Dark Matter constraint from the Fermi-LAT diffuse data

on behalf of the Fermi-LAT collaboration

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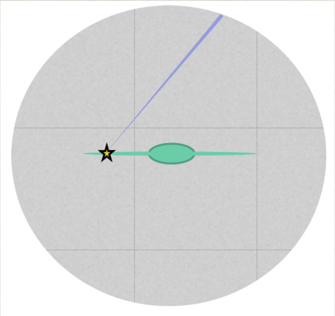
INDIRECT DARK MATTER DETECTION IN GAMMA RAYS

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.



Bergstrom, L., talk at DM2010.

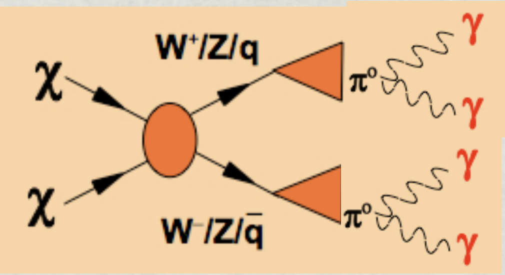
Flux of gamma rays produced in DM annihilations:

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

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

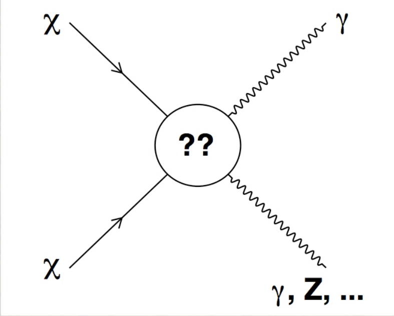
γ ray production channels

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



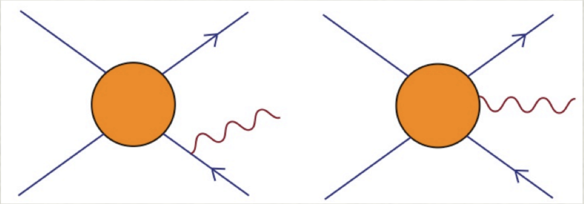
Dominant production for DM annihilating to quarks and gauge bosons (i.e. SUSY) .

  - line:



Loop suppressed, but unique, smoking gun, signature.

  - final state radiation:



- through **radiative processes**:

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

ambient backgrounds and fields

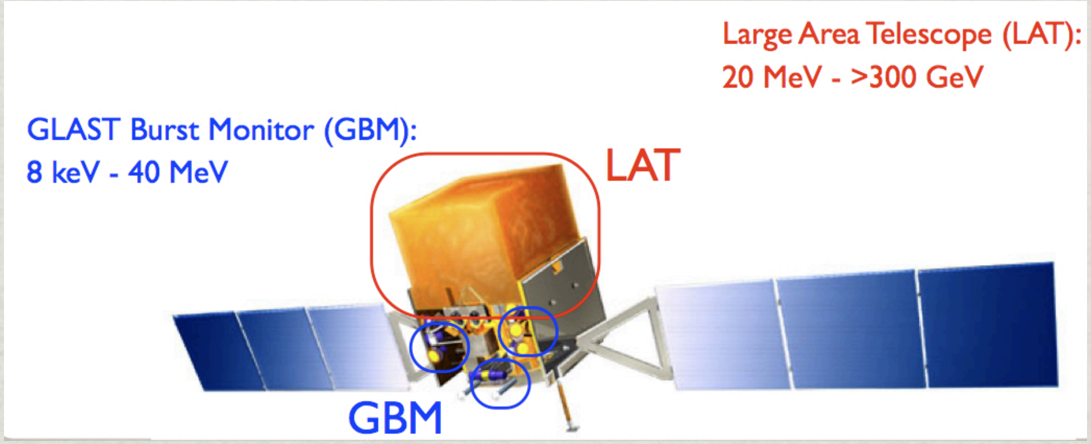
$$\begin{cases} \text{Synchrotron} \\ \text{Inv. Compton} \\ \text{Bremstrahlung} \\ \text{Coulomb} \\ \text{Ionization} \end{cases} \begin{cases} \text{radio} \\ \text{IR} \\ \text{X-rays} \\ \gamma\text{s} \end{cases}$$

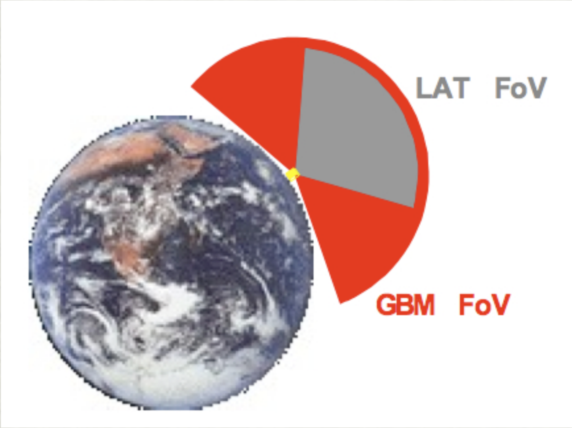
Important if there is a significant branching to leptons.

Fermi-LAT instrument: excellent in measuring the ***gamma ray diffuse emission***.

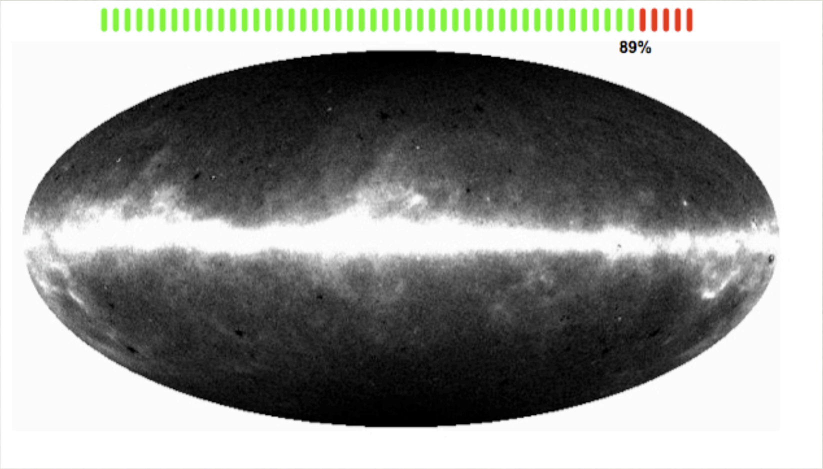
* Large field of view: 20% of the sky at any instant. In the survey mode exposes every part of the sky for ~30 min, every 3 hours.

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





*Diffuse emission has high potential for DM searches -- contains information on the morphology as well as in the DM annihilation/decay spectral features.



**LAT minus point sources*
[J-M Casandjian, TeVPa2010]

Signal of astrophysical origin challenging to disentangle; possibility based on *differences in signatures* of astrophysical and DM components of the diffuse signal.

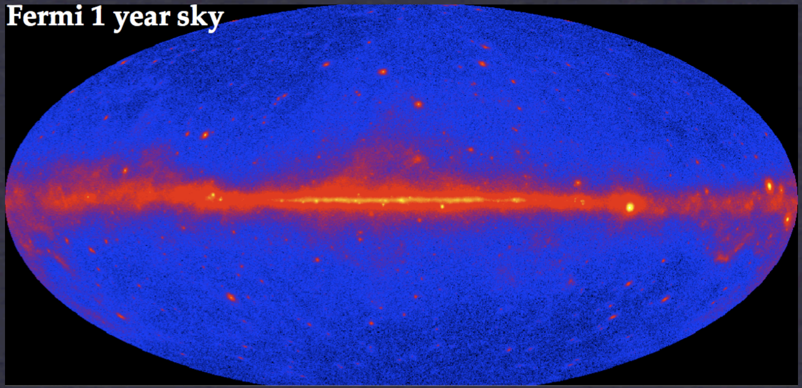
Diffuse DM analysis by the Fermi team:*

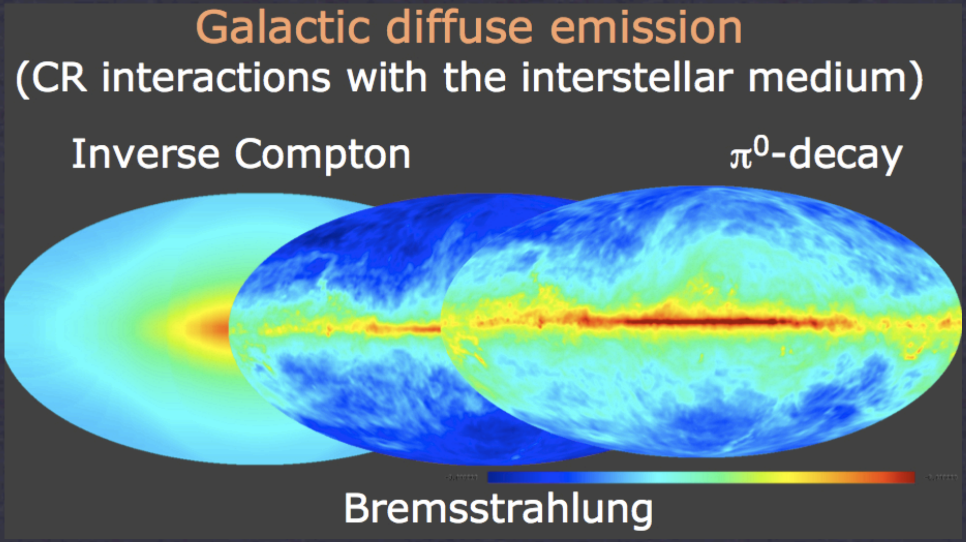
- ****analysis of the Extragalactic (Isotropic) Signal, by using the intensity and spectral shape of the signal or angular anisotropies (by J. Siegal-Gaskins)***

