30 GeV Dark Matter and b quarks: Particle Physics Implications

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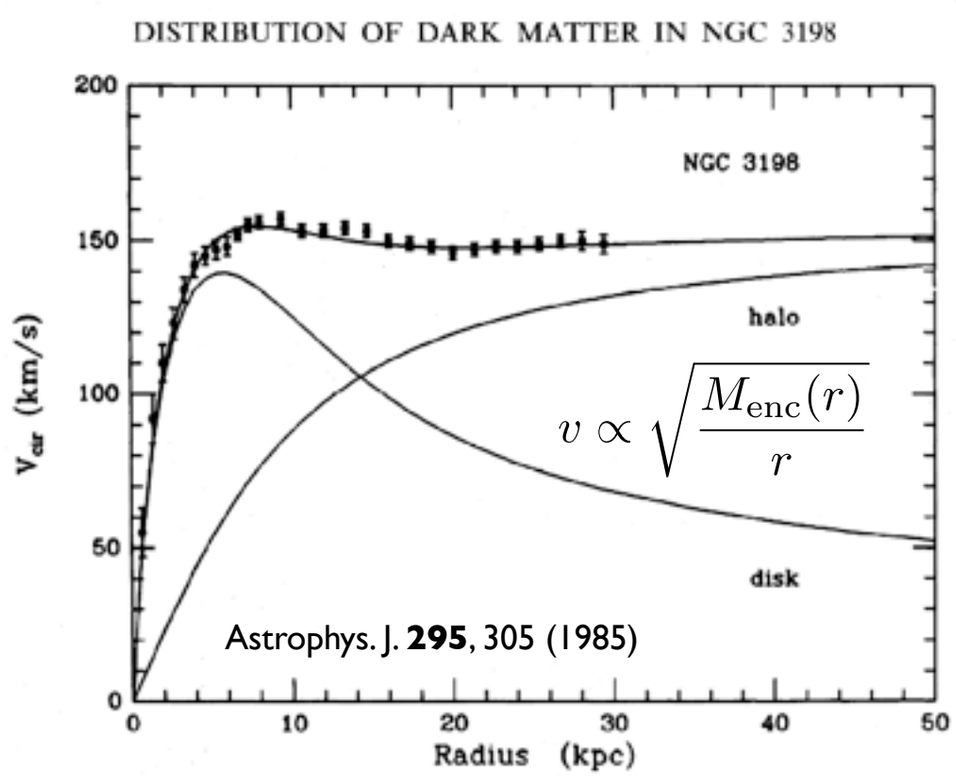
University of Washington
FNAL Theory Seminar April 15, 2014

Based on:
Ipek, McKeen, & Nelson, arXiv:1404:3716

Outline

- (Very) briefly: Why DM?
- How to learn about DM
- Has it been seen?
- A simple model and its consequences

Why Dark Matter?



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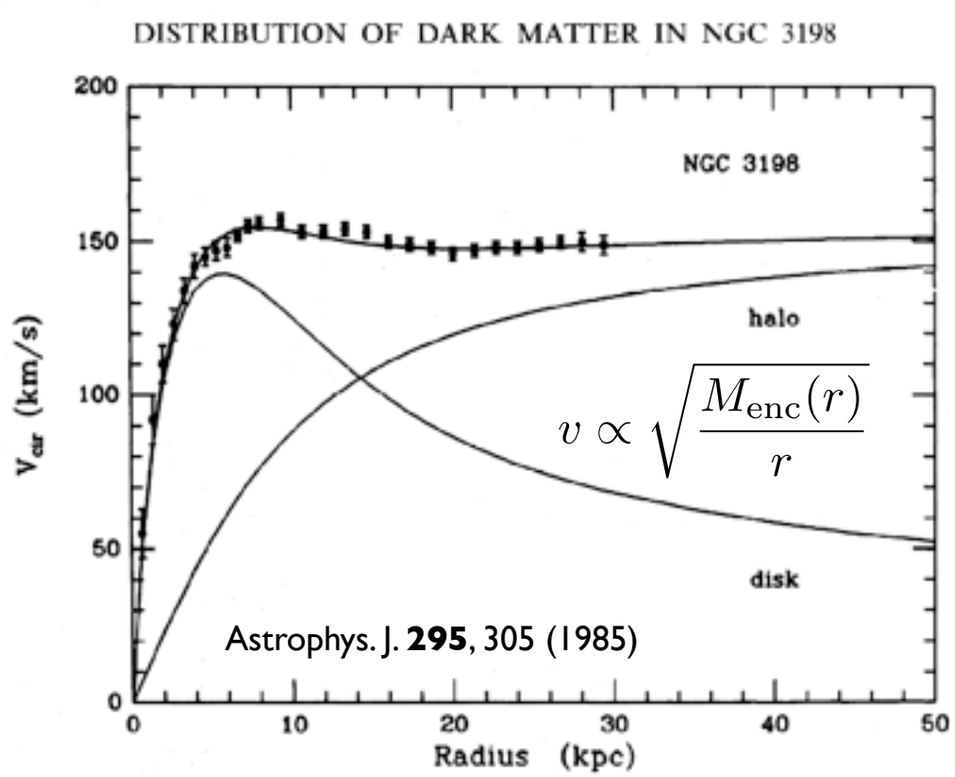

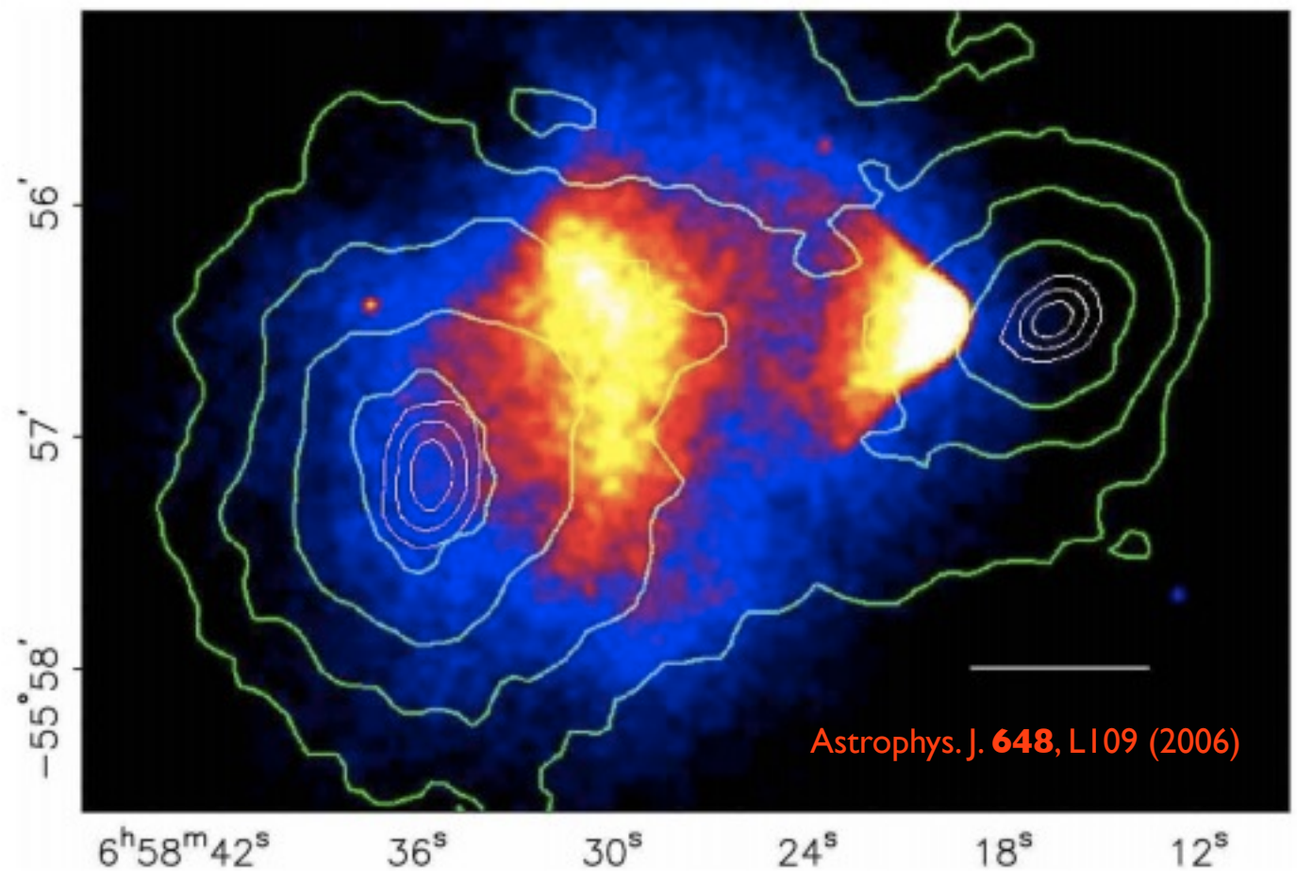

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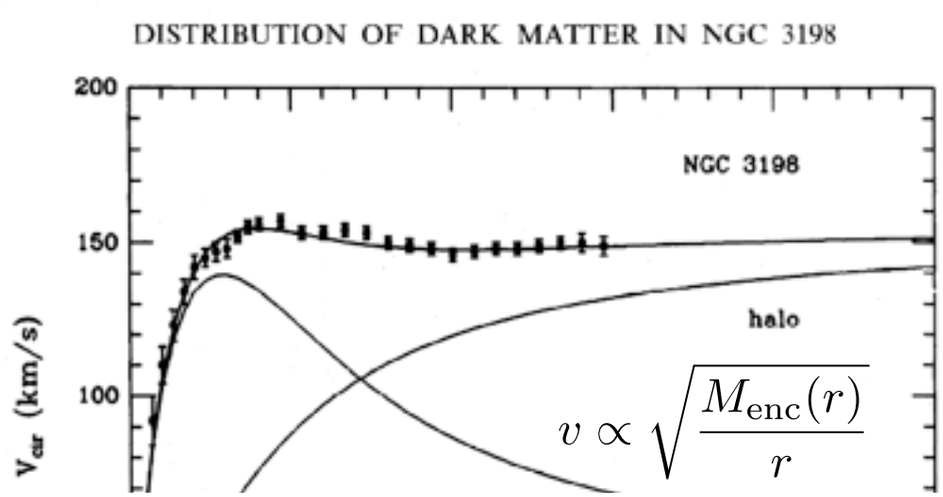
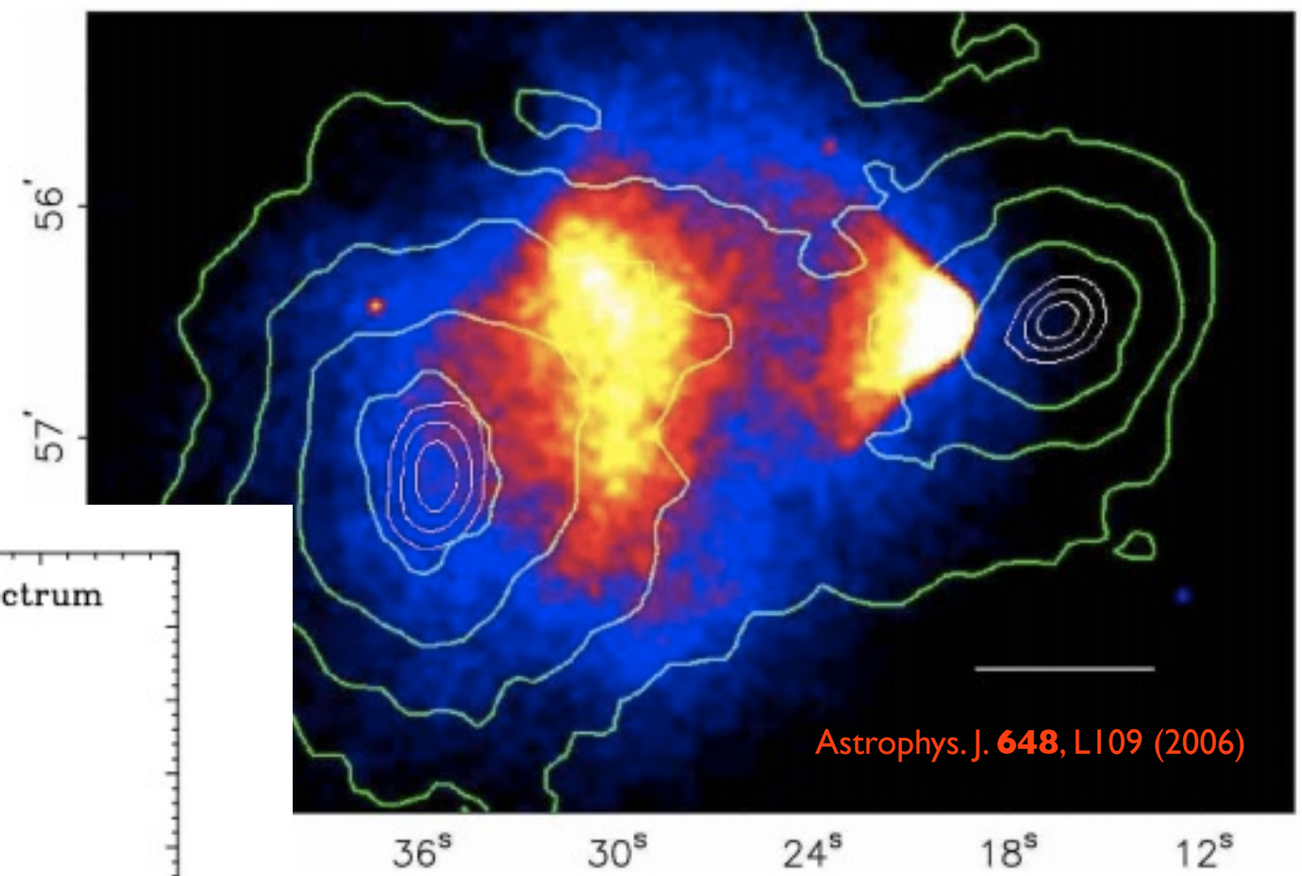
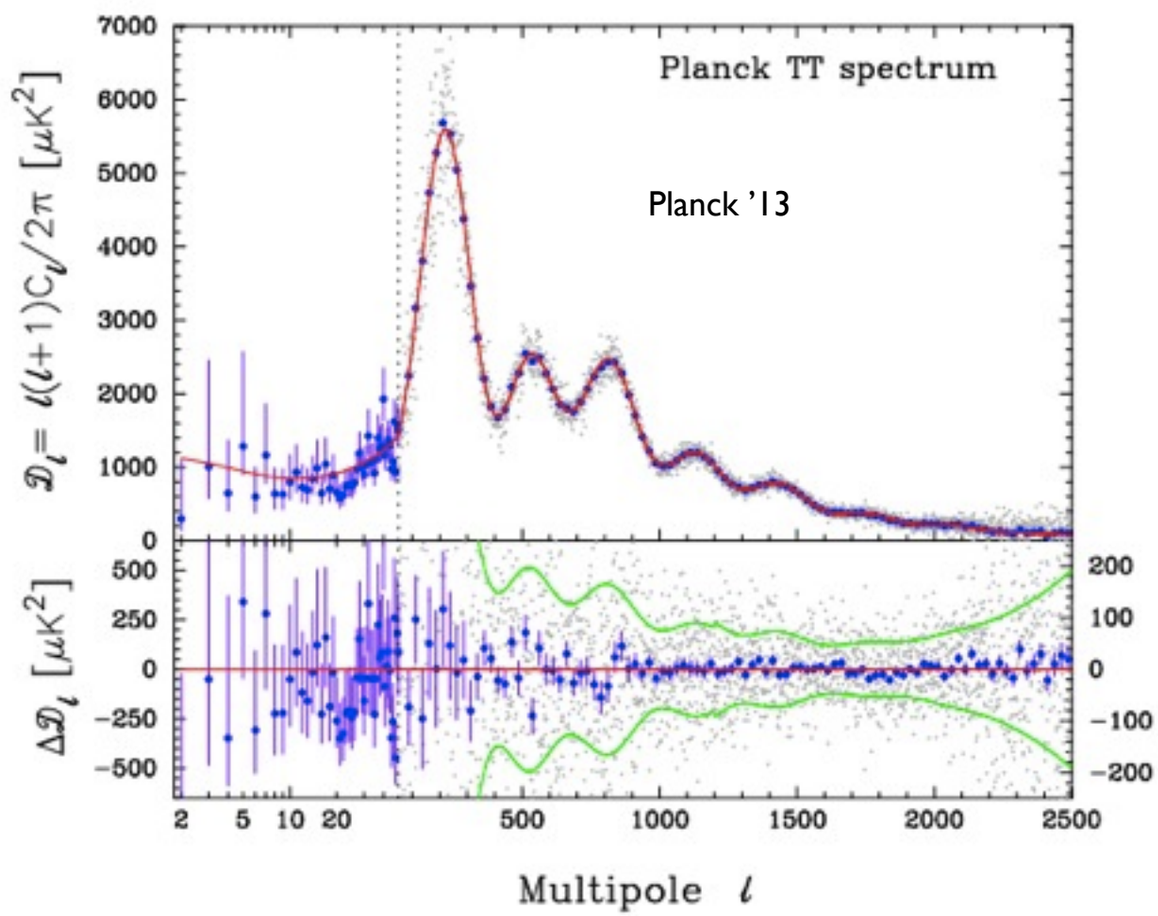


