Dark matter constraints from Fermi-LAT gamma-ray measurements

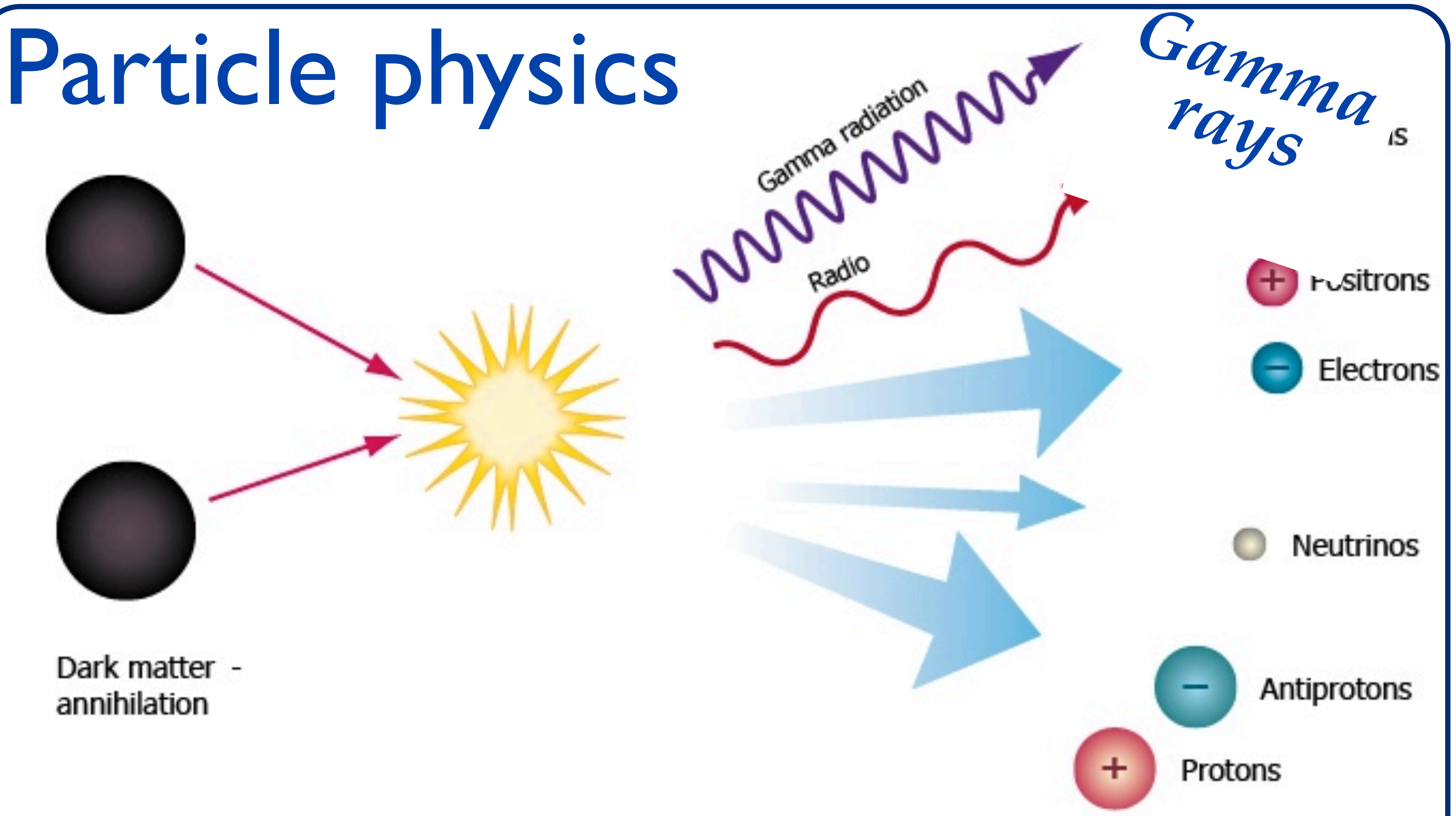
Michael Gustafsson

UniverseNet INFN/Padova

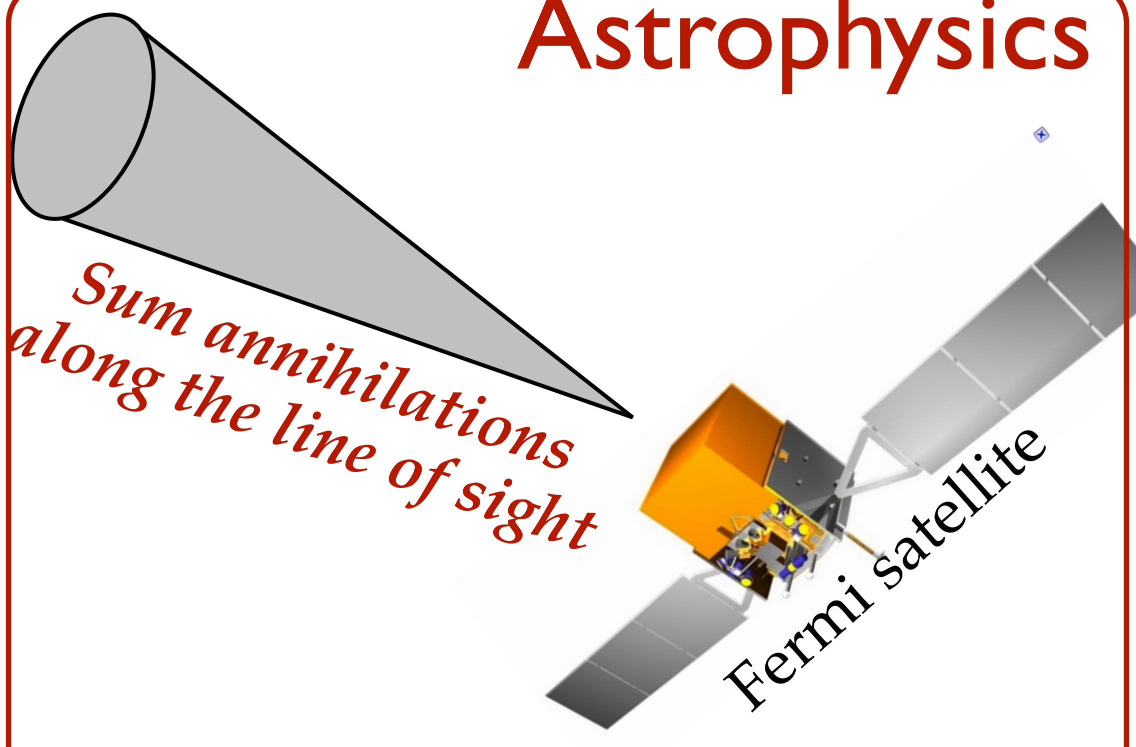
On behalf of the Fermi Collaboration

DARK MATTER signal in gamma rays

Particle physics



Astrophysics



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

Flux of gamma-rays produced in DM annihilations:

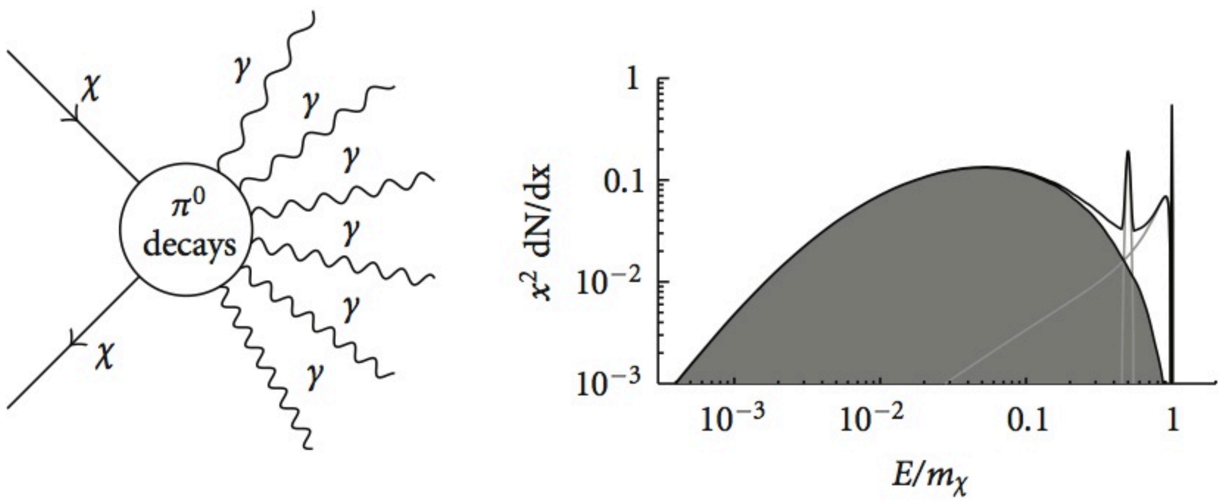
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\theta,\phi) = \frac{1}{4\pi} \boxed{\frac{\langle\sigma v\rangle_{T_0}}{2\,M_\chi^2} \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f} \cdot \boxed{\int_{\Delta\Omega(\theta,\phi)} d\Omega' \int_{l.o.s.} dl\; \rho_\chi^2(l)}$$

Particle physics — Astrophysics

DM SIGNAL: SPECTRAL SHAPE:

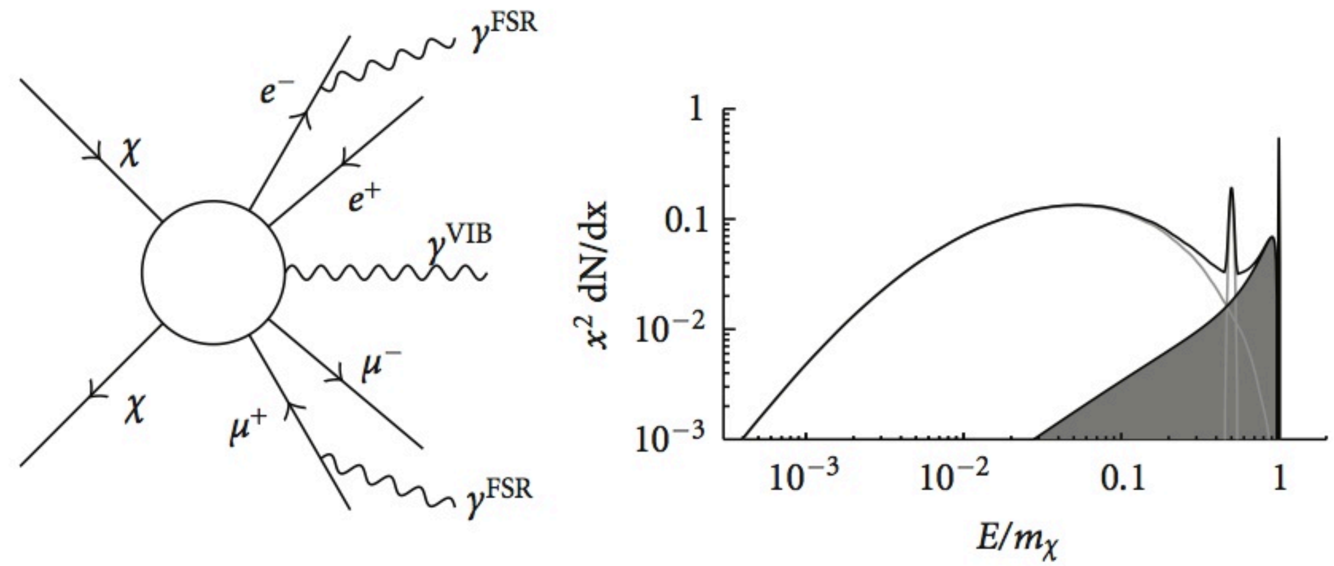
Secondary photons

Secondary photons (tree level)



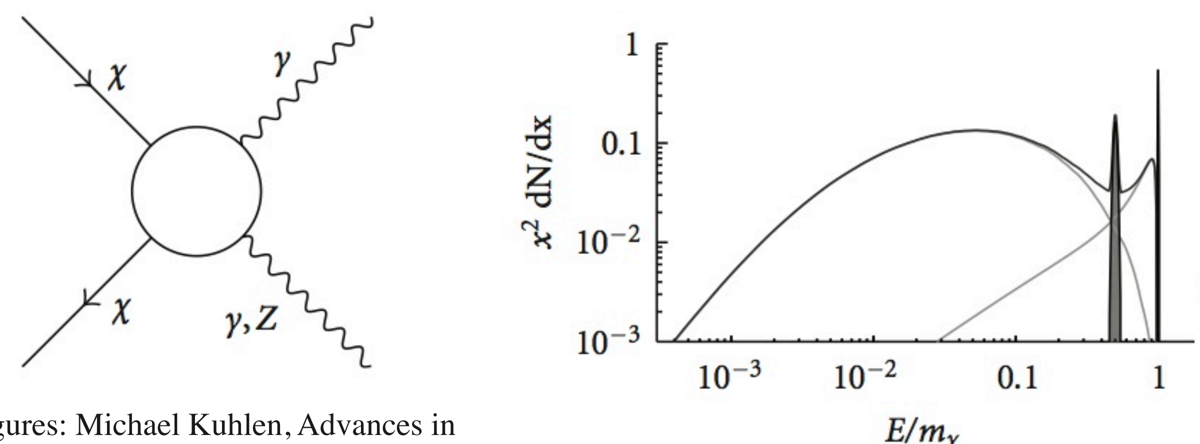
Internal Bremsstrahlung

Internal bremsstrahlung $\mathcal{O}(\alpha)$



Monochromatic lines

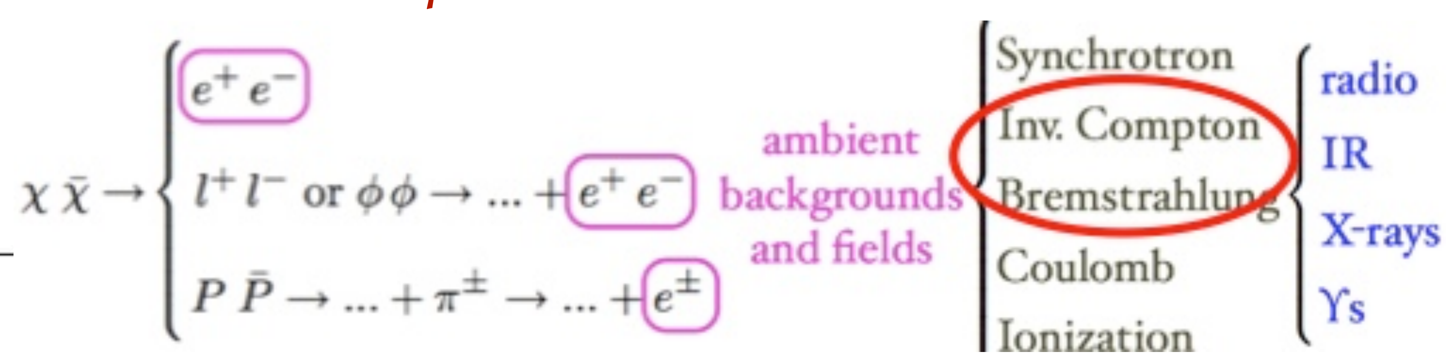
Line signal (loop level $\mathcal{O}(\alpha^2)$)



