Optimal Observing Strategies for Velocity-Suppressed Dark Matter Annihilation

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PHENO
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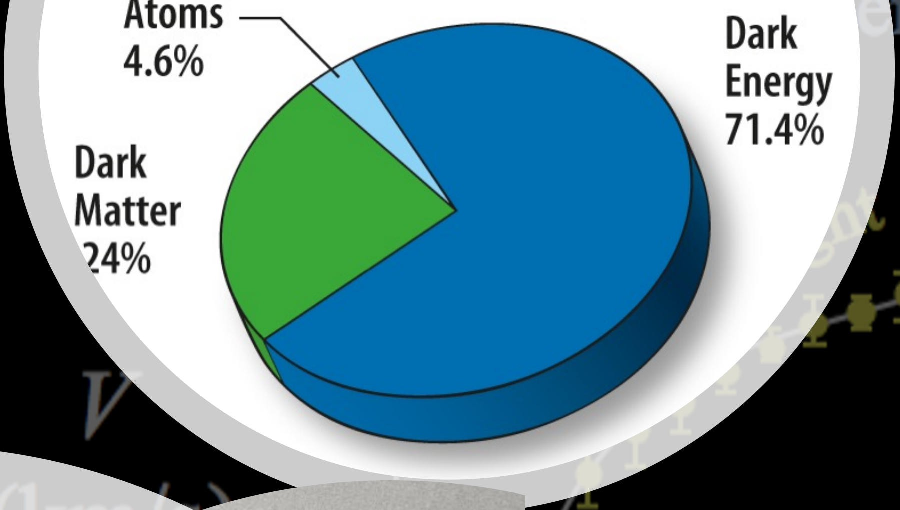
Road Map:
The whole talk in 20 seconds

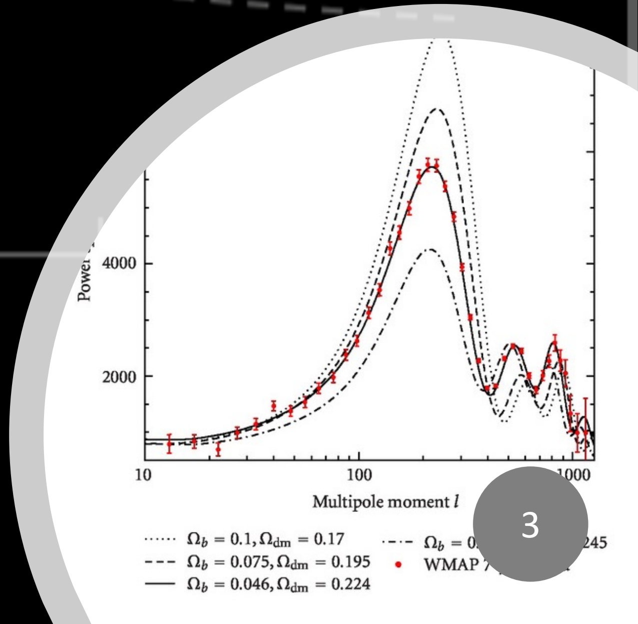
Indirect Detection is a powerful probe of DM

Velocity-dependent DM annihilation requires different theoretical tools

Outcome: **Optimizing the signal-to-noise ratio implies non-trivial observation strategies**

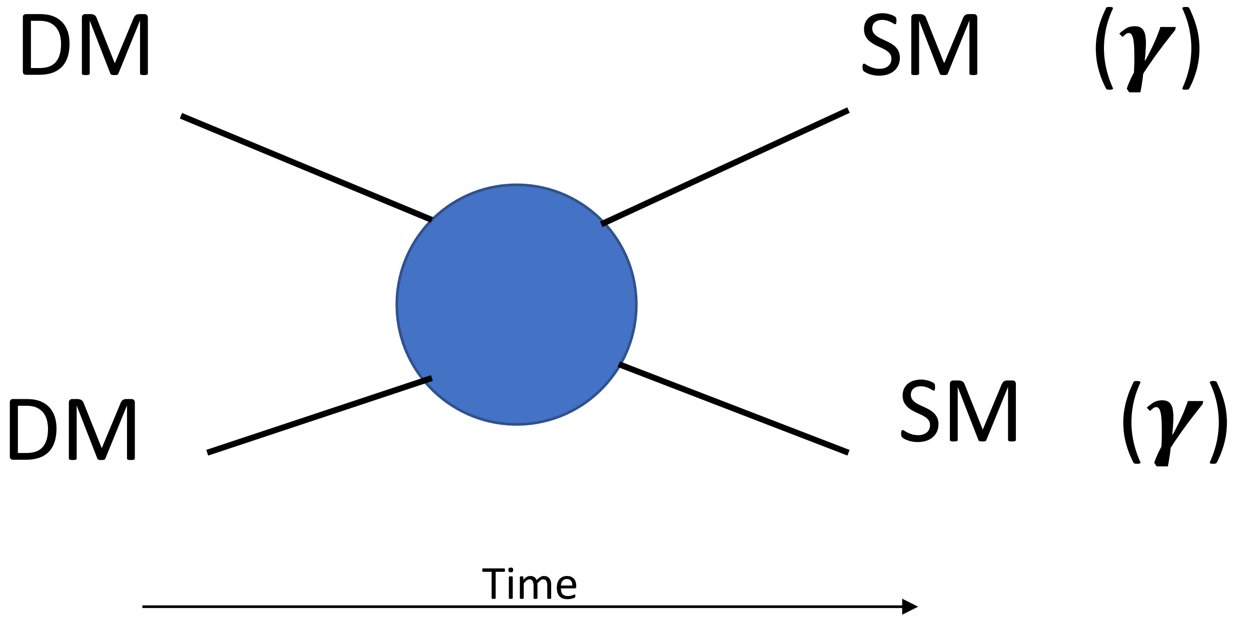


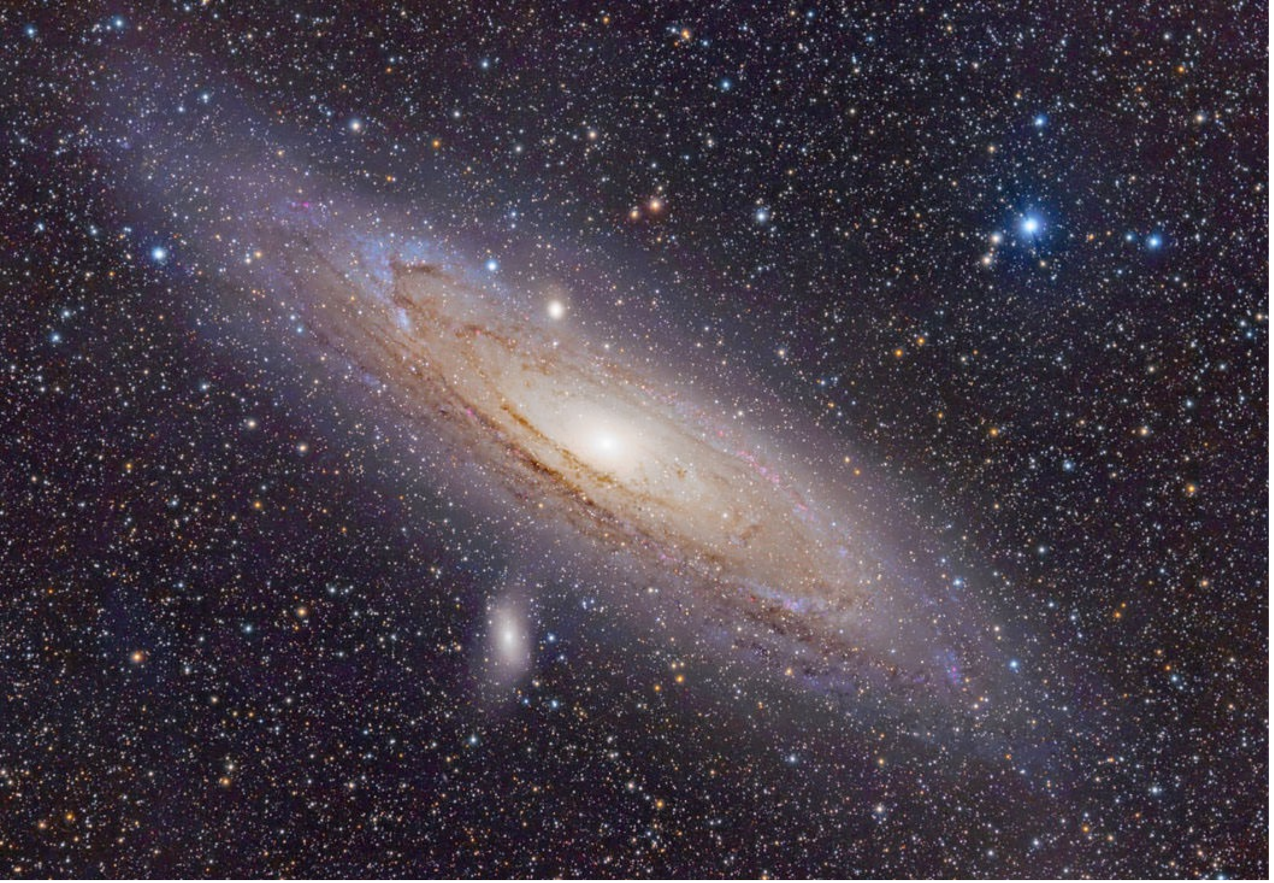
Dark Matter Exists!

