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

Amin Rezaei Akbarieh

IPP13

(based on: Y.Farzan and A.R.A , arXiv:1211.4685)

Outline

- Dark Matter

Evidence, Direct and indirect dark matter searches

130 or 135 GeVline in FermiLATdata,...

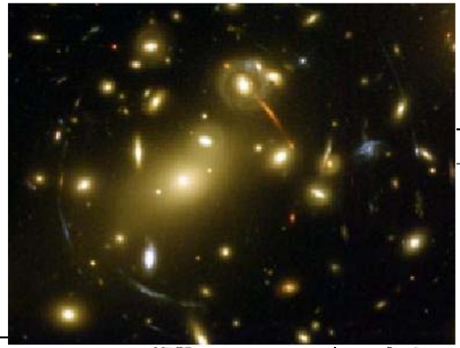
- Our Model

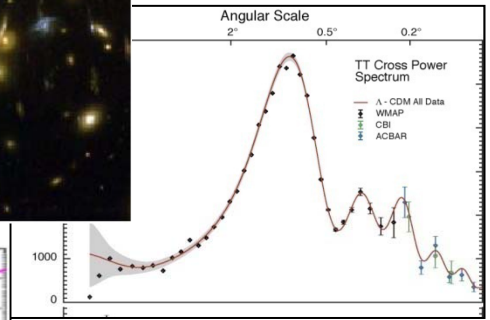
Phenomenological consequences

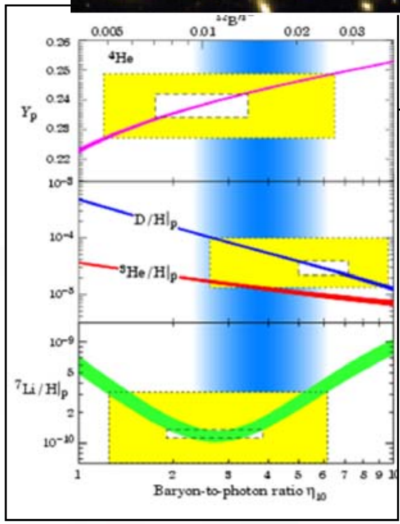
- Conclusion

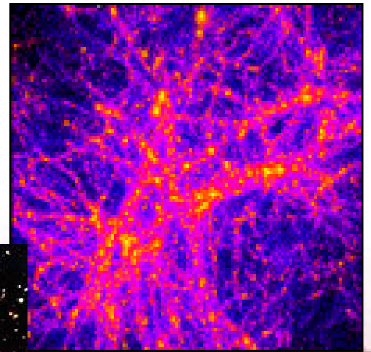
Evidence For Dark Matter

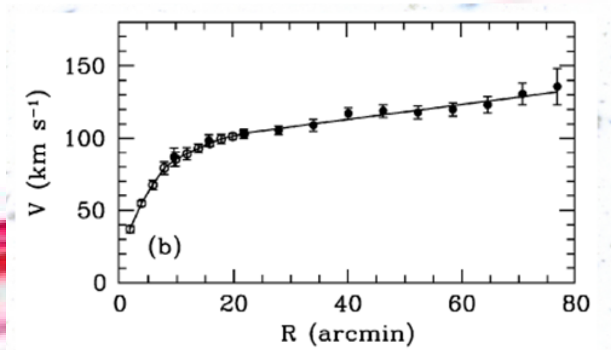
- Galactic rotation curves
- Gravitational lensing
- Light element abundances
- CMB anisotropies
- Large scale structure
- Etc…











What is the nature of Dark Matter?

Dark Matter

Stable

Neutral under color, electromagnetism

Relic density

Spin

Mass

Portal

Production Mechanism

Dark Matter

- Stable
- Neutral under color, electromagnetism
- Relic density

Dark Matter

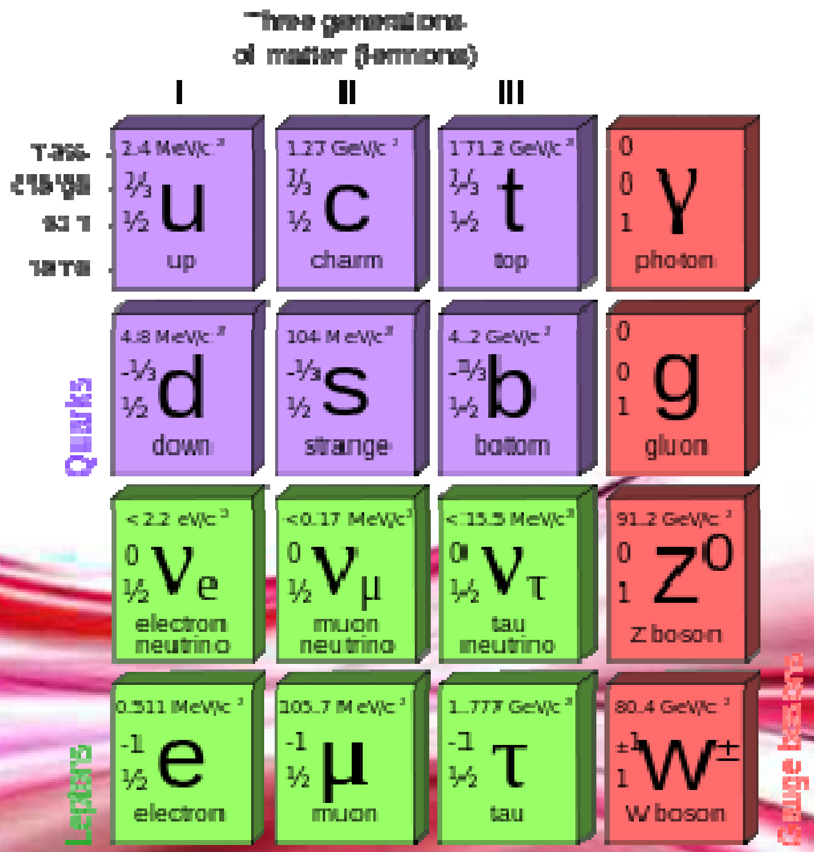
Stable

Neutral under color, electromagnetism

Relic density

Beyond the SM

SM



SPIN of dark matter?

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

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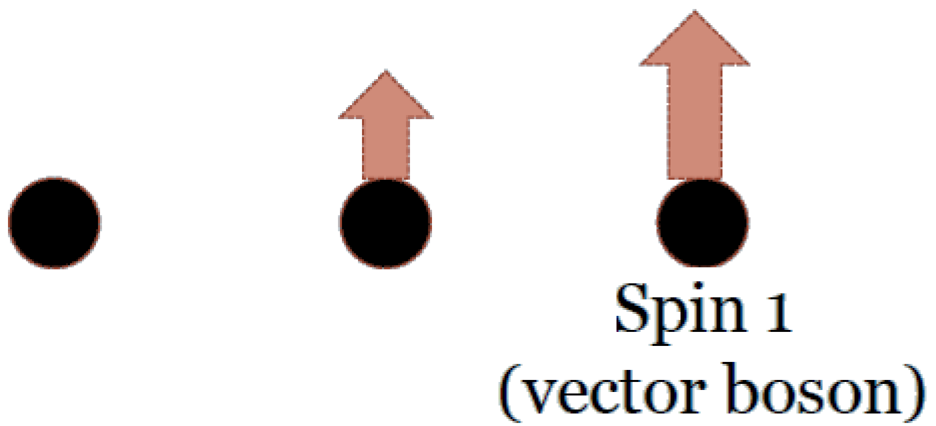
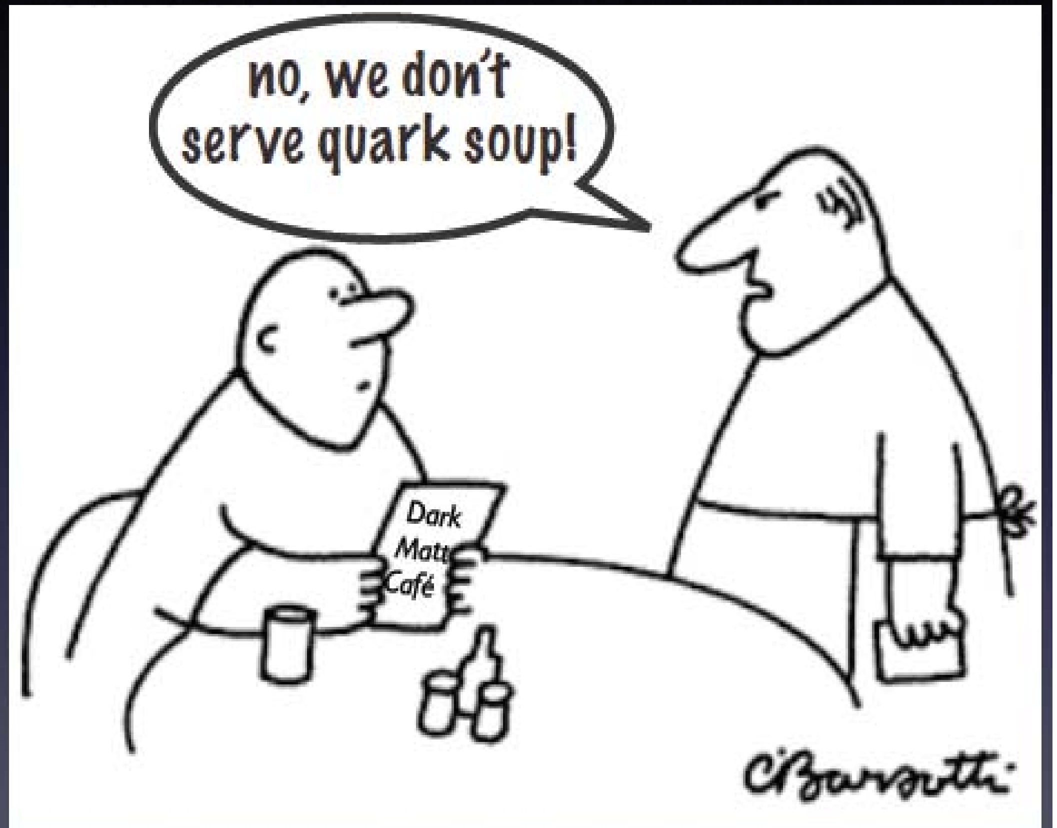


The Dark Matter Café

- Axions
- Axino
- Gravitino
- Sterile Neutrinos
- WIMPs
- And many more others that can fit the bill...



