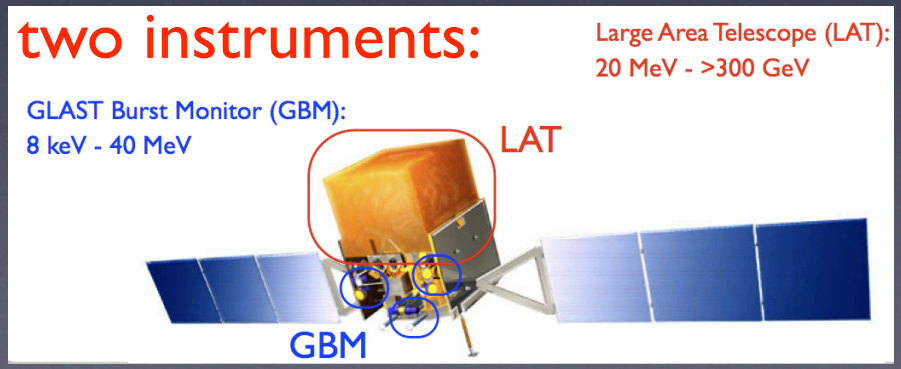
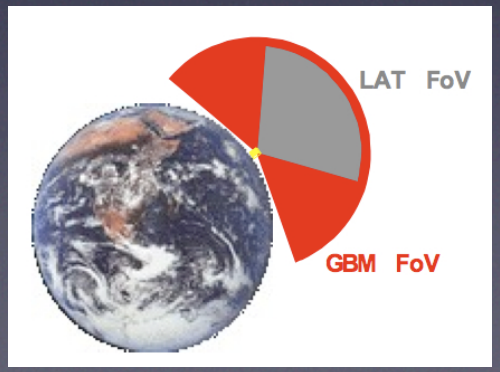
Dark Matter constraint from the Fermi-LAT data

on behalf of the Fermi-LAT collaboration
Gabrijela Zaharijas,
IPhT/CEA Saclay and Stockholm University

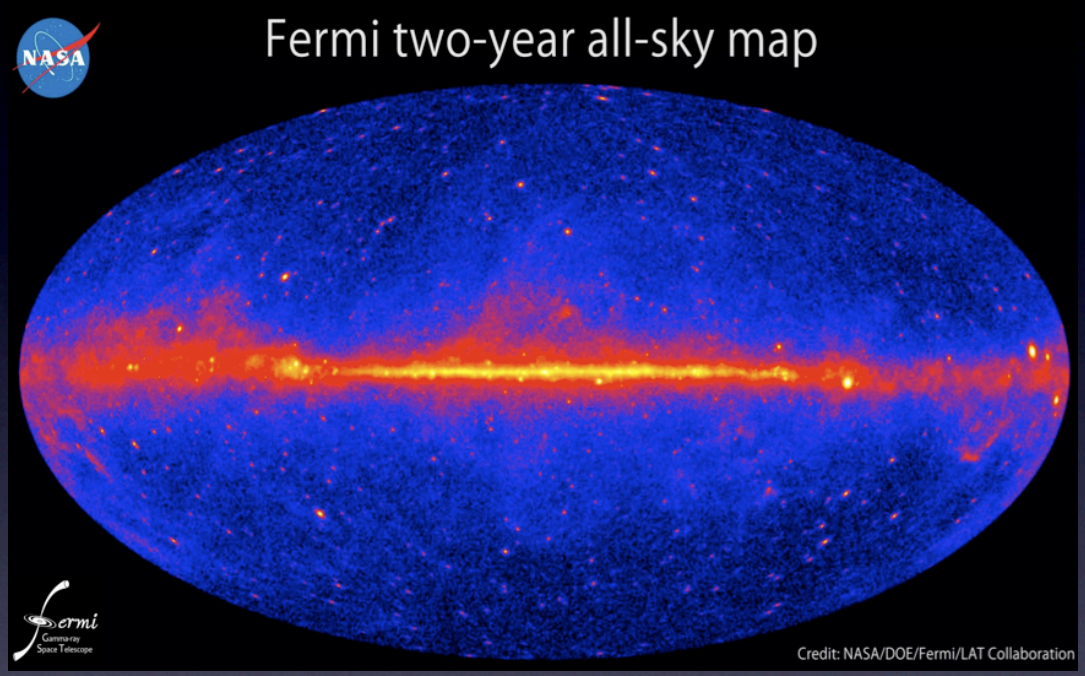
The LAT instrument

- Key features: *Large field of view* (20% of the sky at any instant).
- Energy range: *20 MeV to >300 GeV* (includes previously unexplored energy band 10-100 GeV).
- *good angular resolution* ~ 0.1 deg above 10 GeV.
- *excellent charged particle discrimination* (critical in separating gamma rays from the background cosmic rays).



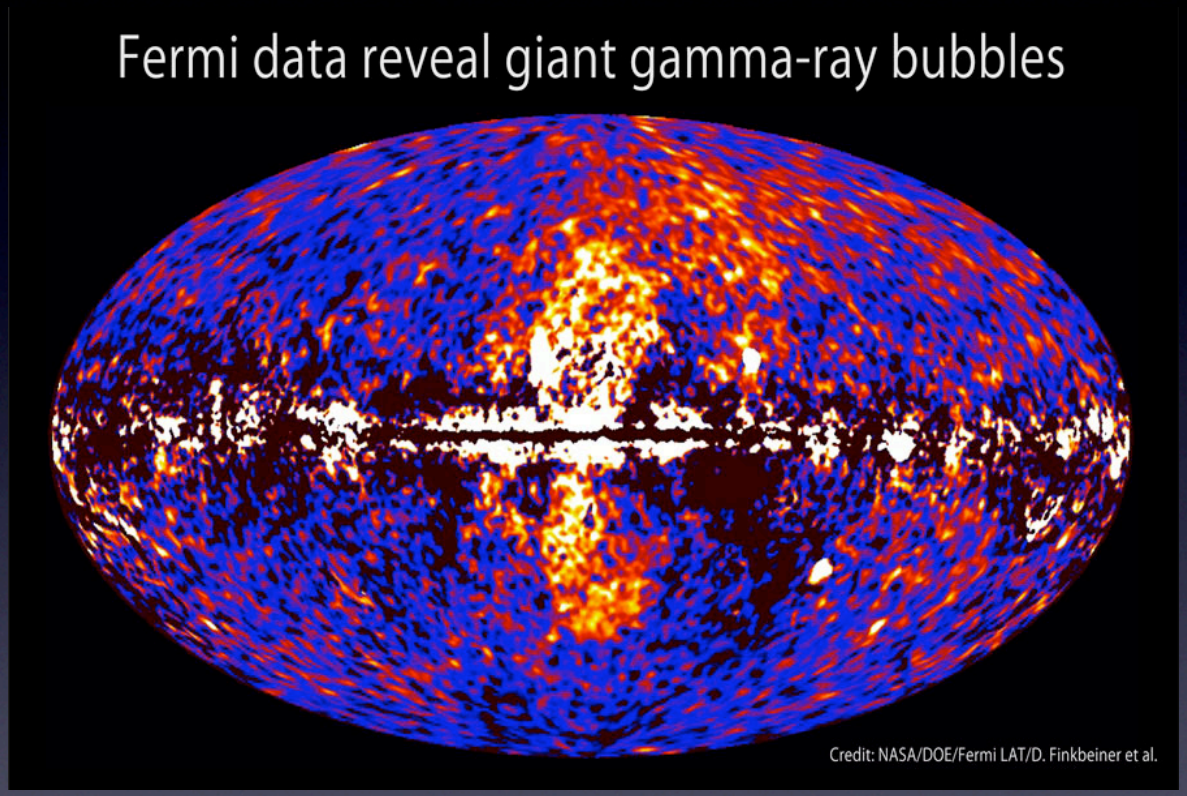


Science with Fermi-LAT



- Diffuse (whole sky) emission: measured for the first time, with good energy and angular resolution, for energies >~10 GeV.

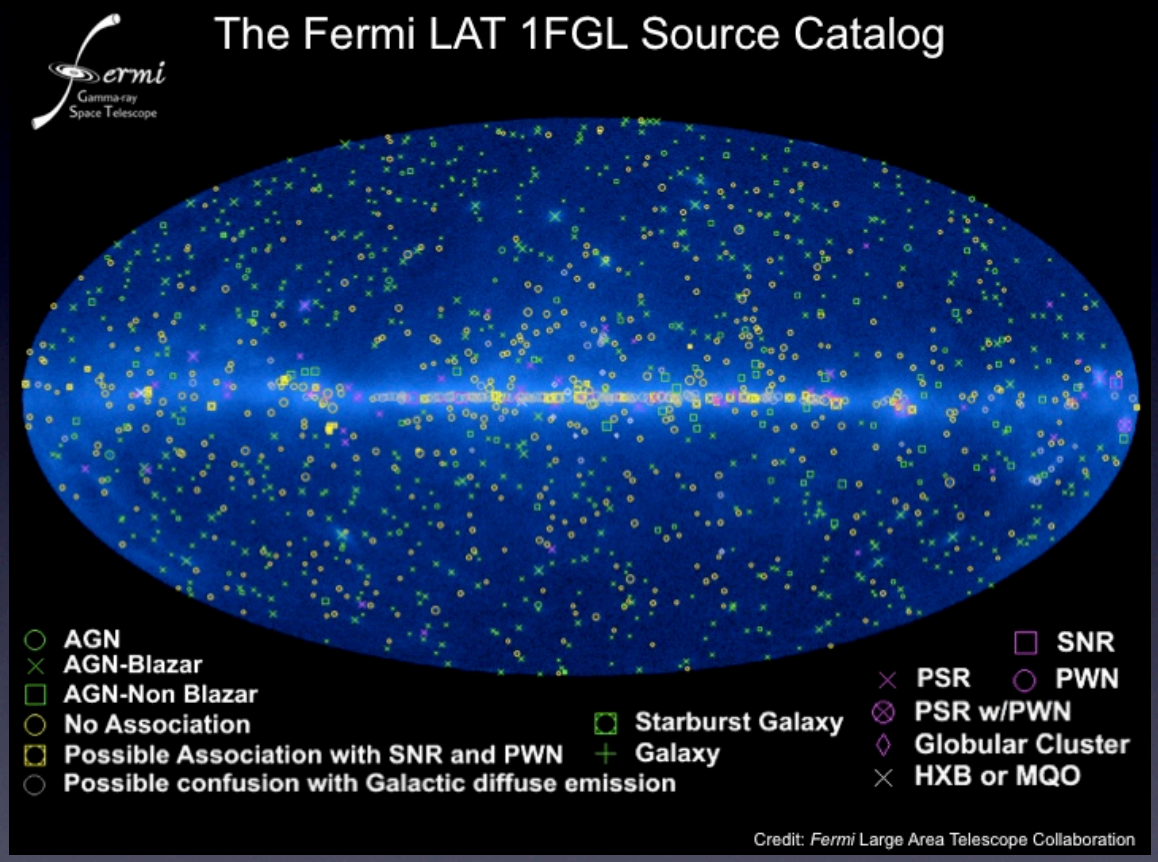
Science with Fermi-LAT



[Su, Slatyer, Finkbeiner, ApJ 724 (2010)]

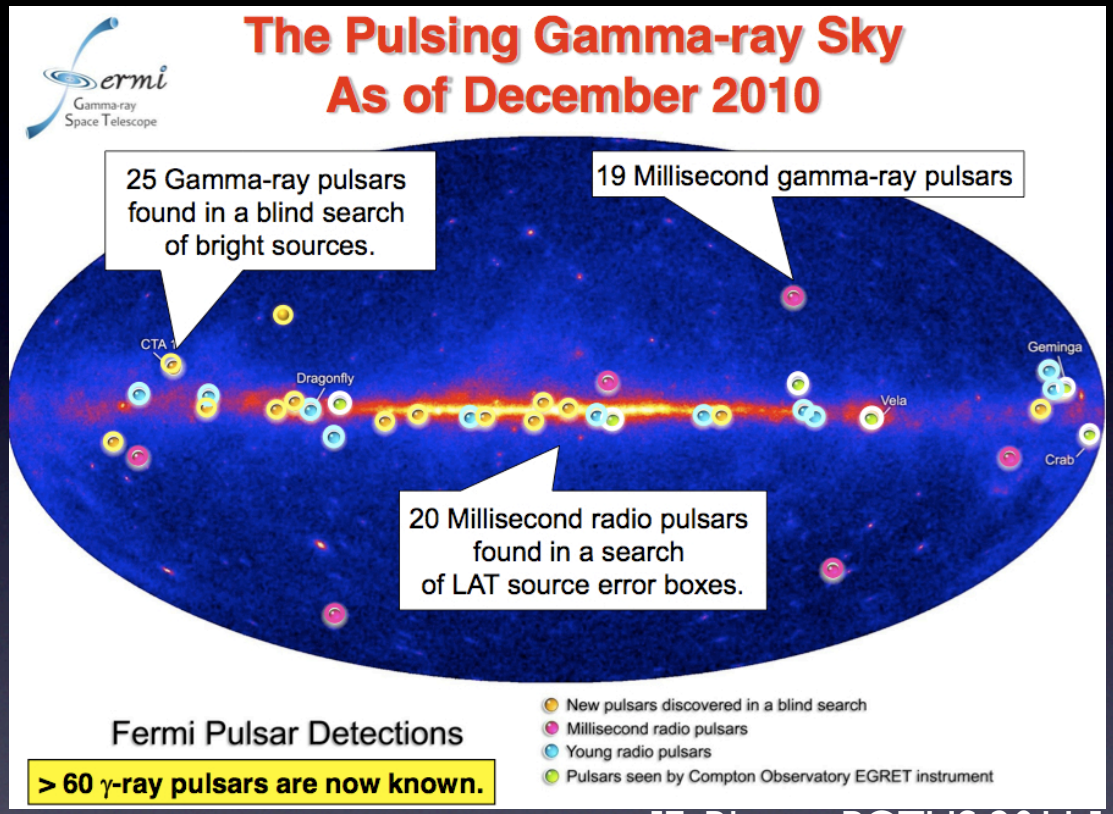
- Diffuse (whole sky) emission: residuals in the diffuse emission reveal bubbles in the region of the Galactic Center.

