Update on DM t-channel signatures

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with embedded contributions by

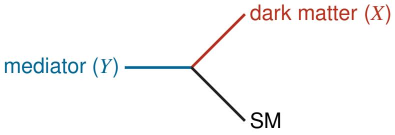
C. Arina, M. Baker, A. Cornell, R. Costa Batalha Pedro and J. Heisig

Motivation

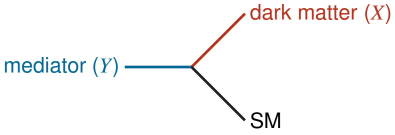
Joint effort TH-EXP to provide guidelines and benchmarks for new analysis during Run 3 and future upgrades

Coordinators: B. Fuks, B. Maier and D. Yu
and $50+$ authors

Study of scenarios based on the schematic interaction



Guiding questions



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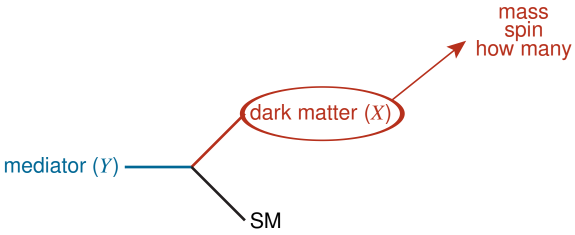

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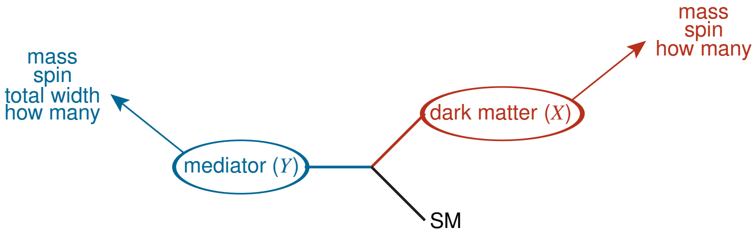

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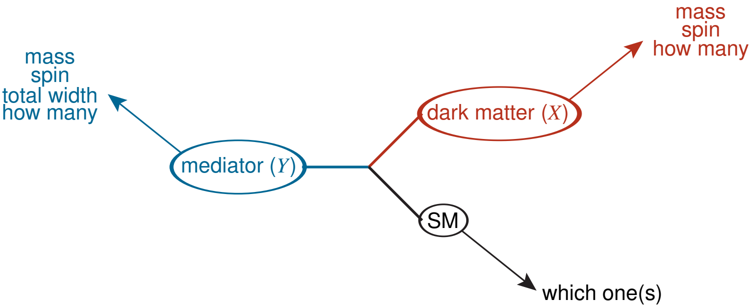

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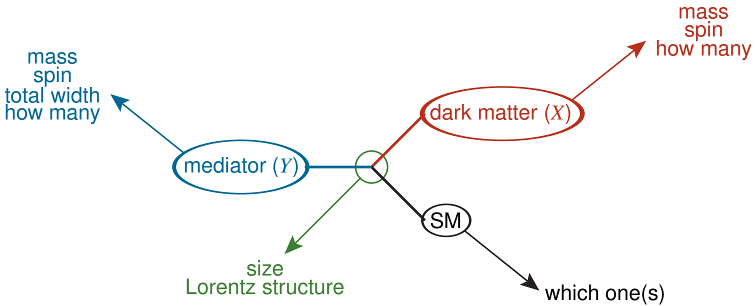

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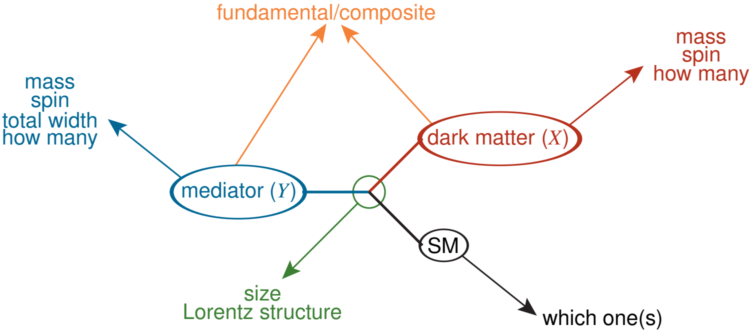
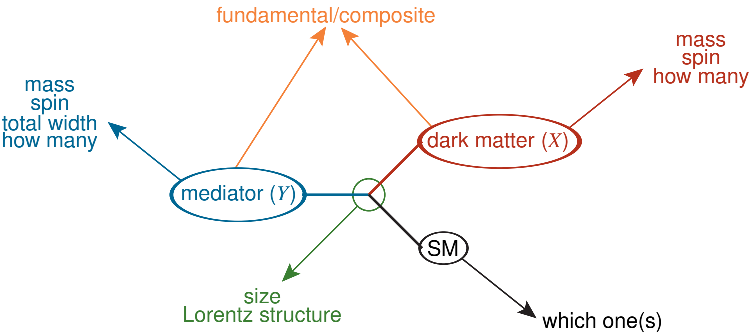


Guiding questions



Depending on the possibilities:

- Can we observe a signal? And how?
- How does cosmology constrain the parameters?
- How do we reinterpret results?
- Can we define benchmarks for LHC to cover the widest range of possibilities?

Temporary structure

To be reorganized
once all contributions
are in advanced state

The models

Simplified models suitable for performing MC simulations at NLO in QCD
and testing against cosmological observables

Coloured mediators

DMSimpt : A general framework for t-channel dark matter models at NLO in QCD

Contact Information

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See arXiv:2001.05024 [hep-ph].

Model Description and FeynRules Implementation

We extend the Standard Model by a dark matter candidate X and a coloured mediator Y. The model includ
or bosonic dark matter) or 0 (fermionic dark matter). The model Lagrangian is given by

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \mathcal{L}_F(\chi) + \mathcal{L}_F(\tilde{\chi}) + \mathcal{L}_S(S) + \mathcal{L}_S(\tilde{S}) + \mathcal{L}_V(V) + \mathcal{L}_V(\tilde{V}) \,.$$

The first term consists in the Standard Model Lagrangian, the second one includes gauge-invariant kinetic
Dirac fermion, Majorana fermion, complex scalar, real scalar, complex vector and real vector dark matter,

$$\begin{aligned}
\mathcal{L}_F(X) &= \Big[\lambda_{\bf Q}\bar{X}Q_L\varphi_Q^\dagger + \lambda_{\bf u}\bar{X}u_R\varphi_u^\dagger + \lambda_{\bf d}\bar{X}d_R\varphi_d^\dagger + \text{h.c.}\Big]\,,\\
\mathcal{L}_S(X) &= \Big[\hat{\lambda}_{\bf Q}\bar{\psi}_Q Q_L X + \hat{\lambda}_{\bf u}\bar{\psi}_u u_R X + \hat{\lambda}_{\bf d}\bar{\psi}_d d_R X + \text{h.c.}\Big]\,,\\
\mathcal{L}_V(X) &= \Big[\hat{\lambda}_{\bf Q}\bar{\psi}_Q\gamma^\mu X_\mu Q_L + \hat{\lambda}_{\bf u}\bar{\psi}_u\gamma^\mu X_\mu u_R + \hat{\lambda}_{\bf d}\bar{\psi}_d\gamma^\mu X_\mu d_R + \text{h.c.}\Big]\,,
\end{aligned}$$

where φ and ψ consists in coloured scalar and fermionic mediators.

http://feynrules.irmp.ucl.ac.be/wiki/DMsimpt

	Spin	
Mediator	0	1/2
Dark matter	1/2	0 or 1

- DM real or complex
- Couplings with any SM quark
- Restrictions to select representations or coupling hierarchies (only one generation, universal couplings. . .)

C. Arina, B. Fuks and L. Mantani, Eur. Phys. J. C **80** (2020) no.5, 409, [arXiv:2001.05024 [hep-ph]].

Other models will be used for specific problems
(leptophilic DM, multi-component DM. . .)

Mapping results from simplified models to theoretical scenarios

Cosmology

contribution by C. Arina

Cosmology of t-channel DM models

Goals of the section

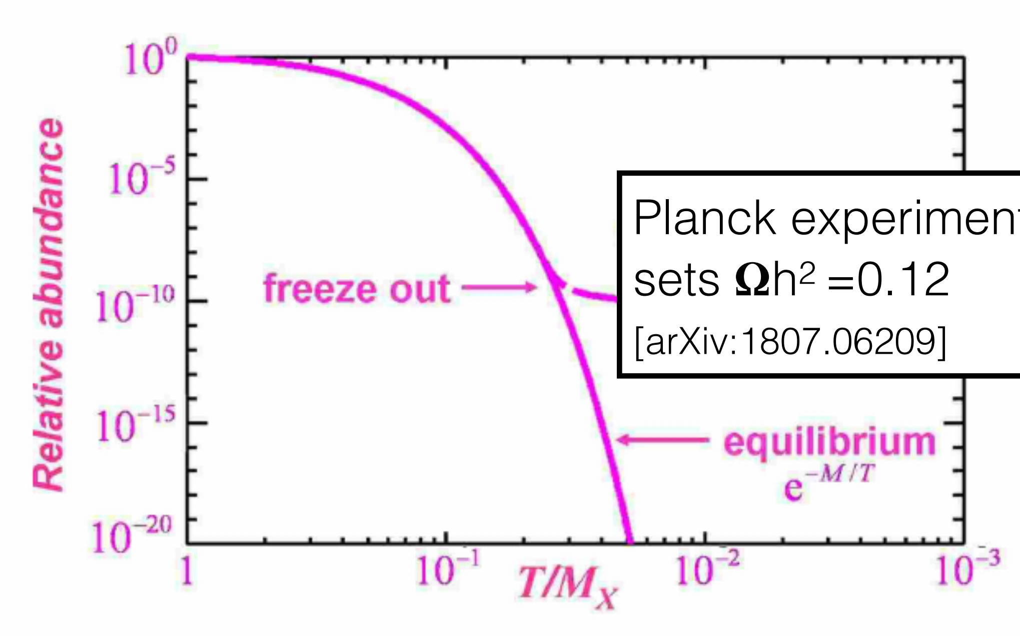
- Provide a general overview of the cosmology of t-channel models and point to the relevant literature
- Give overview of production mechanisms
- Give overview of main searches for:
- Direct detection
- Indirect detection
- Illustrate cosmological bounds for the models selected in the t-channel paper (minimal model, universal couplings, flavored, leptophilic, …)
- From parameter space available define viable benchmarks for collider searches

Contributors: C. Arina (section coordinator), M. Becker, E. Coppello, J. Harz, J. Heisig, A. Ibarra, S. Khalil, M. Kirtiman, M. Kraemer, L. Lopez-Honorez, L. Panizzi, D. Sengupta, Y. Sheng, S. Tentori

If you are interested in joining please contact Chiara Arina (Chiara.arina@uclouvain.be)

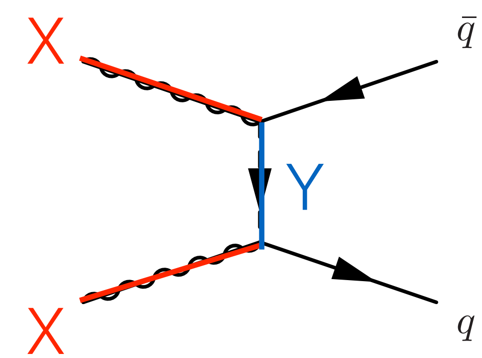
Dark Matter production in the early universe

Relic abundance via freeze-out
Standard mechanism



Planck experiment sets $\Omega h^2 = 0.12$
[arXiv:1807.06209]

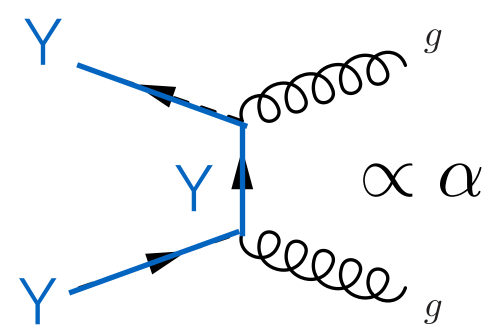
LO processes



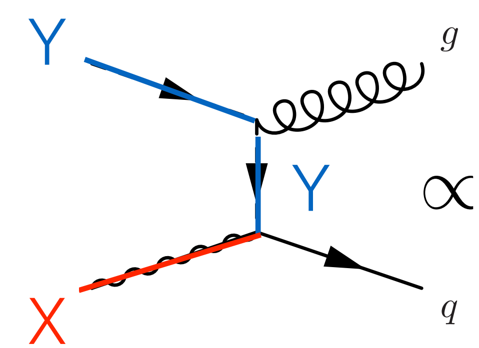
DM annihilation

$\propto \lambda_\varphi^4$

coannihilation (compressed spectrum)