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

Radiative processes

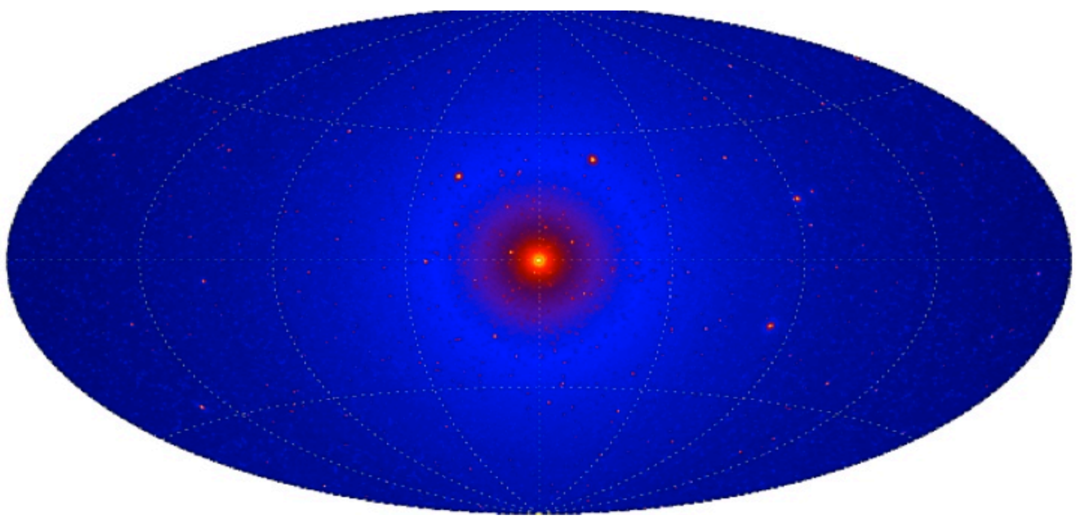
Important if there is a significant branching ratio to leptons



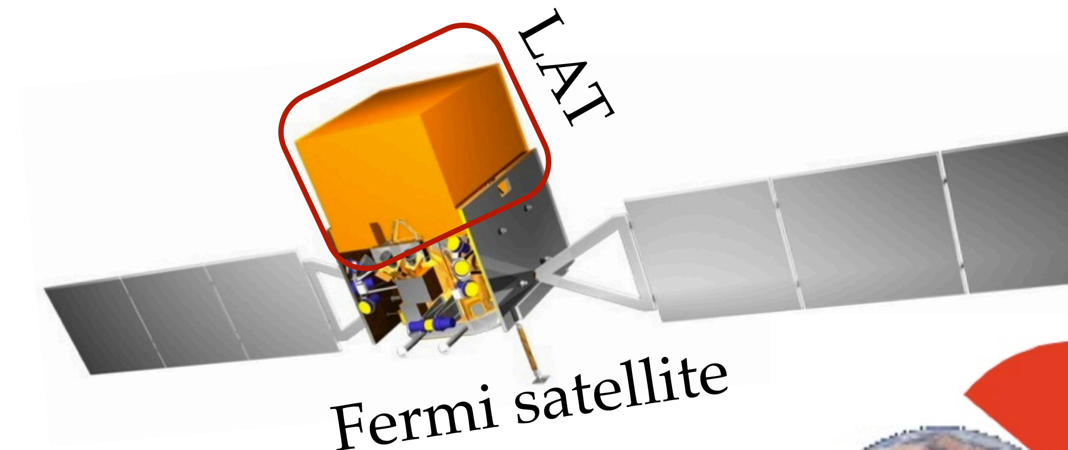
N.B.: electroweak corrections, Alfredo Urabano's talk yesterday

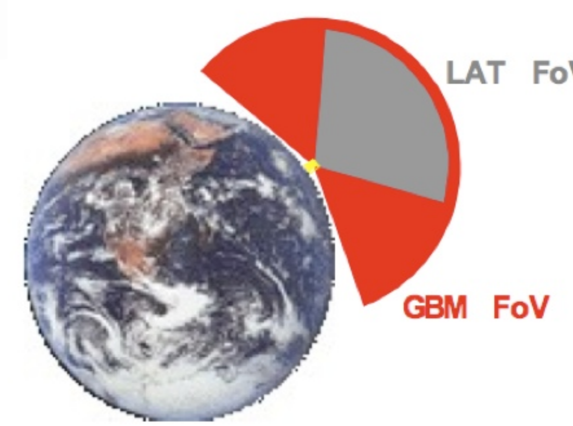
DM SIGNAL: SPATIAL VARIATION

Cold dark matter
(Via Lactea)



Observation
(Fermi-LAT)



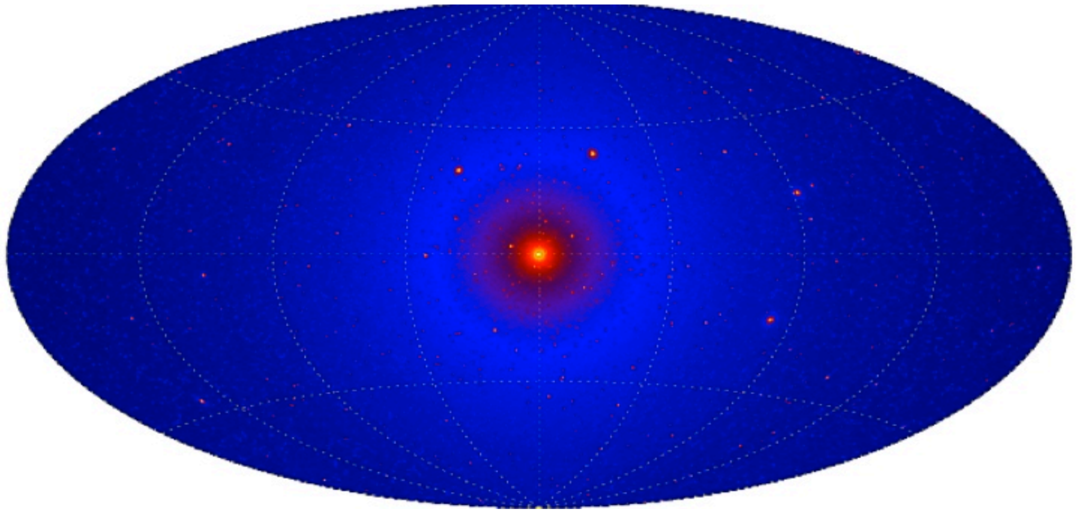


Fermi-LAT instrument:

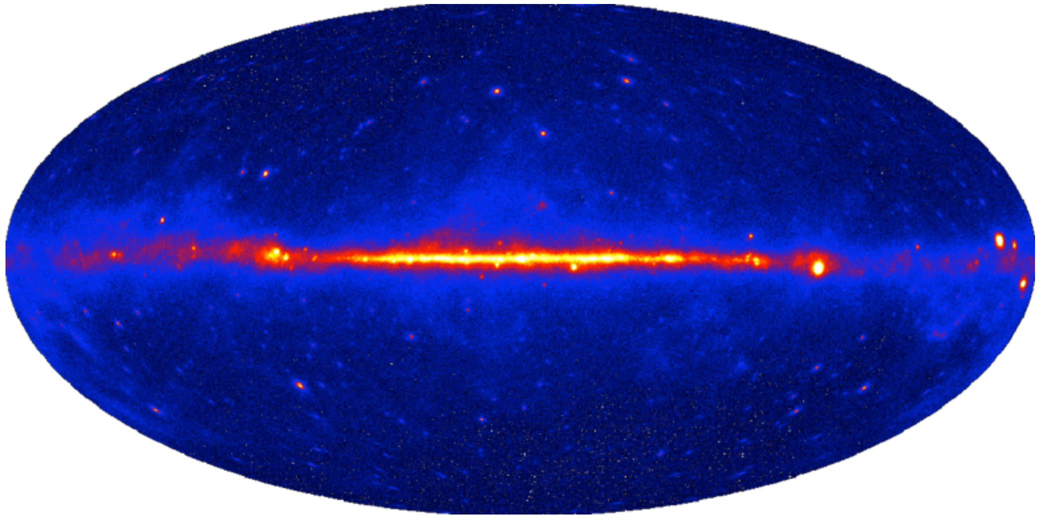
* *Full sky coverage; 20% of sky at any instance*
* *Energy range 20 MeV to >300 GeV; includes previous unexplored energy band ~10-100 GeV*
* *Effective area ~ 0.8 m^2*
* *Energy resolution ~ 10 %, angular res ~ 0.1. deg*

DM SIGNAL: SPATIAL VARIATION

Cold dark matter
(Via Lactea)



Observation
(Fermi-LAT)

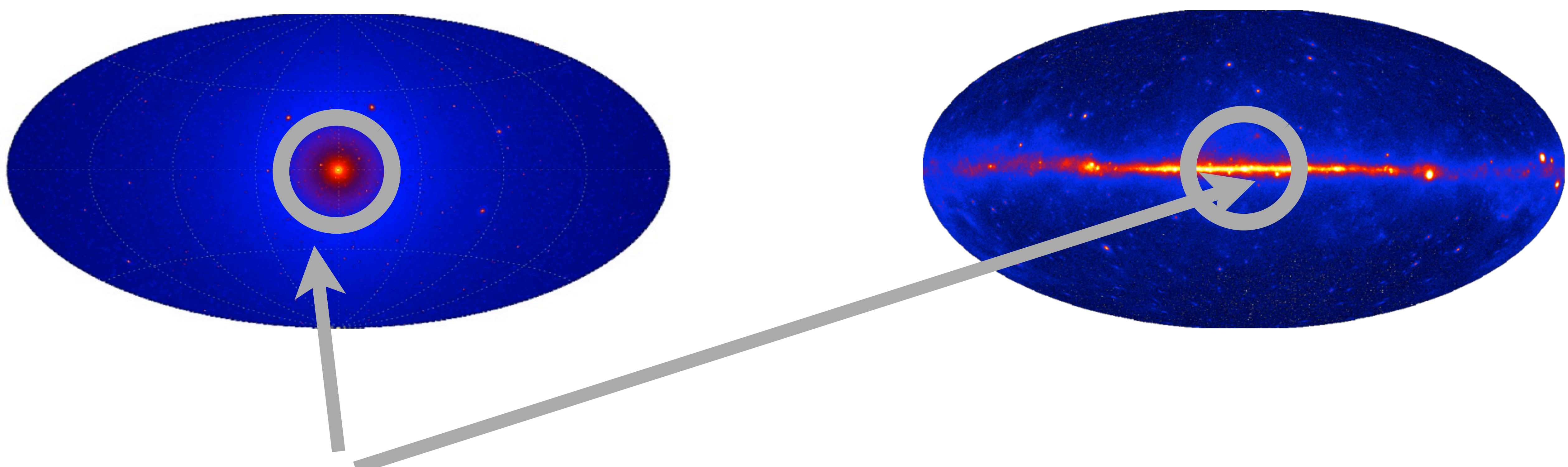


Fermi-LAT instrument:

* *Full sky coverage; 20% of sky at any instance*
* *Energy range 20 MeV to >300 GeV; includes previous unexplored energy band ~10-100 GeV*
* *Effective area ~ 0.8 m^2*
* *Energy resolution ~ 10 %, angular res ~ 0.1. deg*

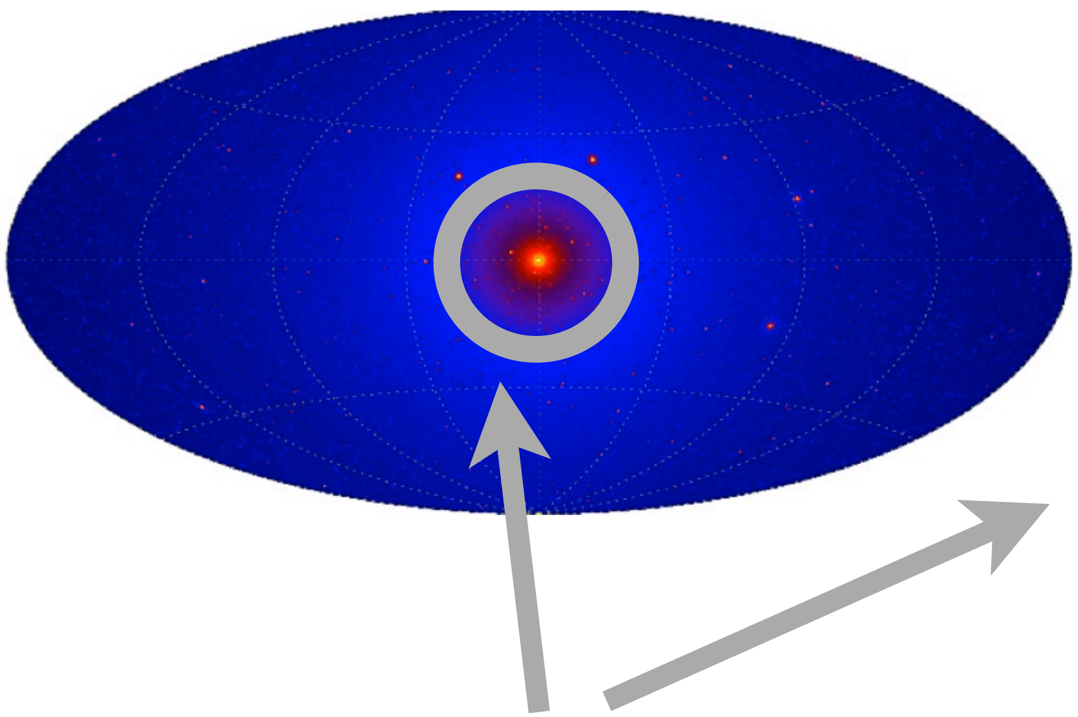
Cold dark matter
(Via Lactea)

Observation
(Fermi-LAT)