Science with Fermi-LAT



- Point sources: ~1450 sources in the first year catalog.

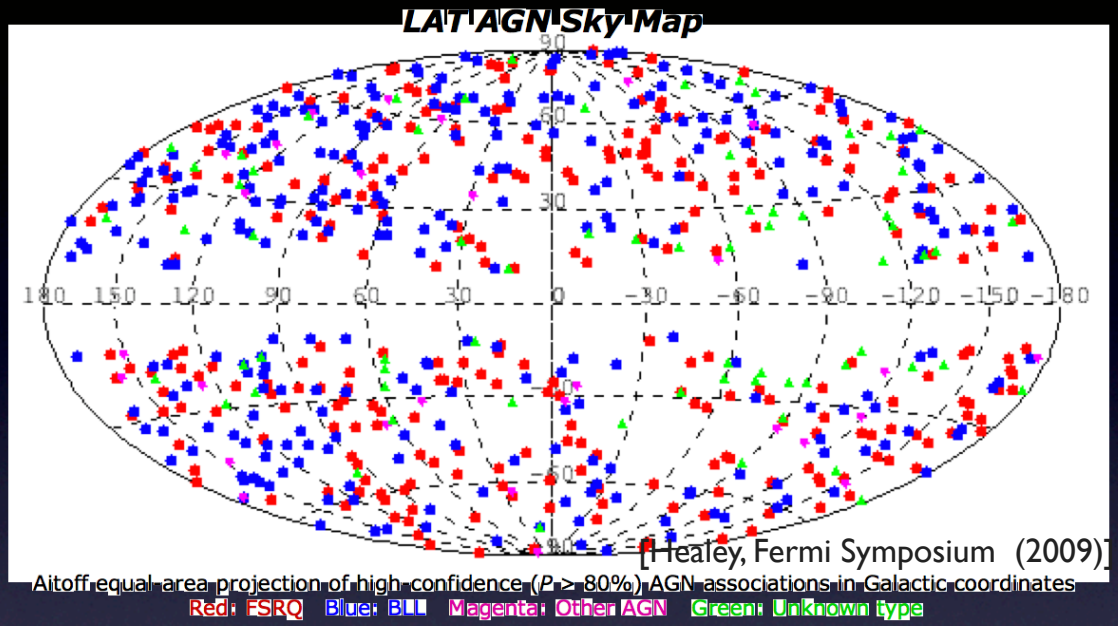
Science with Fermi-LAT



[E. Bloom, POTUS 2011.]

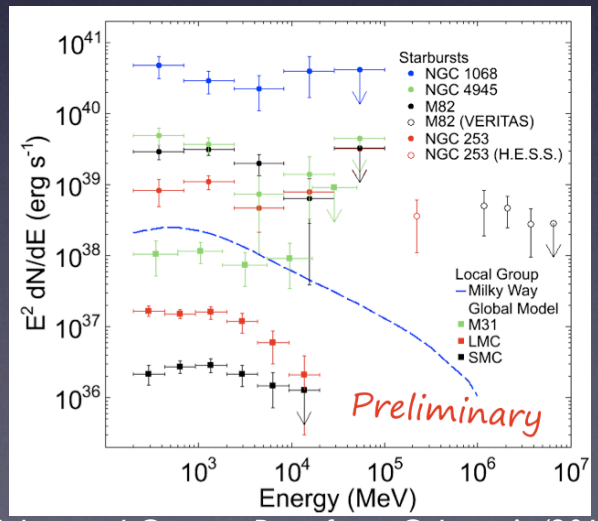
- Point sources: Galactic sources:
  - pulsars: in the first catalog: ~50 pulsars+discovery of 10 MSPs.
  - SNR, PWN...

Science with Fermi-LAT



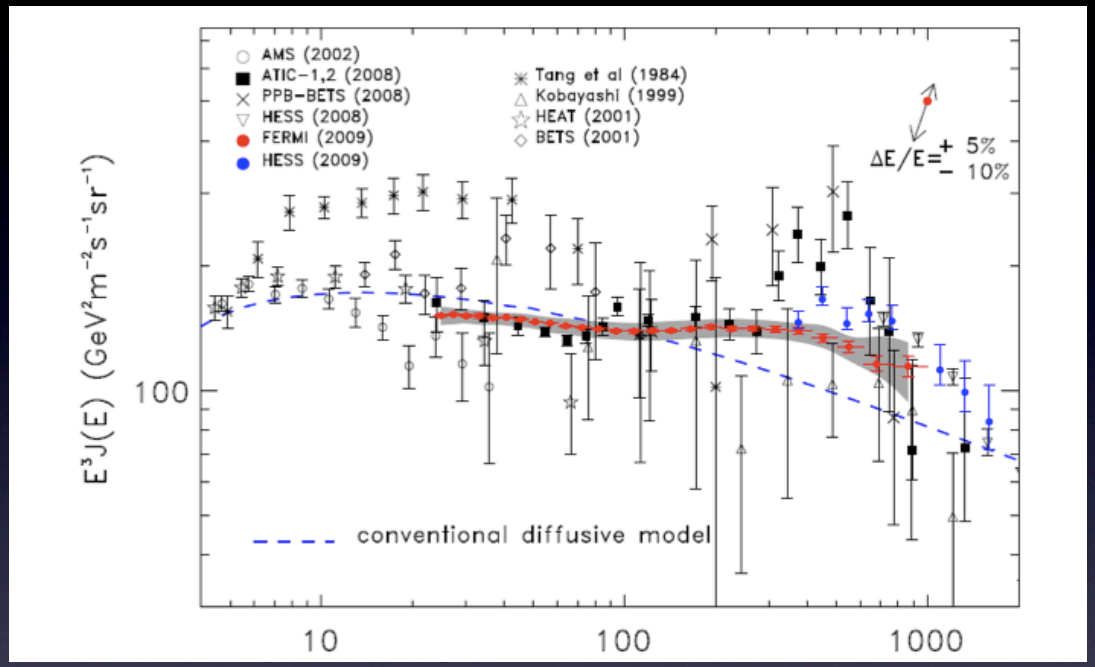
[Healey, Fermi Symposium (2009)]

- Point sources: Extragalactic sources:
  - AGNs (~700 (EGRET ~60))
  - Star-forming galaxies: Local Group: LMC, SMC, M31.
  - Star-burst Galaxies (beyond the local group): M82 & NGC 253, NGC 1068 & NGC 4945



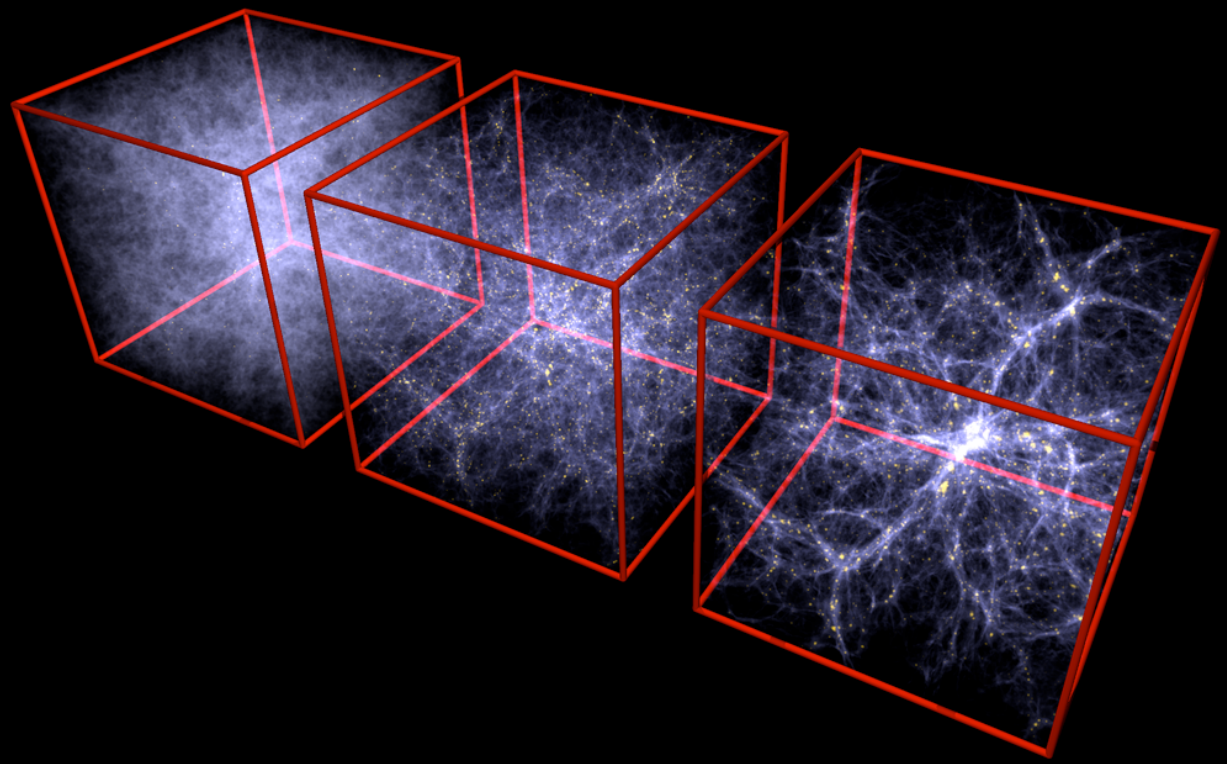
[Bechtol, 'Beamed and Unbeamed Gamma-Rays from Galaxies' (2011)]

Science with Fermi-LAT



- Cosmic ray electrons

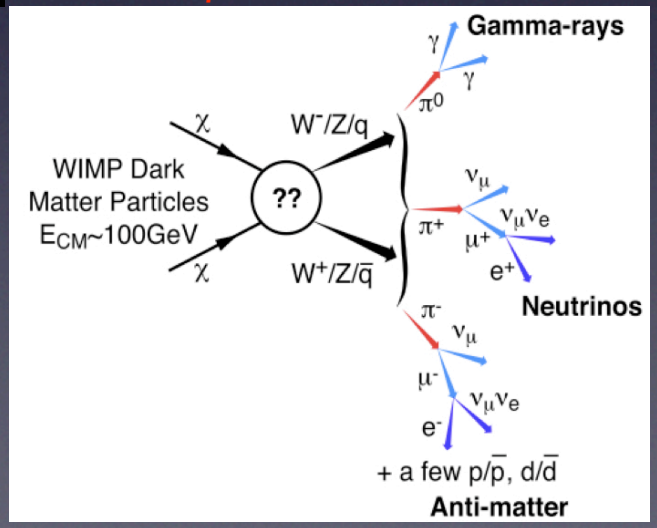
+ Discovery/constraints:
- New source classes?
- Dark matter?



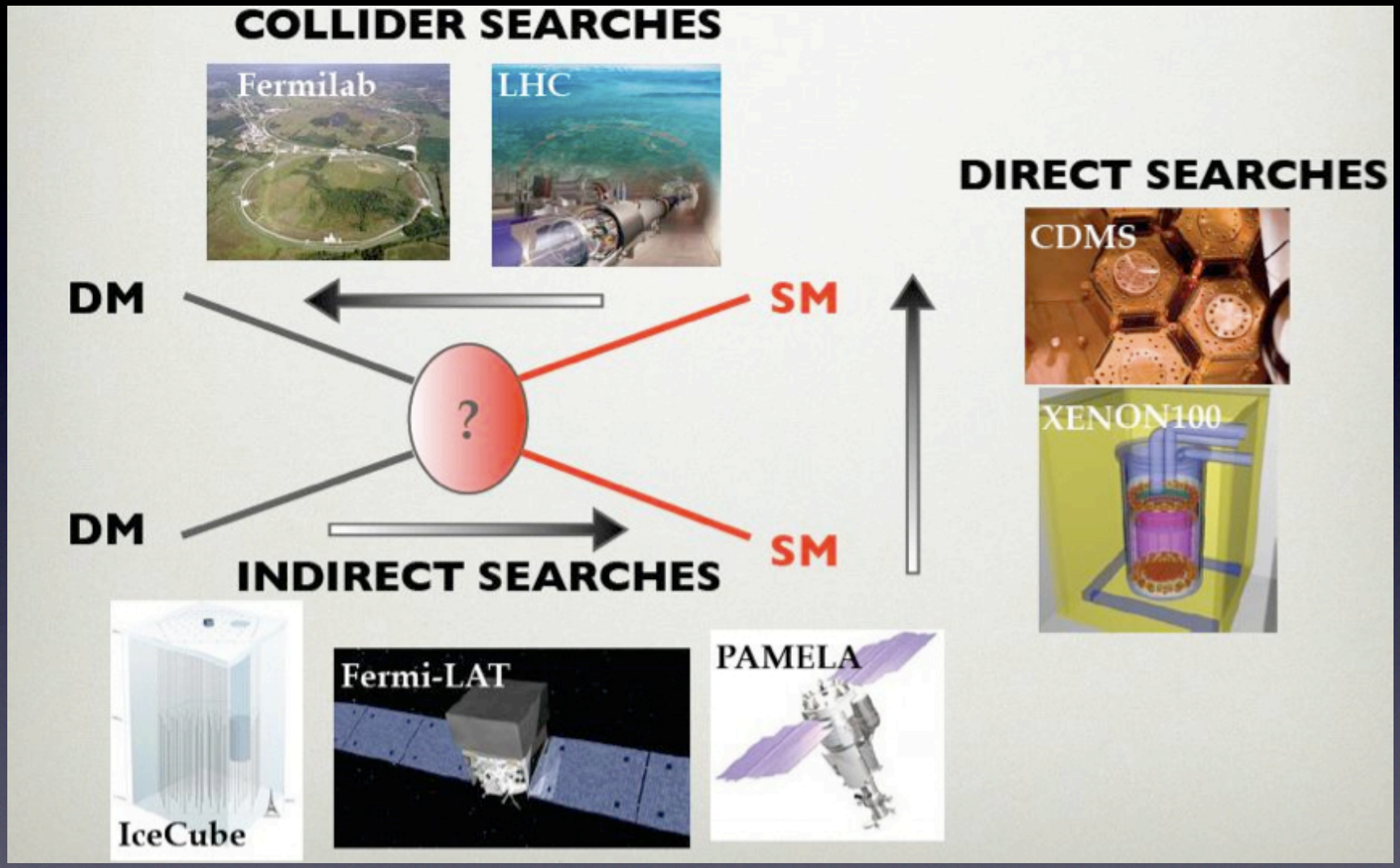
An attractive possibility: *WIMP candidates*-- the annihilation rate comes purely from particle physics and automatically gives the right answer for the relic density!

