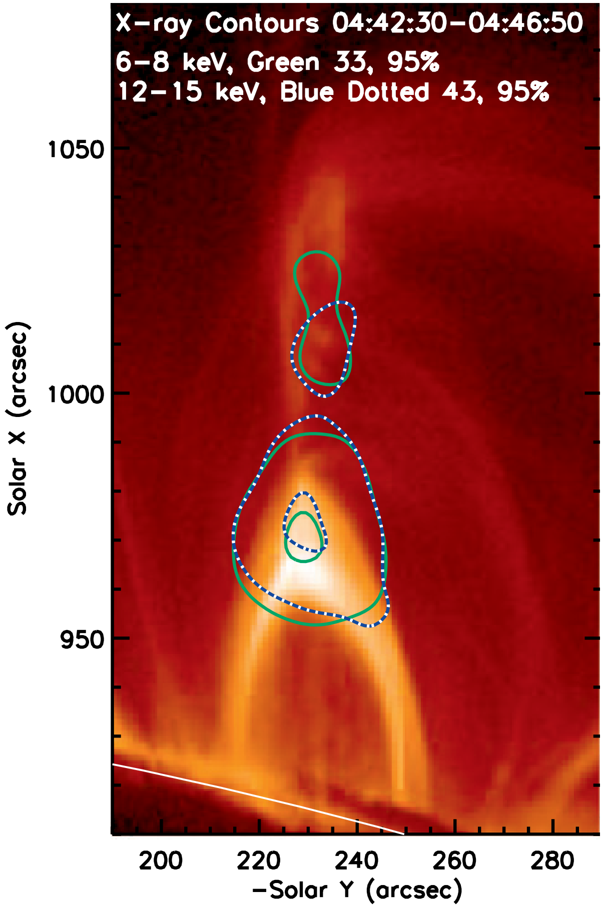
- First discovered by Lin et al. 1981 from balloon-borne observations
- Too hot for chromospheric evaporation (require extreme conditions)
- Appear in the pre-impulsive phase → evaporation has not begun
- Direct heating in the corona (collapsing trap? shock?), or, collisional relaxation from the nonthermal tail?

Above-the-X-point HXR sources

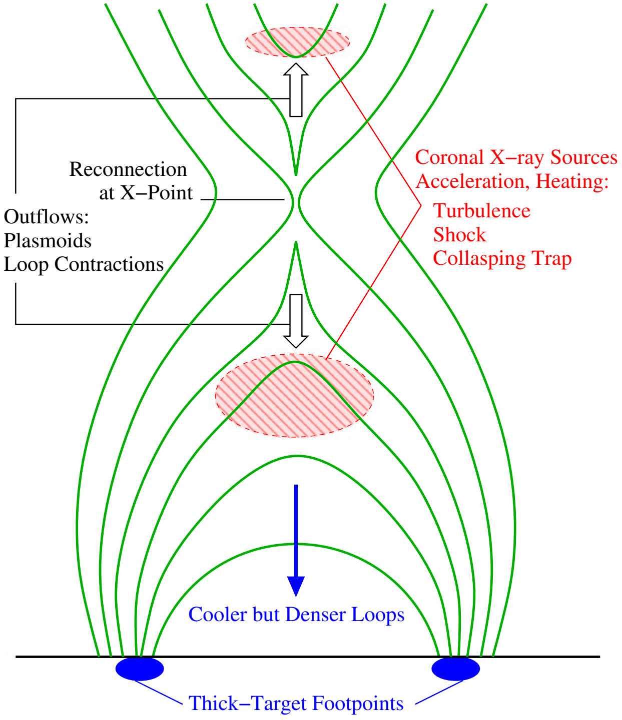
Higher energy sources "converge" to, perhaps, the reconnection site



