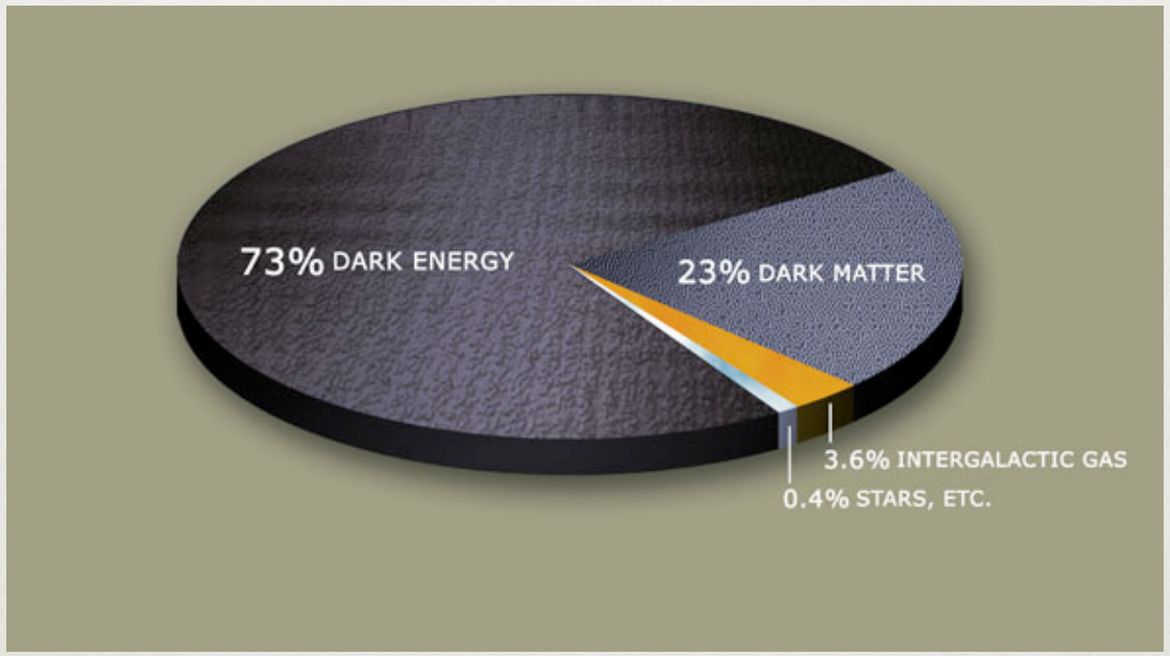
Dark Matter Leaves a Trace

w/ A. de Simone (MIT) and H. Sato (YorkU)

arXiv:1004.1567 [hep-ph]

In the Universe

DM is around us

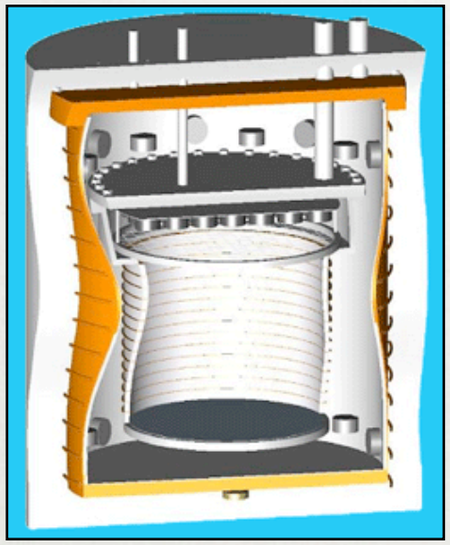


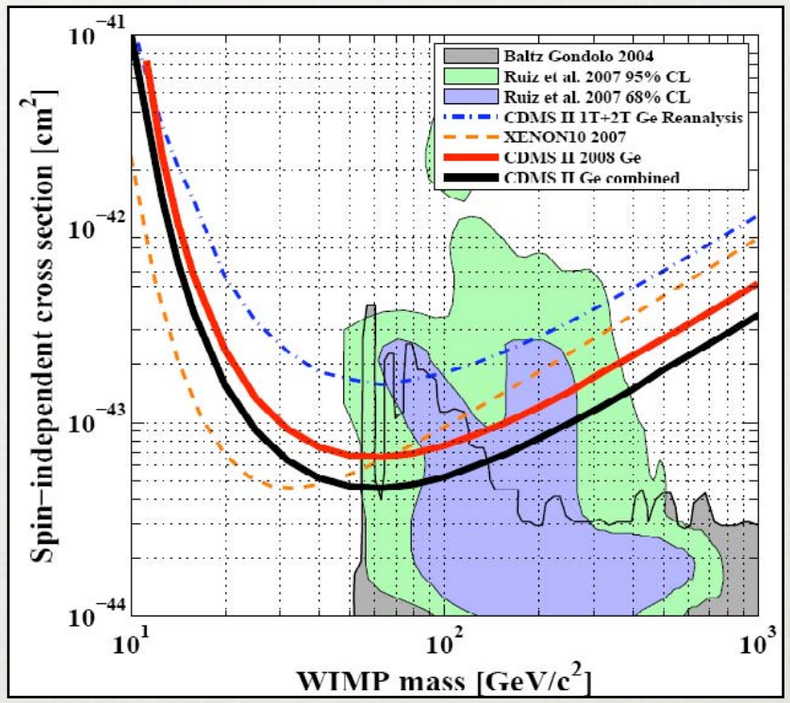
measurement

$$\Omega\, h^2$$

In direct searches

DM is not yet seen



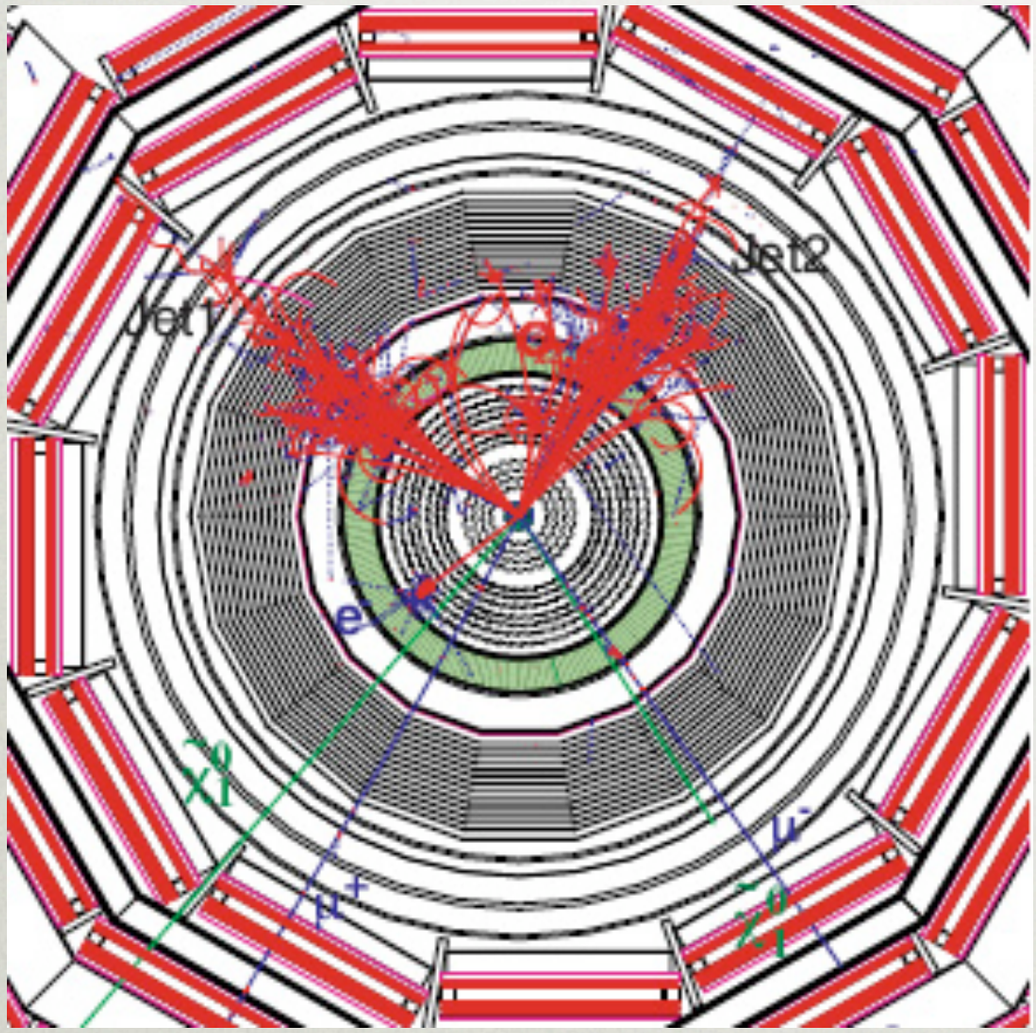


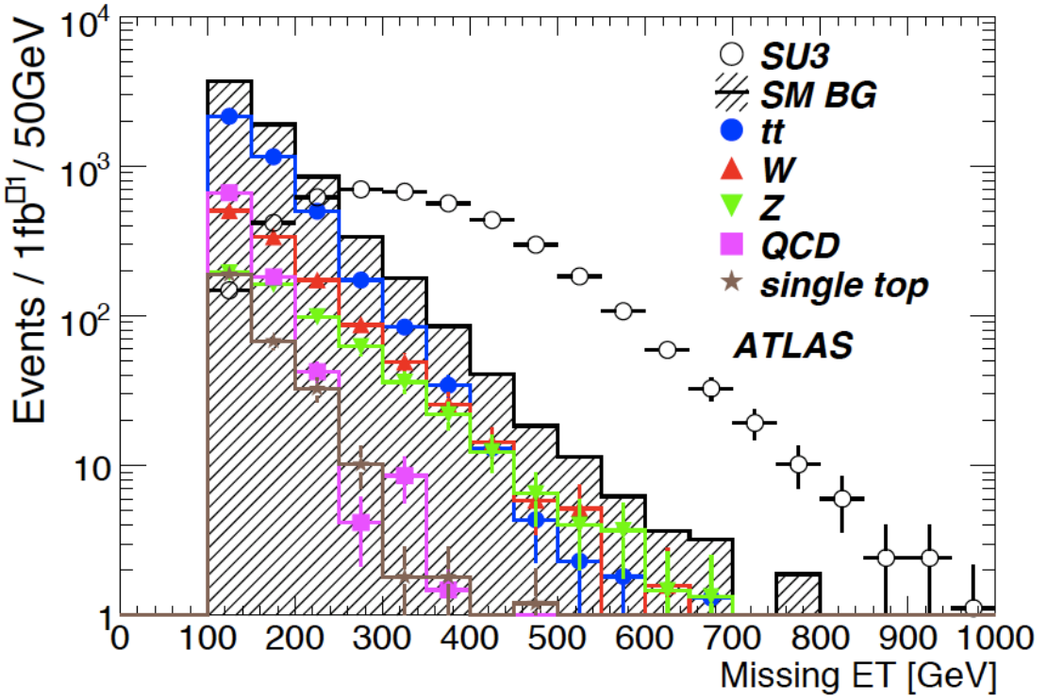
bounds

$$\sigma^{SI} \quad \sigma^{SD}$$

At colliders

DM leaves no trace





Problem:

