Title: Gamma Rays at 130 GeV and How They Might Come from Dark Matter

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Abstract: Gamma Rays at 130 GeV and How They Might Come from Dark Matter"

I'll discuss the exciting (but somewhat controversial) new discovery of a sharp gamma ray feature at 130 GeV from near the galactic center and review some other evidence that might link it to annihilation of dark matter. I will then explain the challenges in understanding how dark matter might produce this signal and explain a model or two that overcome these difficulties.

Gamma Rays at 130 GeV and How They Might Come from Dark Matter

Andrew Frey

University of Winnipeg

21 Feb 2013

Outline

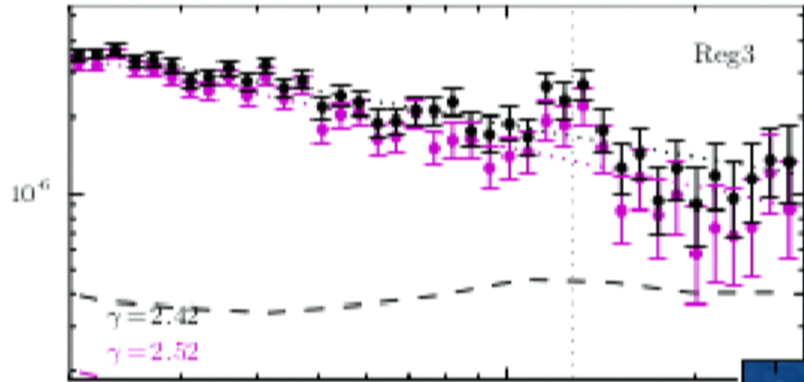
1. A Line at 130 GeV?
2. Dark Matter with Magnetic Dipole Moments
3. Composite Magnetic Dark Matter

A Line at 130 GeV?

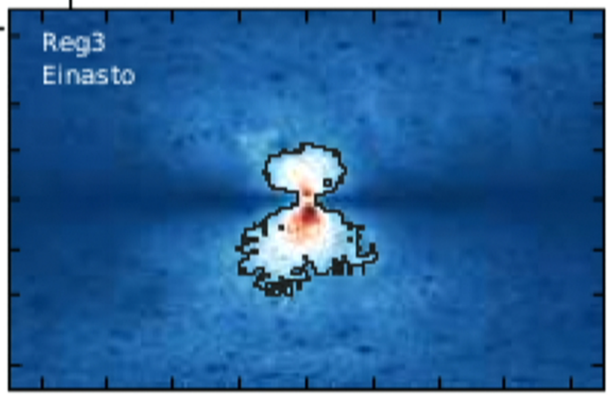
1. **A Line at 130 GeV?**
   - Detection Near Galactic Center
   - Evidence for DM Interpretation?
   - Challenges for DM Interpretation
2. **Dark Matter with Magnetic Dipole Moments**
3. **Composite Magnetic Dark Matter**

A Line at 130 GeV?
Detection Near Galactic Center

(*Bringmann et al, Weniger*)



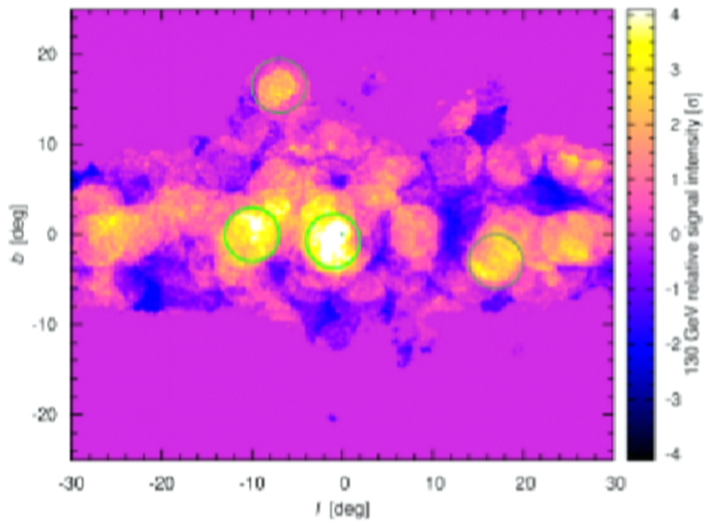
Examine regions near GC
SNR optimized



- Excess over power law near 130 GeV
- Locally: 4.6σ
  Globally: 3.3σ
- Very narrow

A Line at 130 GeV?
Detection Near Galactic Center

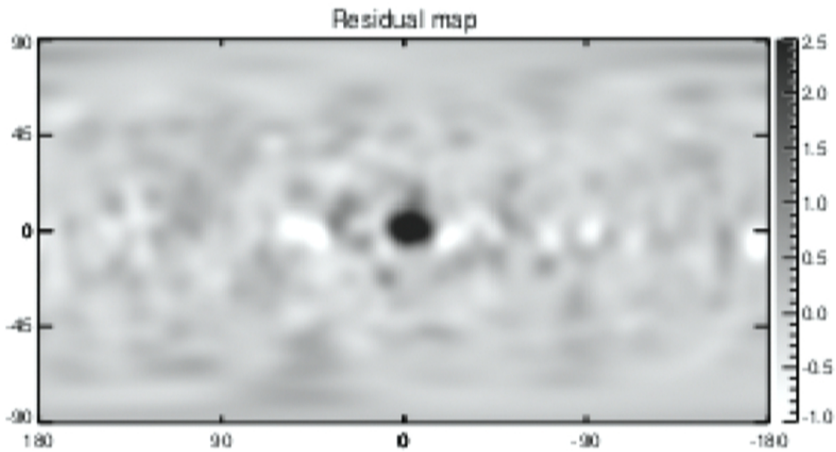
(*Tempel, Hektor, & Raidal*)



- Similar analysis to verify excess
- Found regions of significant excess around galaxy

