Fermi

Gamma-ray Space Telescope

Gamma-ray Observations and their Dark Matter Interpretations

Michael Gustafsson
Padova University
On behalf of the Fermi Collaboration

PPC 2011
@ CERN, June 14, 2011

I – Basics of Dark Matter Searches in Gamma-rays

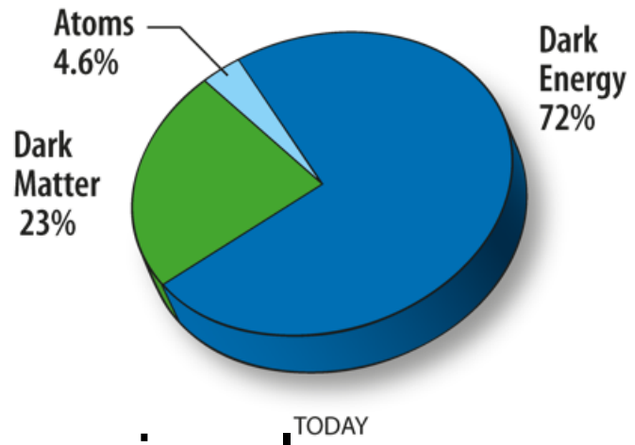
WIMPs

Spectra

Targets

WIMP Dark Matter properties

$$\Omega_{DM} = 0.233 \pm 0.0013$$ (in ΛCDM)



↳ **Beyond standard model physics needed!**

Two 'popular' DM scenarios that give gamma-ray signals:

Weakly
Interacting
Massive
Particle

DM particles with EW properties. Typical mass ~ 100 GeV and required DM relic density thermally produced with x-section:

$$\langle \sigma v \rangle_{\rm thermal} \sim 3 \times 10^{-26} {\rm cm}^3/{\rm s}$$

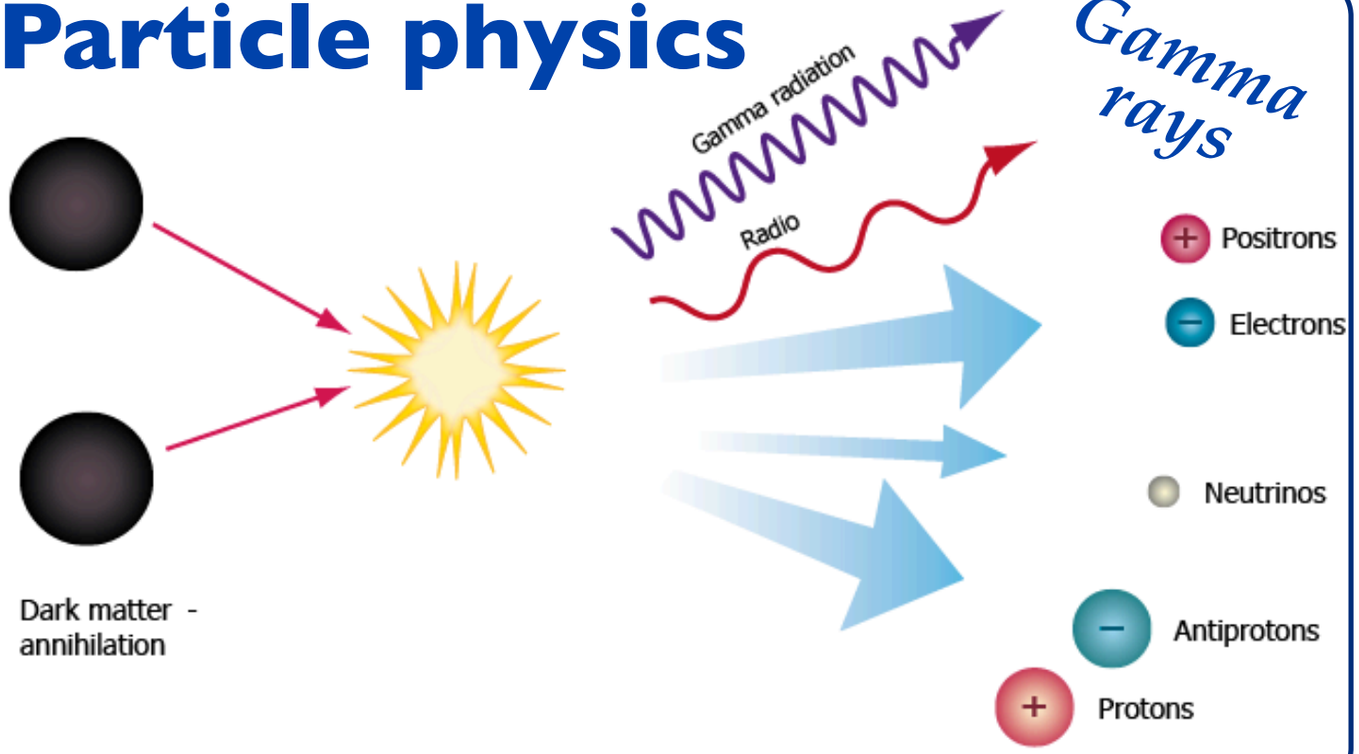
Lepto-**p**hilic dark matter

High annihilation/decay rates into leptons to fit the PAMELA/FERMI electron and positron observations: mass ~ 1 TeV, and an annihilation rate

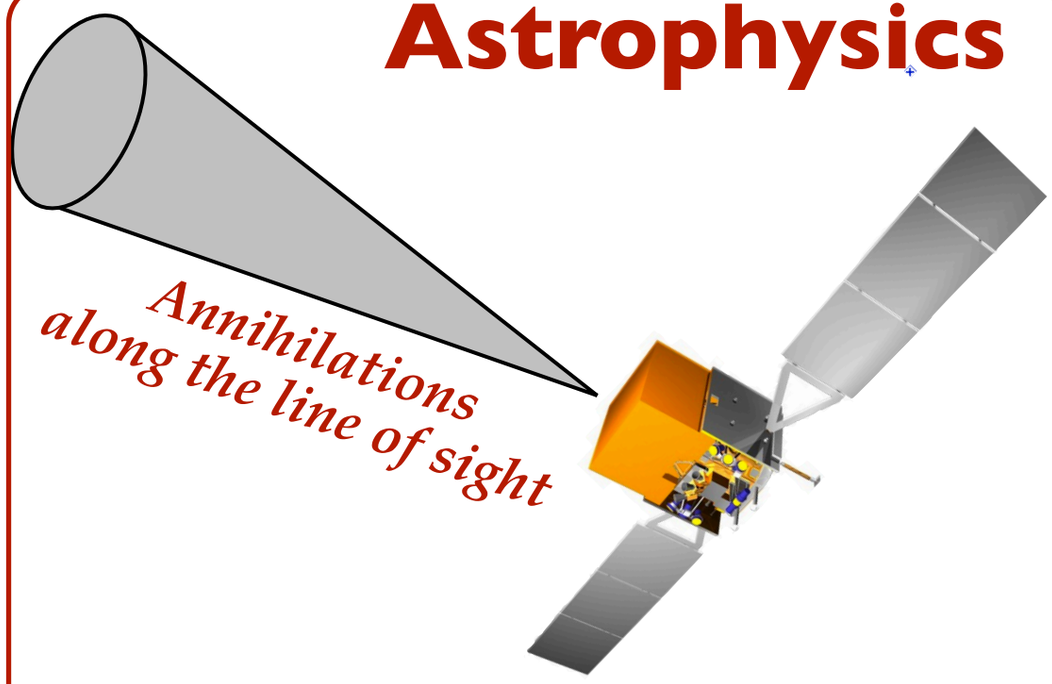
$$\langle \sigma v \rangle \sim 10^{-23} {\rm cm}^3/{\rm s}$$

A WIMP signal in gamma rays

Particle physics



Astrophysics



Prompt flux:

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

Advantages of gamma-ray: Simple propagation, signatures in **energy spectra** & **spatial distribution**

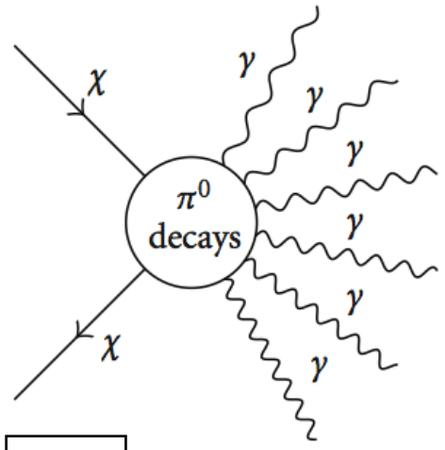
Energy Spectra

$$\frac{\langle\sigma v\rangle_{T_0}}{2\,M_\chi^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f$$

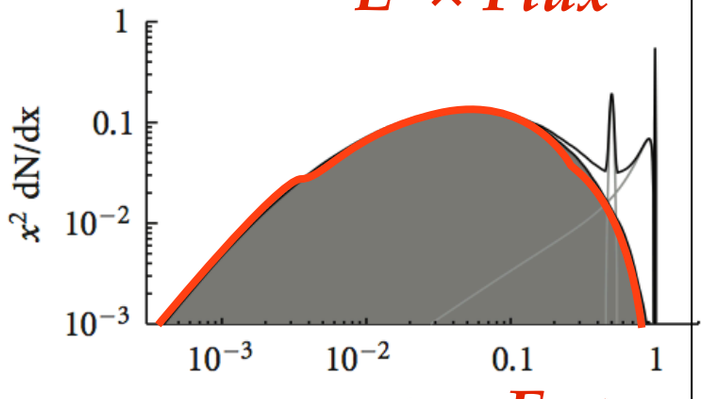
Particle physics

Secondary photons

Secondary photons (tree level)



'$E^2 \times$ Flux'

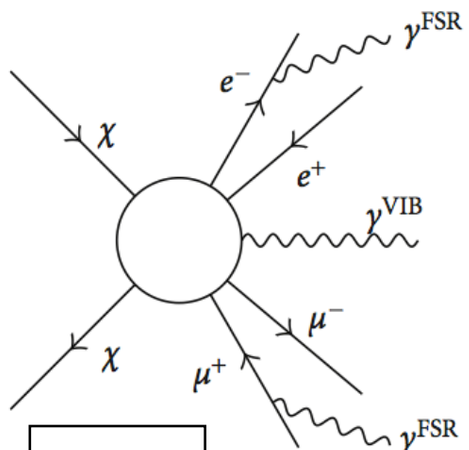


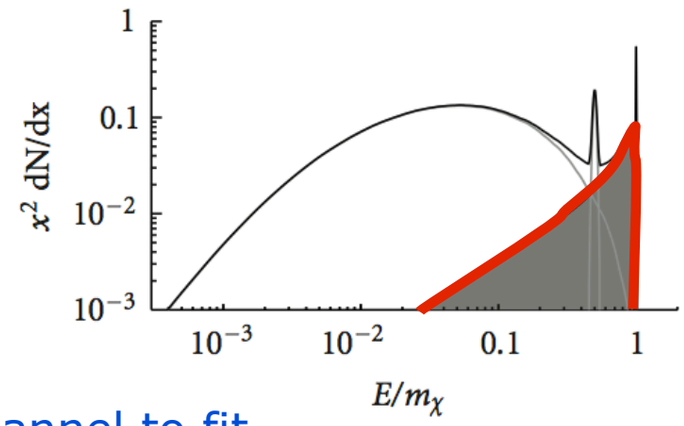
$E \rightarrow$

$b\bar{b}$ a proxy for hadronic channels (quarks and gauge bosons)

Internal Bremsstrahlung

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

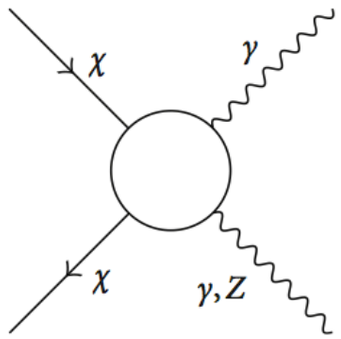


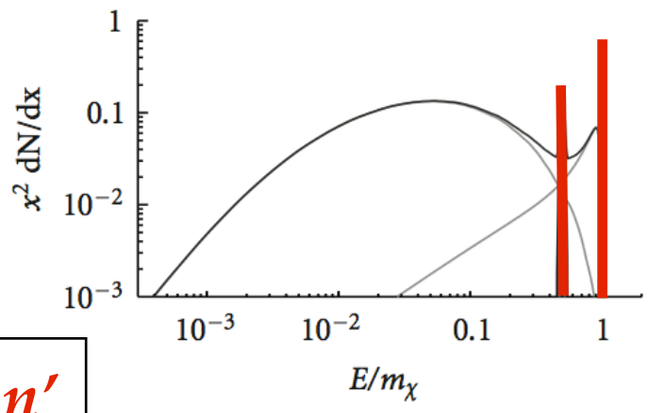


$\mu^+\mu^-$ typical channel to fit PAMELA/Fermi e^+ and e^- data

Monochromatic lines

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





DM 'smoking gun'

Radiative processes

e, μ

DM induced $e^\pm$ interacts with ambient background fields

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

ambient backgrounds and fields

- Synchrotron → radio
- Inv. Compton → IR, X-rays
- Bremstrahlung → X-rays, γs
- Coulomb
- Ionization

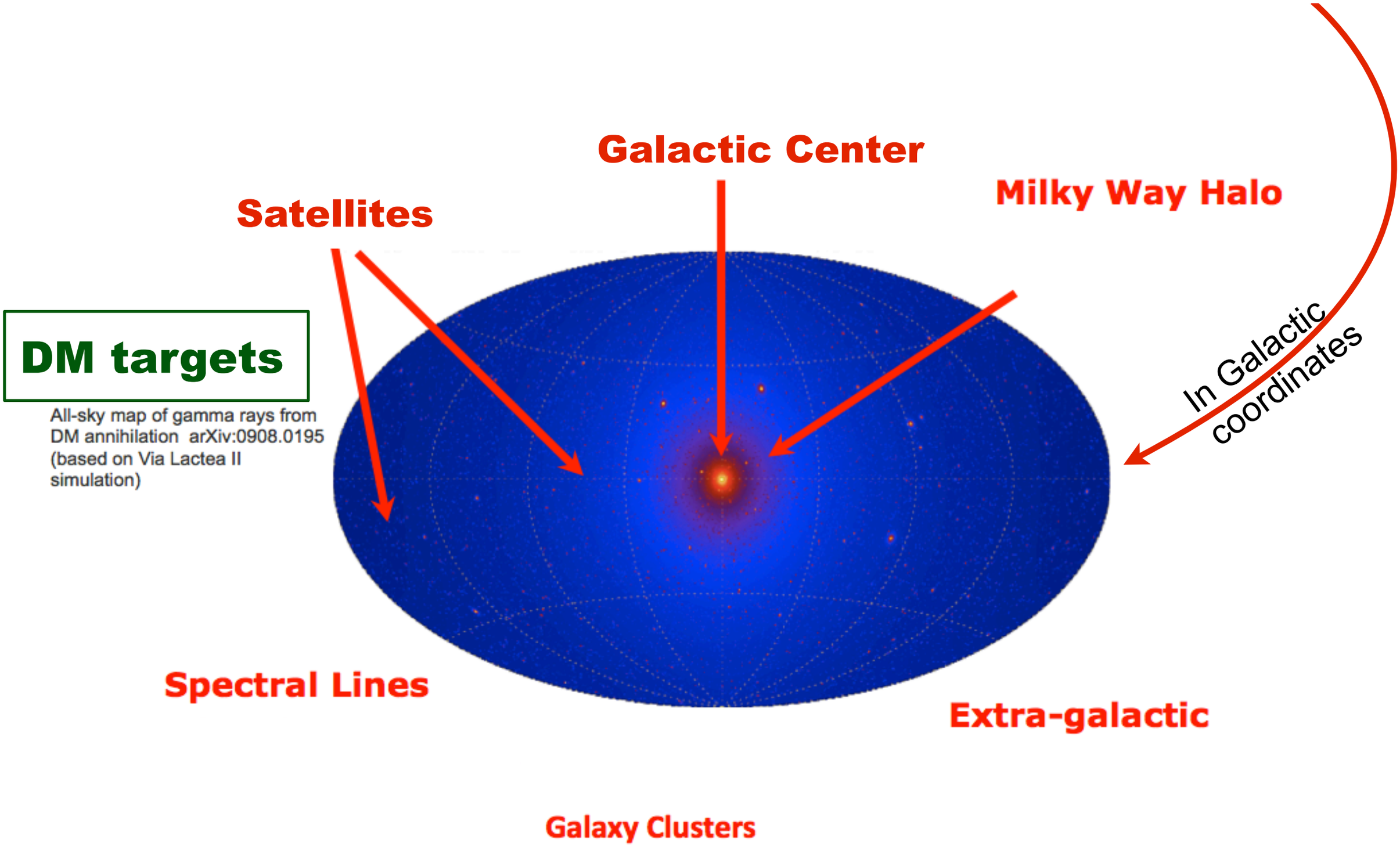
$e^\pm$ up-scattering bkg. light into γ-rays

