Pseudoscalar-mediated dark matter models: LHC vs cosmology

Based on: S. Banerjee, D. Barducci, G. Bélanger, B. Fuks, A. G., B. Zaldivar, arXiv:1705.02327

Birmingham, 15/11/2017

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Outline

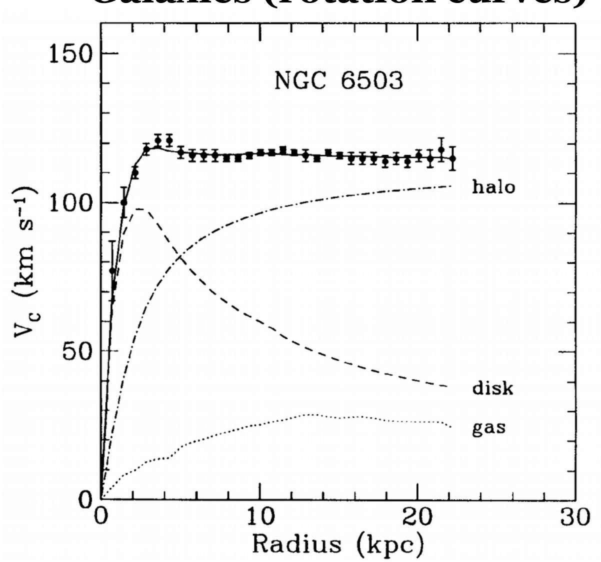
- What's special about pseudoscalar mediators?
- A simplified description
- Experimental probes
- Results
- Outlook

First things first : why dark matter

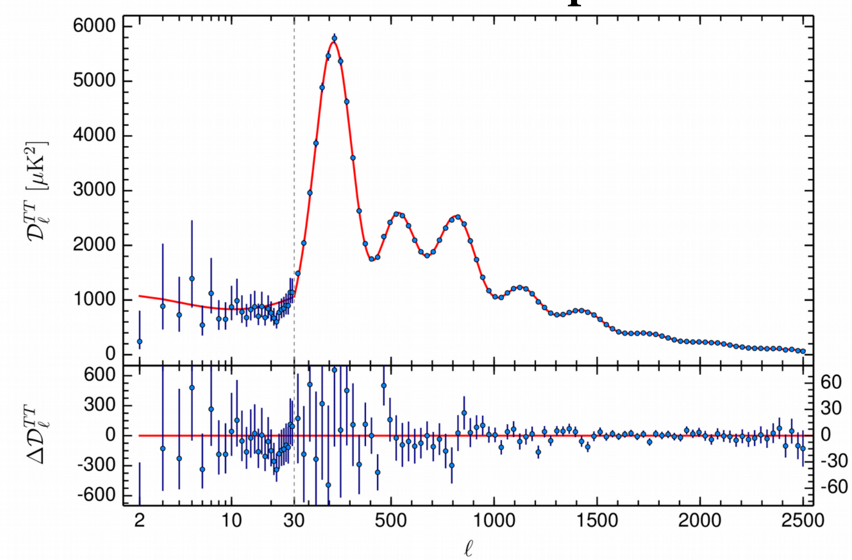
By now, the existence of Cold(-ish) Dark Matter (CDM) is pretty well-established.

Evidence at multiple scales

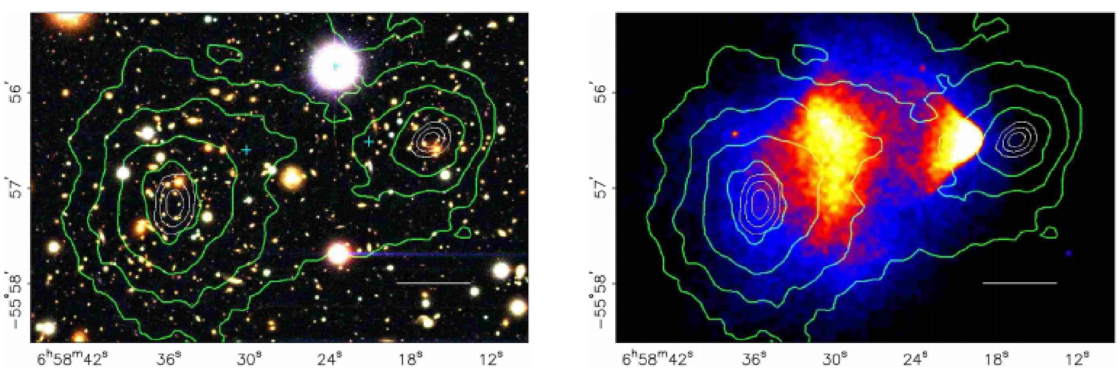
Galaxies (rotation curves)



CMB anisotropies



Galaxy clusters (X-ray spectroscopy VS lensing)



In a nutshell:

No known cosmological model can explain all these observations simultaneously, without introducing some amount of dark matter.

