Confronting Galactic and Extragalactic gamma-ray observed by Fermi-LAT with Annihilating Dark Matter in Inert Higgs Doublet Model

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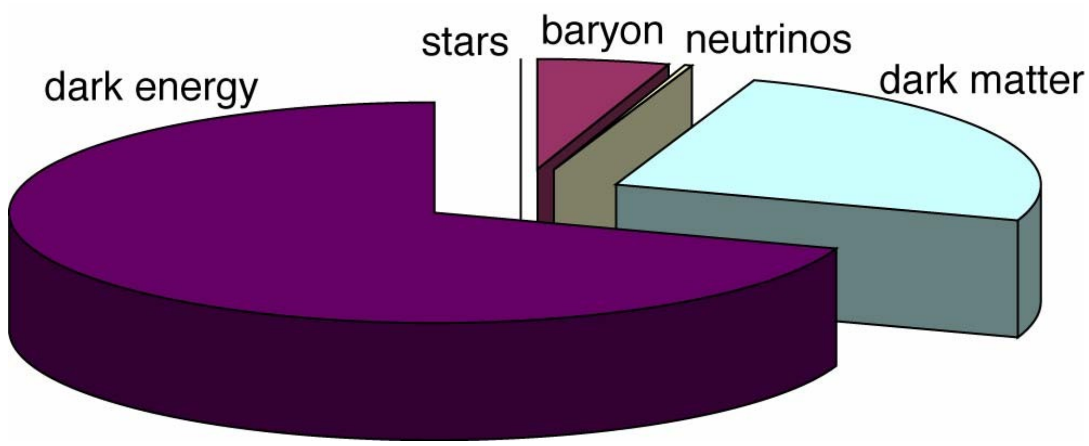
What is *Dark Matter* ?

- An Unknown, non-luminous matter with almost no interactions with other particles except gravity
- Contains more than 80% of the matter content of the universe
- All pervading across the galaxies, clusters, super-clusters

Energy Budget of Universe

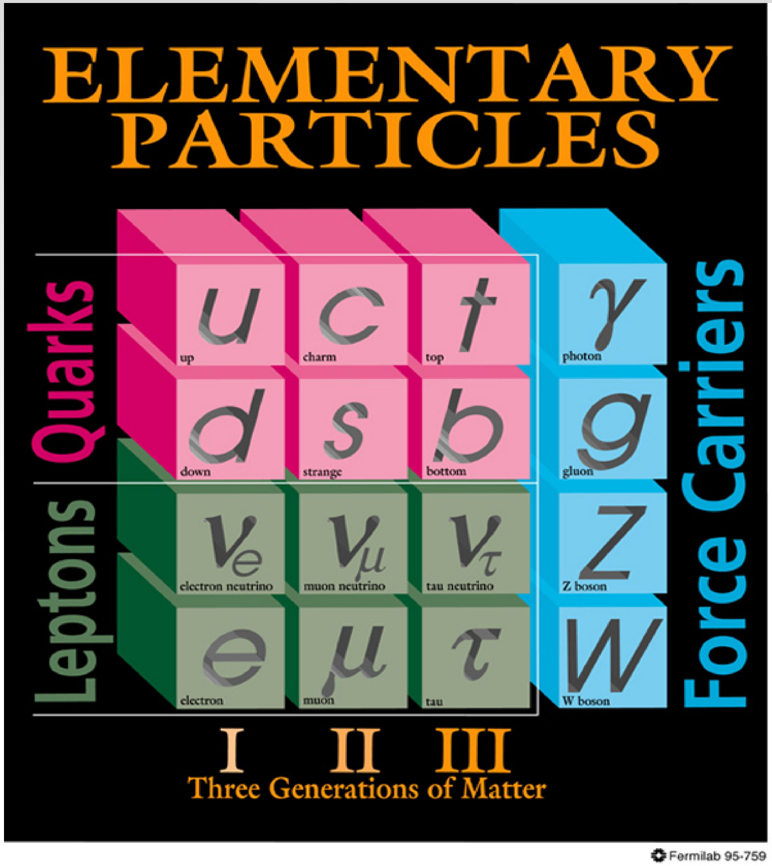
PLANCK 2013 RESULTS !!!
(March 21, 2013)

- Baryonic Matter are ~ 4.8%
- Dark Matter ~ 26.5%
- Dark Energy ~ 68.4%



General Properties of Dark Matter

- Should be neutral
- Gravitationally interacting
- Stable
- Very weak interaction with other particles



➔ Major constituent is perhaps heavy (massive) particles (non-relativistic while decoupling)

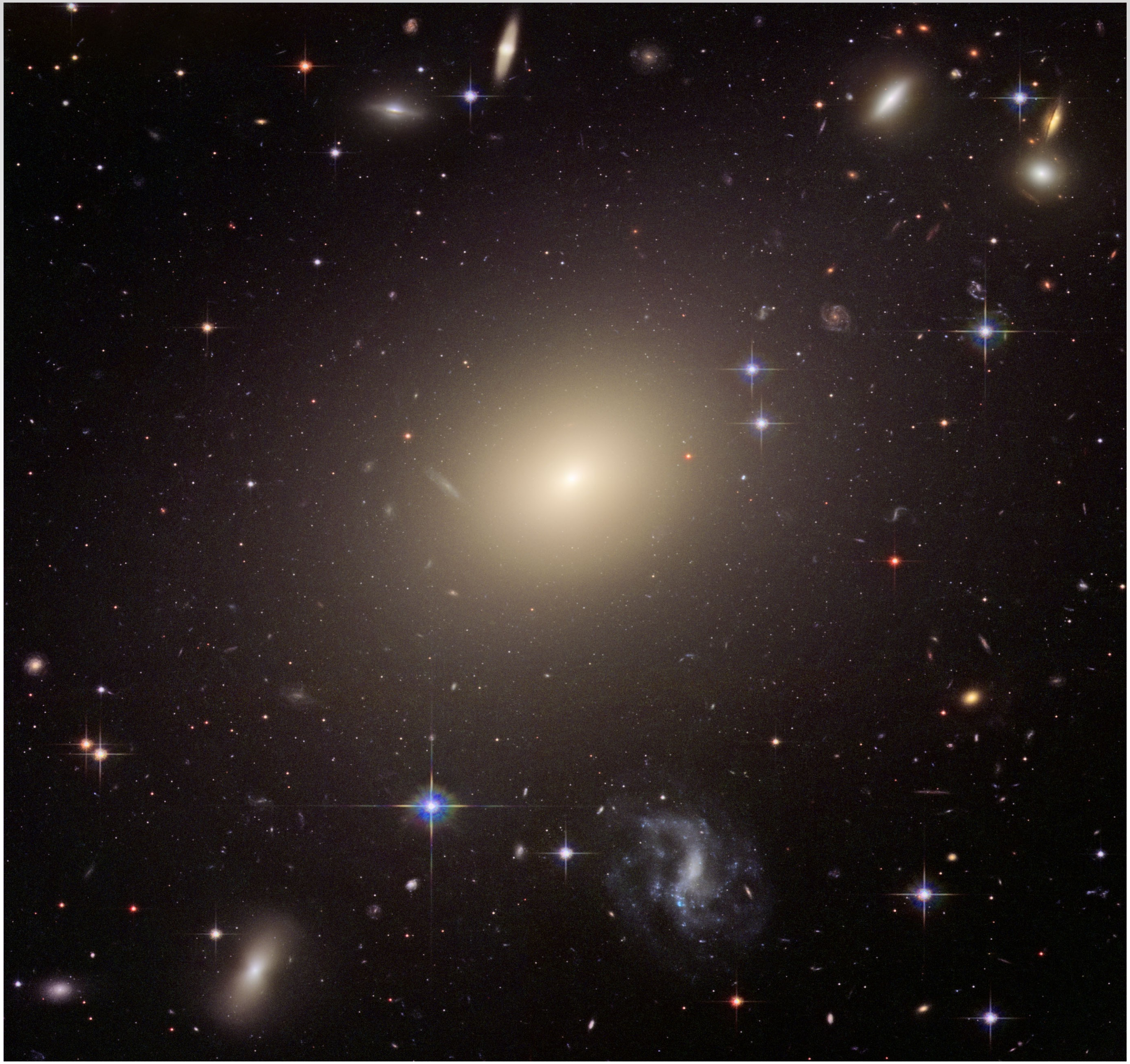
➔ Mainly non-baryonic in nature

Evidence of Dark Matter in the Universe

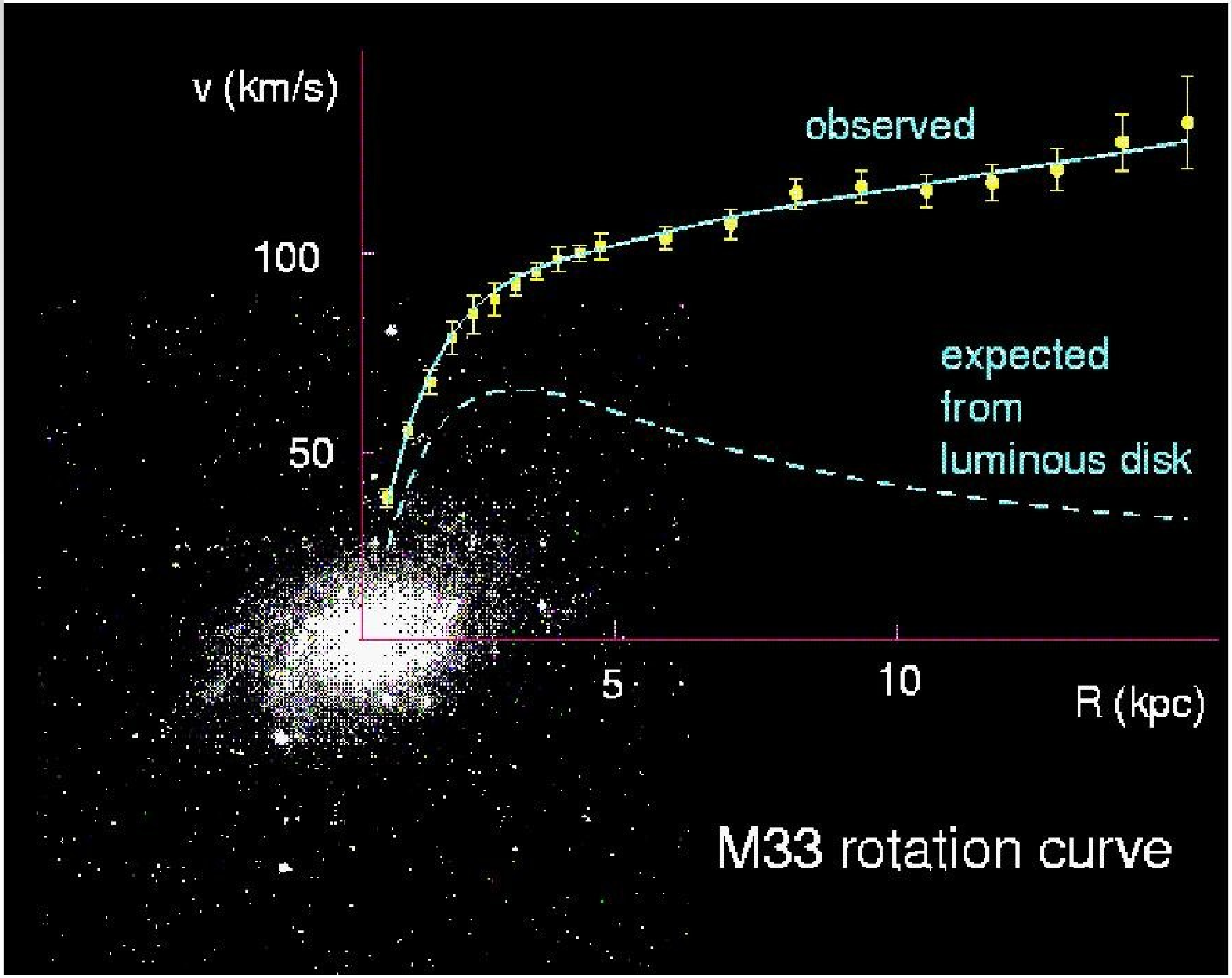
- Flatness of the rotation curves of spiral galaxies at large radius
- Gravitational lensing
- Bullet Clusters
- Anisotropy of cosmic microwave background radiation.
- Difference in gravitational mass and luminous mass in galaxy clusters
- Difference in total mass and observed mass

Spiral Galaxy

Elliptical Galaxy



Flatness of Rotational Curve



Flatness of Rotational Curve

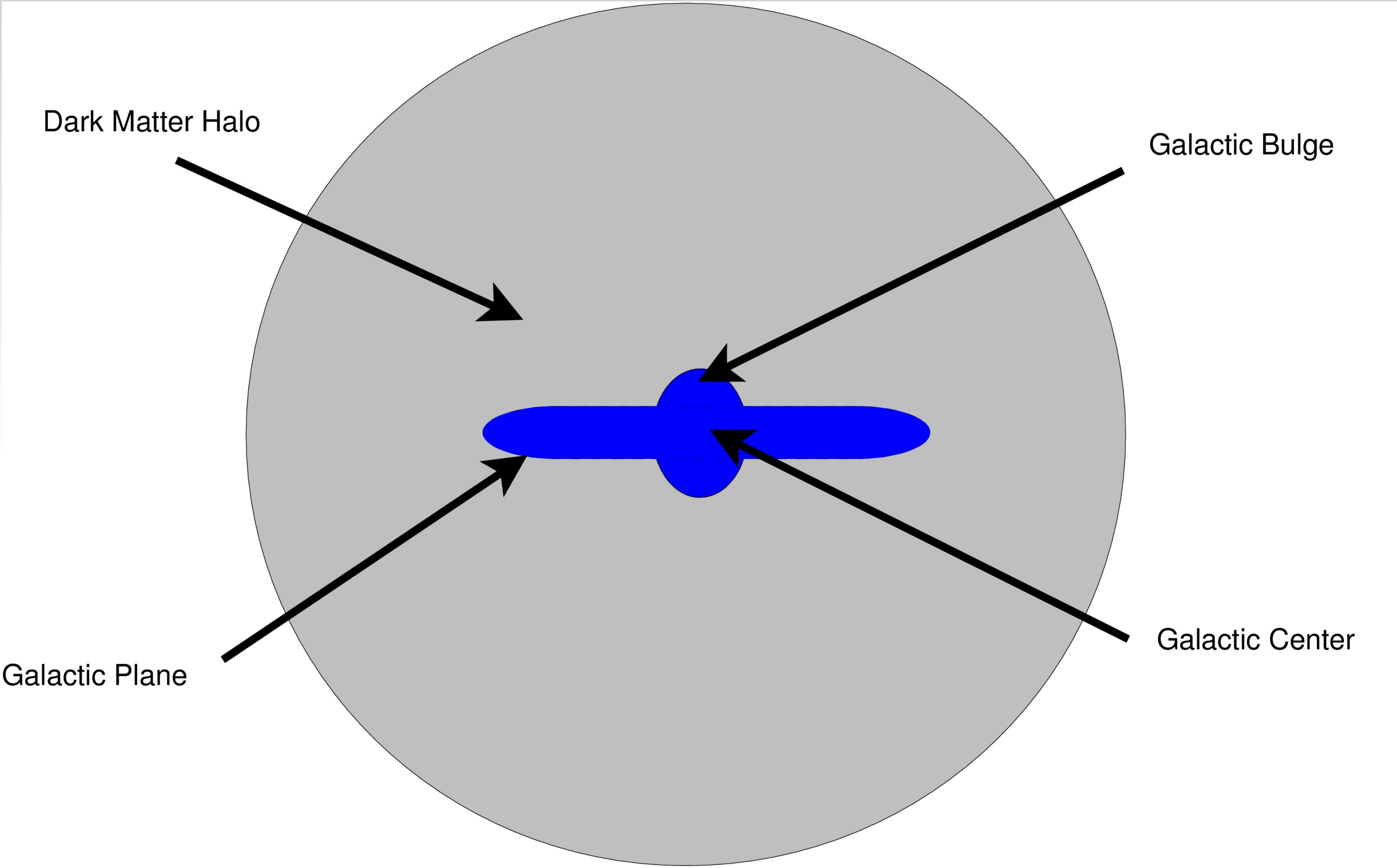
$$\frac{mv_r^2}{r} = \frac{GM_r m}{r^2}$$

