Title: FERMI 130 GeV Line: Dark Interpretations

Date: Feb 26, 2013 01:00 PM

URL: http://pirsa.org/13020150

Abstract: Last year strong evidence was
claimed for a 130 GeV gamma ray line from the galactic center in the FERMI
telescope data. In the first half of the talk I will review the status of
the evidence, including recent suggestions which call it into question.
 In the second half of the talk, under the bold assumption that the line
is a genuine signature of dark matter, I will review some of the properties
required of dark matter to explain the line and the general features of models
proposed to explain it. This second half will include material from
recent work with Francesco D'Eramo and Jesse Thaler (arxiv:1210.7817), which
suggests that the line is readily explained by dark matter
"semi-annihilation" rather than the standard annihilation
interpretation.

FERMI 130 GeV Line: Dark Interpretations

Perimeter Institute
February 26th 2013

Based on D'Eramo, MM, Thaler:
"Multiple Gamma Lines from Semi-Annihilation"

Matthew McCullough, MIT

Outline

- Overview of the FERMI Gamma Line
  - Evolution of the signal / significance
  - The Earth Limb. Cause for concern?
  - FERMI Symposium update
  - Solar lines too?

- Dark Matter Interpretations
  - Decaying?
  - Annihilating?
  - Semi-annihilating?
    - Predictions and models

FERMI LAT

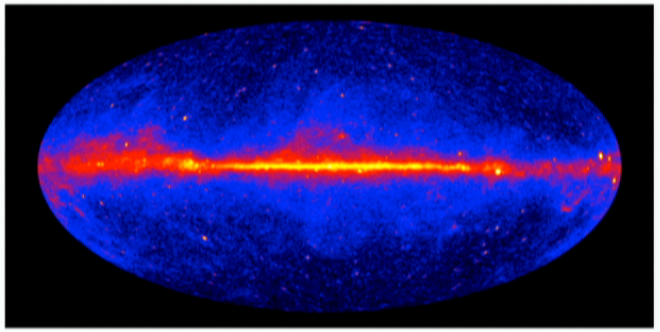
$\$196 \times 10^6 =$ 

$+$ 

FERMI LAT

$\$196 \times 10^6 =$ 

$+$ 

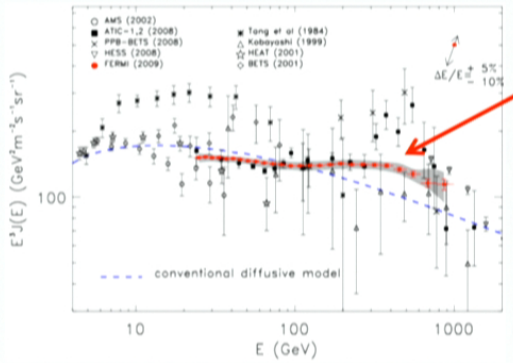
$\equiv$  $+$ 

FERMI LAT

- Gamma Ray Telescope
  - 20 MeV up to 300 GeV
  - About 20 % of sky
  - Orbits Earth every 95 Minutes
- Notching up discoveries / records
  - Pulsar discoveries
  - Milky Way Bubbles
  - …
- No strong evidence of BSM particle physics yet

Gamma Rays and BSM Physics

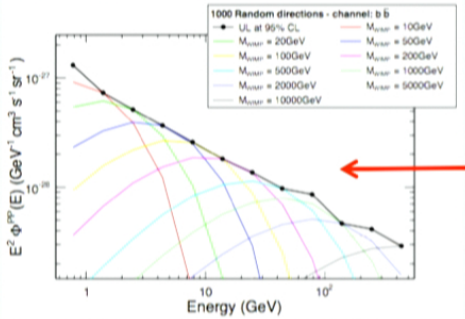
- Dark matter best candidate for discovery
  - Annihilations or decays into SM final states



Electron and positron spectrum.
(Isn't FERMI a gamma ray telescope?)

Interesting hints from PAMELA/HESS/FERMI AMS-02? (Not discussed further here)

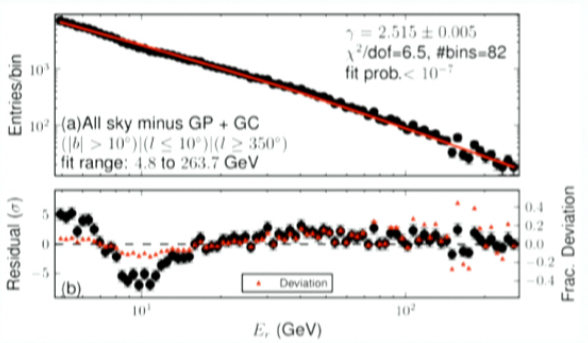
  - DM annihilation final states leads to a continuum

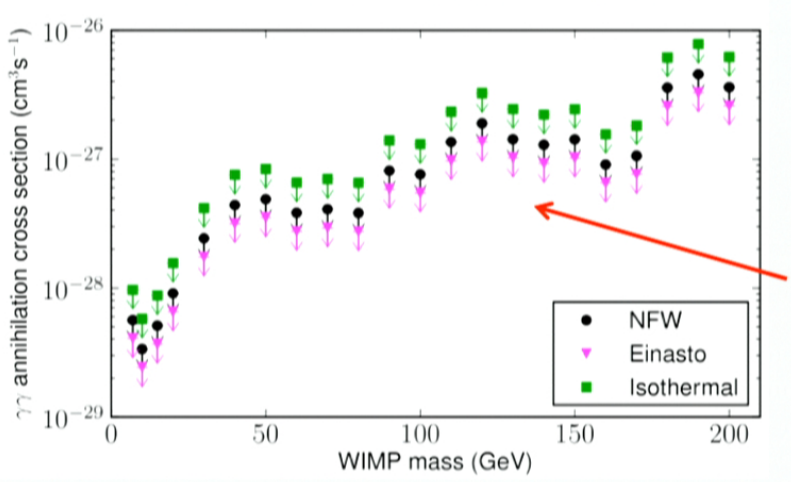


Can constrain annihilating DM models

Gamma Rays and BSM Physics

- Dark matter best candidate for discovery
  - Or, DM could annihilate directly into photons, giving a gamma ray line!
  - FERMI, May 2012:

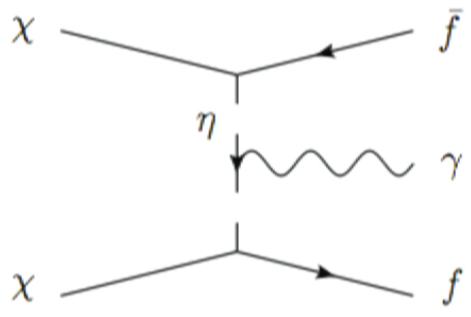




Limits on annihilation cross section

Gamma Rays and BSM Physics

- Search for "internal Bremsstrahlung"
- March 2012:



Fermi LAT Search for Internal Bremsstrahlung Signatures from Dark Matter Annihilation

Torsten Bringmann[a] Xiaoyuan Huang[b] Alejandro Ibarra[c] Stefan Vogl[c] Christoph Weniger[d]

[a]II. Institute for Theoretical Physics, University of Hamburg, Luruper Chaussee 149, DE-22761 Hamburg, Germany
[b]National Astronomical Observatories, Chinese Academy of Sciences, Beijing, 100012, China
[c]Physik-Department T30d, Technische Universität München, James-Franck-Straße, 85748 Garching, Germany
[d]Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 Munich, Germany

E-mail: torsten.bringmann@desy.de, x.huang@bao.ac.cn, ibarra@tum.de, stefan.vogl@tum.de, weniger@mppmu.mpg.de

Abstract. A commonly encountered obstacle in indirect searches for galactic dark matter is how to disentangle possible signals from astrophysical backgrounds. Given that such signals are most likely subdominant, the search for pronounced spectral features plays a key role for indirect detection experiments; monochromatic gamma-ray lines or similar features related to internal bremsstrahlung, in particular, provide smoking gun signatures. We perform a dedicated search for the latter in the data taken by the Fermi gamma-ray space telescope during its first 43 months. To this end, we use a new adaptive procedure to select optimal target regions that takes into account both standard and contracted dark matter profiles. The behaviour of our statistical method is tested by a subsampling analysis of the full sky data and found to reproduce the theoretical expectations very well. The limits on the dark matter annihilation cross-section that we derive are stronger than what can be obtained from the observation of dwarf [illegible] considered here, collider searches. While these limits are still not quite strong enough to probe annihilation rates expected for thermally produced dark matter, future prospects to do so are very good. In fact, we already find a weak indication, with a significance of 3.1σ (4.3σ) when (not) taking into account the look-elsewhere effect, for an internal bremsstrahlung-like signal that would correspond to a dark matter mass of $\sim$150 GeV; the same signal is also well fitted by a gamma-ray line at around 130 GeV. Although this would be a fascinating possibility, we caution that a much more detailed analysis and additional data will be necessary to rule out or confirm this option.

thermally produced dark matter, future prospects to do so are very good. In fact, we already find a weak indication, with a significance of 3.1σ (4.3σ) when (not) taking into account the look-elsewhere effect, for an internal bremsstrahlung-like signal that would correspond to a dark matter mass of $\sim$150 GeV; the same signal is also well fitted by a gamma-ray line at around 130 GeV. Although this would be a fascinating possibility, we caution that a much

The FERMI 130 GeV Line

- Since then a number of studies have been performed. With varying results.
  - Weniger: 4.6 σ (Local significance)
  - Tempel, Hektor, Raidal: 4.6 σ (Local significance)
  - Su, Finkbeiner: 6.5 σ (Local significance)

