



Probing Blazar-Jet Structure with Multi-Zone Synchrotron Polarization Modelling

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INTRODUCTION

The lower-energy component of a blazar's spectral energy distribution (SED) is predominantly attributed to synchrotron radiation, originating from relativistic electrons within the jet [1]. This emission is intrinsically polarized, and polarization signatures can place constraints on the geometry of the magnetic field, the electron distribution and the viewing geometry [2,3]. While one-zone models are often able to approximate the observed emission well, their assumption of a single homogeneous emission region does not take into account spatial complexities which can affect polarization. In order to account for these complexities, we are developing a multi-zone model, specifically to investigate how they influence polarization. In this model, the emission region is divided into individual cells, each with a defined electron density and magnetic-field vector [4]. The synchrotron emissivity, self-absorption and Stokes parameters are then calculated throughout the cell grid. The contributions from all the cells are combined to obtain the observables SED, polarization degree and position angle, for a chosen line of sight. Through this model, we investigate how the magnetic-field geometry and the observer's line of sight influence the integrated emission and polarization signatures.

THEORY

The synchrotron radiation is calculated from the predefined magnetic field vector and electron distribution, following the formalism of Rybicki & Lightman [2] and Bandiera & Petruk [3]. For both the orthogonal and parallel polarization modes ($m = -1, 1$ respectively), emissivity is determined as:

$$j'_m = \frac{\sqrt{3}e^3}{2m_e c^2} \int_{\gamma_{\min}}^{\gamma_{\max}} \frac{n'_e(\gamma')}{4\pi} |\vec{B}' \times \vec{n}'_{\text{los}}| [F(x') + mG(x')] d\gamma' \quad (1)$$

Similarly, the absorption is calculated as:

$$\alpha'_m = \frac{\sqrt{3}e^3}{8\pi m_e^2 c^2 \nu'^2} \int_{\gamma_{\min}}^{\gamma_{\max}} \left[-\gamma'^2 \frac{d}{d\gamma'} \left(\frac{n'_e(\gamma')}{\gamma'^2} \right) \right] |\vec{B}' \times \vec{n}'_{\text{los}}| [F(x') + mG(x')] d\gamma' \quad (2)$$

The emissivity and absorption are transformed for relativistic bulk motion [5], and used to construct the Stokes propagation matrix. The polarized radiation is then propagated through the cell grid using the Stokes transfer equation [6]:

$$\frac{d\vec{S}}{ds} = \vec{J} - \vec{K}\vec{S}, \quad \vec{S} = (I, Q, U, V)^T \quad (3)$$

After transforming to the observer frame, the contributions from each line-of-sight are combined via summation of the Stokes parameters [3,5]. The resulting degree of linear polarization and position angle are:

$$\Pi = \frac{\sqrt{F_Q^2 + F_U^2}}{F_I}, \quad \text{PA} = \frac{1}{2} \text{atan2}(F_U, F_Q) \quad (4)$$

MODEL PARAMETERS

The parameters of this model were based on Schutte et al. [7]:

Parameter	Value
Grid (Cubic)	$4 \times 4 \times 1$ cells
Characteristic Spatial Scale (L)	3.0×10^{17} cm
Grid size	$2L \times 2L \times 0.5L$
Magnetic Field Strength (B_0)	0.82 G
$\gamma_{\min}$	54.8
γ_b	727
γ_c	3.0×10^3
$\gamma_{\max}$	10^6
p_1	2.62
p_2	3.00
Electron Density (n'_0)	$2.918 \times 10^{-4} \text{ cm}^{-3}$
Luminosity Distance (d_L)	4.95×10^{28} cm