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

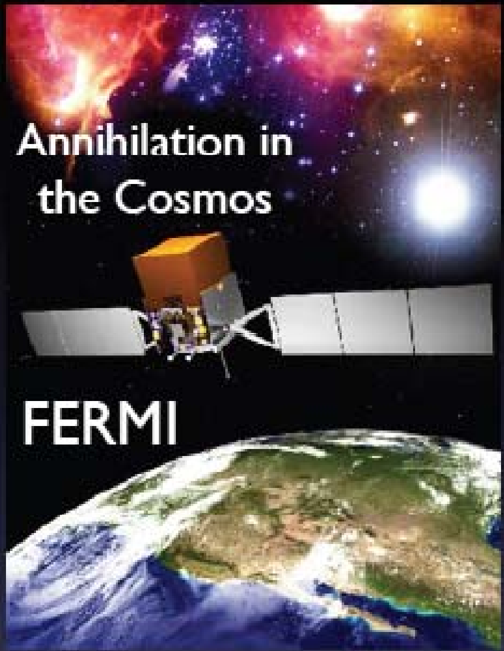
Vector Higgs-portal dark matter and invisible Higgs

Lebedev, Lee, Mambrini, Phys Let B 707

VDM: vector dark matter

Y. Farzan, A.R.A, JCAP

How to Detect DM



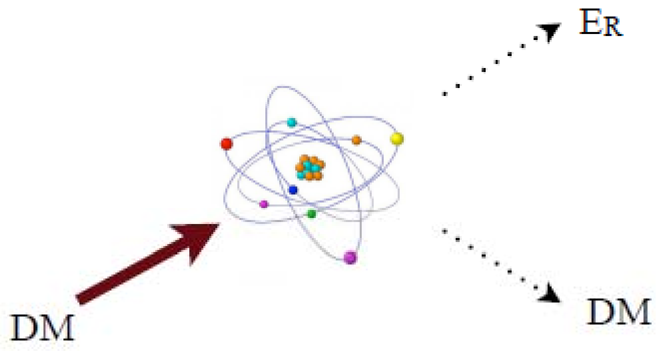
Production in Colliders

Scattering of Relic DM
Particles in Terrestrial
Detectors

Direct Detection

Dark matter scatters off of nuclei in detectors

Measure recoil energy of nuclei

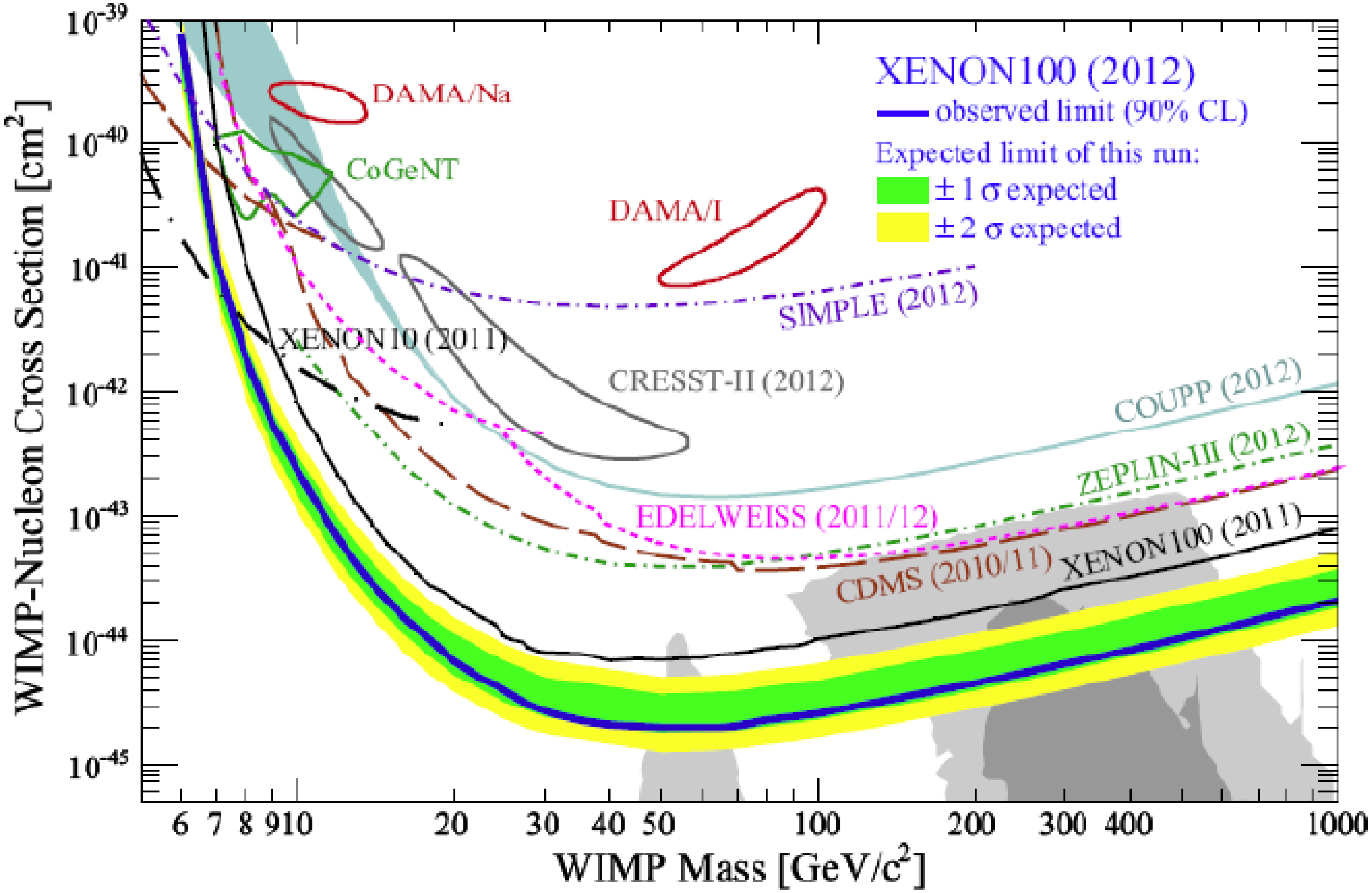


Average scattering rate depends on dark matter velocity distribution

$$\frac{dR}{dE_R} = n_{\rm dm} \left\langle v \frac{d\sigma}{dE_R} \right\rangle$$