The FERMI 130 GeV Line

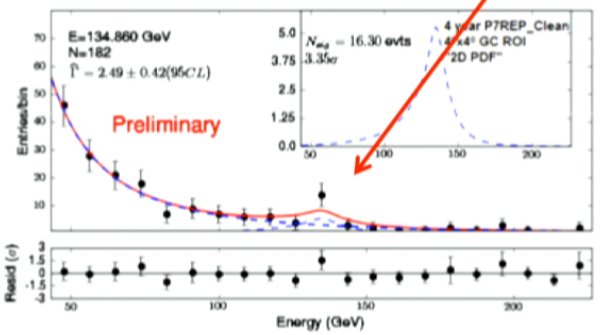
- Since then a number of studies have been performed. With varying results.
  - Weniger: 4.6 σ (Local significance)
  - Tempel, Hektor, Raidal: 4.6 σ (Local significance)
  - Su, Finkbeiner: 6.5 σ (Local significance)
- Weaker evidence claimed in subhalos
  - Su, Finkbeiner: 3.3 σ (Local significance)
  - Hektor, Raidal, Tempel: Not significant

The FERMI 130 GeV Line

- The final word. FERMI Symposium:

Line-like Feature near 135 GeV

- Our blind search does not find globally significant feature near 135 GeV
  - Reprocessing shifts feature from 130 GeV to 135 GeV
  - Most significant fit was in R0, 2.23σ local (<0.5σ global)
- Much interest after detection of line-like feature localized in the galactic center at 130 GeV
  - See C. Weniger JCAP 1208 (2012) 007 arXiv:1204.2797
- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of P_E)
- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of P_E)
- 3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI
  - Use 2D PDF
    - P_E in data → feature is slightly narrower than expected
  - <2σ global



Note: Fit in 4°x4° GC ROI
Not one of our a priori ROIs

10 Fermi LAT Spectral Line Search 11/02/2012

Energy shifted

Bump still there

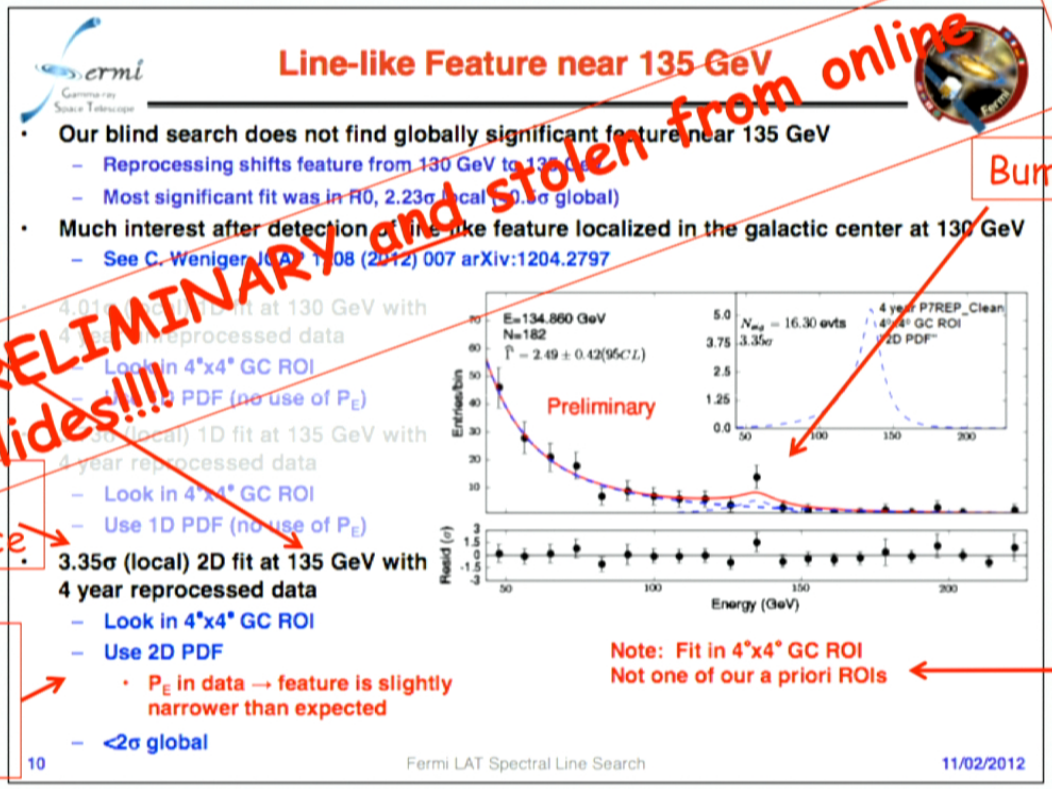
Reduced significance

Energy resolution included

Region of interest considered

The FERMI 130 GeV Line

- The final word. FERMI Symposium:



PRELIMINARY and stolen from online slides!!!!

Energy shifted

Bump still there

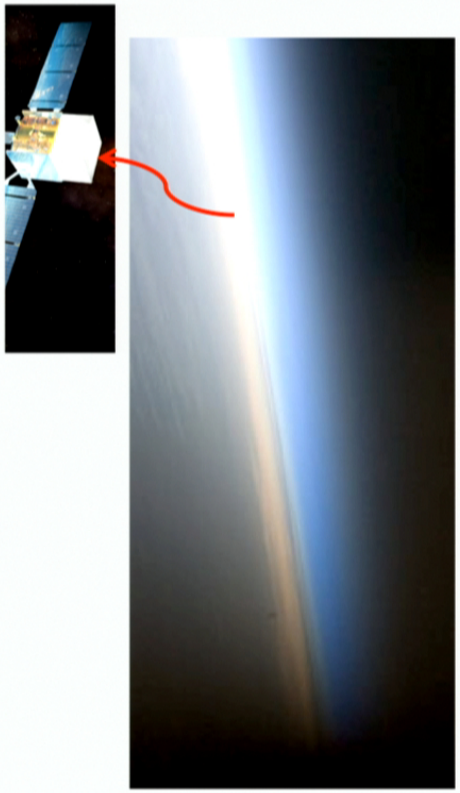
Reduced significance

Energy resolution included

Region of interest considered

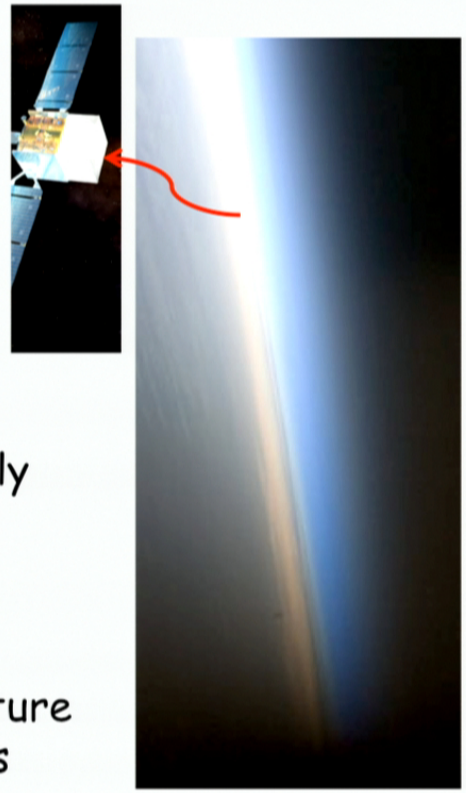
Out on a Limb

- Cause for concern: Earth Limb Data
  - Some hint for a 130 GeV line
  - Is line a systematic effect?



Out on a Limb

- Cause for concern: Earth Limb Data
  - Some hint for a 130 GeV line
  - Is line a systematic effect?

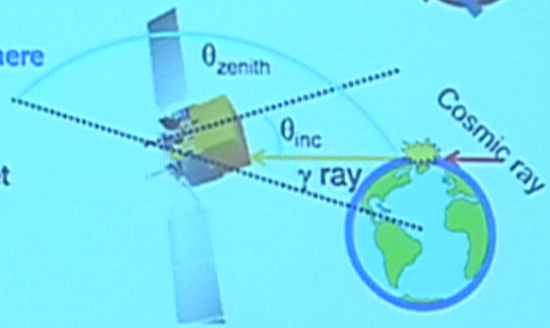


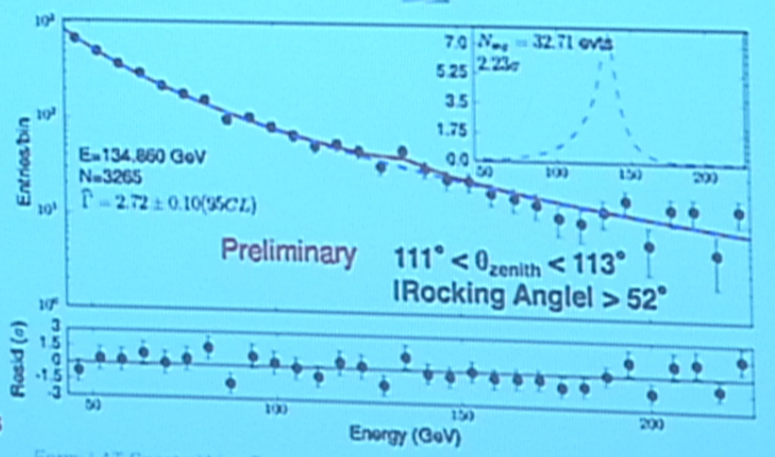
- Hektor, Raidal, Tempel:
  - Limb: just statistical fluctuations
- Finkbeiner, Su, Weniger:
  - No instrumental systematics could plausibly explain GC line
- FERMI symposium:
  - "The LAT Collaboration does not have a consistent interpretation of the GC structure originating from a systematic error at this time"

