The Dark Matter Annihilation Signal from Galactic Substructure

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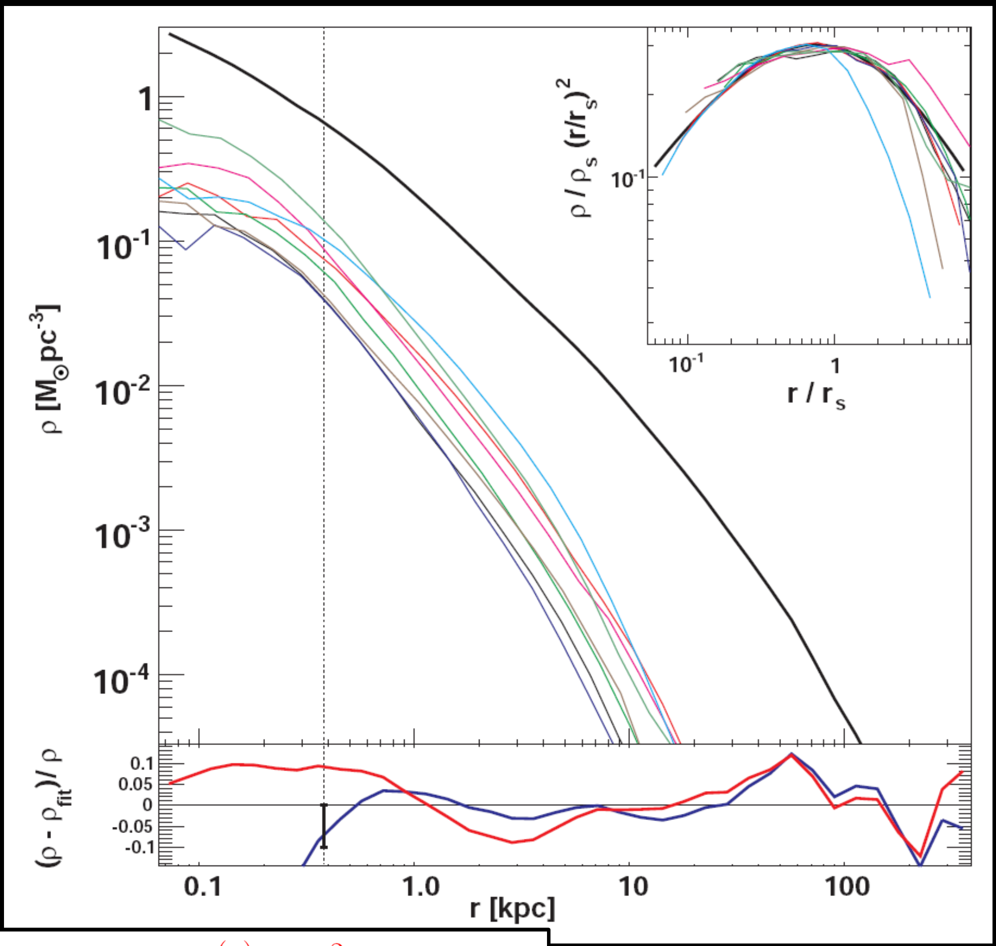
KITP, Oct. 2nd 2008

Recap: The Via Lactea II Subhalo Population

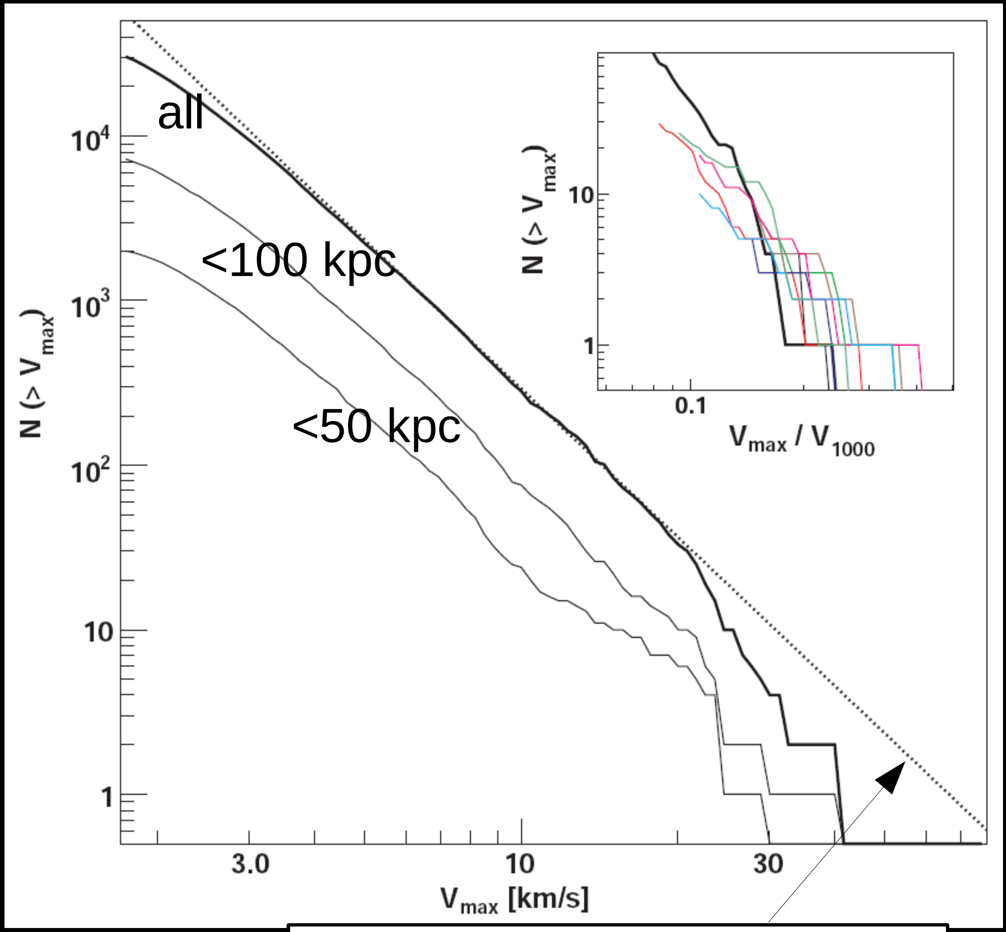
Subhalos have a “cuspy” inner density profile down to our resolution limit...



$$\text{Einasto}: \quad \ln \frac{\rho(r)}{\rho_s} = -\frac{2}{\alpha}\left[(r/r_s)^{\alpha} - 1\right]$$

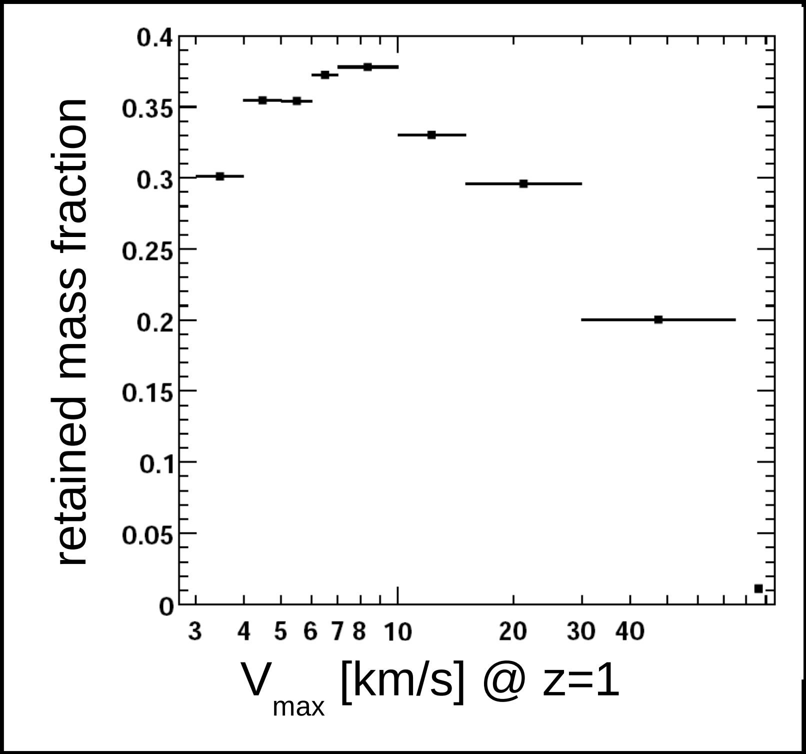
$$\text{GNFW}: \quad \rho(r) = \frac{\rho_s}{(r/r_s)^{\gamma}(r/r_s+1)^{3-\gamma}}$$

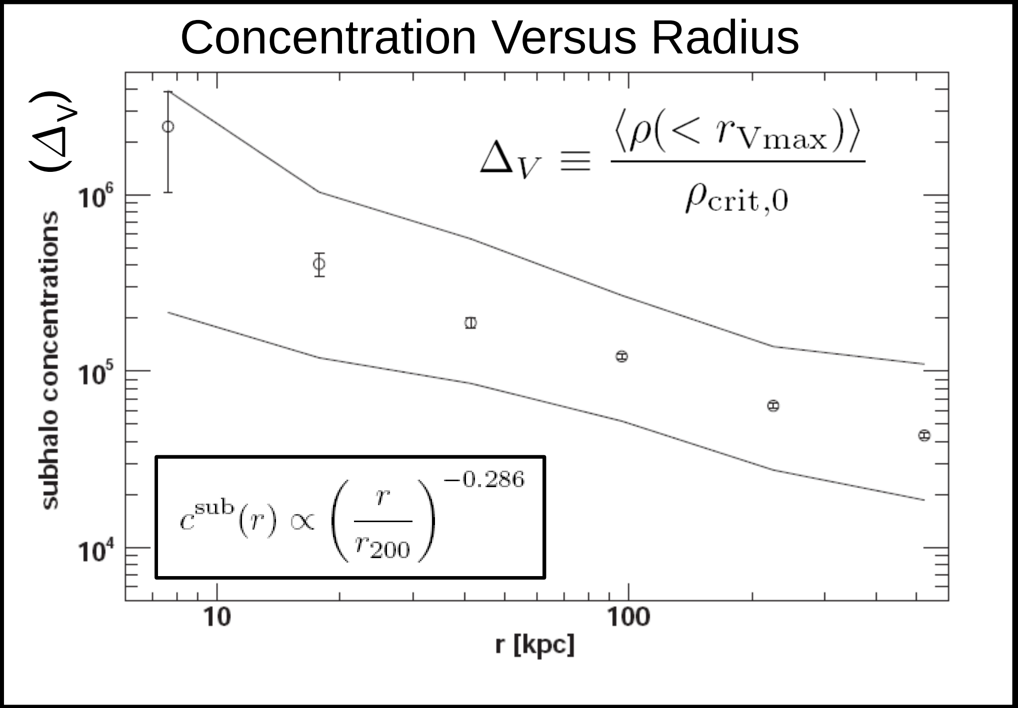
...and have a steeply rising V_{max} function. A single power law down to ~3 km/s.



$$N(>V_{\rm max}) = 0.036 \left(\frac{V_{\rm max}}{V_{\rm max,host}}\right)^{-3}$$

The Subhalo Population – Tidal Mass Loss

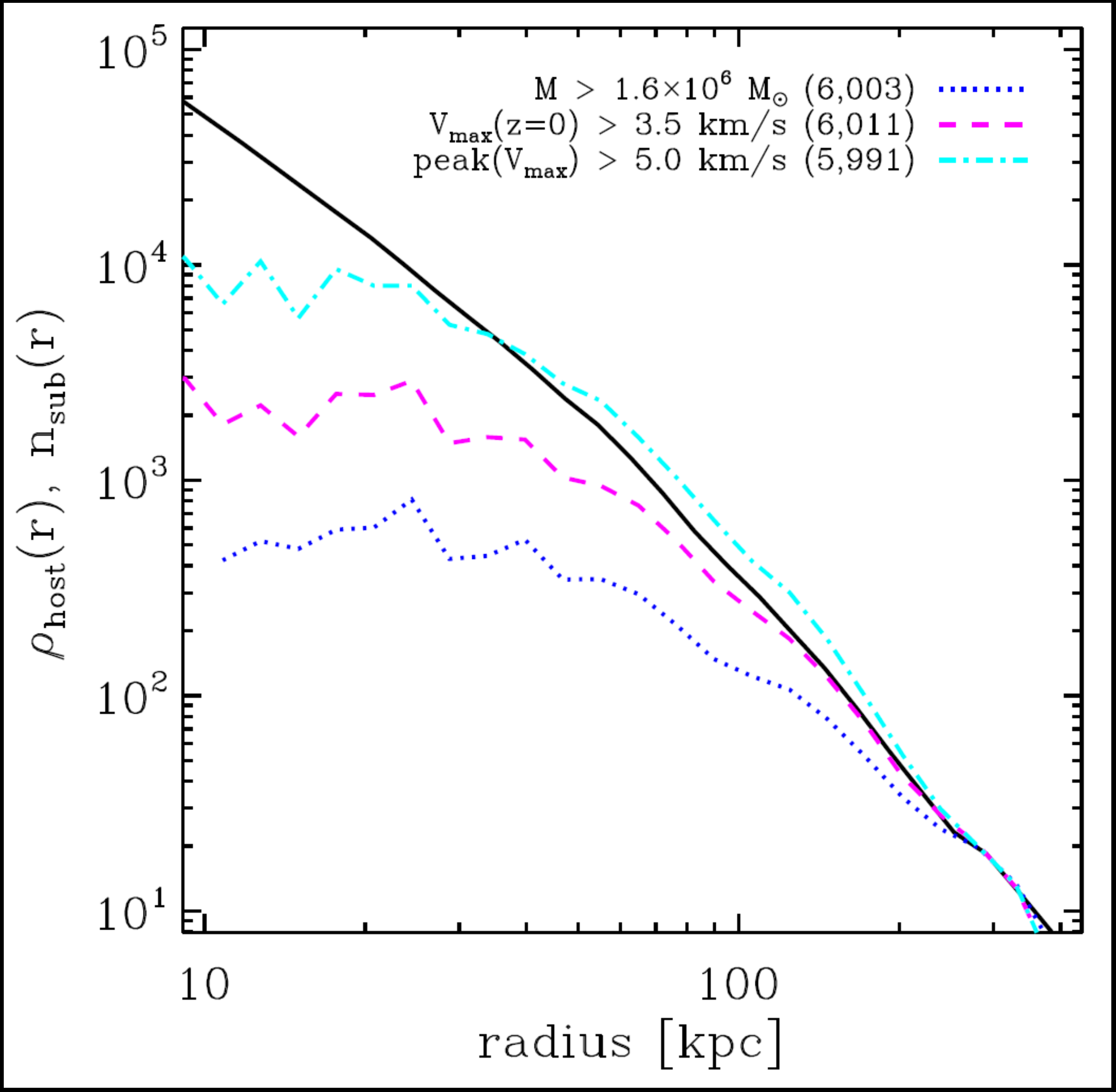




- Tidal mass loss is stronger for more massive halos (higher V_{max} @ z=1).
- Halos with V_{max}=10 km/s retain about 40% of their mass from z=1 to today.
- 97% of all z=1 subhalos still have an identifiable remnant at z=0.