In turn, we expect dark matter to annihilate to Standard Model particles, with *cross sections which are within near reach of current experiments*.

The gravitational effects of DM have been has been demonstrated from plethora of astrophysical and cosmological observations.

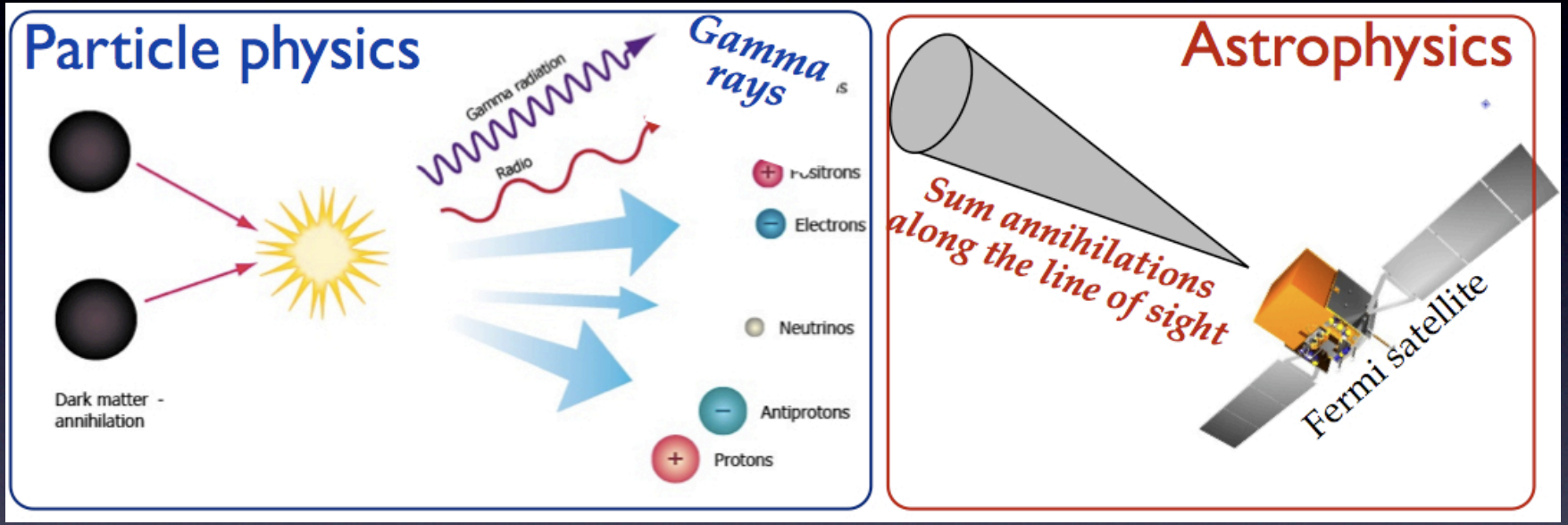


Search strategies:



[E. Bloom, POTUS 2011.]

DM signal in gamma-rays

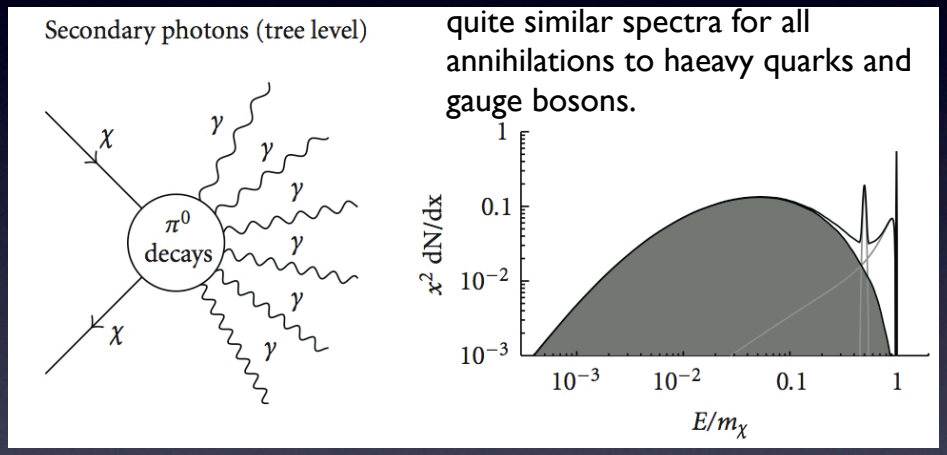


Advantages of gamma-rays: Not affected by propagation in the Galaxy. Can give clear signatures both in spectral shape and in spatial variation.

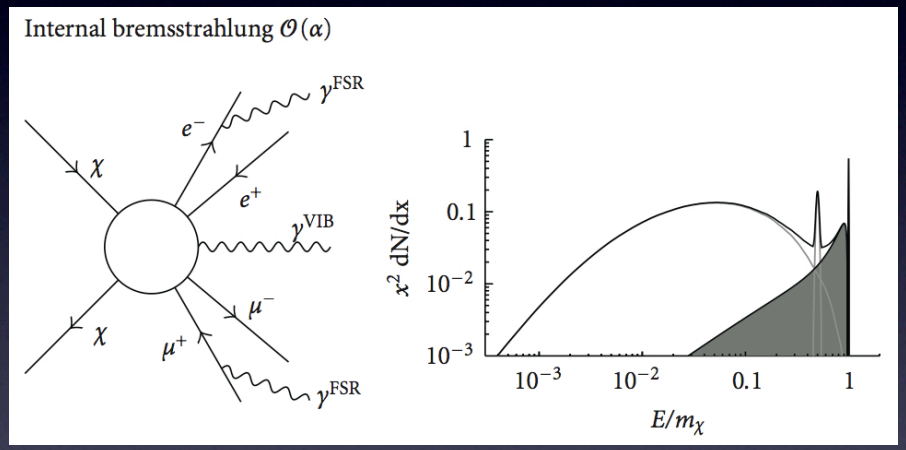
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\theta,\phi) = \frac{1}{4\pi}\boxed{\frac{\langle\sigma v\rangle_{T_0}}{2\,M_\chi^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f}\cdot\boxed{\int_{\Delta\Omega(\theta,\phi)} d\Omega' \int_{l.o.s.} dl\ \rho_\chi^2(l)}$$

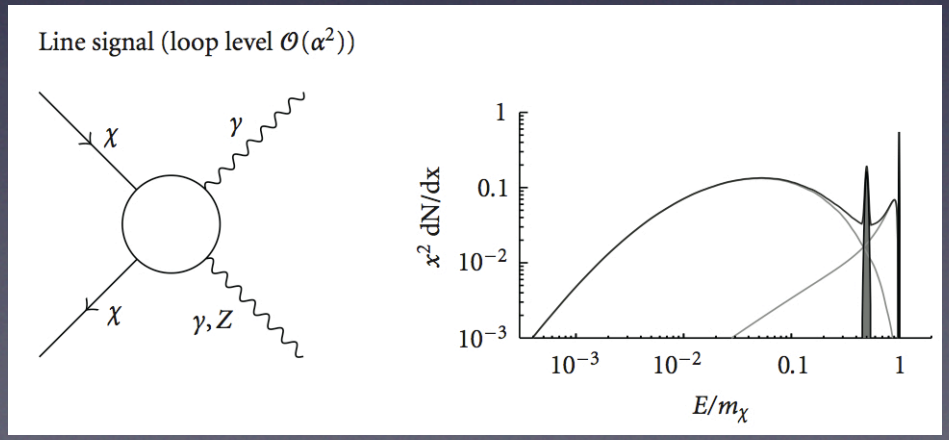
Particle physics Astrophysics

DM signal: spectral shape



quite similar spectra for all annihilations to haeavy quarks and gauge bosons.





Figures: Michael Kuhlen, Advances in Astronomy Volume 2010, Article ID 162083

+ electroweak corrections (arXiv:1009.0224 and arXiv:0911.0001), important for ~TeV DM.

the annihilation spectra is known considerably well. however we are still learning.

DM signal: spectral shape

Or, through *radiative losses* in ambient backgrounds and fields. Important if there is a *significant branching ratio to leptons* (models covered in Tracy's talk).

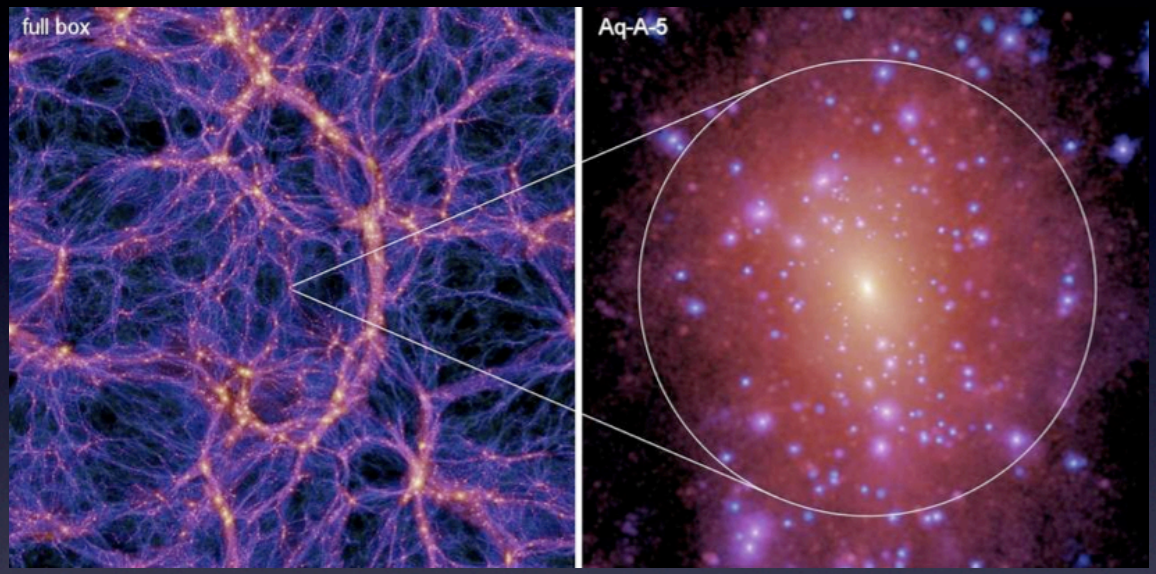
$$\chi\,\bar{\chi} \rightarrow \begin{cases} e^+\,e^- \\ l^+\,l^- \text{ or } \phi\,\phi \rightarrow \ldots + e^+\,e^- \\ P\,\bar{P} \rightarrow \ldots + \pi^\pm \rightarrow \ldots + e^\pm \end{cases}$$

ambient backgrounds and fields

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

- radio
- IR
- X-rays
- γs

DM signal: morphology

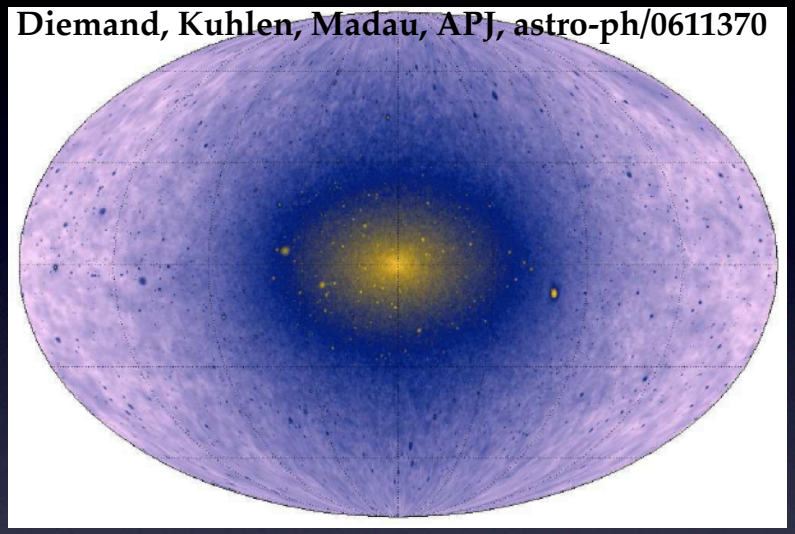


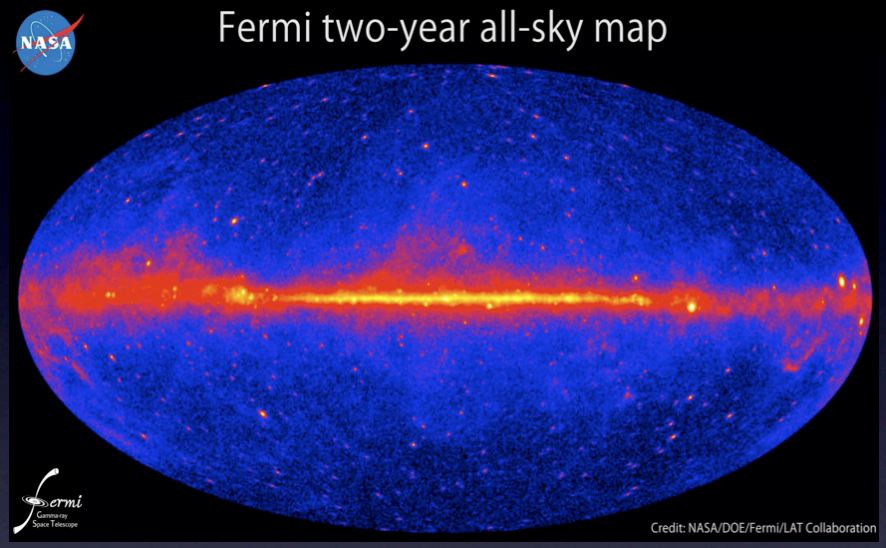
Springel, V. et al, Mon.Not.Roy.Astron.Soc.
391:1685-1711,2008.

