Complementary Approaches to Dark Matter Searches

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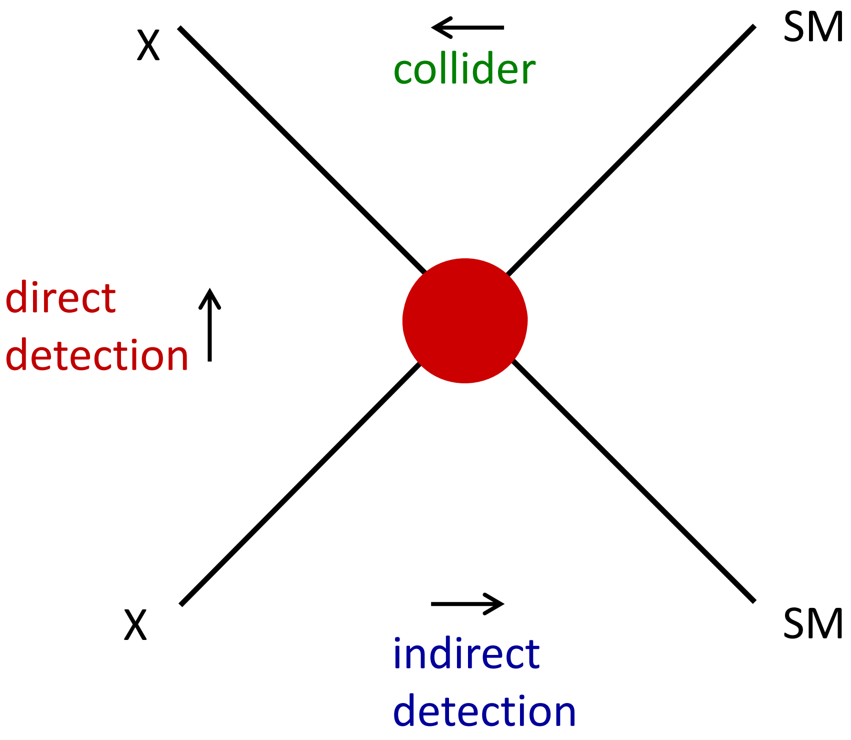
    - 1102.4331, 1103.3270, 1108.0518, 1112.4849, 1204.5120, 13xx.xxxx

searching for dark matter....

- usually start with some standard assumptions about dark matter interactions
  - single particle candidate
  - elastic scattering
  - contact interaction
  - isospin-invariant
- main motivations are
  - simplicity
  - largely valid for MSSM WIMP models (actually, more restricted than that)
- but recent data hints only marginally consistent with MSSM WIMP models
  - not clear whether these assumptions are really desirable
- basic question: how does the role of different detection strategies change once we relax these assumptions?

dark matter detection strategies

- direct detection
  - measure recoil from dark matter scattering against nuclei
- indirect detection
  - dark matter annihilation in sun, Galactic center, satellites, etc.
  - look for the resulting Standard Model particles
- collider search
  - dark matter produced at the LHC
  - look for the missing momentum
- quantum matrix elements for all three processes related by crossing symmetry



issue: models and searches

- there is already a host of uncertainties
    - astrophysics → not really an isothermal sphere → affects velocity distribution
    - nuclear physics → to know how dark matter scatters off nuclei, need to know nucleon structure
    - I'll focus on the remaining particle physics uncertainties....
- many assumptions usually made about dark matter interactions with Standard Model
    - mostly based on WIMPs (MSSM) (actually, usually CMSSM/mSUGRA)
- possible problems
    - search strategies may not be optimized for non-standard dark matter
    - if dark matter is non-standard, data may not be interpreted correctly
- our goal... understand how changes to the standard paradigm can alter our interpretation of data, and give us new detection options

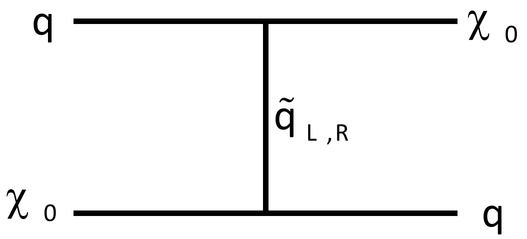
low-mass dark matter

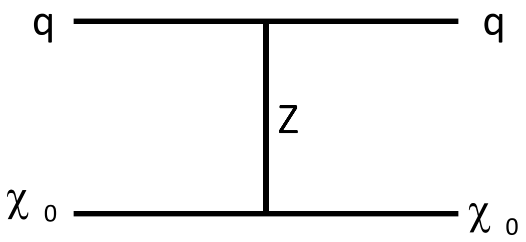
- recent hints from DAMA, CoGeNT, CRESST, CDMS-SI could be DM
  - 5-20 GeV
  - light for MSSM WIMPs
- CDMS-Ge and XENON10/100 are not seeing a signal
  - could be a background....
- experimental issues with all of these experiments
  - some will be resolved soon
  - I won't focus on that.....
  - treat low-mass as a test case
- for theory, the question is, how to study low-mass dark matter?

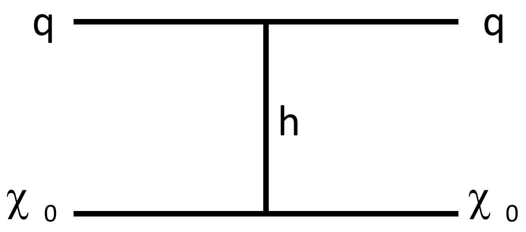
- direct detection
  - low-mass = low recoil energy (E_R)
  - need $\mathcal{O}$(keV) threshold
    - set by where you can distinguish signal from background
  - challenging for experiments aimed at WIMPs
- assumptions about f_n / f_p, contact interactions, etc. all play a role in interpretation of the data
- need to keep track of the options, as well other detection strategies....
- start with f_n / f_p and why?

why is $f_n / f_p \approx 1$ in MSSM?

- if dark matter is mostly bino
  - scatters by squark exchange
  - coupling (Y) is isospin-violating
  - SI term arises from squark-mixing
    - small in minimal flavor violation for first generation quarks
- if dark matter has some wino/higgsino component
  - scatters by Z, higgs exchange
  - Z → isospin-violating, but SD or v^2
  - h → SI, but isospin-conserving
    - higgs coupling scales with quark mass
    - $m_u \sim m_d$







really needed three fairy godmothers!....

