Dark Matter Theory and Fermi

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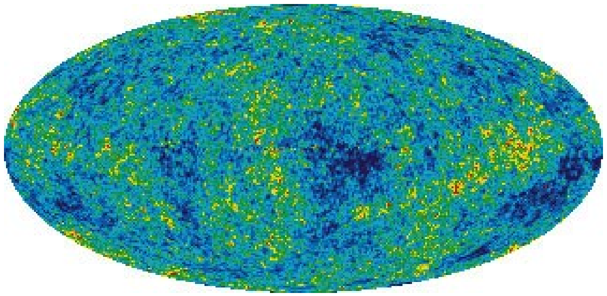
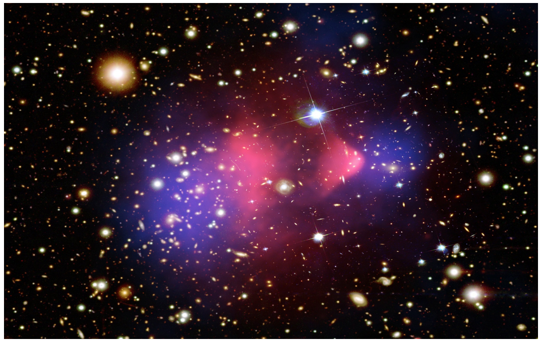
Dark Matter

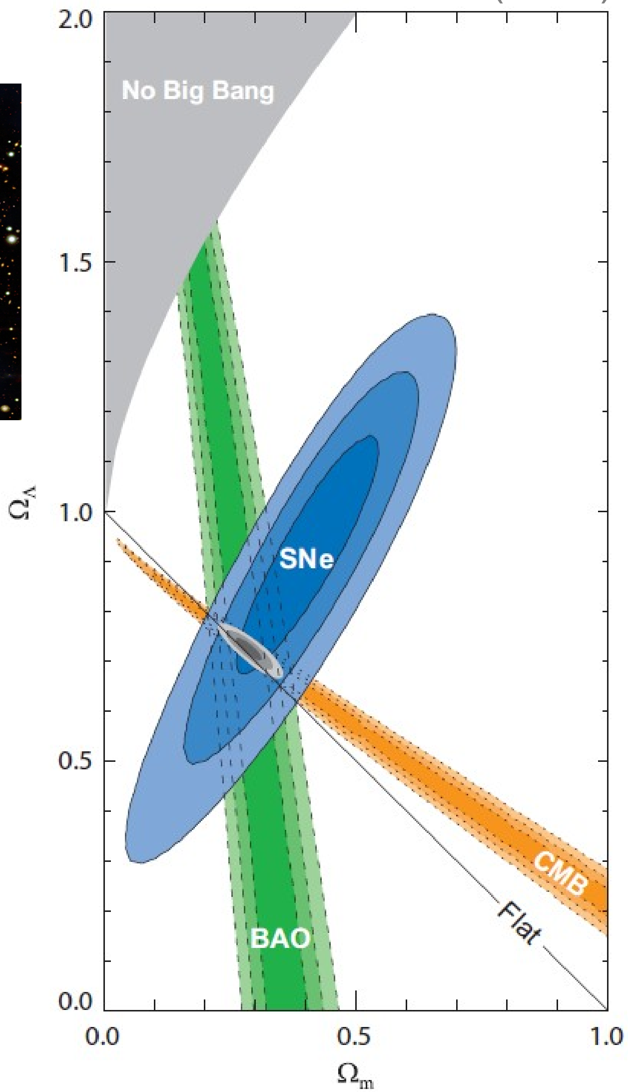
WMAP



Clowe et al. (2006)



Kowalski *et al.* (2008)



- Ω_{DM}= 0.233 ± 0.0013 Komatsu *et al.* (2009)
- It's non-baryonic (BBN+CMB, structure formation).
- It's stable or very long-lived.
- It's not charged (heavy isotope abundances).
- It's largely non-relativistic (cold).

What could it be?

- Standard Model particles?
  - ✔ No cold DM in the SM!

