Particle Velocity Effects in the Anisotropy of Extragalactic Diffuse Gamma-rays from Dark Matter Annihilation

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Continuation of work done with

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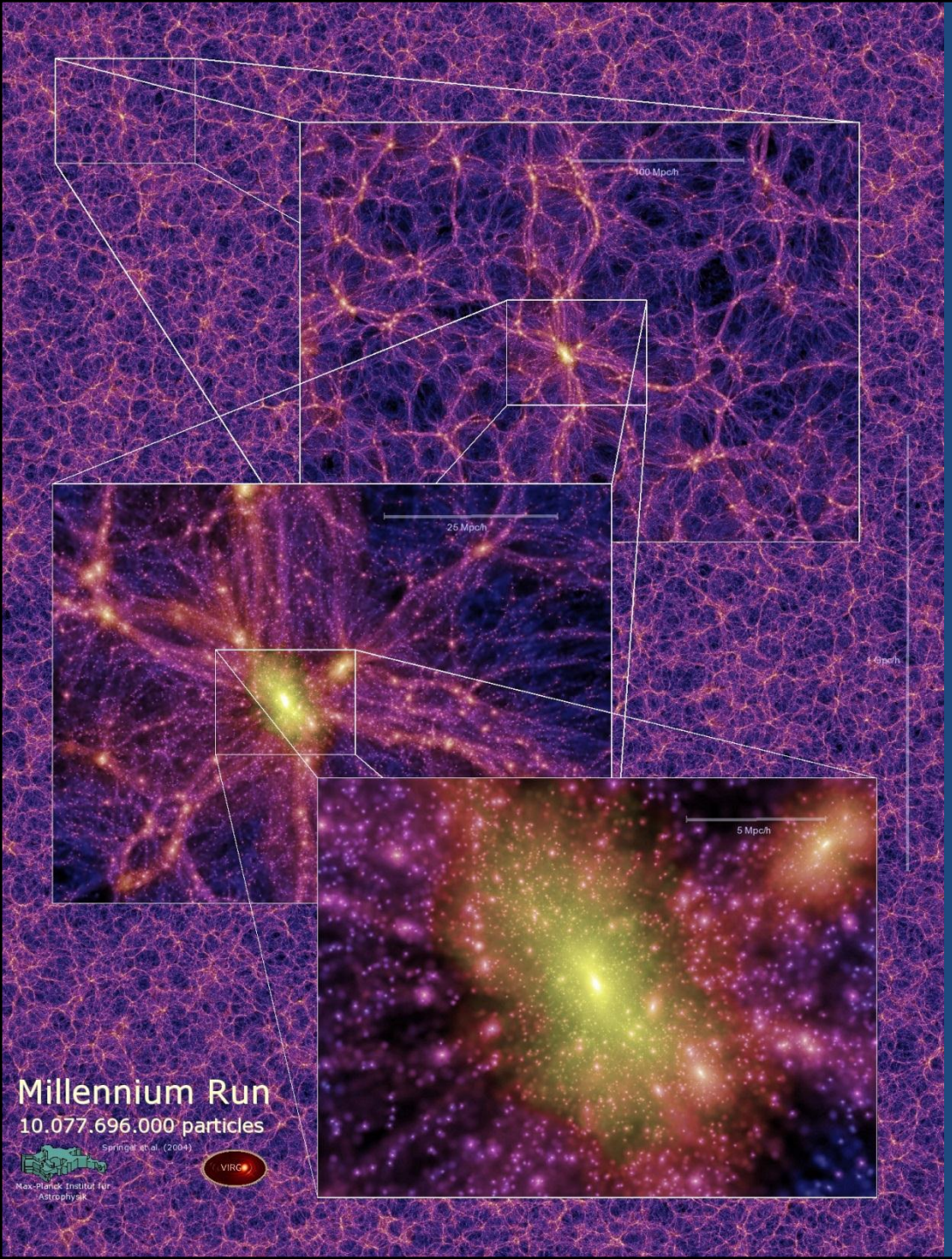
In this talk…

I will present brand new results on the p-wave annihilation's effect on extragalactic dark matter signals.

