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Minimal Dark Matter

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Nucl. Phys. B753 (2006)
+ work in progress

Dark Matter today

Dark Matter is there.

- galaxy rotation curves
- clusters (lensing etc.)
- cosmological fits (CMB+LSS+...)

- *alternatives have a hard time*

What is Dark Matter?

- a WIMP has the correct relic abundance
- popular candidates: SuSy Neutralino, Kaluza-Klein DM, Little Higgs DM...

Ok, but...

- "fine tuning"?
- DM stability?
- DM phenomenology?

is there something more "minimal"?

Minimalistic approach

On top of the SM, add only one extra multiplet $\mathcal{X} = \begin{pmatrix} \mathcal{X}_1 \\ \mathcal{X}_2 \\ \vdots \end{pmatrix}$

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X}$$ if $\mathcal{X}$ is a fermion

$$\mathscr{L} = \mathscr{L}_{\rm SM} + |D_\mu \mathcal{X}|^2 + M^2|\mathcal{X}|^2$$ if $\mathcal{X}$ is a scalar

gauge interactions

the only parameter,
and will be fixed by $\Omega_{\rm DM}$.

(other terms in the scalar potential)

and sistematically search for the ideal DM candidate...

The ideal DM candidate is

weakly int., massive, neutral, stable

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weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin
$\underline{2}$		
$\underline{3}$		
$\underline{4}$		
$\underline{5}$		
$\underline{7}$		

these are all possible choices:

$n \leq 5$ for fermions

$n \leq 7$ for scalars

to avoid explosion in the running coupling

$$\alpha_2^{-1}(E') = \alpha_2^{-1}(M) - \frac{b_2(n)}{2\pi} \ln \frac{E'}{M}$$

←($\underline{6}$ is similar to $\underline{4}$)

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$SU(2)_L$	$U(1)_Y$	spin
$\underline{2}$	$1/2$	
$\underline{3}$	0	
	1	
$\underline{4}$	$1/2$	
	$3/2$	
$\underline{5}$	0	
	1	
	2	
$\underline{7}$	0	

Each multiplet contains a neutral component with a proper assignment of the hypercharge, according to

$$\boxed{Q = T_3 + Y} \equiv 0$$

$$\text{e.g. for } n = 2\text{: } T_3 = \begin{pmatrix} +\frac{1}{2} \\ \\ -\frac{1}{2} \end{pmatrix} \Rightarrow |Y| = \frac{1}{2}$$

$$\text{e.g. for } n = 3 : T_3 = \begin{pmatrix} +1 \\ 0 \\ -1 \end{pmatrix} \Rightarrow |Y| = 0 \text{ or } 1$$

etc.

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$SU(2)_L$	$U(1)_Y$	spin
$\underline{2}$	$1/2$	S
		F
$\underline{3}$	0	S
		F
	1	S
		F
$\underline{4}$	$1/2$	S
		F
	$3/2$	S
		F
$\underline{5}$	0	S
		F
	1	S
		F
	2	S
		F
$\underline{7}$	0	S

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etc.

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$SU(2)_L$	$U(1)_Y$	spin	M (TeV)
$\underline{2}$	$1/2$	S	0.43
		F	1.2
$\underline{3}$	0	S	2.0
		F	2.6
	1	S	1.4
		F	1.8
$\underline{4}$	$1/2$	S	2.4
		F	2.5
	$3/2$	S	2.4
		F	2.5
$\underline{5}$	0	S	5.0
		F	4.5
	1	S	3.5
		F	3.2
	2	S	3.5
		F	3.2
$\underline{7}$	0	S	8.5

The mass M is determined by the relic abundance:

