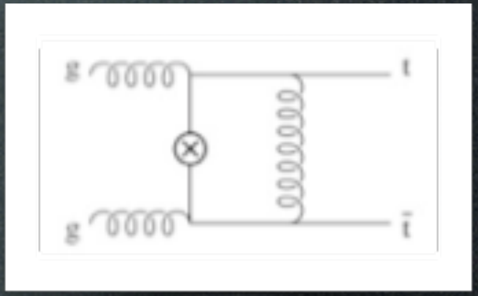
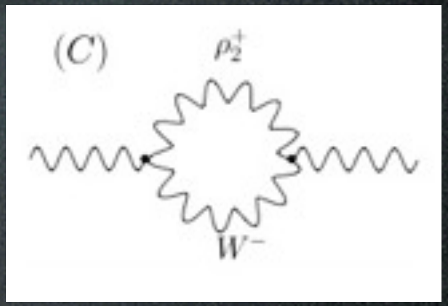
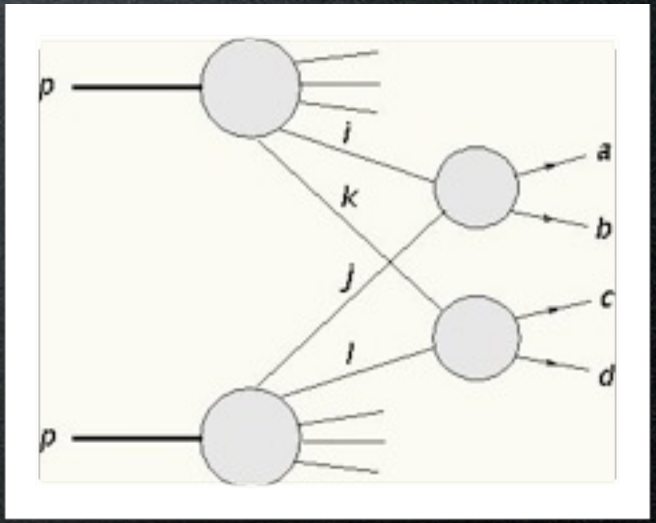
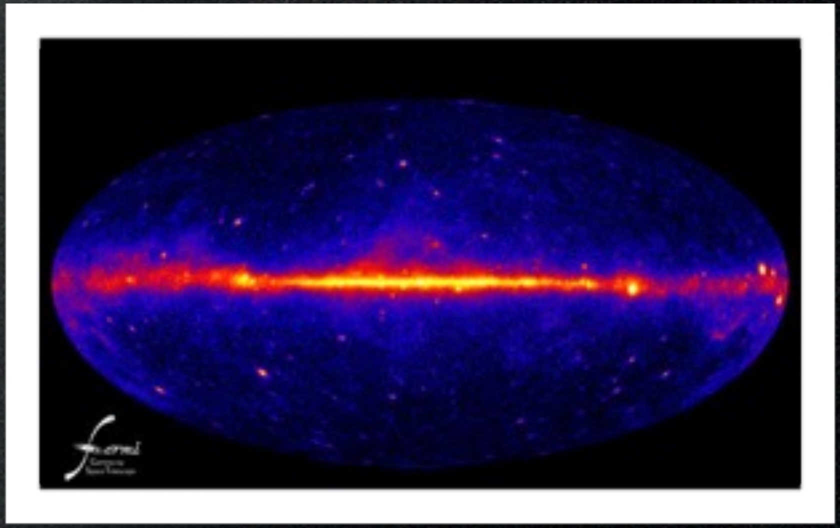
UTA HEP Theory “Group”

- Radiative corrections:
    - NLO QCD corrections to Higgs production with heavy quarks (tops and bottoms)
    - Testing models of new physics against precision EW constraints (Higgsless models and Higgs triplet models)
- Collider studies:
    - Predictions for SM Higgs production at the “early” LHC
    - Double parton scattering at the LHC (bbjj and Wbb)
- Indirect detection of dark matter
    - “WIMP Forest”
    - “Higgs in Space!”









Higgs in Space!

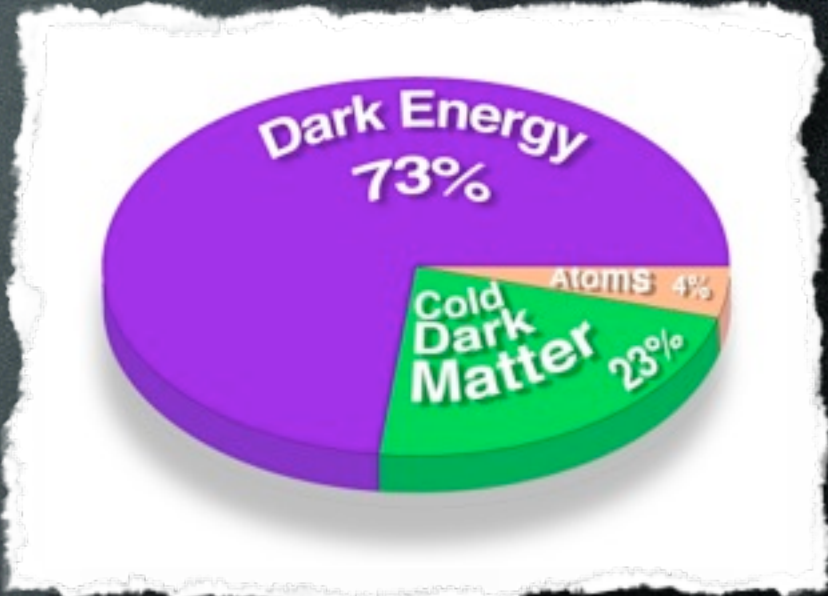
Chris Jackson
Univ. of Texas - Arlington

in collaboration with:
G. Bertone, G. Servant,
G. Shaughnessy, T. Tait, M. Taoso
and A. Vallinotto

based on:
Phys. Rev. D80, 023512 (2009),
JCAP 1004 (2010) 004
& arXiv:1009.5107

outline

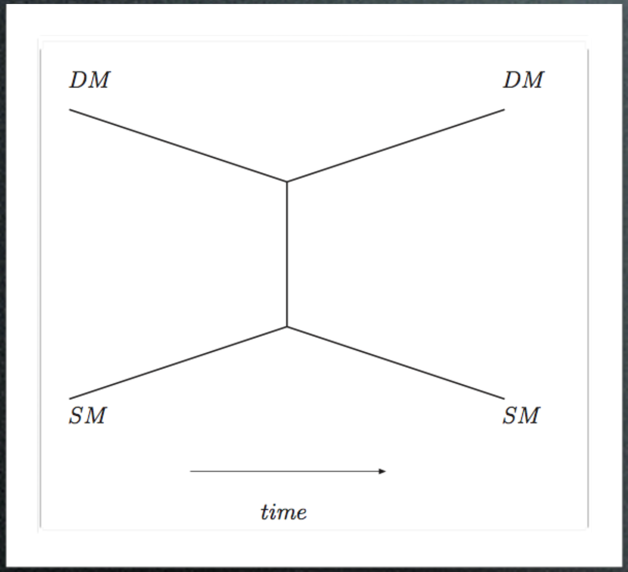
- The evidence is overwhelming that 20% of our Universe is composed of Cold Dark Matter

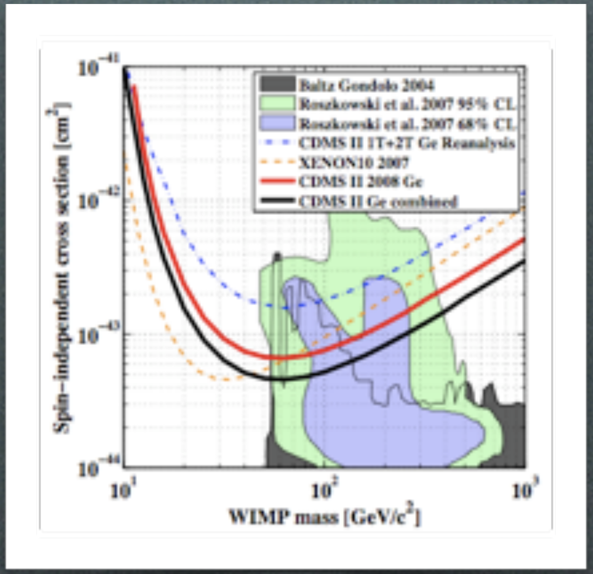


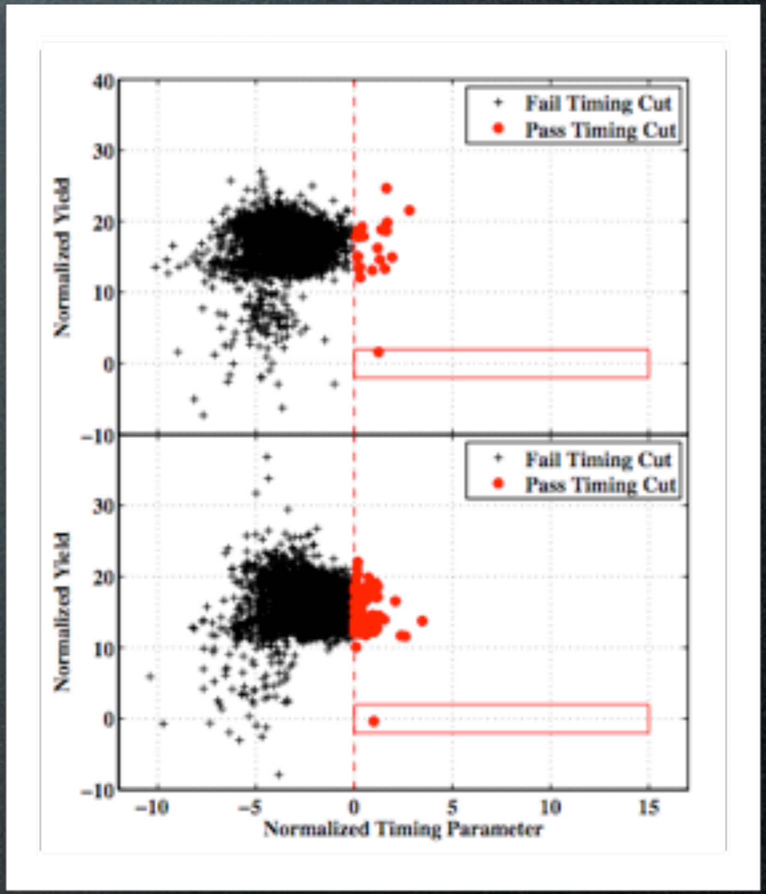
- If DM is particle physics issue, particles with electroweak couplings/masses can naturally explain the observed abundance ("WIMPs")
- In this talk:
    - Indirect detection of DM through its annihilation into γ rays
    - In particular, I will focus on SPECTRAL LINES that may be observable in the γ-ray spectrum (via loop-level processes)
- Two scenarios:
    - If the "dark sector" contains MORE exotic states which are kinematically accessible, there may be a whole "forest" of lines
    - If there exists a connection between EWSB and DM dynamics, our best hope for detecting the Higgs (in the next couple of years) may be "in Space".

direct methods

- Direct detection:

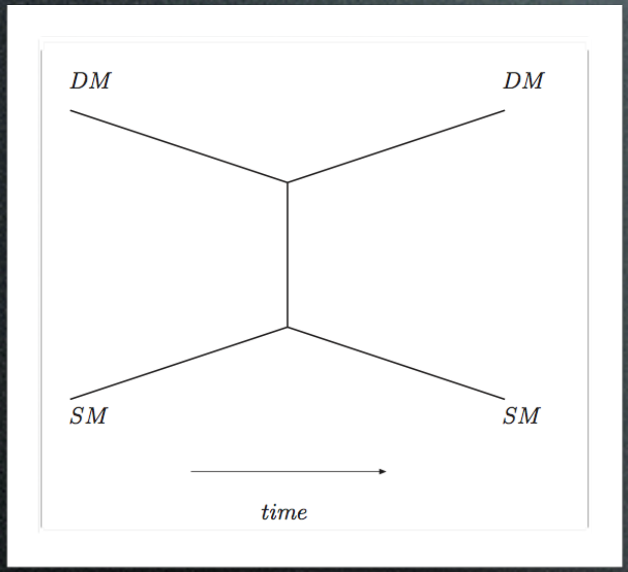


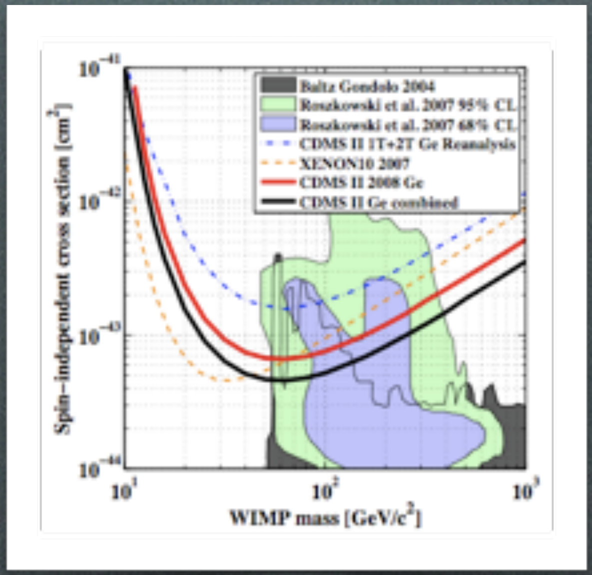


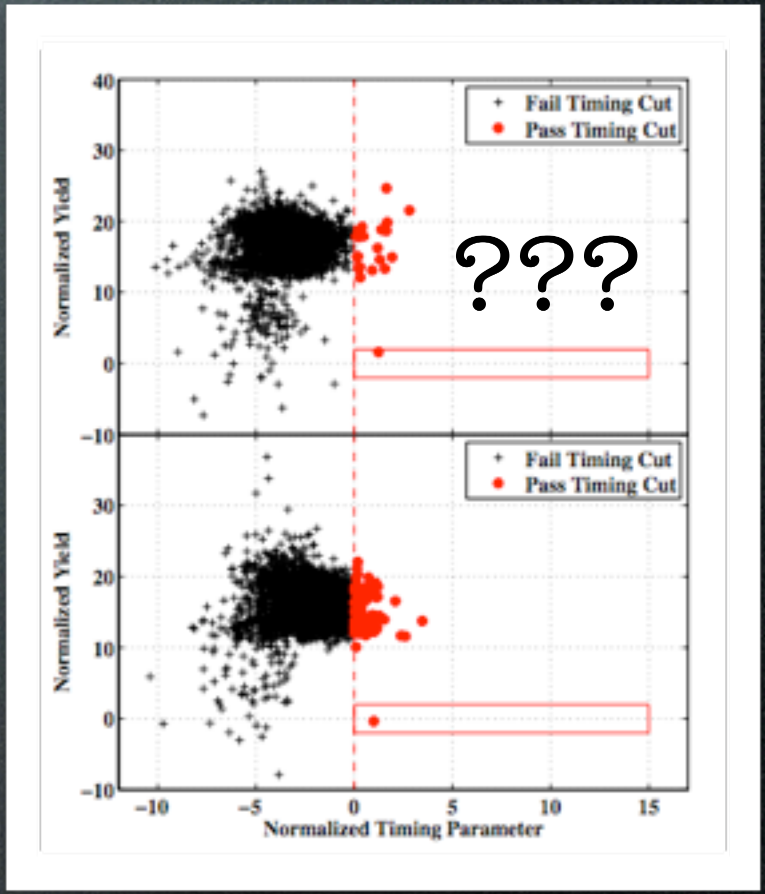


direct methods

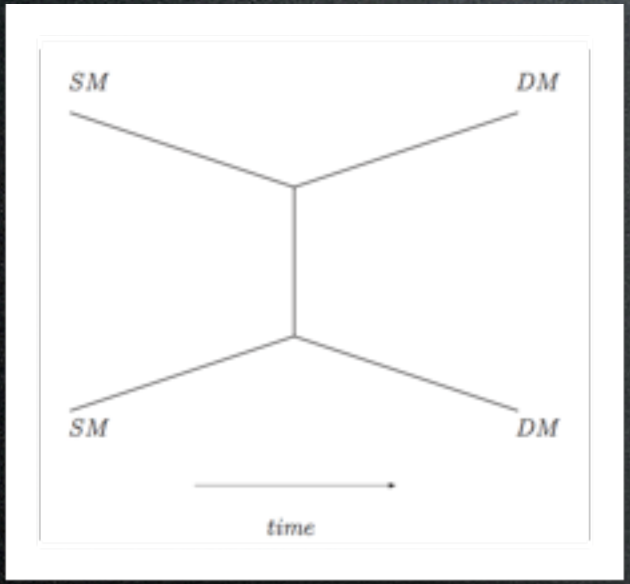
- Direct detection:

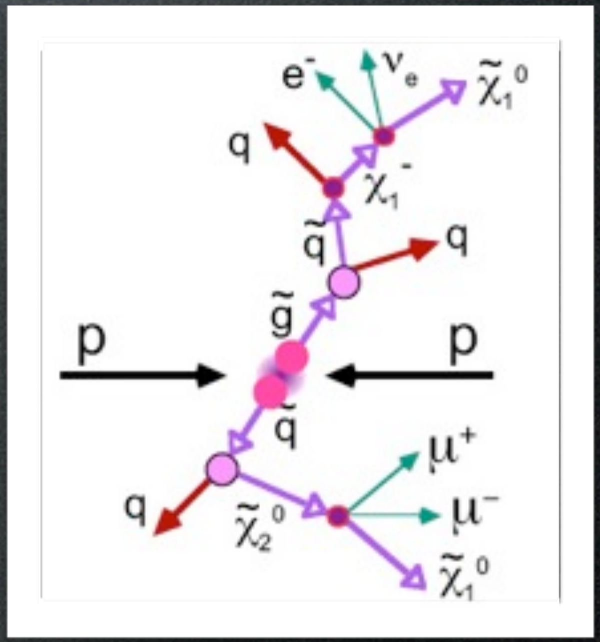






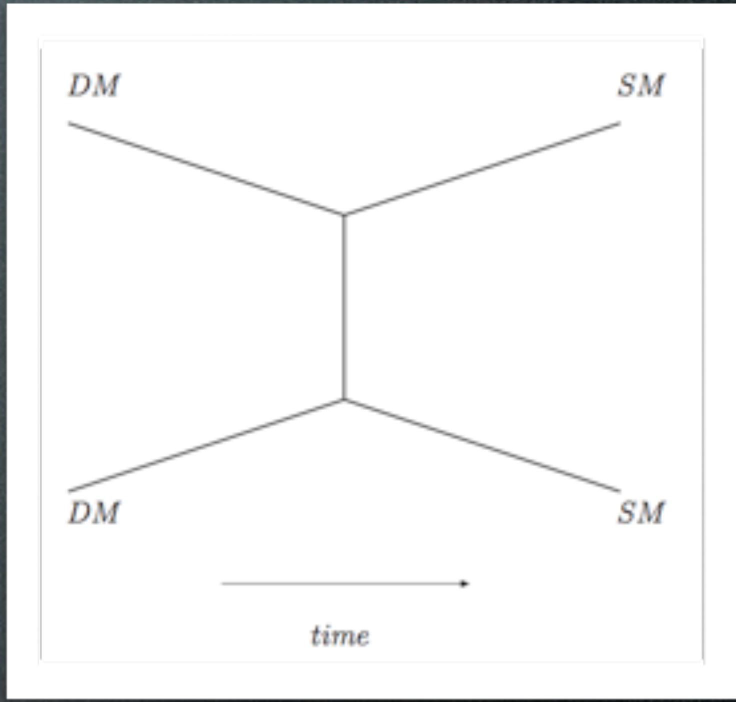
- Direct production at hadron colliders:



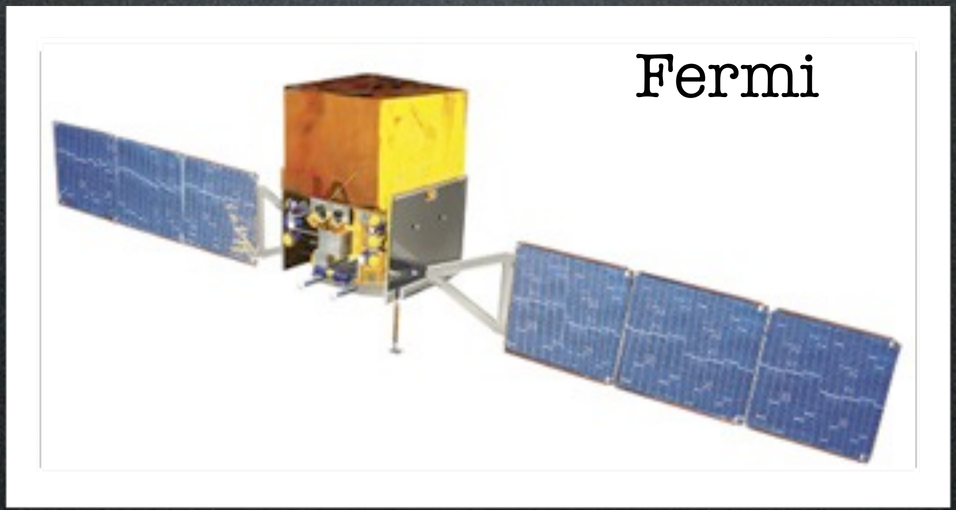


indirect methods

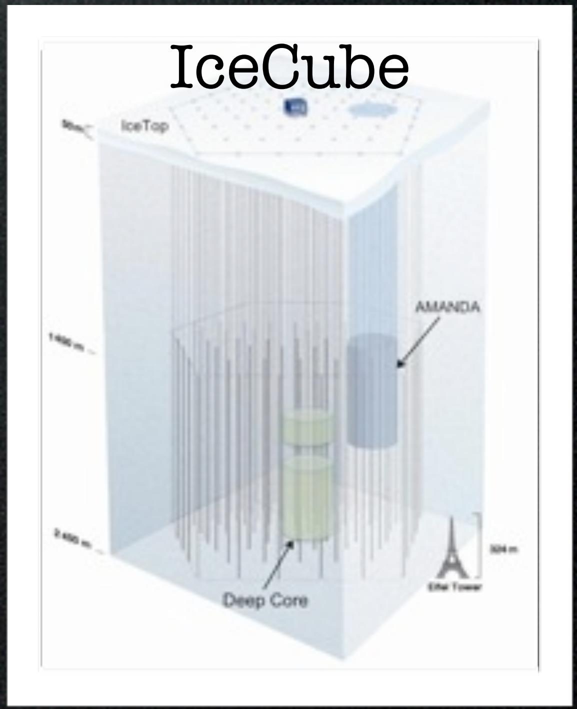
- Indirect detection experiments look for signs of DM from its annihilation (or decay) products into SM particles
- Ranges:
  - charged products: “local” sources
  - neutral products: more distant sources
- All shapes and sizes...



Charged: $e^{\pm}$, p



γ rays, $e^{\pm}$, p

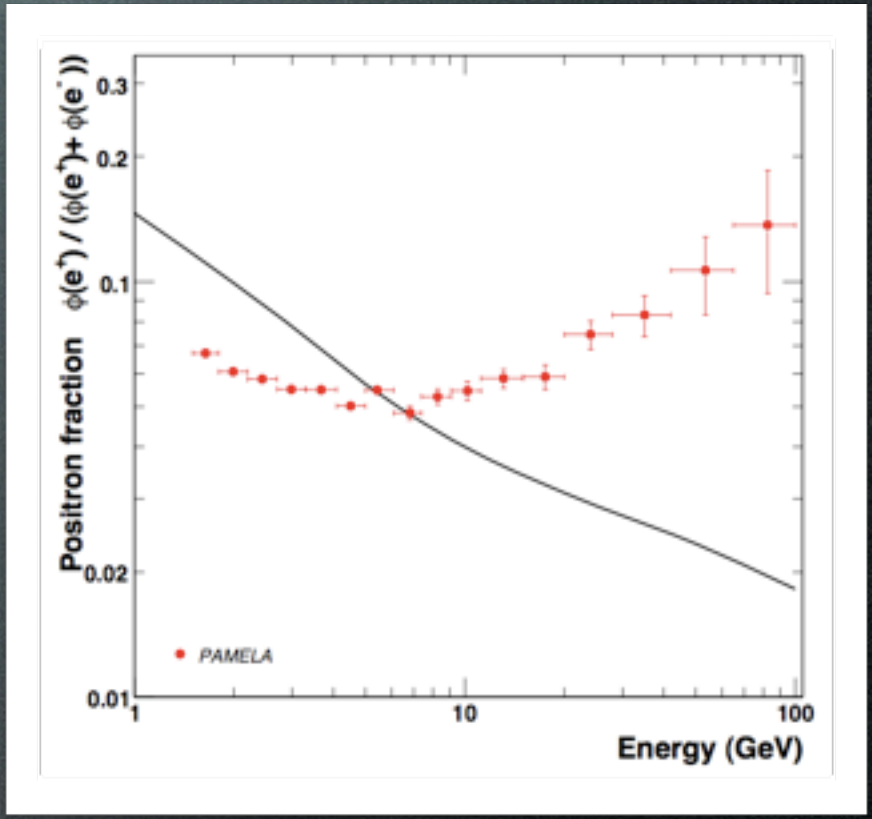


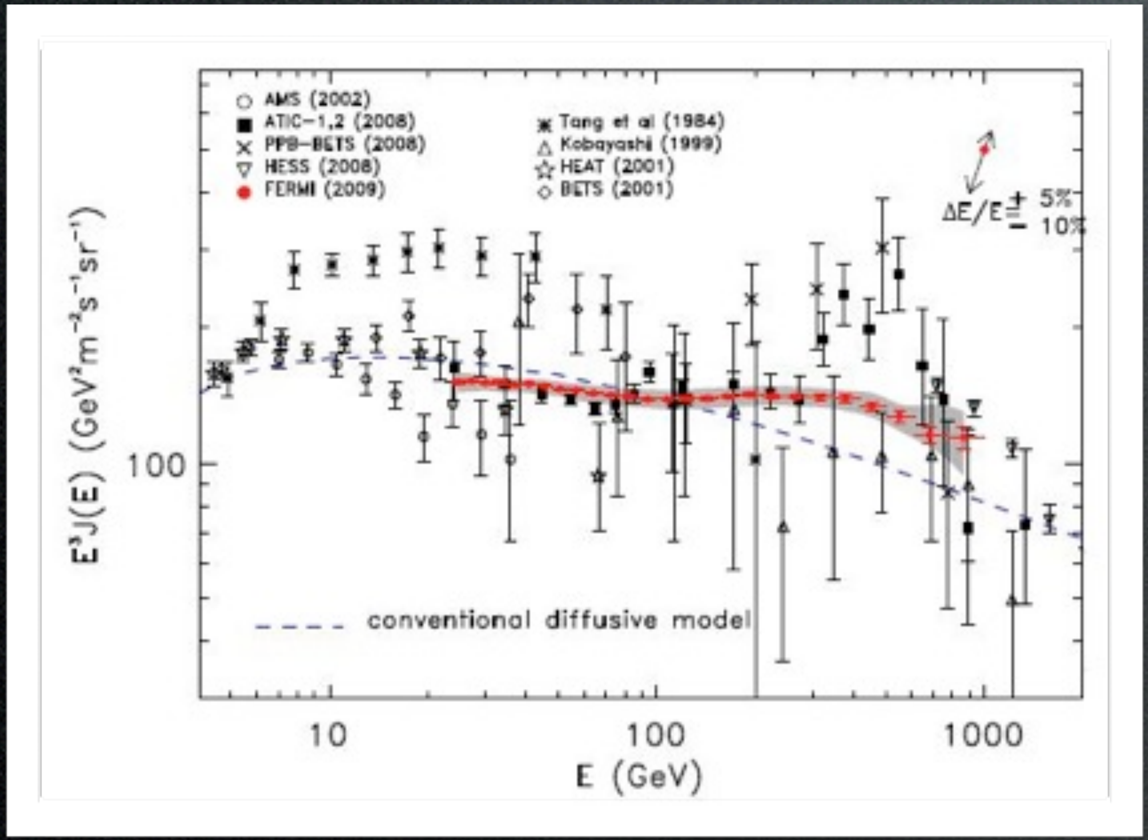
neutrinos

recent indirect results

PAMELA anomaly:

- Excess in positron fraction
- No excess seen in anti-protons
- Astrophysical in nature (pulsars, cosmic rays, etc.)





ATIC/Fermi "anomaly":

- "Excess" in $e^+ + e^-$
- Particle physicist: "Dark matter!"
- Astrophysicist: "Cosmic rays!"
- Jury still out…

seeing the light... from dark matter

- WIMP annihilations also produce photons!
  - Through charged SM particles which then radiate or hadronize and then decay
  - Direct annihilation into γ+X final states (loop-induced processes)
- Expected flux:

$$\phi_{WIMP}(E,\psi) = \frac{1}{2}\frac{<\sigma v>}{4\pi}\sum_f \frac{dN_f}{dE} B_f \int_{\mathrm{l.o.s}} dl(\psi)\frac{\rho(l)^2}{m_{WIMP}^2}$$

- Searches focus on regions of the sky where we expect Dark Matter to "clump" (i..e, towards the Milky Way GC, dwarf galaxies, etc.)
- Fluxes from DM annihilation expected to be much weaker than those from astrophysical sources

searching for the light

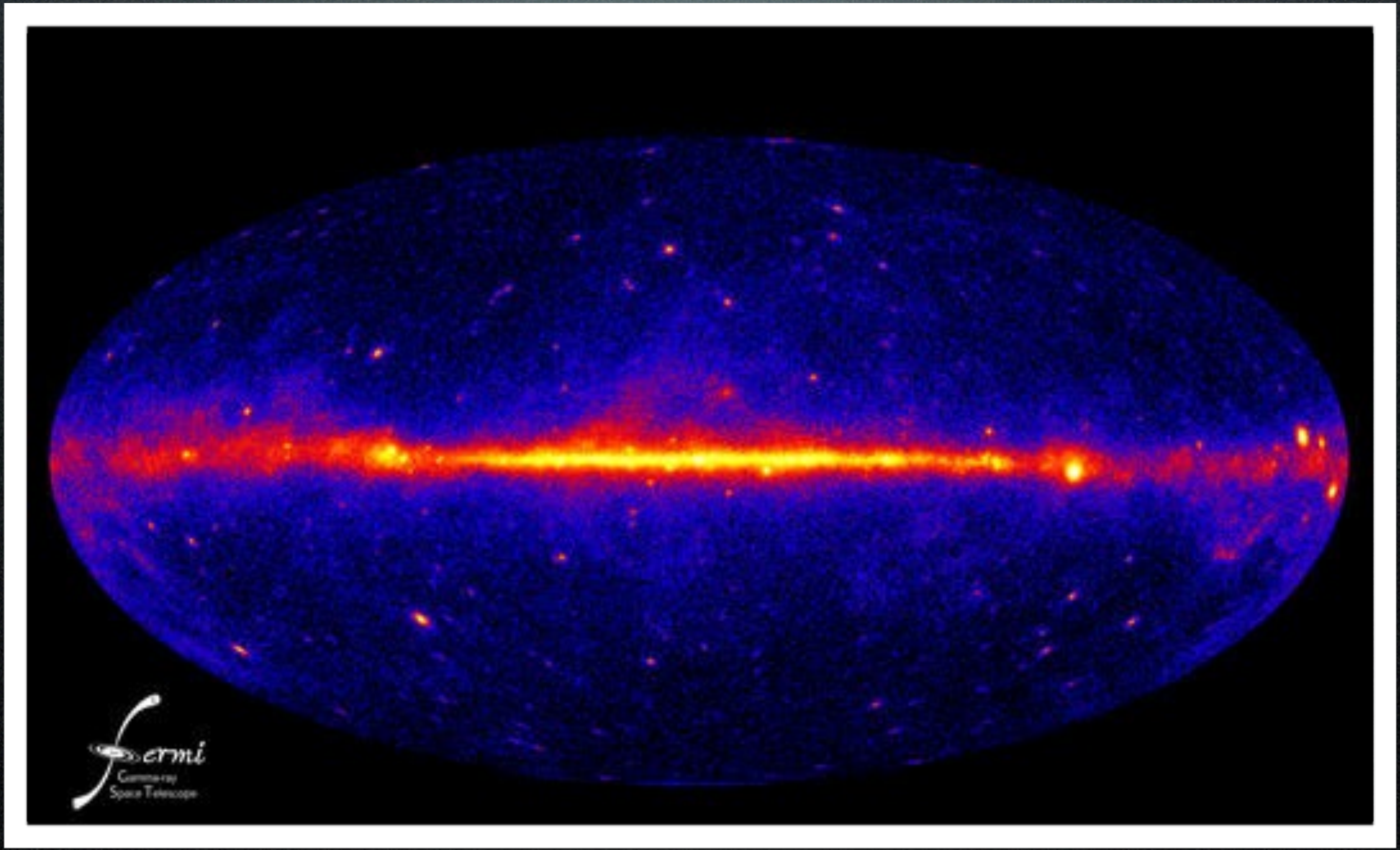
Fermi Space Telescope

- Scans entire sky (in matter of hours!!!)
- Sensitive up to 100's GeV
- $\Delta E/E \sim 10$ %
- See arXiv:0806.2911

