Natural explanation for 130 GeV photon line within vector boson dark matter model

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IPM, TEHRAN

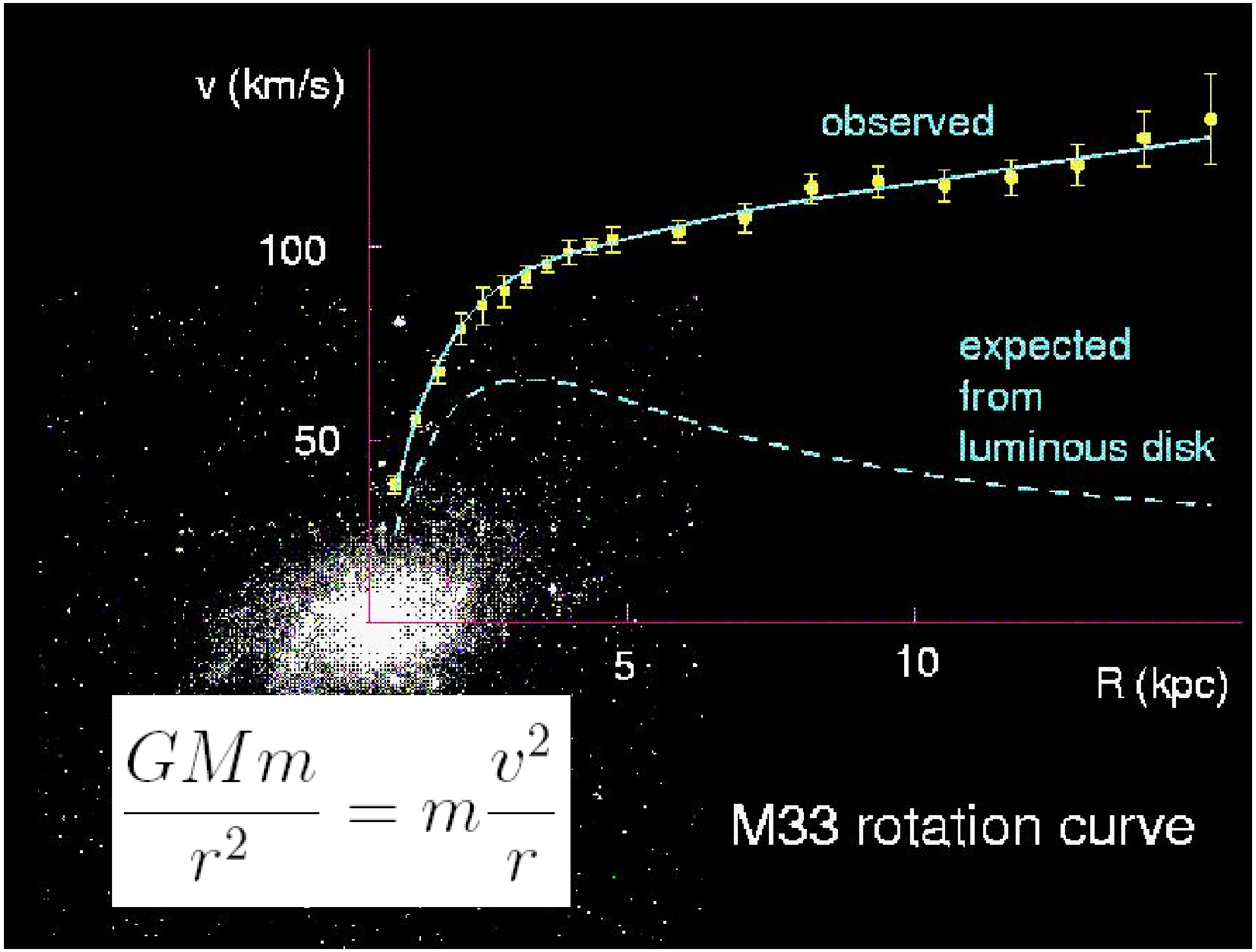
Plan of talk

- Introduction to dark matter
- Direct and indirect dark matter searches
- 130 or 135 GeV line in FermiLAT data
- Challenges for model building
- Our model
- Phenomenological consequences
- Conclusions

Why dark matter?

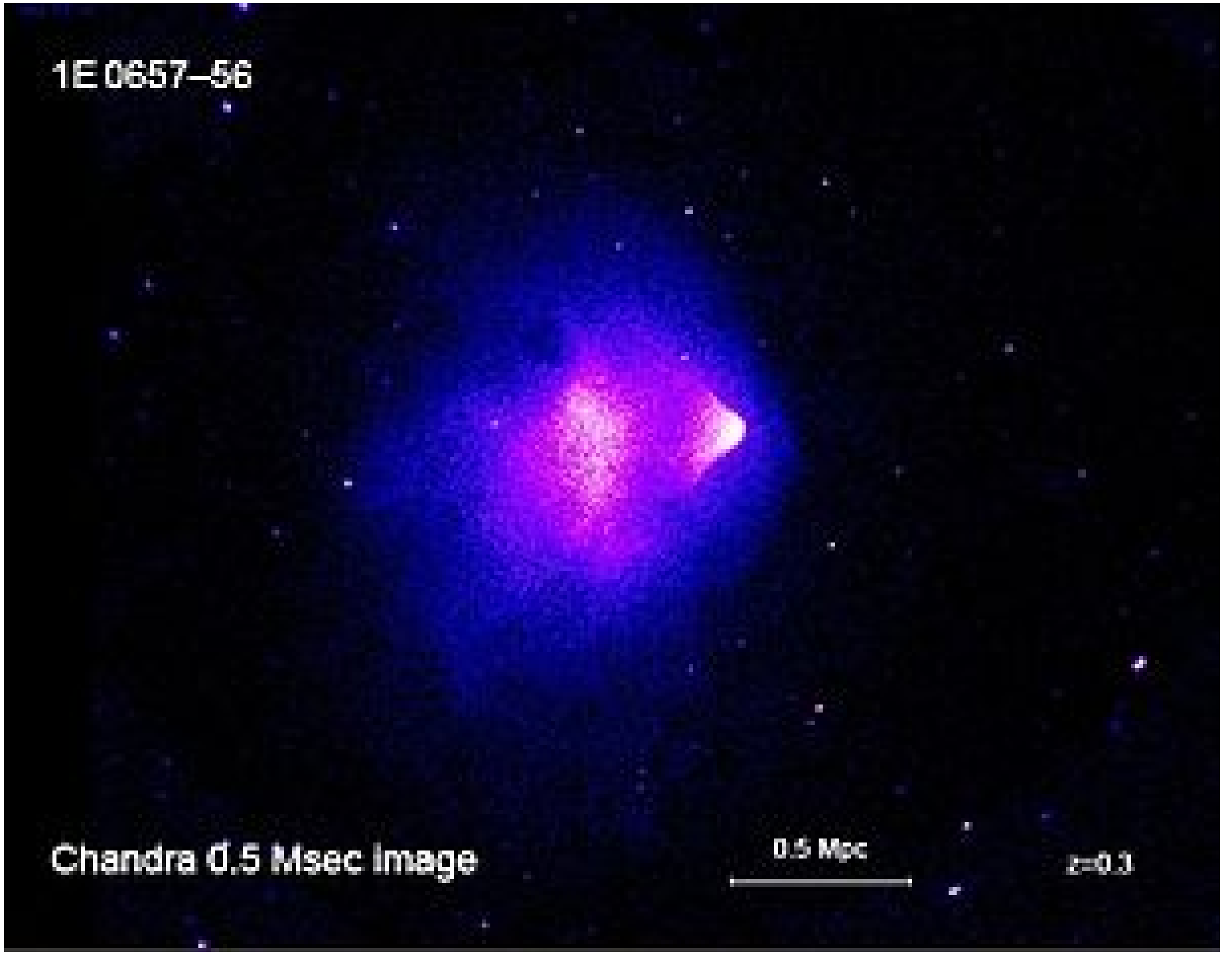
- Rotation curve
- Galaxy clusters
- Bullet galaxy
- Cosmic Microwave background
- Structure Formation

