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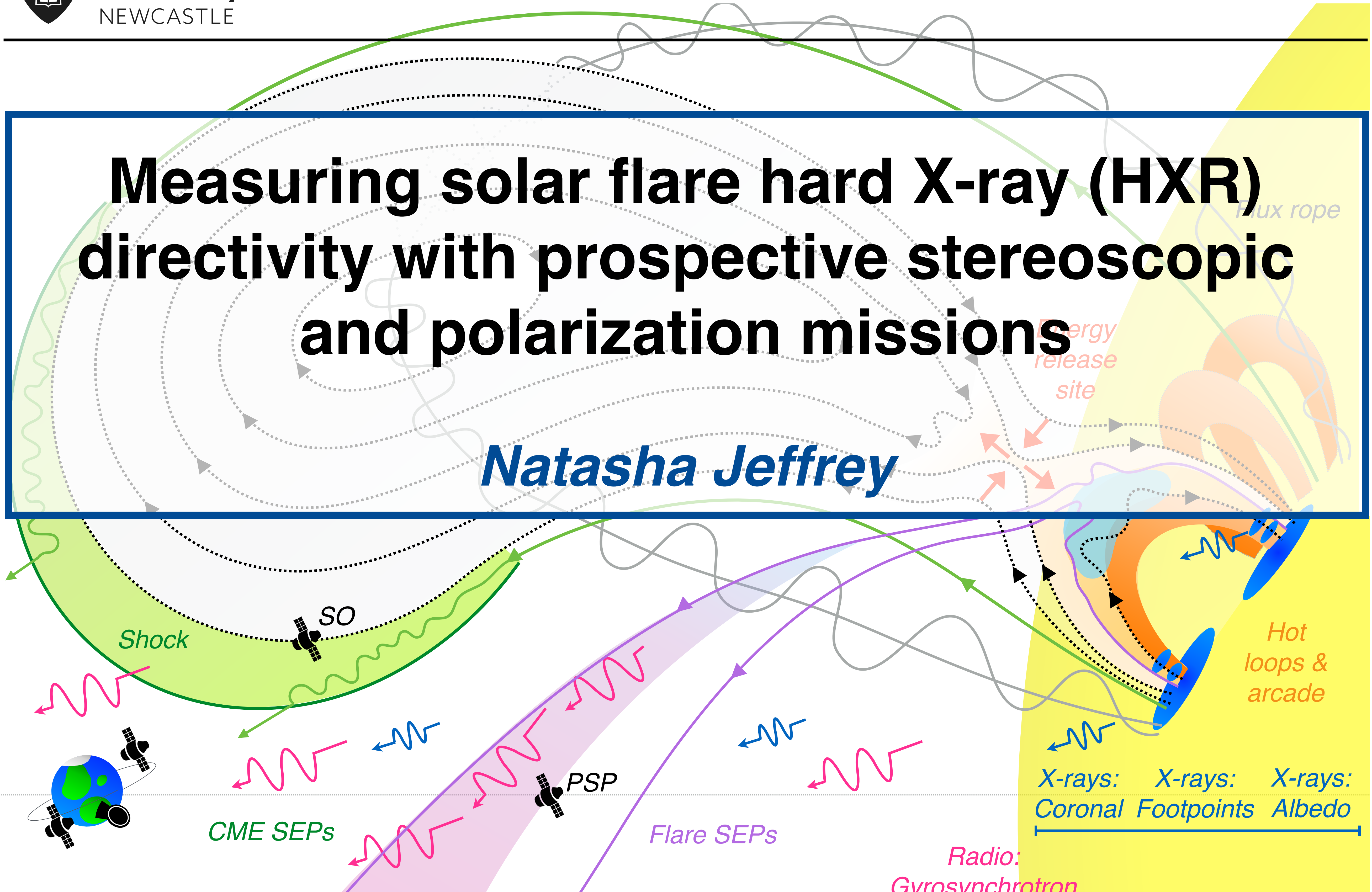
Measuring solar flare hard X-ray (HXR) directivity with prospective stereoscopic and polarization missions

Natasha Jeffrey



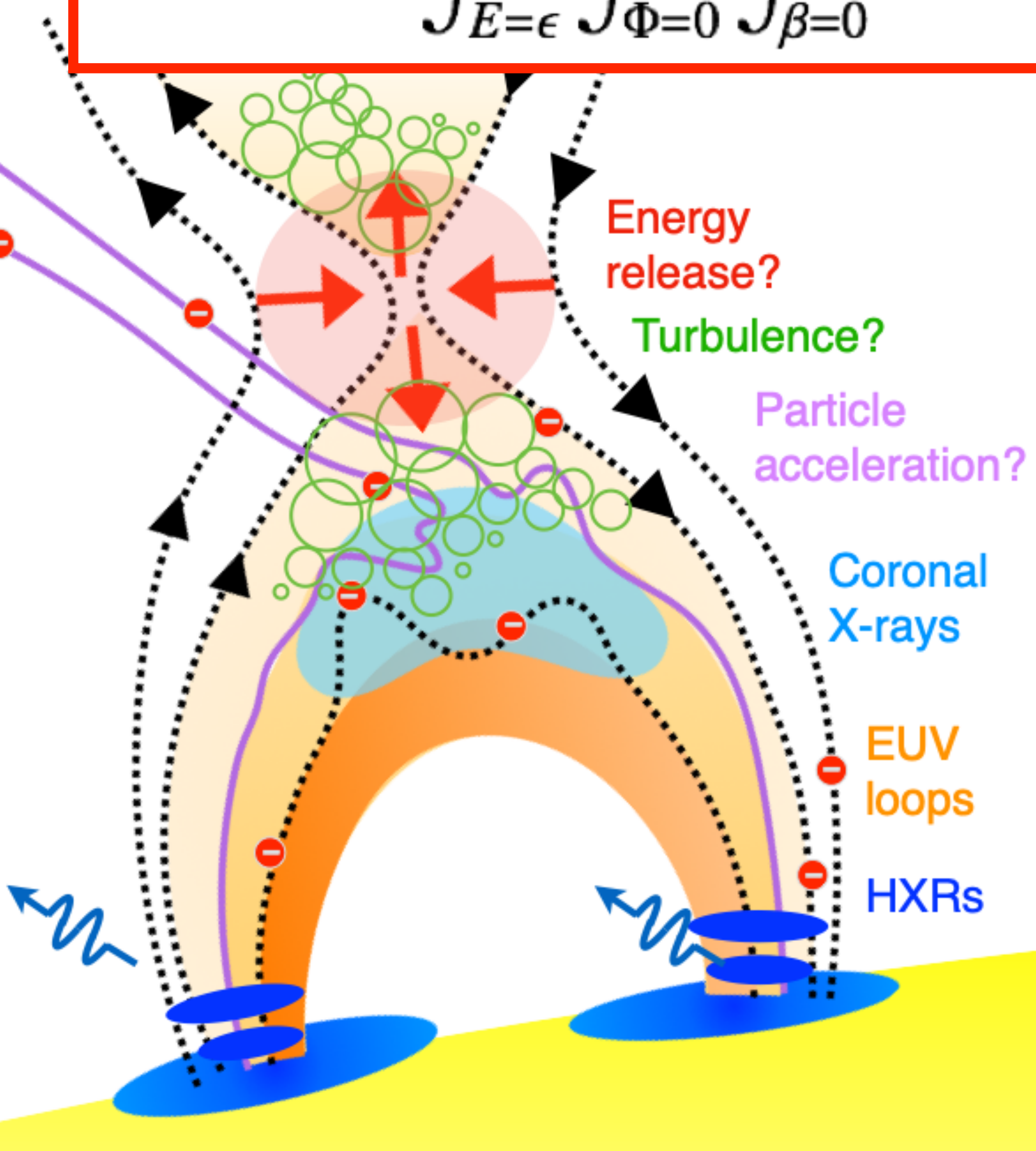
RHESSI Virtual Meeting July 2020

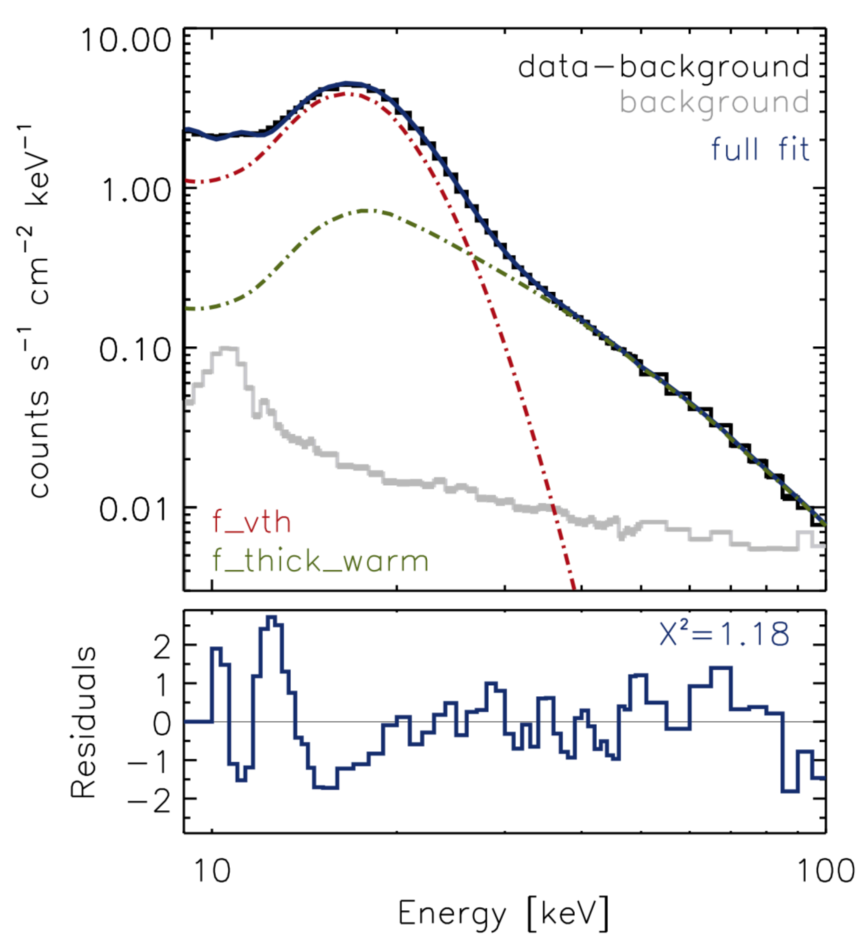
X-ray diagnostics of electrons

X-rays are a direct diagnostic of solar flare accelerated electrons.