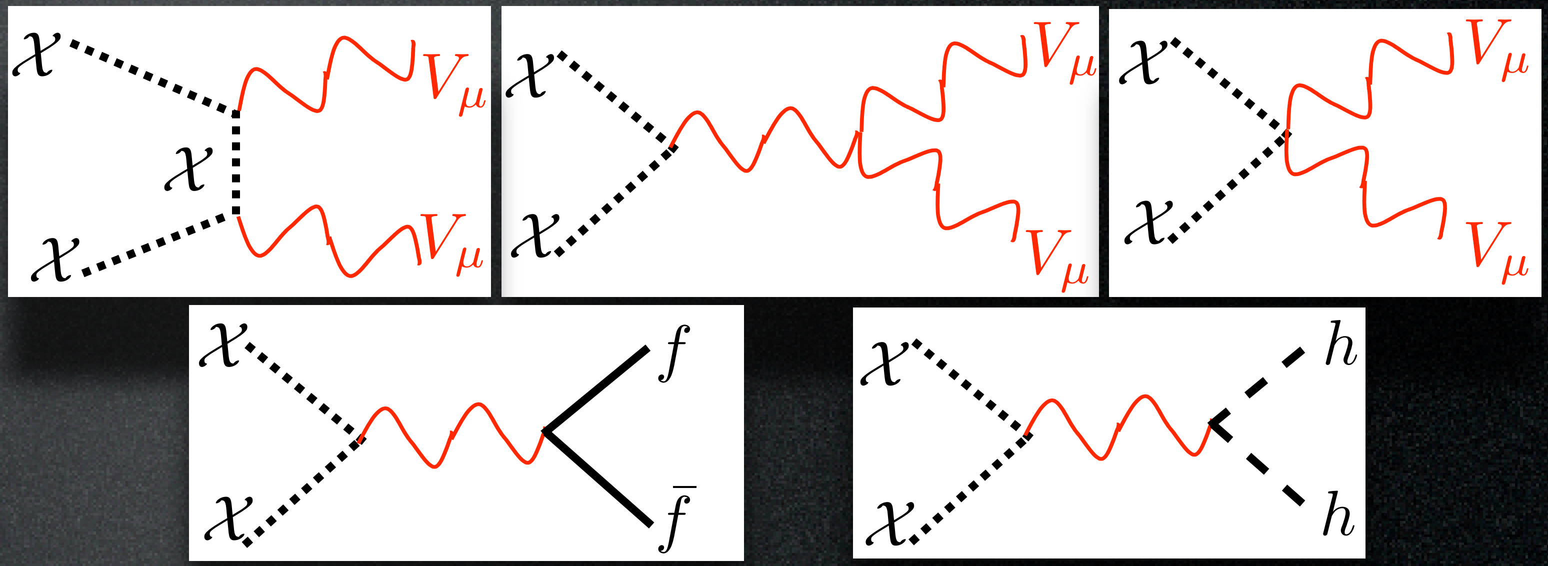
$$\Omega_{\rm DM} = \frac{6\ 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle \sigma_{\rm ann} v \rangle} \cong 0.24$$

for $\mathcal{X}$ scalar

$$\langle \sigma_{\rm ann} v \rangle \simeq \frac{g_2^4\ (3 - 4n^2 + n^4) + 16\ Y^4 g_Y^4}{64\pi\ M^2\ g_{\mathcal{X}}}$$

for $\mathcal{X}$ fermion

$$\langle \sigma_{\rm ann} v \rangle \simeq \frac{g_2^4\ (n^4 + 11n^2 - 12) + 8Y^2 g_Y^4 (11 + 2Y^2)}{64\pi\ M^2\ g_{\mathcal{X}}}$$



(- include co-annihilations)
(- computed for $M \gg M_{Z,W}$)

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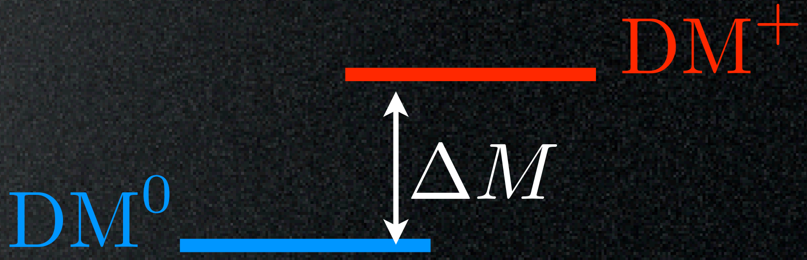
$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)
2	1/2	S	0.43	348
		F	1.2	342
3	0	S	2.0	166
		F	2.6	166
	1	S	1.4	540
		F	1.8	526
4	1/2	S	2.4	353
		F	2.5	347
	3/2	S	2.4	729
		F	2.5	712
5	0	S	5.0	166
		F	4.5	166
	1	S	3.5	537
		F	3.2	534
	2	S	3.5	906
		F	3.2	900
7	0	S	8.5	166