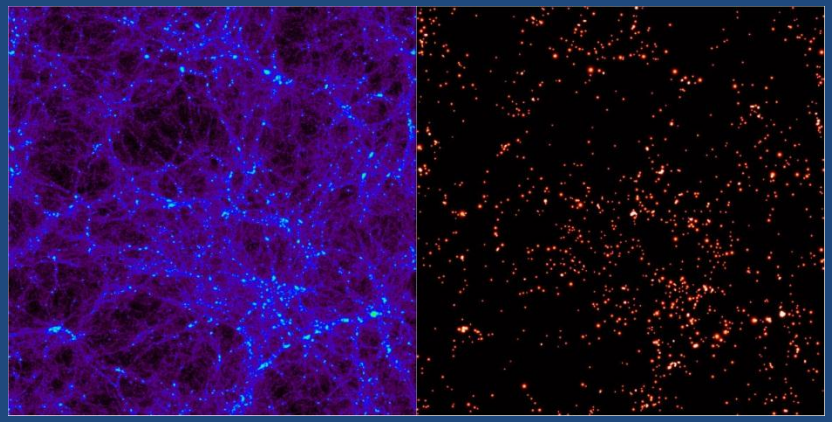
1. Statistical description of large scale structure.
2. Review the p-wave effects on the mean intensity spectrum of the annihilation gamma-rays.
3. Present p-wave effects on the angular power spectrum of the signal.



Distribution of Dark Matter

- Detailed information from simulations.
- Dark Matter collapses into halos.
- The dominant contribution to annihilation is from the densest core regions of halos.
- For annihilation signals, we can model dark matter as an ensemble of halos.
- These simulations indicate that halos have universal properties:
  - spherically-averaged density profiles,
  - velocity variance profiles.

The Spherical Halo Model



Simulations show the densest regions of dark matter are well described by an ensemble of disjoint, spherical halos with universal profiles.

Same mean density and power spectrum!

The Point Distribution of Halos

1) Mass Function $\frac{\mathrm{d}n}{\mathrm{d}M}(M,z)$

(Sheth, Tormen 1999)

Determines number density of mass M halos.

2) Halo Bias $b(M,z)$

(Sheth, Mo, Tormen 2001)

Relates the halo power spectrum to matter power spectrum.

$$P_h(k,M,z,M',z') = b(M,z)b(M',z')P_\rho(k,z,z')$$

Universal Halo Profiles

1) Density Profile $\rho_h(r|M,z)$

(Navarro, Frenk, White 2001)

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

2) Velocity Variance Profile $\sigma_{vh}^2(r|M,z)$

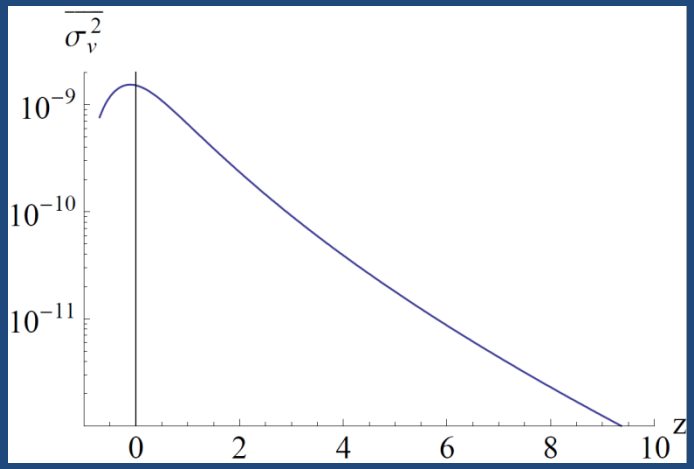
Related to density profile via pseudo-phase-density: $\rho_h(r)/\sigma_{vh}^3(r) \propto r^{-35/18}$.

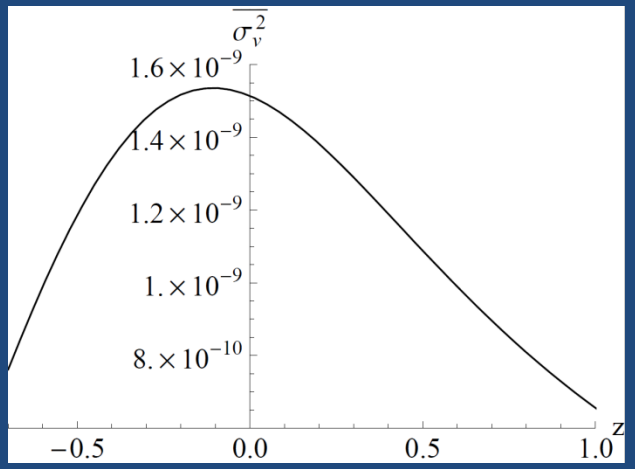
(Dehnen, McLaughlin 2005)

$$\sigma_{vh}^2(r) = \frac{\sigma_s^2\left(\frac{r}{r_s}\right)^{17/27}}{\left(1+\frac{r}{r_s}\right)^{4/3}}$$

