Little Higgs Dark Matter

Andrew Noble
in collaboration with
Andreas Birkedal, Maxim Perelstein, and Andrew Spray

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Littlest Higgs with T Parity

- The "Little Higgs" question: Could the Higgs be a pseudo-GSB of a global symmetry broken at a scale f ~ 1TeV?

Georgi, et. al. (1974)

- Higgs mass unstable: With 1-loop corrections, $m_h \rightarrow f$.
Solution: Collective Symmetry Breaking ("Bosonic SUSY").

Arkani-Hamed, Cohen, Georgi (2002)

- An economical implementation: The "Littlest Higgs" model.
a) EW sector embedded in an SU(5)/SO(5) nlsm.
b) Heavy vector quark, triplet scalar, and four GB's.

Arkani-Hamed, Cohen, Katz, Nelson (2002)

- Little Hier. Problem: Violates EWPM without fine-tuning.
Solution: A Z_2 symmetry dubbed "T Parity" (LH's R Parity).

Cheng and Low (2004)

600GeV < f < 3TeV OK!

Hubisz, Meade, AN, and Perelstein (2005)

Heavy Particle Spectrum

m

f T_+ T_- Φ

$W_H \sim g\, f$ $\tilde{Q} \sim \kappa\, f$

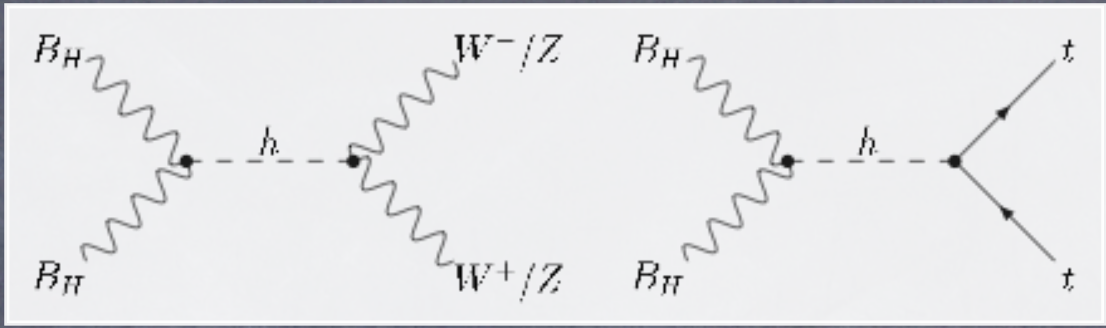
v $B_H \sim g' f/\sqrt{5}$

Generic DM
(100GeV<M<500GeV)

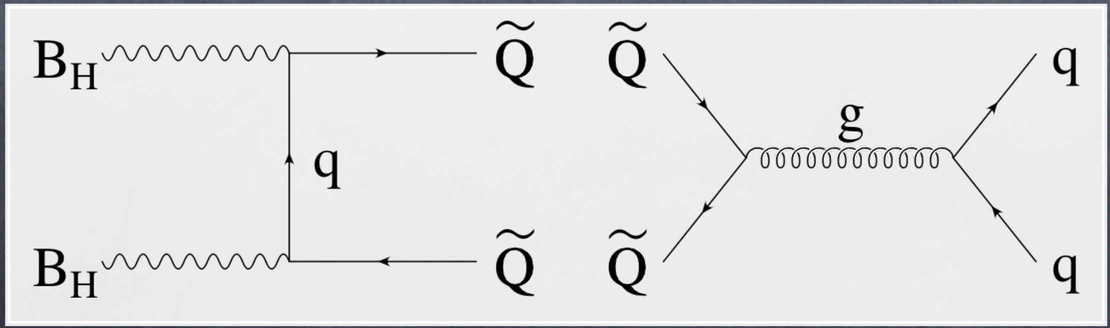
Coannihilator
$\tilde{M}$>M

Relic Density

- ✳ Pair annihilation: $\langle \sigma v \rangle$ gives $\Omega_{dm} h^2$. B_H is an s-ann.