stable DM → parity

→ pair production

→ two sources MET

At colliders

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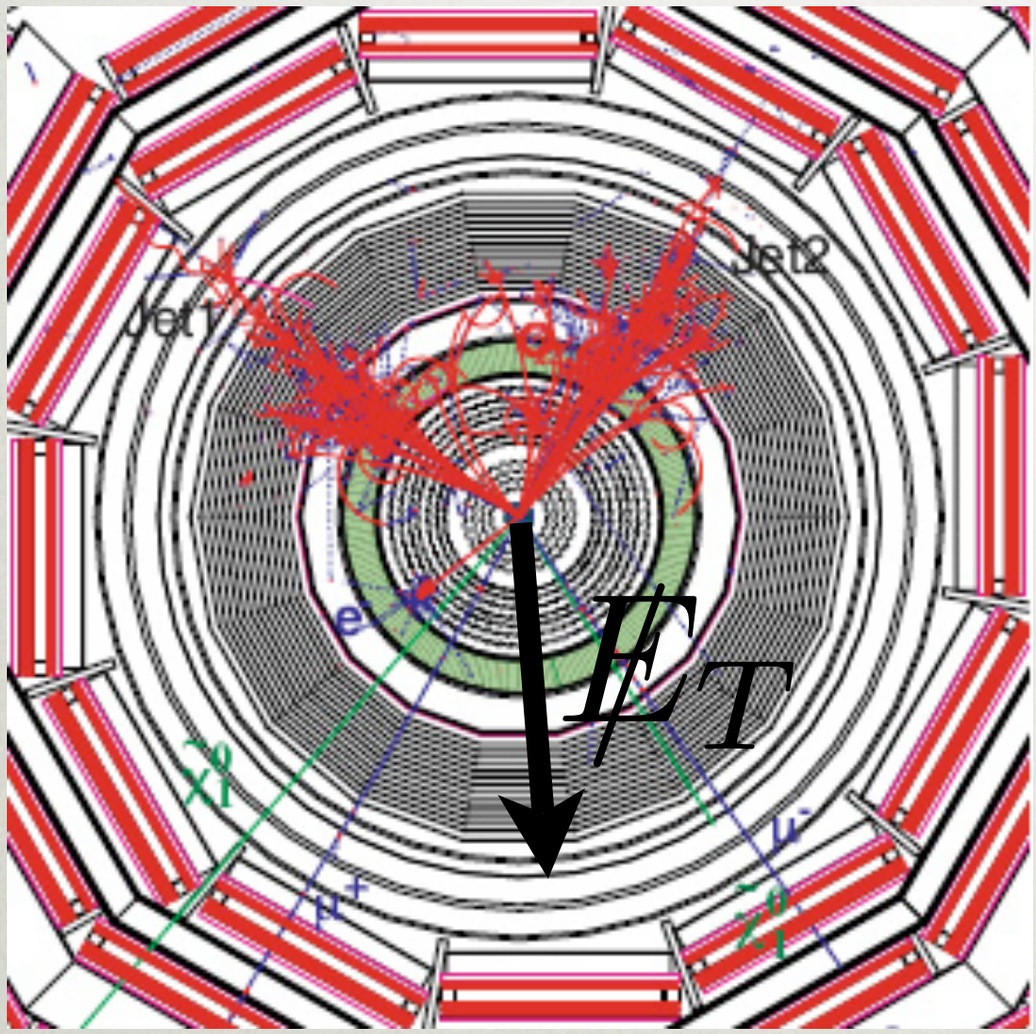

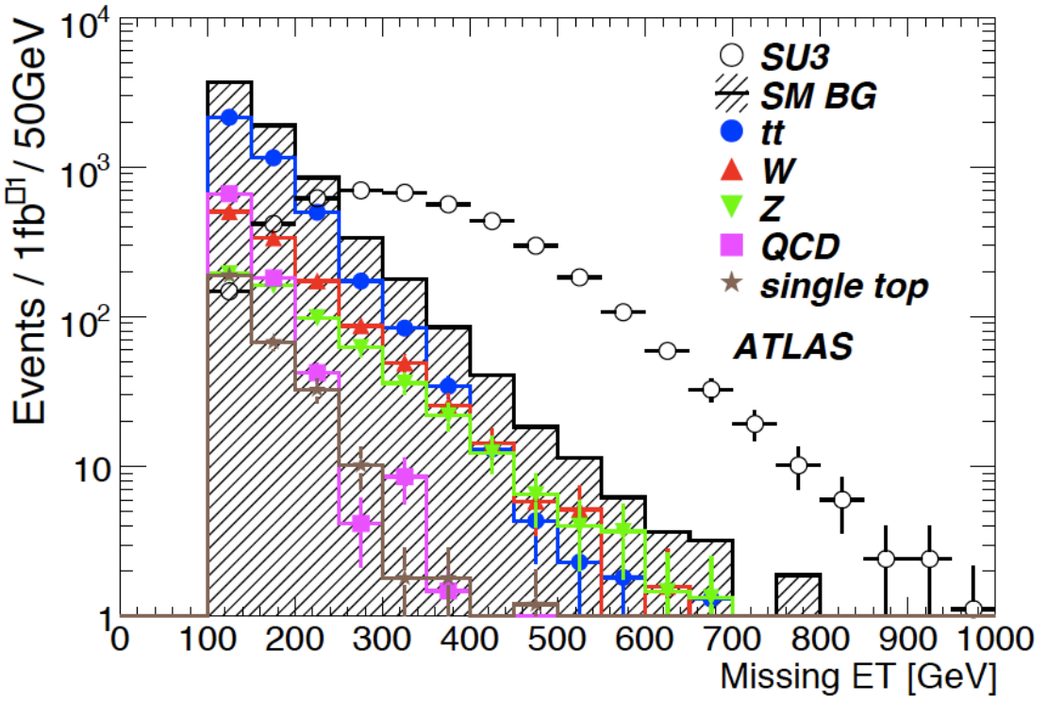

Problem:

stable DM → parity

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→ two sources MET

DM is massive and neutral

what if it is a fermion?

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$$M\,\bar{\Psi}\,\Psi$$

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what if it is a fermion?

$$M\,\bar{\Psi}\,\Psi \quad \text{and/or} \quad m\,\bar{\Psi}^{C}\,\Psi$$

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Dirac

Majorana

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what if it is a fermion?

$M\bar{\Psi}\,\Psi$ and/or $m\bar{\Psi}^{C}\,\Psi$

Dirac

Majorana

MSSM is here

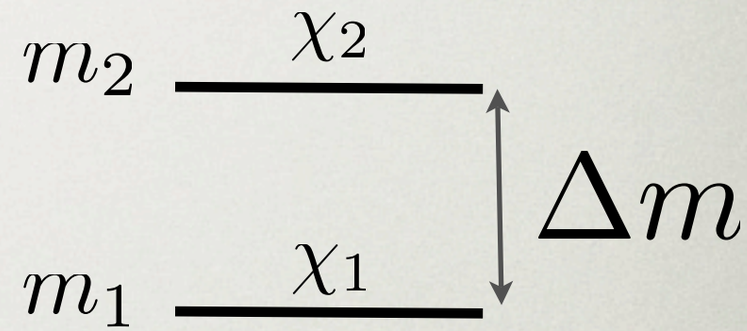
In general

$$L_0 = \bar{\Psi}(i\partial - M_D)\Psi - \frac{m_L}{2}(\bar{\Psi}^c P_L \Psi + \text{h.c.}) - \frac{m_R}{2}(\bar{\Psi}^c P_R \Psi + \text{h.c.})$$

Mass eigenstates

$$\chi_1 \simeq \frac{i}{\sqrt{2}}(\Psi - \Psi^c)$$

$$\chi_2 \simeq \frac{1}{\sqrt{2}}(\Psi + \Psi^c)$$



Three relevant parameters

$$m_1 \qquad \Delta m \qquad \delta = \frac{m_L - m_R}{M_D}$$

In general

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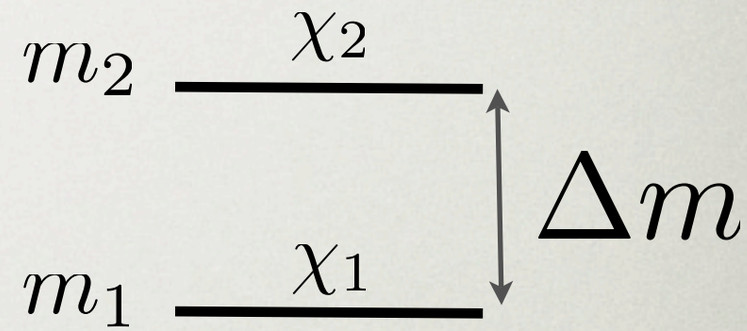
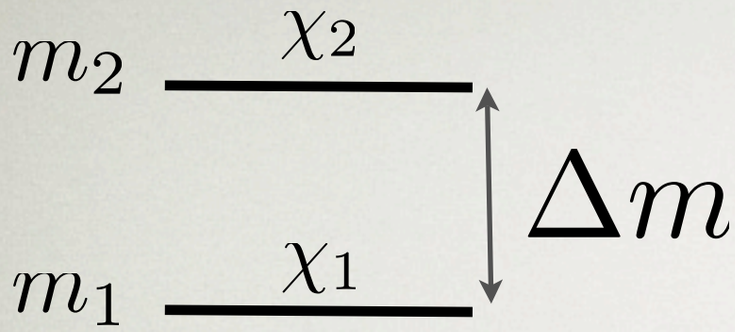


Three relevant parameters

m_1	Δm	$\delta = \dfrac{m_L - m_R}{M_D}$

direct detection only

ask me later...



Dirac: $\delta, \Delta m = 0$

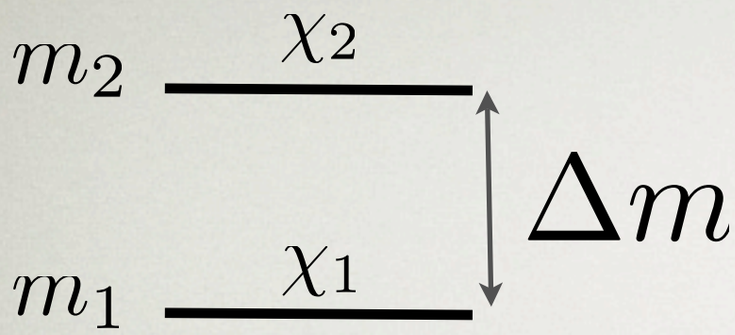
Dirac technically natural:

$$\text{U(1) symmetry} \longrightarrow \delta, \Delta m = 0$$

$$\text{Parity} \longrightarrow \delta = 0$$

Nearly degenerate fermions natural

pseudo-Dirac scenario



SUSY?

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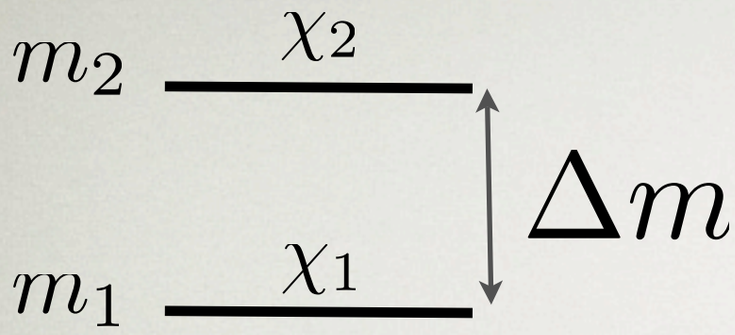

SUSY?

