based on work with A. Vincent and J. Cline
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# COSMIC RAY ANOMALIES, GAMMA RAY CONSTRAINTS AND SUBHALOS IN MODELS OF DARK MATER ANNIHILATION

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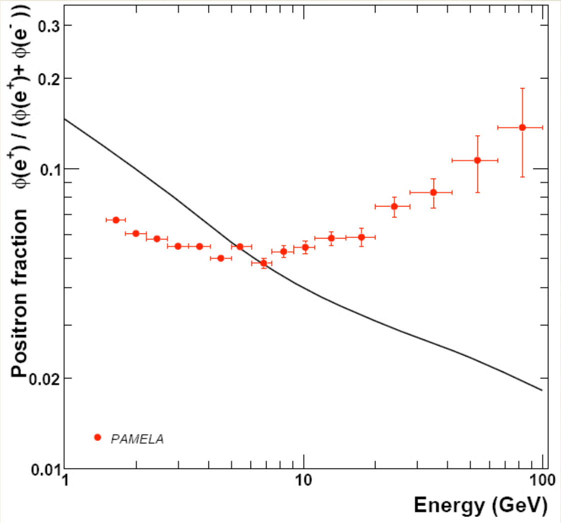
# OUTLINE

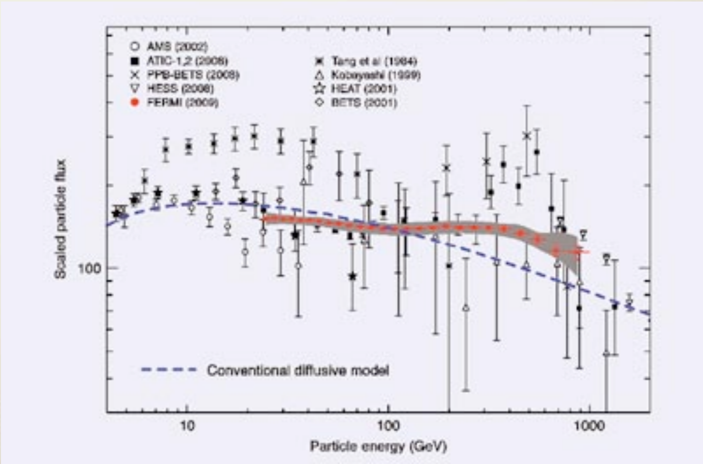
* Cosmic Anomaly
* Dark Matter Subhalos outside
* Dark Matter subhalos inside
* Particle Physics realization

# Cosmic Ray Anomaly

* Charged Cosmic Particles
  * Positron fraction(>10Gev) PAMELA




  * Electron+Positron Peaking around 500Gev Fermi



# Dark Matter

- The Phenomena have no known astrophysics origin (Could be pulsar?)
- Attractive explanation: 1 Tev WIMP

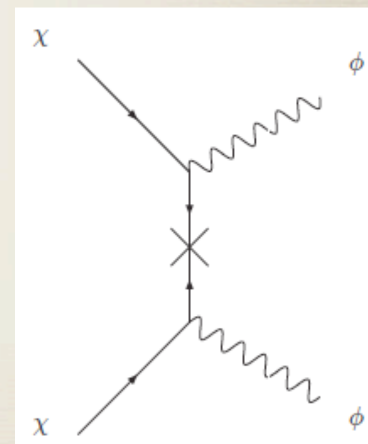
  DM + DM → messengers fields $\phi$ (on shell)

  → SM particles.

  $m_\phi < 2m_{proton}$

  Sommerfeld enhancement to cross section

  $<\sigma v> = BF \times 3\times10^{-26} cm^3 s^{-1}$




- Two issues:

  Gamma Ray?

  substructure?

