Interplay of direct and collider searches for dark matter

GRAPPA

GRavitation AstroParticle Physics Amsterdam

Christopher McCabe

with thanks to my collaborators:
Oliver Buchmueller, Matthew Dolan & Sarah Alam Malik

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Outline

- The dark matter problem

- Detection principles of dark matter searches at…
  - …direct detection experiments
  - …the LHC

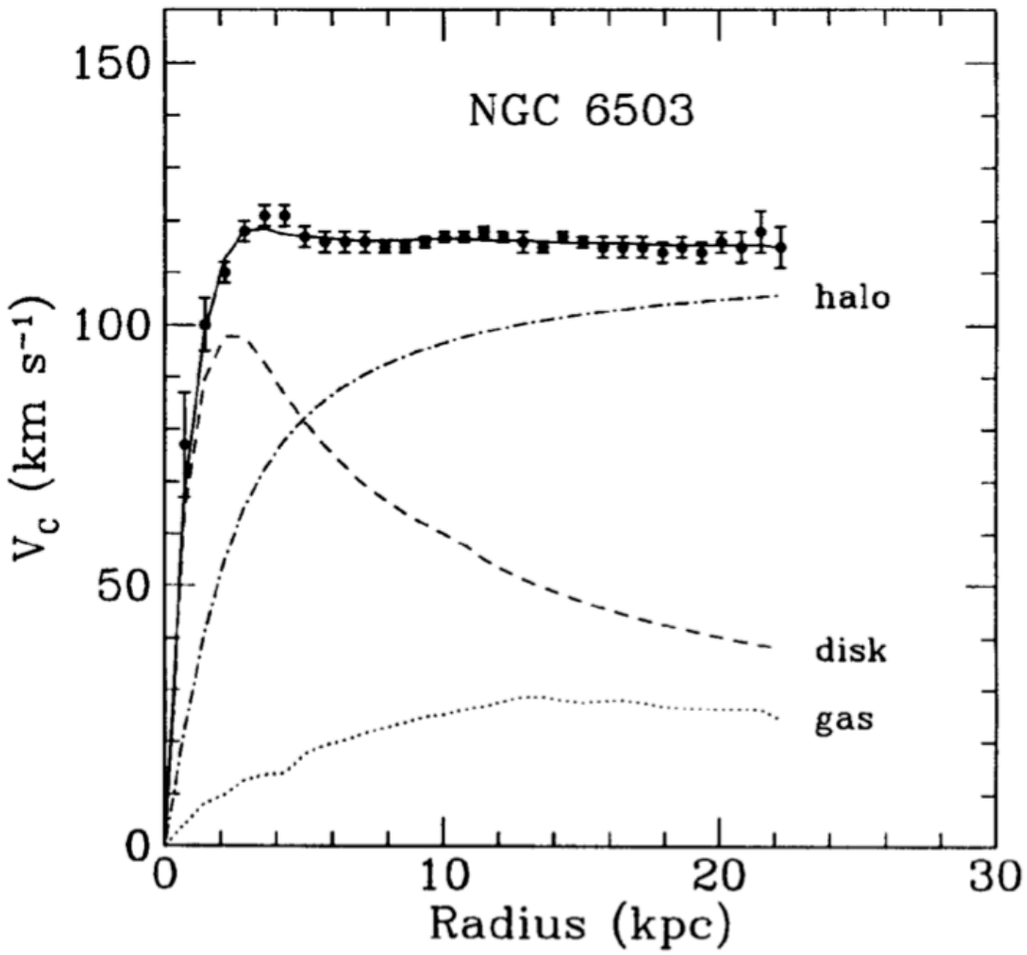
- Interpreting dark matter searches at…
  - …direct detection experiments
  - …the LHC

- A framework to interpret both

Dark matter is everywhere

- Dark matter is a necessary component in our Universe:

- Galaxies



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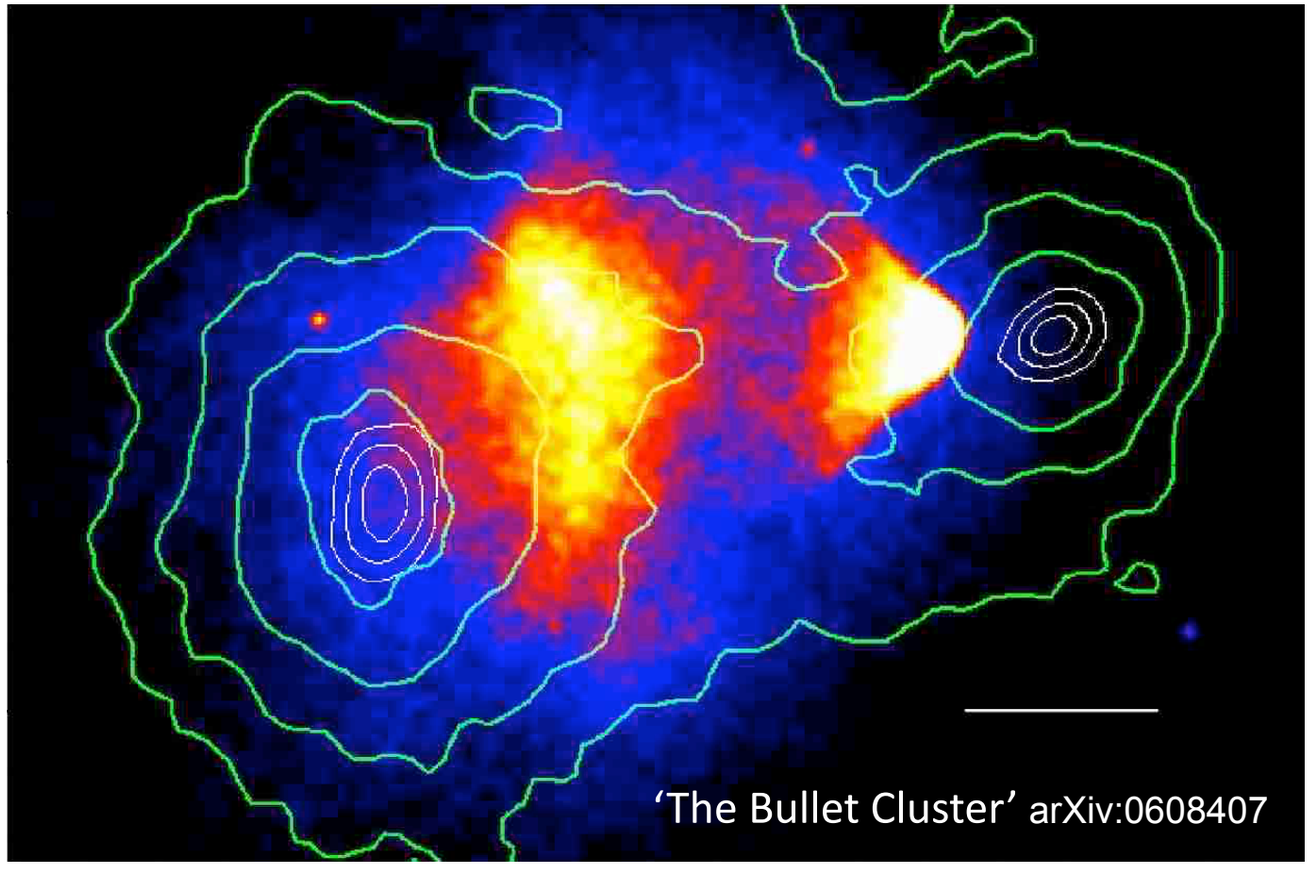

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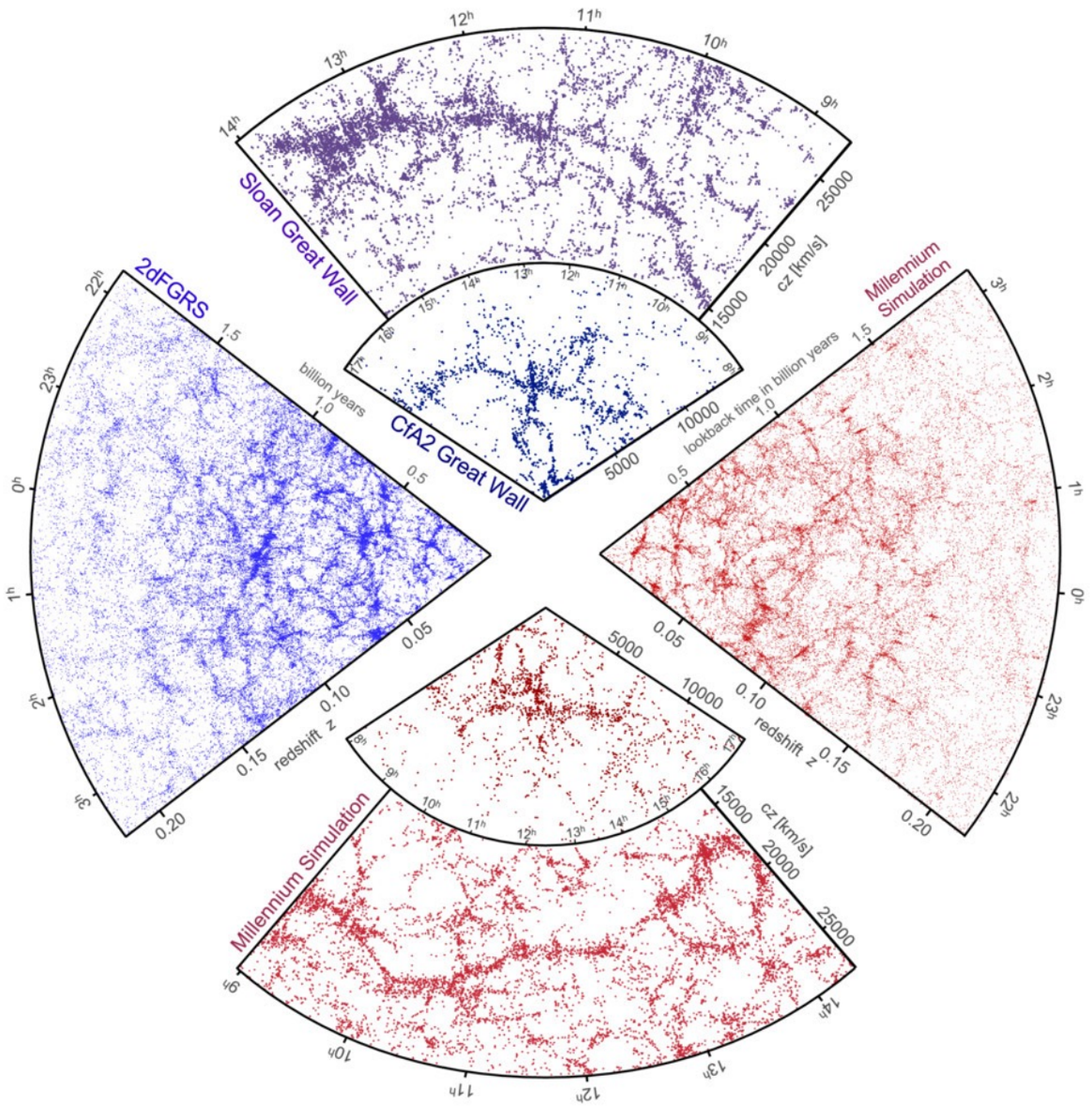
- Galactic clusters

- Large scale structures



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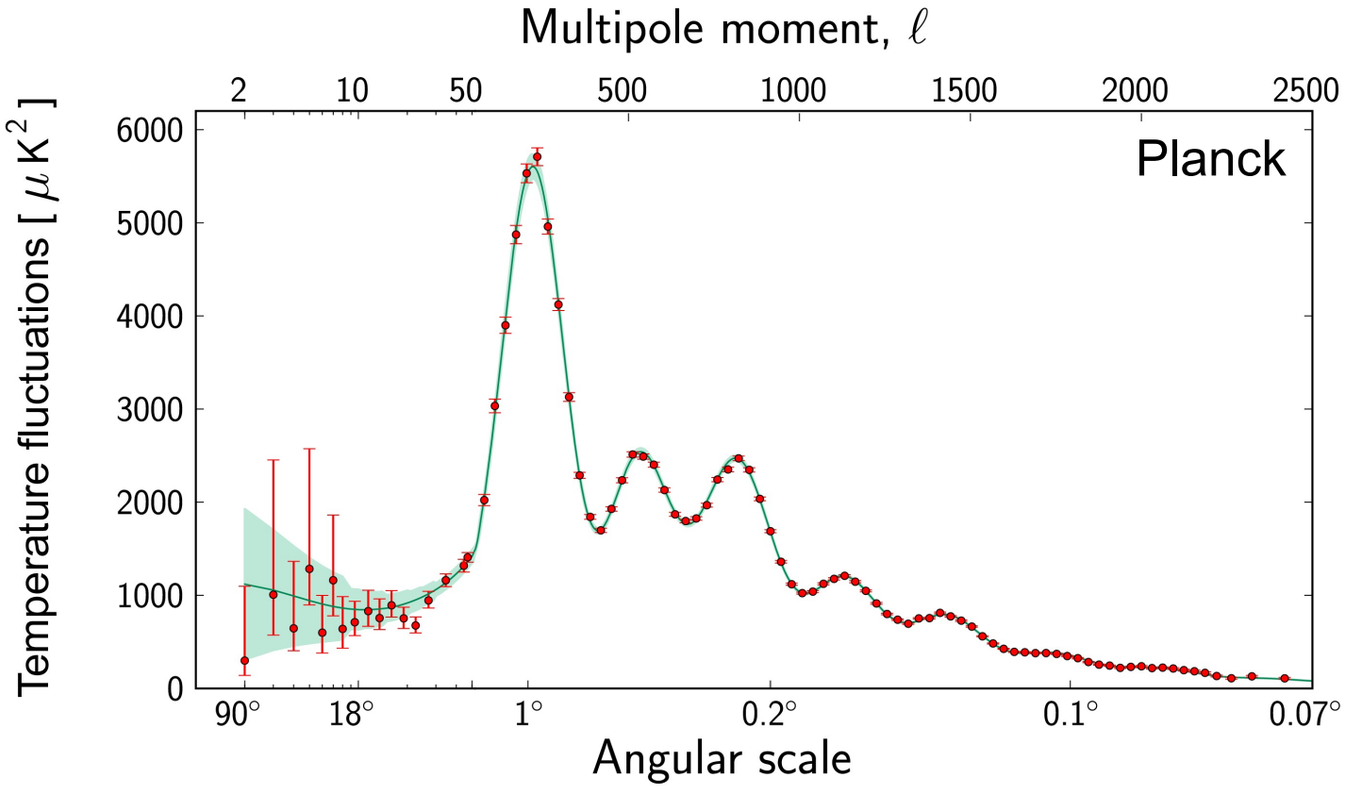
- Galactic clusters

- Large scale structures

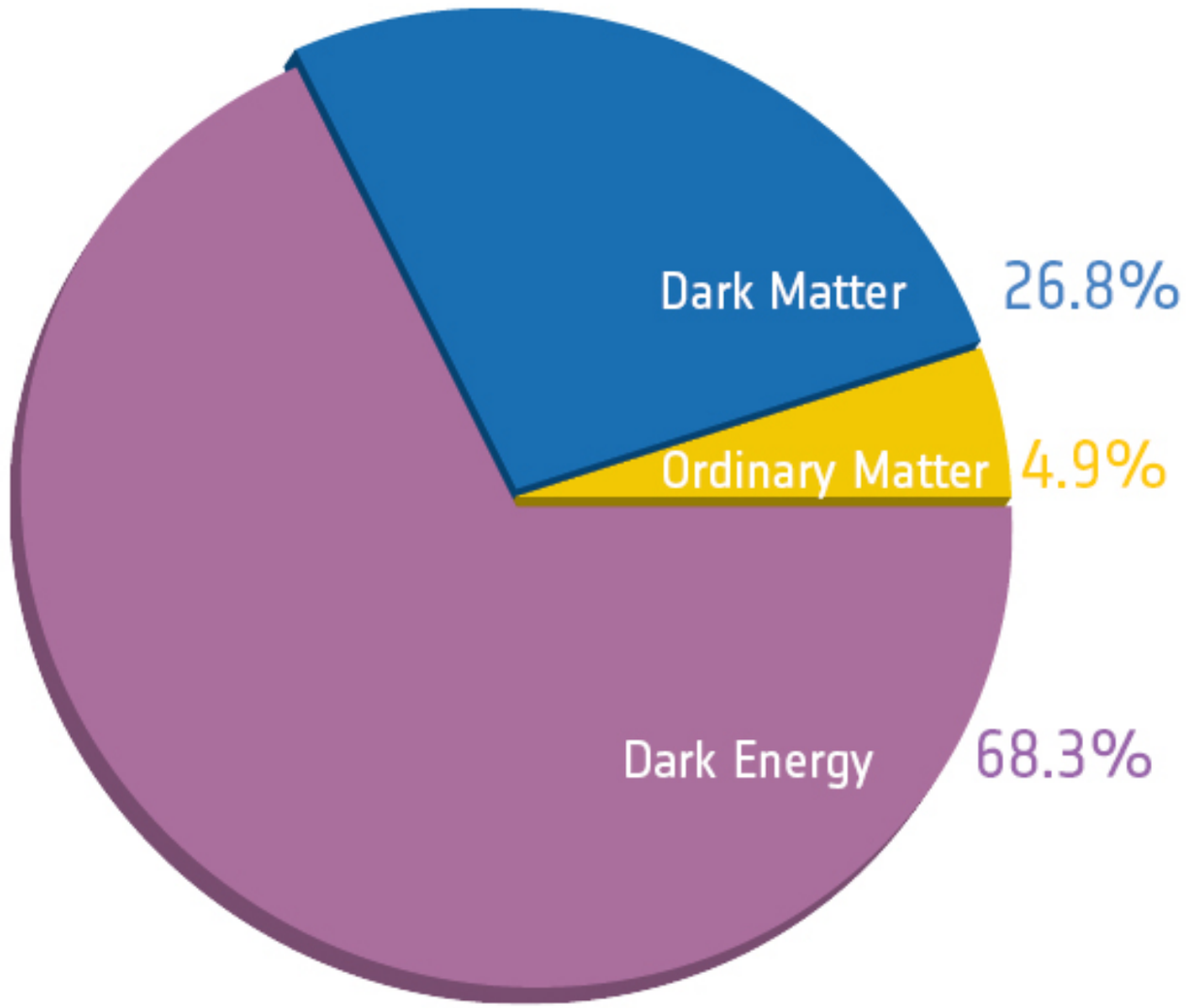
- CMB fluctuations



Dark matter is abundant

After Planck

$$\Omega_{\rm DM} h^2 = 0.1187 \pm 0.0017$$

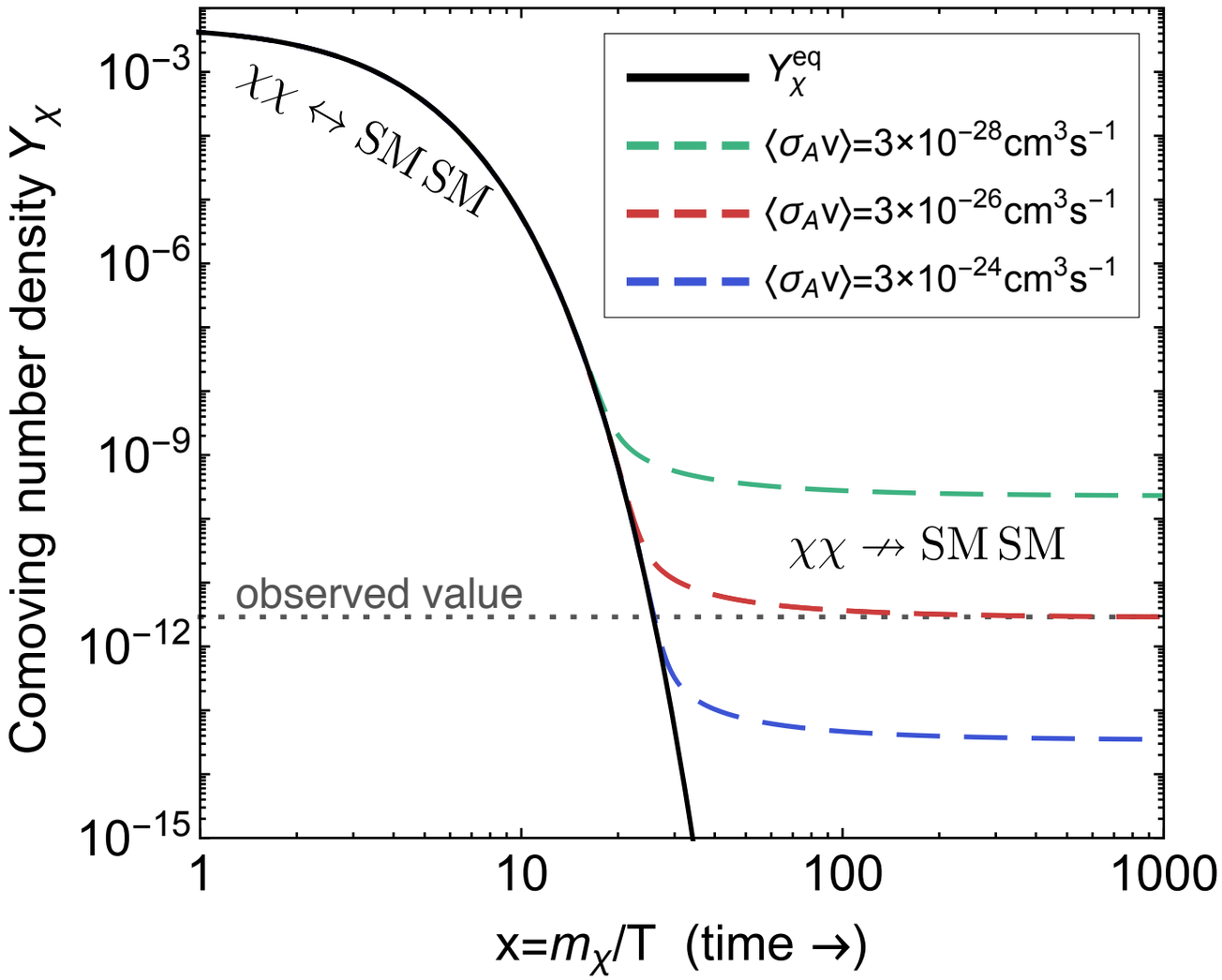


Dark matter candidates

- WIMPs: Weakly Interacting Massive Particles
- Asymmetric dark matter
- Axions
- Sterile neutrinos
- Topological configurations
- SuperWIMPs
- FIMPs: Feebly Interacting Massive Particles
- … *(theorists are inventive)*

WIMPs: thermal freeze out

- Weak-scale interactions + thermal freeze out gives the observed abundance



$$\Omega_{\rm DM} h^2 \simeq 0.1 \, \frac{3 \times 10^{-26} \ {\rm cm}^3 {\rm s}^{-1}}{\langle \sigma_A v \rangle}$$