Rotation curve

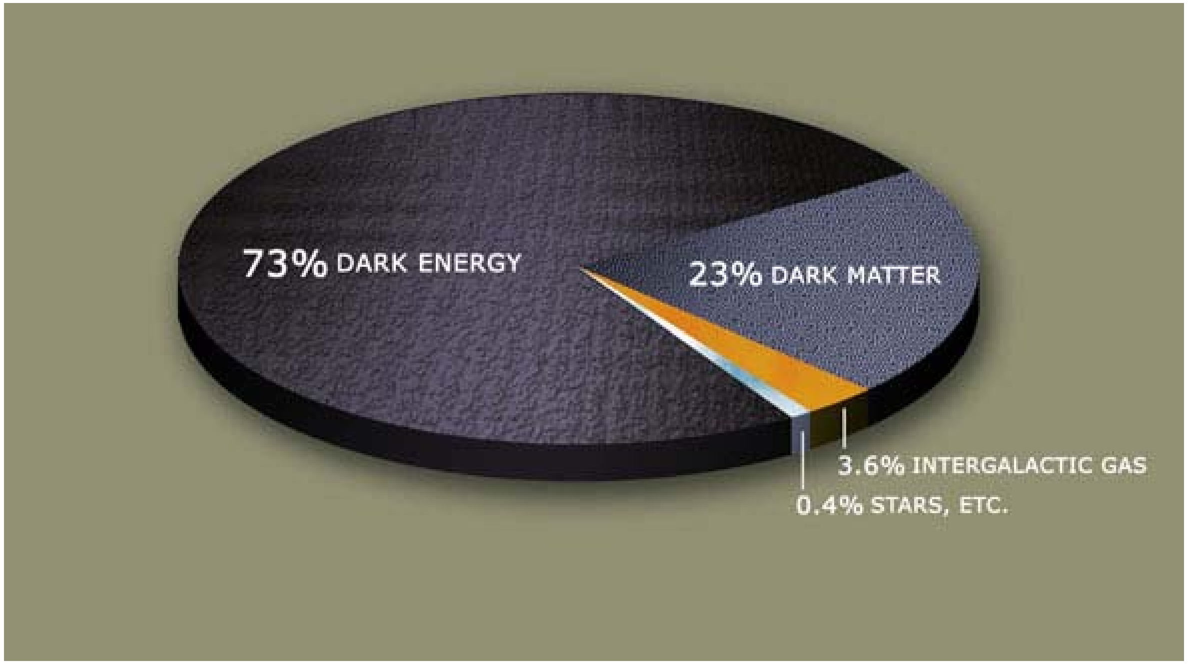


$$\frac{GMm}{r^2} = m\frac{v^2}{r}$$

Bullet clusters



ΛCDM

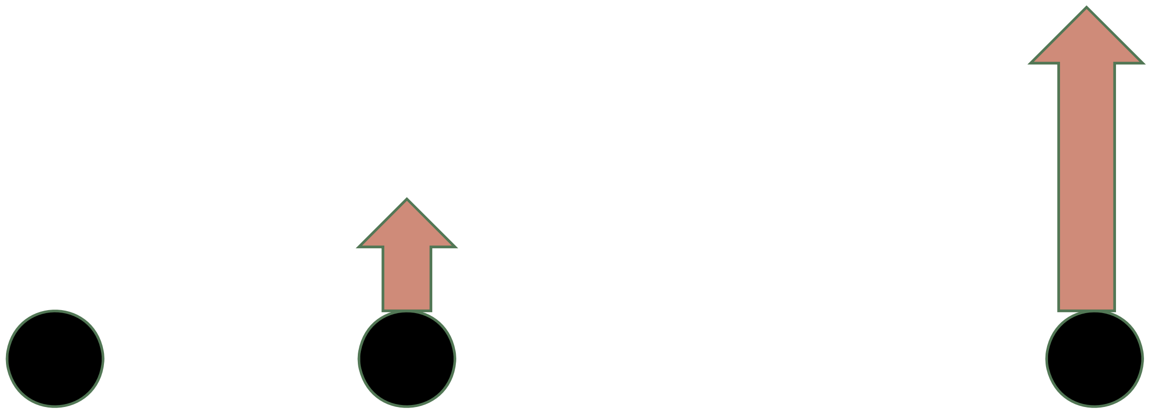

73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

Nature of Dark Matter

- Mass?
- Interactions?
- Spin?

SPIN of dark matter?

- Spin 0, 1 /2, 3/2 are all extensively studied.



SPIN of dark matter?