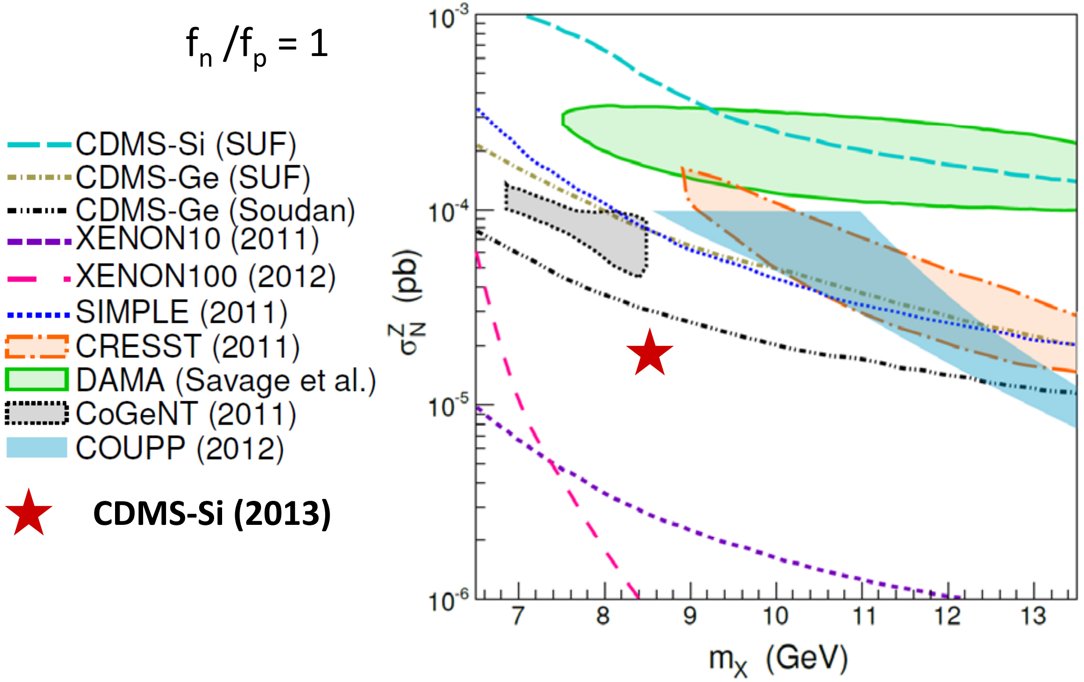
IVDM

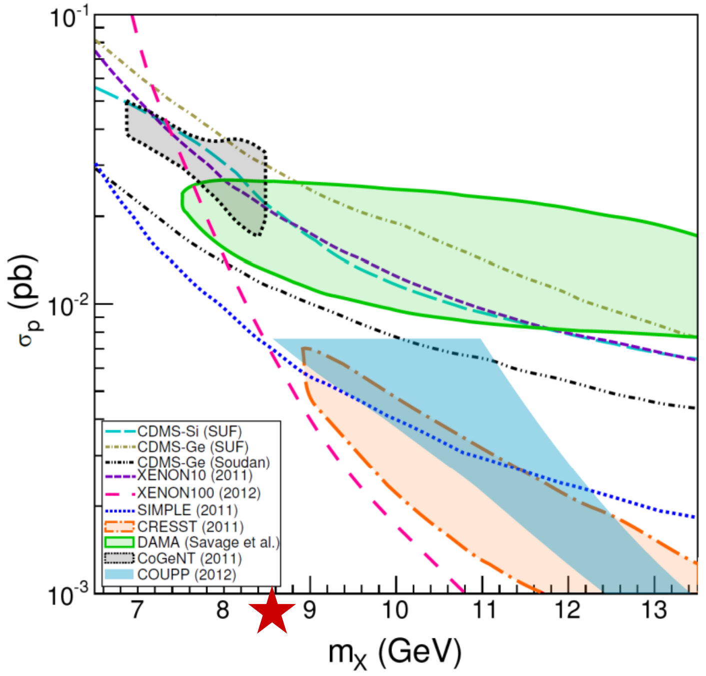
- direct detection bounds normalized to nucleon
  - assume $f_n / f_p = 1$
  - big change if $f_n / f_p \neq 1$
- consider $f_n / f_p = -0.7$
  - see CLPWY also (1004.0697)
- if m_X small, no reason for $f_n = f_p$
  - must account for this possibility!
  - need multiple experiments

$$\sigma_A = \frac{\mu_A^2}{M_*^4}\left[f_p Z + f_n\left(A - Z\right)\right]^2 \times FF$$

$$\sigma_p = \frac{\mu_p^2 f_p^2}{M_*^4}$$

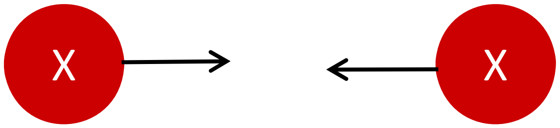
figures courtesy of David Sanford


$f_n / f_p = 1$


$f_n / f_p = -0.7$
(1004.0697
1102.4331)

complementary searches

- what can we learn from other search strategies?
- annihilation → s-wave or p-wave?
  - annihilation from L=1 state suppressed by $v^2 \sim 10^{-6}$
  - higher energy scales
- is pair-creation enhanced?
  - production at LHC occurs at higher energies than annihilation or scattering ($> 2m_X$)
  - energy enhancement could make LHC searches more promising
  - depends on boson vs. fermion, E dependence of perturbation



