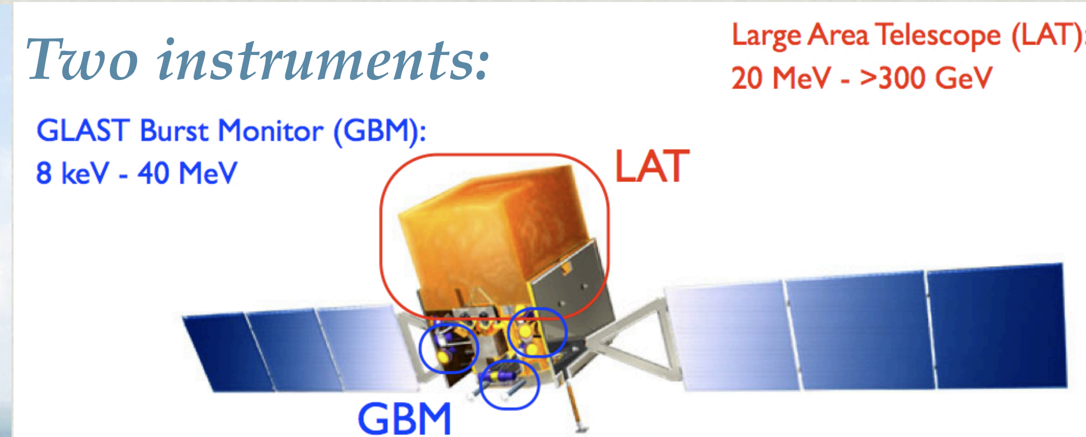
Constraining DM with the Fermi extragalactic diffuse measurement

on behalf of the Fermi collaboration

Gabrijela Zaharijas,
IPhT/CEA Saclay and Stockholm University

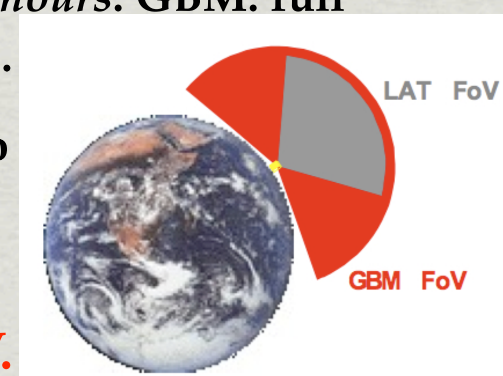
Fermi observatory



Key features:

* *large field of view*: **LAT: 20% of the sky at any instant.** ***In the survey mode exposes every part of the sky for ~30 min, every 3 hours.*** **GBM: full unocculted sky at any time.**

* **energy range: 20 MeV to >300 GeV (LAT),** ***includes previously unexplored energy band*** **10-100 GeV.**



Fermi observatory

Launch 11 June, 2008.

Lifetime: 5 yr (min)

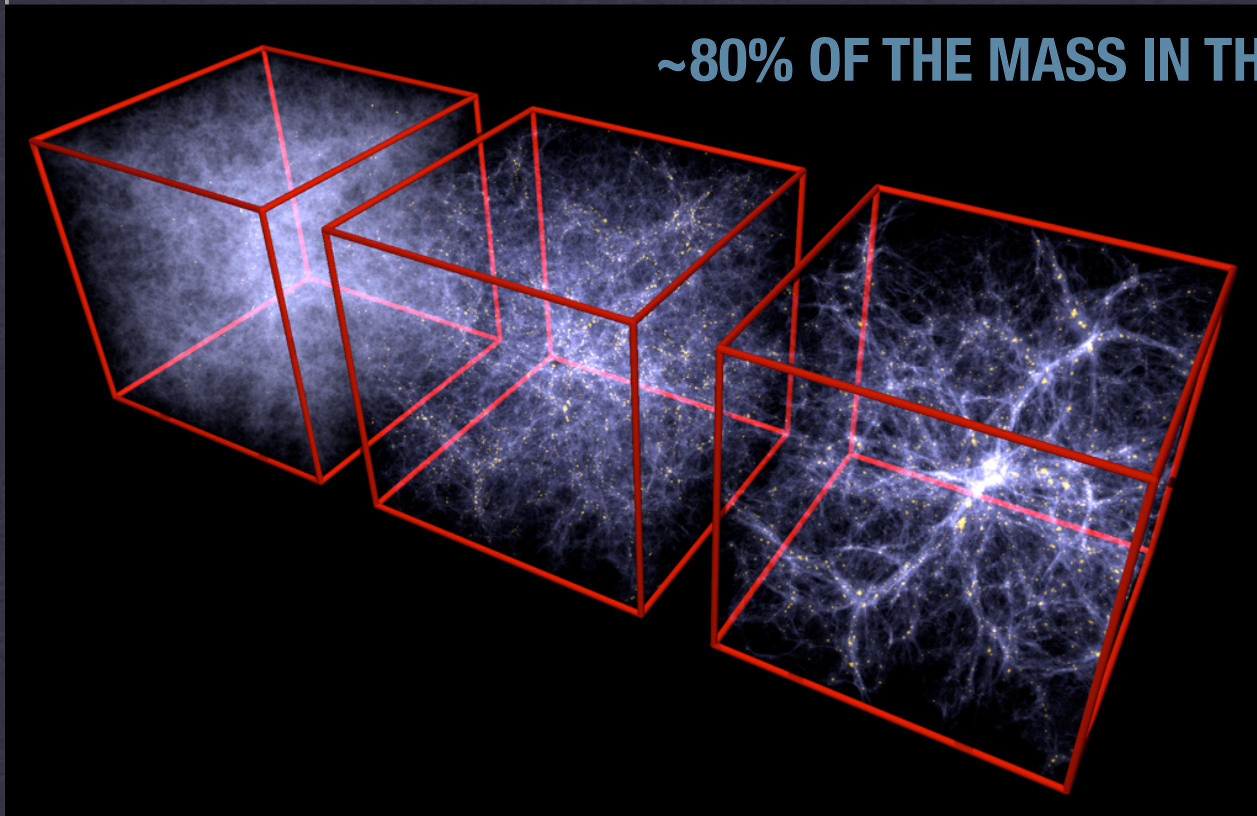
Science with Fermi:

- ***AGN**s (~700 + discovery of 2 Star Burst Galaxies; (EGRET ~60))*
- ***Pulsars** (~50 in a first catalog+discovery of ~10 MSPs)*
- ***SNRs and PWN***
- ***Gamma Ray Bursts***
- ***Source populations and identification***
- ***Diffuse emission***
- ***Cosmic ray electrons***
- ***Solar system** (Sun flares, Moon,...)*

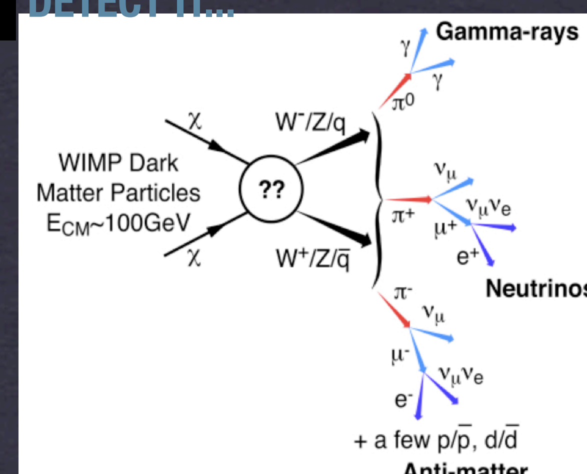
\+ *Discovery/constraints:*

- ***New source classes?***
- ***Dark matter?***

~80% OF THE MASS IN THE UNIVERSE IS "DARK".

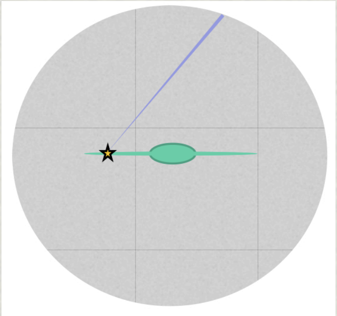


WIMP PARADIGM: THE ANNIHILATION RATE COMES PURELY FROM PARTICLE PHYSICS AND AUTOMATICALLY GIVES THE RIGHT ANSWER FOR THE RELIC DENSITY!
IN TURN, WE EXPECT DARK MATTER TO ANNIHILATE TO STANDARD MODEL PARTICLES. THAT IS HOW WE HOPE TO DETECT IT...



STRUCTURES FORMED THROUGH GRAVITATION PULL OF DARK MATTER, ON THE SEEDS FROM INITIAL QUANTUM OVERDENSITIES IN THE INFLATON FIELD -- FOCUS IN THIS TALK ON ΛCDM COSMOLOGY.

INDIRECT DARK MATTER DETECTION IN GAMMA RAYS



Bergstrom, L., talk at DM2010.

Advantage of gamma-rays: propagation not affected by the Galaxy.
*Can give a specific signature both in **spatial variation** (line-of-sight cone) and **spectral shape**.*

Flux of gamma rays produced in DM annihilations:

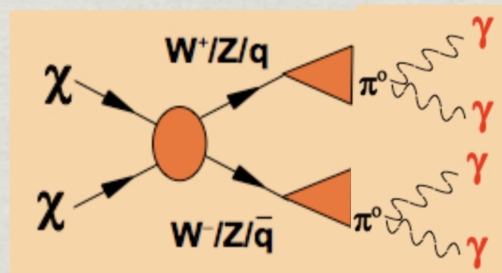
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\theta,\phi) = \frac{1}{4\pi}\left[\frac{\langle\sigma v\rangle_{T_0}}{2\,M_\chi^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f\right]\cdot\left[\int_{\Delta\Omega(\theta,\phi)} d\Omega' \int_{l.o.s.} dl\ \rho_\chi^2(l)\right]$$

* **<σv>**, *fixed by measured DM density today (for a thermally decoupled relic).*
* *dN/dE fixed by particle physics*
* ρ *- from N-body simulations;*

Idea: measure dΦ/dE, and under assumptions for DM density distribution, constrain particle physics.

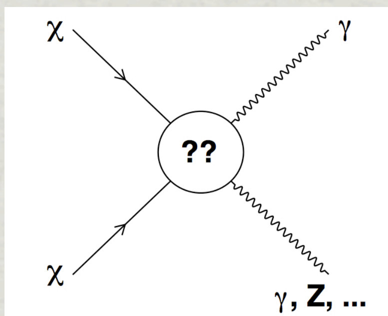
How are DM γ ray fluxes produced?

- **Prompt (direct) radiation:**
  - continuum spectra:



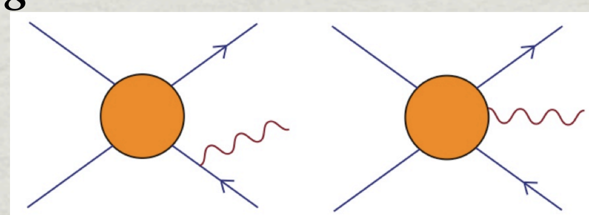
Dominant production for DM annihilating to quarks and gauge bosons (i.e. SUSY) .

  - line:



Loop suppressed, but unique, smoking gun, signature.

  - final state radiation:



- through **radiative processes**:

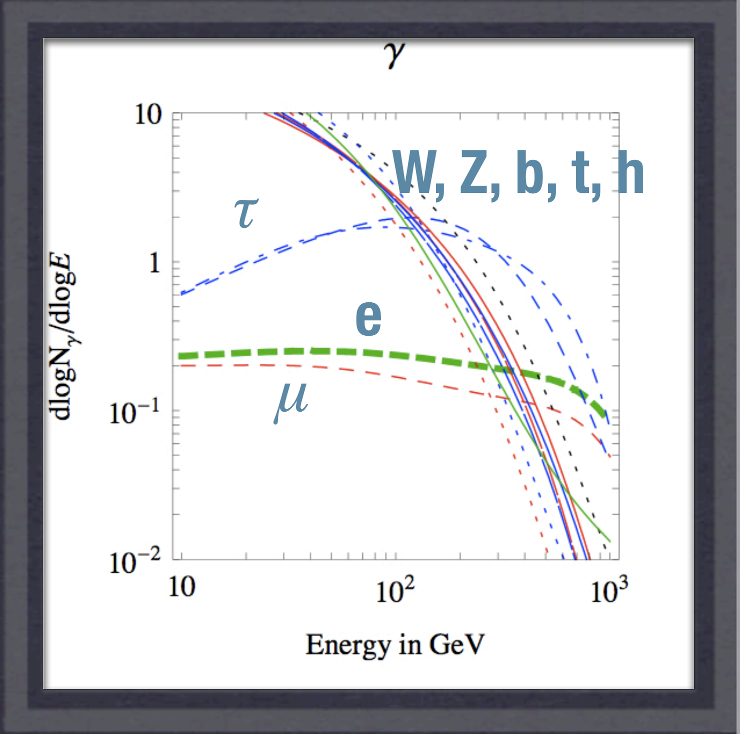
$$\chi\,\bar{\chi} \rightarrow \begin{cases} e^+\,e^- \\ l^+\,l^- \text{ or } \phi\,\phi \rightarrow \ldots + e^+\,e^- \\ P\,\bar{P} \rightarrow \ldots + \pi^\pm \rightarrow \ldots + e^\pm \end{cases} \text{ambient backgrounds and fields} \begin{cases} \text{Synchrotron} \\ \text{Inv. Compton} \\ \text{Bremstrahlung} \\ \text{Coulomb} \\ \text{Ionization} \end{cases} \begin{cases} \text{radio} \\ \text{IR} \\ \text{X-rays} \\ \gamma\text{s} \end{cases}$$

Important if there is a significant branching to leptons.