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RESULTS

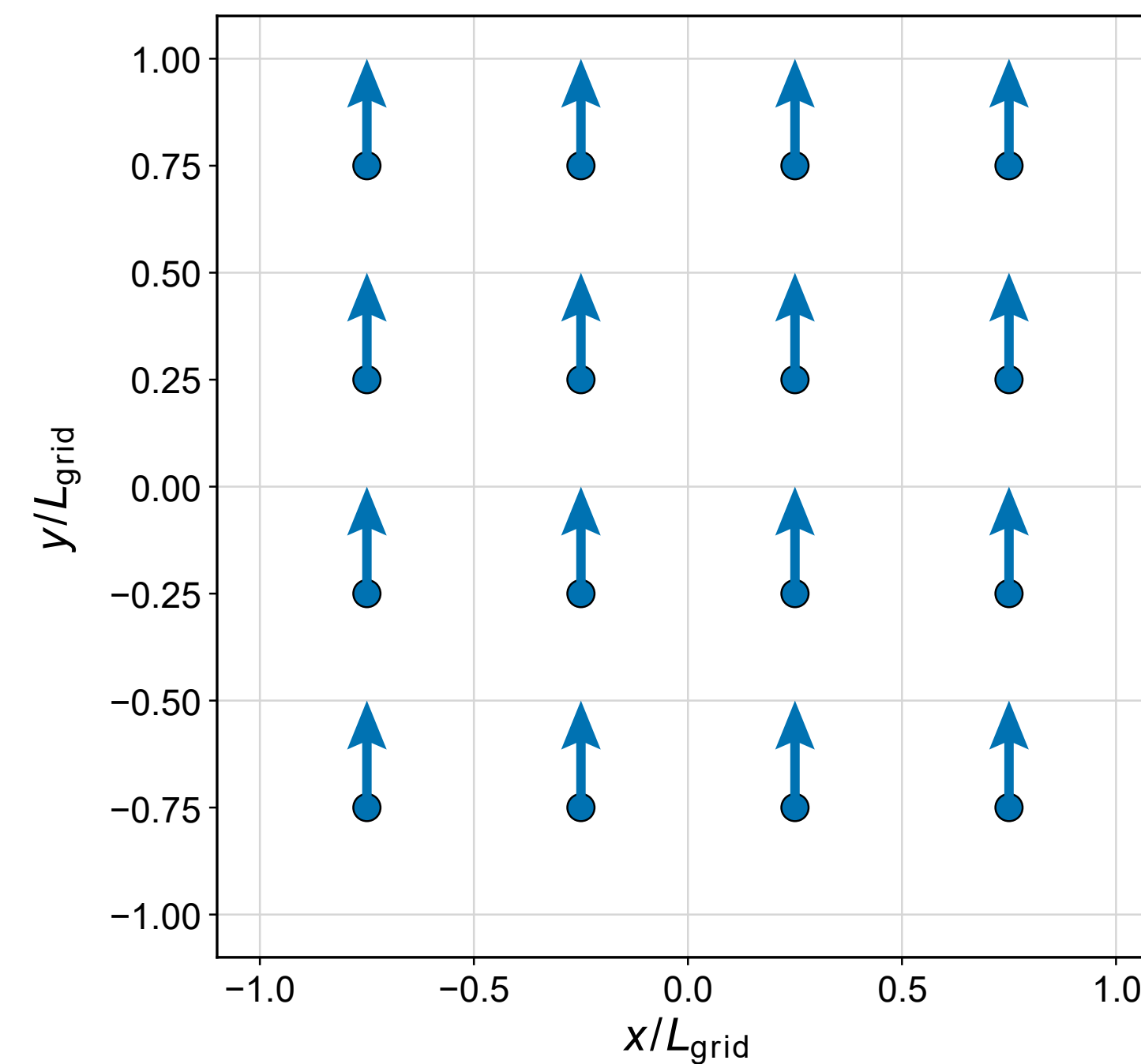


Figure 1: Uniform y-directed magnetic field along the (+z) jet direction.

