

Multiwavelength Indirect Dark Matter Searches With Radio- and Gamma-Ray Astronomy

TeV Particle Astrophysics 2026 | Session: DM

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September 1, 2026

Astroparticle Physics | RG Rhode/Elsässer



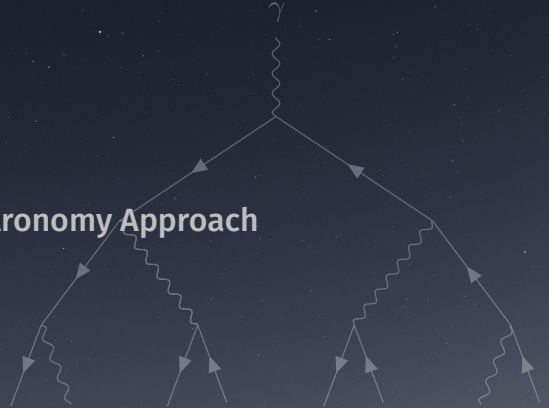
Motivation

How can we use gamma-ray and radio data to jointly constrain
DM upper limits?

Rotation Exclusion Method
& Asimov Datasets

Deep-learning-based Radio Simulations
& Cleaning

Gamma-ray Astronomy Approach

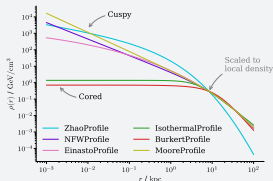


The Signal in Gamma-Ray Astronomy

$$\frac{d^2\phi(\langle\sigma v\rangle, I)}{dE d\Omega} = \text{AP} \times \text{PP}$$

AP

$$\text{Astrophysical Fractor} = \frac{1}{4\pi} \int_{\text{L.O.S.}} \rho_X^2(r(s, \theta)) ds$$



[S. Fröse. PhD thesis. 2025. [10.17877/DE290R-25426](#)]

PP

$$\text{Particle Physics} = \left(\frac{\langle\sigma v\rangle}{2m_X^2} \sum_f \text{BR}_f \frac{dN_f}{dE} \right)$$

- Input from Standard Model
- Unknown quantities $\langle\sigma v\rangle$ and m_X

The MAGIC Telescopes

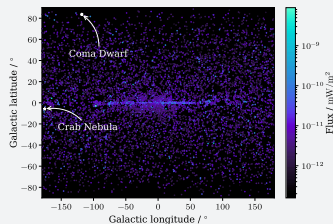


[Credit: Robert Wagner]

- Stereo System of Imaging Atmospheric Cherenkov Telescopes
- Roque de Los Muchachos Observatory, La Palma, Spain
- Energy above ~ 50 GeV
- Showers have to be seen by both telescopes

The Coma Berenices dSph

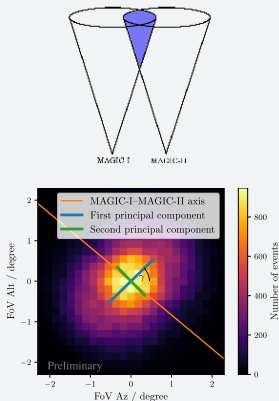
- Distance 44 kpc
- Mass-to-light ratio 448(297)
- J-Factor $19.02^{+0.41}_{-0.37} \text{ GeV}^2 \text{ cm}^{-5}$
- 50 h of data available from observations
 - 25 h after selection
- Extend search into 3 dimensions (energy and spatial)
- Requires robust background model
 - ⇒ Introduce **exclusion rotation method**



[S. Fröse. PhD thesis. 2025, [10.17877/DE290R-25426](#)]

- Traditionally test statistic from toy Monte Carlos
 - ⇒ Approximate test statistic with **Asimov Datasets** instead
 - ⇒ Python package  **TITRATE**

Acceptance of the MAGIC Telescopes



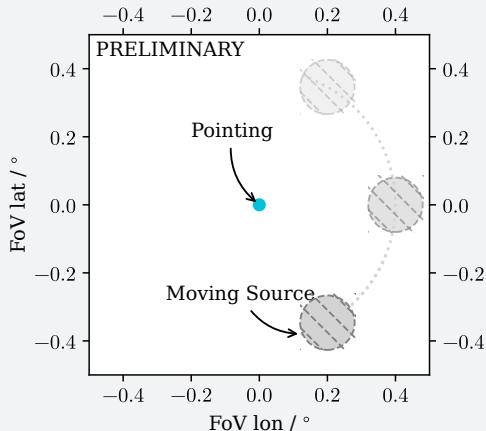
[S. Mender et al. In: PoS(Gamma2022). **10.22323/1.417.0215**]

- Acceptance region asymmetric stereo blob
- Azimuth dependent rotation

$$\gamma_{\text{theory}} = \text{Az} - 34.23 \text{ deg}$$

- Determine Background in Azimuth bins $\rightarrow$ reduced Statistics
- Introduce **Exclusion Rotation Method**

The Rotation Exclusion Method



[S. Fröse et al. In: PoS(ICRC2025). 10.22323/1.501.0649]