Spectra (dN/dE):

1) <u>**DM annihilation dominantly to quarks/gauge bosons:**</u> (SUSY, Universal Extra Dimensions, Little Higgs models) mainly produces **direct (prompt) gamma radiation.** All channels produce relatively similar spectra, mostly due to **hadronization and pion decay.**

PROMPT GAMMAS



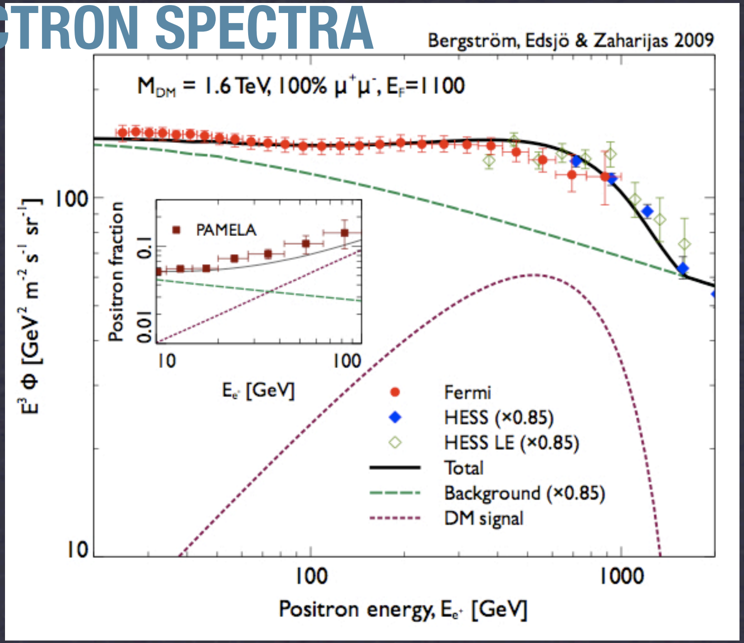
Cirelli, M. et al, Nucl.Phys.B813:1-21,2009.

Spectra (dN/dE):

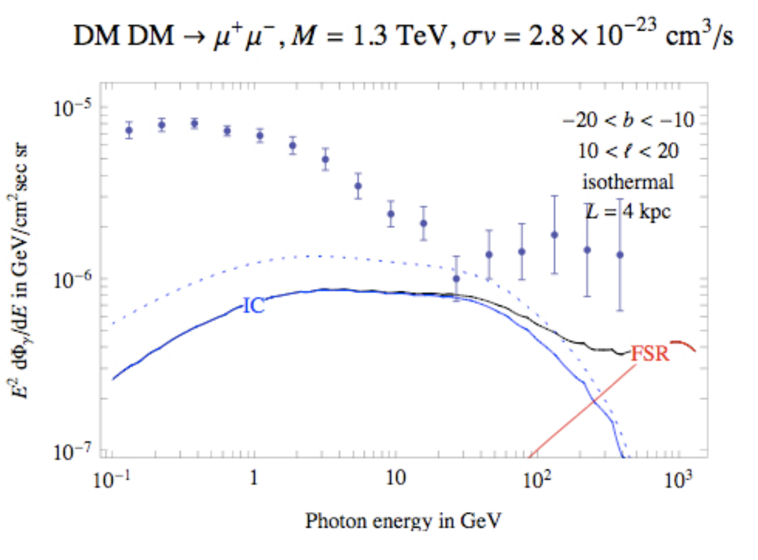
2) DM annihilation dominantly to leptons :

introduced somewhat ad hoc from the particle physics side, typically invoked to explain cosmic ray measurements.

ELECTRON SPECTRA



GAMMA RAY SPECTRA

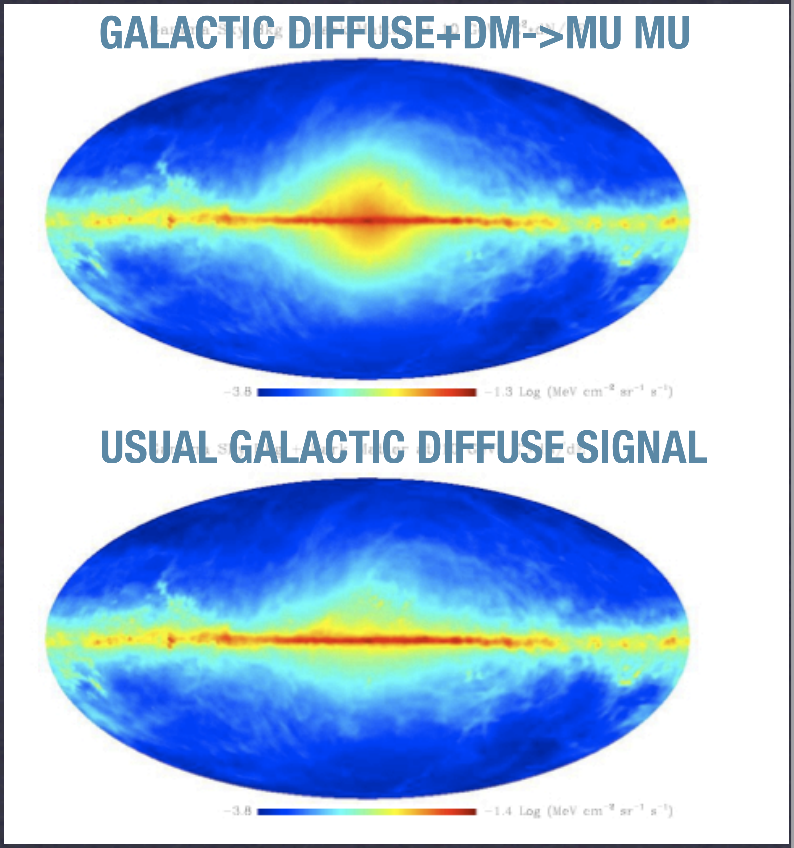


Papucci, M. et al, arXiv:0912.0742

Bergstrom, L., Edsjo, J., GZ, Phys.Rev.Lett.103:031103,2009.
NOTE: in this type of models DM cross section has to be ~100, 1000 times stronger than the standard value (could be achieved, for example, thorough Sommerfield enhancement...).

2) DM annihilation dominantly to leptons :

High energy (>~1 GeV) gamma rays are most importantly produced by Inverse Compton scatter of these electrons on the CMB, starlight or Infrared photons.
For example, in our galaxy, those electrons would diffuse out of the Galactic Center (where their density is the highest) and produce extended gamma ray emission in inverse scattering, of starlight photons.

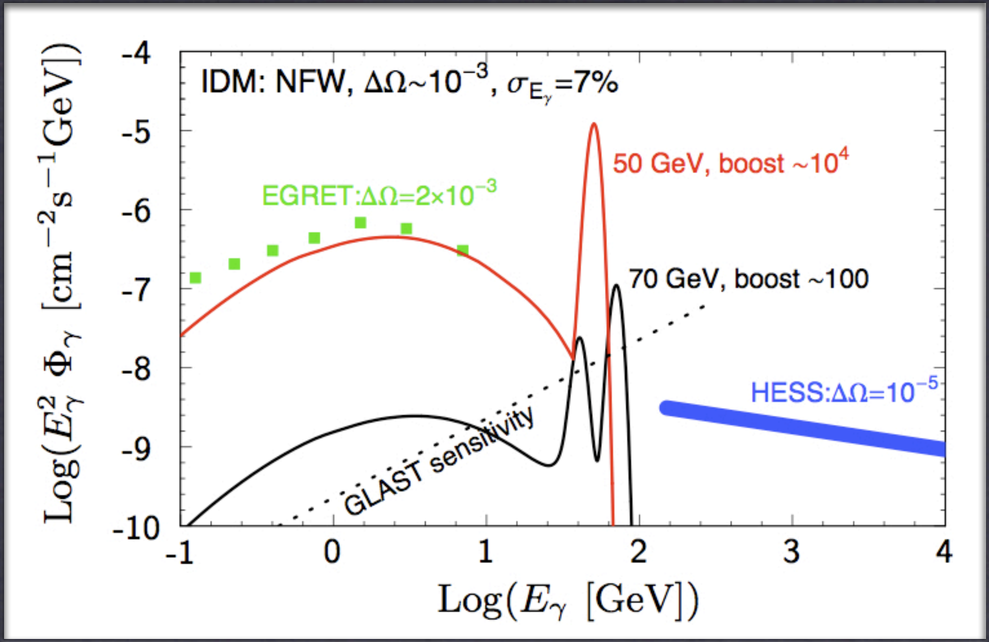


Cuoco, A. et al, Astrophys.J.699:L59-L63,2009

Spectra (dN/dE):

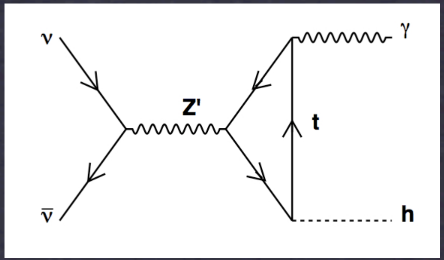
3) DM annihilations into two photons, or gamma Z

$$\frac{dN_\gamma}{dE} = 2\, b_{\gamma\gamma}\delta(E - m_X)$$



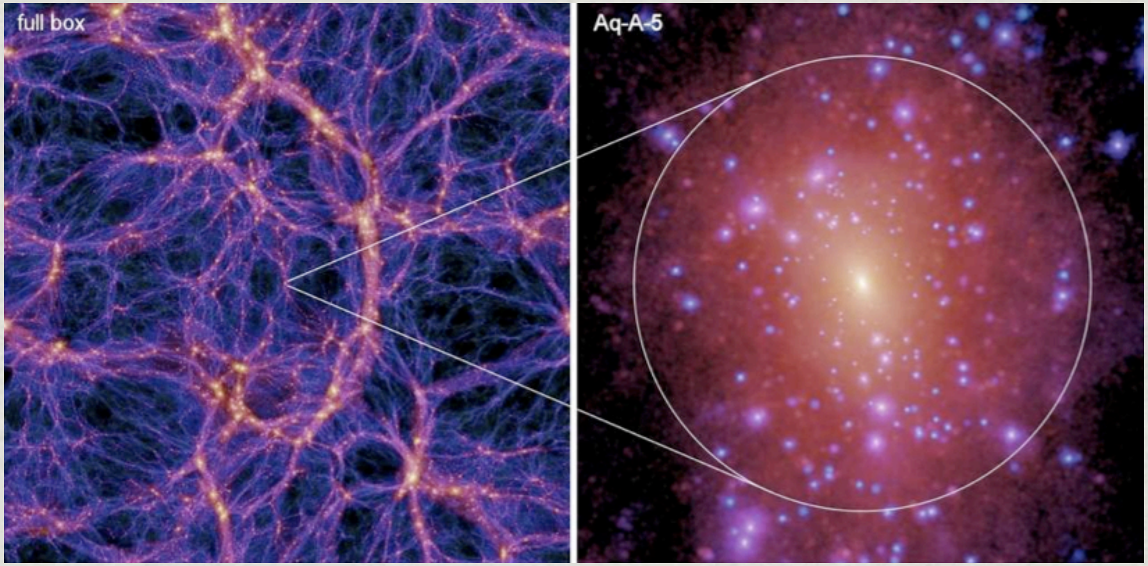
Gustafsson, M. et al, Phys.Rev.Lett.99:041301,2007

In general line signature is loop suppressed (DM has charge zero and doesn't couple to photons directly) b~10^{-3}. In some models, however, this branching can be enhanced, for example if the Z' is the only portal to SM particles, as in the case of Dirac DM, discussed in "Higgs in space!".



Jackson, C.B. et al, arXiv: 0912.0004

Dark matter profile (ρ):



Springel, V. et al, Mon.Not.Roy.Astron.Soc.391:1685-1711,2008.

Obtained from N-body simulations which find cuspy host halos (NFW or Einasto DM density profile) with numerous subhalos (which themselves contain subhalos...).

N-body simulations have impressive agreement with large scale structures.

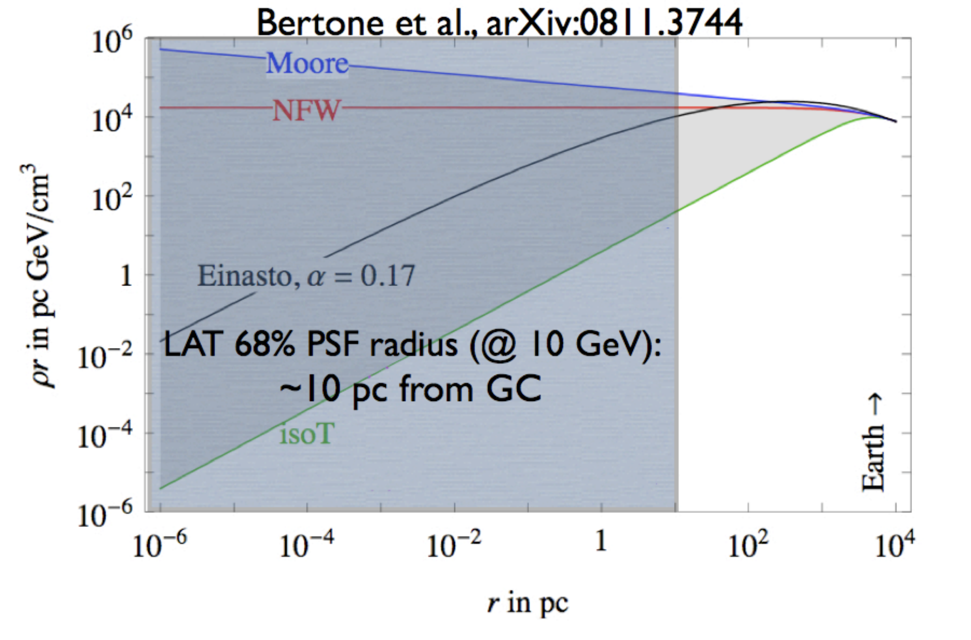
However,

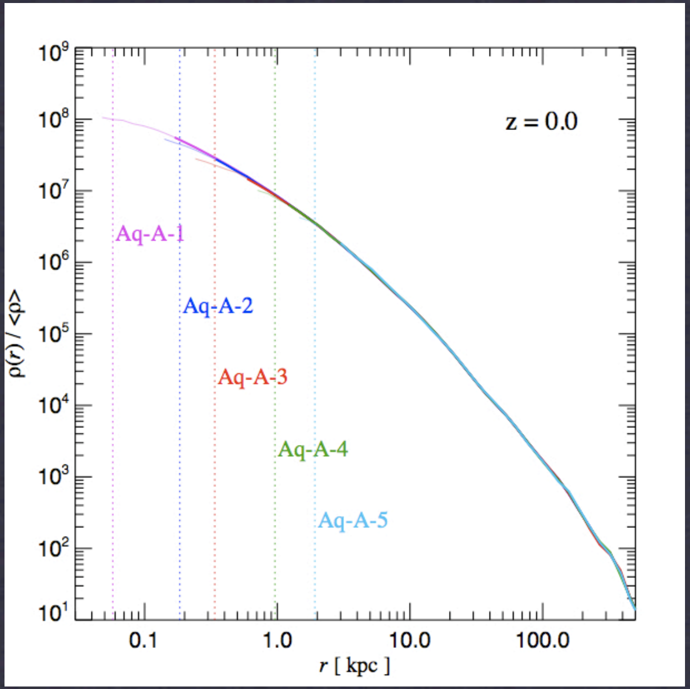
- *Do not resolve the inner most region of the halo (<~100 pc);*
- *They have also limited mass resolution to >~10^5 M_{sol} (sub) halos.*
- *the highest resolution simulations do not typically include interaction with baryons (which e.g. in the Galactic Center might play an important role!);*

Related uncertainties in estimating the DM signal can be ~ order(s) of magnitude.

