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Observations and simulations of energised electrons in the flaring corona to chromosphere

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Introduction & Motivation

- **RHESSI's HXR observations have challenged the standard interpretation of flare energy release/transport**
  – But how do we progress?

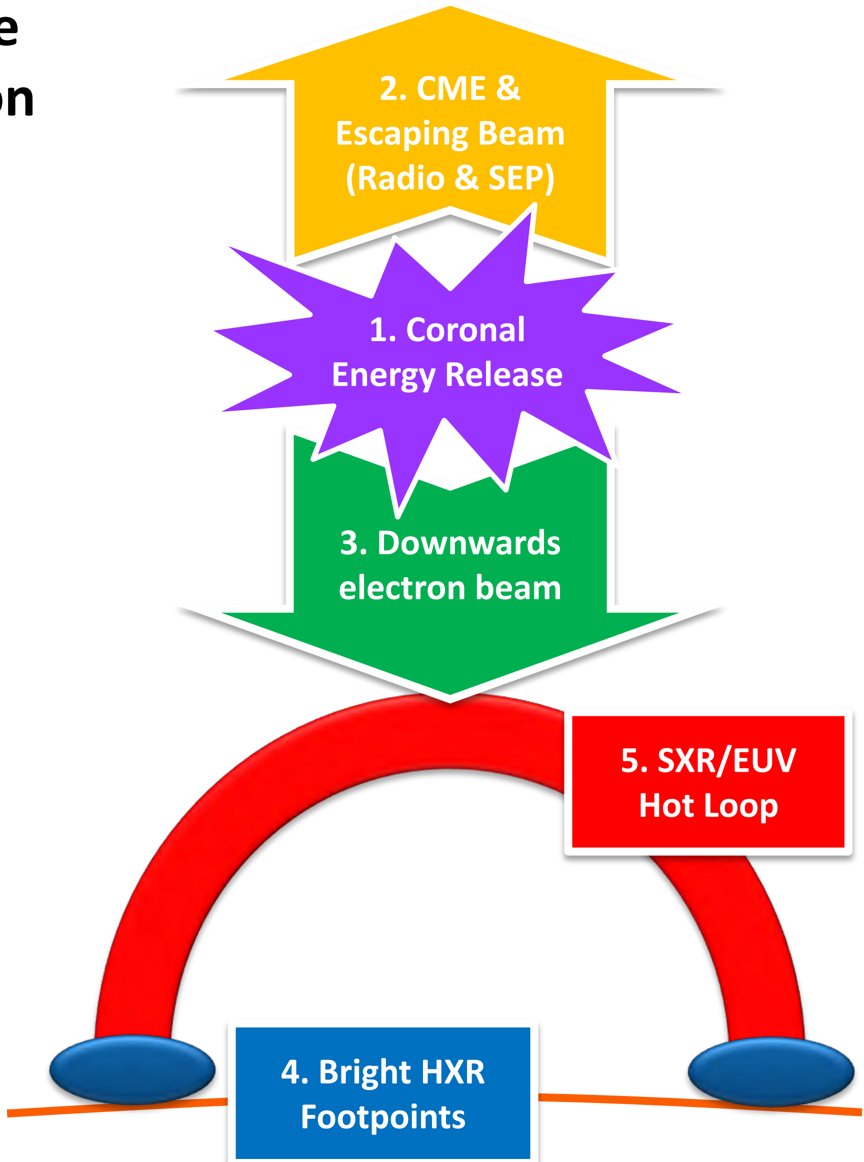
- **Presented here are two complimentary approaches**

1. **Get as much information as possible from the RHESSI observations**
   – e.g. Interrogate the structure of bright HXR chromospheric footpoint sources using visibility forward fitting
2. **Take steps towards a more complete description of electron transport in flares**
   – e.g. Simulations in which we consider non-collisional processes (wave-particle) interactions as well as the spatial evolution

..... of course additional radio information would be very useful too.

“Typical” Flare X-ray Scenario*

1. **Starts with a coronal energy release facilitated by magnetic reconnection**
2. **Outwards CME and electron beam**
   - Latter via Radio Type III or in-situ
3. **Downwards beam of accelerated electrons**
   - X-ray “thin-target” emission, very faint
   - Also get microwaves
4. **Electron beam stopped in Chromosphere**
   - Bright X-ray “thick-target” footpoints
   - Stopped beam heats local plasma
5. **Hot material expands into coronal loops**
   - Initially observe this at hottest temperatures in SXR (>10 MK) then cools and seen in EUV

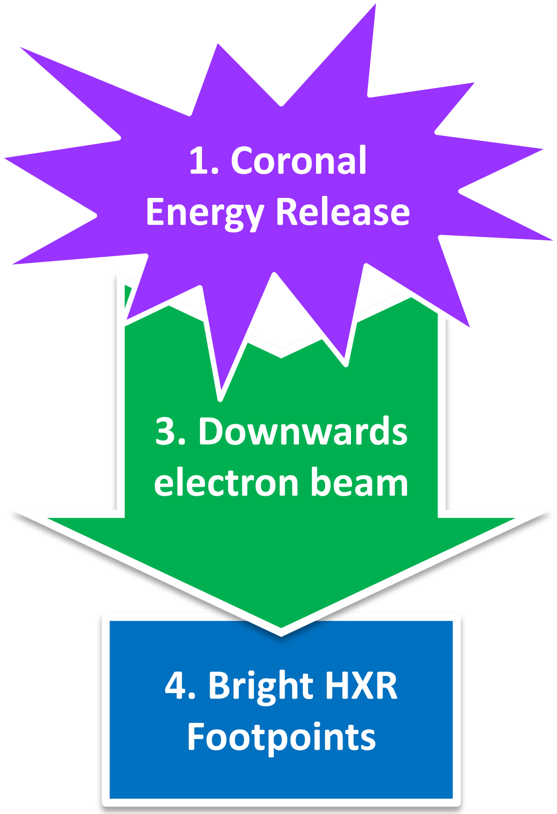


What does the HXRs tell us?

- **We want to learn about the processes of**
  - The **coronal energy release**
  - The **transport (propagation/energy change)** from corona to chomosphere
- **With RHESSI we (mostly) observe the HXR emission I(ε) of the bright footpoints**

$$I(\epsilon) \propto \int_{\epsilon}^{\infty} \int_{V} n(r) F(E,r) Q(\epsilon, E) dE d^3 r$$

- **Which will give us info about**
  - **n(r)** local (chromospheric) plasma density
  - **F(E,r)** local electron distribution
    - Or Initial accelerated coronal distribution that has undergone transport effects



Standard Model Predictions

- **1D model with simple decreasing density profile and only Coulomb collisions as transport**
  - Thick target model, Brown '71

- **Then can analytically find (Brown 2002) that as energy increases**
  - Height of source location decreases
  - Vertical extent of source will decrease

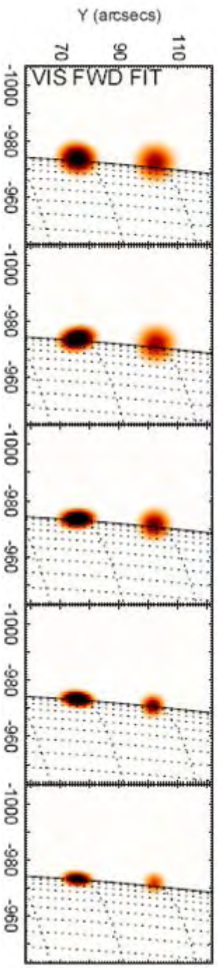
$$F(E,z) = F_{IN} E \left[\sqrt{(E^2 + 2KN(z))} \right]^{-\delta-1}$$

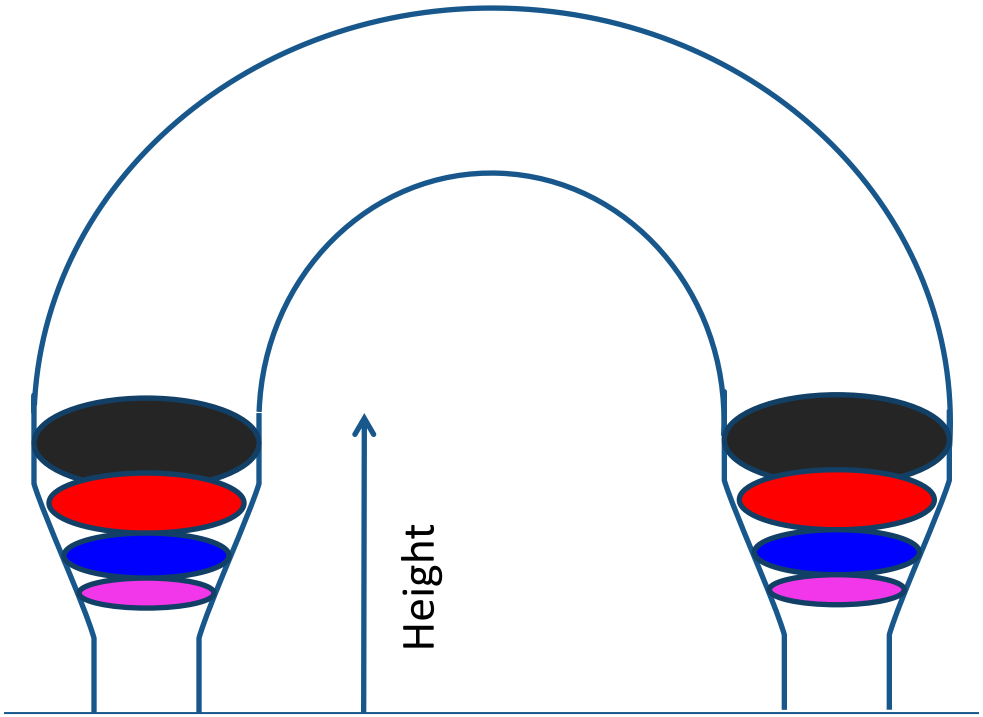
$$I(\epsilon, s) = \frac{1}{4\pi R^2} An(s) \int_{\epsilon}^{\infty} F(E,s)\sigma(E,\epsilon) dE$$