# From N-body Simulation

- ★Via Lactea II

  1 DM main halo in the centre
  100 inside the visible galaxy
  20,047 resolved DM subhalos

- ★Extend as far out as 4,000 kpc

  Our Visible galaxy is 40 kpc aross

# Subhalos contributions

- Positive contribution

  Large Number 20,000 subhalos

  High density

  small dispersion velocity

  sub-substructure

- Negative contribution

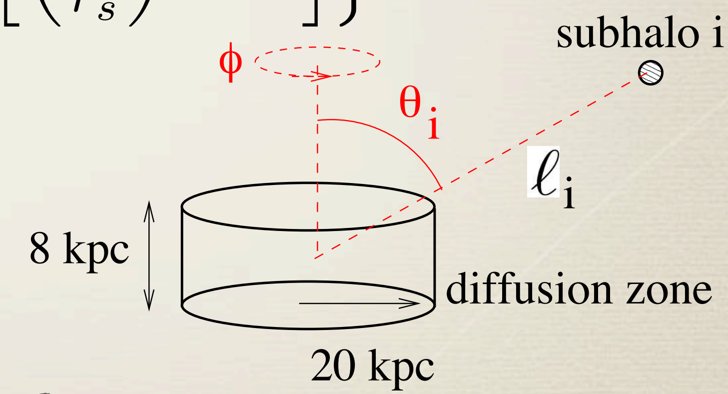
  long distance to the milky way

# GALPROP+Via Lactea II

- GALPROP Numerically solve diffusion equation of electrons and positrons

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

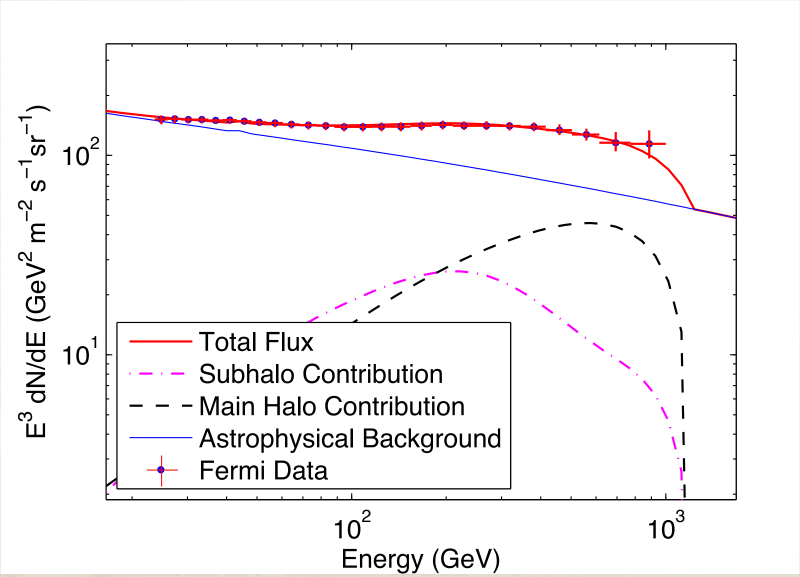
- Source
  - Main halo: $\rho_{Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^\alpha - 1\right]\right\}$
  - Subhalos:
    similar density profile,

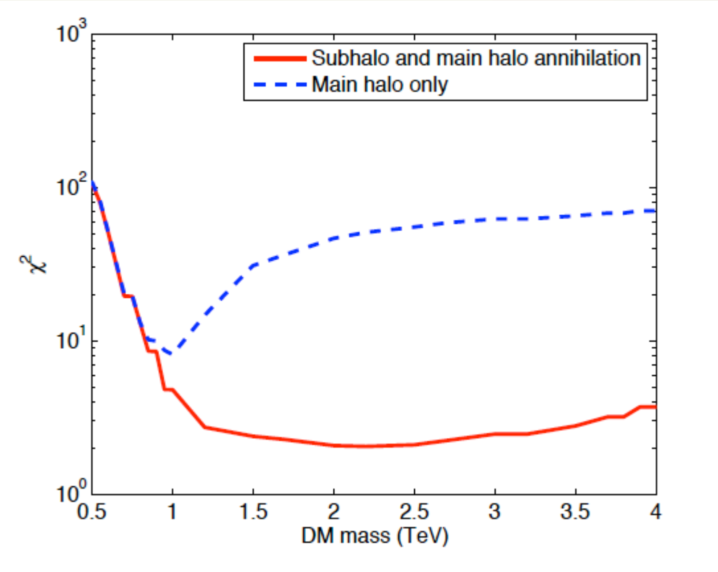



- Change the boundary condition of GALPROP by using the subhalos data from Via Lactea II

# Mainhalo+Subhalo

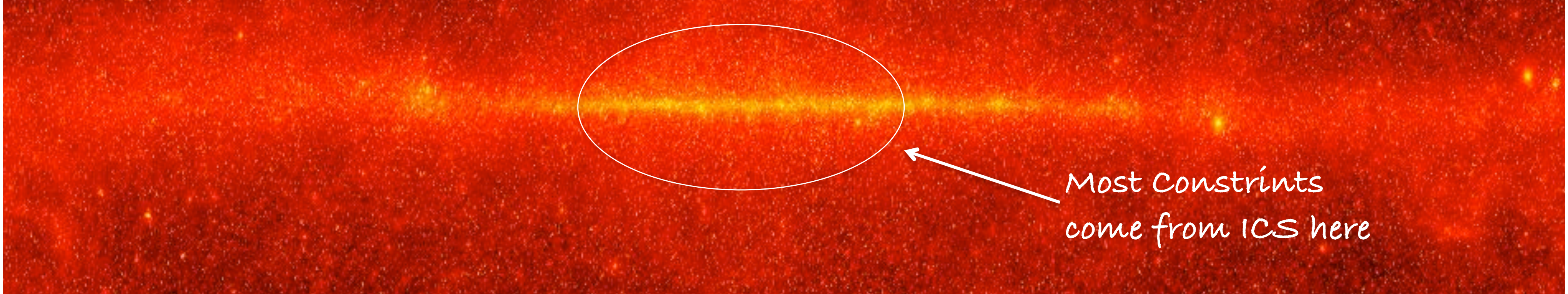
- better fit to PAMELA and Fermi with 2.2 Tev WIMP when subhalos are included ($BF_{SH}$=3744, $BF_{MH}$=92)
- Larger mass is because of larger propagation distance. The energy loss is due to Inverse Compton Scattering with CMB, IR and Starlight



# Gamma Ray

- Best DM annihilation models predict much larger gamma ray fluxes near the galactic center(GC) from Final state radiation (Bresstrahlung) and Inverse Compton Scattering(ICS)



