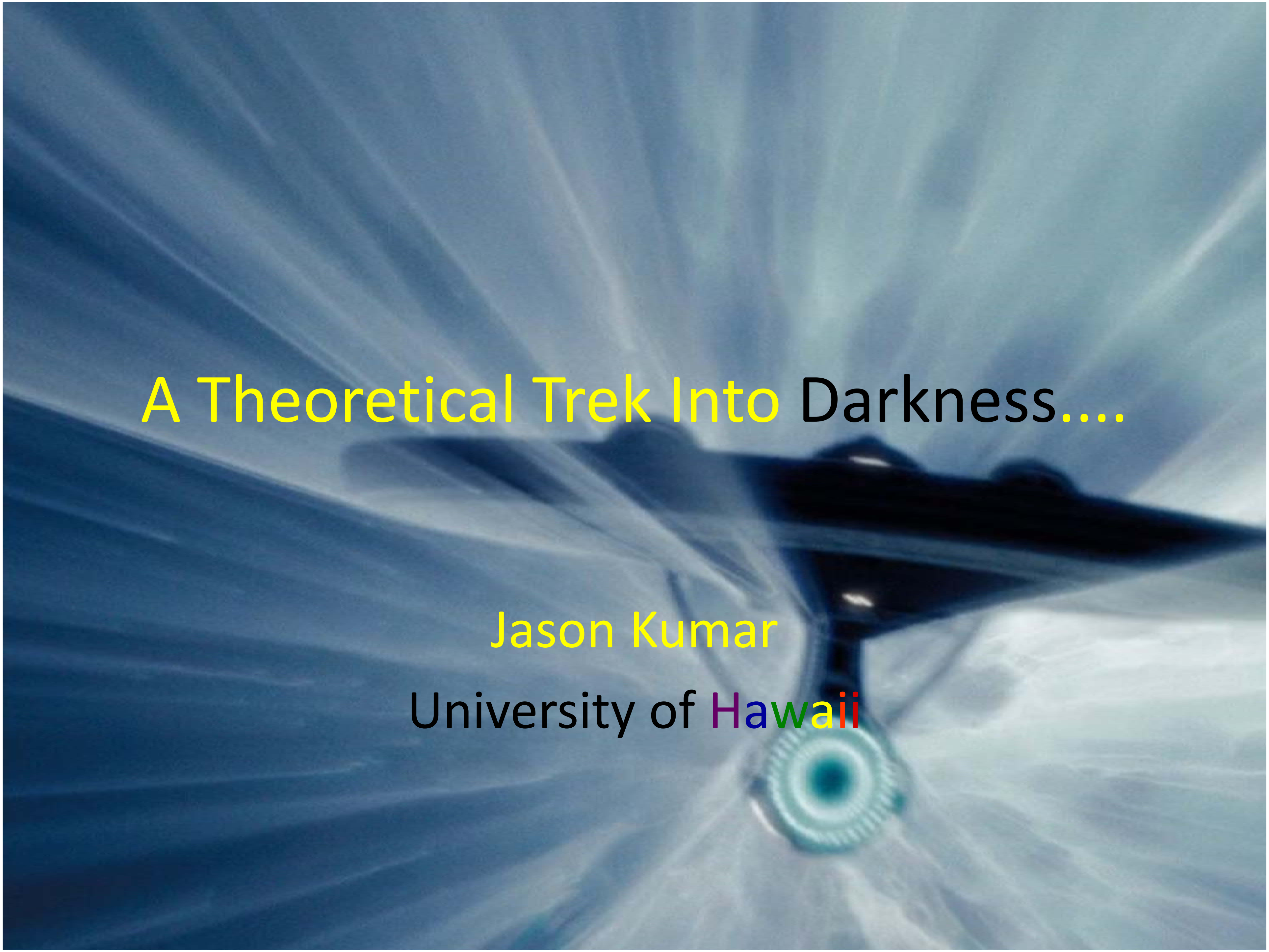

A Theoretical Trek Into Darkness….

