Fitting the Fermi line with neutralino dark matter

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arXiv:1211.5154. JCAP02(2013)016

Cambridge - 8th February 2013

Outline

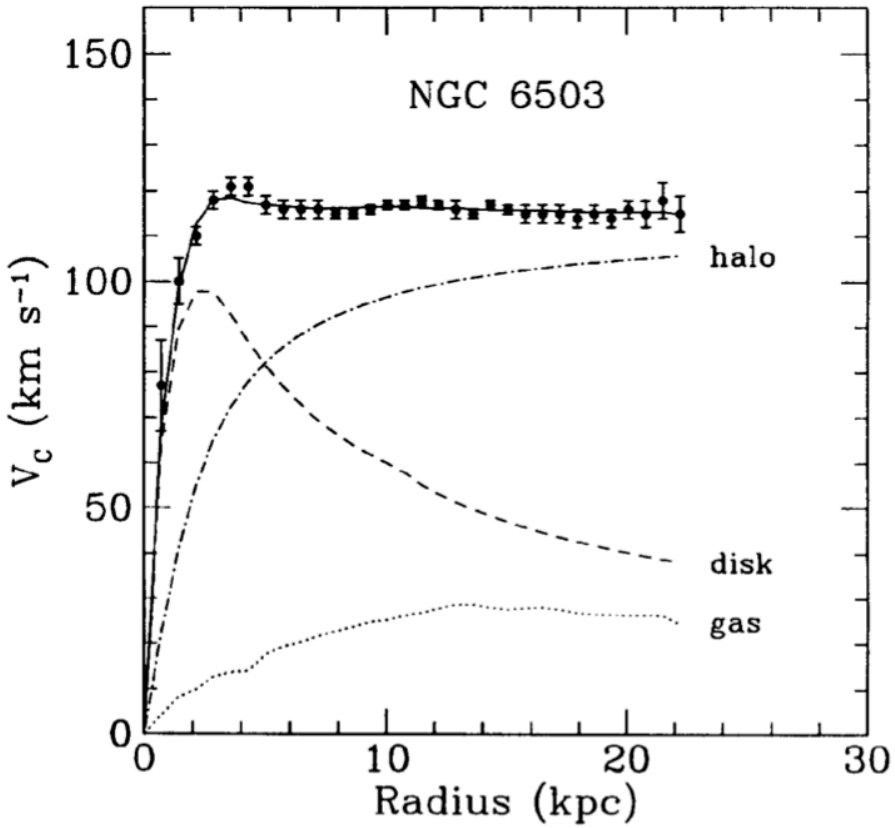
1. The Fermi line

2. Fitting the Fermi line with neutralino dark matter

Why dark matter?

- Dark matter is a necessary component in our Universe:

- Galaxies



Why dark matter?

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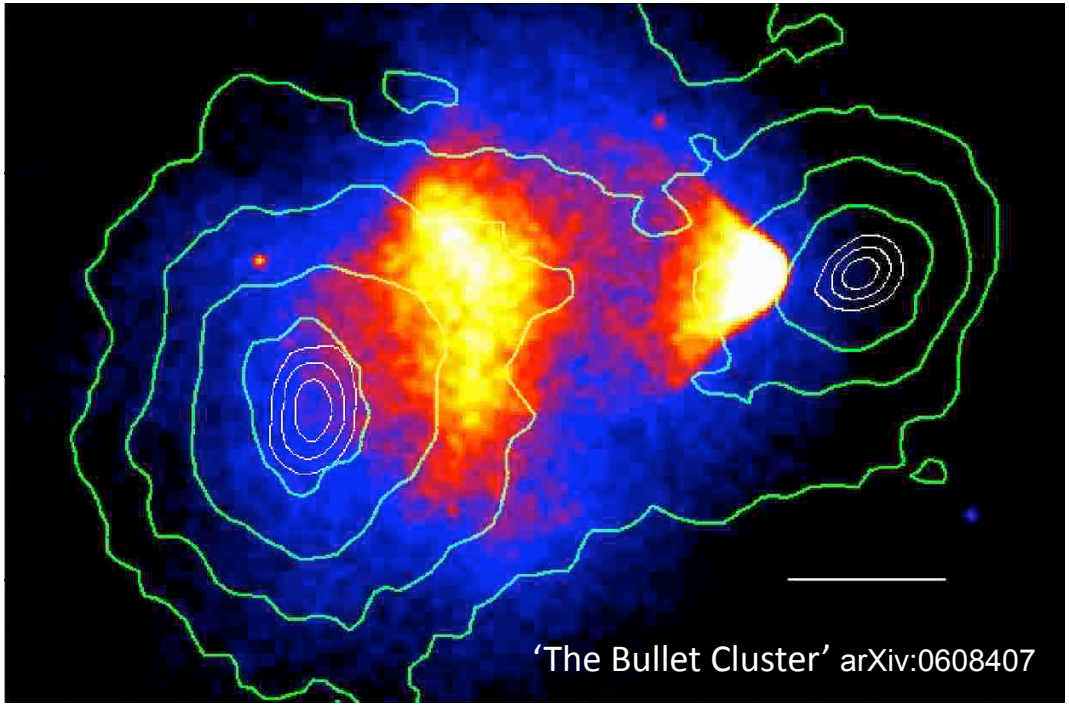
- Galactic clusters



Why dark matter?

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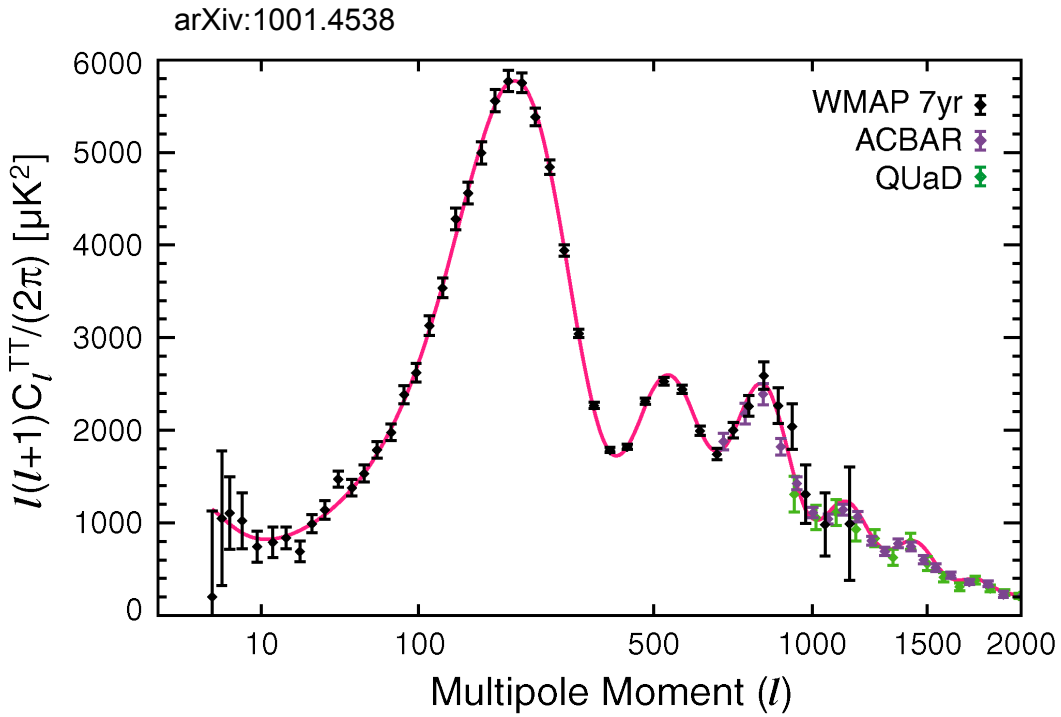
- Galactic clusters
- CMB fluctuations



WMAP find: $\Omega_{\rm DM} h^2 = 0.11$

Why dark matter?

- Dark matter is a necessary component in our Universe:
- Galaxies
- Galactic clusters
- CMB fluctuations

So...what is it?

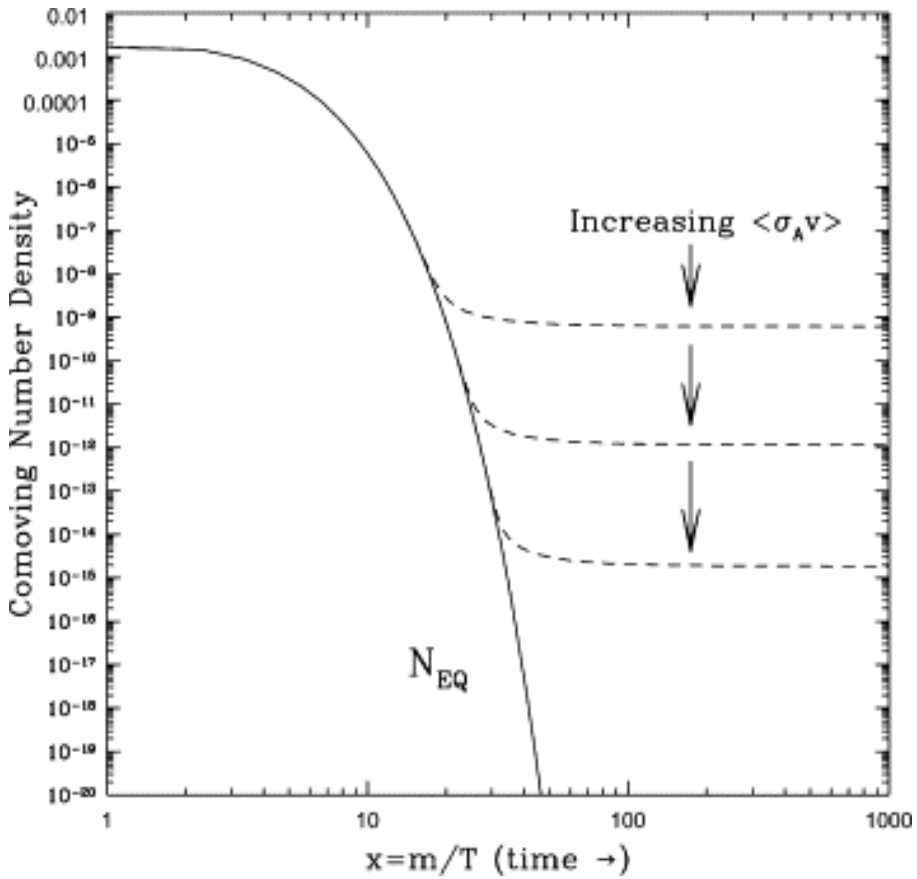
The candidates

- WIMPs (Weakly interacting massive particles)
- Axions
- Asymmetric dark matter
- Sterile neutrinos
- FIMPs (Feebly interacting massive particles)
- ...