    (Neutrinos are HOT DM)
- Beyond the SM:
  - axions, sterile neutrinos, SUSY particles (LSP = neutralino, gravitino, axino, or sneutrino), Kaluza Klein states (LKP), Little Higgs heavy photons (LTP) or scalars, mirror matter, WIMPzillas, solitons (Q-balls)...

Weakly
Interacting
Massive
Particles

Weak Scale in Cosmology

1. New (heavy) particle χ in thermal equilibrium:

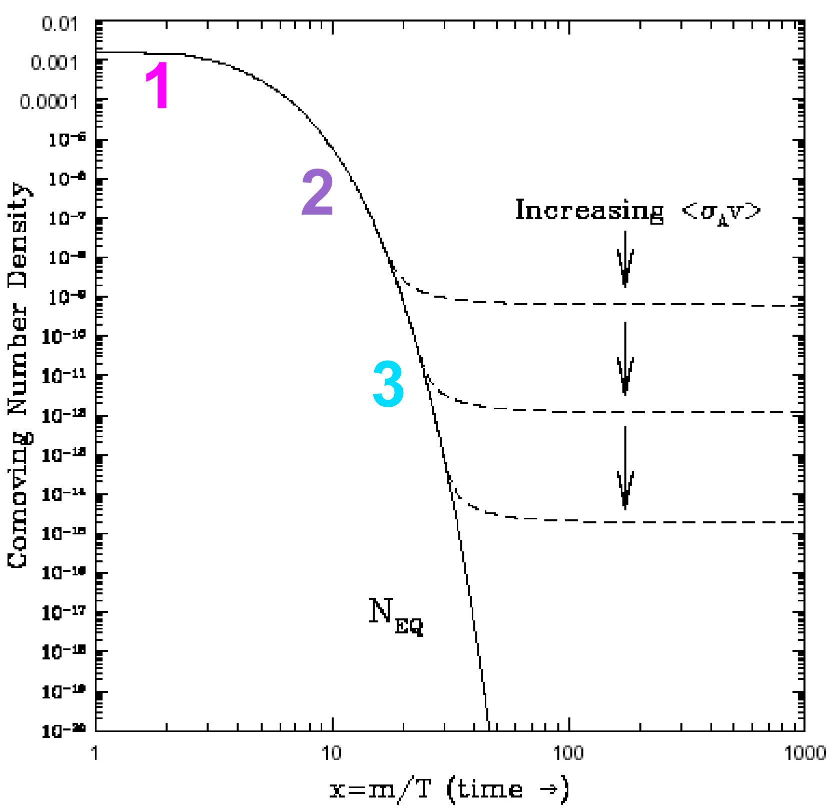
$$\chi\,\chi \rightleftarrows f\,\bar{f}$$

2. Universe expands and cools:

$$\chi\,\chi \not\rightleftarrows f\,\bar{f}$$

3. χ's "freeze out"