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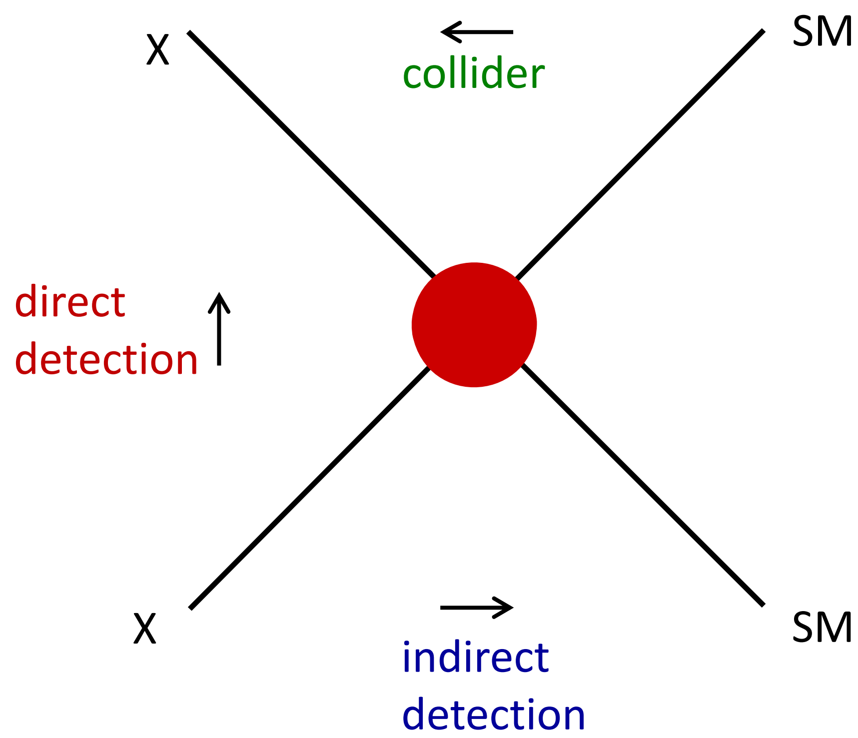
- 1112.4849, 1303.2384, 1305.1611, 13xx.xxxx, 13xx.xxxx

searching for dark matter....

- usually start with some standard assumptions about dark matter interactions
  - single particle candidate (Majorana fermion)
  - 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 do the roles 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.
- collider search
  - dark matter produced at the LHC
- quantum matrix elements for all three processes related by crossing symmetry
- allows us to probe dark matter interaction structure with multiple approaches



issue: models and searches

- there is already a host of uncertainties
  - astrophysics → uncertainties in velocity distribution
  - nuclear physics → uncertainties in nucleon structure affect scattering
  - I'll focus on the remaining particle physics uncertainties...
- ... arise from the 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