EW loops induce a mass splitting ΔM inside the n-uplet:

$$M_Q - M_{Q'} = \frac{\alpha_2 M}{4\pi}\left\{(Q^2 - Q'^2) s_{\rm W}^2 f(\tfrac{M_Z}{M}) \right.$$
$$\left. + (Q-Q')(Q+Q'-2Y)\left[f(\tfrac{M_W}{M}) - f(\tfrac{M_Z}{M})\right]\right\}$$

with $f(r) \xrightarrow{r\to 0} -2\pi r$

The neutral component is the lightest



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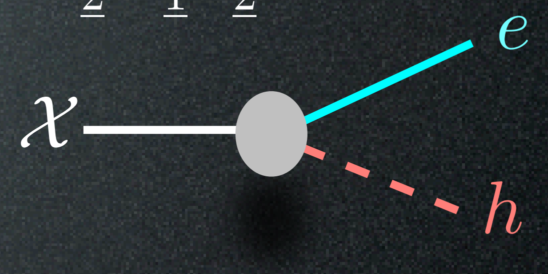
List all allowed SM couplings:

← e.g. $$\underset{\underline{2}\quad\underline{1}\quad\underline{2}}{\overset{1/2\ \ -1\ \ 1/2}{\mathcal{X}EH}}$$



← e.g. $$\underset{\underline{2}\quad\underline{2}\quad\underline{2}\quad\underline{2}}{\overset{1/2\ \ -1/2\ \ 1/2\ \ -1/2}{\mathcal{X}LHH^*}}$$

dim=5 operator, induces

$\tau \sim \Lambda^2 \mathrm{TeV}^{-3} \ll t_{\mathrm{universe}}$

for $\Lambda \sim M_{\mathrm{Pl}}$

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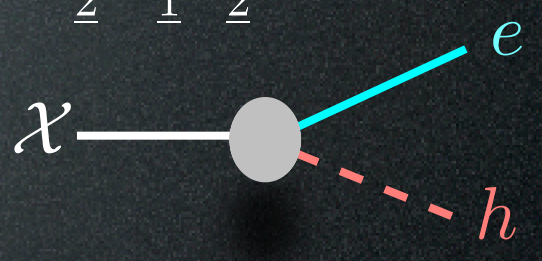
List all allowed SM couplings:

e.g. $\underset{\underline{2}}{\overset{1/2}{\chi}}\,\underset{\underline{1}}{\overset{-1}{E}}\,\underset{\underline{2}}{\overset{1/2}{H}}$



e.g. $\underset{\underline{2}}{\overset{1/2}{\chi}}\,\underset{\underline{2}}{\overset{-1/2}{L}}\,\underset{\underline{2}}{\overset{1/2}{H}}\,\underset{\underline{2}}{\overset{-1/2}{H^*}}$

dim=5 operator, induces $\tau \sim \Lambda^2 \mathrm{TeV}^{-3} \ll t_{\rm universe}$ for $\Lambda \sim M_{\rm Pl}$

No allowed decay!

Automatically stable!

The ideal DM candidate is

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and

not excluded

by direct searches!

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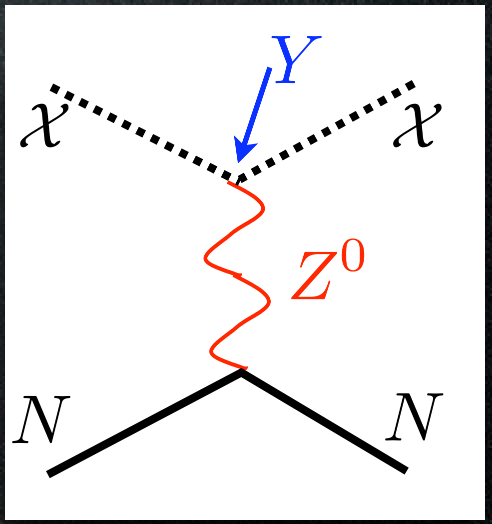
Candidates with $Y \neq 0$ interact as



$$\sigma \simeq G_F^2 M_N^2 Y^2$$

$\gg$ present bounds

e.g. CDMS

need $Y = 0$

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by direct searches!

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We have a winner!

and a 2° place

Recap:

A fermionic $SU(2)_L$ quintuplet with $Y = 0$
provides a DM candidate with $M = 4.5\ \mathrm{TeV}$,
which is fully successful:
- neutral
- ***automatically*** stable

like proton stability

and
not yet discovered by DM searches.

