Direct detection — see Tongyan. Lewin + Smith

DM locally : $\rho \sim 0.4\,\mathrm{GeV/cm^3}$

$$f(v) \sim MB = e^{-(v/v_0)^2}\,\Theta(v_{esc}-|v_{esc}|)$$

$$\hookrightarrow e^{-(\vec{v}+\vec{v}_{earth})^2/v_0^2}\,\Theta\left(v_{esc}^2-(v+v_E)^2\right)$$

$$\int d^3v\, f(v) = 1.$$

$v_0 \sim 220\,\mathrm{km\,s^{-1}}$

$v_{esc} \sim 600-700\,\mathrm{km\,s^{-1}}$

$\Downarrow$

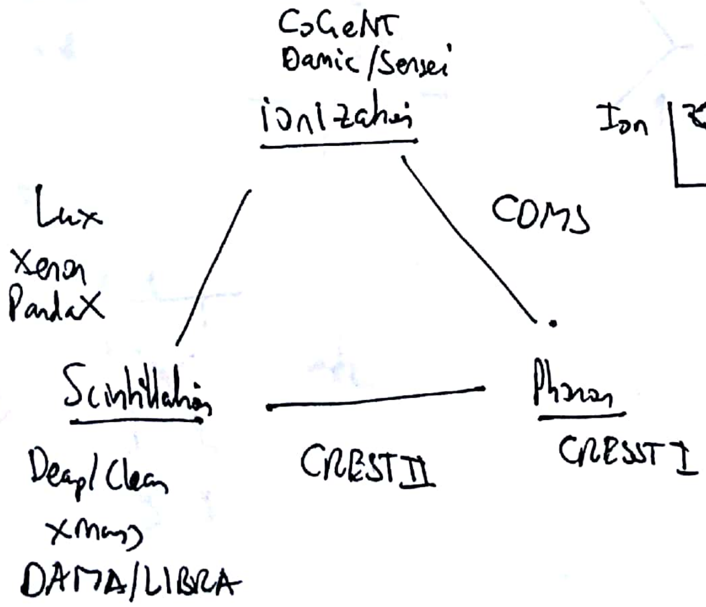
$q^2 = 2\mu_{N\chi}^2 v^2(1-\cos\theta_{cm})$ N.R. and $10^4\,\mathrm{cm^{-2}\,s^{-1}}$ (?, !)

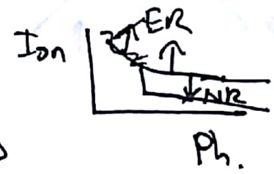
σ ??

Simple mechanics. $q \sim \mu v \sim 100\,\mathrm{MeV} \Rightarrow E_R \sim \frac{q^2}{2m_N} \sim 10\,\mathrm{keV}$

Go deep, go quiet, go massive. Try to distinguish DM from α,γ bckgd.

neutrons harder, multiple scatter.





For most WIMP/SUSY models

$$v_{min} = \sqrt{\frac{m_N E_R}{2\mu_{N\chi}^2}}$$

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{min}}^{v_{max}} d^3v\, f(v(t))\, \frac{d\sigma}{dE_R}|v|$$

iDM

$$v_{min} = \frac{1}{\sqrt{2m_N E_R}}\left(\frac{m_N E_R}{\mu_{N\chi}} + \delta\right)$$

[Resolutions, eff., quenching etc.]

.27

Scattering cross section.

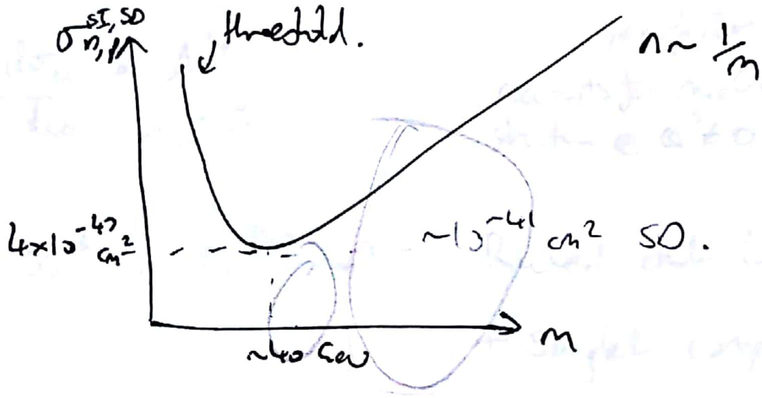
Ex. $\bar\chi \Gamma \chi \, \bar q \Gamma' q \;\to\; \bar\chi \tilde\Gamma \chi \, (\underbrace{\bar n \tilde\Gamma' n}_{\text{neutron}} + \underbrace{\bar p \tilde{\tilde\Gamma}' p}_{\text{proton}})$ Matrix element.