$$\chi\,\chi \not\rightleftarrows f\,\bar{f}$$



Jungman, Kamionkowski and Griest, PR 1996

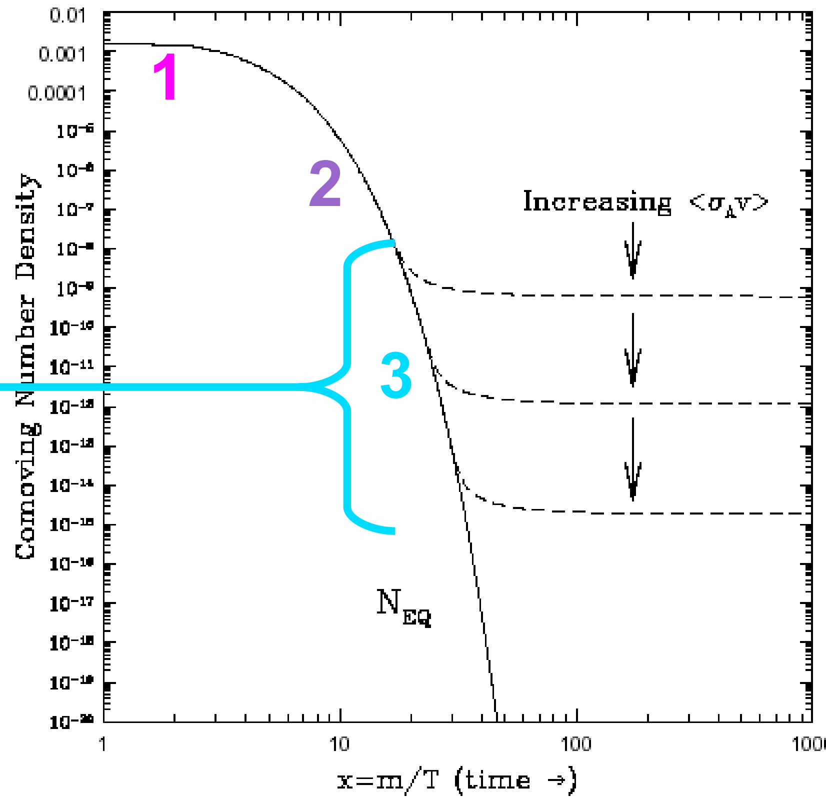
Weak Scale in Cosmology

Expansion and annihilation compete to determine the number density:

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v_{rel} \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

Stable matter with GeV-TeV mass and weak-scale interaction strength yield

$$\Omega h^2 \sim 0.1$$



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What could it be?

•Standard

✔ No cold

(Neutrin

Theories that address the shortcomings of the Standard Model involve new physics at the weak scale, and therefore address the dark matter puzzle, as well.

- Beyond the SM

  - axions, sterile neutrinos, SUSY particles (LSP = neutralino, gravitino, axino, or sneutrino), Kaluza Klein states (LKP), Little Higgs heavy photons (LTP) or scalars, mirror matter, WIMPzillas, solitons (Q-balls)...

Additional Ingredient

- It's not enough to have a theory with extra particles at the weak scale; also need a symmetry to make the lightest new particle stable.
- No problem! We need this anyway (proton stability, neutron-antineutron oscillations, large neutrino masses...)

Theory	Z_2 Parity	Dark Matter
SUSY	R-parity	LSP
UED	KK-parity	LKP
Little Higgs	T-parity	LTP

Dark Matter Detection

Indirect Detection

DM + DM → SM + SM

- ➔ Observe products of WIMP annihilation (decay) in terrestrial or space-based detectors

• Direct Detection

SM + DM → SM + DM

- ➔ Observe WIMPs through interactions with matter in terrestrial detectors

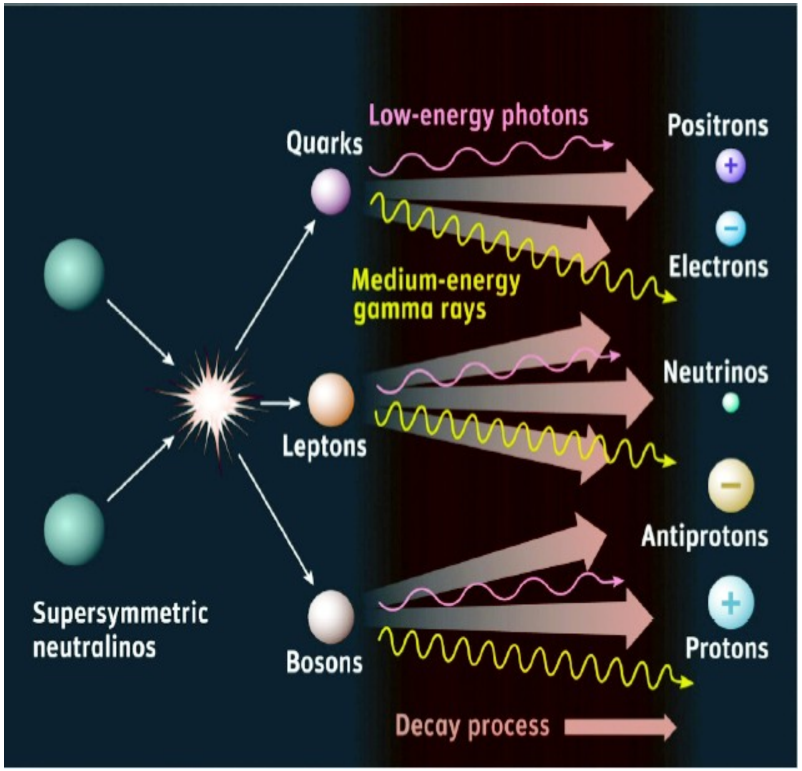
• Colliders

SM + SM → DM + DM

- ➔ Produce WIMPs directly: missing energy signature
- ➔ Observe decays of Next-to-Lightest Particles to DM

