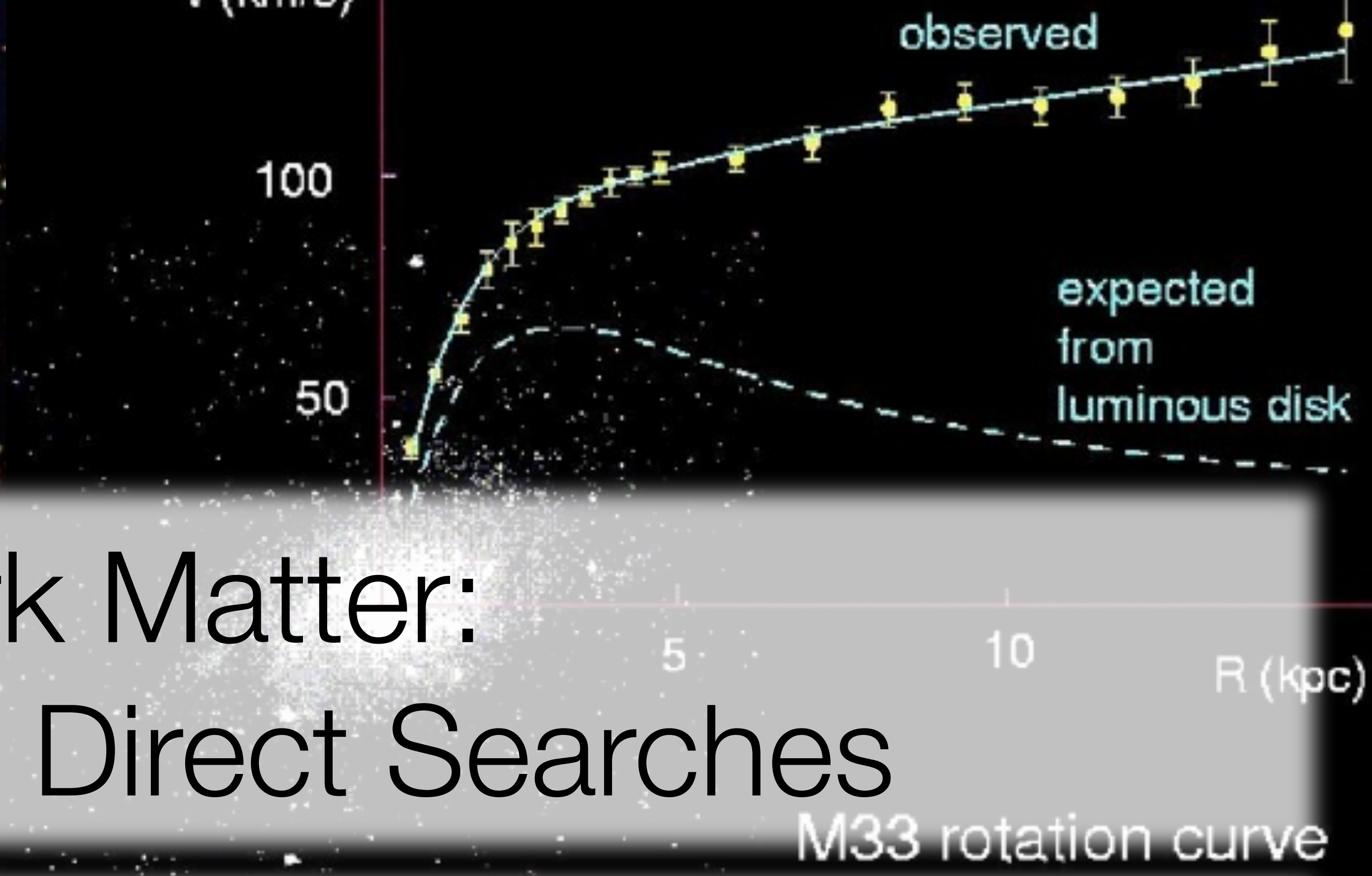
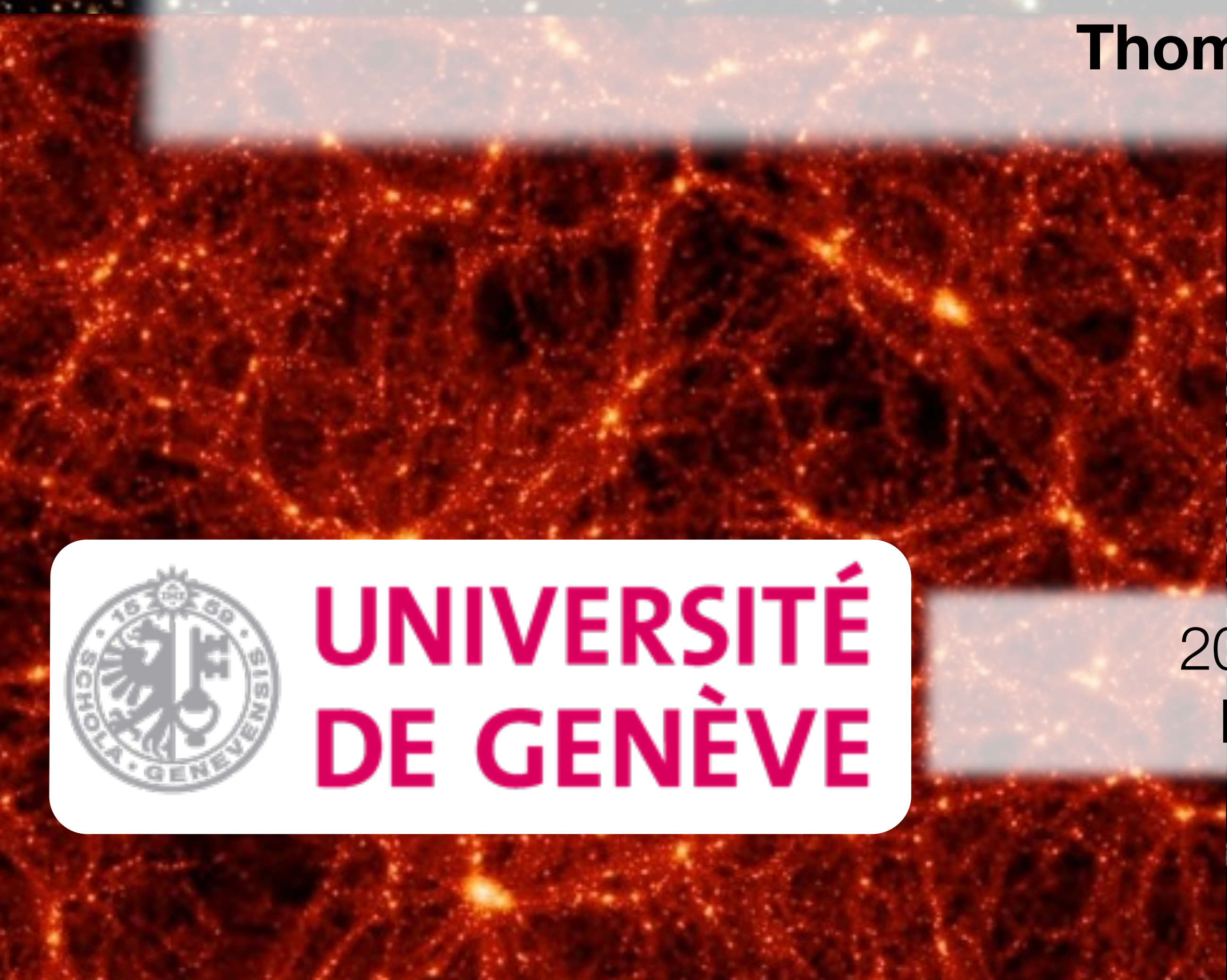
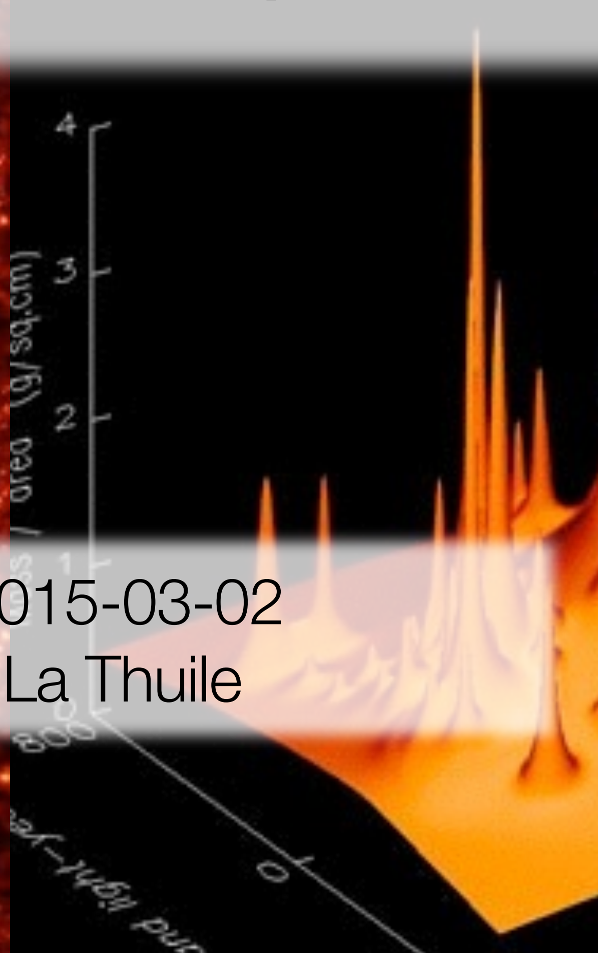