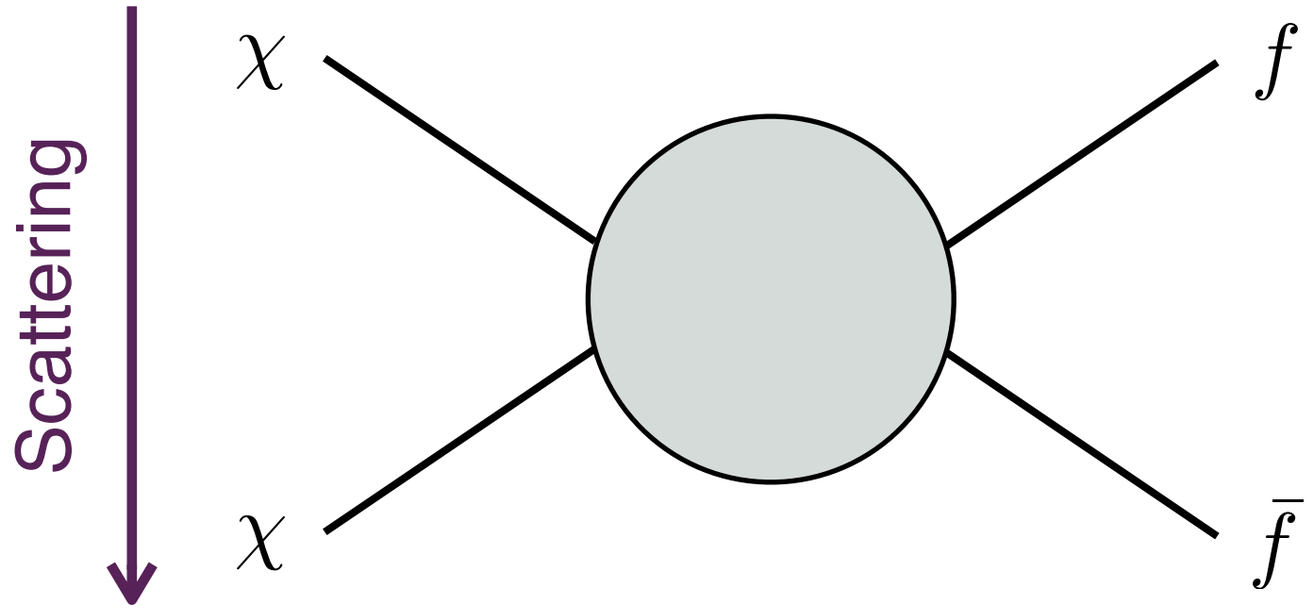
$$\begin{aligned} \text{weak scale} &\sim 3 \times 10^{-26} \ {\rm cm}^3 {\rm s}^{-1} \\ &\simeq 1 \ {\rm pb} \\ &\simeq 10^{-36} \ {\rm cm}^2 \end{aligned}$$

Weak scale interactions are testable

Detecting WIMPs

- There are three main detection strategies:

- Direct detection



Detecting WIMPs

- There are three main detection strategies:

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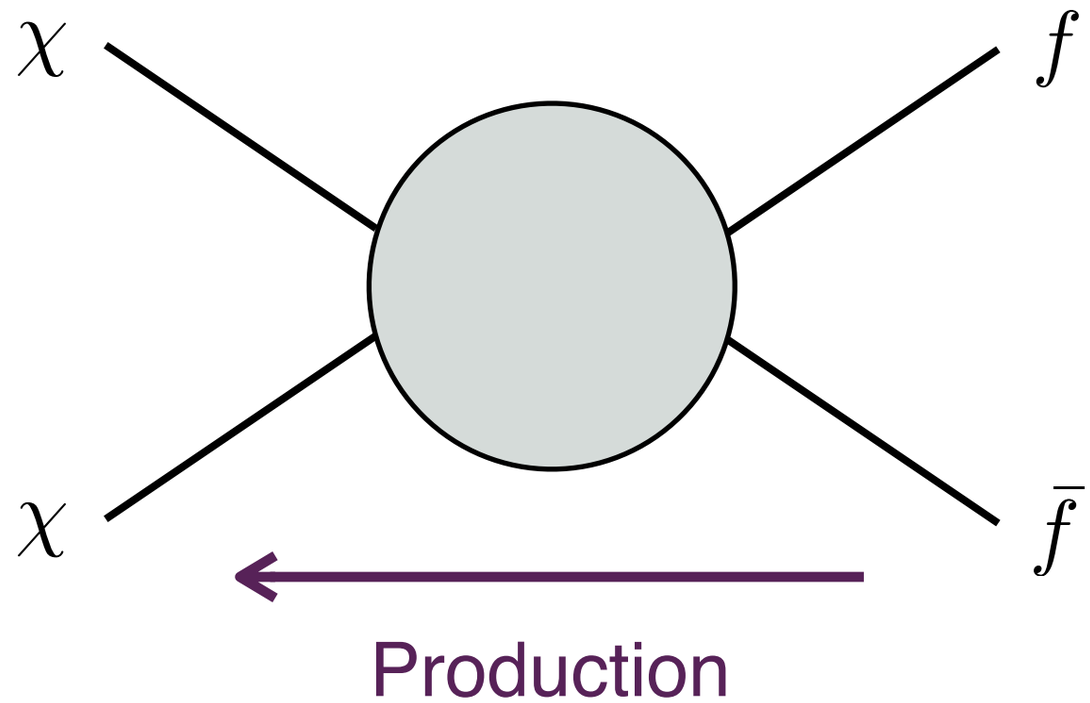
- Collider production



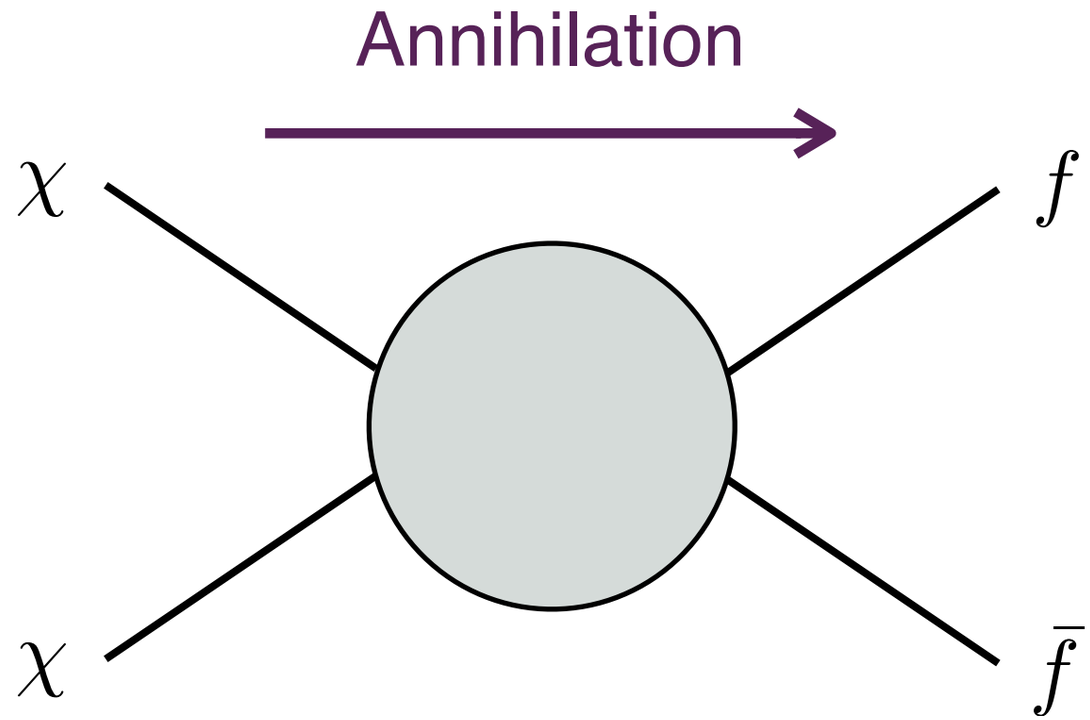
Detecting WIMPs

- There are three main detection strategies:

- Direct detection

- Collider production

- Indirect detection



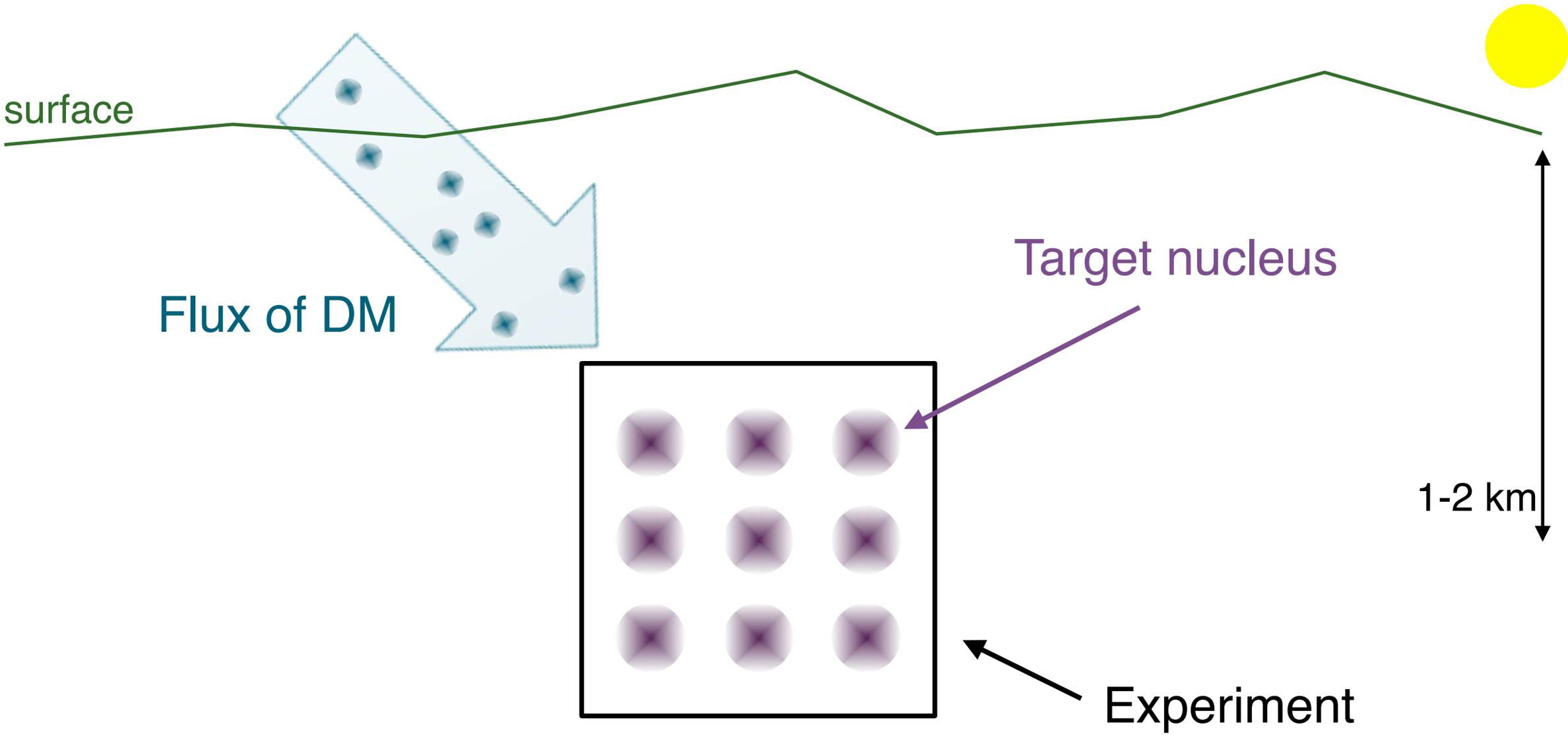
Interpreting searches

- We don’t know the correct theory of dark matter

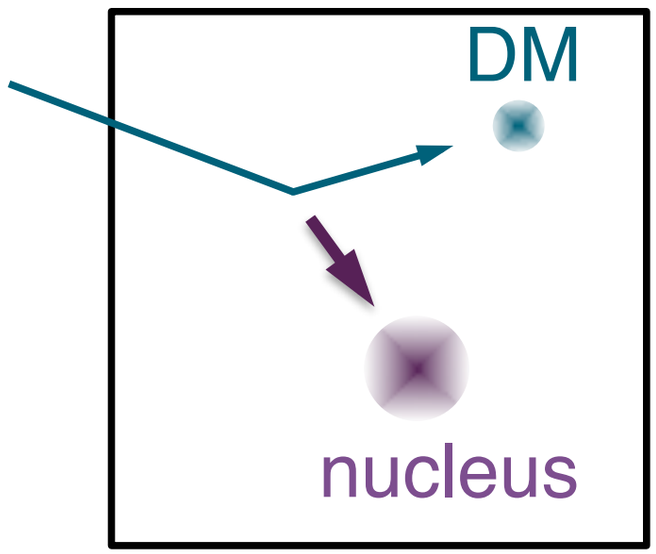
- Search results should be presented within a general framework that constrains a large number of theories

- Interpret searches from
  1. Direct detection (LUX)
  2. Collider (LHC monojet)

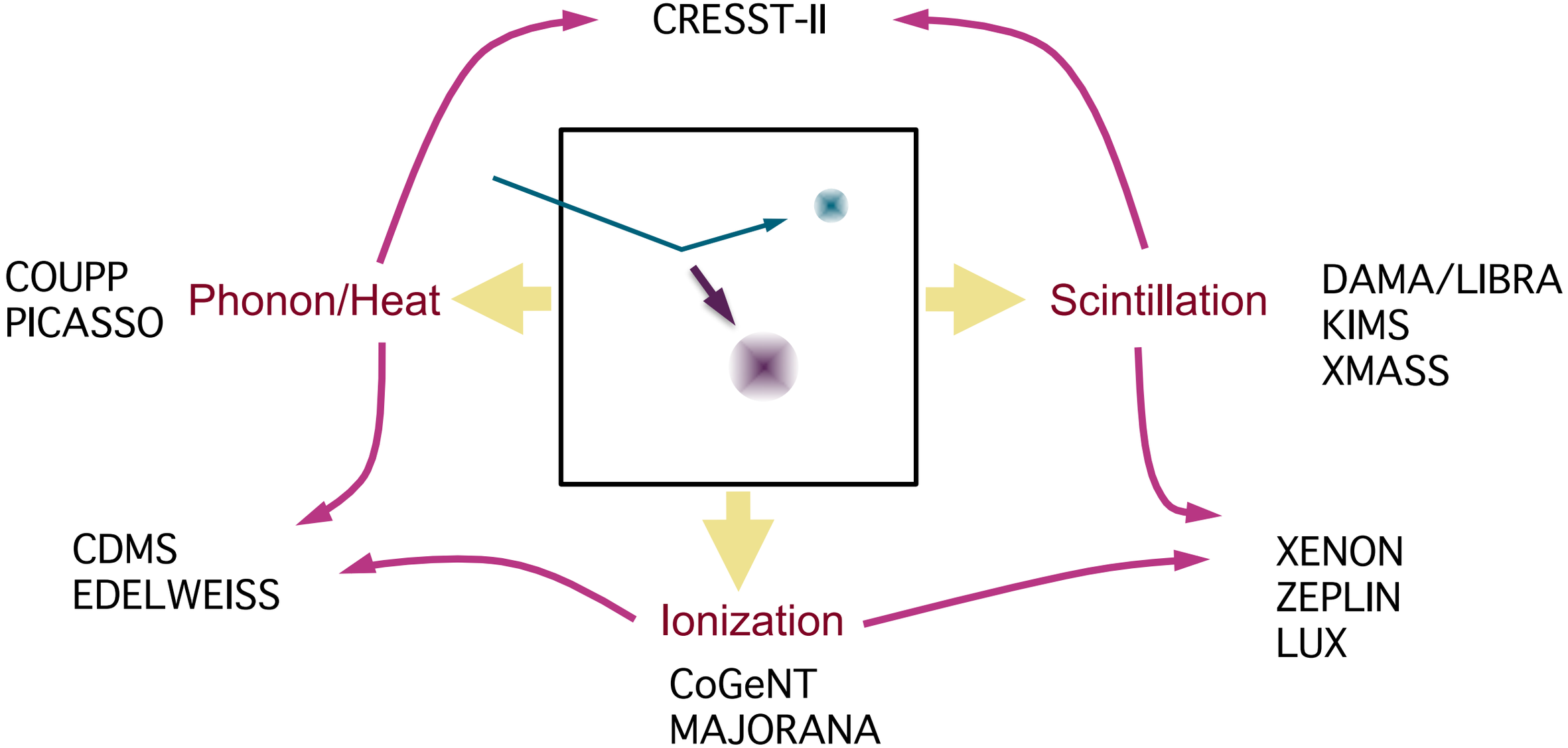
Direct detection: basics



Direct detection: basics

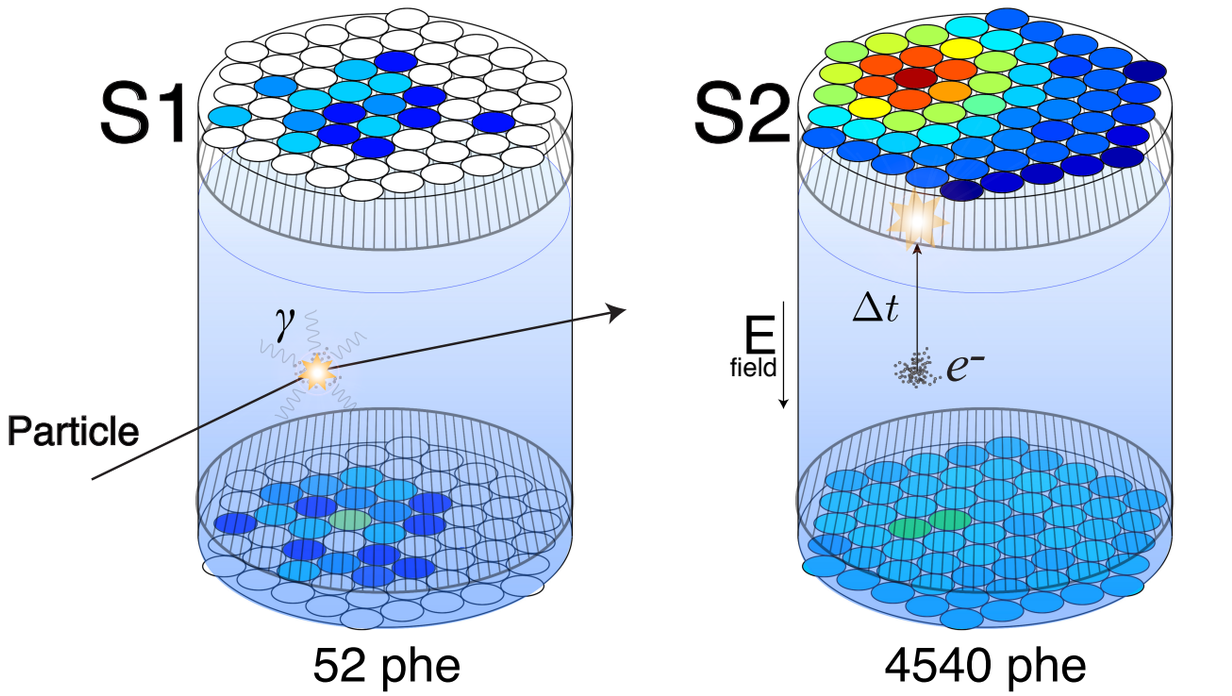


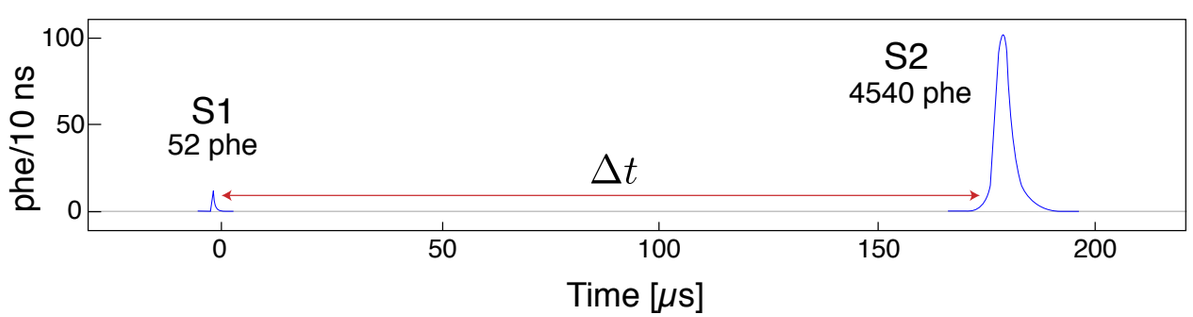
Direct detection: basics



LUX

- A two-phase experiment (liquid and gas)
- Scattered particles create two pulses: S1 and S2

