Dark matter constraints from the first year Fermi data

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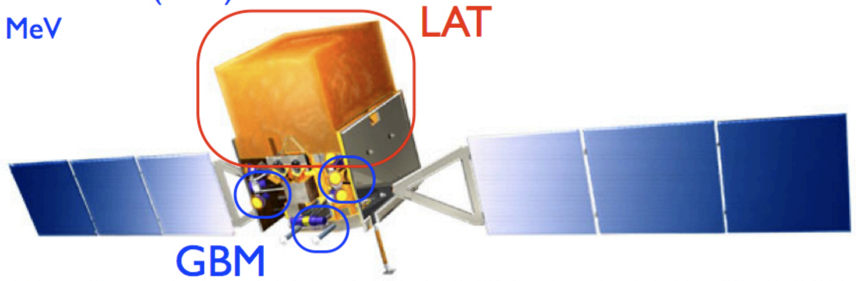
FOR THE FERMI-LAT COLLABORATION

Fermi observatory

Launch 11 June, 2008.

Lifetime: 5 yr (min)

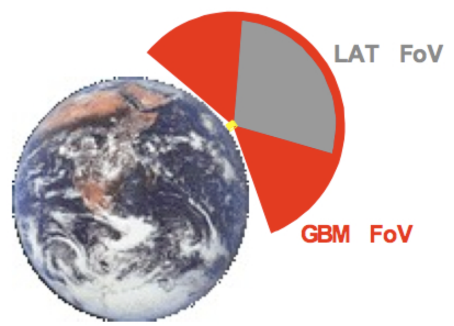
Two instruments:



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 unoccluted sky at any time.**

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



Fermi observatory

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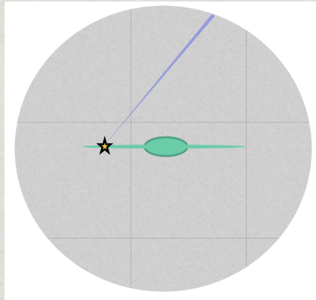
Science with Fermi:

- *AGNs (~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?*

INDIRECT DARK MATTER DETECTION IN GAMMA RAYS



Bergstrom, L., talk at DM2010.

Advantage of gamma-rays: Not affected by the Galaxy.

Can give a specific signature both in spatial variation (line-of-sight cone) and spectral shape.

Flux of DM induced gamma rays

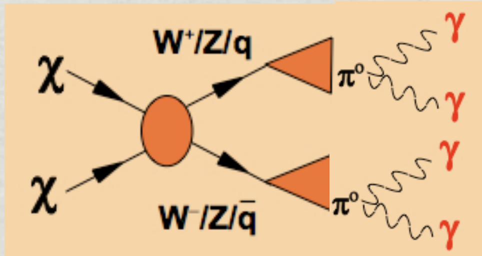
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\theta,\phi) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle_{T_0}}{2\,M_\chi^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f \cdot \int_{\Delta\Omega(\theta,\phi)} d\Omega' \int_{l.o.s.} dl\ \rho_\chi^2(l)$$

- **<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.

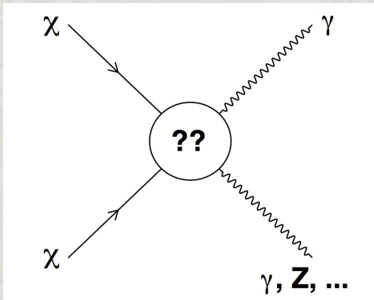
How are DM γ ray fluxes produced?

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



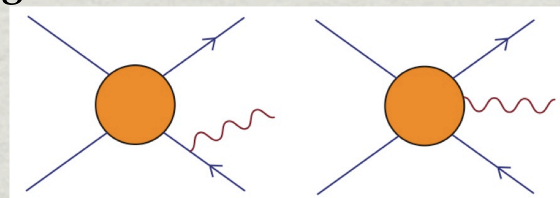
Dominant production for DM annihilating to quarks and gauge bosons (i.e. SUSY) .

- line:



Loop suppressed, but unique, smoking gun, signature.

- final state radiation:



- through **radiative processes**:

$$\chi\,\bar{\chi} \rightarrow \begin{cases} e^+\,e^- \\ l^+\,l^- \text{ or } \phi\,\phi \rightarrow \ldots + e^+\,e^- \\ P\,\bar{P} \rightarrow \ldots + \pi^\pm \rightarrow \ldots + e^\pm \end{cases}$$

ambient backgrounds and fields

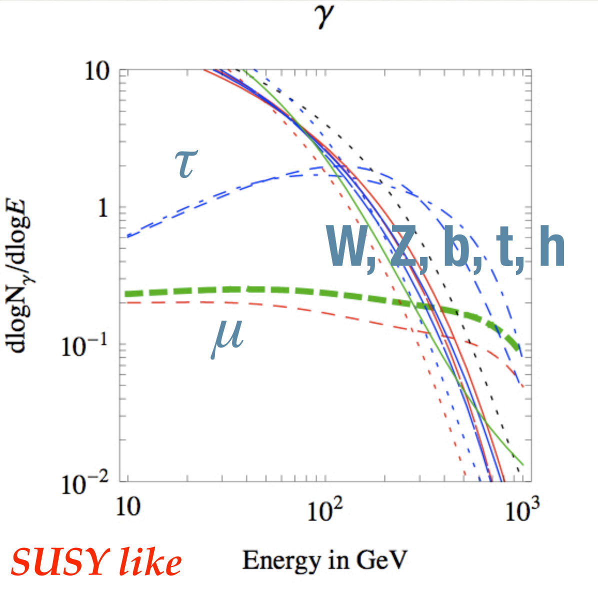
- Synchrotron
- Inv. Compton
- Bremstrahlung
- Coulomb
- Ionization

→ radio, IR, X-rays, γs

Important if there is a significant branching to leptons.

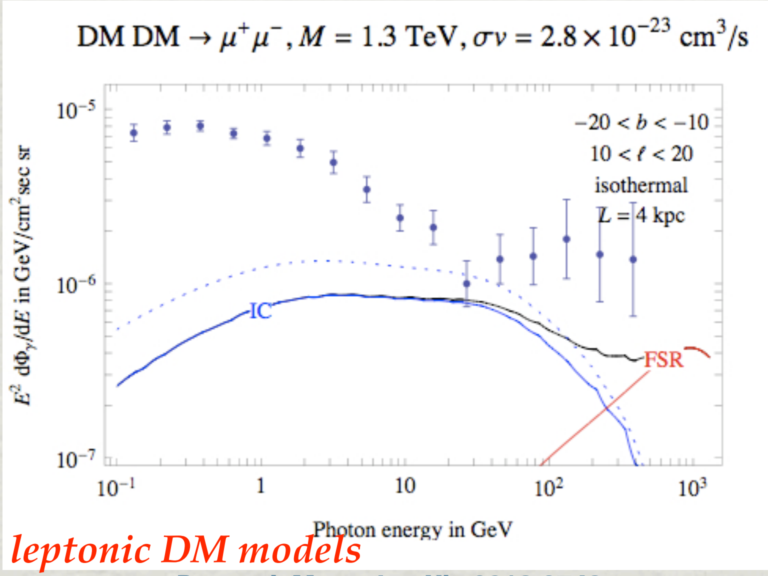
Examples of spectra (dN/dE):

PROMPT GAMMAS



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

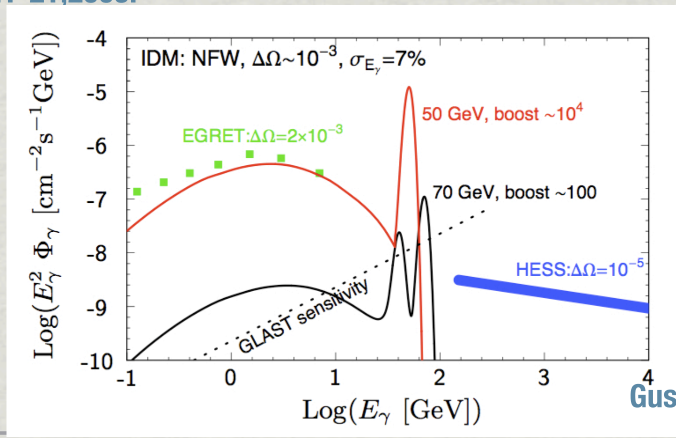
INVERSE COMPTON AND FSR



Papucci, M. et al, arXiv:0912.0742

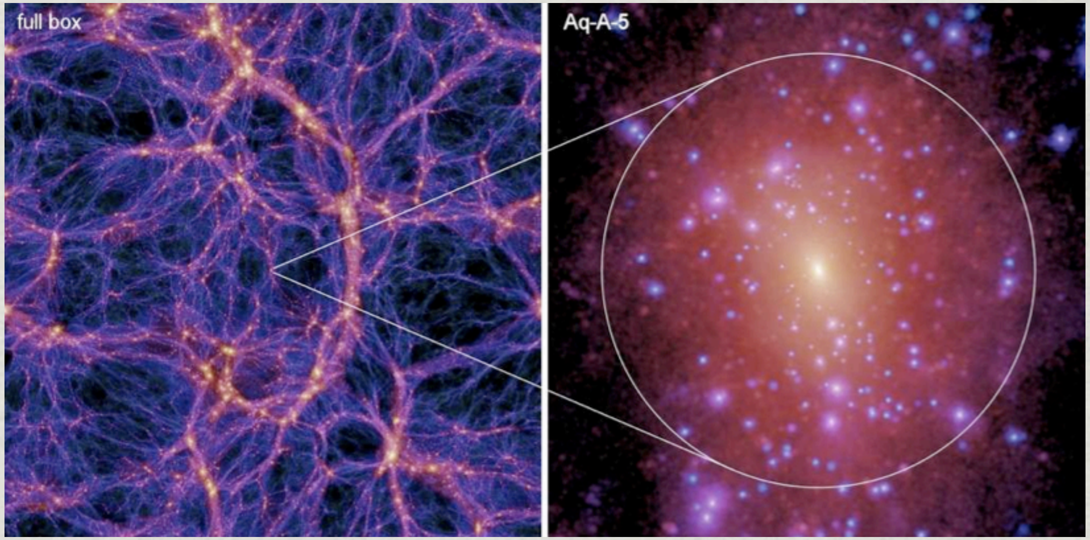
"Leptonic" models invoked recently, since they could fit PAMELA &FERMI electron/positron data. Gamma rays produced in these scenarios are one of the ways to test viability of these models.

LINE SPECTRA



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

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,

∗simulations do not typically include interaction with baryons (which e.g. in the Galactic Center might play an important role!);

∗Do not resolve the inner most region of the halo (<~100 pc);

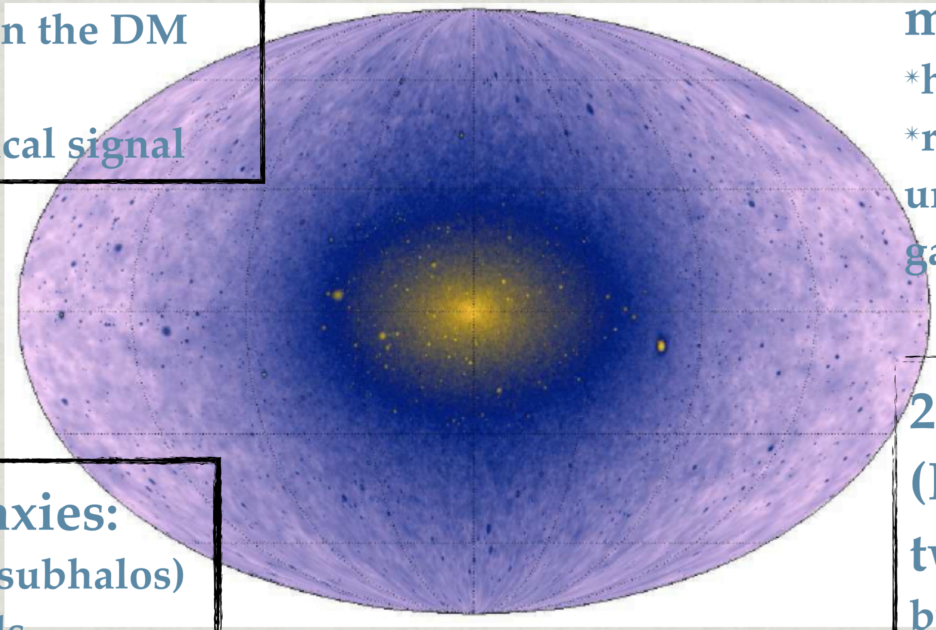
∗They have also limited mass resolution to >~10^5 M_{sol} (sub) halos.