Cosmic Mean Velocity Variance

$$\overline{\sigma_v^2}(\mathrm{z}) = \int \mathrm{d}^3\boldsymbol{r}\,\mathrm{d}M\,\frac{\mathrm{d}n}{\mathrm{d}M}(M,z)\sigma_{vh}^2(r|M,z)$$





Particle motions are virial (not thermal), within self-gravitating systems.

Relative Velocity Distribution

For locally thermal velocity distributions (Maxwell-Boltzmann distribution), the mean relative velocity v is: $v^2 = 6\,\sigma_v^2$.

Generalize with postulate $v^2 = \lambda\sigma_v^2$ for constant λ.

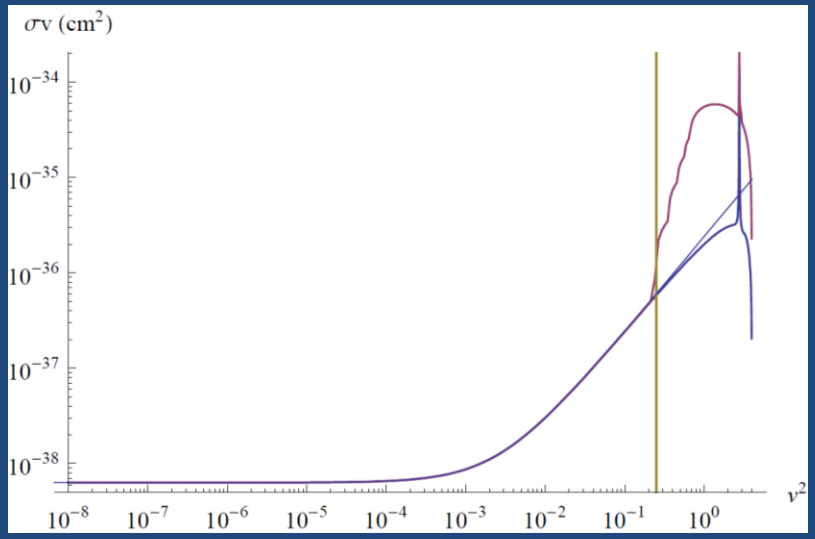
Calculating γ-ray intensity: What does particle physics contribute?

1. Annihilation Cross Section $\sigma(v)$
   - Function of relative velocity v.
   - Determines rate of annihilation per volume in a gas with number density n.

$$\Gamma = \frac{1}{2} n^2 [\sigma v](v)$$

2. Particle Mass M_{DM}
   - Converts density to needed number density.
   - Normalizes the energy of annihilation products.
3. Photon Spectrum per Annihilation $\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}(E_\gamma)$
   - Function of photon energy E_γ.
   - Include radiative emission by charged products and decays of unstable products.

Annihilation Cross Section with p-wave



150 GeV neutralino dark matter with stau co-annihilations in CMSSM with $\tan\beta = 10$, has $b/a = 380$.

$$\sigma v = a + bv^2$$

At a position $\boldsymbol{r}$, integrate $\sigma v(v)$ over the local velocity distribution to find the mean $[\sigma v](\boldsymbol{r})$.

Use halo velocity profile to find universal halo annihilation cross section profile $[\sigma v]_h(r|M,z)$.