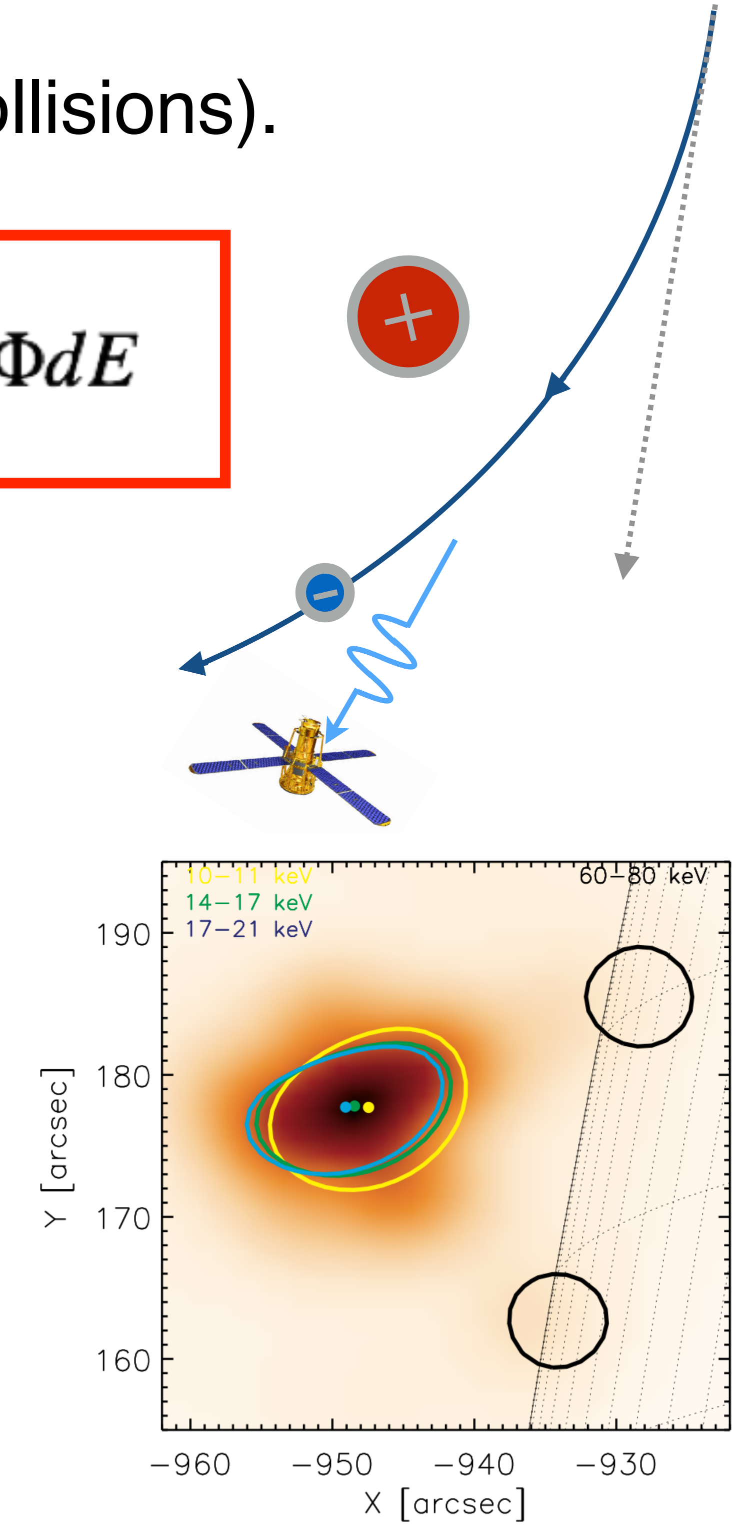
- X-rays are produced as bremsstrahlung (mainly e-i collisions).

$$I(\epsilon,\theta) \propto \int_{E=\epsilon}^{\infty}\int_{\Phi=0}^{2\pi}\int_{\beta=0}^{\pi} F(E,\beta)Q_T(E,\epsilon,\beta,\Phi,\theta)\sin\beta d\beta d\Phi dE$$





X-ray spectroscopy



X-ray imaging

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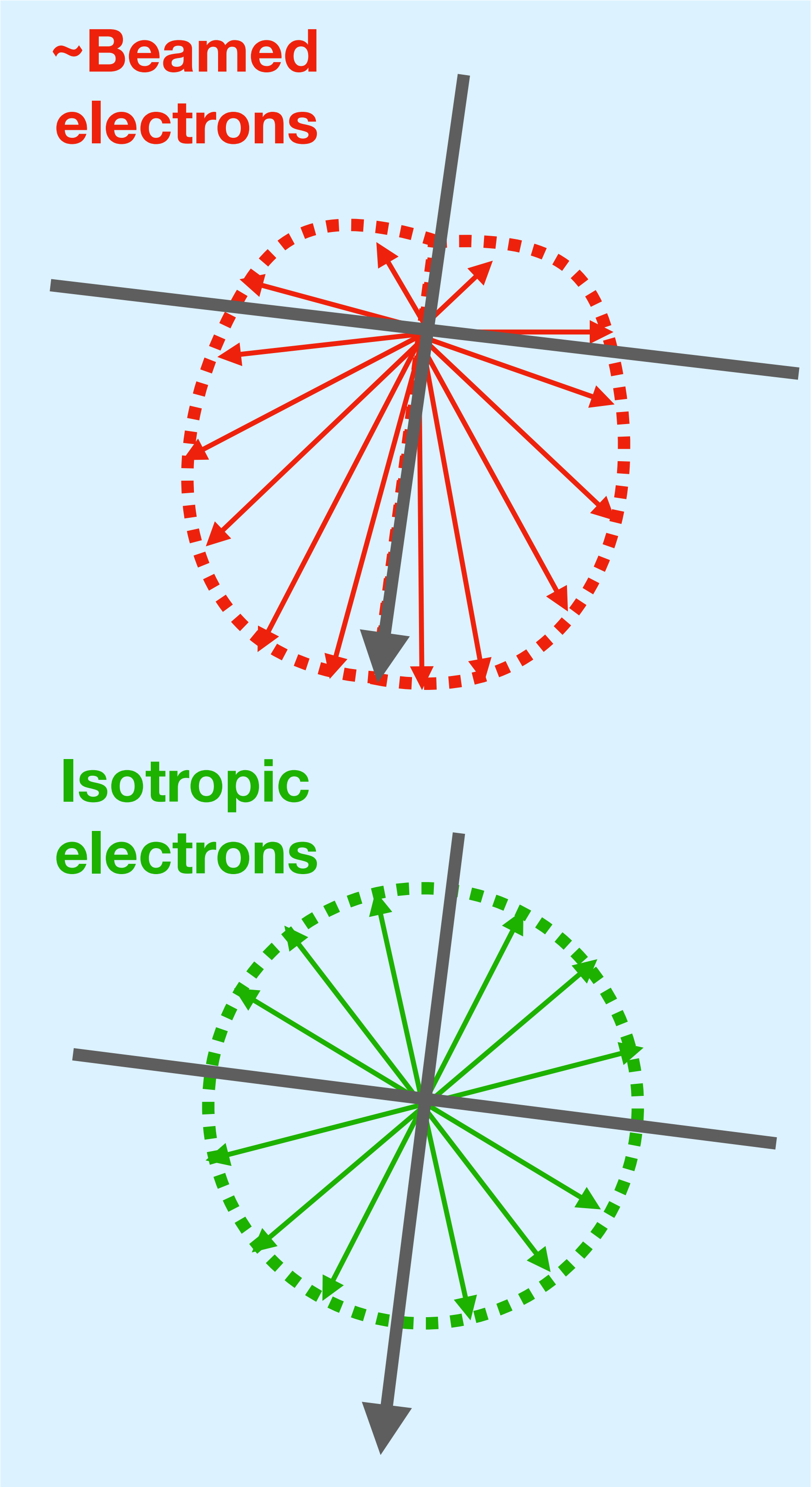
HXR and electron anisotropy

In most solar flares, the directivity of flare-accelerated electrons is an unknown.

