Neutrino point source searches for dark matter spikes

black hole remnants of the first stars under the lamp shade

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June 28, 2022

2202.01126 with Katherine Freese, Irina Galstyan and Pearl Sandick

Outline

1. Introduction
   - Minihalos in the Milky Way
   - Dark matter spikes
2. Neutrino point source searches
   - Summary of ANTARES analysis
   - Repurpose for DM spikes
3. Constraints on DM spikes
   - $D_{\rm min}$ surface
   - Pop III.1 star formation
4. Summary and outlook

N-body simulations suggest there are many $\sim 10^6 M_\odot$ halos

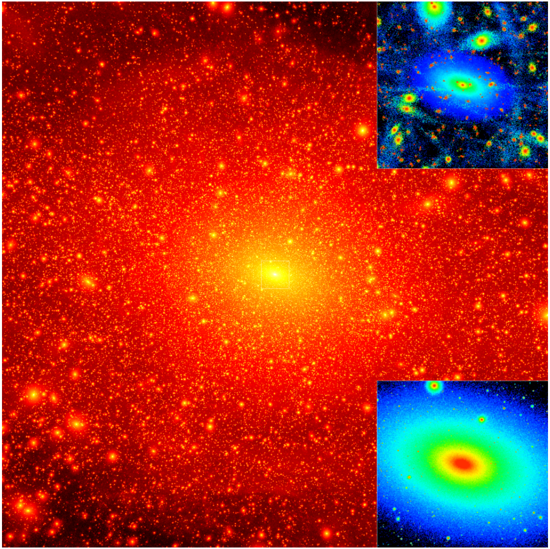


Figure: DM density in 800 kpc of VL-II, insets show inner 40 kpc (0805.1244)

Density profiles and distribution of subhalo masses

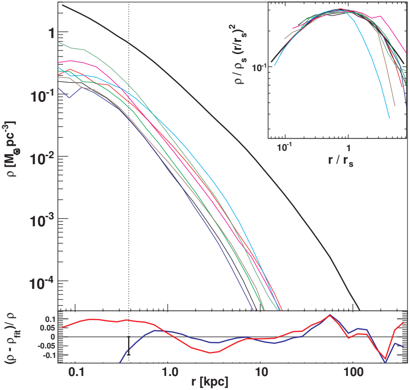


Figure: Compare density of **MW halo** to 8 larger subhalos. $\gtrsim$ 40k total evenly distributed by decade $10^6 - 10^9 M_\odot$

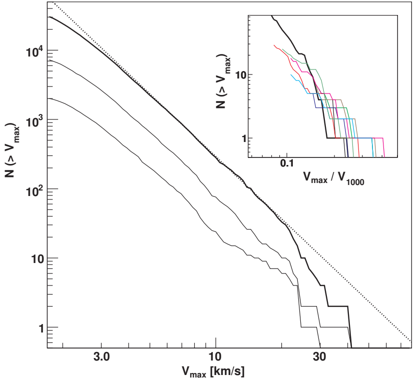


Figure: Peak height for circular velocity $\propto \sqrt{M^{\rm halo}}$ of subhalos contained within **402**, 100, 50 kpc of galactic center

Minihalos contract around BH remnants of the first stars

Criteria for Pop III.1 star formation

$$M^{\rm halo} \gtrsim 10^5 M_\odot \left(\frac{1+z}{31}\right)^{-2}$$

$\gtrsim 10^2 M_\odot$ star collapses into IMBH

- NFW for initial DM (85%) and baryon (15%) densities
- Gravitational potential pulls DM into central object
- Estimate adiabatic contraction following Blumenthal et al. (1986) prescription

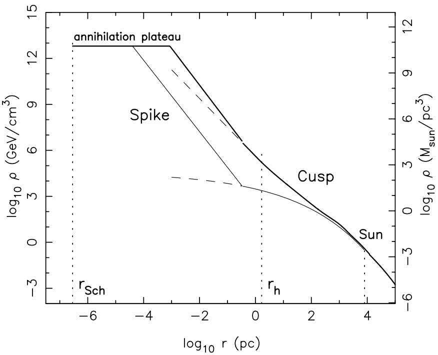


Figure: Comparison of SHM to **DM spike** formed around SMBH, with **central density cutoff** $\simeq m_\chi/\langle\sigma v\rangle t_{BH}$ (astro-ph/0504422)

