An All-Sky Search for Moving Gamma-Ray Sources with Fermi-LAT

arXiv:2610.14058

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October 24–25, 2026
MIT PRIMES Conference

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Motivation

Dark Matter

- Dark matter makes up about **85% of the Universe's matter**.
- Its gravity shapes galaxies, yet its physical makeup remains unknown.
- In some particle models, dark matter annihilation or decay produces gamma rays that telescopes can detect.

Primordial Black Holes (PBHs)

- Primordial black holes are hypothetical black holes that would have formed in the early Universe and could make up part of dark matter if they exist.
- A PBH surrounded by a dense halo of annihilating particle dark matter could appear as a gamma-ray source.
- A nearby source could move appreciably across the sky over time, motivating a search for moving gamma-ray emitters.

Dark Matter Annihilation

Annihilation luminosity

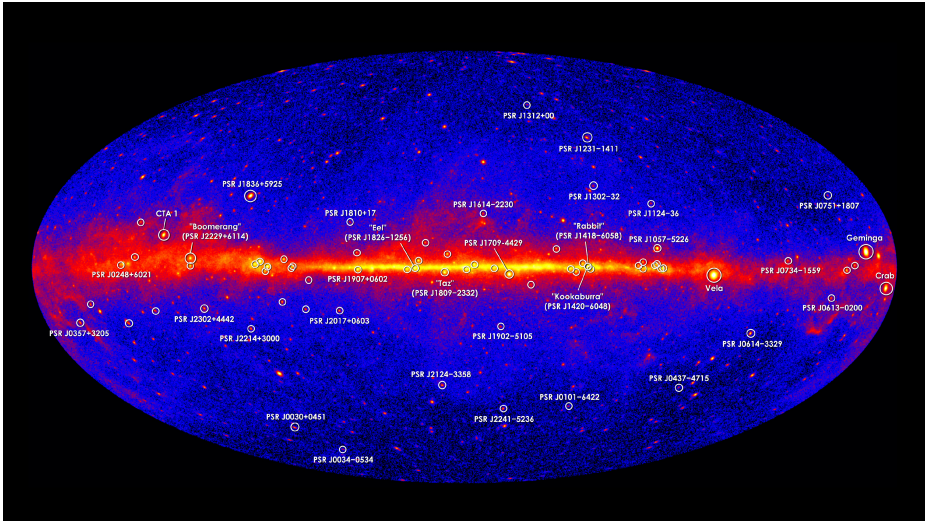
$$L_\gamma = \frac{\langle \sigma v \rangle N_\gamma}{2m_\chi^2} \int \rho_\chi^2(\mathbf{x})\, d^3x.$$

- Dark matter particles can annihilate, producing gamma rays.
- Emission scales with the square of dark matter density.

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Fermi-LAT Telescope



Fermi-LAT Information

For each detected gamma-ray photon, Fermi-LAT records:

- Direction (°)
  - Right ascension (RA)
  - Declination (Dec)
- Energy (MeV)
- Arrival time (s)

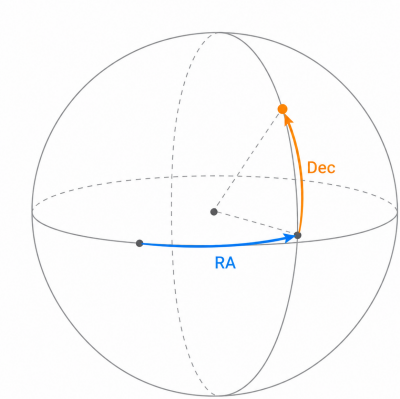
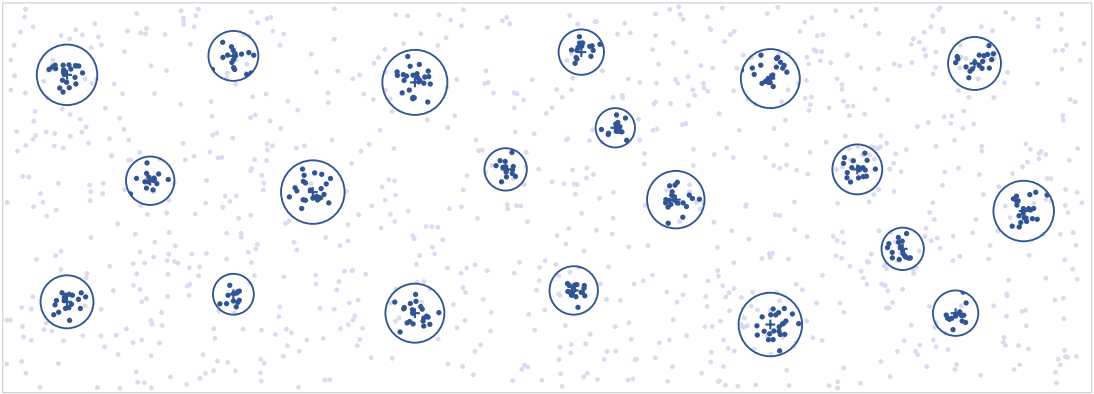