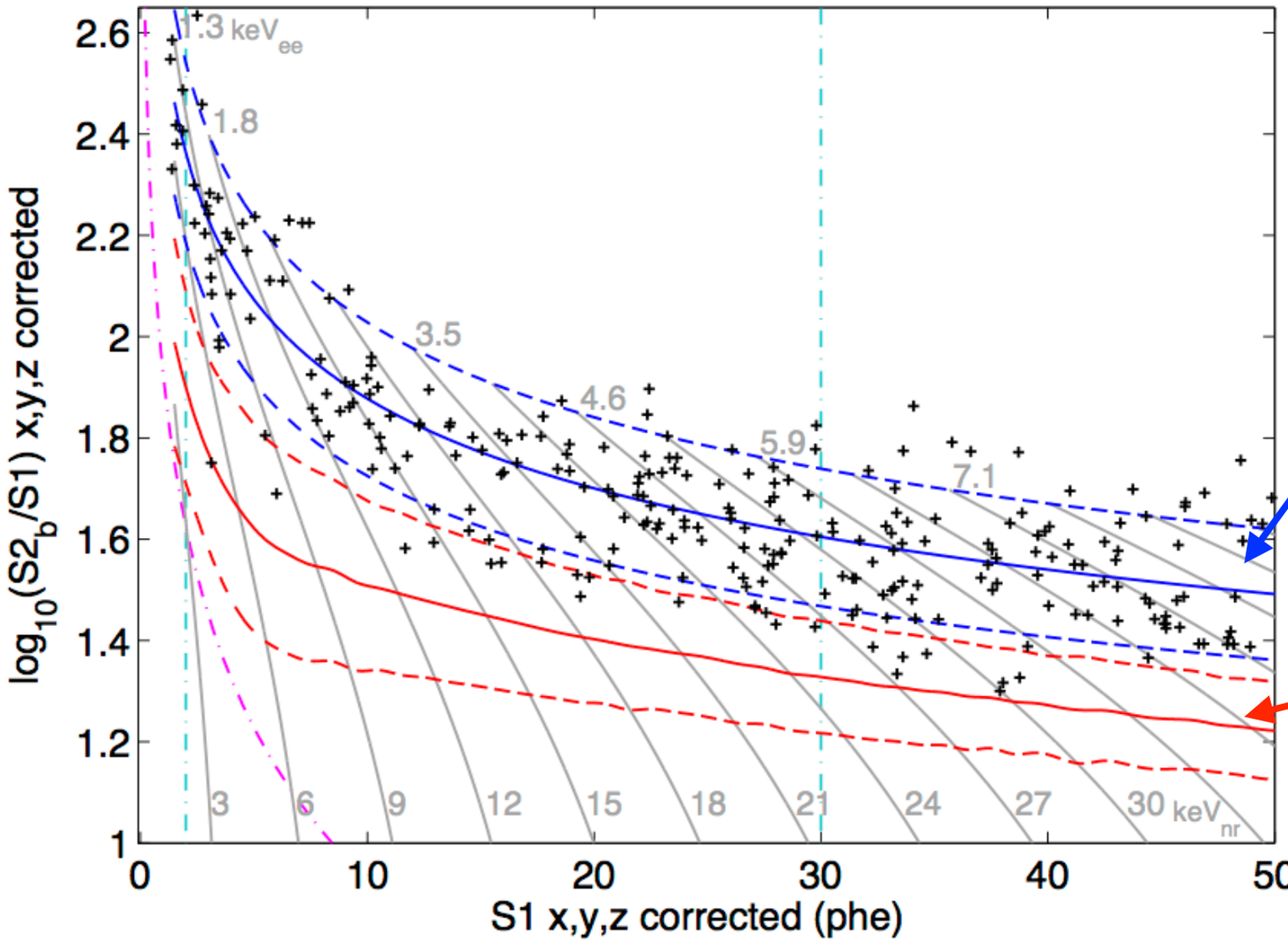




LUX

- Can discriminate between electromagnetic and nuclear recoils

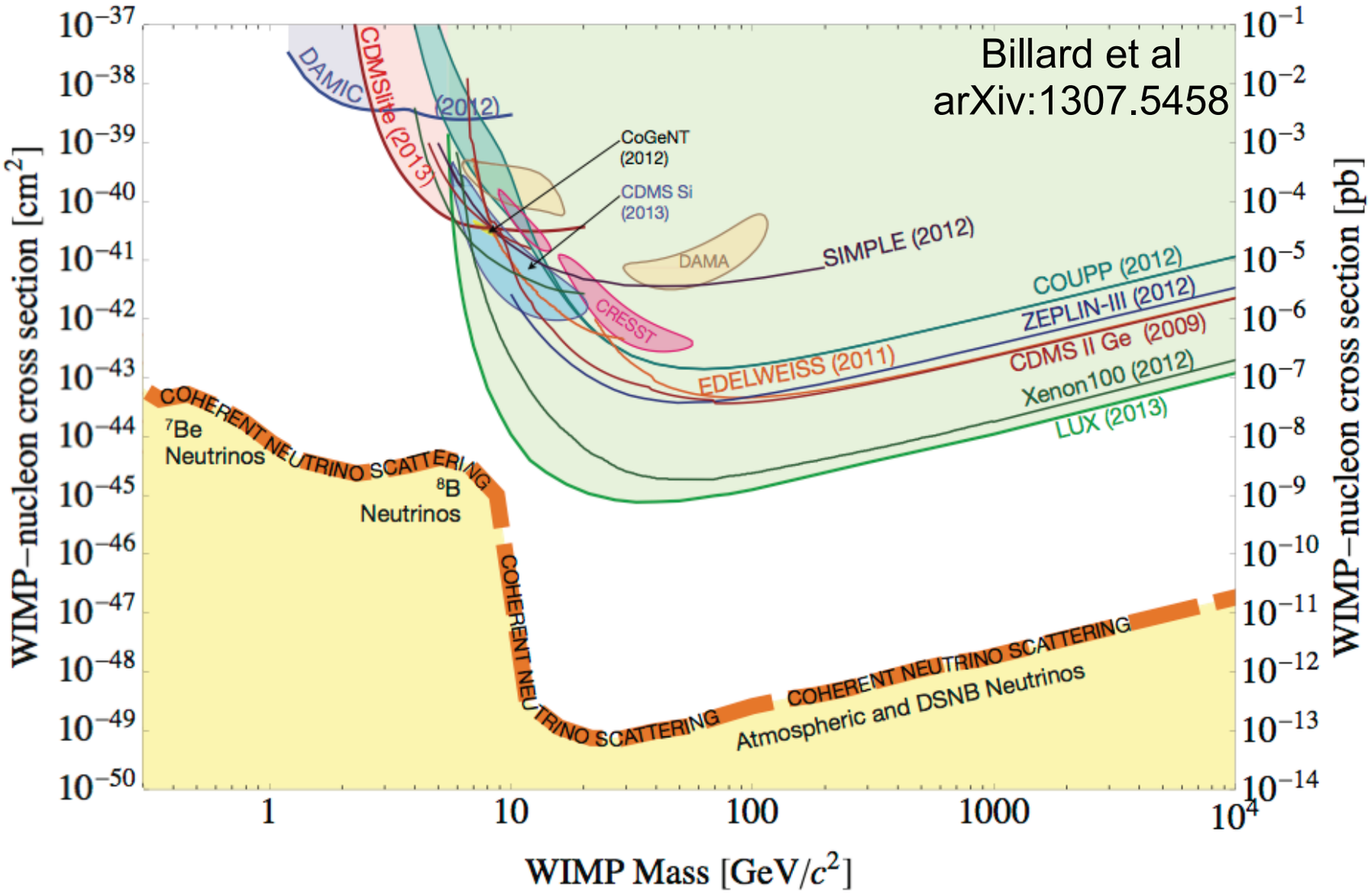
LUX arXiv:1310.8214



Electronic events

Nuclear events

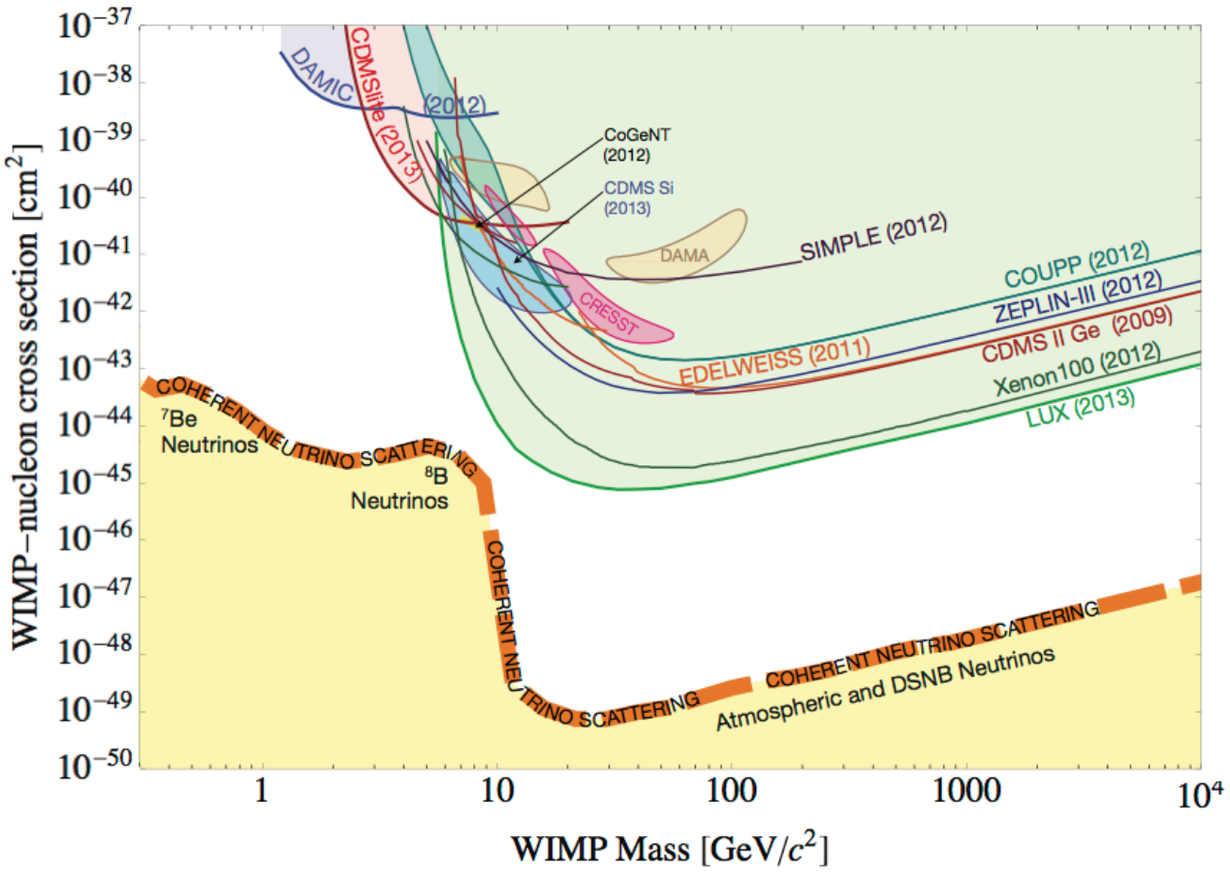
LUX: limits

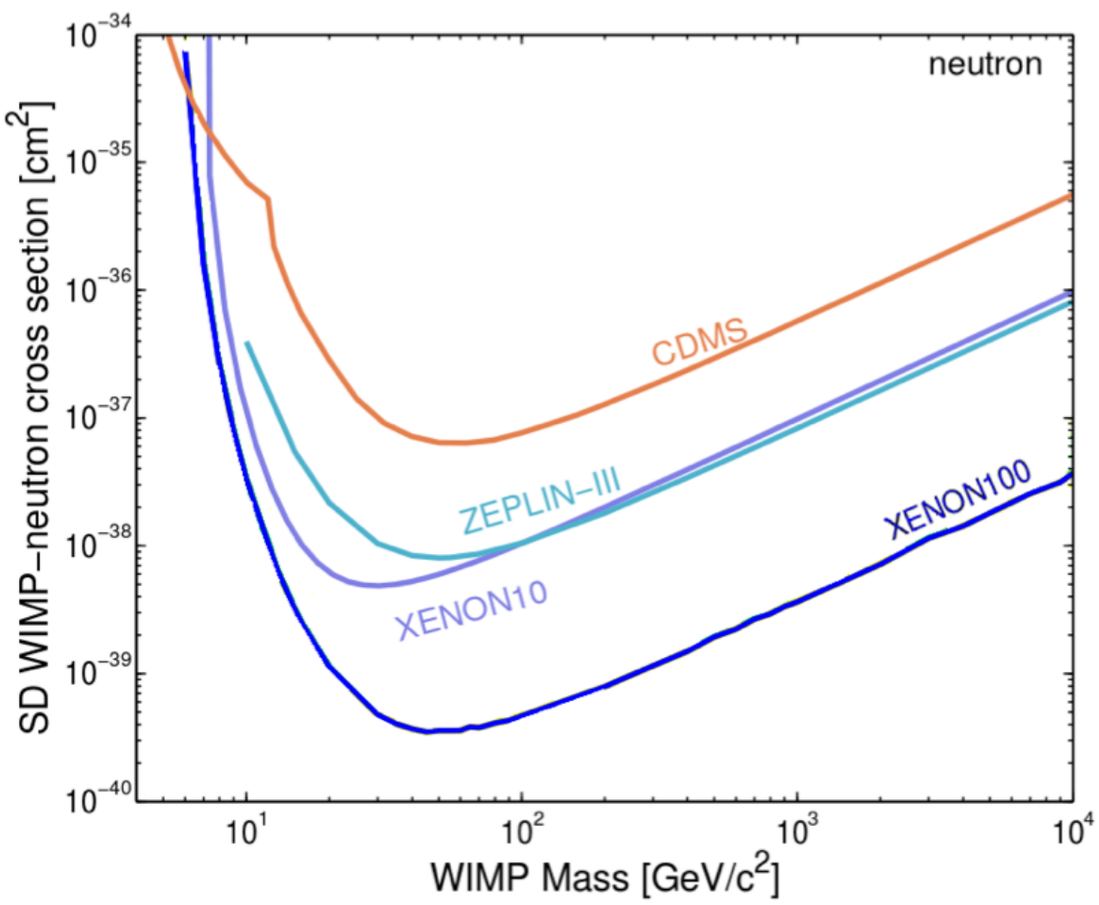


- Limits are quoted in terms of the ‘WIMP-nucleon cross-section’
  - Is this limit applicable to all theories…? No…

SI vs SD interactions

- Dark matter can also couple to the nuclear spin



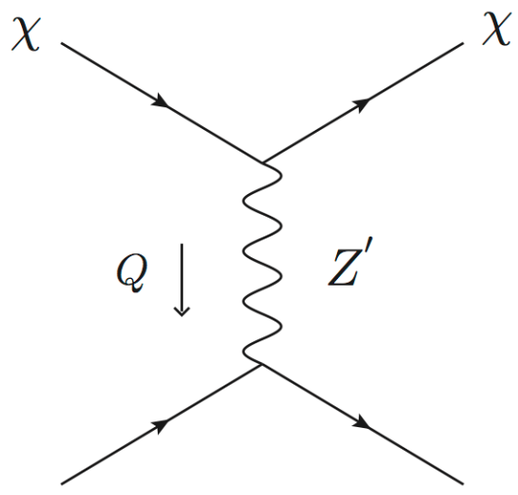


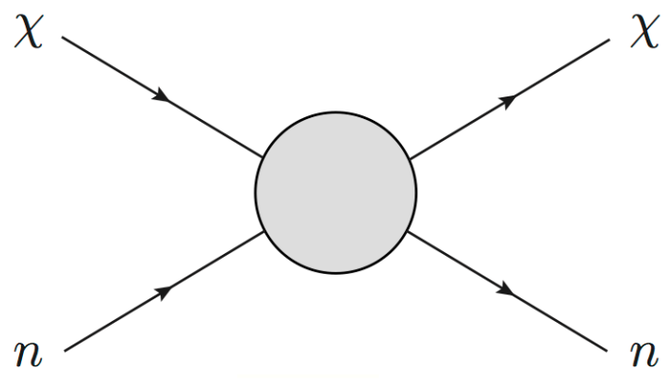
- Other interactions suppressed by powers of $v_{\mathrm{DM}} \sim \mathcal{O}\left(10^{-3}\right)$

A useful way to parameterise results

Contact interaction

- Assumes a ‘contact interaction’





$$\sigma_n \sim \left(\frac{g_n g_\chi}{Q^2 - m_{Z'}^2} \right)^2 \approx \frac{g_n^2 g_\chi^2}{m_{Z'}^4} \left(1 + \frac{Q^2}{m_{Z'}^2} + \cdots \right)^2$$

- Contact interaction if $m_{Z'} \gg Q = \sqrt{2 m_n E_{\mathrm{R}}} \approx 50 \text{ MeV}$
- Lots of theories satisfy this

A useful way to parameterise results

Direct detection: mini-summary

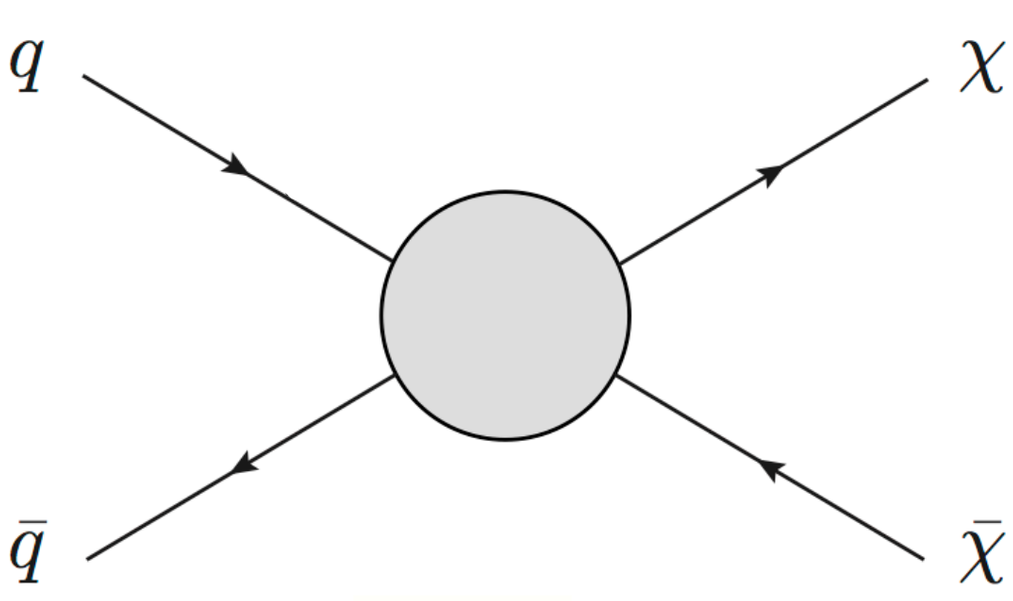
- Assumes
  - interaction is spin-independent or spin-dependent
  - contact interaction

- From a particle physics perspective, this is fine — lots of theories fall into these categories

The constraints are useful

Collider search: basics

- Dark matter pair production at the LHC

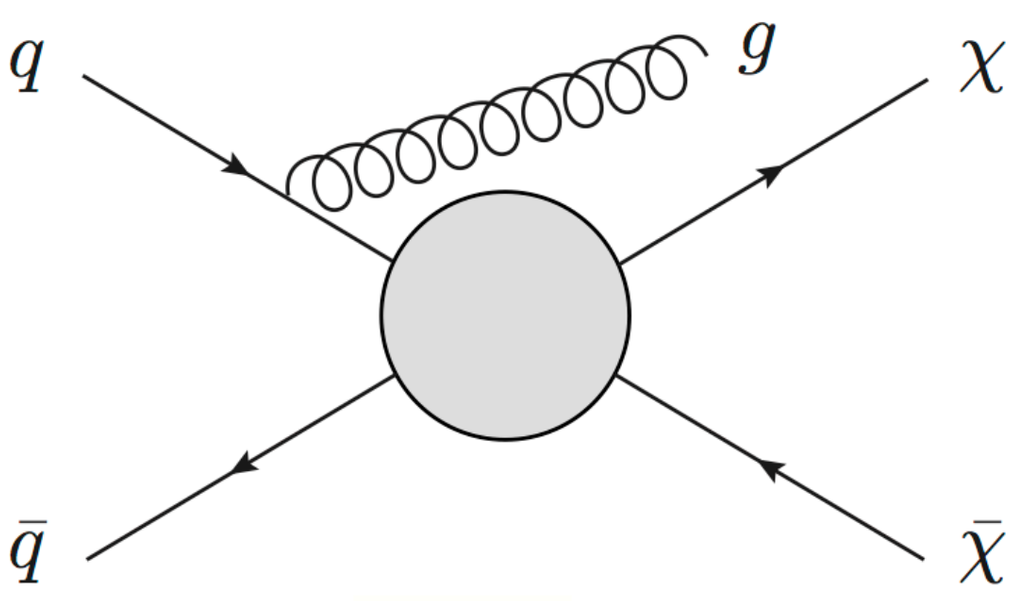


Dark matter escapes the detector unseen

Collider search: basics

Goodman et al
arXiv:1005.1286
Bai et al
arXiv:1005.3797

- Dark matter pair production at the LHC
  - Need to trigger on something!

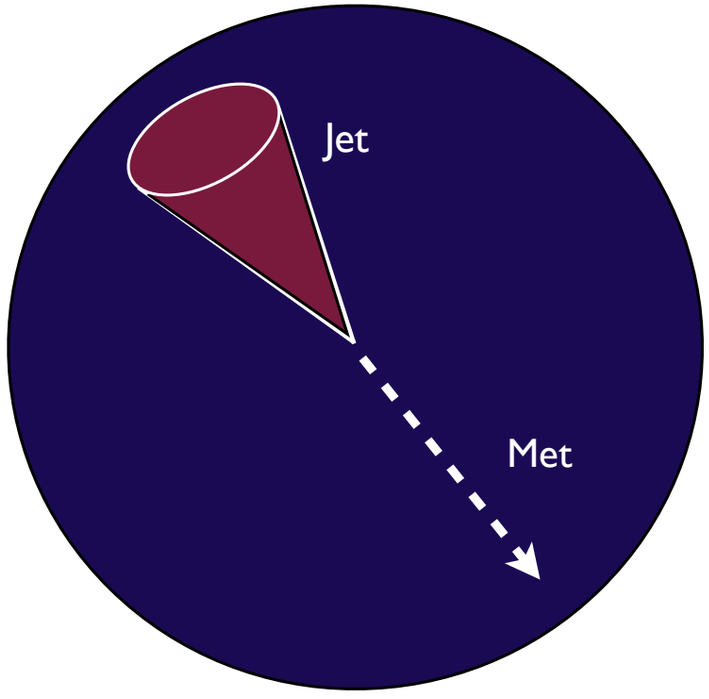


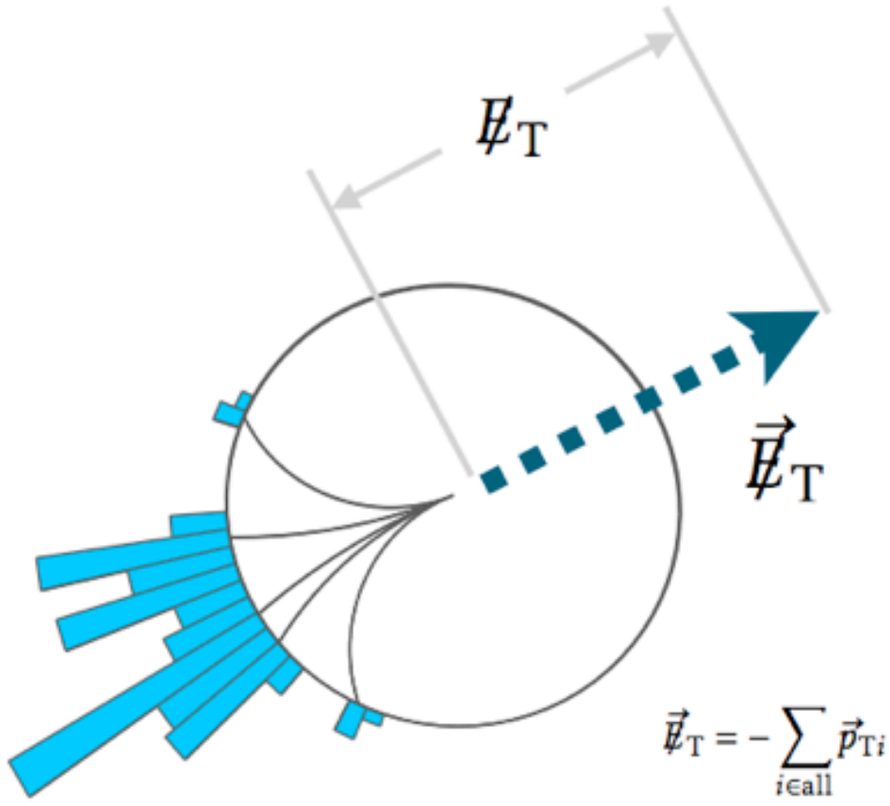
monojet +
Dark matter escapes
the detector unseen

