Direct Detection from ElectroWeak Loops

A. Crivellin, FD, M. Procura, PRL 112(2014) (arXiv:1402.1173)

FD and M. Procura, to appear in JHEP (arXiv:1411.3342)

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BERKELEY LAB
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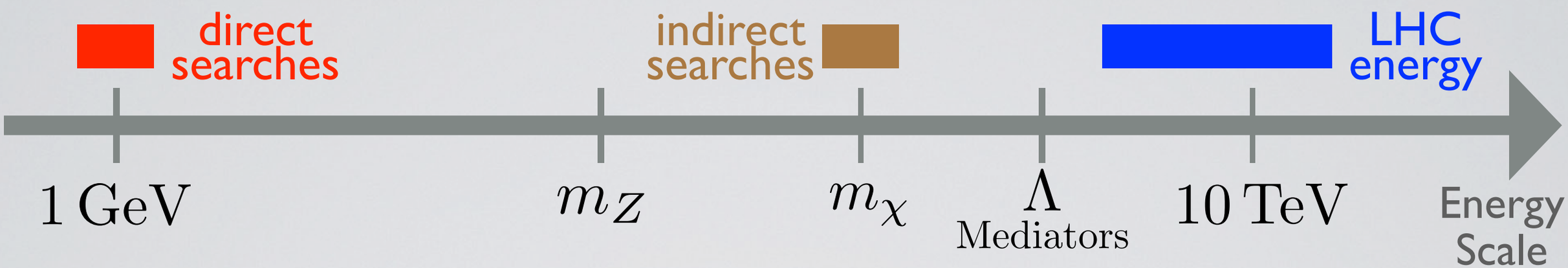
EFT and DM MITP Workshop - 16 March 2015

Energy Scales

WIMP searches probe widely different energies



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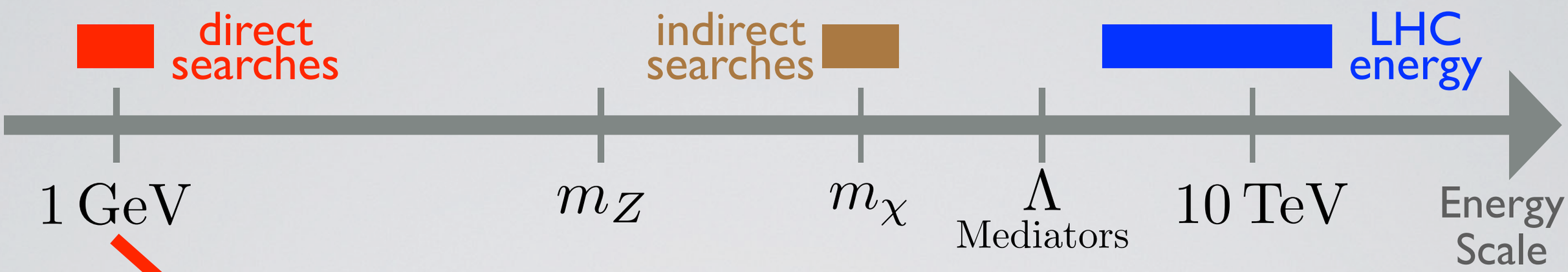


$\Lambda \gtrsim$ 1 TeV and probing E $\ll \Lambda$

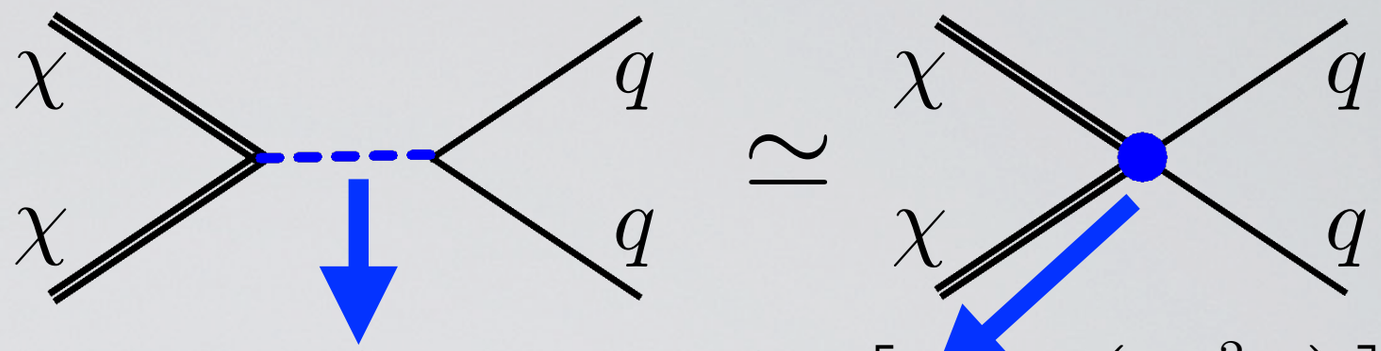
$$\mathcal{L}^{\rm eff}_{\mu\leq\Lambda} = \sum_i \frac{c_i(\mu)}{\Lambda^{d_i-4}}\mathcal{O}_i(\mu)$$

$$\sigma \propto |c_i(\mu_N)|^2 \, |\langle \mathcal{N}| \, \mathcal{O}_i(\mu_N) \, |\mathcal{N}\rangle|^2$$

($\mu_N \sim$ 1 GeV)

Interaction with quarks

Particles mediating DM interactions integrated out



$$\frac{1}{p^2 - M_{\rm med}^2} = -\frac{1}{M_{\rm med}^2}\left[1 + \mathcal{O}\left(\frac{p^2}{M_{\rm med}^2}\right)\right]$$

Model Independent (m_χ, M_{med})

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	$m_q/M_{\rm med}^3$
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	$im_q/M_{\rm med}^3$
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	$im_q/M_{\rm med}^3$
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$m_q/M_{\rm med}^3$
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_{\rm med}^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_{\rm med}^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_{\rm med}^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_{\rm med}^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_{\rm med}^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	$i/M_{\rm med}^2$

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, PRD 82 (2010)

Current-current

D5

$$\mathcal{L}_{\mathrm{D5}} = \frac{1}{\Lambda^2}\,\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q$$

D8

$$\mathcal{L}_{\mathrm{D8}} = \frac{1}{\Lambda^2}\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5 q$$

How well can be constrained by collider and direct detection?

D7

$$\mathcal{L}_{\mathrm{D7}} = \frac{1}{\Lambda^2}\,\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu\gamma^5 q$$

D6

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Current–current

D5

$$\mathcal{L}_{\rm D5} = \frac{1}{\Lambda^2}\,\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q$$

~ same as the others

Spin-Independent (SI), no suppression

D8

$$\mathcal{L}_{\rm D8} = \frac{1}{\Lambda^2}\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5 q$$

~ same as the others

Spin-Dependent (SD), no suppression

How well can be constrained by collider and direct detection?

D7

$$\mathcal{L}_{\rm D7} = \frac{1}{\Lambda^2}\,\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu\gamma^5 q$$

~ same as the others

SD with v^2 and q^2 suppression

D6

$$\mathcal{L}_{\rm D6} = \frac{1}{\Lambda^2}\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu q$$

~ same as the others

SI with v^2 sup. and SD with q^2 sup.

Why ElectroWeak Loops?

Direct detection rates extremely sensitive to the type of DM interaction

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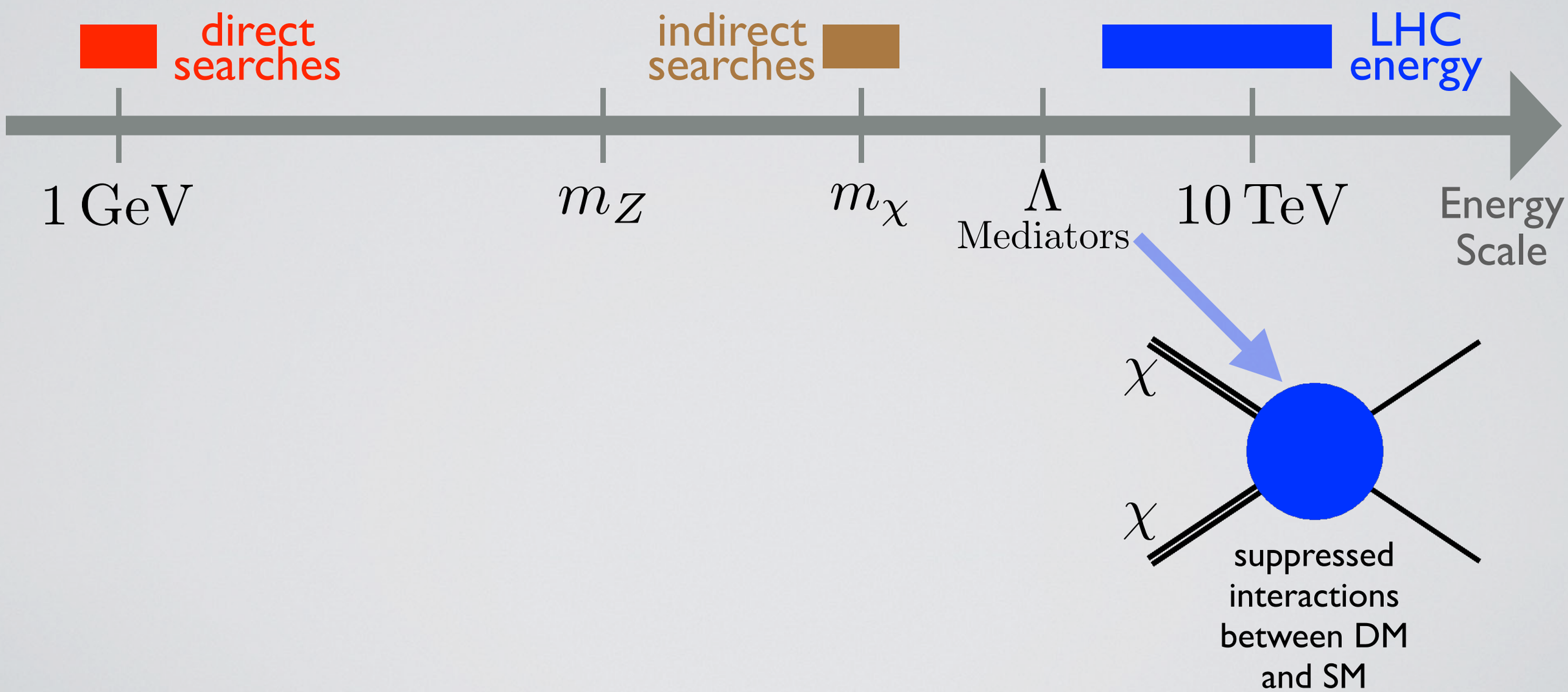

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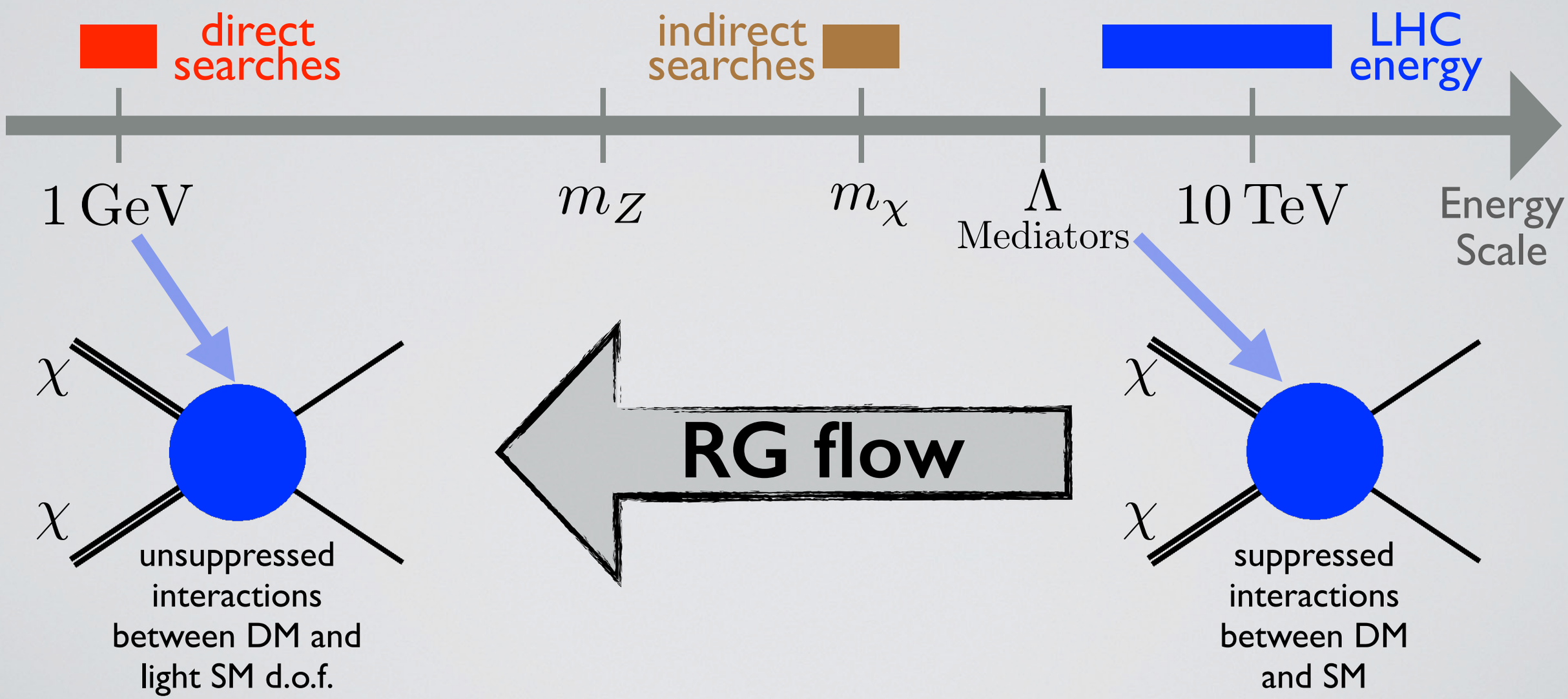

