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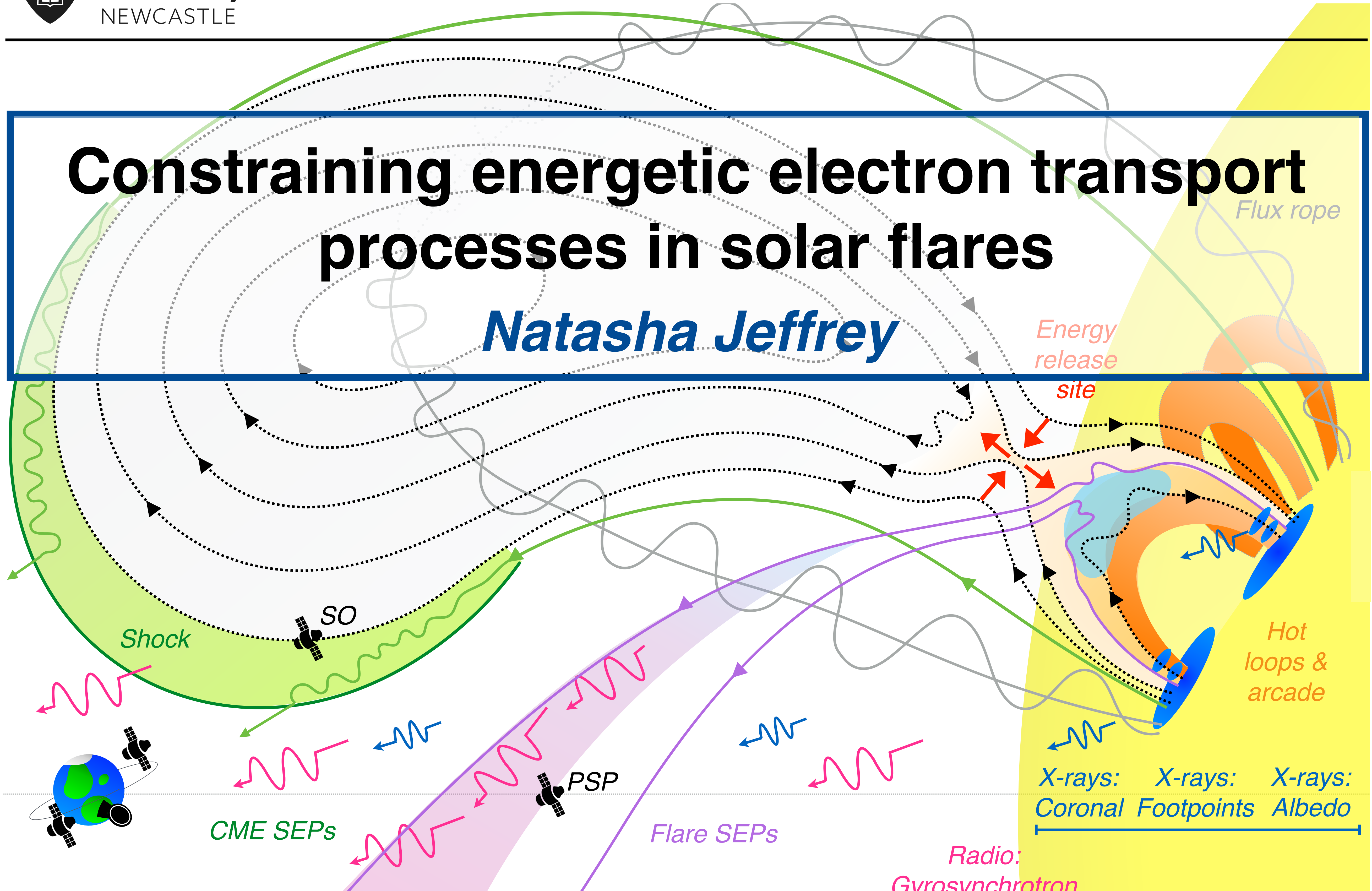
# Constraining energetic electron transport processes in solar flares

***Natasha Jeffrey***




***SolFER (Particle transport session) May 2021***

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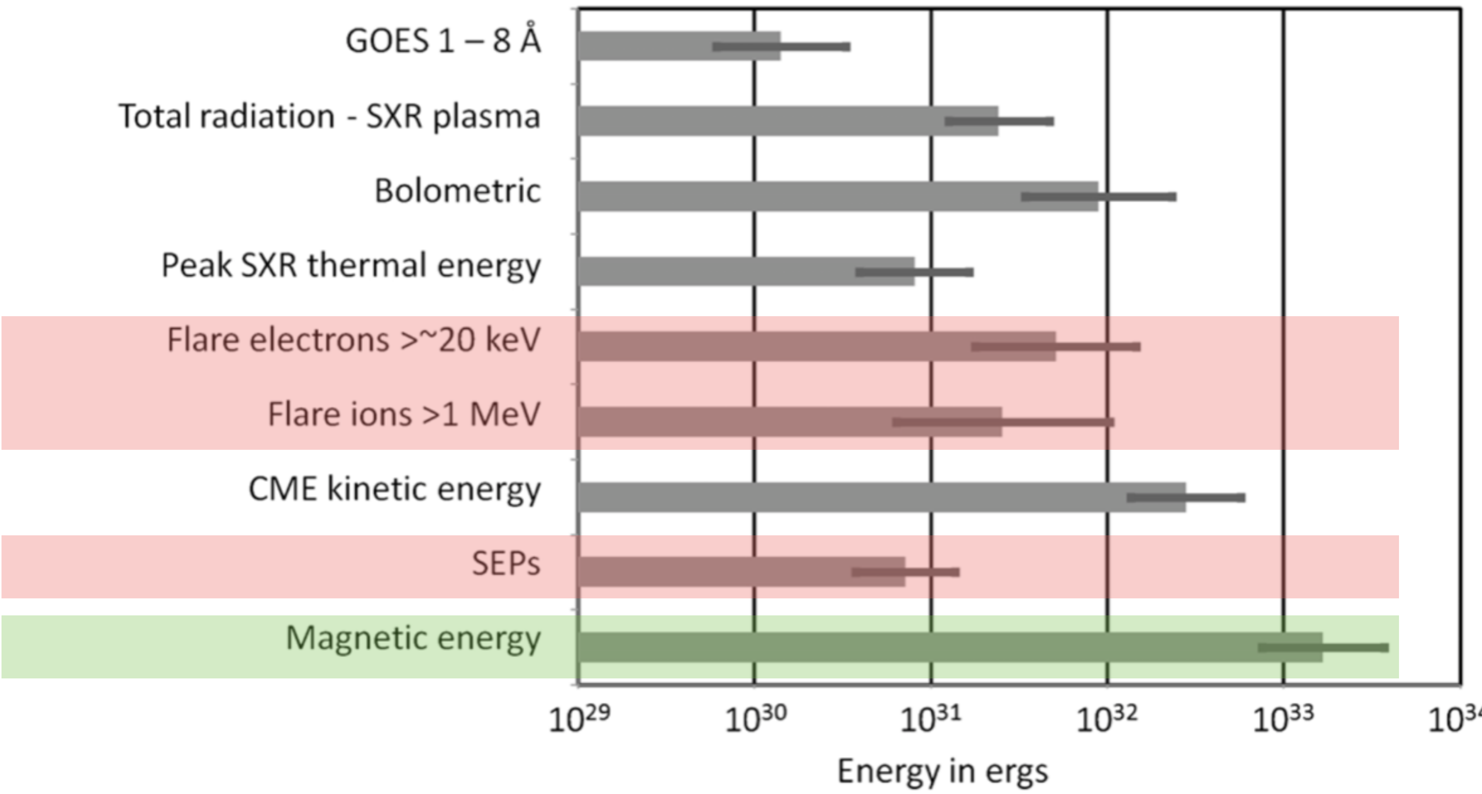
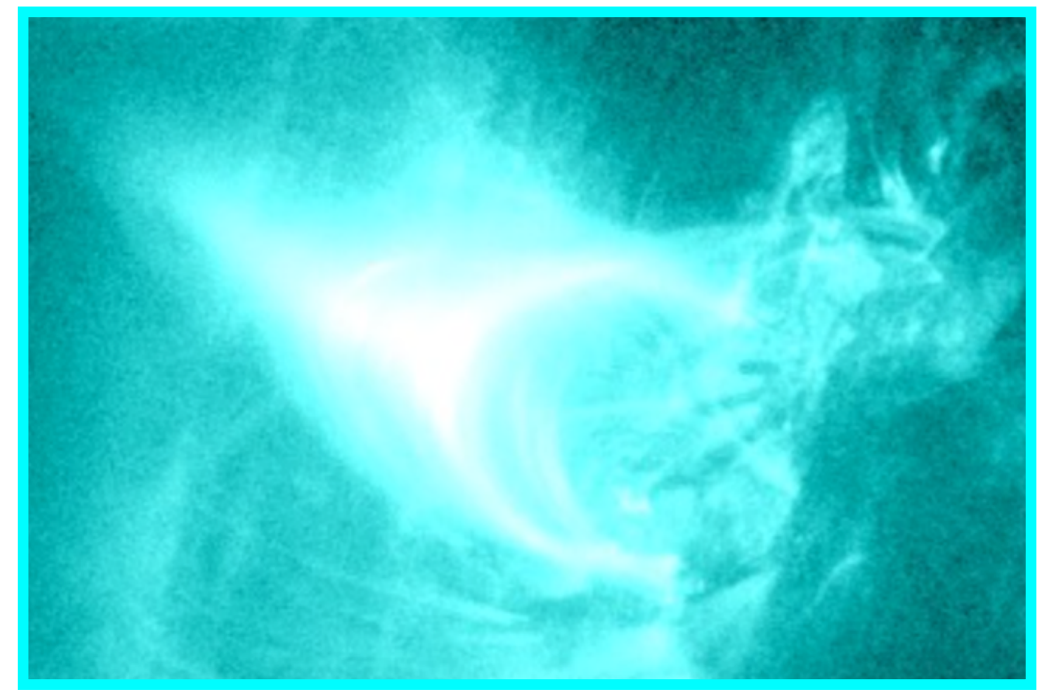
# Solar flare energy partition

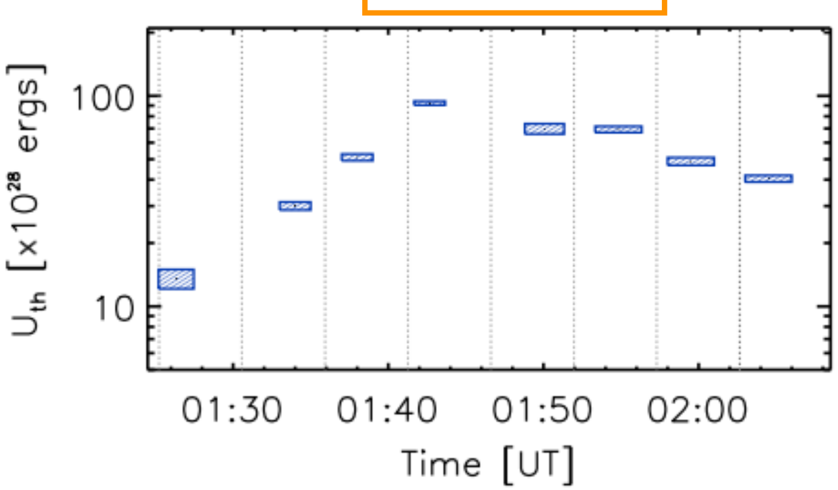
- During a flare, **magnetic energy** is converted into other forms of energy:

*Emslie et al. 2012*

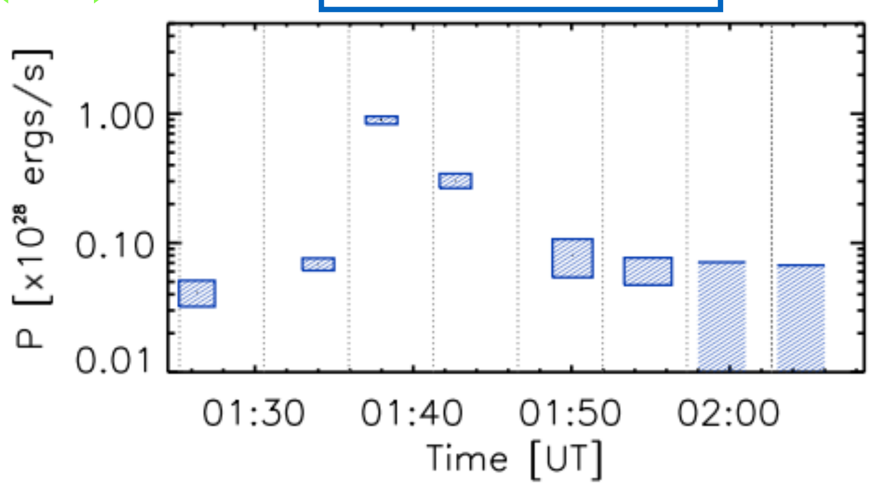


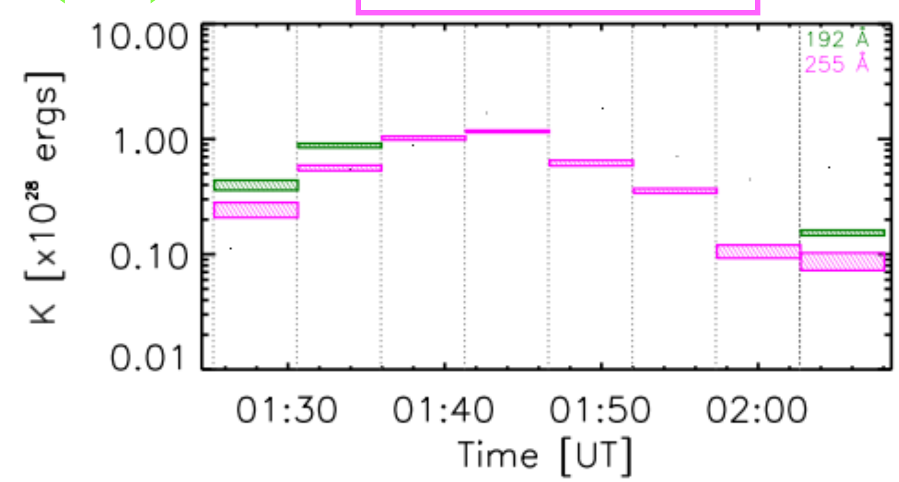
*thermal*




*non-thermal*




*kinetic (turbulence)*




**A substantial fraction of released energy goes into non-thermal electrons!**

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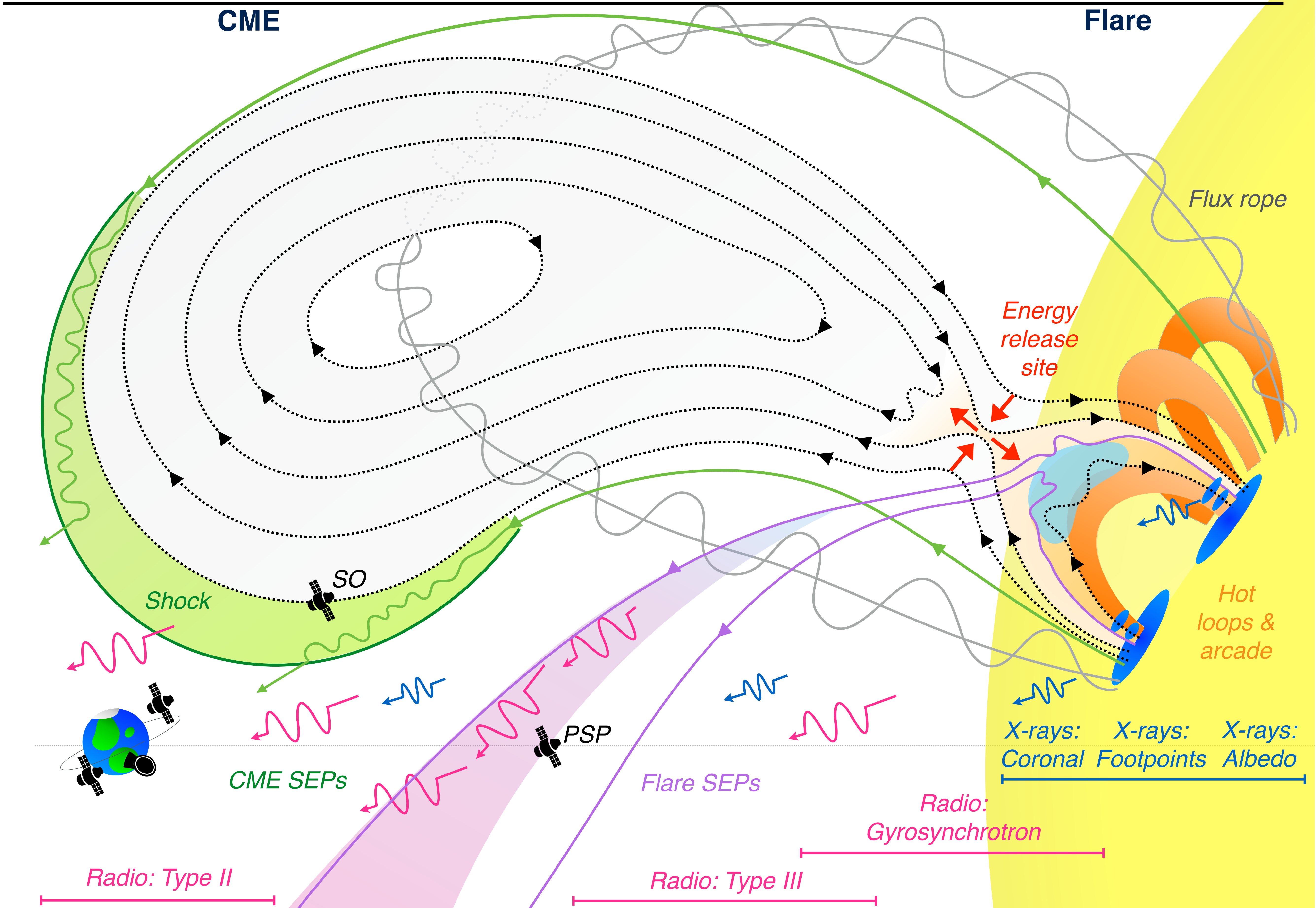
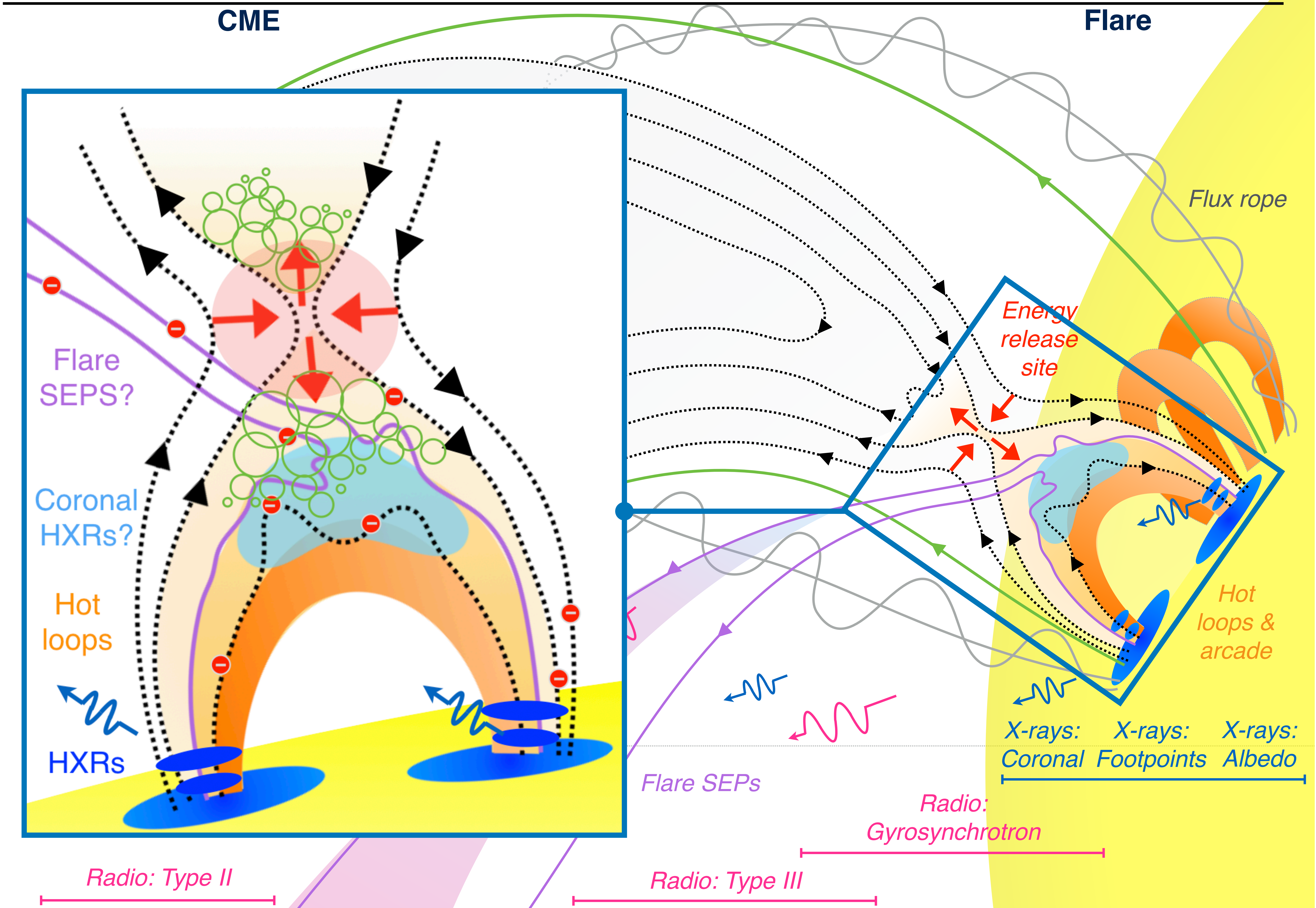
# Flare-accelerated electron transport



# Flare-accelerated electron transport



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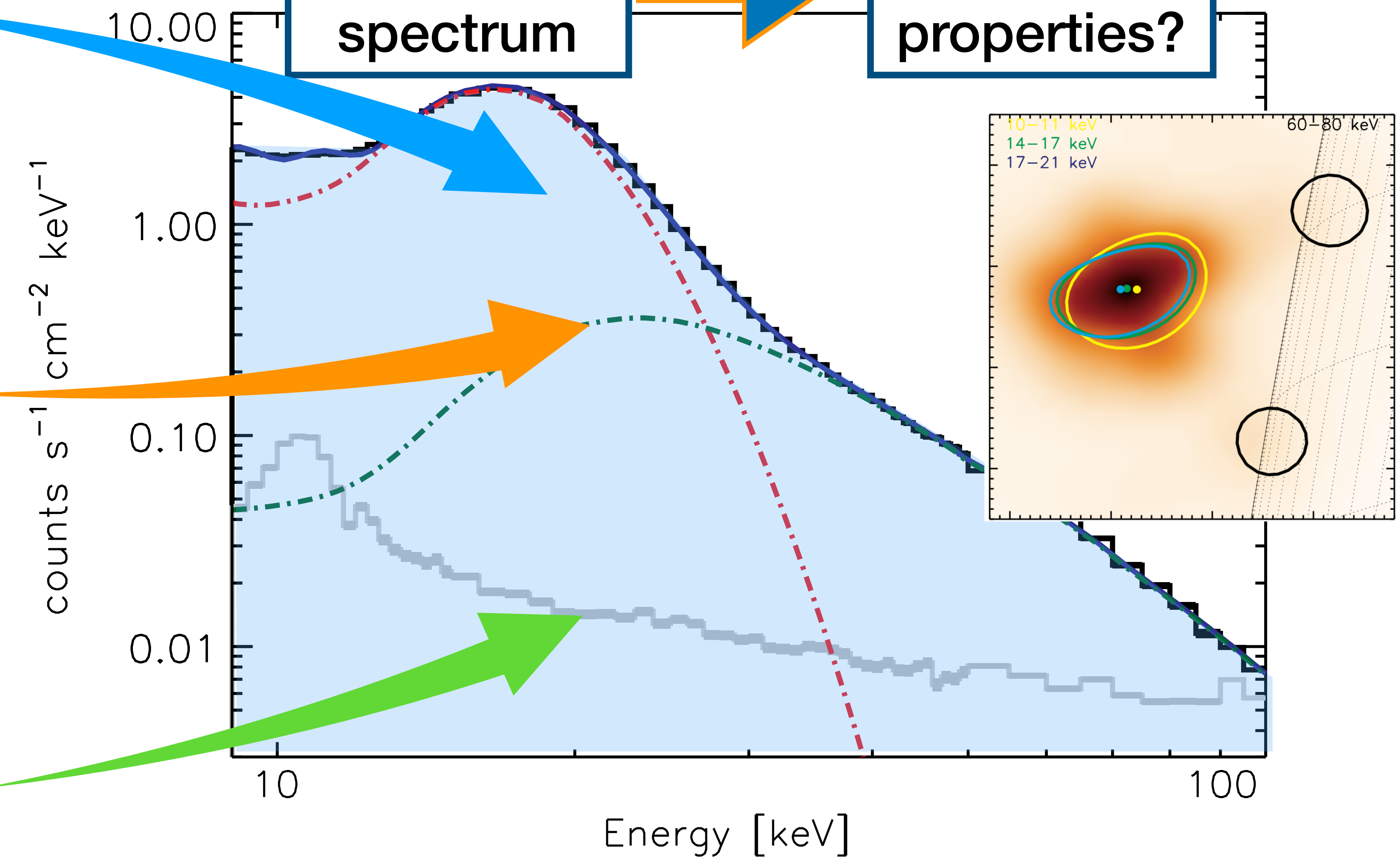
# Electron transport at the Sun