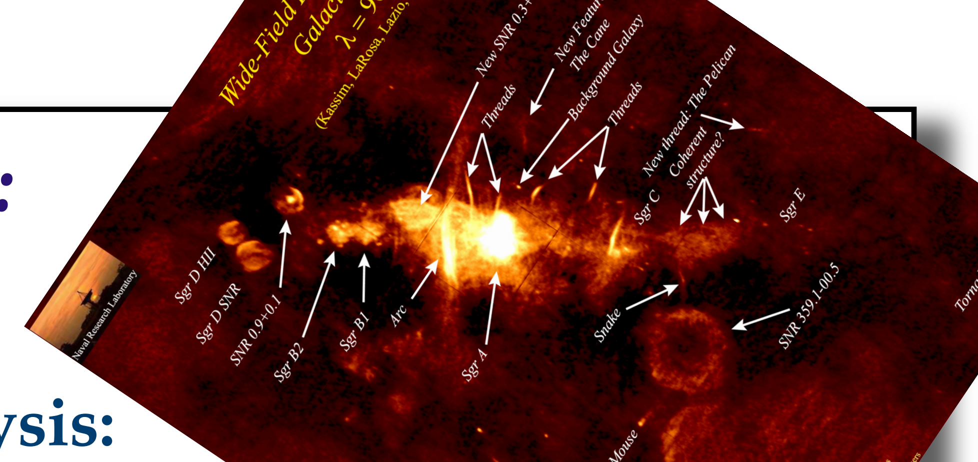
Galactic center

Cold dark matter
(Via Lactea)



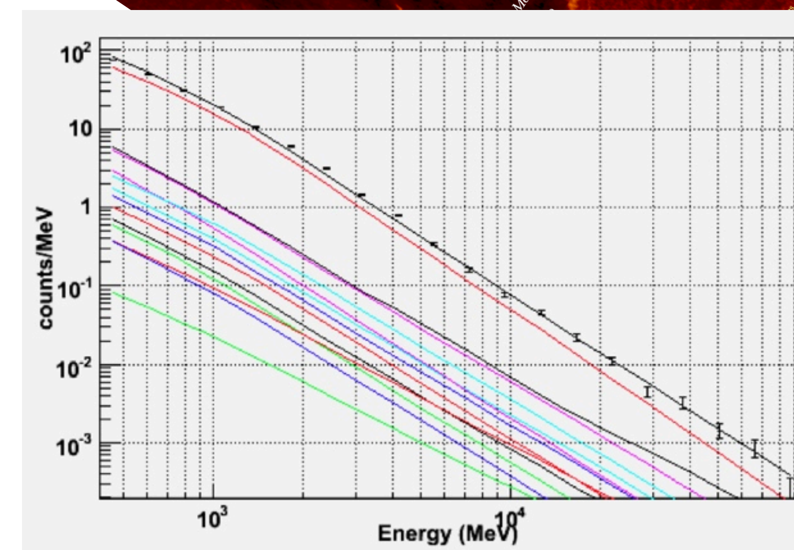
Galactic center

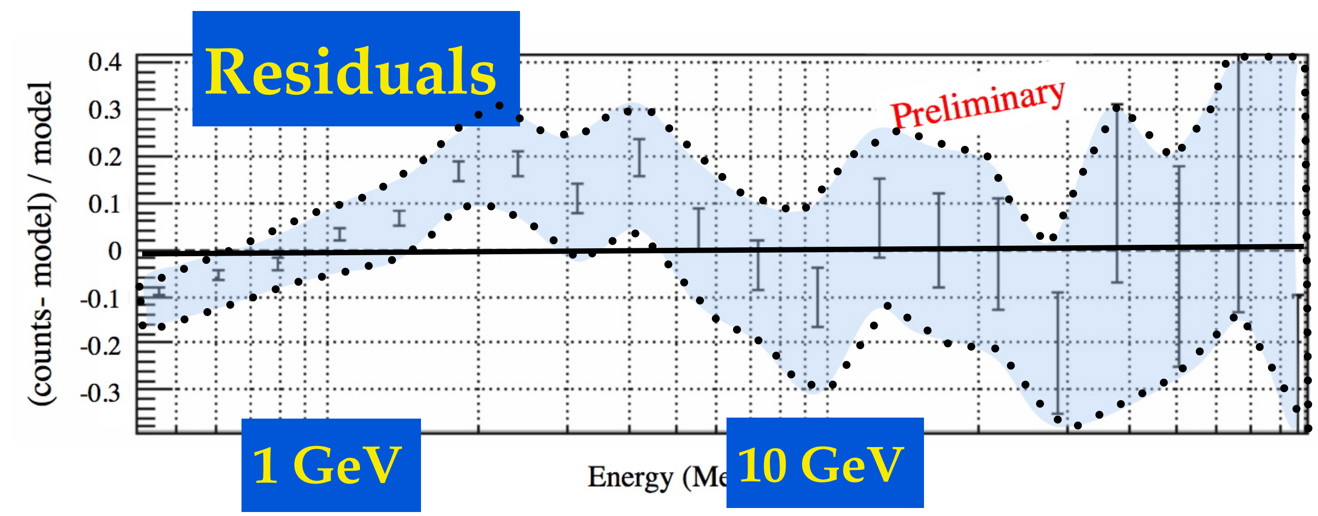
Complex region:



Preliminary Analysis:

- 11 month data
- 7x7 deg ROI
- Model:
  - Gal. Diffuse (Galprop)
  - Isotropic
  - Point sources



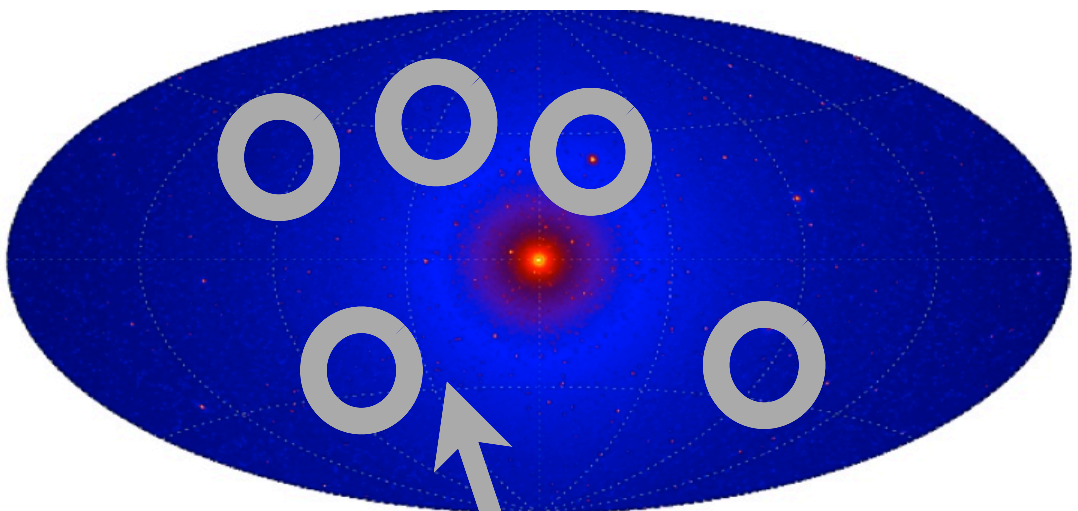


Residuals under investigation:

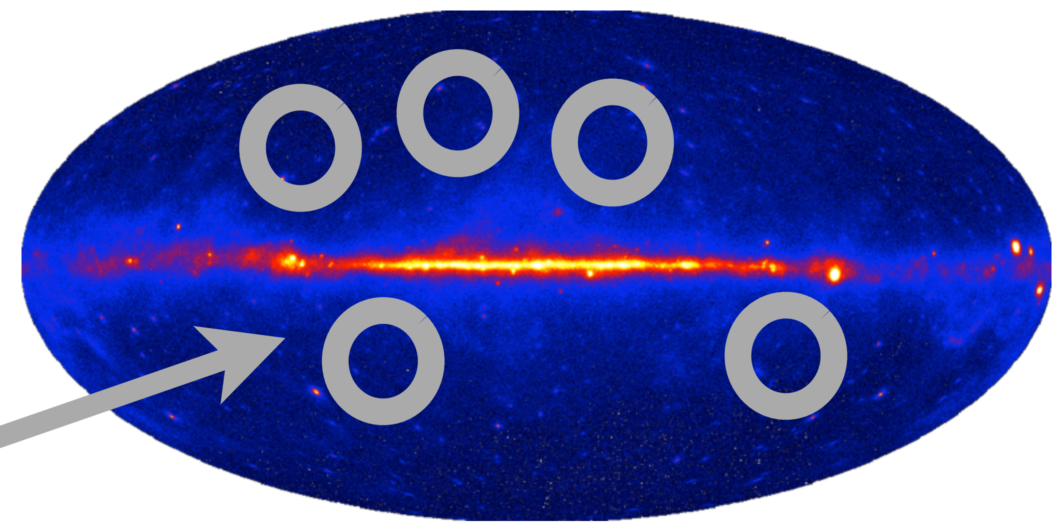
- **Galactic diffuse emission?**
- **effective area systematics ?**

...

Cold dark matter
(Via Lactea)

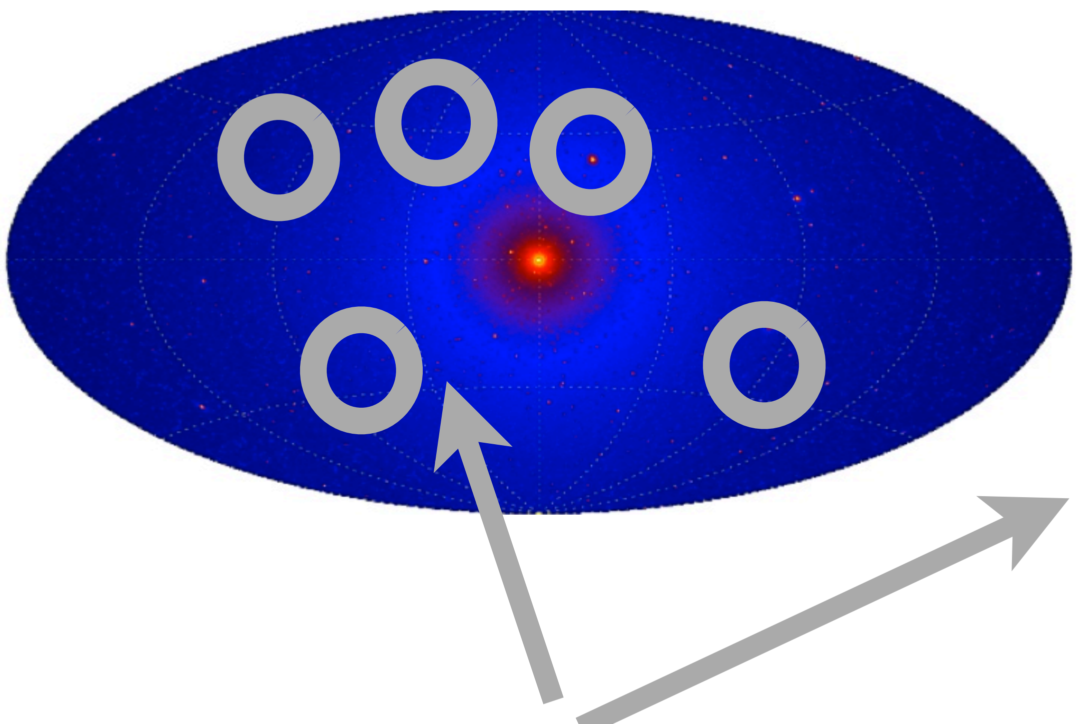


Observation
(Fermi-LAT)



Galaxy clusters
Dwarf galaxies
DM clumps

Cold dark matter
(Via Lactea)



Galaxy clusters
Dwarf galaxies
DM clumps

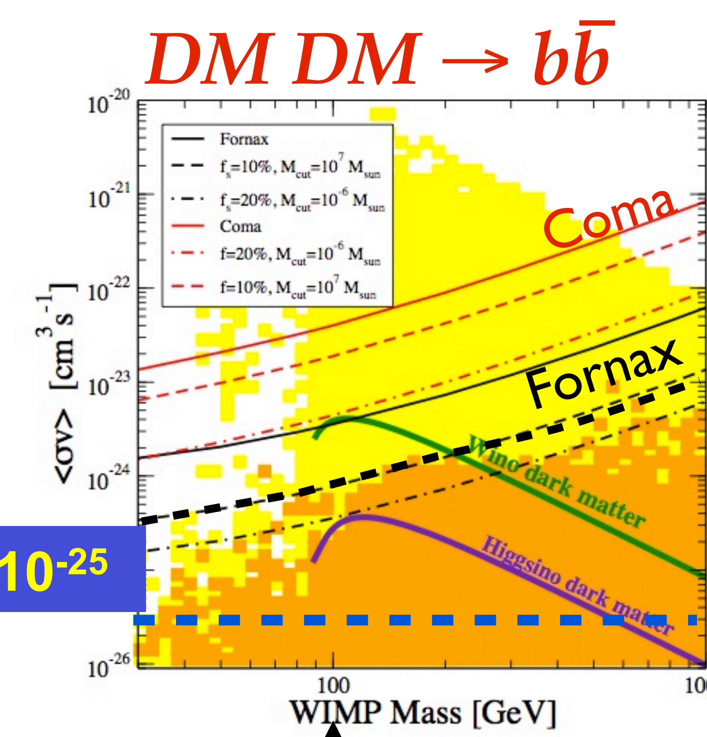
Large DM dominated distant objects

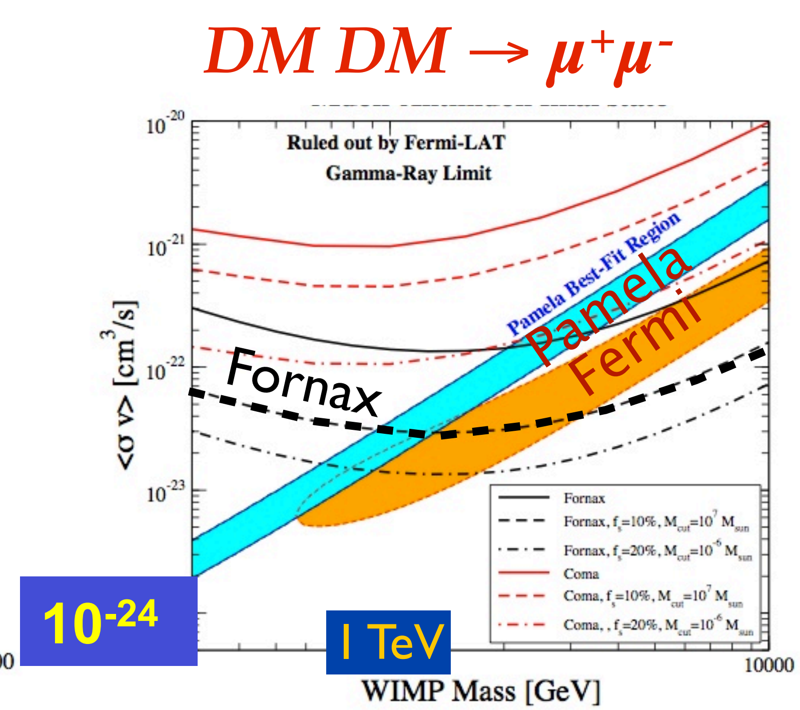
- ~ 1 year Fermi-LAT data, 0.1-100 GeV energy range
- No detection by Fermi-LAT