- Subhalos are more concentrated in the inner regions.
- This due to both tidal stripping and an earlier formation time.
- c(r=8kpc) $\approx$ 3 $\times$ c(field)

The Subhalo Population – Spatial Distribution



The subhalo radial distribution is **anti-biased** with respect to the DM density: fewer subhalos in the center.

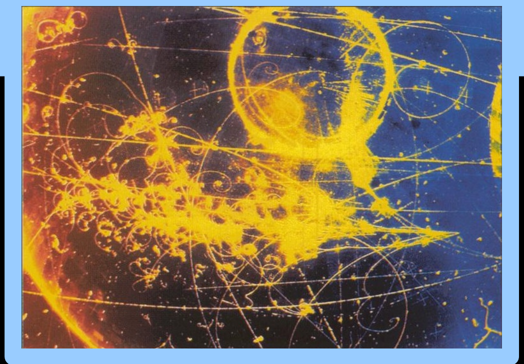
(cf. Ghigna et al. 2000; de Lucia et al. 2004)

Depends on selection:

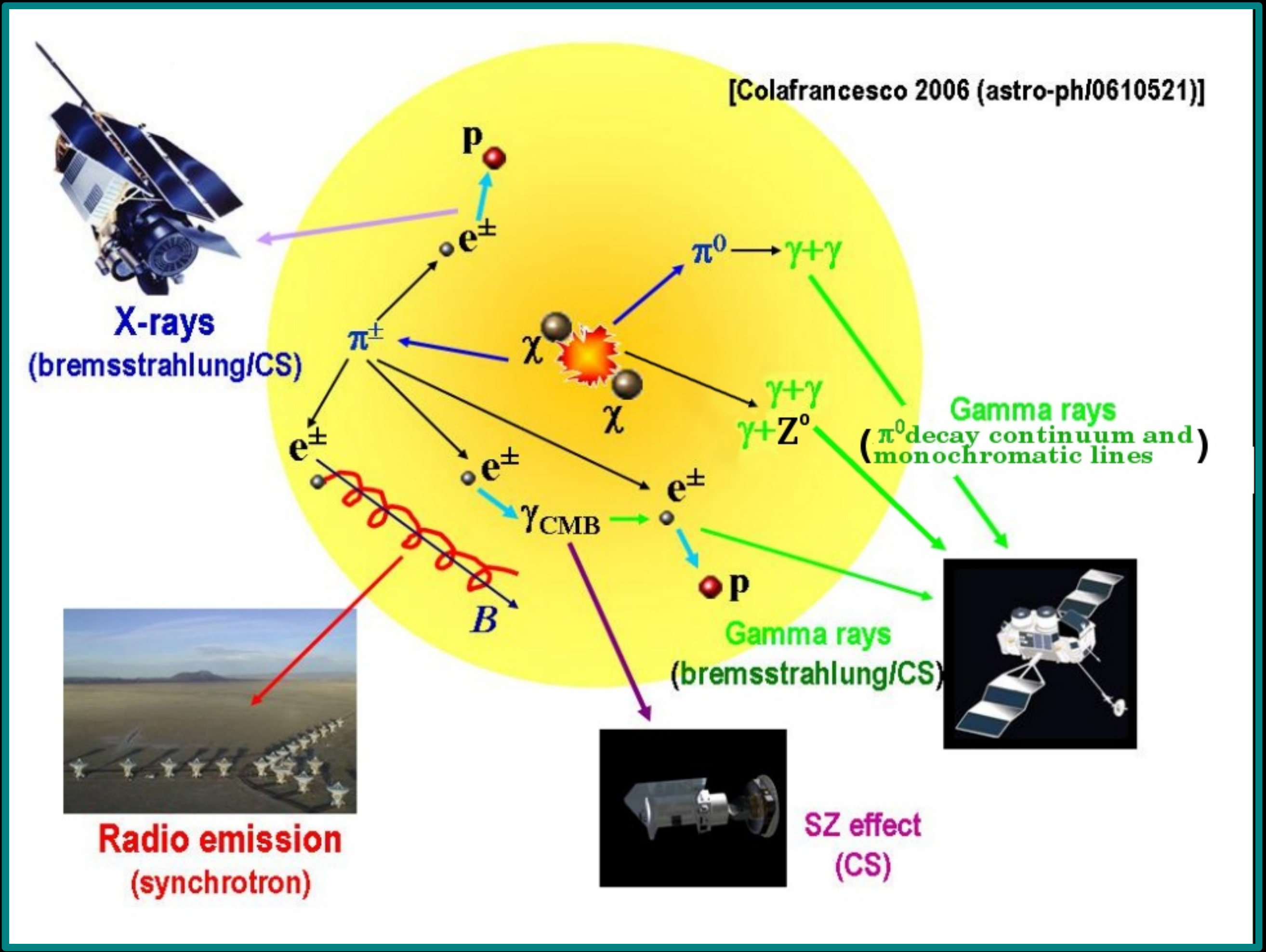
- strongest for M(z=0)-selected,
- weaker for Vmax(z=0)-selected,
- disappears down to ~30 kpc for peak(Vmax)-selected.

(cf. Nagai & Kravtsov 2005; Faltenbacher & Diemand 2006)

Gamma rays from WIMP annihilations



DM (WIMP) annihilation signal



Many different DM candidates: axions, WIMPs (neutralino, Kaluza-Klein, ...), etc.

In the following: DM = lightest SUSY particle (neutralino)

γ's from neutralino annihilation:

a) $\chi\chi \rightarrow \gamma\gamma$

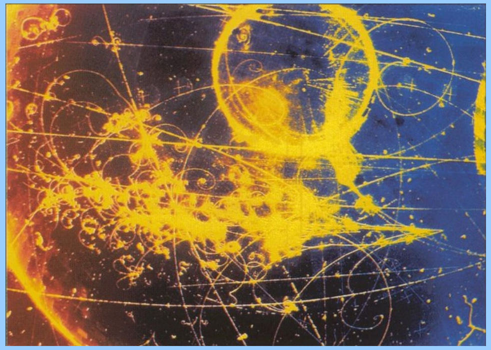
b) $\chi\chi \rightarrow \gamma Z^0$

c) $\chi\chi \rightarrow \{WW, Z^0Z^0, b\bar{b}, t\bar{t}, u\bar{u}\}$

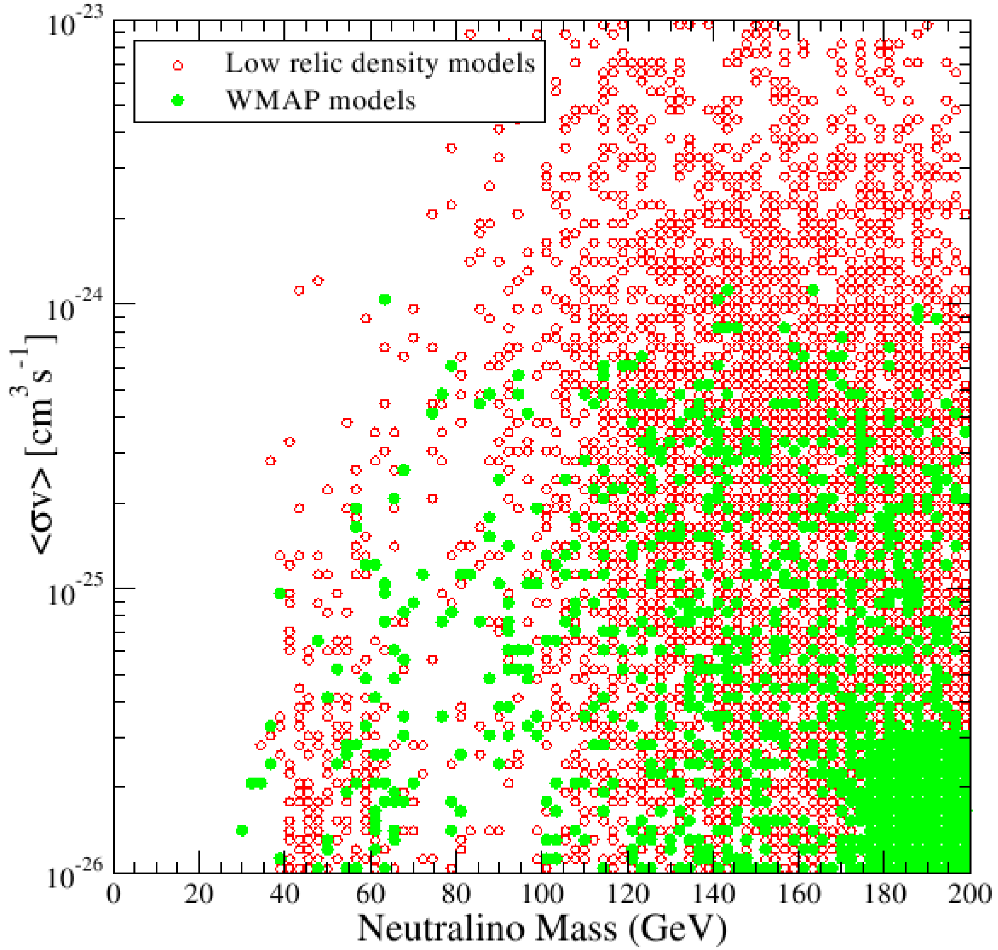
a)+b) spectral line, lower $<\sigma v>$

c) photon continuum from π^0 decay, higher $<\sigma v>$, more ambiguous signal

Gamma rays from WIMP annihilations



Cross section <σv> and particle mass very uncertain!



Colafrancesco et al. (2006)

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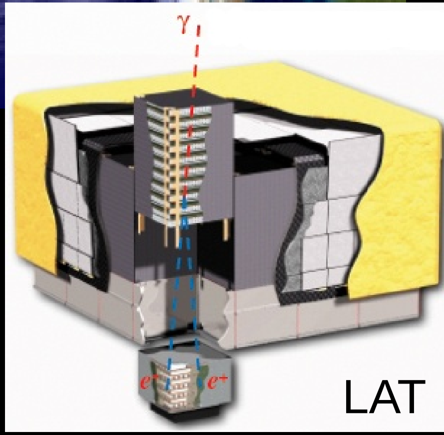
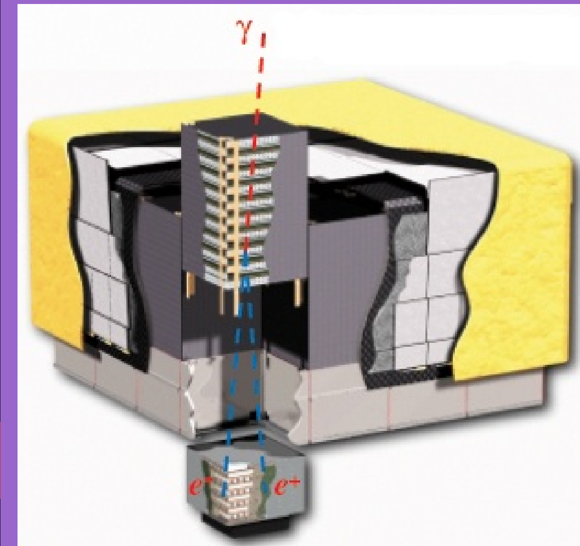
~~GLAST~~

Quantity	LAT (Minimim Spec.)	EGRET
Energy Range	20 MeV - 300 GeV	20 MeV - 30 GeV
Peak Effective Area[1]	> 8000 cm^2	1500 cm^2
Field of View	> 2 sr	0.5 sr
Angular Resolution[2]	< 3.5° (100 MeV) < 0.15° (>10 GeV)	5.8° (100 MeV)
Energy Resolution[3]	< 10%	10%
Deadtime per Event	< 100 μs	100 ms
Source Location Determination[4]	< 0.5'	15'
Point Source Sensitivity[5]	$< 6 \times 10^{-9}$ cm^{-2} s^{-1}	$\sim 10^{-7}$ cm^{-2} s^{-1}



- Launched successfully on June 11th, 2008. Has completed 60 day calibration period. First Light images released.
- Possible local DM annihilation sources:
  - Galactic Center (Berezinsky et al. 1994, Calcaneo-Roldan & Moore 2000, Hooper & Dingus 2004)
  - Dwarf galaxies (Bergstrom & Hooper 2004, Colafrancesco et al. 2007)
  - Nearby subhalo (Bi 2006, Pieri et al. 2005)
  - Coma cluster (Colafrancesco et al. 2006)
- Cosmic Gamma Ray Background (Bergstrom et al. 1999, 2001, Ullio et al. 2002)