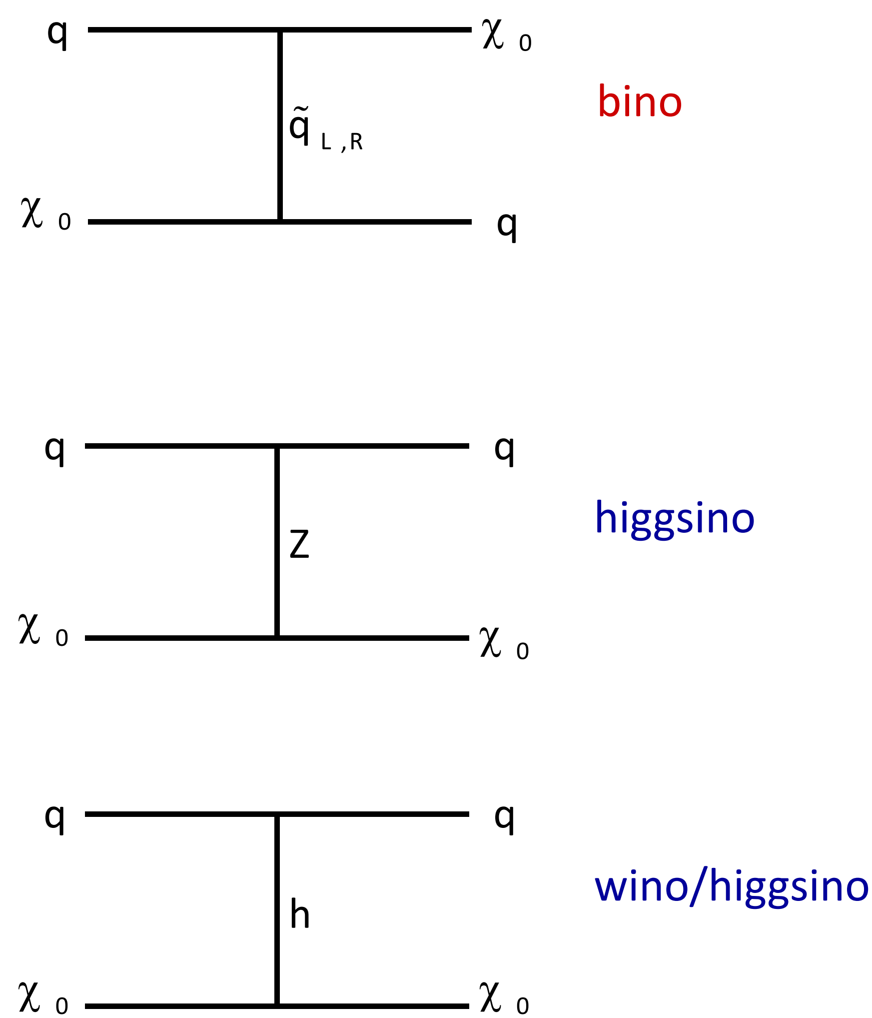
low-mass dark matter

- hints from DAMA, CoGeNT, CRESST, CDMS-Si could be DM
  - 5-20 GeV
  - light for MSSM WIMPs
- XENON100 is not seeing a signal
  - could be a background....
- experimental issues still under study
  - 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
  - need $\mathcal{O}$(keV) threshold
  - challenging for experiments aimed at WIMPs
  - other detection strategies?
- assumptions play a role in interpretation of the data
  - need to keep track of the options
- start with Isospin-Violating Dark Matter
  - LSP interactions are assumed isospin-invariant, but why?

why are LSP interactions isospin-invariant?

- if dark matter is mostly bino
  - scatters by squark exchange
  - coupling (Y) is isospin-violating
  - SI term arises from squark-mixing
    - small for first generation quarks in minimal flavor violation
- 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
    - $m_u \sim m_d \ll m_p$




really needed three fairy godmothers!....