Out on a Limb

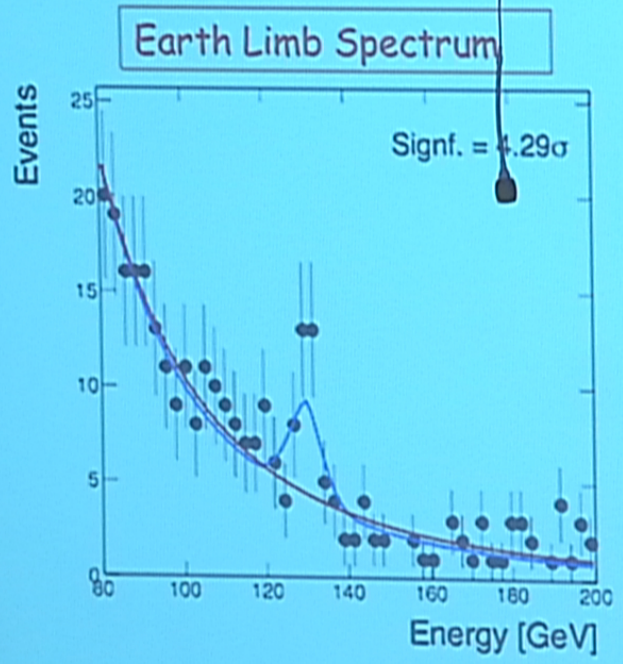
135 GeV in the Earth Limb spectrum

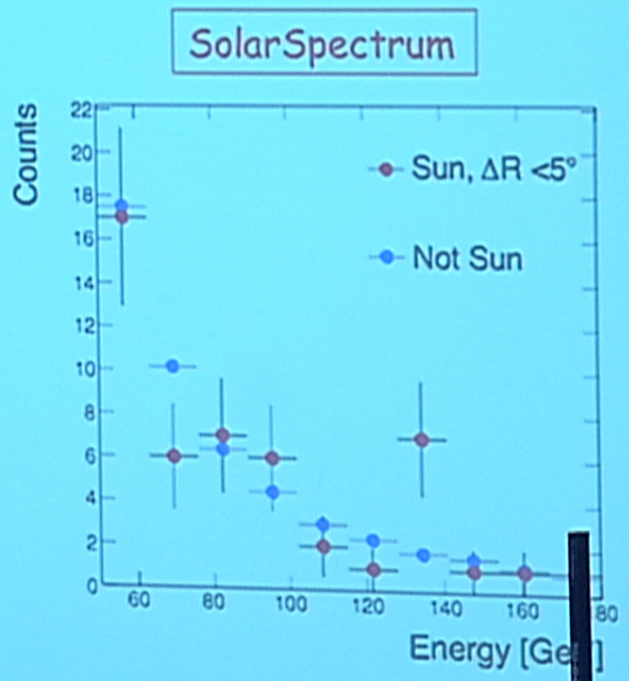
- Earth Limb is a bright gamma-ray source
  - From cosmic-ray interactions in the atmosphere
    - Expected to be a smooth power-law
  - Can be used to study instrumental effects
- Have made changes to increase our Limb dataset
  - Pole-pointed observations each week
  - Extended "targets of opportunity" (ToOs)
    - Trace limb while target is occulted
- Line-like feature in the limb at 135 GeV
  - Appears when LAT is pointing at the Limb
    - |RockAngle| > 52°
  - Surprising since limb should be smooth
  - On-going systematic studies have found interesting results
    - See talk by E. Bloom
    - See talk by E. Charles





Sunny Side Down?

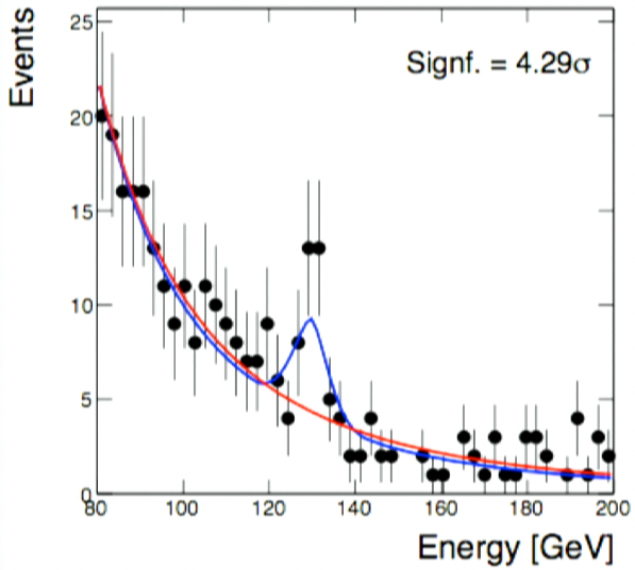




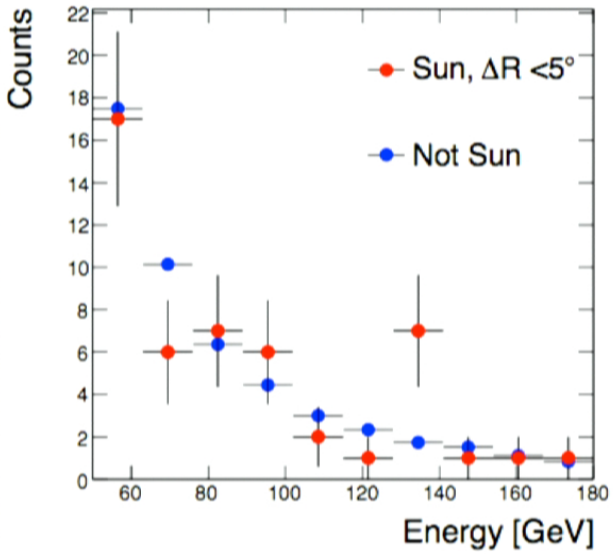
- Daniel Whiteson, 2013

Sunny Side Down?

Earth Limb Spectrum



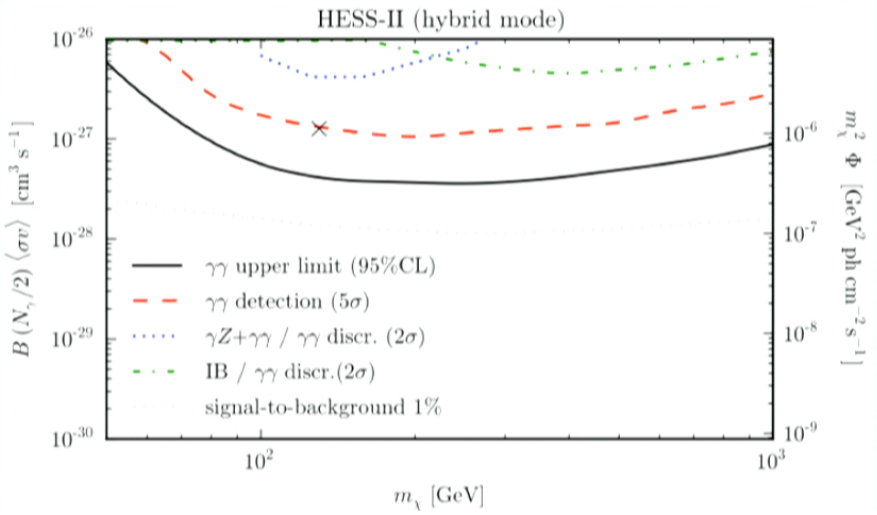
SolarSpectrum



- Daniel Whiteson, 2013

The FERMI 130 GeV Line

- The future:
  - Additional data from FERMI will help
    - Data doubled by 2014 or so
  - Better understanding of instrumental effects?
  - HESS-II could confirm (at 5σ) or exclude a line in 2013!
- Bergstrom et al



The FERMI Line: Dark Matter?

- It is clear that there is a feature around 135 GeV in the FERMI data.
  - Is it statistically significant? Time will tell.
- Shouldn't get too excited, shouldn't ignore it.
- If it is real, what is it?
  - Astrophysical: possible, but difficult to fit profile
  - Dark matter: potentially…
- If it isn't real, still motivation to re-think phenomenology of gamma lines from DM.
- Lets entertain this possibility and see where it leads…

Decaying or Annihilating?

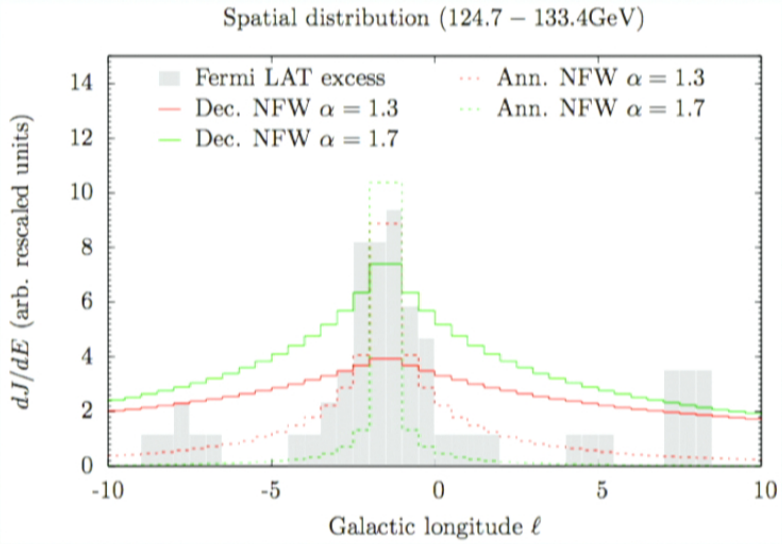
- Clues from the morphology of the excess?
- Buchmuller and Garny:

Better fit for annihilating DM since signal peaked at galactic center.

$$R_{Ann} \propto \int \rho^2 \, dV$$

But… looks like still room for a decaying DM interpretation too.

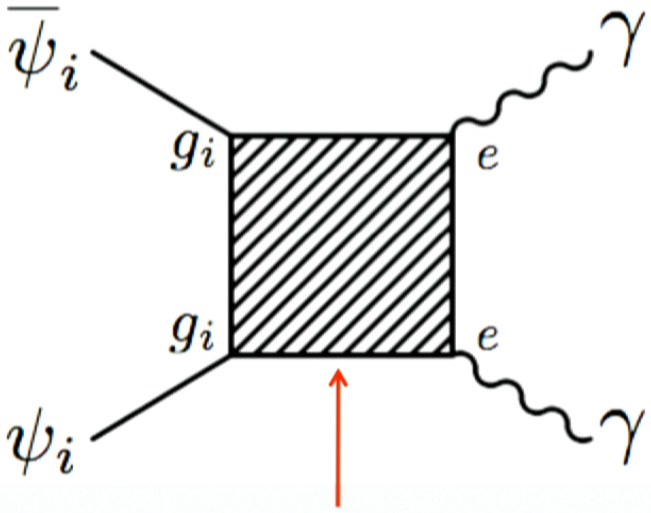
$$R_{Decay} \propto \int \rho \, dV$$



- Considering annihilating from now on.