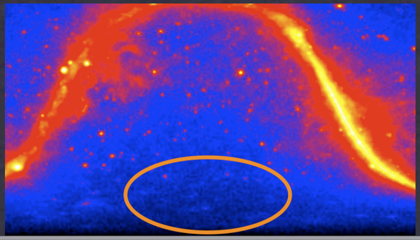
- ****analysis of the the Galactic diffuse signal, (me INTRO, more by A. Cuoco and B. Anderson).***

Isotropic diffuse signal

THE GAMMA RAY FERMI SKY:





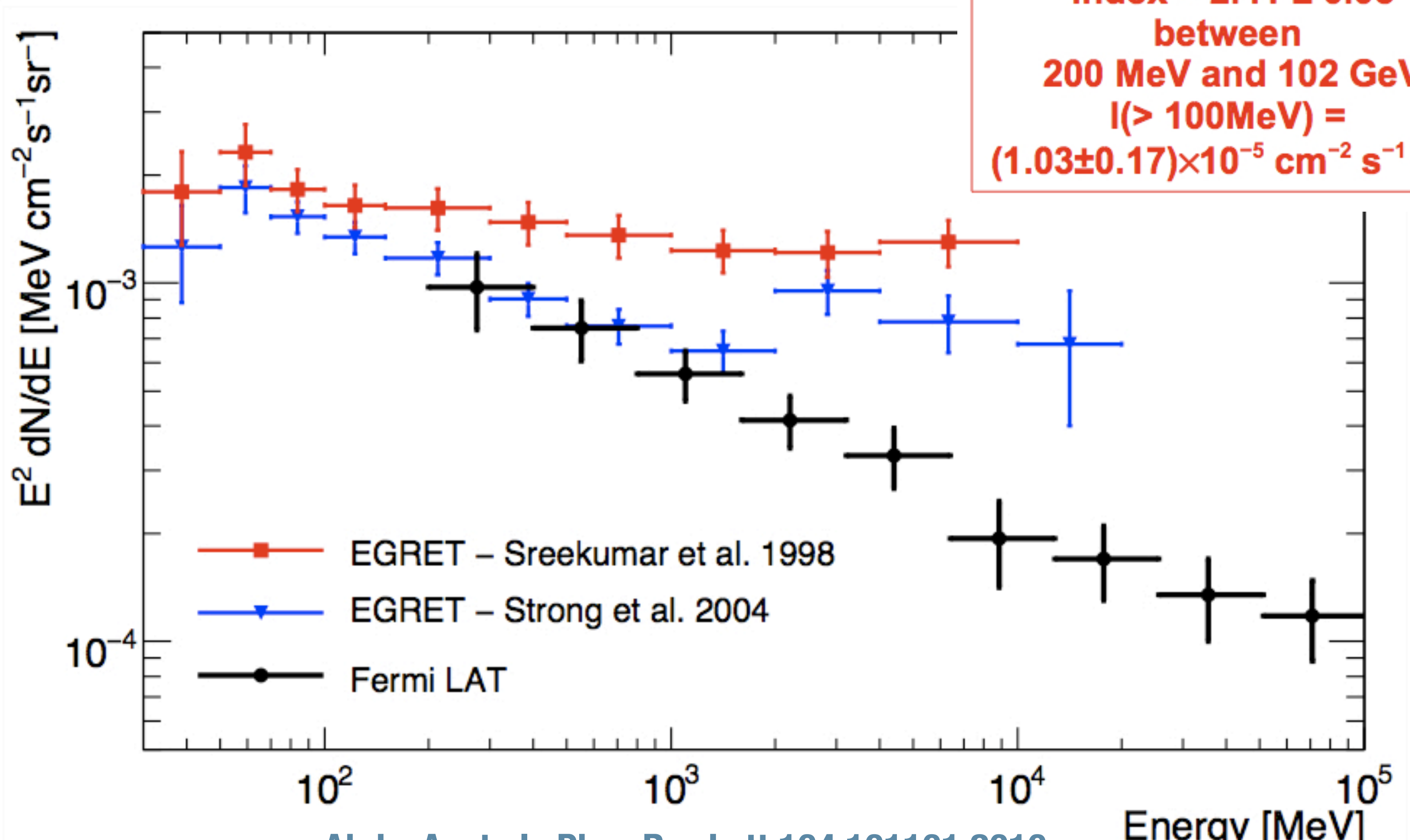


After the contribution from the Galactic diffuse emission, point sources+residual cosmic rays ... are subtracted ***we are left with the isotropic diffuse emission.***

Ackermann, M., talk at TeVPa, 2009.

Isotropic diffuse signal

spectrum compatible with a power law of index = 2.41 ± 0.05 between 200 MeV and 102 GeV
$I(> 100\mathrm{MeV}) = (1.03 \pm 0.17) \times 10^{-5}\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}$

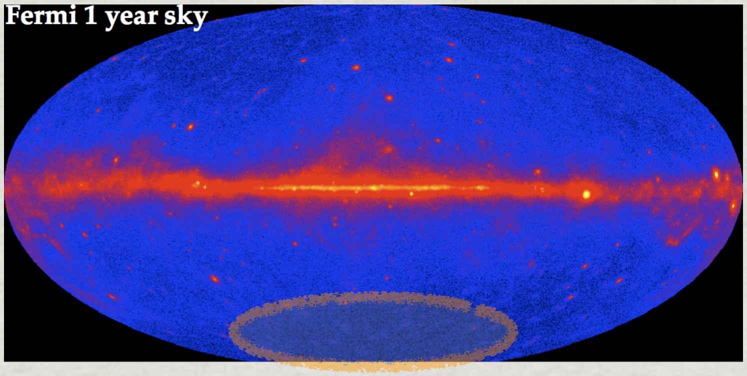


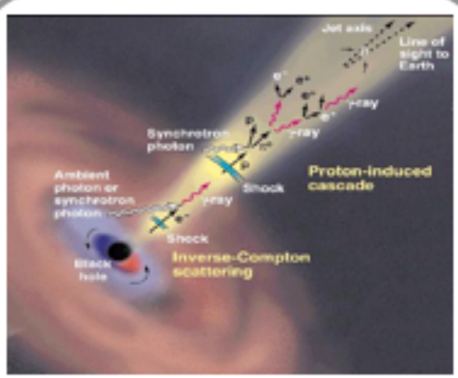
Abdo, A. et al., Phys.Rev.Lett.104:101101,2010.

Isotropic diffuse signal

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

What makes the GeV extragalactic signal?

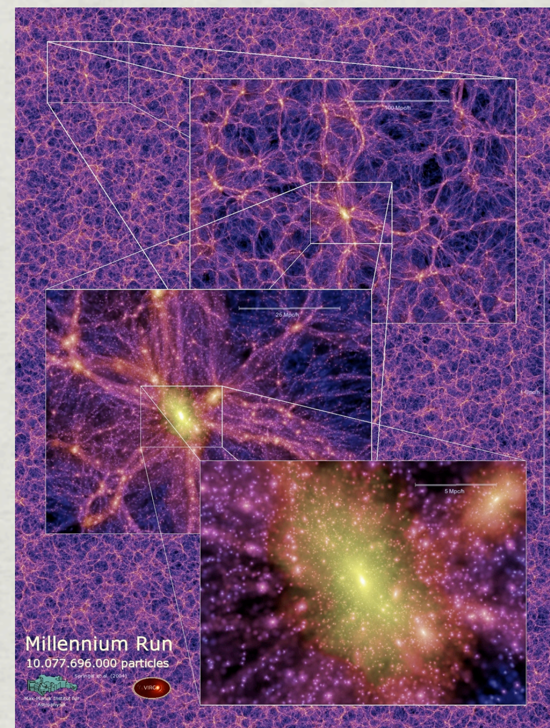




Credit: J. Buckley 1998 (Science), illustration: K. Sutliff

Guaranteed contribution: ***unresolved extragalactic sources***: blazars, star forming and star burst galaxies,...

Dark matter *annihilation in all halos at all red-shifts should contribute, too.*



Cosmological signal of DM

DM forms structures (halos) in gravitational collapse, within which DM self-annihilation signal is greatly enhanced (ρ^2).

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

Ullio, P. et al.,2002.

Δ^2: *describes clustering properties of DM: number of halos of a given mass, at a given red-shift and the inner structure of halos (through their concentration) -- N body simulations. Depends sensitively on the resolution of N-body simulations.*

τ: *attenuation of photons due to pair production on Extragalactic Background Light (from UV to far-IR)*

dN/dE: DM annihilation spectrum at emission.

Cosmological signal of DM

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

Ullio, P. et al.,2002.

Information in OVERALL NORMALIZATION and SPECTRAL SHAPE.