Dark Matter:
Collider vs. Direct Searches

Thomas Jacques

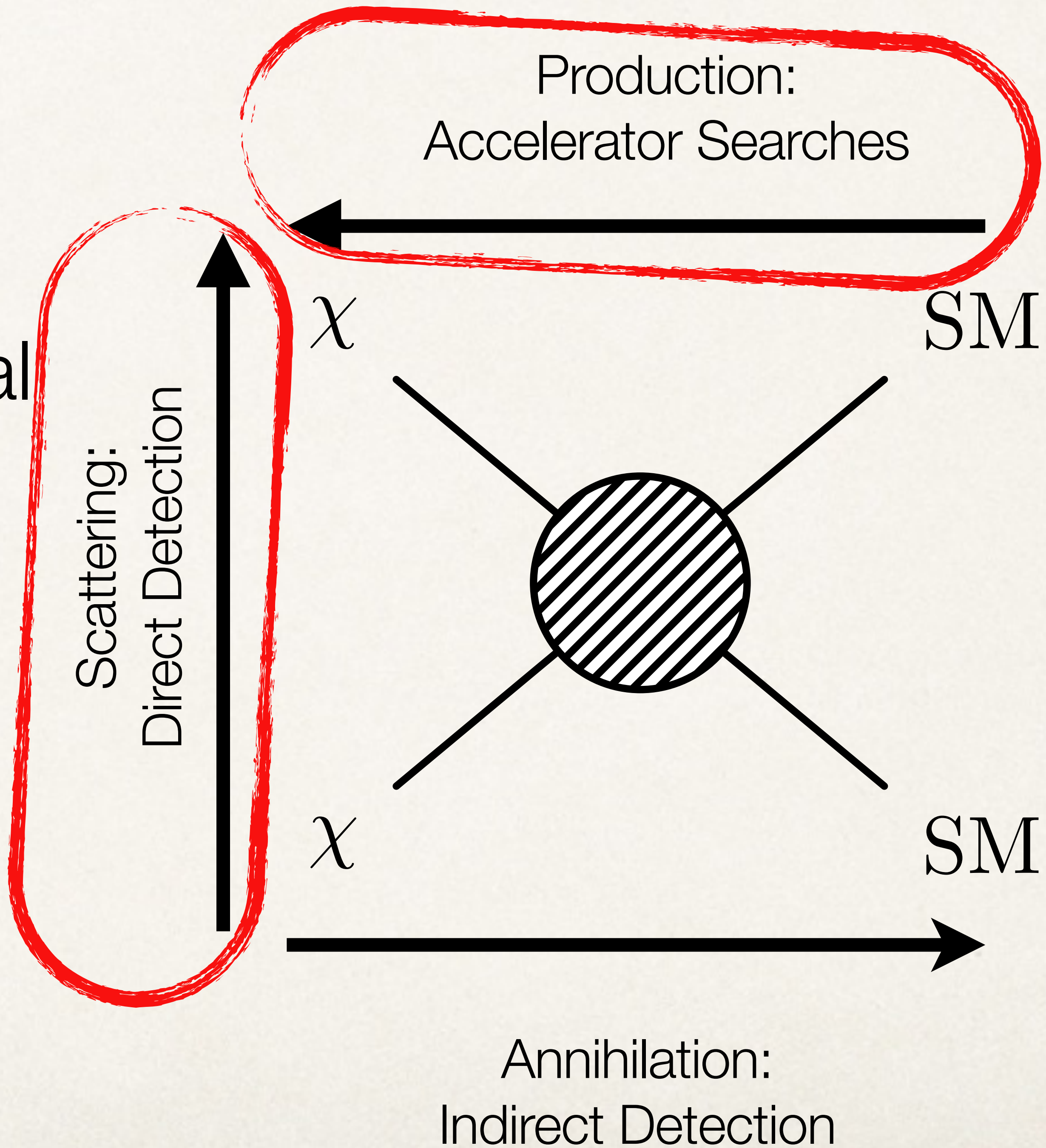




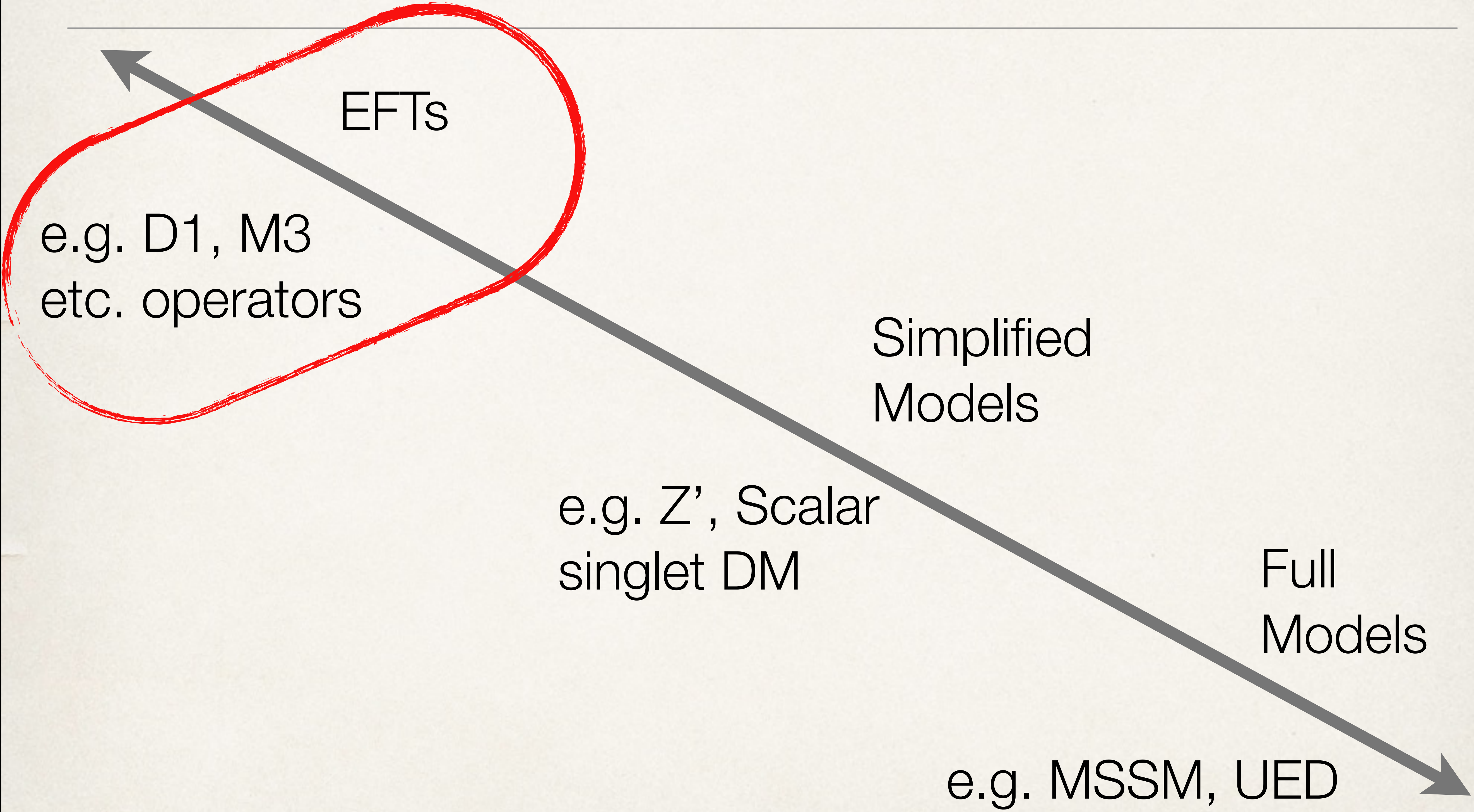
2015-03-02
La Thuile

Dark Matter Searches

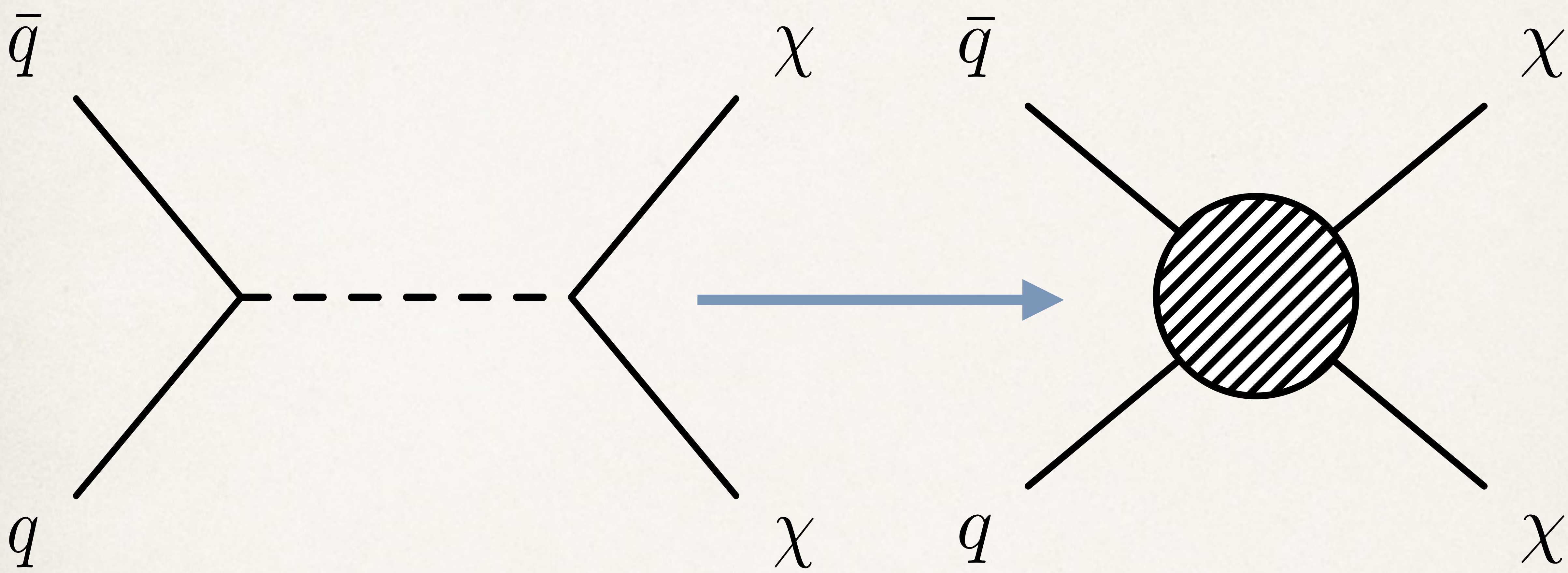
- Regardless of the underlying particle physics, there are several complementary ways to search for DM
- Each technique has its own strengths and challenges



What exactly are we constraining?



Effective Field Theories



$$\frac{g_a g_b}{Q_{\rm tr}^2 - M^2} = -\frac{g_a g_b}{M^2}\left(1 + \frac{Q_{\rm tr}^2}{M^2} + \mathcal{O}\left(\frac{Q_{\rm tr}^4}{M^4}\right)\right) \simeq -\frac{1}{\Lambda^2}$$

$$\mathrm{D1} = (\bar{\chi}\chi)(\bar{q}q)$$
$$\mathrm{D5} = (\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q)$$
$$\mathrm{D8} = (\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{q}\gamma_\mu\gamma^5 q)$$

$$\mathrm{M1} = (\chi\chi)(\bar{q}q)$$
$$\mathrm{C1} = (\chi^\dagger\chi)(\bar{q}q)$$
$$\mathrm{C3} = (\chi^\dagger\partial_\mu\chi)(\bar{q}\gamma^\mu q)$$