Dark matter distribution

Inner region of a halo is largely unresolved...



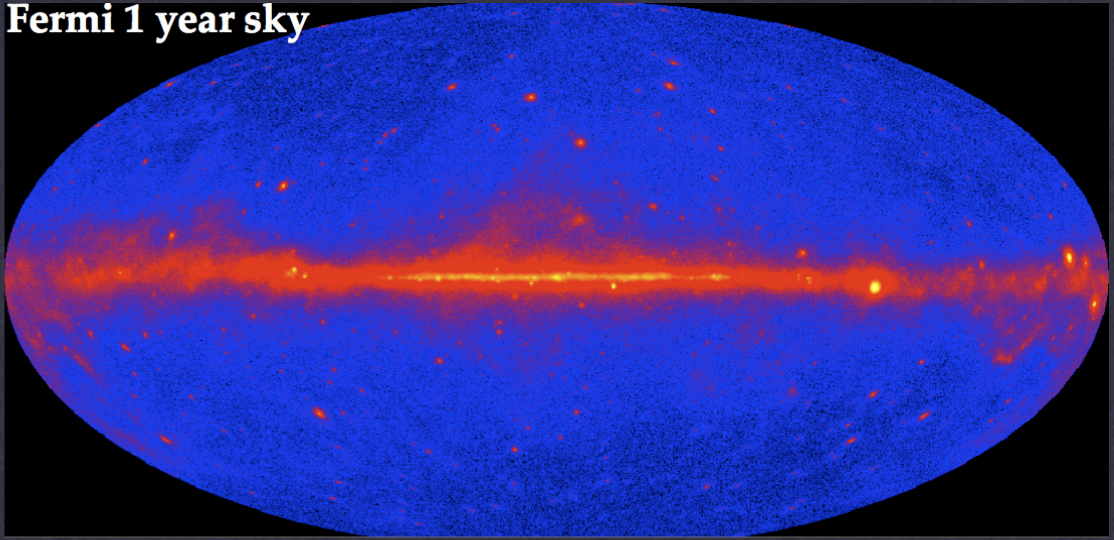


Springel, V. et al, Mon.Not.Roy.Astron.Soc.391:1685-1711,2008.

DM signal depends on ρ^2, and therefore is very sensitive to the DM profile.
Some targets, which mainly probe outer regions of DM halos (e.g. dwarf galaxies, Galactic Halo...) are less sensitive to the actual profile shape, while for some (e.g. GC) it is the main source of uncertainty...

THE FERMI GAMMA RAY SKY

1451 sources in first Fermi LAT source catalog (11 months)
57% of the sources have positional associations, mostly with blazars and pulsars
small number of other sources: PWN, SNR, straburst galaxies, ...

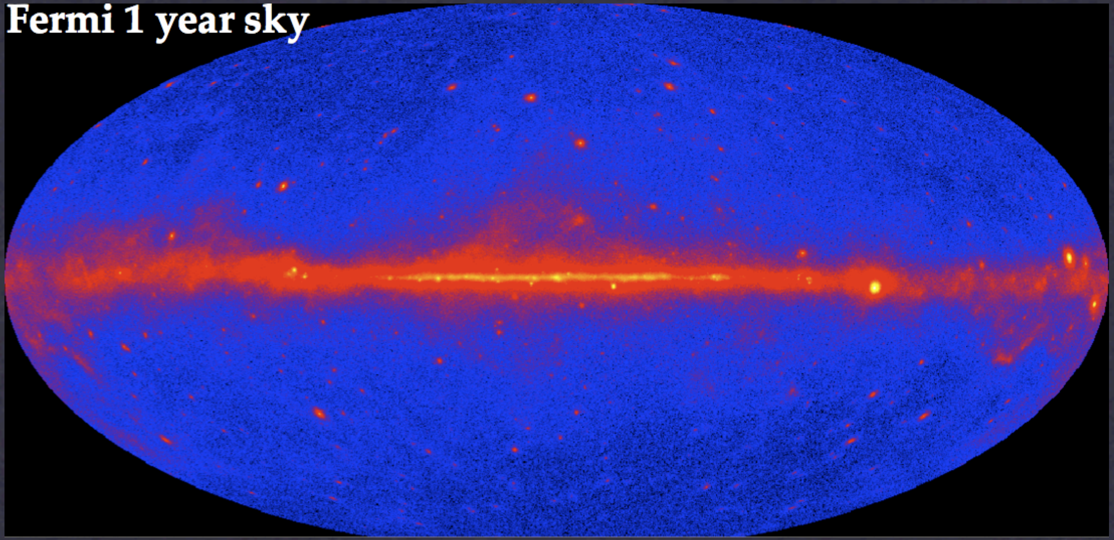


THE FERMI DM SEARCH STRATEGIES

SATELLITES

GALACTIC CENTER

GALACTIC DIFFUSE
HALO



SPECTRAL LINE SEARCH

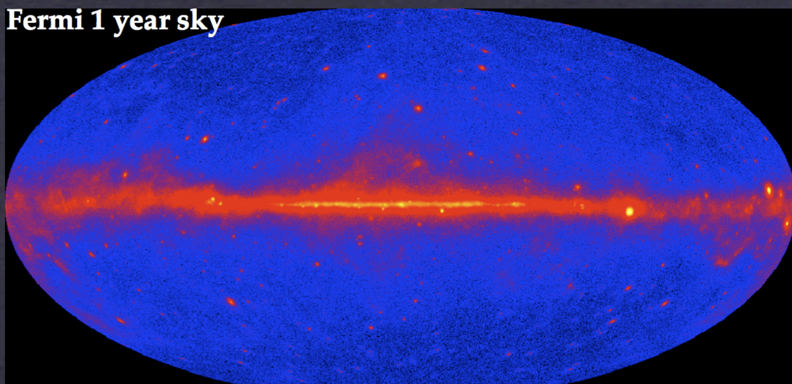
GALAXY CLUSTERS

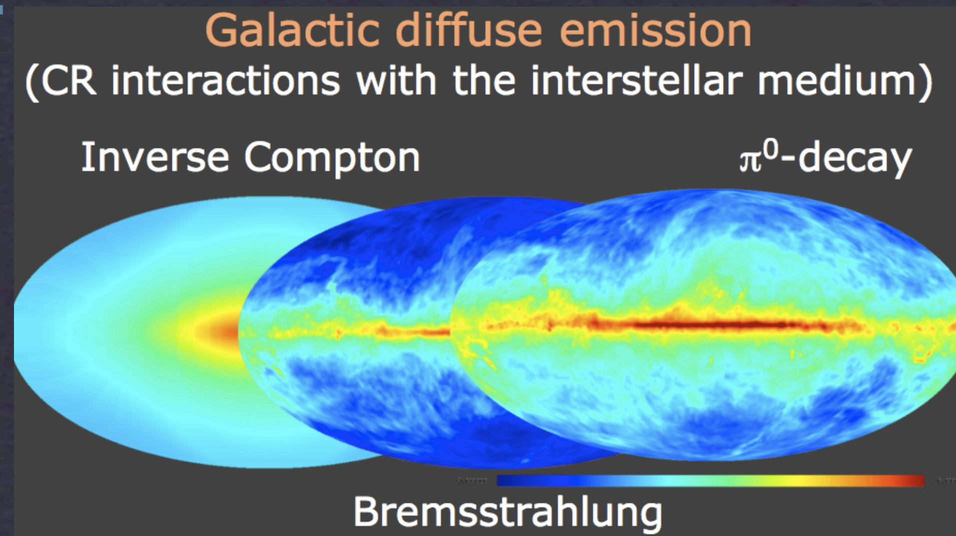
EXTRAGALACTIC DIFFUSE
SIGNAL

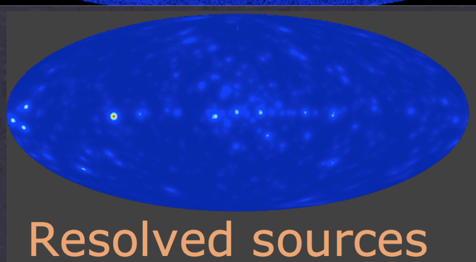
Murgia, S., talk at APS, 2010.

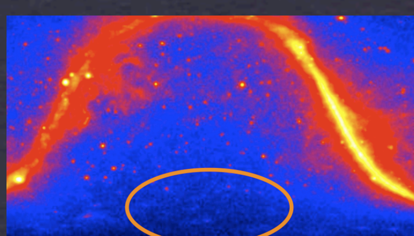
Search for DM in the Isotropic diffuse signal - THE SIGNAL

THERE ARE MANY CONTRIBUTIONS TO THE GAMMA RAY FERMI SKY:





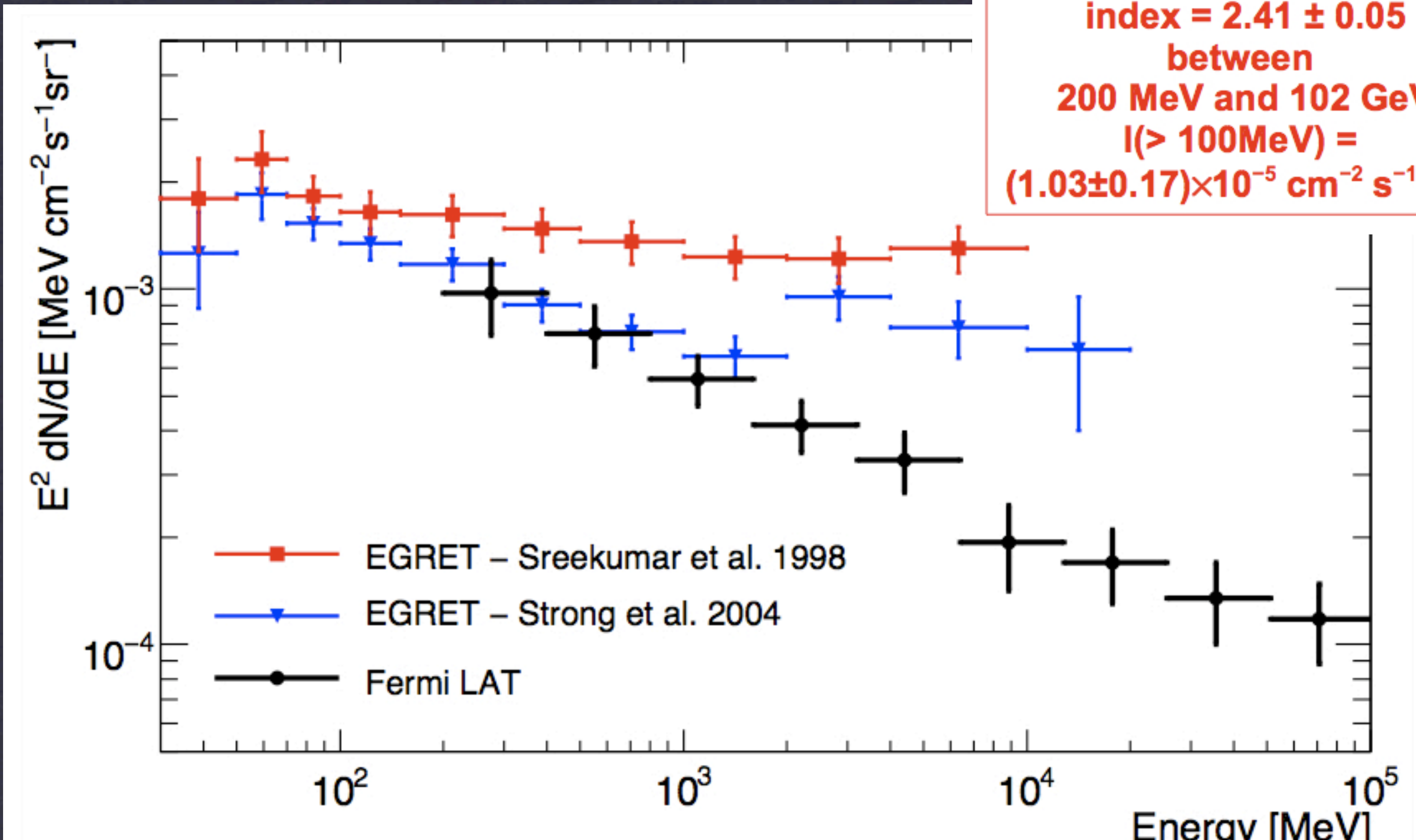




- RESIDUAL COSMIC RAYS (SURVIVING BACKGROUND REJECTION FILTERS)
- MISS-RECONSTRUCTED GAMMAS FROM THE EARTH'S ALBEDO
- AND ISOTROPIC DIFFUSE EMISSION!

