"Observing" GRMHD Simulations: M87 & Positron Effects on Circular Polarization

Lani Oramas, Richard Anantua, Joaquin Duran, Hayley West, Brandon Curd
The University of Texas at San Antonio, San Antonio TX, 78249

Abstract

Horizon-scale observations of the jetted active galactic nucleus M87 are compared with simulations spanning a broad range of dissipation mechanisms and plasma content in three-dimensional general relativistic flows around spinning black holes. Synchrotron radiation from radio to X-ray frequencies is compared to simulation parameters dictating the electron-positron distribution function and corresponding radiative transfer coefficients. Time-varying simulations with different spins, plasma magnetization, heating, and emission mechanisms showcase distinct possibilities for the M87 jet/accretion flow/black hole (JAB) system. Simulation jet morphology, polarization, and variation are then 'observed' and compared with observations to infer what governs the polarized emissivity. Net linear and circular polarization constraints favor magnetically arrested disc (MAD) models whereas resolved linear polarization favors standard and normal evolution (SANE) in our parameter space. Additionally, some MAD cases dominated by intrinsic circular polarization have near-linear V/I dependence on unpaired electron or positron content. In contrast, SANE polarization exhibits markedly greater positron-dependent Faraday effects.

Positron Physics in JAB Systems

Positrons can be created in AGN JAB systems through photon-photon interactions and spark-gap processes. In the former, Breit-Wheeler pair production is at play. In this type of pair production, interactions in Comptonized clouds can scatter photons in the accretion disk causing the production of electron positron pairs (Laurent & Titarchuk 2018). Photon annihilation can also occur in jet funnel walls (Moscibrodzka et al. 2011). In the latter effect, jet morphology is more important. Since AGN jets typically host a spark gap in which plasma moves away from the black hole beyond the outer light cylinder but must fall toward the central black hole , a stagnation surface at smaller radii from the hole surface may replenish the vacuum by producing pairs accelerated by spark gap (Levinson & Segev 2017).