Complementarity

$$q\bar{q} \to \chi\chi$$

$$N\chi \to N\chi$$

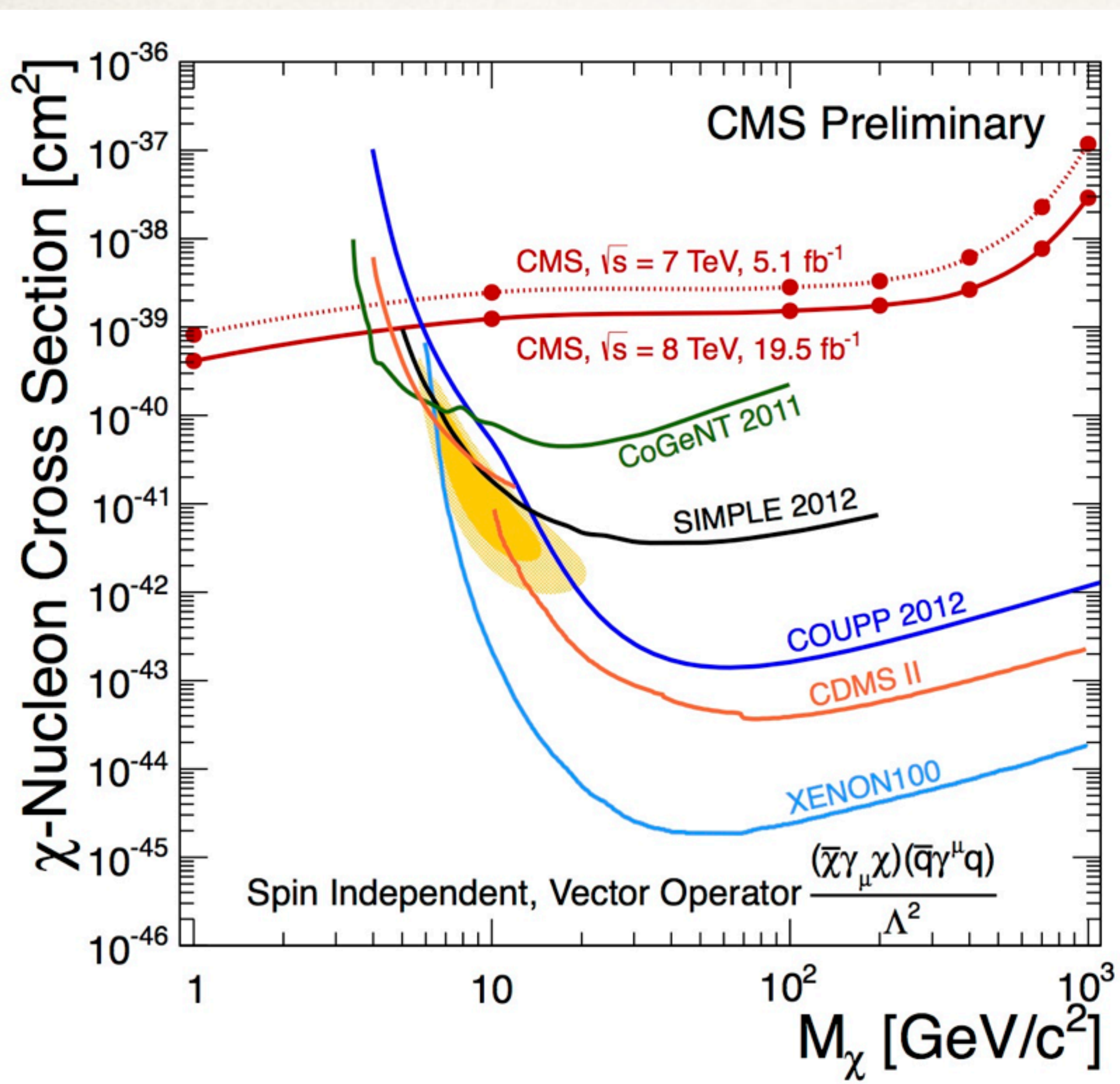
$$\chi\chi \to q\bar{q}$$

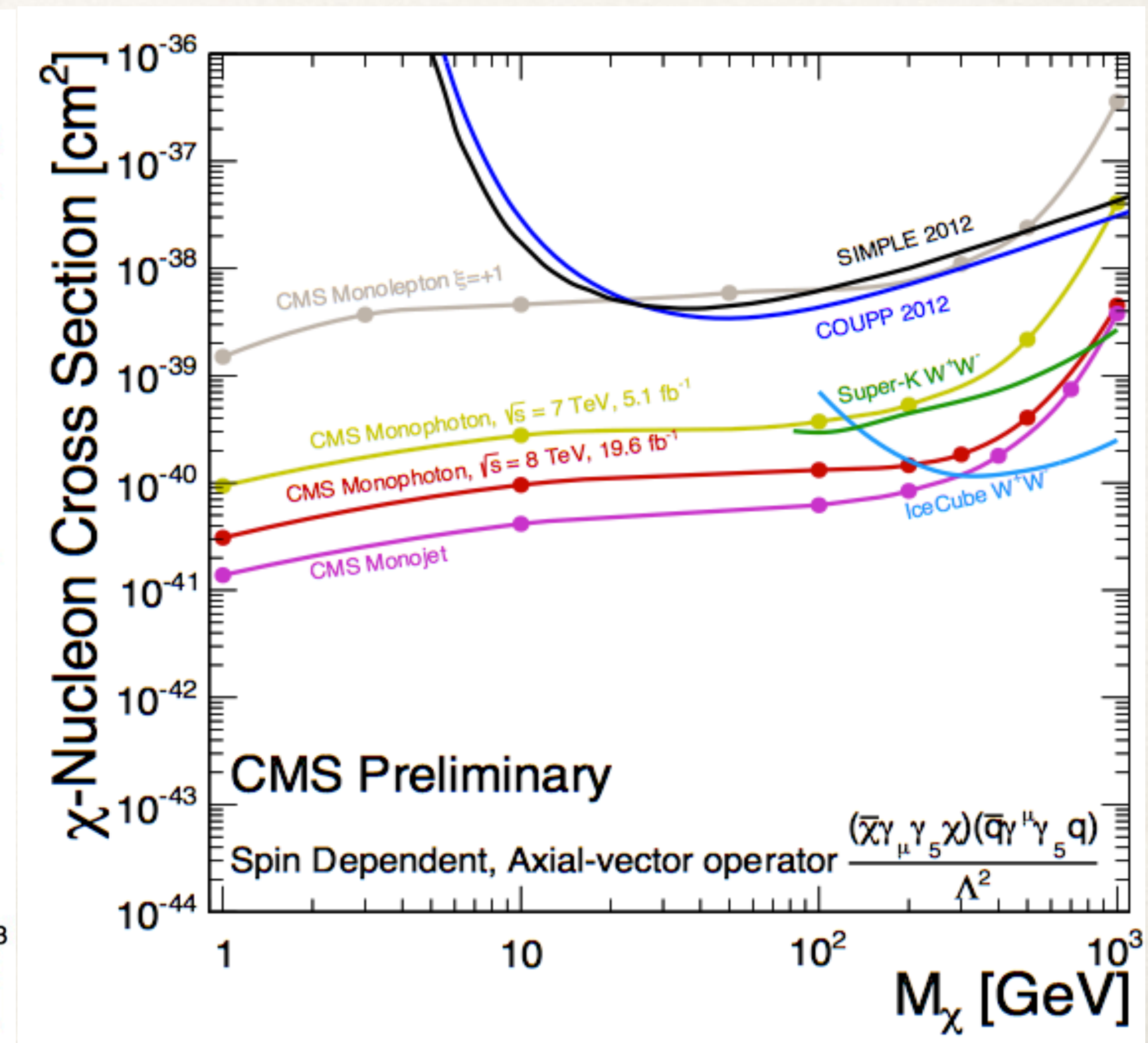
$$\Lambda$$

$$\sigma_{q\bar{q}\to\chi\chi}$$

$$\sigma_{N\chi\to N\chi}$$

$$\sigma_{\chi\chi\to q\bar{q}}$$





Effective Operators and Direct Detection

Spin Independent scattering rate:

$$\frac{dR}{dE_R} = \frac{\sigma_{\rm SI}}{2m_\chi \mu_{\chi N}}(Z + \frac{f_n}{f_p}(A - Z))^2 \mathrm{F}^2(E_R) \int_{v_{\rm min}}^{\infty} \rho_0 \frac{f(\vec{v})}{|\vec{v}|} d^3v$$

applies to the scalar DM-nucleon coupling;

But other DM-nucleon operators lead to the same non-relativistic operator,

$$(\bar{\chi}\chi)(\bar{N}N), (\bar{\chi}\gamma^\mu\chi)(\bar{N}\gamma_\mu N), (\phi^*\phi)(\bar{N}N), i(\phi^* \overleftrightarrow{\partial_\mu} \phi)(\bar{N}\gamma^\mu N)$$

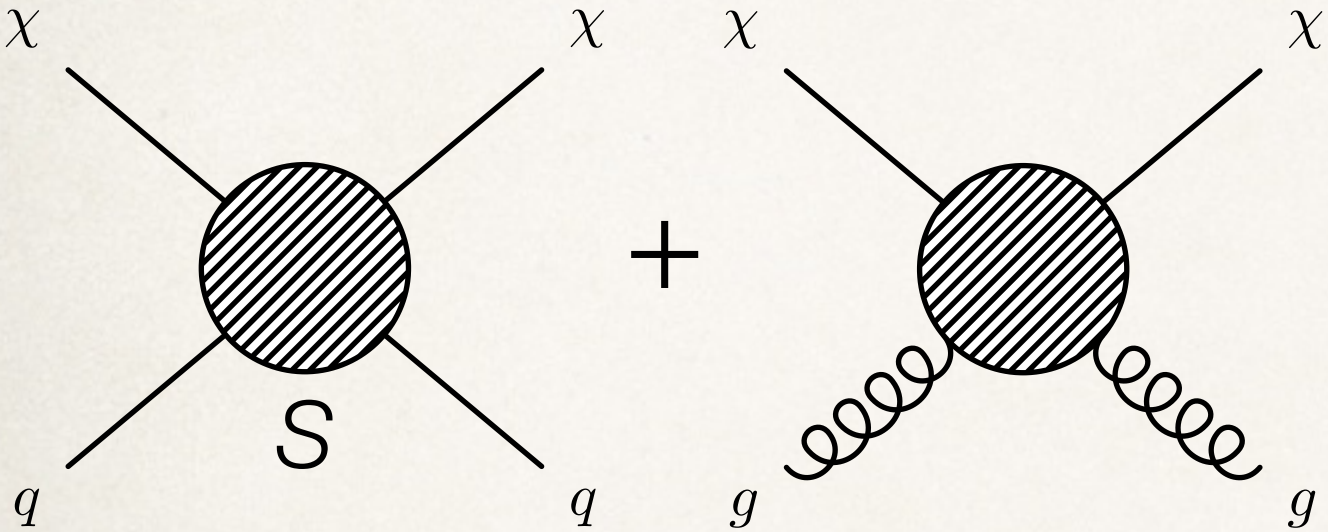
so constraints on $\sigma_{\rm SI}$ still apply after renormalisation.

Similarly, spin dependent scattering comes from operators:

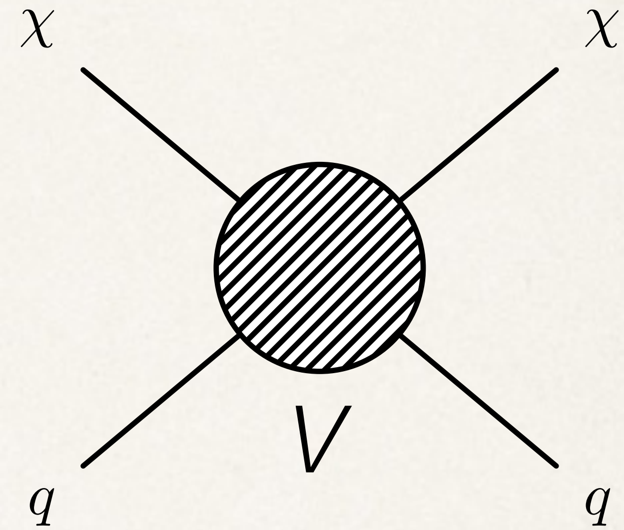
$$(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{N}\gamma_\mu\gamma^5 N), (\bar{\chi}\sigma^{\mu\nu}\chi)(\bar{N}\sigma_{\mu\nu}N)$$

Effective Operators and Direct Detection

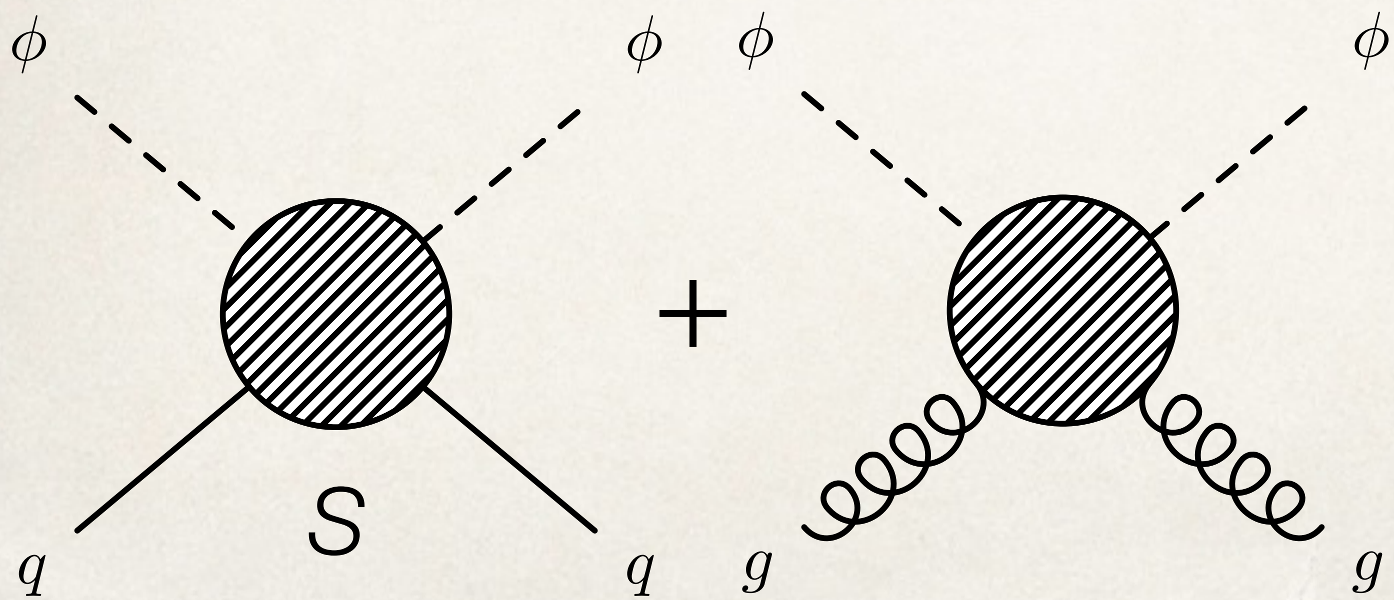
$$\bar{\chi}\chi\,\bar{N}N = f\left(\bar{\chi}\chi\,\bar{q}q, \bar{\chi}\chi\,G^a_{\mu\nu}G^a_{\mu\nu}\right)$$



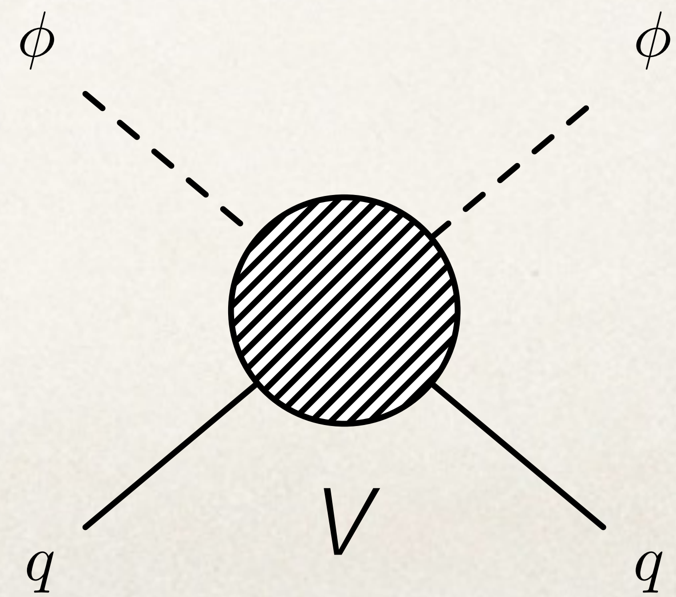
$$\bar{\chi}\gamma^\mu\chi\,\bar{N}\gamma_\mu N = f\left(\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q\right)$$



$$\phi^*\phi\,\bar{N}N = f(\phi^*\phi\,\bar{q}q, \phi^*\phi\,G^a_{\mu\nu}G^a_{\mu\nu})$$