Figures: Michael Kuhlen, Adv. in Astron. 2010,

DM γ-rays morphology

$$\int_{\Delta\Omega(\theta,\phi)} d\Omega' \int_{l.o.s.} dl\ \rho_\chi^2(l)$$

DM distribution



DM targets

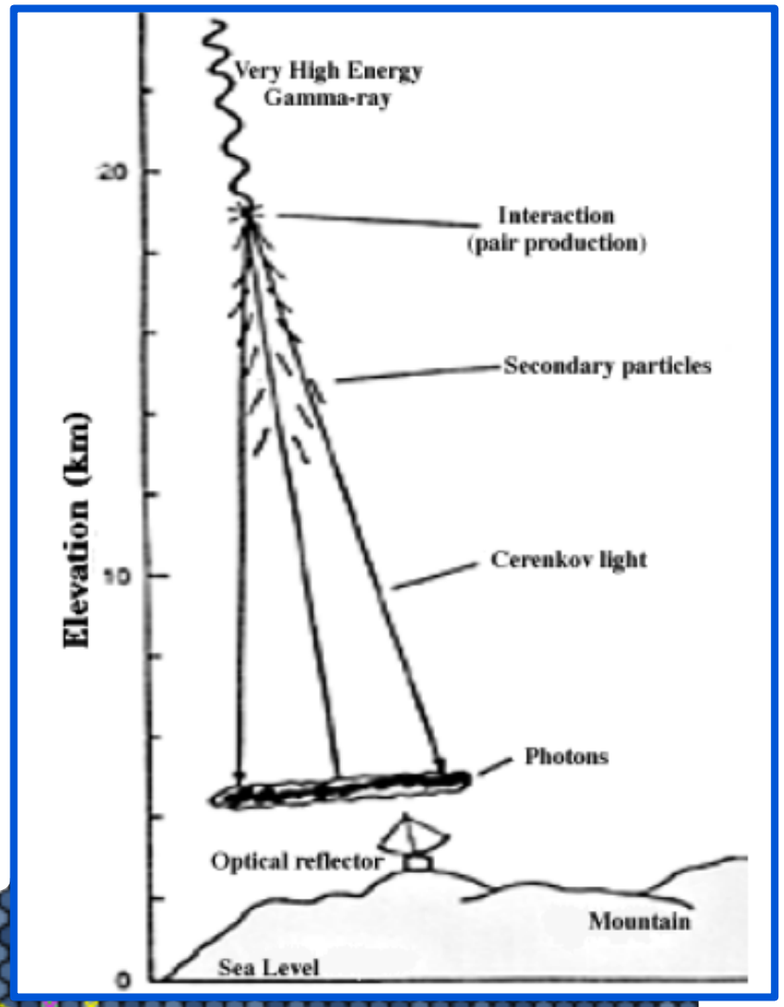
All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)

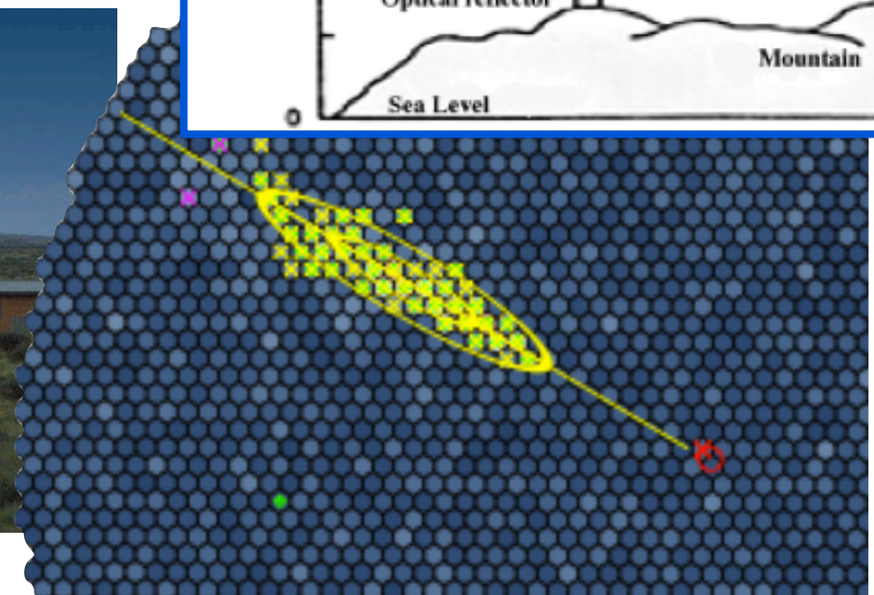
II – Gamma-rays from the ground

Air Cherenkov Telescopes (ACT)

- Wide mirror telescopes with atmosphere as calorimeter
  Shower topology to separates EM from hadronic signals.
  - ~ 10^4 m^2 effective area
  - ~ 0.1° angular resolution
  - ~ 100 GeV Energy threshold

- Limited field of view (few degrees), so duty cycle challenges
  - DM compete with astrophysical targets
  - Typical time for DM targets ~30 hrs

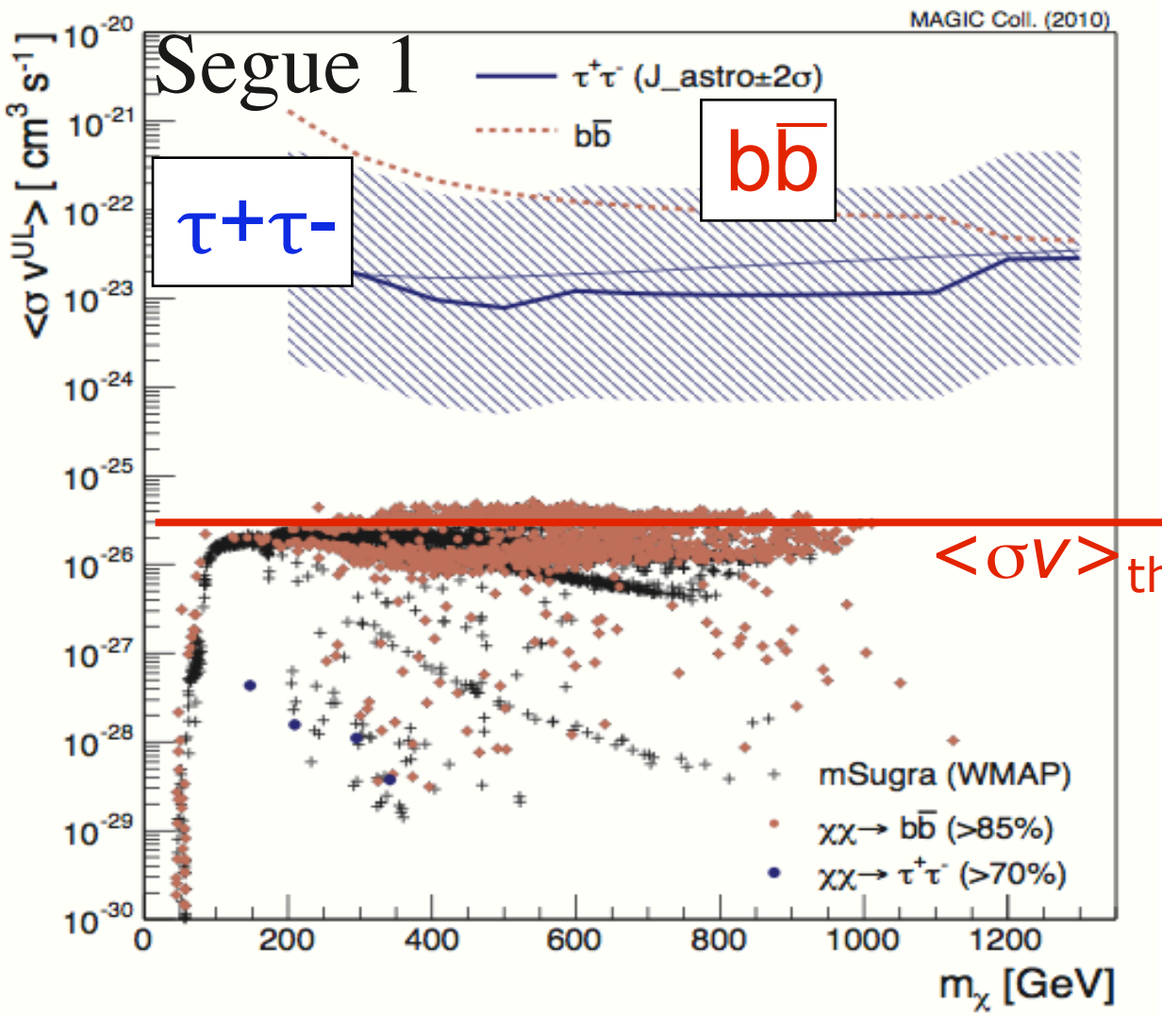




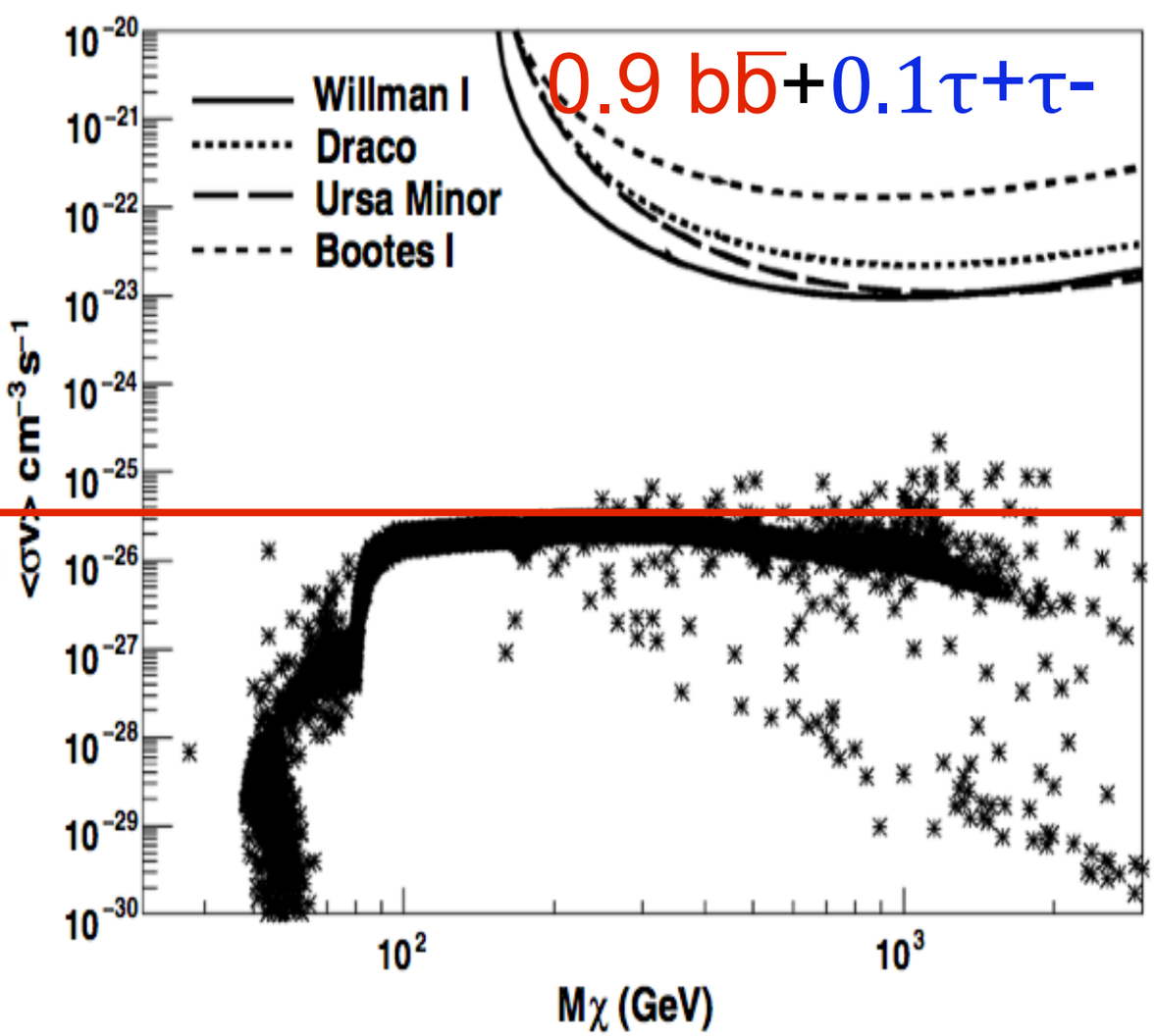
ACT – Pointing to Dwarf Galaxies

- No detection set upper limits on DM annihilation x-sections
  - Stellar kinematics to determine DM mass/profile
  - $\langle\sigma v\rangle$ less than $\sim[10^3\text{-}10^4]\times\langle\sigma v\rangle_{thermal}$

MAGIC (ArXiv 1103.0477)



VERITAS (ApJ 720, 2010)



$\langle\sigma v\rangle_{thermal}$

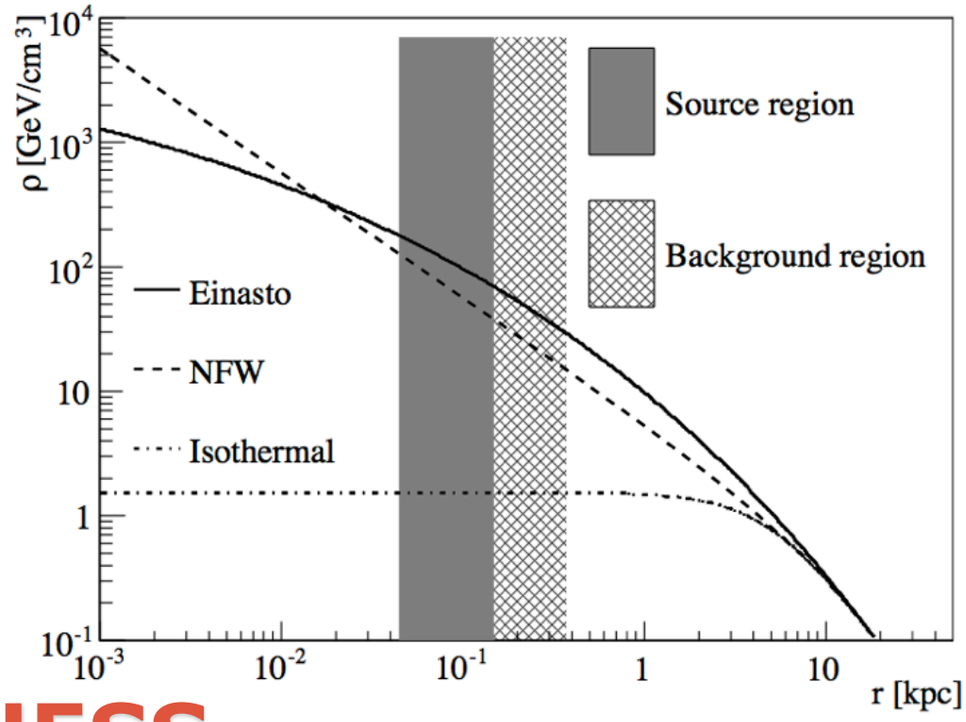
Observations of the Galactic Centre Region