$$v \propto \sqrt{\frac{M_{\rm enc}(r)}{r}}$$



Astrophys. J. **648**, L109 (2006)



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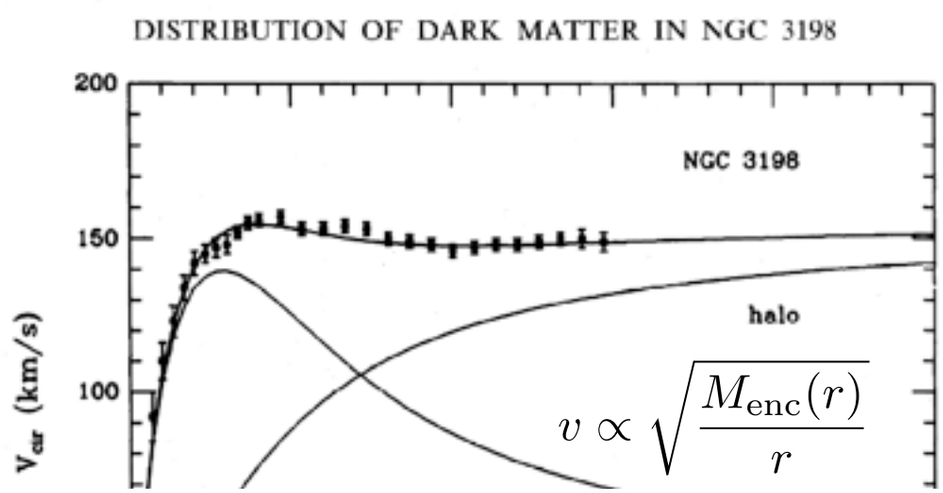

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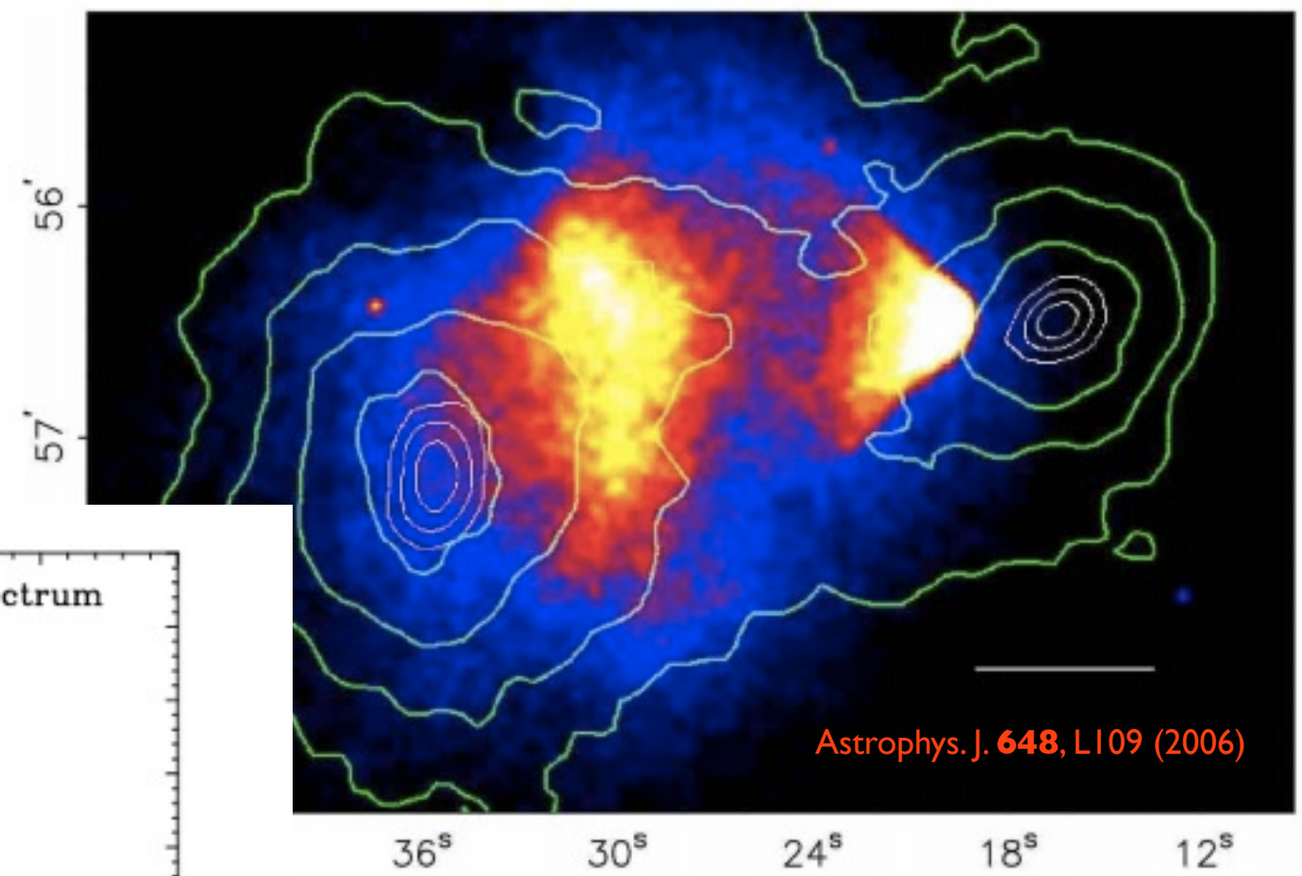

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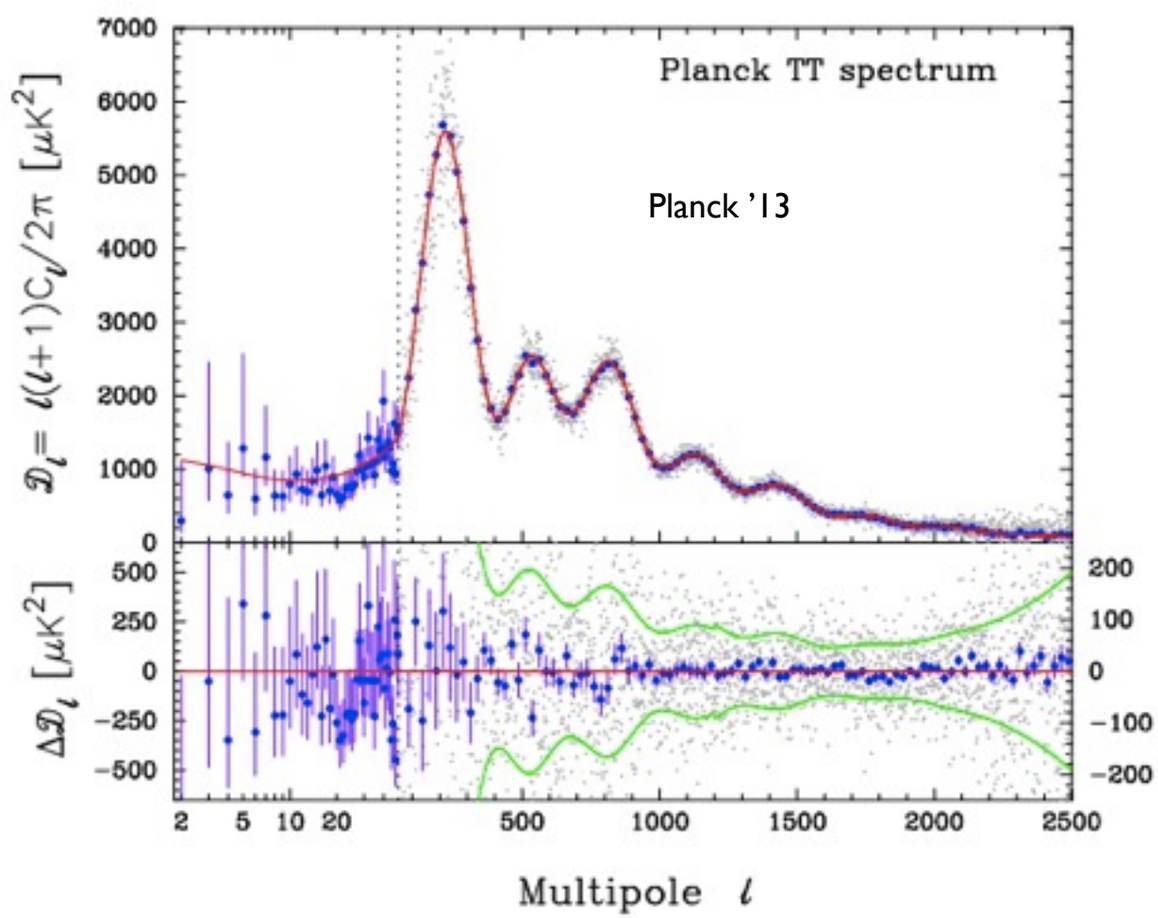
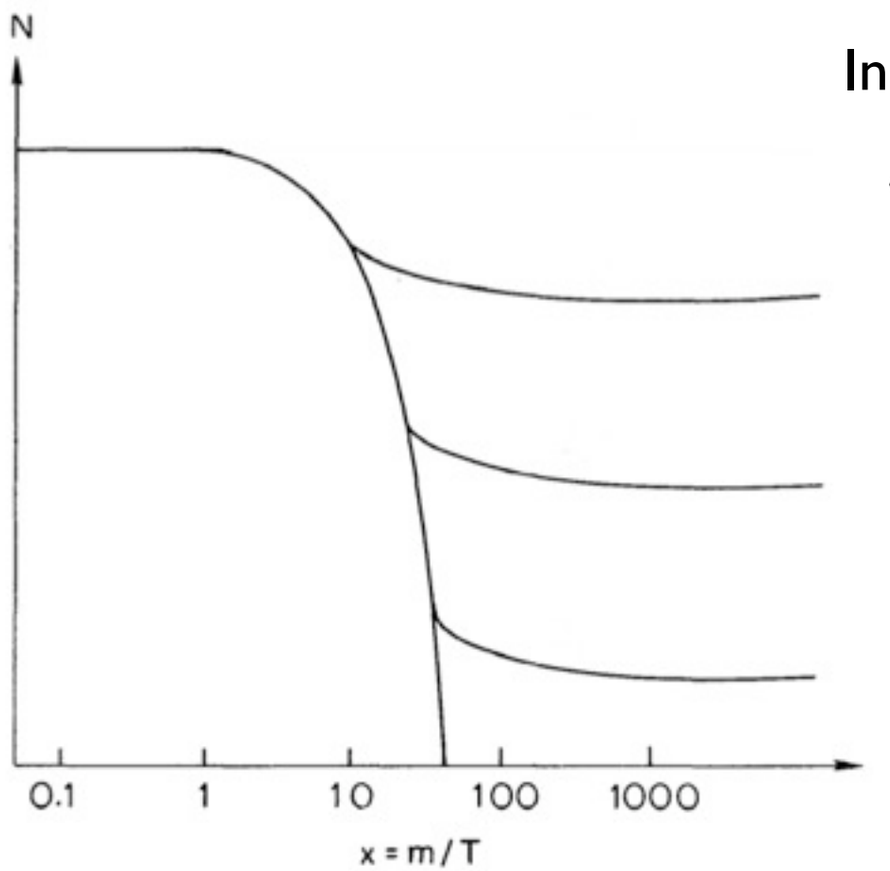