$$M_r = \frac{4}{3}\pi r^3 \rho$$

$$v_r \sim r$$

$$v_r \sim \frac{1}{r^{1/2}} \quad \text{(Keplerian Decline)}$$

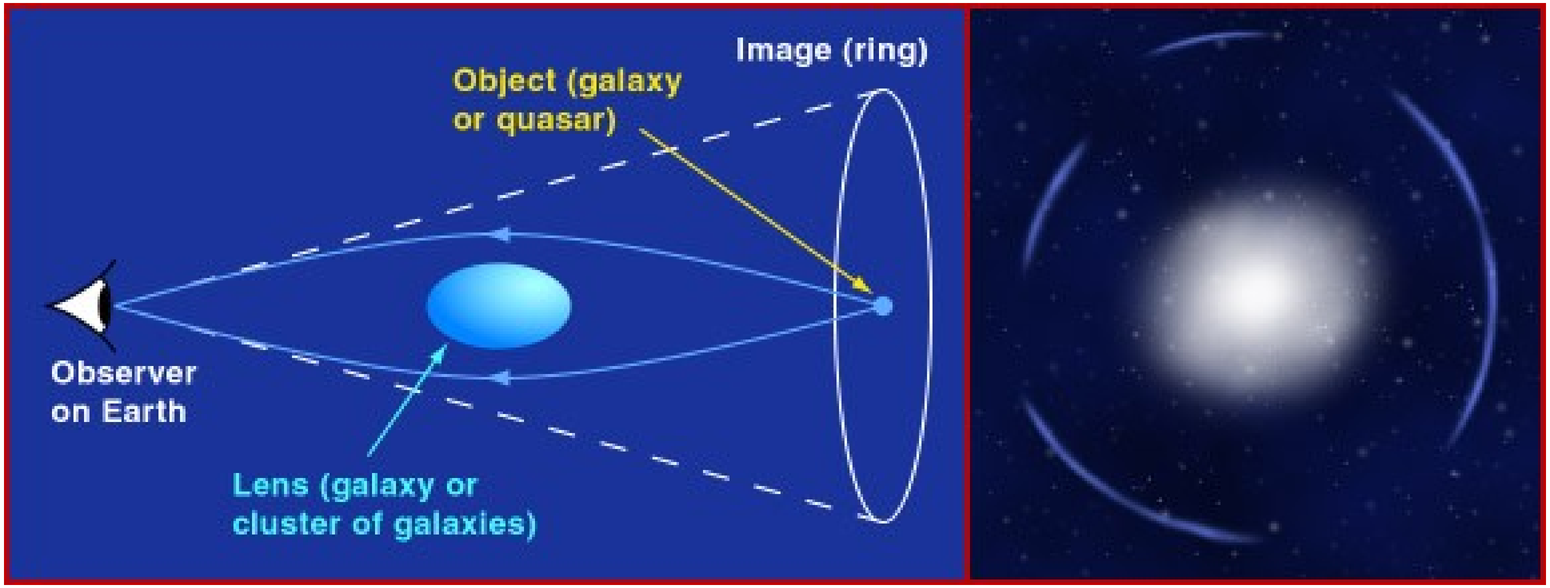
$$M_r \sim r$$

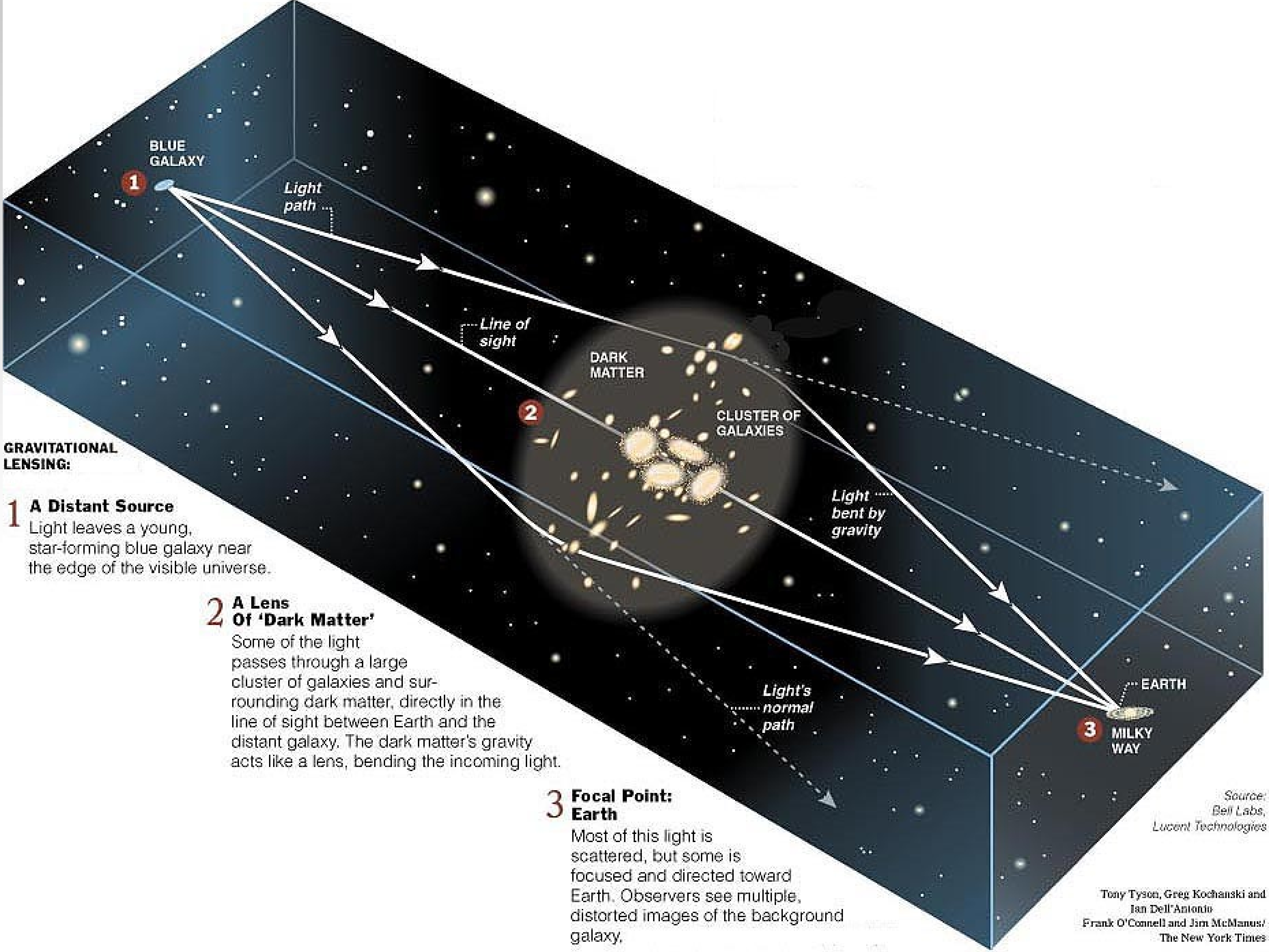

Dark Matter Halo
Galactic Bulge
Galactic Plane
Galactic Center

Lensing

Another method used to study mass/distance relationships among the far reaches of our Universe is called lensing.

Lensing occurs when an object's gravity distorts light behind it.

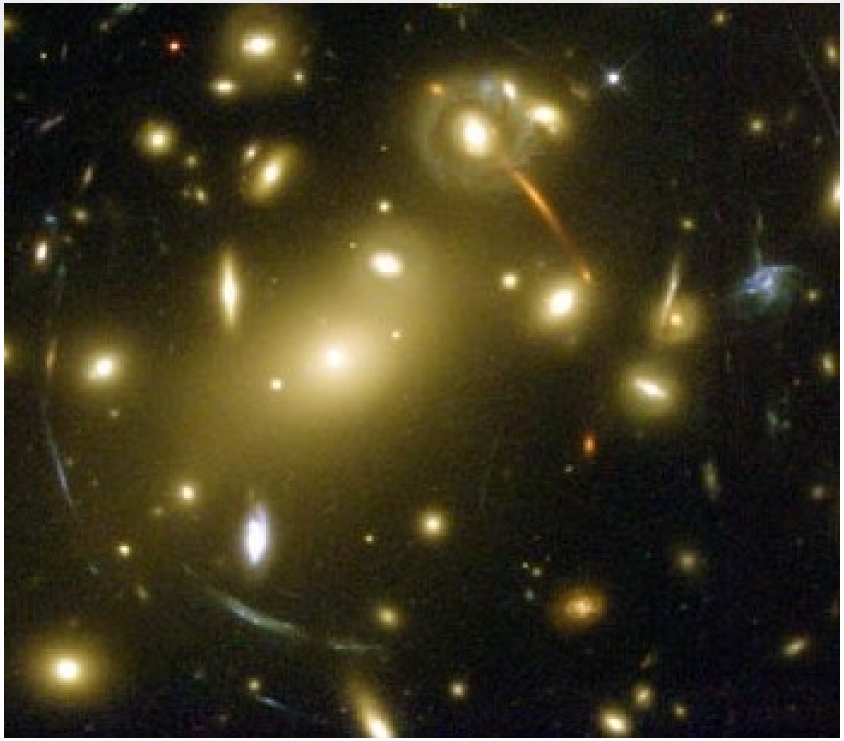



BLUE GALAXY
1
Light path
Line of sight
DARK MATTER
2
CLUSTER OF GALAXIES
Light bent by gravity
Light's normal path
EARTH
3
MILKY WAY
GRAVITATIONAL LENSING:
1 A Distant Source
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.
2 A Lens Of 'Dark Matter'
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.
3 Focal Point: Earth
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.
Source: Bell Labs, Lucent Technologies
Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/ The New York Times

In 1997, a Hubble Space Telescope image revealed light from a distant galaxy cluster being bent by another cluster in the foreground.

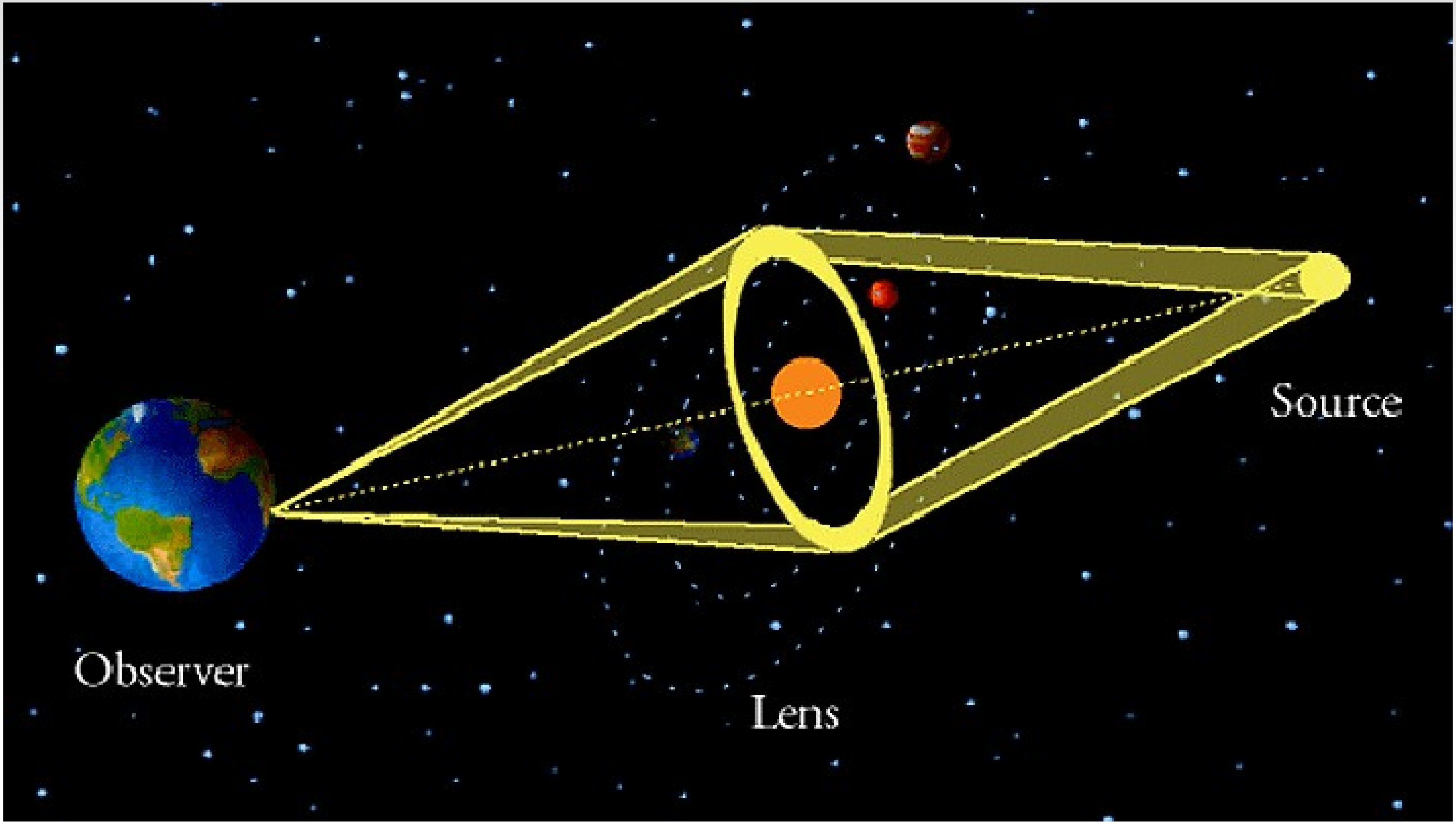
Based on the way the light was bent, it is estimated the mass of the foreground cluster to be 250 times greater than the visible matter in the cluster.

It is believed that dark matter in the cluster accounts for the unexplained mass.



Gravitational Lens Created by Galaxy Cluster Reveals Presence of Dark Matter

Lensing



Bullet Cluster

WHO: The "Bullet Cluster," named for its distinctive shape, is formally known as 1E 0657-56, and is the result of the collision of two enormous clusters of galaxies.

WHAT: The collision that created the Bullet Cluster was one of the most energetic events since the Big Bang.

WHERE: At a distance of nearly 4 billion light years from Earth, the Bullet Cluster is located in the constellation Carina, or the "keel" (bottom of a ship).

WHEN: The speed and shape of the bullet, and other information from various telescopes suggest that the smaller cluster passed through the core of the larger one about 150 million years earlier.

HOW: When these two enormous objects collided, they did so at speeds of several million miles an hour. The force of this event was so great that it wrenched the "normal" matter in the form of hot gas (seen in pink) away from the dark matter (blue).

WHY: The separation between the hot gas and the dark matter in this system is direct evidence that dark matter does, in fact, exist. The exact nature of dark matter remains unknown, but it is thought to account for about 25% of the matter in the Universe.

More at: http://chandra.harvard.edu

Bullet Cluster

Dark Matter Hunt

Through Direct Detection

CDMS II

CoGeNT

CRESST II

XENON 100

LUX

Through Indirect Detection

Final products of Dark Matter Annihilation, e.g. Gamma Ray, neutrinos etc.

Types of Dark Matter

- ***Cold Dark Matter (WIMP)***

  moves very non-relativistically, so has a short free-streaming length

- ***Hot Dark Matter***

  moves relativistically

- ***Warm Dark Matter***

- ***Baryonic DM***
- ***Non-baryonic DM***

WIMP Hunting

- ➔ **Hadron colliders** produce WIMPs through decays of new particles
  - – e.g., gluino production followed by a long cascade ending in a neutralino
- ➔ Production rate depends on details of the particle spectrum
  - – If a WIMP is found, it's hard to identify it with the cosmic Dark Matter
    - Does it live cosmologically long? What is its coupling?

Indirect searches rely on WIMP pair annihilation in the regions of high WIMP densities

- – e.g., Galactic center, Solar core

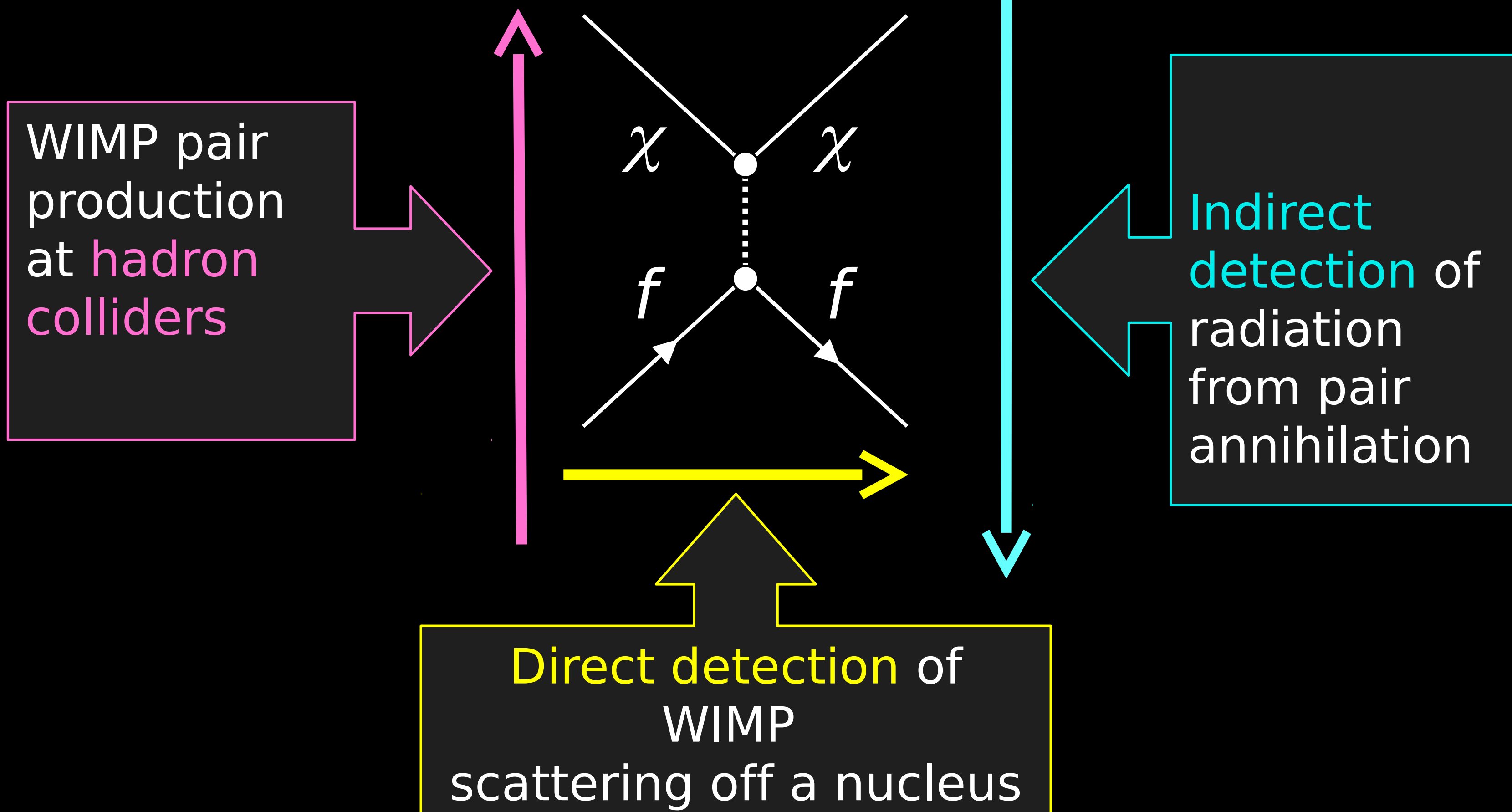
- ➔ Annihilation rate depends on the local density profile
  - – Backgrounds are poorly understood
    - Are there local sources of energetic radiations, e.g., pulsars?