- Monojet search: look for a hard jet and missing energy

Monojet signature

- Simple and striking signature

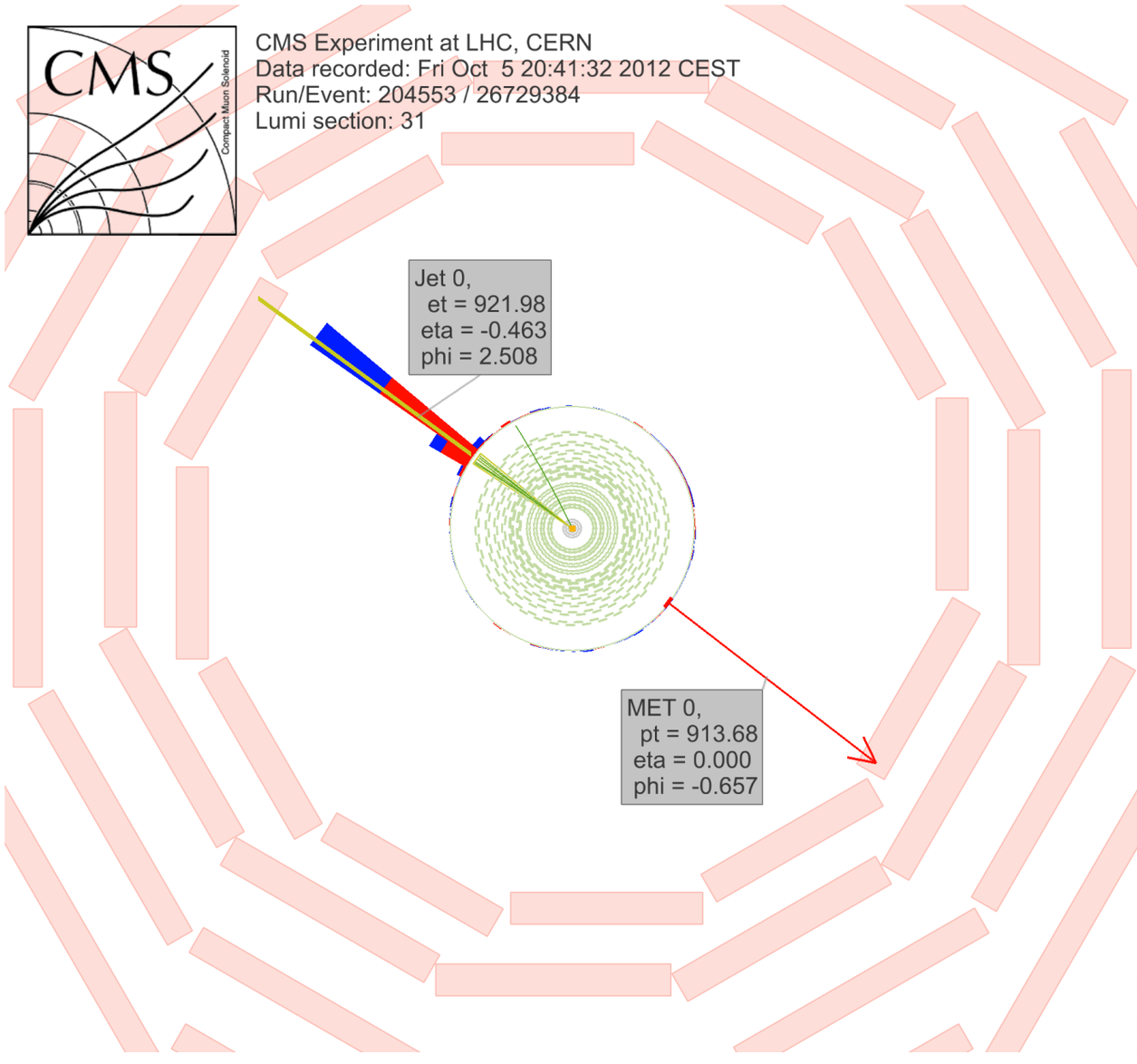


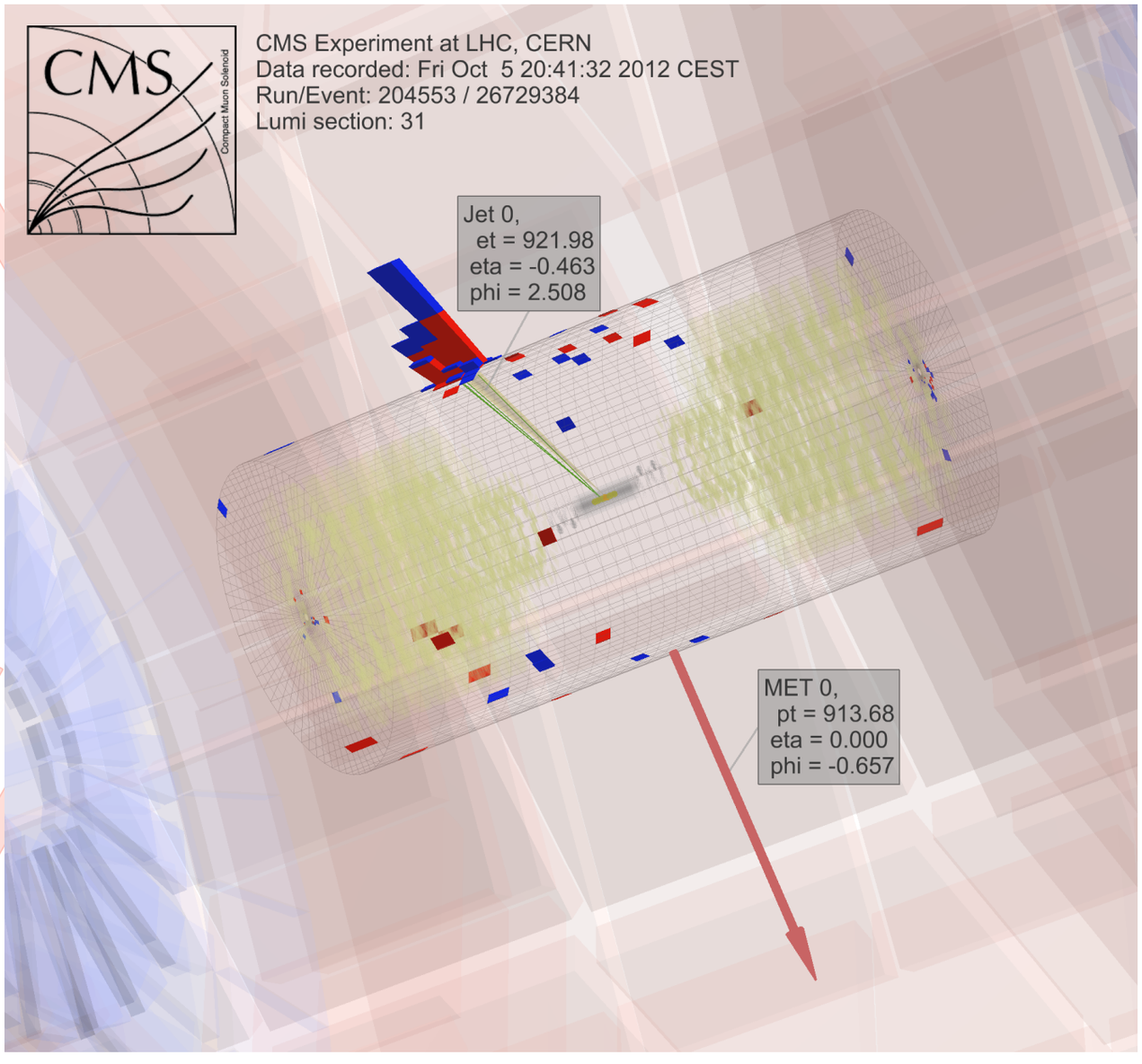


- Visible energy from jet
- Missing transverse energy (MET or $\not{E}_T$) is negative the sum of the transverse momenta of all reconstructed particles

MET is at the heart of all dark matter searches at colliders

Monojet: a real event





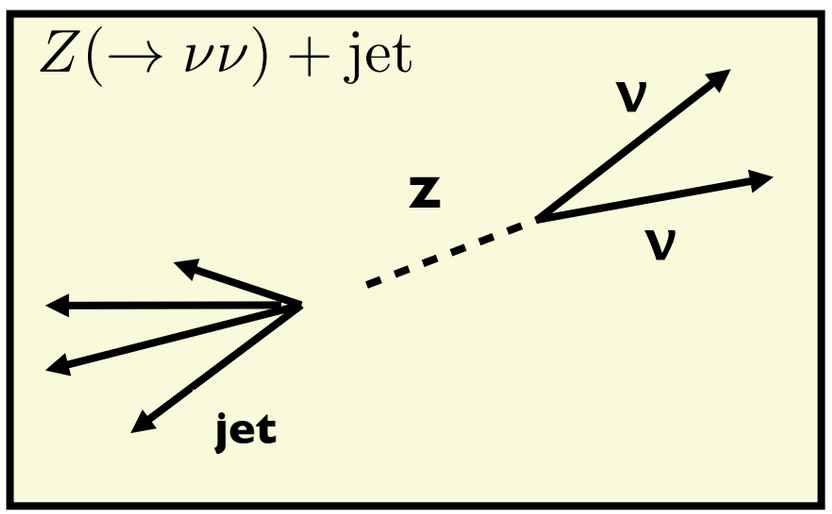
CMS search

arXiv:1408.3583

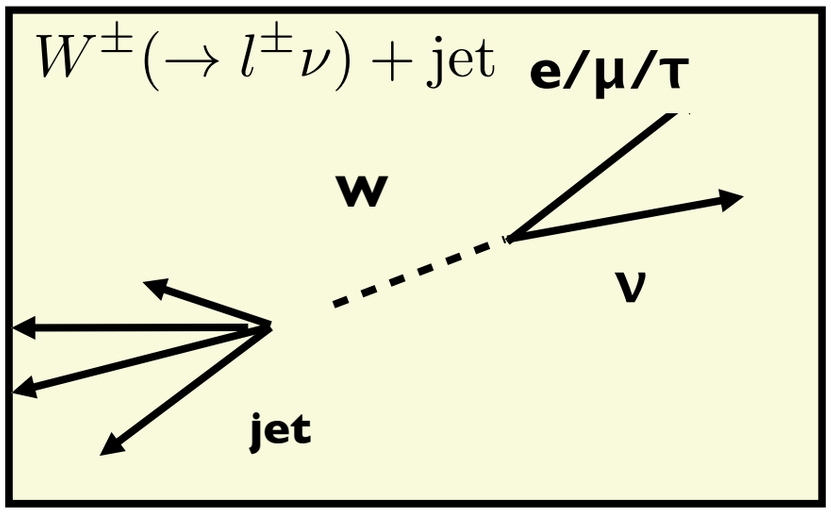
- Event selection:
  - Large missing transverse energy: $\not{E}_{\mathrm{T}} > 500\ \mathrm{GeV}$
  - One energetic jet: $p_{\mathrm{T}} > 100\ \mathrm{GeV}$
  - One additional jet if $p_{\mathrm{T}} > 30\ \mathrm{GeV}$ and $\Delta\phi(j_1, j_2) < 2.5$

- Main backgrounds:

Irreducible background;
looks like signal

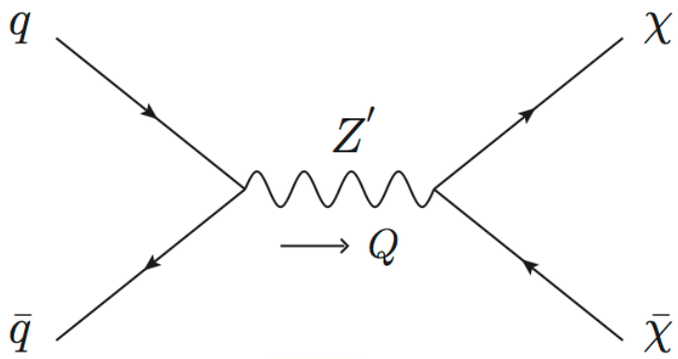


e/μ not detected
τ decays hadronically



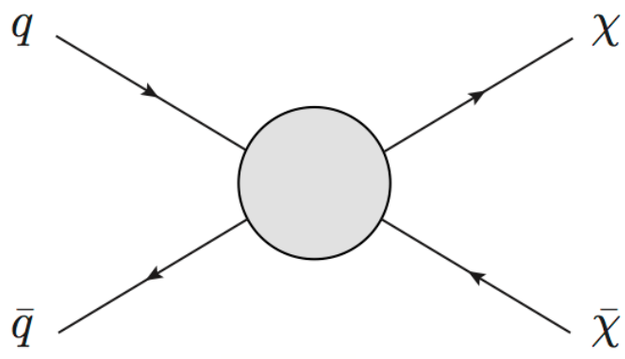
EFT interpretation

- Use effective field theory (EFT) to interpret the search



$$\mathcal{L} \sim g_\chi Z'_\mu \bar{\chi}\gamma^\mu\chi + g_q Z'_\mu \bar{q}\gamma^\mu q + \frac{1}{2} m^2_{Z'} Z'_\mu Z'^\mu + \cdots$$

'Integrate out the mediator'



$$\mathcal{L} \sim \frac{1}{\Lambda^2} \bar{q}\gamma_\mu q\, \bar{\chi}\gamma^\mu\chi$$

- Parameter of interest is the contact interaction scale Λ
- Related to parameters in the full theory: $\Lambda = \dfrac{m_{Z'}}{\sqrt{g_q g_\chi}}$

This is not a new idea

- Fermi could describe β-decay without knowing the microscopic details:

$$\mathcal{L} = \frac{G_{\rm F}}{\sqrt{2}} \left[\bar{\psi}\gamma^{\mu}(1-\gamma^{5})\psi\right] \left[\bar{\psi}\gamma_{\mu}(1-\gamma^{5})\psi\right] \text{ where } G_{\rm F} \propto \frac{g^2_{\rm weak}}{M^2_W}$$

- It is a very useful idea
- we don't need to know all details of the full theory

- Can (in principle) constrain many different theories:

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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

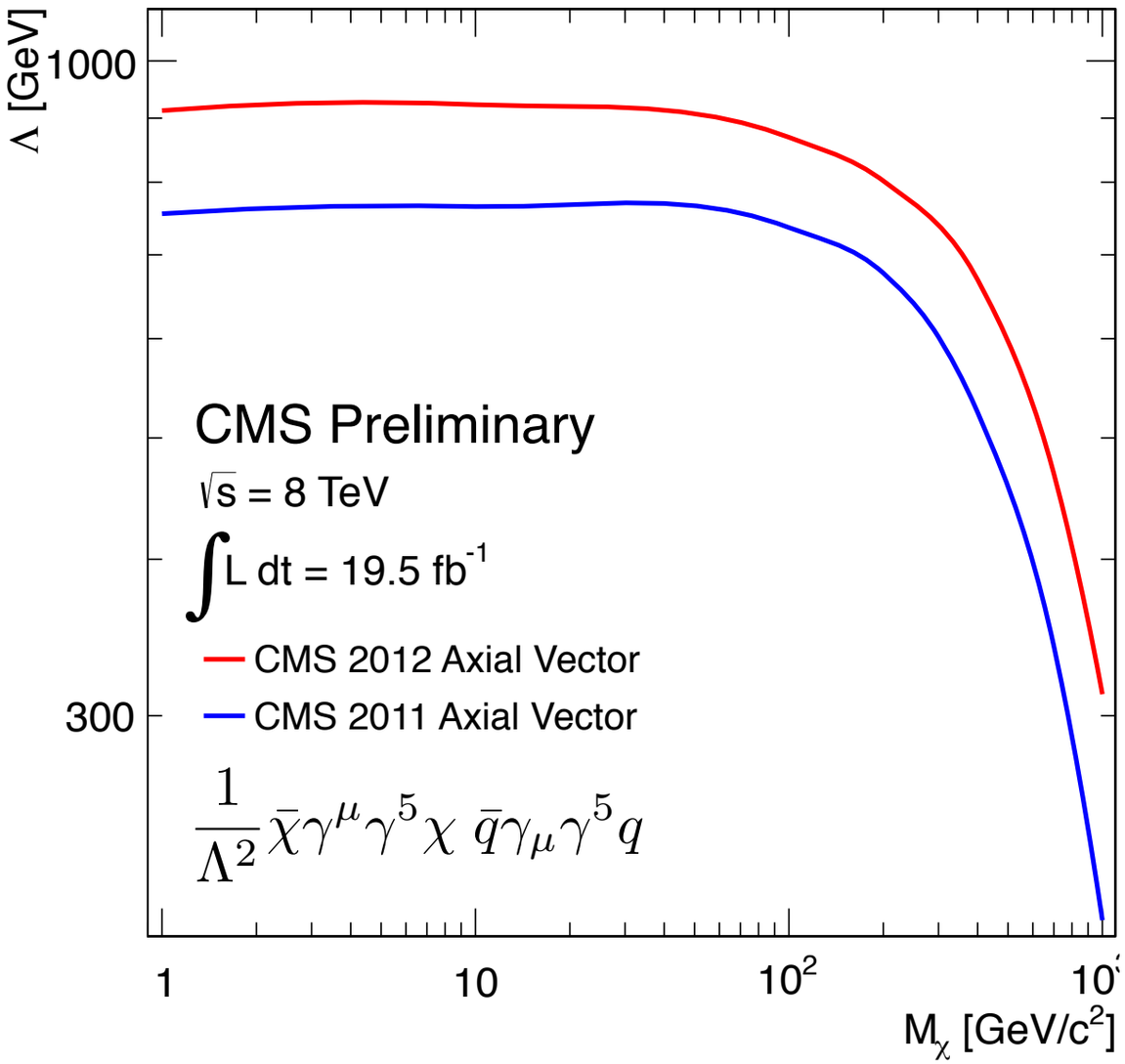
Name	Operator	Coefficient
C1	$\chi^{\dagger}\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^{\dagger}\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^{\dagger}\partial_{\mu}\chi\bar{q}\gamma^{\mu}q$	$1/M_*^2$
C4	$\chi^{\dagger}\partial_{\mu}\chi\bar{q}\gamma^{\mu}\gamma^5 q$	$1/M_*^2$
C5	$\chi^{\dagger}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^{\dagger}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

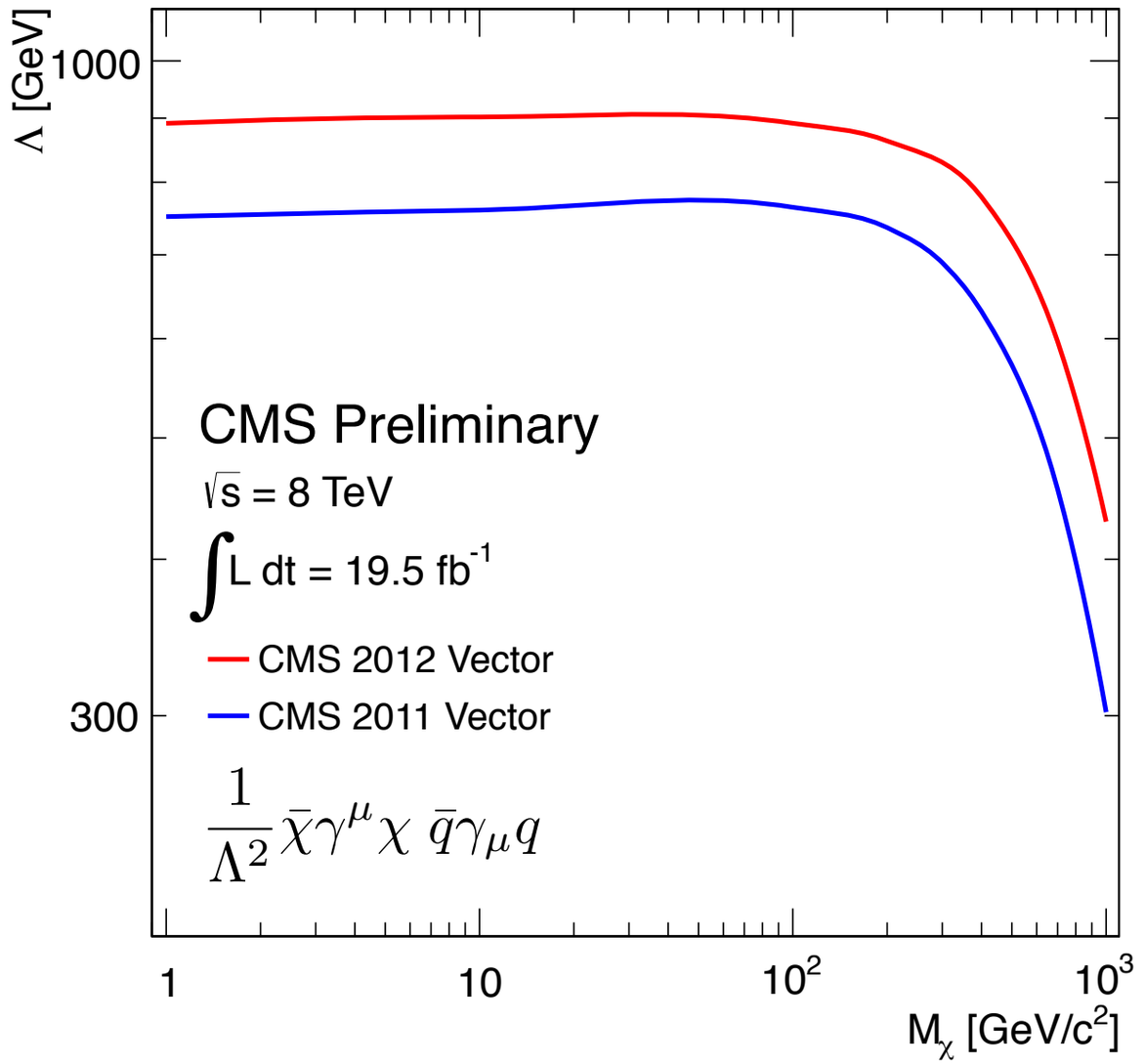
Goodman et al
arXiv:1008.1783

Advantage of EFT approach

CMS-PAS-EXO-12-048

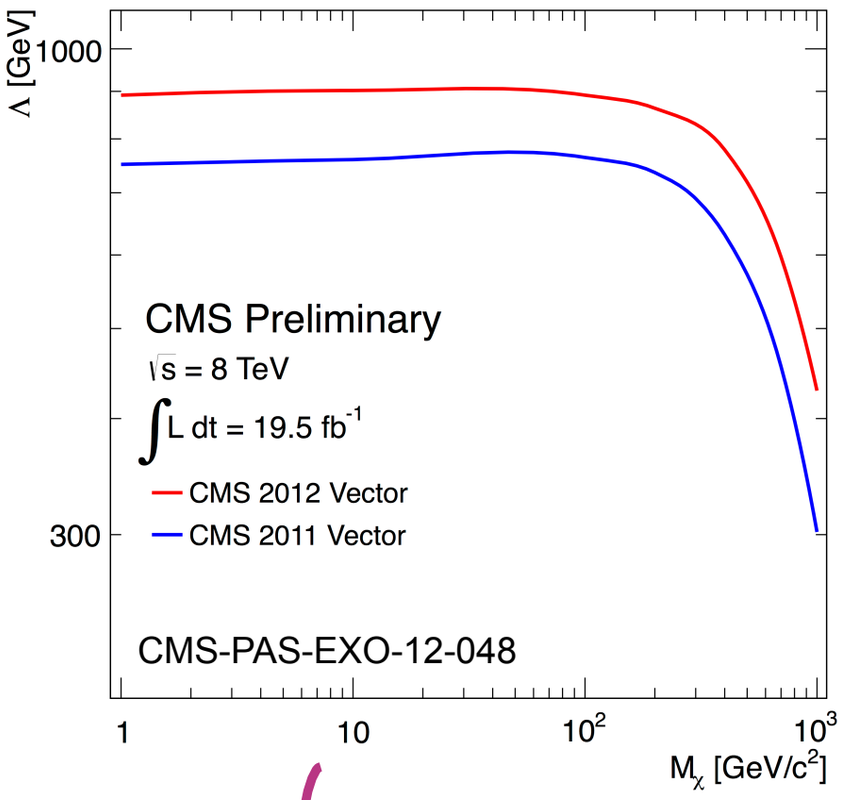
- Straightforward to constrain Λ for various operators