Astro physics

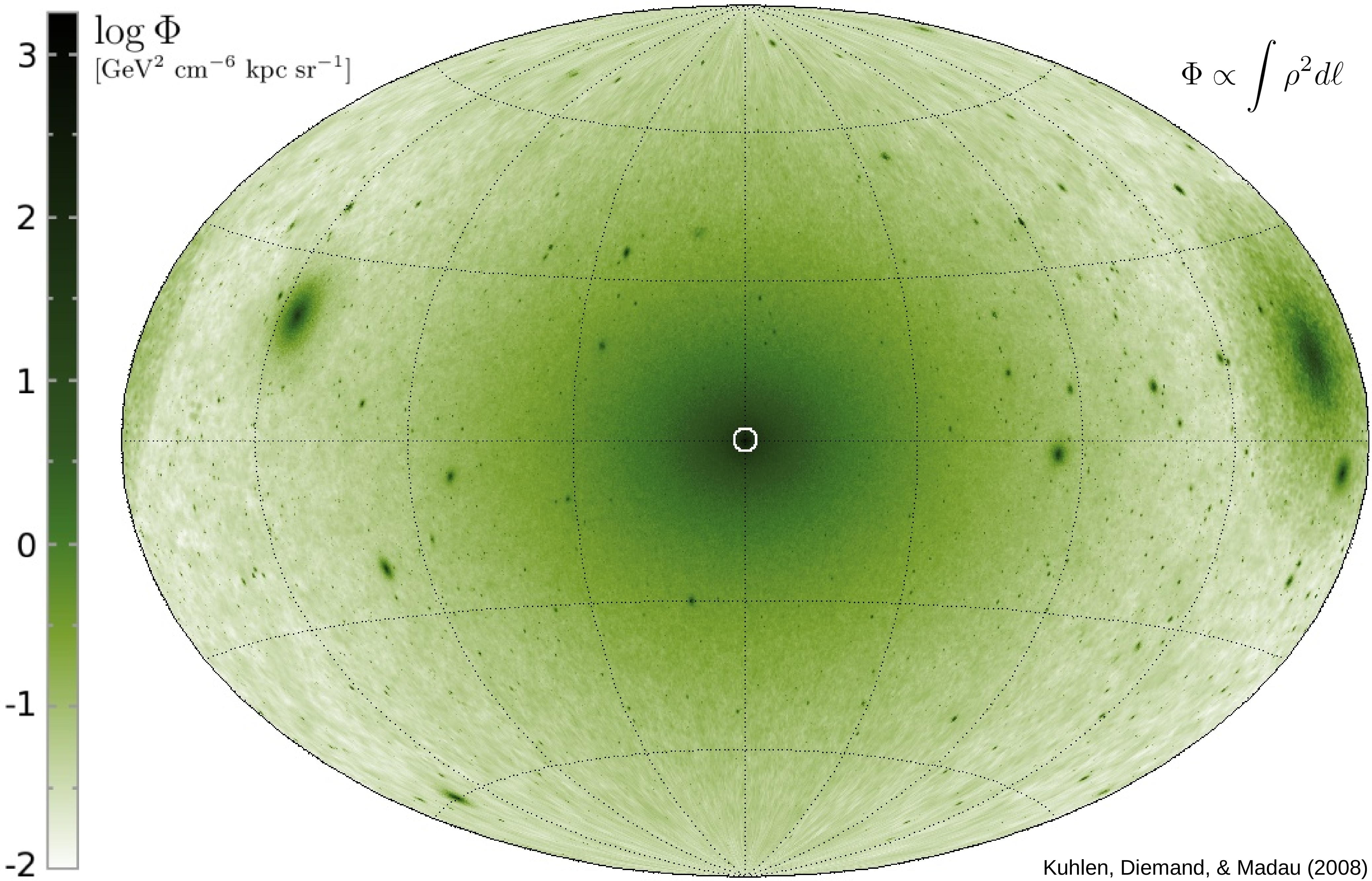


Detector properties

$$N_\gamma = \left[\int_{\text{line of sight}} \rho^2_{\rm DM}\, dl(\psi)\right] \frac{\langle\sigma v\rangle}{2M_\chi^2} \left[\int_{E_{th}}^{M_\chi} \left(\frac{dN_\gamma}{dE}\right)_{\rm SUSY} A_{\rm eff}(E)\,dE\right] \frac{\Delta\Omega}{4\pi}\,\tau_{\rm exp}$$

Particle physics

Simulated Dark Matter Annihilation Map

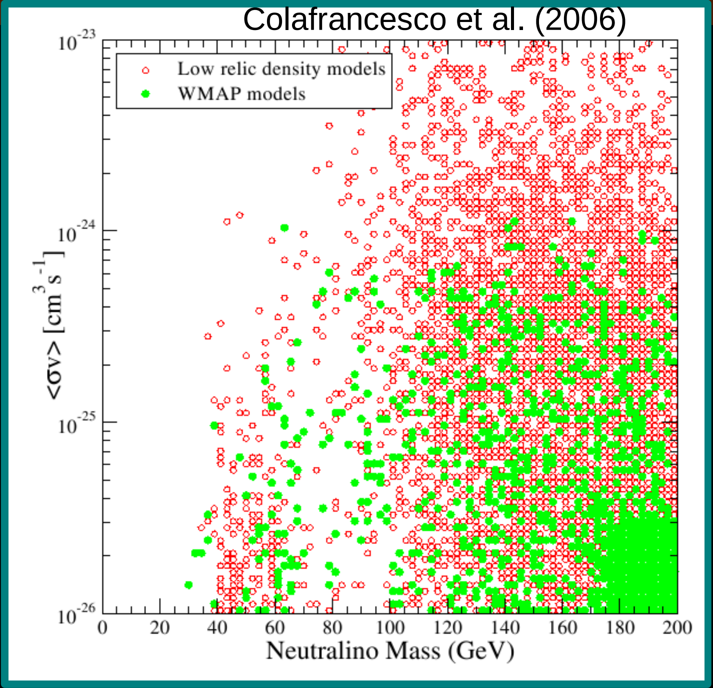


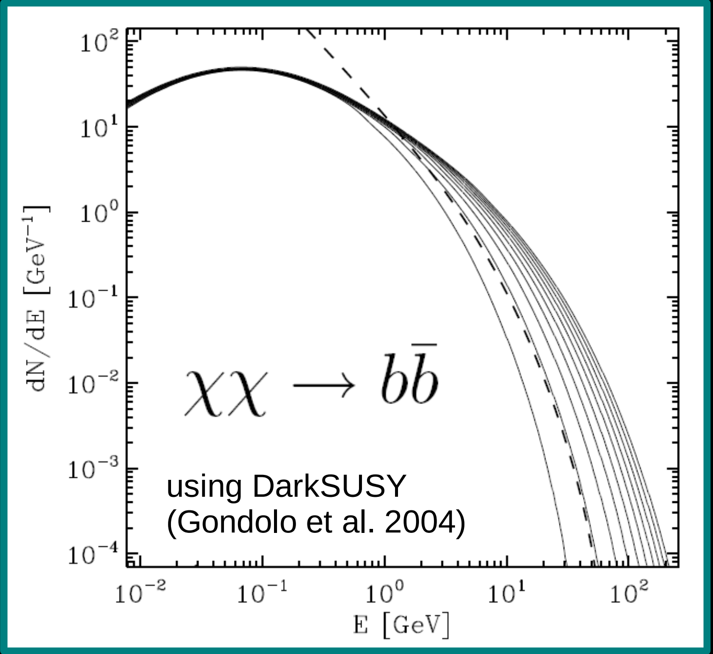
Kuhlen, Diemand, & Madau (2008)

Can We Make Quantitative Predictions?

$$N_\gamma = \left[\int_{\text{line of sight}} \rho_{\rm DM}^2 \, dl(\psi)\right] \frac{\langle\sigma v\rangle}{M_\chi^2} \left[\int_{E_{th}}^{M_\chi} \left(\frac{dN_\gamma}{dE}\right)_{\rm SUSY} A_{\rm eff}(E) dE\right] \frac{\Delta\Omega}{4\pi} \tau_{\rm exp}$$

1) Assume a DM particle: mass and cross section, consistent with relic abundance (Ω_m from WMAP).





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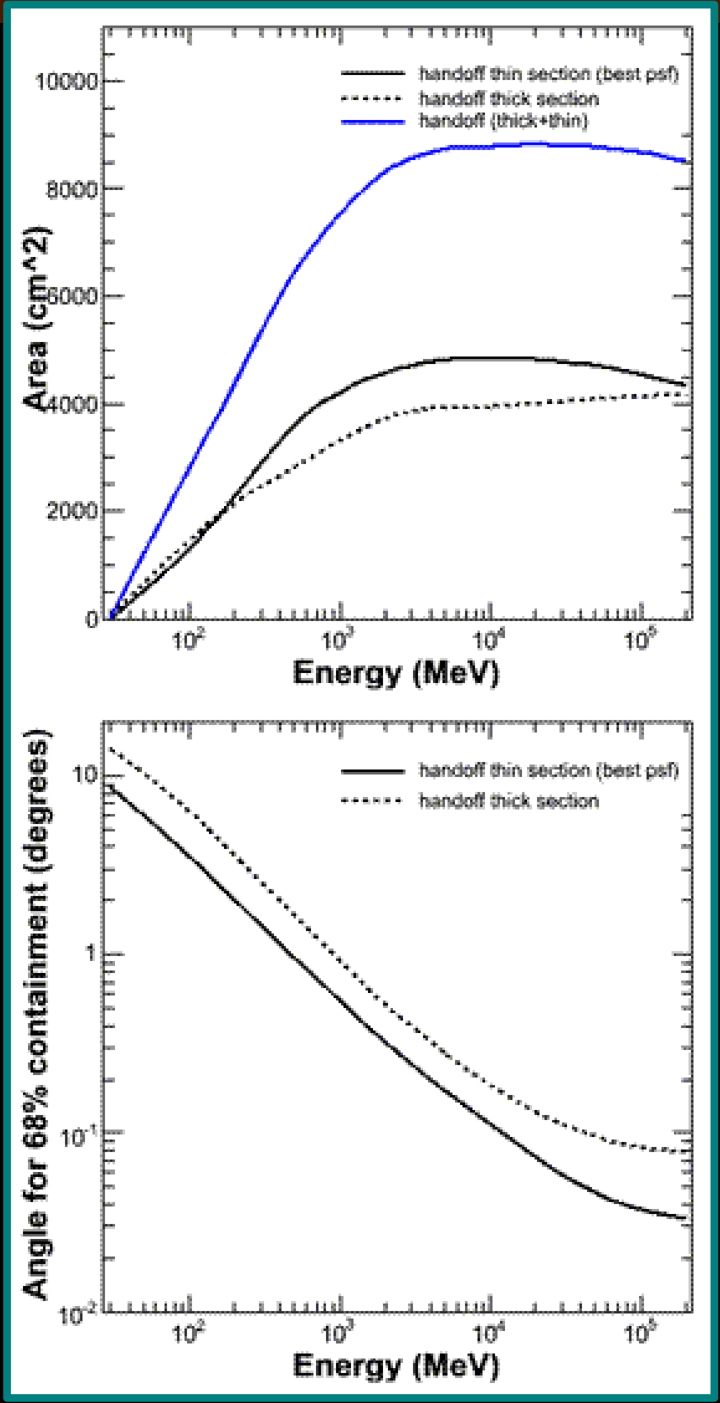
1) Assume a DM particle: mass and cross section, consistent with relic abundance (Ω_m from WMAP).

2) Use expected Fermi/LAT detector sensitivity:
   - $A_{eff}(E)$
   - angular resolution (~9 arcmin)
   - effective exposure time (~2 years)



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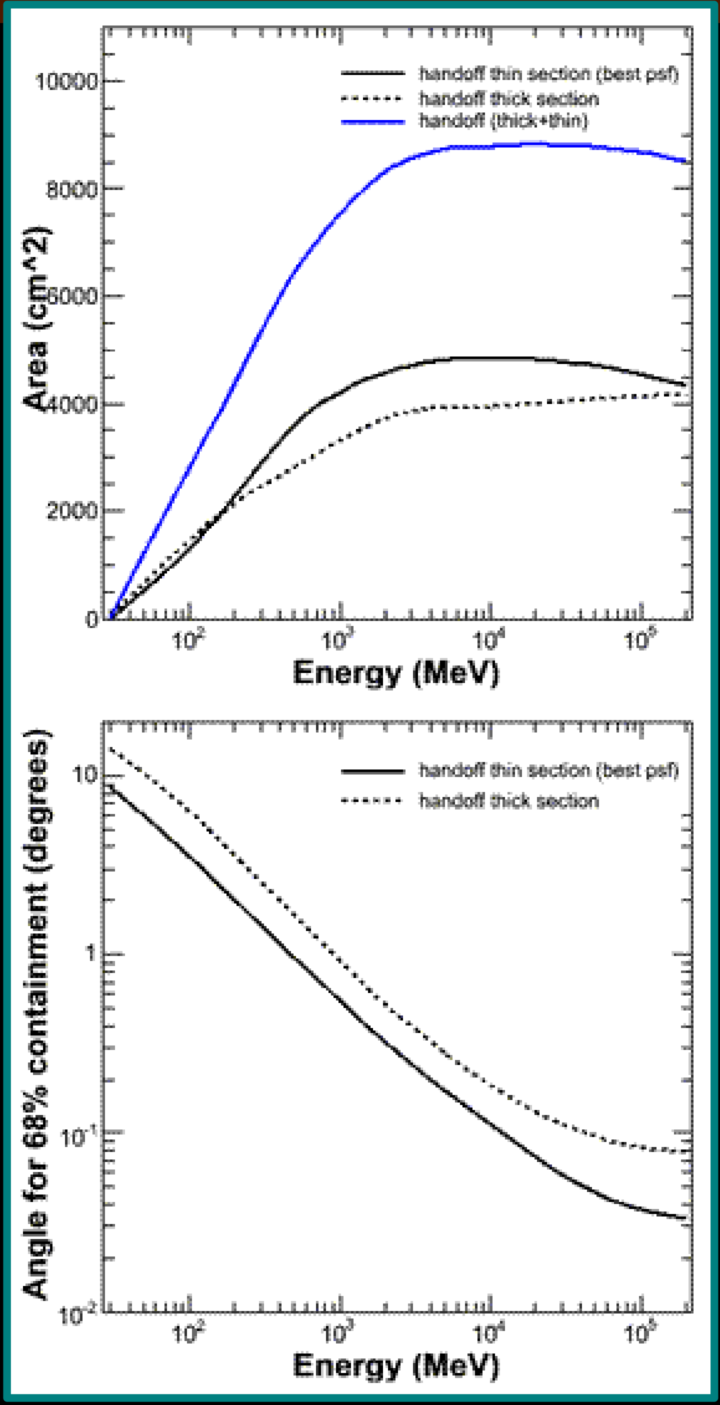
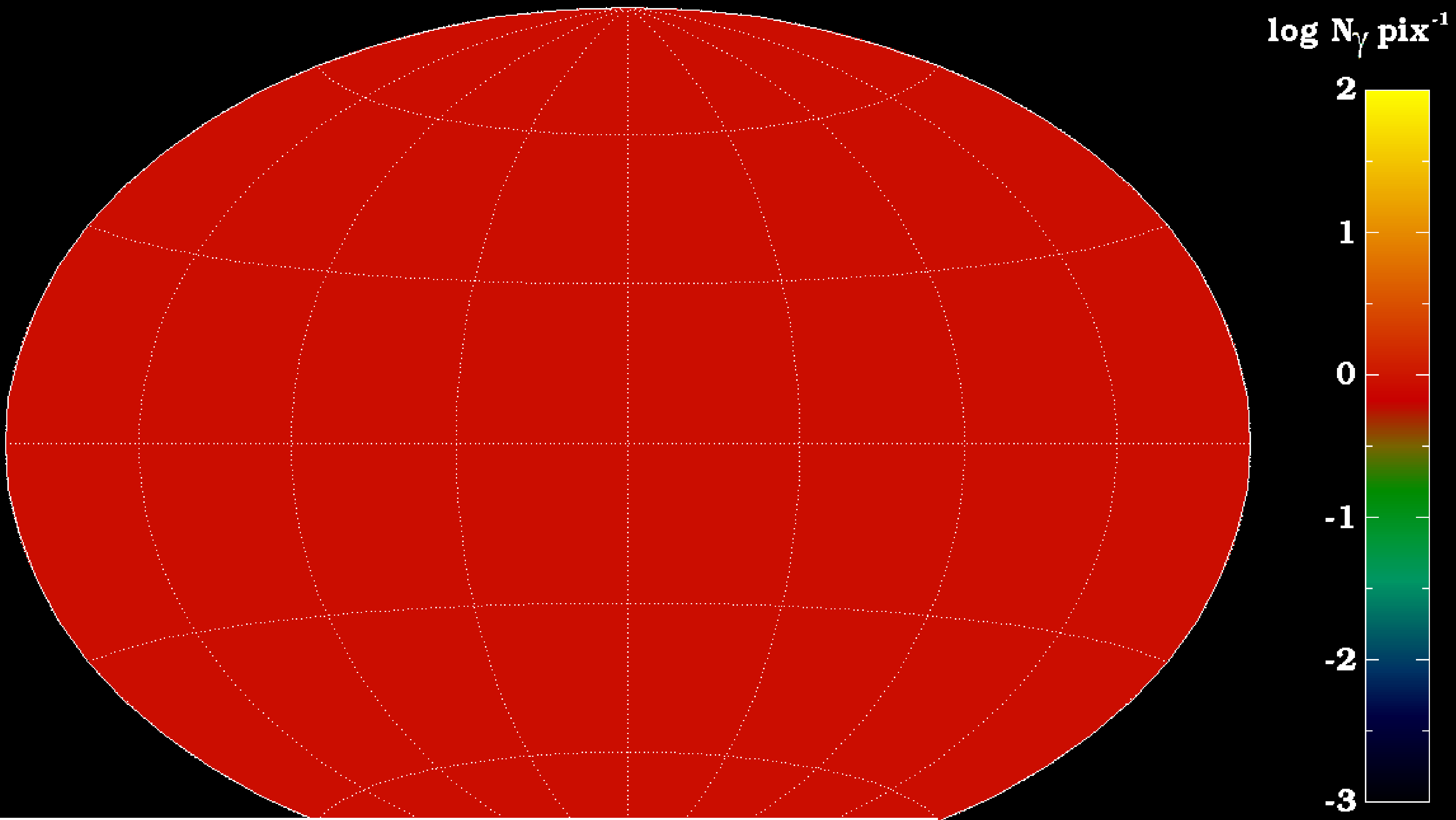
3) Consider both astrophysical and DM annihilation backgrounds.