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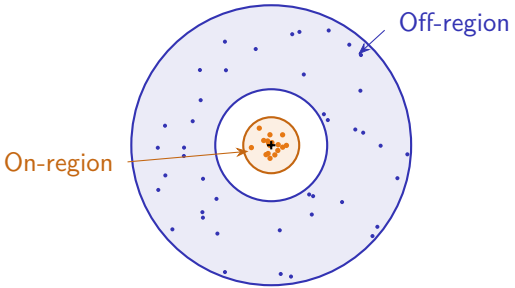
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Reconstructing a Moving Source

1. **Clusters Per Year** | 2. Centers | 3. Links | 4. Best Tracks



Li–Ma Significance



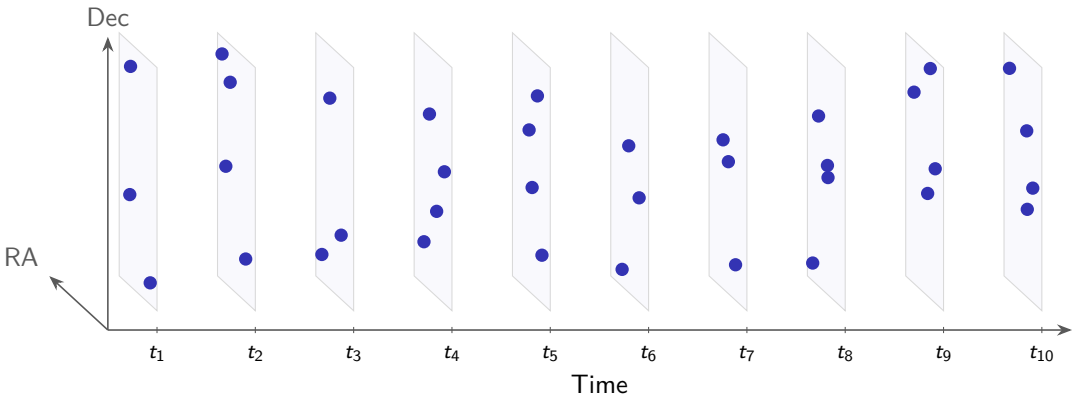
- On-region: $r \leq r_{\mathrm{DB}}$
- Off-region: $2r_{\mathrm{DB}} \leq r \leq 5r_{\mathrm{DB}}$

Li–Ma significance

$$S_{\mathrm{LM}} = \left\{ 2 \left[N_{\mathrm{on}} \ln\left(\frac{1+\kappa}{\kappa} \frac{N_{\mathrm{on}}}{N_{\mathrm{on}} + N_{\mathrm{off}}} \right) + N_{\mathrm{off}} \ln\left((1+\kappa) \frac{N_{\mathrm{off}}}{N_{\mathrm{on}} + N_{\mathrm{off}}} \right) \right] \right\}^{1/2}$$