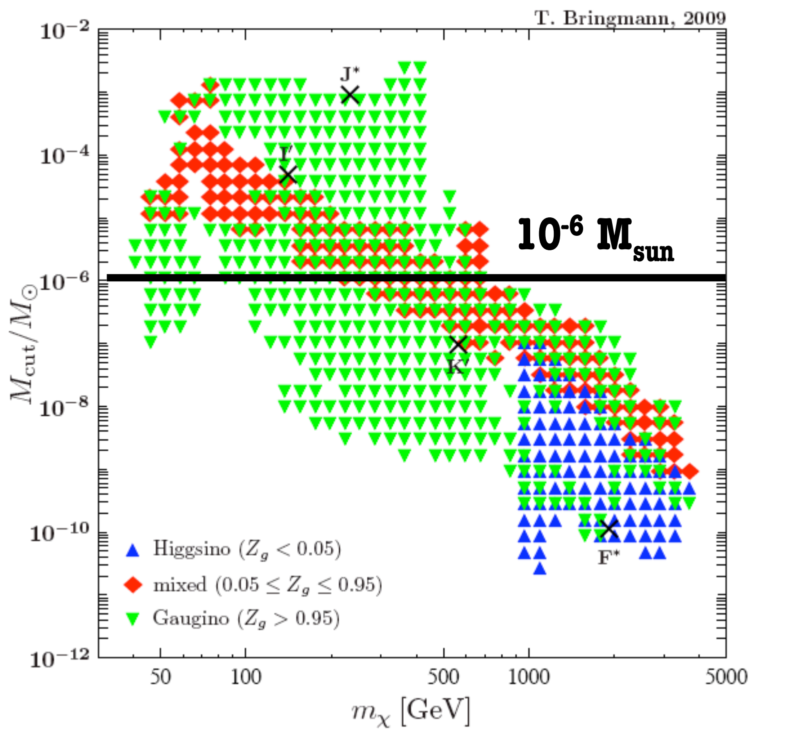
⋆*Overall normalization is degenerate, most notably between the DM annihilation rate and* Δ^2.

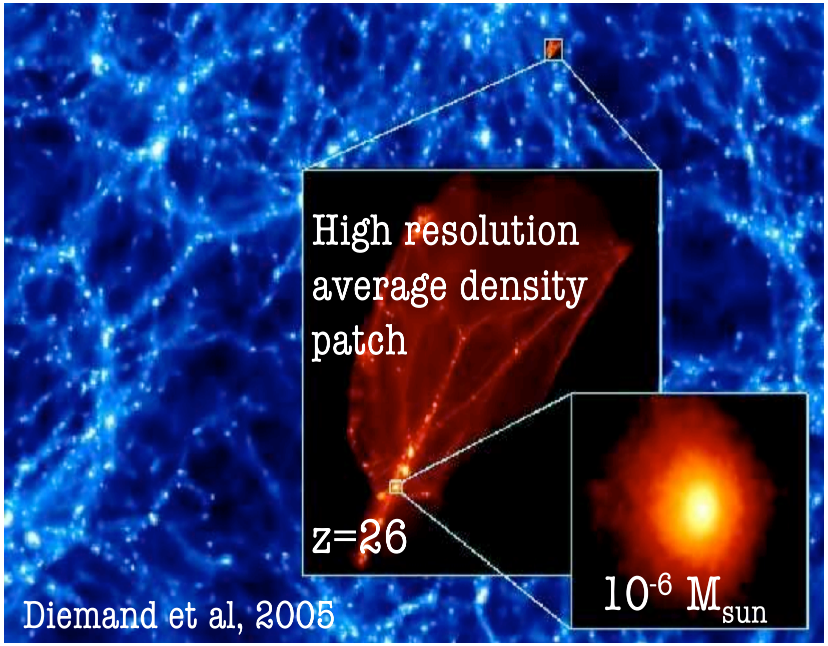
Δ^2: ***depends sensitively on the mass resolution of N-body simulations! - Introduces large uncertainties in limits one could place on*** $\langle \sigma v \rangle$

Normalization

⋆*The dominant contribution to* Δ^2 *comes from the smallest, most concentrated halos, which are unresolved in simulations - sensitive to the resolution limitations! (>$10^5 M_{sol}$, while theoretical lowest mass scale <$10^{-3} M_{sol}$).*

Typical M_{min} for a WIMP = 10^{-6} M_{sun}



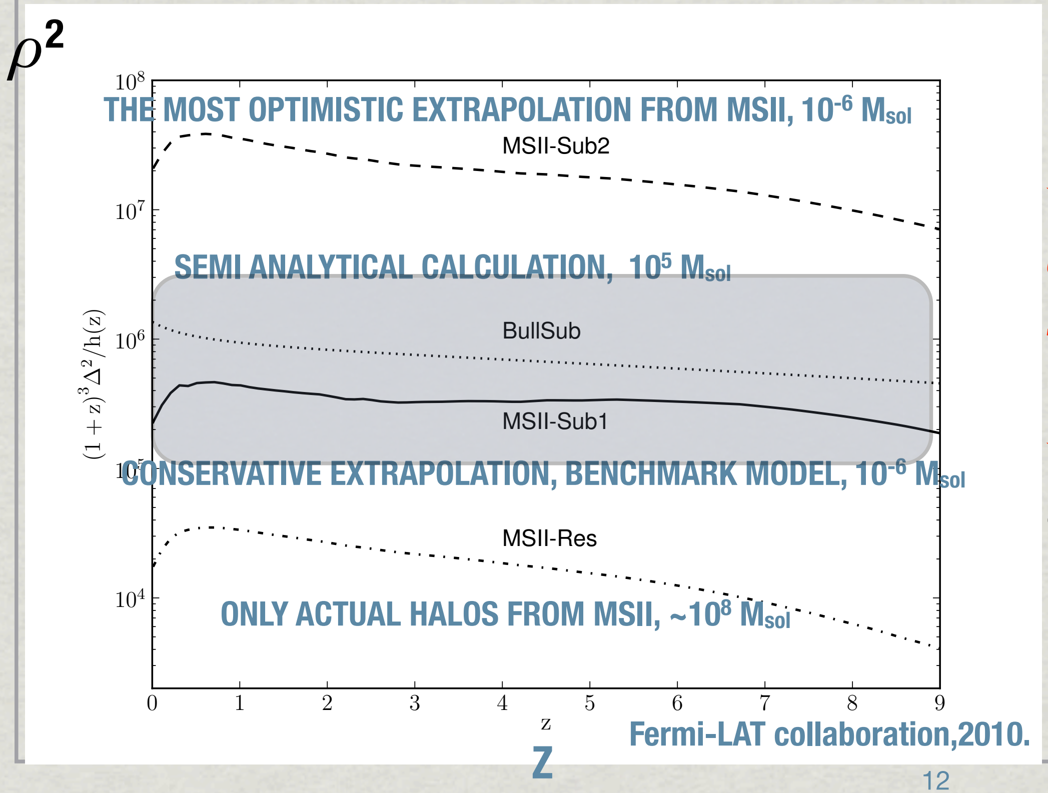


Existence confirmed in a small high resolution patch of the universe, nested within a hierarchy of larger and lower resolution grids of particles - uncertainty in how measured properties at z=26 propagate to z=0.

Two approaches used to determine **Δ²**:

⋆***direct results from Millennium Simulation II:** mass resolution* $10^8 M_{sol}$, ***extrapolation to smaller halo masses is done using simple power law, with carefully chosen index- optimistic/conservative choice),*** *[Zavala et al., 2009]*

⋆***In the semi-analytic approach:** halo mass function from a Virgo simulation AND the mass-concentration toy-model relation from Bullock et al. 2001 (soft physically motivated extrapolation of halo concentration to lower masses, below the resolution)***



⋆***Note: both semi-analytic approach and conservative extrapolation give similar prediction.***

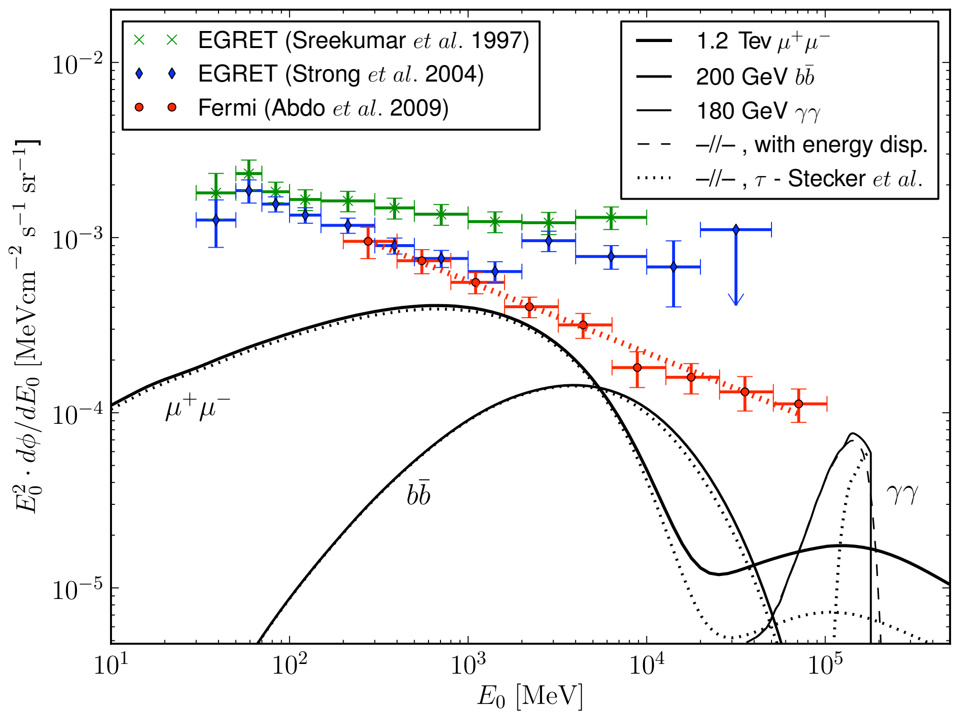
⋆***However, uncertainties in the overall normalization are large.***