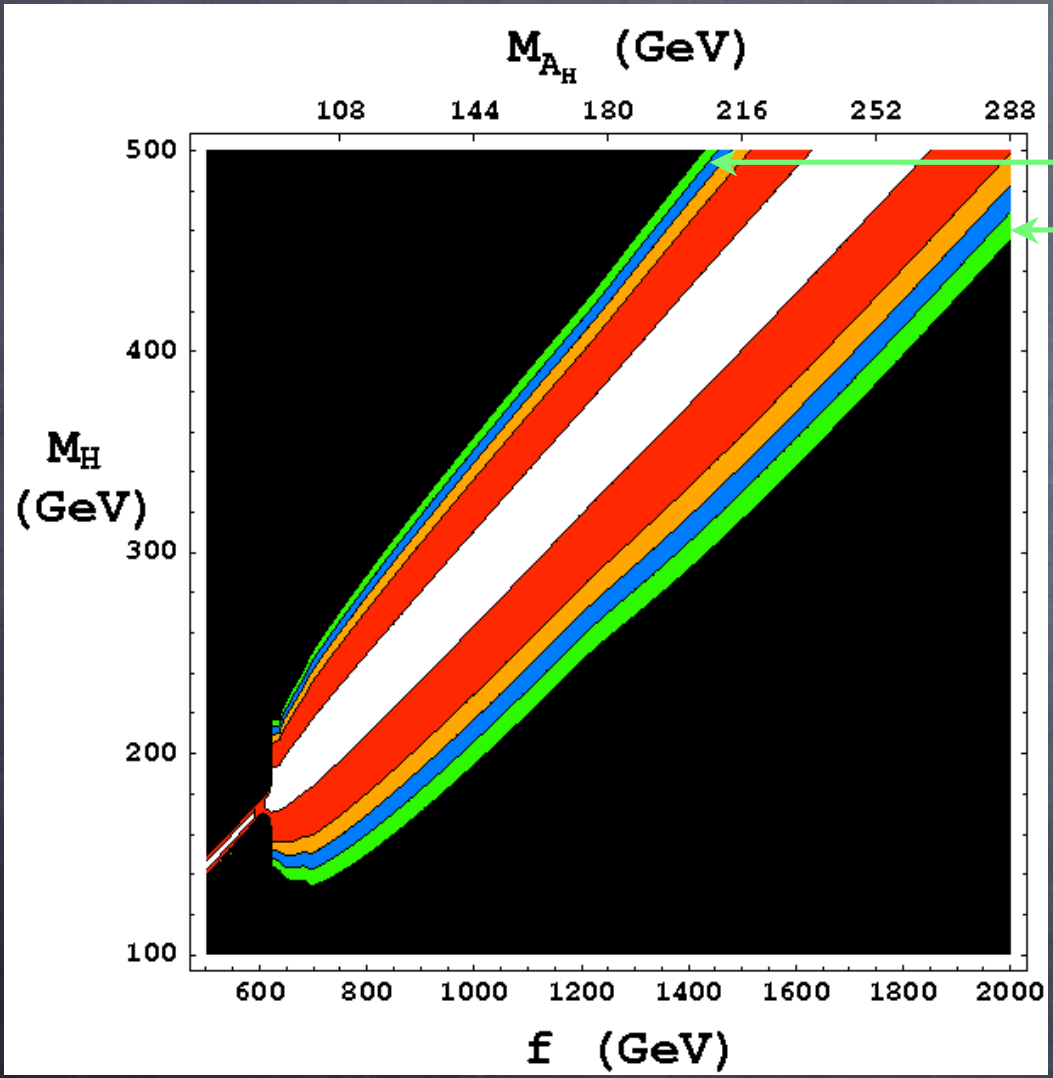


- ✳ Coannihilation: Solve two coupled Boltzmann equations.



Pair-Annihilation

Hubisz and Meade (2004)



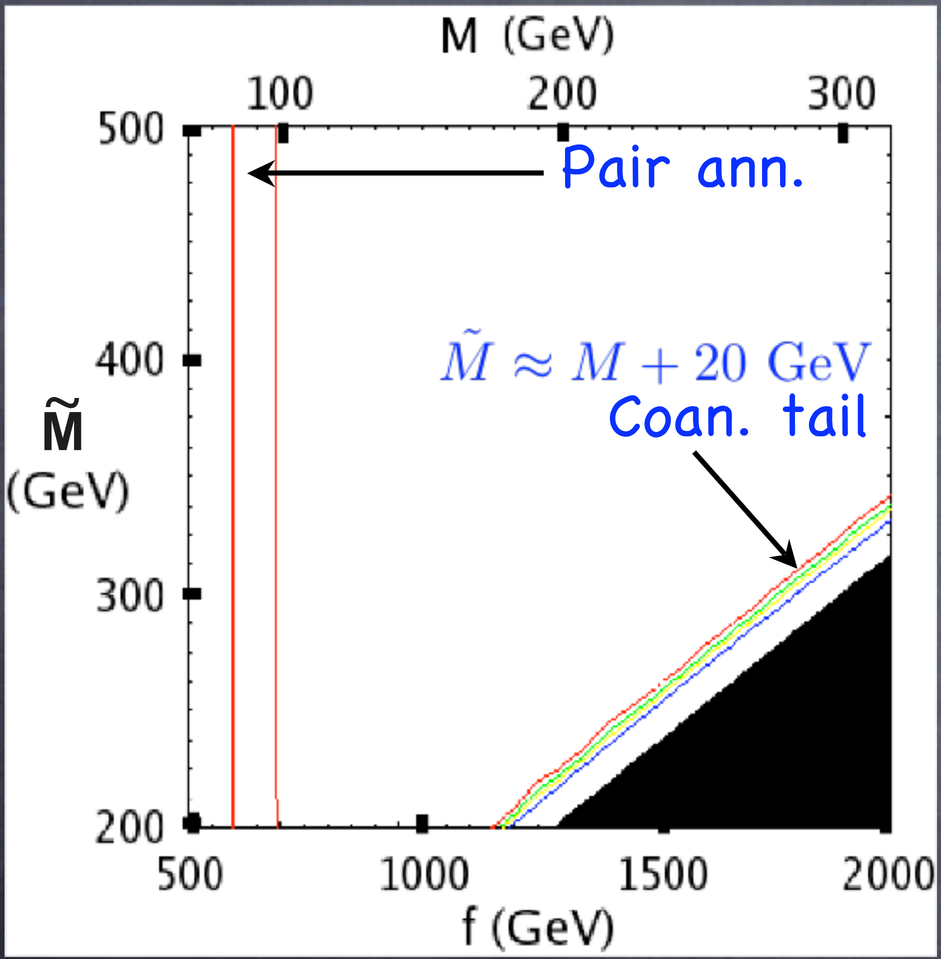
"High" $m_h \approx 2.38M + 24\text{GeV}$

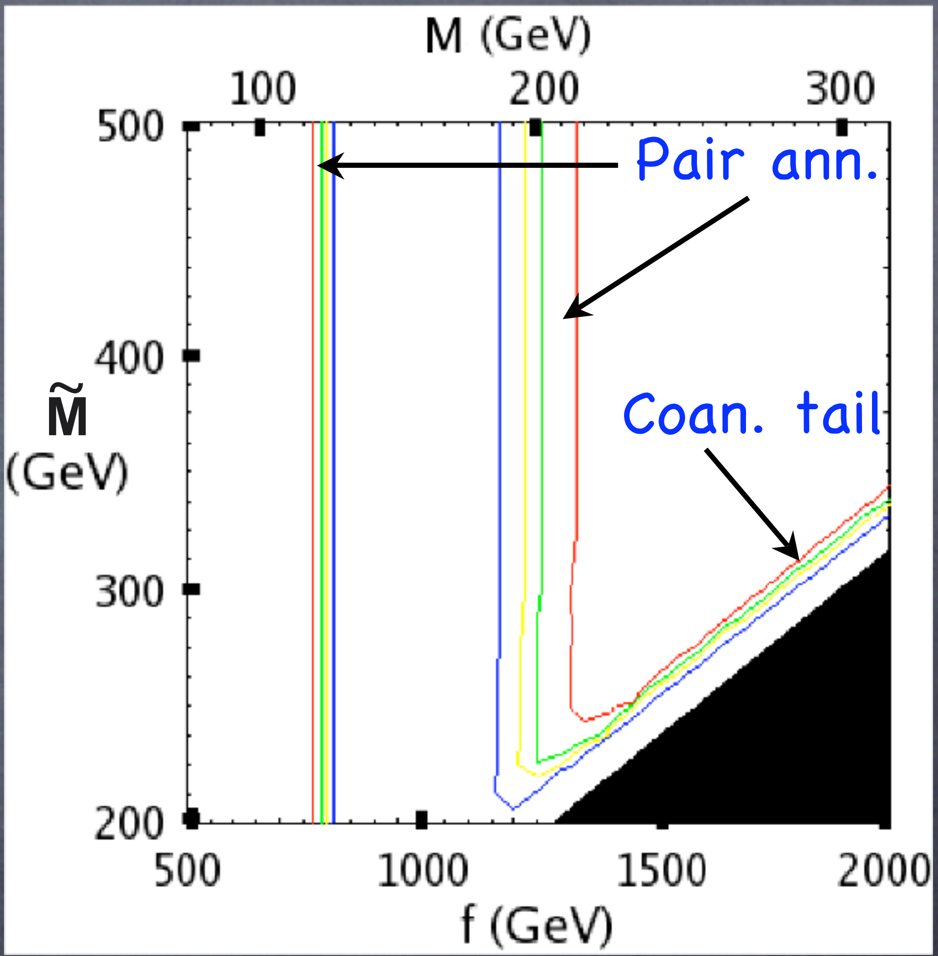
"Low" $m_h \approx 1.89M - 83\text{GeV}$