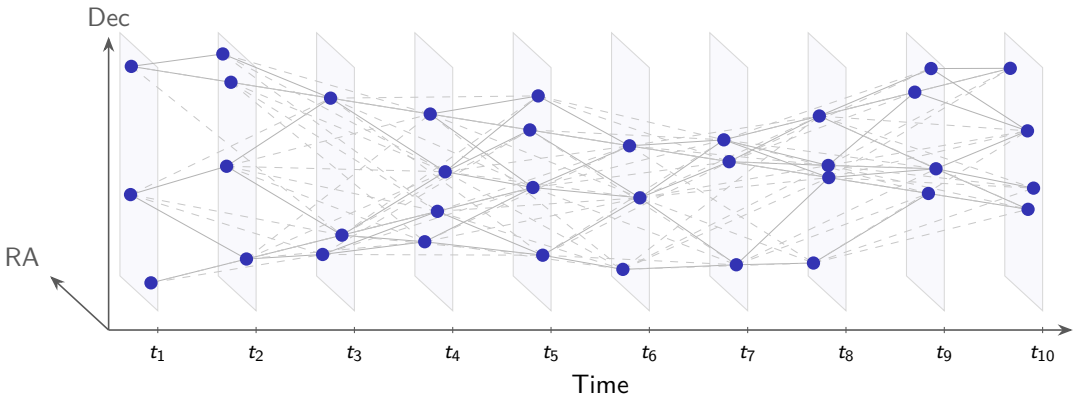
Reconstructing a Moving Source

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Dynamic Programming Linker

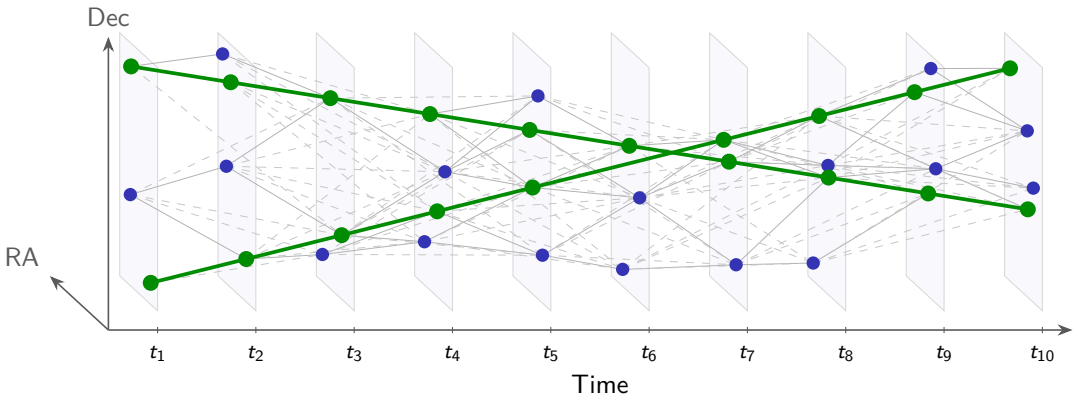
Score update when appending cluster j

$$Q(T \,\|\, j) = Q(T) + S_{\mathrm{LM,j}} - \left[\frac{d_{ij}}{g_{ij}} + 0.5(g_{ij} - 1)\right]$$

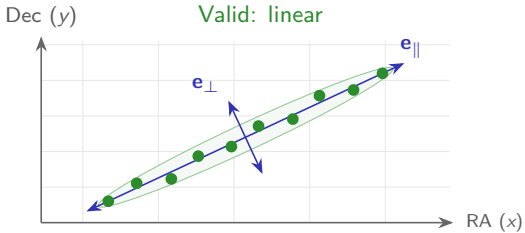
- **Reward:** add $S_{\mathrm{LM,j}}$, the new cluster's Li–Ma significance.
- **Motion penalty:** d_{ij} is the separation in degrees and g_{ij} the bin-index difference. Subtract d_{ij}/g_{ij}, the angular step per bin.
- **Missing-bin penalty:** $g_{ij} - 1$ counts skipped annual bins. Subtract 0.5 per skipped bin, in addition to the motion penalty.

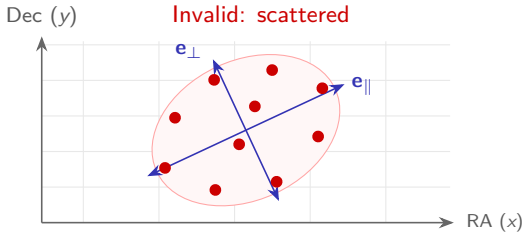
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Anisotropy Safeguard