**At the Sun, electrons undergo collisional and non-collisional transport processes**

X-ray energy spectrum → Accelerated electron properties?




## Collisional effects:

- cold-target model.
  *e.g. Brown 1971*
- **warm-target** model.
  *e.g. Jeffrey et al. 2014*
  *Kontar et al. 2015, 2019*

## X-ray transport effects:

- Compton scattering in the photosphere (albedo).
  *e.g. Bai & Ramaty 1978,*
  *Jeffrey & Kontar 2011*

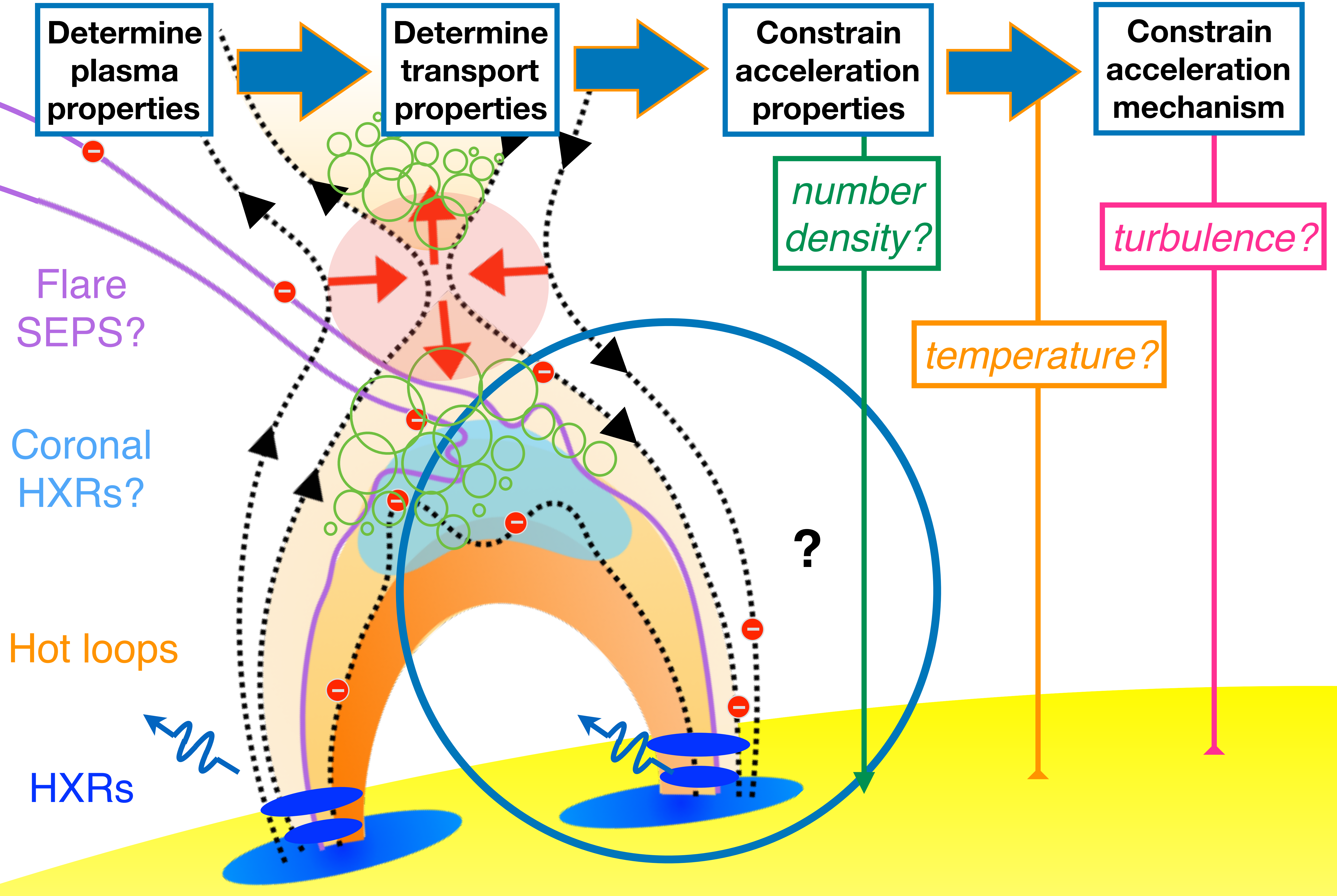
## Non-collisional effects:

- **turbulent scattering**
  *e.g. Kontar et al. 2014*
  *Musset et al. 2018*
- **return currents**
  *e.g. Knight & Sturrock 1977, Zharkova & Gordovskyy 2006, Alaoui et al. 2021*

*Next talk: L Vlahos*

*Posters today: M. Alaoui, V. Zharkova*

# Transport and plasma properties



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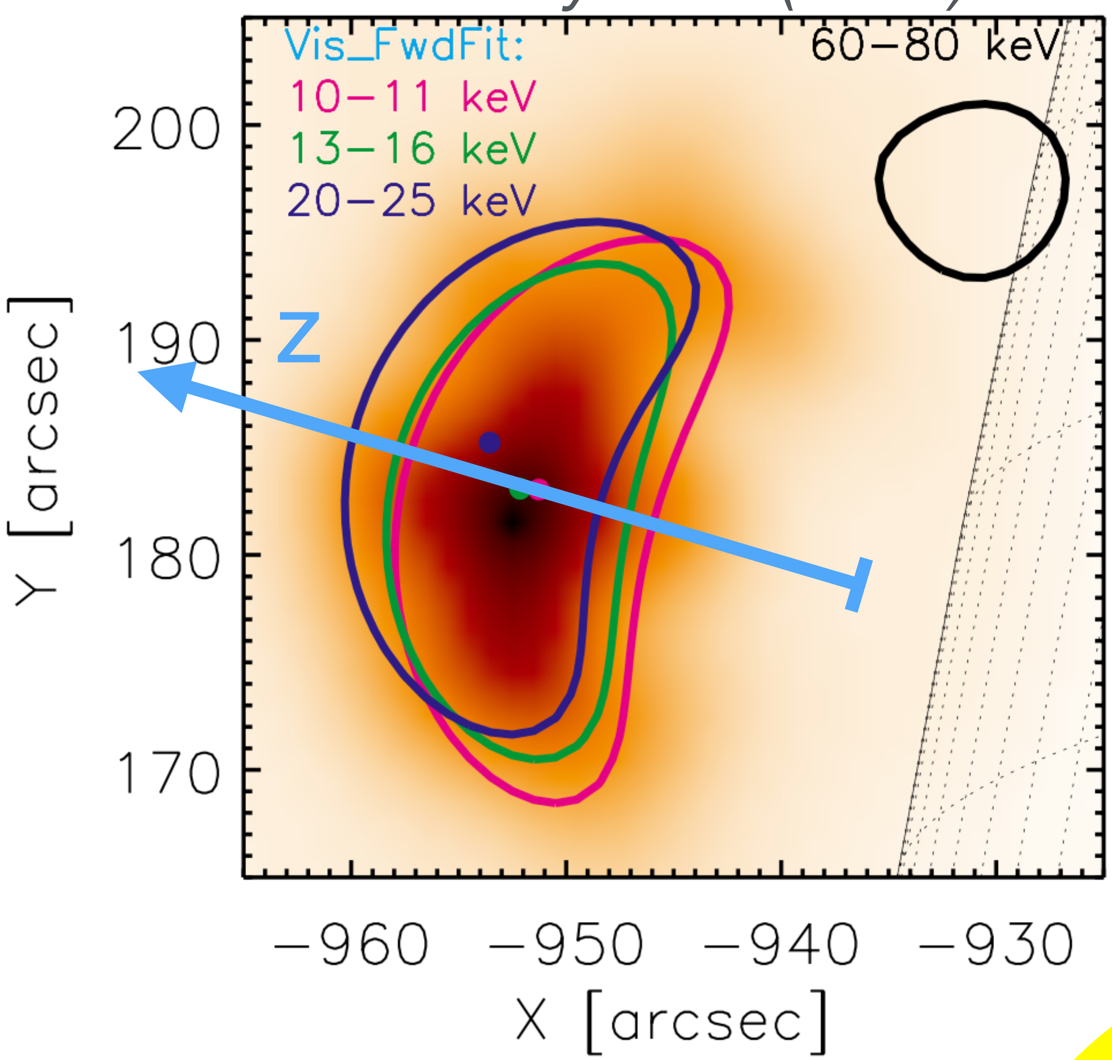
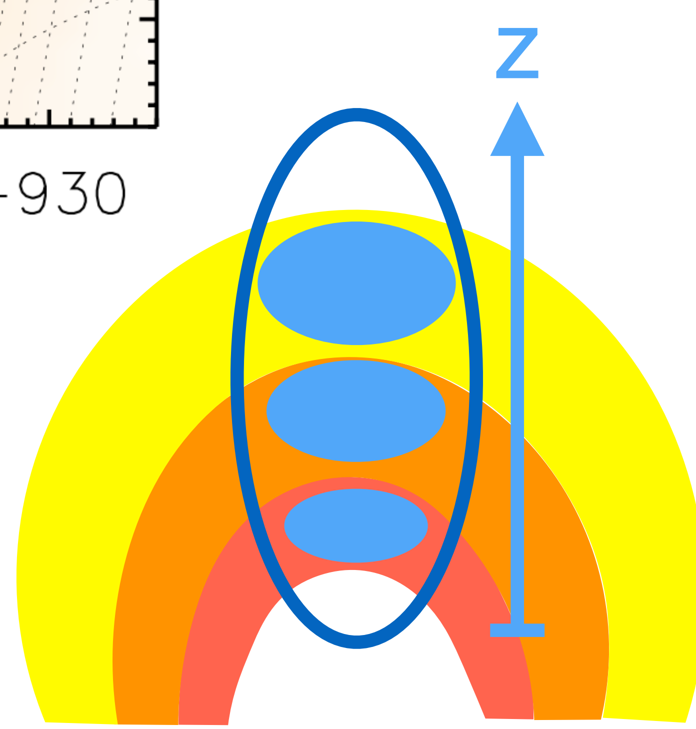
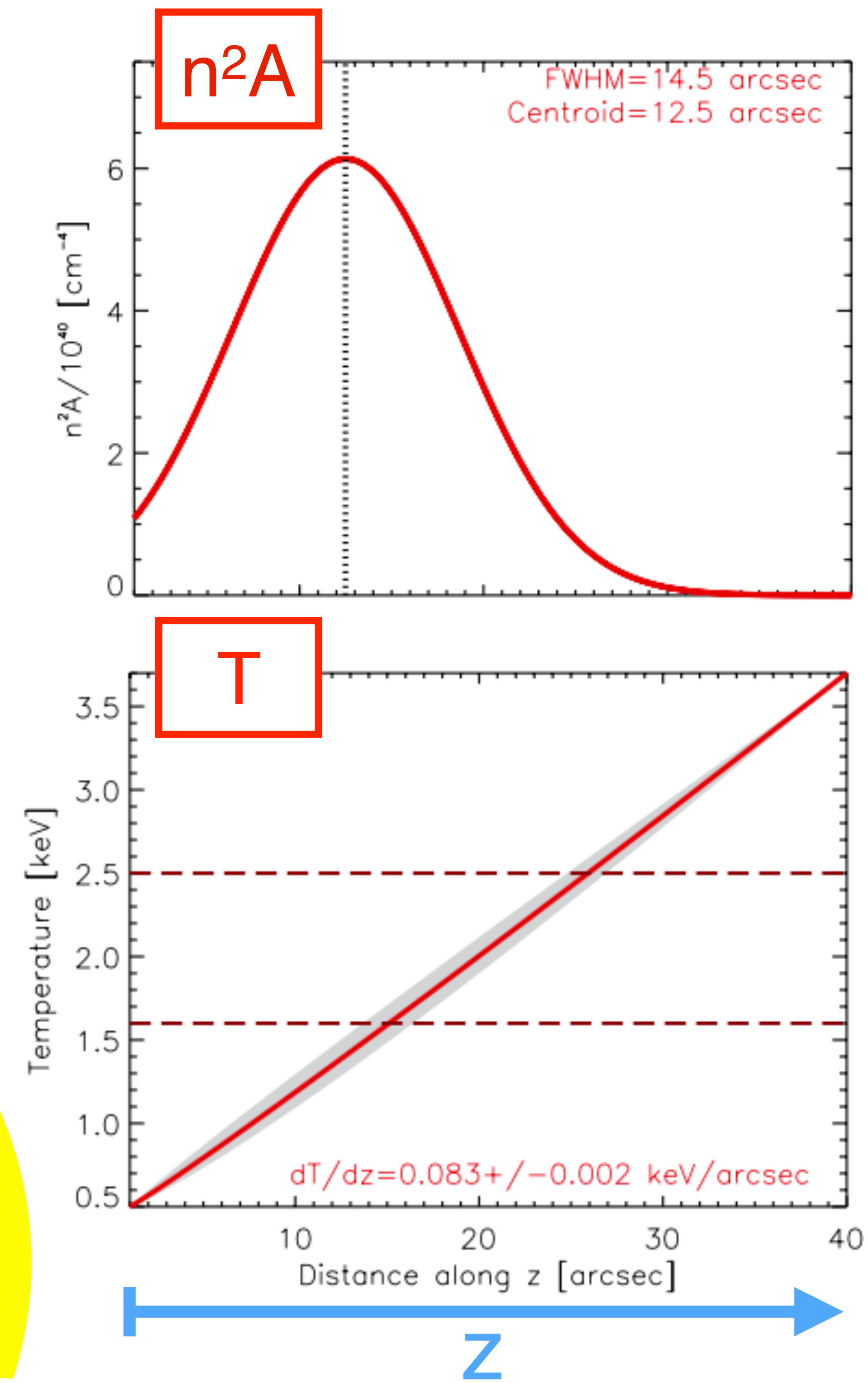
# Flaring coronal plasma properties