Indirect Detection

- WIMP annihilation.. (decay???)
- Need lot of dark matter:
  - Near the Milky Way GC
    Gondolo and Silk, 2000
  - In the Milky Way halo
    Ellis, Freese et al. 1987
  - In the Sun or the Earth
    Silk et al. 1985, Krauss et al. 1986, Freese 1986
  - In nearby dwarf galaxies
    Evans, Ferrer, and Sarkar, PRD 69, 2004,
    Sandick et al. 2009
  - In Milky Way substructure
    Evans, Ferrer, and Sarkar, PRD 69, 2004,
    Sandick et al. 2010, **Sandick** & Watson 2011



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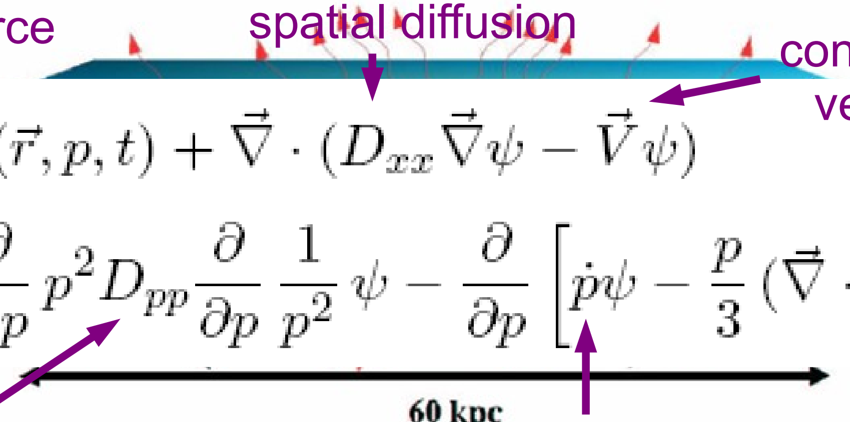
- neutrinos
  ➔ SuperK, IceCube
- high energy photons
  ➔ EGRET, **Fermi,** VERITAS, MAGIC...
- synchrotron radiation
  ➔ WMAP, Planck
- positrons/antiprotons
  ➔ HEAT, ATIC, PAMELA, **Fermi**, AMS

Neutral vs. Charged Products

- Neutral: Propagate directly from source

$$\frac{d\Phi_f}{dE} = \frac{B_f \Gamma}{m_\chi} \frac{dN_f}{dE} \int_0^{\theta_{max}} d\theta \, 2\pi \sin\theta \int_0^{s_{max}} ds \, \rho_{DM}(r)$$

- Charged: Path and energy altered along the way



$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p,t) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