Obtained from N-body simulations which have impressive agreement with large scale structures.
They find cuspy host halos (NFW or Einasto DM density profile) with numerous subhalos.
However:

- Do not resolve the inner most region of the halo (>100 pc);
- have limited mass resolution to >10^5 Msol (sub) halos (minimum WIMP halo mass ~10 orders of magnitude smaller)

DM targets

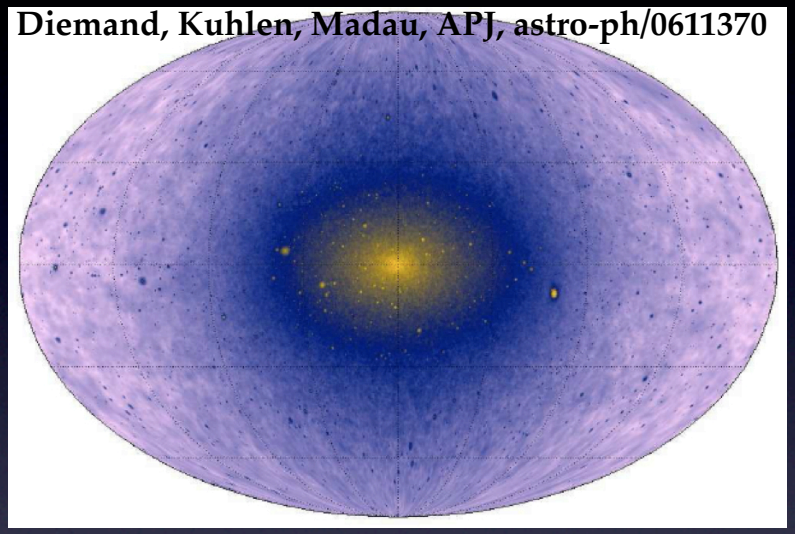


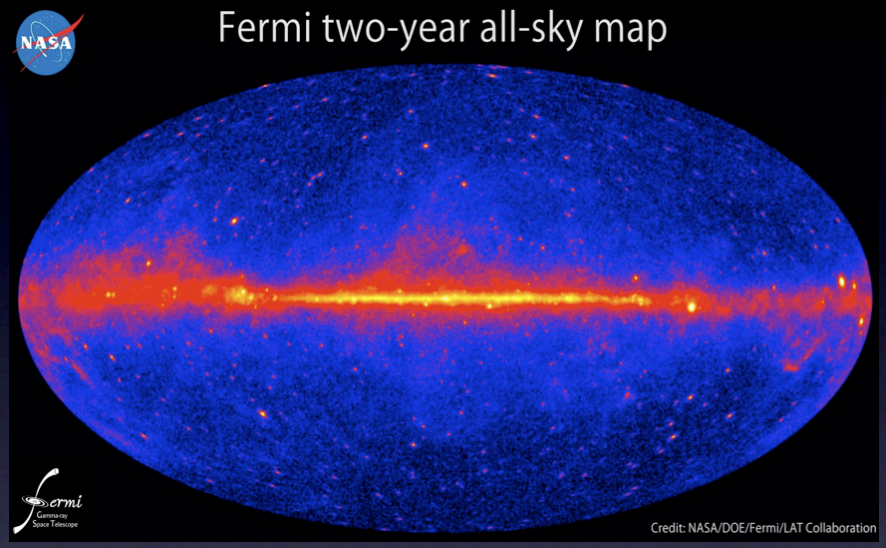


Point sources:

- *Galactic Center*: ✔
- *Dwarf Satellites*: the biggest Galactic subhalos (contain stars) ✔
- *dark subhalos*: search for sources which shine only in gamma-rays
- *Galaxy clusters*: the biggest DM halos yet to form

DM targets



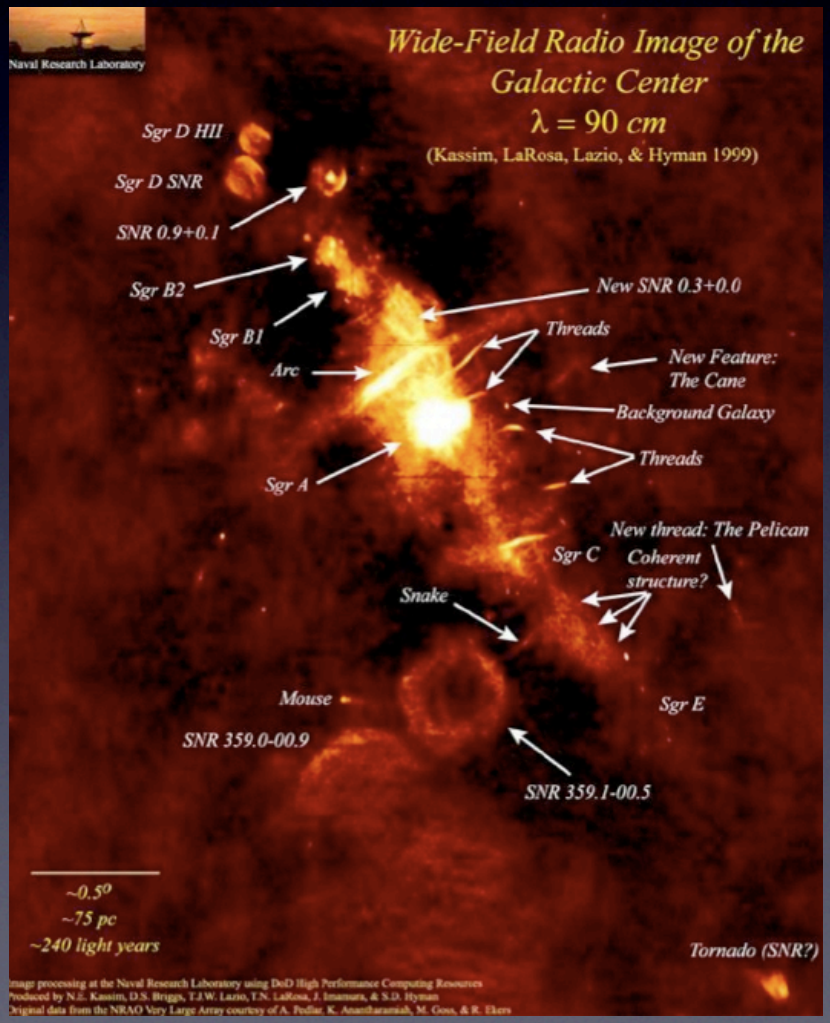


Diffuse emission:

Made possible with the Fermi telescope! (good angular and energy resolution, large field of view, good charge particle rejection)

- Isotropic (*extragalactic*) signal ✔
- *Galactic* diffuse emission ✔
- search for a line feature in the spectra

Point Sources - Galactic Center



Source in the central parsecs of our Galaxy:

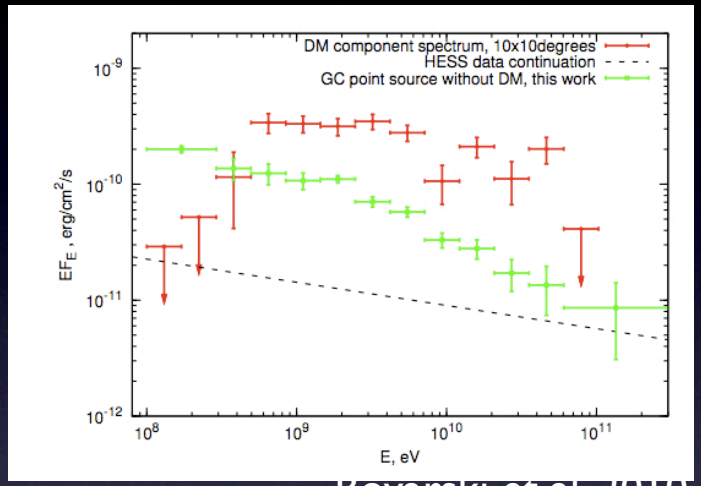
- from radio to X-rays, signal originates from the Sgr A*,
- 25 formal associations based on position for *GeV γ-ray emissions* (due to a relatively large angular resolution).

The inner Galaxy region has huge diffuse emissivity due to CRs streaming through dense clouds + Large Pulsar population ! Inferred population of ~2000 active radio pulsars! +massive star clusters, SNRs, PWN...

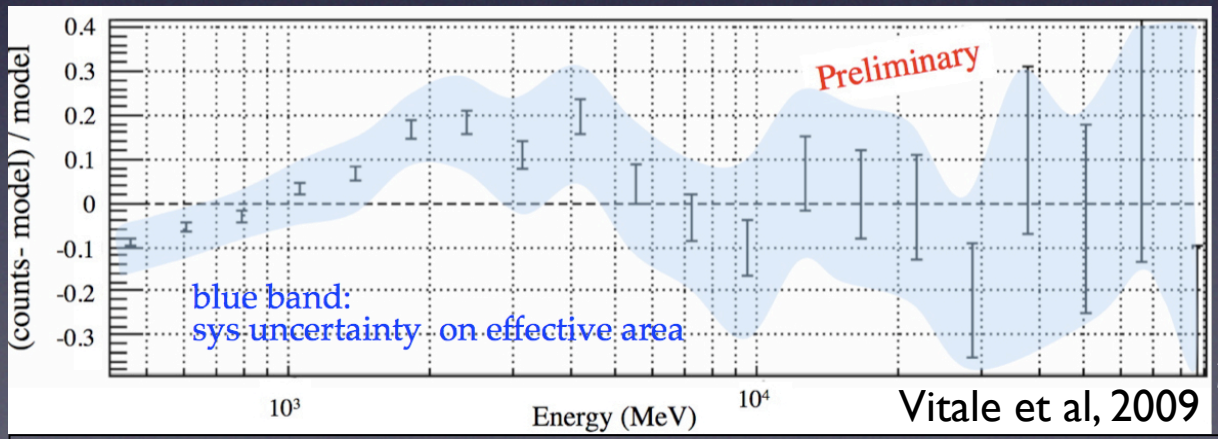
Point Sources - Galactic Center

Fermi-LAT analysis:

- *Unbinned Likelihood analysis of 7x7 deg region around GC*
- *11 months of data, events > 400 MeV, front-converting (narrower PSF)*
- *Galactic Diffuse emission from GALPROP*
- *Sources from Fermi catalog*
- **Possible reasons for the residuals:**
- *Small-scale diffuse emission*
- *Sources in the region*
- *Instrumental effects*



Boyarski et al, 2010



Vitale et al, 2009

Non Fermi-LAT analysis:

- *Finds similar residuals.*
- *DM claims too, see [Hooper & Goodenough (arXiv:1010.2752)].*

However, modeling of this complicated region is at an early stage, and other possibilities have to be studied before exotic claims are made.

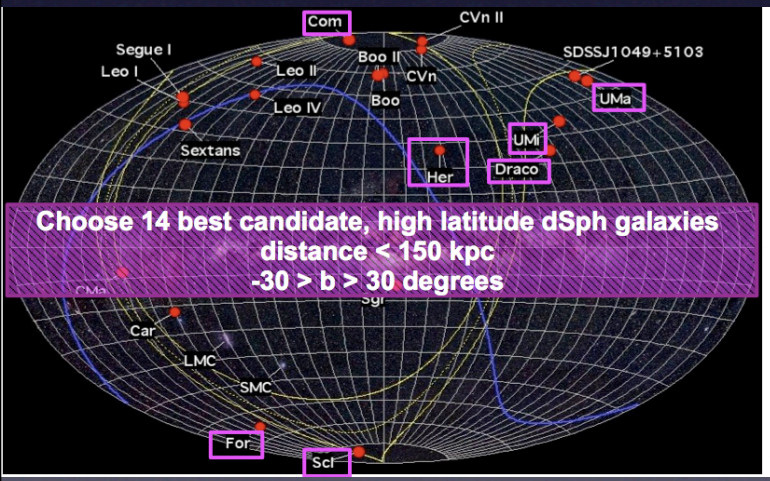
New results to be shown at the Fermi Symposium, Rome, May 8-12.