- **WHY?** HXR directivity cannot be easily obtained from a single flare X-ray spectrum.
- Electron directivity is a diagnostic of the acceleration mechanism, e.g. stochastic acceleration will produce isotropic distributions (Melrose 1994; Miller et al. 1996; Petrosian 2012).
- Collisional and non-collisional transport effects: create isotropic electron and HXR distributions.
- The X-ray energy spectrum is also dependent on the angular distribution (e.g. Massone et al. 2004)
- The **X-ray albedo** (photospheric Compton backscattering) must always be taken into account.



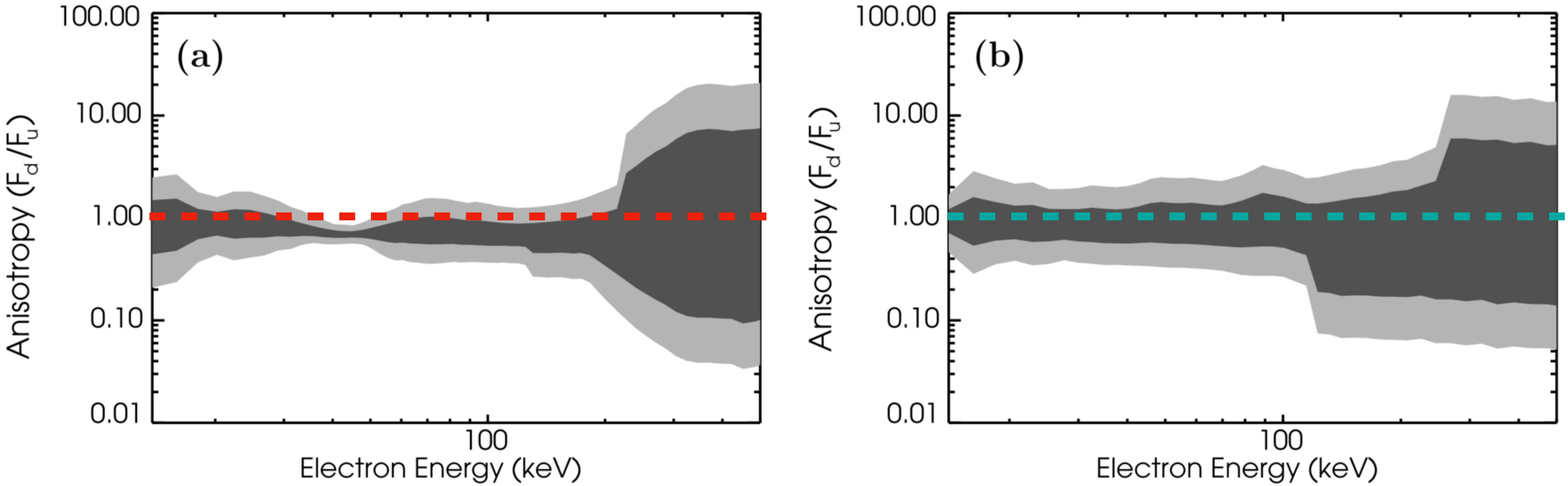
Measuring HXR and electron anisotropy

- So, how can we measure HXR and hence electron anisotropy at the Sun???

1. Statistical flare studies of centre-to-limb variations in flux or spectral index (e.g. Ohki 1969; Kašparová et al. 2007).

2. Albedo mirror analysis of strong solar flares (e.g. Kontar & Brown 2006; Dickson & Kontar 2013).

- Suggests close to isotropic/lack of electron anisotropy below 150 keV.



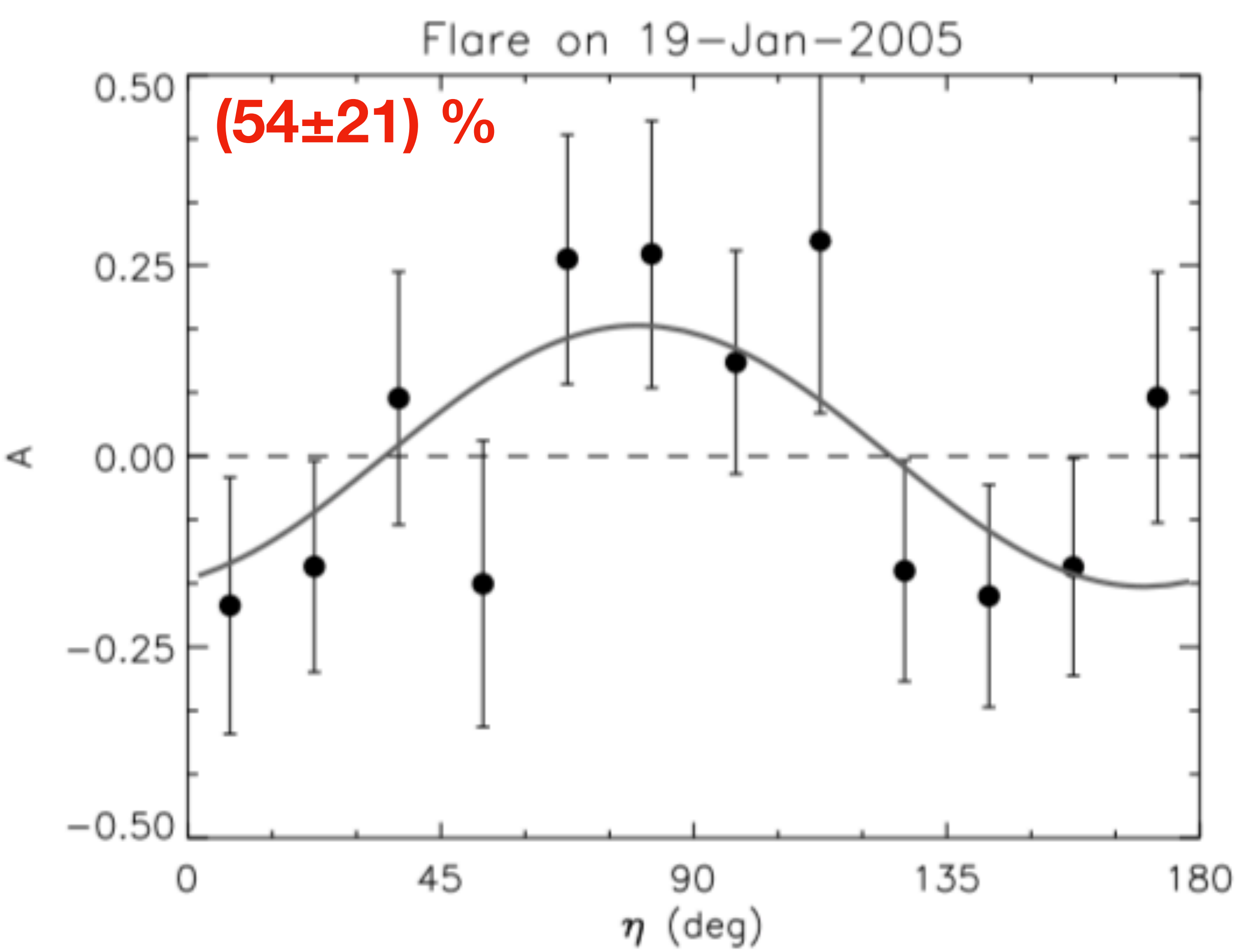
Dickson & Kontar 2013

Measuring HXR and electron anisotropy

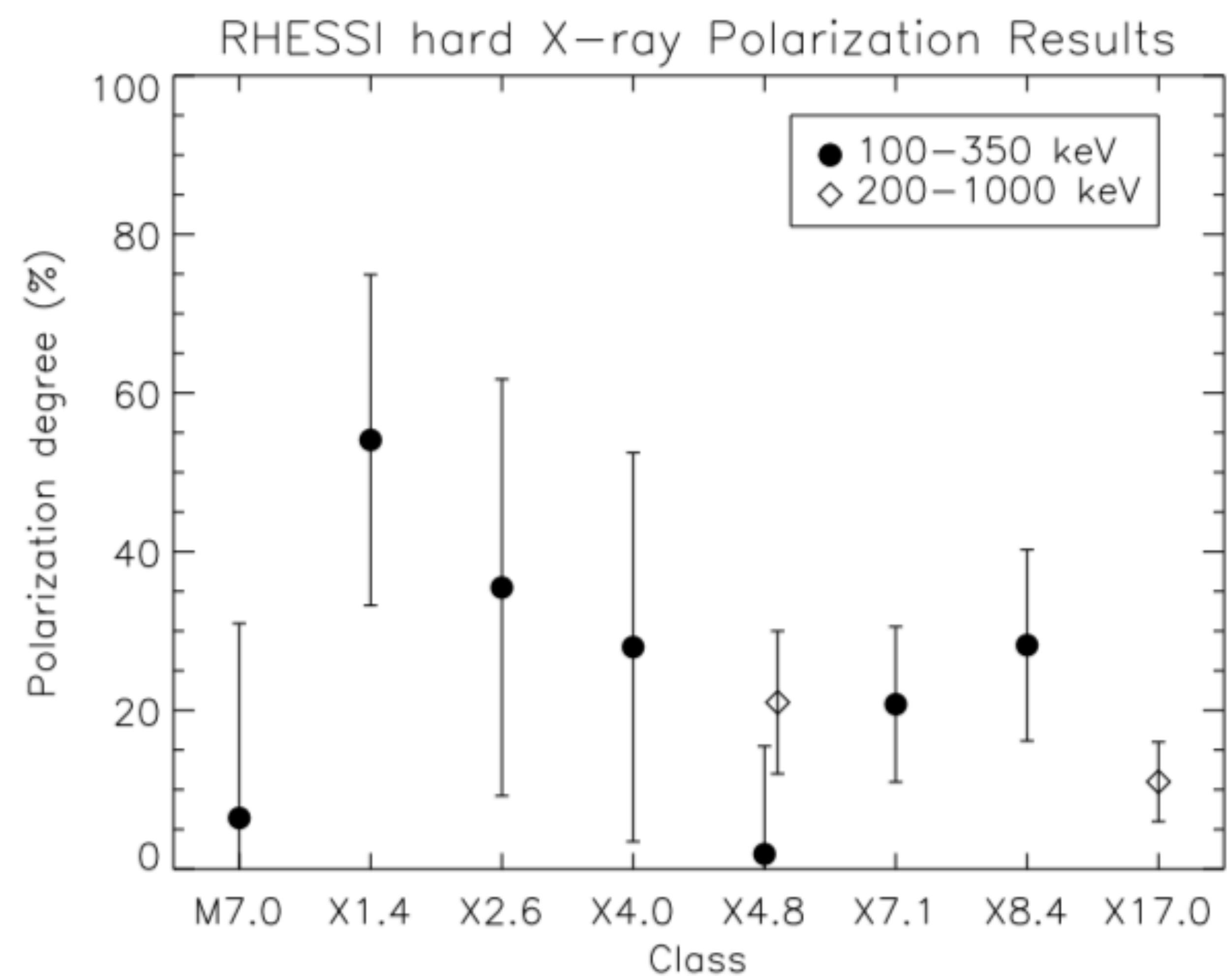
- So, how can we measure HXR and hence electron anisotropy at the Sun???