NB: Of course, this is not proof!

Pseudoscalars and dark matter physics

Pseudoscalars are very common in extensions of the Standard Model: 2HDM (incl. MSSM), Composite Higgs models, ALPs (incl. The QCD axion).

Essentially all SM extensions w/ complex scalar fields

They couple to fermions through interactions that look like: $\mathcal{L}_{\rm f} \sim A\bar{f}\gamma_5 f$

i.e. like the Higgs, but with a γ_5

What about dark matter physics? There is no *a priori* reason why answering the dark matter question should involve invoking an extended scalar sector. But:

· Dark matter could be a (pseudo-)scalar.

· If dark matter is comprised of particles (in the particle physics sense), it should get its mass from somewhere. An extended scalar sector could be involved.

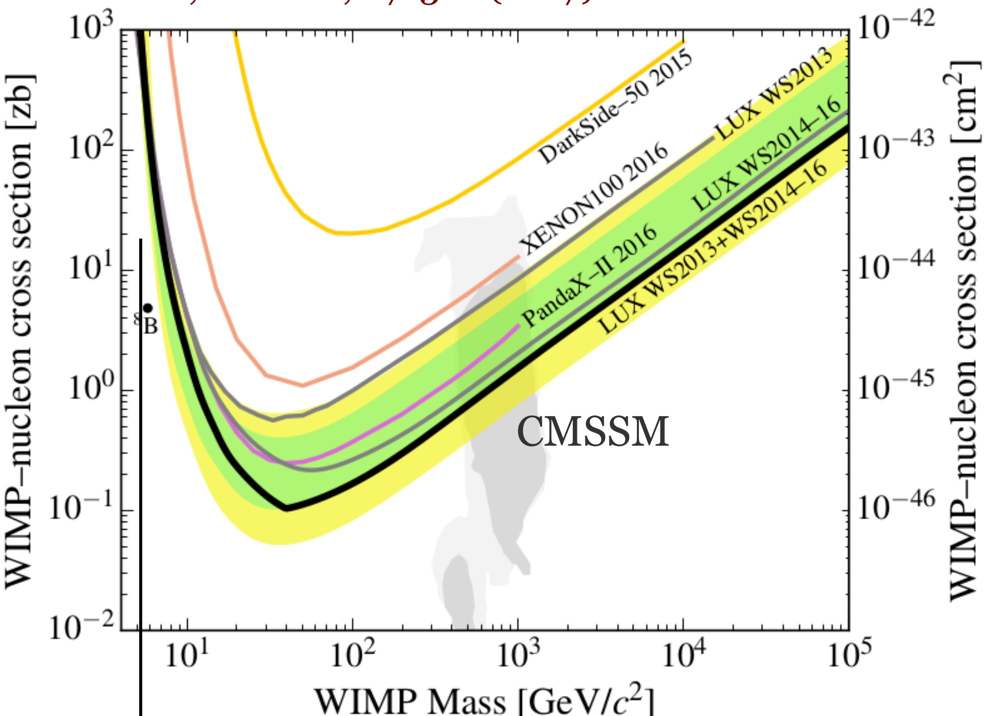
· New scalar degrees of freedom could mediate the dark matter interactions with the Standard Model.

· DM could annihilate into new scalar degrees of freedom (freeze-out) or be produced through decays/annihilations of such dof's (freeze-in).