Backgrounds: Extragalactic GR Background

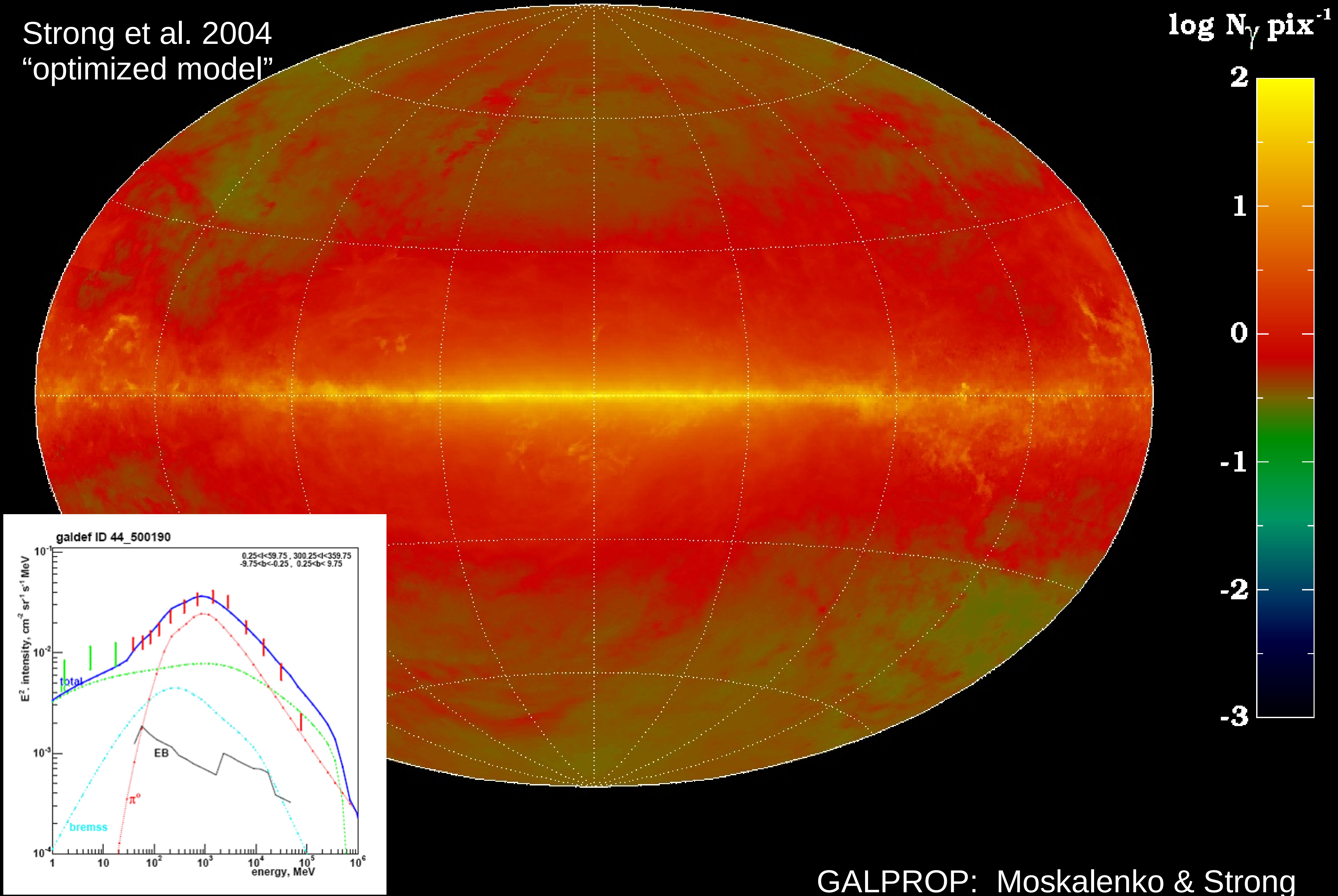


$$\frac{dN}{dE\,dA\,dt\,d\Omega} = 1.32 \times 10^{-6} \left(\frac{E}{1\mathrm{GeV}}\right)^{-2.1} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

From EGRET: Sreekumar et al. 1998 and Baltz et al. 1999

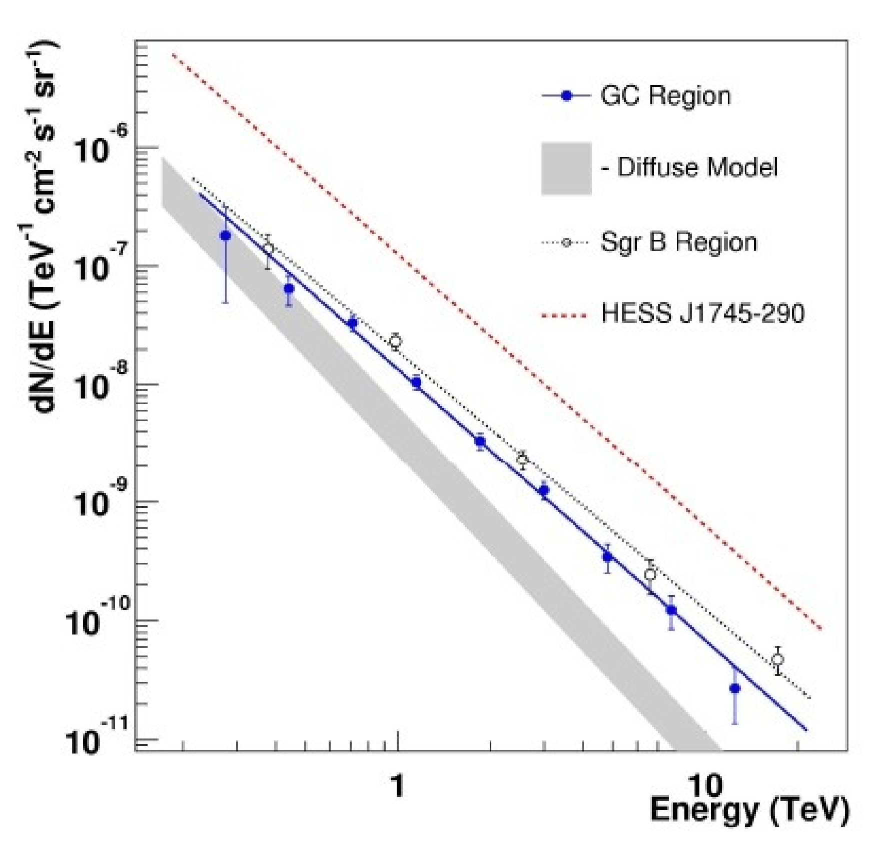
Backgrounds: Galactic GR Background

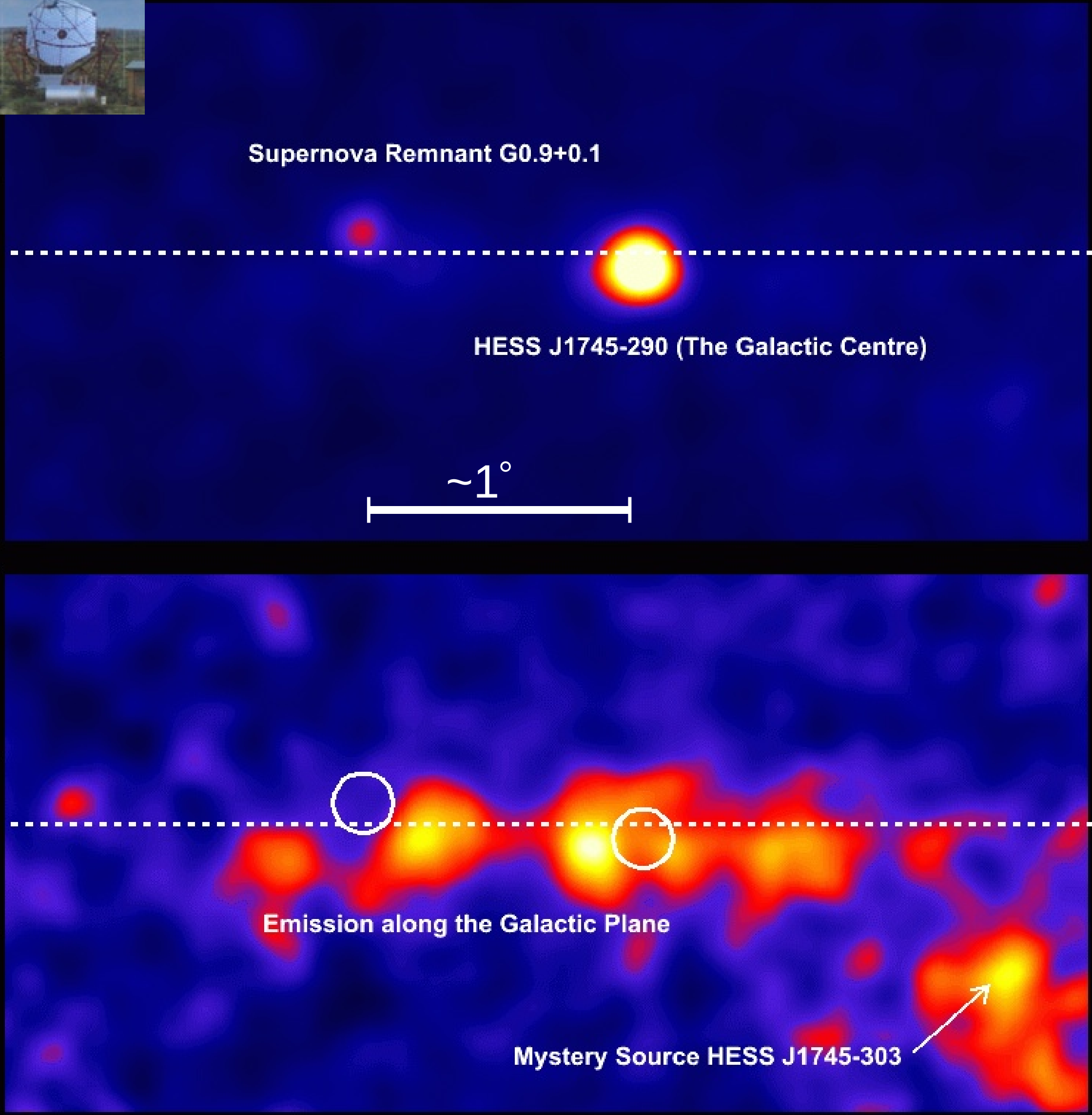
Strong et al. 2004
“optimized model”



