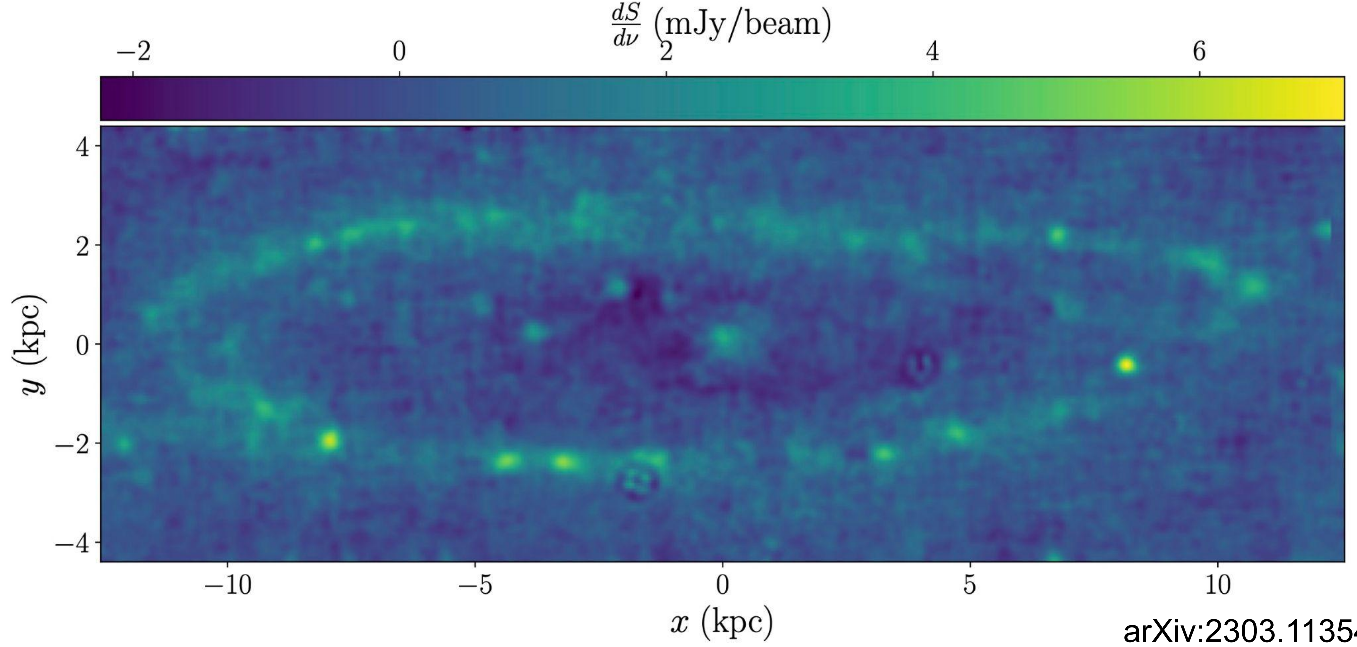
Limits on Dark Matter Annihilation from the Shape of Radio Emission in M31

Mitchell Weikert

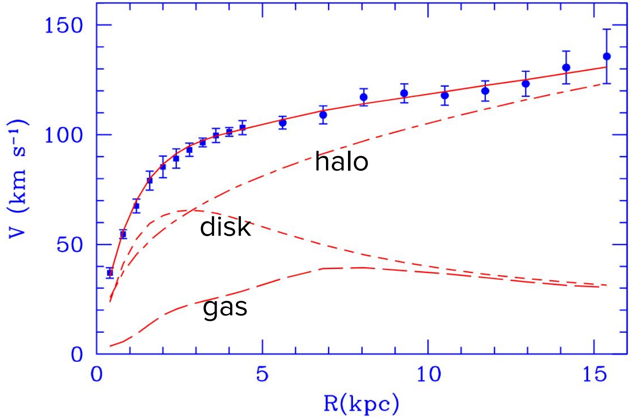


arXiv:2303.11354 w/ Matthew Buckley

Gravitational Anomalies

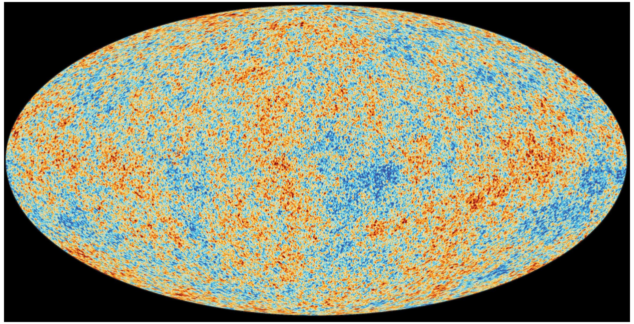
- SM tension with astrophysical and cosmological observations

Galactic Rotation Curves



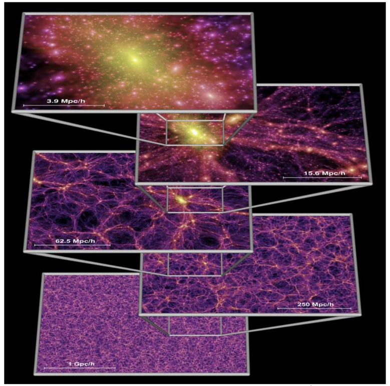
astro-ph/9909252 (Corbelli & Salucci 1999)

Cosmic Microwave Background



www.esa.int (ESA/Planck Collaboration)

Large Scale Structure



Springel et al. 2005 [astro-ph/504097]

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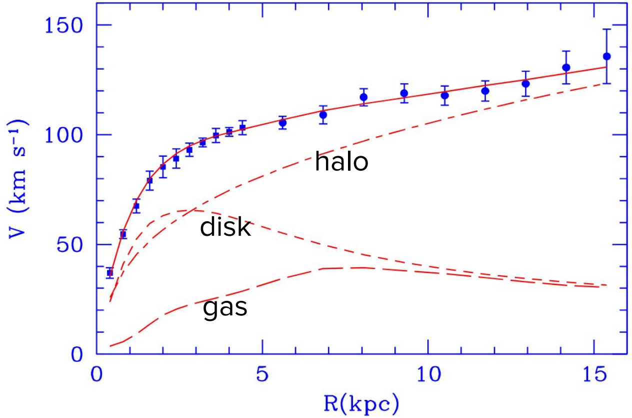

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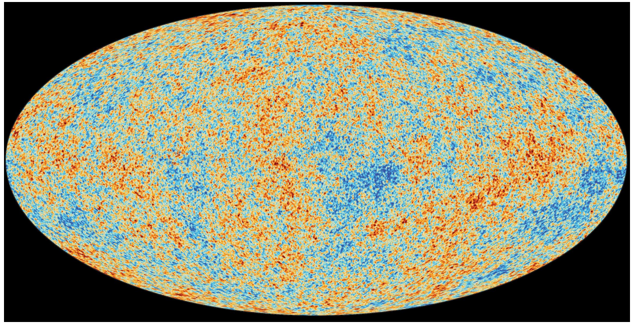

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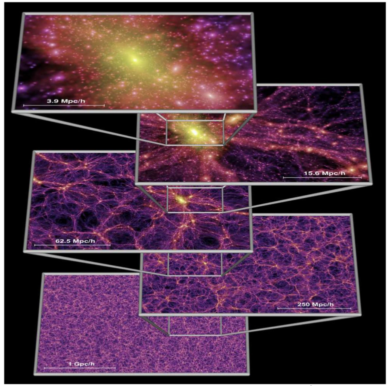
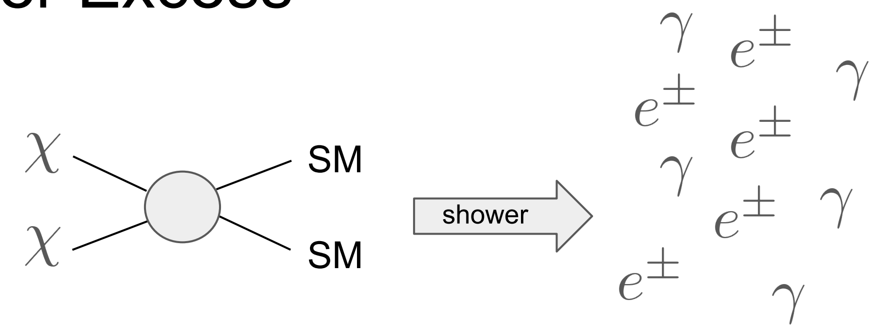


Springel et al. 2005 [astro-ph/504097]

- Dark matter is the best way to fit these observations
  - While astrophysical and cosmological data tell us some features of dark matter, its particle physics nature remains a mystery

Galactic Center Excess



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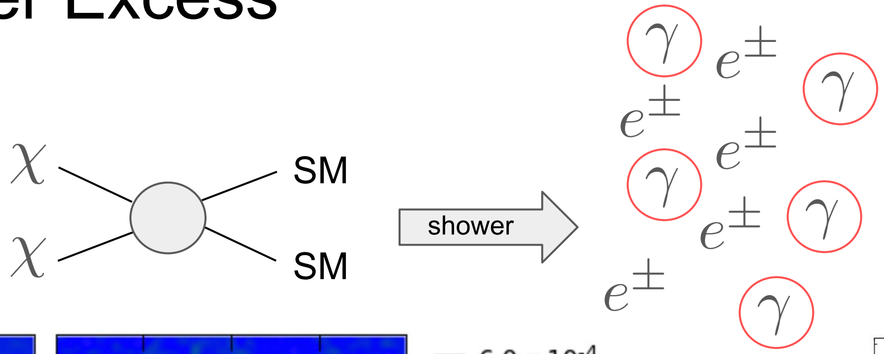
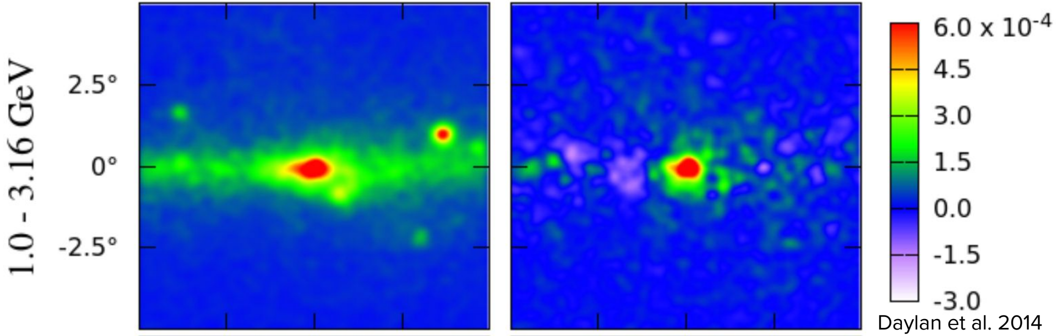
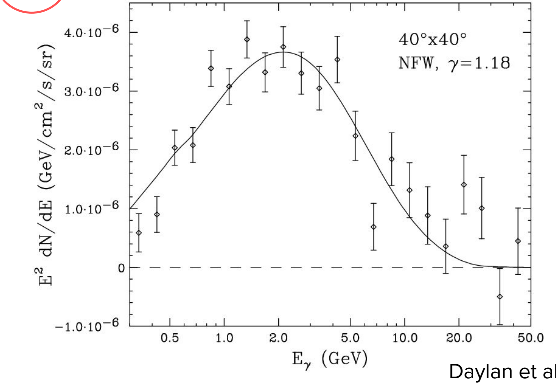