$\propto \alpha_s^2$



$\propto \lambda_\varphi^2 \alpha_s$

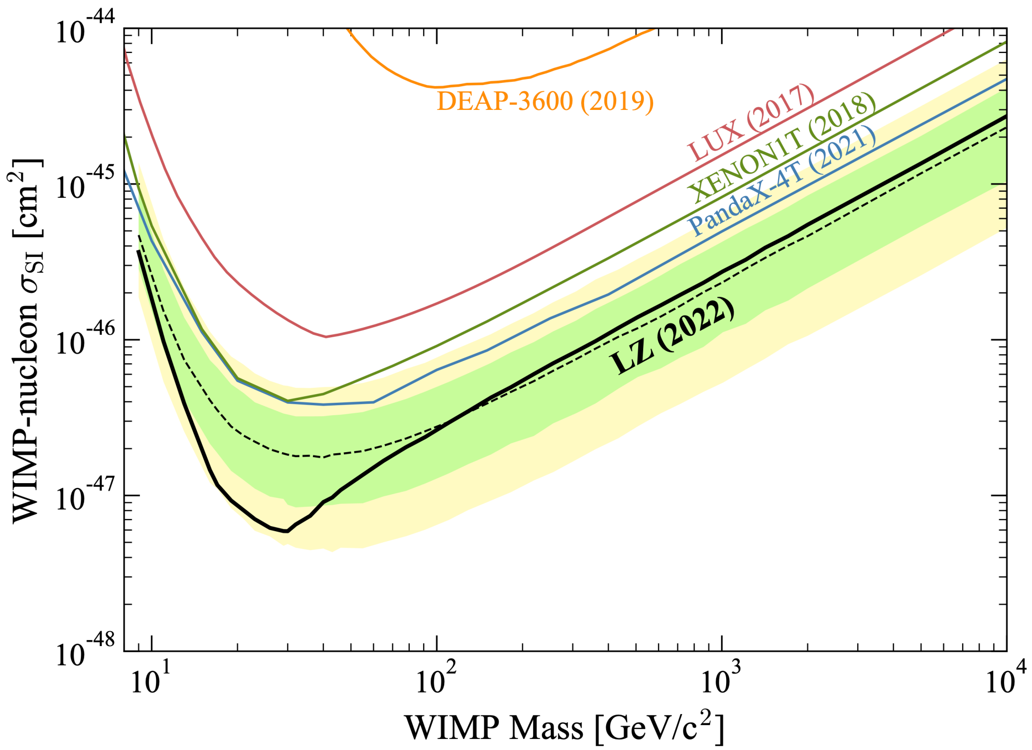
LO processes + non perturbative corrections (Sommerfeld enhancement + bound states)

Freeze-in, SuperWIMPs achieve relic density via decay of heavy species and provide LLPs signatures also detailed

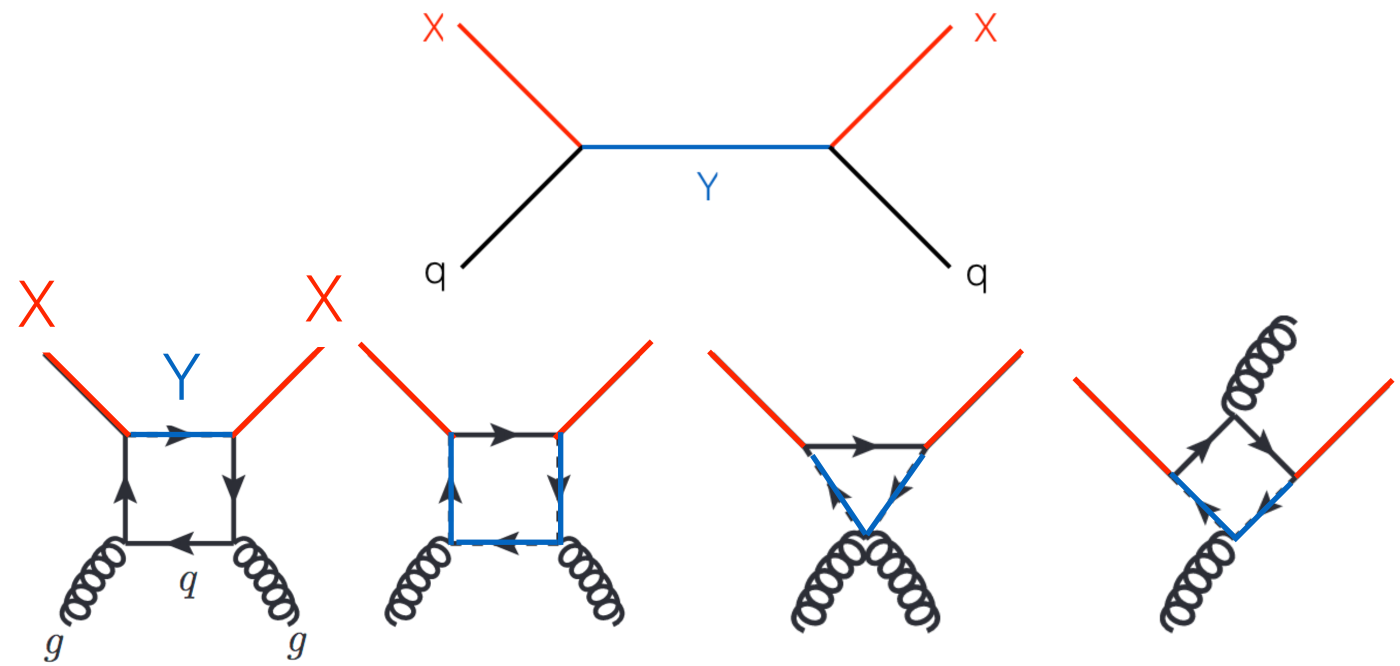
T-channel white paper - Cosmology section

Dark Matter direct and indirect searches

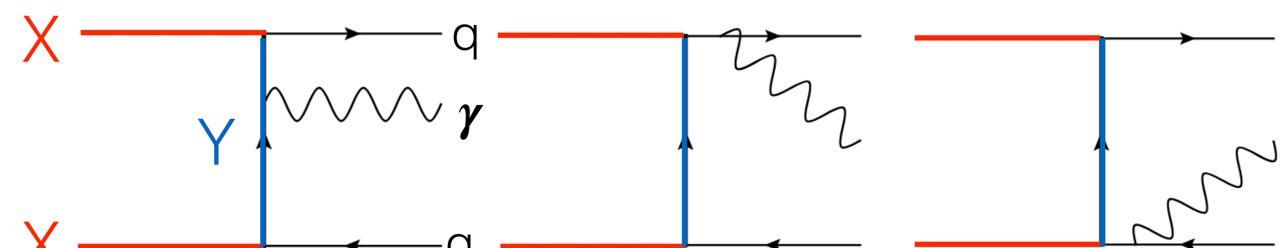
Direct detection

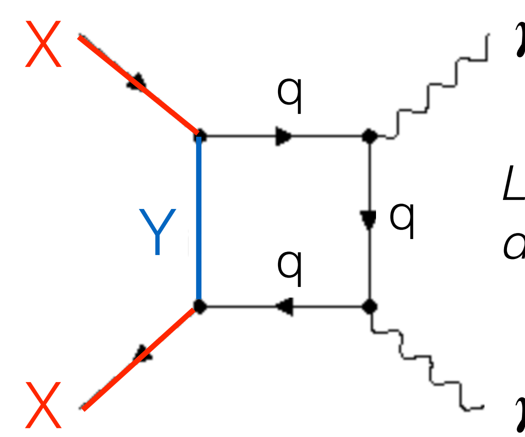


LO and/or NLO/loop processes



Virtual internal bremsstrahlung (VIB)





Loop-induced diphotons

Indirect detection

- In many models LO annihilation is p-wave suppressed
- NLO processes uplift the suppression and produce a sharp feature in the gamma-ray energy spectrum

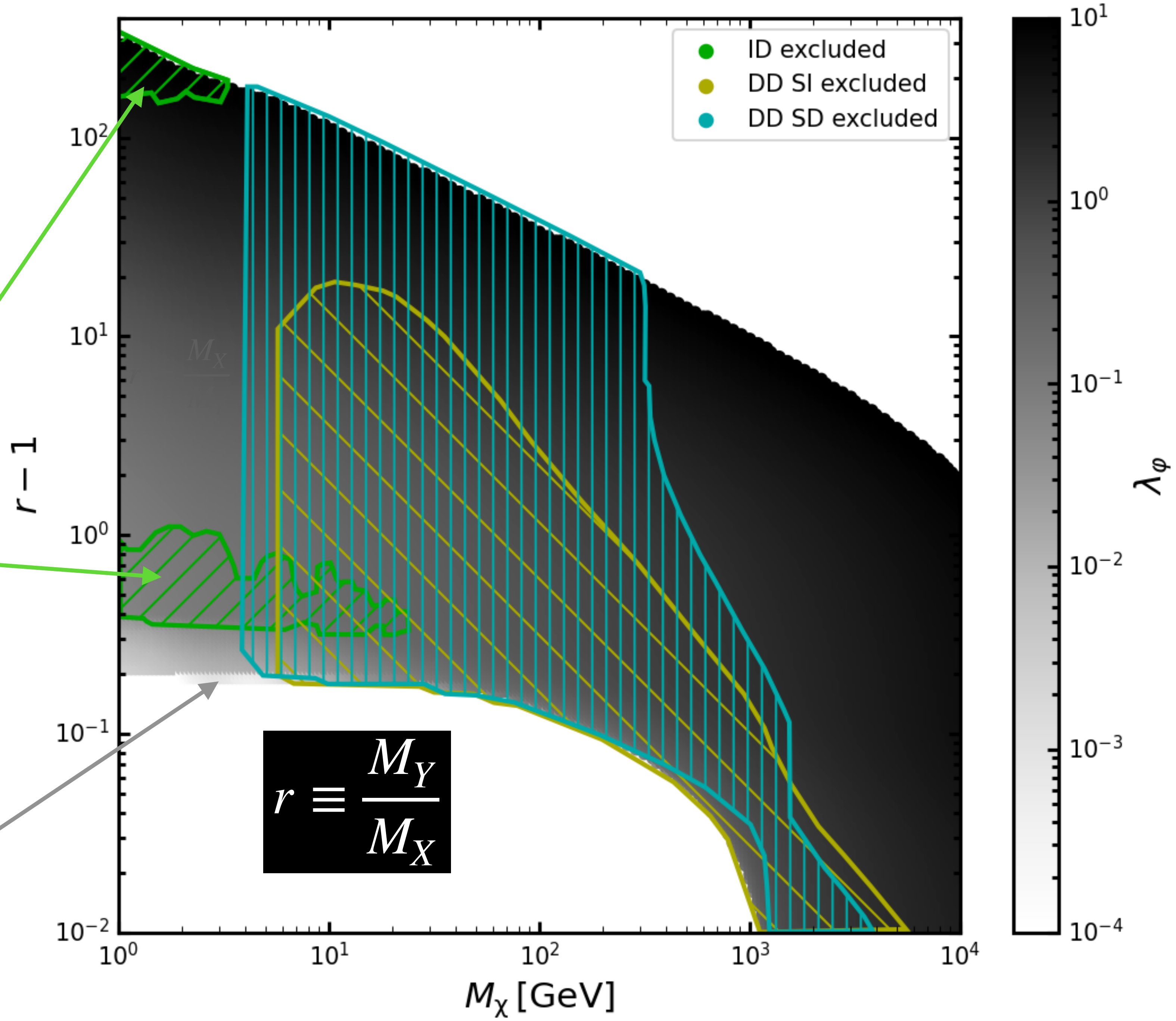
T-channel white paper - Cosmology section

Example of benchmark model study*

* from Arina et al. 2021, Phys. Lett. B 813

Majorana DM coupling to up-right quark via scalar mediator (S3M_uR)

Viable parameter space compatible with relic density via freeze-out



Gamma-ray bounds from lines and VIB

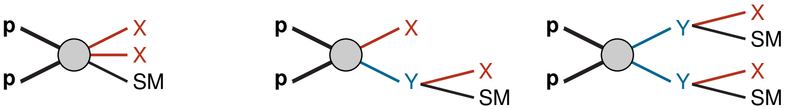
Region with small couplings gives rise to LLP

Region can be much bigger including freeze-in, not shown here

T-channel white paper - Cosmology section

Collider signatures

Which signatures

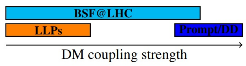


Not all processes might be possible at tree-level

depending on coupling or mass splitting

Long-lived mediators

Bound states
Displaced vertices
Delayed jets/photons



Mediators with prompt decay

MET+SM

depending on which SM particle

quark-philic { 1st generation / 2st generation / 3st generation / universal / . . . } **lepto-philic**

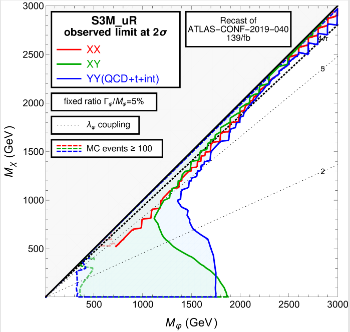
Interacting with SM gauge bosons (Z/W) or the Higgs boson