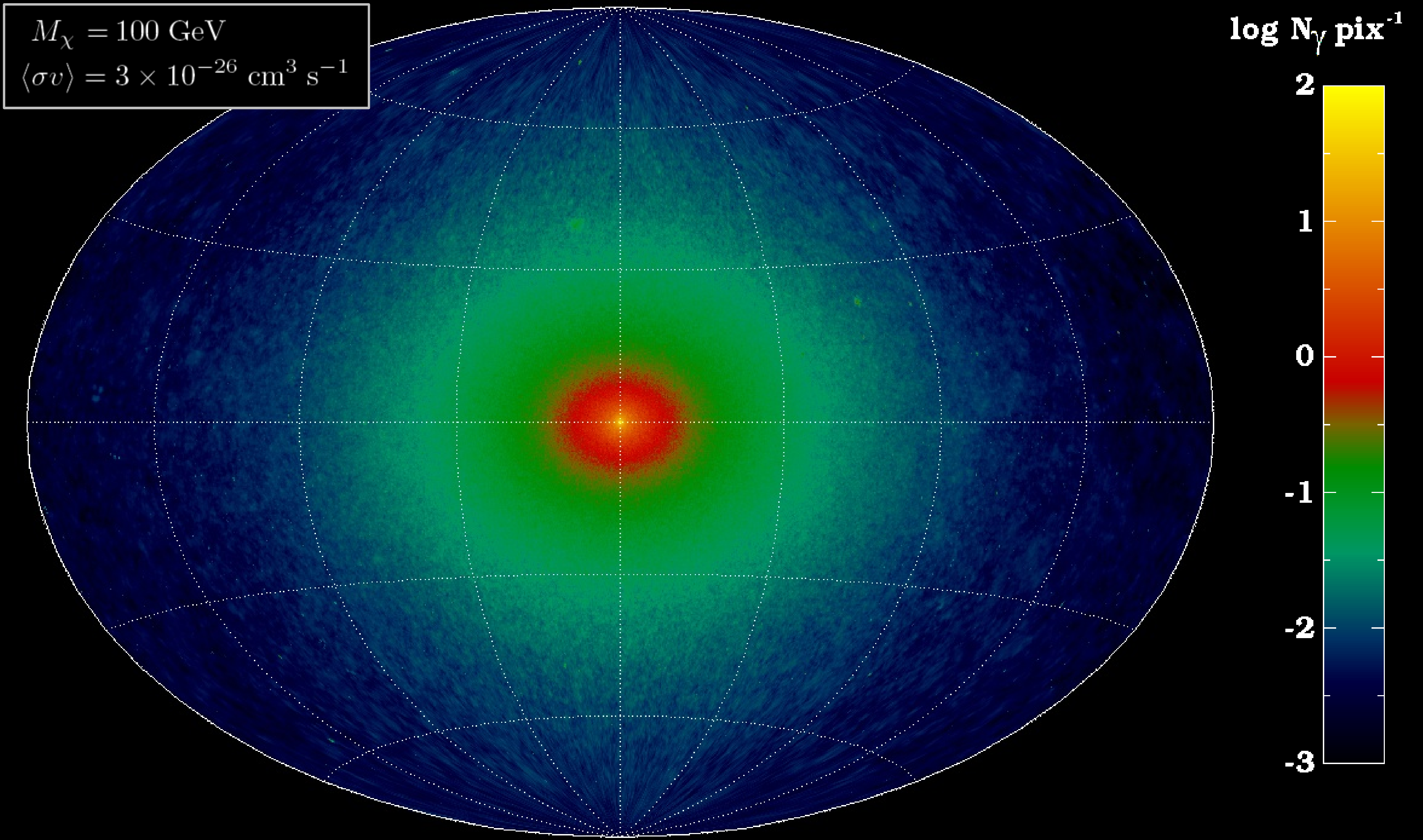
GALPROP: Moskalenko & Strong

Galactic Center: GR Point Sources



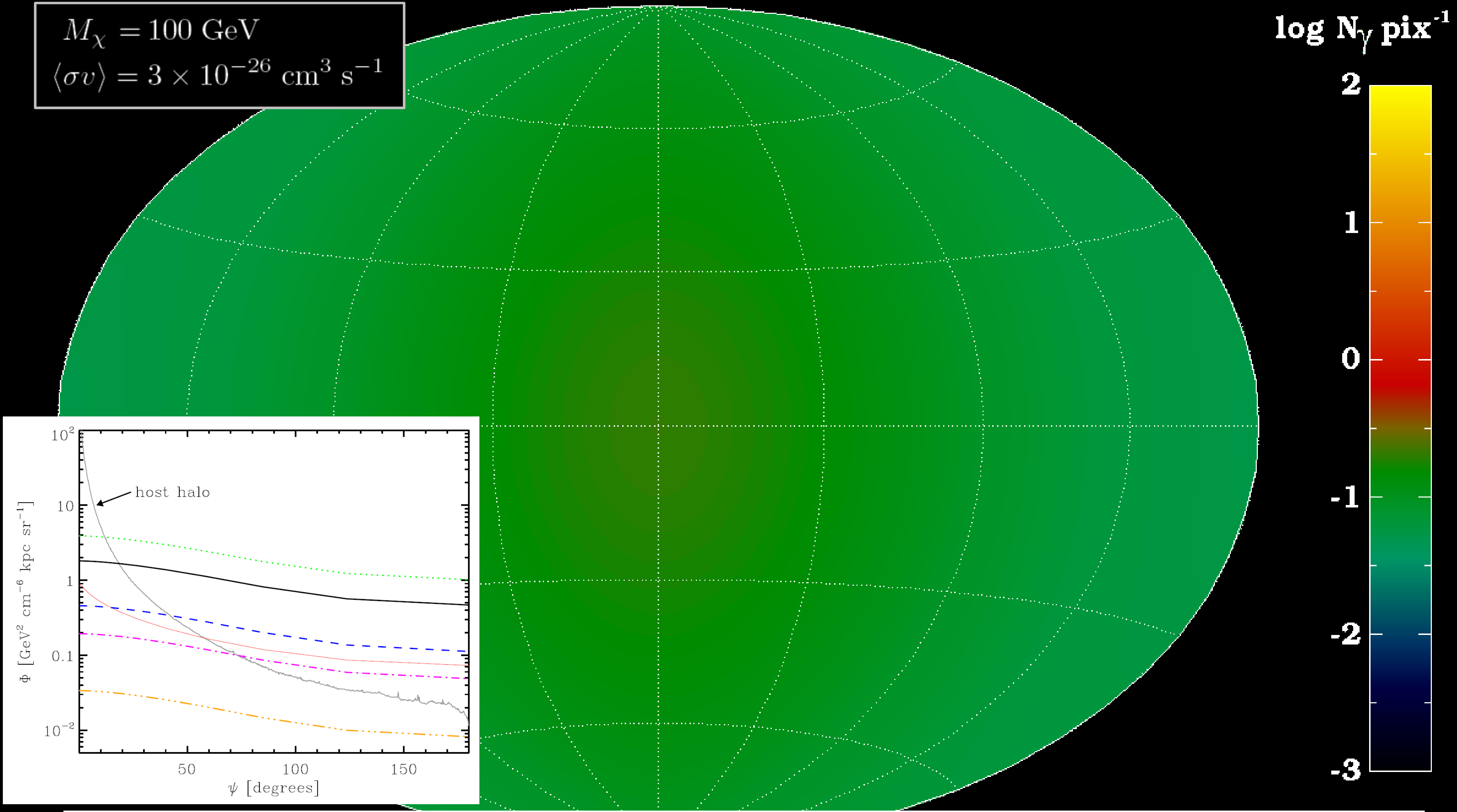


Backgrounds: Smooth Host Halo DM Annihilation



Backgrounds: Unresolved Subhalos DM Annihilation

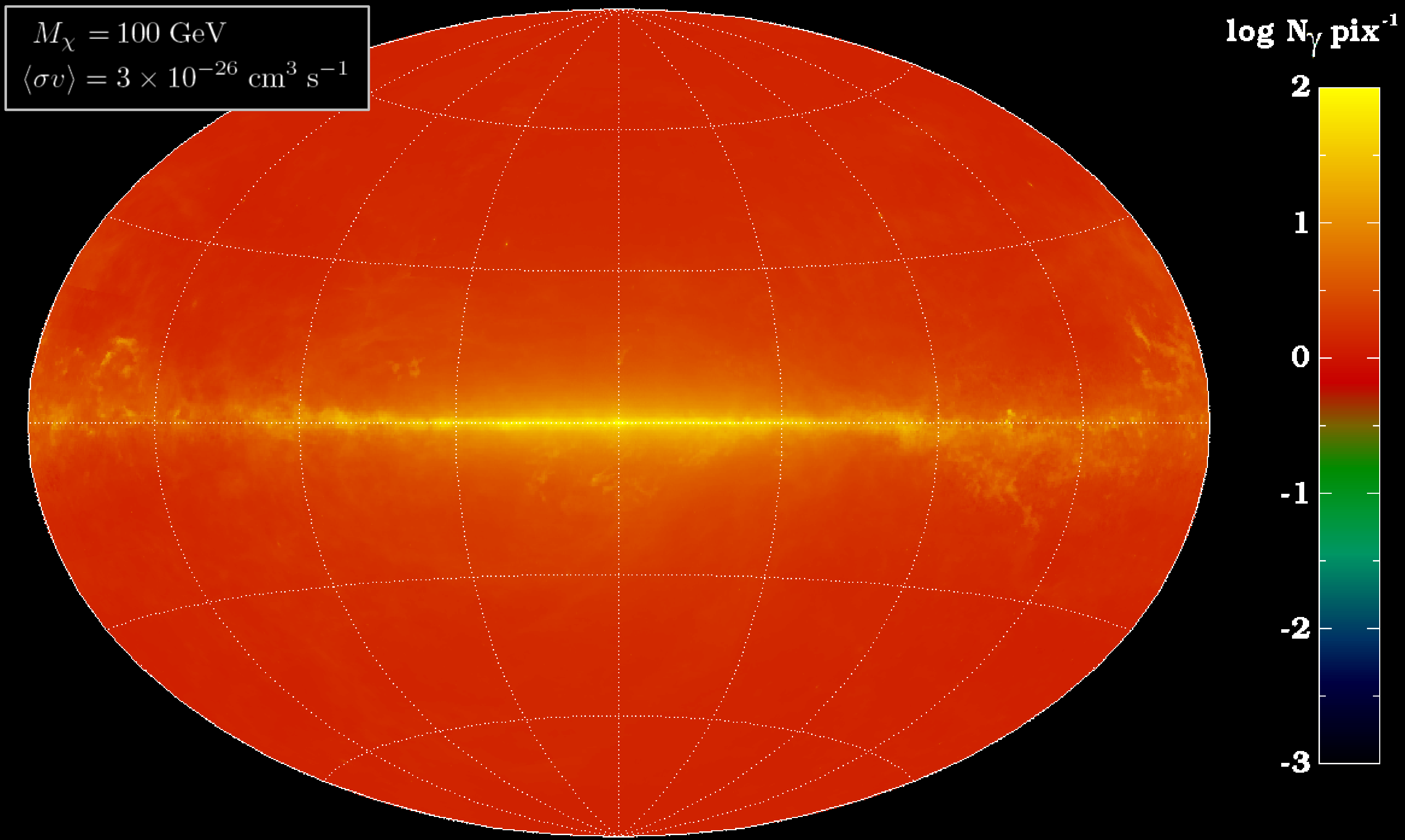
$M_\chi = 100$ GeV
$\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^3 s^{-1}



$$\mathcal{F}(\psi, \Delta\Omega) = \int_{\Delta\Omega} d\cos\theta \, d\phi \int_M dM \int_{\text{l.o.s.}} d\lambda \, \lambda^2 \int_c dc \, P(c; M, R) \, \mathcal{F}_{\text{halo}}(M, c, \lambda, \Delta\Omega) \, \frac{dn_{\text{sub}}}{dM}(M, R),$$

Pieri et al. (2008), Kuhlen et al. (2008)

The Total Signal



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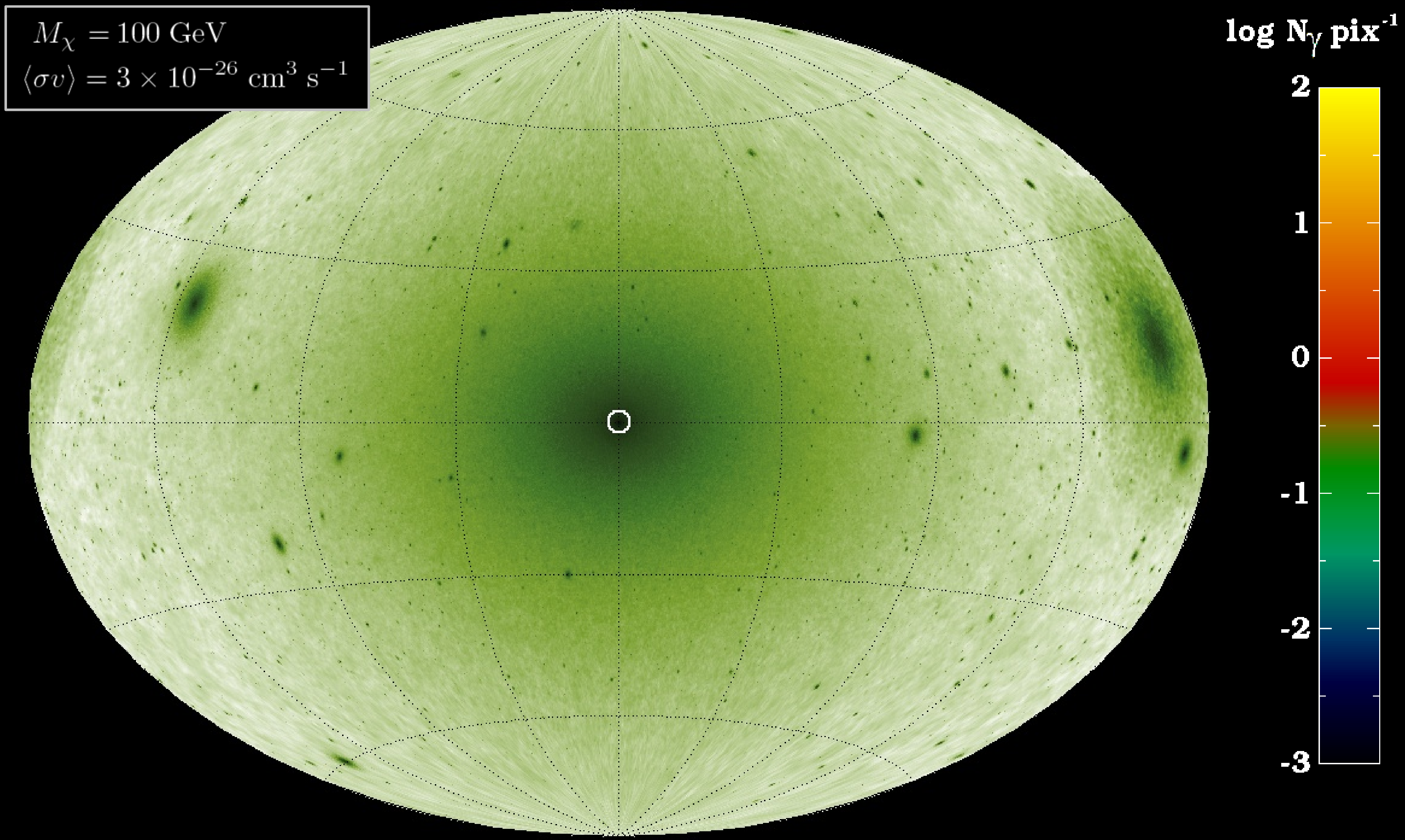