- Combined RHESSI X-ray imaging and X-ray spectroscopy suggests the presence of **strong vertical temperature, T, and number density, n, gradients** in the corona.

*Jeffrey et al. (2015)*




- *Different conditions…*
- *Continued acceleration…*
- *Different electron properties…*

# Flare electron transport: collisions

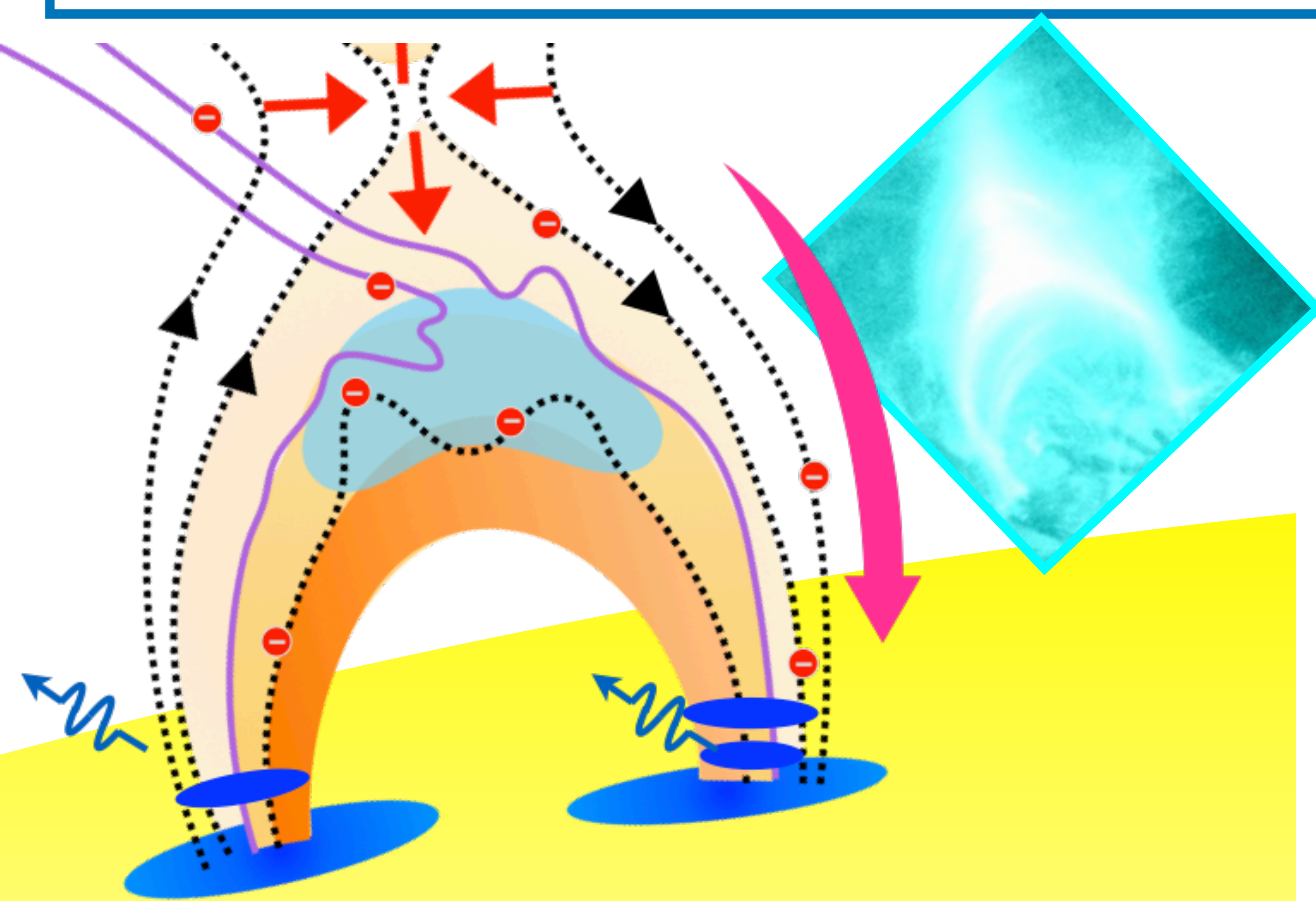
- In the past, electron transport was described by a **cold thick-target model (CTTM)** e.g. Brown 1971, Brown & Emslie 1988
- But, we need **full collisional modelling**: e.g. Jeffrey et al. 2014, Jeffrey et al. 2019

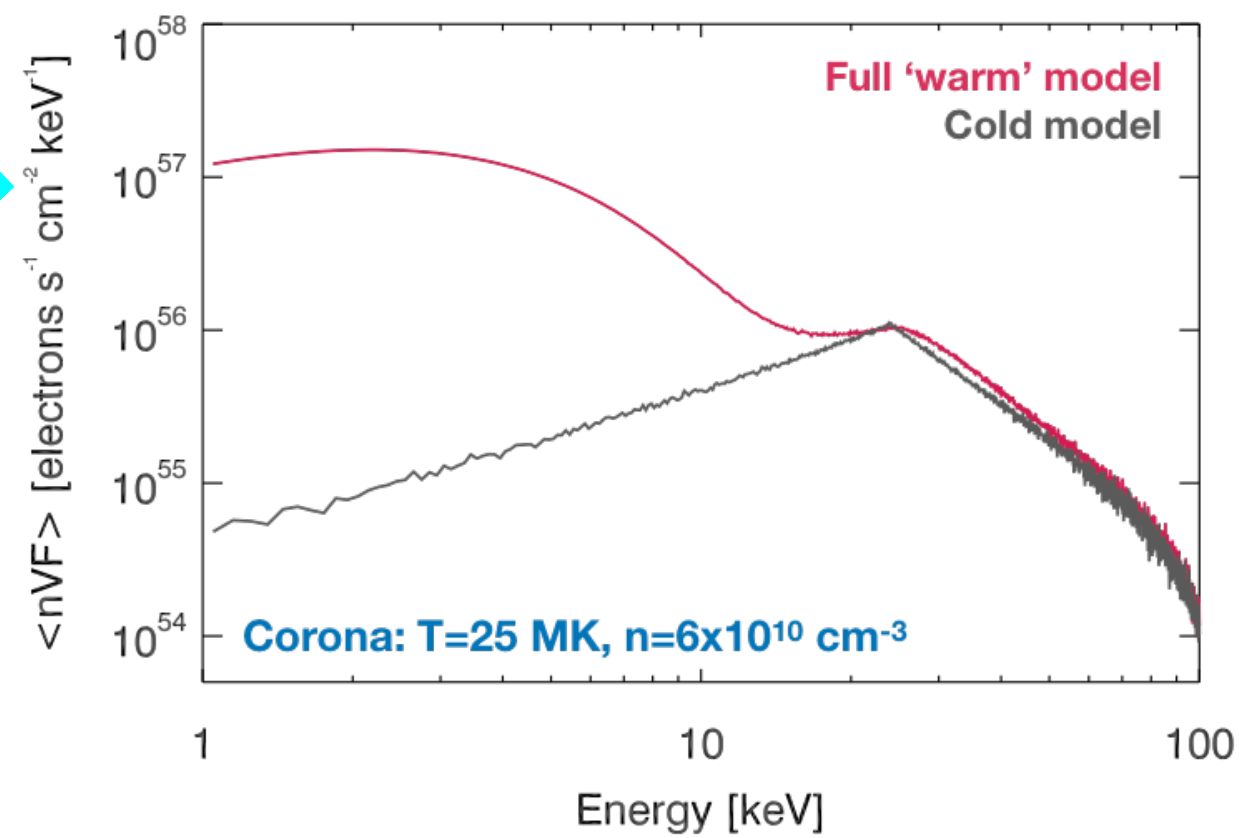
$$\mu\frac{\partial F}{\partial z} = \Gamma m_e^2 \frac{\partial}{\partial E}\left[G(u[E])\frac{\partial F}{\partial E} + \frac{G(u[E])}{E}\left(\frac{E}{k_B T} - 1\right)F\right] + \frac{\Gamma m_e^2}{4E^2}\frac{\partial}{\partial \mu}\left[(1-\mu^2)\left(\mathrm{erf}(u[E]) - G(u[E])\right)\frac{\partial F}{\partial \mu}\right]$$

