Dark matter in view of recent experiments

Kathryn Zurek
Fermilab

Rencontres de Moriond

Collider DM Searches

- To solve at Tevatron/LHC:

1. EW symmetry breaking (Higgs)
2. Dark Matter
    1. Focus on supersymmetry
    2. MET searches (hard cut)
    3. Measure mass, couplings to SM states

The traditional view on DM

- Single stable weakly interacting particle
- Solution to hierarchy problem $m_{DM} \sim 100$ GeV
- Annihilation cross-section sets abundance

$$\Omega h^2 \approx \frac{2 \times 10^{-10} \mathrm{GeV}^{-2}}{\langle \sigma v \rangle}$$

$$\sigma v \approx \frac{g^4}{1\ \mathrm{TeV}^2} \approx 3 \times 10^{-26} \frac{\mathrm{cm}^3}{\mathrm{s}}$$

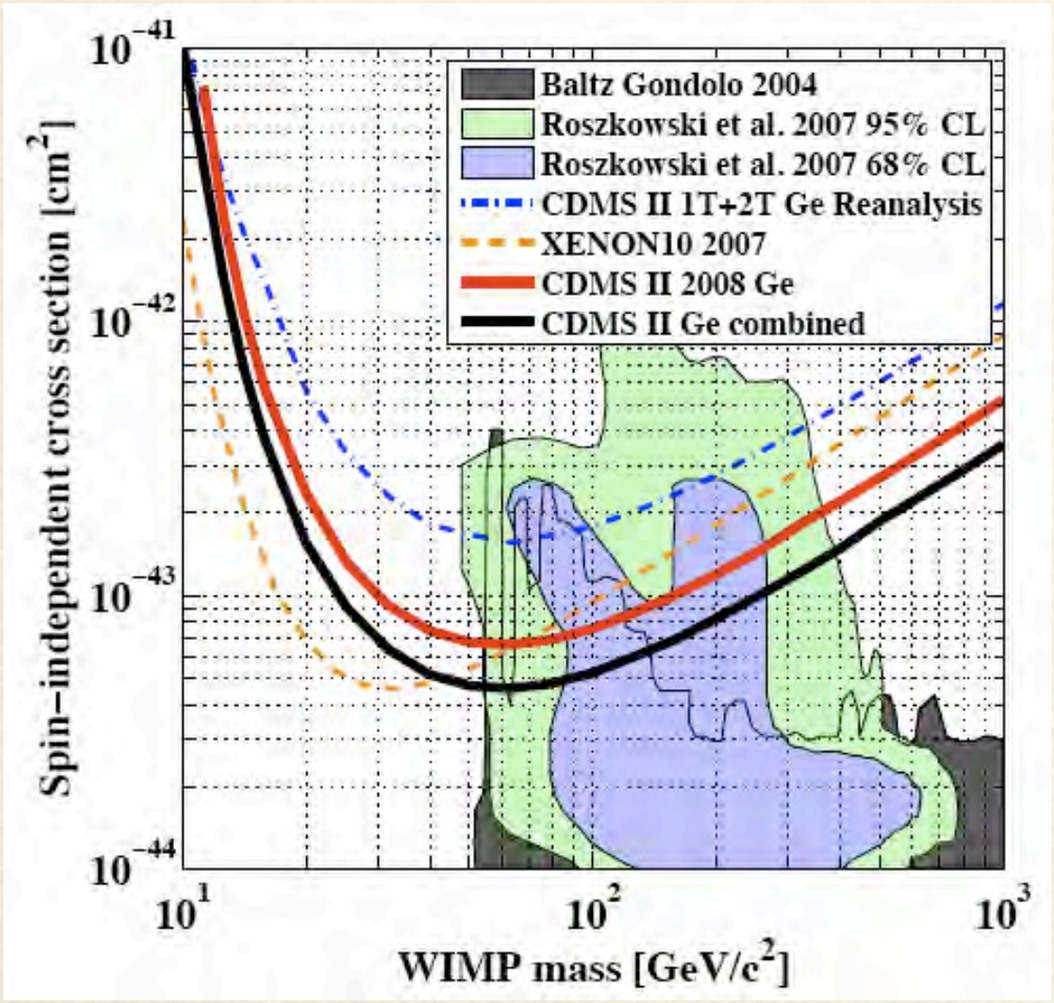
$$\Omega_c h^2 = 0.114 \pm 0.003$$

- Predicts annihilation rate to SM states
- Predicts annihilation modes

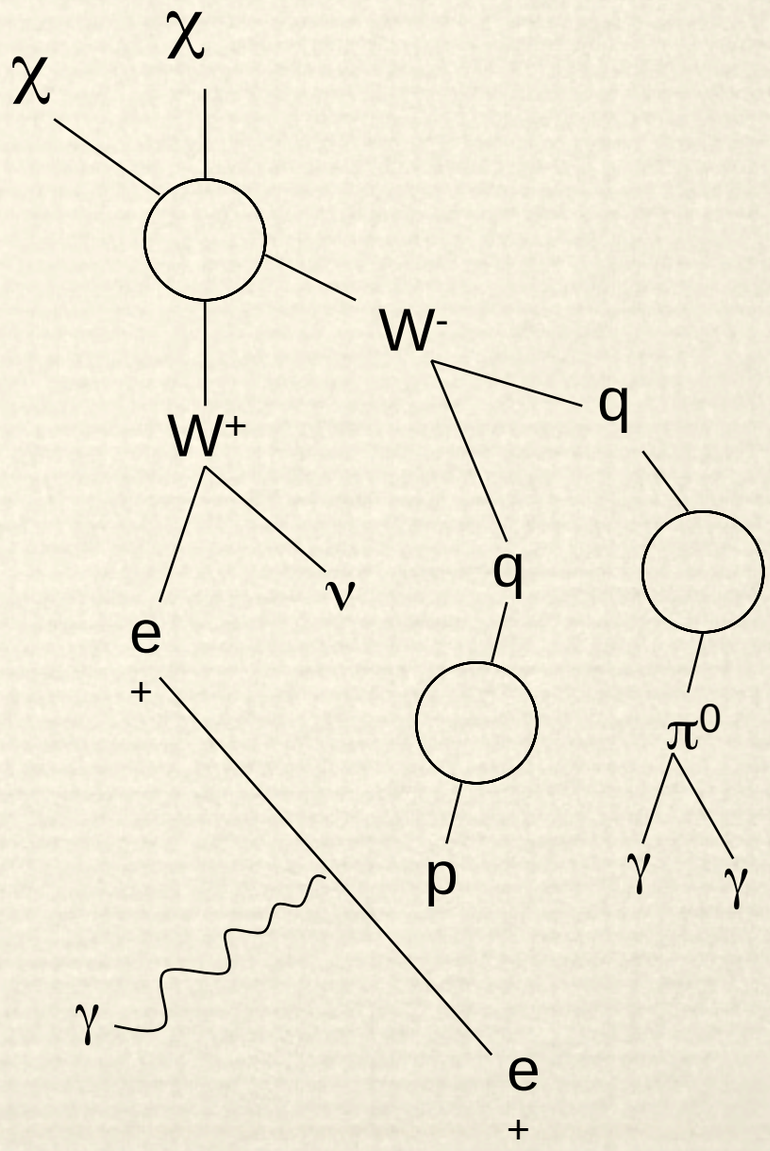
$$\rightarrow W^+W^-, \bar{b}b, \tau^+\tau^-$$

Astrophysical DM Searches

- Direct--scattering WIMP



- Indirect--annihilation products



DM searches designed with these features in mind

- e.g. triggers tuned to CMSSM

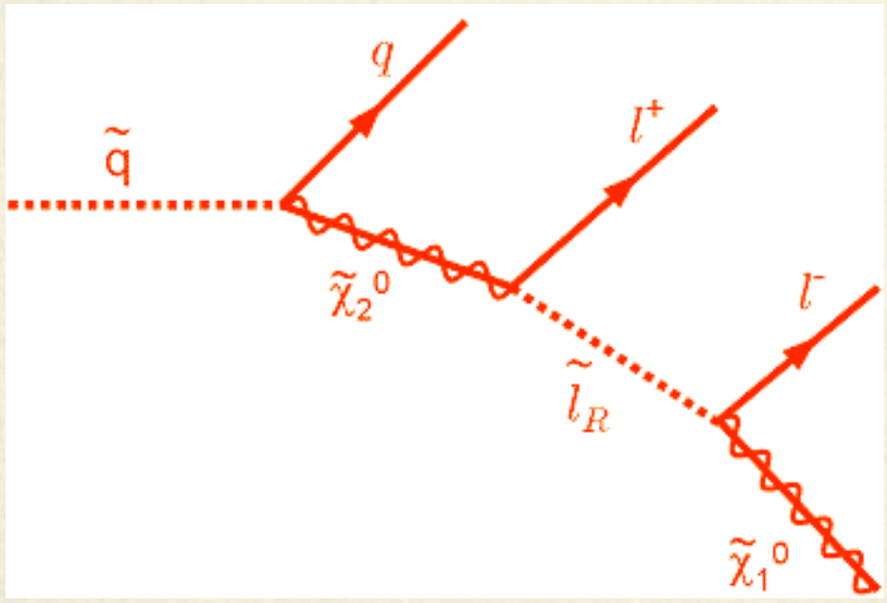
$$\tilde{\nu} \qquad \tilde{B},\ \tilde{W}_3,\ \tilde{H}$$