- Fill data cubes $N_{\text{eff}}, T_{\text{eff}}, T_{\text{tot}}$, Axes $\mathbf{A} = (\hat{E}, \hat{\text{FoV}}_{\text{Az}}, \hat{\text{FoV}}_{\text{Alt}})$
 - eff: without values from excluded Source region

Algorithm:

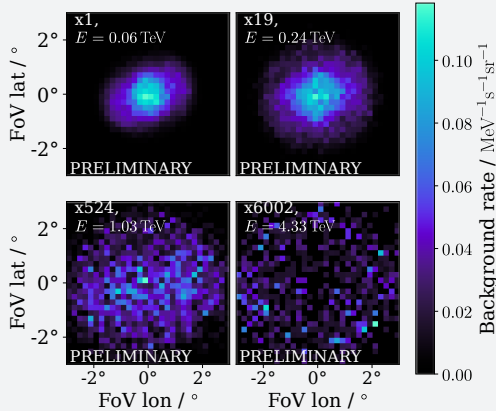
- Split observations into subobservations
- Derotate subobservation with γ_{PCA}
- Rerotate events for every Observation
- Fill data cubes

Background Formula

$$\frac{dN}{dtdE d\Omega} = \frac{N_{\text{eff}}}{\left(\frac{T_{\text{eff}}}{T_{\text{tot}}} \Delta\Omega \Delta E T_{\text{obs}}\right)}$$

- Implementation in  BAccMod provided in Pull request 40

The Rotation Exclusion Method



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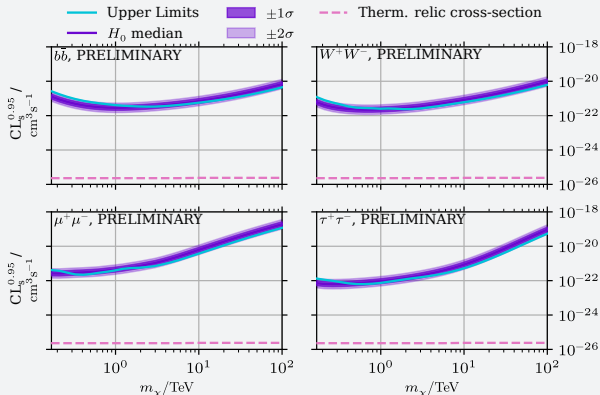
Asimov Datasets

- Detailed explanation in **Cowan, Glen et al. 2011. 10.1140/epjc/s10052-011-1554-0**
- Need distribution $f(q_\mu, \mu, \vec{\theta})$ of profile Log Likelihood q_μ for p-value
 - Strength parameter μ , nuisance parameters $\vec{\theta}$
 - Physical meaning lost if $\hat{\mu} < 0$
 - Toy Monte Carlo Simulations necessary to compute sensitivity
- Modified test statistic $\tilde{q}$
- Asimov Dataset
 - $\hat{\mu}$ and $\hat{\vec{\theta}}$ give true values
 - Distribution approximated as non central chi square distribution
- New formula for upper limits and expected sensitivity bands ($1 - \alpha$ confidence level):

$$p_\mu \stackrel{!}{=} \frac{1 - \Phi(\sqrt{\tilde{q}})}{\Phi(\sqrt{\tilde{q}_{\mu,A}} - \sqrt{\tilde{q}_\mu})}$$

$$\mu_{\text{exp}} = \sigma(\Phi^{-1}(1 - \alpha\Phi(N)) \pm N)$$

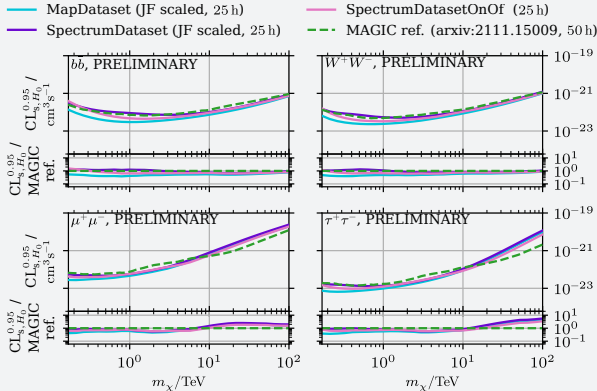
Preliminary Upper Limits and Sensitivity Bands



- No significant excess
- Upper limits, median expected limits and confidence bands for $m_\chi \in [0.17, 100]\text{TeV}$
- Observed limits lie in confidence bands

[S. Fröse et al. In: PoS(ICRC2025). 10.22323/1.501.0649]

Preliminary Upper Limits and Other Methods



[S. Fröse et al. In: PoS(ICRC2025). 10.22323/1.501.0649]

Comparison with other Methods

- MapDataset $\rightarrow$ 3D : Energy + Spatial
- SpectrumDataset $\rightarrow$ 1D : MapDataset integrated $\theta^2 = 0.03^\circ^2$
- SpectrumDatasetOnOff $\rightarrow$ 1D : Background from off-regions
- MAGIC results with full 50 h
- 3D analysis improves on MapDataset
- Most sensitive for non-leptonic (low m_χ leptonic)
- SpectrumDatasetOnOff most sensitive at m_χ leptonic