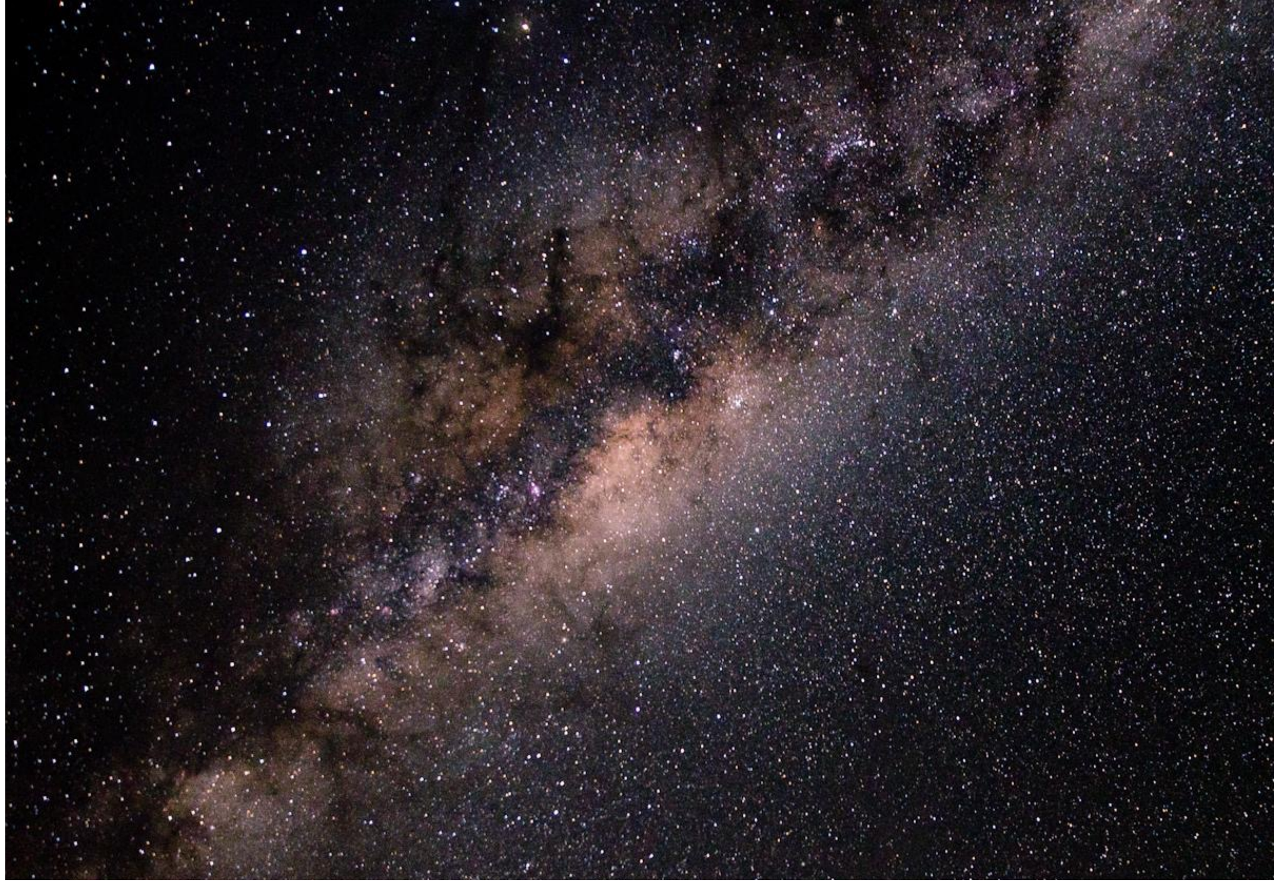


Indirect Detection

Looking for Standard Model particles produced from the annihilation or decay of dark matter.







Where should we point our telescopes?

Common sense: Look at where the DM density is highest!

M31, M87, dSphs

Galactic Center

Annihilation Flux – Quantifying the Signal

Typically, the photon flux for DM annihilation is decomposed as

$$\Phi = \frac{<\sigma v>}{8\pi\, m_\chi^2} \frac{dN_\gamma}{dE} \int dl\ \rho[r(l,b)]^2$$

Particle Physics

J-Factor

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Particle Physics

J-Factor

Relies on the assumption that the cross section is velocity-independent!

Velocity-Dependent J-factor

$$\langle \sigma v \rangle = \langle \sigma v \rangle_0 S(v/c)$$

$$S(v/c) \stackrel{\text{def}}{=} (v/c)^n$$

$$\mathcal{J}(b) = \int dl \int d\boldsymbol{v}^3 \, f(\boldsymbol{v}) \, (v/c)^n \rho[r(l,b)]^2$$

e.g. Board et al. 2101.06284

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n = 0: s-wave

n = 2: p-wave

n = 4: d-wave

e.g. Board et al. 2101.06284

Velocity-Dependent J-factor

Think simple! Assume Maxwell-Boltzmann distribution

$$f(\mathbf{v}) \propto (\sigma_v^2)^{-3/2} e^{-\mathbf{v^2}/\sigma_v^2}$$

From equipartition theorem:

$$\sigma_v^2 = \frac{\langle v^2 \rangle}{3}$$

Where (virialized)

$$< v^2 >^{1/2} \propto \quad v_c(r) = \sqrt{\frac{2GM(<r)}{r}}.$$

Velocity-Dependent J-factor

Average *relative* velocity

$$\langle v_{\rm rel}^2 \rangle = \langle (\mathbf{v} - \mathbf{v}')^2 \rangle = \int d^3\mathbf{v} \int d^3\mathbf{v}' (\mathbf{v} - \mathbf{v}')^2 f(\mathbf{v}) f(\mathbf{v}') \; = 2\langle v^2 \rangle = 2 v_c^2$$

So in this case,

$$\mathcal{J}_n(b) \propto \int dl \, (v_c/c)^n \rho[r(l,b)]^2$$

Velocity-Dependent J-factor

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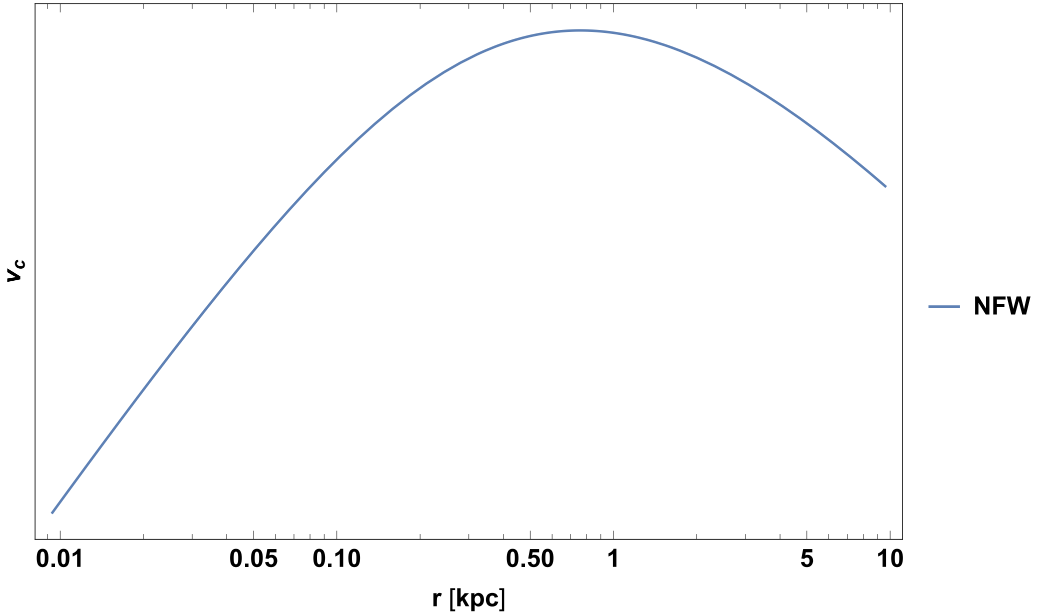
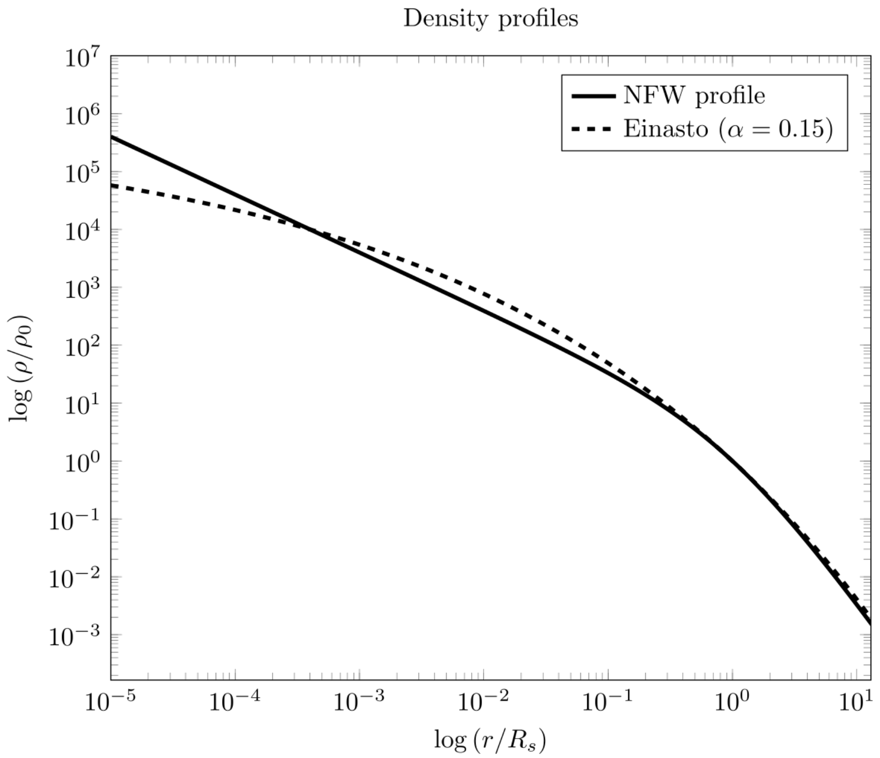
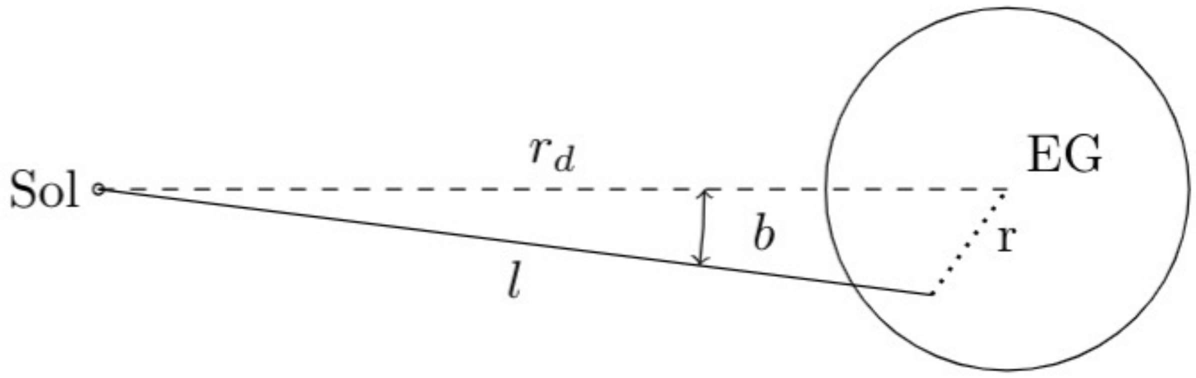