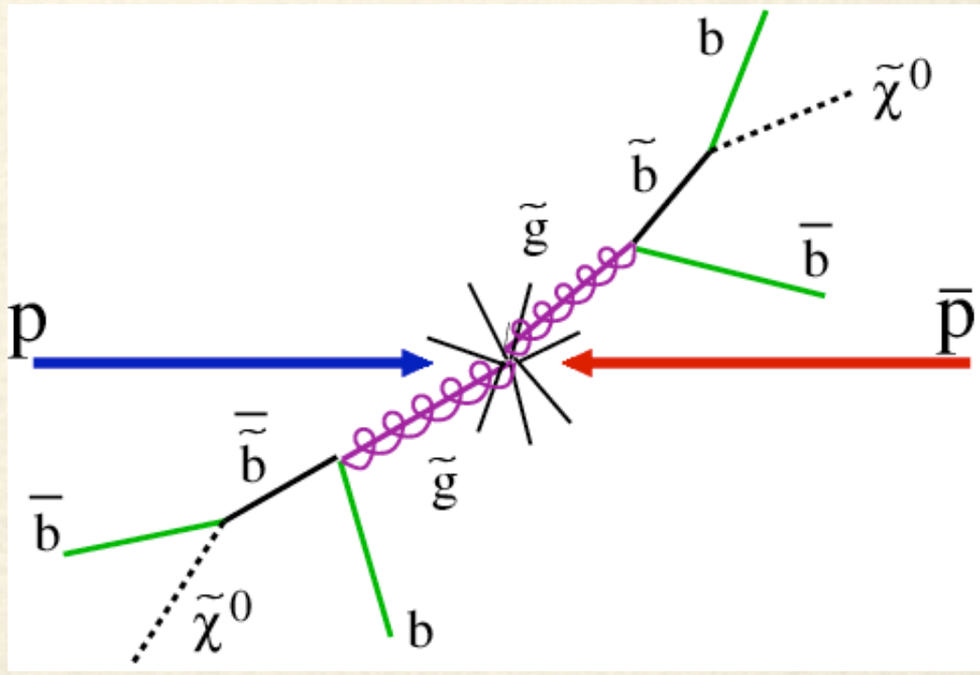
$$\tilde{\chi}$$

annihilation to heavy modes

$$\rightarrow W^+W^-, \bar{b}b, \tau^+\tau^-$$

- fairly hard MET cuts

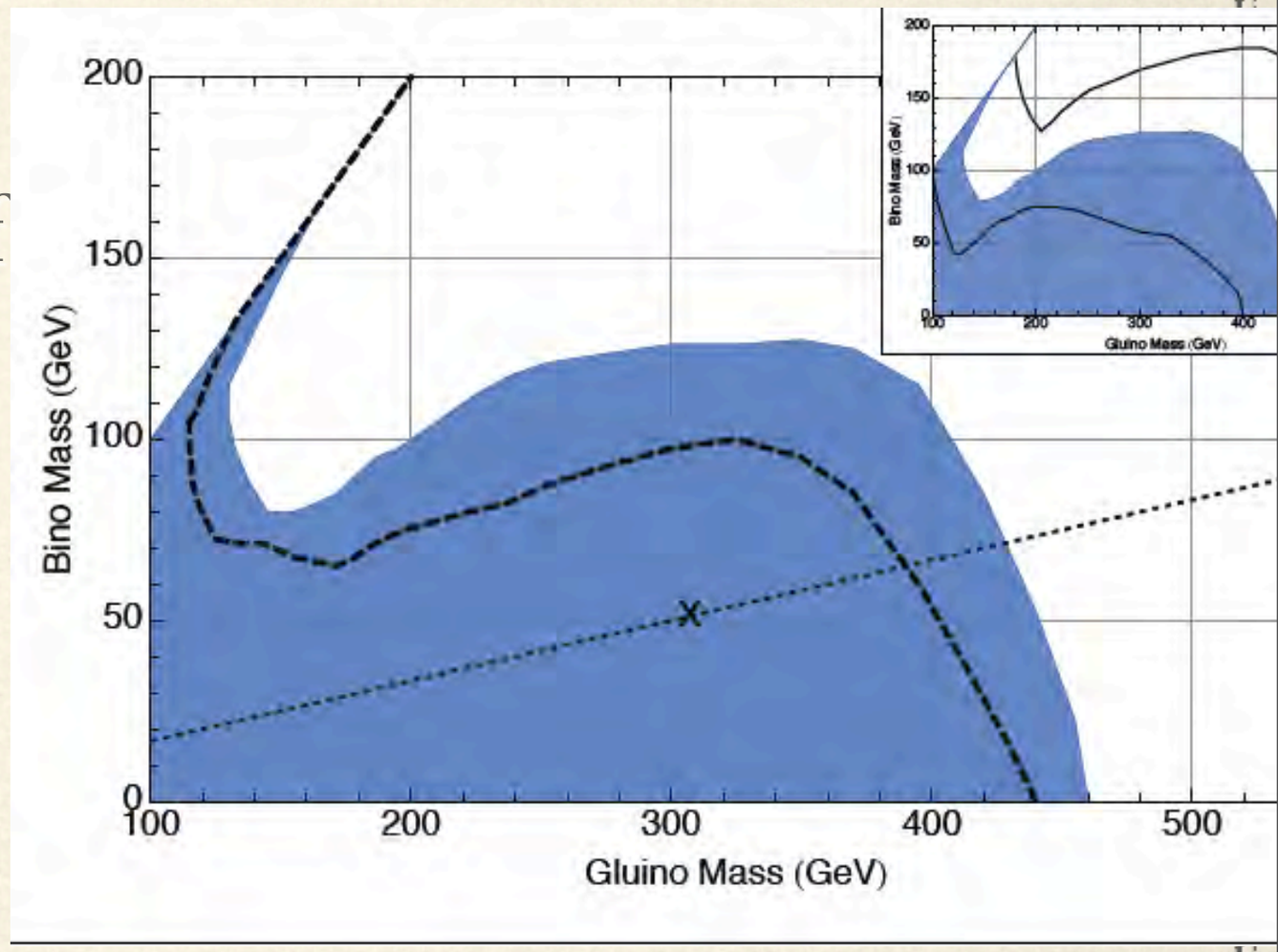




- Can be problematic even in SUSY

Important features for DM searches

- E_T^{miss} features set by TeV mass particle carrying off substantial momentum
- --> hard E_T^{miss} cut
- Relies on large coupling to colored (hadronic) states



Alwall, Le, Lisanti, Wacker

Recent DM experiments and colliders

Recent DM experiments and colliders

- IF any hints of DM suggested by recent experiments are real, the canonical model is not nature's choice

Recent DM experiments and colliders

- IF any hints of DM suggested by recent experiments are real, the canonical model is not nature's choice
- DM will not be found in standard channels

Recent DM experiments and colliders

- IF any hints of DM suggested by recent experiments are real, the canonical model is not nature's choice
  - DM will not be found in standard channels
  - In some (not all) cases, DM can be observed by excesses in other channels

Recent DM experiments and colliders

- IF any hints of DM suggested by recent experiments are real, the canonical model is not nature's choice
  - DM will not be found in standard channels
  - In some (not all) cases, DM can be observed by excesses in other channels
- Non-standard collider searches required

Recent experiments

- PAMELA and ATIC electron/positron excesses
  - This morning's talks
- 511 keV line
  - No time
- DAMA
  - Focus of this talk
- None suggest ordinary SUSY WIMP DM
- Suggest that DM dynamics may be more complex

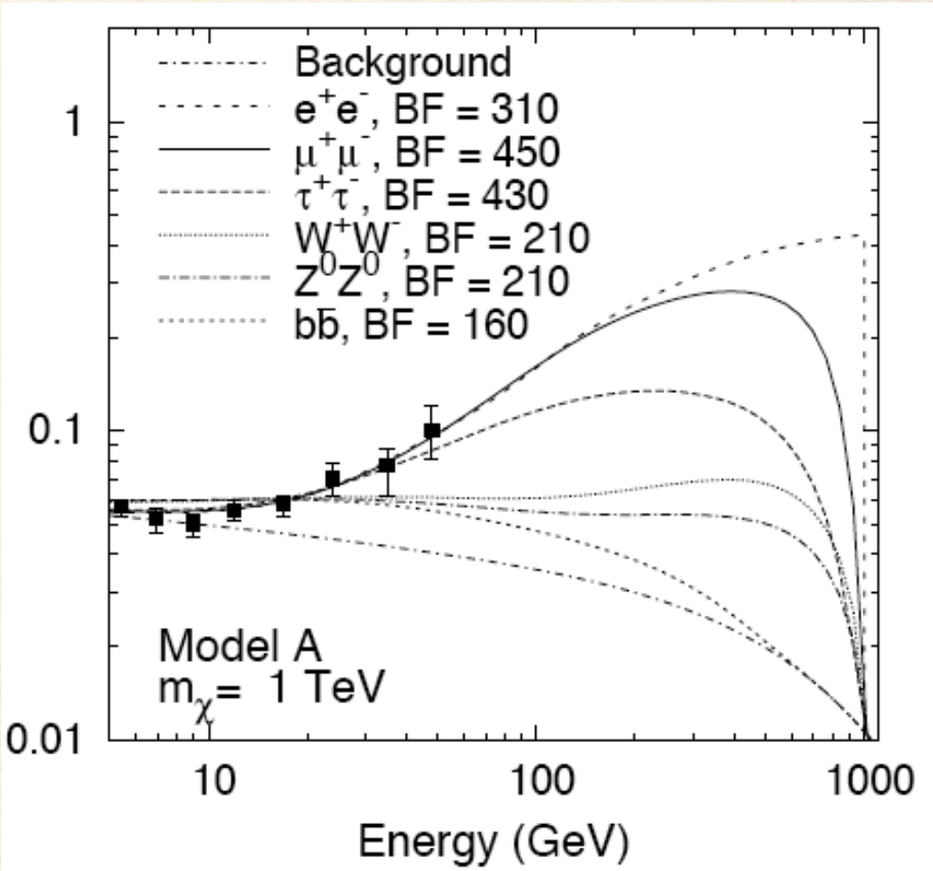
Non-standard requirements of PAMELA/ATIC

- Not an ordinary WIMP
- Non-standard annihilation modes $\rightarrow W^+W^-, \bar{b}b, \tau^+\tau^-$
- Non-standard annihilation cross-section

$$B\langle\sigma_{ann}v\rangle \simeq 10^{-23}\ \mathrm{cm}^3/\mathrm{s}$$

- Anti-protons--would expect an excess

Cholis, Goodenough, Hooper, Simet, Weiner

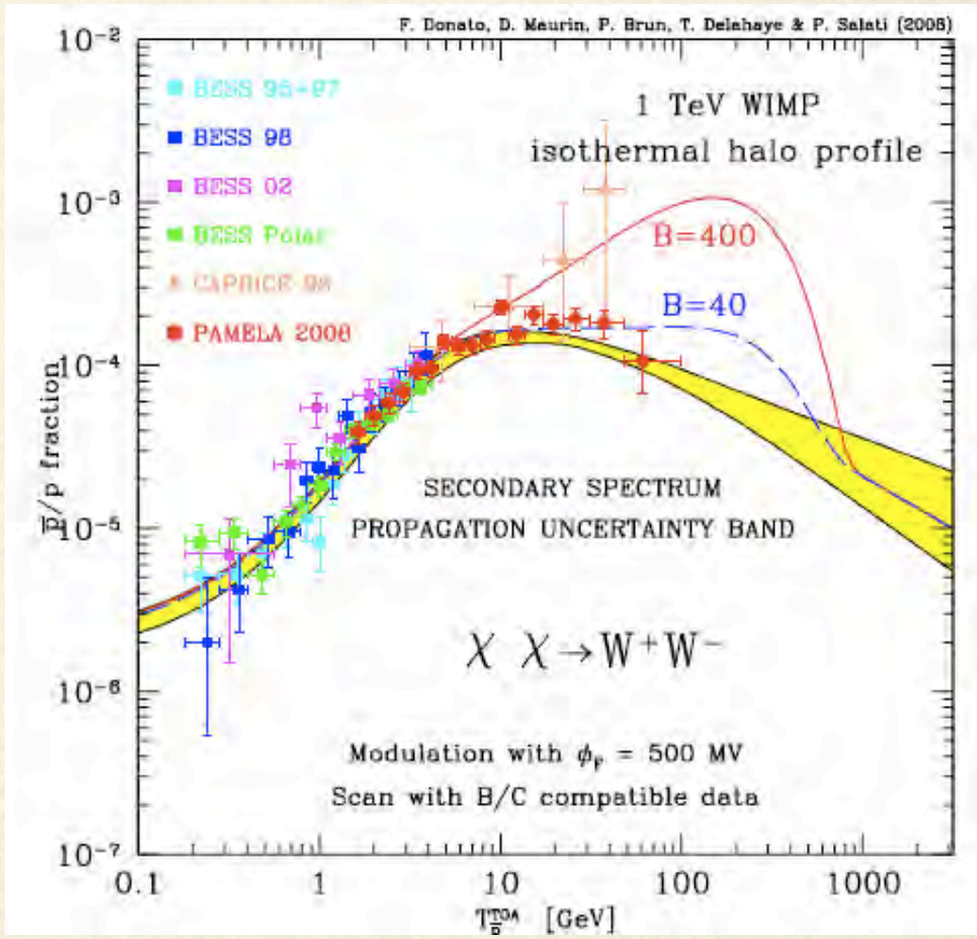


Non-standard requirements of PAMELA/ATIC

- Not an ordinary WIMP
- Non-standard annihilation modes $\rightarrow W^+W^-, \bar{b}b, \tau^+\tau^-$
- Non-standard annihilation cross-section

$$B\langle\sigma_{ann}v\rangle \simeq 10^{-23}\ \mathrm{cm}^3/\mathrm{s}$$

- Anti-protons--would expect an excess

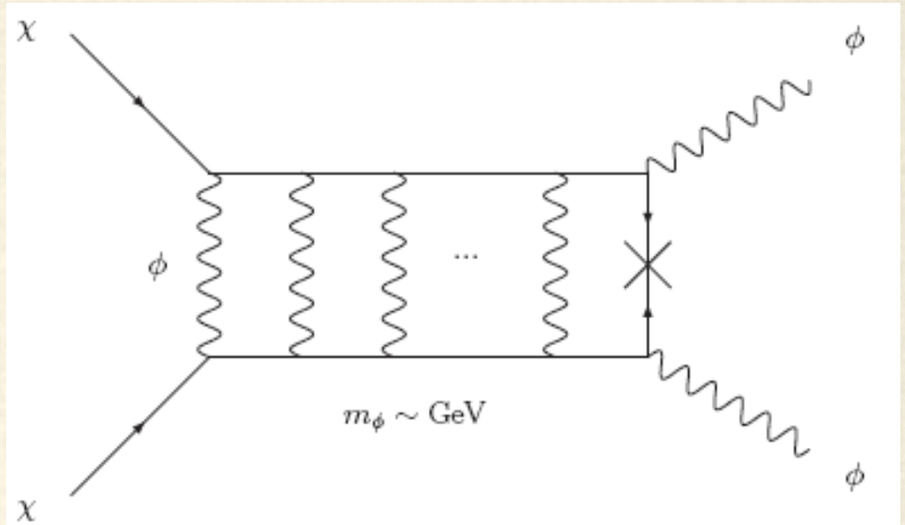


New dynamics?