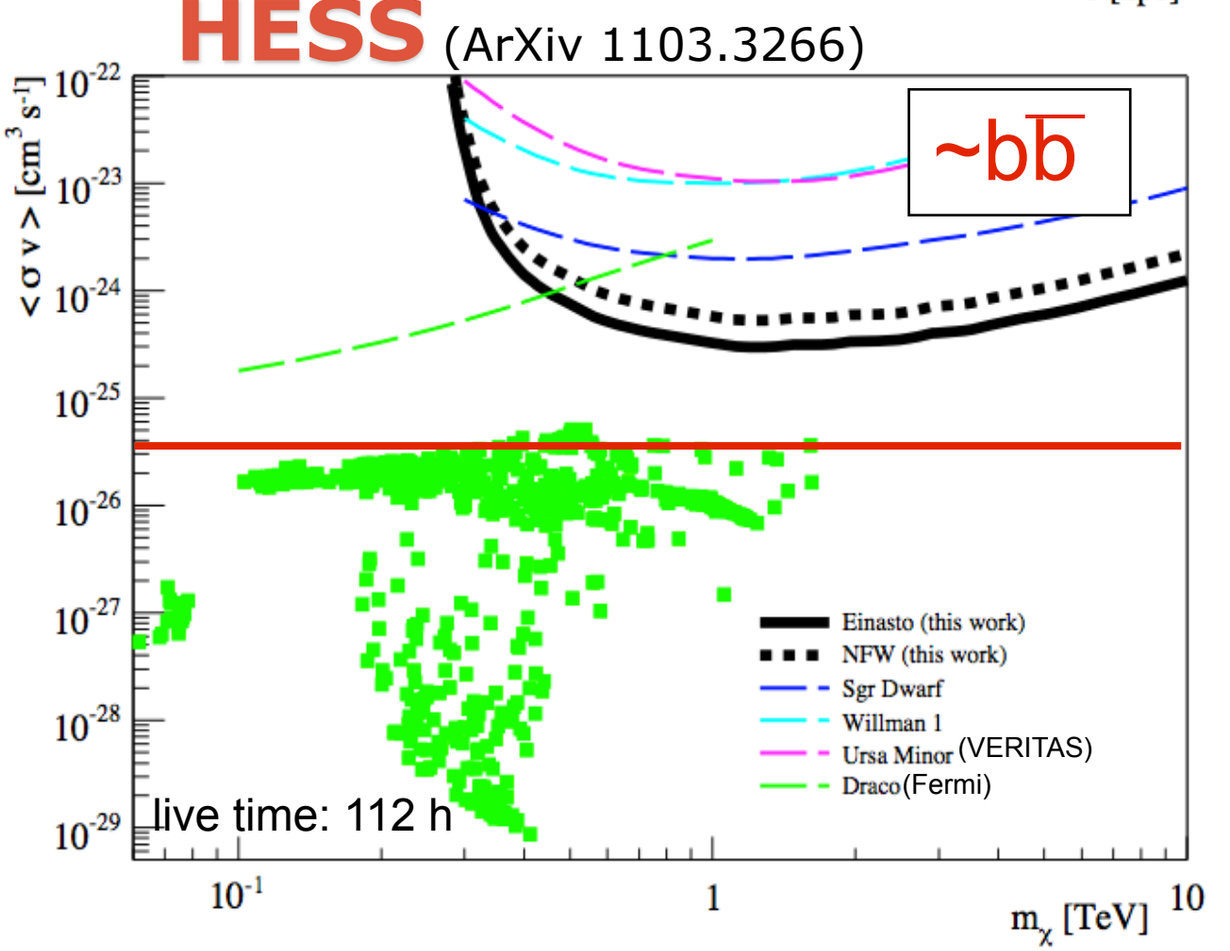
- **Galactic center analyses:**
  - ACT flux measurements require definition of Source and Bkg. regions:

$$\text{Signal} = S_{\text{DM}} - B_{\text{DM}}$$
$$= S_{\text{obs.}} - B_{\text{obs.}}$$

  - HESS constraints:
    ~$O(10)$ × $\langle\sigma v\rangle_{\text{thermal}}$
    Insensitive to cored DM density profiles

Significant improvement could come from CTA
(×10 sensitivity, energy range ~0.01-100 TeV [1008.3703])



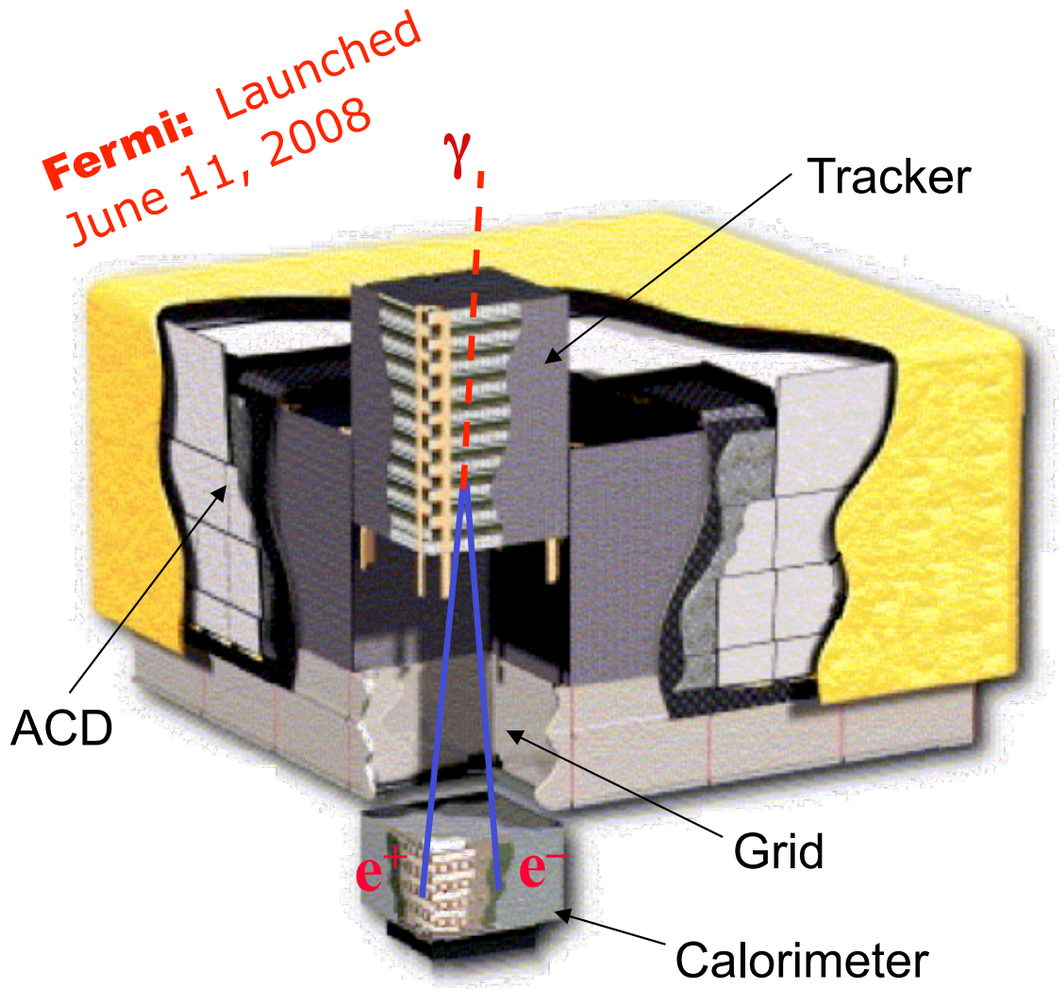


III – Gamma-rays from space

Fermi - Large Area Telescope

❑ Key features in DM searches

- ~0.8 m^2 peak effective area
- Energy range and resolution
  - ~20 MeV – >300 GeV with $7\% < \sigma_E < 15\%$
- <0.2° angular resolution at energies >10 GeV
  - From point sources to full-sky diffuse emission
- Full-sky coverage
  - All targets at same time
    - all sky in 2 orbits (3 hrs)
    - No competition in observing time
  - 3 years in space, 5 years minimum lifetime, 10 planned.