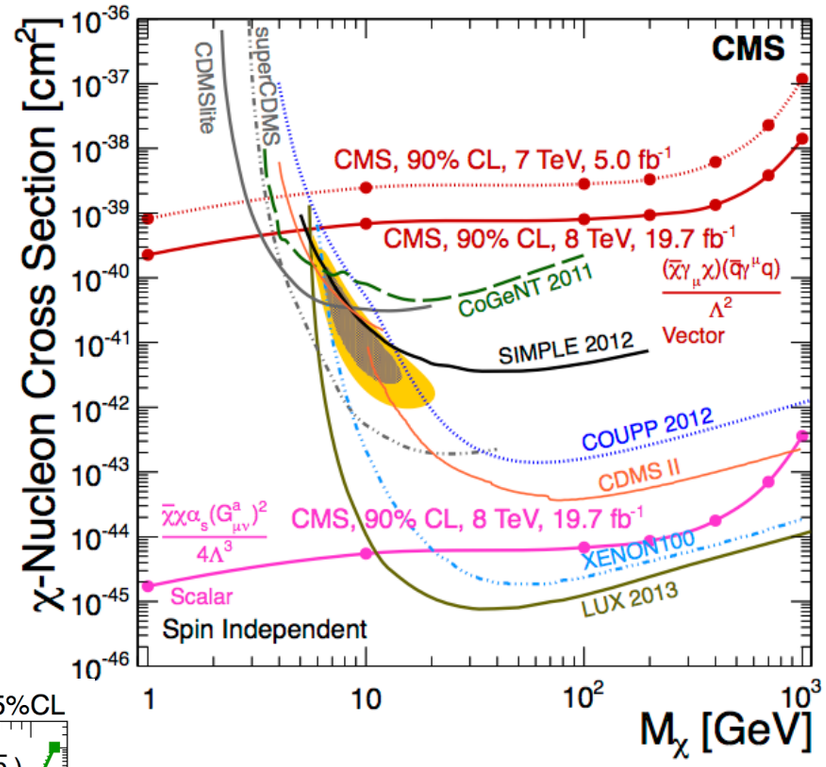


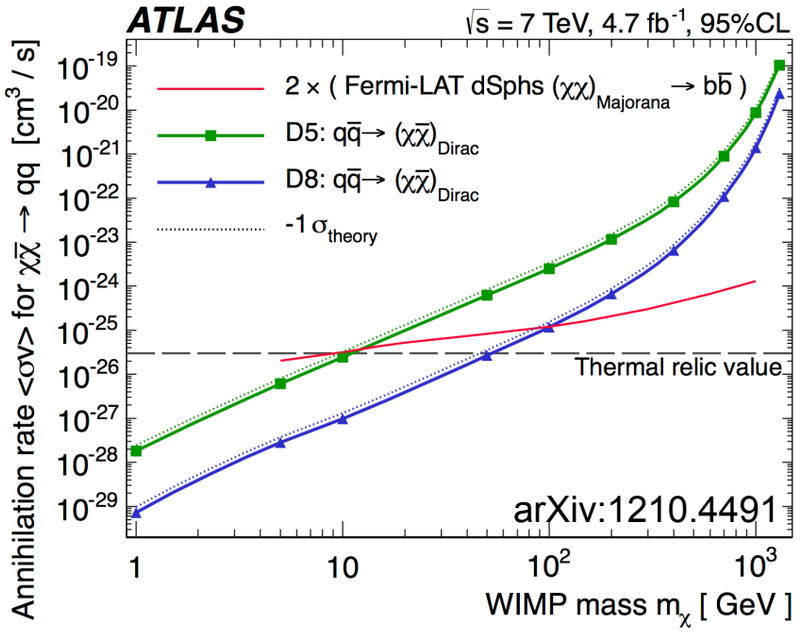


Advantage of EFT approach

- Comparison with other dark matter searches is straightforward

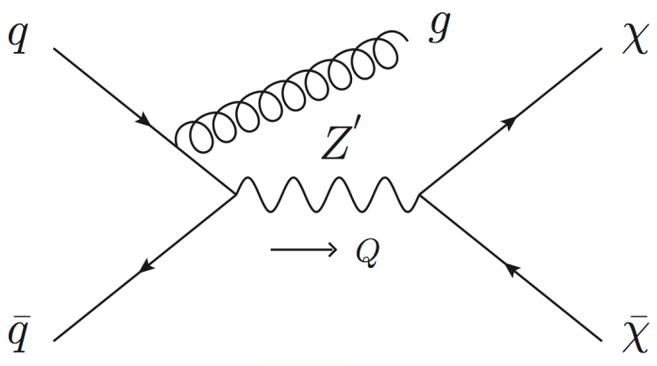






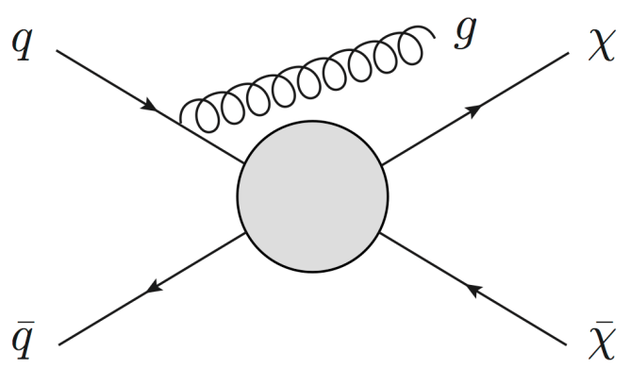
Disadvantage of EFT approach

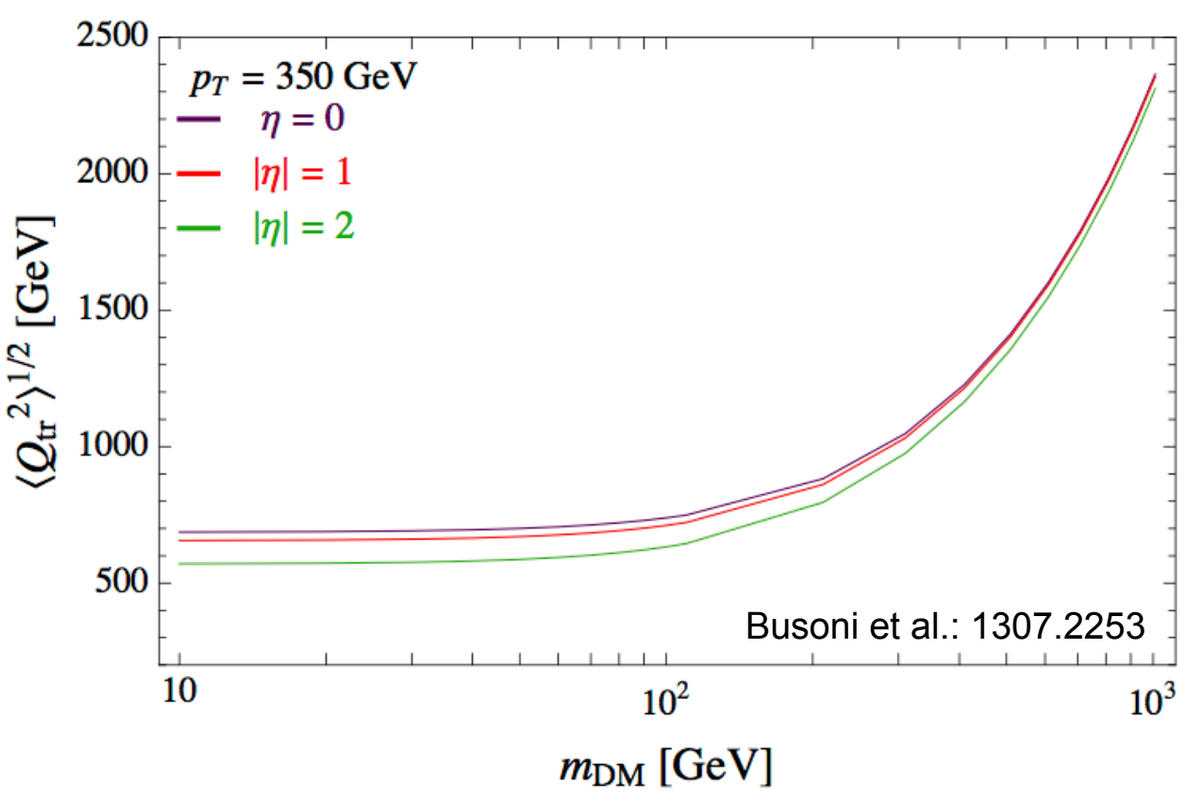
- Is it valid…?



Good approximation if

$$M_{Z'} \gg Q$$



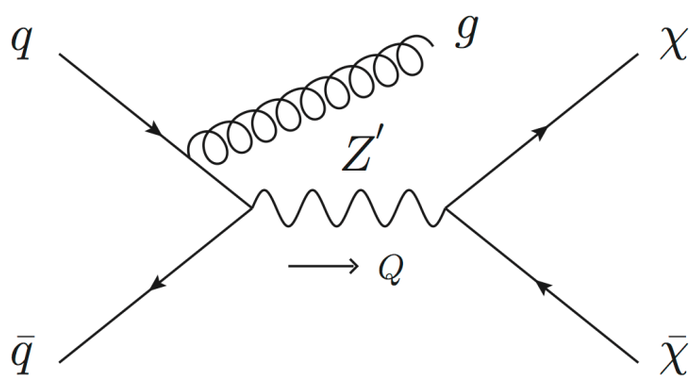


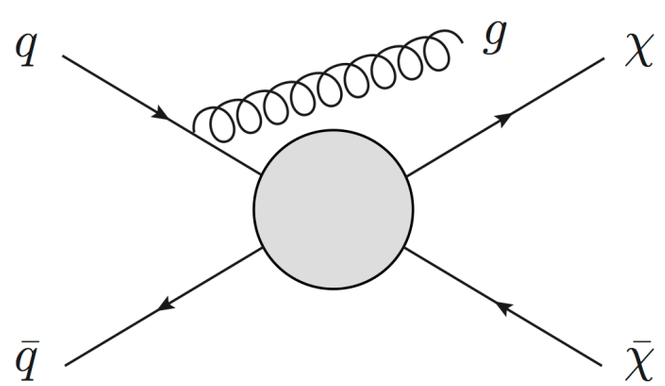
$$\rightarrow M_{Z'} \sim \text{TeV}$$

EFT validity

Buchmueller, Dolan, CM
arXiv:1308.6799

- Better estimate: Compare a simple model with EFT result





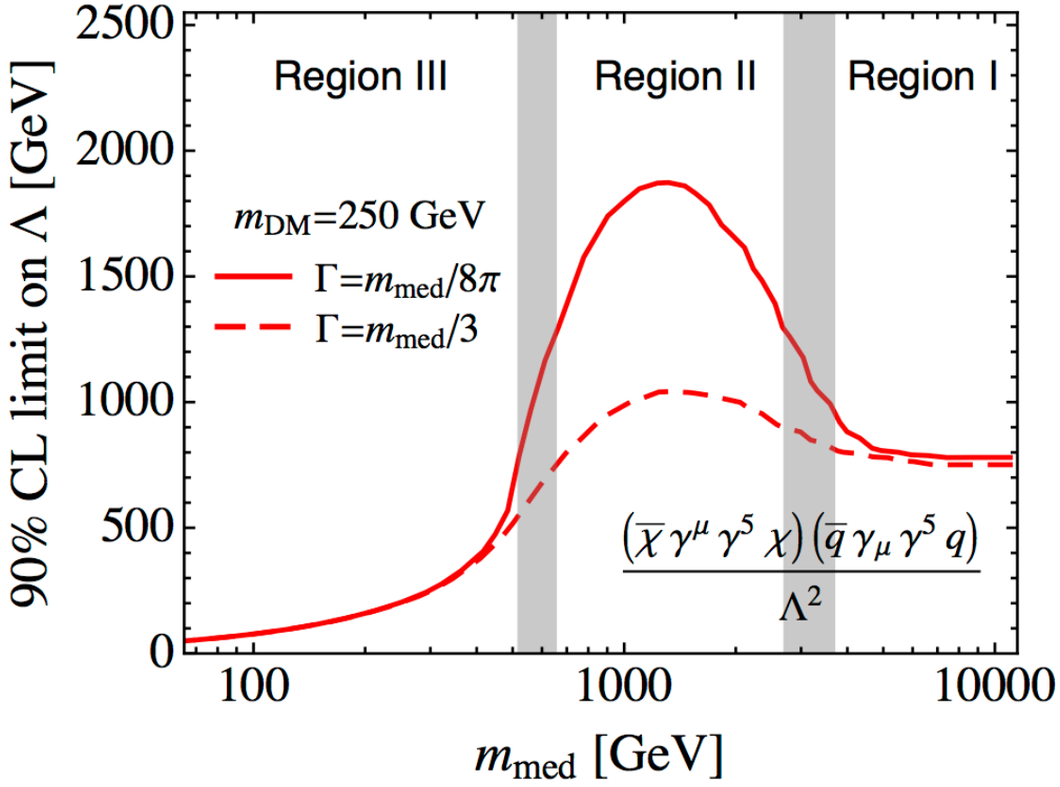
- Assumptions:
  1. s-channel axial-vector mediator
  2. Equal couplings to all quarks
  3. No coupling to leptons or SM gauge bosons

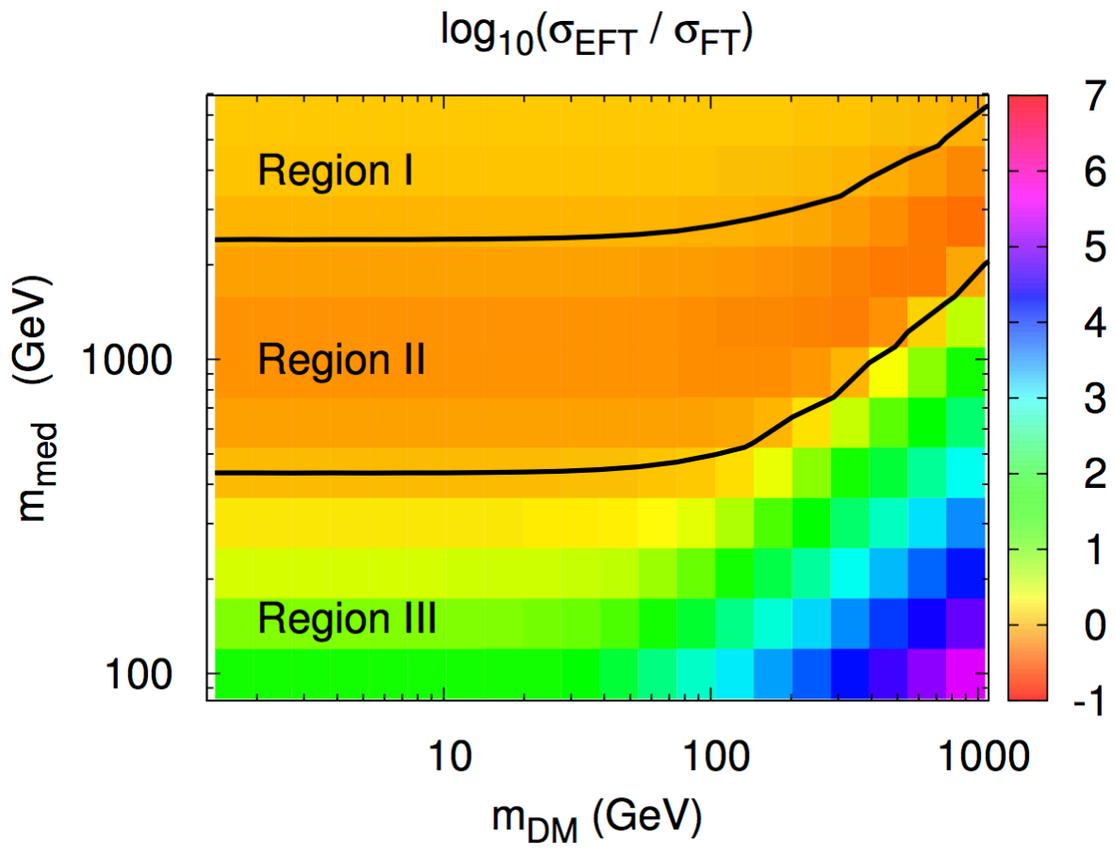
- Said in Lagrangians:

$$\mathcal{L} \supset g_\chi Z'_\mu \bar{\chi}\gamma^\mu\gamma^5\chi + g_q Z'_\mu \bar{q}\gamma^\mu\gamma^5 q \quad \text{vs} \quad \mathcal{L} \supset \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{\chi}\gamma_\mu\gamma^5\chi$$

EFT validity

- Consider limit on $\Lambda = \dfrac{m_{\rm med}}{\sqrt{g_q g_\chi}}$





- Region I: EFT limit is valid $m_{\rm med} \gtrsim 3\ {\rm TeV}$
- Region II: EFT limit is too weak
- Region III: EFT limit is too strong $m_{\rm med} \lesssim 500\ {\rm GeV}$

Region I: EFT valid

EFT limit applies to a small class of theories

- Large mediator mass:

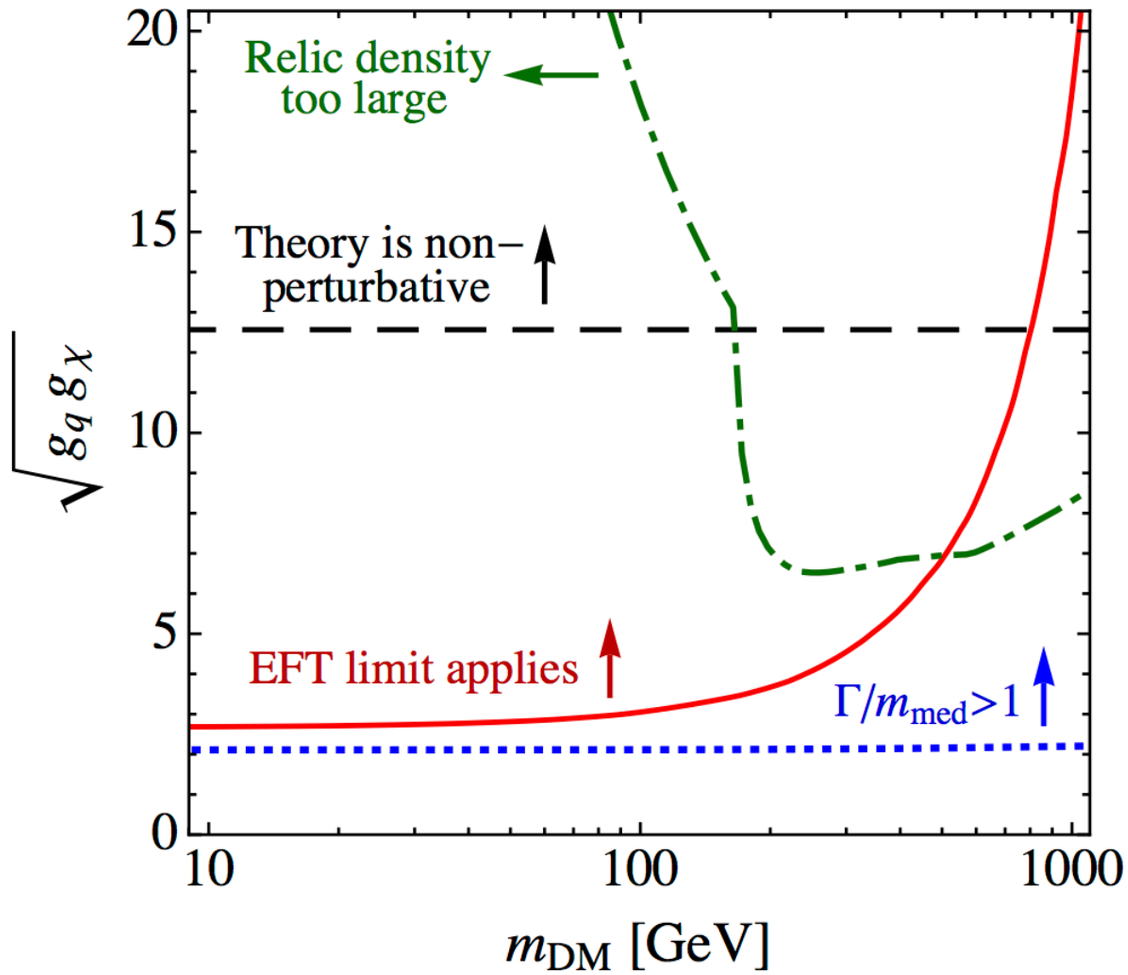
$$m_{\rm med} \gtrsim 3 \text{ TeV}$$

- Large couplings:

$$\sqrt{g_q g_\chi} = \frac{m_{\rm med}}{\Lambda}$$

- Large mediator width:

$$\Gamma > m_{\rm med}$$

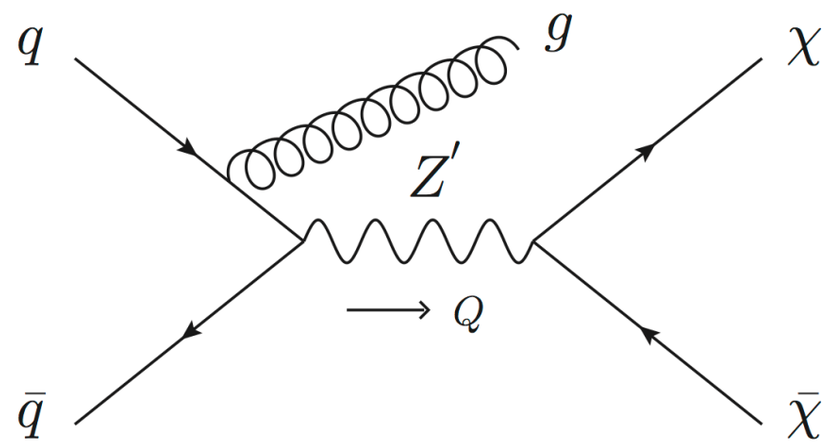


Region II: EFT too weak

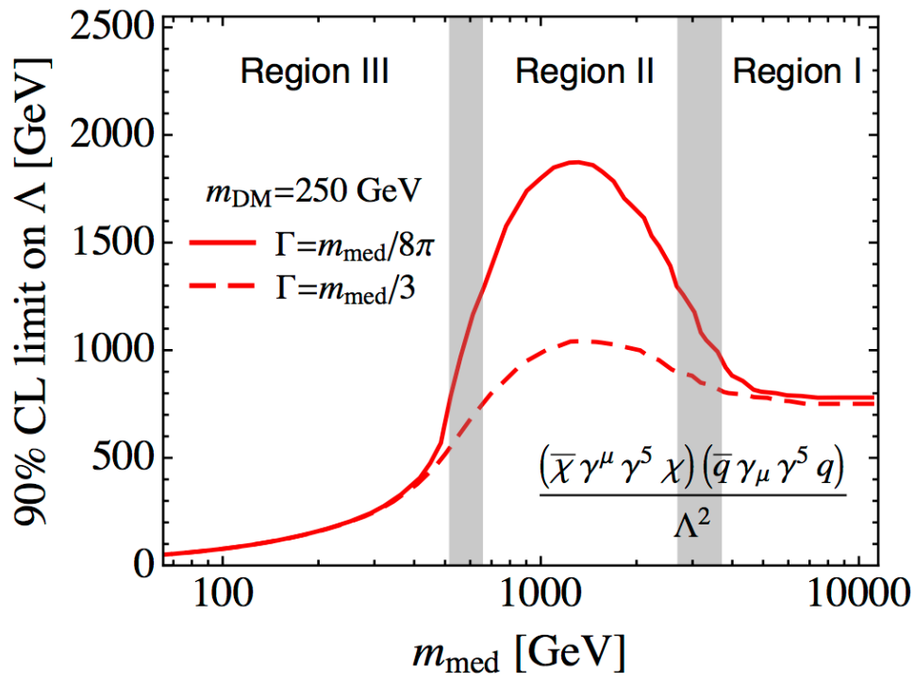
EFT does not account for s-channel resonant enhancement