Radio Astronomy Approach



DM Signals from dSph

- Injection rate of $e^\pm$ into dSph halo:

$$s(\mathbf{r}, E_{e^\pm}) = \frac{1}{2m_\chi^2} \rho^2(\mathbf{r}) \frac{d\langle\sigma v\rangle}{dE_{e^\pm}}$$

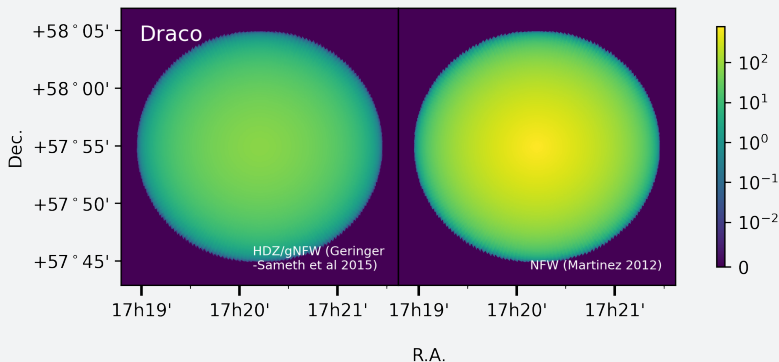
- CR distribution given by spherical diffusion-loss equation

$$D(E) \frac{1}{r} \frac{\partial^2}{\partial r^2} [n_e(r, E)r] + \frac{\partial}{\partial E} [b(E, B)n_e(r, E)] + s(r, E) = 0 \quad (1)$$

DM Signals from dSph

Solve equation and simulate radiation with packages such as  **diffSph**

I_ν [Jy/sr]



[M. Vollmann, F. Welzmüller, and L. Gajovič. 2024. [10.1088/1475-7516/2024/12/046](#)]

Radio Interferometry

Angular resolution limited by Rayleigh criterion:

$$\theta = 1.22 \cdot \frac{\lambda}{D}$$

λ : Wavelength

D : Diameter



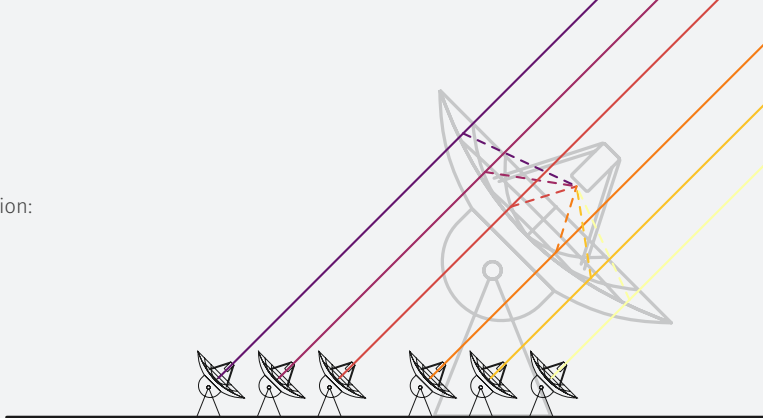
Radio Interferometry

Angular resolution limited by Rayleigh criterion:

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λ : Wavelength

D : Baseline



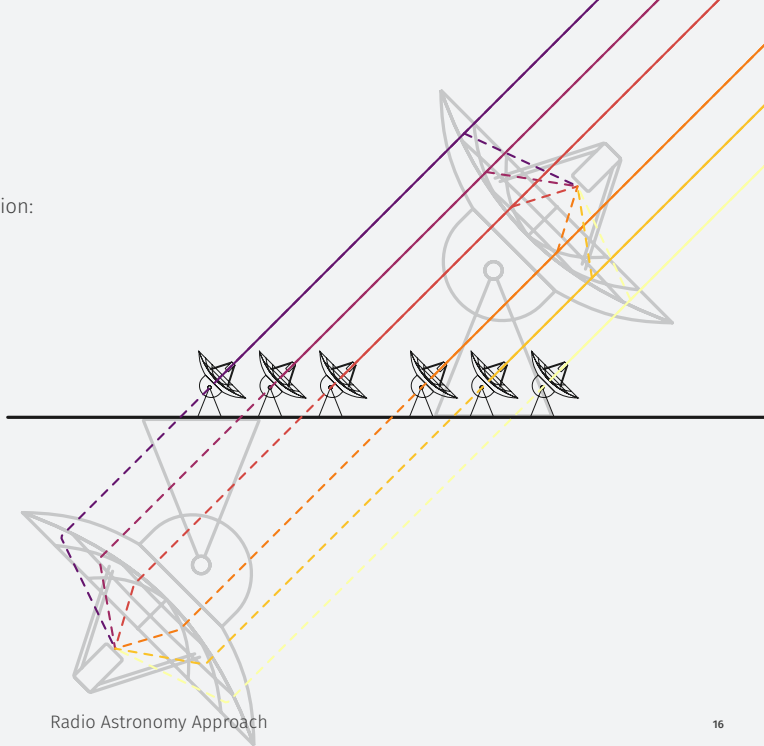
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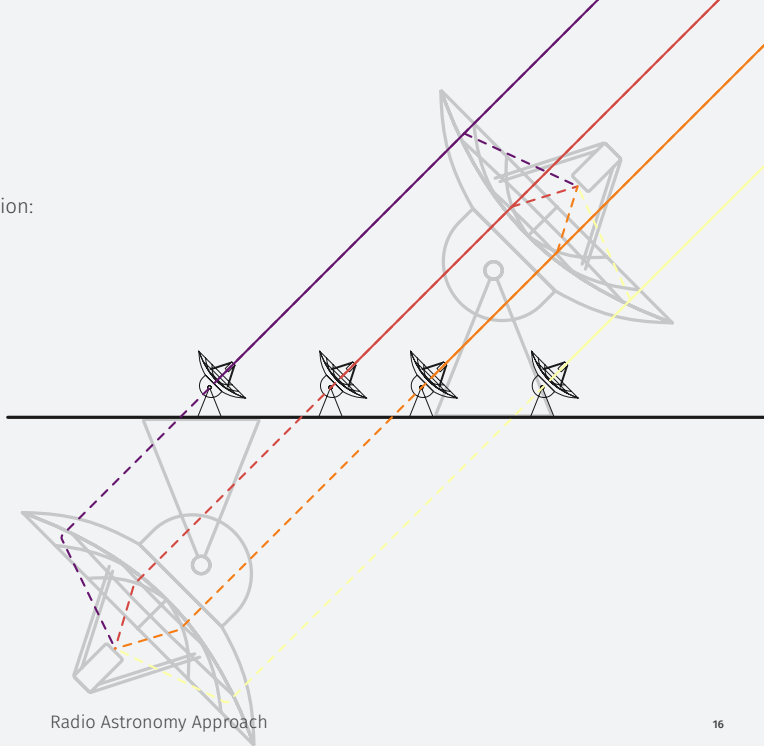
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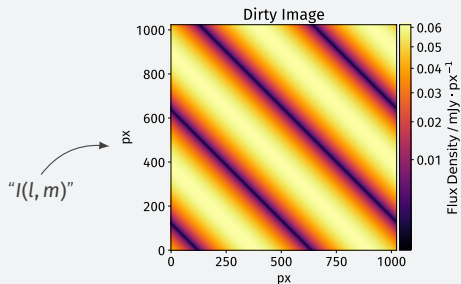
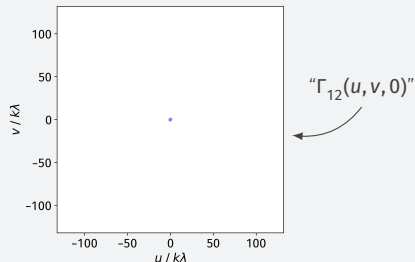


(u, v) Coverage

$$\Gamma_{12}(u, v, 0) = \iint I(l, m) e^{-2\pi i(ul+vm)} dl dm$$

- (u, v) : Coordinates in Fourier space of the sky brightness distribution
- Shows where on the Fourier plane the sky has been sampled
- Long baselines: fine structures; Short baselines: coarse structures
- Earth's rotation helps fill in the (u, v) space

2 Antennas; 10 s

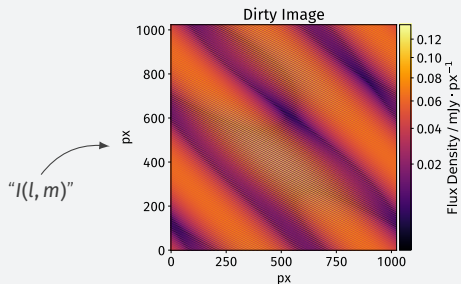
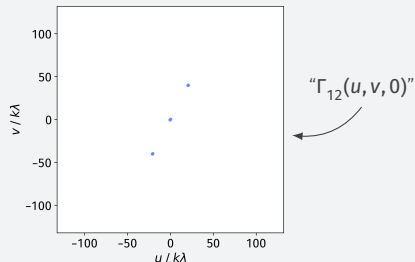


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3 Antennas; 10 s

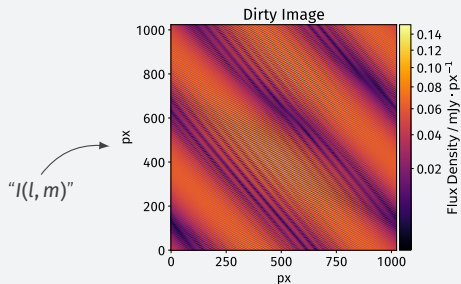
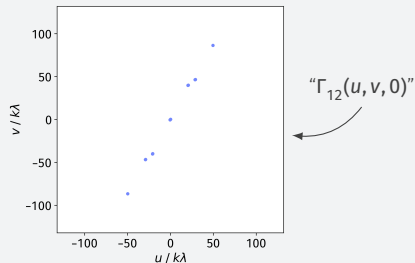


