Dark Matter Searches at the LHC: Theory

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IDM 2012

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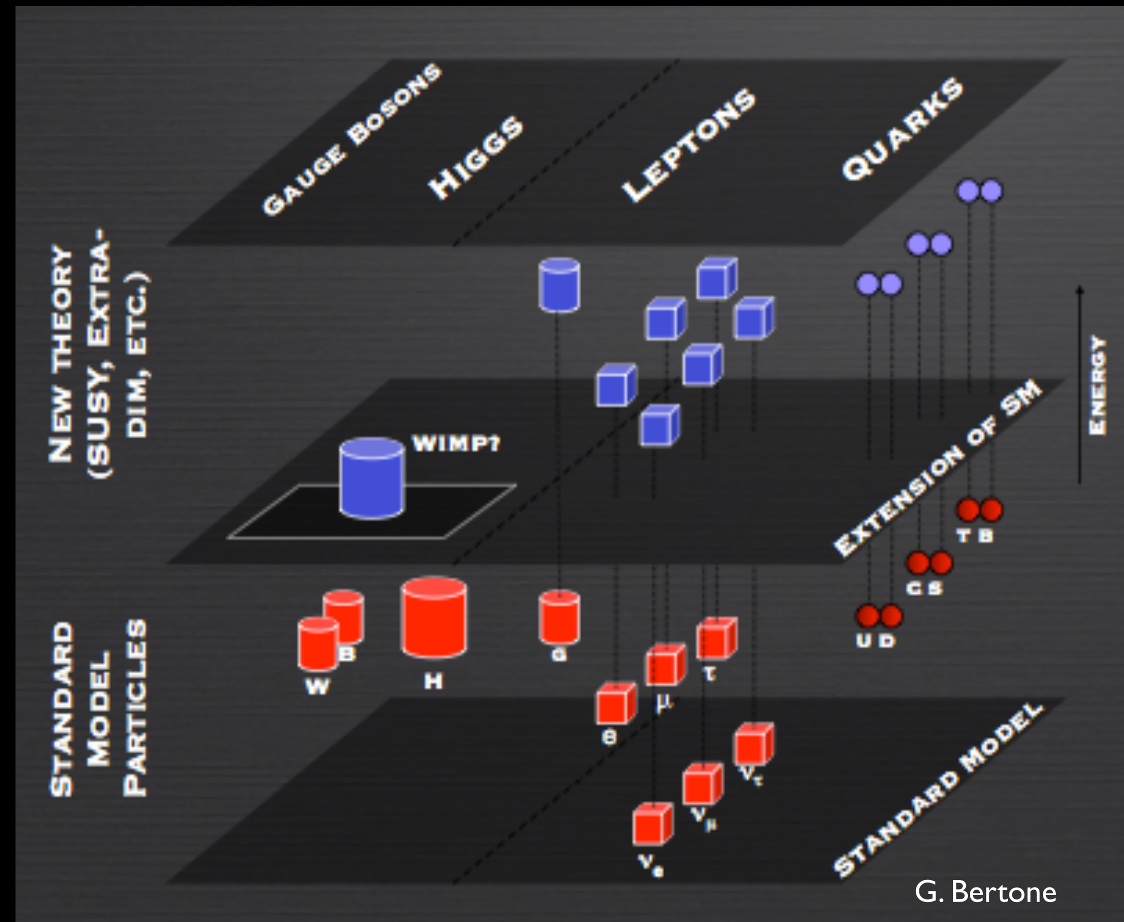
Missing Energy Signals

- Missing energy signals are a big part of the new physics menu at colliders, largely because of the potential connection to dark matter.
- We still don't know what dark matter is, but we know it is at most weakly interacting.
  - We know it should look like "nothing" to a collider detector.
- We have reason to think it should have reasonably large couplings to at least some of the Standard Model, in order to explain its abundance in the Universe.

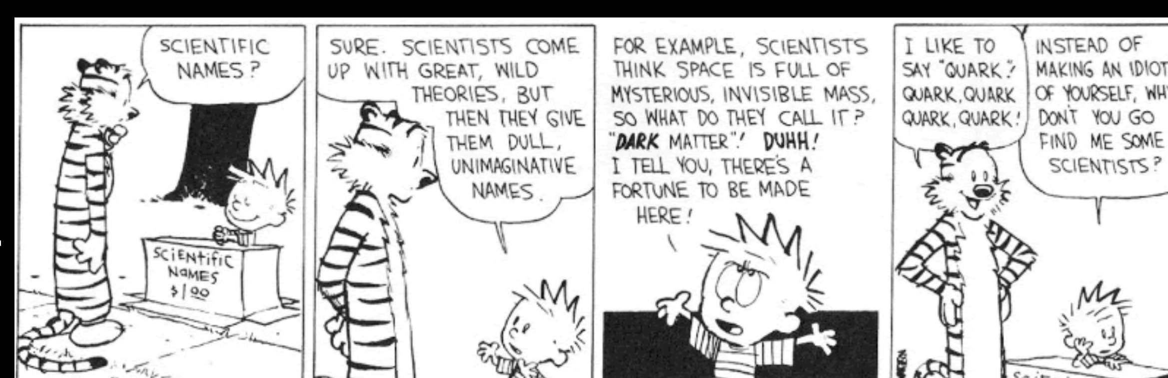
"Cold Dark Matter: An Exploded View" by Cornelia Parker

A Cartoon WIMP Theory

- A typical WIMP theory has a whole "layer" of new particles.
  - E.g. SUSY, UED, Little Higgs, ...
- The WIMP is the lightest of these new states, and must be neutral and ~stable to be viable dark matter.
- Most of the heavier "WIMP siblings" usually are colored and/or charged, and thus interact much more strongly with the Standard Model particles than the WIMP does.
- They decay into the WIMP itself plus Standard Model particles.



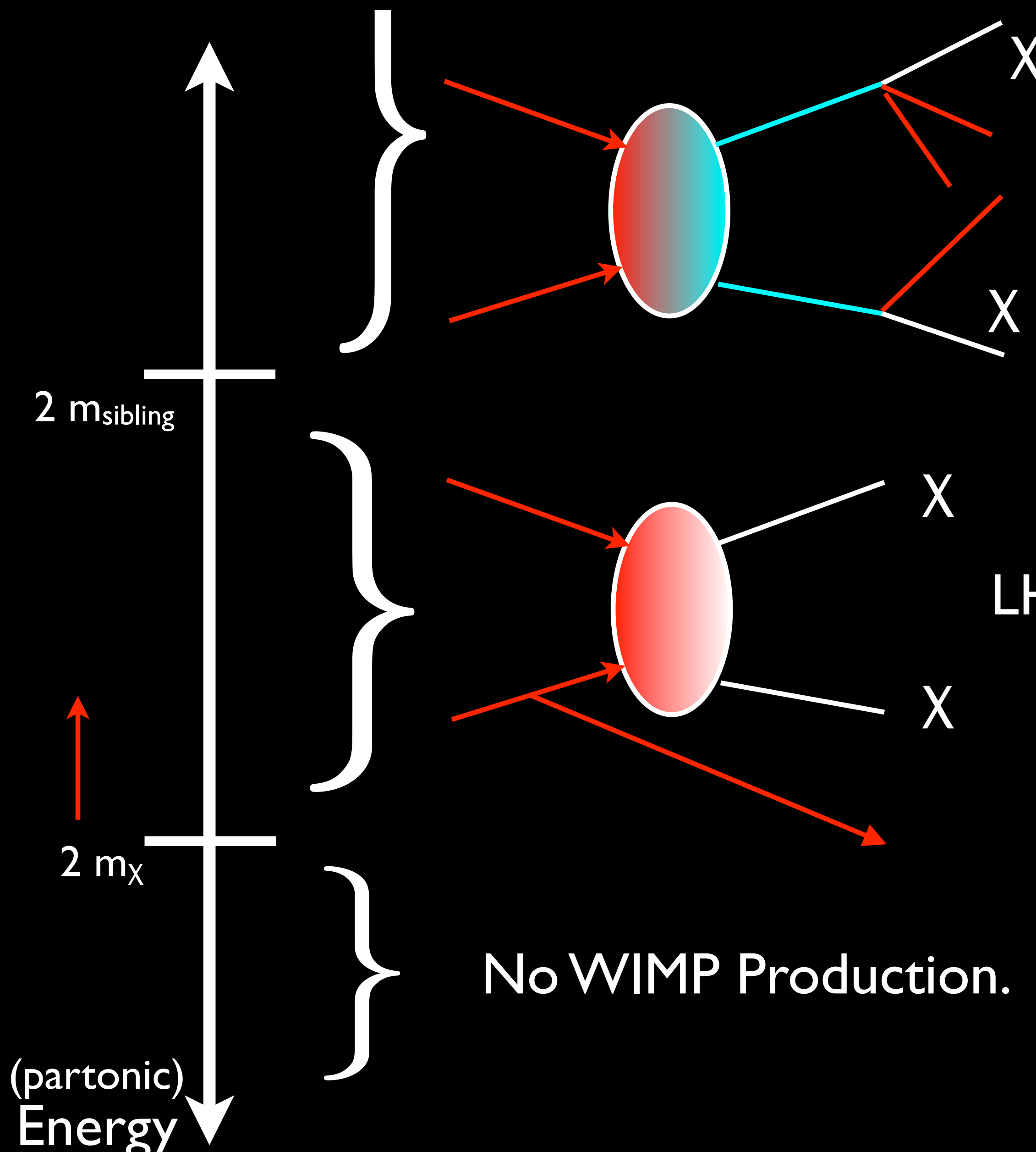
G. Bertone



LHC WIMP Production

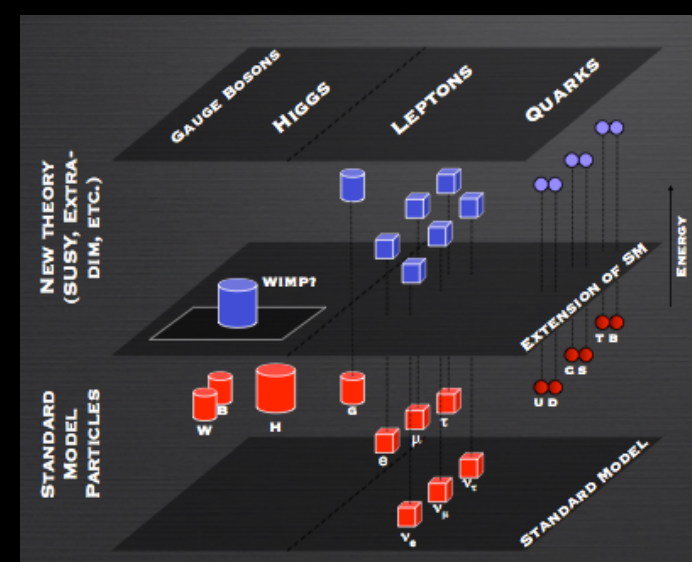
LHC can produce WIMP siblings, which decay into WIMPs and other SM particles.

“KK Sgluquarkino Pair Production Followed by Decay into WIMPs”



LHC can directly produce WIMP pairs.