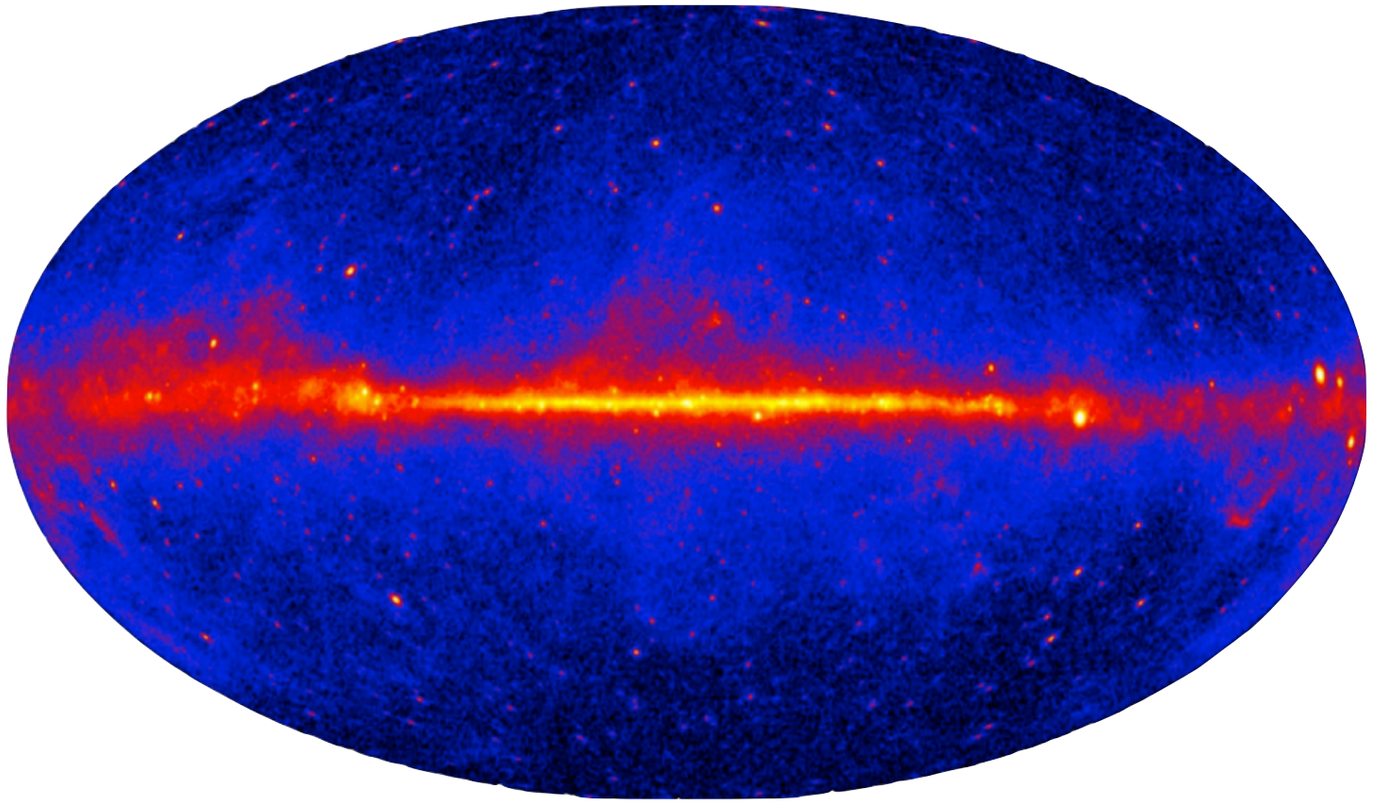


γ-ray sky

Fermi all-sky

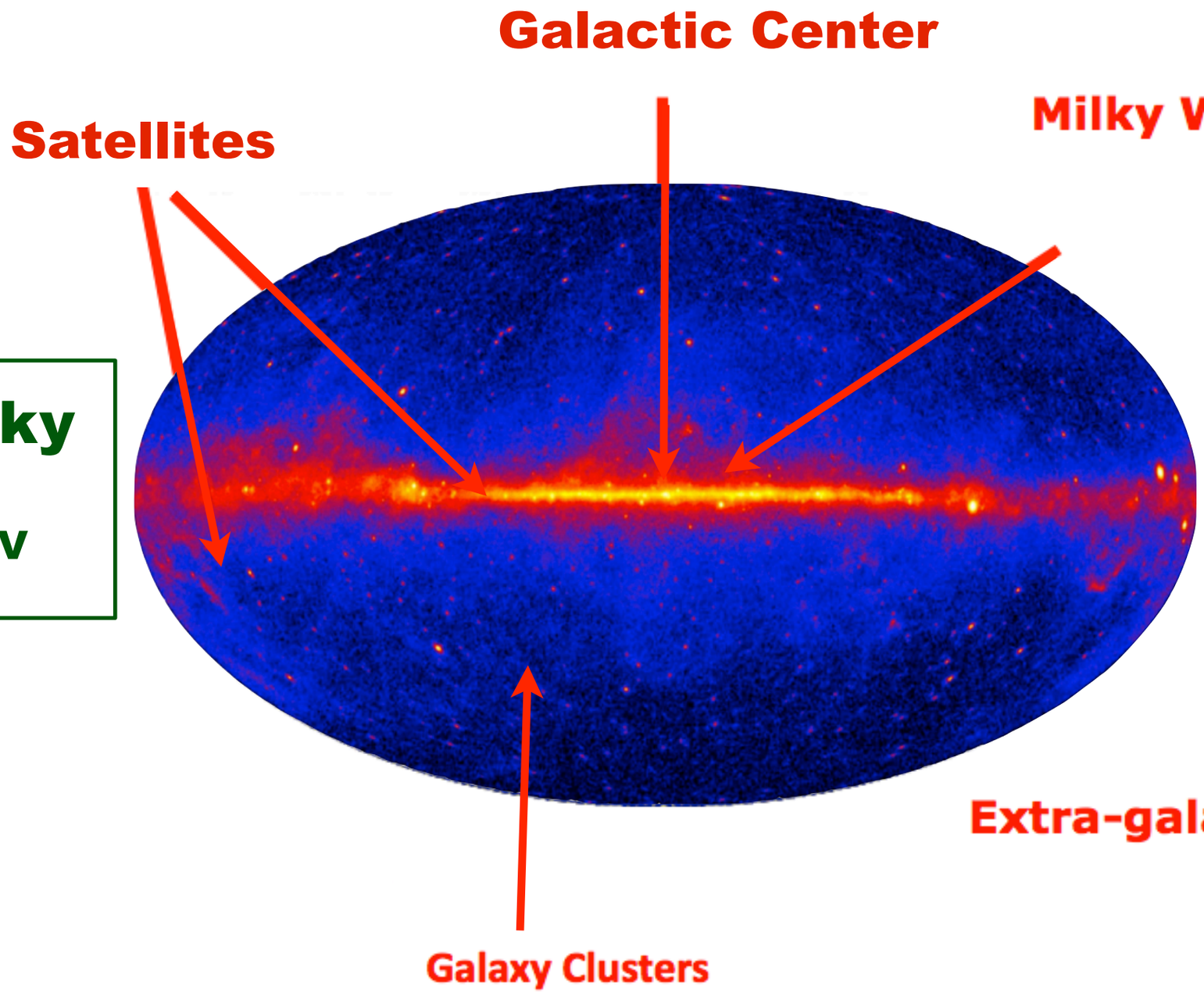
2-years,

energies > 1 GeV

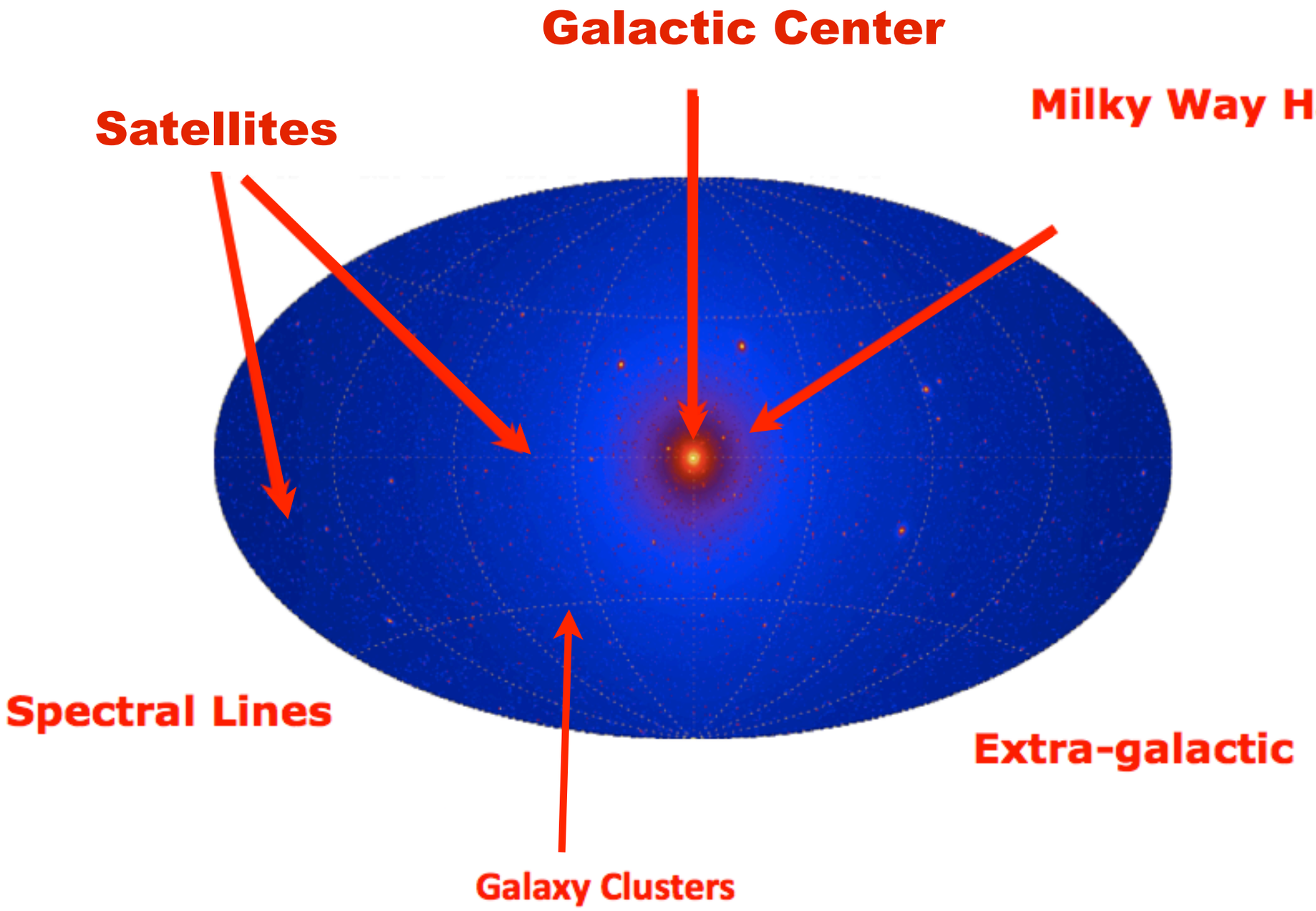


γ-ray sky

Fermi all-sky
2-years,
energies > 1 GeV



γ-ray sky

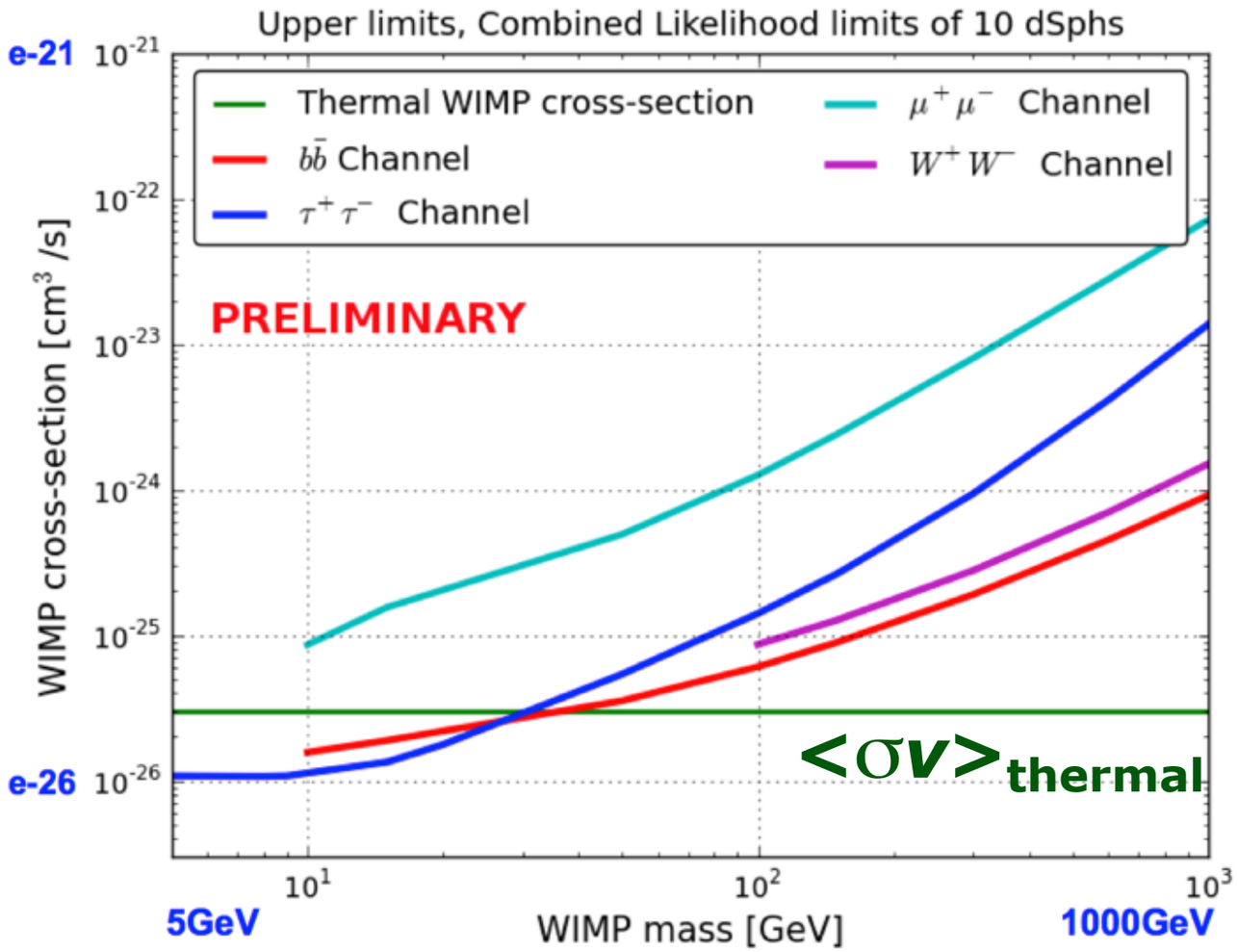


– Point Sources

Dwarfs
Clusters
Unidentified sources

Dwarf Galaxies

- Largest known DM clumps in our halo
  - No astrophysical emission expected in γ-ray
  - 1st yr Fermi: $\langle\sigma v\rangle < \sim 10 \times \langle\sigma v\rangle_{thermal}$ @ 100 GeV (Draco, Ursa Minor...)



Preliminary: A combined likelihood analysis of 10 dSph galaxies; including DM density uncertainties (i.e. J-factor). [M.L. Garde, FS 2011]

Non detection ⇒ Strong Robust Upper limits

The limits cut into the thermal WIMP regime for:

$b\bar{b}$ and $\mu^+\mu^-$ channels

for WIMP < 30 GeV

Galaxy clusters

- A place to search for ~TeV mass Lepto-philic DM models
  - Clusters constitute the largest DM halos
  - Leptons IC on CMB (+star+dust light) producing γ-rays
  - 'No' diffusion on cluster scales
  - DM signal enhanced due to subhalos

No clusters detected by Fermi (so far)

⇒ Flux limits on individual clusters

Annihilation: $\mu^+\mu^-$ channel

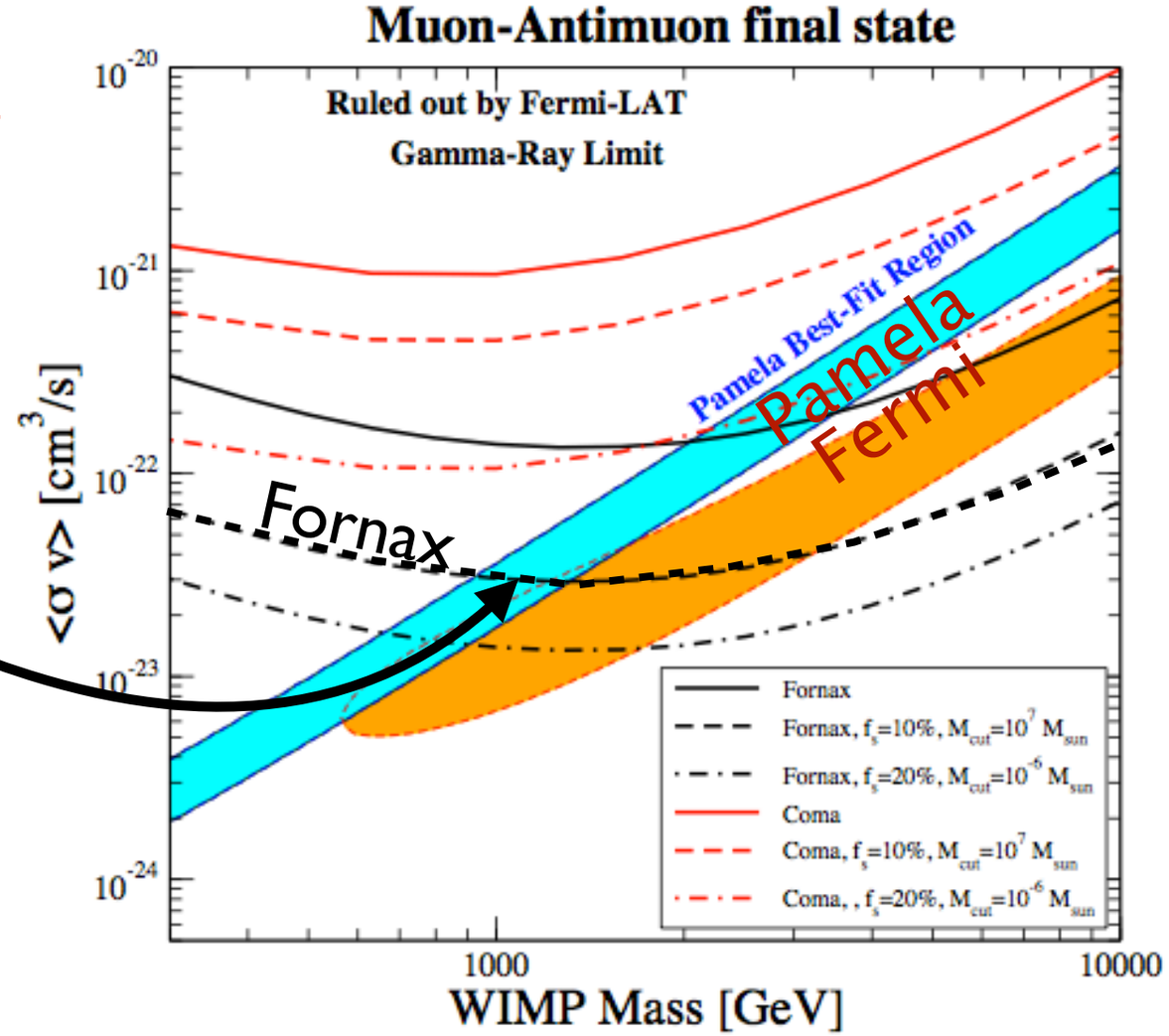
10% in sub halos down to 10^7 M_{Sun} (11 months data).

[Fermi:JCAP 1005:025,2010]

FERMI work in progress:

Incl. 24 month data + a stacking analysis to improve statistics

Factor ~2.5 improvement



Galaxy clusters - II

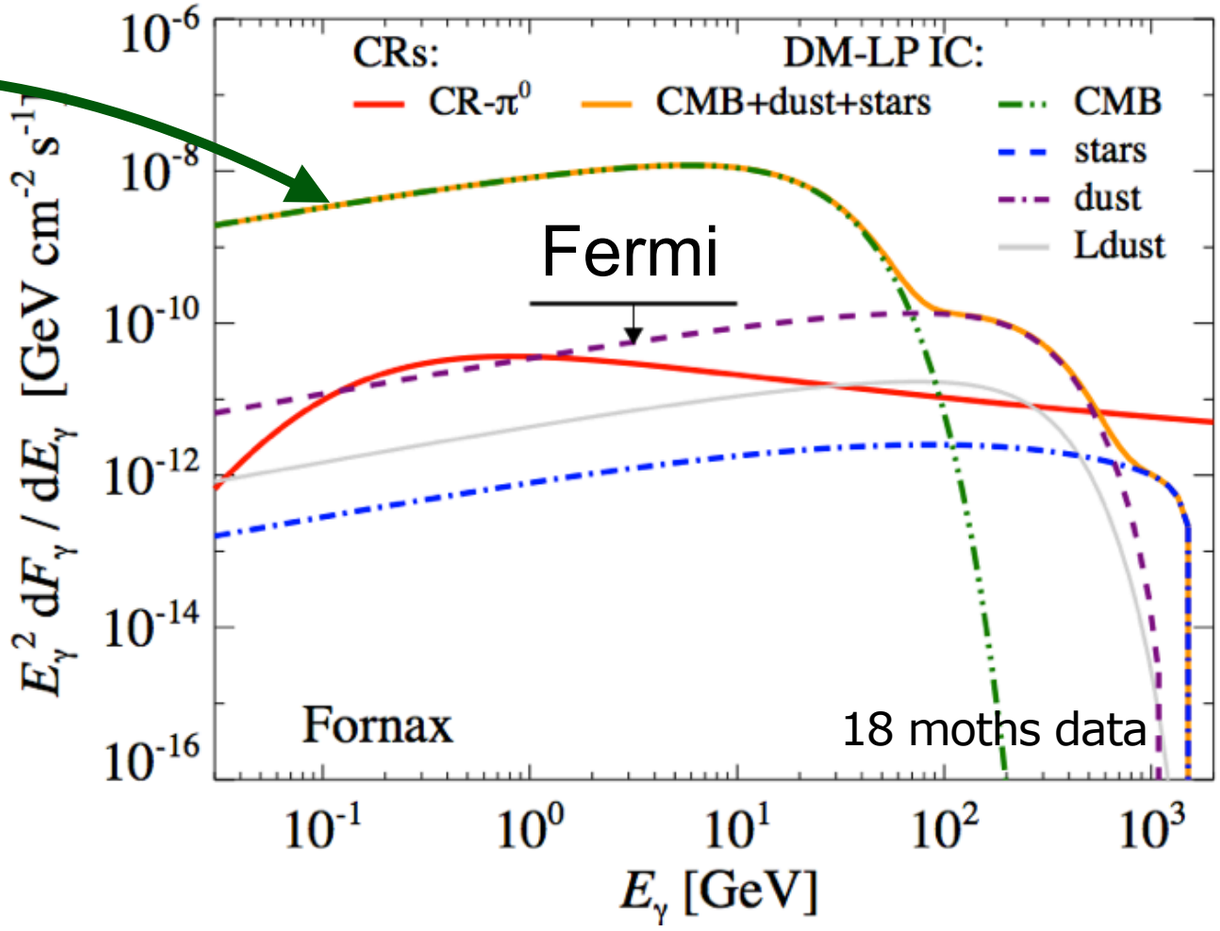
[Pinzke *et al*. 2010, ArXiv: 1105.3240]