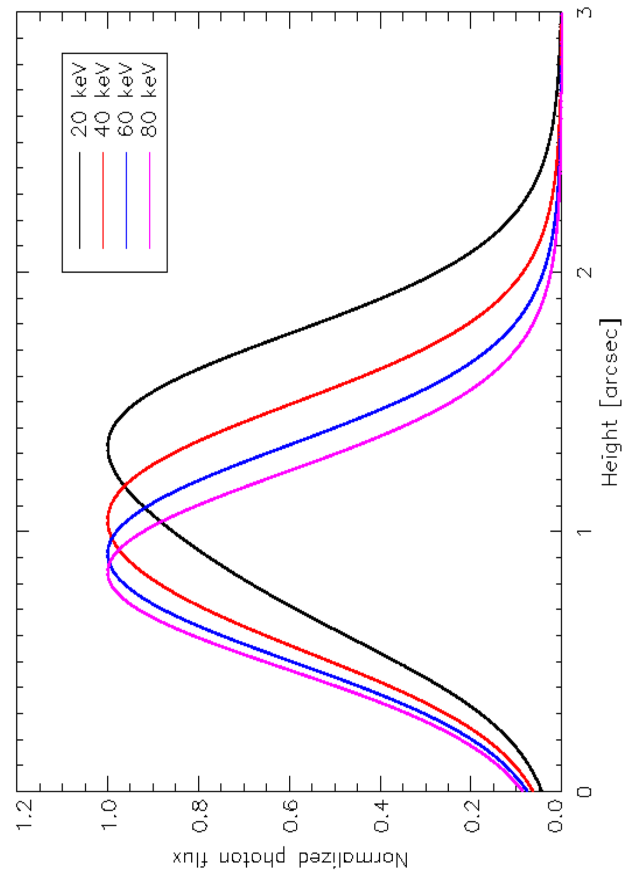
$$N(z) = \int_0^z n(z) dz \qquad K = 2\pi e^4 \ln \Lambda$$

  - Also width of source will decrease with energy
    - conservation of magnetic flux

Easier to see as Cartoon





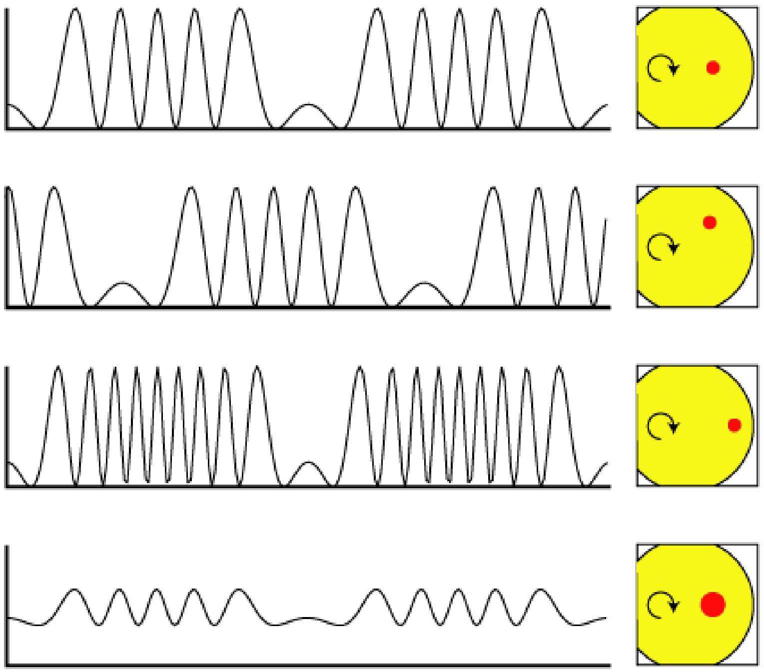


Battaglia

- **So want to very accurately (<1”) measure the location and shape of the source as function of energy**

RHESSI Spatial Information

- **RHESSI's 9 Rotation Modulation Collimators (RMCs) time encode the spatial information about the source in the detected counts**
- **Several imaging algorithms to convert this back into pictures**
- **Could measure shapes in images but subject to reconstruction errors**
- **So moments of X-ray distribution can be more accurately determined directly from time profile**
  - Forward Fit source models (Gaussian etc) to time profile
- **A faster, more robust method is to do this fitting on the *visibilities* not time profile**



Hurford

RHESSI Visibilities

- **For a given RMC, energy and time range the RHESSI spatial info can be as two dimensional Fourier components or X-ray visibility**

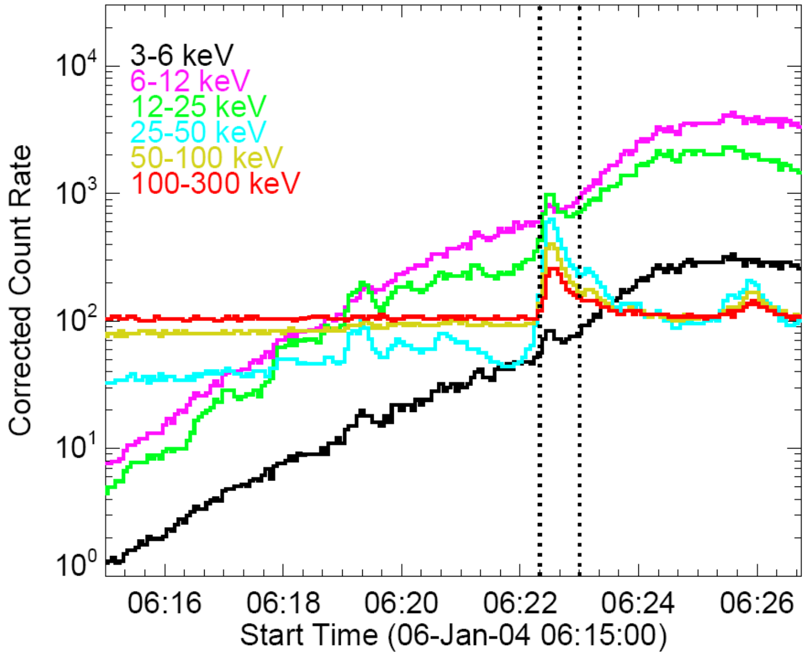
$$V(u,v;\epsilon) = \int_x \int_y I(x,y;\epsilon) e^{2\pi i(xu+yv)} dxdy = Ae^{i\phi}$$

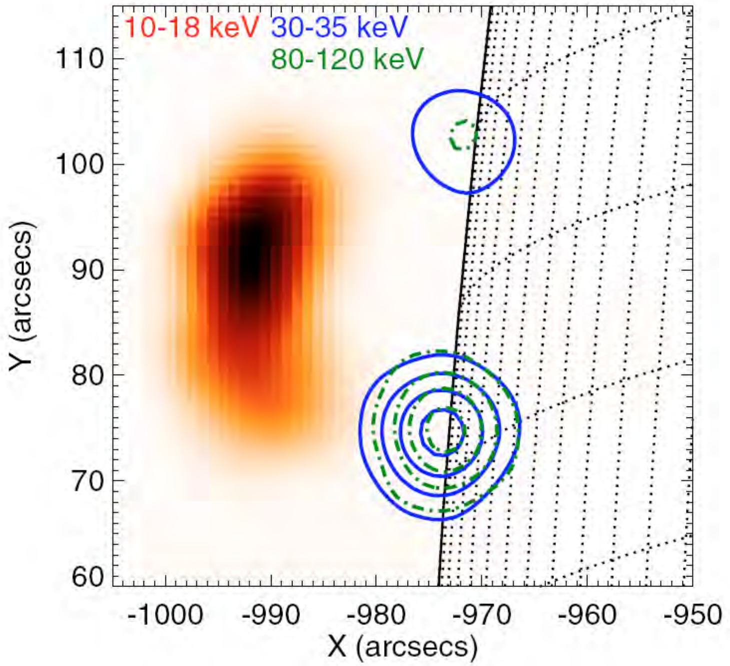
- **Practically, done by stacking the time profile as a function of roll angle and aspect phase.**
  - For each roll bin a sinusoidal fit gives the amplitude and phase of the visibility

- **So data is now is a small "bag" of visibilities over the RMCs for the time and energy range**
  - Easy to handle errors
  - Quick to forward fit shapes to
  - And can reconstruct actual images