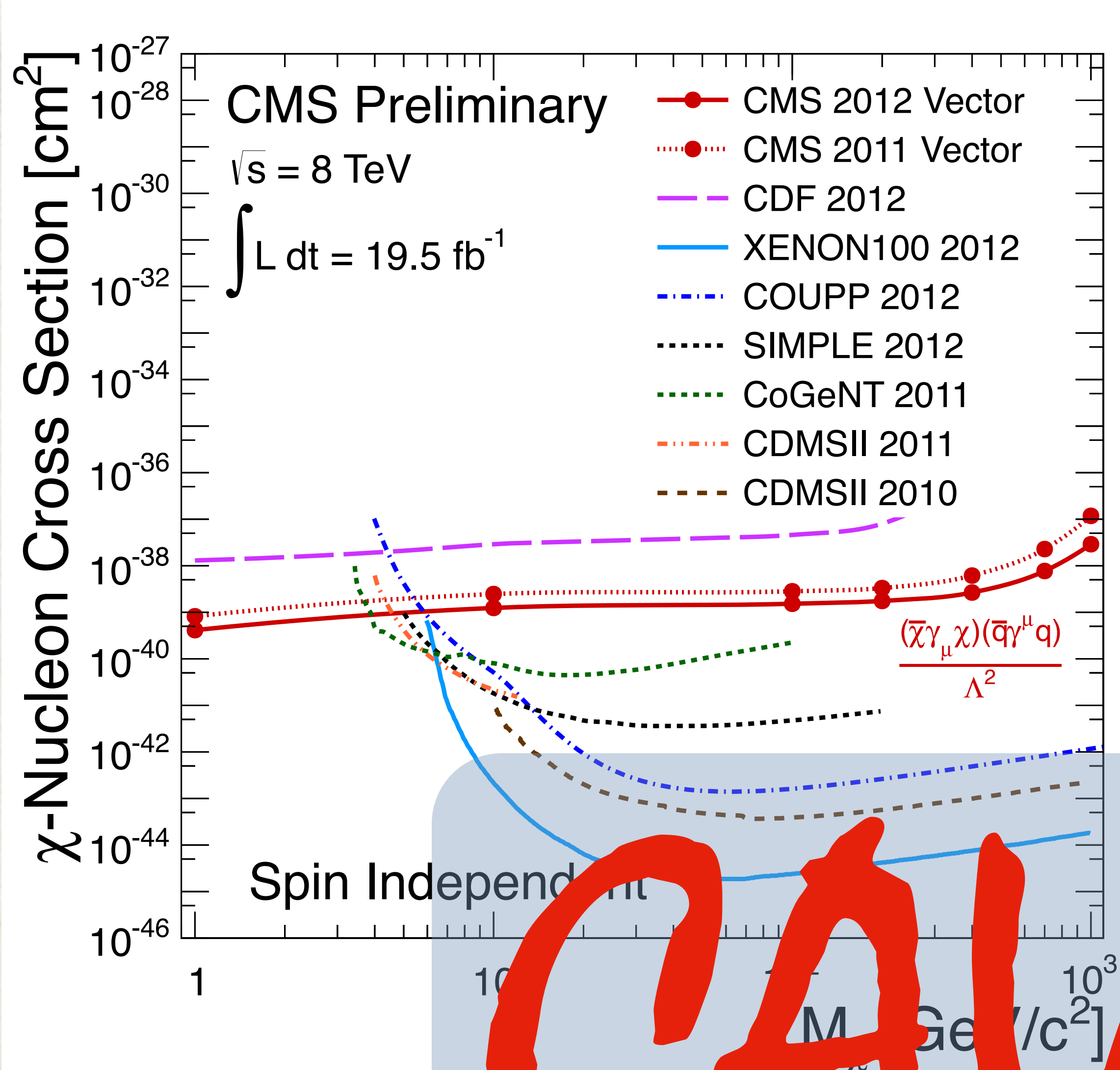


$$\phi^*\overleftrightarrow{\partial_\mu}\phi\,\bar{N}\gamma^\mu N = f(\phi^*\overleftrightarrow{\partial_\mu}\phi\,\bar{q}\gamma^\mu q)$$



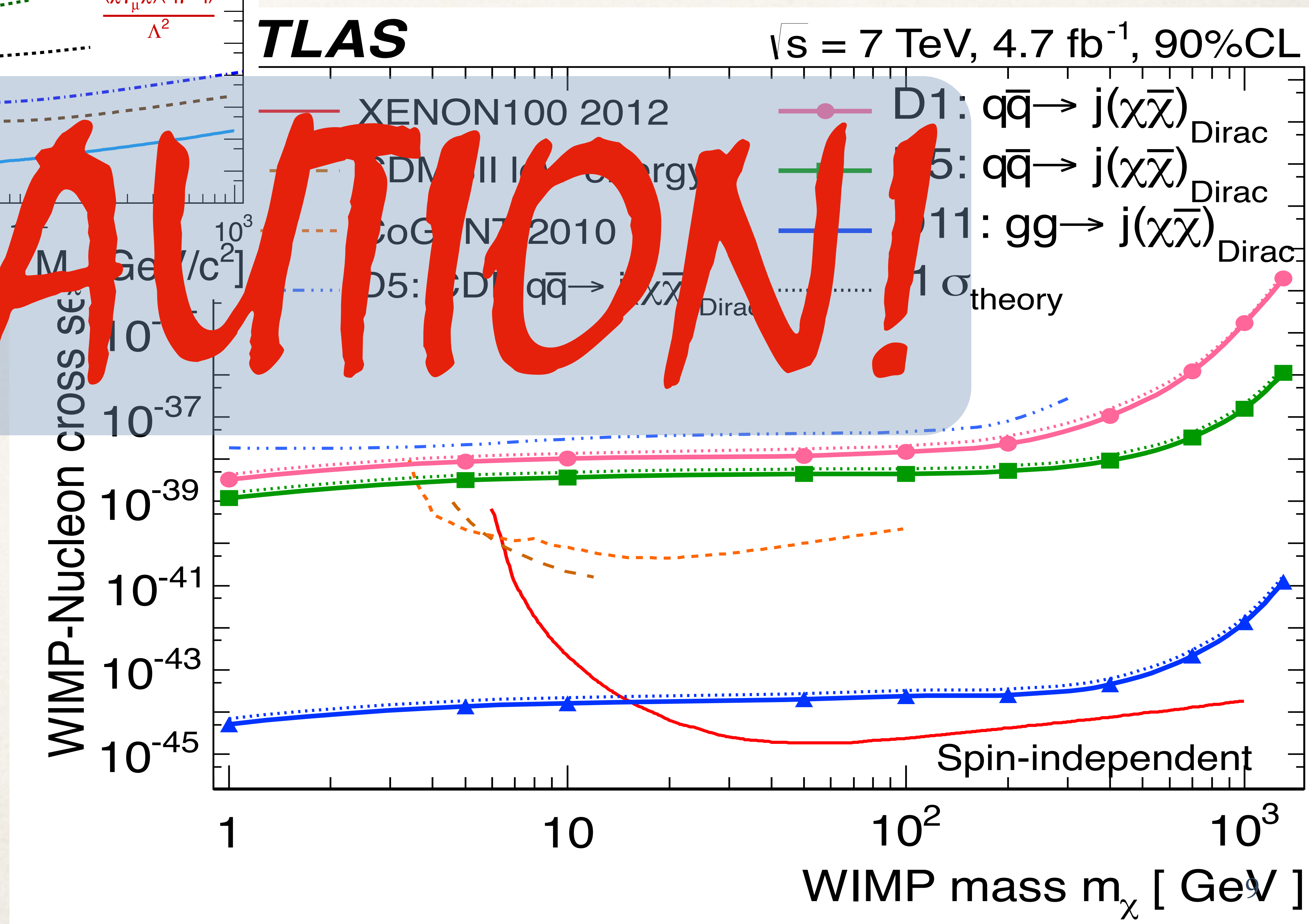
Effective Operators and Direct Detection

$$\left.\begin{array}{r}(\bar{\chi}\chi)(\bar{q}q) \\ (\bar{\chi}\gamma^{\mu}\chi)(\bar{q}\gamma_{\mu}q) \\ (\bar{\chi}\chi)(G^{a}_{\mu\nu}G^{a}_{\mu\nu}) \\ (\phi^{*}\phi)(\bar{q}q) \\ (\phi^{*}\overleftrightarrow{\partial_{\mu}}\phi)\,(\bar{q}\gamma^{\mu}q) \\ (\phi^{*}\phi)(G^{a}_{\mu\nu}G^{a}_{\mu\nu})\end{array}\right\} \leftrightarrow \sigma_{\mathrm{SI}}$$



CMS Preliminary
√s = 8 TeV
∫L dt = 19.5 fb^-1
CMS 2012 Vector
CMS 2011 Vector
CDF 2012
XENON100 2012
COUPP 2012
SIMPLE 2012
CoGeNT 2011
CDMSII 2011
CDMSII 2010
χ-Nucleon Cross Section [cm²]
Spin Independ
1
10^3

CAUTION!



TLAS
√s = 7 TeV, 4.7 fb^-1, 90%CL
XENON100 2012
D1: qq̄→ j(χχ̄)Dirac
5: qq̄→ j(χχ̄)Dirac
11: gg→ j(χχ̄)Dirac
σtheory
WIMP-Nucleon cross se
10^-37
10^-39
10^-41
10^-43
10^-45
Spin-independent
1
10
10^2
10^3
WIMP mass mχ [GeV]

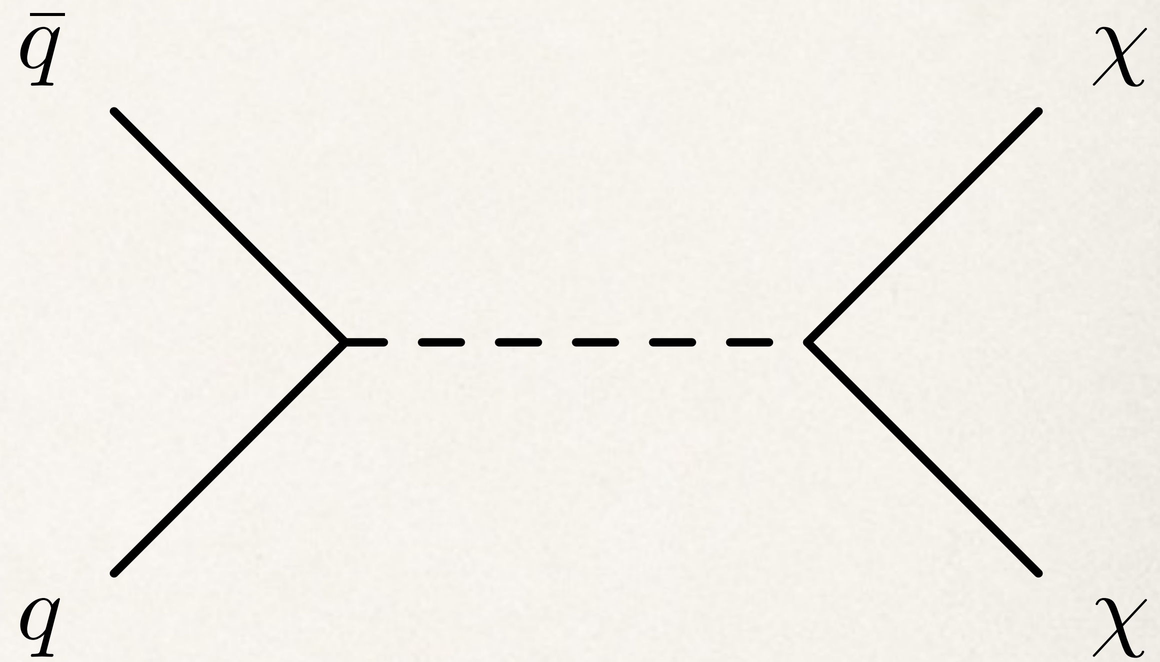
Fundamental Limit to Validity

- In s-channel:

$$Q_{\rm tr} > 2m_{\rm DM}$$

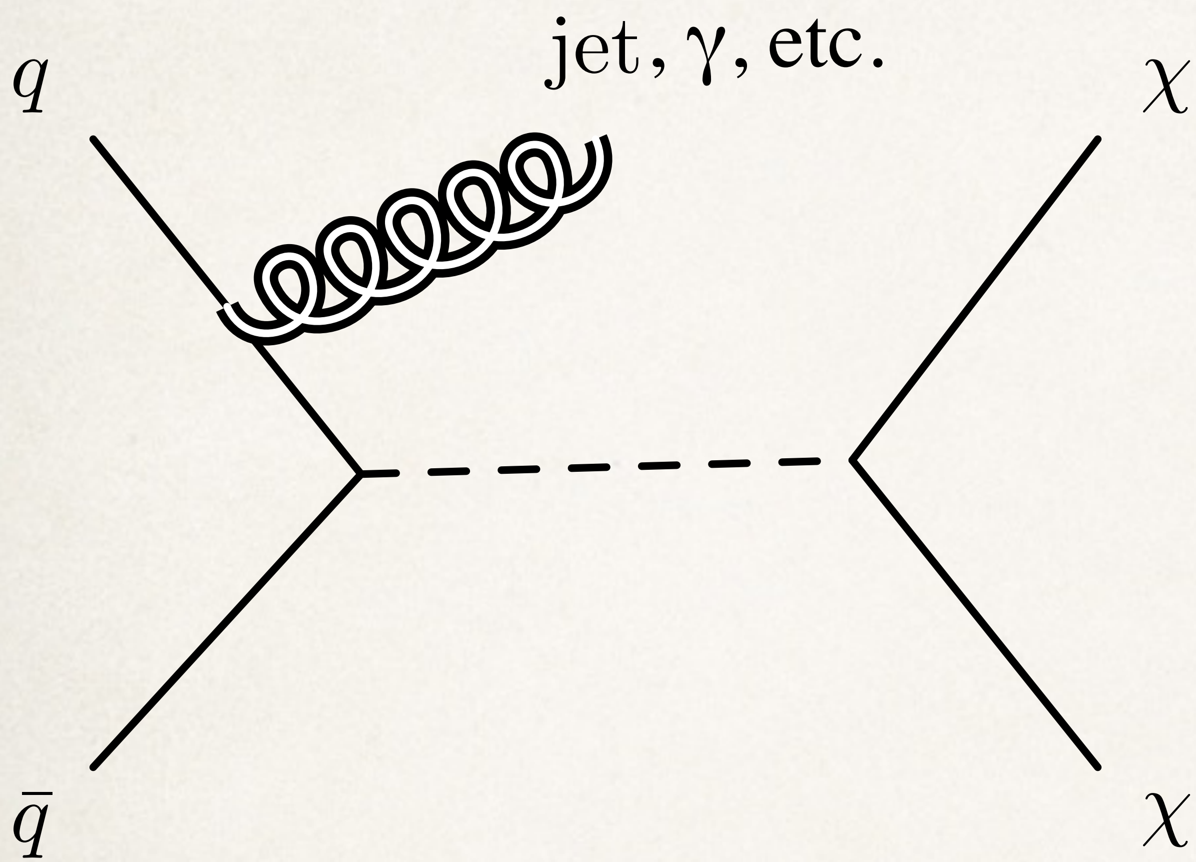
$$M > 2m_{\rm DM}$$

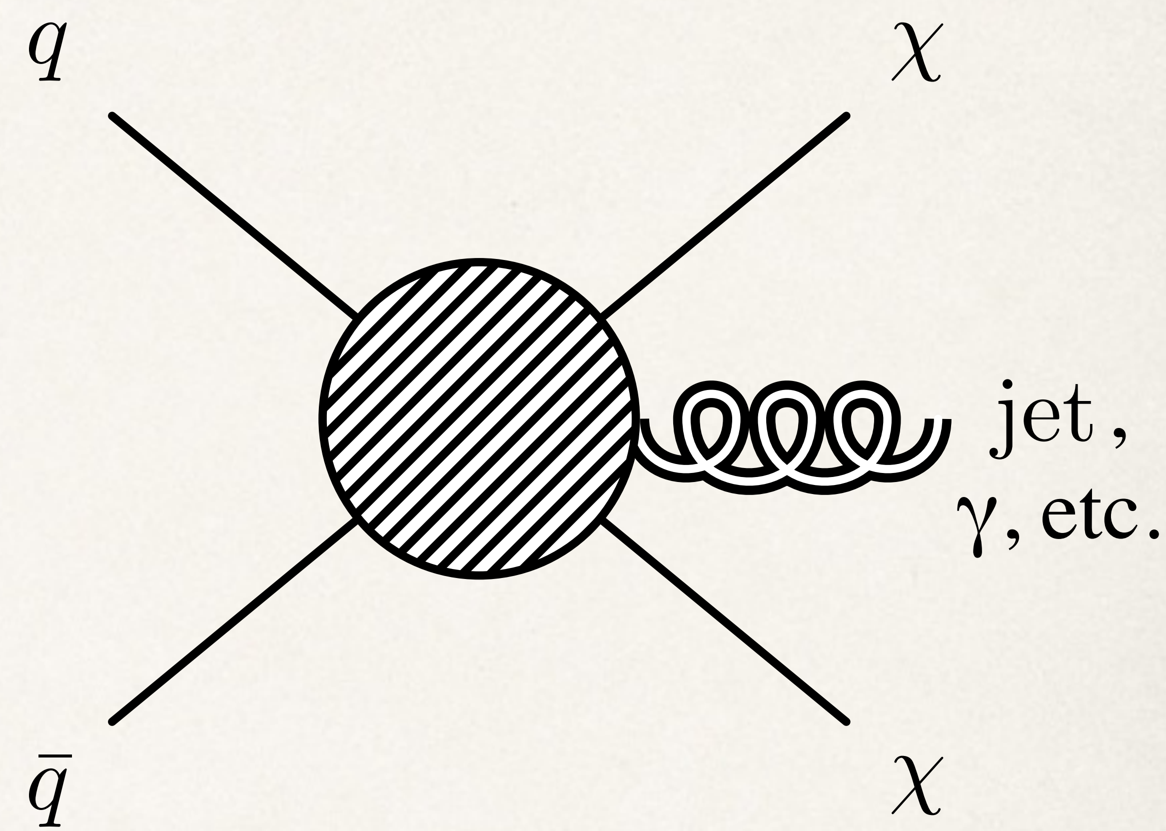
$$\Lambda = \frac{M}{\sqrt{g_a g_b}} \geq \frac{M}{4\pi}$$



$$\Lambda \gtrsim \frac{m_{\rm DM}}{2\pi}$$

Effective Field Theories





$$\frac{g_a g_b}{Q_{\rm tr}^2 - M^2} = -\frac{g_a g_b}{M^2}\left(1 + \frac{Q_{\rm tr}^2}{M^2} + \mathcal{O}\left(\frac{Q_{\rm tr}^4}{M^4}\right)\right) \simeq -\frac{1}{\Lambda^2}$$

~~$$\Lambda \gtrsim \frac{m_{\rm DM}}{2\pi}$$~~

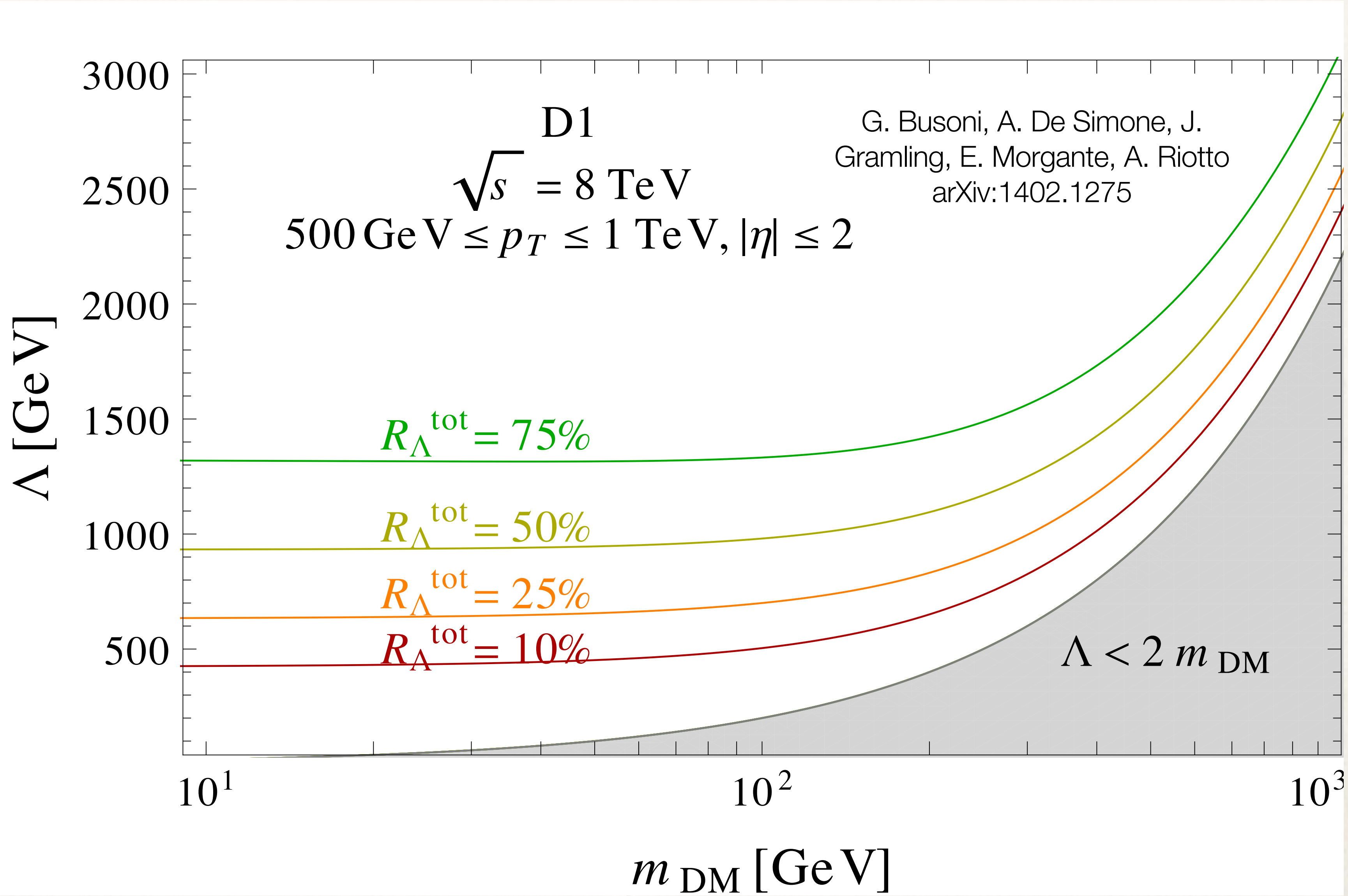
$$Q_{\rm tr} < M$$

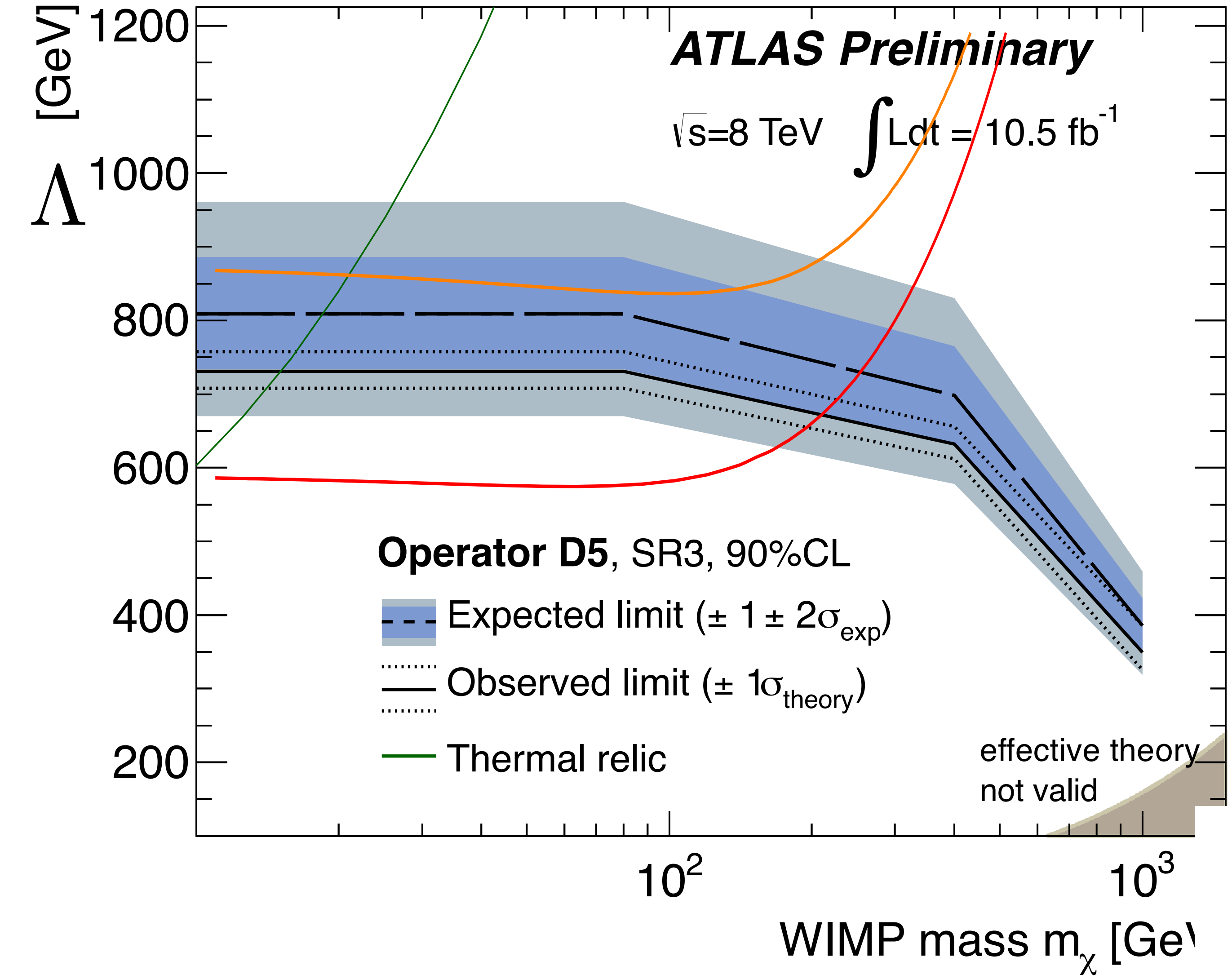
Measuring the Validity

Calculate or measure the fraction of events that pass the condition $Q_{tr} < \Lambda$, for a given choice of Λ and m_{DM}, and assuming g ≥1.

$$R_\Lambda^{\text{tot}} = \frac{\sigma_{\text{eff}}\big|_{\Lambda > Q_{\text{tr}}}}{\sigma_{\text{eff}}}$$