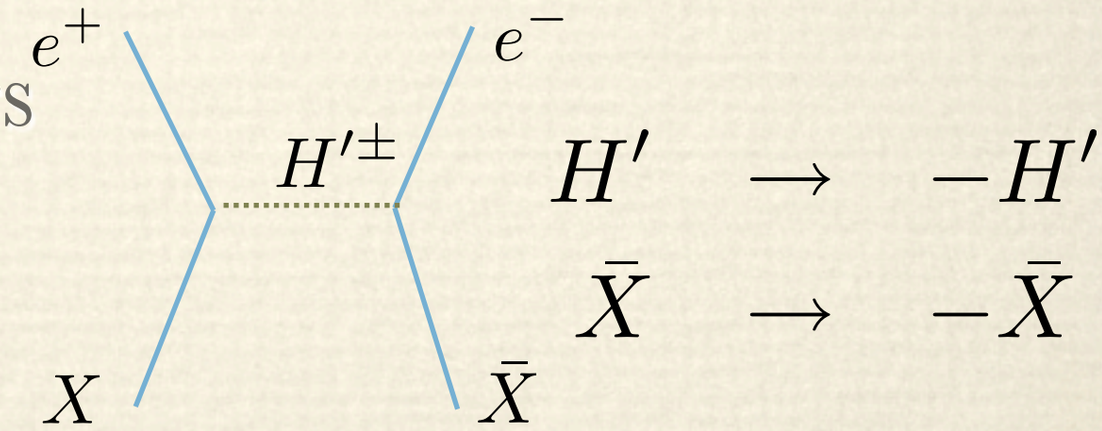
- Dark sector may be complicated!
- New dark forces to boost annihilation cross-section

$$\alpha m_{DM} \gtrsim m_\phi \sim 1 - 10 \text{ GeV}$$

  - WIMPonium--suggests light new force mediators
- Lepto-philic DM (sterile neutrino DM)



Nojiri et al.
Cirelli et al.
Arkani-Hamed et al.



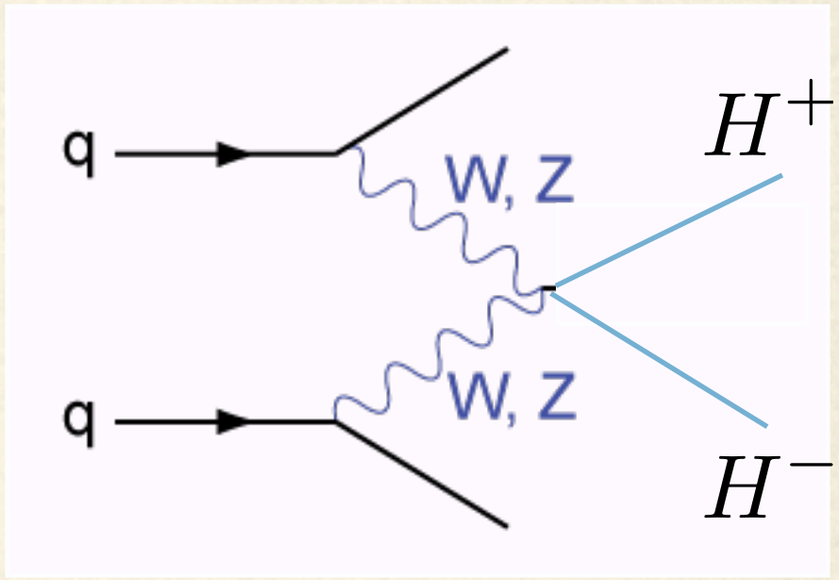
$$H' \rightarrow -H'$$
$$\bar{X} \rightarrow -\bar{X}$$

$$\mathcal{L} = yLH'\bar{X}$$

KZ '08
Cao et al. '09

New dynamics?

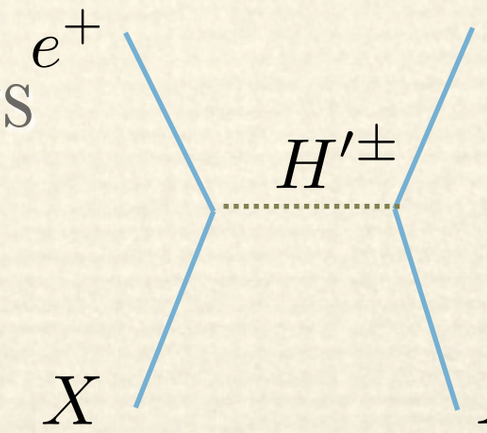
$$H^- \to \ell^- + X$$



- Dark sector may be complicated!
- New dark forces to boost annihilation cross-section

$$\alpha m_{DM} \gtrsim m_\phi \sim 1 - 10 \text{ GeV}$$

  - WIMPonium--suggests light new force mediators



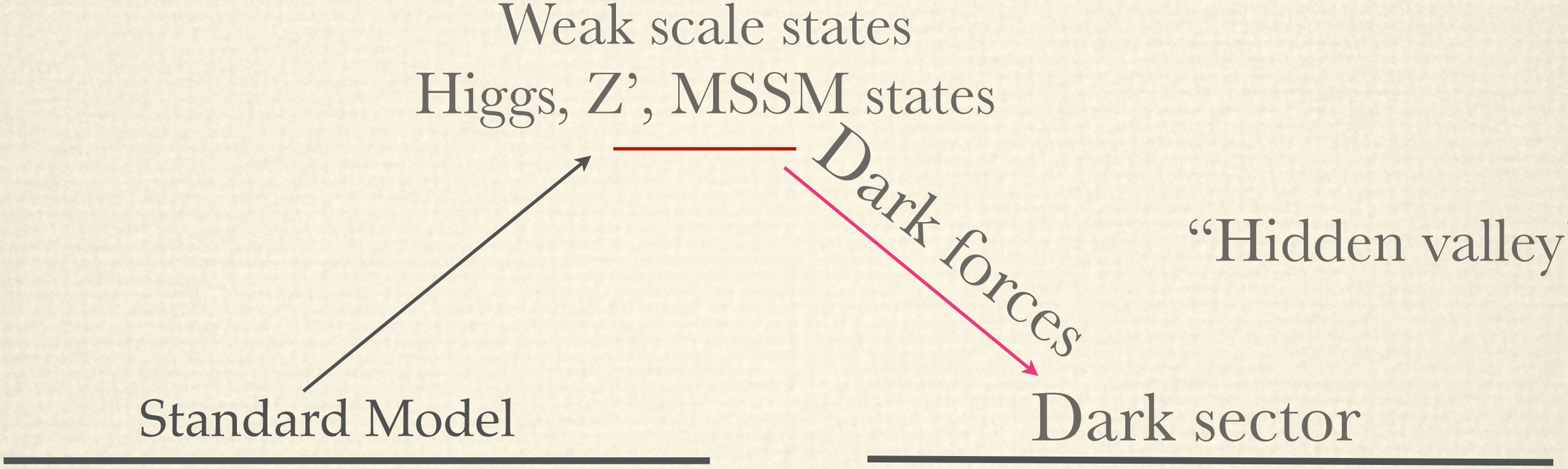
$$H' \to -H'$$
$$\bar{X} \to -\bar{X}$$

- Lepto-philic DM (sterile neutrino DM)

$$\mathcal{L} = yLH'\bar{X}$$

KZ '08
Cao et al. '09

Complex dark sectors

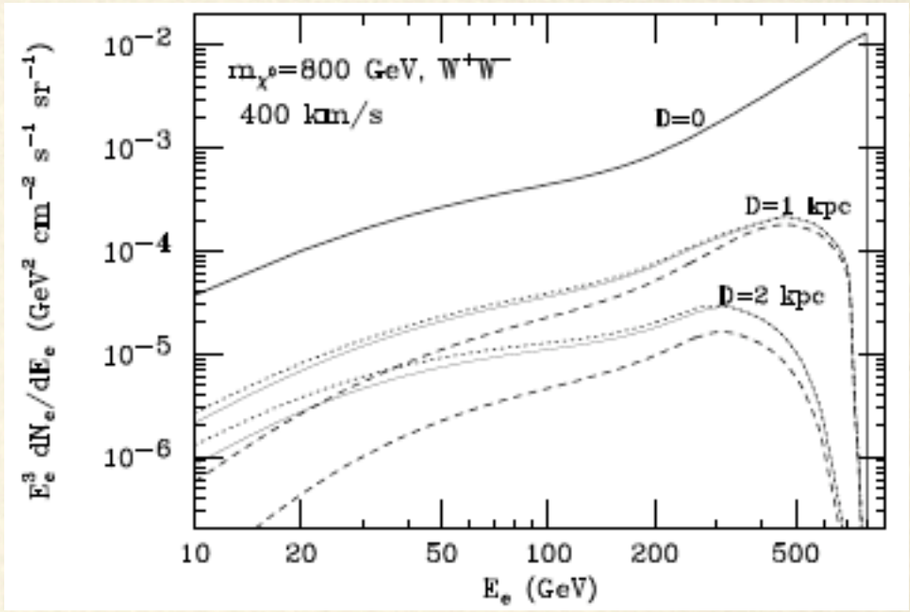


- Multiple stable states?
- New light forces?

An exception for ordinary dynamics

Hooper, Stebbins, KZ

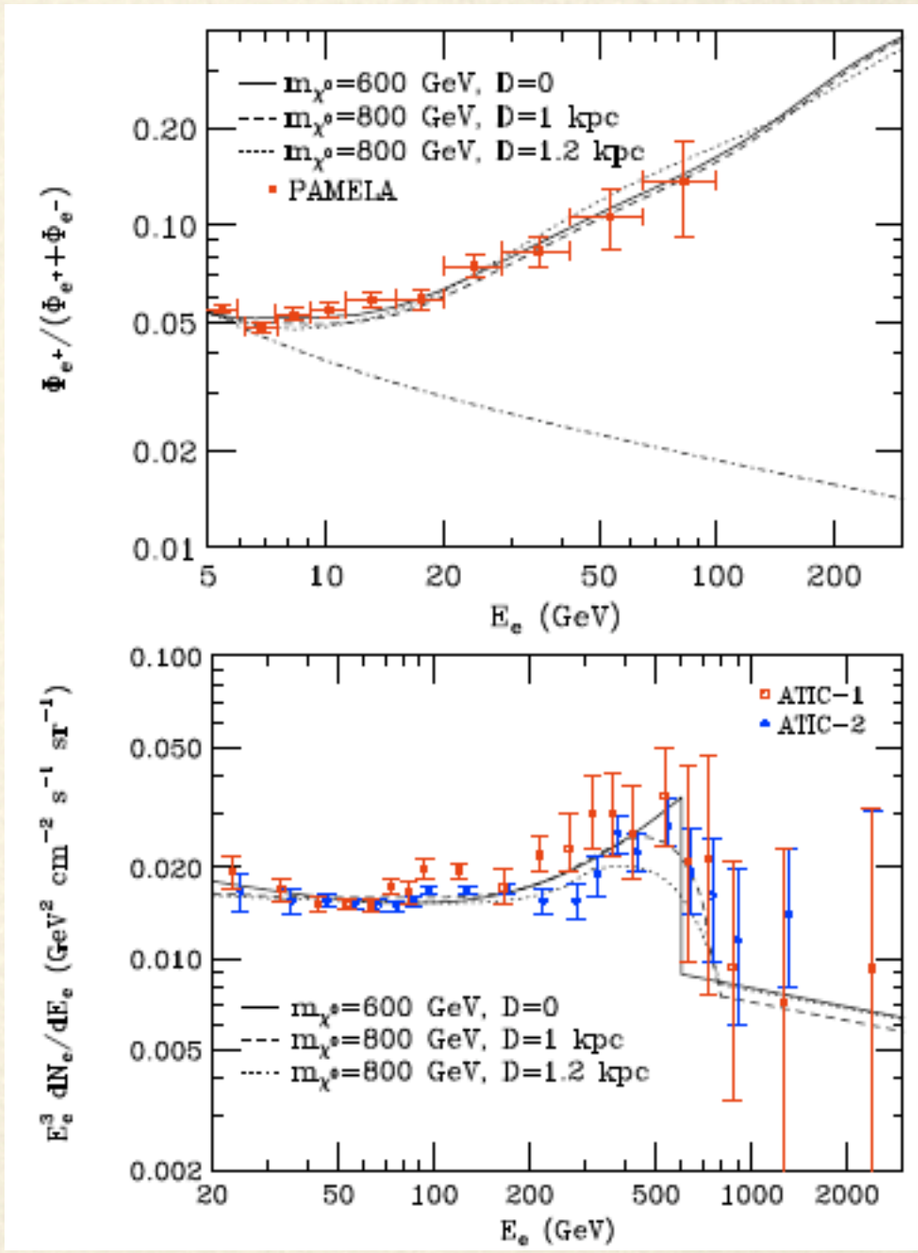
- Live next to dwarf size clump
- Spectrum from XX->W+W- harder because close by
- Avoids pbar constraints
- Probability? 0.2%