- Enhanced when

$$m_{\rm med}^2 \sim 4m_{\rm DM}^2 + \not{E}_{\rm T}^2$$



- The width plays a crucial role
- Peak height scales as $\Gamma^{-1/4}$



Region III: EFT too strong

EFT does not account for off-shell production

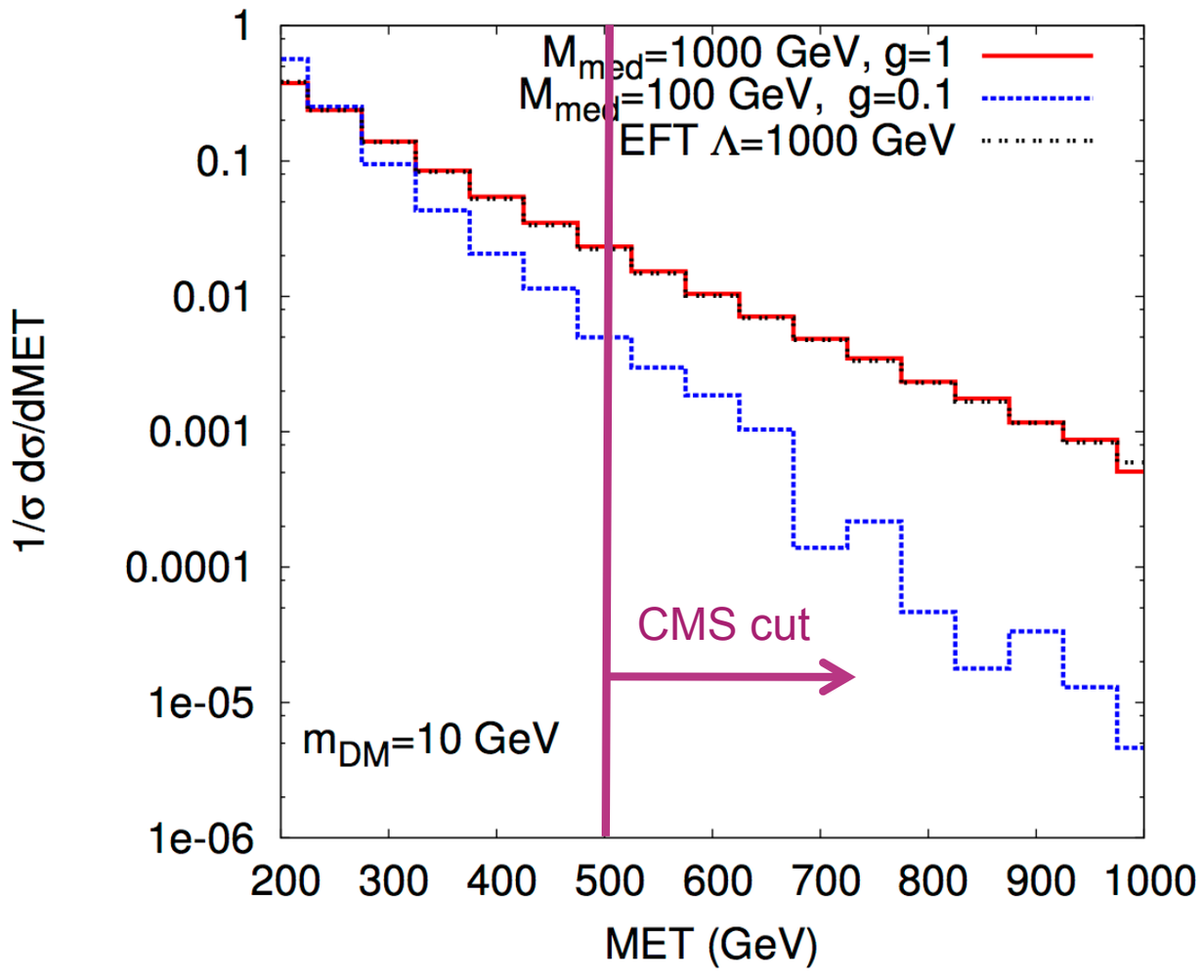
- Light mediator masses

$$m_{\mathrm{med}} < 500\ \mathrm{GeV}$$

- Events with a light mediator are much softer

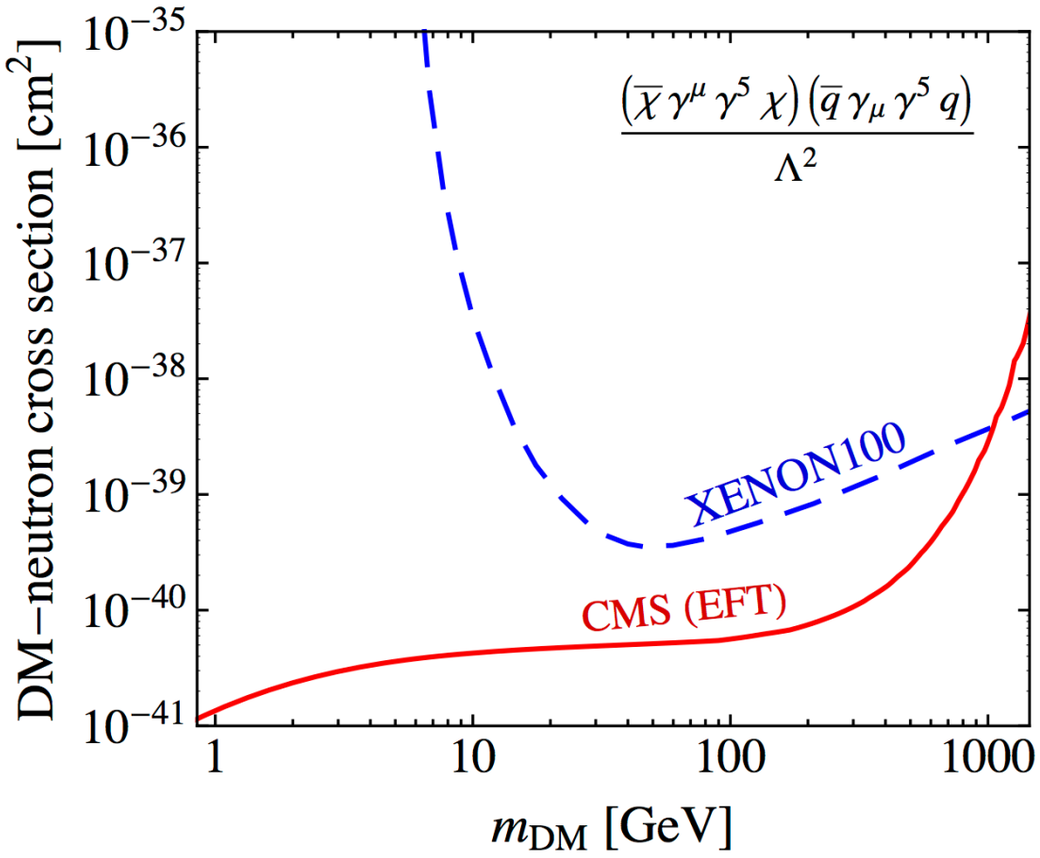
- EFT limit on g weaker

  ➡ limit on $\Lambda \sim \dfrac{m_{\mathrm{med}}}{g}$ is strong



Other problems

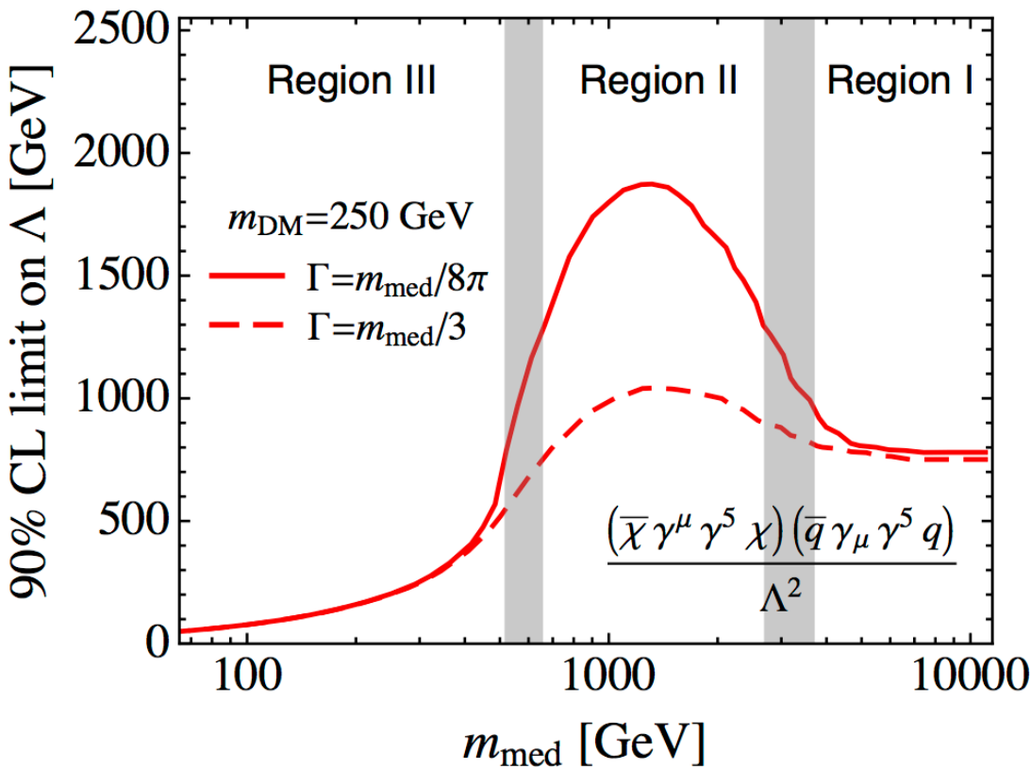
- Comparison with direct detection:

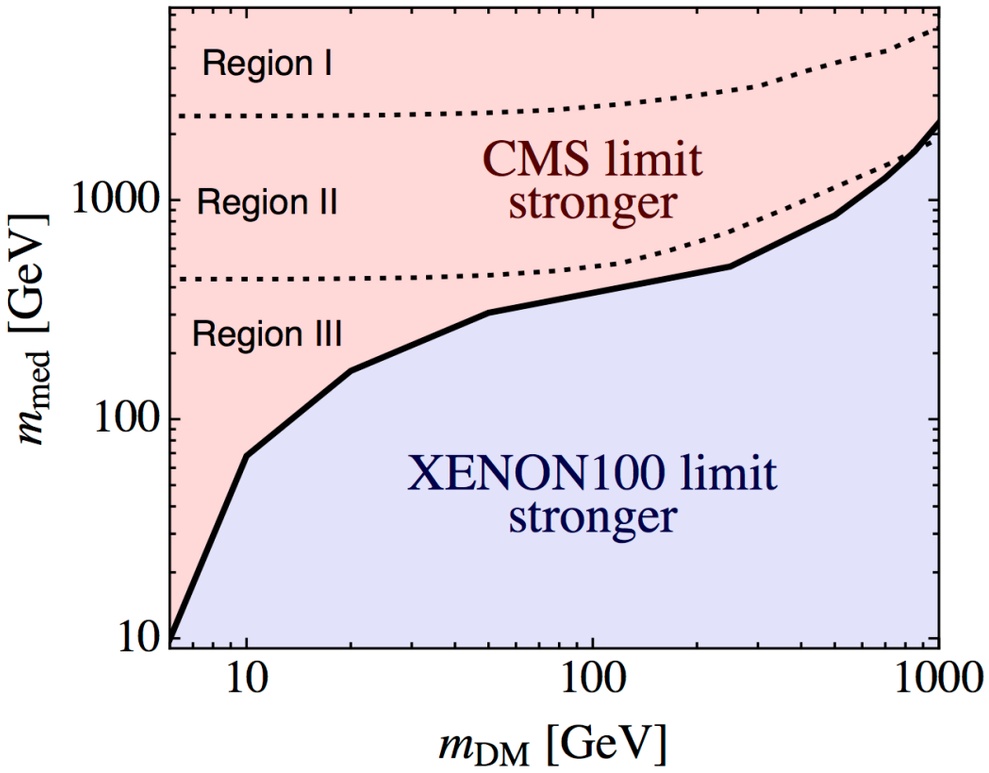


- Naive application of EFT limit gives the impression that the LHC limit is stronger for $m_{\rm DM} \lesssim 1\ \mathrm{TeV}$

Other problems

- Comparison with direct detection:
  - Important to remember dependence on $m_{\rm med}$
- Scattering cross section $\sigma_n \propto \Lambda^{-4}$





- As $m_{\rm med}$ decreases, direct detection limit is stronger

EFT interpretation: mini-summary

- EFT doesn't capture kinematics of search
  - no resonance, no off-shell mediator production
- EFT limit applies to small class of theories
  - large couplings, broad mediator
- Naive comparison with direct searches can be misleading

Is there a better approach…?

A different approach

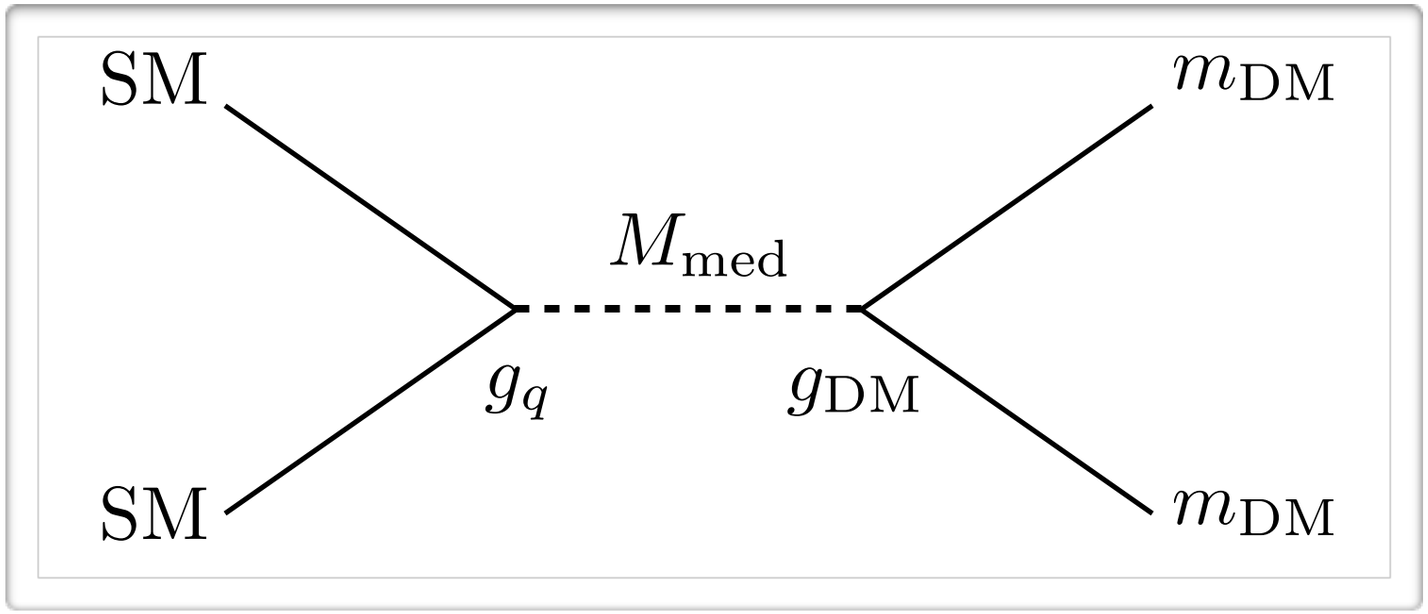
- What do we want?
- A framework that holds for all dark matter searches (at colliders, direct and indirect searches)
- It seems impossible to give an interpretation of monojet searches were you read off a constraint for any theory
  - at least give approximation/intuition for what the constraints will be

- Minimal/simple
- Extendable:
  - Different mediators (vector/axial-vector/scalar/pseudoscalar…)
  - Different dark matter (Dirac/Majorana/Scalar…)
  - Different production modes (s-, t-channel…)

Minimal simplified DM model

Buchmueller, Dolan, Malik, CM
arXiv:1407.8257

- Characterise collider dark matter production with a small number of variables



Minimum 4 parameters	
$m_{\rm DM}$	$M_{\rm med}$
g_q	g_χ

Mediators	
Vector	Axial-Vector
Scalar	Pseudo-scalar

Dark matter	
Dirac	Complex scalar
Majorana	Real scalar

Minimal simplified DM model

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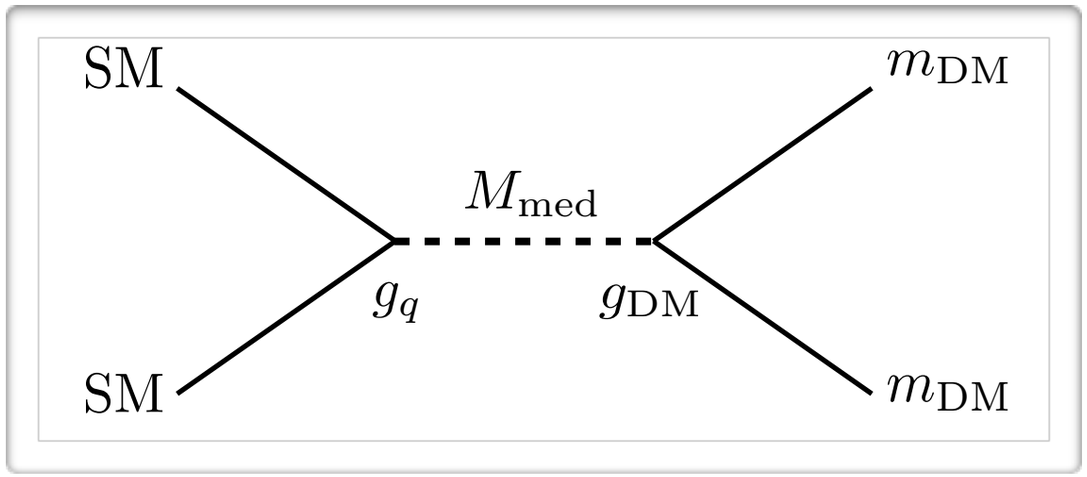
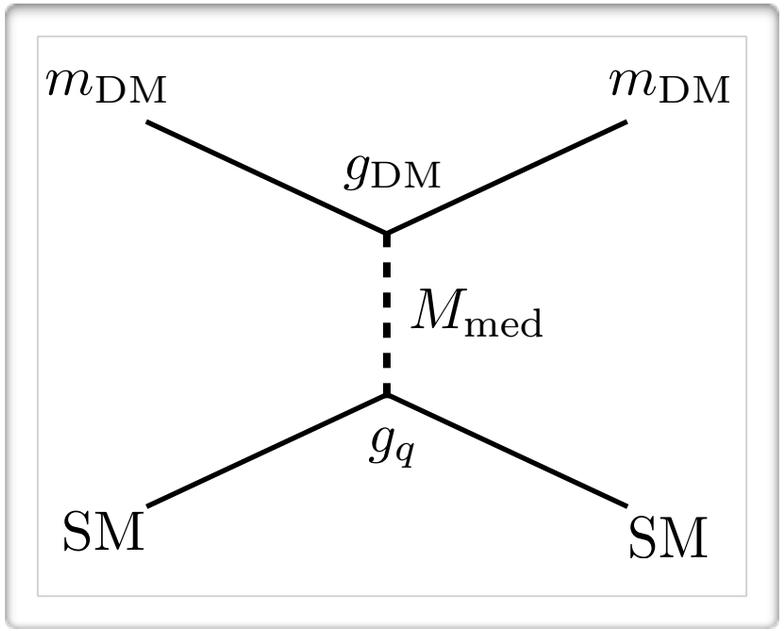
- Same parameters also characterise direct searches





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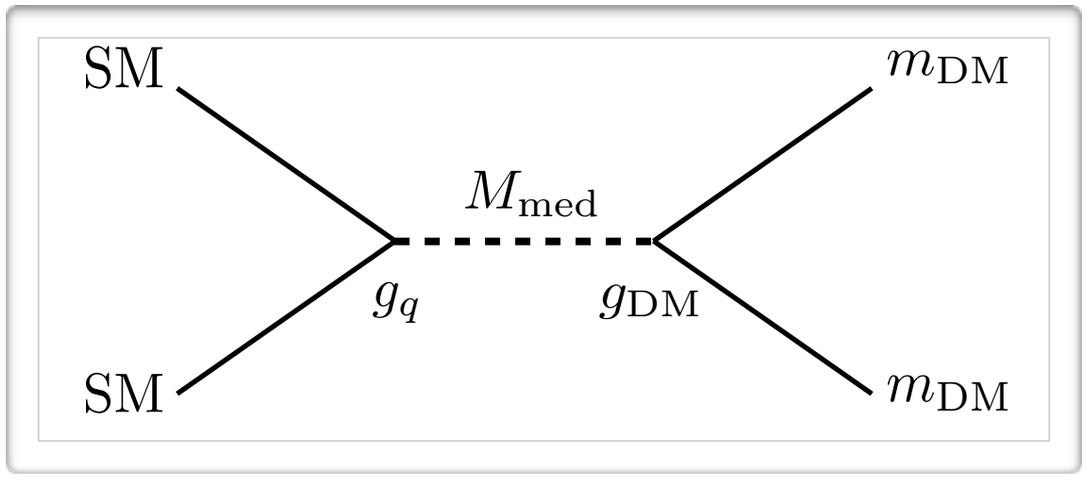

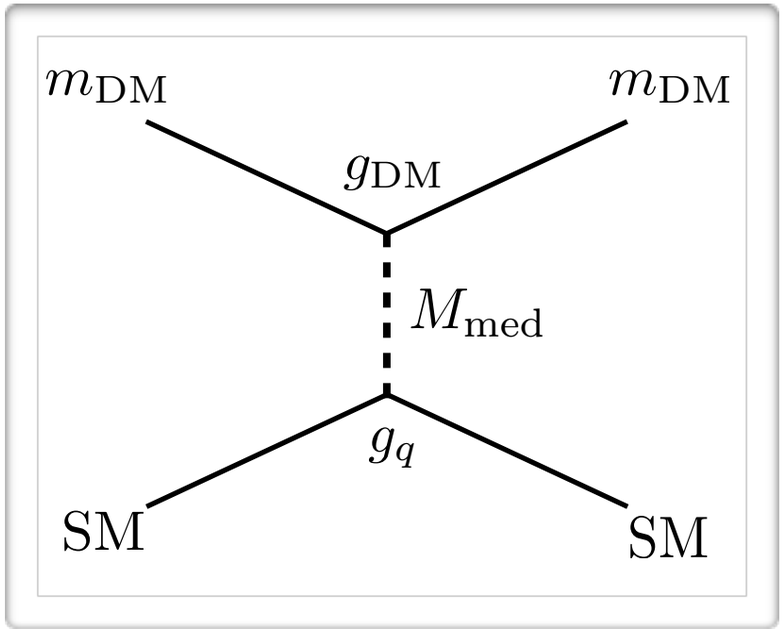

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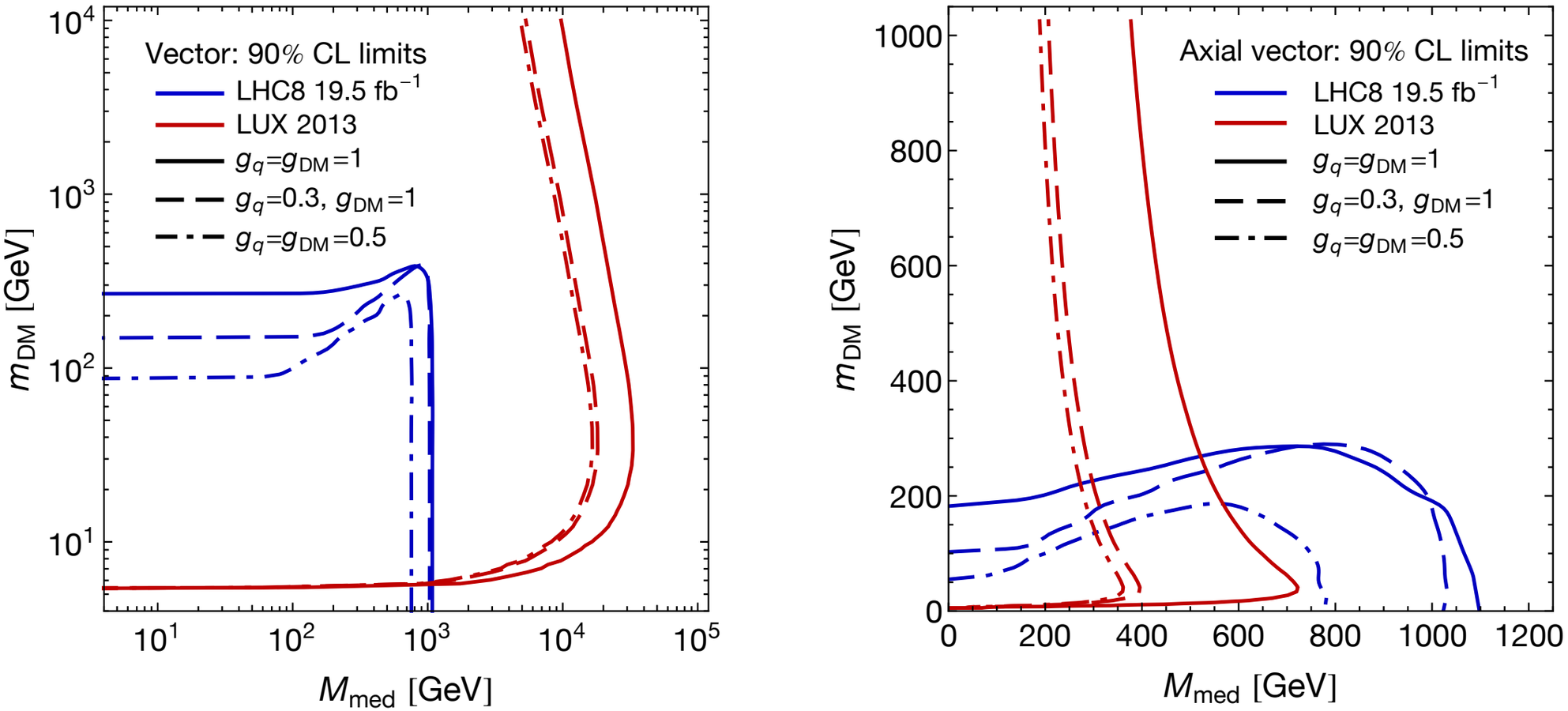
Slicing through parameter space

- We need to fix two parameters to show results:

$m_{\rm DM}$	g_χ
$M_{\rm med}$	g_q



- Better elucidation of the complementarity between collider and direct searches

Slicing through parameter space

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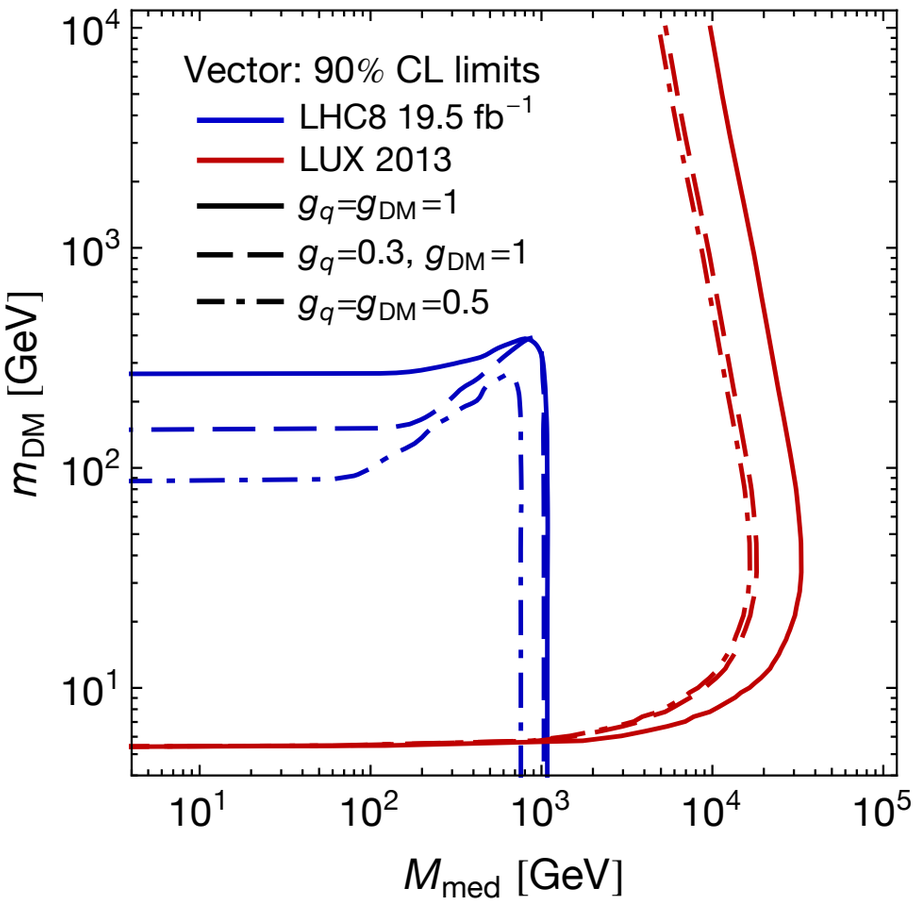