  ⇒ 95% gamma-ray flux upper limits ⇒

DM to b-quark channel constraints
(limits depend on substructures assumptions)
DM to $\mu^+\mu^-$ channel constraints
(mainly inverse Compton scattering of the CMB)

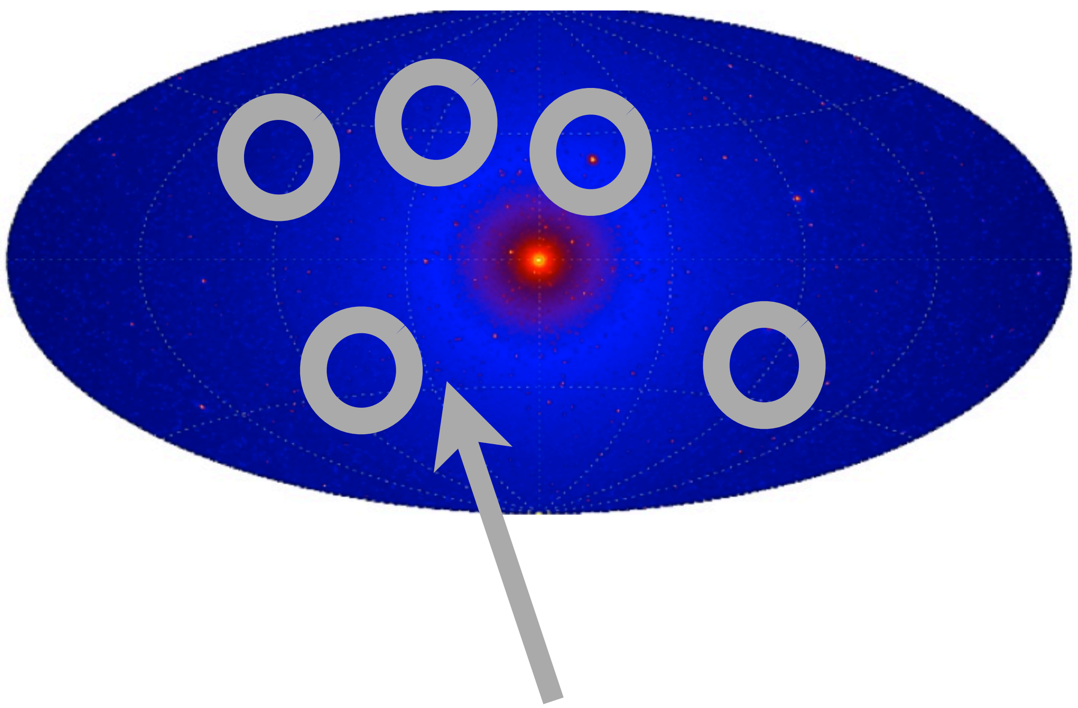
Canonical WIMP: $<\sigma v> \sim few \cdot 10^{-26}$ cm^3/s





Fermi-LAT: JCAP 1005:025,2010

Cold dark matter
(Via Lactea)

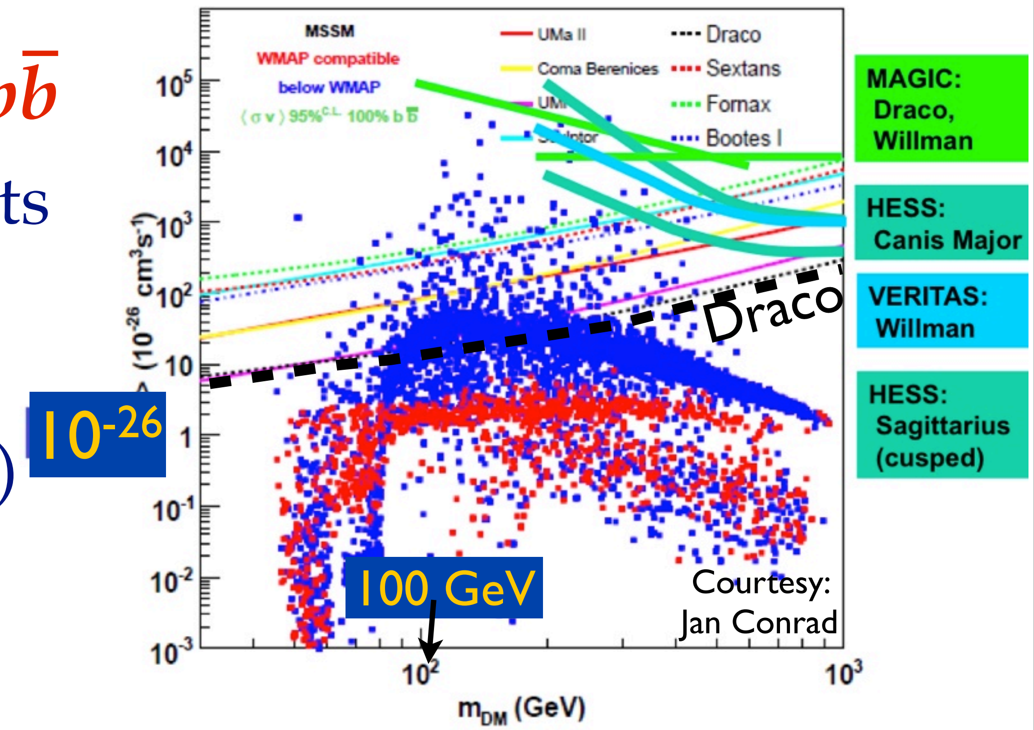


Galaxy clusters
Dwarf galaxies
DM clumps

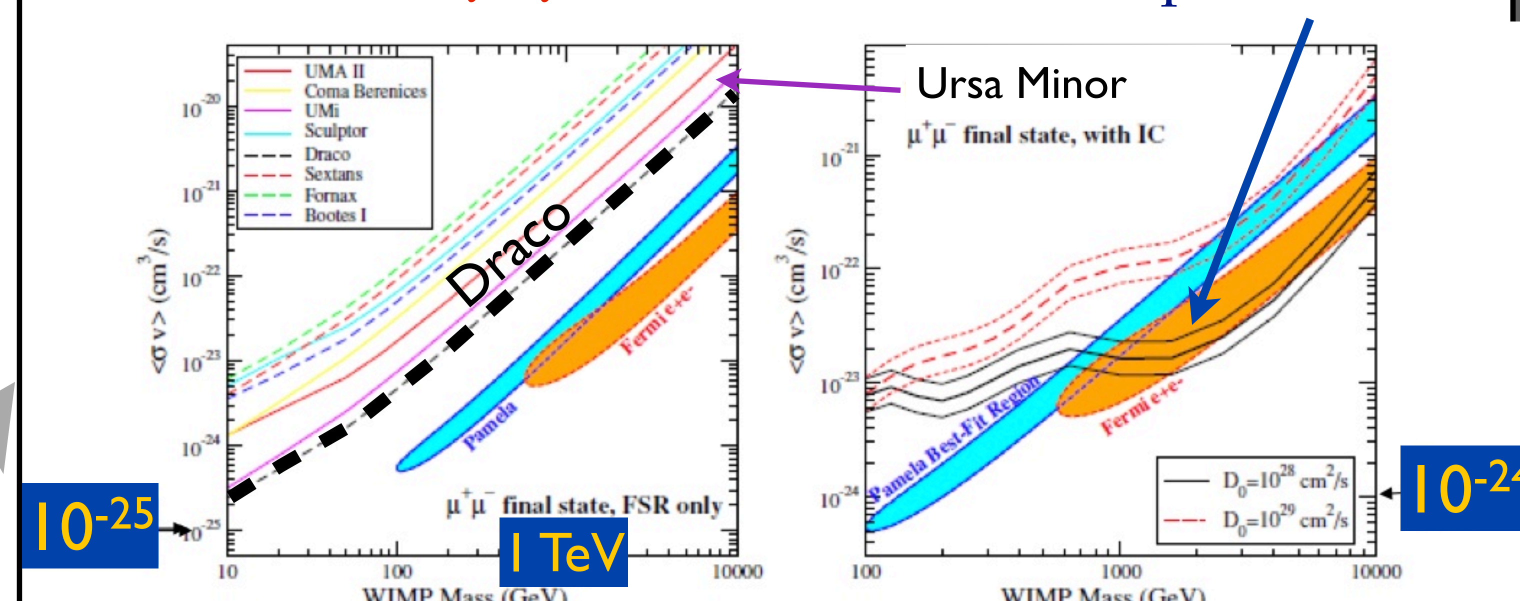
Smaller DM dominated closer objects

DM DM → $b\bar{b}$

(stronger limits than from clusters, no substructures)

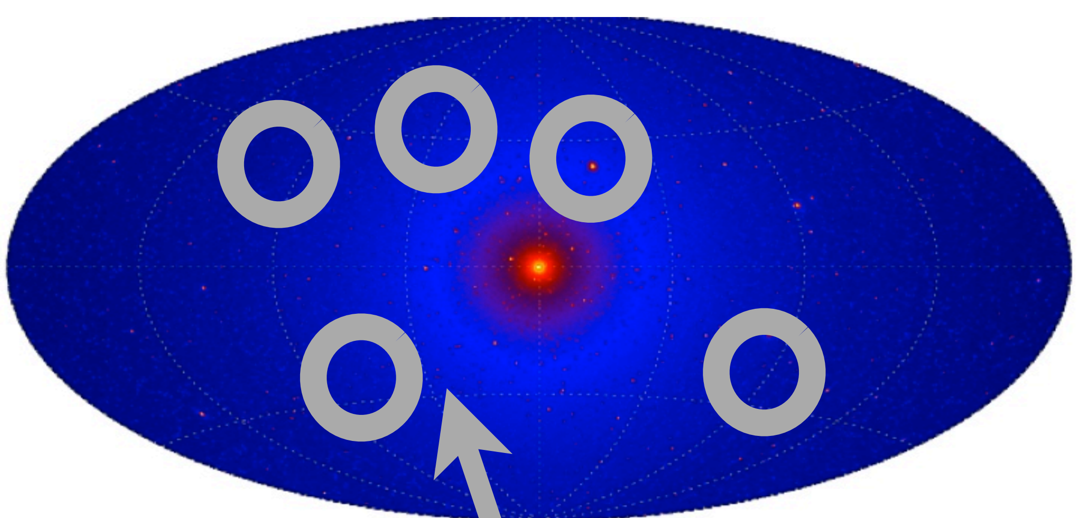


DM DM → $\mu^+\mu^-$ (diffusion-model dependent)



Fermi-LAT: Astrophys.J.712:147-158,2010

Cold dark matter
(Via Lactea)



Galaxy clusters
Dwarf galaxies
DM clumps

⇒ Search of possible DM clump candidates among the Fermi unassociated sources.

Good Criteria:
- No counterpart at other wavelengths
- Steady emission
- Spatial extension

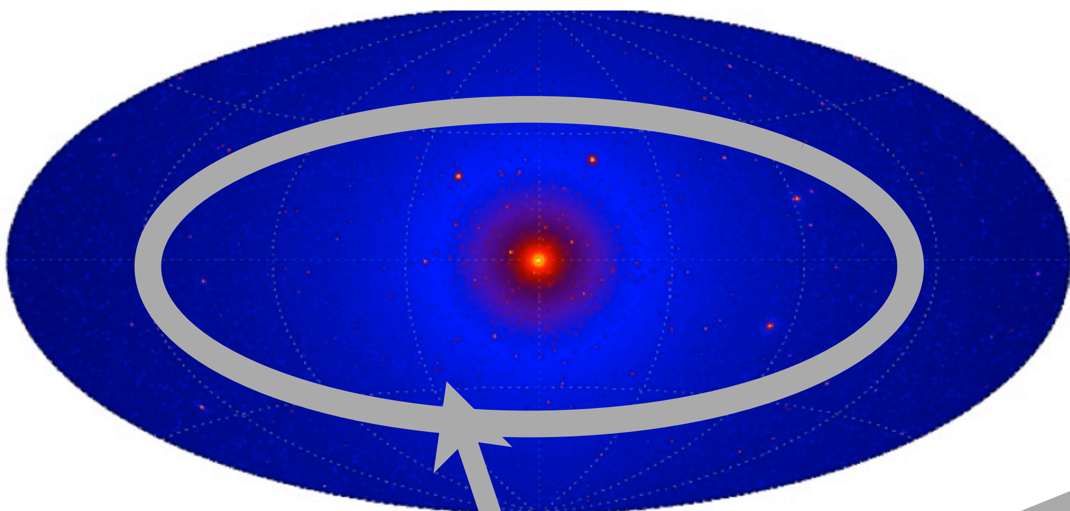
Investigate the gamma-ray spectral shapes:

Very preliminary (E. Bonamente/Fermi SciNeGHE 2010):
- No evidence for DM annihilation features in the *bb* or in the $\mu^+\mu^-$channel.

Work in progress!