Status of WIMP searches: direct detection

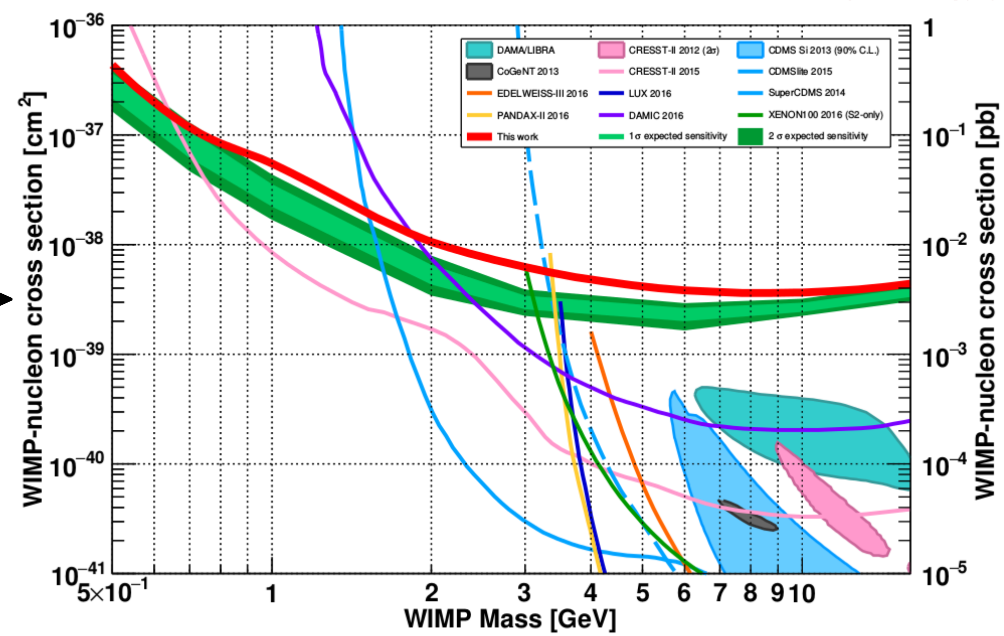
Conventional searches (spin-independent scattering)

LUX, PRL 118, 021303 (2017)
PANDA-X, PRL 118, 071301 (2017)



+ ideas on how to probe lower masses: s-fluid He, semi/super-conductors...

NEWS-G, arXiv:1706.04934



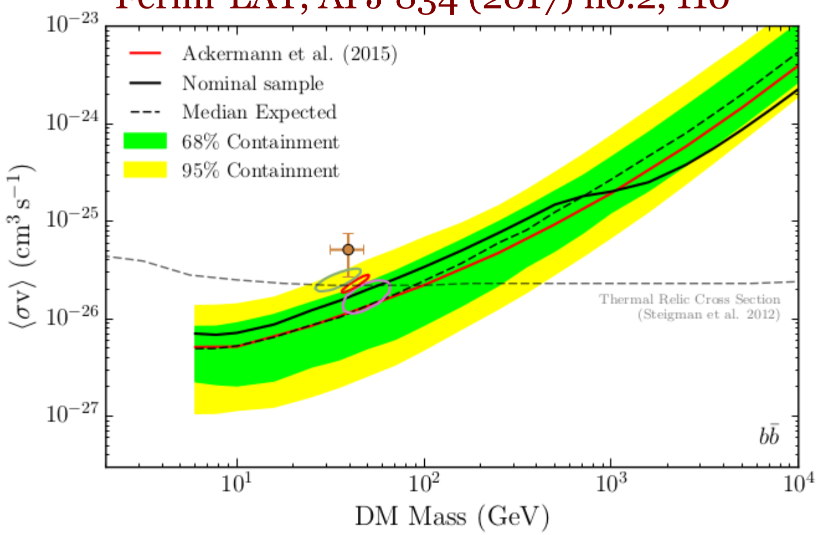
Xe detector threshold limitations for low-mass WIMPs, covered by dedicated experiments (*e.g.* CRESST, NEWS-G)

