Pitfalls of Dark Crossings

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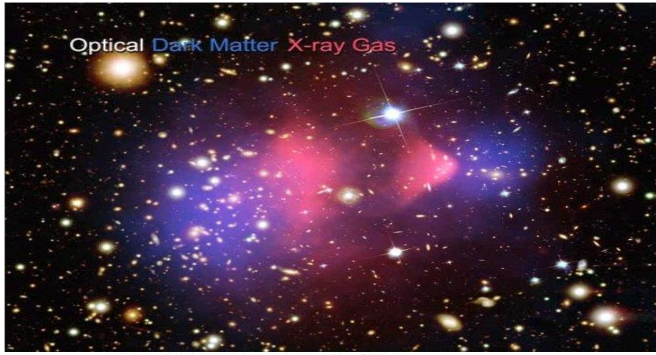
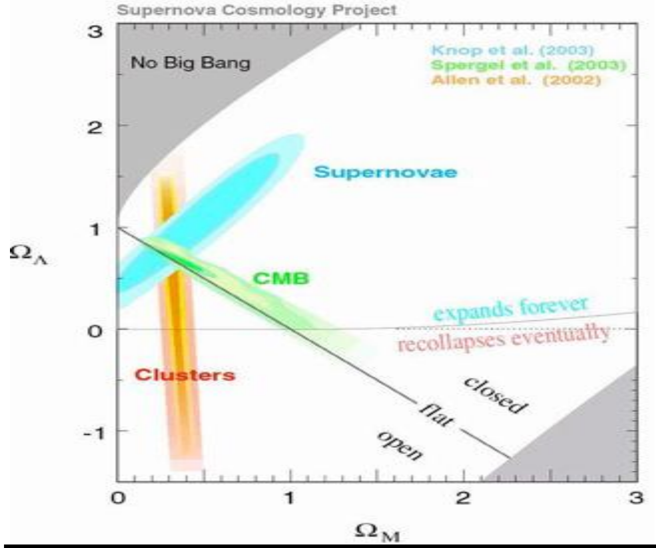
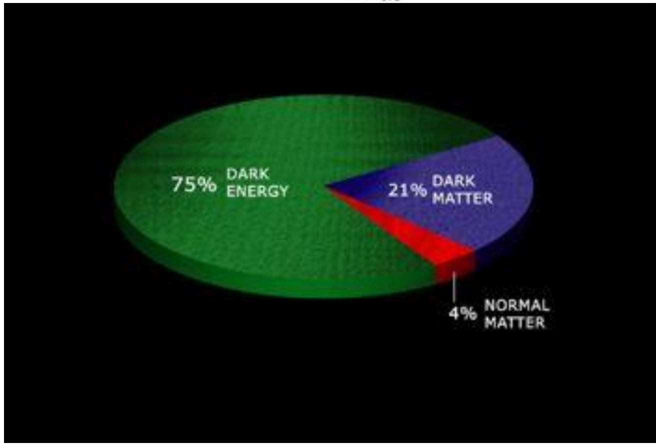
Dark Matter

- The evidence for dark matter is myriad and well-known.
- This evidence is one of the only truly experimental signs that we must have physics beyond the Standard Model.
- Cosmological observations tell us how much dark matter is needed to match observations.
- From the particle physics perspective, we're left asking what dark matter is and how it fits into a microscopic understanding of nature.





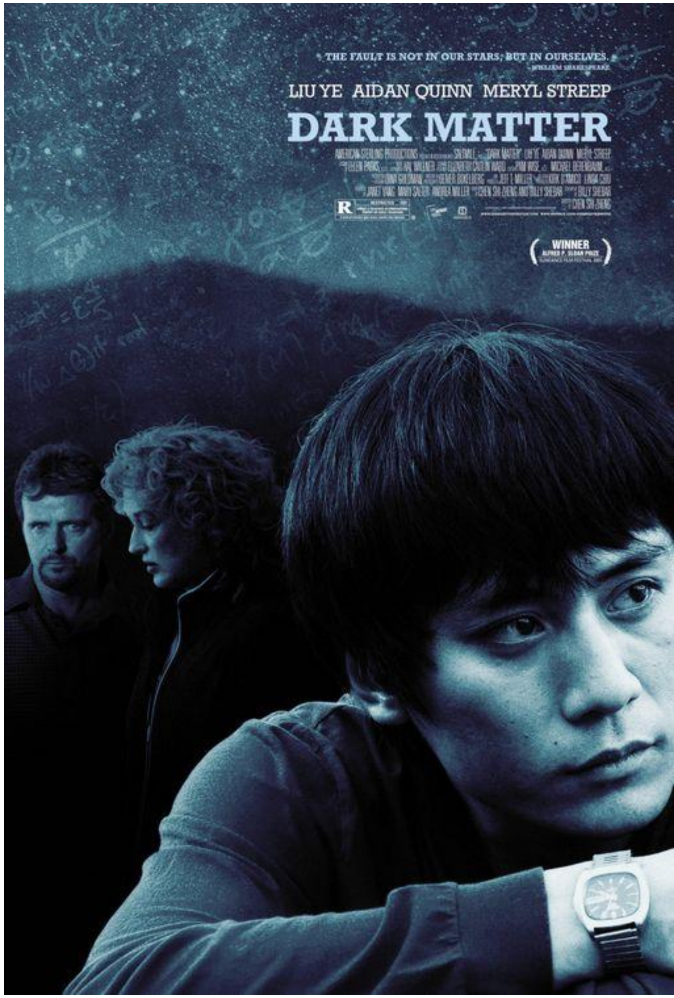


WIMP Dark Matter

- One of the most attractive proposals to explain dark matter is that it is a Weakly Interacting Massive Particle.
  - WIMPs naturally lead to the correct amount of dark matter in the universe.
  - WIMPs are automatic ingredients of many models of physics beyond the Standard Model, such as supersymmetric models.
- Instead of the usual approach of assuming a specific particle model for dark matter, I'll look for generic behavior common to all of them.

What We Know about WIMPs

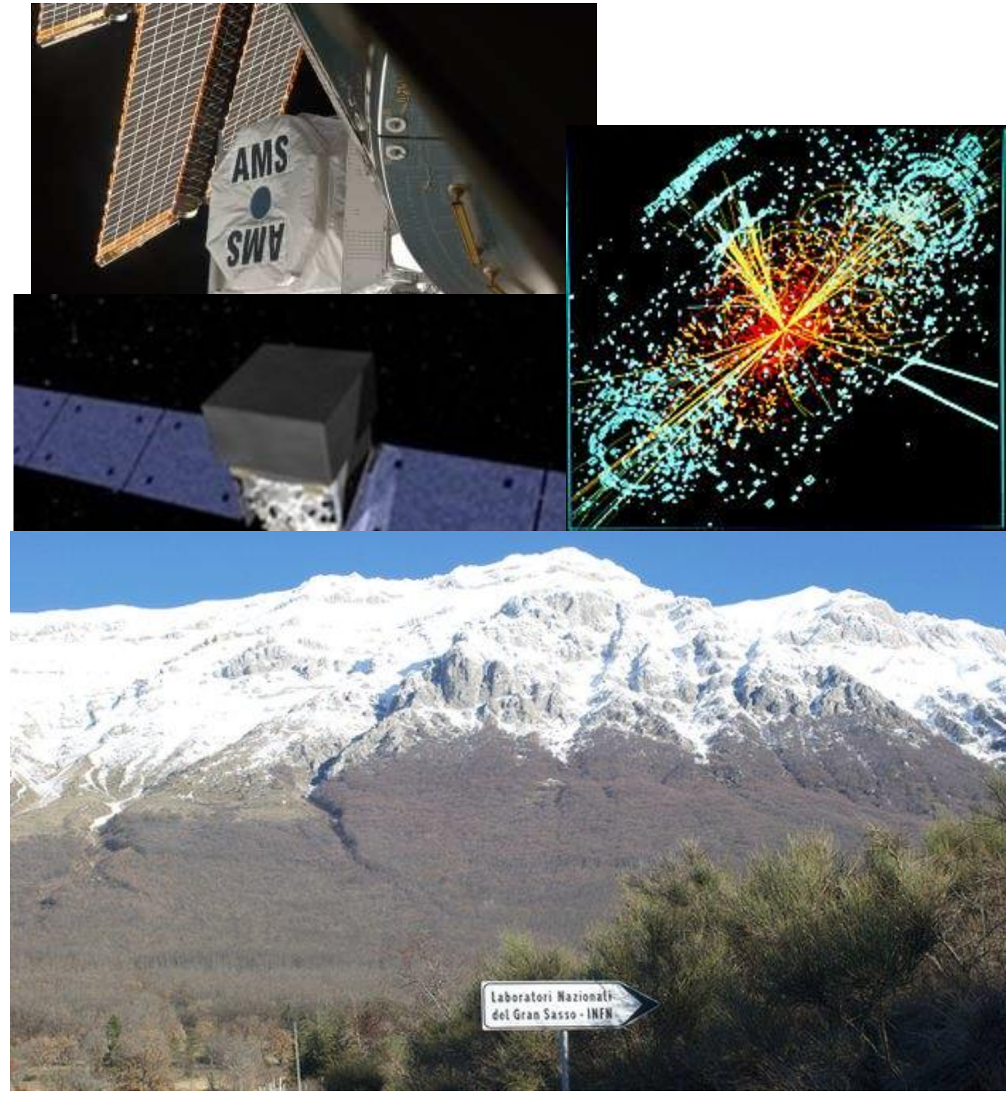
- Dark matter is, first of all, a new particle.
  - It is neutral, massive, and (at least cosmologically) stable.
- We still have a lot to learn (or guess at)
  - Spin
  - Electroweak charge
  - Self-conjugacy
- We want an understanding of all the possibilities if we hope to say anything true about dark matter in general.