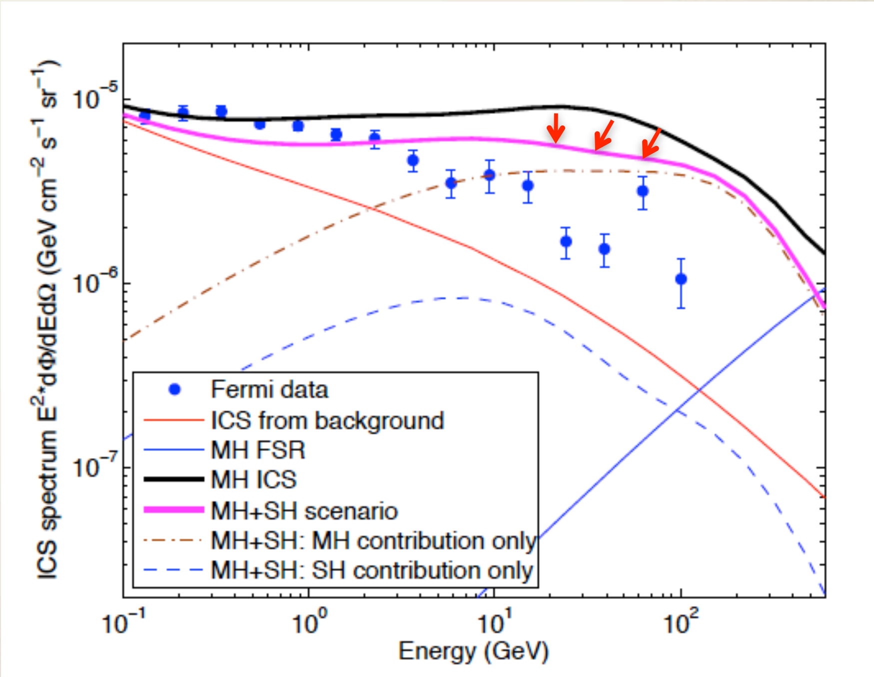

- We used the first year of Fermi LAT difuse gamma ray(Aug 8 2008 to Aug 25 2009) data available from NASA to constrain the allowable DM annhihilaiton

# Numerical Result

* Adding subhalos and still explaining PAMELA and Fermi only slightly reduce the gamma ray constraints