Ackermann, M., talk at TeVPa, 2009.

Search for DM in the Isotropic diffuse signal - THE SIGNAL



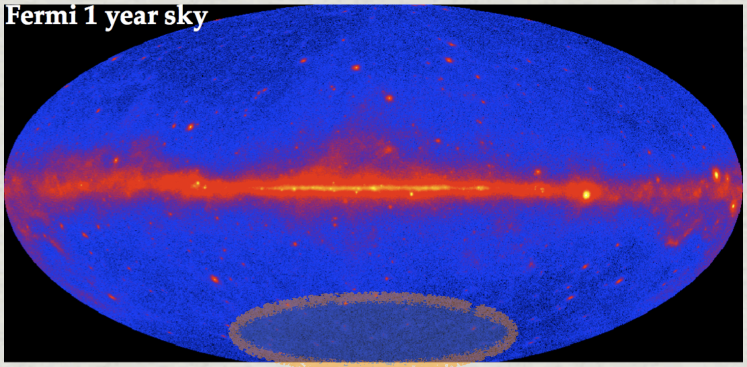
spectrum compatible with a power law of index = 2.41 ± 0.05 between 200 MeV and 102 GeV
I(> 100MeV) = $(1.03\pm0.17)\times10^{-5}$ cm^{-2} s^{-1} sr^{-1}

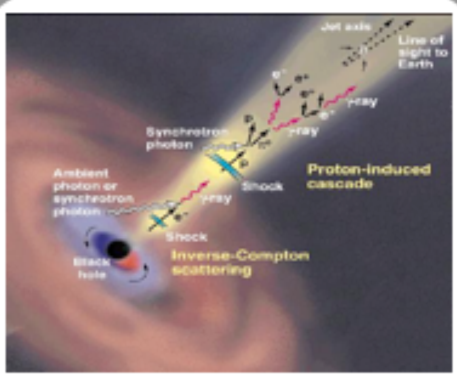
Abdo, A. et al., Phys.Rev.Lett.104:101101,2010.

Search for DM in the Isotropic diffuse signal

Fermi-LAT collaboration, JCAP 1004:014,2010.

What makes the GeV extragalactic signal?

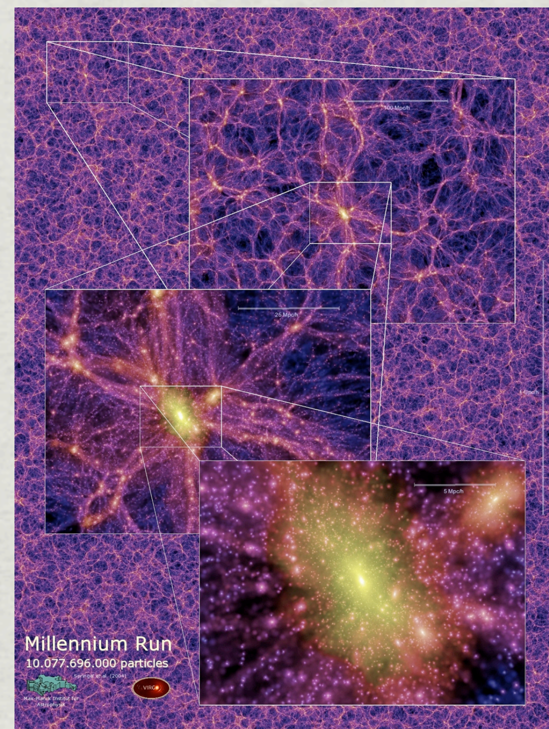




Credit: J. Buckley 1998 (Science), illustration: K. Sutliff

Guaranteed contribution: ***unresolved extragalactic sources***: blazars (AGNs with jets aligned with out line of sight), star forming and star burst galaxies...

Dark matter annihilation in all halos at all redshifts should contribute, too.



Ullio et al., Phys.Rev.D66:123502,2002.

DM cosmological signal

$$\frac{d\phi_\gamma}{dE_0} = \frac{\sigma v}{8\pi} \frac{c}{H_0} \frac{\bar{\rho}_0^2}{M_\chi^2} \int dz\, (1+z)^3 \frac{\Delta^2(z)}{h(z)} \frac{dN_\gamma(E_0\,(1+z))}{dE} e^{-\tau(z,E_0)}$$

$$\Delta^2(z) \equiv \int dM \frac{\nu(z,M) f\,(\nu(z,M))}{\sigma(M)} \left| \frac{d\sigma}{dM} \right| \Delta_M^2(z,M)$$

$$\Delta_M^2(z,M) \equiv \frac{\Delta_{vir}(z)}{3} \int dc'_{vir}\, \mathcal{P}(c'_{vir}) \frac{I_2(x_{min}, c'_{vir}(z,M)\, x_{-2})}{[I_1(x_{min}, c'_{vir}(z,M)\, x_{-2})]^2} (c'_{vir}(z,M)\, x_{-2})^3$$

Semi-analytic approach:

Ullio et al., Phys.Rev.D66:123502,2002.

DM cosmological signal

$$\frac{d\phi_\gamma}{dE_0} = \frac{\sigma v}{8\pi}\frac{c}{H_0}\frac{\bar{\rho}_0^2}{M_\chi^2}\int dz\,(1+z)^3\frac{\Delta^2(z)}{h(z)}\frac{dN_\gamma(E_0\,(1+z))}{dE}e^{-\tau(z,E_0)}$$

Enhancement of the annihilation signal due to structure formation (~ρ^2)!

$$\Delta^2(z) \equiv \int dM \frac{\nu(z,M) f\left(\nu(z,M)\right)}{\sigma(M)}\left|\frac{d\sigma}{dM}\right|\Delta_M^2(z,M)$$

Halo mass function (number density of halos of a given mass)

νf(ν) calculated as in Sheth and Tormen formalism

$$\Delta_M^2(z,M) \equiv \frac{\Delta_{vir}(z)}{3}\int dc'_{vir}\,\mathcal{P}(c'_{vir})\frac{I_2(x_{min},c'_{vir}(z,M)\,x_{-2})}{\left[I_1(x_{min},c'_{vir}(z,M)\,x_{-2})\right]^2}(c'_{vir}(z,M)\,x_{-2})^3$$

Enhancement (~ρ^2) for halos of a fixed mass M.

Depends on the profile (NFW, Moore, ...), concentation parameter c(M,z) and its scatter P(c).

Semi-analytic approach: **Ullio et al., Phys.Rev.D66:123502,2002.**

DM cosmological signal

$$\frac{d\phi_\gamma}{dE_0} = \frac{\sigma v}{8\pi}\frac{c}{H_0}\frac{\bar{\rho}_0^2}{M_\chi^2}\int dz\,(1+z)^3\frac{\Delta^2(z)}{h(z)}\frac{dN_\gamma(E_0\,(1+z))}{dE}e^{-\tau(z,E_0)}$$

DM spectra, calculated at energy of emission $E=E_0(1+z)$.

E_0 is redshifted, measured energy, at $z=0$.

$$\Delta^2(z) \equiv \int dM \frac{\nu(z,M) f\left(\nu(z,M)\right)}{\sigma(M)}\left|\frac{d\sigma}{dM}\right|\Delta_M^2(z,M)$$

$$\Delta_M^2(z,M) \equiv \frac{\Delta_{vir}(z)}{3}\int dc'_{vir}\,\mathcal{P}(c'_{vir})\frac{I_2(x_{min},c'_{vir}(z,M)\,x_{-2})}{\left[I_1(x_{min},c'_{vir}(z,M)\,x_{-2})\right]^2}(c'_{vir}(z,M)\,x_{-2})^3$$

Semi-analytic approach:

Ullio et al., Phys.Rev.D66:123502,2002.

DM cosmological signal

$$\frac{d\phi_\gamma}{dE_0} = \frac{\sigma v}{8\pi}\frac{c}{H_0}\frac{\bar{\rho}_0^2}{M_\chi^2}\int dz\,(1+z)^3\frac{\Delta^2(z)}{h(z)}\frac{dN_\gamma(E_0\,(1+z))}{dE}e^{-\tau(z,E_0)}$$

Absorption of high energy photons on the Extra Galactic Background Light.

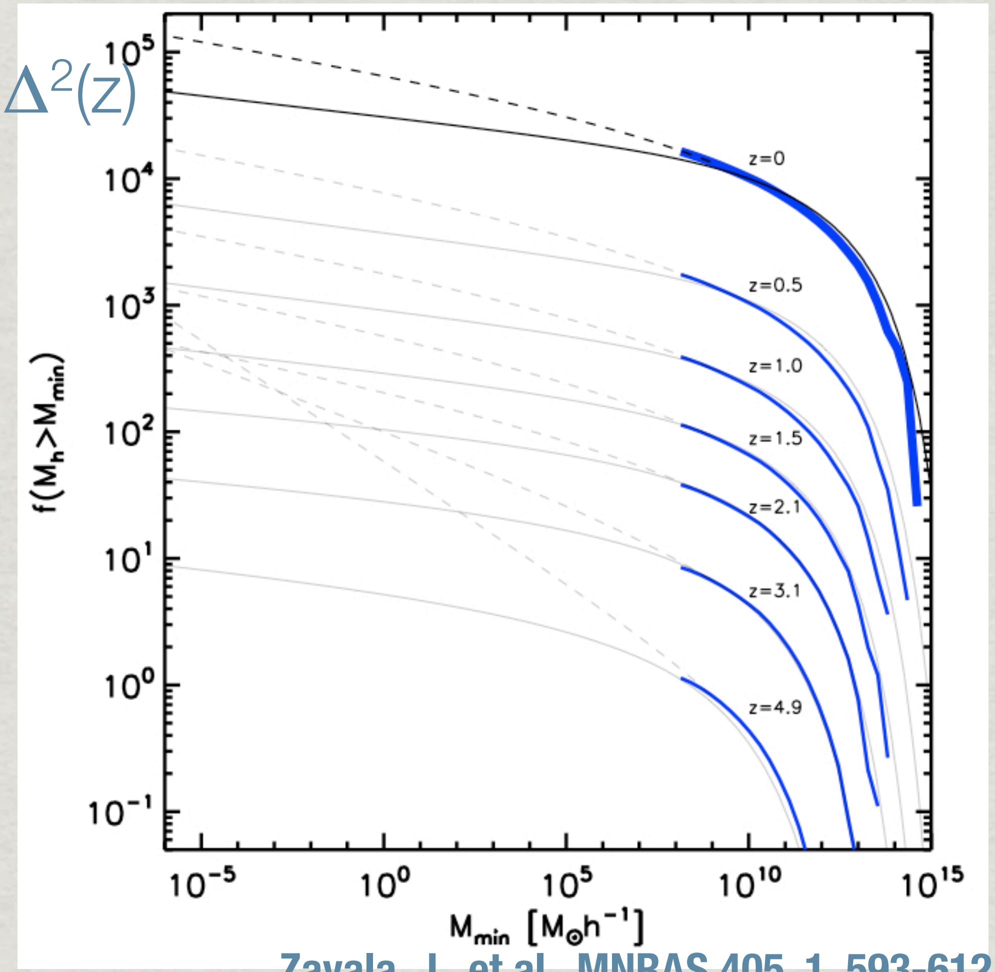
$$\Delta^2(z) \equiv \int dM \frac{\nu(z,M) f\,(\nu(z,M))}{\sigma(M)}\left|\frac{d\sigma}{dM}\right|\Delta_M^2(z,M)$$

$$\Delta_M^2(z,M) \equiv \frac{\Delta_{vir}(z)}{3}\int dc'_{vir}\,\mathcal{P}(c'_{vir})\frac{I_2(x_{min},c'_{vir}(z,M)\,x_{-2})}{[I_1(x_{min},c'_{vir}(z,M)\,x_{-2})]^2}(c'_{vir}(z,M)\,x_{-2})^3$$

$\Delta^2(z)$ - enhancement of annihilation flux due to the formation of gravitational structures

We use results of Millennium simulation II, as well as "semi-analytical approach" described on previous slides and tuned to simulations.

The most critical point is the mass resolution: the smallest resolution, at z=0 in simulations is >~10^5 M_{sol},(Aquarius), while DM is expected to form halos down to ~10^{-6} M_{sol} (free streaming length).