Gamma Lines from Annihilating DM

- DM is neutral, so annihilation is quantum effect:

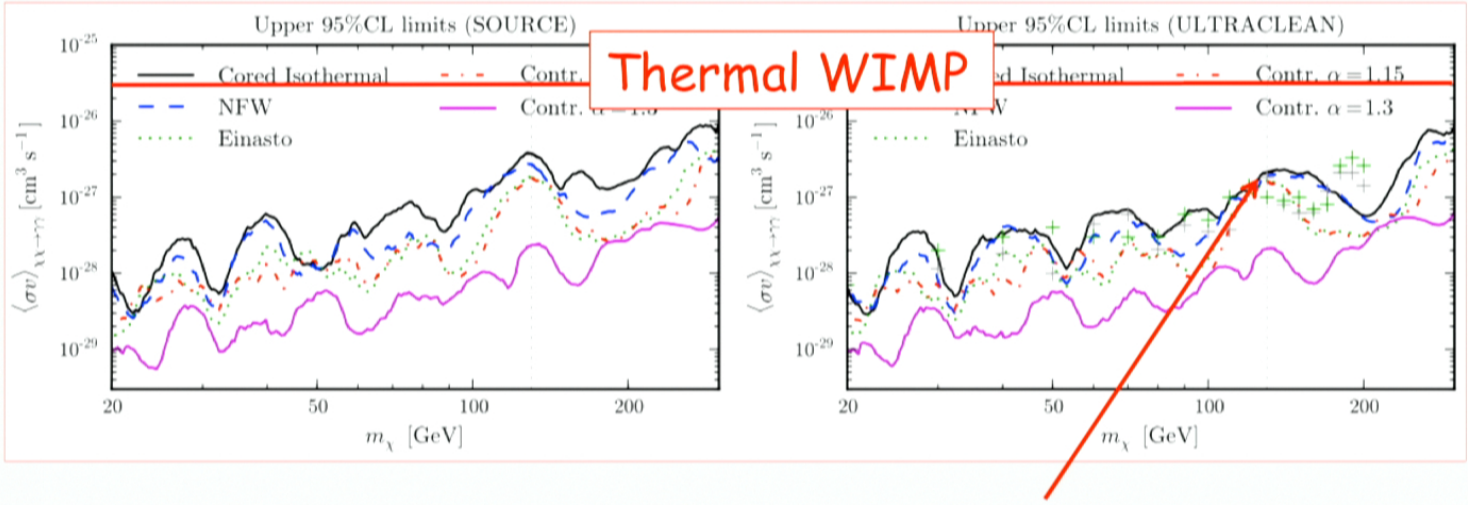


$$\rightarrow \langle \sigma v \rangle_{\gamma\gamma} \propto \alpha_{EM}^2$$

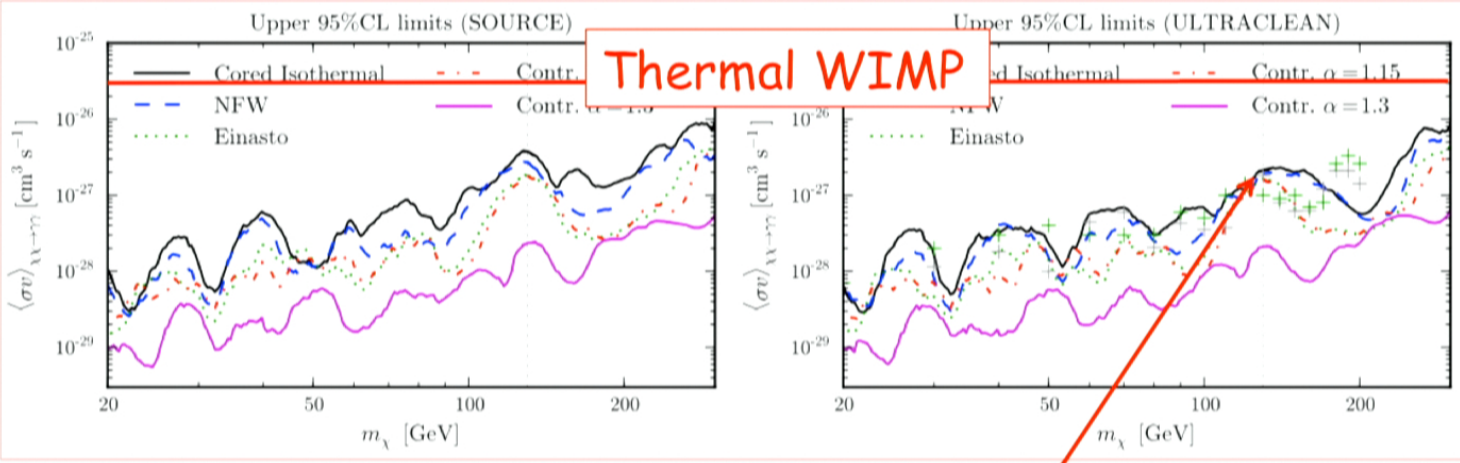
Charged particles in loop ("Messengers")

- Strict DM mass relation: $E_\gamma = M_{DM}$

What Sort of Cross Section?



What Sort of Cross Section?

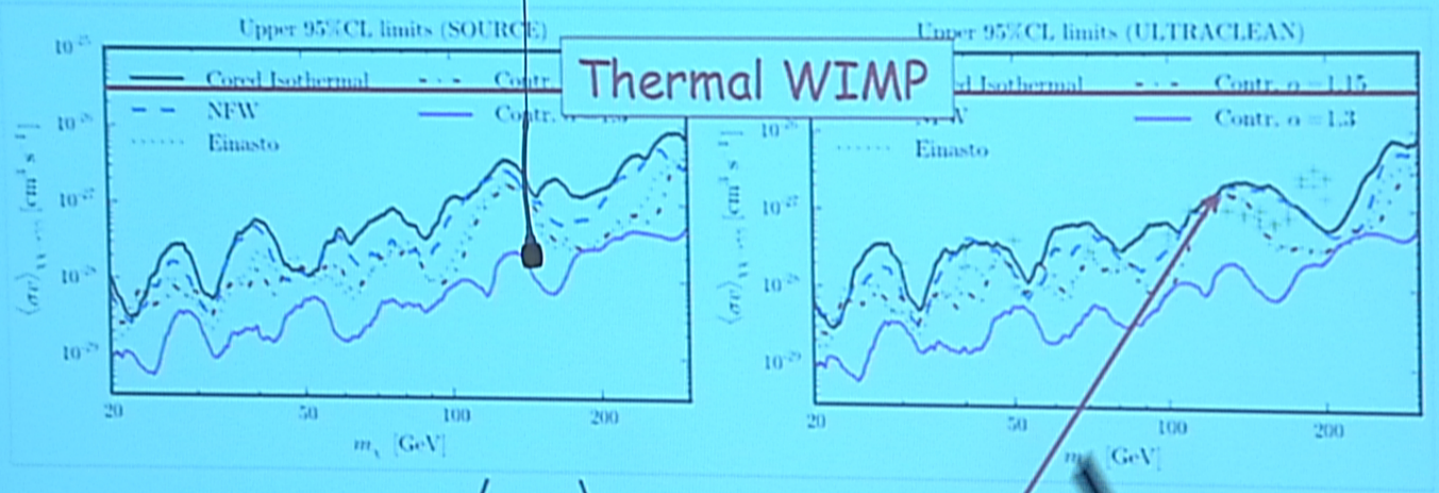


$$\langle\sigma v\rangle_{\gamma\gamma} \sim \frac{\langle\sigma v\rangle_{\rm Thermal}}{30} \sim 10^{-27}{\rm cm}^3{\rm s}^{-1}$$

- This is actually larger than you would expect from:

$$\langle\sigma v\rangle \propto \alpha_{EM}^2$$

What Sort of Cross Section?



Thermal WIMP

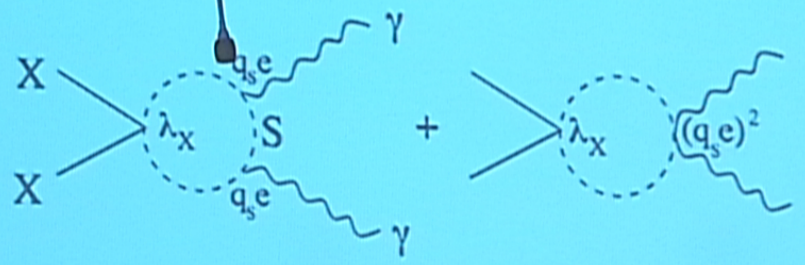
$$\langle \sigma v \rangle_{\gamma\gamma} \sim \frac{\langle \sigma v \rangle_{\text{Thermal}}}{30} \sim 10^{-27}\,\text{cm}^3\,\text{s}^{-1}$$

- This is actually larger than you would expect from:

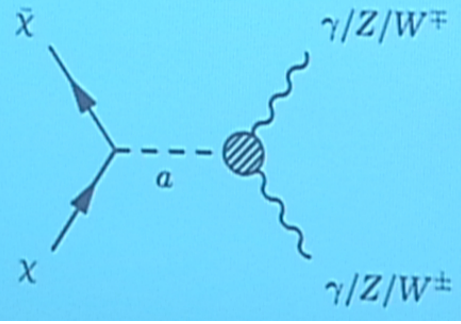
$$\langle \sigma v \rangle \propto \alpha_{EM}^2$$

Gamma Lines from Annihilating DM

- Annihilating DM works, but need boosted cross section
- Models have been constructed:
  - Cline

