Top and dark matter

Top LHC France meeting
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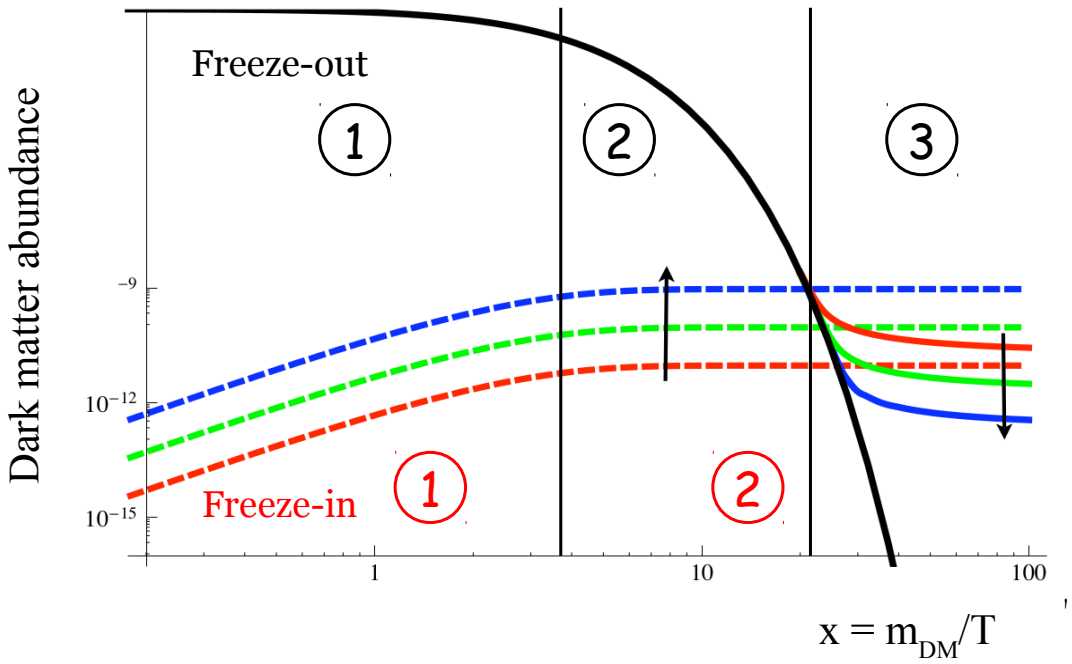
Outline

- The top quark and dark matter physics
- Simplified descriptions
- Phenomenology

Reminder: the DM abundance

Evolution of dark matter abundance with time

L. J. Hall *et al*, arXiv:0911.1120



Freeze-out:

(strong enough DM-SM interactions)

1. DM + DM ↔ SM + SM efficient in both directions.
2. DM + DM ← SM + SM disfavoured.
3. $n_{DM} \langle\sigma v\rangle < H$: Equilibrium lost → Freeze-out.

Freeze-in:

(feeble DM-SM interactions)

1. Negligible initial density, DM produced from decays/annihilations of other particles.
2. DM production disfavoured → Freeze-in

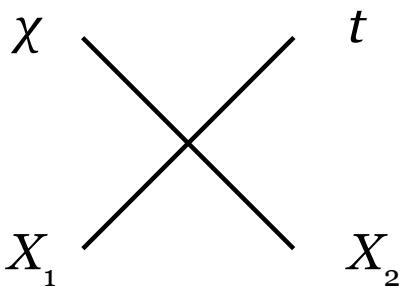
What about the top quark?

There is no obvious connection between top and dark matter physics. However:

If dark matter couples non-gravitationally to the Standard Model, odds are it does so to top quarks. This coupling could be the dominant one.

What could the DM-SM interactions look like? Consider an interaction as:

$$\chi\ (Z_2\text{-odd}) - X_1\ (Z_2\text{-odd}) - t\ (Z_2\text{-even}) - \underbrace{X_2\ (Z_2\text{-even})}_{\text{Optional}}$$



- If $X_2 = t$, then X_1 is needed. Only realizable at an "effective" level.

  In the sense of "indirect" couplings

- If $X_2 \neq t$, then X_1 is needed. Only realizable at an "effective" level.