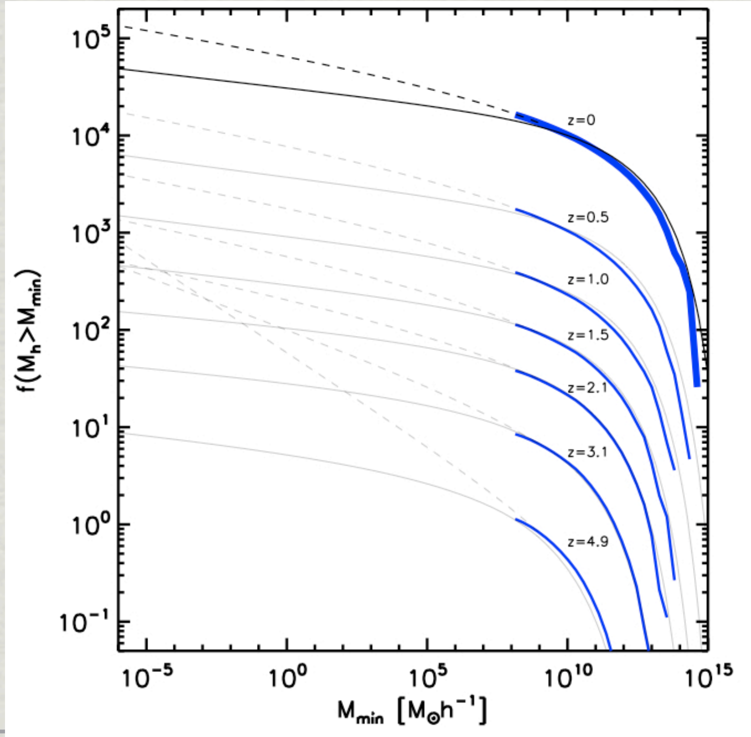
Zavala, J., et al., MNRAS 405, 1, 593-612

EXTRAPOLATION BELOW THE MASS RESOLUTION OF SIMULATIONS:

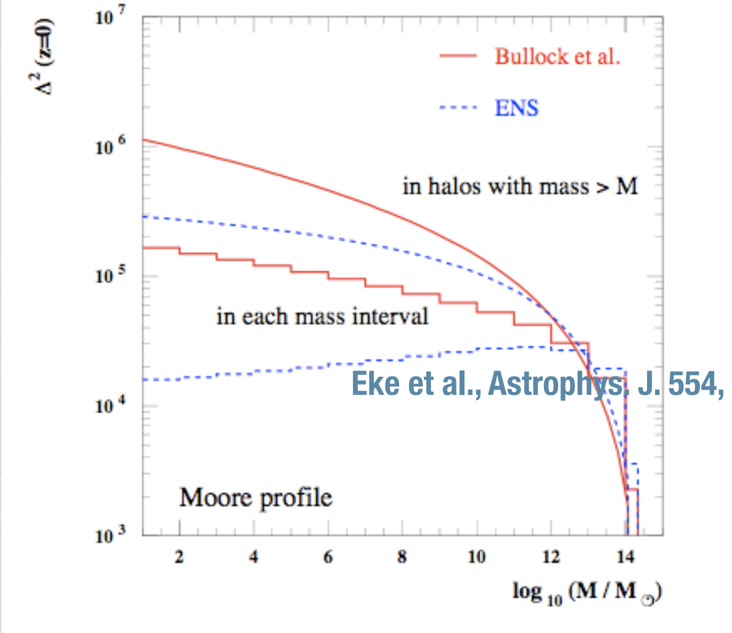
The dominant contribution to Δ^2 comes from very small halos!

In the semi-analytic approach: *physically motivated dependence of concentration parameter with red shift:*

$$c_{vir}(M,z) = K\frac{1+z_c}{1+z} = \frac{c_{vir}(M,z=0)}{(1+z)}$$



Bullock et al., Mon.Not.Roy.Astron.Soc. 321:559-575,2001



Eke et al., Astrophys. J. 554, 114 (2001).

Ullio et al., Phys.Rev.D66:123502,2002.

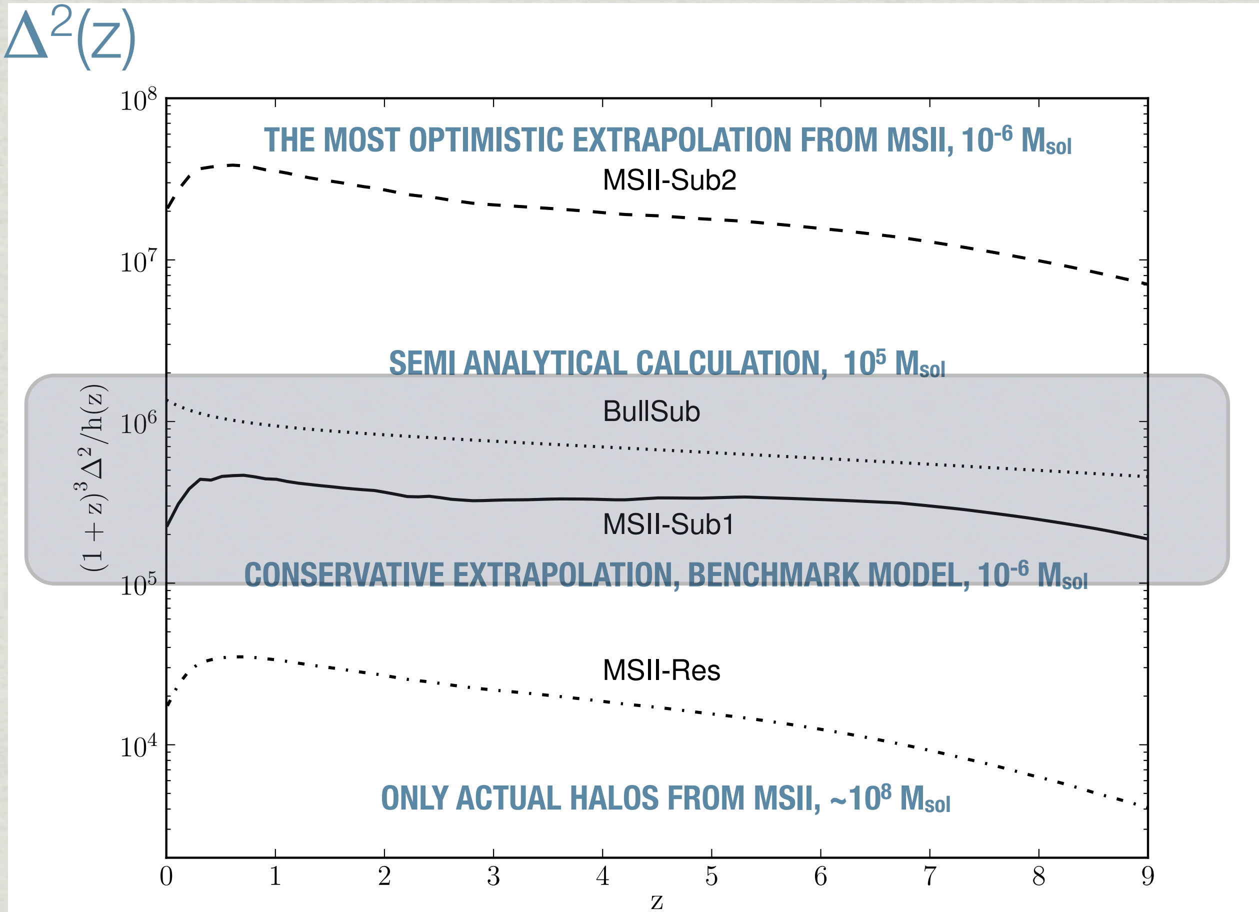
Results of Millennium Simulation II: *power law extrapolation to lower masses.*
However, a scatter in power law slope carefully checked, in the case of substructures.

Zavala, J., et al., MNRAS 405, 1, 593-612

$\Delta^2(z)$ - enhancement of annihilation flux due to the formation of gravitational structures

Conservative extrapolation from Millennium simulation II, and "semi-analytical approach" agree well in predicted fluxes.

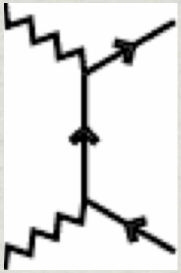
Ongoing effort to minimize this uncertainty: by using the "semi analytical" approach, together with the most recent N-body simulations.

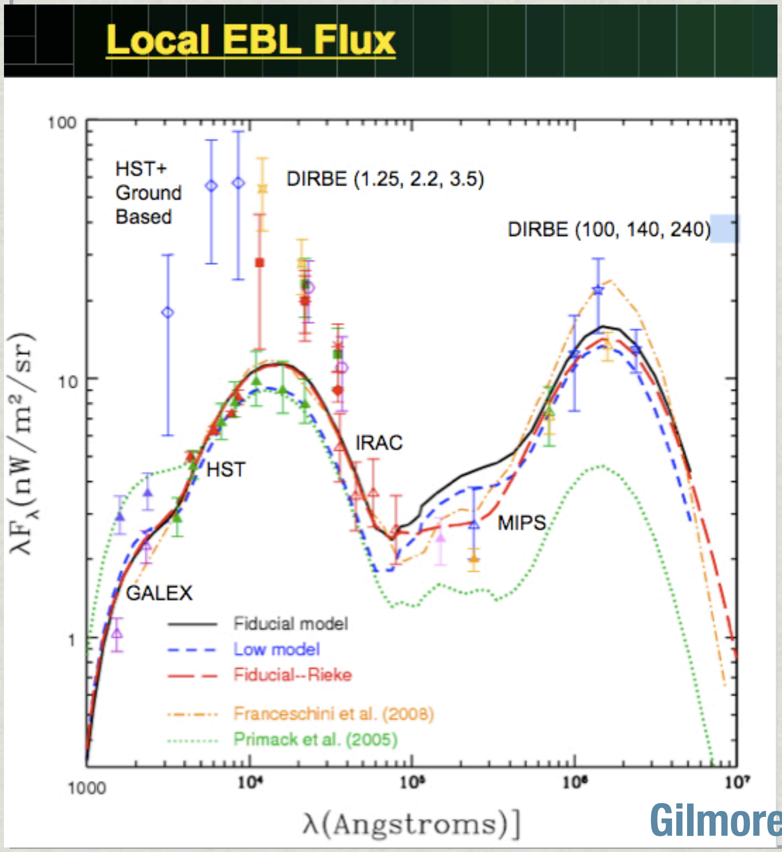


Abdo, A. et al., JCAP 1004:014,2010.

$e^{-\tau}$ - absorption of photons along the line of sight

High energy photons scatter with Extra galactic Background Light (from the UV to far-IR), and get attenuated through electron pair production.

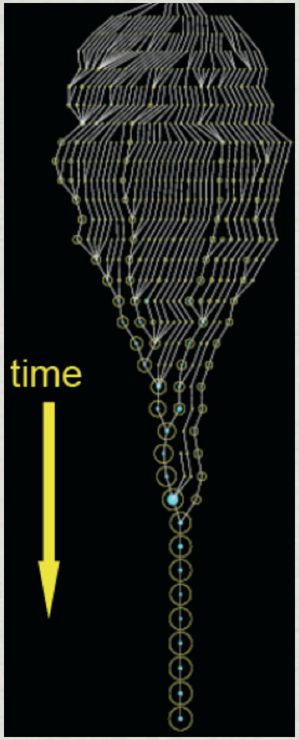




Measurement of local EBL as well as modeling of red shift evolution of EBL is very challenging!

We use the most recent results of the Semi-Analytic Model by Primack, Gilmore, Somerville, arXiv: 0811.3230.

It treats evolution of AGN, black holes, and galaxies in ΛCDM framework

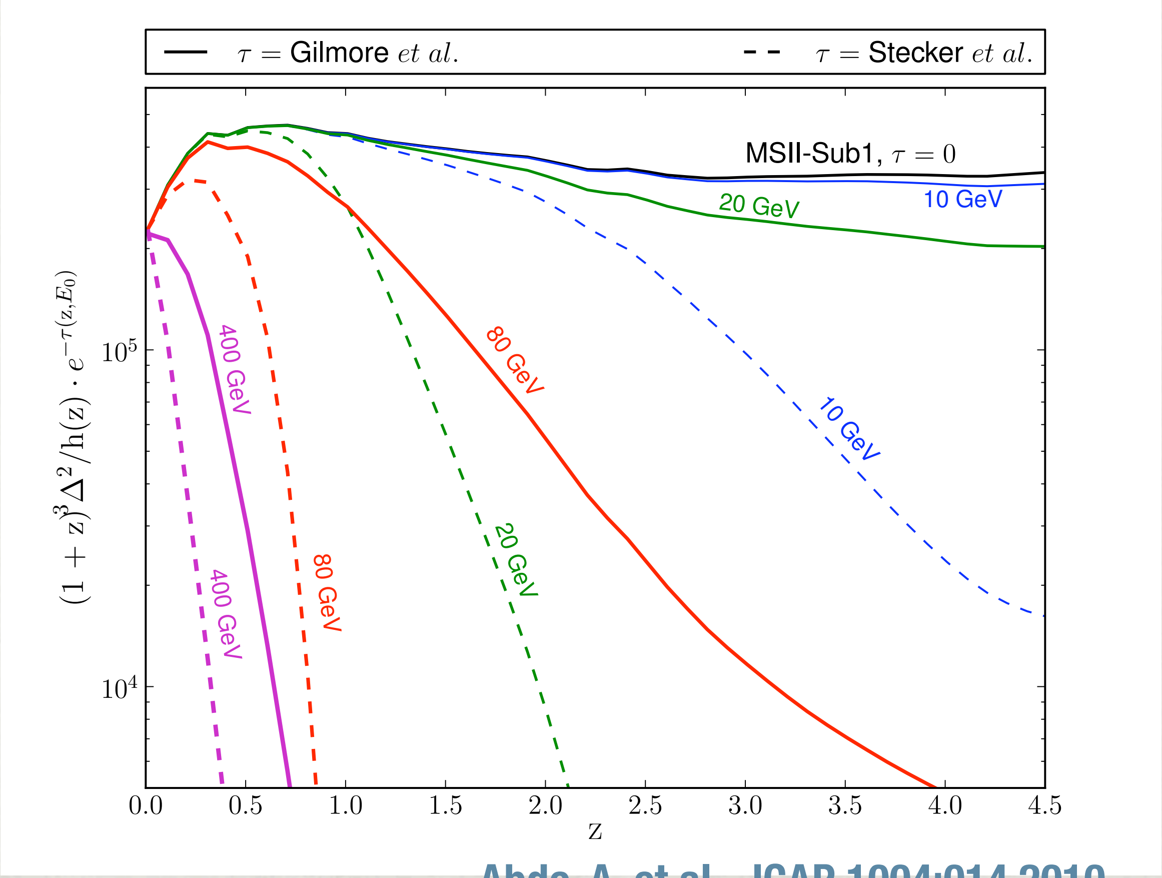


Gilmore, R., talk at TeVPa, 2009.

$e^{-\tau}$ - absorption of photons along the line of sight

Comparison of the most recent modeling (Gilmore et al., arXiv:0905.1144) with the older, commonly assumed absorption model (Stecker et al.,astro-ph/0510449), which over predicts the absorption.

Notice: dominant contribution to the signal comes only from z<~2.



Abdo, A. et al., JCAP 1004:014,2010.