Status of WIMP searches: indirect detection

Continuum

Fermi-LAT limit from dSPhs

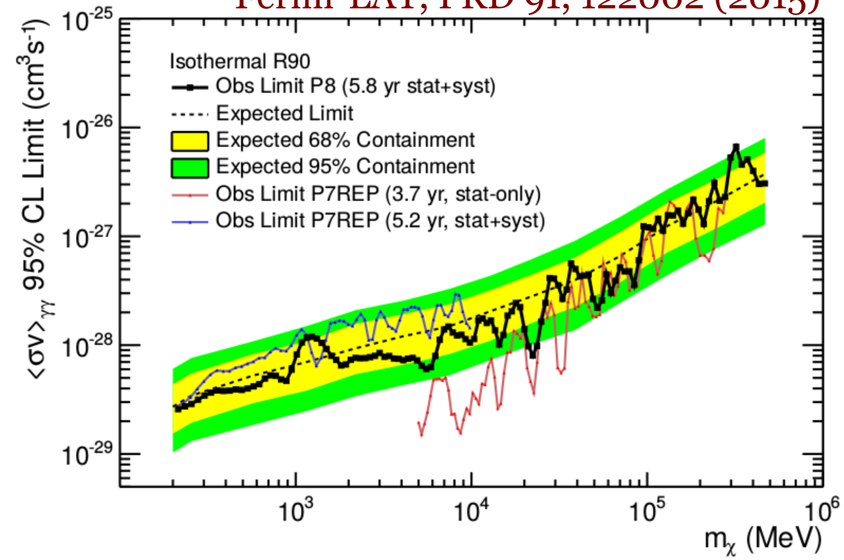
Fermi-LAT, APJ 834 (2017) no.2, 110



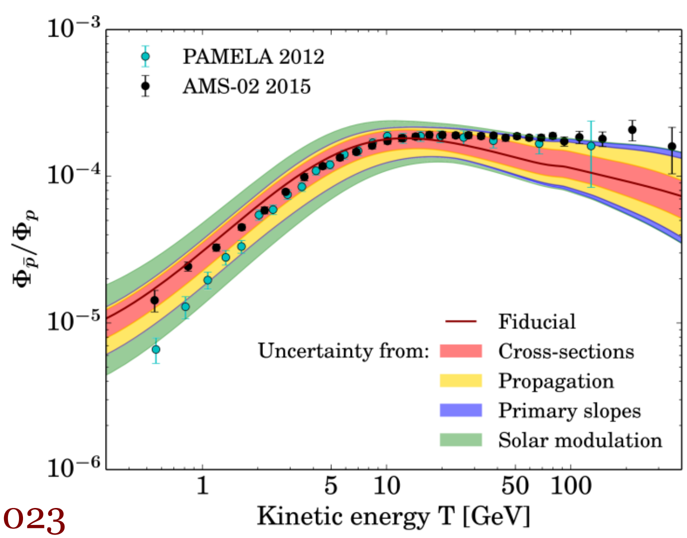
Spectral features

Fermi-LAT limit from Galactic Centre

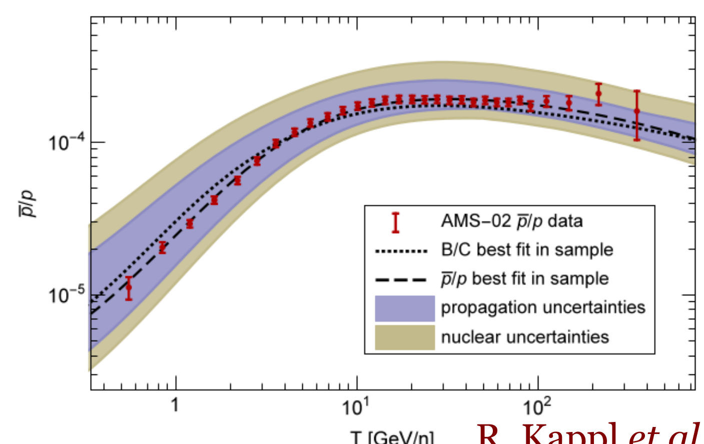
Fermi-LAT, PRD 91, 122002 (2015)