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

WHERE DO WE LOOK FOR DM W FERMI?

1.The Galactic Center:
*brightest spot on the DM sky
*high astrophysical signal

The Galactic dark matter Halo:
*high statistics
*requires detailed understanding of galactic diffuse signal



Diemand, Kuhlen, Madau, APJ, astro-ph/0611370

2. Extragalactic (Isotropic)Signal: two approaches:
by using the size and shape of the spectra or small scale angular anisotropies
* high statistics
*hard to separate from backgrounds

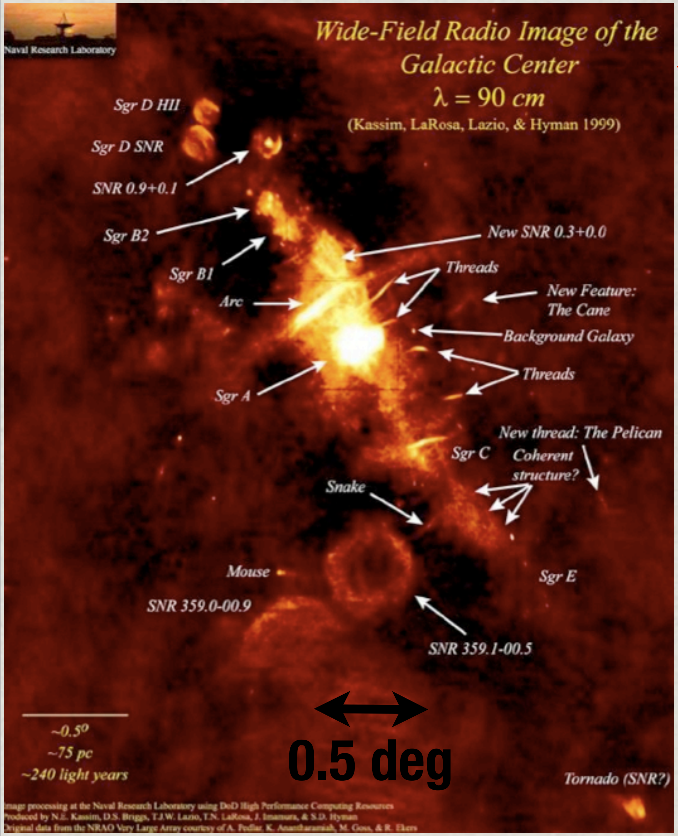
3. Dwarf Galaxies:
(largest Galactic subhalos)
*low backgrounds
*but low statistics, too.

Dark subhalos

4. Galaxy Clusters
5. Spectral Line search

Search for DM in the Galactic Center

"HELL'S KITCHEN" REGION



Cohen-Tanugi, J., talk at Fermi Symposium, 2009.

Source in the central parsecs of our Galaxy:

-- from radio to X-rays, signal originates from the Sgr A,*

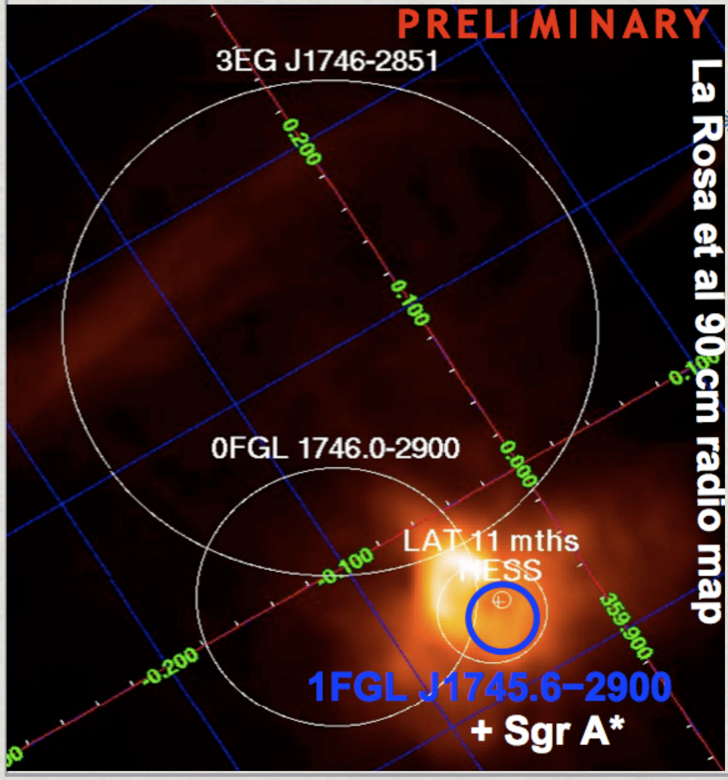
--but several possible counterparts for the hard X-rays / GeV / TeV **γ***-ray emissions.*

- *Huge diffuse emissivity due to CRs streaming through very dense clouds + Large Pulsar population ! Inferred population of ~2000 active radio pulsars! +star clusters, SNRs, PWN...*

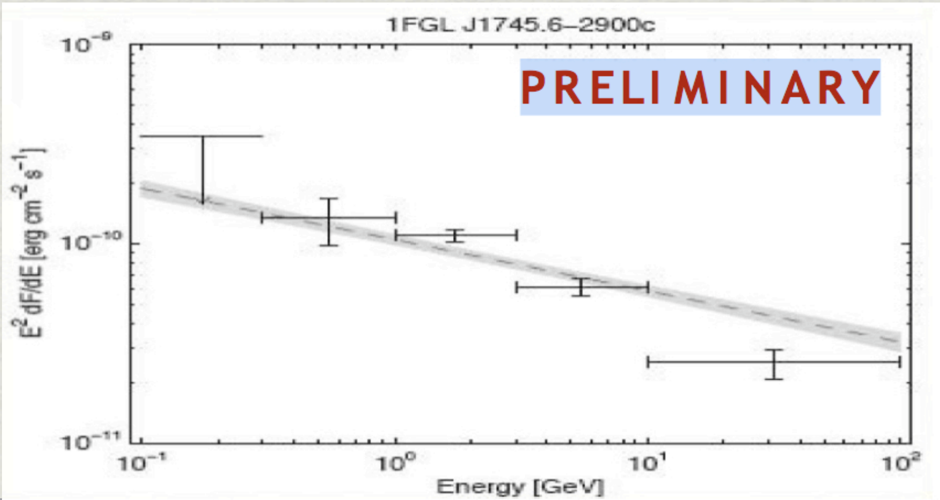
Search for DM in the GC :

- *Expected large DM annihilation/decay signal due to steep DM profiles.*
- *Good understanding of the astrophysical background is crucial to extract a potential DM signal from this complicated region of the sky : source confusion / diffuse emission modeling (very difficult !)*

Search for DM in the Galactic Center

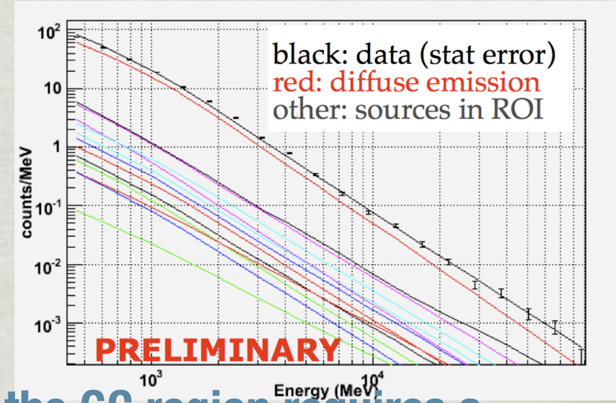


- *Fermi's year 1 catalog point source closest to the Galactic Center: 1FGL J1745.6−2900c, Location: l, b = (359.941, -0.051) deg (95% confinement radius: 1.1′)*
- *25 formal associations based on position (1 pulsar wind nebula, 1 supernova remnant, 4 low mass X-ray binaries, etc.)*



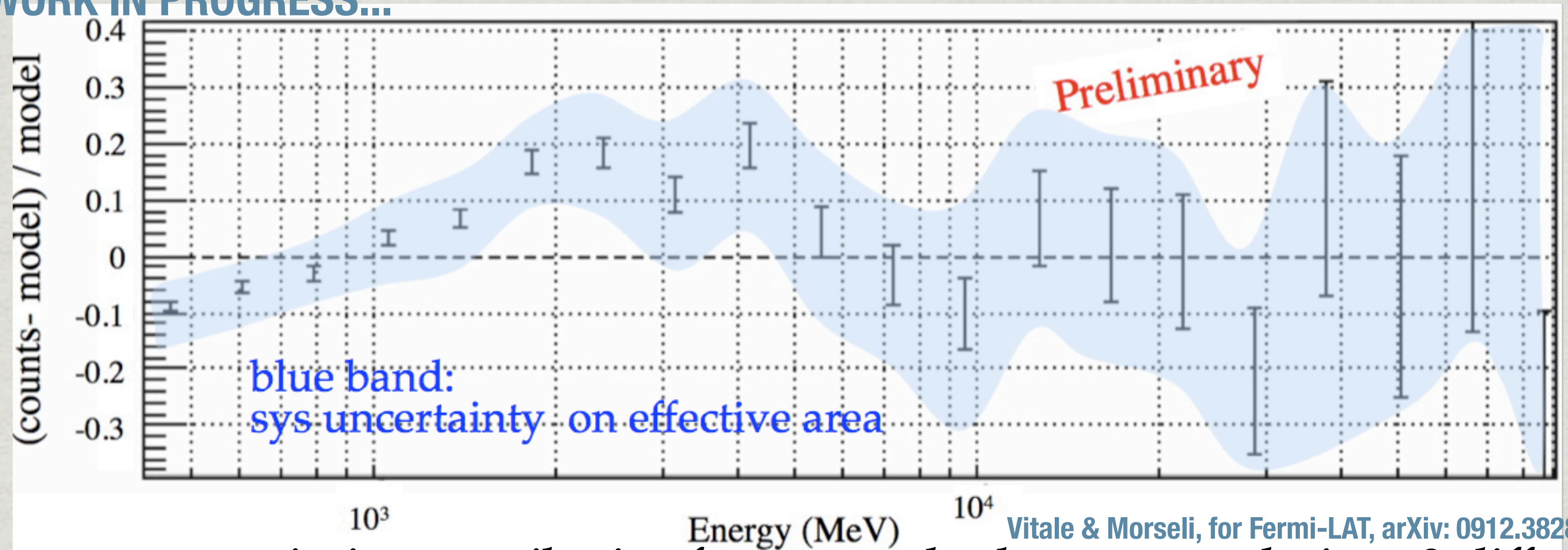
Preliminary analysis of a 7x7 deg region centered at the GC:

11 sources + galactic diffuse (GALPROP) in the ROI. Model generally reproduces data well within uncertainties. The model somewhat underpredicts the data in the few GeV range .



Any attempt to disentangle a potential DM signal from the GC region requires a detailed understanding of the conventional astrophysics. More prosaic explanations must be ruled out before invoking a contribution from DM if an excess is found.

WORK IN PROGRESS...