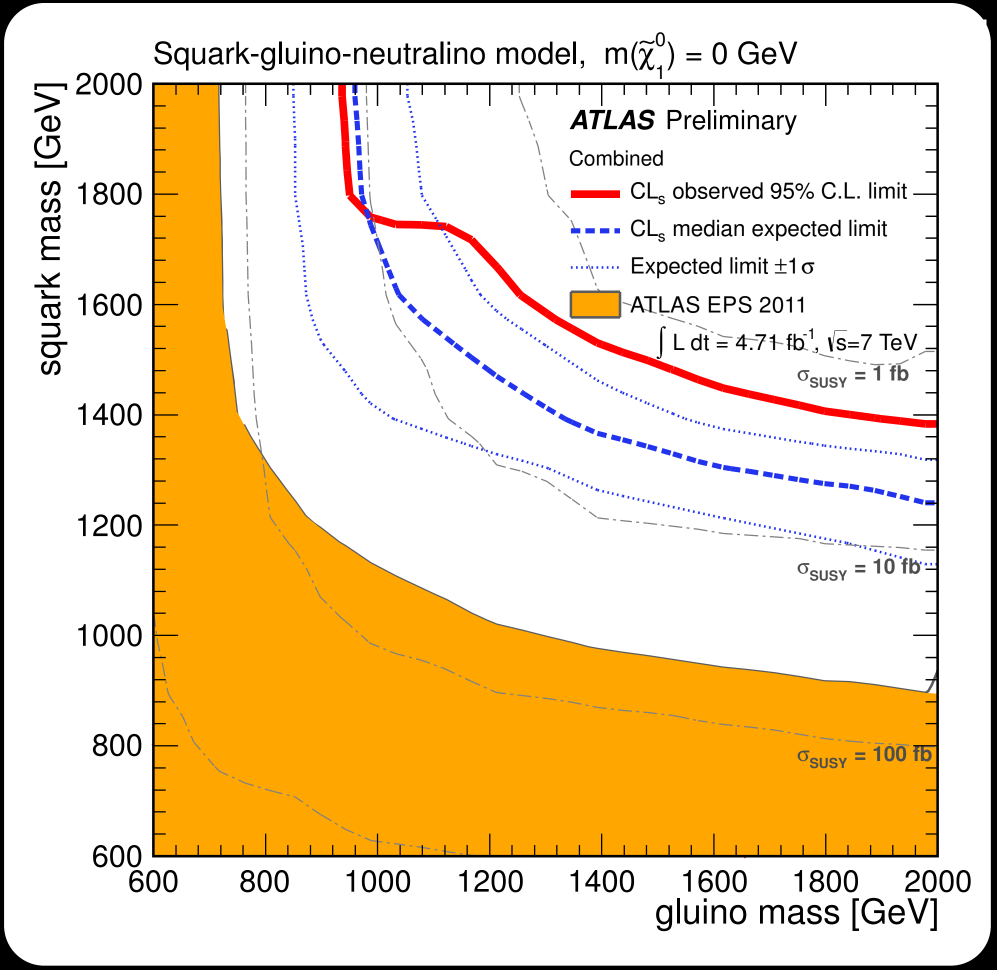
No WIMP Production.



WIMP Sibling Production

Squarks and Gluinos

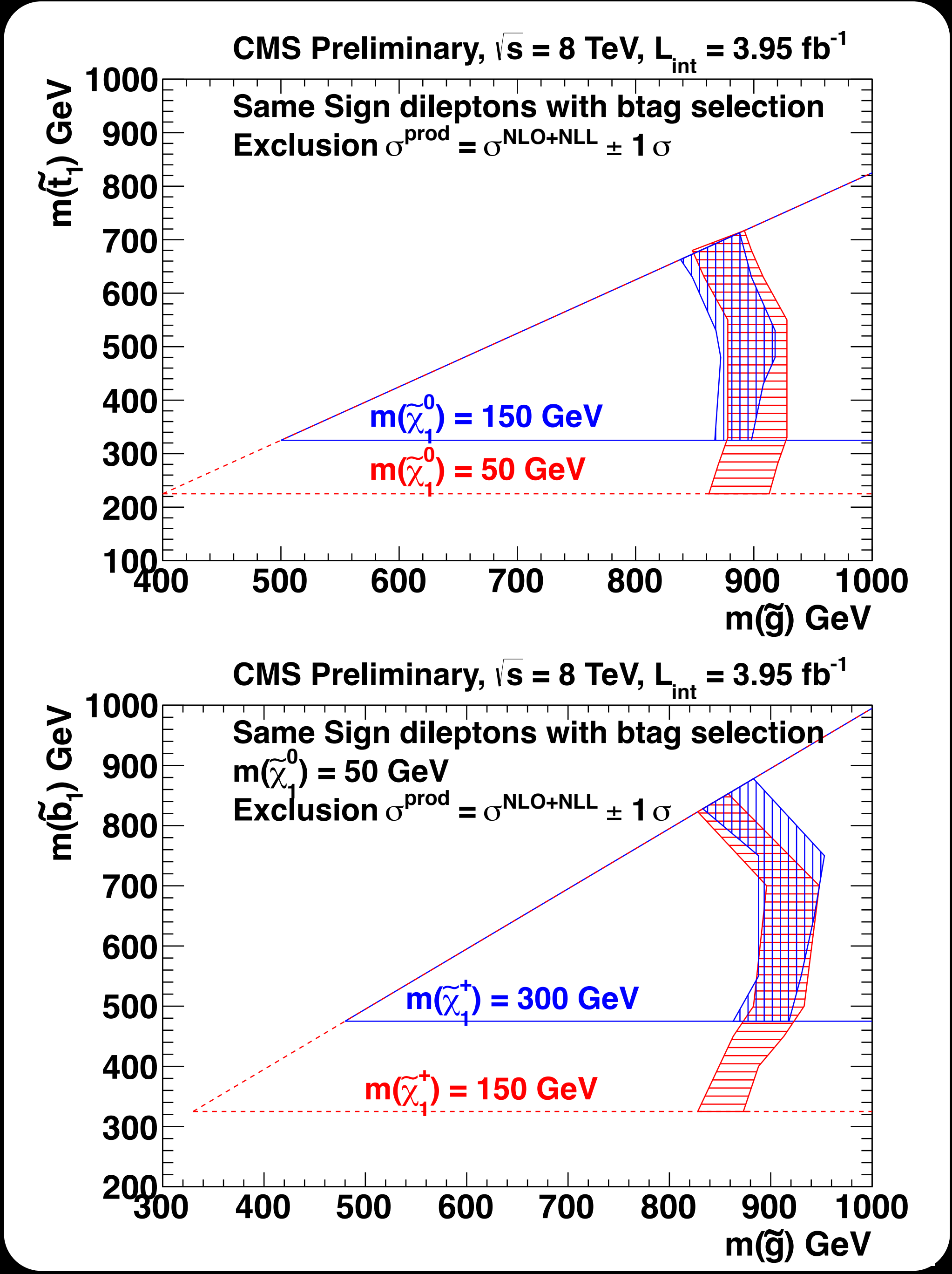
- Searches for missing energy plus various numbers of jets put bounds on squark and/or gluino ("colored sibling") production.
  - Gluinos decay to two jets + WIMP
  - Squarks into one jet + WIMP
- For equal masses, searches require them to be larger than about 1.5 TeV
- Limits are still several hundred GeV when one or the other is very heavy.
- These limits hold assuming the WIMP mass is less than 200 GeV.



More from Matt about the status of SUSY shortly!

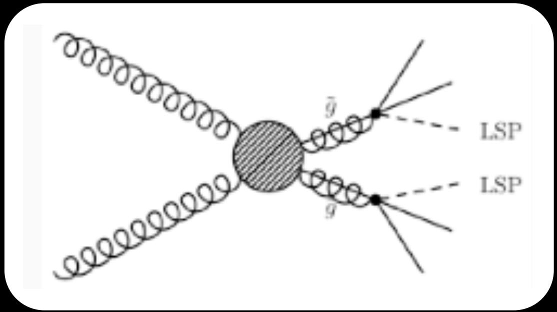
3rd Generation Squarks

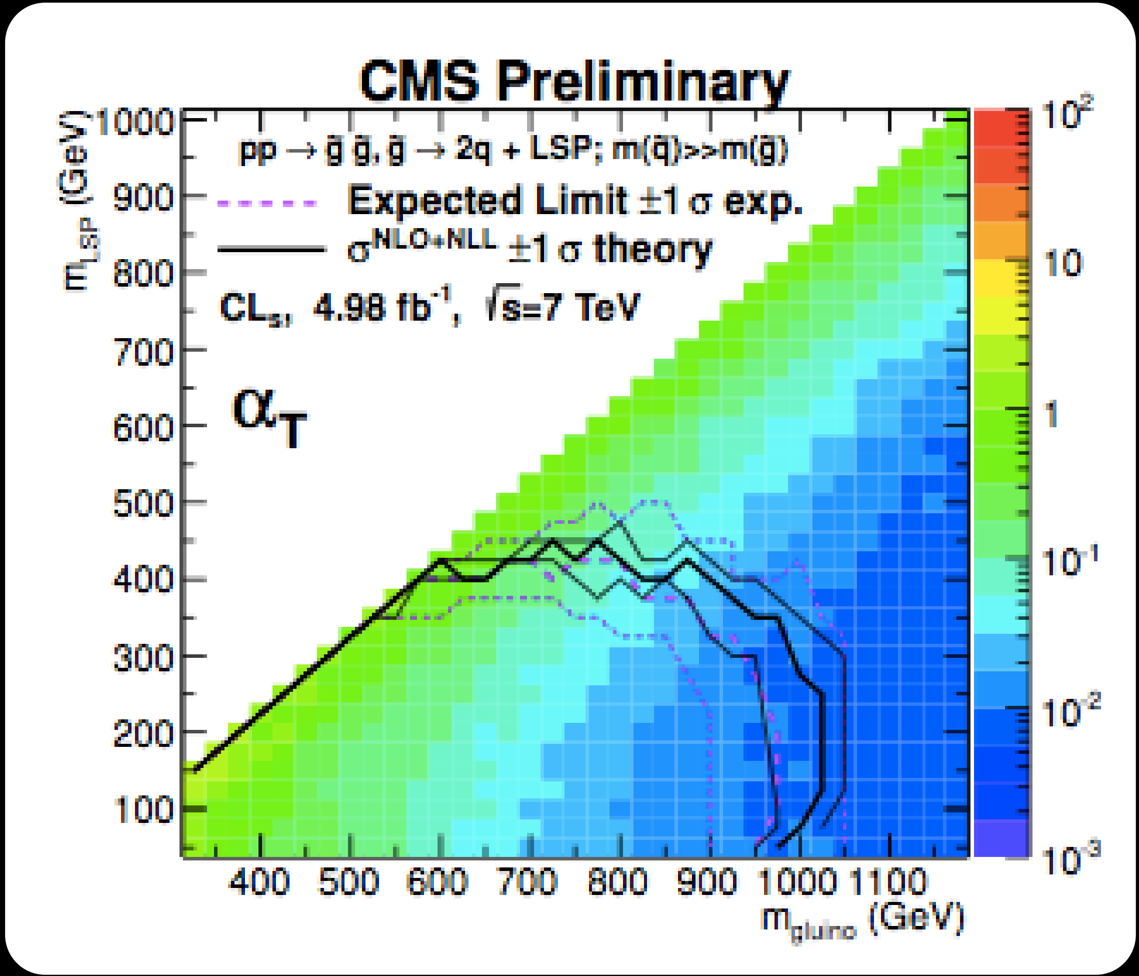
- Naturalness requires SUSY to have light(ish) stops, but is more agnostic about the ``light squarks''.
- The left-handed stop comes along with a sbottom with a roughly similar mass.
- The squark masses are also rather tightly coupled to the gluino mass through the renormalization group.
- Searches for single flavors of squarks are becoming very interesting. Already, the results are coming in.
- The next year is likely to be very enlightening!



Simplified Models

- One can step away from specific MSSM assumptions by working with simplified models.
  - These are phenomenological sketches of theories.
- The experimental collaborations have been willing to explore casting their SUSY searches into this framework, allowing for a much more flexible interpretation of limits.
- It also reveals more about the WIMP mass dependence of the results -- larger LSP masses severely erode the gluino limits!





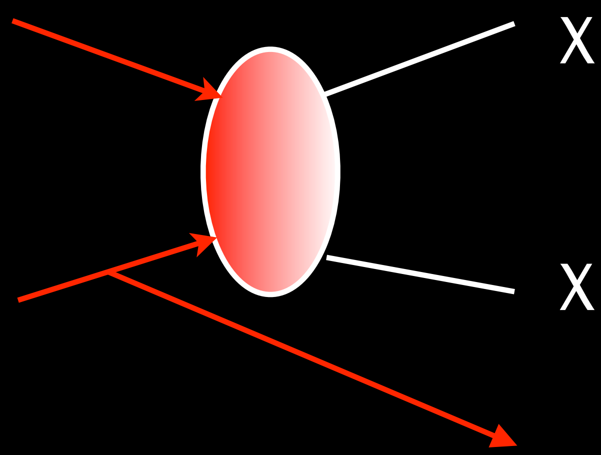
Direct WIMP Production

Maverick WIMP Production

- Producing WIMPs directly requires there to be some kind of initial radiation from the incoming quarks or gluons.
- In some limits of theories, we're not very sensitive to the details of how the WIMP couples to quarks and gluons: we can use effective field theories containing contact interactions to parameterize all leading contributions.
- Initial studies recycled existing ADD searches. Now the collaborations are doing their own, optimized searches.