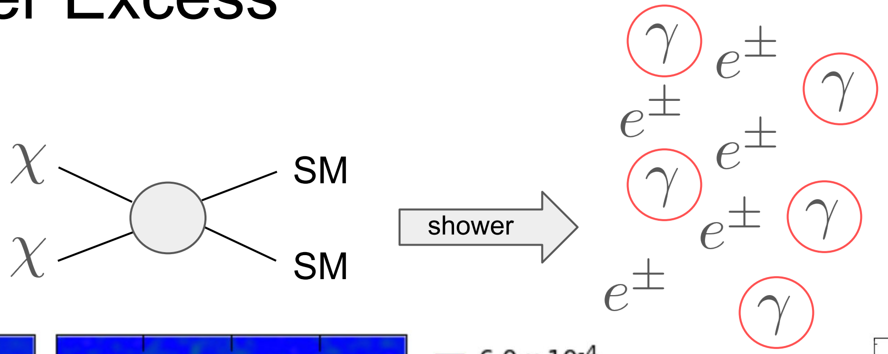
Daylan et al. 2014

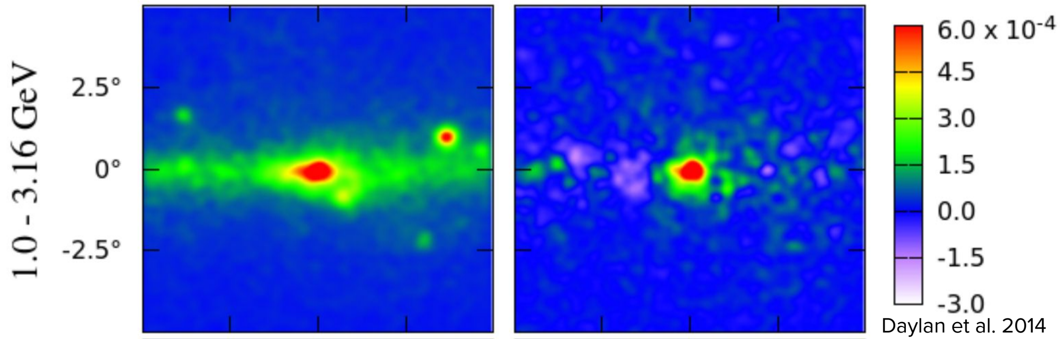


Daylan et al. 2014

- Best fit with $\chi\chi \to b\bar{b}$ and $m_\chi \simeq 40\,\mathrm{GeV}$ with cross sections $\mathcal{O}(10^{-26}\,\mathrm{cm}^3/\mathrm{s})$

Galactic Center Excess





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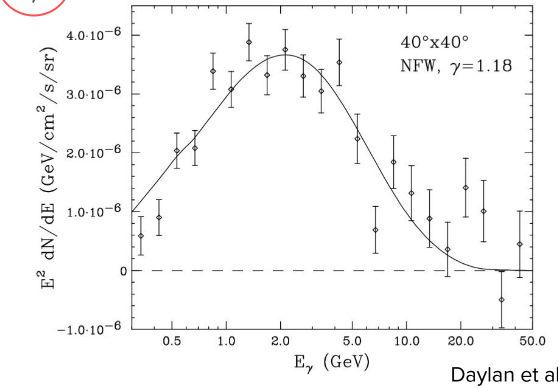

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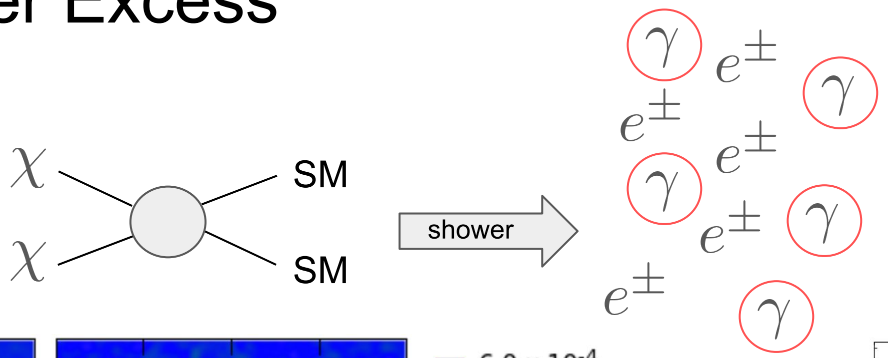

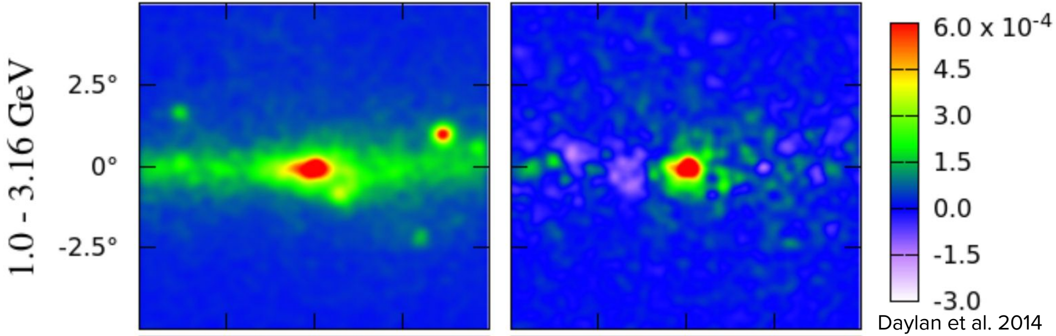

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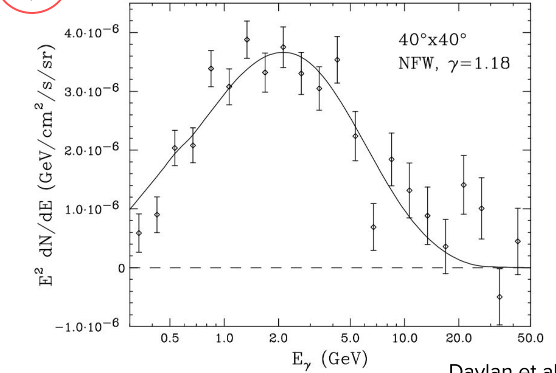

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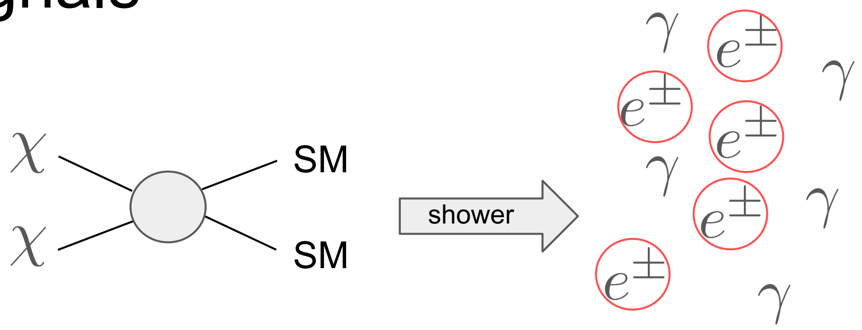
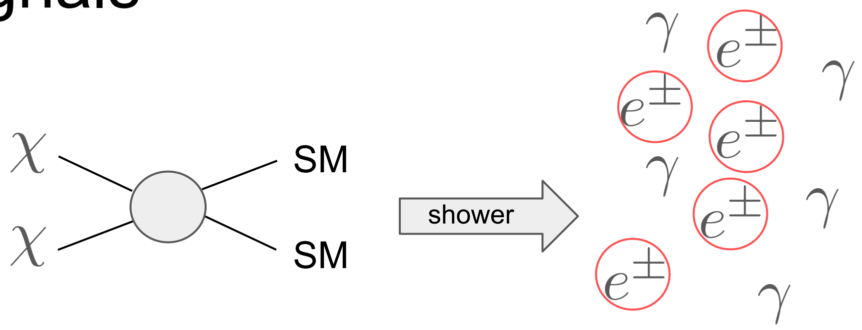
- Best fit with $\chi\chi \to b\bar{b}$ and $m_\chi \simeq 40\,\mathrm{GeV}$ with cross sections $\mathcal{O}(10^{-26}\,\mathrm{cm}^3/\mathrm{s})$
- Alternative explanation: Unresolved millisecond pulsars
- Similar excess exists in M31

Secondary Signals



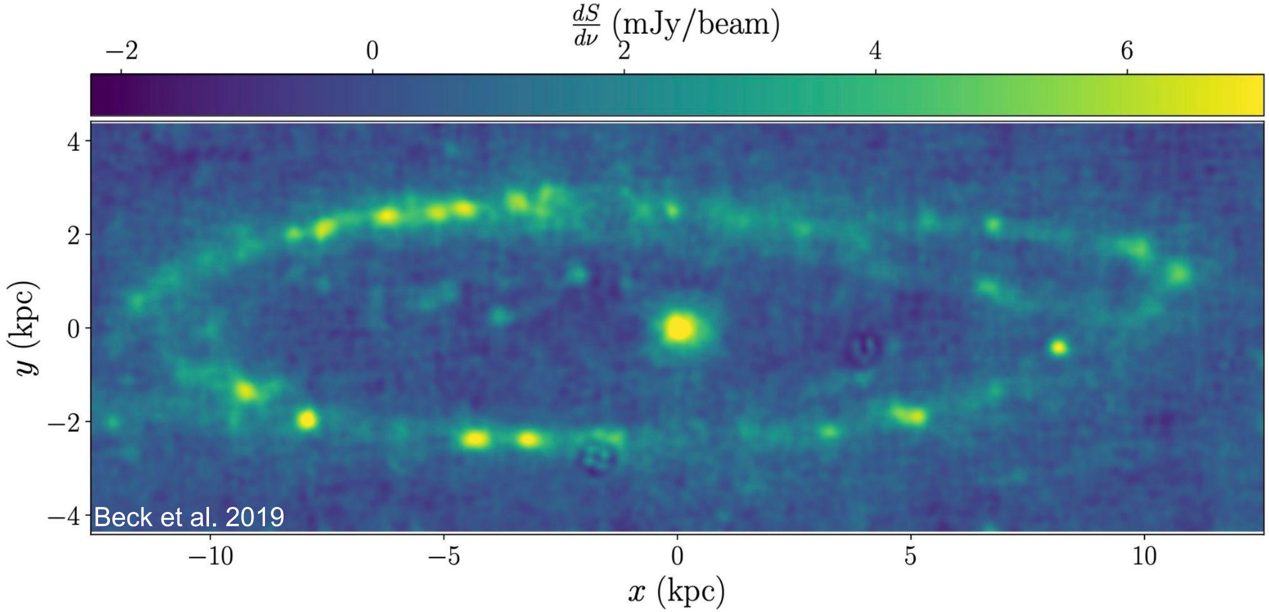
- Population of relativistic electrons and positrons