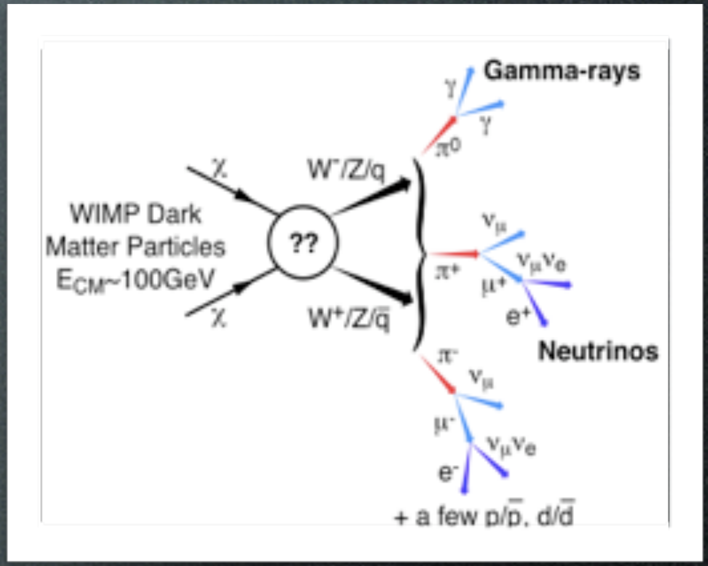
Air Cerenkov Telescopes

- Observes small sections of the sky
- Most sensitive to multi-TeV scales
- $\Delta E/E \sim 15\text{-}20$ %

the gamma ray sky



γ-ray continuum from DM annihilation



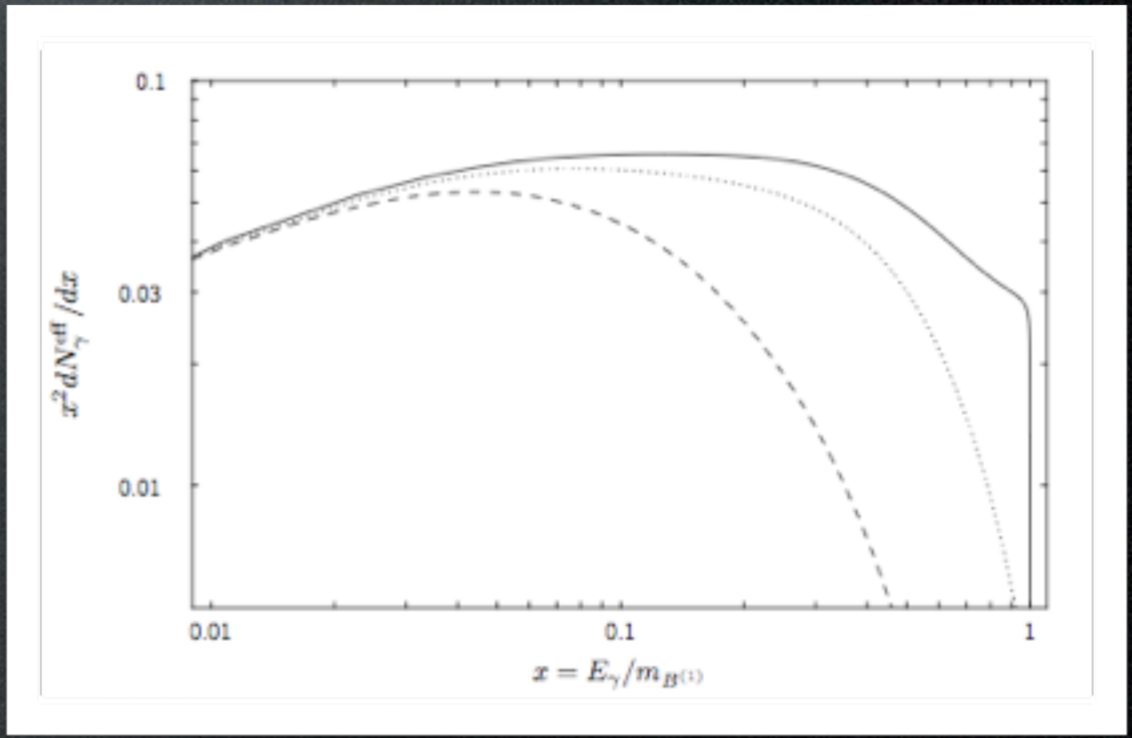
- Direct annihilation into SM particles produces a continuum of γ rays
  - Light quark hadronization ($\pi^0 \to \gamma\gamma$)
  - Final-state radiation:

$$\frac{dN_{X\bar{X}}}{dx} \approx \frac{\alpha Q_X^2}{\pi} \mathcal{F}_X(x) \log\left(\frac{s(1-x)}{m_X^2}\right)$$

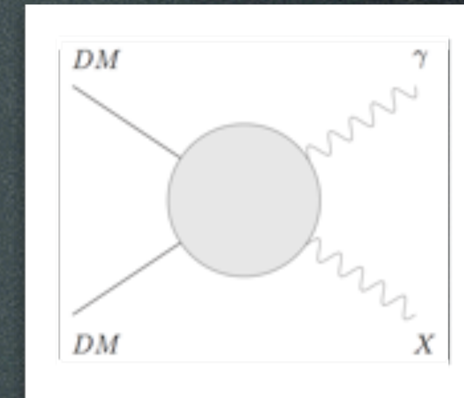
$$\mathcal{F}_{\mathrm{boson}}(x) = \frac{1-x}{x}$$

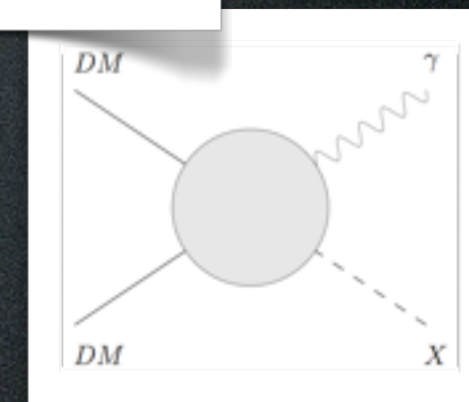
where $x = 2E_\gamma/\sqrt{s}$ and $s \approx 4(M_{DM})^2$

- The spectrum:
  - $\pi^0 \to \gamma\gamma$ featureless and soft
  - FSR provides a harder spectrum with a sharp cutoff @ WIMP mass
  - Besides WIMP mass-dependence, shape (almost) model-independent



spectral lines





- Loop-induced annihilation into γ + X final states

- Naively, cross sections should be loop-suppressed compared to continuum... (10^{-4} - 10^{-1})

- BUT, observation of such lines provides a “smoking gun”! (such features not expected in astro. backgrounds)

- Wealth of information can be extracted from position and relative size of line(s)

    - For γ + X final state, photons emitted mono-energetically:

$$E_\gamma = m_{DM}\left(1 - \frac{M_X^2}{4m_{DM}^2}\right)$$

(from phase space)

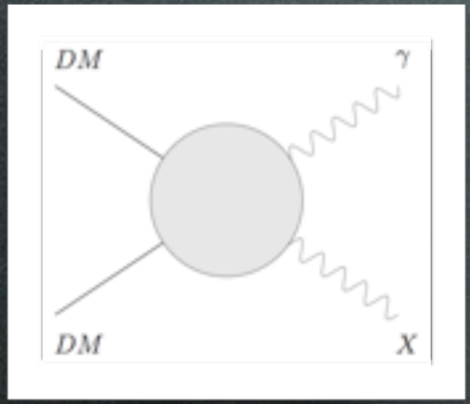
    - Position of $\gamma\gamma$ line → “precise” measurement of WIMP mass
      Position of γX line → measurement of X mass

    - Relative size of $\gamma\gamma$ vs. γZ line: couplings of WIMP to SM singlets/doublets

what can ‘X’ be?

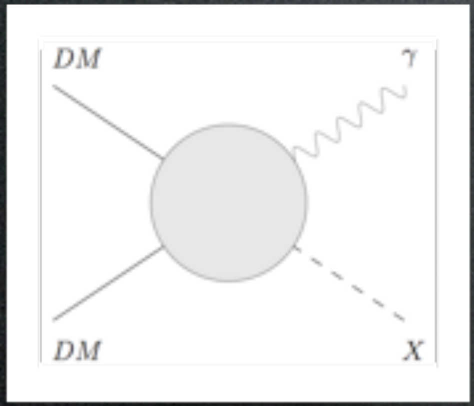
- WIMPs are non-relativistic!
- Depending on spin of WIMP, only certain γ + X final states are possible... others are VELOCITY-SUPPRESSED

X = vector



DM can be:
Scalar
Vector Gauge Boson
Dirac Fermion
Majorana Fermion

X = scalar



DM can ONLY be:
Vector Gauge Boson
Dirac Fermion

- In conjunction with measurements at the LHC, observation of spectral lines will allow measurement of DM spin!

results from Fermi!

- Fermi is currently searching for lines (30 < E_γ < 200 GeV) centered on GC:

E_γ (GeV)	95%CLUL (10^{-9} cm^{-2}s^{-1})	$\langle\sigma v\rangle_{\gamma\gamma}$ [γZ] (10^{-27} cm^{3}s^{-1}) NFW	Einasto	Isothermal	$\tau_{\gamma\gamma}$ [γZ] (10^{28} s) NFW	Einasto	Isothermal
30	3.5	0.3 [2.6]	0.2 [1.9]	0.5 [4.5]	17.6 [4.2]	17.8 [4.2]	17.5 [4.2]
40	4.5	0.7 [4.2]	0.5 [3.0]	1.2 [7.2]	10.1 [2.9]	10.3 [2.9]	10.0 [2.9]
50	2.4	0.6 [2.7]	0.4 [1.9]	1.0 [1.6]	15.5 [5.0]	15.7 [5.1]	15.4 [5.0]
60	3.1	1.1 [4.2]	0.8 [3.0]	1.8 [7.3]	9.8 [3.5	10.0 [3.5]	9.7 [3.5]
70	1.2	0.6 [2.0]	0.4 [1.4]	1.0 [3.4]	21.6 [8.2]	21.9 [8.3]	21.5 [8.1]
80	0.9	0.5 [1.7]	0.4 [1.2]	0.9 [2.9]	26.0 [10.4	26.4 [10.5]	25.8 [10.3]
90	2.6	2.0 [6.0]	1.5 [4.3]	3.5 [10.3]	7.7 [3.2	7.8 [3.2]	7.6 [3.1]
100	1.4	1.4 [3.8]	1.0 [2.8]	2.4 [6.6]	12.6 [5.4]	12.8 [5.4]	12.5 [5.3]
110	0.9	1.0 [2.7]	0.7 [1.9]	1.7 [4.6]	18.9 [8.2]	19.2 [8.3]	18.8 [8.2]
120	1.1	1.6 [4.0]	1.1 [2.9]	2.7 [6.9]	13.3 [5.9]	13.5 [6.0]	13.2 [5.9]
130	1.8	3.0 [7.3]	2.1 [5.3]	5.1 [12.6]	7.6 [3.4	7.8 [3.5]	7.6 [3.4]
140	1.9	3.5 [8.4]	2.5 [6.0]	6.0 [14.3]	7.0 [3.2	7.1 [3.3]	7.0 [3.2]
150	1.6	3.5 [8.2]	2.5 [5.9]	6.0 [14.1]	7.5 [3.5	7.6 [3.5]	7.4 [3.4]
160	1.1	2.7 [6.3]	2.0 [4.5]	4.7 [10.9]	10.2 [4.8]	10.4 [4.8]	10.1 [4.7]
170	0.6	1.7 [4.0]	1.3 [2.9]	3.0 [6.8]	17.0 [8.0]	17.2 [8.1]	16.9 [7.9]
180	0.9	2.7 [6.1]	1.9 [4.4]	4.6 [10.4]	11.6 [5.5]	11.8 [5.6]	11.6 [5.4]
190	0.9	3.2 [7.1]	2.3 [5.1]	5.5 [12.2]	10.4 [4.9]	10.5 [5.0]	10.3 [4.9]
200	0.9	3.3 [7.3]	2.4 [5.2]	5.7 [12.5]	10.6 [5.1]	10.8 [5.1]	10.5 [5.0]

see talk by Y. Edmonds at winter Aspen meeting and arXiv:1001.4836

- Note: limits still about 1 to 2 orders of magnitude weaker than cross sections expected for a typical thermal WIMP

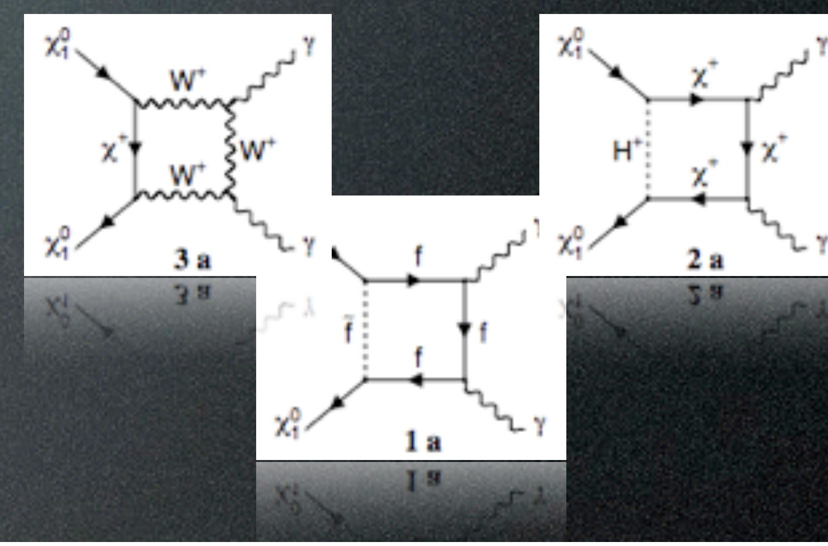
- However, models with ENHANCED cross sections are constrained.