Direct searches depend on the local WIMP density and velocity

- – Assumed density at solar location to be 0.3 GeV/cm^3, Maxwell distribution

WIMP Hunting

Going beyond gravity, three ways to detect WIMPs

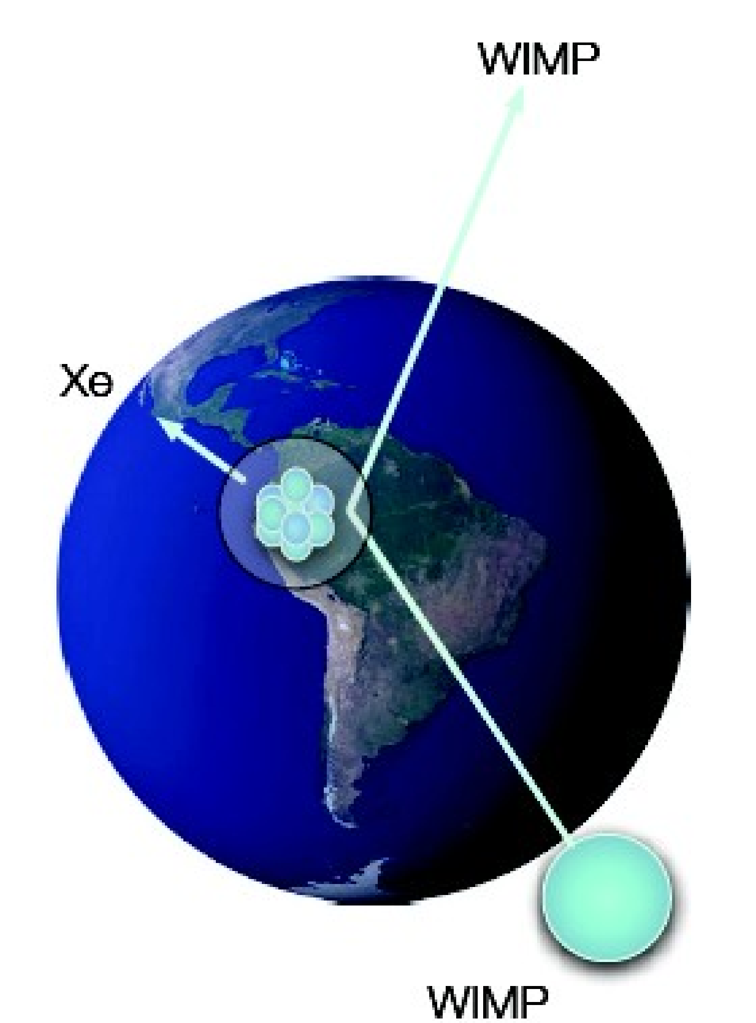


Detection of Dark Matter
Direct Detection

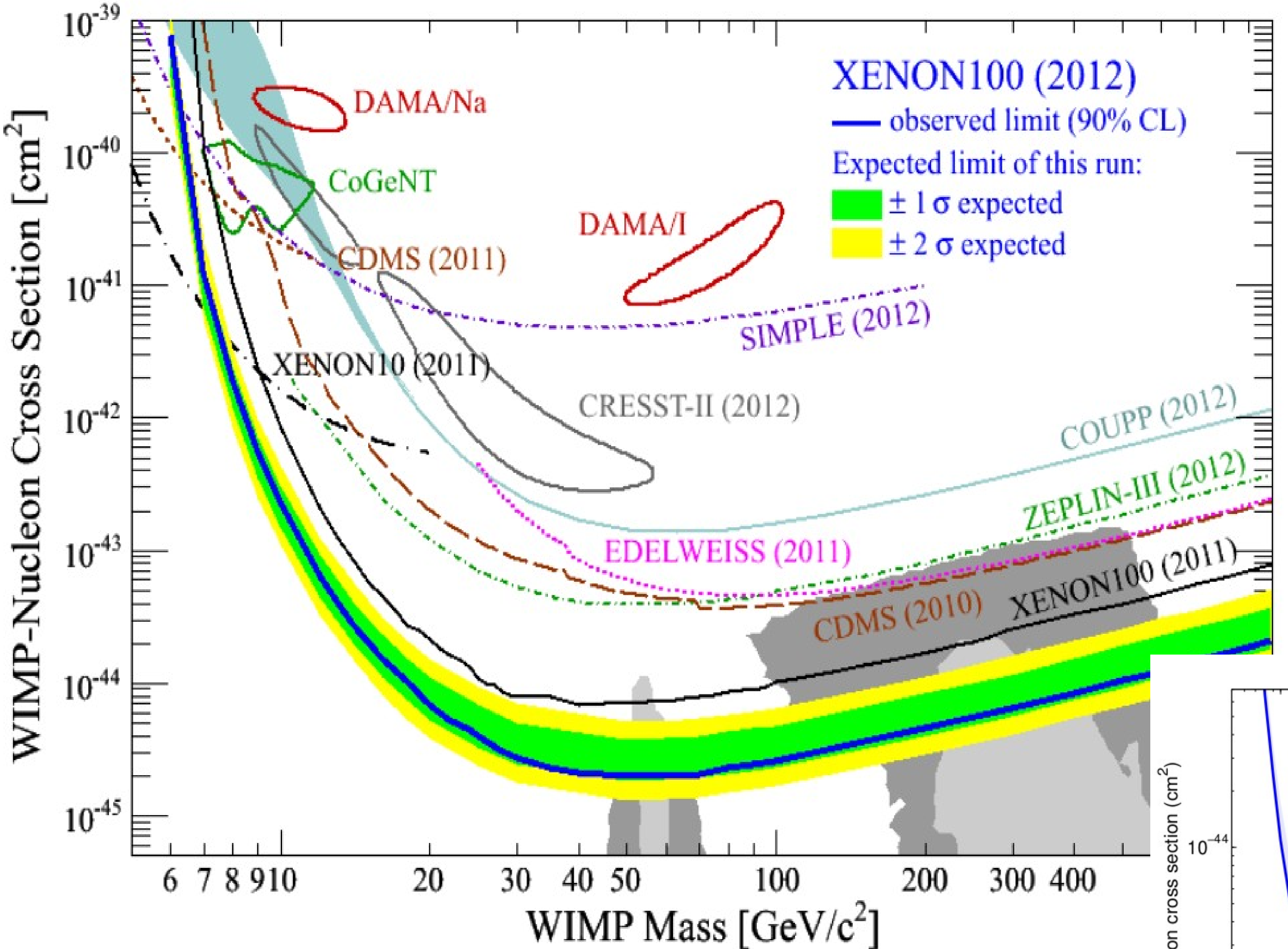
- Rotation of galactic disc through the halo of Dark Matter causes the earth to experience an apparent wind of Dark Matter

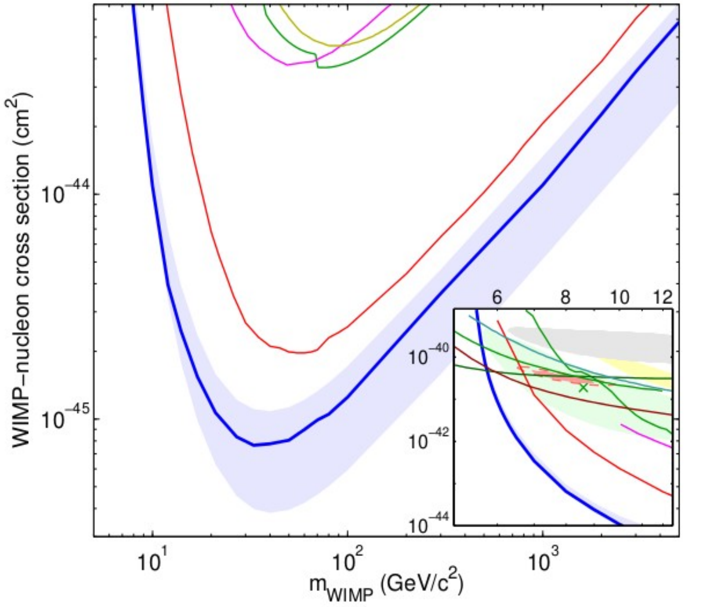
- Elastic collision of WIMP with detector nuclei

- The recoil energy of the nucleus is measured



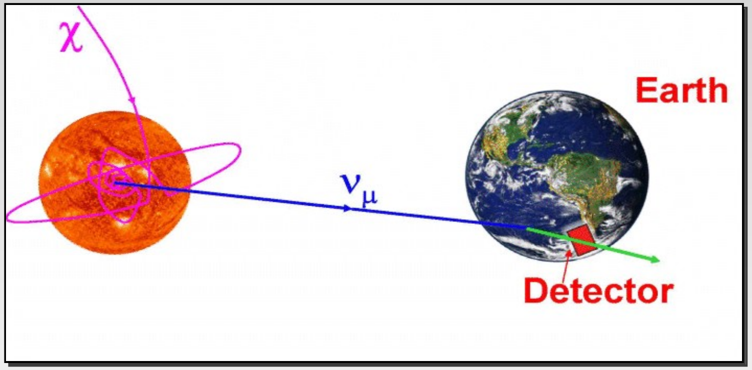
Direct Detection Results

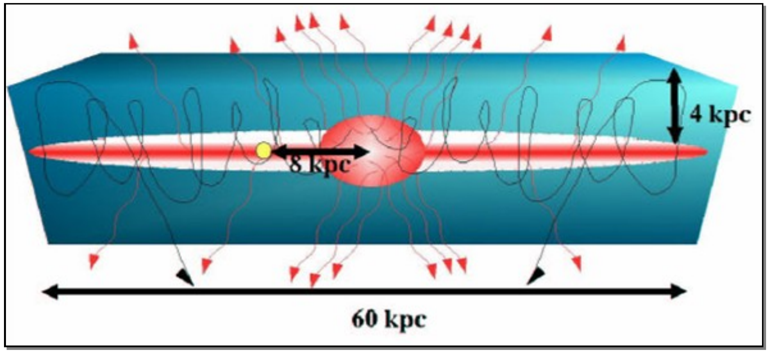




Indirect Detection of DM

- **Gamma Rays** from annihilations in the galactic halo, near the galactic center, in dwarf galaxies, etc.
- **Neutrinos** from annihilations in the core of the Sun
- **Positrons/Antiprotons** from annihilations throughout the galactic halo
- **Synchrotron Radiation** from electron/positron interactions with the magnetic fields of the inner galaxy





Indirect Detection (Signatures?)

Excess Gamma Emission from Galactic Centre Region (Fermi Gamma Ray Space Telescope (FGST) searches Gamma ray around GC)

Gamma Emission from Extragalactic sources (Fermi-LAT)

Gamma Emission from *Fermi Bubble*

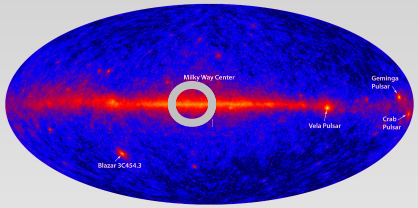
Excess positron fraction (AMS 02 @ ISS, PAMELA etc.)

Antiproton excess (BESS)

Neutrinos at ICECUBE, ANTARES ?

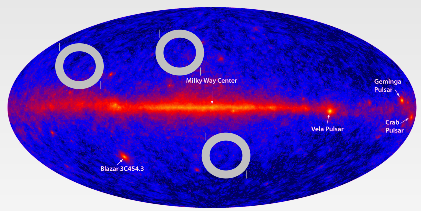
Targets for Indirect Detection of Dark Matter

Galactic Centre



Strongest signal expected, most difficult background
Hard sources, not well understood diffuse emission

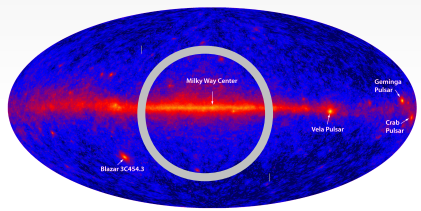
Dwarf galaxies and Galaxy Clusters



Dwarfs: weak signal, but relatively well controlled Dark Matter Distribution and essentially no background (if at high latitude).

Clusters: DM density not well constrained, but provides boost factor (extended emission), so good for discovery (if lucky)

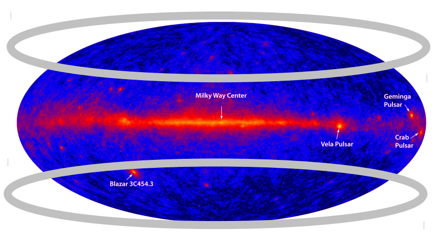
Galactic Halo



Fermi-LAT: spatial and spectral discrimination, good statititstics, extreme freedom in galactic diffuse emission.

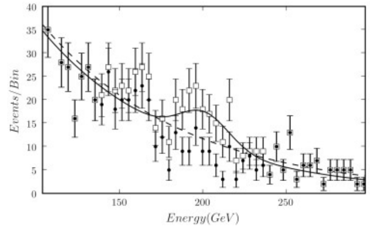
IACT: best potential, small systematics due to diffuse emission, ~100 hour observation time (GC halo)

Extra Galactic



Very model dependent, good as target for spatial analysis.

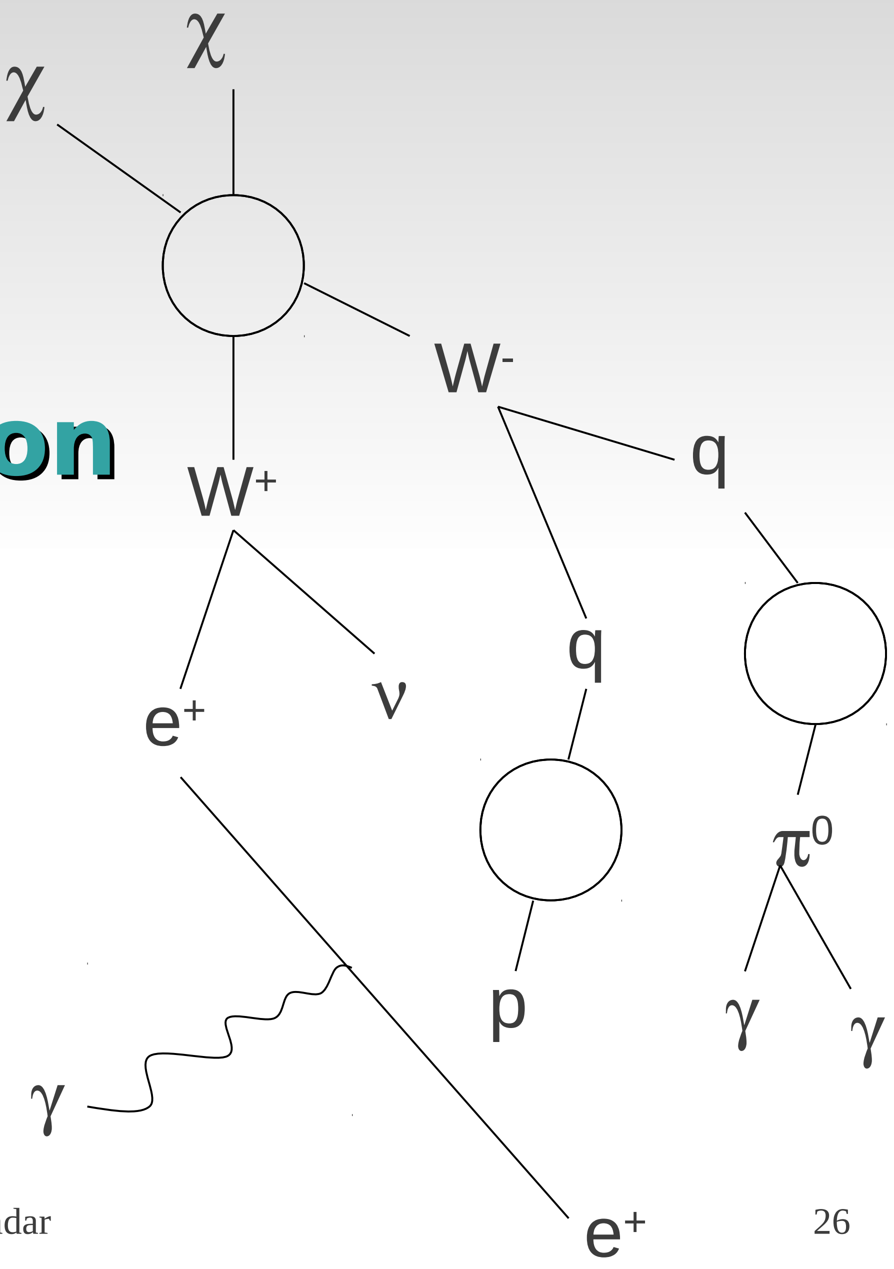
Lines



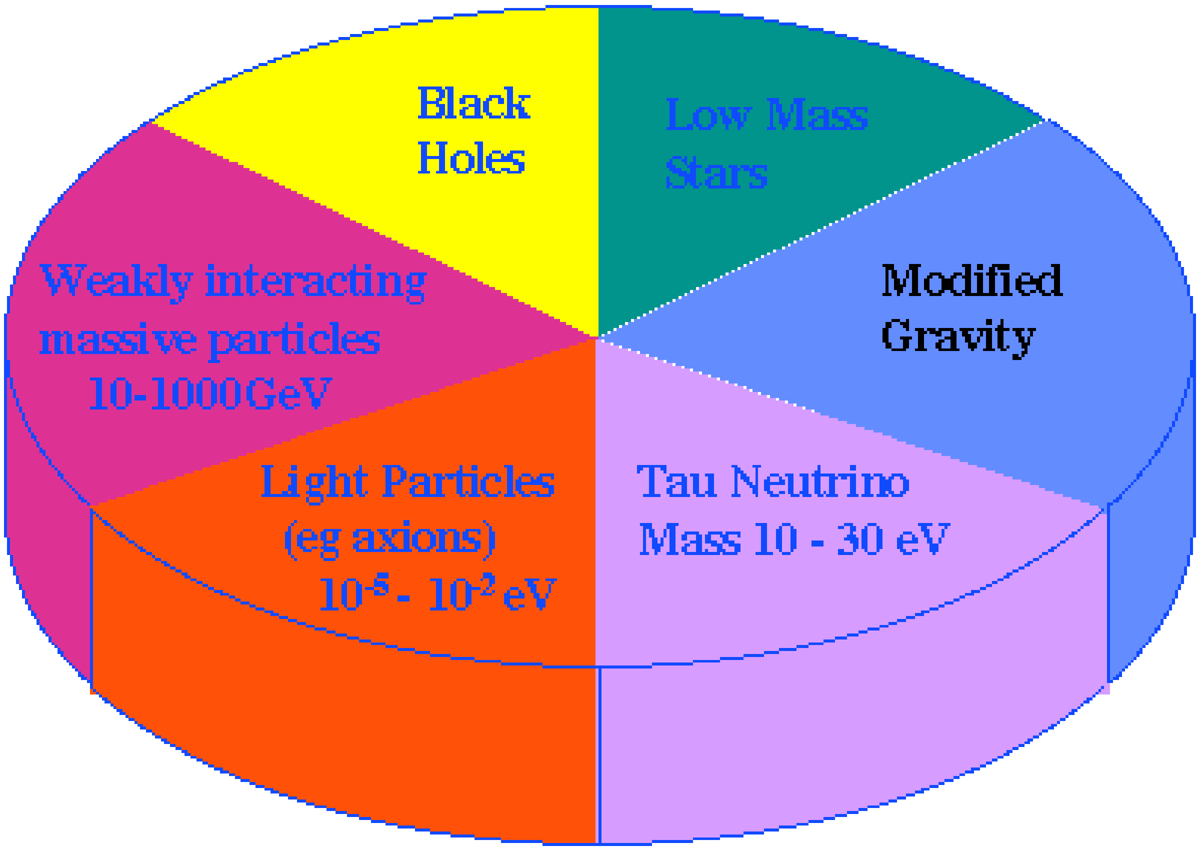
Smoking gun*, got to get lucky.

Indirect Detection of DM

- **Annihilation**
- **Fragmentation**
- **Synchrotron Radiation**



Likely Candidates for Dark Matter



A Model for Dark Matter

Inert Doublet Model

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h^0 + iG^0\right) \end{pmatrix}, \qquad \Phi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(H^0 + iA^0\right) \end{pmatrix};$$

$$H = (0, v) \qquad \Phi = -\Phi \qquad \Phi = (0, 0)$$

$$V_0 = \mu_1^2|H|^2 + \mu_2^2|\Phi|^2 + \lambda_1|H|^4 + \lambda_2|\Phi|^4 + \lambda_3|H|^2|\Phi|^2 + \lambda_4|H^\dagger\Phi|^2 + \frac{\lambda_5}{2}\left[(H^\dagger\Phi)^2 + \text{h.c.}\right]$$

$$\begin{aligned} M_{h^0}^2 &= -2\mu_1^2 = 2\lambda_1 v^2 \ , \\ M_{H^0}^2 &= \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2 = \mu_2^2 + \lambda_L v^2 \ , \\ M_{A^0}^2 &= \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2 = \mu_2^2 + \lambda_S v^2 \ , \\ M_{H^\pm}^2 &= \mu_2^2 + \frac{1}{2}\lambda_3 v^2 \ . \end{aligned}$$

$$\lambda_L = \frac{1}{2}\left(\lambda_3 + \lambda_4 + \lambda_5\right), \qquad \lambda_S = \frac{1}{2}\left(\lambda_3 + \lambda_4 - \lambda_5\right).$$

Inert Doublet Model (contd.)

$$\{\lambda_1, \quad \lambda_2, \quad \lambda_3, \quad \lambda_4, \quad \lambda_5, \quad \mu_2\}$$

$$\{M_{h^0}, \quad M_{H^0}, \quad M_{A^0}, \quad M_{H^\pm}, \quad \lambda_L, \quad \lambda_2\}$$

Constraints

Perturbative calculations $|\lambda_i| < 8\pi$

Vacuum stability conditions

$$\lambda_{1,2} > 0 \quad \text{and} \quad \lambda_3 + \lambda_4 - |\lambda_5| + 2\sqrt{\lambda_1\lambda_2} > 0 \quad \text{and} \quad \lambda_3 + 2\sqrt{\lambda_1\lambda_2} > 0$$

Unitarity Conditions

$$\lambda_3 \pm \lambda_4 < 8\pi \quad , \quad \lambda_3 \pm \lambda_5 < 8\pi \quad ,$$

$$\lambda_3 + 2\lambda_4 \pm 3\lambda_5 < 8\pi \quad , \quad -\lambda_1 - \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + \lambda_4^2} < 8\pi \quad ,$$

$$-3\lambda_1 - 3\lambda_2 \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + (2\lambda_3 + \lambda_4)^2} < 8\pi \quad ,$$

$$-\lambda_1 - \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + \lambda_5^2} < 8\pi \quad .$$

Constraints (contd.)