3. Linear X-ray polarization from a single flare with one satellite (e.g. Tindo et al. 1970; McConnell et al. 2004; Suarez-Garcia et al. 2006).

- Many polarimeters were not optimised for flares or were secondary ‘add-on’ missions.



Suarez-Garcia et al. (2006)



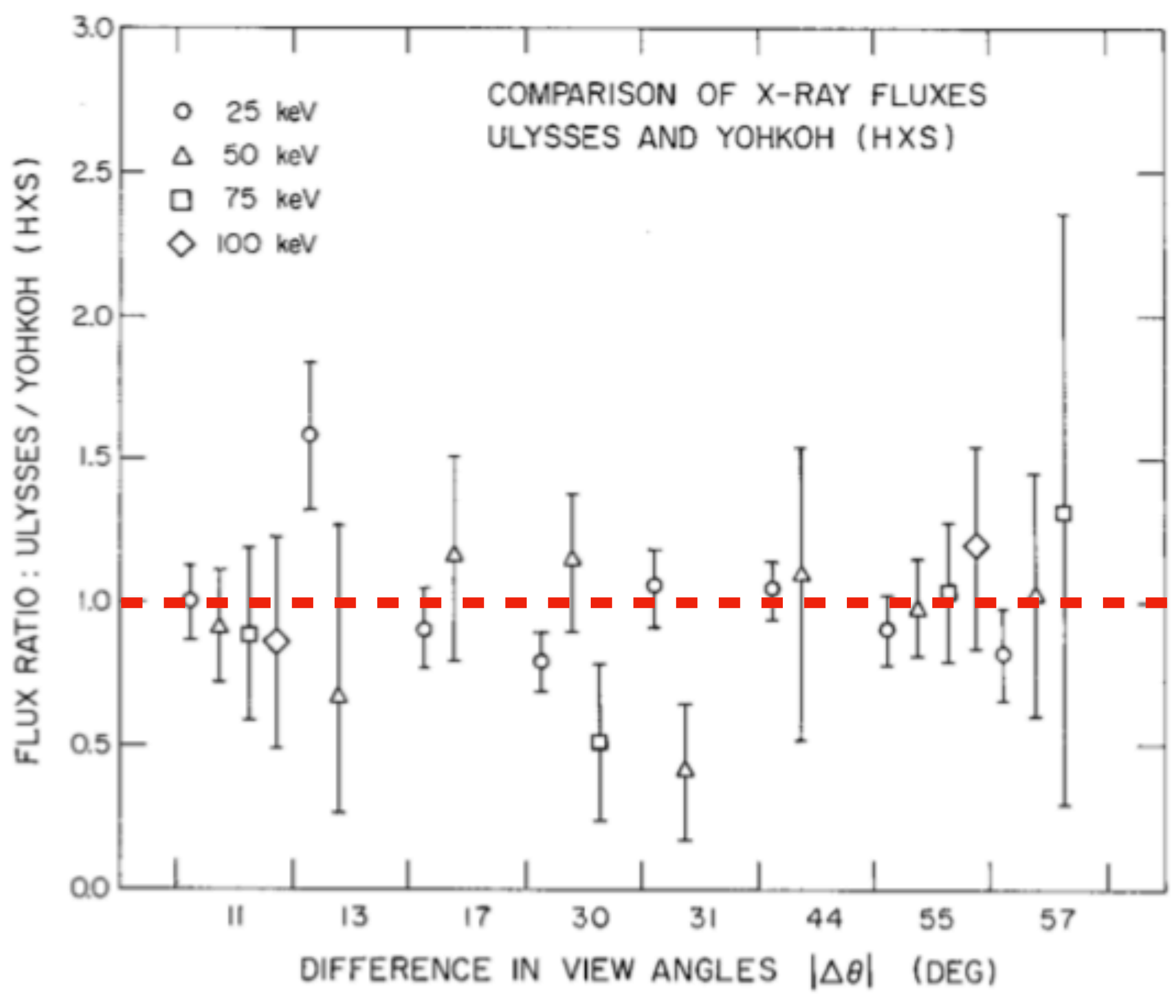
Taken from Kontar et al. (2011)

Measuring HXR and electron anisotropy

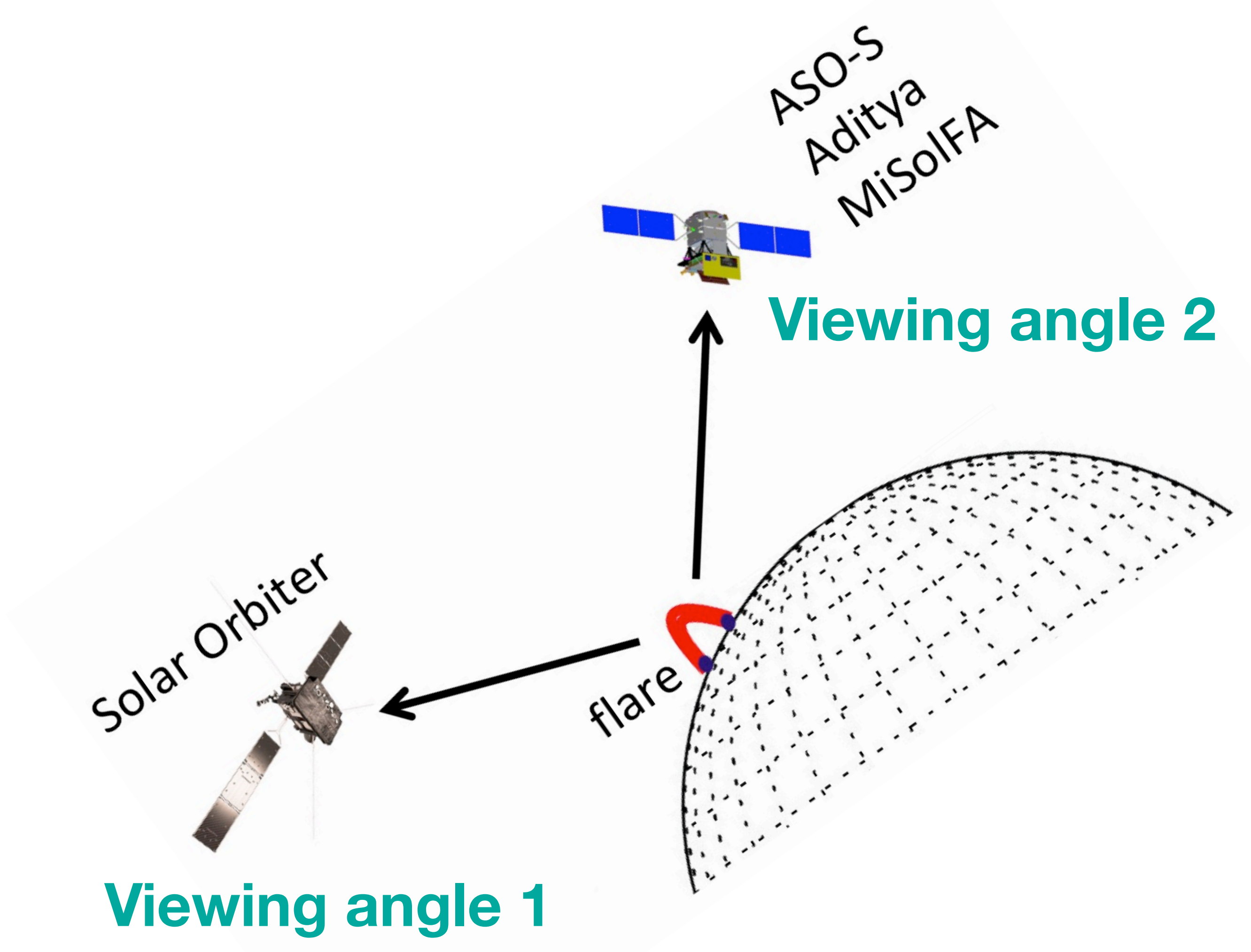
- So, how can we measure HXR and hence electron anisotropy at the Sun???