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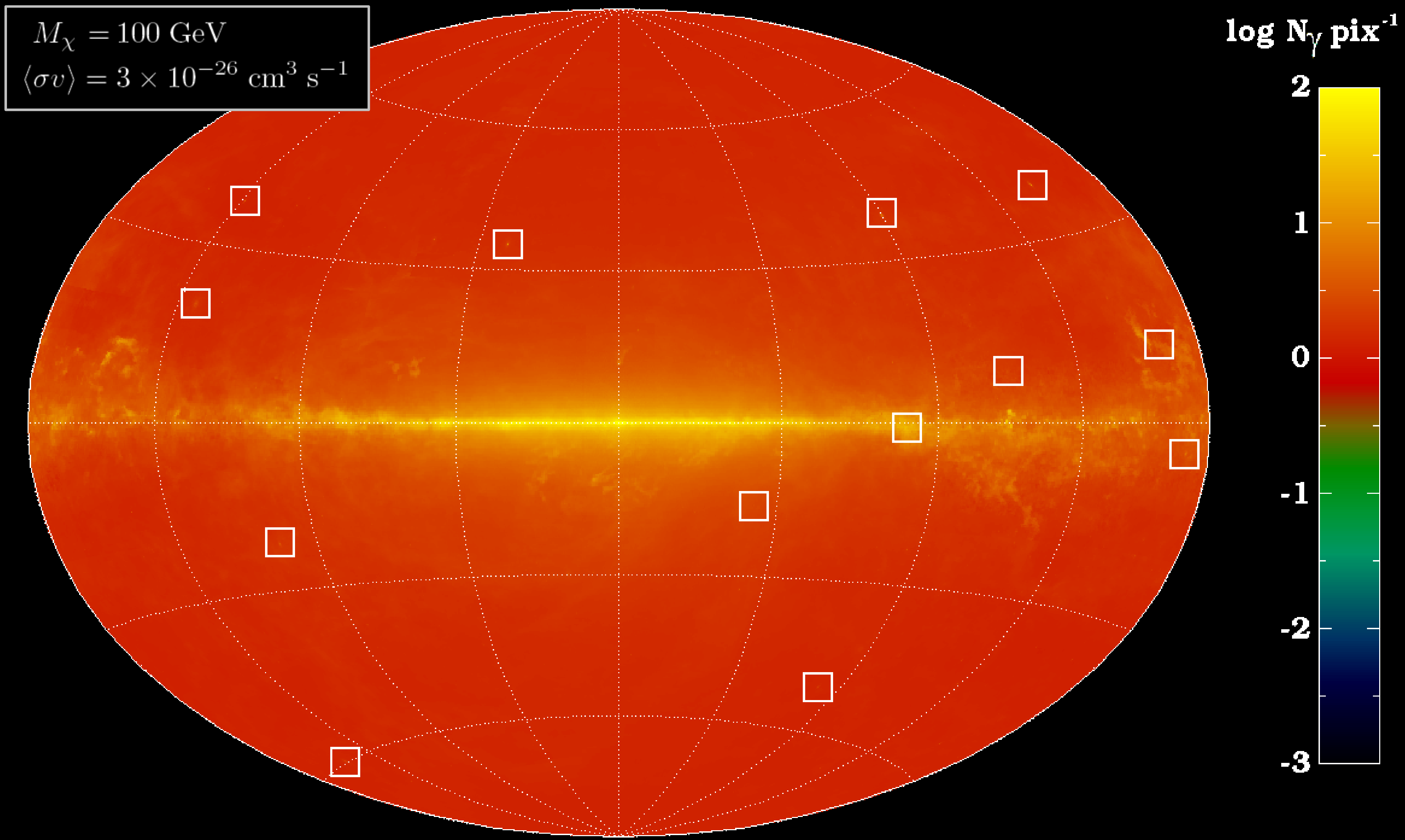

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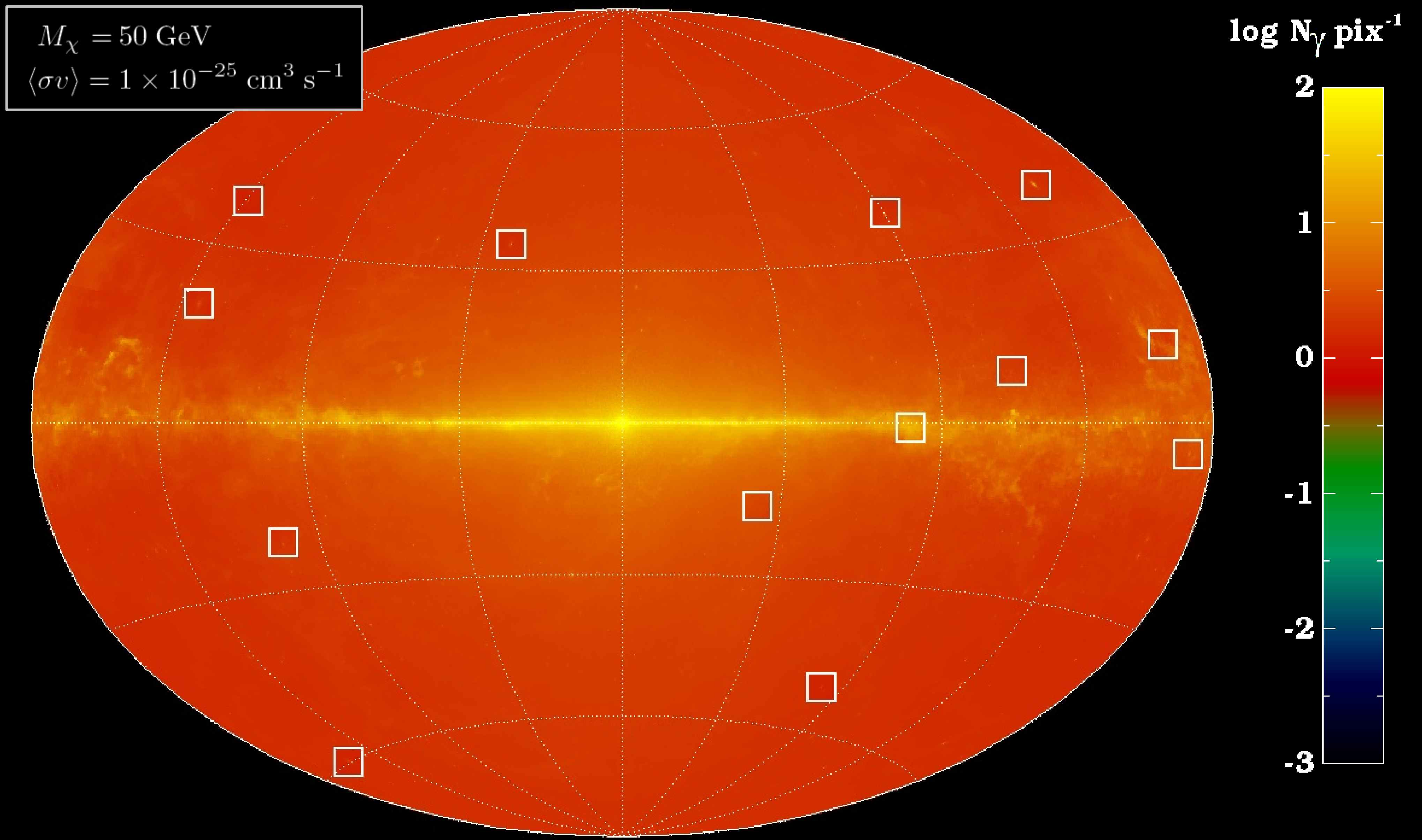
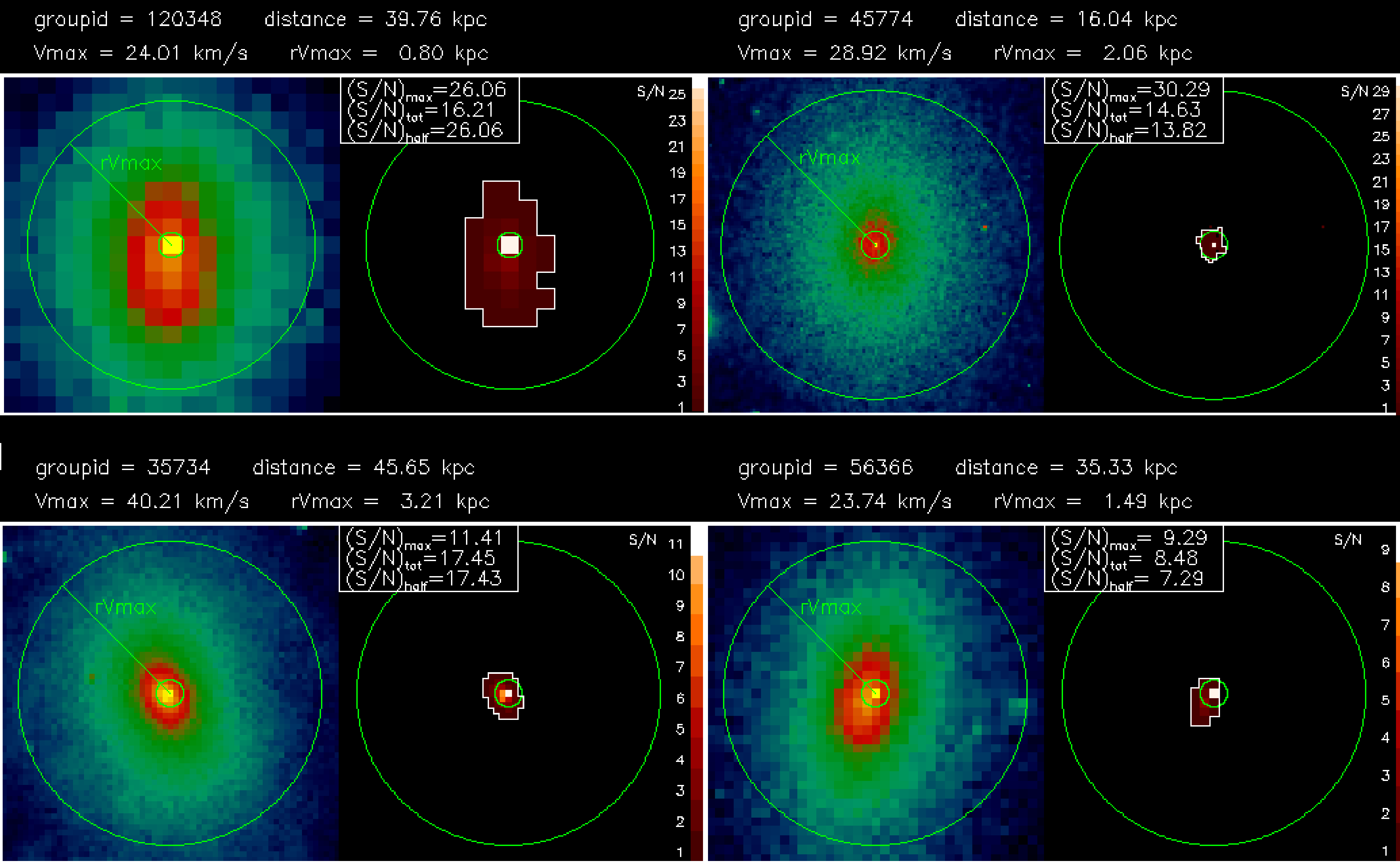


