Reconstructing the Heliospheric Magnetic Field with Radio Observations

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The majority of astrophysical radio sources are found in turbulent & magnetised environments. As the emitted radio-waves propagate through such background media, they can scatter from ambient density inhomogeneities, resulting in a variety of effects such as shifts in apparent position & angular broadening.

- During solar flares, energetic electrons can escape into interplanetary space along magnetic field lines & are responsible for type III solar radio bursts (**Fig. 1a**).
- Solar radio bursts can be observed simultaneously from multiple spacecraft at different vantage points, providing a unique opportunity to study their propagation through the heliosphere.

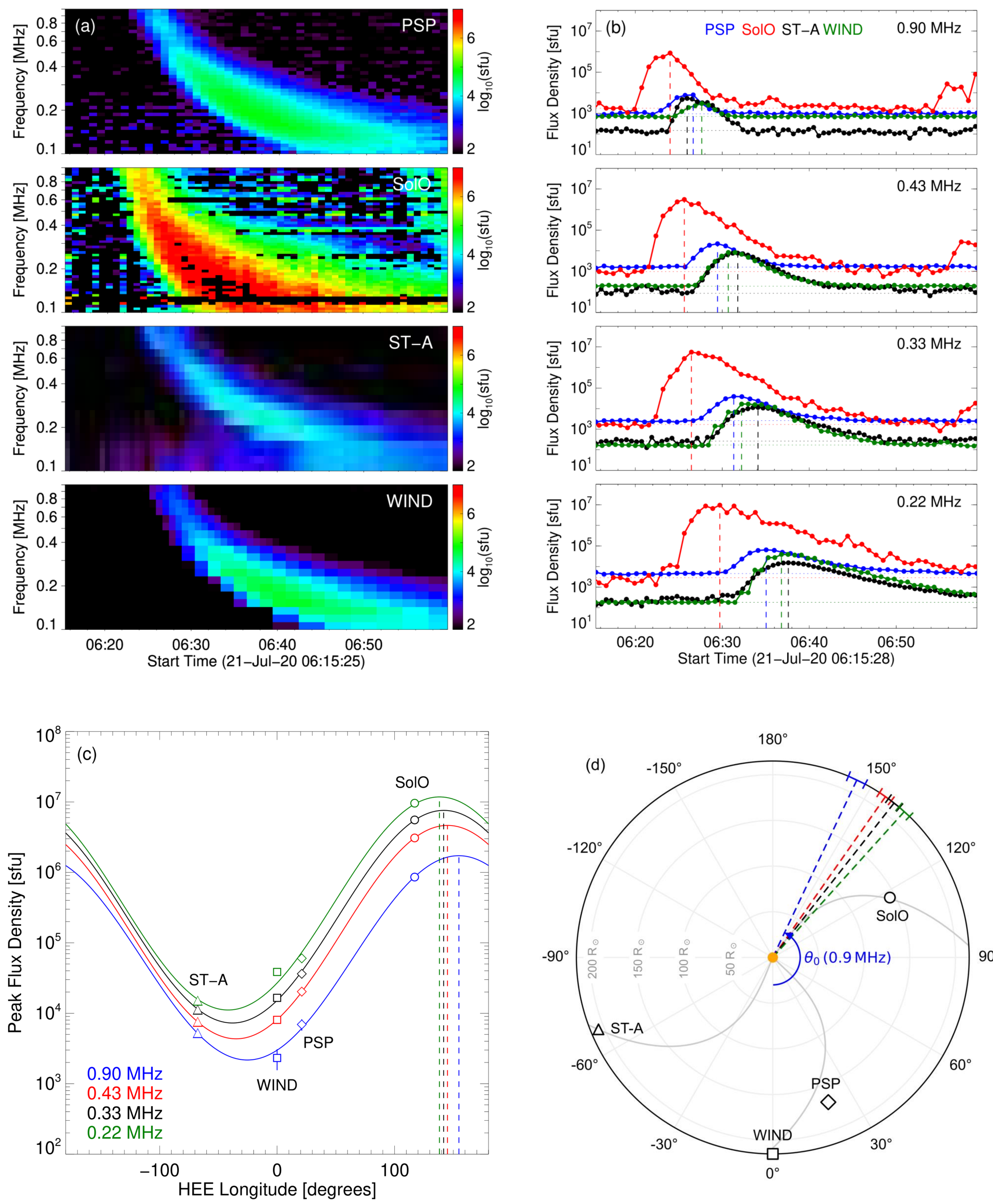

Figure 1 Type III burst observed by multiple spacecraft. All flux densities are scaled to 1 au. **(a)** Dynamic spectra. **(b)** Time profiles from each spacecraft. **(c)** Peak intensities at each frequency against observing longitude, fit with the model of eq. 1. **(d)** Polar representation of the fitted longitudes of peak intensity at each frequency.

Observations

Using up to 4 spacecraft (*Parker Solar Probe, Solar Orbiter, STEREO-A, WIND*), we investigate the directivity of 20 type III radio bursts (e.g. **Fig. 1a**) via intensity fitting. The peak flux values at four frequencies (**Fig. 1b**) are fit with the model of eq. 1 (**Fig. 1c**) to determine the direction of maximum flux (**Fig. 1d**). Changes in θ_0 are quantified by $\Delta\theta$ (eq. 2).

$$I_{sc} = I_0 \exp\left(-\frac{1-\cos(\theta_{sc}-\theta_0)}{\Delta\mu}\right) \quad \text{(eq. 1)}$$