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4 Antennas; 10 s

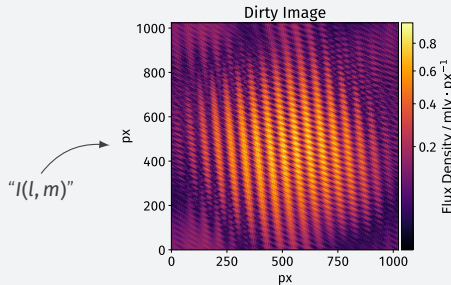
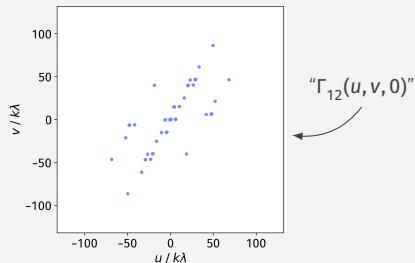


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20 Antennas; 10 s

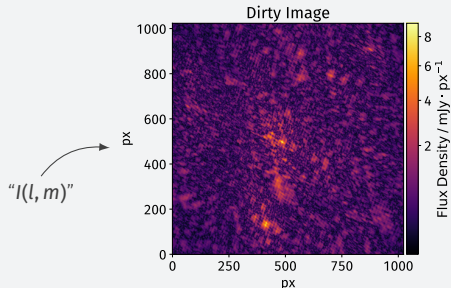
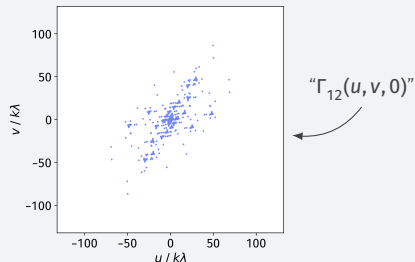


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62 Antennas; 10 s

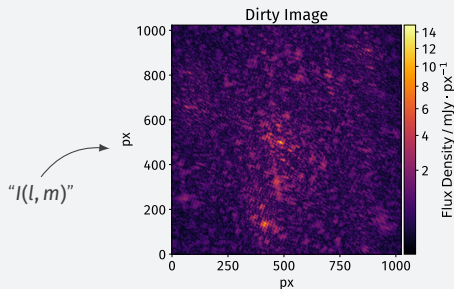
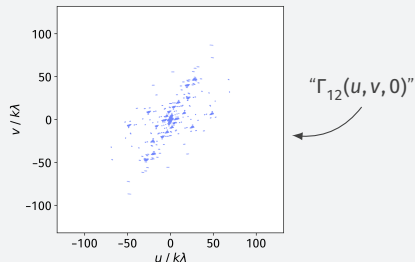


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62 Antennas; 60 s

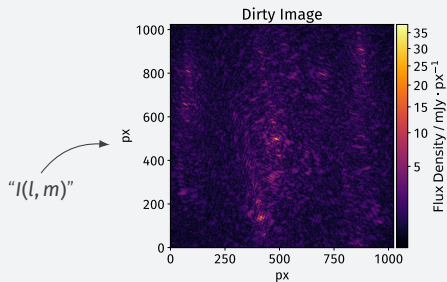
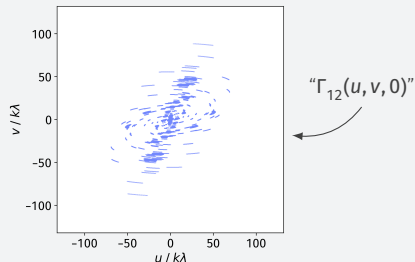


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62 Antennas; 1 h

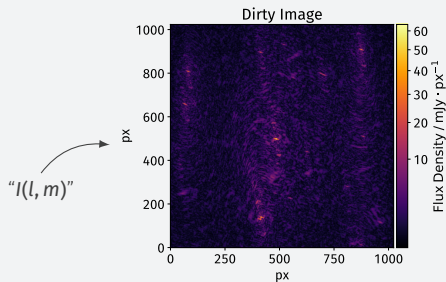
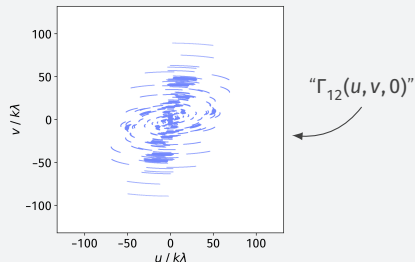


(u, v) Coverage

$$\Gamma_{12}(u, v, 0) = \iint I(l, m) e^{-2\pi i(u l + v m)} dl dm$$

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62 Antennas; 2 h

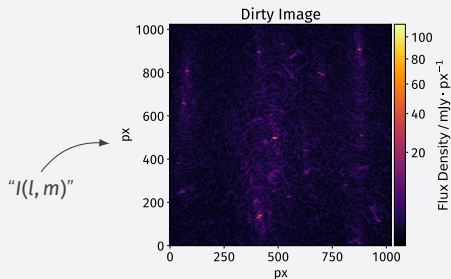
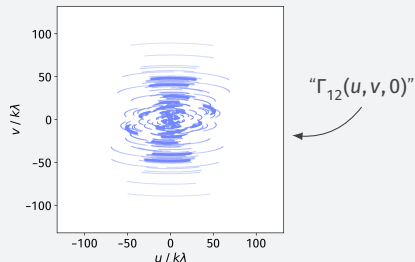