source

spatial diffusion

convection velocity

radioactive decay

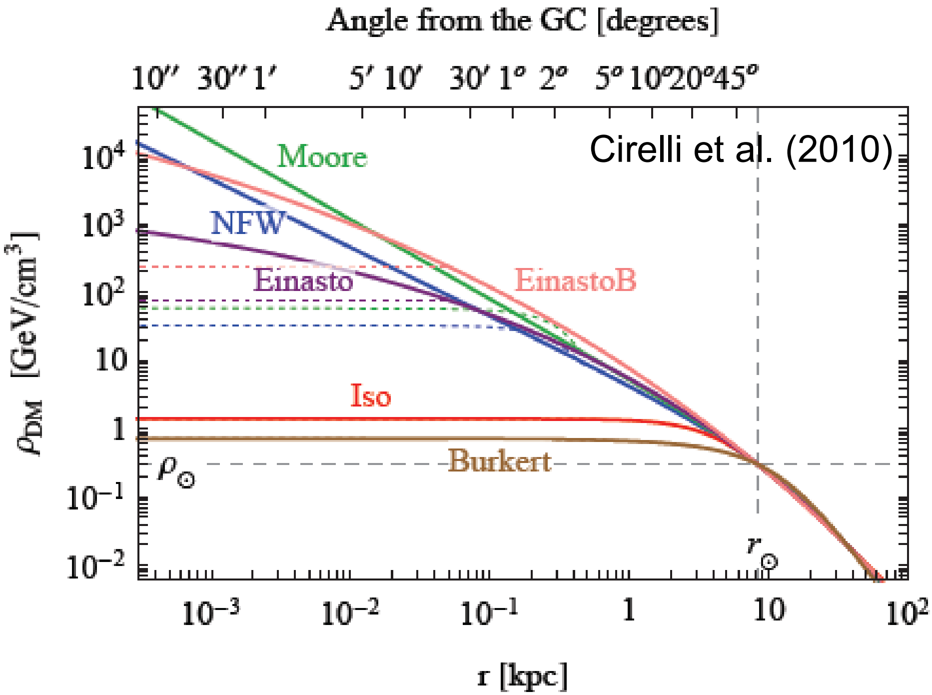
diffusive reacceleration

momentum change rate

fragmentation losses

See eg. Strong, Moskalenko & Ptuskin (2007)

Dark Matter Distribution



Simulations:

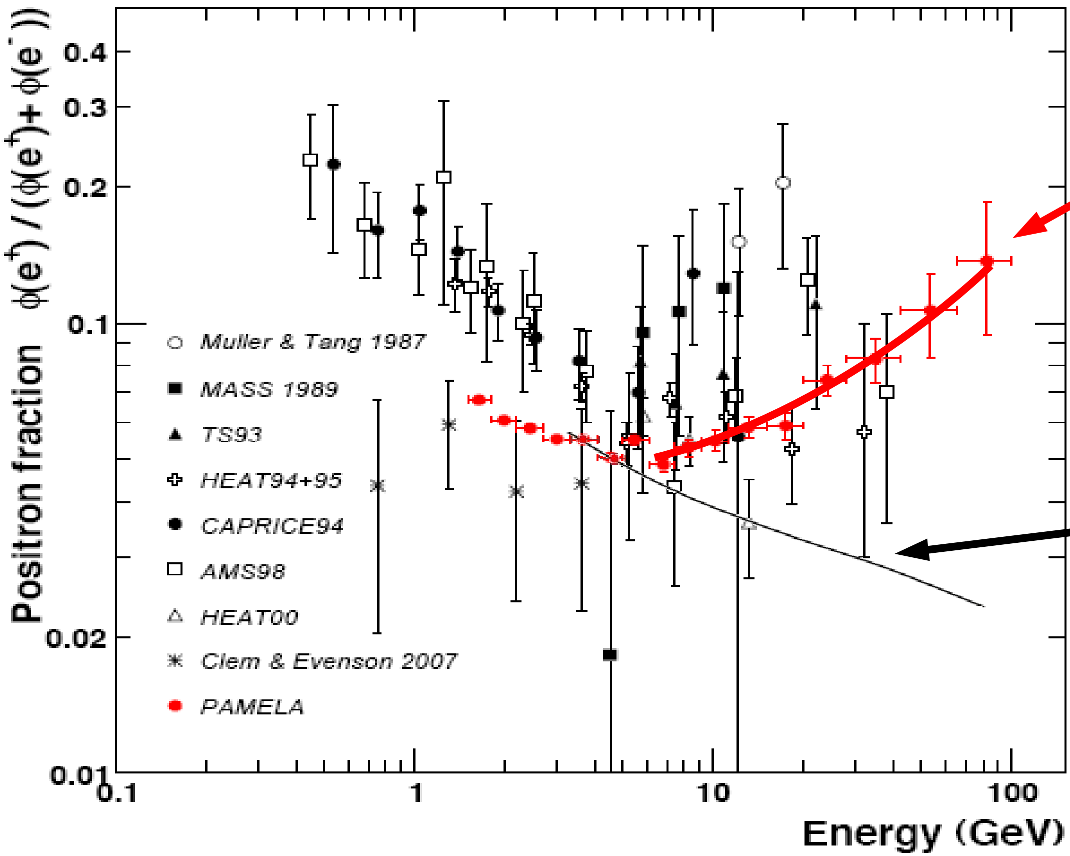
Diemand et al. 2008

- NFW: $$\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$
- Einasto: $$\rho(r) = \rho_s e^{\frac{-2}{\alpha}[(r/r_s)^\alpha - 1]}$$
- Isothermal: $$\rho(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

PAMELA positron fraction

Elena Vannuccini's talk on Tuesday

Adriani *et al.* 2008



Steep rise above 10 GeV
(must have some primary source of energetic cosmic ray positrons)

expectation
(secondaries)

Warrit Mitthumsiri's talk Monday: Confirmed by Fermi!