Velocity



Density

Velocity-Dependent J-factor - Calculation



$$r = \sqrt{r_d^2 - 2lr_d\cos(b) + l^2}$$

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2}$$

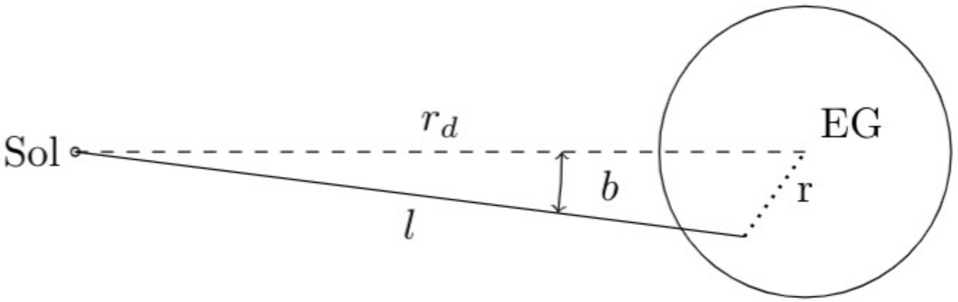
$$M(<r) = 4\pi\rho_0 r_s^3\left(\frac{r_s}{r_s+r} - 1 + \log\left(1+\frac{r}{r_s}\right)\right)$$

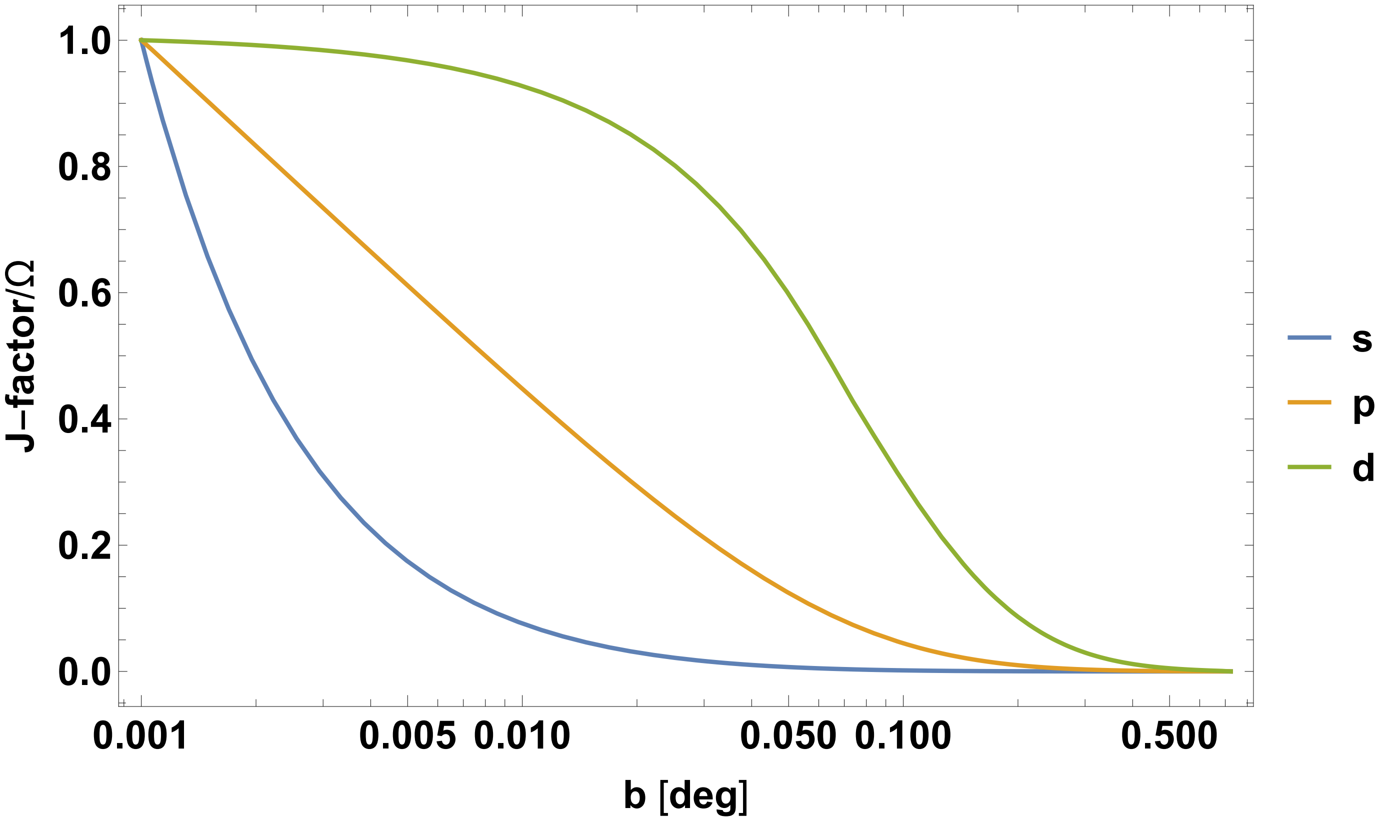
$$v_c(r) = \sqrt{\frac{2GM(<r)}{r}}.$$

$$\mathcal{J}_n(b) \propto \int dl\,(v_c/c)^n \rho[r(l,b)]^2$$

Everything is known once density profile is defined!

Velocity-Dependent J-factor





Velocity-dependent channels are less sharply peaked at the center!