Point Sources - Dwarf Galaxies

- Optically observed dSph are *the largest DM clumps in our halo*. ~25 have been discovered so far (many more expected).
- Dark matter dominated systems, no significant high energy gamma rays originating from astrophysical sources expected.
- DM mass determined based on kinematics of stellar component (KECK data).
- *No detection of dSph in 2 year Fermi data* → *upper limts on a DM component.*

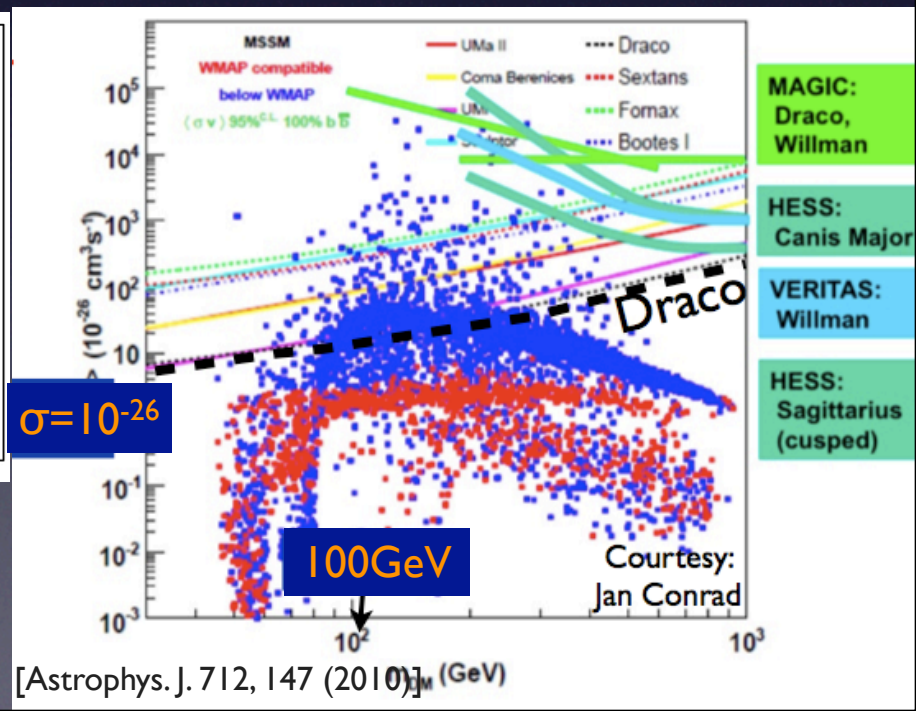
Point Sources - Dwarf Galaxies

Advantage: 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

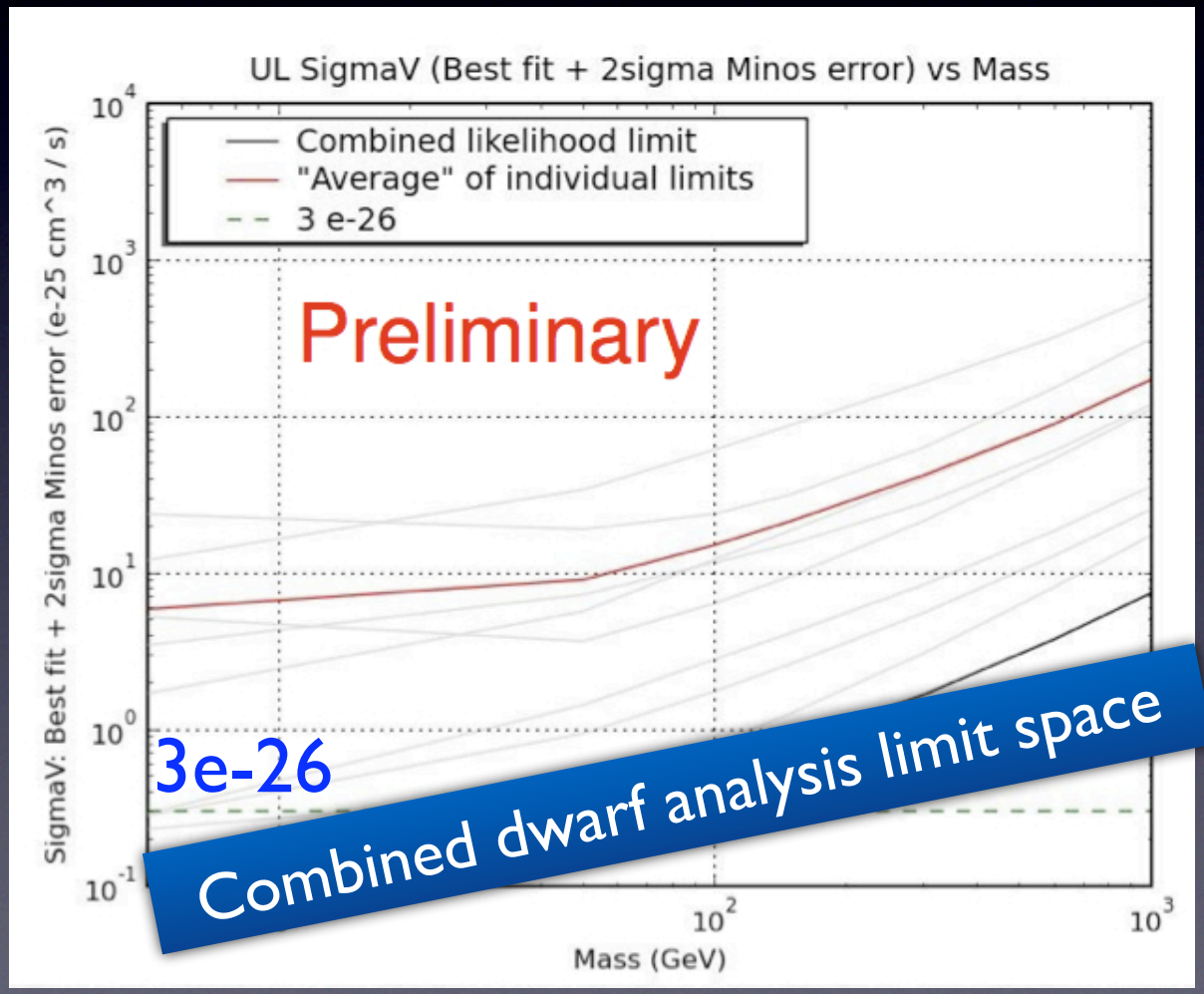


[Astrophys. J. 712, 147 (2010)]

Point Sources - Dwarf Galaxies

Combined limits for 8 dSph, using 21 months data.

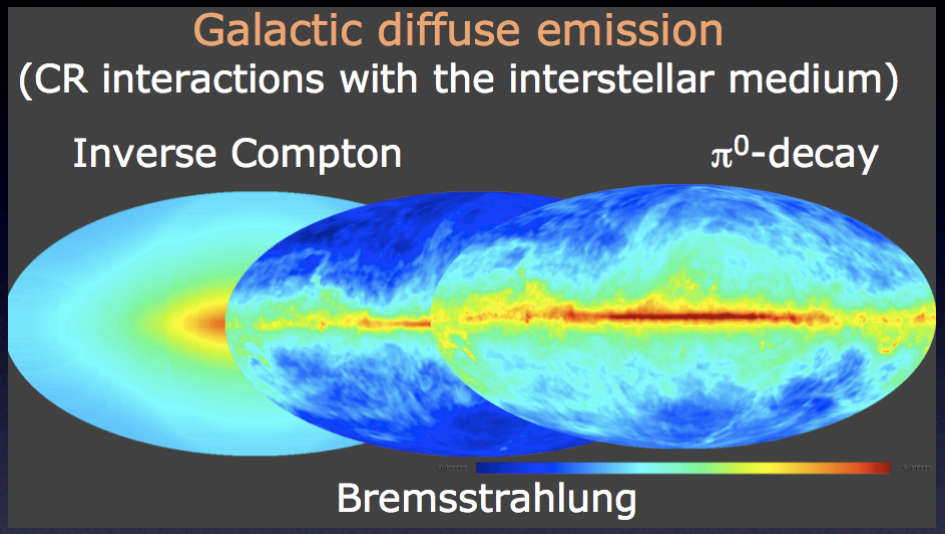
Improvements of DM limits by a factor of ~ 2, 3 expected.



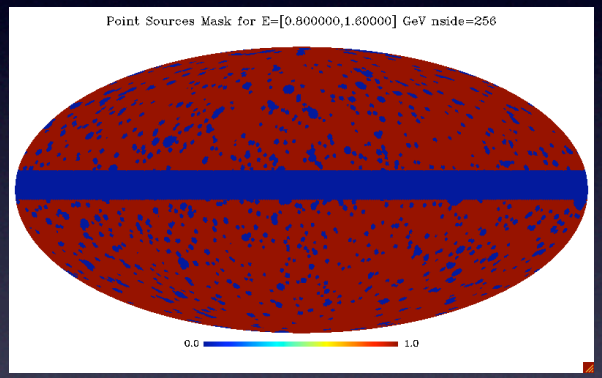
‘Diffuse’ DM searches by the Fermi team

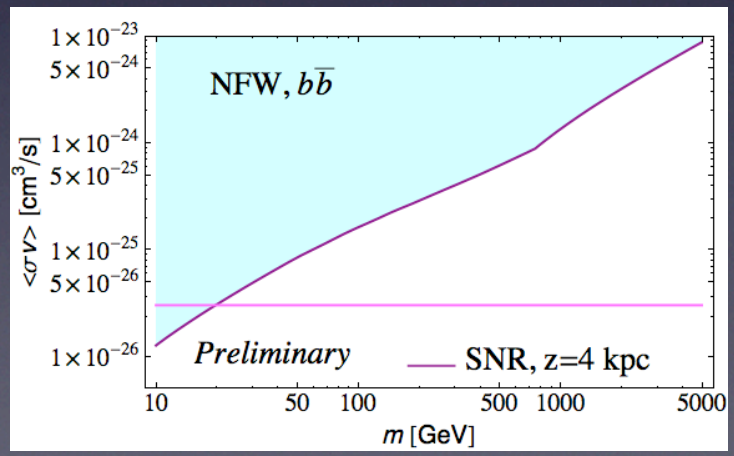
- analysis of the diffuse emission in terms of DM signal from the DM halo of our Galaxy.
- analysis of the diffuse Extragalactic (Isotropic) Signal to study DM annihilation at the cosmological scales, by using:
  - the *intensity spectrum* or
  - *angular anisotropies*.

- *Full diffuse signal*: *Constraints on DM annihilation in the* ***Milky Way Halo***



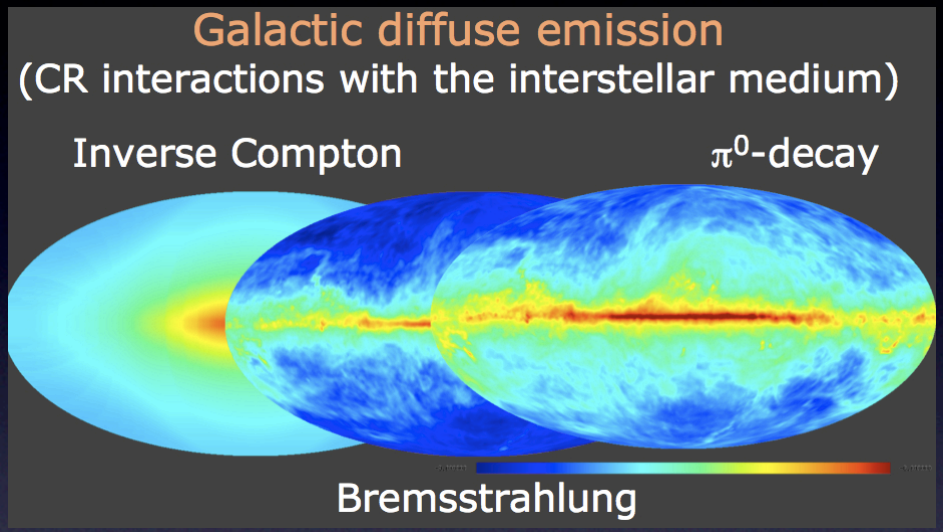
The maximum likelihood fit in each *pixel* and *energy bin* in the ROI: exploits both spectral and spatial features to *break degeneracies* with astrophysical diffuse emission.





Uncertainties related to modeling of distribution of CR source distribution, CR propagation, gas maps, Galactic magnetic fields... limits prove robust to most of these parameters.
Limits shown are derived making conservative/reasonable choices for the rest of few key parameters.
New results at the Fermi Symposium.

- *Full diffuse signal*: *Constraints on DM annihilation in the* ***Milky Way Halo***



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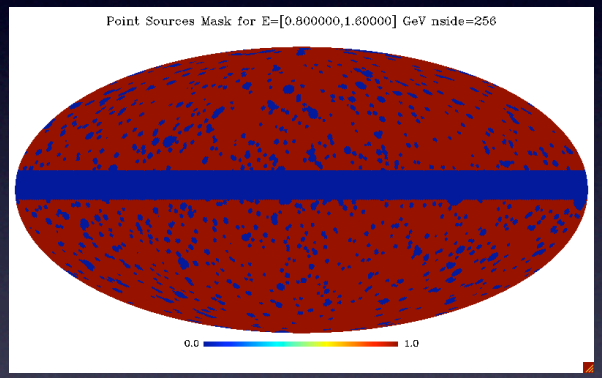
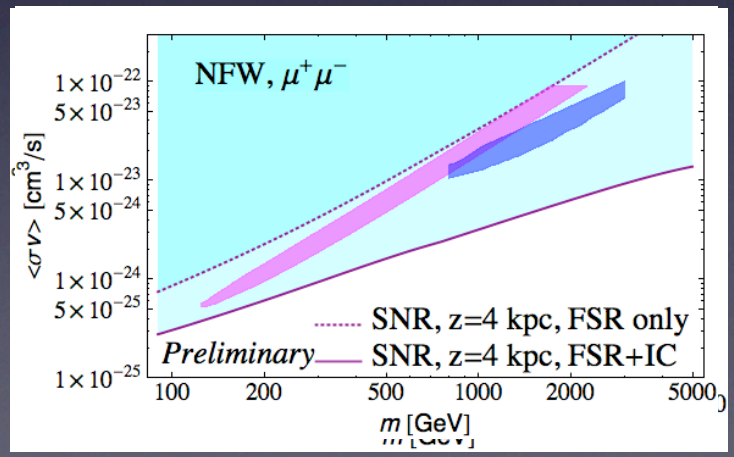
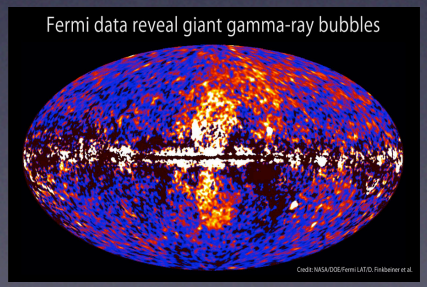
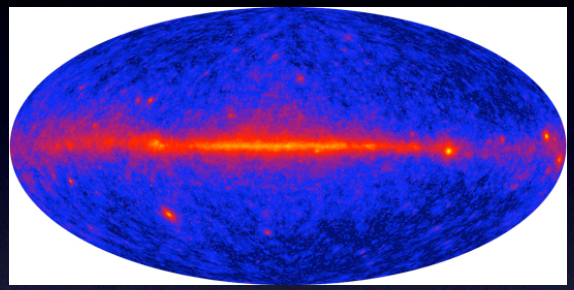




Uncertainties related to modeling of distribution of CR source distribution, CR propagation, gas maps, Galactic magnetic fields... limits prove robust to most of these parameters.
However, propagation of CR and DM electrons challenging in the inner Galaxy (Tracy's talk).