Results from past studies...

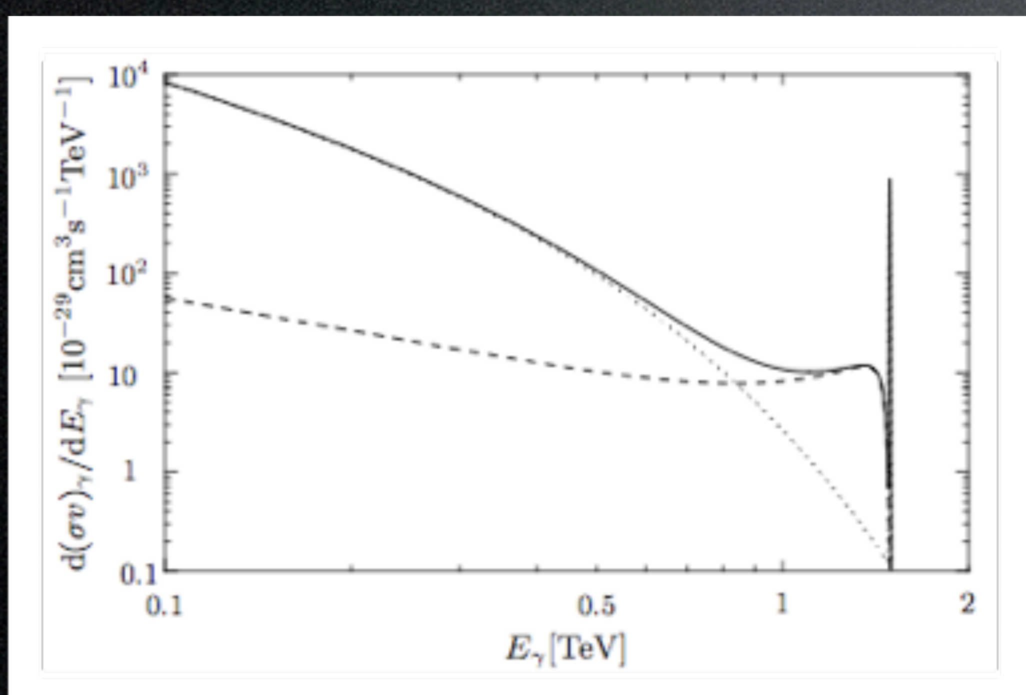
lines from susy

(e.g., see series of papers by Bergstrom et al.)

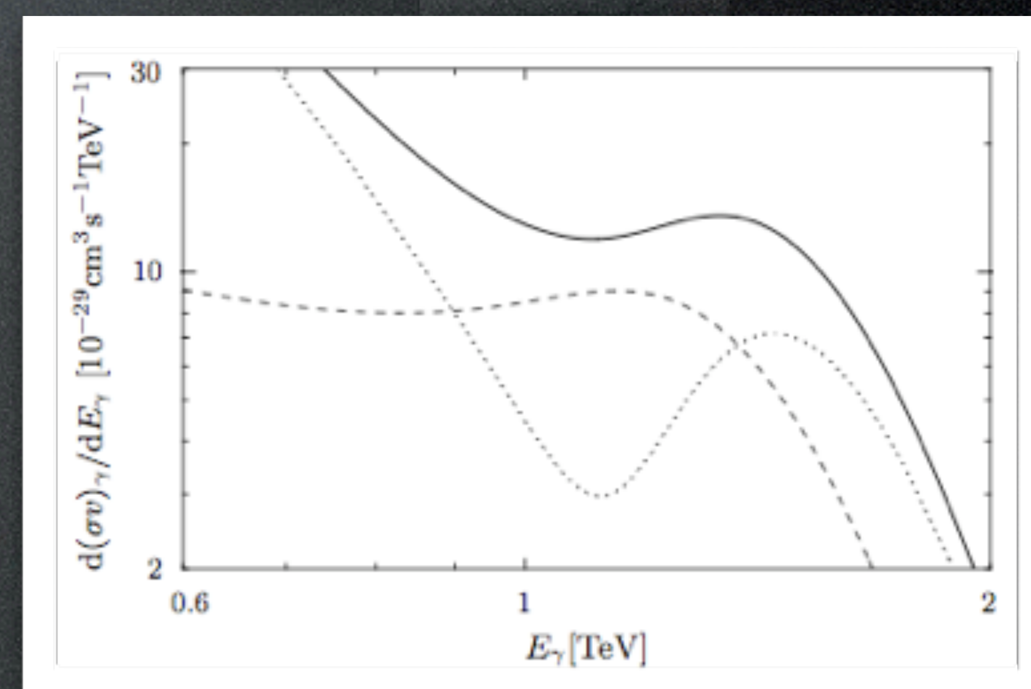
- Majorana nature of WIMP implies a few things:
    - Soft component of continuum suppressed (annihilation into light quarks chirally-suppressed)
    - FSR component could be observable (upturn? bump?)
    - Only possible lines: $\gamma\gamma$ and γZ



- Results for heavy SUSY:



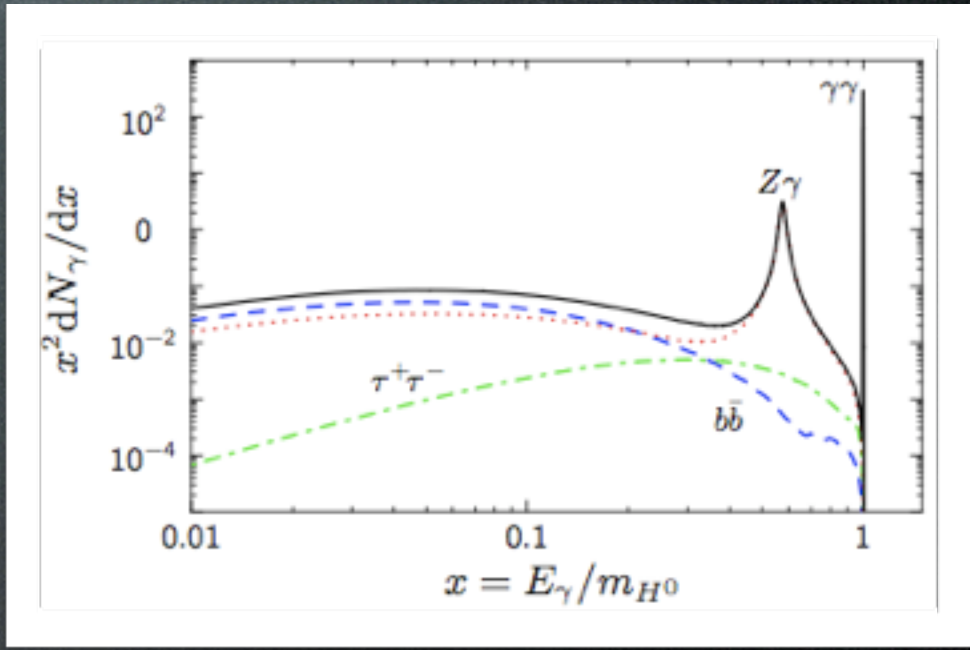
$\Delta E/E$ = 15%

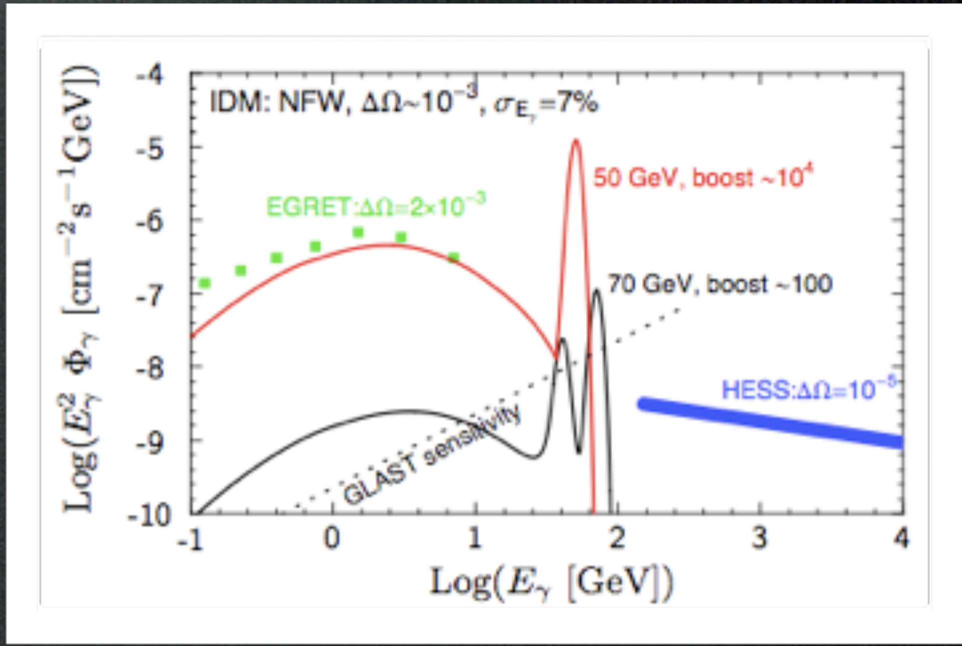


lines from an "inhert" higgs

(Gustaffson et al., PRL99:041301 (2007))

- Extend SM by one additional Higgs doublet (H_2) which transforms under a Z_2 symmetry... all other fields are invariant
- Scalar WIMP ("LIP"):
  - (Chirally-)suppresed continuum
  - Only γγ and γZ lines possible
- Relic density → $M_{DM} \simeq M_W$
- Annihilation mainly via loops of W's
  - Virtual W's nearly on-shell
  - Threshold enhancements!
- Extremely pronounced peak(s)!!! (Beware: line shapes VERY sensitive to detector resolutions!)





a dark forest?

- In order to observe lines, you need TWO things (besides a good detector):
  - Suppression of the continuum
  - Loop-annihilation via “largish” couplings and/or threshold enhancements
- To observe multiple lines, you need comparable masses between the WIMP and the X particle

$$E_\gamma = m_{DM}\left(1 - \frac{M_X^2}{4m_{DM}^2}\right)$$

- Consider scenarios where other particles in the “dark sector” have appreciable masses but < 2 M_{DM}
  - Series of lines...
    i.e., a “WIMP Forest”!!!
  - DM Spectroscopy?

universal extra dimensions

- All SM fields propagate in FLAT extra dimension(s)
- Residual spacetime symmetry → stable WIMP candidate ("LKP")

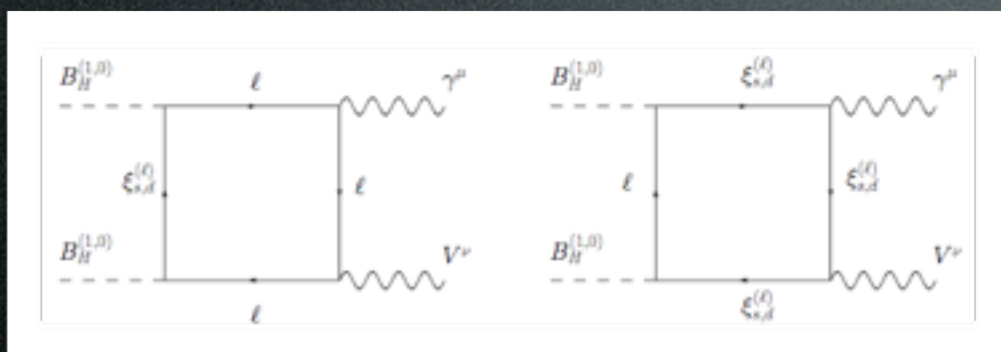
	5-d	6-d
Compactification	Line	Square
KK Masses	$m^{(n)} = \sqrt{(n/R)^2 + m_{\mathrm{EW}}^2}$	$M_{(j,k)}^2 = M_0^2 + \pi^2 \frac{j^2+k^2}{L^2}$
WIMP candidate	Vector ($B^{(1)}$)	Scalar ($B^{(1,0)}$)
Preferred WIMP mass	≈ 0.5 - 1 TeV	≈ 200 - 500 GeV
γ+X final states	γγ, γZ & γH	γγ, γZ & γ$B^{(1,1)}$

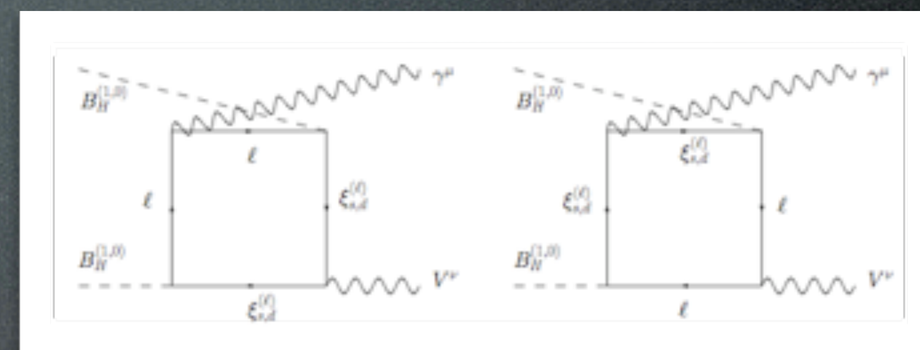
- 5-d scenario studied extensively in literature
- 6-d case studied less... but better scenario for LHC!

γ-ray flux from UEDs

Bertone, CJ, Shaughnessy, Tait and Vallinotto, PRD80, 023512 (2009)

- Compute the γ-ray flux from continuum + lines ($\gamma\,\gamma$, γZ and $\gamma B^{(1,1)}$)
  - used micrOMEGAs for continuum
- Annihilation to γ+V final states proceeds via BOX diagrams:





- The amplitude:

$$\mathcal{M} = \epsilon_A^{\mu *}(p_A)\epsilon_B^{\nu *}(p_B)\mathcal{M}^{\mu\nu}(p_1, p_2, p_A, p_B)$$

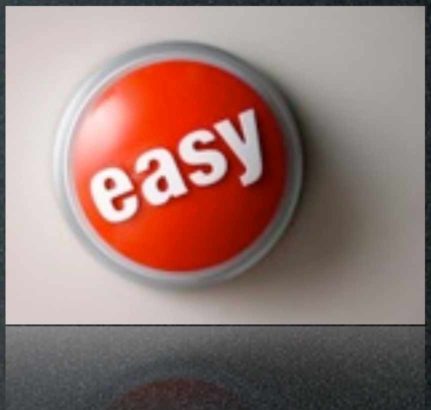
$\longrightarrow$

$$\begin{aligned}\mathcal{M}^{\mu\nu} &= A_1\ g^{\mu\nu} + B_1\ p_1^\mu p_1^\nu + B_2\ p_2^\mu p_2^\nu + B_3\ p_1^\mu p_2^\nu \\ &+\ B_4\ p_1^\nu p_2^\mu + B_5\ p_A^\nu p_B^\mu + B_6\ p_1^\mu p_A^\nu + B_7\ p_1^\nu p_B^\mu \\ &+\ B_8\ p_2^\mu p_A^\nu + B_9\ p_2^\nu p_B^\mu\,.\end{aligned}$$

- Tricks: 1) WIMPs are non-relativistic (identify two incoming momenta)
  2) Conservation of momentum
  3) Choose frame such that $\varepsilon \cdot p = 0$

$\boxed{A_1 \text{ is the dominant term}}$

nothing's ever easy



- Non-relativistic nature of WIMPs cases havoc in loops
- Passarino-Veltman tensor integral coefficients depend INVERSELY on Gram Determinant (GD):

$$GD = \det(p_i \cdot p_j)$$

Identical incoming momenta: GD = 0 and scattering amplitude blows up!