Prompt mediator decays

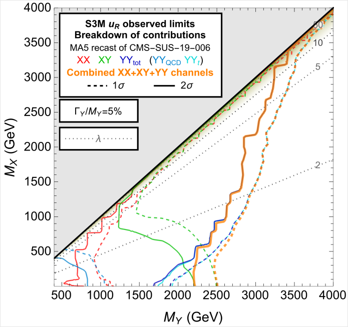
interaction with the up quark

goals and status

- Go beyond existing results



C. Arina, B. Fuks, L. Mantani, H. Mies, LP and J. Salko, Phys. Lett. B **813** (2021), 136038



C. Arina, B. Fuks, Jan Heisig, Michael Krämer, L. Mantani and LP, in preparation

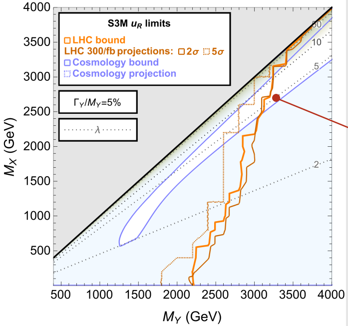
Combination of all channels, relevance of NLO corrections and interference effects

Prompt mediator decays

interaction with the up quark

goals and status

- Go beyond existing results
- Identify benchmarks allowed by LHC and cosmology observables



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	M_Y	M_X	λ
S3M_uR	3300	2700	4.79563
F3S_uR	3400	2500	4.88088
F3V_uR	3500	1500	1.0066

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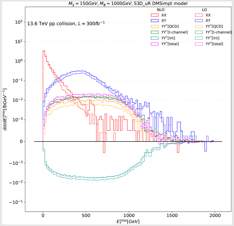
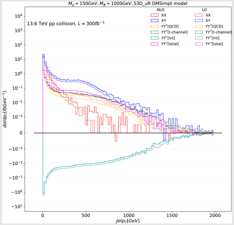
- Store event samples and kinematical distributions for subsequent analyses





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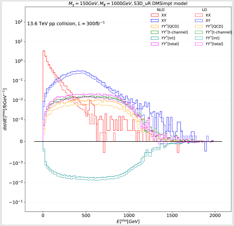
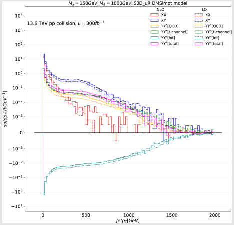




Repeat for mediators coupling to other flavours or having universal couplings to all flavours

We need people with access to computing resources to perform parameter scans

Flavoured dark matter

contribution by R. Costa Batalha Pedro

M. Blanke, G. Polesello, H. Acaroglu, M. Krämer

Top-philic Dark Matter

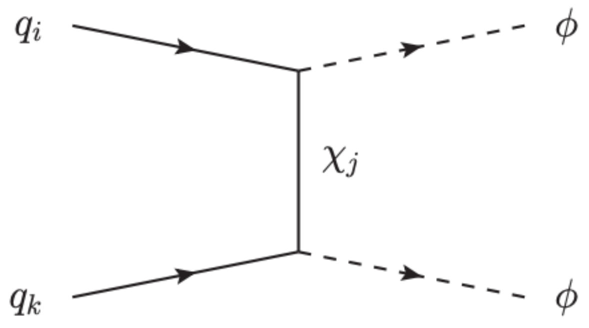
$$\lambda^{ij}\bar{q}_i\chi_j\phi$$

q_i	SM quarks
χ_j	DM fermion, flavoured
ϕ	coloured scalar mediator
λ	flavour-violating coupling matrix

- **Models of flavoured DM beyond Minimal Flavour Violation**
  - 1702.08457 1702.08457
  - Flavour carried by the DM candidate and not by the mediator
  - DM is either a Dirac or Majorana fermion
  - Quark-flavoured DM coupling to the SM quarks
    - Lepton-flavoured models may link to the $(g-2)_\mu$ anomaly 2212.08142

- **Constrains from LHC for top-philic scenario**
  - Mainly on mediator pair production
  - $tj + \not{E}_T$ and $t\bar{t} + \not{E}_T$ final states (common to searches for SUSY squarks)

- **Majorana-specific phenomenology**
  - t-channel ϕ-pair-production leading to same-sign $tt + \not{E}_T$
  - Enhanced cross-section at the LHC due to the *up*-quark PDF in the protons



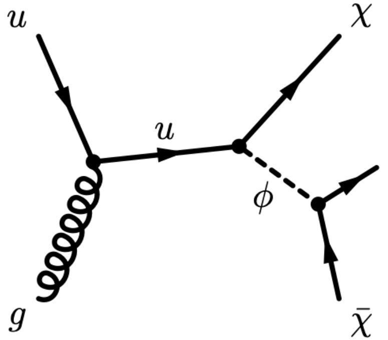
(b) $\phi\phi$ production

Majorana-specific

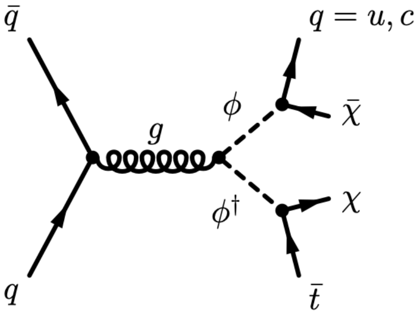
M. Blanke, G. Polesello, H. Acaroglu, M. Krämer

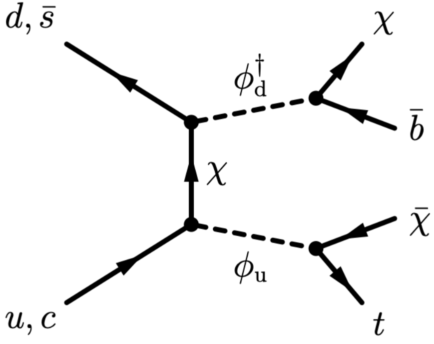
Single top signatures

- **Simplified models of top-flavoured Dark Matter**
  - 2010.10530
  - Within the framework of Minimal Flavour Violation
  - ϕ coloured mediator
    - Right-handed model: couplings to up-type quarks only
    - Left-handed model: couplings to up/down-type quarks (more constrained by flavour physics)



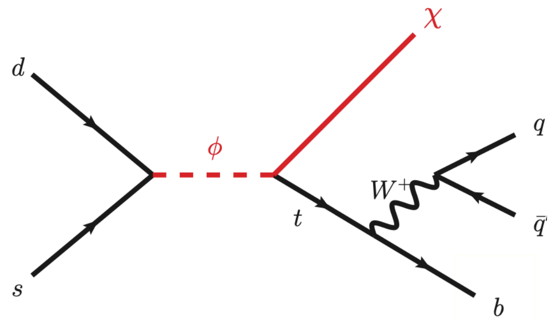
- **Single top signatures**
  - $t + \not{E}_T$
  - $tq + \not{E}_T$, where $q = \{u, d, s, c\}$
  - $tb + \not{E}_T$





N. Castro, M. Moreno Llacer, M.J.Costa Mezquita, J.E. Garcia , R.C. Batalha Pedro

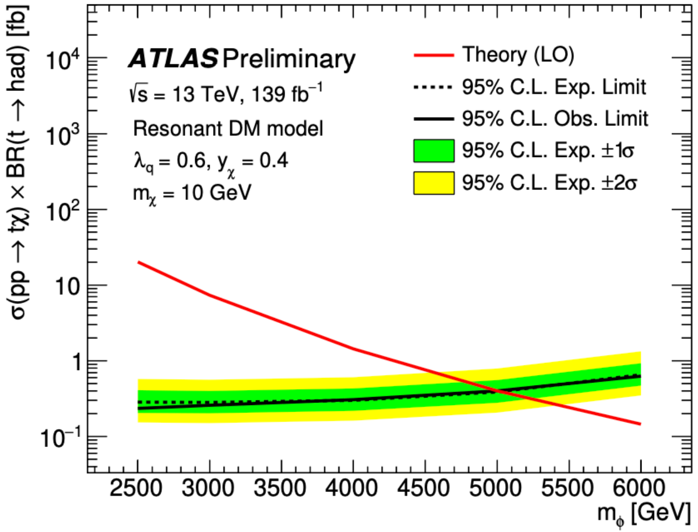
Boosted top probes for top-philic DM



- **Recent ATLAS search in $t + E\!\!\!/_T$ final state, with boosted hadronic top** ATLAS-CONF-2022-036
  - Probes Simplified Models of Dark Matter 1106.6199
  - Resonant production of coloured scalar ϕ mediator

- **Current upper limits on the production cross-section**
  - m_ϕ > 5 TeV, m_V > 2.8 TeV
  - Assuming specific couplings and m_χ=10 GeV

- **HL-LHC sensitivity study drawn from this analysis**



Charm/strange-philic DM

F. Benoit, A. Diyar, B. Fuks, M. Godsell, F. Parraud, D. Tuckler

- **Review/draw constrains on charm-flavoured DM**
  - Limits for the charm-philic model using four jets+MET searches
  - Phenomenology investigations of charm tagging
- **Similar content for a strange-philic model?**

Leptophilic models

contribution by M. Baker

Physics Case

- The WIMP paradigm is being probed and no signal has yet been seen
- A simple possibility that may explain the null result is that DM couples preferentially to leptons rather than quarks
- In that case direct detection only happens at loop level, so is naturally suppressed
- If two DM particles meet in the galaxy, the leptons produce fewer photons than quarks, so indirect detection limits are weaker
- At hadron colliders, since there are no new coloured particles or direct couplings to quarks, production of the particles in these models is suppressed
- However, there are still ways of probing these models at hadron colliders and beyond!

Goals

- Classify all leptophilic t-channel dark matter models
- Summarise key phenomenology in motivated regions of parameter space
- Define benchmark models
    - Muon-philic
    - Flavour universal
- Present existing limits (and possibly up to HL-LHC projections) and relic surfaces for benchmark models for motivated mass scenarios
    - Decoupled $\Longrightarrow$ hard leptons + MET
    - Coannihilation $\Longrightarrow$ soft leptons (tagging challenges, can be ameliorated by ISR boost)
    - Quasi-degenerate + small couplings $\Longrightarrow$ long lived particles, disappearing tracks, displaced leptons, etc
- Discuss Direct Detection and Indirect Detection, as well as future opportunities

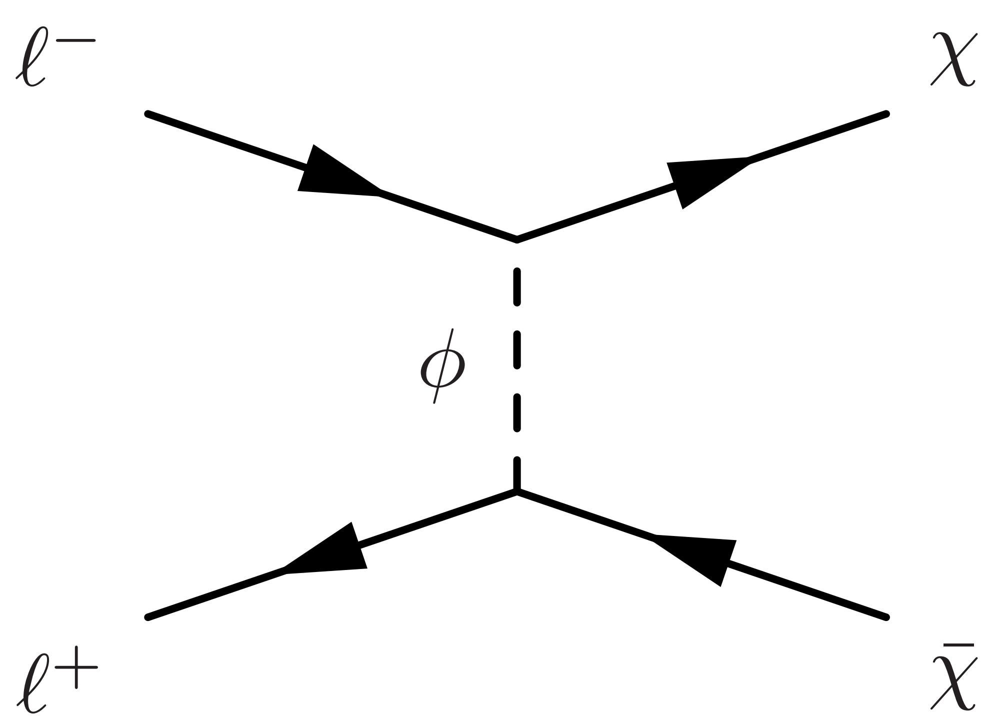
Leptophilic Models: Classification

Leptophilic t-channel models:

DM **only** couples to SM leptons via a t-channel diagram

- DM can couple to RH and/or LH e, μ and/or τ
- DM is gauge singlet $\implies$ charged mediator
- Fermionic DM $\implies$ bosonic mediator and vice versa
- DM could be a real or complex scalar, a Majorana or Dirac fermion or a real or complex vector
- The mediator must be complex/Dirac

E.g.,



RH Model Parameters:

- m_χ
- $\Delta = (m_\phi - m_\chi)/m_\chi$
- y_R^i

$$\mathcal{L} \supset y_R^{ij} \phi^j \overline{\chi} \ell_R^i + y_L^{ik} \varphi^k \overline{\chi} L_L^i + h.c.$$