Cosmic Ray Anomalies

- Could be astrophysical in origin (pulsars, reacceleration of positrons in/around SN remnants)
- Could be annihilating or decaying dark matter
  - Challenges:
    - ➔ Very hard spectrum
    - ➔ No substantial excess in antiprotons or gamma rays
    - ➔ High annihilation rate

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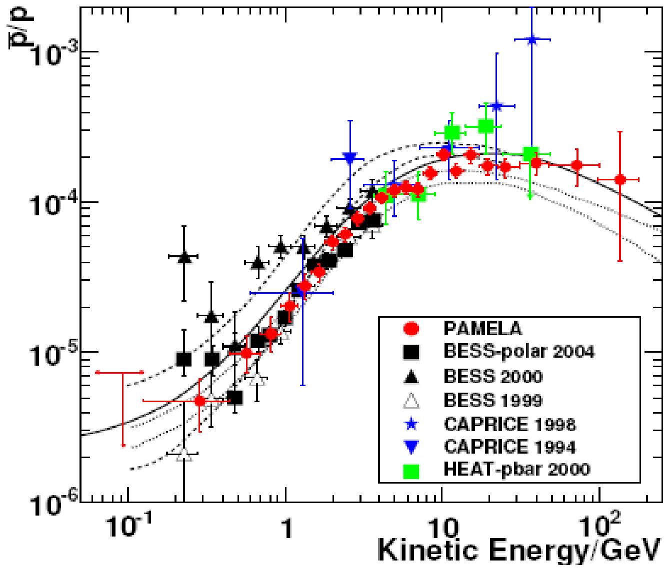
Adriani *et al.* (2010)



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} "leptophilic" annihilations $\chi\chi \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$

➔ High annihilation rate ⇨ "boosted" annihilation cross section

Boosted Annihilation Rate

- **Thermal WIMP:** $\langle \sigma v \rangle_{th} = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$

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

- **Boosted Rate from Particle Physics:**
  - Sommerfeld or Breit-Wigner Enhancement, or non-thermal production mechanism $\langle \sigma v \rangle \gg \langle \sigma v \rangle_{th}$
  - Significant annihilation at high redshift → reionization (constrained by CMB) Galli et al. (2009)
- **Boosted Rate from Astrophysics:**
  - Dark Matter Substructure $\int \rho_{DM}^2 r^2 dr > \int (\rho_{DM}^{smooth})^2 r^2 dr$
  - For most dark matter models, this is not enough to explain the PAMELA excess.