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U(1) symmetry $\longrightarrow$ $\delta, \Delta m = 0$

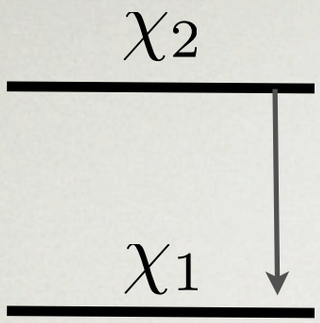
Parity $\longrightarrow$ $\delta = 0$

$U(1)_R$

Nearly degenerate fermions natural

pseudo-Dirac scenario

$\mathcal{N} = 2$

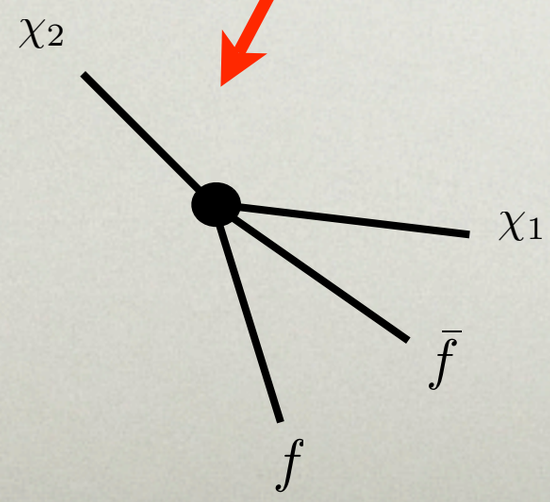


Now, how does it decay?

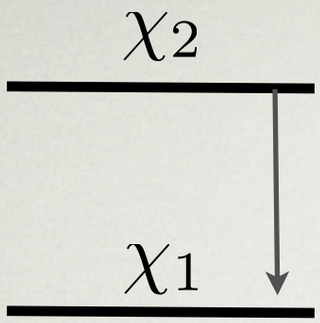
$$\frac{1}{\Lambda^2}\bar{\Psi}\gamma^\mu(c_L P_L + c_R P_R)\Psi\ \bar{f}\gamma_\mu(c_L^{(f)} P_L + c_R^{(f)} P_R)f\ =$$

$$\frac{1}{\Lambda^2}\left[\frac{i}{2}(c_R + c_L)\bar{\chi}_1\gamma^\mu\chi_2 + \frac{1}{4}(c_R - c_L)\left(\bar{\chi}_1\gamma^\mu\gamma^5\chi_1 + \bar{\chi}_2\gamma^\mu\gamma^5\chi_2\right)\right]$$

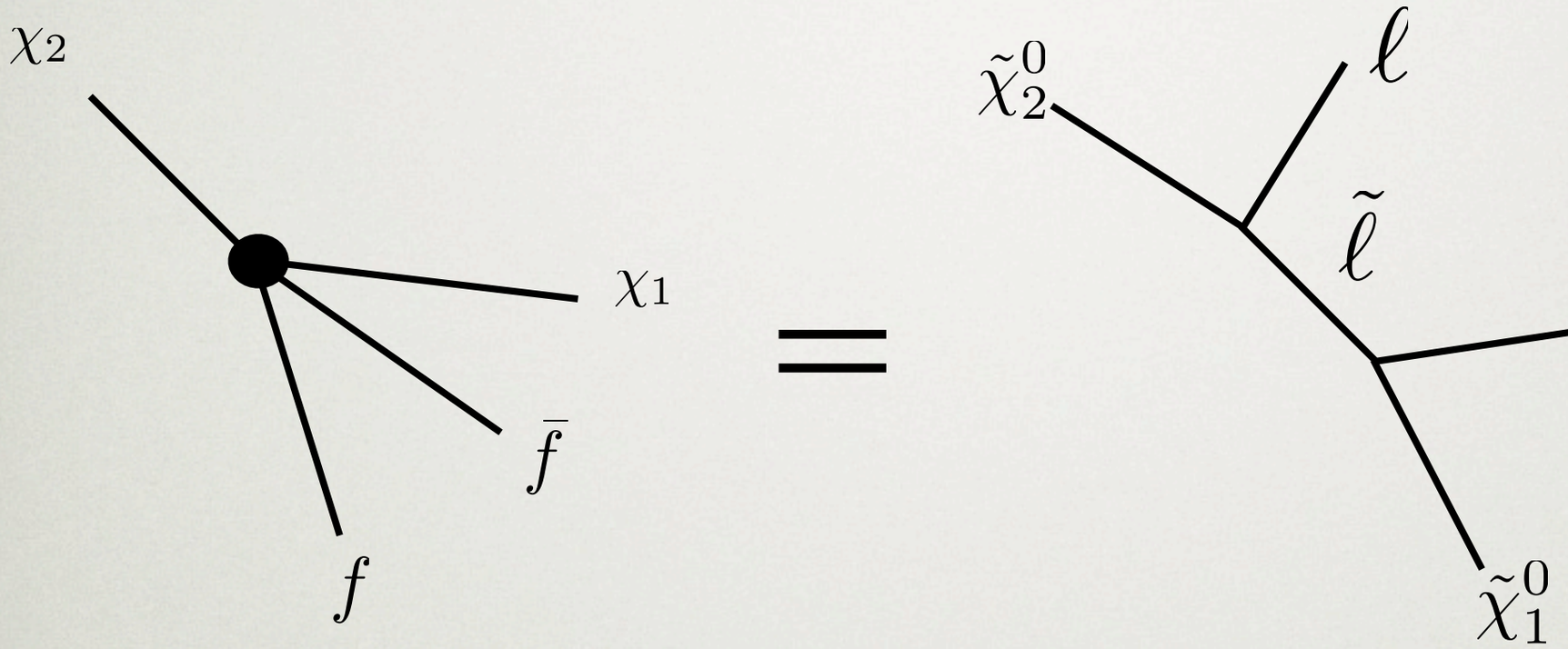
$$\times\left[\bar{f}\gamma_\mu(c_L^{(f)} P_L + c_R^{(f)} P_R)f\right]$$



Decay into SM fermions
very small mass splitting



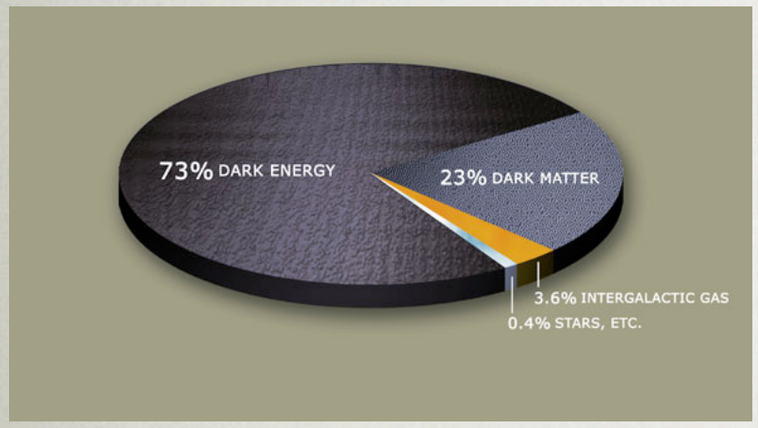
SUSY?



$$\frac{c}{\Lambda} \sim \frac{g'}{m_{\tilde{\ell}}}$$

Why pDDM?

Generally speaking

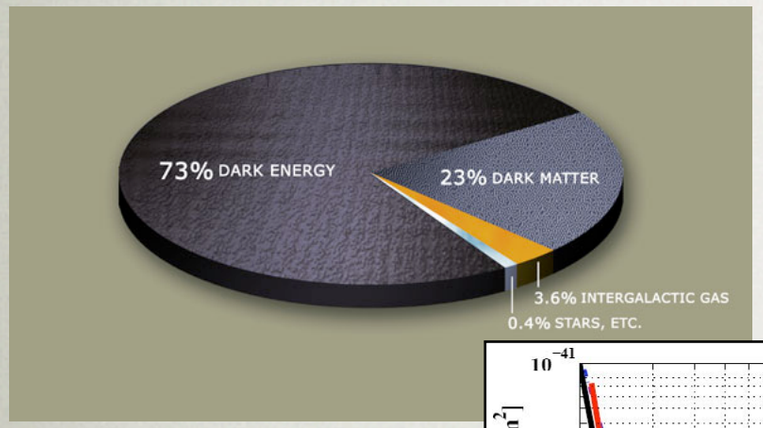


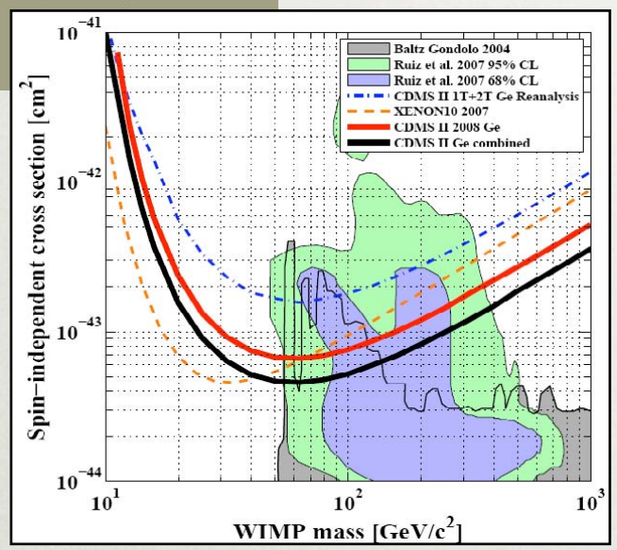
If MAJORANA

p-wave annihilations not efficient

may lead to overabundance

Generally speaking





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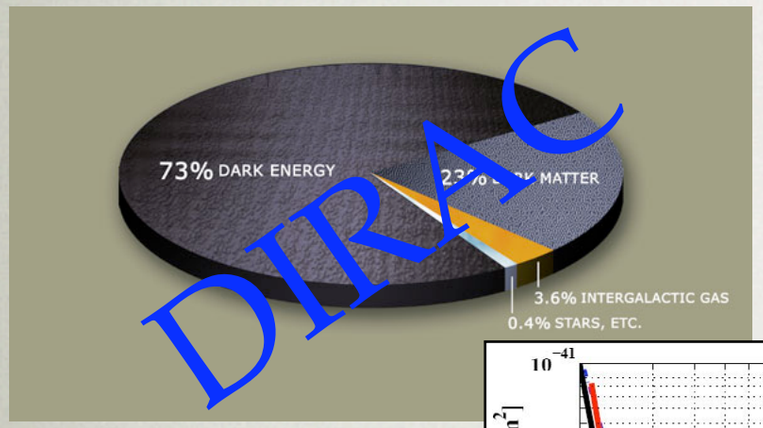
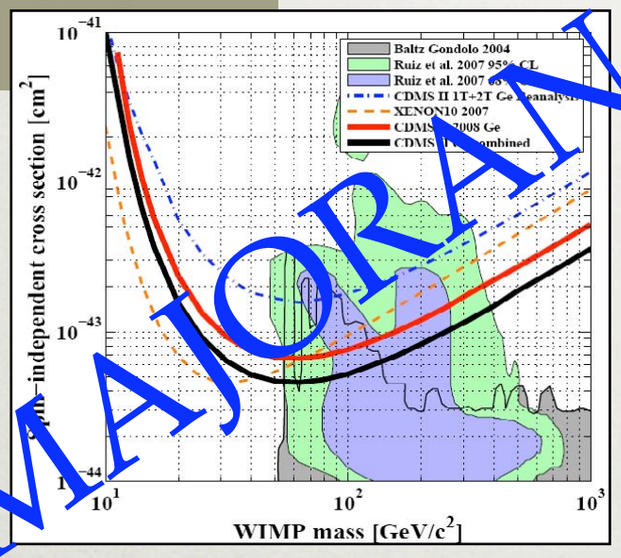
If DIRAC

nucleon-DM vector interactions

surpass present limits

Generally speaking





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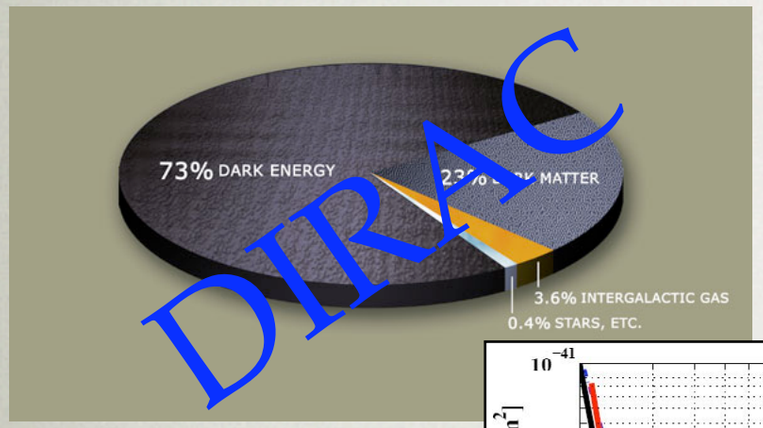