$\langle n | \bar q \Gamma' q | n \rangle$

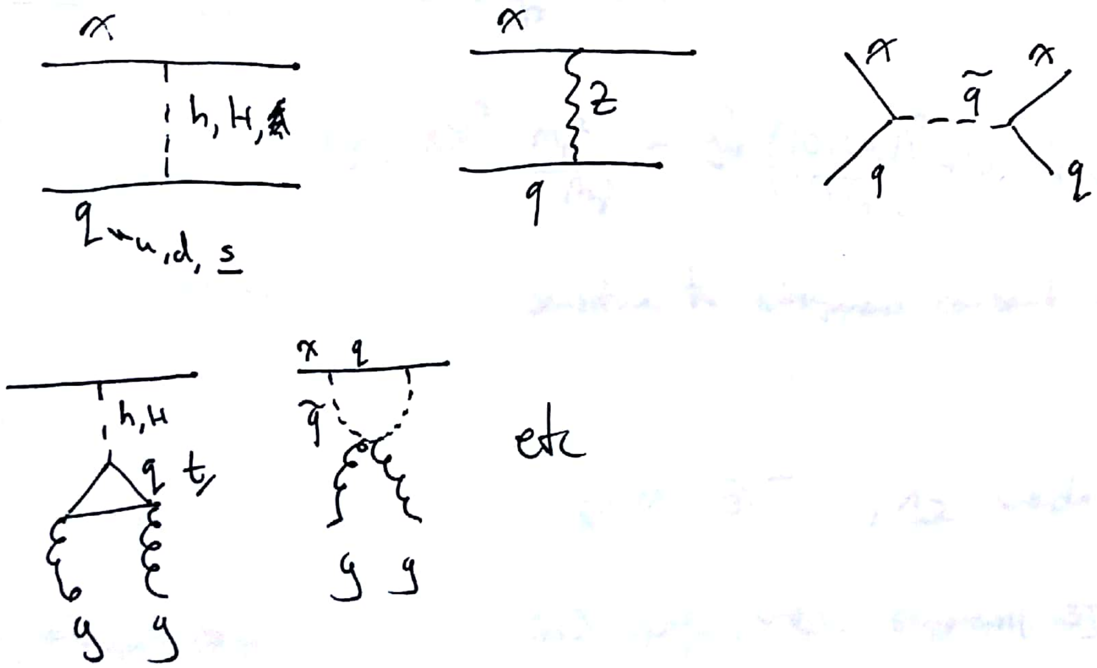
$\downarrow$

$(\bar\chi \Gamma \chi)(\bar N \Gamma N)$ nucleons. Form factor

Results quoted as



Scattering x-sec in SUSY.



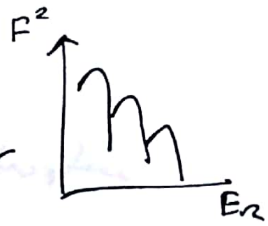
$q^2 \ll M_{weak}^2 \Rightarrow$ contact ops. (not true for light dark sector)

Standard Candle 1 – Z

$$\frac{d\sigma_{\chi p}}{d\cos\theta} \sim \mu_{n\chi}^2 G_F^2 \begin{cases} 1 \\ 1-4s_w^2 \end{cases} \Rightarrow \frac{d\sigma_N}{d\cos\theta} = \frac{\mu_{N\chi}^2}{\mu_{n\chi}^2} G_F^2 \left[Z(1-4s_w^2)+(A-Z)\right]^2$$

$$\times \left|F^2(E_R)\right|^2$$

↑ formfactor accounts for nuclear structure @ $Q^2 \neq 0$



For WIMP $\gtrsim$ 100 GeV $\mu_N \sim m_N$.

$$\Rightarrow \frac{d\sigma_N}{d\cos\theta} \propto A^4$$

Heavy nuclei best $\sigma_n^{(Z)} \sim 10^{-39}\,cm^2$. Ruled out long time ago + singlet components.