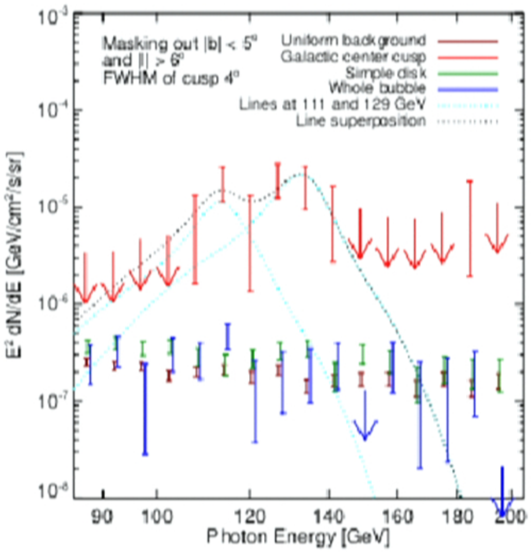
A Line at 130 GeV?
Detection Near Galactic Center

(*Su & Finkbeiner*)



- Bin gamma rays by energy
- Residual at GC in 120-140 GeV bin
- 5.0σ before trials factor
- 6.5σ before trials with template

Double-line fit



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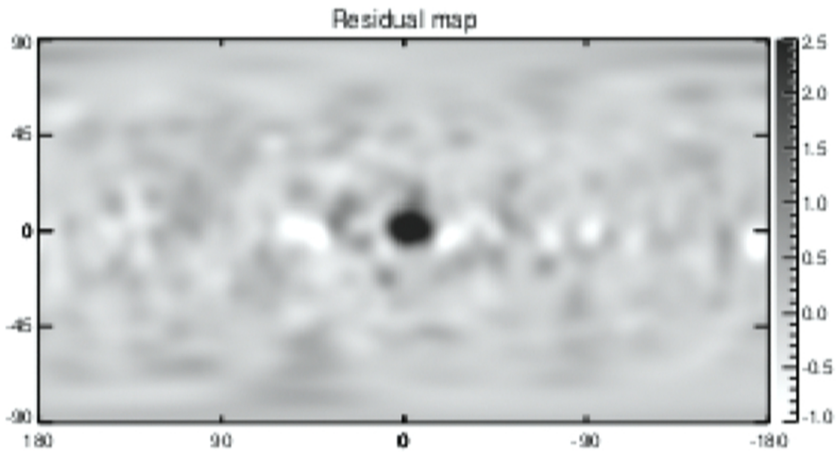

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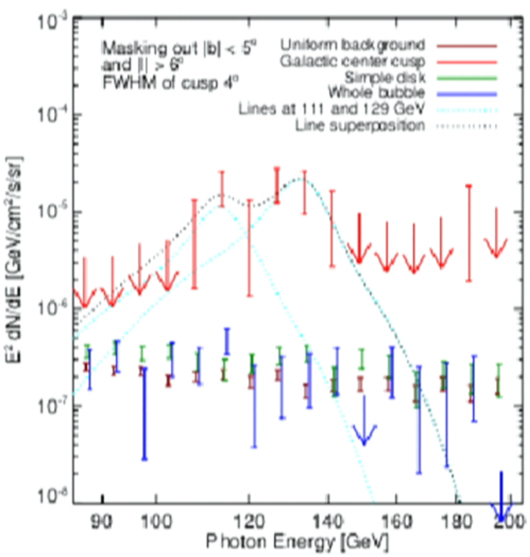

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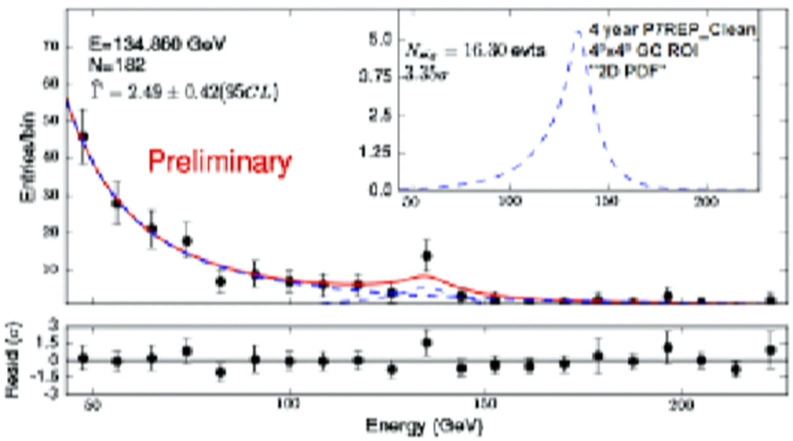
A Line at 130 GeV?
Detection Near Galactic Center

(*Fermi-LAT*)



Preliminary analysis
Not published, no preprint

Signal seen at 3 to 4σ depending on processing

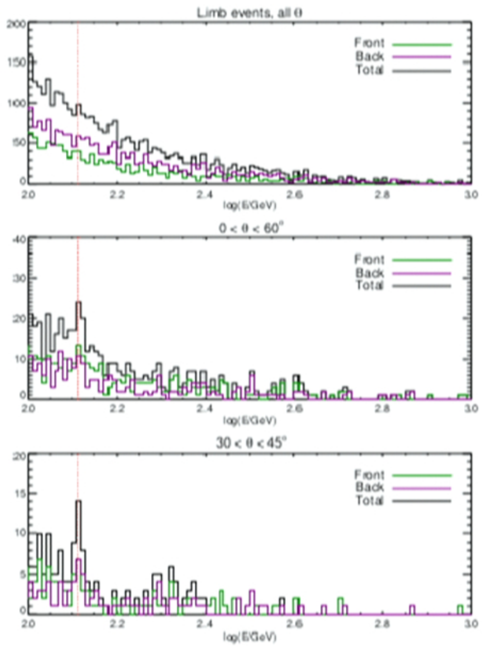
Reprocessing:

- shifts line to 135 GeV
- reduces significance

Possibly finds other bumps
Search areas not as sophisticated

A Line at 130 GeV?

Detection Near Galactic Center



(*Su, Finkbeiner, & Weniger*)

Instrumental or Other Spurious Effect?