$$[\sigma v]_h(r) = a + b\lambda\sigma_{vh}^2(r)$$

Thermal Relic Density

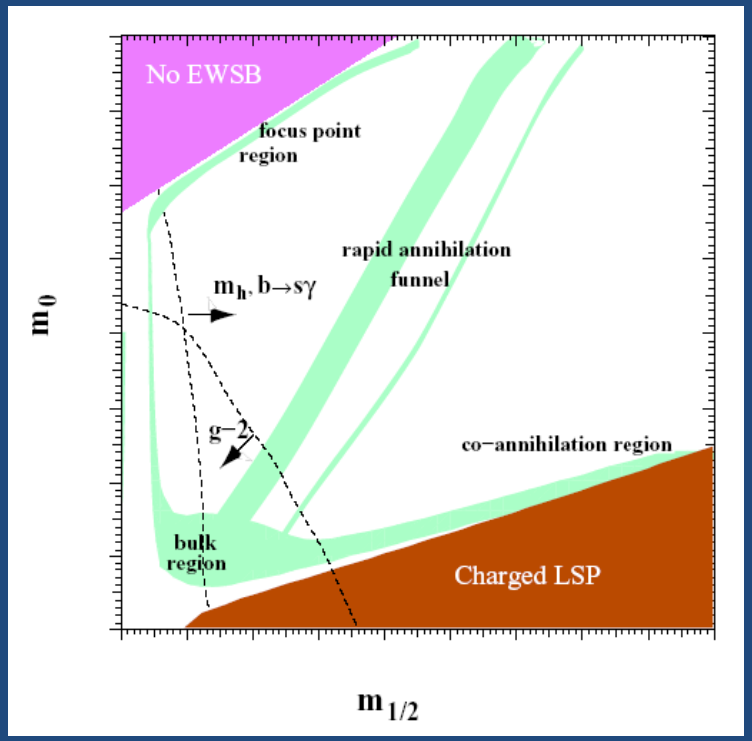
- At freezeout, this constraint requires $\sigma v \approx 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s} = 10^{-36}\mathrm{cm}^2$.
- High b/a lowers the cross section at small v: p-wave suppression.

Non-thermal Relic Density

A reheating after thermal freezeout would wash out the thermal relic. For the new relic to have the right density, the low-velocity cross section is scaled by a factor of $\frac{T_f}{T_r} = \frac{v_f^2}{v_r^2}$.

(Dutta, Leblond, Sinha 2009)

I'll present results for 5 different models for comparison.



CMSSM neutralino dark matter with $\tan\beta = 10$:

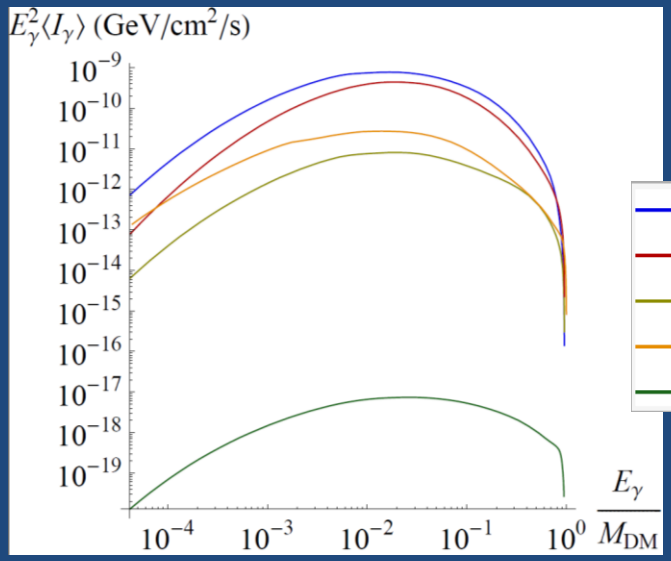
1) 150 GeV in focus point region……b/a=1.9.
2) 62.3 GeV in bulk region……..b/a=57.5.
3) 150 GeV in co-annihilation region…..b/a=378.8.

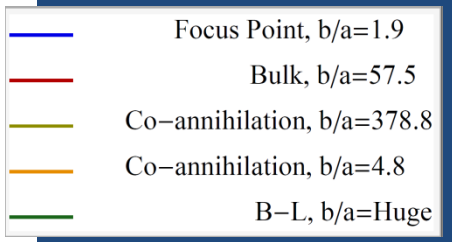
CMSSM with $\tan\beta = 50$:

4) 550 GeV in co-annihilation region…..b/a=4.8.

5) MSSM$\otimes U(1)_{B-L}$ with 550 GeV sneutrino dark matter annihilating via Z'…… b/a$\gtrsim 10^8$.