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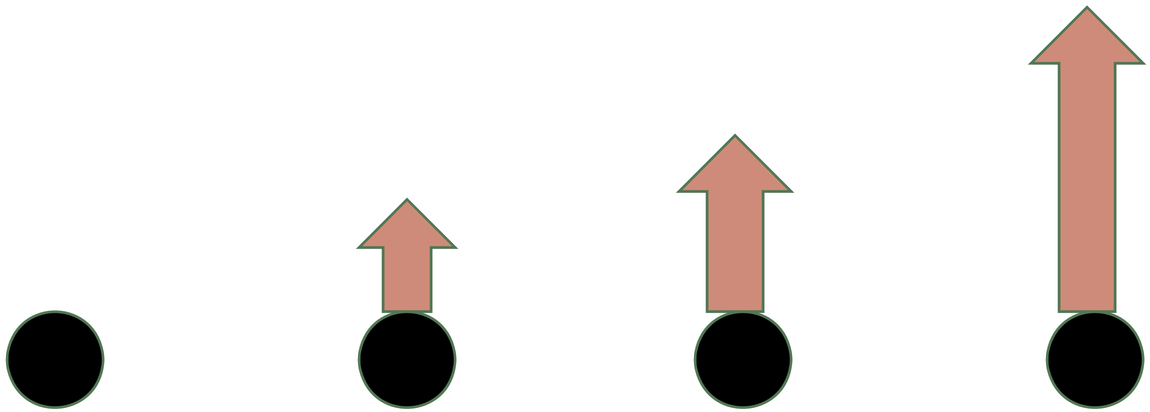


Spin 1 (vector boson)

VDM: vector dark matter

Thomas Hambye and Tytgat, PLB683; T. Hambye, JHEP 0901;Bhattacharya, Diaz-Cruz, Ma and Wegman, Phys Rev D85

Extra Large Dimension
Servant and Tait, Nucl Phys B650
The little Higgs model
Birkedal et al, Phys Rev D 74
Linear Sigma model
Abe et al, Phys Lett B
Vector Higgs-portal dark matter and invisible Higgs
Lebedev, Lee, Mambrini, Phys Let B 707
VDM: vector dark matter
YF and Rezaei, JCAP

Mass range and interactions

- WIMP
- SuperWIMP
- Axion
- …….

Direct DM Detection

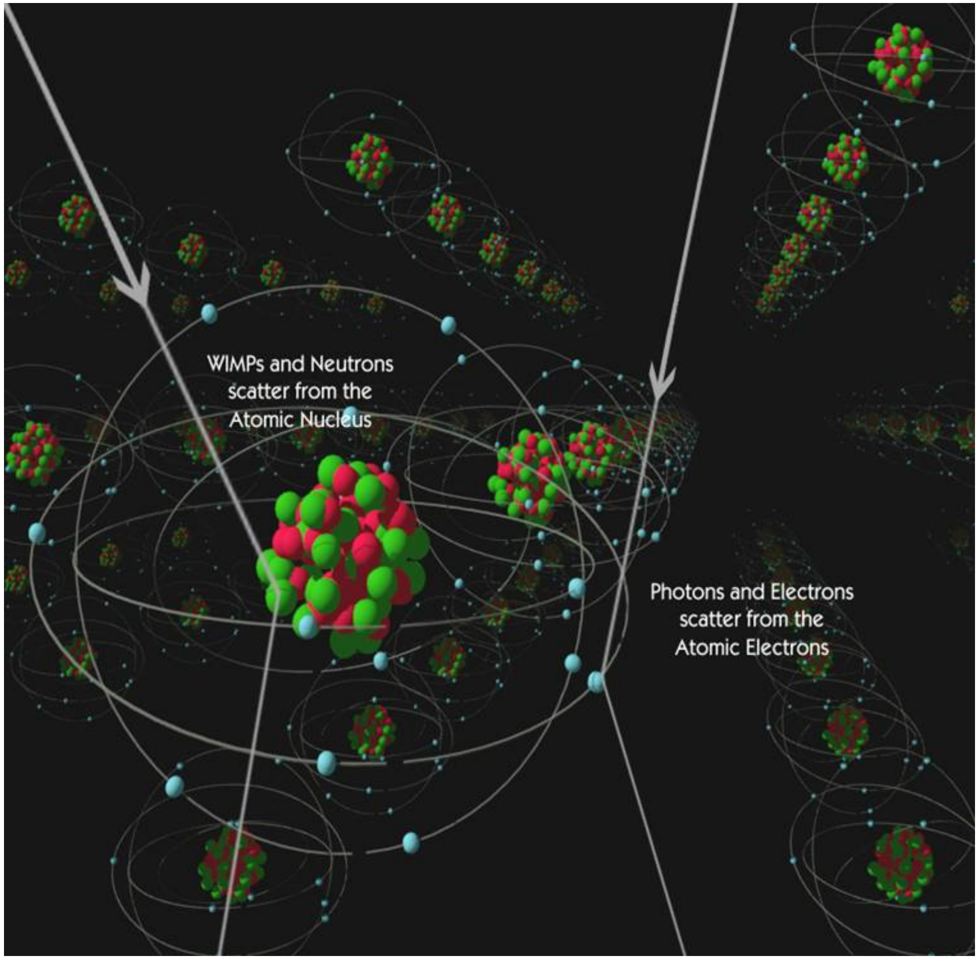
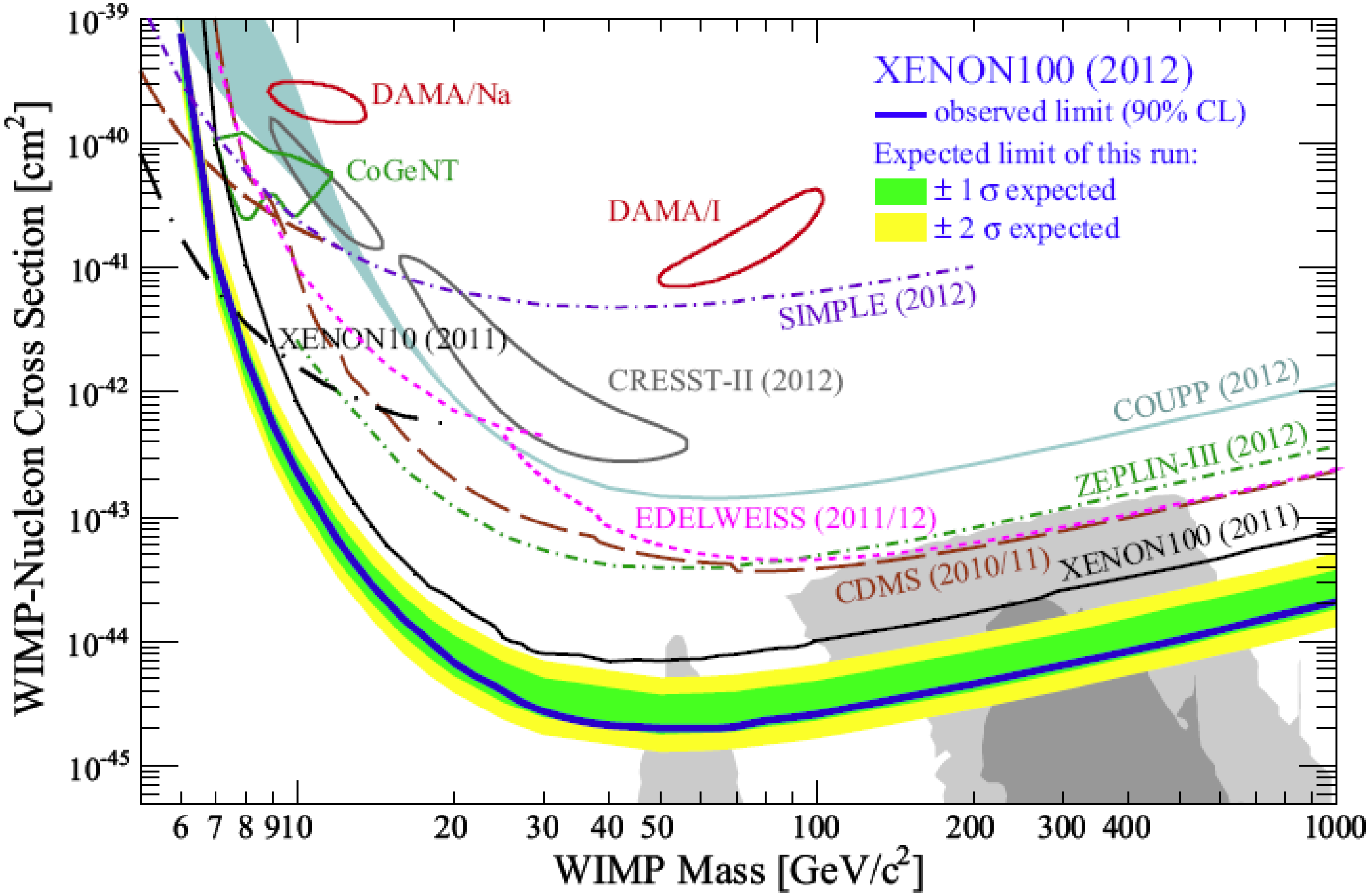