**"warm-target model"**

*2nd order effects - energy diffusion/thermalisation.* ✓

*Takes into account the coronal plasma properties.* ✓

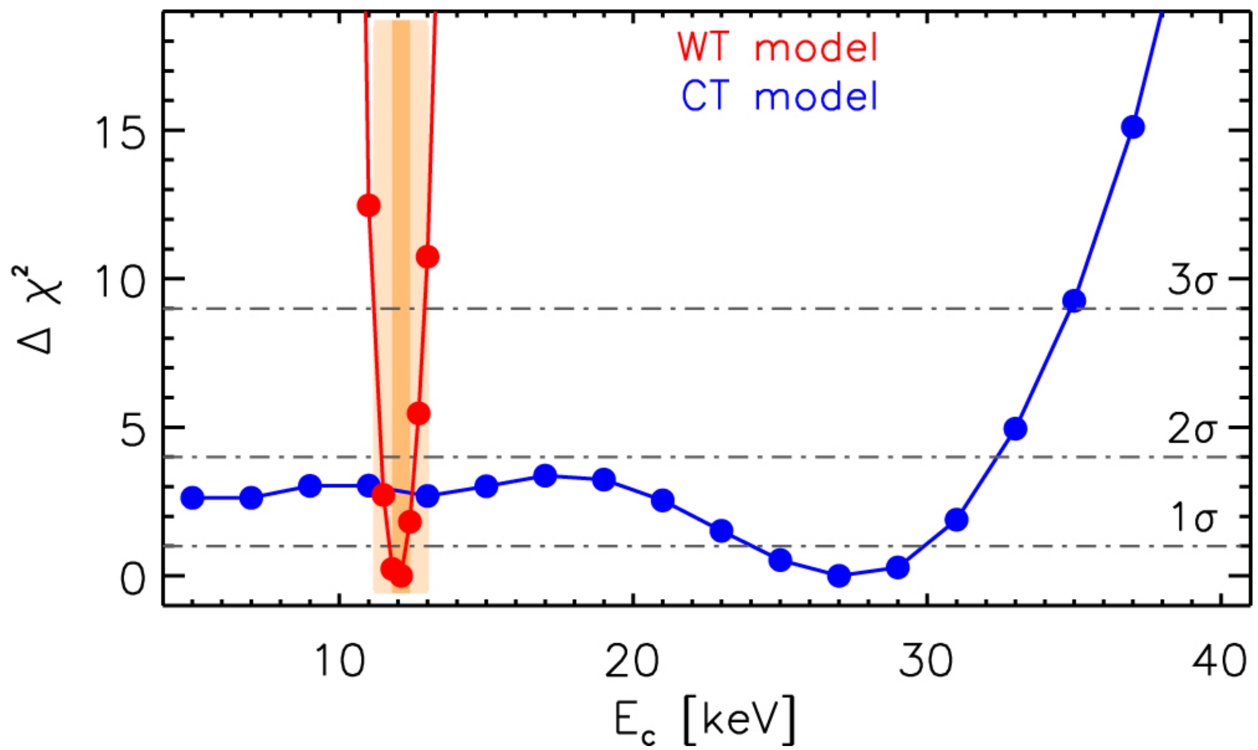


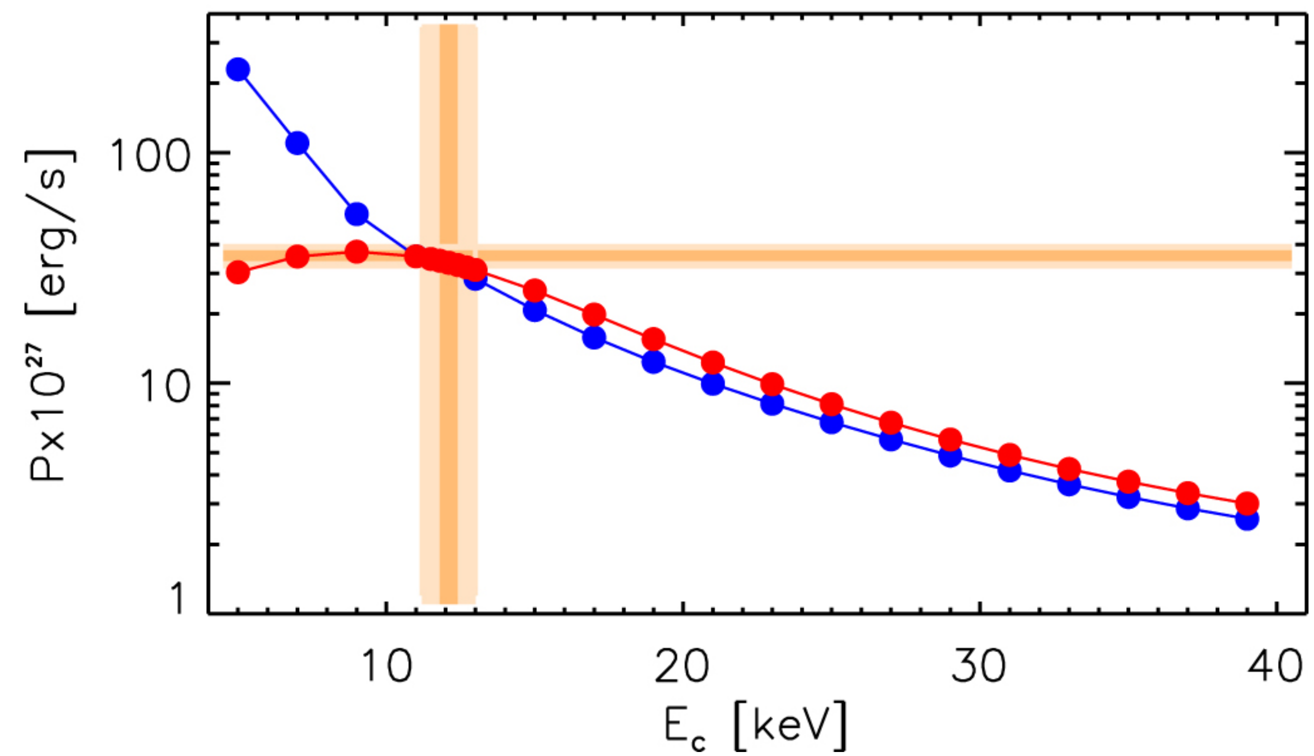


# Flare electron transport: collisions

**The determination of electron parameters is sensitive to the coronal parameters**

*e.g. Kontar et al. 2015, Kontar, Jeffrey, Emslie 2019*




$$\langle nVF\rangle(E) \simeq \Delta\mathrm{EM}\sqrt{\frac{8}{\pi m_e}}\,\frac{E}{(k_B T)^{3/2}}\,e^{-E/k_B T} + \frac{E}{K}\int_E^{\infty}\dot{N}(E_0)\,dE_0$$

'Thermal part' 'Non-Thermal part'

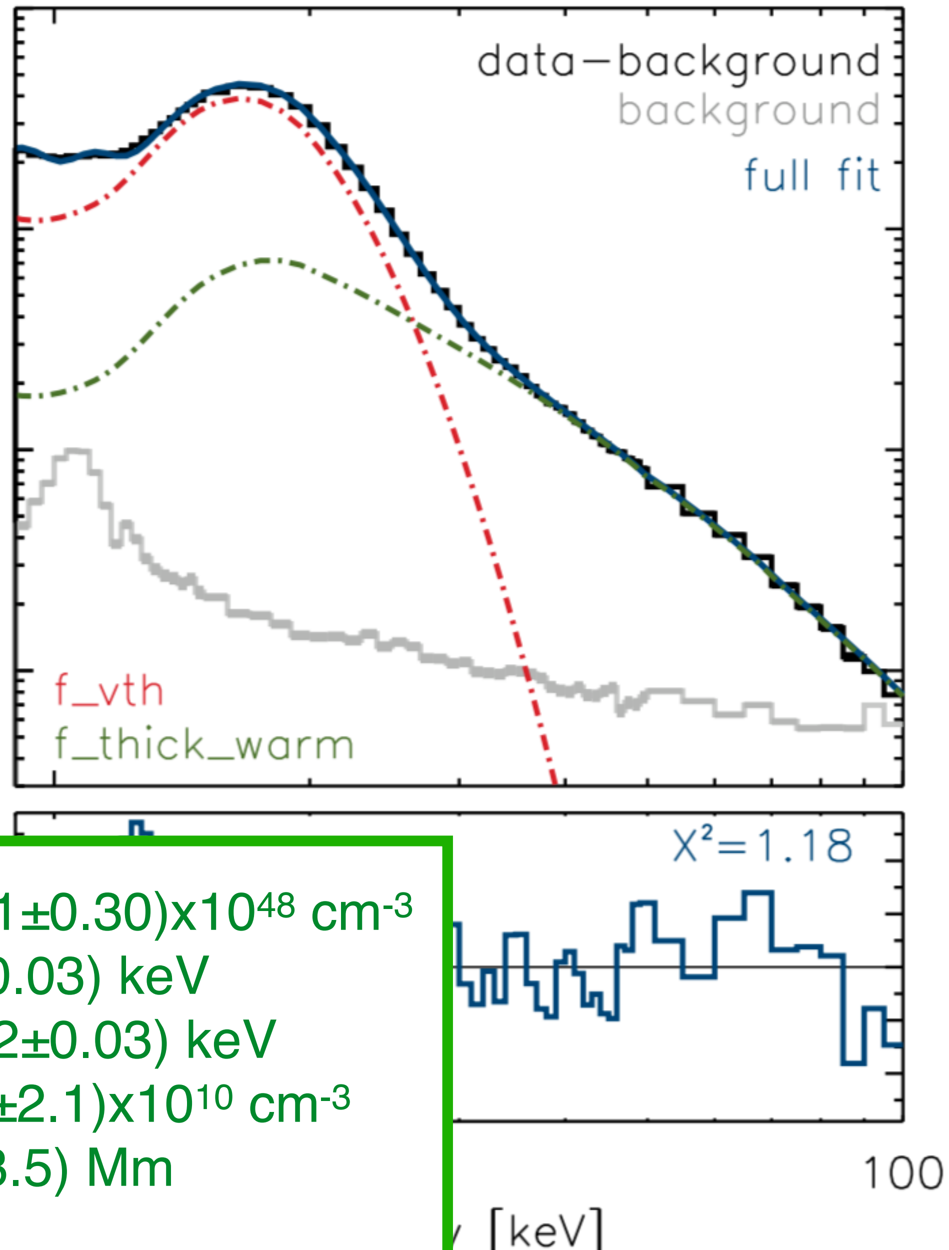
- where: $\Delta\mathrm{EM} \simeq \frac{\pi}{K}\sqrt{\frac{m_e}{8}}\,(k_B T)^2\,\frac{\dot{N}_0}{E_{\min}^{1/2}}$

ΔEM = emission measure from the thermalization of electrons.