The Subhalo Signal



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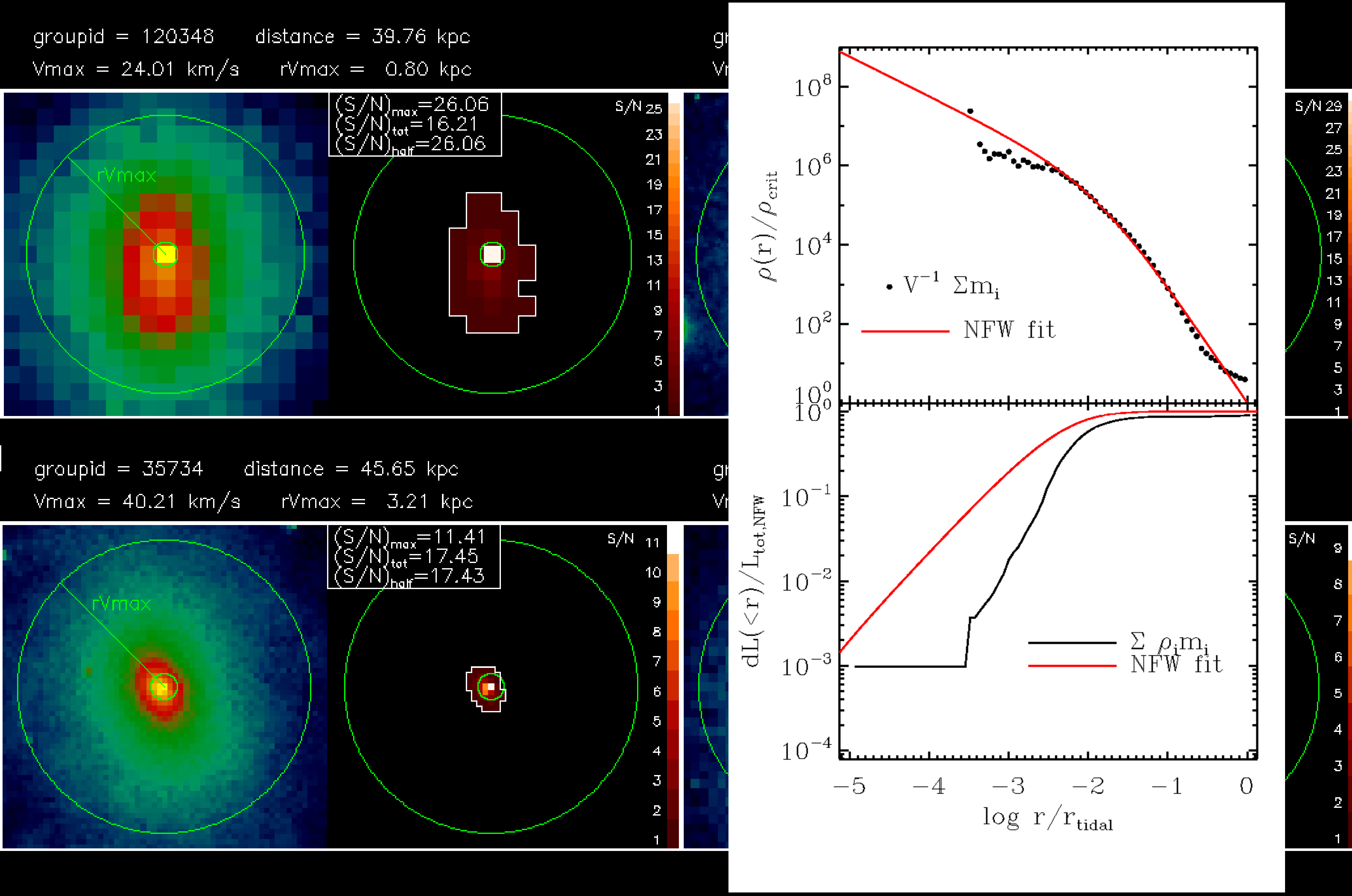
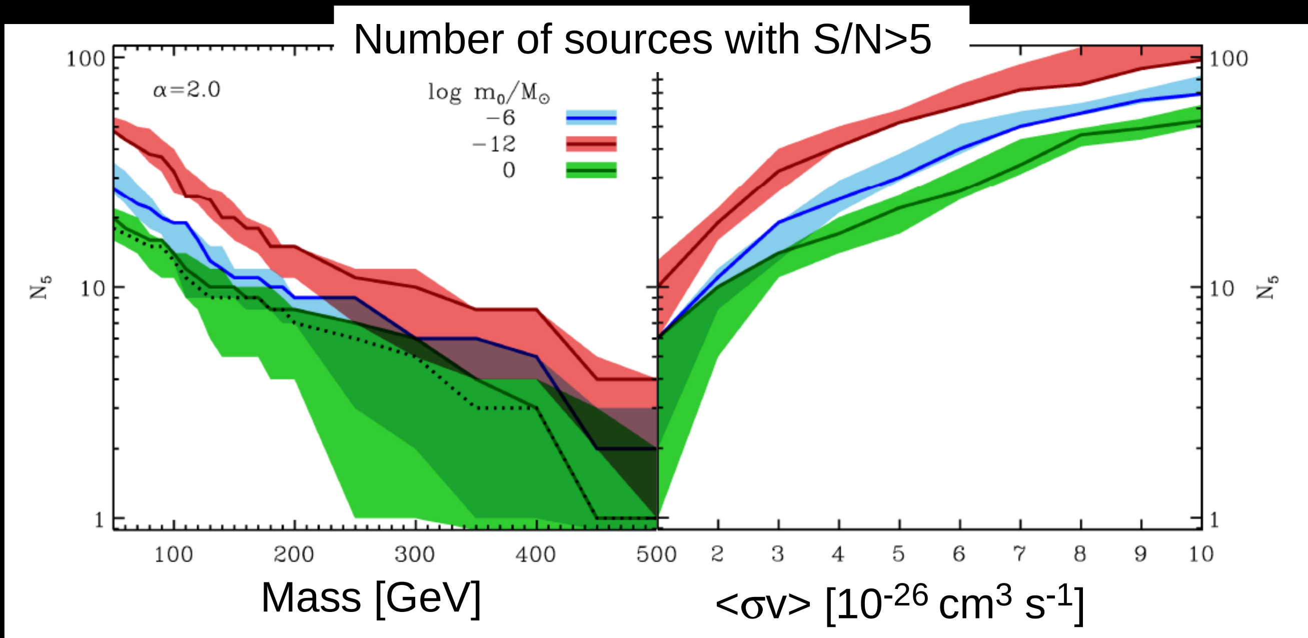
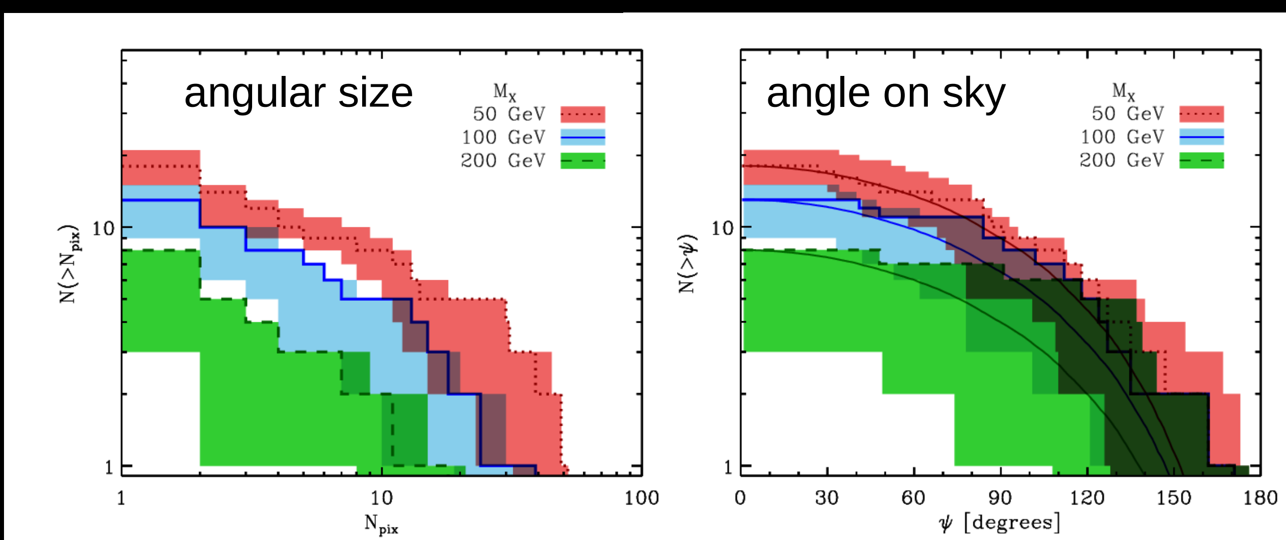
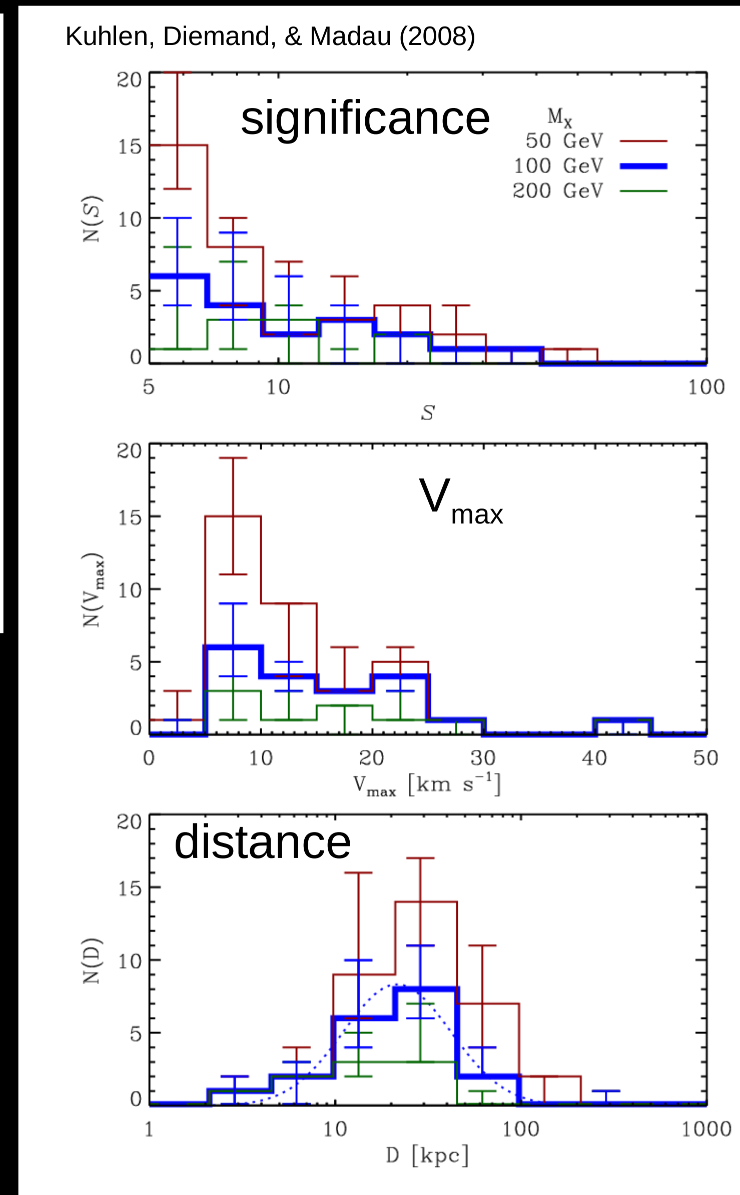


Predictions for the Gamma Ray Large Area Space Telescope







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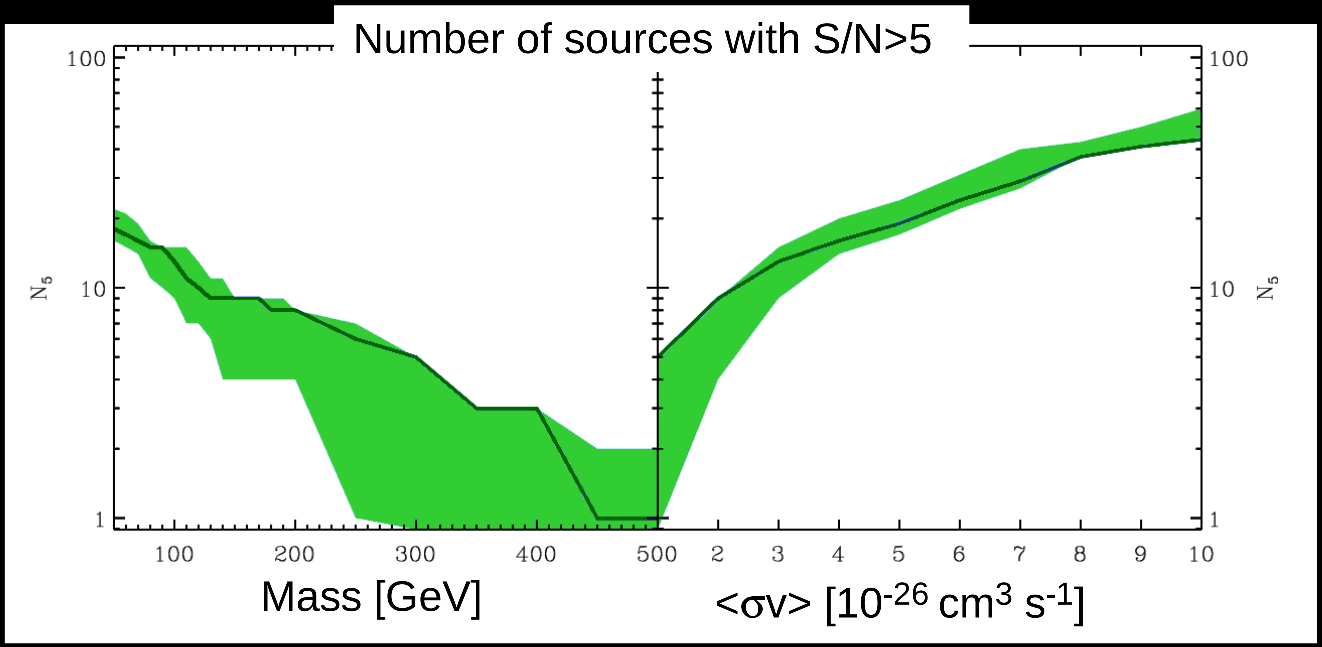
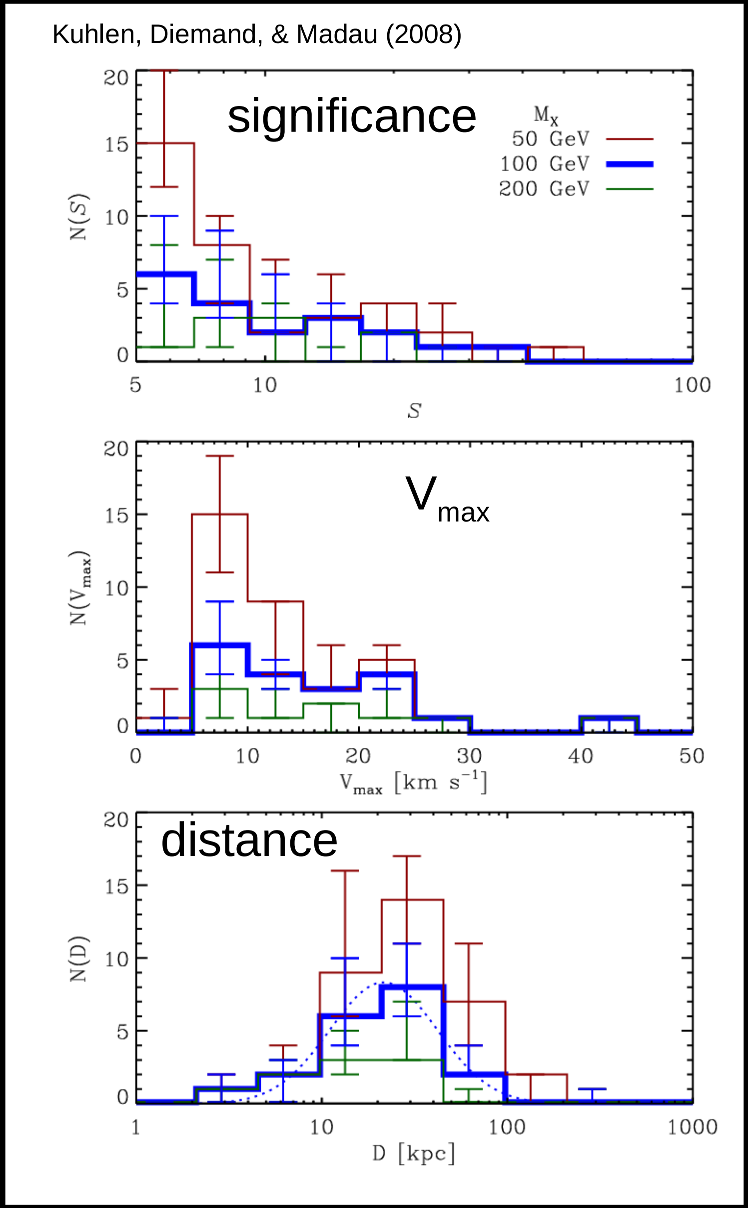
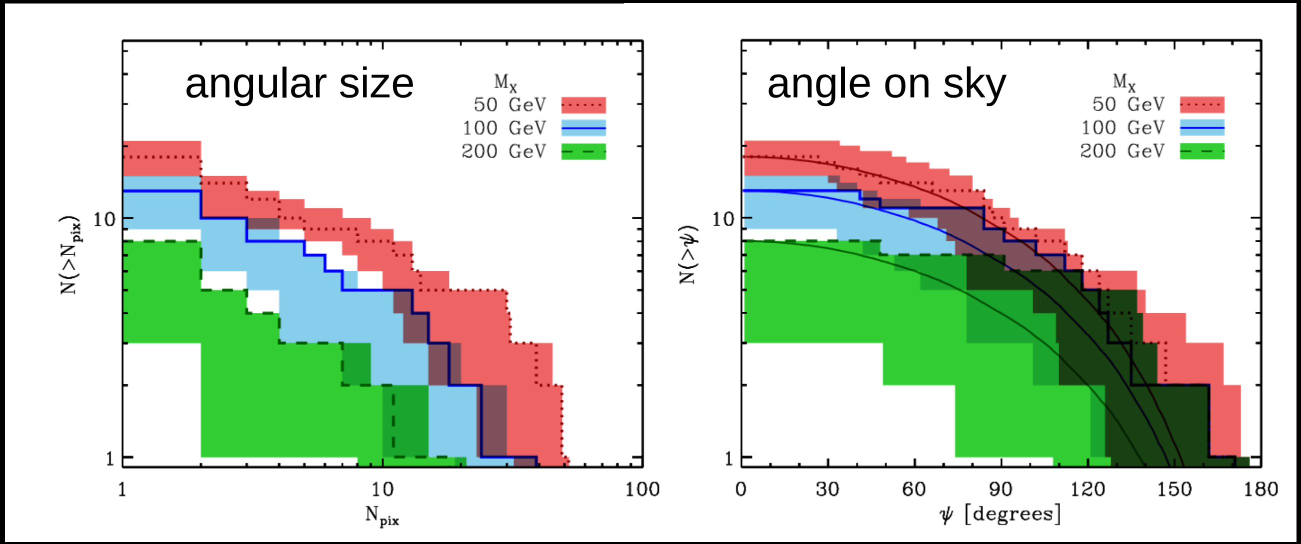
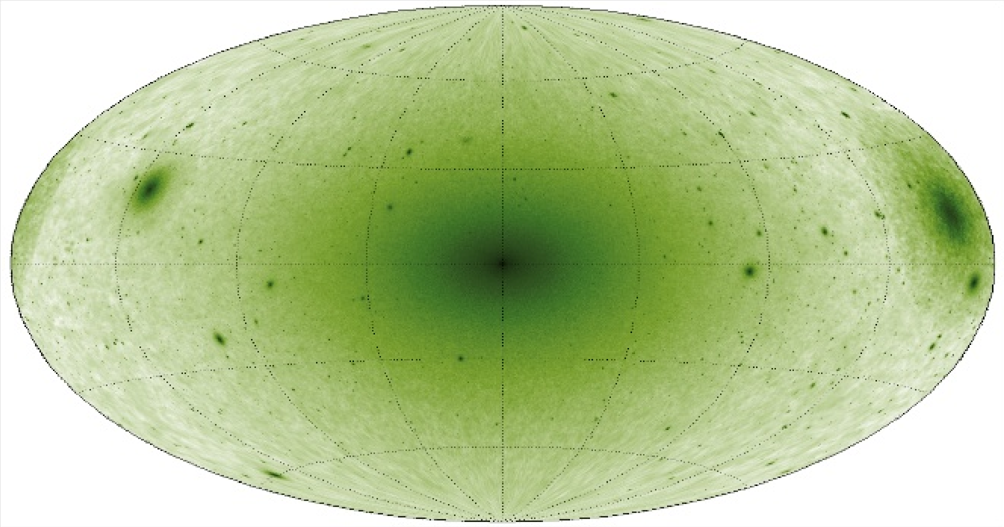