* Density of DM main halo in the GC is still high

* DM profile and final state (4e,4μ,π,e) has some impact on it, but not enough

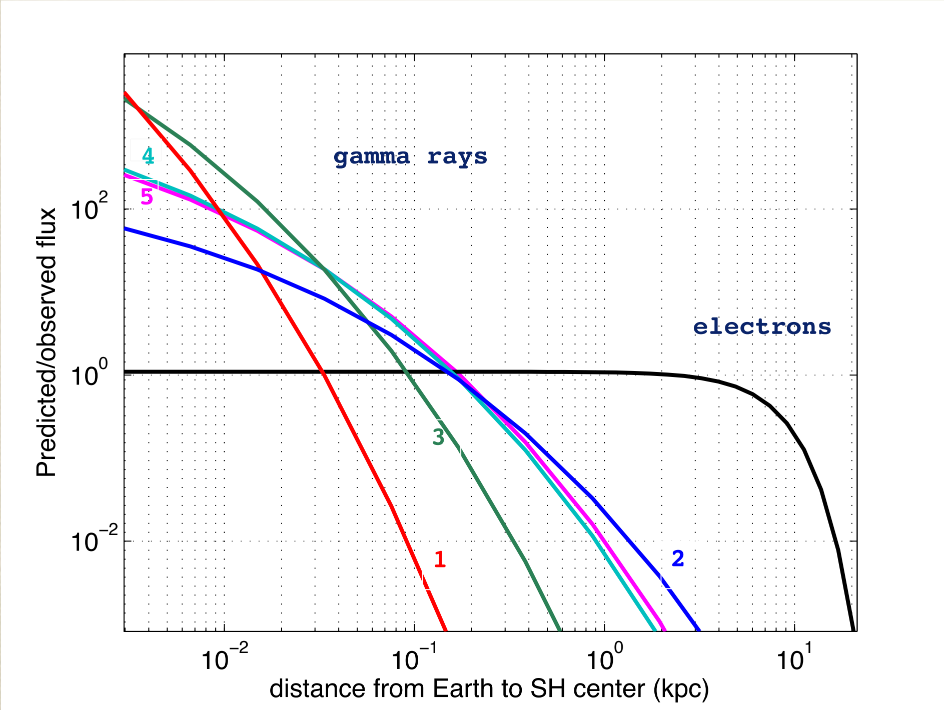


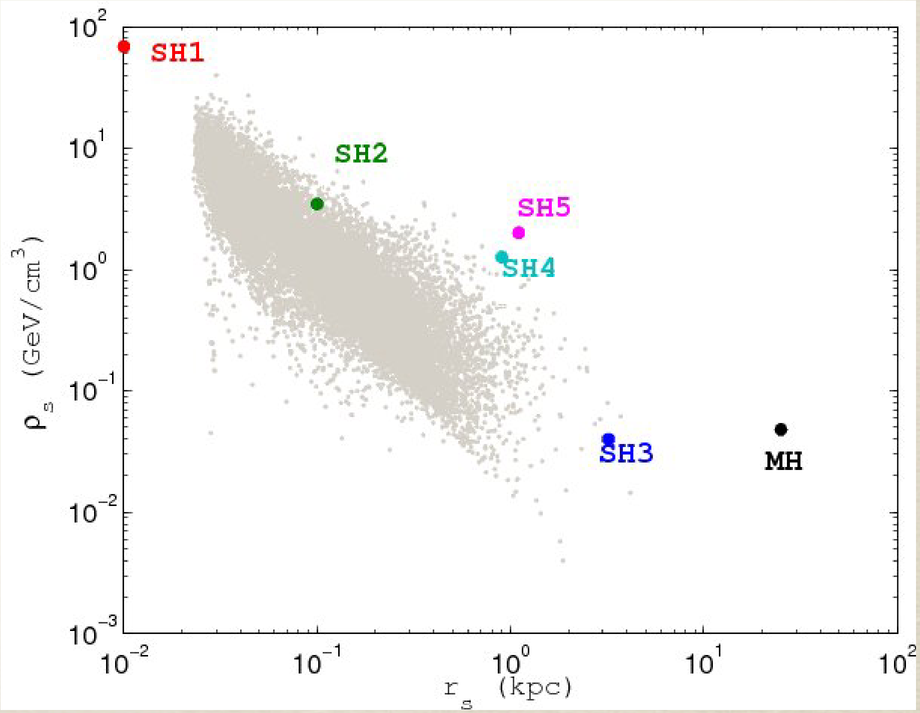
# What about local subhalo?

- 100(s)  subhalos inside the galaxy from Via Lactrea
- small velocity, high density and close to us
- PAMELA and Fermi excess can come from the close subhalo
- We are within 3 kpc of subhalo centre, but further away than 20pc.

# Where is the subhalo

- SH1 - SH4 are from Via Lactea , and SH5 is engineered by choosing parameters close to SH4. SH5 is with a higher density (so lower BF)



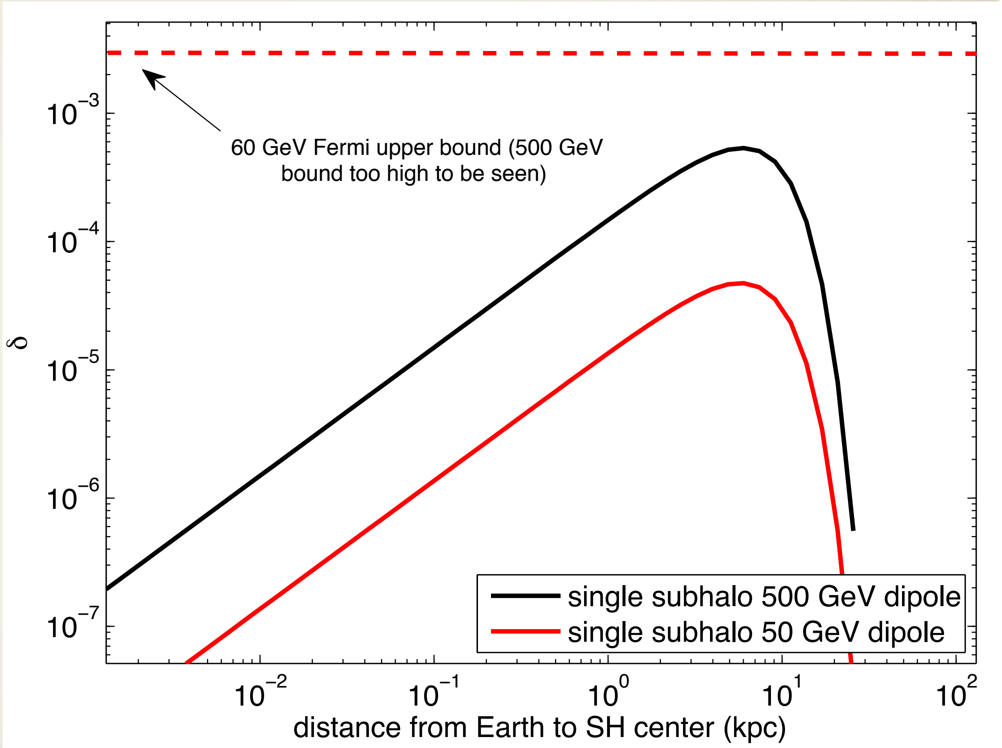
# The five subhalos

* They are atypical in the sense of needing a higher - than average central density.
* a large $r_s$ is unlikely at small distances from the GC due to tidal disruption.
* Each subhalo was situated along an optimal axis, namely that connecting the earth to the GC.
* The biggest contribution of Gamma Ray is from final -state bremsstrahlung rather than ICS.

# Close Subhalo anisotropy

* Fermi Dipole anisotropy of electron and positron

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

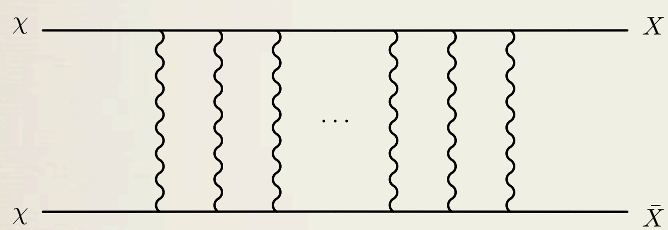


# Particle Physics Realization

- certain values for the cross  section BF are needed for the subhalos
- upper bound of BF for main halo
- Is there simple Particle Physics model can be consistent with the requirements.