# Warm-target model and data

**The determination of electron parameters is sensitive to the coronal parameters**

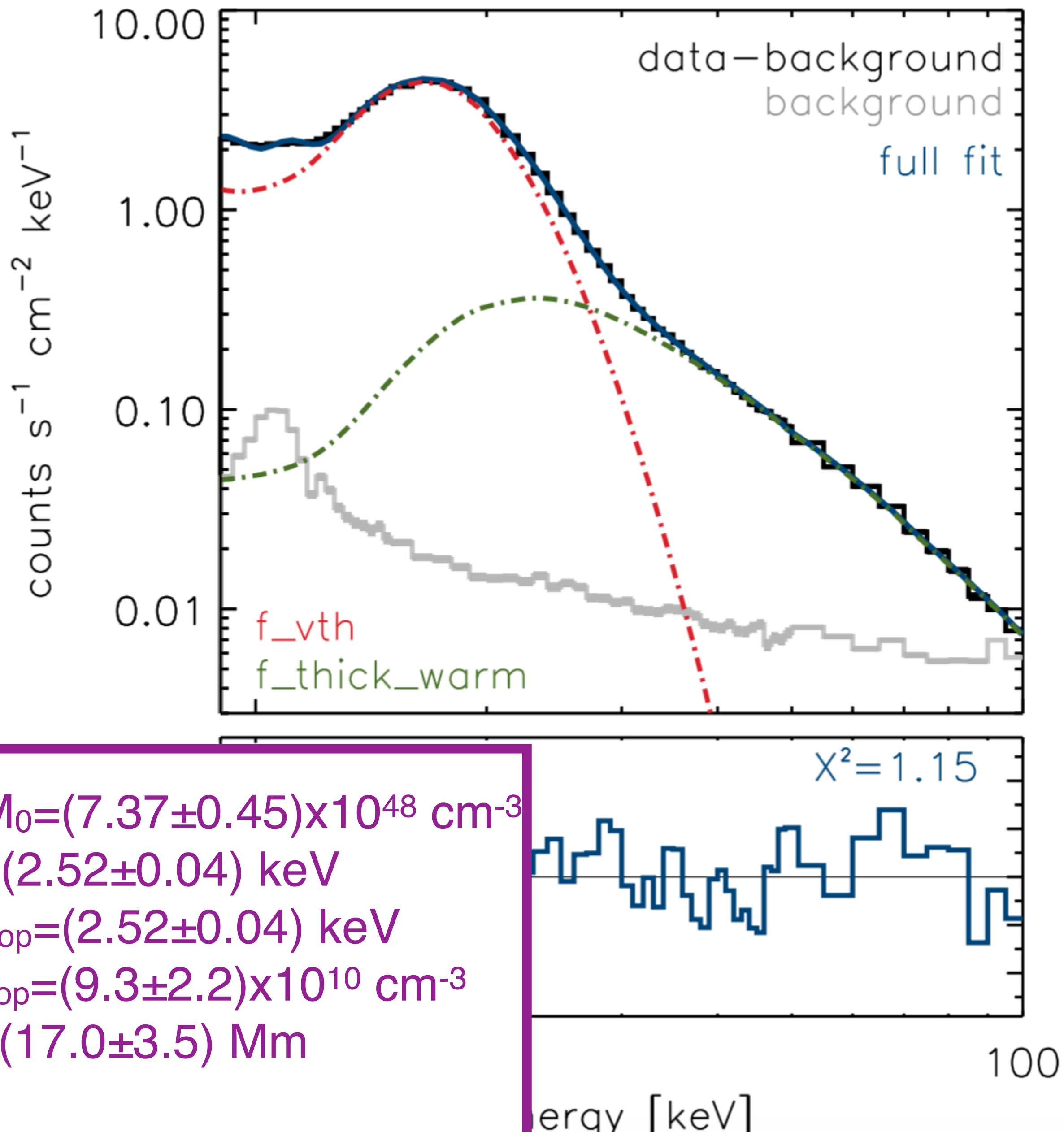
1.




$EM_0$=(6.51±0.30)x10$^{48}$ cm$^{-3}$
T=(2.52±0.03) keV
$T_{loop}$=(2.52±0.03) keV
$n_{loop}$=(8.7±2.1)x10$^{10}$ cm$^{-3}$
L=(17.0±3.5) Mm

$\dot{N}_0$ =(12.8±0.6)x10$^{35}$ s$^{-1}$
$\delta_{low}$=4.25±0.02
$E_c$=(12.1±0.3) keV
P=(35.8±1.9)x10$^{27}$ erg s$^{-1}$

2.




$EM_0$=(7.37±0.45)x10$^{48}$ cm$^{-3}$
T=(2.52±0.04) keV
$T_{loop}$=(2.52±0.04) keV
$n_{loop}$=(9.3±2.2)x10$^{10}$ cm$^{-3}$
L=(17.0±3.5) Mm

$\dot{N}_0$ =(0.7±0.1)x10$^{35}$ s$^{-1}$
$\delta_{low}$ =4.14±0.03
$E_c$=(29.0±1.9) keV
P=(4.8±0.8)x10$^{27}$ erg s$^{-1}$

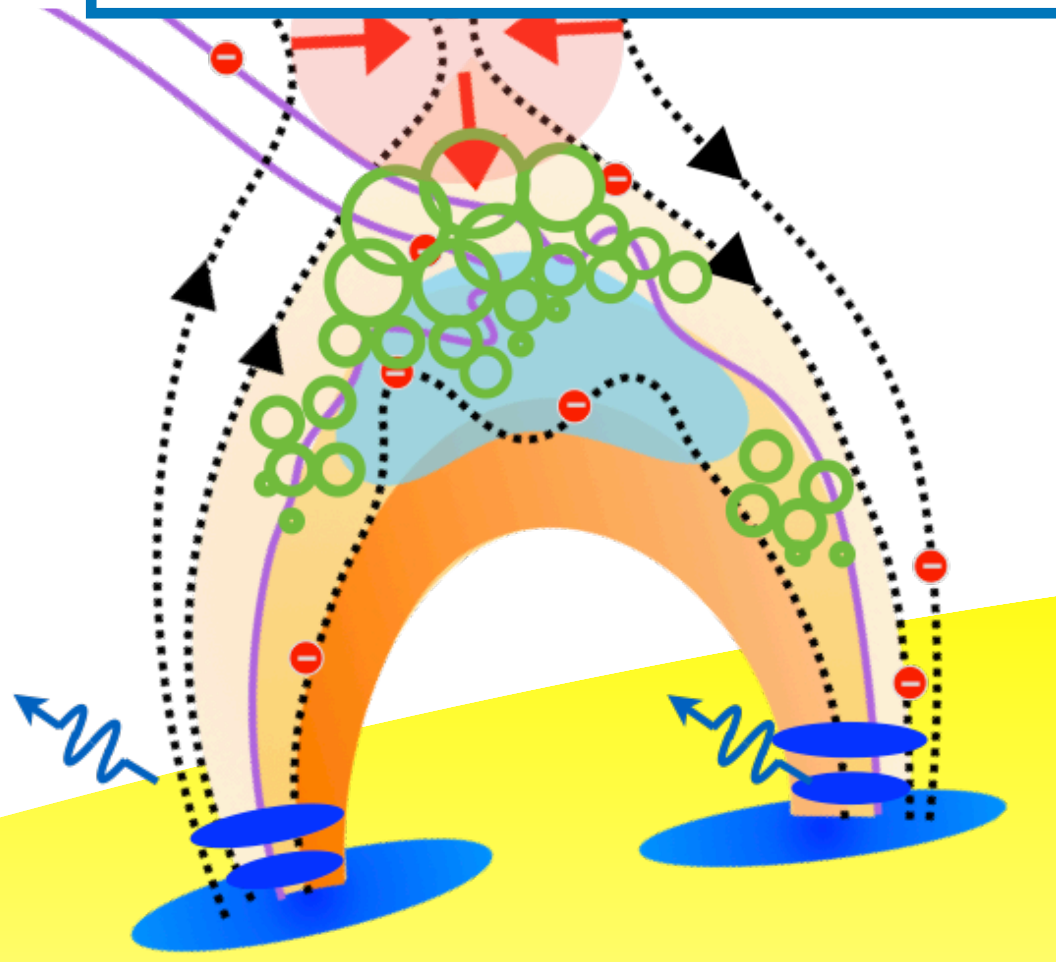
# Flare electron transport: turbulence

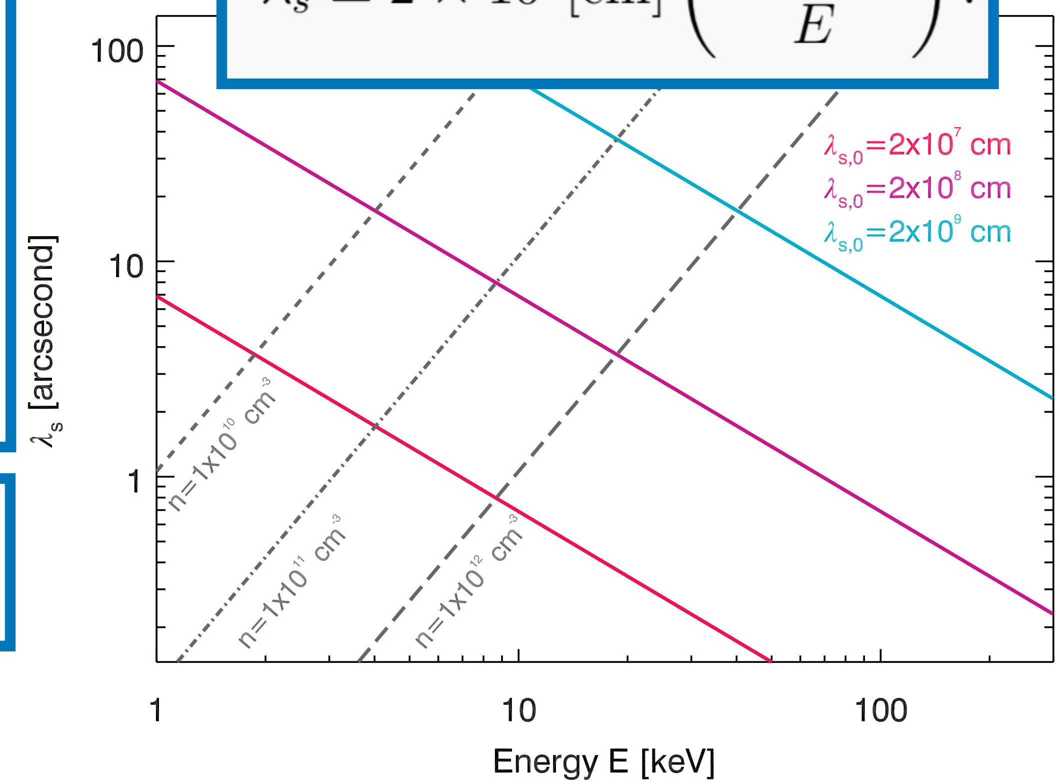
- **Turbulent scattering** can lead to diffusive transport of electrons and trapping
  *e.g. Schlickeiser 1989, Bian et al. 2011, Kontar et al. 2014, Musset et al. 2018.*

$$\mu \frac{\partial F}{\partial z} = \Gamma m_e^2 \frac{\partial}{\partial E}\left[G(u[E])\frac{\partial F}{\partial E} + \frac{G(u[E])}{E}\left(\frac{E}{k_B T} - 1\right)F\right] + \frac{\Gamma m_e^2}{4E^2}\frac{\partial}{\partial \mu}\left[(1-\mu^2)\Big(\mathrm{erf}(u[E]) - G(u[E])\Big)\frac{\partial F}{\partial \mu}\right] + \frac{1}{2\lambda_s(E)}\frac{\partial}{\partial \mu}\left[(1-\mu^2)\frac{\partial F}{\partial \mu}\right] + S(E,z,\mu),$$

$$\lambda_s \simeq 2\times 10^8[\mathrm{cm}]\left(\frac{25[\mathrm{keV}]}{E}\right).$$

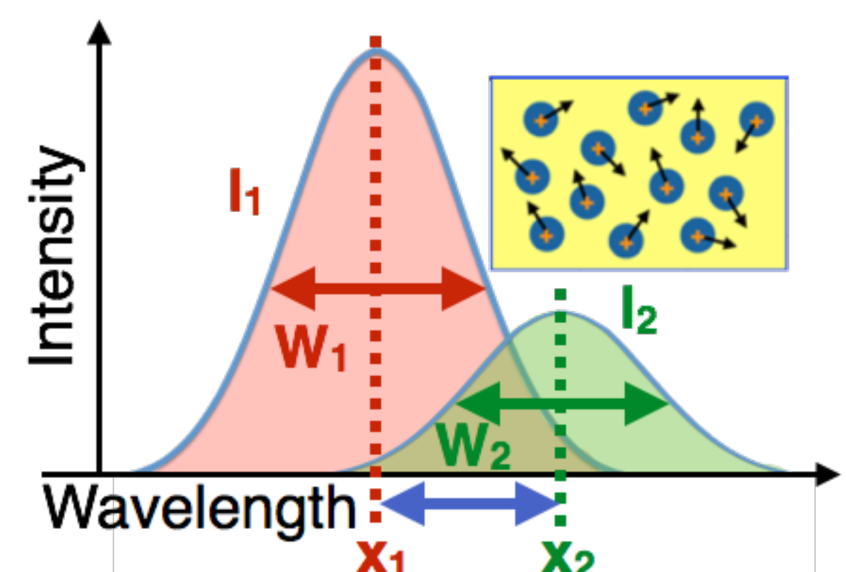
$$D_{\mu\mu}^T \simeq \frac{v}{2\lambda_s}(1-\mu^2)$$