$$\Omega_d \sim 0.2$$

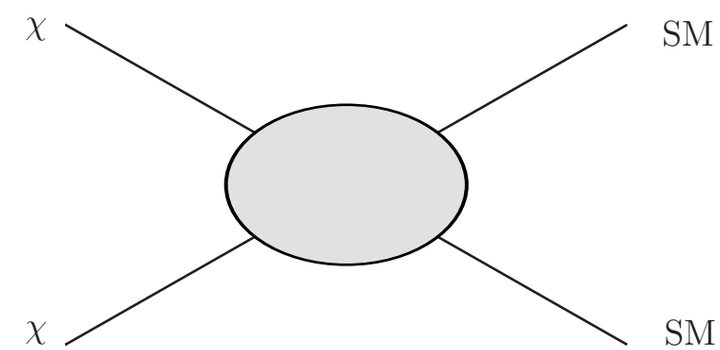
$$\Omega_b \sim 0.04$$

Thermal Relic WIMPs



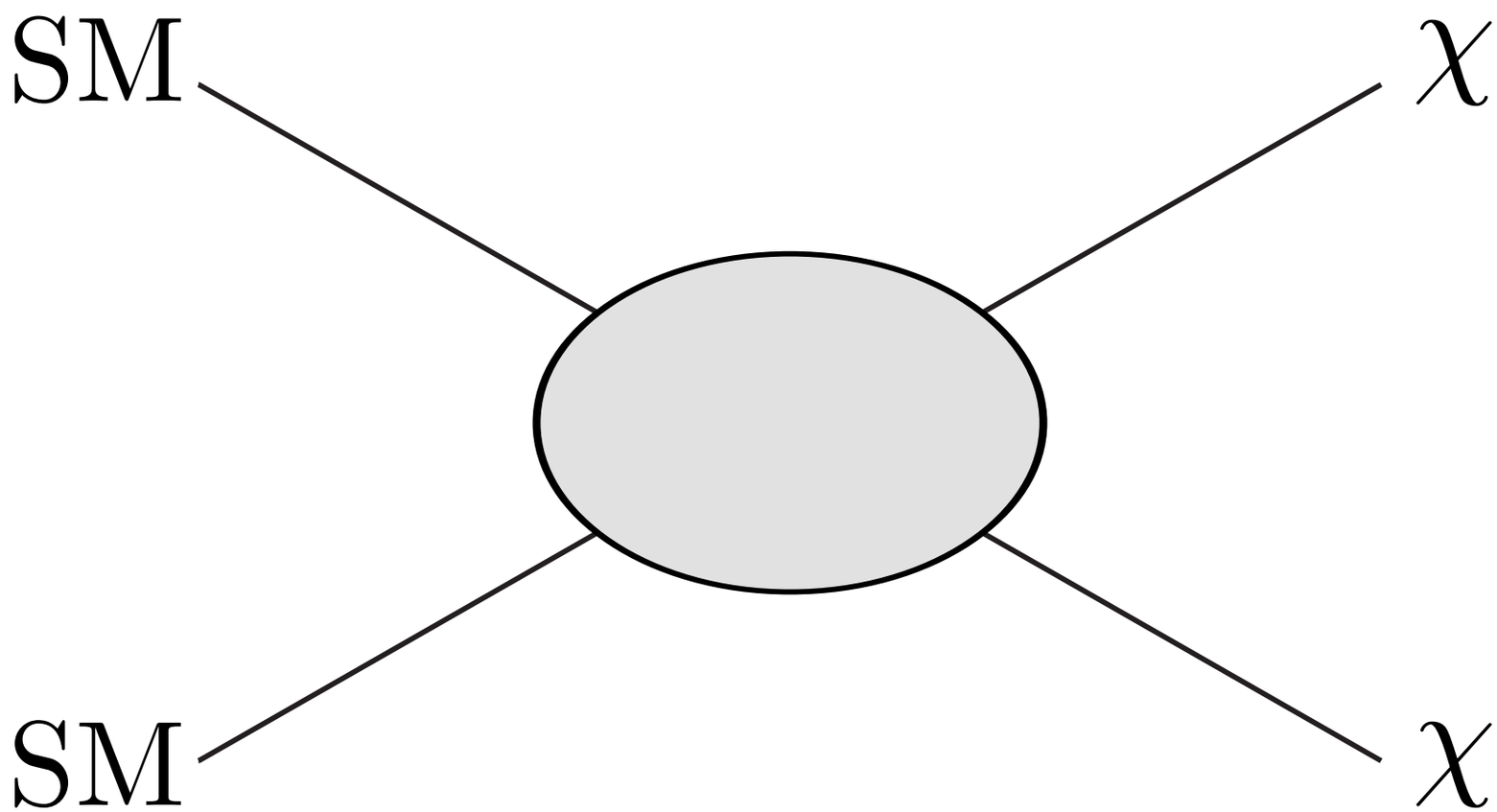
Increasing

$\langle \sigma v \rangle$



$$\Omega_d \sim 0.2 \left(\frac{3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}{\sigma v} \right)$$

How do we find it?



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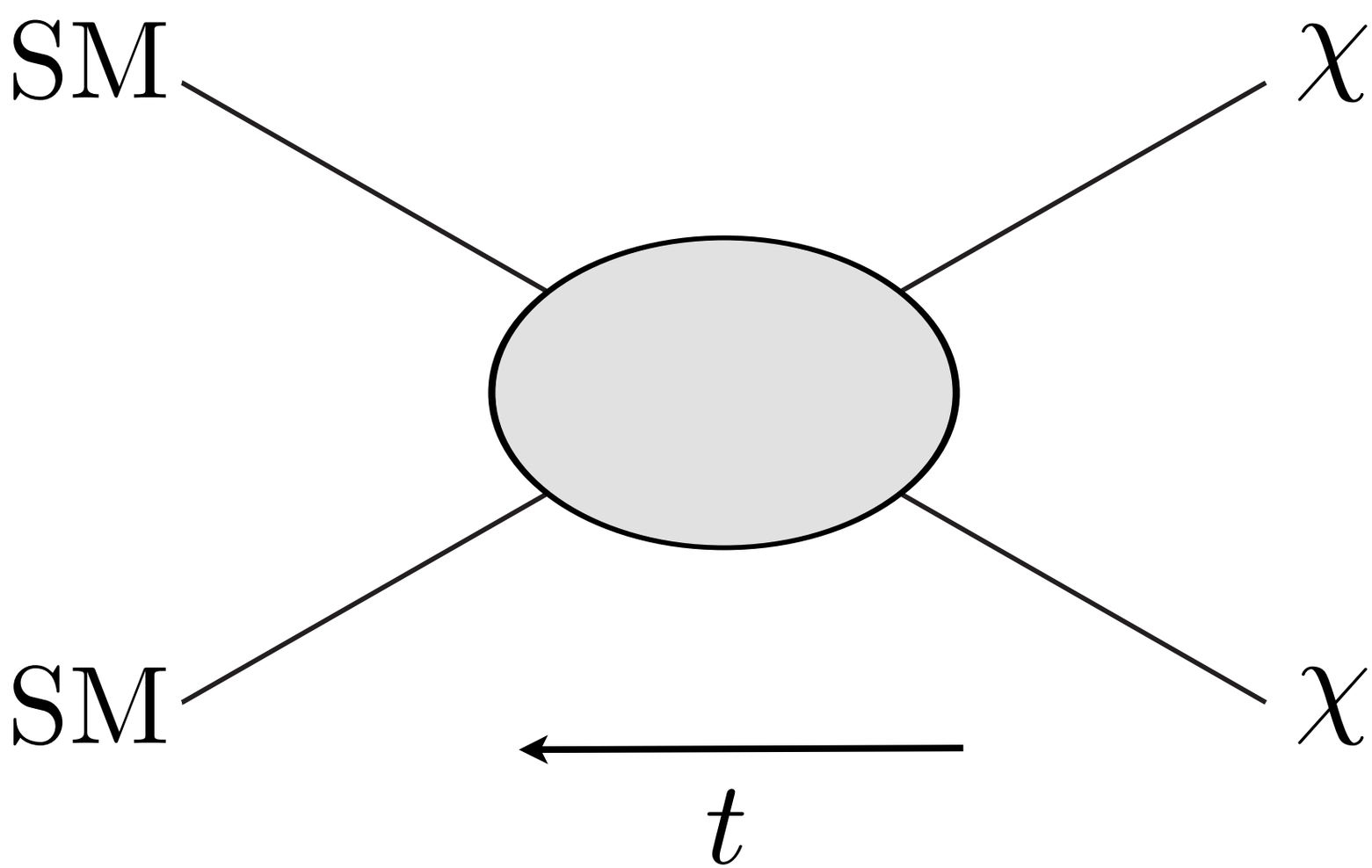
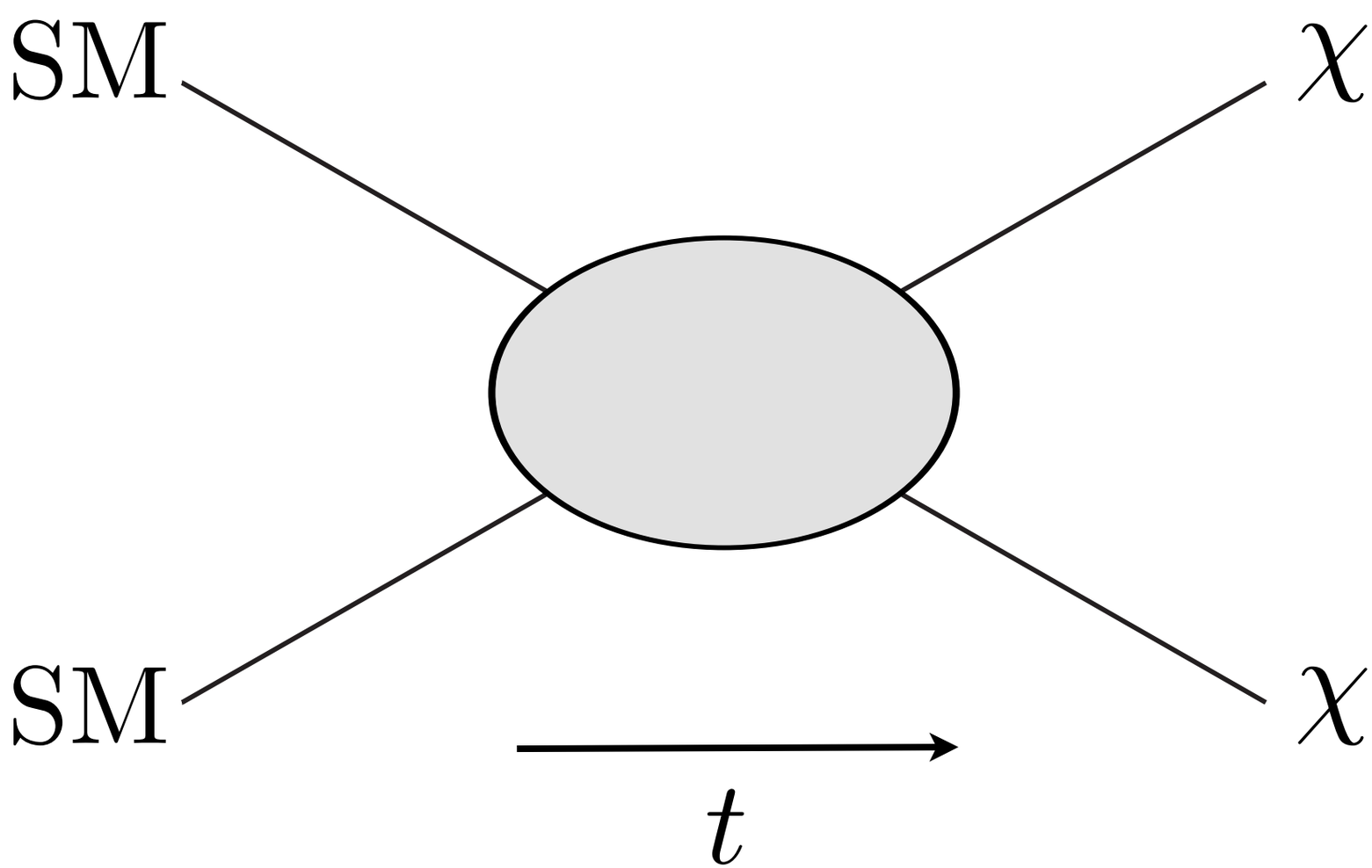


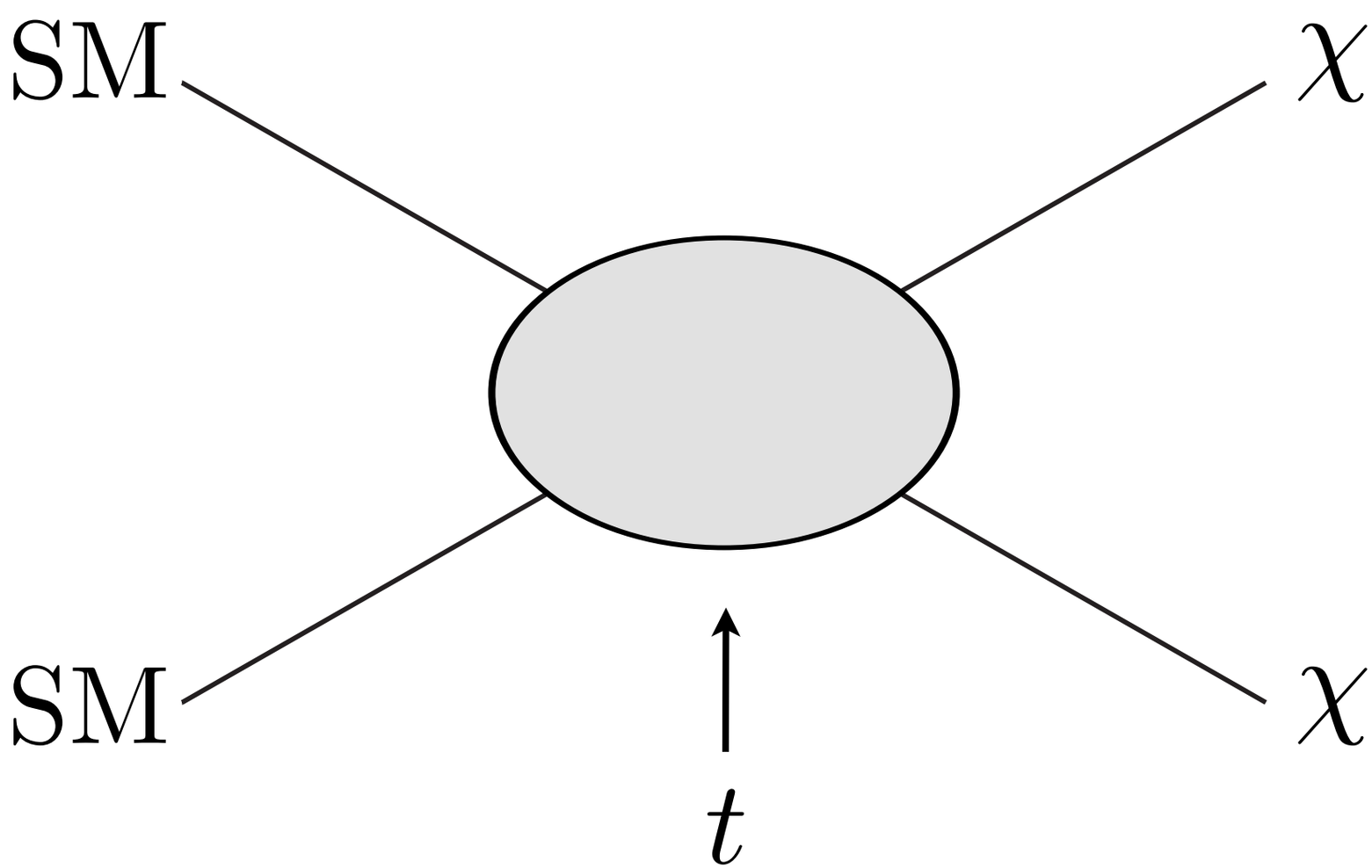
Indirect Detection

How do we find it?



Collider

How do we find it?