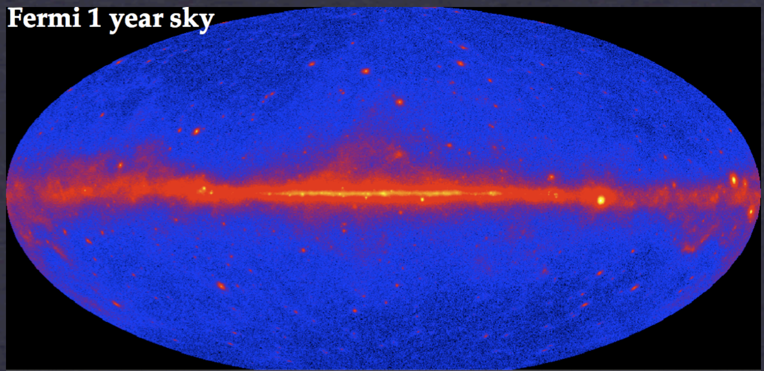


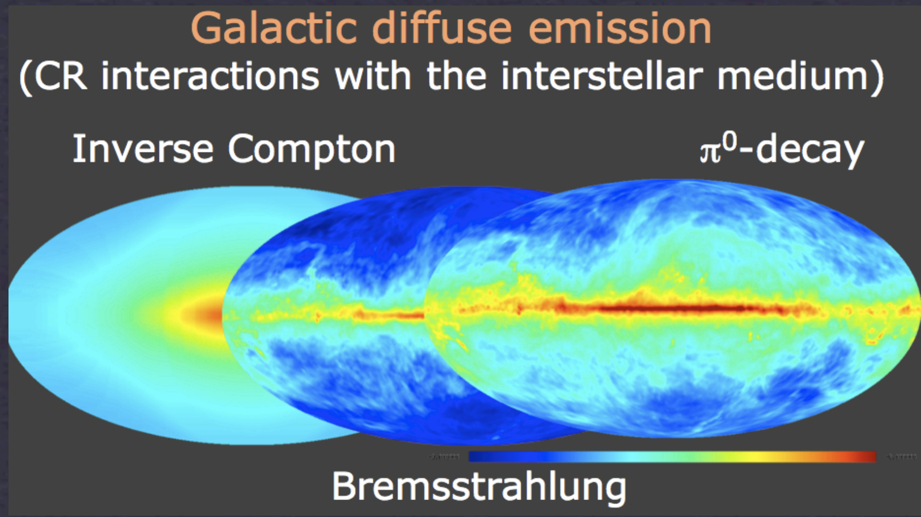
Vitale & Morseli, for Fermi-LAT, arXiv: 0912.3828.

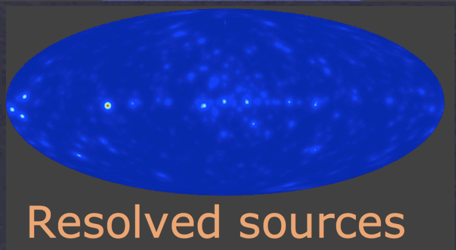
Largest uncertainties: contribution from unresolved source populations & diffuse emission (source distribution, ISRF and gas content significantly unconstrained).

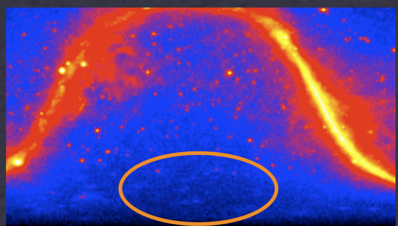
Search for DM in the Isotropic diffuse signal - THE SIGNAL

THERE ARE MANY CONTRIBUTIONS TO THE GAMMA RAY FERMI SKY:







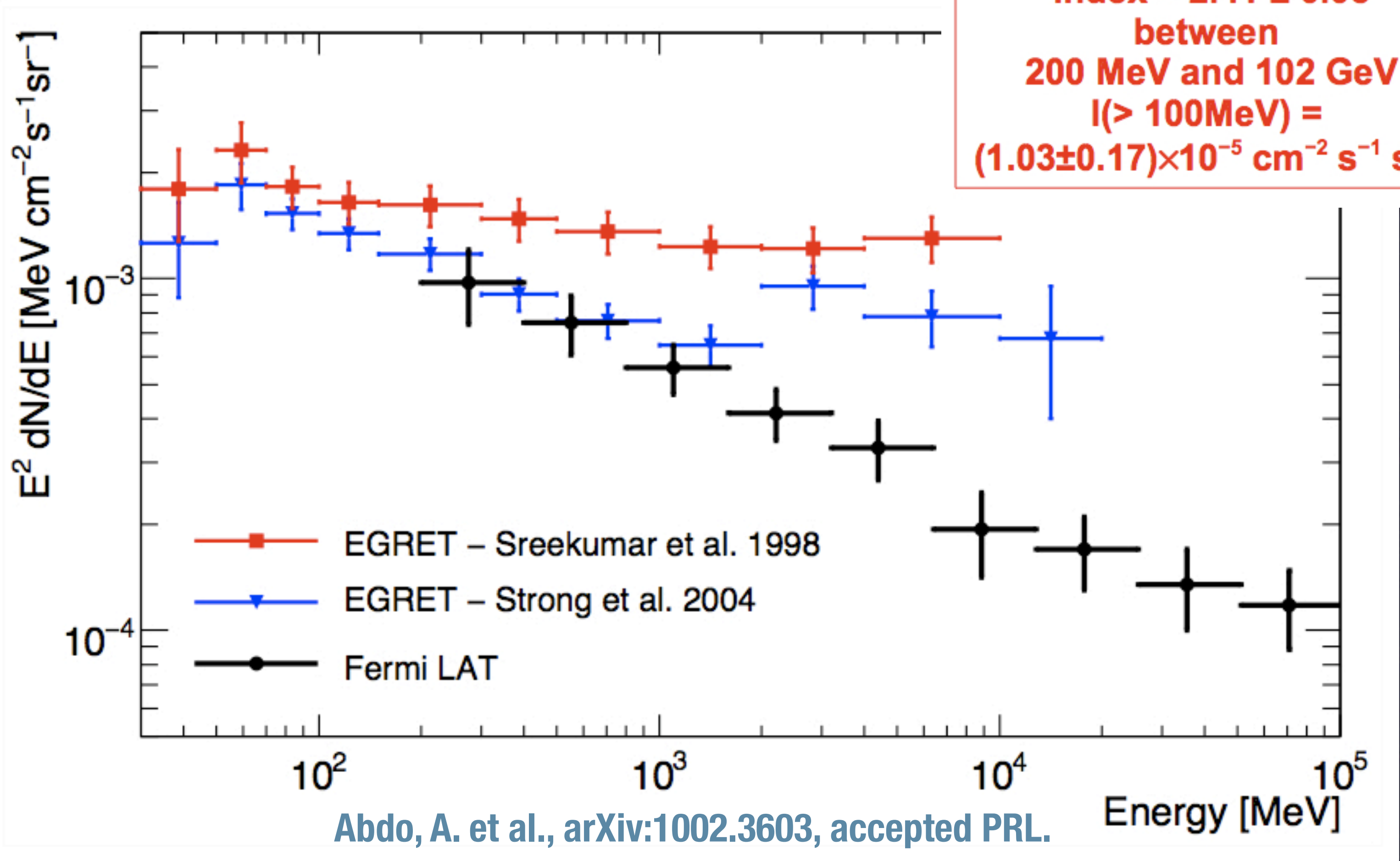


*After these contributions have been subtracted (+residual cosmic rays & miss-reconstructed gammas from the Earth's albedo) **we are left with the isotropic diffuse emission!***

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
$I(> 100\text{MeV}) = (1.03 \pm 0.17) \times 10^{-5}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$

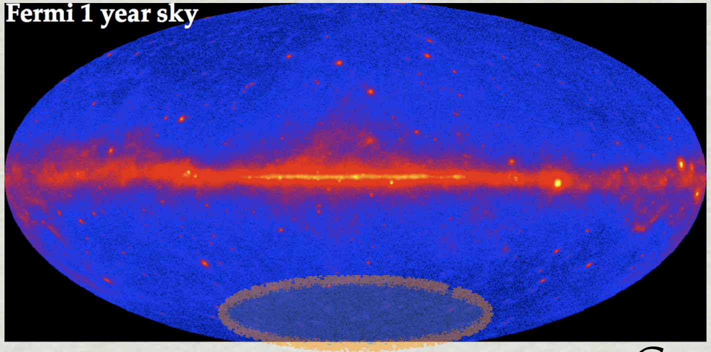


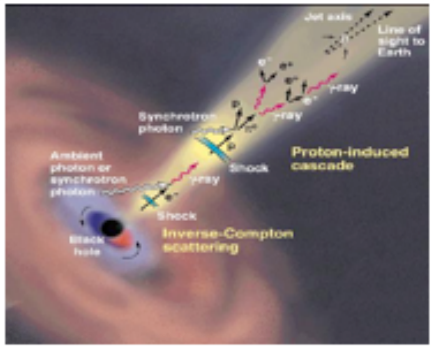
Abdo, A. et al., arXiv:1002.3603, accepted PRL.

Search for DM in the Isotropic diffuse signal

Fermi-LAT collaboration, arxiv:1002.4415, accepted JCAP.

What makes the GeV extragalactic signal?

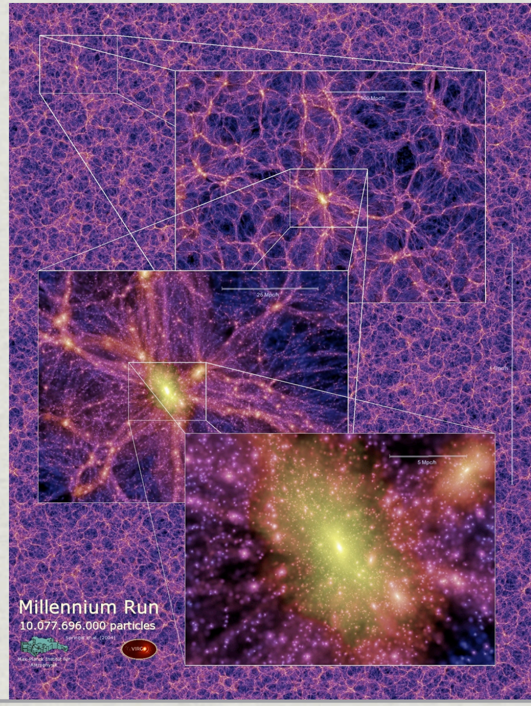




Credit: J. Buckley 1998 (Science), illustration: K. Sutliff

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.



Search for DM in the Isotropic diffuse signal - ρ^2

DM forms structures in gravitational collapse, and in those over-dense regions, DM self-annihilation signal is largely enhanced. But how much?

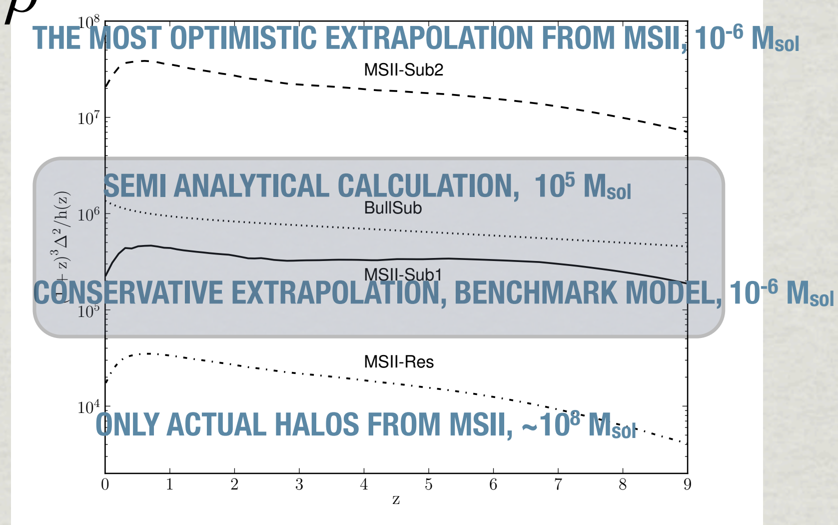
We have results from N-body simulations, but they are severely limited by mass resolution (resolution >$10^5 M_{sol}$, while theoretical lowest mass scale ~$10^{-6} M_{sol}$).