Spectral shape

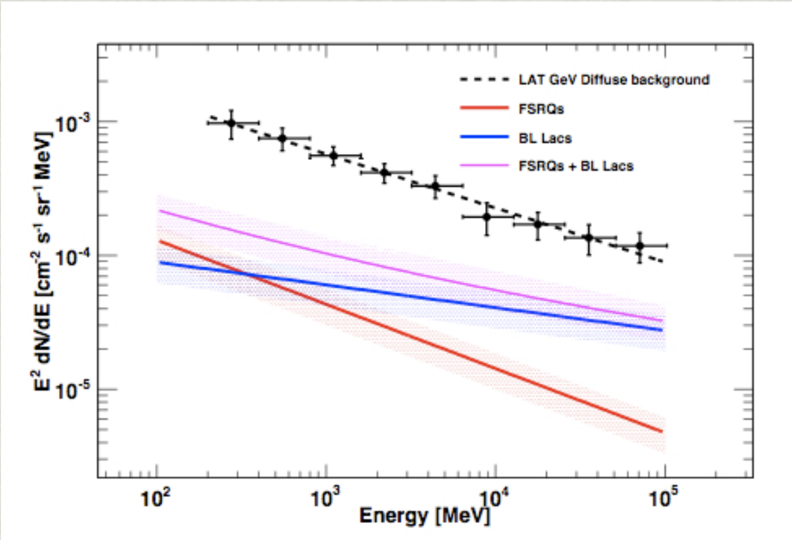
$$\frac{d\phi_\gamma}{dE_0} = \frac{\sigma v}{8\pi} \frac{c}{H_0} \frac{\bar{\rho}_0^2}{M_\chi^2} \int dz\, (1+z)^3 \frac{\Delta^2(z)}{h(z)} \frac{dN_\gamma(E_0\,(1+z))}{dE} e^{-\tau(z,E_0)}$$

★*spectral shape -- Potentially a way to disentangle the signal from the backgrounds:* *due to red-shift, the spectrum measured at energy E_0 depends on the particle physics, BUT also on the attenuation effects AND the halo formation history vs. redshift.*

Fermi-LAT collaboration,2010.



Intensity and Spectra of astrophysical contribution

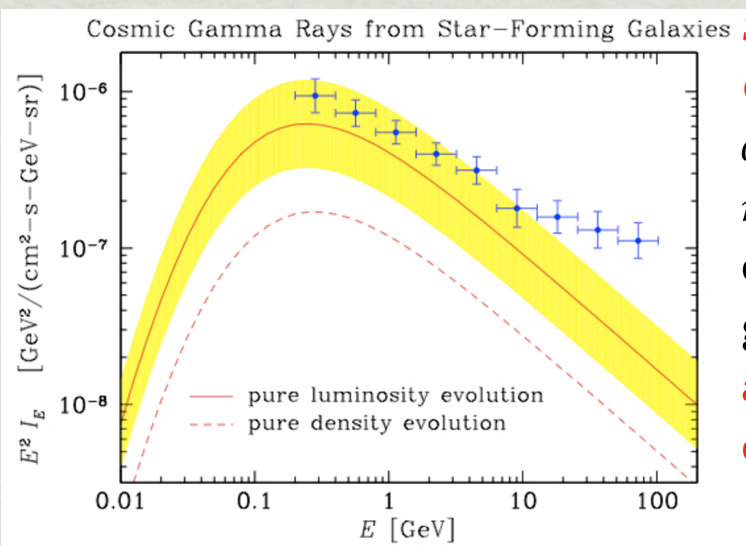


AGNs, based on Fermi observation of ~700 AGNs, and a break in their luminosity function, -> **maximally 30% of the extragalactic signal.**

Fermi-LAT collaboration, 2010.

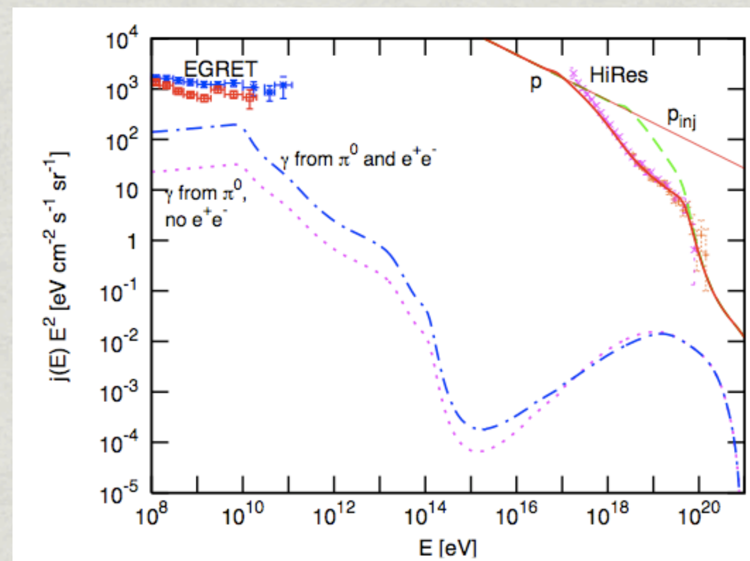
EM cascades from *UHECR proton interactions -- hard spectrum*

Kalashev et al., 2007.



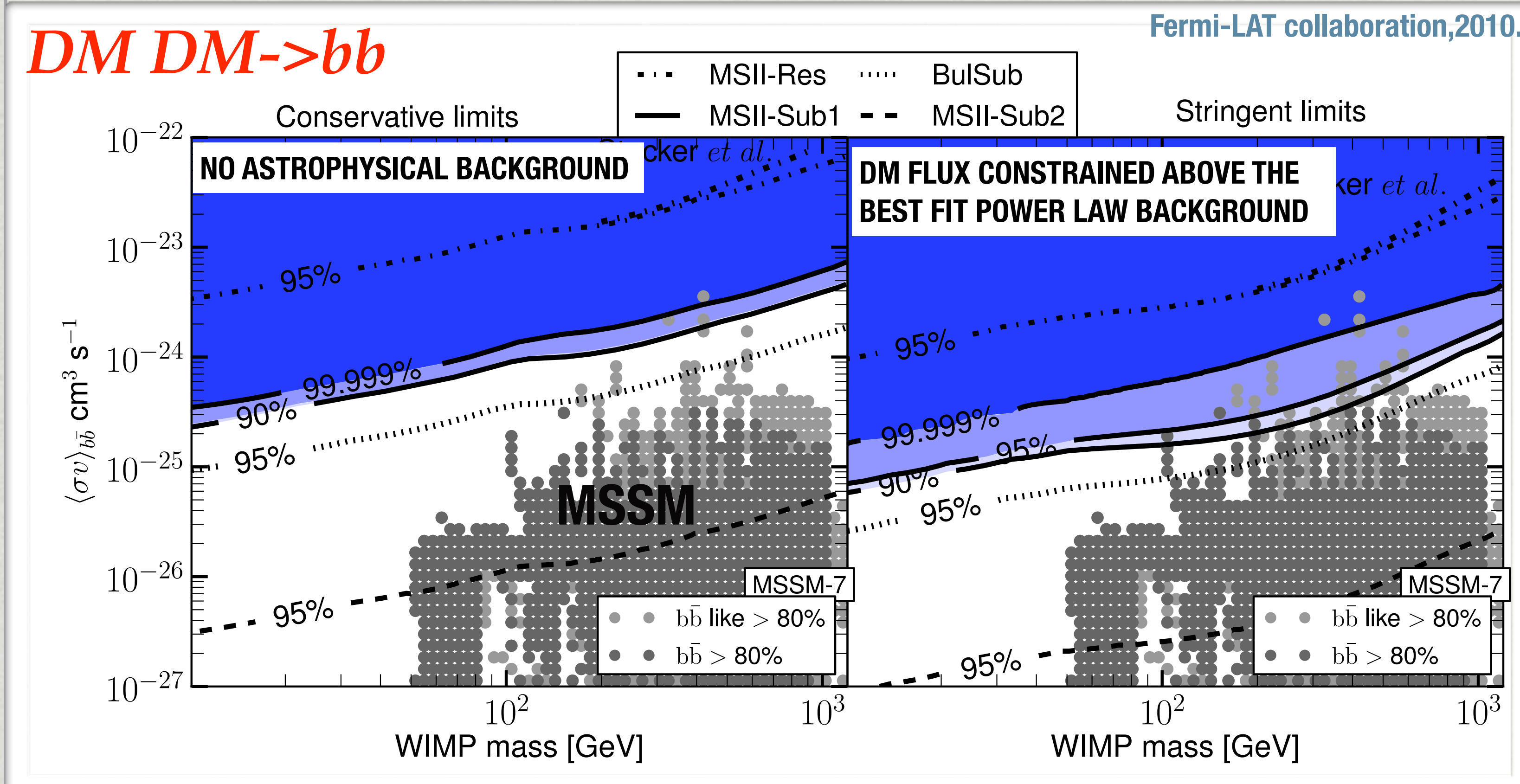
Star Forming Galaxies (like our own):could make up **most of the extra galactic signal at lower energies.**

Fields et al., 2010.