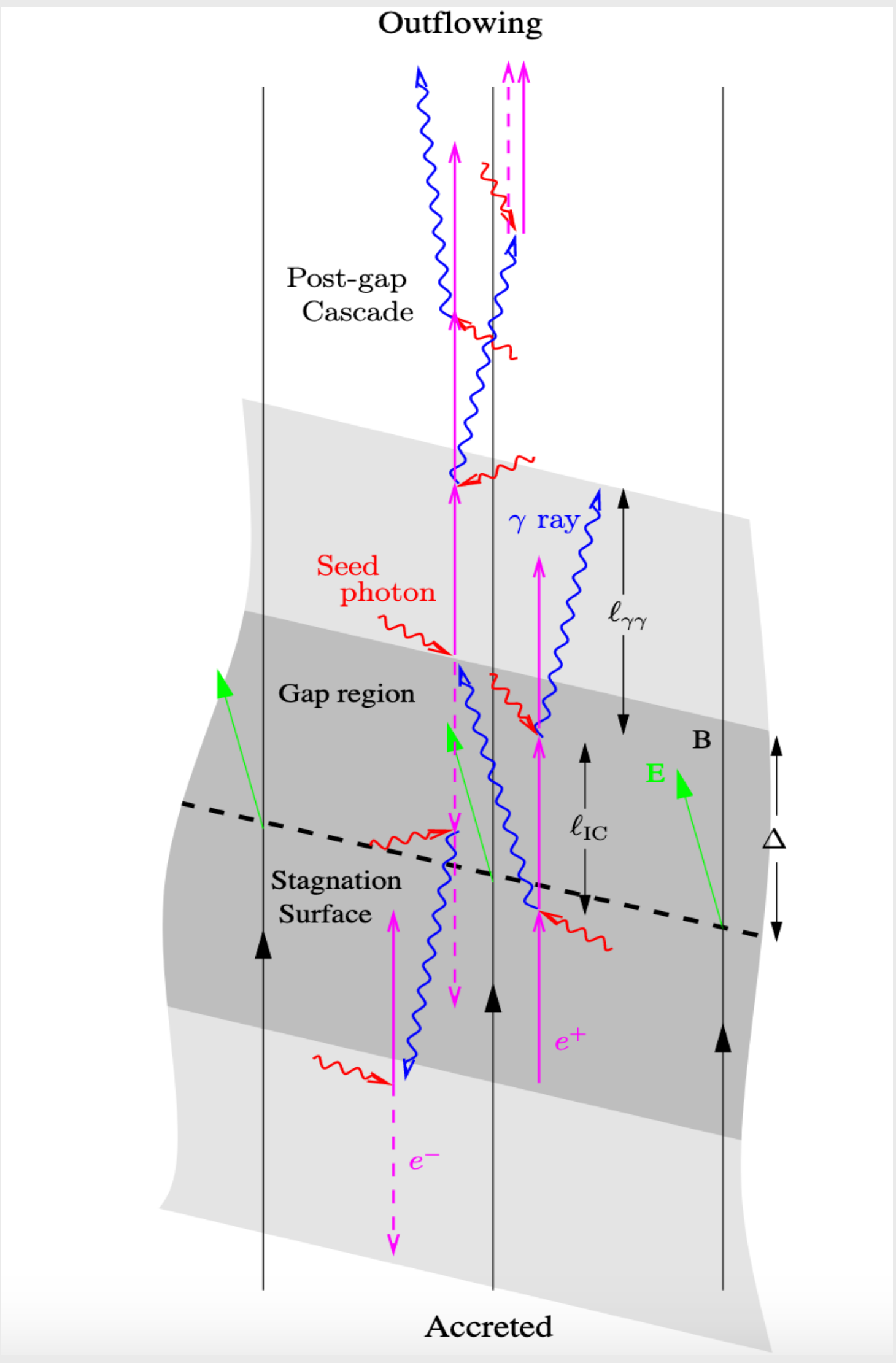

Figure 1. Broderick and Tchekhovskoy (2015) ApJ, 801, 1

Diagram showing the spark gap in an AGN jet and detailing the pair production caused by the stagnation surface.

Methods

The main code used in the post-processing and ray-tracing of simulations we produce is the general relativistic radiative transfer code IPOLE. There are two turbulent heating models considered:

$$\text{R-}\beta,\ R = \frac{T_i}{T_e} = \frac{1}{1+\beta^2} R_{\text{low}} + \frac{\beta^2}{1+\beta^2} R_{\text{high}}$$

$$\text{Critical-}\beta,\ \frac{T_e}{T_p+T_e} = f\ \text{Exp}\left[-\frac{\beta}{\beta_c}\right], 0 < \text{f} < 1$$

The former model is a similar turbulent heating model to the Critical-β in that electrons are preferentially heated over protons at low β and vice versa. The latter allows us to modulate the curvature of the ratio of electron to proton temperatures as a function of β between high and low values by increasing the critical-β parameter to smooth the transition. This model exponentially cools electrons at high β whereas the R-β model takes electron temperature to $\frac{T_i}{R_{high}}$.

Once a snapshot is modeled using one of these prescriptions, positrons are added globally in post-processing. The fraction of positrons can be varied by positron, allowing us to see how the gradual addition of positrons affects polarization across a simulation at individual timesteps.