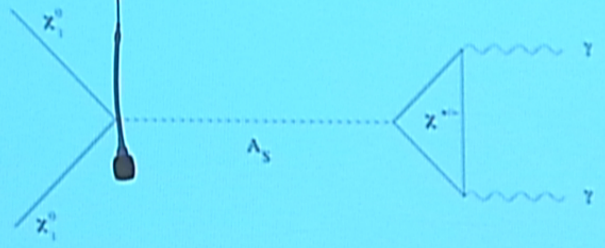


  - Min Lee, Park, Park: "Axion-mediated"

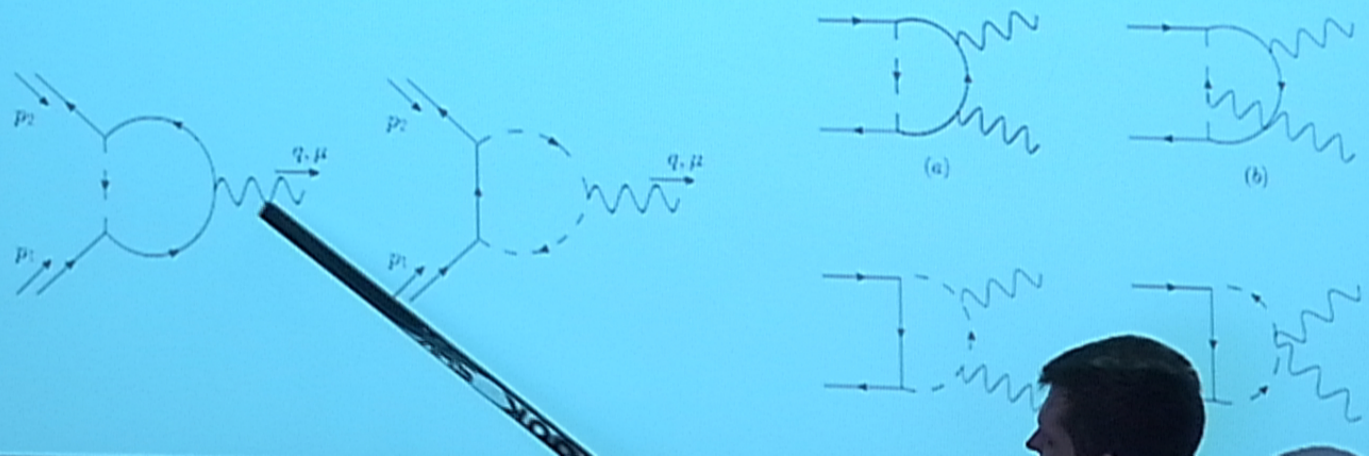


Gamma Lines from Annihilating DM

– Das, Ellwanger, Mitropoulos: "NMSSM"

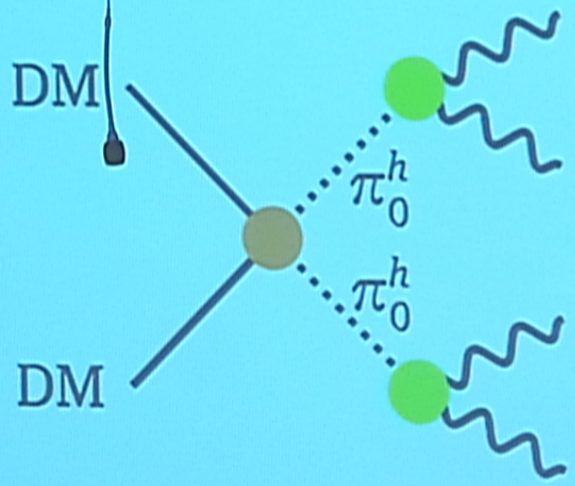


– Weiner, Yavin: "MiDM" and RayDM



Gamma Lines from Annihilating DM

– Fan and Reece: "Simple Recipe"

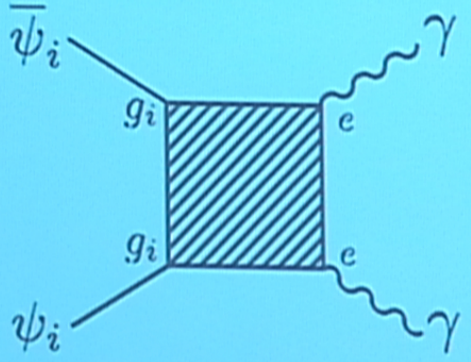


– Are there any qualitatively different DM explanations?

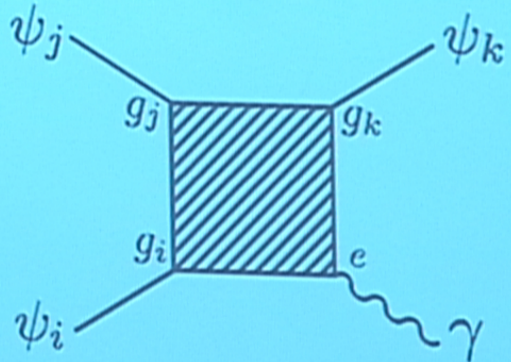
Gamma Lines from Semi-Annihilation

- Yes: Semi-annihilation (SA) (Hambye; D'Eramo, Thaler)
  - Imagine dark sector consists of multiple states
  - Stabilization symmetry greater than $\mathcal{Z}_2$

- Gamma lines from SA (D'Eramo, MM, Thaler)



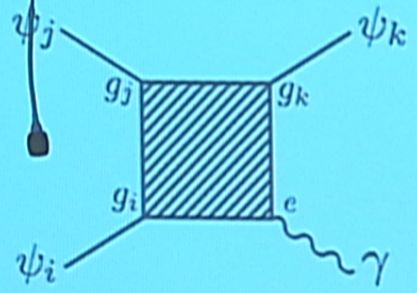
Annihilation



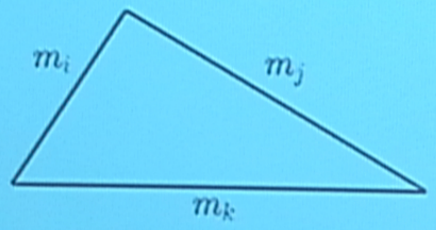
Semi-Annihilation

Semi-Annihilation and DM Stability

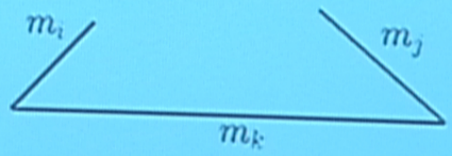
- Crossing symmetry in SA diagram: decays!



- Decays forbidden if masses satisfy triangle:



Decays kinematically forbidden



Decays allowed

Semi-Annihilation: Features

- Range of DM masses possible:

$$E_\gamma^{ij\to k} = \frac{(m_i + m_j + m_k)(m_i + m_j - m_k)}{2(m_i + m_j)}$$

- Annihilating DM:

$$E_\gamma^{\psi\psi} = m_\psi \quad (= 130 \text{ GeV if } m_\psi = 130 \text{ GeV})$$

- Degenerate Semi-Annihilating DM:

$$E_\gamma^{\psi\psi\psi} = \frac{3}{4} m_\psi \quad (= 130 \text{ GeV if } m_\psi = 173 \text{ GeV})$$

- General: DM mass a free parameter, potential to explain signatures well into TeV range!

Semi-Annihilation: Features

- Range of DM masses possible:

$$E_\gamma^{ij\to k} = \frac{(m_i + m_j + m_k)(m_i + m_j - m_k)}{2(m_i + m_j)}$$

- Annihilating DM:

$$E_\gamma^{\psi\psi} = m_\psi \quad (= 130 \text{ GeV if } m_\psi = 130 \text{ GeV})$$

- Degenerate Semi-Annihilating DM:

$$E_\gamma^{\psi\psi\psi} = \frac{3}{4} m_\psi \quad (= 130 \text{ GeV if } m_\psi = 173 \text{ GeV})$$

- General: DM mass a free parameter, potential to explain signatures well into TeV range!

Semi-Annihilation: Features

- Range of DM masses possible:

$$E_\gamma^{ij\to k} = \frac{(m_i + m_j + m_k)(m_i + m_j - m_k)}{2(m_i + m_j)}$$

- Annihilating DM:

$$E_\gamma^{\psi\psi} = m_\psi \quad (= 130 \text{ GeV if } m_\psi = 130 \text{ GeV})$$

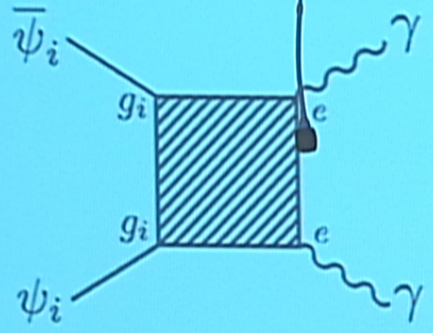
- Degenerate Semi-Annihilating DM:

$$E_\gamma^{\psi\psi\psi} = \frac{3}{4} m_\psi \quad (= 130 \text{ GeV if } m_\psi = 173 \text{ GeV})$$

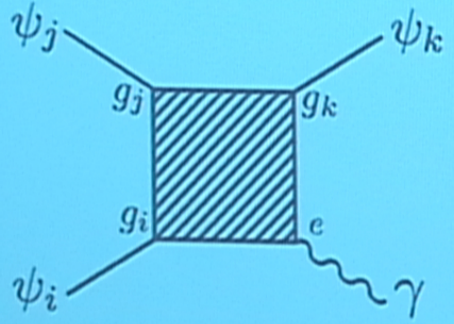
- General: DM mass a free parameter, potential to explain signatures well into TeV range!