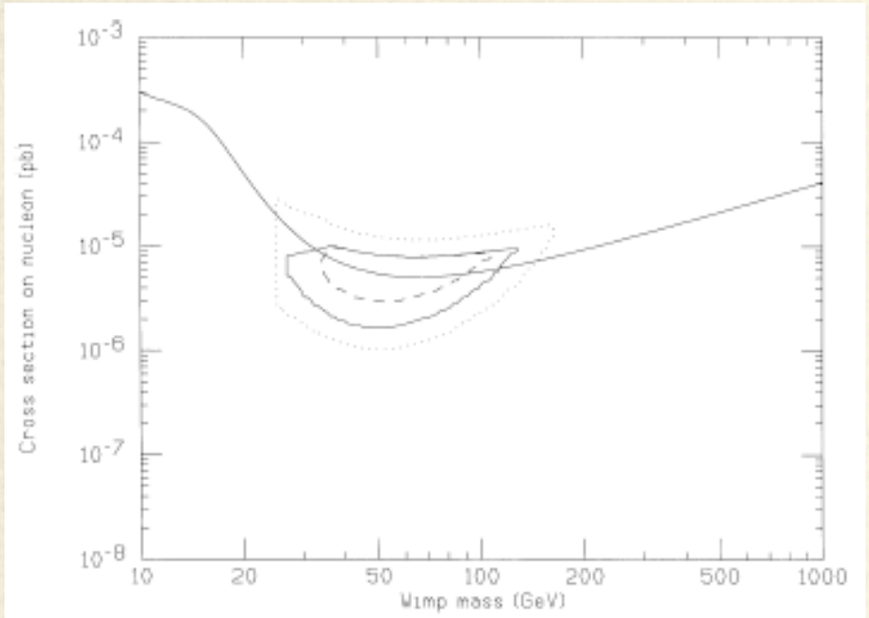
An exception for ordinary dynamics

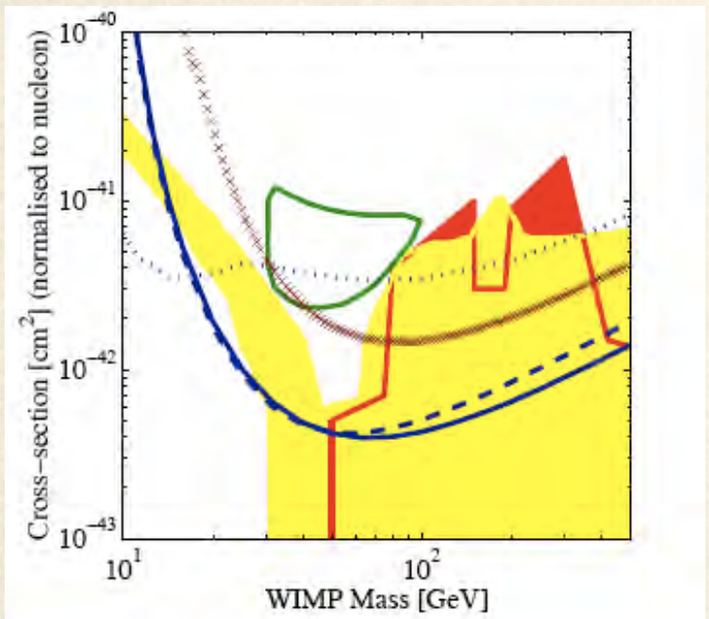
- Live next to dwarf size clump
- Spectrum from XX->W+W- harder because close by
- Avoids pbar constraints
- Probability? 0.2%

Hooper, Stebbins, KZ



DAMA and WIMP DM, pre-2007





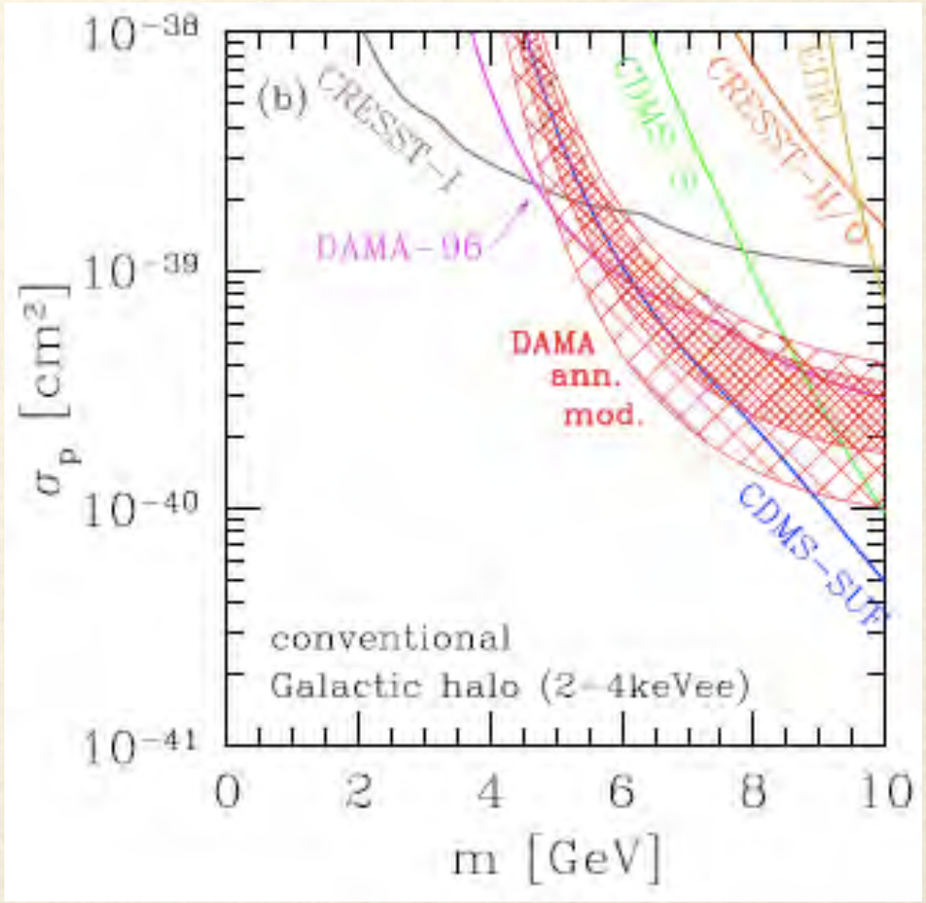
Bottino et al.

Baltz et al.