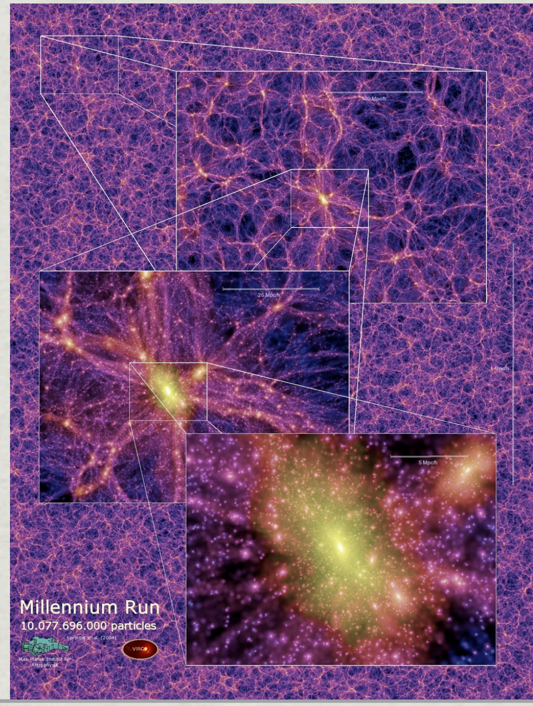
We used ***BOTH****:*

⋆***direct results from Millenium Simulation II,***

⋆*and* ***semi-analytical result*** *obtained by combining results of different simulations.*

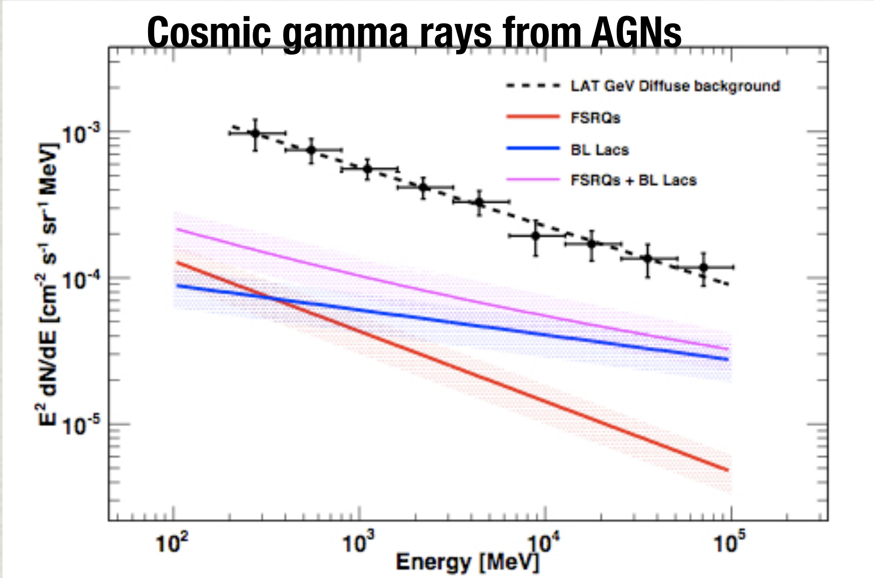
ρ^2



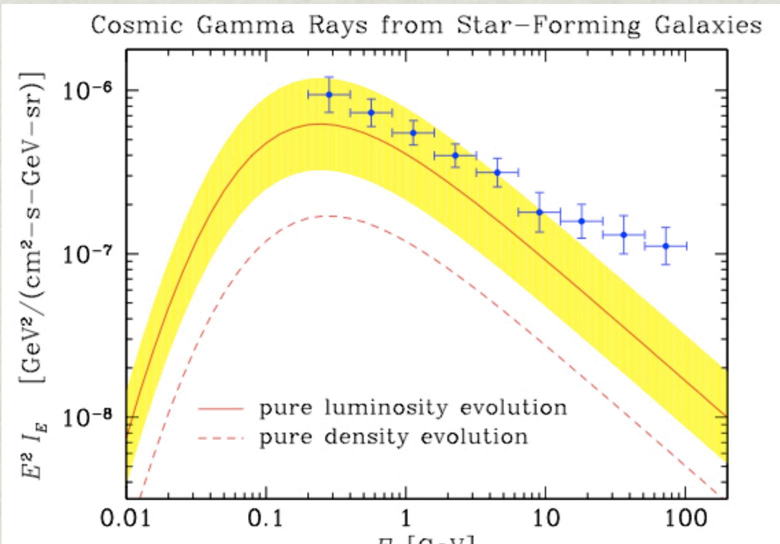


Search for DM in the Isotropic diffuse signal - backgrounds

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.**

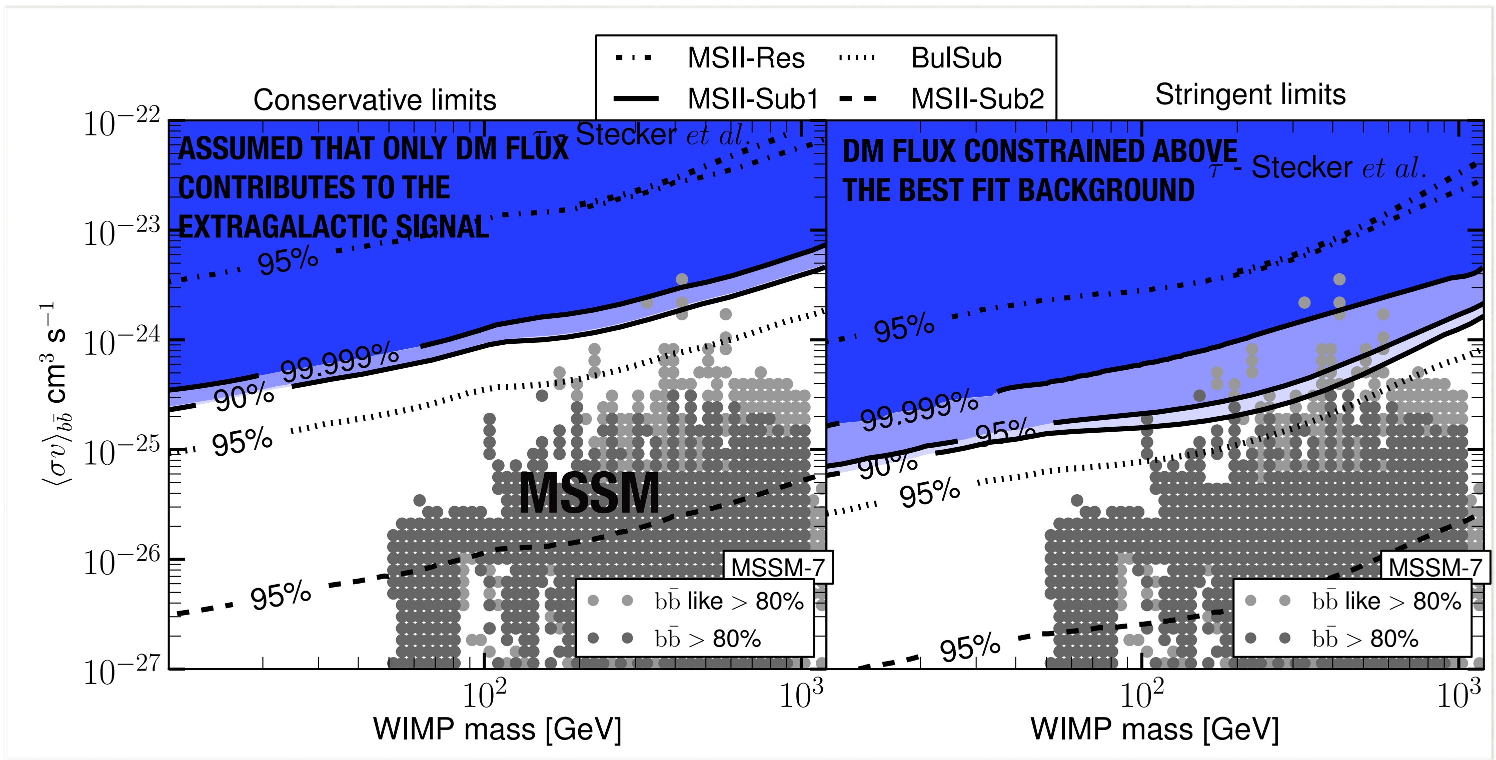
Search for DM in the Isotropic diffuse signal - constraints

Fermi-LAT collaboration, arxiv:1002.4415, accepted JCAP.

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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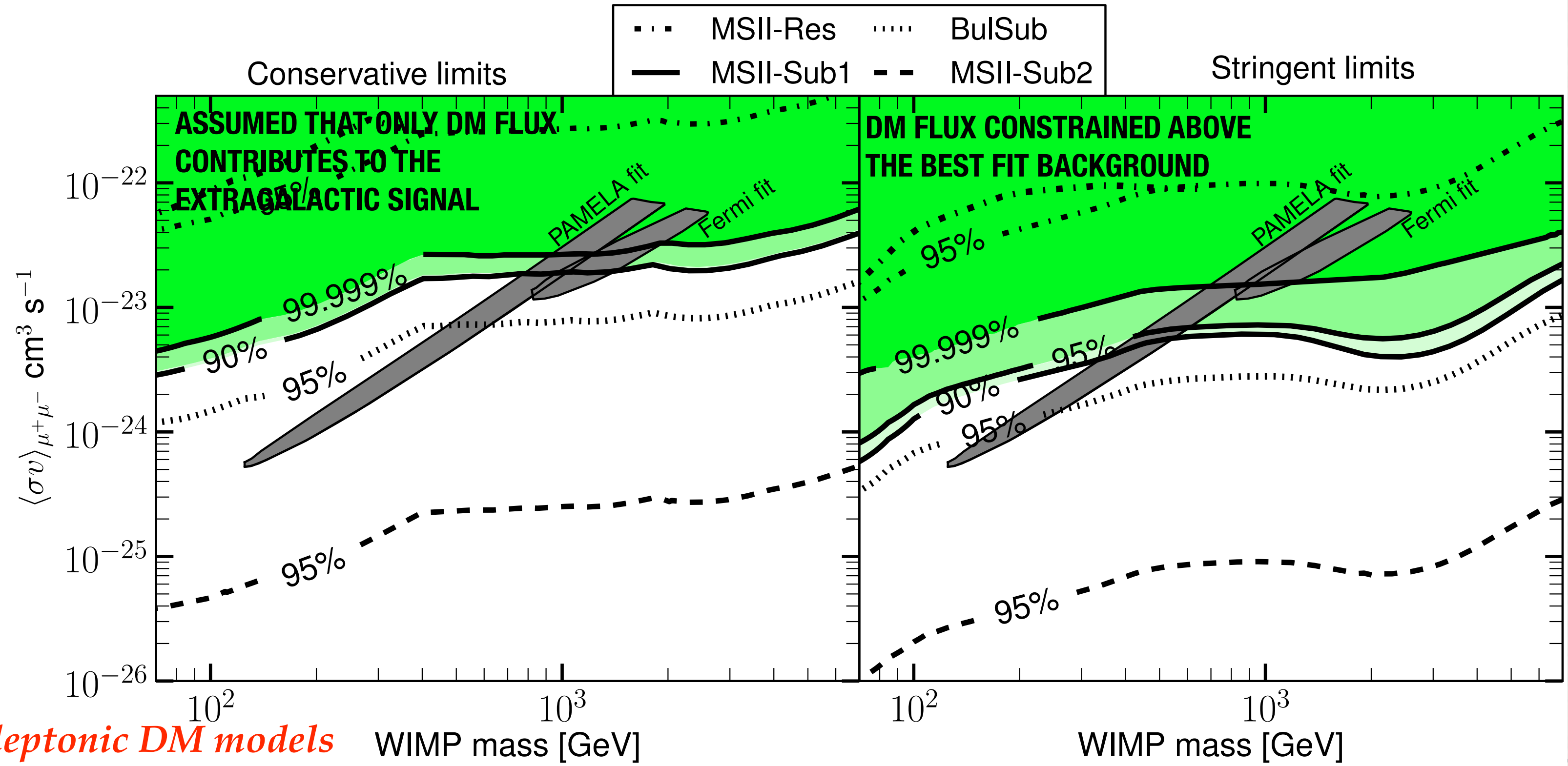
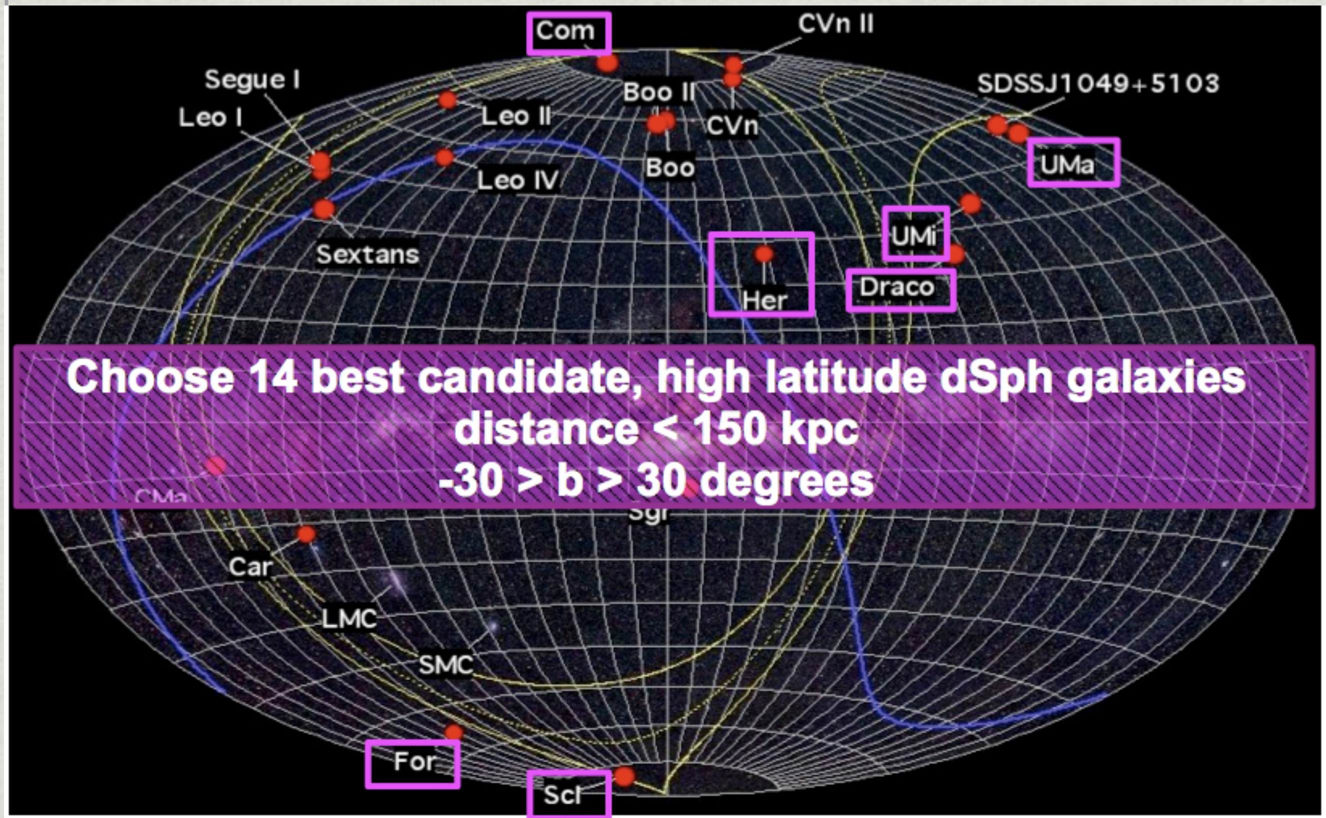