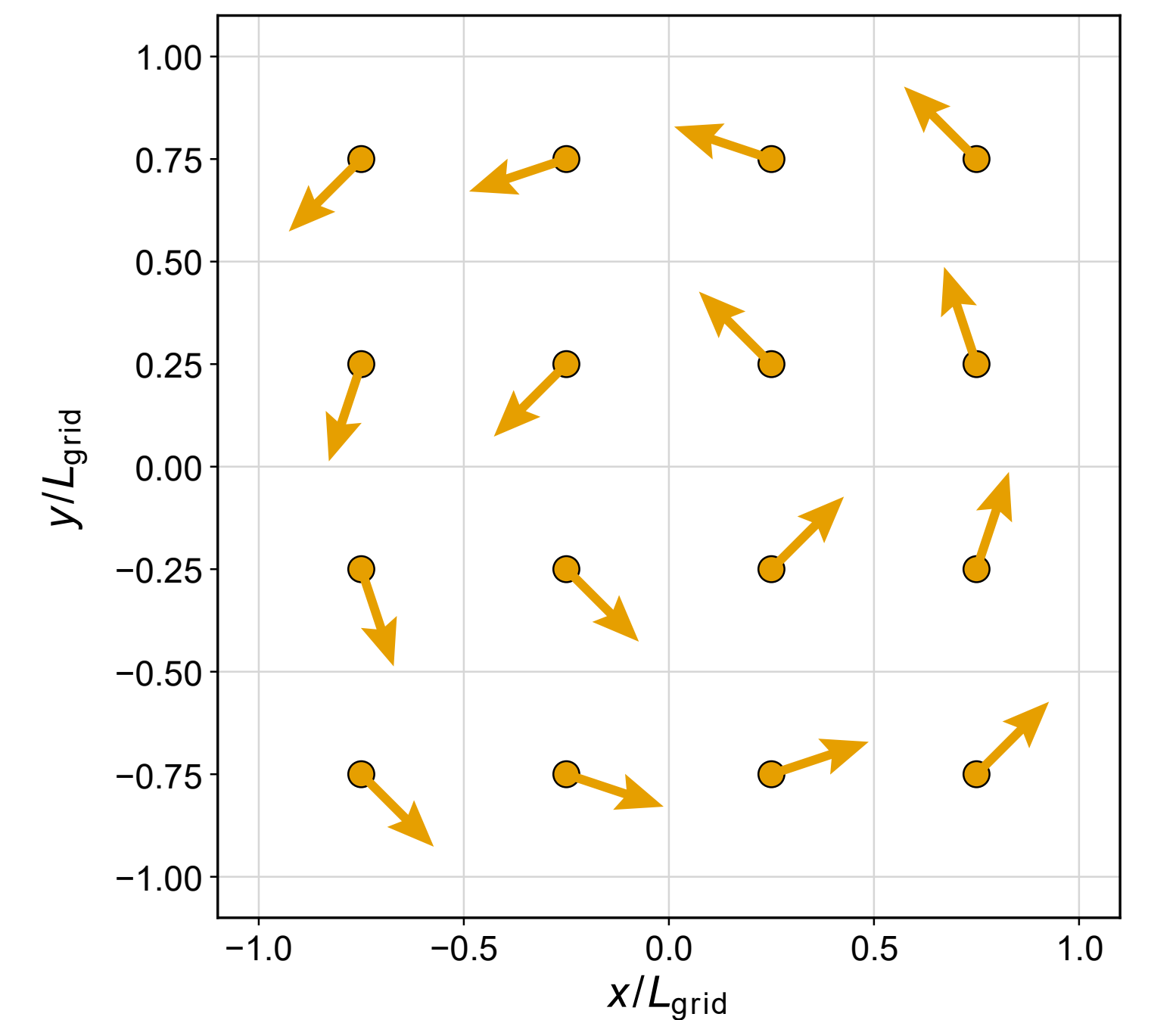


Figure 2: Smooth helical magnetic field along the (+z) jet direction.