WIMP Interactions

- When it comes to searching for dark matter, WIMPs are also quite exciting, since they have “strong” interactions with the Standard Model.
  - “Strong” means similar to electroweak strength here – much stronger than gravity.
  - The interesting point is that we can actually search for these particles outside gravitational observations.
  - A non-gravitational observation would teach us a lot.

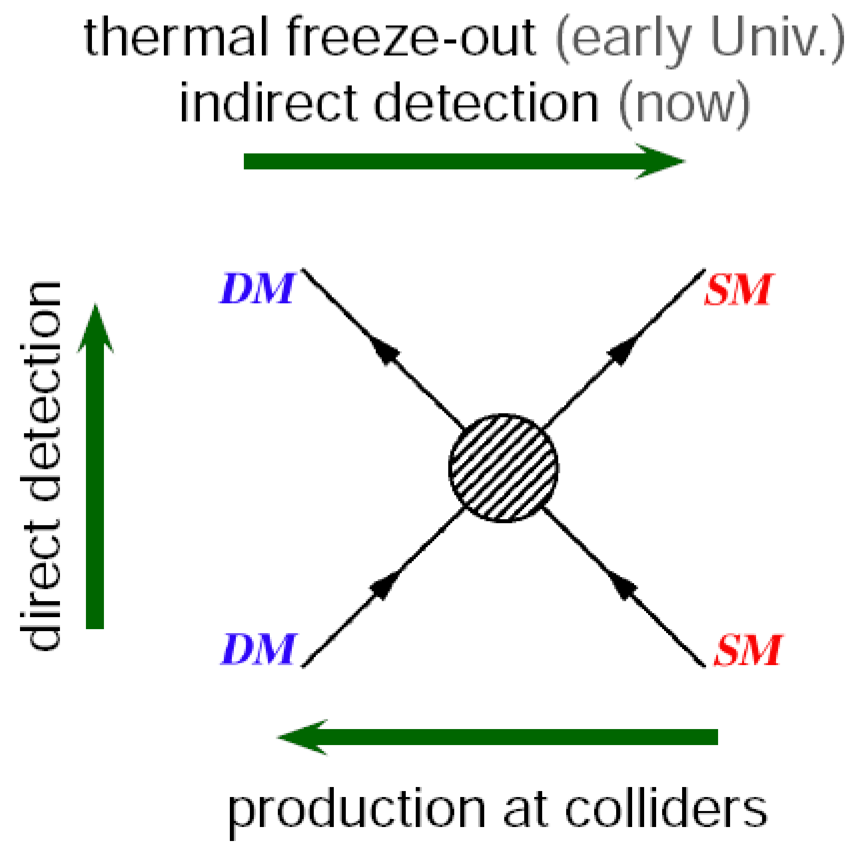
Dark Matter Searches



- We’re trying to find dark matter in many ways
  - Collider Production
  - Direct Detection
  - Indirect Detection
- We hope to understand how these are correlated

Crossing Symmetry Bedtime Story

- We may not understand the detailed dynamics of DM interactions, but we can think of them as some interaction, and look for it in different ways.
- Everything should be weak-scale, since we like the thermal WIMP.



Effective Theory

- We can hope to capture the physics of WIMP models in a way that is fairly insensitive to the details of the models themselves – effective theories give us a tool to try and do just that.
- As effective theories, they can only describe physics correctly within some energy range, and they have very specific assumptions built into them. Whether they work or not will depend on what kind of WIMP nature has given us for study.
- They provide a dictionary for studying the interactions of WIMPs with Standard Model fields. Using this dictionary we can translate results from one type of experiment onto the signal space of another.

Fundamental EFT Assumptions

- We have to make assumptions for the DM's:
  - Spin
    - I'll guess ½
  - Charges
    - SM singlet
  - Stability
    - Completely stable
  - Other spectrum
    - Let's guess everything else is very heavy
  - Coupling structure

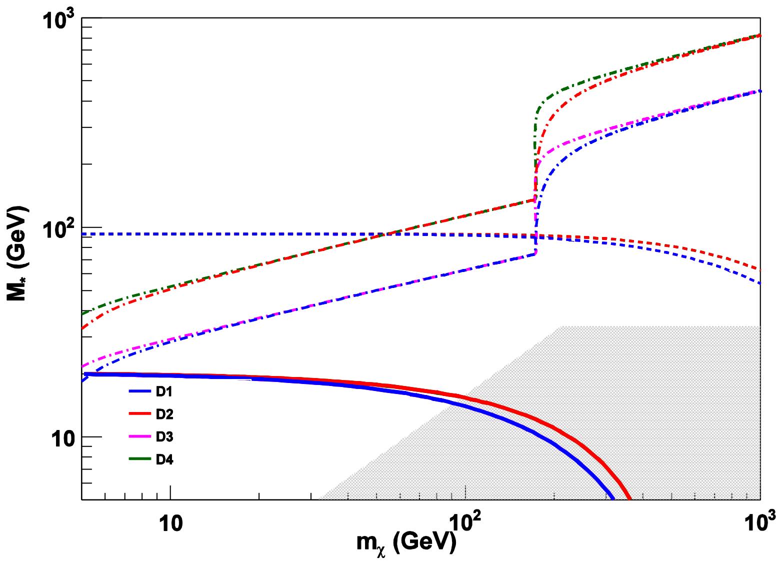
Coupling Structures

- Stability tells us we must have two DM fields in each interaction
- Gauge invariance is the additional remaining constraint
- Here I’ve given all couplings to hadronic matter
  - If I think the LHC has something to say, this is where it will be

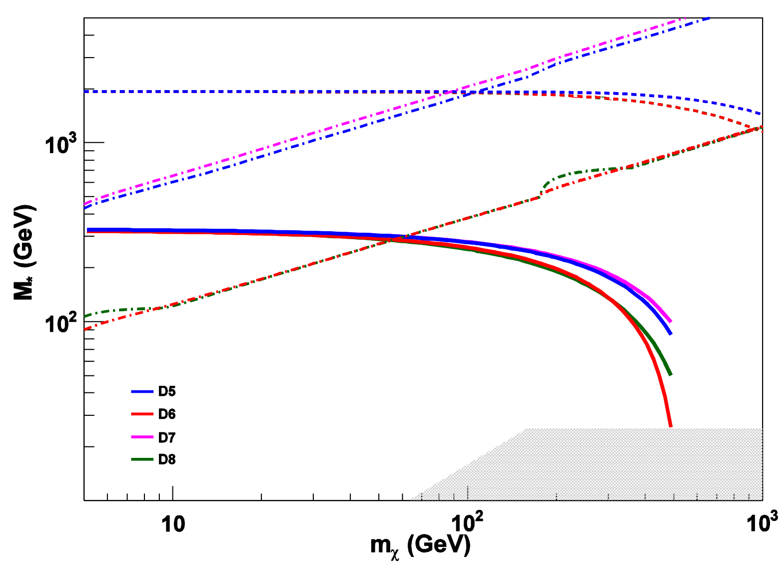
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