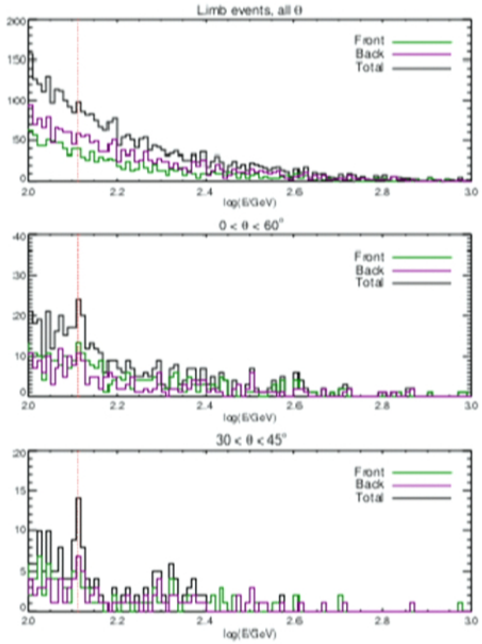
(*Su, Finkbeiner, & Weniger; Hektor, Raidal, & Tempel; Whiteson*)

Focus on intrumental incidence angle

- Comparison to earth limb photons
- $> 3\sigma$ feature at 130 GeV
  Only at small incidence angles
- GC γ at all incidence angles
- Galactic center line looks real
  Limb line probably a fluke

But still many caveats

A Line at 130 GeV?
Detection Near Galactic Center



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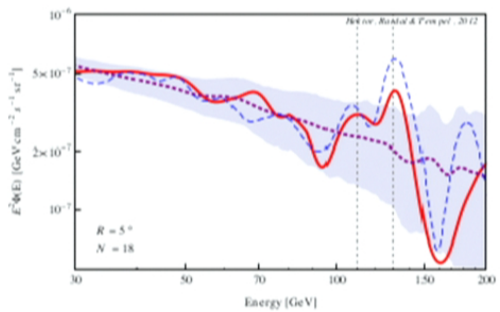
Other Suggested Astrophysical Sources

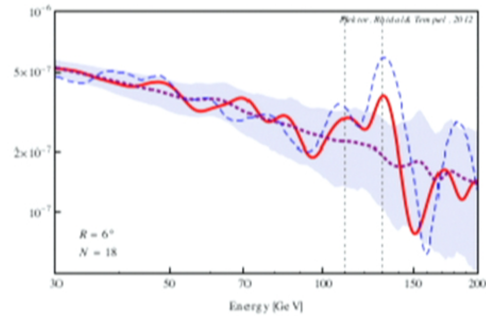
- Something from the Fermi bubbles? Have broken power law
  (*Profumo & Linden*)
- Inverse Compton from cold ultrarelativistic e^- pulsar wind?
  (*Aharonian, Khangulyan, & Malyshev*)
- IC from secondary e^- from knee CRs plus fluctuation
  (*Gupta et al.*)

But some issues with these possibilities

A Line at 130 GeV?
Evidence for DM Interpretation?

Assuming all DM annihilates, $\langle \sigma_{\gamma\gamma} v \rangle \approx (1 - \text{few}) \times 10^{-27} \text{cm}^3/\text{s}$
You might think to see this happen elsewhere





(*Hektor, Raidal, & Tempel*)

Galaxy Clusters

(*Hektor, Raidal, & Tempel*)

- "Stacked" 6 nearby clusters
- Varied acceptance radius
- 3.6σ significance at $5°$ radius
  Decreases at larger radius

(*Huang et al.*)

- Individual clusters
- Limit consistent with line

As expected

A Line at 130 GeV?
Evidence for DM Interpretation?

DM Subhalos

A bit controversial

- Claimed detection from Fermi unassociated sources
  (*Su & Finkbeiner*)
- Spectra do not match expected DM annihilation
  (*Hooper & Linden; Mirabal*)
- Line detection due to selection bias
  (*Hektor, Raidal, & Tempel*)
- Might not expect to see subhalos yet
  (*Hooper & Linden*)

A Line at 130 GeV?

Evidence for DM Interpretation?

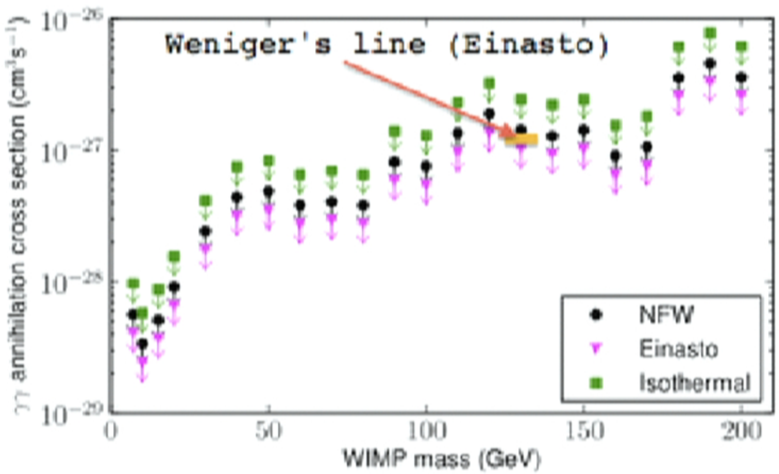
Null Results/Constraints

- Dwarf satellite galaxies: constraint near $\langle \sigma v \rangle_0$

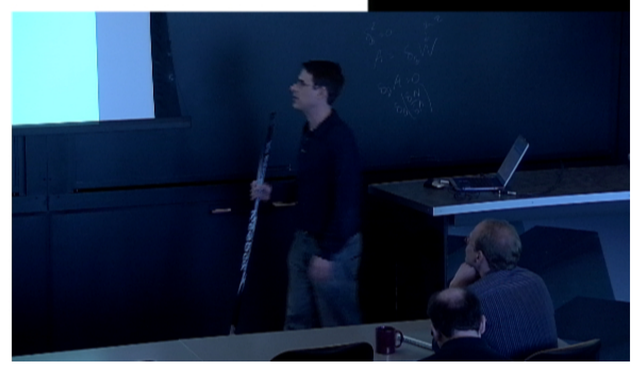
  (*Geringer-Sameth & Koushiappas; Huang et al.*)

- Diffuse emission line searches in tension

  (*Fermi collaboration*)



(*Fermi, modified by Résonaances blog*)