$\Delta E \sim 2m_X$

$$|\text{spin}-0\rangle \propto 1$$

$$|\text{spin}-1/2\rangle \propto \sqrt{E}$$

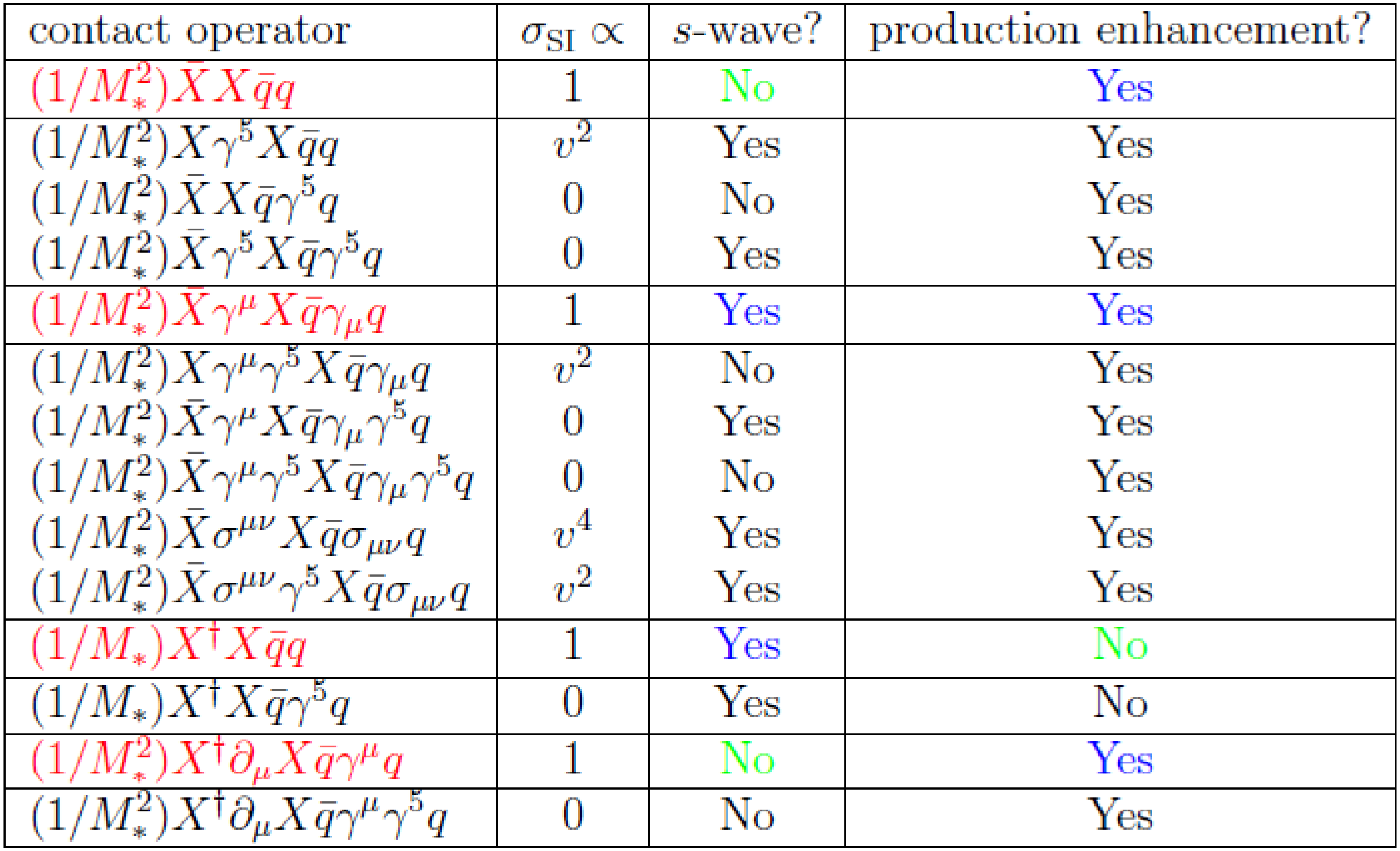
$$\left(\phi^* \partial^\mu \phi\right) \tilde{A}_\mu$$

$$\phi^* \phi \chi$$

$\sim E$

effective operator analysis

also gluon couplings, spin-1, etc.....



contact operator	$\sigma_{\mathrm{SI}} \propto$	s-wave?	production enhancement?
$(1/M_*^2)\bar{X}X\bar{q}q$	1	No	Yes
$(1/M_*^2)X\gamma^5 X\bar{q}q$ $(1/M_*^2)\bar{X}X\bar{q}\gamma^5 q$ $(1/M_*^2)\bar{X}\gamma^5 X\bar{q}\gamma^5 q$	v^2 0 0	Yes No Yes	Yes Yes Yes
$(1/M_*^2)\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$	1	Yes	Yes
$(1/M_*^2)X\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$ $(1/M_*^2)\bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5 q$ $(1/M_*^2)\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu\gamma^5 q$ $(1/M_*^2)\bar{X}\sigma^{\mu\nu} X\bar{q}\sigma_{\mu\nu} q$ $(1/M_*^2)\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu} q$	v^2 0 0 v^4 v^2	No Yes No Yes Yes	Yes Yes Yes Yes Yes
$(1/M_*)X^\dagger X\bar{q}q$	1	Yes	No
$(1/M_*)X^\dagger X\bar{q}\gamma^5 q$	0	Yes	No
$(1/M_*^2)X^\dagger\partial_\mu X\bar{q}\gamma^\mu q$	1	No	Yes
$(1/M_*^2)X^\dagger\partial_\mu X\bar{q}\gamma^\mu\gamma^5 q$	0	No	Yes

a general model can interact through multiple operators....

indirect detection

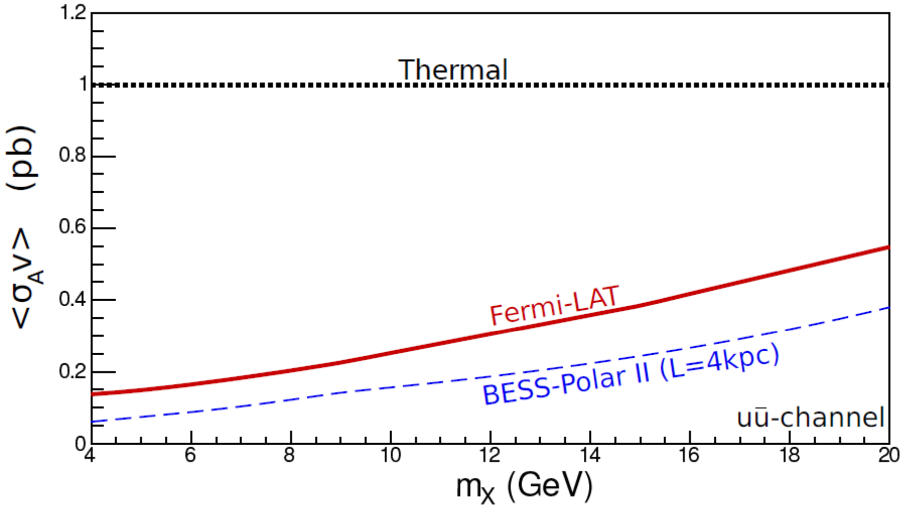
- look for γ, $e^{\pm}$, $p^{\pm}$, ν produced by dark matter annihilation
- main targets are... anywhere there's a lot of dark matter
- many techniques and targets, but upshot is the same
  - rate of annihilations $\propto \int dV\, \eta^2 \langle \sigma_{ann.} v \rangle$
  - estimate $\int dV\, \eta^2$ from astrophysics data (with uncertainty!)
  - choice of annihilation products relates number of annihilations to number of particles seen
  - putting the above together with observations yields a bound on $\langle \sigma_{ann.} v \rangle$
- since scattering and annihilation matrix elements are related, we probe the matrix element in a different kinematic regime (2m_X instead of keV)
  - determine matrix element structure and coupling to different SM particles
- strong signal only if matrix element allows annihilation from s-wave state
- good at low mass, since $\eta \propto \rho / m_X$