Analyzed with constraint

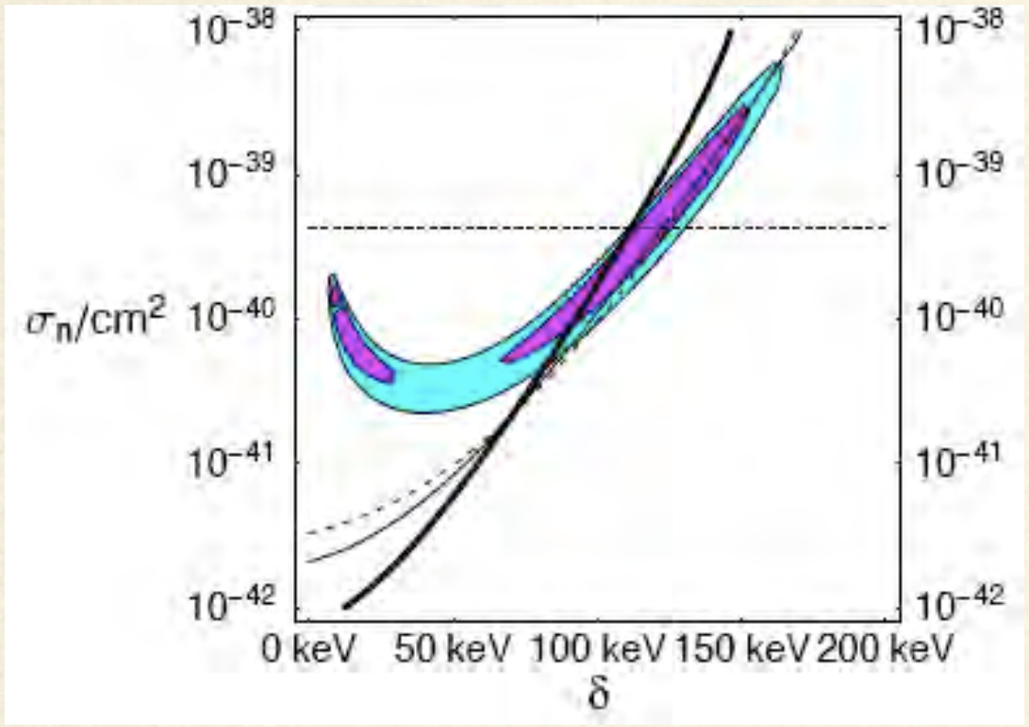
$m_{DM} \geq 25$ GeV

Gelmini, Gondolo '04

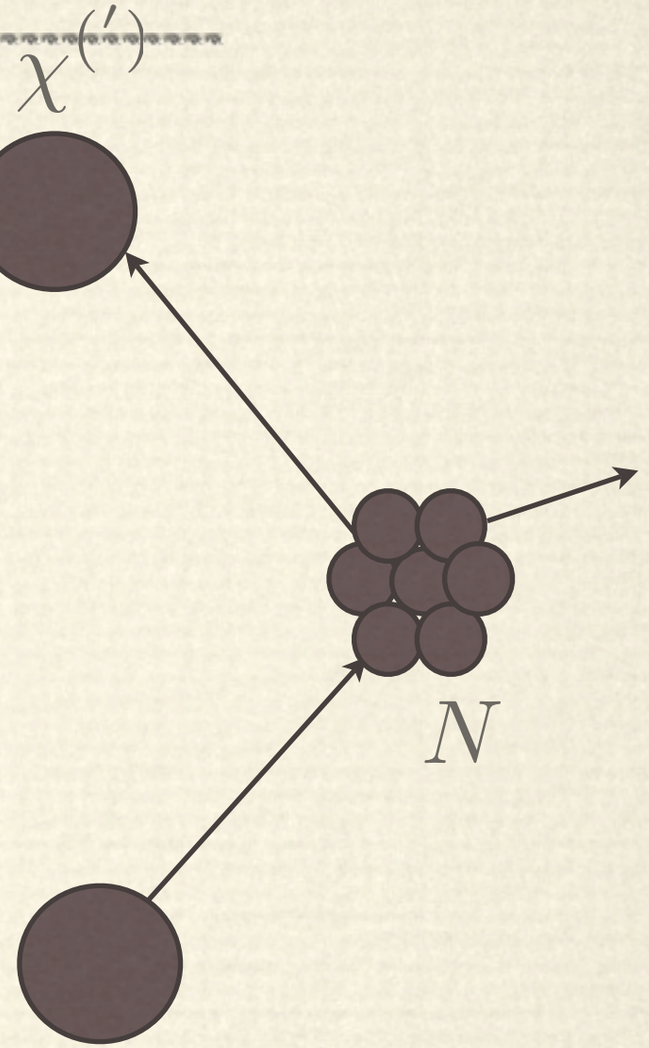


Inelastic DM

Tucker-Smith, Weiner '04



Inelastic $\chi \to \chi'$ off I
Thought to have *higher* 22 keV threshold

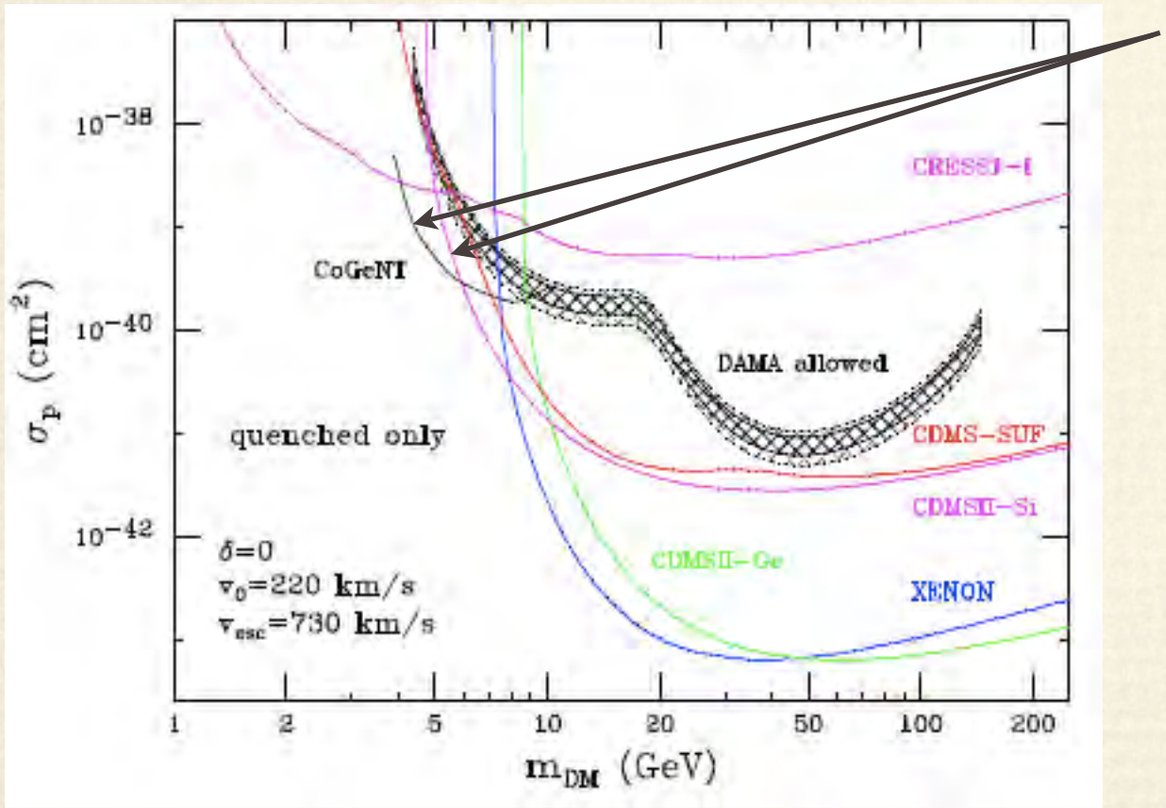


DAMA: NaI
CDMS: Si, Ge
Xenon

DAMA and WIMP DM

- However,

Petriello, KZ '08

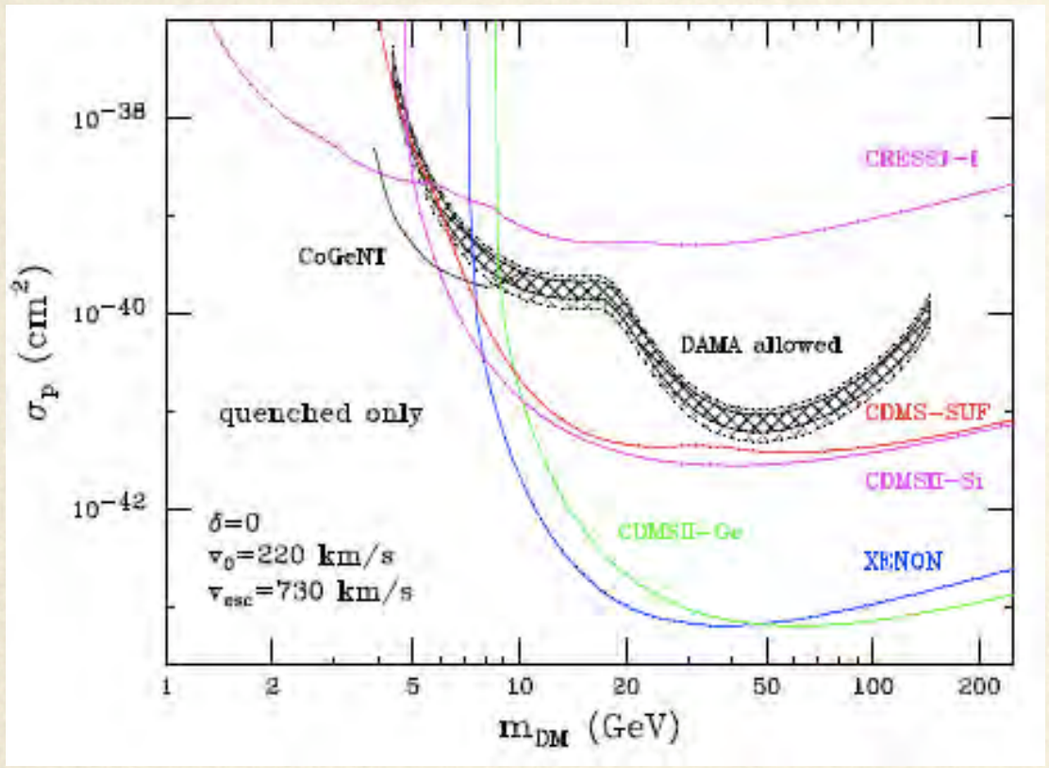


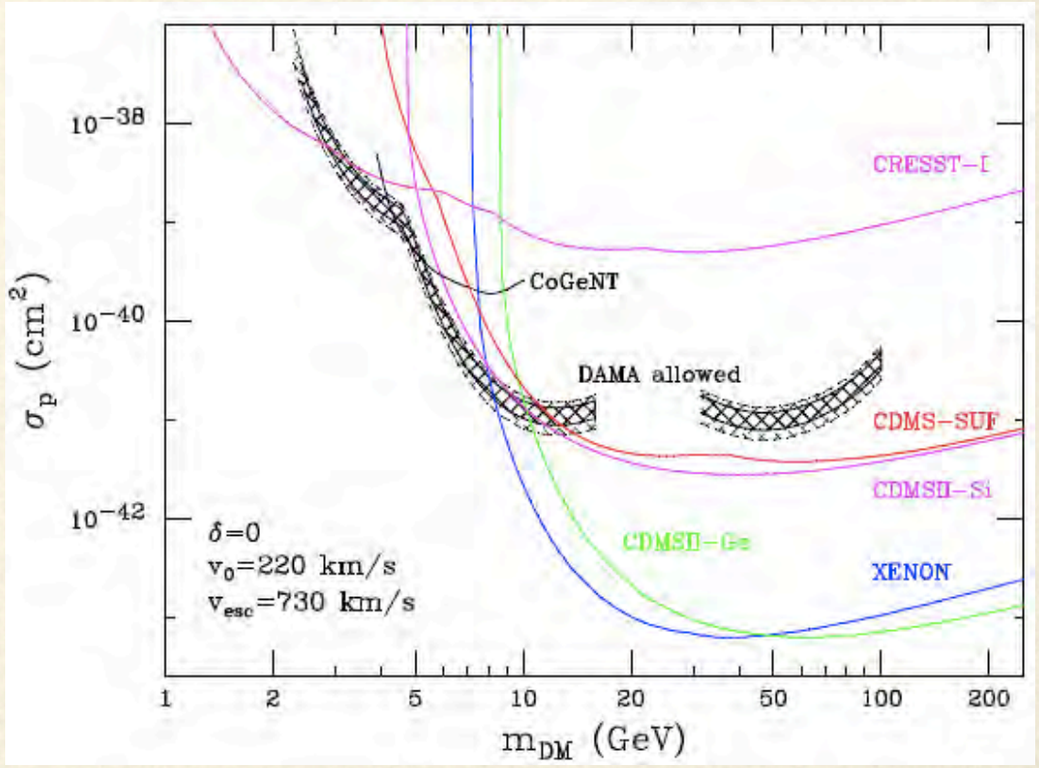
Several new results (7 keV CDMS silicon, CoGeNT) seem to close the light-WIMP window

DAMA and WIMP DM

- New unaccounted for (?) systematic which shifts the threshold: channeling

Petriello, KZ '08





$E_{thresh} = 7$ keV (Na), 22 keV (I)

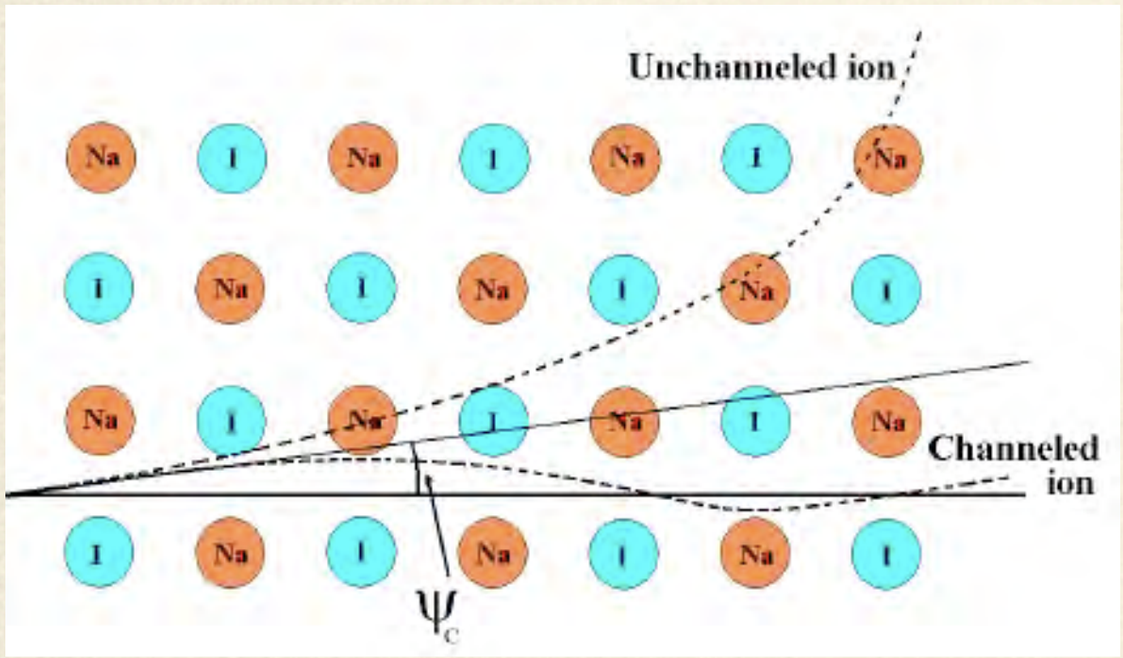
$E_{thresh} = 2$ keV

$$v^2 \geq \frac{m_N E_R^{thresh}}{2\mu_{DM}^2}$$

Channeling

For channeled events:

DAMA ‘08



$$E_{meas} = q_N E_{nuc.\ rec.}$$

~~$q_{Na} \approx 0.3,\ q_I \approx 0.1$~~

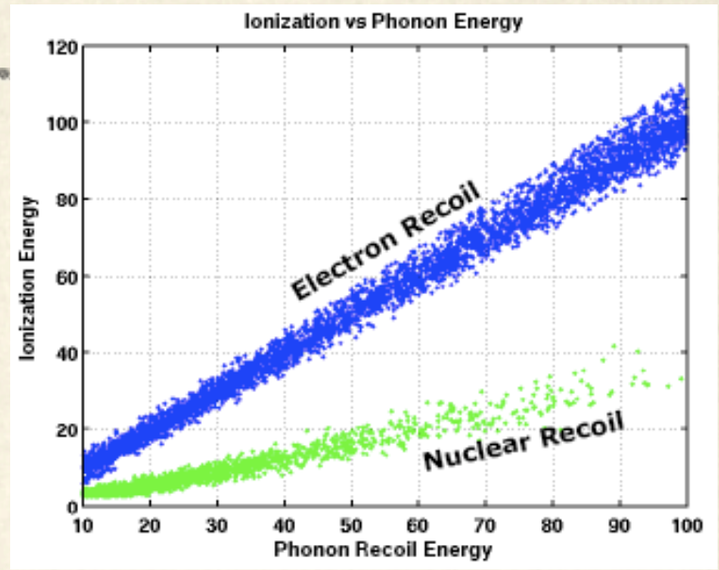
$$q_N \approx 1$$

q_N’s are quenching factors

2 keV in ionization energy off Na corresponds to 2 keV nuclear recoil

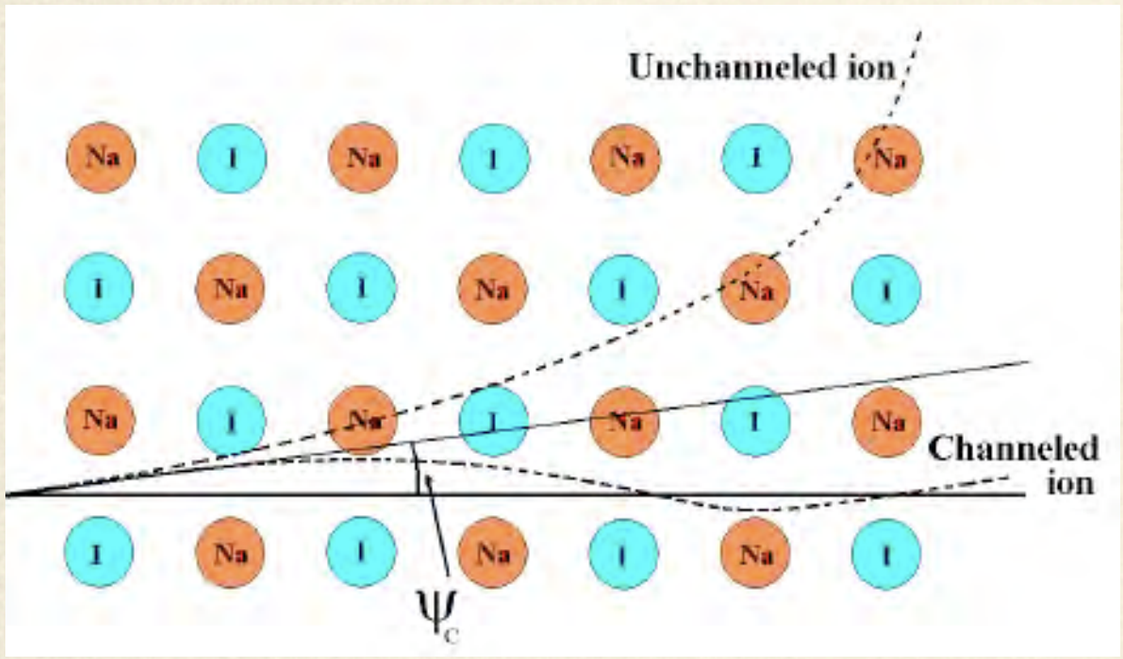
Channeling

Mahapatra, CDMS '08



For channeled events:

DAMA '08



$$E_{meas} = q_N E_{nuc.\ rec.}$$

~~$q_{Na} \approx 0.3,\ q_I \approx 0.1$~~

$$q_N \approx 1$$

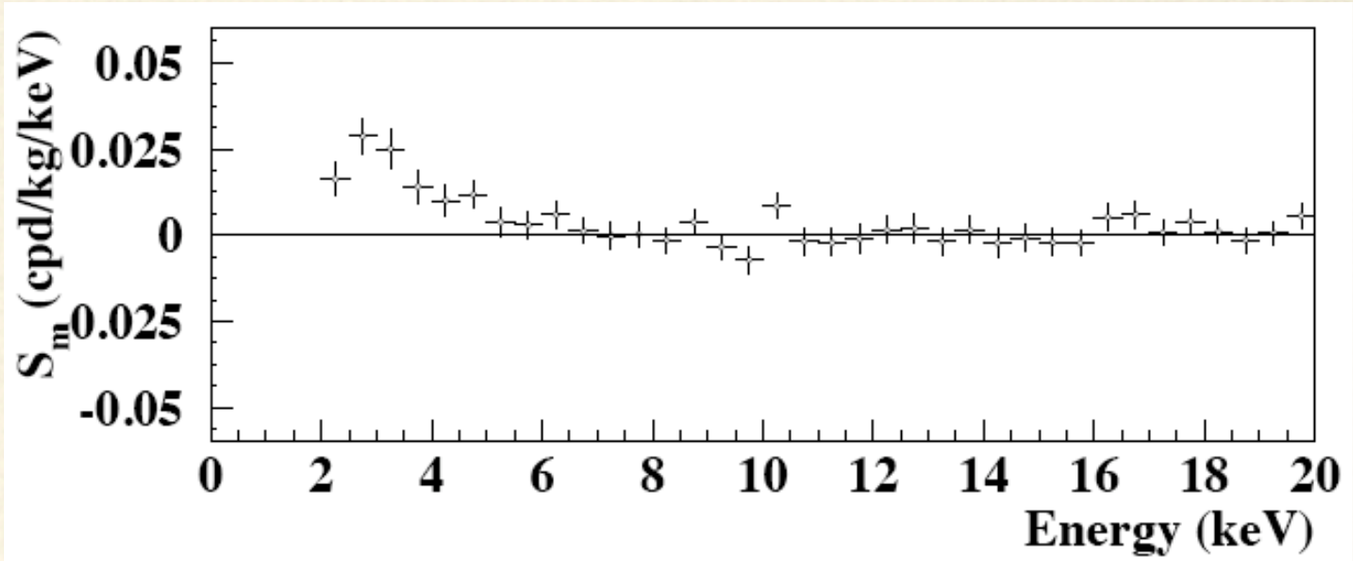
q_N's are quenching factors

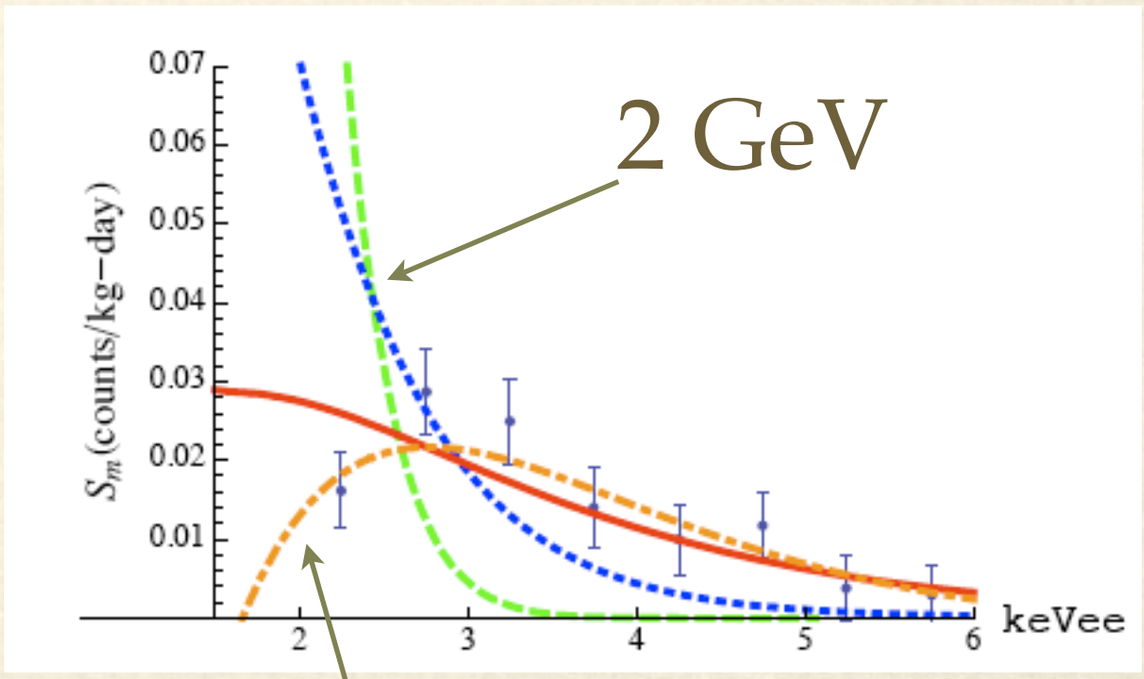
2 keV in ionization energy off Na corresponds to 2 keV nuclear recoil

Spectral information

Energy	S_i^1 (cpd/kg/keVee)
$2-4$ keVee	0.0223 ± 0.0027
$2-5$ keVee	0.0178 ± 0.0020
$2-6$ keVee	0.0131 ± 0.0016
$6-14$ keVee	0.0009 ± 0.0011

DAMA '08

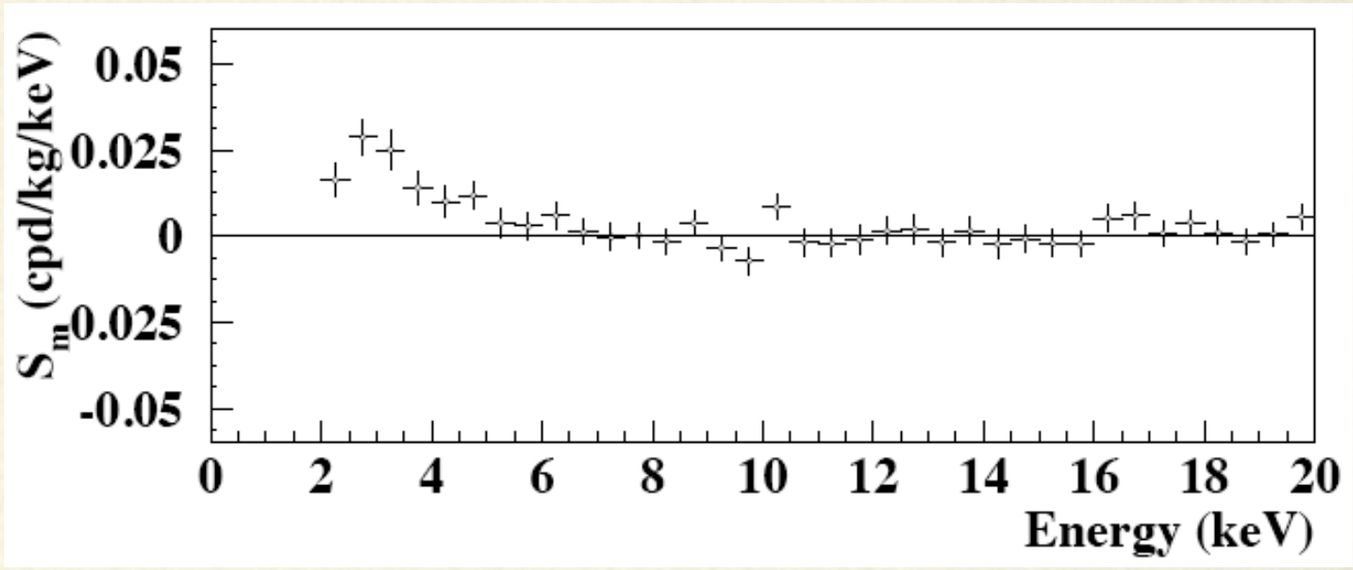




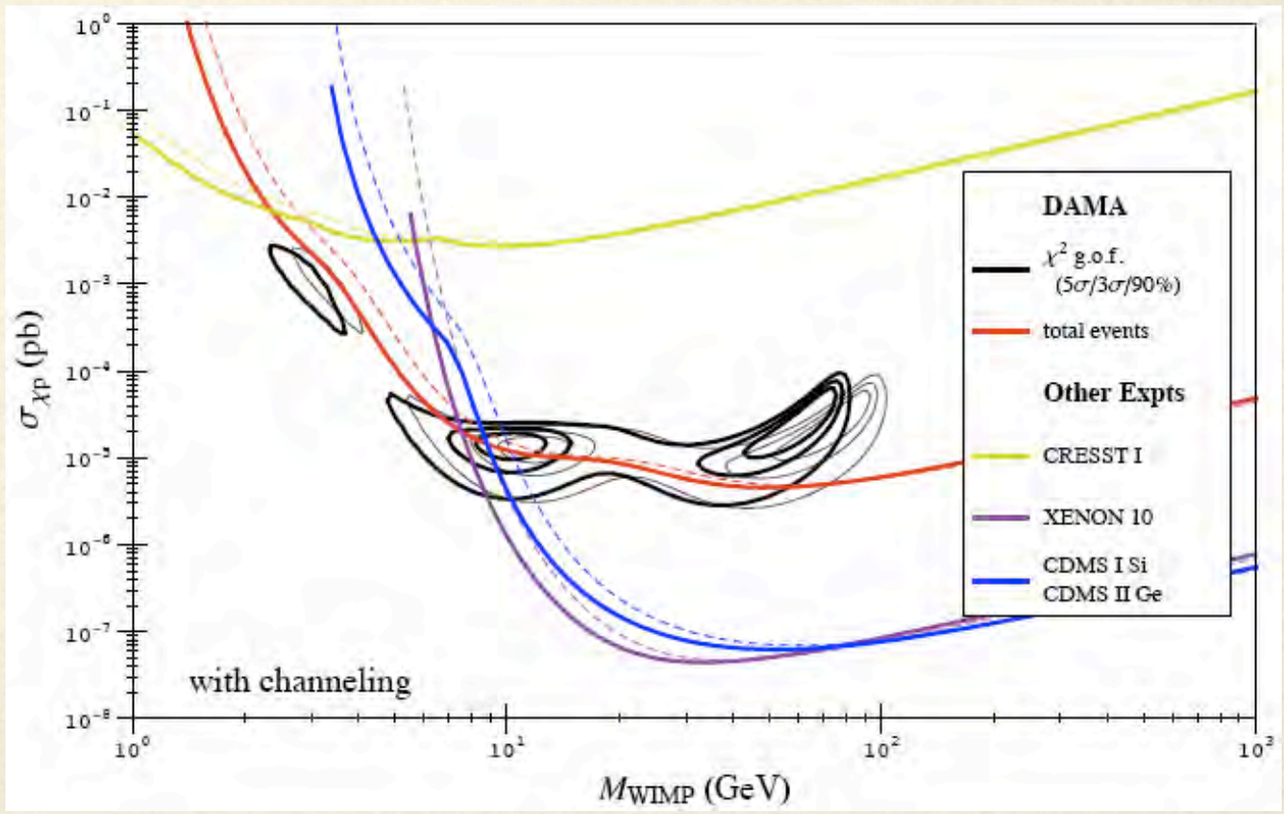
Chang, Pierce, Weiner

Spectral information

Energy	S_i^1 (cpd/kg/keVee)
$2-4$ keVee	0.0223 ± 0.0027
$2-5$ keVee	0.0178 ± 0.0020
$2-6$ keVee	0.0131 ± 0.0016
$6-14$ keVee	0.0009 ± 0.0011