- WIMPs are attractive because they have weak scale interactions with Standard Model particles
  - Testable!

WIMPs

- Weak scale interactions + thermal freeze out give the observed relic abundance

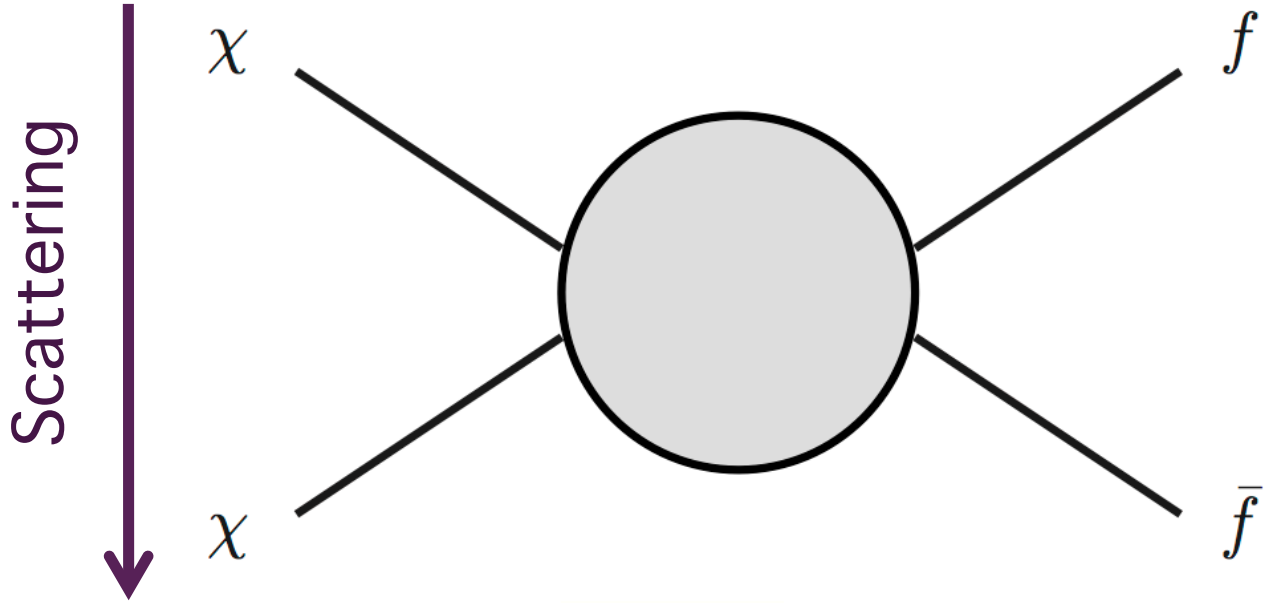


$$\Omega_{\rm DM} h^2 \sim 0.1 \, \frac{3 \times 10^{-26} \ {\rm cm}^3 {\rm s}^{-1}}{\langle \sigma_{\rm ann} v \rangle}$$

Detecting WIMPs

- There are three main detection strategies:

1. Direct



Detecting WIMPs

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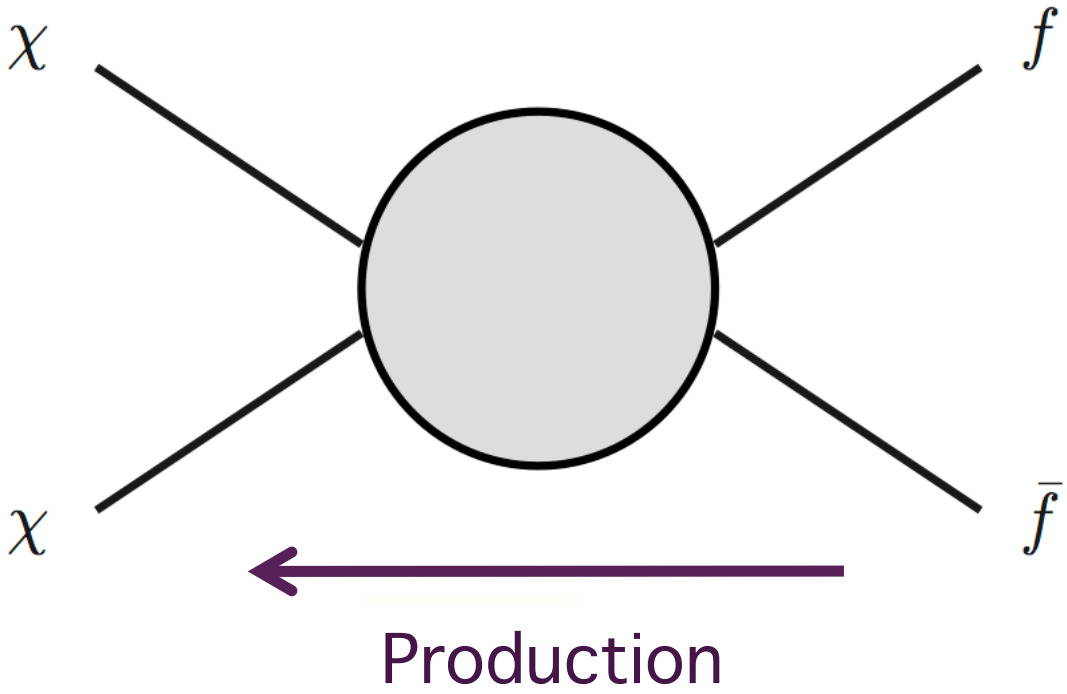
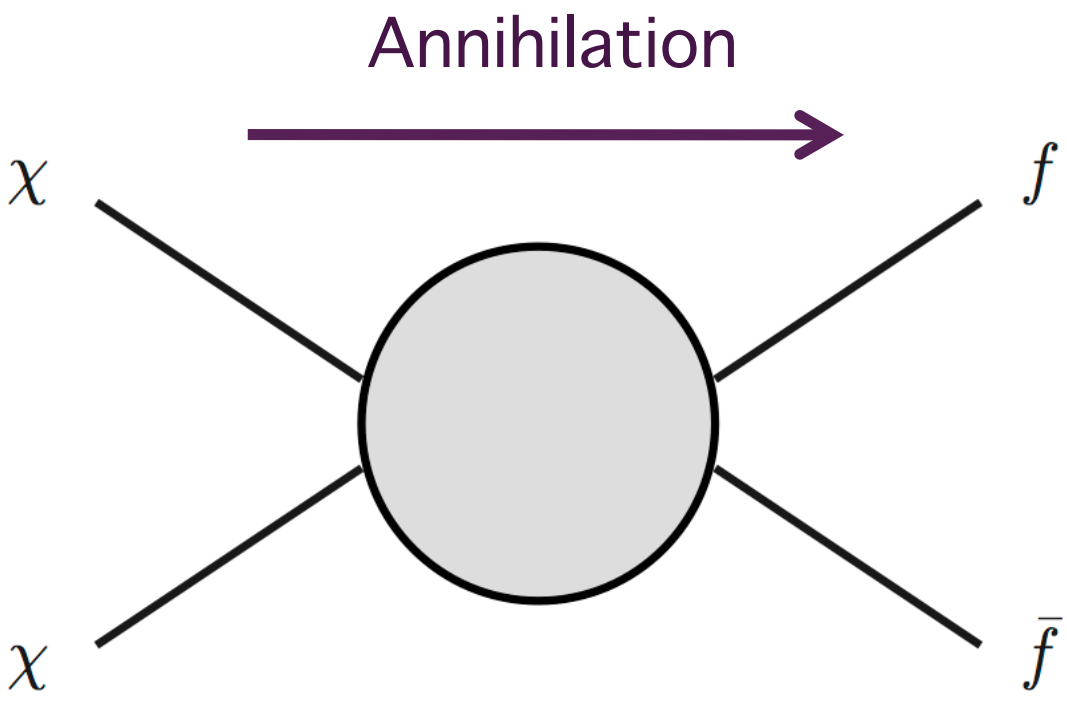
1. Direct
2. Collider



Detecting WIMPs

- There are three main detection strategies:

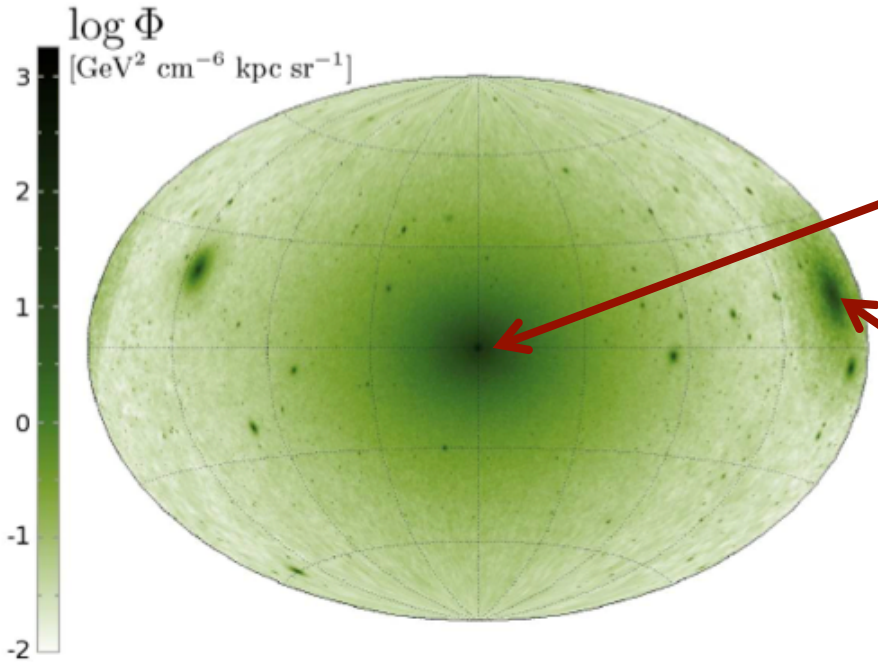
1. Direct
2. Collider
3. Indirect



Indirect detection

- Detect photons from dark matter annihilation or decay
- Look in regions where the dark matter density is large:

$$\mathrm{Flux}_{\mathrm{ann}} \propto \rho_{\mathrm{DM}}^2 \qquad \mathrm{Flux}_{\mathrm{decay}} \propto \rho_{\mathrm{DM}}$$