Regions where B_H accounts for 100% of the WMAP DM value.

$$\Omega_{dm}h^2 = 0.111 \pm 0.018$$

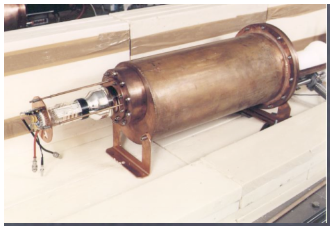
Coannihilation





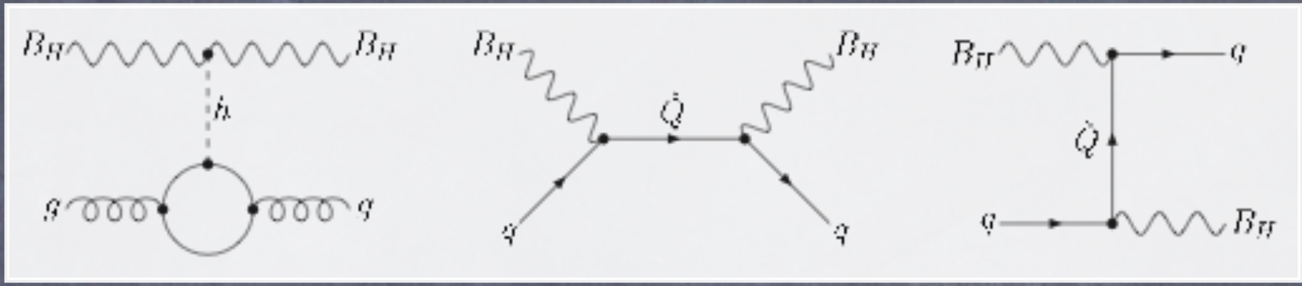
$m_h = 120$GeV

$m_h = 300$GeV



Direct Detection

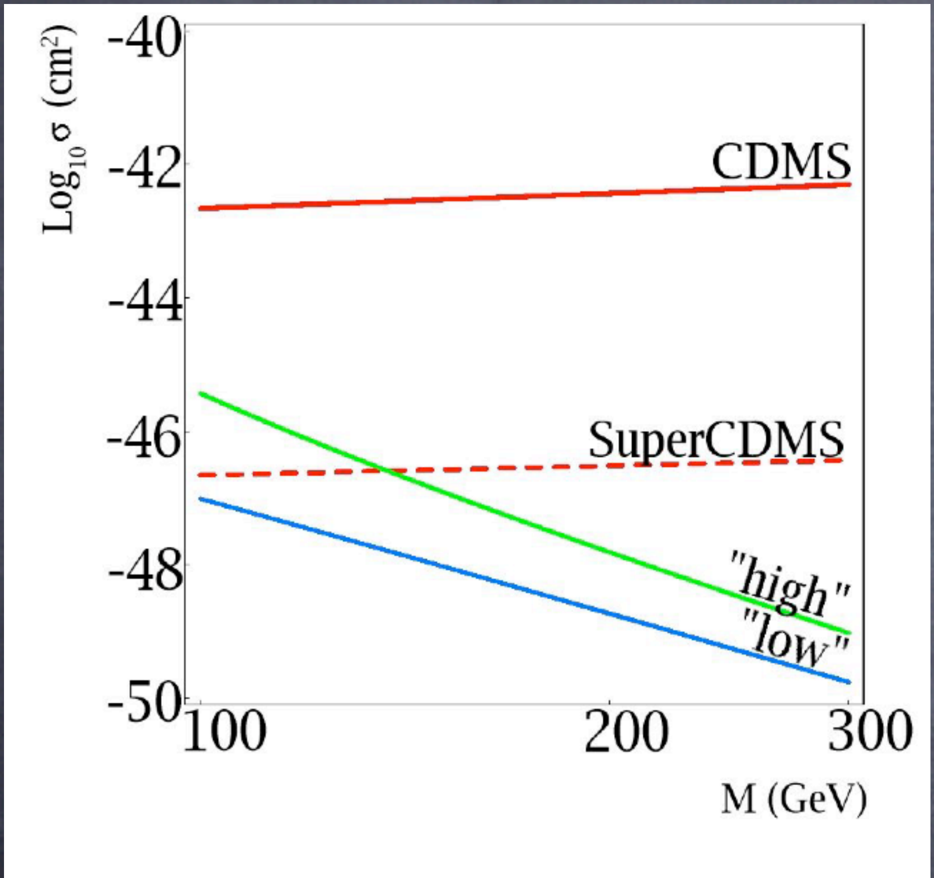
- Measuring the recoil energy of a nucleus due to an elastic collision with a WIMP.