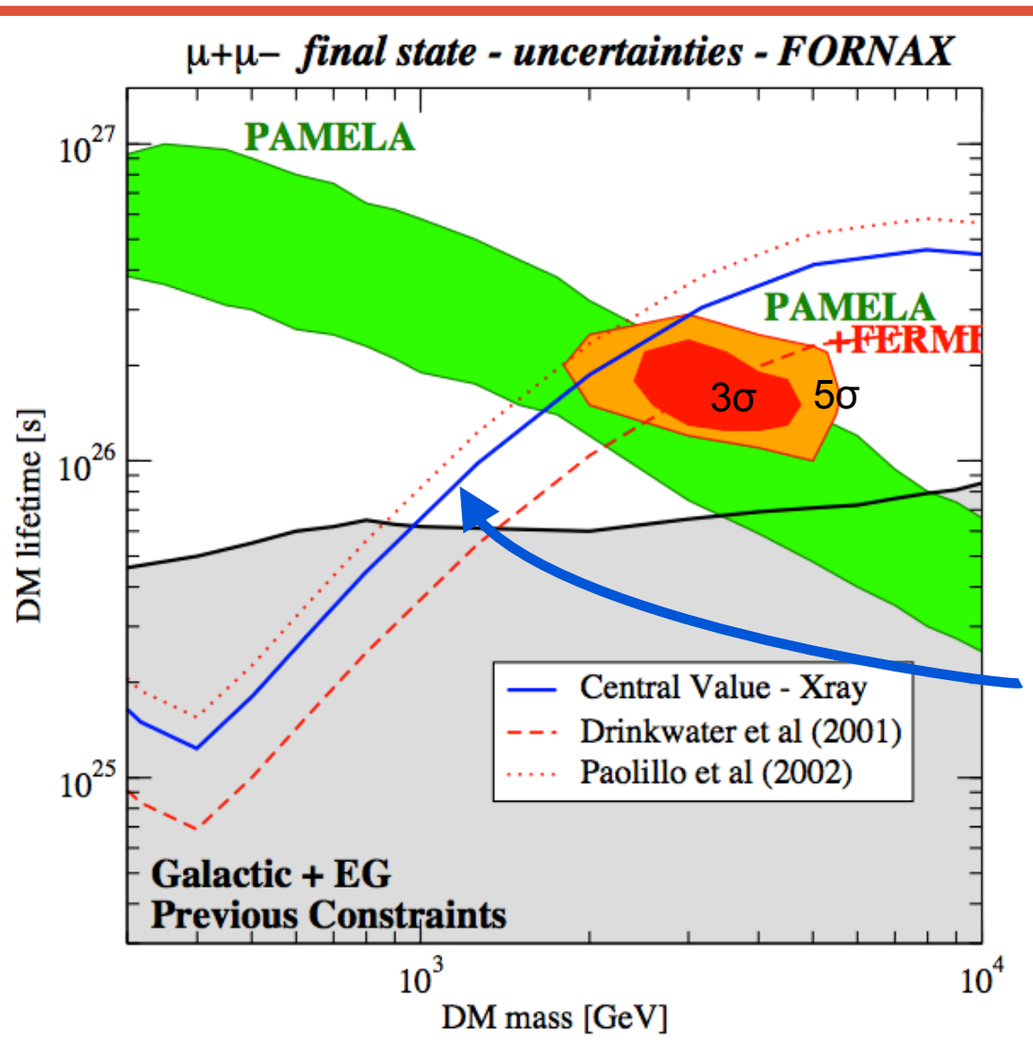
Annihilating: $\mu^+\mu^- + e^+e^-$

with $M_{sub} > 10^{-6}\ M_{sun}$

A DM model claimed to provide a consistent DM scenario to fit the Fermi+PAMELA e^+/e^- 'excess'

[According to Douglas et al. ArXiv:1011.3082]





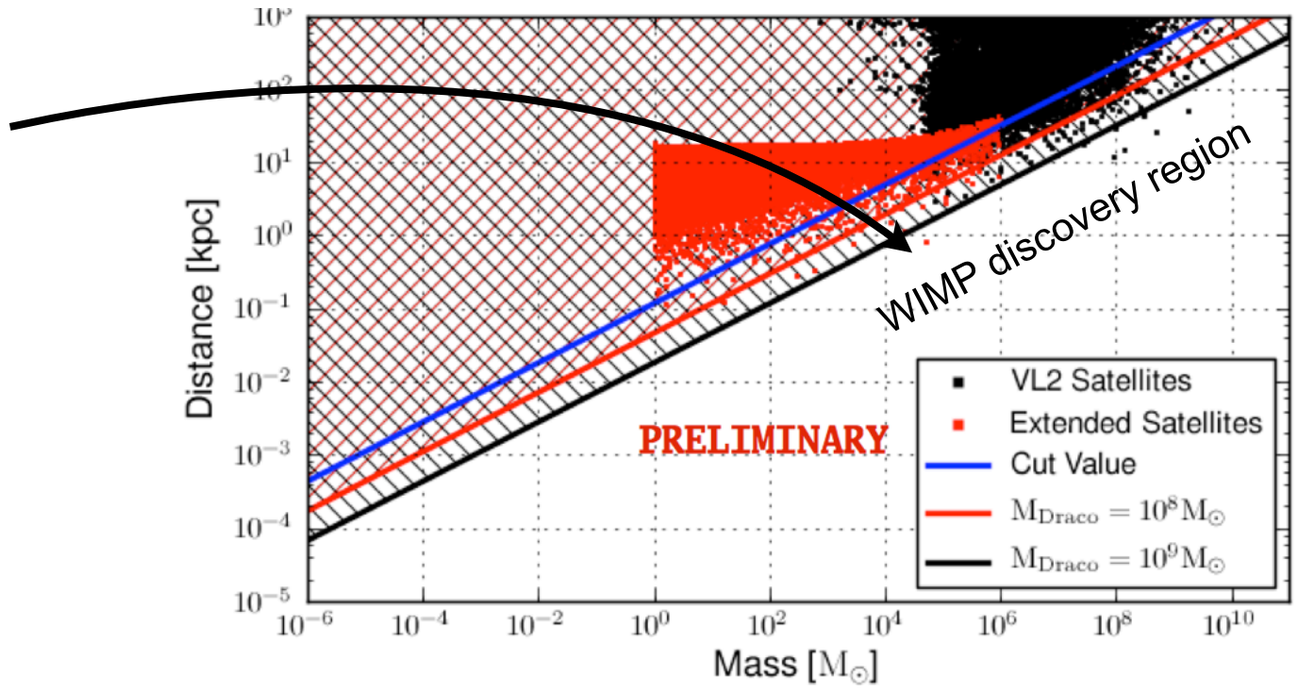
Decaying DM: $\mu^+\mu^-$ channel

11 months data,

[Dugger, Jeltema, Profumo, ArXiv:1009.5988]

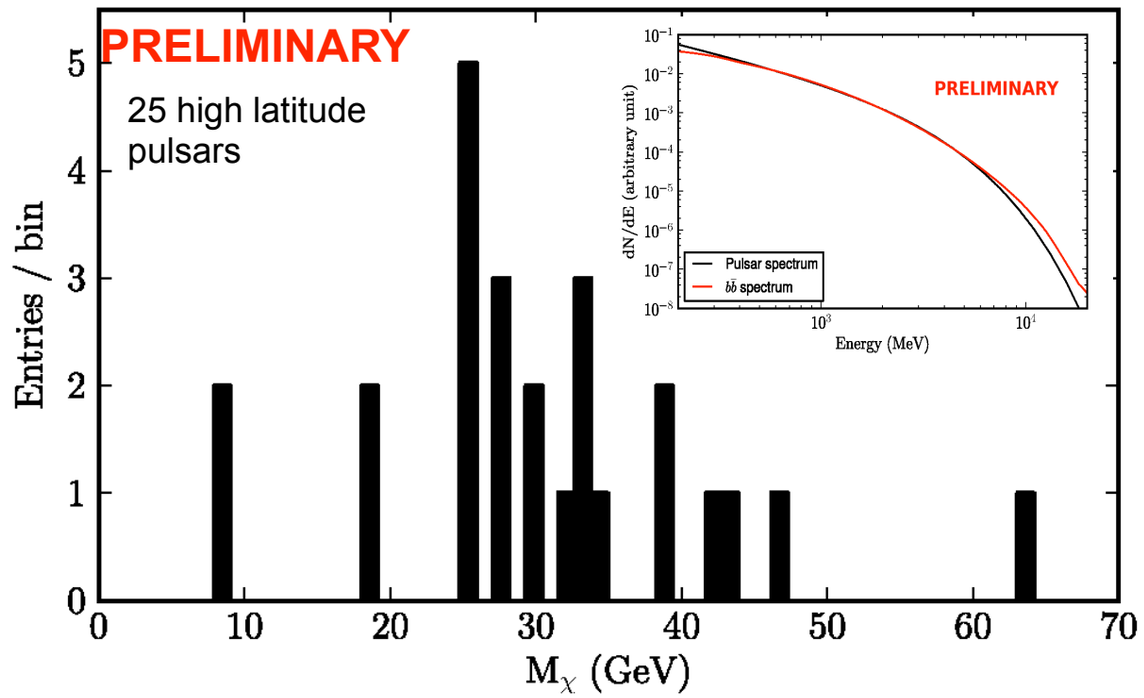
DM in Unidentified Sources

- Few low-mass DM clumps potentially detectable
- 385 unassociated sources tested (b>10) against:
  - Non-power-law spectra
  - Spatially extended



- No DM satellites candidates found in 1-year of data:
  - 2 sources passed spatial extension. 1 of them also the spectral test; which subsequently was found coincident with a millisecond pulsar

Most pulsars pass simple spectral tests



– Extended regions

Caveats

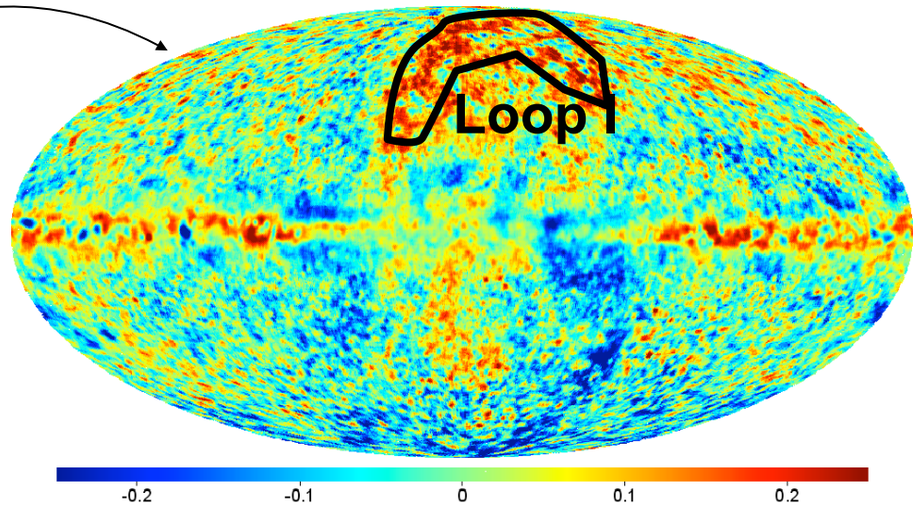
Line search

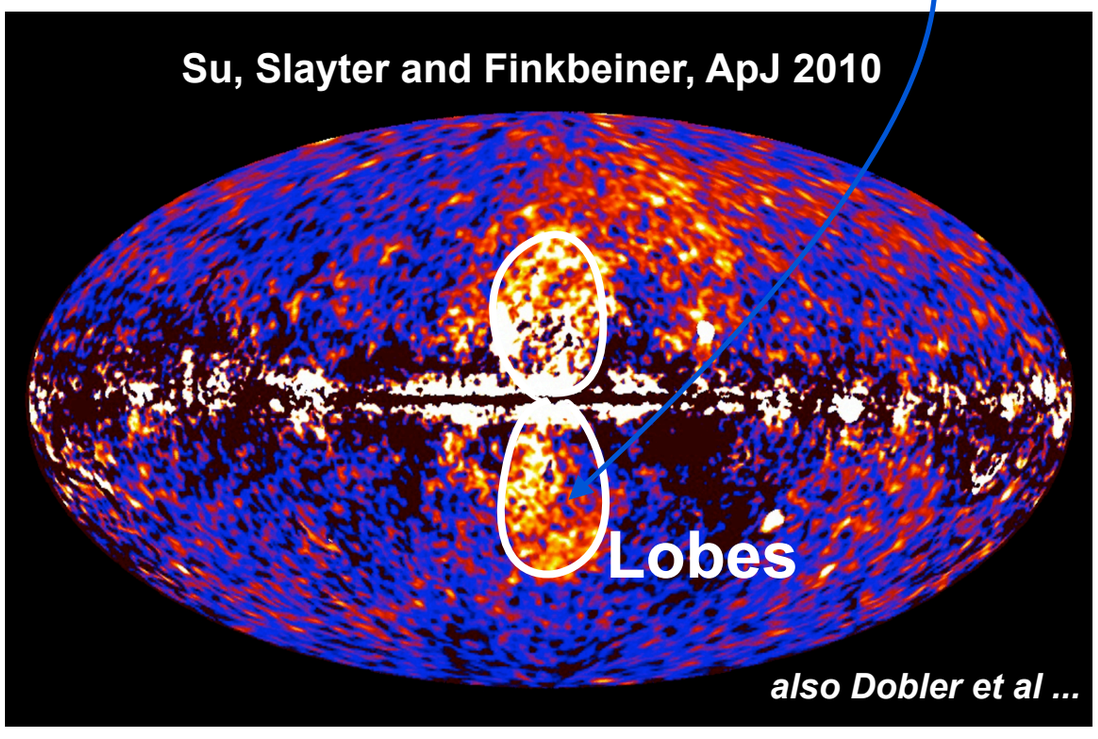
Galactic Halo

Extra Galactic

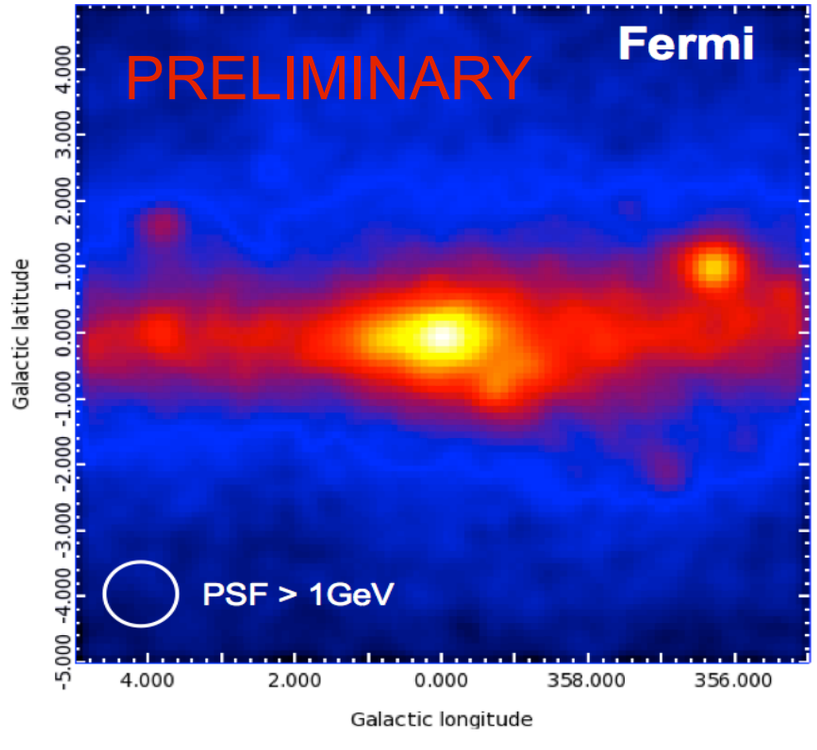
All sky – Challenges in Analysis

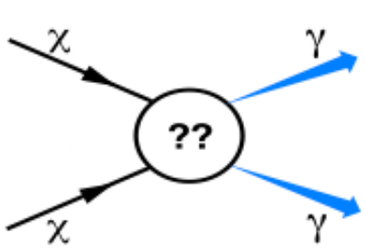
- Residual maps from GALPROP models show large scale structures
  - Fermi lobes/bubbles, Loop I, dark gas ...