As Daniel will tell us next...

- This kind of process works best for very light WIMPs, because they can be produced easily with a lot of kinetic energy, leading to large missing energy.

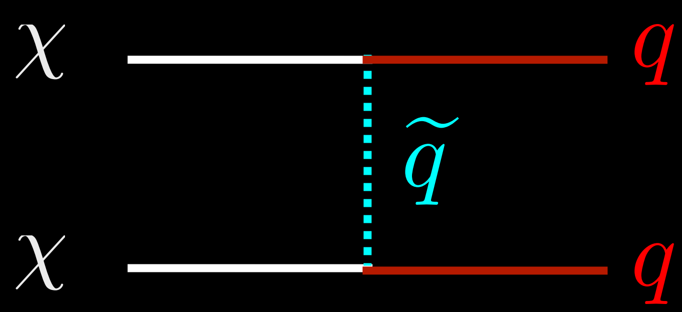


Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037

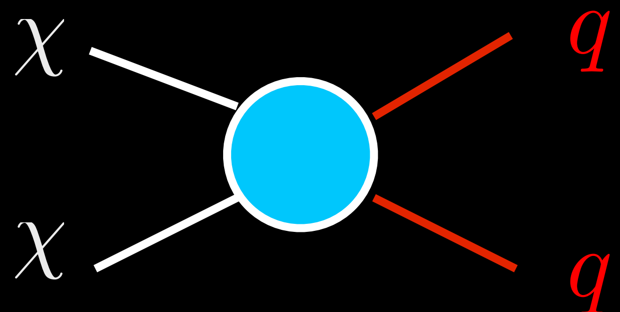
Example EFT: Majorana WIMP

- As an example, we can write down operators of interest for a Majorana WIMP.
- There are 10 leading operators consistent with Lorentz and SU(3) x $U(1)_{EM}$ gauge invariance coupling the WIMP to quarks and gluons.
- Each operator has a (separate) coefficient M_* which parametrizes its strength.

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-



$$\frac{g^2}{M_{\tilde{q}}^2} \leftrightarrow \frac{1}{M_*^2}$$



Dirac WIMPs

- We can repeat this exercise for other choices of WIMP spin.
- For a Dirac WIMP, we have a few more Lorentz structures, such as the vector and tensor combinations.
- On top of the operators we had for the Majorana WIMP, magnetic and electric dipole moment operators are possible as well.
- For a Dirac WIMP, in some mappings we need to decide whether the halo is made of just WIMPs. I'll opt for an equal mixture.

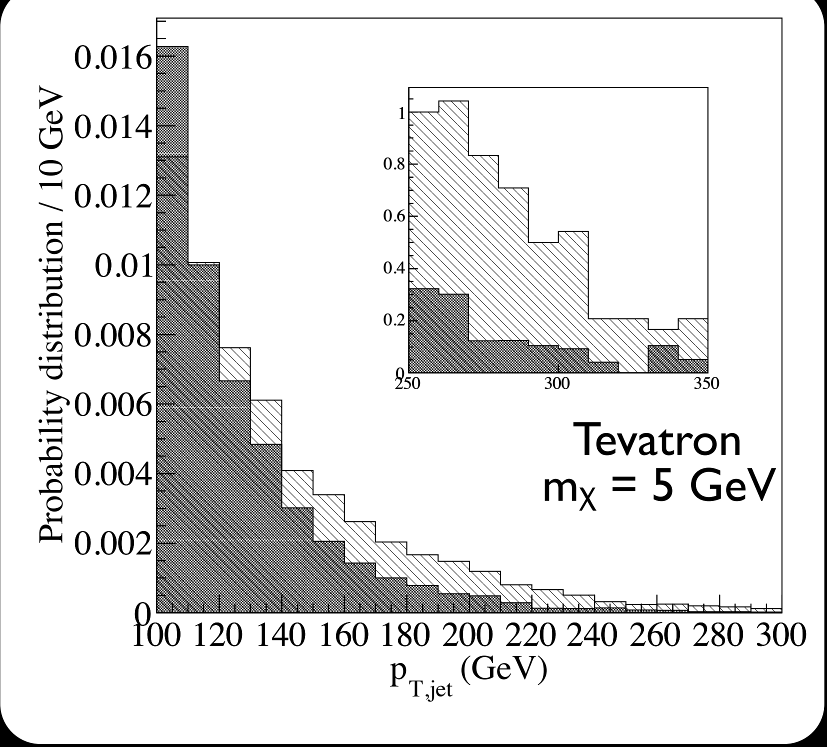
"Asymmetric" dark matter would also be interesting!

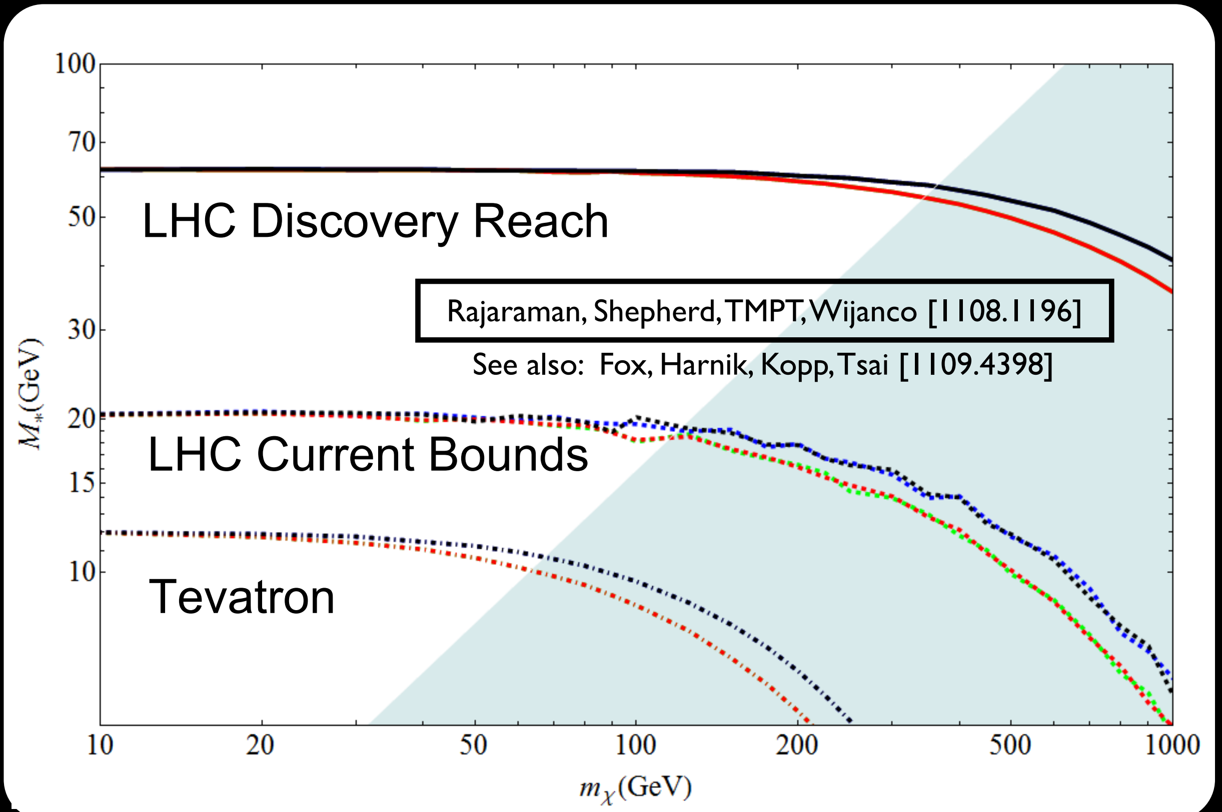
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
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	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu} q$	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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D

Mono-jets

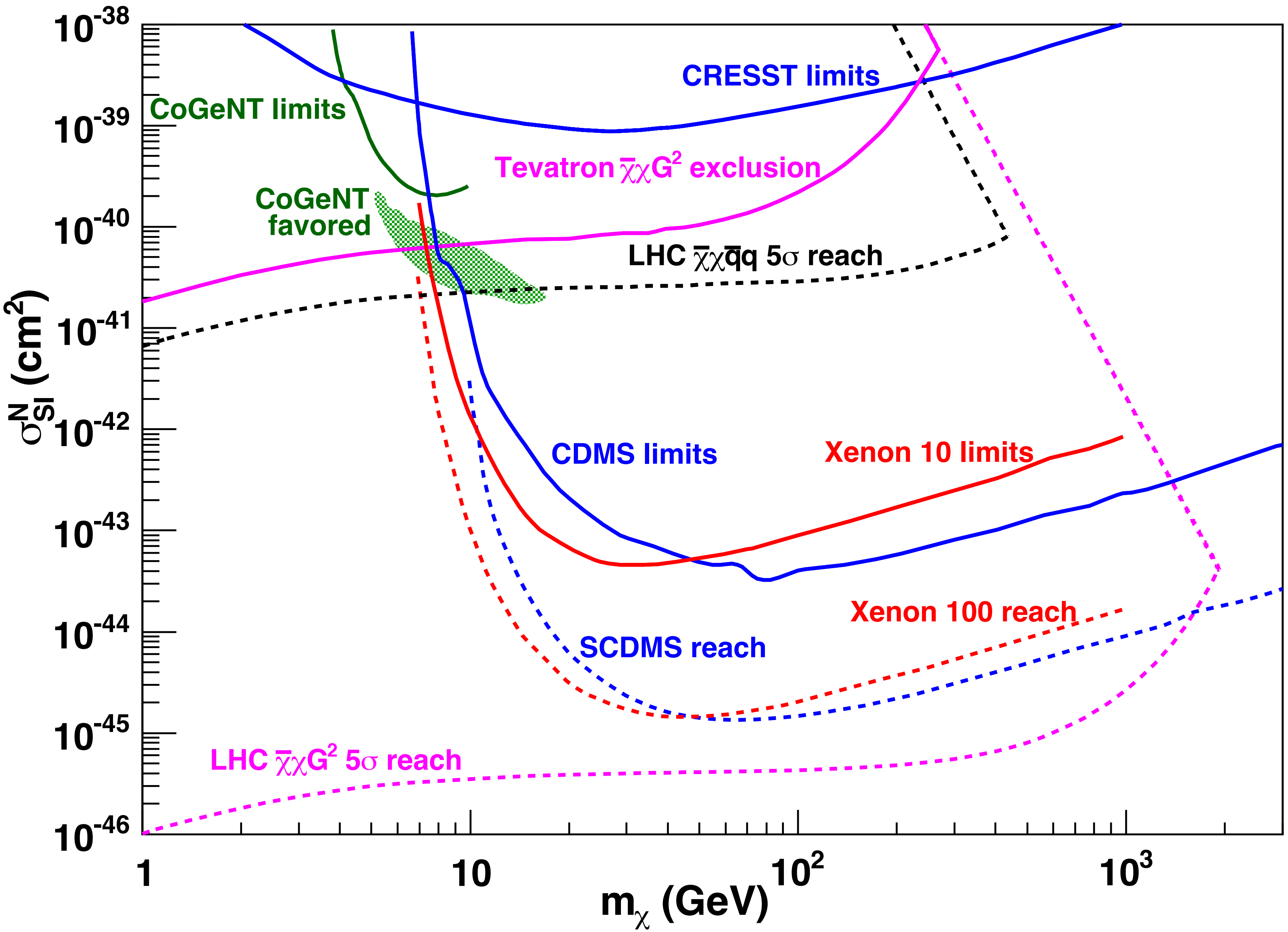
Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037 (2010)

- In terms of the WIMP mass and for a given choice of interaction with quarks and/or gluons, we can predict the rate of monojet production.
- There are SM backgrounds from producing a Z which decays into neutrinos plus a jet of hadrons as well as fakes.
- We can put bounds on the coefficients M* that parameterize the interaction strength.