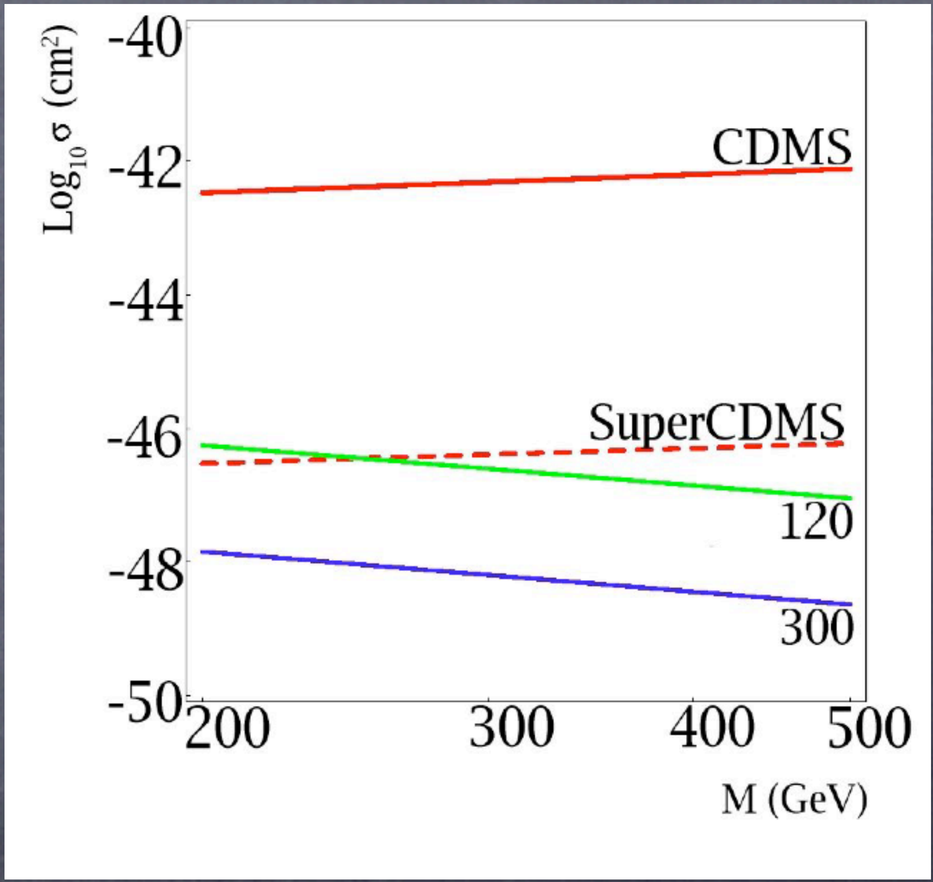
- In the NRL, the cross-sections can be divided into spin-independent and spin-dependent contributions.

- The small couplings of B_H to partons result in DD cross-sections significantly below current sensitivities.