4. Simultaneous observations of a flare with two satellites at different viewing angles (e.g. Kane et al. 1988, 1998; McTiernan & Petrosian 1990).

- Past direct measurements by multiple spacecrafts suffered from calibration issues, owing to the use of different types of detectors.



Kane et al. (1998)



Cartoon: Säm Krucker

Prospective HXR 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 (2021/22)	Aditya-HEL1OS (2021)	MiSolFA
Chinese mission	Indian mission	NASA CubeSat
3-200 keV	10-150 keV	10-100 keV
Imaging ✓	No imaging ✓	Imaging ?
Zhang et al. 2019 *Su et al. 2019*		*Casadei et al. 2017* *Lastufka et al. 2019*

1st joint observations: STIX and HEL1OS will be available in the 2nd half of 2021.

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Chinese mission
3-200 keV
Imaging ✓
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Aditya-HEL1OS (2021)
Indian mission
10-150 keV
No imaging ✓

MiSolFA
NASA CubeSat
10-100 keV
Imaging ?
Casadei et al. 2017
Lastufka et al. 2019

MiSolFA is proposed for stereoscopy with STIX carrying identical detectors.

Prospective HXR polarization missions?

PhoENiX

(proposed)

Japanese PhoENiX mission (Physics of Energetic and Non-thermal plasmas in the X (= magnetic reconnection) region).

Energy range: 60-300 keV

(20-300 keV for spectroscopy)

Sapphire

(proposed)

NASA Sapphire (Solar Polarimeter for Hard X-rays) concept aims to do spatially-integrated spectro-polarimetry of solar flares from CubeSat platforms.

Energy range: 10-100 keV

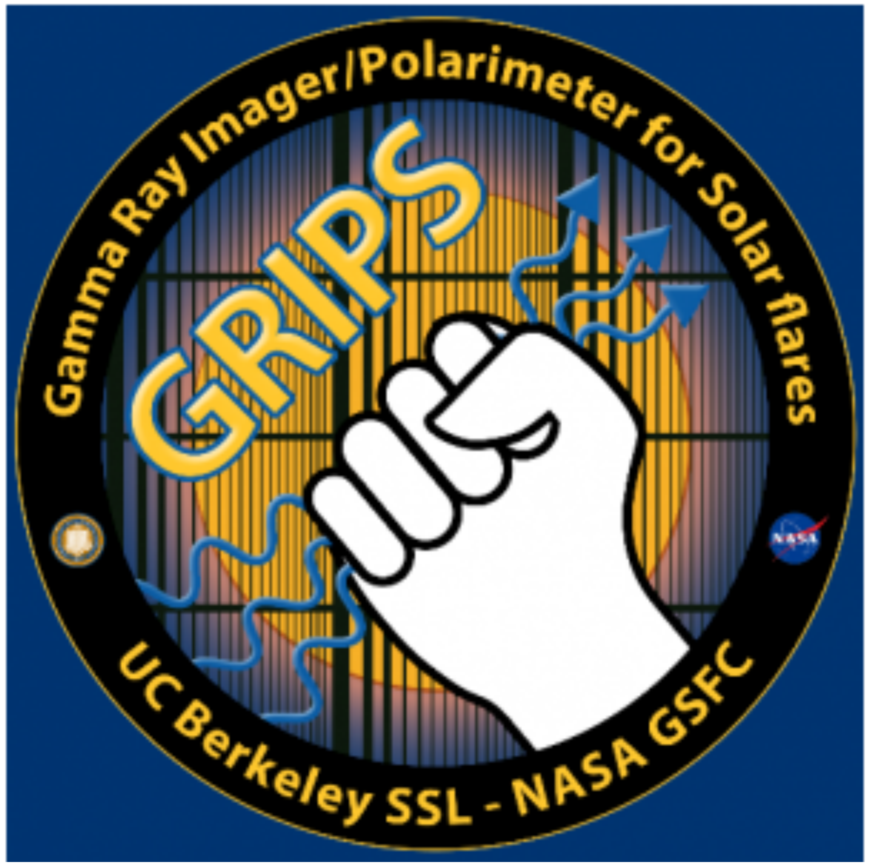
GRIPS

(balloon leading to spacecraft?)

Gamma-Ray Imager/Polarimeter for Solar flares (GRIPS; **Duncan et al. (2016)**)

Imaging spectro-polarimetry of flares in the 150 keV to 10 MeV

(angular resolution of ~ 12.5”)



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Electron and X-ray Simulations

- To understand the new X-ray data (**stereoscopic and polarization**) we need realistic electron and X-ray transport simulations:

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

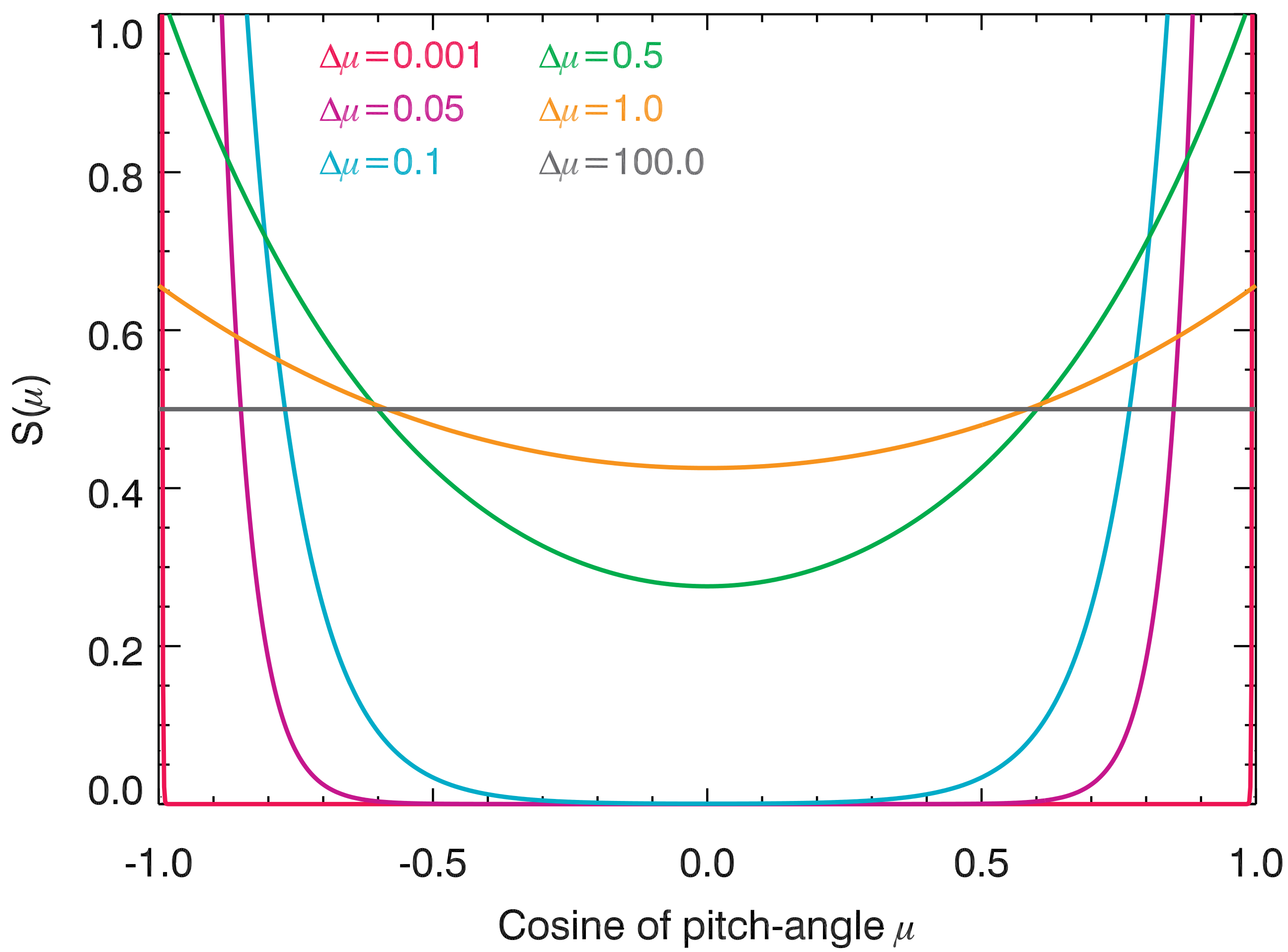
- ***Full collisional warm target model (Jeffrey et al 14., Kontar et al. 15,19).***
- ***Simple turbulent scattering component.***
- ***Additional code that accounts for the X-ray albedo component.*** ✓

