McGill

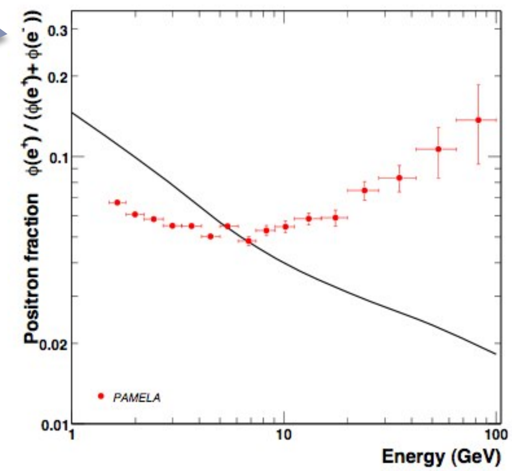
Based on work with Wei Xue and Jim Cline
arXiv:1001.5399
arXiv:1009.5383

Cosmic Ray Anomalies, Gamma Ray Constraints and Subhalos in Models of Dark Matter Annihilation

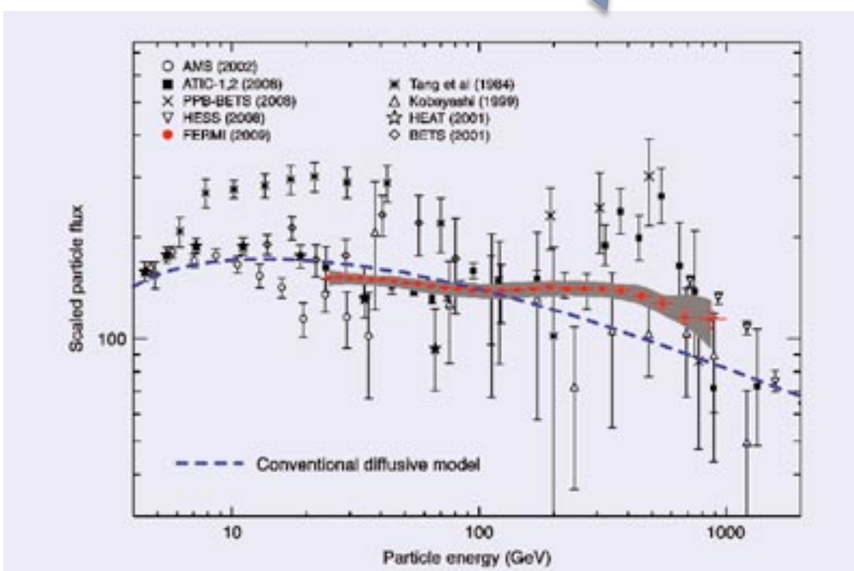
Aaron C. Vincent
McGill University

Motivation

- Cosmic ray “anomalies”:
  - PAMELA positron fraction



  - ~~ATIC~~ Fermi electron + positron data

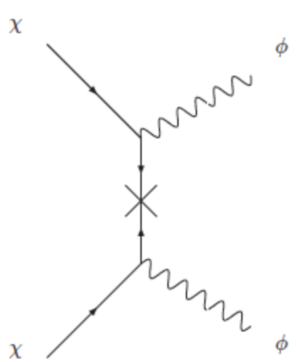


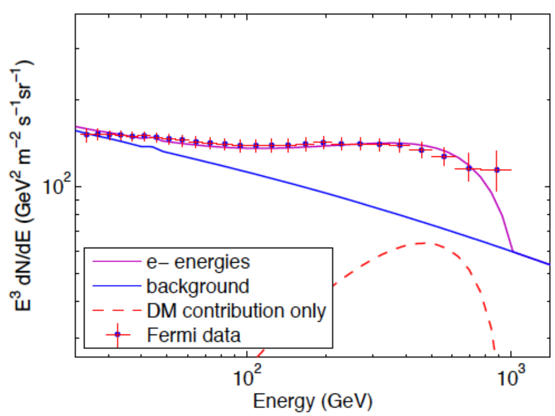
Dark matter annihilation

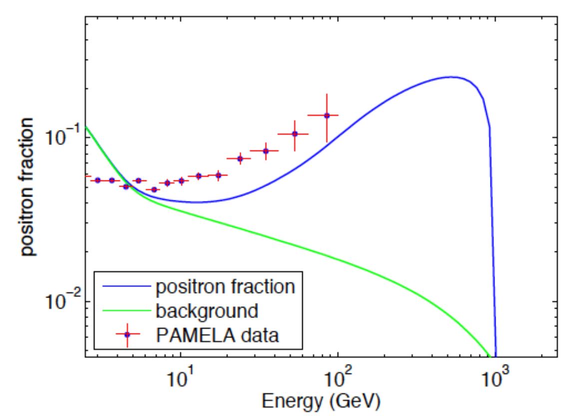
- These phenomena have no known astrophysical origin (could be pulsars?)
- Most promising scenario: a M = 1 TeV WIMP, annihilating to electrons and positrons via some intermediate gauge boson ϕ lighter than $2m_{proton}$ (Investigated by many authors). Requires some boost factor BF:

$$<\sigma v> = BF \times 3 \times 10^{-26}\ cm^3 s^{-1}$$