Limb Flare: 06-Jan-2004 06:15 (M6)

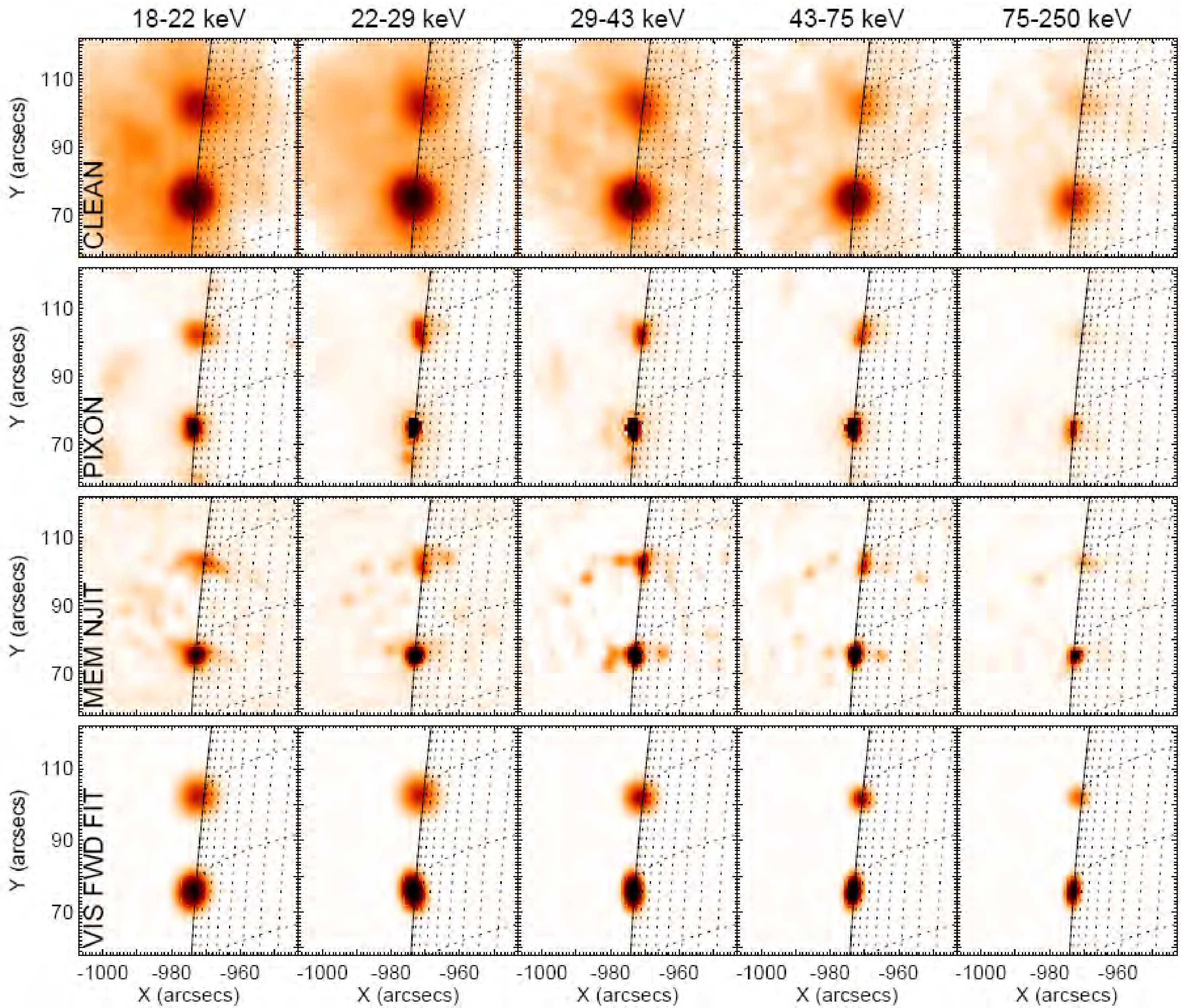
- **Nice limb flare example**
- **Side on view gives cross-sectional info about loop and footpoints**
  - Northern source might be occulted >120keV
  - Southern is not occulted





Kontar, Hannah, Mackinnon A&A 489 2008
Kontar, Hannah, Jeffery, Battaglia, ApJ 2010

Imaged with various methods



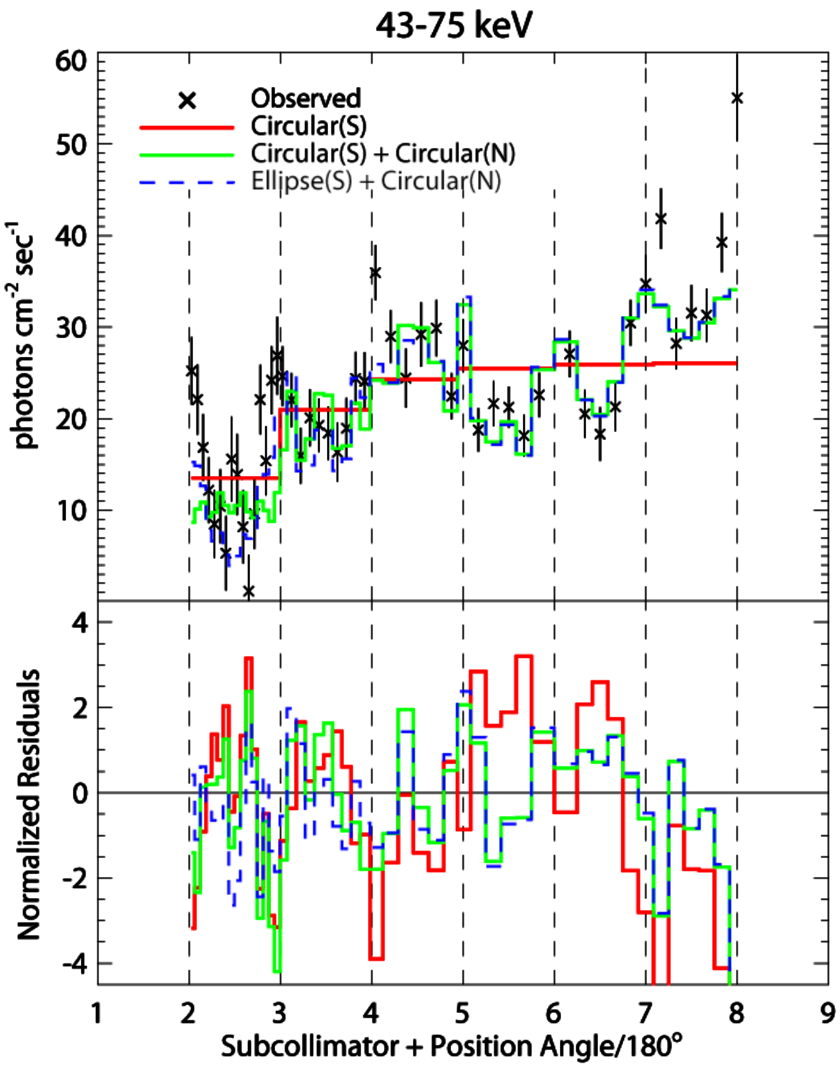
Circular (N)
Elliptical (S)

RHESSI Visibility Forward Fitting

- **Images showed fitted circular Gaussian (N) and elliptical Gaussian (S)**

$$I(x,y;\epsilon) = \frac{I_0(\epsilon)}{2\pi\sigma_x\sigma_y}\exp\left(-\frac{(x-x_0(\epsilon))^2}{2\sigma_x^2} - \frac{(y-y_0(\epsilon))^2}{2\sigma_y^2}\right),$$

- **Can do single circular or 2 circular sources but fit not as good**
- **Northern footpoint not bright enough for an elliptical fit**
- **So best is circular (N) + elliptical (S)**
  - get interested in Southern bright footpoint and can fit many