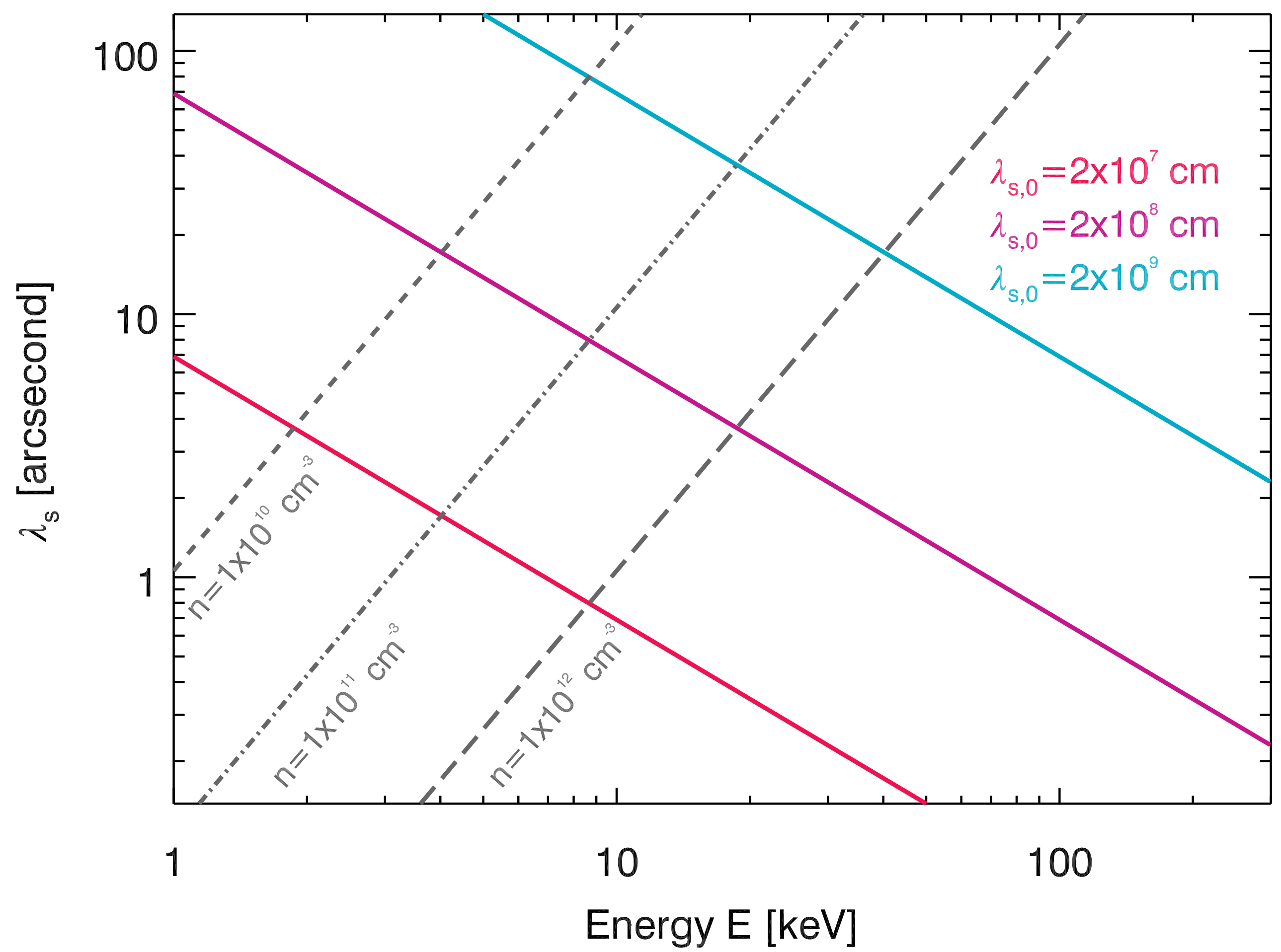
We want to produce outputs to match current or upcoming abilities of missions.

Electron and X-ray Simulations

- **Pitch-angle distribution:**

$$S(\mu) \propto \frac{1}{2}\exp\left(-\frac{(1-\mu)}{\Delta\mu}\right) + \frac{1}{2}\exp\left(-\frac{(1+\mu)}{\Delta\mu}\right)$$



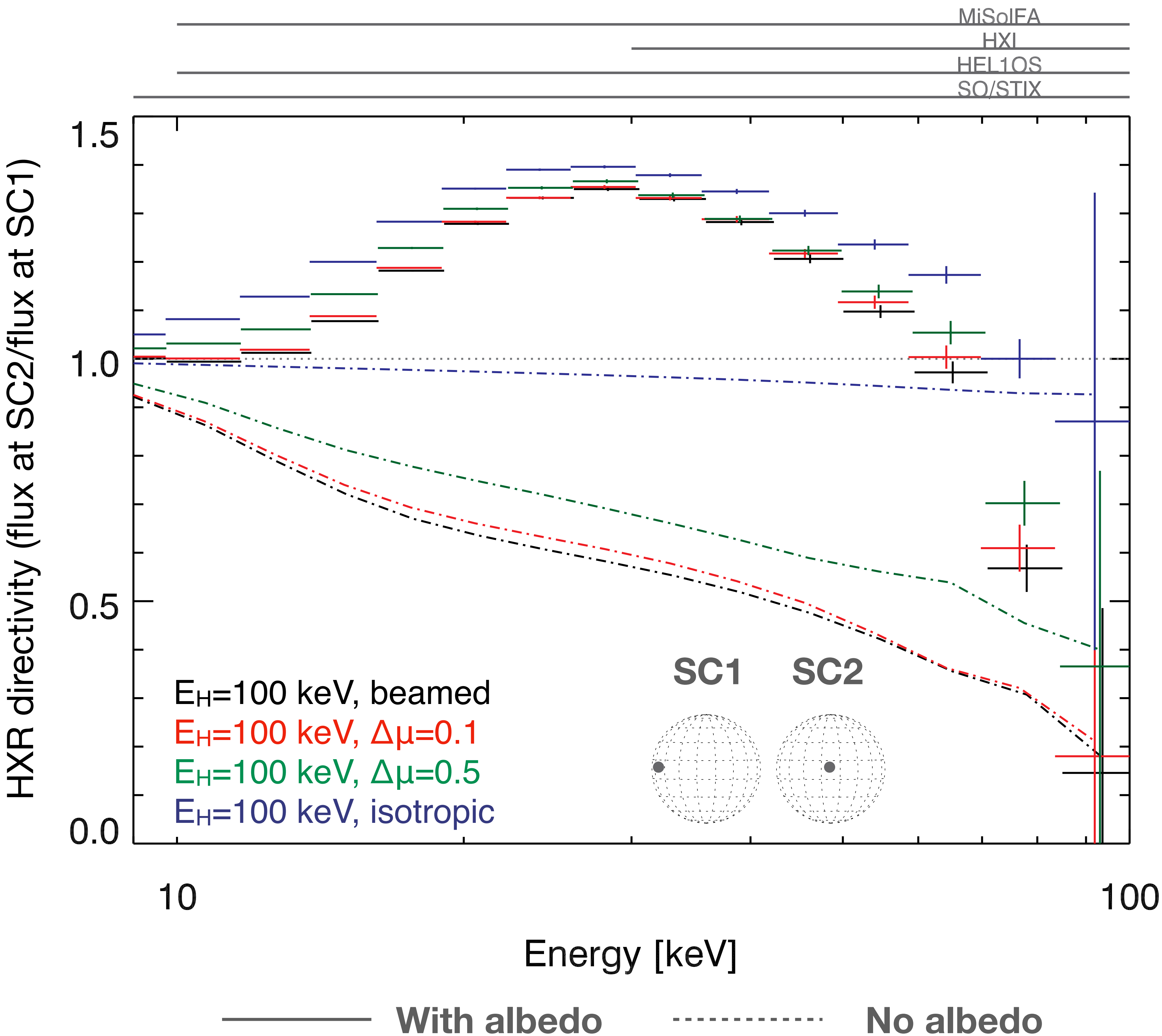


- **Isotropic turbulent scattering model taken from Musset et al. (2018).**

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

Stereoscopic example 1: anisotropy

- Identical plasma and spectral properties
- Identical high energy cutoffs
- *Different anisotropies*
- Viewing angles of 20° (SC2) and 60° (SC1).