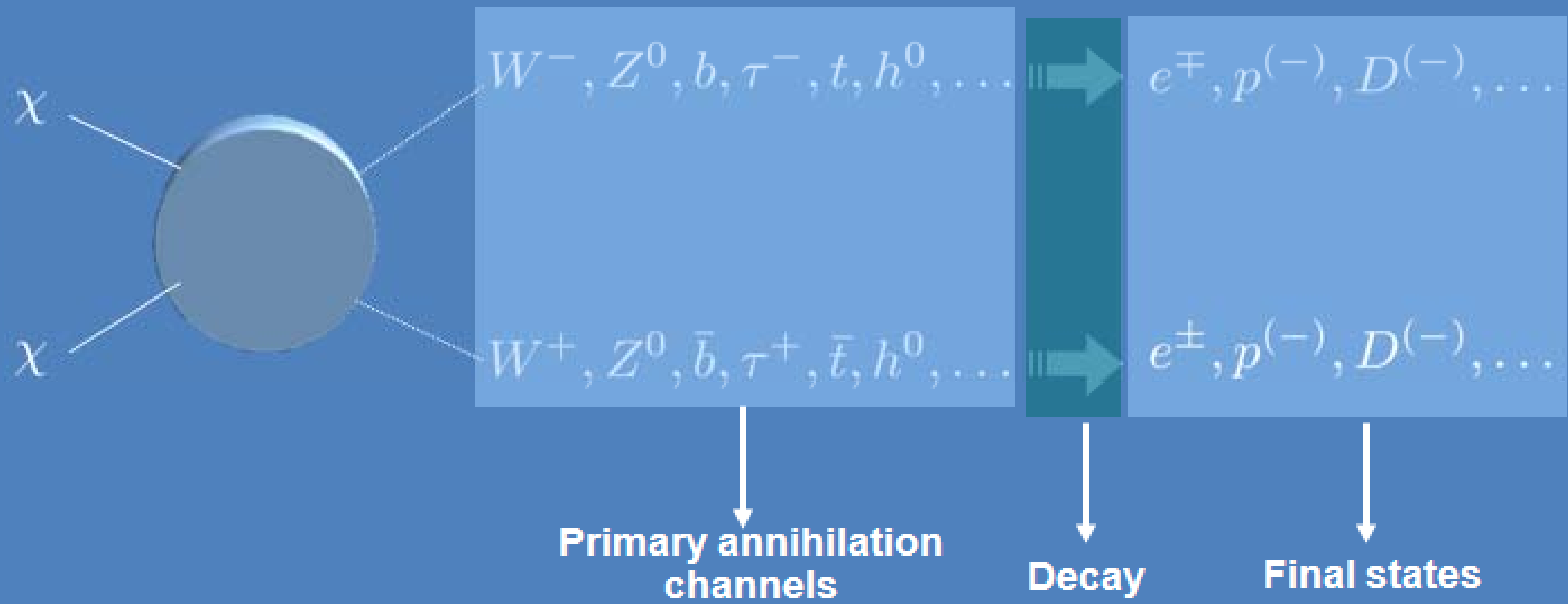
Direct search results

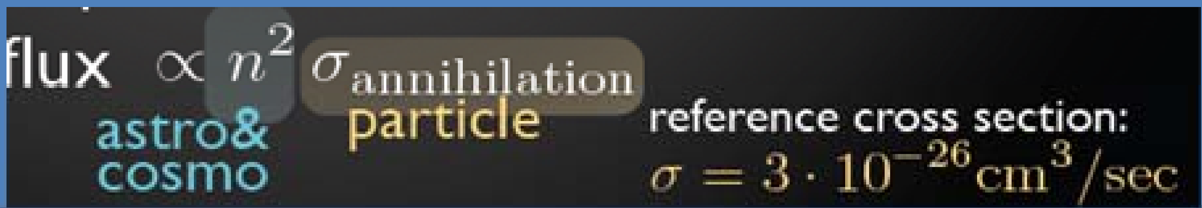
XENON collaboration, PRL 109 (2012) 181301

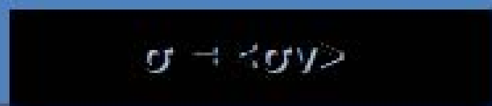


DM annihilations

DM particles are stable. They can annihilate in pairs.





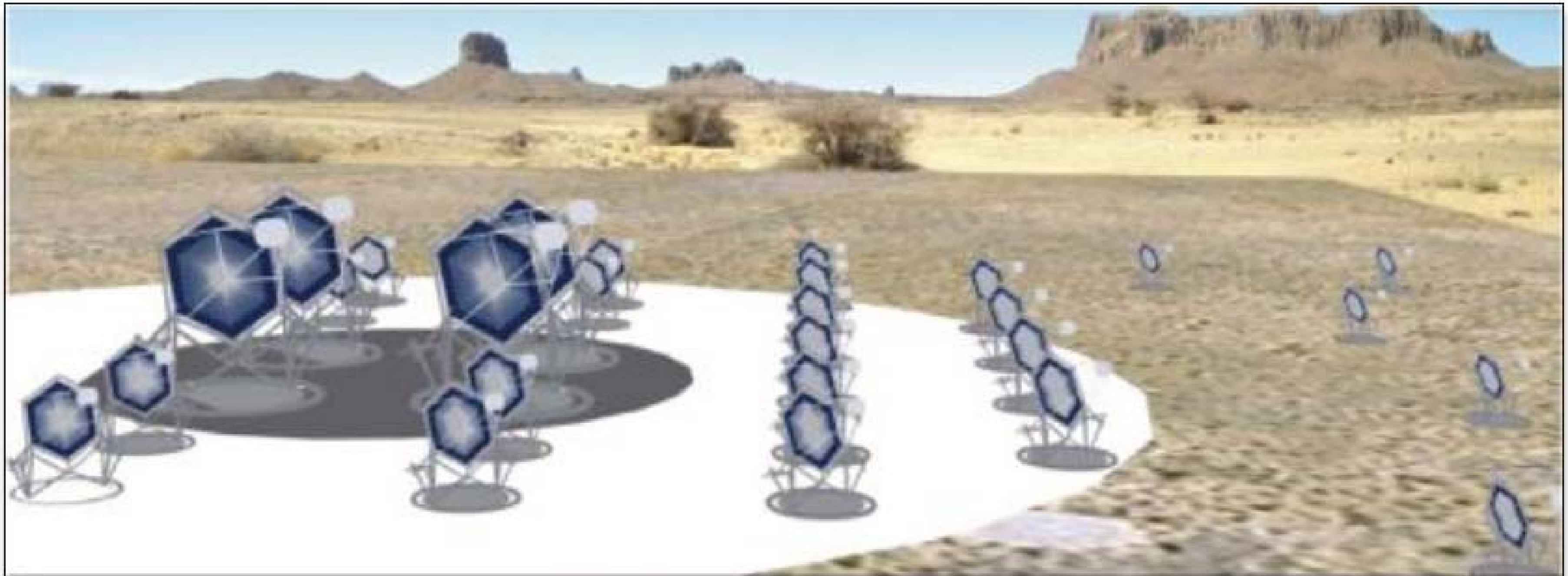


Indirect detection through γ-rays from DM annihilation

Fermi-LAT (Fermi Large Area Telescope)

H.E.S.S. & H.E.S.S.-2

VERITAS



CTA (Cherenkov Telescope Array)

Fermi Gamma Ray Space Telescope

Two Instruments:

LAT: 20 MeV → 300 GeV

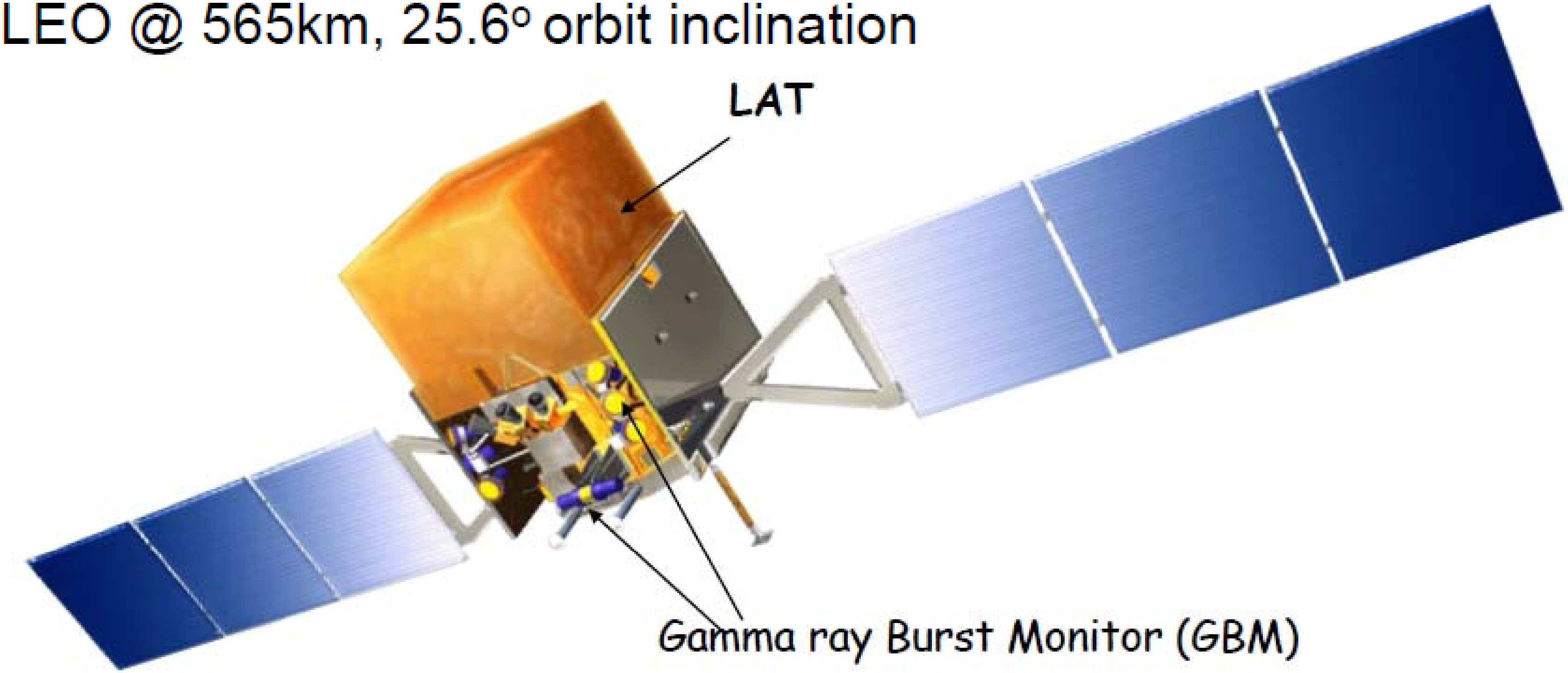
GBM: 10 keV → 30 MeV

Launch: June 11, 2008

5-year mission (10-year goal)