$$\Delta\theta = \theta_0 - \theta_0(0.9\text{ MHz}) \quad \text{(eq. 2)}$$

- The average behaviour of $\Delta\theta$ varies with frequency, deviating eastward by $-(30 \pm 11)°$ at 0.2 MHz (**Fig. 3a**).
- This is too steep to be caused by the electron motion along the Parker spiral (see the coloured bands in **Fig. 3a**) unless the solar wind speed is abnormally low (50 km s^{-1}).

➢ **Either typical observed solar wind speeds and Heliospheric magnetic field structure is incorrect, or there is an additional mechanism driving the strong flux variation with longitude.**

Anisotropic radio-wave propagation

Radio-waves scatter off density inhomogeneities in turbulent plasma. All observed characteristics of radio bursts are explained simultaneously only with turbulence anisotropy (Kontar+2019); i.e. density fluctuations are elongated parallel to the field → preferential scattering in the perp. direction, leading to **channelling of radio-waves *along* the field.**

- Adding the Parker spiral to an anisotropic scattering model (Kontar+2019, 2023), we traced photons from numerous point-sources between 0.9-0.2 MHz out to 1 au (**Fig. 2**).
- The scattering rate decreases with distance, forming a "surface of last scattering". Here, the directivity pattern has a maximum that is tangent to the local field.

➢ **Combining anisotropic scattering with the Parker field model shows excellent agreement with observations (Fig. 3b): *large-scale field structures are encoded in the observed radio emission directivity, revealed via intensity fitting.***

Anisotropic scattering means that triangulating radio sources with multi-spacecraft observations yields only the *apparent* source. The longitudinal shift must be disentangled to infer the intrinsic emission location.