- *Extra Galactic diffuse signal*: the isotropic gamma-ray emission derived using a multicomponent fit to Fermi-LAT gamma-ray data.



full sky data

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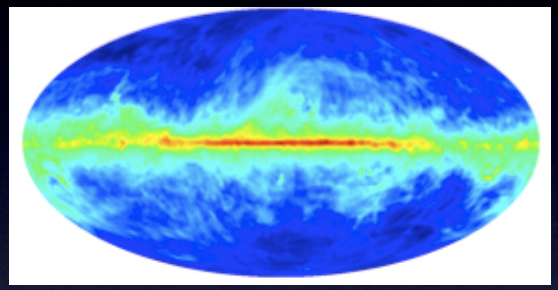
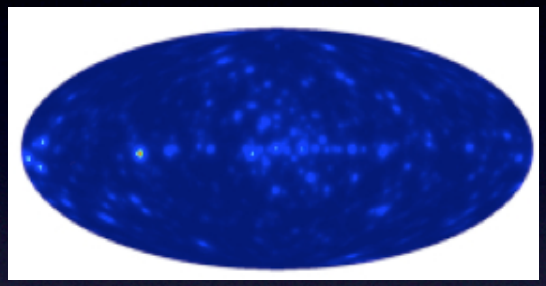


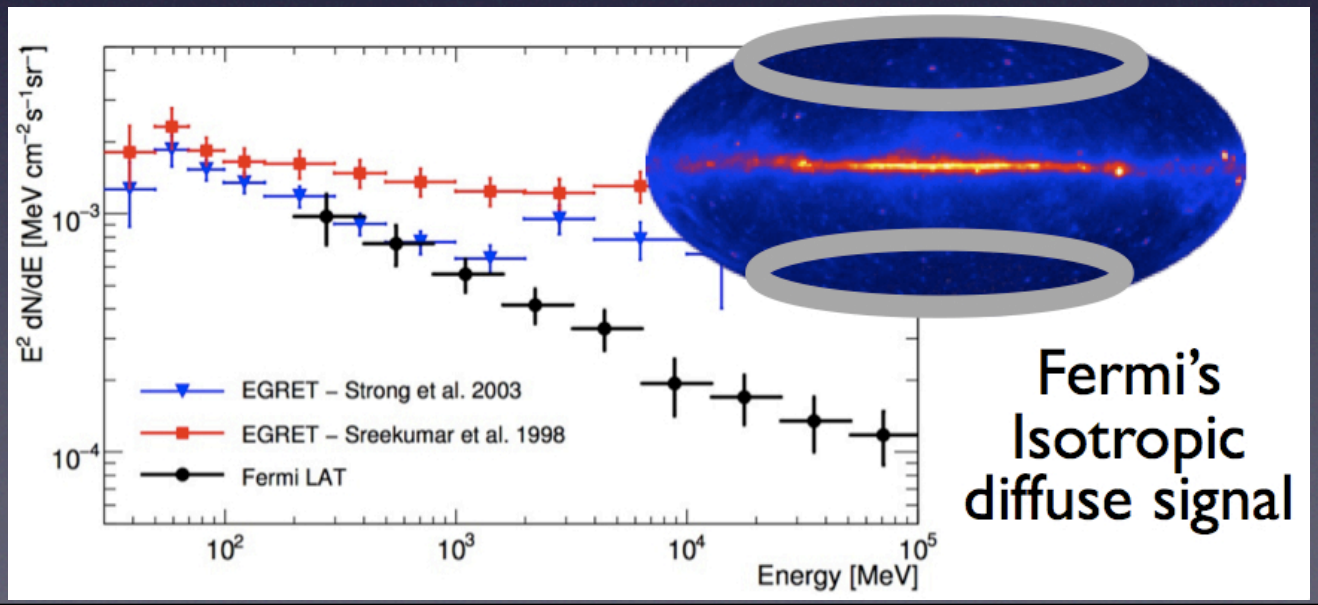
galactic diffuse emission

-



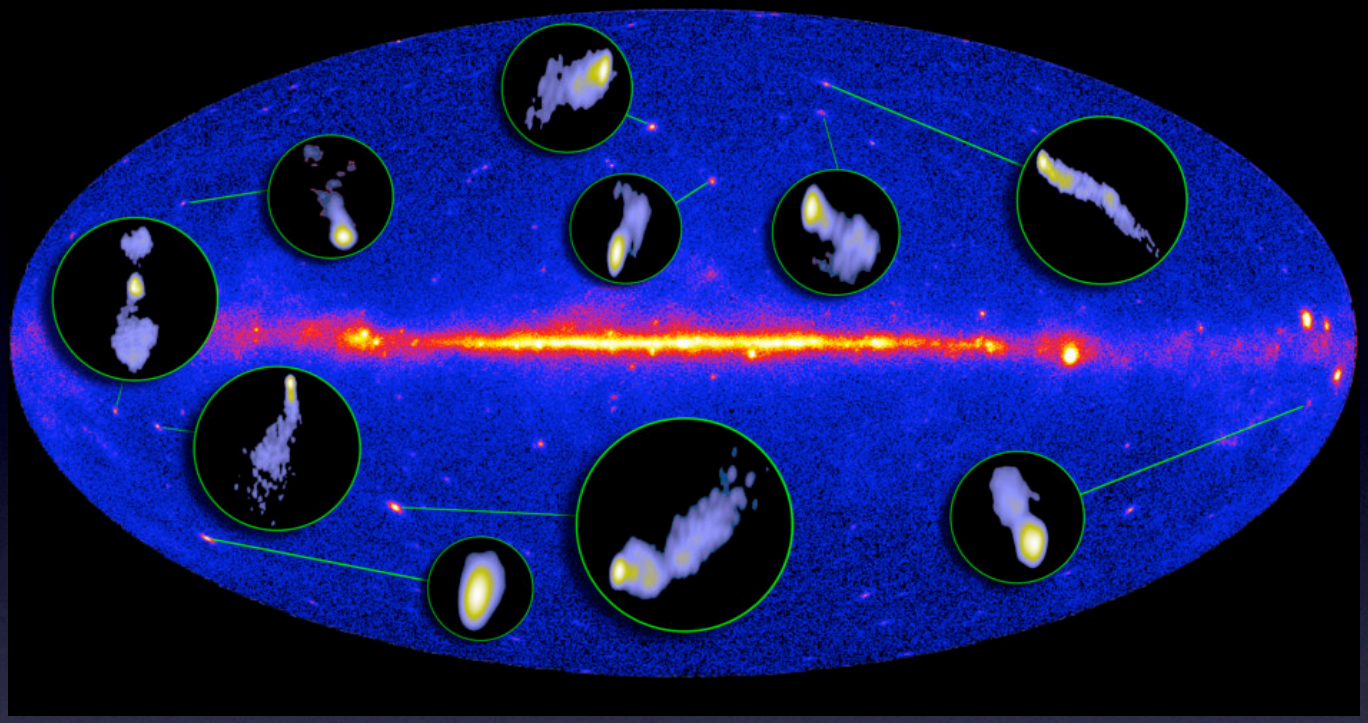
point sources

NB: the features of the inferred isotropic signal depend on the modeling of the galactic diffuse emission. Estimates of error~20%.

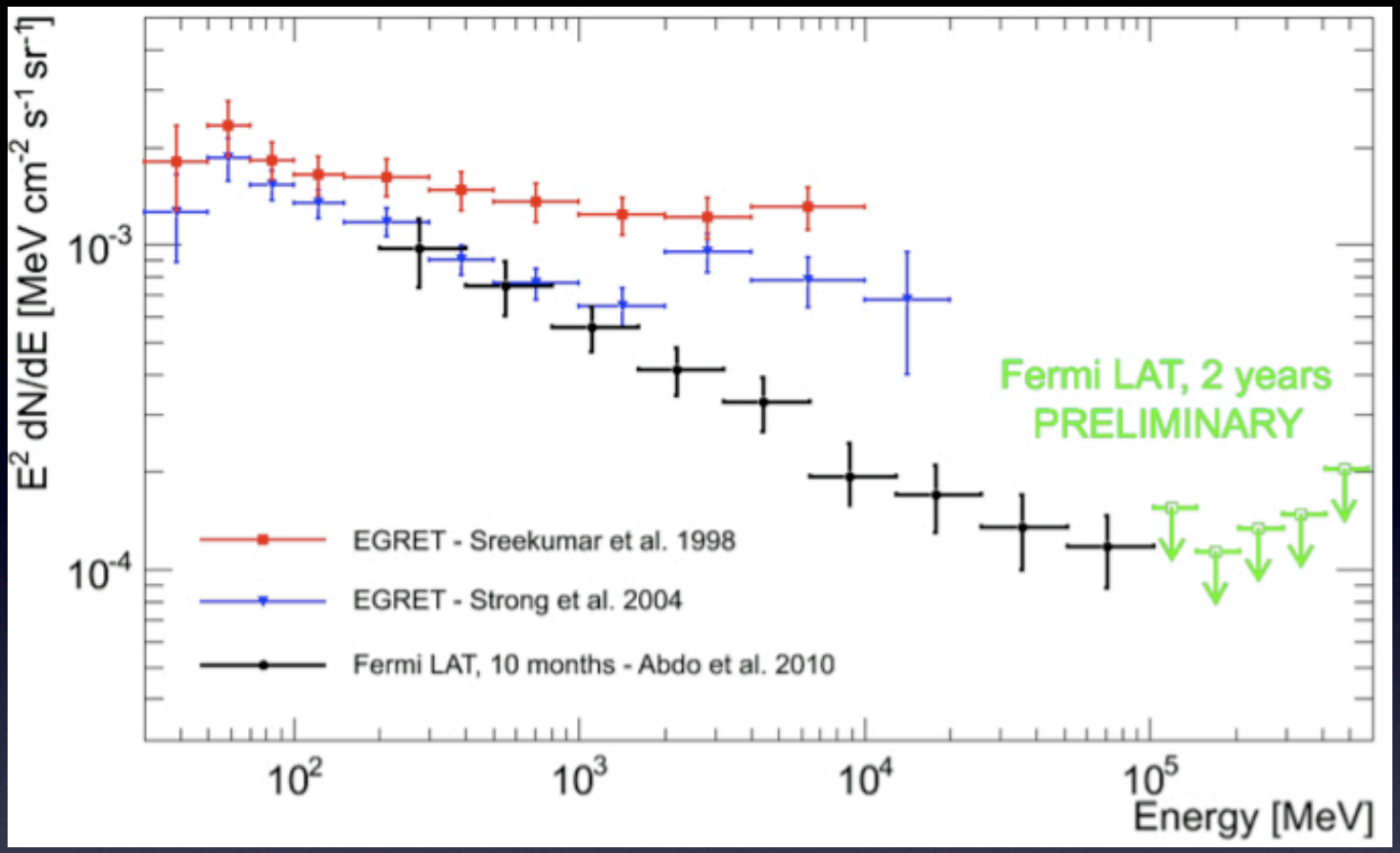


Produced by *unresolved* energetic phenomena over cosmological scales:

I) AGN
II) star burst and star forming galaxies
III) DM...?



Selected Active Galactic Nuclei observed in radio by the VLBA (which has a million times better resolution than the Fermi-LAT) and gamma-rays by the Fermi-LAT.



First year spectrum extends to 100 GeV.
>100 GeV the available Fermi MC simulation of residual CR contamination is too statistically limited.
A dedicated MC simulation analysis is ongoing.
Only *upper limits* for data >100 GeV shown here, full spectrum expected during the summer.