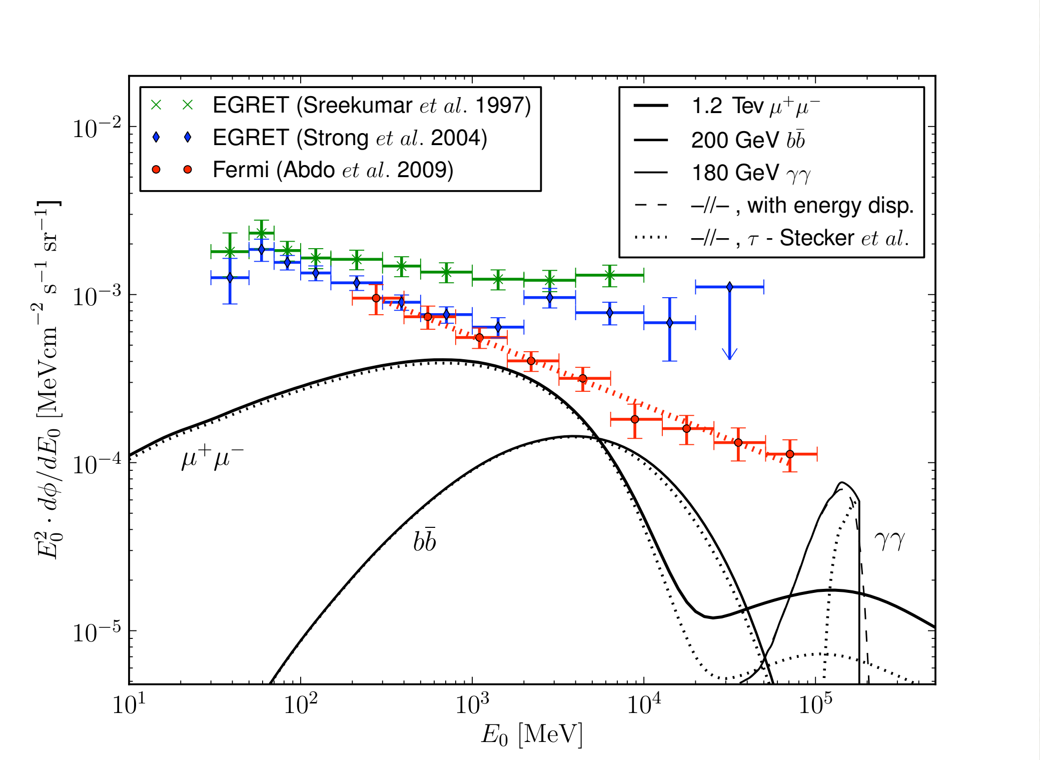
Particle physics models

Abdo, A. et al., JCAP 1004:014,2010.

- DM annihilating dominantly to quarks and gauge bosons (we choose bbar channel); photons produced in hadronization and pion decay of final products.

- DM annihilating to muons: GeV photons produced in inverse Compton scatter off of the CMB photons + Final State Radiation at higher energies.

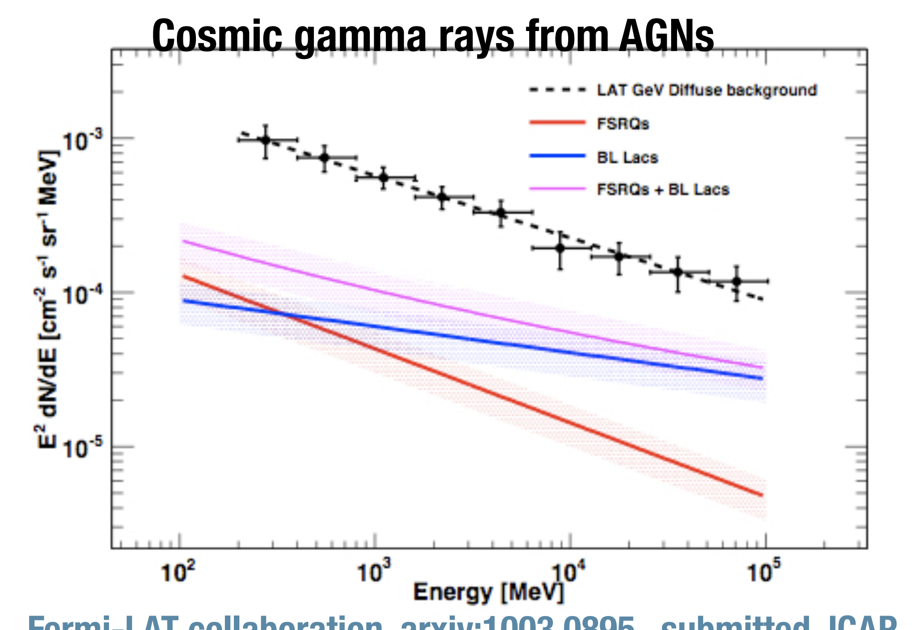
- potential line signature, at DM mass.



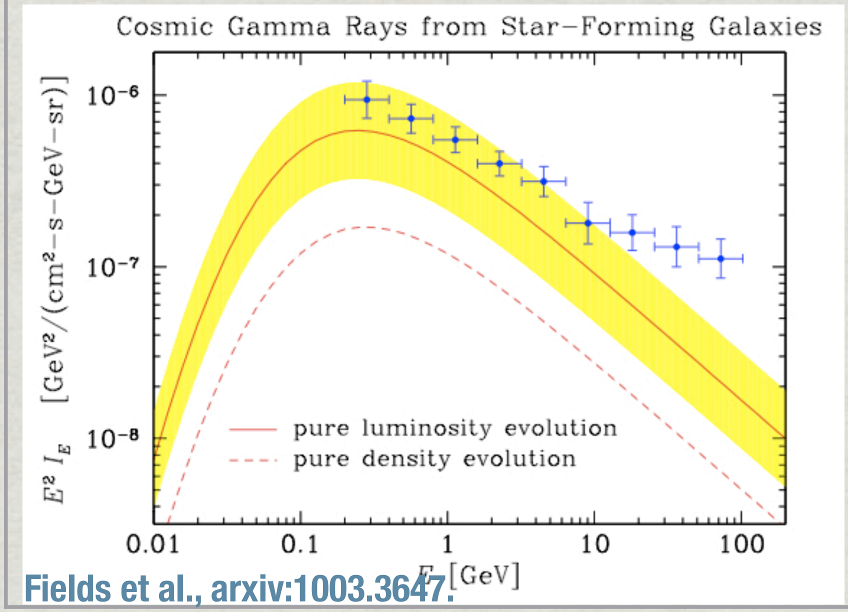
NOTE: the absorption affects the high energy end of the signal.

Search for DM in the Isotropic diffuse signal - backgrounds

AGNs have been the favored candidates, (the brightest extragalactic sources in the gamma-ray sky).
However, ***based on Fermi measurement of blazar luminosity function, ->*** *they can make up* **maximally 30% of the extragalactic signal.**



Fermi-LAT collaboration, arxiv:1003.0895., submitted JCAP.



Fields et al., arxiv:1003.3647.

Star Forming Galaxies (like our own): based in part on the Fermi measurement of the Galactic diffuse emission, Fields et al. conclude that SFG could make up **most of the extra galactic signal at lower energies.**

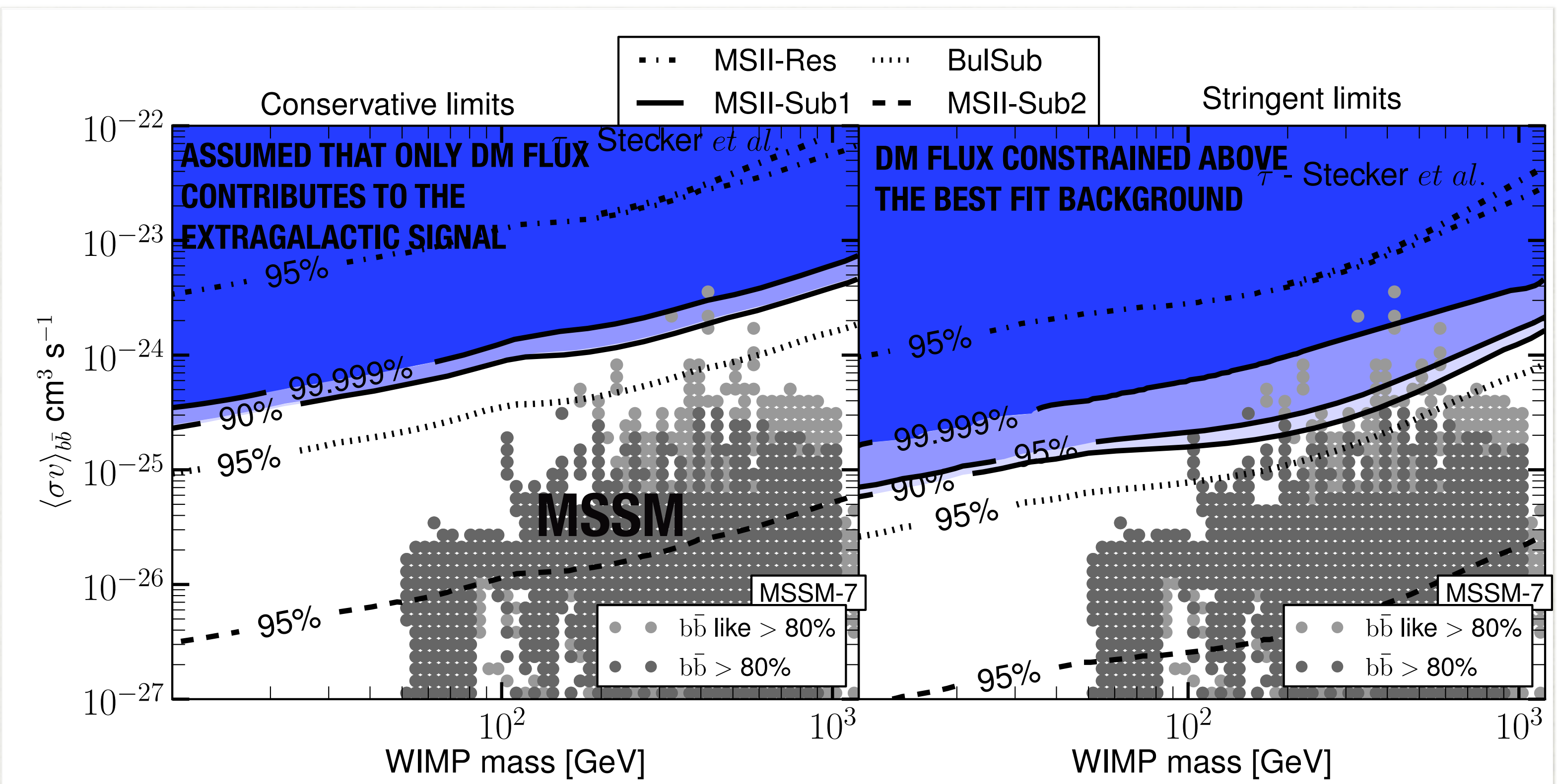
Search for DM in the Isotropic diffuse signal - constraints

Fermi-LAT collaboration, JCAP 1004:014,2010.

Cosmological DM signal can be very constraining.

The isotropic flux should get lower as Fermi continuos to resolve more extra galactic sources -> increased sensitivity for DM searches.

Current work to minimize/quantify uncertainty due to limited mass resolution of N-body simulations.