# Sommerfeld enhancement

- The non-relativistic particles are moving in some potential. The wave function is distorted by the attractive potential. Or Summing over all the ladder Feynman diagram (QFT)




$$\frac{1}{m}\frac{d^2\psi(r)}{dr^2} - V(r)\psi(r) = -m\beta^2\psi(r)$$

- Consider a DM particle with a U(1) coupling to a dark gauge boson of mass $\mu$ (O(1) GeV)

- Using realistic velocity distribution and correct $\alpha$, this typically predicts too much enhancement. Gamma ray constraints are immediately saturated.

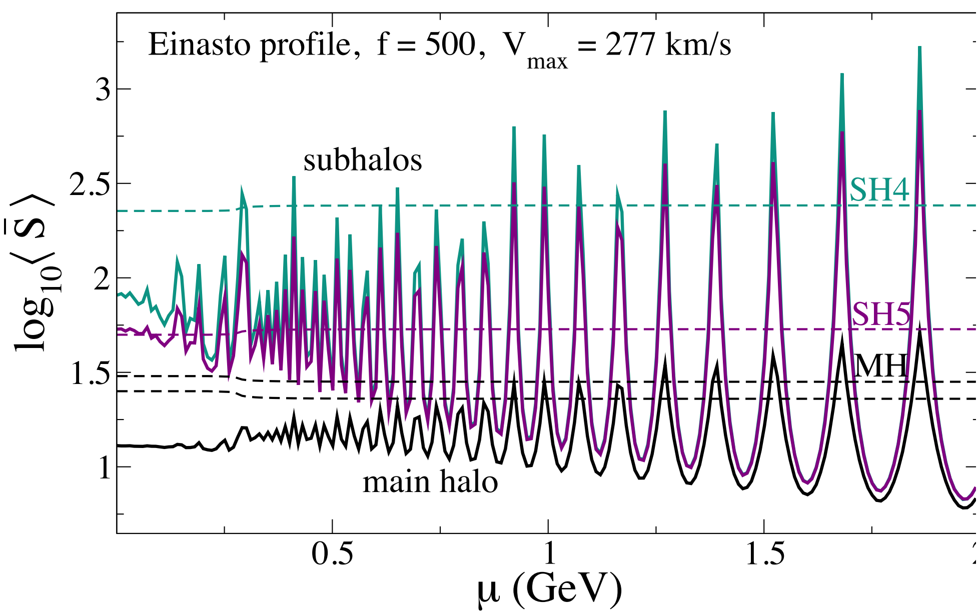
# Effective Boost Factor

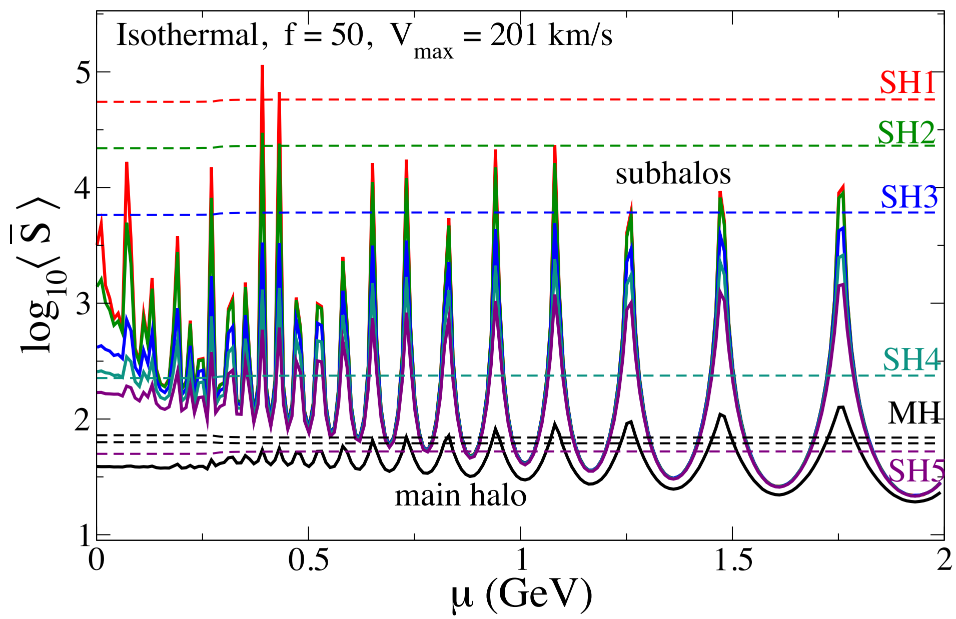
- It is not obvious that one can find models with the desired BF for subhalos and main halo.
- leptophilic DM is a subdominant component of the total DM, comprising some fraction 1/f.
- Cross section $\langle\sigma v\rangle \sim \alpha^2/M^2$
  Parametrize $\alpha=\sqrt{f}\,\alpha_{th}$,
  By solving Boltzmann eq., the relic density is proportional to $\langle\sigma v\rangle^{-1}$
  Therefore, the rate of annihilations goes like
  $\rho^2\sigma \propto 1/f$. Accordingly, we define an effective BF

$$\bar{S} = \frac{S}{f}$$

# Theoretical fits

* Given α ⇒ boost factors for main and subhalos
* The working example (larger f is needed for a cuspy main halo)



