A Possible Explanation of Low Energy gamma-ray Excess from Galactic Centre and Fermi Bubble by a Dark Matter Model with Two Real Scalars

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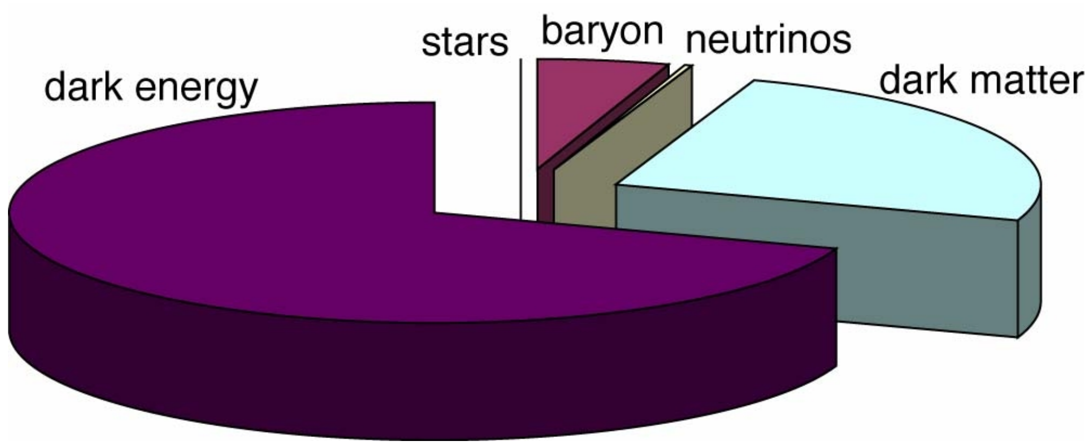
Energy Budget of Universe

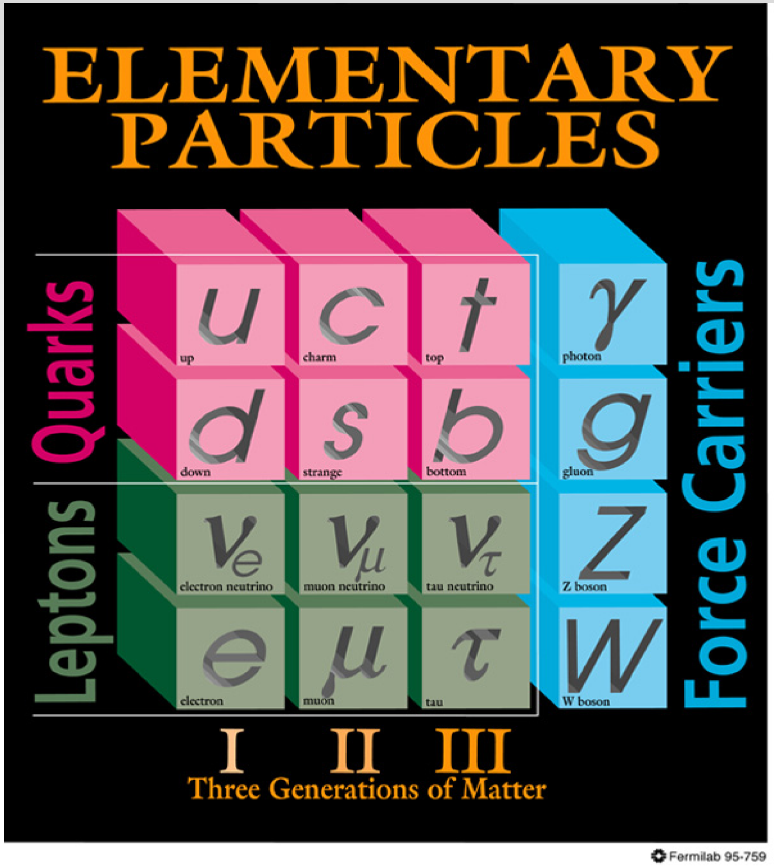
PLANCK 2013 RESULTS !!!
(March 21, 2013)