- Two issues:
  - This assumes a smooth central halo. What about substructure?
  - Where there are high energy electrons, there are gamma rays. These are particularly troublesome in the GC. Can we lower their flux?





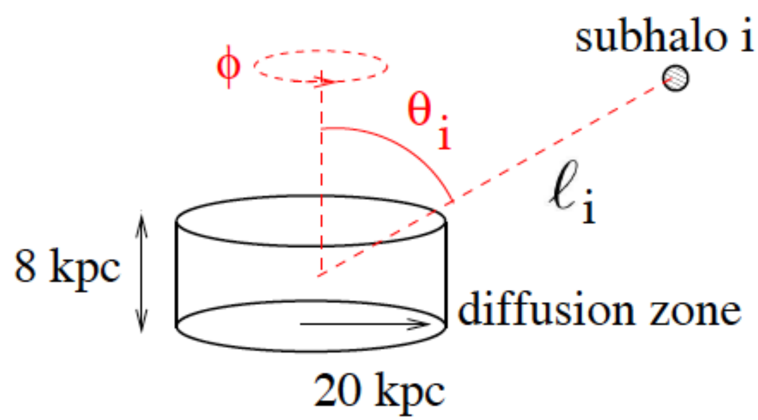


Why substructure is interesting

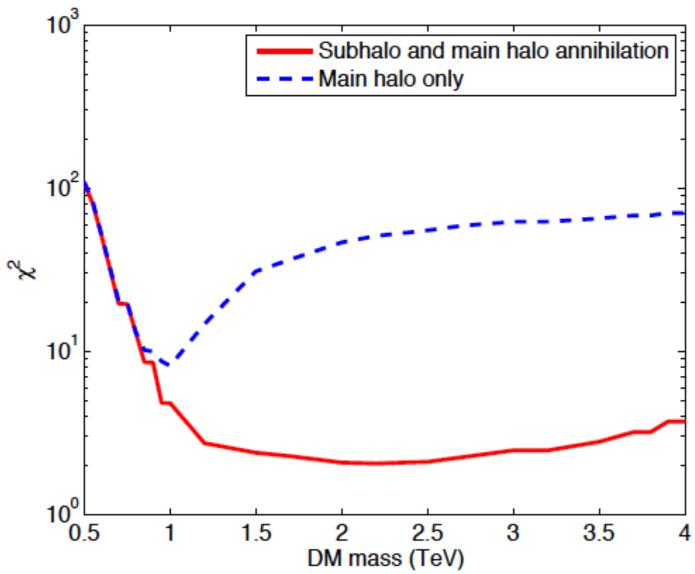
- Numerical simulations of DM universally predict a large number of local overdensities within the main dark matter halo, extending far beyond the baryonic component of the galaxy.
- These subhalos can augment dark matter annihilation into leptons in two ways:
  - I. Larger local density
  - II. Small velocities mean large boosts in Sommerfeld-enhanced models.
- Other studies: subhalos as a source of gamma rays (to constrain models), but not necessarily as sources for the PAMELA and Fermi leptons themselves.