Spin-Independent

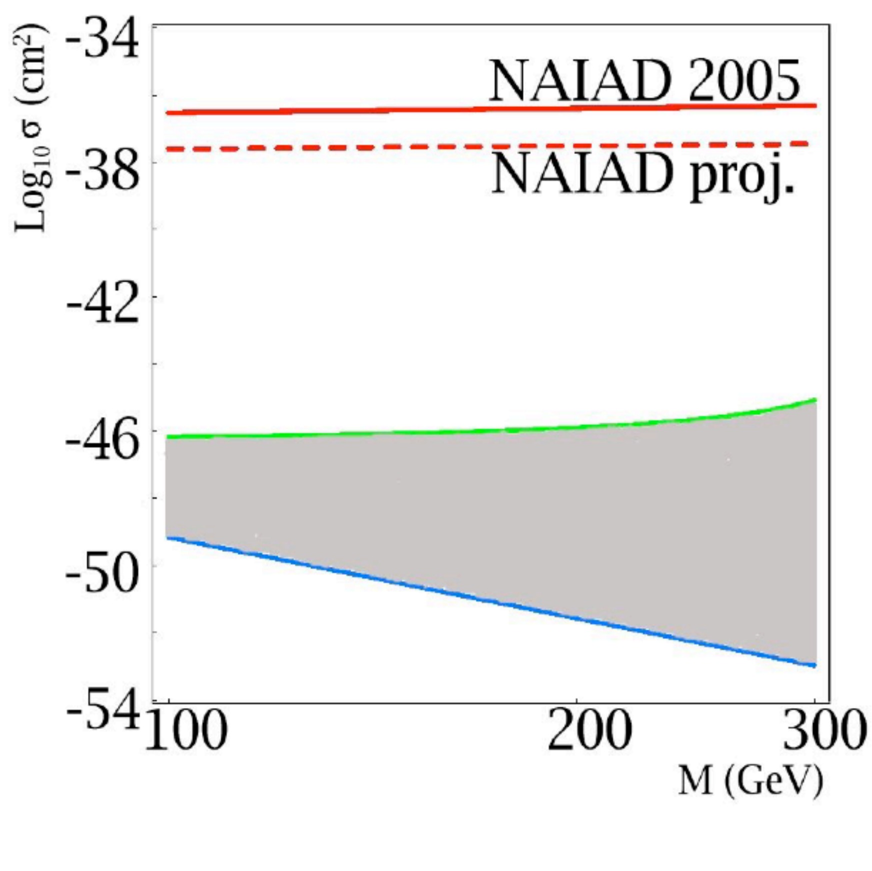


Pair annihilation

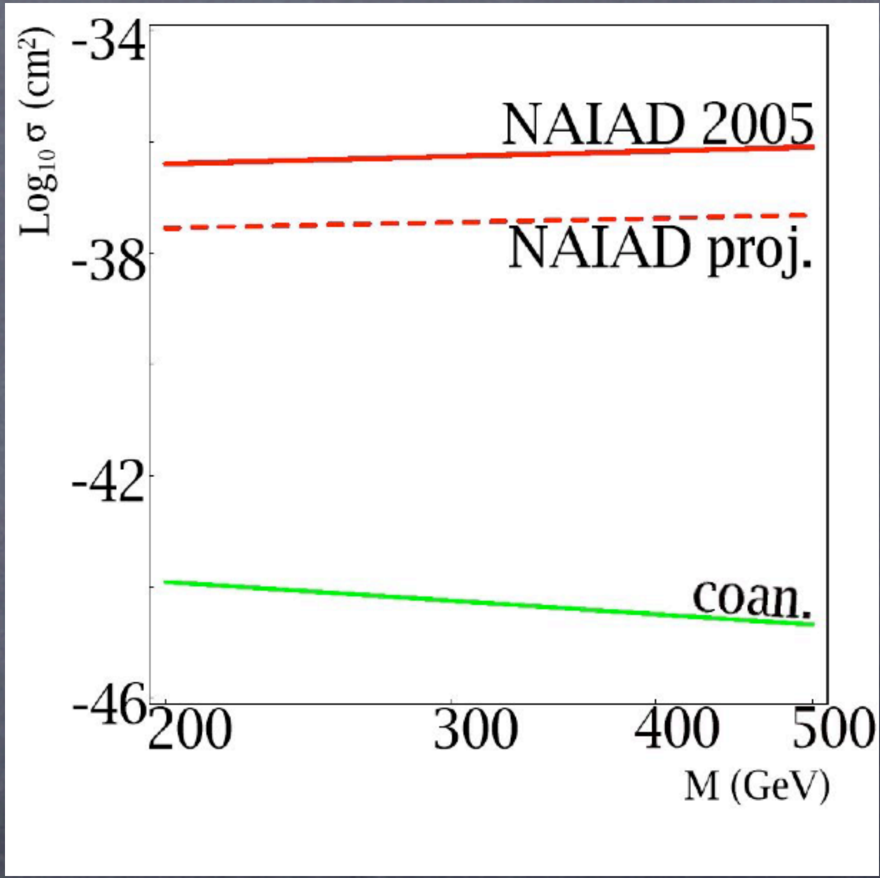


Coannihilation Tail

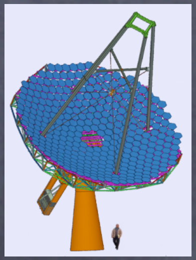
Spin-Dependent



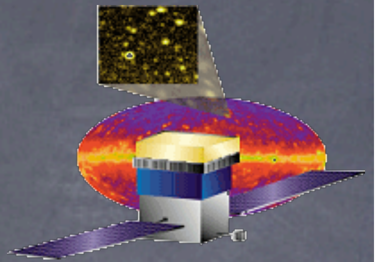
Pair annihilation



Coannihilation Tail



Gamma Ray Indirect Detection

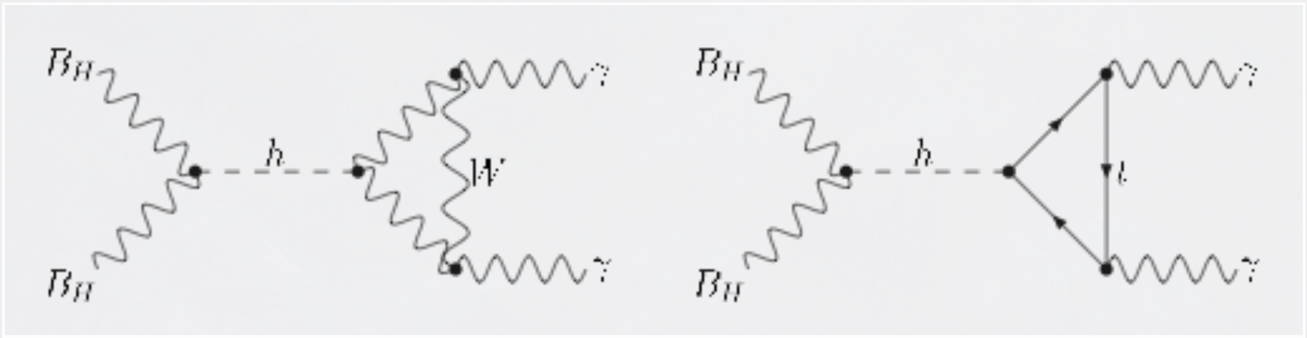


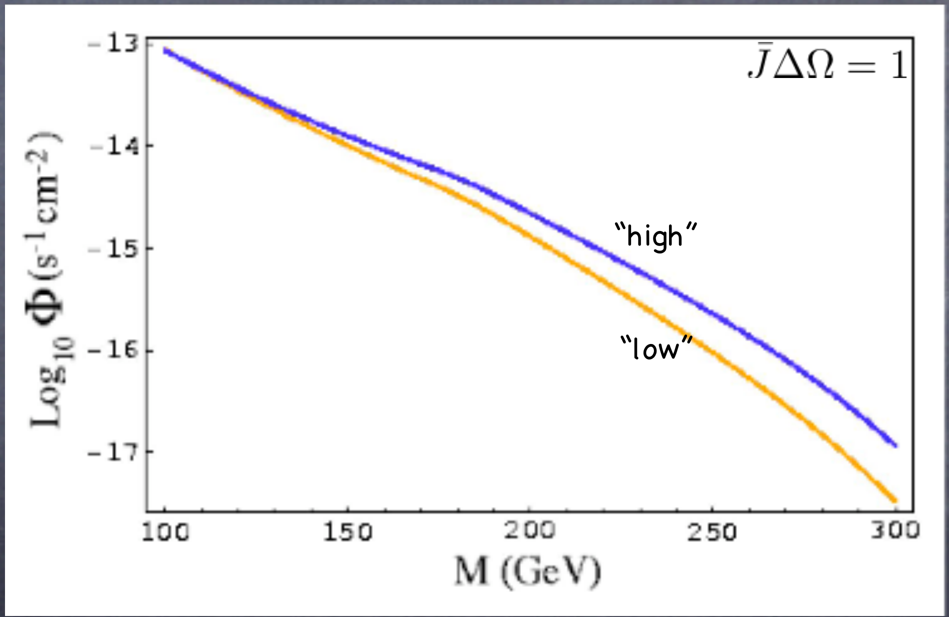
- Goal: Distinguish fluxes due to WIMP annihilation in the galactic center from astrophysical backgrounds.

$$\Phi \sim \frac{\sigma v}{M^2} \bar{J}(\theta, \phi, \Delta\Omega) \Delta\Omega$$

- Since B_H is an s-annihilator, LHT DM fluxes are larger than those for Bino-like SUSY DM.
- $\bar{J}$ contains the dependence on the halo dark matter density squared.
- For $\Delta\Omega = 10^{-3}\mathrm{sr}$, typical of ACTs, estimates of $\bar{J}$ near the galactic center range from 10^3 to 10^7.

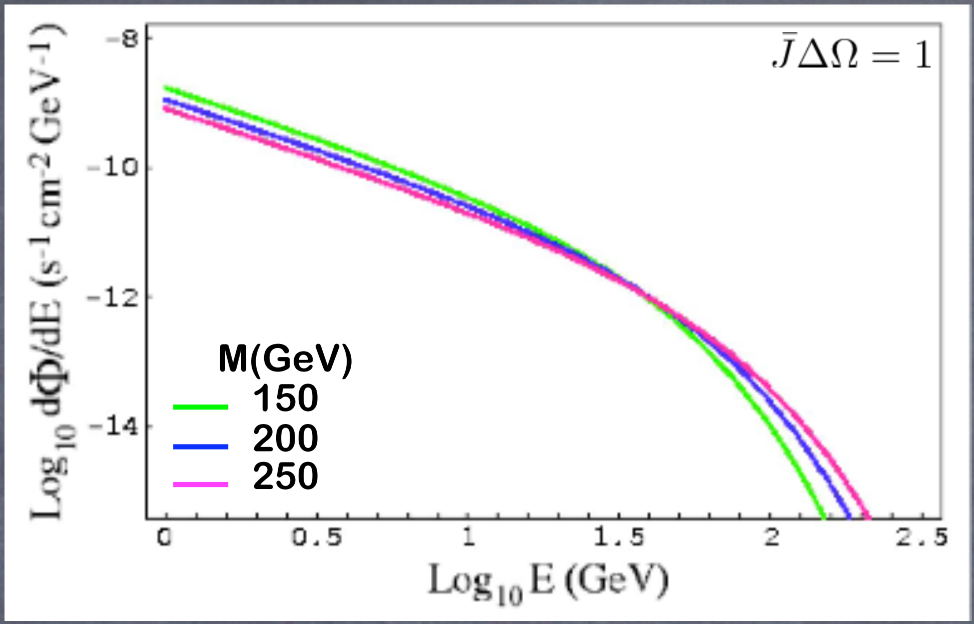
Monochromatic "Line" Flux





ACT sensitivity $\Phi \sim (1-5) \times 10^{-12} \mathrm{cm}^{-2} \mathrm{sec}^{-1}$