The Brothers Grimm Version

Scalar-type operators



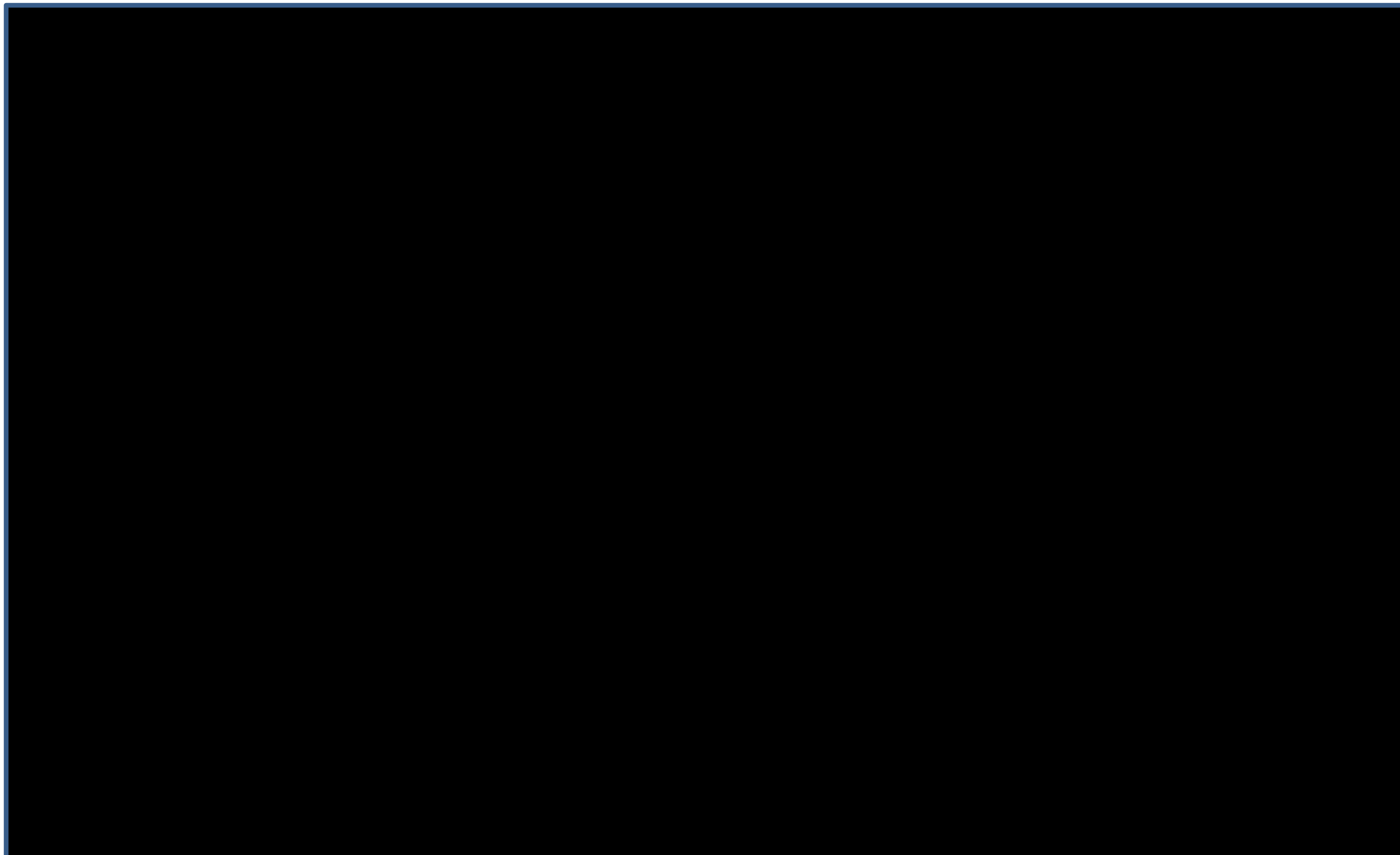
Vector-type operators



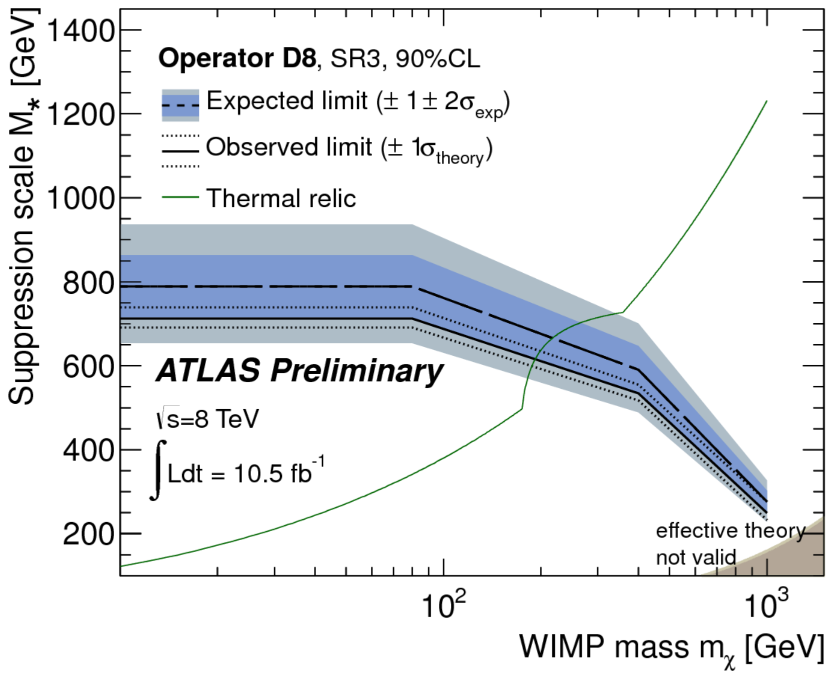
Collider production and annihilation have very different behaviors as I vary my choice of operators.

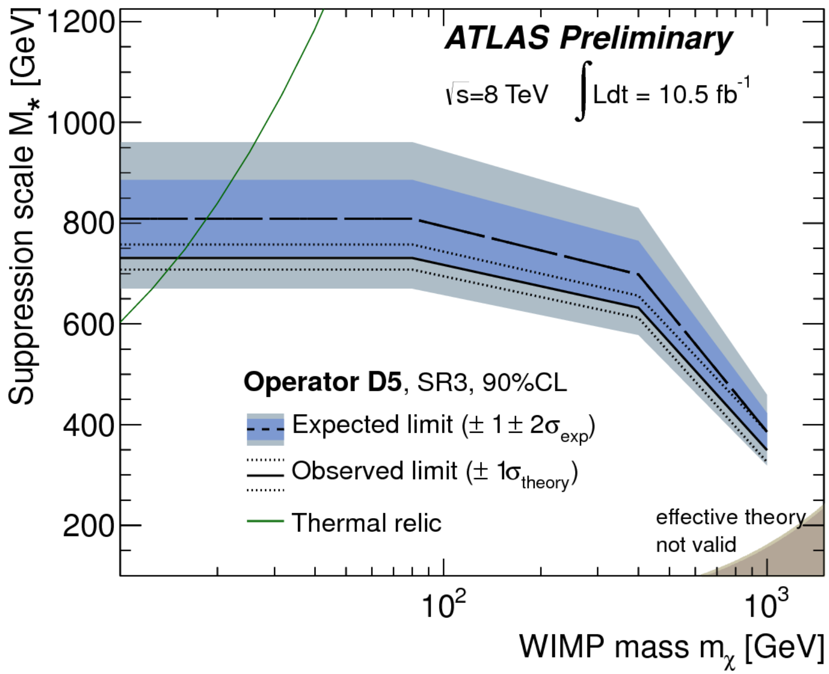
Goodman et al, 1008.1783

Perilous Bridges to Cross



Collider Searches





ATLAS-CONF-2012-147

Mapping to Direct Detection

- Since we have considered precisely the couplings of WIMPs to quarks and gluons, we can translate our bounds on effective operator couplings into bounds on the direct detection plane.
- There are two distinct classes of direct detection searches to compare with:
  - Spin-independent (SI) scattering looks for direct scattering of the WIMP from the nucleons in the nucleus.
  - Spin-dependent (SD) scattering looks for interactions coupling the WIMP's spin to that of the nucleus.
- We're more used to looking at the SI plane, because various predictions tell us that we'll see WIMPs there first due to the enhancement gained by scattering off of nucleon number rather than nucleon spin, which largely cancels in a nucleus.

Direct Detection

- Only certain operators contribute to WIMP scattering with a nucleus at zero velocity.
  - Three operators contribute to SI scattering.
  - Two operators contribute to SD scattering.
- We follow the usual procedure and quote WIMP-nucleon cross sections.
- Many operators have very weak direct detection bounds due to velocity suppression of the scattering.