Positrons from Dark Matter

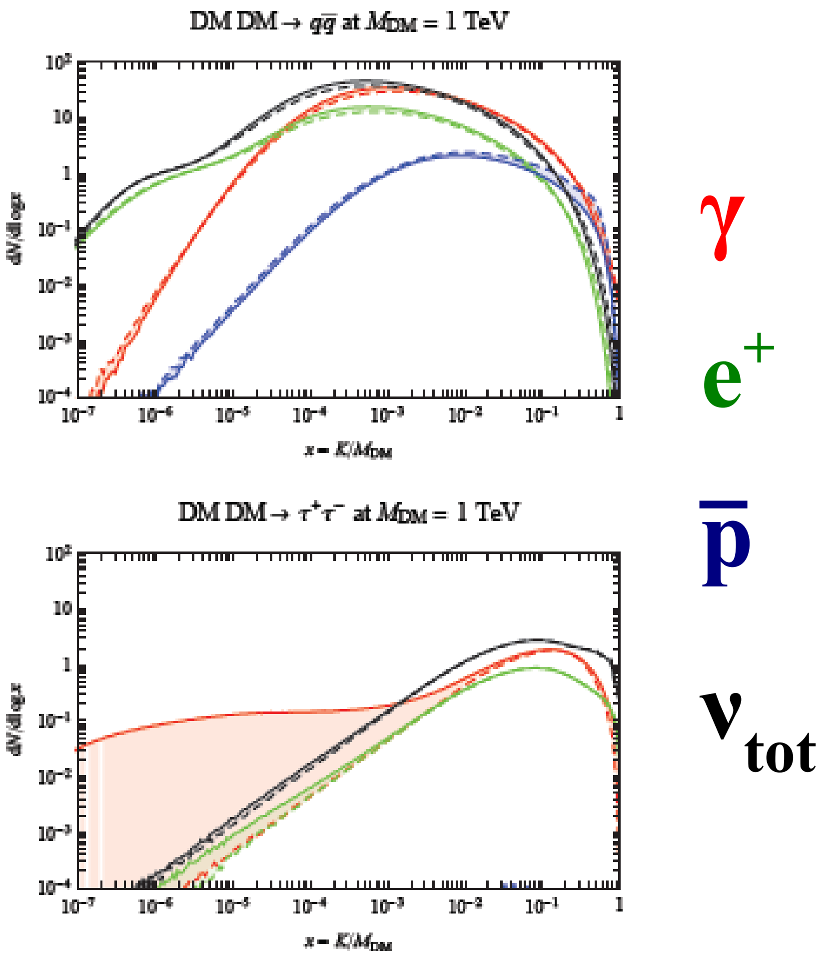
- IF positron excess is due to dark matter, it is not your standard WIMP.

  ➔ Dark matter scenarios that explain the positron excess have serious consequences for other indirect searches.

- If it's NOT dark matter, WIMP hypothesis lives another day...

Photons

- Continuum Spectrum:



Cirelli et al. (2010)

- Monochromatic Line:

Elliott Bloom's talk yesterday

- $\chi\chi \rightarrow \gamma\gamma$

  $E_\gamma = m_\chi$

- $\chi\chi \rightarrow \gamma Y$

  $Y = Z, h^0$, etc.

  $$E_\gamma = m_\chi - \frac{m_Y}{4m_\chi}$$

Predicted γγ branching fractions typically small: 10^{-4} to 10^{-1}

Continuum Spectrum

- Galactic Center
- Galactic Diffuse
- Extragalactic
- Dark Matter Subhalos
- Dwarf Galaxies and Galaxy Clusters

Galactic Center

It's Complicated.

The Galactic Center radiates brilliant insight to anyone connected with it. This infrared information reveals how to let go of what is in the way to make a clear path for the next step. **astrodynamics.net**

Galactic Center

It's Complicated.

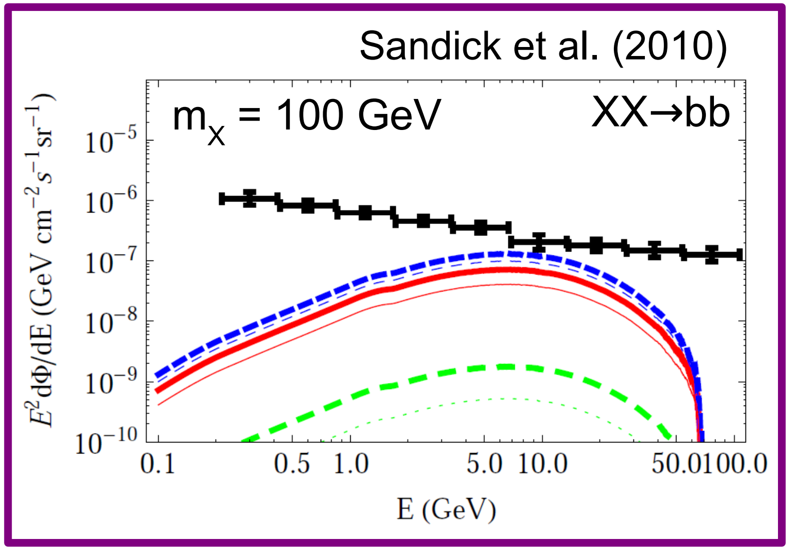
Troy Porter's update on Monday:

It is, indeed, complicated.