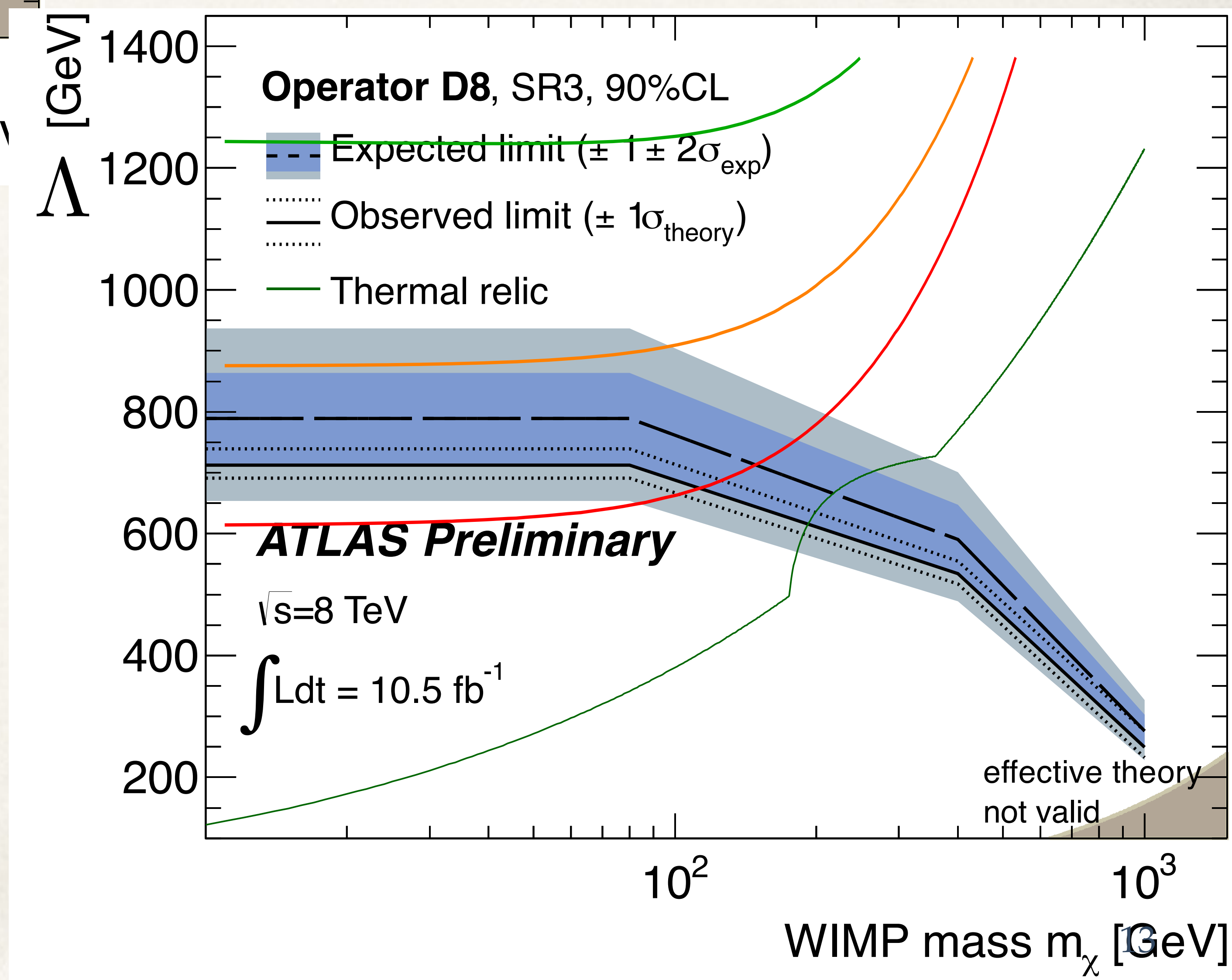
$$\text{D1} = (\bar{\chi}\chi)(\bar{q}q) \qquad q\bar{q} \to \chi\chi + \text{jet} \qquad Q_{\text{tr}} = p_q + p_{\bar{q}} - p_{\text{jet}}$$





EFT Validity

R = 10%	
R = 25%	
R = 50%	

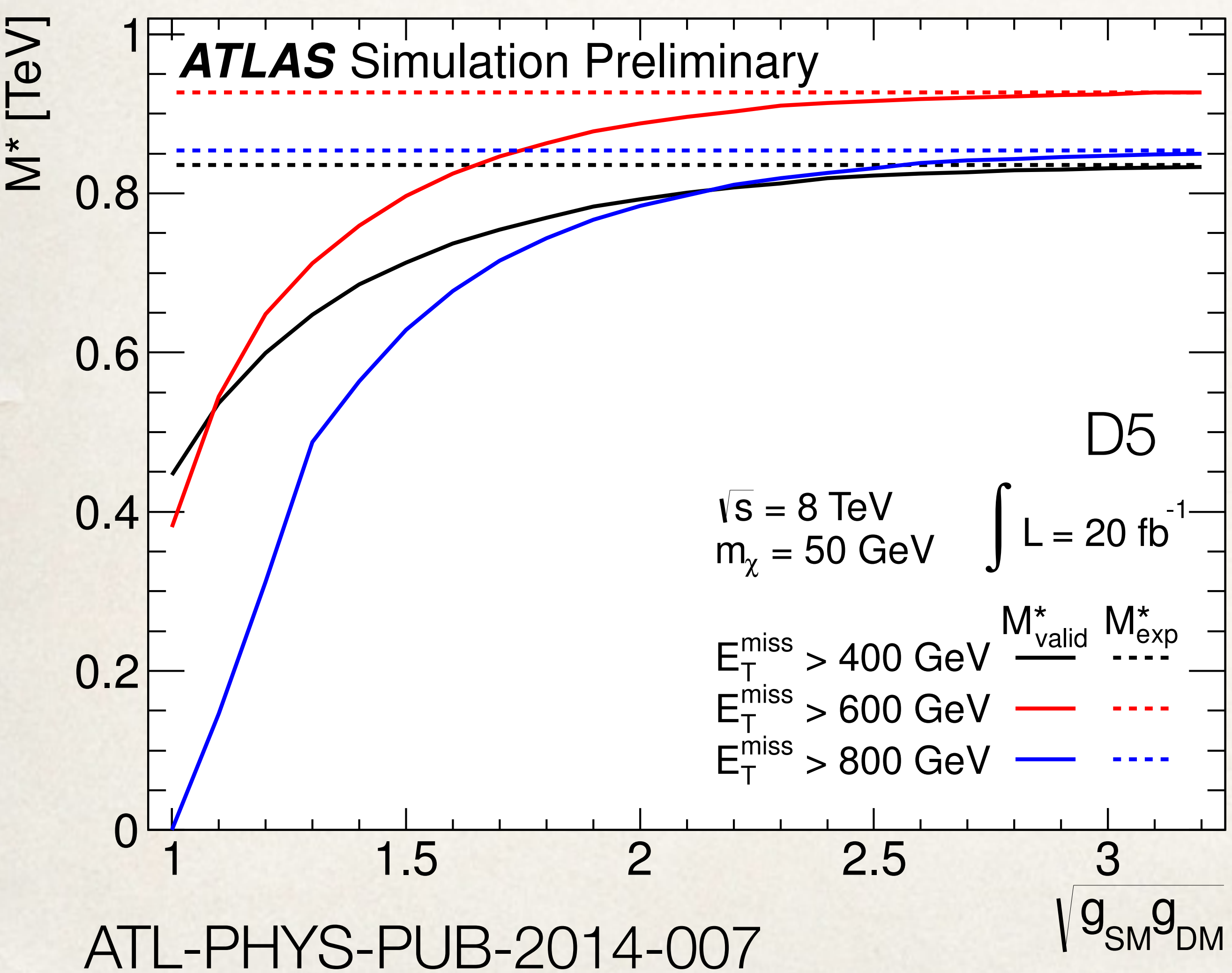


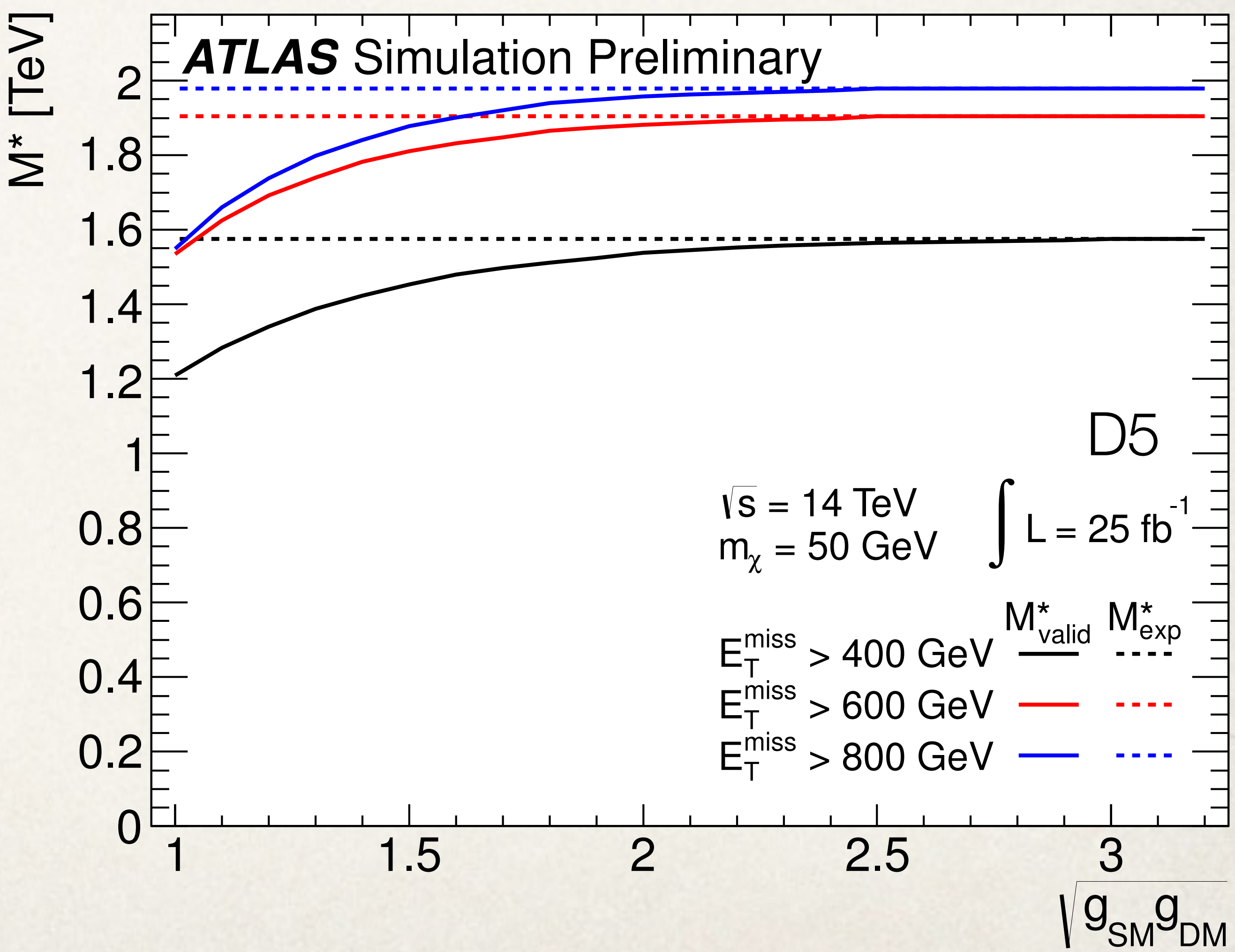
$$R_{\Lambda}^{\mathrm{tot}} = \frac{\sigma_{\mathrm{eff}}\big|_{\Lambda > Q_{\mathrm{tr}}}}{\sigma_{\mathrm{eff}}}$$