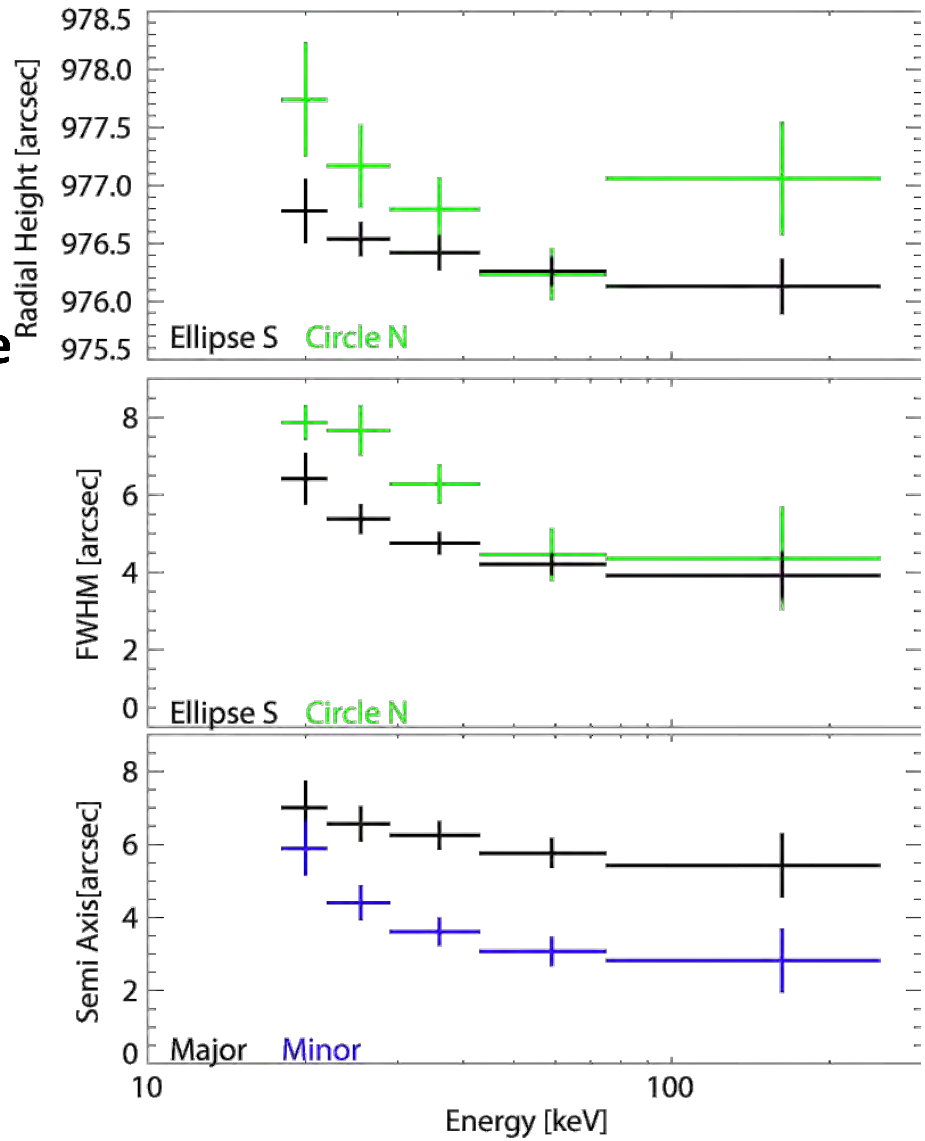


Forward Fitted Parameters

- **The source maximum does decrease in height as energy increases**

- **FWHM of sources also decrease with energy**

- **Southern footpoint both axes decrease with energy**
  - semi-major (width, parallel to limb)
  - semi-minor (vertical extent, perpendicular to limb)



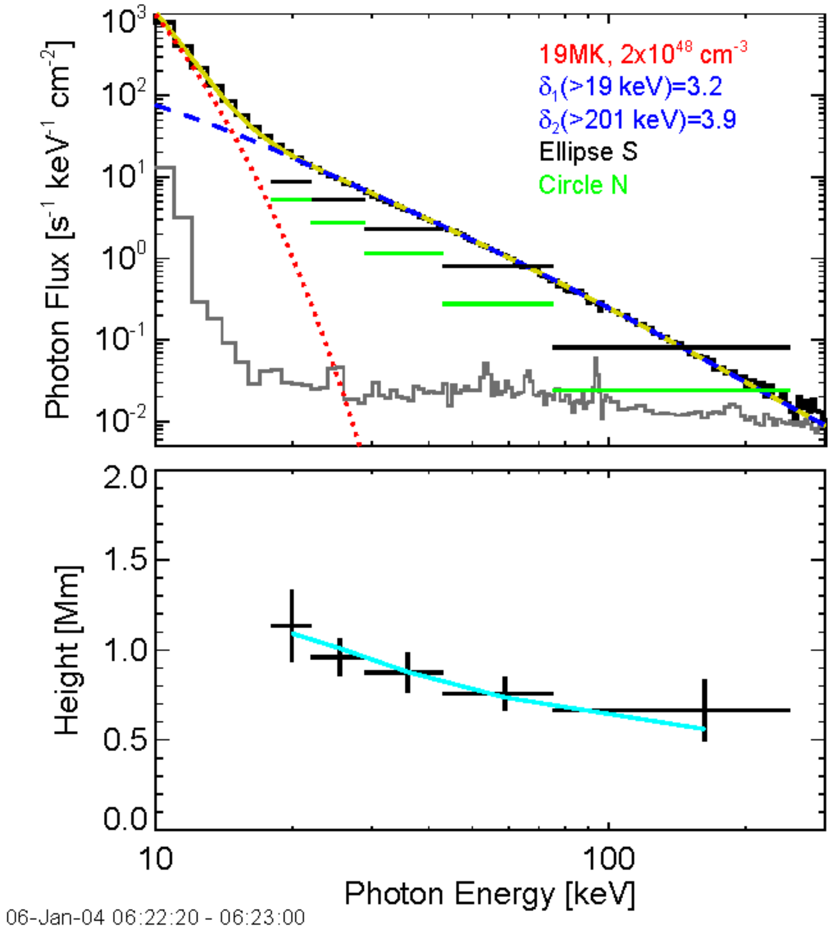
Southern footpoint **WIDTH** **VERTICAL EXTENT**

Fit Density Profile

- **From position of maximum emission can infer parameters of background plasma density model**
  - Ashwanden 2002 did this using a power-law
  - Kontar et al 2008 and 2010 using an

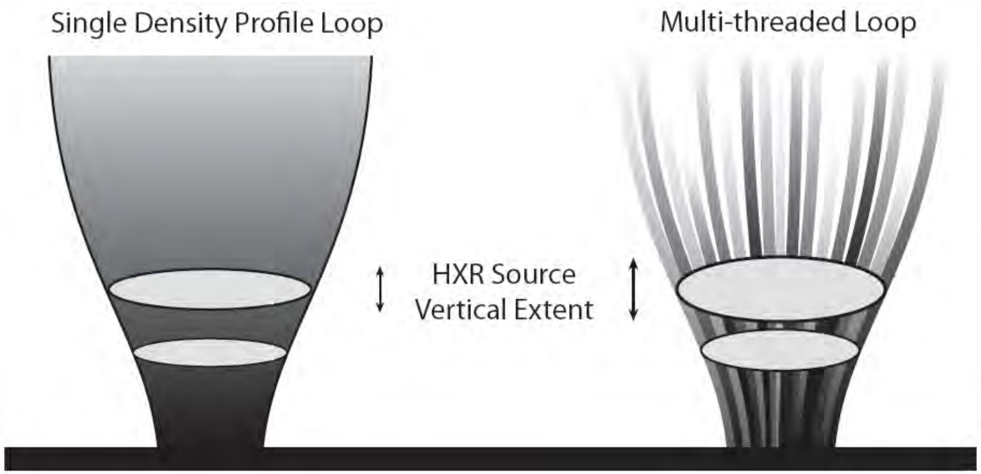
$$n(h = r - r_0) = n_0 \exp\left[\frac{-(r - r_0)}{h_0}\right]$$

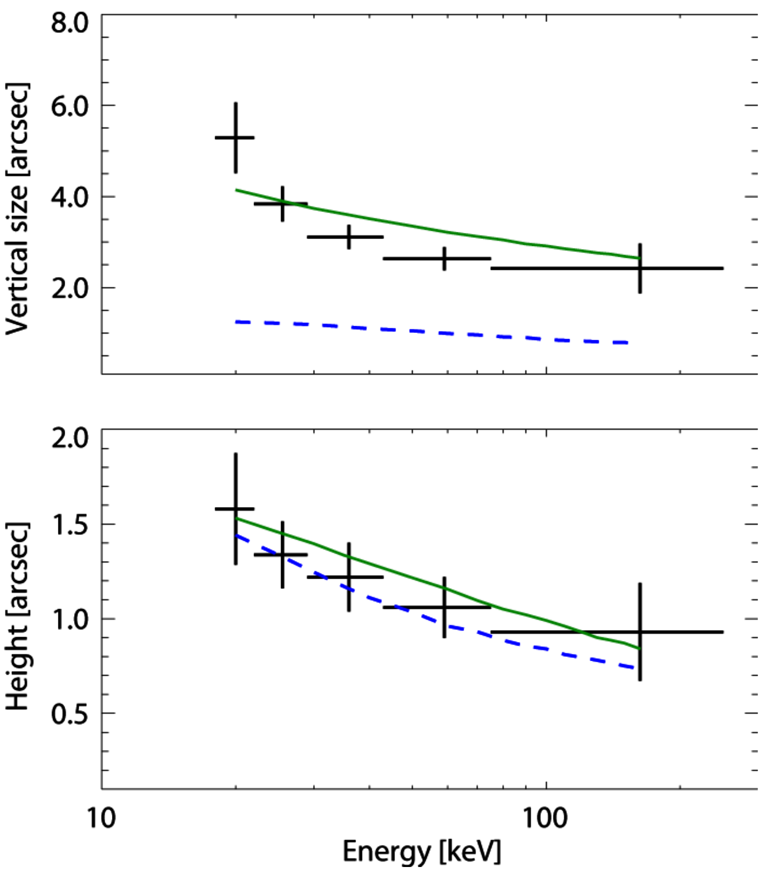
  - r_0: radial distance of bottom of loop, h_0 density scale height, n_0 number density at height h=0 (from models, $n_0 = 1.16\times10^{17}$ cm^{-3}
  - Best fit gives scale height of 150km



But.... Problems with Vertical Extent

- **The vertical extent of the footpoint is also predicted by the thick-target model and with this density profile**
  - But doesn't work
- **Possible solution: consider multiple threads of different scale heights**
  - 50 km to 500 km





Better but still not perfect.... Non-collisional effects?