- 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

Dark Matter Hunt

Through Direct Detection

CDMS II

CoGeNT

CRESST II

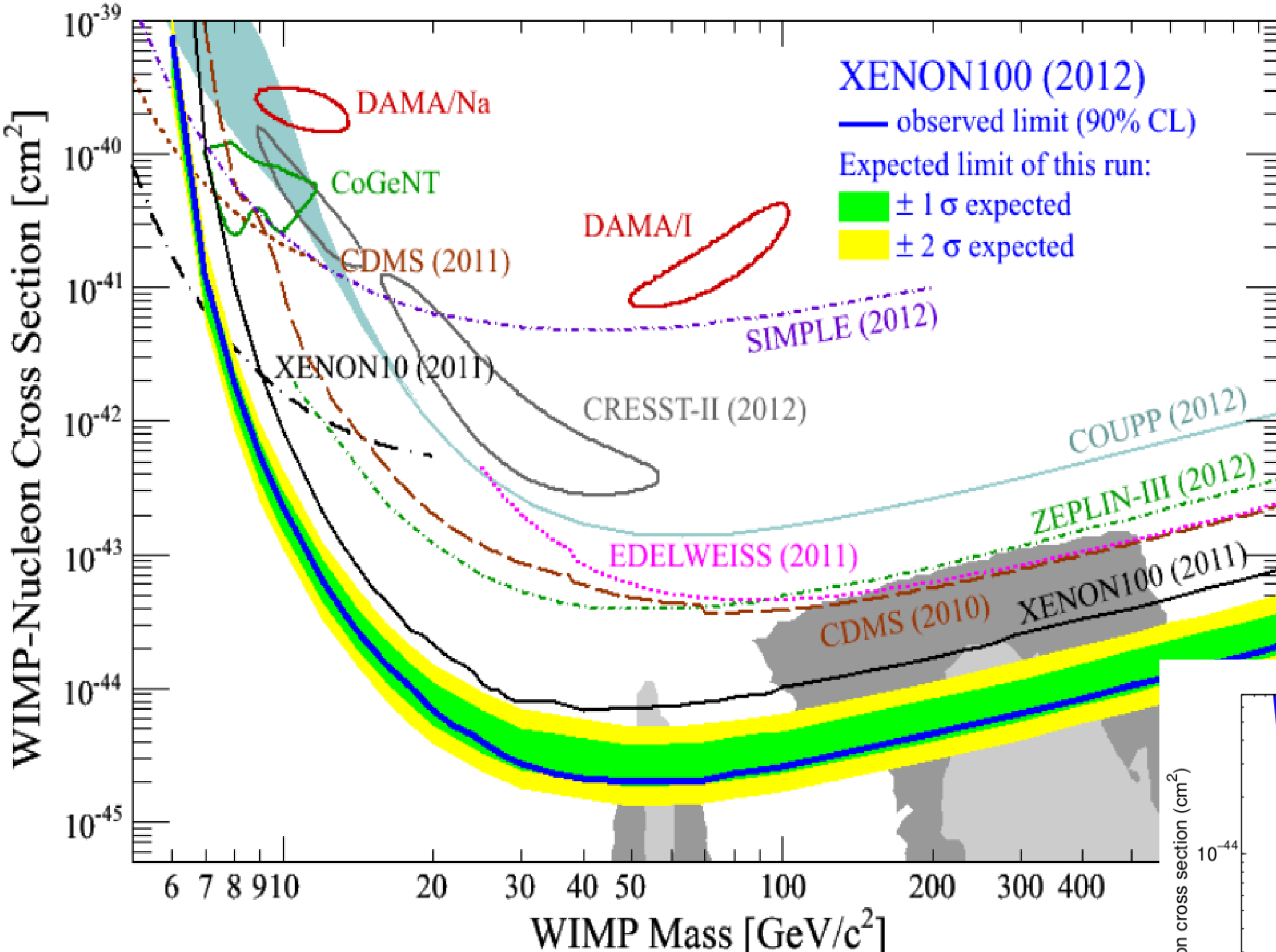
XENON 100

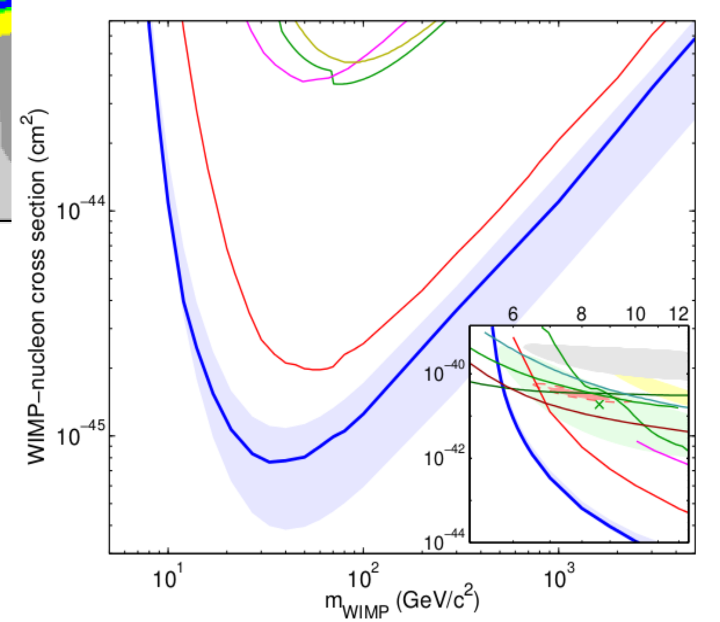
LUX

Through Indirect Detection

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

Direct Detection Results

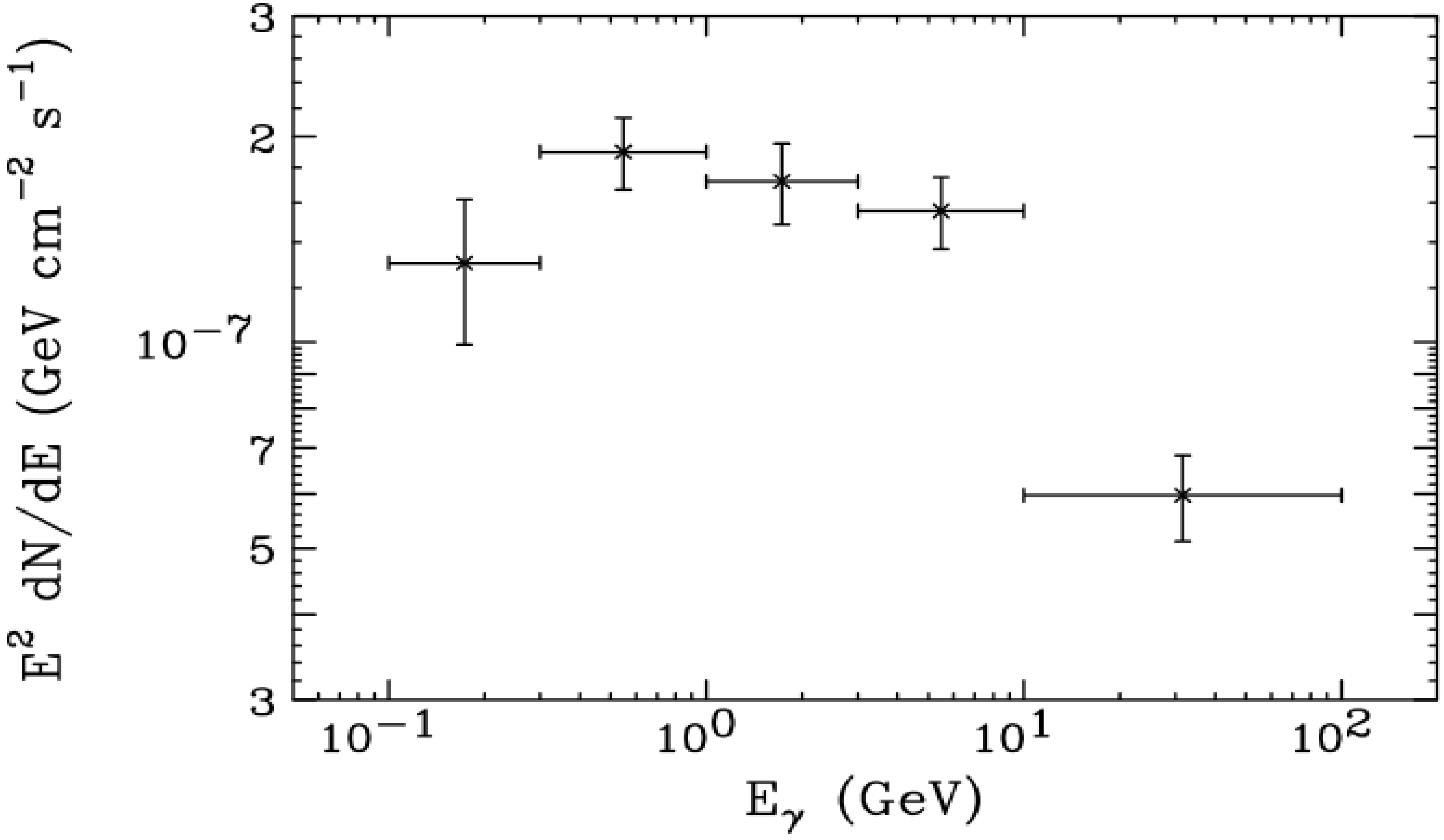




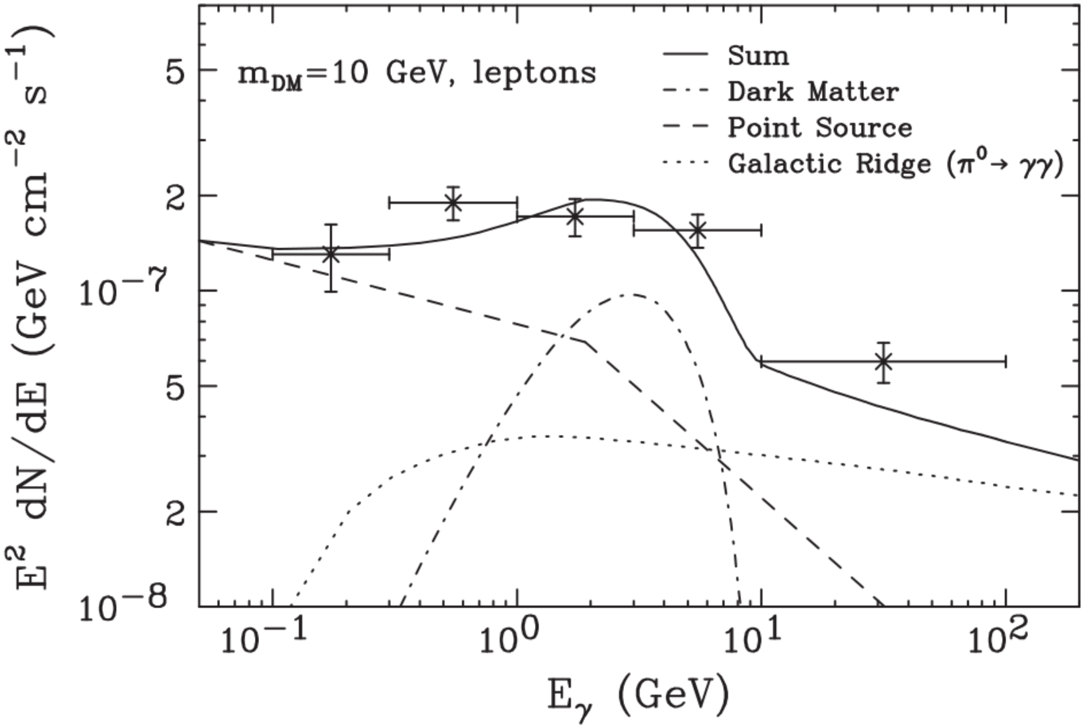
Indirect Detection (Signatures?)

- **Excess Gamma Emission from Galactic Centre Region (*Fermi Gamma Ray Space Telescope (FGST) searches Gamma ray around 5 degrees surrounding GC*)**
  - **Gamma Emission from *Fermi Bubble***
- **Excess positron fraction (AMS 02 @ ISS, PAMELA etc.)**
  - **Antiproton excess (BESS)**
  - **Neutrinos at ICECUBE, ANTARES ?**