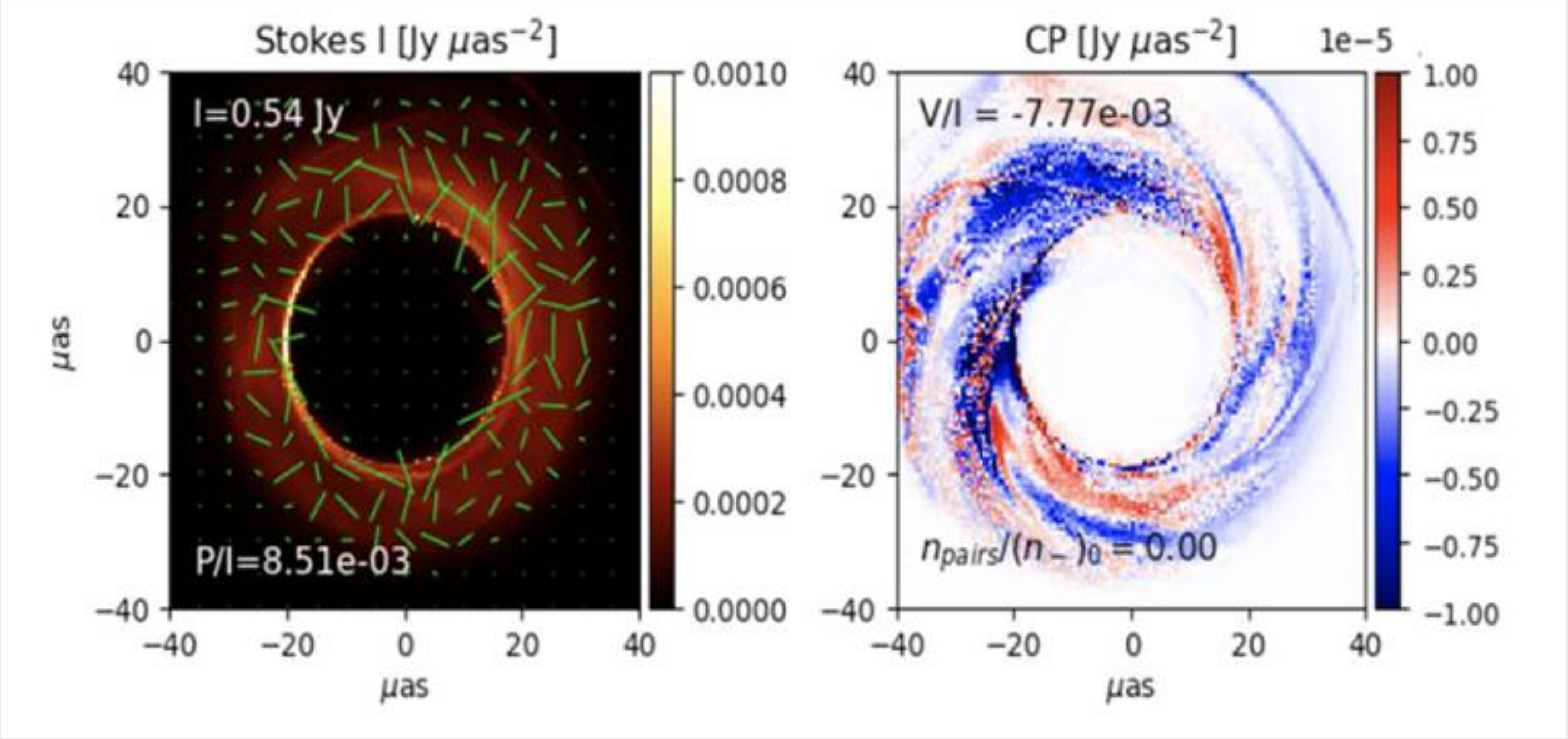

Figure 2. Anantua et. al (2024) MNRAS, 528, 1

An example R-β simulation for a=-0.5 SANE at T=25000M which shows the 230 GHz emission without positrons