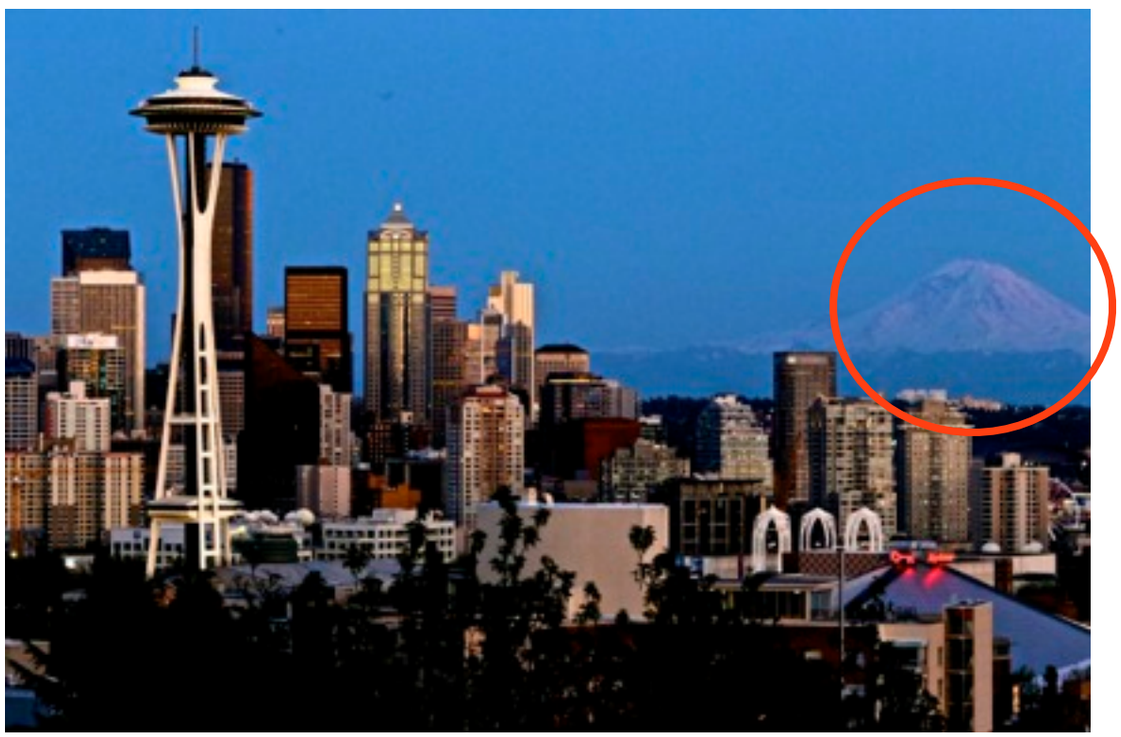
Direct Detection

Indirect vs. direct/ collider

Seattle

Chicago (April 15!)

Indirect vs. direct/ collider



Seattle

Chicago (April 15!)

An Indirect Detection in Galactic Center Gamma Rays?

Persistent excess over standard astrophysical models in gamma rays ~GeV found by a number of groups

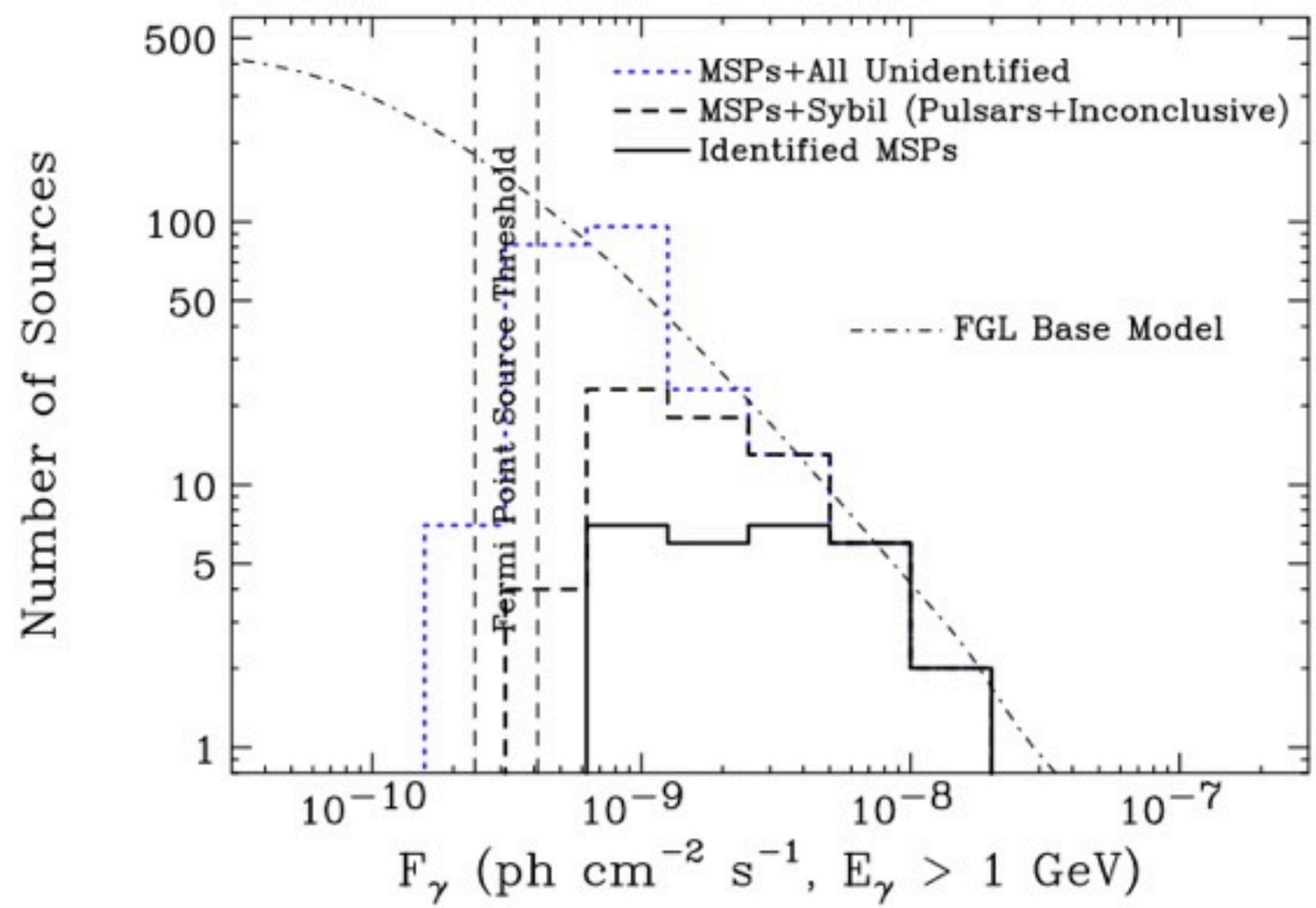
Goodenough, Hooper 0910.2998
Hooper, Goodenough 1010.2752
Hooper, Linden 1110.0006
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703
Abazajian, Kaplinghat 1207.6047
Gordon, Macias 1306.5725
Abazajian, Canac, Horiuchi, Kaplinghat 1402.4090
...

-Spherically symmetric
-Centered at but extends beyond the immediate GC
-Intensity agrees with square of standard DM profile (e.g. NFW)
-Annihilation cross section as expected

Astrophysics Backgrounds?

Millisecond pulsars could be responsible

Hooper, Cholis, Linden, Siegal-Gaskins, Slatyer 1305.0830



But accounting for the excess with MSPs overpredicts sources Fermi could ID

Morphology (extending to ~10° from GC) also makes it difficult

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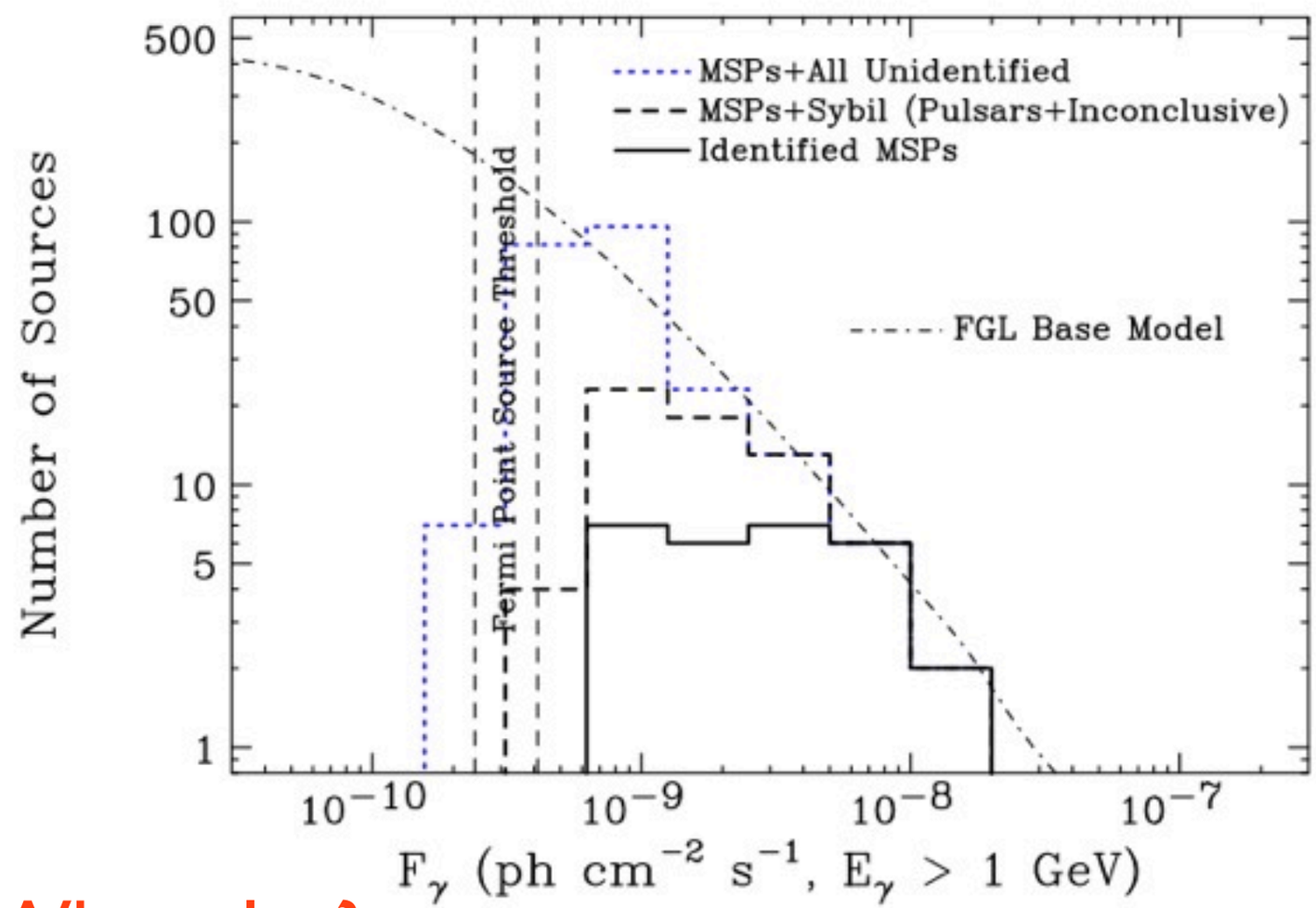

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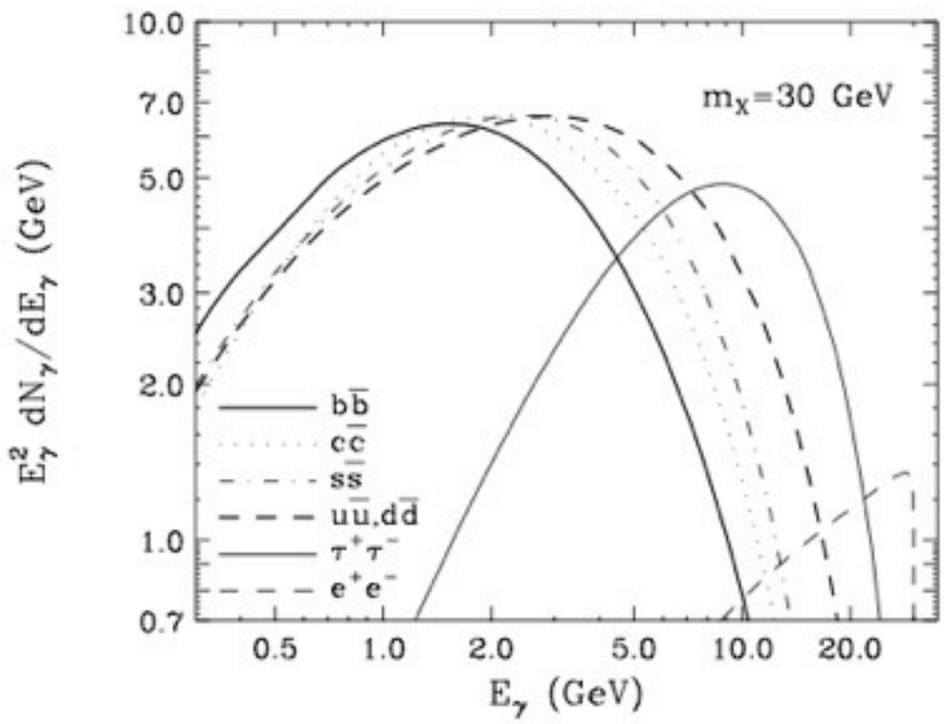
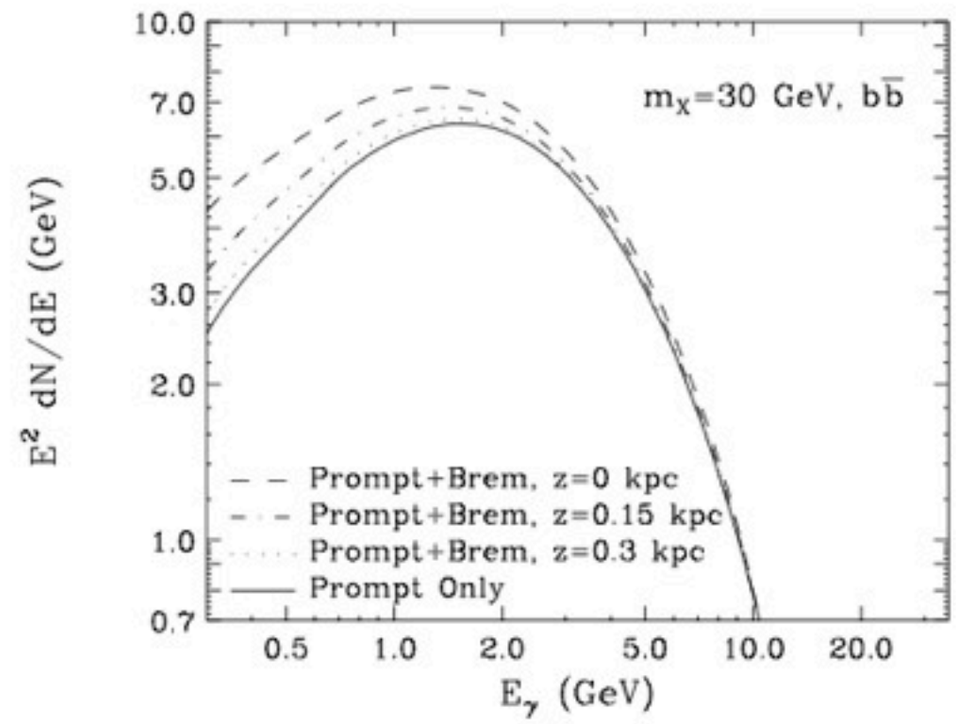
What else?