Observations vs. Theory

- **So this one example shows how the standard assumption not consistent with the data**
  - Not a single simple background density profile and/or
  - Not just Coulomb collisions

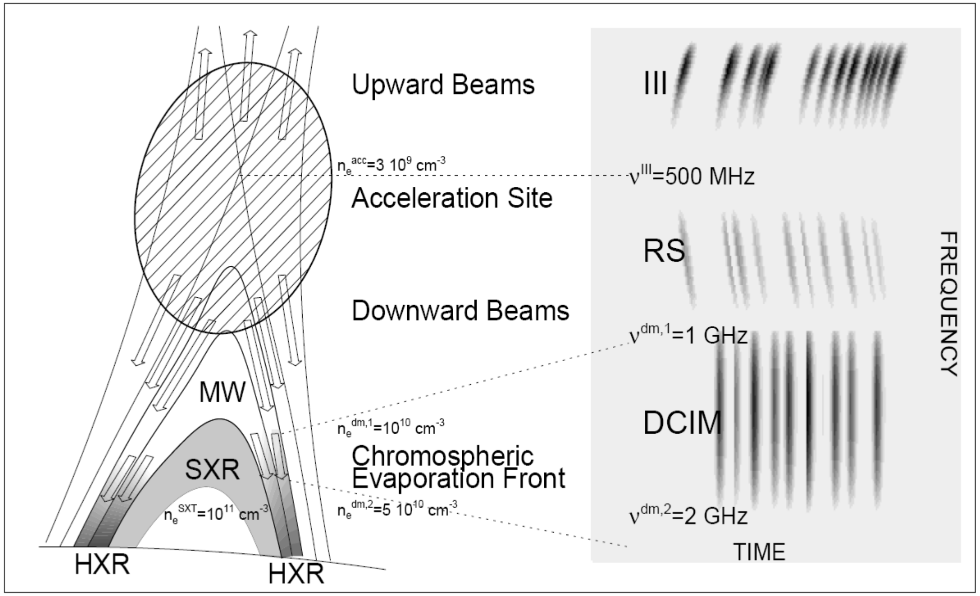
- **But many other observational features insufficiently described by the standard approaches**
  - Number of electrons that need to be accelerated to produce thick-target emission
  - Difference between the HXR spectral index of a coronal and footpoint source

- **So now we simulate the propagation of an electron beam in not only subject to Coulomb collisions but non-collisional**
  - Wave-particle interactions, like Hamish's work but downwards beam

Wave-particle interactions

- **We are going to consider the background plasma response in form of electron-beam driven Langmuir waves**
  - In addition to Coulomb collisions
- **This is a non-collisional process occurring faster than collisions**
  - So may have an important effect
    - Zheleznyakov & Zaitsev 1970
- **Also get downward radio bursts so know that Langmuir waves are present**
  - Reverse Slope (RS)
  - e.g. Klein et al 1997, Aschwanden & Benz 1997
  - etc

Aschwanden & Benz 1997



Quasi-linear Relaxation

- **Been studied for the case of flares in 1D ($k_{||}$) but found little effect**
  - Analytical steady-state and spatially independent solutions
    - Emslie & Smith 1984, Hamilton & Petrosian 1987, McClements 1987
  - We however consider time and spatial evolution ($v_{||}$,x,t)

- **Has been studied by many authors in general**
  - Self-consistent 1D equations of quasi-linear relaxation i.e.
    - Vedenov & Velikhov 1963, Drummond & Pines 1964, Ryutov 1969, Emslie & Smith 1984, Hamilton & Petrosian 1987, McClements 1987, Kontar 2001
  - Also in 2D ($k_\perp$, $k_{||}$)
    - e.g. Churaev & Agapov 1980
    - Although only recently has the 2D system been fully numerically solved (Ziebell et al. 2008)
    - Again these ignore the spatial and temporal evolution

1D Quasi-linear Relaxation

- We are numerically solving

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} = \frac{4\pi^2 e^2}{m^2}\frac{\partial}{\partial v}\left(\frac{W}{v}\frac{\partial f}{\partial v}\right) + \gamma_{\mathrm{C_f}}\frac{\partial}{\partial v}\left(\frac{f}{v^2}\right)$$

$$\frac{\partial W}{\partial t} + \frac{3v_{\mathrm{T}}^2}{v}\frac{\partial W}{\partial x} + \frac{v^2}{L}\frac{\partial W}{\partial v} = \left(\frac{\pi\omega_{\mathrm{p}}}{n}v^2\frac{\partial f}{\partial v} - \gamma_{\mathrm{C_W}} - 2\gamma_{\mathrm{L}}\right)W + Sf$$

- Electron distribution $f(v,x,t)$, Wave spectral energy density $W(v,x,t)$
- Describes the resonant interaction of e⁻ & Langmuir waves $\omega = kv$

$$L^{-1} = \omega_p/(\partial\omega_p/\partial v)$$

- Coulomb collisions for e⁻ and waves $\gamma_{C_f}, \gamma_{C_W}$ Landau dampening γ_L
- Spontaneous emission of waves Sf
- Weak turbulence regime => energy density of Langmuir waves generated << background plasma

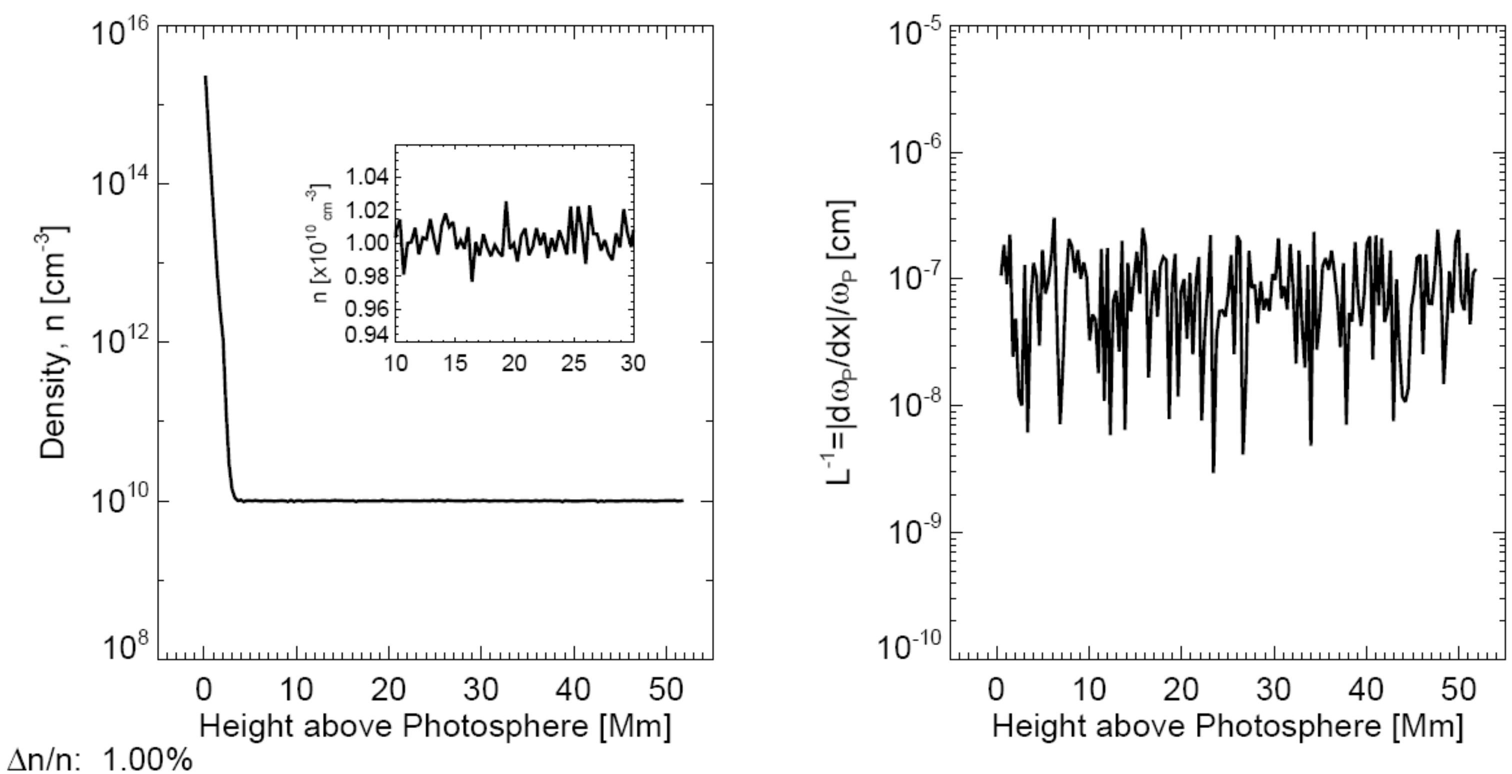
$$\int W dk/(nk_B T) << (k\lambda_D)^2$$