A scalar $SU(2)_L$ eptaplet with $Y = 0$ also does.

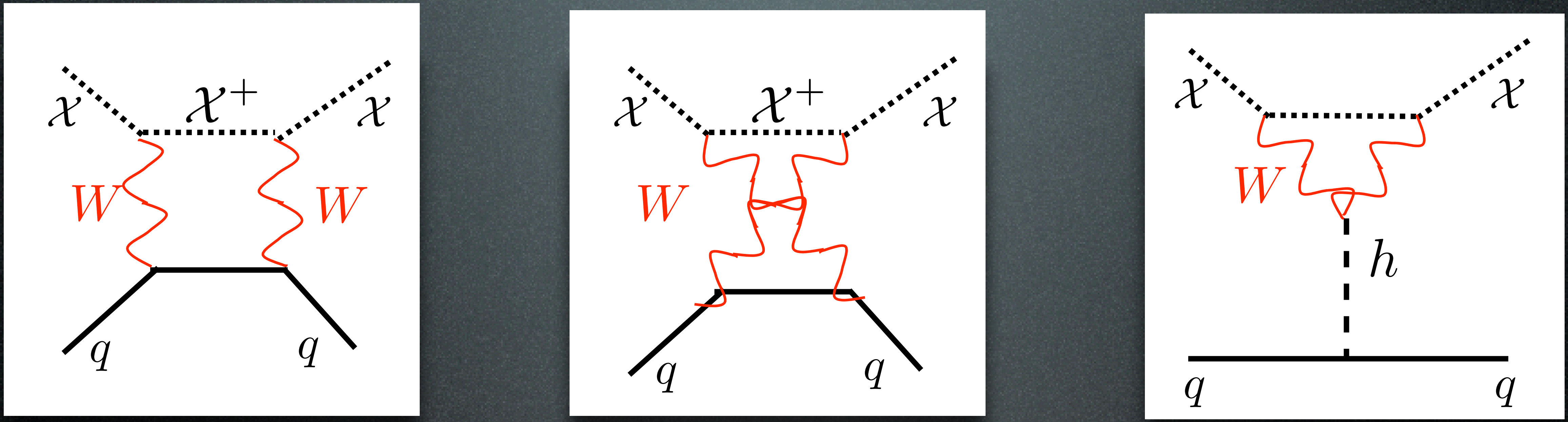
(Other candidates can be cured via non-minimalities.)

DM detection

- direct detection like CDMS
- production at colliders
- indirect
  - γ from annihil in galactic halo or center (line + continuum) EGRET, WMAP
  - e^+ from annihil in galactic halo or center HEAT
  - $\bar{p}$ from annihil in galactic halo or center
  - $\bar{D}$ from annihil in galactic halo or center
  - $\nu, \bar{\nu}$ from annihil in massive bodies in neutrino telescopes

Direct Detection

one-loop processes



$$\mathscr{L}^W_{\rm eff} = (n^2-(1-2Y)^2)\frac{\pi\alpha_2^2}{16M_W}\sum_q\left[(\frac{1}{M_W^2}+\frac{1}{m_h^2})[\bar{\mathcal{X}}\mathcal{X}]m_q[\bar{q}q]-\frac{2}{3M}[\bar{\mathcal{X}}\gamma_\mu\gamma_5\mathcal{X}][\bar{q}\gamma_\mu\gamma_5 q]\right]$$