LEP measurements of Z decay width

$$M_{H^0} + M_{A^0} \geq M_Z \text{ and } 2M_{H^\pm} \geq M_Z$$

ALTAS and CMS bounds on diphoton signal strengths (LHC Constraints)

$$R_{\gamma\gamma} \equiv \frac{\sigma(gg \to h) \times \mathrm{BR}(h \to \gamma\gamma)}{\sigma(gg \to h)^{\mathrm{SM}} \times \mathrm{BR}(h \to \gamma\gamma)^{\mathrm{SM}}}$$

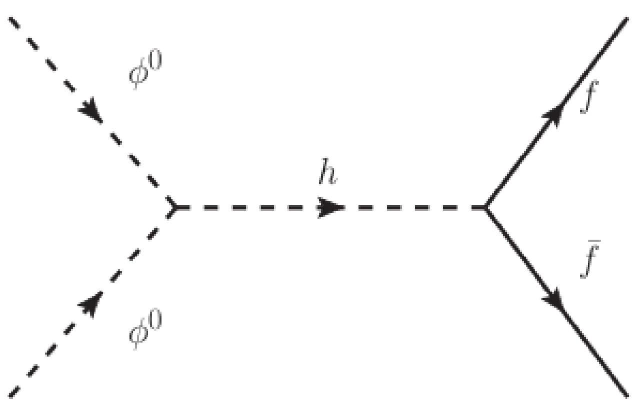
$1.55^{+0.33}_{-0.28}$ (ATLAS) 0.78 ± 0.28 (CMS)

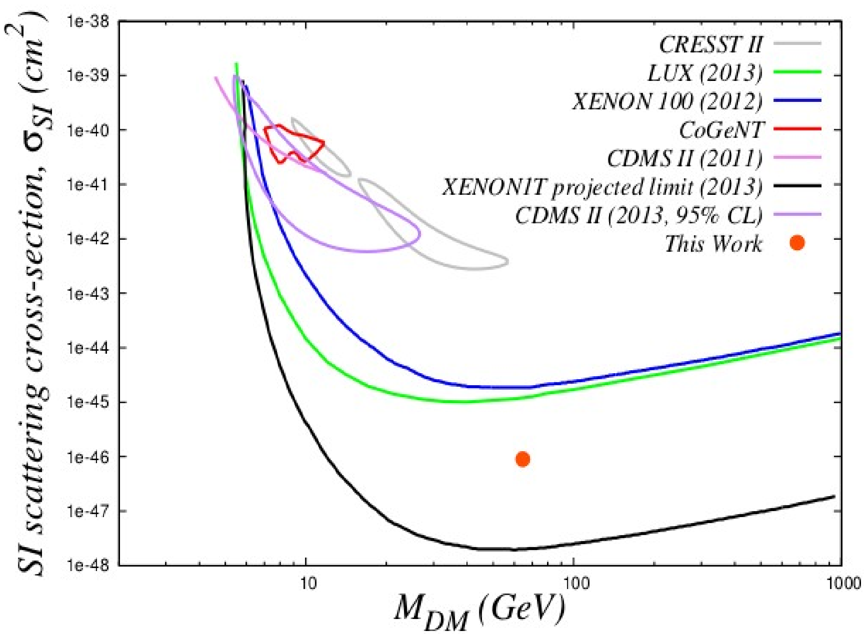
PLANCK bound on CDM relic density

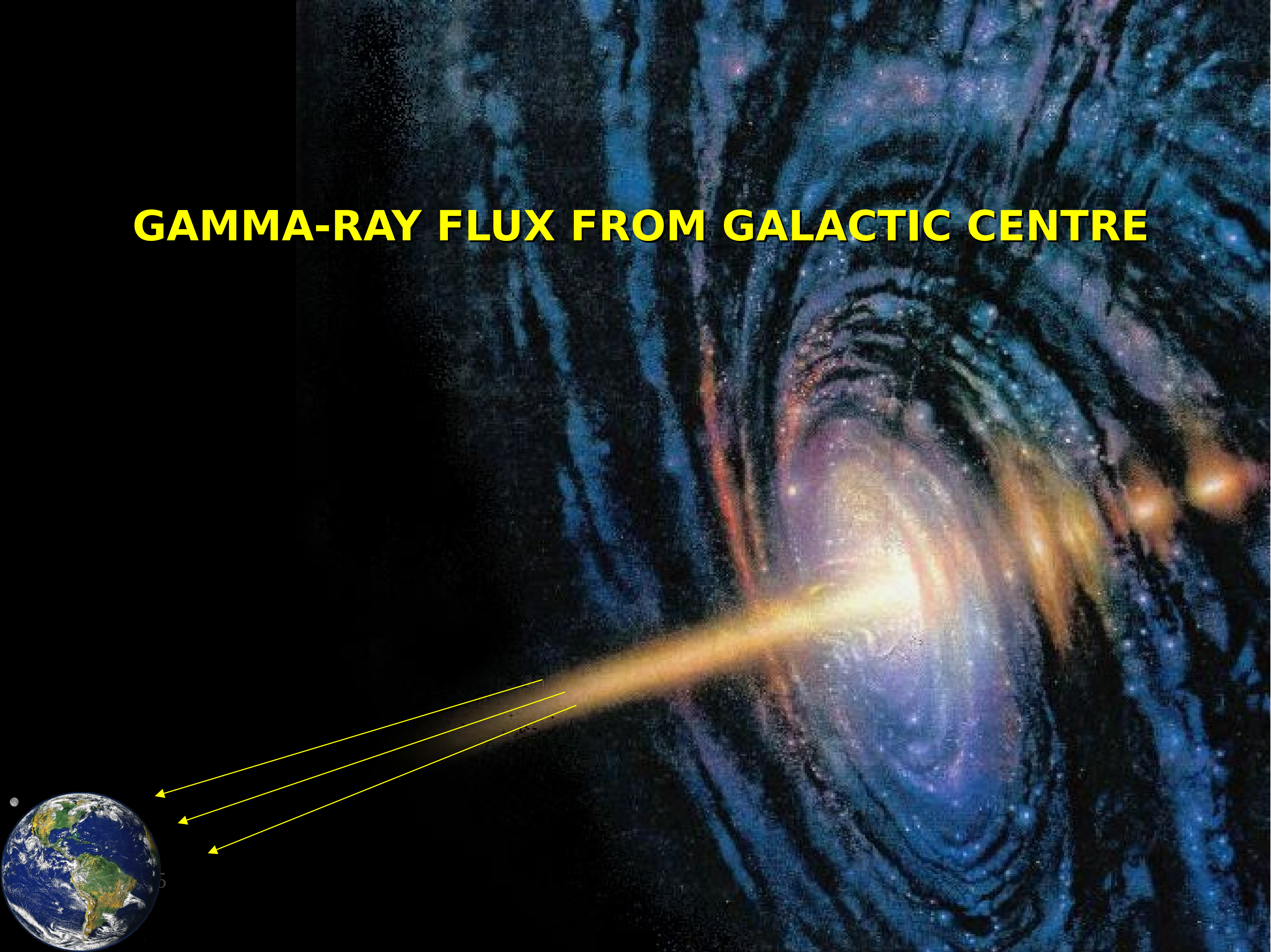
$$\Omega_{\mathrm{DM}} = 0.1199 \pm 0.0027$$

Best Fit Point for Low Mass DM in IHDM

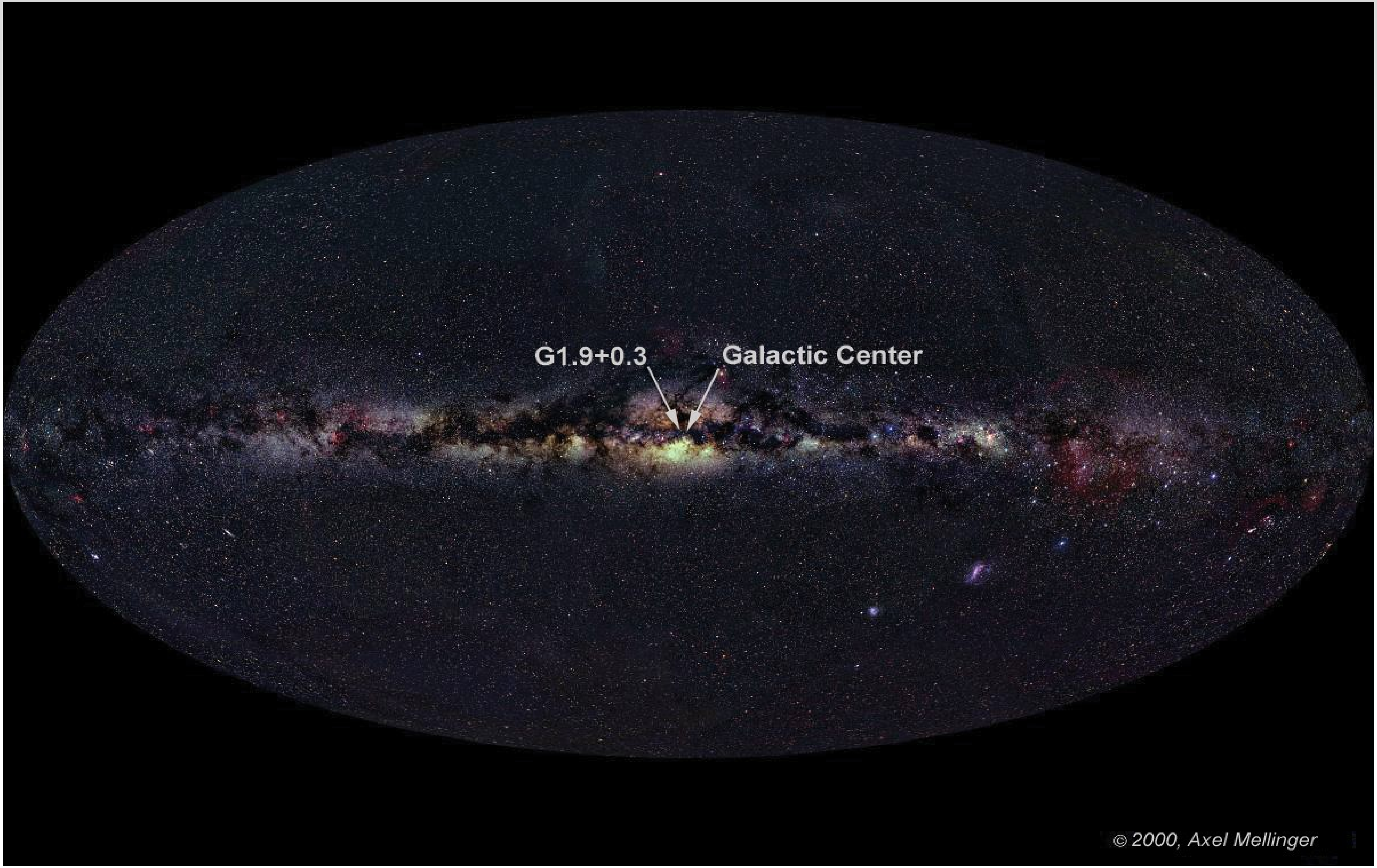
Model Parameters	M_{h^0} (GeV)	$M_{H^\pm}$ (GeV)	M_{H^0} (GeV)	M_{A^0} (GeV)	λ_L	λ_2
	126.016	73.78	63.54	166.16	-3.29×10^{-3}	5.67×10^{-4}
DM Observables	Ωh^2		$\langle \sigma v \rangle$ (cm^{3}s^{-1})		$\sigma_{\rm SI}$ (pb)	
	0.1173		2.37×10^{-26}		8.89×10^{-11}	
Annihilation Cross-section	$H^0H^0 \to b\bar{b}$	$H^0H^0 \to W^+W^-$	$H^0H^0 \to gg$	$H^0H^0 \to l\bar{l}$	$H^0H^0 \to c\bar{c}$	$H^0H^0 \to ZZ$
	69.2%	9.61%	9.49%	7.37%	3.29%	0.48%





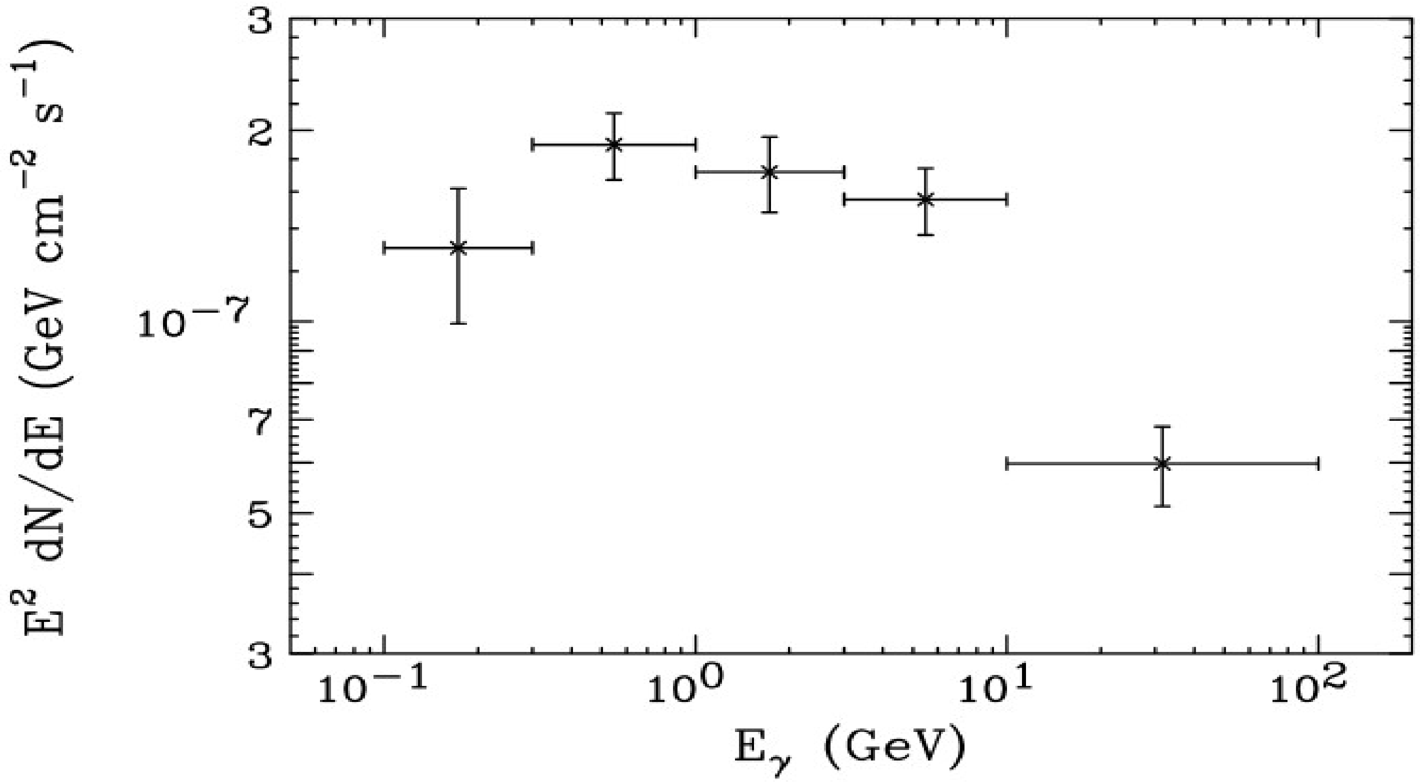

GAMMA-RAY FLUX FROM GALACTIC CENTRE

Galactic Centre : a suitable target



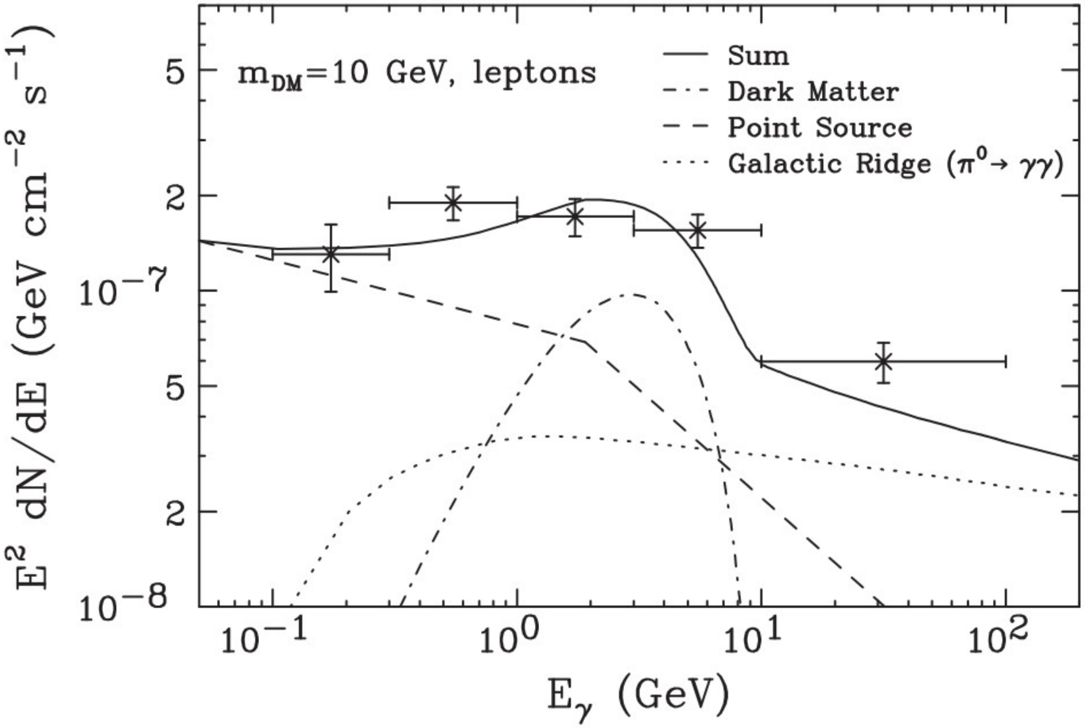
Galactic Centre : a suitable target

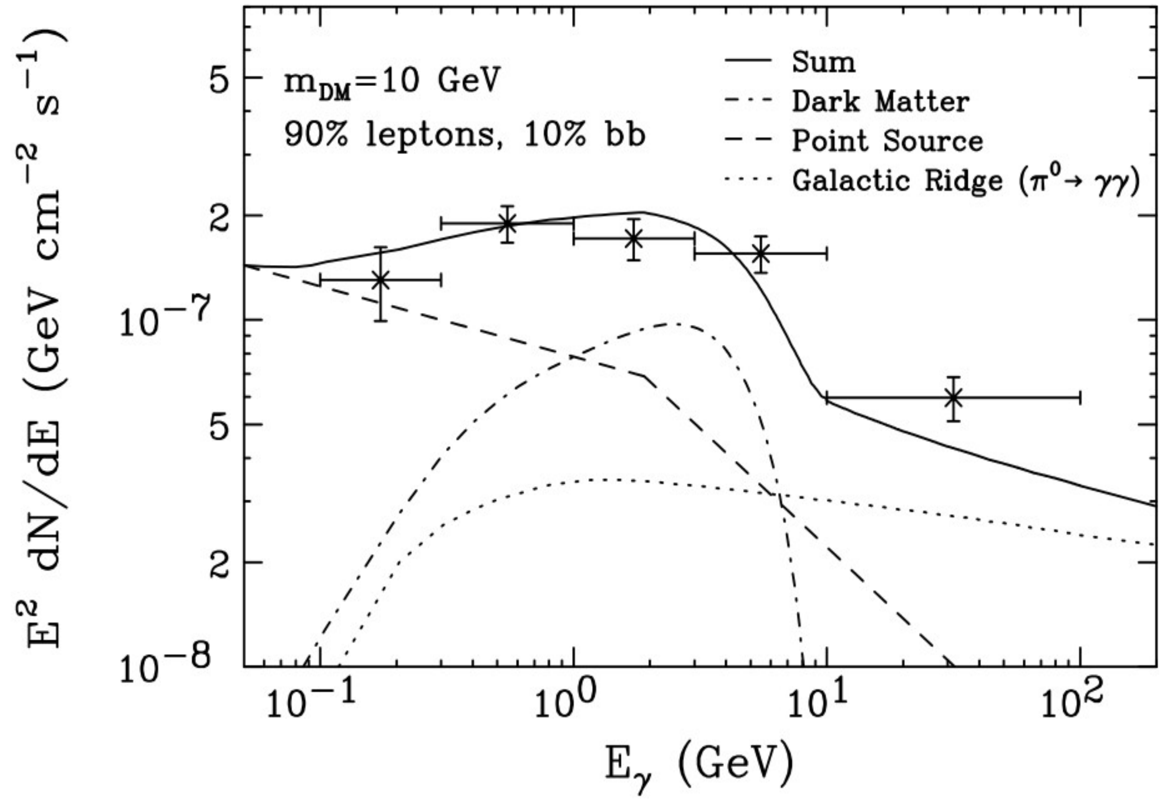
Hint of Dark Matter around 10 GeV



Observed gamma flux bump from 5 degree around GC by FGST

Fits to DM proposals





Calculation of gamma-ray flux

$$\frac{d\Phi_\gamma}{d\Omega dE_\gamma} = \frac{1}{8\pi\alpha} \sum_f \frac{\langle \sigma v \rangle_f}{M^2_{H^0,A^0}} \frac{dN^f_\gamma}{dE_\gamma} r_\odot \rho^2_\odot J$$