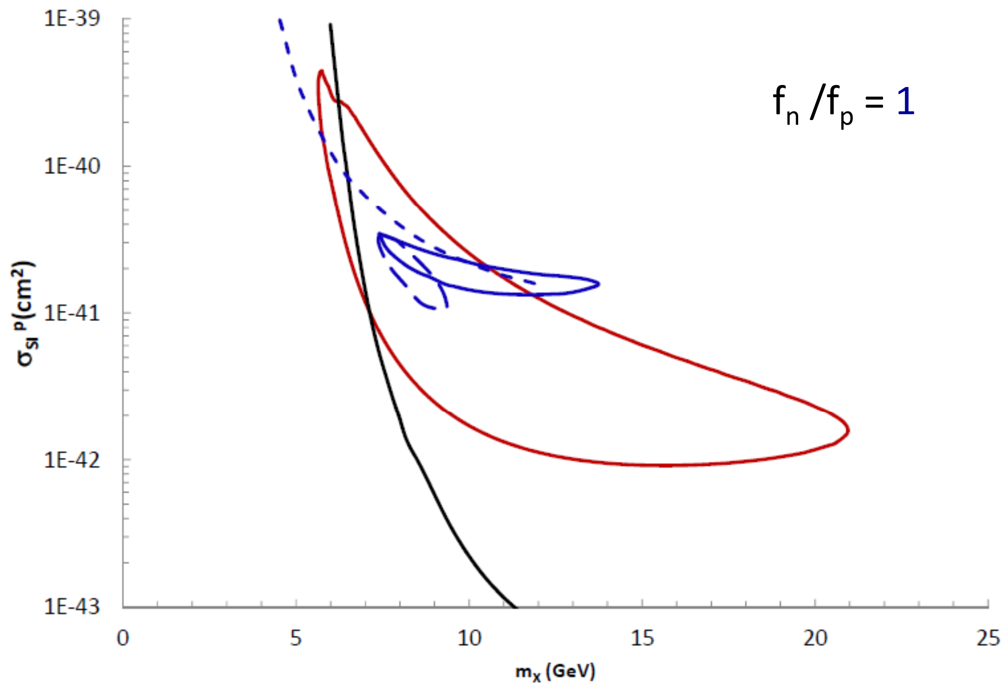
IVDM

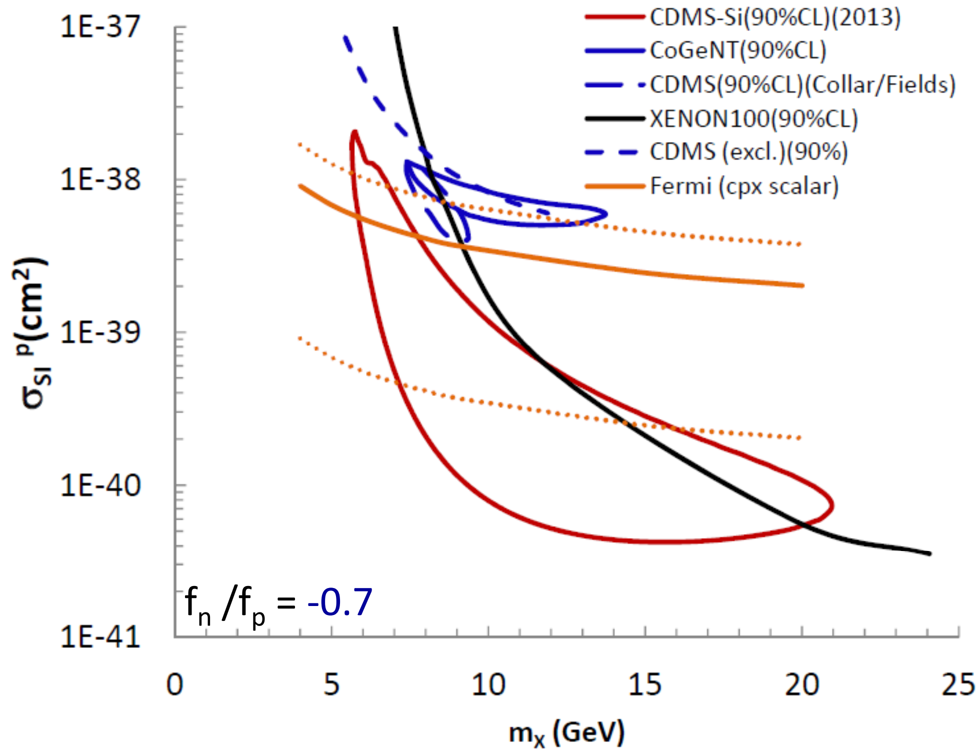
consider low mass as a test case!

- direct detection bounds normalized to nucleon (f_n / f_p = 1)
  - big change if f_n / $f_p \neq 1$
- consider f_n / f_p = -0.7
  - see CLPWY (1004.0697)
  - FKMS (1102.4331)
  - target isotopes, NLO (1205.2695) important
- if m_X small, no reason for $f_n = f_p$
  - must account for this possibility!

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

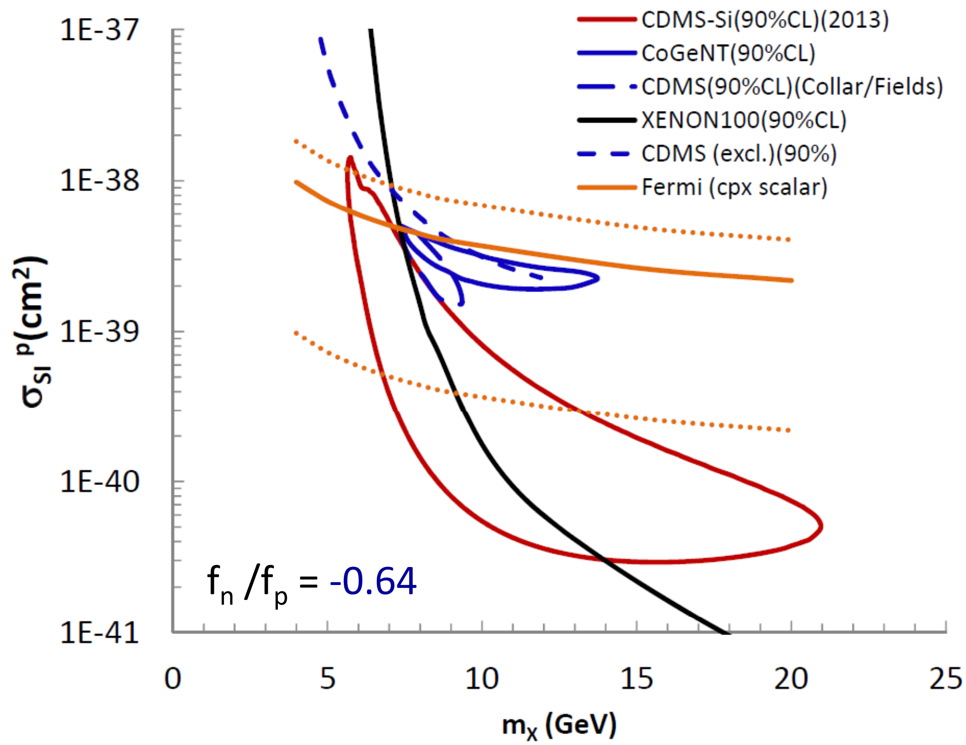
$$\sigma_p = \frac{\mu_p^2 f_p^2}{M_*^4}$$