DM Annihilation

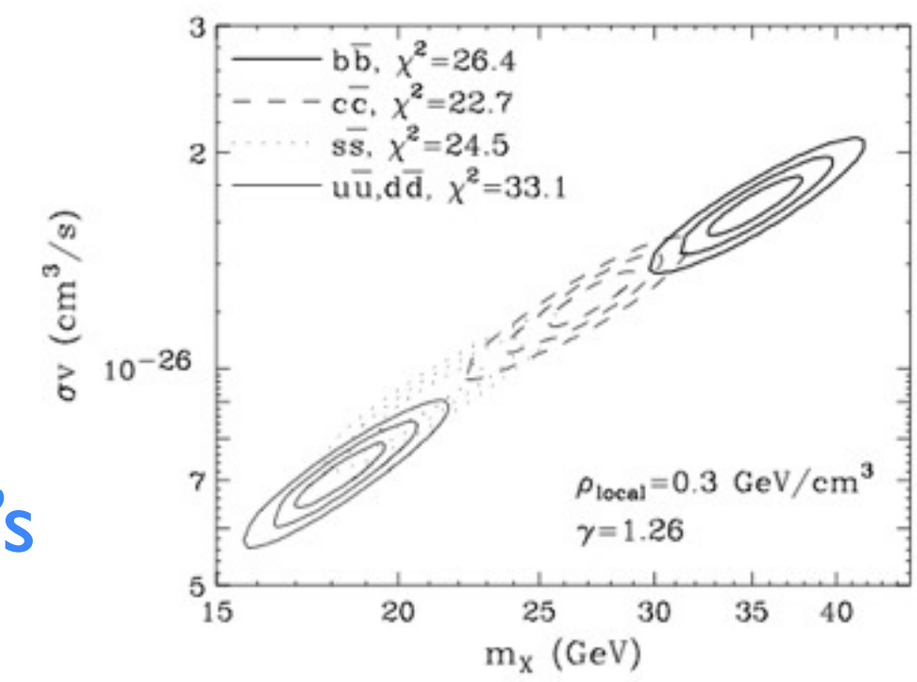




Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703

Well fit by 30 GeV DM annihilating to b quarks

Cross section roughly comparable to a thermal relic's



EFT Analyses

Many groups have focused on the dim.-6/7 operator:

$$\mathcal{L}_{\rm eff} = \frac{m_b}{\Lambda^3}\bar{\chi} i\gamma^5 \chi \bar{b} i\gamma^5 b$$

Boehm, Dolan, McCabe, Spannowsky, Wallace: 1401.6458
Alves, Profumo, Queiroz, Shepherd: 1403.5027
Berlin, Hooper, McDermott: 1404.0022
...

-Annihilation is s-wave
-Direct Detection is highly velocity suppressed
-Spin-0 exchange: favors b

-But this isn't SM singlet: $\bar{b} i\gamma^5 b = i\left(\bar{b}_L b_R - \bar{b}_R b_L\right)$

⇒Any model is going to have other interesting consequences!

A Simple Model

Pseudoscalar coupled to DM $\mathcal{L}_{\rm dark} = y_\chi a_0 \bar{\chi} i \gamma^5 \chi$

Mixes with 2HDM

$$V = V_{\rm 2HDM} + \frac{1}{2} m_{a_0}^2 a_0^2 + \frac{\lambda_a}{4} a_0^4 + V_{\rm port}$$

$$V_{\rm port} = i B a_0 H_1^\dagger H_2 + \text{h.c.}$$

$$\begin{aligned} V_{\rm 2HDM} = {} & \lambda_1 \left(H_1^\dagger H_1 - \frac{v_1^2}{2} \right)^2 + \lambda_2 \left(H_2^\dagger H_2 - \frac{v_2^2}{2} \right)^2 \\ & + \lambda_3 \left[\left(H_1^\dagger H_1 - \frac{v_1^2}{2} \right) + \left(H_2^\dagger H_2 - \frac{v_2^2}{2} \right) \right]^2 \\ & + \lambda_4 \left[\left(H_1^\dagger H_1 \right) \left(H_2^\dagger H_2 \right) - \left(H_1^\dagger H_2 \right) \left(H_2^\dagger H_1 \right) \right] \\ & + \lambda_5 \left[\text{Re} \left(H_1^\dagger H_2 \right) - \frac{v_1 v_2}{2} \right]^2 + \lambda_6 \left[\text{Im} \left(H_1^\dagger H_2 \right) \right]^2 \end{aligned}$$

A Simple Model

Mass eigenstates $$\mathcal{M}_A^2 = \begin{pmatrix} m_{A_0}^2 & Bv \\ Bv & m_{a_0}^2 \end{pmatrix}, \quad m_{A_0}^2 = \frac{\lambda_6 v^2}{2}$$

$$\begin{pmatrix} A_0 \\ a_0 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A \\ a \end{pmatrix}, \quad \tan 2\theta = \frac{2Bv}{m_{A_0}^2 - m_{a_0}^2}$$

$$m_{a,A}^2 = \frac{1}{2}\left[m_{A_0}^2 + m_{a_0}^2 \pm \sqrt{\left(m_{A_0}^2 - m_{a_0}^2\right)^2 + 4B^2v^2}\right]$$

Can trade $m_{a_0},\ m_{A_0},\ B$ for $m_a,\ m_A,\ \theta$

$$B = \frac{1}{2v}\left(m_A^2 - m_a^2\right)\sin 2\theta$$

$$\mathcal{L}_{\rm dark} = y_\chi \left(\cos\theta\, a + \sin\theta\, A\right)\bar{\chi} i\gamma^5 \chi$$

Portal becomes: $$V_{\rm port} = \frac{1}{2v}\left(m_A^2 - m_a^2\right)\left[s_{4\theta} aA + s_{2\theta}^2\left(A^2 - a^2\right)\right] \times \left[\sin\left(\beta-\alpha\right)h + \cos\left(\beta-\alpha\right)H\right]$$

$$\left(\tan\beta = \frac{v_2}{v_1},\ v_1^2 + v_2^2 = v^2 = (246\ \text{GeV})^2\right)$$

Couplings to SM

Type II 2HDM:

$$\mathcal{L}_{\rm Yuk} = -\bar{L} Y_e H_1 e_R - \bar{Q} Y_d H_1 d_R - \bar{Q} Y_d \tilde{H}_2 u_R + \text{h.c.}$$

Can forbid $\cancel{\bar{L} Y_\chi \tilde{H}_1 \chi_R + \text{h.c.}}$

Yukawa interactions become

$$\mathcal{L}_{\rm Yuk} \to -\xi_f^\phi \frac{m_f}{v} \phi \bar{f} f$$

$$\xi_e^h = \xi_d^h = -\frac{\sin\alpha}{\cos\beta},\ \xi_u^h = \frac{\cos\alpha}{\sin\beta},$$
$$\xi_e^H = \xi_d^H = \frac{\cos\alpha}{\cos\beta},\ \xi_u^H = \frac{\sin\alpha}{\sin\beta},$$
$$\xi_e^A = \xi_d^A = \tan\beta\cos\theta,\ \xi_u^A = \cot\beta\cos\theta,$$
$$\xi_e^a = \xi_d^a = -\tan\beta\sin\theta,\ \xi_u^a = -\cot\beta\sin\theta$$

Couplings to gauge bosons: $\xi_V^h = \sin(\beta-\alpha)\,,\ \xi_V^H = \cos(\beta-\alpha)$

Decoupling limit: $\alpha \simeq \beta - \pi/2$

$m_h \ll m_H \simeq m_{H^\pm} \simeq m_{A_0}$

h is SM-like

Aside: DM CP Problem

Consider effective operator

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2}\frac{m_q}{v}\bar{\chi}\left(a_\chi + ib_\chi\gamma^5\right)\chi\bar{q}\left(a_q + ib_q\gamma^5\right)q$$

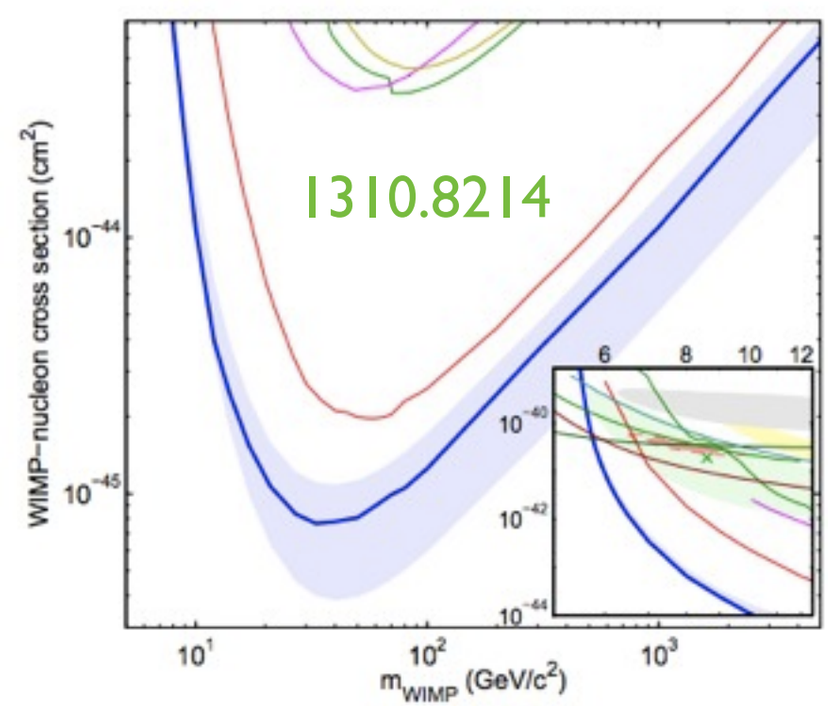
Gives an annihilation cross section

$$\sigma v_{\rm rel} = \frac{1}{2\pi}\left(\frac{m_\chi m_b}{\Lambda^2 v}\right)^2\left(b_\chi^2 + a_\chi^2 v_{\rm rel}^2\right)\left(b_b^2 + a_b^2\right)$$
$$\simeq 3\times 10^{-26}\ \frac{\rm cm^3}{\rm s}\left(\frac{m_\chi}{30\ {\rm GeV}}\right)^2\left(\frac{54\ {\rm GeV}}{\Lambda}\right)^4$$
$$\times\left(b_\chi^2 + a_\chi^2 v_{\rm rel}^2\right)\left(b_b^2 + a_b^2\right)$$

and SI direct detection

$$\sigma_{\rm SI} = \frac{\mu^2}{\pi}\left(\frac{\langle N|\sum_q a_q m_q \bar{q}q|N\rangle}{\Lambda^2 v}\right)^2 a_\chi^2$$
$$\simeq 2.6\times 10^{-41}\ {\rm cm}^2\left(\frac{54\ {\rm GeV}}{\Lambda}\right)^4$$
$$\times\left(\frac{\langle N|\sum_q a_q m_q \bar{q}q|N\rangle}{330\ {\rm MeV}}\right)^2 a_\chi^2$$

LUX: $\sigma_{\rm SI} < 8\times 10^{-46}\ {\rm cm}^2$



Aside: DM CP Problem

- Need 5 order of magnitude suppression of scalar-scalar coupling compared to pseudoscalar-pseudoscalar
- Solved by asserting CP is a symmetry (except for SM Yukawas)
- y_X, B, V_{2HDM} real (technically natural but strange...)
- Generic issue with spin-0 exchange

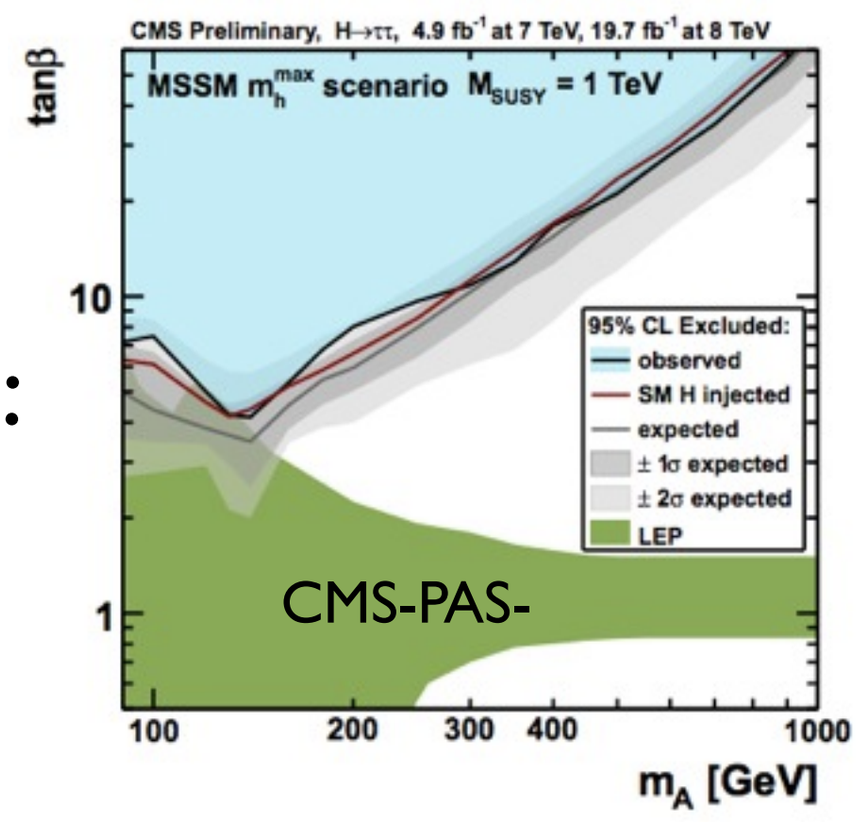
DM Annihilation

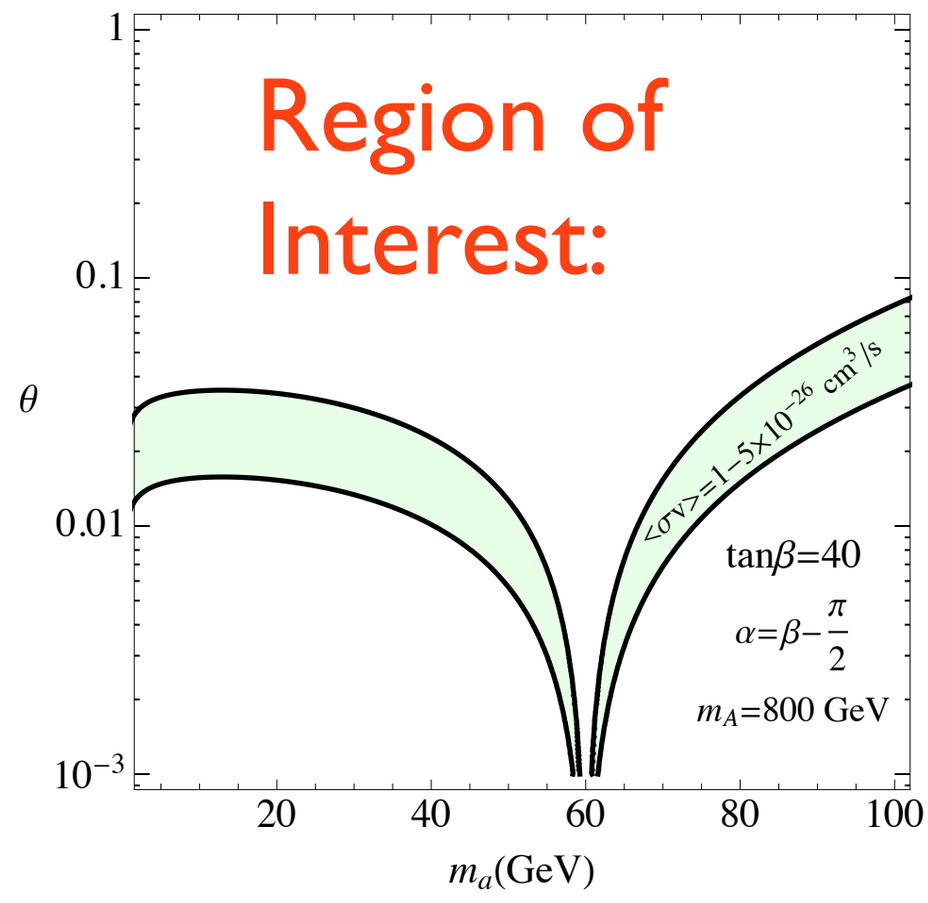
Annihilation cross section is

$$\langle \sigma v_{\rm rel} \rangle = \frac{y_\chi^2}{8\pi}\frac{m_\chi^2}{m_a^4} s_{2\theta}^2 \tan^2\beta \left[\left(1-\frac{4m_\chi^2}{m_a^2}\right)^2 + \frac{\Gamma_a^2}{m_a^2}\right]^{-1} \sum_{f=b,\tau,\ldots} N_C \frac{m_f^2}{v^2}\sqrt{1-\frac{m_f^2}{m_a^2}}$$