Mean Intensity of Extragalactic Annihilation Photons



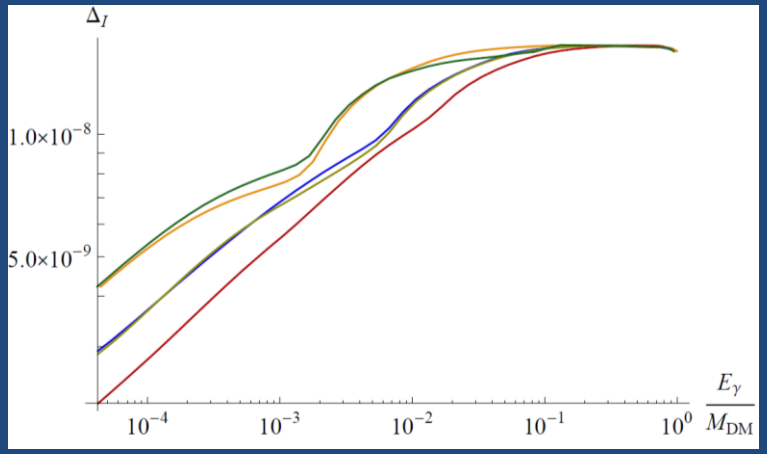


$$\langle I_\gamma\rangle(E_\gamma) = \int \frac{\mathrm{d}z}{H(z)}\, W\Big((1+z)E_\gamma, z\Big)\langle\rho^2[\sigma v]\rangle(z)$$

Window Function:

$$W = \frac{1}{8\pi(1+z)^3 M_{\rm DM}^2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}e^{-\tau}$$

τ is gamma-ray opacity.
(Stecker, Malkan, Scully 2006)



The p-wave effect on spectral shape determined by Δ_I:

$$\frac{\langle I_\gamma(E_\gamma|\sigma v = a + bv^2)\rangle}{\langle I_\gamma(E_\gamma|\sigma v = a)\rangle} = 1 + \lambda\frac{b}{a}\Delta_I(E_\gamma)$$

$$\Delta_I(E_\gamma) \equiv \frac{\int \frac{\mathrm{d}z}{H(z)}\, W\Big((1+z)E_\gamma, z\Big)\langle\rho^2\sigma_v^2\rangle(z)}{\int \frac{\mathrm{d}z}{H(z)}\, W\Big((1+z)E_\gamma, z\Big)\langle\rho^2\rangle(z)}$$

Angular Power Spectrum

To calculate, we derive from the model:

$$C_\ell(E_\gamma) = \int \frac{\mathrm{d}z}{H(z)} \left[\frac{W\left((1+z)E_\gamma, z\right)}{\langle I_\gamma \rangle (E_\gamma)} \right]^2 \frac{k^2}{\ell^2} \bar{P}_{\rho^2 \sigma v}(k, z) \Bigg|_{k=\frac{\ell}{r(z)}}$$

where

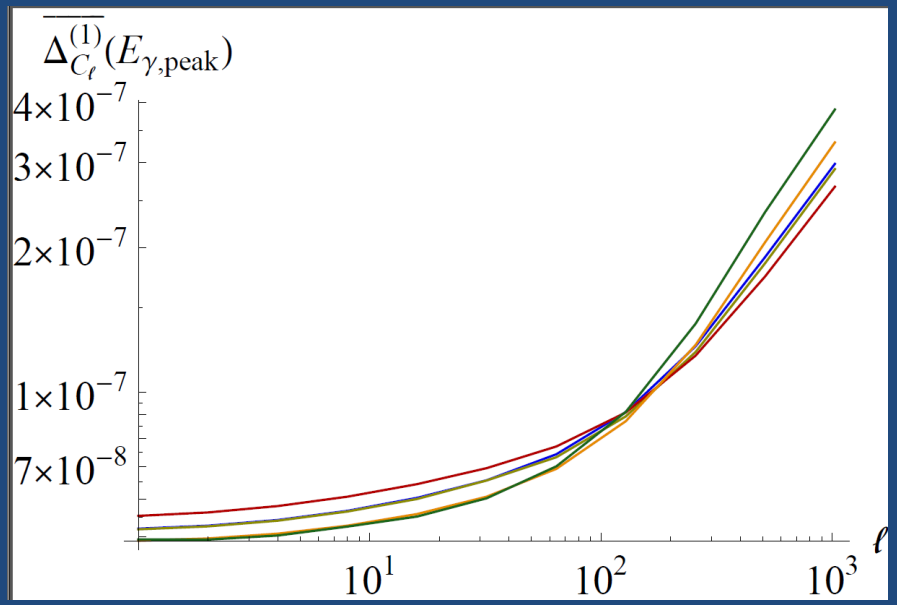
$$\bar{P}_{\rho^2 \sigma v}(k, z) = \int \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M}(M, z)\, \mathcal{FT}\{[\rho^2 \sigma v]_h\}^2\, (k|M, z) +$$