Image courtesy of:
http://cdms.berkeley.edu/Education/DMpages/science/directDetection.shtml

Direct search results

XENON collaboration, PRL 109 (2012) 181301



Indirect detection

- Detection of the products of DM pair annihilation

in the DM halo, galaxy center, Sun, Earth ….

$$\mathrm{DM} + \mathrm{DM} \rightarrow e^- e^+ \qquad \mathrm{DM} + \mathrm{DM} \rightarrow \gamma\gamma$$

$$\text{Inverse Compton}: \quad e^\pm + \gamma \rightarrow e^\pm + \gamma$$

$$\text{pair annihilation}: \quad e^+ e^- \rightarrow \gamma\gamma$$

Annihilation rate

$$\Gamma(\mathrm{DM} + \mathrm{DM} \rightarrow \mathrm{anything}) \propto n_{DM}^2$$

Dark matter density

- Average DM density in universe today $10^{-6} \, \frac{\mathrm{GeV}}{\mathrm{cm}^3}$

- Local dark matter density $0.38 \, \frac{\mathrm{GeV}}{\mathrm{cm}^3}$

Catena and Ullio, JCAP (2010)

- NFW profile

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

Signal from the Sun

$$\mathrm{DM}(v_i) + N \rightarrow \mathrm{DM}(v_f) + N$$

Trapped inside the gravitational well

$$v_i \sim 200 \text{ km/sec} \quad v_i > v_f$$

n_{DM} Grows .

$$\Gamma(\mathrm{DM} + \mathrm{DM} \rightarrow \text{anything}) \propto n_{DM}^2$$

Only ν and $\bar{\nu}$ come out of the Sun center and reach our detectors.

FERMI TELESCOPE

- FERMI GAMMA RAY TELESCOPE

- Old name: GLAST

Photon production from DM

$$\mathrm{DM} + \mathrm{DM} \to e^- e^+$$

$$\text{Inverse Compton :} \quad e^\pm + \gamma \to e^\pm + \gamma$$

$$\text{pair annihilation :} \quad e^+ e^- \to \gamma\gamma$$

$$\mathrm{DM} + \mathrm{DM} \to \text{hadrons}$$

$$\pi^0 \to \gamma\gamma$$

Monochromatic photon line

$$\mathrm{DM} + \mathrm{DM} \to \gamma + \gamma \quad E_\gamma = m_{DM}$$

$$\mathrm{DM} + \mathrm{DM} \to \gamma + h \quad E_\gamma = \frac{4m_{DM}^2 - m_h^2}{4m_{DM}}$$

$$\mathrm{DM} + \mathrm{DM} \to \gamma + Z \quad E_\gamma = \frac{4m_{DM}^2 - m_Z^2}{4m_{DM}}$$

Fermi-LAT

- LAT=Large Area Telescope
- 20 GeV-300GeV
- Good energy and angular resolution
- Angular resolution better than 1 degree

Search for monochromatic line

- A Tentative Gamma-Ray Line from Dark Matter Annihilation at the Fermi Large Area Telescope

Weniger, JCAP 1208 (2012)

4.6 C.L (3.3 CL look elsewhere effect)

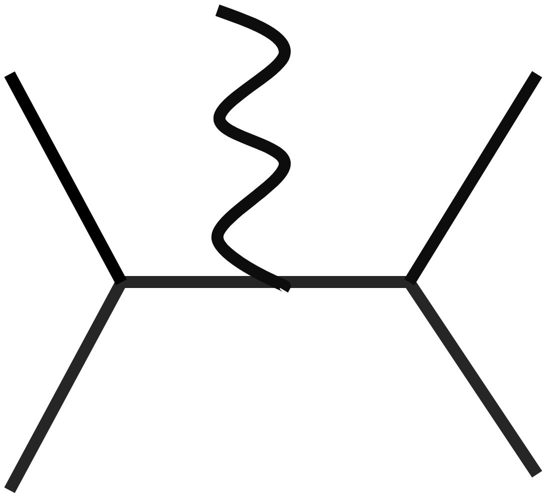
50 photons

$$E_\gamma \simeq 130 \text{ GeV}$$

$$\langle \sigma(\text{DM} + \text{DM} \to \gamma + \gamma) v \rangle \simeq 1.27 \times 10^{-27} \text{ cm}^3 \text{sec}^{-1}$$

Sharp spectrum with nonzero width

- Fermi LAT Search for Internal Bremsstrahlung Signatures from Dark Matter Annihilation
  Bringmann, Huang, Ibarra, Vogl and Weniger
- JCAP 1207 (2012) 54