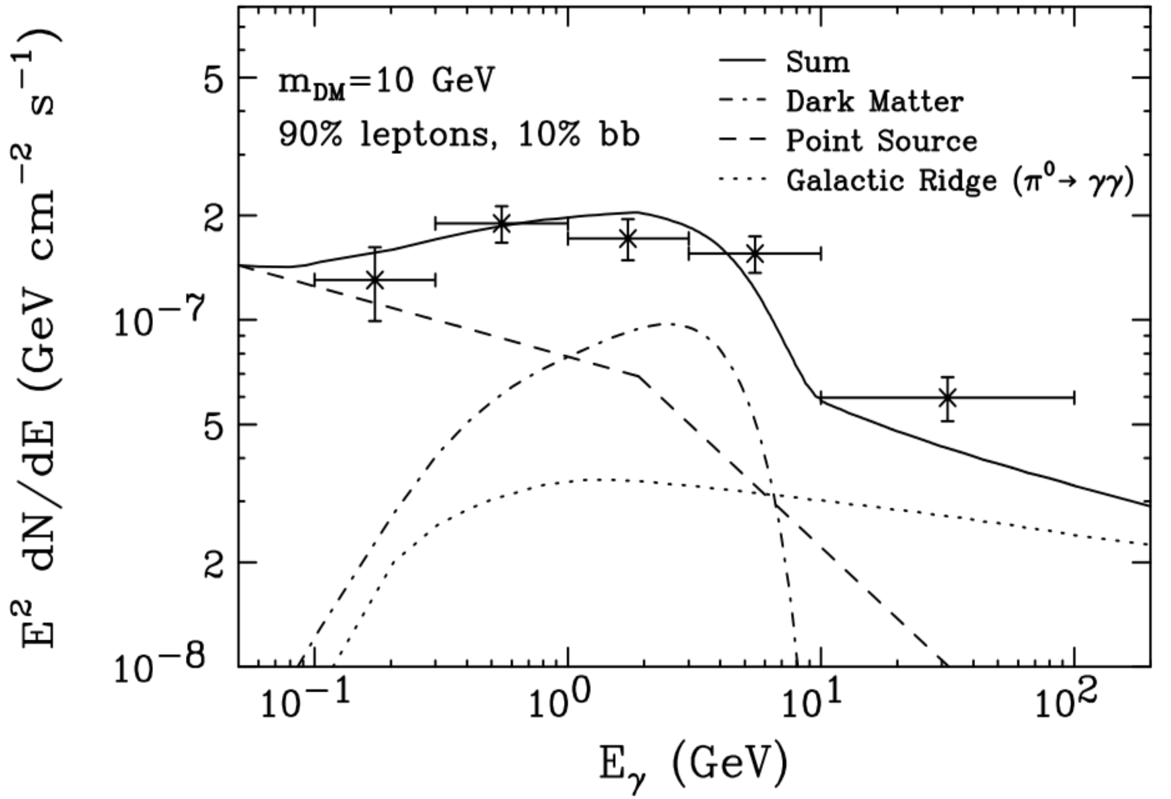
Hint of Dark Matter around 10 GeV



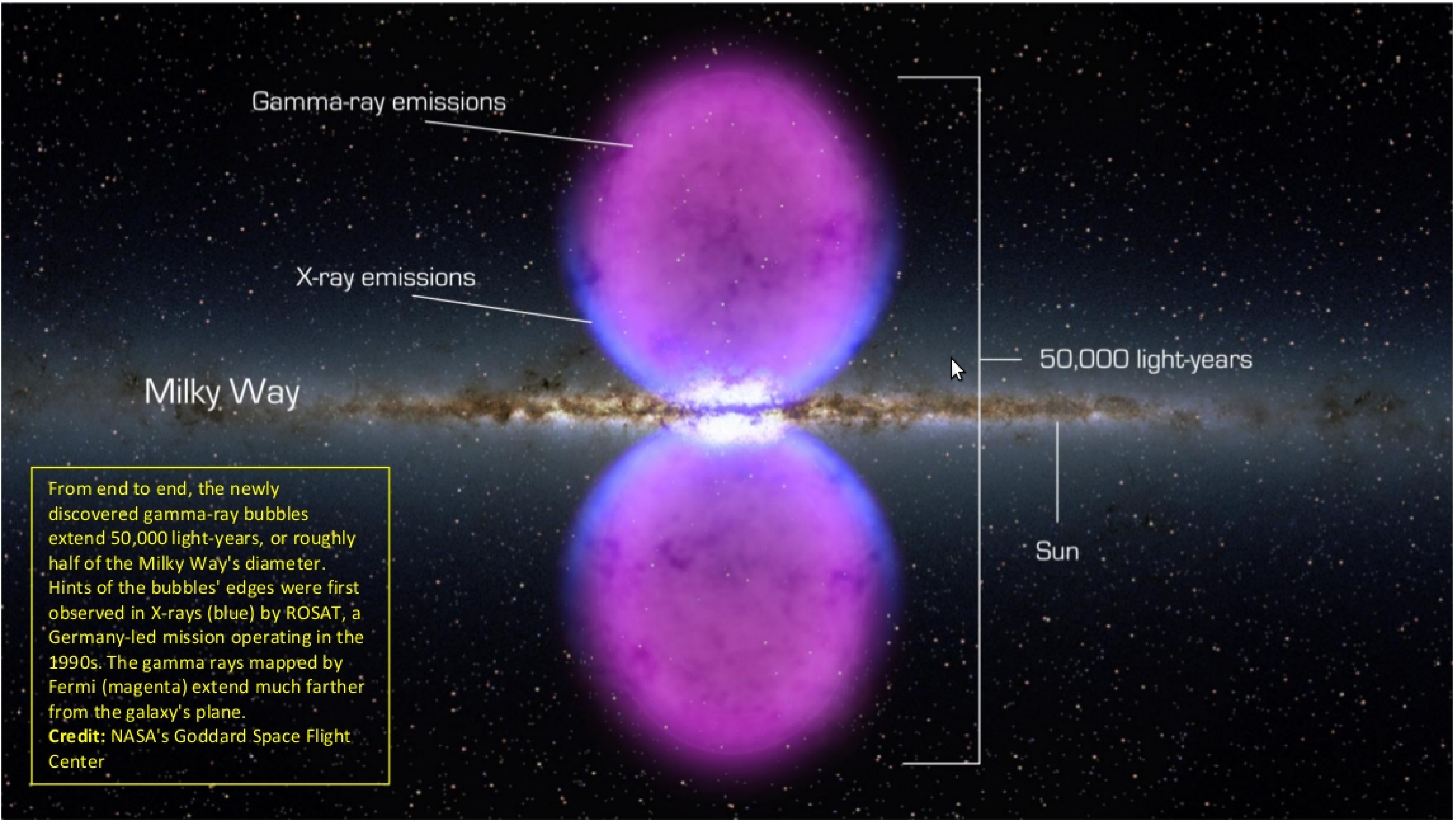
Observed gamma flux bump by FGST

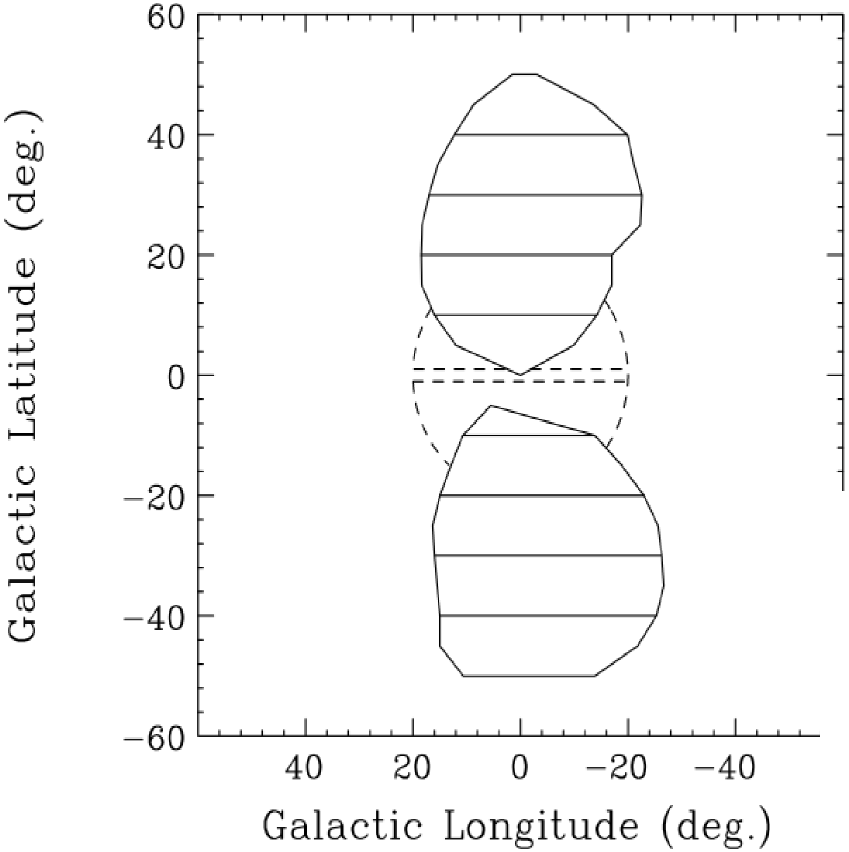


Fits to DM proposals

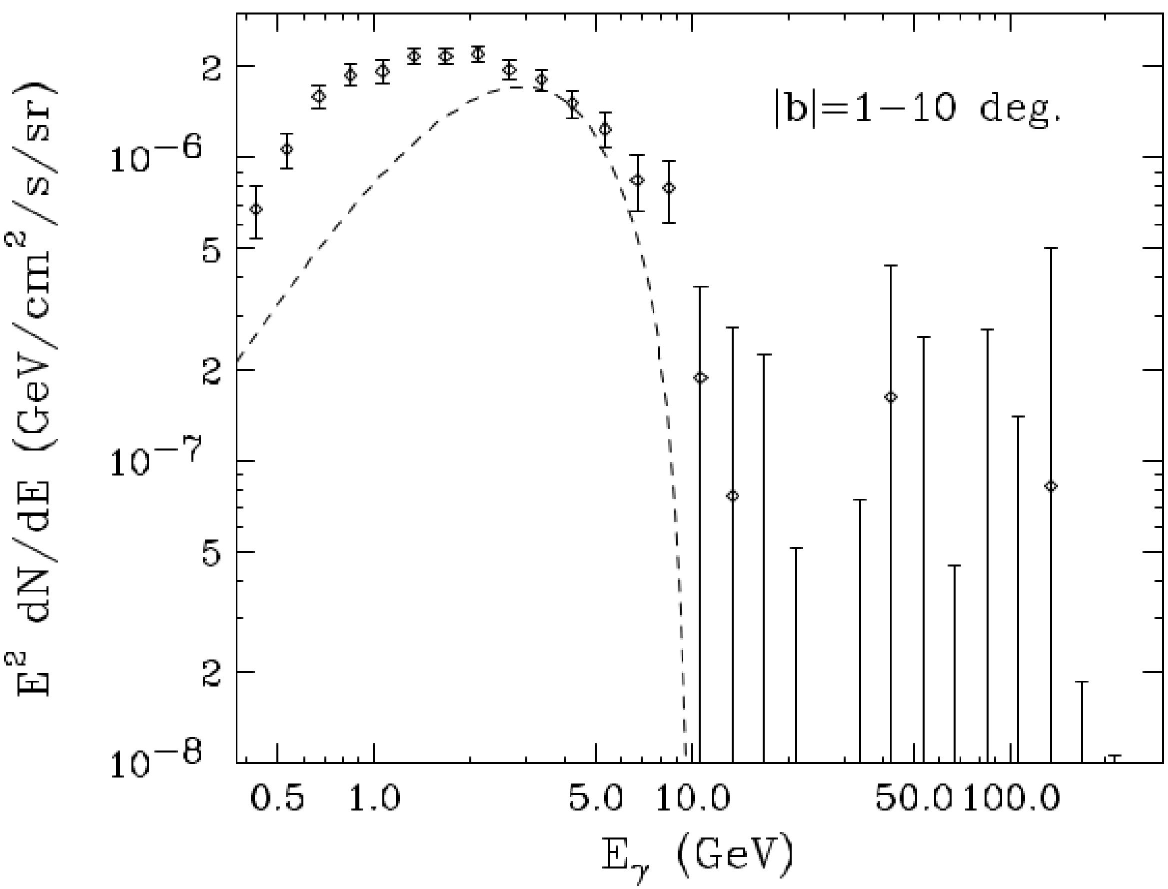


Fermi Bubble





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



$|b|=1-10$ deg.
E^2 dN/dE (GeV/cm^2/s/sr)
E_γ (GeV)

A Model for Dark Matter that may simultaneously explain

- **Direct detection results**
- **Planck results for DM abundance**
- **10 GeV Gamma ray excess from Galactic Centre region**
- **Low energy gamma emission from Fermi Bubble**

Two Scalar Singlet Model for Dark Matter

We Propose SM with additional 2 SM gauge singlets $S_1 \,, S_2$

Stability ensured by $\mathbb{Z}_2 \times \mathbb{Z}_2$ **or** $\mathbb{Z}_2 \times \mathbb{Z}_2'$

$$\begin{pmatrix} S \\ S' \end{pmatrix} \xrightarrow{\mathbb{Z}_2 \times \mathbb{Z}_2} \begin{pmatrix} -S \\ -S' \end{pmatrix}$$

$$S \xrightarrow{\mathbb{Z}_2} -S \;\; \text{and} \;\; S' \xrightarrow{\mathbb{Z}_2'} -S'$$

$\mathbb{Z}_2 \times \mathbb{Z}_2$

$$V(H,S,S') = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2$$
$$+\frac{\delta_2}{2}H^\dagger H S^2 + \frac{k_2}{2}S^2 + \frac{k_4}{4}S^4$$
$$+\frac{\delta'_2}{2}H^\dagger H S'^2 + \frac{k'_2}{2}S'^2 + \frac{k'_4}{4}S'^4$$
$$+\frac{\delta''_2}{2}H^\dagger H S'S + \frac{k''_2}{2}SS'$$
$$+\frac{1}{4}(k_4^a SSS'S' + k_4^b SSSS' + k_4^c SS'S'S')$$

After SSB

$$M_{SS'} = \begin{pmatrix} k_2 + \delta_2 v^2/2 & \delta''_2 v^2/4 + k''_2/2 \\ \delta''_2 v^2/4 + k''_2/2 & k'_2 + \delta'_2 v^2/2 \end{pmatrix} \equiv \begin{pmatrix} M_{11} & M_{12} \\ M_{12} & M_{22} \end{pmatrix}$$

$$M^2_{S_1} = \cos^2\theta M_{11} + \sin^2\theta M_{22} + 2\cos\theta\sin\theta M_{12}$$
$$M^2_{S_2} = \cos^2\theta M_{22} + \sin^2\theta M_{11} - 2\cos\theta\sin\theta M_{12}$$

$$\tan 2\theta = \frac{2M_{12}}{M_{11} - M_{22}}$$

$\mathbb{Z}_2 \times \mathbb{Z}_2'$

$$V(H,S,S') = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2$$
$$+\frac{\delta_2}{2}H^\dagger H S^2 + \frac{k_2}{2}S^2 + \frac{k_4}{4}S^4$$
$$+\frac{\delta_2'}{2}H^\dagger H S'^2 + \frac{k_2'}{2}S'^2 + \frac{k_4'}{4}S'^4$$
$$+\frac{1}{4}(k_4^a SSS'S')$$

$$M_S^2 = k_2 + \frac{\delta_2 v^2}{2}$$
$$M_{S'}^2 = k_2' + \frac{\delta_2' v^2}{2}$$

Vacuum Stability Bounds

$$\lambda \geqslant 0, k_4 \geqslant 0, k_4^p \geqslant 0,$$

$$\delta_2 + \sqrt{\lambda k_4} \geqslant 0,$$

$$\delta_2^p + \sqrt{\lambda k_4^p} \geqslant 0,$$

$$k_4^a + \sqrt{k_4 k_4^p} \geqslant 0,$$

$$\sqrt{\lambda k_4 k_4^p} + \delta_2 \sqrt{k_4^p} + \delta_2^p \sqrt{k_4} + 2k_4^p \sqrt{\lambda} + \sqrt{(\delta_2 + \sqrt{\lambda k_4})(\delta_2^p + \sqrt{\lambda k_4^p})(k_4^a + \sqrt{k_4 k_4^p})} \geqslant 0.$$

Perturbative Unitarity Bounds

$$|\delta_2| \leq 8\pi$$

$$|k_4^a| \leq 8\pi$$

$$k_4 \leq \frac{8}{6}\pi$$

$$k_4' \leq \frac{8}{6}\pi$$

The Potential

$$V(H,S,S') = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2$$

$$+\frac{\delta_1}{2}H^\dagger H S + \frac{\delta_2}{2}H^\dagger H S^2 + \frac{\delta_1 m}{2\lambda}S + \frac{k_2}{2}S^2 + \frac{k_3}{3}S^3 + \frac{k_4}{4}S^4$$

$$+\frac{\delta'_1}{2}H^\dagger H S' + \frac{\delta'_2}{2}H^\dagger H S'^2 + \frac{\delta'_1 m}{2\lambda}S' + \frac{k'_2}{2}S'^2 + \frac{k'_3}{3}S'^3 + \frac{k'_4}{4}S'^4$$

$$+\frac{\delta''_2}{2}H^\dagger H S' S + \frac{k''_2}{2}SS' + \frac{1}{3}(k_3^a SSS' + k_3^b SS'S')$$

$$+\frac{1}{4}(k_4^a SSS'S' + k_4^b SSSS' + k_4^c SS'S'S')$$

$$\mathbb{Z}_2 \times \mathbb{Z}_2 \longrightarrow \delta_1 = k_3 = \delta'_1 = k'_3 = k_3^a = k_3^b = 0$$

$$\mathbb{Z}_2 \times \mathbb{Z}'_2 \longrightarrow \delta''_2 = k''_2 = k_4^b = k_4^c = 0 \quad \text{(in addition)}$$

Relic Density Calculation for comparing with Planck result

$$0.1165 < \Omega_{\rm DM} h^2 < 0.1227$$

Boltzmann Eqns.