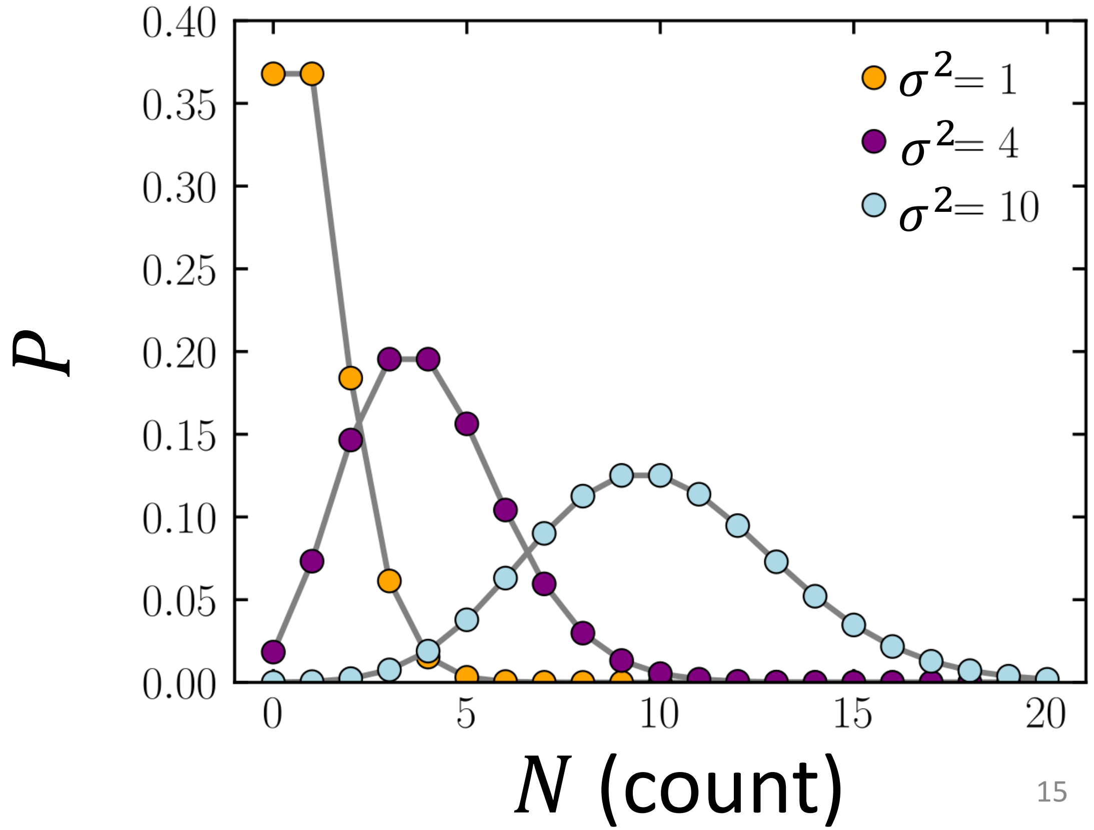
Signal to noise ratio

Photon counts: independent, random events at a constant rate. Well described by a Poisson distribution!

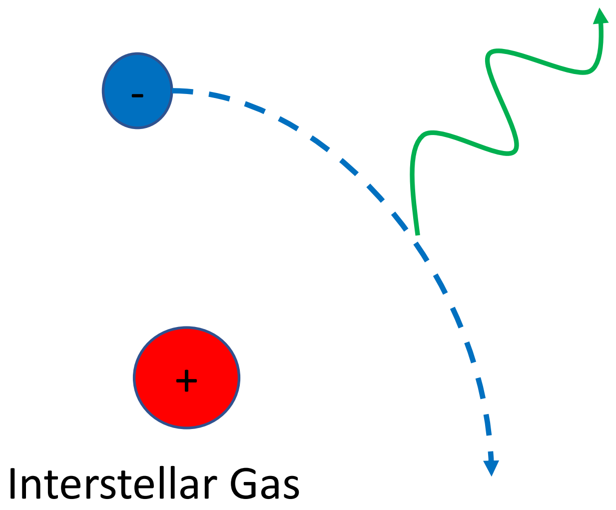
$$\sigma = N^{1/2}$$

Define optimal field of view as the one that maximizes the quantity

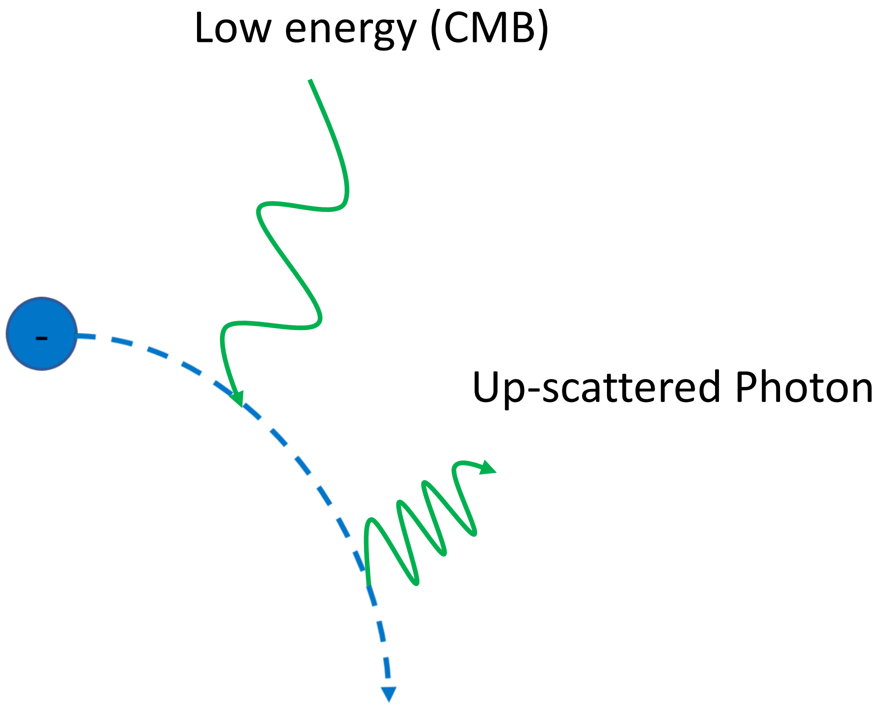
$$\frac{\mathcal{J}}{N^{1/2}}$$



Gamma Ray Background – Diffuse, Isotropic



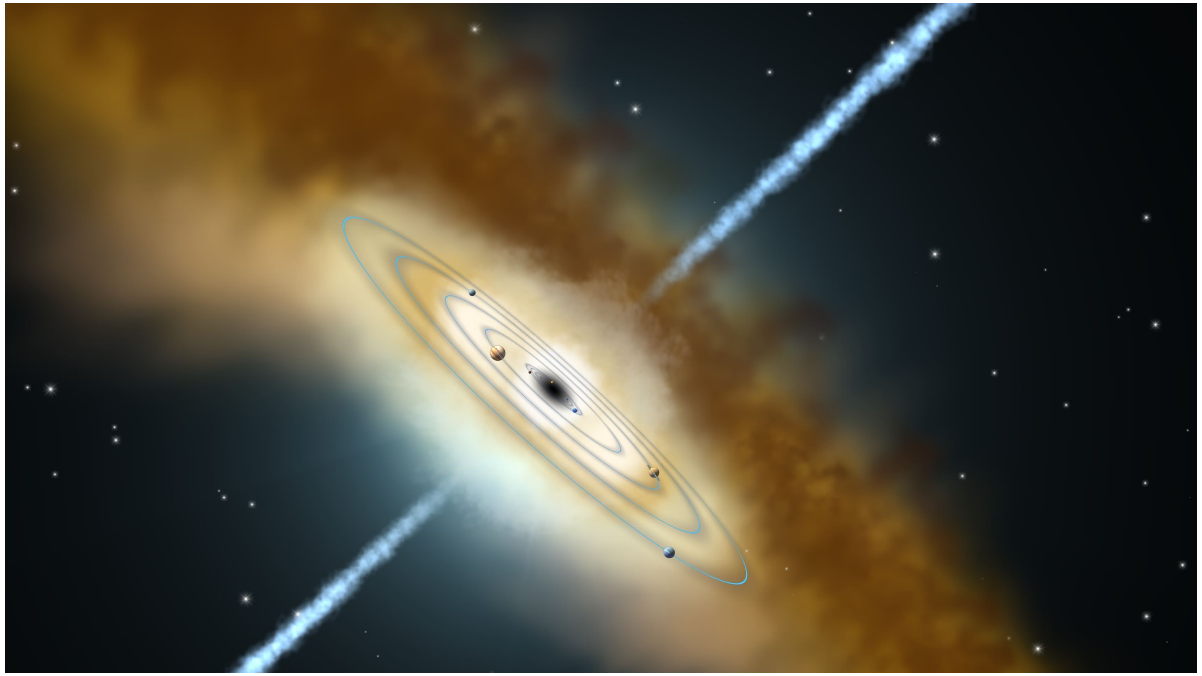
Bremsstrahlung



Inverse Compton

$N_{Itot} \propto$ Field of View

Gamma Ray Background – Point Sources



σ: Width due to instrument-dependent point spread function

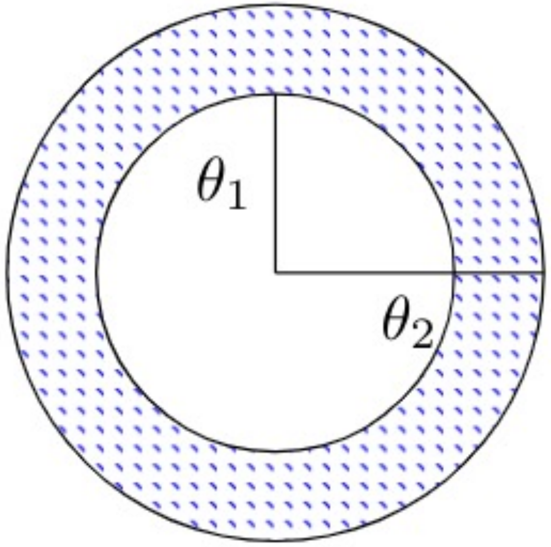
$$N_G(b) \propto \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{b^2}{\sigma^2}\right)}$$