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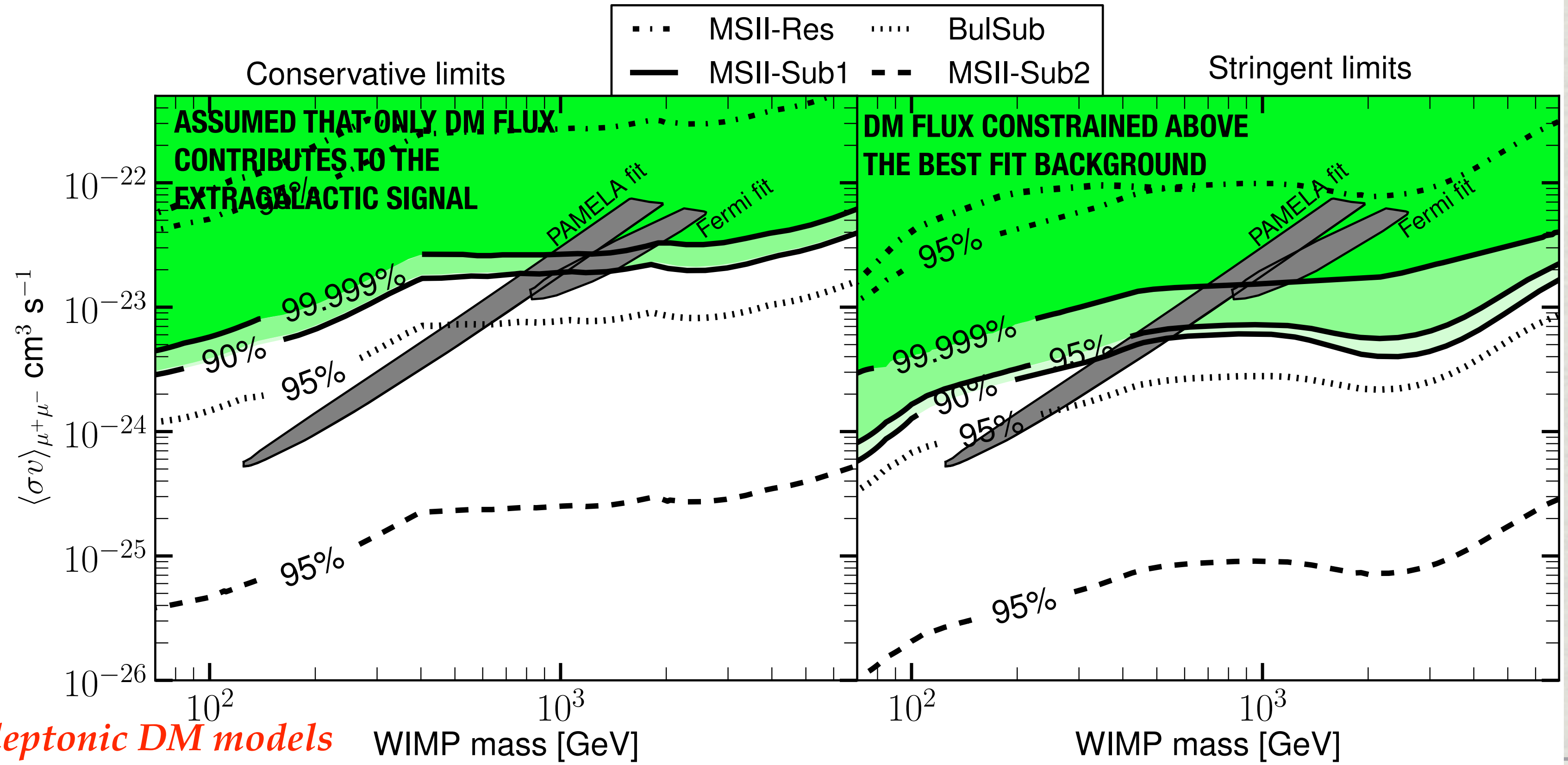
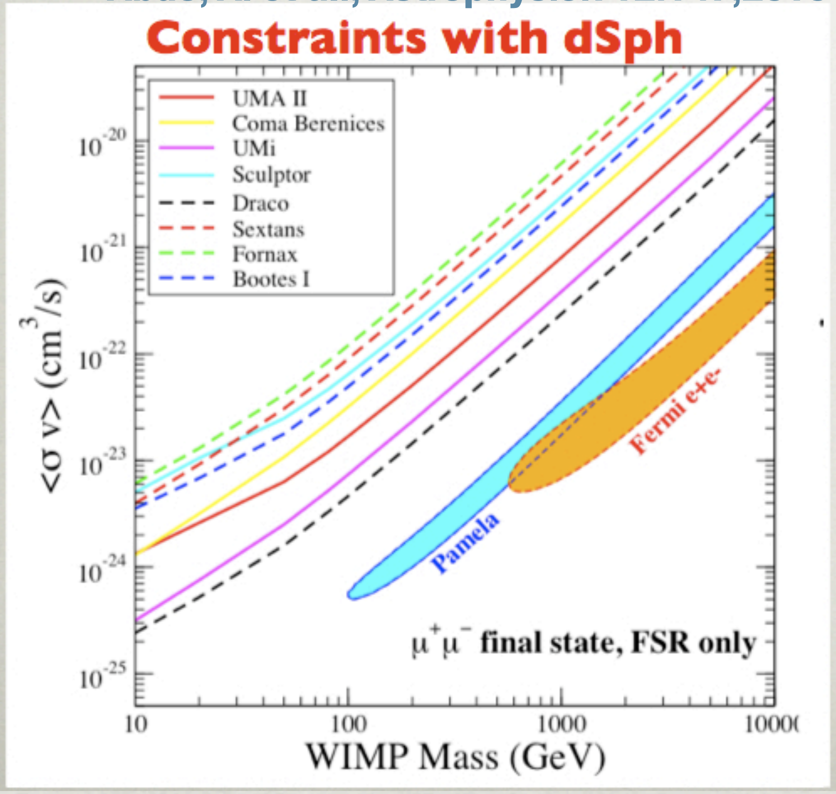


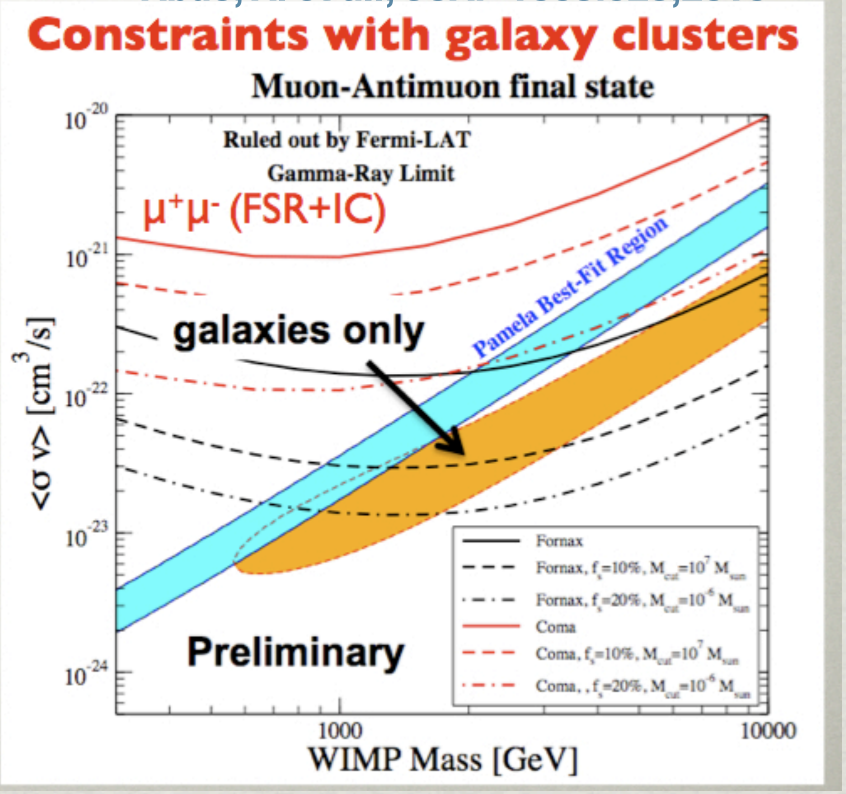
leptonic DM models

Comparison: muon channel

Abdo, A. et al., Astrophys.J.712:147,2010



Abdo, A. et al., JCAP 1005:025,2010



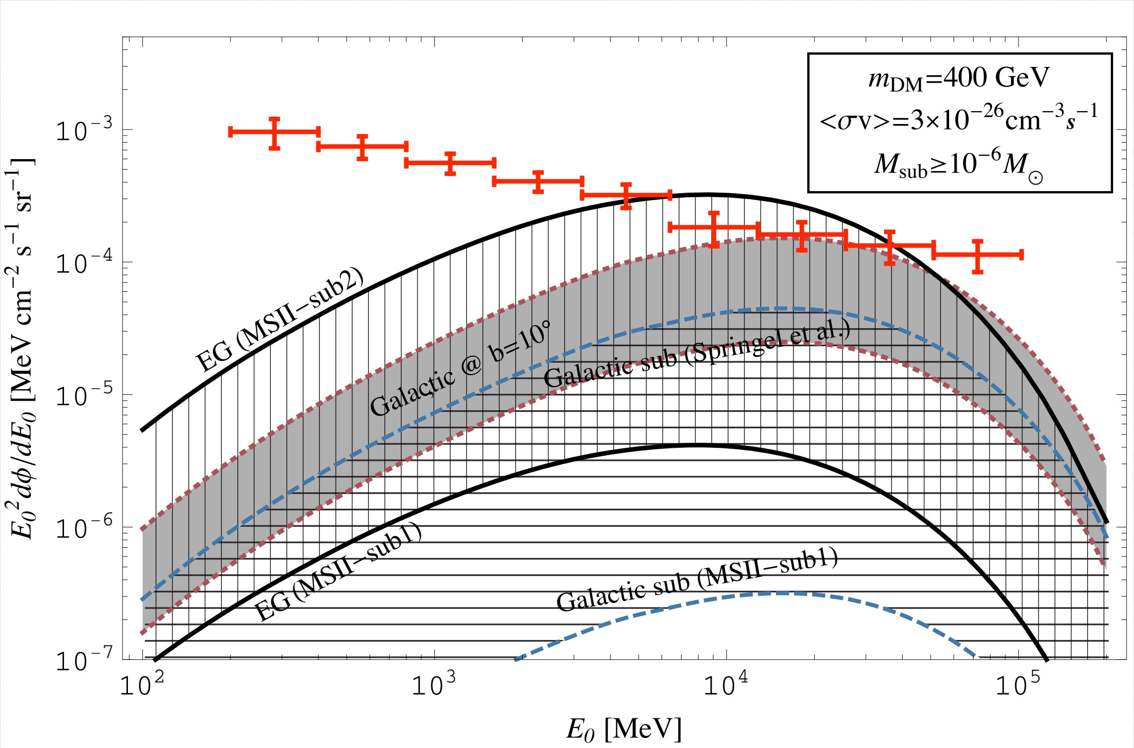
Dwarf galaxies are smaller objects and electrons diffuse before scattering. Galaxy clusters pose stronger limits on this channel, similar to the extragalactic benchmark model.

DM in the Milky Way halo

While looking at the Extra Galactic signal we are looking through the DM annihilation haze from our halo!

Milky Way halo is expected to produce ISOTROPIC signal due to the annihilation is MW subhalos.

MW host halo would produce bright ANISOTROPIC signal (following DM profile) in annihilations in the host MW halo - possibly dominant compared to the extragalactic signal.

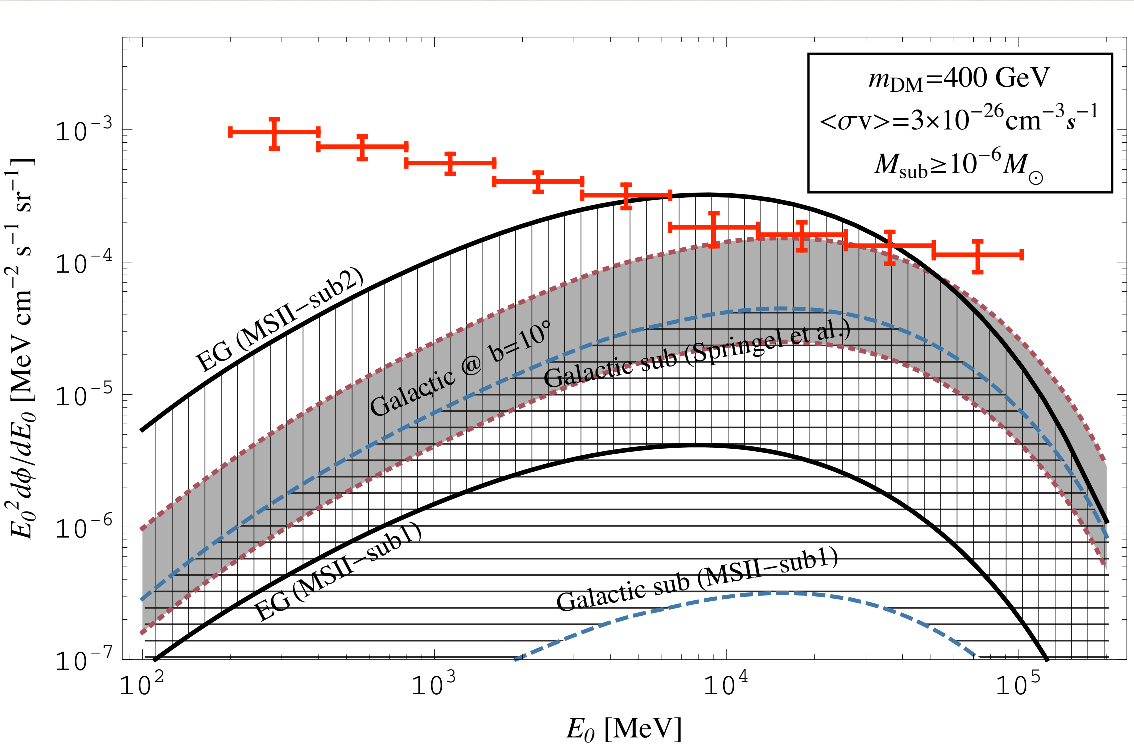


Abdo, A. et al., JCAP 1004:014,2010.

DM in the galactic halo

The relative size of these three contributions is not uniquely determined.

Next step: considering self consistently galactic and extragalactic signal should give a more robust handle on the size of the expected signal.



Abdo, A. et al., JCAP 1004:014,2010.