Field	$(su(3)_C, su(2)_L, u(1)_Y)$	Spin
ℓ_R	$(1, 1, -1)$	$1/2$
L_L	$(1, 2, -1/2)$	$1/2$
χ	$(1, 1, 0)$	$0, 1/2, 1$
ϕ	$(1, 1, 1)$	$1/2, \{0, 1\}, 1/2$
φ	$(1, 2, 1/2)$	$1/2, \{0, 1\}, 1/2$

Leptophilic Models: Phenomenology

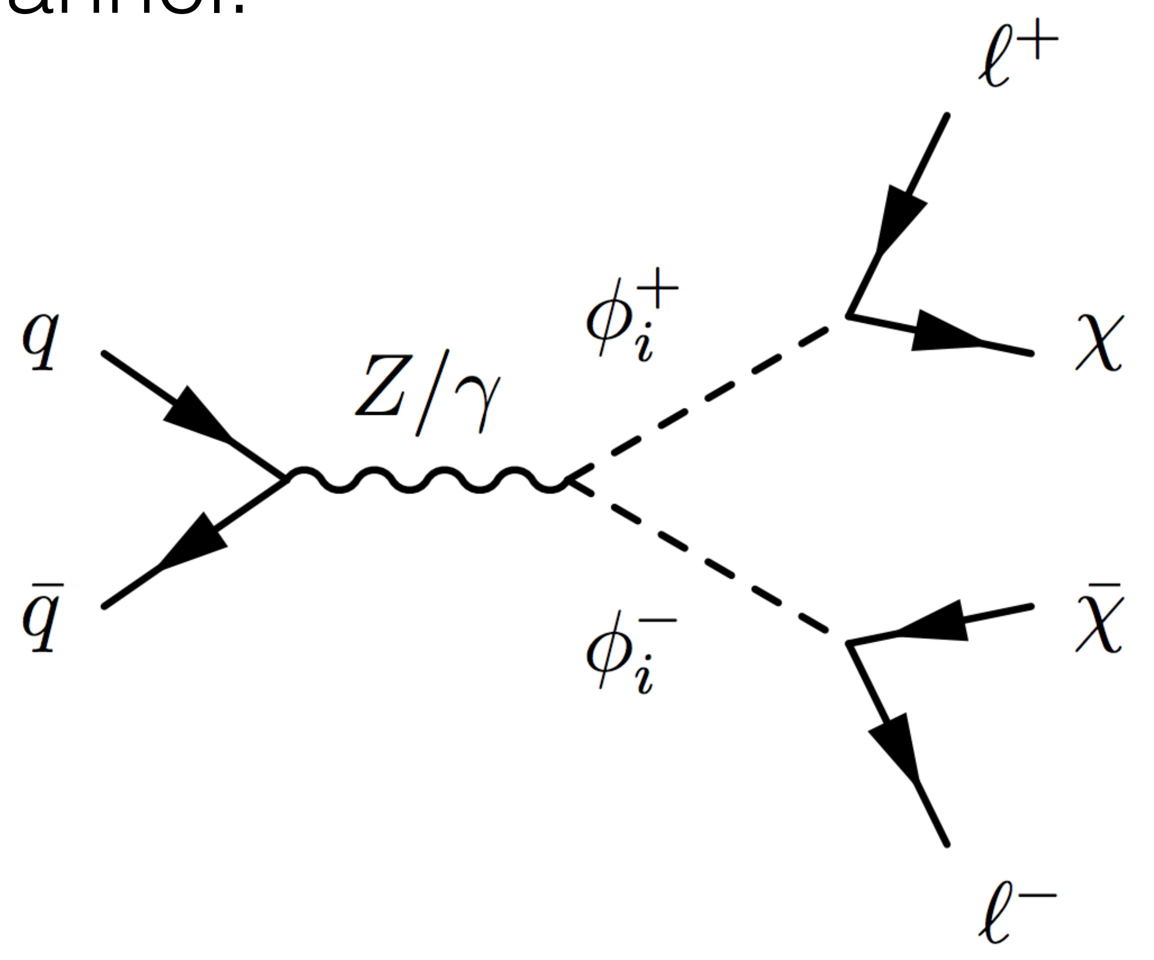
Phenomenology depends on

Mass Regime
- Decoupled: $0.3 \lesssim \Delta$
- Coannihilation: $0.02 \lesssim \Delta \lesssim 0.3$
- Quasi-degenerate: $\Delta \lesssim 0.02$

DM Production Mechanism (3 → 2 parameters)
- Freeze-out
- Freeze-in
- Other
- Undefined (3 parameters)

DM Particle Identity
- Real scalar and Majorana fermion has velocity suppressed freeze-out, direct detection and indirect detection processes
- Not directly relevant at LHC, but important when comparing with other searches or using production as constraint

Main LHC channel:



Two (SF) OS leptons + MET

(Also one lepton + MET in LH models from $W^{\pm} \to \phi^0\phi^{\pm}$)

Mass Regimes:
- Decoupled: $\Longrightarrow$ hard leptons
- Coannihilation: $\Longrightarrow$ soft leptons (ISR boost?)
- Quasi-degenerate and small couplings: $\Longrightarrow$ long-lived mediator

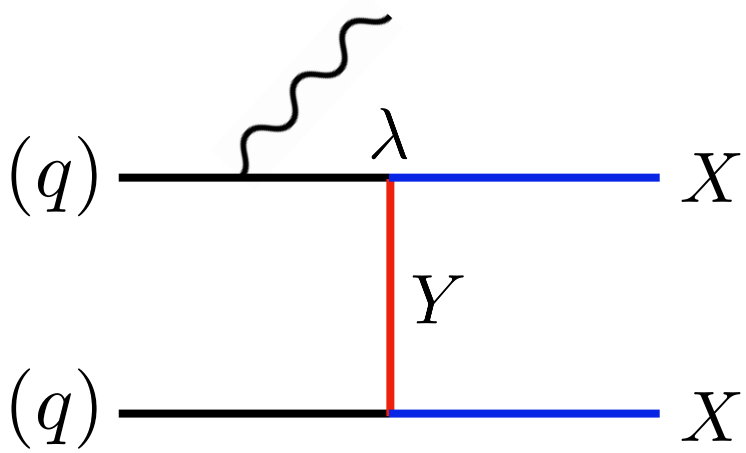
Status

- Classification complete
- Benchmark models defined
- Completing work on combining existing limits and relic surfaces

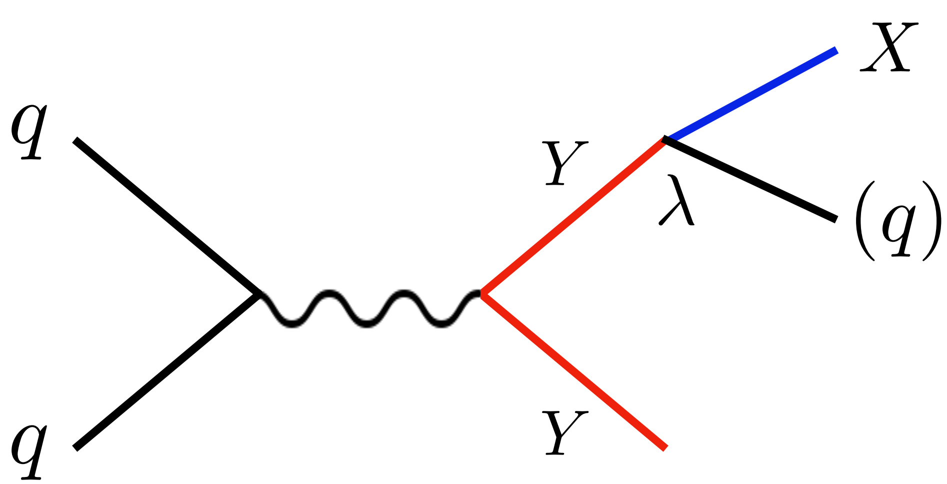
Long-lived mediators

contribution by J. Heisig

Why long-lived particles (LLPs)?