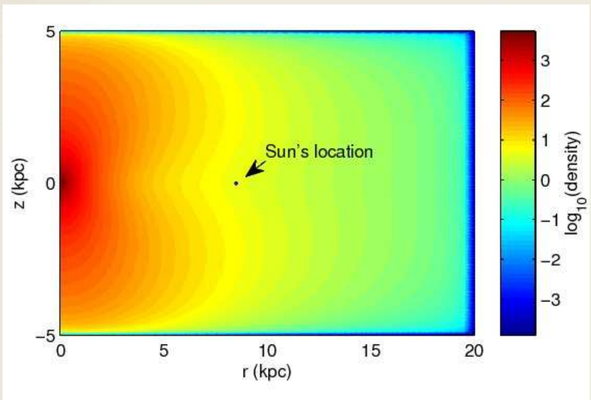
# Summary

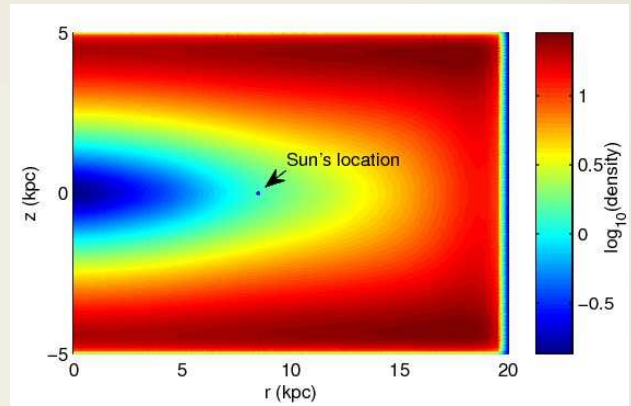
* We can get better fit to the lepton data by including all the DM subhalos, but the gamma ray constraints are still too strong
* close subhalo can explain PAMELA/Fermi, also consistent with Fermi LAT diffuse gamma ray survey
* Caveat: Need large, dense subhalos
* A realistic U(1) model typically produce too much enhancement. This can be solved if only part of the DM can annihilate to SM particles in this channel.

Thank you

# Release Gamma Ray Constraints

- Electron-positron distribution




- subhalos gamma rays are from all the directions outside

- Main halo gamma rays are largely from the centre of the galaxy, because of the peak of the density profile of DM

# Gamma Ray Constraints

- We obtained the constraints for the MH boost factor in the case of Einasto DM profile, annihilation to 4e
  BF<25(35) at $1\sigma(2\sigma)$ for $M_{DM}$=1Tev
  BF<42(52) at $1\sigma(2\sigma)$ for $M_{DM}$=2.2Tev
- Increasing intermediate gauge boson to allow decay to $\mu$ and $\pi$
  BF<23(38) at $1\sigma(2\sigma)$ for $M_{DM}$=1.2Tev
- And choosing a flatter isothermal DM density profile
  BF<62(72) at $1\sigma(2\sigma)$ for $M_{DM}$=1.2Tev

# Diffusion Equation

* Semi-analytic approach to solve the diffusion eq.

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

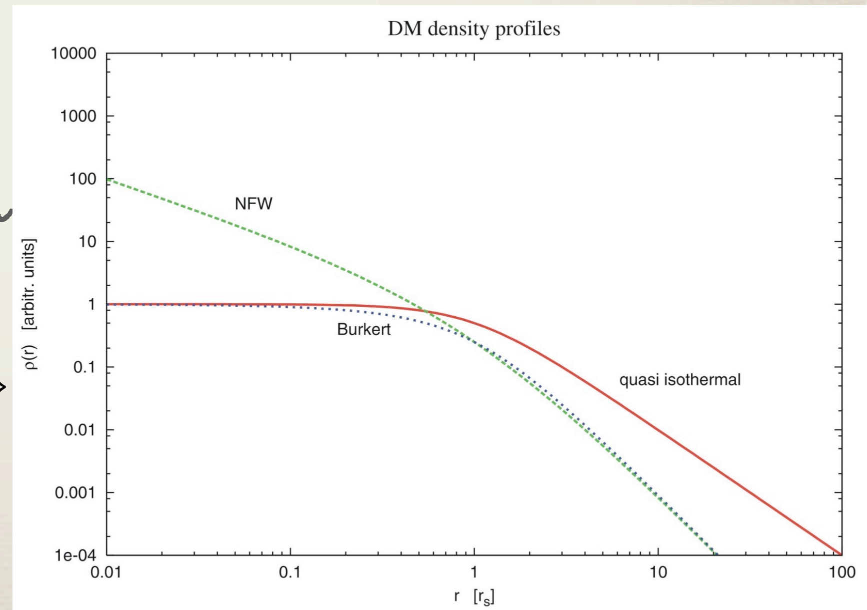
* Q is the source term from subhalo

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

* Subhalo has the similar DM density distribution as the main halo.