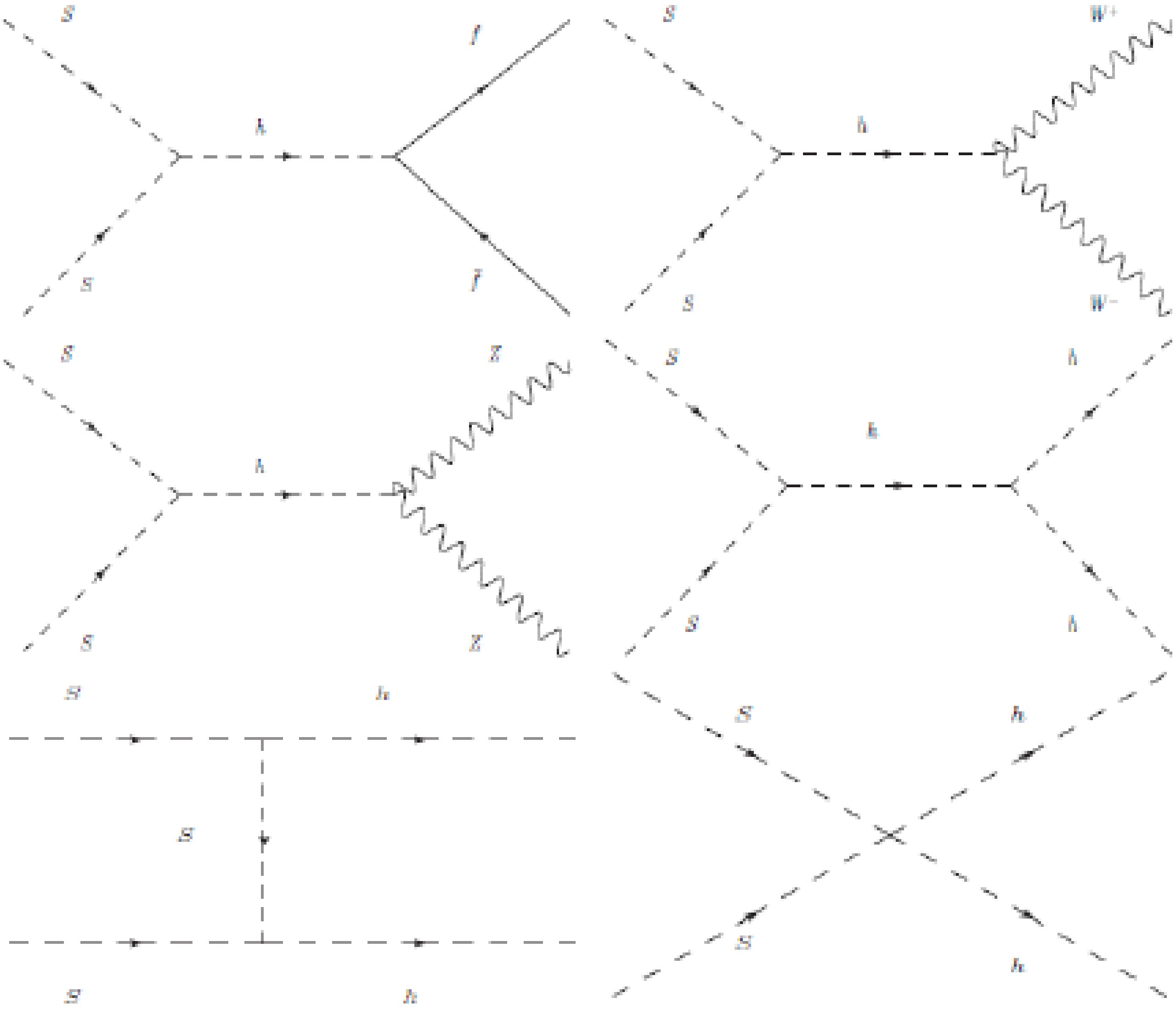
$$\frac{dn_1}{dt} + 3Hn_1 = -\langle\sigma v\rangle_{11\to XX}(n_1^2 - n_{1_{\rm eq}}^2) - \langle\sigma v\rangle_{11\to 22}\left(n_1^2 - \frac{n_{1_{\rm eq}}^2}{n_{2_{\rm eq}}^2} n_2^2\right)$$

$$\frac{dn_2}{dt} + 3Hn_2 = -\langle\sigma v\rangle_{22\to XX}(n_2^2 - n_{2_{\rm eq}}^2) - \langle\sigma v\rangle_{22\to 11}\left(n_2^2 - \frac{n_{2_{\rm eq}}^2}{n_{1_{\rm eq}}^2} n_1^2\right)$$

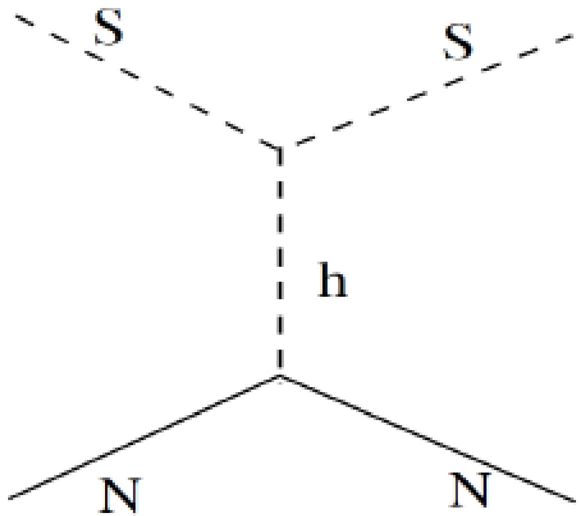
Total relic density $\Omega = \Omega_S + \Omega_{S'}$

$\langle\sigma v\rangle_{11\to XX}, \langle\sigma v\rangle_{22\to XX} >> \langle\sigma v\rangle_{11\to 22} \Rightarrow$ decoupled

Annihilation Channels

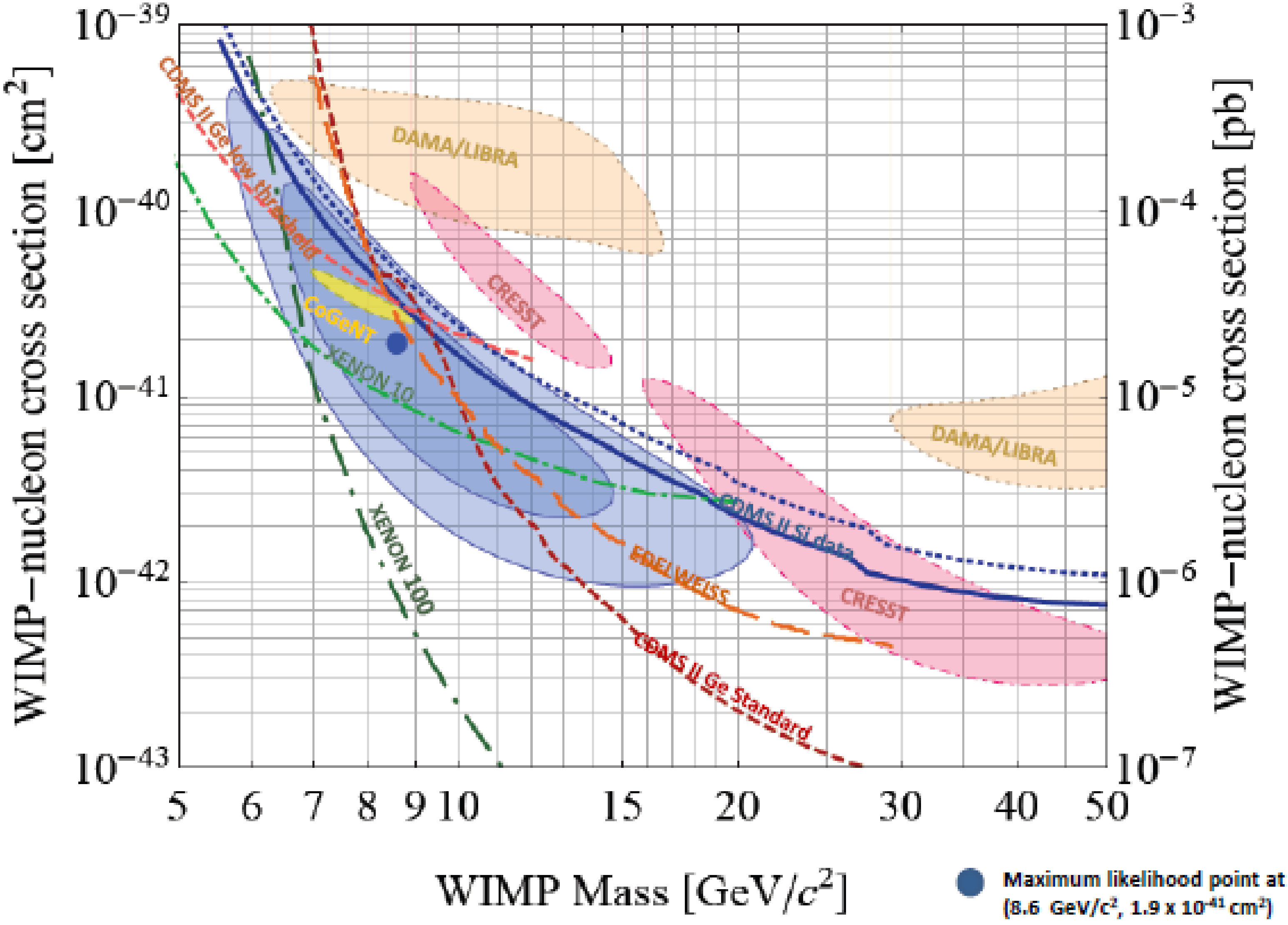


Direct Detection



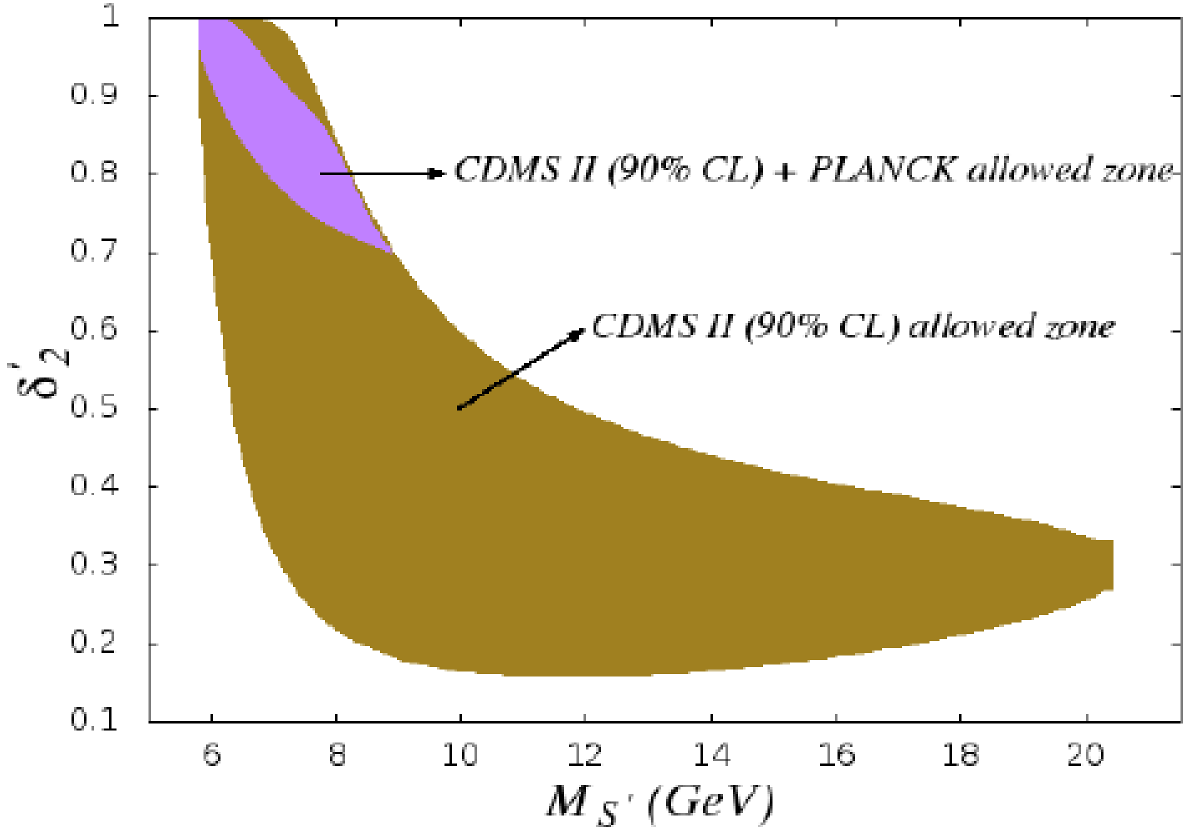
$$\sigma^{SI}_{\rm nucleon} = (\delta_2)^2 \left(\frac{100\ {\rm GeV}}{M_h}\right)^4 \left(\frac{50\ {\rm GeV}}{M_S}\right)^2 (5 \times 10^{-42} {\rm cm}^2)$$

Direct Detection Bounds



CDMS collaboration,
arXiv:1304.4279 [hep-ex]