Sui & Holman 2003

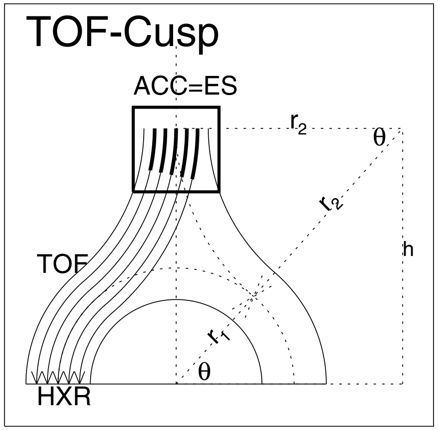


Liu et al. 2013

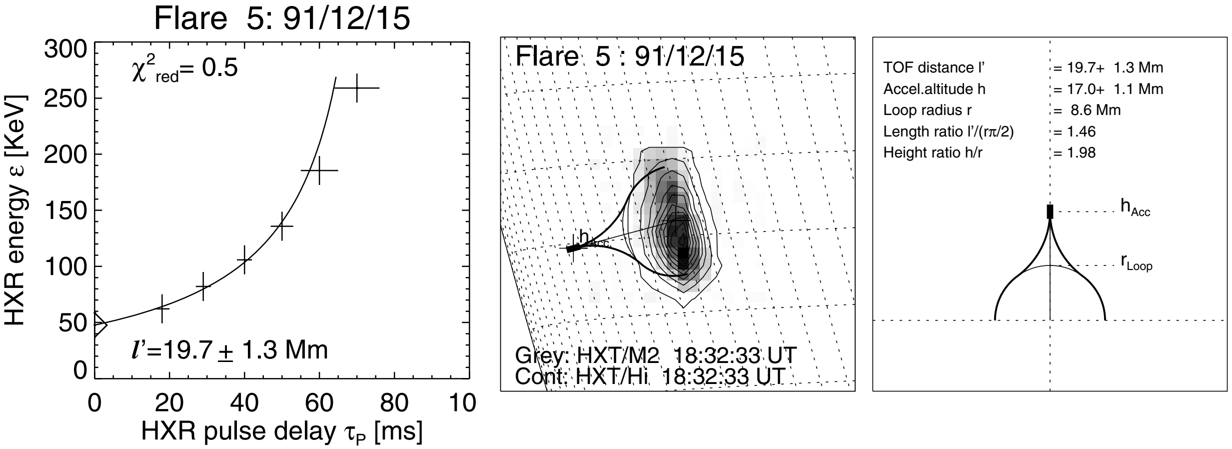


HXR spectra: Time of flight delays

- If acceleration site is in the corona, lower-energy electrons need more time to reach the chromosphere



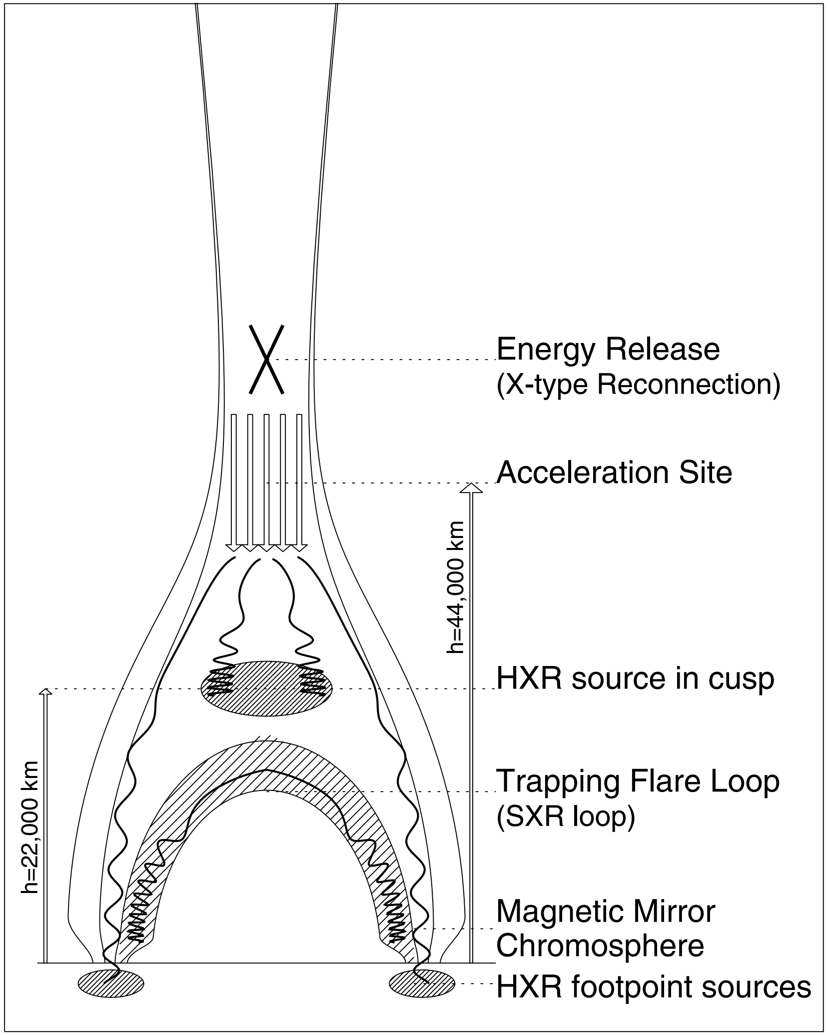
$$l_{TOF} = c\tau_{ij}\left(\frac{1}{\beta_i}-\frac{1}{\beta_j}\right)^{-1}$$



TOF distance l' := 19.7+ 1.3 Mm
Accel.altitude h := 17.0+ 1.1 Mm
Loop radius r := 8.6 Mm
Length ratio l'/(rπ/2) := 1.46
Height ratio h/r := 1.98

Aschwanden et al. 1996

Back to the Masuda flare



Time of flight analysis seems to place the acceleration site *above* the ALT HXR source (Aschwanden et al. 1996)