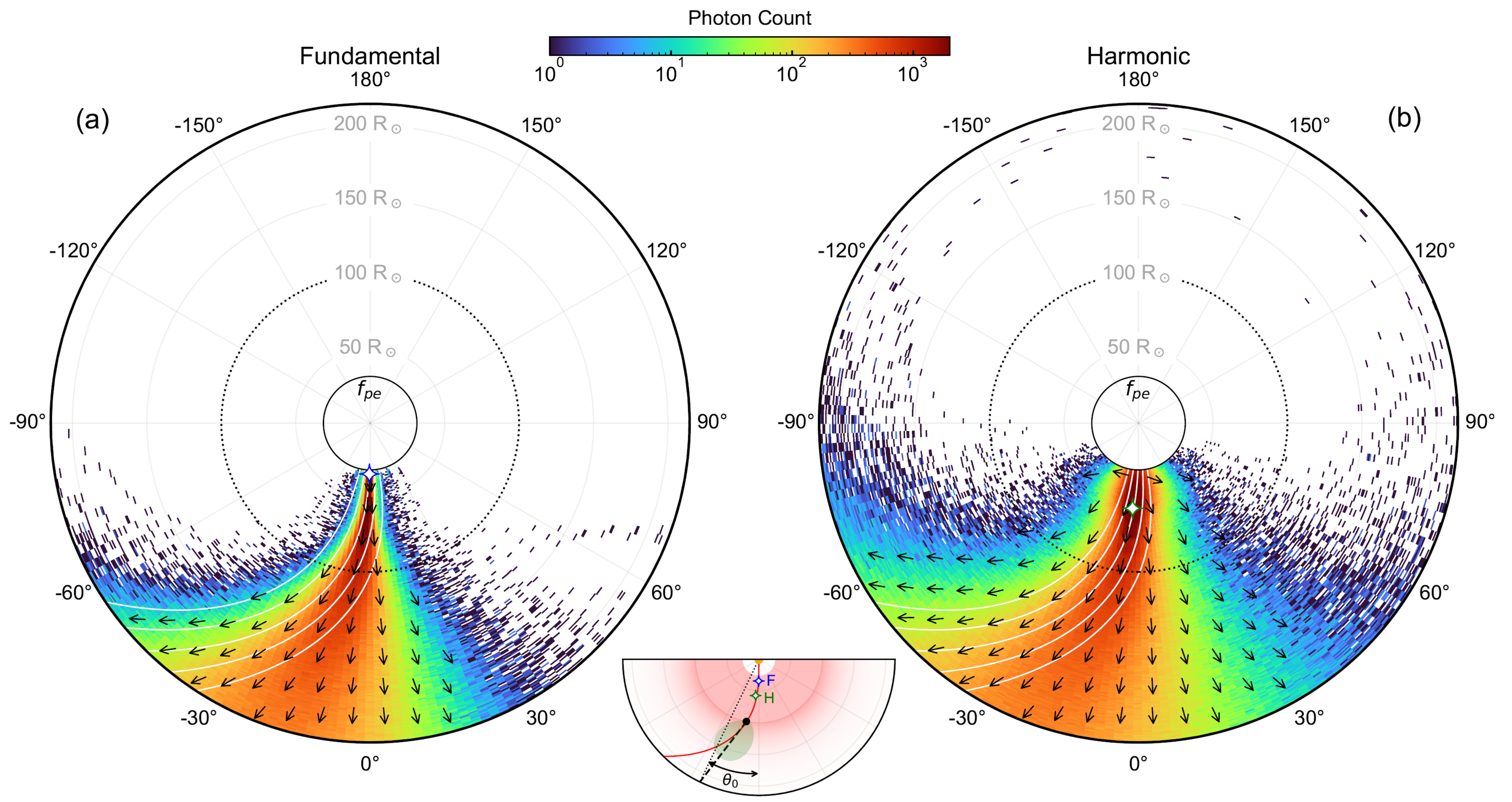

Figure 2 Simulated photon propagation in the heliosphere for **(a)** fundamental (blue star) & **(b)** harmonic (green star) emitters. The 2D histograms show the aggregate photon positions, overlaid with wavevectors. White curves show the Parker spiral. The inner rings denote the plasma frequency surface. The inset shows the resulting emission directivity.