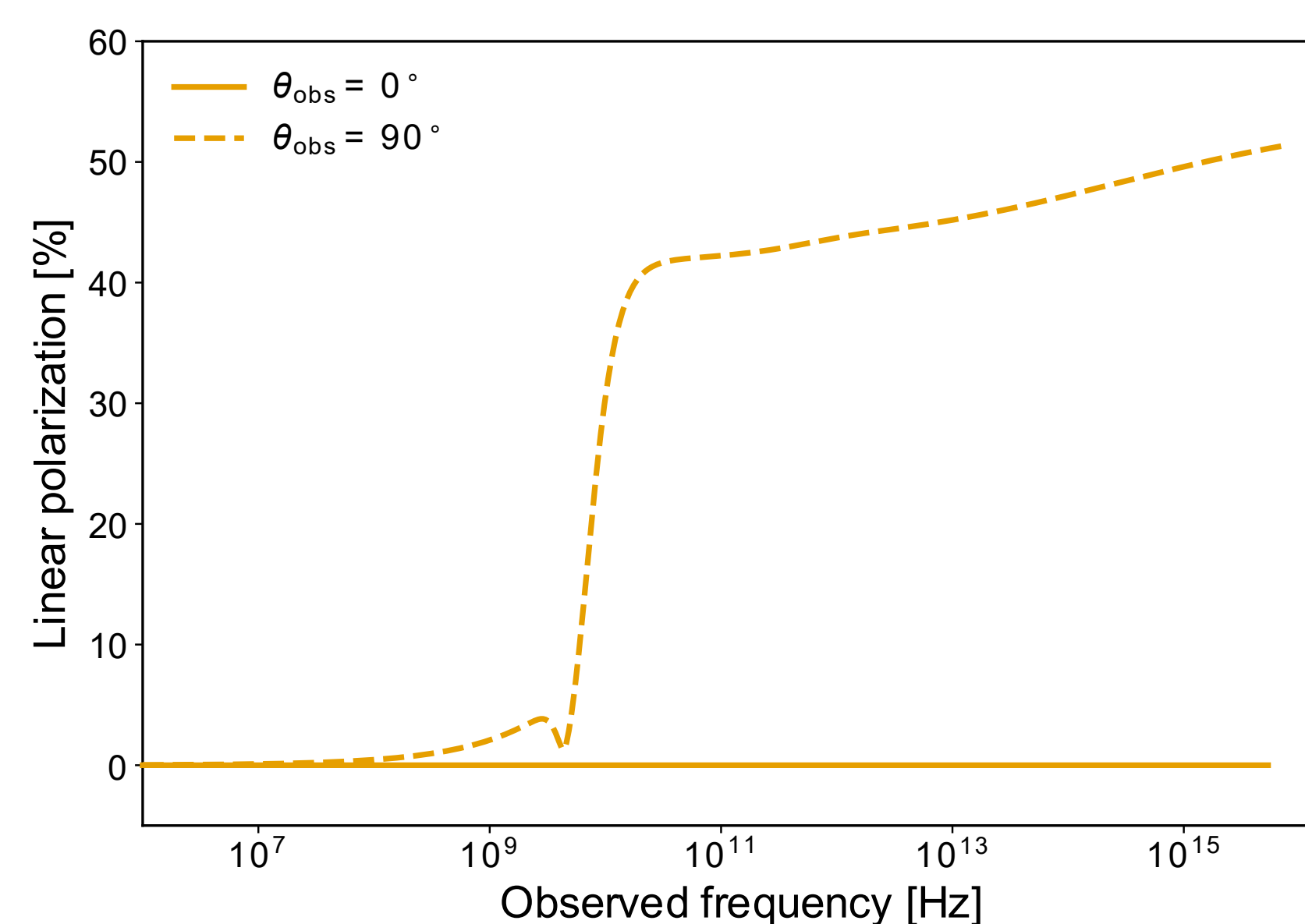


Figure 3: Viewing angle dependence of the helical field with $\Gamma = 1$. Face-on geometry produces cancellation, while a substantial amount of polarization remains for the side on view.