The studies of angular anisotropy of the isotropic background:

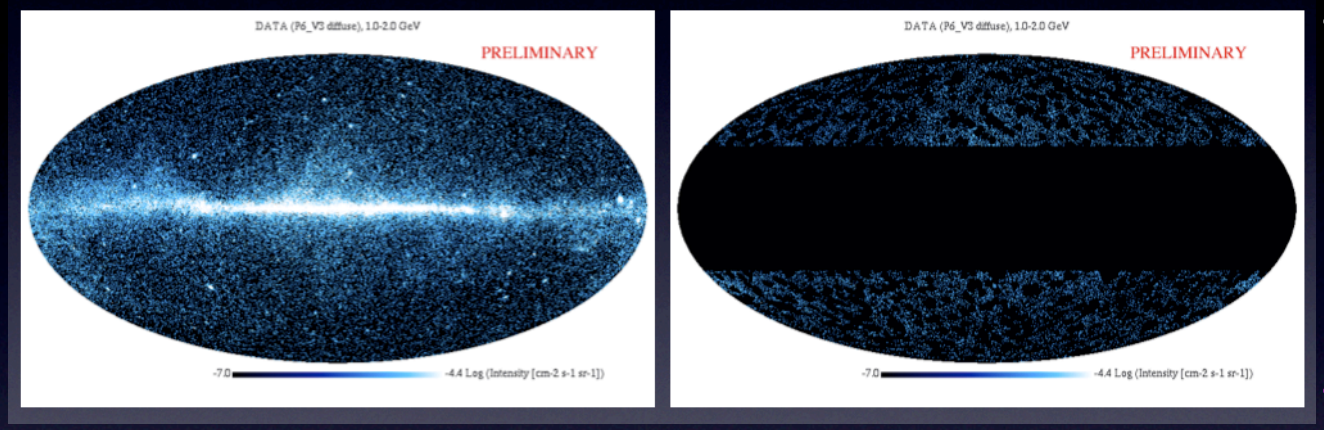
$$\delta I(\psi) \equiv \frac{I(\psi) - \langle I \rangle}{\langle I \rangle} \Rightarrow \delta I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi) \Rightarrow C_\ell = \langle |a_{\ell m}|^2 \rangle$$

- if the diffuse emission originates from an unresolved source population, the diffuse emission will contain *fluctuations on small angular scales*
- angular information in the diffuse gamma-ray background can be used to identify dark matter and other source classes

1 - 2 GeV

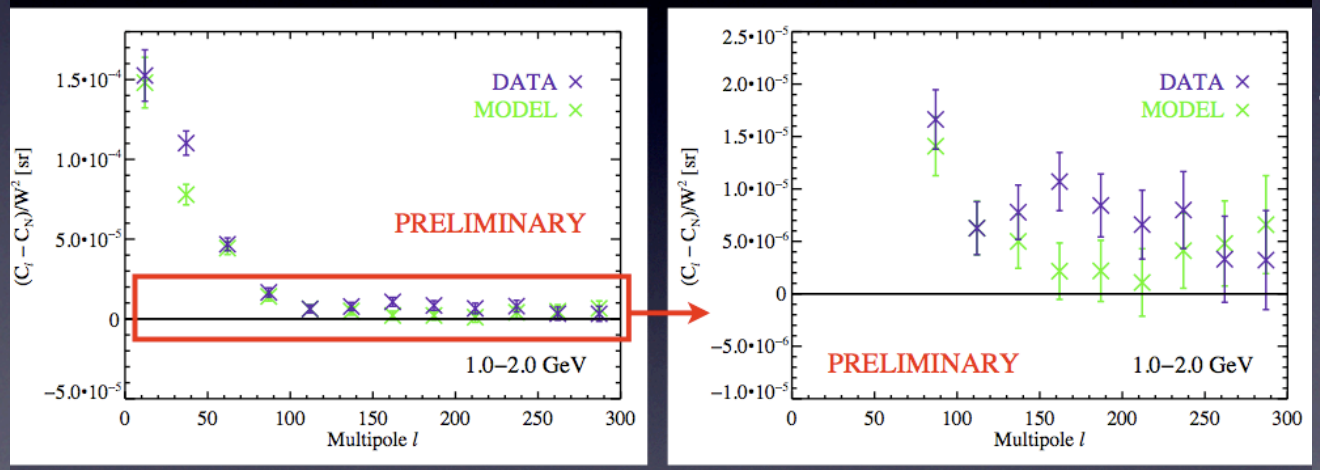
All-sky map

Masked-sky map used in this analysis



fluctuation angular power spectra

1 - 2 GeV

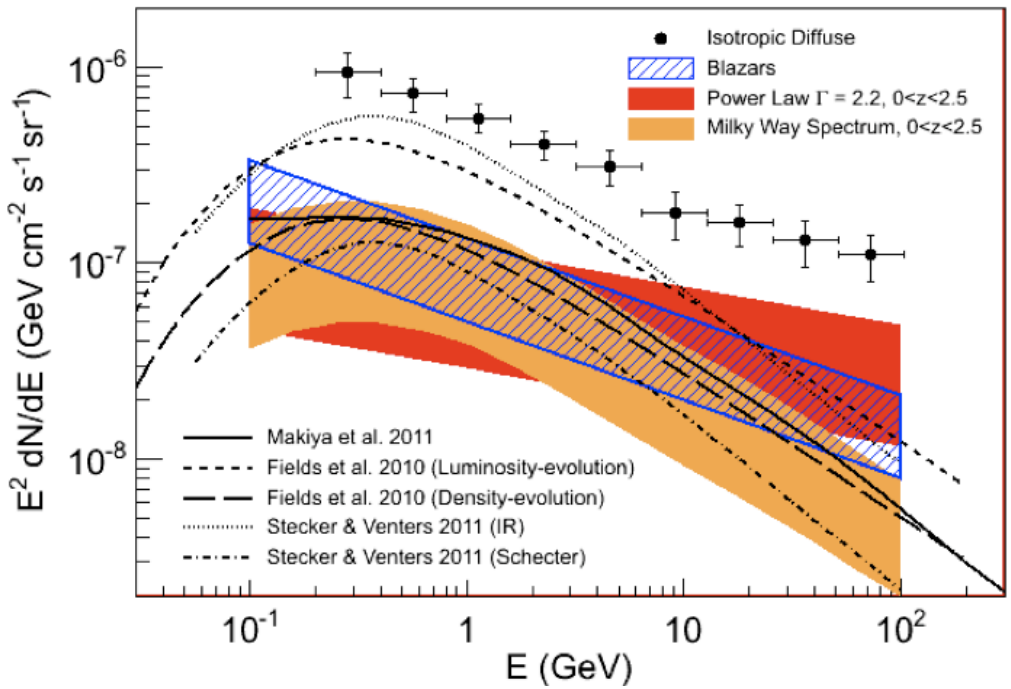


[Siegal-Gaskins, IDM 2011]

- at multipoles *less than ~ 100 (1 deg)* angular power above the noise is seen in the data AND the model, and is likely due to contamination from the Galactic diffuse
- at multipoles *greater than ~ 100* angular power above the photon noise level is measured in the data at energies from 1 to 5 (10) GeV;
- due to decreasing photon statistics, the measurement at *>10 GeV* energies currently does not exclude the presence of anisotropies at those energies at the level detected at 1 - 10 GeV

Comparison of the Extragalactic Diffuse γ –ray Background[1] to Calculations of Contributions from Blazars[2] + Star-forming Galaxies[3]

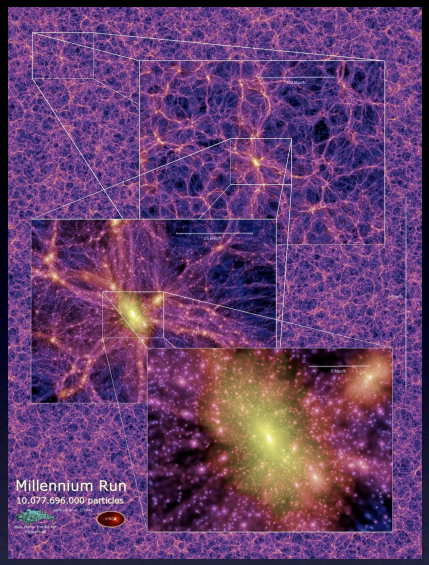
Preliminary



1) Abdo, A. A. et al. 2010, Phys. Rev. Letts. **104**, 101101;
2) Abdo, A. A., et al. 2010, ApJ. **720**, 435; 3) Fermi LAT Collaboration Preliminary.

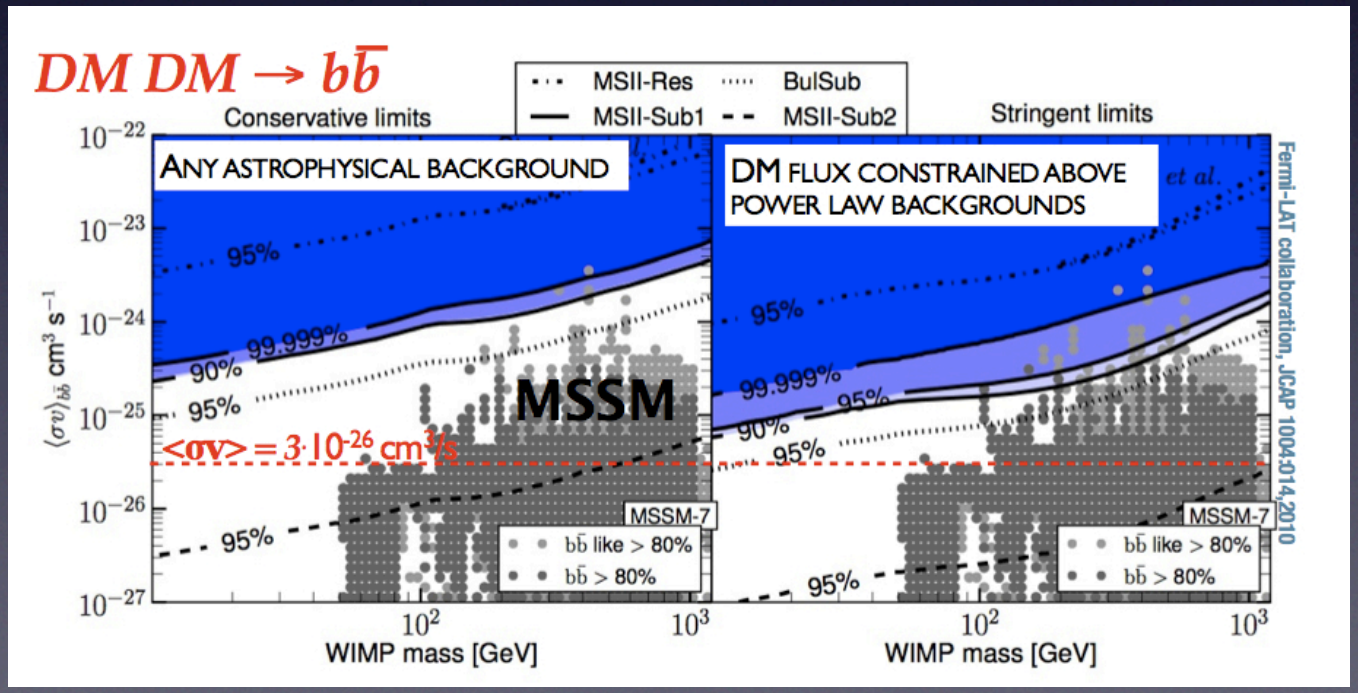
Blazar contribution is derived from *a source population study*, while the starburst contribution is coming from deriving the luminosity function based on multi-wavelength tracers of star-burst galaxies, having only detected *a few (4) in gamma-rays* → *indicates that the majority of the IGRB does not originate from members of the source classes already detected by Fermi.*

Predictions for the DM extragalactic signal:



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

Issues: *prediction and uncertainty* in the DM signal from N-body simulation results (limited by computer power).



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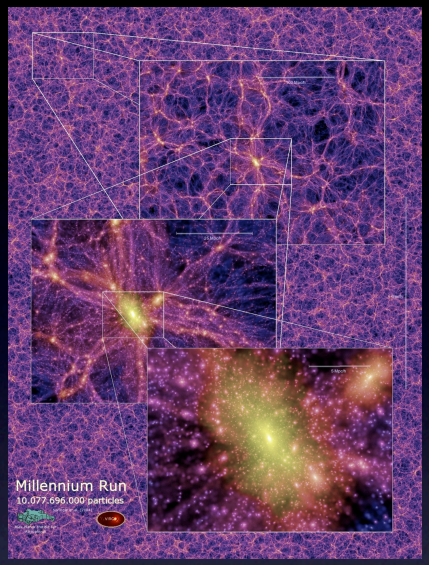