- If X_2 is absent, then X_1 must carry SM charges.

  "Direct" couplings

s-channel portals

Coupling indirectly to top quark pairs: scalar Higgs-like portals

$$\mathcal{L}_{\rm DS} = \frac{1}{2}(\partial^\mu A)(\partial_\mu A) - \frac{m_A^2}{2}A^2 + \frac{1}{2}\bar{\chi}\left(i\partial - m_\chi\right)\chi - i\frac{y_\chi}{2}A\bar{\chi}\gamma_5\chi$$

$$\mathcal{L}_{\rm f} = -i\sum_{f_u} c_u \frac{m_{f_u}}{v} A\bar{f}_u\gamma_5 f_u - i\sum_{f_d} c_d \frac{m_{f_d}}{v} A\bar{f}_d\gamma_5 f_d$$

Considering pseudoscalar interactions to avoid direct detection constraints.

· MFV – type couplings → DM dominantly interacting with top quarks.

· In a type-2 2HDM model, we'd have $c_u = \cot\beta$ and $c_d = \tan\beta$.

b-dominated scenario also possible

· The Lagrangian also induces interactions with gluons/photons at 1-loop

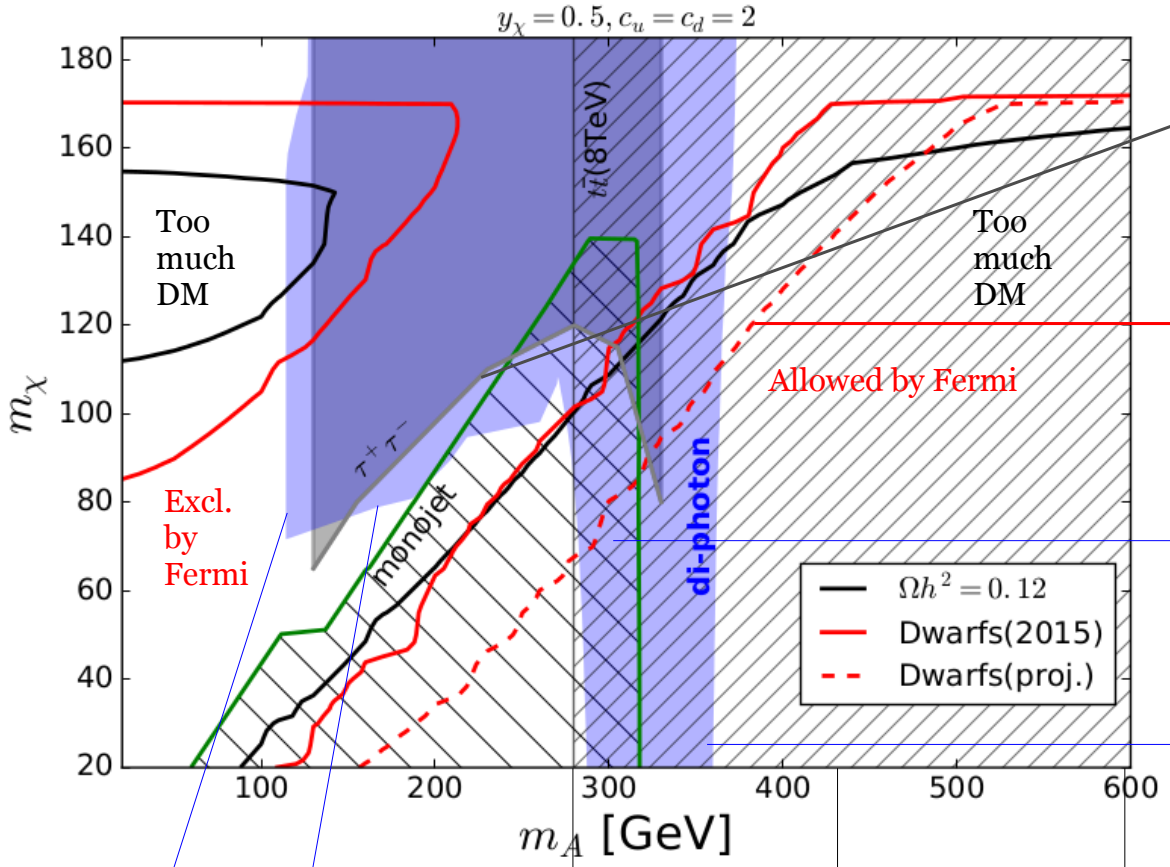
$$\mathcal{L}_{Agg/A\gamma\gamma} = \frac{\alpha}{4\Lambda_\gamma}A\tilde{F}_{\mu\nu}F^{\mu\nu} + \frac{\alpha_s}{4\Lambda_g}A\tilde{G}_{\mu\nu}G^{\mu\nu}$$