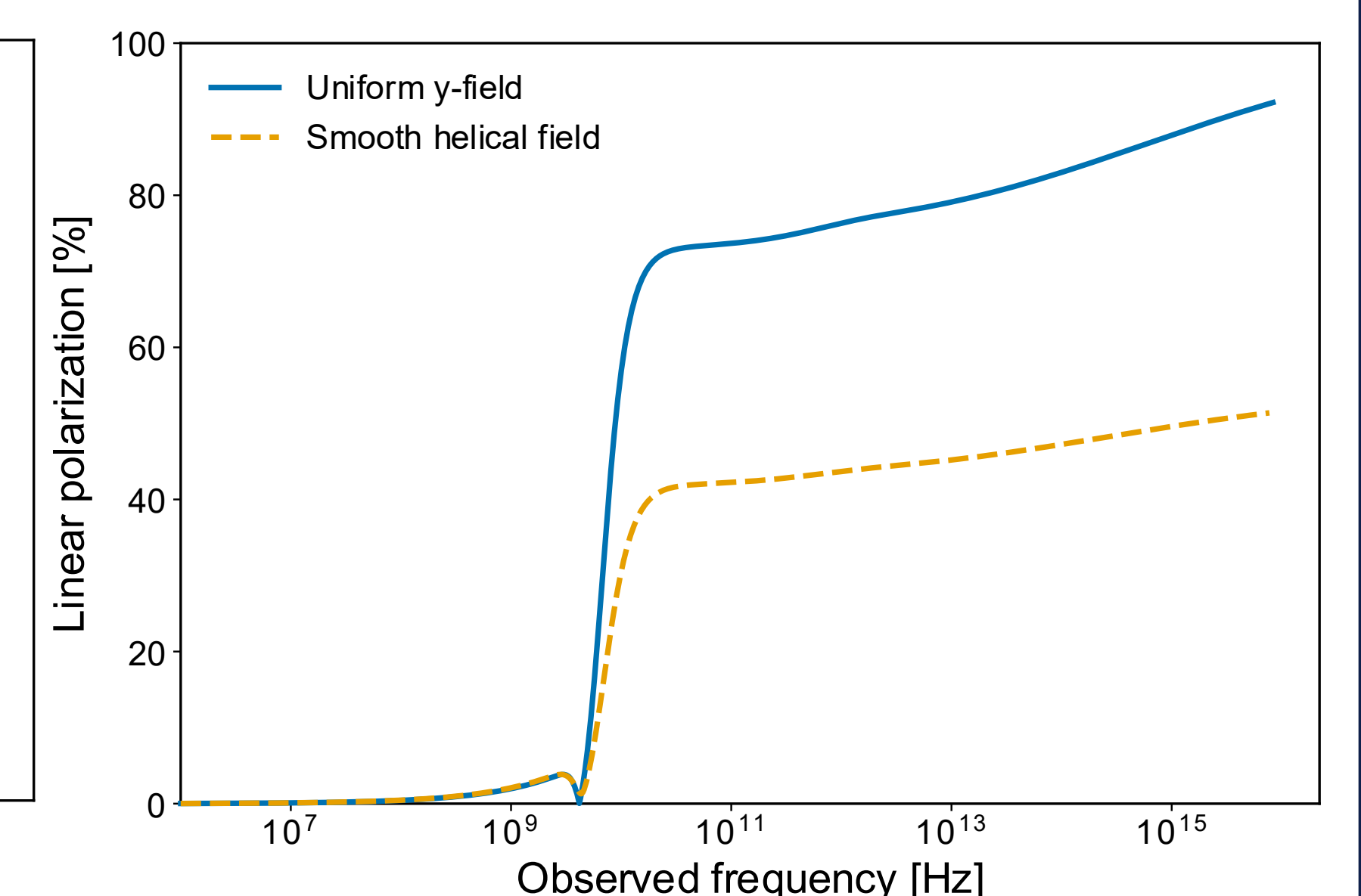


Figure 4: Linear polarization for the uniform and helical fields at $\Gamma = 1$ and $\theta_{\text{obs}} = 90^\circ$. Geometric dependence of the magnetic field reduces the polarization through partial Stokes cancellation.