Spin-independent:

$$\sum_q m_q \bar{q} q$$

$$\sum_q \bar{q}\gamma^\mu q$$

$$\alpha_s G^{a\,\mu\nu} G^a_{\mu\nu}$$

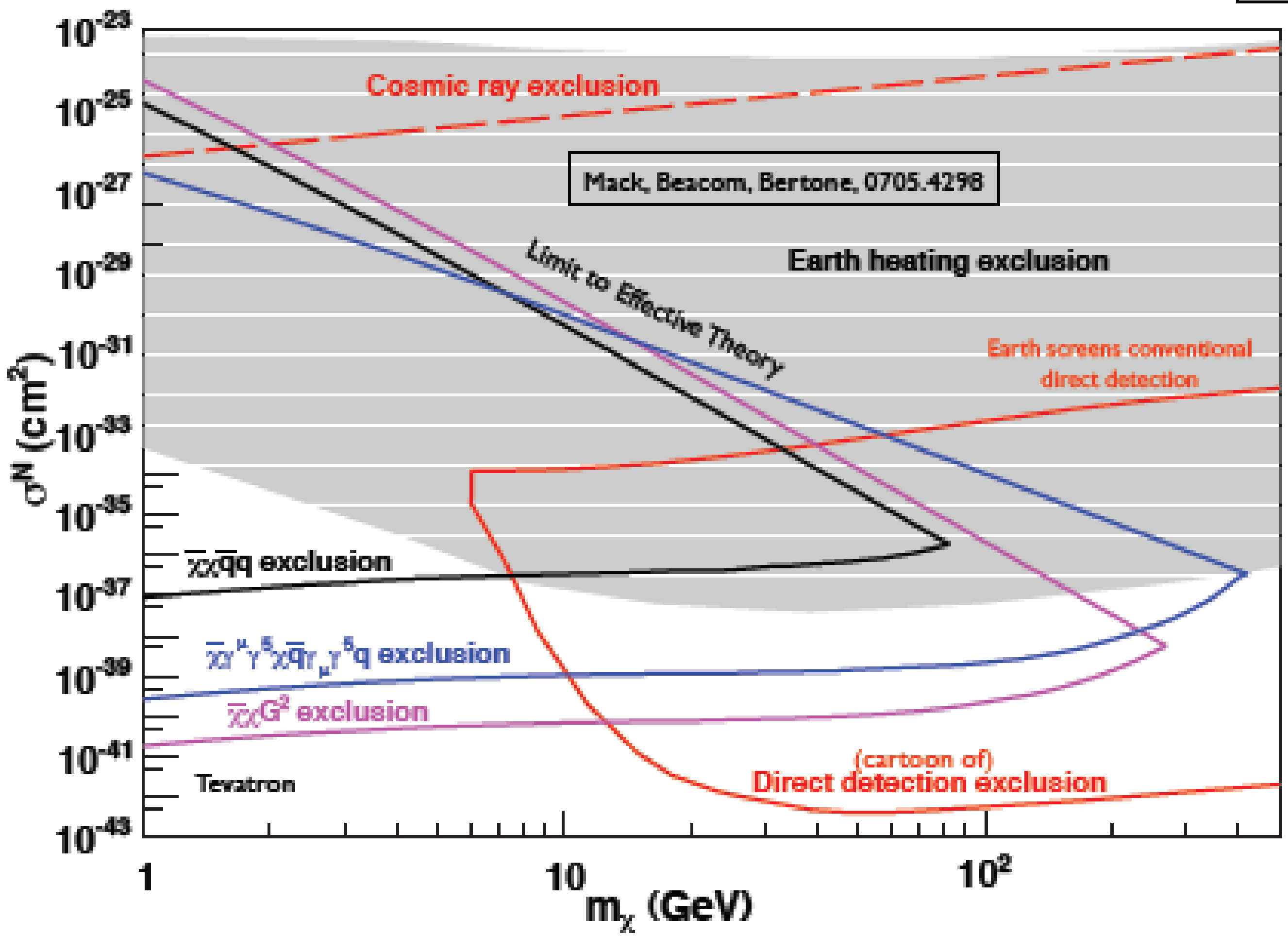
Spin-dependent:

$$\sum_q \bar{q}\gamma^\mu \gamma_5 q$$

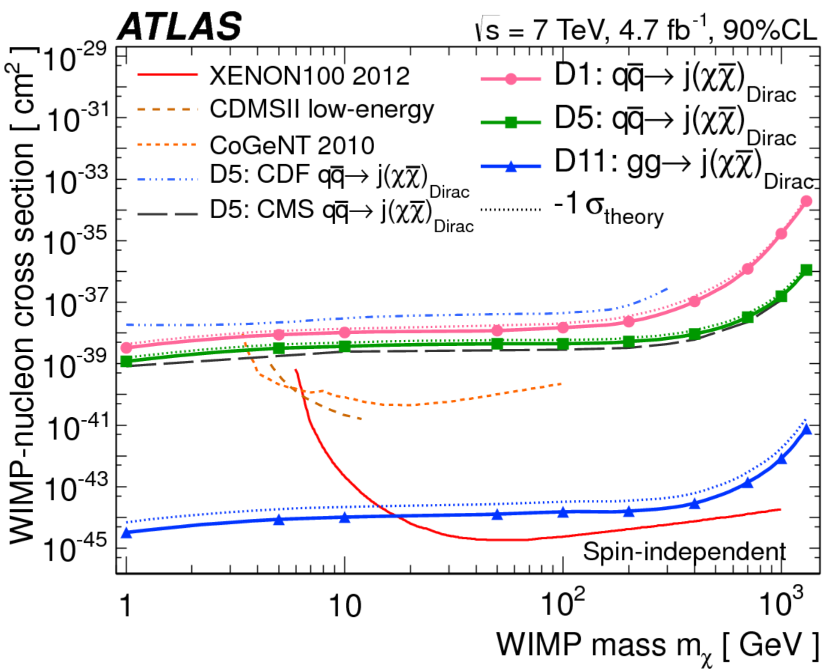
$$\sum_q \bar{q}\sigma^{\mu\nu} q$$

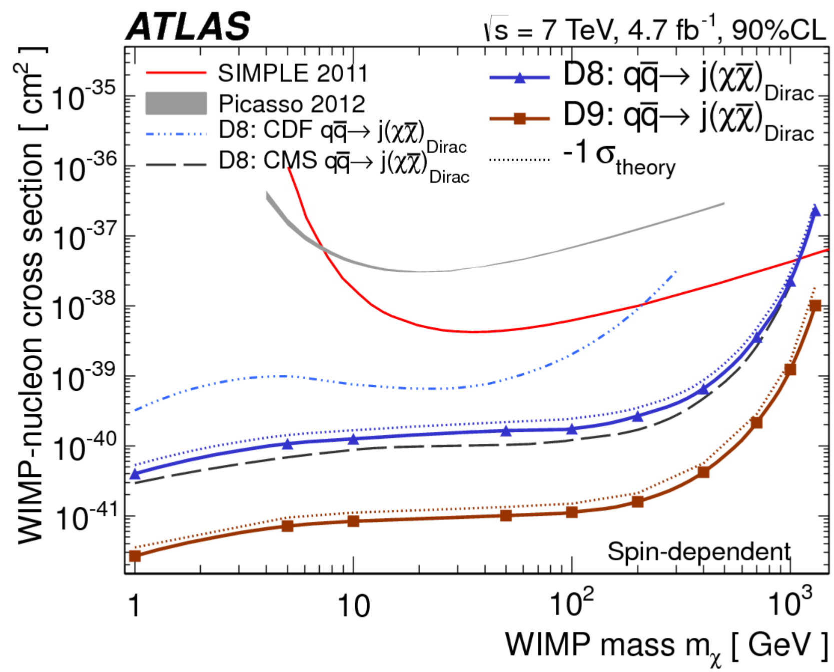
Leading Bounds on Strong Interactions

1005.1286



Mapping to Direct Detection



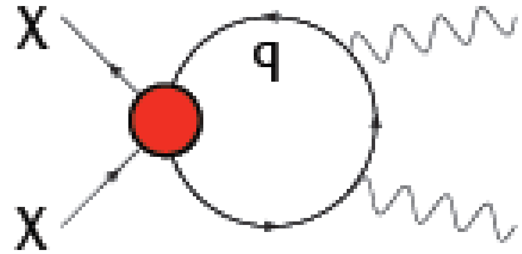


arXiv:1210:4491

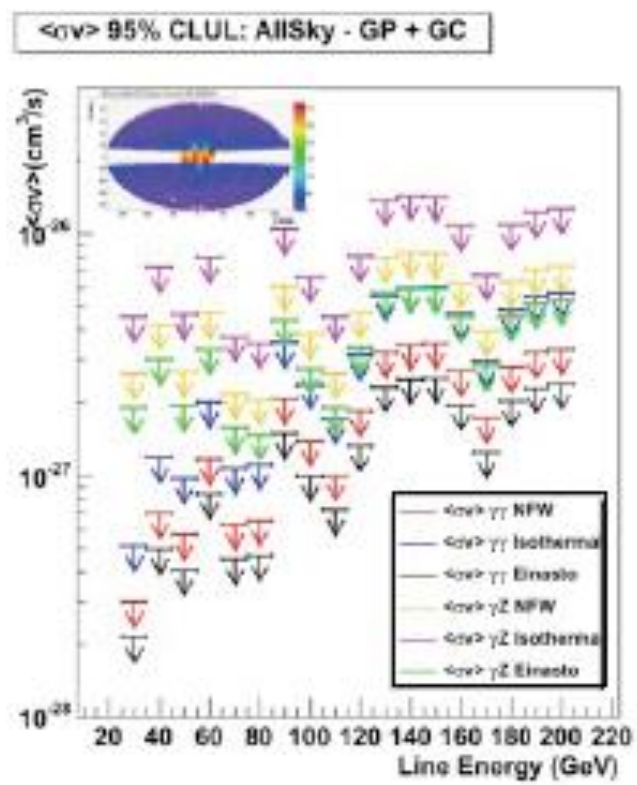
Indirect Detection

- Like direct searches, indirect searches for dark matter have the advantage that they are looking for the actual dark matter present in the galactic halo.
  - Collider missing energy could be due to other new physics than just dark matter.
- Unlike collider searches, they suffer from complicated and irreducible astrophysical backgrounds.
  - As a particle theorist, understanding these backgrounds is above my pay grade.
- I'll focus on one signal that doesn't have any known background mechanism.

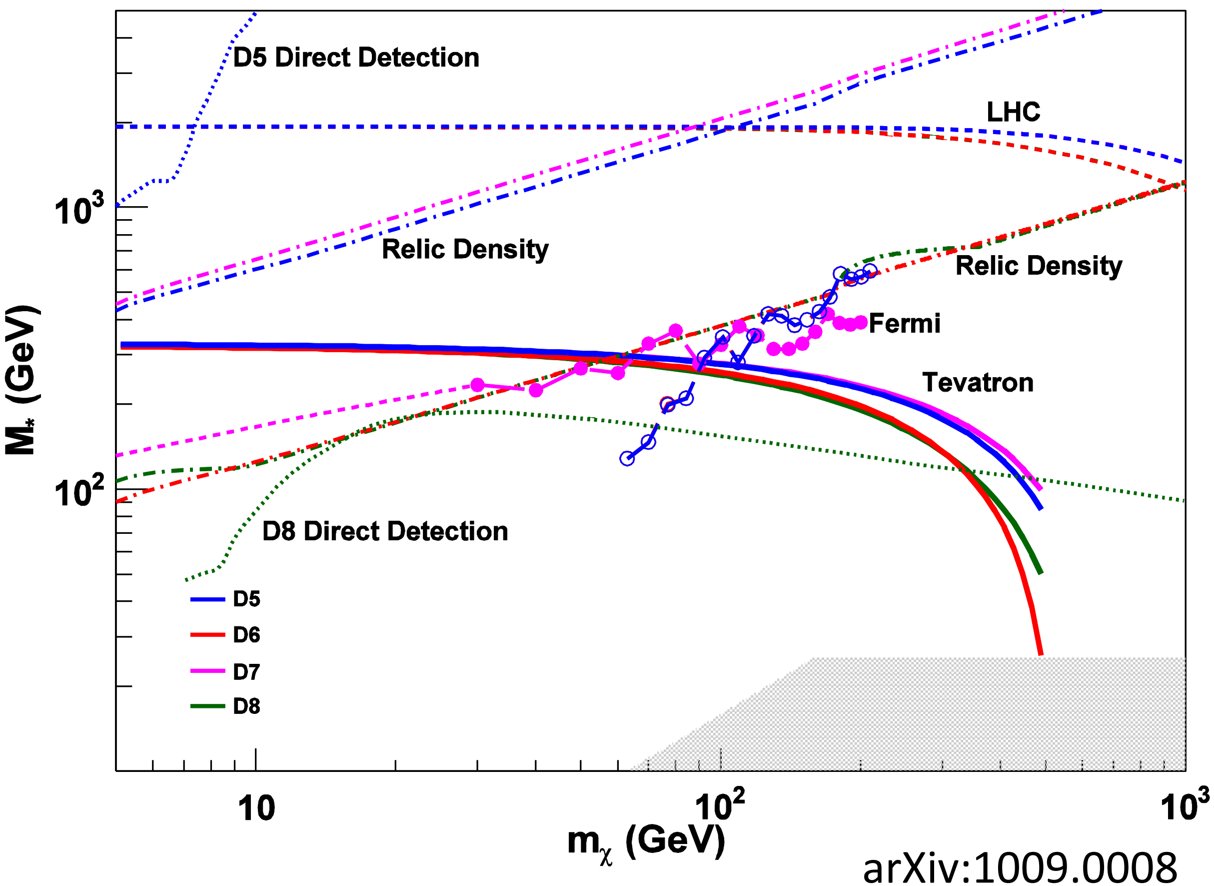
Gamma Ray Lines



- A new spectral line would be a smoking gun signature of dark matter annihilation.
- Our effective operators can lead to such a signal at one loop.
- We use the most conservative bounds quoted by Fermi/GLAST:
  - Dark matter halo in an isothermal profile.
  - These bounds are about 3x those for an NFW profile.