LEO @ 565km, 25.6° orbit inclination

fermi
Gamma-ray
Space Telescope



spacecraft partner:
General Dynamics

Photon production from DM

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

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

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

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

$$\pi^0 \rightarrow \gamma\gamma$$

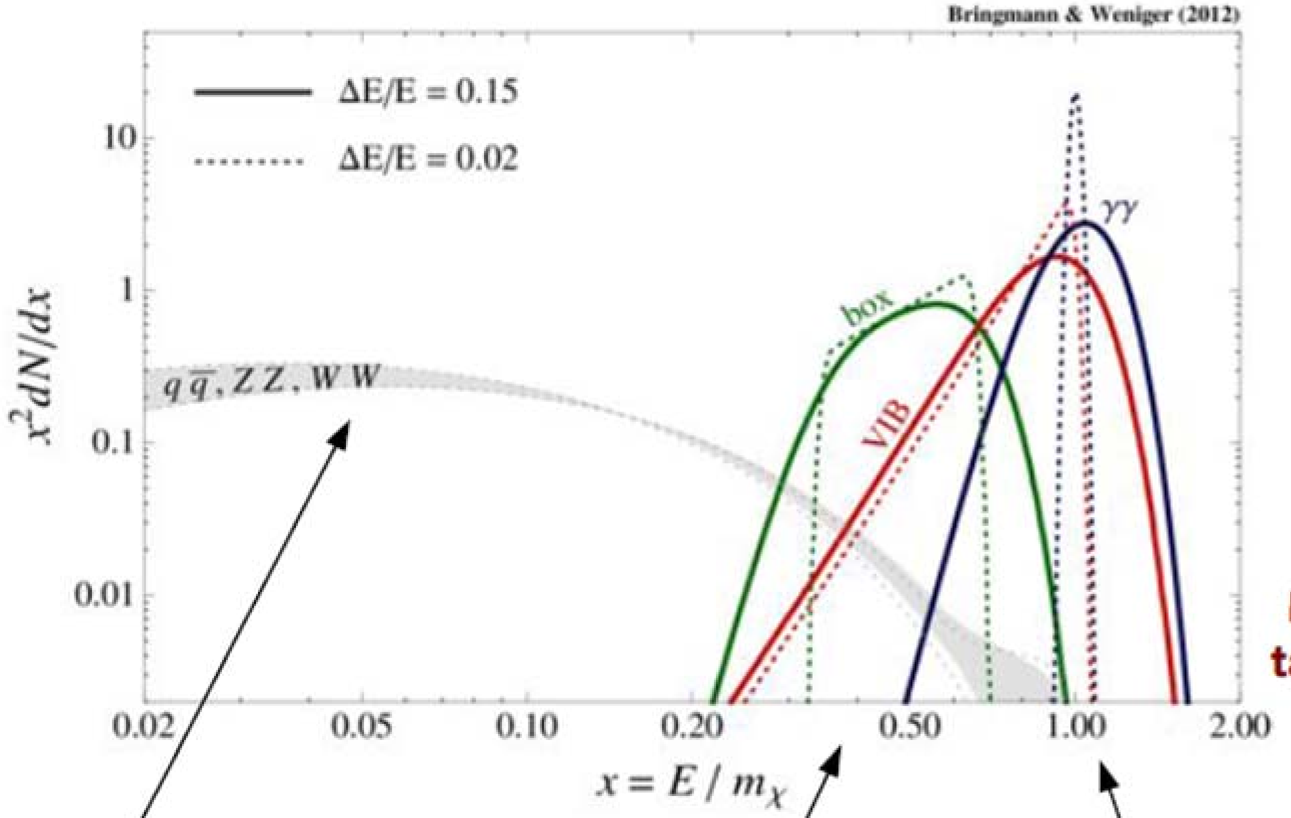
Monochromatic photon line

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

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

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

Various DM annihilation gamma-ray spectra



Lars Bergström's talk

Continuum emission
("Secondary photons")
- from fragmentation of quarks/massive gauge bosons (via pi0 decay)

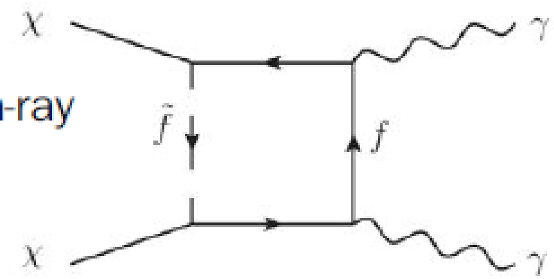
Virtual Internal Bremsstrahlung (VIB)
- radiative correction to processes with charged final states
- Generically suppressed by O(α)

Gamma-ray lines
- from two-body annihilation into photons
- forbidden at tree-leve, generically suppressed by O(α²)

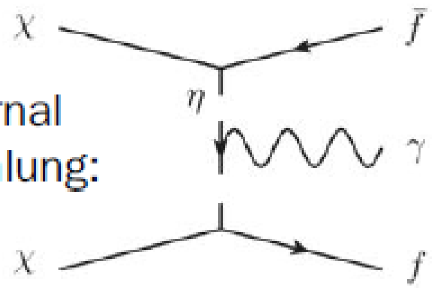
"Smoking guns" (high-risk-high-gain)^2

Gamma-ray line claims since March 2012

Gamma-ray lines:



Virtual Internal Bremsstrahlung:



1) Fermi LAT Search for Internal Bremsstrahlung Signatures from Dark Matter Annihilation
Bringmann, Huang, Ibarra, Vogl & CW, JCAP 1207 (2012) 054

2) A tentative gamma-ray line from dark matter annihilation at the Fermi LAT
CW, JCAP 1208 (2012) 007

> "In regions close to the Galactic center, we find a 4.6 sigma indication for a gamma-ray line at 130 GeV."

3) Fermi 130 GeV gamma-ray excess and dark matter annihilation in sub-haloes and in the Galactic center
Tempel, Hektor and Raidal, JCAP 1209 (2012) 032

4) Strong evidence for gamma-ray lines in the inner galaxy
Su & Finkbeiner, arxiv:1206.1616

> "Even better fits are obtained for off-center Einasto and power-law profiles, which are preferred over the null (no line) hypothesis by 6.5 sigma (...)."

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)

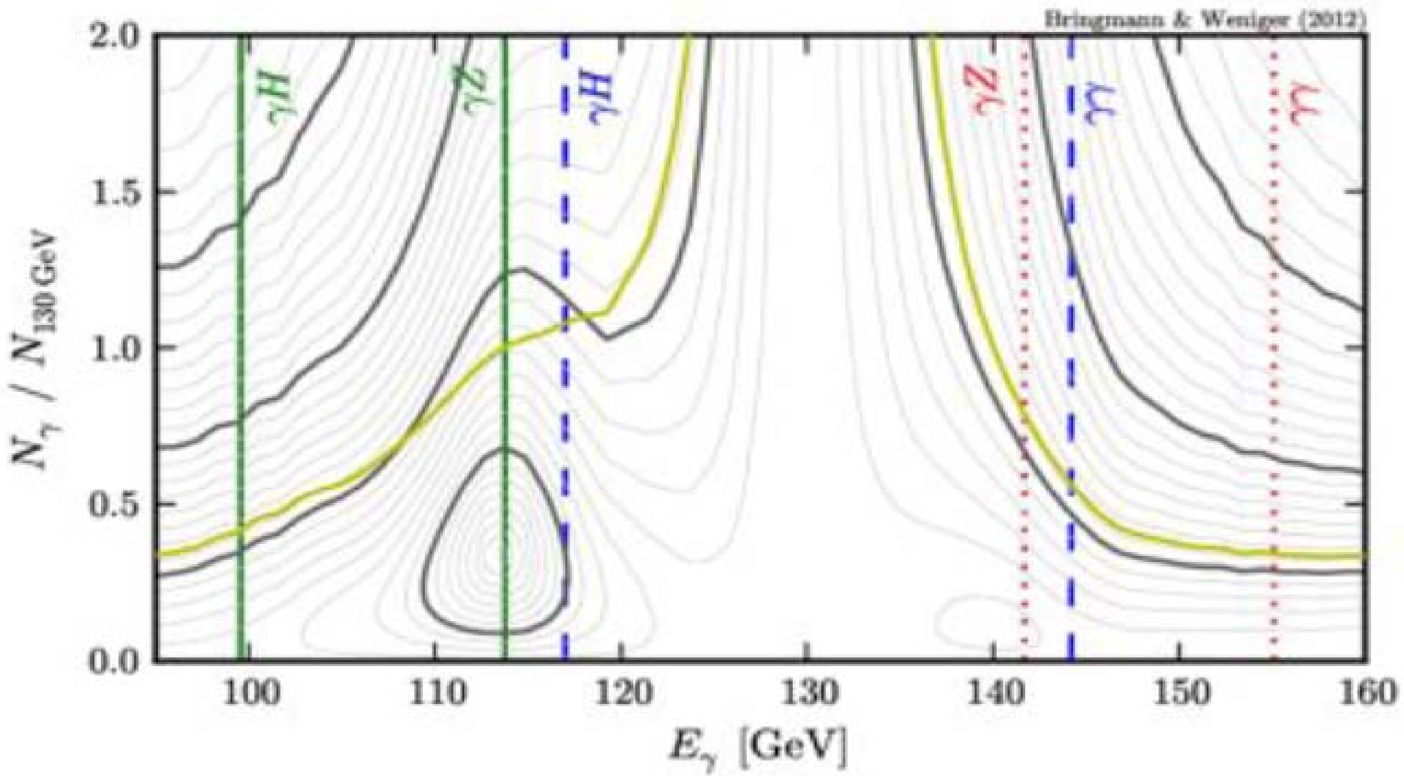
50 photons

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

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

Indications for a second line?

$$\chi\chi \to \gamma\gamma,\ \gamma Z^0,\ \gamma H^0$$



- 1.4 sigma hint for second line, compatible with gamma Z
- Upper limits in other cases
  (fits performed in SOURCE class Reg4)

See also [1205.4723, 1206.1616]

The LAT data contains an excellent candidate for a gamma-ray line from DM annihilation. It's cause is unclear.