Antiprotons



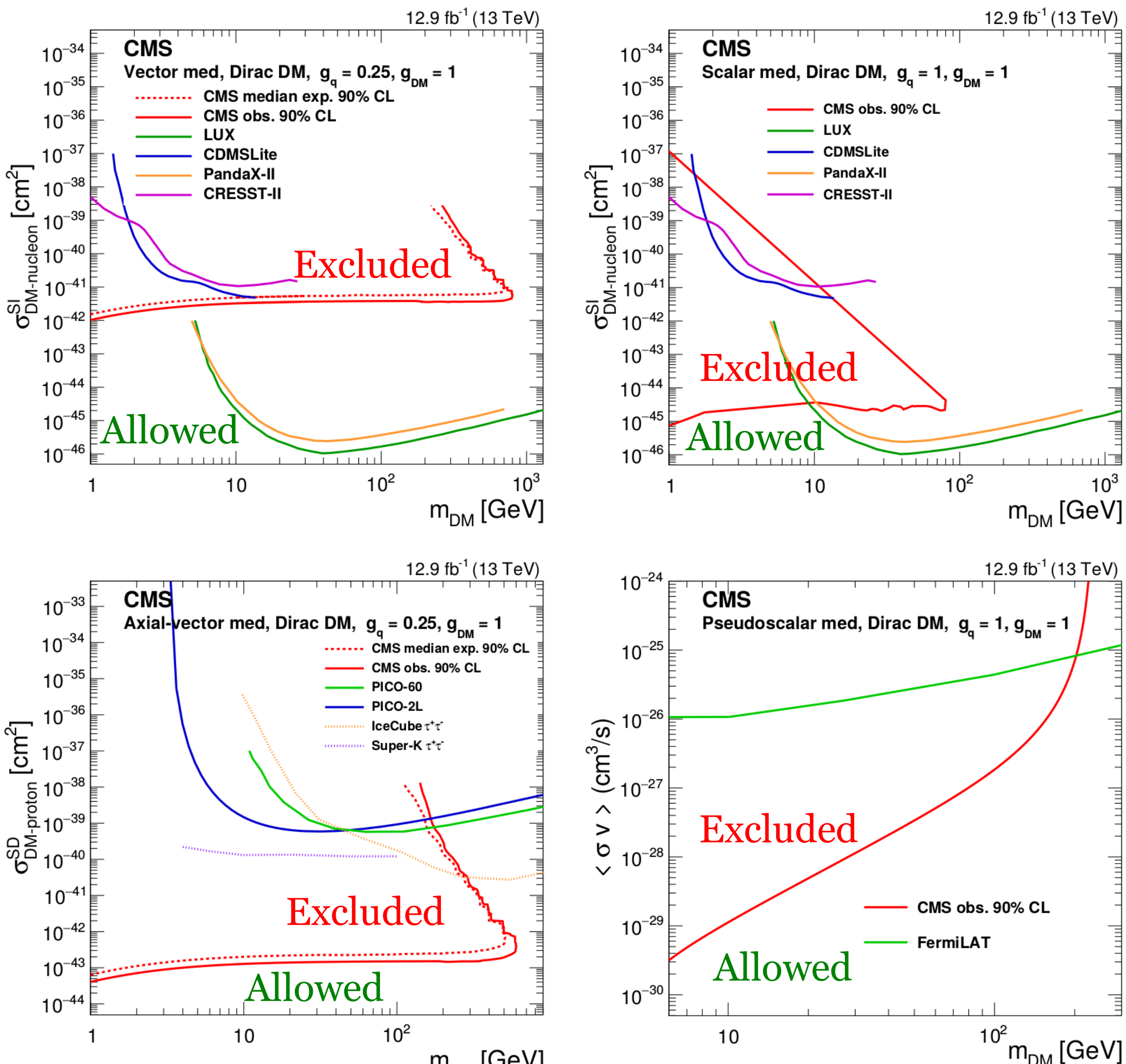
G. Giesen *et al*,
JCAP 1509 (2015) 023



R. Kappl *et al*,
JCAP 1510 (2015) 034

Status of WIMP searches: colliders

Most celebrated LHC dark matter searches: mono-X, in particular mono-jets



CMS, arXiv:1703.01651

· Four benchmark models: Dirac DM with vector, axial-vector, scalar and pseudoscalar mediator coupling to quarks.

· Robust handle on light DM.

As opposed to DD

· Crucial assumption: $m_{DM} < m_{Med}/2$.

Otherwise limits vanish

· Colliders are relatively insensitive to the underlying Lorentz structure.

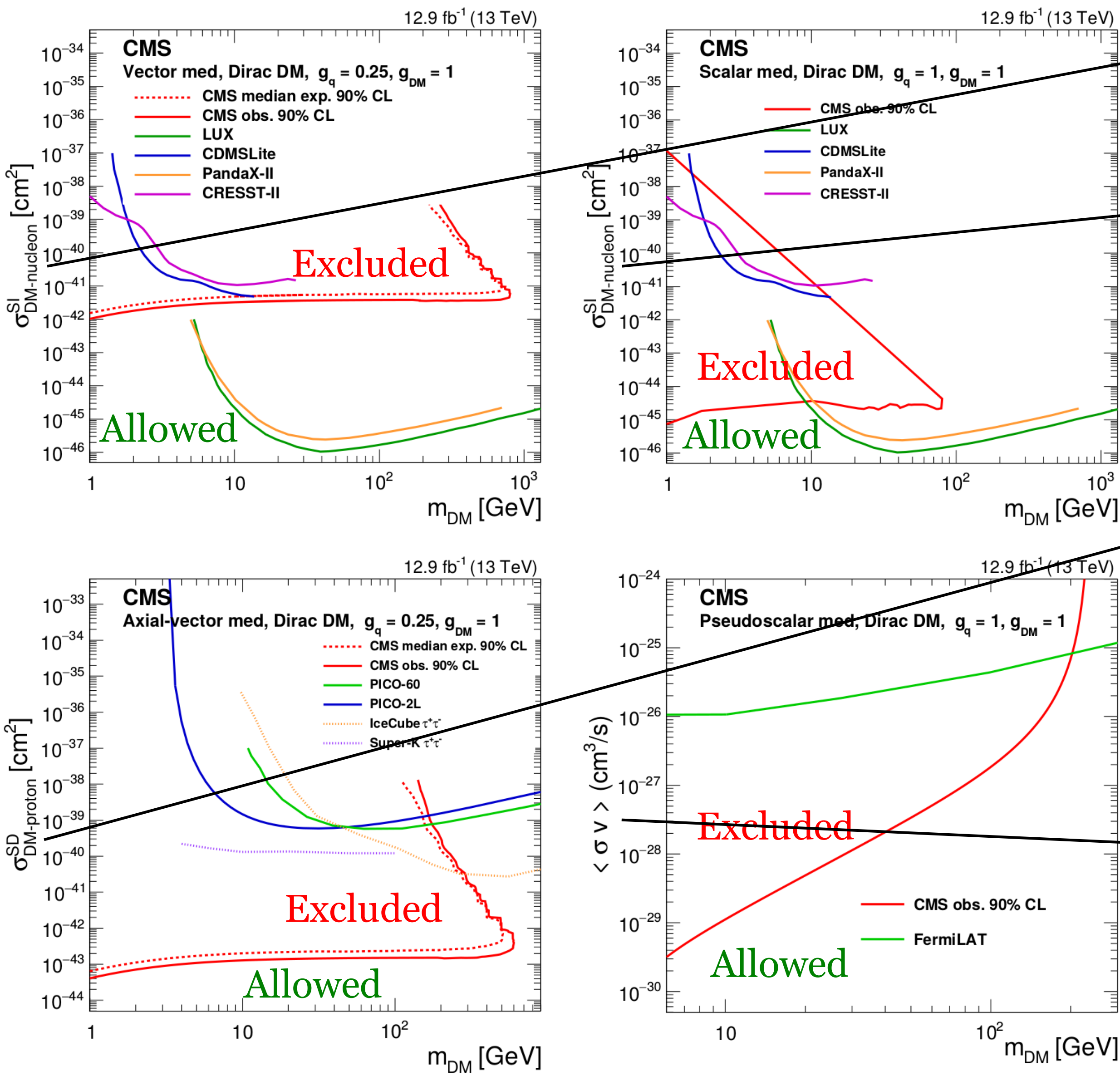
Very strong point!