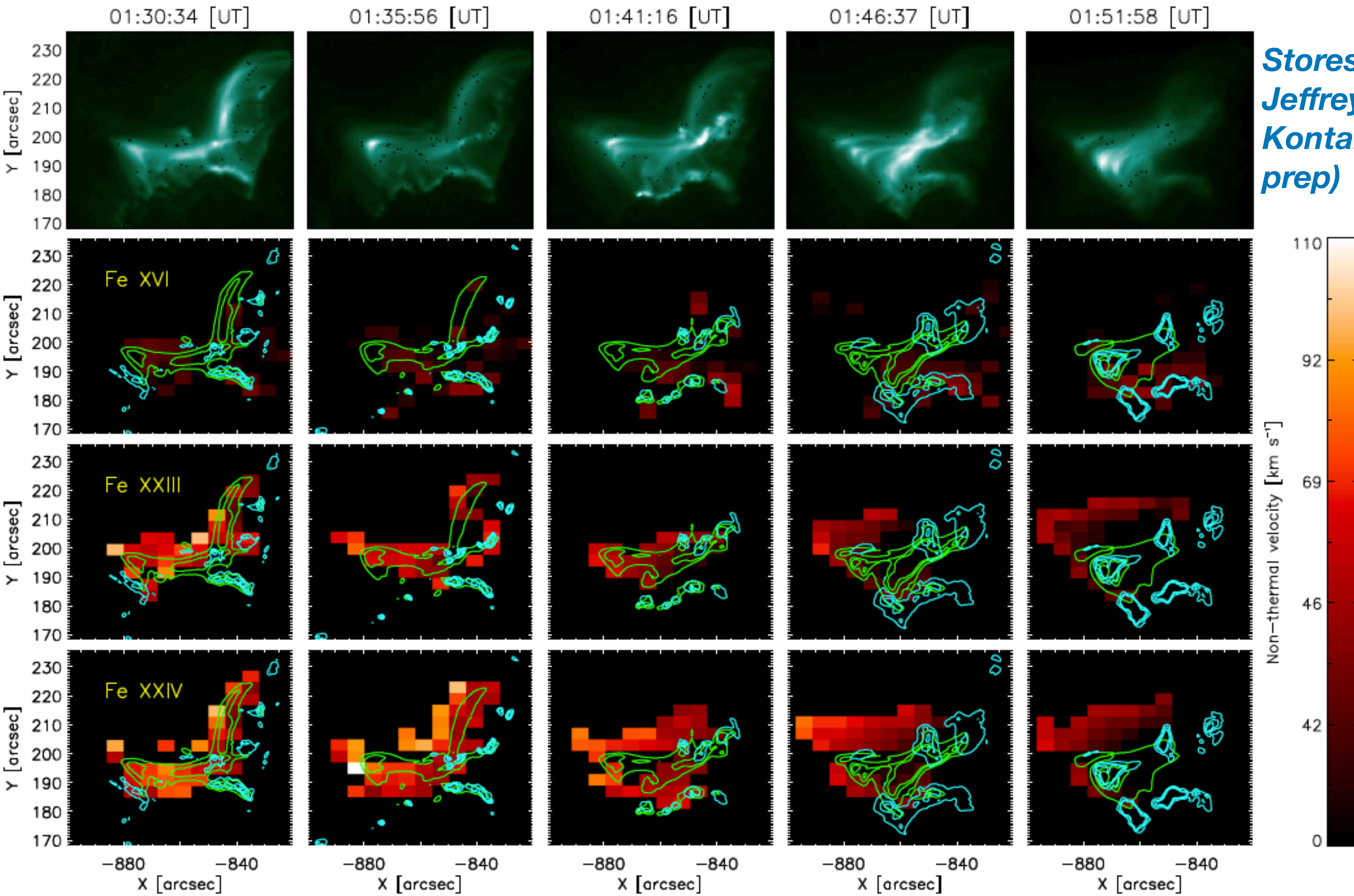

Optically thin lines: **ion/plasma velocities determine *width*.**

The **non-thermal velocity** is attributed to **plasma turbulence**.



# Flare electron transport: turbulence

**Turbulence is intimately linked with both acceleration and transport**




*Stores, Jeffrey & Kontar (in prep)*

# Flare electron transport: turbulence

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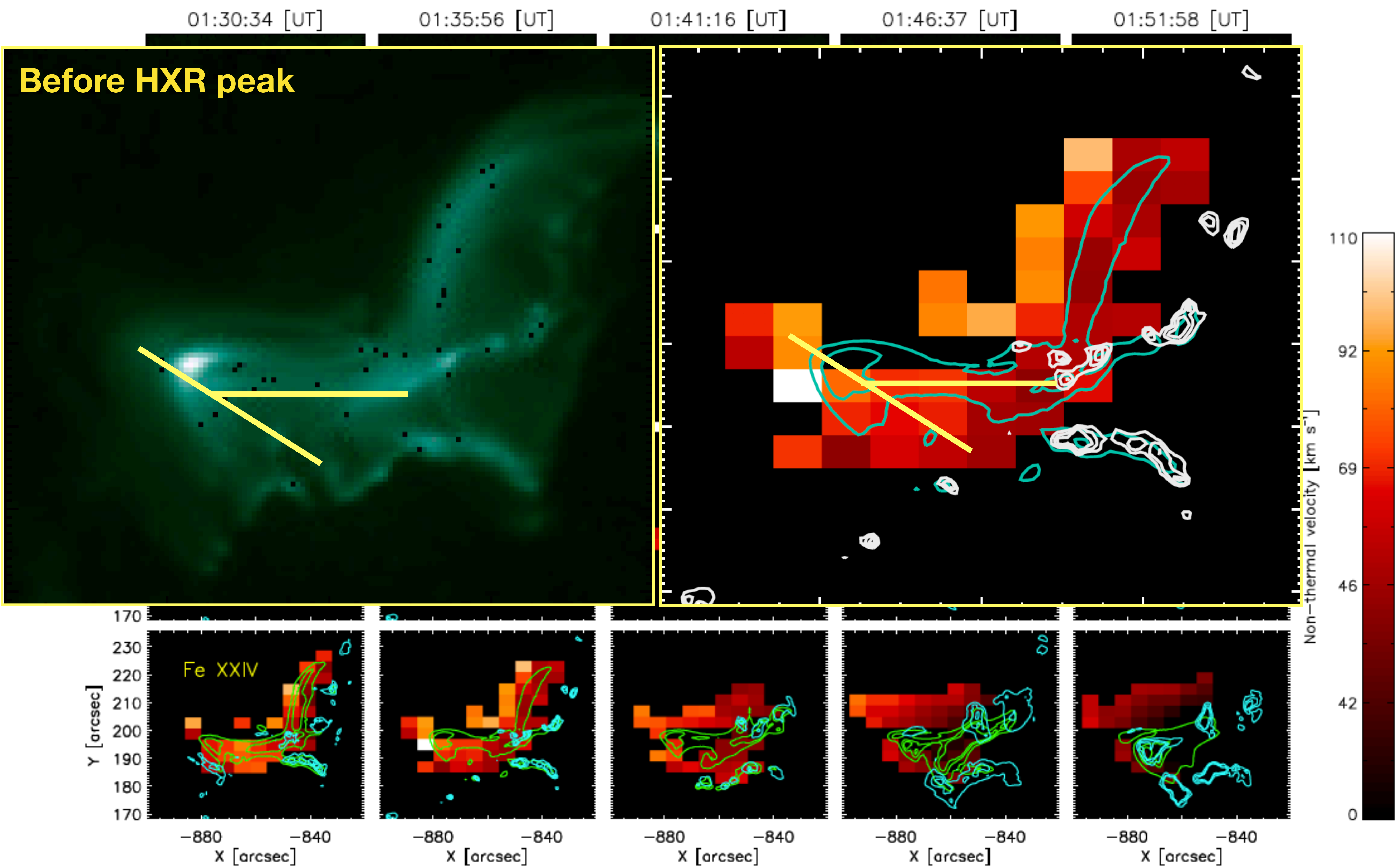
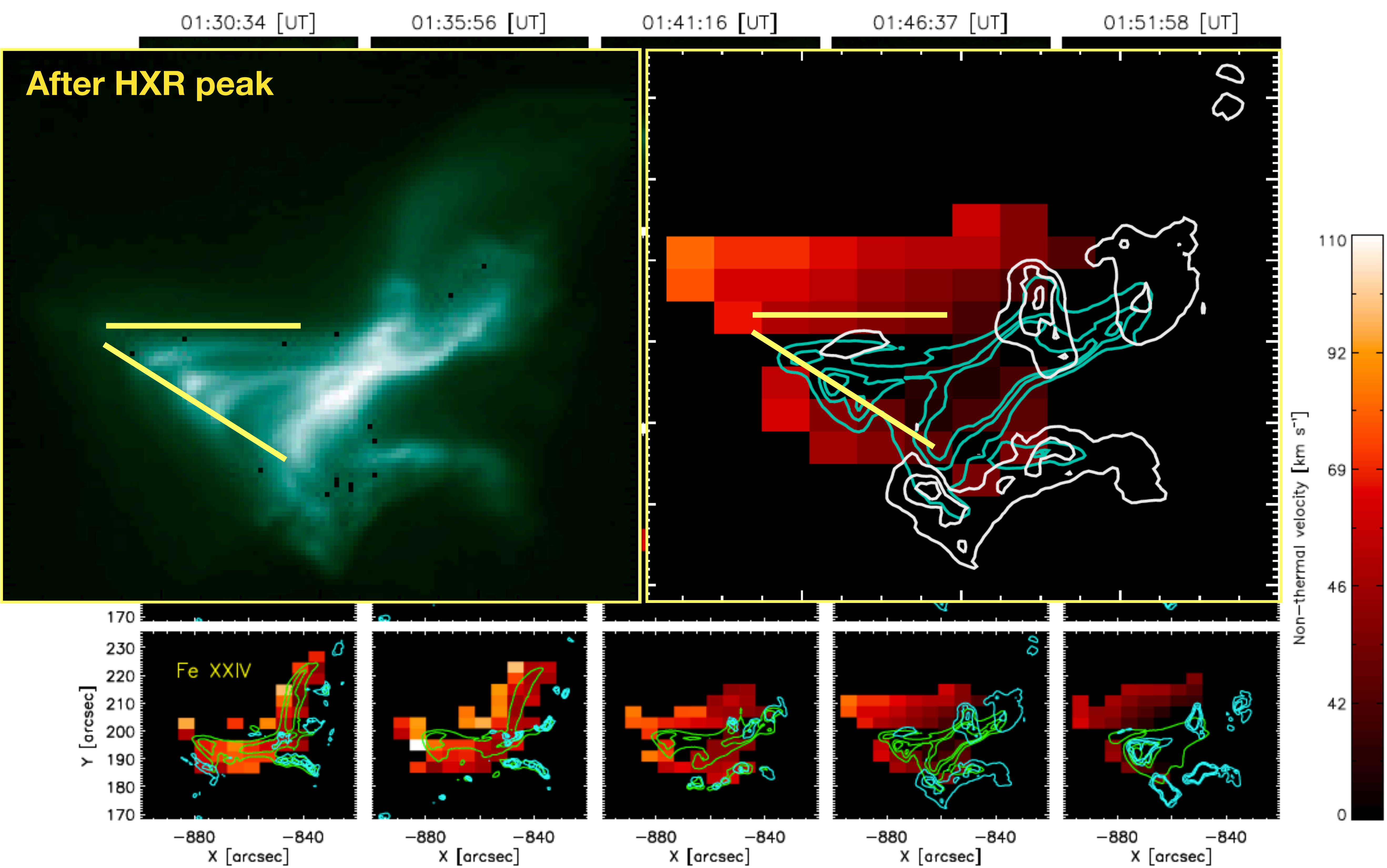