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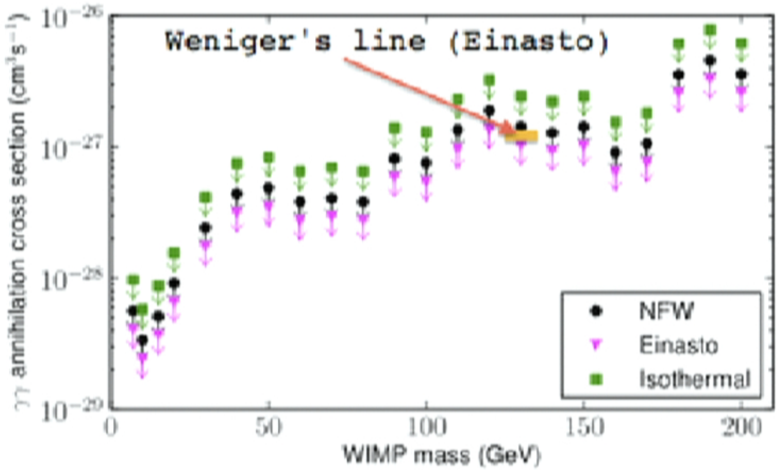

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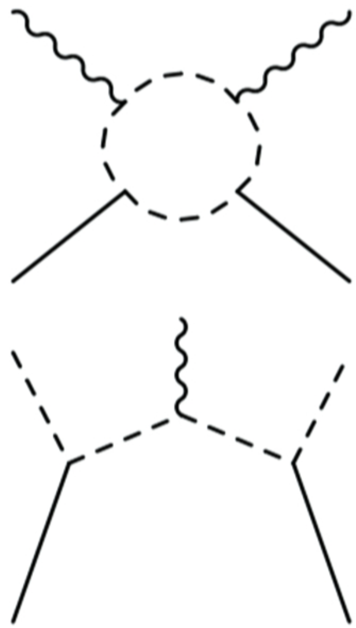
Challenges for DM Interpretation

Recall $\langle \sigma_{\gamma\gamma} v \rangle \approx (1 - \text{few}) \times 10^{-27} \text{cm}^3/\text{s}$



- Compare to thermal cross section

$$\langle \sigma v \rangle_0 \approx 3 \times 10^{-26} \text{cm}^3/\text{s}$$

- DM must be chargeless
  $\chi\chi \to \gamma\gamma$ a loop effect
- Alternately, virtual internal bremsstrahlung
- Both suppressed
- Slightly more massive charged particles help (*Cline*)

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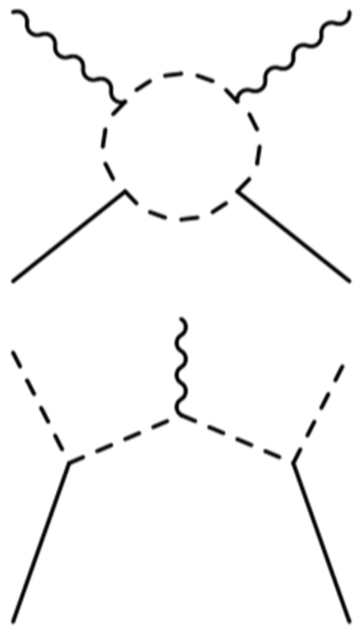

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Challenges for DM Interpretation

Constraints on Continuum Emission

(*Buckley & Hooper; Cohen et al; Cholis, Tavakoli, & Ullio; Huang et al.*)

- DM→SM annihilation generates final state radiation, prompt γ from decays, inverse Compton, bremsstrahlung
- $\langle\sigma\rangle \lesssim$ (few to dozens)$\langle\sigma_{\gamma\gamma}v\rangle$
- Already rules out some SUSY models

Offset from GC

- Some evidence that DM cusp is 200 pc from GC

  (*Su & Finkbeiner*)
- Possible agreement from DM+baryon simulations

  (*Kuhlen et al.*)

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Dark Matter with Magnetic Dipole Moments

1. **A Line at 130 GeV?**
2. **Dark Matter with Magnetic Dipole Moments**
   - Dipole Moment Operator
   - Relic Density & Gamma Ray Signal
   - Large Enough Moments?
3. **Composite Magnetic Dark Matter**

Dark Matter with Magnetic Dipole Moments

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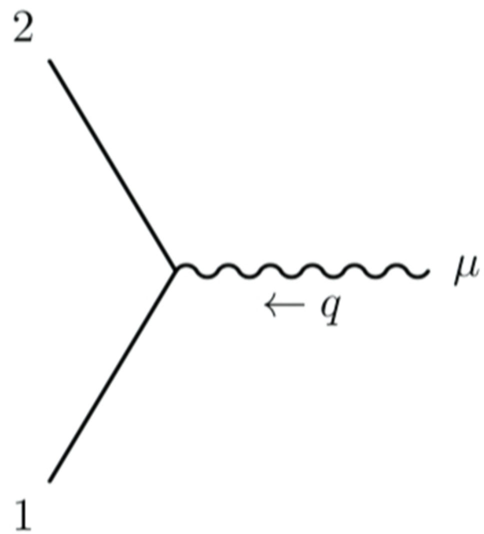
Dark Matter with Magnetic Dipole Moments
Dipole Moment Operator

Even uncharged classical matter can have dipole moments

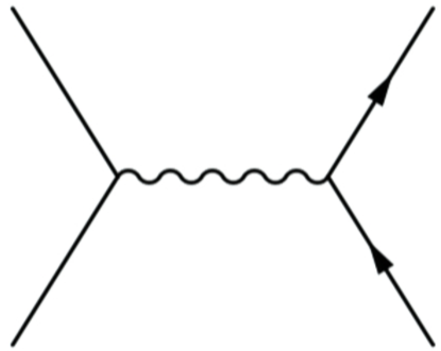


$$-i\mu\gamma^{\mu\nu}q_\nu$$

- For fermions: spin-field coupling
$$\frac{i}{2}\mu\bar{\chi}\gamma_{\mu\nu}\chi F^{\mu\nu}$$
- Transition magnetic moment
$$\chi_1 \to \chi_2$$
- Really hypercharge magnetic moment
$$\mu_Z = -\tan\theta_W \mu_\gamma$$

Dark Matter with Magnetic Dipole Moments

Dipole Moment Operator



Direct Detection

(*many authors*)

Scattering from nucleons

- From nuclear charge or dipole
- For elastic scattering $\mu \lesssim 6 \times 10^{-5} \mu_N$ (assuming canonical density)
- Transition magnetic moment allowed $\Delta m \gtrsim 150$ keV at $\mu \sim 1/\text{TeV}$
- Electric dipoles more suppressed

