Unveiling Dark Matter in Reticulum II Using MeerKAT

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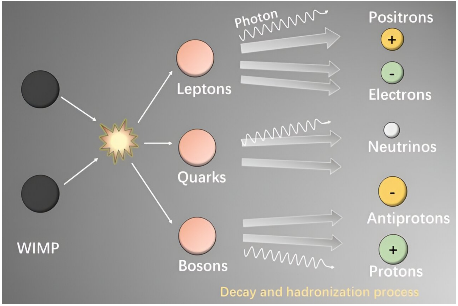
Indirect Detection in Radio

WIMPs → Standard Model Particles → Synchrotron Emission



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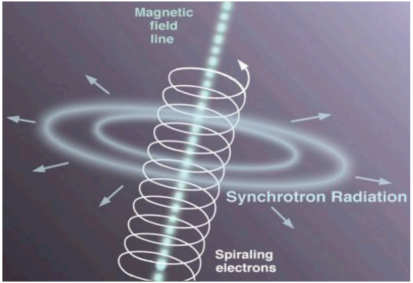

Diffusion and Energy Losses

$$\frac{\partial}{\partial t}\frac{dn_e}{dE} = \underbrace{\nabla \cdot \left(D(E,r)\nabla \frac{dn_e}{dE} \right)}_{\text{Diffusion term}} + \underbrace{\frac{\partial}{\partial E}\left(b(E,r,z)\frac{dn_e}{dE} \right)}_{\text{Energy loss term}} + \underbrace{Q(E,r)}_{\text{Source term}}$$

where

$$b(E,r,z) = b_{\text{sync}} + b_{\text{IC}} + b_{\text{brem}} + b_{\text{coul}}$$

with the synchrotron loss term approximated as

$$b_{\text{sync}} \approx 0.0254 \left(\frac{E}{1\text{ GeV}}\right)^2 \left(\frac{B(r)}{1\,\mu\text{G}}\right)^2$$

And

$$Q(E,r) = \frac{\langle \sigma v \rangle \rho_\chi^2(r)}{2m_\chi^2} \frac{dN}{dE}$$

Where: $\langle \sigma v \rangle$ is the dark matter particle annihilation cross-section, m_χ is the mass of the dark matter particle, $\rho_\chi(r)$ is the dark matter density and dN/dE is the energy spectrum of the electrons and positrons produced by the annihilations

Modelling

- ***DarkMatters*** tool was used. Developed by Dr Michael Sarkis and Dr Geoff Beck [arXiv:2408.07053]
- Key Parameters
  - Dark matter properties
    - Density profile
    - Annihilation cross section
    - WIMP mass
  - Environments
    - Magnetic field
    - Diffusion
    - Energy loss
- Output $\longrightarrow$ Radio Flux

Radio Regime for Indirect Search

- Advantages
  - Can probe lower dark matter masses
  - Complements other wavelength searches
  - Excellent sensitivity for diffuse emission
    - Potential dark matter signal
- These requires
  - Large collecting area
  - Ability to detect faint, diffuse emission
  - Good resolution
  - Solution: Interferometry

Radio Interferometry

- A network of antennas working together to function as one large telescope
- Pair of antennas in the array creates a baseline
  - Resulting in
    - Short and Long baselines; based on the distance between the antennas

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Short vs Long Baselines

- Short baselines
  - Better sensitivity to diffuse emission
  - Important for detecting faint, extended signals
- Long baselines
  - Better angular resolution
  - Important for resolving fine structure
- Combination provides complete picture
  - Sensitive to both diffuse emission and fine details
  - Crucial for dark matter searches

The MeerKAT Radio Telescope Array

- A radio interferometer of 64 dishes and precursor to the SKA
- Built in South Africa, Northern Cape
- Operated by the South African Radio Astronomy Observatory (SARAO)

Figure: MeerKAT

Astronomical Targets

- Dwarf Spheroidal galaxies (dSphs)
  - One of the best targets for indirect dark matter searches: Dark matter-dominated objects
  - Clean environments
    - Less astrophysical background

dSphs of the Local Group

- Newly being discovered and nearby
- No recent/ongoing star formation
- Very high M/L ratio
- High and known J factor

Our target: Reticulum II ; a Milky Way Satellite

- Very high dark matter-dominated object with M/L ratio of $\sim$500
- distance of 30 kpc
- Well below the galactic plane

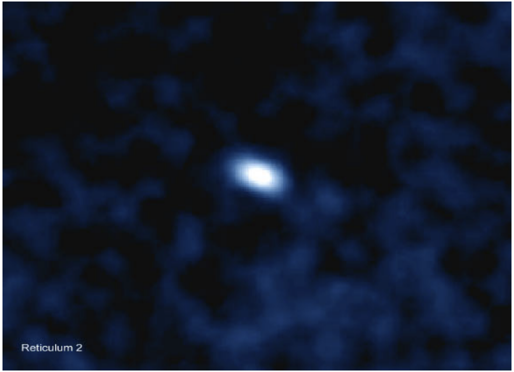


Figure: Discovered by DES (2015)