- Rare statistical fluctuation: maybe. But in light of the importance of such a result, there is no way around following this up carefully.

- Instrumental cause: cannot be excluded right now (beware the Earth limb!). But: why distribution compatible with NFW/Einasto profiles? Why just at the Galactic center?

- Dark Matter Annihilation? Right now nothing more than an optimistic interpretation. But the signature **is** there, has all the properties one would like to see from a DM signal, and it needs to be understood.

- ...we need more data (→ a matter of time, PASS8, HESS-II, Limb Observations, ToO)

Fermi symposium in October

130 GeV → 135 GeV

The Model

- Y.Farzan and A.R.A, 1211.4685

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

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

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

Coupling to photon

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

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

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

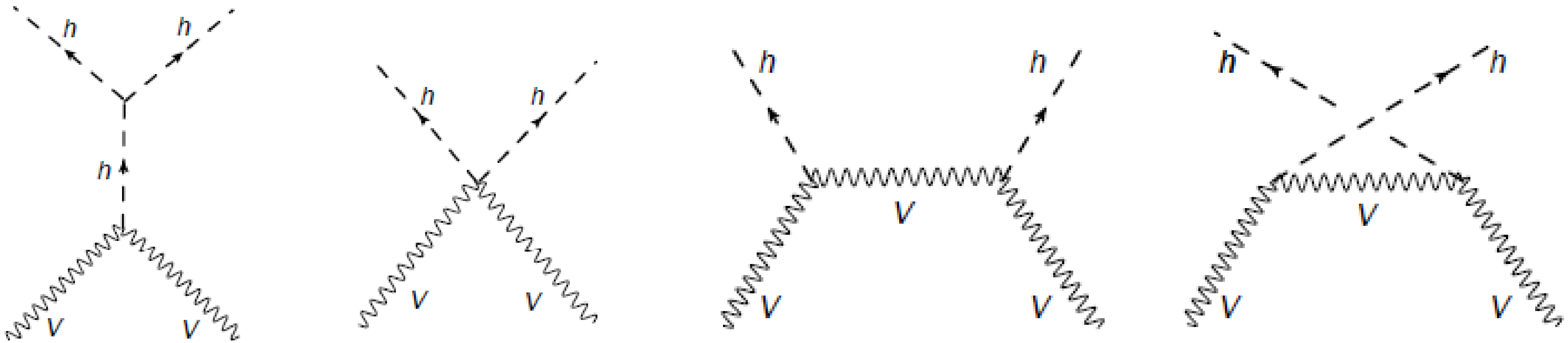
Higgs portal

- The dimensionless gauge and Z_2 invariant couplings to the Higgs:

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

Annihilation of the V pair

- Setting $\lambda_3 = 0$ ⇨ V V → hh & $f\bar{f}$



To account for the observed dark matter abundance within the thermal production scenario , the total DM pair annihilation cross section should be equal to 1 pb.

For $m_V = 130\ \mathrm{GeV}$

⇨ $\lambda_1 = 0.09$

Annihilation to W pair

- Like Higgs portal scenarios:

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

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

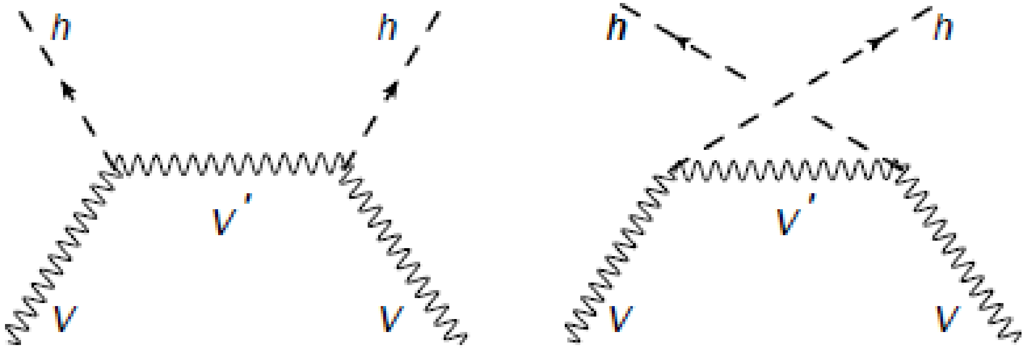
- The total annihilation cross section falls well below the bound from Fermi-LAT continuum gamma-ray constraint as well as the

- bounds from the PAMELA constraint on the anti-proton flux

- More data from Fermi-LAT and AMS02 may make it possible to probe the model in future.

Annihilation of the V pair

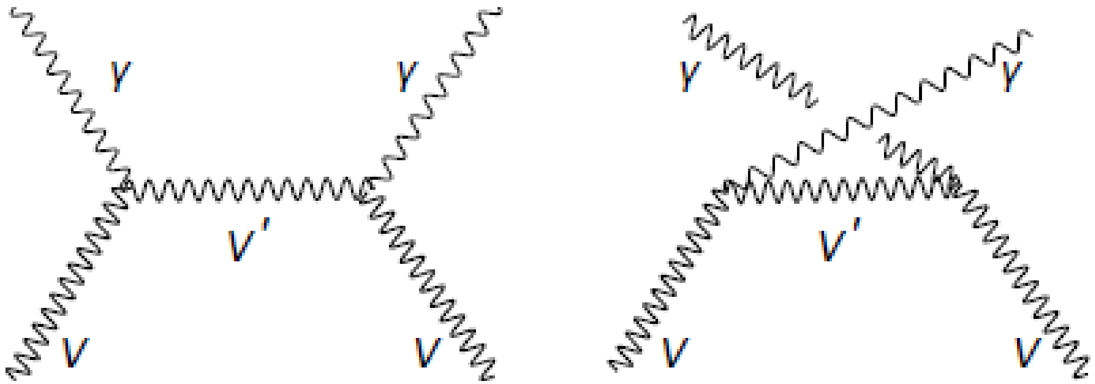
- Setting $\lambda_1 = 0$ ⇨ V V $\rightarrow hh$



Taking $\sigma(VV \rightarrow hh) = 1$ pb, for $\lambda_1 = 0$ and $m_V = 130$ GeV, we find $\lambda_3 \simeq 0.4(m_{V'}/300 \text{ GeV})$. Notice that for $\lambda_1 = 0$ and $m_{V'} > O(3 \text{ TeV})$ the required λ_3 enters the non-perturbative regime.

Coupling to photon

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



Annihilation of the V pair to a photon pair

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

Two line feature

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

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

- Relative intensity:

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

Observation favors double line structure over a single line. however, more data is required to resolve such a double line feature .

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

$$0.14 < f < 0.66$$

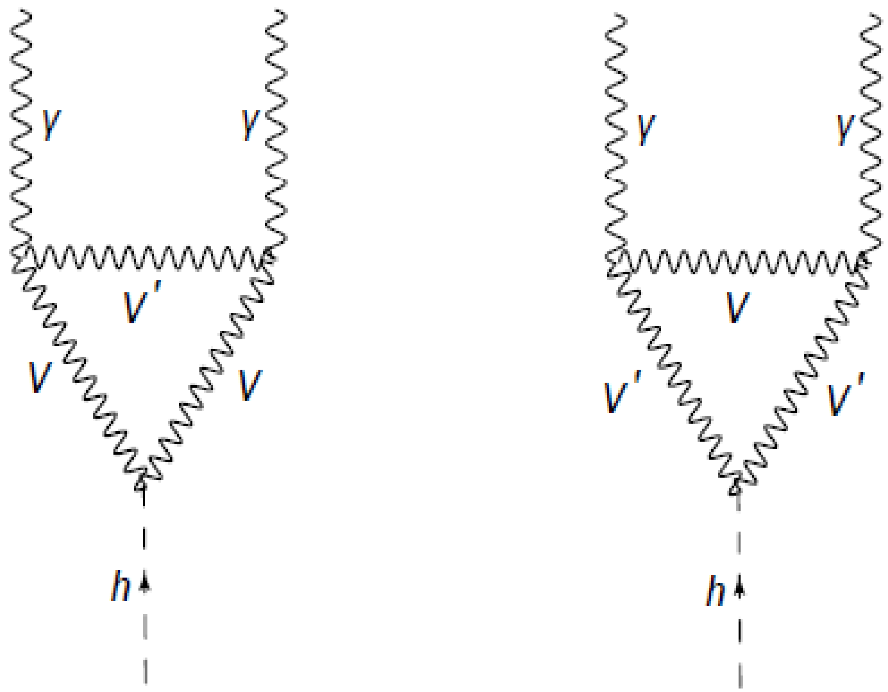
$\lambda_1 = 0.12,$ ⇒ $\sigma = 4.4 \times 10^{-45} (f/0.2)^2 \mathrm{cm}^2$