larger for higher n

Spin-Independent

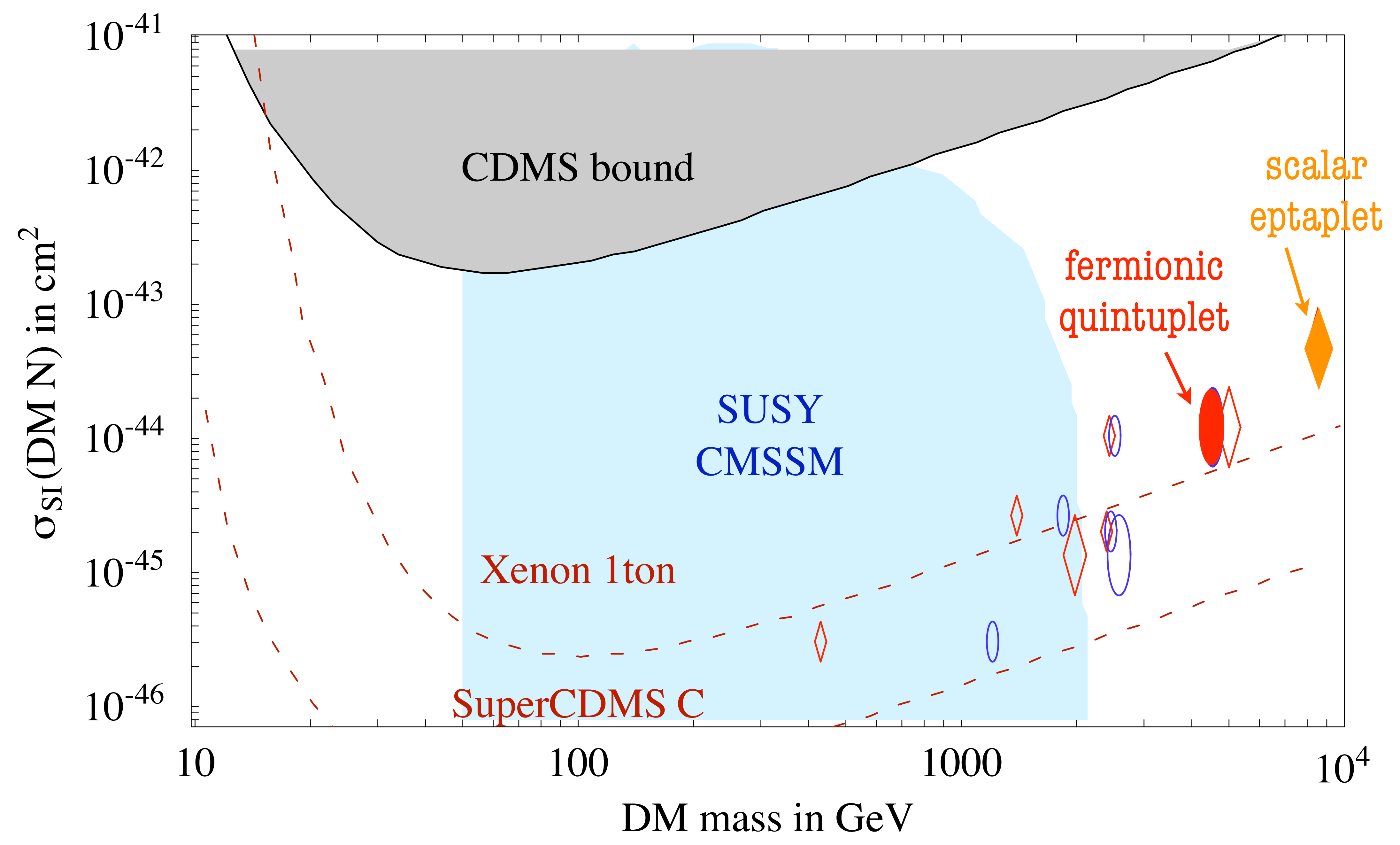
$$\propto \frac{m_q}{M_W^3}$$

Spin-Dependent

$$\propto \frac{1}{M M_W}$$

$$\langle N|\sum_q m_q\bar{q}q|N\rangle \equiv f m_N \quad \left(f \simeq \frac{1}{3}\right)$$

Direct Detection



(NB: no free parameters => one predicted point per candidate)

[skip to conclusions]

Conclusions

The DM problem requires physics beyond the SM.

Introducing the minimal amount of it,
we find a few fully successful DM candidates:
massive, neutral, *automatically* stable.

The "best" is the
fermionic $SU(2)_L$ quintuplet with $Y=0$.
$(M = 4.5\ \text{TeV})$

Its phenomenology is precisely computable:
- can be found in next gen direct detection exp's,
- could give signals in indirect detection exp's,
- too heavy to be produced at LHC.

(Other candidates have different properties.)