· When direct detection works, it dominates.

When doesn't it "work" ?

WIMP detection: subtleties

Let's take a better look at the y axes in these plots:



CMS, arXiv:1703.01651

Dirac DM + vector mediator: σ^{SI}

Dirac DM + scalar mediator: σ^{SI}

Limits driven by DD

Dirac DM + axial-vector mediator: σ^{SD}

Limits driven by LHC

Dirac DM + pseudoscalar mediator: $\langle\sigma v\rangle$

No DD limits!

Why is that?

Scattering through pseudoscalars

Pseudoscalar-mediated (contact) interactions of WIMPs with nucleons are described by a Lagrangian of the form

$$\mathcal{L}_{\chi \mathrm{n}} = \frac{g_{DM} g}{2m_A^2} \sum_{N=p,n} g_N \bar{\chi}\gamma^5\chi\bar{N}\gamma^5 N$$

Computing the WIMP-nucleus scattering cross-section we obtain a result that behaves as

$$\frac{d\sigma}{dE_R} = \frac{q^4}{m_A^4} \times f(\{m_i\}, \{g_i\}, v, FF(q^2))$$

For typical q~100 MeV and mA~(1-1000) GeV, WIMP-nucleon scattering is extremely suppressed.

NB: And mostly spin-dependent

Direct detection is inefficient in constraining such interactions

On the other hand, the LHC makes relatively little distinction between scalars and pseudoscalars, whereas indirect detection only works through pseudoscalars.

For scalars <σv> is ~ v_χ, and v_χ is small!

A simple description

We consider a simple Lagrangian description as

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

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

A few remarks:

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

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

· We have assumed MFV-type couplings to avoid as much as possible flavour constraints.

· In a type-2 2HDM model, we'd have c_u = cotβ and c_d = tanβ. Concretely, we take:

$$c_u = c_d = 1, \qquad c_u = c_d = 2, \qquad c_u = 0.2,\ \ c_d = 20$$

tanβ = 1 with standard Yukawas	tanβ = 1 with enhanced Yukawas	tanβ = 10 with enhanced Yukawas

Constraints: cosmology and astrophysics

· Within standard ΛCDM, Planck constrains the DM abundance in the Universe to be

$$\Omega_{\rm DM} h^2 = 0.1187 \pm 0.0012$$

where DM pairs can annihilate into SM fermions, or pseudoscalars.

· Fermi-LAT searches for gamma-rays from dSphs, re-weighted according to actual annihilation channels (+ 15-year projection).

NB: Annihilation into pseudoscalars is p-wave-suppressed, so it doesn't contribute to the gamma-ray flux.

· AMS-02 antiproton searches.