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62 Antennas; 4 h

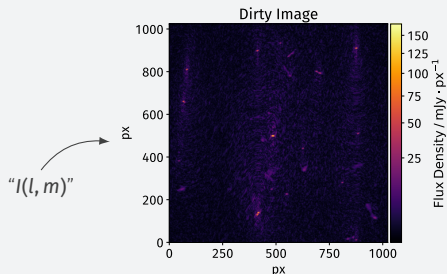
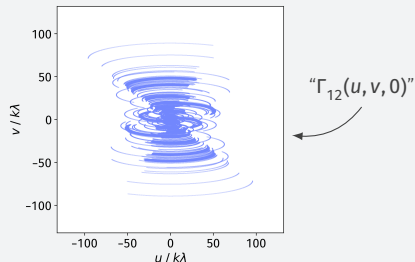


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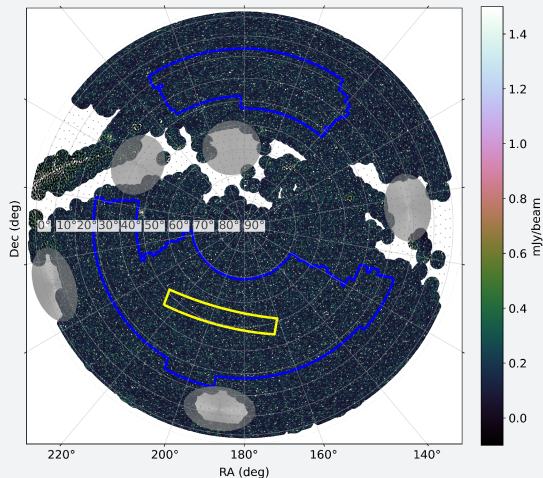
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62 Antennas; 8 h



LOW-Frequency ARray (LOFAR) Two-metre Sky Survey (LoTSS)

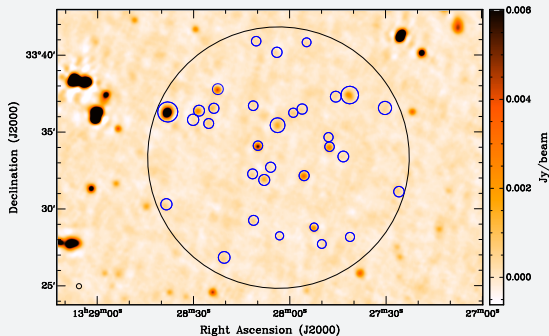
- 12 950 h data from ~2014 to 2024
- Between 6 h and 8 h observation time per pointing
- 120 MHz – 168 MHz covering 88 % of the northern sky @ 6 arcmin resolution
- Provides opportunities to search for diffuse DM signals



[Shimwell, T. W. et al. 2026. [10.1051/0004-6361/202557749](https://arxiv.org/abs/10.1051/0004-6361/202557749)]

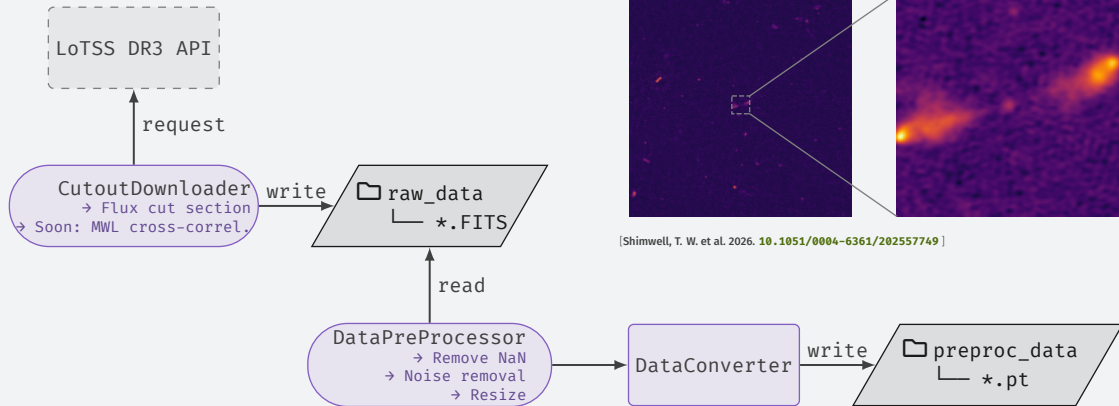
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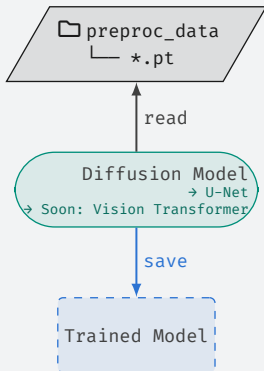


[M. Vollmann et al. 2020. [10.1093/mnras/staa1657](https://arxiv.org/abs/10.1093/mnras/staa1657)]