# Flare electron transport: turbulence

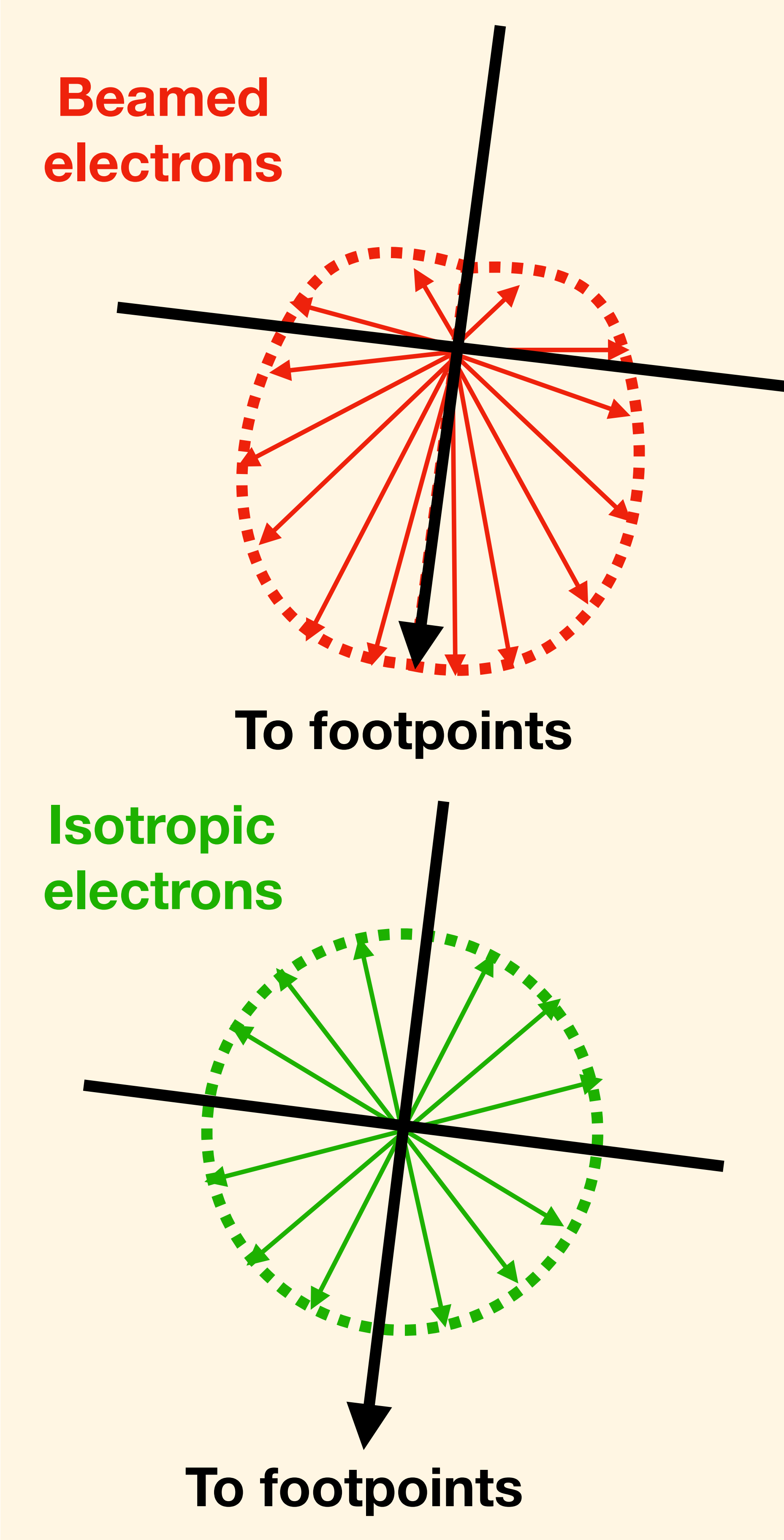
**Turbulence is intimately linked with both acceleration and transport**



# Electron anisotropy at the Sun

In the majority of flares, the directivity of flare-accelerated electrons at the Sun is an unknown.

- This property cannot be easily obtained from a single flare X-ray flux observation (BUT X-ray albedo).
- The electron directivity is a vital diagnostic for the method of acceleration, e.g. stochastic acceleration methods will produce isotropic distributions (e.g. Melrose 1994; Miller et al. 1996; Petrosian 2012).
- **Also vital for constraining coronal plasma conditions and transport properties.**
- It is possible to determine anisotropy from X-ray linear polarization and X-ray stereoscopic observations.



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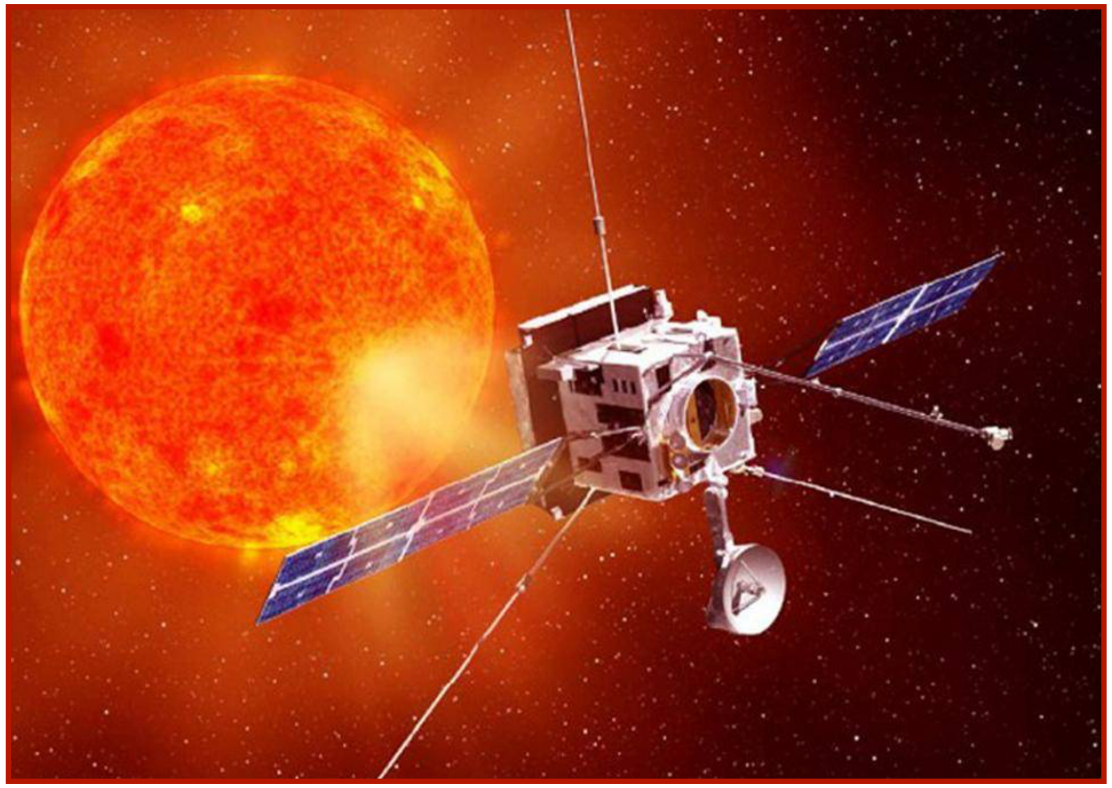
# Prospective Stereoscopic Missions



- STIX (Krucker et al. 2020) onboard Solar Orbiter will observe solar flare X-rays between 4 and 150 keV.
- STIX will observe as close as 0.28 AU.
- STIX will observe out of the ecliptic up to 25$^{o}$.

- At the same time, we will have a new fleet of X-ray missions at LEO/L1:

| ASO-S/HXI | Aditya-HEL1OS | ? |
|---|---|---|
| Chinese mission | Indian mission | NASA CubeSat |
| 3-200 keV | 10-150 keV | 10-100 keV |
| Imaging ✓ | No imaging ✓ | ? |
| Launch 2021/2022 | Launch in 2021 | |

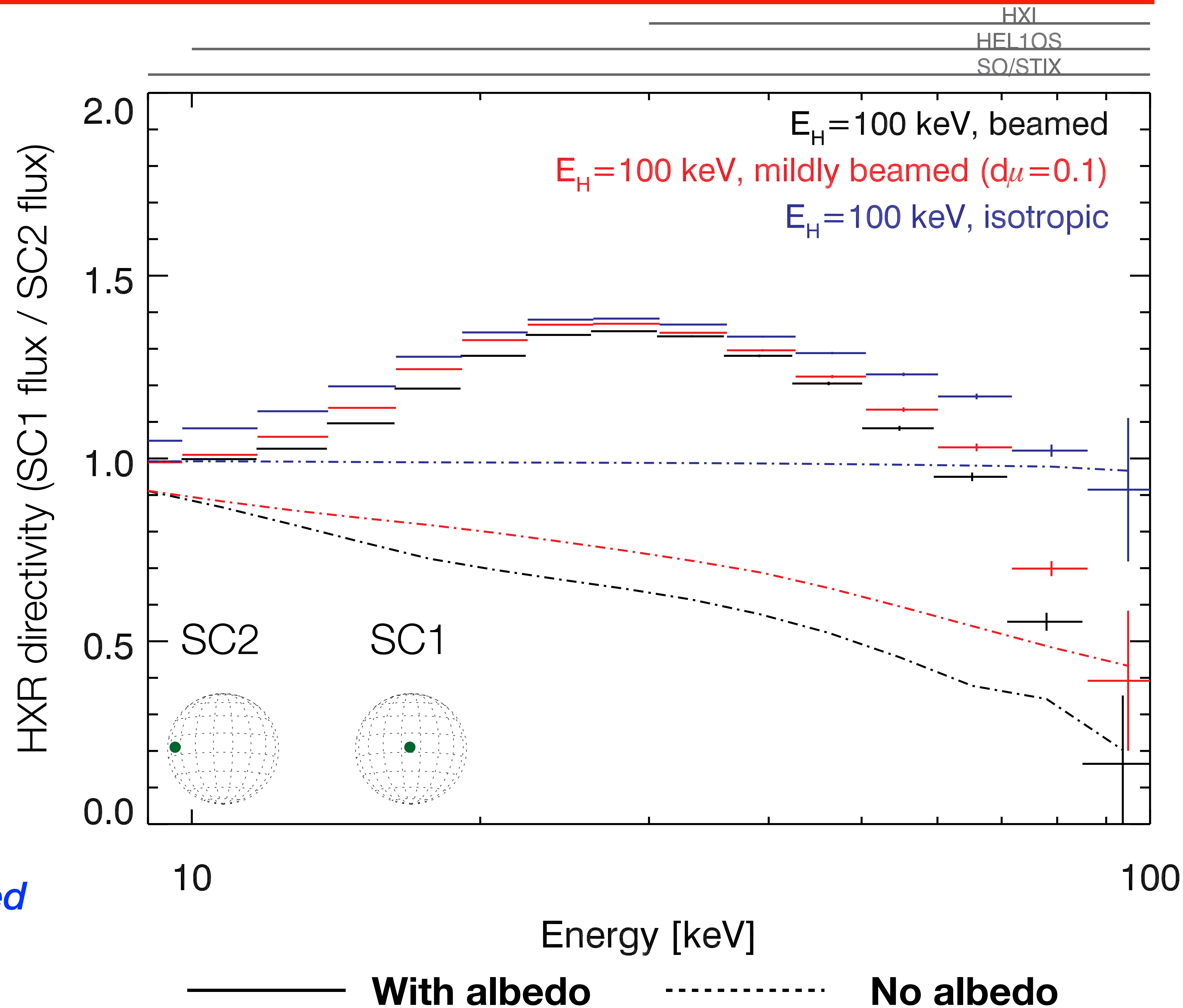
**The first joint observations between STIX and Aditya-HEL1OS will be available in the second half of 2021.**

# X-ray stereoscopic modelling

**Realistic transport modelling will be important for determining the directivity**

- Identical plasma and spectral properties
- Identical high energy cutoffs
- *Different anisotropies*
- Viewing angles of 20° and 60°.

*The use of X-ray polarization is discussed in Jeffrey et al. 2020, A&A*



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# Summary and Discussion Questions

**Determine plasma properties** → **Determine transport properties** → **Constrain acceleration properties** → **Constrain acceleration mechanism**

- **Understanding and constraining electron transport is crucial for constraining the electron acceleration environment and mechanism(s).**

- **Recent advances show the importance of using observationally driven models and making diagnostic tools that take into account the realistic flaring plasma properties.**

**Some question for the discussion session:**

- **Can turbulent acceleration produce electron directivity - what if new observations suggest this? No turbulent scattering?**

- **How do spatial changes in plasma properties affect our determination of flare-accelerated electron properties?**