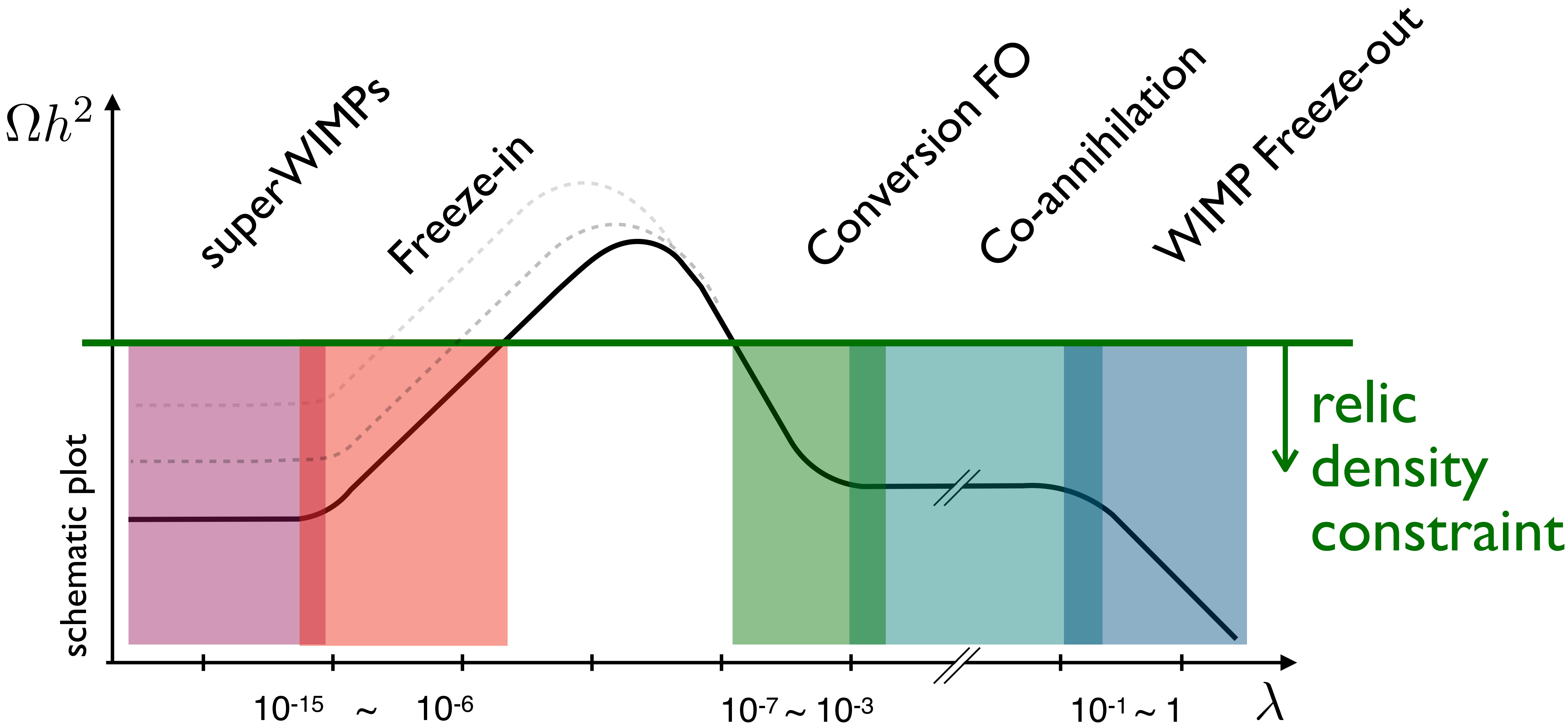
$\Rightarrow$ MET signature



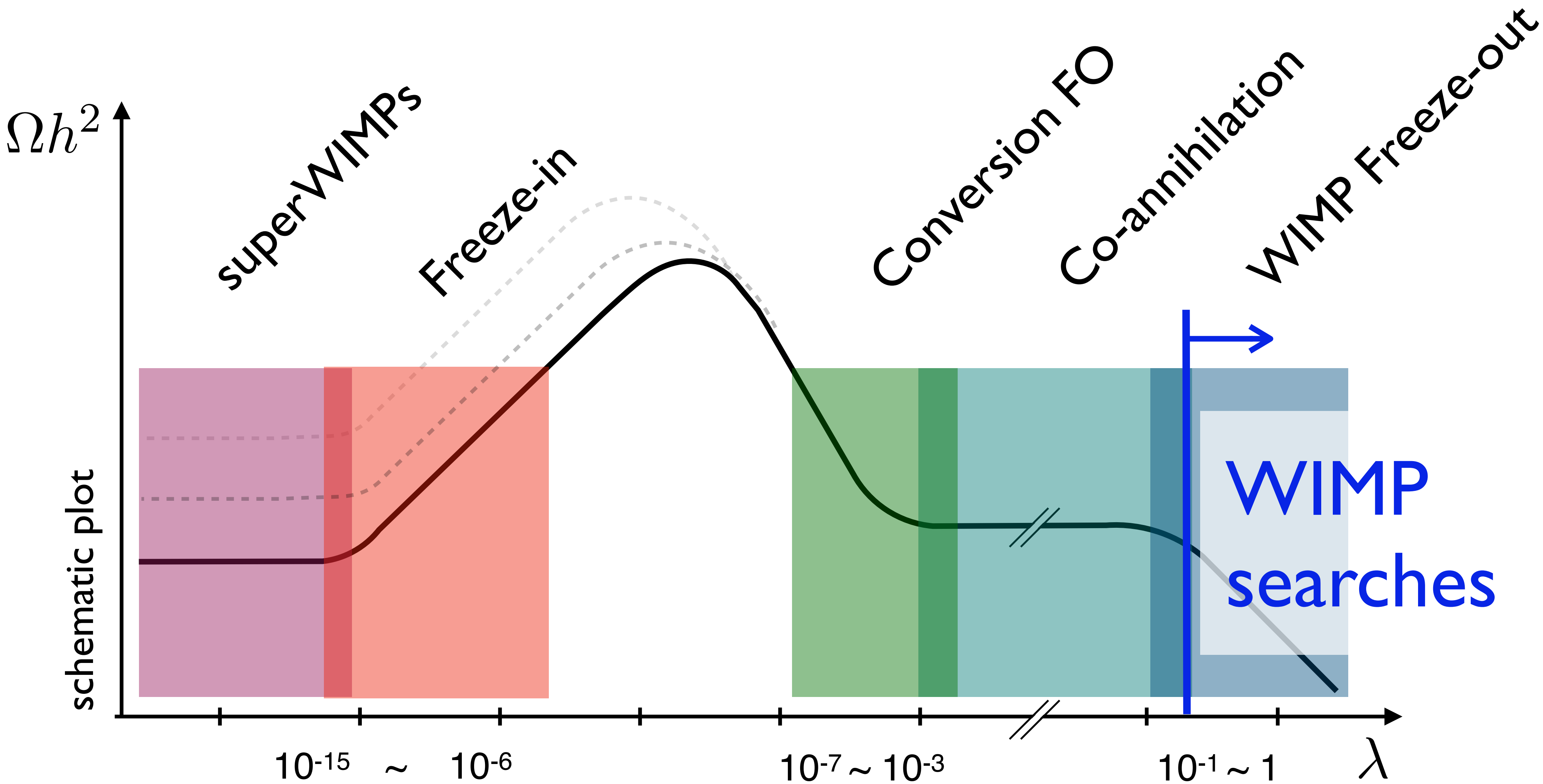
$\Rightarrow$ LLPs if:

- λ small or/and
- Small mass splitting, in particular:
  $\Delta m = m_Y - m_X < m_{(q)}$

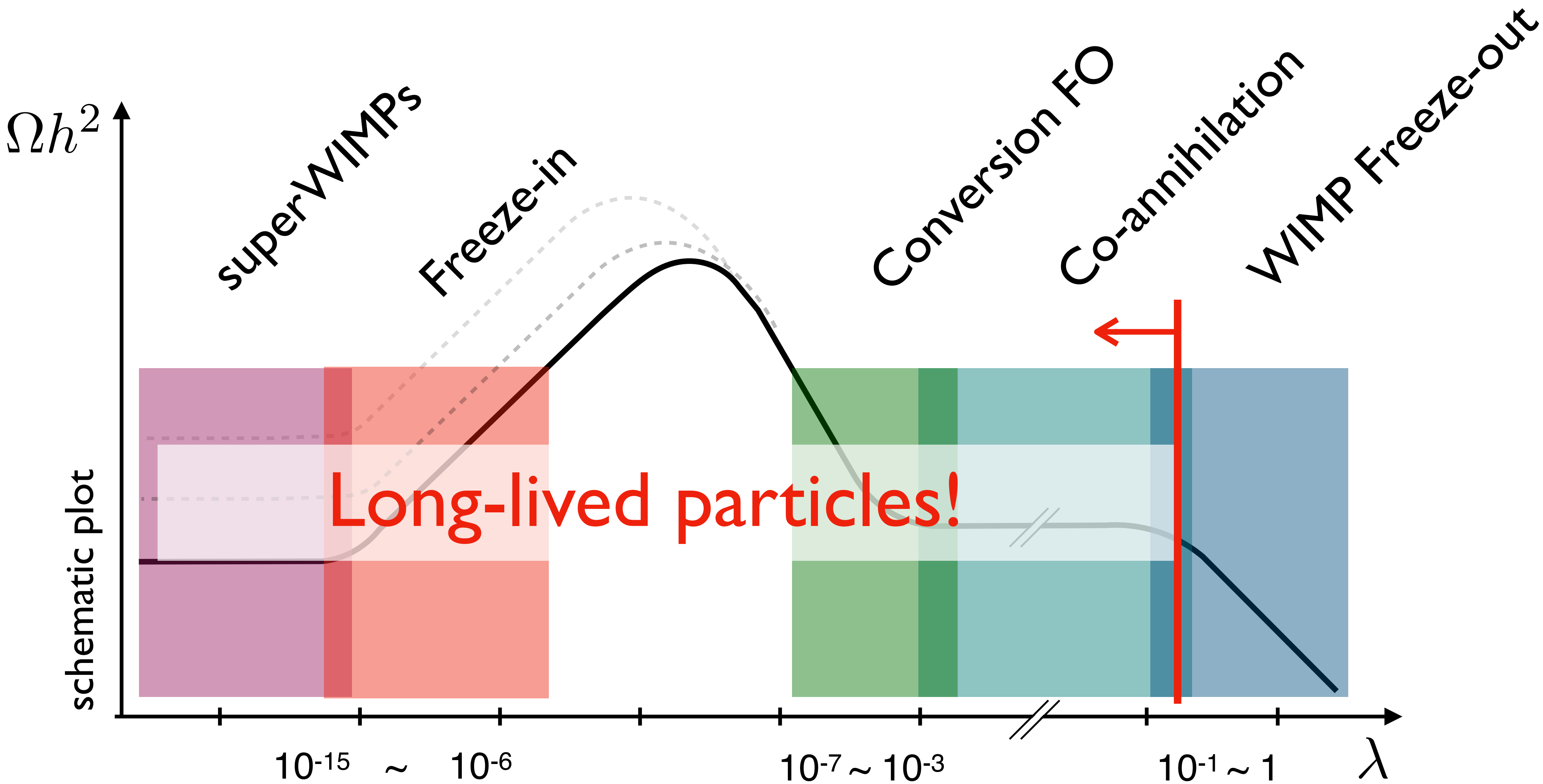
Range of dark matter couplings



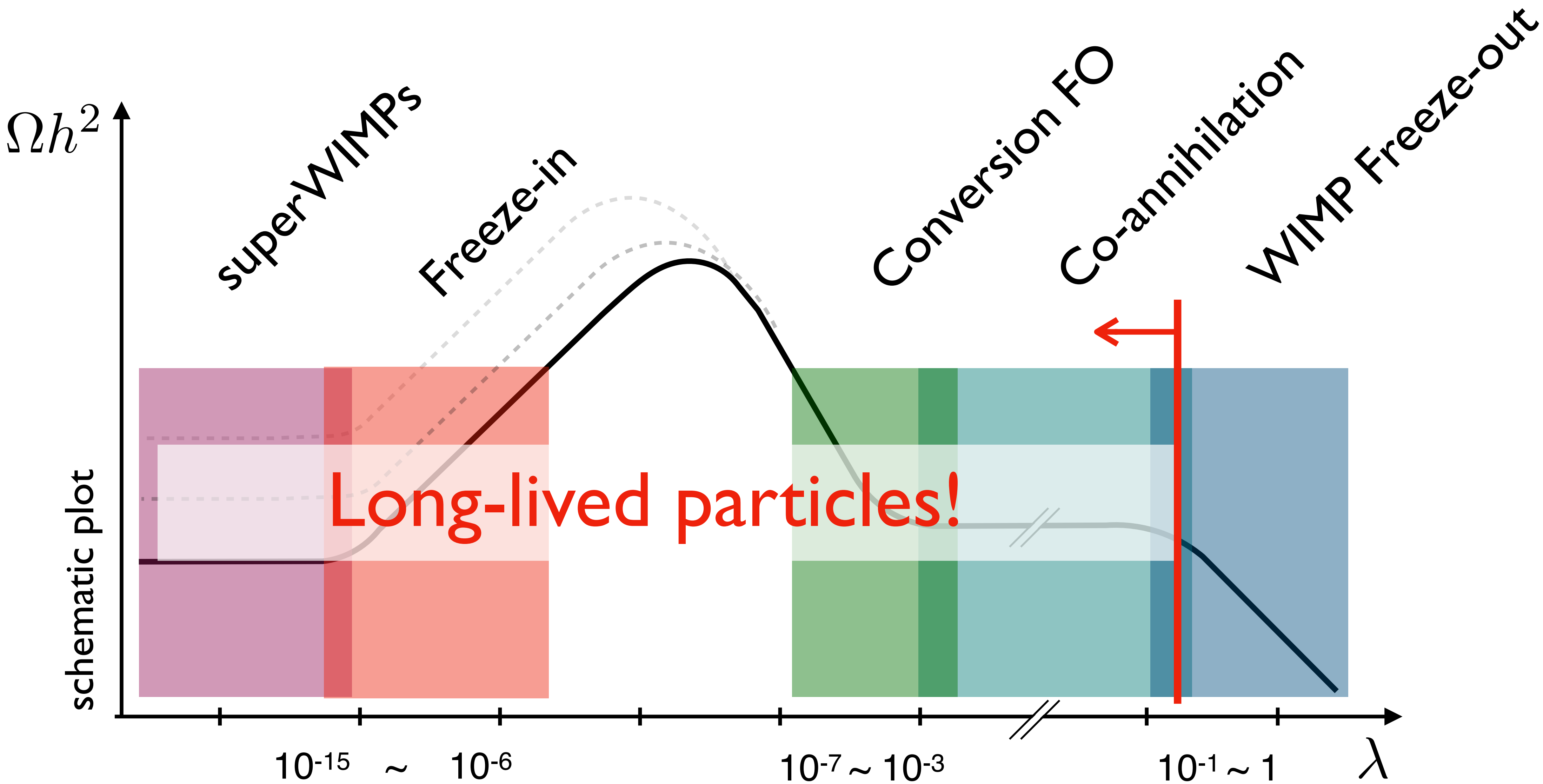
Range of dark matter couplings



Range of dark matter couplings

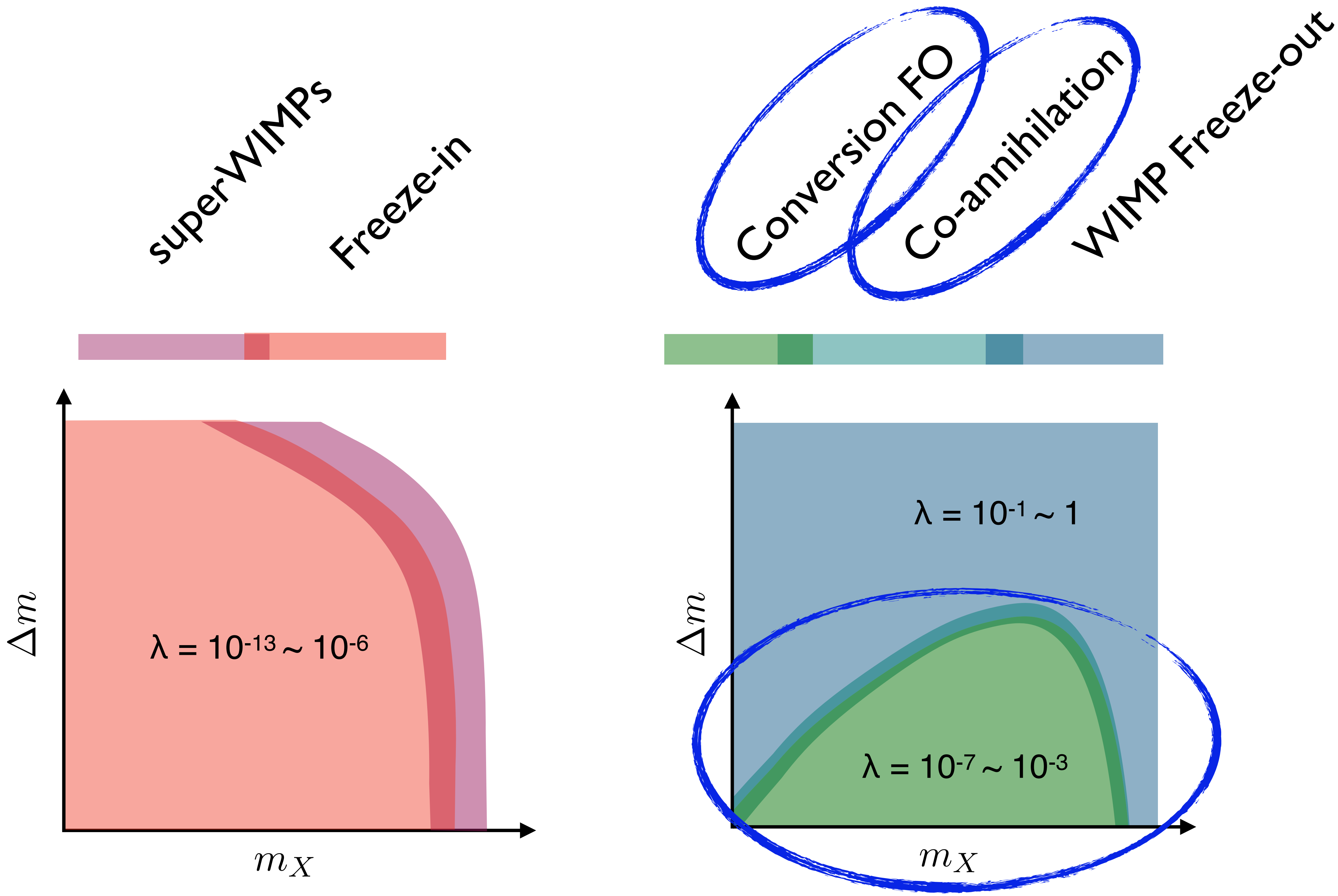


Range of dark matter couplings



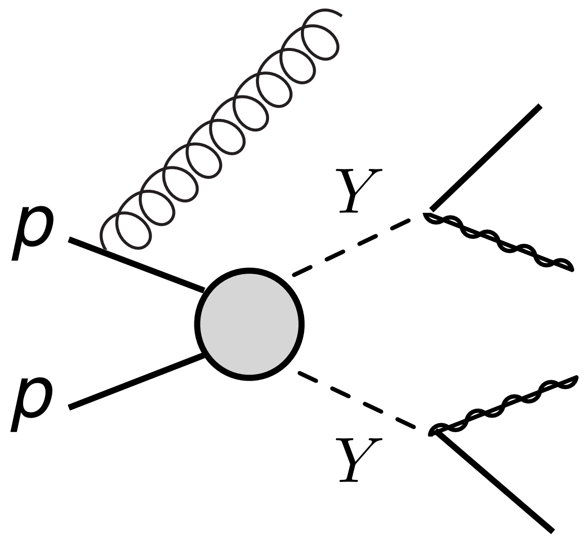
Small mass splittings?