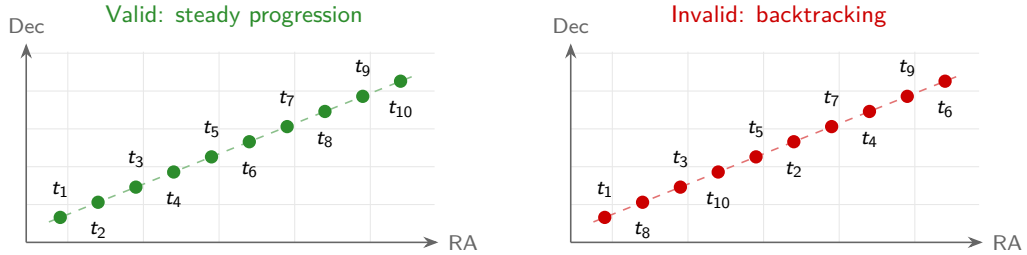




- Moving sources should trace a thin, elongated line.
- Project the m_T centroids in track T onto a tangent plane, giving positions (x_i, y_i) with means $(\bar{x}, \bar{y})$.
- For each point i, measure its displacement from the center: $d_{\parallel,i}$ along the best-fit axis and $d_{\perp,i}$ across it.

$$A = 1 - \frac{\sum_i d_{\perp,i}^2}{\sum_i d_{\parallel,i}^2}$$

Constant Direction Safeguard



- A moving source should show steady progression along the track's long axis.
- Project each linked cluster center onto the track's main axis to get position ξ_i. Let t_i be the bin midpoint in years.
- Compute the Pearson correlation, with means $\bar{t}$ and $\bar{\xi}$:

$$r = \frac{\sum_i (t_i - \bar{t})(\xi_i - \bar{\xi})}{\sqrt{\sum_i (t_i - \bar{t})^2}\,\sqrt{\sum_i (\xi_i - \bar{\xi})^2}}.$$

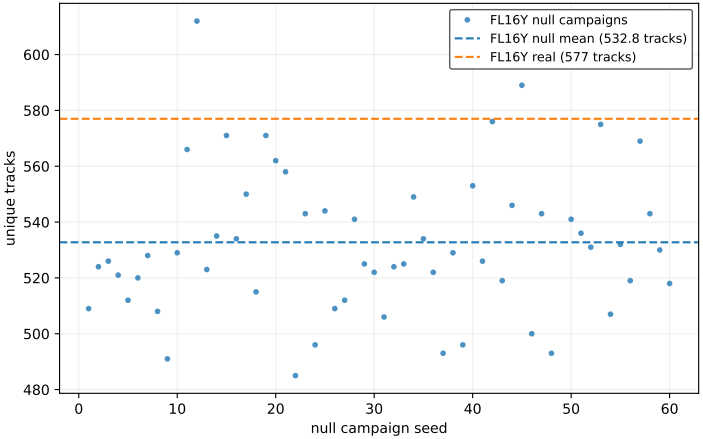
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Injection Recovery Efficiency

Galactic latitude $\lvert b\rvert$	Angular speed μ ($^\circ\,\mathrm{yr}^{-1}$)	Detected photons per annual bin 8	12	18	25	35
0–10°	0.25	2%	10%	8%	24%	34%
0–10°	0.50	0%	0%	8%	16%	34%
0–10°	0.80	0%	2%	2%	4%	12%
10–30°	0.25	2%	16%	50%	70%	76%
10–30°	0.50	2%	6%	40%	66%	90%
10–30°	0.80	2%	0%	12%	44%	68%
30–90°	0.25	12%	24%	70%	88%	86%
30–90°	0.50	8%	10%	62%	90%	96%
30–90°	0.80	4%	4%	30%	64%	80%

Search Results



- **Time scrambling:** Randomize photon times to estimate the background.
- **Track counts:** 577 candidates in real data vs. 532.8 candidates on average per scramble.
- A 1.5σ excess, which we do not consider significant.

Conclusion

- We performed the first all-sky search for moving gamma-ray sources.
- We found an approximately 1.5σ moving-source excess ($p = 0.066$), which we do not consider statistically significant.
- The upper limits constrain populations of dressed and quasi-steady evaporating primordial black holes.
- The search only covers a narrow energy window (1-100 GeV) with modest background calibration. Thus, the main novelty of this project lies in the methodology rather than the results.
- Full paper: arXiv:2610.14058

Acknowledgments

I am extremely grateful to **Prof. James Unwin** (University of Illinois Chicago) for his outstanding mentorship throughout this project.

I also thank the **MIT PRIMES** program for the opportunity to undertake this research and **Dr. Thomas Rüd** for his valuable suggestions on this presentation.

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