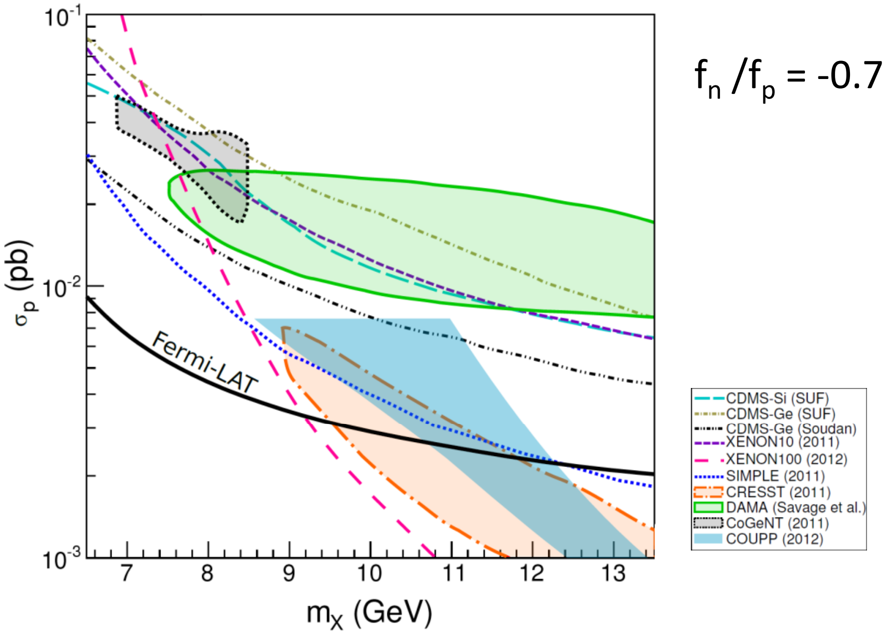
Fermi-LAT and dwarf spheroidals

- less astrophysics uncertainty, less background
- for any matrix element, can translate from $\langle \sigma_{ann.} v \rangle$ to σ_{SI}
- example → annihilation to u/d-quarks only, fixed f_n/f_p
- consider elastic contact operators with spin-independent scattering and s-wave annihilation (unique!)
- enhanced $\sigma_{ann.}$ if f_n/f_p=-0.7
  - tighter bounds
- signal (or lack of it) can point to a model choice....
  - p-wave annihilation?, $M_* \sim$ GeV?

complex scalar

1112.4849

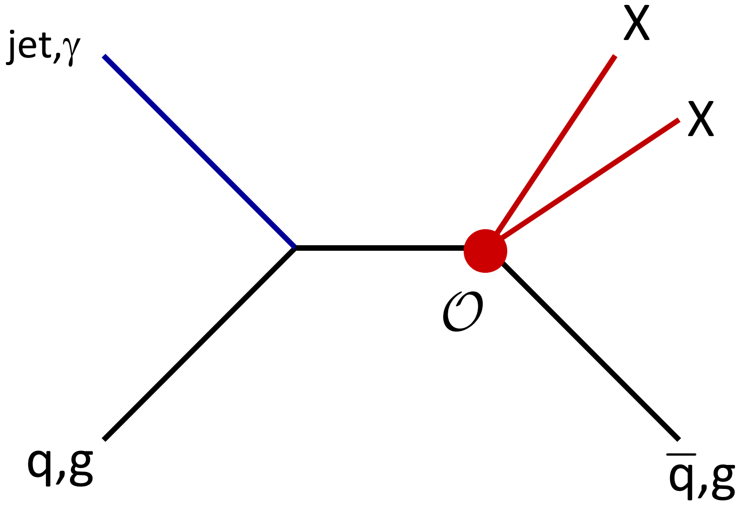



f_n/f_p = -0.7

collider searches

- roughly two strategies
  - produce heavy, QCD-coupled particle which decays to DM
    - standard search for MSSM LSP
    - produce squarks or gluinos
  - produce dark matter directly through DM-SM interaction
- I’ll focus on the second strategy
- complementary to direct/indirect detection
  - no p-wave suppression
  - can b-tag spectator jets to gain info about b-quark coupling

- example of second strategy
  - monojet searches at LHC
  - pp→ XX +jet = jet + “nothing”
  - creation and scattering matrix elements related
  - yields bounds on the scattering cross-section



models and monojet searches

- compare number of monojets seen to prediction of SM
  - excess could indicate dark matter
- # of events depends on model
  - contact operator at LHC energy?
  - energy dependence of matrix element?
  - flavor? → IVDM could ramp up couplings
- consider SI-scattering, s-wave annihilation, coupling to u/d
- points to a model in a way complementary to direct/indirect detection