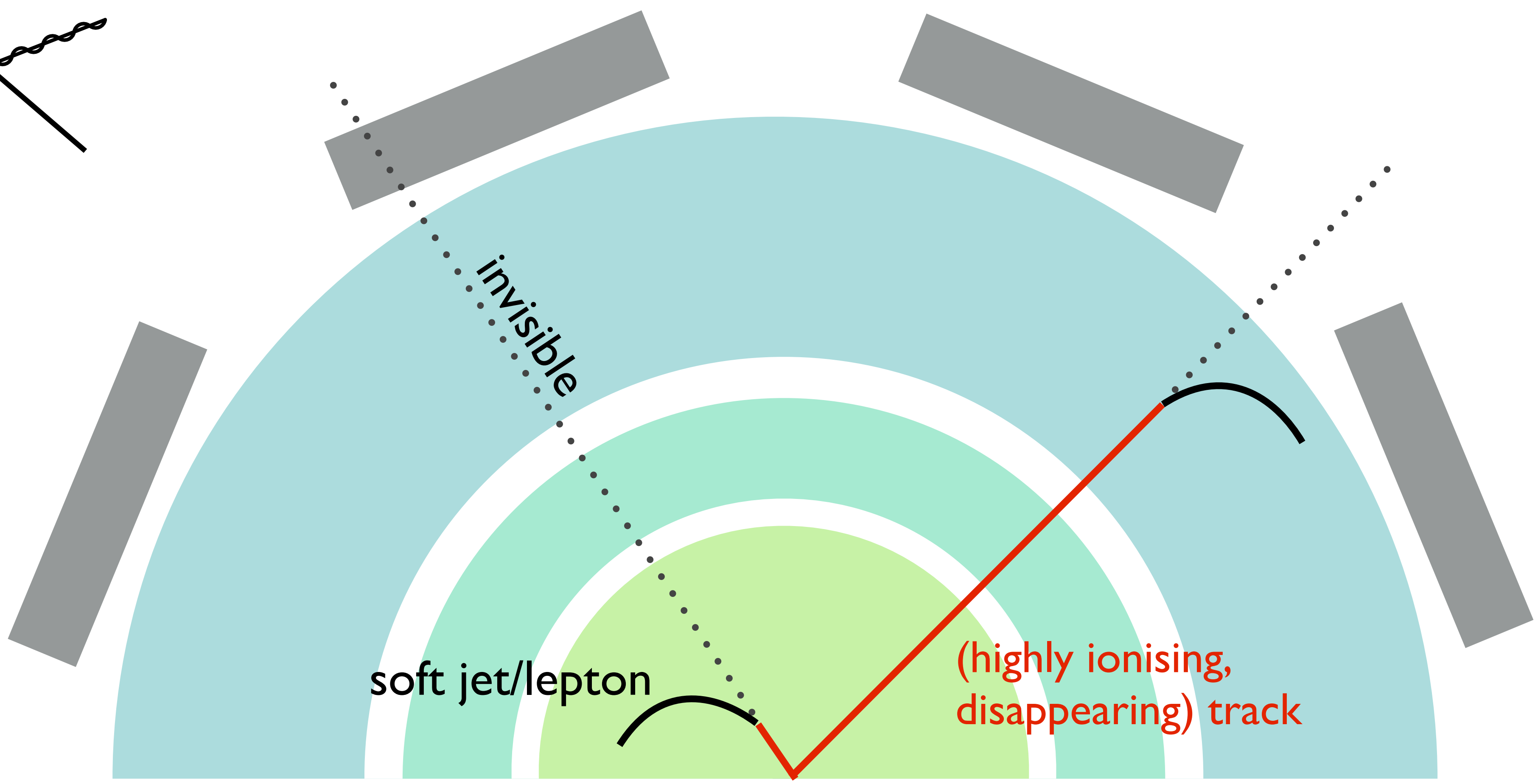
Range of dark matter couplings



LLP Signatures: small mass splitting

(Conversion FO, Co-annihilation)

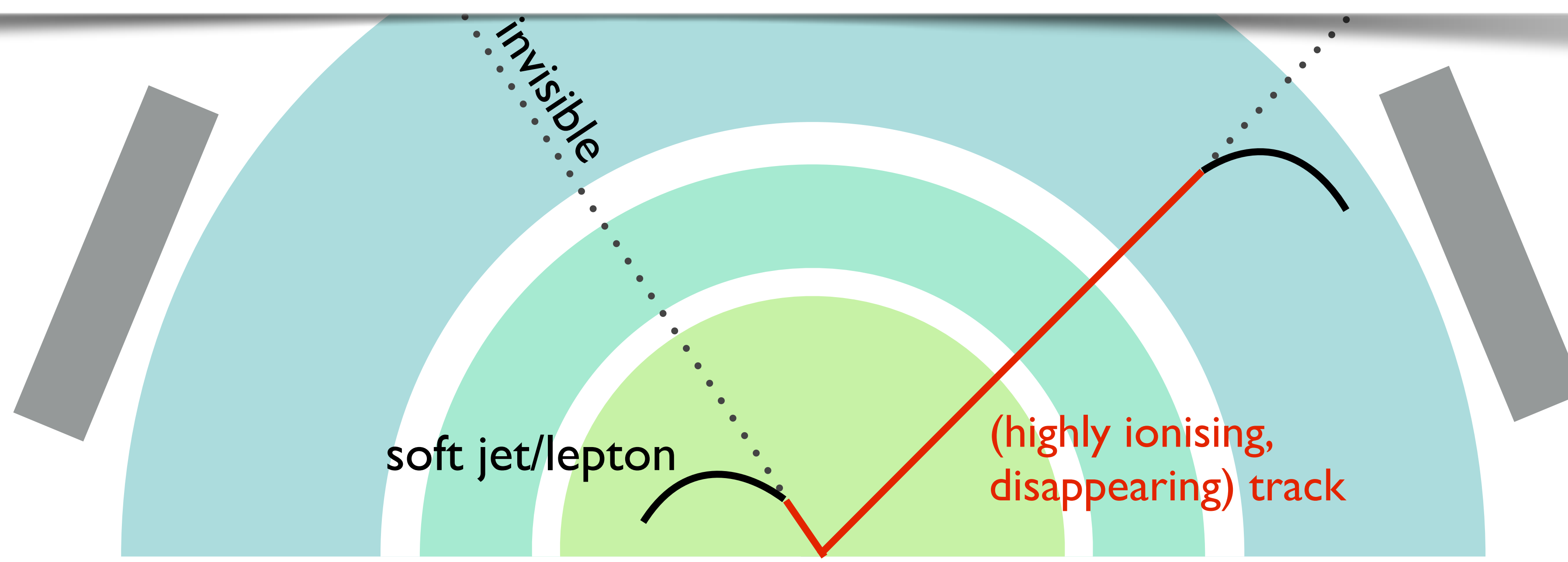




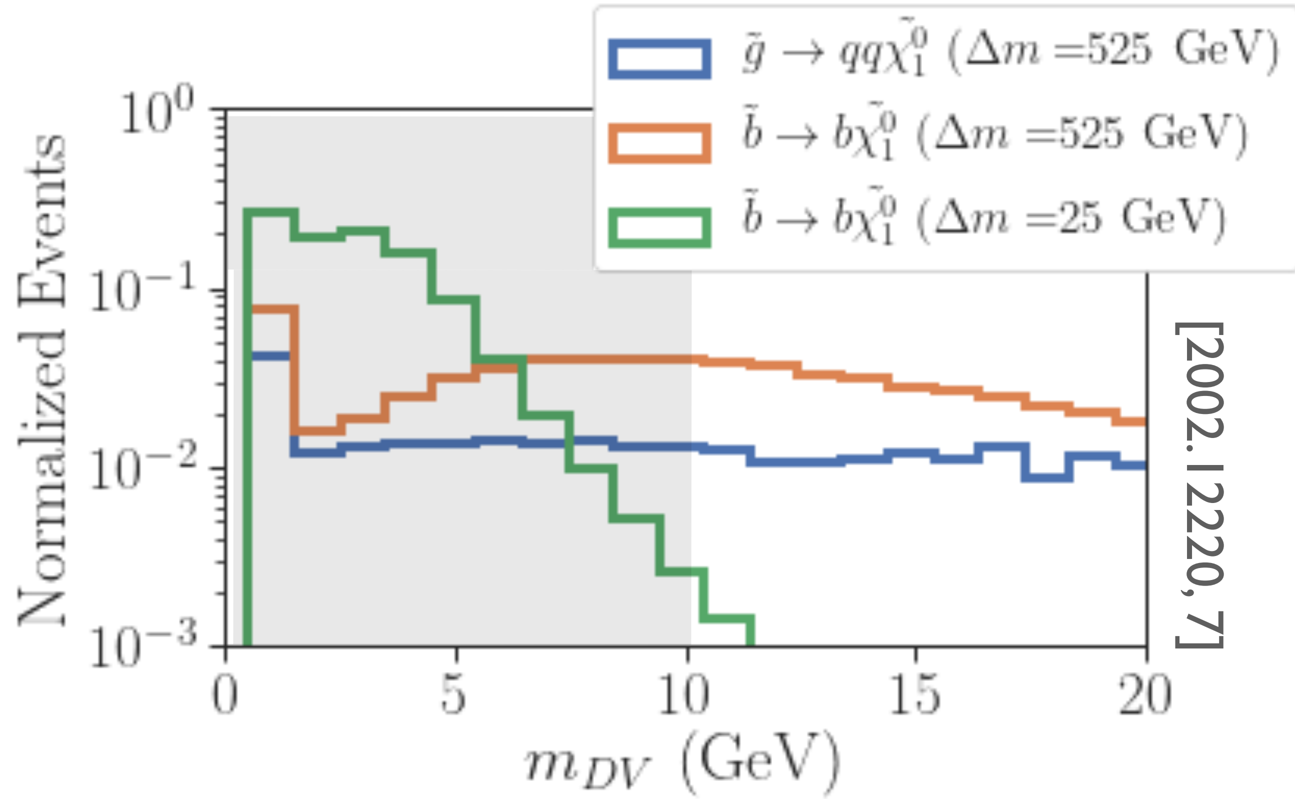
LLP Signatures: small mass splitting

Closing experimental gaps:

- How far do MET searches cover LLP regime? (transition prompt-LLP)
- How to tackle small mass splittings, i.e. softish displaced objects?