Secondary Signals



- Population of relativistic electrons and positrons
- Can possibly be observed through:
  - **Synchrotron from interactions with galactic magnetic fields $\longrightarrow$ radio**
  - Inverse compton from scattering with ambient photons $\longrightarrow$ X-rays and gamma rays
  - Bremsstrahlung from scattering with nuclei and ionized gas $\longrightarrow$ gamma rays

Data

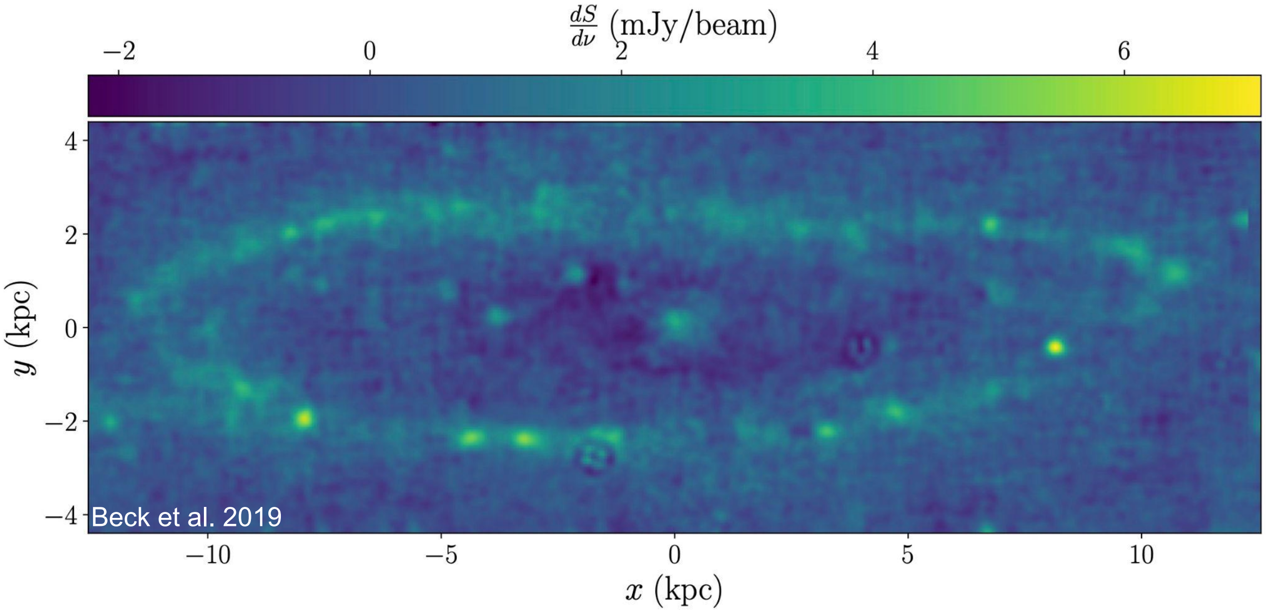


$$\nu = 8.35\,\mathrm{GHz}$$

$$HPBW = 0.34\,\mathrm{kpc}$$

$$\sigma_{\mathrm{rms}} = 0.25 - 0.30\,\mathrm{mJy/beam}$$

Data



$$\nu = 8.35\,\mathrm{GHz}$$

$$HPBW = 0.34\,\mathrm{kpc}$$

$$\sigma_{\mathrm{rms}} = 0.25 - 0.30\,\mathrm{mJy/beam}$$

- Relativistic $e^{\pm}$ produce non-thermal emission $\longrightarrow$ subtract thermal

Calculation of Radio Signal

Propagation with Diffusion Loss equation

$$\frac{\partial f_e}{\partial t} = \overbrace{\partial_i \left[\mathcal{D}_{ij}(\boldsymbol{x}, E)\partial_j f_e\right]}^{\text{Diffusion}} + \overbrace{\frac{\partial}{\partial E}\left[b(\boldsymbol{x}, E) f_e\right]}^{\text{Energy Loss}} + \overbrace{Q_e(\boldsymbol{x}, E)}^{\text{DM Source}}$$

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$$Q_e(\boldsymbol{x}, E) = \frac{\langle \sigma v \rangle}{2m_\chi^2}\frac{dN_e}{dE}\rho_\chi(\boldsymbol{x})^2$$

$$\rho_\chi = \frac{\rho_0}{(r/r_s)^\gamma (1+r/r_s)^{3-\gamma}} \qquad \gamma = 1$$

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Simulate with `pythia`

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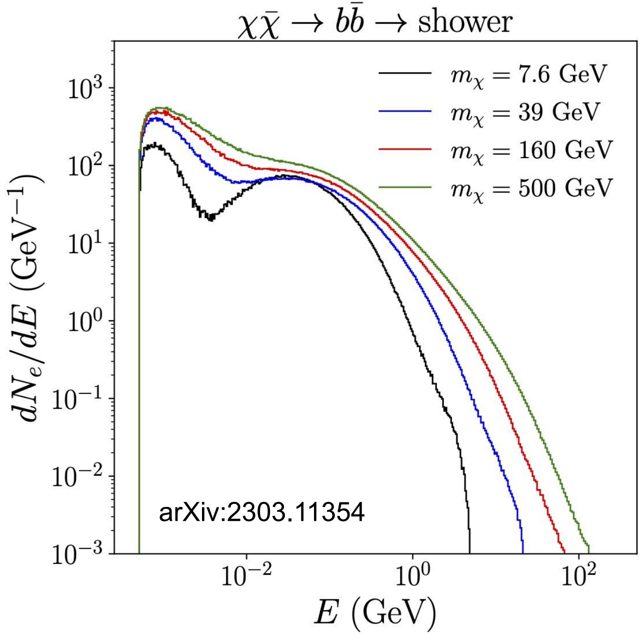

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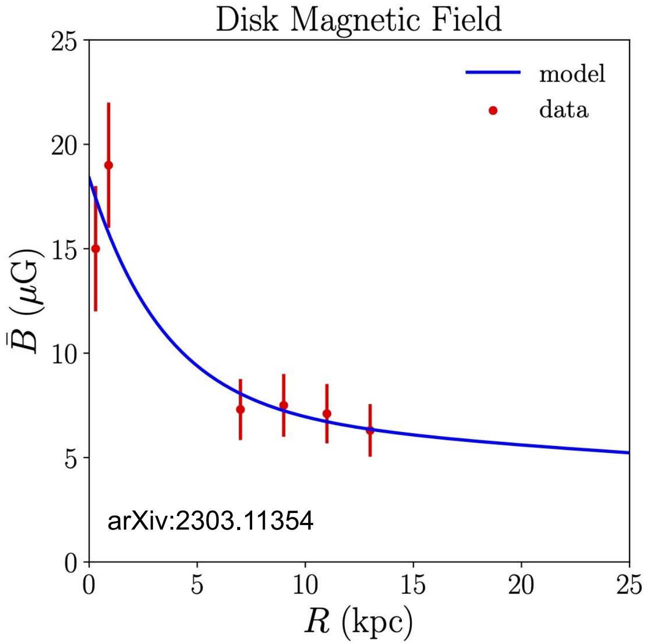
$$\mathcal{D}_{ij} = \delta_{ij} D_0 \left(\frac{10\mu\mathrm{G}}{\bar{B}}\right)^{1/3} \left(\frac{E}{1\mathrm{GeV}}\right)^{1/3}$$

$$D_0 \in [3 \times 10^{27}, 8 \times 10^{28}]\,\mathrm{cm}^2/\mathrm{s}$$



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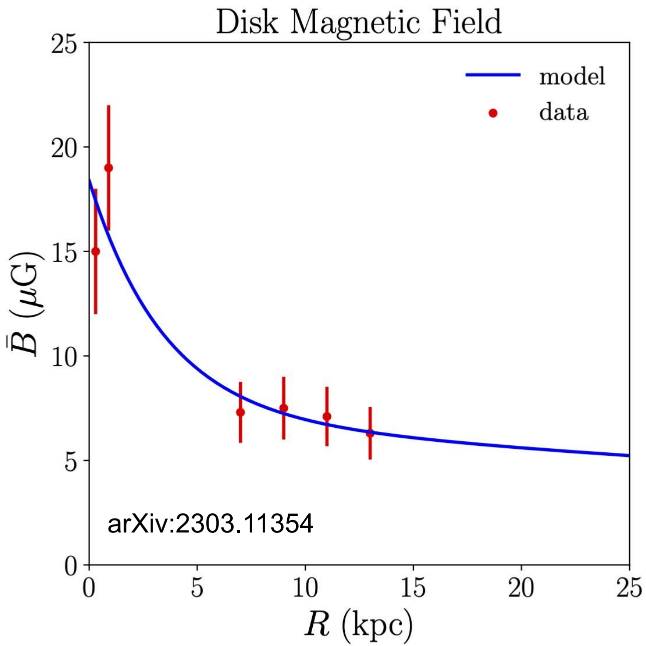
Default Value: $D_0 = 1 \times 10^{28}\,\mathrm{cm}^2/\mathrm{s}$



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Depends on the Photon Energy Density

$$b_{\mathrm{IC}} = b_{\mathrm{IC}}^{(0)} \left(\frac{\rho(\boldsymbol{x})}{10\,\mathrm{eV/cm^3}}\right) \left(\frac{E}{1\,\mathrm{GeV}}\right)^2$$

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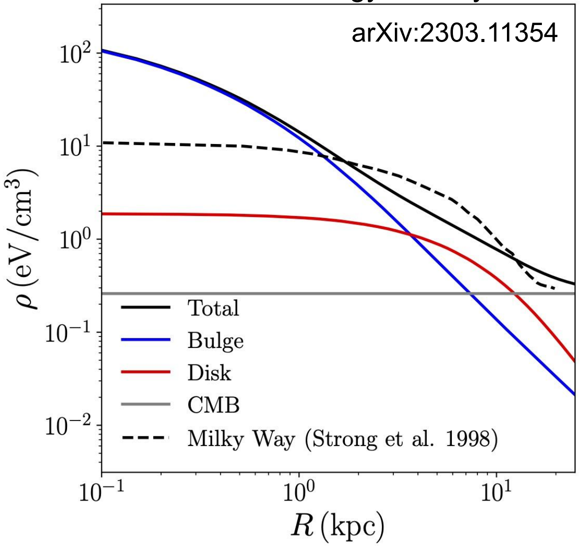
Photon Energy Density