Back-up slides

Non-Minimal terms in the scalar case

Quadratic and quartic terms in $\mathcal{X}$ and H :

$$\lambda_H(\mathcal{X}^* T^a_{\mathcal{X}} \mathcal{X})\,(H^* T^a_H H) + \lambda'_H |\mathcal{X}|^2 |H|^2 + \frac{\lambda_{\mathcal{X}}}{2} (\mathcal{X}^* T^a_{\mathcal{X}} \mathcal{X})^2 + \frac{\lambda'_{\mathcal{X}}}{2} |\mathcal{X}|^4$$

[1] [2] [3] [4]

- do not induce decays (even number of $\mathcal{X}$, and $\langle \mathcal{X} \rangle = 0$)

- [3] and [4] do not give mass terms

- after EWSB, [2] gives a common mass $\sqrt{\lambda'_H} v \approx \mathcal{O}(\lesssim 100 \text{ GeV})$
  to all $\mathcal{X}_i$ components;
  negligible for $M = \mathcal{O}(\text{TeV})$

- after EWSB, [1] gives mass splitting $\Delta M_{\text{tree}} = \dfrac{\lambda_H v^2 |\Delta T^3_{\mathcal{X}}|}{4M} = \lambda_H \cdot 7.6 \text{ GeV} \dfrac{\text{TeV}}{M}$
  between $\mathcal{X}_i$ components;
  assume $\lambda_H \lesssim 0.01$ so that $\Delta M_{\text{tree}} \ll \Delta M$

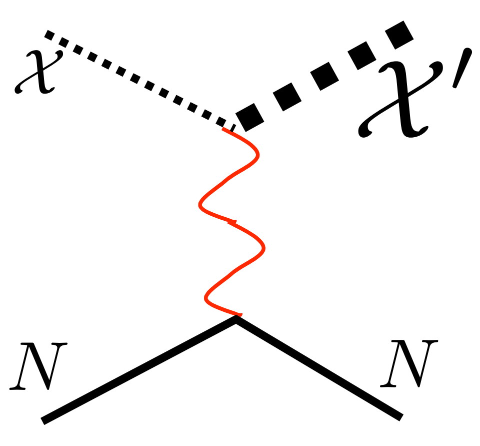
(Anyway, scalar MDM is less interesting.)

[back to Lagrangian]

If you want to cure ill candidates...

$Y \neq 0$: introduce some mechanism to forbid coupling with Z^0 anyway

e.g. mixing with an extra singlet splits the 2 components of $\mathcal{X}$; if splitting is large enough, NC scattering is kinematically forbidden...



stability: impose some symmetry to forbid decays (e.g. R-parity)...

...the case of SuSy higgsino

Production at colliders

$$\hat{\sigma}_{u\bar{d}} = \frac{g_{\mathcal{X}} g_2^4 (n^2-1)}{13824\ \pi \hat{s}} \beta \cdot \begin{cases} \beta^2 & \text{if } \mathcal{X} \text{ is a fermion} \\ 3-\beta^2 & \text{if } \mathcal{X} \text{ is a scalar} \end{cases}$$

(similarly $\hat{\sigma}_{u\bar{u}}, \hat{\sigma}_{d\bar{d}}, \hat{\sigma}_{d\bar{u}}$) $\qquad \beta = \sqrt{1-4M^2/\hat{s}}$

Large production for small M.

$2 \times$ LHC to produce heavy candidates.

A clean signature:

$\mathcal{X}^\pm \to \mathcal{X}^0 \pi^\pm$	:	$\Gamma_\pi = (n^2-1)\dfrac{G_F^2 V_{ud}^2 \Delta M^3 f_\pi^2}{4\pi}\sqrt{1-\dfrac{m_\pi^2}{\Delta M^2}},$	$\mathrm{BR}_\pi = 97.7\%$
$\mathcal{X}^\pm \to \mathcal{X}^0 e^\pm \overset{(-)}{\nu}_e$	:	$\Gamma_e = (n^2-1)\dfrac{G_F^2 \Delta M^5}{60\pi^3}$	$\mathrm{BR}_e = 2.05\%$
$\mathcal{X}^\pm \to \mathcal{X}^0 \mu^\pm \overset{(-)}{\nu}_\mu$	:	$\Gamma_\mu = 0.12\ \Gamma_e$	$\mathrm{BR}_\mu = 0.25\%$