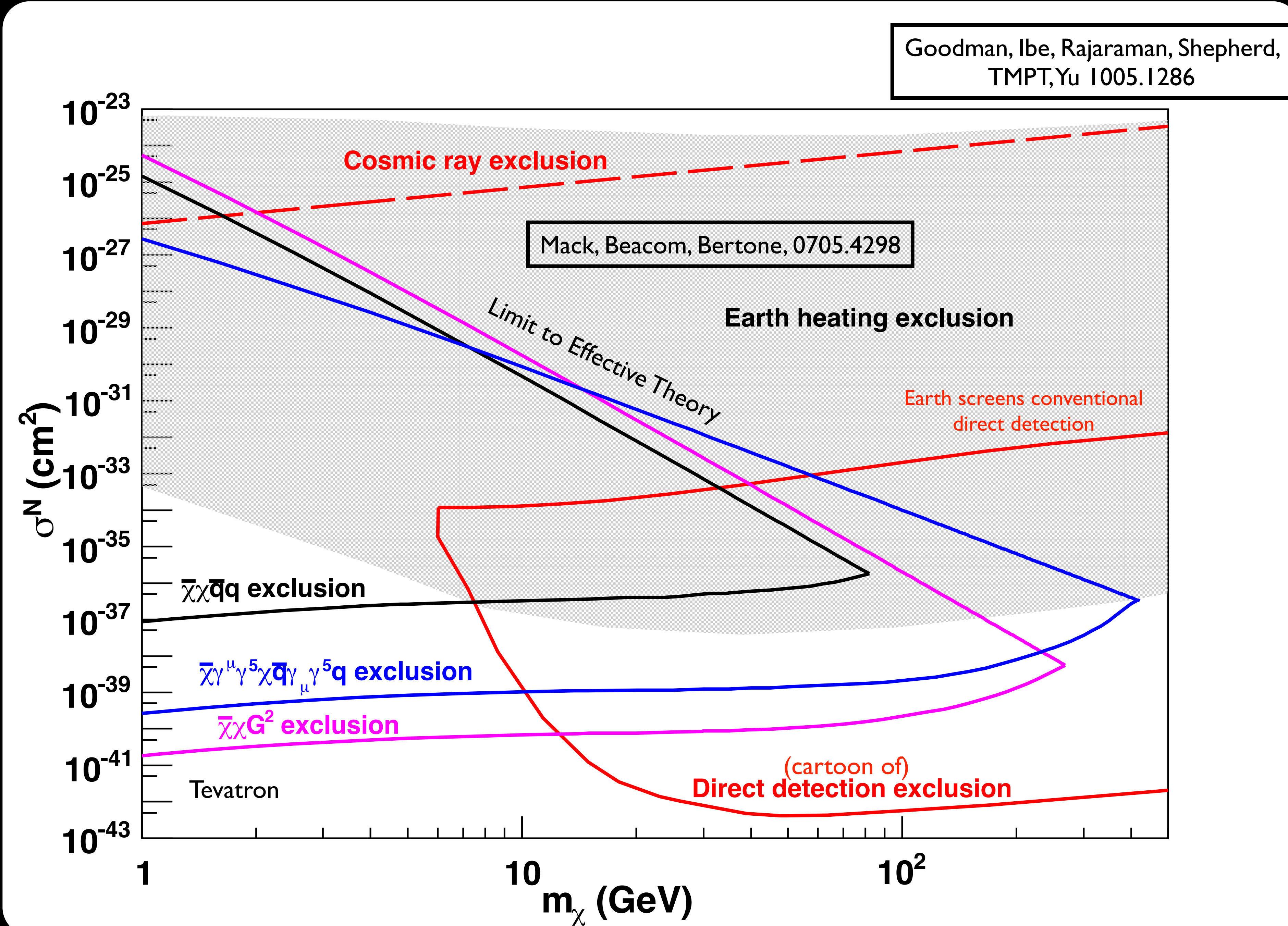




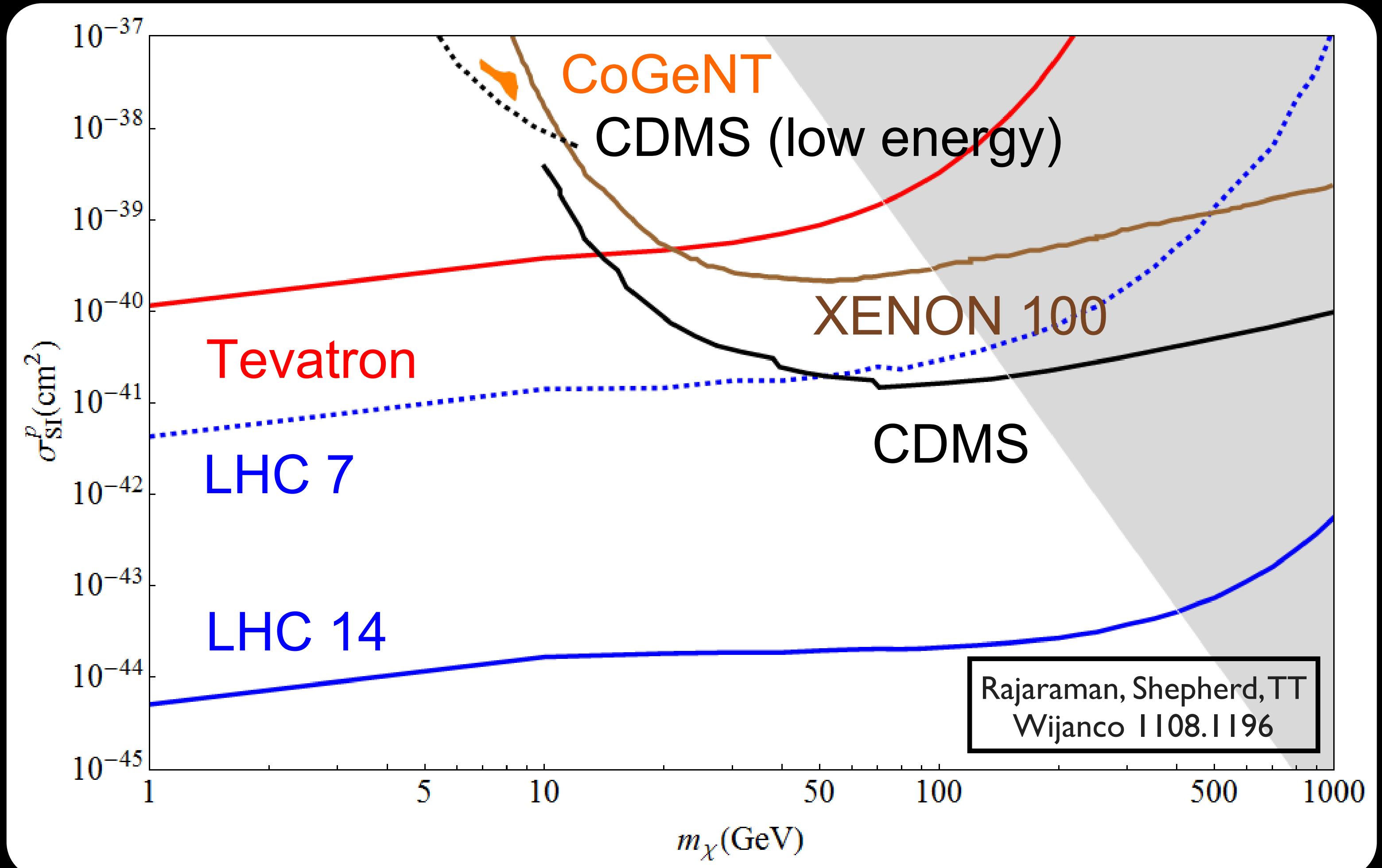
Colliders - Direct Detection



From WIMPs to SIMPs...



Iso-spin Violating



- For up- and down-quark couplings adjusted such that fn ~ -0.7 fp, constraints from Xenon are much weaker than the CoGeNT ``signal”.
- Naive MFV implementations are ruled out by colliders, but specific non-MFV constructions survive.

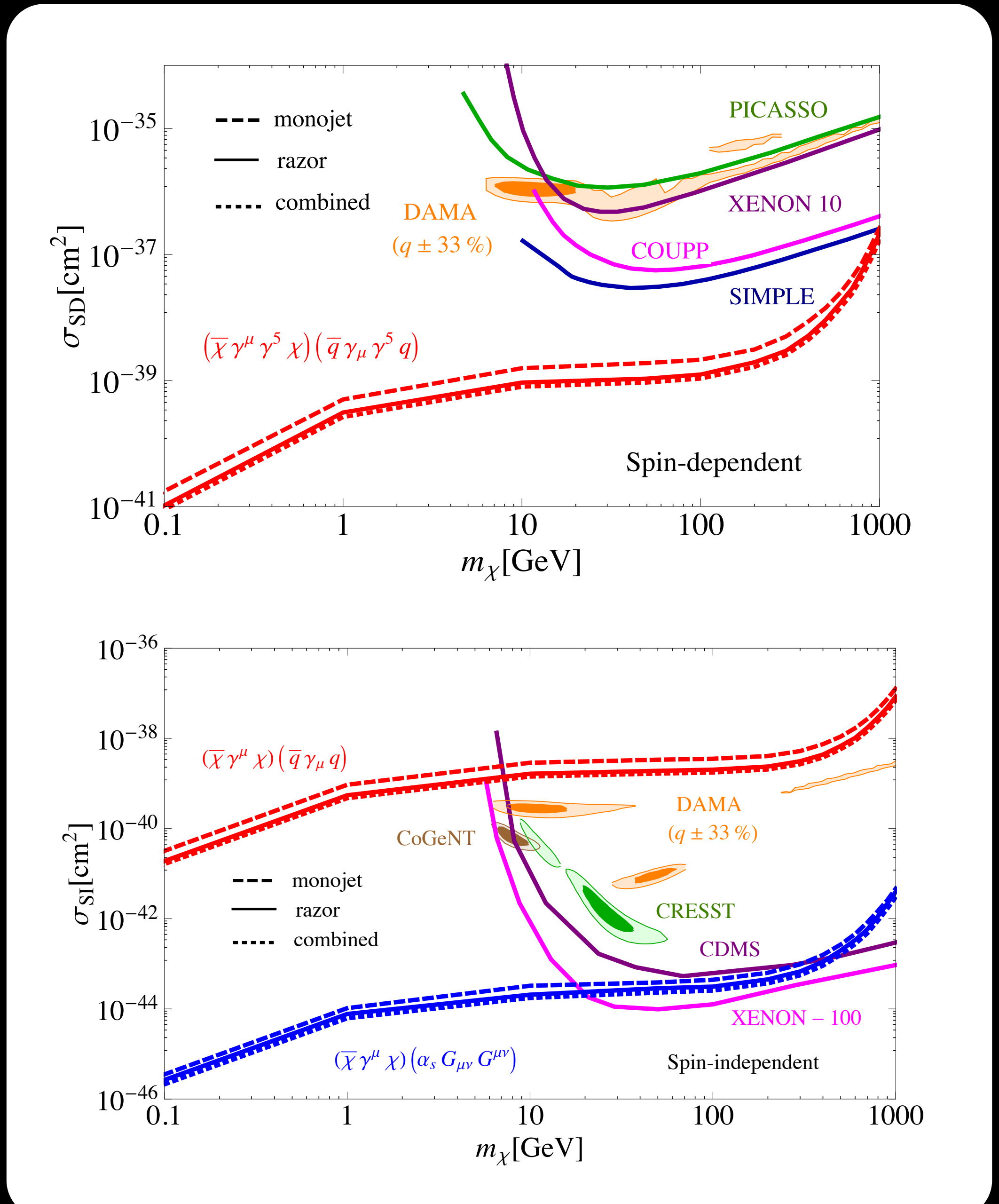
Feng, Kumar, Marfatia, Sanford 1102.4331 (see also: Chang, Pierce, Weiner 1004.0697)

Razoring Monojets

- A recent study applies the CMS razor analysis to the dark matter production signal.