Rescaling the Limits

- For a given $\sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}}$, cut all events that don't pass

$$M \equiv \sqrt{g_{\mathrm{SM}} g_{\mathrm{DM}}} \Lambda \geq Q_{\mathrm{tr}}$$





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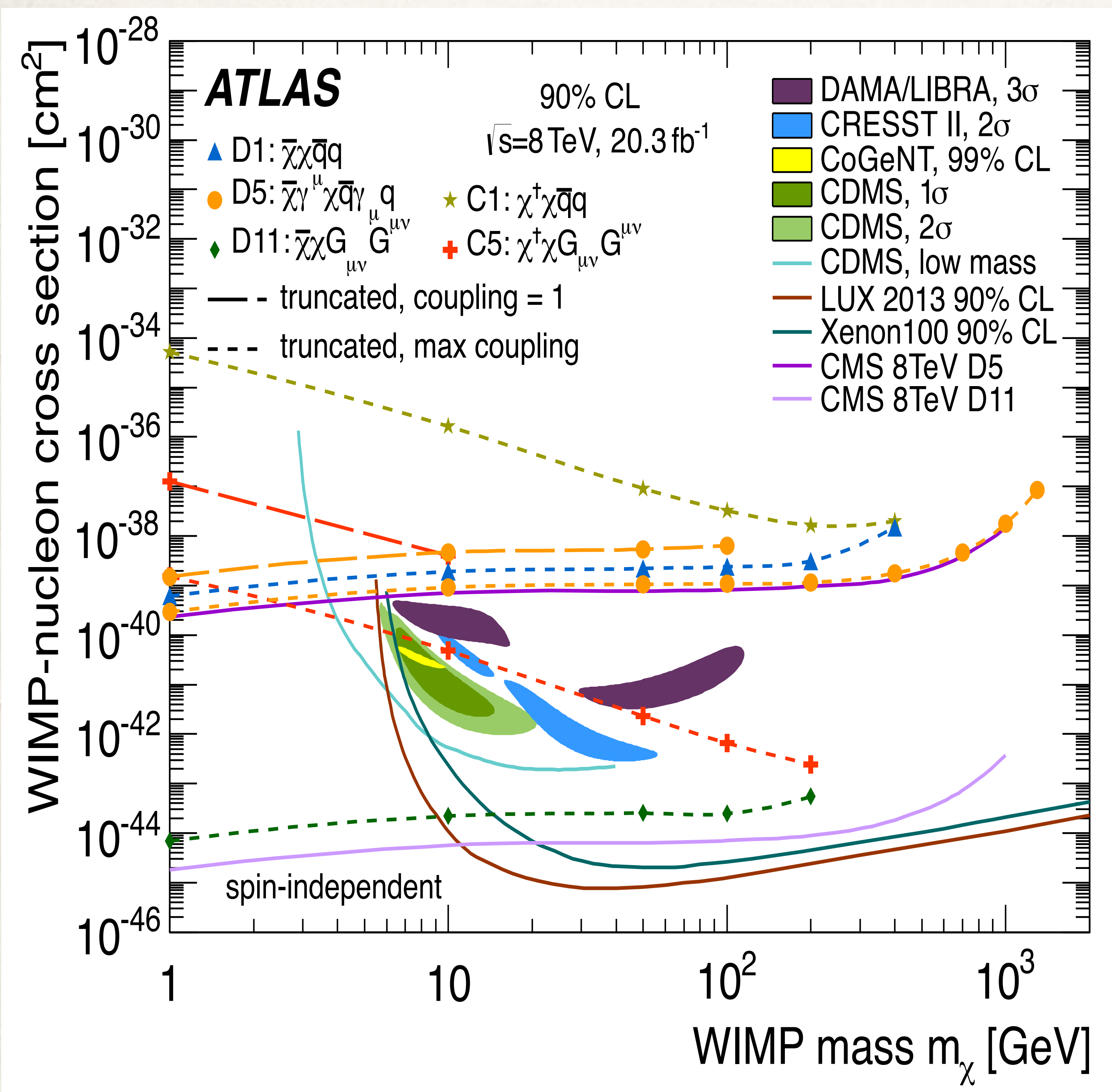
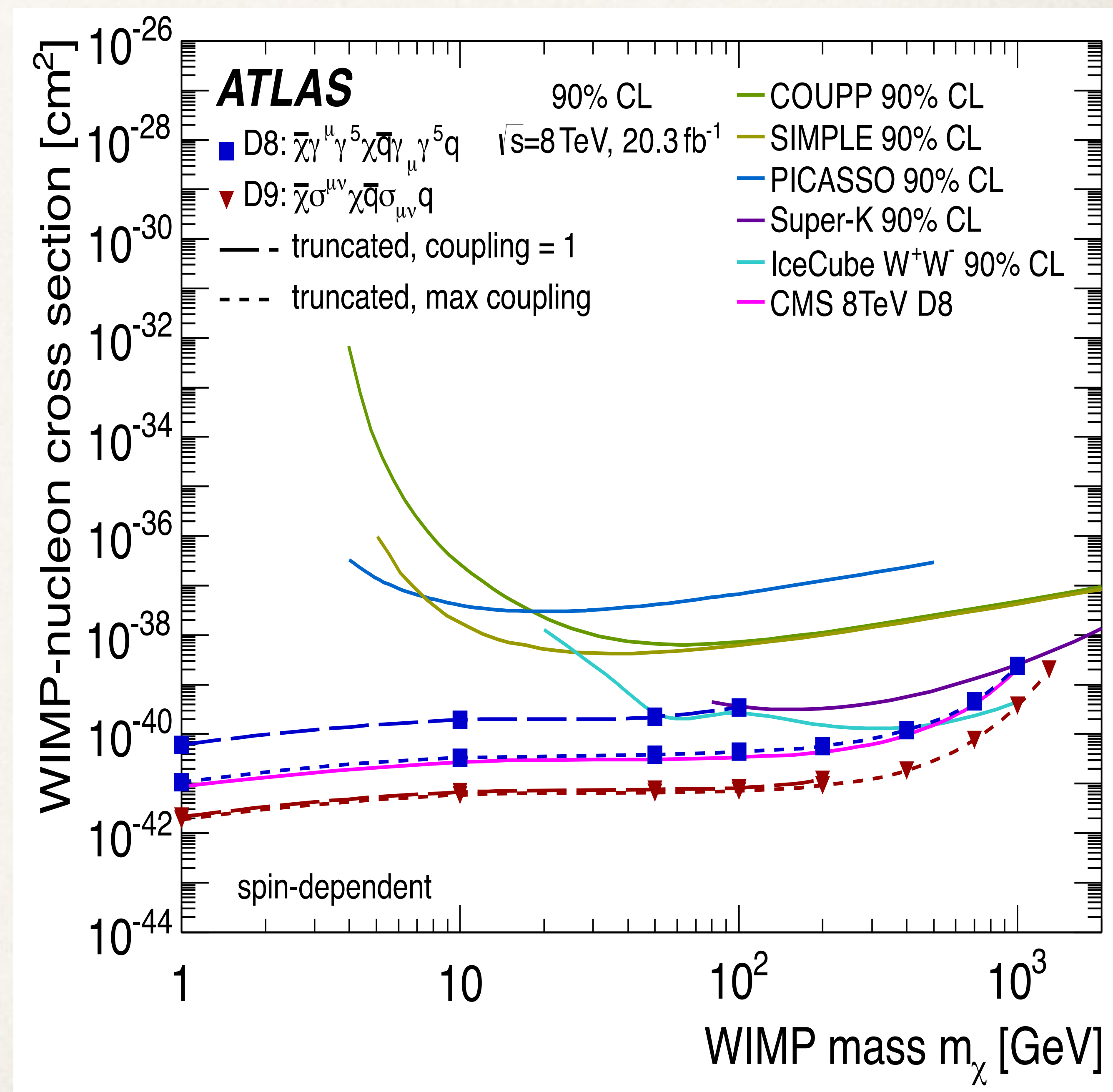
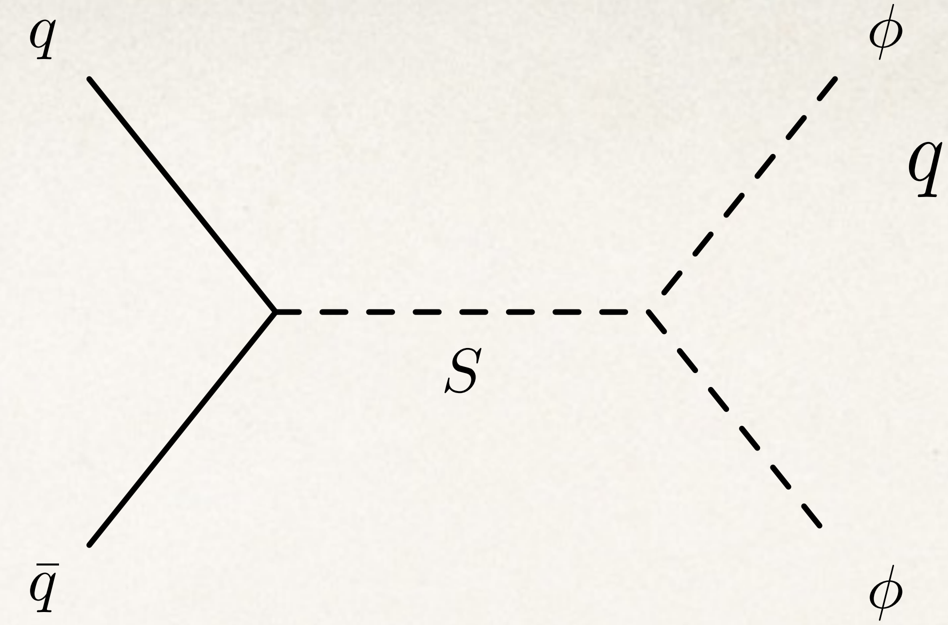
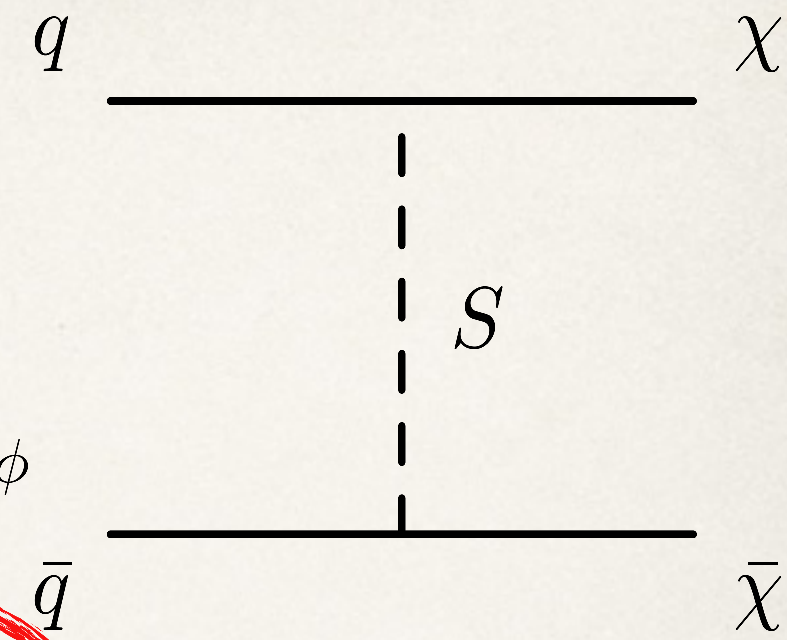
Effective Operators and Direct Detection





So what now?