GALPROP and Via Lactea II

- The diffusion eq. for e+e- was solved numerically using the public GALPROP (Strong & Moskalenko, some mods from I. Cholis & ourselves)
- **Source Terms**
  - **Main Halo**: $$\rho_{\mathrm{Ein}}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right\}$$
  - **Subhalos**: Used results from the Via Lactea II N-body simulation (about 20 000 "typical subhalos")
- **By adding a contribution from the large amount of substructure, can we get a better fit to the data while reducing the gamma ray constraints from the galactic center?**
- Yes we can!



Numerical results 1: Adding subhalos means a better fit to the data



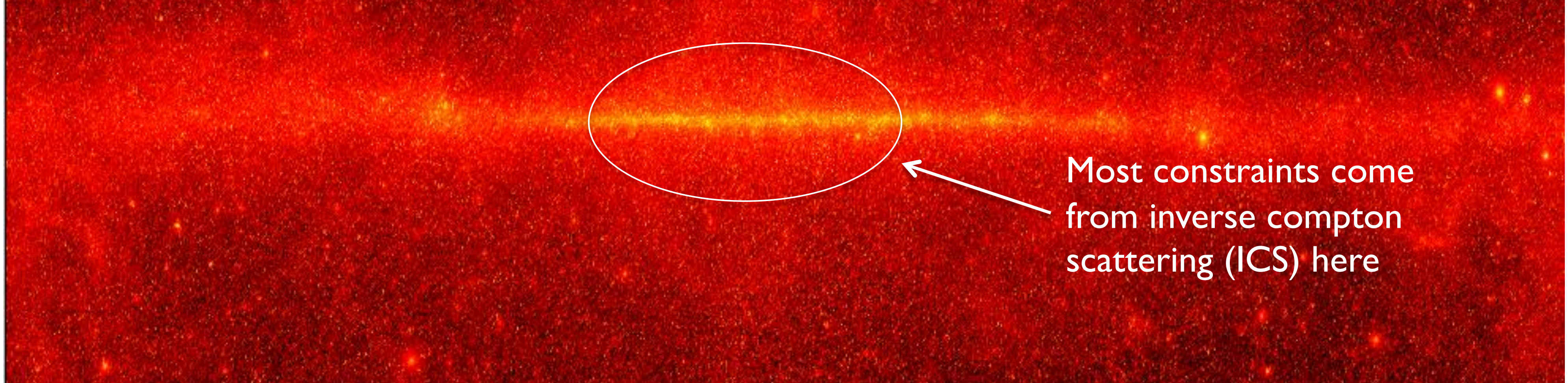
Better fit to PAMELA and Fermi with 2.2 TeV WIMP when subhalos are included

Larger mass is because of larger propagation distance – energy loss to Inverse Compton scattering with CMB, IR and Starlight

(4e final state. Going to a larger gauge boson mass allows mu and pi production, but results are ostensibly the same)

Gamma Rays

- Best DM annihilation models predict much larger gamma ray fluxes near the galactic center (GC) from **Final-state radiation** (Bremsstrahlung) **and Inverse Compton Scattering** (ICS)
- Fermi Large Area Telescope measured gamma rays from the entire sky in the exact range we're interested in (10-300 GeV)