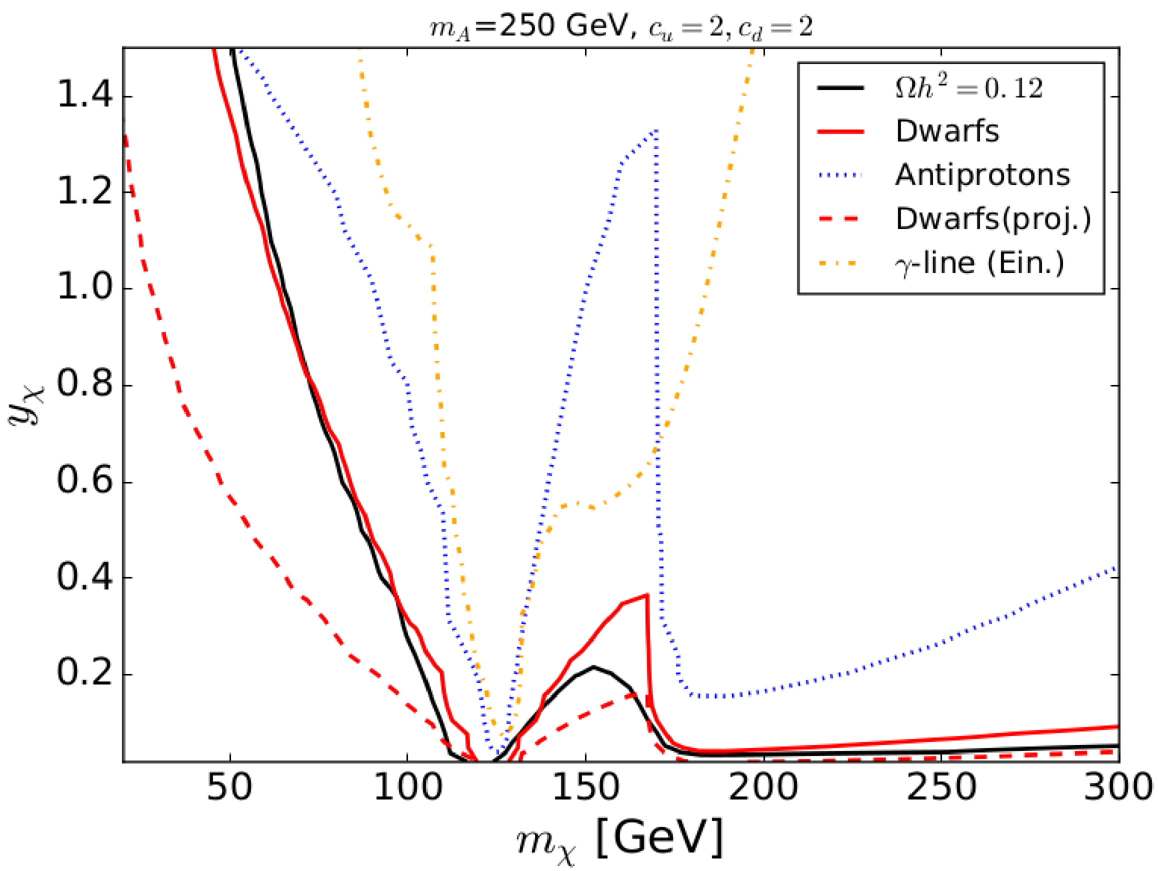
· Fermi-LAT searches for spectral features at the Galactic Centre. Cross section computed through EFT Lagrangian by matching the A diphoton width to

$$\Gamma(A \to \gamma\gamma) = \frac{G_f \alpha^2 m_A^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c \; Q_f^2 \; c_f \; A_{1/2}^A(\tau_f) \right|^2$$

but replacing $\tau_f = 4m_\chi^2 / 4m_f^2$ in the form factor A^A.

Comparison of astro/cosmo constraints

Before looking into LHC constraints, let's inspect how the various astrophysical constraints compare amongst them



· The shape of the curves is dictated by the available annihilation channels + the behaviour of the A resonance in the early Universe/today.

· Antiproton constraints correspond to the MED propagation model with an Einasto profile. Switching to MAX → constraints stronger by ~1 order of magnitude, but we deem this assumption to be rather aggressive.

· Within uncertainties, dSphs constraints are stronger than antiproton/γ-ray line ones. We will only consider those in the following.

Collider constraints w/ *A* decaying invisibly

· Standard monojet and multijet (SUSY) searches:

- ATLAS "monojet" and SUSY multijet searches w/ 3.2 fb^{-1} @ 13 TeV.

- Events generated with up to one hard extra jet at the matrix element level (incl. jet coming from the fermion loop) and matched to Pythia 6. Stability of results in case of two jets at the matrix element level checked within an EFT framework.

- SUSY multijet searches turn out to be less constraining due to loss of statistics.

"Monojets" are actually multijets, and they have been optimised for DM searches.