Distribution depends on star formation history, BH mergers

Termination of first star formation

- More minihalos become sufficiently massive to host Pop III.1 stars over time
- History is not well constrained, assume benchmark termination redshifts $z_f = 20, 15, 10$

BH mergers can destroy spikes

- Fraction of suitable minihalos $f_{DS} = f_{DS}^0(1 - f_{\rm merged})$ which host spikes
- For $M_{BH} \lesssim 10^3 M_\odot$ or $f_{DS}^0 \ll 1$ mergers are not relevant

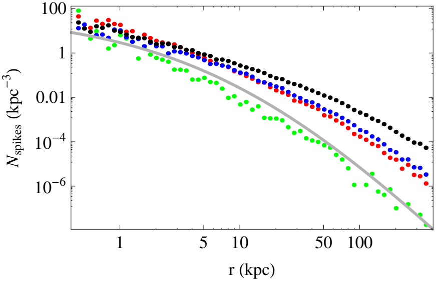


Figure: 1008.3552

Total number of spikes for $f_{DS} = 1$

$$\int d^3\mathbf{R}\, N_{\rm sp}^{z_f}(R) = 409, 7983, 12416$$

Density profiles and annihilation rate for DM spikes

Density of spike depends on M_{BH}

- More DM contracts around more massive central objects
- Standard models of stellar evolution suggest the collapse of fusion-powered Pop III.1 stars yields $10, 10^2 M_\odot$ BHs
- Extended Dark Star phase powered by DM annihilation can yield $10^3, 10^4, 10^5 M_\odot$ BHs

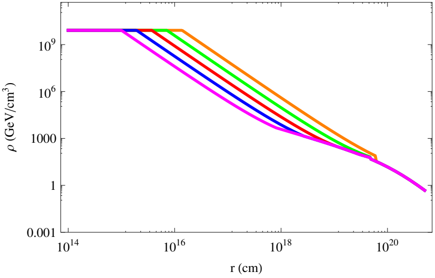


Figure: $100\,\mathrm{GeV}$ WIMPs around IMBH formed in $10^6 M_\odot$ subhalo at $z = 15$

$$\Gamma = \frac{\langle \sigma v \rangle}{2 m_\chi^2} \int_{r_{\min}}^{r_{\max}} dr\, 4\pi r^2 \rho_{DM}^2$$

For spike $10\,\mathrm{pc}$ away, $> 99\%$ of flux from within 0.01°, i.e. $r \lesssim 0.002\,\mathrm{pc}$

Search for clusters in $1^\circ \times 1^\circ$ grid across visible sky

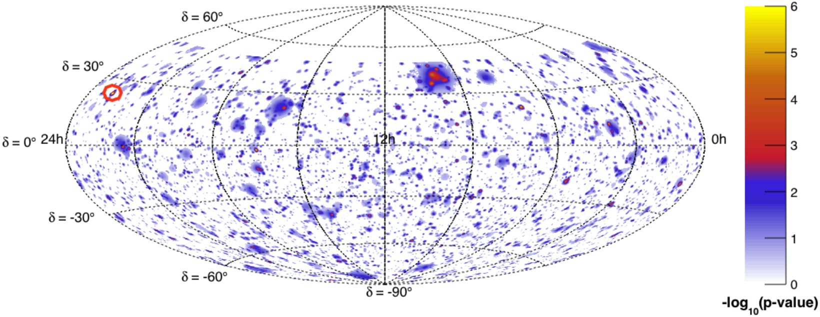
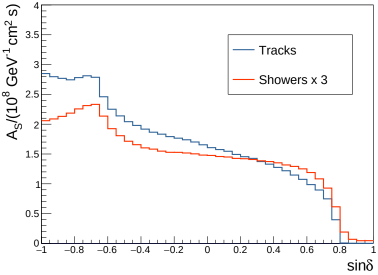
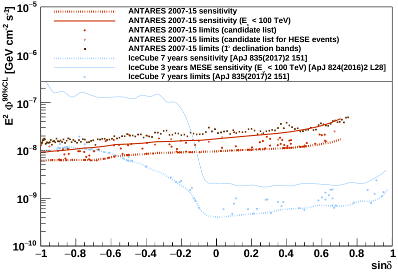