- Used a technique developed by R. Stuart (CPC48, 367 (1988))
- Extension of usual P-V formalism... assuming "usual" GD is exactly zero
- Expand higher-pt. tensor coefficients in terms of (safe) lower-pt. ones:

$$\begin{aligned} D_{27} &= \alpha_{123} C_{24}(123) + \alpha_{124} C_{24}(124) \\ &+ \alpha_{134} C_{24}(134) + \alpha_{234} C_{24}(234)\,, \end{aligned}$$

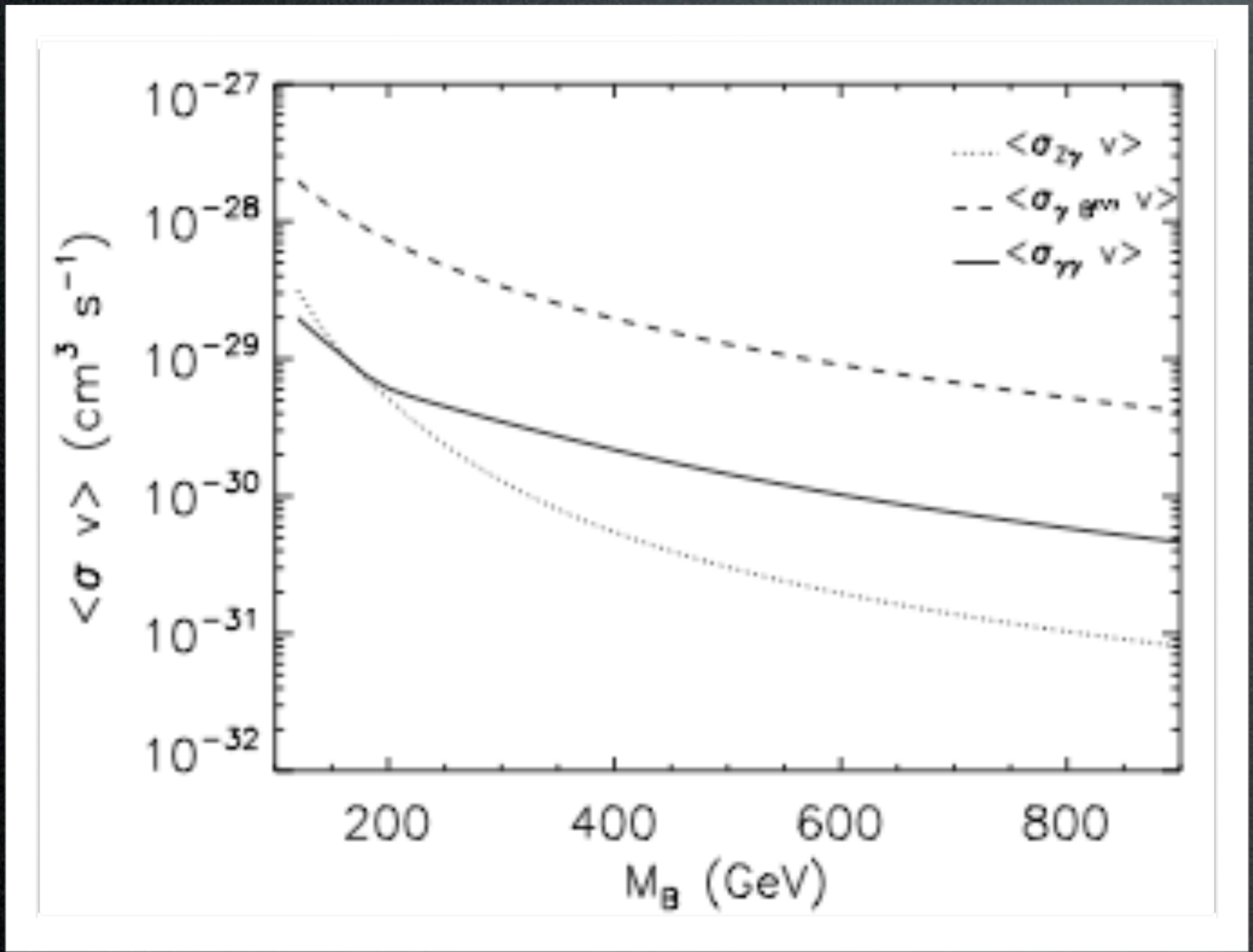
$$\downarrow$$

$$\begin{pmatrix} 1 & 1 & 1 & 1 \\ 0 & p_1^2 & (p_1^2 - p_2^2 + p_5^2)/2 & (p_1^2 + p_4^2 - p_6^2)/2 \\ 0 & (-p_1^2 - p_2^2 + p_5^2)/2 & (-p_1^2 + p_2^2 + p_5^2)/2 & (-p_1^2 - p_3^2 + p_5^2 + p_6^2)/2 \\ -m_1^2 & p_1^2 - m_2^2 & p_5^2 - m_3^2 & p_4^2 - m_4^2 \end{pmatrix} \begin{pmatrix} \alpha_{234} \\ \alpha_{134} \\ \alpha_{124} \\ \alpha_{123} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

6-d line cross sections

Summing over 24 diagrams...

$$
\begin{aligned}
A_1^{(\ell)} = & -\alpha_Y \alpha_{em} Q_\ell^2 (Y_L^2 + Y_R^2) \Big\{ 2 + \frac{2}{1-\eta} B_0(M_{B_H}^2; M_L^2, 0) - B_0(4M_{B_H}^2; 0, 0) - \frac{1+\eta}{1-\eta} B_0(4M_{B_H}^2; M_L^2, M_L^2) \\
& + M_{B_H}^2 \Big[-(1+\eta)(C_0(M_{B_H}^2, 4M_{B_H}^2, M_{B_H}^2; M_L^2, 0, 0) + C_0(M_{B_H}^2, 4M_{B_H}^2, M_{B_H}^2; 0, M_L^2, M_L^2)) \\
& - 2C_0(M_{B_H}^2, 0, M_{B_H}^2; 0, M_L^2, M_L^2) + 4\eta C_0(0, 0, 4M_{B_H}^2; M_L^2, M_L^2, M_L^2) \Big] \Big\}, \qquad (13)
\end{aligned}
$$



- Mass of KK fermions in loops close to WIMP mass... threshold enhancements!
- Significant cancellations in γγ, γZ
- B(1,1) has loop-suppressed couplings to SM fermions... less cancellation!
- Enhanced γB(1,1) cross section!

known unknowns

- Largest uncertainties due to ignorance of DM distributions:

$$J \equiv \int_{\mathrm{l.o.s.}} \frac{ds}{r_\odot} \left[\frac{\rho[r(s,\psi)]}{\rho_\odot}\right]^2$$

- Two "benchmarks":
    - Navarro-Frenk-White (NFW)
    - "Adiabatic": include baryons in DM simulations (cuspier!)

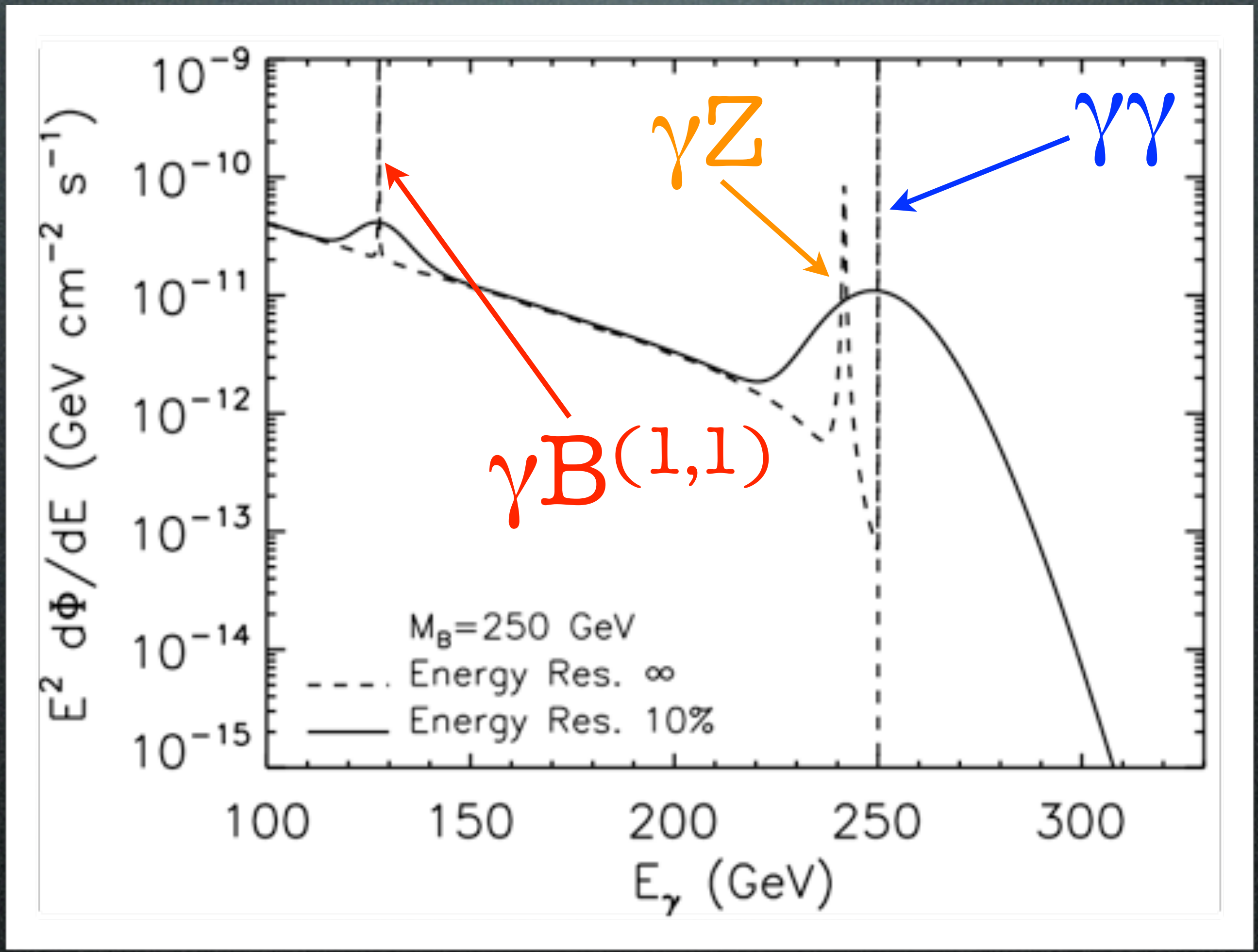
Model	$\bar{J}\,(10^{-5})$
NFW	1.5×10^4
Adiabatic	4.7×10^7

Three orders of magnitude!!!

- Good news:
    - Identify sources
    - With help from LHC (WIMP mass, couplings), trace DM density? (see Hooper and Serpico, arXiv:0902.2539)

results for the 6-d case

- In a perfect world, three lines (“WIMP Forest”):



- After detection resolution effects ($\Delta E/E \sim 10$ %), two DISTINCT BUMPS!!!

- Well-separated $\gamma B^{(1,1)}$ bump!

- Contributing factors: 1) Mass of $B^{(1,1)}$ on the order of WIMP mass
  2) Enhanced $\gamma B^{(1,1)}$ cross section

“higgs in space!”

CJ, Servant, Shaughnessy, Tait and Taoso, JCAP 1004 (2010) 004

“higgs in space!”

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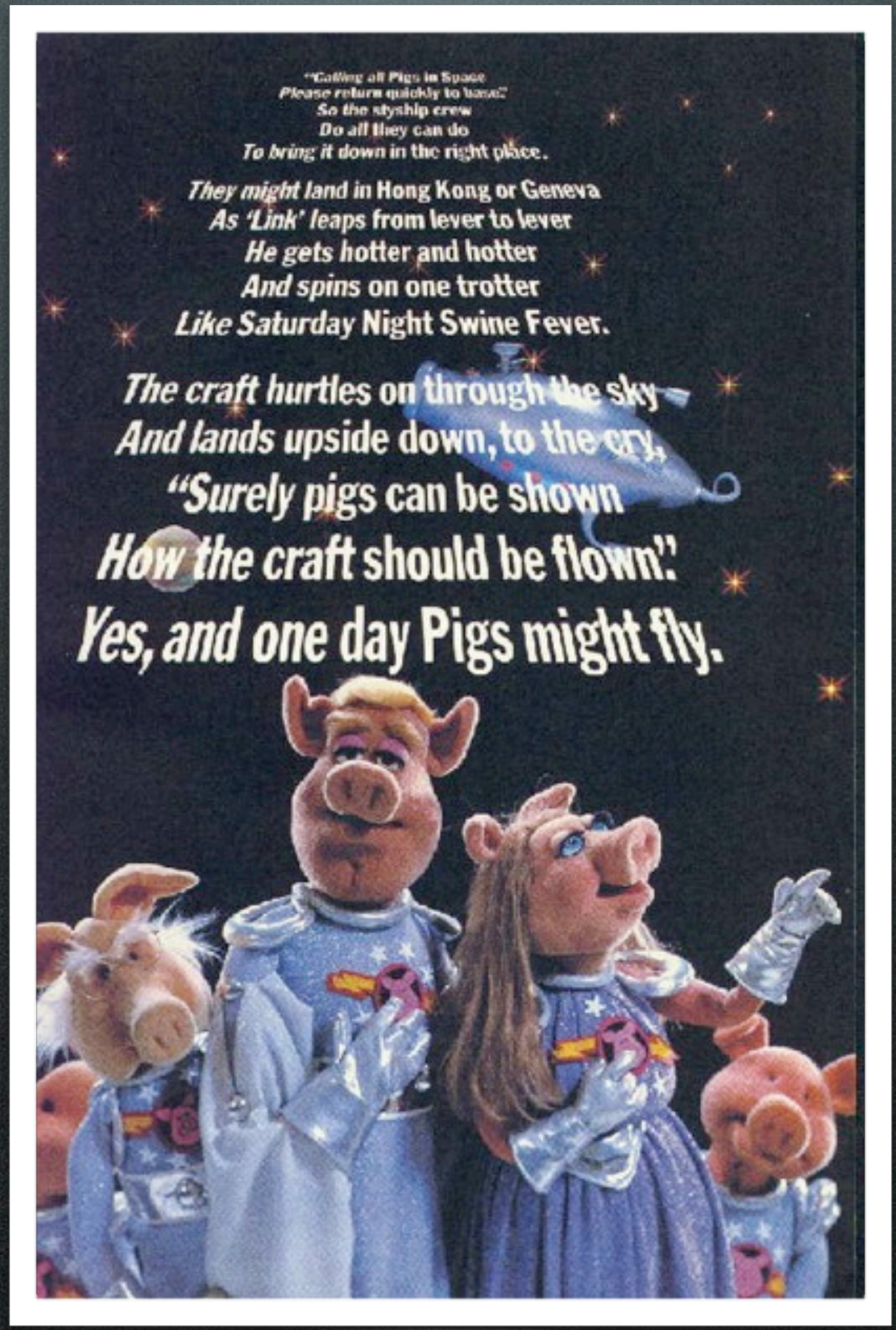