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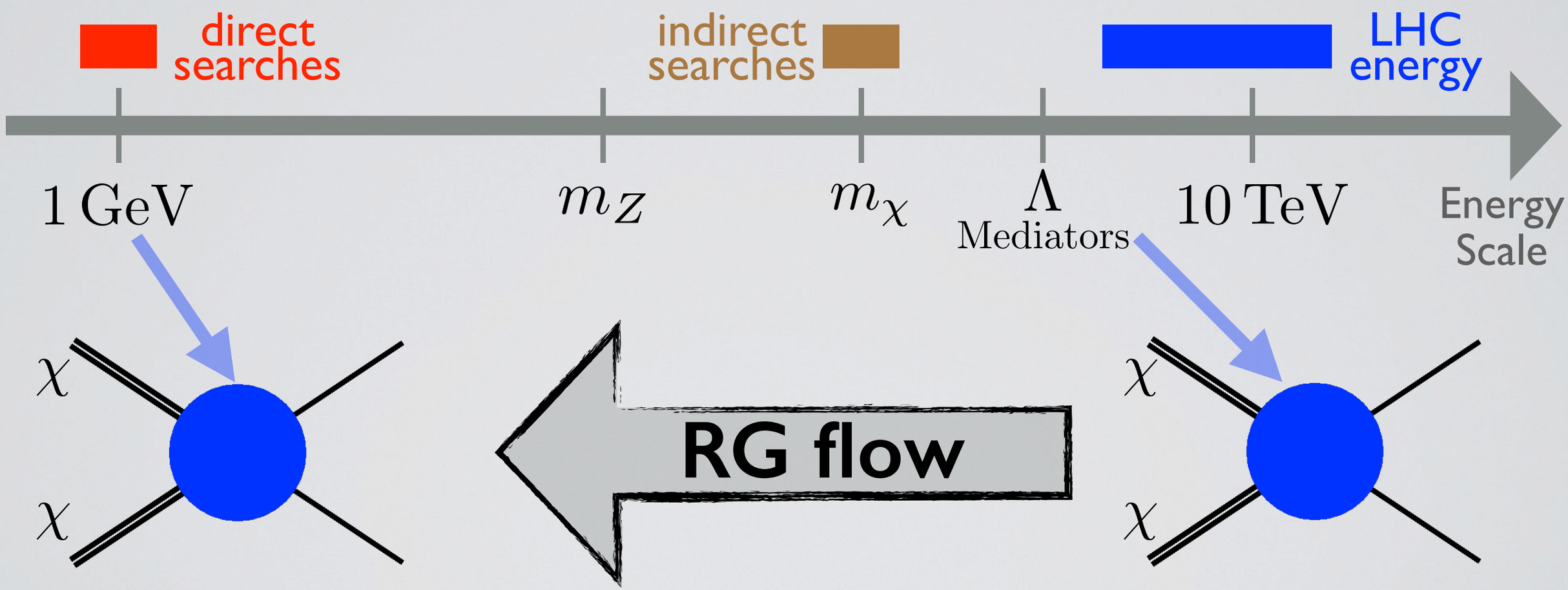

D operators: unsuppressed interactions with light quarks can be generated at low scale, but QCD cannot induce such a mixing

Plan for Today's Talk

Singlet Fermion WIMP

Application to Direct Searches

Conclusions and Outlook

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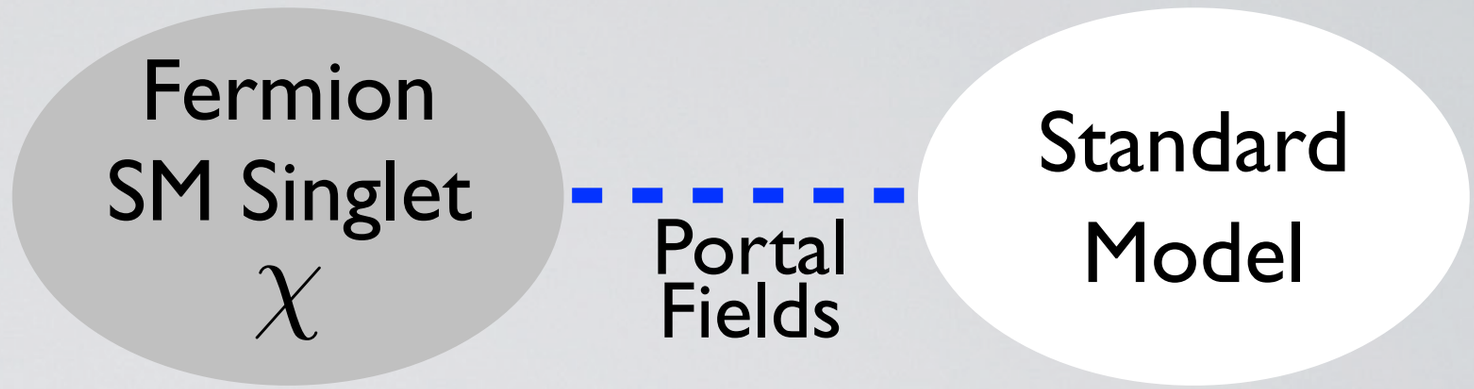
No renormalizable interactions with SM

A famous realization: MSSM bino



Integrating out mediators at mass scale Λ (step 0)

Left with an EFT for DM+SM

$$\mathcal{L}_{\mathrm{SM}_\chi} = \mathcal{L}_{\mathrm{SM}} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \sum_{\alpha, d>4} \frac{c_\alpha^{(d)}}{\Lambda^{d-4}} \mathcal{O}_\alpha^{(d)}$$

EFT for Direct Detection

Direct Detection:
WIMP bilinears

$$\frac{c_{\mathcal{O}}^{(d)}}{\Lambda^{d-4}}\,\overline{\chi}\Gamma^A\chi\,\mathcal{O}_A^{(\mathrm{SM})}$$

$$\Gamma^A = (1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu})$$

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Dimension 5: *Higgs Portal* and *Dipole Moments*

$$\mathcal{L}_{\mathrm{SM}_\chi}^{(\mathrm{dim.5})} = \frac{c_S}{\Lambda}\overline{\chi}\chi H^\dagger H + \frac{c_P}{\Lambda}\overline{\chi}\gamma^5\chi H^\dagger H + \frac{c_E}{\Lambda}\overline{\chi}\sigma^{\mu\nu}\chi B_{\mu\nu} + \frac{c_M}{\Lambda}\epsilon_{\mu\nu\rho\sigma}\overline{\chi}\sigma^{\mu\nu}\chi B^{\rho\sigma}$$

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Shifman et al. PLB 78 (1978)

Barger et al. PLB 696 (2011)
Banks et al. arXiv:1007.5515
Fortin and Tait PRD 85 (2012)

EFT for Direct Detection

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Dimension 6: *Current-Current* Interactions

$$\mathcal{L}_{\mathrm{SM}_\chi}^{(\mathrm{dim.6})} = \frac{1}{\Lambda^2}\,\bar{\chi}\Gamma^\mu\chi\left[c_q\bar{q_L}\gamma_\mu q_L + c_U\bar{u_R}\gamma_\mu u_R + \bar{d_R}\gamma_\mu d_R + c_l\bar{l_L}\gamma_\mu l_L + c_e\bar{e_R}\gamma_\mu e_R\right] + \frac{c_H}{\Lambda^2}\,\bar{\chi}\Gamma^\mu\chi\,H^\dagger i\overleftrightarrow{D_\mu}H$$

$$\Gamma^\mu = (\gamma^\mu, \gamma^\mu\gamma^5)$$

EFT for Direct Detection

Generated in many UV completions
(e.g. s-channel vector mediators, t-channel scalar mediator)

Focus on this 2 x (15 + 1) = 32 operators
and perform a complete RGE Analysis

FD and Procura, to appear in JHEP (arXiv:1411.3342)

Dimension 6: *Current-Current* Interactions

$$\mathcal{L}_{\mathrm{SM}_\chi}^{(\mathrm{dim.6})} = \frac{1}{\Lambda^2}\,\bar{\chi}\Gamma^\mu\chi\left[c_q\bar{q_L}\gamma_\mu q_L + c_U\bar{u_R}\gamma_\mu u_R + \bar{d_R}\gamma_\mu d_R + c_l\bar{l_L}\gamma_\mu l_L + c_e\bar{e_R}\gamma_\mu e_R\right] + \frac{c_H}{\Lambda^2}\,\bar{\chi}\Gamma^\mu\chi\, H^\dagger i\overleftrightarrow{D}_\mu H$$

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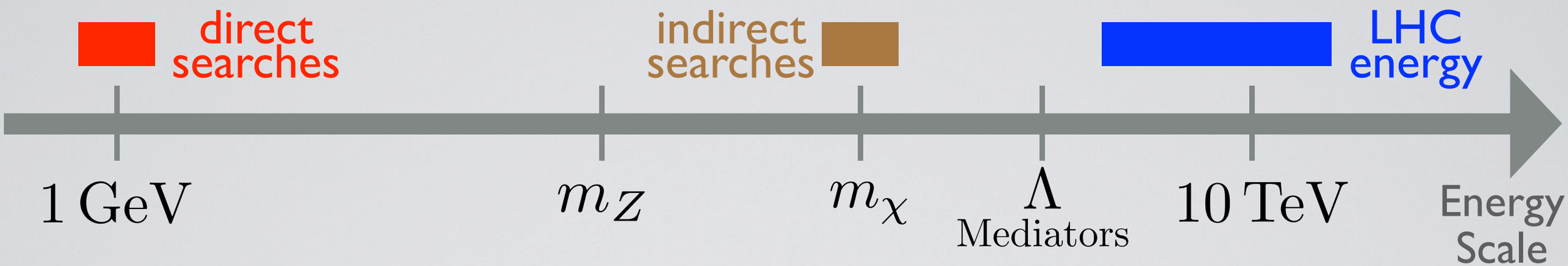
RGE – General Strategy



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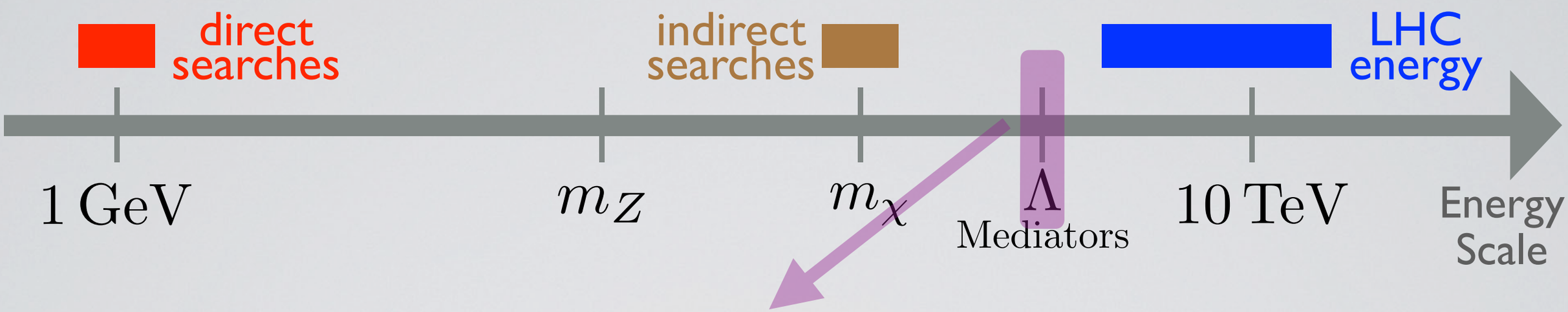
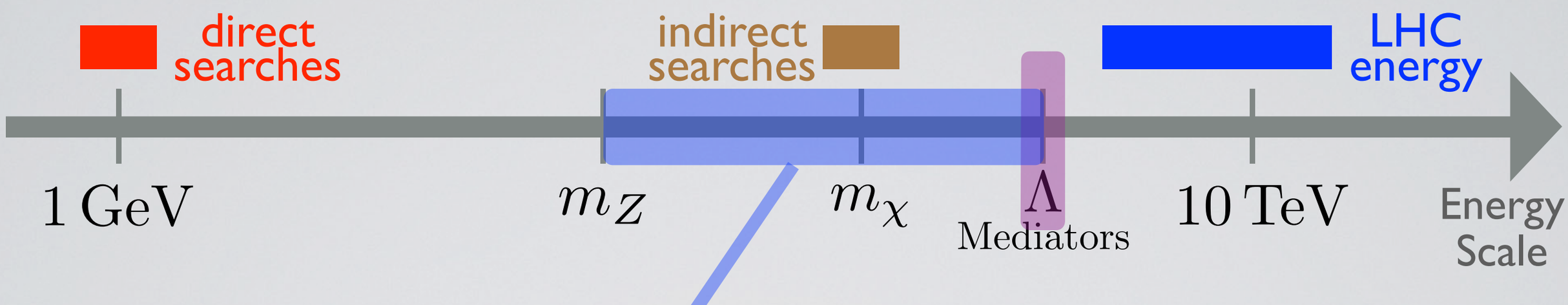