Figure: 1706.01857

Limits on PS flux normalization Φ_0 for E_ν^{-2} spectrum





Signal events = Acceptance$\times\Phi_0$

$$A_S = \Phi_0^{-1} T_{\rm exp} \int dE_\nu A_{\rm eff} \frac{d\Phi}{dE_\nu}$$

Focus on $E_\nu \lesssim 100\,\mathrm{TeV}$ for WIMPs

- AN better visibility for $\delta \lesssim 0^\circ$
- IC very sensitive for $\delta \gtrsim 0^\circ$
- Need $N_{\rm EV}$ limits to estimate sensitivity to DM spikes

Effective area after track (shower) selection cuts

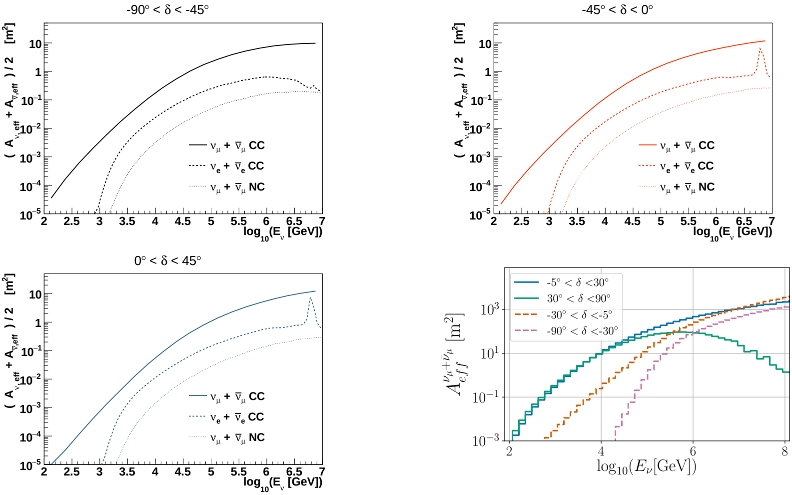
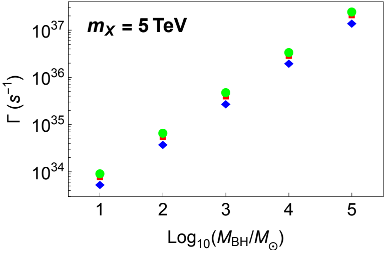
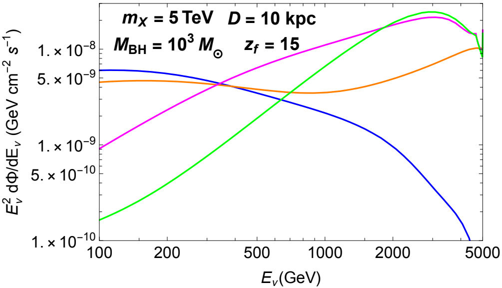


Figure: IceCube 1910.08488

Calculate the neutrino signal from DM spikes





Observable neutrino flux

- Normalization depends on m_χ, M_{BH}, $z_f = 20, 15, 10$
- Shape from source after vacuum oscillations
- Depends on $\nu_{\ell'}$ flavor and annihilation channel

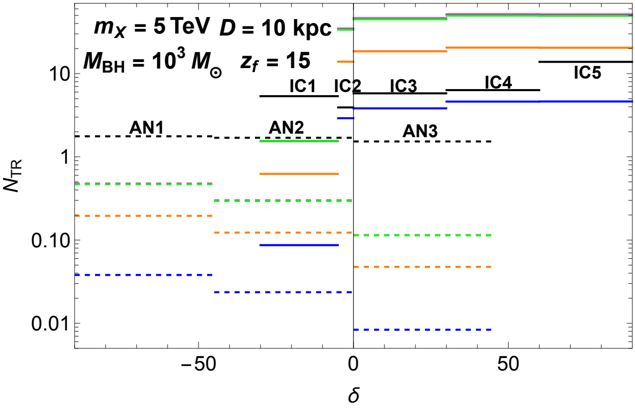
Plot different channels for fixed Γ and D

$$\frac{d\Phi}{dE_\nu} = \frac{\Gamma}{4\pi D^2} \sum_{\ell=e,\mu,\tau} P\left(\nu_\ell \to \nu_{\ell'}\right) \frac{dN}{dE_\nu}$$