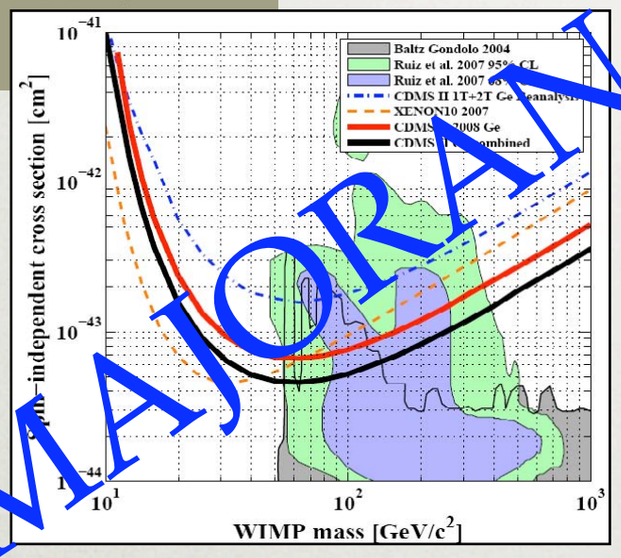

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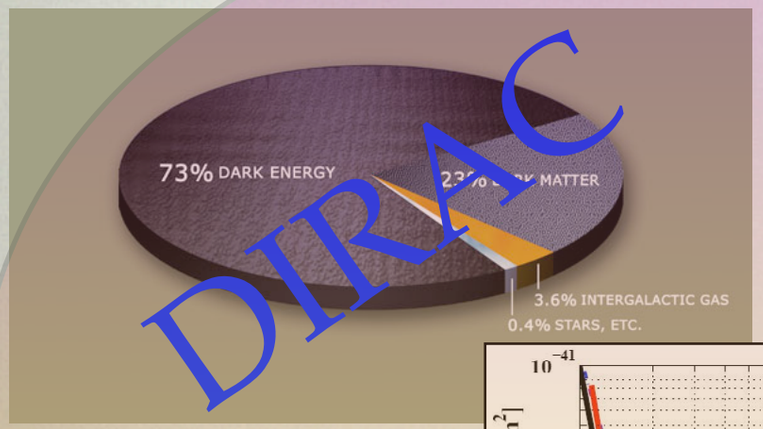
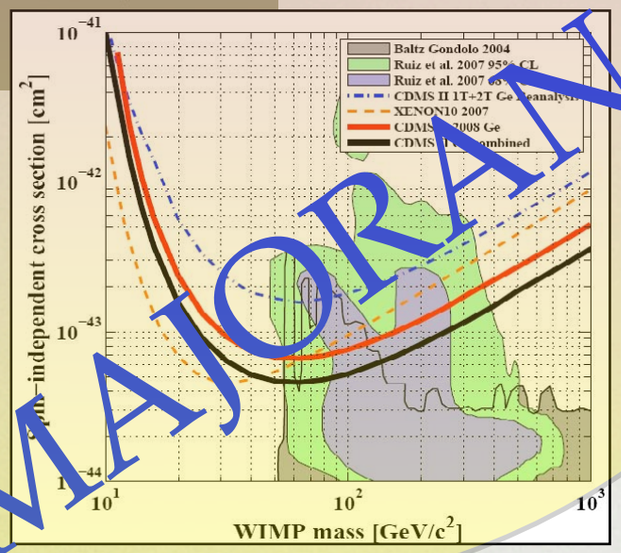
pseudo-Dirac Dark Matter does precisely that, and....

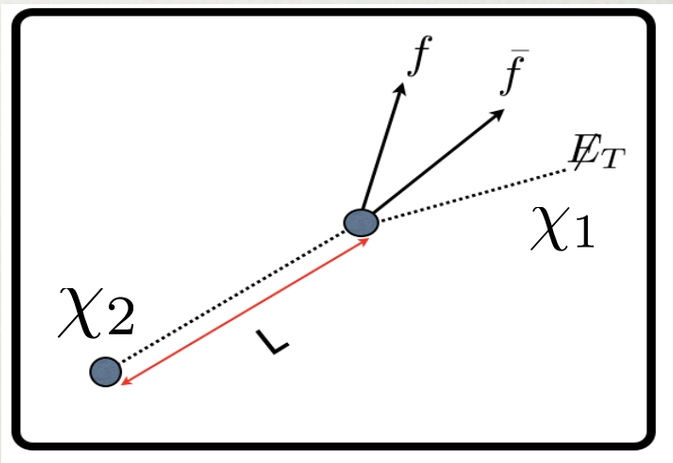


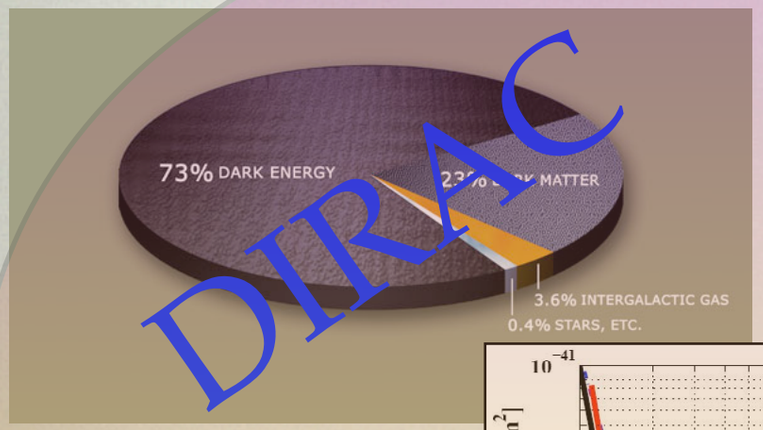


DIRAC

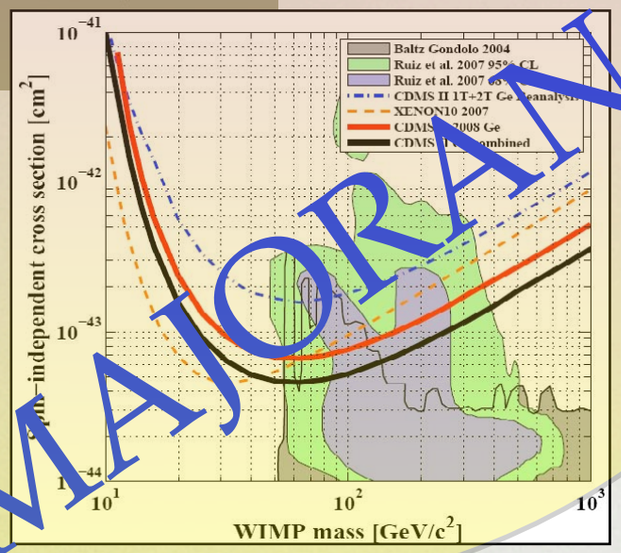
MAJORANA

Displaced vertex at colliders



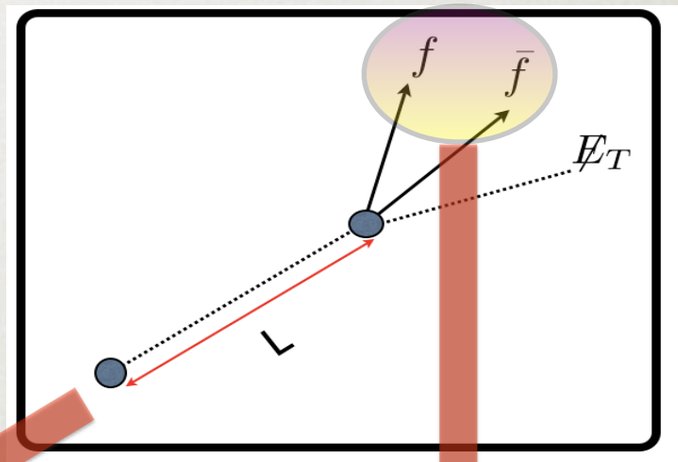


DIRAC



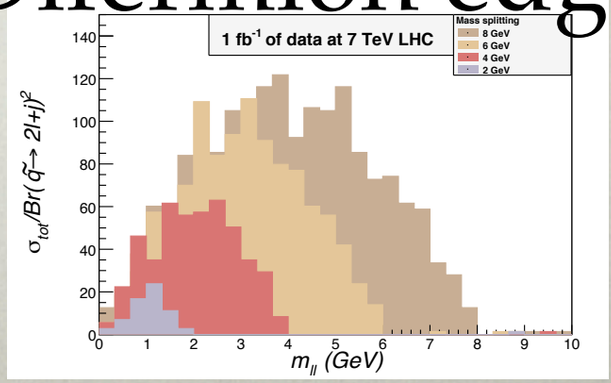
MAJORANA

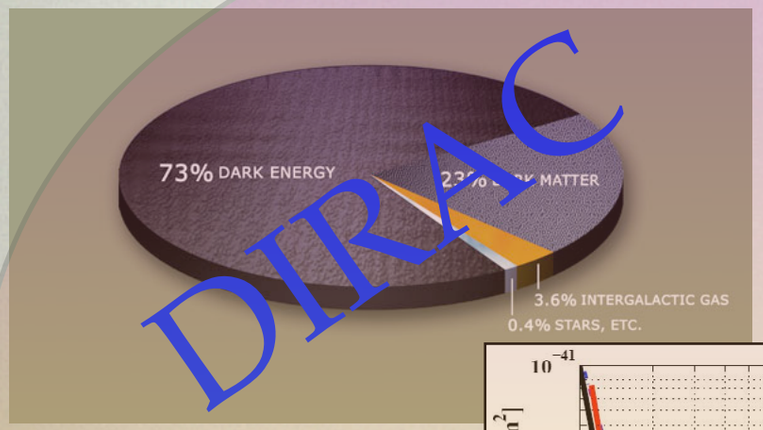
Displaced vertex at colliders



Length measurement

Difermion edge





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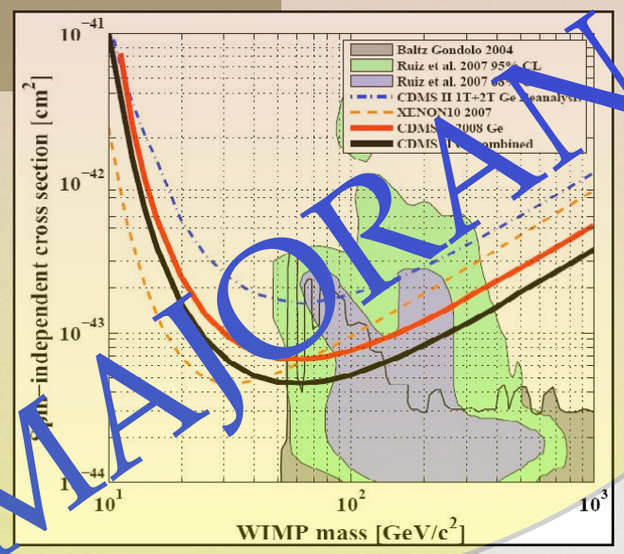