Kuhlen et al
arXiv:0810.3614

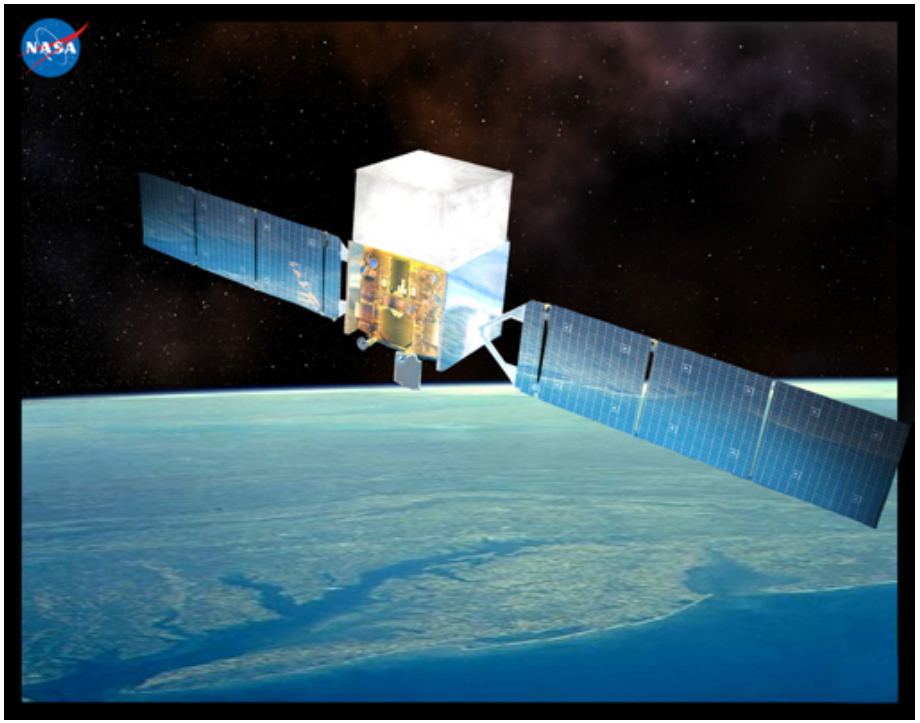
Galactic centre is the brightest source in the sky...
but large backgrounds

Sub-halos *may* also be detectable

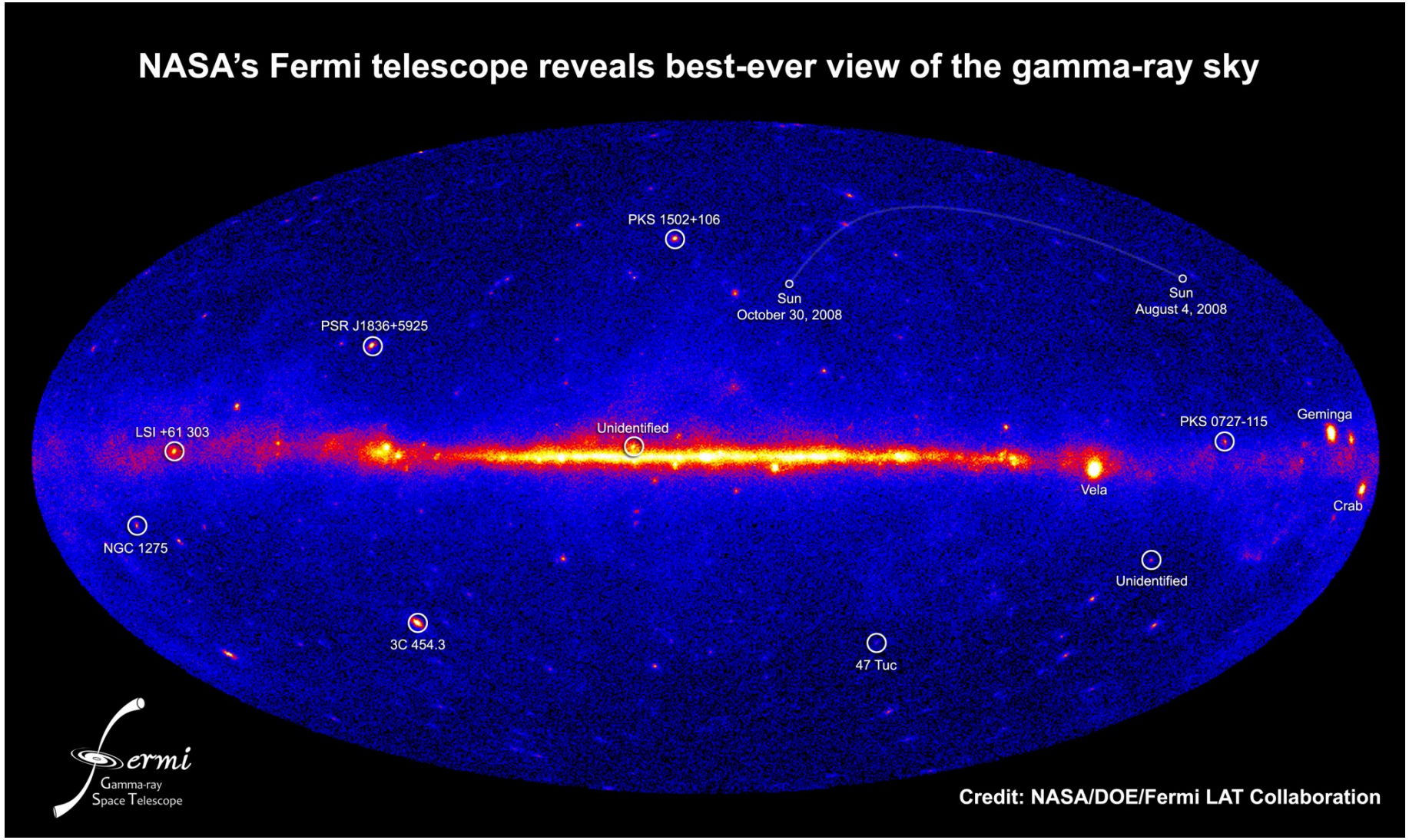
Fermi-LAT

- Fermi is a gamma ray satellite

  - Launched in June 2008
  - Orbits Earth every ~ 95 minutes
  - Views ~20% of the sky
  - Energy range 30 MeV – 300 GeV

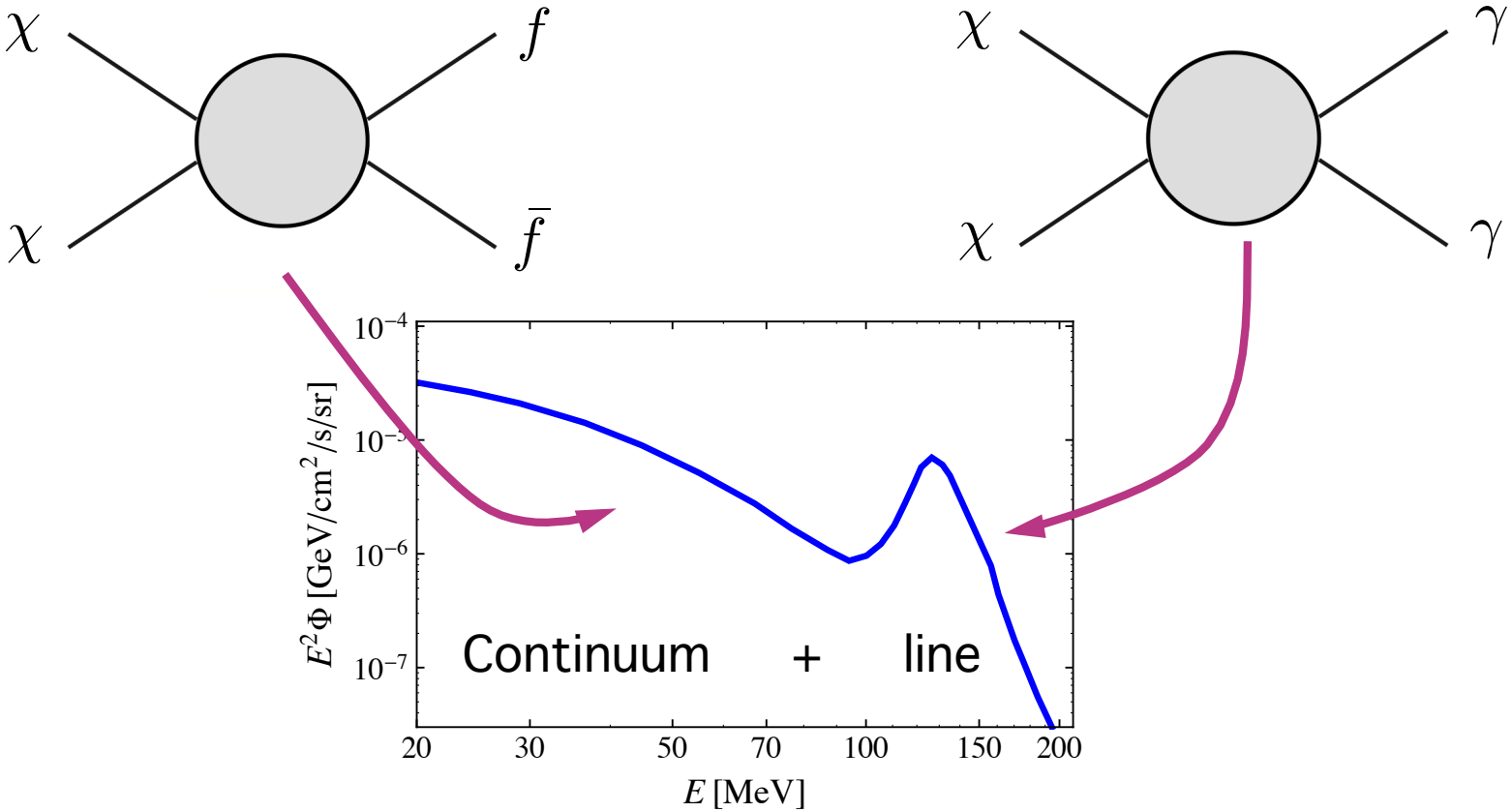


Fermi-LAT


NASA's Fermi telescope reveals best-ever view of the gamma-ray sky
PKS 1502+106
Sun
October 30, 2008
Sun
August 4, 2008
PSR J1836+5925
LSI +61 303
Unidentified
PKS 0727-115
Geminga
Vela
Crab
NGC 1275
Unidentified
3C 454.3
47 Tuc
Fermi
Gamma-ray
Space Telescope
Credit: NASA/DOE/Fermi LAT Collaboration