Standard Candle 2 – h $\mathcal{L} < y_\chi \chi\chi h$

$$\sigma_p \sim \frac{y_\chi^2}{m_h^4} \left|\langle p| y_q \bar{q} q |p\rangle\right|^2 \frac{m_p^2}{m_\chi^2} \sim y_\chi^2 \left(\frac{100\,\text{GeV}}{m_\chi}\right)^2 \times 10^{-43}\,cm^2$$

Investigating now. – sensitive to strangeness content of nucleon, lattice

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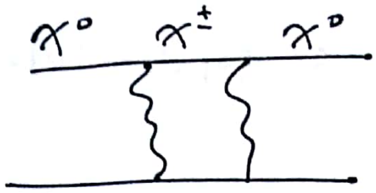
χ is majorana → $\chi \gamma^\mu \gamma_5 \chi Z_\mu$, no vector coupling

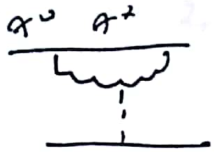
Low energy coupling is SD or vel. suppressed SI.

No A^2 enhancement. Bounds weaker.

Another weird process



Hill + Solon 1401.3339

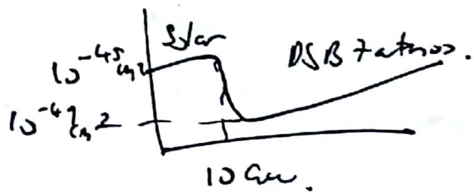


~~Cancellation~~ Loop + cancellation $\Rightarrow \sigma \sim 10^{-48}\ \mathrm{cm}^2$

How far can we go?

ν-floor. Solar ν + DSB + cosmic-ray initiated atmospheric

$\sigma \sim 10^{-49}\ \mathrm{cm}^2$ @ $M \sim 40$ GeV.



Blind spots. 1211.4873

SD – Z, SI – h.

$$\mathcal{L} = \frac{C_{h\chi\chi}}{2} h(\chi\chi + \chi^\dagger\chi^\dagger) + C_{Z\chi\chi}\chi^\dagger\bar{\sigma}^\mu\chi Z_\mu .$$

$$\sigma_{SI} \sim 10^{-44}\ \mathrm{cm}^2 \left(\frac{C_{h\chi\chi}}{0.1}\right)^2$$

$$\sigma_{SD} \sim 10^{-39}\ \mathrm{cm}^2 \left(\frac{C_{Z\chi\chi}}{0.1}\right)^2$$

Where do these couplings come from in MSSM?

Only $\tilde{h}$ couples to Z.

h coupling off diagonal $(H^\dagger e^v H) \to \left.h\tilde{h}\tilde{W},\ h\tilde{h}\tilde{B}\right\}$ pure states don't have direct detection @ tree-level.

If not pure but $C_{h\chi\chi} = 0$ then still no bound

$$\frac{\partial m}{\partial v} = C_{h\chi\chi} \qquad \det(M_\chi - m_\chi \mathbb{1}) \to 0.$$

$$\frac{\partial}{\partial v}\det(M_\chi - m_\chi\mathbb{1}) \Rightarrow (m_\chi + \mu\sin 2\beta) \times \left[m_\chi(v) - \tfrac{1}{2}\left((M_1 + M_2) + c_{2w}(M_1 - M_2)\right)\right] = 0.$$

$$\Rightarrow C_{h\chi\chi} = 0$$

If $\partial_{\overline{x}} m_\chi(V) = 0 \Rightarrow m_\chi(v) = m_\chi(0) \Rightarrow m_\chi = M_1, M_2, -\mu$.

So $m_1 = M_1, M_2, -\mu$ and $m_1 + \mu S_{2\beta} = 0$

or $m_1 = M_1 \mp M_2$.

m_χ	Cond.	sgn
M_1	$M_1 + \mu S_{2\beta} = 0$	$\mathrm{sgn}\,\frac{M_1}{\mu} = -1$
M_2	"	$\mathrm{sgn}\,\frac{M_2}{\mu} = -1$
$-\mu$	$t_\beta = 1$	$\mathrm{sgn}\,\frac{M_{1,2}}{\mu} = -1$
M_2	$M_1 = M_2$	$\mathrm{sgn}\,\frac{M_{1,2}}{\mu} = -1$

So $t_\beta = 1 \quad Z\chi\chi_1 \to 0$

(χ maj $\Rightarrow Z\chi_1\chi_2$ only from higgsino, $t_\beta \to 1$ has $H_u \Leftrightarrow H_d$ sym $\Rightarrow Z\chi_1\chi_1 = 0$).