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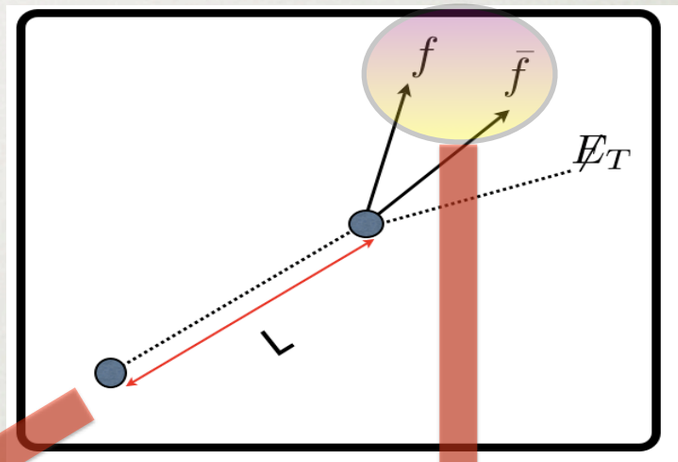
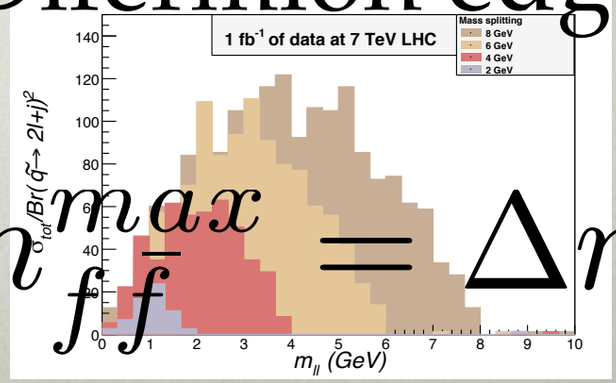


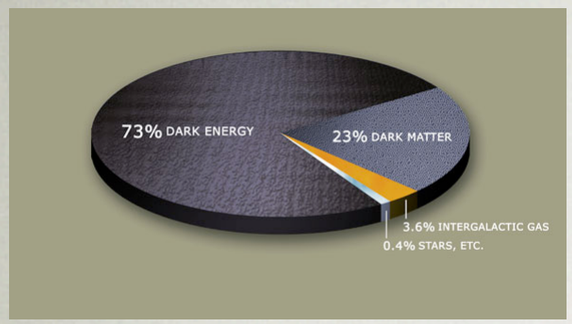
Length measurement

$$L \propto \Omega h^2$$

Difermion edge

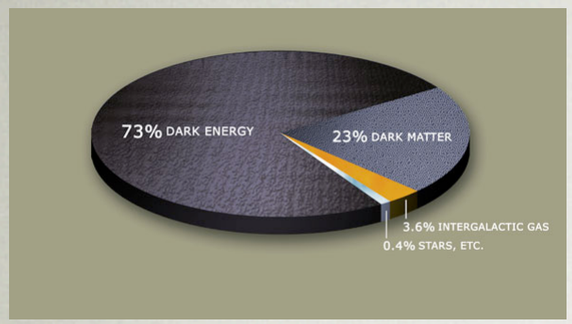


$$m_{f\bar{f}}^{max} = \Delta m$$



Relic Abundance

$$\langle \sigma_{\text{eff}} v \rangle \propto \left[\langle \sigma_{11} v \rangle + 2 \left(1 + \frac{\Delta m}{m_1} \right)^{3/2} e^{-x \frac{\Delta m}{m_1}} \langle \sigma_{12} v \rangle \right]$$



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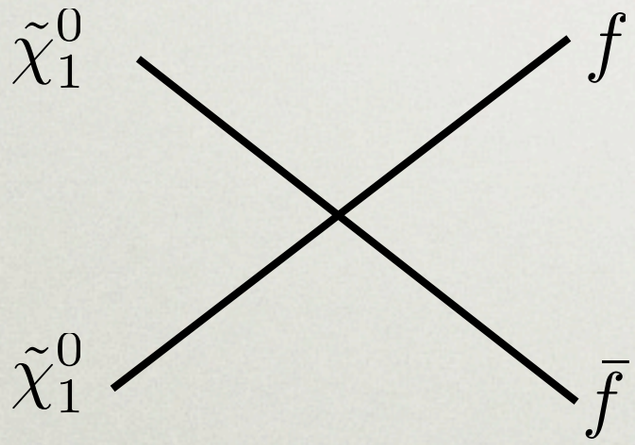
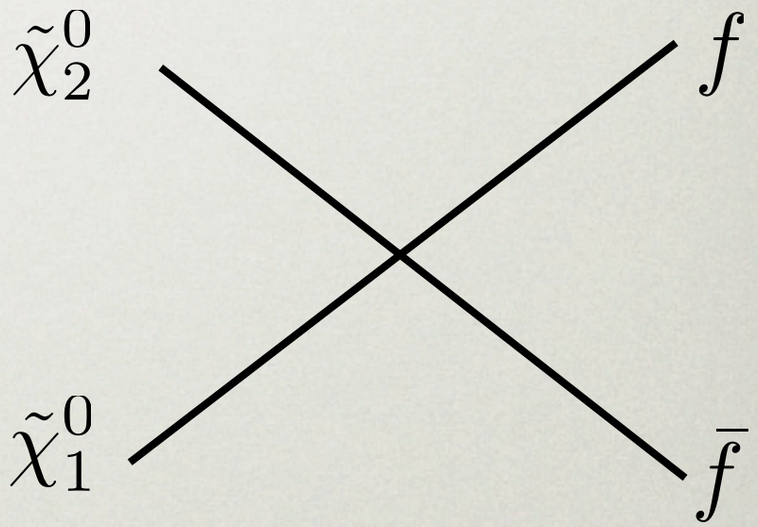
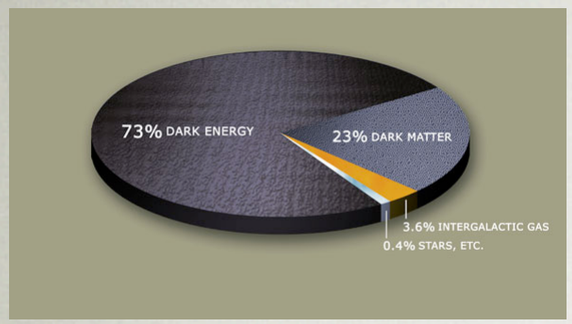
annihilations



co-annihilations





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$$\frac{1}{\Lambda^2} \bar{\Psi} \gamma^\mu (c_L P_L + c_R P_R) \Psi \, \bar{f} \gamma_\mu (c_L^{(f)} P_L + c_R^{(f)} P_R) f \; =$$

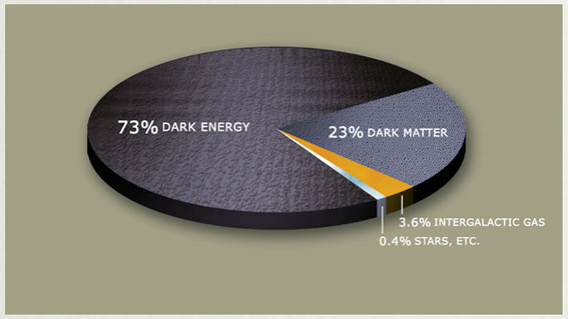
$$\frac{1}{\Lambda^2} \left[\frac{i}{2} (c_R + c_L) \bar{\chi}_1 \gamma^\mu \chi_2 + \frac{1}{4} (c_R - c_L) \left(\bar{\chi}_1 \gamma^\mu \gamma^5 \chi_1 + \bar{\chi}_2 \gamma^\mu \gamma^5 \chi_2 \right) \right]$$