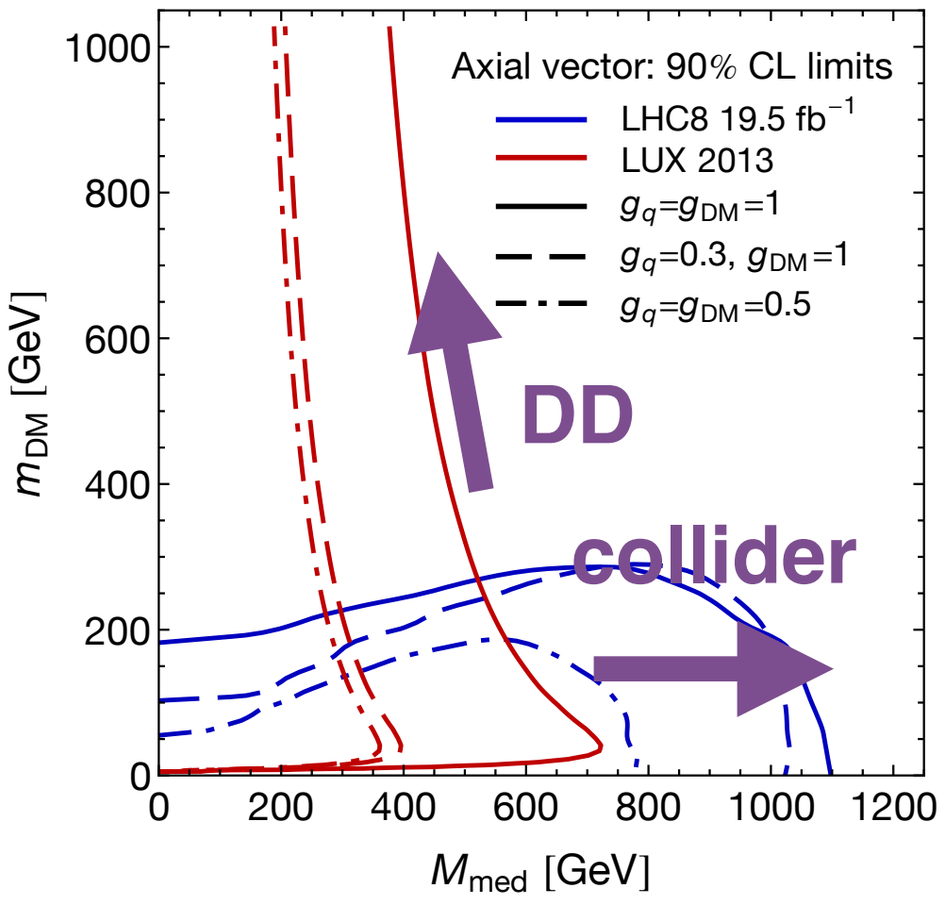

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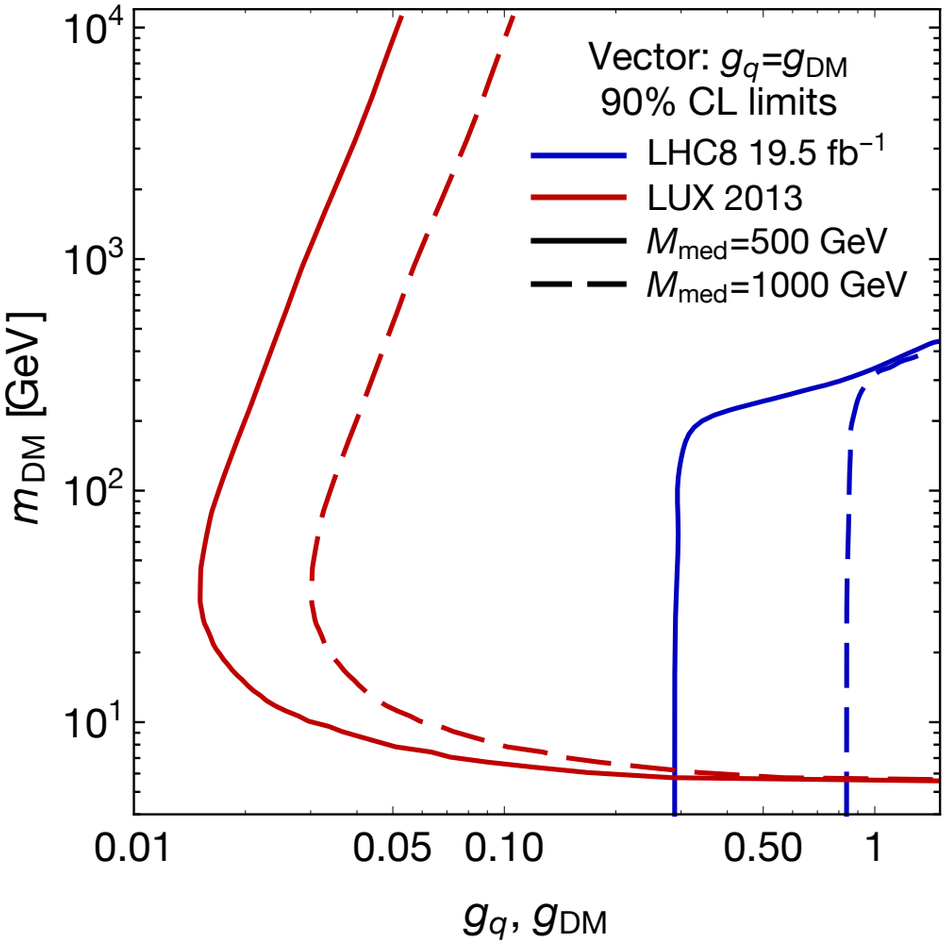

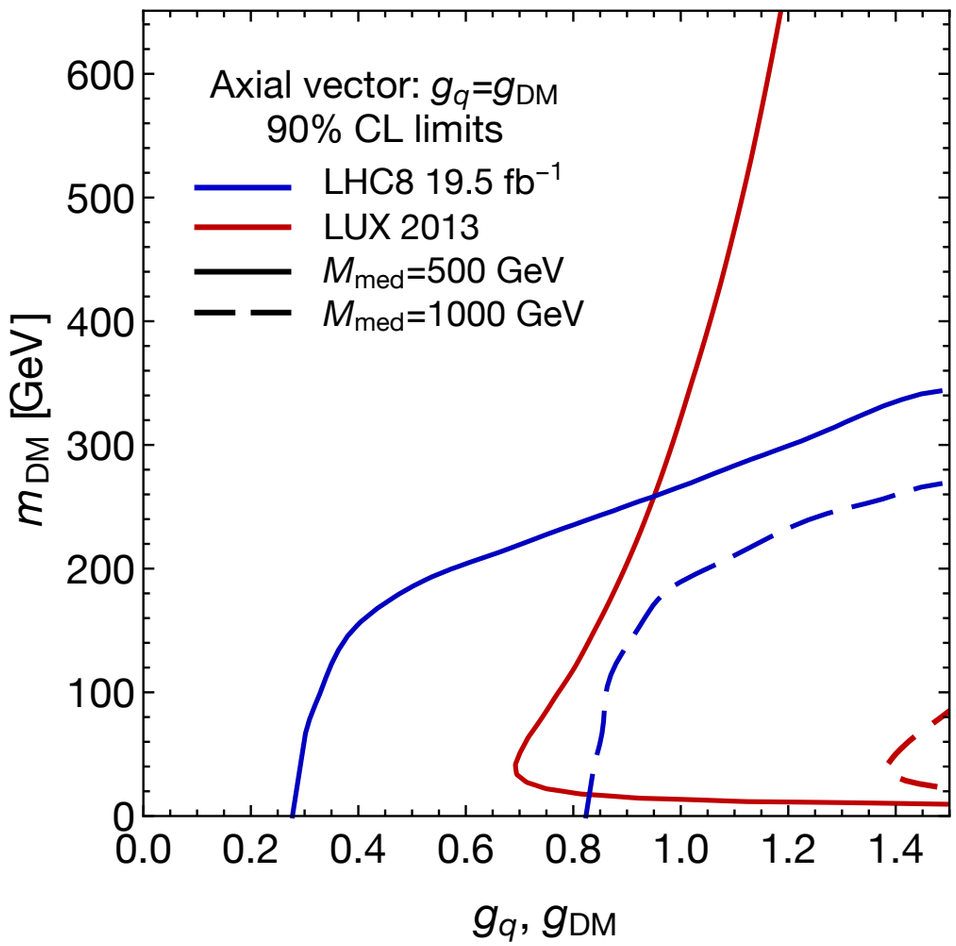

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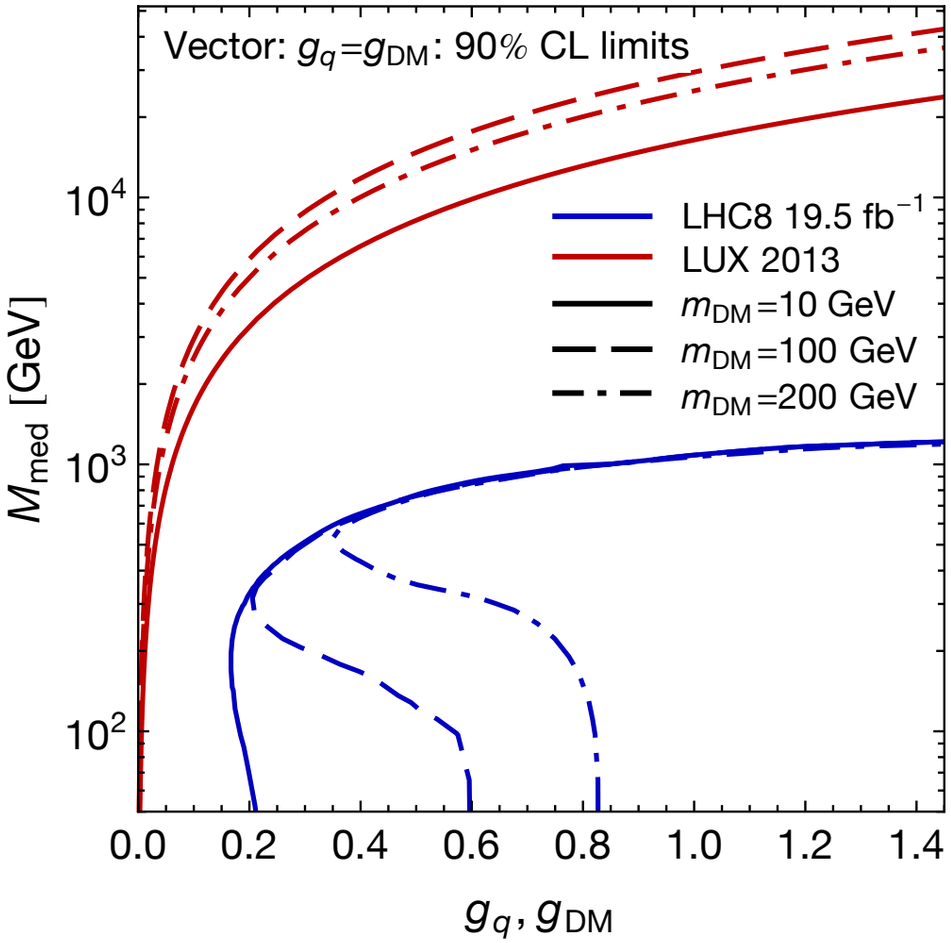
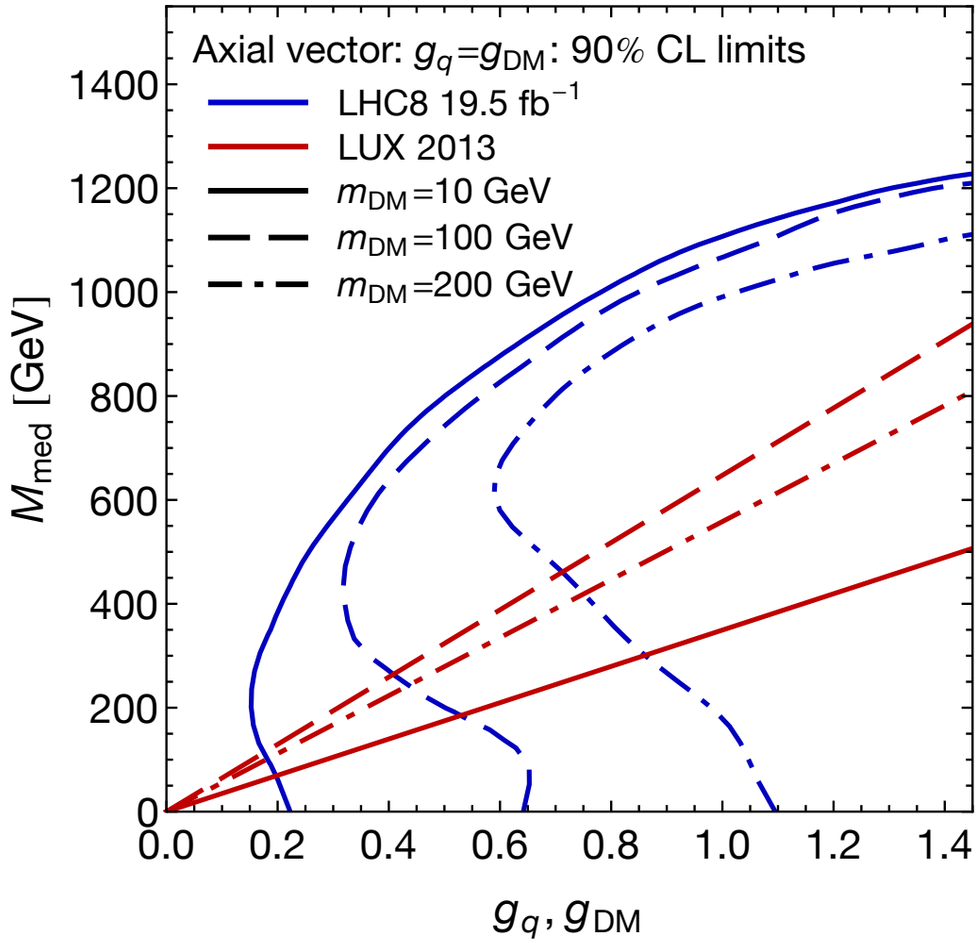
m_{DM}	g_χ
M_{med}	g_q





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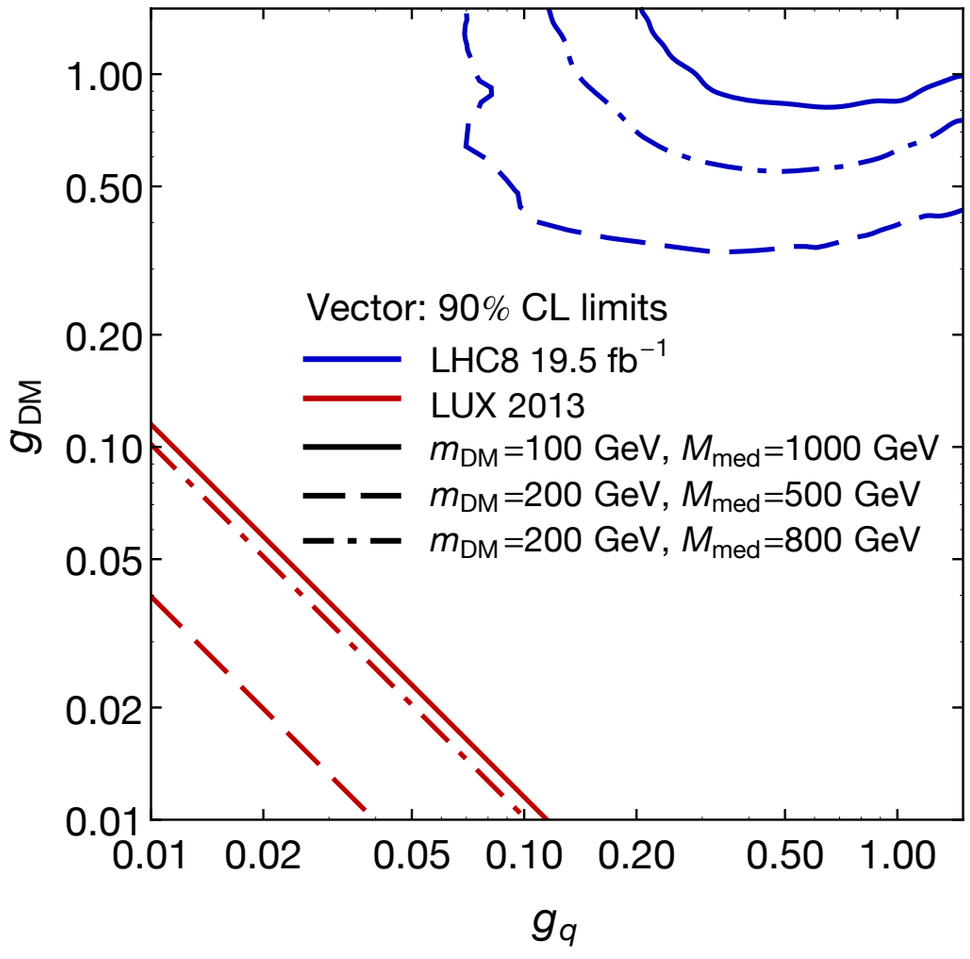
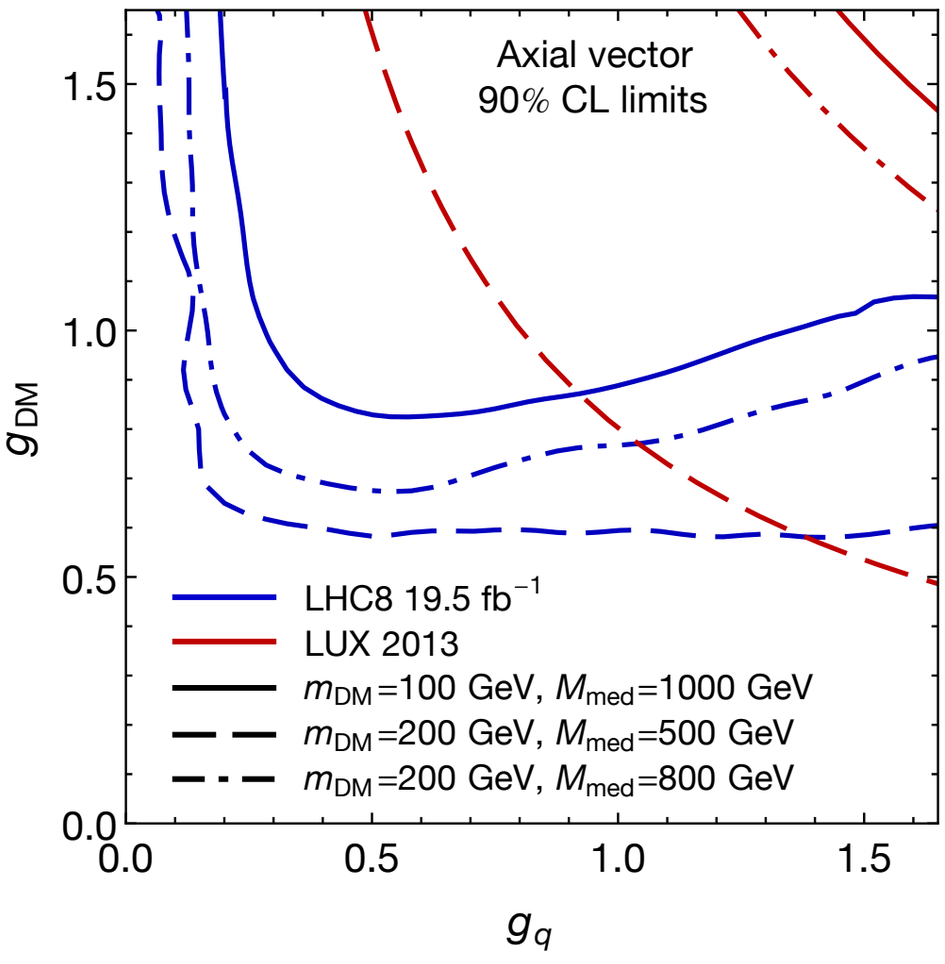