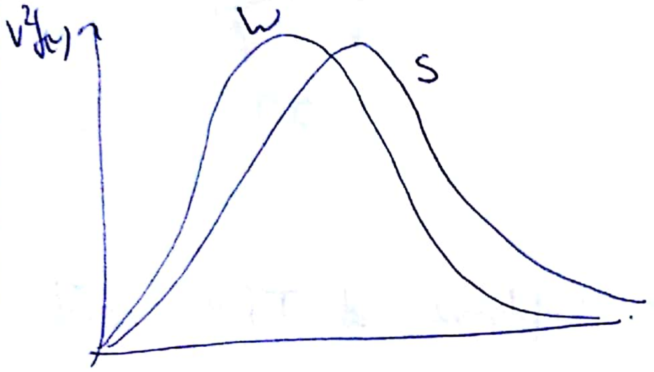
Modulation — DAMA.

Modulation

1312.1355

Galactic frame

$$f(v) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-v^2/v_0^2}$$



Earth frame

$$f(\vec{v}, \vec{v}_\oplus) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-(\vec{v}+\vec{v}_\oplus)^2/v_0^2}$$

$$\vec{v}_\oplus \simeq [(11, 230, 7) + u_E(t)]\ \mathrm{km\,s^{-1}}$$

$$u_\oplus(t) \sim \left(30 \sin\omega(t-t_0^x),\ 15 \sin\omega(t-t_0^y),\ -26 \sin\omega(t-t_0^z)\right).$$

Speed $\simeq [230 + 14 \sin\omega(t-t_0)]\ \mathrm{km\,s^{-1}}$,

$t_0 \sim$ June 2nd.

Use modulation to separate signal from backgnd.

DAMA/NaI + DAMA/LIBRA : ~~[illegible]~~ ~ 2.5 ton-yr exposure over ~ 14 yrs.

Single-hit, 2–6 keVee ~~[illegible]~~ $12.9\,\sigma$ evidence for modulation!
(not seen in multiple-hits)

Typically expect ~~α~~ $\alpha \simeq 0.02$, $S = S_0(1 + \alpha\cos\omega(t-t_0))$.

DAMA sees $\alpha \gtrsim 0.1$.

iDM and other models introduced to explain

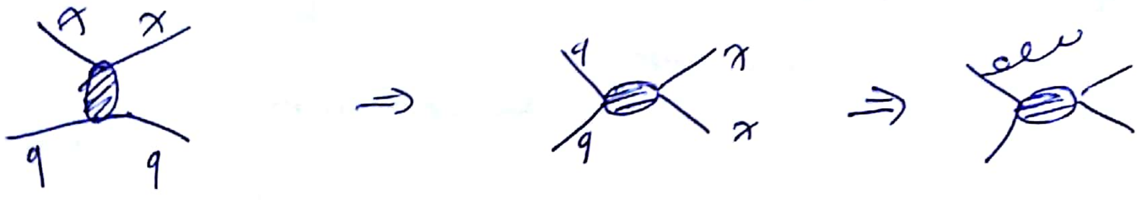
Severe tension w/ null results.

DM @ Colliders

Direct detection ⇒ collider production.

Often (e.g. SUSY) collider production is through channels unrelated to DM, DM appears as final product in decay eg $\tilde{g} \to$ jets $+ \not{E}_T$

But



D.D LHC. Monojet

Monophoton

Mono-X.

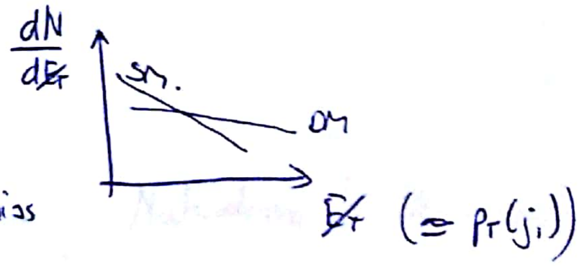
From EFT to simplified model,

$$\mathcal{O}_V = \frac{1}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q) \longrightarrow \text{SI}$$

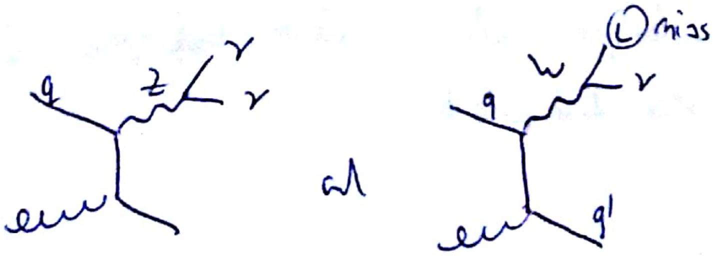
$$\mathcal{O}_A = \frac{1}{\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q) \longrightarrow \text{SD}$$

$\vdots$

Now need to plot for a monojet event.