s-wave

$$\times \left[\bar{f} \gamma_\mu (c_L^{(f)} P_L + c_R^{(f)} P_R) f \right]$$

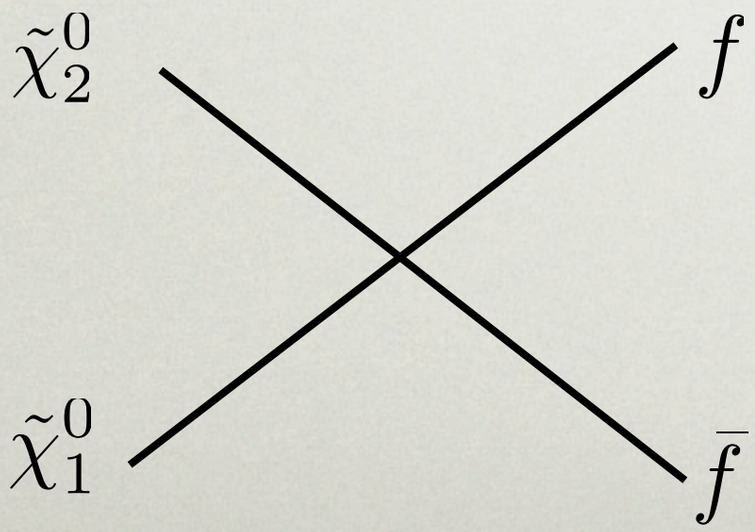
p-wave
=velocity suppressed

Relic Abundance and decay length

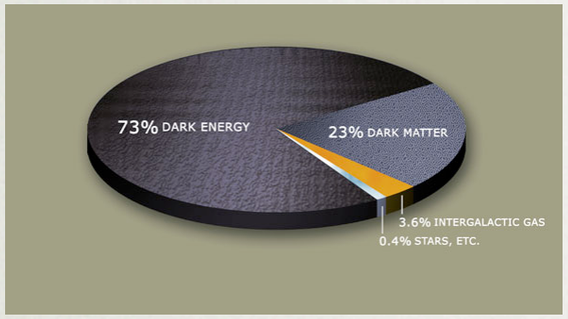


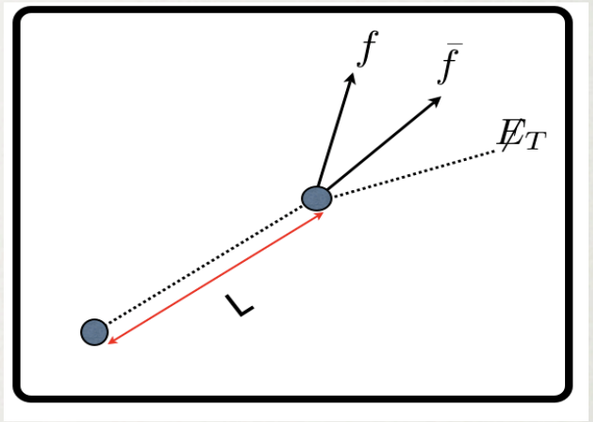
$$\Omega\, h^2$$

co-annihilations



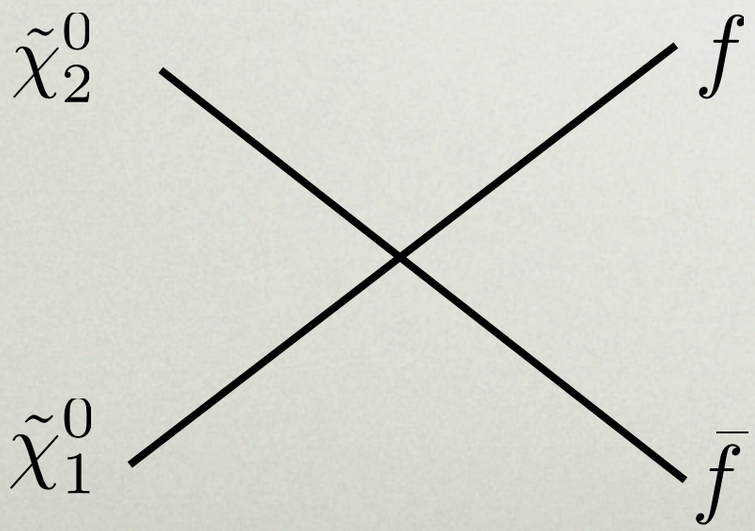
Relic Abundance and decay length



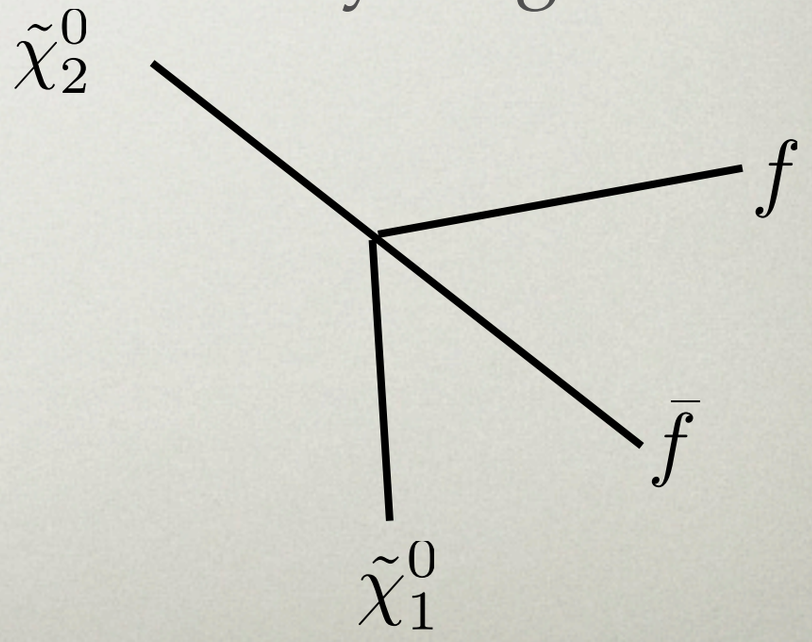


$$\Omega h^2 \propto L$$

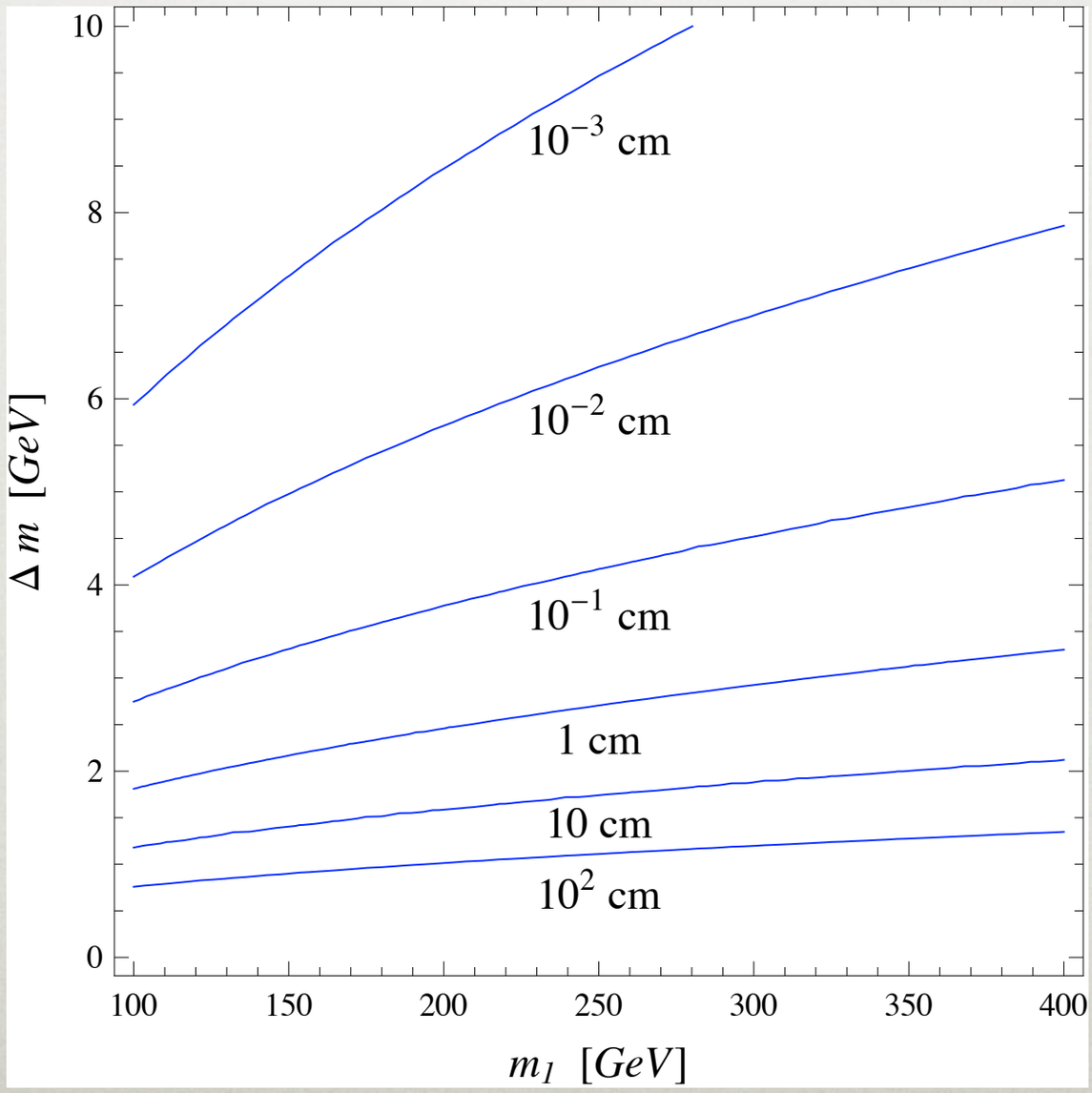
co-annihilations



decay length



$$L_0 \simeq 15 \text{ cm} \left(\frac{\Omega_{\rm DM} h^2}{0.11}\right) \left(\frac{m_1}{100 \text{ GeV}}\right)^2 \left(\frac{1 \text{ GeV}}{\Delta m}\right)^5 e^{-24 \frac{\Delta m}{m_1}}$$