$\ell' = \mu$ for $\to \bar{b}b, W^+W^-, \tau^+\tau^-, \mu^+\mu^-$

Compare to AN and IC limits in different sky regions

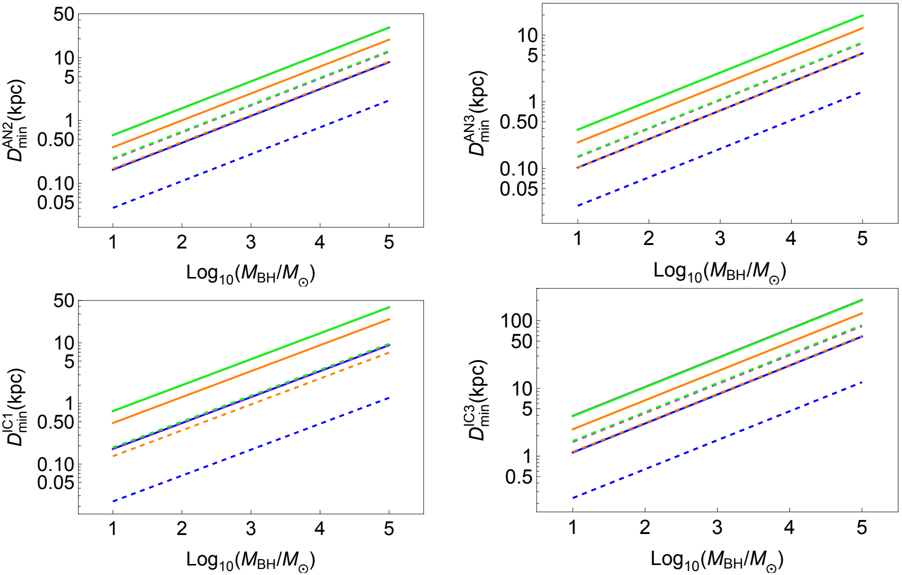
EXi	δ Range
AN1	$[-90°, -45°]$
AN2	$[-45°, 0°]$
AN3	$[0°, 45°]$
IC1	$[-30°, -5°]$
IC2	$[-5°, 0°]$
IC3	$[0°, 30°]$
IC4	$[30°, 60°]$
IC5	$[60°, 90°]$



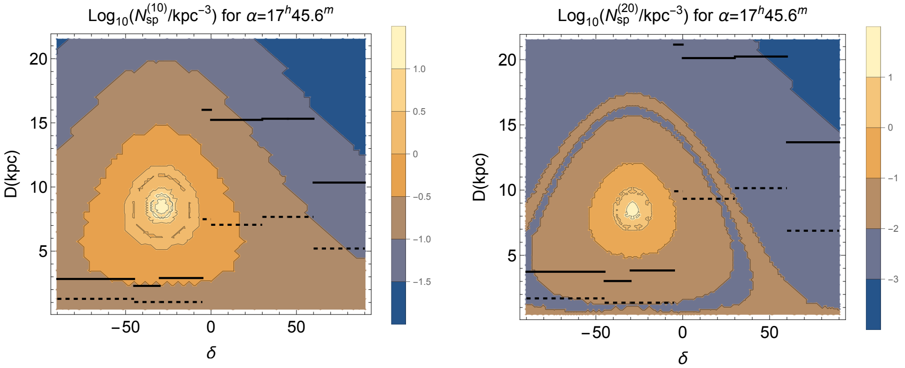
Number of TR or SH events from a DM spike in EXi

$$N_{\rm EV}^{{\rm EX}i} = \sum_{j\in {\rm EX}i} T_{\rm exp}^{j} \sum_{\ell'\in {\rm EV}} \int_{E_{\rm th}}^{m_\chi} dE_\nu \frac{d\Phi_{f\to\nu_{\ell'}}}{dE_\nu} A_{\ell'{\rm EV}}^{j}(E_\nu)$$