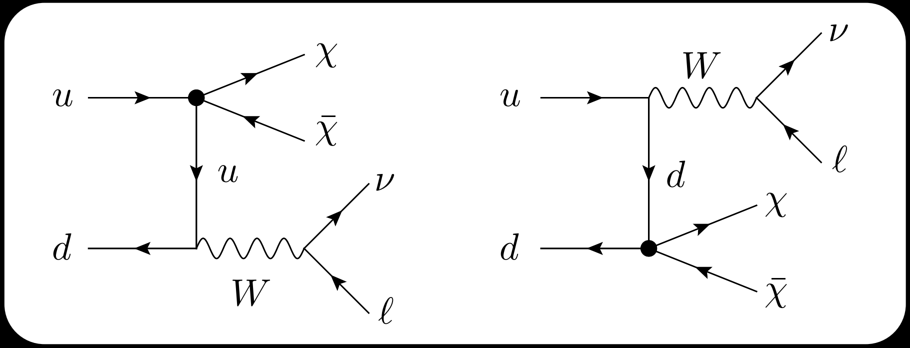
Fox, Harnik, Primulando, Yu 1203.1662

- Though it requires more than one jet, these processes often contain extra radiation, so the loss of acceptance is modest.
- They find modest improvements on the bounds extracted from the monojet analysis alone!



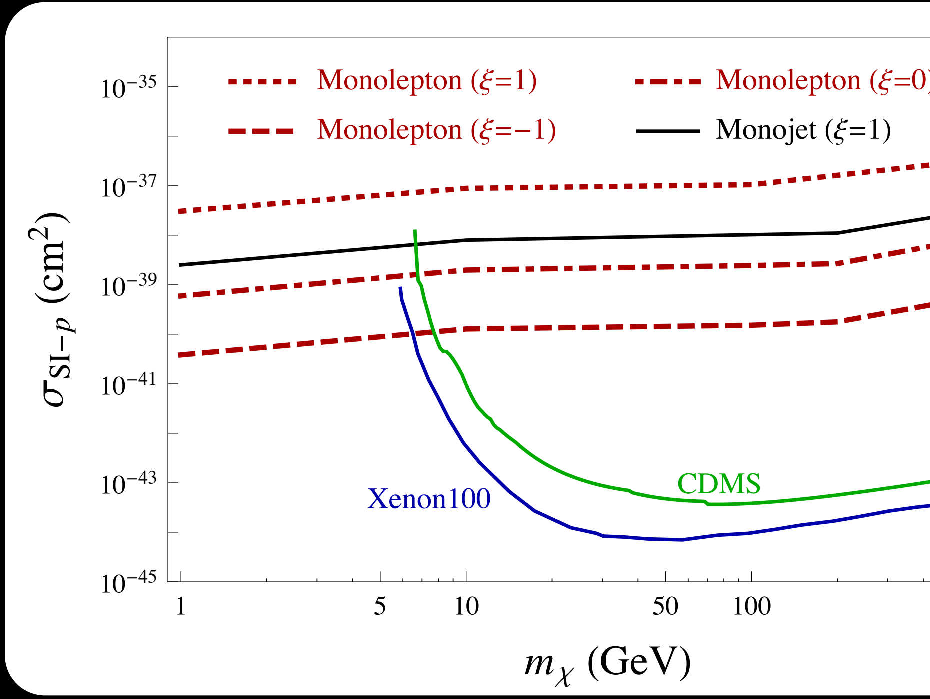
Mono-Whatever

- We've already heard a lot about mono-jets and mono-photons.
- One can imagine similar searches involving other SM particles, such as mono-Ws (leptons), mono-Zs (dileptons), or even mono-Higgs.
- If we're just interested in the interactions of WIMPs with quarks and gluons, these processes are not going to add much.
- But they are also sensitive to interactions directly involving the bosons, and thus are complementary.
- And even for quarks, if we do see something, they can dissect the couplings to different quark flavors, etc.



CMS W' Search

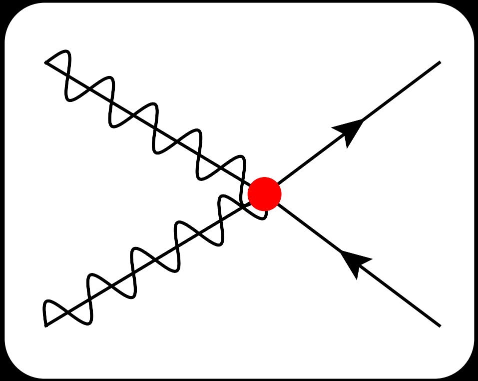
Y. Bai, TMPT, 1207.mono-whenever

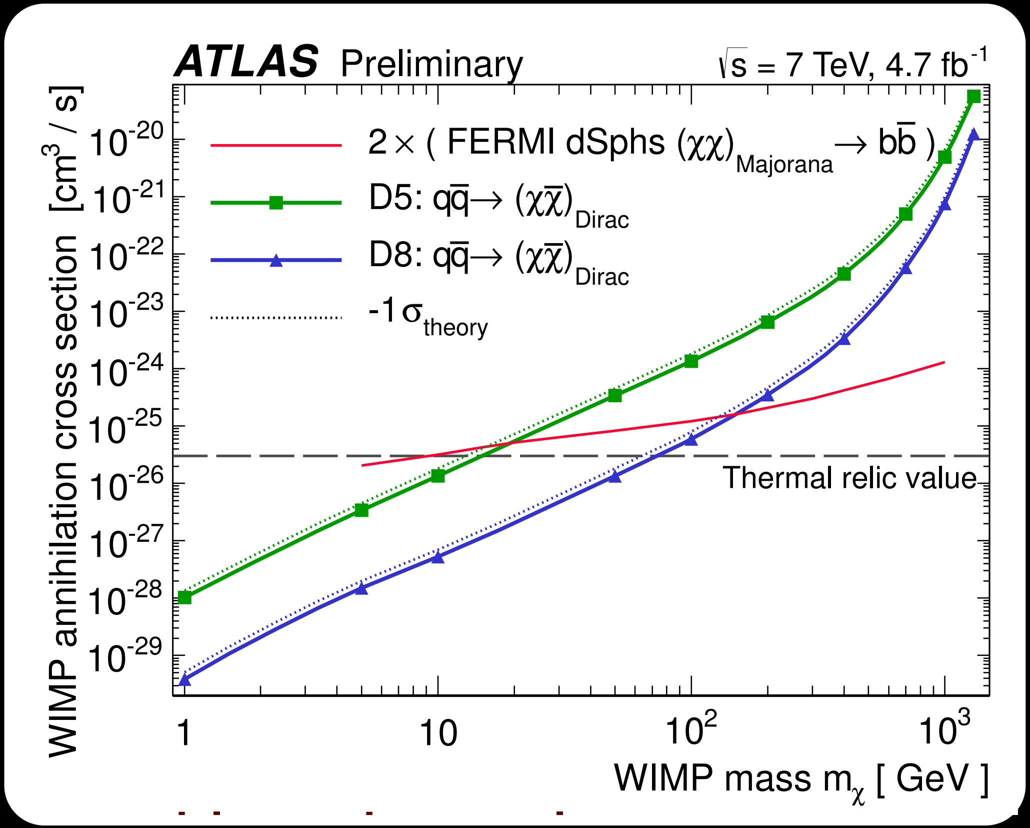


(d coupling) = ξ x (u coupling)

Annihilation into γ-Rays

- We can also map interactions into predictions for WIMPs annihilating.
- For example, into continuum photons from a given tree level final state involving quarks or gluons.
- ATLAS has already presented their results in terms of a corresponding annihilation cross section.
- With assumptions, this maps onto a relic density.
- For operators which lead to p-wave annihilations, the colliders can lead to more stringent bounds than Fermi LAT.



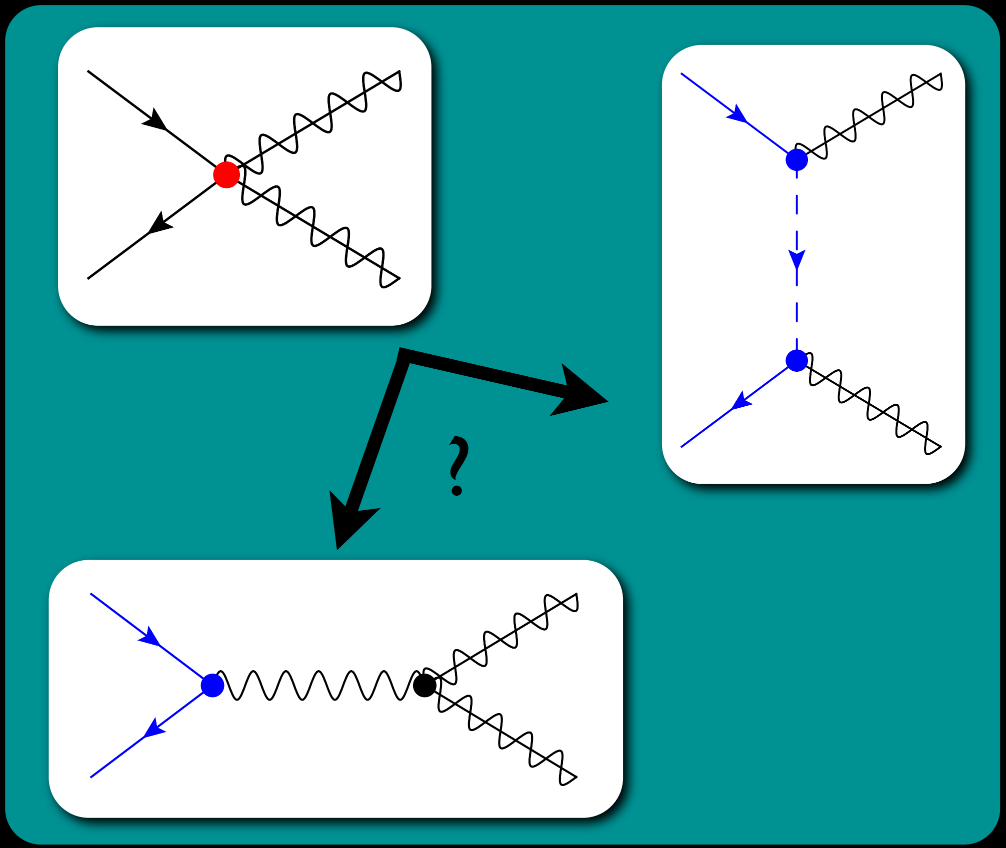


How Effective a Theory?

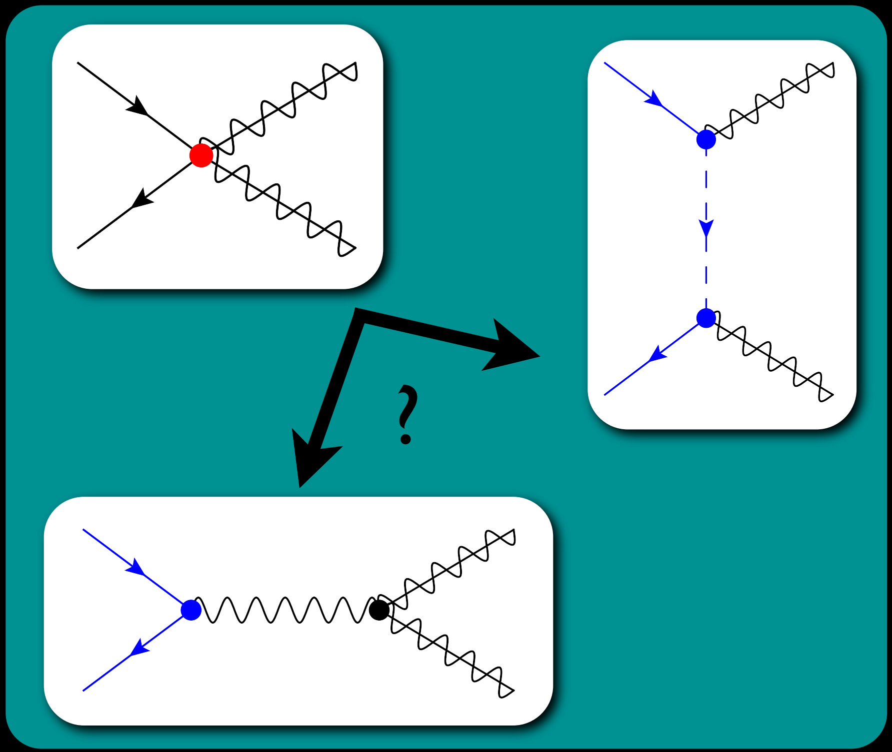
- How good is the EFT approximation?