- 1D in velocity so assuming $v \approx v_{||} > v_{\perp}$

Inhomogeneous Background Plasma

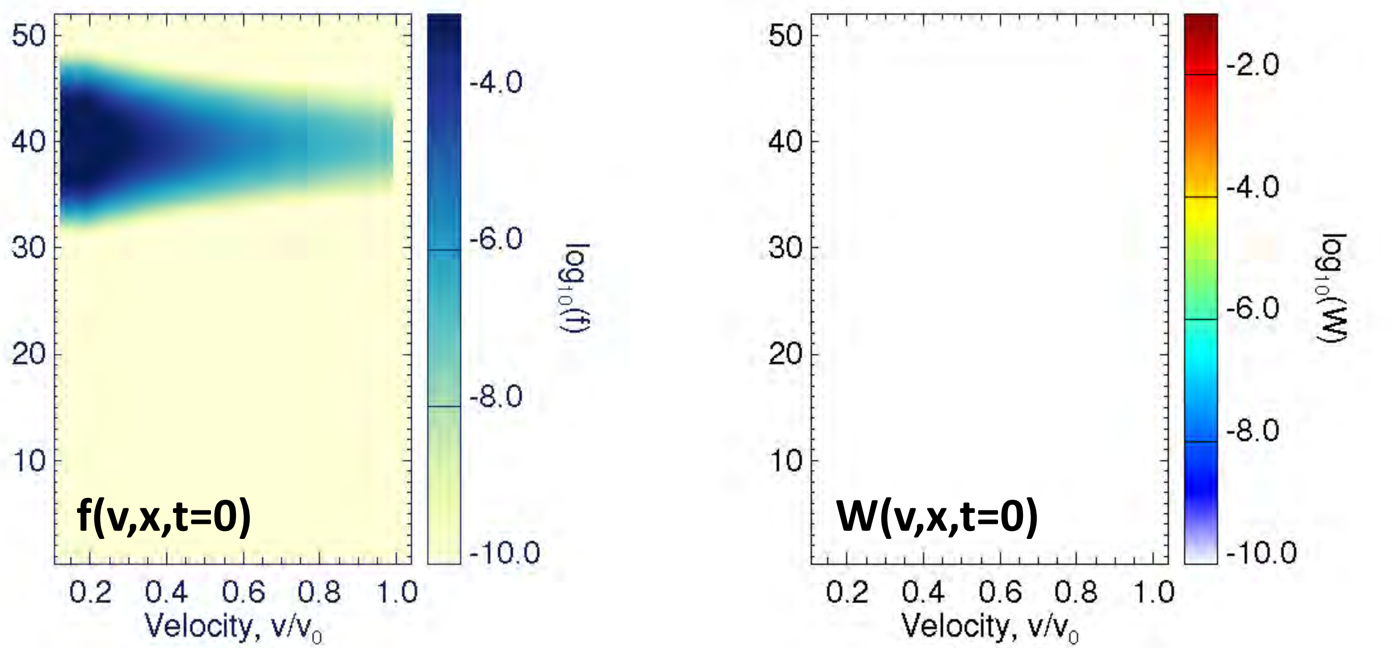
- **Inhomogeneous background plasma n(x) + turbulent perturbation**
  - 1000 perturbations randomly drawn from a β=5/3 Kolmogorov-type power density spectrum with $\Delta n/n \approx 1\%$ and wavelengths $10^{3.5} < \lambda < 10^6$ cm

$$n(x) = n_0(x)\left[1 + C\sum_{n=1}^{N} {\lambda_n}^{\beta/2} \sin\left(2\pi x/\lambda_n + \phi_n\right)\right]$$



Initial Distribution

- **Instantaneous injection of power law of -α above cut-off in velocity**
- **Gaussian in x-space** $$f(v,x,t=0) \propto n_{\mathrm{B}} v^{-\alpha} \exp\left(-\frac{x^2}{d^2}\right) \quad \text{if } v \geq v_{\mathrm{C}}$$
- **Take thermal background of waves, so W(t=0)≈0**



E_C=15 keV, $n_B=10^8 cm^{-3}$, α=8, => δ=4, d=2x10^8 cm, T=1MK

$v_0=2.6\times10^{10}$ cms^{-1}, $v_{min}=7v_T=2.7\times10^9$ cms^{-1}

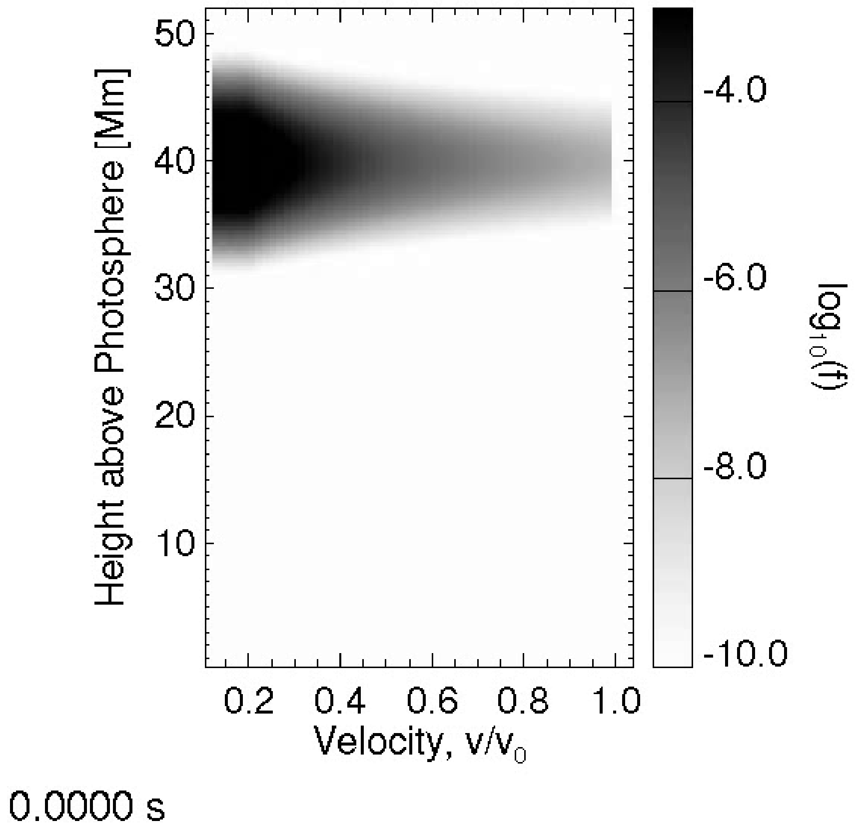
Coulomb Collisions Only

- **Similar to thick-target approximation but adds time and spatial dependence**

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} = \gamma_{C_f}\frac{\partial}{\partial v}\left(\frac{f}{v^2}\right)$$

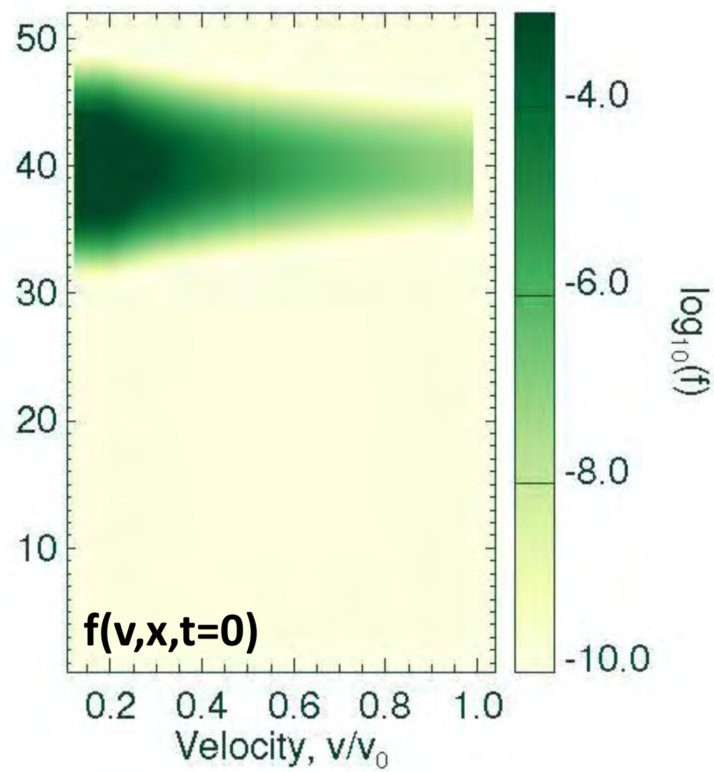
- **Fastest electrons move down to chromosphere first.**