$$\tau \simeq 44\text{cm}/(n^2-1)$$

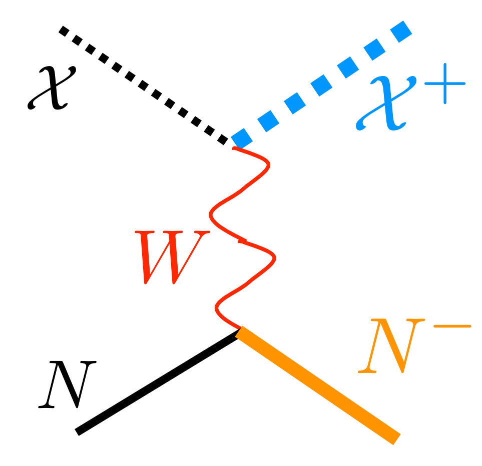
Events at LHC $\int \mathcal{L}\, dt$ =100/fb
$(0.7 \div 2) \cdot 10^3$
$120 \div 260$
$0.2 \div 1.0$
$0.4 \div 2.2$
$11 \div 33$
$26 \div 80$
$0.1 \div 0.7$
$3.6 \div 18$
$0.1 \div 0.6$
$2.7 \div 14$
$\ll 1$ ●
$\ll 1$
$\ll 1$ ◆

[skip to conclusions]

Interlude: the “DMtron”

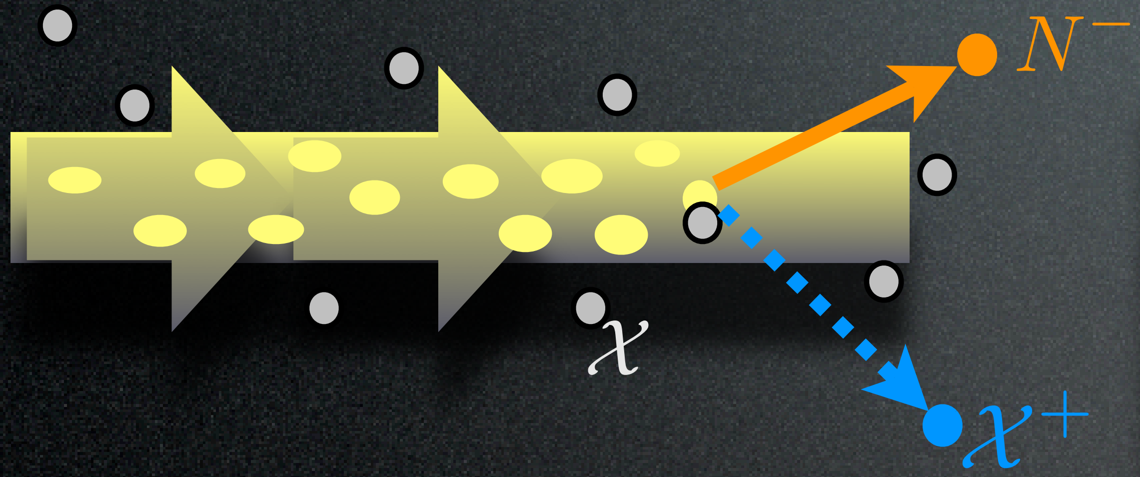
Can one have CC DM interactions?

(tree level!)



Need to provide $\Delta M = M_{\mathcal{X}^+} - M_{\mathcal{X}} = 166\ \text{MeV}$

Accelerate nuclei and use DM as diffuse target.



$$\hat{\sigma}(a\,\mathcal{X} \to a'\,\mathcal{X}^{\pm}) = \sigma_0 \frac{n^2-1}{4}\left[1 - \frac{\ln(1+4E^2/M_W^2)}{4E^2/M_W^2}\right]$$

$$\sigma_0 = \frac{G_{\rm F}^2 M_W^2}{\pi} = 1.1\,10^{-34}\ \text{cm}^2$$

$$\frac{dN}{dt} = \varepsilon N_p \sigma \frac{\rho_{\rm DM}}{M} = \varepsilon \frac{10}{\text{year}} \frac{N_p}{10^{20}} \frac{\rho_{\rm DM}}{0.3\text{GeV}/\text{cm}^3} \frac{\text{TeV}}{M} \frac{\sigma}{3\sigma_0}$$

number of targets

number of bullets

“efficiency”

not unreasonable?

tagging $\mathcal{X}^+$....