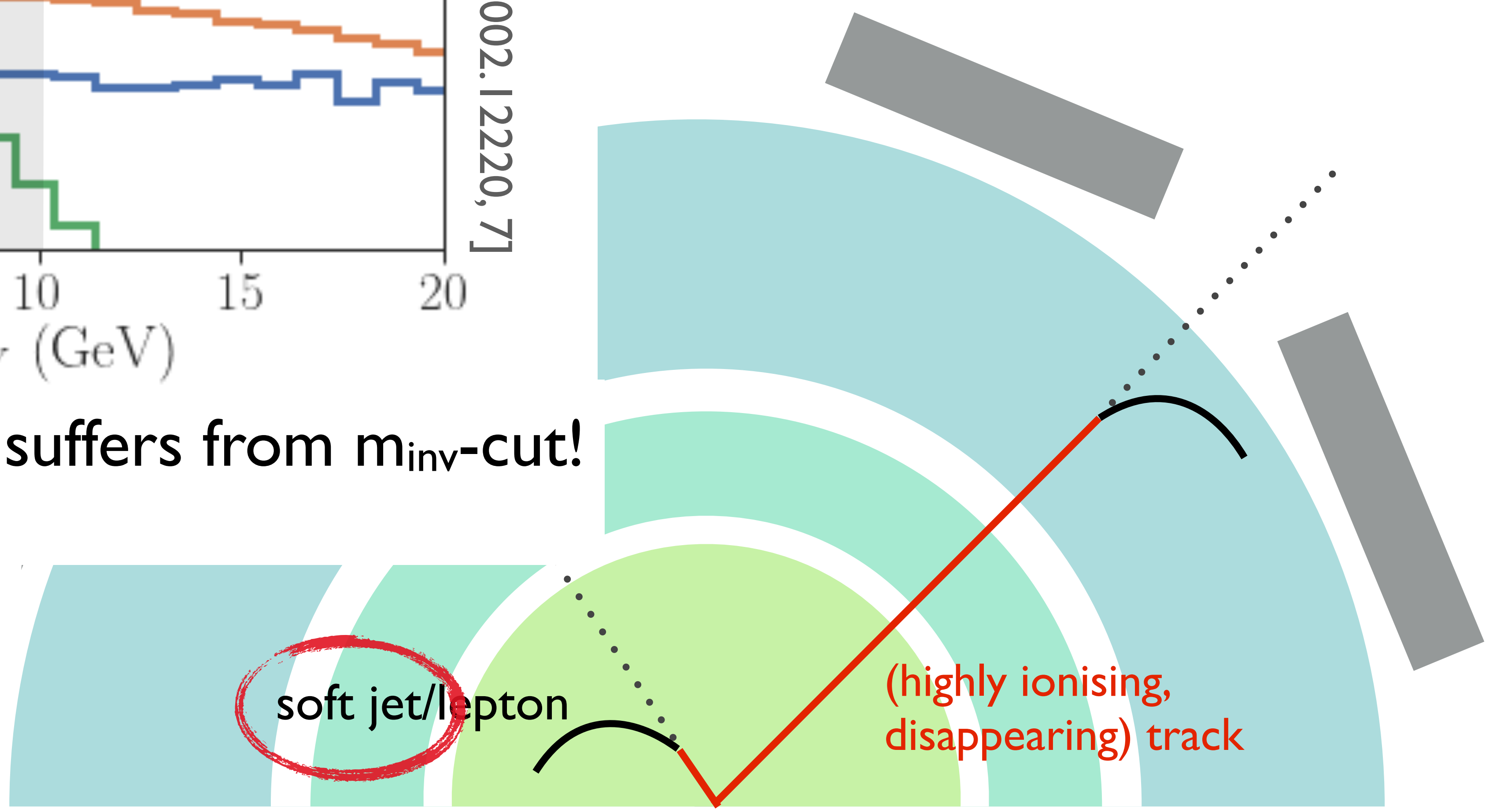


LLP Signatures: small mass splitting



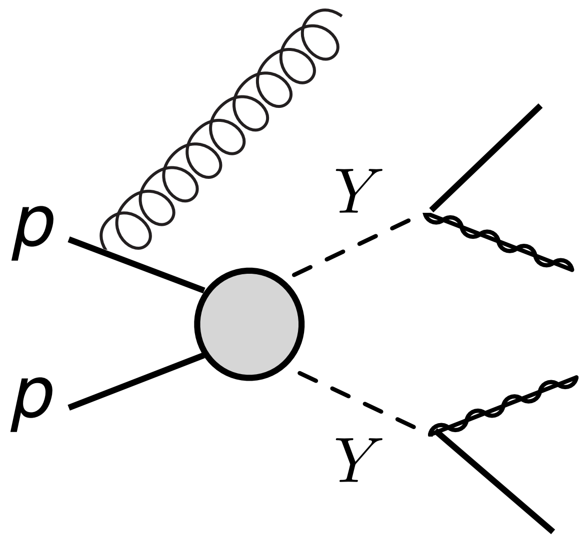
- Displaced jets+MET suffers from m_{inv}-cut!

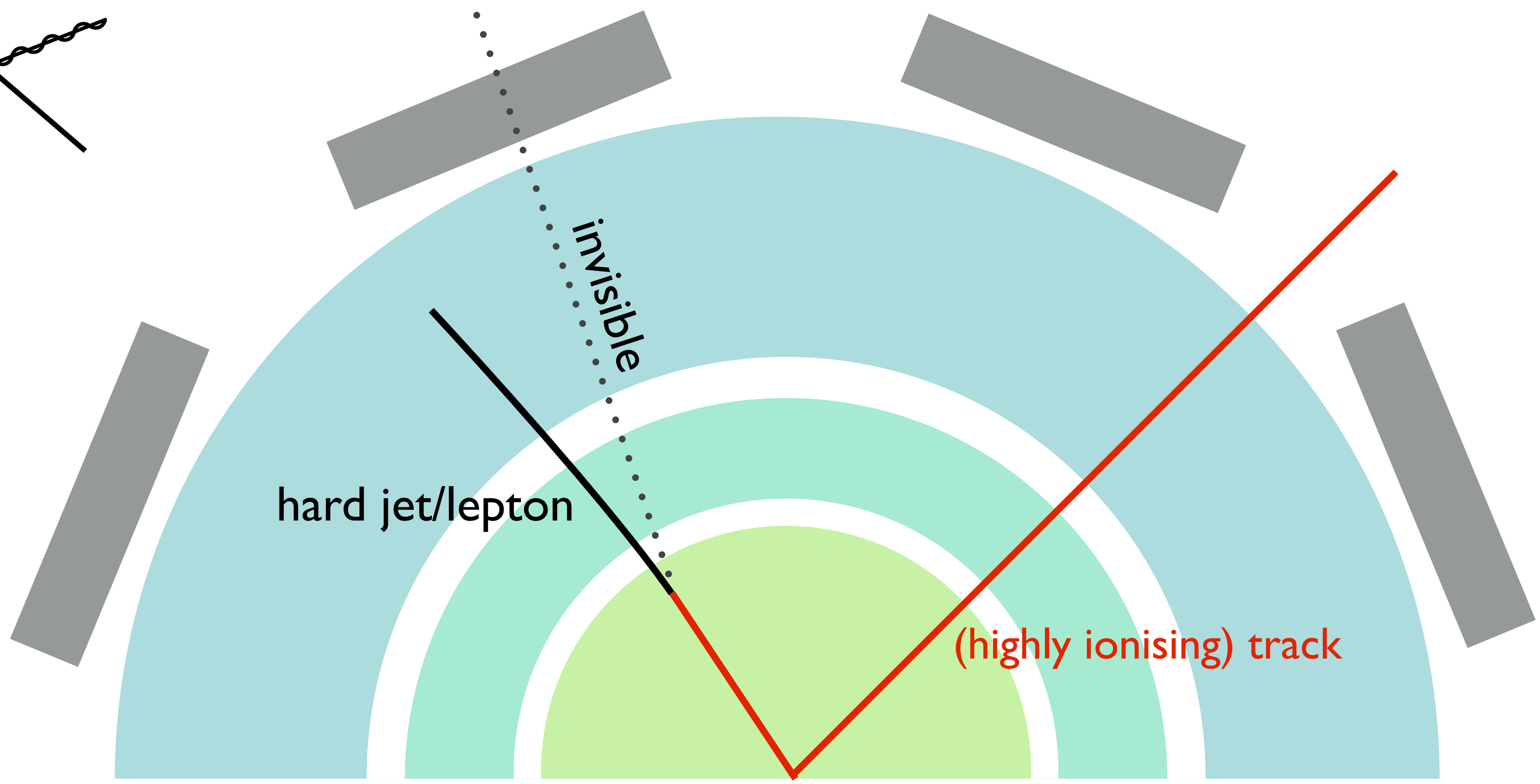
[ATLAS, 1710.04901]



LLP Signatures: light dark matter

(superWIMPs, Freeze-in)





Going beyond the minimal setup

contribution by A. Cornell

Subsection 8.1

Top-philic composite dark matter

- Top-philic scalar DM models represent very simple, testable and viable models of WIMP DM:
  [S.W. Baek, P. Ko, P. Wu (2016)],[Colucci, Fuks, Giacchino etal. (2018)]
  - very few new particles and parameters
    (one DM scalar *S* and a vector-like fermion mediator *T*),
  - renormalizable,
  - simple cosmology (thermal relic, standard evolution),
  - testable in DM direct detection, indirect detection (photons), and at colliders.

- VLQs which primarily couple to the SM top quark are common in many SM extensions (extra dimensions, little Higgs, twin Higgs, VLQ extensions of SUSY, Composite Higgs Models ….)

- If *S* and *T* are part of a UV completion with additional states/dynamics at typical scale Λ (of a few TeV), integrating out the additional states induces higher-dimensional operators in the top-philic scalar DM Lagrangian.

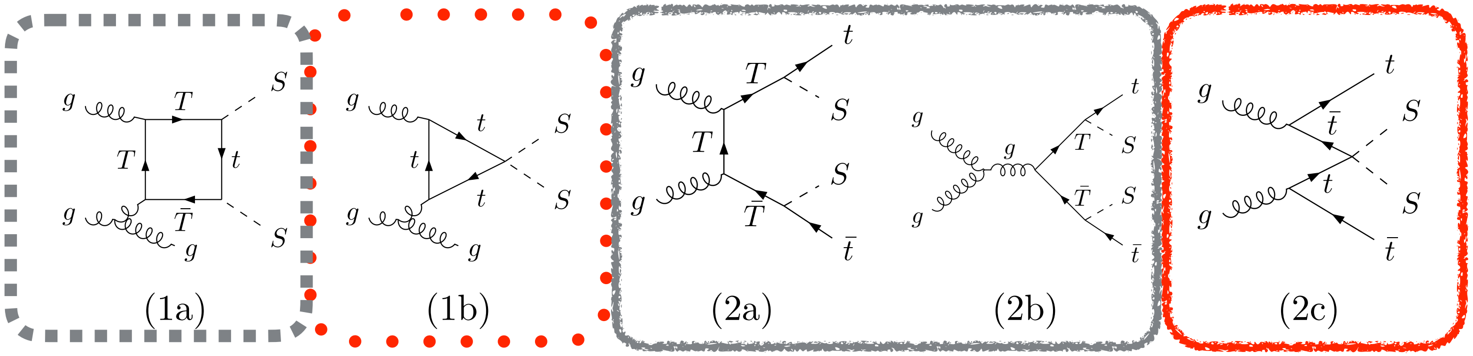
$$\mathcal{L} = i\bar{T}\not{D}T - m_T\bar{T}T + \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{1}{2}m_S^2 S^2 + \left[\tilde{y}_t S\bar{T}P_R t + h.c.\right] + \frac{1}{2}\lambda S^2\phi^\dagger\phi + \frac{C}{\Lambda}SSt\bar{t}.$$

top-philic DM

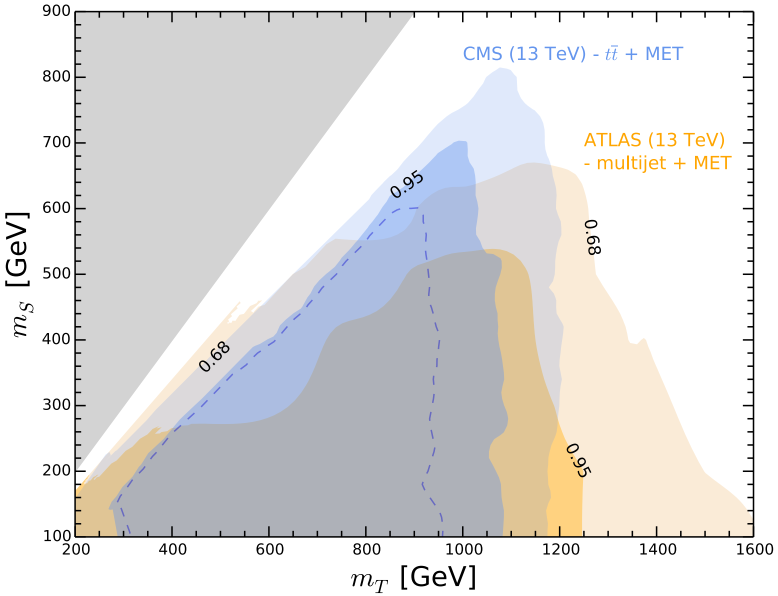
new !