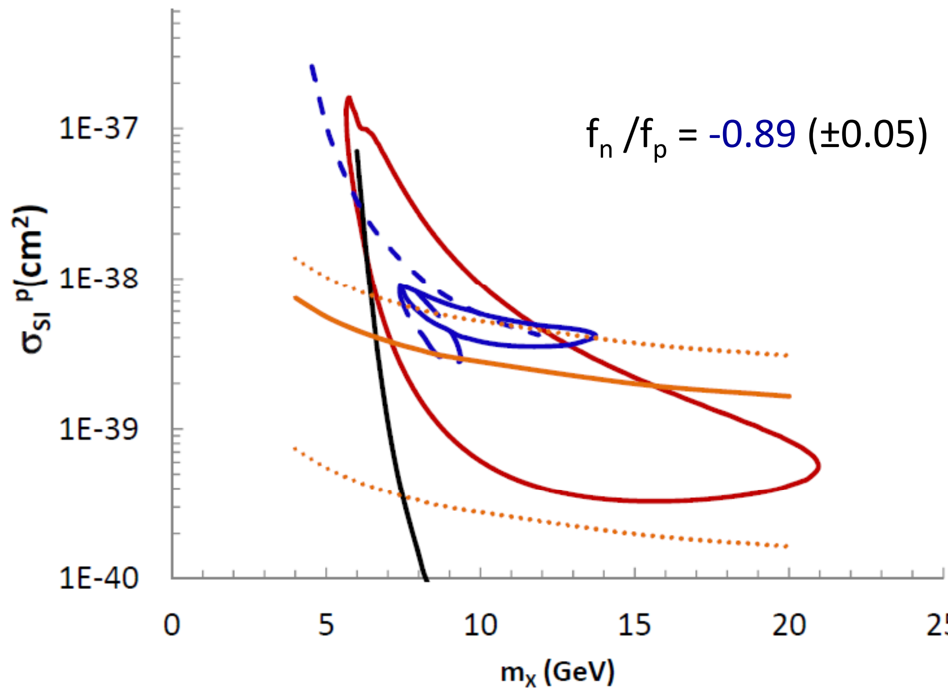




multiple experiments

- suppose there is a real dark matter signal from multiple experiments with different target
- define
  - $F_Z = \sigma_p / \sigma_N^Z$, $R[Z_1,Z_2] = F_{Z_2}/F_{Z_1}$
  - two signals amount to a measurement of $R[Z_1,Z_2]$
- quadratic equation for f_n / f_p
- can determine f_n / f_p up to a two-fold ambiguity
- need a third target material to resolve the ambiguity
- complementary searches useful
  - need a framework