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Underestimating ρ leads to overprediction of signal

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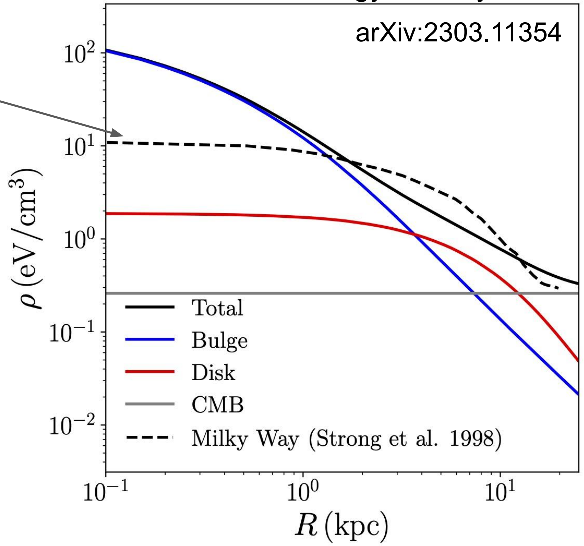

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Depends on the local RMS Magnetic Field

$$b_{\rm sync} = b_{\rm sync}^{(0)} \left(\frac{\bar{B}(R,z)}{10\,\mu{\rm G}}\right)^2 \left(\frac{E}{1\,{\rm GeV}}\right)^2$$

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Depend on densities of He, H and ionized gas

Propagation with Diffusion Loss equation

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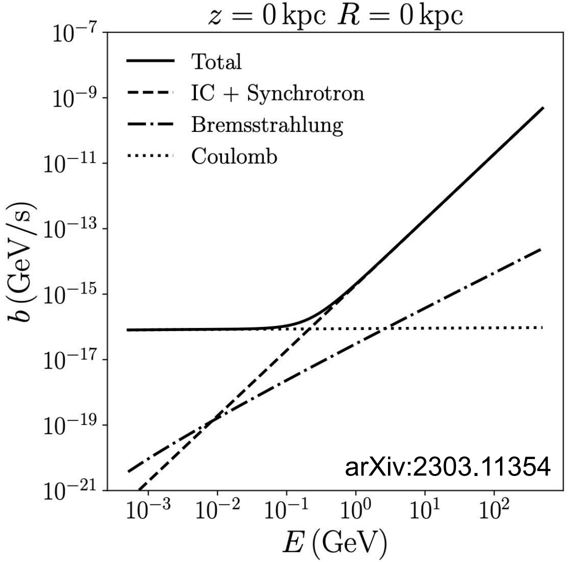

Solving Diffusion Loss Equation

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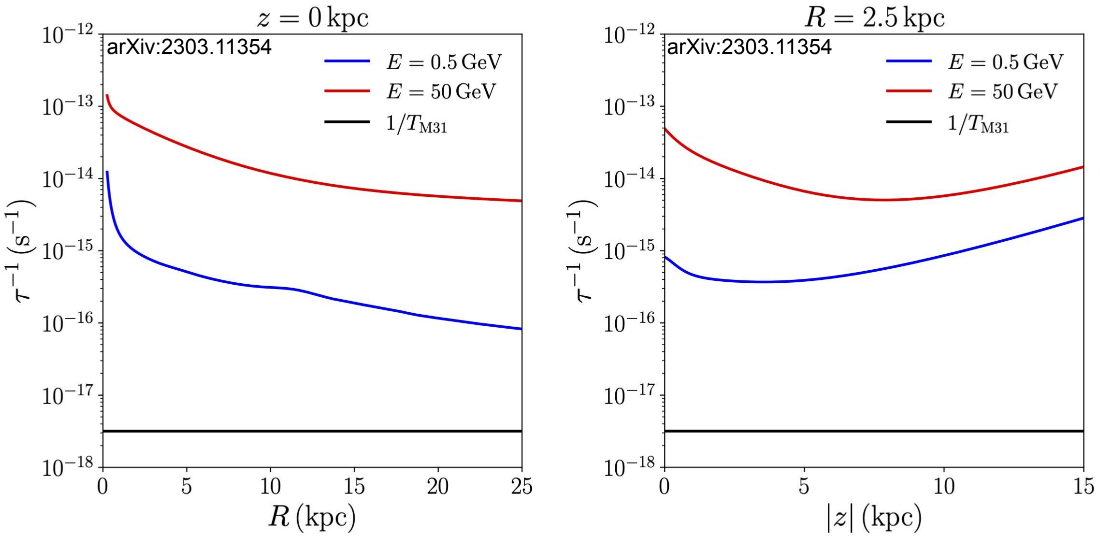
- Inverse dynamical timescale is larger than $1/T_{\mathrm{M31}}$

$\Longrightarrow$ Equilibrium Reached



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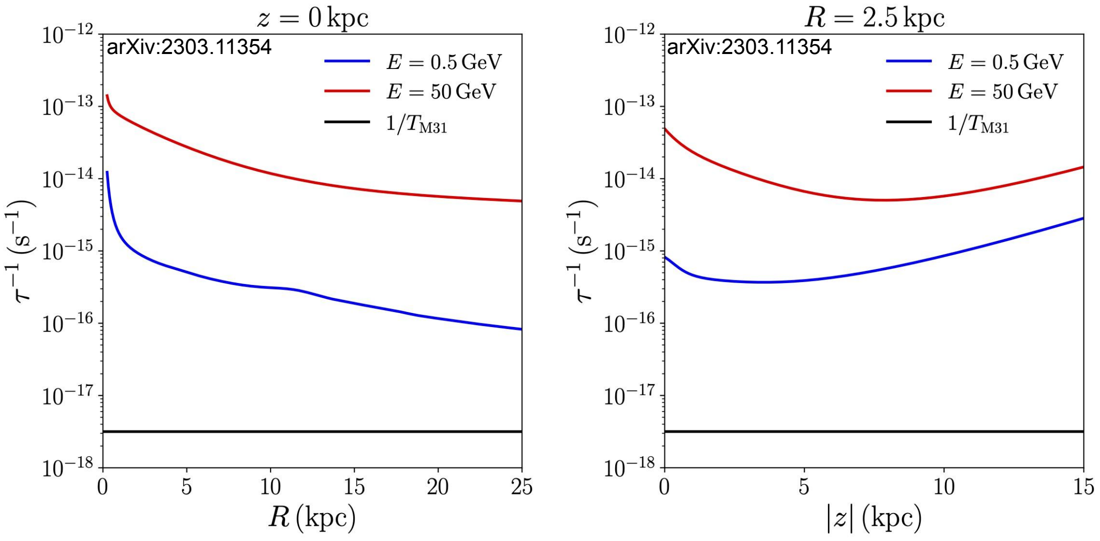
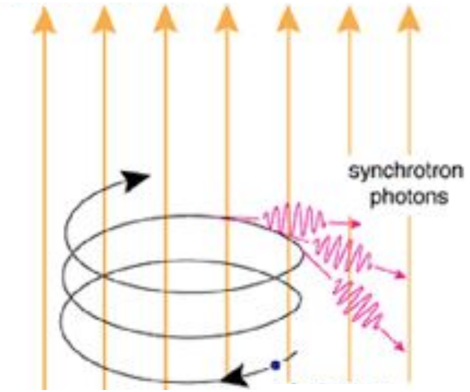
- Developed first numerical method to solve this equation with a non-uniform diffusion coefficient



Production of Radio

- Convolve phase-space density with standard formula for synchrotron emission of a single particle in a magnetic field



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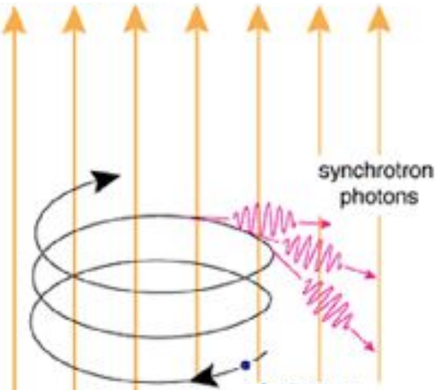
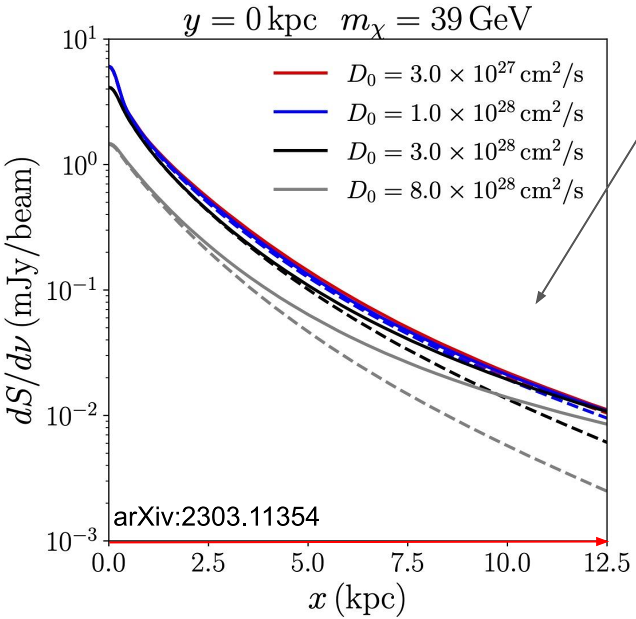
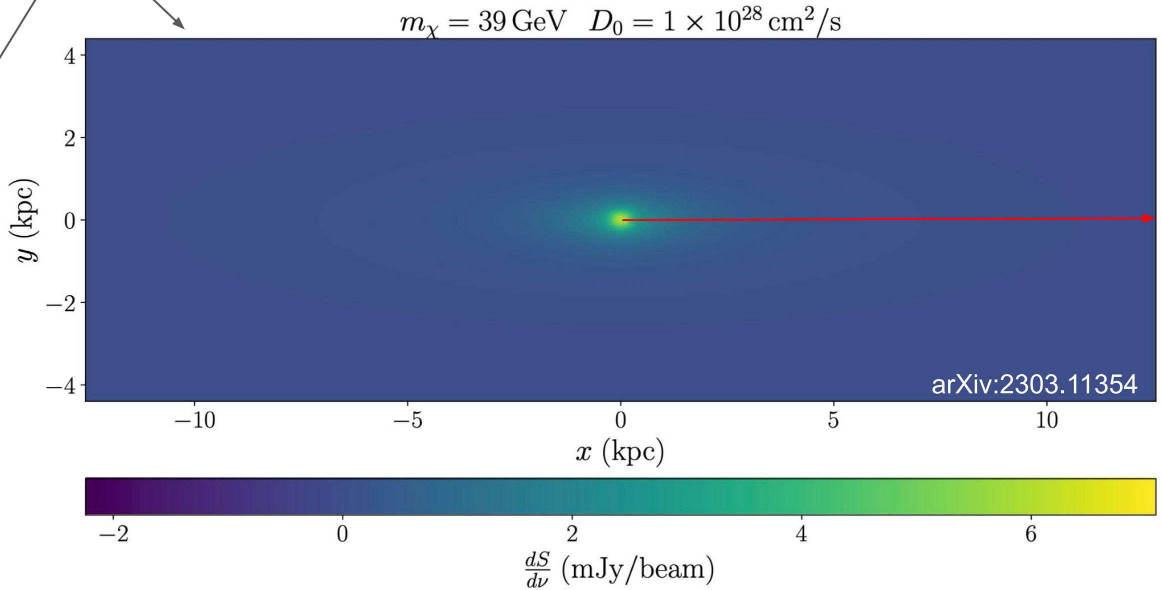