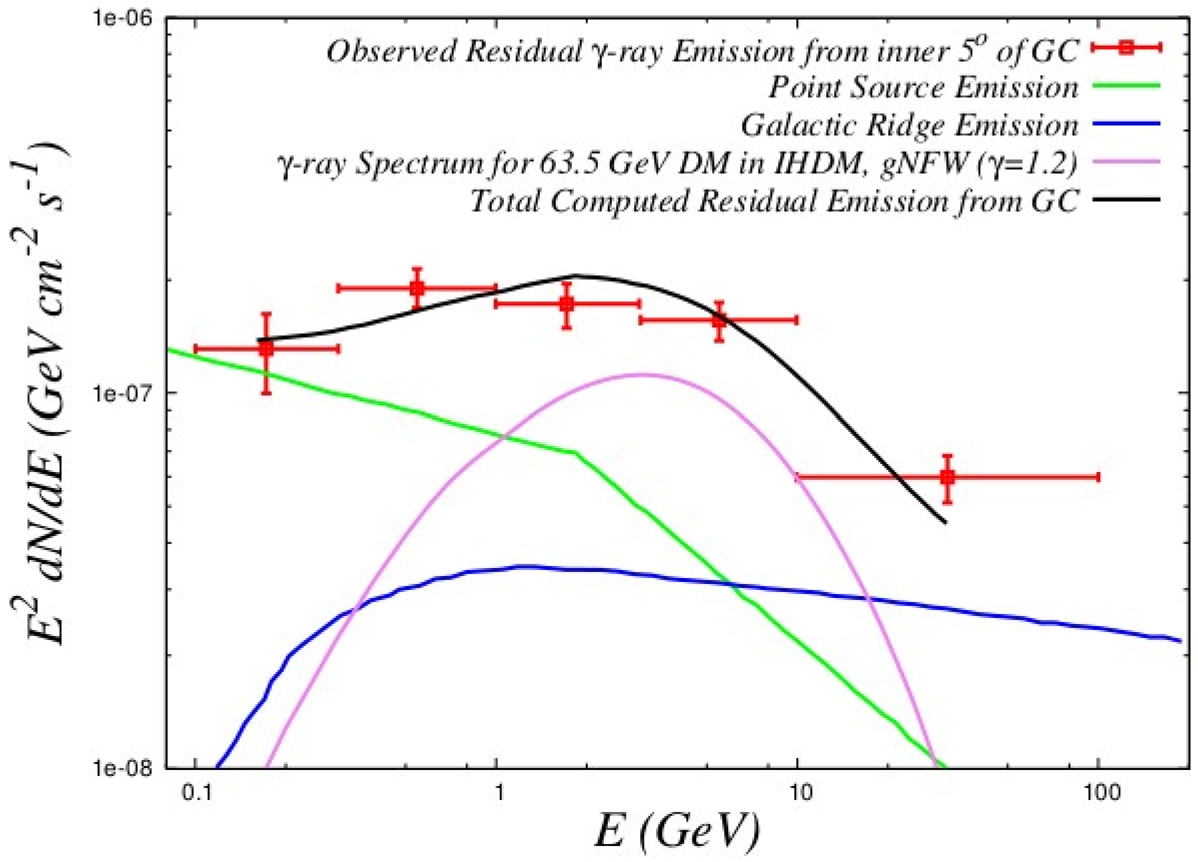
$$J = \int_{l.o.s} \frac{ds}{r_\odot} \left(\frac{\rho(r)}{\rho_\odot} \right)^2$$

$$r = \begin{cases} \left(s^2 + r^2_\odot - 2sr_\odot \cos l \cos b\right)^{1/2} & \text{(galactic } l, b \text{ coordinate)} \\ \left(s^2 + r^2_\odot - 2sr_\odot \cos\theta\right)^{1/2} & \text{(galactic } r, \theta \text{ coordinate)} \end{cases}$$

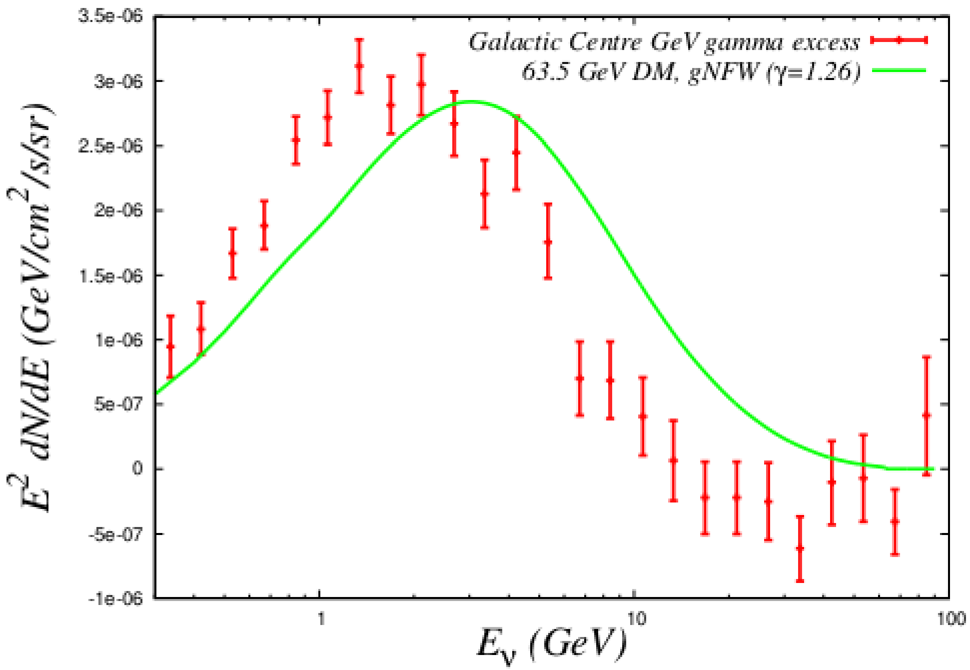
$$\rho(r) = \frac{\rho_0}{(r/r_c)^\gamma [1 + (r/r_c)^\gamma]^{(3.0-\gamma)}}$$

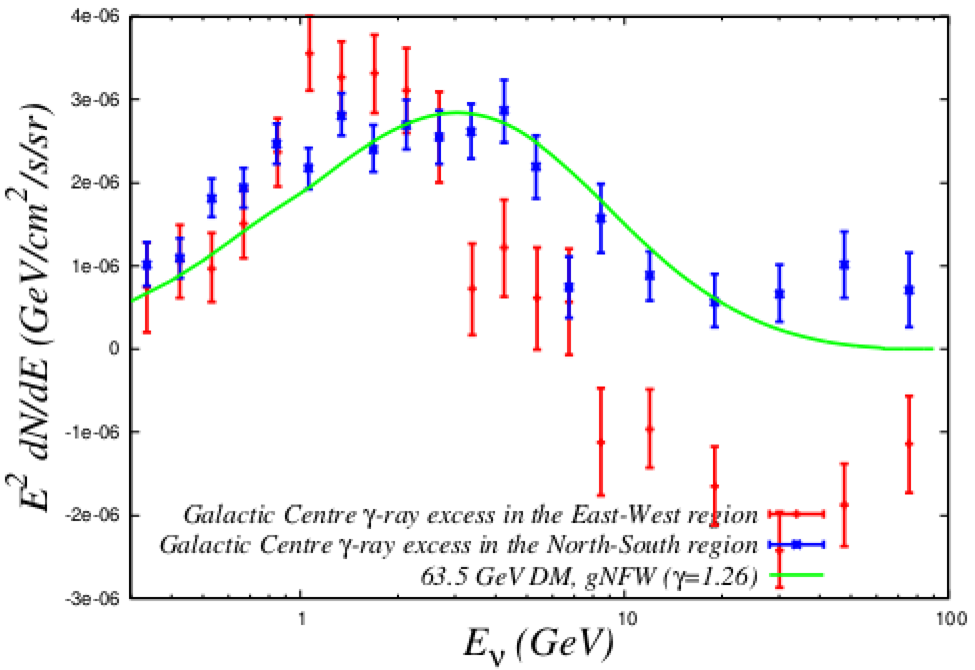
$$\langle \sigma \mathrm{v}_{\phi^0\phi^0 \to f\bar{f}} \rangle = \left(\frac{g_{\phi^0\phi^0 h}}{v} \right)^2 \frac{m_f^2}{\pi} \frac{\left(1 - \frac{m_f^2}{m^2_{\phi^0}}\right)^{3/2}}{\left[(4m^2_{\phi^0} - m_h^2)^2 + (\Gamma_h m_h)^2\right]} ,$$

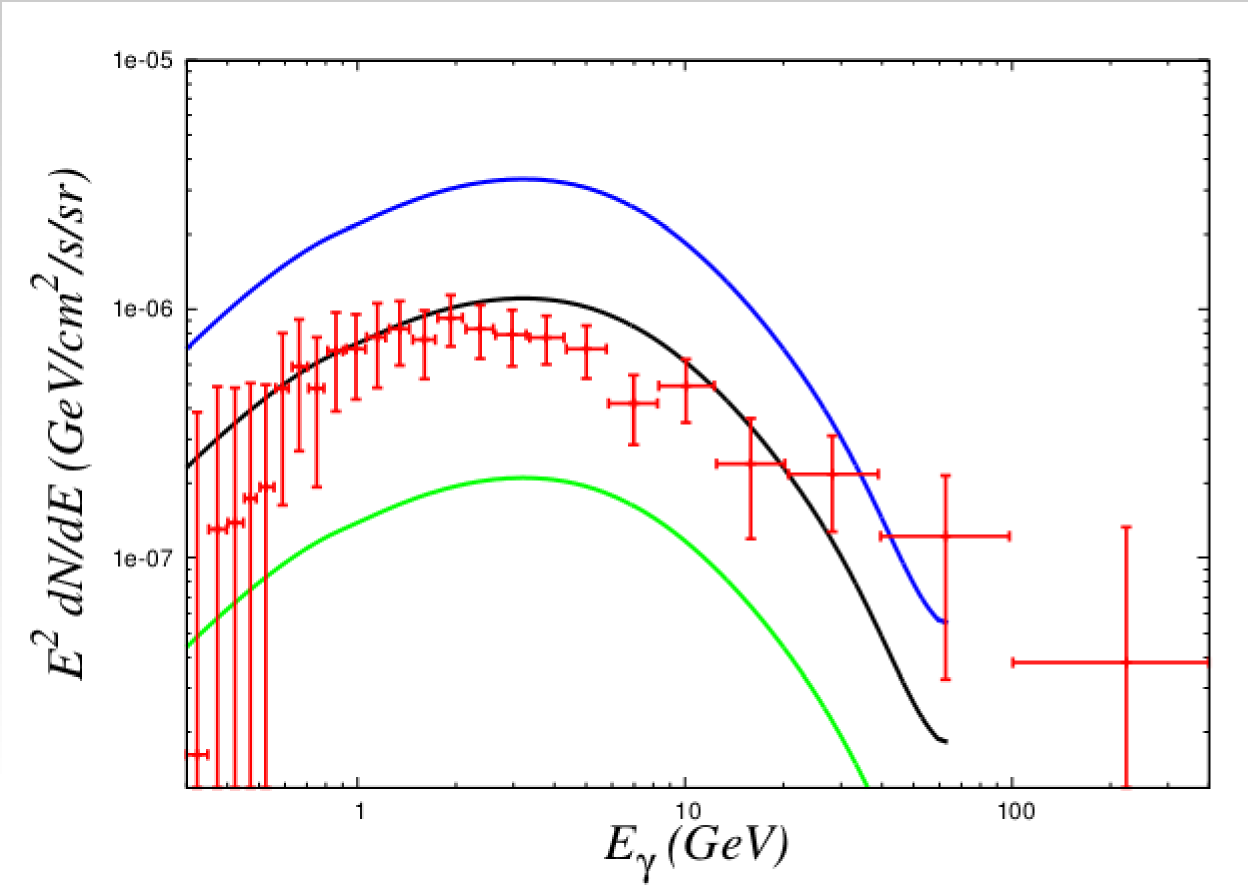
GAMMA-RAY FLUX FROM 5 DEGREE AROUND GALACTIC CENTRE



~1-3 GeV Gamma-Ray Excess from 5 deg around GALACTIC CENTRE







$$20^\circ \times 20^\circ \ (-20^\circ < \ell < 20^\circ,\ -20^\circ < b < 20^\circ)$$

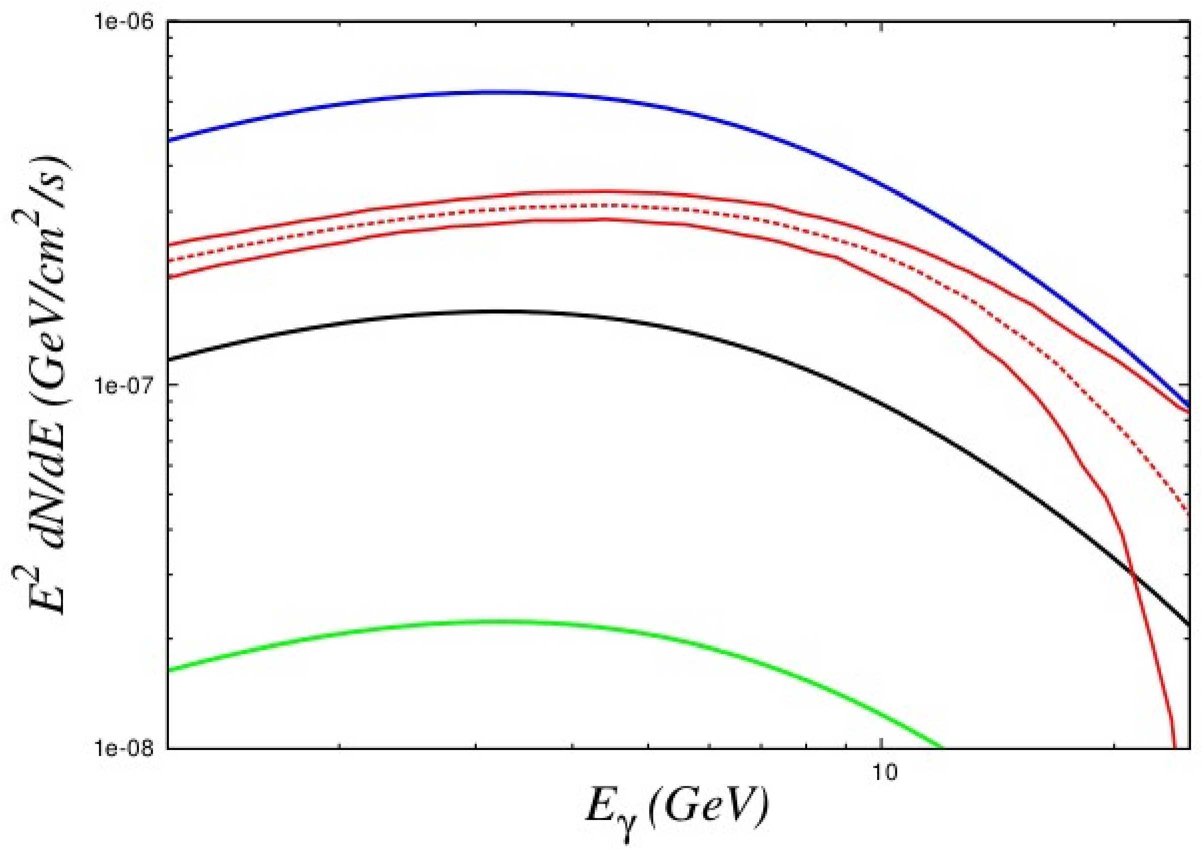
with $2^\circ \ (|b| < 2^\circ)$ region masked out