Indirect detection

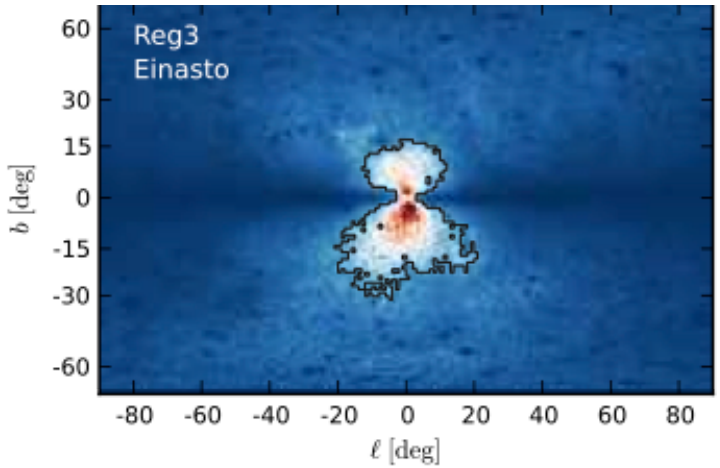
- Spectrum from dark matter annihilation:

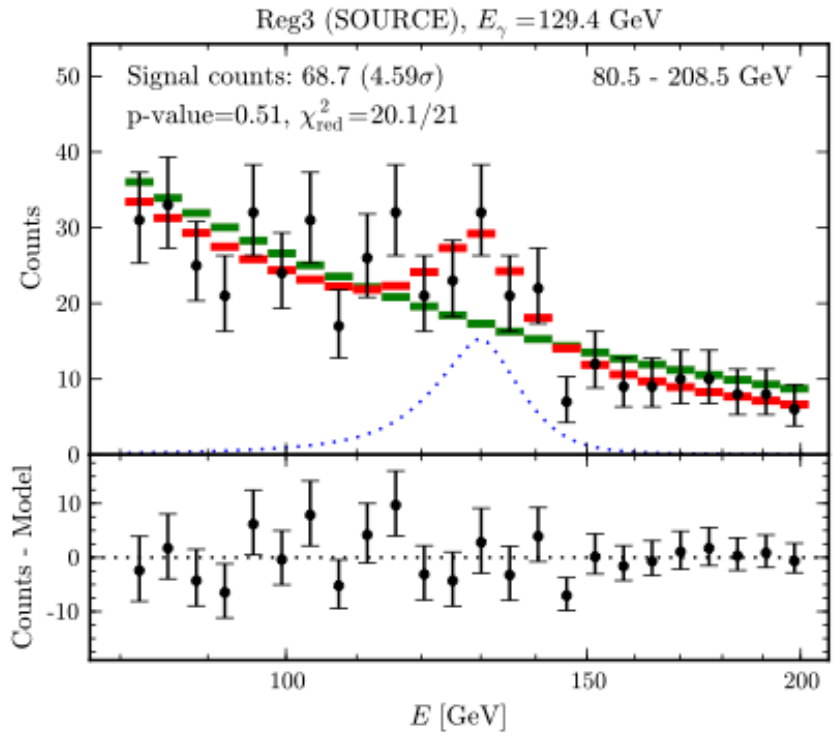


- Line: a distinct spectral feature - ‘smoking gun’

A line is observed!

- *A tentative gamma-ray line from dark matter annihilation at the Fermi LAT* - Weniger, arXiv:1204.2797



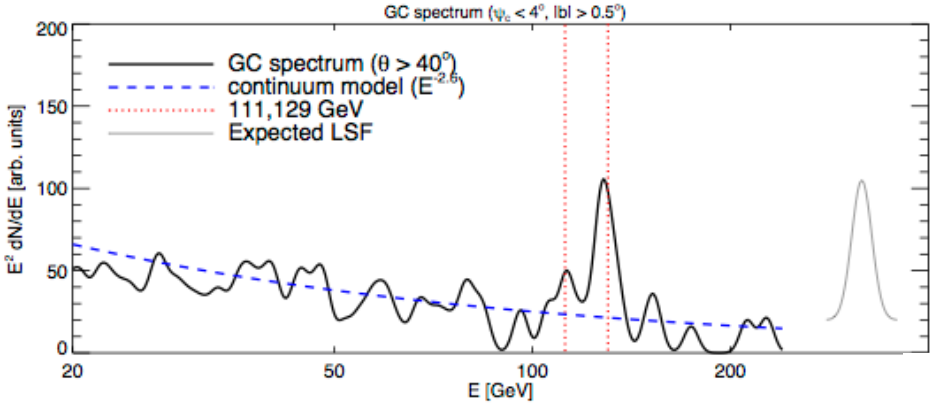


"...we find a 4.6σ indication for a gamma-ray line at 130 GeV. With the look elsewhere effect, the significance is 3.2σ."

- Similar results later by Tempel et al, arXiv:1205.1045

More evidence

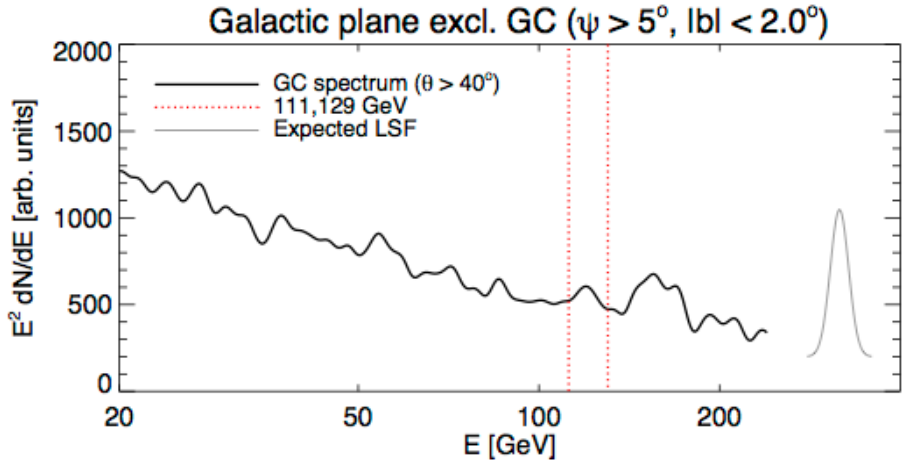
- *Strong evidence for gamma-ray line emission from the inner galaxy* – Su, Finkbeiner, arXiv:1206.1616



"A pair of lines at 110 GeV and 128 GeV provides a marginally better fit"

See also Rajaraman, Tait, Whiteson, arXiv:1205.4723

"...preferred over the no line hypothesis by $5.0\sigma/5.4\sigma$ after trails factor correction for one/two line case"

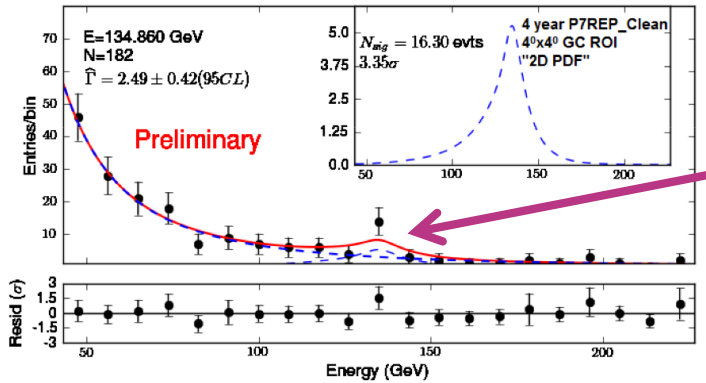


What do Fermi say?

Slide from A. Albert; Fermi Symposium 2012

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

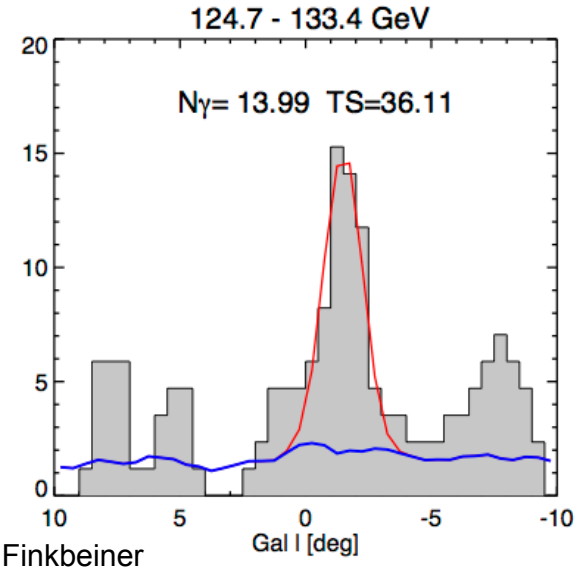
Position shifted slightly

A bump is still there

Lower significance

10 Fermi LAT Spectral Line Search 11/02/2012

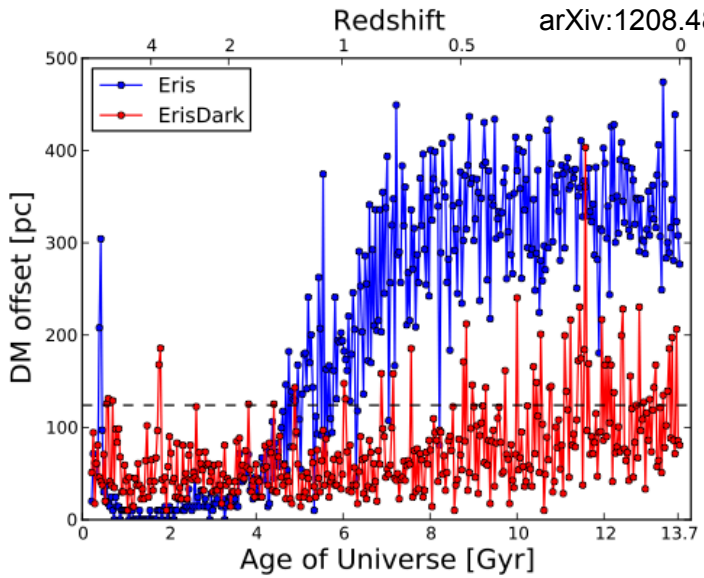
Issues: displaced from galactic centre



Su, Finkbeiner
arXiv:1206.1616

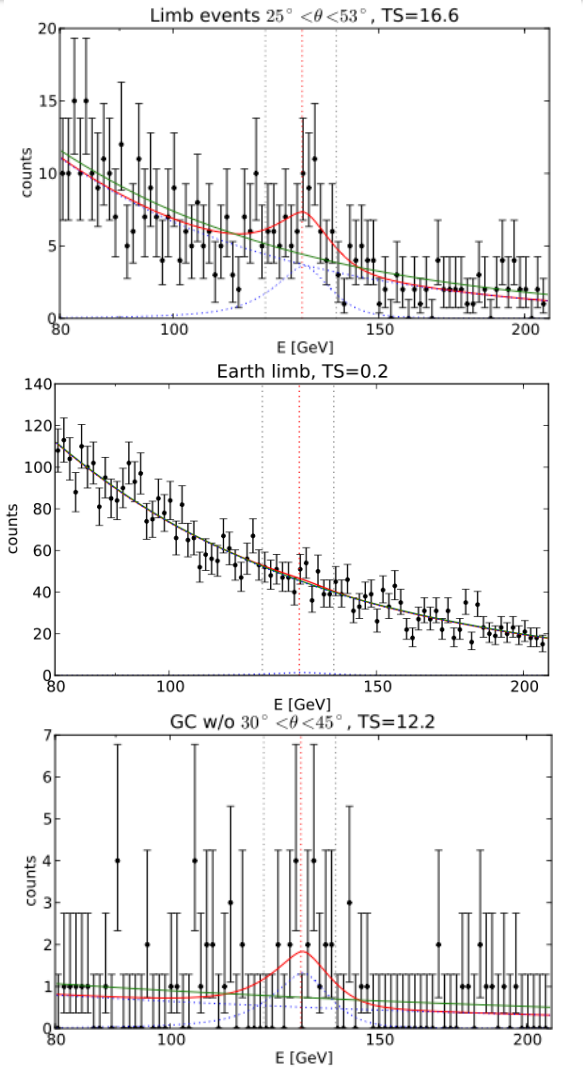
- Signal is displaced from the galactic centre (potential minimum) by ~200 pc
- Should dark matter be at the centre...?