$$\langle \sigma v \rangle = 2.2 \times 10^{-25}\,\mathrm{cm}^3/\mathrm{s}$$





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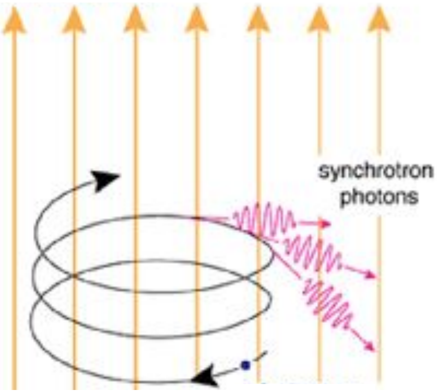

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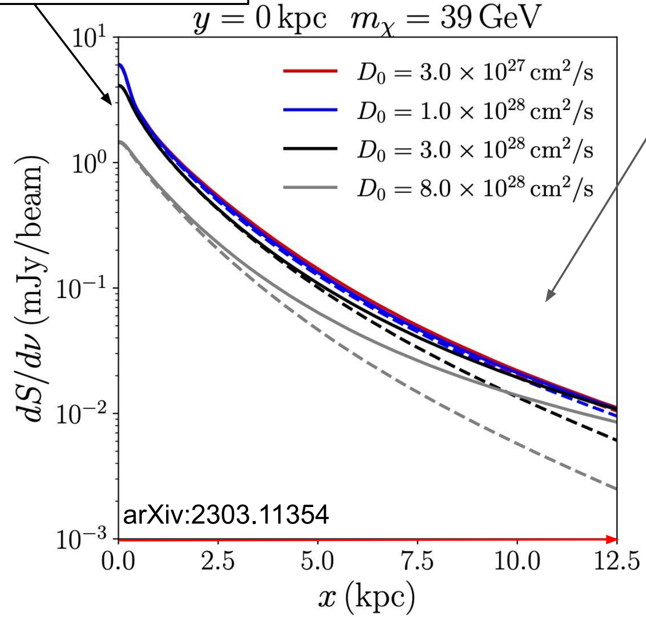
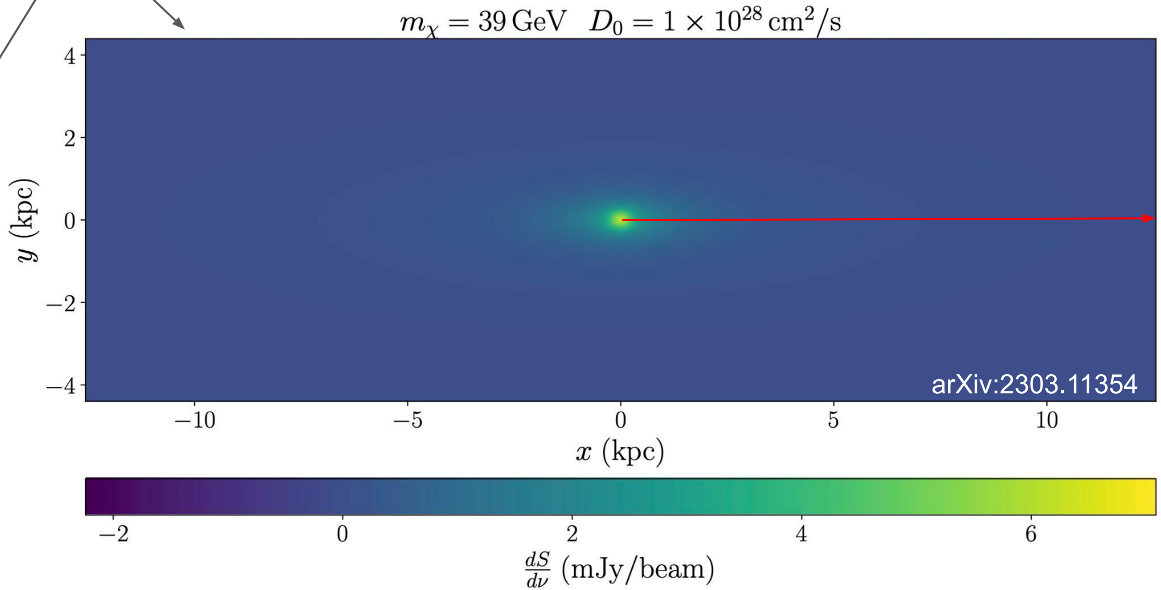
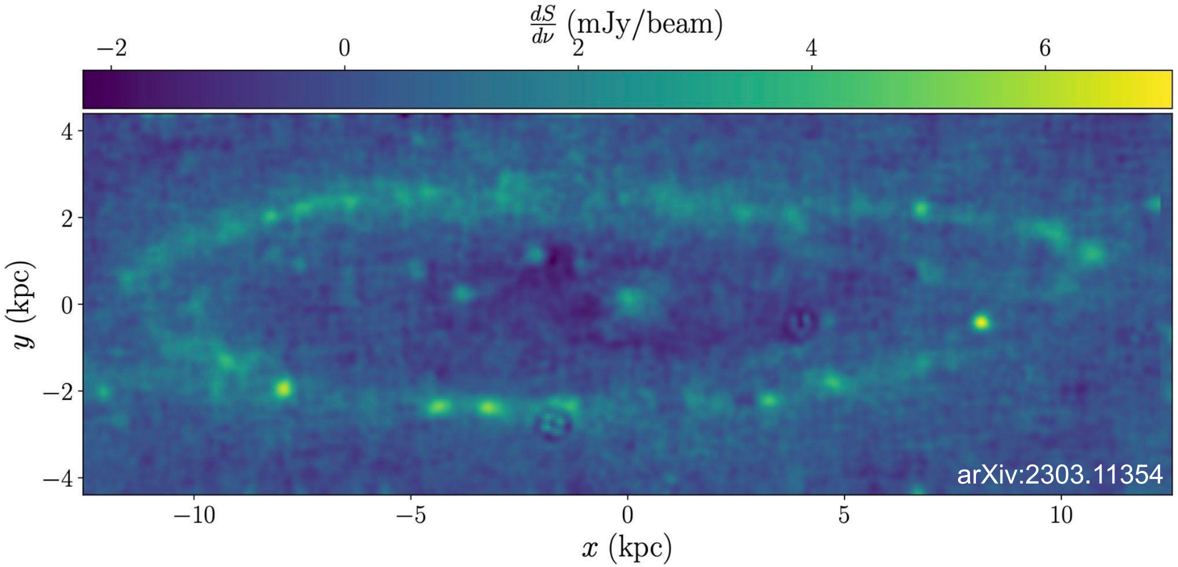
Sensitivity to D_0





Statistical Method

Masking Unmodeled Features



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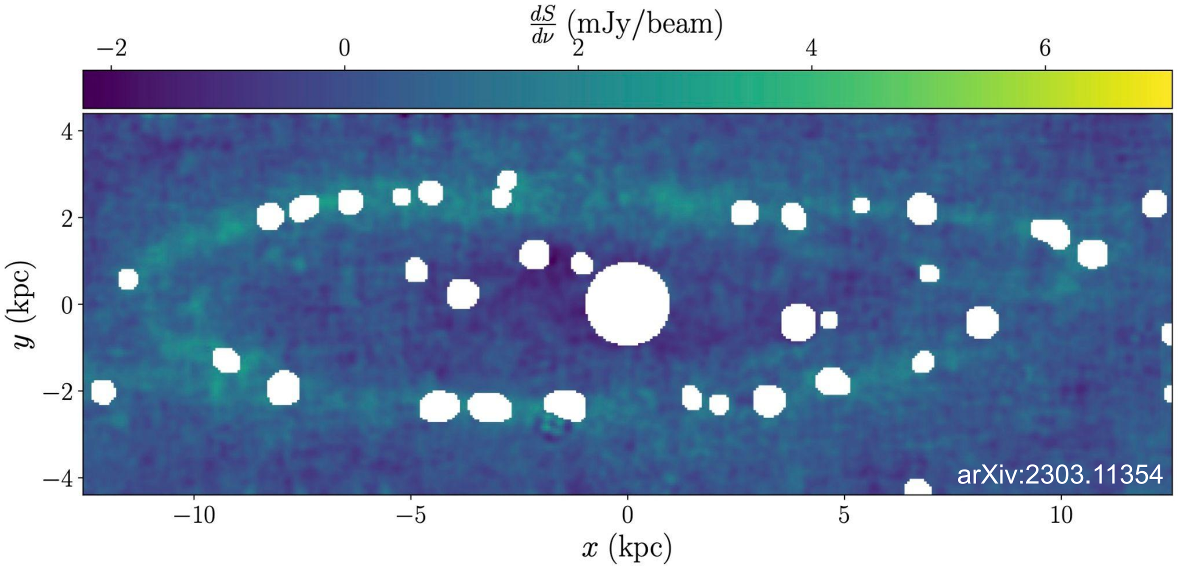