Further confirmation

- Tempel, Hecktor and Raidal, JCAP 1209 (2012)
- Su and Finkbeiner, 1206.1616
- Gamma Ray Features between 110-140 GeV

(one or two lines)

Doubts about signal

- Earth Limb data

Finkbeiner, Su and Weniger, JCAP 1301 (2013) 29

- Spectral and Spatial variation of diffuse gamma-ray background

Boyarsky Malyshev and Ruchayskiy,arXiv:1205.4700

- 130 GeV line from the vicinity of the Sun (3.2 Sigma CL)

Whiteson, 1302.0427

Fermi symposium in October

130 GeV → 135 GeV

Any astrophysical explanation

- Cold ultrarelativistic pulsar wind

Aharonian, Khangulyan and Malyshev, arXiv:1207.0458

Dark matter

- Dark matter annihilation

$$\mathrm{DM} + \mathrm{DM} \rightarrow \gamma + \gamma \quad E_\gamma = m_{DM}$$

$$\mathrm{DM} + \mathrm{DM} \rightarrow \gamma + h \quad E_\gamma = \frac{4m_{DM}^2 - m_h^2}{4m_{DM}}$$

$$\mathrm{DM} + \mathrm{DM} \rightarrow \gamma + Z \quad E_\gamma = \frac{4m_{DM}^2 - m_Z^2}{4m_{DM}}$$

- Dark matter decay

Enhanced DM density near GC (Buchmuller and Garny, JCAP1208)

Challenge for model building

- Scalar dark matter

$$i(\phi^* \partial_\mu \phi - \phi \partial_\mu \phi^*) A^\mu$$

- Fermion dark matter

$$\bar{\psi} \gamma^\mu \psi A_\mu$$

Solution

- Effective Lagrangian employing

$$F_{\mu\nu}$$

- Annihilation via loop

Challenge for model building

Loop level effect:

$$\langle \sigma(\mathrm{DM} + \mathrm{DM} \to \gamma + \gamma) v \rangle \simeq 1.27 \times 10^{-27}\ \mathrm{cm}^3 \mathrm{sec}^{-1}$$

Tree level effect should be bigger by a factor ~100.

Total cross section may exceed the thermal expectation:

$$\langle \sigma_{tot} v \rangle = 3 \times 10^{-26}\ \mathrm{cm}^3 \mathrm{sec}^{-1}$$

Indirect bound

- We should worry about the decay products from the main annihilation mode: Continuous gamma ray, antiprotons and etc.

Continuous gamma ray spectrum

- Main annihilation mode $W^+W^-,\ ZZ,\ b\bar{b}$

- Continuous spectrum with the same morphology

Cohen et al, JHEP 1210 (2012) 134; Buchmuller and Garny, JCAP 1208 (2012) 35

MSSM and NMSSM

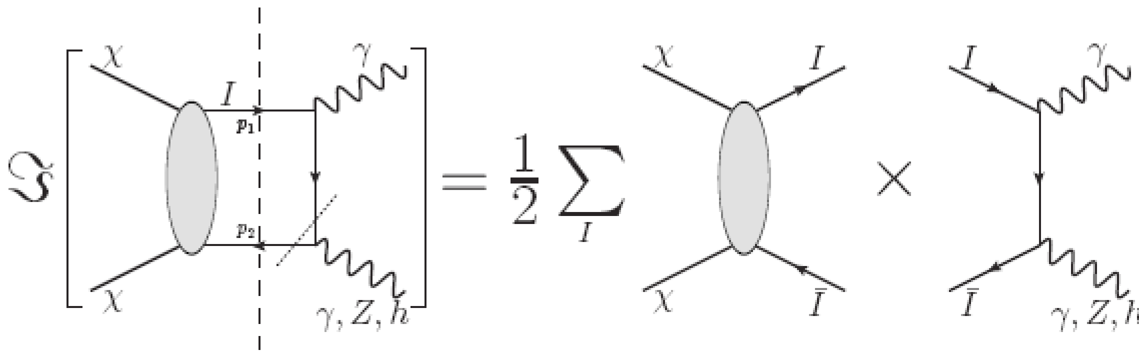
- Neutralino of MSSM is ruled out

Cohen et al, JHEP 1210 (2012) 134; Buchmuller and Garny, JCAP 1208 (2012) 35

- However, Neutralino of NMSSM survives.

Kozaczuk, Profumo and WainWright, arXiv:1302.4781

Optical theorem



Asano et al, arXiv: 1211.6739

Continuum gamma rays, radio and antiproton data

"I" cannot be any SM particle except top.

Our suggestion

- Vector boson as dark matter candidate
- Farzan and Rezaei Akbarieh, 1211.4685

$$-\left[V_{\mu\nu}V^{\mu\nu}+V'_{\mu\nu}V'^{\mu\nu}\right]/4$$

$$V_{\mu\nu}^{(\prime)}\equiv\partial_\mu V_\nu^{(\prime)}-\partial_\nu V_\mu^{(\prime)}$$