[skip to conclusions]

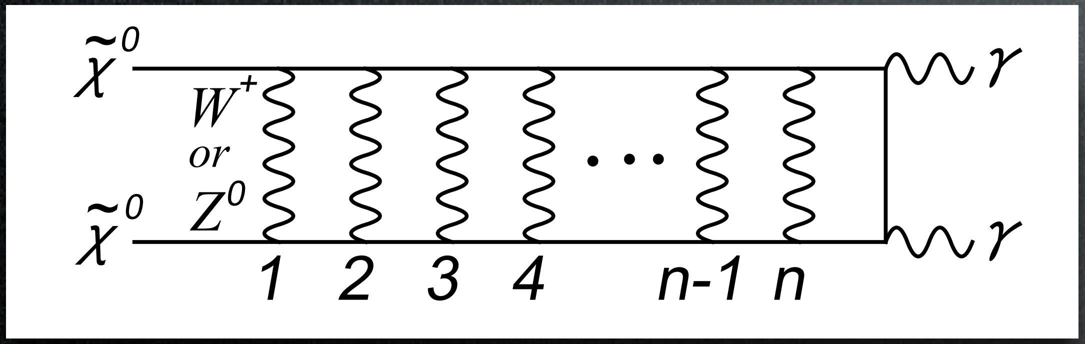
Indirect Detection

i.e. $\nu, \bar{p}, e^{+}, \gamma, \bar{D}$ from MDM annihilations in halo or body.

Signal in ν: promising at neutrino telescopes

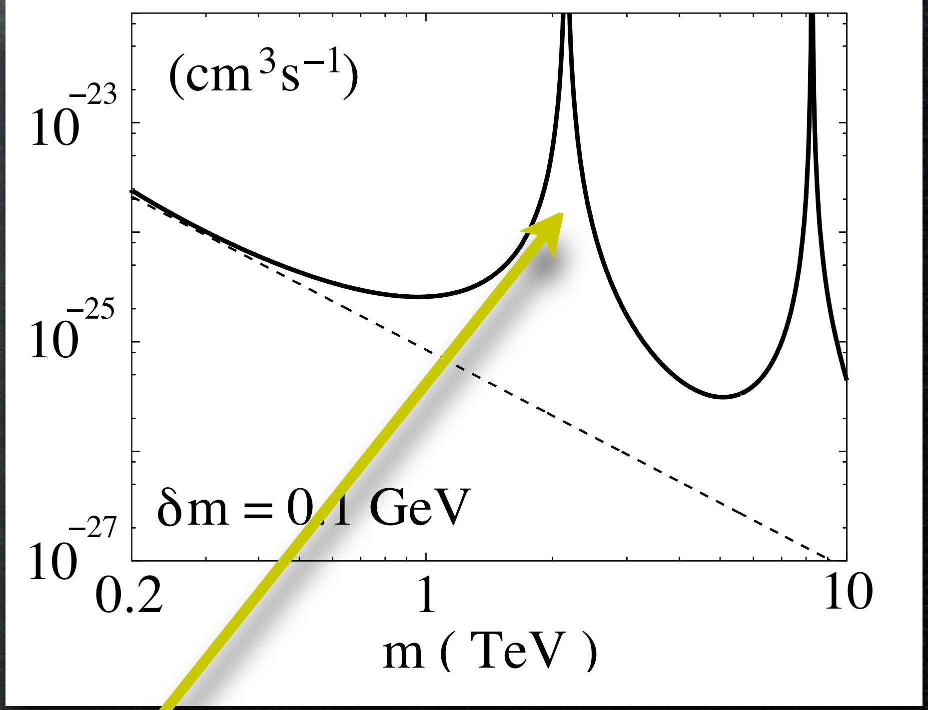
Enhanced cross section in vector bosons due to resummed diagrams when Non-Relativistic $\bar{\mathcal{X}}\mathcal{X}$ are a “bound state”:

$$\alpha_2 M_W \sim \Delta M \approx E_B \sim \alpha_2^2 M$$



Hisano et al., 2004,
Hisano et al., 2005

e.g.



resonances match M for $n = \underline{3}$

Signal in $\bar{p}, e^{+}, \gamma$: promising if enhanced

Comparison with SplitSuSy-like models

Arkani-Hamed, Dimopoulos and/or Giudice, Romanino 2004
Arkani-Hamed, Dimopoulos, Kachru 2005
Mahbubani, Senatore 2005

SplitSuSy-like	MDM
- mainly Higgsino (a fermion doublet)	- arbitrary multiplet, scalar or fermion
- + something else (a singlet)	- nothing else (with Y=0)
- stabilization by R-parity	- automatically stable
- want unification also	- forget unification, it's SM
- unification scale is low, need to embed in 5D to avoid proton decay Mahbubani, Senatore 2005	- nothing

Common feature: the focus is on DM, not on SM hierarchy problem.