See also e.g. Buckley & Hooper, arXiv:1004.1644

Cold dark matter
(Via Lactea)



Observation
(Fermi-LAT)

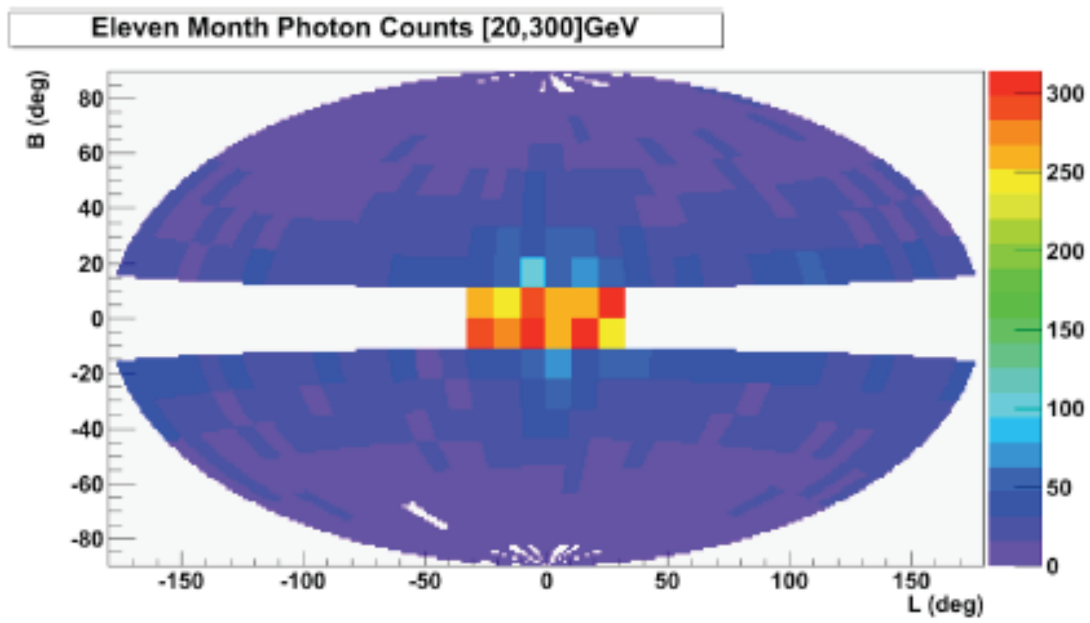
Talks by
Gabrijela Zaharijas
and Paolo Panci

Large scale
Galactic diffuse

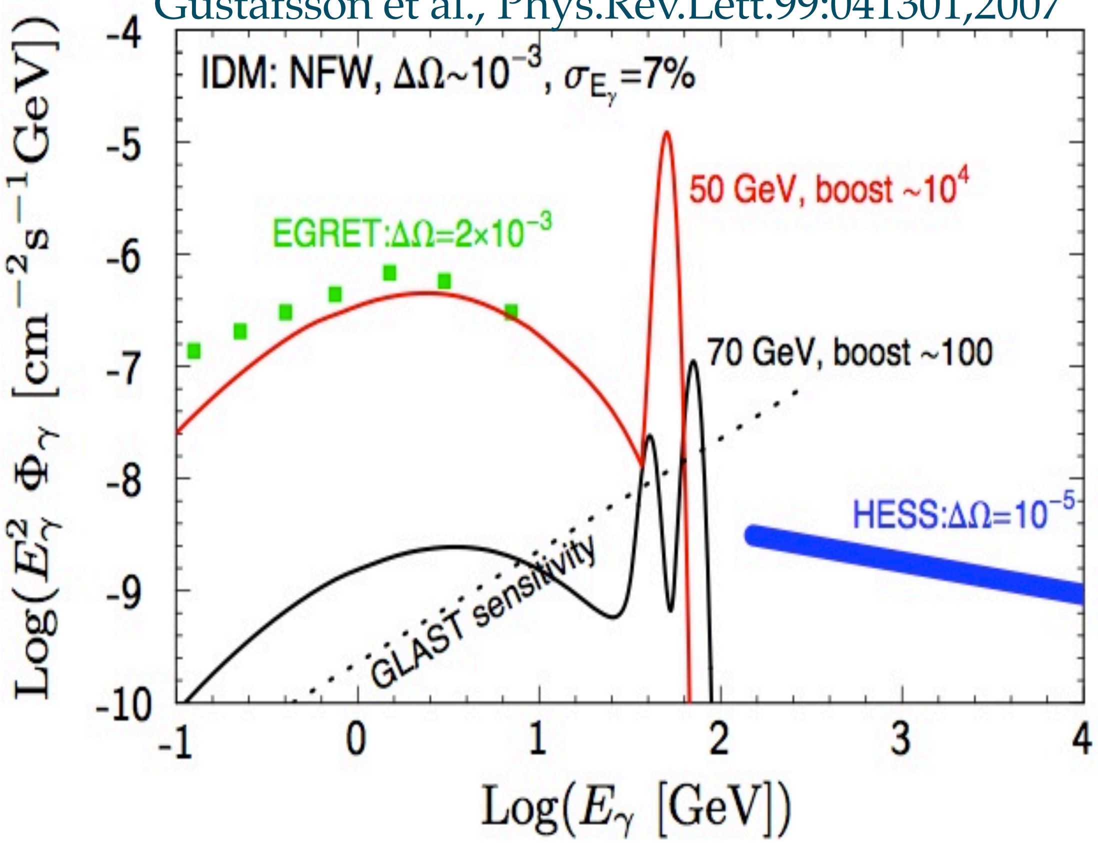
Fermi line Analysis

Unibinned profile likelihood analysis, with background determined from data

Region of interest b>10 and 20x20 deg around GC, sources removed for b>10, energy range 20 -200 GeV.

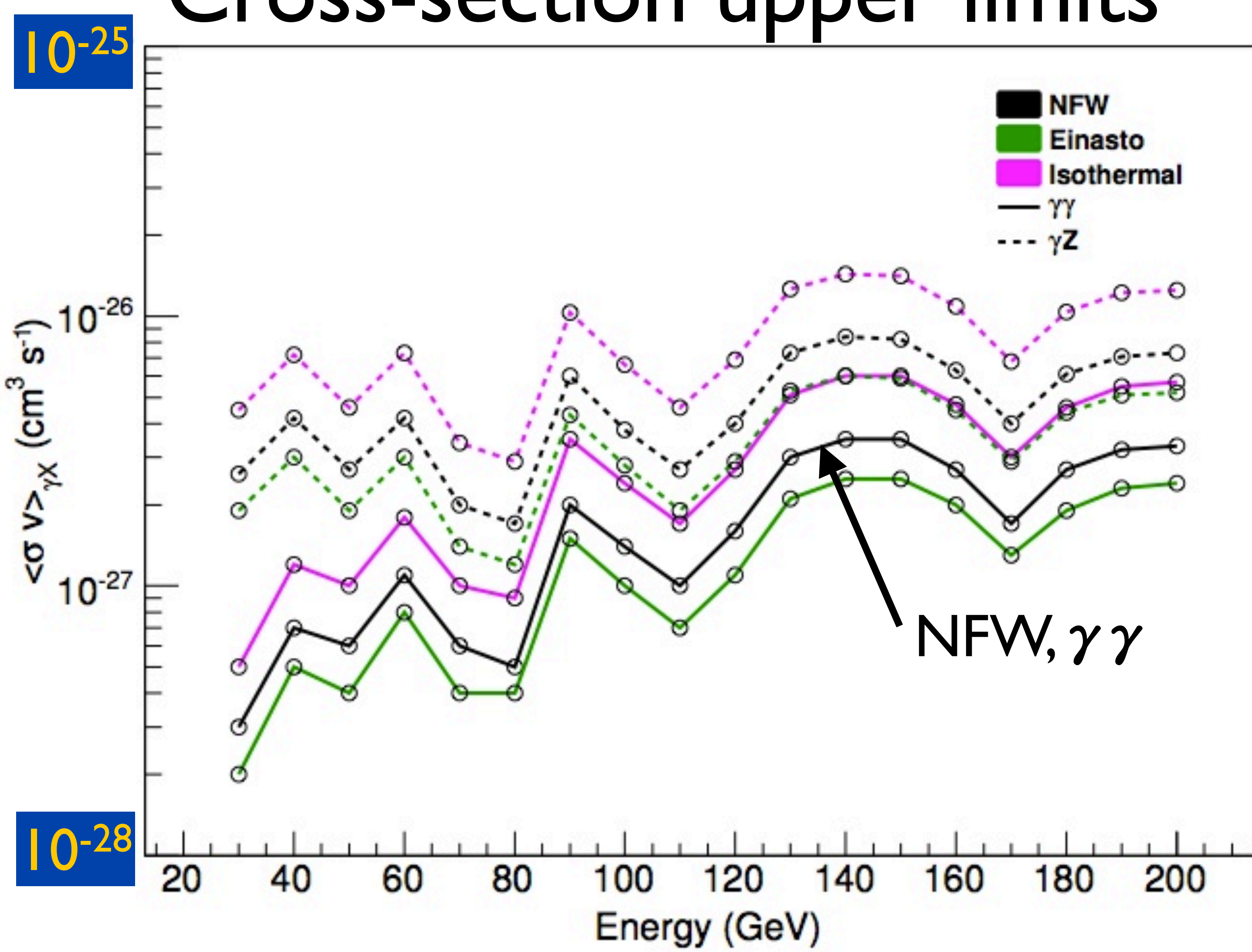


Gustafsson et al., Phys.Rev.Lett.99:041301,2007



Model	$v\sigma_{tot}^{v\to 0}$ [$\mathrm{cm^3 s^{-1}}$]	Branching ratios [%]: $\gamma\gamma$	$Z\gamma$	$b\bar{b}$	$c\bar{c}$	$\tau^+\tau^-$	$\Omega_{\rm CDM}h^2$
I	1.6×10^{-28}	36	33	26	2	3	0.10
II	8.2×10^{-29}	29	0.6	60	4	7	0.10

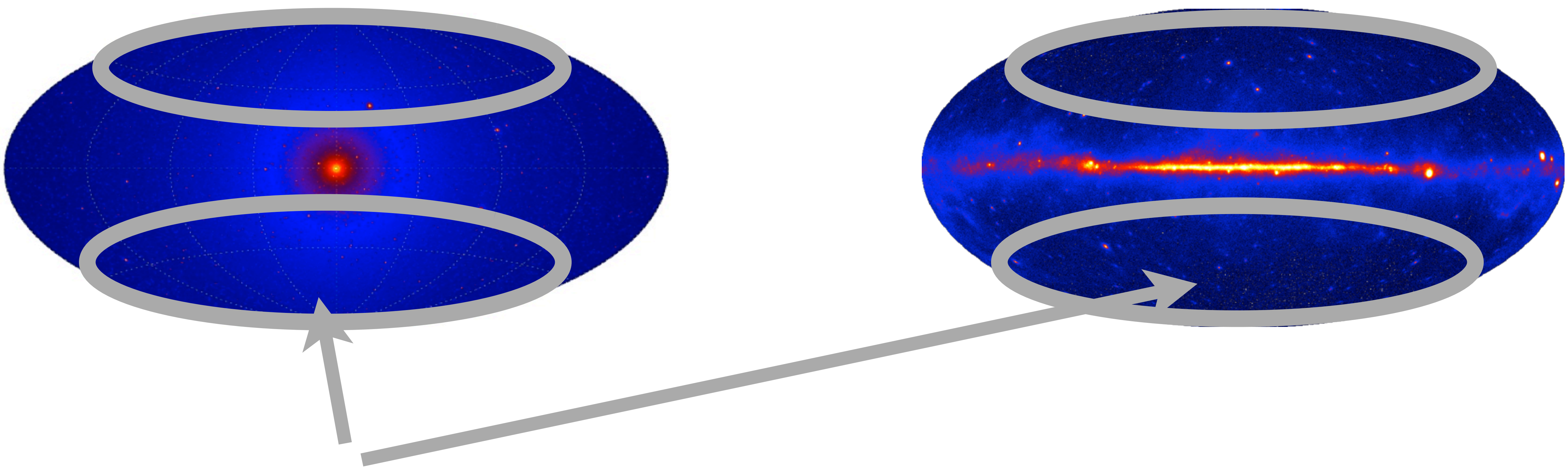
Cross-section upper limits



Fermi-LAT: Phys.Rev.Lett.104:091302,2010

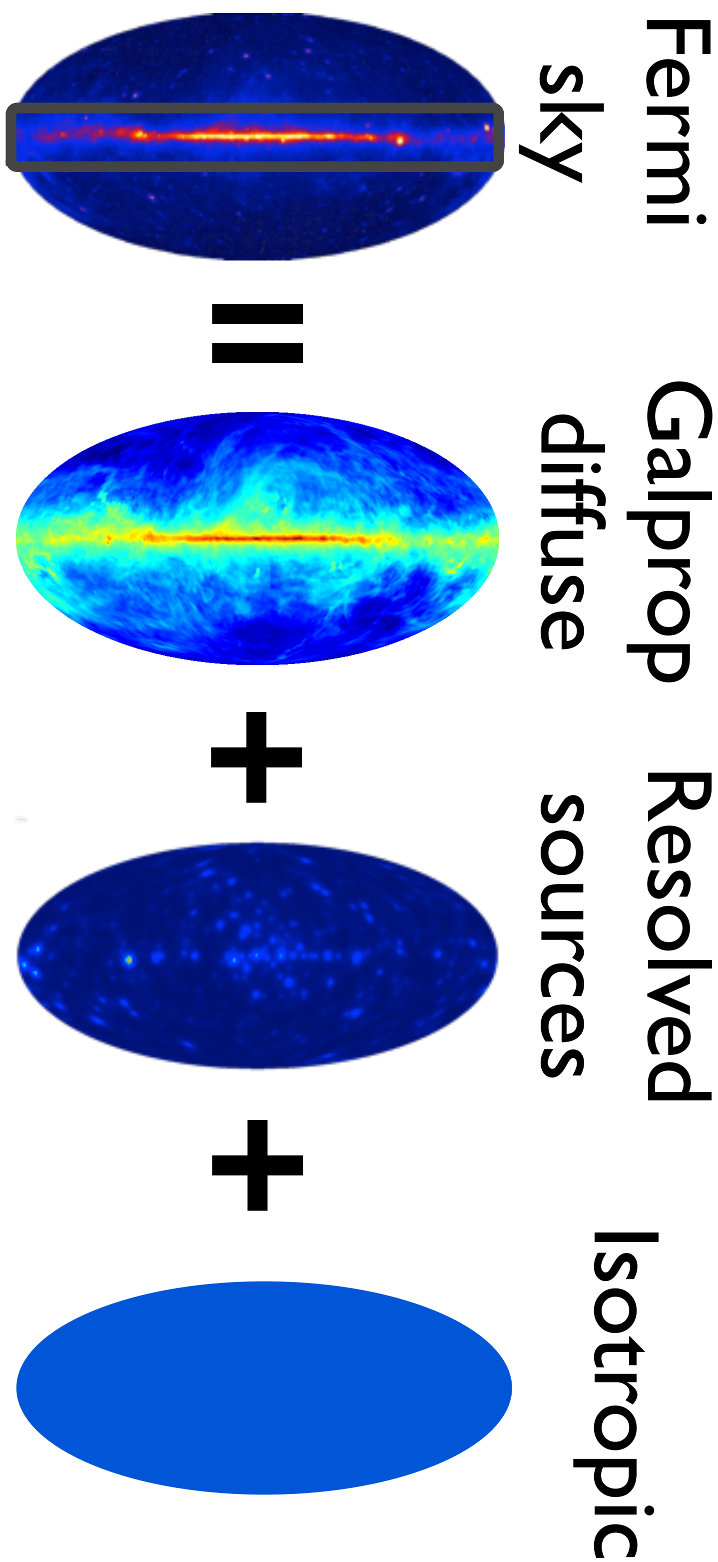
Cold dark matter
(Via Lactea)