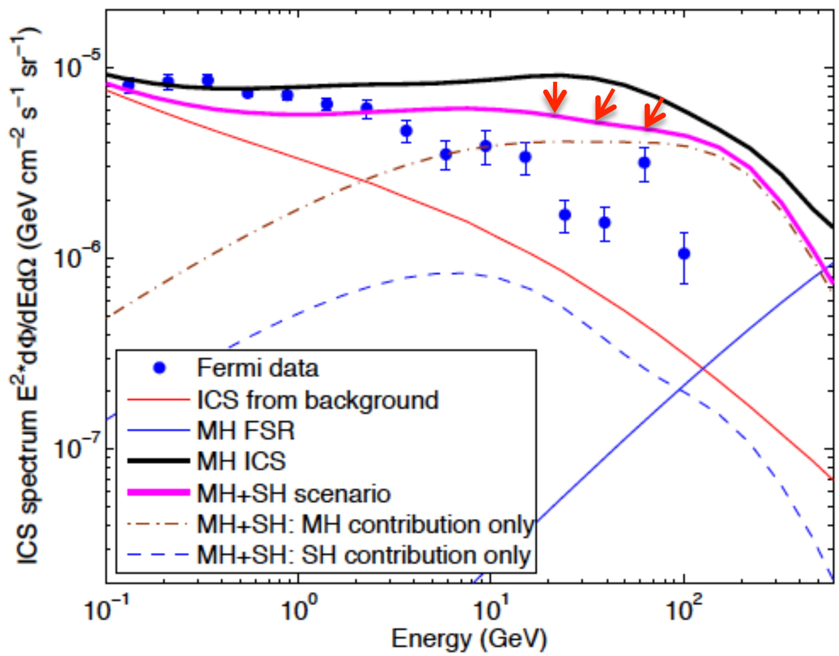


- We used the first year of Fermi LAT diffuse gamma ray (Aug 8 2008 to Aug 25 2009) data available from NASA to constrain the allowable DM annihilation
- Error estimates are from Porter et al. 2009

Numerical Resuts II: Gamma rays

- Unfortunately adding subhalos and still explaining PAMELA and Fermi only slightly reduces the gamma ray constraints.
- Issue: DM is still in the galactic center, annihilating.

- The DM profile (Einasto vs Isothermal, Burkert) and the final state (4e, 4 mu, pi, e) have some impact on this, but not enough



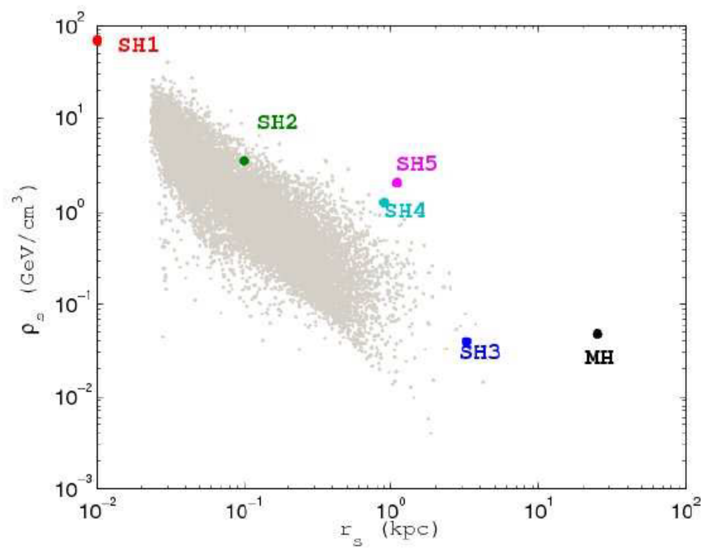
Gamma rays cont.

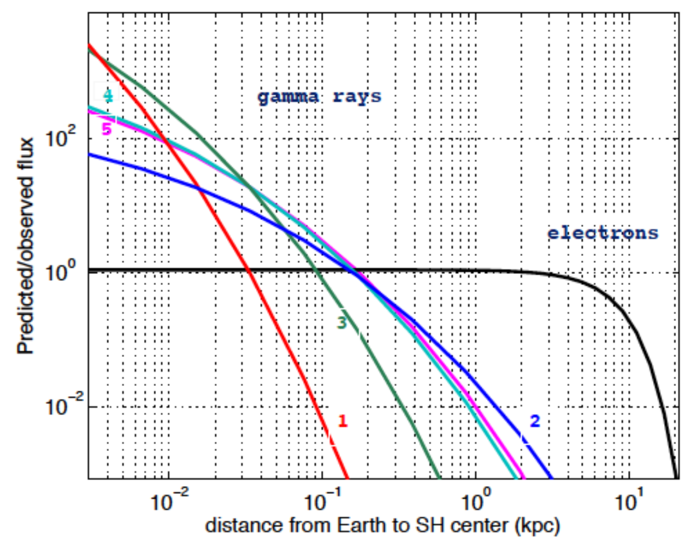
- We obtained constraints for the MH boost factor in the case of an Einasto DM profile, annihilation to 4e:
  - BF < 25 (35) at 1 σ (2 σ) for M = 1.0 TeV
  - BF < 42 (52) at 1 σ (2 σ) for M = 2.2 TeV
- Increasing intermediate gauge boson mass to allow decay to muons & pions:
  - BF < 23 (28) at 1 σ (2 σ) for M = 1.2 TeV
- …and choosing a flatter isothermal DM profile:
  - BF < 62 (72) at 1 σ (2 σ) for M = 1.2 TeV