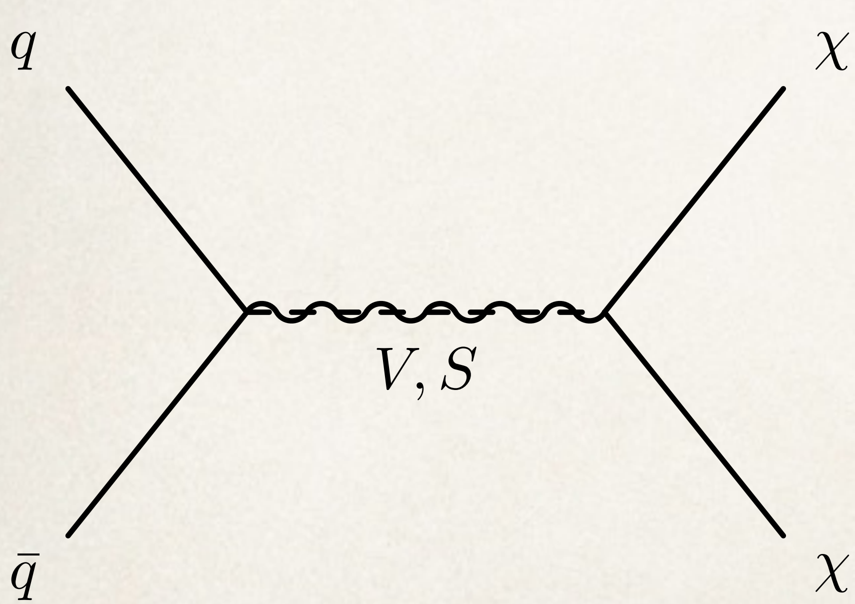


EFTs

e.g. D1, M3
etc. operators

Simplified
Models

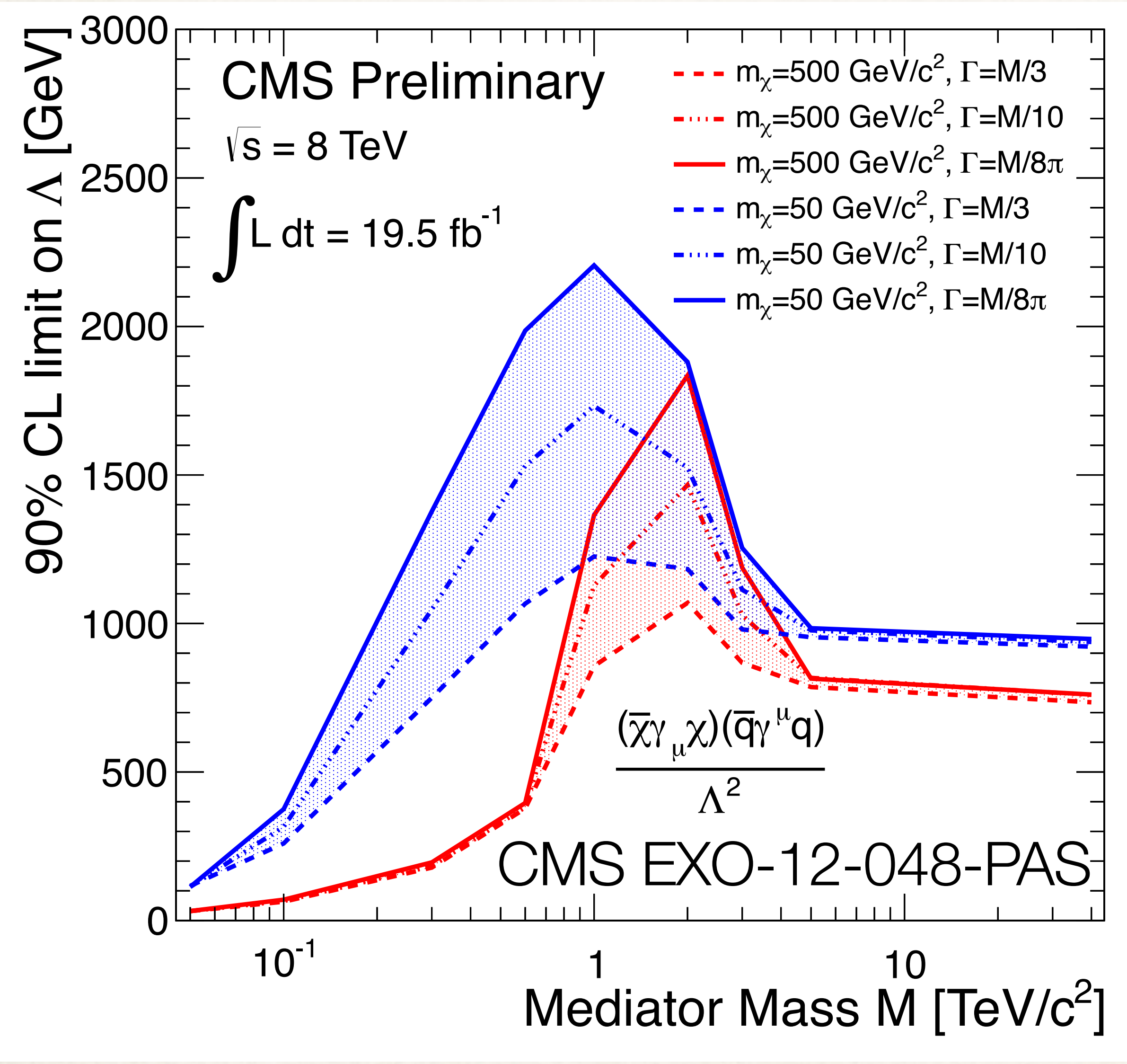
e.g. Z', Scalar
singlet DM



Full
Models

e.g. MSSM, UED

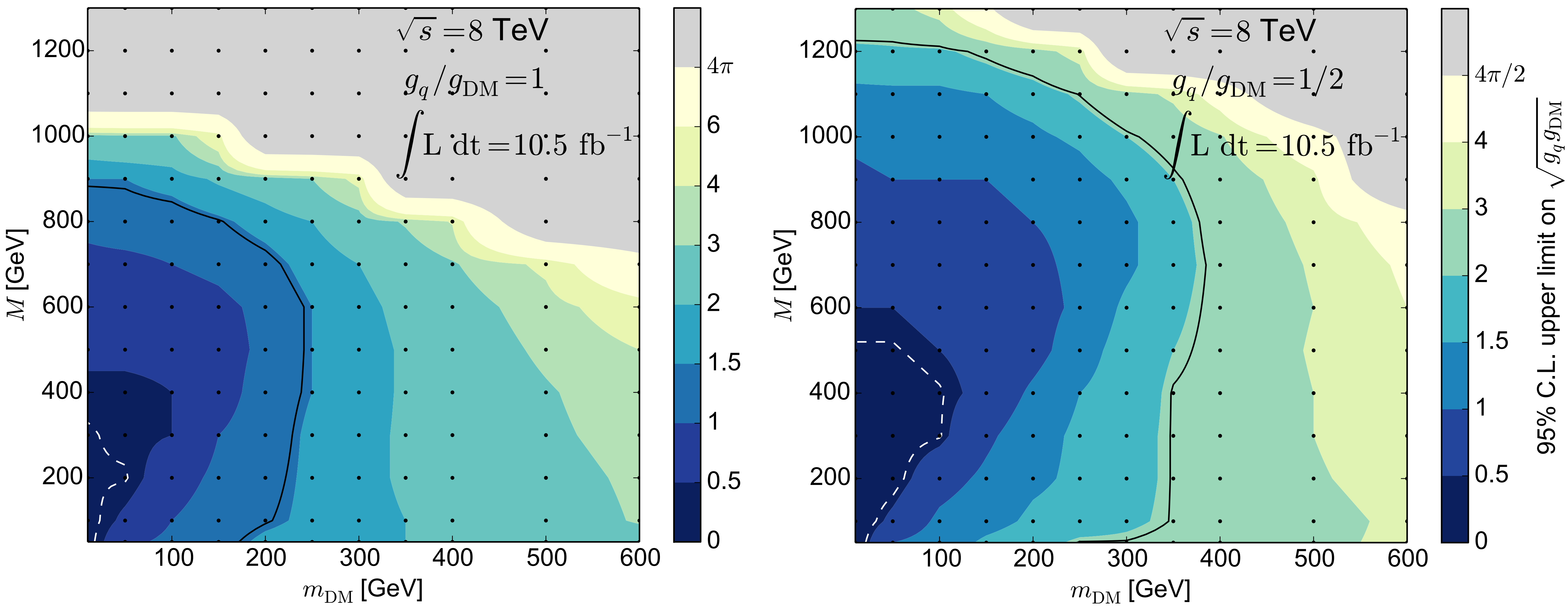
Resonances & Widths



- Resonance strengthens constraints relative to EFT, but width adds more parameters
- Opens mediator searches
- Min width fixed by the model: Beware arbitrary widths

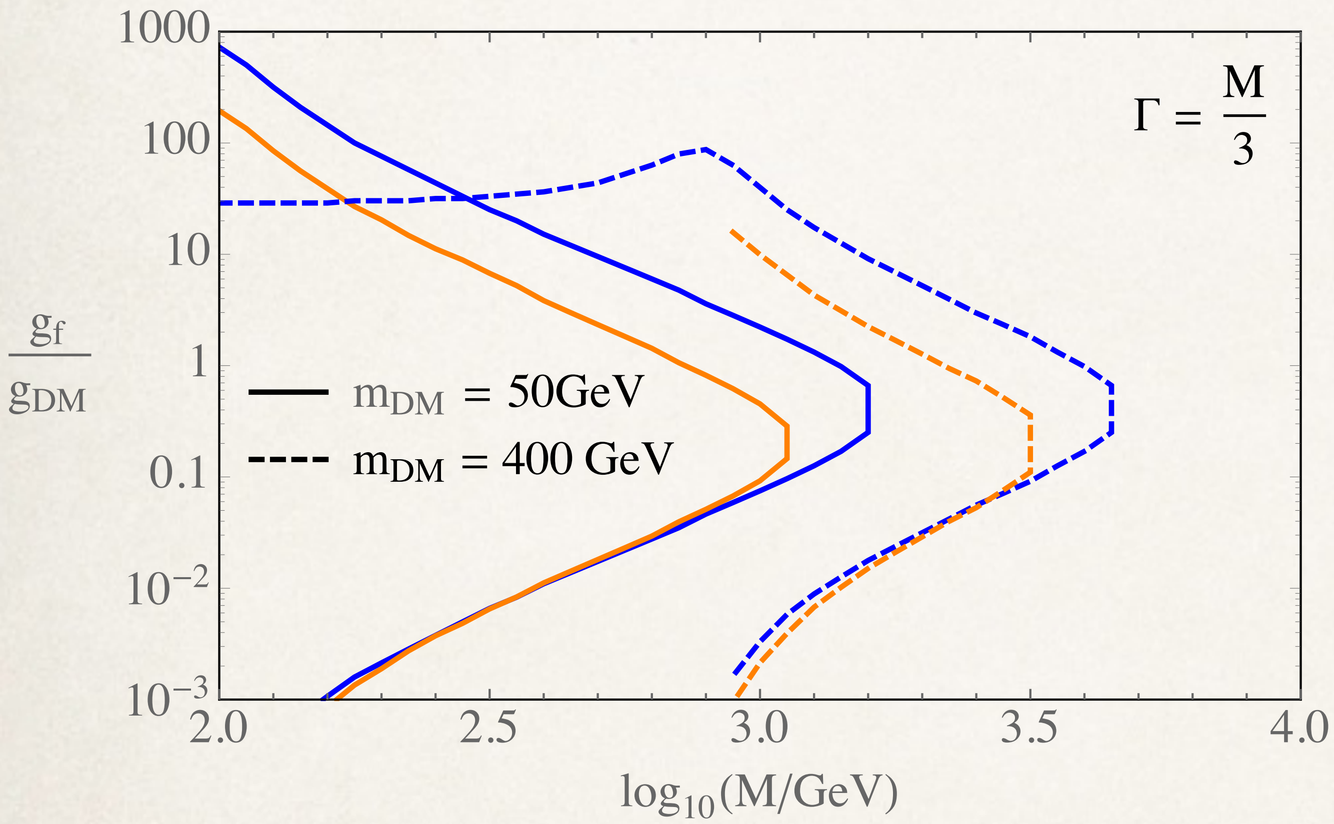
Constraining Simplified Models

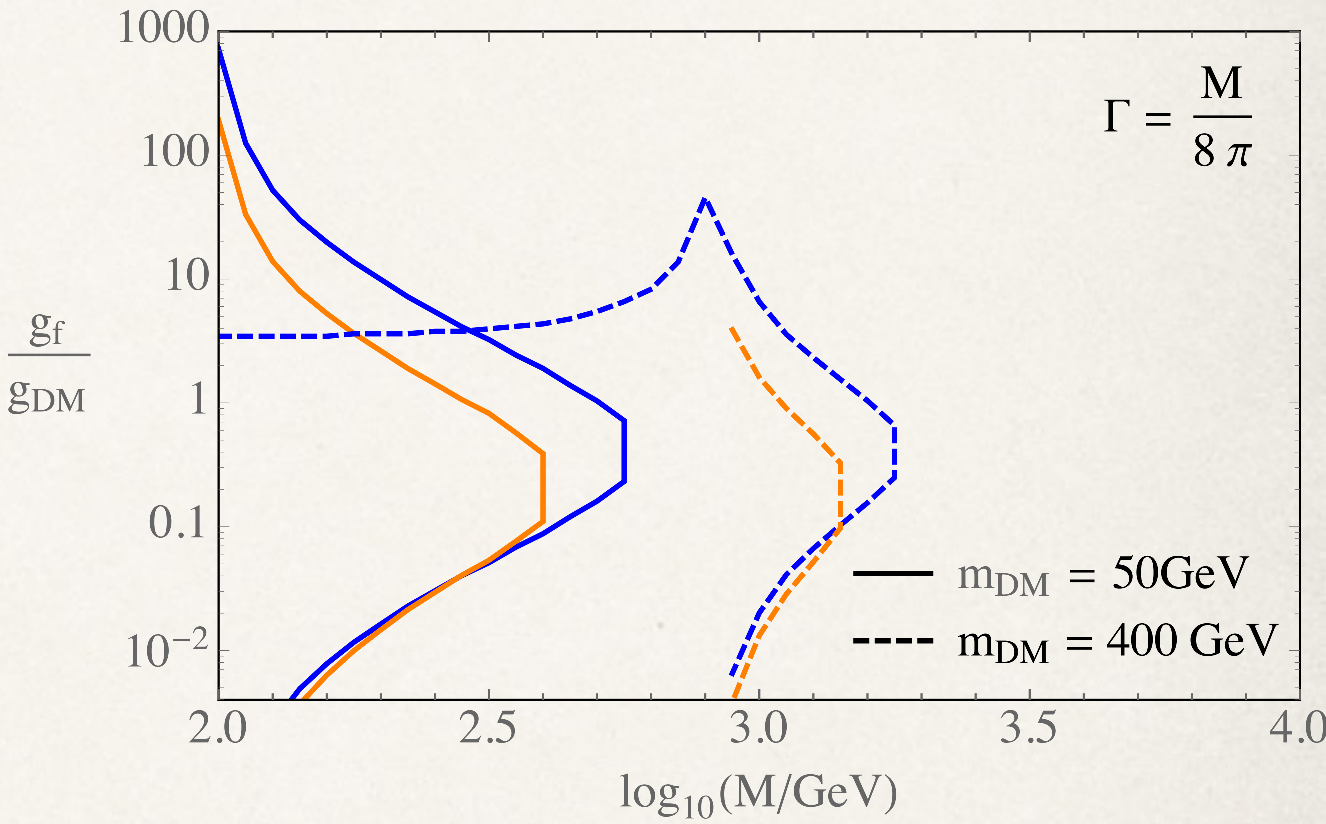
$$m_{\rm DM},\ \Lambda \rightarrow m_{\rm DM},\ M_{\rm med},\ g_{\rm DM},\ g_{q_i}$$



TDJ, Karl Nordstrom, arXiv:1502.05721

Treatment of the width





To summarise

- Effective Field Theories are a powerful tool allowing comparisons between different classes of experiment

- Facilitates complementary and powerful comparisons between Direct Detection and LHC constraints

- At LHC energies, the approximation begins to break down, and remain fully valid only for large couplings

- Truncation can make EFT constraints robust, but weaker; Simplified Models will give stronger constraints at LHC energies