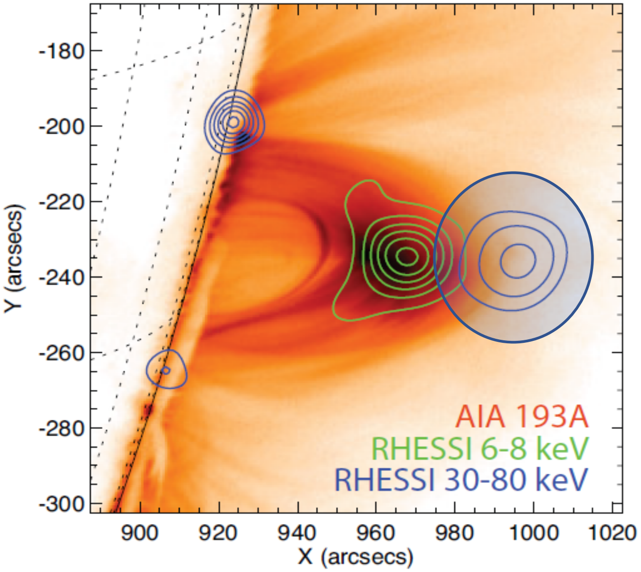
ALT HXR source due to transport mechanisms (e.g., trapping?)

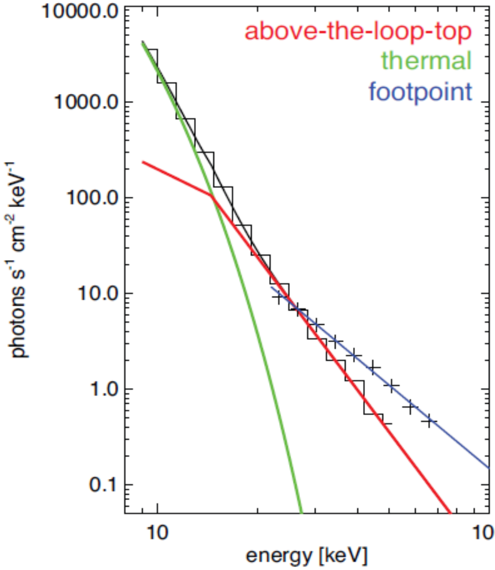
Alternative view: ALT HXR source **is** the primary acceleration site

Krucker & Battaglia 2014:

RHESSI imaging spectroscopy to infer density of accelerated electrons: $n_{nt} \sim 10^9\ \mathrm{cm}^{-3}$