0 - Integrate out the Mediator Fields

RGE – General Strategy



0 - Integrate out the Mediator Fields

1 - Renormalization Group Evolution between Λ and Weak Scale

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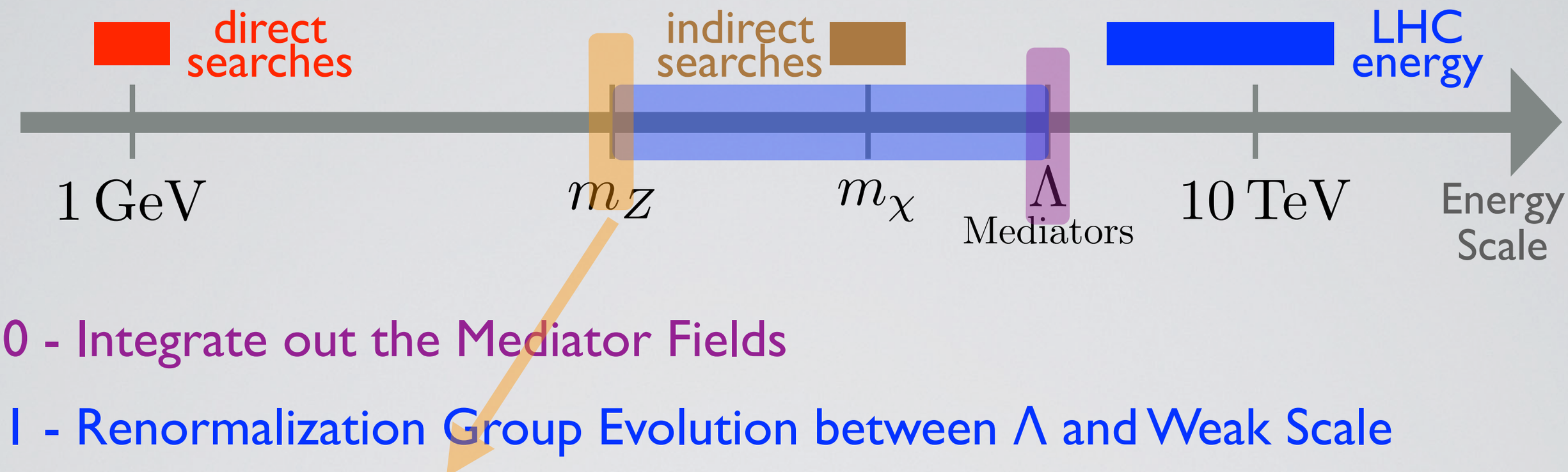

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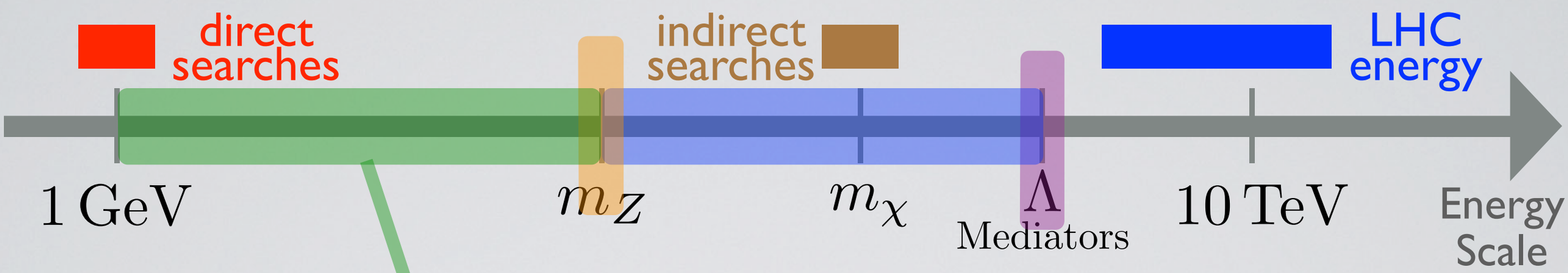

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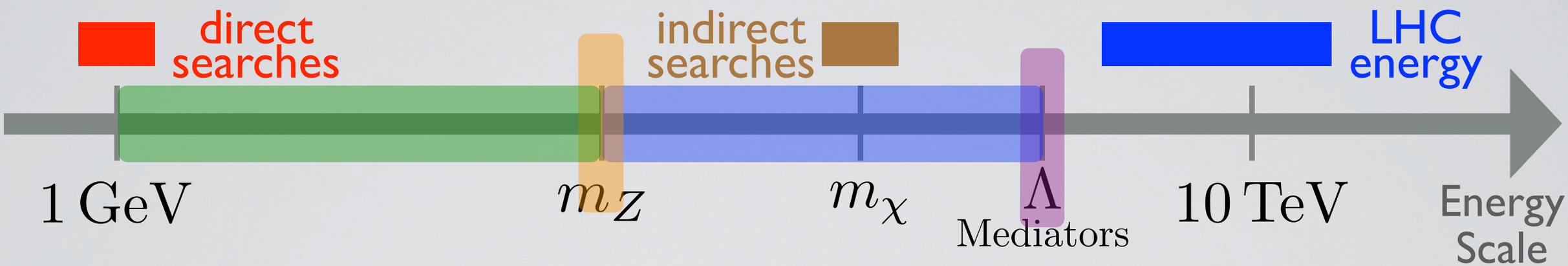

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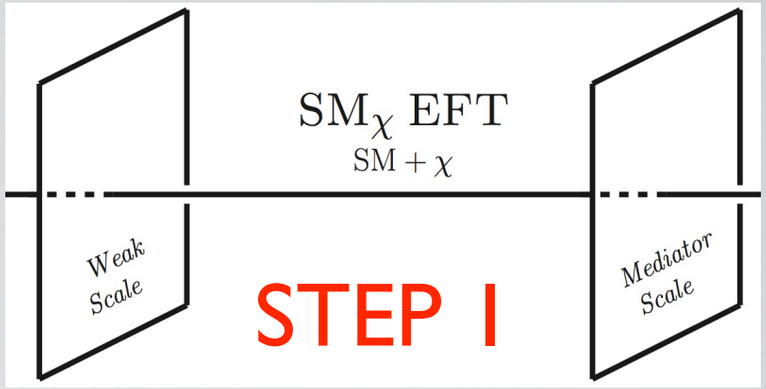
RGE – Fermion Singlet

$$\frac{d\, c_{\mathrm{SM}_\chi}}{d \ln E} = \gamma_{\mathrm{SM}_\chi} c_{\mathrm{SM}_\chi}$$

Solve from E = Λ to E = m_{weak}



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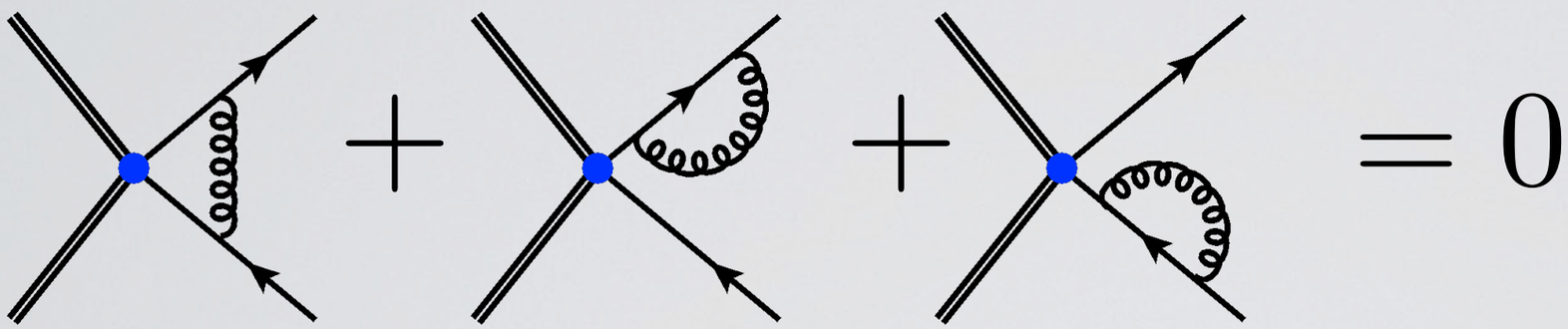
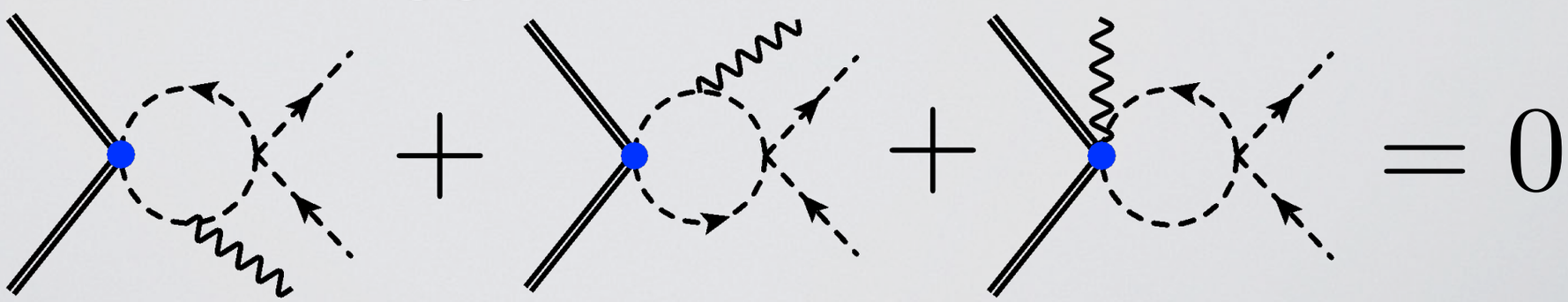
Solve from E = Λ to E = m_{weak}

Gauge Interactions



Higgs Self-Interactions



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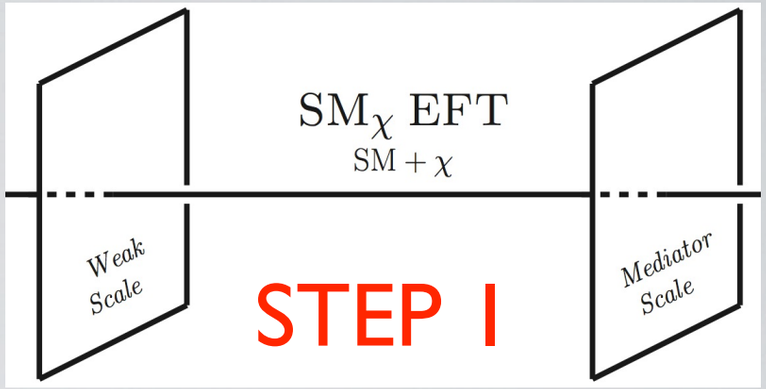
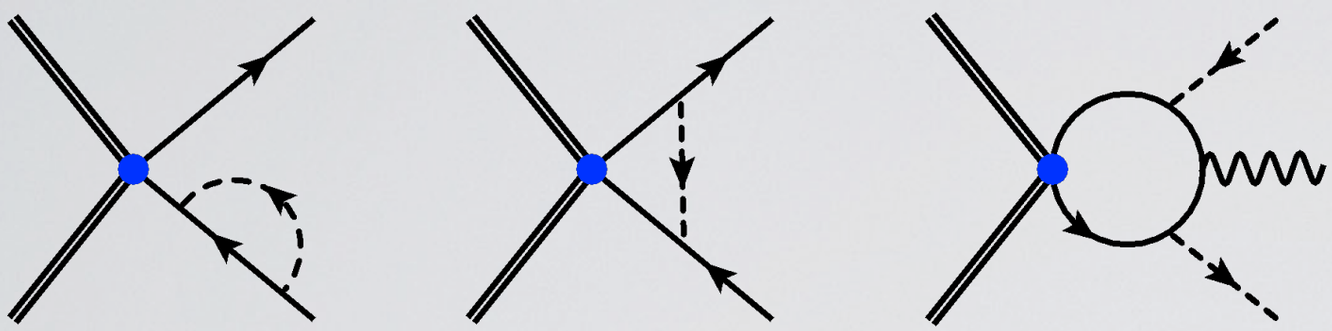
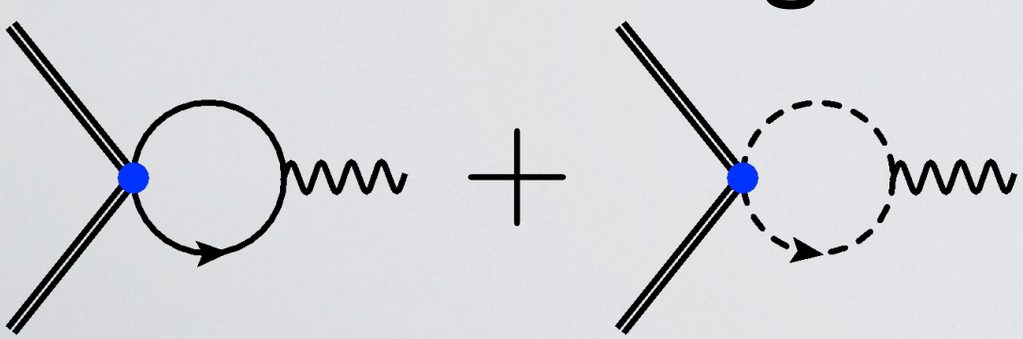


Yukawa Interactions



- Diagonal renormalization different for each operator
- Operator Mixing

Inducing a Redundant Operator



$$\propto \frac{g'}{\Lambda^2}\, \bar{\chi}\Gamma^\mu \chi\, \partial^\nu B_{\nu\mu} \;\rightarrow\; -\frac{g'^{\,2}}{\Lambda^2}\, \bar{\chi}\Gamma^\mu \chi\, J_\mu^{(Y)}$$