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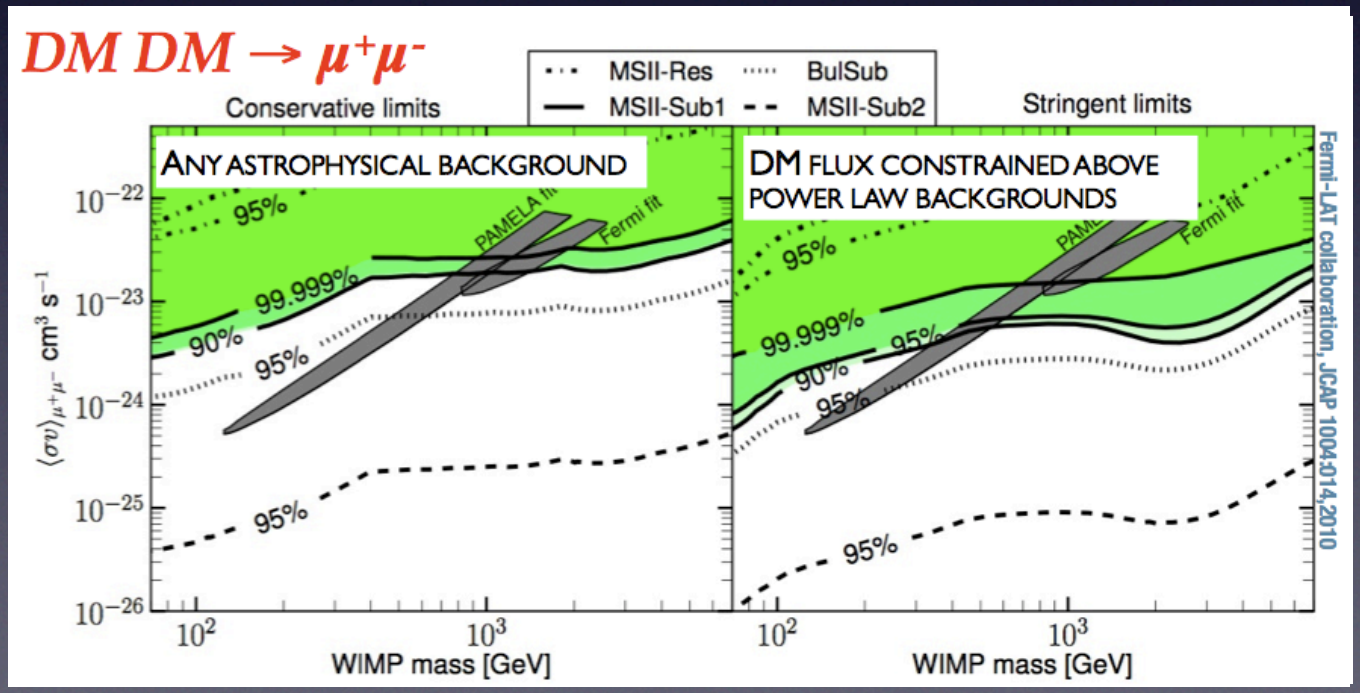
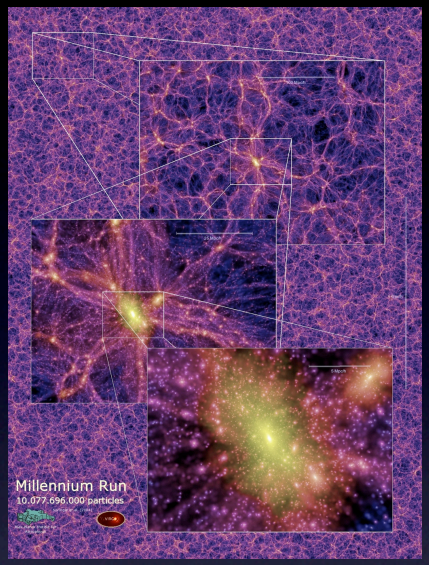


Predictions for the DM extragalactic signal:



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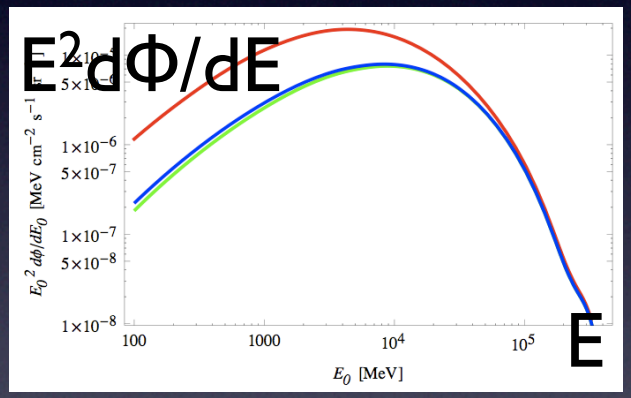
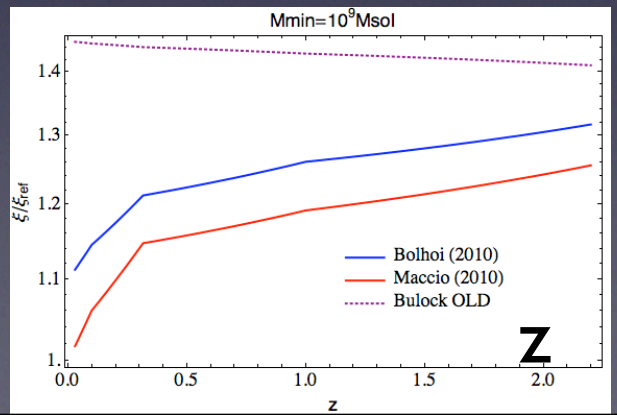
Issues: *prediction and uncertainty* in the DM signal from N-body simulation results (limited by computer power).

Astrophysical and cosmological uncertainties' (w/ Serpico, Gustafsson, Sefusatti.):



Theoretical reassessment of the predictions for extragalactic DM signal:

- full error budget
- impact of non-standard cosmologies
- the impact on the spectra when different simulations and theoretical assumptions are varied.



Summary

- The DM signal from our halo is potentially a strong DM search tool (due to the strength of the signal). It heavily relies on the models of the diffuse emission.
- High latitude (extraGalactic) diffuse emission:
  - The excess power measured in the data at multipoles >~100 suggests a contribution from a point source population not present in the model.
  - A large number of detected extragalactic source classes makes possible more accurate modeling of a contribution of extragalactic source classes to the isotropic signal.
  - Work on new DM limits, both from the angular and intensity spectrum.
- The combined limits from dwarf spheroidal galaxies are cutting into the WIMP parameter space.
- many other DM analysis ongoing within Fermi: Galactic Center, dark subhalos....

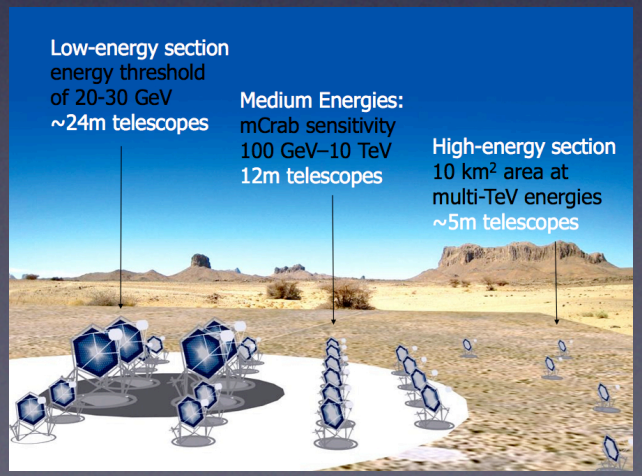
Future prospects

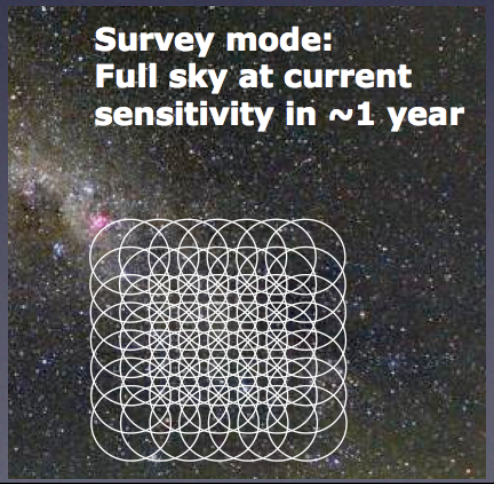
- Cosmic ray experiments (*AMS02, CREAM*...), are will improve our knowledge of the cosmic ray propagation in our Galaxy.

- *Planck* will determine cosmological parameters with improved sensitivity and aid in the predictions for the DM cosmological signal. The measure the dust emission of our Galaxy will improve our modeling of the gas content, and therefore that of the Galactic diffuse emission. Multiwavelength studies with synchrotron band will also bring in improvements.

- *LHC* is expected to give us first hints of the new physics at the EW breaking scale soon, and hopefully aid us in where to look (in terms of the energy spectra) for the dark matter signatures.

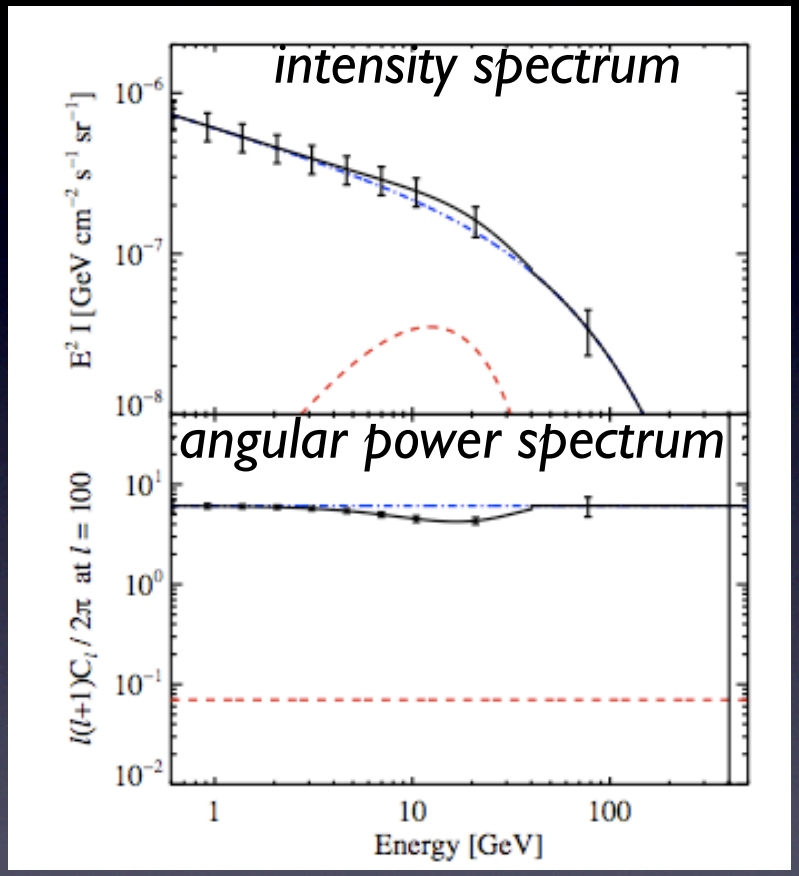
- *CTA*, a kilometer square array of Cerenkov telescopes will have a sensitivity improvement of over order of magnitude with respect to Fermi and current ACTs. It will have a superior angular resolution and due to the large number of telescopes employed, might also have a significant potential to measure extended (diffuse) emission.





Back-up slides

The anisotropy energy spectrum:



[Hensley et al., APJ 2010]

Observation of a feature in the anisotropy energy spectrum of the IGRB would strongly *indicate a contribution from at least two source classes.*

All sky search of possible candidates among the Fermi unassociated sources:

- no counterpart at other wavelengthsno counterpart at other wavelengths
- steady emissionsteady emission
- only sources far from Galactic Plane (|b|>10 deg) have been tested.
- DM spectrum has been tested only versus a PowerLaw hypothesis:

No evidence for sources with DM annihilation features in the in the μ+μ- channel.
No evidence for a population of sources in the b/bbar channel.

Work in progress:
determining reliable selection parameters: discrimination of a candidate DM source from other known objects (Pulsars, AGNs);

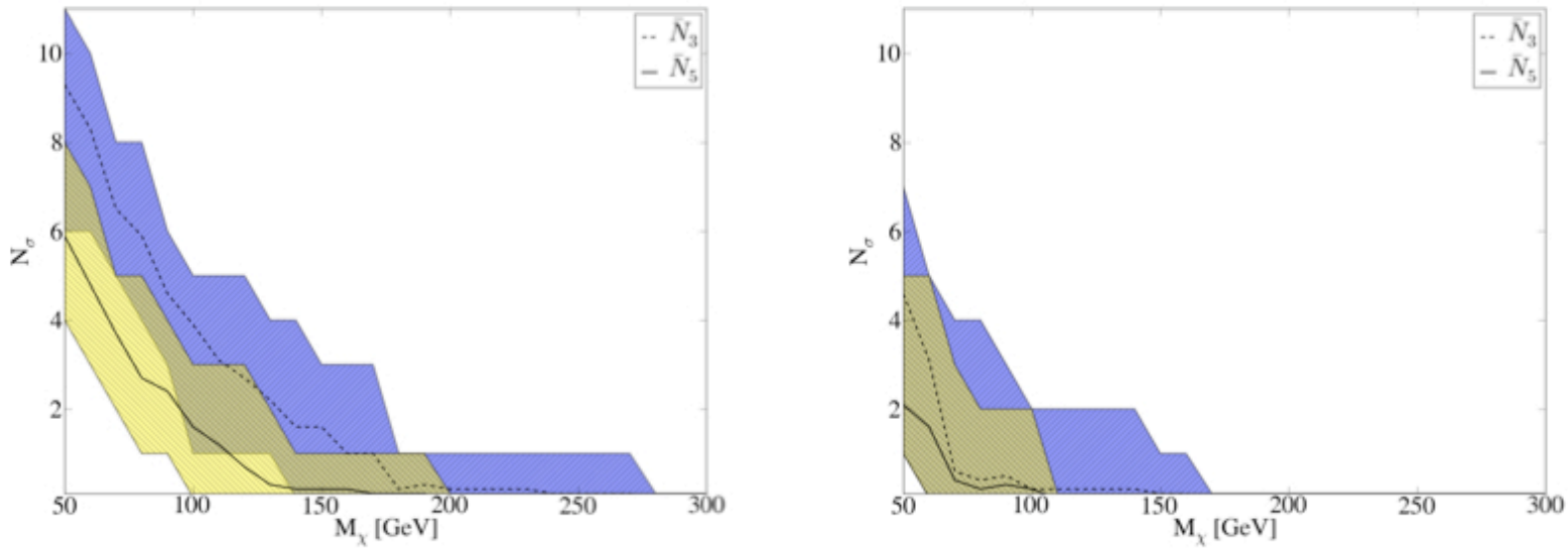


Fig. 4.—: The number of subhalos above five (and three) standard deviations significance, N_5 (N_3), as a function of WIMP mass, M_χ, for $\langle \sigma v \rangle = 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$. The shaded regions show the range of variation among ten different observer positions, while the dashed and solid lines represent the average over all positions. The subhalos on the left have been boosted for unresolved substructure while those on the right have not. The simulations represent a Fermi-LAT observation time of ten years.

ANDERSON, B, ET AL, ARXIV:1006.1628