Arxiv:1409.0042[hep.ph]

$$\bar{J} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} J(\psi)d\Omega \equiv \mathbb{J} \times \bar{J}_{\rm canonical}$$

$$\bar{J}_{\rm canonical} = 2.0 \times 10^{23}\ {\rm GeV}^2\ {\rm cm}^{-5}$$

$$\mathbb{J} \in [0.19, 3]$$



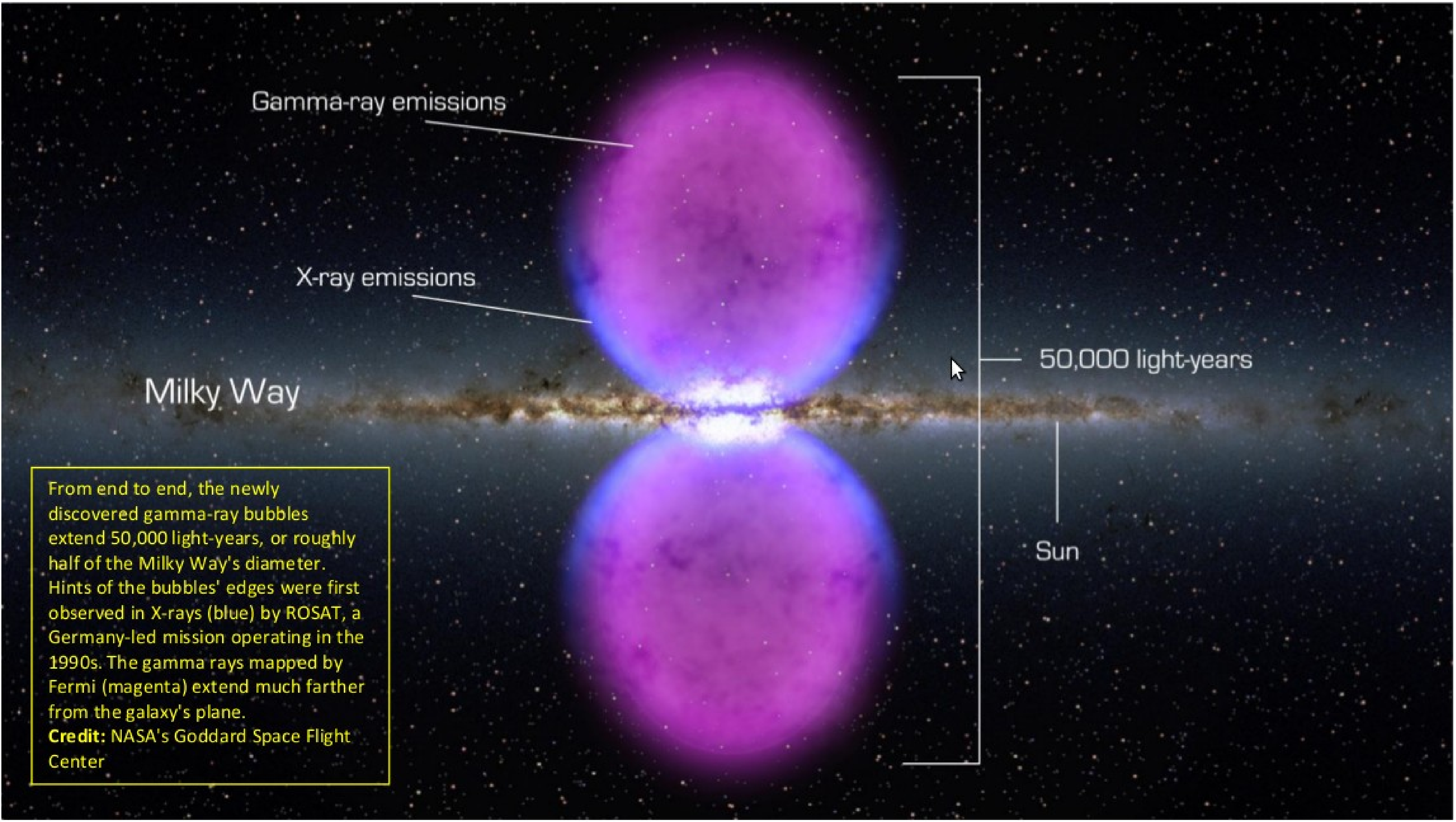
S. Murgia et al.
(Fermi Collaboration)

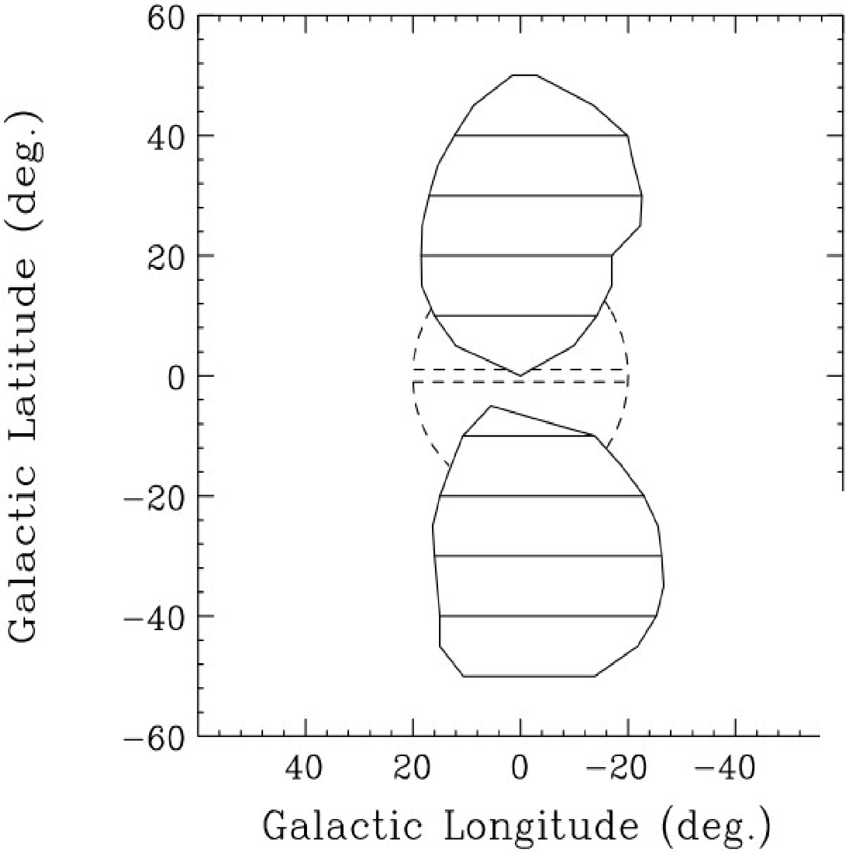
$15^\circ \times 15^\circ$ region subtending the galactic centre

$$\bar{J} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} J(\psi)d\Omega \equiv \mathbb{J} \times \bar{J}_{\text{canonical}} \qquad \bar{J}_{\text{canonical}} = 1.58 \times 10^{24}\ \text{GeV}^2\ \text{cm}^{-5}$$

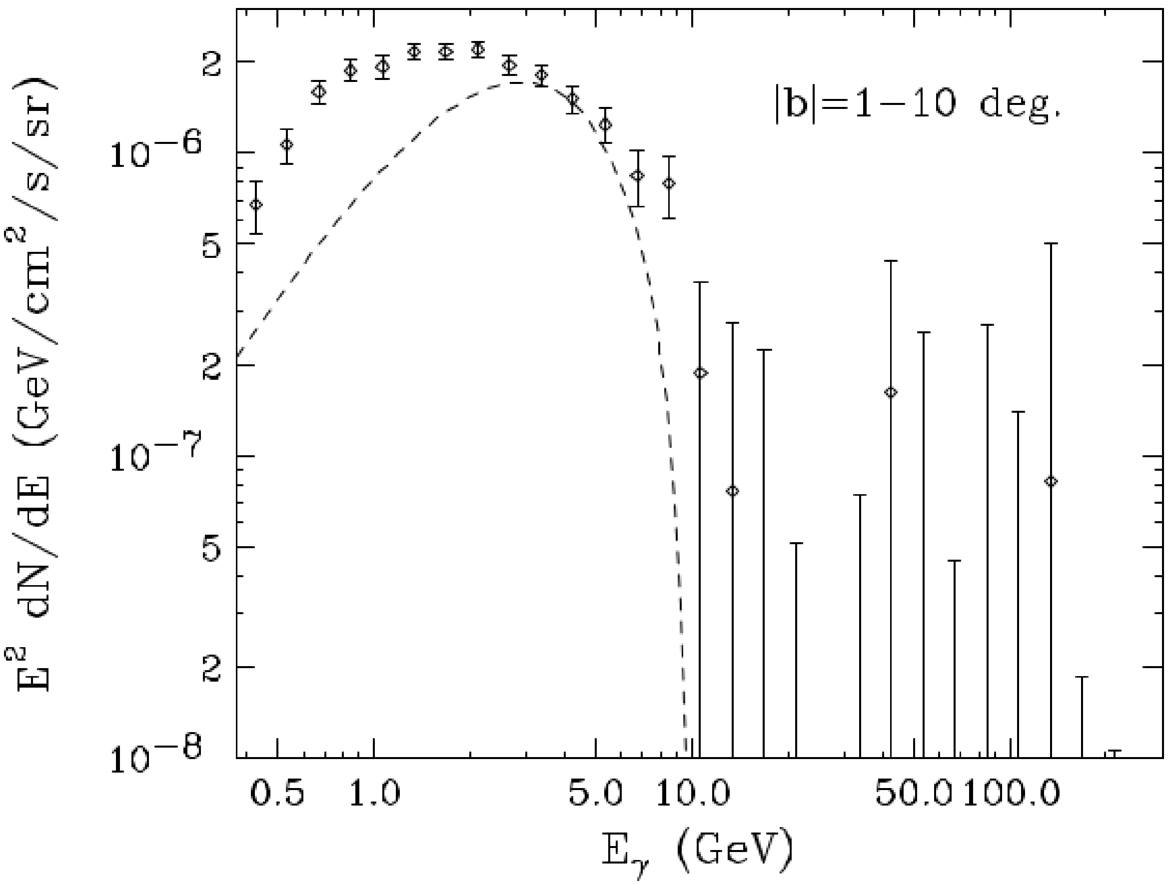
$$\mathbb{J} \in [0.14, 4.0]$$

Fermi Bubble

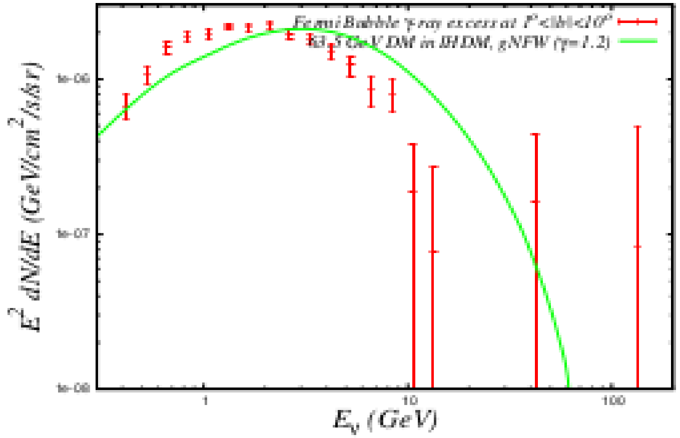


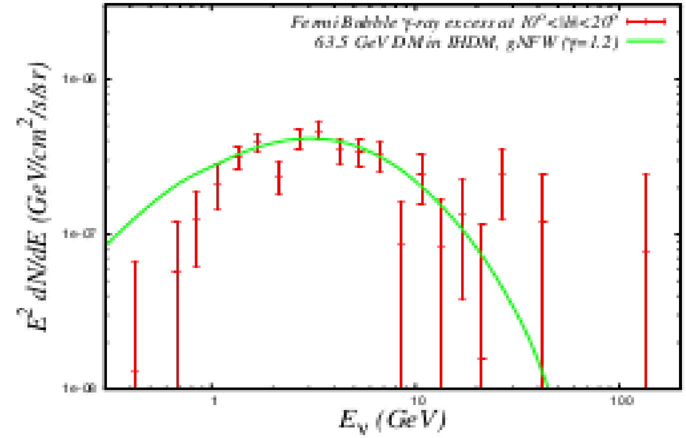


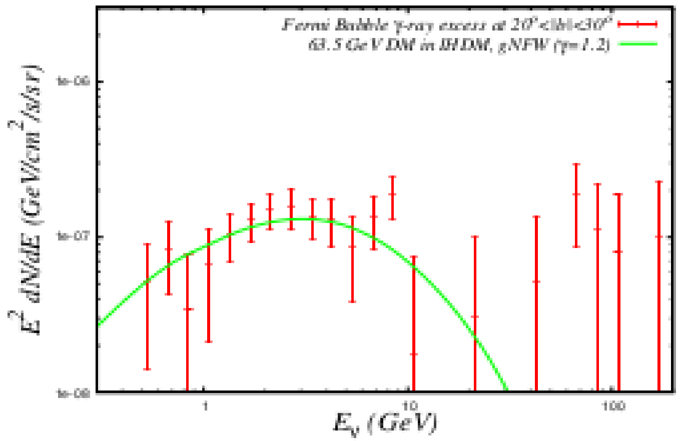
Galactic Latitude (deg.)
Galactic Longitude (deg.)

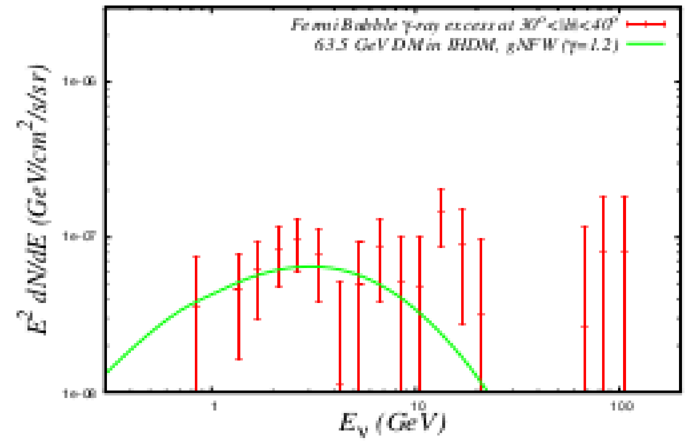


|b|=1−10 deg.
E² dN/dE (GeV/cm²/s/sr)
E_γ (GeV)

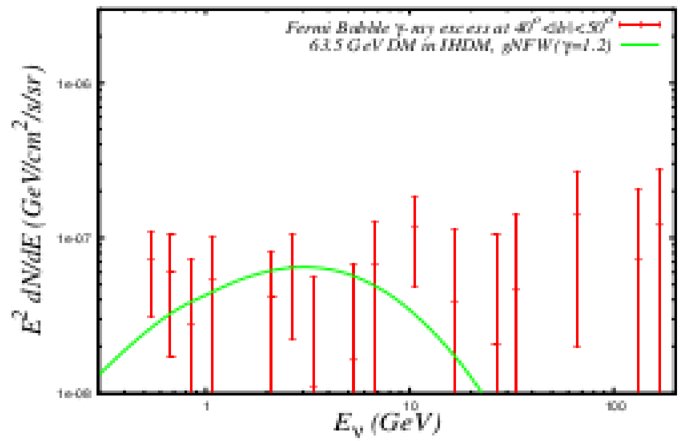




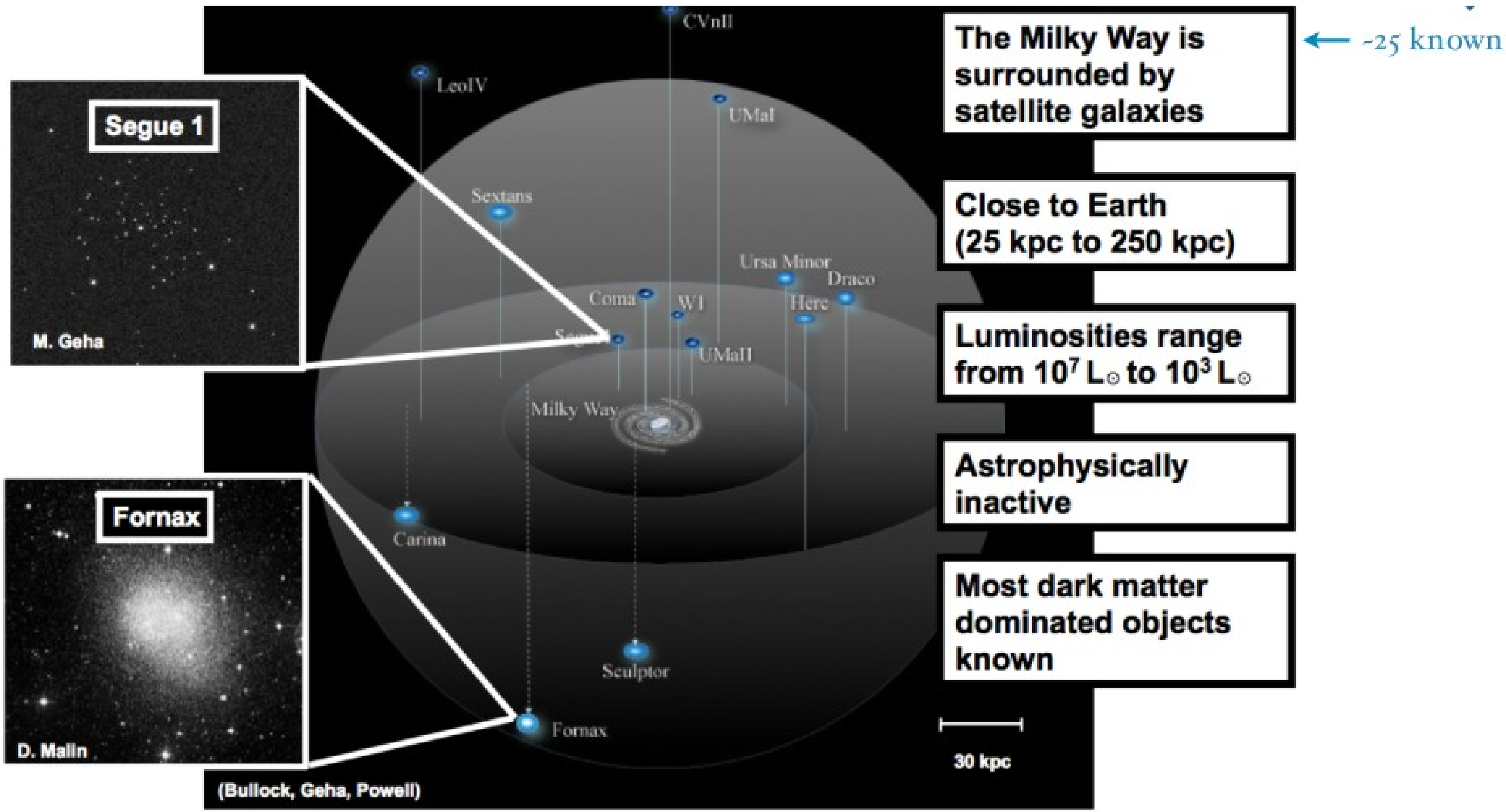




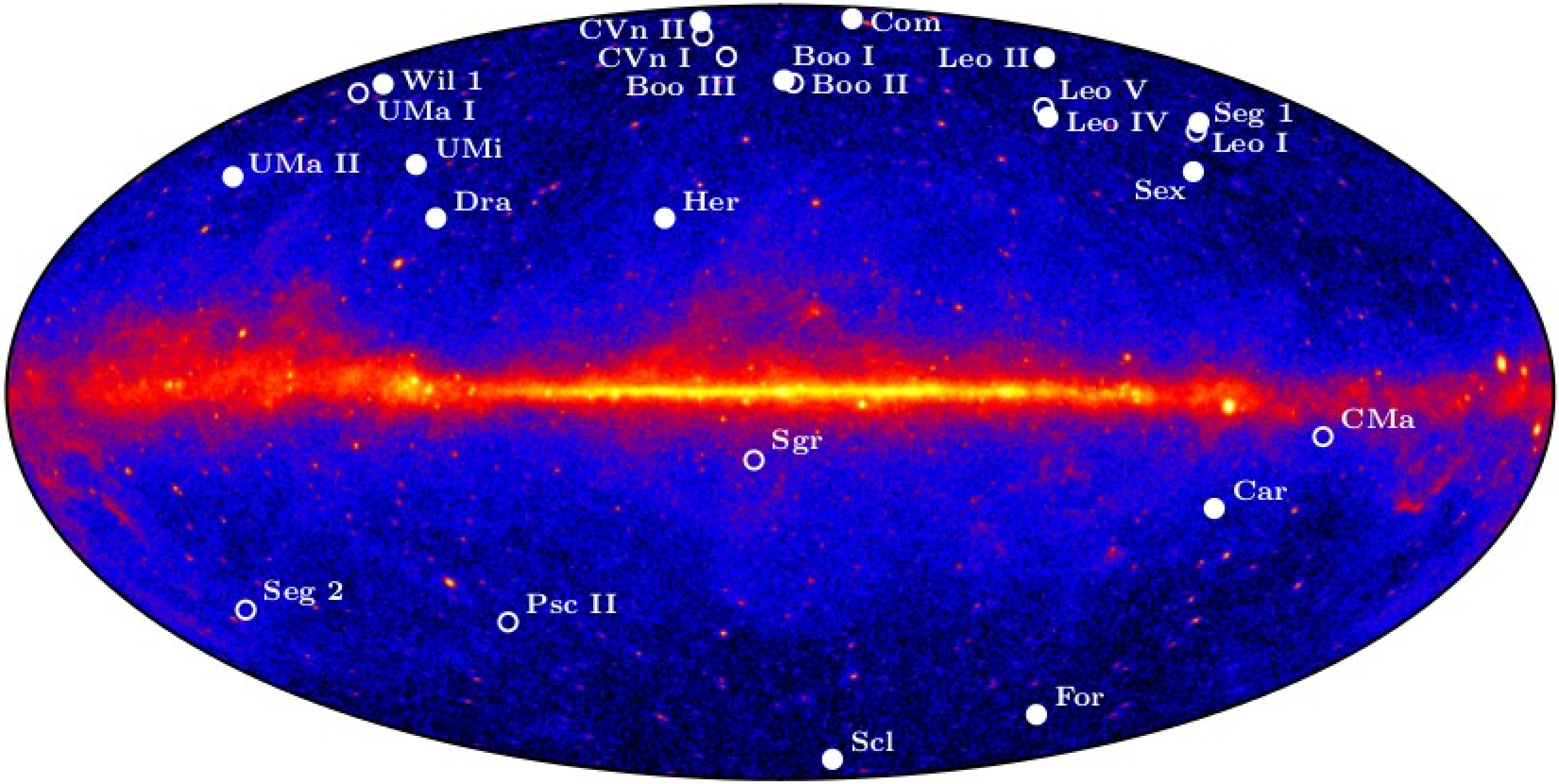
Comparing with Fermi Bubble



Dwarf Spheroidal Galaxies (dSphs)