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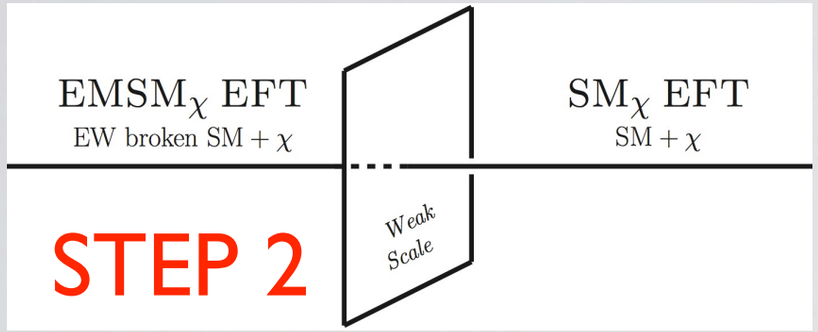
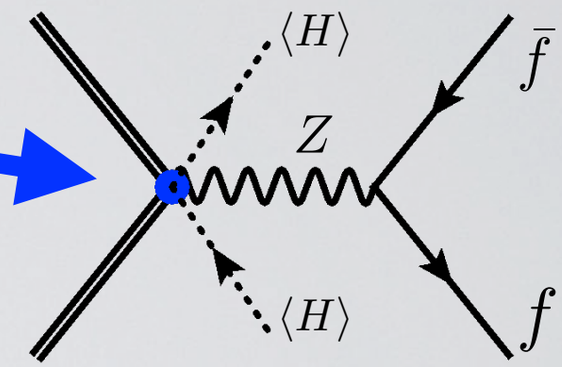
Solve from E = Λ to E = m_{weak}



$$c_{\mathrm{EMSM}_\chi} = c_{\mathrm{SM}_\chi} + \delta_{\mathrm{m}}$$



Matching the two EFTs at weak scale

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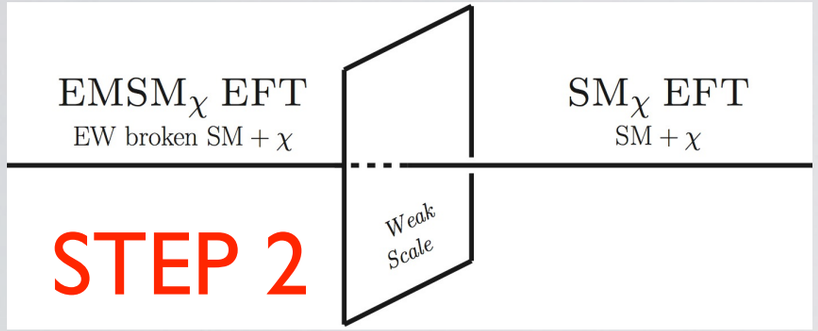

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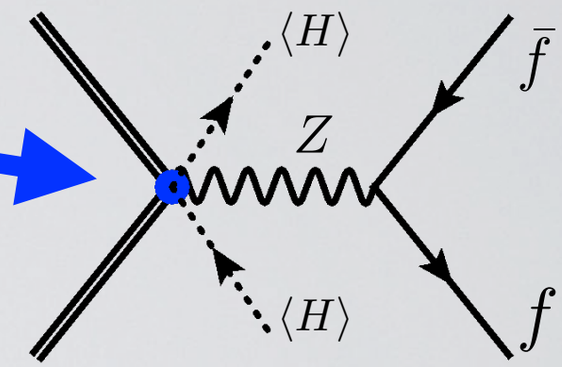
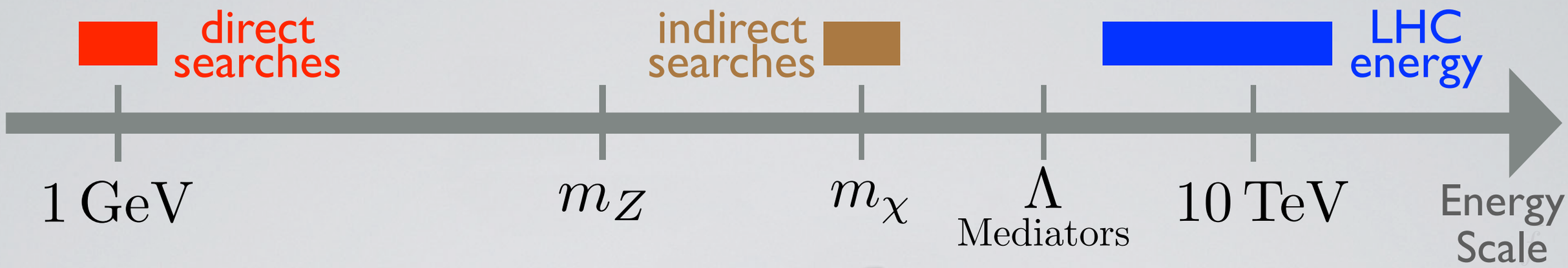


Matching the two EFTs at weak scale

$$\frac{d\, c_{\mathrm{EMSM}_\chi}}{d \ln E} = \gamma_{\mathrm{EMSM}_\chi}\, c_{\mathrm{EMSM}_\chi}$$

Solve from E = m_{weak} to E = 1 GeV

RGE for Fermion Singlet



Mediator and Nuclear Scales Connected

- applicable to UV complete models of fermion singlet
- bound effective couplings in a model independent fashion

Plan for Today's Talk

Singlet Fermion WIMP

Application to Direct Searches

Conclusions and Outlook

Spin–Independent DD

Coherent WIMP-Nucleus Scattering

$$\sigma_{\rm SI} = \frac{m_\chi^2 m_{\mathcal{N}}^2}{(m_\chi + m_{\mathcal{N}})^2 \pi} \left| Z\, f_p + (A - Z) f_n \right|^2$$

Goodman and Witten, PRD 31 (1985)

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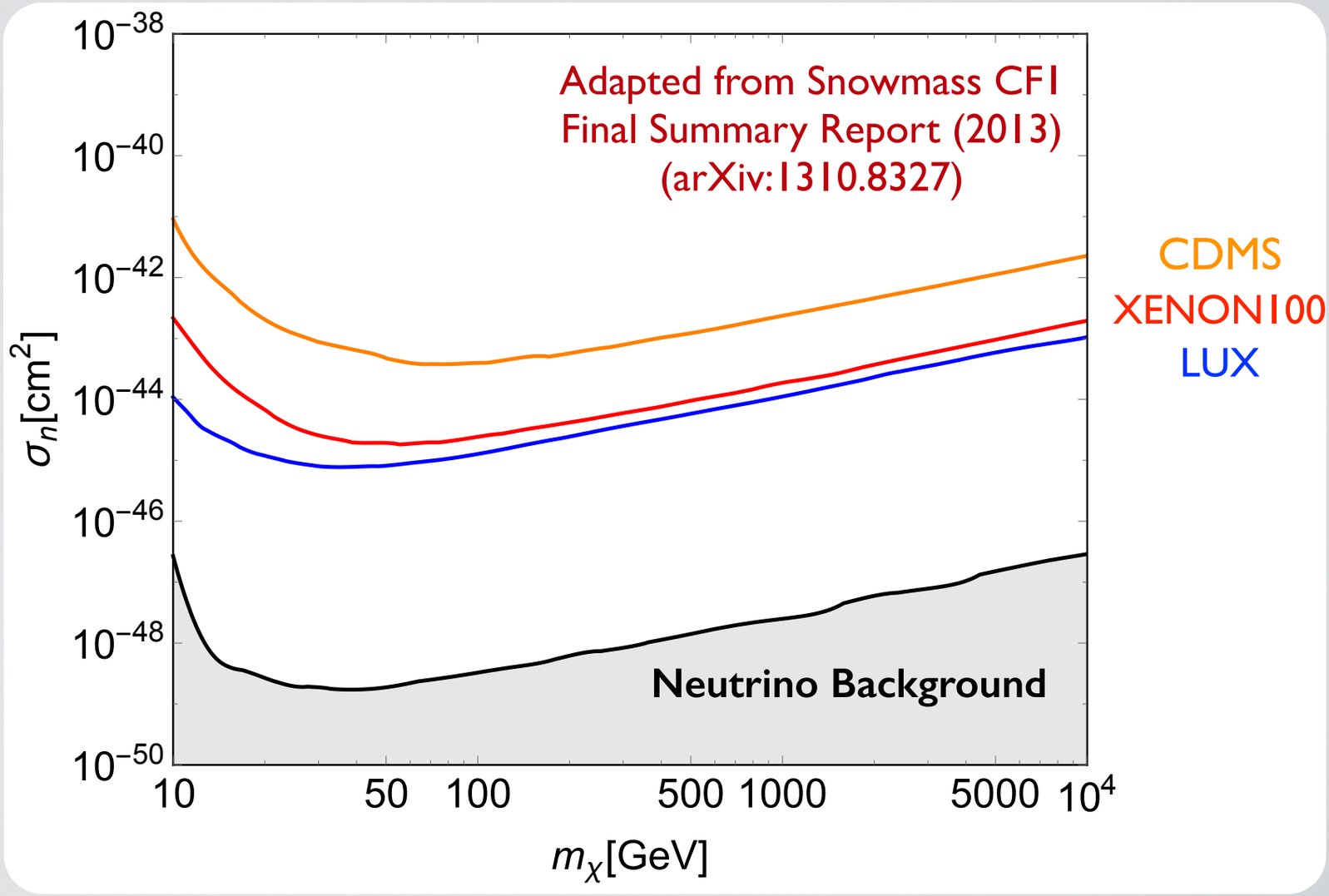
Experimental Limits



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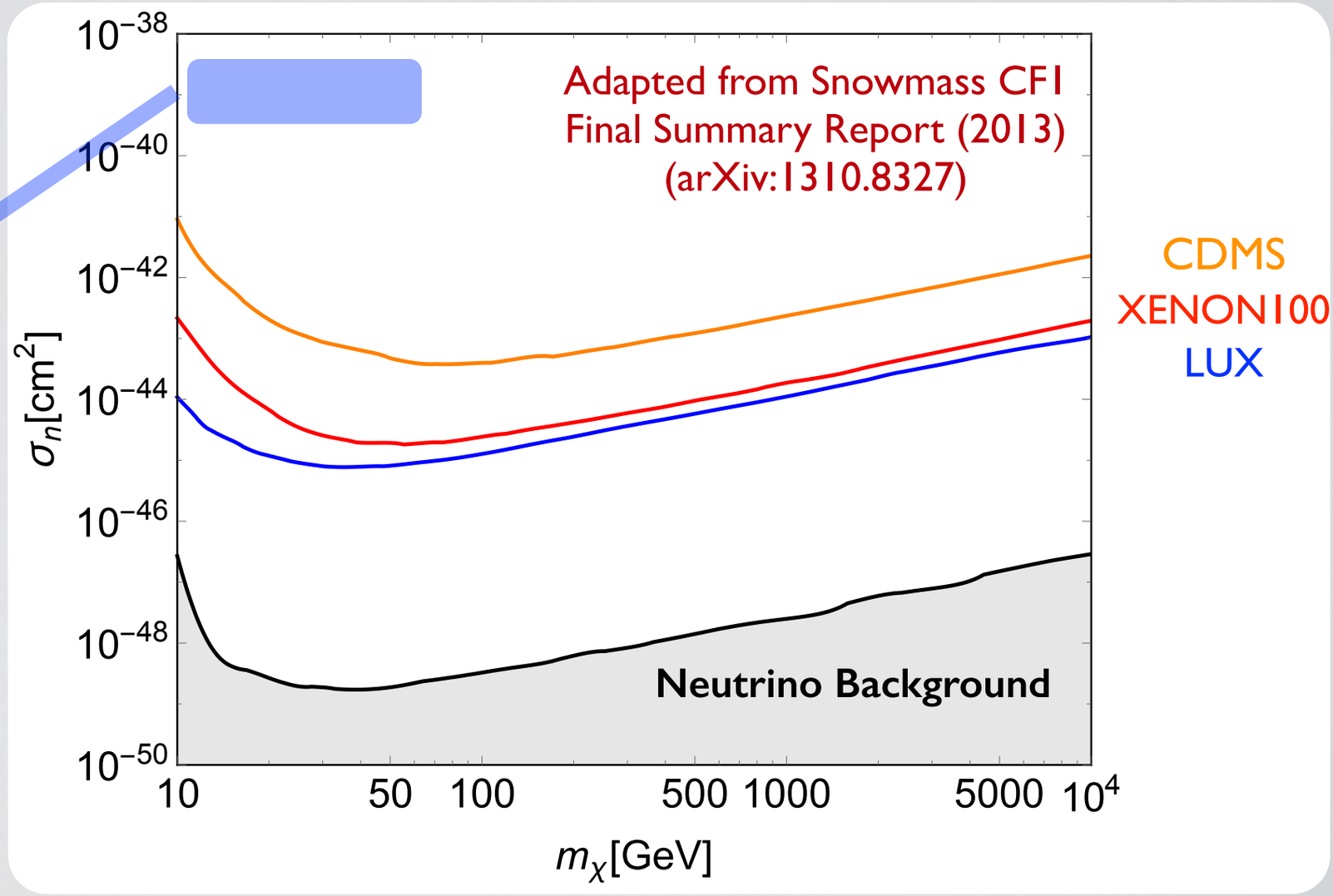
Goodman and Witten, PRD 31 (1985)