LHC DM production driven by top quark

· Vector portals tend to couple more "democratically" to the SM fermions.

Constraints on *s*-channel portals

Let's fix the couplings and vary the masses



Inv. decays dominate

Eventually Fermi will probe most of the parameter space for small enough m_A

Form-factor enhancement

tt decays dominate

+ ttA constraints subleading

Inv. decays dominate

tt cross section measurements @ 8 TeV

tt resonance searches @ 8 TeV

Diphoton BR suppressed + reduced LHC sensitivity

Dark matter searches are complementary!

Top-philic models - 1

Dirac fermion singlet coupled to RH top quarks through coloured/charged SU(2)-singlet scalar

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\chi}\ \partial\!\!\!/\chi - M_\chi \bar{\chi}\chi + (D_\mu\phi)^*\,(D^\mu\phi) - M_\phi^2\phi^*\phi + (g_{DM}\phi^*\bar{\chi}t_R + h.c.)$$

M. A. Gomez *et al*, arXiv:1404.1918
Flavour structure *e.g.* in M. Blanke, S. Kast, arXiv:1702.08457
Majorana variant *e.g.* in M. Garny *et al*, arXiv:1802.00814

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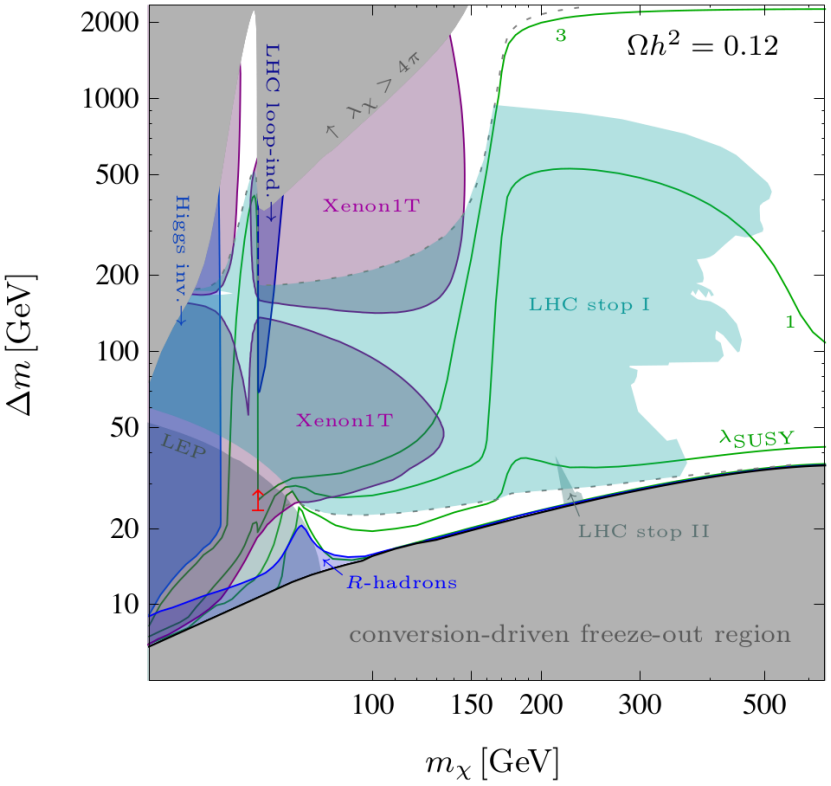


· Interesting cosmology, viable within freeze-out/conversion-driven freeze-out/freeze-in frameworks.