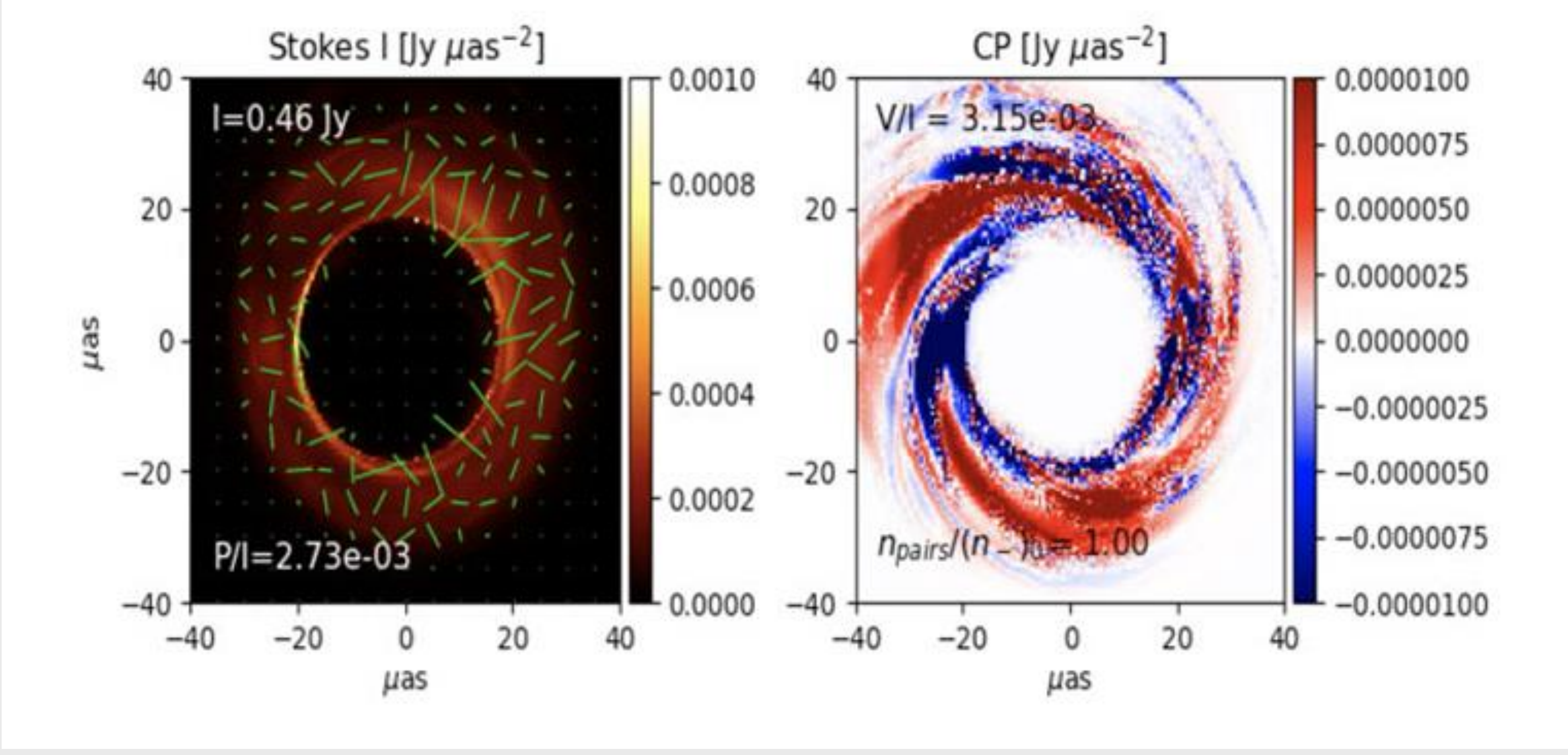

Figure 3. Anantua et. al (2024) MNRAS, 528, 1

An example R-β simulation for a=-0.5 SANE at T=25000M which shows the 230 GHz emission with an even mix of positrons and electrons.

Results & Conclusions

- ➢MADs fluctuate between domination by Faraday effects and intrinsic polarization.
- ➢MAD simulations with decreasing V/I as positron fraction increases show this behavior due to positrons canceling intrinsic circular polarization.
- ➢Similarly, those with increasing V/I as positron fraction increases are the Faraday dominated simulations.
- ➢MAD simulation models have lower Faraday depth than Standard and Normal Evolution (SANE), resulting in slower rates of EVPA rotation.