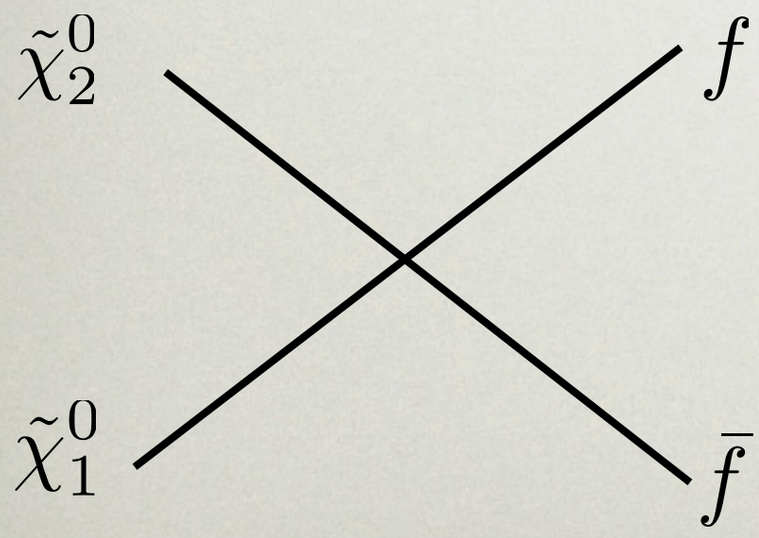


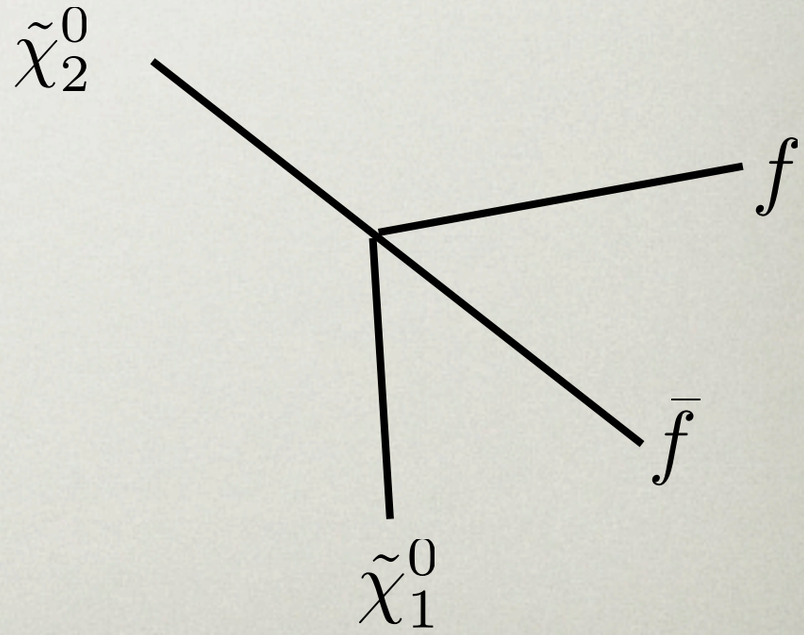
pDDM means

$$\Delta m \ll m_1$$

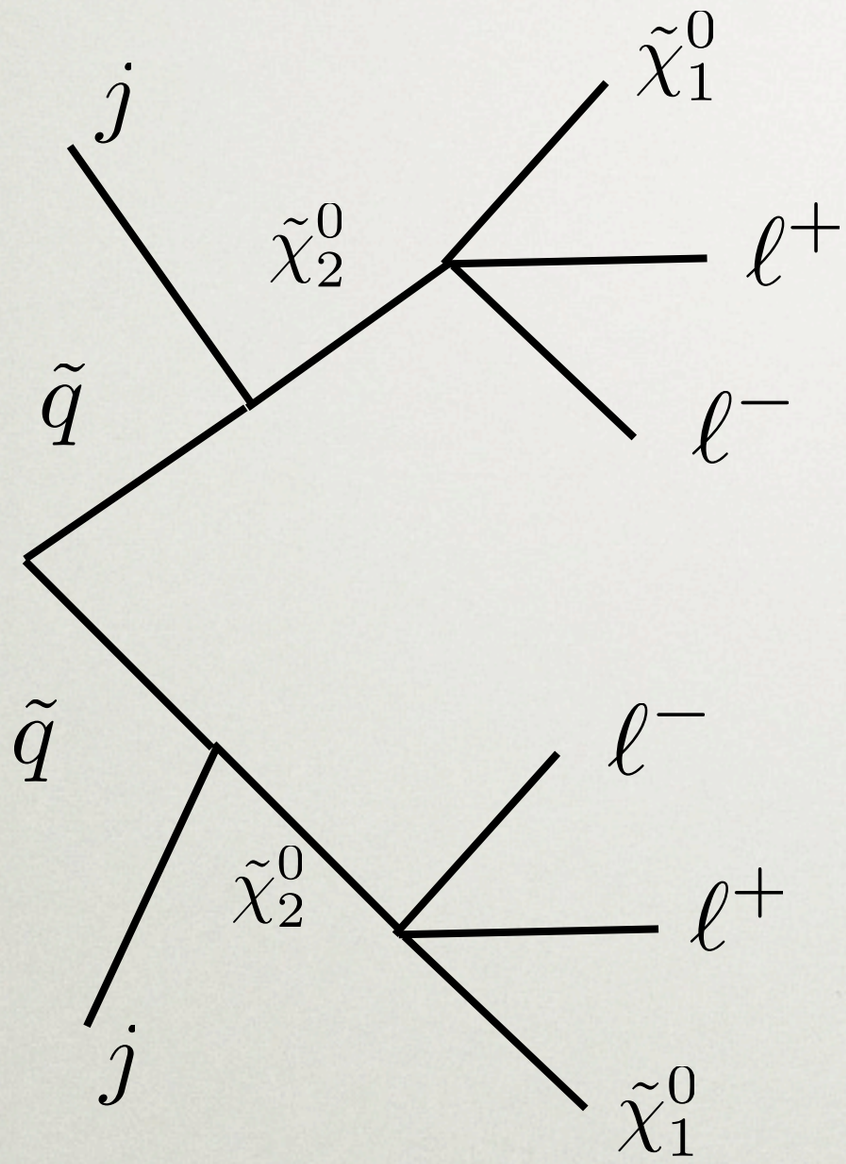
s-wave unsuppressed
co-annihilations
no overabundance

long decay length
displaced vertices





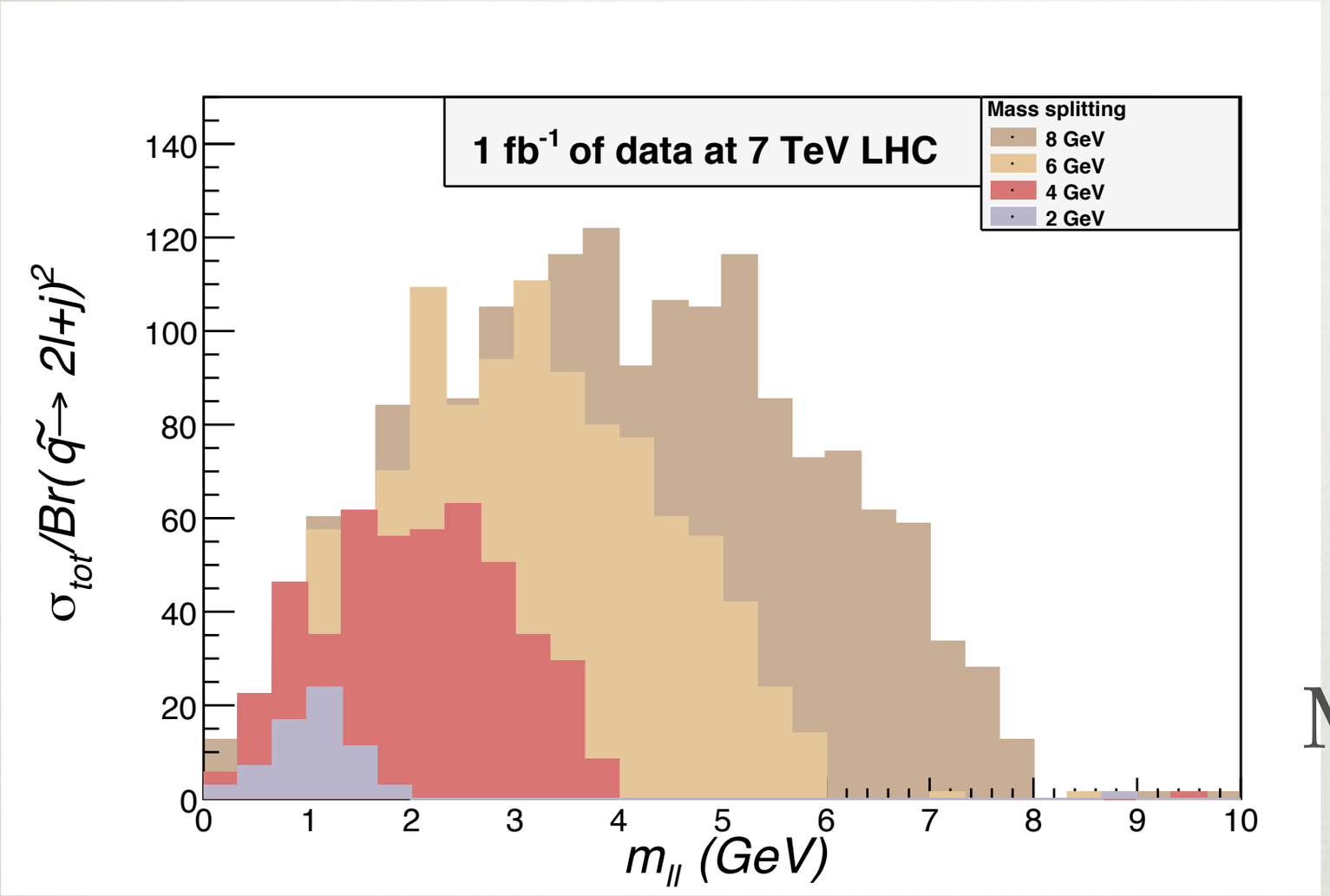
Simulation SUSY scenario



MadGraph/
MadEventv4.4

$$4\ell + 2j + \not{E}_T$$

Dilepton edge $m_{f\bar{f}}^{max} = \Delta m$

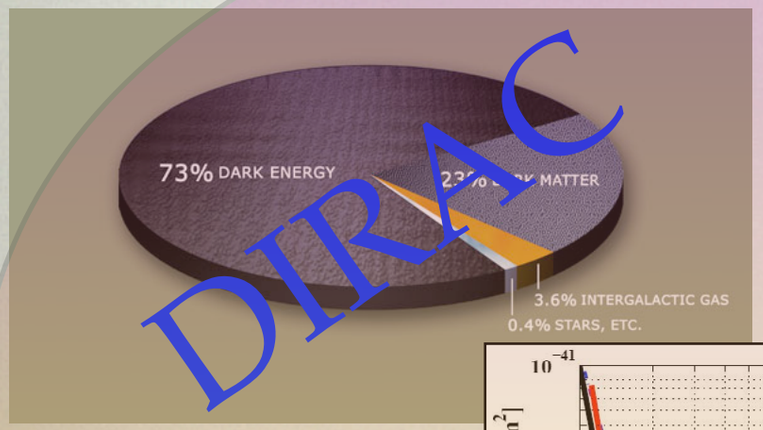


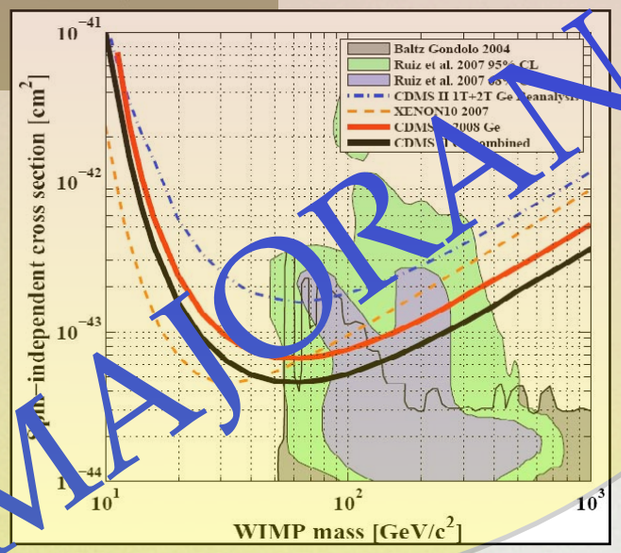
$p_T > 4$ GeV, $|\eta| < 3.5$

Triggers
MET+2 high-pT jets

momentum resolution few percent

Conclusions

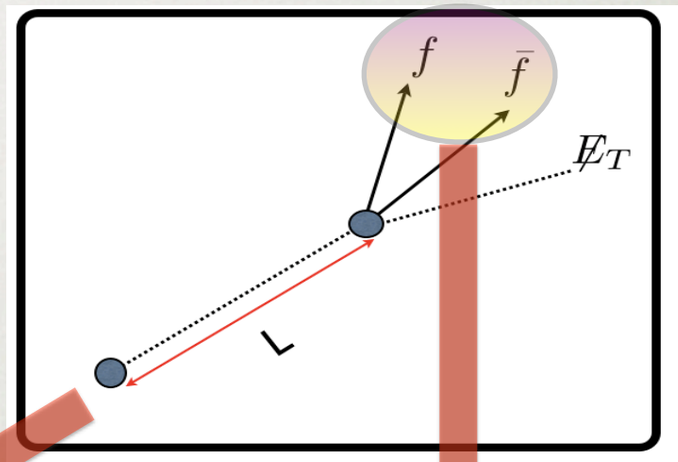




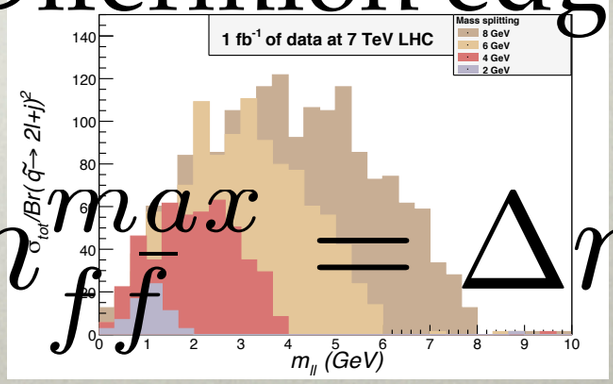
DIRAC

MAJORANA

Displaced vertex at colliders



Difermion edge



Length measurement

$$L \propto \Omega h^2$$

$$m_{f\bar{f}}^{max} = \Delta m$$

Direct detection

Nuclei-DM interactions sensitive to KeV range energy
splitting more than few tenths of KeV, only lightest state relevant

$$b_q[\bar{\chi}_1\gamma^\mu\chi_1][\bar{q}\gamma_\mu q]\,, \qquad d_q[\bar{\chi}_1\gamma^\mu\gamma^5\chi_1][\bar{q}\gamma_\mu\gamma^5 q]\,,$$