Dwarf Spheroidal Galaxies (dSphs)



Positions of 25 dSphs observed so far

Limits on dark matter from dSphs

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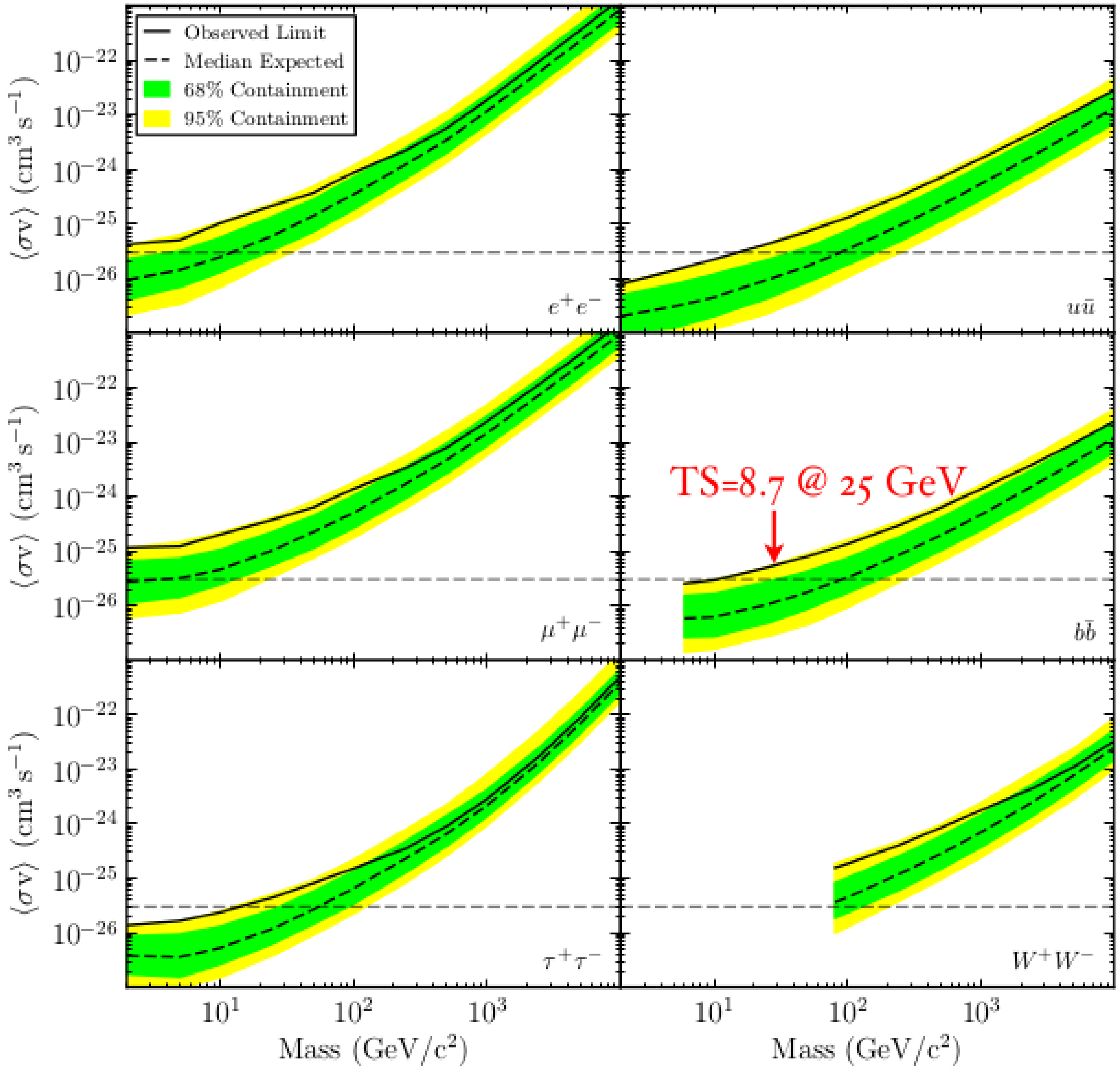
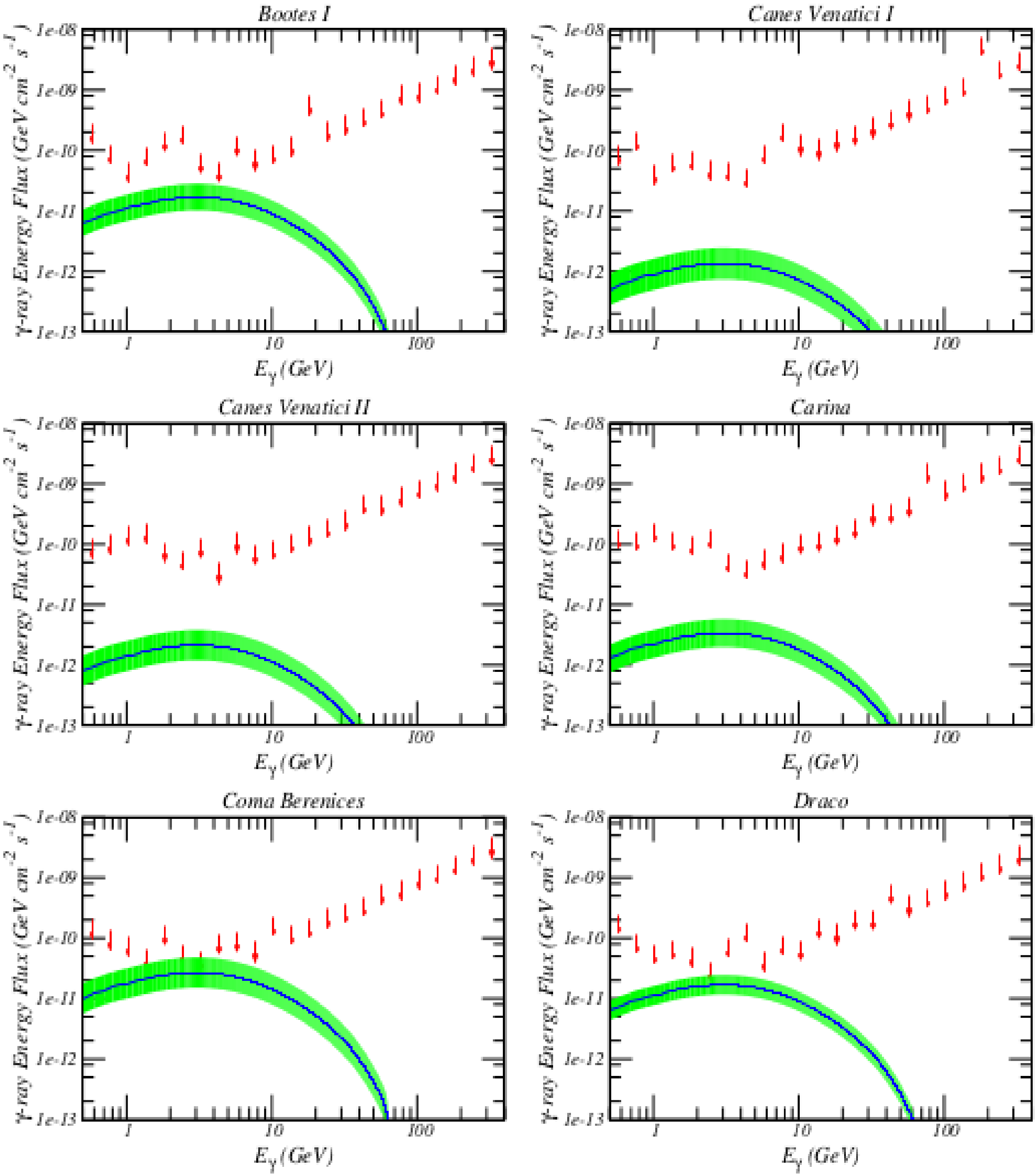


dSphs name	longitude l (deg)	latitude b (deg)	distance (kpc)	$\overline{log_{10}(J^{NFW})}$ [a] ($log_{10}[GeV^2 cm^{-5} sr]$)	$\overline{log_{10}(\alpha_s^{NFW})}$ ($log_{10}[deg]$)	upper limit on $\langle\sigma v\rangle$ ($cm^3 s^{-1}$)
Bootes I [?]	358.1	69.6	66	18.8 ± 0.22	-0.6 ± 0.3	2.33×10^{-24}
Bootes II	353.7	68.9	42	–	–	–
Bootes III	35.4	75.4	47	–	–	–
Canes Venatici I [?]	74.3	79.8	218	17.7 ± 0.26	-1.3 ± 0.2	9.65×10^{-25}
Canes Venatici II [?]	113.6	82.7	160	17.9 ± 0.25	-1.1 ± 0.4	8.14×10^{-25}
Canis Major [?]	240.0	-8.0	7	–	–	–
Carina [?]	260.1	-22.2	105	18.1 ± 0.23	-1.0 ± 0.3	2.28×10^{-25}
Coma Berenices [?]	241.9	83.6	44	19.0 ± 0.25	-0.6 ± 0.5	1.11×10^{-24}
Draco [?]	86.4	34.7	76	18.8 ± 0.16	-0.6 ± 0.2	3.87×10^{-25}
Fornax [?]	237.1	-65.7	147	18.2 ± 0.21	-0.8 ± 0.2	2.53×10^{-25}
Hercules [?]	28.7	36.9	132	18.1 ± 0.25	-1.1 ± 0.4	9.97×10^{-26}
Leo I [?]	226.0	49.1	254	17.7 ± 0.18	-1.1 ± 0.3	4.37×10^{-25}
Leo II [?]	220.2	67.2	233	17.6 ± 0.18	-1.1 ± 0.5	3.88×10^{-25}
Leo IV [?]	265.4	56.5	154	17.9 ± 0.28	-1.1 ± 0.4	3.72×10^{-24}
Leo V	261.9	58.5	178	–	–	–
Pisces II	79.2	-47.1	182	–	–	–
Sagittarius	5.6	-14.2	26	–	–	–
Sculptor [?]	287.5	-83.2	86	18.6 ± 0.18	-0.6 ± 0.3	3.41×10^{-24}
Segue 1 [?]	220.5	50.4	23	19.5 ± 0.29	-0.4 ± 0.5	1.16×10^{-24}
Segue 2	149.4	-38.1	35	–	–	–
Sextans [?]	243.5	42.3	86	18.4 ± 0.27	-0.9 ± 0.2	1.14×10^{-25}
Ursa Major I [?]	159.4	54.4	97	18.3 ± 0.24	-1.0 ± 0.3	1.64×10^{-25}
Ursa Major II [?]	152.5	37.4	32	19.3 ± 0.28	-0.5 ± 0.4	1.33×10^{-24}
Ursa Minor [?]	105.0	44.8	76	18.8 ± 0.19	-0.5 ± 0.2	6.54×10^{-24}
Willman 1 [?]	158.6	56.8	38	19.1 ± 0.31	-0.6 ± 0.5	4.03×10^{-24}

[a] J-factors are calculated over a solid angle of $\Delta\Omega \sim 2.4 \times 10^{-4}$ sr.

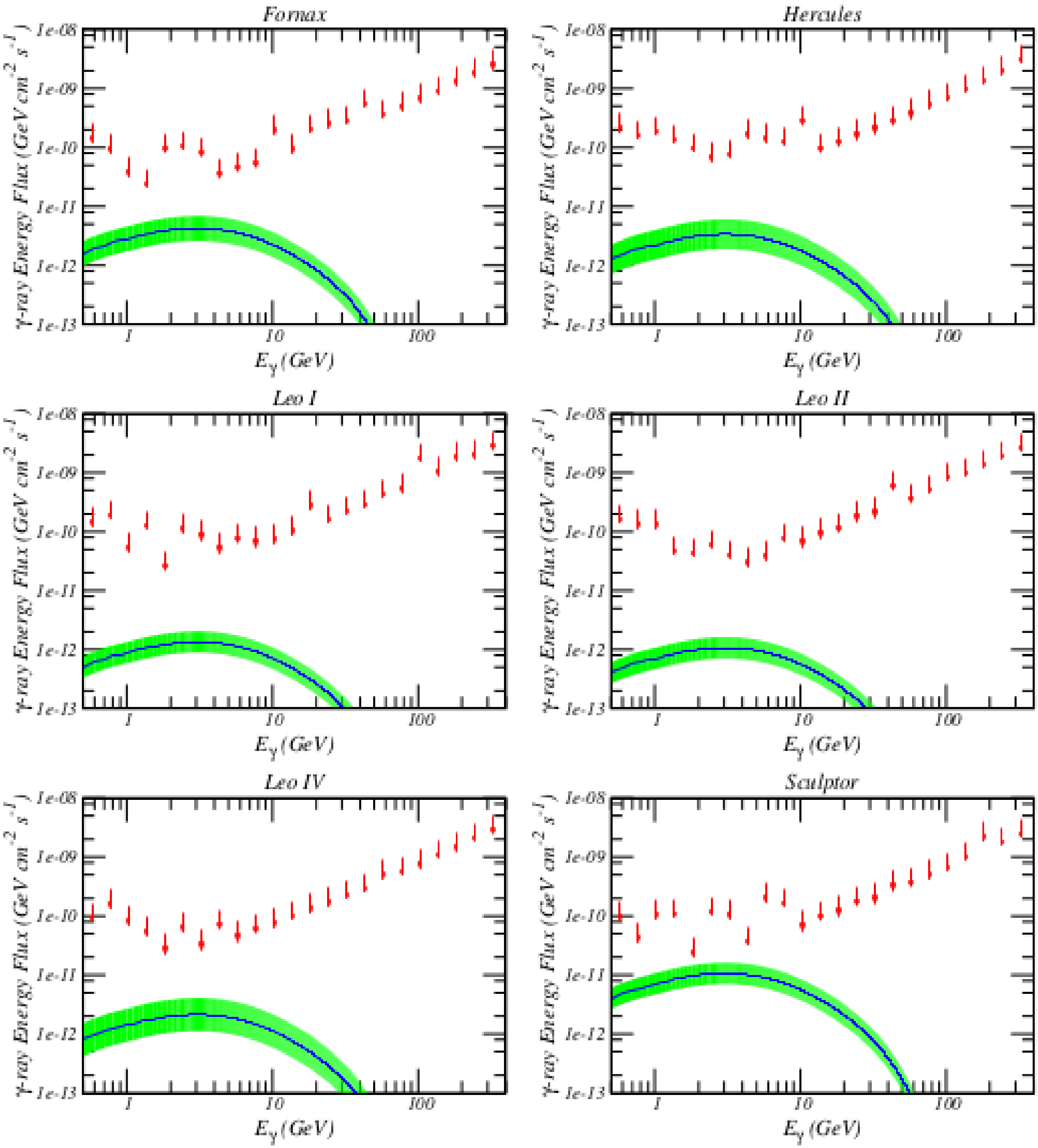
Comparison of gamma-ray flux with dSphs

1. Bootes I
2. Canes Venatici I
3. Canes Venatici II
4. Carina
5. Coma Berenices
6. Draco

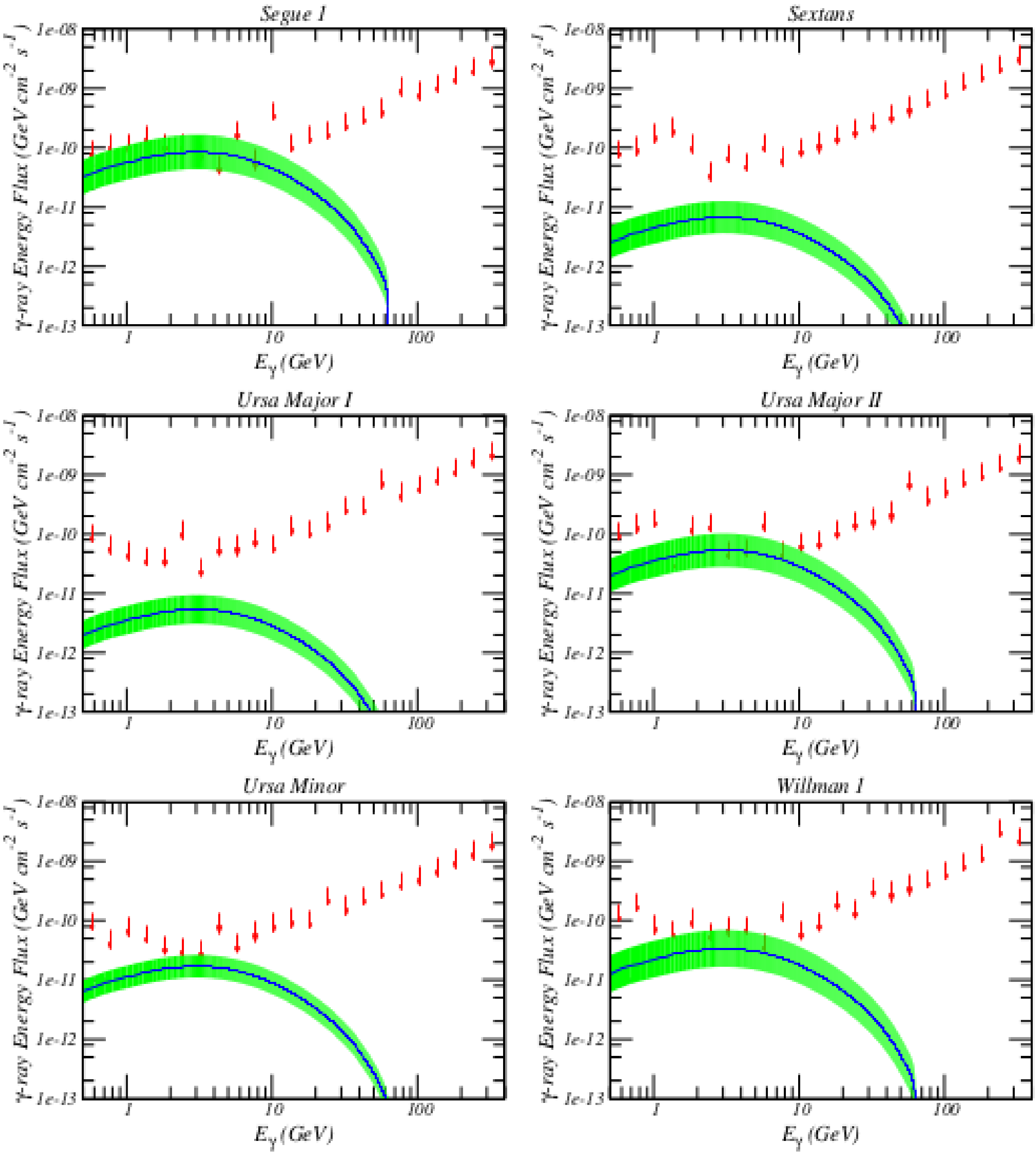


Comparison of gamma-ray flux with dSphs

7. Fornax
8. Hercules
9. Leo I
10. Leo II
11. Leo IV
12. Sculptor



Comparison of gamma-ray flux with dSphs
13. Segue 1
14. Sextans
15. Ursa Major I
16. Ursa Major II
17. Ursa Minor
18. Willman 1