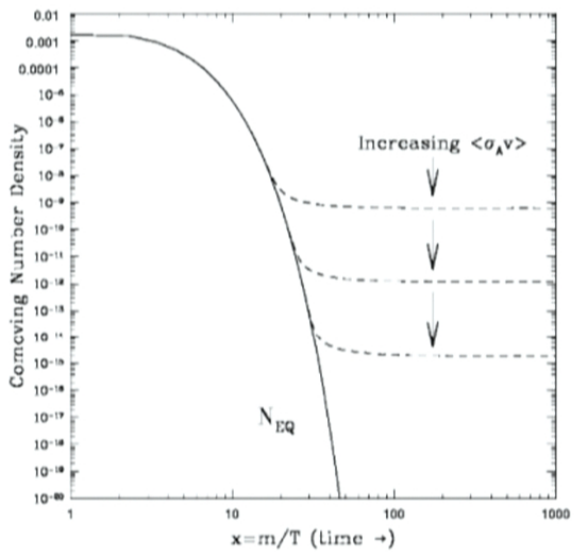
Consider lower density, allowing larger μ

But too large splitting

Dark Matter with Magnetic Dipole Moments

Relic Density & Gamma Ray Signal

Need compatible DM density and γ flux



(*A. Green*)

- γ flux $\Phi \propto \langle\sigma_{\gamma\gamma} v\rangle + \langle\sigma_{\gamma Z} v\rangle/2$
- Need

  $\langle\sigma_{tot} v\rangle > \langle\sigma_{\gamma\gamma} v\rangle(+\langle\sigma_{\gamma Z} v\rangle + \langle\sigma_{ZZ} v\rangle)$

  Or ρ_{DM} too large
- Add coannihilations
  $\chi_1\chi_2 \to$SM-SM
- Adjust δm with σ_{tot} fixed
  Increases μ & $\langle\sigma_{\gamma\gamma} v\rangle$

(*Tulin, Yu, Zurek*)

Dark Matter with Magnetic Dipole Moments
Relic Density & Gamma Ray Signal

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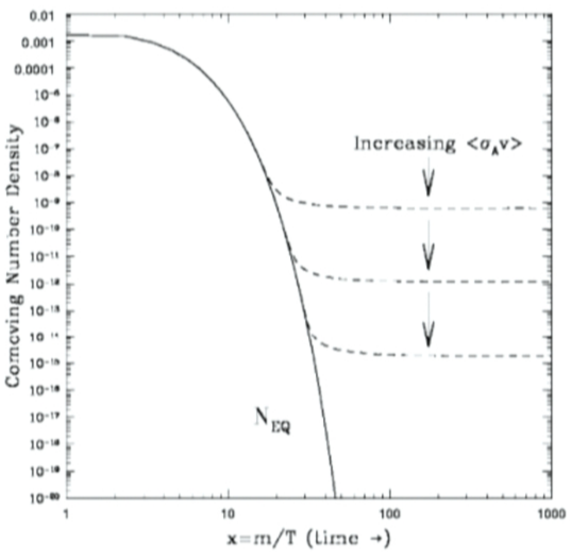

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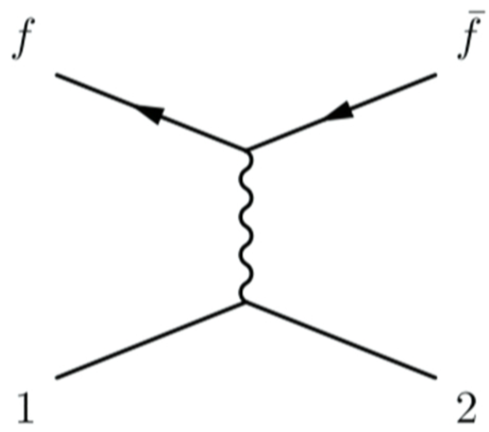

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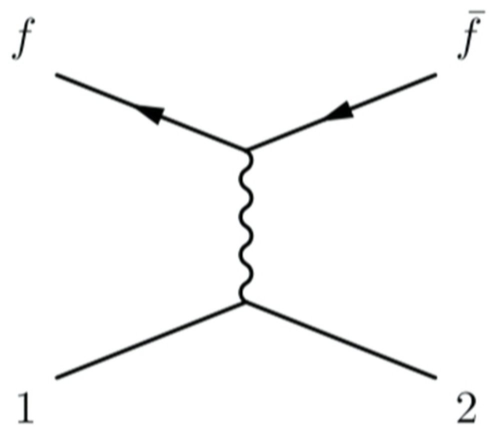

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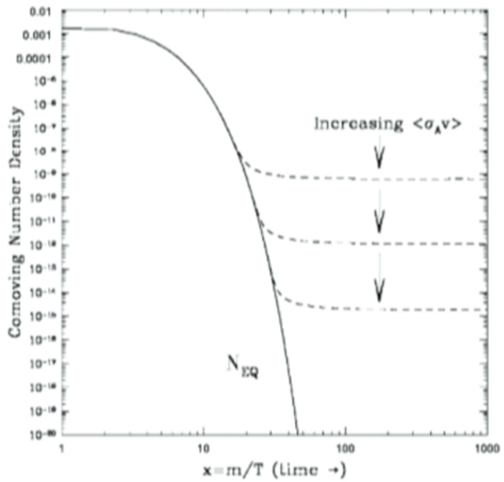
Relic Density & Gamma Ray Signal



(*A. Green*)

Re-examine relic density

- $n \propto \langle \sigma_{tot} v \rangle^{-1}$ at fixed mass
- Suppose

$$\langle \sigma_{tot} v \rangle = \langle \sigma_{\gamma\gamma} v \rangle + \langle \sigma_{\gamma Z} v \rangle + \langle \sigma_{ZZ} v \rangle \propto \mu^4$$

- γ flux $\Phi \propto n^2 \langle \sigma_{\gamma\gamma} v \rangle \propto \mu^{-4}$
- Need $\mu \sim 2/\text{TeV}$
- Subdominant component of DM
  Adding some coannihilation reduces n