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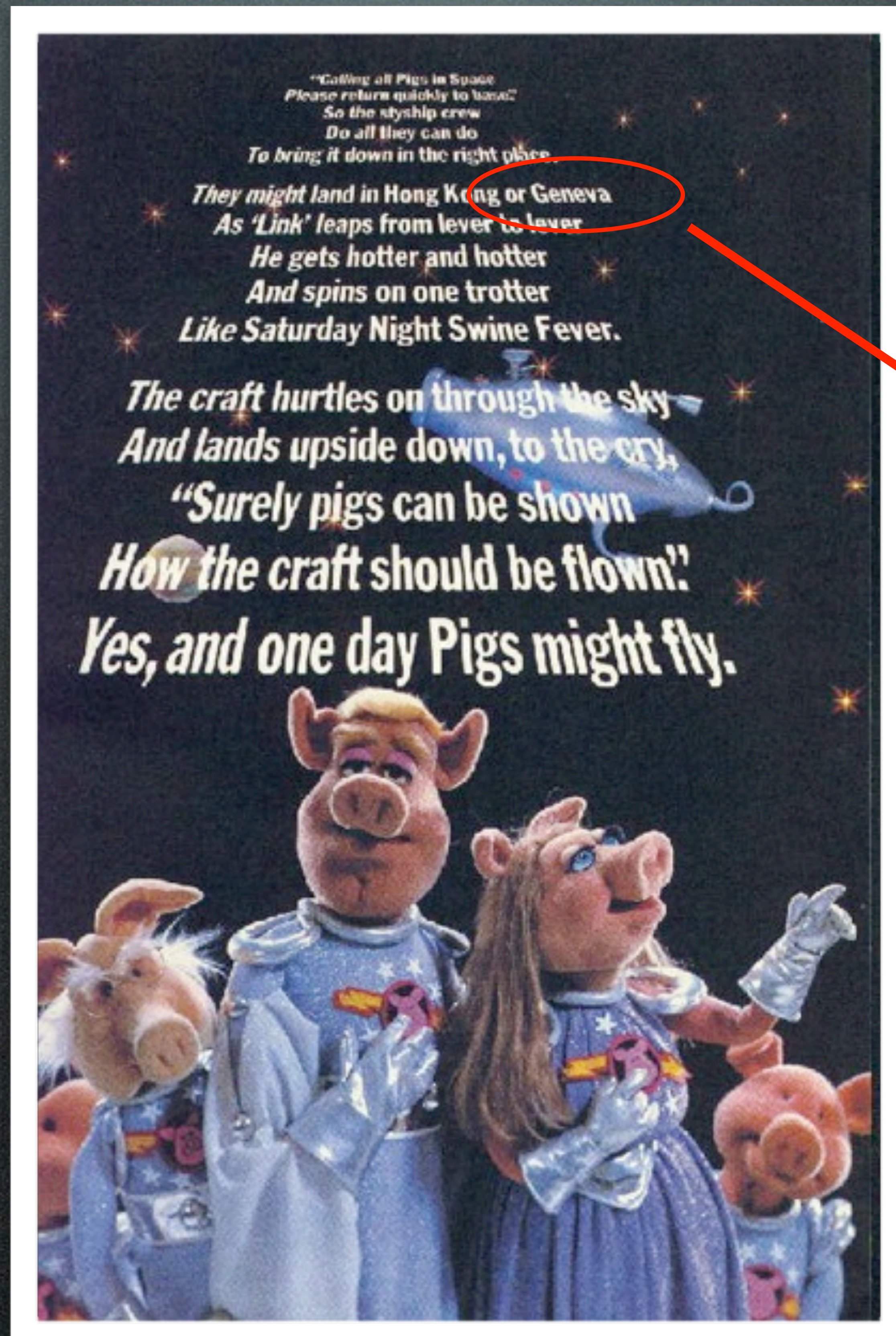

Geneva!

"higgs in space!"

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eva!

higgs in space!

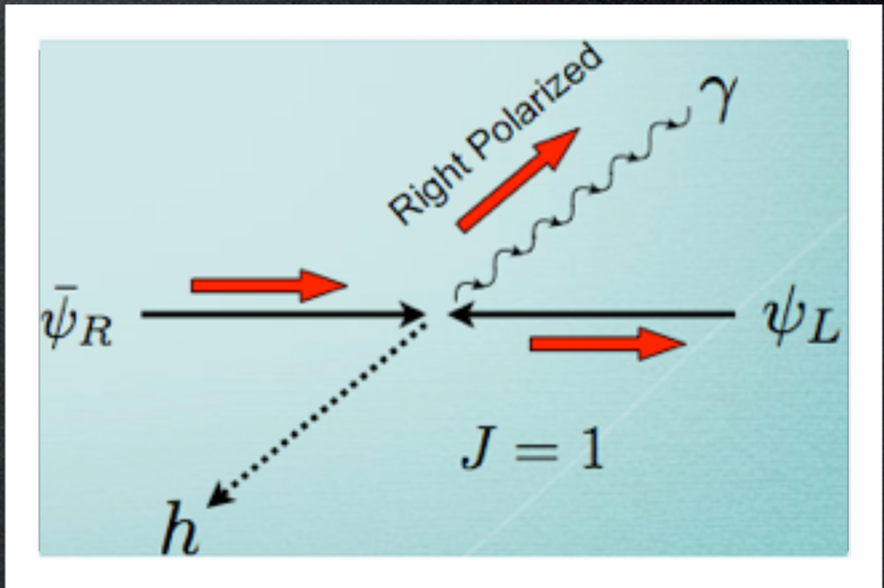
- "WIMP miracle": EW-size masses and couplings can naturally account for measured thermal relic abundance

- DM and EWSB dynamics related? If so, WIMPs may have enhanced couplings to massive states (tops, W/Z's, Higgs) much like the Higgs itself

- Could DM annihilations already be producing Higgs bosons... in space?!?

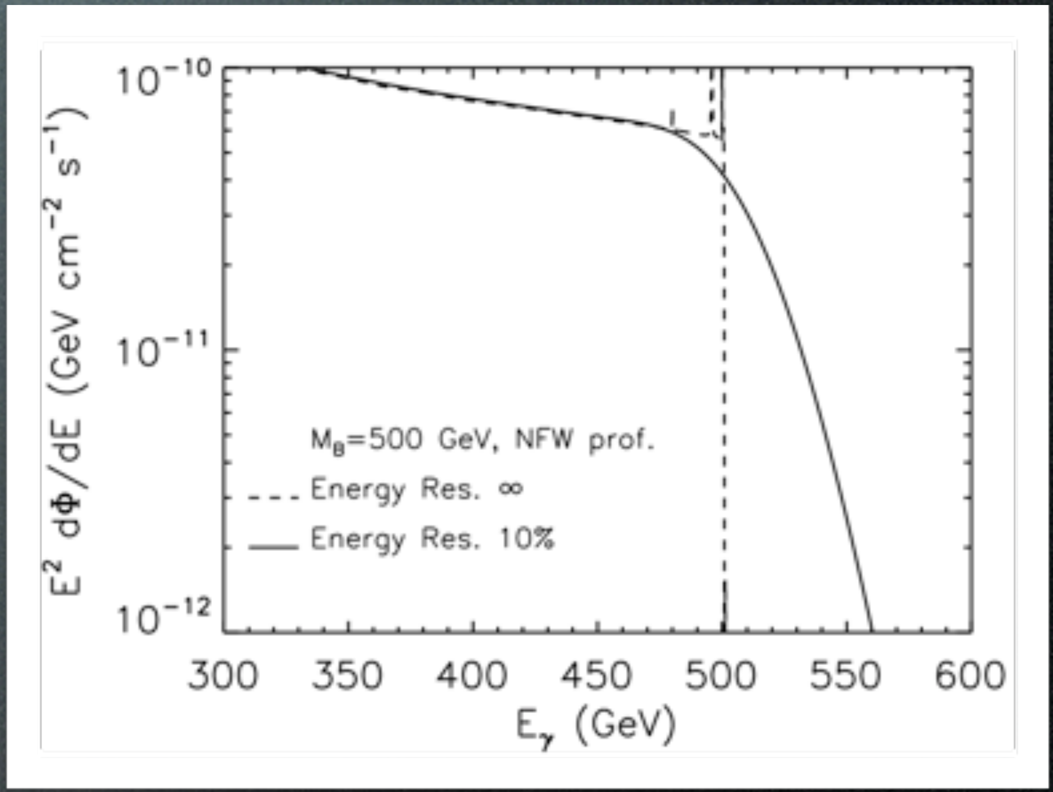
- If so, it's possible that the Fermi telescope could "scoop" the Tevaton and/or the LHC?!?

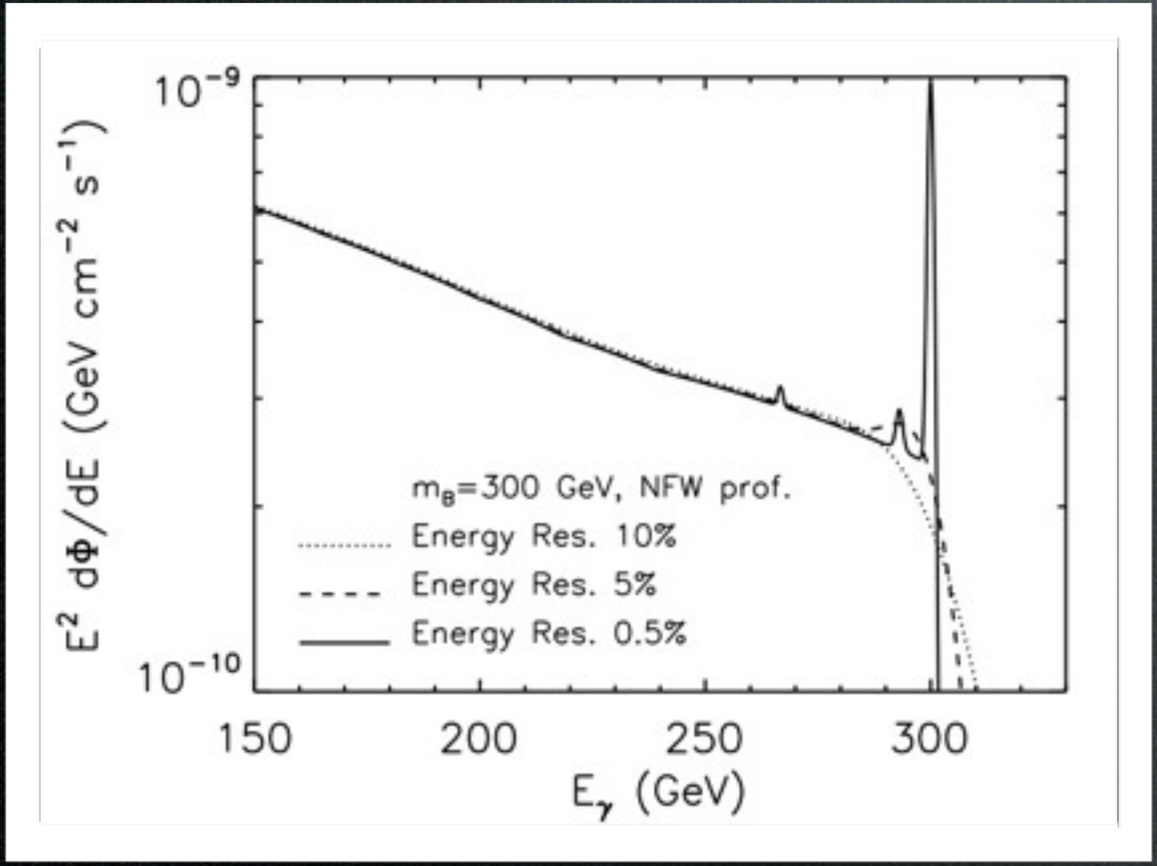
- Identification of a γH line:
  - Spin determination? (WIMP = Dirac fermion or vector)
  - Give credence to DM-EWSB connection



it's not easy... to see a higgs in space

- 5d UED: WIMP = Vector gauge boson
- Annihilation to $\gamma\gamma$, γZ and γH final states via closed fermion (box) diagrams
- Continuum not suppressed!
- Current detector resolutions completely wipe out lines





- Need futuristic (unrealistic?) detector resolutions
- Really have to push the limits of the model

a DM-top quark connection

- Consider a scenario where WIMPs have sizable (indirect) couplings to tops
- Simple example: WIMP is a Dirac fermion (ν)
- Work with an Effective Field Theory (EFT)
  - Usual SM gauge group with an additional U(1)'
  - ONLY the new Dirac fermion and the top are charged under U(1)'
  - U(1)' broken at some higher scale: the resulting massive Z' acts as a "portal" between SM and "dark sector"

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}\hat{F}'_{\mu\nu}\hat{F}'^{\mu\nu} + M^2_{\hat{Z}'}\hat{Z}'_\mu\hat{Z}'^\mu + \frac{\chi}{2}\hat{F}'_{\mu\nu}\hat{F}^{\mu\nu}_Y + \hat{g}^{Z'}_t\,\bar{t}\gamma^\mu P_R\hat{Z}'_\mu t + i\bar{\nu}\gamma^\mu\left(\partial_\mu - i\hat{g}^{Z'}_\nu P_R\hat{Z}'^\mu\right)\nu + M_\nu\bar{\nu}\nu$$

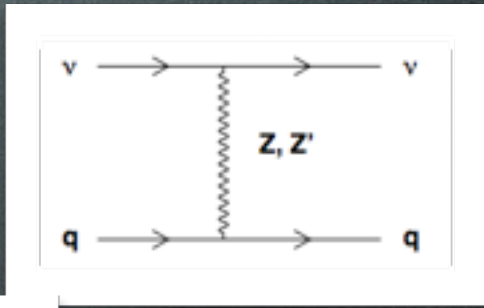
- Free parameters: masses (WIMP, Z' and Higgs), couplings of Z' to ν and tops and mixing parameter χ

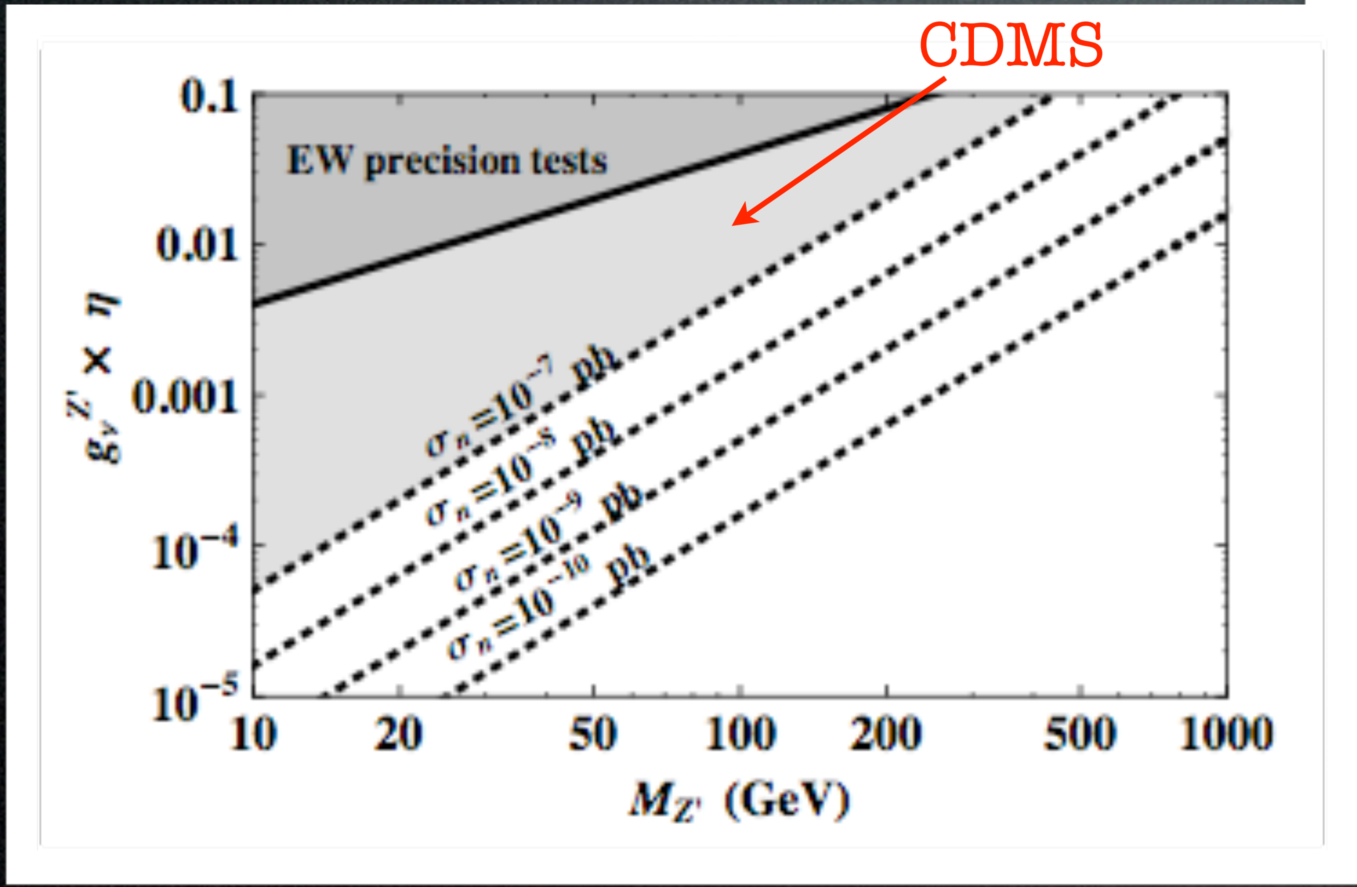
hypercharge-Z' mixing

- Mixing term is consistent with gauge symmetries... and even if absent in the UV, would be generated by loops of tops in the IR

- Generates effective couplings of SM states (e.g., light quarks) to the Z'... as well as a coupling between our WIMP (ν) and the SM Z

- Constraints from direct detection?