Isotropic diffuse signal - DM constraints

Much still to be understood about the contribution from astrophysical source classes. Here we take too bracketing approaches in treating the DM backgrounds:

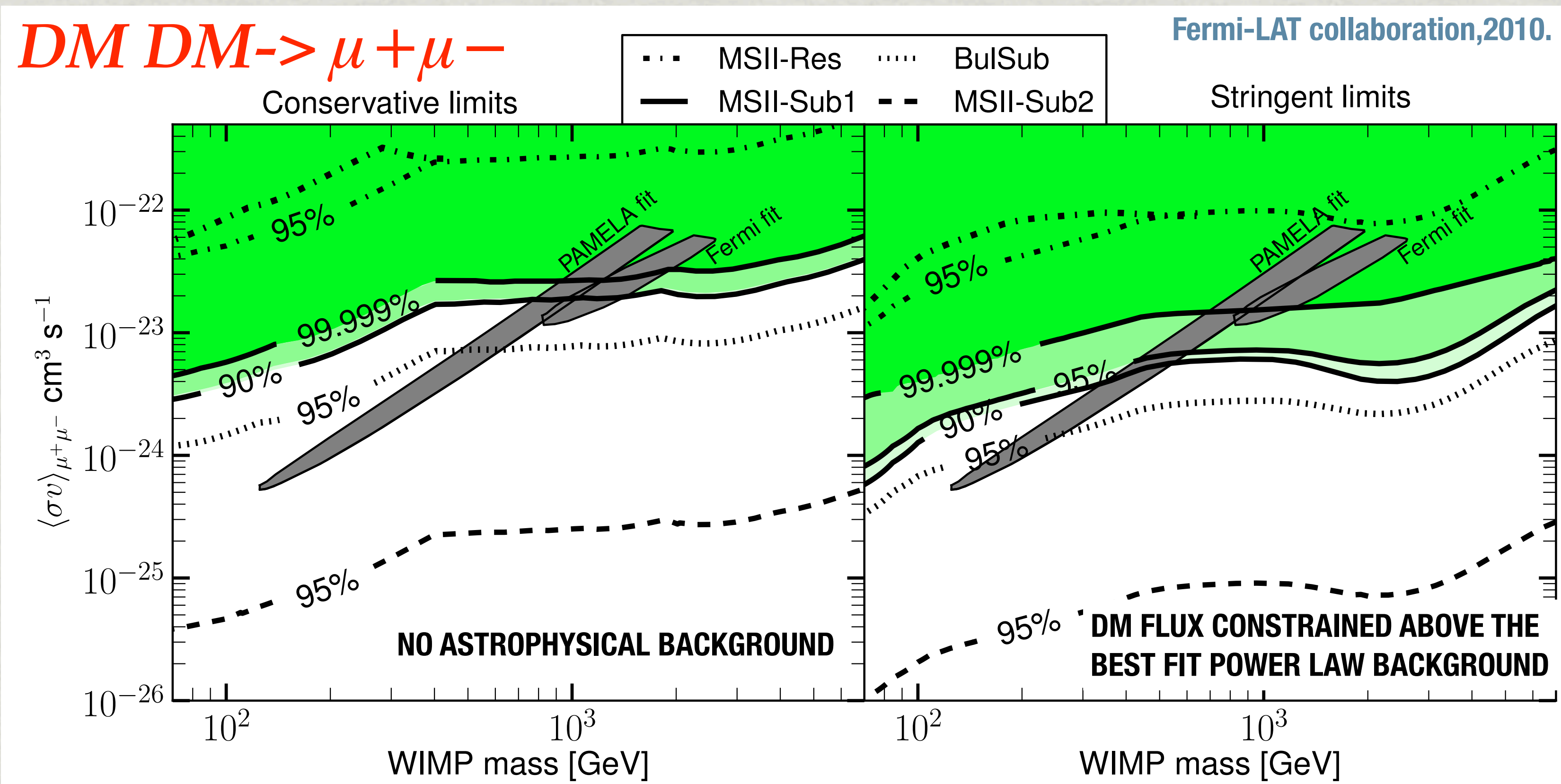


Limits based on the 1st-year data.

Cosmological DM signal has good constraining potential, but the total DM flux prediction uncertain due to the resolution limitations of N-body simulations. (spectral information could potentially be used to disentangle DM galactic/extragalactic signatures).

Isotropic diffuse signal - DM constraints

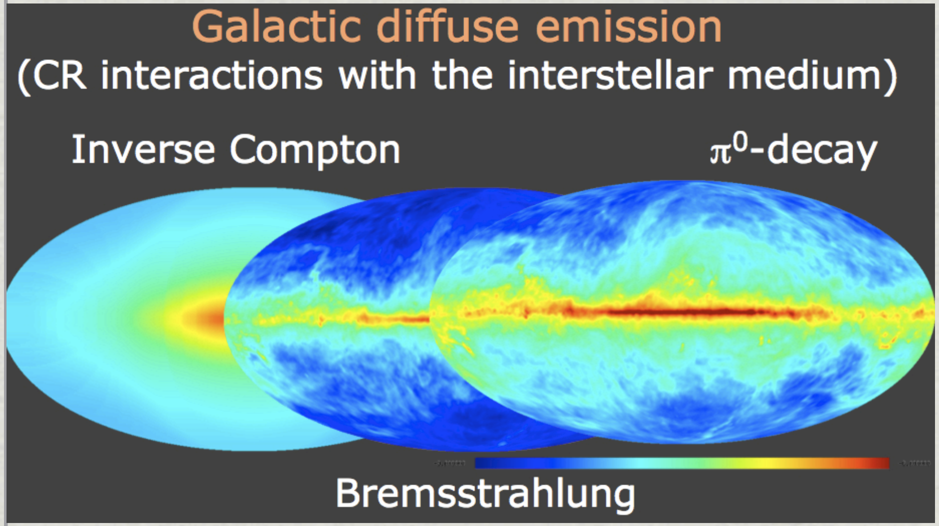
The isotropic flux should get lower as Fermi continues to detect more extra galactic sources. Also, increased number of detected sources will result in the improved modeling of the contribution of the extragalactic source populations to the Isotropic signal (through the angular anisotropy studies, too!) -> increase in sensitivity for DM searches.



Limits based on the 1st-year data.

Galactic halo DM analysis

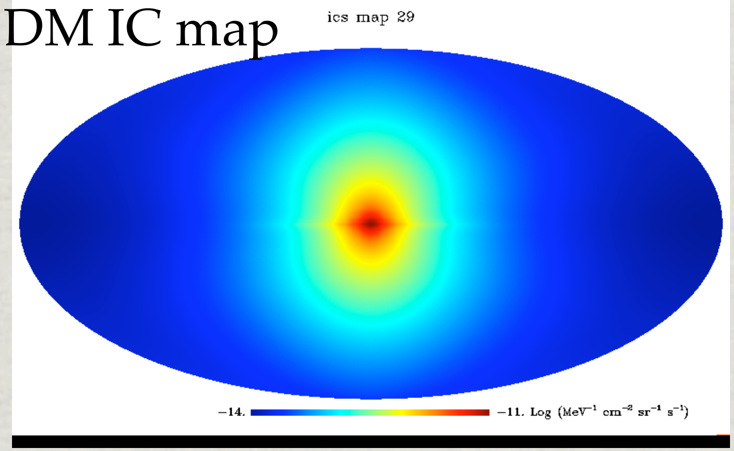
[Ongoing work - preliminary results]



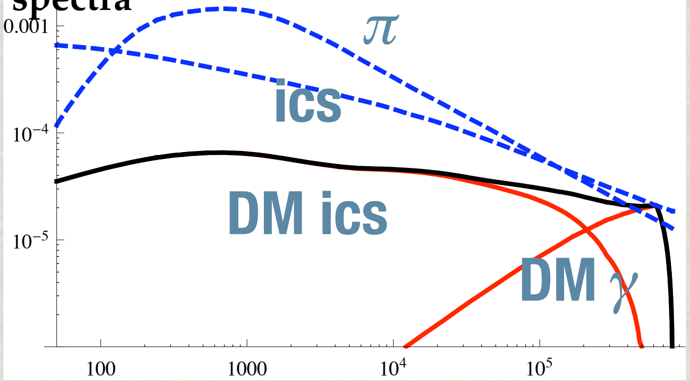
The full sky fit to the Galactic diffuse data can probe DM efficiently, ***by exploiting both, spatial and spectral information.***

However, to constrain the dark matter contribution, a rigorous understanding of the astrophysical signal is needed.

DM IC map



astrophysical and DM annihilation spectra



Astrophysical models

- Studies of diffuse emission of *astrophysical origin* are based on:
  - modeling of the diffuse emission with the GALPROP code, for plausible diffusive configurations: ***size of diffusive halo, CR source distributions***, etc.. with a condition that ***the obtained cosmic-ray spectra is consistent with local observations***
  - the maximum likelihood fits on the whole sky ***of a linear combination of such produced template maps***, using the GaRDiAN package. (soon public)
- Models are further ***refined*** using the ***iterative procedure***, between these two steps, since the model parameters depend on the outcome of fits.

Astrophysical models

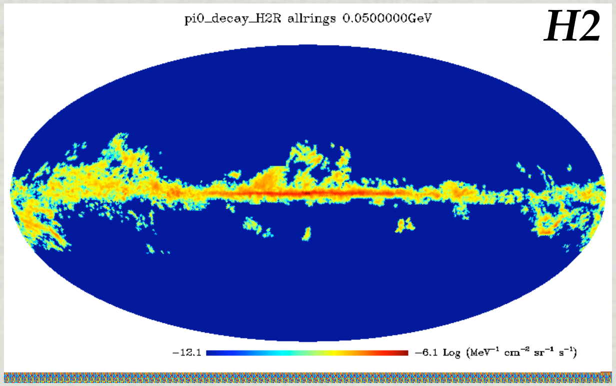
- Templates used,
  - in part correlate with the *gas content of the Galaxy* (describing *pp interactions and electron bremsstrahlung* scattering):
    - H I (*atomic* H) / *about 50% of diffuse photons*, column density estimates depend on the assumption on the the spin temperature T_s. H II (*ionized* hydrogen) is added to this map, (only 1% in density but important because it extends far from the plane ~2kpc).
    - H_2 templates (*molecular* gas) / *~ 10% of diffuse photons* traced by the CO, depends on the assumption on the conversion factor $N_{H2}=X_{CO}(R)\ N_{CO}$
  - at the intermediate latitudes, correction based on the dust emission (SFD) is used.
  - IC maps (describing *electron IC on ISRF, IR and CMB photons)*, *~ about 15% of diffuse photons*, all obtained with the GALPROP code using a consistent set of propagation parameters, as above,
  - isotropic template *~ about 15% of diffuse photons*, (with a spectrum as discussed previously)