Minimum distance to have not been detected as a PS



Combine $D_{\rm min}$ from AN and IC sky regions

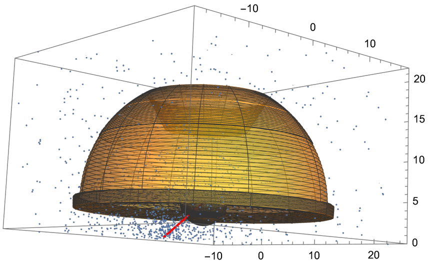


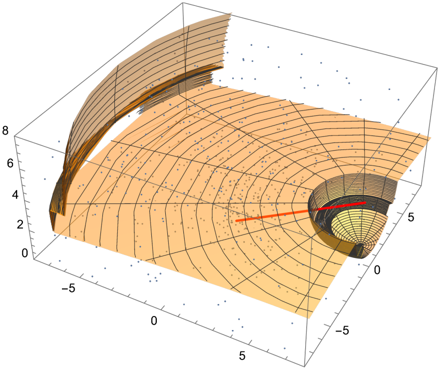
$D_{\rm min}$ surface across full sky for
$M_{BH} = 10^3 M_\odot$ $\chi\chi \to W^+W^-$
$m_\chi = (500\,\mathrm{GeV})$ and $5\,\mathrm{TeV}$

Compare to $N_{\rm sp}^{z_f}$ with α towards GC

- GC visible for larger M_{BH}
- Many spikes away from GC

PS searches sensitive to DM spikes under the lamp shade





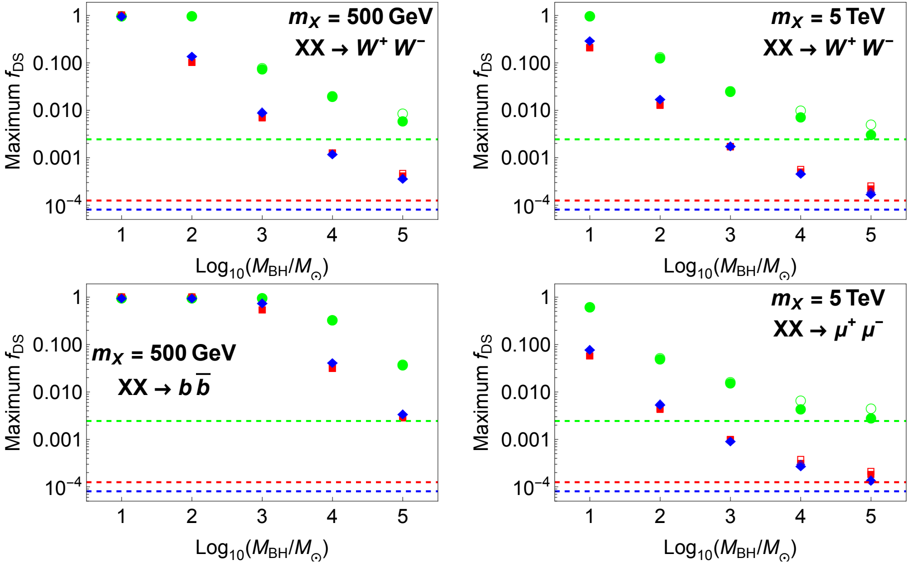
$D_{\rm min}$ surface above the galactic plane, fix $z_f = 10$ and $m_\chi = 5\,\mathrm{TeV}$

- Line from GC to solar system
- Compare to spherical shells from $N_{\rm sp}^{10}(R)$, random (θ, ϕ)

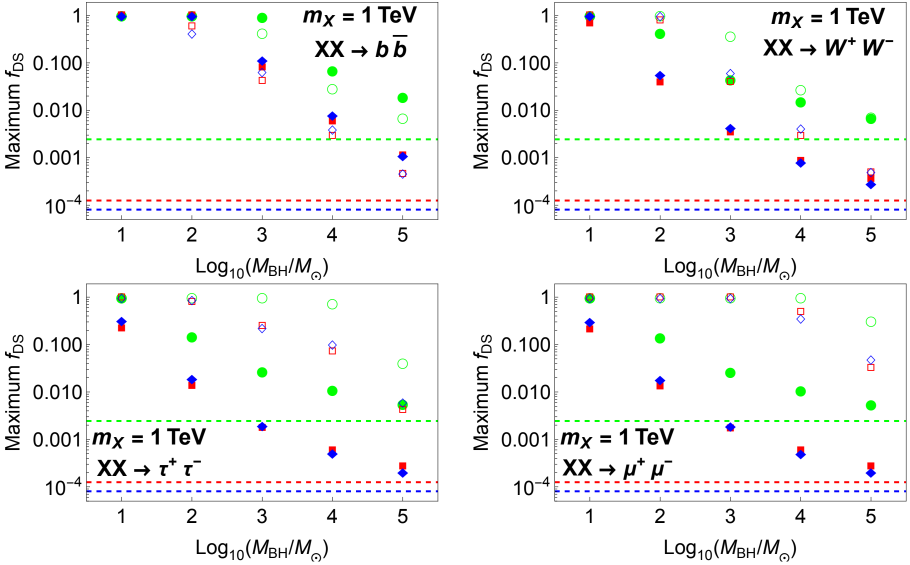
$N_{\rm sp}$ contained within $D_{\rm min}$ surface