Kuhlen et al
arXiv:1208.4844



- Numerical simulations show that a displacement of this size can occur
- Not fully understood...interaction with the stellar bar?

Issues: systematic effect?

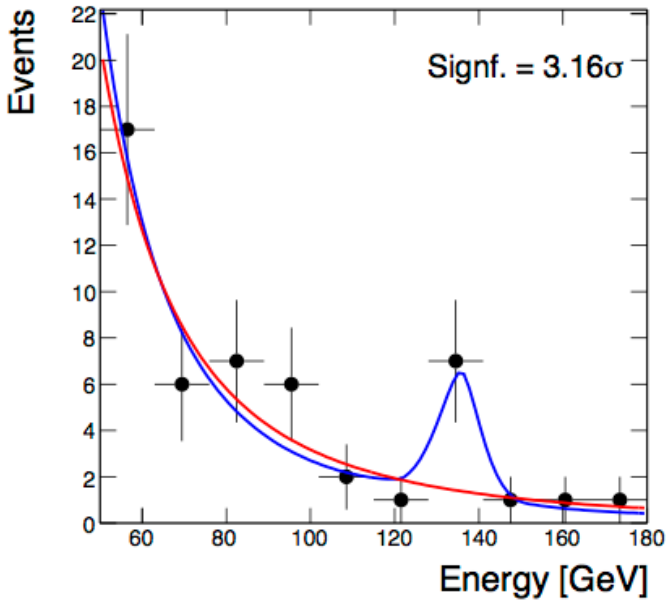


Finkbeiner, Su, Weniger arXiv:1209.4562

- Photons from the Earth limb show an excess ($> 3\sigma$) at 130 GeV for limited range of angles
- Galactic centre signal still present when 'problematic' sample is removed
- "We find no significant instrumental systematics that could plausibly explain the excess Galactic centre emission observed at 130 GeV"

Issues: systematic effect?

Whiteson arXiv:1302.0427



- New this week! Photons from the Sun also show an excess at 130 GeV for all angles
- "While this does not give a definitive instrumental explanation for these spectral features, it casts significant further doubts on the dark matter hypothesis."

Fermi summary

- The Fermi data does contain an excess at ~130 GeV coming from the galactic centre

- This could simply be...
  a statistical fluctuation in the data
  an instrumental systematic effect

- Or is this the 'smoking gun' signature of dark matter?

- Ultimately, time will tell as more data accumulates and other experiments search for this feature

Dark matter interpretation

- Annihilation preferred over decays:

  "decaying dark matter...would require an enhancement of the dark matter density near the galactic centre." Buchmuller, Garny arXiv:1206.7056

- What annihilation cross-section is required?

γX	m_χ [GeV]	$\langle\sigma v\rangle_{\gamma X}$ [$10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}$]	$\frac{\langle\sigma v\rangle_{\gamma\gamma}}{\langle\sigma v\rangle_{\gamma X}}$	$\frac{\langle\sigma v\rangle_{\gamma Z}}{\langle\sigma v\rangle_{\gamma X}}$	$\frac{\langle\sigma v\rangle_{\gamma H}}{\langle\sigma v\rangle_{\gamma X}}$
$\gamma\gamma$	$129.8 \pm 2.4^{+7}_{-14}$	$1.27 \pm 0.32^{+0.18}_{-0.28}$	1	$0.66^{+0.71}_{-0.48}$	< 0.83
γZ	$144.2 \pm 2.2^{+6}_{-12}$	$3.14 \pm 0.79^{+0.40}_{-0.60}$	< 0.28	1	< 1.08
γH	$155.1 \pm 2.1^{+6}_{-11}$	$3.63 \pm 0.91^{+0.45}_{-0.63}$	< 0.17	< 0.79	1

Bringmann, Weniger arXiv:1208.5481

Energy given by $E_{\gamma X} = m_\chi \left(1 - \frac{m_X^2}{4m_\chi^2}\right)$.

e.g. $E_{\gamma\gamma} = 130\ \mathrm{GeV}$ and $E_{\gamma Z} = 114\ \mathrm{GeV}$ when $m_\chi = 130\ \mathrm{GeV}$

- Compare: $\langle\sigma_{\mathrm{ann}} v\rangle = 3 \times 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$ for relic abundance

Supersymmetry

- The Higgs looks like it's a light, fundamental(?) scalar
  ...is SUSY just around the corner?

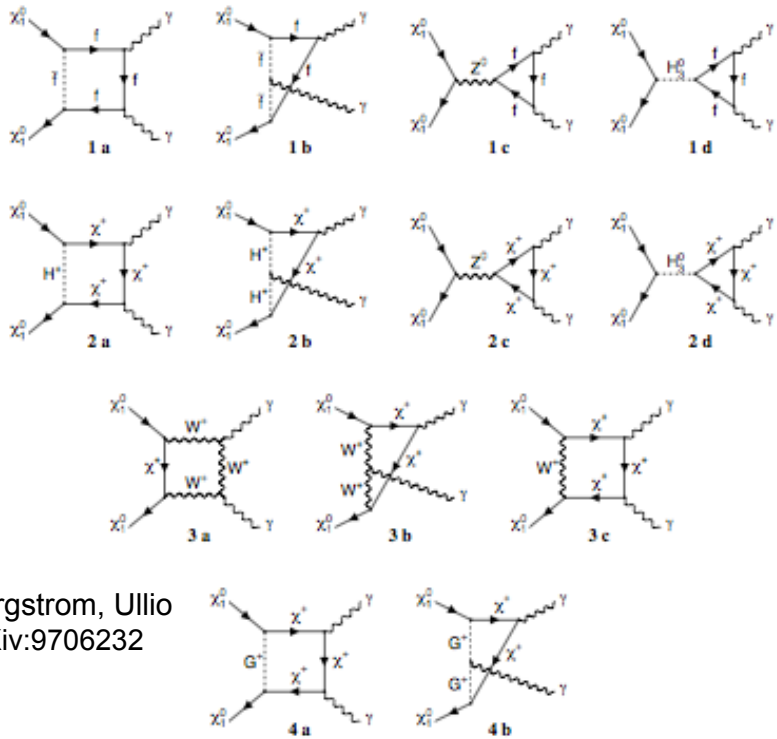
- LHC is ruling out the simplest, minimal SUSY extensions of the Standard Model

- Perhaps some of the usual ideas will have to go
  ...for now, let's keep R-parity so that the LSP is stable

Neutralino dark matter

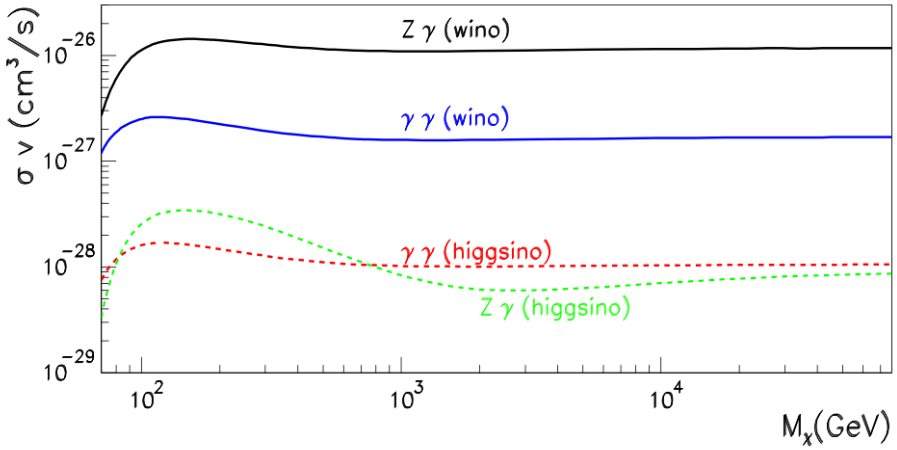
- In the MSSM, the lightest neutralino is composed of

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u$$



Bergstrom, Ullio
arXiv:9706232

Boudjema et al
arXiv:0507127



- Annihilation cross section can be large enough

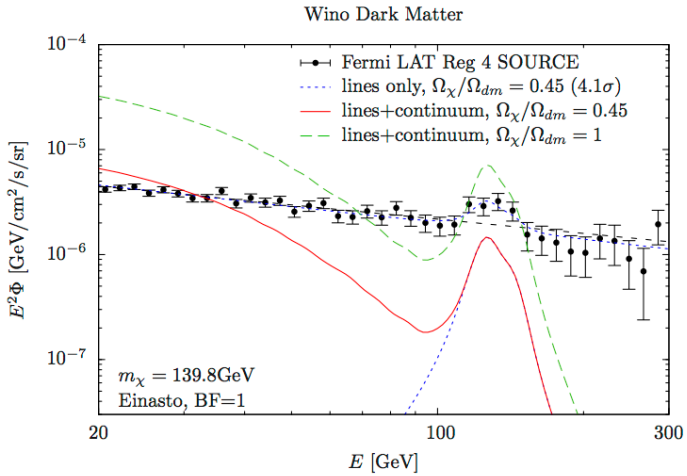
Problems

- Neutralino is neutral so $\gamma\gamma$ rate is loop suppressed

$$\langle \sigma v \rangle_{\gamma\gamma} \sim \alpha_{\rm EM}^2 \langle \sigma_{\rm ann} v \rangle$$

- This leads to two problems:

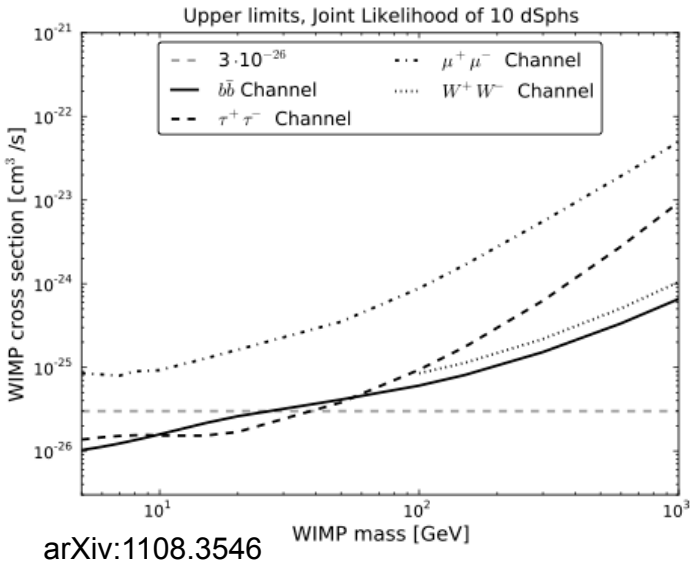
1. If $\langle \sigma v \rangle_{\gamma\gamma} = 10^{-27}\ {\rm cm}^3{\rm s}^{-1}$, then $\langle \sigma_{\rm ann} v \rangle \gg 3 \times 10^{-26}\ {\rm cm}^3{\rm s}^{-1}$
   - Thermal relic abundance is too small
2. Continuum flux is above current limits



Buchmuller, Garney
arXiv:1206.7056

Problems

- Fermi's limits on the continuum flux:



arXiv:1108.3546

- If relic density is OK, continuum limits will also be OK
  - Need to boost $\langle \sigma v \rangle_{\gamma\gamma}$ while keeping $\langle \sigma_{\rm ann} v \rangle$ the same
  - Can't be done in the MSSM!

Buchmuller et al. arXiv:1206.7056
Cohen et al. arXiv: 1207.0800
Cholis et al. arXiv:1207.1468

Beyond the MSSM: the NMSSM

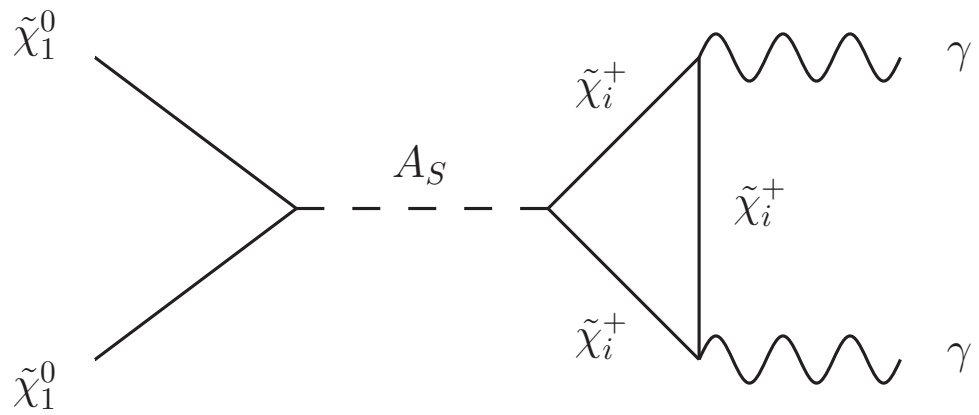
- Add singlet superfield with new interactions

$$\mathcal{W}_{\rm NMSSM} = \mathcal{W}_{\rm Yukawa} + \lambda S H_u \cdot H_d + \frac{\kappa}{3} S^3$$

- New CP-even and CP-odd Higgs boson and extra contribution to the neutralino:

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_d + N_{14}\tilde{H}_u + N_{15}\tilde{S}$$

- New contribution to $\langle \sigma v \rangle_{\gamma\gamma}$:



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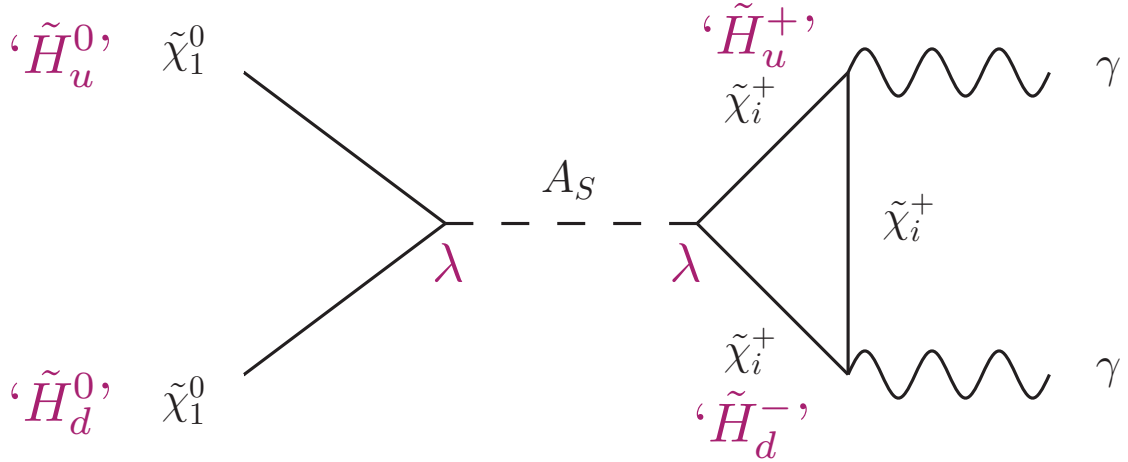

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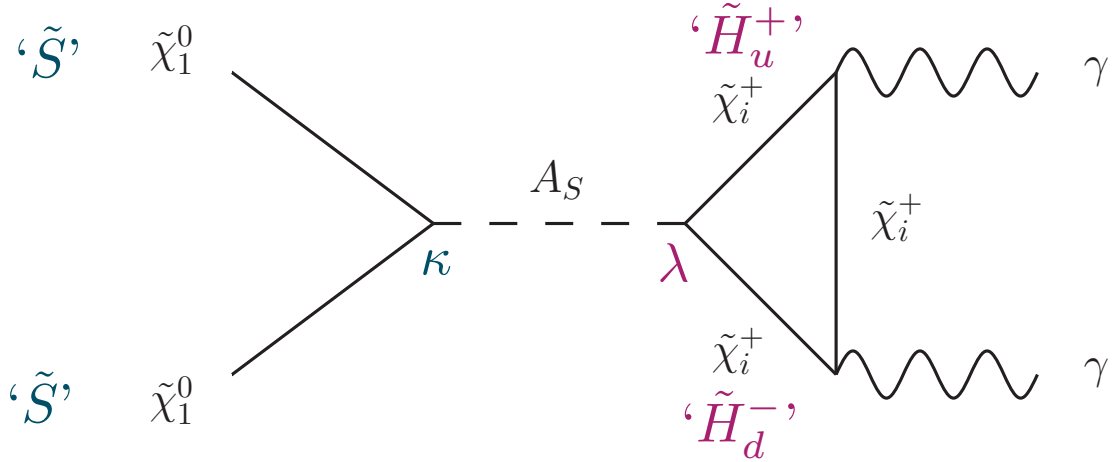
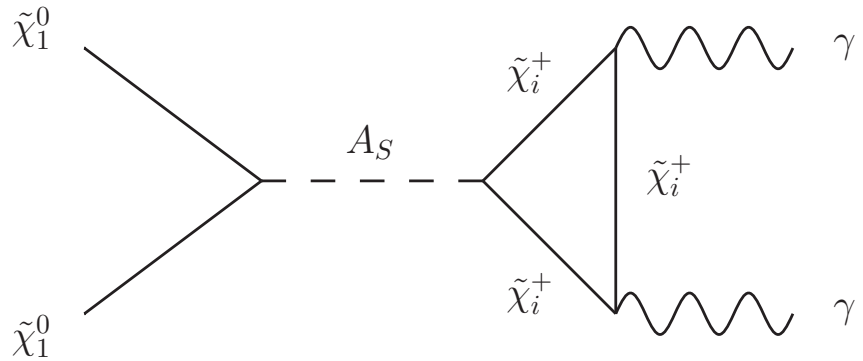


Why this helps

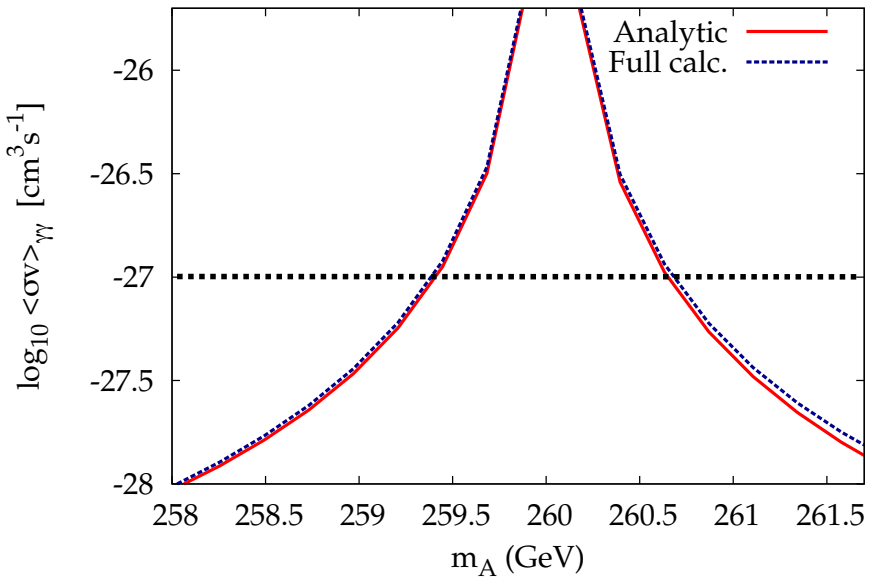


- If A_S is a singlet, then no coupling to SM particles
- $m_{\tilde{\chi}_1^+} > m_{\tilde{\chi}_1^0}$ so no other extra tree contribution to $\langle \sigma_{\rm ann} v \rangle$
- Means that we can (almost) independently boost $\langle \sigma v \rangle_{\gamma\gamma}$ while leaving $\langle \sigma_{\rm ann} v \rangle = 3 \times 10^{-26}\ {\rm cm}^3 {\rm s}^{-1}$
- Will be boosted if close to resonance