leptonic DM models

Search for DM in Dwarf Galaxies

Advantages: high M/L ratio (but, total mass model dependent), and low astrophysical activity (discovery in high energy gamma ray would be indicative of DM presence).



Selected dSph

Ursa Major II
Segue 2
Willman 1
Coma Berenices
Bootes II
Bootes I
Ursa Minor
Sculptor
Draco
Sextans
Ursa Major I
Hercules 1
Fornax
Leo IV

Nuss, E., talk at MORIOND, 2010.

Search for DM in Dwarf Galaxies

FERMI-LAT COLLABORATION, APJ, 712, 147 (2010).

- *11 months data analysis, 100 MeV<E<50 GeV.*

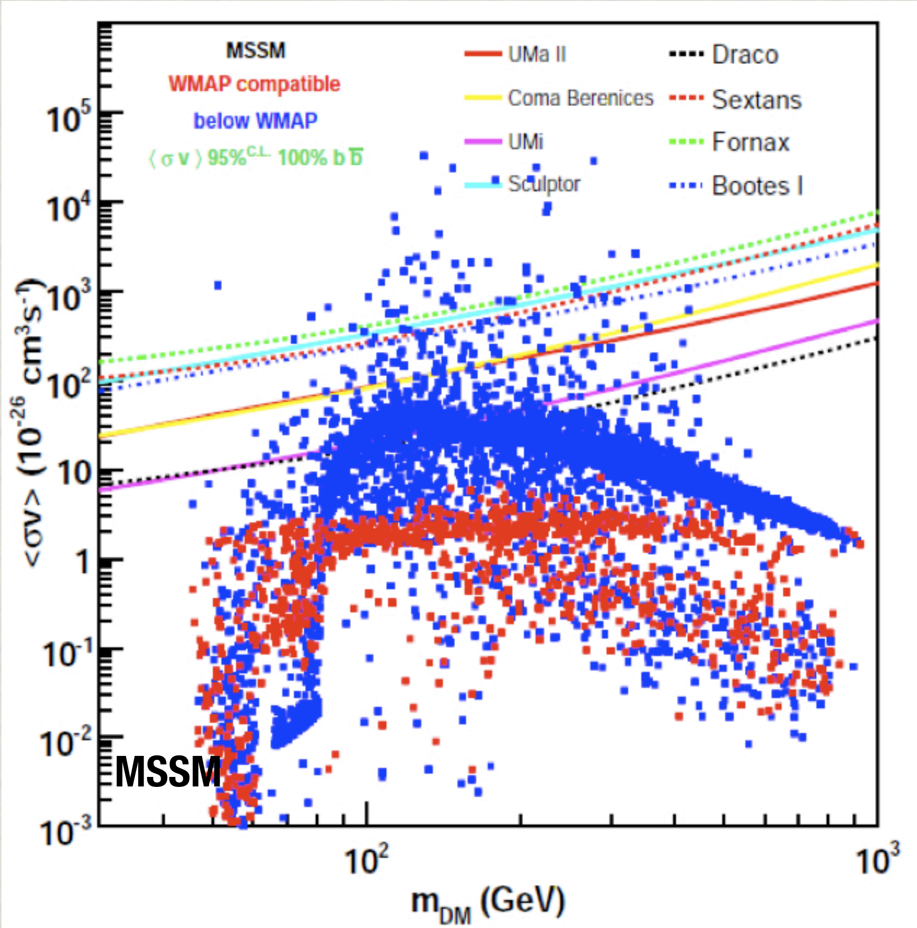
- *dSph modeled as point sources, with a power law spectra (spectral indices 1-2.4) and fit to data performed-> No dwarf spheroidal Galaxy detected so far.*

- *Limits on DM annihilation set based on:*
  - *background: point sources from Fermi Catalog (within 10 deg from dSph) + galactic and isotropic diffuse emission.*
  - *DM signal calculated assuming NFW profile, and modeling of stellar kinematic data (Keck observatory, Martinez, Bullock and Kaplinghat).*

Search for DM in Dwarf Galaxies

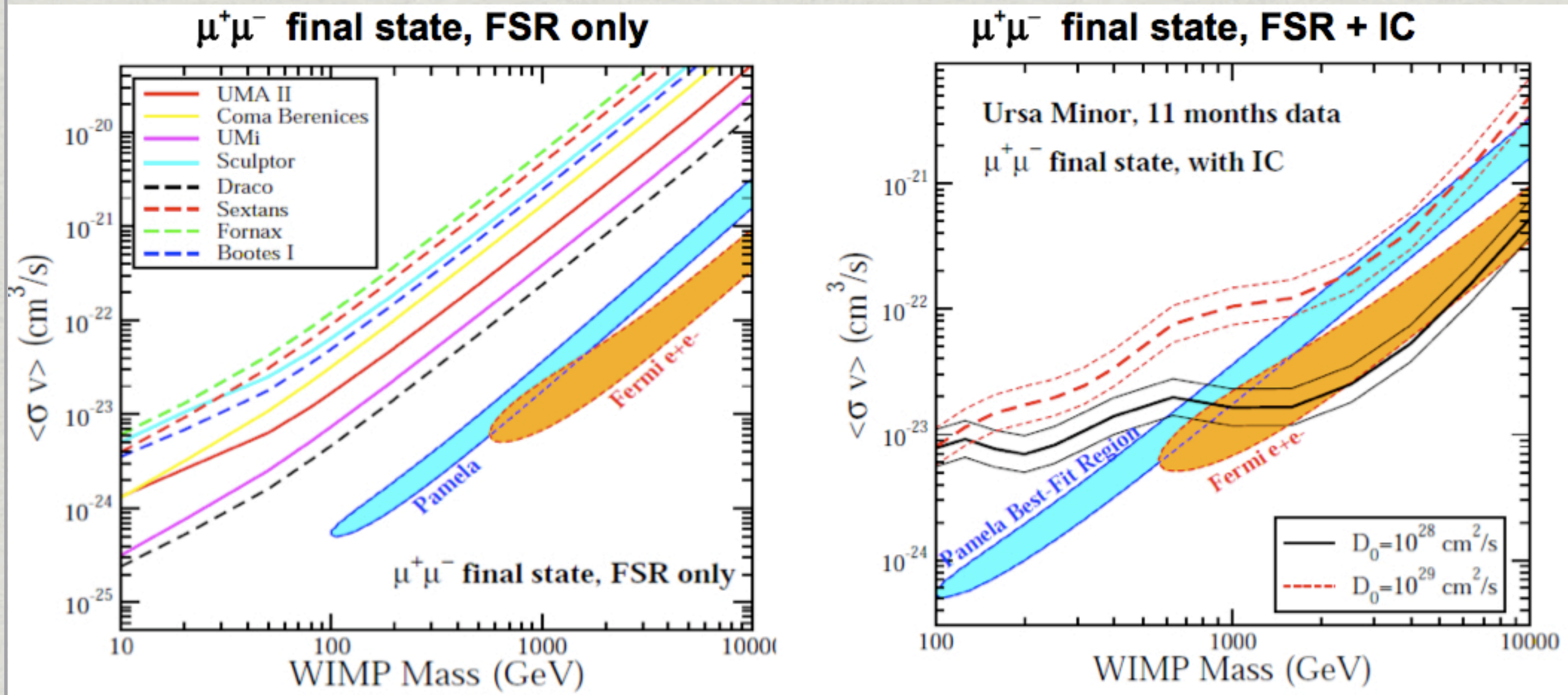
NFW profile, no substructure. (Note: results not critically sensitive to the choice of DM profile, cored profiles result in fluxes only factor of a few lower...).

After 11 months data, cutting into interesting parameter space.



FERMI-LAT COLLABORATION, APJ, 712, 147 (2010).

Search for DM in Dwarf Galaxies



Inverse Compton spectra depends on the diffusion parameter assumed, MODEL DEPENDENT. Dwarfs are not the best place to constrain leptonic channels, they are small objects electrons potentially diffuse out before IC scatter.

Search for DM in Galaxy Clusters

FERMI-LAT COLLABORATION, ARXIV: 1002.2239, SUBMITTED TO JCAP.

The most massive halos formed in the Universe.
Dark matter dominated objects, but, unlike dSpH, they are ***expected to be sources of high energy gamma rays***, due to a population of cosmic rays accelerated in merger and accretion shocks.

Select 6 clusters (observed in X rays) expected to have the brightest DM gamma ray emission, and Fermi-LAT data analyzed within 10 deg of each position.