$$f_{\rm DS} \int d^3\mathbf{s}\, N_{\rm sp}^{z_f}(s < D_{\rm min}) < 1$$

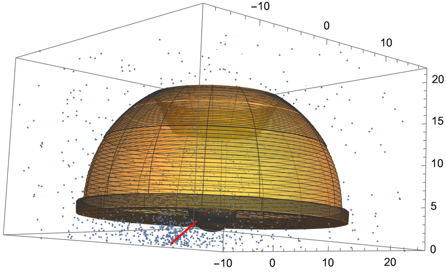
Limits on f_{DS} given lack of confirmed PS by AN or IC

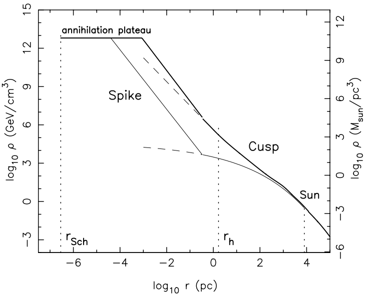


Compare to gamma-ray limits from Fermi-LAT



Neutrino PS searches ideal for detecting DM spikes





Probe nature of DM, substructure and models of stellar evolution

- $f_{DS} \lesssim 10\%$ for $5\,\mathrm{TeV}$ WIMPs around $\gtrsim 10^3 M_\odot$ BHs
- Robust to BH mergers and tidal disruption near GC
- Complement γ-ray limits

Interesting (?) ideas for future work

- KM3Net combines visibility of AN with larger exposure of IC
- Consider heavier (non-thermal) DM for $E_\nu \gtrsim 100\,\mathrm{TeV}$
- Diffuse emission around SMBHs

Thermal WIMP production motivates ID searches

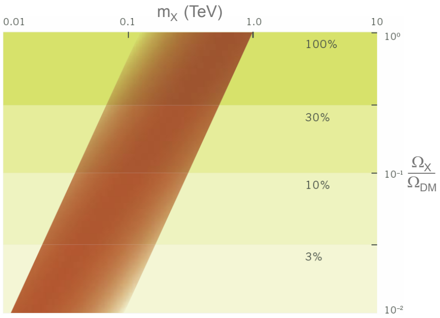


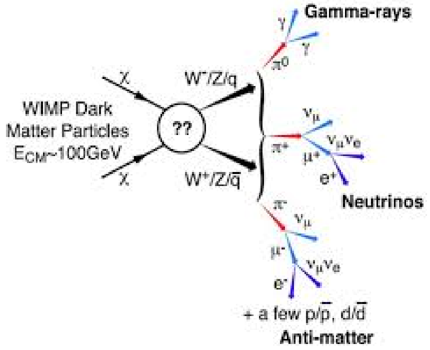
Figure: 1003.0904

Thermal freeze-out relic abundance

$$\Omega_X h^2 \sim 0.1 \left(\frac{1\,\mathrm{pb}}{\langle \sigma_A v \rangle} \right)$$