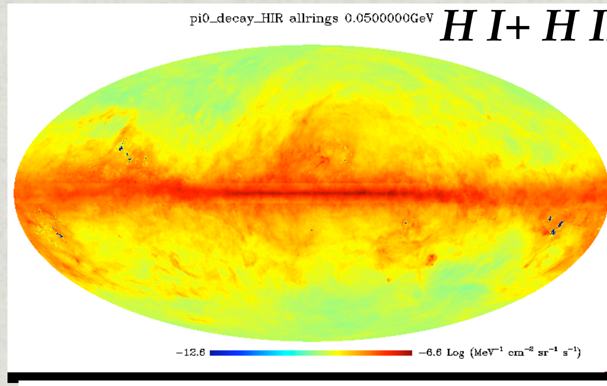
DM searches

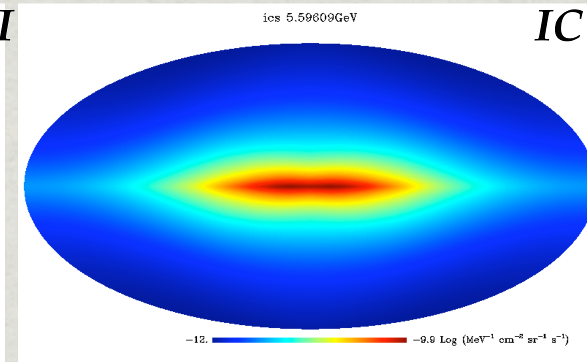
- Within a set of *astrophysical models refined to match the data* (and characterized by *source distribution, halo size, Ts*...), we choose *a model considered to be* ***'conservative' for DM searches***. 'Conservative' being that it under-predicts the data in the regions where DM component can compensate for it efficiently (more on this later, in Alex's talk).

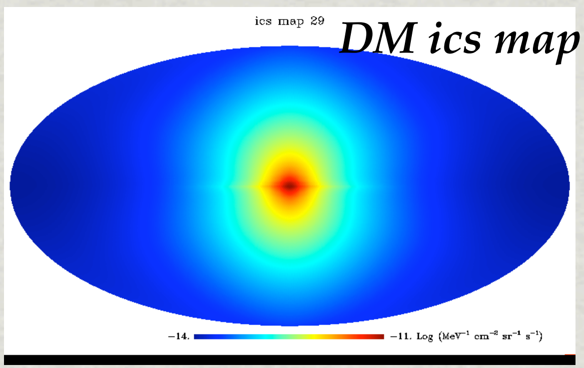
- To set DM constraints, we add DM template sky maps to *a chosen set of templates*. DM maps are obtained with a GALPROP code, with a set of propagation parameters consistent with the astrophysical model assumed.

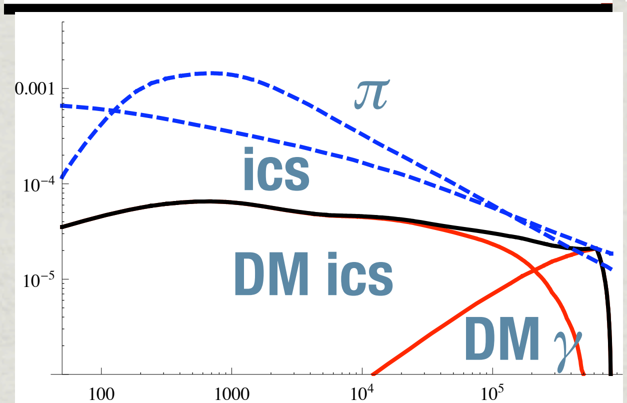
- We perform a full sky fit with the following free parameters: overall normalization of H2, HI, IC (3) and DM maps (1 or 2); normalization of the isotropic component (1) and residual contribution from point sources (1).

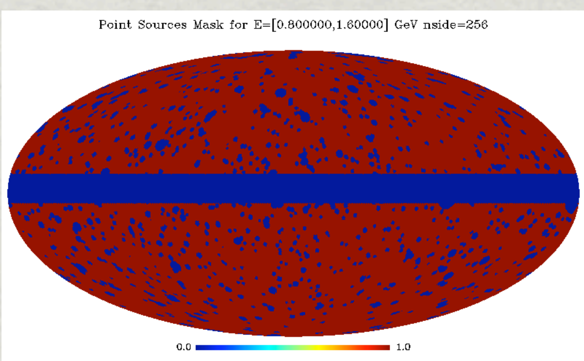




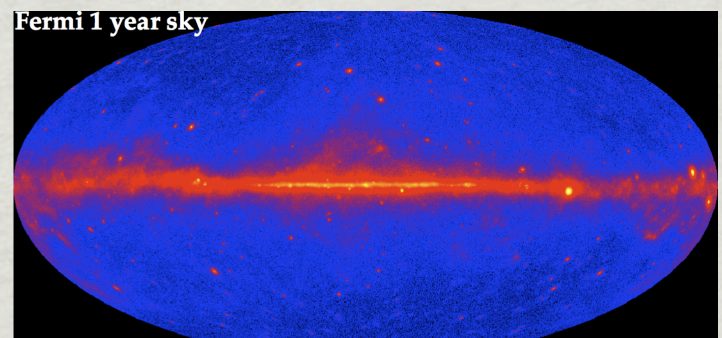








mask: point sources and the galactic plane (-5<b<10 deg):



Template maps and key features of our fitting procedure:

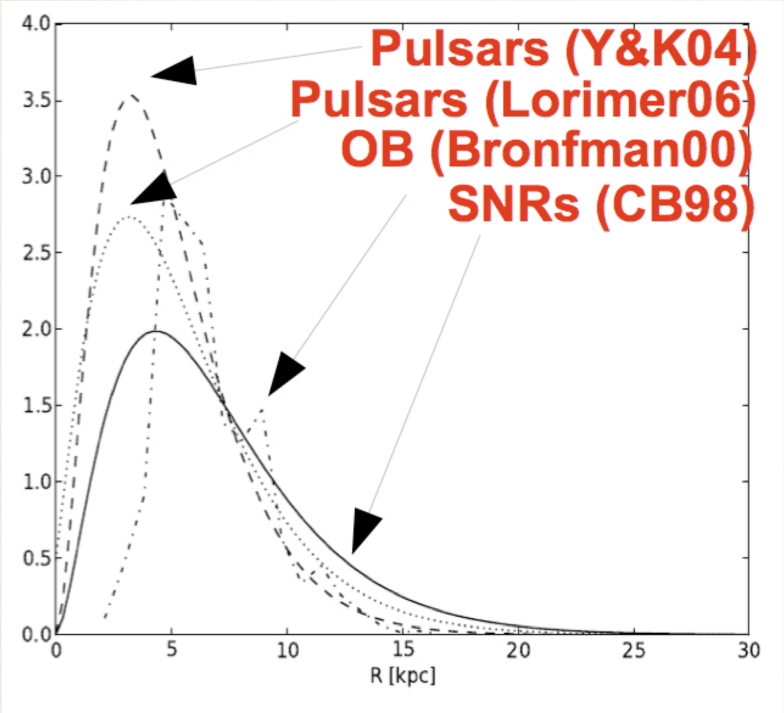
- ***DM density is the highest in the Galactic Center***, and DM limits are the most critically determined by the fit in that region. Note: H2 and HI are mostly confined to the plane *IC map is the most extended* and is expected to influence the DM limits the most.

- Astrophysical template maps depend on number of parameters of which, the ***source distribution*** and the cosmic ray ***propagation parameters*** -- *are the most critical parameters for DM constraints.*

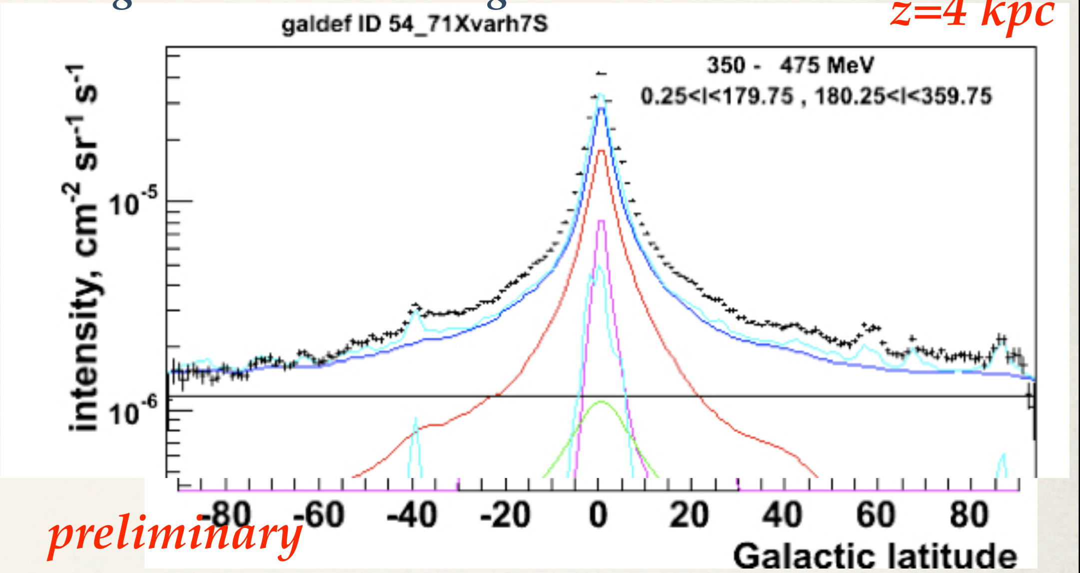
- other parameters like T_s, X_{CO}... mostly concern the signal along the plane and are not critical for DM considerations.