σ^{SD}

same as MSSM
very suppressed
OK present limits

σ^{SI}

new interaction
sets limits on

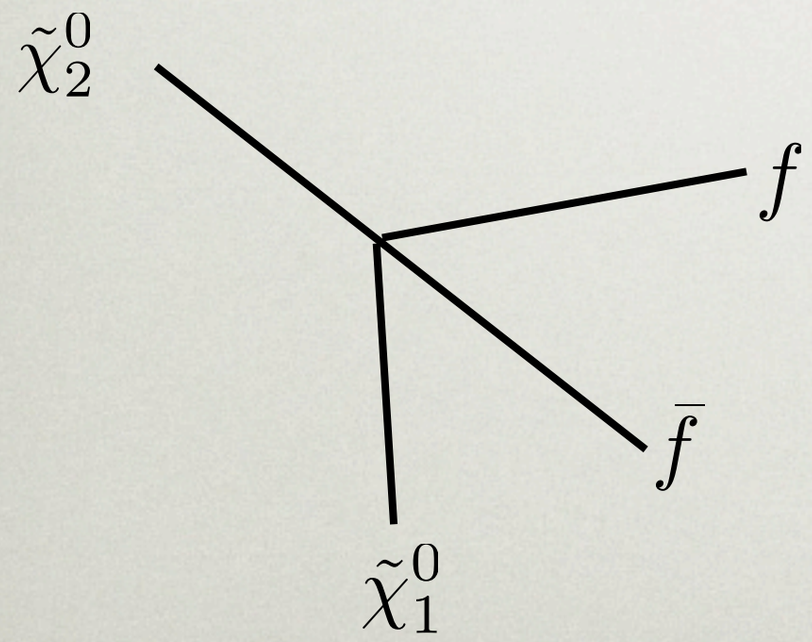
$$\delta \simeq 0.03 \left(\frac{\sigma_n^{\rm SI}}{10^{-43}\ {\rm cm}^2}\right)^{1/2} \left(\frac{\Lambda/B_n}{1\ {\rm TeV}}\right)^2$$

2 BUT's

$$L_{\rm lab} = \frac{|\vec{p}_2|}{m_2} L_0$$

how do we measure it?

is it important?



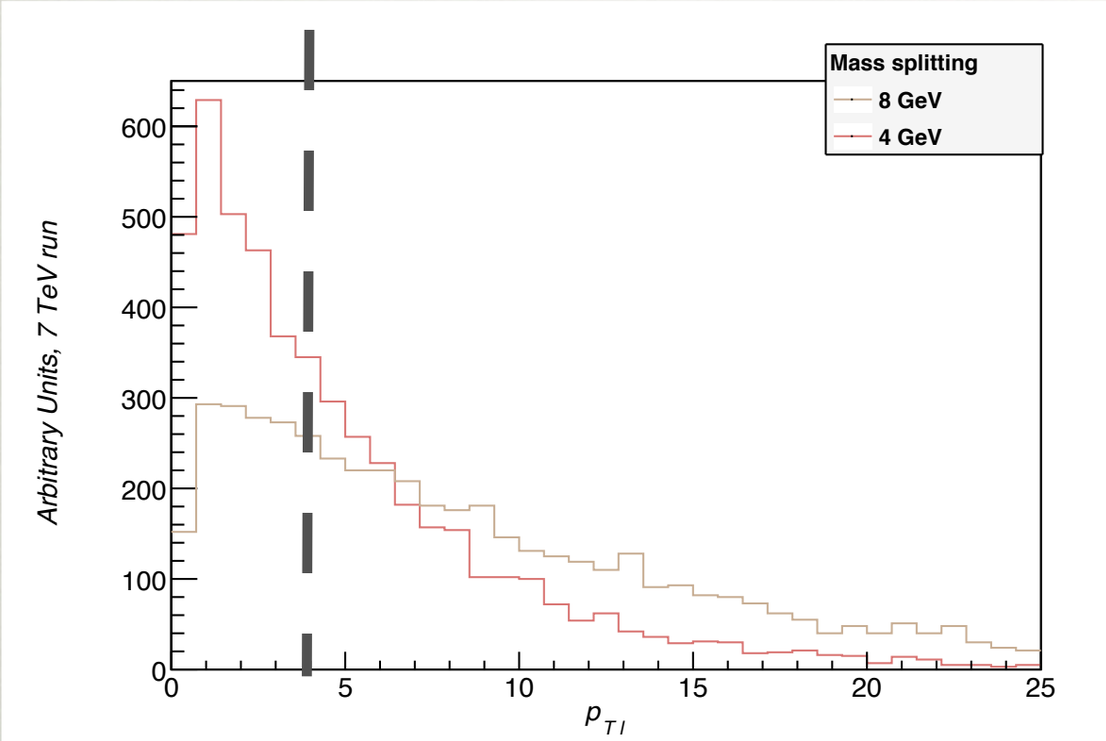
In CM, fermions share very little energy

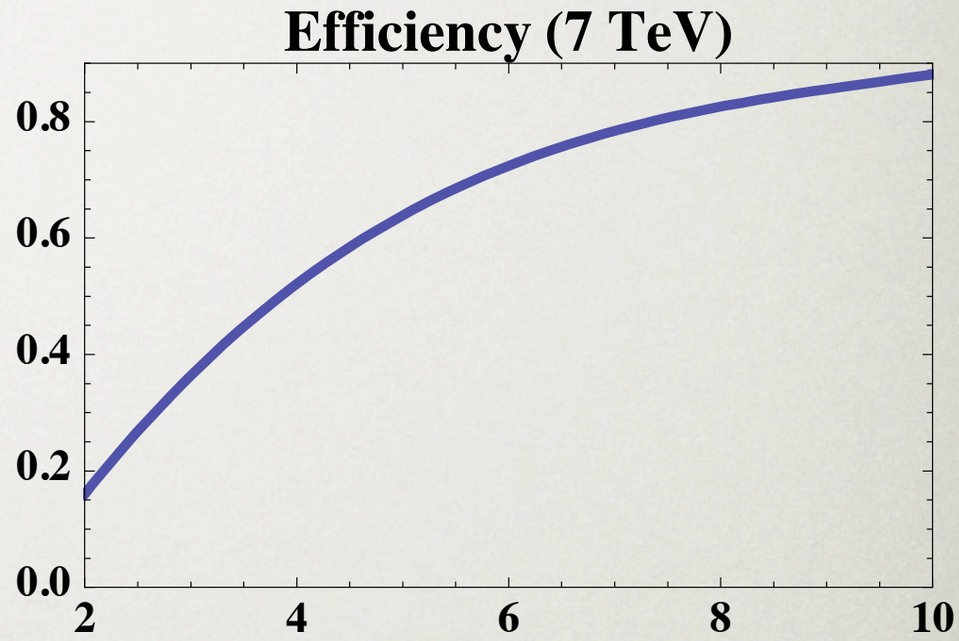
$p_f \sim \Delta m$

trigger?

LAB boost enough?

Momentum distribution depends on the collider energy

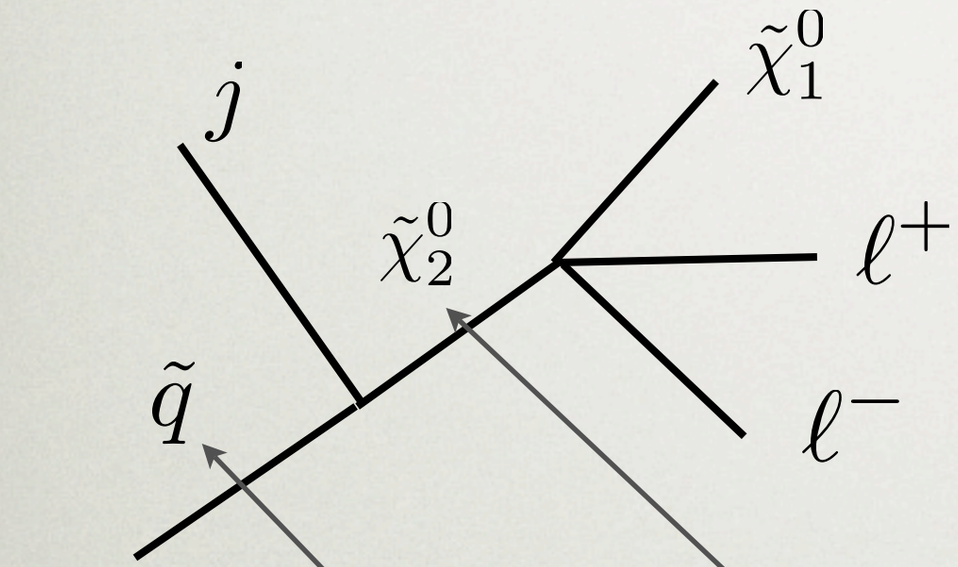




Efficiency at least 2 leptons with

$$p_T > 4 \text{ GeV}$$

$$L_{\rm lab} = \frac{|\vec{p}_2|}{m_2} L_0 \ ?$$

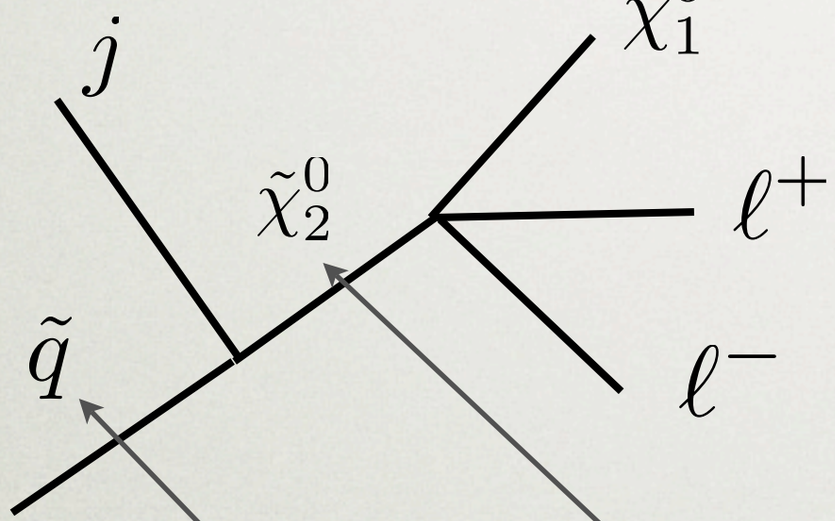


heavy, little boost

$$|\vec{p}_j| \simeq |\vec{p}_2| \simeq \frac{m_{\tilde{q}}}{2}$$

$$\frac{|\vec{p}_2|}{m_2} \simeq \frac{|\vec{p}_j|}{m_1}$$

$$L_{\rm lab} = \frac{|\vec{p}_2|}{m_2} L_0 \ ?$$



heavy, little boost

$$\frac{|\vec{p}_2|}{m_2} \simeq \frac{|\vec{p}_j|}{m_1}$$

$$|\vec{p}_j| \simeq |\vec{p}_2| \simeq \frac{m_{\tilde{q}}}{2}$$

$$L_0 \simeq 15 \text{ cm} \left(\frac{\Omega_{\rm DM} h^2}{0.11}\right) \left(\frac{m_1}{100 \text{ GeV}}\right)^2 \left(\frac{1 \text{ GeV}}{\Delta m}\right)^5 e^{-24 \frac{\Delta m}{m_1}}$$

DM is massive and neutral

what if it is a fermion?

$M\,\bar{\Psi}\,\Psi$ and/or $m\,\bar{\Psi}^{C}\,\Psi$

Dirac Majorana

Mass eigenstates