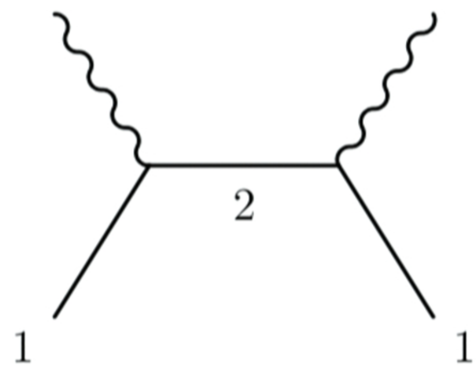
Another Route

(*Weiner & Yavin*)

- Coannihilations dominate early
- Then $\Phi \propto \mu^0$
- Can be subdominant again

Dark Matter with Magnetic Dipole Moments

Relic Density & Gamma Ray Signal



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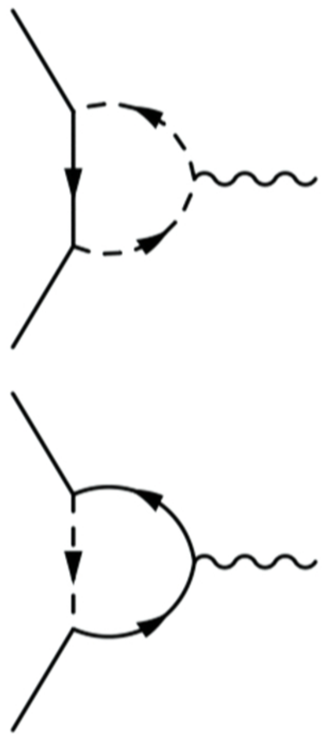
Large Enough Moments?

How might you build DM with a dipole moment?



- Ingredients:
  - Fermionic DM χ
  - Hypercharged scalar ϕ, fermion ψ
  - Yukawa $y\phi\bar{\psi}\chi$
- Dipole generated at 1 loop

$$\mu \sim \frac{y^2 g'}{4\pi M}$$

- $\mu \sim 1/\text{TeV}$ difficult perturbatively
  Need $M \gtrsim m_\chi$
- Can be done, but messy (*Weiner & Yavin*)
- Motivates composite models

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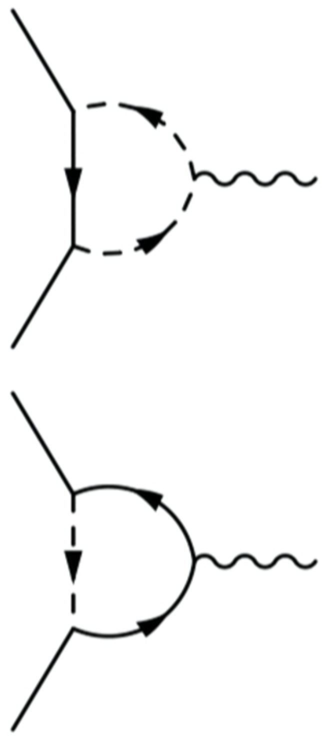

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Composite Magnetic Dark Matter

Large Moments for Dark Hadrons

Neutral baryons have moments $\mu \sim e/m$ (sum of constituents)

- Consider a confining dark gauge group ($SU(2)$)
- Matter: scalar S, fermion ψ with charges $-(n + 1/2)$
- Leads to dipole moments $\mu \sim (2n + 1)$/TeV

Mesons (Neutral)

- $\eta = S\psi$
- $\tilde{\eta}_S = S^* S$
- $\tilde{\eta}_\psi = \bar{\psi}\psi$
- $\tilde{\eta}_S, \tilde{\eta}_\psi$ heavier: S^4, spin-spin interactions

Baryons

- $N^- = S^* \psi$
- $\tilde{N}^+_\mu = S \partial_\mu S$
- $\tilde{N}^-_\psi = \psi \psi$

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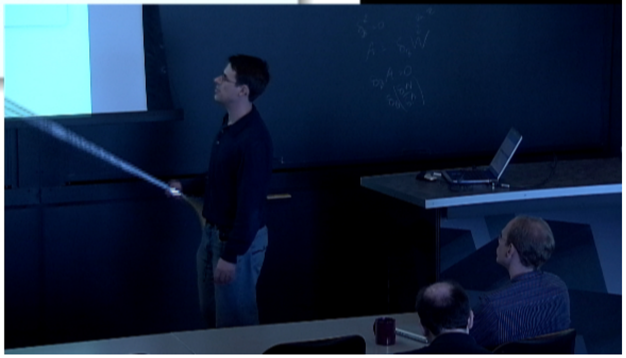

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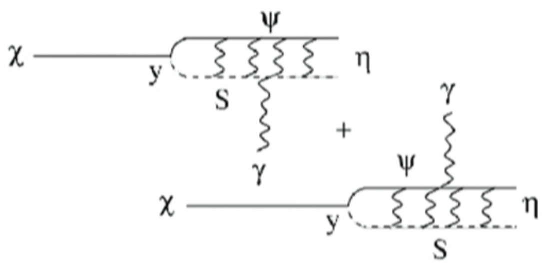
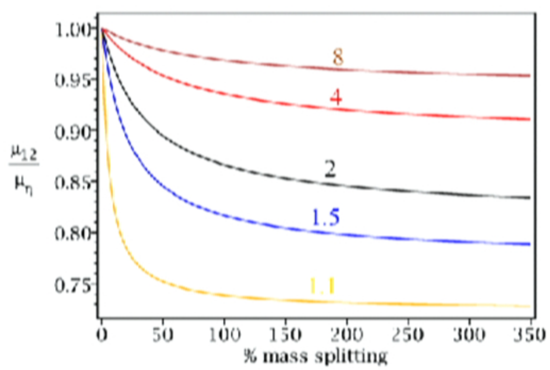
Large Moments for Dark Hadrons

Only a transition magnetic moment is allowed by direct detection





- Add Majorana singlet χ with $y\bar{\chi}S\psi$
- Becomes $\eta - \chi$ mass mixing
- With parity, exactly diagonalizable
  Leaves 3 Majorana fermions
- χ_1 mostly η, χ_3 mostly χ
  χ_2 is purely composite (η)
- Transition moments μ_{12}, μ_{23} only