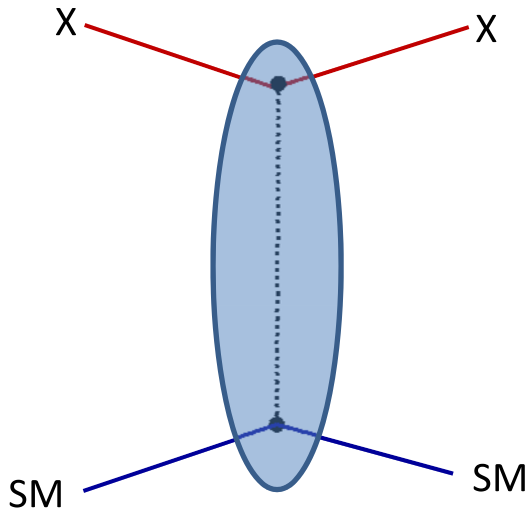
m_X (GeV)	$\sigma_p^{(\mathrm{ferm.})}$ (pb)	$\sigma_p^{(\mathrm{scal.})}$ (pb)
4	0.00079	10.8
7	0.00092	4.2
10	0.00097	2.3
15	0.00106	1.1
20	0.00107	0.62

$p_T > 350$ GeV, $\not{E}_T > 350$ GeV
ATLAS monojet search with 1 fb^{-1}

elastic contact scattering, $f_n / f_p = -0.7$

long-range interactions

- essentially, use the Born approximation in QM scattering
- Fourier transform of scattering amplitude is the potential
- $q \sim r^{-1}$
- if $q \ll M_*$, very short-range
- if $q \gg M_*$, like Rutherford scattering
- there are many astrophysics constraints on LR interactions
  - see talks from Harnik and An, work of Michigan group....
- we'll focus on the impact on direct detection strategies....



$$\mathcal{M} \propto \frac{1}{\vec{q}^2 + M_*^2} \rightarrow V(r) \propto \frac{e^{-M_* r}}{r}$$

$$\mathcal{M} \propto \frac{1}{\vec{q}^2} \rightarrow V(r) \propto \frac{1}{r}$$

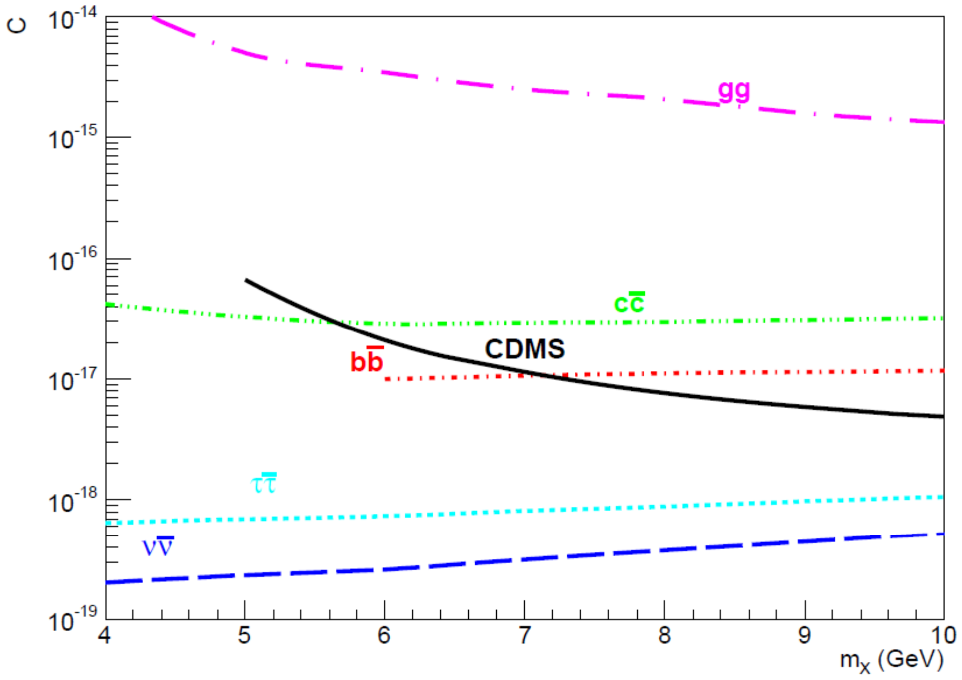
long-range interactions

- depends on momentum transfer
  - E_R threshold → ~ keV
- smaller m_A = larger event rate
- ν–detectors have an advantage
  - hydrogen best target and lots of it in the sun to capture DM
- complementary to CDMS etc.
  - though CDMS result is really just an estimate (efficiency)
  - $\times(70)^2$ enhancement!
- hydrocarbon gas target would be ideal for this class of models....
  - gas TPCs under consideration ....
- also liquid helium detectors

$$\frac{d\sigma_A}{dE_R} = C\frac{4\pi\alpha^2\mu_A^2}{m_A^2 E_R^2 E_{max}}\left[Z+\frac{f_n}{f_p}(A-Z)\right]^2 \times \left|F_A(E_R)\right|^2$$