CDMS II + PLANCK

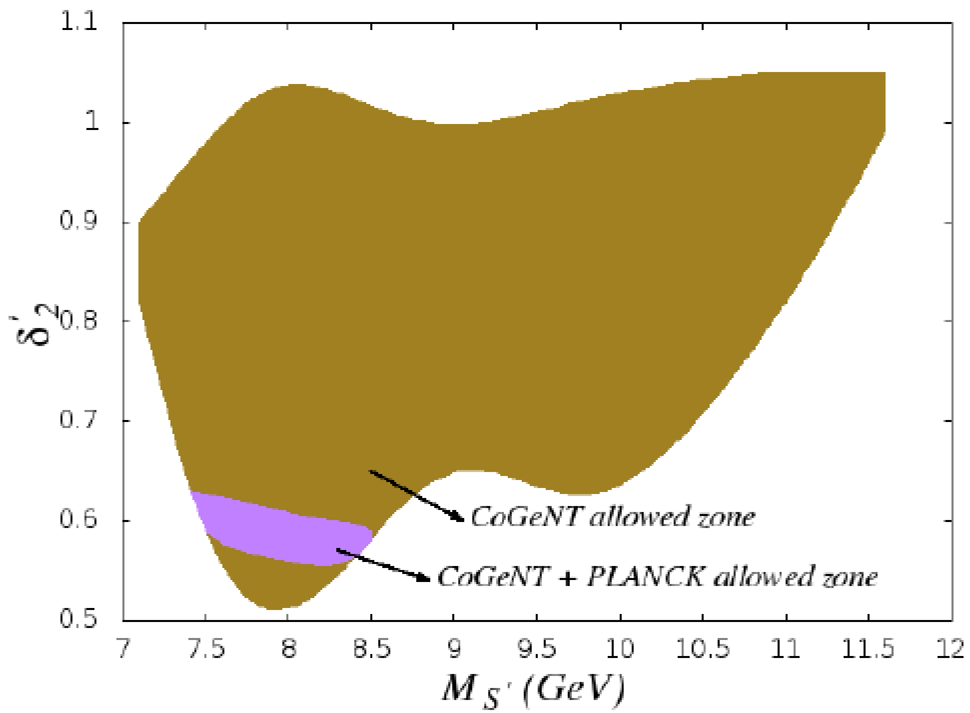


The hatched olive region is the parameter space allowed in the $M_{S'} - \delta_2'$ *(or* $M_S - \delta_2$*) plane by CDMS II 90%CL data. Choosing* $(M_S = 8.6\ GeV,\ \delta_2 = 0.45)$ *in the* $M_S - \delta_2$ *plane, the only parameter space allowed in the* $M_{S'} - \delta_2'$ *by Planck data is shown as the blue shaded region.*

CDMS II + PLANCK

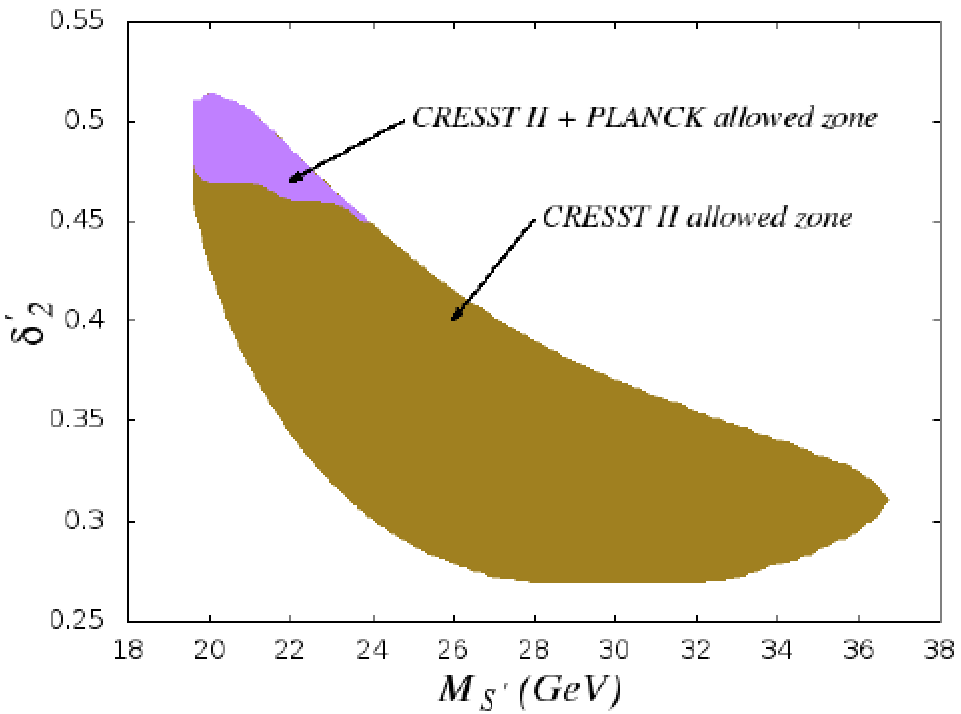
M_S (or $M_{S'}$) (GeV)	δ_2 (or δ_2')	$\sigma^{\rm SI}$ ($\times 10^{-41}$ cm^2)	$\langle \sigma v \rangle$ ($\times 10^{-26}$ cm^3/s)		Contribution in $\Omega_{\rm S}$ (or $\Omega_{\rm S'}$)
8.6	0.45	1.9	3.2	2.6 ($b\bar{b}$)	81%
				0.4 ($c\bar{c}$)	12%
				0.2 ($l\bar{l}$)	7%
6.7	0.82	9.9	8.3	6.3 ($b\bar{b}$)	77%
				1.2 ($c\bar{c}$)	15%
				7.2 ($l\bar{l}$)	8%

CoGeNT + PLANCK

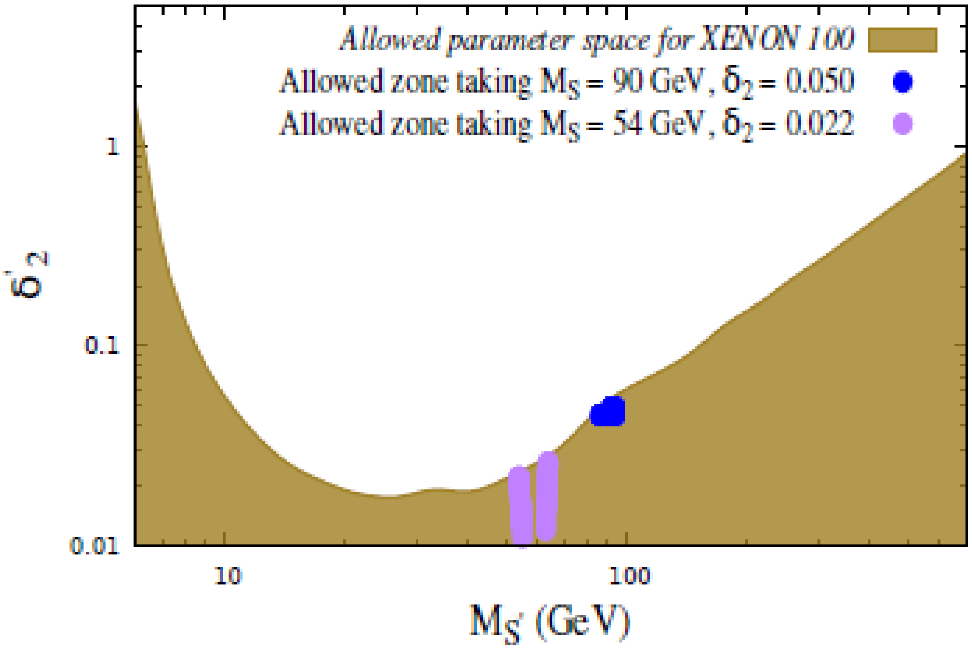


M_S (or $M_{S'}$) (GeV)	δ_2 (or δ_2')	$\sigma^{\rm SI}$ ($\times 10^{-41}$ cm^2)	$\langle \sigma v \rangle$ ($\times 10^{-26}$ cm^3/s)		Contribution in Ω_S (or $\Omega_{S'}$)
7.8	0.56	9.0	4.6	3.7 ($b\bar{b}$)	80%
				0.6 ($c\bar{c}$)	12.5%
				0.4 ($l\bar{l}$)	7.5%
8.2	0.61	9.8	5.7	4.6 ($b\bar{b}$)	81%
				0.7 ($c\bar{c}$)	12%
				0.4 ($l\bar{l}$)	7%

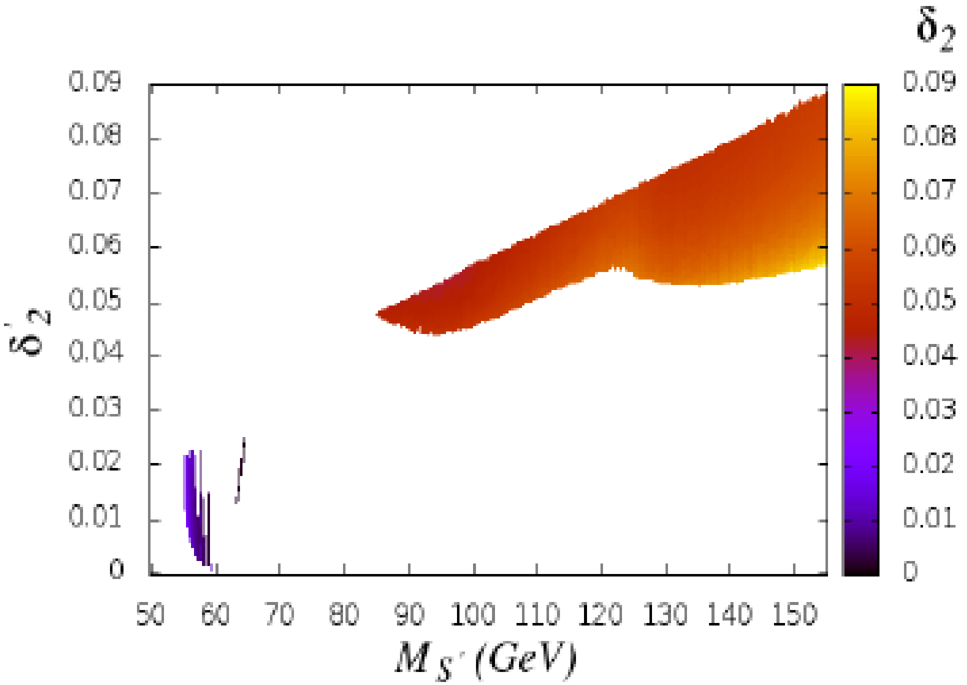
CRESST II + PLANCK



M_S (or $M_{S'}$) (GeV)	δ_2 (or δ'_2)	σ^{SI} ($\times 10^{-41}$ cm^2)	$\langle \sigma v \rangle$ ($\times 10^{-26}$ cm^3/s)		Contribution in Ω_S (or $\Omega_{S'}$)
25.3	0.36	1.6	3.0	2.4 ($b\bar{b}$)	81%
				0.4 ($c\bar{c}$)	12%
				0.2 ($l\bar{l}$)	7%
23.3	0.47	3.2	4.8	3.9 ($b\bar{b}$)	81%
				0.6 ($c\bar{c}$)	12%
				0.3 ($l\bar{l}$)	7%