SDO/AIA DEM analysis to determine ambient thermal density n_0

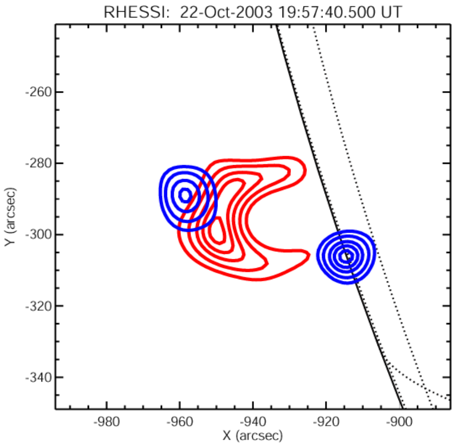




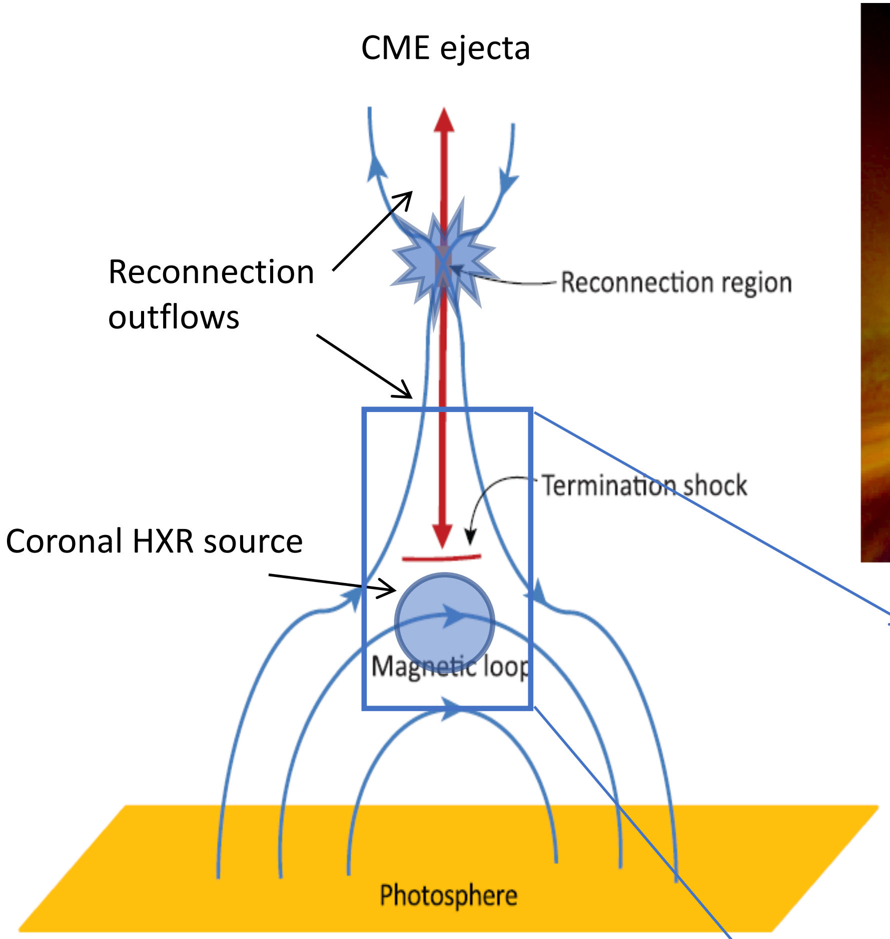
→ ratio n_{nt}/n_0 is close to 1

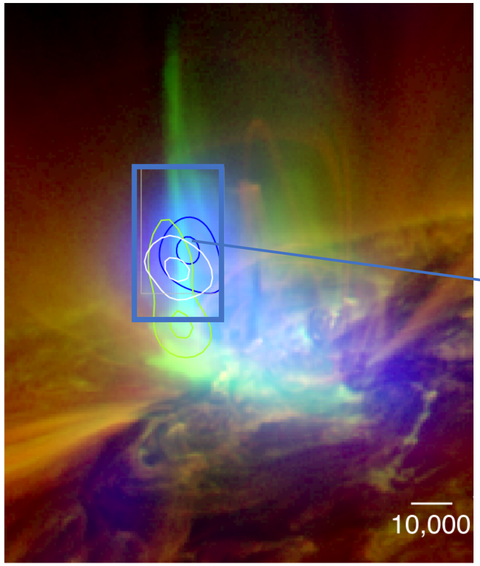
→ bulk acceleration takes place within the ALT HXR source?

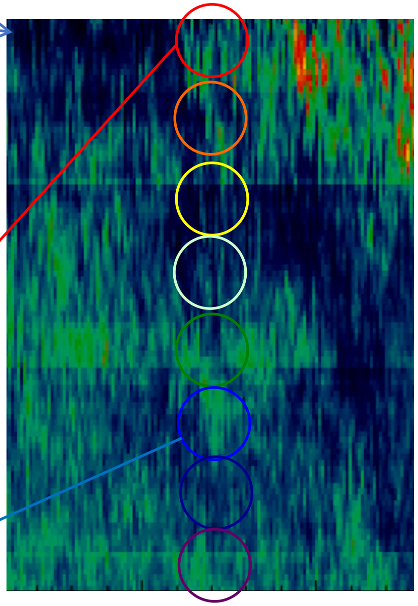
Similar findings were reported for partially occulted flares (Krucker et al. 2010)

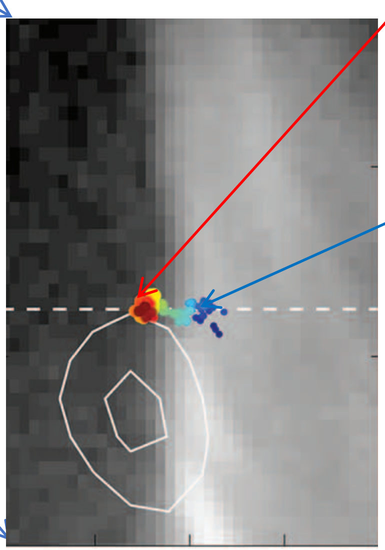


Coherent radio radiation is another excellent probe





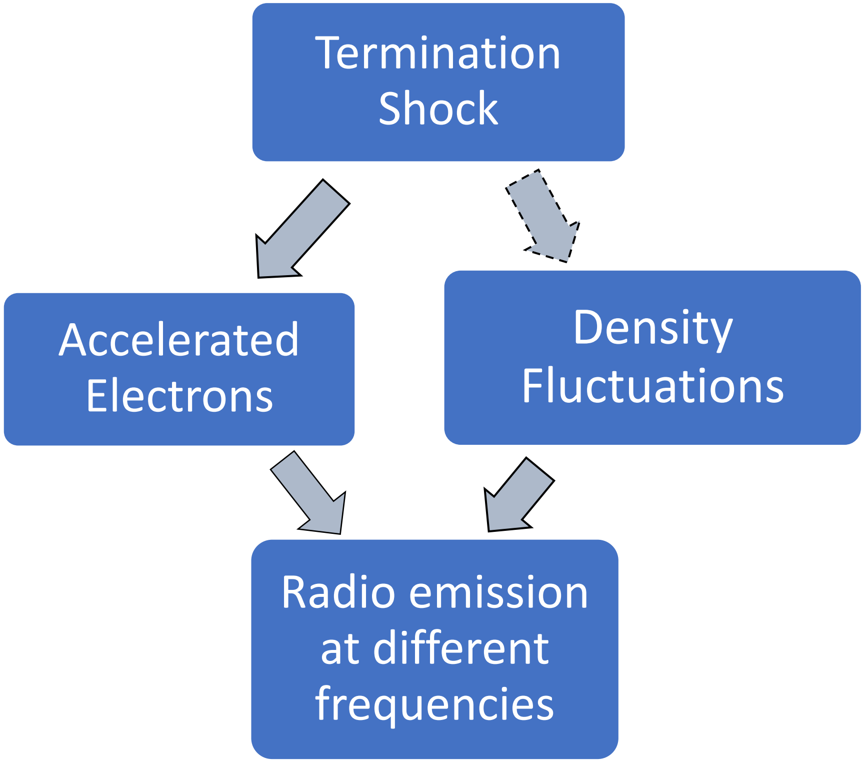




- Unlike HXR, **no need** for sufficient ambient density
- Coherent radiation → very efficient emission