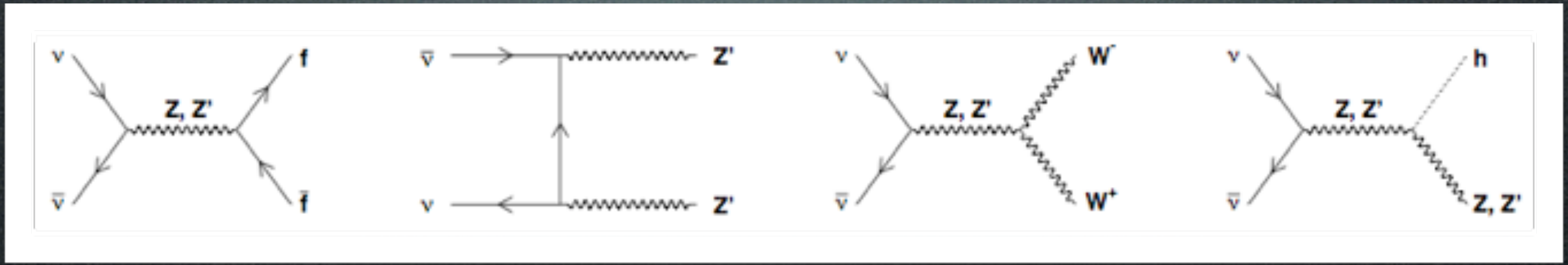
- Unlike Majorana fermions, Dirac fermions have vector interactions which remain large in NR-limit

- Constraints consistent with order one coupling between ν and Z'... and loop-induced value of η

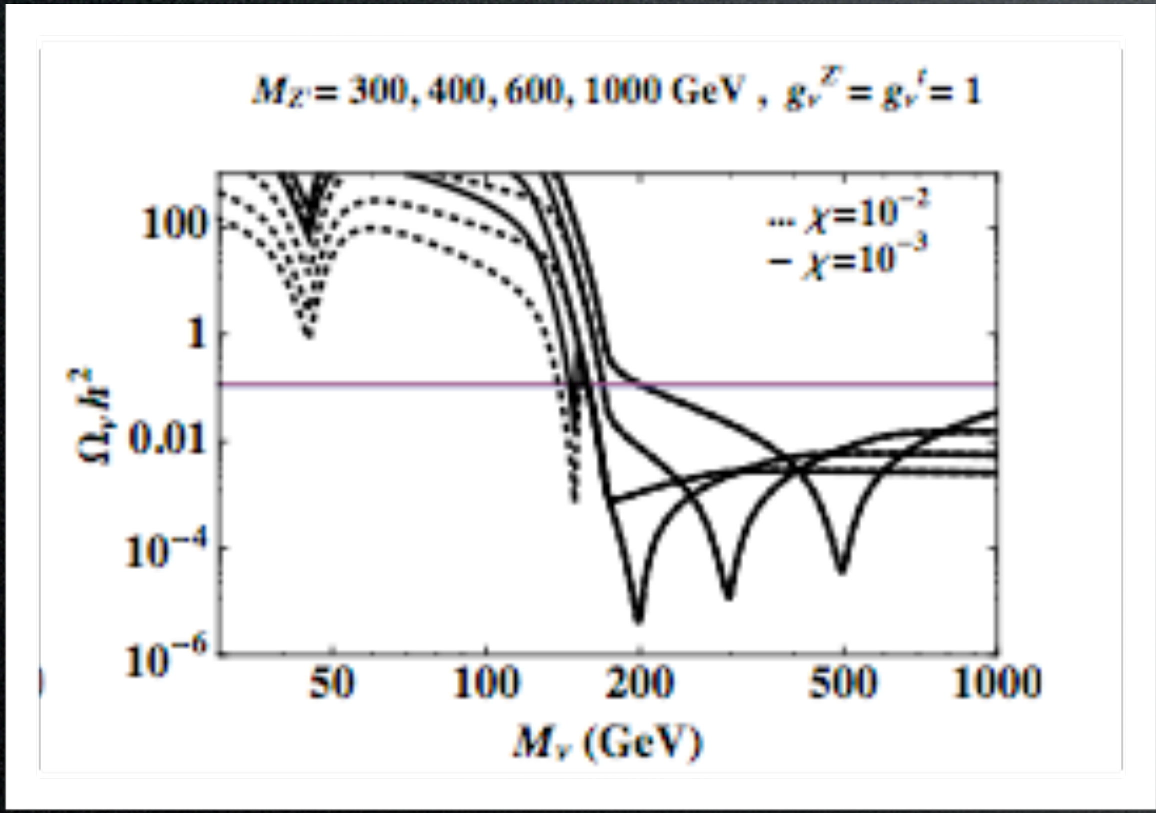
$$\eta \equiv \frac{\chi}{\sqrt{1-\chi^2}}$$

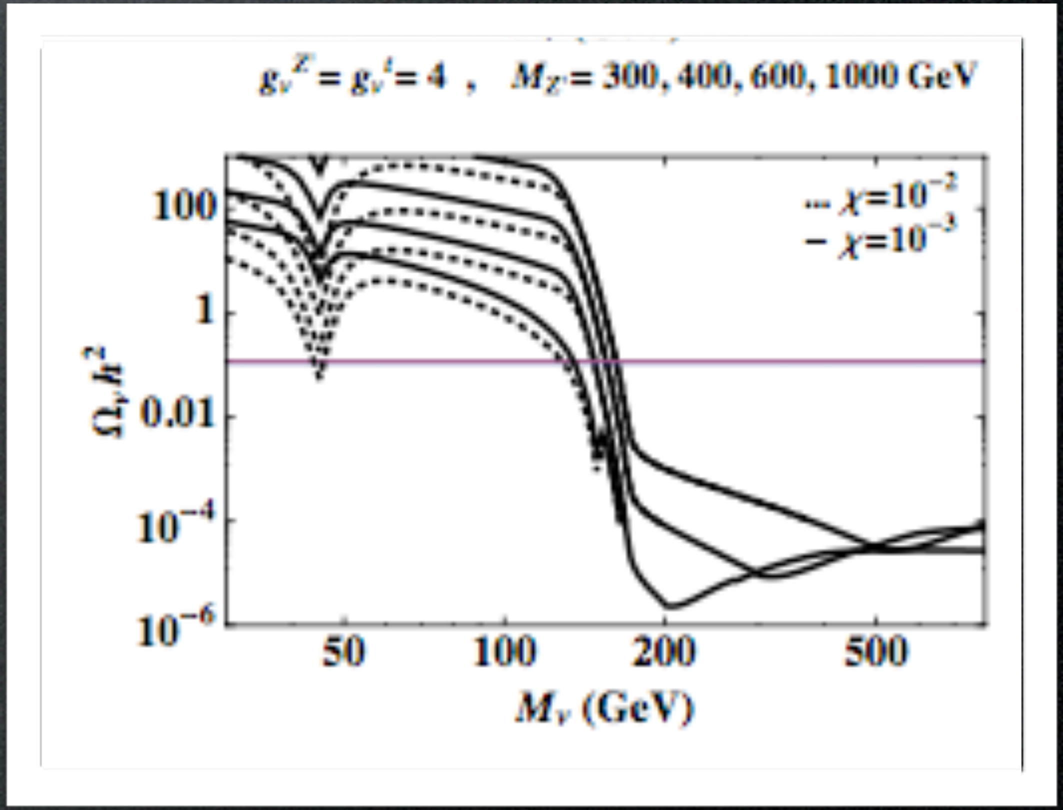
relic density

- Relic density controlled by annihilation into SM particles (and Z'):



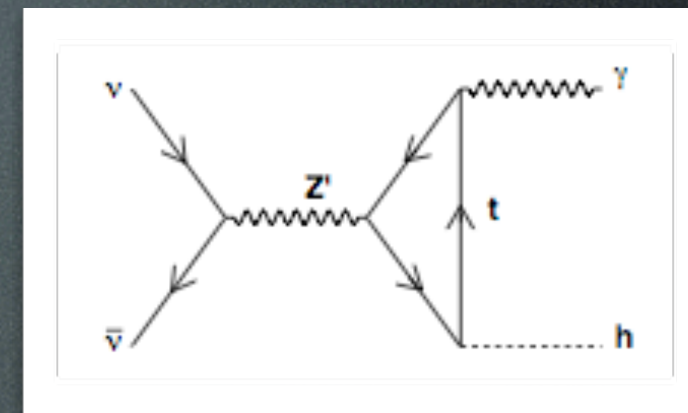
- For $M_Z/2 < M_\nu <$ m_t, loop-level annihilations into γZ, γH and bb also
- For range of parameters we're interested in, $M_\nu \approx m_t$





calculation of lines

- Annihilation proceeds via an s-channel Z' and a closed loop of top quarks



- As a consequence, no γγ line! (Landau-Yang theorem)

- Possible lines include γZ, γH... and maybe γZ'

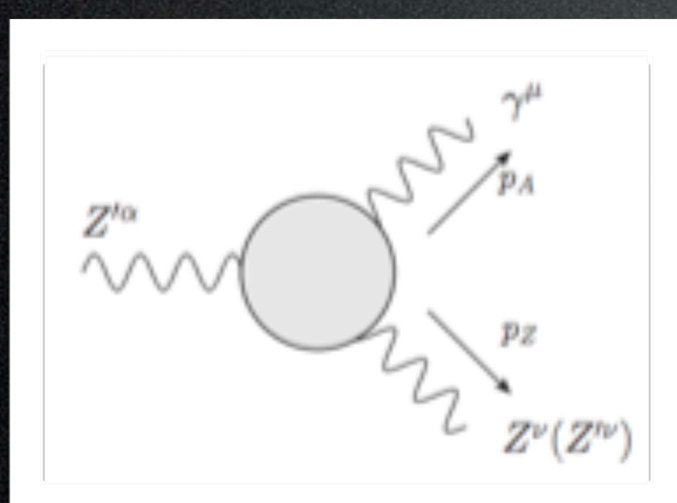
- The γH cross section:

$$\sigma v = \frac{1}{64\pi M^2}\left(1 - \frac{M_X^2}{4M^2}\right)\overline{|\mathcal{M}|^2}$$

$$\overline{|\mathcal{M}|^2}_{\gamma h} = \frac{\alpha\alpha_t N_c^2}{72\pi^2}\mathcal{V}^2 \frac{\left(g_t^{Z'} g_\nu^{Z'}\right)^2 M_\nu^2 m_t^2}{\left(4M_\nu^2 - M_{Z'}^2\right)^2 + M_{Z'}^2\Gamma_{Z'}^2}$$

$$\begin{aligned} \mathcal{V}_{\gamma h} &= \frac{8M_\nu^2}{(m_h^2 - 4M_\nu^2)}\left[B_0\left(m_h^2; m_t, m_t\right) - B_0\left(4M_\nu^2; m_t, m_t\right)\right] \\ &+ \left[4M_\nu^2 + 4m_t^2 - m_h^2\right] C_0\left(m_h^2, 0, 4M_\nu^2; m_t, m_t, m_t\right) + 2 \end{aligned}$$

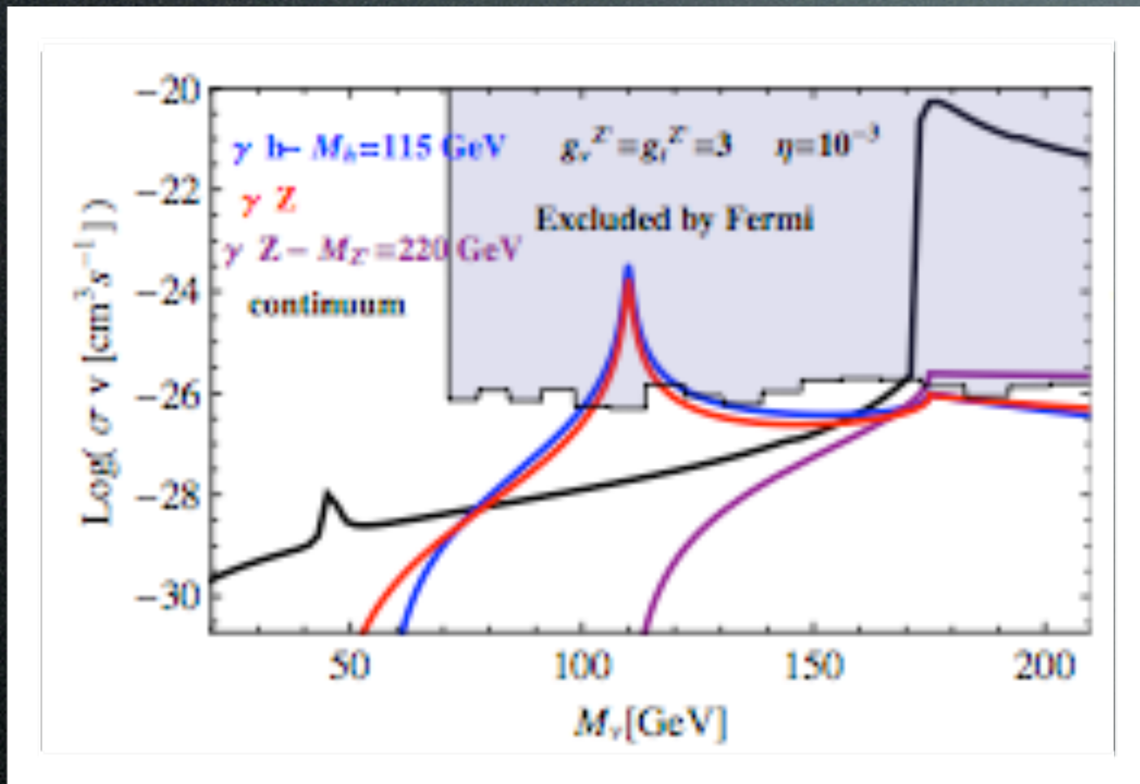
- The γZ (γZ') vertex:



$$\Gamma^\alpha = \epsilon_\mu^*(p_A)\epsilon_\nu^*(p_Z)\sum_{i=1}^{5} C_i M_i^{\alpha\mu\nu}$$