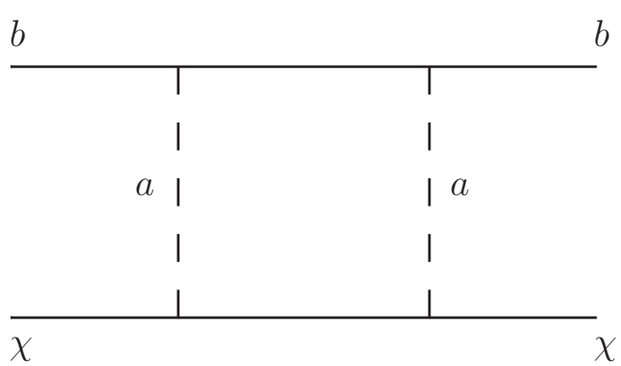
$$= 3\times 10^{-26}\ \frac{\rm cm^3}{\rm s}\left(\frac{y_\chi \sin 2\theta \tan\beta}{2.4}\right)^2$$

Limits on tanβ:

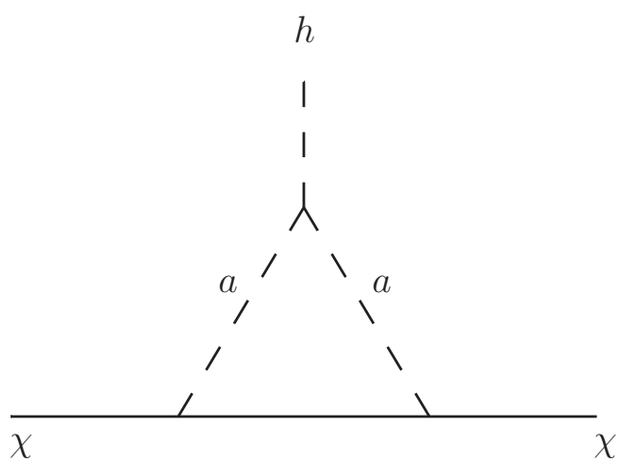




One loop SI direct detection



$$\mathcal{L}_{\rm box} = \sum_{q=d,s,b} \frac{m_q^2 y_\chi^2 \tan^2\beta \sin^2 2\theta}{128\pi^2 m_a^2 \left(m_\chi^2 - m_q^2\right)} \times \left[F\left(\frac{m_\chi^2}{m_a^2}\right) - F\left(\frac{m_q^2}{m_a^2}\right)\right] \frac{m_\chi m_q}{v^2} \bar{\chi}\chi\bar{q}q$$



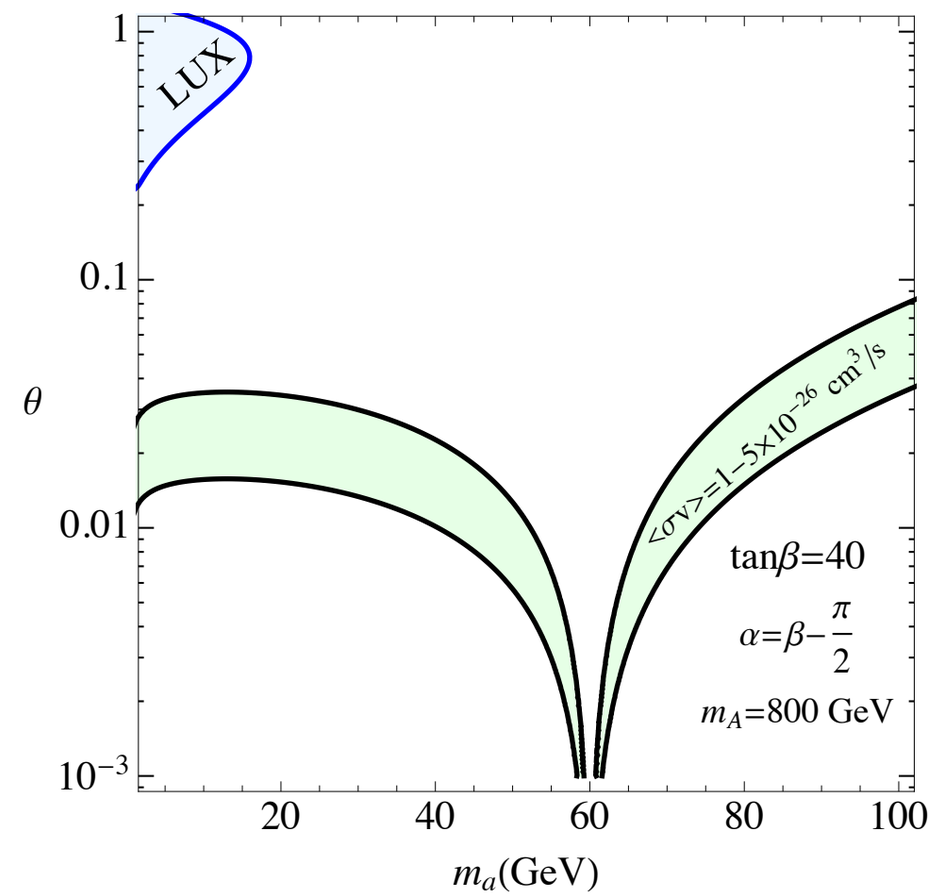
$$\mathcal{L}_{h\chi\chi} = -\frac{\left(m_A^2 - m_a^2\right)\sin^2 2\theta y_\chi^2}{64\pi^2 m_a^2} G\left(x_\chi, x_q\right) \frac{m_\chi}{v} h\bar{\chi}\chi$$

$$\Rightarrow \mathcal{L}_h = \frac{\left(m_A^2 - m_a^2\right) s_{2\theta}^2 y_\chi^2}{64\pi^2 m_h^2 m_a^2} G\left(x_\chi, 0\right) \frac{m_\chi m_q}{v^2} \bar{\chi}\chi\bar{q}q$$

For $\tan\beta \lesssim 100 \left(\frac{m_A}{800\ \mathrm{GeV}}\right)$: *h*-exchange>box

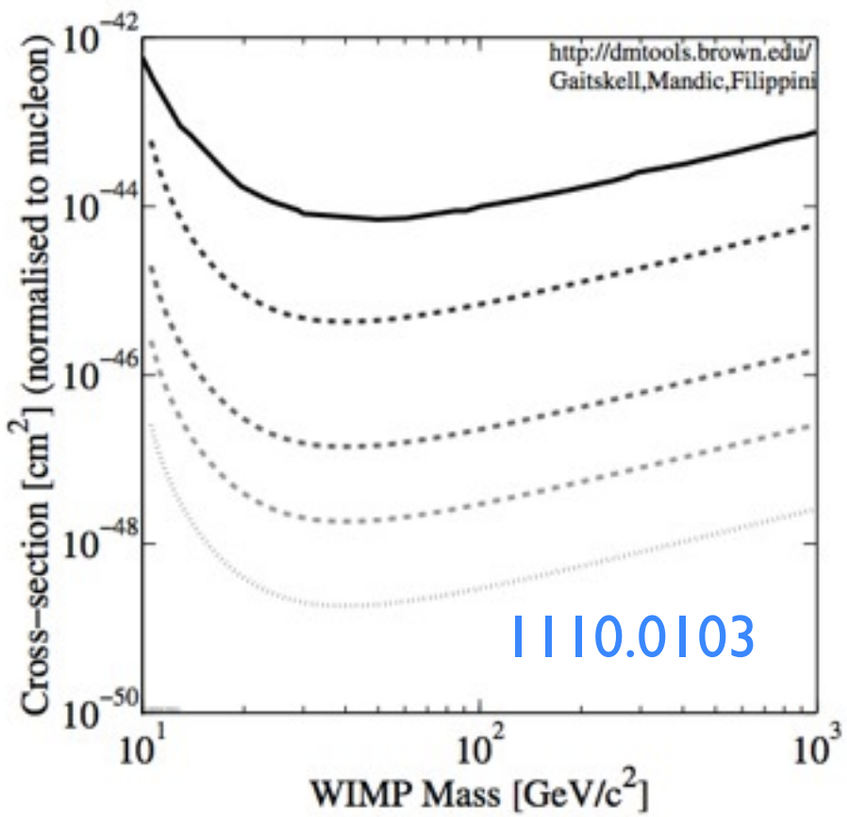
One loop SI direct detection

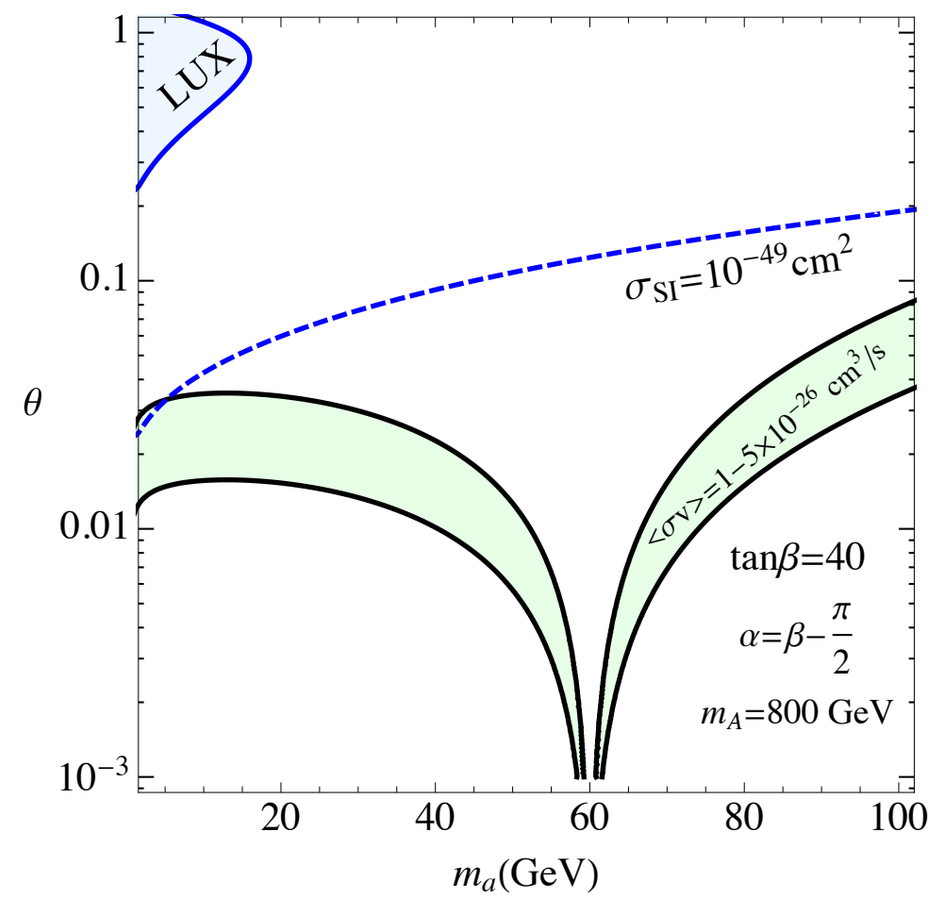
Including these:



One loop SI direct detection

but...