$$\rho_{Ein}(r) = \rho_s\exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^\alpha - 1\right]\right\}$$

$$\rho_{\rm iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$



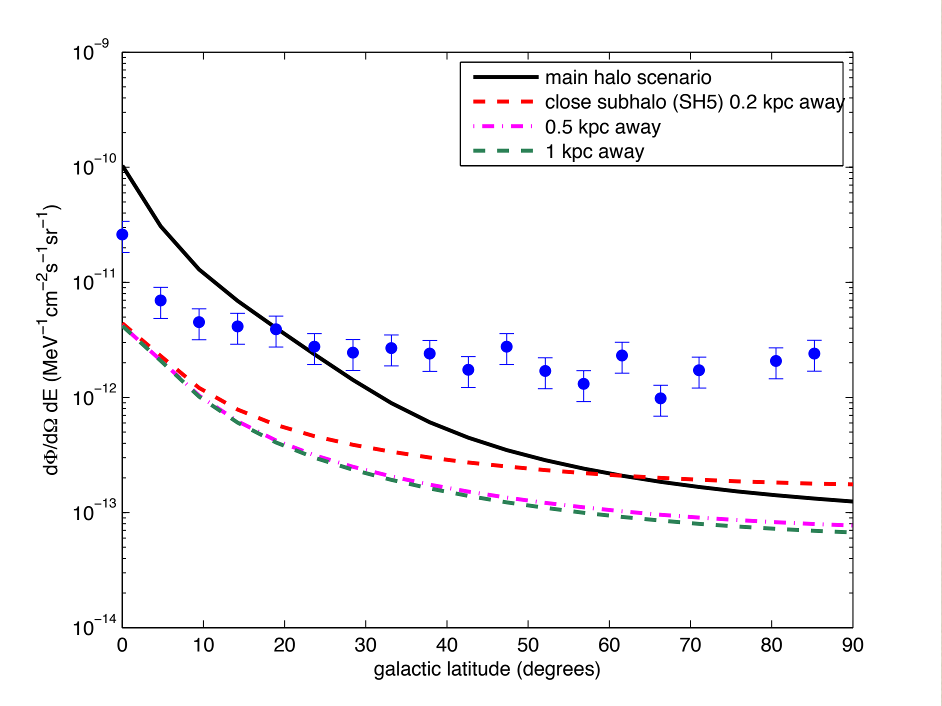
# Five subhalos

* Sample subhalos from the Via Lactea II simulation. Using them fitting the PAMELA/Fermi lepton fluxes and Fermi gamma ray fluxes.

| Subhalo | $r_s$ (kpc) | $\rho_s$ | $\log BF$ | $d_{\min}$ (pc) | $V_{\max}$ (km/s) |
|---|---|---|---|---|---|
| 1 | 0.01 | 69 | 4.74 | 33.9 | 2.9 |
| 2 | 0.1 | 3.46 | 4.34 | 95.5 | 6.7 |
| 3 | 3.2 | 0.04 | 3.76 | 178 | 22 |
| 4 | 0.9 | 1.27 | 2.35 | 165 | 36 |
| 5 | 1.1 | 2.0 | 1.70 | 170 | 55 |
| Main halo, 4e channel | | | | | |
| Einasto | 25 | 0.048 | $< {}^{1.40}_{1.48}$ | – | 201 – 277 |
| Isothermal | 3.2 | 2.32 | $< {}^{1.81}_{1.88}$ | – | 201 – 277 |
| Main halo, $4e + 4\mu + 4\pi$ channel | | | | | |
| Einasto | 25 | 0.048 | $< {}^{1.36}_{1.45}$ | – | 201 – 277 |
| Isothermal | 3.2 | 2.32 | $< {}^{1.80}_{1.86}$ | – | 201 – 277 |

# Close Subhalo vs. main hao

* Gamma ray fluxes on galactic latitude b, in the region -9°<l<9° at E=23 Gev.



# Relic Density Constraint

- Sommerfeld enhancement sensitively relies on $\alpha$
- Model: DM has a U(1) gauge symmetry.
  Kinetic mixing $\varepsilon B_{\mu\nu}F^{\mu\nu}$.
- There are two kinds of final states for annihilation of DM

$$\frac{1}{4}\sum|\mathcal{M}|^2 = \begin{cases} 4g^4(1+2v^2), & \chi\chi \to BB \\ \frac{1}{2}g^4q^2(1-v^2\cos^2\theta), & \chi\chi \to h\bar{h} \end{cases}$$

q is the U(1) charge of h relative to $\chi$.