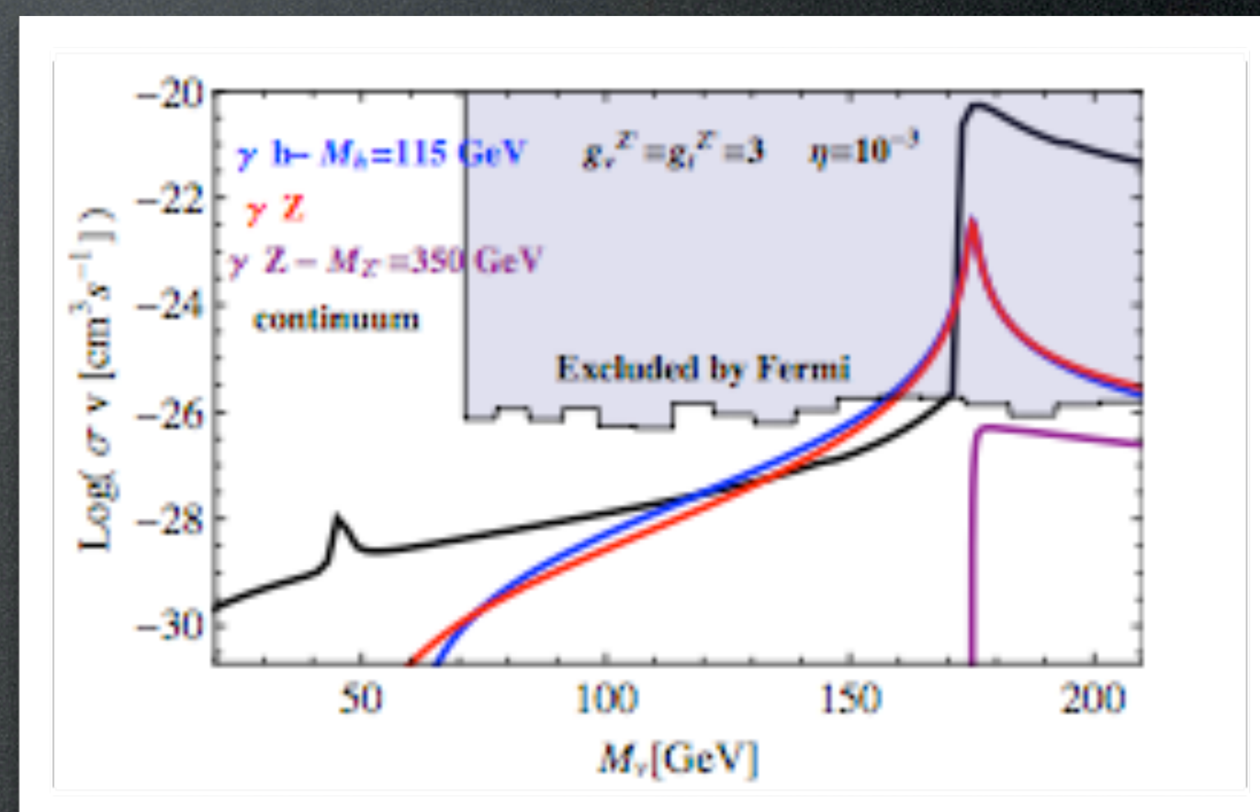
$$C_4 = \frac{4\left(a_t g_V^t + v_t g_A^t\right)}{M_Z^2 - 4M_\nu^2}\left(B_0(4M_\nu^2; m_t^2, m_t^2) - B_0(M_Z^2; m_t^2, m_t^2)\right),$$

cross sections

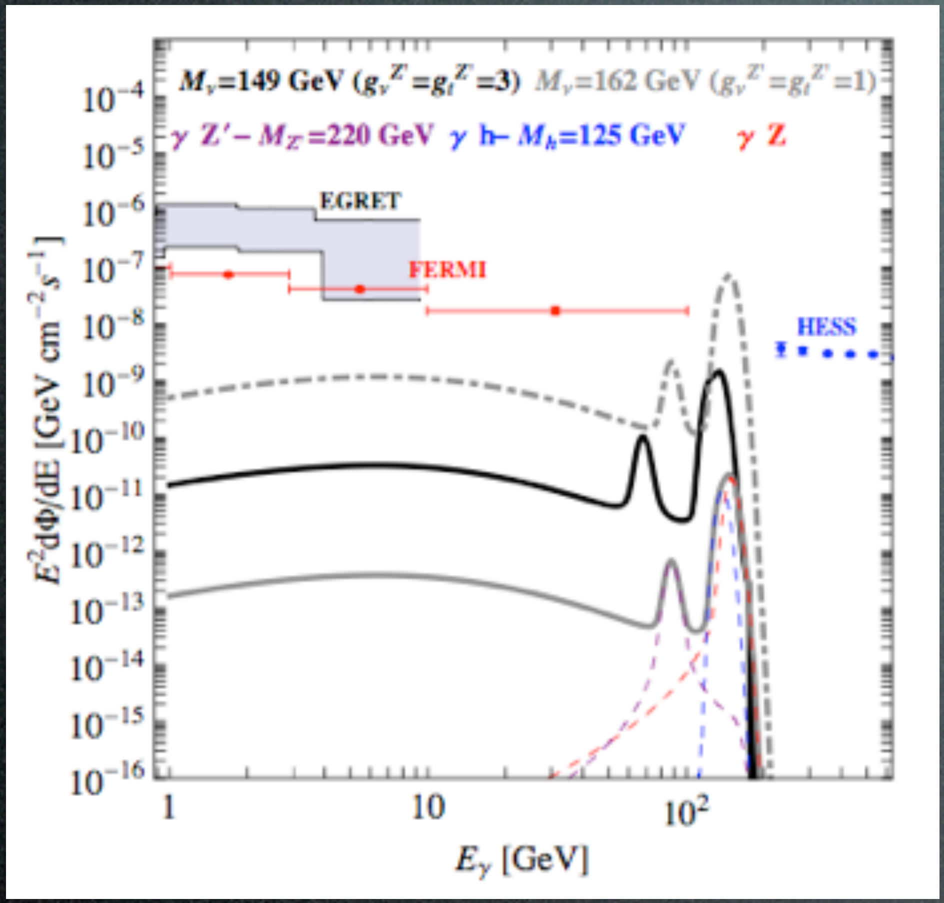


- Below tt threshold, continuum emission mainly through light quarks… SUPPRESSED!
    - small kinetic mixing η
    - loop-suppressed Z'bb coupling

- Line cross sections can be strongly-enhanced due to Z' resonance!
- Early Fermi data already restricting model's parameter space!



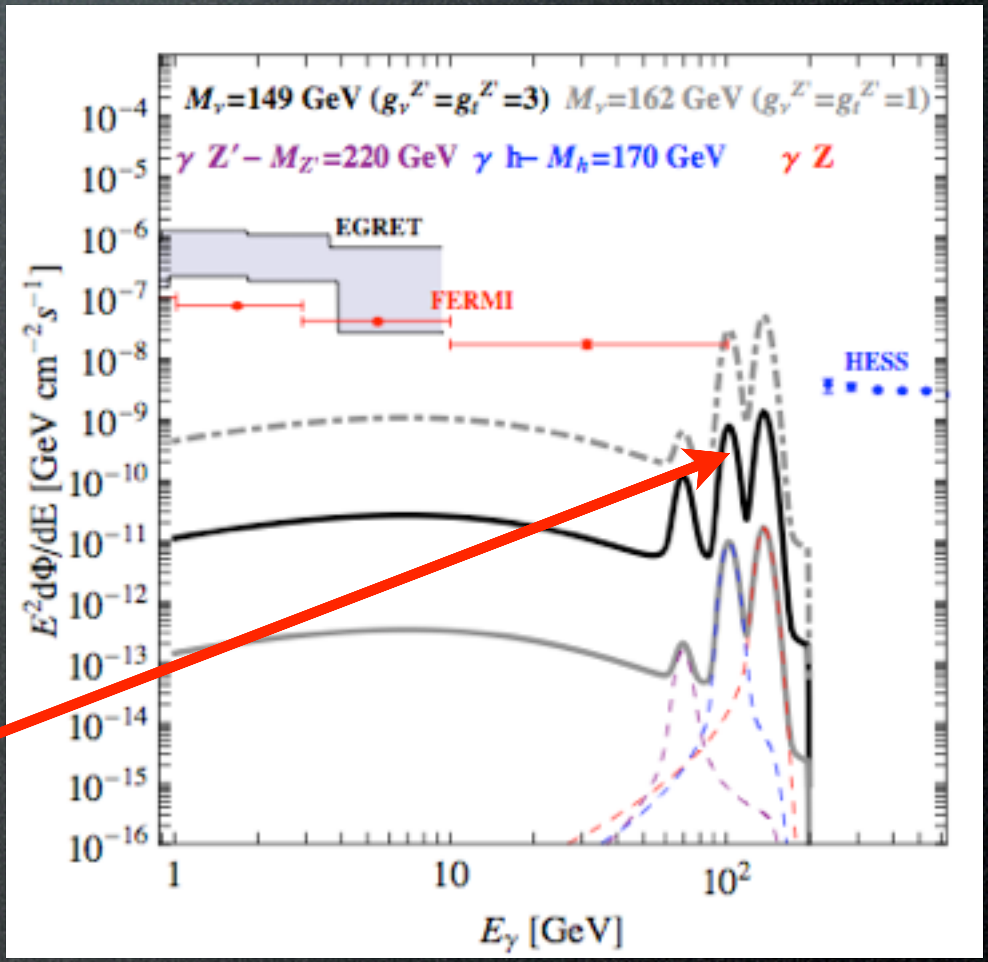
the γ-ray spectrum



- Source = Galactic Center
- Solid black = NFW profile
  Dot-dashed gray = Adiabatic profile
- Detector resolution = 10%
- WIMP mass of 162 GeV and
  Z' mass of 220 GeV

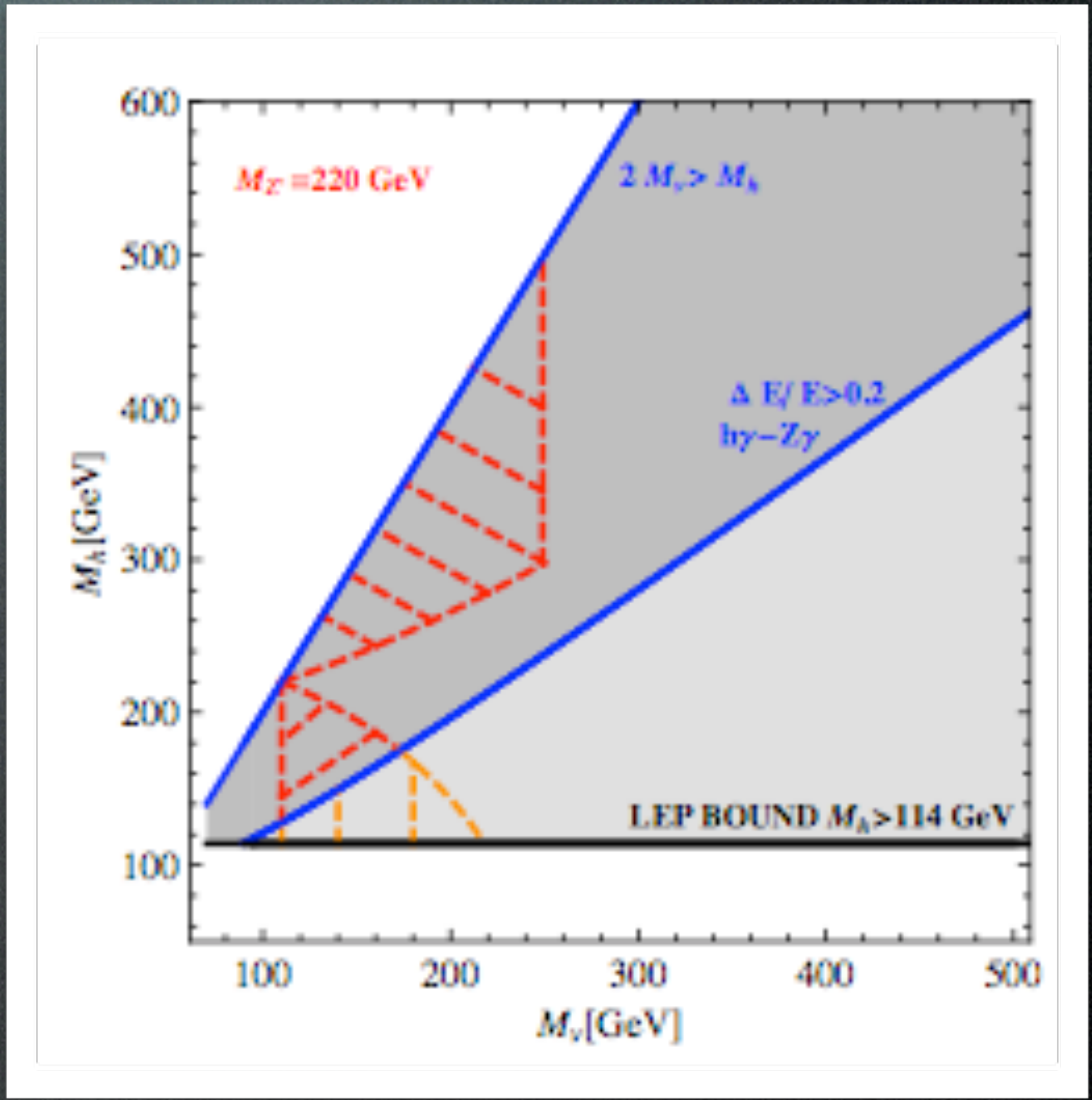
- For lighter Higgs masses, the γZ and γH lines merge
- However, for heavier Higgs masses, THREE LINES!

Higgs in Space!



how many lines?

- Scan over parameter space to see when γH can be resolved
- γH discernible from γZ when energy separation ~ $2(\Delta E/E)$
- Anything below this, γH and γZ merge into one bump (light grey)
- Huge part of parameter space produces (at least) two lines!
- Significant chunk of parameter space produces three lines! (red dashed)



conclusions

- Exciting times in the search for Dark Matter!
- The search for γ-ray lines from DM annihilation is playing a significant part
- Besides confirming the existence of WIMPs, observations of multiple γ-ray lines from DM annihilation may illuminate the “dark sector”
- A “WIMP Forest”? Dark Matter spectroscopy? (best examples: Inert Doublet Model, 6-d UEDs)
- Higgs in Space!
  - Dynamics of EWSB and DM related? If so, WIMPs may have enhanced couplings to massive states (just like the Higgs!)
  - DM-top quark connection: huge region of parameter space allows for observation of γH line!
  - Might be seeing the Higgs sooner than expected!

backup slides...

issues with our model

- UV completion: RS model studied by Agashe and Servant
  - Based on SUSY paradigm where R-parity (which is initially imposed to conserve baryon number) results in stable LSP
  - RS setup with a bulk SO(10) GUT symmetry... plus a Z_3 discrete symmetry (protect against too rapid proton decay)
  - ν is a bulk field with (-,+) BCs... Z' represents lowest KK mode of U(1) contained in the SO(10)
- $[U(1)']^3$ and U(1)'-SM gauge anomalies:
  - assume these are cancelled by the presence of additional massive fermions... whose presence don't really affect γ-ray signals
  - these massive fermions also contribute to χ

more issues...

- Not renormalizable!
- Which quantities (that are important for our analysis) can be computed reliably?
- Finite: Z'γZ, Z'γH and Z'γZ' (loops of top quarks)
- Log-divergent: Z'bb coupling...
    - Precise value ill-defined, but we expect it to be of order:

$$g_{Z'b\bar{b}} \sim g_t^{Z'} \frac{\alpha}{32\pi s_W^2} \frac{m_t^2}{M_W^2} \log\left(\frac{\Lambda^2}{Q^2}\right)$$

with $\log(\Lambda^2/Q^2) = 1$