- Point sources
- Center - sensitive to D_0

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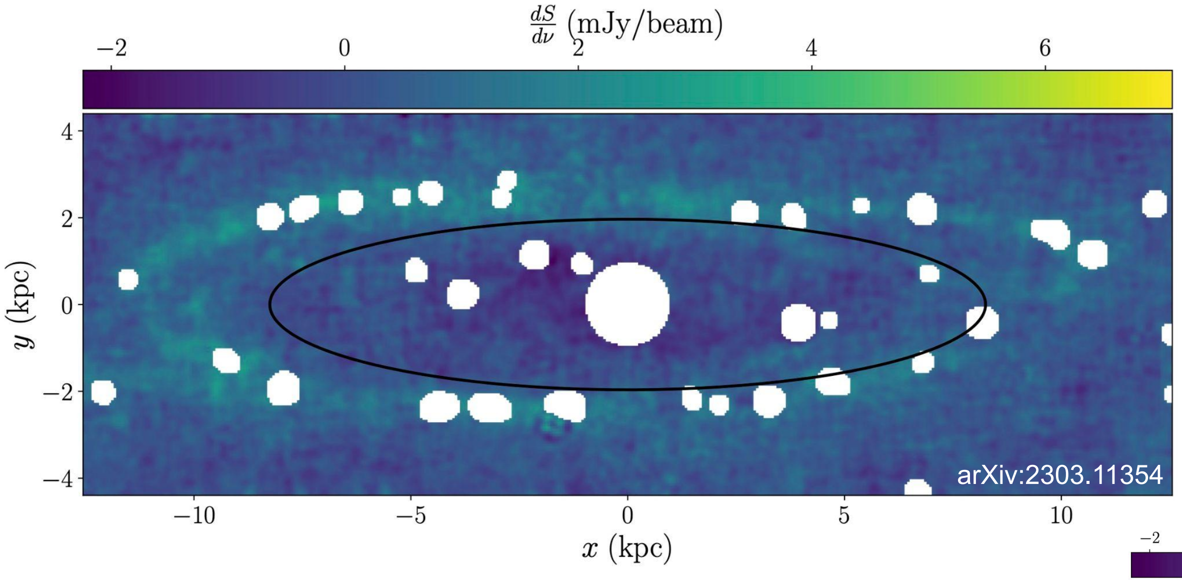
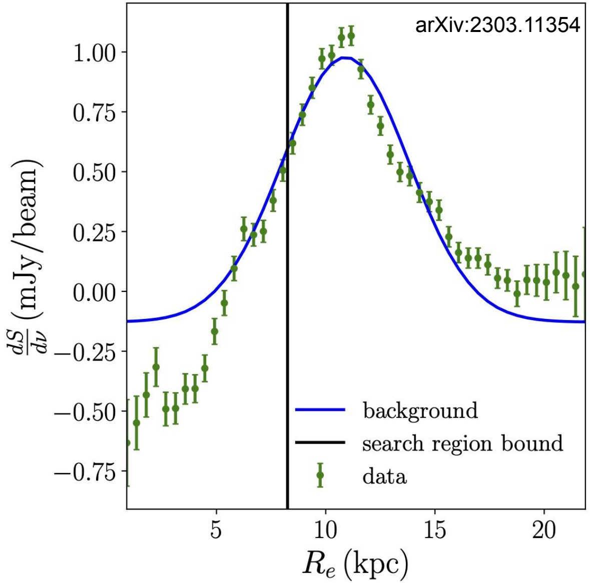
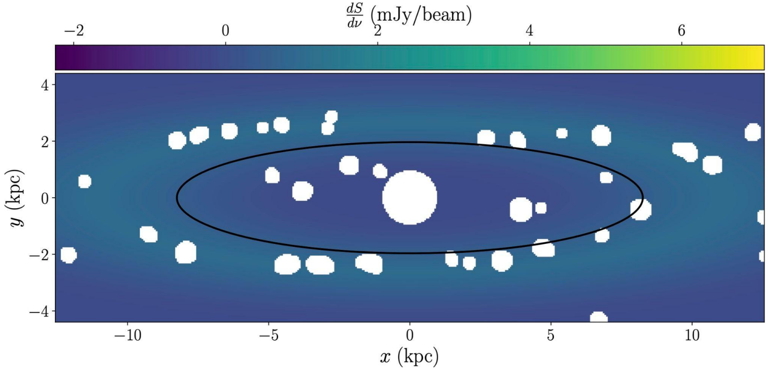
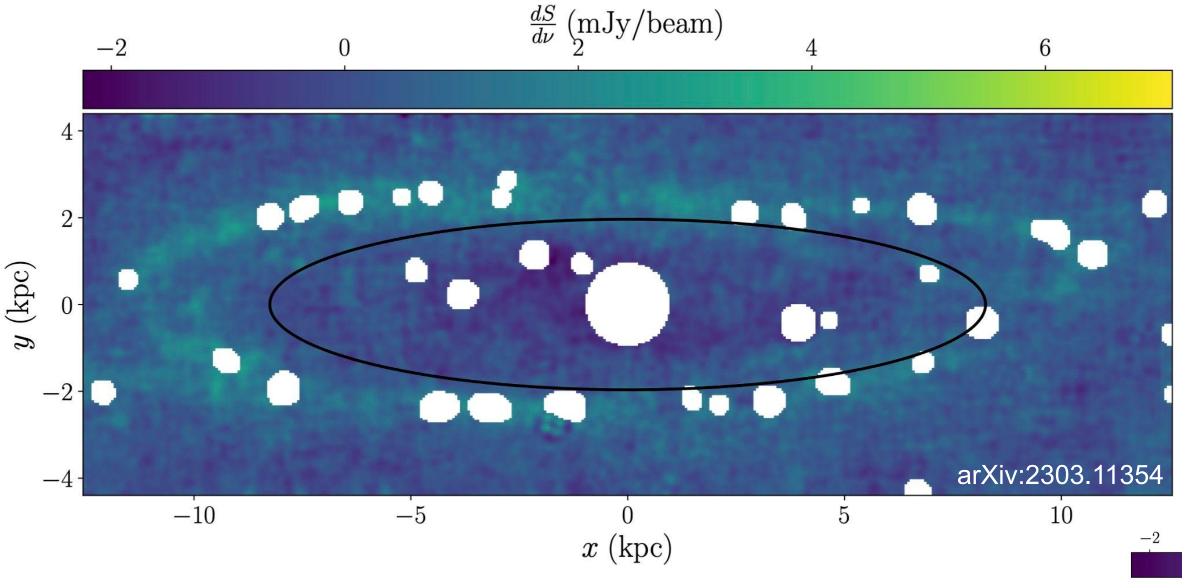




- Point sources
- Center - sensitive to D_0
- Elliptical ring



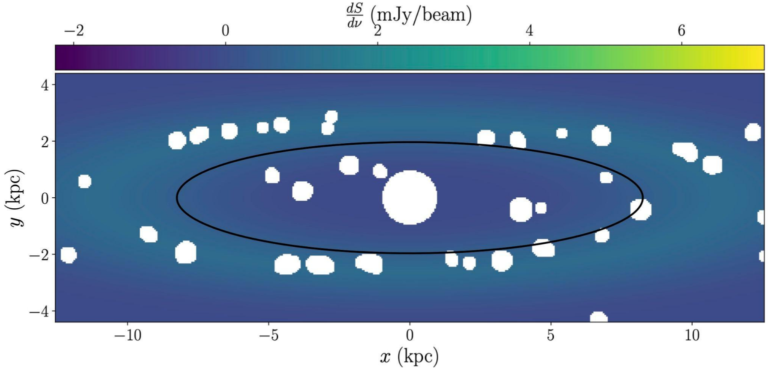
Constructing Background Model



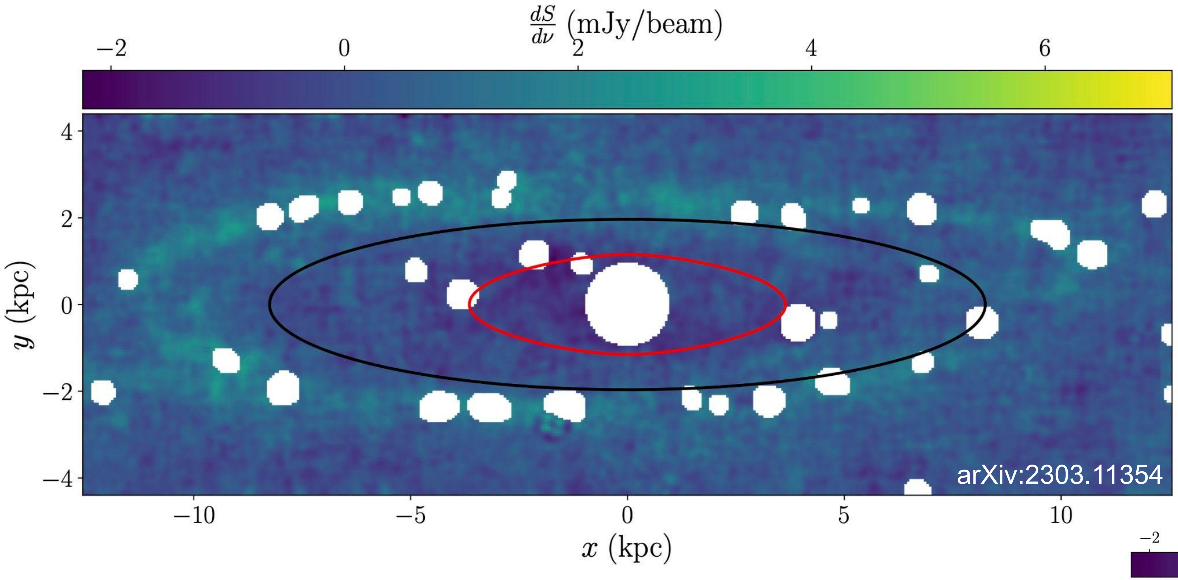
$$\Phi^b(\boldsymbol{x}; \boldsymbol{w}, \boldsymbol{\mu}) = w_1 + w_2 \exp\left[-\frac{(R_e(\boldsymbol{x},\mu_1)-\mu_2)^2}{2\mu_3^2}\right]$$

w_1, w_2 : background coefficients

μ_1, μ_2, μ_3 : morphological parameters



Constructing Background Model



- Fix morphological parameters with signal indep fit
    - Test to ensure that fit does not absorb signal present in the data
- Background coefficients remain free

$$\Phi^b(\boldsymbol{x}; \boldsymbol{w}, \boldsymbol{\mu}) = w_1 + w_2 \exp\left[-\frac{(R_e(\boldsymbol{x},\mu_1)-\mu_2)^2}{2\mu_3^2}\right]$$

w_1, w_2 : background coefficients

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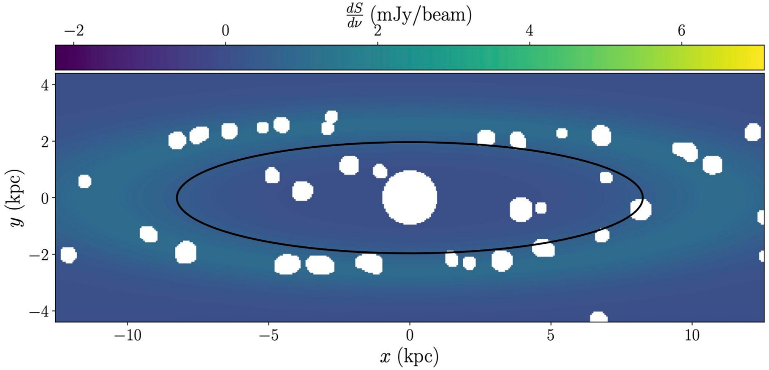