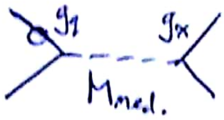


Backgrounds :



What does $\frac{1}{\Lambda^2}(\bar{\chi}\Gamma\chi)(\bar{q}\Gamma q)$ mean?

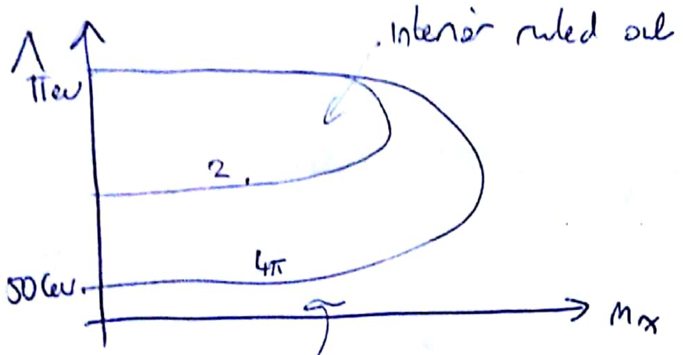
"UV complete"



$$\rightarrow \quad \frac{g_q g_\chi}{M_{med}^2}(\bar{\chi}\Gamma\chi)(\bar{q}\Gamma q)$$

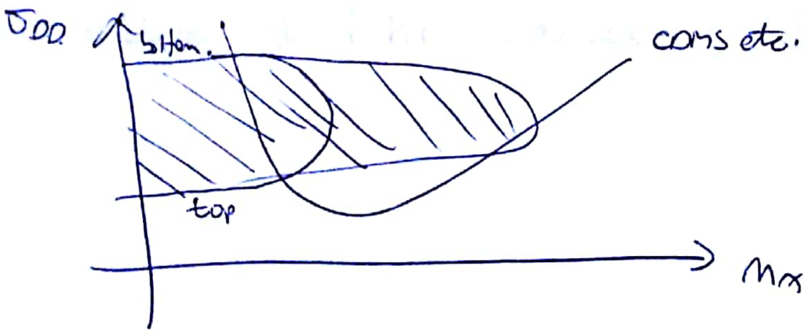
$$\Lambda = \frac{M_{med}}{\sqrt{g_\chi g_q}}$$

$M_{med} > \hat{s}^{1/2}$ and $g < 4\pi$. $\Rightarrow \Lambda \gtrsim \mathcal{O}(100)$ GeV makes sense.



no bound since no events w/ $q^2 < M_{med}$.

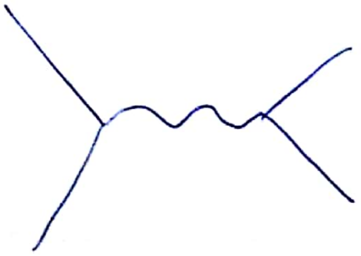
$\Downarrow$ Compare to direct detection



LHC complementary to direct detection

Better to go to simplified model. UV completion? Naturalness? Anomalies? Consistent etc?

In simplified model also have mediator ← dijets, dileptons etc.



Mediator $\propto g_q^{2}$

Monojet $\propto g_q^2 g_\chi^2$.

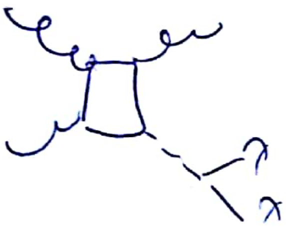
to compete w/ direct detection need AV

⇒ anomalies

bounds on $\frac{M_{med}}{m_\chi}$

$$m_\chi \leq \frac{\sqrt{4\pi}}{g_\chi} M_{av}.$$

If mediator is scalar MFV arguments ⇒ largest couplings to b, t.



or

Many analyses at LHC, recasts + LEP etc.