Astrophysical models

Assumed distributions of CR sources have different behavior in the Galactic Center...



Different choices of diffusive halo size affect critically radial profiles...
The effects of choice of this two parameters can be degenerate with DM signatures.



•*More details on the choice of the 'conservative' astrophysical model and the actual limits will be shown in the following talk by Alessandro, and Brandon (but, for a different analysis approach)!*

Outlook

- *Extragalactic signal has good potential for DM searches. Improvements in our understanding of the halo assembly process (i.e. Galaxy size simulations, baryon effects) , and possible imprints on the DM spectrum, critical for DM searches/could be important in confirmation of hints from LHC/direct detection experiments...*

- *Galactic halo DM limits:* Alessandro...

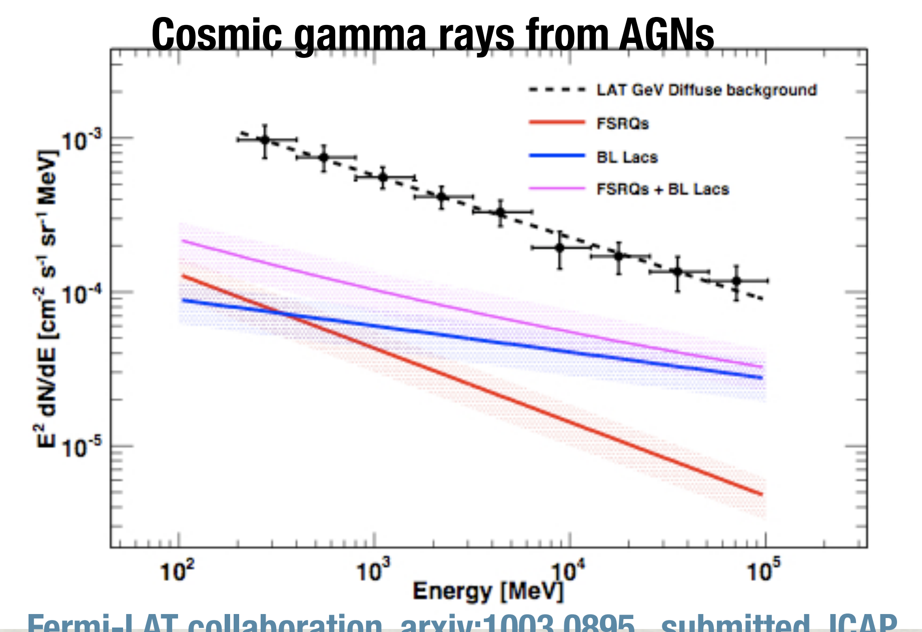
- *Near-term improvements: include better modeling of the extragalactic source classes (based also on the Fermi catalog data, AND angular anisotropy studies) and improvements in modeling of the Galactic diffuse emission.*

- *These are early attempts in DM searches, Fermi is a 5-10 year mission (+HESS-II, MAGIC-II, Planck, AMS-02,CTA...).*

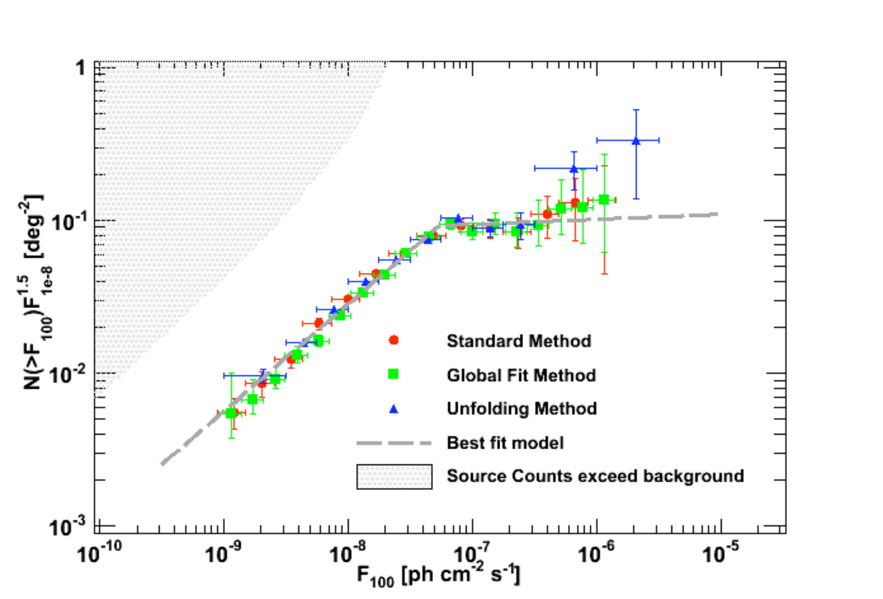
extra slides

Isotropic diffuse signal - astrophysical contribution

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.



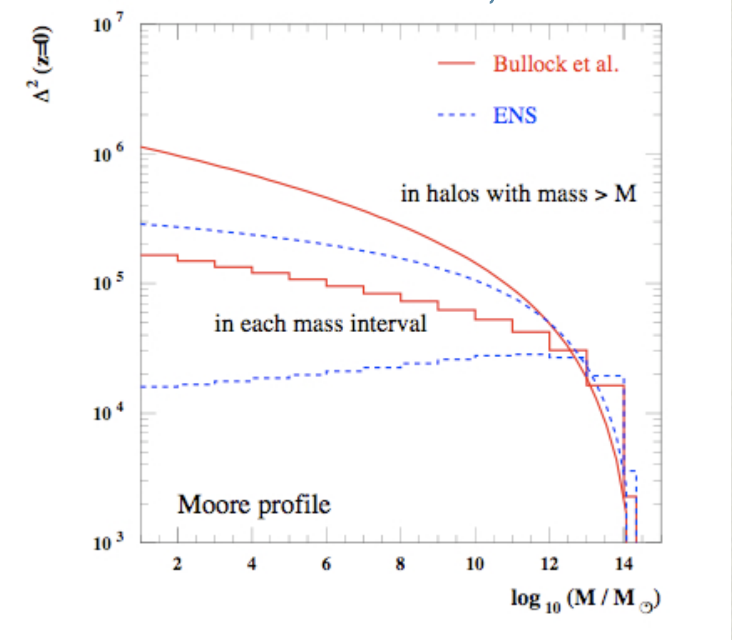
Mostly due to a break observed in the LogN-LogS distribution...

HOW/WHETHER TO EXTRAPOLATE TO LOWER MASSES?

Brings in largest uncertainty.

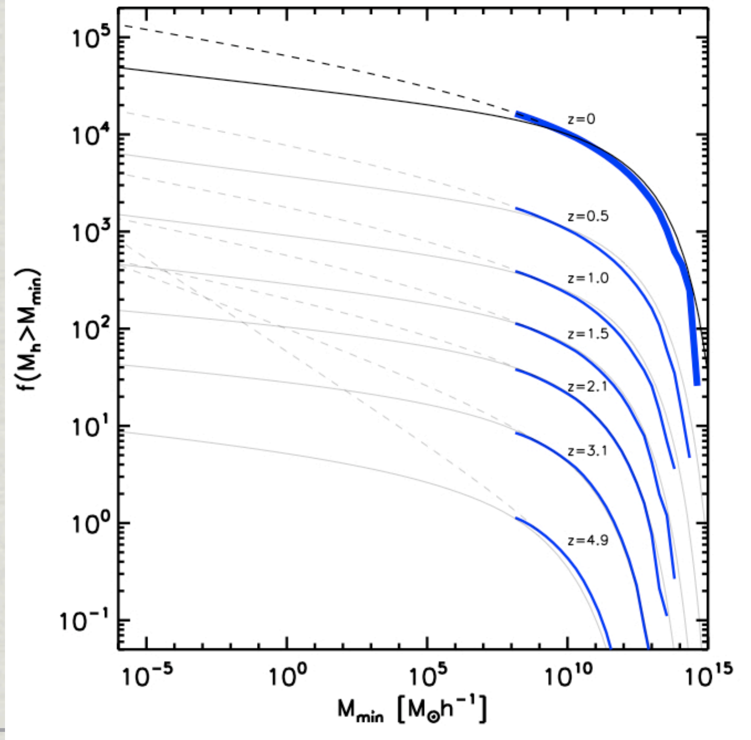
In the semi-analytic approach: halo mass function from a Virgo simulation AND the mass-concentration toy-model relation from Bullock et al. 2001.

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



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

Direct 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)-> and bracketed between conservative and optimistic estimates.



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

Cosmological signal of DM

DM forms structures in gravitational collapse, and in those over-dense regions, DM self-annihilation signal is greatly enhanced ($\Delta(z)$).