MeerKAT Observation of Reticulum II

- Observed for 8 hours
- In UHF Band [544 to 1088 MHz]

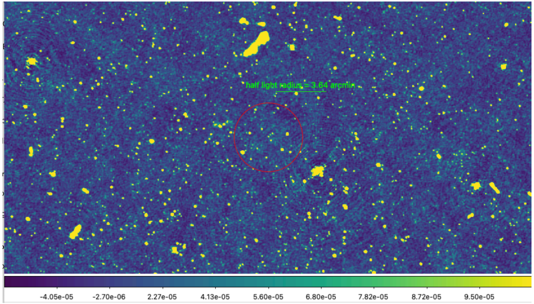


Figure: Reticulum II: From MeerKAT

Data Reduction: Imaging and Calibration

- **Cross Calibration**
  - The process of calibrating the calibrators to apply the solutions to the target
  - Calibrators are sources of known flux and spectra
- ***CARACAl pipeline*** (https://github.com/caracal-pipeline)

- **Imaging and self-calibration**
  - Imaging the calibrated target
  - Iterative self-calibration using the initial image
  - ***WSClean*** (arXiv:1407.1943) and ***Quartical*** (https://github.com/ratt-ru/QuartiCal) were used
- Bright Sources Subtraction
  - ***pybdsf*** (https://github.com/lofar-astron/PyBDSF)

Reticulum II for different weights and taper

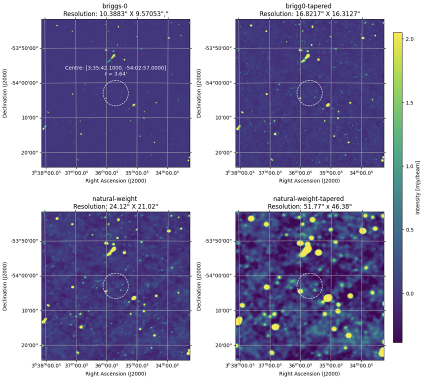


Figure: Before source subtraction

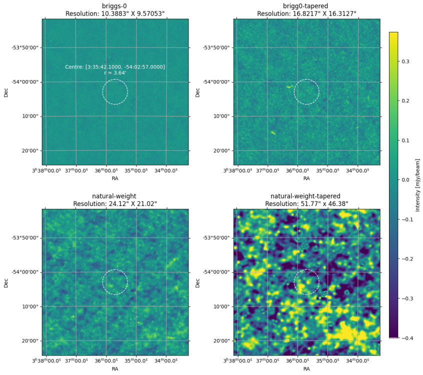


Figure: Residudals

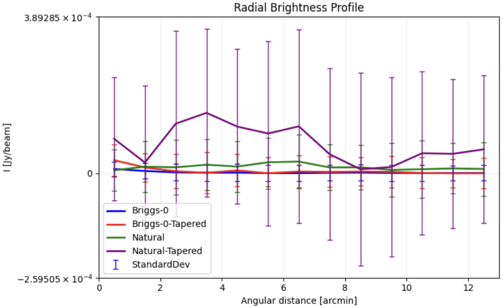
Why weight and taper?

- Weight
  - Trade-off between sensitivity and resolution
- Taper
  - de-imphasizing longer baselines $\rightarrow$ prioritizing sensitivity to diffuse faint emission over resolution

Signal Analysis

- Steps:
  - Radial brightness profiles
    - Calculated mean brightness in concentric annuli
    - From center outwards
  - Statistical analysis (chi-square)

Radial Brightness Profiles



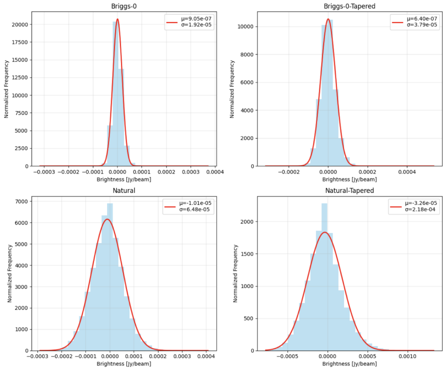


Figure: Histogram: Residuals

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- A residual consistent with noise
- No signal that stands out above the noise
- We can calculate the upper limits since we see no dark matter signal
- We require a model flux for the chi-square

Model flux Calculation

- *DarkMatters tool [arXiv:2408.07053]* (introduced earlier...) was used
- We assumed Einasto Profile for the density distribution,

$$\rho(r) = \rho_{-2}^{-2/\alpha((r/r_{-2})^{\alpha}-1)}$$

where the index $\alpha = 0.4$ and the characteristic scale radius $r_{-2} = 0.2$ kpc (for our target)

- Calculated for
  - Frequency: 0.7960 (GHz)
    - The same frequency (central) as the image from the observation
  - Annihilation cross section = 10^{-26} cm³/s
  - Ranges of WIMP masses
  - 3 output channels