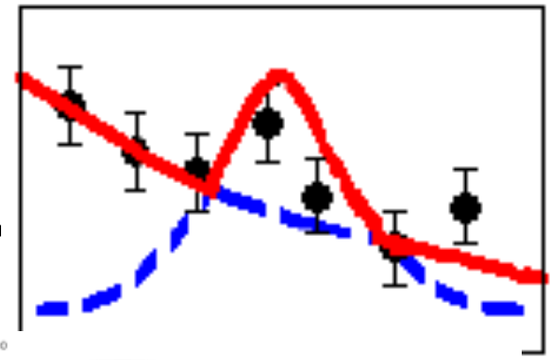


- Galactic center, inner <15°
  - Low level residual structures and points sources are under study
  - Forthcoming paper will describe method and results.



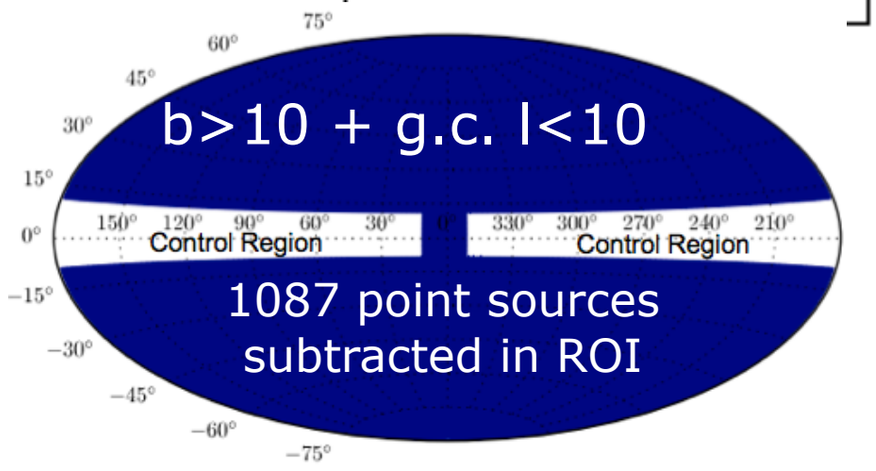


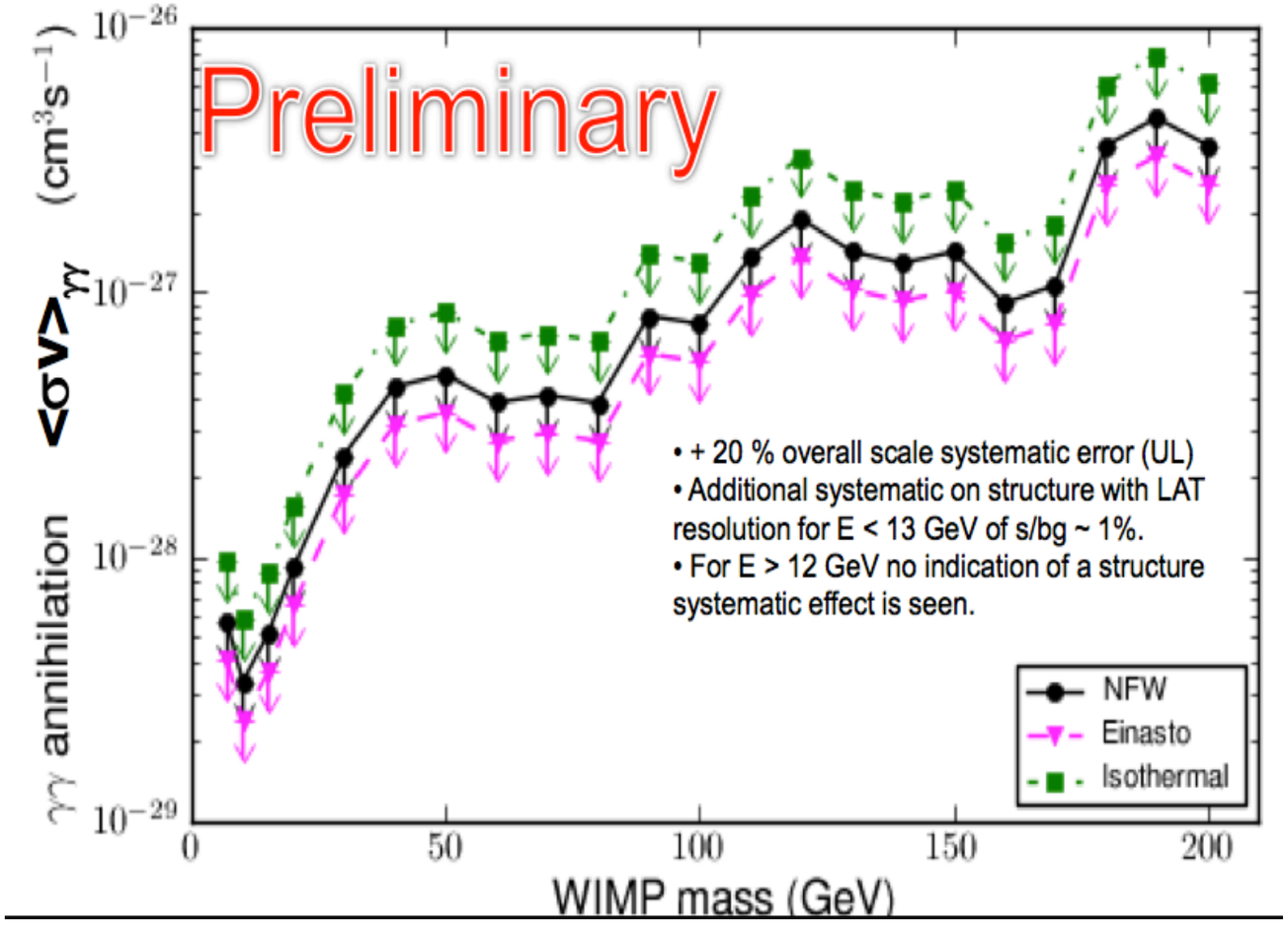
Spectral Line search



- Search for γ-ray lines in all-sky spectrum
  - No astrophysical bkg.
  - A uniquely DM signal.
    Typically a loop suppressed signal

$$\langle \sigma v \rangle_{\gamma\gamma} \sim 10^{-4} \times \langle \sigma v \rangle_{\text{thermal}}$$





2-year data, update to PRL 104, 091302, 2010

- No line feature detected:
  - Energies scanned from 7 to 200 GeV
  - Upper limits

$$\langle \sigma v \rangle_{\gamma\gamma} < (10^{-3}\text{-}0.1) \times \langle \sigma v \rangle_{\text{thermal}}$$

  - Constrain some scenarios
    (Higgs in Space, Gravitino decay, non thermal WIMPs ...)

N.B. spurious effects (CTBCORE) in Pass6v3 @ ~7GeV, solved with Pass 7

Limits on the Milky Way DM halo

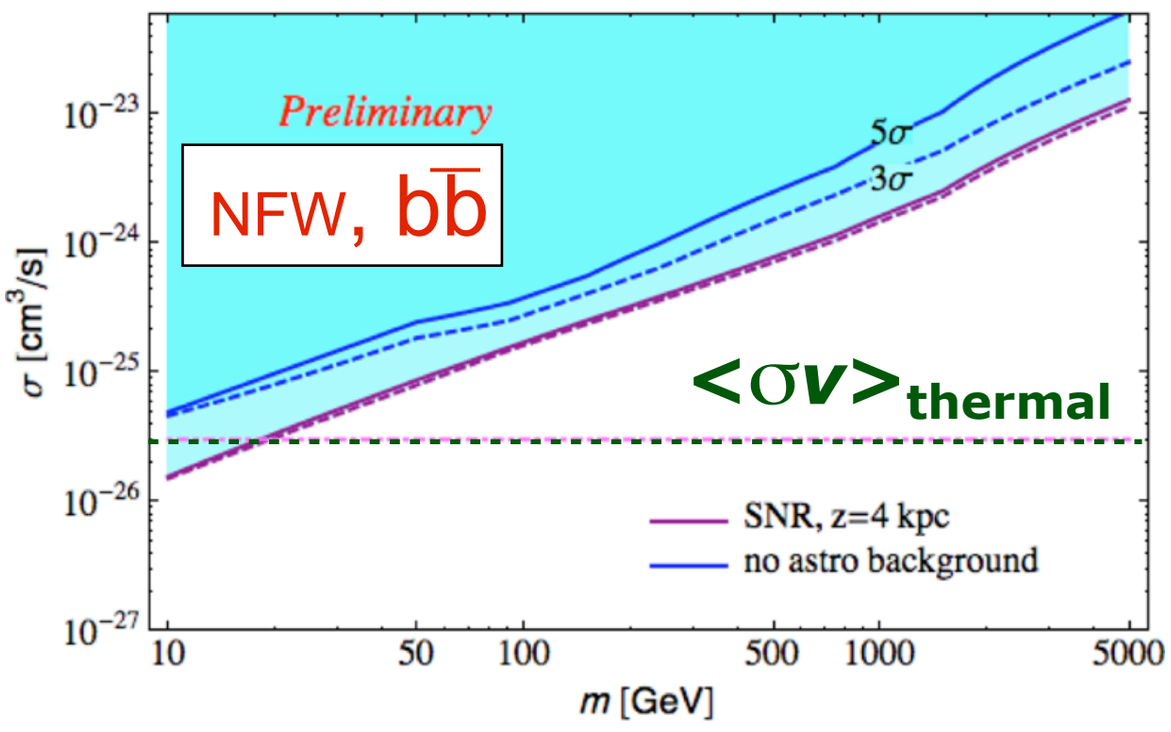
- Exploits both spectral and spatial information
  - Data binned in both energy and angle
  - Large scale residuals favor DM components (e.g. the Fermi lobes; although the DM model do not fit their signal+sharp edges)
  - Restrict sky region 5°<|b|<15°, |l|<80° (use 2-yrs data)

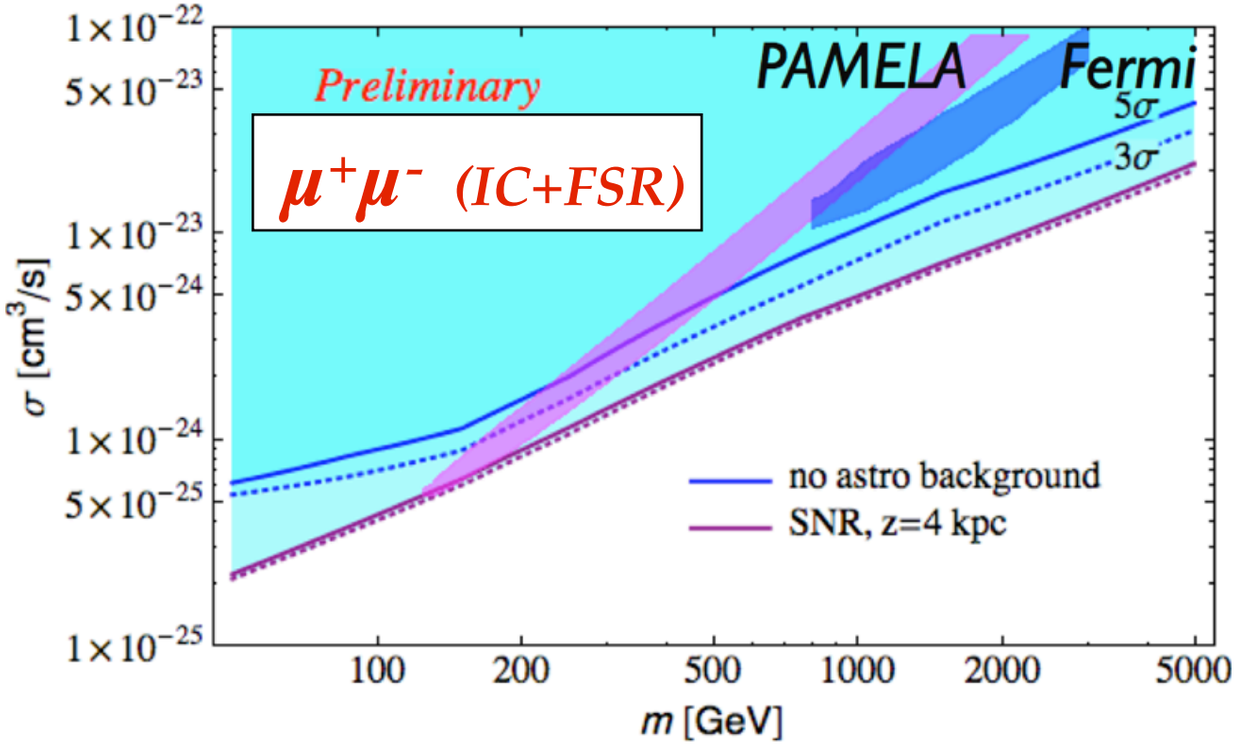
Preliminary

- Upper limits

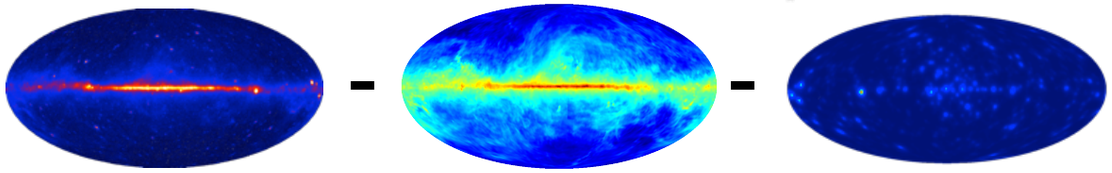
  1) Incl. model of MW Galactic diffuse emission (purple lines);
  Varying individual CR param. effect limits up to ~40%

  2) Conservative: DM fluxes kept below diffuse emission (blue lines)