Resulting line strength

$$\langle \sigma v \rangle_{\gamma\gamma} = \frac{\alpha^2 \lambda^2}{4\pi^3} \frac{\left(\lambda N_{13} N_{14} - \kappa N_{15}^2\right)^2 \left(m_{\tilde{\chi}_1^+} U_{12} V_{12}\right)^2}{(4m_{\tilde{\chi}_1^0}^2 - m_A^2)^2 + \Gamma_A^2 m_A^2} \arctan^4 \left(\sqrt{\frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\chi}_1^+}^2 - m_{\tilde{\chi}_1^0}^2}} \right)$$

$$\sim 1.2 \times 10^{-27}\ \mathrm{cm}^3\mathrm{s}^{-1} \left(\frac{\lambda}{0.7}\right)^2 \left(\frac{\lambda N_{13} N_{14} - \kappa N_{15}^2}{0.05}\right)^2 \left(\frac{1.5\ \mathrm{GeV}}{\delta_\chi}\right)^2 .$$



Boosted when:

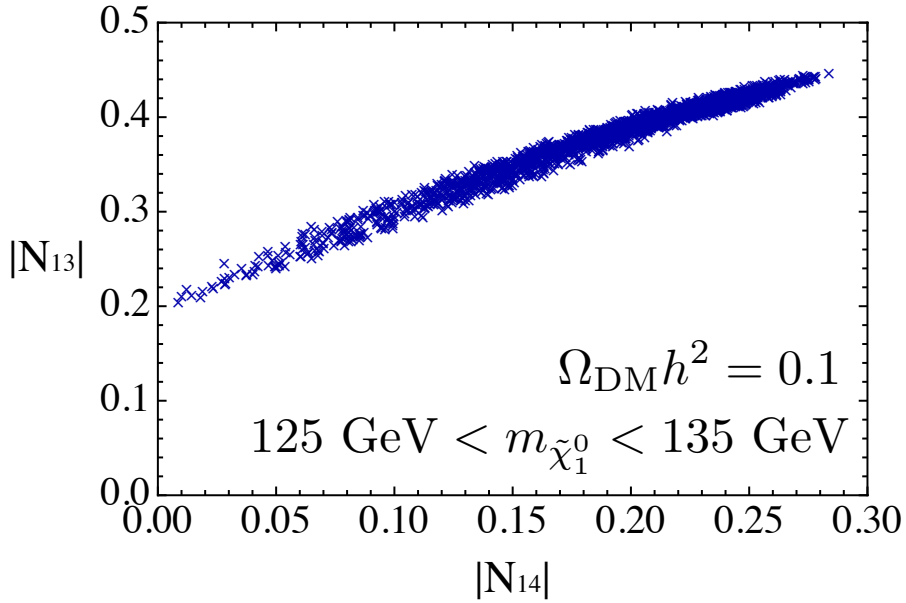
- λ , κ large
- N_{13} , N_{14} or N_{15} large
- Light higgsino-like $\tilde{\chi}_1^+$
- $m_A \approx 2m_{\tilde{\chi}_0^+}$

Higgsino-like case

- In ($\mathbb{Z}_3$ -symmetric) NMSSM, the singlino-component is small

$$m_{\tilde{S}} = 2\left(\frac{\kappa}{\lambda}\right)\mu_{\rm eff} \geq \mu_{\rm eff}$$

- Size of higgsino-fraction set by relic density requirement and can be as large as 25%



- Bino is the dominant component

Benchmark points

- We looked at three benchmark points

Parameter	Well-Tempered	Intermediate-Slepton	λ-SUSY
λ	-0.7	-0.7	-1.5
κ	-0.863	-0.77	-2.19
$\tan\beta$	4.0	4.0	5.45
A_λ [GeV]	-369.9	-378.0	-478.3
A_κ [GeV]	75.5	74.95	-55.9
$\mu_{\rm eff}$ [GeV]	-150.0	-190.0	-168.0
M_1 [GeV]	135.0	135.5	128.4
$m_{\tilde{\chi}_1^0}$ [GeV]	130.0	133.7	129.9
N_{11}, N_{15}	-0.89, 0.1	0.96, -0.06	0.975, -0.083
N_{13}, N_{14}	0.39, 0.19	-0.26, -0.09	-0.21, 0.012
m_A [GeV]	259.45	267.27	259.33

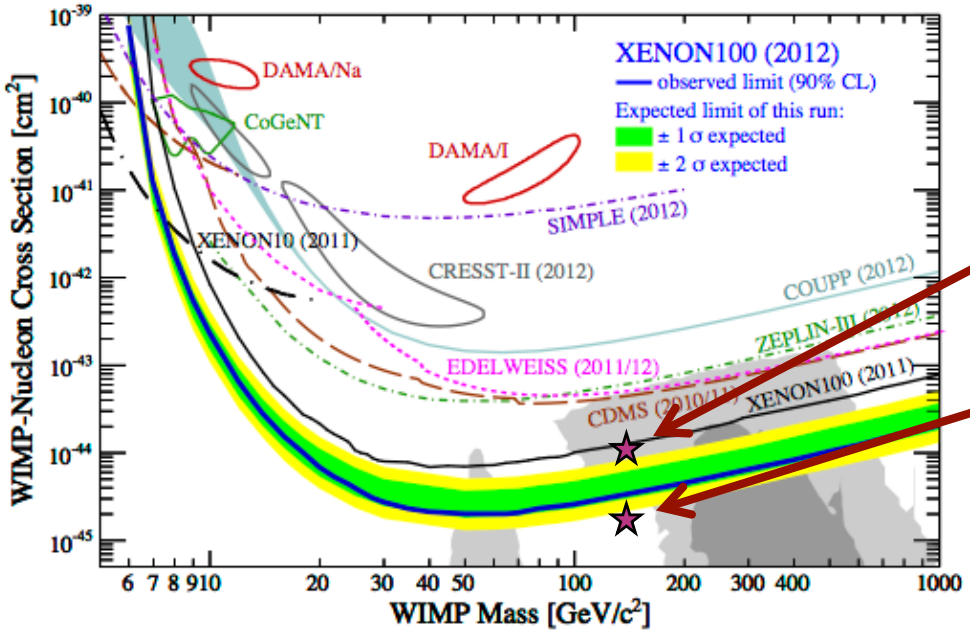
- I'll describe generic signatures at direct detection, LHC and indirect detection experiments

Direct detection – Spin independent

- Spin independent scattering from CP-even higgs exchange with nucleons

$$\sigma_{\rm SI} \propto \sum_{i=\rm higgs}^{3} \frac{(\text{gaugino} \times \text{higgsino})^2}{m_{\rm higgs}^4}$$

- Cancellation in sum when $\mathrm{sgn}(N_{13}) = \mathrm{sgn}(N_{14}) \rightarrow \mu_{\rm eff} < 0$



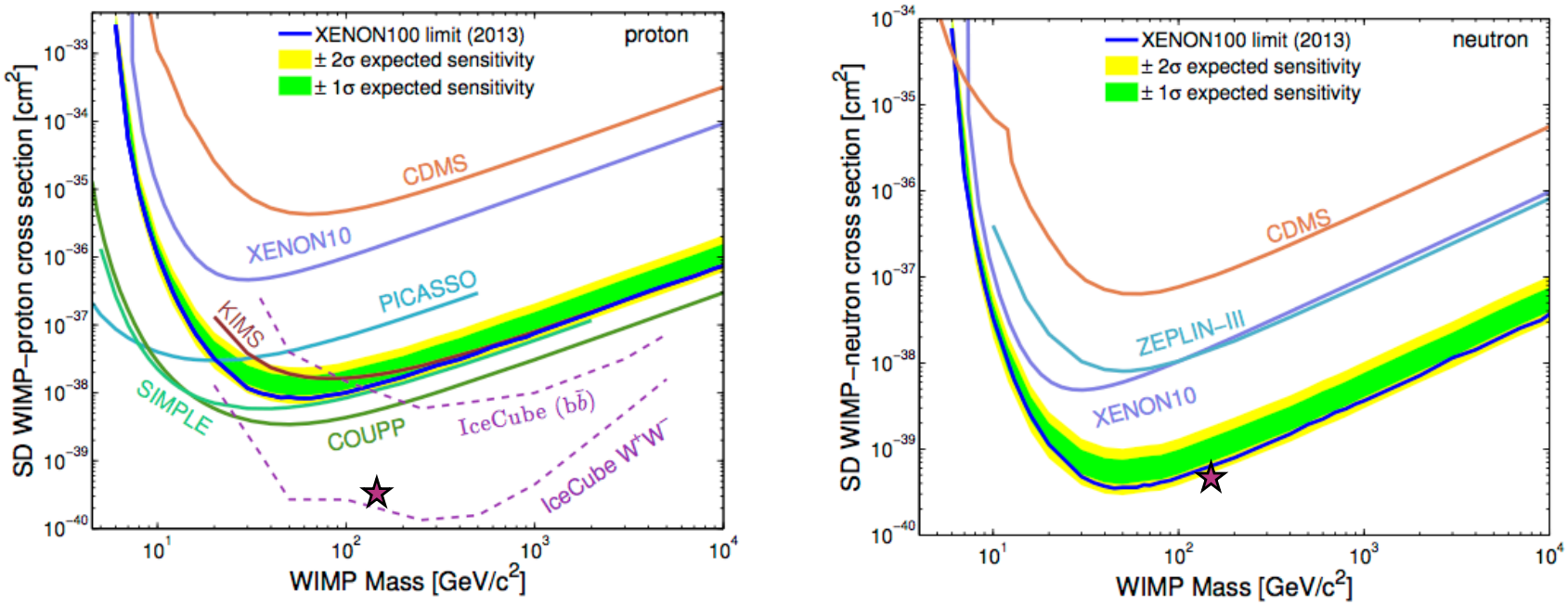
$\mu_{\rm eff} > 0$

$\mu_{\rm eff} < 0$

Direct detection – Spin dependent

- Spin dependent scattering from *Z* exchange with nucleons

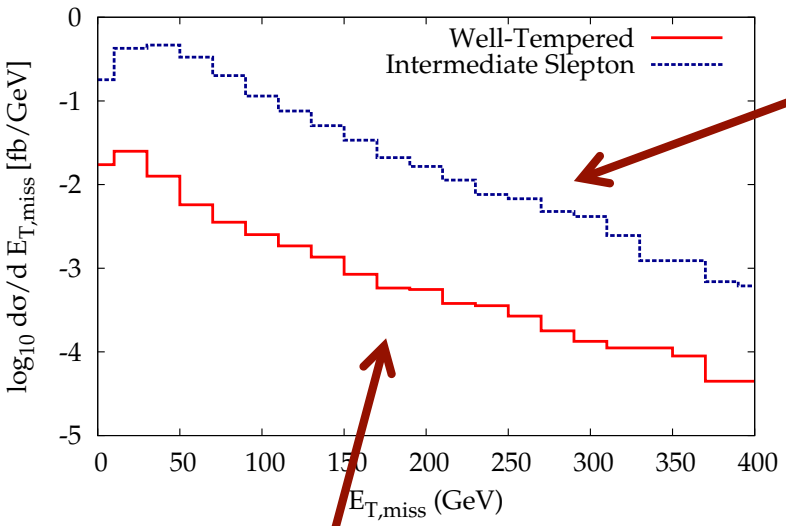
$$\sigma_{\rm SD} \propto \left(|N_{13}|^2 - |N_{14}|^2\right)^2$$