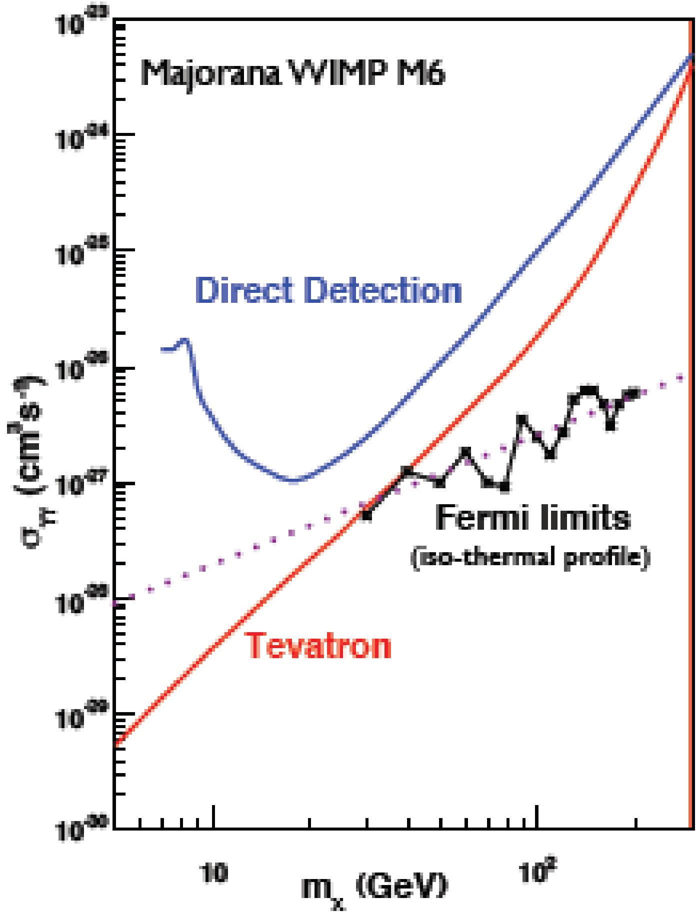


Indirect Detection



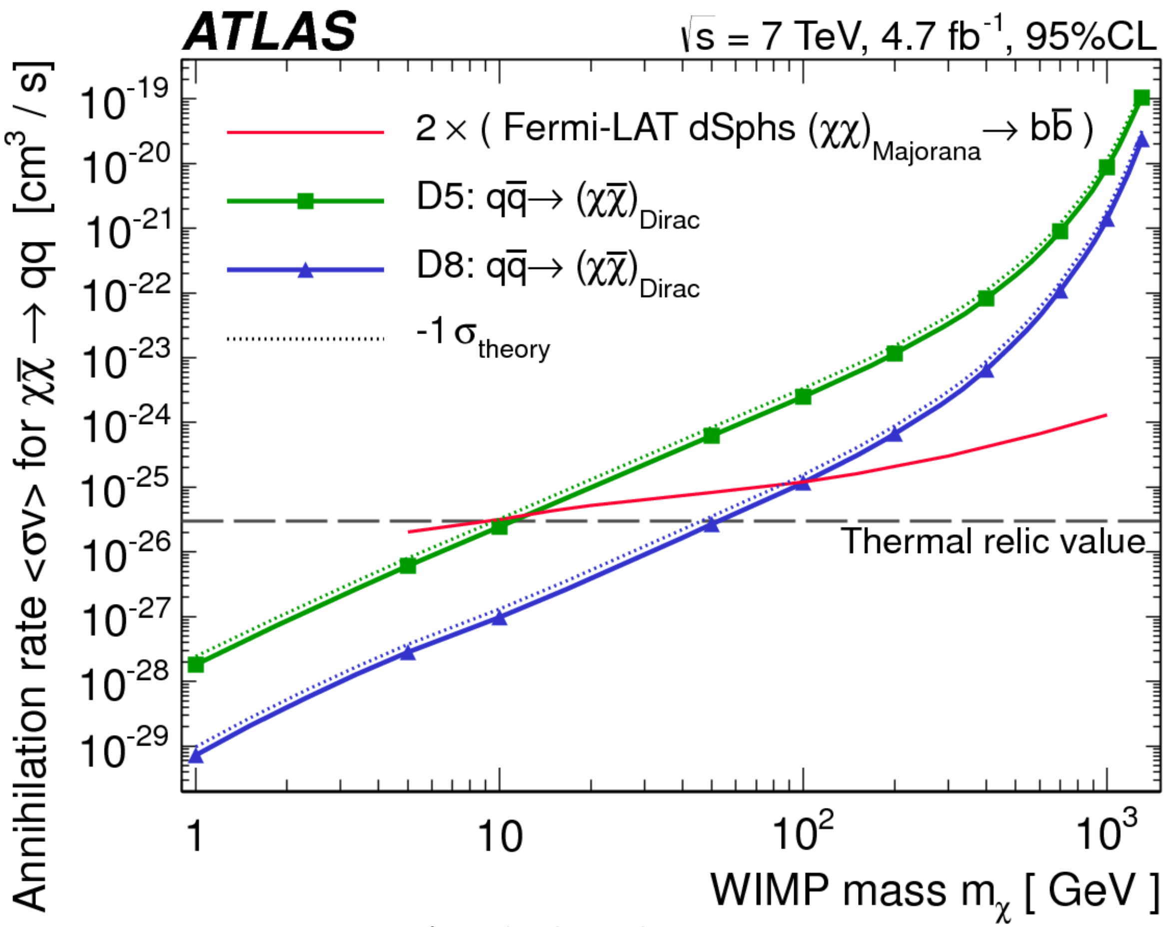
arXiv:1009.0008

Line Cross Section



- We can also map parameter space onto other planes, for example here we have the gamma ray line annihilation cross section.

Total* Annihilation Cross Section



arXiv:1210:4491

Offshoots

- Loop-induced direct detection
  - » Haisch & Kahlhoefer
- NLO LHC predictions
  - » Huang et al, Fox & Williams
- ILC predictions
  - » Dreiner et al, Chae & Perelstein
- New loop-level signals at LHC
  - » Haisch, Kahlhoefer & Unwin
- And many, many more

Fundamental EFT Assumptions

- We have to make assumptions for the DM's:
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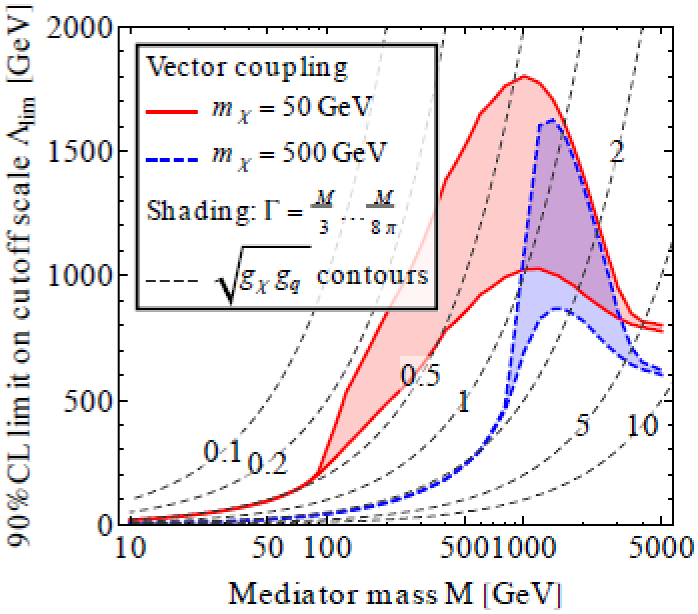
    - I'll guess ½
  - Charges
    - SM singlet
  - Stability
    - Completely stable
  - Other spectrum
    - Let's guess everything else is very heavy
  - Coupling structure

Light Mediators

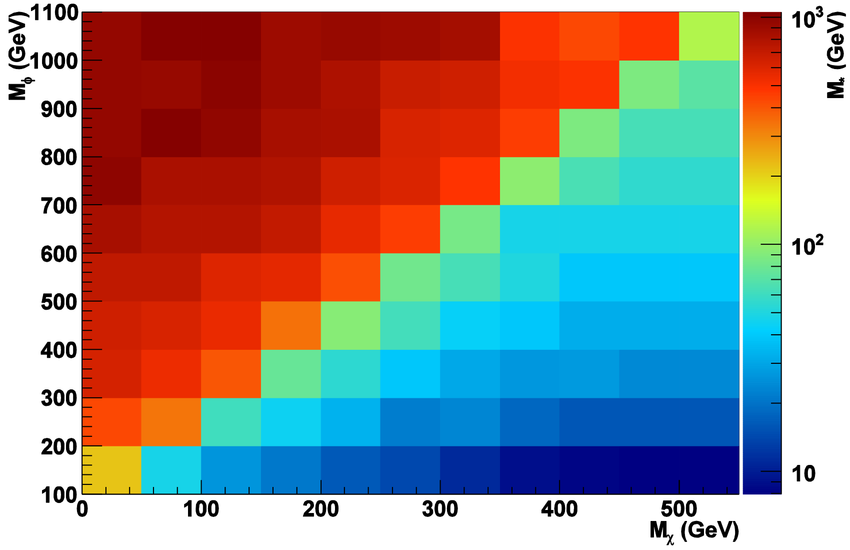
- Bringing the mediator mass down into range can have large effects!
  - Note that here the width is assumed to be linear in the mediator mass
- This is one possible cause of 'conflict' between different DM search techniques



Fox, Harnik, Kopp, Tsai 1109.4398

Light Mediators

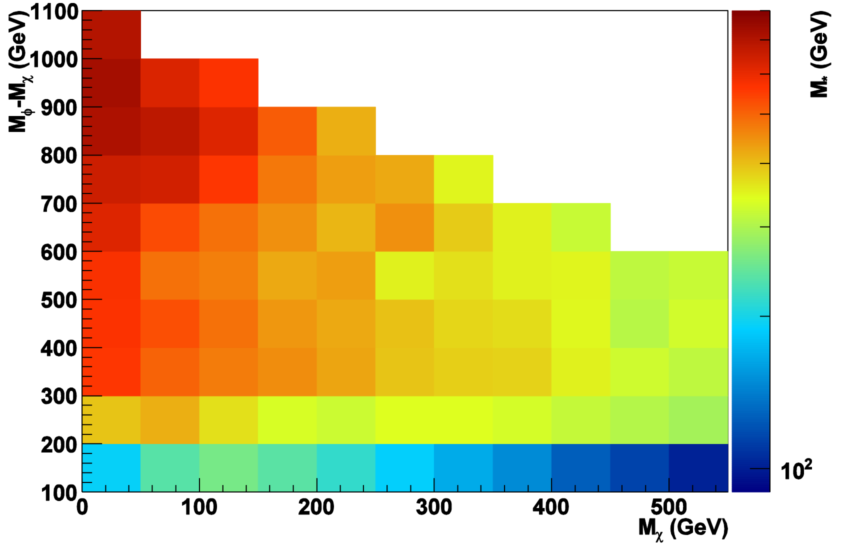
- Another presentation of the same idea, light mediators can matter
  - Here we chose a fixed width, to see the impact of the choice
- The true characteristic behavior in mediator mass is a step-function



Goodman and WS 1111.2359

t-Channel Mediators

- Internal kinematics also matter once mediators are accessible
- This is a squark-type UV completion
- Note the step-function is again the dominant behavior



Breakdowns in Crossing Symmetry

- Crossing symmetry isn't manifest in all models
  - Annihilations may be to non-hadronic states
  - Dark matter may be inelastic, asymmetric, Sommerfeld enhanced…
- Where do we want to look for crossing symmetry violations? How severe can these effects be?