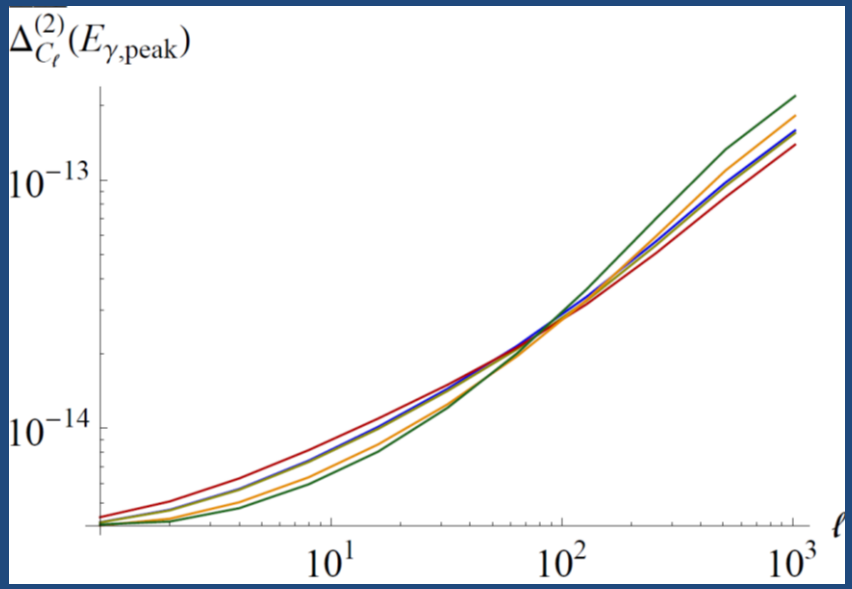
$$\left[\int \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M}(M, z)\, b(M, z)\, \mathcal{FT}\{[\rho^2 \sigma v]_h\}(k|M, z) \right]^2 P_{\mathrm{lin}}(\mathrm{k}, \mathrm{z}).$$

Adding p-wave to σv adds new terms to C_ℓ

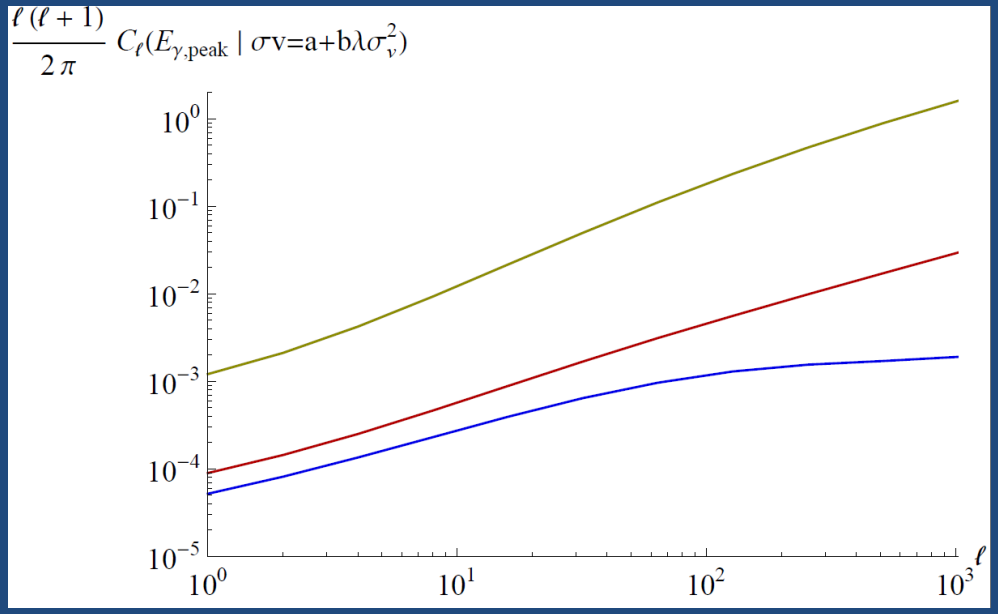
$$\frac{C_\ell(E_\gamma|\sigma v = a + bv^2)}{C_\ell(E_\gamma|\sigma v = a)} = 1 + \frac{\frac{\lambda b}{a}\overline{\Delta^{(1)}_{C_\ell}}(E_\gamma) + \frac{\lambda^2 b^2}{a^2}\overline{\Delta^{(2)}_{C_\ell}}(E_\gamma)}{\left[1 + \frac{\lambda b}{a}\Delta_I(E_\gamma)\right]^2}$$