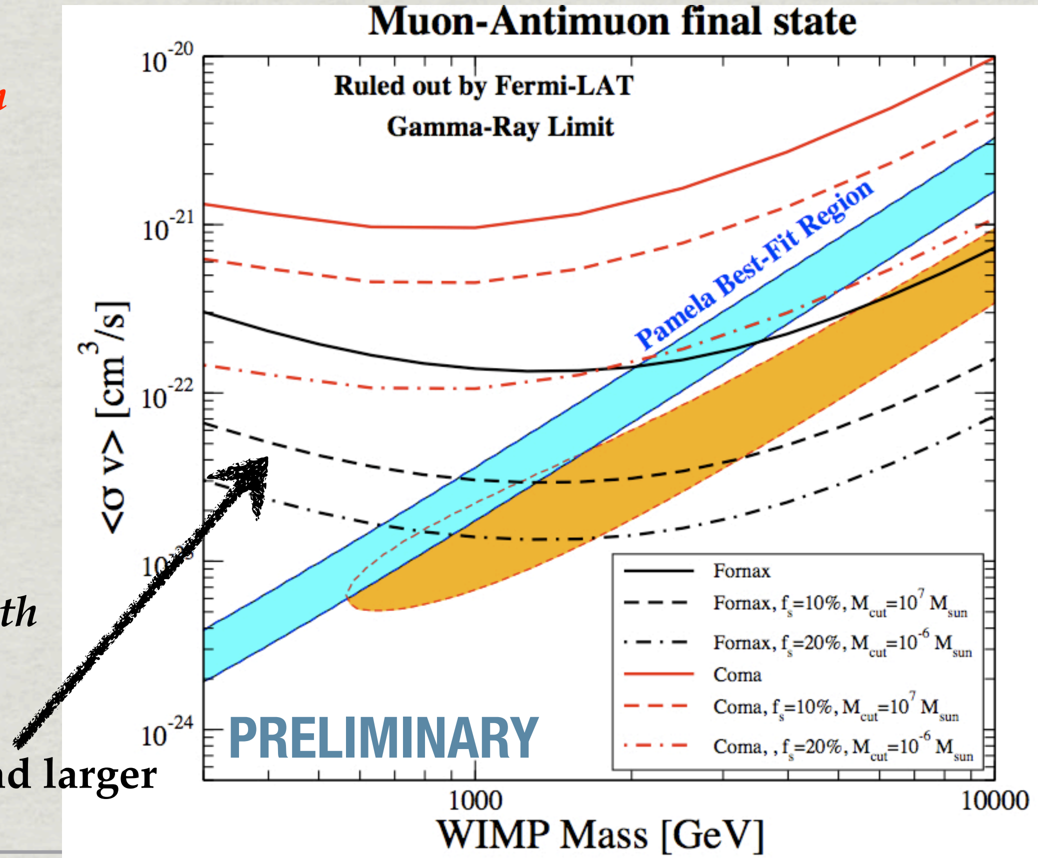
The background model including nearby point sources, galactic and isotropic diffuse gives a good fit -> no Galaxy cluster discovery in 11 months data.

Search for DM in Galaxy Clusters

FERMI-LAT COLLABORATION, ARXIV 1002.2239, SUBMITTED TO JCAP.

For comparison with dSpH: Galaxy Clusters set much stronger limits on the leptonic DM channels (electron deposit all energy in IC on CMB within a cluster).

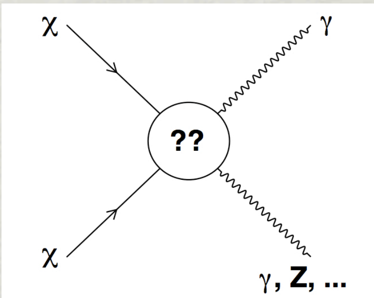
Constraints for a b-bbar final state are weaker than or comparable to (depending on the assumption on substructures) the ones obtained with dSph.



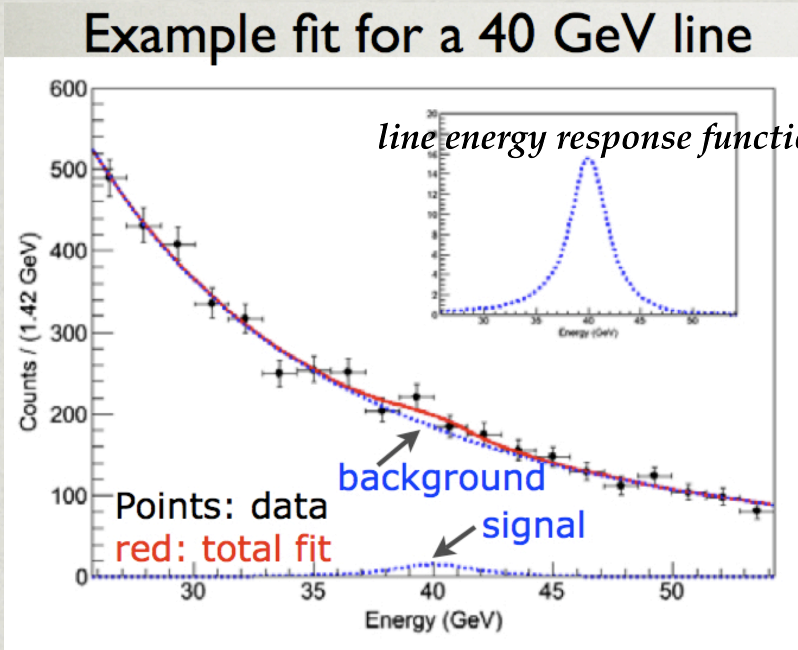
Search for spectral lines

Fermi-LAT collaboration, arxiv:1001.4836, accepted PRL.

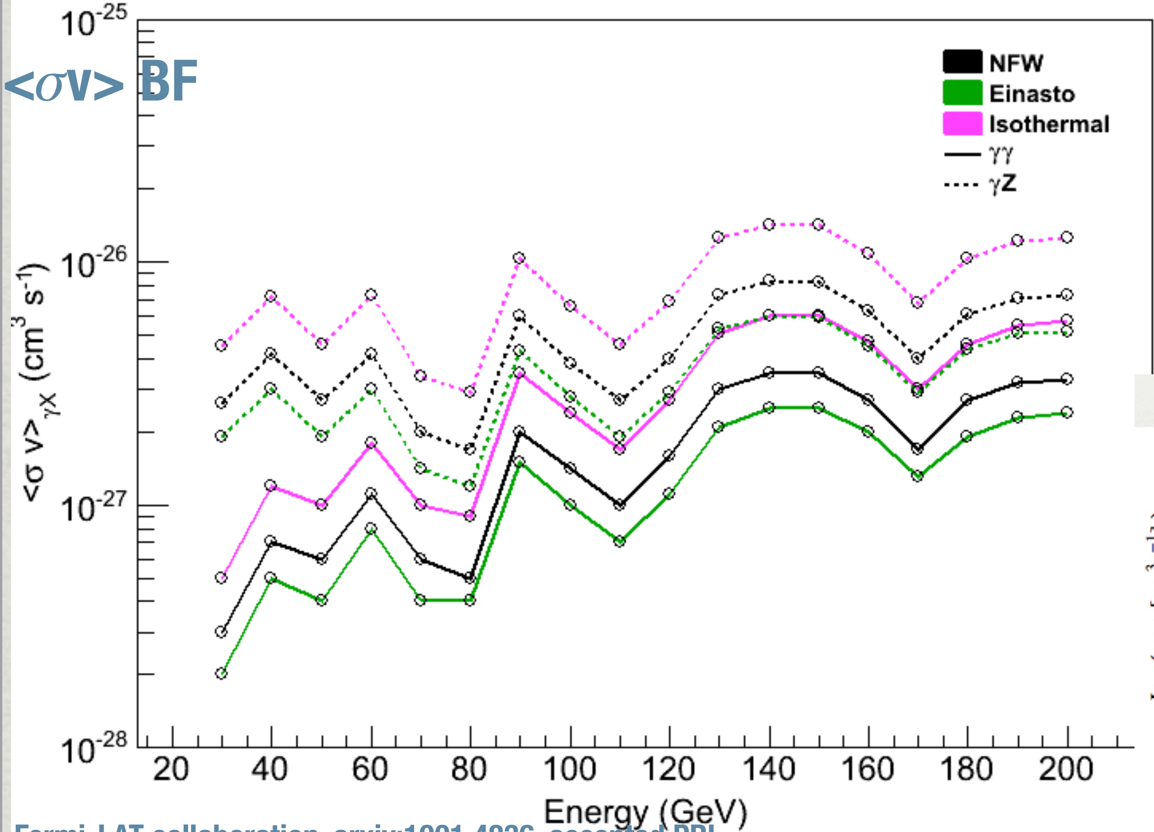
- 11 months data analysis, 30 GeV<E<200 GeV.
- Search region: |b|>10 deg *plus* 20 deg x 20 deg around the Galactic Center.
- Spectral Line search:
  - the background is modeled by a power law function and determined by the fit -> no astrophysical uncertainties.
  - *the signal is the LAT line response function (average energy resolution 11%, for 20<E<100 GeV.*



- loop suppressed processed, branching typically <~10^{-3}.



Search for spectral lines

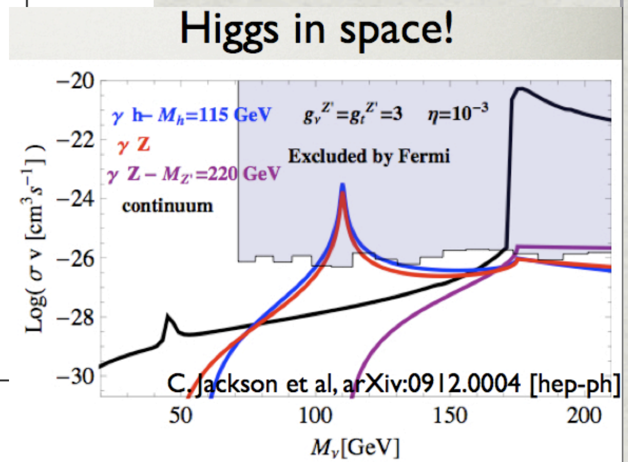


<σv> BF

Fermi-LAT collaboration, arxiv:1001.4836, accepted PRL.

Constraints placed on models which have prominent line signatures:

- *non-thermally produced DM (Wino, (Kane 2009), with $\langle\sigma v\rangle_{\gamma Z}\sim 10^{-26}cm^3s^{-1}$.*
- *DM annihilating dominantly to γHiggs:*



OUTLOOK

- No dark matter discovery, yet.

- *Sensitivity to DM will increase in time:*
  - with a knowledge we inquire about the ***astrophysical signal*** (understand properties of different source classes, cosmic rays sources and propagation, Galaxy gas distribution...) ; using Fermi data and from other experiments (e.g. Planck, AMS-02...),
  - with better understanding of ***instrumental response*** (background rejection, low energy acceptance),
  - ***more sources being resolved***...

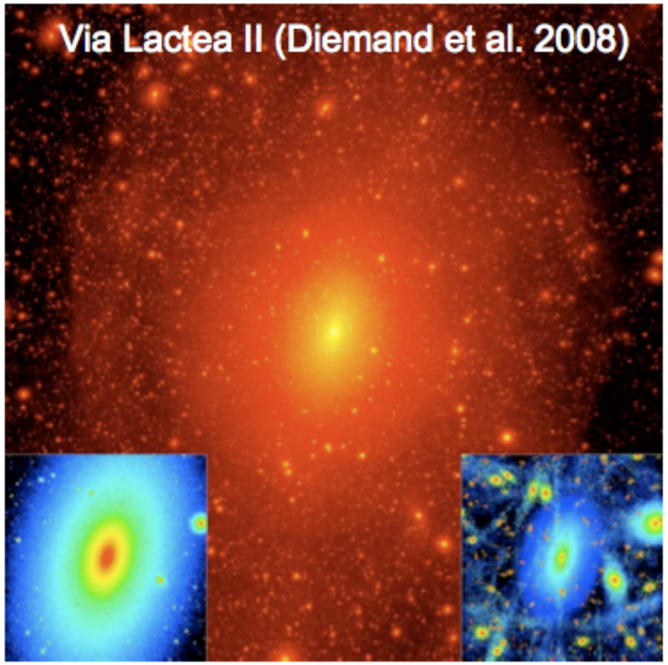
- DM hints from other experiments (***direct detection, LHC***) would significantly increase detection prospects.