A Known Example

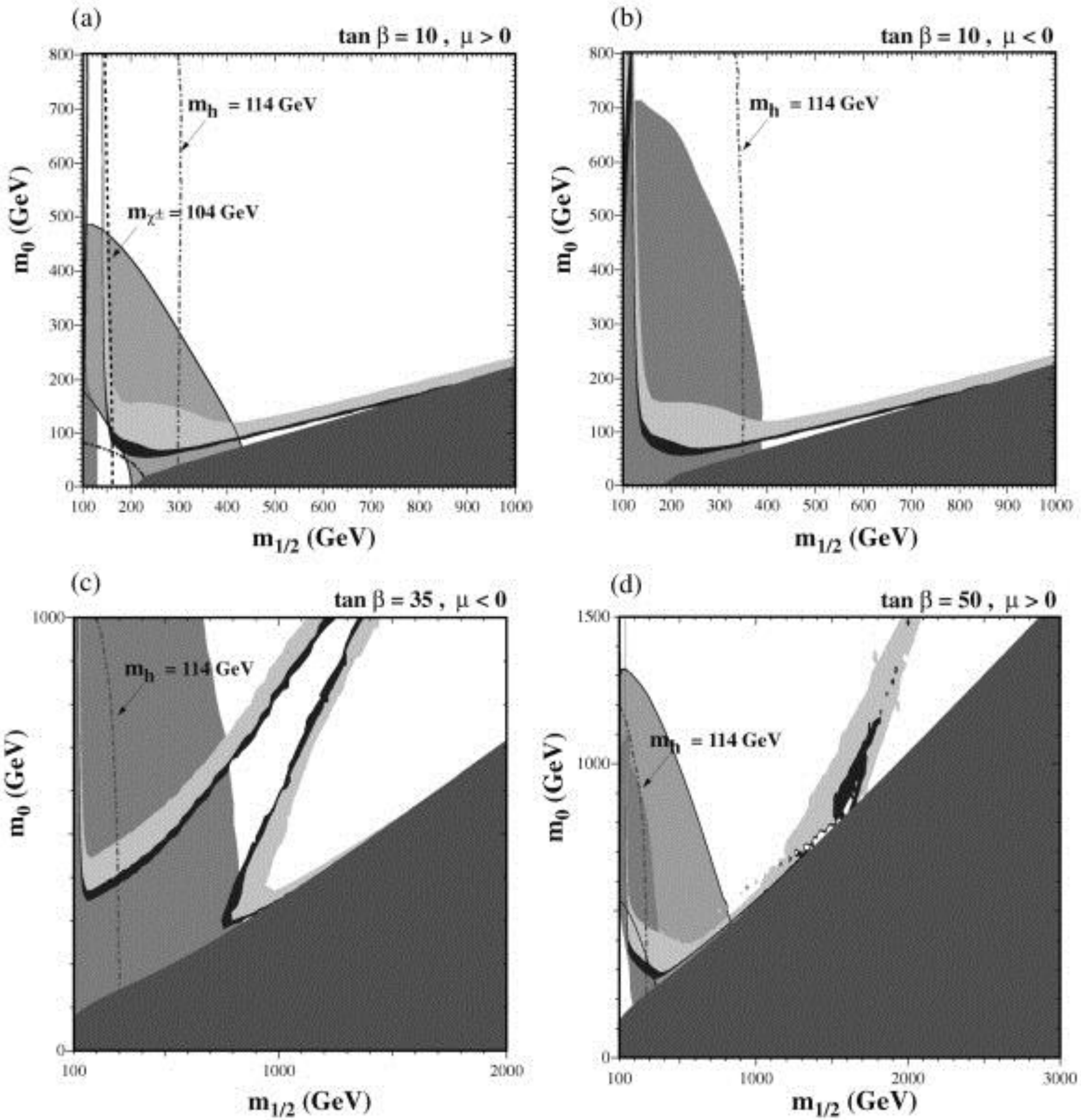
Strong Production, Weak Decay

- The Standard Model has a weakly-interacting particle; let's look at what it does.
- Probability of neutrino production in a given hadron collision is ~ 1
- Probability of neutrino annihilation into hadrons is ~ 0
- Charged pions are strongly produced, and can only decay to give neutrinos.
- What happened to our crossing symmetry here?

Crossing Symmetry in the SM?

Do we Believe in Dark Crossing?

- Certainly we have models of dark matter where crossing symmetry is good
  - We just looked at effective models where that is explicitly assumed.
- Many of our favorite models are more like neutrinos than effective WIMPs.
- Chief among these is SUSY dark matter.



(a)
tan β = 10 , μ > 0
m_h = 114 GeV
m_χ± = 104 GeV
m_0 (GeV)
m_1/2 (GeV)
(b)
tan β = 10 , μ < 0
m_h = 114 GeV
m_0 (GeV)
m_1/2 (GeV)
(c)
tan β = 35 , μ < 0
m_h = 114 GeV
m_0 (GeV)
m_1/2 (GeV)
(d)
tan β = 50 , μ > 0
m_h = 114 GeV
m_0 (GeV)
m_1/2 (GeV)

A Known Example

Strong Production, Weak Decay

- The MSSM has a weakly-interacting particle; let’s look at what it does.
- Neutralino production is in decays of colored sparticles
- Neutralino annihilation is generically very small
  - We work hard to find parts of parameter space where it is large enough
- Here again, we’ve lost our crossing symmetry’s predictivity

SUSY Benchmarks

- To be concrete, we need some parameter points.
  - LHC seems to tell us we don't have light colored particles, so send gluino and squarks heavy
  - Choose benchmarks for their relic density mechanism, then explore the crossing back to colliders and the current dark matter search signatures

SUSY Benchmarks

- Models 1 and 2 are chosen to be ‘vanilla’
  - Above or below top threshold
- Model 3 has stau coannihilations
- Models 4 and 5 are on the A funnel
  - Above or below the resonance

Model	M_1	μ	$m_{\tilde{\tau}_1}$	m_A	$m_{\chi_1^0}$	m_h
Model 1	200	239	10^4	10^3	182	127
Model 2	194	220	10^4	10^3	172	128.6
Model 3	200	10^3	201	10^3	199	130
Model 4	200	10^3	10^4	427.7	199	126
Model 5	200	10^3	10^4	345	199	126

Collider Signals

Model	Total EW σ (fb)	χ_1^0 σ (fb)	fermion σ (fb)	stau σ (fb)
Model 1	625	0.2	625	0
Model 2	850	0.3	850	0
Model 3	9.9	0.001	2.8	7.1
Model 4	2.8	0.001	2.8	0
Model 5	2.8	0.001	2.8	0

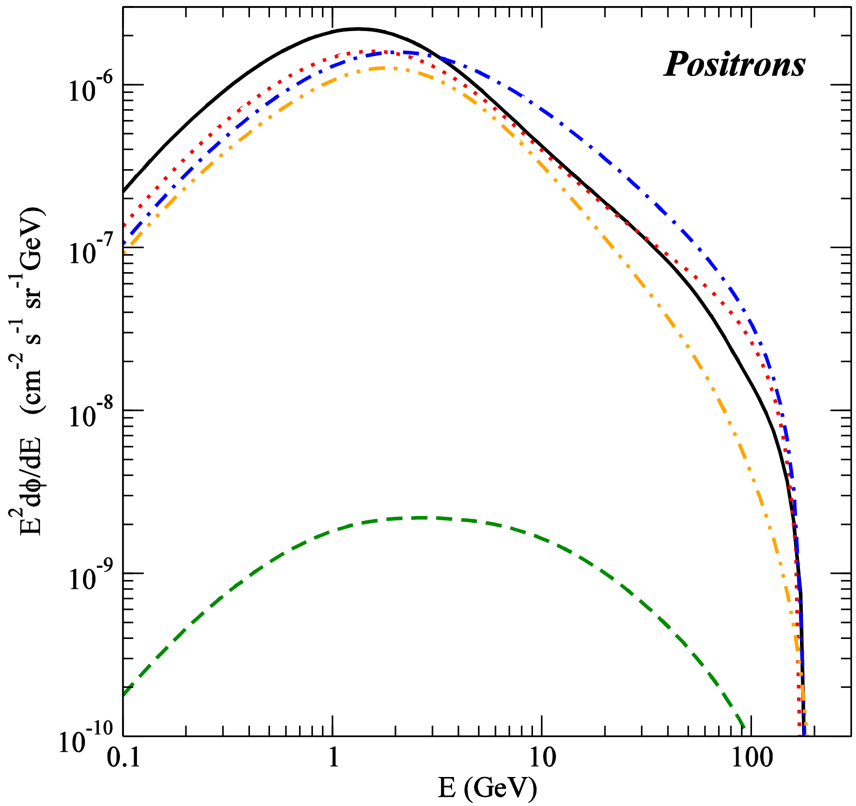
- Total and specific production cross sections change by orders of magnitude
  - Note that the monojet signal is a QCD radiation factor down from the χ pair cross section, which changes by two orders of magnitude