Fragmentation Flux



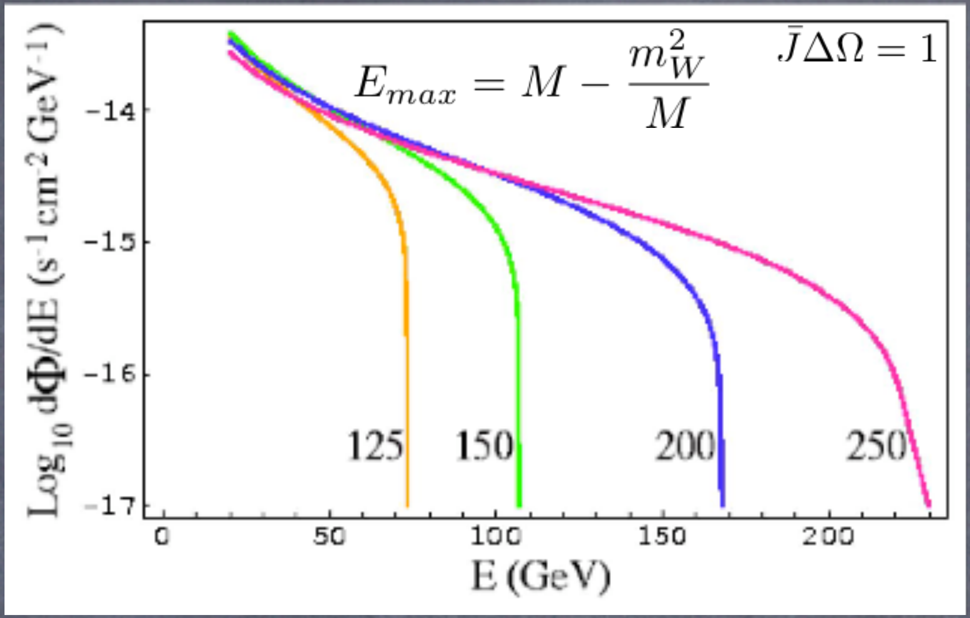
- Dominant production process:

$$B_H + B_H \rightarrow W^+W^-, ZZ \;/\; W, Z \rightarrow q\bar{q} \;/\; q \rightarrow \pi^0 \ldots \;/\; \pi^0 \rightarrow \gamma\gamma$$

- GLAST should see ~50 zero bkg events above 2GeV.

- But a soft, featureless spectrum makes this signal difficult to distinguish from astrophysical backgrounds.

Final State Radiation Flux



- Dominant production process: $B_H + B_H \rightarrow W^+W^-\gamma$
- Flux reduced by a factor of α compared to fragmentation photons.
- Observation of the edge feature would strengthen the case for WIMPs and provide a measurement of M.

Birkedal, Matchev, Perelstein, and Spray (2005)

Conclusions

- The "heavy photon" B_H in the Littlest Higgs with T Parity provides a potential DM candidate.
- B_H can account for 100% of observed DM in both the pair annihilation and coannihilation scenarios.
- Current direct detection prospects are low, but SuperCDMS would be sensitive to these cross-sections.
- Indirect detection with the current ACT sensitivities would require $\bar{J} \gtrsim 10^5 - 10^6$.
- GLAST has the sensitivity to observe ~50 anomalous gamma rays due to the fragmentation flux.

The NLΣM Structure of the Littlest Higgs Model

An effective field theory for physics below $\Lambda \sim 4\pi f$ ($f \sim 1$TeV), the scale where strong dynamics induces SSB.

Globally $SU(5) \rightarrow SO(5)$

Gauged subgroup $[SU(2) \times U(1)]^2 \rightarrow SU(2)_L \times U(1)_Y$

Gauged generators

$$Q_1^a = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad Y_1 = \mathrm{diag}(3,3,-2,-2,-2)/10$$

$$Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*}/2 \end{pmatrix} \qquad Y_2 = \mathrm{diag}(2,2,2,-3,-3)/10$$

LHT Mass Spectrum

$$m_t = \frac{\lambda_1 \lambda_2 v}{\sqrt{\lambda_1^2 + \lambda_2^2}} \qquad m_{T_+} = \sqrt{\lambda_1^2 + \lambda_2^2} f \qquad m_{T_-} = \lambda_2 f$$

$$m_{\tilde{Q}} = \sqrt{2}\kappa f$$

$$m_{W_H} = g f \qquad m_{B_H} = \frac{g' f}{\sqrt{5}}$$

$$m_\Phi = \frac{\sqrt{2} m_h f}{v}$$

Collective Symmetry Breaking

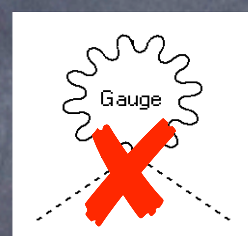
Idea from Arkani-Hamed, Cohen, Georgi (2001)

If we turn off either the g_1 or g_2 coupling, the higgs is an exact Goldstone boson of an unbroken SU(3) symmetry.

g_1 turned off → only gauge

$$Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*}/2 \end{pmatrix}$$

$$Y_2 = \mathrm{diag}(2,2,2,-3,-3)/10$$



$SU(3)_1$

$$\Pi = \begin{pmatrix} 0 & \frac{H}{\sqrt{2}} & \phi \\ \frac{H^\dagger}{\sqrt{2}} & 0 & \frac{H^T}{\sqrt{2}} \\ \phi^\dagger & \frac{H^*}{\sqrt{2}} & 0 \end{pmatrix}$$

$SU(3)_2$

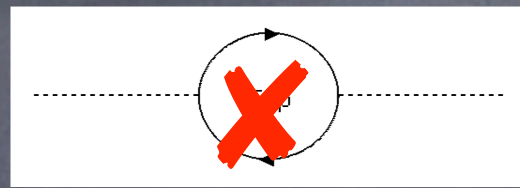
g_2 turned off → only gauge

$$Q_1^a = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$Y_1 = \mathrm{diag}(3,3,-2,-2,-2)/10$$

Top Sector Modification:

$\mathcal{L}_{T_{even}}$ must follow the collective symmetry breaking pattern to cancel,



Extend the two fermion doublets in this sector to SU(3) representations.