Setting Limits Using CL_s

- Construct test statistic

$$\lambda_{\langle\sigma v\rangle,\boldsymbol{\theta}}(\{d_i\}) = \Delta\chi^2 = \chi^2_{s+b} - \chi^2_b$$

$$= \sum_i \frac{\left[d_i - \hat{\Phi}_i^{s+b}(\langle\sigma v\rangle, \boldsymbol{\theta}, \boldsymbol{w^{s+b}})\right]^2}{\sigma^2_{\mathrm{rms},i}} - \sum_i \frac{\left[d_i - \hat{\Phi}_i^{b}(\boldsymbol{w^{b}})\right]^2}{\sigma^2_{\mathrm{rms},i}}$$

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Pixel-level data

Setting Limits Using CL_s

- Construct test statistic

Background-only model

$$\lambda_{\langle\sigma v\rangle,\boldsymbol{\theta}}(\{d_i\}) = \Delta\chi^2 = \chi^2_{s+b} - \chi^2_b$$

$$= \sum_i \frac{\left[d_i - \hat{\Phi}_i^{s+b}(\langle\sigma v\rangle, \boldsymbol{\theta}, \boldsymbol{w^{s+b}})\right]^2}{\sigma^2_{\mathrm{rms},i}} - \sum_i \frac{\left[d_i - \hat{\Phi}_i^{b}(\boldsymbol{w^{b}})\right]^2}{\sigma^2_{\mathrm{rms},i}}$$

Pixel-level data

Signal plus background model

$$\boldsymbol{\theta} = (m_\chi, D_0, \ldots)$$

- Lower scores more s+b-like, higher scores more b-like

Setting Limits Using CL_s

- Construct test statistic

Background-only model

$$\lambda_{\langle\sigma v\rangle,\boldsymbol{\theta}}(\{d_i\}) = \Delta\chi^2 = \chi^2_{s+b} - \chi^2_b$$

$$= \sum_i \frac{\left[d_i - \hat{\Phi}_i^{s+b}(\langle\sigma v\rangle, \boldsymbol{\theta}, \boldsymbol{w^{s+b}})\right]^2}{\sigma^2_{\mathrm{rms},i}} - \sum_i \frac{\left[d_i - \hat{\Phi}_i^{b}(\boldsymbol{w^{b}})\right]^2}{\sigma^2_{\mathrm{rms},i}}$$

Pixel-level data

Signal plus background model

$\boldsymbol{\theta} = (m_\chi, D_0, \ldots)$

Most likely values of background coefficients under each hypothesis

- Lower scores more s+b-like, higher scores more b-like
- Independent of absolute flux

Setting Limits Using CL_s

- Construct test statistic

$$\lambda_{\langle\sigma v\rangle,\boldsymbol{\theta}}(\{d_i\}) = \Delta\chi^2 = \chi^2_{s+b} - \chi^2_b$$

$$= \sum_i \frac{\left[d_i - \hat{\Phi}_i^{s+b}(\langle\sigma v\rangle, \boldsymbol{\theta}, \boldsymbol{w^{s+b}})\right]^2}{\sigma^2_{\mathrm{rms},i}} - \sum_i \frac{\left[d_i - \hat{\Phi}_i^{b}(\boldsymbol{w^{b}})\right]^2}{\sigma^2_{\mathrm{rms},i}}$$

Pixel-level data

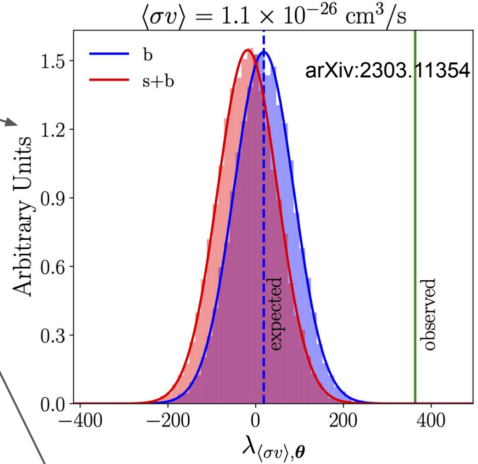
Signal plus background model

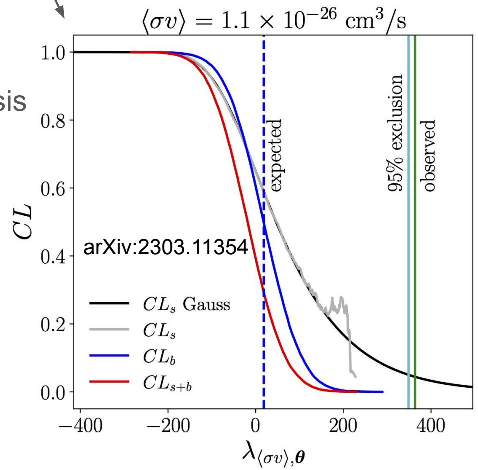
$\boldsymbol{\theta} = (m_\chi, D_0, \ldots)$

Background-only model

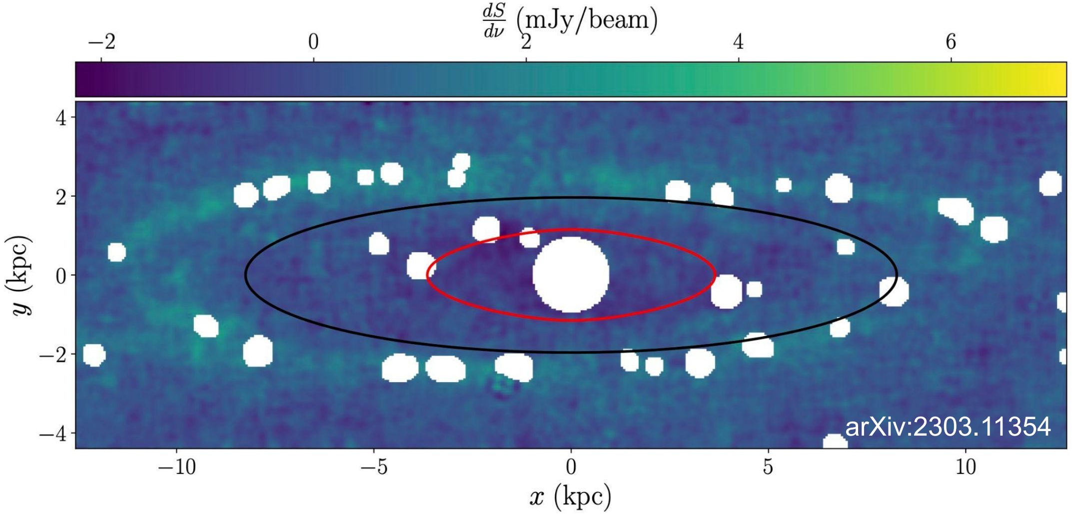
Most likely values of background coefficients under each hypothesis

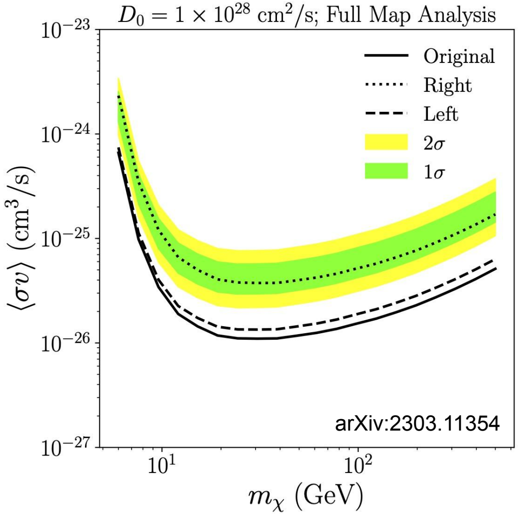
$D_0 = 1 \times 10^{28}\ \mathrm{cm}^2/\mathrm{s}$
$m_\chi = 39\ \mathrm{GeV}$