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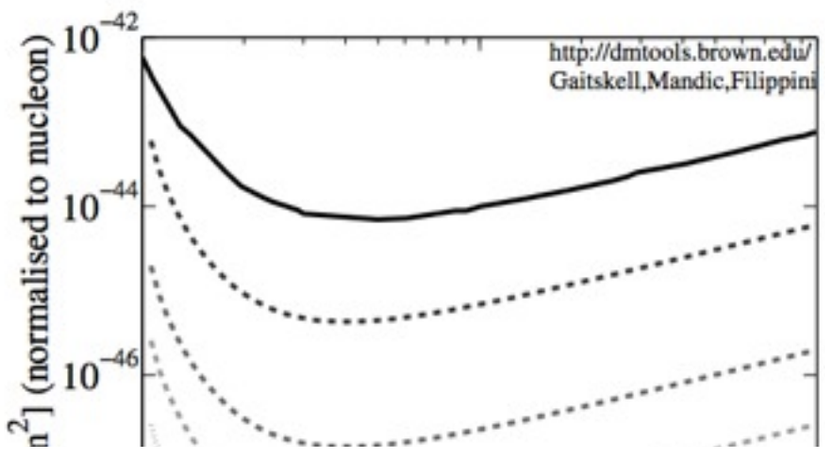
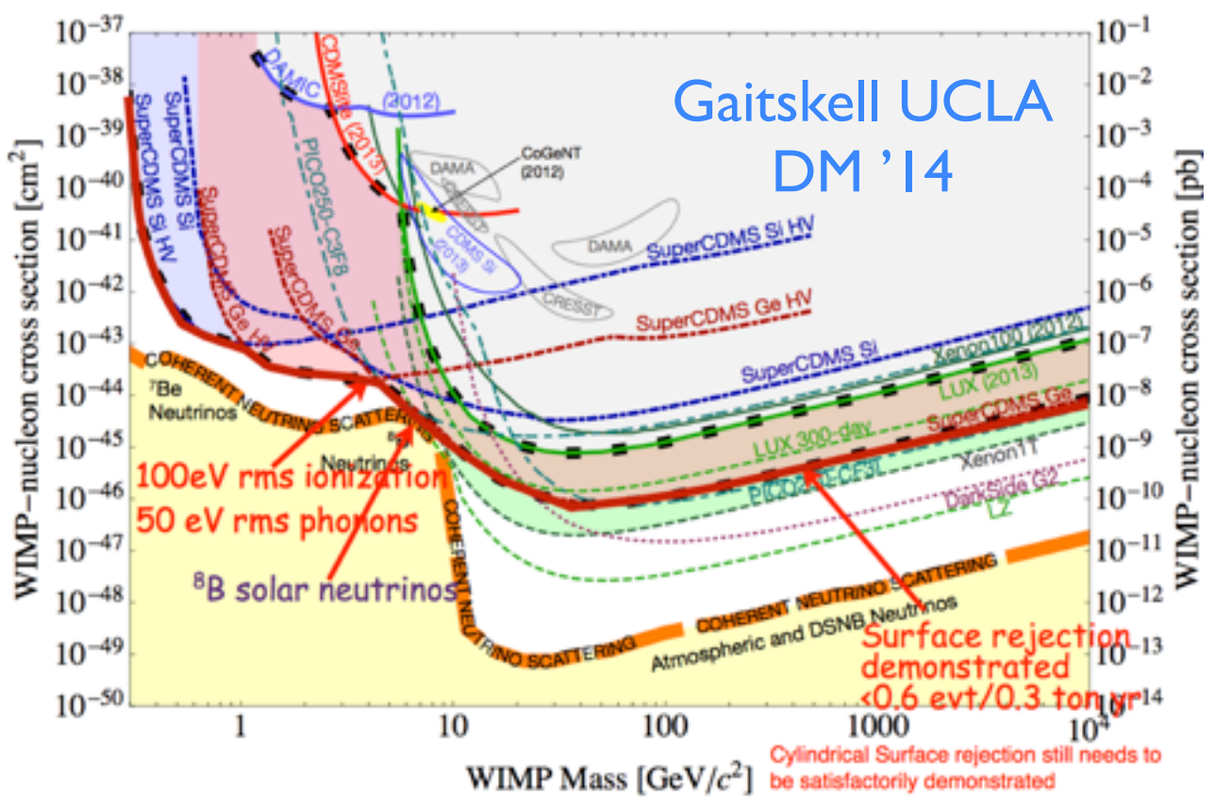
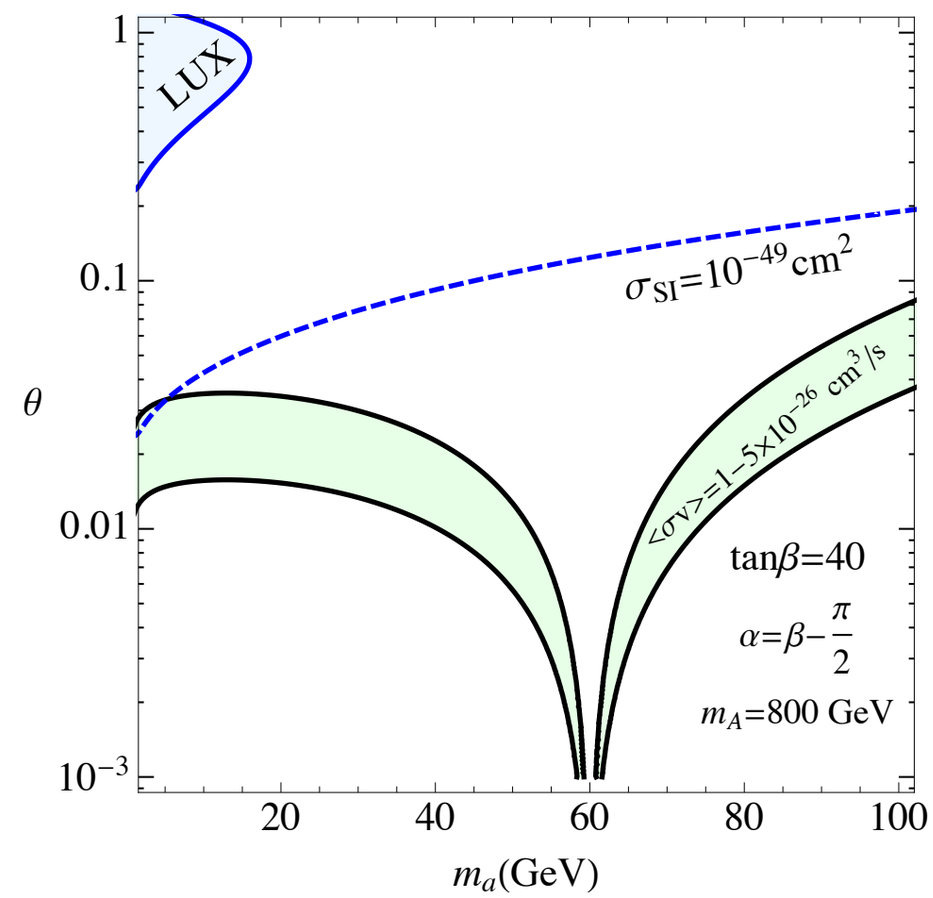






Higgs decays

Recall $V_{\rm port} = \frac{1}{2v}\left(m_A^2 - m_a^2\right)\left[s_{4\theta} a A + s_{2\theta}^2\left(A^2 - a^2\right)\right]$
$\times \left[\sin\left(\beta-\alpha\right) h + \cos\left(\beta-\alpha\right) H\right]$

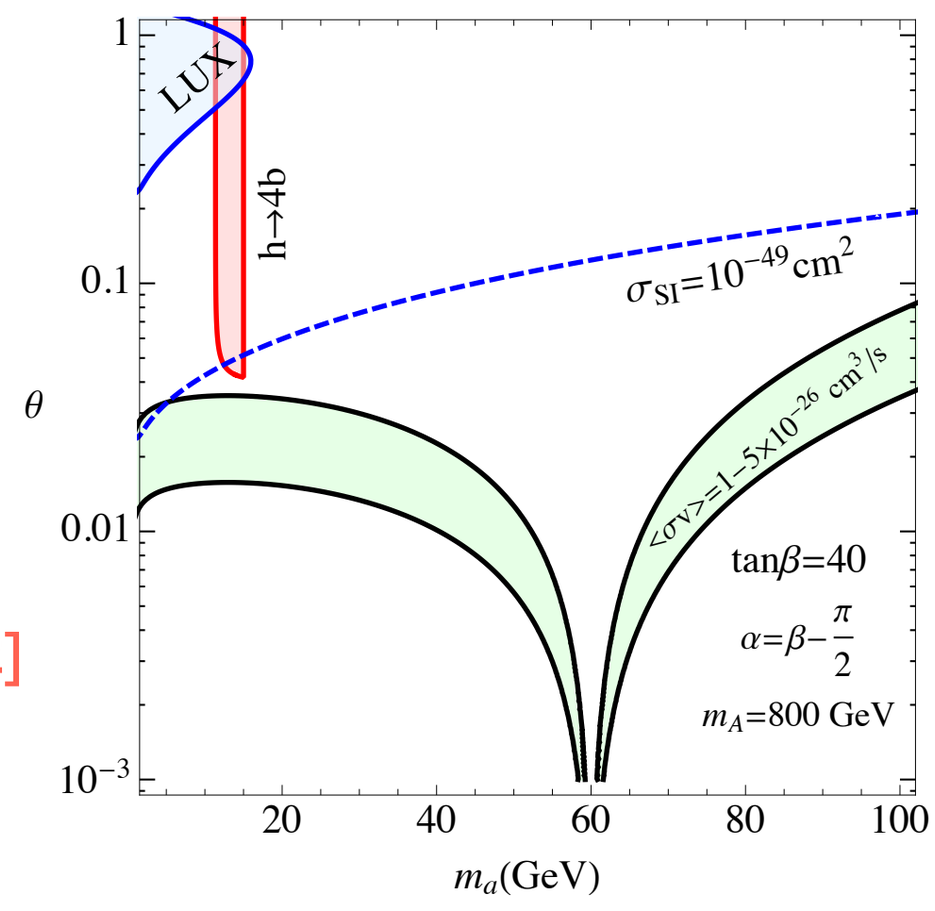
So, if kinematically allowed,

$$\Gamma\left(h \to aa\right) = \frac{\left(m_A^2 - m_a^2\right)^2 \sin^4 2\theta}{32\pi m_h v^2}\sqrt{1 - \frac{4m_a^2}{m_h^2}}$$

$$\simeq 840 \text{ MeV}\left(\frac{m_A}{800 \text{ GeV}}\right)^4\left(\frac{\theta}{0.1}\right)^4$$

$\Gamma_h^{\rm SM} = 4$ MeV
so this can be a serious constraint

limits from CMS (1310.3687)
h→2b search [see 1312.4992]



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Recall $$V_{\rm port} = \frac{1}{2v}\left(m_A^2 - m_a^2\right)\left[s_{4\theta} a A + s_{2\theta}^2\left(A^2 - a^2\right)\right] \times \left[\sin\left(\beta-\alpha\right) h + \cos\left(\beta-\alpha\right) H\right]$$

So, if kinematically allowed,

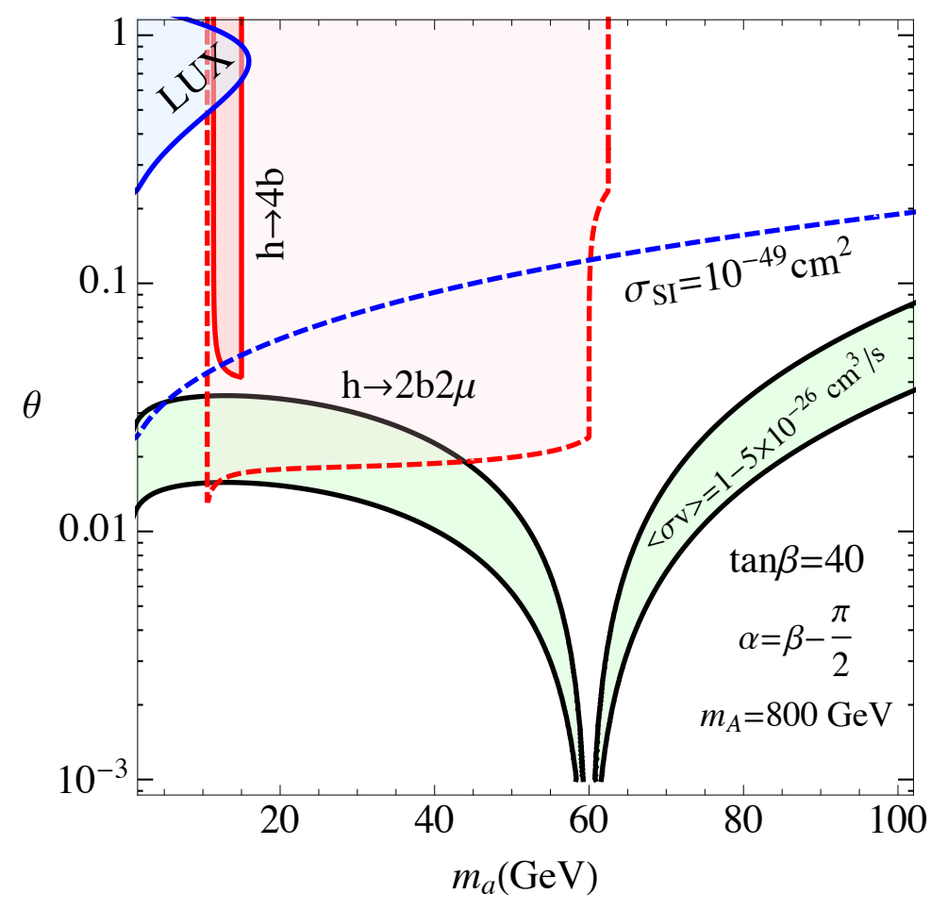
$$\Gamma\left(h \to aa\right) = \frac{\left(m_A^2 - m_a^2\right)^2 \sin^4 2\theta}{32\pi m_h v^2}\sqrt{1 - \frac{4m_a^2}{m_h^2}}$$

$$\simeq 840 \text{ MeV}\left(\frac{m_A}{800 \text{ GeV}}\right)^4\left(\frac{\theta}{0.1}\right)^4$$

$\Gamma_h^{\rm SM} = 4$ MeV

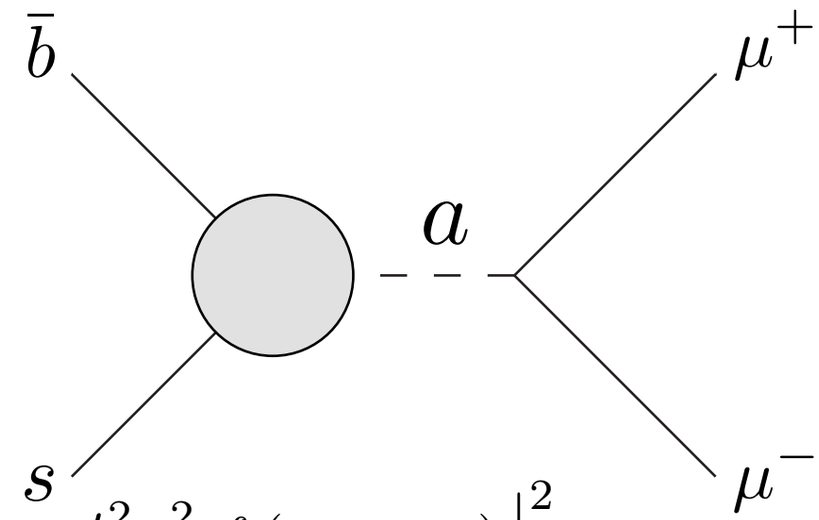
so this can be a serious constraint

h→2b2μ can do quite well [see 1312.4992]
Roughly, Br(h→aa)<0.2



$B_s \to \mu^+\mu^-$

Light a can contribute:



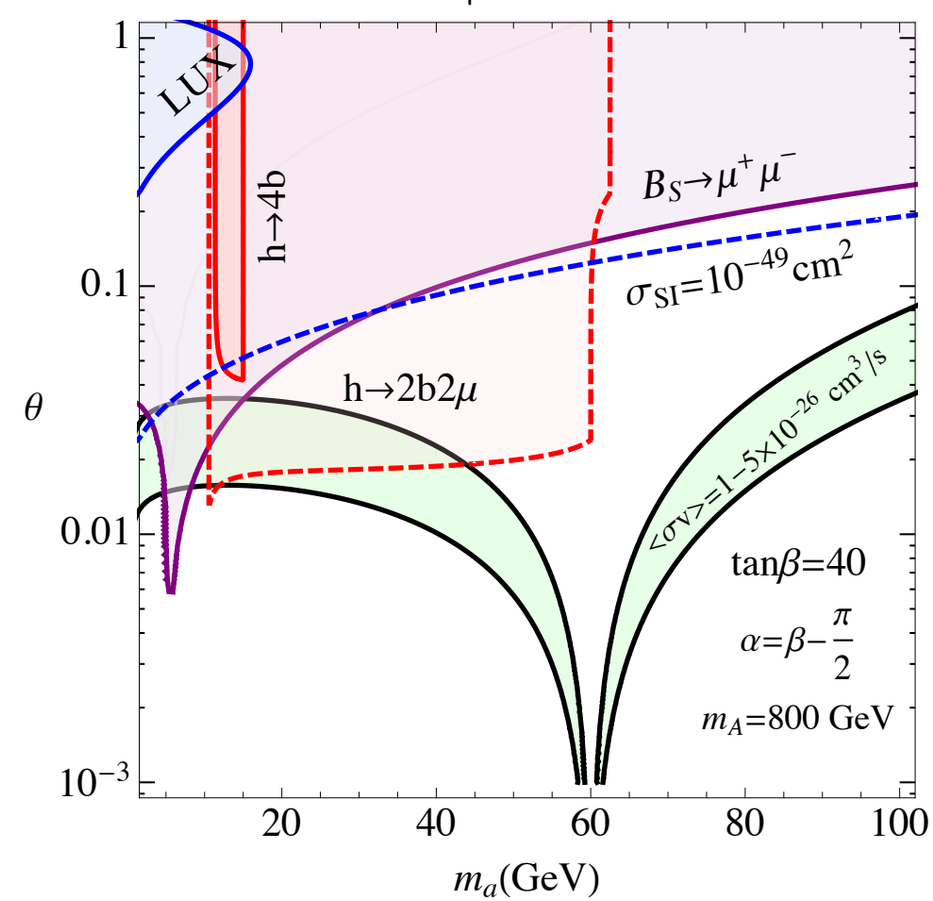
$$\mathrm{Br}\left(B_s \to \mu^+\mu^-\right) \simeq \mathrm{Br}\left(B_s \to \mu^+\mu^-\right)_{\mathrm{SM}} \left|1 + \frac{m_b m_{B_s} t_\beta^2 s_\theta^2}{m_{B_s}^2 - m_a^2} \frac{f\left(x_t, y_t, r\right)}{Y\left(x_t\right)}\right|^2$$

LHCb (1211.2674):

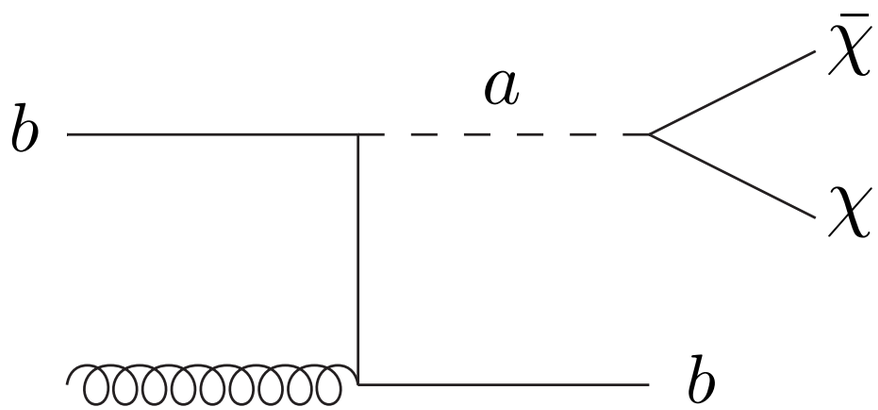
$$\mathrm{Br}\left(B_s \to \mu^+\mu^-\right) = 3.2^{+1.5}_{-1.2} \times 10^{-9}$$

Buras et al. (1303.3820):

$$\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)_{\mathrm{SM}} = (3.25 \pm 0.17) \times 10^{-9}$$

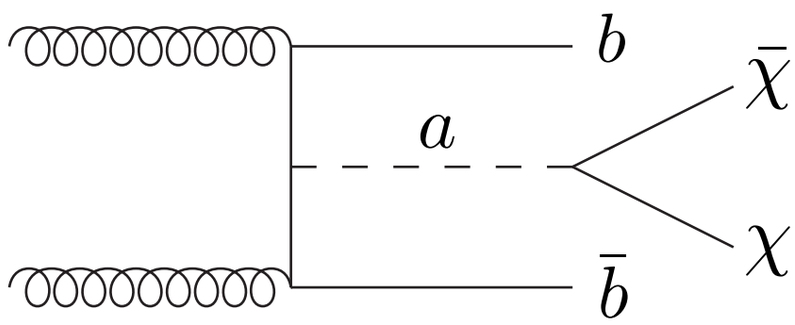


Monojets

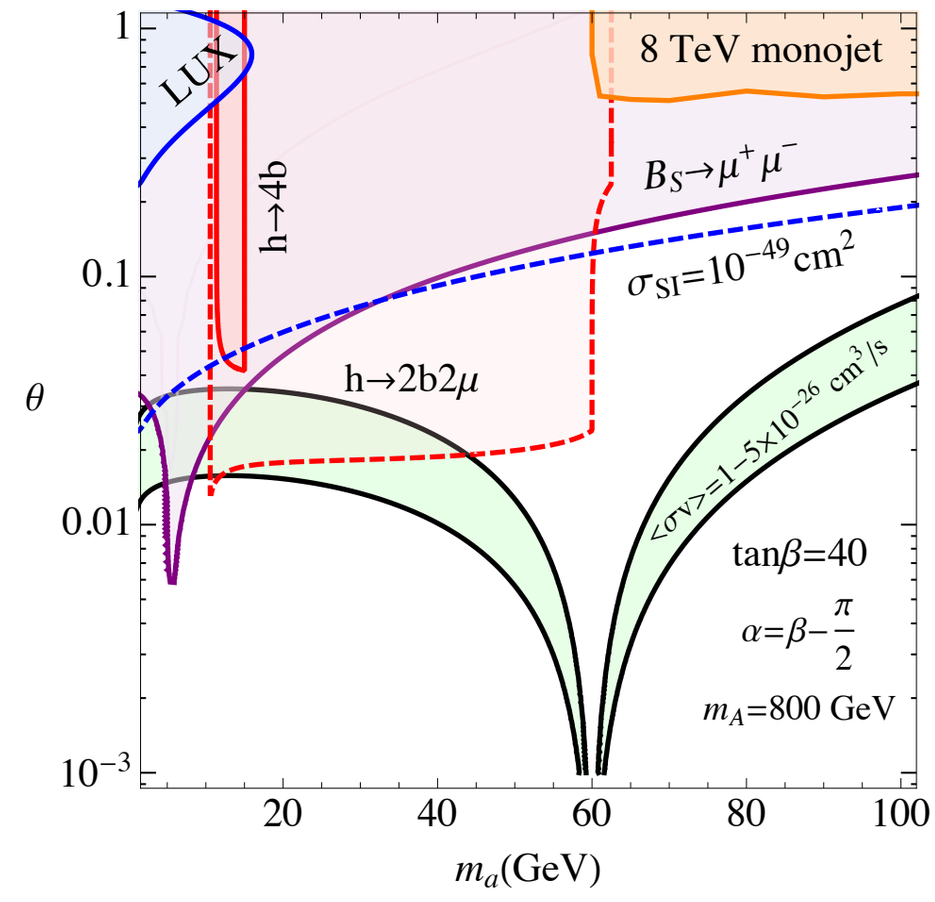


$$pp \to j + \text{inv.}$$

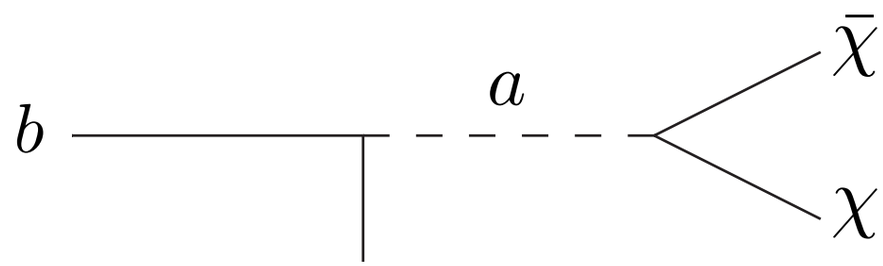
Lin, Kolb, Wang (1303.6638): do better if *j* is b-tagged



up to 2 jets
MET> 350 GeV
b-tagged jet with p_T>100 GeV
isolation requirements



Monojets



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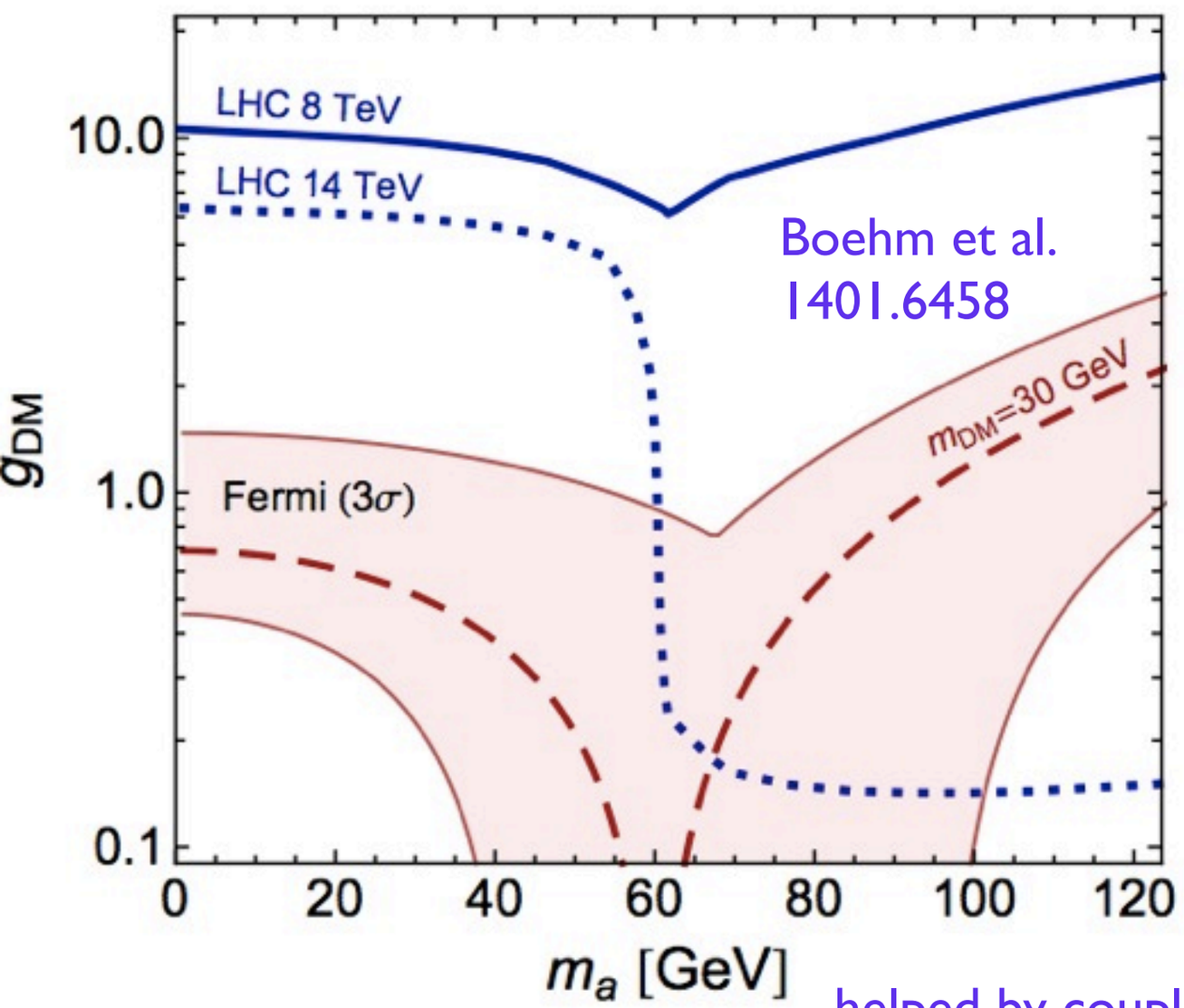
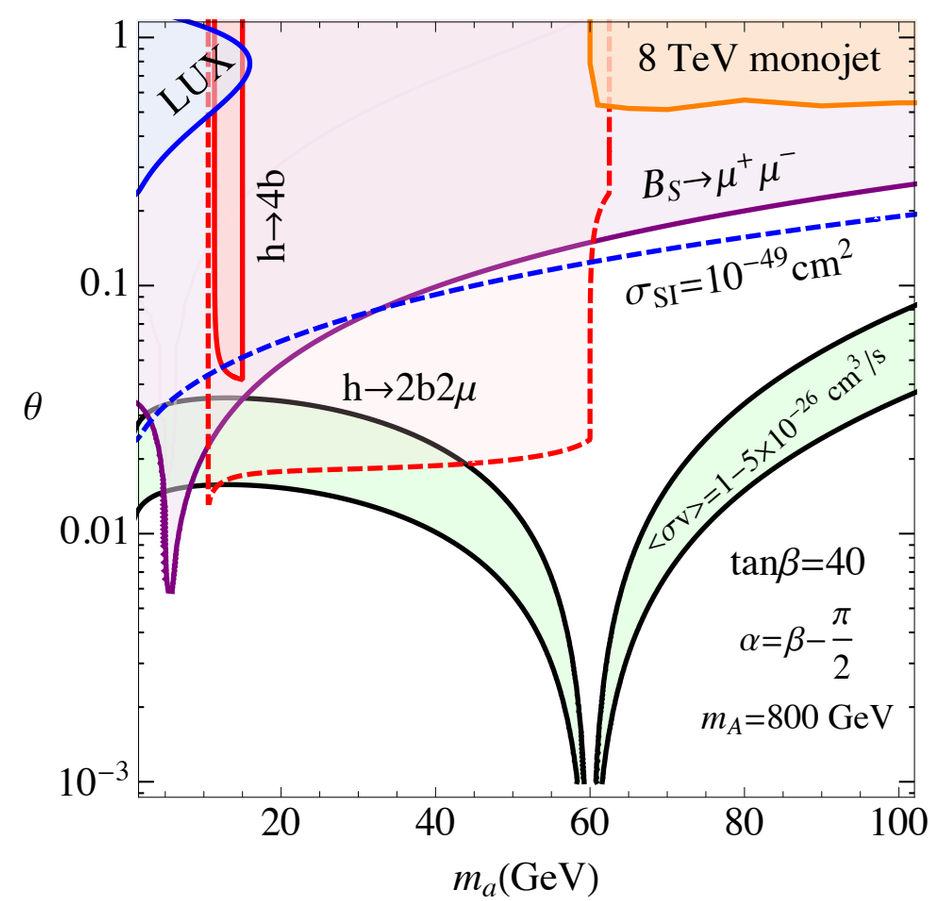


Boehm et al. 1401.6458



helped by coupling to top

Conclusions

- Gamma ray excess hard to explain with conventional astrophysics
- DM interpretation is nice but somewhat puzzling
- Any actual model should have other handles