χ^2 Likelihood Analysis for Upper Limits

- Compared residual data and models at different annihilation cross sections $\langle \sigma v \rangle$ via chi-square

$$\chi^2 = (1/N_{beam}) \times \sum [(\text{model} - \text{data})^2/\sigma^2]$$

- Number of independent beams (N_{pix}/N_{beam}) in our 1024×1024 pixel analysis region are:
  - Briggs-0: 83,886 independent beams
  - Briggs-0-tapered: 30,358 independent beams
  - Natural-weighted: 16,461 independent beams
  - Natural-weighted-tapered: 3,472 independent beams

- Calculated chi-square difference from minimum

$$\Delta\chi^2 = \chi^2 - \chi^2_{\text{minimum}}$$

- Excluded cross sections where $\Delta\chi^2 > 2.71$ (at 95% CL)
- Set upper limits on the excluded annihilation cross sections

Reticulum II upper limits of MeerKAT (Preliminary. i.e. In prep yet)

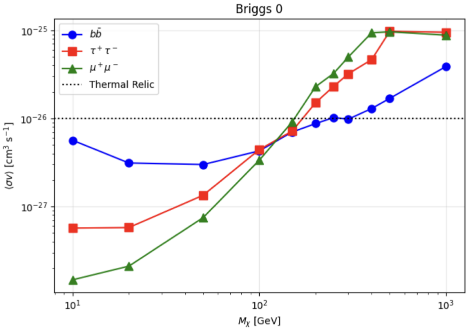

Figure: Briggs-0

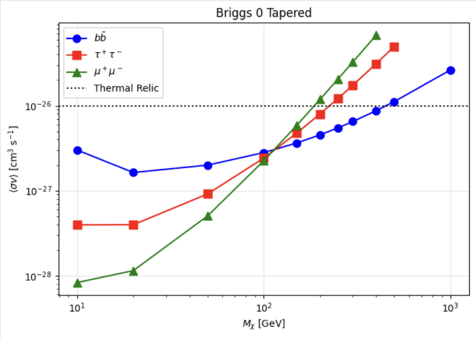

Figure: Briggs-0-Tapered

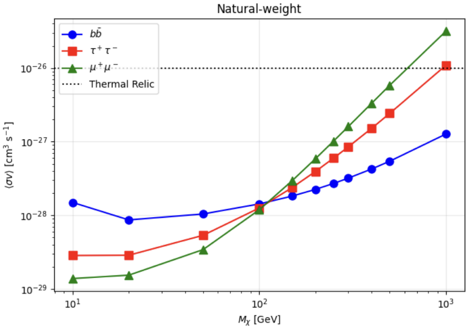

Figure: Natural Weight

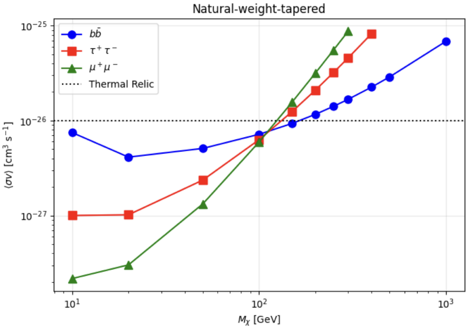

Figure: Natural-Weight-Tapered

What we are saying ...

- These excluded cross sections over predicts the dark matter signal
- The signal must be below this; we would have seen it otherwise

Reticulum II upper limits Compared to ATCA's

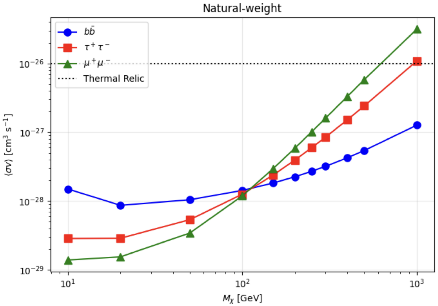

Figure: Natural Weight

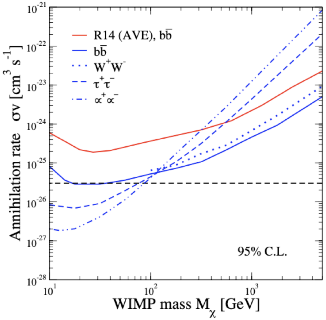

Figure: ATCA's: Regis 2017: https://doi.org/10.48550/arXiv.1703.09921

Sensitivity Comparison of MeerKAT to ATCA for Reticulum II observations

- MeerKAT
  - Observed for 8 hours
  - rms sensitivity: 0.0015 mJy/beam
- ATCA
  - Observed for 30 hours
  - rms sensitivity: 0.01mJy/beam
- MeerKAT is doing much better than ATCA for dark matter searches
  - From one to two orders of magnitude improvements on the upper limit

Summary and Outlook

- Our results showed radio is a promising regime to rule out WIMP models at lower masses
- Will be capable of detecting the signal, as sensitivity increases (i.e. SKA)
- The more sensitive we are the more we get to rule out over-predicting models
- Sensitivity is the most important parameter and we need resolution for accurate source subtraction

Thank You!