EW coupling ⇒ weak scale mass

Can look for products of WIMP dark matter annihilation today



Interact around the detector, measure charged products

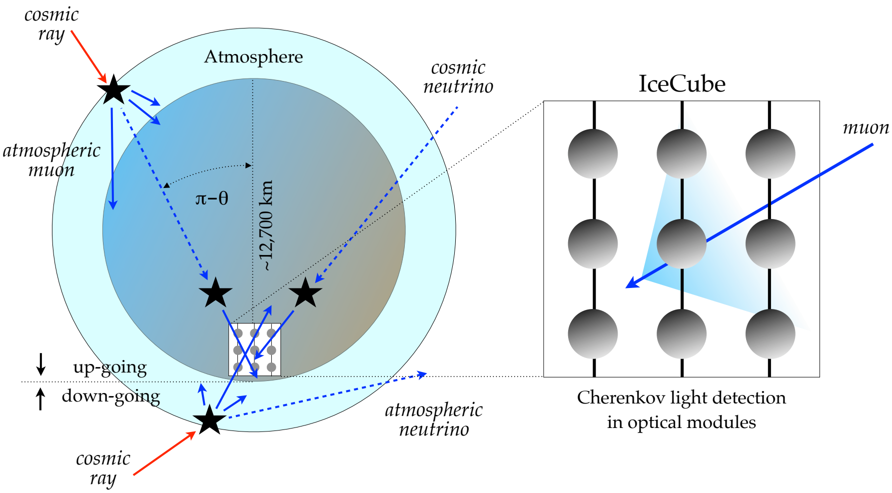


Figure: 1805.11112

Estimate number of events for a source flux and declination

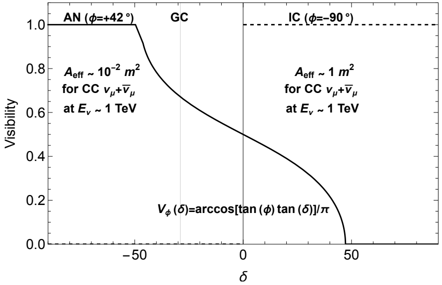
Event rate depends on effective area

$$\frac{dN_{\rm EV}}{dt} = \int dE_\nu A_{\rm eff}(E_\nu, \delta) \frac{d\Phi}{dE_\nu}$$

$$A_{\rm eff} = V_{\rm gen} \times \frac{N_{\rm det}}{N_{\rm gen}} \times \rho N_A \times \sigma \times P_{\rm Earth}$$

Calculated from event simulation

- Simulated target volume, detection efficiency
- Target nucleon density
- ν-nucleon cross section, absorption in Earth



Visibility of sources below horizon

$$= \begin{cases} 0, & \text{if } |\delta| > \pi/2 - |\phi|, \delta \cdot \phi > 0 \\ V_\phi(\delta), & \text{if } |\delta| \le \pi/2 - |\phi| \\ 1, & \text{if } |\delta| > \pi/2 - |\phi|, \delta \cdot \phi < 0 \end{cases}$$

Neutrino telescopes typically only most sensitive for $\to \nu\nu$

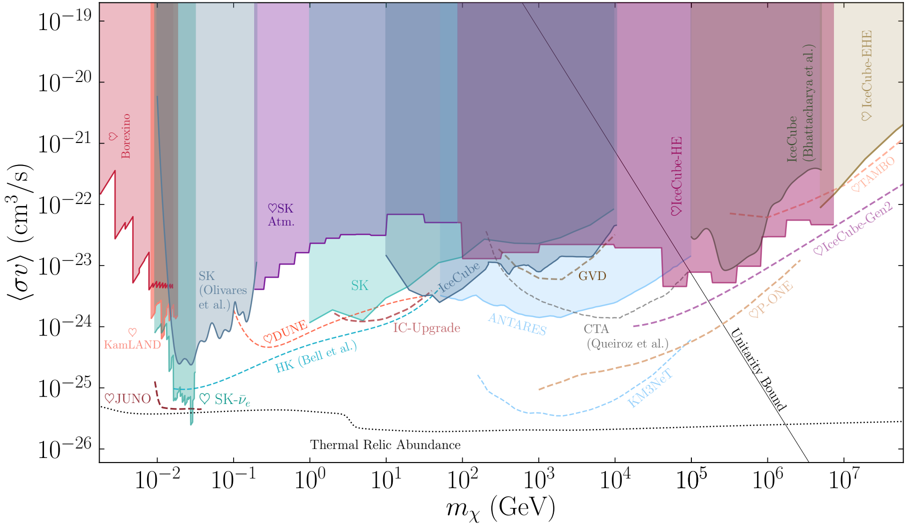
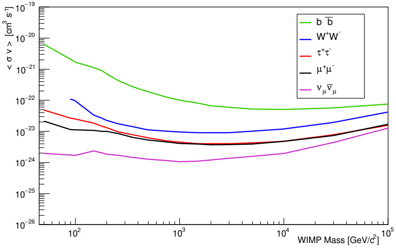