Observation
(Fermi-LAT)



Isotropic diffuse
= ‘Extragalactic’

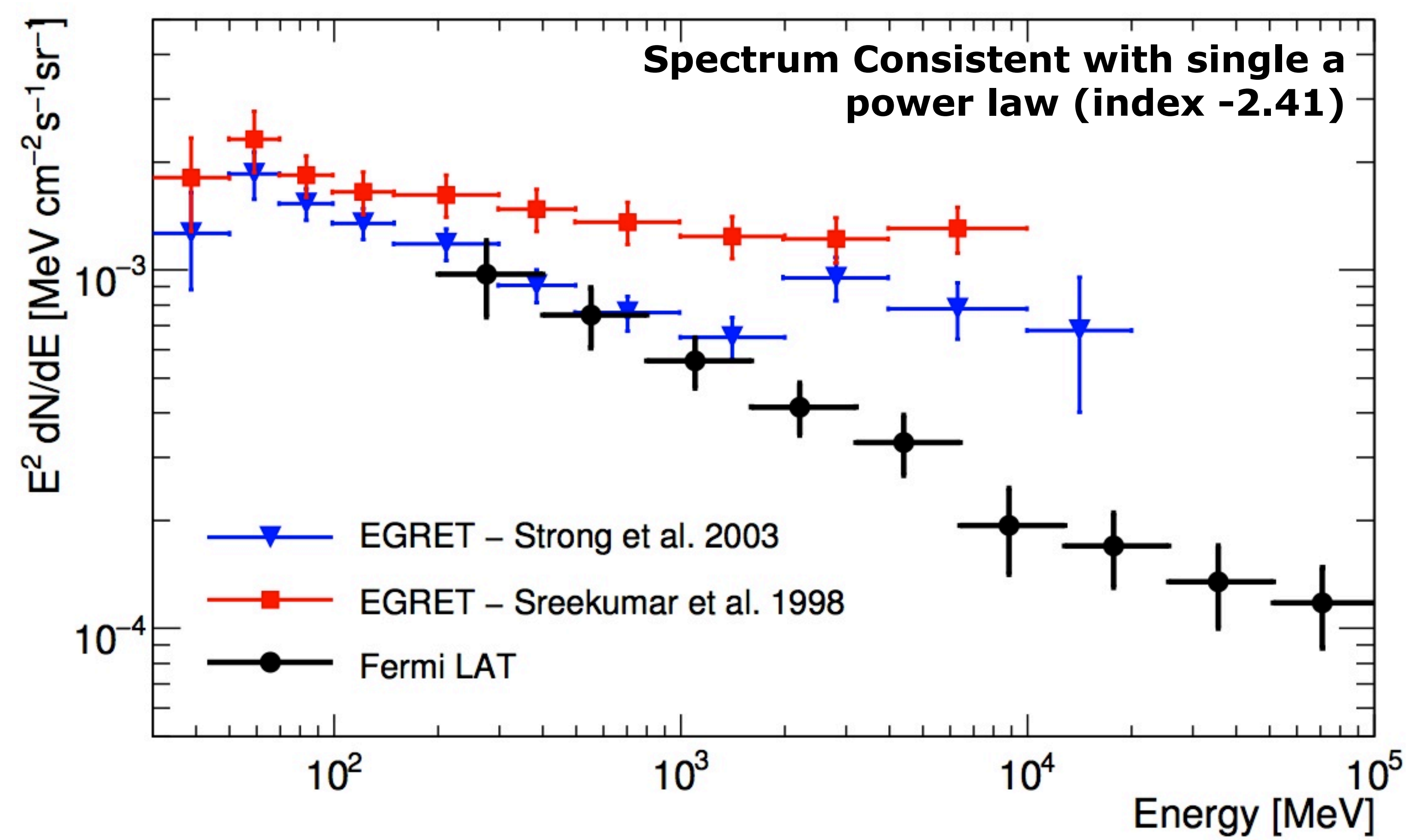
ISOTROPIC DIFFUSE MEASUREMENT



Infer the isotropic gamma-ray emission by multi-component fit to Fermi-LAT gamma-ray data

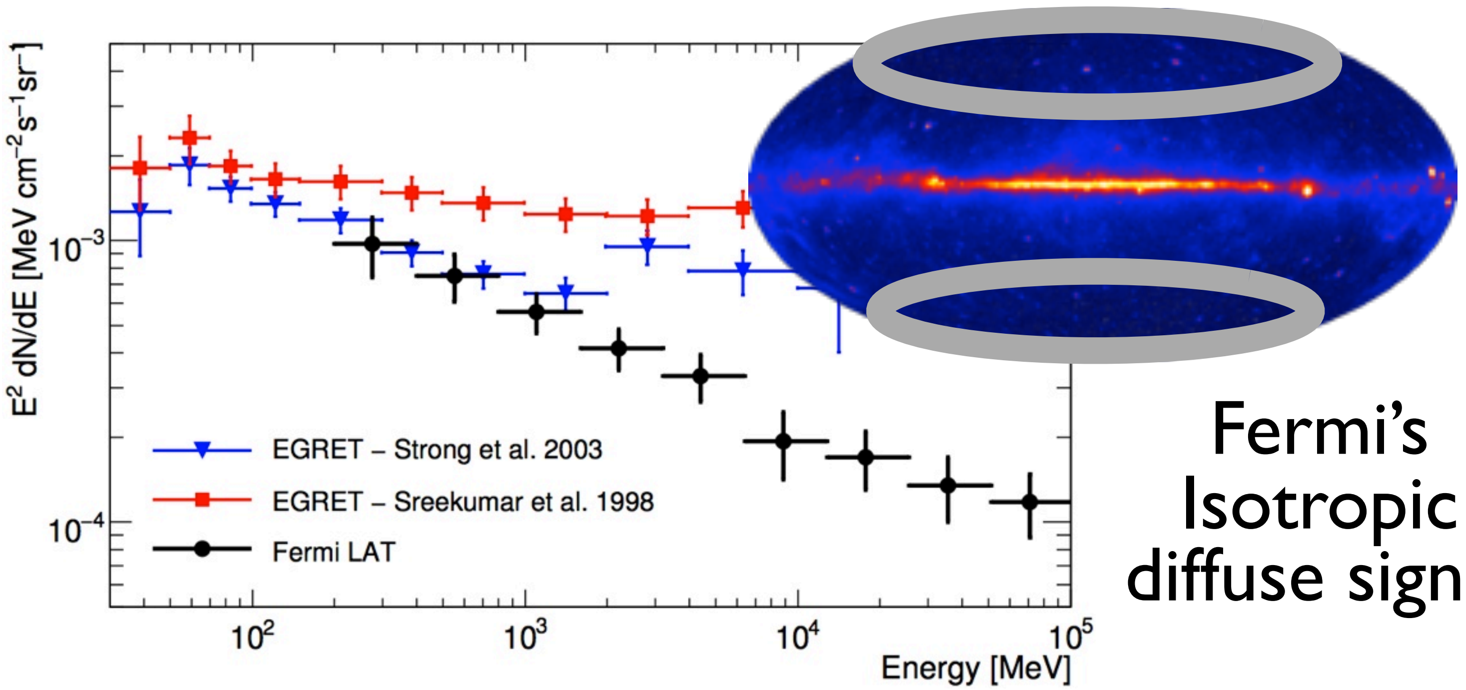
(Pixel by pixel ~1 deg^2 likelihood fit of sky |b|>10° for each energy bin, including residual cosmic-rays)

Fermi-LAT: Phys.Rev.Lett.104:101101,2010



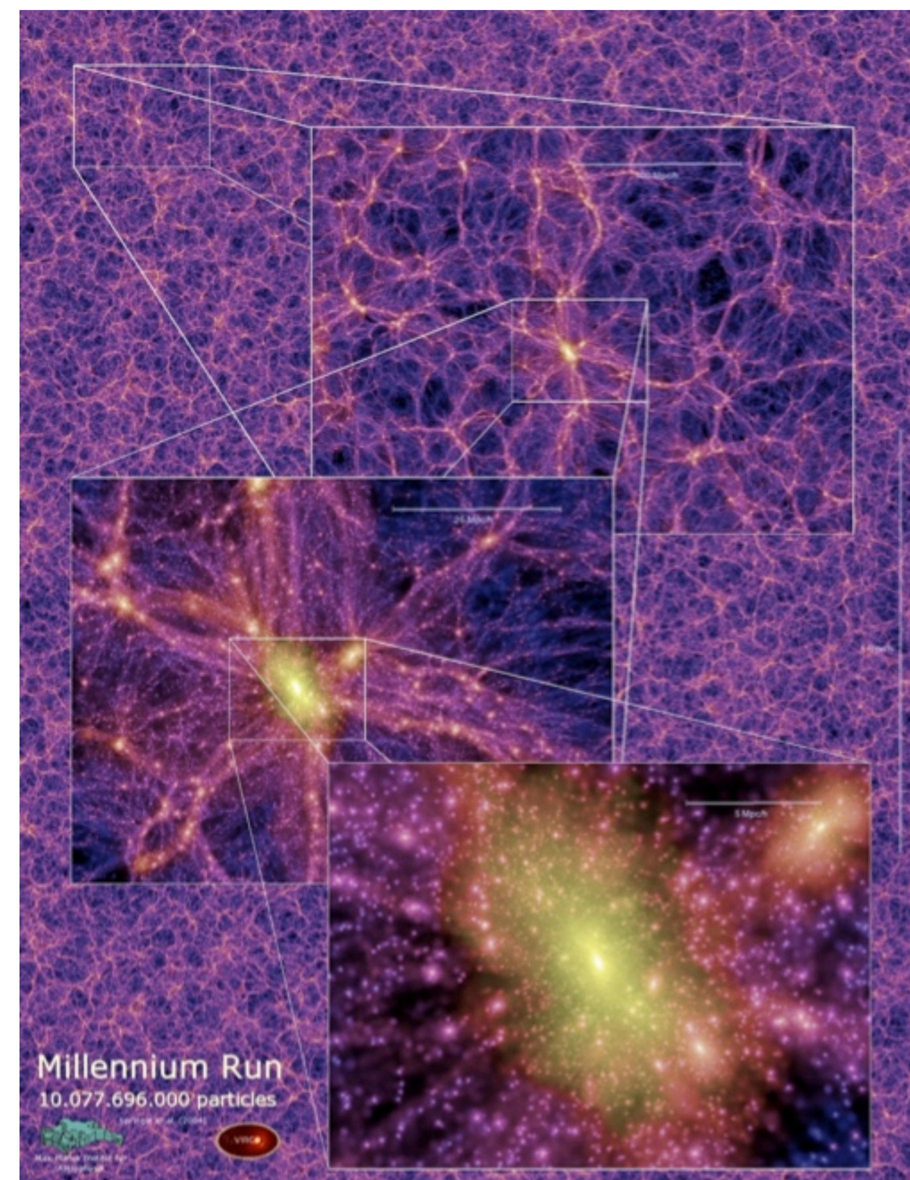
ISOTROPIC DIFFUSE SIGNAL

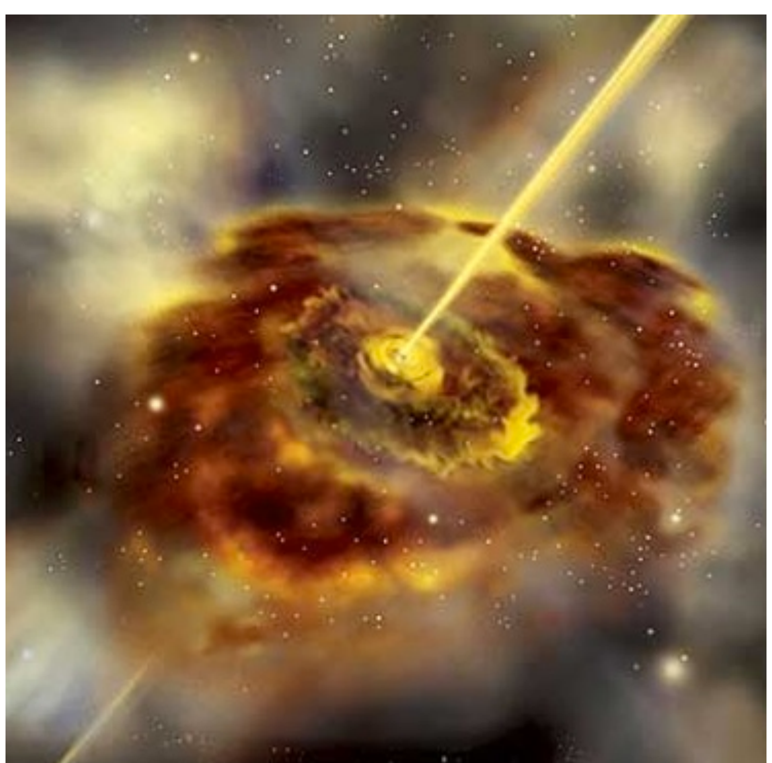
What can give a GeV extragalactic signal?