$M_* \lesssim 1$ MeV

1204.5120 (51 kT , LAr, 17 days) $f_n/f_p = 1$

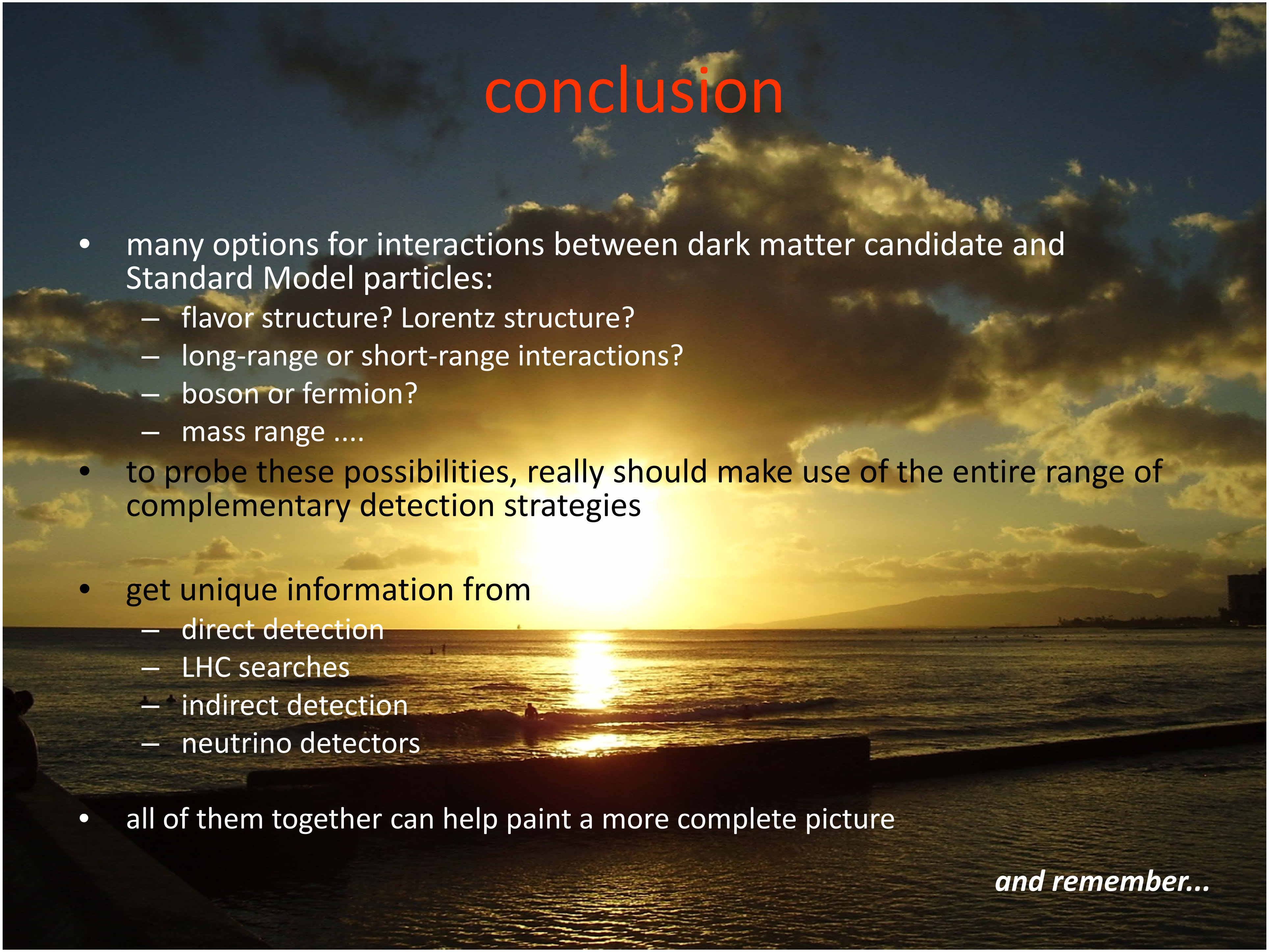


start of an analysis...?

- for example, suppose we really detected low-mass dark matter....
- we can get a handle on SI vs. SD, couplings to protons and neutrons from multiple direct detection experiments
- with estimate of couplings, what can we learn about the dark matter candidate?
- some options arise just from whether or not we see something at indirect detection searches or the LHC

if...?	collider, indirect	collider, indirect	collider, indirect	collider, indirect
could be...	Dirac fermion exchanging a “heavy” gauge boson (spin-1)	fermion exchanging heavy spin-0, or spin-0 exchanging heavy gauge boson	spin-0 exchanging a spin-0 mediator	(semi) long-range interaction

not complete, just some options... →in general, need spectral info, etc. ....



conclusion

- many options for interactions between dark matter candidate and Standard Model particles:
  - flavor structure? Lorentz structure?
  - long-range or short-range interactions?
  - boson or fermion?
  - mass range ....
- to probe these possibilities, really should make use of the entire range of complementary detection strategies

- get unique information from
  - direct detection
  - LHC searches
  - indirect detection
  - neutrino detectors

- all of them together can help paint a more complete picture

and remember...

CosPA 2013

Nov. 12-15, 2013

Honolulu, USA

hosted by

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http://www.phys.hawaii.edu/cospa2013

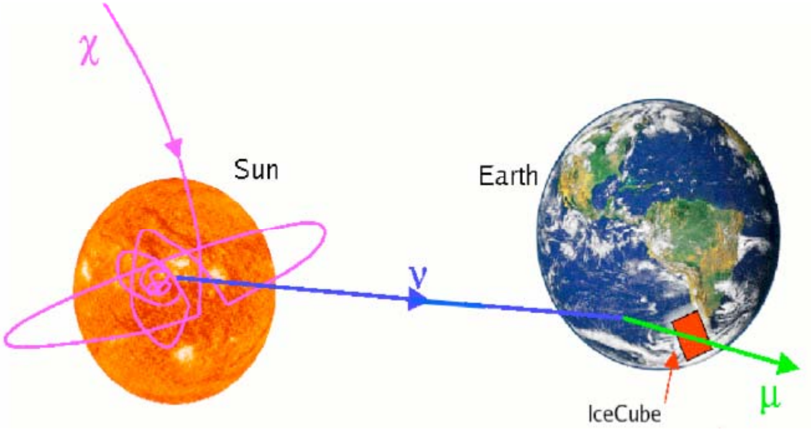
Aloha!

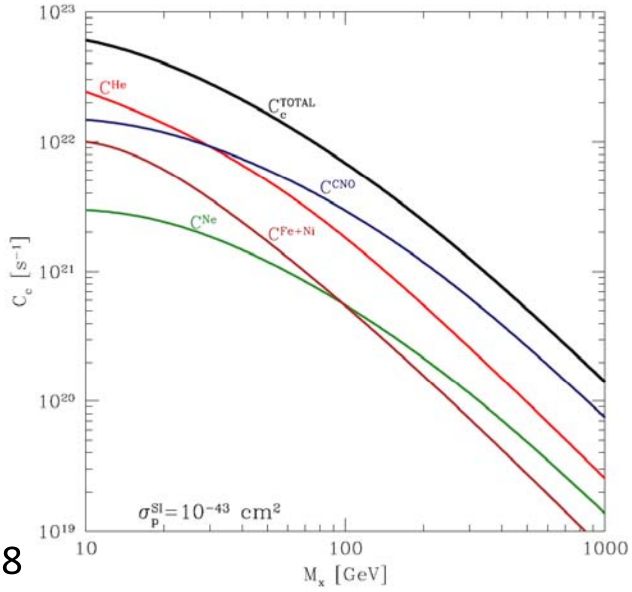
Back-up slides

neutrinos from the sun

- basic idea
  - DM scatters off solar nuclei, loses energy through elastic scattering
  - if it falls below escape velocity, captured
    - orbits, eventually collects in core
  - DM annihilates to SM matter
  - SM matter showers off neutrinos → seen at detector
  - DM in equilibrium → $\Gamma_C = 2\Gamma_A$
  - so neutrino event rate probes DM capture rate (and σ_{SI} ,σ_{SD})
- heavy elements dominate for SI
  - hydrogen dominates for SD