· Constraints from:

- direct detection
- stop searches
- monojets
- inv. Higgs decays
- R-hadron searches
- LEP stop searches

Mostly relevant for conversion-driven FO

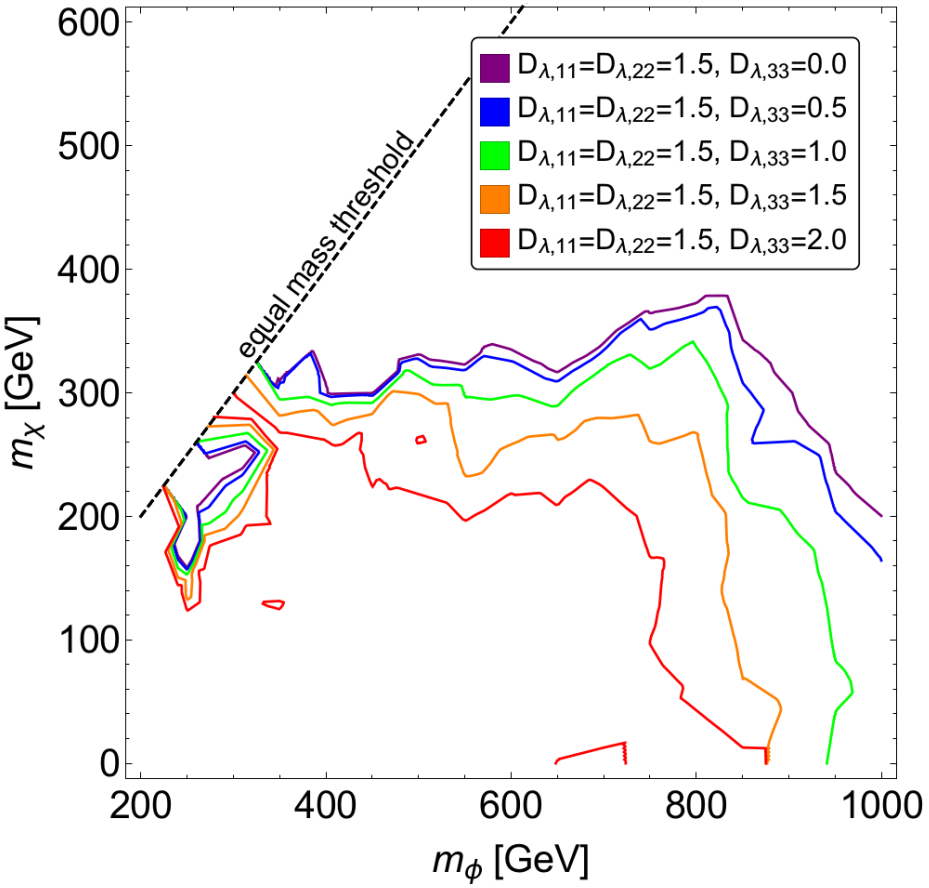
Top-philic models - 2

Dirac fermion triplet coupled to LH quarks through coloured/charged SU(2)-doublet scalar

$$\mathcal{L}_{\rm int} = -\lambda'_{ij}\bar{q}'_{Li}\chi_j\Phi + h.c.$$

M. Blanke *et al*, arXiv:1711.10493

M. Blanke *et al*, arXiv:1711.10493



· In this scenario DM couples to all six quark flavours.

· Constraints from:

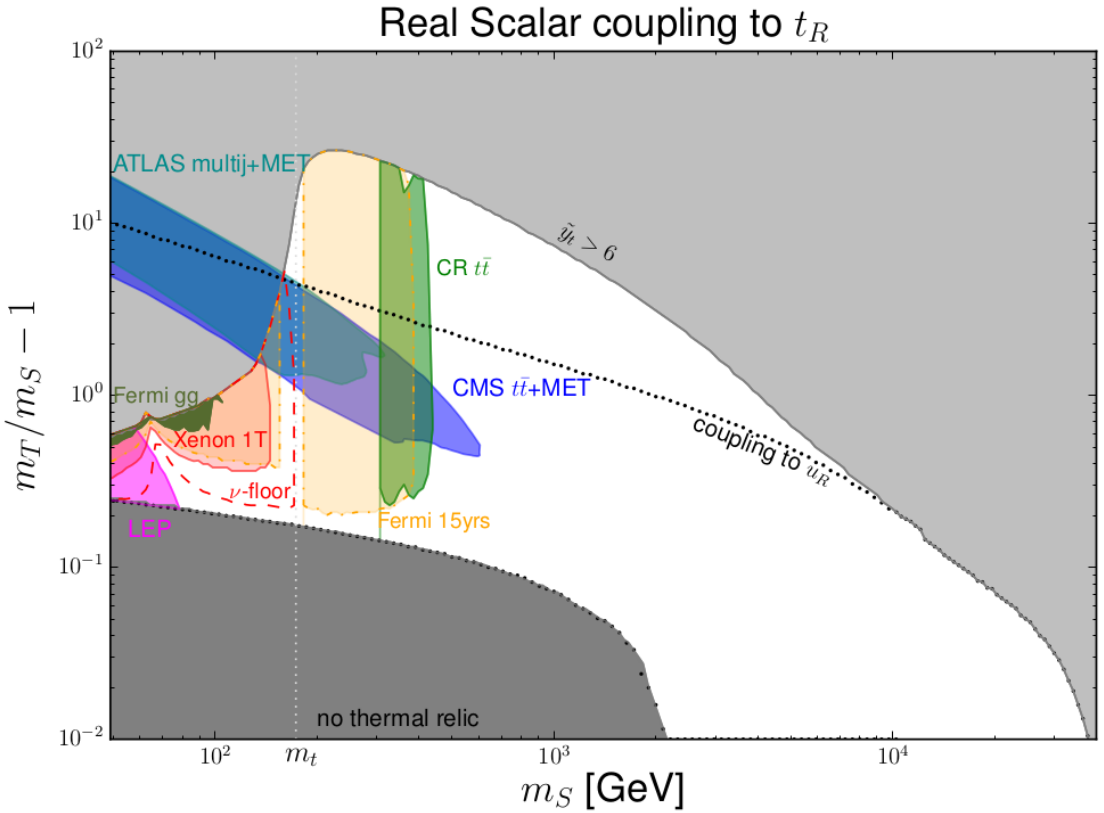
- jets + MET
- bb/tt + MET
- D/K/B meson mixing
- Direct detection
- Future: tb + MET

Top-philic models - 3

Scalar singlet coupled to RH top through vector-like SU(2)-singlet fermion top partner

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{T}\not{D}T - m_T\bar{T}T + \frac{1}{2}\partial_\mu S\partial^\mu S - \frac{1}{2}m_S S^2 + \left[\tilde{y}_t\, S\, \bar{T}P_R t + \text{h.c.}\right] - \frac{1}{2}\lambda S^2\Phi^\dagger\Phi$$

S. Colucci *et al*, arXiv:1804.05068



S. Colucci *et al*, arXiv:1804.05068

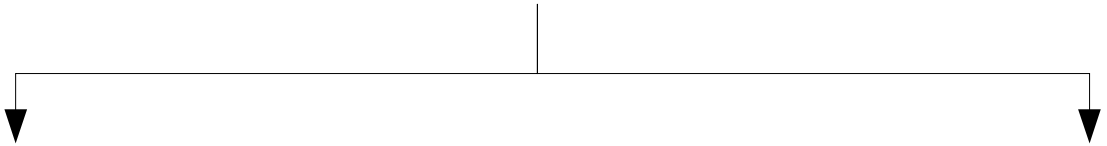
· Constraints from:

- (mono)jets + MET
- tt + MET
- Indirect detection (CR's, γ's)
- Direct detection
- LEP t-partner searches
- LHC t-partner searches

· Note that in the conversion-driven/freeze-in regimes (charged) LLP searches become highly relevant!

Summary

· The top quark can play an important role in dark matter phenomenology.



It can enter the dominant dark matter annihilation/production channels.

It can drastically affect the dark matter collider phenomenology.

… and it is perfectly possible to write down models where such effects take place.

· Top-related LHC measurements are crucial to probe *s*-channel models: tt total cross-section, searches for resonances, ttA(A → inv).

· Top partner searches (typically involving MET) probe top-philic DM models, whereas searches like tb + MET can shed light on potentially non-trivial flavour properties of the dark sector.

· Searches for LLPs such as R-hadrons can probe the opposite, more weakly coupled regime (conversion-driven/freeze-in scenarios).