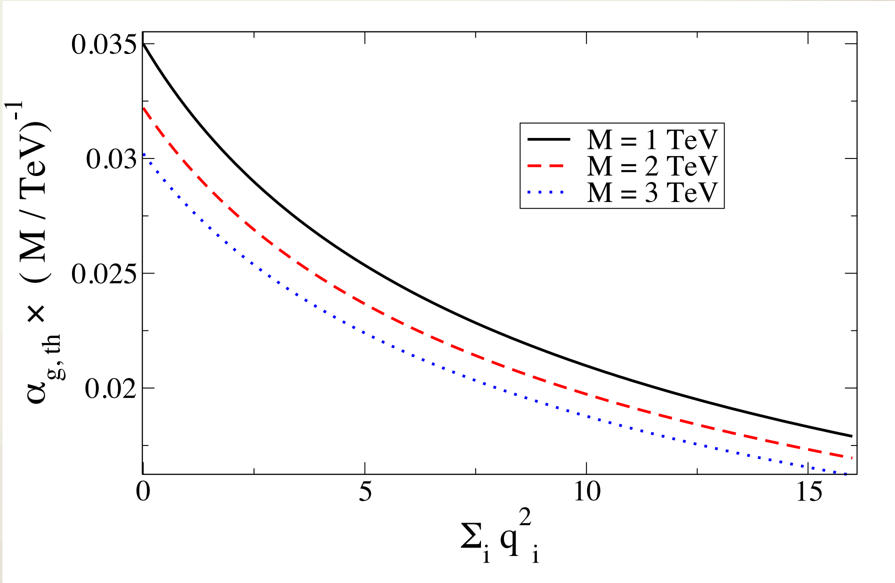
# Relic Density Constraint

- Include approximately the effect of Sommerfeld enhancement, the cross section is given by (Cline, Frey, Fang 1008.1784)

$$\langle \sigma v_{\rm rel} \rangle \cong \frac{\pi \alpha_g^2}{2M^2}\left( a\left(1+\alpha_g\sqrt{\pi\frac{M}{T}}\right) + \frac{T}{M}(b-\tfrac{4}{3}a)\left(\tfrac{3}{2}+\alpha_g\sqrt{\pi\frac{M}{T}}\right)\right)$$

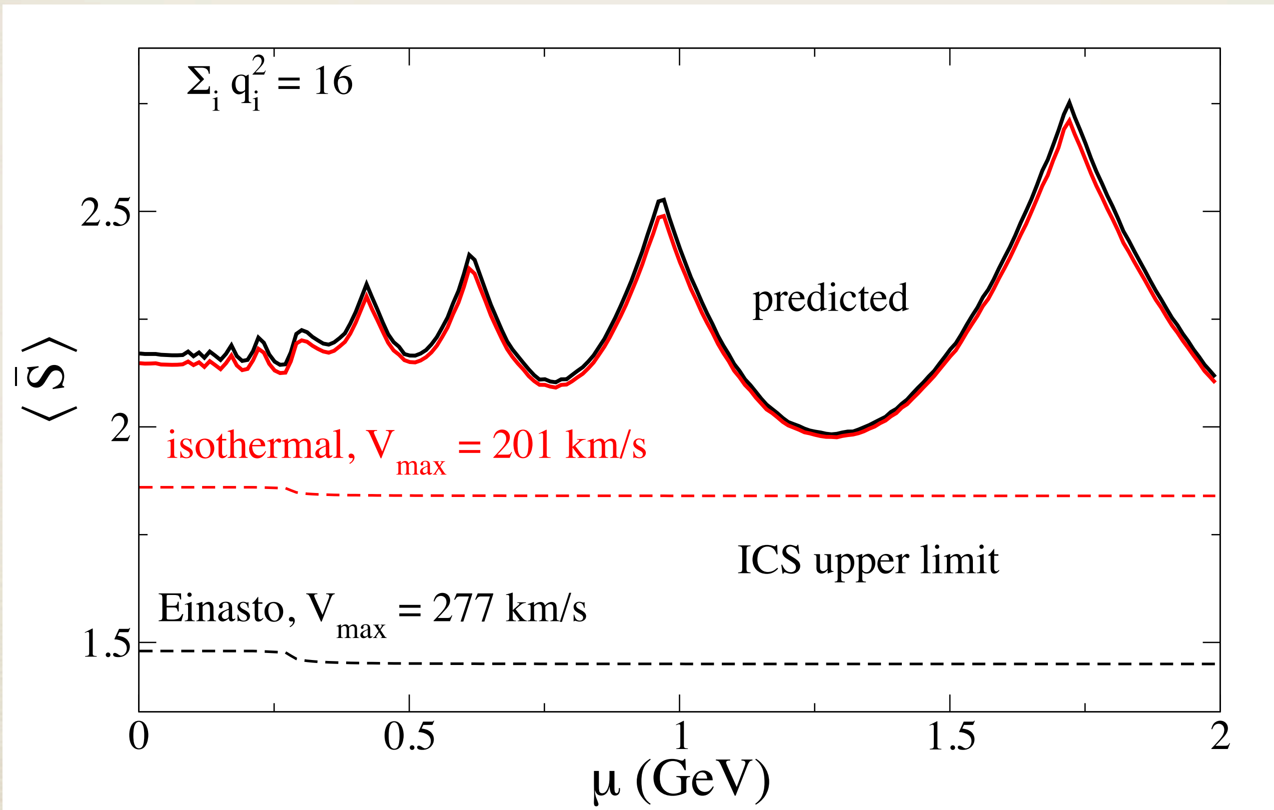
$$a = 1+\tfrac{1}{4}\textstyle\sum_i q_i^2, \quad b = 2(1-\tfrac{1}{12}\textstyle\sum_i q_i^2)$$

- $\alpha = \sqrt{f}\,\alpha_{th}$, $f>1$



# Why f?

* The failure to satisfy the bounds drives us to consider f



# CMB and Relic Density constraints

- the dilution of DM density by 1/f insures that the model satisfies stringent CMB constraints from changing the optical depth (Slatyer, etc, 0906.1197, Cirelli and Cline, 1005.1779)