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

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

Depends sensitively on the results of N-body simulations:

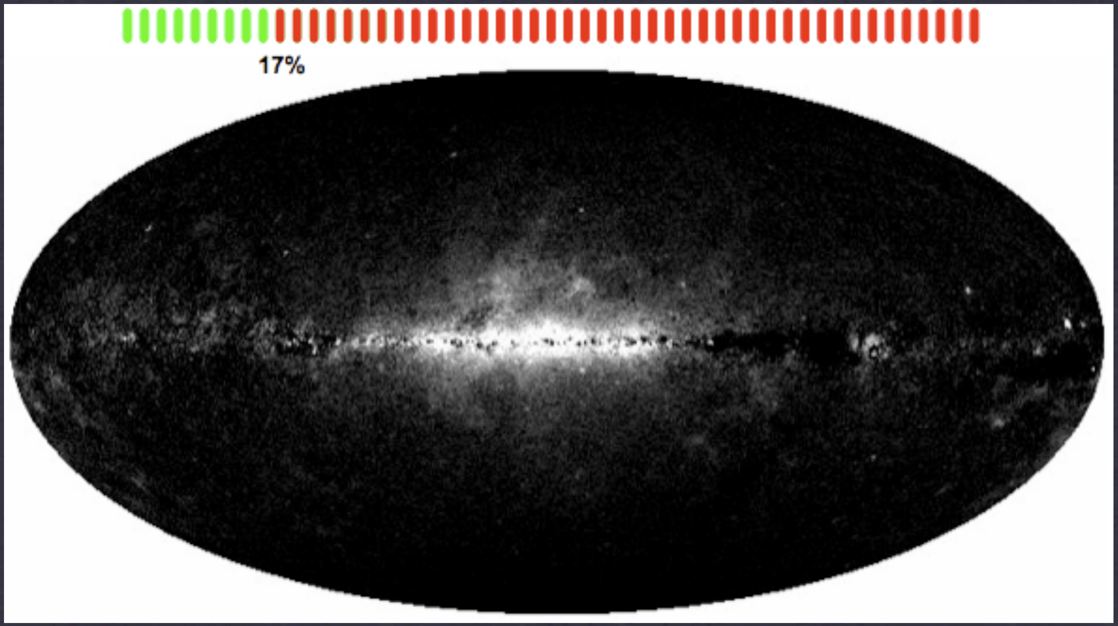
$$\Delta^2(z) \equiv \int dM \frac{\nu(z,M) f\left(\nu(z,M)\right)}{\sigma(M)} \left|\frac{d\sigma}{dM}\right| \Delta_M^2(z,M)$$

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

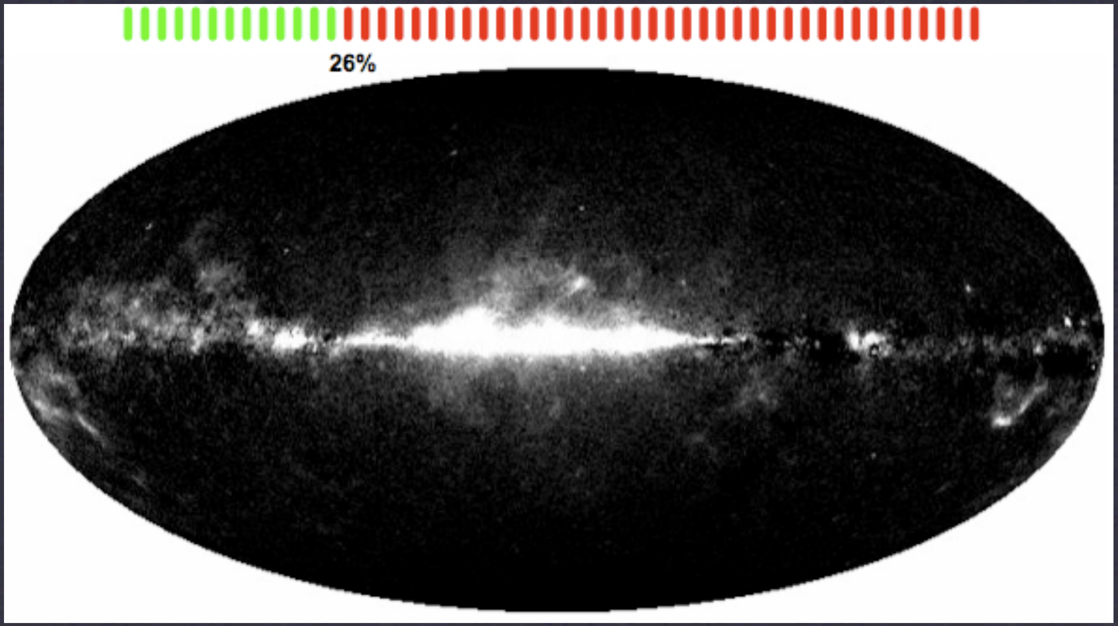
$\nu f(\nu)$ calculated as in Sheth and Tormen formalism

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

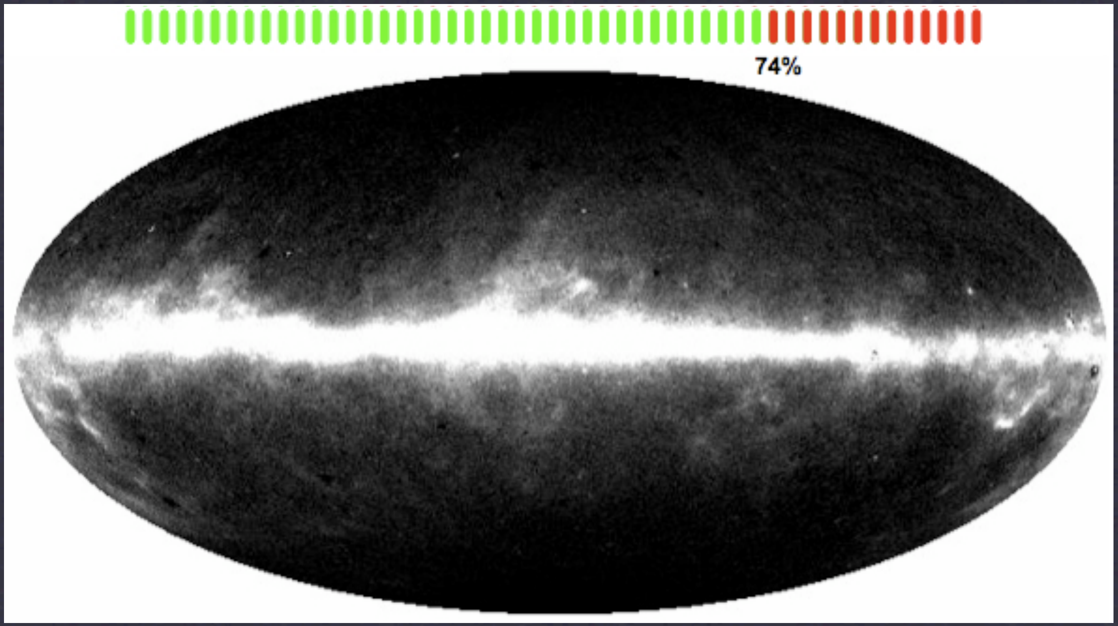
Enhancement ($\sim \rho^2$) for halos of a fixed mass M; Depends on the profile (NFW, Moore, ...), concentration parameter $c(M,z)$ and its scatter $P(c)$.



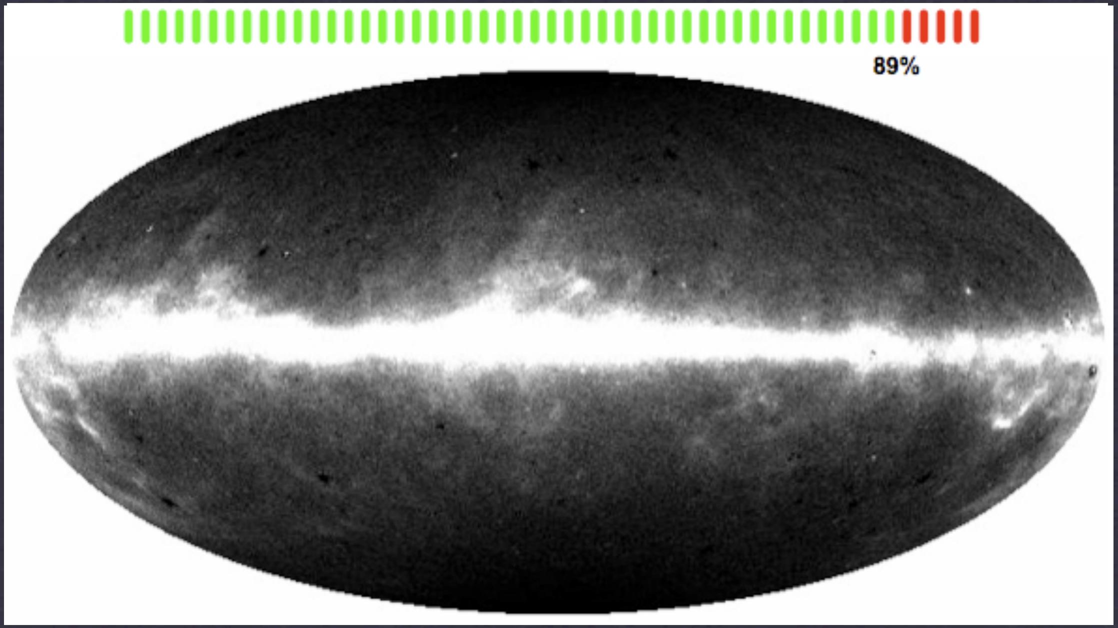
- Fermi sky: containing Inverse Compton emission and residuals <1 %



- Inverse Compton + emission traced by H2 (molecular gas):
- H_2 templates (*molecular* gas traced by the CO J=1→0 line,) -- depends on the assumption on the conversion factor $N_{H2}=X_{CO}(R)\ N_{CO}$



- Inverse Compton + emission traced by H2 (molecular gas) + HI (atomic)/HII (ionized hydrogen):
- H I (*atomic* H), traced by the 21 cm line; the column density of H I can be determined under the assumption on the the spin temperature T_s. H II (*ionized* hydrogen) is added to this map, based on pulsar dispersion measurements - (only 1% in density but important due to *the large scale hight* ~2kpc).


89%

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

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

Comparison of the most recent modeling (Gilmore et al., 2009) with the older, commonly assumed absorption model (Stecker et al., 2005), which over predicts the absorption.

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