- All well short of the required boost factors to explain PAMELA and Fermi electron excesses.

What about local substructure?

- We picked a few subhalos from the Via Lactea II population, and put them between us and the GC (lowest GR constraints)
- If we're within ~ 3 kpc of the subhalo center, but farther away than 3 ~ 20 pc, the PAMELA and Fermi excesses could come from such a subhalo

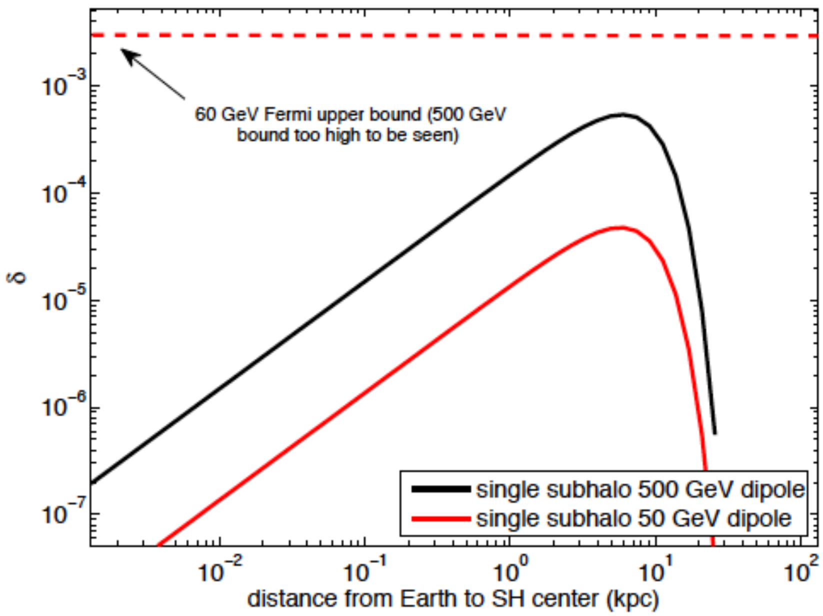




Possible constraints on this scenario

- Fermi dipole anisotropy of e+ + e-

$$\delta = \frac{3D(E)}{c} \frac{|\vec{\nabla} n_e|}{n_e},$$



- Bounds from dwarf spheroidals are not very constraining.
- Bounds from CMB => ok

Particle Physics Realization

- Consider a DM particle χ with a U(1) coupling to a dark gauge boson of mass μ
- This gives rise to an attractive Yukawa interaction (aka Sommerfeld Enhancement) which grows with decreasing relative velocity. Can approximately write:

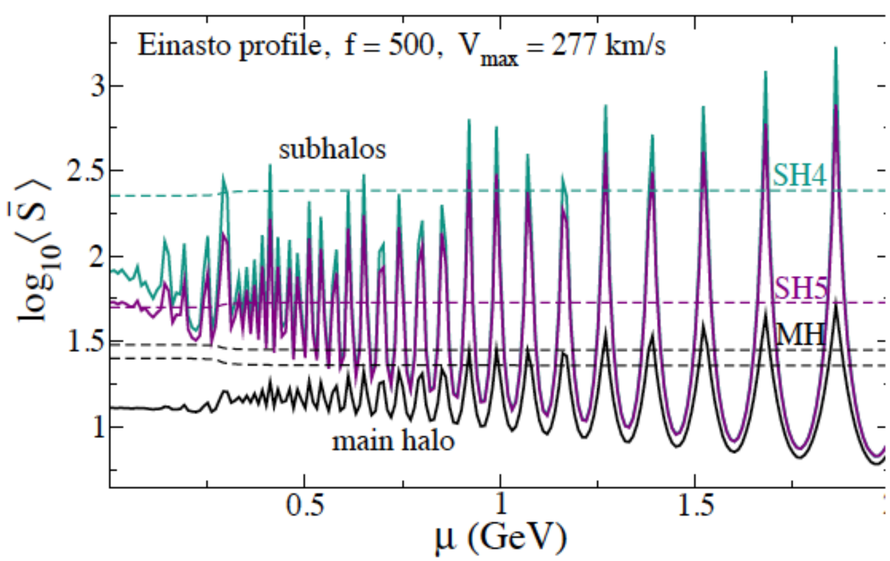
$$S = \frac{\pi}{\epsilon_v} \frac{\sinh X}{\cosh X - \cos\sqrt{\frac{2\pi}{\bar{\epsilon}_\phi} - X^2}}$$

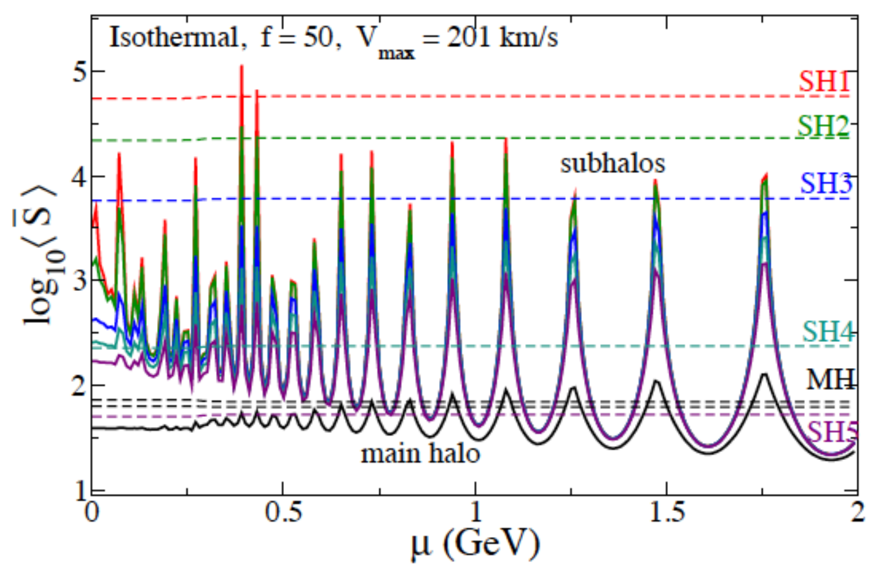
$$\epsilon_v = v/(\alpha_g c)$$
$$\epsilon_\phi = \mu/(\alpha_g M)$$
$$X = \epsilon_v/\bar{\epsilon}_\phi$$

- Using realistic velocity distributions and correct α_g this typically predicts too much enhancement! Gamma ray constraints are immediately saturated.

Particle physics, cont’

- Solution: only a fraction *1/f* contributes to the enhanced annihilation with *f* ~ 50-500
- In this way, relic density is correct, gamma ray constraints are respected, and PAMELA and Fermi anomalies can be addressed:





Conclusion

- Substructure is an interesting place to look for constraints on annihilating DM models
- We can't solve the gamma ray problem with a heavier WIMP annihilating in faraway subhalos, but a close subhalo may be the key
- Caveat: need large, dense subhalos: these should be rare around our location in the Milky Way.
- A realistic U(1) model typically produces too much Sommerfeld enhancement. This can be solved if only part of the DM can annihilate to the Standard Model through this channel.