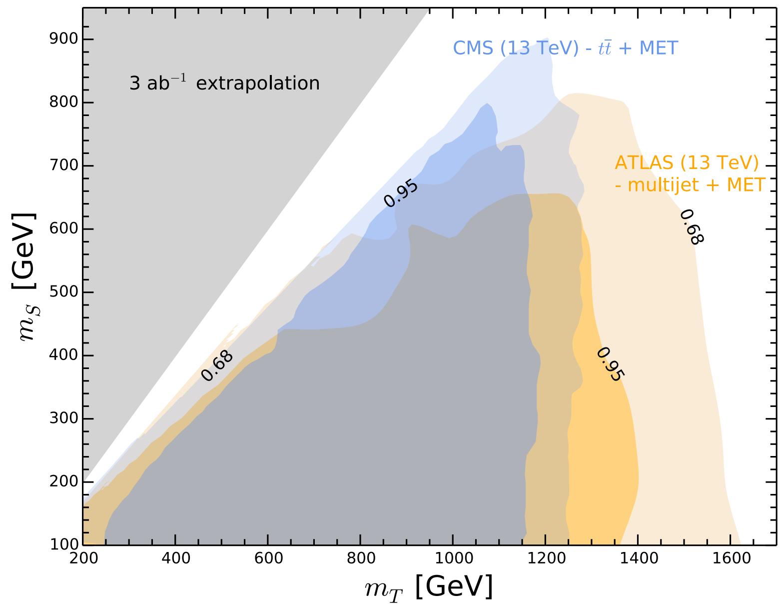
3 (+1) +1 parameters

small cross *dominant* *subdominant*



... but since [Colucci, Fuks, Giacchino et al. (2018)], new searches are available so we at least update collider





Sub-section 8.2

Frustrated dark matter models

- All mediator fields couple both to χ and to SM fields

  carry SM gauge charges that preclude renormalizable gauge-invariant interactions between the DM and any SM fermion.

- Interactions of the DM are ***frustrated*** in the sense that the specific mediator assignments preclude its tree level interaction with the SM

$$\text{SM} \longleftrightarrow \text{mediators} \begin{Bmatrix} \varphi \ (\text{scalar}) \\ \psi \ (\text{Dirac}) \end{Bmatrix} \longleftrightarrow \text{DM } \chi$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{med}} + \mathcal{L}_{\chi},$$

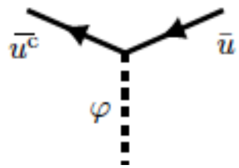
$$\mathcal{L}_{\text{med}} = (D_\mu \varphi)^{\dagger s} (D^\mu \varphi)_s - m_\varphi^2 \varphi^{\dagger s} \varphi_s + \bar{\psi}^s (\mathrm{i} \not{D} - m_\psi) \psi_s + \mathcal{L}_{\text{decay}}$$

$$\mathcal{L}_\chi = \bar{\chi}(\mathrm{i}\not{\partial} - m_\chi)\chi + y_\chi(\varphi^{\dagger s} \bar{\chi} \psi_s + \text{H.c.})$$

Sextet Mediators

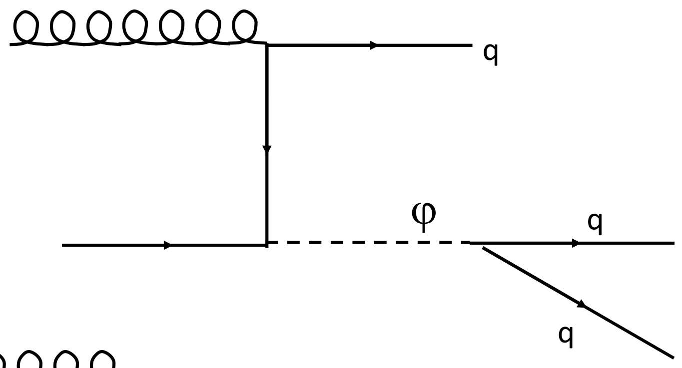
Field	Description	$SU(3)_c \times SU(2)_L \times U(1)_Y$ representation	Couples to SM?
χ	Dark matter	$(\mathbf{1}, 1, 0)$	
φ	Scalar mediator	$(\mathbf{6}, 1, \frac{4}{3})$	✓
ψ	Dirac mediator	$(\mathbf{6}, 1, \frac{4}{3})$	

$$\mathcal{L}_{\rm decay} = \lambda_{IJ} K_s{}^{ij}\, \varphi^{\dagger s} \overline{q^c_{\rm R}}_{Ii} q_{{\rm R}Jj} + {\rm H.c.} \quad \text{with} \quad q \in \{u, d\},$$

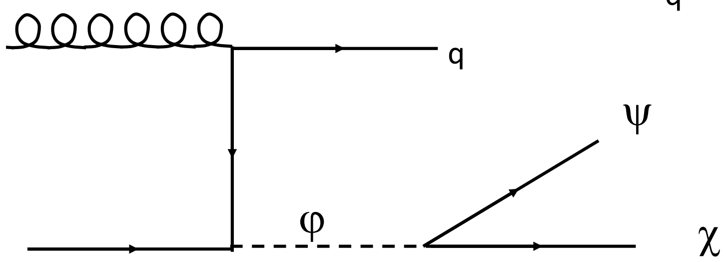


$Y = 4/3.$

T channel Single Mediator Production

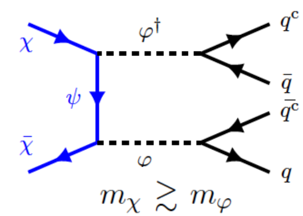


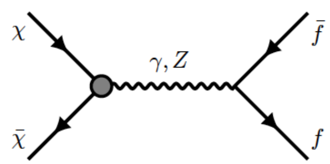
Quark pair

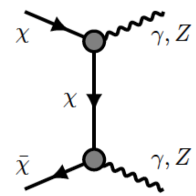


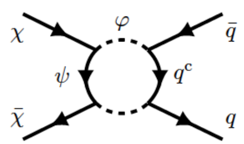
Cascade decay

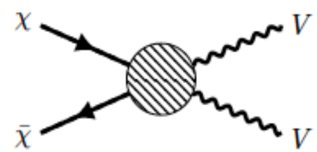
DM annihilation channels











Sub-section 8.3

B-mesogenesis models

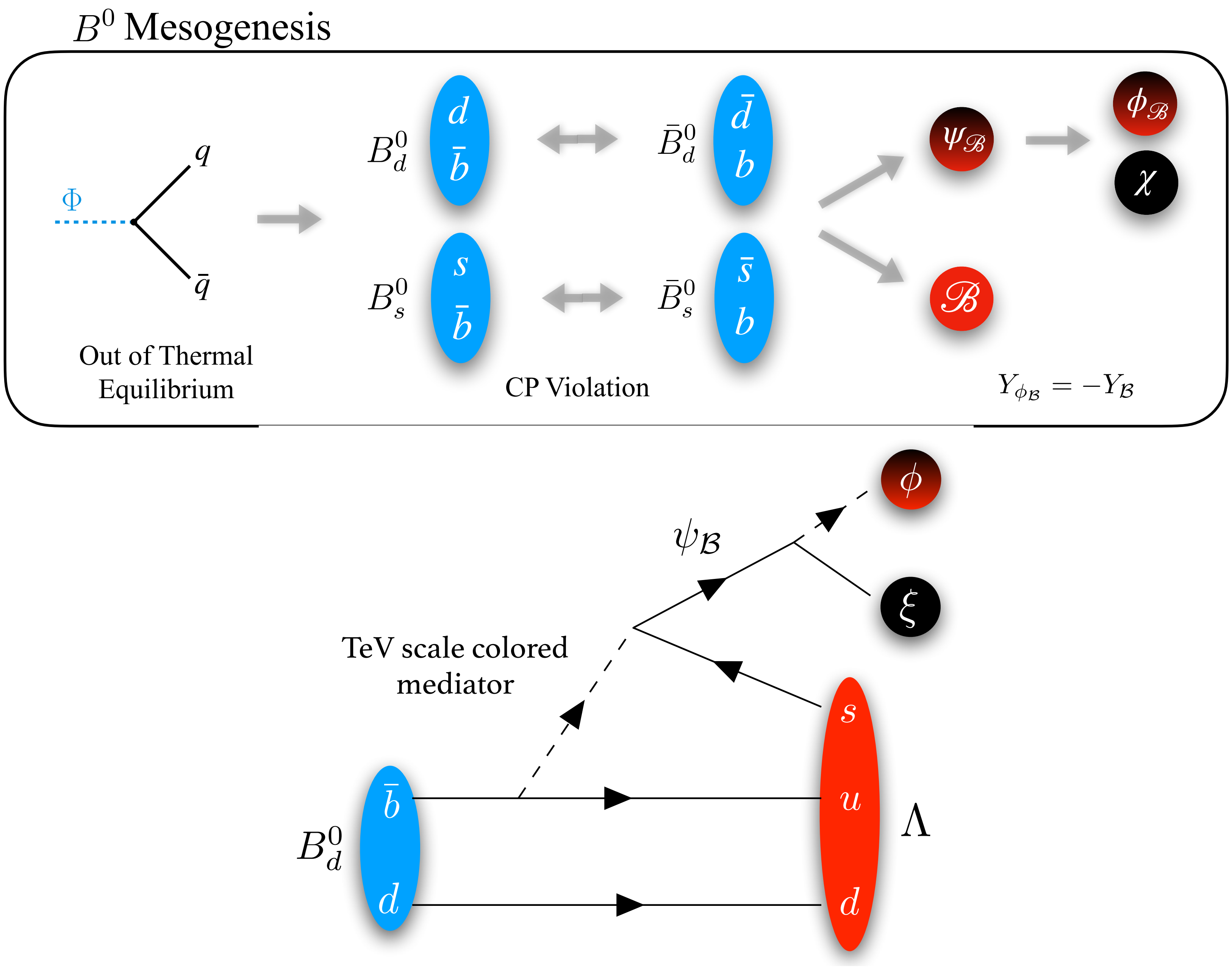
- Mesogenesis is a recent experimentally testable mechanism of baryogenesis and dark matter production which utilizes CP violation in Standard Model mesons

- In the Mesogenesis mechanism, a scalar field Φ with a mass of 10 to O(100 GeV) decays at a low temperature $T_R \sim$O(MeV) to equal numbers quarks and anti-quarks pairs.

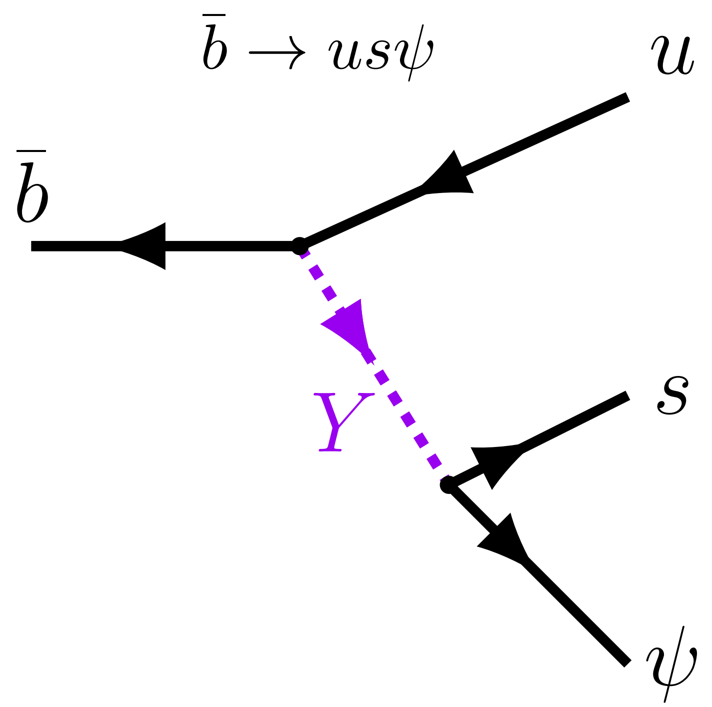
- Critical to the setup of these mechanisms is a t-channel coloured scalar mediator which mediates the decays of mesons in to dark sector baryons

- In neutral B mesogenesis, the CP violation of $B^0_{s,d}$–$\bar{B}^0_{s,d}$ is leveraged

$$\mathcal{L}_Y = \sum_{i,j} Y^* \bar{u}_{i,R} d^c_{j,R} - \sum_k y_{\psi_{\mathcal{B}} k} Y d^c_{kR} \psi_{\mathcal{B}} + \text{h.c.}$$



B^0 Mesogenesis
Φ
q
$\bar{q}$
Out of Thermal Equilibrium
B_d^0
d
$\bar{b}$
$\bar{B}_d^0$
$\bar{d}$
b
B_s^0
s
$\bar{b}$
$\bar{B}_s^0$
$\bar{s}$
b
CP Violation
$\psi_{\mathscr{B}}$
$\phi_{\mathscr{B}}$
χ
$\mathscr{B}$
$Y_{\phi_{\mathcal{B}}} = -Y_{\mathcal{B}}$
ϕ
$\psi_{\mathcal{B}}$
ξ
TeV scale colored mediator
B_d^0
$\bar{b}$
d
s
u
d
Λ



Y: Colored Triplet Scalar

$$Y \sim (3, 1, -1/3)$$

$$Y \sim (3, 1, 2/3)$$

Same Quantum Numbers as a SUSY squark!

$$\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \simeq 10^{-3} \left(\frac{m_B - m_\psi}{2\,\mathrm{GeV}}\right)^4 \left(\frac{1.6\,\mathrm{TeV}}{M_Y} \frac{\sqrt{y_{ub} y_{\psi s}}}{0.6}\right)^4$$

Perturbativity requires: $M_Y < 10\,\mathrm{TeV}$

Conclusion

Intensive work in progress on multiple fronts

Person-power (especially from the EXP side) would be appreciated

Contact the coordinators if anyone can help with any section