Field of View Geometry

θ_1 = 0: Disk

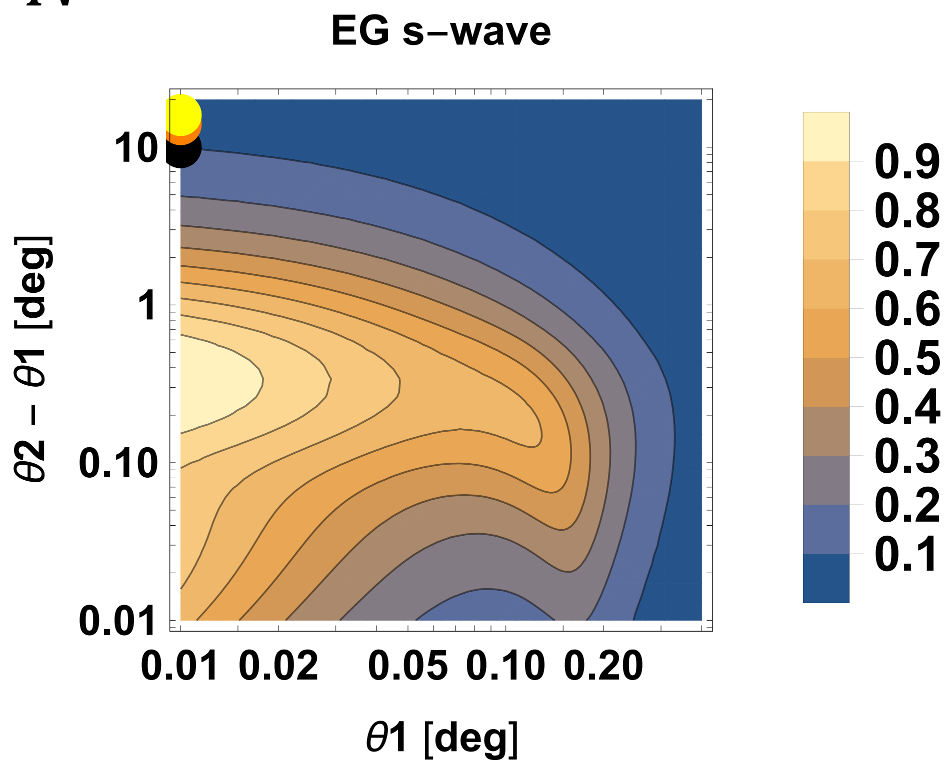
$\theta_1 \neq 0$: Annulus

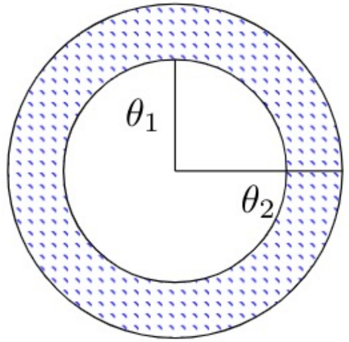
θ_2- θ_1: Thickness



Extragalactic Results

$$\frac{\mathcal{J}}{N^{1/2}}$$





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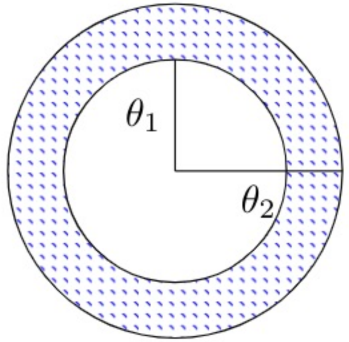
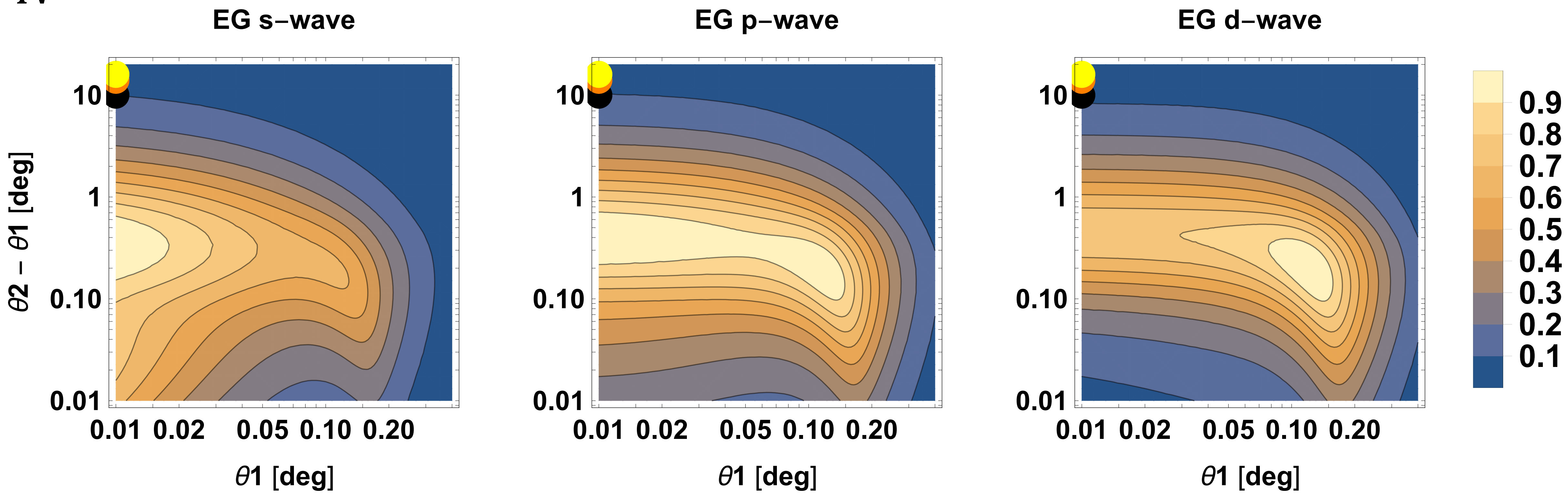
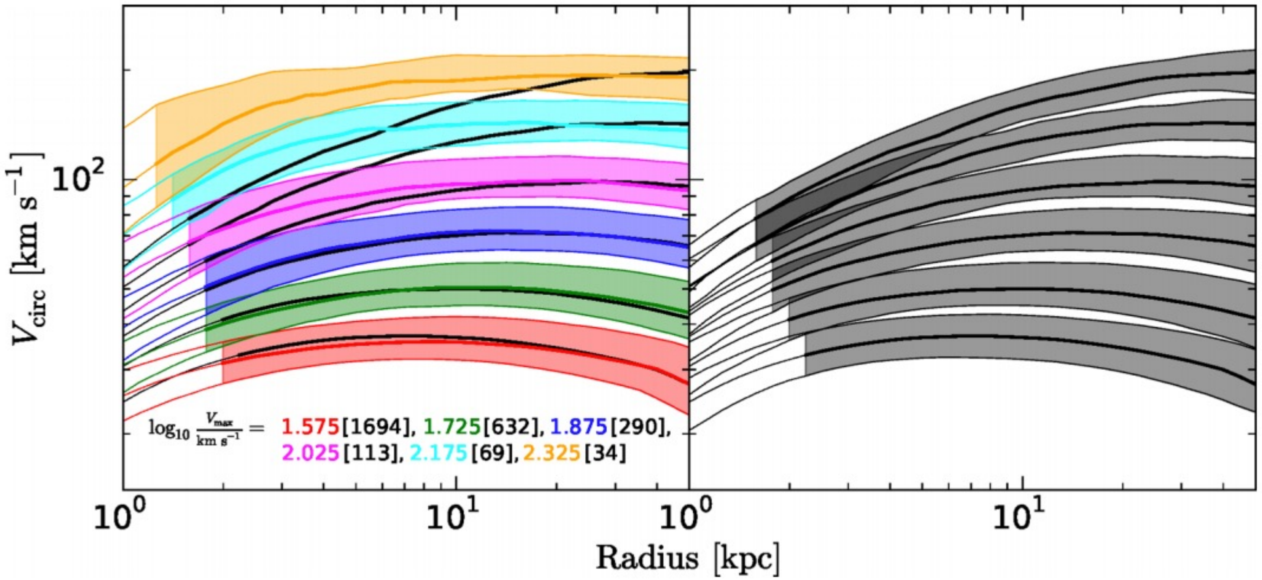




Dots: Fermi-LAT Surveys (Mauro et al.; Feng et al.; Abddo et al.)

Caveats and Future Work

No two sources are alike (e.g. dSphs). Results are dependent on background, ρ, and v.