As with Δ_I, the Δ_{C_ℓ}'s variations between different particle models are due to different annihilation spectra, or different energies interacting with the opacity.





C_ℓ using the focus point model spectrum and mass.



All five models give similar results.

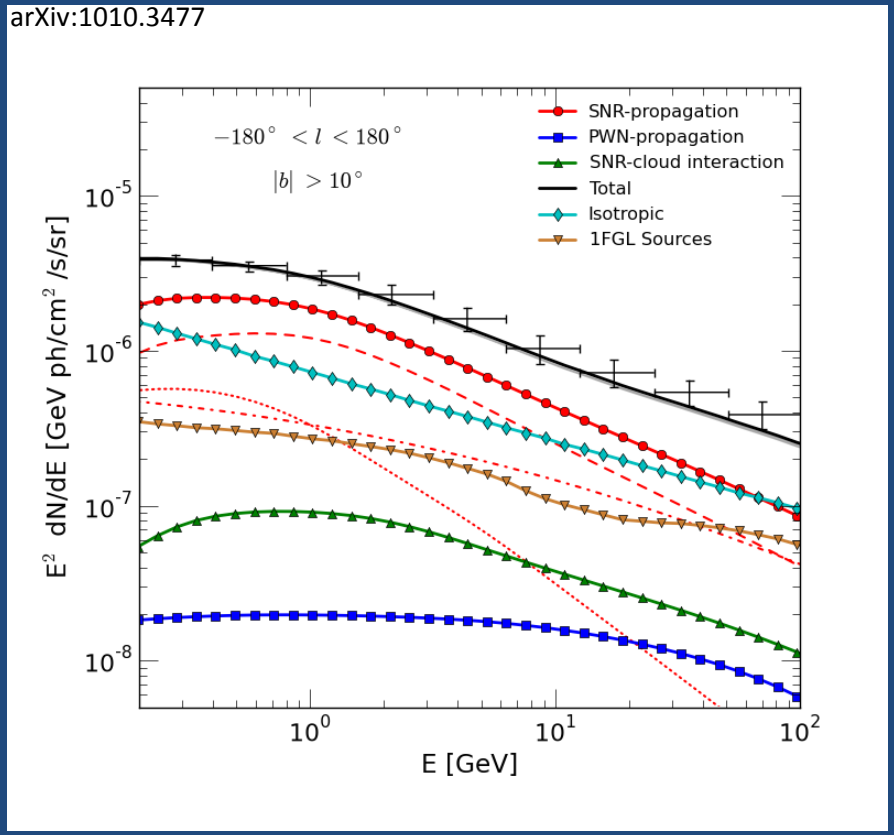
Significant p-wave effects in C_ℓ require $\lambda b/a \gtrsim 10^7$. But a p-wave this strong renders the signal unobservable due to p-wave suppression, even for non-thermal relics.

Summary

1) We have succeeded in modeling the relative velocity distribution of cosmic dark matter to determine its possible effects in an extragalactic annihilation signal.
2) Effects due to p-wave annihilation are only important for $b/a \gtrsim 10^6$ in both the mean intensity and angular power spectrum.
3) The p-wave suppression effect may make this scenario unobservable, even if there are non-thermal relic enhancements.
4) These methods can now be applied to effects that are likely to be observable, such as annihilation resonances, or Sommerfeld enhanced annihilation.

The Gamma-Ray Spectrum from Fermi

arXiv:1010.3477



Here, the observed gamma-ray sky is well described by models of emissions by supernova remnants (SNRs) and pulsar wine nebulae (PWNs).

Included are the catalog of point sources (1FGL).

Diffuse extragalactic gamma-rays contribute to the isotropic component.

This model makes a prediction for the gamma-ray anisotropy.

These sources also have consequences for the cosmic ray observations.