- Dark matter density expected to be quite large, but...
- Many sources near/along our line of sight to the GC
  $\longrightarrow$ Source Confusion!
- Diffuse emission??? Good handle on astrophysical background emission is crucial to extracting a DM signal.

Galactic Diffuse Flux

- There's a log of dark matter out there, but...
- Diffuse background is complicated (again with the diffuse emission modeling problem)
  - Major components: π^0 decay, e^+/e^- IC with ISRF, e^+/e^- bremsstrahlung with IS gas, point sources
  - Understanding backgrounds reduces wiggle room for dark matter model-building!
- Substructure changes the expected gamma-ray flux from annihilations or decays



Extragalactic (Cosmological) Dark Matter

- Structures: much larger signal than naïve expectation from average DM abundance in the Universe

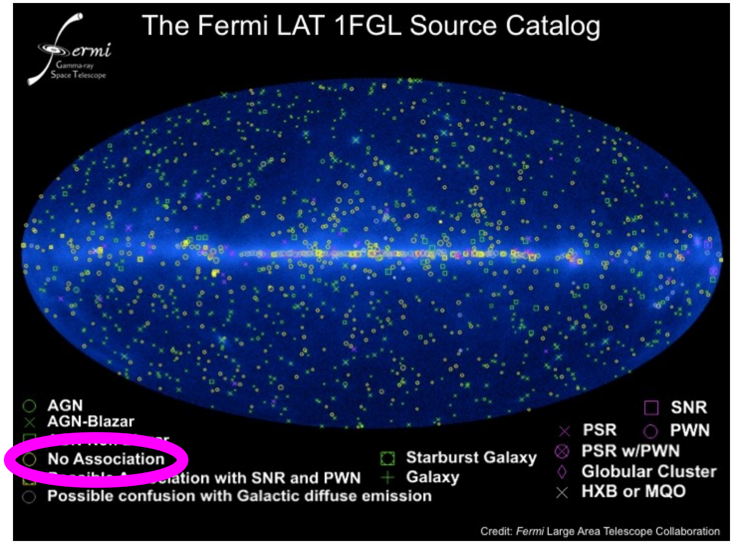
$$\frac{d\phi_\gamma}{dE_{\gamma,0}} = \frac{\langle\sigma v\rangle}{8\pi}\frac{c}{H_0}\frac{\bar{\rho}_X^2}{m_X^2}\int dz(1+z)^3\frac{\Delta^2(z)}{h(z)}\times\frac{dN_\gamma}{dE_\gamma}(E_\gamma(1+z))e^{-\tau(z,E_\gamma)}$$

- Astrophysical uncertainties and complicated backgrounds:
  - Extragalactic BG from unresolved gamma-ray sources (eg. Blazars)
  - Residual contamination from Galaxy (including Galactic DM signal)
    - Look to high galactic latitudes → Is signal extragalactic or from DM substructure in the halo?

Subhalos, Dwarfs, and Clusters, oh MY!

DM objects with unknown locations?

Point Sources: Buckley & Hooper (2010), Sandick et al. (2010)
Extended Sources: Talk by Joshua Lande



DM-dominated objects with known locations:

Dwarf Spheroidal Galaxies	Galaxy Clusters
Near (10's to 100's kpc) & localized	Farther (>Mpc), but more massive
No star-forming regions Little-to-no gas or dust → Few sources	May contain AGN (gamma ray sources)
Stella ... ts of DM distri ... , but central region (cusp) and substructure uncertain	X-ray ... hydro ... ilibrium (lots of dark matter), but distribution uncertain

More from
Maja Llena Garde

No significant excess!
-Stephan Zimmer

Summary & Outlook

- Dark Matter is unambiguous evidence that the Standard Model of particle physics is not complete!
- There are many ways in which Fermi measurements can probe the properties of particle dark matter and theories of physics beyond the Standard Model (ex. Berenji & Bloom: constraints on KK models with Large Extra Dimensions – better than LHC in some cases!)
    - Apologies to those whose work wasn't mentioned
- There is great hope that dark matter will reveal itself in gamma-rays, and we must be ready – increasing wealth of analysis techniques and new ideas.
- Indirect detection + direct detection + LHC = good forecast for uncovering the nature of dark matter and what lies beyond the Standard Model of particle physics.