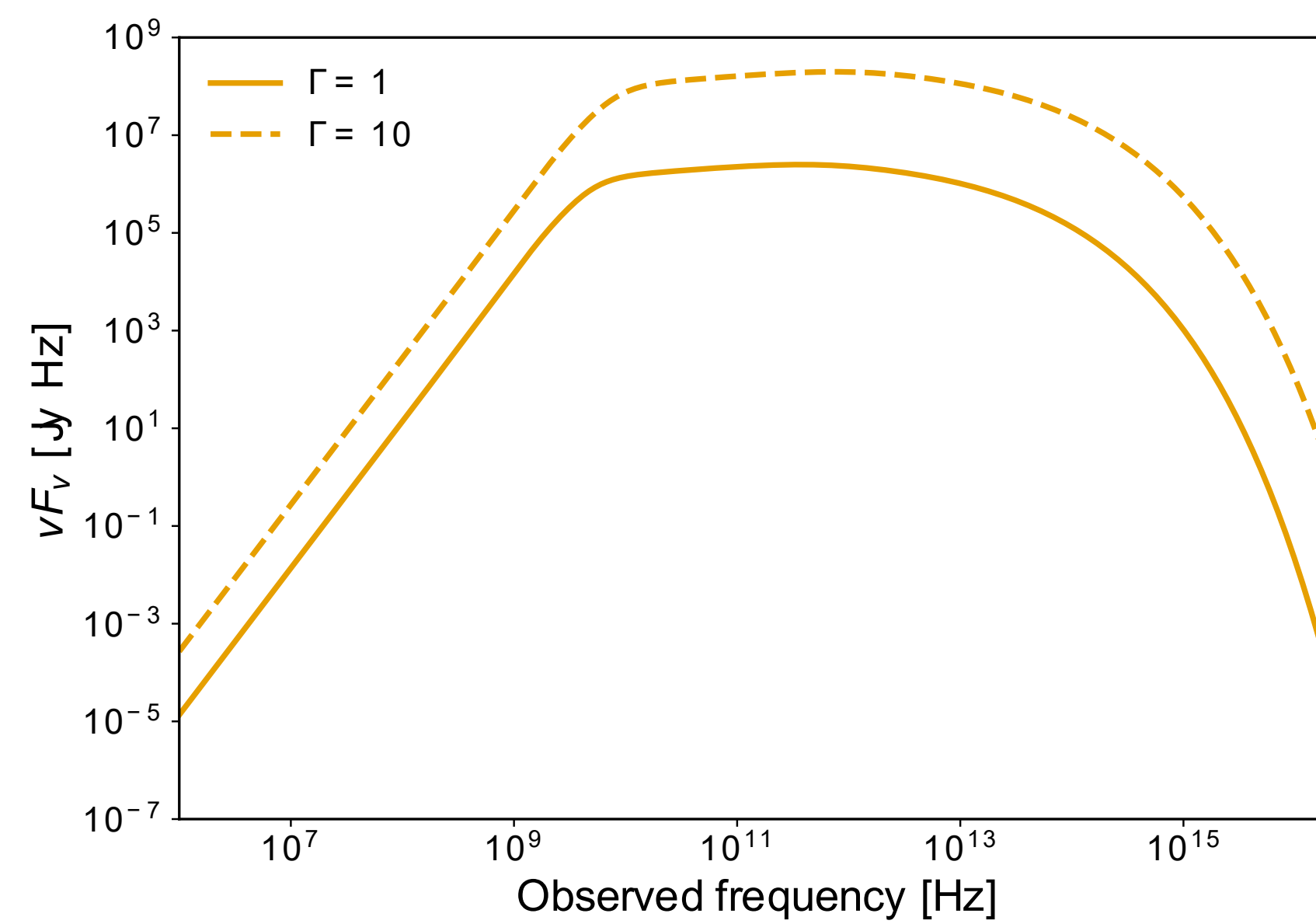


Figure 5: Effect of relativistic motion on the SED of the helical field at $\theta_{\text{obs}} = 0^\circ$. Increasing Γ varies the Doppler factor, observed frequency and the transformed magnetic field projection.