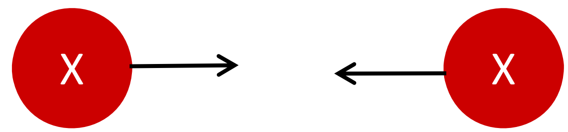


matrix element approach

- worth thinking about a general approach to dark interactions
- consider a dark matter – Standard Model interaction structure
  - $\Gamma_X \Gamma_f F(s, t, u)$
  - Γ_X and Γ_f are dark matter and SM bilinears (might need a Fierz trans.)
  - F is an interaction form factor (F=1 for a pure contact interaction)
- matrix element for scattering, annihilation and production all arise from this interaction structure
  - all related by crossing symmetry
- what do we want to know about this structure regarding scattering?
  - spin-independent vs. spin-dependent
  - $f_n / f_p = ?$
  - suppressed by factors of q or $v^\perp$?
    - direct detection sensitivity is already very good and getting better, so reasonable models with suppressed scattering are coming into range

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



$\Delta E \sim 2m_X$

$$\left|spin-0\right\rangle \propto 1$$

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

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

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

$\sim E$

matrix element analysis

also gluon couplings, etc. ....

Name	Interaction Structure	$\sigma_{\rm SI}$ suppression	$\sigma_{\rm SD}$ suppression	s-wave?
F1	$\bar{X}X\bar{q}q$	1	$q^2 v^{\perp 2}$ (SM)	No
F2	$\bar{X}\gamma^5 X\bar{q}q$	q^2 (DM)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	Yes
F3	$\bar{X}X\bar{q}\gamma^5 q$	0	q^2 (SM)	No
F4	$\bar{X}\gamma^5 X\bar{q}\gamma^5 q$	0	q^2 (SM); q^2 (DM)	Yes
F5	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$ (vanishes for Majorana X)	1	$q^2 v^{\perp 2}$ (SM) q^2 (SM); q^2 or $v^{\perp 2}$ (DM)	Yes
F6	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$	$v^{\perp 2}$ (SM or DM)	q^2 (SM)	No
F7	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5 q$ (vanishes for Majorana X)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	$v^{\perp 2}$ (SM) $v^{\perp 2}$ or q^2 (DM)	Yes
F8	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu\gamma^5 q$	$q^2 v^{\perp 2}$ (SM)	1	$\propto m_f^2/m_X^2$
F9	$\bar{X}\sigma^{\mu\nu}X\bar{q}\sigma_{\mu\nu}q$ (vanishes for Majorana X)	q^2 (SM); q^2 or $v^{\perp 2}$ (DM) $q^2 v^{\perp 2}$ (SM)	1	Yes
F10	$\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu}q$ (vanishes for Majorana X)	q^2 (SM)	$v^{\perp 2}$ (SM) q^2 or $v^{\perp 2}$ (DM)	Yes

a general model can interact through multiple structures...
interference effects for both annihilation and scattering.

spin-0 and spin-1

S1	$\phi^\dagger\phi\bar{q}q$ or $\phi^2\bar{q}q$	1	$q^2 v^{\perp 2}$ (SM)	Yes
S2	$\phi^\dagger\phi\bar{q}\gamma^5 q$ or $\phi^2\bar{q}\gamma^5 q$	0	q^2 (SM)	Yes
S3	$\phi^\dagger\partial_\mu\phi\bar{q}\gamma^\mu q$	1	$q^2 v^{\perp 2}$ (SM) q^2 (SM); $v^{\perp 2}$ (DM)	No
S4	$\phi^\dagger\partial_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$	0	$v^{\perp 2}$ (SM or DM)	No
V1	$B^\dagger_\mu B^\mu\bar{q}q$ or $B_\mu B^\mu\bar{q}q$	1	$q^2 v^{\perp 2}$ (SM)	Yes
V2	$B^\dagger_\mu B^\mu\bar{q}\gamma^5 q$ or $B_\mu B^\mu\bar{q}\gamma^5 q$	0	q^2 (SM)	Yes
V3	$B^\dagger_\nu\partial_\mu B^\nu\bar{q}\gamma^\mu q$	1	$q^2 v^{\perp 2}$ (SM) q^2 (SM); $v^{\perp 2}$ (DM)	No
V4	$B^\dagger_\nu\partial_\mu B^\nu\bar{q}\gamma^\mu\gamma^5 q$	0	$v^{\perp 2}$ (SM or DM)	No
V5	$(B^\dagger_\mu B_\nu - B^\dagger_\nu B_\mu)\bar{q}\sigma^{\mu\nu}q$	$q^2 v^{\perp 2}$ (SM)	1	Yes
V6	$(B^\dagger_\mu B_\nu - B^\dagger_\nu B_\mu)\bar{q}\sigma^{\mu\nu}\gamma^5 q$	q^2 (SM)	$v^{\perp 2}$ (SM)	Yes
V7	$B^\dagger_\nu\partial^\nu B_\mu\bar{q}\gamma^\mu q$ or $B_\nu\partial^\nu B_\mu\bar{q}\gamma^\mu q$	$v^{\perp 2}$ (SM); q^2 (DM)	q^2 (SM); q^2 (DM)	No
V8	$B^\dagger_\nu\partial^\nu B_\mu\bar{q}\gamma^\mu\gamma^5 q$ or $B_\nu\partial^\nu B_\mu\bar{q}\gamma^\mu\gamma^5 q$	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	q^2 (DM)	$\propto m_f^2/m_X^2$
V9	$\epsilon^{\mu\nu\rho\sigma}B^\dagger_\nu\partial_\rho B_\sigma\bar{q}\gamma_\mu q$ or $\epsilon^{\mu\nu\rho\sigma}B_\nu\partial_\rho B_\sigma\bar{q}\gamma_\mu q$	$v^{\perp 2}$ (DM or SM)	q^2 (SM)	No
V10	$\epsilon^{\mu\nu\rho\sigma}B^\dagger_\nu\partial_\rho B_\sigma\bar{q}\gamma_\mu\gamma^5 q$ or $\epsilon^{\mu\nu\rho\sigma}B_\nu\partial_\rho B_\sigma\bar{q}\gamma_\mu\gamma^5 q$	$q^2 v^{\perp 2}$ (SM)	1	No