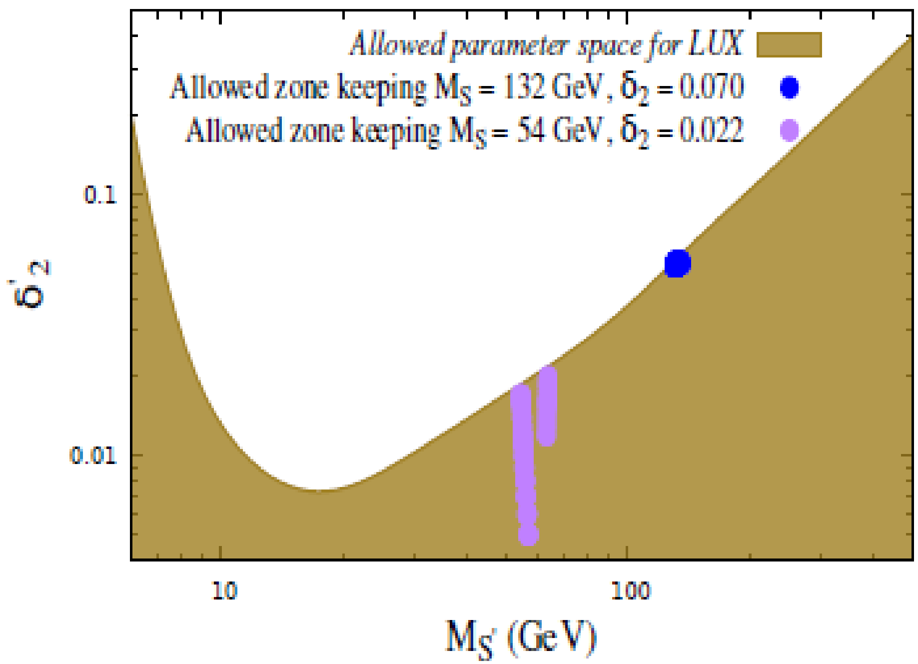


XENON 100 + PLANCK



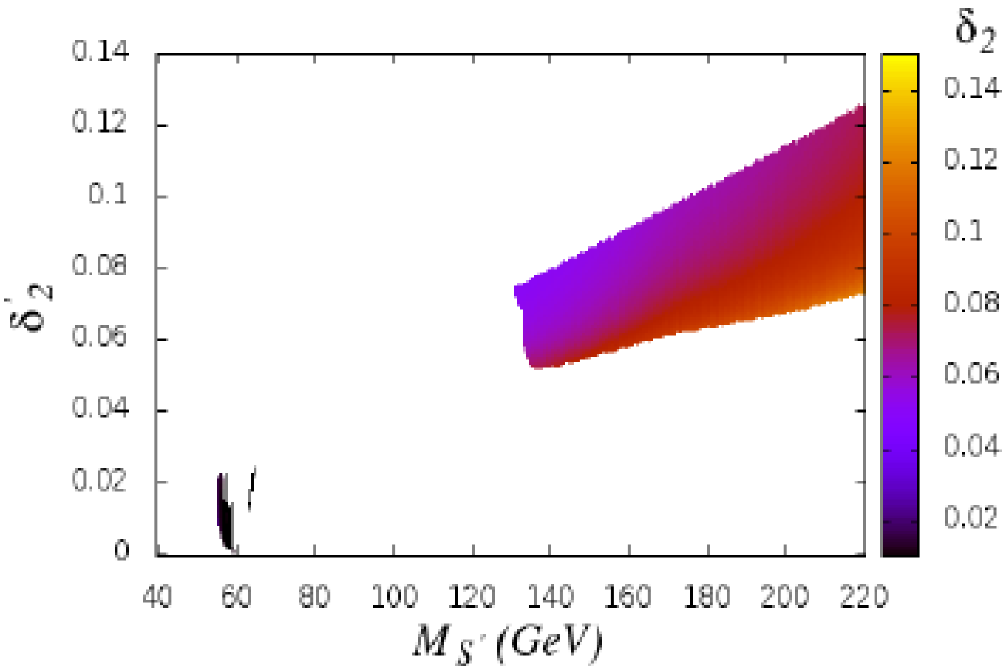
XENON 100 + PLANCK

M_S (or $M_{S'}$) (GeV)	δ_2 (or δ_2')	$\sigma^{\rm SI}$ ($\times 10^{-45}$ cm^2)	$\langle \sigma v \rangle$ ($\times 10^{-26}$ cm^3/s)		Contribution in Ω_S (or $\Omega_{S'}$)
54.0	0.022	1.4	9.94	7.83 ($b\bar{b}$)	78.8%
				1.29 ($c\bar{c}$)	13.2%
				0.82 ($l\bar{l}$)	8.2%
56.0	0.011	0.8	3.95	3.11 ($b\bar{b}$)	78.7%
				0.52 ($c\bar{c}$)	13.2%
				0.32 ($l\bar{l}$)	8.1%
90.0	0.050	2.6	4.32	4.29 (W^+W^-)	99.3%
				0.024 ($b\bar{b}$)	0.55%
				0.004 ($c\bar{c}$)	0.10%
				0.002 ($l\bar{l}$)	0.05%
92.0	0.045	2.0	3.78	3.28 (W^+W^-)	86.6%
				0.48 (ZZ)	12.8%
				0.016 ($b\bar{b}$)	0.43%
				0.003 ($c\bar{c}$)	0.08%
				0.002 ($l\bar{l}$)	0.05%



Allowed parameter space for LUX
Allowed zone keeping M_S = 132 GeV, δ_2 = 0.070
Allowed zone keeping M_S = 54 GeV, δ_2 = 0.022
0.1
0.01
10
100
δ'_2
$M_{S'}$ (GeV)

LUX + PLANCK



δ_2
δ'_2
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
40 60 80 100 120 140 160 180 200 220
$M_{S'}$ (GeV)

Dark Matter Halo Profile

$$\rho(r) = \rho_0 F_{\rm halo}(r) = \frac{\rho_0}{(r/r_c)^\gamma [1 + (r/r_c)^\gamma]^{(\beta-\gamma)/\alpha}}, \quad \rho_0 = 0.4\,{\rm GeV/cm^3}$$

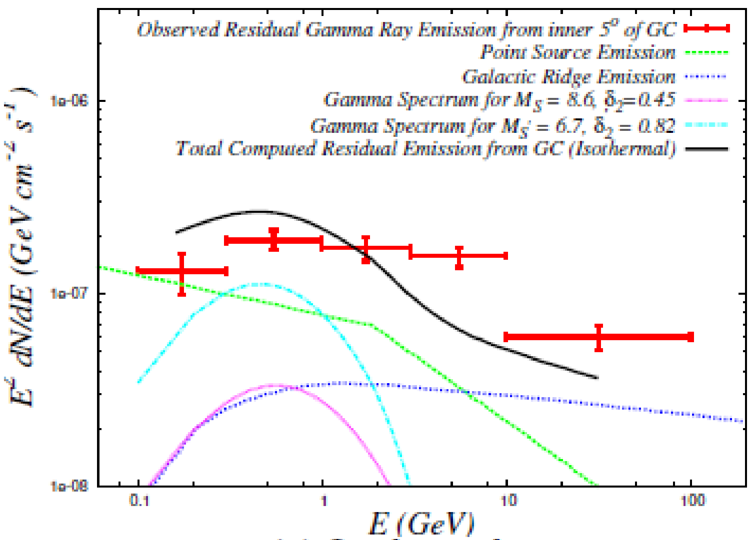
Halo Model	α	β	γ	r_c (Kpc)
Navarro, Frenk, White (NFW)	1	3	1	20
Moore	1.5	3	1.5	28
Isothermal	2	2	0	3.5

Einasto halo profile:

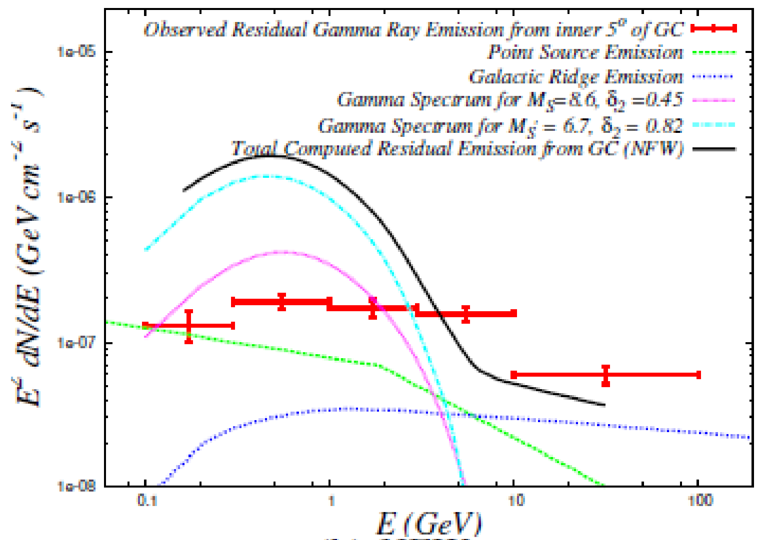
$$F^{Ein}_{\rm halo}(r) = exp\left[\frac{-2}{\tilde{\alpha}}\left(\left(\frac{r}{r_\odot}\right)^{\tilde{\alpha}} - 1\right)\right], \quad \tilde{\alpha} = 0.17$$

Isothermal $\rightarrow$ flat profile, Moore, Einesto $\rightarrow$ cuspy profile