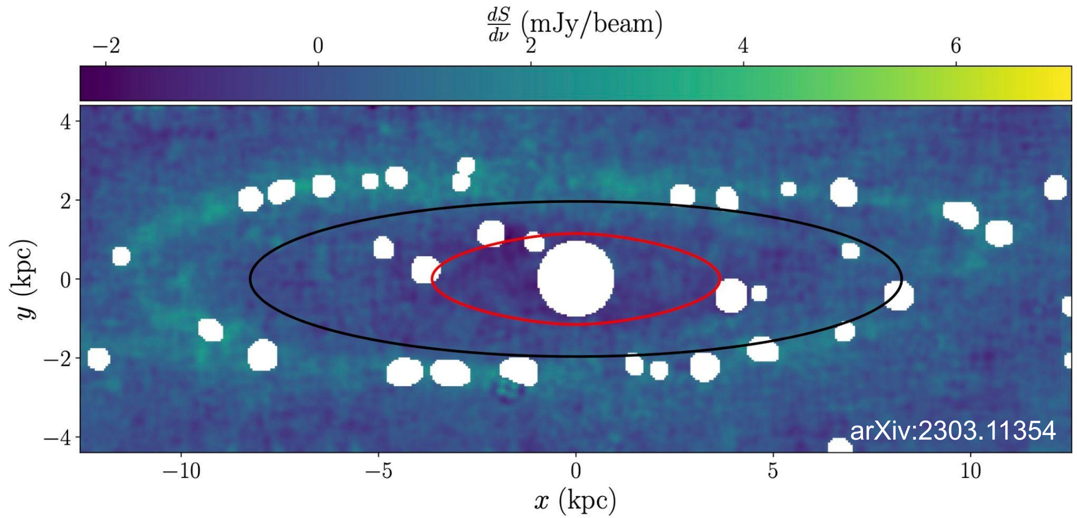


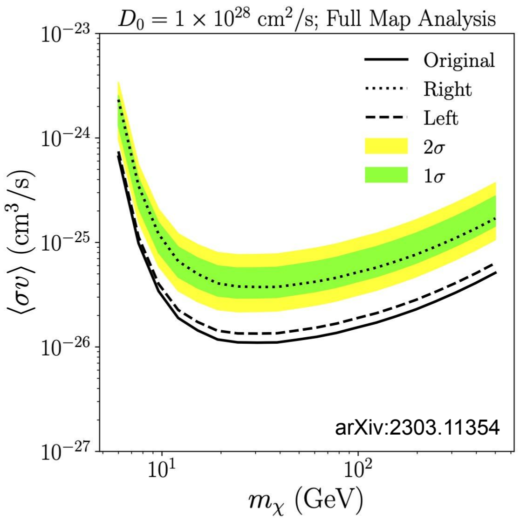


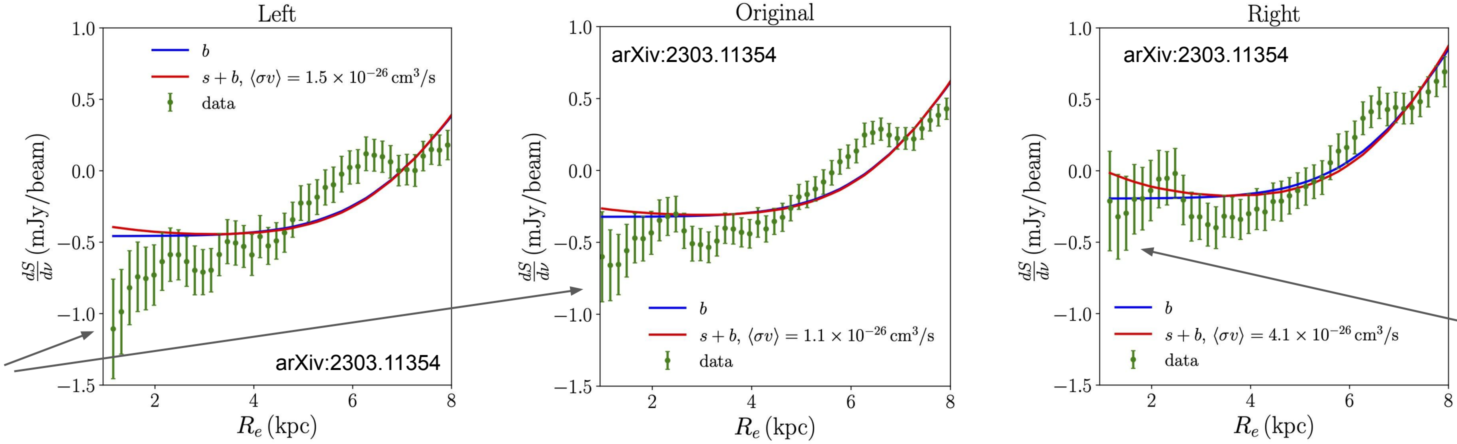
- Lower scores more s+b-like, higher scores more b-like
- Independent of absolute flux
- Simulate ensembles of synthetic observations to approximate pdfs of test statistic


$\frac{dS}{d\nu}$ (mJy/beam)
−2
0
2
4
6
4
2
0
−2
−4
y (kpc)
−10
−5
0
5
10
x (kpc)
arXiv:2303.11354


$D_0 = 1 \times 10^{28}$ cm^2/s; Full Map Analysis
Original
Right
Left
2σ
1σ
$\langle \sigma v \rangle$ (cm^3/s)
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{1}
10^{2}
m_χ (GeV)
arXiv:2303.11354



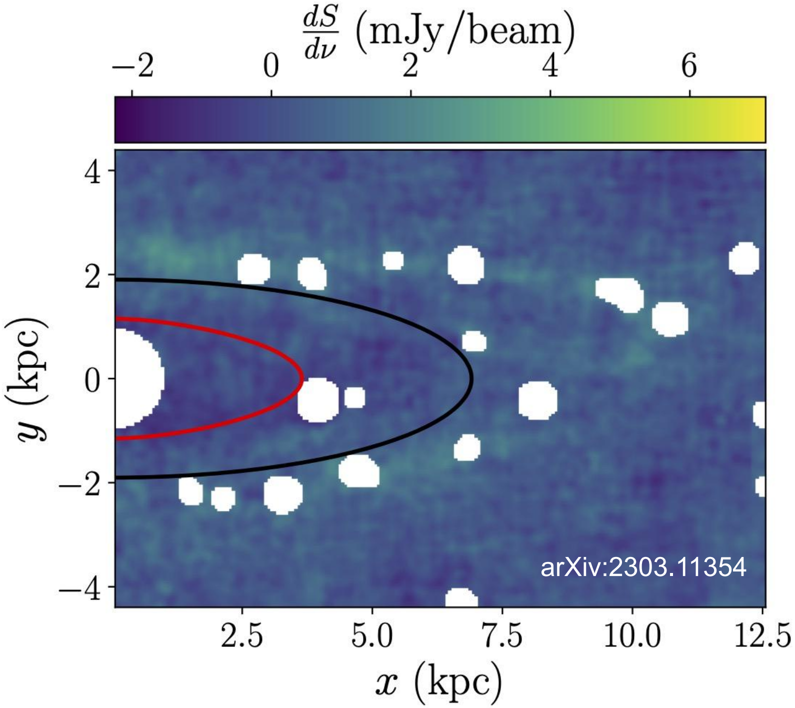


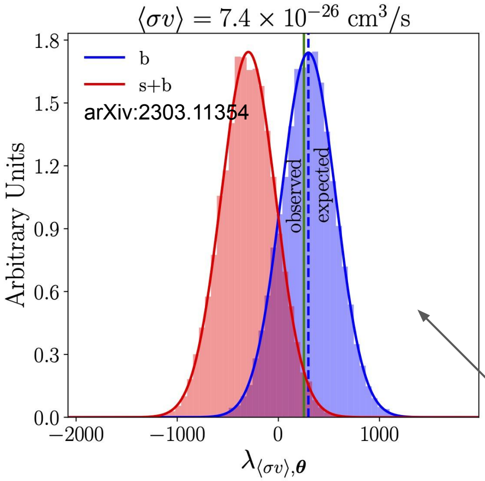


Downward Fluctuation

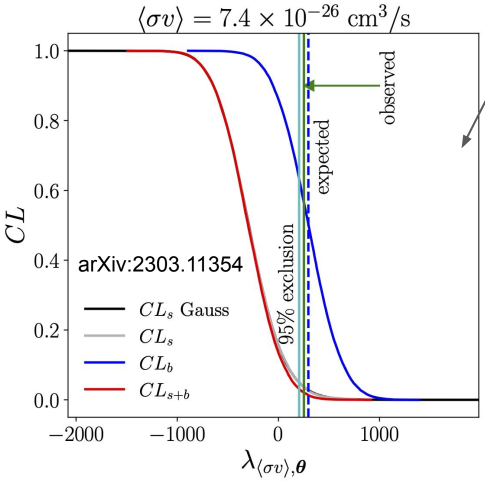
No Downward Fluctuation

Exclusion Limits for Right-only Analysis

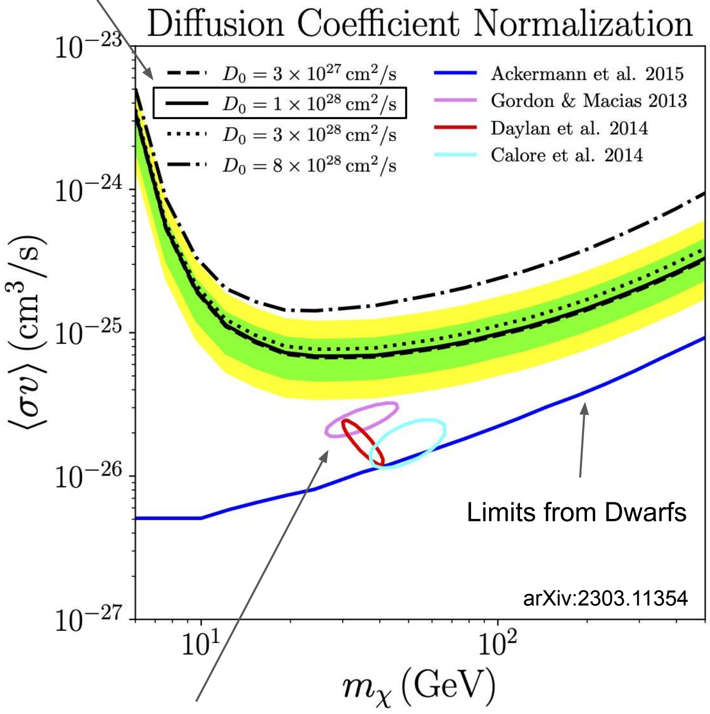




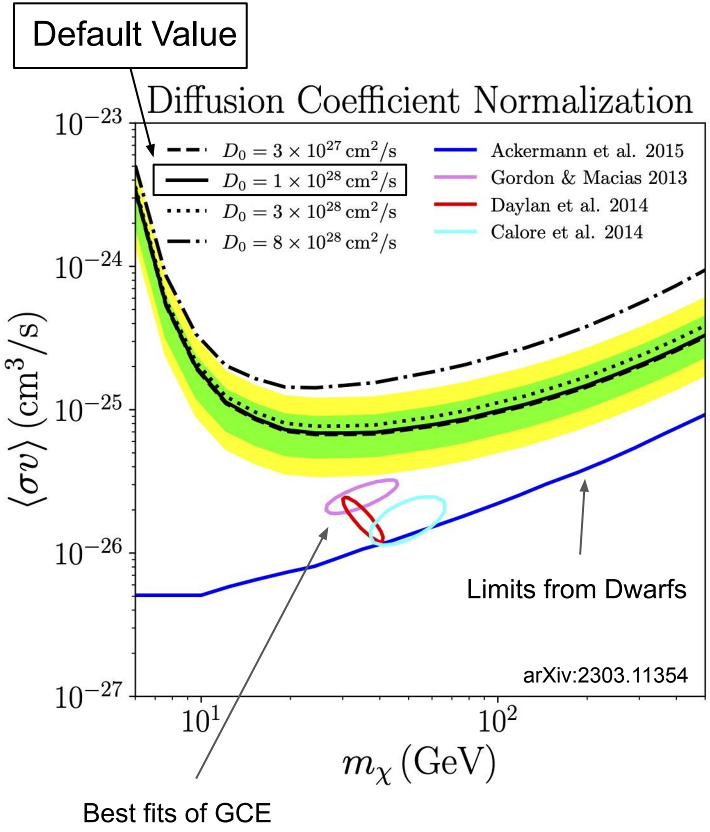
$D_0 = 1 \times 10^{28}\ \mathrm{cm}^2/\mathrm{s}$
$m_\chi = 39\,\mathrm{GeV}$



Default Value



Best fits of GCE



Conclusions

- Limits on DM annihilation in M31 using morphology of radio data
- First work modeling propagation of $e^{\pm}$ with position dependent diffusion coefficient
- Limits are weaker than in previous work but are robust to variations of the diffusion coefficient
  - Starlight model suggests more energy emitted in X-ray
  - Excluding the center likely lowers the sensitivity but makes result more robust
- Search in X-ray
- Search more frequencies of radio