$$Z_2: \qquad V_\mu\to -V_\mu \ \text{ and } \ V'_\mu\to -V'_\mu$$

Lighter one is DM

Coupling to photon

$$g_V B^{\mu\nu} V_\mu V'_\nu$$

$$B_{\mu\nu} = \cos\theta_W F_{\mu\nu} - \sin\theta_W Z_{\mu\nu}.$$

Coupling to photon

$$g_V B^{\mu\nu} V_\mu V'_\nu$$

$$B_{\mu\nu} = \cos\theta_W F_{\mu\nu} - \sin\theta_W Z_{\mu\nu}.$$

$$[g_V] = 1$$

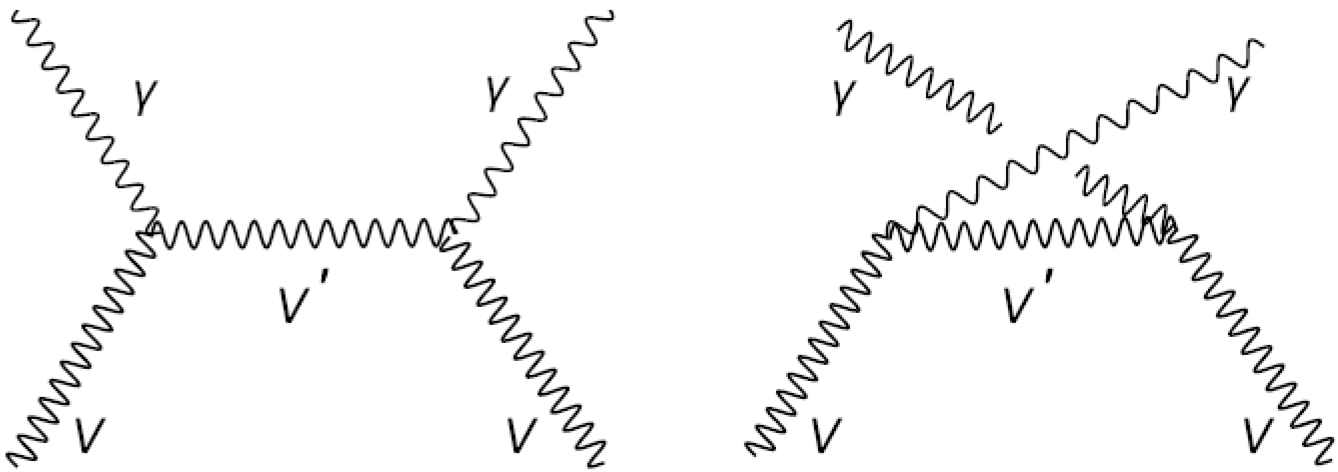
However, not necessarily renormalizable.
Vector bosons can be promoted to be gauge bosons
By Stuckelberg mechanism.

Coupling to photon

$$g_V B^{\mu\nu} V_\mu V'_\nu$$

$$B_{\mu\nu} = \cos\theta_W F_{\mu\nu} - \sin\theta_W Z_{\mu\nu}.$$

g_V is effective coupling below Λ.



$$g_V \simeq 0.27(m_{V'}/300\ \text{GeV}).$$

Two line feature

$$\mathrm{DM} + \mathrm{DM} \to \gamma + \gamma \quad E_\gamma = m_{DM}$$

$$\mathrm{DM} + \mathrm{DM} \to \gamma + Z \quad E_\gamma = \frac{4m_{DM}^2 - m_Z^2}{4m_{DM}}$$

- Relative intensity:

$$\sigma(V + V \to \gamma Z)/[2\sigma(V + V \to \gamma\gamma)] < (\tan^2\theta_W) = 0.3.$$

- FAVORED?! Su and Finkbeiner, 1206.1616

Can g_V be large?

Yes!

(In)visible Z-prime and dark matter

Dudas, Mambrini, Pokorski and Romagnoni, JHEP 0908 (2009) 14;

Extra (1) as natural source of monochromatic gamma ray

Dudas, Mambrini, Pokorski and Romagnoni, JHEP 1210 (2012) 123

Where else this large coupling show up?

- At colliders such as LHC

$$\sigma(f\bar{f} \to VV') = \frac{(eQ_f g_V \cos\theta_W)^2}{192\pi N_c} \mathcal{K}[E_{cm}^2 + 2(m_V^2 + m_{V'}^2)]$$

$$\times \frac{[(E_{cm} - m_{V'})^2 - m_V^2][(E_{cm} + m_{V'})^2 - m_V^2]}{E_{cm}^6 m_V^2 m_{V'}^2}$$

$$\mathcal{K} = \sqrt{(E_{cm}^2 + m_V^2 - m_{V'}^2)^2 - 4m_V^2 E_{cm}^2}.$$

Signature at collider

Dominant decay mode

$$\Gamma(V' \to V + \gamma) = \frac{g_V^2 \cos^2\theta_W}{96\pi} \frac{(m_{V'}^2 - m_V^2)^3 (m_{V'}^2 + m_V^2)}{m_V^2 m_{V'}^5}.$$

Missing energy + single photon

Search for dark matter at the LHC using missing transverse energy : **arXiv:1206.0753**

Prediction for LHC

$$g_V \simeq 0.27(m_{V'}/300\ \text{GeV}).$$

- For $\sqrt{s} = 7$ TeV and $m_{V'} = 200$ GeV

$$\sigma(p + p \to V + V') = 50\ \text{fb}$$

Already excluded!

Search for dark matter at the LHC using missing transverse energy : **arXiv:1206.0753**

- For $\sqrt{s} = 8$ TeV(14 TeV) and $m_{V'} = 1.5$ TeV

$$\sigma(p + p \to V + V') = 0.5\ \text{fb}(90\ \text{fb})$$

- The whole perturbative regime can be probed by the LHC.

- Model can be falsified

Main annihilation

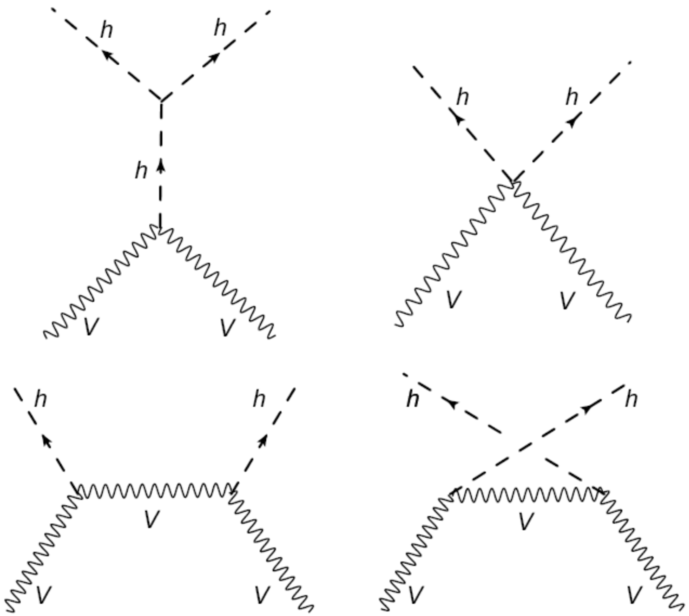
- Thermal abundance:

$$\langle \sigma_{tot} v \rangle = 3 \times 10^{-26}\ \mathrm{cm}^3 \mathrm{sec}^{-1}$$

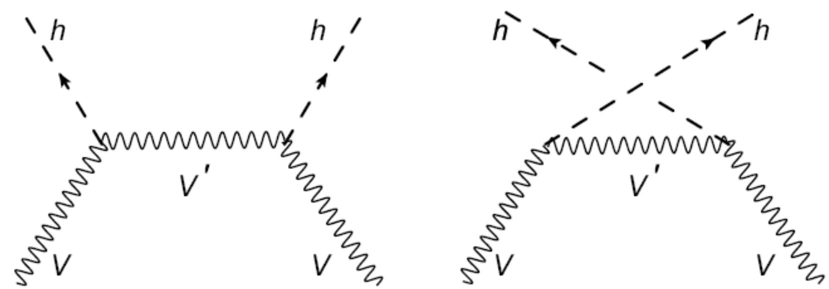
Main annihilation mode

$$\frac{\lambda_1}{2}|H|^2 V_\mu V^\mu + \frac{\lambda_2}{2}|H|^2 V'_\mu V'^\mu + \lambda_3 |H|^2 V'_\mu V^\mu .$$