Oman et al. MNRAS 452, 3650-3665

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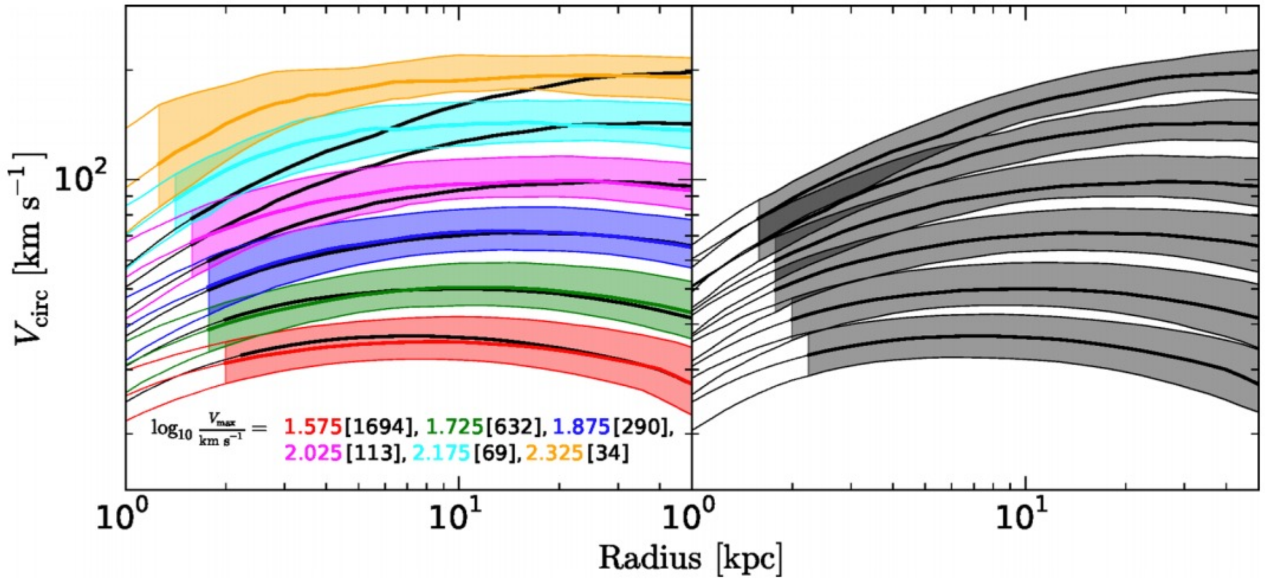

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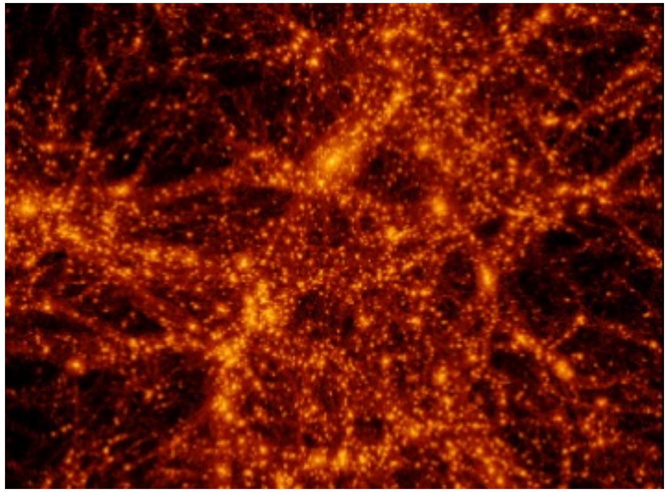


Andrey Kravtsov, arXiv: 0906:3295

Need to account for DM Substructure and baryons

Thank you!

Our recent paper on this subject:

Wonderful Collaborators

Gabby Huckabee

Stefano Profumo

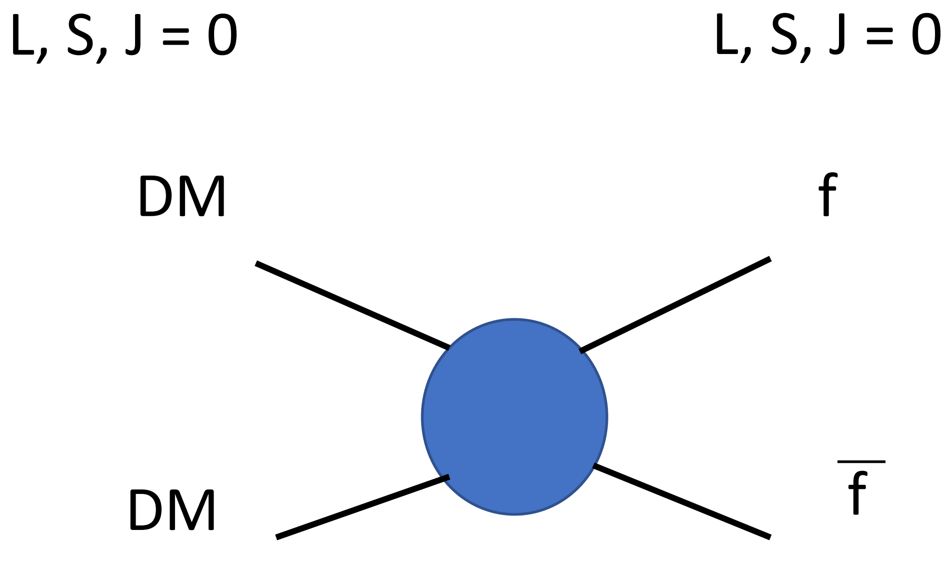
arXiv: 2105.03438

nwsmyth@ucsc.edu

Bonus Slides

Velocity-Suppressed Cross Sections

Example: Majorana DM annihilating to fermion/antifermion pairs



Outgoing fermions must have same helicity (opposite chirality). Coupling must vanish in chiral limit. To get the correct final state spin, the s-wave cross section is chirality suppressed by

$$\mathcal{M} \propto \frac{m_f^2}{m_\chi^2}$$

Kumar and Light 1612.00773

Thermal Average + Velocity Expansion

$$\langle \sigma v \rangle = \frac{\int \sigma v \, dn_1^{\rm eq} \, dn_2^{\rm eq}}{\int dn_1^{\rm eq} \, dn_2^{\rm eq}} = \frac{\int \sigma v \, e^{-E_1/T} \, e^{-E_2/T} \, d^3p_1 \, d^3p_2}{\int e^{-E_1/T} \, e^{-E_2/T} \, d^3p_1 \, d^3p_2} \, .$$

$$\langle \sigma v \rangle = \frac{1}{8m^4 T K_2^2(m/T)} \int_{4m^2}^{\infty} \sigma(\tilde{s} - 4m^2) \sqrt{\tilde{s}} \, K_1(\sqrt{\tilde{s}}/T) \, ds$$

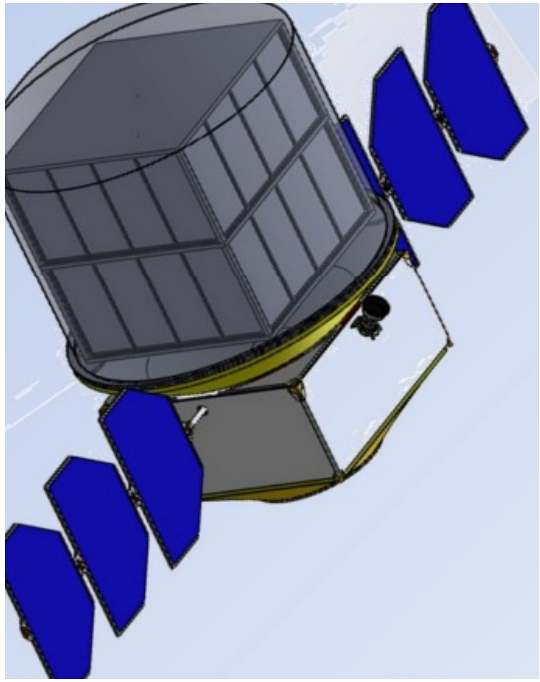
Expand $\langle \sigma v \rangle$ in powers of v:

$$\langle \sigma v \rangle = \langle \sigma v \rangle_0 S(v/c)$$

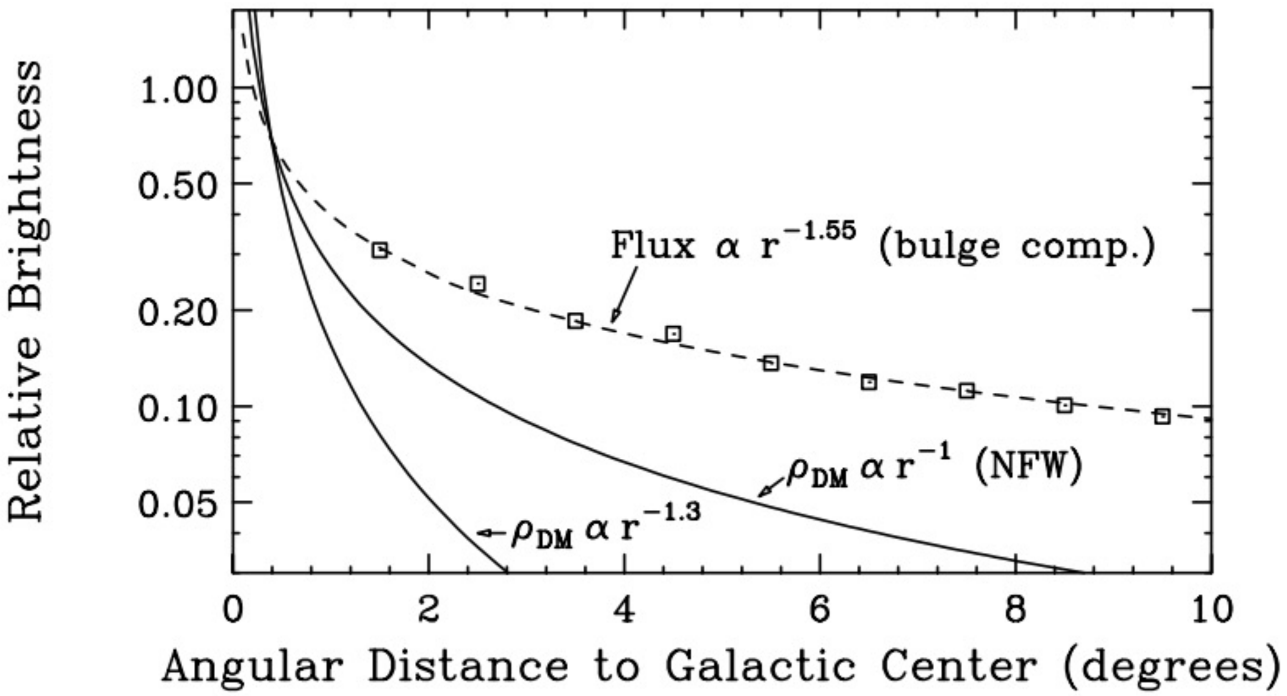
Instrumental Angular Resolution

FERMI-LAT:
~0.15 degrees for >10 GeV
~1 degree for ~1 GeV

AdEPT:
<0.1 degrees for >1 GeV

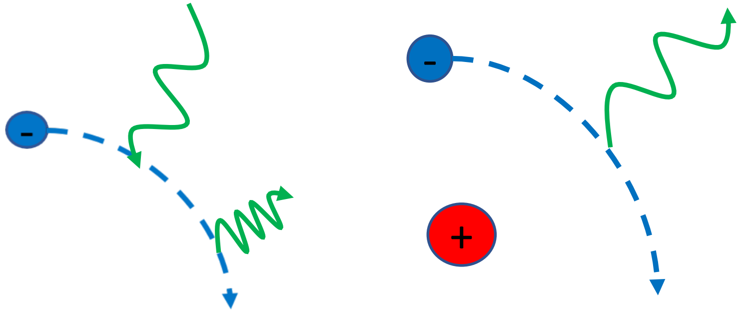


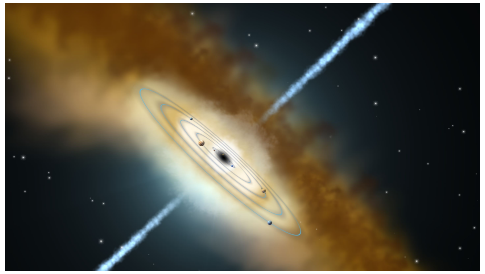
Gamma Ray Background – Bulge



Hooper, Goodenough. arXiv:1010.2752

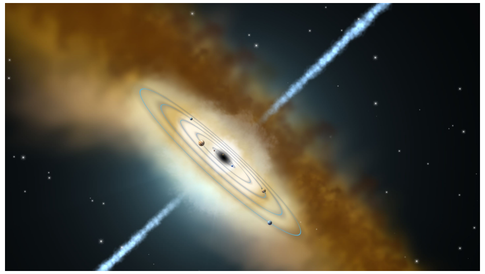
Gamma Ray Background – 2 cases





Extra-galactic

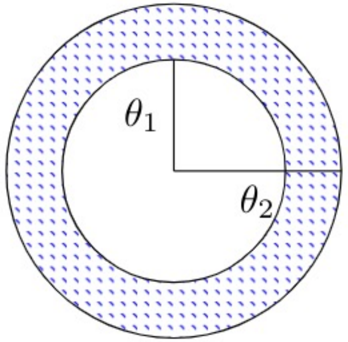
Isotropic + Point Source



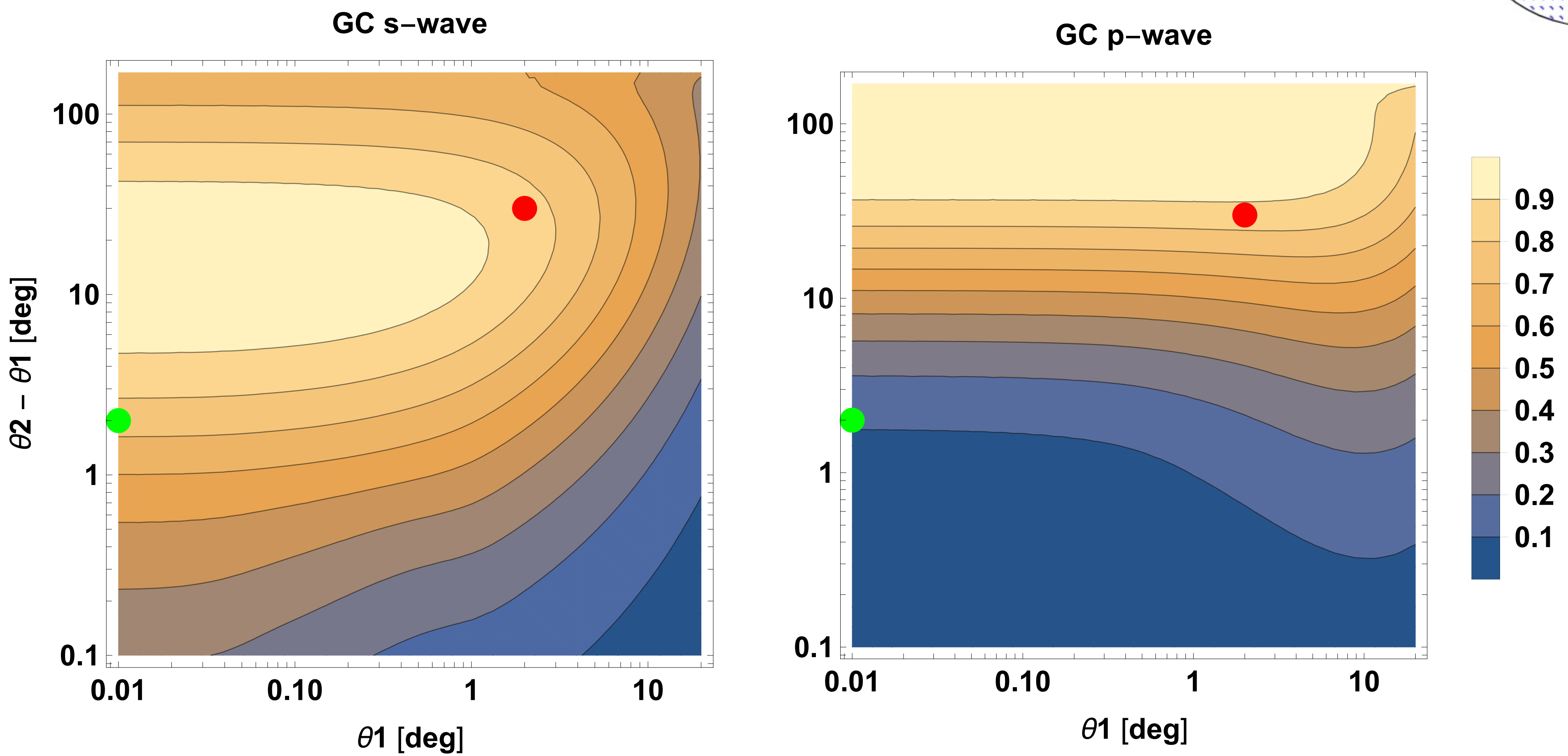
Galactic Center

Bulge + Point Source

Galactic Center – Weak Point Source