Experimental Limits

SU(2) doublet (e.g. 4th generation neutrino) excluded



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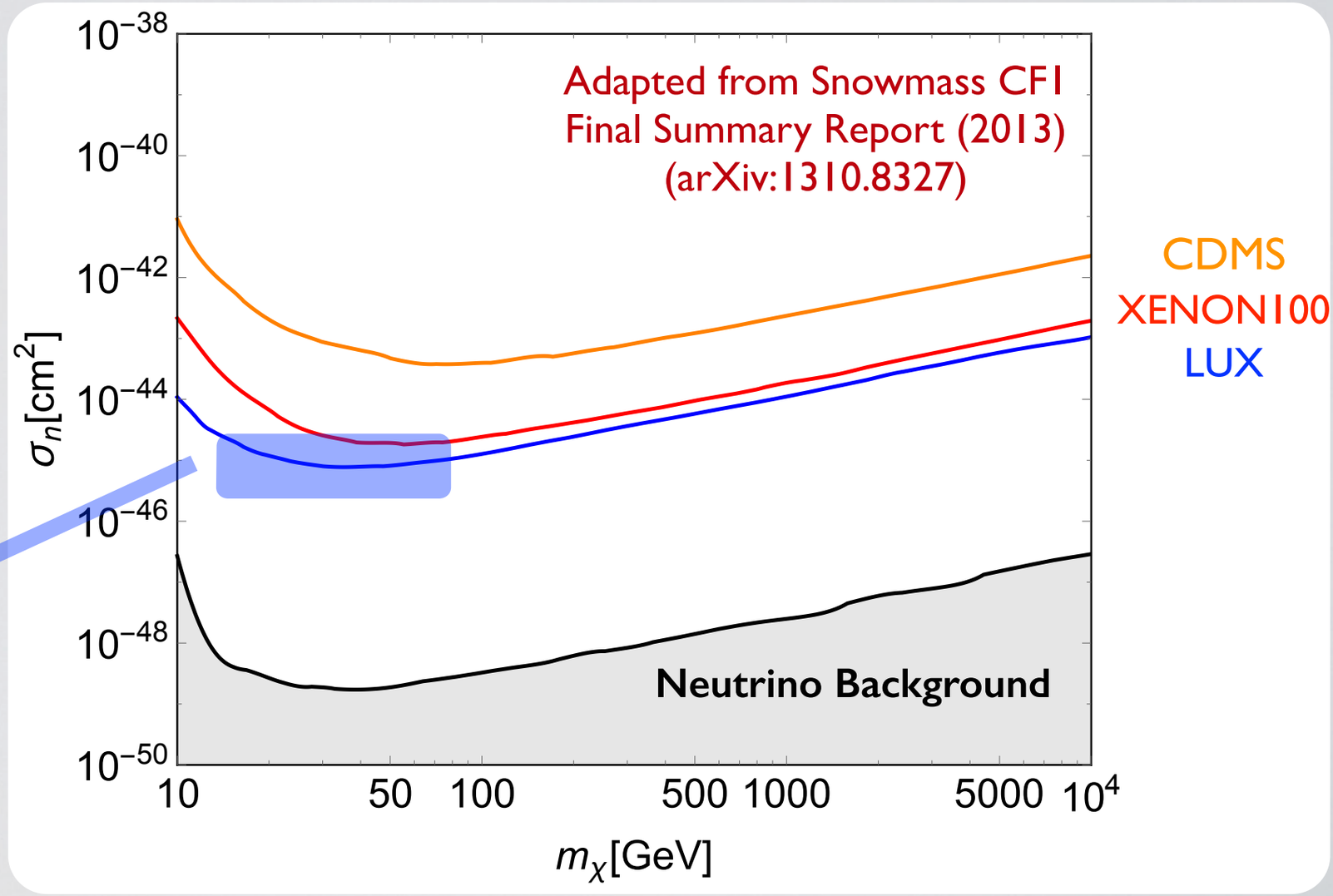

currently probing scattering mediated by the Higgs boson

Spin–Independent DD

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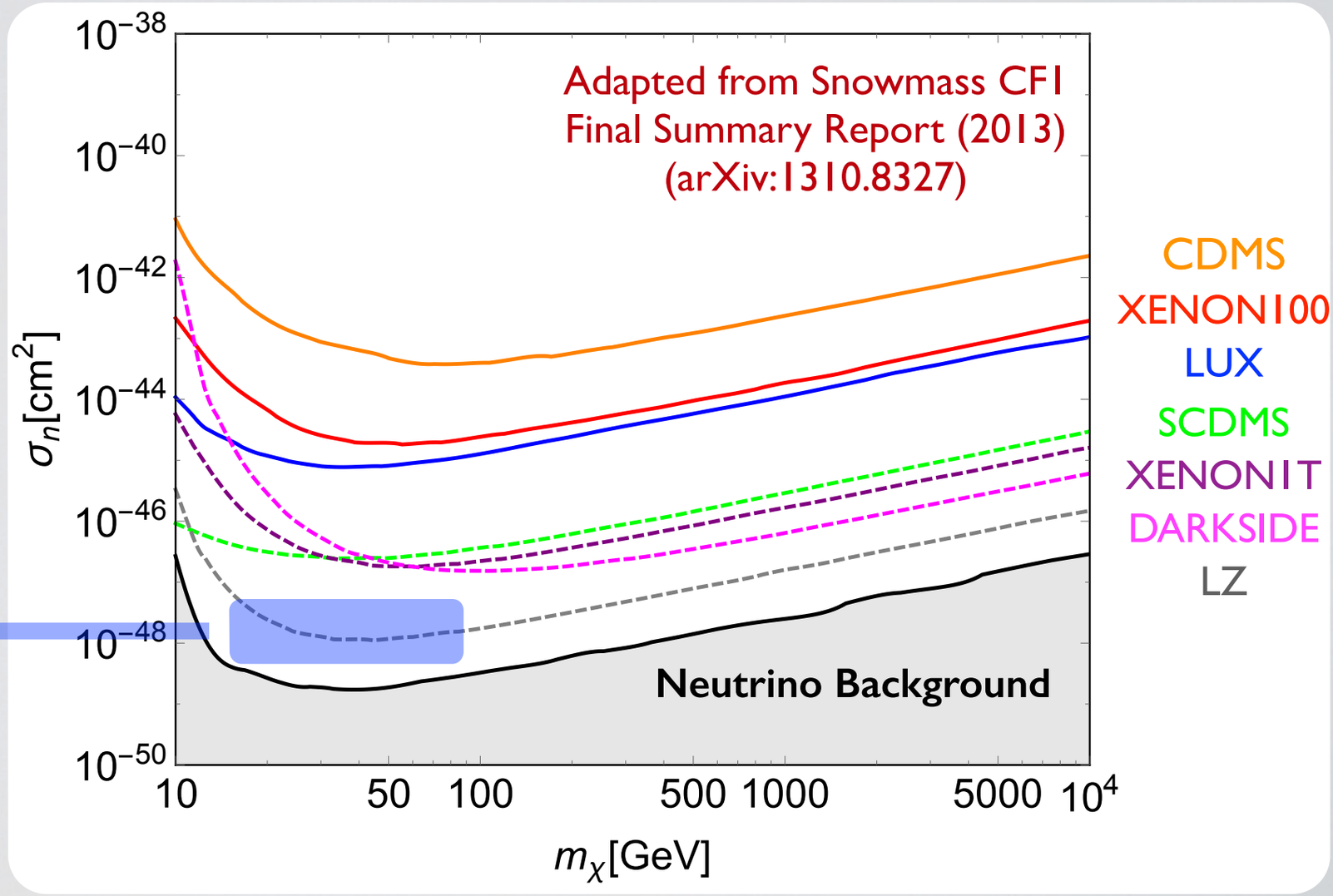

significant improvement in the near future (5 years)

Spin–Independent DD

Coherent WIMP-Nucleus Scattering

$$\sigma_{\rm SI} = \frac{m_\chi^2 m_{\mathcal{N}}^2}{(m_\chi + m_{\mathcal{N}})^2 \pi} \left| Z\, f_p + (A - Z) f_n \right|^2$$

Goodman and Witten, PRD 31 (1985)

Fermion Singlet - Dim. 6

$$\mathcal{L}_{DD}^{\rm eff} = \bar{\chi}\gamma^\mu \chi \left(\frac{c_V^u}{\Lambda^2} \bar{u}\gamma_\mu u + \frac{c_V^d}{\Lambda^2} \bar{d}\gamma_\mu d \right) \Bigg|_{\rm nuclear} \qquad f_p = \frac{2c_V^u + c_V^d}{\Lambda^2} \qquad f_n = \frac{c_V^u + 2c_V^d}{\Lambda^2}$$

Spin–Independent DD

Coherent WIMP-Nucleus Scattering

$$\sigma_{\rm SI} = \frac{m_\chi^2 m_{\mathcal{N}}^2}{(m_\chi + m_{\mathcal{N}})^2 \pi} \left| Z\, f_p + (A - Z) f_n \right|^2$$

Goodman and Witten, PRD 31 (1985)

Fermion Singlet - Dim. 6

$$\mathcal{L}_{DD}^{\rm eff} = \bar{\chi}\gamma^\mu \chi \left(\frac{c_V^u}{\Lambda^2} \bar{u}\gamma_\mu u + \frac{c_V^d}{\Lambda^2} \bar{d}\gamma_\mu d \right) \Bigg|_{\rm nuclear} \qquad f_p = \frac{2c_V^u + c_V^d}{\Lambda^2} \qquad f_n = \frac{c_V^u + 2c_V^d}{\Lambda^2}$$

In what follows

Consider specific choice Wilson coefficients at Λ

RG flow

Constrain parameter space via direct detection bounds

D5 and D7 Operators

$$\mathcal{L}_{\mathrm{D5}} = \frac{c_{\mathrm{D5}}}{\Lambda^2}\,\overline{\chi}\gamma^\mu\chi\left[\sum_i \overline{u^i}\gamma_\mu u^i + \sum_i \overline{d^i}\gamma_\mu d^i\right]$$

Large SI cross section for D5

$$\mathcal{L}_{\mathrm{D7}} = \frac{c_{\mathrm{D7}}}{\Lambda^2}\,\overline{\chi}\gamma^\mu\chi\left[\sum_i \overline{u^i}\gamma_\mu\gamma_5 u^i + \sum_i \overline{d^i}\gamma_\mu\gamma_5 d^i\right]$$

SD and q^2 suppressed for D7

Operators defined at the mediator scale Λ

D5 and D7 Operators

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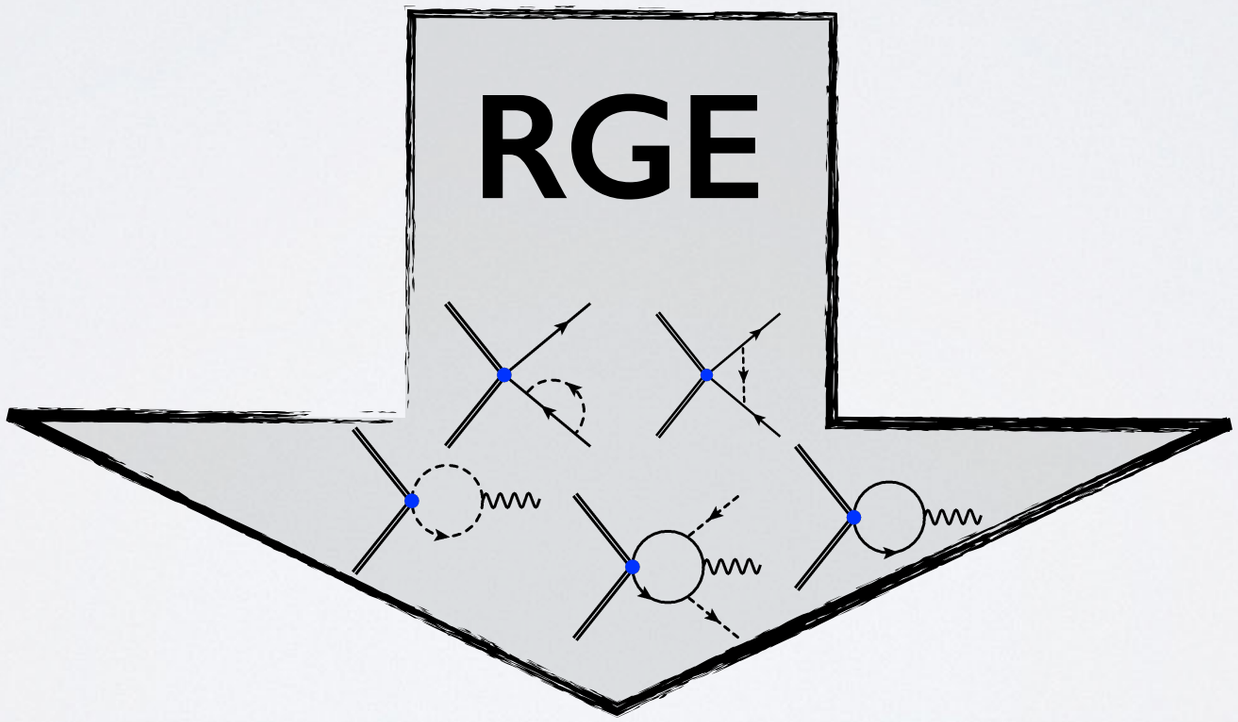