for spin-1 dark matter, longitudinal polarizations give (E / m_X) enhancement for collider production

new frontiers...

- a few unusual things immediately appear from this analysis
- s-wave annihilation from Majorana fermion dark matter to light SM fermions is **not** always chirality-suppressed
  - only if interaction is through time-component of pseudovector SM bilinear
  - interesting IVDM connection
    - to get SI-scattering from squark exchange, need sfermion mixing
    - usually assumed to be proportional to quark mass, but need not be
    - if 1^{st} gen. sfermion-mixing sizeable, can get IVDM for Majorana fermion DM
    - also get interaction structure (F4) which permit unsuppressed s-wave annihilation
- XX → hh (Majorana fermion) need not be p-wave suppressed
  - could have s-wave annihilation, but need CP-violation
- for some interactions (pseudoscalar exchange, or pseudovector exchange with spin-0 dark matter), SI scattering matrix element vanishes
- if new physics introduces CP-violation, many new interesting features

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. ....

as an example....

suppose we see spin-independent scattering with no momentum or velocity suppression....

	σ_{SD}	s-wave?	collider enhancement
$\bar{X}X\bar{q}q$	$q^2 v^{\perp 2}$	No	$(E / m_X)^2$
$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$	$q^2 v^{\perp 2}$	Yes	$(E / m_X)^2$
$\phi^\dagger\phi\bar{q}q$	$q^2 v^{\perp 2}$	Yes	1
$i\,\mathrm{Im}(\phi^\dagger\partial_\mu\phi)\bar{q}\gamma^\mu q$	$q^2 v^{\perp 2}$	No	$(E / m_X)^2$
$B_\mu B^\mu\bar{q}q$	$q^2 v^{\perp 2}$	Yes	$(E / m_X)^4$
$i\,\mathrm{Im}\left(B_\nu^\dagger\partial_\mu B^\nu\right)\bar{q}\gamma^\mu q$	$q^2 v^{\perp 2}$	No	$(E / m_X)^4$

combining direct, indirect and collider searches goes a long way towards isolating the interaction structure....

outlook

- direct detection sensitivity already at levels several orders of magnitude better than the “nominal” WIMP scattering cross-section (10^{-40} cm^2)
  - if momentum/velocity-suppressed, just approaching the sensitivity needed
  - structures with SD-scattering can be probed with suppressed SI-scat. as well
  - directional detection may separate momentum and velocity dependence
- lots of options for dark matter interactions
  - unless wedded to something very specific (like CMSSM), no way to choose
- but we get complementary information from direct detection, indirect detection and collider searches
- all data can help determine structure of dark matter interactions
- with new data coming and new theory frontiers, we should be prepared for exciting times ahead...

...or as Captain Kirk would say...