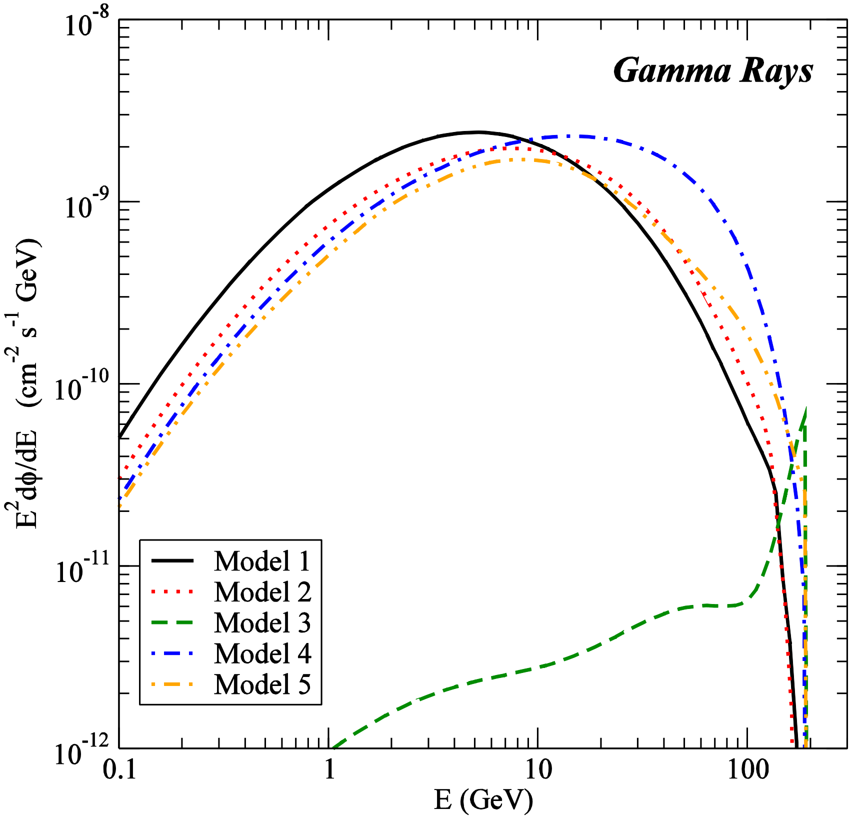
Astrophysical Searches

Model	$\langle\sigma v\rangle_0$	$\langle\sigma v\rangle_{\gamma\gamma}/\langle\sigma v\rangle_0$	$\phi_\gamma(E > 1\text{ GeV})$	$\phi_{\gamma\gamma}$	σ_{XP}^{SI}	σ_{XP}^{SD}
Model 1	2.69523328E-26	3.50133565E-05	1.72770228E-09	6.49795989E-15	1.61682075E-08	0.000153318916
Model 2	2.27592662E-26	0.000131667137	1.26414605E-09	2.30872306E-14	1.80594845E-08	0.000208972418
Model 3	8.60547308E-29	0.00899390492	1.90603557E-12	4.44463958E-15	5.38495458E-11	1.34085691E-07
Model 4	4.89332128E-26	1.6548008E-08	1.21400299E-09	4.65010753E-18	2.95106362E-10	1.34085538E-07
Model 5	1.79062822E-26	1.06972714E-06	9.90476351E-10	1.09997857E-16	4.13427661E-10	1.23544048E-07

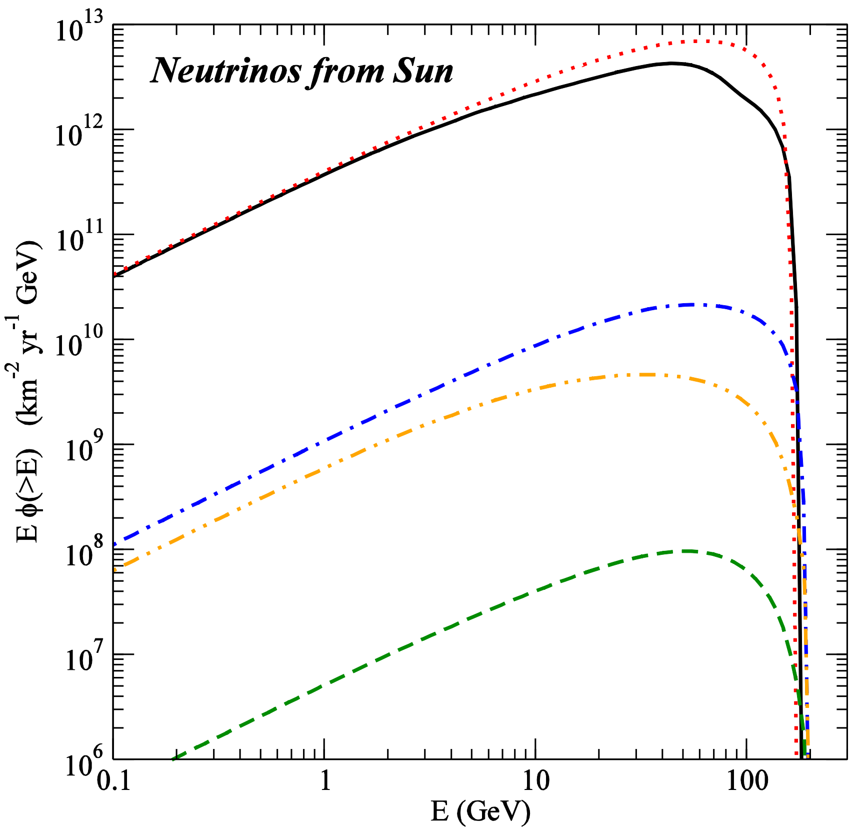
- Dedicated searches also depend very sensitively on the additional parameters
  - Differences of a factor ~ 1000 in direct detection and total indirect fluxes
  - Line signals even more sensitive

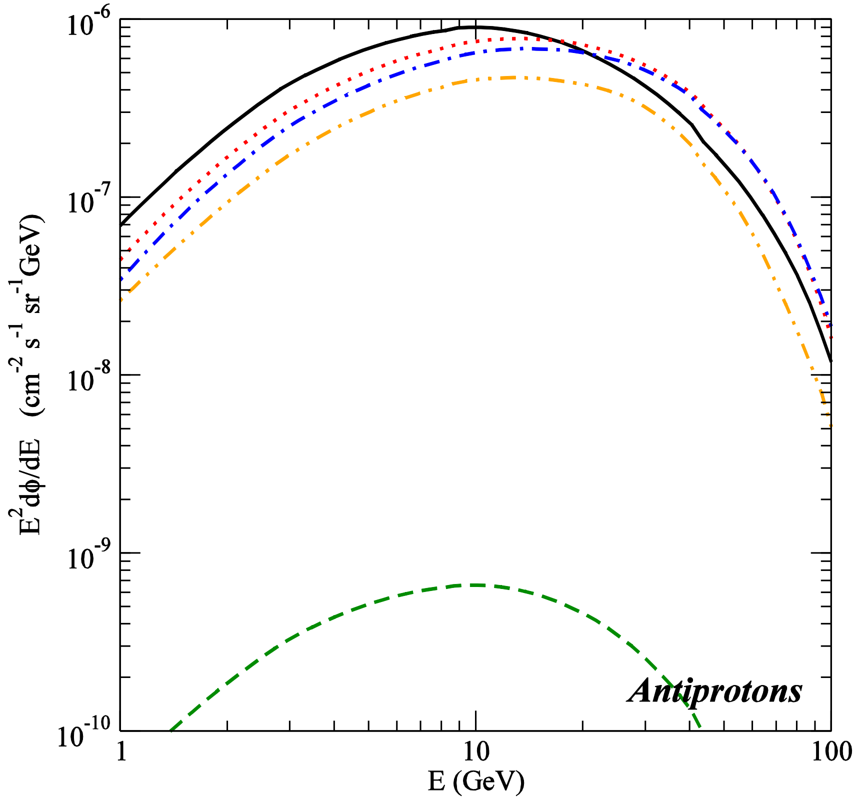
Indirect Detection





Indirect Detection





Indirect Detection Verdict

- Here too we see a large variation with model parameters.
- Keep in mind, all of these benchmarks were chosen to give thermal WIMP dark matter at ~ 200 GeV.
  - Even simply moving from the early universe to the same process at later times gives very significant effects.

Conclusions

- While crossing symmetry and contact operators are a useful tool for comparing different experiments, there are many circumstances where their predictions vary
- Given a known model one shouldn't reduce it to effective operators without good cause
- The presence of multiple mediators can play as large a part in altering predictions as their lightness

Conclusions

- Whether crossings are a good symmetry or not, all channels will provide us valuable information about dark matter.

- Finding either bridge will be exciting!