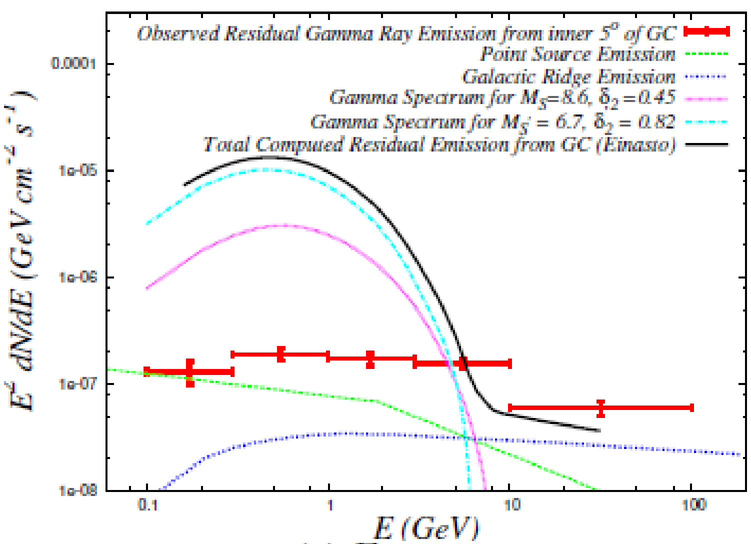
CDMS II + PLANCK for GC gamma excess



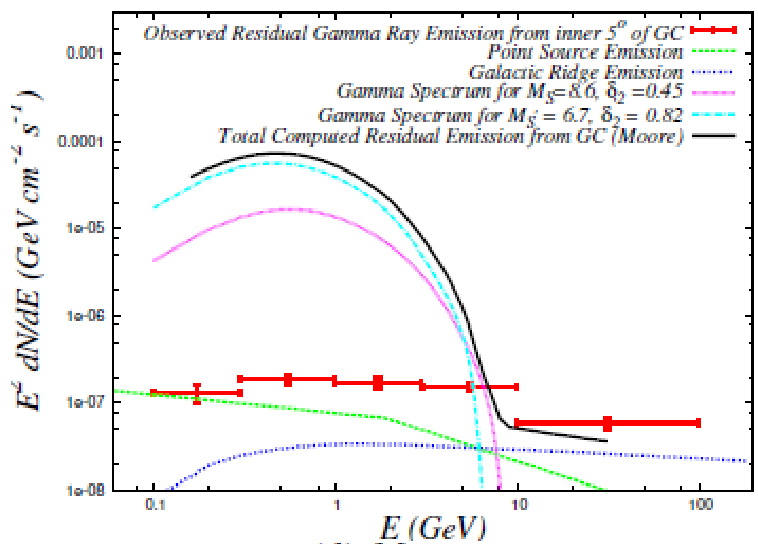
(a) Isothermal



(b) NFW

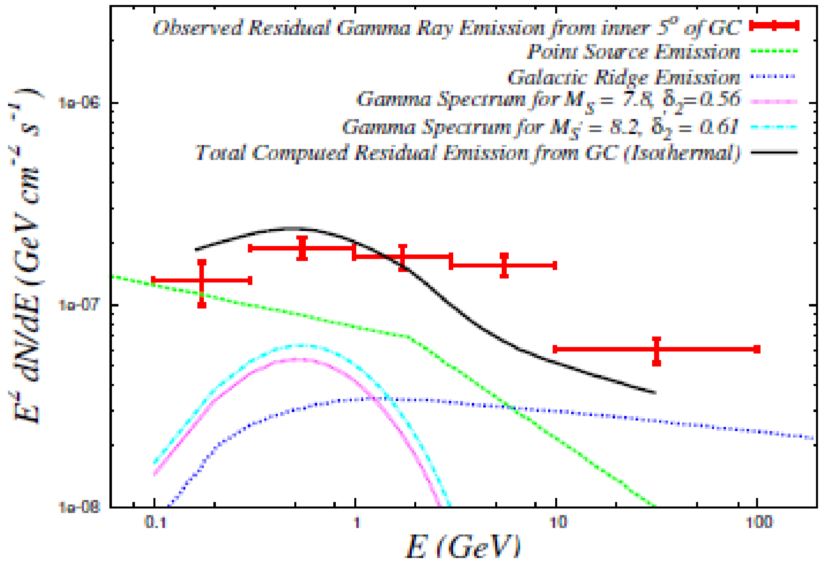


(c) Einasto

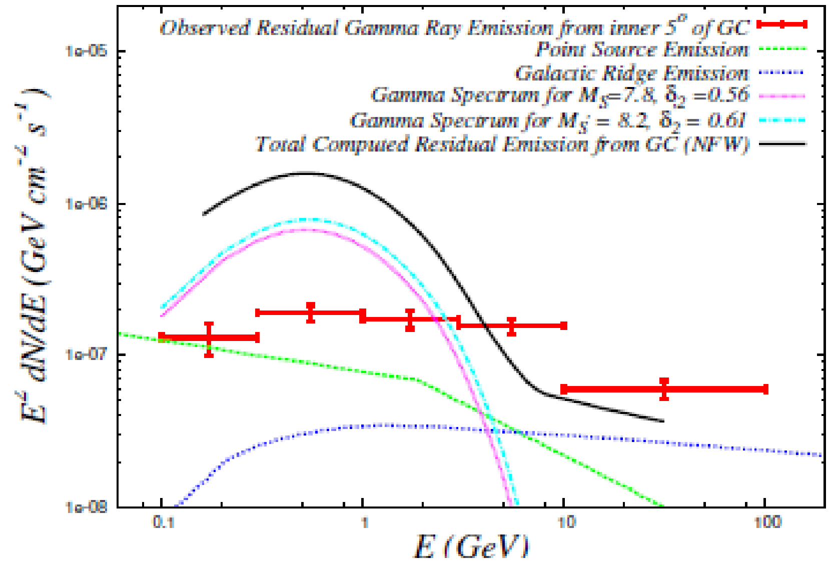


(d) Moore

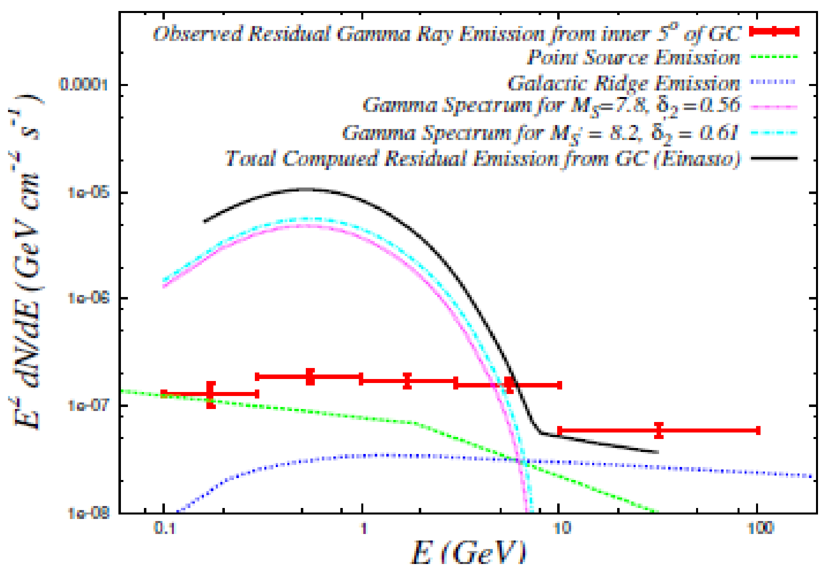
CoGeNT + PLANCK for GC gamma excess



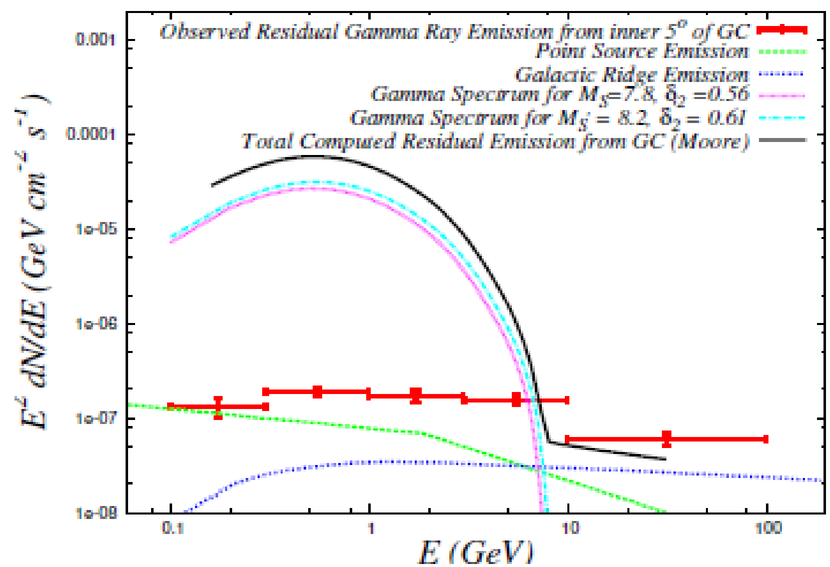
(a) Isothermal



(b) NFW

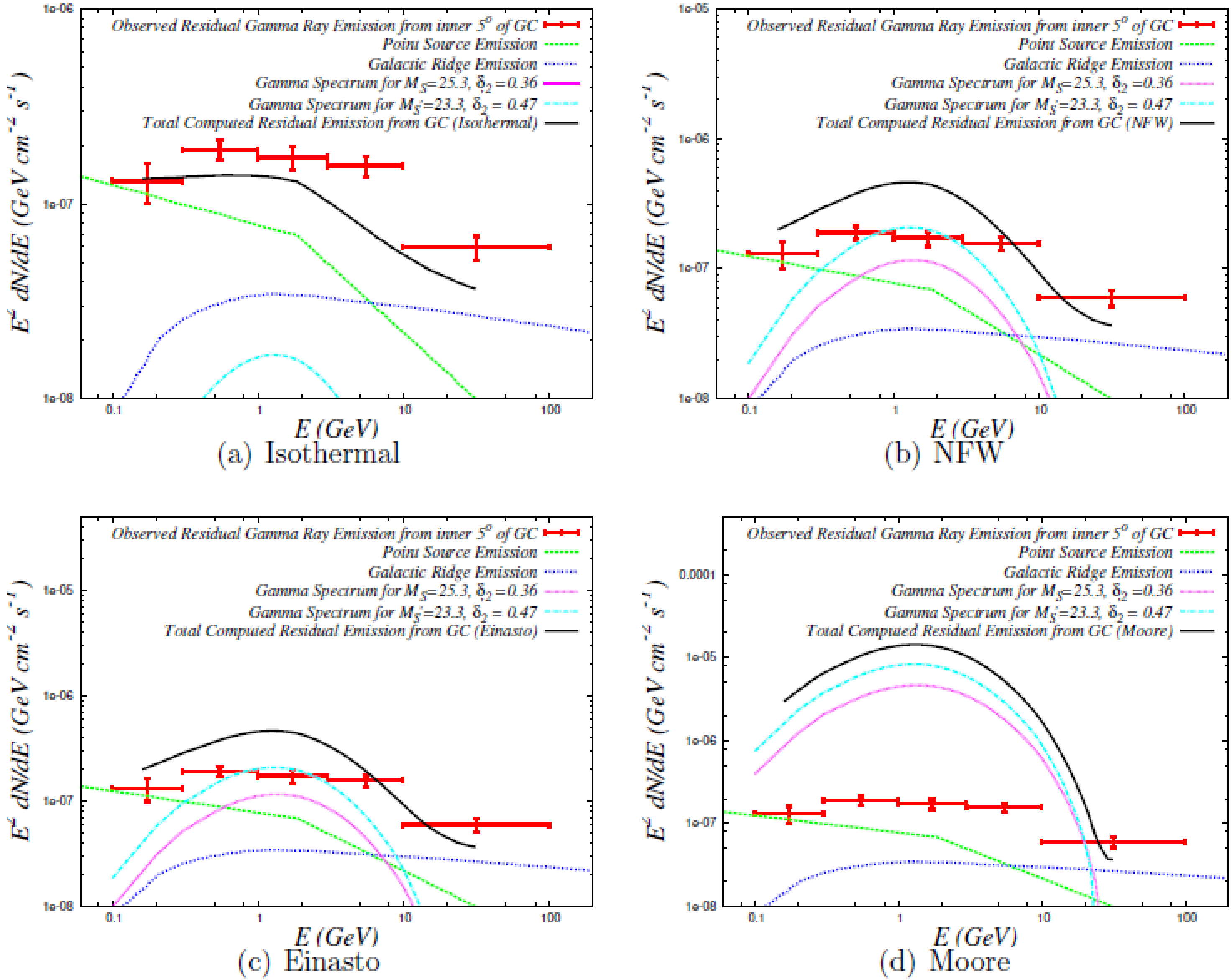


(c) Einasto

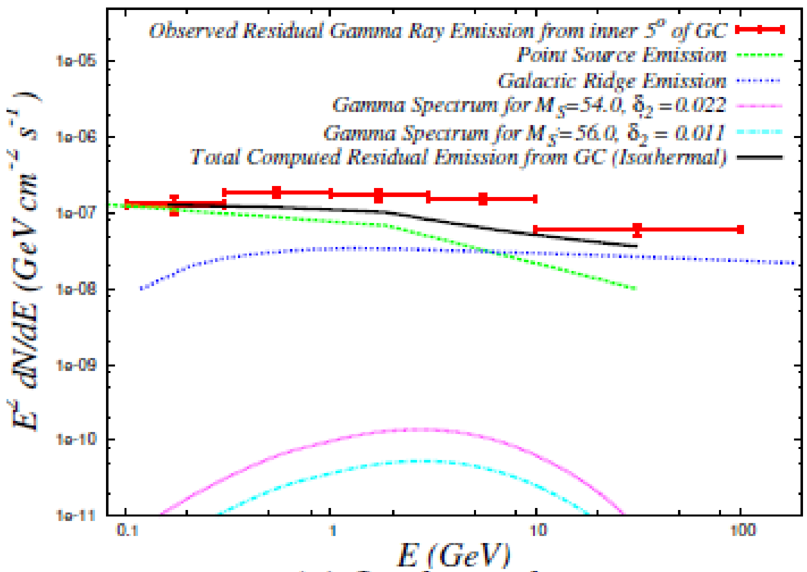


(d) Moore

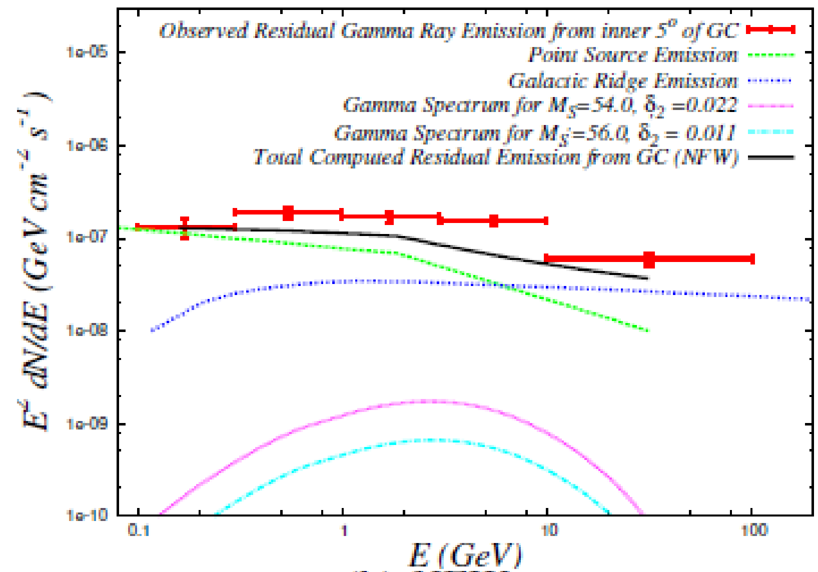
CRESST II+PLANCK for GC gamma excess



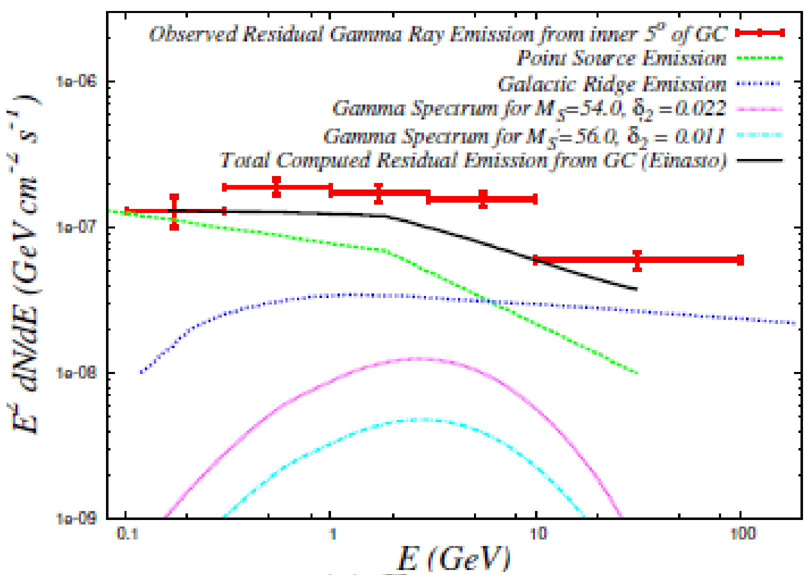
XENON100+PLANCK for GC gamma excess



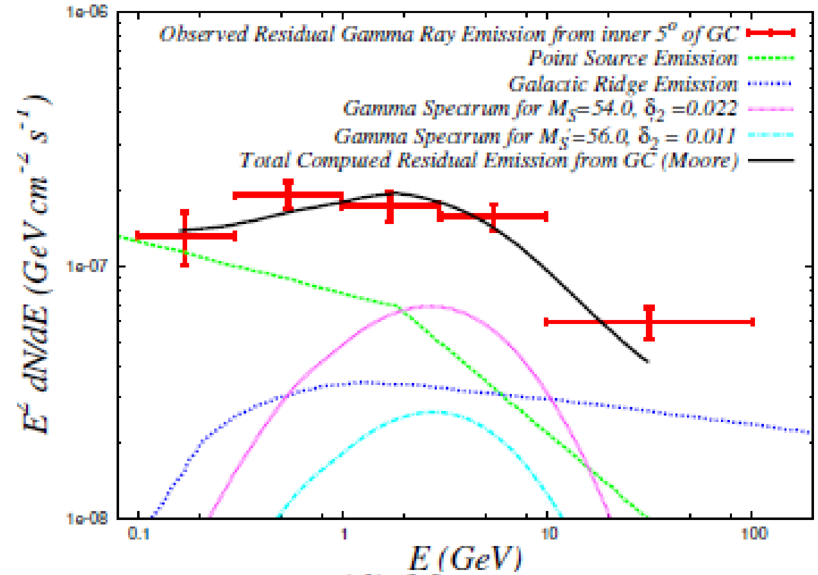
(a) Isothermal



(b) NFW

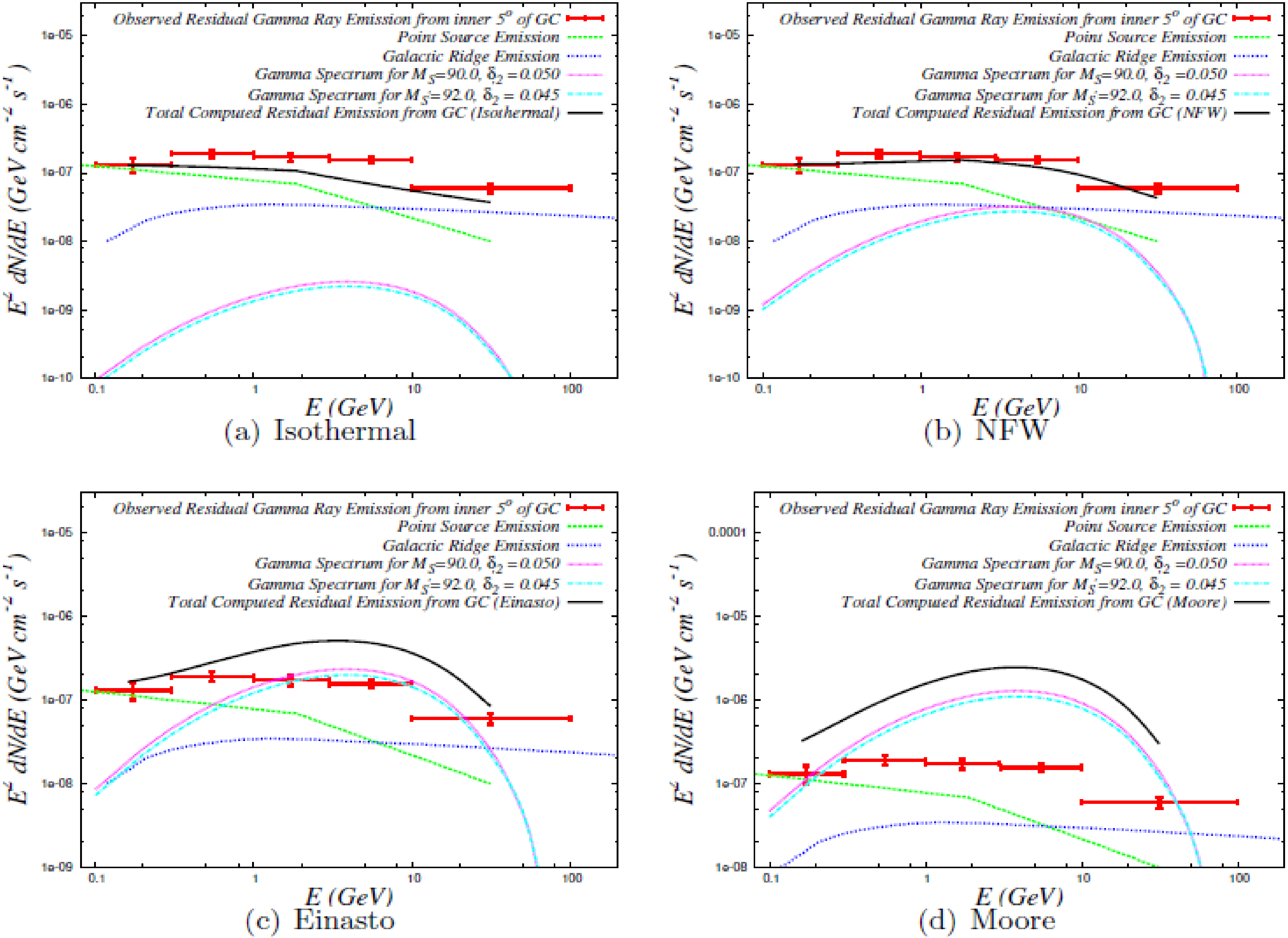


(c) Einasto

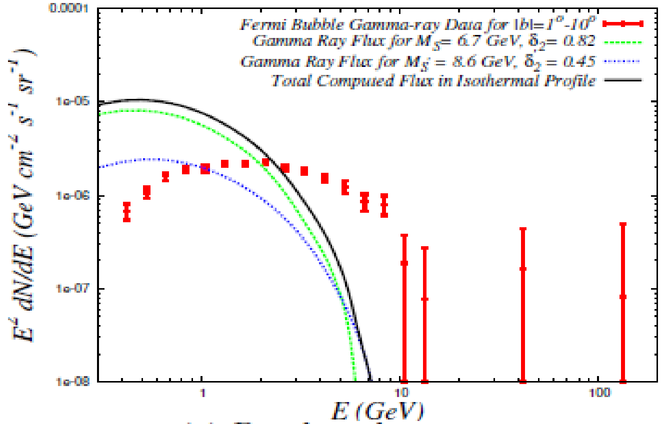


(d) Moore