Figure: 1912.09486

γ-ray experiments more sensitive to visible channels



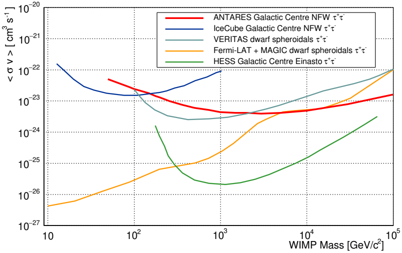


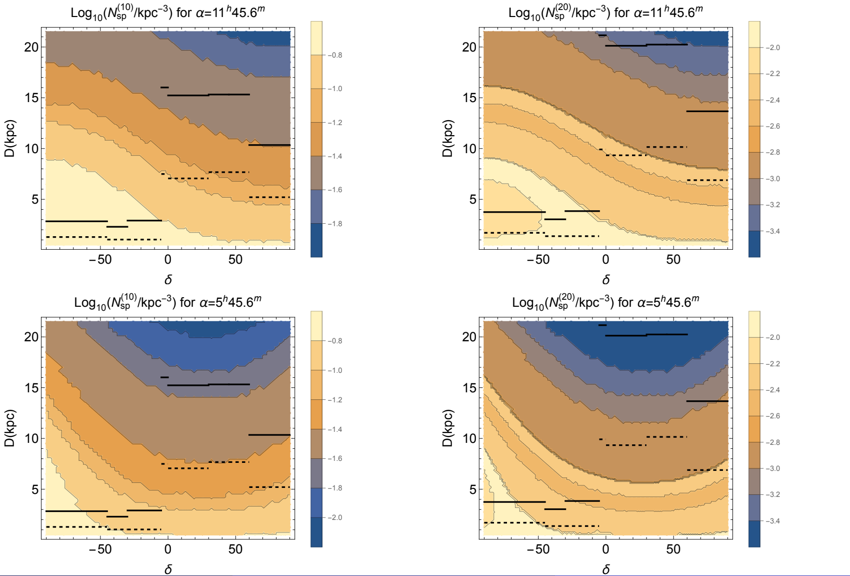
Figure: ANTARES limits on WIMP annihilation in GC (1912.05296)

Limits on annihilation weaken as final state becomes more hadronic

γ-ray signals are easier to detect

- GC limits 10-100 stronger
- Limits from dSphs can exclude $\lesssim 100\,\mathrm{GeV}$ thermal WIMP
- What about DM spikes?

$D_{\min}$ surface compared to $N_{\rm sp}^{z_f}$ at different α



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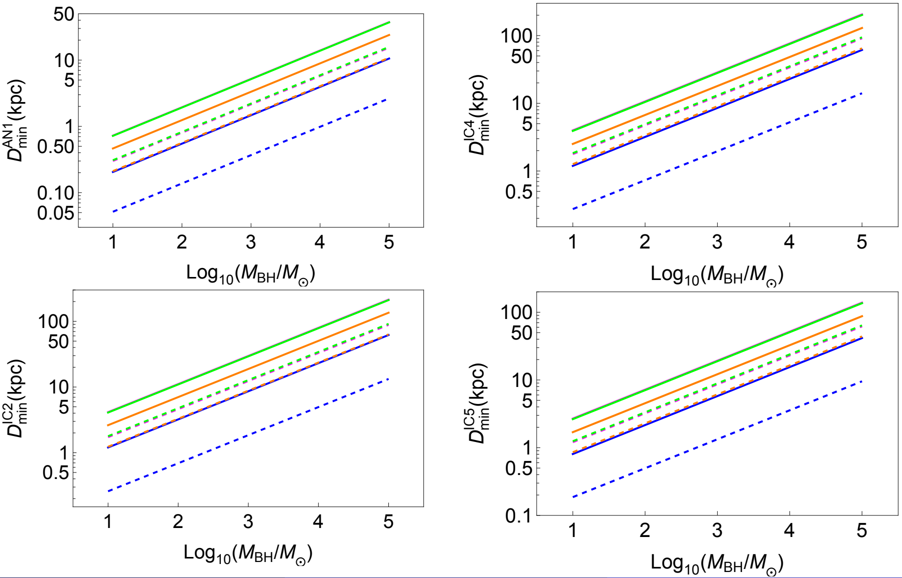

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