“Buckle up!”
- Captain James T. Kirk
and remember...

CosPA 2013

Nov. 12-15, 2013

Honolulu, USA

hosted by

the University of Hawaii

Aloha!

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

registration opens July 1....

Back-up slides

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 $\eta \propto \rho / m_X$

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

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

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

1108.2914

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

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

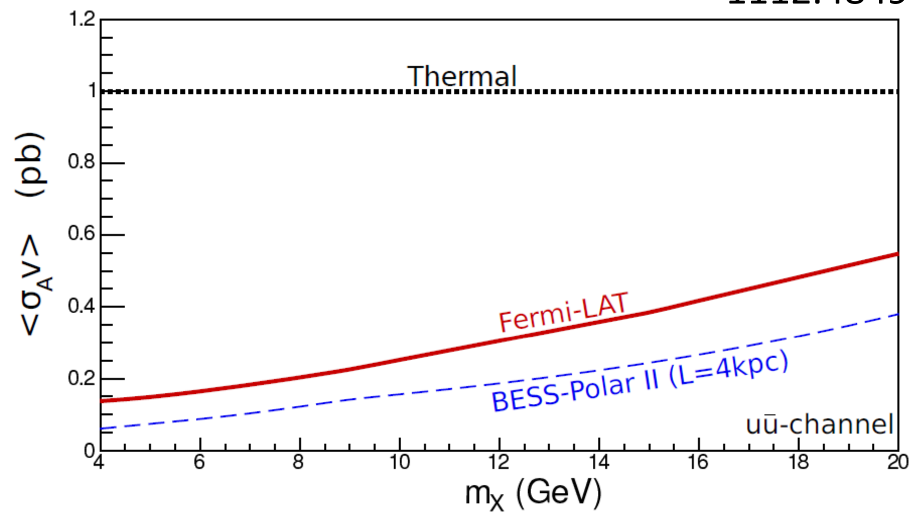
- cosmic ray propagation
- background
- solar modulation

Fermi-LAT and dwarf spheroidals

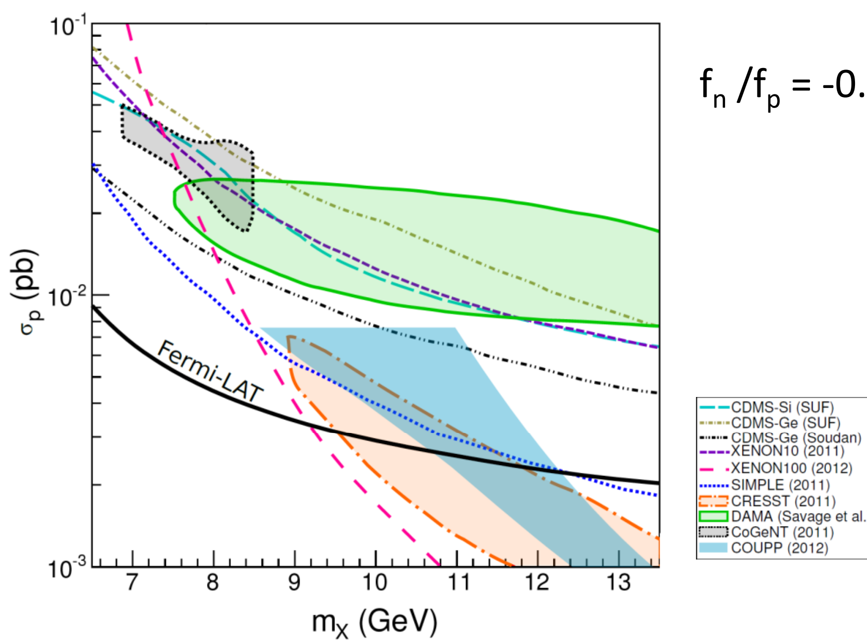
- less astrophysics uncertainty, less background
- for any matrix element, can translate from $\langle \sigma_{ann.} v \rangle$ to σ_{SI}
- example → annihilation to u/d-quarks only, fixed f_n/f_p
- consider elastic contact operators with spin-independent scattering and s-wave annihilation (unique!)
- 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



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)	$\sigma_p^{(ferm.)}$ (pb)	$\sigma_p^{(scal.)}$ (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, $f_n / f_p = -0.7$