Chen et al. 2015

Coherent Radio Emission at a Termination Shock

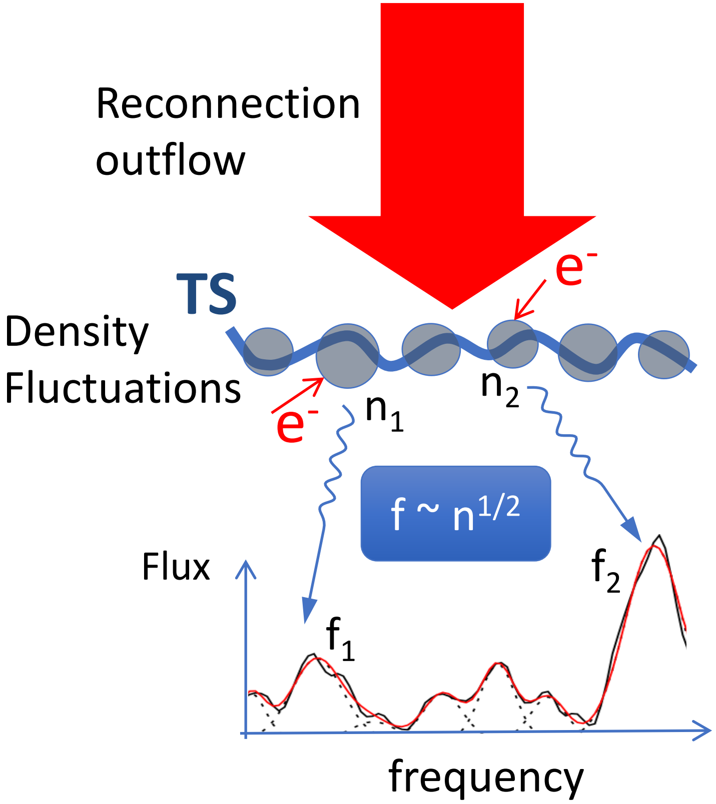


Termination Shock

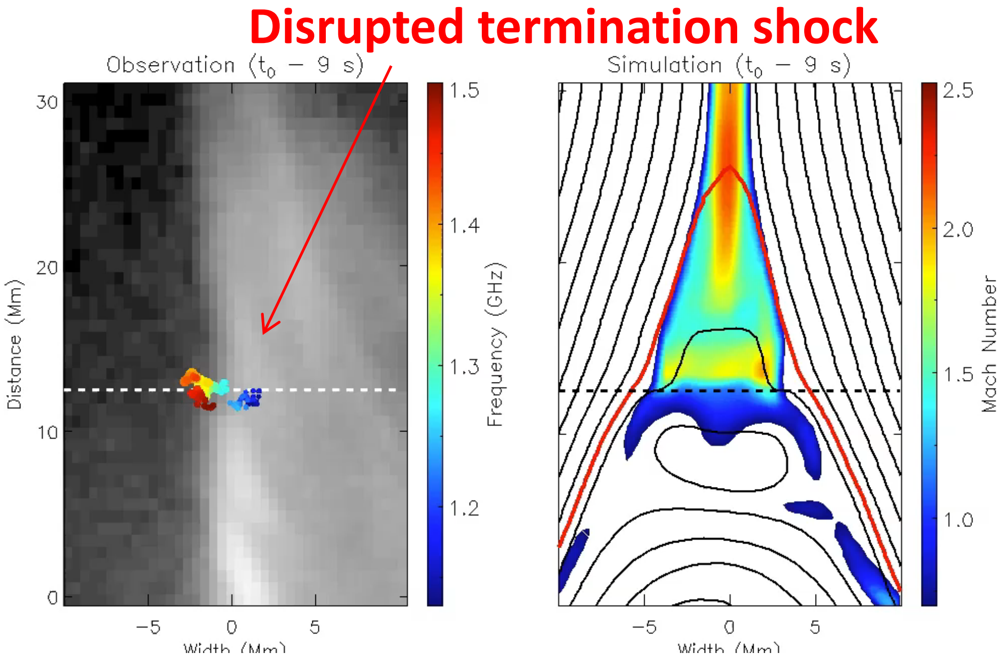
Accelerated Electrons

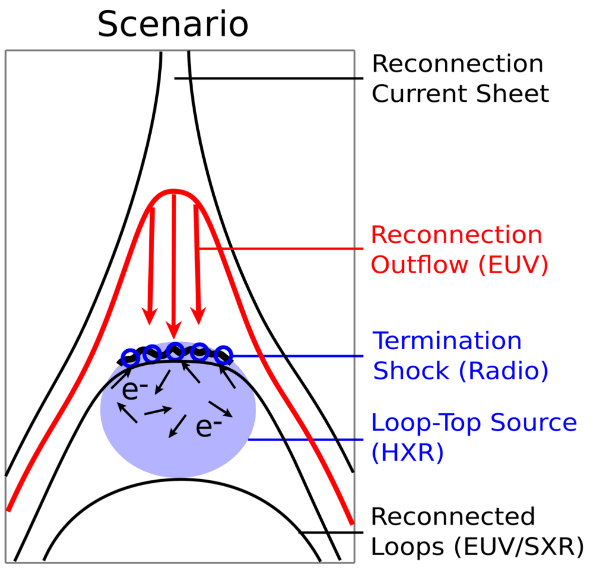
Density Fluctuations

Radio emission at different frequencies



Coherent radiation allows diagnostics of highly dynamic phenomena


Disrupted termination shock


Scenario

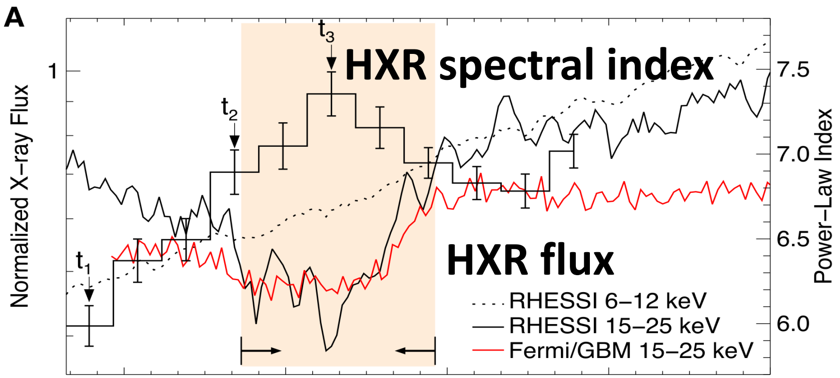
Reconnection Current Sheet

Reconnection Outflow (EUV)

Termination Shock (Radio)

Loop-Top Source (HXR)

Reconnected Loops (EUV/SXR)