- It depends on the momentum transfer of the process.
- Direct Detection: $Q^2 \sim (50\ \text{MeV})^2$.
  - EFT should work well unless you have ultralight mediators.
- Annihilation: $Q^2 \sim M^2$.
  - Fine in SUSY-like theories, problematic for quirky WIMPs or maybe co-annihilators.
- Colliders: $Q^2 \sim p_T^2$
  - Bounds are generically too conservative for colored mediators.

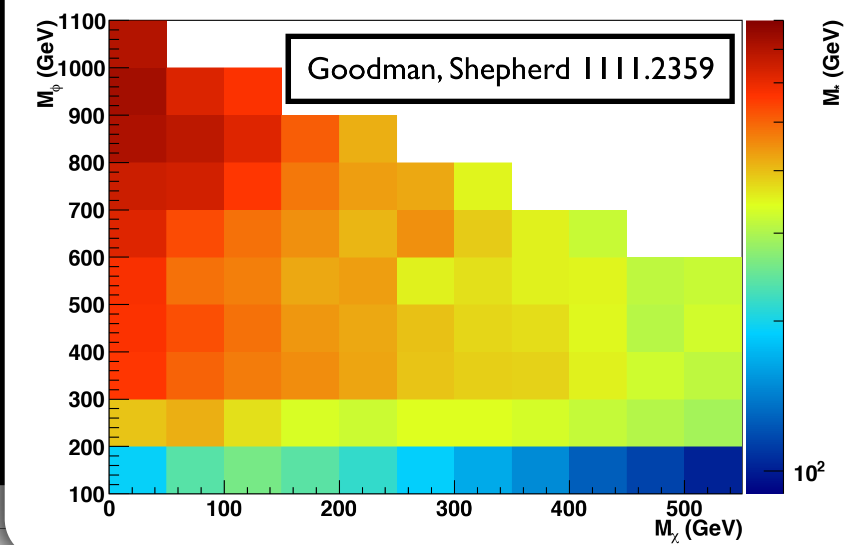
  - Too stringent for light neutral mediators.



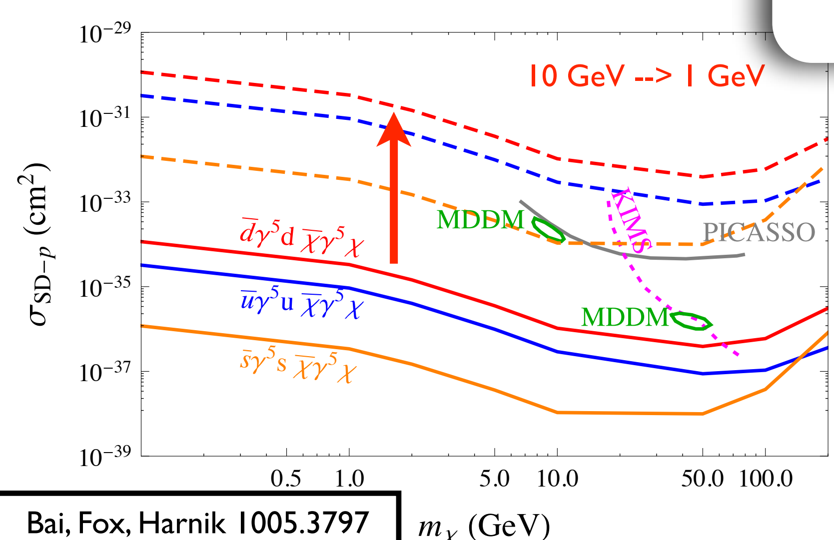
How Effective a Theory?



"t-channel" mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass.



"s-channel" mediators are not protected by the WIMP stabilization symmetry. They can couple to SM particles directly, and their masses can be larger or smaller than the WIMP mass itself.



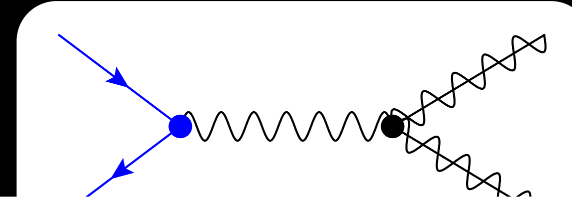
Bai, Fox, Harnik 1005.3797

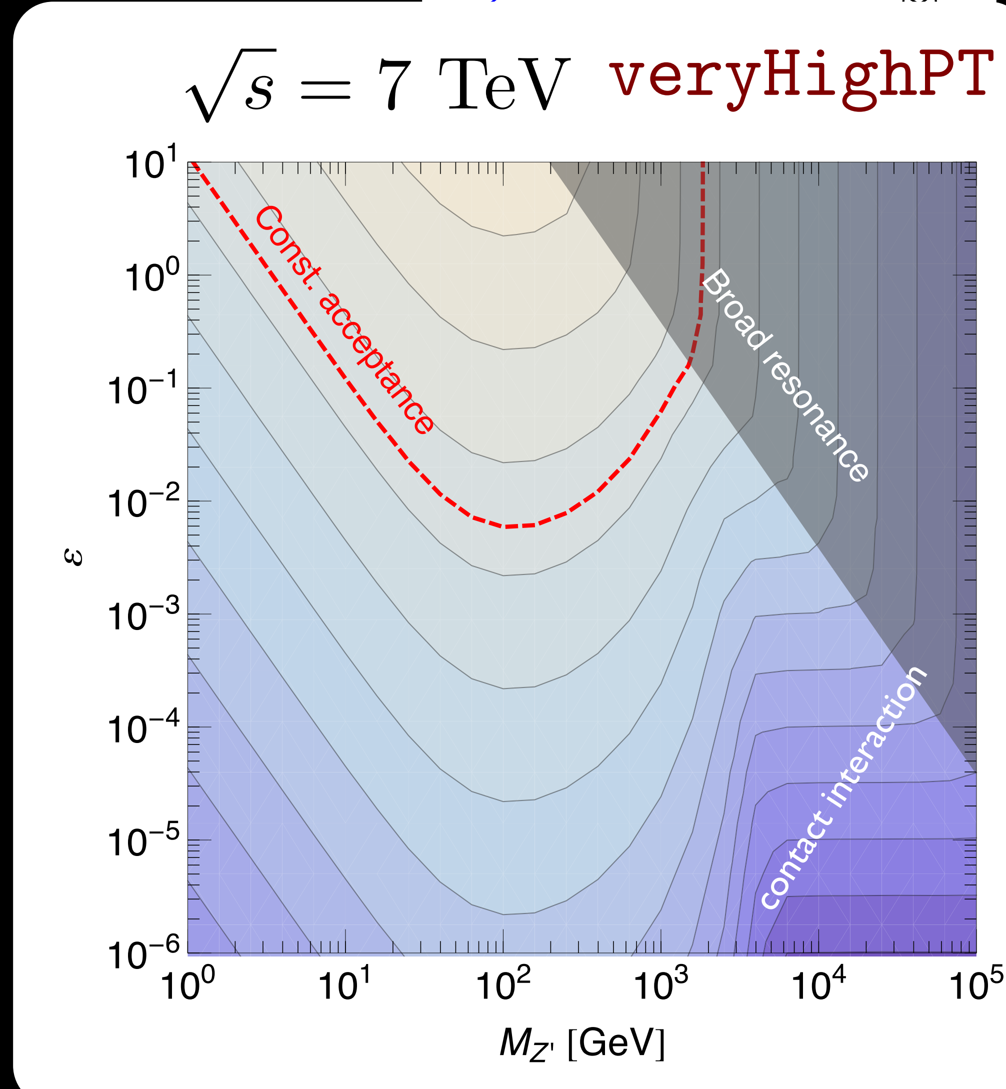
Resolving Mediators

- The EFT is only a particular limit of a space of simplified models which can describe WIMPs.
- For example, the mediating particles can be included explicitly.
- In this way contact interactions can be resolved into simplified models.
- For example, a Z' UV completion.

Frandsen, Kahlhoefer, Preston, Sarkar, Schmidt-Hoberg 1204.3839

- For a given collider energy and, we can see the different regimes of Z' mass and coupling.
- t-channel completions map easily onto existing simplified models.



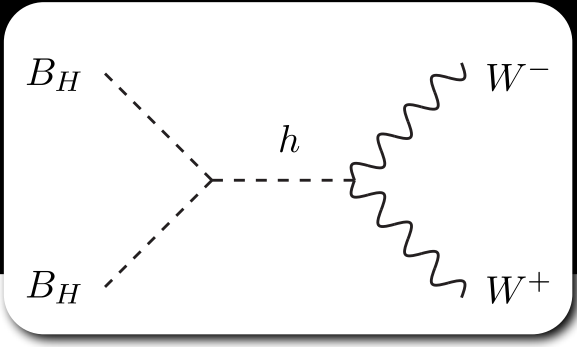


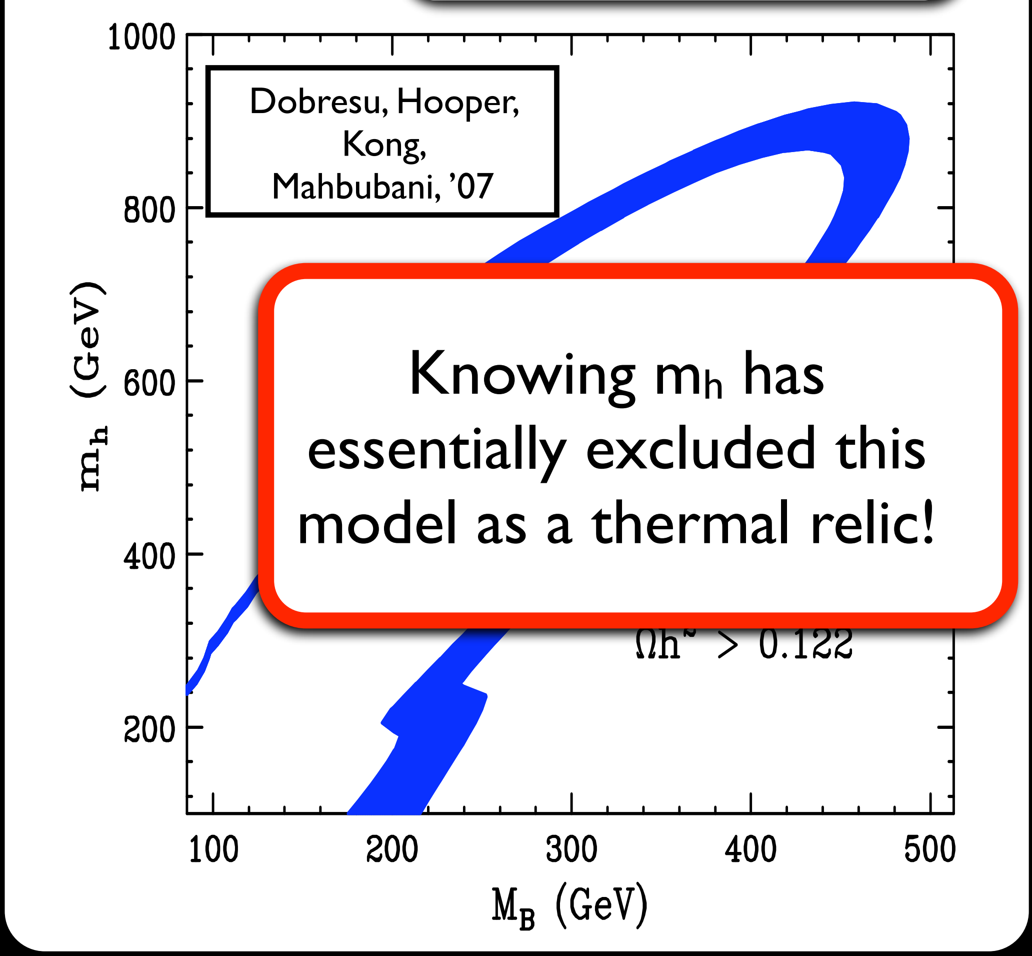
$$\epsilon = g^2/M_{Z'}^2$$

Ian Shoemaker, talk at UC Davis 4/13/2012

Higgs, Higgs, Higgs

- In a 6d UED model, the WIMP primarily interacts with the SM through Higgs exchange.
- Annihilation typically goes through an s-channel SM Higgs boson.
- Generally, the relic density favors LKP masses between 50 to about 500 GeV, provided the Higgs mass is chosen to match.
- For a Higgs mass around 125 GeV, we would expect a host of colored KK modes with masses around 60 GeV which would decay to jets plus missing energy.