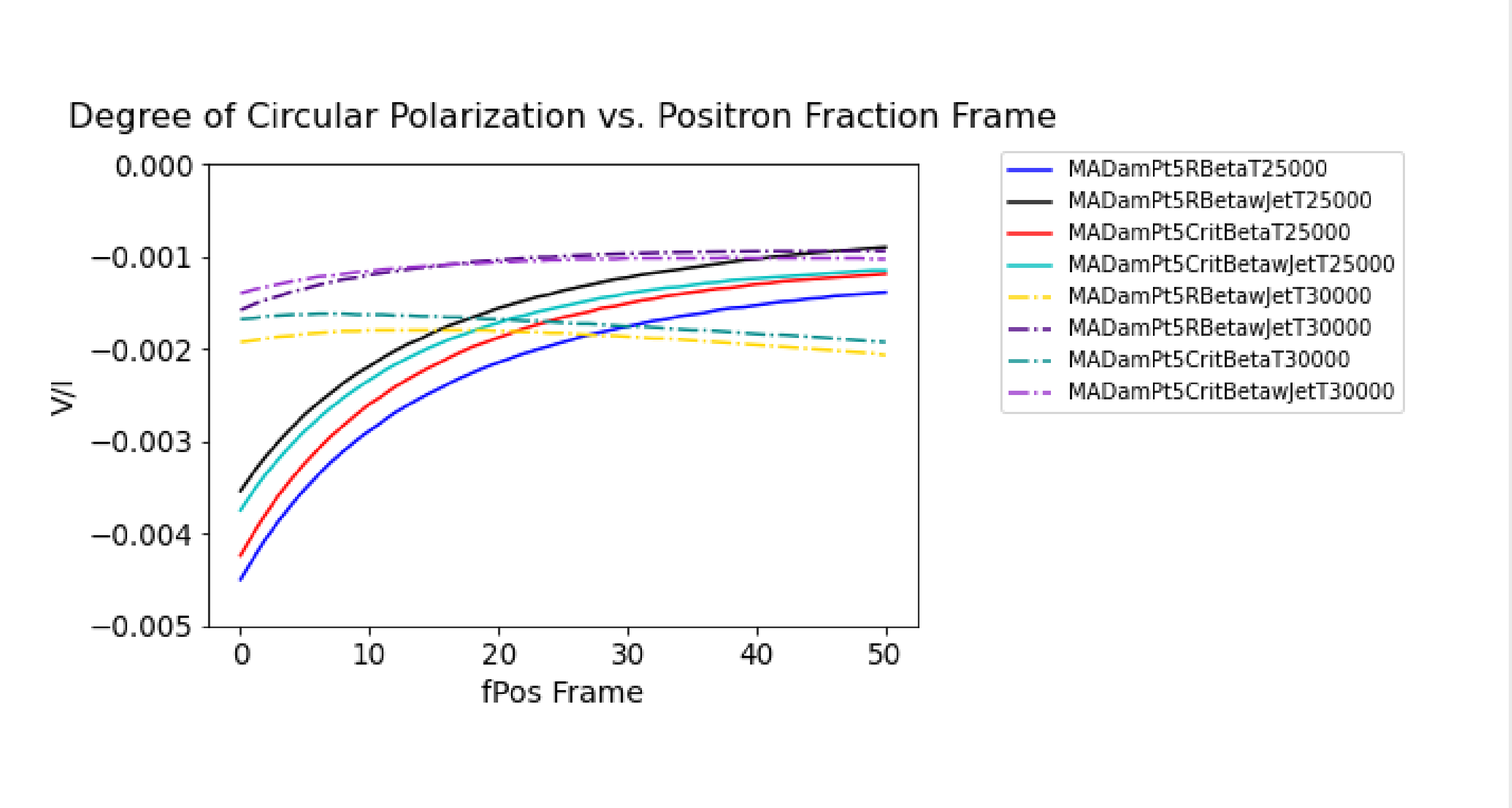

Figure 4. Degree of circular polarization as a function of positron fraction per simulation snapshot frame for a=-0.5 MAD at T=25000M for both turbulent heating models.