Fermi's Isotropic diffuse signal

Dark matter in all halos at all red-shift should contribute too





Guarantied *contribution from unresolved sources: blazars, star forming galaxies and cluster shocks …*

Cosmological Dark Matter Signal

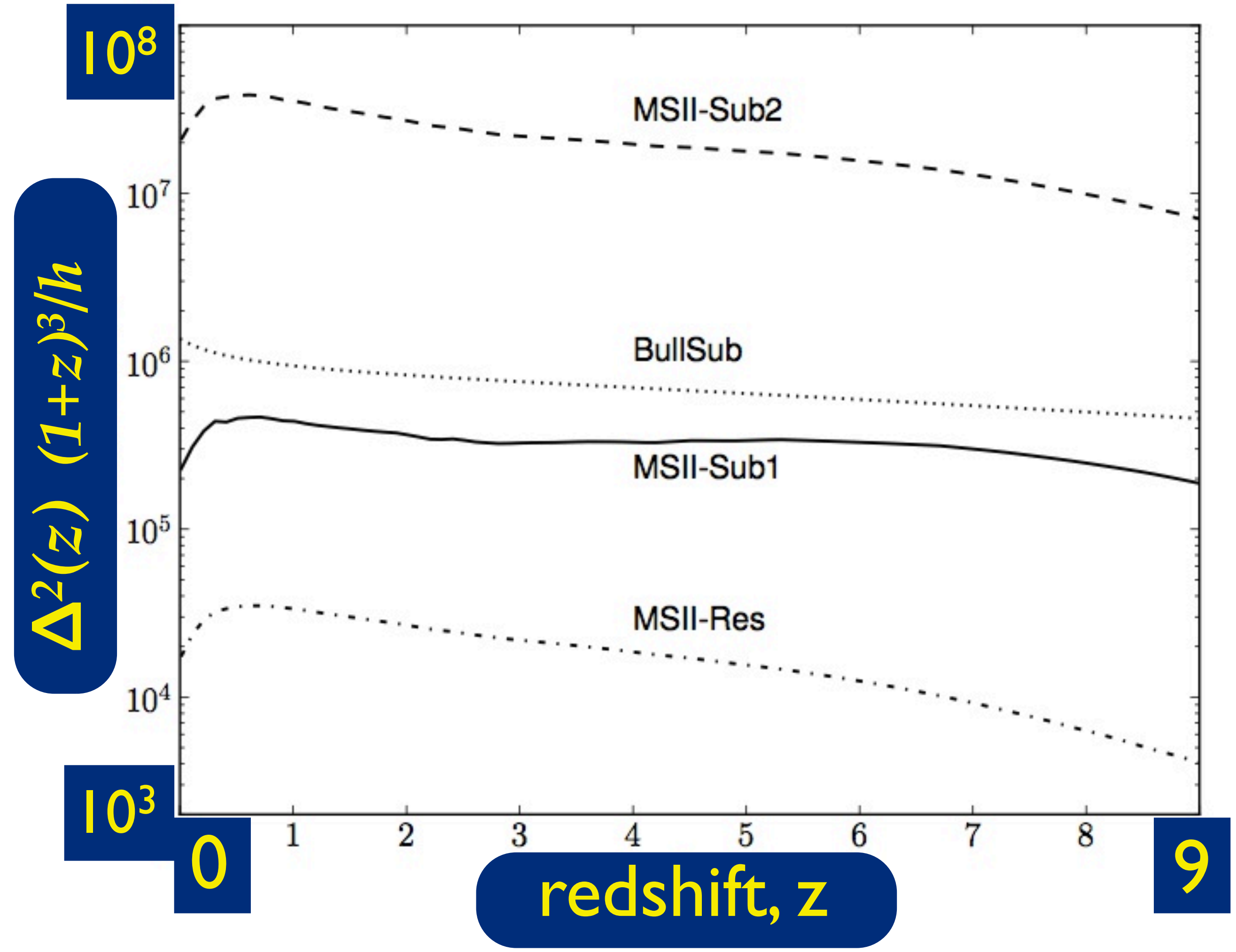
***DM forms structures by gravitational collapse, and in those over-dense regions the DM self-annihilation signal is greatly enhanced** (ρ^2).*

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

★ *STRUCTURE ENHANCEMENT $\Delta^2(z)$*

Two approaches to determine Δ^2:

Fermi-LAT collaboration, JCAP 1004:014,2010



Cosmological Dark Matter Signal

DM forms structures by gravitational collapse, and in those over-dense regions the DM self-annihilation signal is greatly enhanced (ρ^2).

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

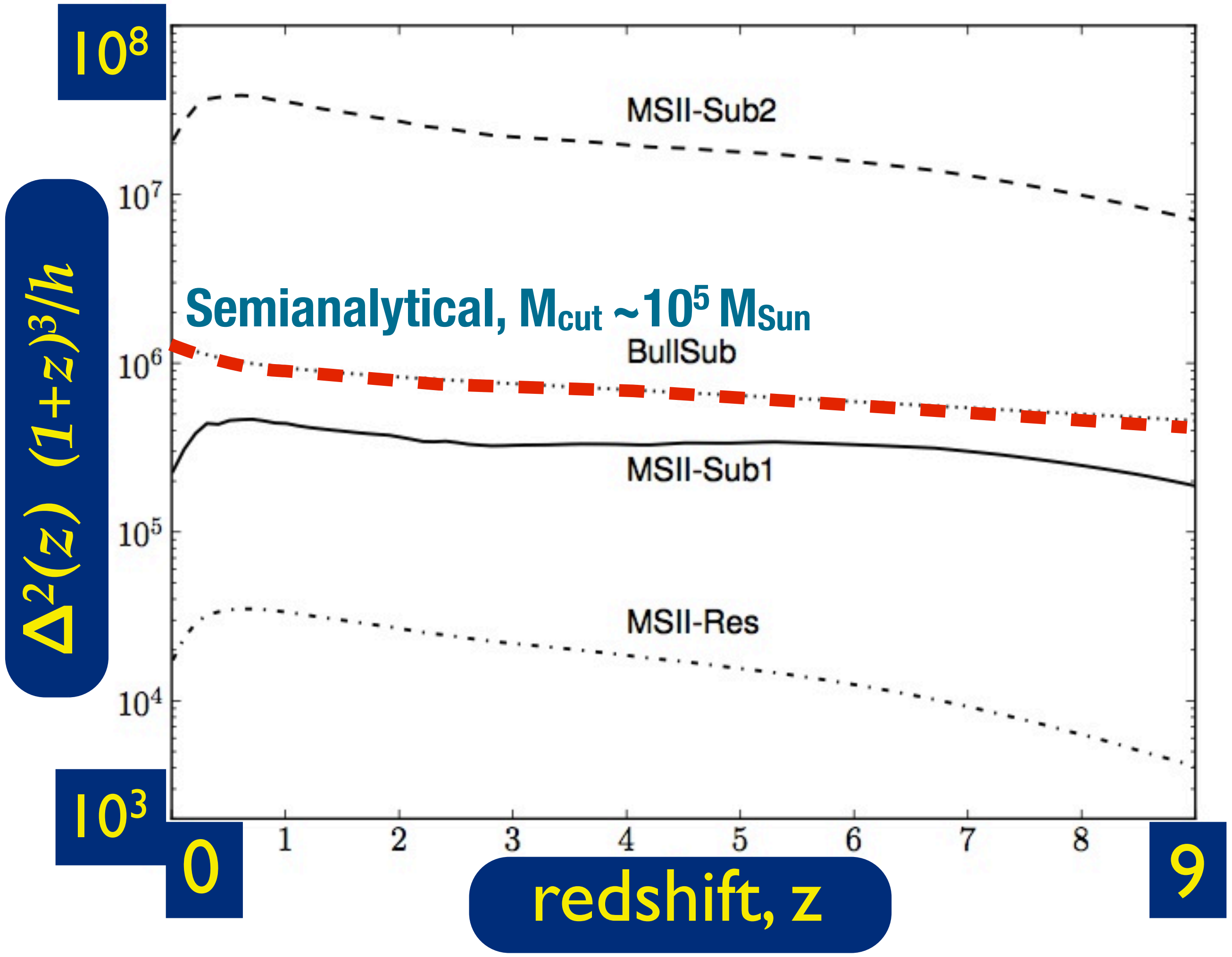
★ *STRUCTURE ENHANCEMENT $\Delta^2(z)$*

Two approaches to determine Δ^2:

★ ***Semi-analytic approach:* *halo mass function normalization from a Virgo simulation AND a mass-concentration toy-model by Blumenthal et al.***

[Ullio et al. 2002]

Fermi-LAT collaboration, JCAP 1004:014,2010



Cosmological Dark Matter Signal

DM forms structures by gravitational collapse, and in those over-dense regions the DM self-annihilation signal is greatly enhanced (ρ^2).

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

★ *STRUCTURE ENHANCEMENT* $\Delta^2(z)$

Two approaches to determine Δ^2:

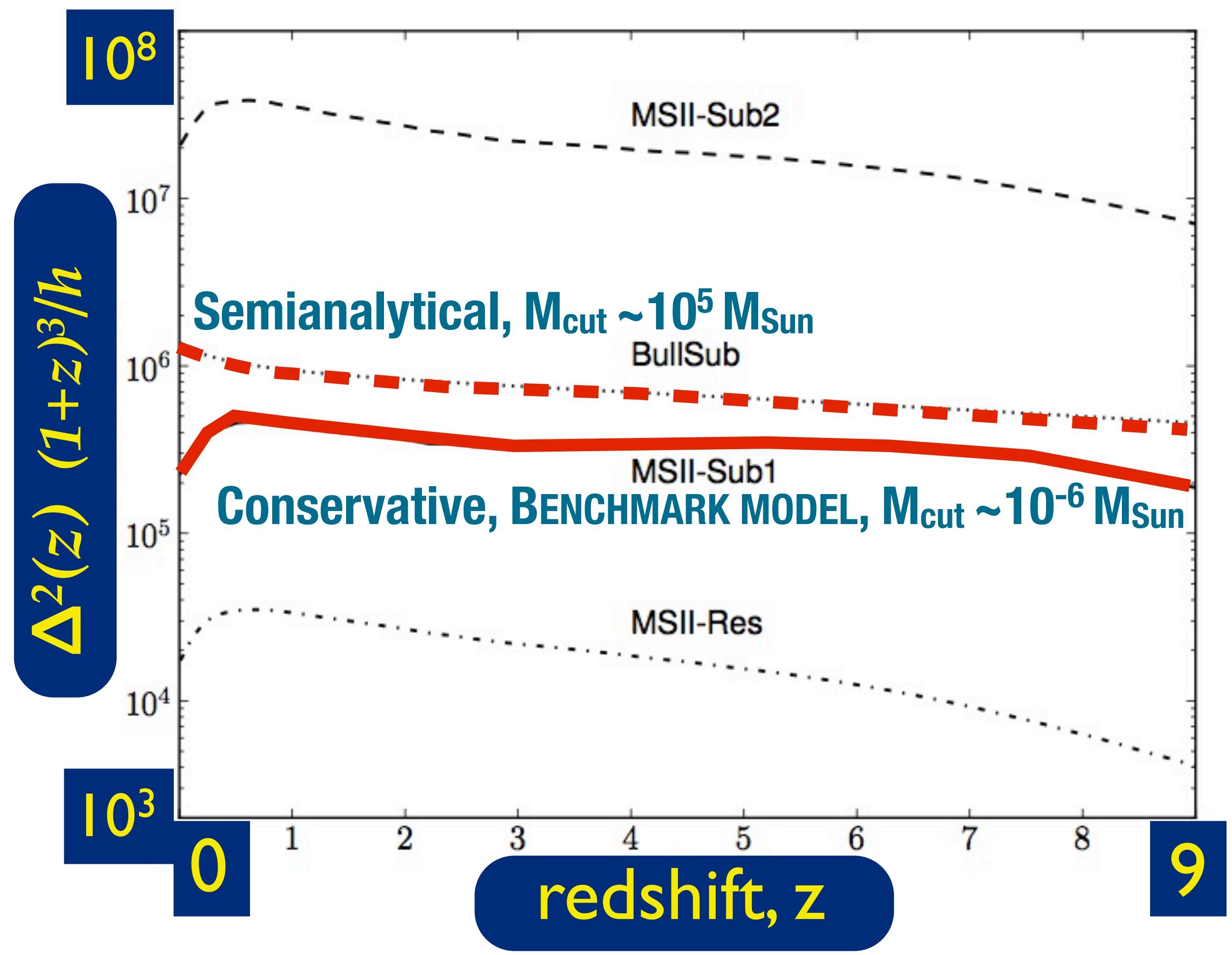
★ ***Semi-analytic approach:** halo mass function normalization from a Virgo simulation AND a mass-concentration toy-model by Blumenthal et al.*

[Ullio et al. 2002]

★ ***Results from Millennium Simulation II:** mass resolution* $10^8\,M_{Sun}$*, simple power law extrapolations of the luminosity vs halo mass - conservative/optimistic choices.*

[Zavala et al., 2009]

Fermi-LAT collaboration, JCAP 1004:014,2010



Cosmological Dark Matter Signal

*DM forms **structures** by gravitational collapse, and in those over-dense regions the **DM self-annihilation signal is greatly enhanced** (ρ^2).*

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

★ *STRUCTURE ENHANCEMENT $\Delta^2(z)$*

Two approaches to determine Δ^2:

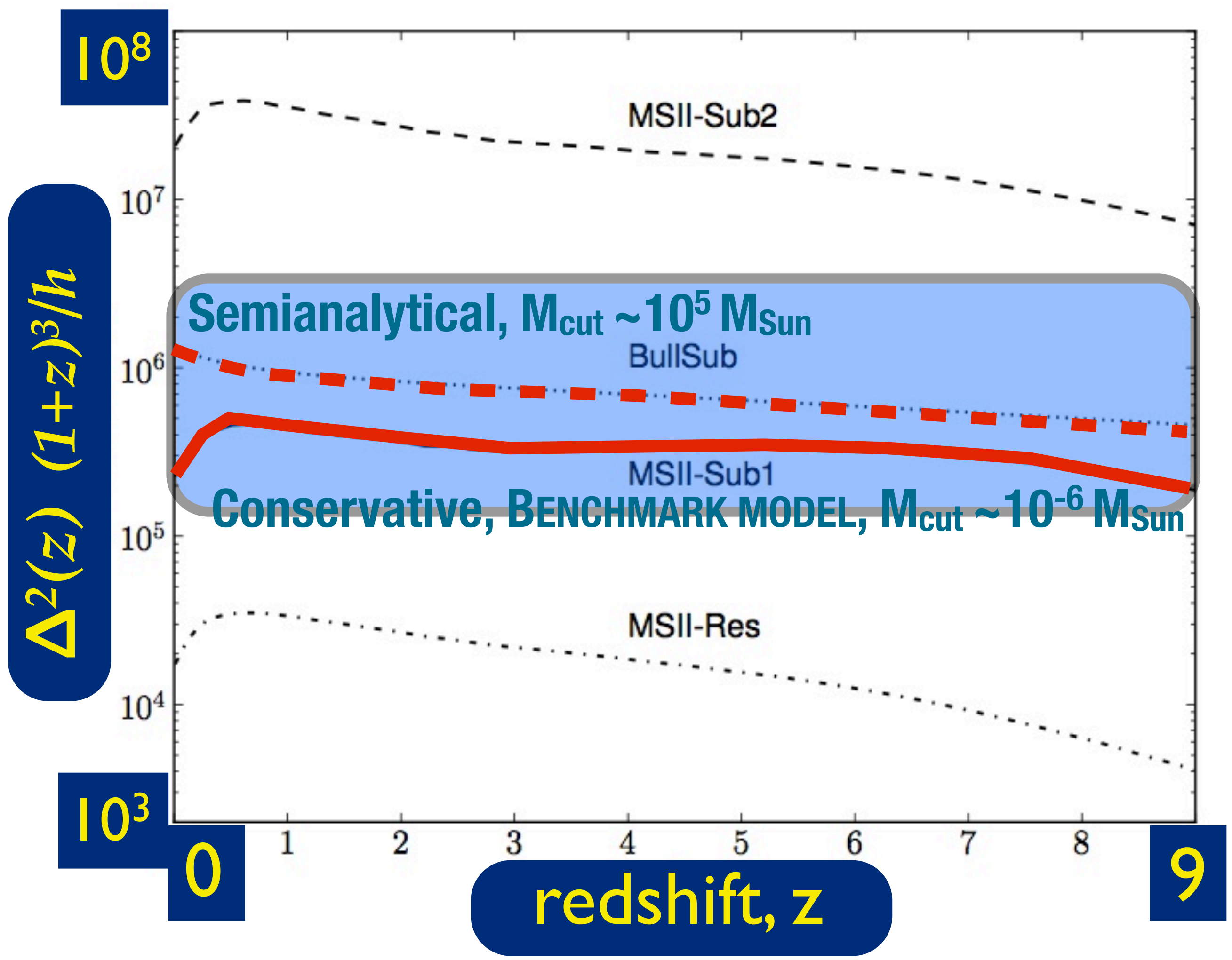
★ ***Semi-analytic approach:** halo mass function normalization from a Virgo simulation AND a **mass-concentration toy-model** by Blumenthal et al.*