Outlook

- *Lots of work still ahead! Fermi is a 5-10 year mission...*

- *Extragalactic signal has a significant potential for DM searches. Better modeling of the background (blazar and other potential contributions), as well as improvement in N body simulations and their application, crucial to constrain/discover DM (inclusion of effects of baryons needed, too).*

- *galactic and extragalactic DM+astrophysical signal fit to the full sky data, natural and needed next step.*

- *(hints from other experiments (direct detection, LHC) Would significantly increase detection prospects.)*

Extra slides

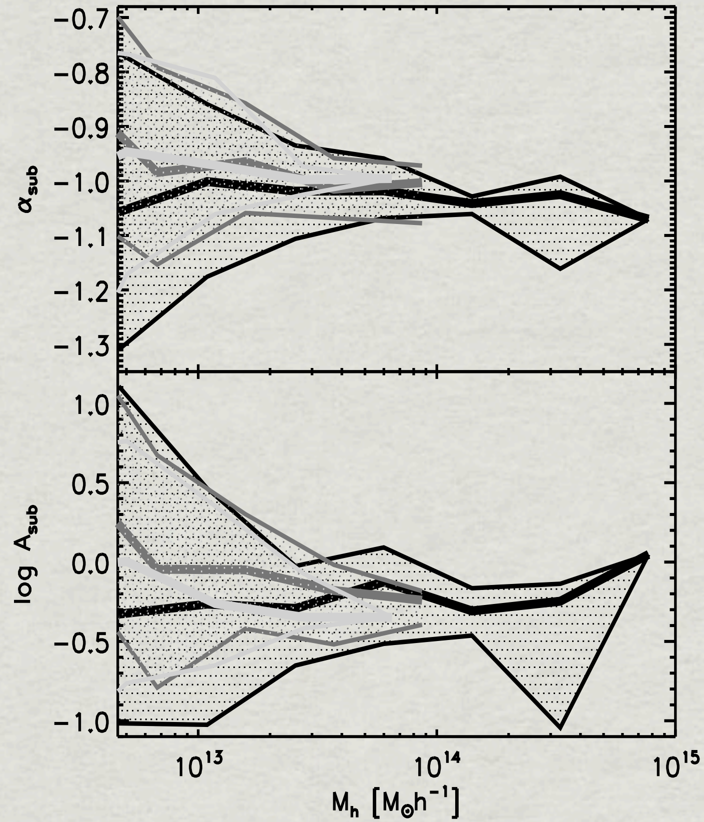
Specifically, we use the "Millennium-II" simulation (MS-II) of Boylan-Kolchin et al. (2009) which has the same particle number (2160^3) and cosmological parameters ($\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $h = 0.73$, $\sigma_8 = 0.9$ and $n_s = 1$,

redshift zero) as the Millennium simulation (MS-I) (Springel 2005) but with a box size that is 5 times smaller, equal to $L = 100\,h^{-1}$Mpc on a side, thus having a mass resolution of $6.89 \times 10^6\ h^{-1}\mathrm{M}_\odot$, 125 times smaller than in MS-I. Typical Milky-Way sized haloes are resolved with several 10^5 particles, while clusters of galaxies have about 50 million particles.

$$F_h(M_h) = \frac{\sum L_h}{\bar{M}_h \Delta \log M_h},$$

$$f(M_h > M_{\rm min}) \sim \frac{1}{\bar{\rho}_B^2 V_B} \int_{M_{\rm min}}^{\infty} \frac{F_h(M_h)}{\ln 10} \, \mathrm{d}M_h.$$

$$F_h(M_h, z) = A_h(z) M_h^{\alpha_h(z)}.$$

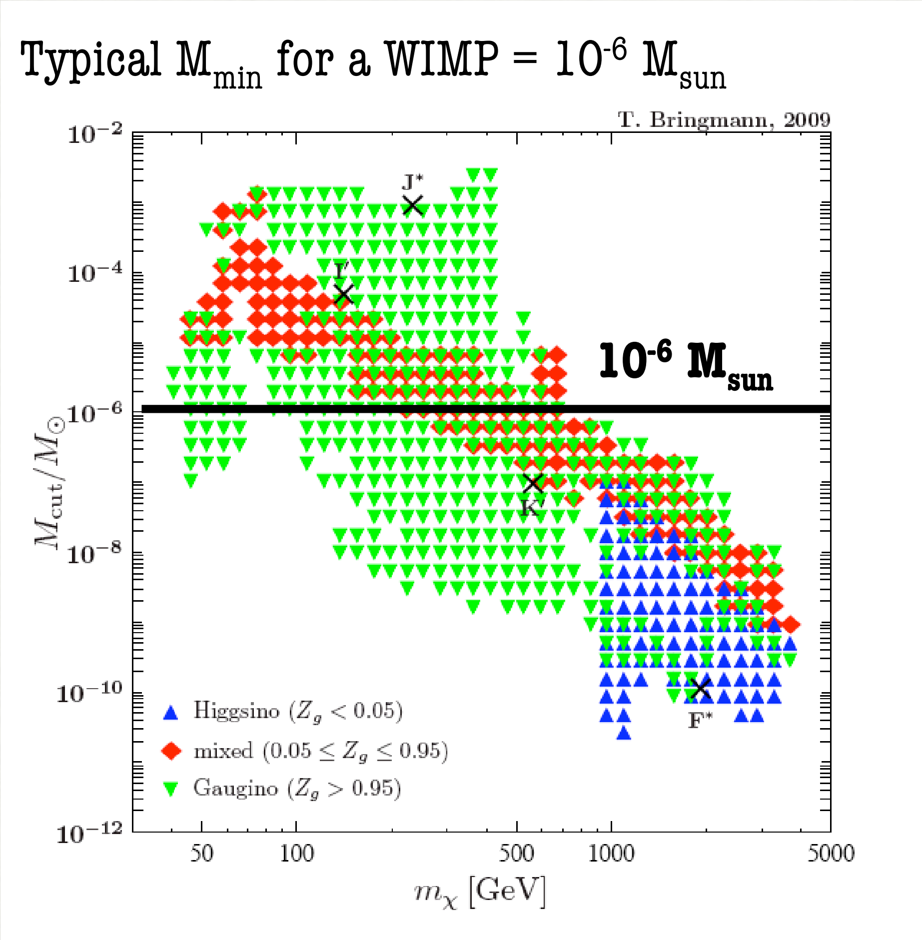


$$F_{\rm sub}\left(\frac{M_{\rm sub}}{M_h}\right) \sim A_{\rm sub}\left(\frac{M_{\rm sub}}{M_h}\right)^{\alpha_{\rm sub}}$$

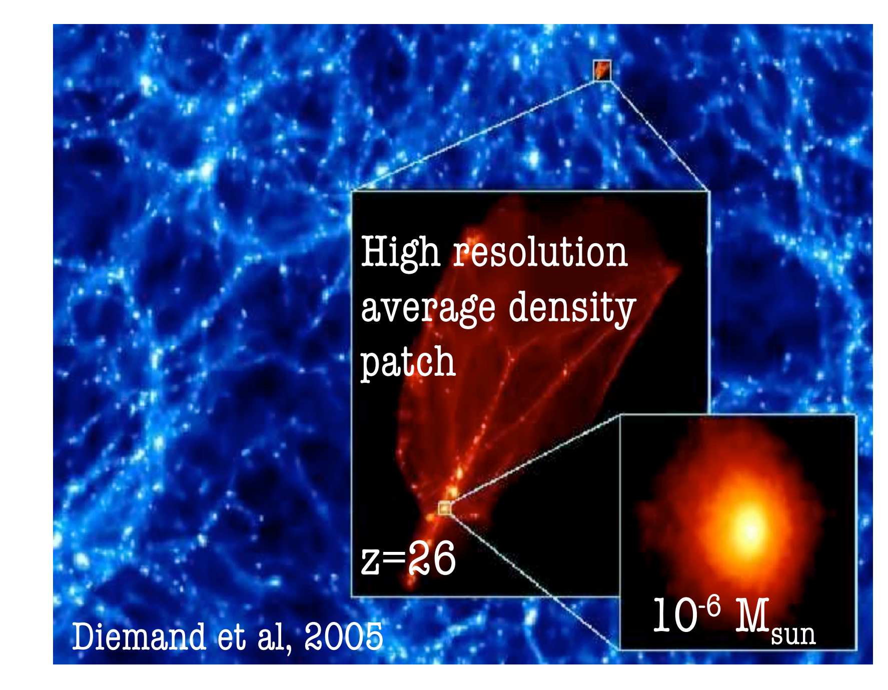
$$-0.95 \leqslant \alpha_{\rm sub} \leqslant -1.15$$

$$-0.5 \leqslant \log A_{\rm sub} \leqslant 0.1.$$

$$f_{\rm sub}(f_{\rm max}, M_h) \sim \frac{1}{L_h} \int_{10^{-6}}^{f_{\rm max} M_h} \left(\frac{L_h}{M_h}\right) \frac{F_{\rm sub}\left(\frac{M_{\rm sub}}{M_h}\right)}{\ln 10} \mathrm{d}M_{\rm sub}, \quad (25)$$



Typical M_min for a WIMP = 10^-6 M_sun
T. Bringmann, 2009
10^-6 M_sun
J*
I'
K'
F*
Higgsino (Z_g < 0.05)
mixed (0.05 ≤ Z_g ≤ 0.95)
Gaugino (Z_g > 0.95)
M_cut/M_⊙
m_χ [GeV]



High resolution average density patch
z=26
10^-6 M_sun
Diemand et al, 2005

Measurement of the Local Background

Direct Measurement

Photometry measurements must contend with difficult foreground subtraction and calibration issues!

- **Optical** - Bernstein (2002, 2007) using Hubble and ground-based data in 3 optical bands
- **IR** - DIRBE detections in near-IR (e.g. Wright 2001, Levenson et al. 2007) and far- IR (Hauser et al. 1998, Wright 2004)
  FIRAS - absolute measurement of CMB and EBL >125 μm (Fixsen et al. 1998)

Galaxy Number Counts

Can provide robust lower limits, but degree of convergence often controversial

Available in many bands, including UV (GALEX), optical/NIR (HST, various ground-based), mid and far IR (Spitzer, ISO), and submillimeter (SCUBA, BLAST)

Limits in optical and near-IR generally below direct photometry estimates

Extragalactic Gamma-ray Observations

Assumption that intrinsic spectra is softer than $-\Gamma = 1.5$ (e.g. Aharonian et al. 2006; Albert et al. 2008; also Costamante et al. 2004; Mazin & Raue 2007)

Modeling of the galaxy population

- Evolution inferred from observations

Kneiske et al. 2004; Finke et al. 2009 - models based on star formation rate density, stellar synthesis models, dust reradiation

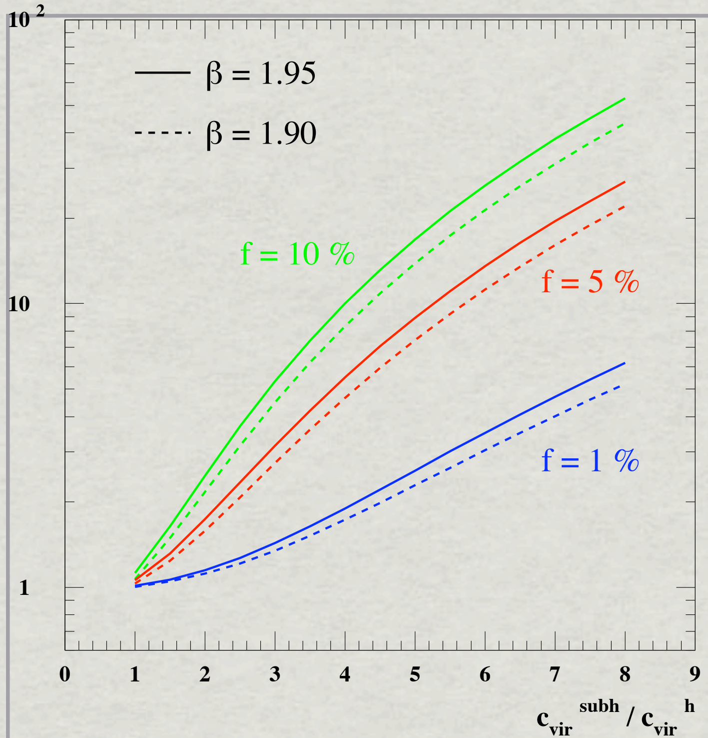
Franceschini et al. 2008 - sophisticated model based on measured LFs, separate treatment of optical and IR, and different galaxy population.

- Backwards evolution of the existing galaxy population

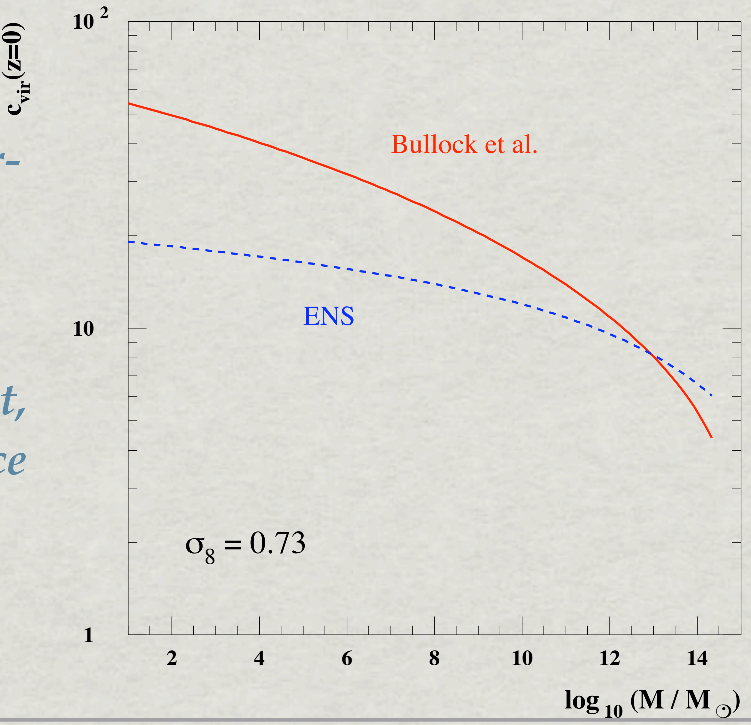
Stecker et al. 2006 - based on power law evolution of existing galaxy pop.

- Forward evolution, begin from cosmological initial conditions

Primack et al. 2001, 2005, and this work



*we set 10% of a halo mass in substructures and assume that the subhalo mass function has a power-law behavior in mass M^−***β***, with a slope* **β** *= 1.9. This is in broad agreement with findings of new simulations for Milky Way-size halos. The concentration parameter of subhalos is not constant, but depends on the subhalo mass and on the distance from the center of the halos. We here associate a concentration parameter four times higher in substructures, compared to a main halo of the same mass.*



$$\frac{dn}{dM} = \frac{\bar{\rho}_0}{M^2} \nu f(\nu) \frac{d\,log\nu}{d\,logM}$$

$$\nu \equiv \delta_{sc}(z)/\sigma(M),$$

$$\nu f(\nu) = 2A\left(1 + \frac{1}{\nu'^{2q}}\right)\left(\frac{\nu'^2}{2\pi}\right)^{1/2} \exp\left(-\frac{\nu'^2}{2}\right)$$

multiplicity function: ellipsoidal collapse model, by Sheth and Torman

$$\sigma(M)^2 \propto \int d^3k\, \tilde{W}(kR)^2\, P(k)\,,$$

$$g_{\rm NFW}(x) = \frac{1}{x\,(1+x)^2},$$

$$c_{vir} = \frac{R_{vir}}{r_{-2}} \qquad d/dr\,\left(r^2 g(r)\right)\big|_{r=r_{-2}} = 0.$$

EFFECTS OF SIGMA_8

In our semi-analytic approach: 0.73 (used) $< \sigma_8 < 1$ the halo signal varies by a factor ~ 2 at $z=0$.