Dawn Williams





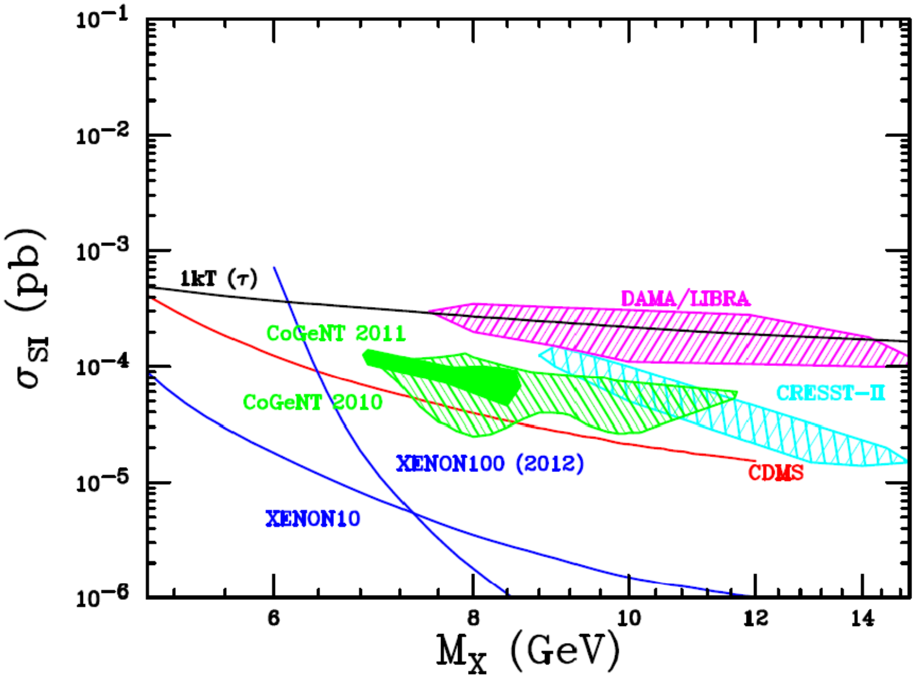
A. Zentner, arXiv:0907.3448

ν_μ or ν_e?

- dark matter searches at neutrino detectors typically use ν_μ
  - the big advantage is the long range of the muon
  - through-going muons allow you to use an effective volume which is much larger than the volume of the detector itself
- but less useful for low-mass dark matter
  - for low-mass dark matter, the muons are less energetic, so they don’t go as far anyway
- from the volume standpoint, electron neutrinos are just as good
- but the atmospheric neutrino background is much smaller for ν_e
- try to reconstruct $e^\pm$ shower direction (won’t go into the exp. issues)
  - water Cherenkov
  - liquid scintillator → try to reconstruct shower direction from photon timing
  - liquid argon

sensitivity to σ_{SI}

assume annihilation to τ channel
search for energetic electron neutrinos
2135 live days (1 kT target)

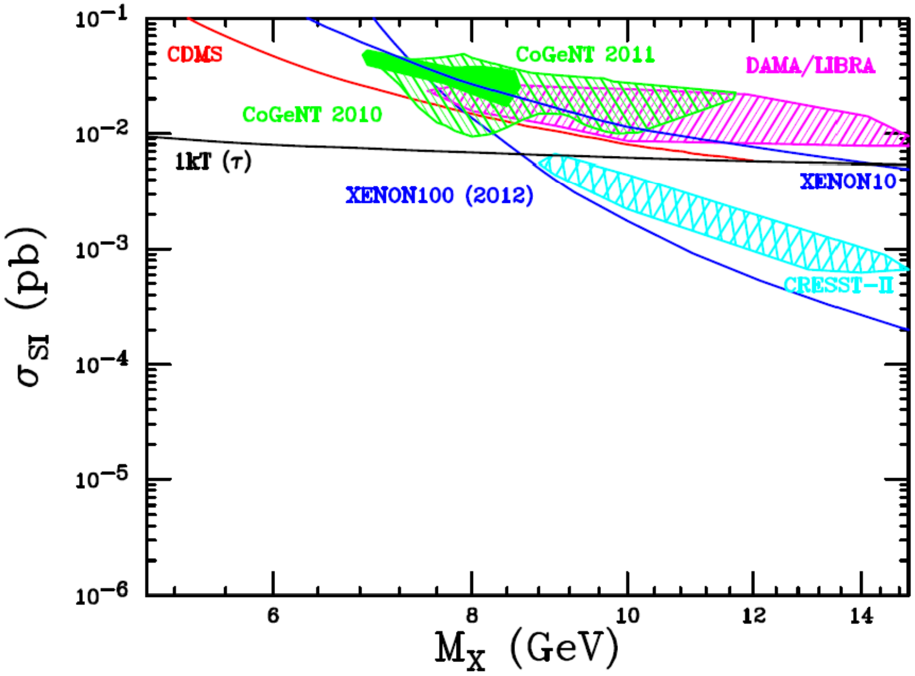


$f_n / f_p = 1$

low-neutron nuclei in sun complement
high-neutron direct detection targets for
IVDM ...

figures courtesy of Stefanie Smith

1103.3270



$f_n / f_p = -0.7$

details of KamLAND analysis

$$R = \Gamma_A \times \frac{\sigma_{\nu N}(m_X) \times N_A}{4\pi R^2} \times \langle Nz \rangle$$

$$\rho = 0.3\ \mathrm{GeV/cm^3}$$

$$\bar{v} = 270\ \mathrm{km/s}$$

$$\sigma_{\nu N} \approx 6.66 \times 10^{-3}\,\mathrm{pb}\left(\frac{E_\nu}{\mathrm{GeV}}\right)$$

$$\sigma_{\bar{\nu} N} \approx 3.25 \times 10^{-3}\,\mathrm{pb}\left(\frac{E_\nu}{\mathrm{GeV}}\right)$$