[Ullio et al. 2002]

★ ***Results from Millennium Simulation II:** mass resolution 10^8 M_{Sun}, simple **power law extrapolations** of the luminosity vs halo mass - conservative/ optimistic choices.*

[Zavala et al., 2009]

Fermi-LAT collaboration, JCAP 1004:014,2010



Cosmological Dark Matter Signal

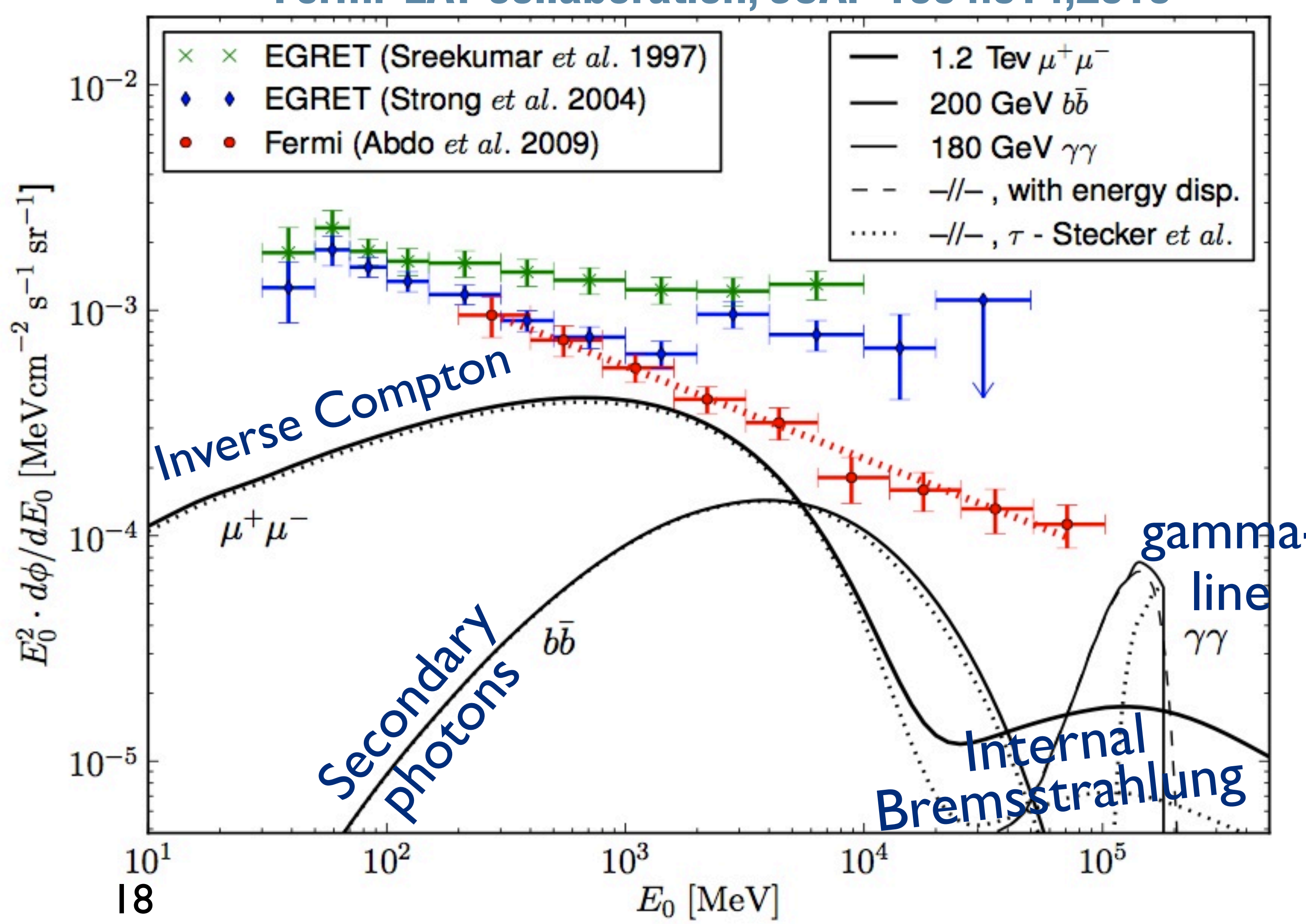
DM forms structures by gravitational collapse, and in those over-dense regions the DM self-annihilation signal is greatly enhanced (ρ^2).

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

★ *GAMMA-RAY SPECTRUM*

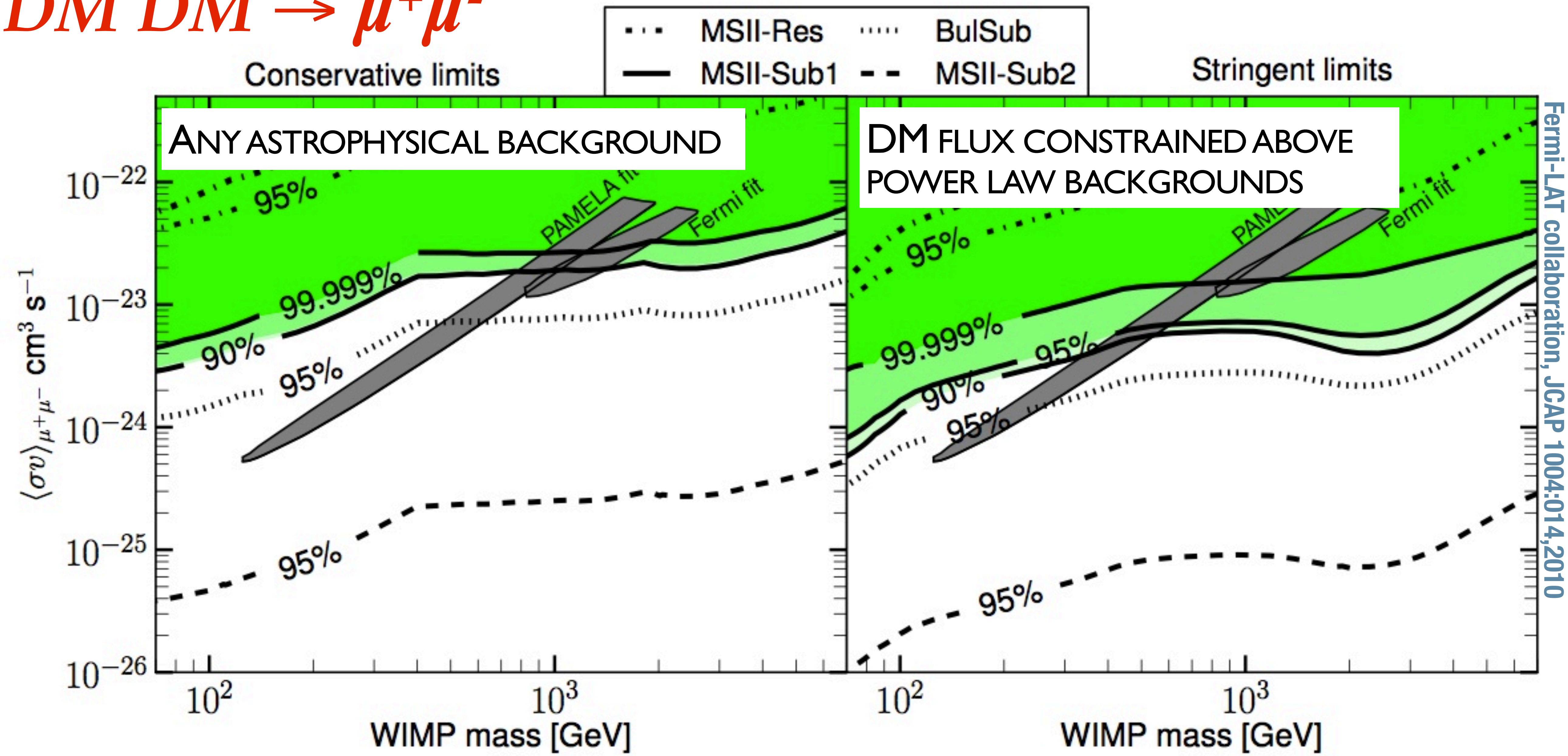
The measured spectrum at energy E_0 depends not only on particle physics, BUT due to red-shift entanglement also on the attenuation effects AND the DM halo formation history.

Fermi-LAT collaboration, JCAP 1004:014,2010



Cosmological DM constraints

DM DM → $\mu^+\mu^-$

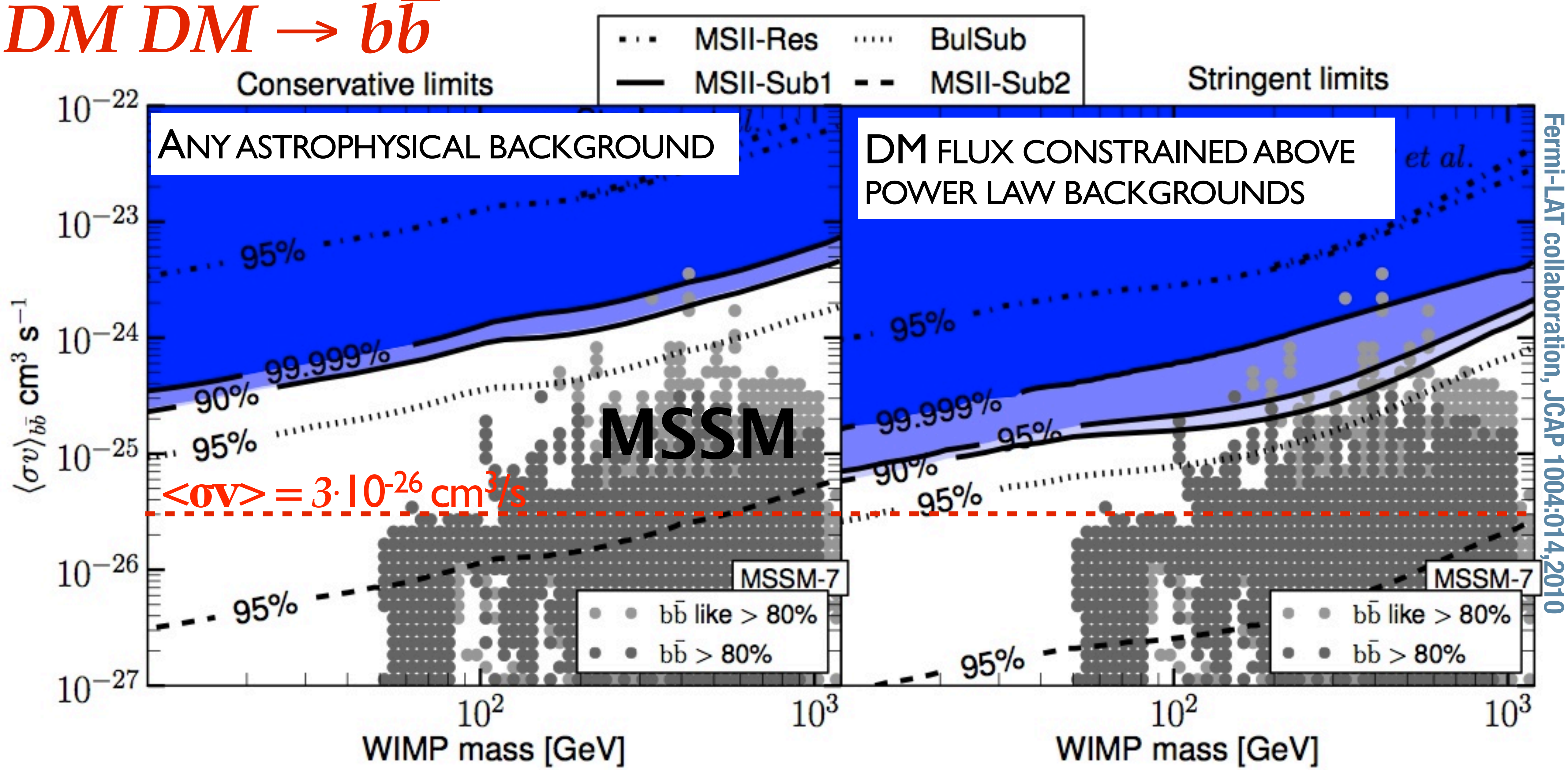


The cosmological DM signal has significant detection/constraining potential, but the total flux has uncertainties due to limitations in knowing the DM structure properties.

(spectral information could potentially also be used to disentangle DM galactic and extragalactic signatures).

Cosmological DM constraints

DM DM → $b\bar{b}$



The Fermi isotropic flux will get lower when Fermi continues to detect faint extragalactic sources. Increased number of detected sources will also lead to improved modeling of the extragalactic source populations (angular anisotropy studies important as well).
→ This will all lead to increased sensitivity for DM searches.

SUMMARY & OUTLOOK

★ *NO DARK MATTER DETECTION BY FERMI-LAT ⇒ CONSTRAINS ON DM*

★ *Many good sky-regions for DM searches:*

- Galactic center:	*Work in progress (Fermi)*
- Dwarf/clusters:	*Existing DM limits, upcoming stacking analysis*
- Unidentified sources:	*Work in progress (Fermi)*
- Extragalactic signal:	*Good potential, but not the most robust*
- Full sky diffuse analysis:	*talks by Gabrijela Zaharijas and Paolo Panci*

OVERALL:. Gamma-ray DM searches started to probe canonical WIMP cross sections $\langle\sigma v\rangle = few \cdot 10^{-26}\,\mathrm{cm^3/s}$ *for GeV mass DM particles. DM interpretations of the Pamela/Fermi cosmic-ray "excess" are uncomfortably with Fermi-LAT gamma-ray data.*

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