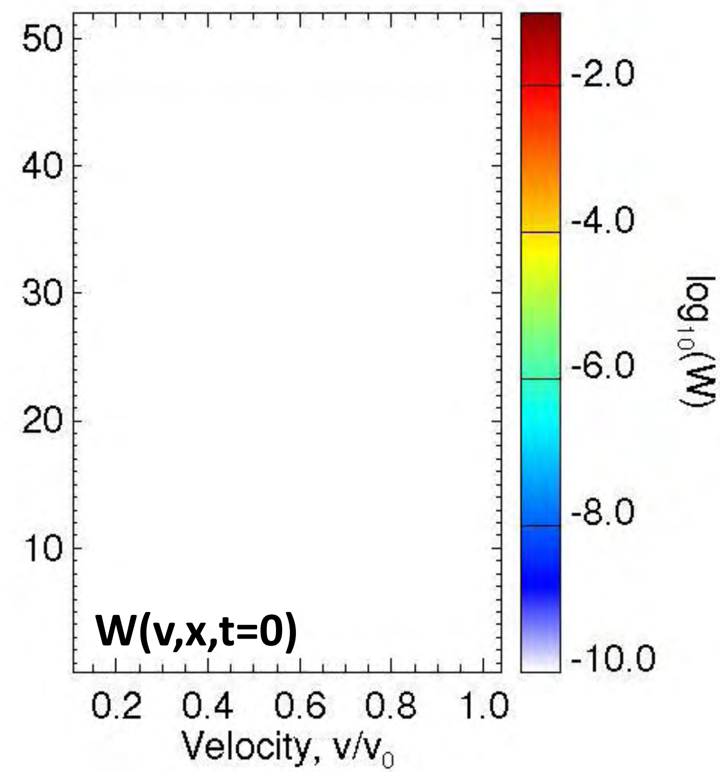
- **All electrons lose energy to heat background plasma via collisions leaving grid to the left**
  – Left edge is $7v_T$



Electron Beam and Waves

- **Addition of wave-particle interactions although no $\partial W/\partial v$ term**
  - $\Delta n(x) \neq 0$ but no wave refraction





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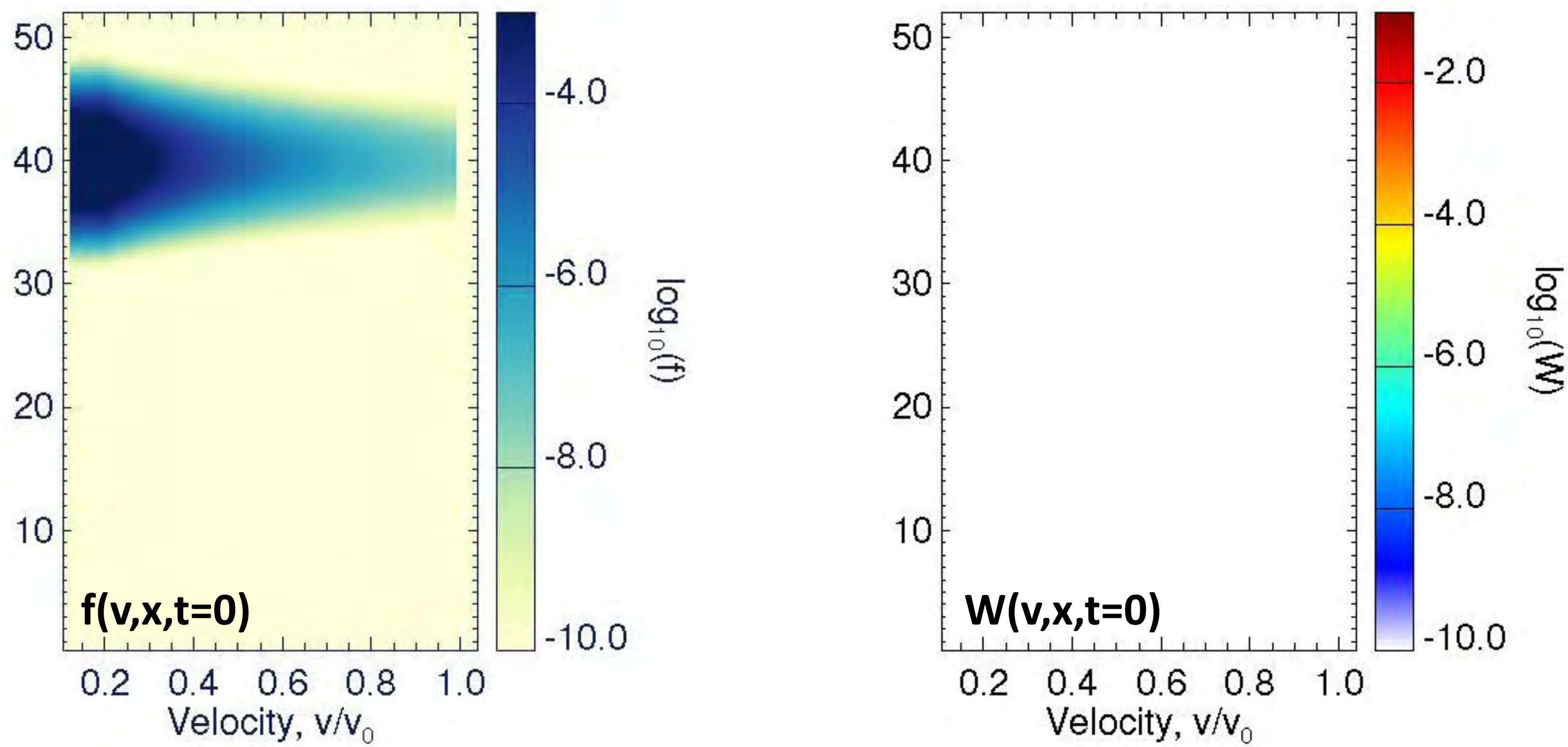
$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} = \frac{4\pi^2 e^2}{m^2}\frac{\partial}{\partial v}\left(\frac{W}{v}\frac{\partial f}{\partial v}\right) + \gamma_{C_f}\frac{\partial}{\partial v}\left(\frac{f}{v^2}\right)$$

$$\frac{\partial W}{\partial t} + \frac{3v_T^2}{v}\frac{\partial W}{\partial x} + \ldots = \left(\frac{\pi\omega_P}{n}v^2\frac{\partial f}{\partial v} - \gamma_{C_W} - 2\gamma_L\right)W + Sf$$

Beam, Waves and ∂W/∂v

- **All terms, including wave refraction**



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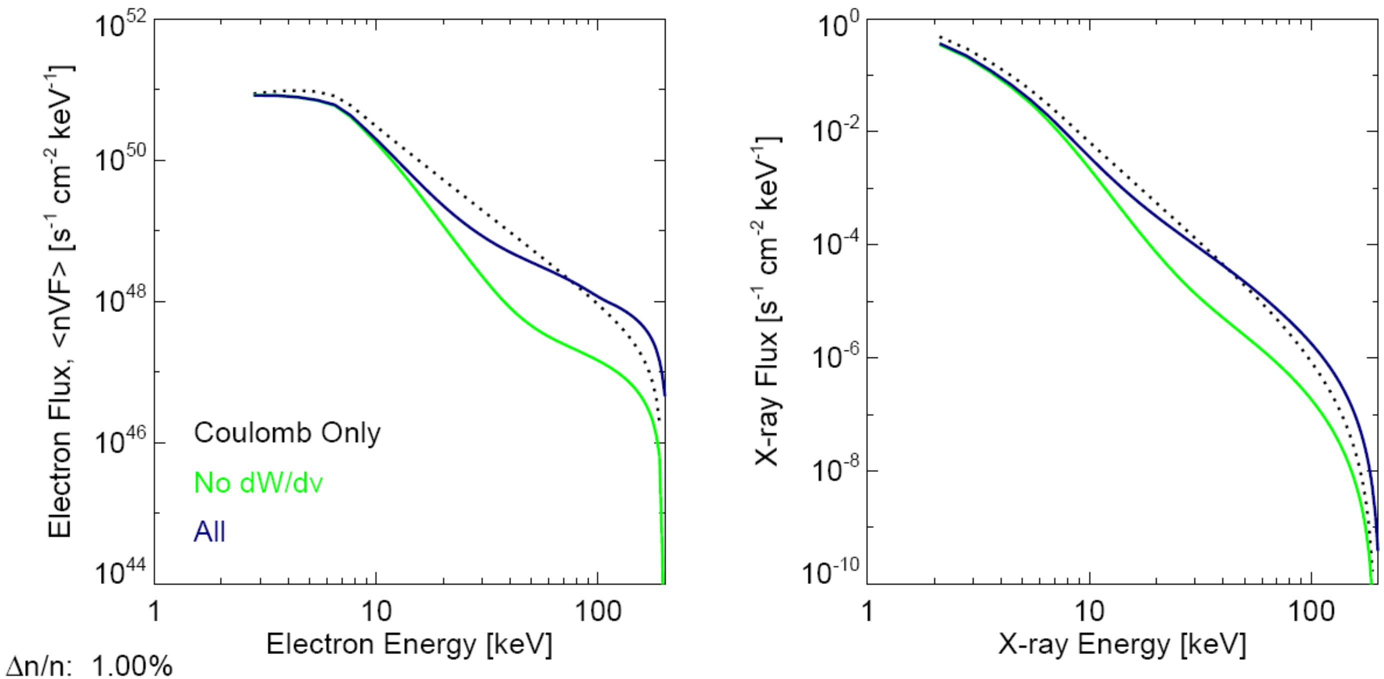
Electron and X-ray Spectra