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

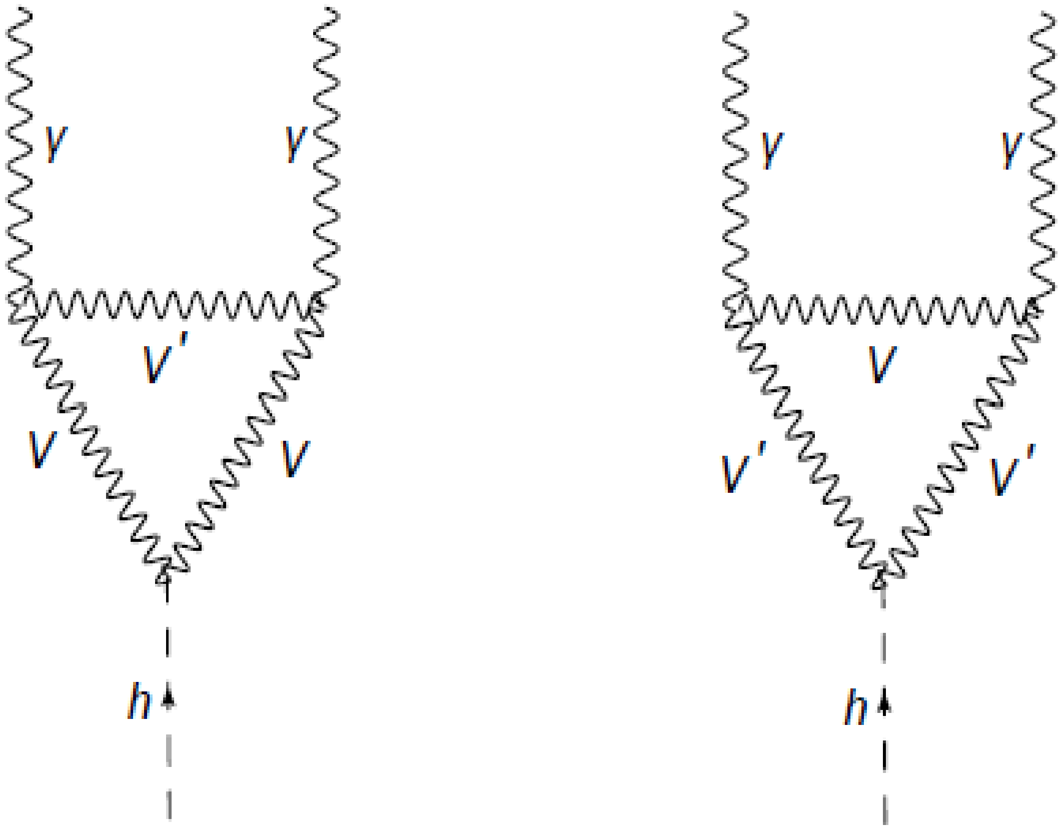
we do not expect an observable eect in the direct searches.

HIGGS DECAY TO A PHOTON PAIR

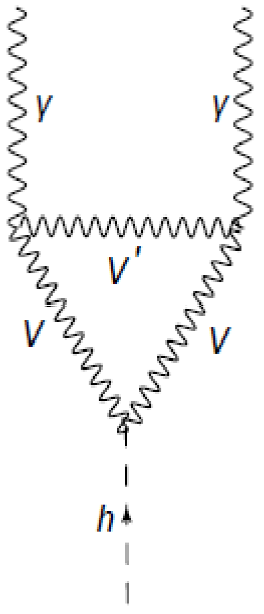
The λ_1 and λ_2 couplings contribute to $h \to \gamma\gamma$ via triangle diagrams within which V and V' propagate

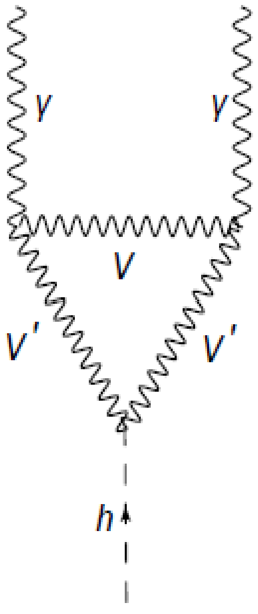


- **These amplitudes have to be summed up with the SM triangle diagrams within which top quark and W boson propagate.**
- Notice that our result is ultra-violet divergent.



Notice that our result is ultra-violet divergent. This is because g_V and λ_1, despite being dimensionless, are non-renormalizable





For $\lambda_1 \log \Lambda^2/m_{V'}^2 \sim 1$

The contribution of λ_1 will be comparable to that in the SM. The observed slight excess can be attributed to this effect.

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 $h \rightarrow Z\gamma$

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

Or Λ may be close!

DIRECT PRODUCTION AT THE COLLIDERS

A pair of V and V' can be produced by the annihilation of a fermion (f) and antifermion ($\bar{f}$) pair via a s-channel photon exchange,

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

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

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

- The energy of center in the **LEP** experiment was too low to allow the production of V and V’ pair.

- However, in the **LHC**, the V and V’ pair can be produced as long as we are in the perturbative regime;

$$m_{V'} < \text{few TeV}.$$

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

The signature of the $V + V'$ production at the LHC will hence be an energetic mono-photon plus missing energy which has only low background and therefore enjoys a good discovery chance.

There is also a decay mode to $V + Z$ suppressed by $\tan^2 \theta_W$.

If the kinematics allows V' can decay to

$$V + H,\ V + W^- + W^+ \text{ and } V + 2H$$

however, the decay into $V + \gamma$ will dominate.

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.

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: $DM + DM \rightarrow h + h$

Antiproton flux to be probed by AMS02.

- λ_1 regime:

Direct DM detection;

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

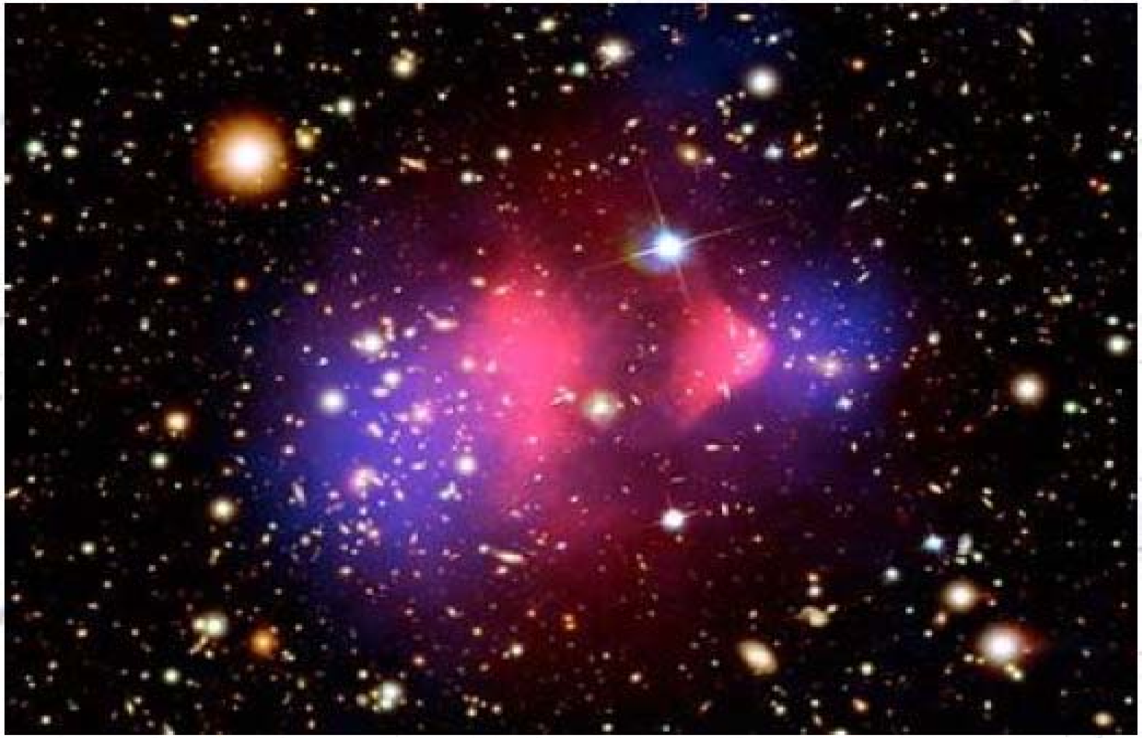
Thanks For Your Attention

Backup Slides

Evidences for Dark Matter

Dark matter in galaxy clusters...