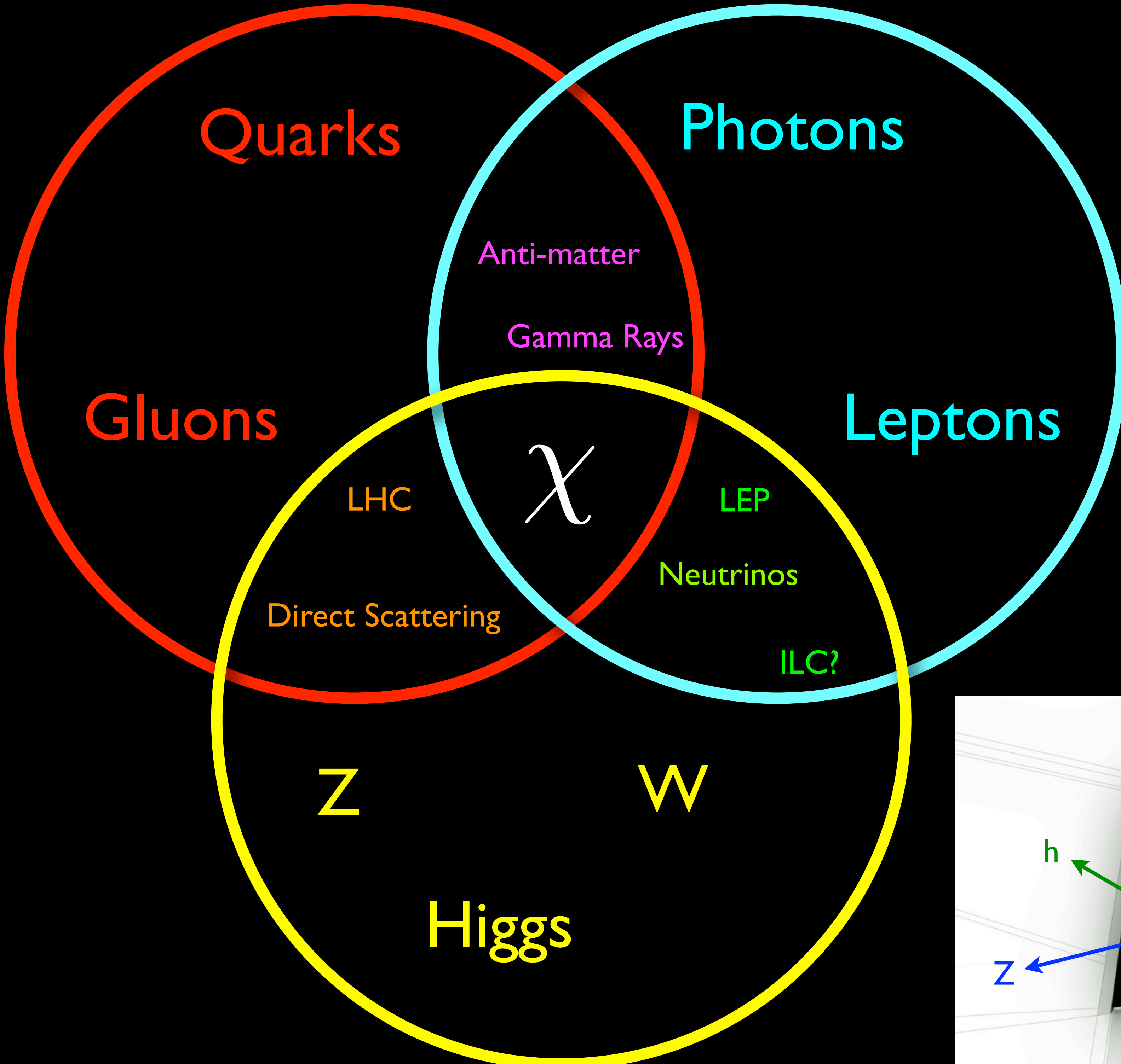




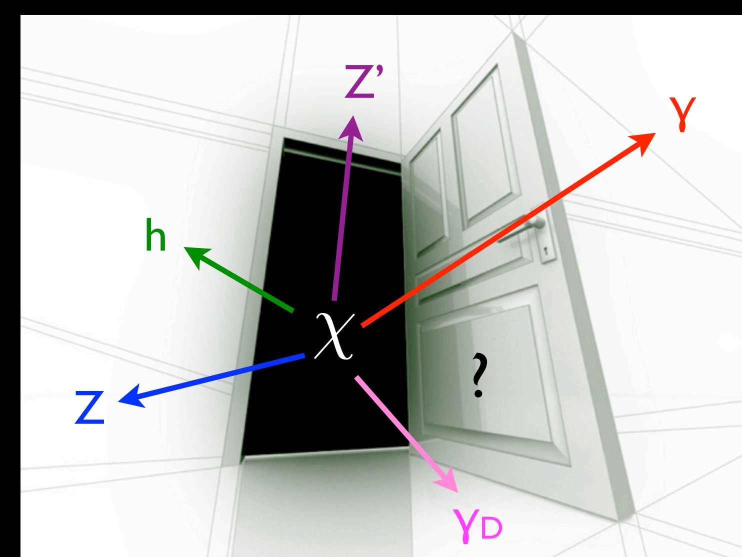
Knowing m_h has essentially excluded this model as a thermal relic!

Outlook

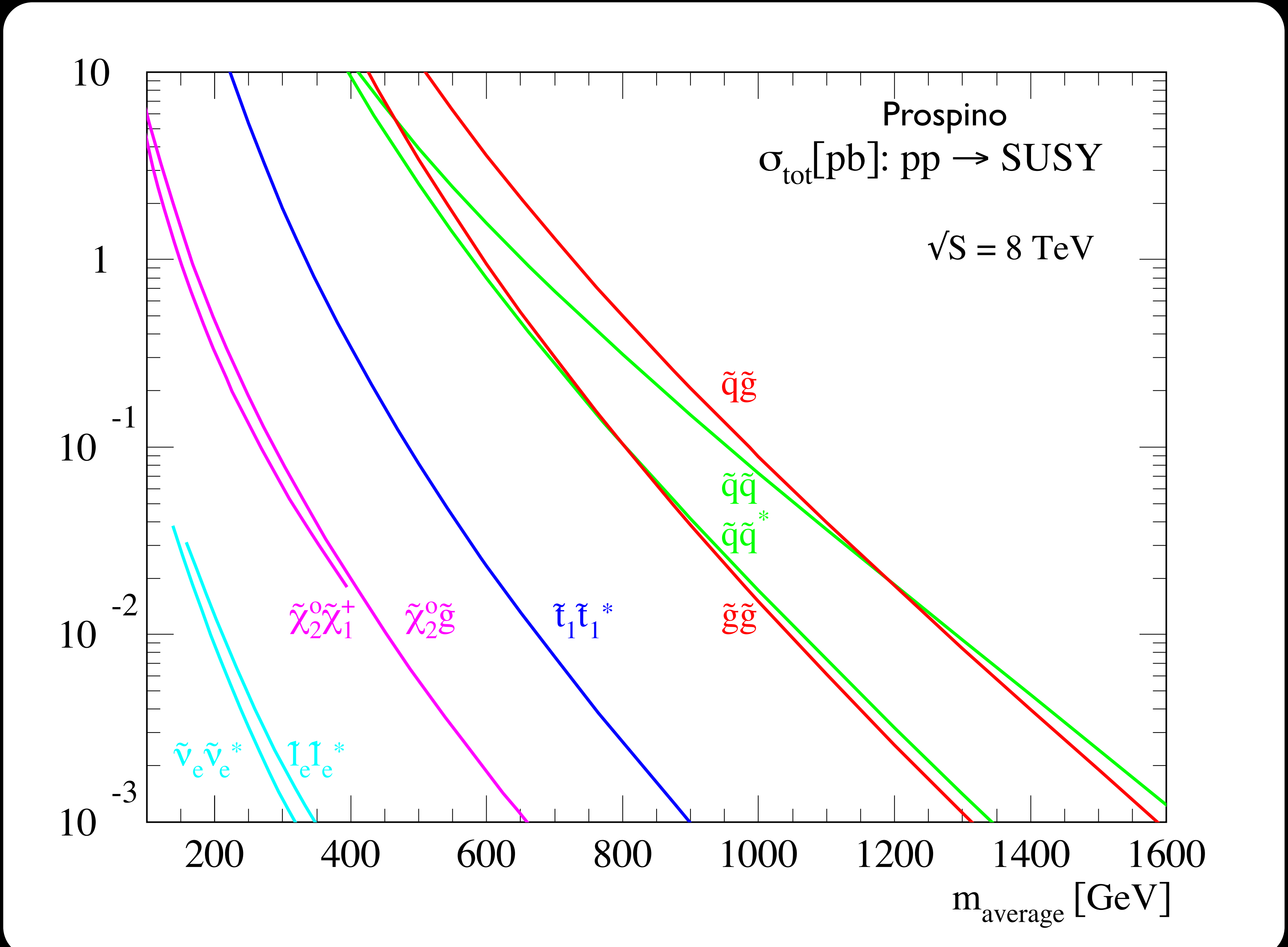
- LHC Searches for new phenomena are going strong!
- Already big statements are being made about missing energy, dark matter, and supersymmetric theories with R-parity conservation.
- The next year will get into very interesting territory, with sensitivity to scalar stops, gluinos, and electroweak gauginos which should cover a lot of well-motivated regions of SUSY parameter space.
  - (And to say nothing about the Higgs mass and the MSSM...)
- More direct maverick production of dark matter is less effective than traditional SUSY searches if we can produce colored mediator particles directly. If they are too heavy, maverick production will be how we fall back to quantify limits on dark matter interactions, and make contact between accelerator data and (in)direct searches.
- We can design simplified models to deal with theories which are not in the contact interaction limit, by including mediators in the effective field theory.


Quarks
Photons
Anti-matter
Gamma Rays
Gluons
Leptons
LHC
χ
LEP
Neutrinos
Direct Scattering
ILC?
Z
W
Higgs


PHYSICS OF THE
dark universe


Z'
γ
h
χ
Z
?
γ_D

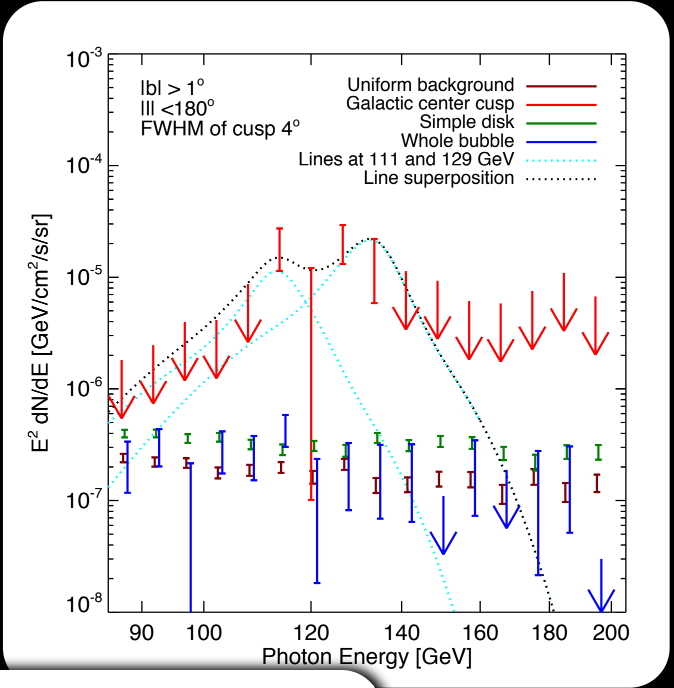
Bonus Material



The beauty of colored particle production is its rate is often largely model-independent (just QCD).