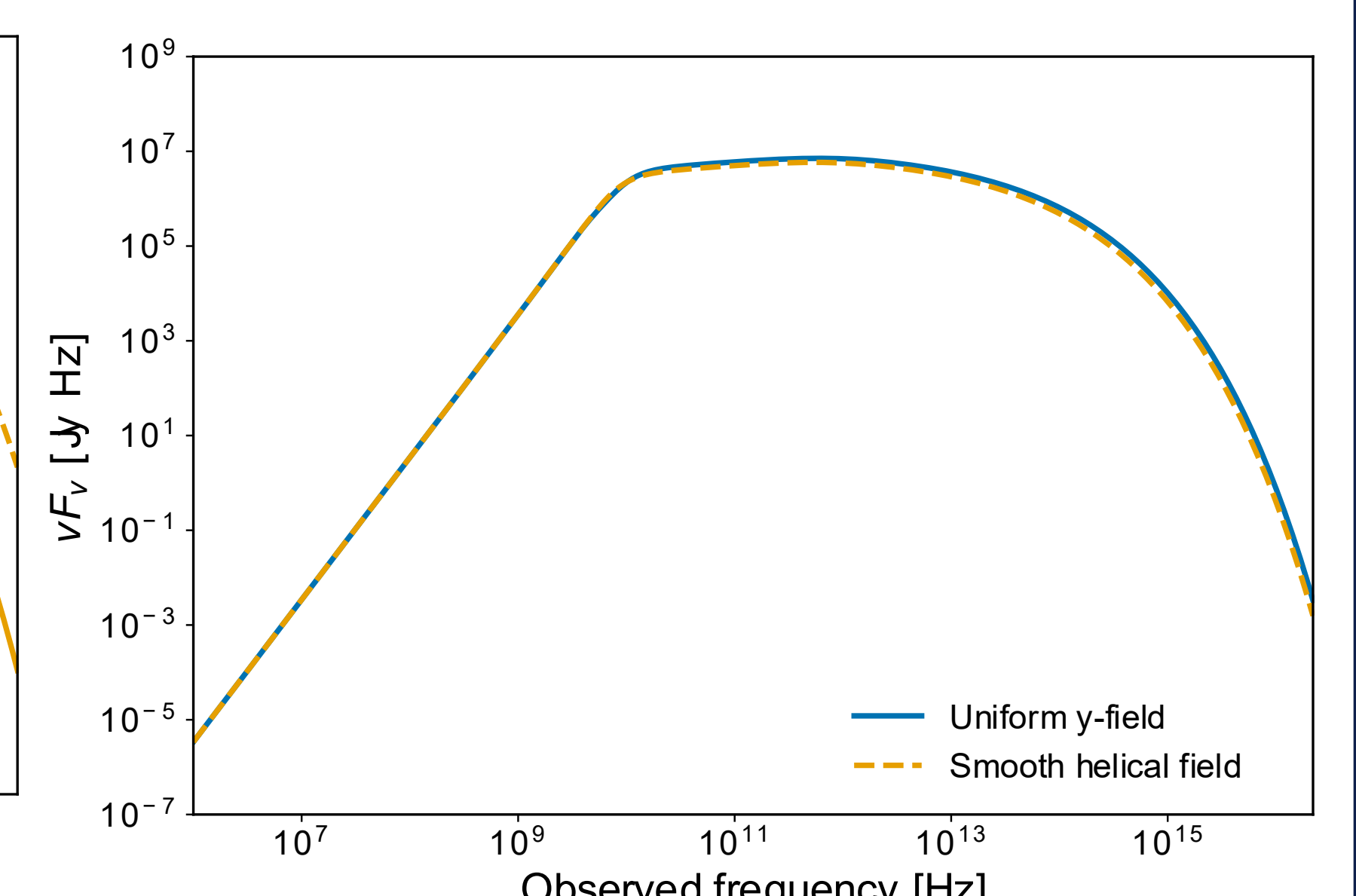


Figure 6: SED for the uniform and helical magnetic fields at $\Gamma = 1$ and $\theta_{\text{obs}} = 90^\circ$. The figure displays the effect of magnetic field geometry on the integrated emission.

DISCUSSION AND CONCLUSIONS

- The validation tests reproduces the expected dependence of synchrotron emission and polarization on magnetic field geometry, relativistic motion, and viewing angle.
- The helical field produces a lower net linear polarization than the uniform y-directed field, because differently orientated projected magnetic fields partially cancel when the cell contributions are combined.
- The viewing angle test produce the expected geometrical behaviour of the helical field. At $\theta_{\text{obs}} = 0^\circ$, the symmetry of the projected field causes strong cancellation of the polarization contributions, while at $\theta_{\text{obs}} = 90^\circ$ a preferred projected orientation remains, which produces a higher net polarization
- Increasing the bulk Lorentz factor changes the observed spectrum through Doppler boosting and relativistic aberration, this shifts the observed spectrum and changes the projected magnetic field geometry.
- Future work will extend the grid and introduce spatially dependent electron distributions, toward a computationally efficient model for investigating how jet structure produces observable polarization signatures.

REFERENCES

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