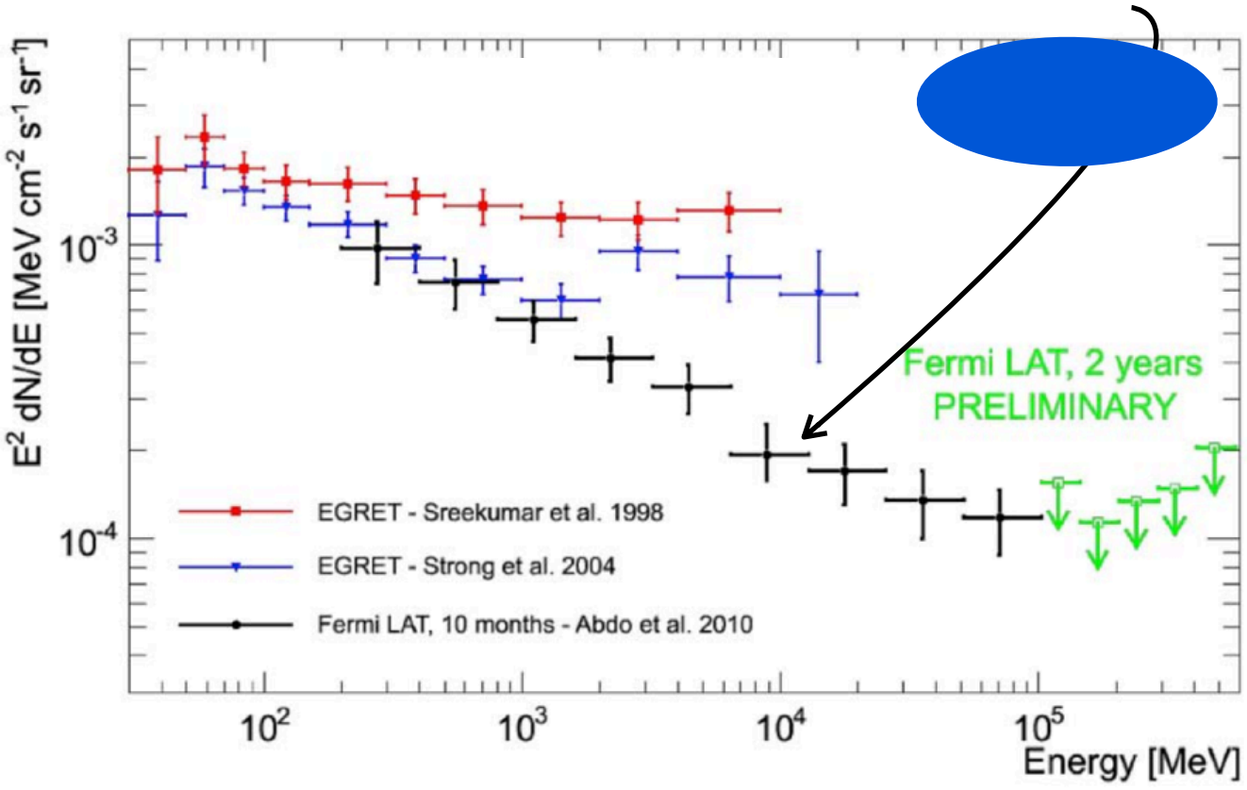


Isotropic gamma-ray Background



Full sky - Galactic diffuse - Point sources

= **Fermi's isotropic diffuse component**



Components:

1) Unresolved point sources:

Blazars, star forming and radio galaxies

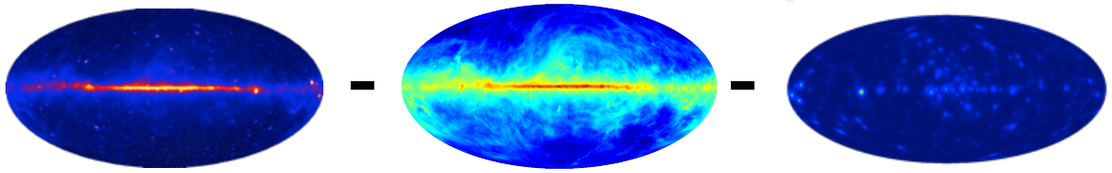
... but these might not be enough

2) Other astrophysical sources

(MeV blazarrs, ms pulsars ...)

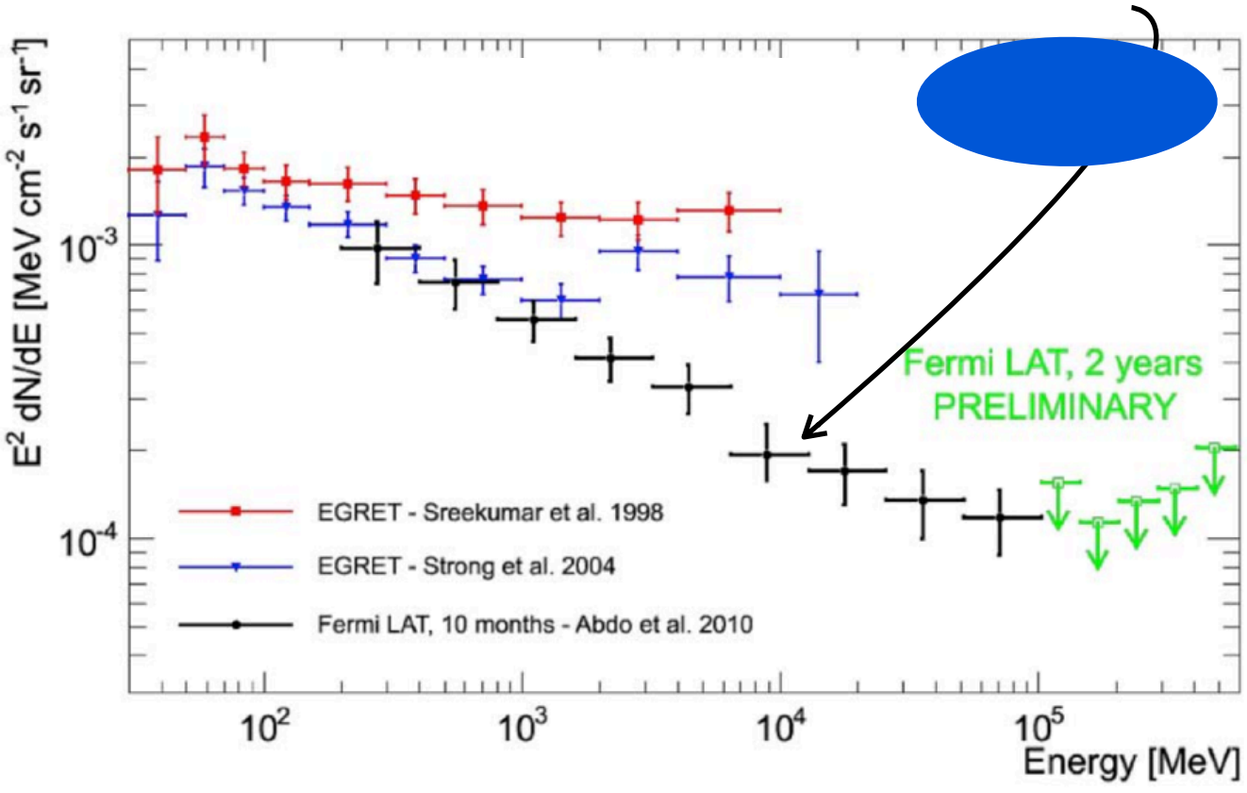
3) DM form over-densities by gravitational collapse: annihilation rates can be greatly enhanced ($\propto\rho^2$). Also substructures in the local MW DM halo could contribute.

Isotropic gamma-ray Background



Full sky - Galactic diffuse - Point sources

= **Fermi's isotropic diffuse component**



Components:

1) Unresolved point sources:

Blazars, star forming galaxies,

... but these might not be enough

2) Other astrophysical sources

(MeV blazarrs, cluster shock, ms pulsars ...)

3) DM form over-densities by gravitational collapse: annihilation rates can be greatly enhanced ($\propto\rho^2$). Also substructures in the local MW DM halo could contribute.

Potentially strong DM signals, but not robust enough predictions to set the strongest limits.

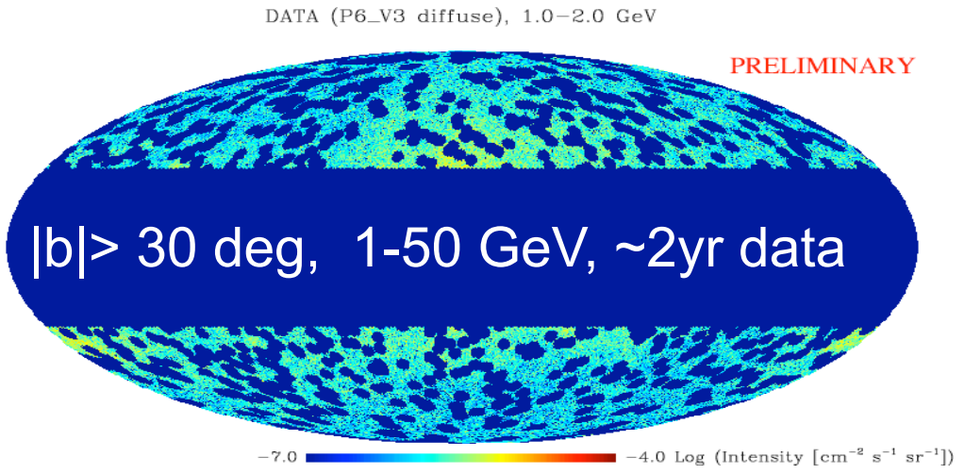
Anisotropies in the 'isotropic'?

Preliminary

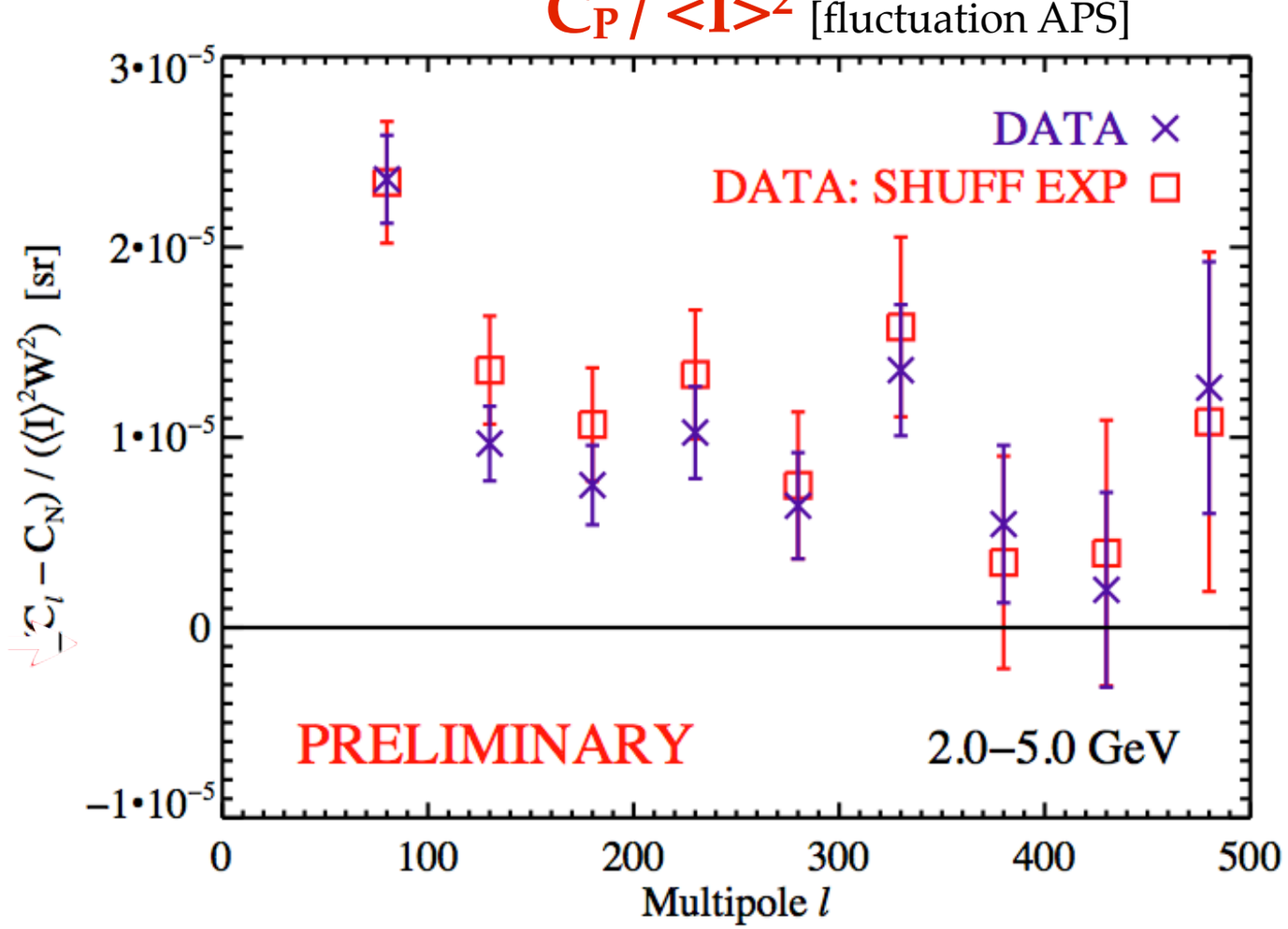
- Search for anisotropies in the diffuse γ-ray emission via the Angular Power Spectrum

$$I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi) \qquad C_\ell = \langle |a_{\ell m}|^2 \rangle$$

  - Potential to reveal un-modeled source classes, including DM



- **Results** (155<l<504)**:**
  - Angular power $C_P / \langle I \rangle^2 \sim 10^{-5}$ sr



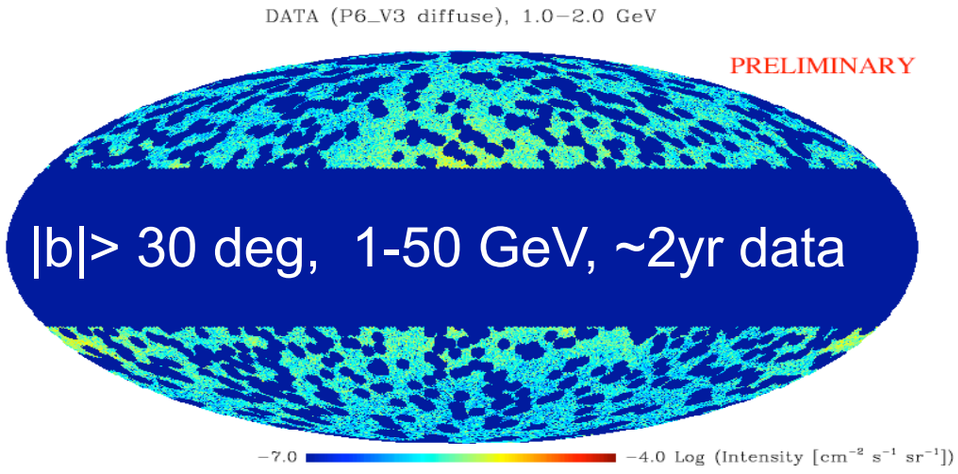
Anisotropies in the 'isotropic'?