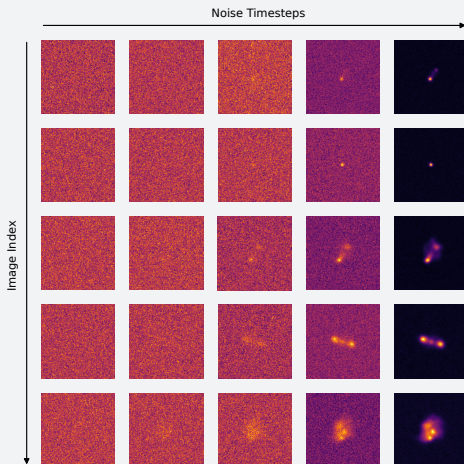
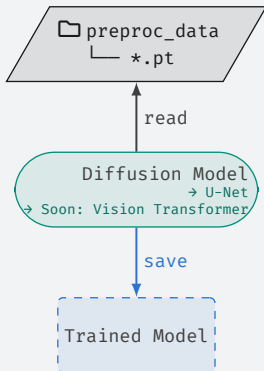
Data Aquisition and Pre-processing



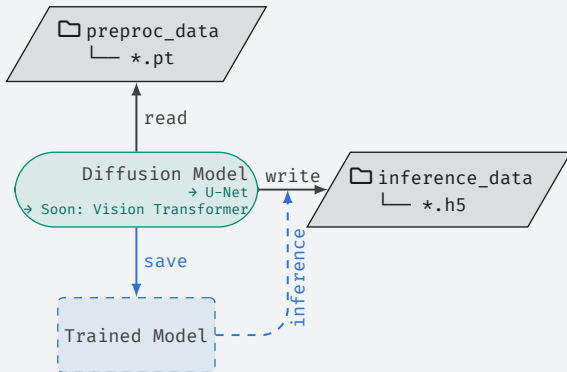
Simulation Pipeline



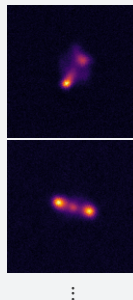
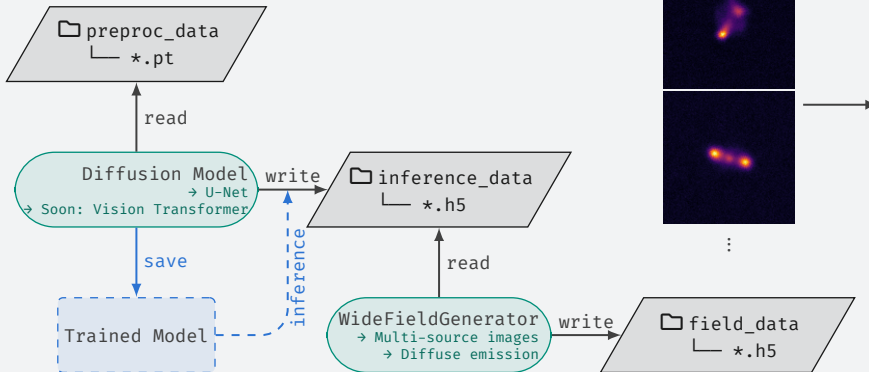
Simulation Pipeline



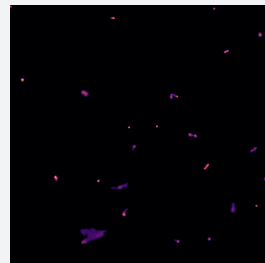
Simulation Pipeline



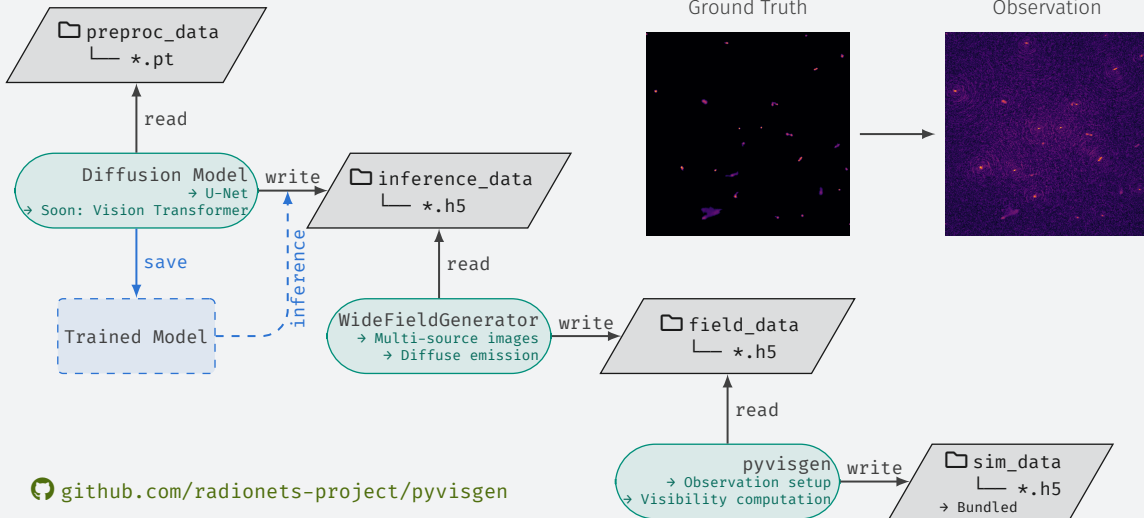
Simulation Pipeline



Wide-field (≈ 26 arcmin)