Composite Magnetic Dark Matter
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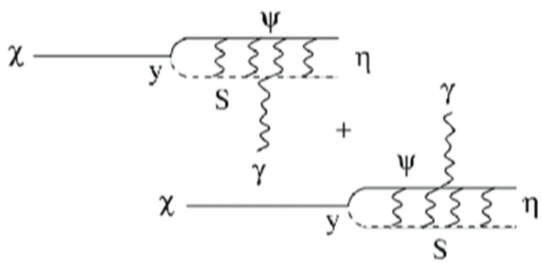
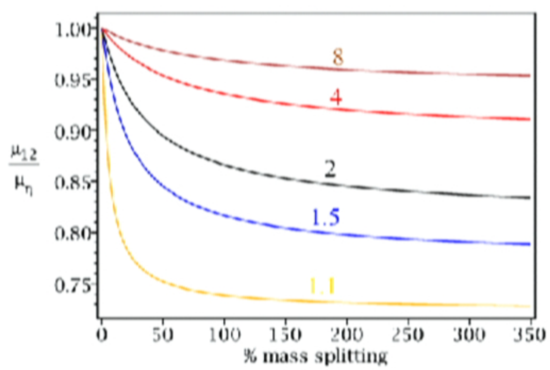
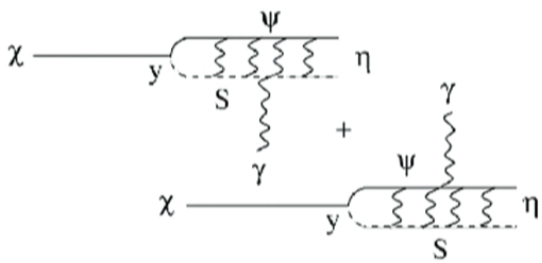


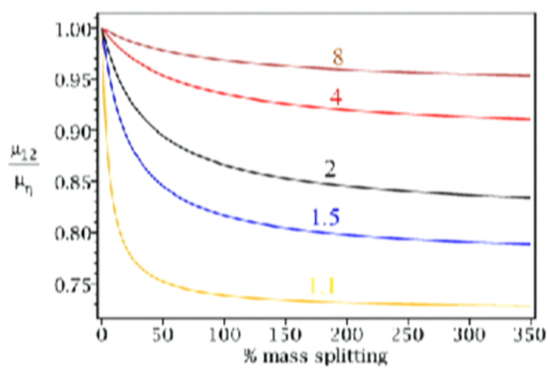


- Add Majorana singlet χ with $y\bar{\chi}S\psi$
- Becomes $\eta - \chi$ mass mixing
- With parity, exactly diagonalizable
  Leaves 3 Majorana fermions
- χ_1 mostly η, χ_3 mostly χ
  χ_2 is purely composite (η)
- Transition moments μ_{12}, μ_{23} only

Composite Magnetic Dark Matter
Large Moments for Dark Hadrons

Only a transition magnetic moment is allowed by direct detection





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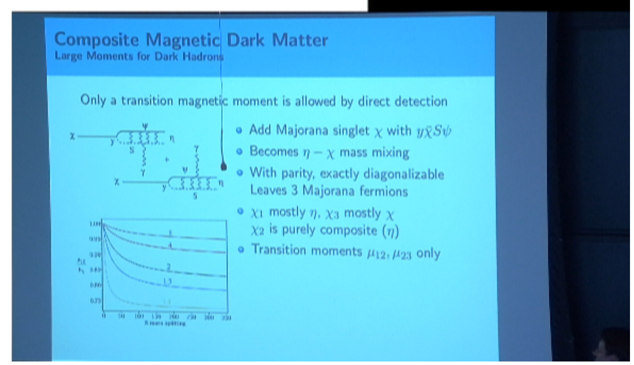
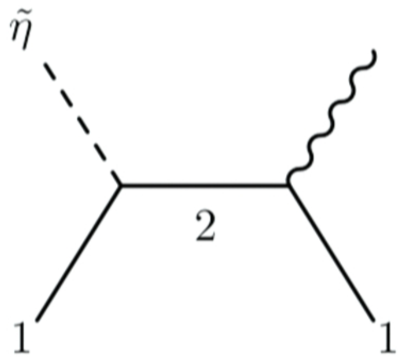
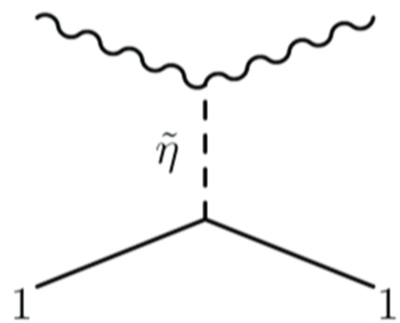


Composite Magnetic Dark Matter
More Ways to Produce Photons

Many more couplings between DM and SM in EFT





Dark Yukawas and Scalar Decays

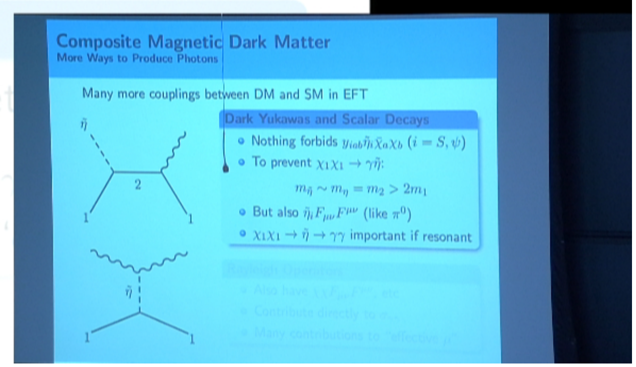
- Nothing forbids $y_{iab}\tilde{\eta}_i\bar{\chi}_a\chi_b$ $(i = S, \psi)$
- To prevent $\chi_1\chi_1 \to \gamma\tilde{\eta}$:

$$m_{\tilde{\eta}} \sim m_\eta = m_2 > 2m_1$$

- But also $\tilde{\eta}_i F_{\mu\nu}F^{\mu\nu}$ (like π^0)
- $\chi_1\chi_1 \to \tilde{\eta} \to \gamma\gamma$ important if resonant

Rayleigh Operators

- Also have $\bar{\chi}\chi F_{\mu\nu}F^{\mu\nu}$, et
- Contribute directly to σ
- Many contributions to "