II. Subhalos: how CRs get from there to here

- Diffusion equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\psi_{e^\pm}(\mathbf{x},\mathbf{p},t) \;=\; Q_{e^\pm}(\mathbf{x},E) + \nabla\cdot\left(D(E)\nabla\psi_{e^\pm}(\mathbf{x},\mathbf{p},t)\right) \;+\; \frac{\partial}{\partial E}\left[b(\mathbf{x},E)\psi_\pm(\mathbf{x},\mathbf{p},t)\right]$$

  - Source term (particle physics of the DM model)

$$Q_{e^\pm} = \frac{1}{2}\left(\frac{\rho(\mathrm{x})}{M}\right)^2 \langle\sigma v\rangle \frac{\mathrm{d}N_{e^\pm}}{\mathrm{d}E} = \frac{n_{DM}^2}{2} BF\langle\sigma v\rangle_0 \frac{\mathrm{d}N_{e^\pm}}{\mathrm{d}E}.$$

  - Diffusion coefficient – species do more or less of a random walk. Parameters set by measured B/C, Sub-Fe/Fe

$$D(E) = D_0\left(\frac{E}{4\ \mathrm{GeV}}\right)^\delta$$

Energy-loss term: Inverse Compton Scattering (ICS), and B field

$$b(x,E) = -\frac{\mathrm{d}E_e}{\mathrm{d}t} = \frac{32\pi\alpha_{em}}{3m_e^4}E_e^2\left[u_B + \sum_{i=1}^{3} u_{\gamma i}\cdot R_i(E_e)\right]$$

- We used both an unconstrained, freely varying the normalization of the background (consistent with some other authors), as well as a set of diffusion parameters from Simet & Hooper (much better approach), who fit GALPROP predictions to B/C & sub-Fe/Fe abundances

$$D_{0xx} = 6.04 \times 10^{28}\ \mathrm{cm^2\ s^{-1}}\ (0.19\ \mathrm{kpc^2/Myr})$$

$$L_{\mathrm{eff}} = 5.0\ \mathrm{kpc}$$

$$\delta = 0.41$$

$$V_A = 31\ \mathrm{km\ s^{-1}}$$

$$\rho_\odot = 0.37\ \mathrm{GeV\ cm^{-3}}$$

(VL2, Catena & Ullio 2009, …)

IV. Gamma Rays

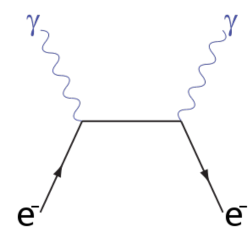
- Where there are electrons there is Bremsstrahlung (final state radiation) …

$$\frac{\mathrm{d}\Phi_{\mathrm{main}}}{\mathrm{d}E_\gamma \mathrm{d}\Omega} = \frac{1}{2}\frac{\langle\sigma v\rangle}{4\pi} r_\odot \frac{\rho_\odot^2}{m_\chi^2}\frac{\mathrm{d}N}{\mathrm{d}E_\gamma}\bar{J}_{main} \quad , \quad \bar{J}_{\mathrm{main}} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega}\mathrm{d}\Omega \int_{\mathrm{l.o.s.}}\frac{\mathrm{d}s}{r_\odot}\left(\frac{\rho_{\mathrm{main}}[r(s,\psi)]}{\rho_\odot}\right)^2$$

particle astro

…and Inverse Compton Scattering

$$\frac{d\Phi_{\gamma'}}{dE_{\gamma'}d\Omega} = \frac{1}{2}\hbar^2 c^3 \alpha_{EM}^2 \int_{\mathrm{l.o.s.}} ds \int\int \frac{dn_e}{dE_e}\frac{du_\gamma}{dE_\gamma}\frac{dE_\gamma}{E_\gamma^2}\frac{dE_e}{E_e^2} f_{IC}$$



Electrons and positrons scatter off radiation from CMB, IR from dust and starlight, producing high-energy gamma rays in the 10-200 GeV range.

- Both of these integrals can be performed numerically along the line of sight for our particular DM model and known radiation distribution, and compared to experimental data.