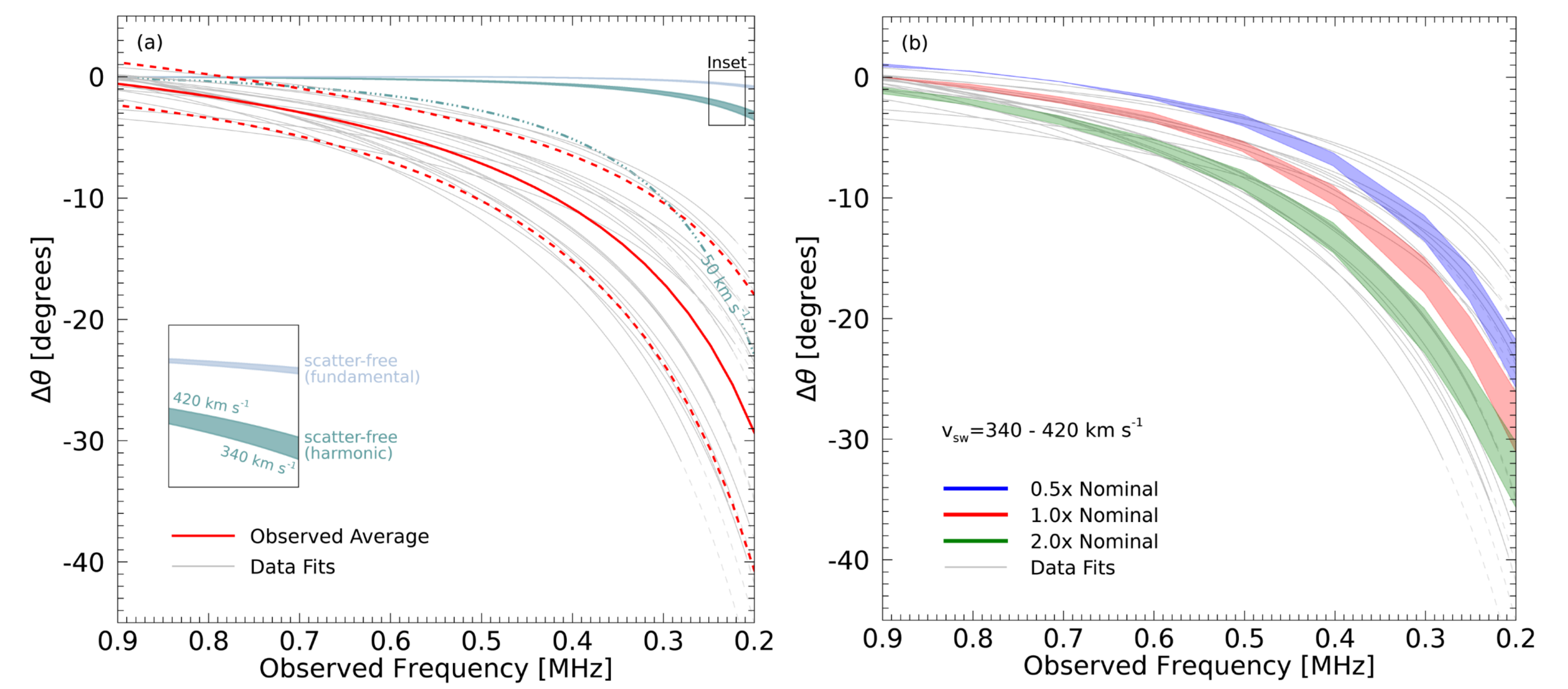

Figure 3 Longitudinal deviation $\Delta\theta$ of the fitted peak intensity. **(a)** Observations (grey) & their average (red). Coloured bands show the scatter-free cases. **(b)** Simulated results for different scattering rates (see Kontar+2023) and v_{sw}.

References: Kontar+(2019), *ApJ*, 884, 122 Kontar+(2023), *ApJ*, 956, 112

Conclusion

➢ **Radio-waves are channelled along magnetic fields** through anisotropic scattering in magnetised plasma.

➢ The interplanetary magnetic field structure is encoded in the observed radio emission directivity.

➢ The longitudinal shift due to anisotropic scattering effects must be disentangled to reveal intrinsic source locations.

➢ Magnetic field structures within turbulent media can be reconstructed using radio observations, offering a novel method for remotely diagnosing the large-scale field structures in astrophysical plasmas.