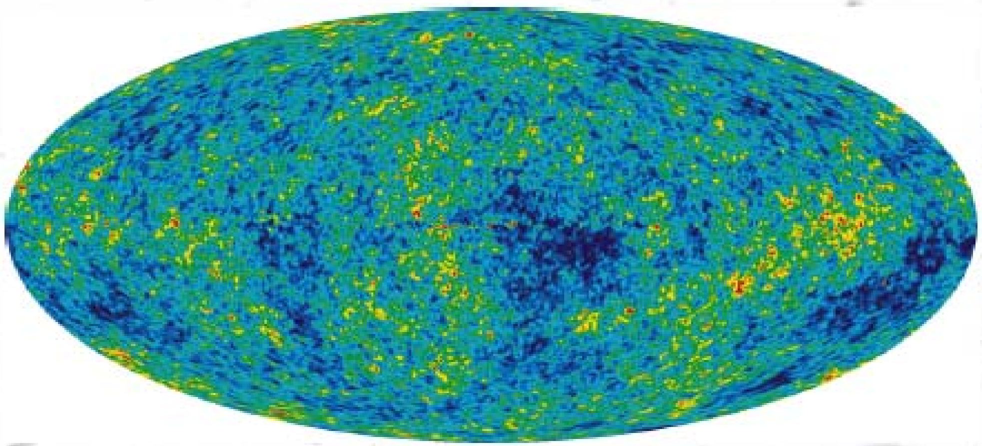
as can be seen for example in the Bullet Cluster through gravitational lensing

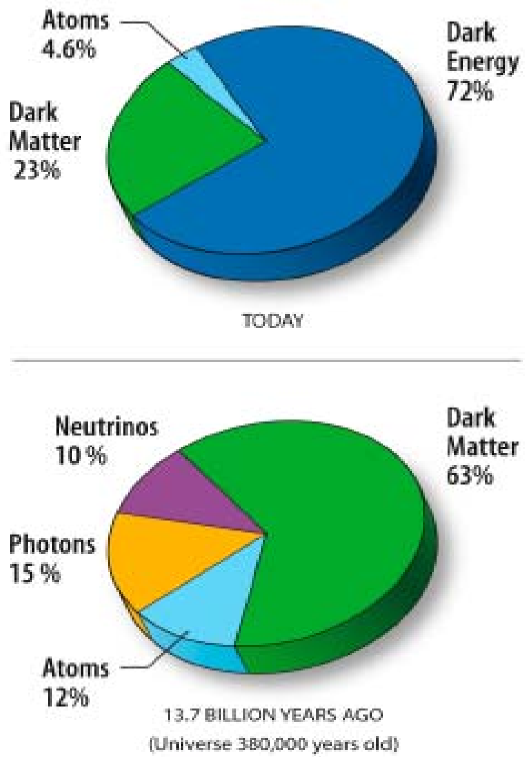


Evidences for Dark Matter

Dark matter from cosmological evolution...

e.g. as measured by WMAP

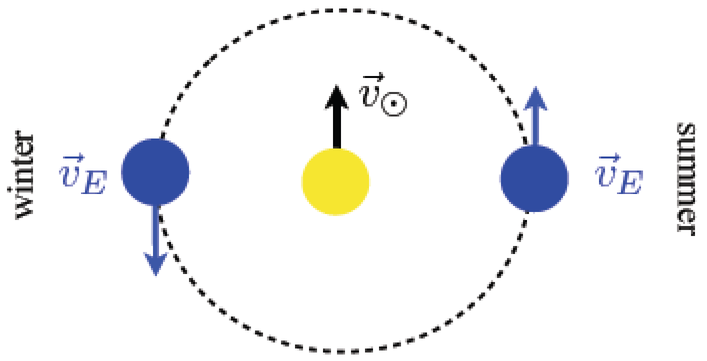




DAMA

NaI Annual Modulation Experiment running for 13 years

Galactic Dark Matter



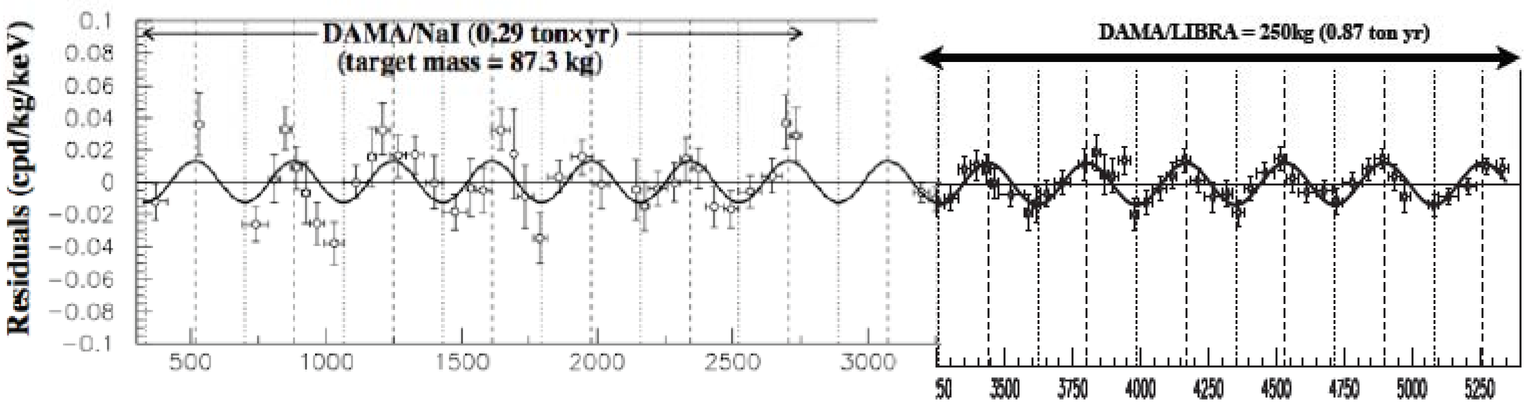
$v \leq v_{\rm esc} + |\vec{v_E} - \vec{v_\odot}|$ $v \leq v_{\rm esc} + |\vec{v_E} + \vec{v_\odot}|$

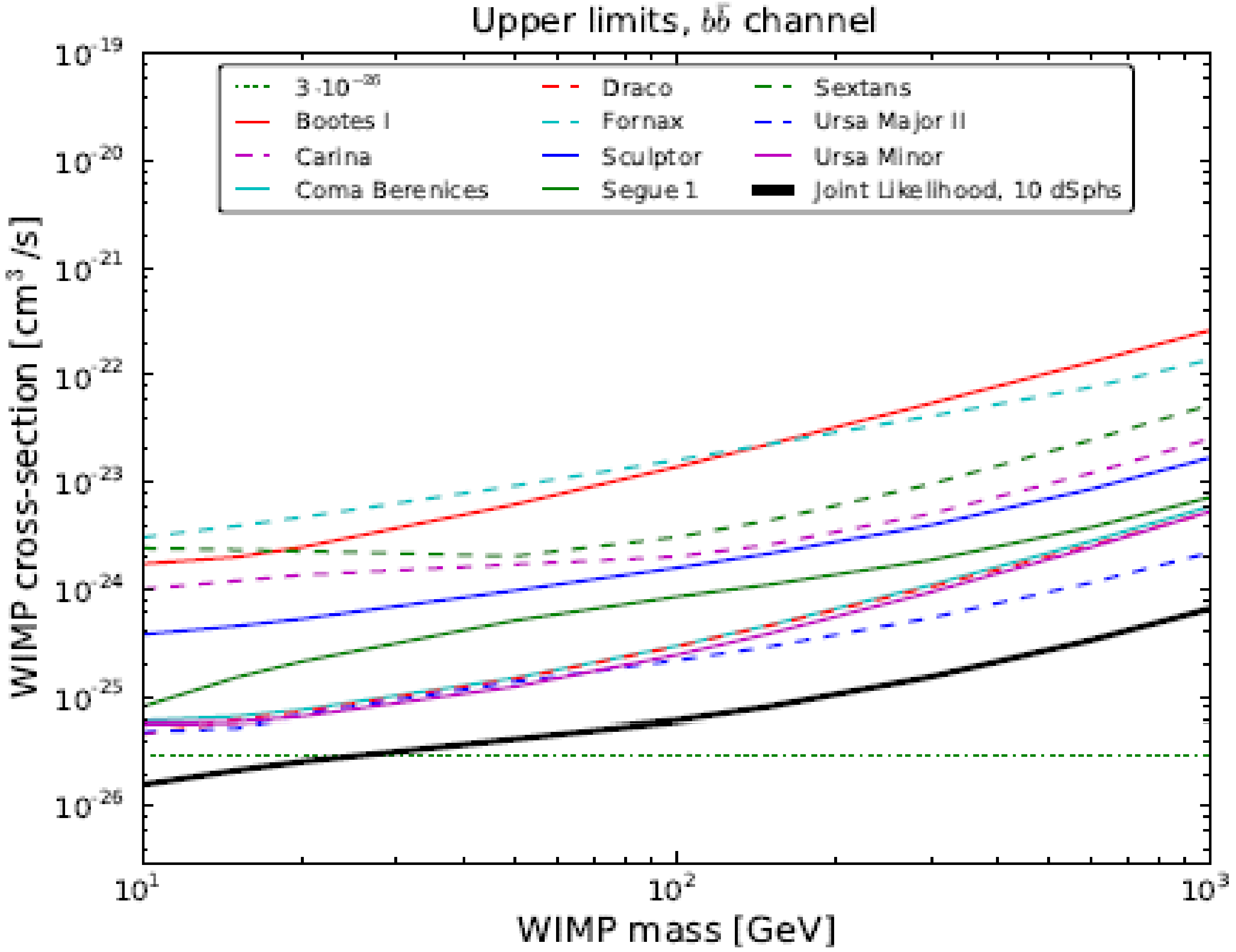
Annual modulation in WIMP signal

$$\Phi_{\rm dm} = n_{\rm dm}\, v$$

$$A_{\rm mod} = R_{\rm Sum} - R_{\rm Win}$$

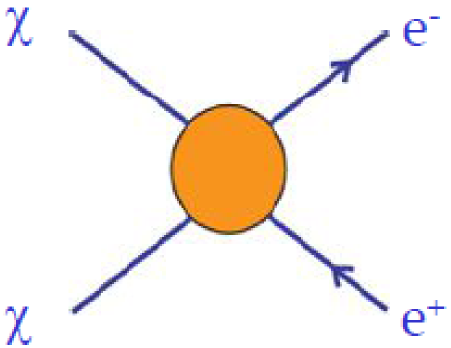
Modulation amplitude ~2.5% for elastic scattering