Semi-Annihilation: Features

- Parametric enhancement of the cross section:



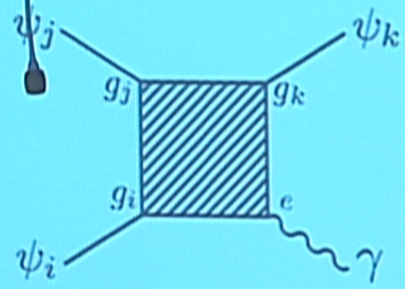
$$\langle \sigma v \rangle \propto \alpha_{EM}^2 \alpha_i^2$$



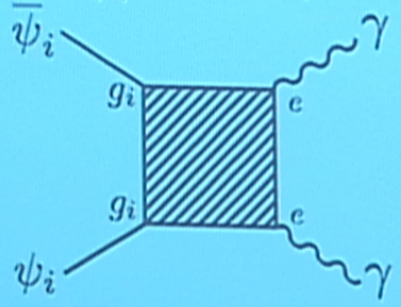
$$\langle \sigma v \rangle \propto \alpha_{EM} \alpha_i \alpha_j \alpha_k$$

Semi-Annihilation: Predictions

- Annihilation signal at higher energies.
  - If 130 GeV line from degenerate semi-annihilation

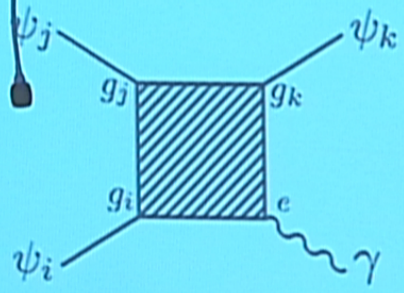


  - Then additional, suppressed, 173 GeV line from annihilation:

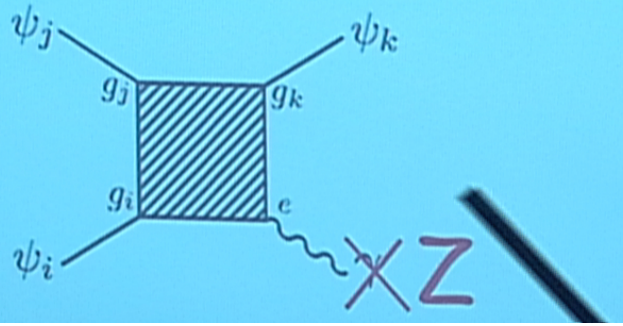


Semi-Annihilation: Predictions

- Annihilation signal at higher energies.
  - If 130 GeV line from semi-annihilation

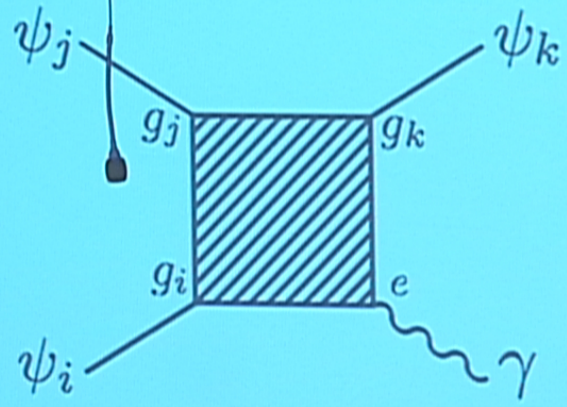


  - Then no 114 GeV line prediction!



Semi-Annihilation: Models

- Can attach different spin fields to external lines.



- If all same spin then scalars or vectors.

- Trying vectors. Many possibilities:
  - Dark composite states?
  - Dark spontaneously broke[n] gauge sector? ✔

Semi-Annihilating Dark $SU(N)_d$

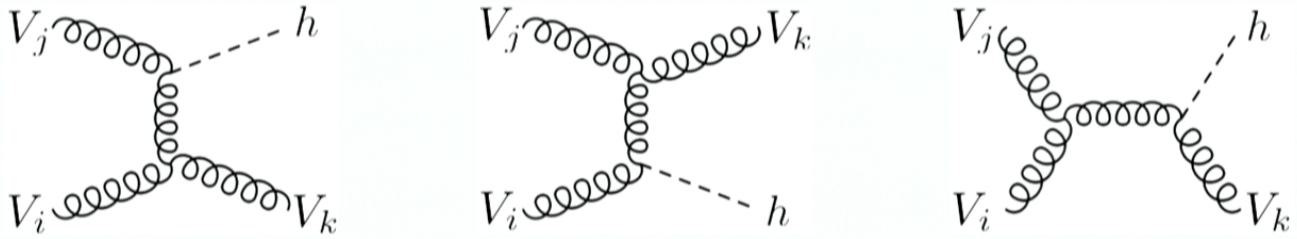
- Imagine a dark $SU(N)_d$ pure gauge sector
- Add Higgs fields ϕ_{ij} respecting $SU(N)_d X SU(N)_f$
- Allow generic symmetry breaking Higgs potential
- Higgs vev $\langle\phi_{ij}\rangle$ along diagonal $\langle\phi\rangle = v_d \mathbb{I}_{N\times N}$
- Equal vector masses. Stable from custodial symmetry
- End up with N^2-1 semi-annihilating DM candidates

Semi-Annihilating Dark $SU(N)_d$

- Imagine a dark $SU(N)_d$ pure gauge sector
- Add Higgs fields ϕ_{ij} respecting $SU(N)_d X SU(N)_f$
- Allow generic symmetry breaking Higgs potential
- Higgs vev $\langle\phi_{ij}\rangle$ along diagonal $\langle\phi\rangle = v_d \mathbb{I}_{N\times N}$
- Equal vector masses. Stable from custodial symmetry.
- End up with N^2-1 semi-annihilating DM candidates

Semi-Annihilating Dark $SU(N)_d$

- Dark Higgs mixes with SM Higgs. Relic density from

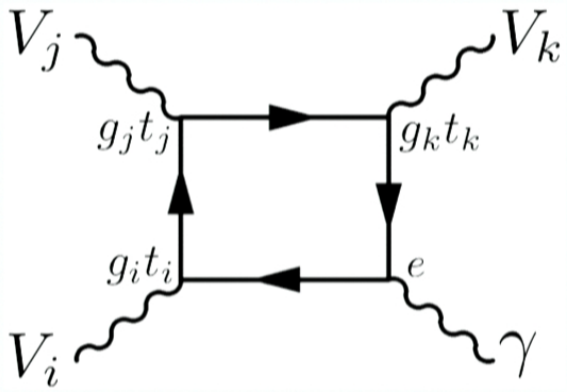


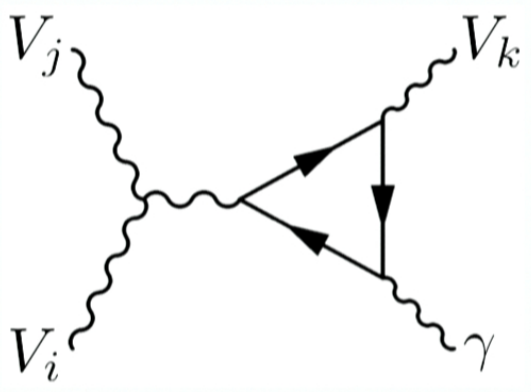
- Only require small mixing for observed relic density

$$\frac{1}{2}\langle\sigma v\rangle_s(VV \to Vh) = 2.9 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}\left(\frac{\alpha_d}{3.55}\right)^2\left(\frac{\sin\theta_h}{0.0055}\right)^2$$

Semi-Annihilating Dark SU(N)

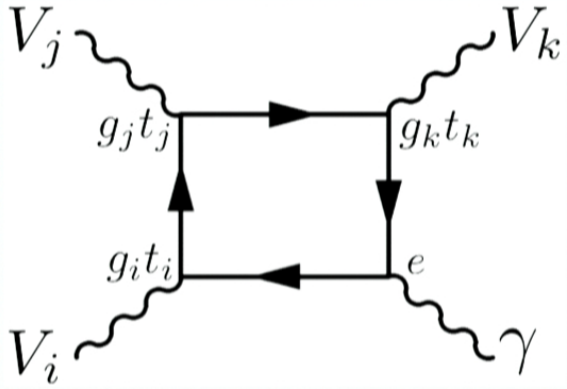
- Gamma line? Matter charged under $U(1)_{EM} X SU(N)_d$
- If fermionic, vector-like mass M_M, then

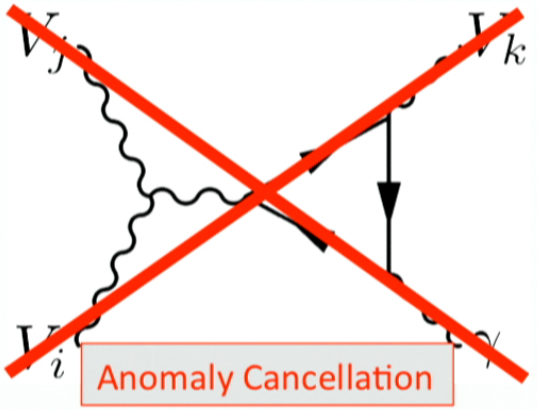




Semi-Annihilating Dark SU(N)

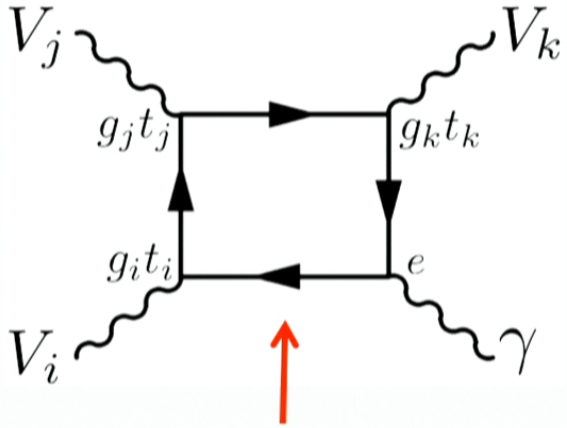
- Gamma line? Matter charged under $U(1)_{EM} \times SU(N)_d$
- If fermionic, vector-like mass M_M, then

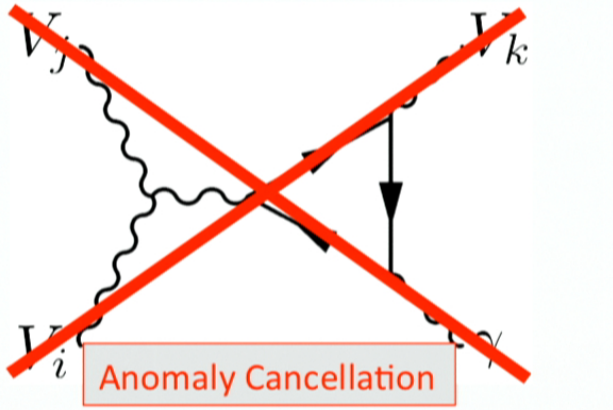




Semi-Annihilating Dark SU(N)