Extragalactic gamma-ray from DM annihilation

$$\frac{d\phi_\gamma}{dE_0} = \frac{\sigma v}{8\pi}\frac{c}{H_0}\frac{\rho_0^2}{M_\chi^2}\int dz\,(1+z)^3\frac{\Delta^2(z)}{h(z)}\frac{dN_\gamma(E_0\,(1+z))}{dE}e^{-\tau(z,E_0)}$$

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

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

Extragalactic gamma-ray from DM annihilation

$$\nu = \delta_{\rm sc}/\sigma(M)$$

Variance of density fluctuations of the linear density field in sphere that contains the mean mass M,

$$\sigma^2(M) \equiv \int d^3k \, \tilde{W}^2(kR) \, P(k)$$

$$\nu f(\nu) = 2A \left(1 + \frac{1}{\nu'^{2p}}\right) \left(\frac{\nu'^2}{2\pi}\right)^{1/2} \exp\left(-\frac{\nu'^2}{2}\right)$$

$$I_n(x_{min}, x_{max}) = \int_{x_{min}}^{x_{max}} dx \, x^2 g^n(x)$$

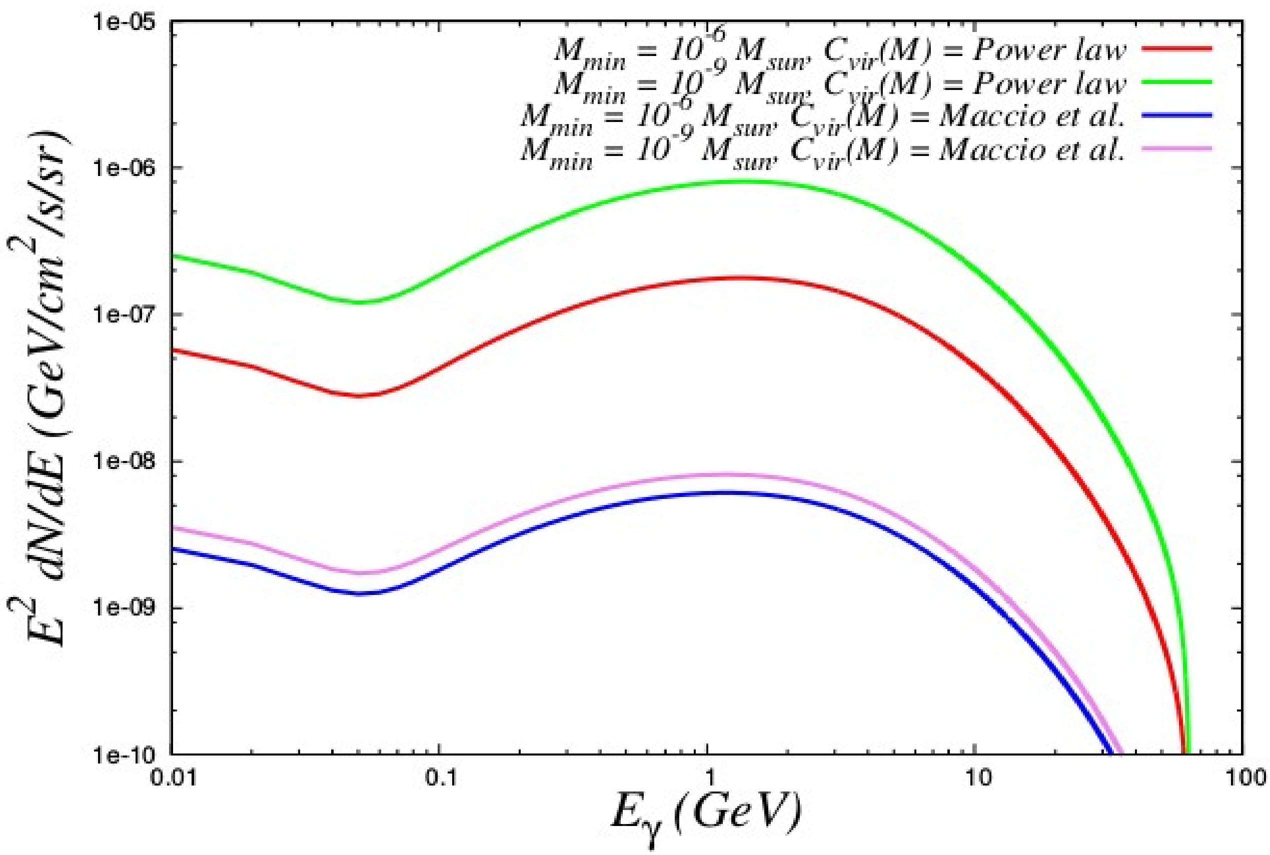
$$g_{\rm NFW}(x) = \frac{1}{x\,(1+x)^2}$$

Concentration parameter

$$c_{vir} = \frac{R_{vir}}{r_s^{(-2)}}$$

Concentration parameter and minimum halo mass are parametrised

Extragalactic gamma-ray from DM annihilation in IHDM



Non-DM contributions to Extragalactic Diffuse Isotropic Gamma-Ray Background

1. **BL Lac Objects** $$\frac{dN_\gamma}{dE}_{\rm BLLac} = 3.9 \times 10^{-8} E_\gamma^{-2.23}\ {\rm GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

2. **FSRQ** $$\frac{dN_\gamma}{dE}_{\rm FSRQ} = 3.1 \times 10^{-8} E_\gamma^{-2.45}\ {\rm GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

3. **MSP** $$\frac{dN_\gamma}{dE}_{\rm MSP} = 1.8 \times 10^{-7} E_\gamma^{-1.5} \exp\left(-\frac{E_\gamma}{1.9}\right)\ {\rm GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

4. **SFG** $$\frac{dN_\gamma}{dE}_{\rm SFG} = 1.3 \times 10^{-7} E_\gamma^{-2.75}\ {\rm GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}} \quad \text{for} \quad E_\gamma > 1\,{\rm GeV}$$

5. **FR** $$\frac{dN_\gamma}{dE}_{\rm FR} = 5.7 \times 10^{-8} E_\gamma^{-2.39} \exp\left(-\frac{E_\gamma}{50.0}\right)\ {\rm GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

6. **UHECR** $$\frac{dN_\gamma}{dE}_{\rm UHECR} = 4.8 \times 10^{-9} E_\gamma^{-1.8} \exp\left[-\left(\frac{E_\gamma}{100.0}\right)^{0.35}\right]\ {\rm GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}} \quad \text{for} \quad E_\gamma > 1\,{\rm GeV}$$

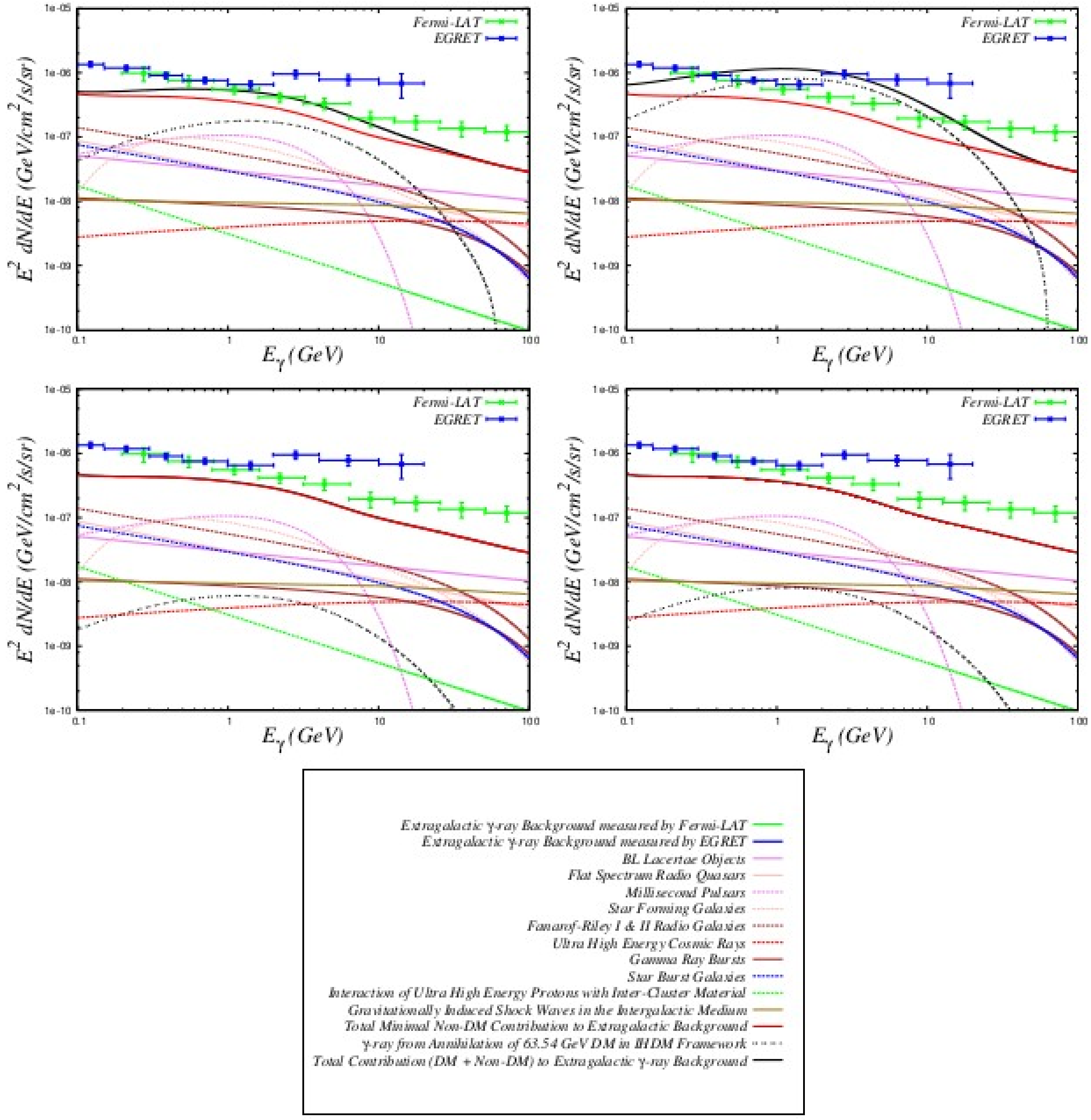
7. **GRB** $$\frac{dN_\gamma}{dE}_{\rm GRB} = 8.9 \times 10^{-9} E_\gamma^{-2.1}\ {\rm GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

8. **SBG** $$\frac{dN_\gamma}{dE}_{\rm SBG} = 0.3 \times 10^{-7} E_\gamma^{-2.4}\ {\rm GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

9. **UHEp ICM** $$\frac{dN_\gamma}{dE}_{\rm UHEp\ ICM} = 3.1 \times 10^{-9} E_\gamma^{-2.75}\ {\rm GeV^{-1}\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

10. **IGS** $$\frac{dN_\gamma}{dE}_{\rm IGS} = 0.87 \times 10^{-10} \times \left\{ \begin{array}{ll} \left(\frac{E_\gamma}{10}\right)^{-2.04} & \text{for } E_\gamma < 10\ {\rm GeV} \\ \left(\frac{E_\gamma}{10}\right)^{-2.13} & \text{for } E_\gamma > 10\ {\rm GeV} \end{array} \right\} {\rm GeV^{-1} cm^{-2} s^{-1} sr^{-1}}$$

DM + Non-DM contributions to EGB



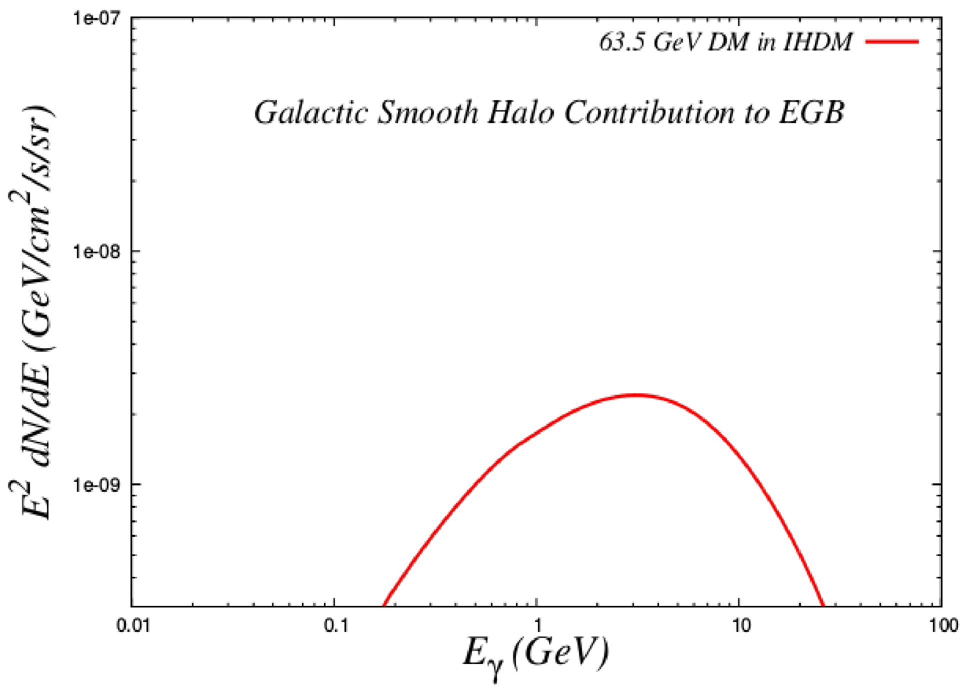
Galactic Smooth Halo and Subhalo Contributions to Extragalactic Diffuse Isotropic Gamma-Ray Background

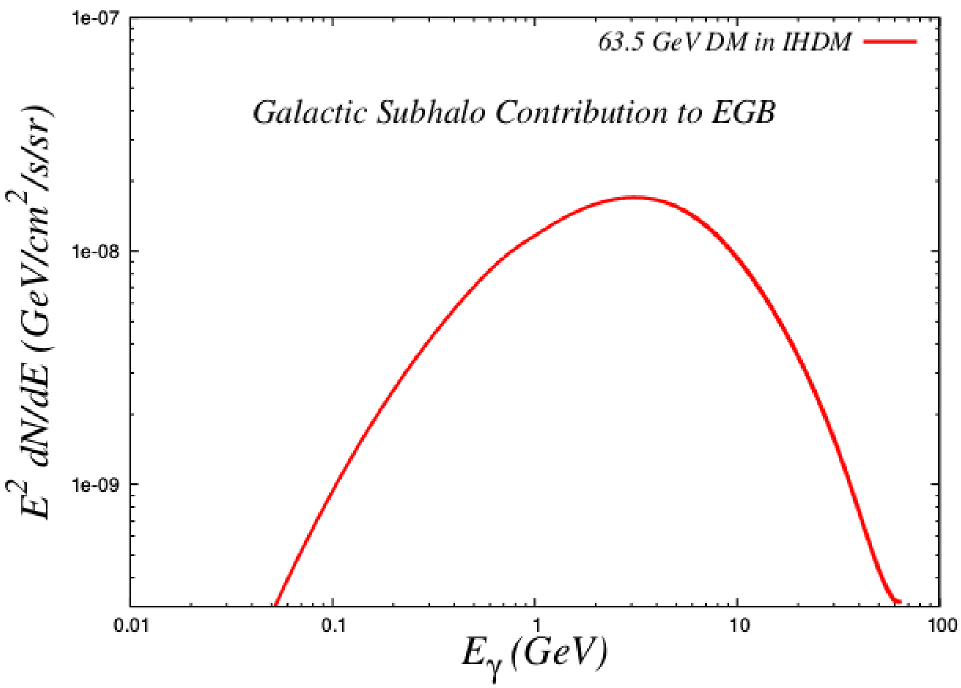
$$\frac{dI_{\rm sm}(E_\gamma)}{dE_\gamma} = \frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\frac{dN_\gamma}{dE_\gamma}\frac{1}{\Omega_e}\int_{V_*} dV\ \frac{\rho_{\rm MW}^2(s,b,\ell)}{4\pi s^2},$$

$$\frac{dI_{\rm sh}(E_\gamma)}{dE_\gamma} = \frac{1}{\Omega_e}\frac{d\mathcal{I}_{\rm sh}(E_\gamma)}{dE_\gamma} = \frac{1}{\Omega_e}\int_{M_*}\int_{V_*(M)} dV\,dM\,\frac{dn_{\rm sh}(M,s,\ell,b)}{dM}\frac{d\mathcal{I}(E_\gamma,s,M)}{dE_\gamma}$$

$$= \int_{M_*} dM \int_{V_*(M)} dV\,\frac{dn_{\rm sh}(M,s,\ell,b)}{dM}\frac{1}{4\pi s^2}\frac{\langle\sigma v\rangle}{m_{\rm DM}^2}\frac{dN_\gamma}{dE_\gamma}\frac{M^2}{r_{s,\rm sh}(M)^3}\mathcal{G}[c_{\rm cut}(M)]($$

Galactic Smooth Halo and Subhalo Contributions to Extragalactic Diffuse Isotropic Gamma-Ray Background





A Model for Dark Matter that may simultaneously explain

- Planck results for DM abundance
- 10 GeV Gamma ray excess from Galactic Centre region
- Low energy gamma emission from Fermi Bubble
- Gamma ray flux from dSphs
- Extragalactic Gamma ray