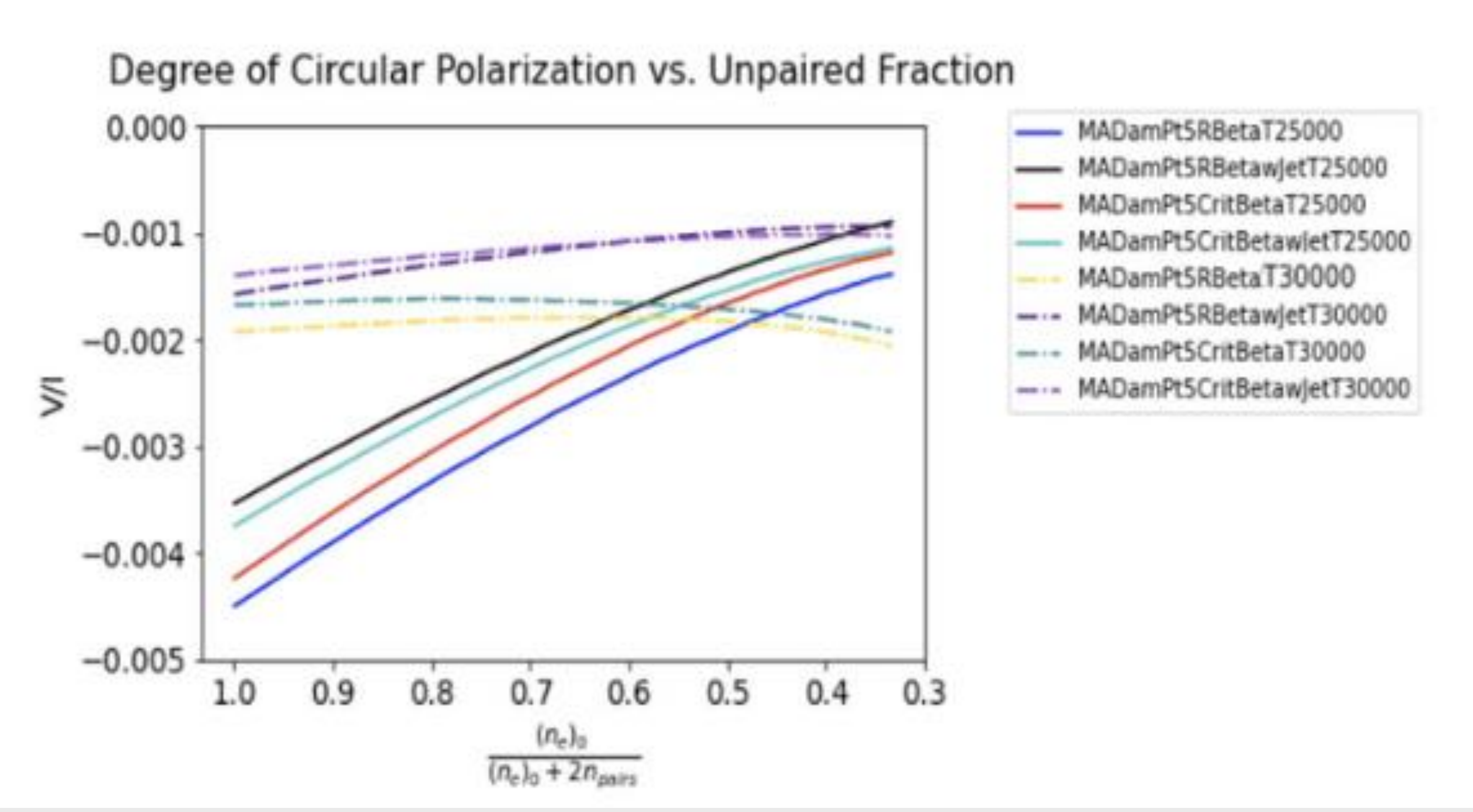

Figure 5. Degree of circular polarization as a function of unpaired emitters for a=-0.5 MAD at T=25000M for both turbulent heating models.

References

Anantua, R., Ricarte, A., Wong, G., et al. 2024, MNRAS, 528, 735
Broderick, A. E., & Tchekhovskoy, A. 2015, ApJ, 809, 97
Laurent, P., & Titarchuk, L. 2018, ApJ, 859, 89
Levinson, A., & Segev, N. 2017, Phys. Rev. D, 96, 123006
Mo´scibrodzka, M., Gammie, C. F., Dolence, J. C., & Shiokawa, H. 2011, ApJ, 735, 9.