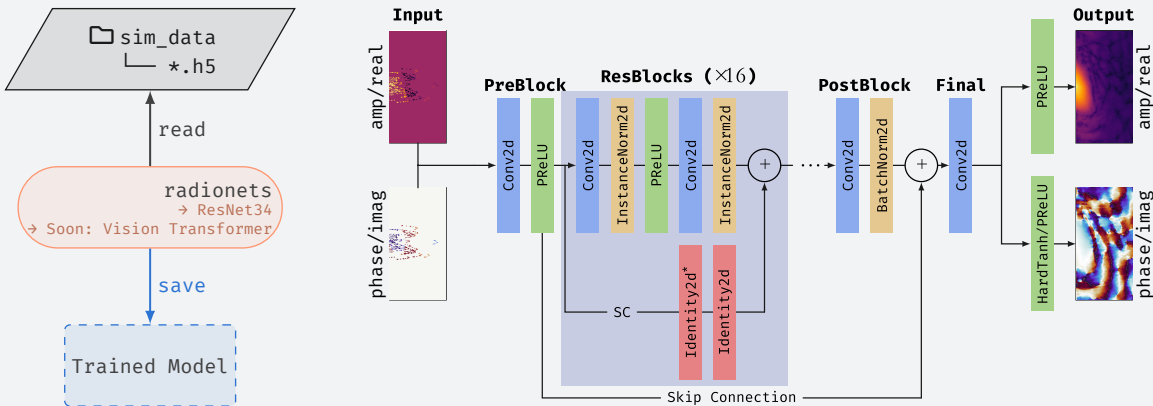


Simulation Pipeline



github.com/radionets-project/pyvisgen

Deep-learning-based Cleaning

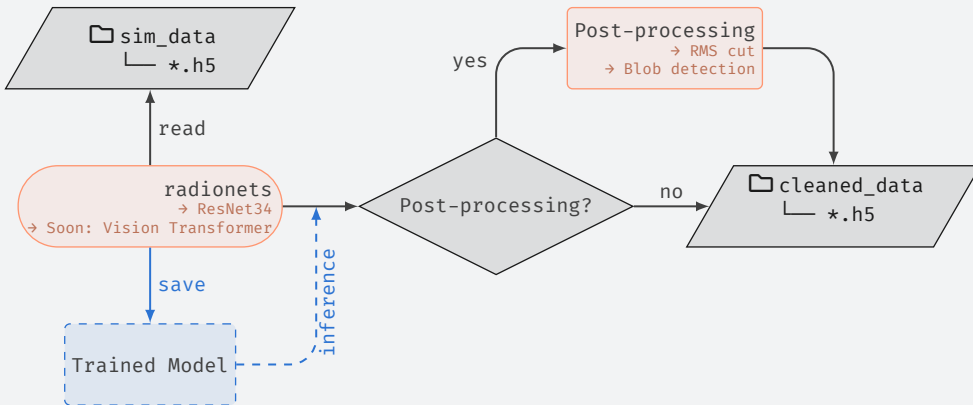


2-4x NVIDIA RTX PRO 6000 Blackwell@96GB

2-4x NVIDIA DGX A100@80GB

github.com/radionets-project/radionets

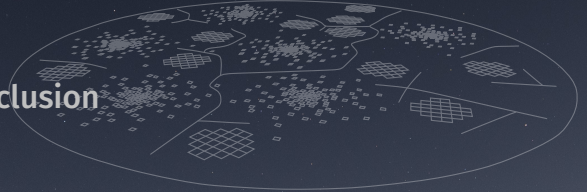
Deep-learning-based Cleaning



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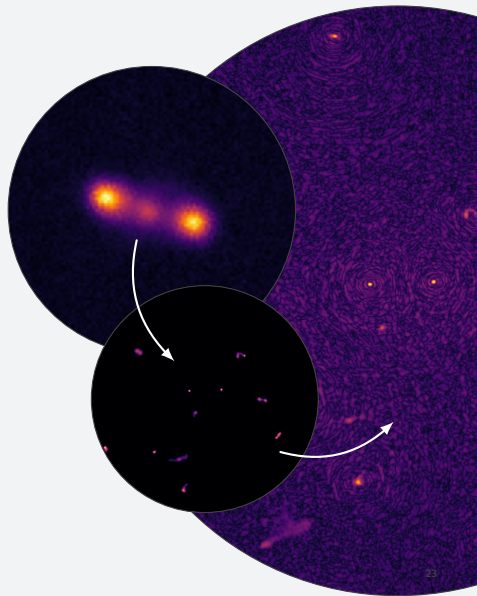
github.com/radionets-project/radionets

Conclusion



Conclusion

- Progress in methods from earlier analyses
 - Novel rotation exclusion method for 3D Background models
 - Python package **TITRATE** integrates Asimov dataset generation into gammapy
- We created a novel simulation pipeline for LoTSS dSph emission
 - Will be published as FOSS @  github.com/aknierim
- Training of **radionets** models is still undergoing
 - New, advanced architectures are being explored



Rotation Exclusion Method: Binning

- Zenith distance bins $5^\circ - 15^\circ$, $15^\circ - 25^\circ$ and $25^\circ - 30^\circ$
- 30 bins $-3^\circ - 3^\circ$ in Azimuth
- 8 bins in energy range 0.05 TeV – 5 TeV