$$\mathcal{Q}_1 = \begin{pmatrix} q_1 \\ U_{L1} \\ 0 \end{pmatrix}, \mathcal{Q}_2 = \begin{pmatrix} 0 \\ U_{L2} \\ q_2 \end{pmatrix}$$ where, under T Parity, $$U_{L1} \leftrightarrow -U_{L2}$$

Then the top sector Lagrangian supporting collective symmetry breaking is,

$$\mathcal{L}_t = \frac{1}{2\sqrt{2}}\lambda_1 f \epsilon_{ijk}\epsilon_{xy}\left[(\bar{\mathcal{Q}}_1)_i\Sigma_{jx}\Sigma_{ky} - (\bar{\mathcal{Q}}_2\Sigma_0)_i\tilde{\Sigma}_{jx}\tilde{\Sigma}_{ky}\right]u_R + \lambda_2 f(\bar{U}_{L1}U_{R1} + \bar{U}_{L2}U_{R2}) + \text{h.c.}$$

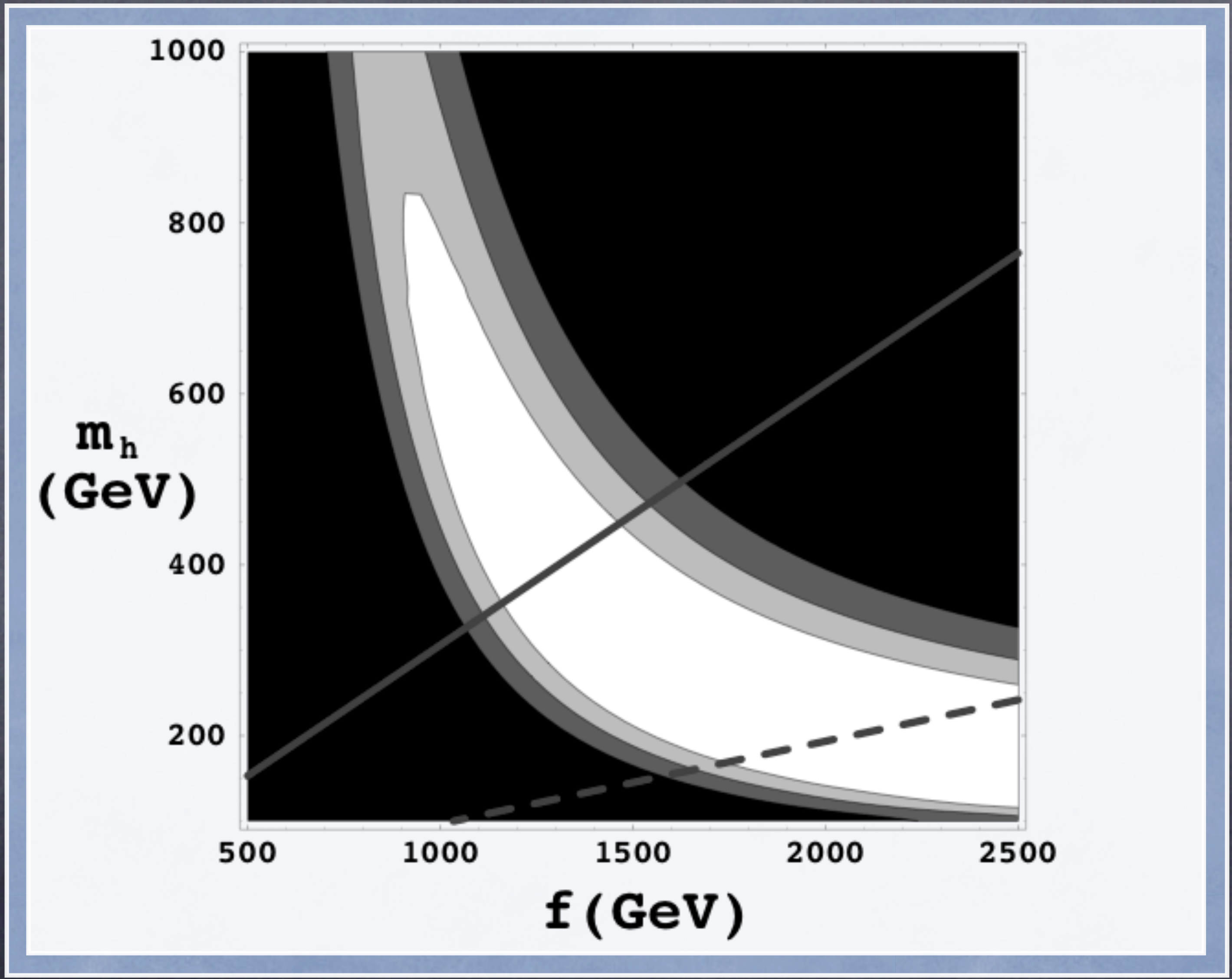
Breaks one T-even SU(3) Breaks other T-even SU(3)

In the mass eigenbasis, we find,

$$t_L = u_{L+} - s_\lambda^2\frac{v}{f}U_{L+} \qquad T_{L+} = U_{L+} + s_\lambda^2\frac{v}{f}u_{L+}$$

$$t_R = c_\lambda u_R - s_\lambda U_{R+} \qquad T_{R+} = c_\lambda U_{R+} + s_\lambda u_R$$

A Heavy Higgs Region



$R = 2,\ \delta_c = 0,\ \kappa = 0$

Relic Abundance

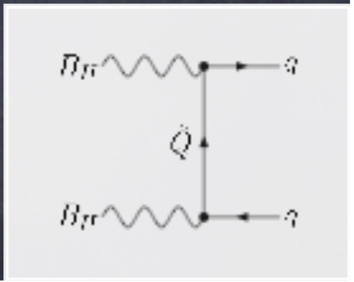
$$a(W^+W^-) = \frac{2\pi\alpha^2}{3\cos^4\theta_W}\,\frac{M^2}{(4M^2 - m_h^2)^2 + m_h^2\Gamma_h^2}\left(1 - \mu_w + \frac{3}{4}\mu_w^2\right)\sqrt{1 - \mu_w}$$

$$a(ZZ) = \frac{\pi\alpha^2}{3\cos^4\theta_W}\,\frac{M^2}{(4M^2 - m_h^2)^2 + m_h^2\Gamma_h^2}\left(1 - \mu_z + \frac{3}{4}\mu_z^2\right)\sqrt{1 - \mu_z}$$

$$a(t\bar{t}) = \frac{\pi\alpha^2}{4\cos^4\theta_W}\,\frac{M^2}{(4M^2 - m_h^2)^2 + m_h^2\Gamma_h^2}\,\mu_t(1 - \mu_t)^{3/2}$$

$$a(hh) = \frac{\pi\alpha^2 M^2}{2\cos^4\theta_W}\left[\frac{\mu_h(1 + \mu_h/8)}{(4M^2 - m_h^2)^2 + m_h^2\Gamma_h^2} + \frac{1}{24M^4}\right]\sqrt{1 - \mu_h}$$

$$a(f\bar{f}) = \frac{16\pi\alpha^2\tilde{Y}^4 N_c^f}{9\cos^4\theta_W}\,\frac{M^2}{(M^2 + \tilde{M}^2)^2}$$