- Fermi is a 5-10 year mission, ***this is just a beginning***.

extra slides

Fermi blind search for DM subhalos

- Search criteria:
  - More than 10° from the galactic plane
  - No appreciable counterpart at other wavelengths
  - Emission constant in time (1 week interval)
  - Spatially extended: ~ 1° average radial extension for nearby, detectable clumps
  - Spectrum determined by DM (both b-bbar and μ+μ- spectra are tested vs a (soft) power law hypothesis)
- Blind analysis: finalize selection method with 3 months of data and apply to 10 months
- Search for sources (>5σ significance) passing these criteria in the 200 MeV to 300 GeV energy range.
- Background: point sources+diffuse Galactic and isotropic emission



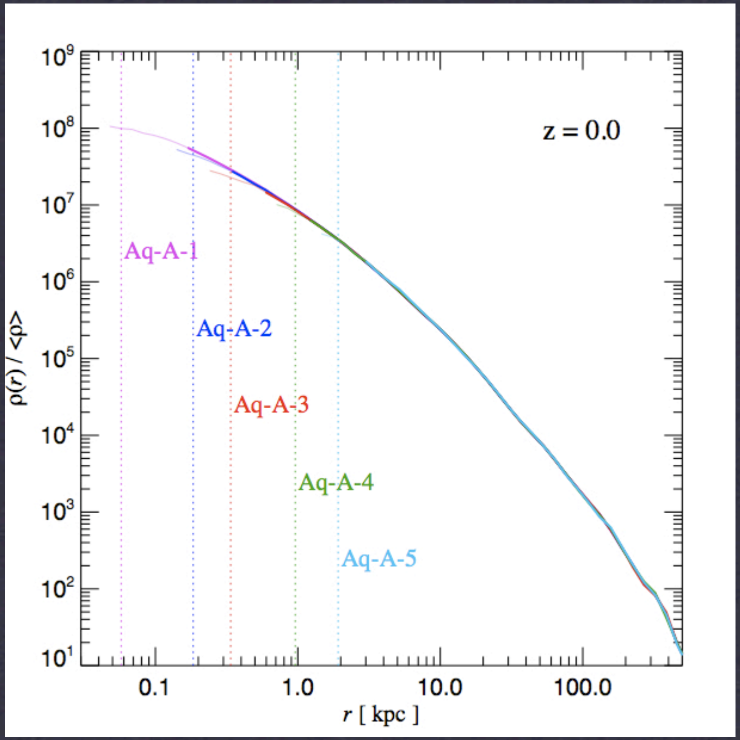
PRELIMINARY

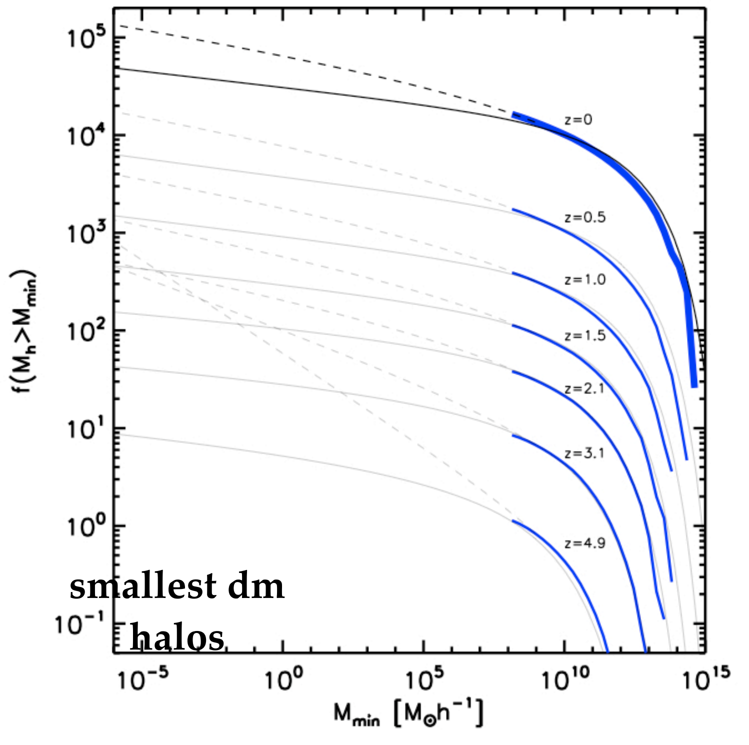
No DM satellite candidates are found in 10 months of data

- ✓ Consistent with result of sensitivity study based on Via Lactea II predictions for the DM distribution for a generic 100 GeV WIMP annihilating into b-bbar, $\langle\sigma v\rangle=3\times10^{-26}$ cm^3 s^{-1} (submitted to ApJ)
- ✓ Work is ongoing to evaluate the sensitivity for other models

Dark matter profile (ρ):

TYPICALLY ONE OF THE BIGGEST UNCERTAINTIES IN DM SEARCHES:



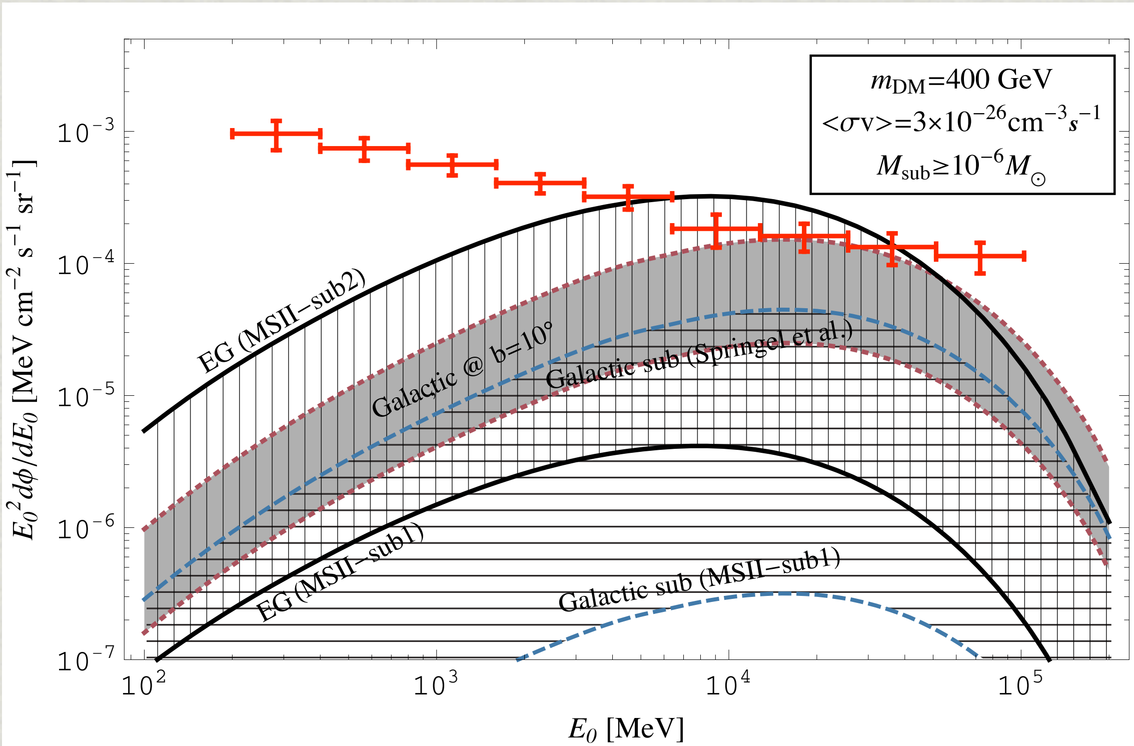


N-BODY SIMULATIONS **DO NOT REACH DESIRED SMALL SCALES OR LOW HALO MASSES** OPTIMAL FOR DM SEARCHES. DEPENDING ON THE TARGET, RELATED UNCERTAINTIES CAN BE ~ ORDER(S) OF MAGNITUDE.

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

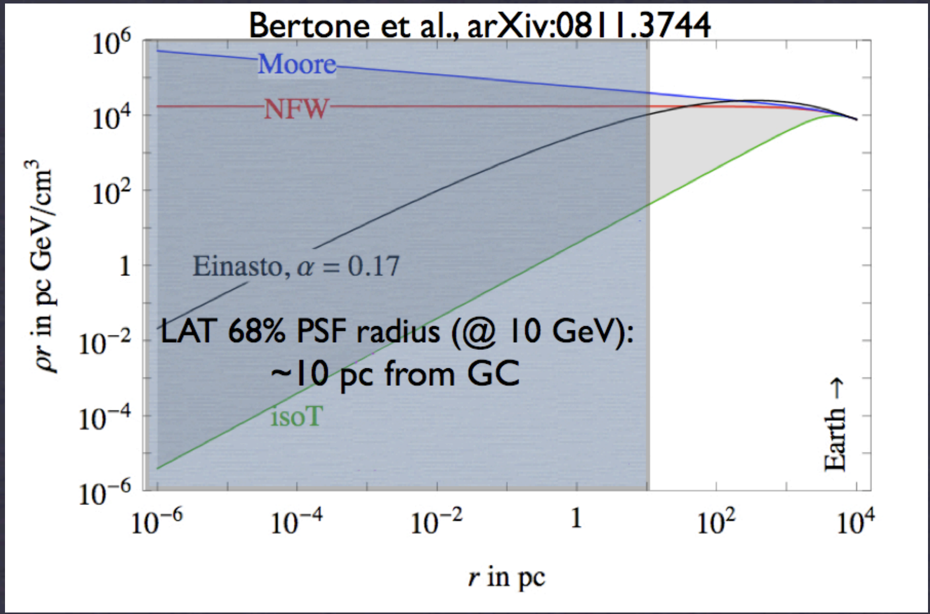
While looking at the Extra Galactic signal we are looking through **the DM annihilation haze from our halo**!

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

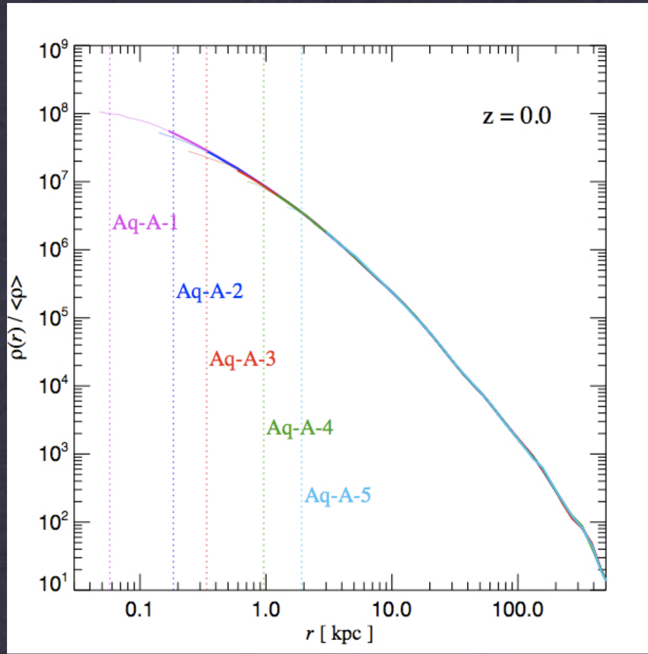


Abdo, A. et al., arXiv: 1002.4415

Dark matter distribution



Inner region of halos is largely unresolved...

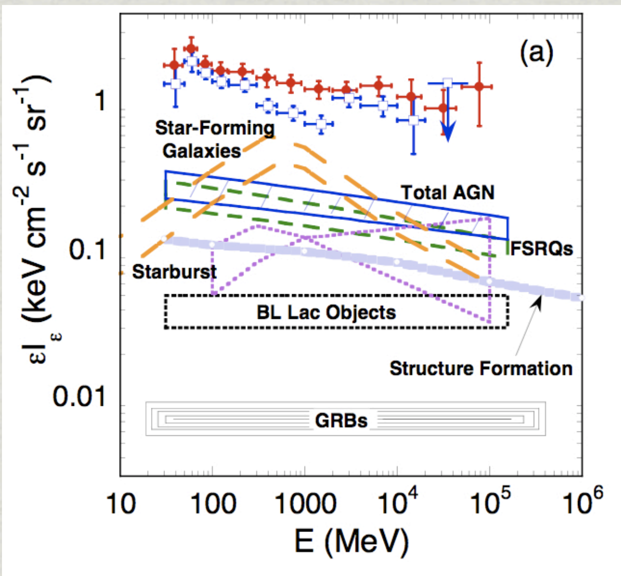


Springel, V. et al, Mon.Not.Roy.Astron.Soc.391:1685-1711,2008.