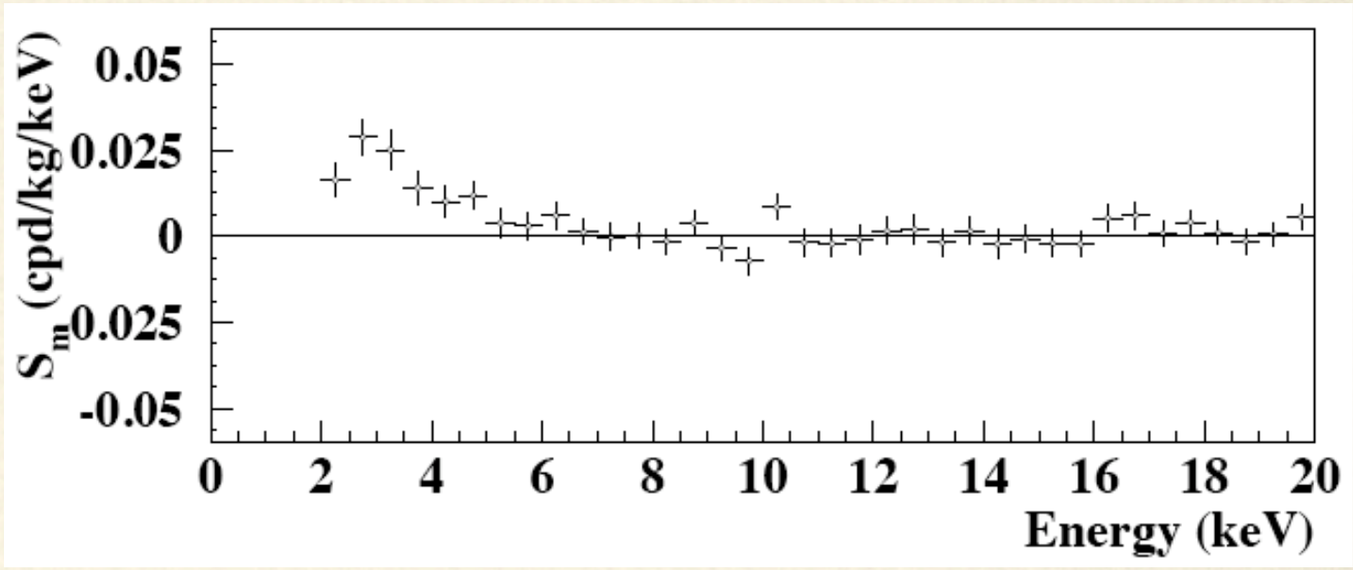
Window is not ruled out



Savage, Freese, Gondolo, Spolyar

Spectral information

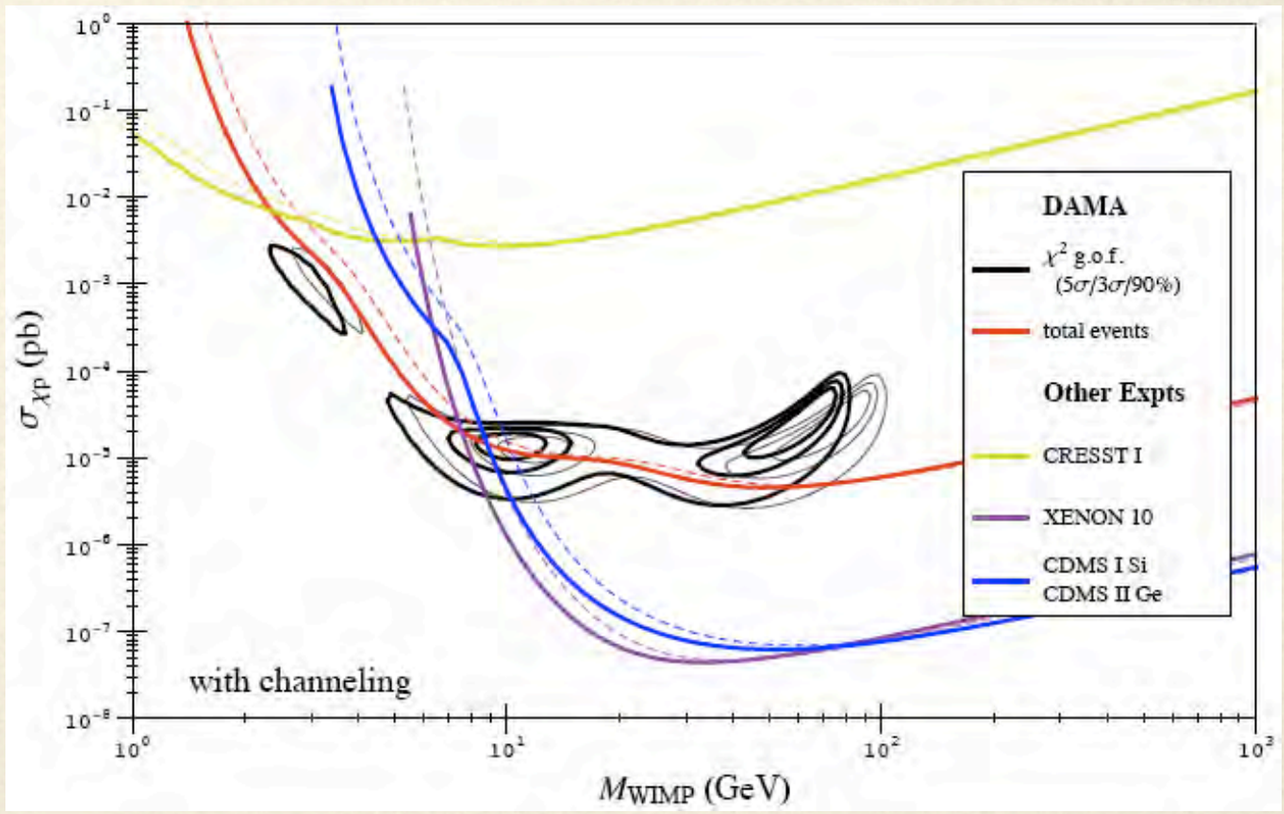
Energy	S_i^1 (cpd/kg/keVee)
$2-4$ keVee	0.0223 ± 0.0027
$2-5$ keVee	0.0178 ± 0.0020
$2-6$ keVee	0.0131 ± 0.0016
$6-14$ keVee	0.0009 ± 0.0011



Window is not ruled out

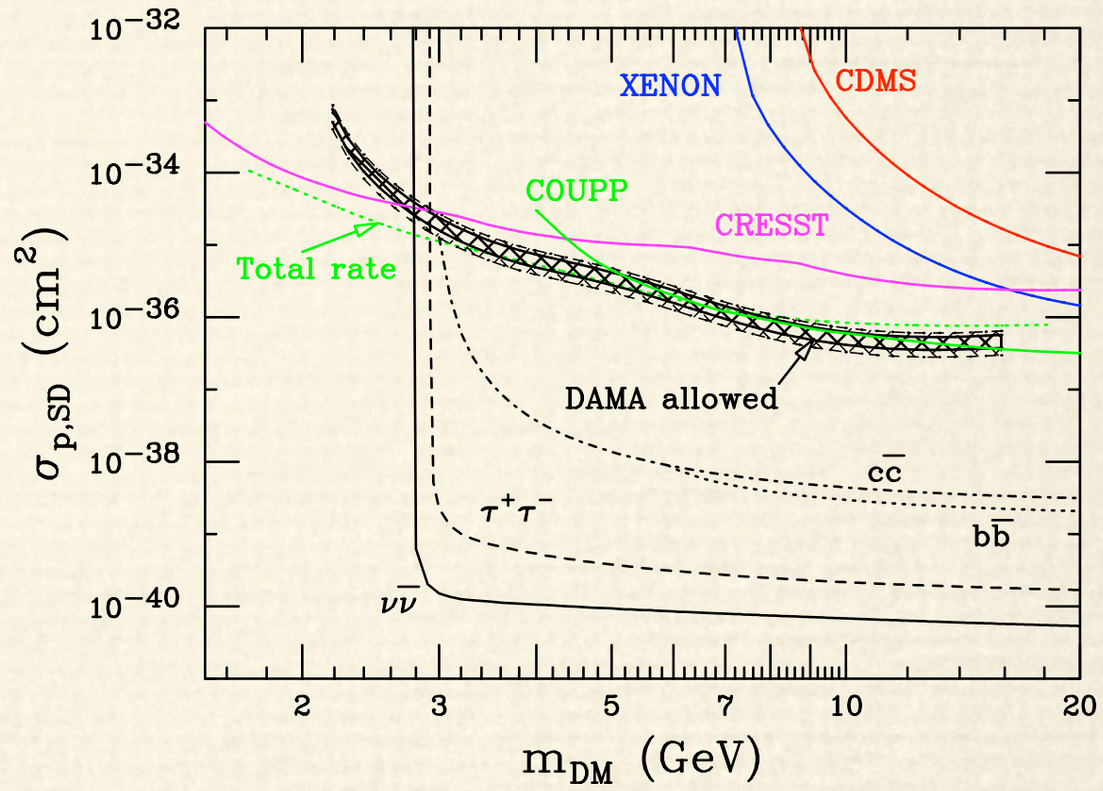
DAMA results has inspired low threshold analyses in other experiments, e.g. CDMS and XENON

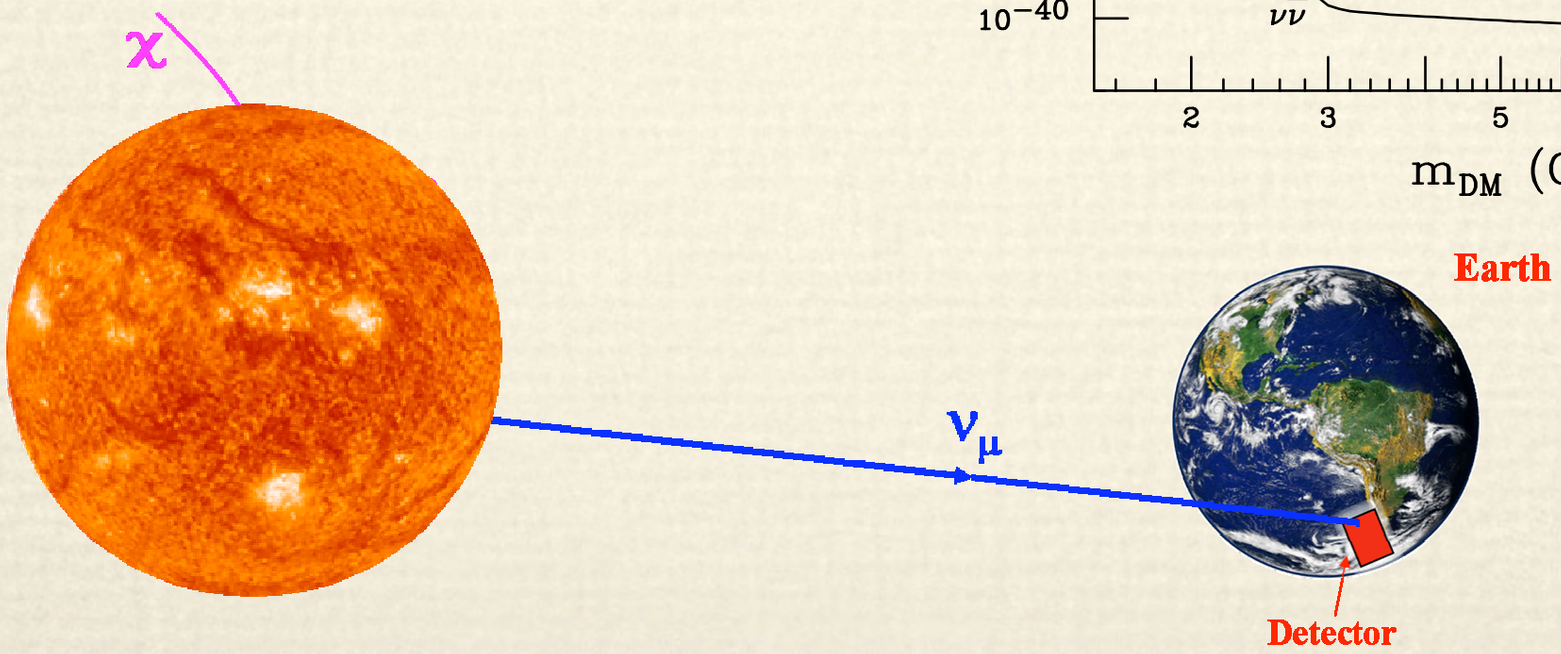
Savage, Freese, Gondolo, Spolyar



Not explained by spin-dependent scattering

- Ruled out by neutrinos in Super-K





Weak scale couplings to SM, and GeV masses. How do we miss that?