Direct Detection: SI

$$\mathcal{L}_{hgg} = \frac{\alpha_s}{12\pi v} h G^a_{\mu\nu} G^{a\mu\nu}$$

$$\frac{\alpha_s \alpha}{6\cos^2\theta_W} \frac{1}{m_h^2} B_{\mathrm{H}\alpha} B^\alpha_{\mathrm{H}} G^a_{\mu\nu} G^{a\mu\nu}$$

$$\mathcal{L}_{\mathrm{eff}} = \frac{e^2}{27\cos^2\theta_W} \frac{m_n}{m_h^2} B_{\mathrm{H}\alpha} B^\alpha_{\mathrm{H}} \bar{\Psi}_n \Psi_n$$

$$\sigma_{\mathrm{SI}} = \frac{4\pi\alpha^2}{729\cos^4\theta_W} \frac{m_n^4}{m_h^4} \frac{1}{(M+m_n)^2}$$

Direct Detection: SD

$$-i\frac{e^2\tilde{Y}^2}{\cos^2\theta_W}\varepsilon^*_\mu(p_3)\varepsilon_\nu(p_1)\;\bar{u}(p_4)\left[\frac{\gamma^\mu\,\not{k}_1\gamma^\nu}{k_1^2-\tilde{M}^2}+\frac{\gamma^\nu\,\not{k}_2\gamma^\mu}{k_2^2-\tilde{M}^2}\right]P_L\,u(p_2)$$

$$\frac{e^2\tilde{Y}^2}{\cos^2\theta_W}\,\frac{M}{M^2-\tilde{M}^2}\,\epsilon_{ijk}\varepsilon_1^i\varepsilon_3^j\bar{u}_4\gamma^k(1-\gamma^5)u_2$$

$$\langle N|\bar{q}\gamma^\mu\gamma^5 q|N\rangle = 2s_N^\mu\lambda_q \qquad \lambda_q = \Delta q_p\frac{\langle S_p\rangle}{J_N}+\Delta q_n\frac{\langle S_n\rangle}{J_N}$$

$$\frac{2e^2\tilde{Y}^2M}{\cos^2\theta_W(M^2-\tilde{M}^2)}\epsilon_{ijk}B_H^iB_H^j\bar{\Psi}_N s_N^k\Psi_N\sum_{q=u,d,s}\lambda_q$$

$$\sigma_{\rm SD} = \frac{16\pi\alpha^2\tilde{Y}^4}{3\cos^4\theta_W}\frac{m_N^2}{(M+m_N)^2}\frac{M^2}{(M^2-\tilde{M}^2)^2}J_N(J_N+1)\left(\sum_{q=u,d,s}\lambda_q\right)^2$$

ID: Line Flux

$$\sigma_{\gamma\gamma} u \equiv \sigma\left(B_H B_H \to \gamma\gamma\right) u = \frac{g'^4 v^2}{72 M^4} \frac{s^2 - 4 s M^2 + 12 M^4}{(s - m_h^2)^2 + m_h^2 \Gamma_h^2} \frac{\hat{\Gamma}\left(h \to V_1 V_2\right)}{\sqrt{s}}$$

$$\hat{\Gamma}(h \to \gamma\gamma) = \frac{\alpha^2 g^2}{1024 \pi^3} \frac{s^{3/2}}{m_W^2} \left|\mathcal{A}_1 + \mathcal{A}_{1/2} + \mathcal{A}_0\right|^2$$

$$\Phi = (1.1 \times 10^{-9} \mathrm{s}^{-1} \mathrm{cm}^{-2}) \left(\frac{\sigma_{\gamma\gamma} u}{1 \text{ pb}}\right) \left(\frac{100 \text{ GeV}}{M}\right)^2 \bar{J}(\Psi, \Delta\Omega) \Delta\Omega$$

$$\bar{J}(\Psi, \Delta\Omega) \equiv \frac{1}{8.5 \text{ kpc}} \left(\frac{1}{0.3 \text{ GeV}/\mathrm{cm}^3}\right)^2 \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{\Psi} \rho^2 dl$$

ID: Fragmentation Flux

$$\frac{dN_\gamma}{dx} \approx \frac{0.73}{x^{1.5}} e^{-7.8x}$$

$$\frac{d\Phi}{dE} = \left(3.3 \times 10^{-12}\mathrm{s}^{-1}\mathrm{cm}^{-2}\mathrm{GeV}^{-1}\right) x^{-1.5} e^{-7.8x} \left(\frac{100\ \mathrm{GeV}}{M}\right)^3 \bar{J}(\Psi, \Delta\Omega)\Delta\Omega,$$

ID: FSR Flux

$$\frac{d\sigma}{dx}\left(B_H B_H \to W^+W^-\gamma\right) = \sigma\left(B_H B_H \to W^+W^-\right)\mathcal{F}(x;\mu_w)$$

$$\mathcal{F}(x;\mu) = \frac{\alpha}{\pi}\frac{1}{\sqrt{1-\mu}}\frac{1}{x}\times\Bigg[(2x-2+\mu)\log\frac{2(1-x)-\mu-2\sqrt{(1-x)(1-x-\mu)}}{\mu}$$
$$+2\left(\frac{8x^2}{4-4\mu+3\mu^2}-1\right)\sqrt{(1-x)(1-x-\mu)}\Bigg]$$

$$\mathcal{F}(x) = \frac{2\alpha}{\pi}\frac{1-x}{x}\left[\log\frac{s(1-x)}{m_W^2} + 2x^2 - 1 + \mathcal{O}(\mu)\right]$$

$$\frac{d\Phi}{dE} = \left(5.6\times 10^{-12}\mathrm{s}^{-1}\mathrm{cm}^{-2}\mathrm{GeV}^{-1}\right)\left(\frac{a(W^+W^-)}{1\ \mathrm{pb}}\right)\mathcal{F}(x;\mu_w)\left(\frac{100\ \mathrm{GeV}}{M}\right)^3\bar{J}(\Psi,\Delta\Omega)\Delta\Omega,$$