- Cross section is generally large

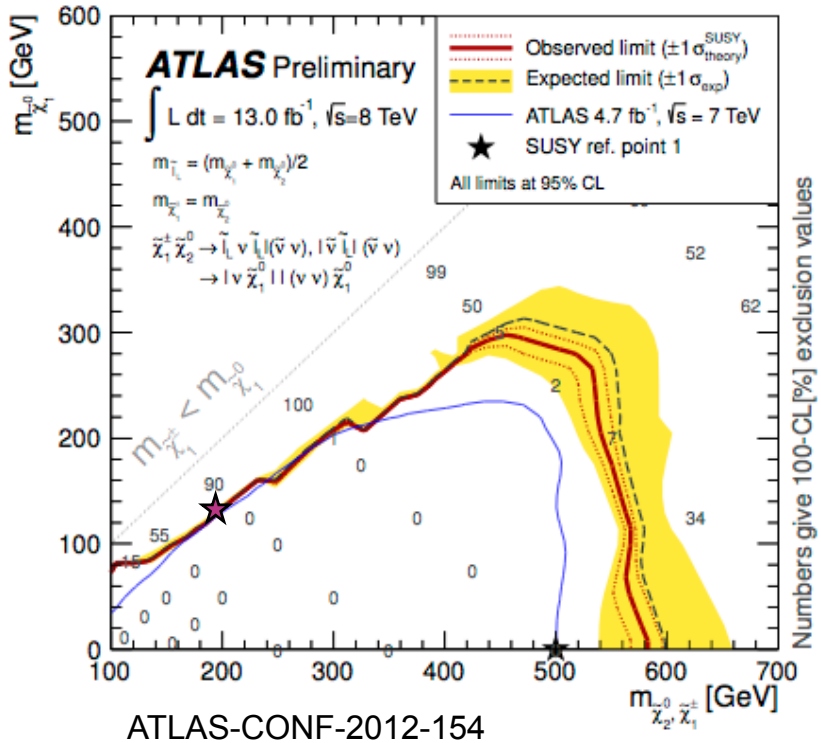
LHC

- Sensitivity if $\tilde{\chi}_2^0, \tilde{\chi}_1^+$ decay via an intermediate slepton



$$m_{\tilde{\chi}_1^+} = 197 \text{ GeV}$$
$$m_{\tilde{e}_R} = 145 \text{ GeV}$$

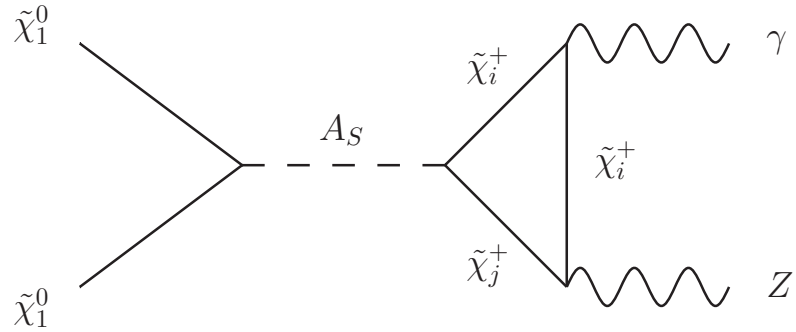
$$m_{\tilde{\chi}_1^+} = 156 \text{ GeV}$$
$$m_{\tilde{e}_R} = 900 \text{ GeV}$$



ATLAS-CONF-2012-154

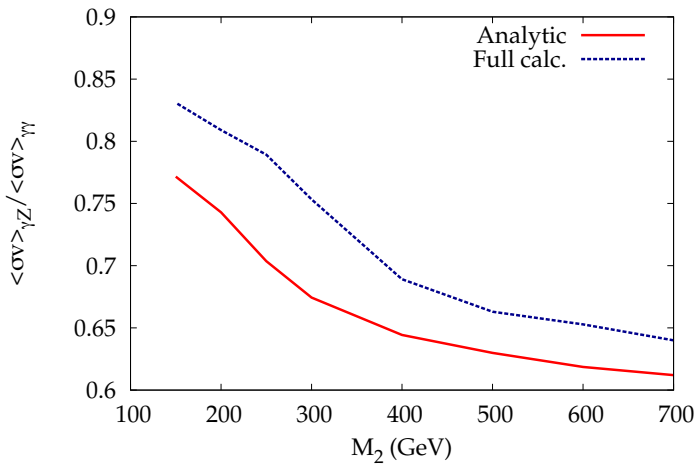
A second gamma line

- A second line at ~114 GeV will be there



- Strength tells you about charginos $\frac{\langle\sigma v\rangle_{\gamma Z}}{\langle\sigma v\rangle_{\gamma\gamma}} = \frac{1}{8\sin^2 2\theta_W}\left(1 - \frac{m_Z^2}{4m_{\tilde{\chi}_1^0}^2}\right)\frac{\mathcal{F}_{\tilde{\chi}^\pm}^2}{\mathcal{G}_{\tilde{\chi}^\pm}^2}$

$$\frac{\langle\sigma v\rangle_{\gamma Z}}{\langle\sigma v\rangle_{\gamma\gamma}} = 0.66^{+0.71}_{-0.48}$$



Future tests

- More data from Fermi on the way
- HESS – gamma ray observatory should have sensitivity by 2015

- Direct detection: LUX is now running: will soon surpass XENON100's sensitivity

- More results from LHC in a couple of years

The future is promising

Summary

- The Fermi data does contain an excess at ~130 GeV
- Potentially the ‘smoking gun’ signature of dark matter
- The neutralino can explain the line, but we have to go beyond the MSSM
- Rich bounty of discoveries ahead if this line is due to dark matter

Backup slides

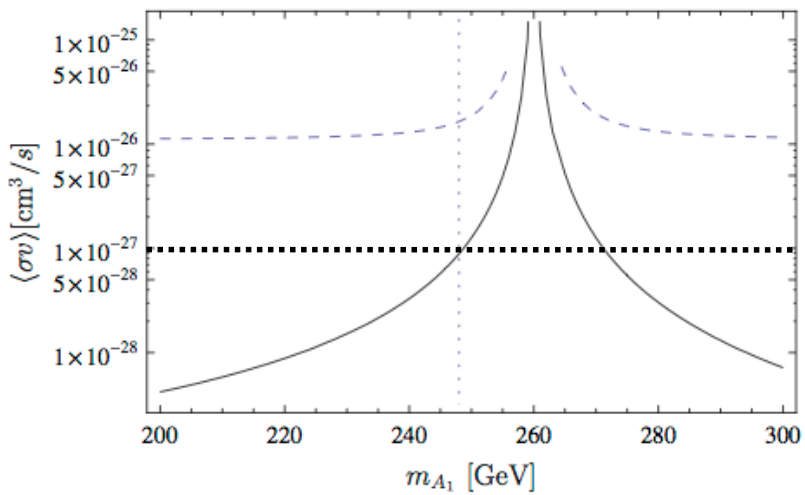
GNMSSM – further from resonance

- Allow explicit mass terms $\mathcal{W} = \mathcal{W}_{\rm NMSSM} + \mu H_u \cdot H_d + \xi S + \frac{1}{2}\mu_S S^2$
- Singlino component can now be large

$$m_{\tilde{S}} = 2\kappa s + \mu_S = 2\left(\frac{\kappa}{\lambda}\right)\mu_{\rm eff} + \left(\mu_S - 2\frac{\kappa}{\lambda}\mu\right)$$

$$\langle\sigma v\rangle_{\gamma\gamma} = \frac{\alpha^2\lambda^2}{4\pi^3}\frac{\left(\lambda N_{13}N_{14} - \kappa N_{15}^2\right)^2\left(m_{\tilde{\chi}_1^+}U_{12}V_{12}\right)^2}{(4m_{\tilde{\chi}_1^0}^2 - m_A^2)^2 + \Gamma_A^2 m_A^2}\arctan^4\left(\sqrt{\frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\chi}_1^+}^2 - m_{\tilde{\chi}_1^0}^2}}\right)$$

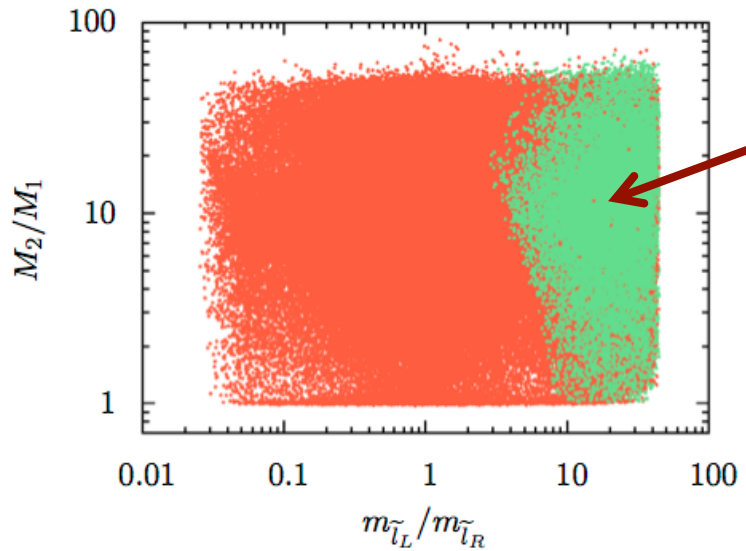
$$\sim 1.2\times 10^{-27}\ {\rm cm}^3{\rm s}^{-1}\left(\frac{\lambda}{0.7}\right)^2\left(\frac{\lambda N_{13}N_{14} - \kappa N_{15}^2}{0.05}\right)^2\left(\frac{1.5\ {\rm GeV}}{\delta_\chi}\right)^2 .$$



Schmidt-Hoberg et al.
arXiv: 1211.2835

Muon magnetic moment

- Negative μ-term usually leads to small or negative contribution to the muon anomalous magnetic moment
- OK if large hierarchy between left- and right- sleptons



a_μ condition satisfied

Grothaus et al.
arXiv: 1207.4434