- Couple DM to SM through higher dimension operators

Weak scale states
Higgs, Z', MSSM states

Dark forces

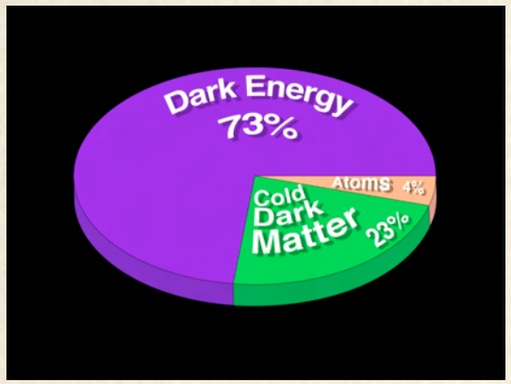
"Hidden Valley"

Standard Model

Dark sector.
May be complex!

- General principle: in some cases will only observe light particles at high energy colliders

Motivated GeV scale WIMPs



Baryon-DM coincidence $\rho_{DM} \approx 5\rho_b$

- In most models (e.g. SUSY) these are set by different (unrelated) quantities
- ρ_b set by CP violating phases
- ρ_{DM} set by dark matter mass, bino/wino/higgsino content of LSP
- In most models, baryogenesis and thermal freeze-out are independent processes

Simple realizations of this solution

Experimentally, $\Omega_{DM} \approx 5\Omega_b$

Find mechanism $n_{DM} \approx n_b$

$$m_{DM} \approx 5 m_p$$

S.M. Barr, D.B. Kaplan

Farrar, Zaharijas

Kitano, Low

Gudnason, Kouvaris, Sannino

Kitano, Murayam, Ratz

Luty, Kaplan, KZ

High scale M

$$W = \frac{X^2 L H}{M}$$

Electroweak scale

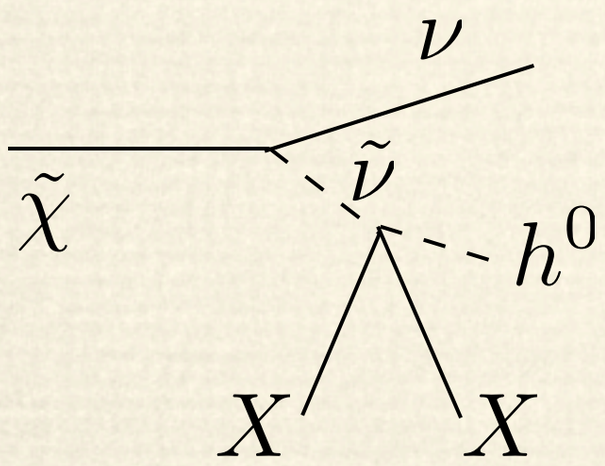
Standard Model

X sector

Implications for colliders

- MSSM LSP is not stable!

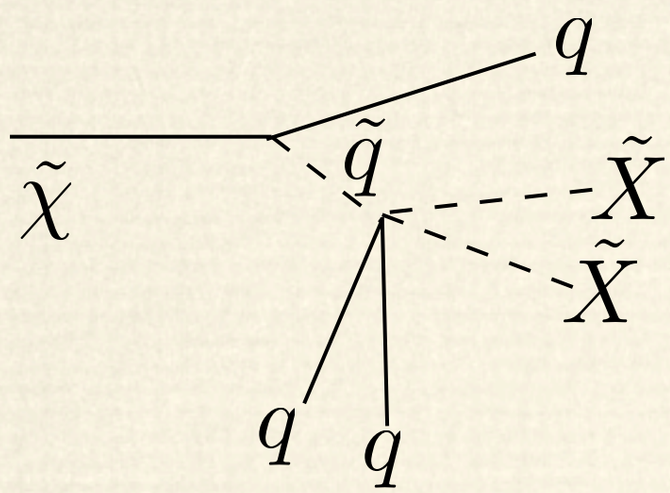
$$W = \frac{X^2 L H}{M} \qquad 2(n_X - n_{\bar{X}}) \approx n_L - n_{\bar{L}}$$



$$m_X \simeq 2.4 \text{ GeV} \frac{\Omega_{DM}}{\Omega_b} \simeq 11 \text{ GeV}$$

$$c\tau(\chi^0 \to h^0 \nu \bar{X} \bar{X}) \sim \text{mm} \left(\frac{M}{10^6 \text{ GeV}}\right)^2 \left(\frac{m_{\tilde{\nu}}}{200 \text{ GeV}}\right)^4 \left(\frac{m_{\chi^0}}{100 \text{ GeV}}\right)^{-7}$$

Collider signatures



$$W = \frac{X^2 udd}{M^2}$$

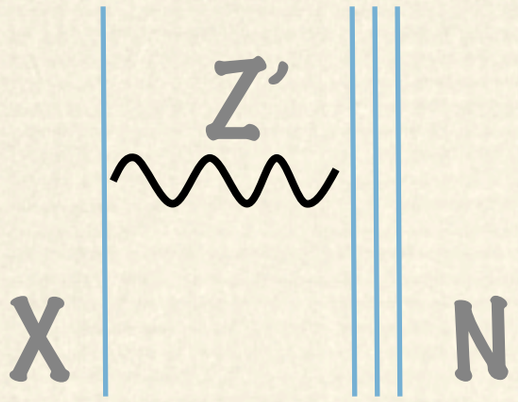
$$m_{DM} \simeq 8 \text{ GeV}$$

$$c\tau(\chi^0 \to qqq\tilde{X}\tilde{X}) \sim 0.3 \text{ mm} \left(\frac{M}{\text{TeV}}\right)^4 \left(\frac{m}{500 \text{ GeV}}\right)^4 \left(\frac{m_{\chi^0}}{100 \text{ GeV}}\right)^{-9}$$

$$c\tau(\tilde{X} \to Xqqq) \sim 3 \text{ mm} \left(\frac{M}{\text{TeV}}\right)^4 \left(\frac{m}{500 \text{ GeV}}\right)^2 \left(\frac{m_{\tilde{X}}}{100 \text{ GeV}}\right)^{-7}$$

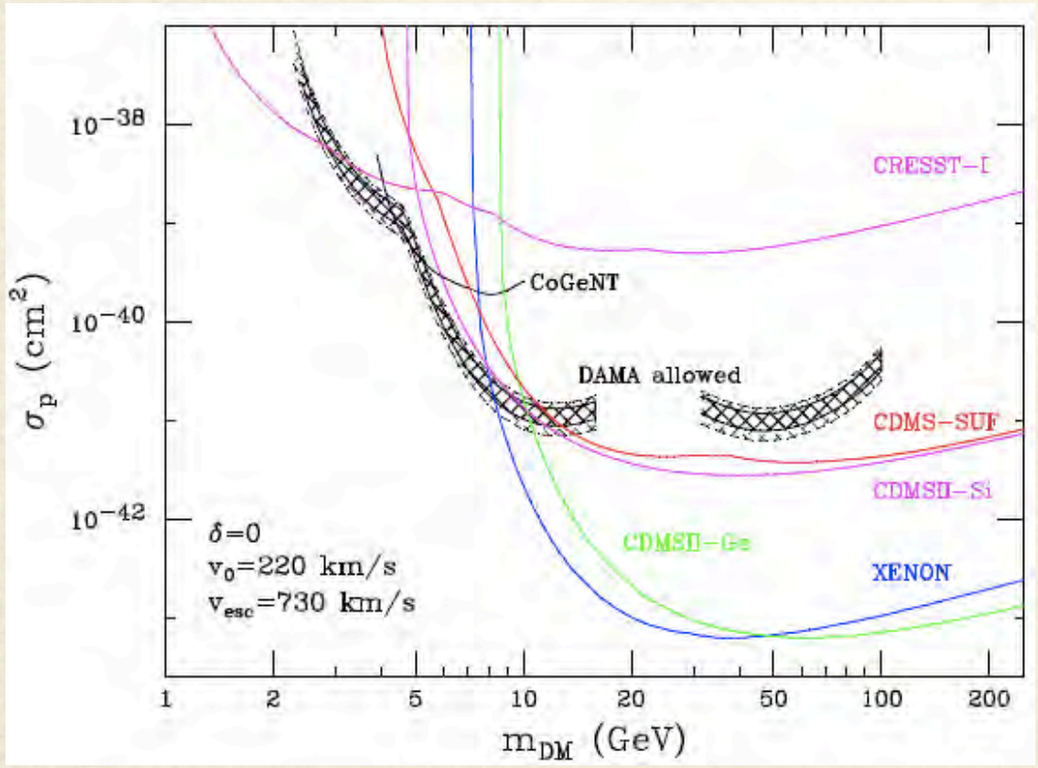
Missing energy largely reduced

DM of this type may explain DAMA

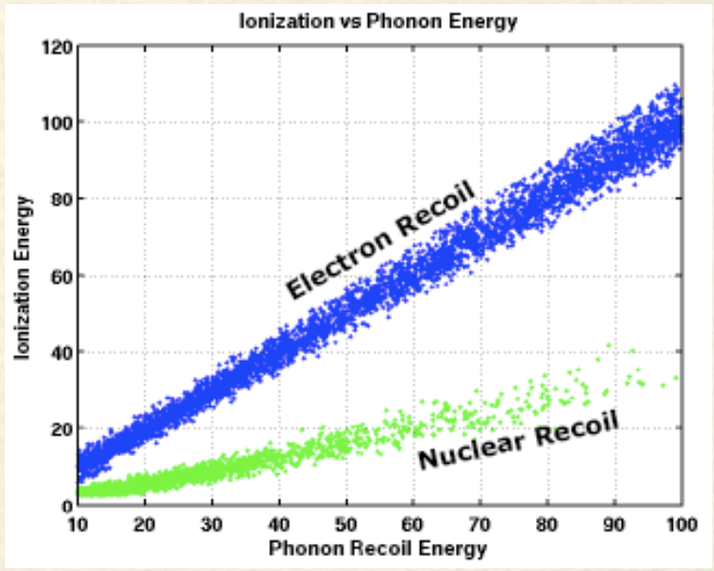


$$\sigma_n^{\rm exp} \simeq 10^{-41}\ {\rm cm}^2 \left(\frac{g_{\bar{X}XZ'} g_{\bar{u}uZ'}}{10^{-1}}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{Z'}}\right)^4$$

Window currently being examined by CDMS and XENON



Mahapatra, CDMS '08



Analysis must not cut out channeled events!

Summary

- Collider searches for DM are mostly based on a canonical model, typically in context of CMSSM
- DM candidates pointed to by recent experiments do not point to anything like the CMSSM
- In some cases, current searches suffice
- New search techniques must be devised
- Exciting time for Dark Matter!