D5 and D7 mix onto each other

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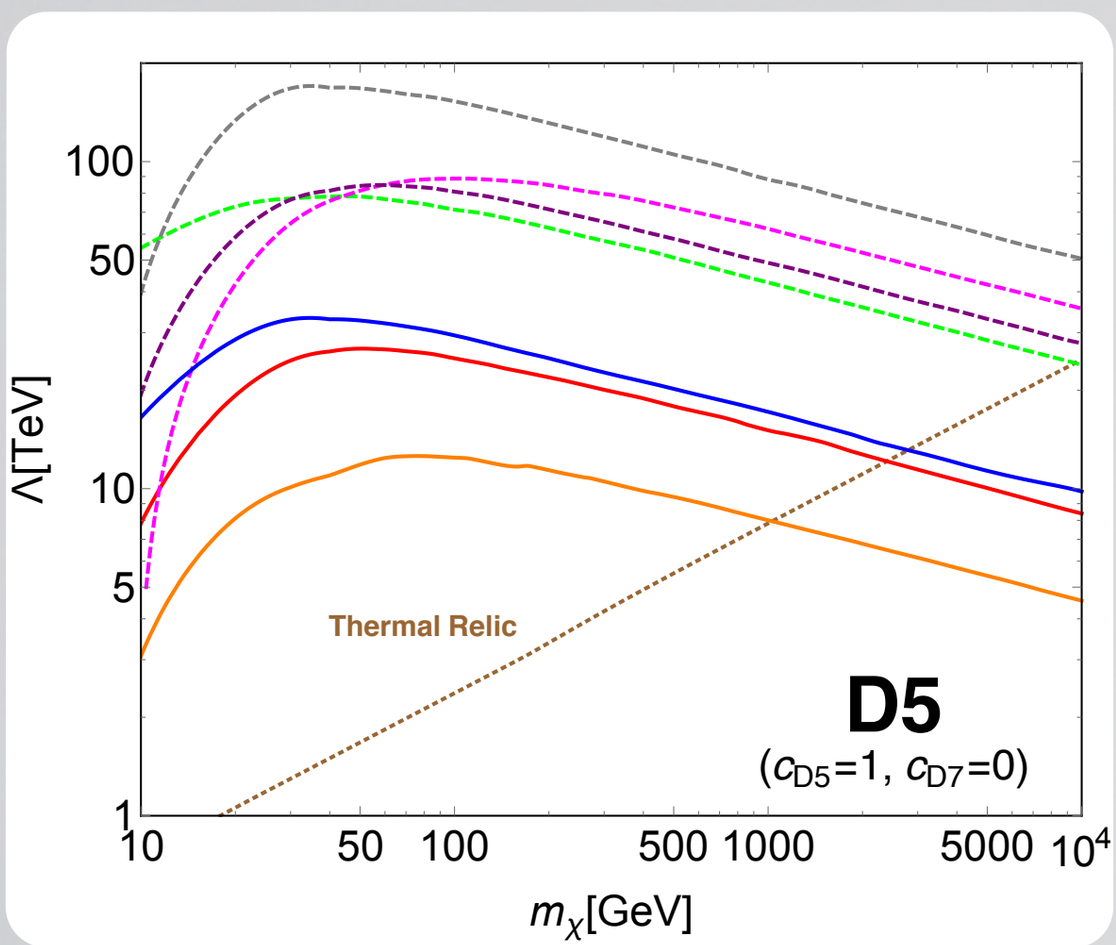

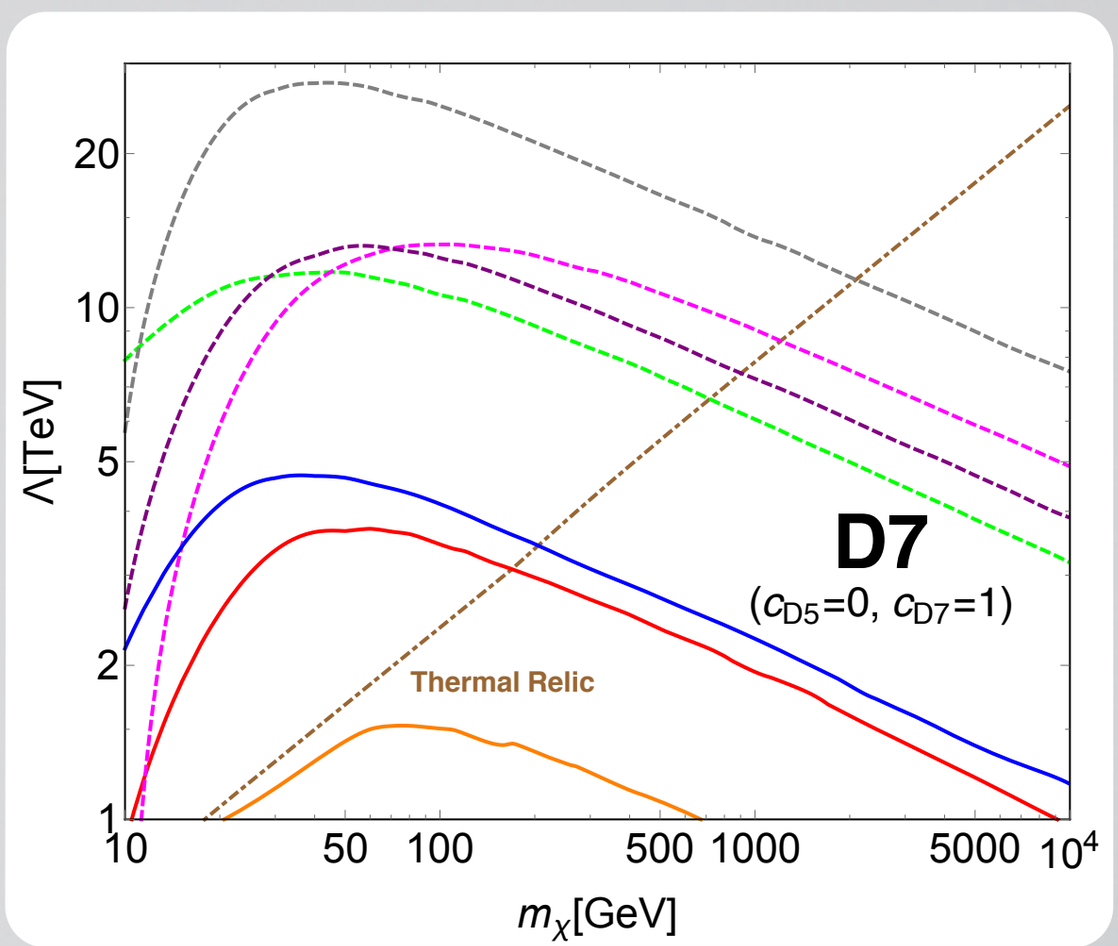

CDMS XENON100 LUX SCDMS XENON1T DARKSIDE LZ

Crivellin, FD, Procura PRL 112 (2014)
FD and Procura, to appear in JHEP (arXiv:1411.3342)

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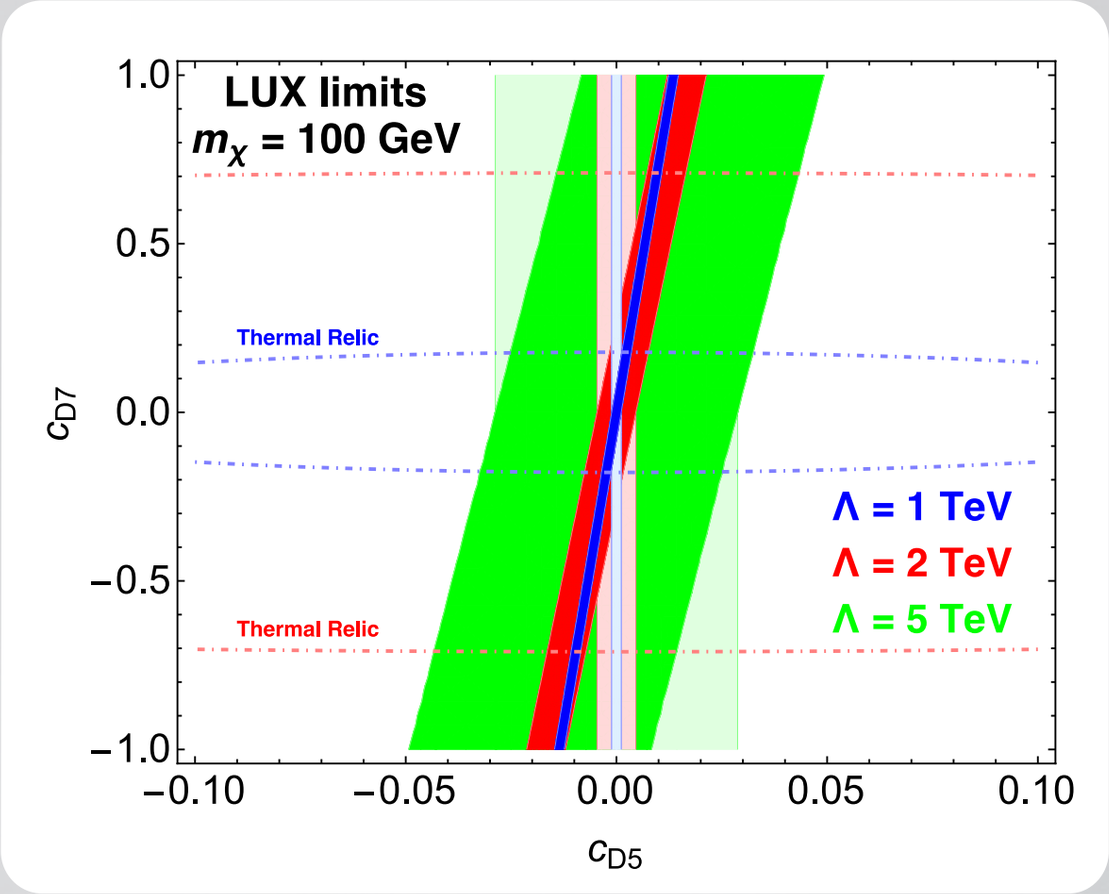
Operators defined at the mediator scale Λ

Generic UV complete model can generate both D5 and D7



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DM and Heavy Quarks

$$\mathcal{L}_{\rm HQ} = \frac{1}{\Lambda^2}\,\overline{\chi}\gamma^\mu\chi\left(c_Q\,\overline{q_L^3}\gamma_\mu q_L^3 + c_U\,\overline{u_R^3}\gamma_\mu u_R^3 + c_D\,\overline{d_R^3}\gamma_\mu d_R^3\right)$$

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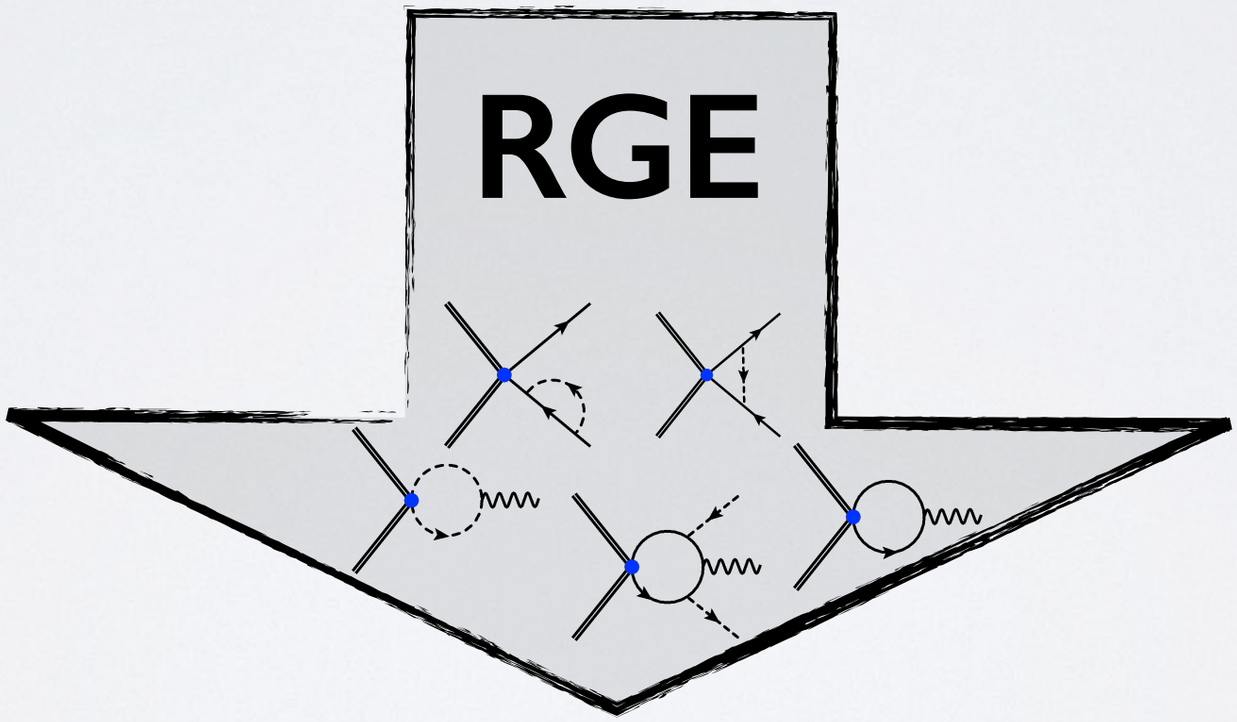