Polarization example 1: anisotropy

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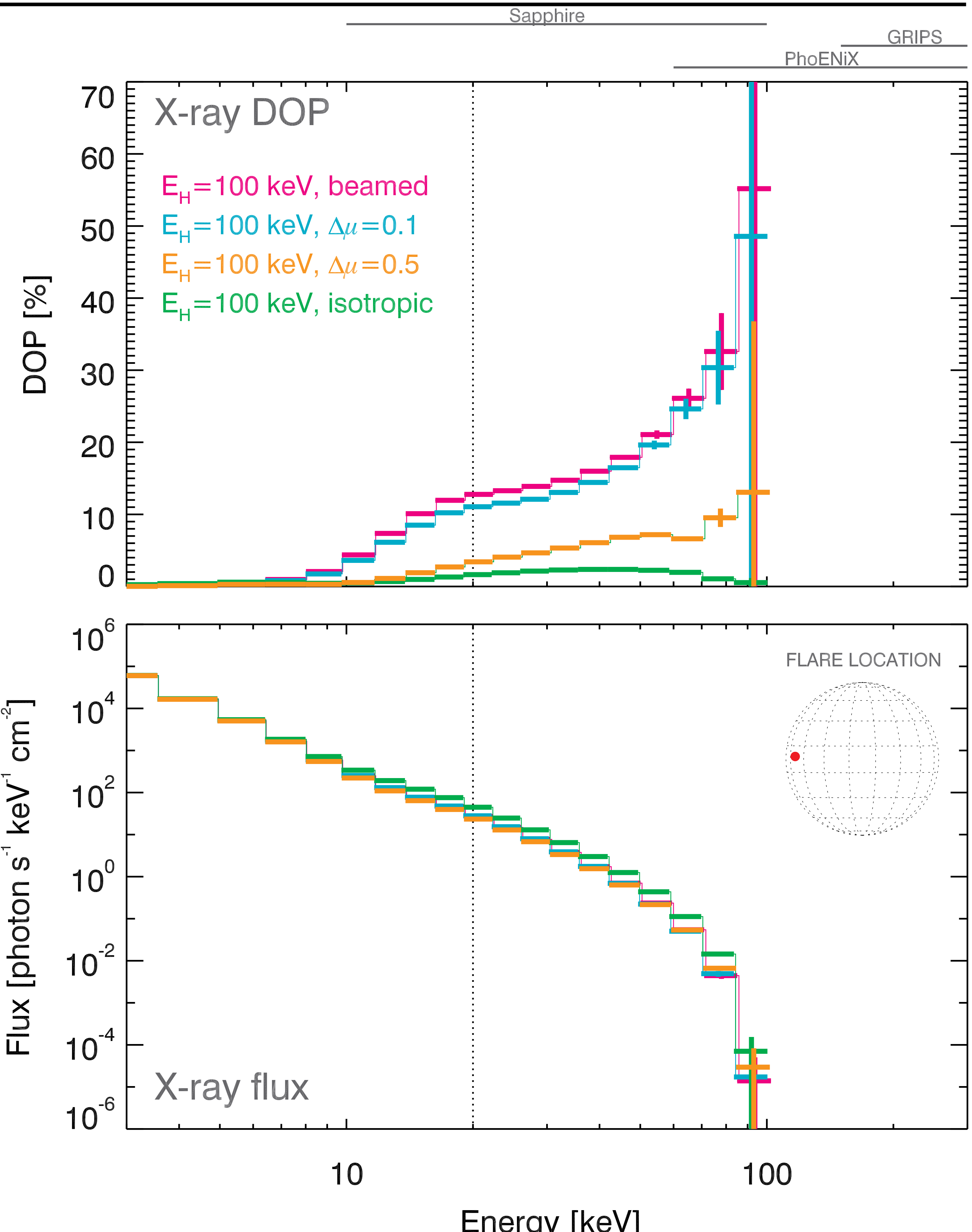
- Identical spectral and plasma properties
- Same high energy cutoff.
- ***Different anisotropies***

It is difficult to extract anisotropy information from the X-ray flux spectrum!

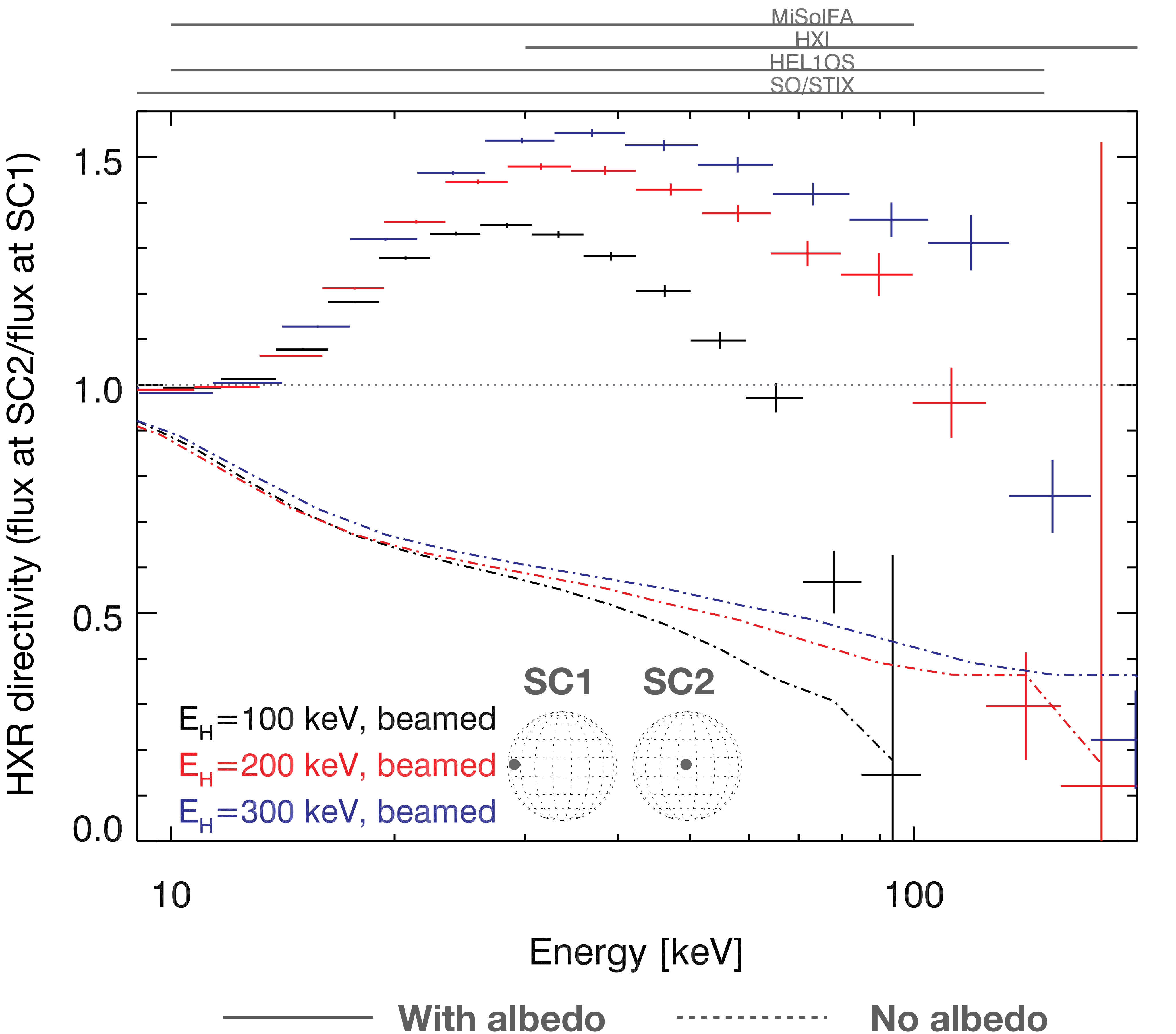
As expected DOP decreases with decreasing anisotropy over all E.



Jeffrey et al. 2020, submitted

Stereoscopic example 2: high energies

- Identical plasma and spectral properties
- *Different high energy cutoffs*
- Identical anisotropies
- Viewing angles of 20° (SC2) and 60° (SC1).



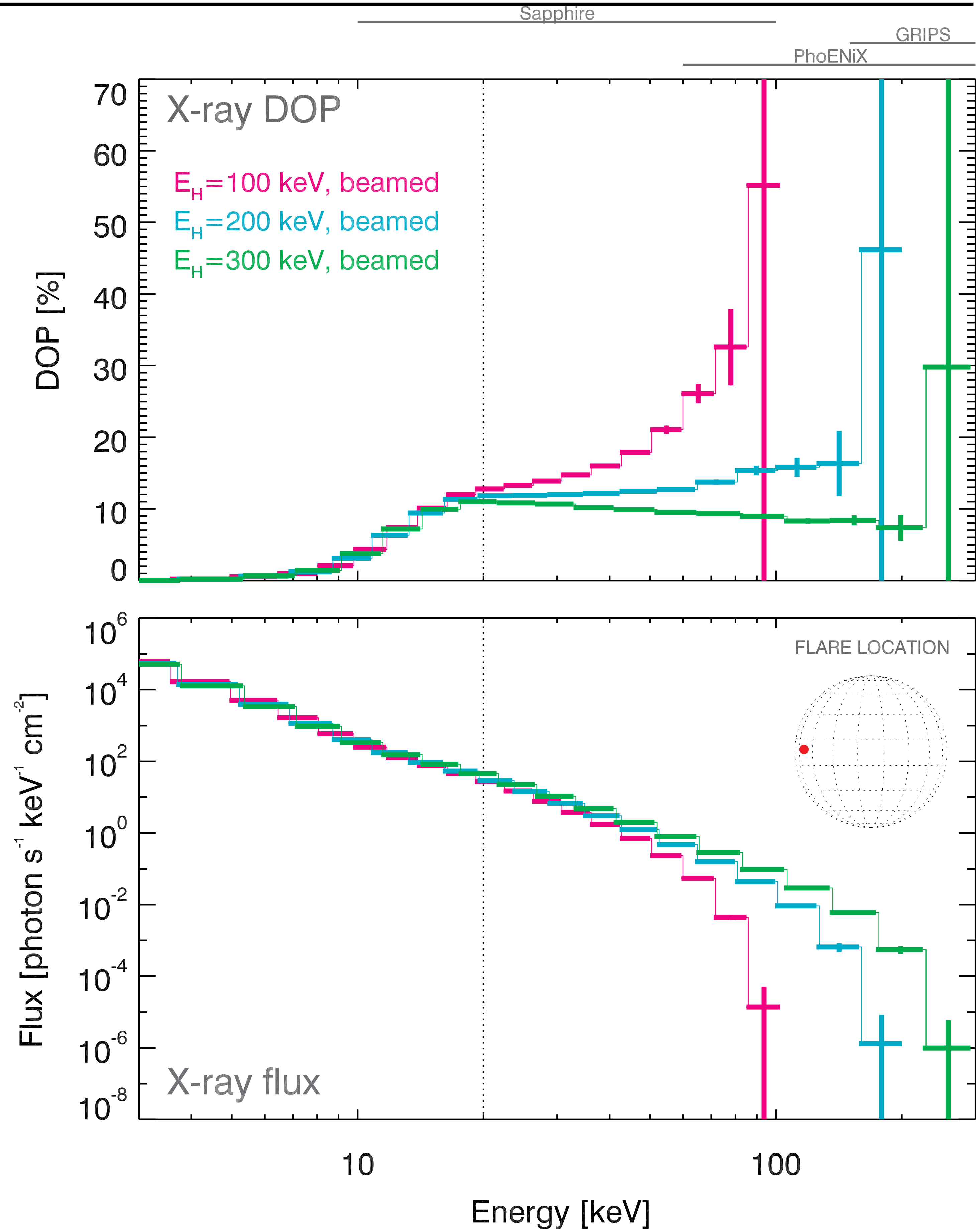
Polarization example 2: high energies

- Identical spectral and plasma properties
- ***Different high energy cutoffs.***
- Identical anisotropy.