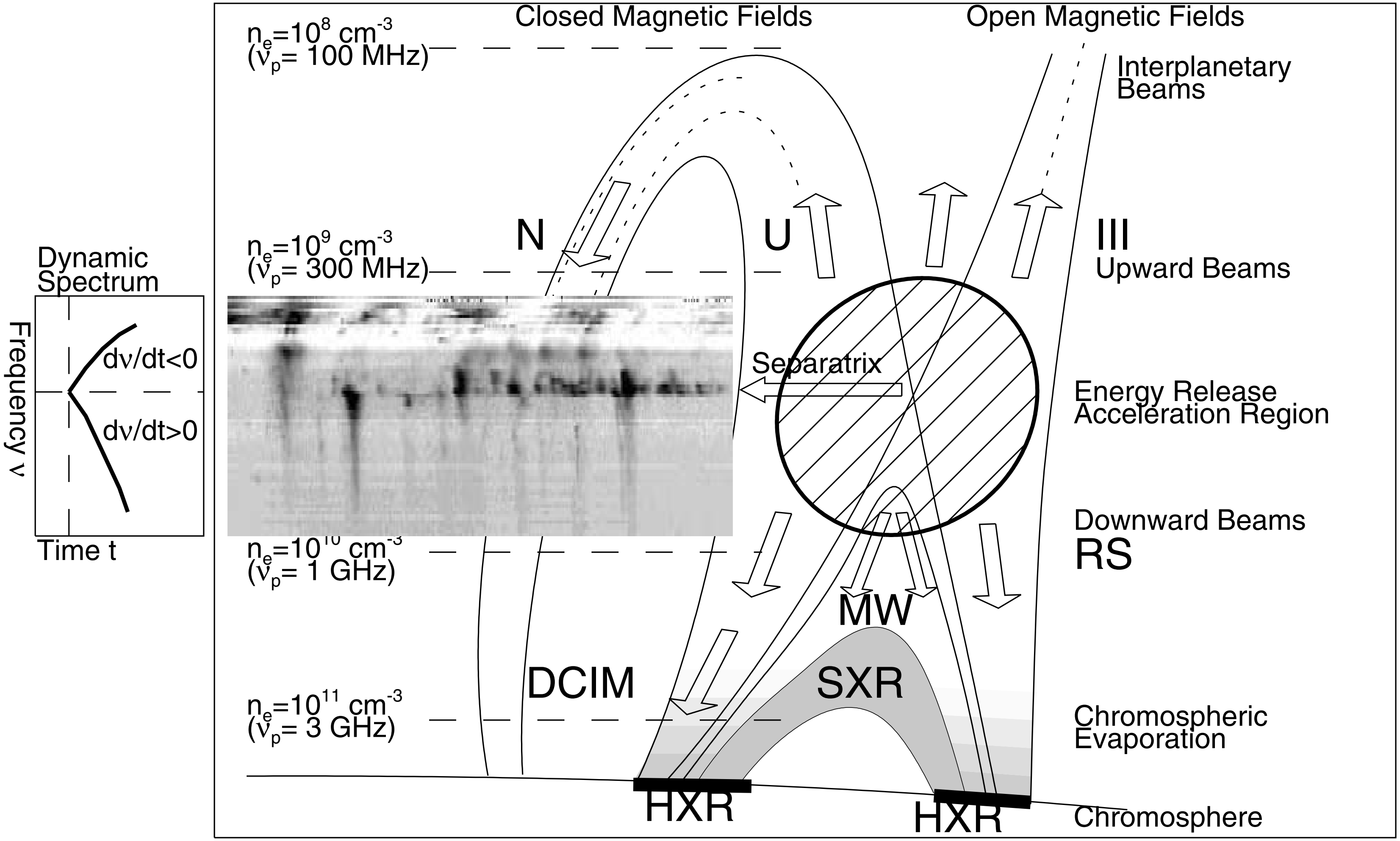

HXR spectral index

HXR flux

- **This termination shock contributes to the acceleration of 10s of keV electrons**