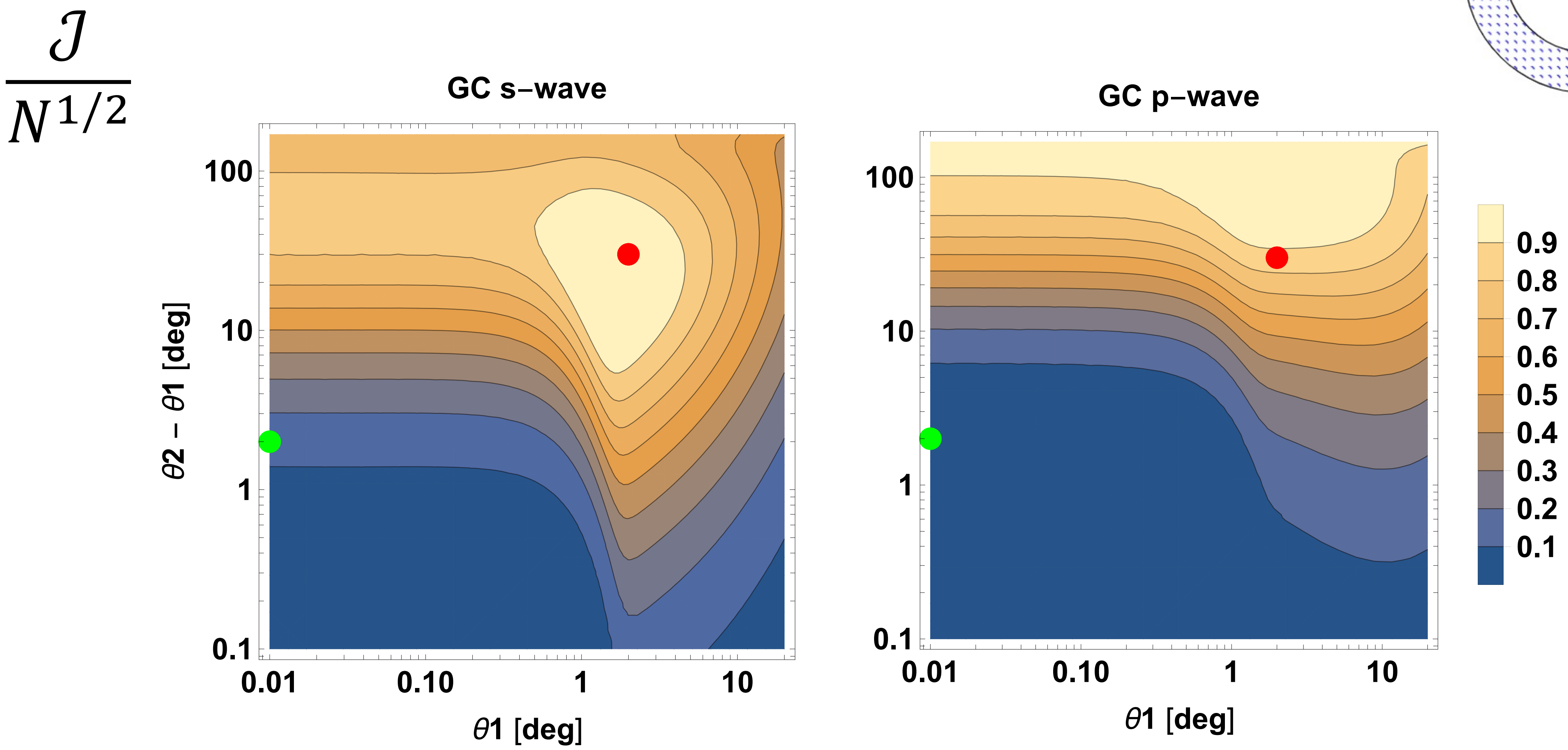


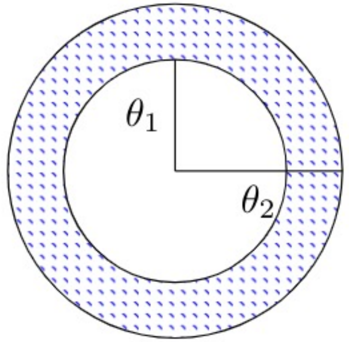
$$\frac{\mathcal{J}}{N^{1/2}}$$



Green: Johnson et al. 1904.06261; Red: Leane and Slatyer. 1904.08430

Galactic Center – Strong Point Source

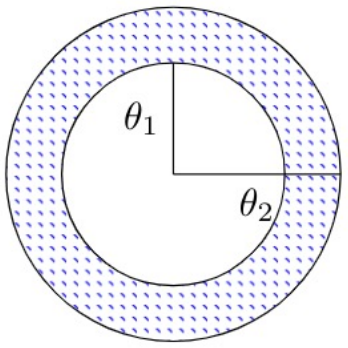


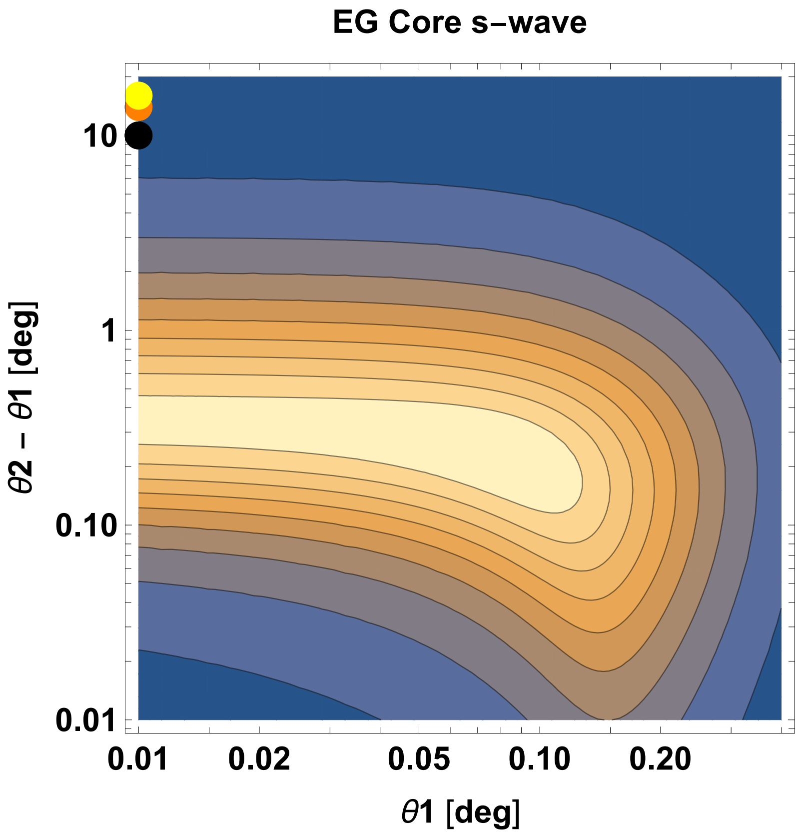


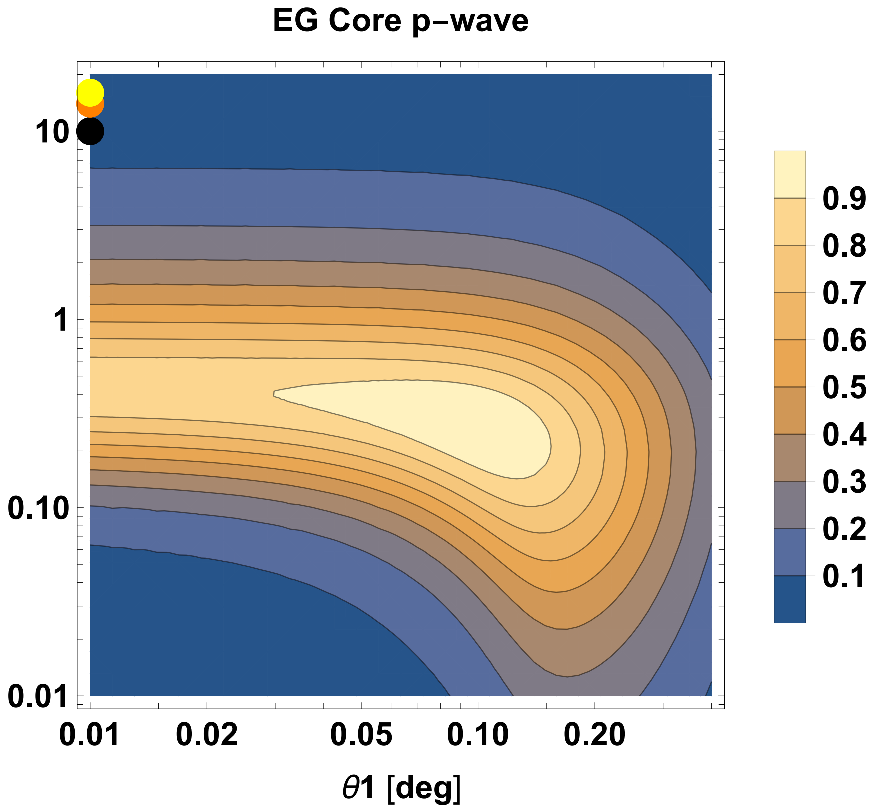
Green: Johnson et al. 1904.06261; Red: Leane and Slatyer. 1904.08430

Signal to Noise Ratio – Extra-galactic, Core

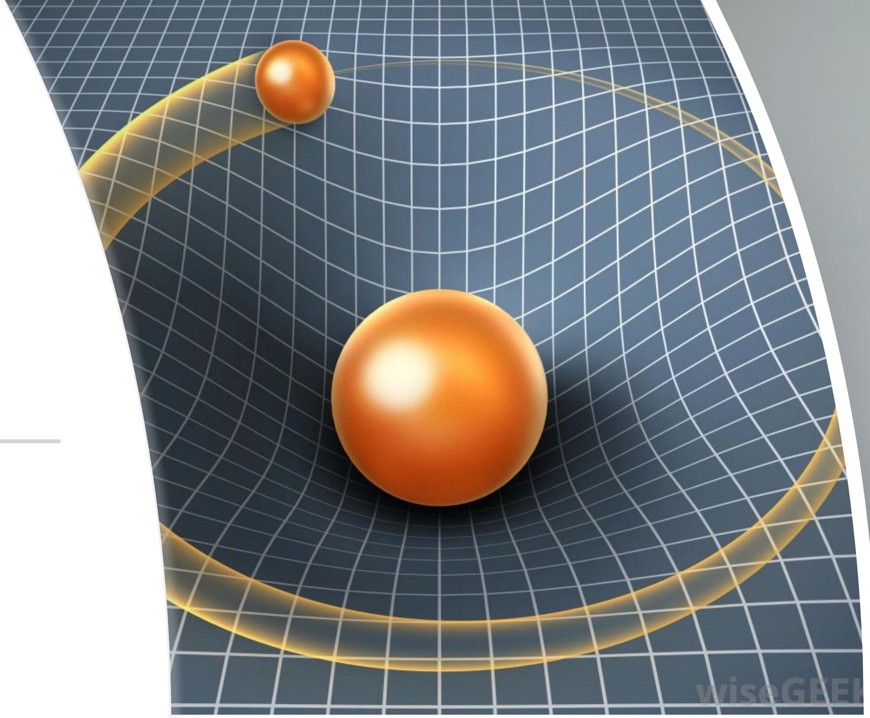
$$\frac{\mathcal{J}}{N^{1/2}}$$







Properties of Dark Matter



Interacts through gravity

Invisible

Stable on long timescales