Preliminary

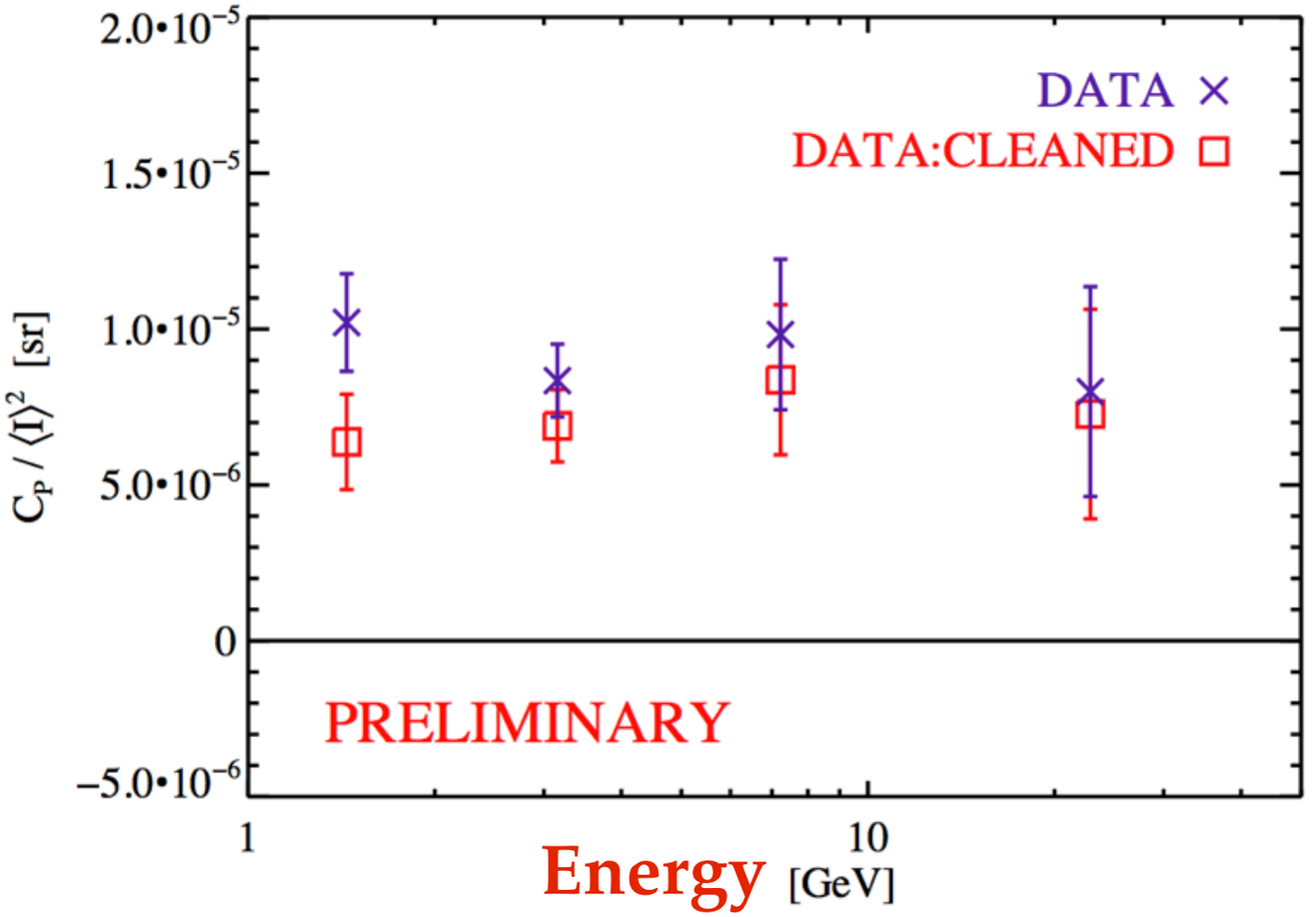
- Search for anisotropies in the diffuse γ-ray emission via the Angular Power Spectrum

$$I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi) \qquad C_\ell = \langle |a_{\ell m}|^2 \rangle$$

  - Potential to reveal un-modeled source classes, including DM



- **Results** (155<l<504)**:**
  - Angular power $C_P / \langle I \rangle^2 \sim 10^{-5}$ sr
  - Consistent with no E-dependence
    - Consistent w. single population



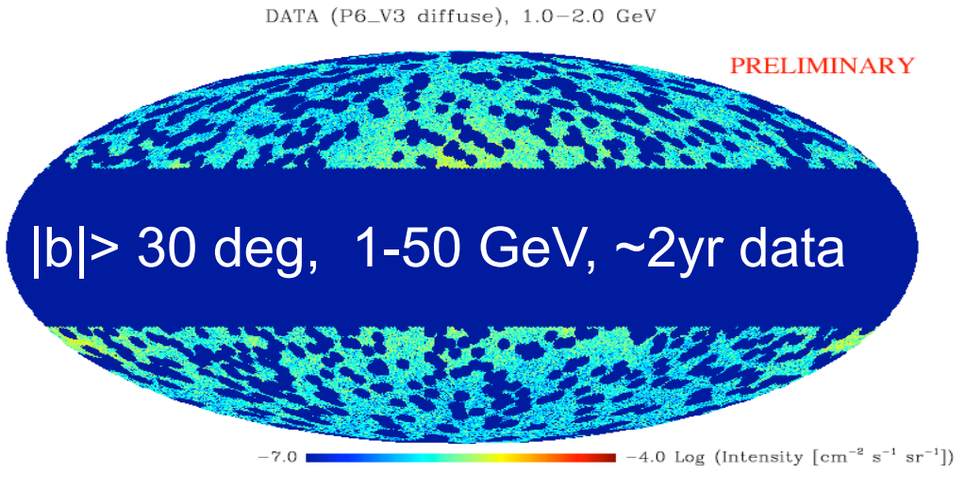
Anisotropies in the 'isotropic'?

Preliminary

- Search for anisotropies in the diffuse γ-ray emission via the Angular Power Spectrum

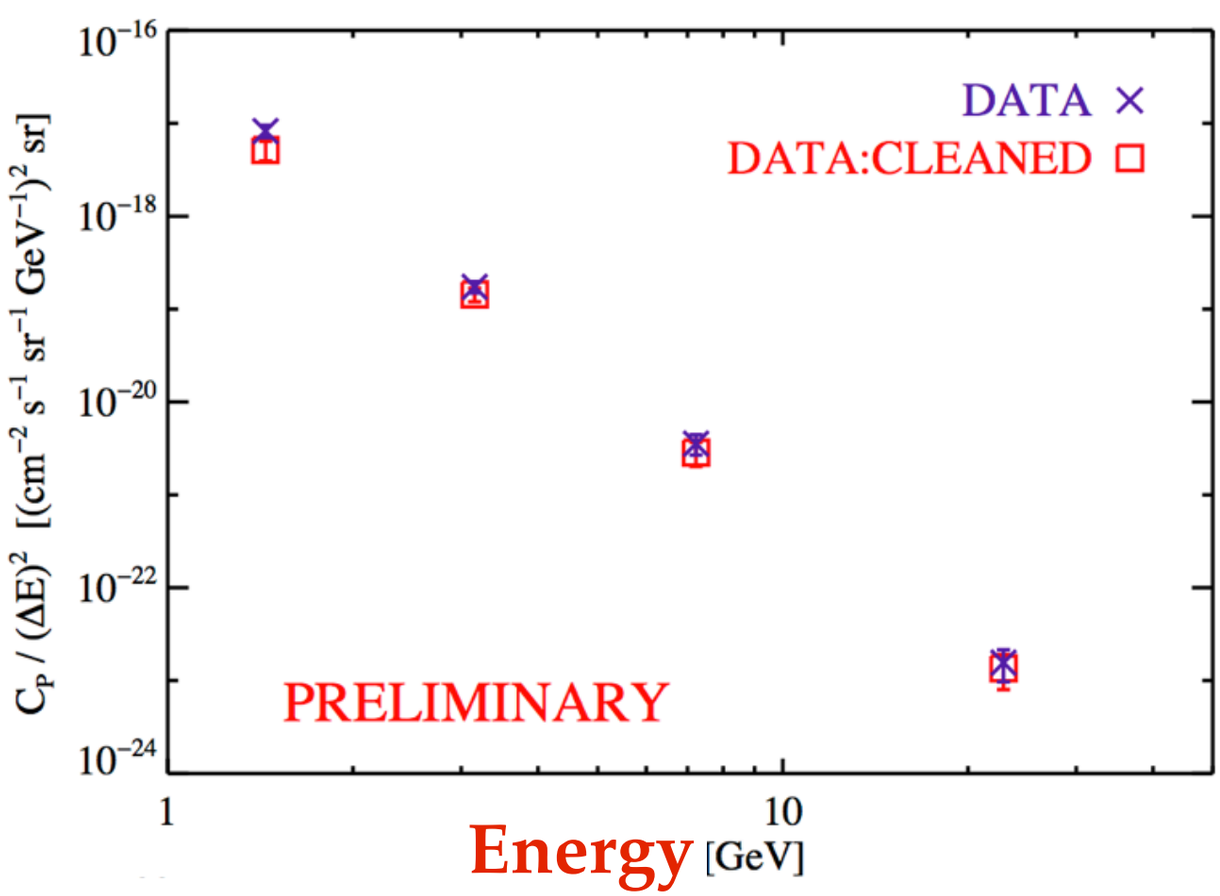
$$I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi) \qquad C_\ell = \langle |a_{\ell m}|^2 \rangle$$

  - Potential to reveal un-modeled source classes, including DM



- **Results** (155<l<504)**:**
  - Angular power C_P / <I>^{2} ~ 10^{-5} sr
  - Consistent with no E-dependence
    - Consistent w. single population
  - Intensity spectra: power law $E^{-2.4}$
    - Unresolved blazars?

      Spectra match resolved blazars



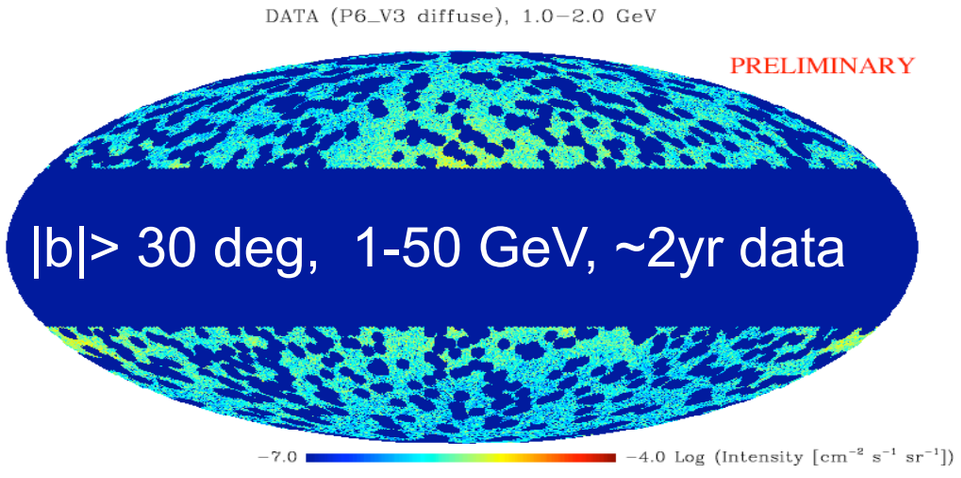
Anisotropies in the 'isotropic'?

Preliminary

- Search for anisotropies in the diffuse γ-ray emission via the Angular Power Spectrum

$$I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi) \qquad C_\ell = \langle |a_{\ell m}|^2 \rangle$$

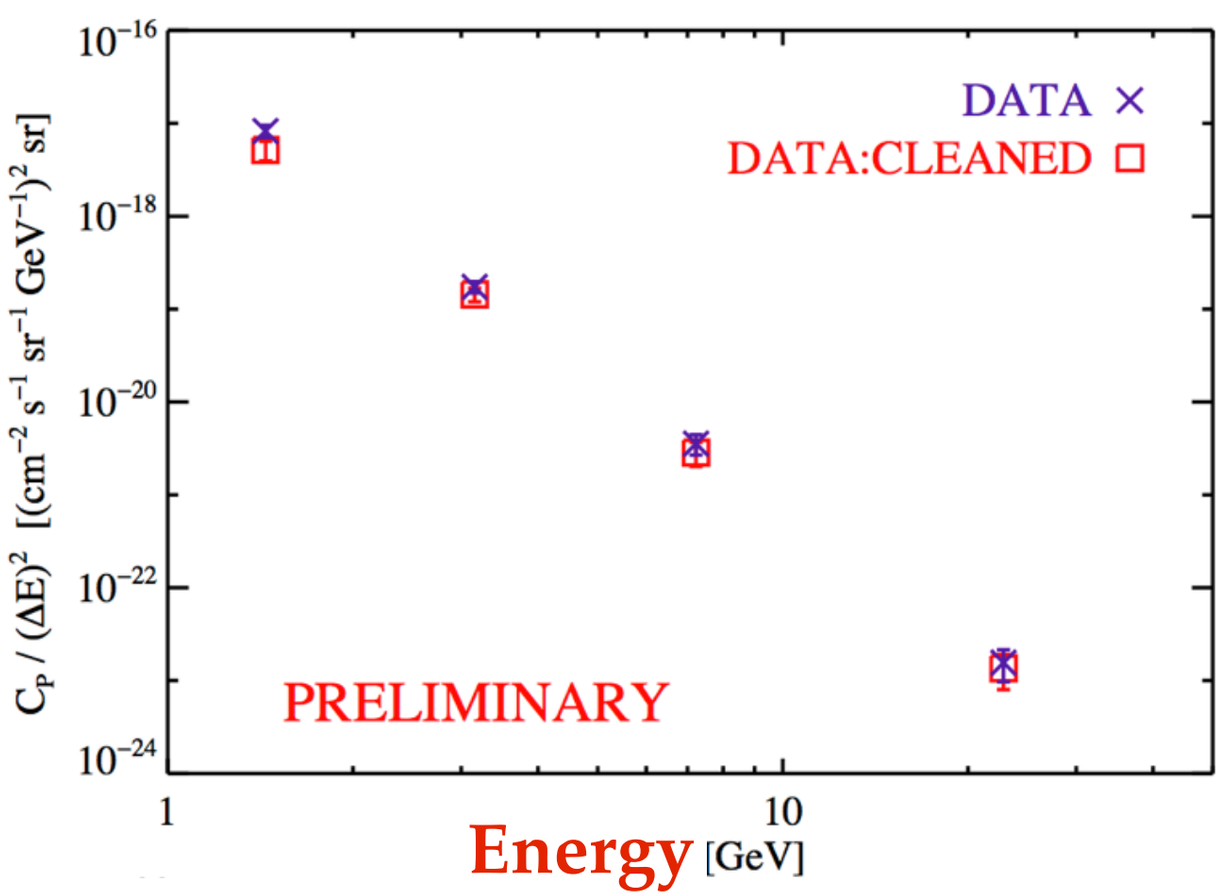
  - Potential to reveal un-modeled source classes, including DM



- **Results** (155<l<504)**:**
  - Angular power C_P / $\langle I \rangle^2$ ~ 10^{-5} sr
  - Consistent with no E-dependence
    - Consistent w. single population
  - Intensity spectra: power law $E^{-2.4}$
    - Unresolved blazars

    Spectra match resolved blazars

- DM: $C_P/\langle I \rangle^2$ ~ 10^{-4}-0.1 @ l=100; if single source class. work in progress ....



Summary – DM searches in γ-ray

Summary – DM searches in γ-ray

- A wealth of new data
  - Point sources cleanest DM targets
    - Fermi limits on dwarfs rule-out benchmark WIMPs with thermal x-section and mass below ~10 GeV
  - All sky (line, EGB, anisotropies) accessible to Fermi
    - No signs of DM → constrain some scenarios
  - Extended regions (MW DM halo, inner Galaxy)
    - Potentially promising but hard
    - Diffuse and point source emission modeling uncertainties
  - MilkyWay halo and galaxy cluster analysis
    - Disfavor lepto-philic DM models from CRE 'excesses'
- Hints from Direct, Accelerator and/or CR searches
  - Reduces DM models phase spaces for γ-ray cross checks
  - Fermi and IACT complementary in energy range