λ_1 regime



λ_3 regime



Phenomenology of λ_1 regime

- Annihilation W pair

- Direct detection

- Excess in $h \to \gamma\gamma$ and $h \to Z\gamma$

Annihilation to W pair

- Like Higgs portal scenarios:

$$\langle \sigma(VV \to f\bar{f}) v_{rel} \rangle = \frac{\lambda_1^2 v_h^2 \Gamma(h^* \to f\bar{f})}{3 m_V (4 m_V^2 - m_h^2)^2},$$

where $f\bar{f}$ can be W^+W^-, ZZ, $b\bar{b}$ and etc.

$$\sigma(VV \to W^+W^-) \sim \sigma(VV \to \gamma\gamma)$$

- The continuous spectrum is below bound

Cohen et al, JHEP 1210 (2012) 134; Buchmuller and Garny, JCAP 1208 (2012) 35

Direct detection

$$\sigma_{SI}(V+N \to V+N) = \frac{\lambda_1^2 f^2}{4\pi} \frac{m_N^2 m_r^2}{m_V^2 m_h^4}$$

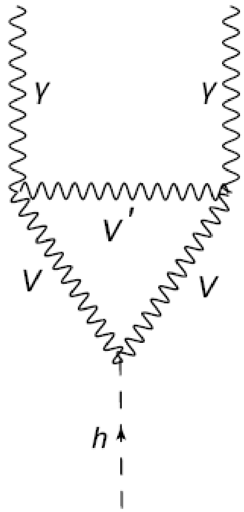
f parameterizes the nuclear matrix element

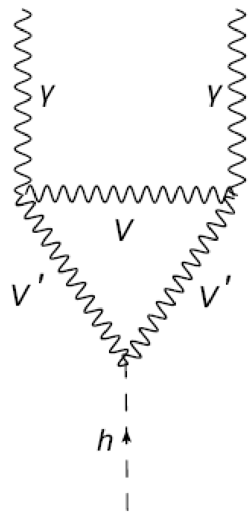
$$0.14 < f < 0.66$$

$\lambda_1 = 0.12,$ ⇒ $\sigma = 4.4 \times 10^{-45} (f/0.2)^2 \text{cm}^2$

XENON collaboration,
PRL 109 (2012) 181301 ⇒ $f < 0.2$ Or $\lambda_1 \ll \lambda_3$

Higgs decay





- Although Higgs couplings are
- dimensionless, they are not
- renormalizable.

$$M(h \to \gamma\gamma) = \frac{v_h \lambda_1 (g_V \cos\theta_W)^2}{8\pi^2} g(x,z) \log \frac{\Lambda^2}{m_{V'}^2},$$

- For $\lambda_1 \log \Lambda^2/m_{V'}^2 \sim 1$, Effect is comparable to the SM

Future prospect

- If excess is confirmed, $\lambda_1 \log \Lambda^2/m_{V'}^2$ will be fixed.

(Including the sign of λ_1)

We can search for excess in $h \to Z\gamma$

- If it is not confirmed , we may be in the λ_3 regime.

Or Λ may be close!

Secondaries

- Annihilation of DM produces Higgs pairs.

$$h \to b\bar{b}$$

- Antiproton and continuous gamma ray flux.

$$m_h \simeq m_V \simeq 130 \text{ GeV}$$ → Higgs decay non-relativistically.

Spectrum of secondaries ⇔

$$DM + DM \to b + \bar{b}$$

$$m_{DM} \simeq \frac{m_h}{2} \simeq 65 \text{ GeV}$$

Normalization of the flux

- Each pair of DM in our model produce 2 pairs of $b+\bar{b}$
- Each pair of DM $DM + DM \to b + \bar{b}$ produce 1 pair of $b+\bar{b}$