(Edsjö)

$$\theta_{\mathrm{cone}} = 20^\circ \sqrt{\frac{10\ \mathrm{GeV}}{E_\nu}}$$

"fully-contained" ≡ 10 radiation lengths within inner detector

$$R = \text{earth-sun distance}$$

$$\approx 1.5 \times 10^{11}\,\text{meters}$$

$$N_A = \text{number of detector nucleons}$$

long-range interactions

- assume capture within Jupiter's orbit
  - needed to cut off Rutherford scattering divergence
- for CDMS estimate, assume Gaussian form factor
  - for Ge and E_R of interest, differs from Helm form factor by <7%
- assume efficiency of analysis band is independent of E_R
  - best assumption we can make

$$C^{\mathrm{bound}} = \sigma_p^{\mathrm{bound}} m_{\mathrm{Ge}}^2 \frac{\int_0^{v_{\mathrm{esc}}} du\left[f(u)/u\right] w^2 E_{\mathrm{max}}^{-1} \int_{E_{\mathrm{thr}}}^{E_{\mathrm{max}}} dE_R \left|F_{\mathrm{Ge}}\left(E_R\right)\right|^2}{\int_0^{v_{\mathrm{esc}}} du\left[f(u)/u\right] w^2 \int_{E_{\mathrm{thr}}}^{E_{\mathrm{max}}} dE_R \left|F_{\mathrm{Ge}}\left(E_R\right)\right|^2 / E_R^2}$$

$$w^2 = u^2 + v_{\mathrm{sun}}^2 + v_{\mathrm{earth}}^2$$

$$v_{\mathrm{sun}} = 42.1\ \mathrm{km/s}$$

$$v_{\mathrm{earth}} = 11.2\ \mathrm{km/s}$$

$$v_{\mathrm{esc}} \sim 600\ \mathrm{km/s}$$

$$E_{\mathrm{thr}} = 2\ \mathrm{keV}$$

$$E_{\mathrm{max}} = \frac{2 m_X^2 m_{\mathrm{Ge}}}{\left(m_X + m_{\mathrm{Ge}}\right)^2} w^2$$

complementary γ-ray bounds from dwarf spheroidal galaxies

- Fermi-LAT search for photons from dwarf spheroidal galaxies (1108.2914,1108.3546)
  - very good at low mass
- very little baryonic matter
  - small background
- systematic uncertainty arising from density profile uncertainty
  - can strengthen bounds by ×10, but only weaken by ×2
  - only issue for very steep profiles
- also anti-proton flux bounds, but more uncertain (×50) →
  - 1108.0664

$$\Phi_{PP} \equiv \frac{\langle \sigma_A v \rangle}{8\pi m_X^2} \int_{E_{thr}}^{m_X} \sum_f B_f \frac{dN_f}{dE} dE$$

$$\Phi_{PP} \le 5.0^{+4.3}_{-4.5} \times 10^{-30}\ \text{cm}^3\ \text{s}^{-1}\ \text{GeV}^{-2}$$

1108.2914

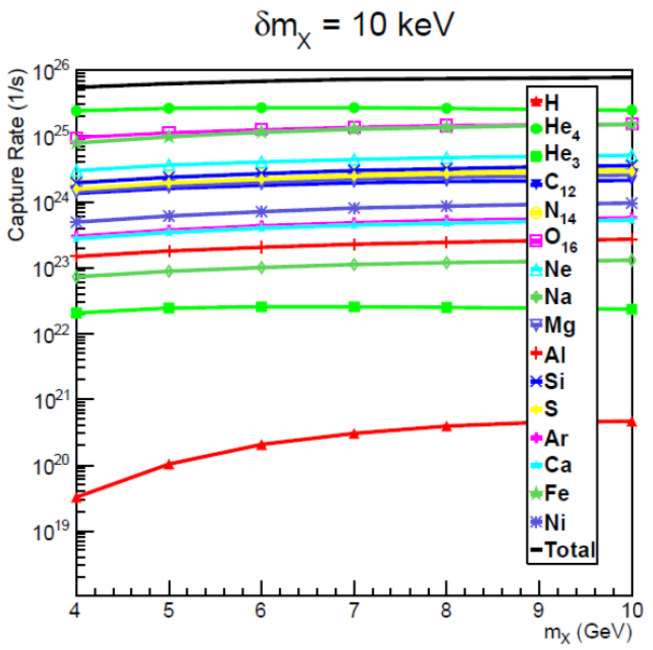
$$E_{thr} = 1\ \text{GeV}$$

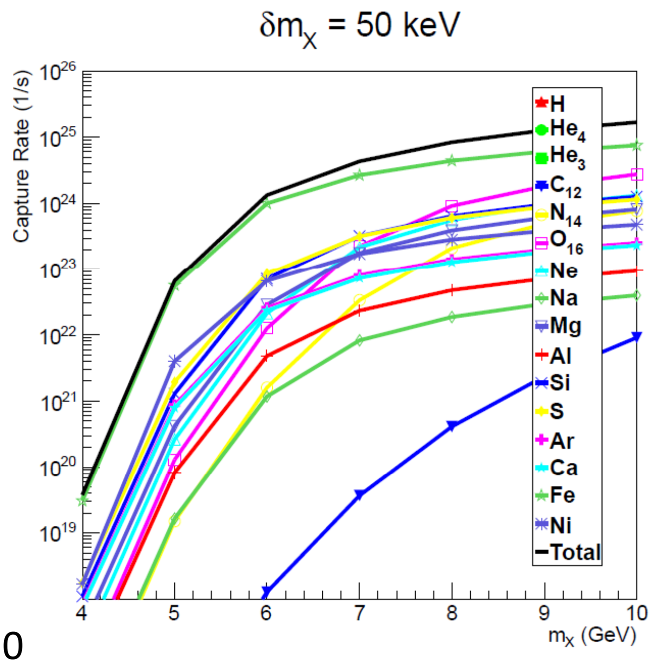
95% CL bound from “stacked” analysis of several Milky Way satellites

- cosmic ray propagation
- background
- solar modulation

Inelastic DM

- not necessarily about DAMA!...
  - generic possibility of splitting in the dark sector
  - XN→X'N matrix element basically same as elastic
  - kinematics very different
- neutrino detectors have interesting role
  - $K_{cm} = (1/2)\mu_A v^2 \geq \delta m_X$
  - gravitational infall increases kinetic energy (~×10)
    - v_{esc} ~ 600 km/s at surface
    - can probe models inaccessible to earth-based detectors
  - lighter elements decouple first





1204.5120