M. Ackermann et al. [Fermi-LAT Collaboration], Phys. Rev. Lett. 107 (2011) 241302 [arXiv:1108.3546 [astro-ph.HE]].

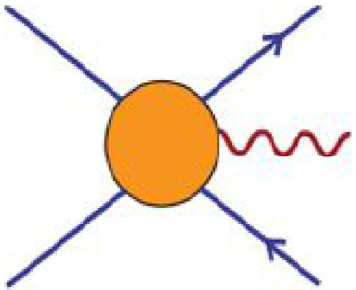
The world record in QED corrections - for slowly moving, annihilating Majorana particles. Example: e^+e^- channel:



WIMP annihilation rate $(\sigma v)_0 \sim 3{\cdot}10^{-26}\ \mathrm{cm}^{-3}\mathrm{s}^{-1}$ at freeze-out.

Annihilation rate today (S-wave),
$\sigma v \sim (m_e/m_\chi)^2 \sim 10^{-37}\ \mathrm{cm}^3\mathrm{s}^{-1}$.

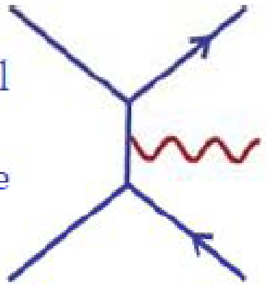
Impossible to detect!



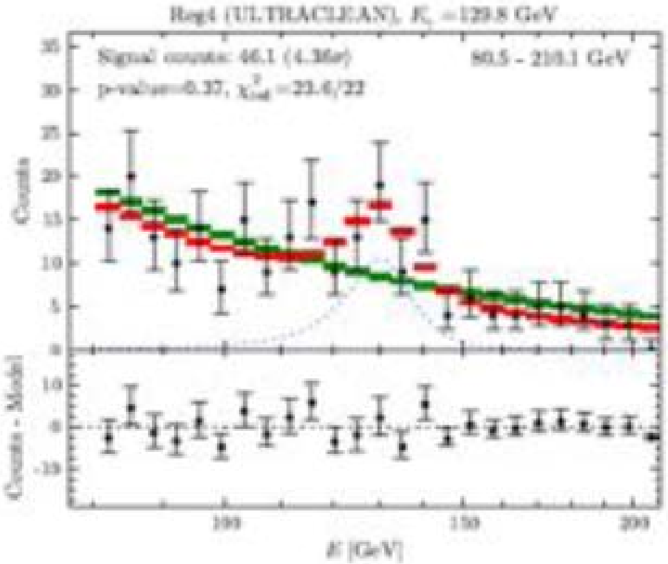
Direct emission (inner bremsstrahlung) QED "correction":
$(\sigma v)_{QED}/\,(\sigma v)_0 \sim (\alpha/\pi)\,(m_\chi/m_e)^2 \sim 10^9 \Rightarrow 10^{-28}\ \mathrm{cm}^3\mathrm{s}^{-1}$

The "expected" QED correction of a few per cent is here a factor of 10^9 instead! May give detectable gamma-ray rates – with good signature!

t-channel scalar exchange

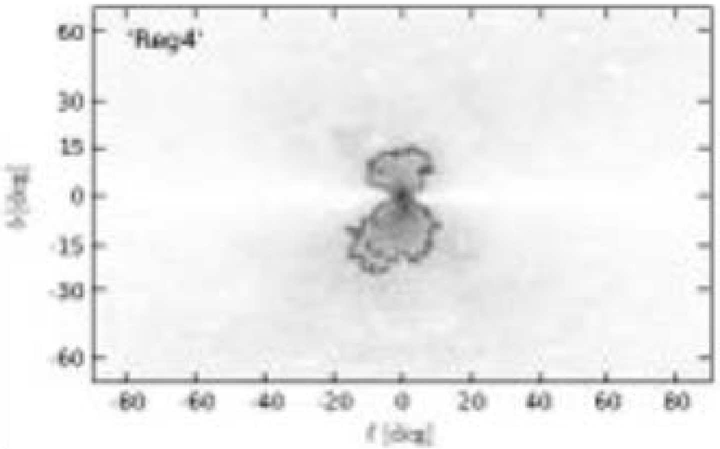


(L.B. 1989; E.A. Baltz & L.B. 2002, T. Bringmann, L.B. & J. Edsjö, 2008; M. Ciafalone, M. Cirelli, D. Comelli, A. De Simone, A. Riotto & A. Urbano, 2011; N. F. Bell, J.B. Dent, A.J. Galea,T.D. Jacques, L.M. Krauss and T.J.Weiler, 2011:;T. Bringmann & al., 2012.)

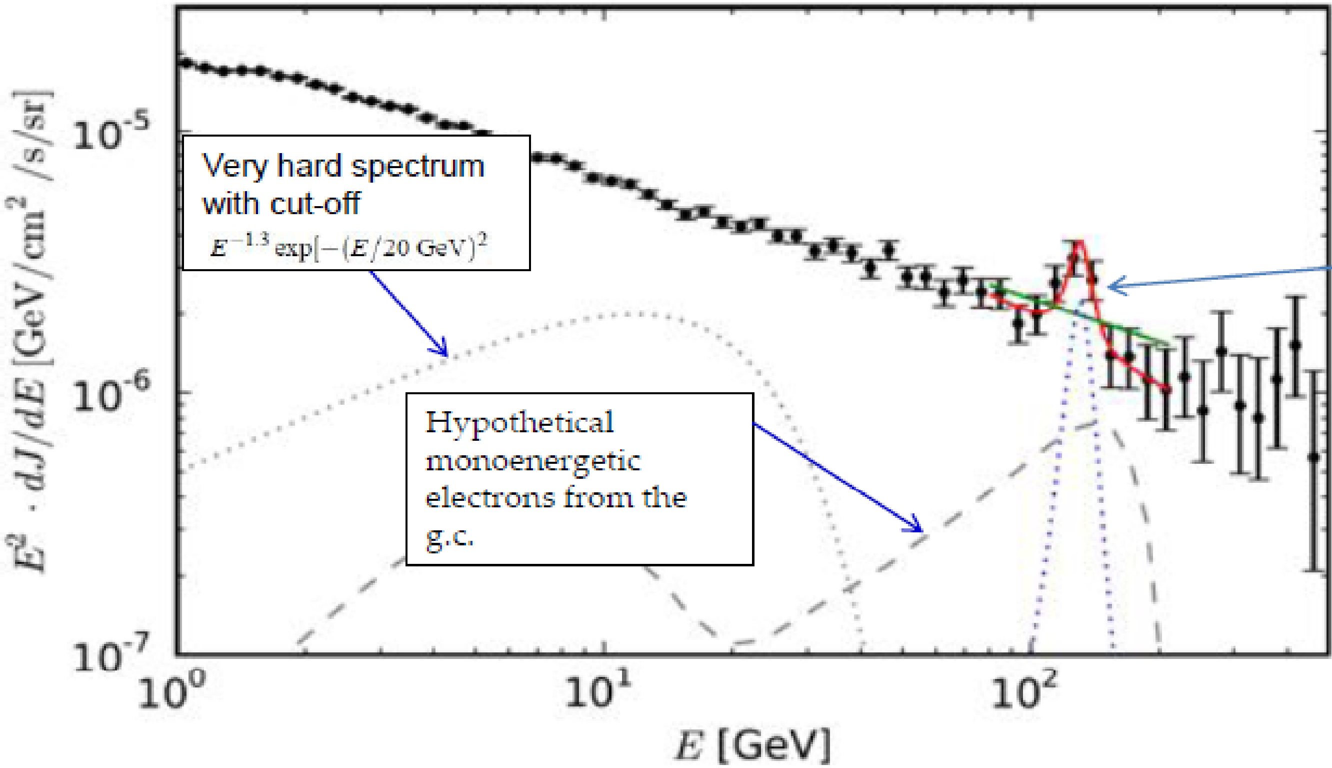


April, 2012:
43 months of (public) Fermi-LAT data.
C. Weniger, JCAP 2012. Fit to gamma-ray line.

See talk by Christoph Weniger.



γ-ray line fit:



Mass = 130 GeV.
Significance 4.6 σ
(3.2 σ if "look elsewhere" effect included) .

C. Weniger Gamma-2012, Heidelberg, Proc.