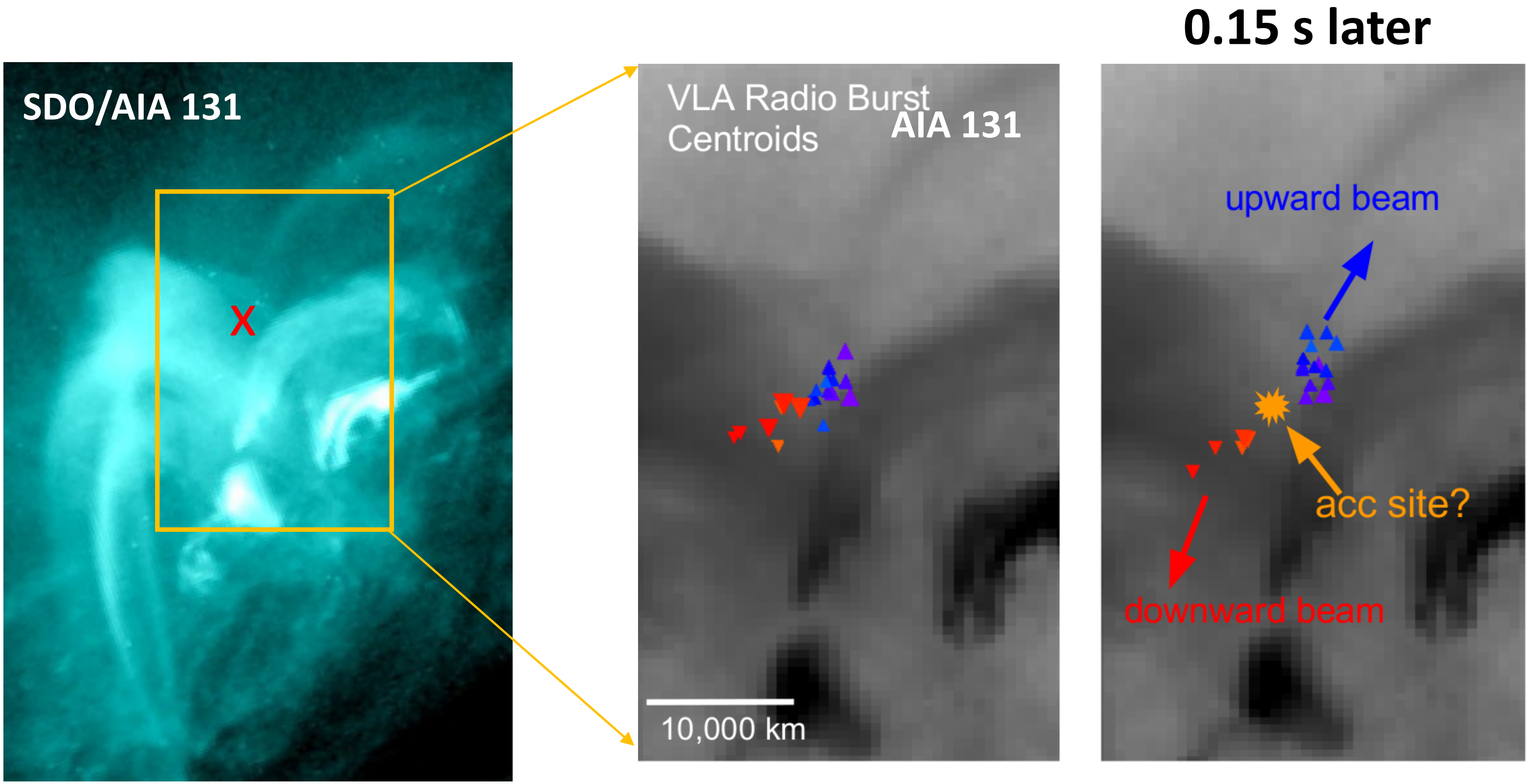
Chen et al. 2015

Decimetric type III bursts: electron beams near the flaring site



From Aschwanden's book

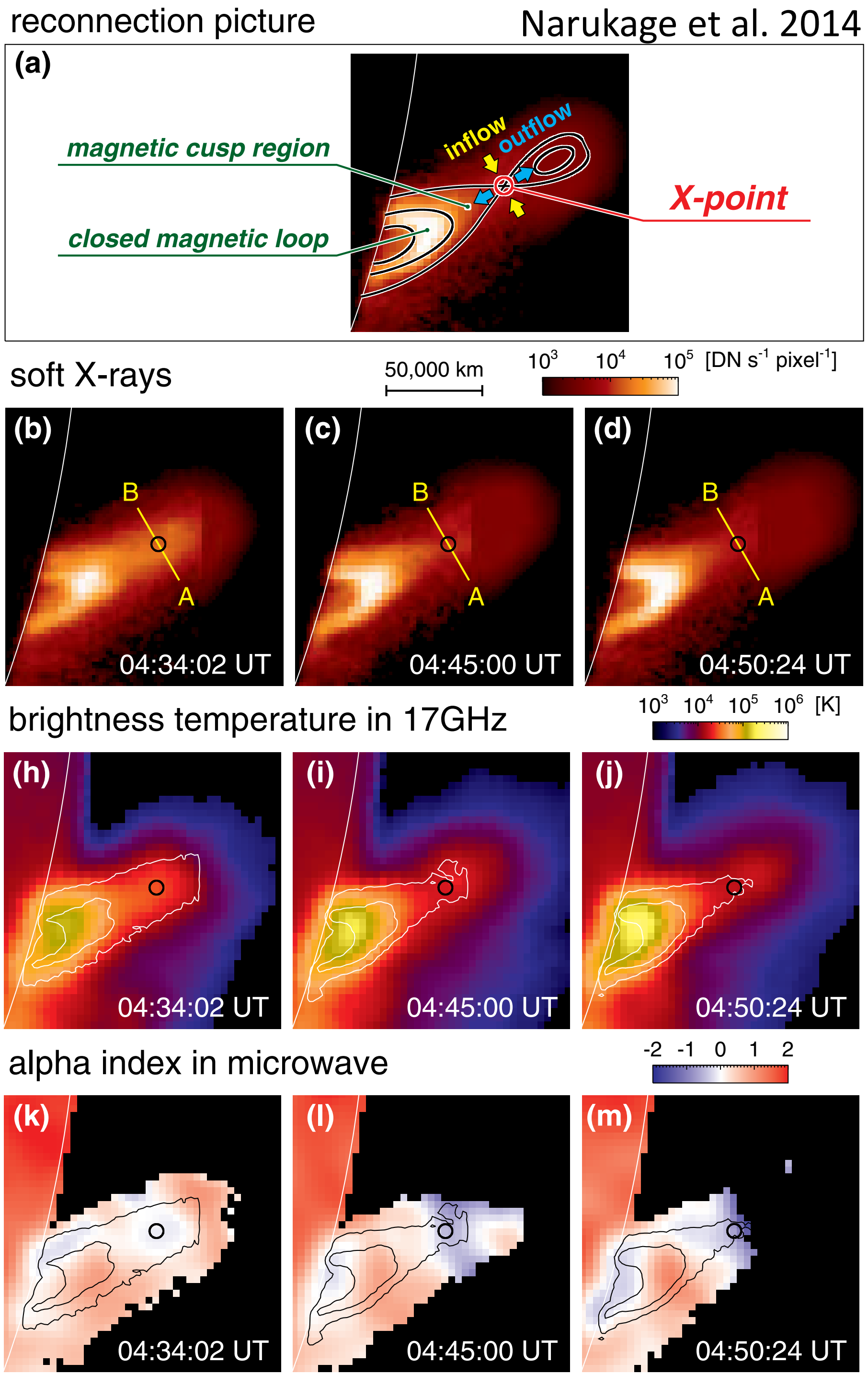
A possible detection with imaging data



Chen et al in prep

Gyrosynchrotron radio emission

- Accelerated electrons also produce (incoherent) gyrosynchrotron emission
- At microwave frequencies (few to x10 GHz), GS emission is mainly from the flare loops (c.f., Lecture 21)
- Sometimes GS emission is seen *above* the flare loops



Summary

- More radiative processes: Inverse Compton and coherent radiation
- **Where?** → Particles are probably accelerated in the **corona**, but exact location unknown
  - ALT HXR sources, type III bursts, GS sources
  - But, ALT HXR sources are rare – only a handful of events observed in >15 years of RHESSI + Yohkoh/HXT → Direct focusing optics and more sensitive X-ray observations would help
  - Radio dynamic spectroscopic imaging is another powerful tool
  - **(Very) active field of research**
- What do the observed spatial, spectral, and temporal properties of the HXR and radio sources imply for the acceleration and/or transport mechanisms?

→ Open question. Topic of next lecture