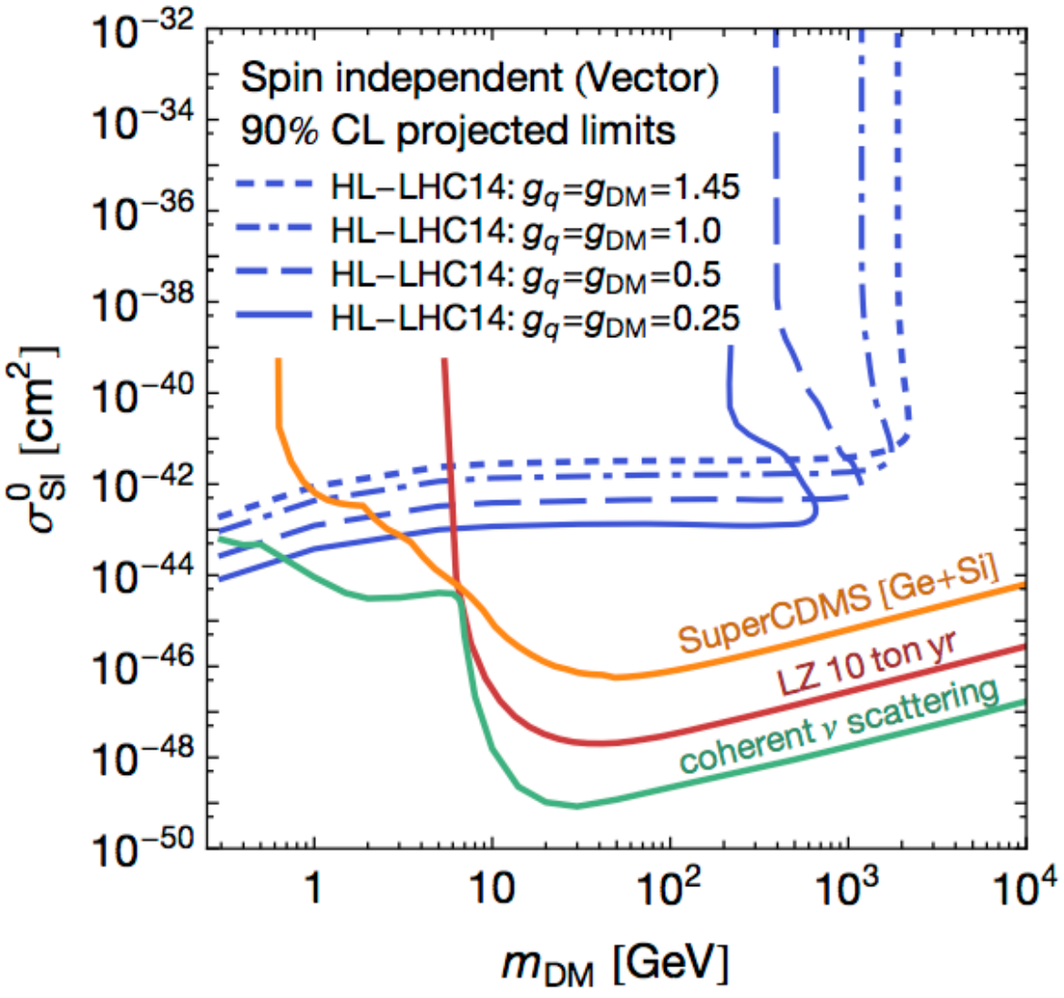


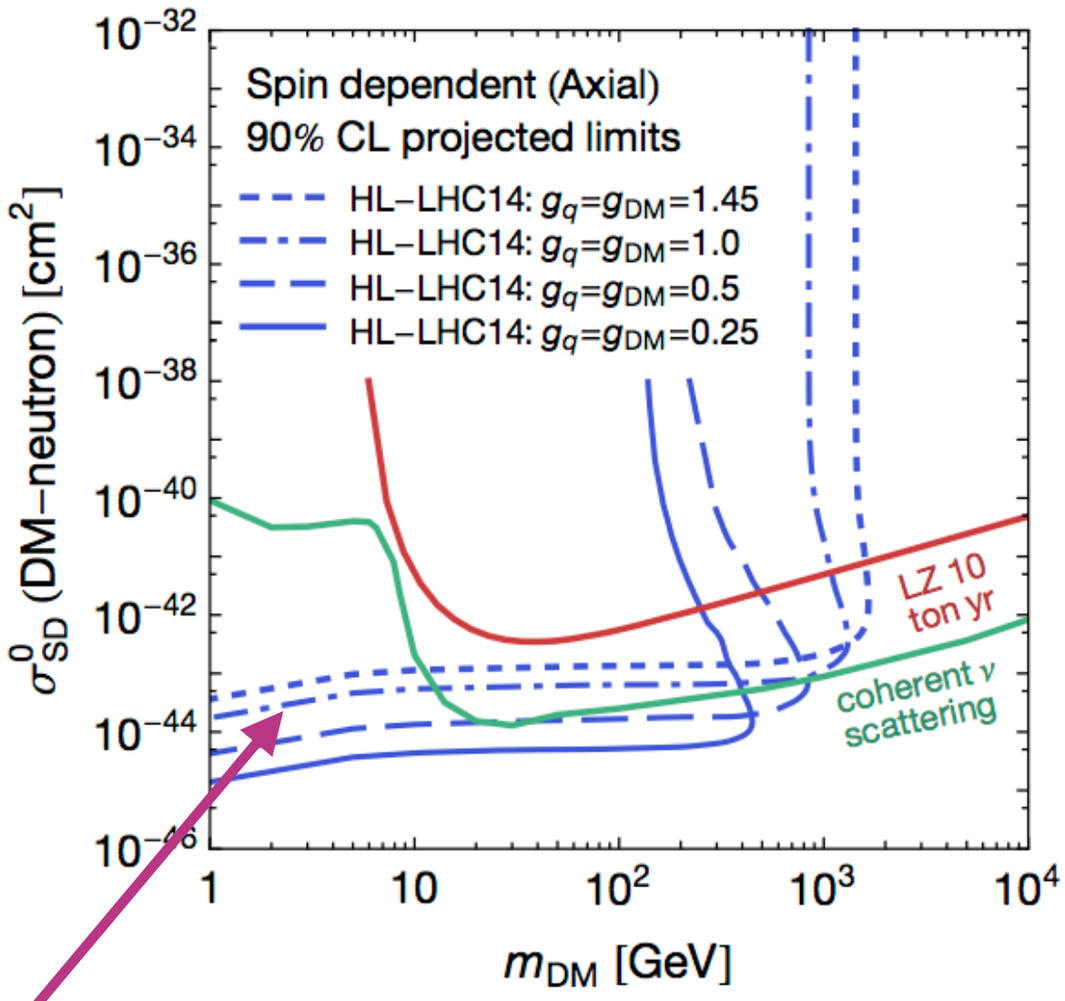
- Better elucidation of the complementarity between collider and direct searches

Future projections

Malik, CM et al
arXiv:1409.4075

- Can also map results into more traditional parameter plots



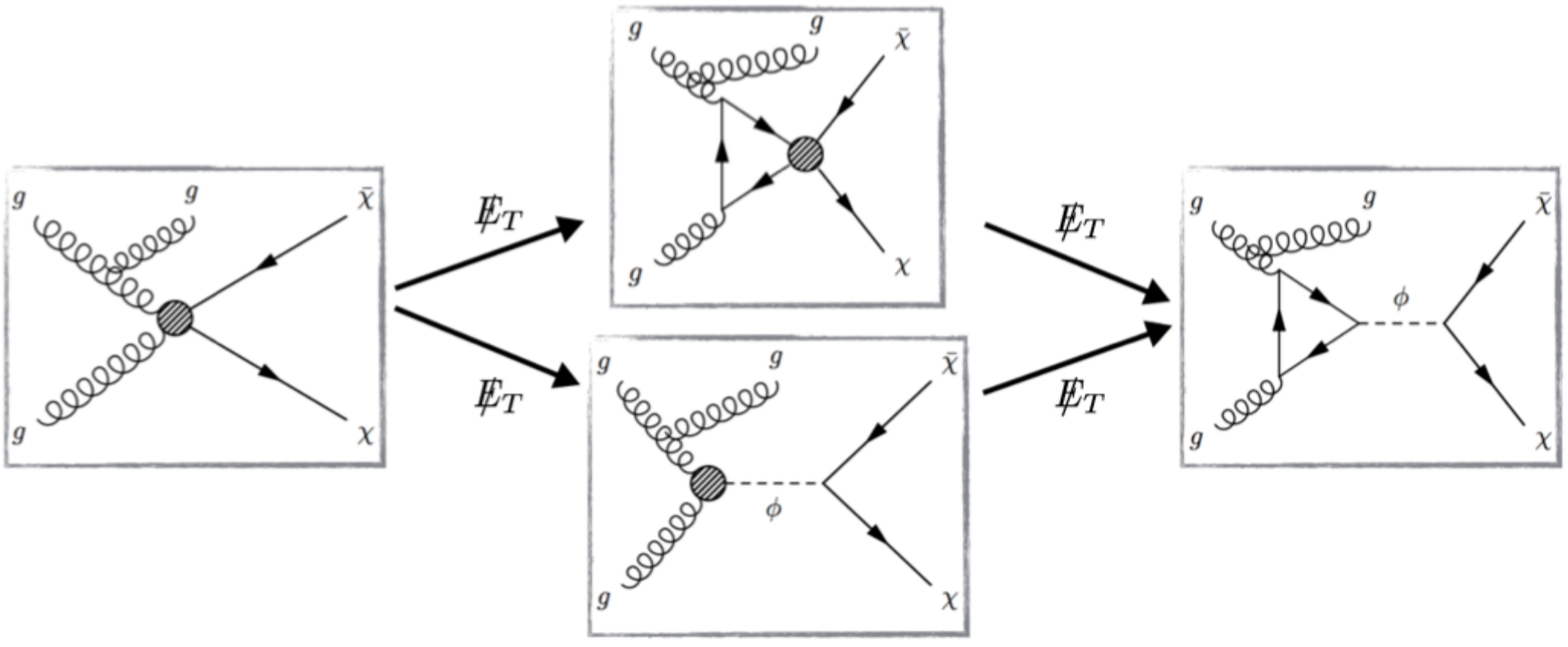


Possible to search below the neutrino floor

Scalar/Pseudoscalar

Buckley, Feld, Goncalves arXiv:1410.6497

- Extendable to other mediators

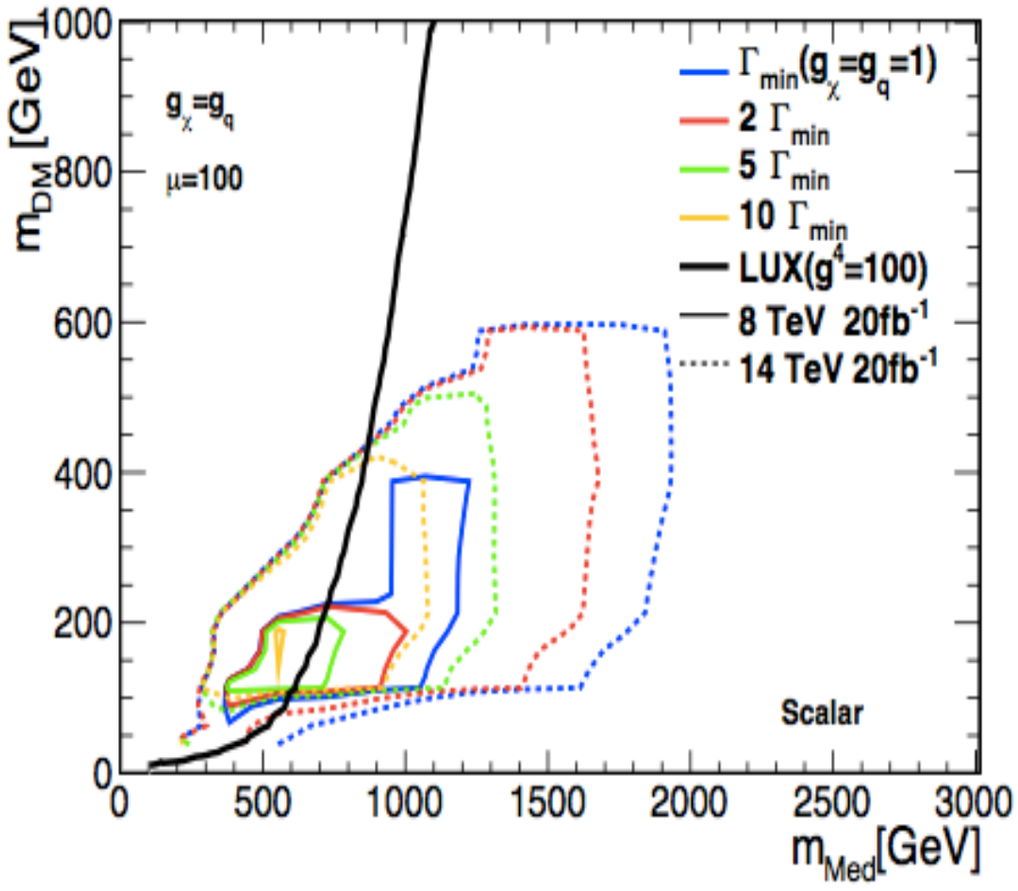


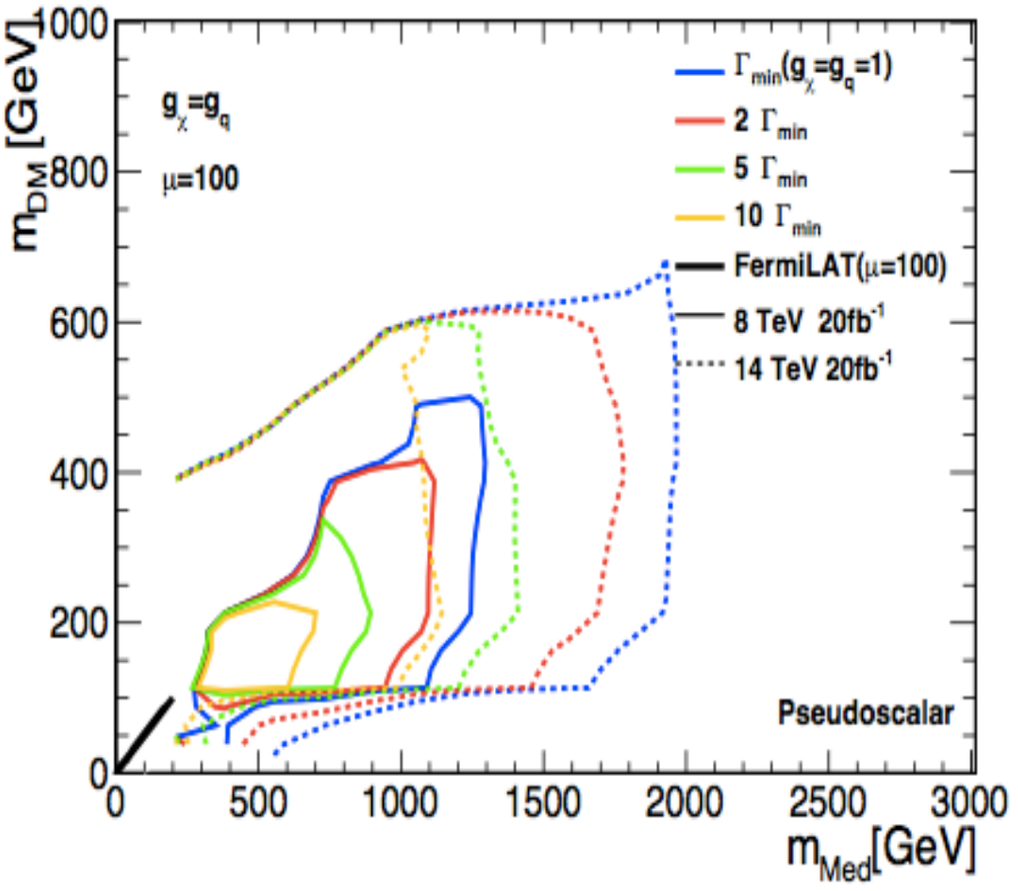
- Additional complexity resolving both the top-loop and mediator

Scalar/Pseudoscalar

Harris, Khoze, Spannowsky, Williams arXiv:1411.0535

- Extendable to other mediators
- Mediator width can also be treated as a free parameter





Direct detection

$$\bar{\chi}\gamma^5\chi\,\bar{N}\gamma^5 N \propto \left(\vec{S}_\chi \cdot \vec{q}\right)\ \left(\vec{S}_N \cdot \vec{q}\right)$$

➡ Spin-dependent interaction

➡ momentum dependent

- Spin information encoded in ‘spin form factor’: $F_{\Sigma''}$
  - non-zero for only certain isotopes (need an unpaired proton or neutron to have net spin)

- momentum transfer $q = \sqrt{2 m_T E_{\mathrm{R}}} \sim 100\ \mathrm{MeV}$

Direct detection

$$\mathscr{L}_{\text{eff}} = \frac{1}{2\Lambda_a^2} \sum_{N=p,n} g_N \, \bar{\chi}\gamma^5\chi \, \bar{N}\gamma^5 N$$

where $\Lambda_a \equiv m_a/\sqrt{g_{\text{DM}} g}$.

The DM interaction cross section with a target nucleus with mass m_T is (in the contact-interaction regime)

$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_{\text{R}}} = \frac{1}{128\pi} \frac{q^4}{\Lambda_a^4} \frac{m_T}{m_{\text{DM}}^2 m_N^2} \frac{1}{v^2} \sum_{N,N'=p,n} g_N g_{N'} F_{\Sigma''}^{(N,N')}(q^2)$$

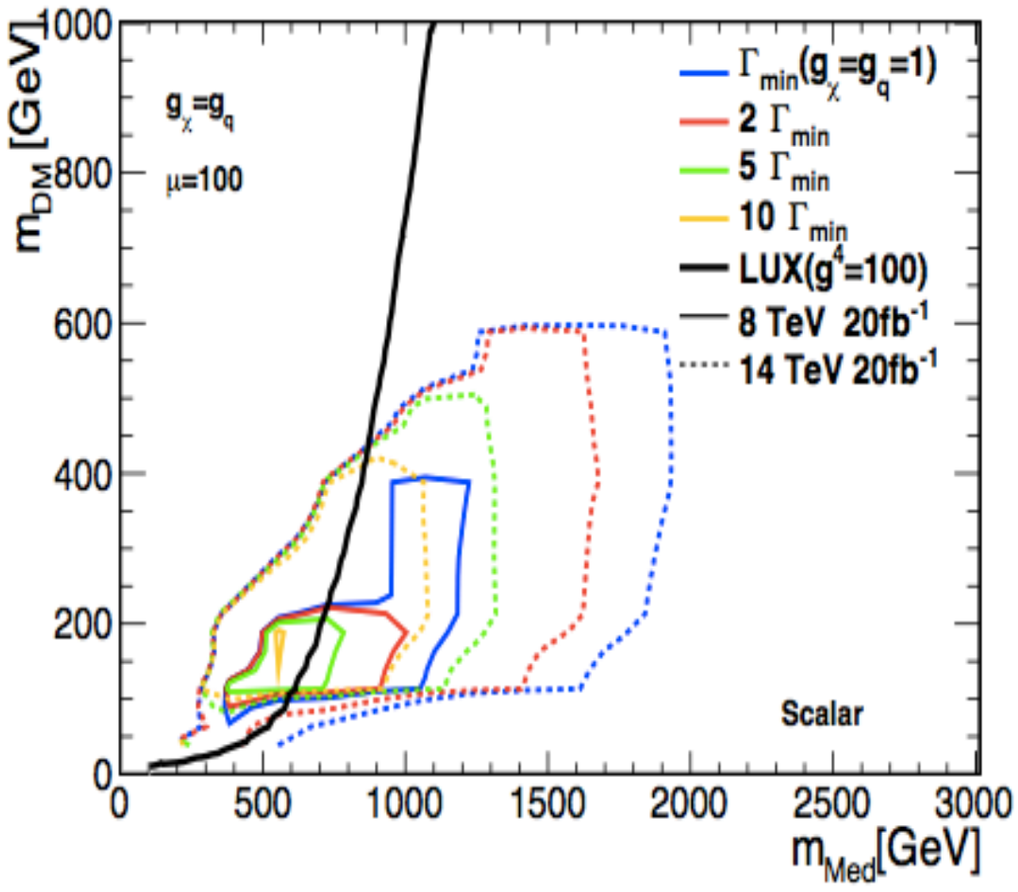
Rate could be very small because of this factor

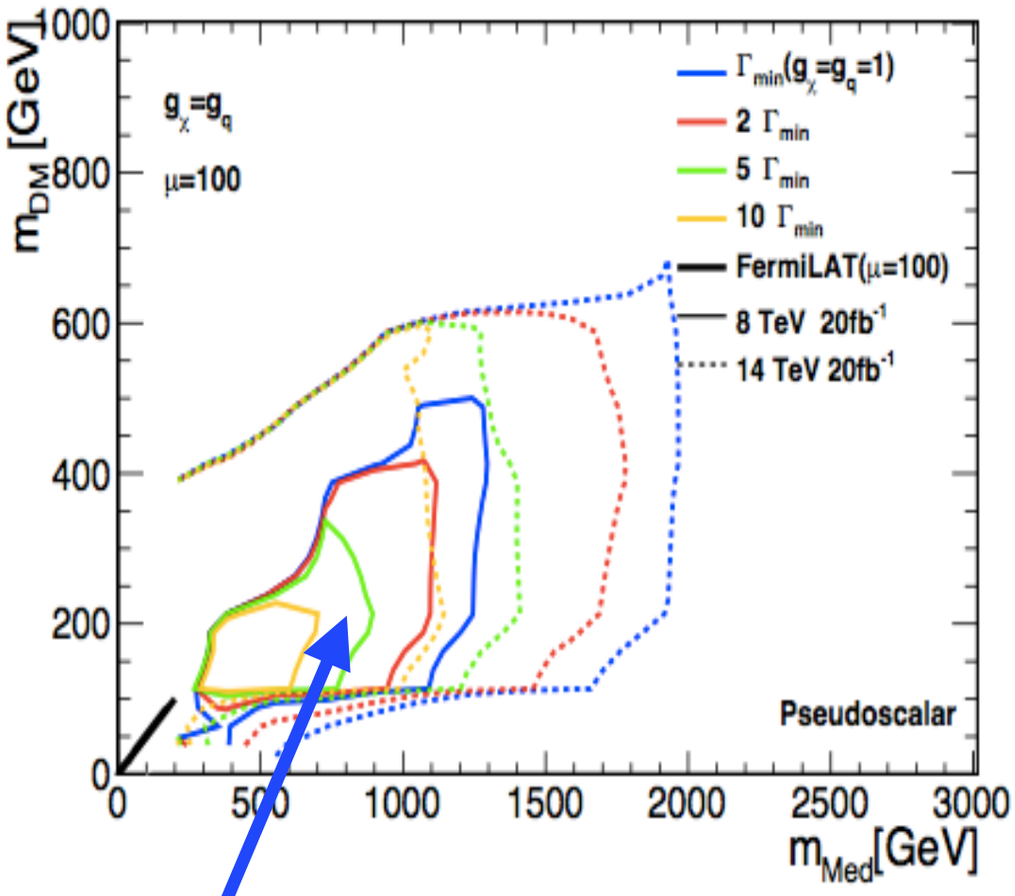
➡ Expect $\Lambda_a \sim m_a \sim q \approx 100 \text{ MeV}$

Scalar/Pseudoscalar

Harris, Khoze, Spannowsky, Williams arXiv:1411.0535

- Extendable to other mediators
- Mediator width can also be treated as a free parameter



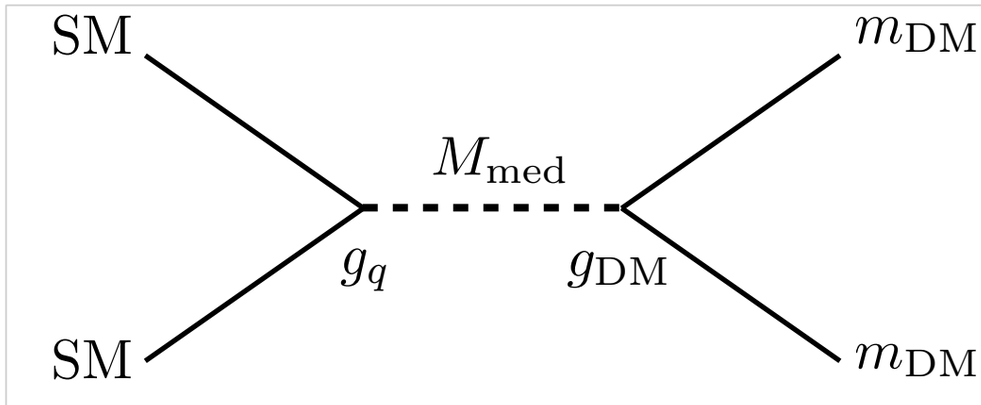


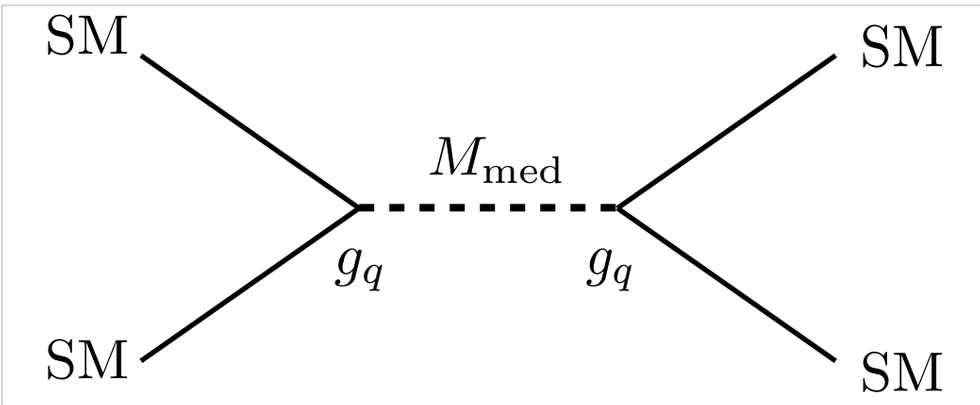
LHC potentially probes much parameter space not covered by direct or indirect searches

Future work

- Does anything substantial change for scalar dark matter particles?

- Natural to consider complementarity of di-jet and monojet searches





- To what extent can collider searches probe parameter space limited by neutrino interactions

- Optimising cuts for specific parameter regions eg light mediators

Summary

- Exciting time for dark matter searches!
  - ➡ WIMPs under assault from many experimental searches
- Crucial to interpret dark matter searches in the right framework
- Comparing LHC monojet searches with other dark matter searches is not straightforward
  - ➡ EFT approach constrains few theories and naïve comparison with direct detection can lead to incorrect conclusions
- Need to go beyond EFT
  - ➡ ‘Minimal simplified DM models’ capture more physics but at the expense of extra parameters

Thank you