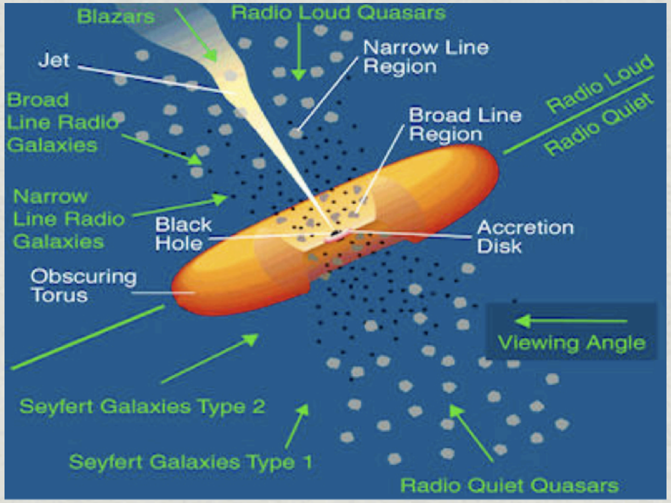
DM signal depends on ρ^2, and therefore is very sensitive to the DM profile.
Some targets, which mainly probe outer regions of DM halos (e.g. dwarf galaxies) are less sensitive to the actual profile shape, while for some (e.g. GC) it is the main uncertainty...

Search for DM in the Isotropic diffuse signal - WHAT MAKES THIS SIGNAL?

- Guaranteed sources:
  - Active Galactic Nuclei (Blazars contribute 20-100% from EGRET)
  - Star forming galaxies



Dermer, C. D., AIP Conf. Proc. 921 (2007) 122



- galaxy clusters
- star burst galaxies...

DM cosmological signal

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

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

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

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)!

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

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

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

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

Depends on the profile (NFW, Moore, ...) and a scatter around mean values of parameters.

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.

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

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

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.

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

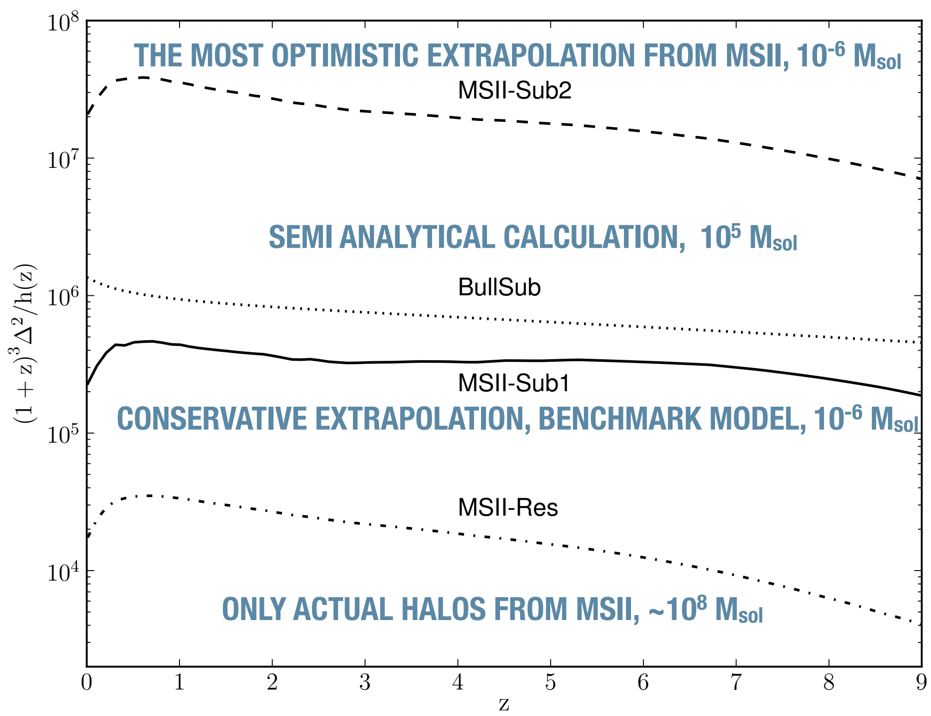
$$\Delta_M^2(z,M) \equiv \frac{\Delta_{vir}(z)}{3} \int dc'_{vir} \, \mathcal{P}(c'_{vir}) \frac{I_2(x_{min}, c'_{vir}(z,M)\, x_{-2})}{[I_1(x_{min}, c'_{vir}(z,M)\, x_{-2})]^2} (c'_{vir}(z,M)\, x_{-2})^3$$

$\Delta^2(z)$ - structure formation enhancement

Necessary to extrapolate:

-both the contribution of host halos, beyond the resolution (from 10^8 M_{sol} to 10^{-6} M_{sol}...) -> boost factor of ~60, in MSII.
- as well as the subhalos within halos of a given mass -> carefully checked the scatter in the extrapolation function.

(Not surprisingly) results of extrapolations span three orders of magnitude!

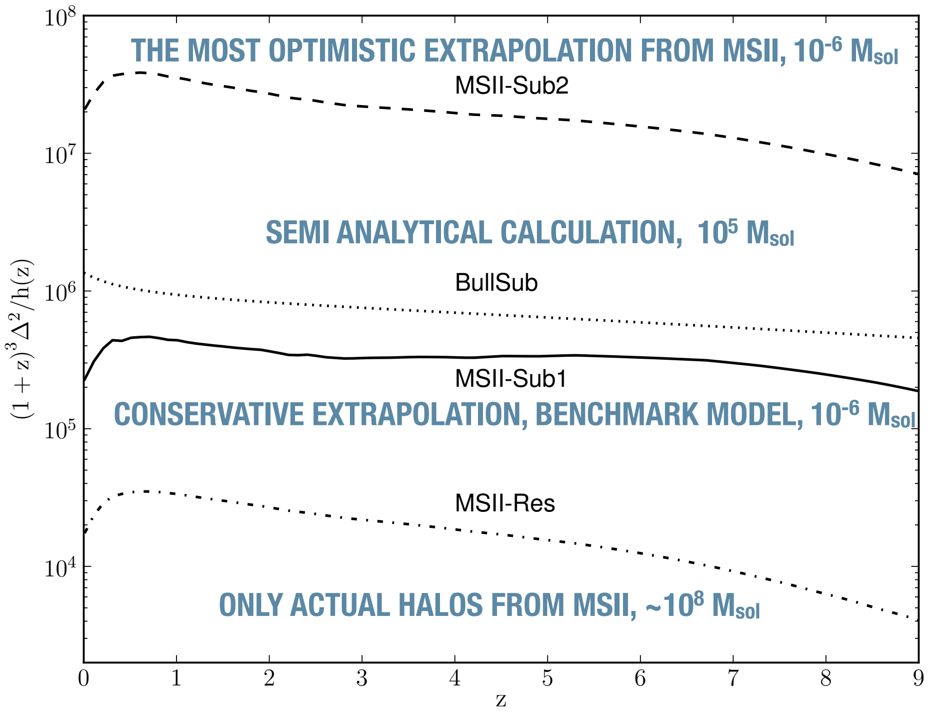


Abdo, A. et al., arXiv: 1002.4415

$\Delta^2(z)$ - structure formation enhancement

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

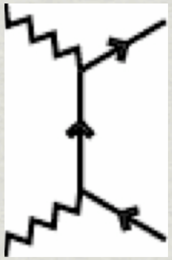
For example, recently significant progress made in quantifying the subhalo mass function, as well as statistical significance of findings of Milky Way size simulations...

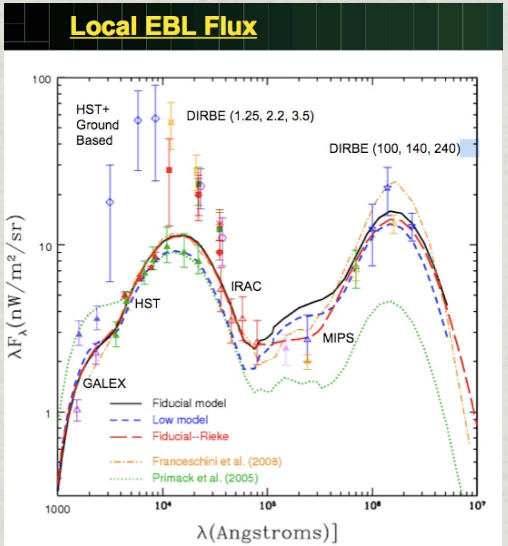


Abdo, A. et al., arXiv: 1002.4415

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

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

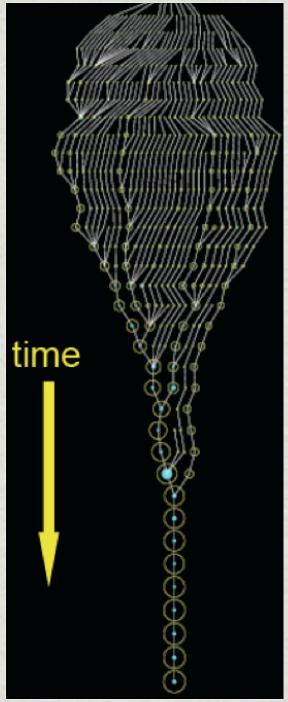




Measurement of local EBL as well as modeling of red shift evolution of EBL is very challenging!

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

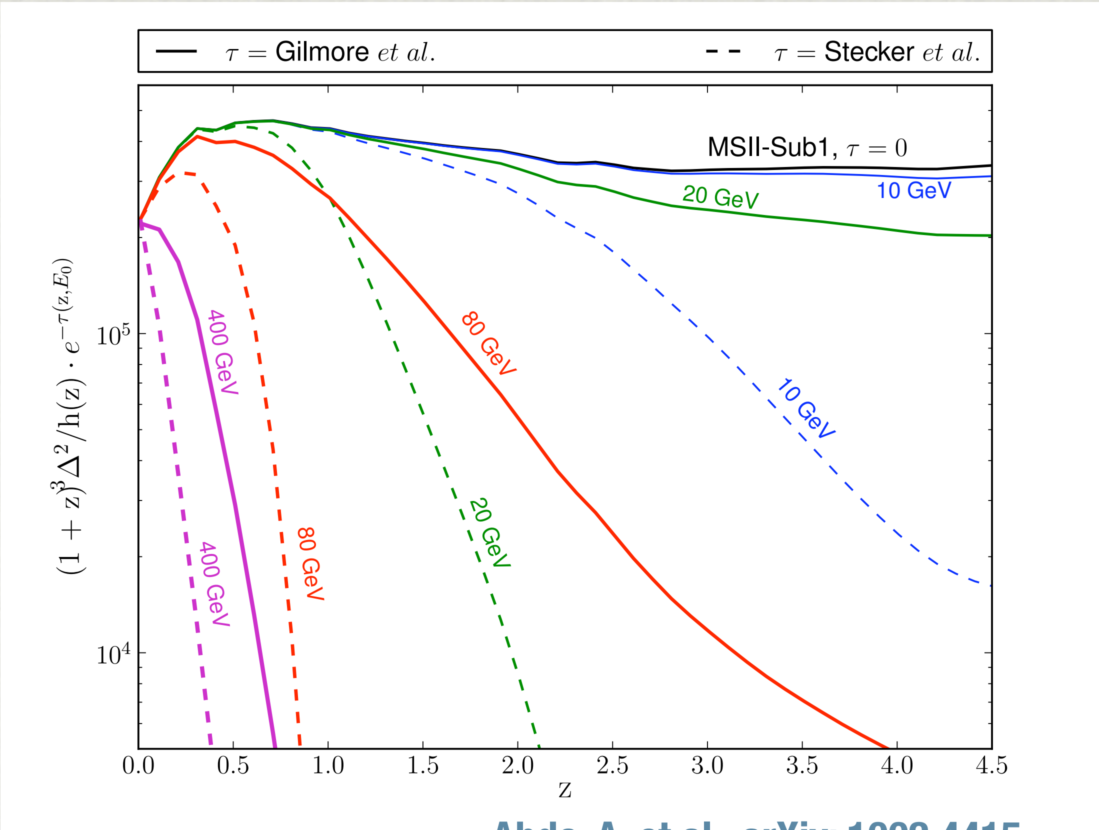


$e^{-\tau}$ - absorption of photons along the line of site

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).

We will illustrate how the differences reflect on the final DM limits.

Dominant contribution to the signal comes only from z<~2...



Abdo, A. et al., arXiv: 1002.4415