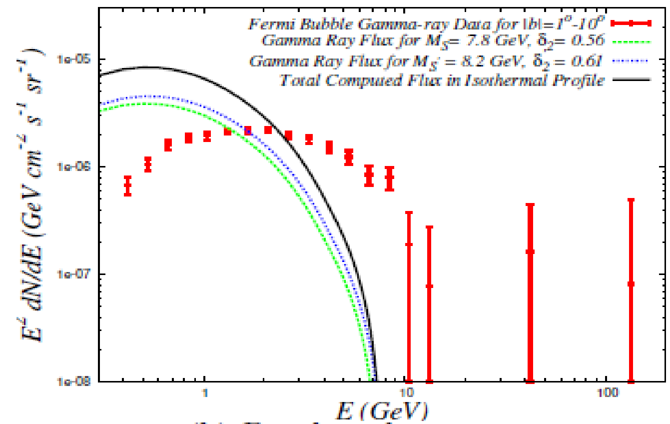
XENON100+PLANCK for GC gamma excess



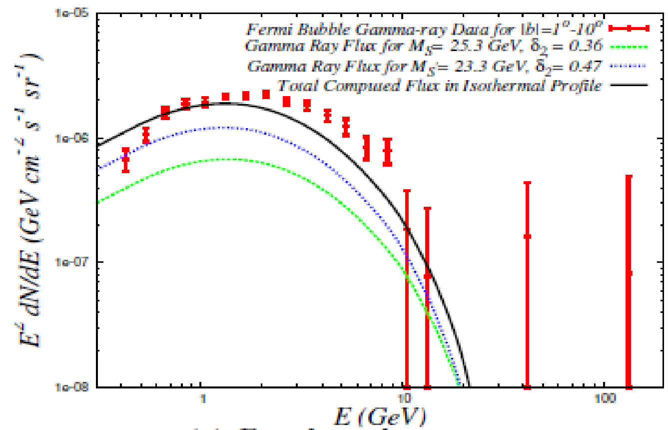
Comparing with *Fermi Bubble*



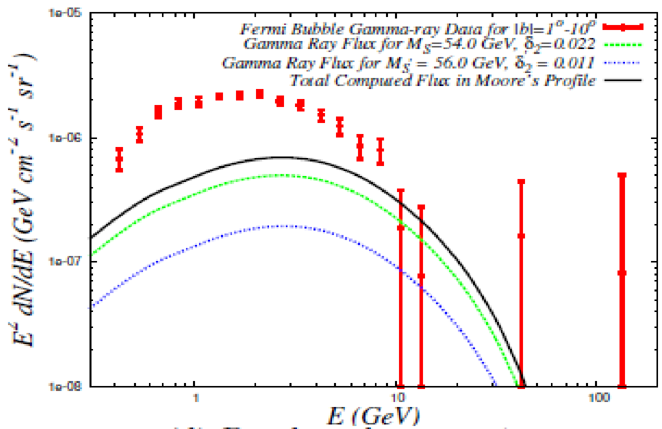
(a) Benchmark point 1



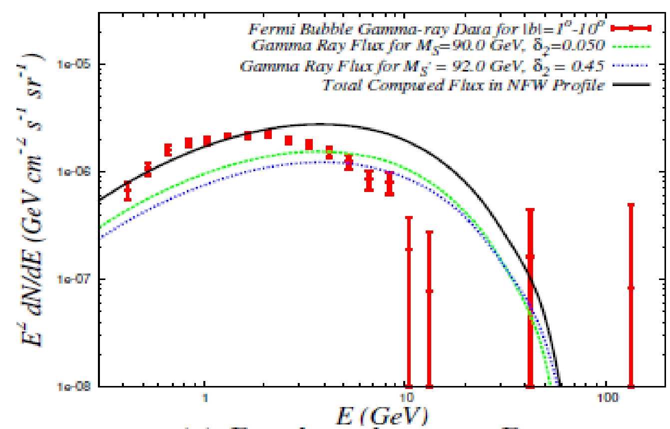
(b) Benchmark point 2



(c) Benchmark point 3



(d) Benchmark point 4A



(e) Benchmark point 4B

Conclusions

- Two real scalar SM gauge singlets odd under $\mathbb{Z}_2 \times \mathbb{Z}_2'$
- (CDMS II, CoGeNT, CRESST II) + Planck + Galactic Centre + Fermi Bubble prefer flat DM halo profile like isothermal/Burkart
- (Xenon 100, LUX) + Planck + Galactic Centre + Fermi Bubble prefer cuspy nature of DM halo profiles such as Moore/Einasto
- This model provides an explanation for excess low energy gamma ray emission from Galactic Centre region as also from the low lattitude Fermi Bubble region from the annihilation of Dark Matter