- **Spatially integrated and temporally averaged spectra**
  - Need to estimate beam cross-sectional area A to get volume from 1D

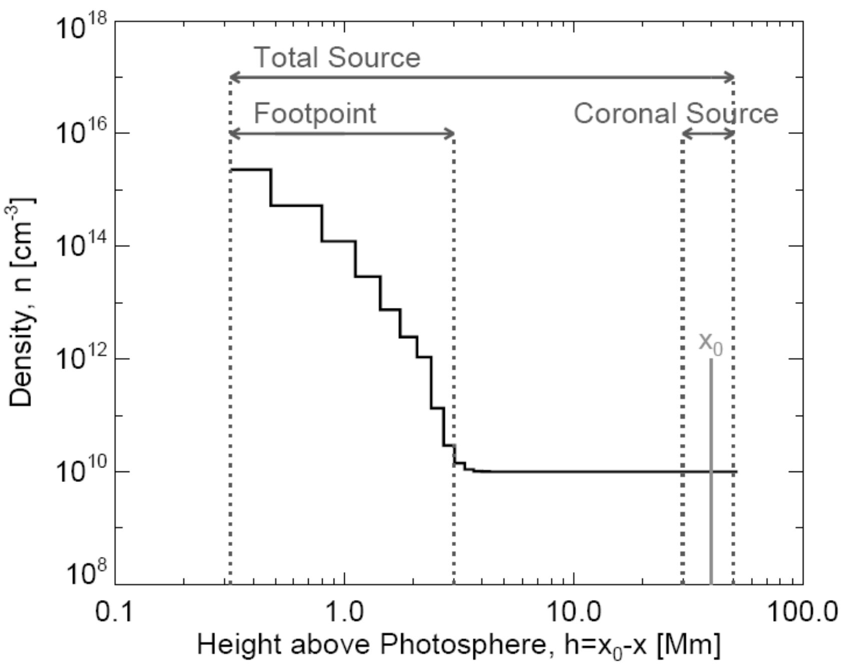
$$I(\epsilon, t) = \frac{A}{4\pi R^2} \sum \left[n(x) \frac{f(v,x,t)}{m_e} Q(\epsilon, E) \right] dEdx$$

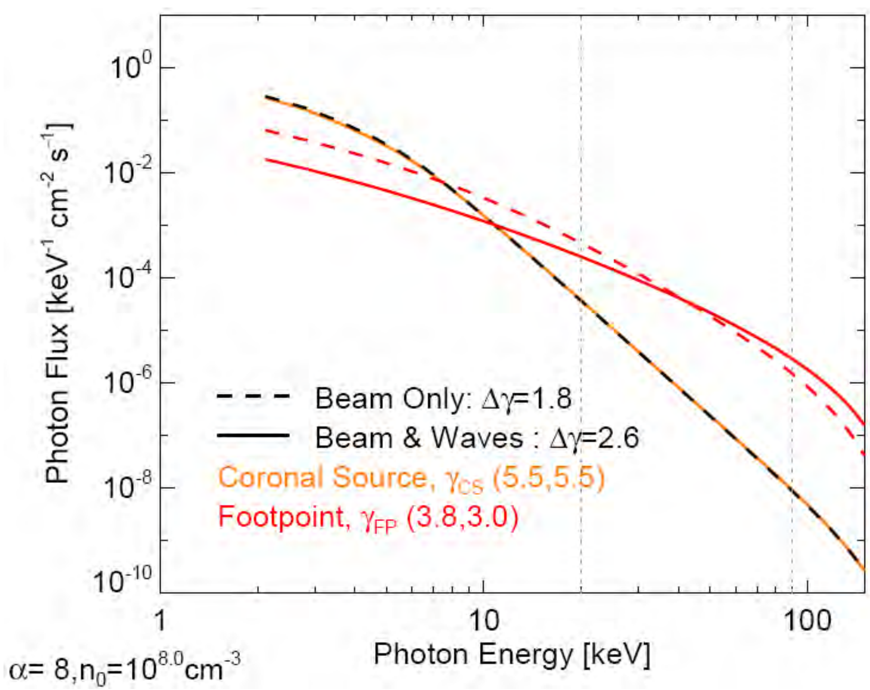


- **Flatter spectrum with Waves**
- **More X-ray emission when including wave refraction**

Corona vs. Chromosphere

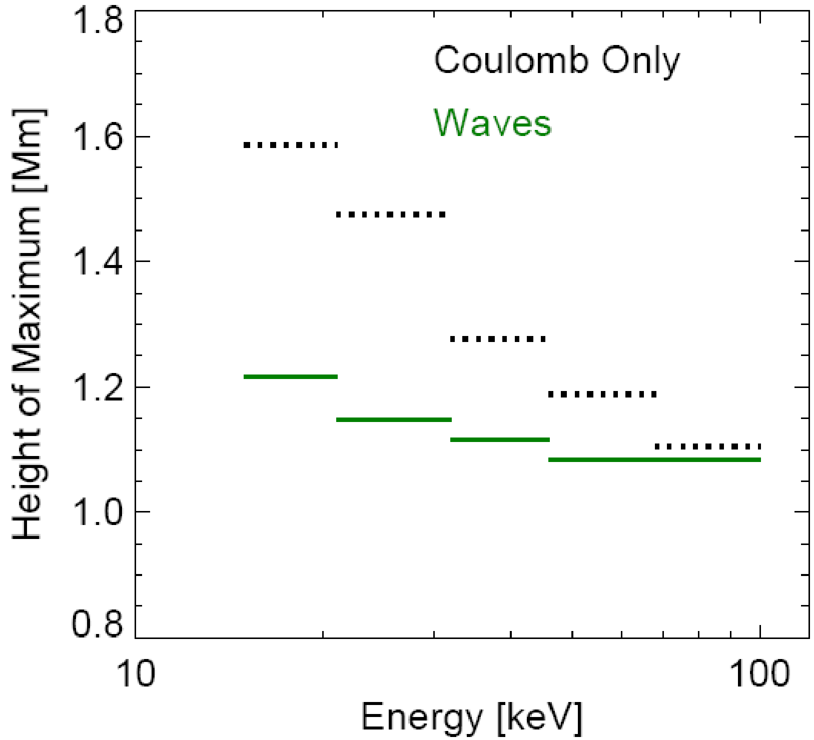
- **Can calculate the X-ray spectrum for the coronal and footpoint region of simulation**
  - Observations have found difference in spectral index greater than what is expected from collisional transport.
- **The non-collisional processes flatten footpoint spectrum, so $\Delta\gamma>2$**

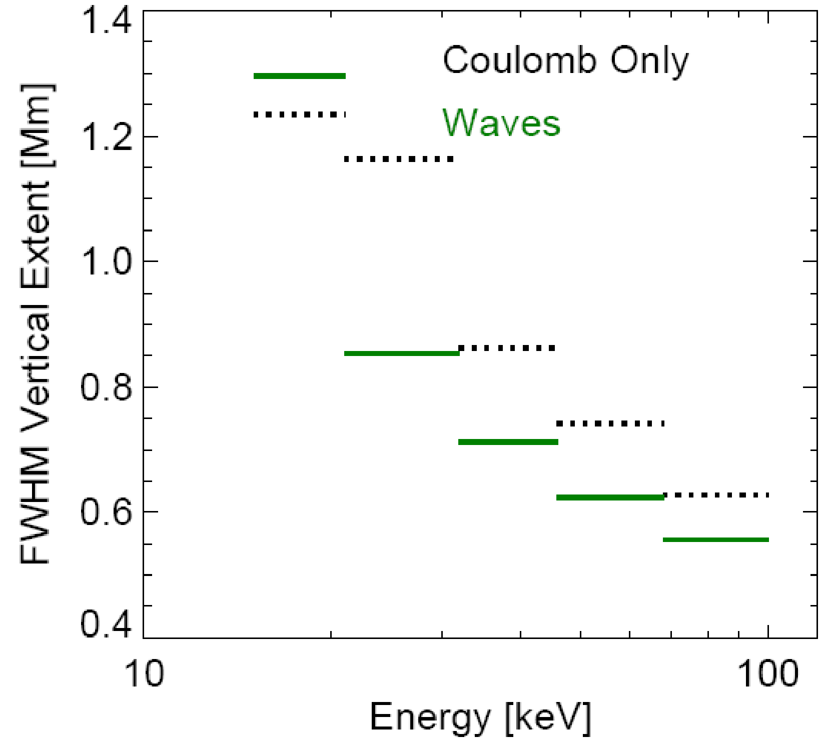




Structure of Chromospheric Footpoints

- **The addition of non-collisional processes does change the structure of the chromospheric footpoints but not doing what we want....**





- **So still work in progress**

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Conclusions & Future Work

- RHESSI's HXR imaging spectroscopy techniques allow unprecedented interrogation of chromospheric footpoints sources in flares
- RHESSI continues to show the inadequacies of the previous models
- Inclusion of non-collisional effects does have an effect on the HXR spectra, producing flatter emission but more work is needed
- Really need to include radio emission from the Langmuir waves giving an additional constraint (radio & x-rays) for the simulations