- Number density= density/ DM mass

$$\Gamma(\mathrm{DM} + \mathrm{DM} \to \mathrm{anything}) \propto n_{DM}^2$$

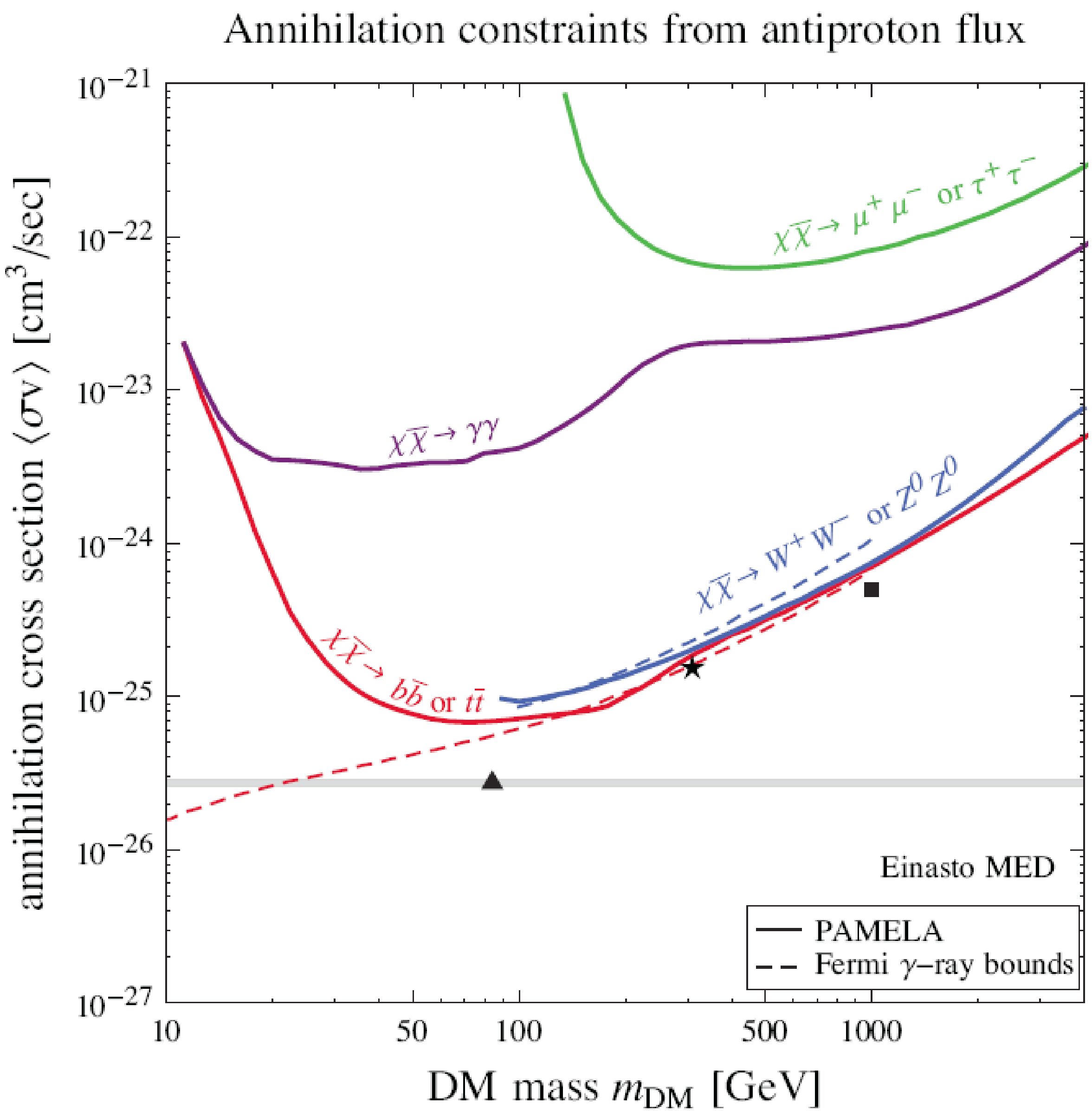
- Number density in our model is ½

- Normalization of secondary flux=1/2*1/2* 2=1/2

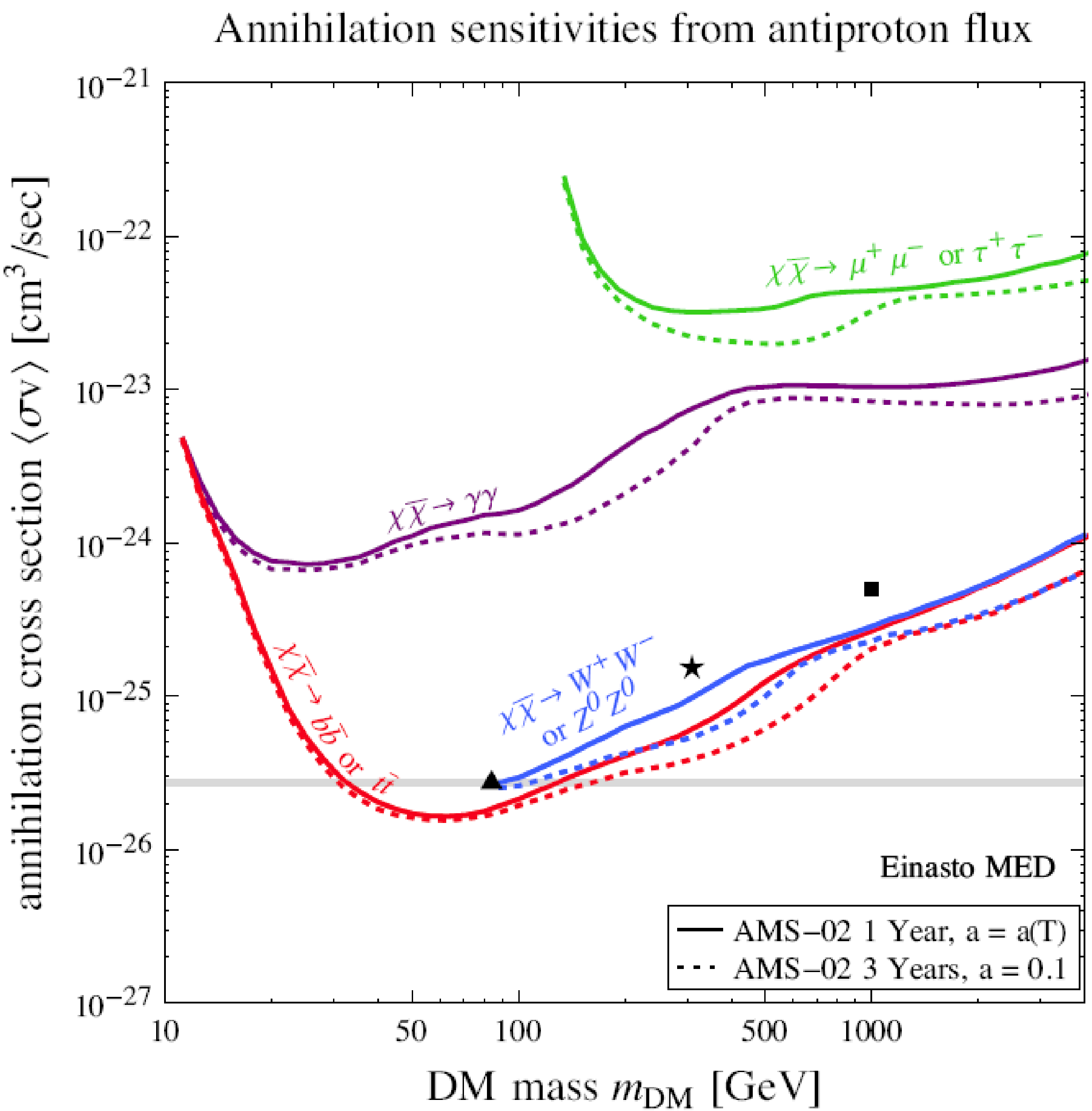
Bottomline

- The bound on $DM + DM \to h + h$ in our model from antiproton flux measured by PAMELA is twice less strong than the bound on $DM + DM \to b + \bar{b}$ for

$$m_{DM} \simeq \frac{m_h}{2} \simeq 60 \text{ GeV}$$



- Cirelli and Giesen,
- arXiv: 1301.7079



arXiv: 1301.7079

Conclusions

- A model to explain the 130 GeV line based on $g_V B^{\mu\nu} V_\mu V'_\nu$

- Missing energy+ photon signal at LHC

(Entire parameter space of the scenario can be probed.)

Main annihilation mode: $DM + DM \to h + h$

Antiproton flux to be probed by AMS02.

Conlusion

$$\frac{\lambda_1}{2}|H|^2 V_\mu V^\mu + \frac{\lambda_2}{2}|H|^2 V'_\mu V'^\mu + \lambda_3 |H|^2 V'_\mu V^\mu.$$

- λ_1 regime:

Direct DM detection;

Contribution to $h \to \gamma\gamma$ and $h \to Z\gamma$