- Gamma line? Matter charged under $U(1)_{EM} \times SU(N)_d$
- If fermionic, vector-like mass M_M, then





- Just light-by-light scattering!
- Leading result: Non-Abelian Euler-Heisenberg

$$\mathcal{L} \supset \sum_{24\ \text{perm}} \frac{g_i g_j g_k e}{180(4\pi)^2 M_M^4} \mathrm{Tr}[t^i t^j t^k] \left(5 G^i_{\mu\nu} G^{j\nu\mu} G^k_{\lambda\rho} F^{\rho\lambda} - 14 G^i_{\mu\nu} G^{j\nu\lambda} G^k_{\lambda\rho} F^{\rho\mu}\right)$$

Semi-Annihilating Dark SU(N)

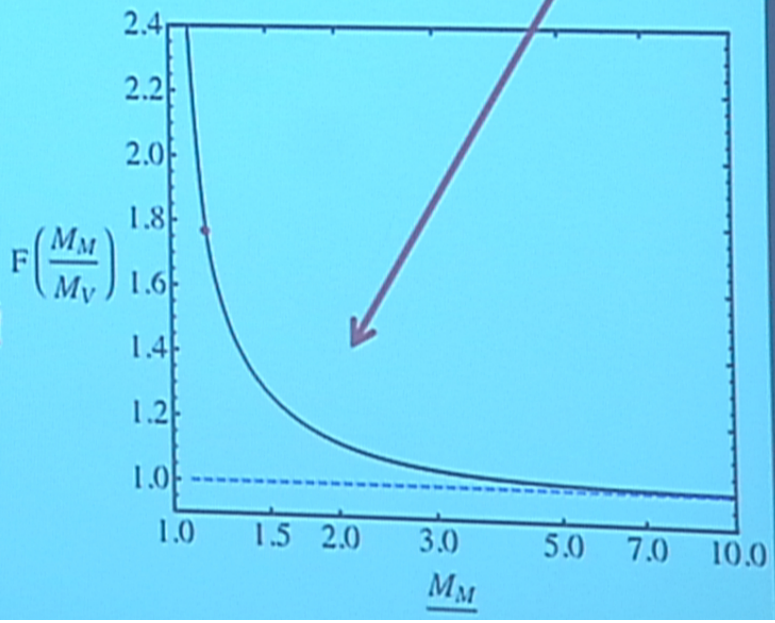
- Full result:

$$\langle \sigma v \rangle_s (ij \to k\gamma) = \frac{1697}{460800\pi} \frac{\alpha_d^3 \alpha_{\rm EM}}{M_V^2} \left(\frac{M_V}{M_M} \right)^8 |T^{ijk}|^2 F \left(\frac{M_M}{M_V} \right)$$

Semi-Annihilating Dark SU(N)

- Full result:

$$\langle \sigma v \rangle_s (ij \to k\gamma) = \frac{1697}{460800\pi} \frac{\alpha_d^3 \alpha_{\rm EM}}{M_V^2} \left(\frac{M_V}{M_M} \right)^8 |T^{ijk}|^2 F\left(\frac{M_M}{M_V} \right)$$



- Form factor not captured By Euler-Heisenberg

Semi-Annihilating Dark SU(N)

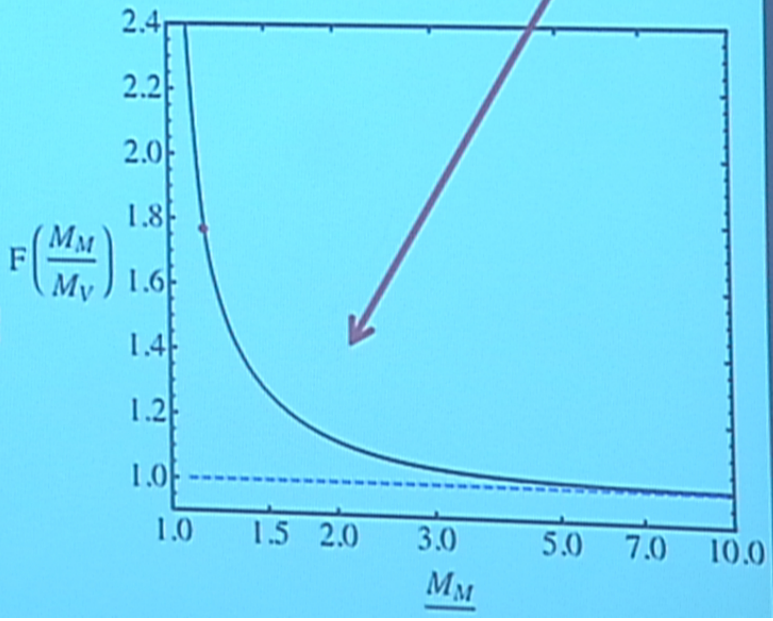
- Full result:

$$\langle \sigma v \rangle_s (ij \to k\gamma) = \frac{1697}{460800\pi} \frac{\alpha_d^3 \alpha_{\rm EM}}{M_V^2} \left(\frac{M_V}{M_M}\right)^8 |T^{ijk}|^2 F\left(\frac{M_M}{M_V}\right)$$

$$T^{ijk} = \sum_t \mathrm{Tr}[t^i t^j t^k + t^i t^j t^k]$$

- Smallest group: $SU(3)_d$

- Form factor not captured By Euler-Heisenberg

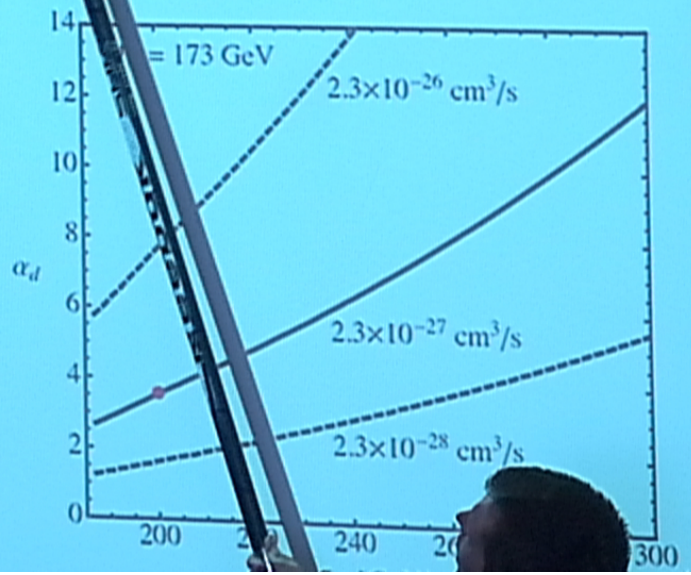


Semi-Annihilating Dark SU(3)$_d$

- Final result:

$$\frac{1}{2}\langle\sigma v\rangle_s(VV \to V\gamma) = \frac{5}{192}\frac{1697}{460800\pi}\frac{\alpha_d^3\alpha}{M_V^2}N_f^2\left(\frac{M_V}{M_M}\right)^8 F\left(\frac{M_M}{M_V}\right)$$

$$\simeq 2.3\times 10^{-27}\,\mathrm{cm}^3/\mathrm{s}\left(\frac{\alpha_d}{3.}\right)^3 N_f^2\left(\frac{200\ \mathrm{GeV}}{M_M}\right)^8\left(\frac{M_V}{173\ \mathrm{GeV}}\right)^6$$



Semi-Annihilating Dark $SU(3)_d$

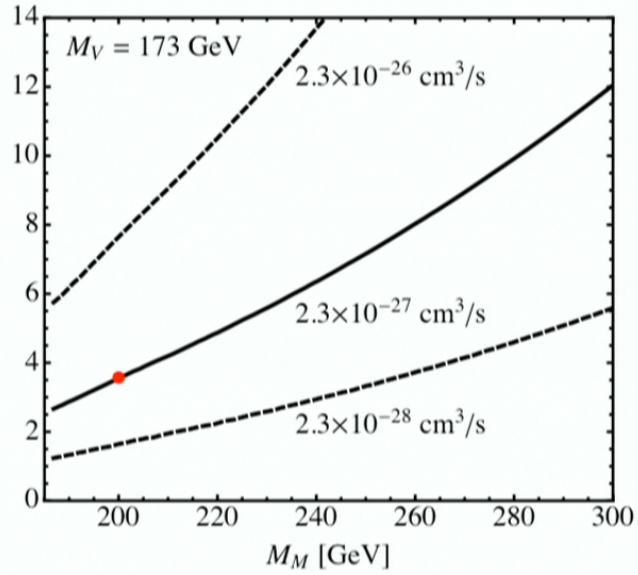
- Final result:

$$\frac{1}{2}\langle\sigma v\rangle_s(VV \to V\gamma) = \frac{5}{192}\frac{1697}{460800\pi}\frac{\alpha_d^3\alpha}{M_V^2}N_f^2\left(\frac{M_V}{M_M}\right)^8 F\left(\frac{M_M}{M_V}\right)$$

$$\simeq 2.3\times 10^{-27}\,\mathrm{cm}^3/\mathrm{s}\left(\frac{\alpha_d}{3.55}\right)^3 N_f^2\left(\frac{200\ \mathrm{GeV}}{M_M}\right)^8\left(\frac{M_V}{173\ \mathrm{GeV}}\right)^6$$

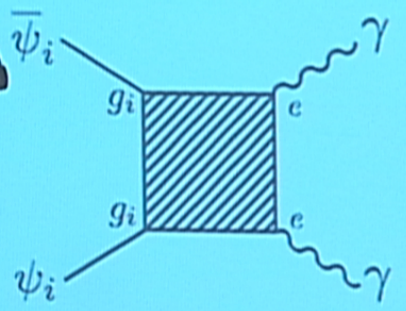
- Still need a pretty large gauge coupling!