Operators with HQ mix onto D5 with light quarks

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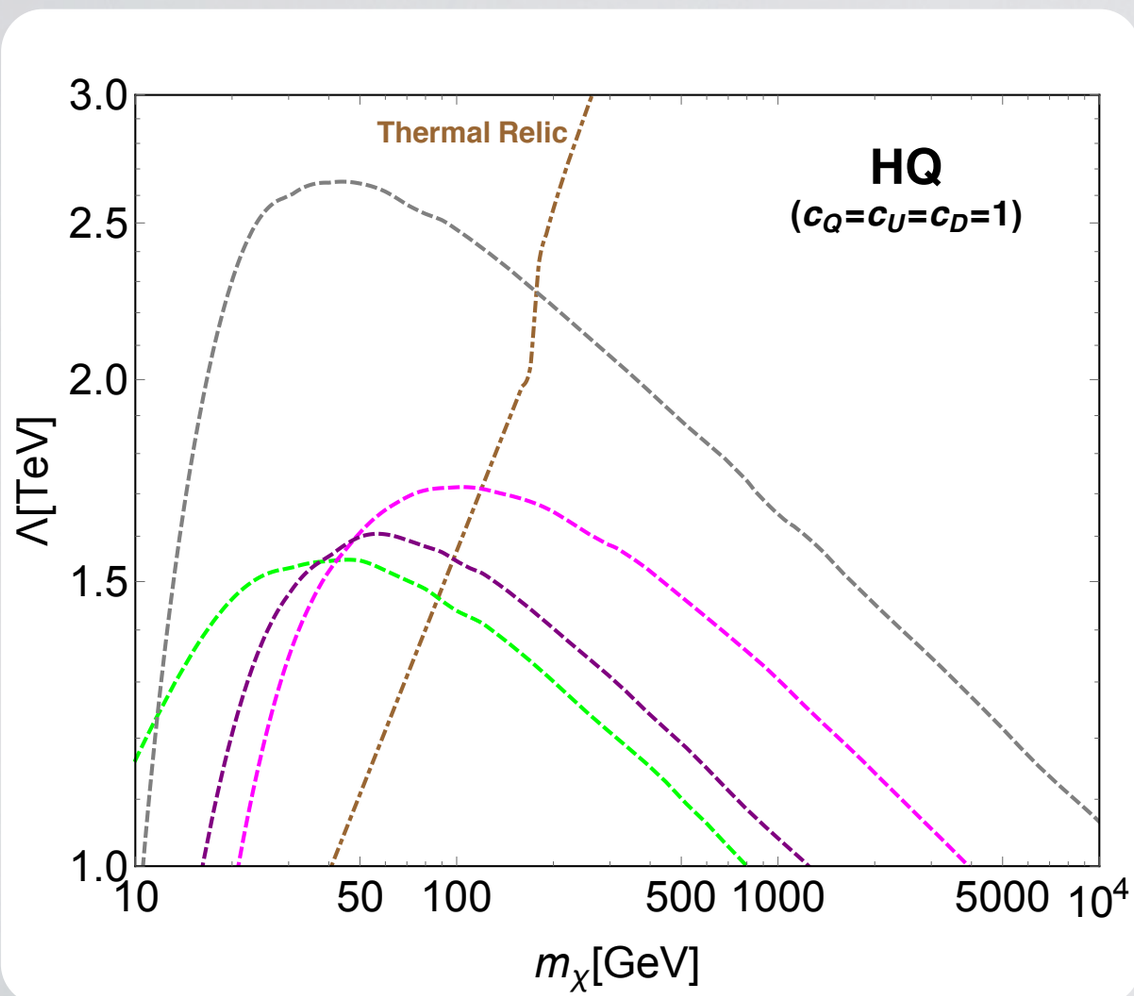

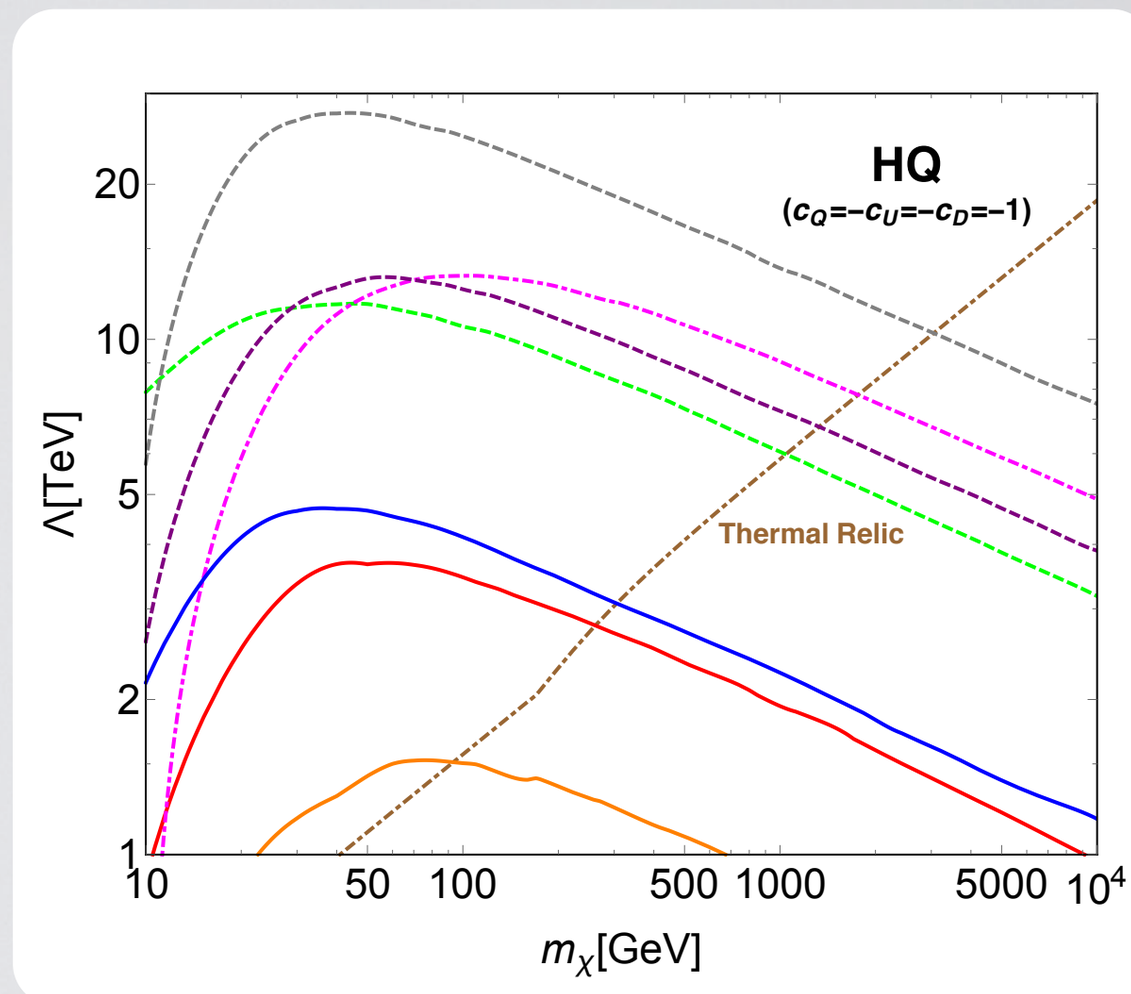

CDMS XENON100 LUX SCDMS XENON1T DARKSIDE LZ FD and Procura, to appear in JHEP (arXiv:1411.3342)

Leptophilic DM

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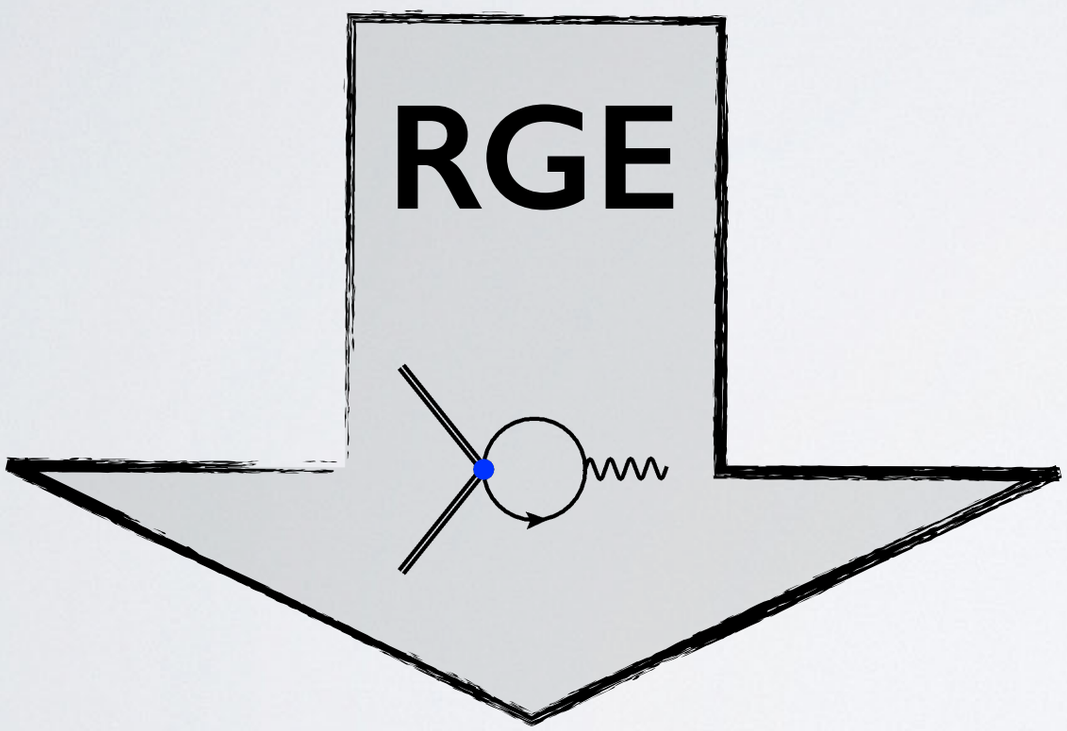

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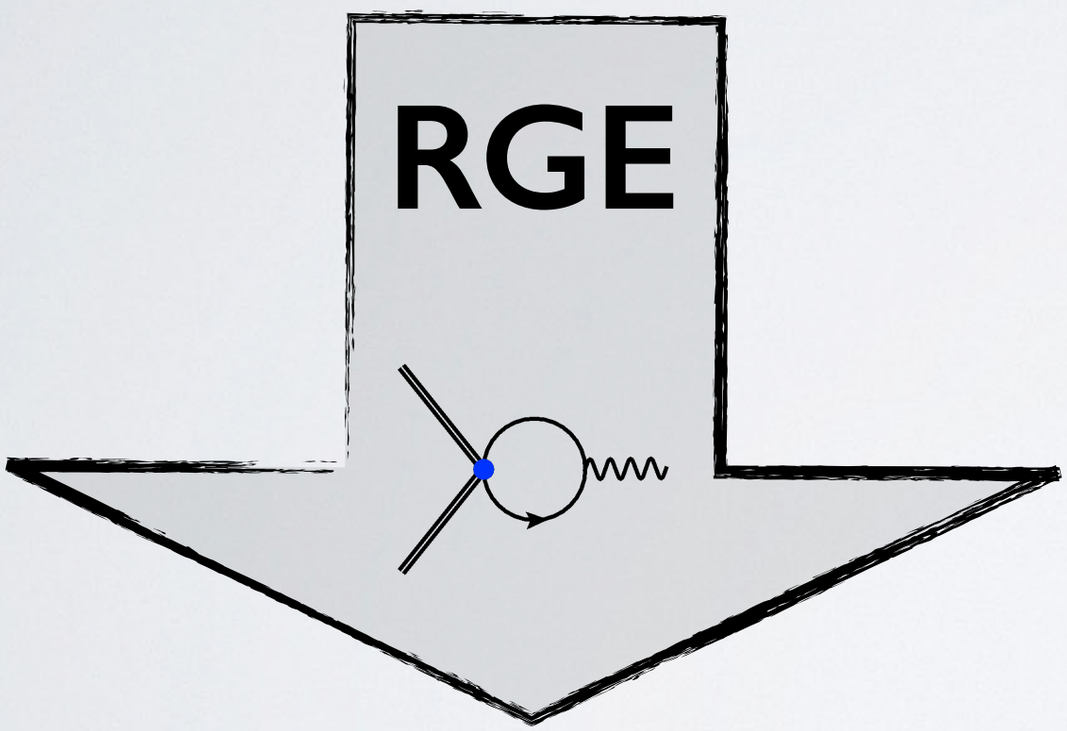