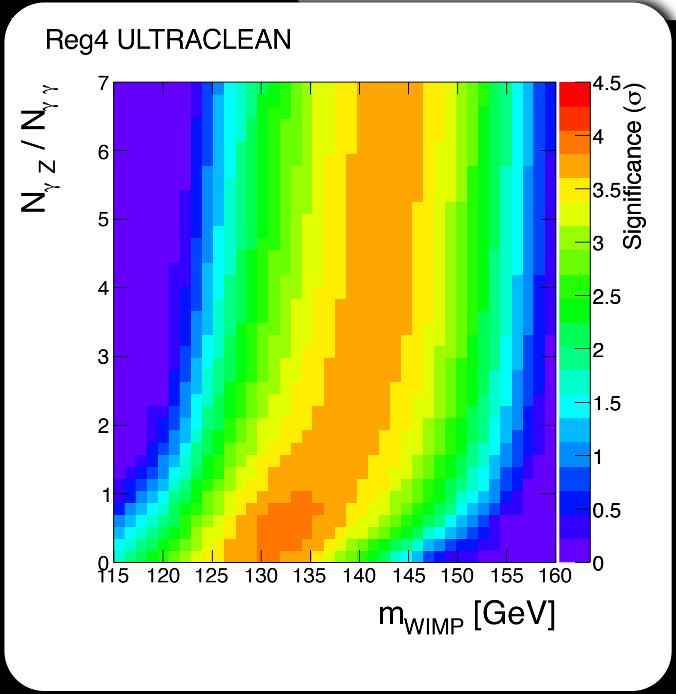
EFTs for Lines

Finkbeiner, Su 1206.1616



- We can play the same games with effective interactions leading *directly* to gamma ray lines.
- The operators consistent with gauge and Lorentz invariance reveal an interesting feature -- every likely operator leads to at least two lines, $\gamma\gamma+\gamma Z$ or $\gamma Z+\gamma h$.

Rajaraman, TMPT, Whiteson 1205.4723

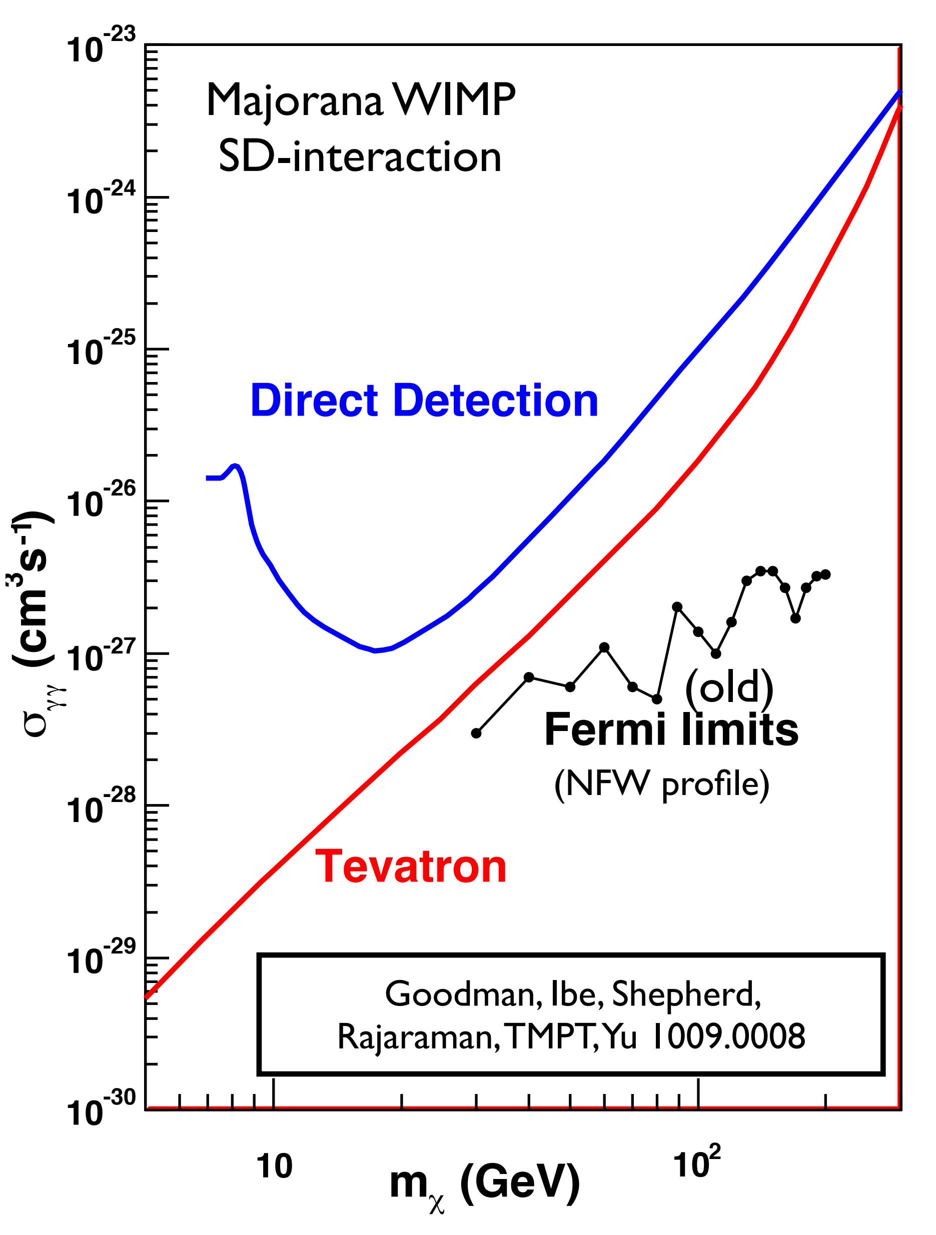


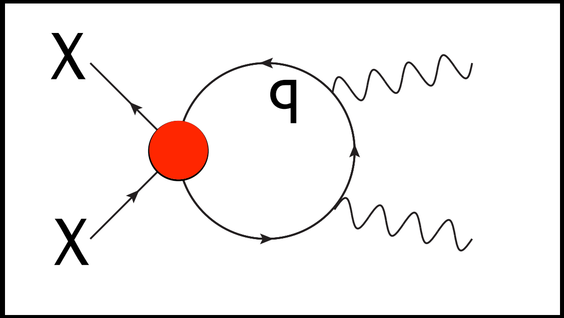
- This is not shocking, but it does suggest a new feature to look for in line searches: two lines at correlated energies!

$$\chi\chi \to \gamma Y \quad : E_\gamma = m_\chi \left(1 - \frac{M_Y^2}{4m_\chi^2}\right)$$

More on the line tomorrow from Simona, Andi, Francesca, ???

Gamma-Ray Lines





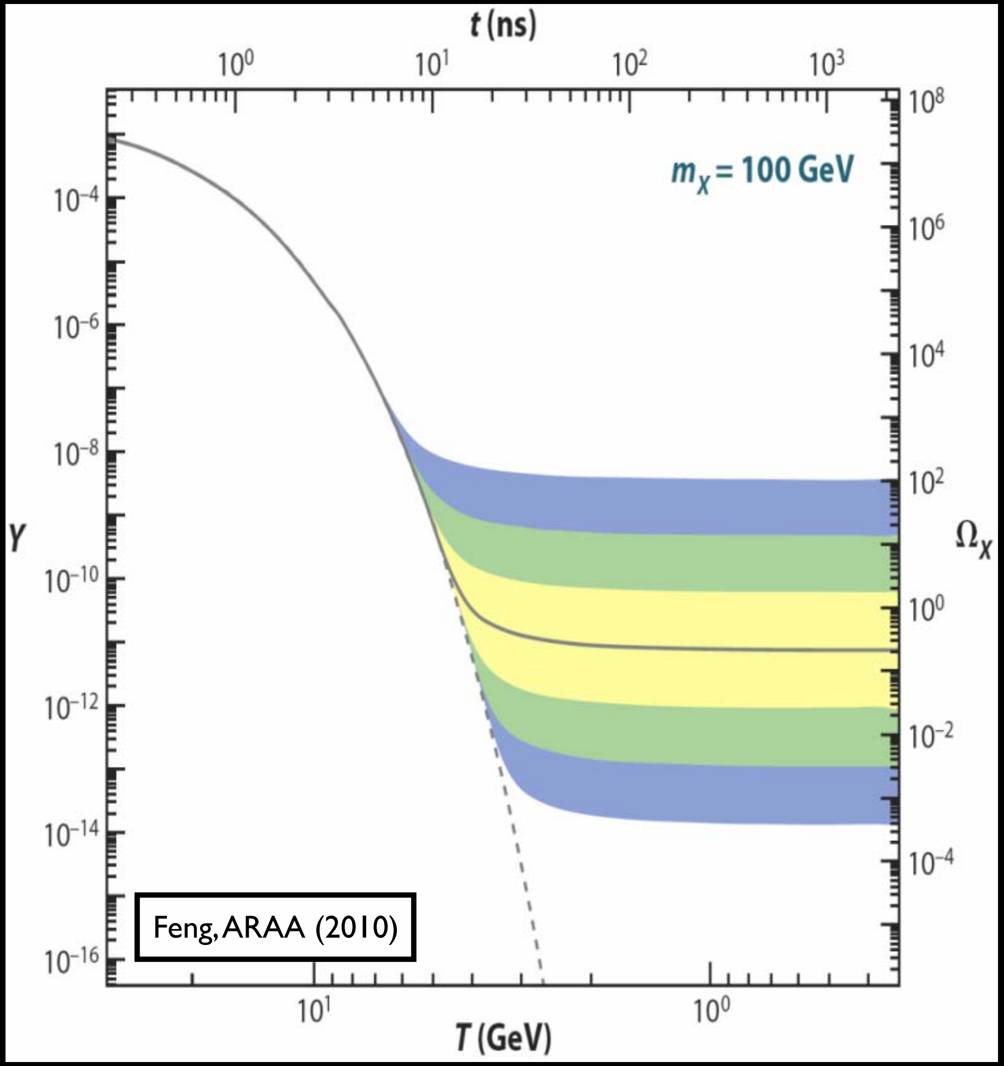
- The effective theory language can also be effectively mapped into indirect searches for dark matter.
- For example, interactions with quarks can be closed into loops and turned into annihilation into gamma ray lines.
- The Fermi limits are actually the best ones for some operators (such as for spin-dependent interactions).
- ATLAS has also studied continuum annihilation signals in the EFT framework.

Relic Density

- If dark matter is a thermal relic, annihilation into the SM control its abundance in the Universe.
  - The observed relic abundance is suggestive of a cross section:

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

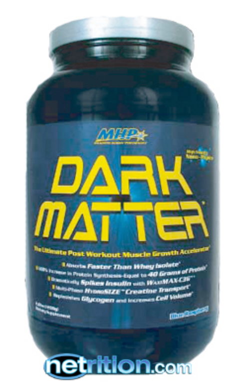
  - Without a detailed model, it isn't clear how to translate it into an LHC or direct detection rate.
  - The dark matter could also be produced non-thermally, or the history of the Universe could be non-standard.



Feng, ARAA (2010)

$49.99 for 20 servings

Available in Blue Raspberry, Fruit Punch, and Grape flavors....



“Bounds” from Unitarity

- Even if we don’t want to worry about a UV theory and whether the EFT is a good approximation to it or not, we can still sometimes tell the EFT description is sick.
- There are regimes where the effective theory admits no perturbative UV completion.
- Non-renormalizable theories are intrinsically sick at high energies, leading to a break-down of perturbative unitarity. If this happens at energies we are interested in, our description at those energies is highly suspect.
    - Where this occurs at the LHC is not trivial to define.

Shoemaker, Vecchi 1112.5457