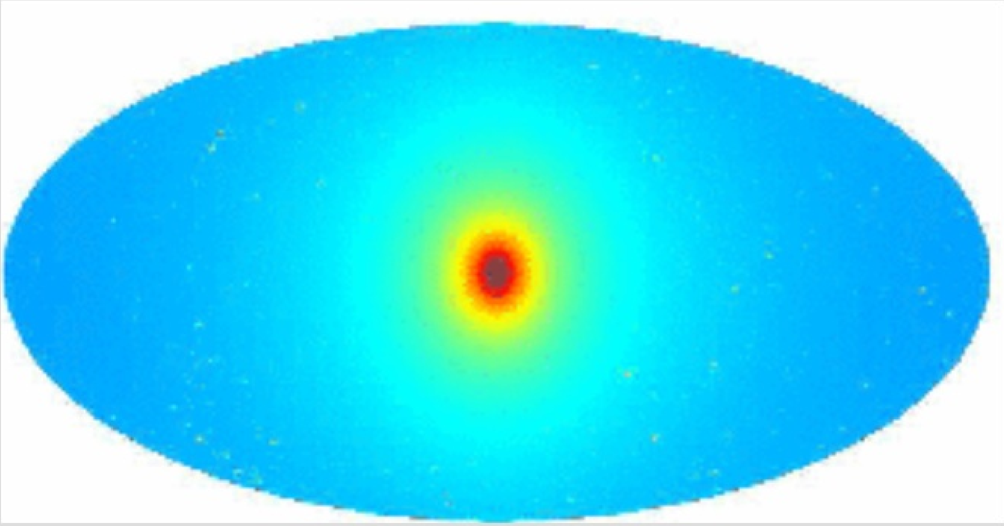




Substructure in the dark halo

- annihilation radiation from WIMP dark matter may be observable by GLAST/Fermi





Kuhlen et al. (2008) Kuhlen

- strongest signal from the sub-halos
- detectable sub-halos resolved by Fermi
- most prominent sub-halo typically has d ~ 20-40 kpc and M ~ 10^7-10^9 $M_\odot$

Springel et al. (2008) Frenk

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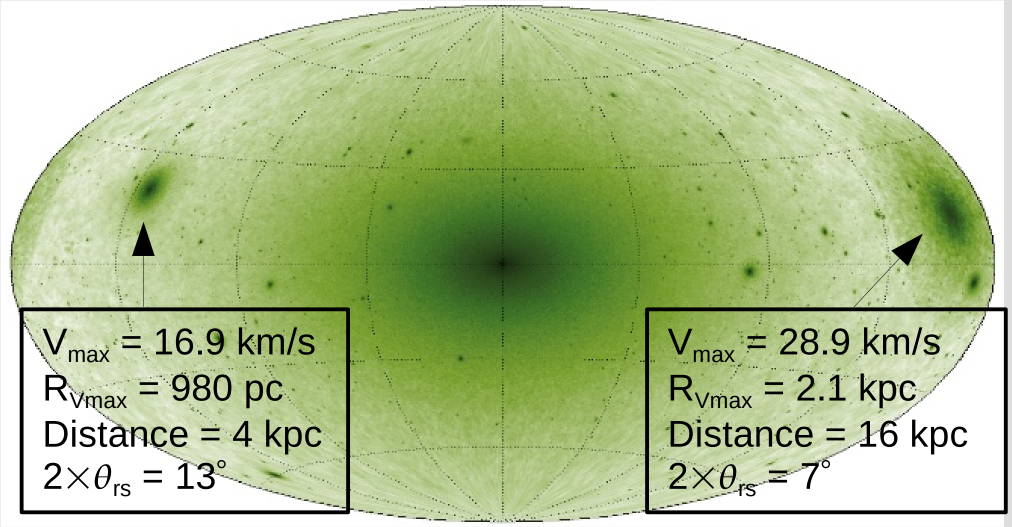

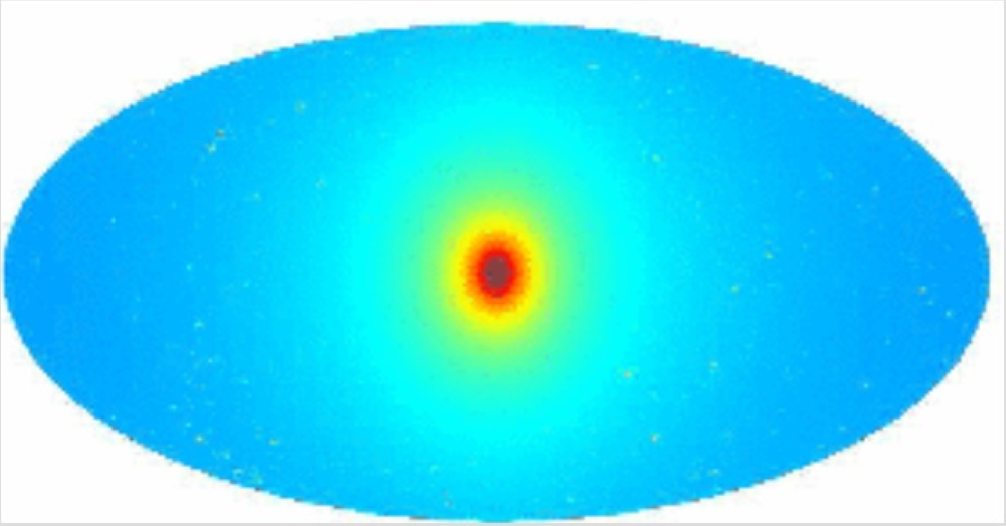

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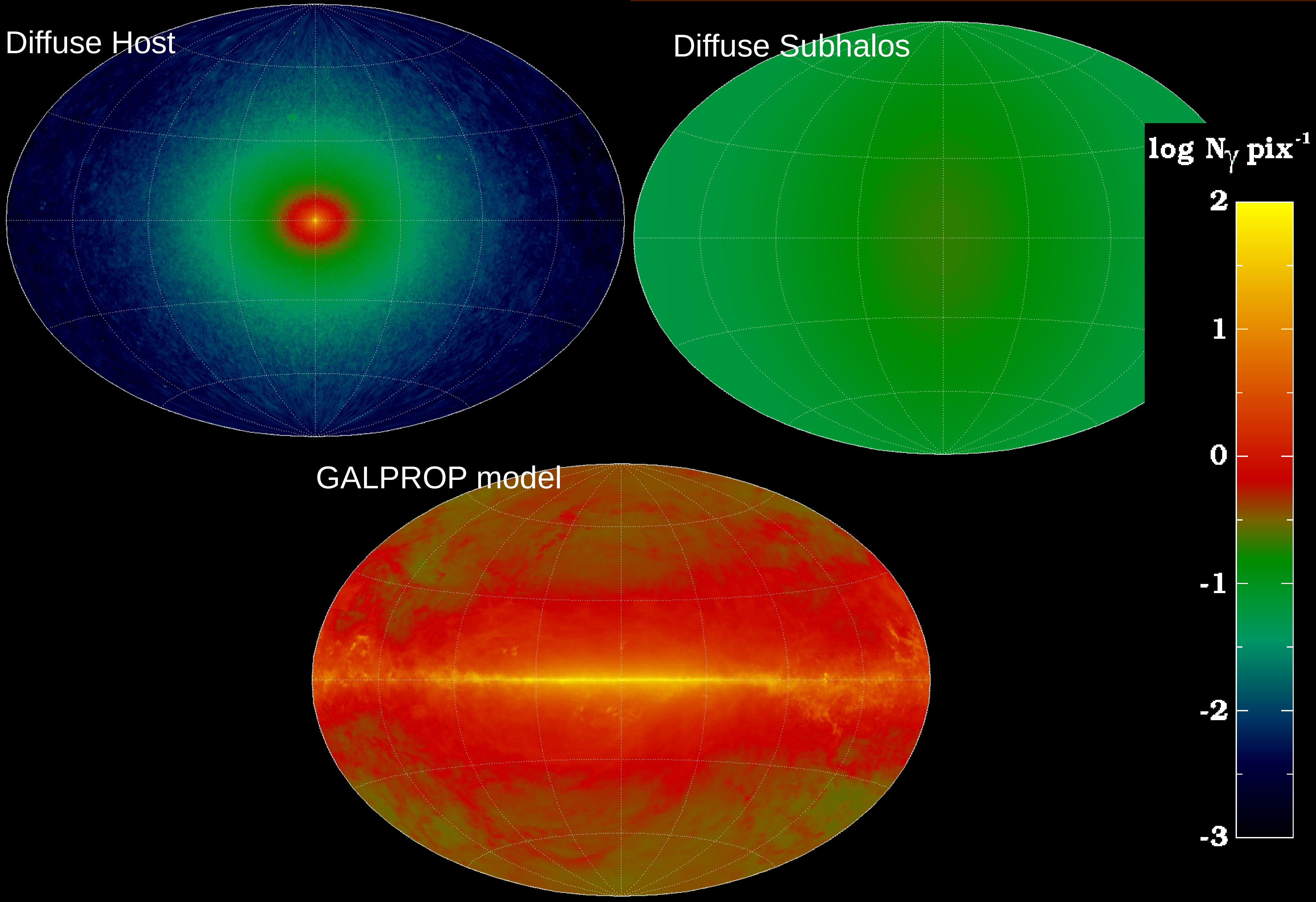
Diffuse host signal vs. individual subhalos?



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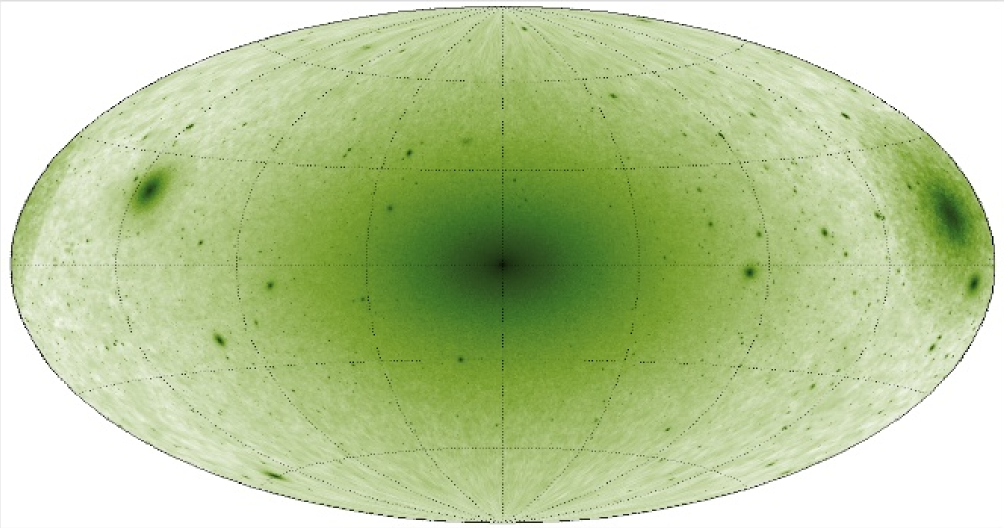

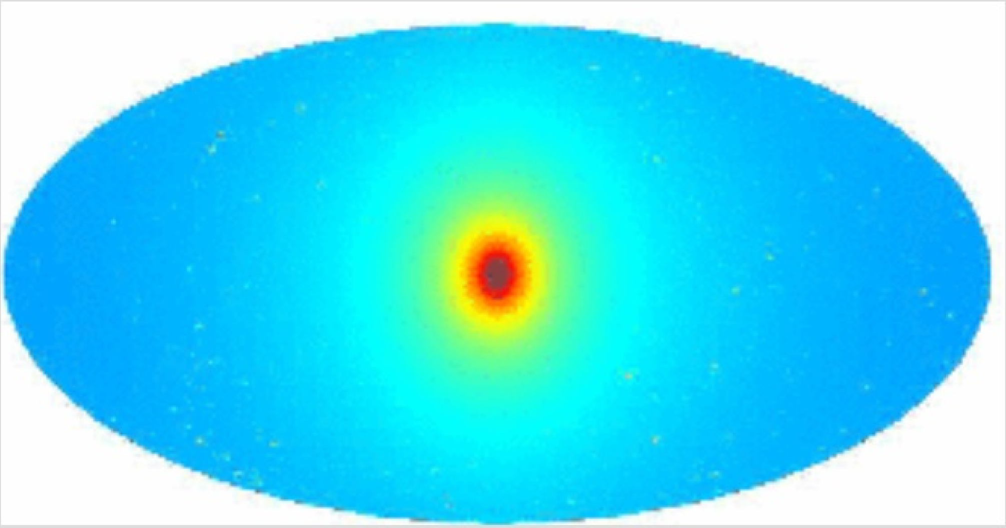

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Indirect Detection: Conclusions

- Indirect detection is a promising way to **test a central prediction of ΛCDM**: abundant small scale structure.
- The observability of such a **signal is very uncertain** and depends on the nature, mass, and cross section of the dark matter particle.
- For reasonable values of the DM particle physics parameters (M_χ=50-500 GeV, $\langle \sigma v \rangle = 1\text{-}10 \times 10^{-26}$ cm^3 s^{-1}) **GLAST/Fermi may detect a handful of subhalos**.
- Detectable subhalos have V_{max} ranging from >~20 km/s down to ~5 km/s.
- Most **detectable subhalos would be resolved**, are more likely to be found away from the Galactic center, and have **typical distances of 20-30 kpc**.