Composite Magnetic Dark Matter

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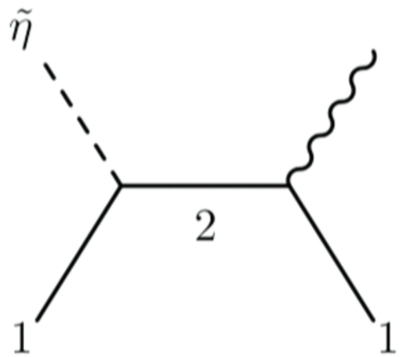

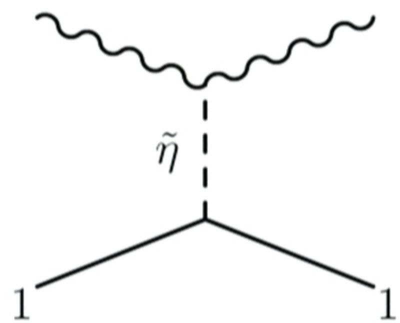

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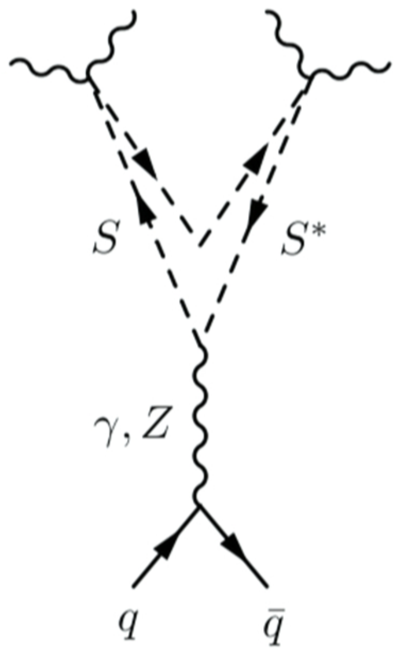
Rayleigh Operators

- Also have $\bar{\chi}\chi F_{\mu\nu}F^{\mu\nu}$, etc
- Contribute directly to $\sigma_{\gamma\gamma}$
- Many contributions to "effective μ"

Composite Magnetic Dark Matter
Collider Signatures

Some spectacular signatures: LHC sees constituents



Meson Production

- Produce dark constituents & hadronize
- DM and excited states
  Monophotons/jets and missing energy
- Or $2\tilde{\eta}_{S,\psi}$
  Pairs of photons w/same m^2
- Cross sections near interesting levels

Composite Magnetic Dark Matter
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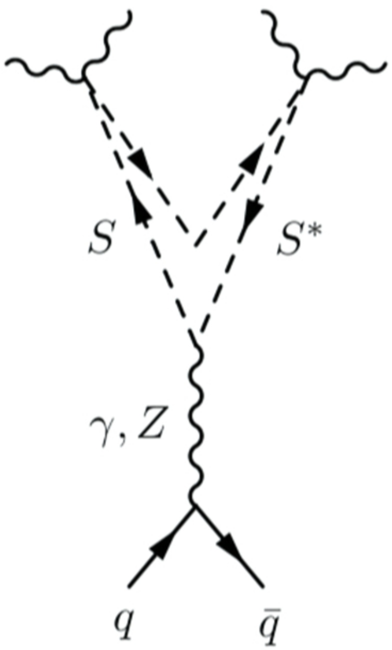

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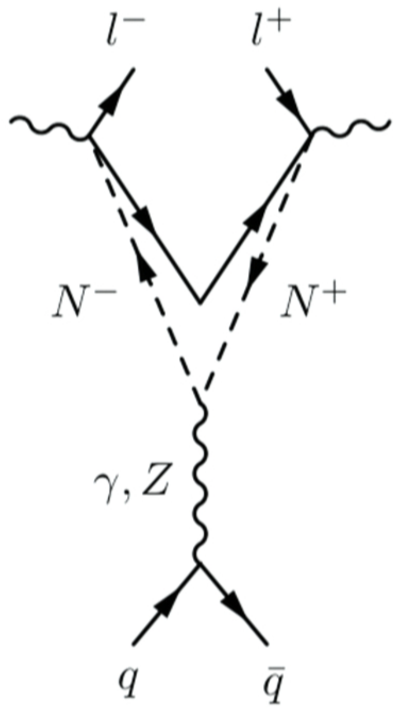

Baryon Production

- N^- can couple to leptons
  $N^- \to \gamma l^-$ or $N^- \to (2n+1)l^-$
- Alternately $N^- \to (2n+1)l^- + \tilde{\eta}$
  Gives leptons plus multiphotons
- $\tilde{N}_\mu^+$ and $\tilde{N}_\psi^+$ decays to DM+l^+
  Under SM background

Summary

1. **A Line at 130 GeV?**
2. **Dark Matter with Magnetic Dipole Moments**
3. **Composite Magnetic Dark Matter**

Maybe first non-gravitational detection of DM
Indicates rich DM physics
Thank You

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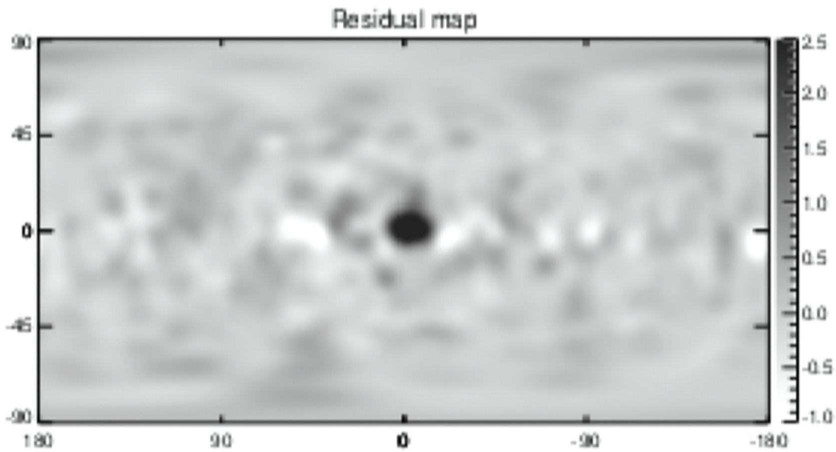
A Line at 130 GeV?

Detection Near Galactic Center

(*Su & Finkbeiner*)



- Bin gamma rays by energy
- Residual at GC in 120-140 GeV bin
- 5.0σ before trials factor
- 6.5σ before trials with template

Double-line fit