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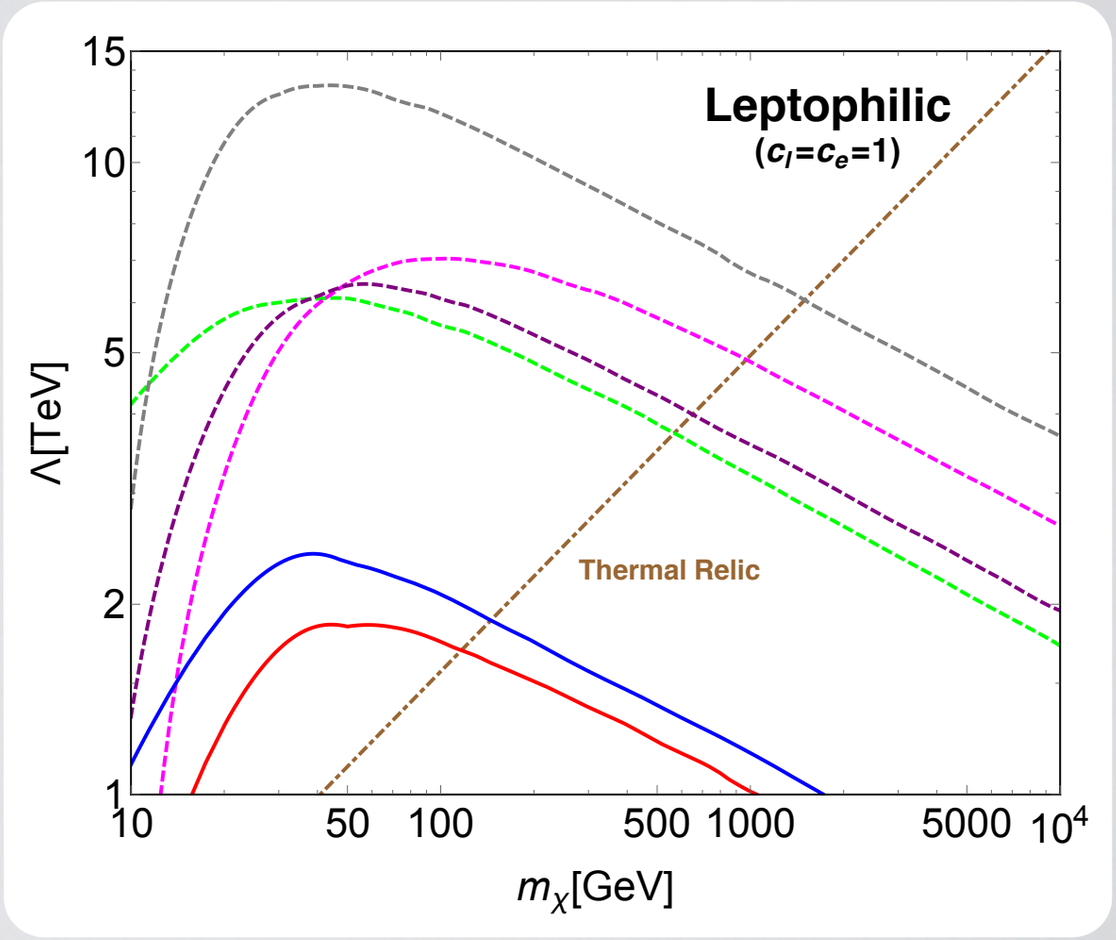

CDMS XENON100 LUX
SCDMS XENON1T DARKSIDE LZ

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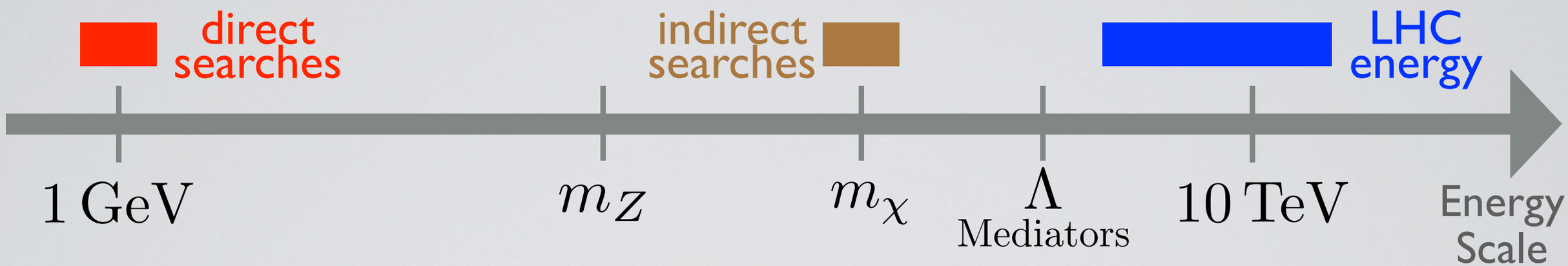
Plan for Today's Talk

Singlet Fermion WIMP

Application to Direct Searches

Conclusions and Outlook

Conclusions



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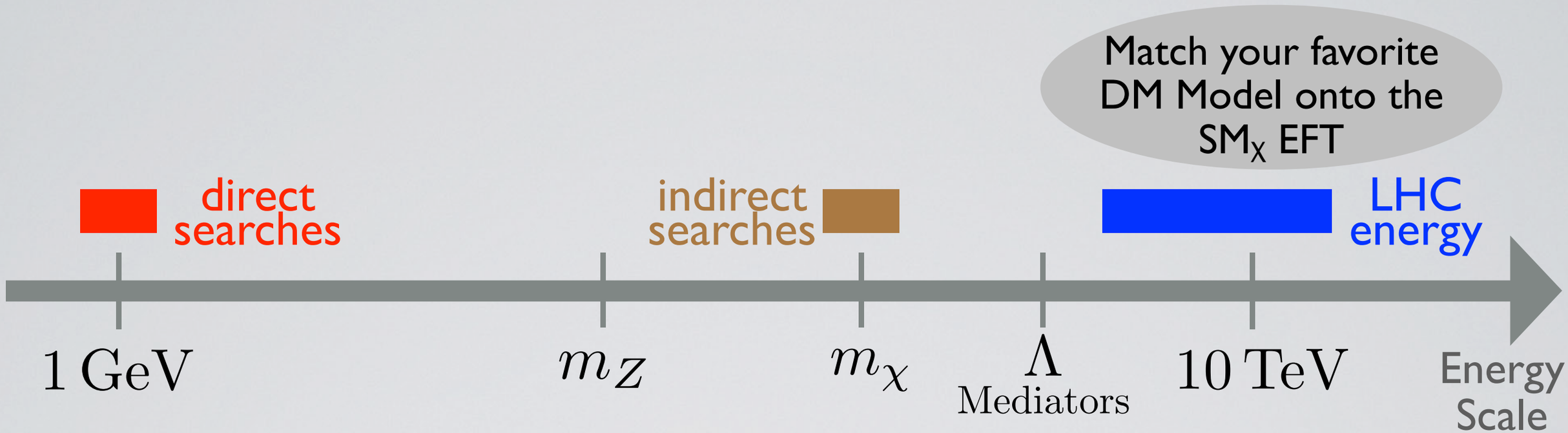

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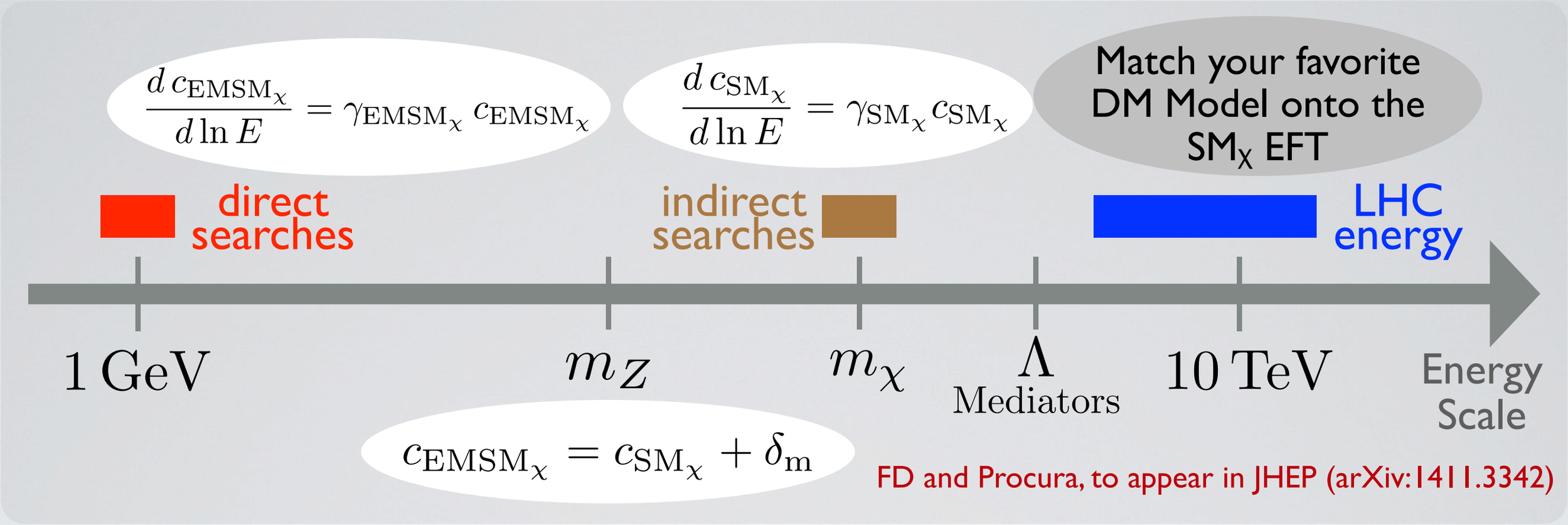

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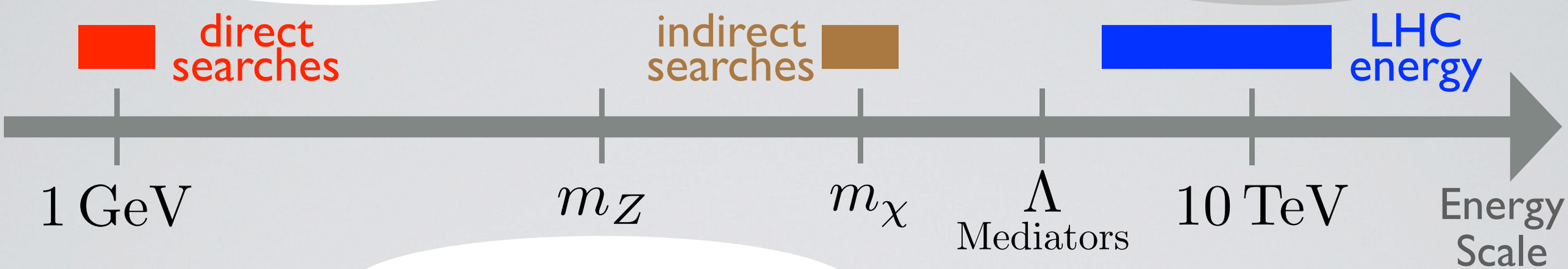
Conclusions

$$\frac{d\,c_{\mathrm{EMSM}_\chi}}{d\ln E} = \gamma_{\mathrm{EMSM}_\chi}\, c_{\mathrm{EMSM}_\chi}$$

$$\frac{d\,c_{\mathrm{SM}_\chi}}{d\ln E} = \gamma_{\mathrm{SM}_\chi}\, c_{\mathrm{SM}_\chi}$$

Match your favorite DM Model onto the SM_χ EFT



$$c_{\mathrm{EMSM}_\chi} = c_{\mathrm{SM}_\chi} + \delta_{\mathrm{m}}$$

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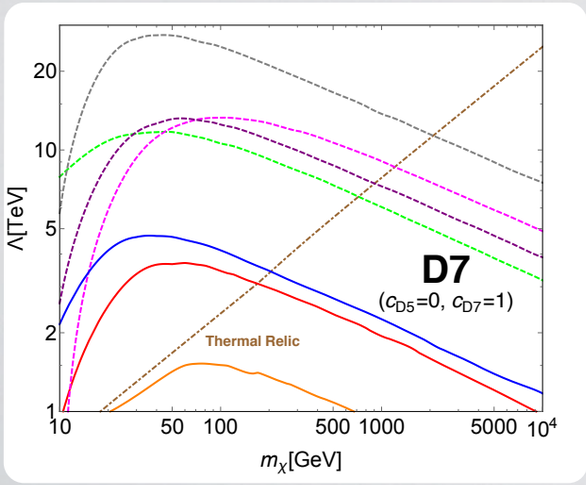
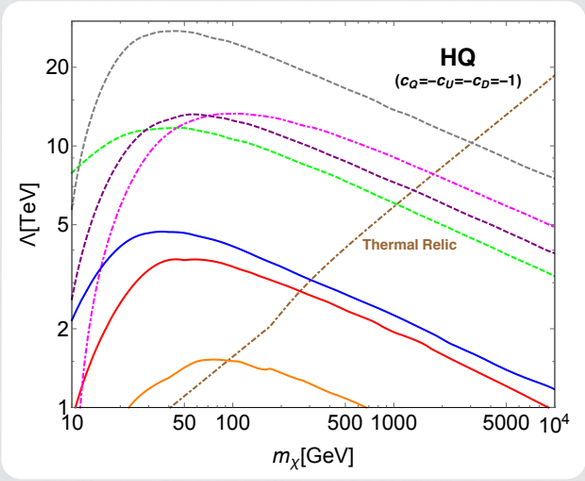
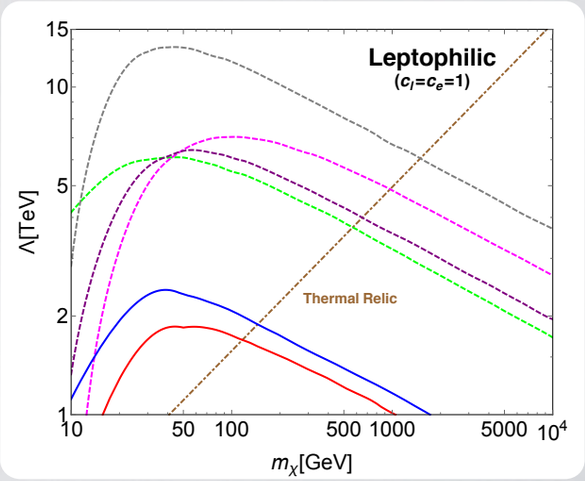
Model-independent constraints to couplings at the scale Λ







Outlook

Pushing EFT Analysis

Singlet fermion at dim. 7:

(nice examples in: Frandsen, Haisch, Kahlhoefer, Mertsch, Schmidt-Hoberg, JCAP1210 (2012)
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Different DM spin and/or SM quantum numbers

(with only gauge interactions: see Hill, Solon, PLB707 (2011) and PRL112 (2014))

Extend the study for lighter mediators ($\Lambda \leq 1$ TeV)

Explicit Models

Apply results to Simplified Models and explore complementarity

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THANK YOU