- Complete model of gamma lines from Semi-Annihilations



Semi-Annihilating Dark $SU(3)_d$

- 173 GeV annihilation line still predicted, but below current sensitivity:

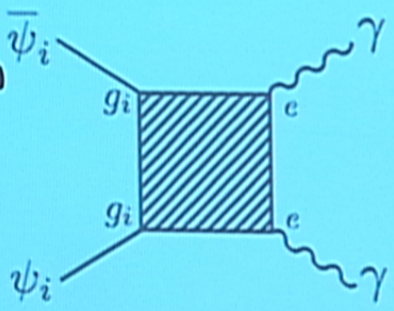


$$\langle \sigma v \rangle_s (VV \to \gamma\gamma) \approx \frac{1}{8} \frac{299 \alpha_d^2 \alpha^2}{36450 \pi M_V^2} N_f^2 \left(\frac{M_V}{M_M} \right)^8$$

$$\simeq 3.0 \times 10^{-29}\, \mathrm{cm}^3/\mathrm{s} \left(\frac{\alpha_d}{3.55} \right)^2 N_f^2 \left(\frac{200\ \mathrm{GeV}}{M_M} \right)^8 \left(\frac{M_V}{173\ \mathrm{GeV}} \right)^6$$

Semi-Annihilating Dark $SU(3)_d$

- 173 GeV annihilation line still predicted, but below current sensitivity:

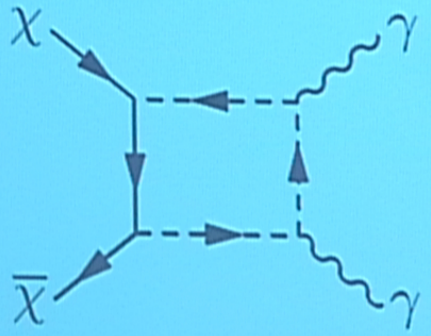


$$\langle \sigma v \rangle_s (VV \to \gamma\gamma) \approx \frac{1}{8} \frac{299 \alpha_d^2 \alpha^2}{36450 \pi M_V^2} N_f^2 \left(\frac{M_V}{M_M} \right)^8$$

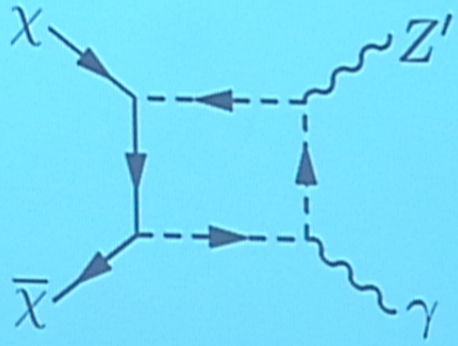
$$\simeq 3.0 \times 10^{-29}\, \mathrm{cm}^3/\mathrm{s} \left(\frac{\alpha_d}{3.55} \right)^2 N_f^2 \left(\frac{200\ \mathrm{GeV}}{M_M} \right)^8 \left(\frac{M_V}{173\ \mathrm{GeV}} \right)^6$$

More Semi-Annihilating Models?

- Many other possibilities...
- Can also retrofit standard annihilation models!
- Retrofit: RayDM (Yavin, Weiner; D'Eramo, MM, Thaler)



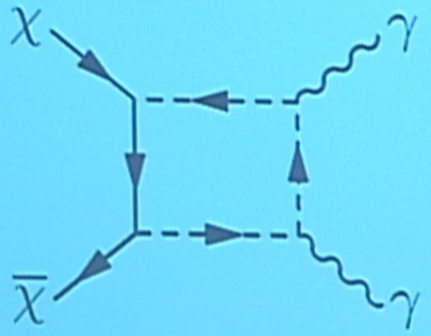
RayDM



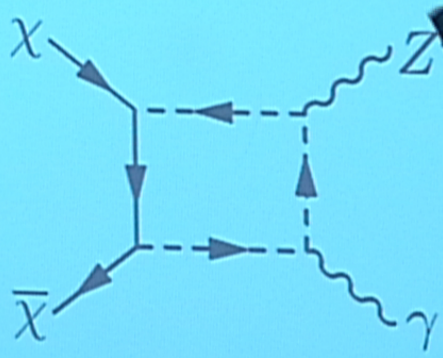
Semi-Annihilating RayDM

More Semi-Annihilating Models?

- Many other possibilities...
- Can also retrofit standard annihilation models!
- Retrofit: RayDM (Yavin, Weiner; D'Eramo, MM, Thaler)



RayDM



Semi-Annihilating RayDM

More Semi-Annihilating Models?

- RayDM:

$$\langle \sigma v \rangle_s(\chi\chi \to \gamma\gamma) = \frac{\alpha_\lambda^2 \alpha_W^2 (\cos\theta_\chi \cos^2\theta_W + \sin\theta_\chi \sin^2\theta_W)^2}{9\pi M_\chi^2} \left(\frac{M_\chi}{M_M}\right)^6$$

$$\simeq 1.3 \times 10^{-27}\,\mathrm{cm}^3/\mathrm{s} \left(\frac{\alpha_\lambda}{1.8}\right)^2 \left(\frac{200\ \mathrm{GeV}}{M_M}\right)^6 \left(\frac{M_\chi}{130\ \mathrm{GeV}}\right)^4$$

- Retrofitted RayDM:

$$\frac{1}{2}\langle \sigma v \rangle_s(\chi\chi \to \gamma Z') = \frac{\alpha_\lambda^2 \alpha_W^2 (\cos\theta_\chi \cos\theta_W \sin\theta_{W'} \cos\theta_{W'})^2}{36\pi M_\chi^2} \left(\frac{M_\chi}{M_M}\right)^6 \left(1 - \frac{M_{Z'}^2}{4M_\chi^2}\right)^3$$

$$\simeq 2.3 \times 10^{-27}\,\mathrm{cm}^3/\mathrm{s} \left(\frac{r'}{10}\right) \left(\frac{\alpha_\lambda}{0.72}\right)^2 \left(\frac{200\ \mathrm{GeV}}{M_M}\right)^6$$

$$\times \left(\frac{M_\chi}{173\ \mathrm{GeV}}\right) \left(\frac{E_\gamma}{130\ \mathrm{GeV}}\right)^3$$

More Semi-Annihilating Models?

- RayDM:

$$\langle \sigma v \rangle_s(\chi\chi \to \gamma\gamma) = \frac{\alpha_\lambda^2 \alpha_W^2 (\cos\theta_\chi \cos^2\theta_W + \sin\theta_\chi \sin^2\theta_W)^2}{9\pi M_\chi^2} \left(\frac{M_\chi}{M_M}\right)^6$$

$$\simeq 1.3 \times 10^{-27}\,\mathrm{cm}^3/\mathrm{s} \left(\frac{\alpha_\lambda}{1.8}\right)^2 \left(\frac{200\ \mathrm{GeV}}{M_M}\right)^6 \left(\frac{M_\chi}{130\ \mathrm{GeV}}\right)^4$$

- Retrofitted RayDM:

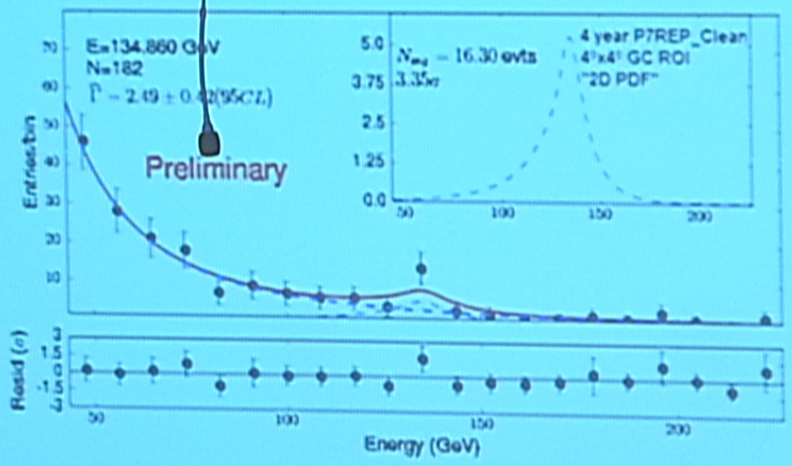
$$\frac{1}{2}\langle \sigma v \rangle_s(\chi\chi \to \gamma Z') = \frac{\alpha_\lambda^2 \alpha_W^2 (\cos\theta_\chi \cos\theta_W r')^2}{36\pi M_\chi^2} \left(\frac{M_\chi}{M_M}\right)^6 \left(1 - \frac{M_{Z'}^2}{4M_\chi^2}\right)^3$$

$$\simeq 2.3 \times 10^{-27}\,\mathrm{cm}^3/\mathrm{s} \left(\frac{r'}{10}\right) \left(\frac{\alpha_\lambda}{0.72}\right)^2 \left(\frac{200\ \mathrm{GeV}}{M_M}\right)^6$$

$$\times \left(\frac{M_\chi}{173\ \mathrm{GeV}}\right) \left(\frac{E_\gamma}{130\ \mathrm{GeV}}\right)^3$$

Conclusions

- Perhaps FERMI has seen a glimpse of the dark side…



- If so, then what does this mean? M_{DM} = 130 GeV?

- Not so fast… It could be the beginnings of dark sector spectroscopy through semi-annihilation!

Conclusions

- The FERMI line may or may not be a signal of DM
- It motivates us to revisit DM gamma ray phenomenology
  - The widely accepted possibility is DM annihilation
  - But the dark sector need not be so simple…
- Previously unexplored: Semi-annihilation:
  - Dark matter mass still a free parameter
  - Should see more lines, about N^3 for N dark sector states
- If the line is from degenerate semi-annihilation:
  - 114 GeV line should probably go away
  - New line near 173 GeV should show up at some point
- Stay tuned throughout 2013!