High energy cutoff changes the DOP spectrum

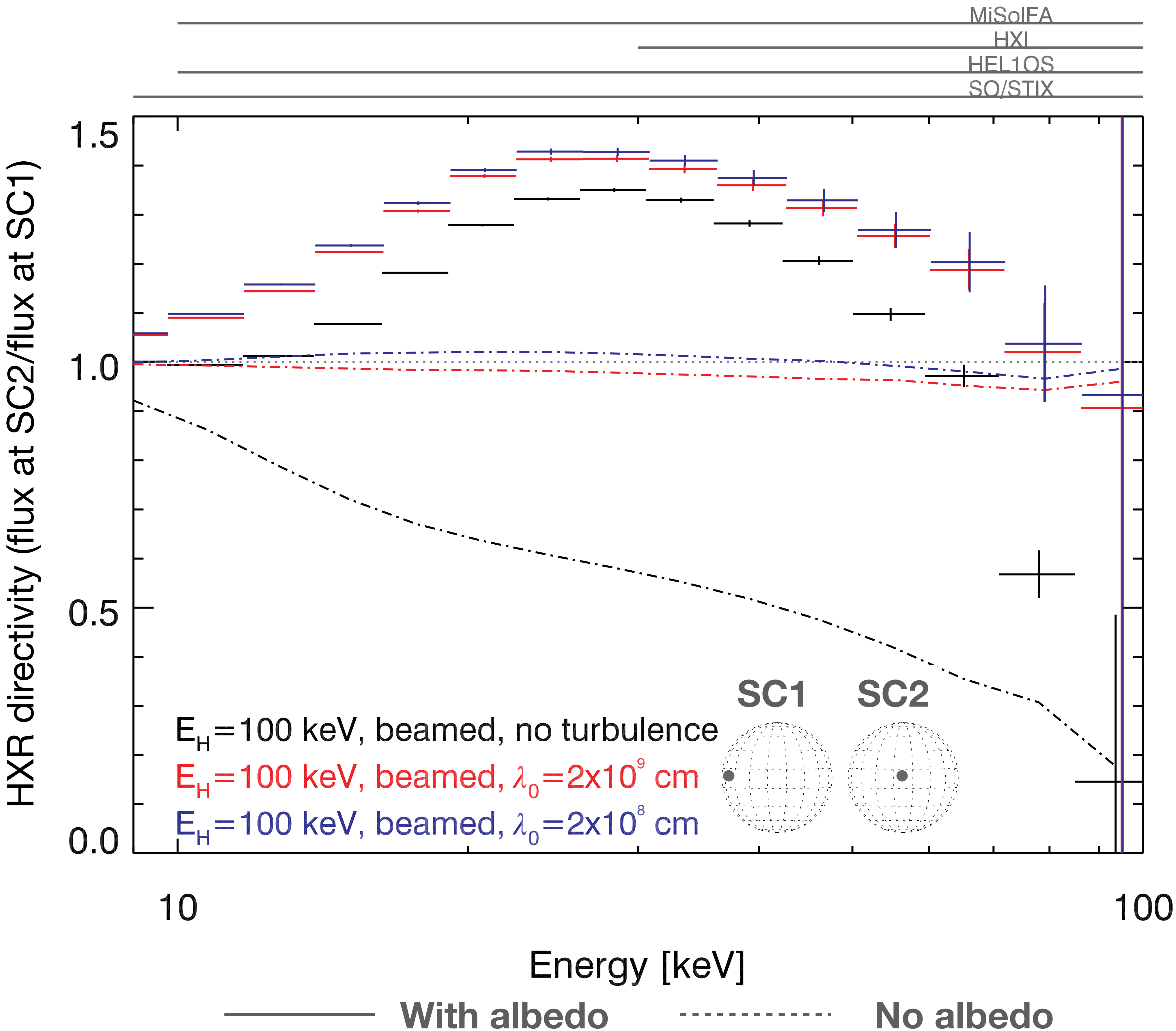
A low DOP vs. E might not be due to beaming!

Jeffrey et al. 2020, submitted



Stereoscopic example 3: turbulence

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



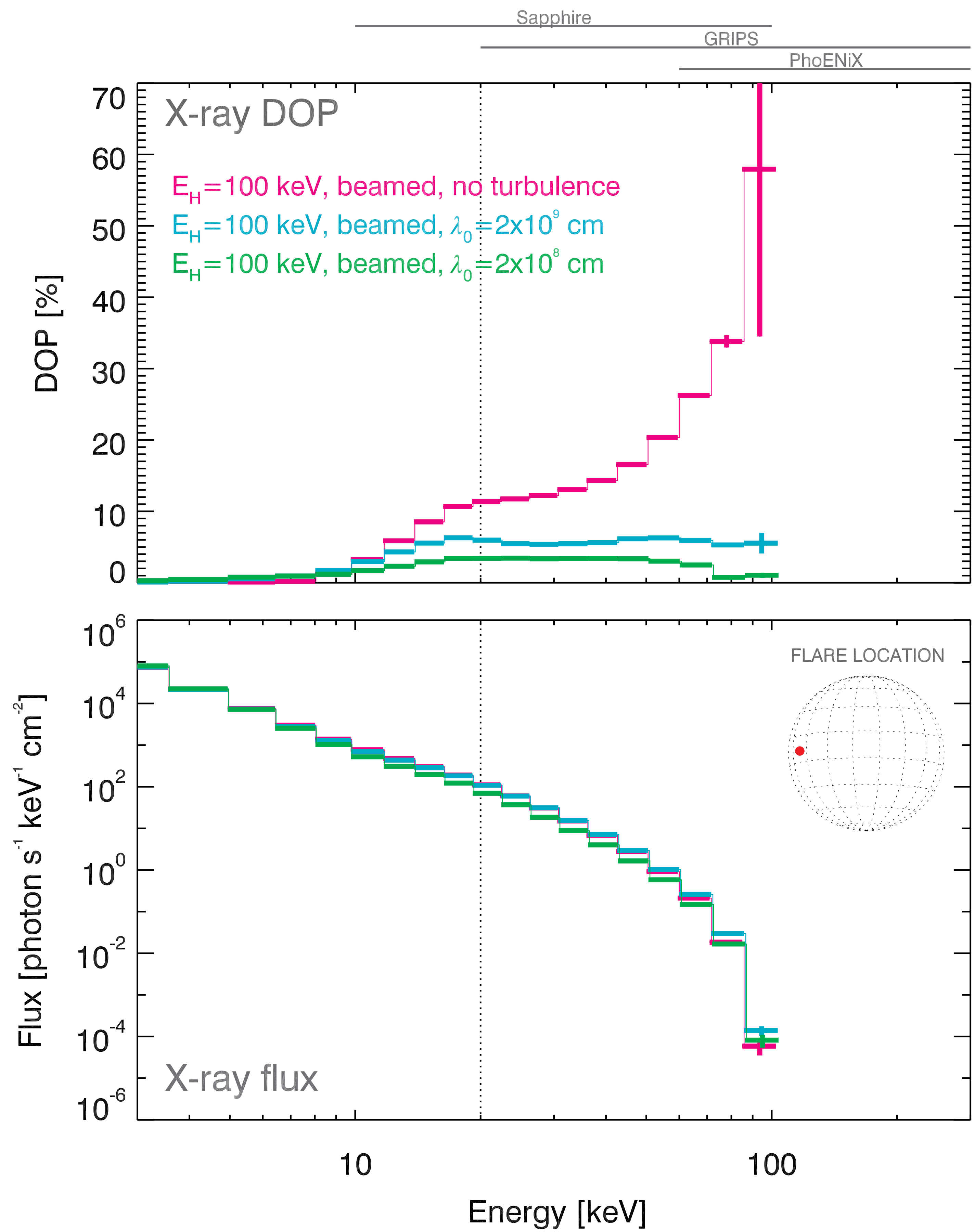
Polarization example 3: turbulence

- Identical spectral and plasma properties
- Identical high energy cutoffs and anisotropies.
- *Varying turbulence.*

Turbulence quickly isotropies the electrons.

Can the level of turbulence also be determined from the DOP spectrum?

Jeffrey et al. 2020, submitted



Summary

HXR directivity is the prime diagnostic of electron directivity.

- Finding electron directivity is important for:

  - Constraining the electron acceleration mechanism

  - Helping to determine coronal transport processes

  - Constraining properties from the X-ray spectrum

- The best chance of constraining directivity will come from upcoming stereoscopic observations with SO/STIX and new missions at Earth.

- Simulations show that spatially integrated polarization missions without imaging (CubeSat missions?) can provide constraints on electron anisotropy and the high energy cutoff.