· Associated production of *A* with a pair of t- or b-quarks, with $A \to \chi\chi$:

- ATLAS search in single lepton+jet+MET channel w/ 13.2 fb^{-1} @ 13 TeV (top-dominated scenarios).

- ATLAS search for b jets+MET w/ 13.3 fb^{-1} @ 13 TeV (bottom-dominated scenario).

- Projections for tt*A* w/ 300 fb^{-1} @ 14 TeV based on shape-based analysis.

U. Haisch, P. Pani, G. Polesello, arXiv:1611.09841

Collider constraints w/ *A* decaying visibly

· ττ searches:

- CMS search for spin-0 resonance decaying into τ pairs (ggF or bb*A*) w/ 12.9 fb^{-1} @ 13 TeV (ignoring interference with the SM).

· tt searches:

- *A* on shell: ATLAS di-top resonance search w/ 20.3 fb^{-1} @ 8 TeV.

- *A* off shell: rely on tt production cross section measurement @ 8 and 13 TeV (incl. interference with the SM).

- In practice, the tt cross section measurement can dominate even in the on-shell region.

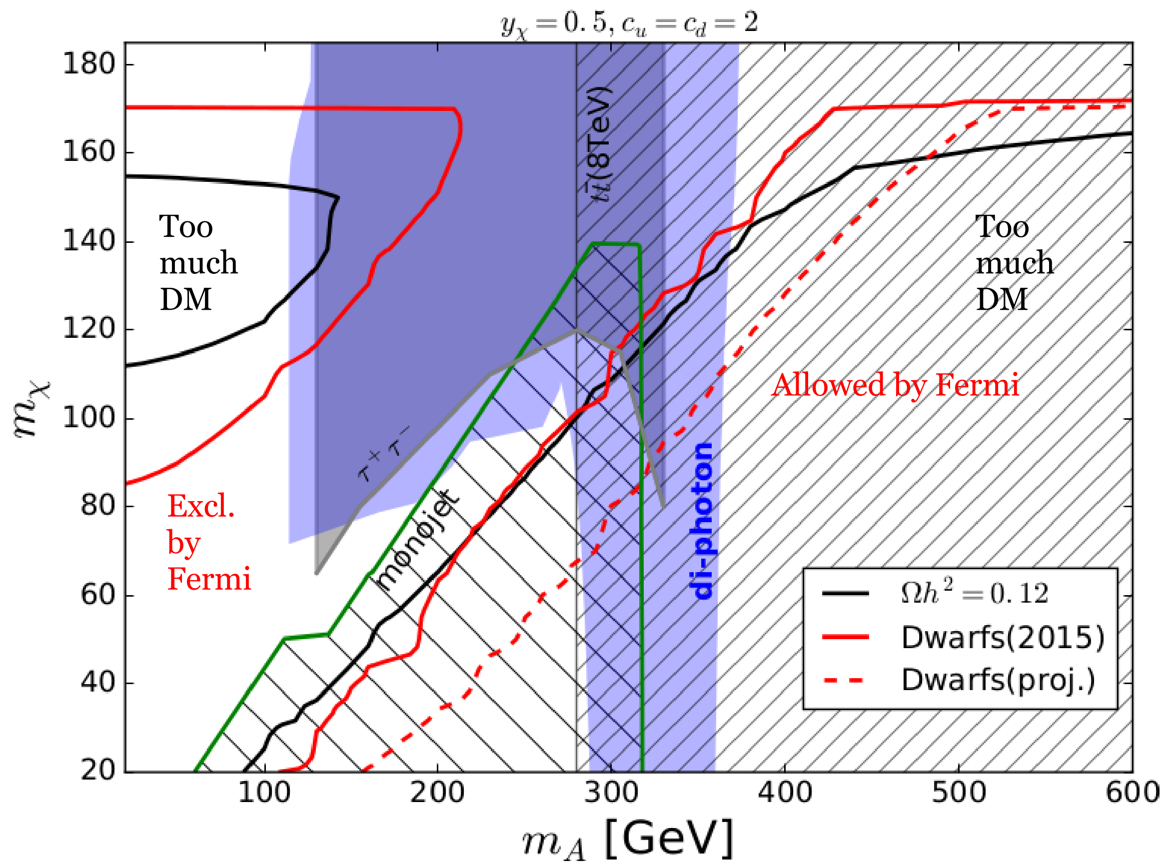
· Diphoton searches (we're dealing with something that resembles the Higgs!):

- ATLAS diphoton resonance search w/ 15.4 fb^{-1} @ 13 TeV (for m_A > 200 GeV).

- ATLAS diphoton resonance search w/ 20.3 fb^{-1} @ 8 TeV (down to m_A ~ 65 GeV).

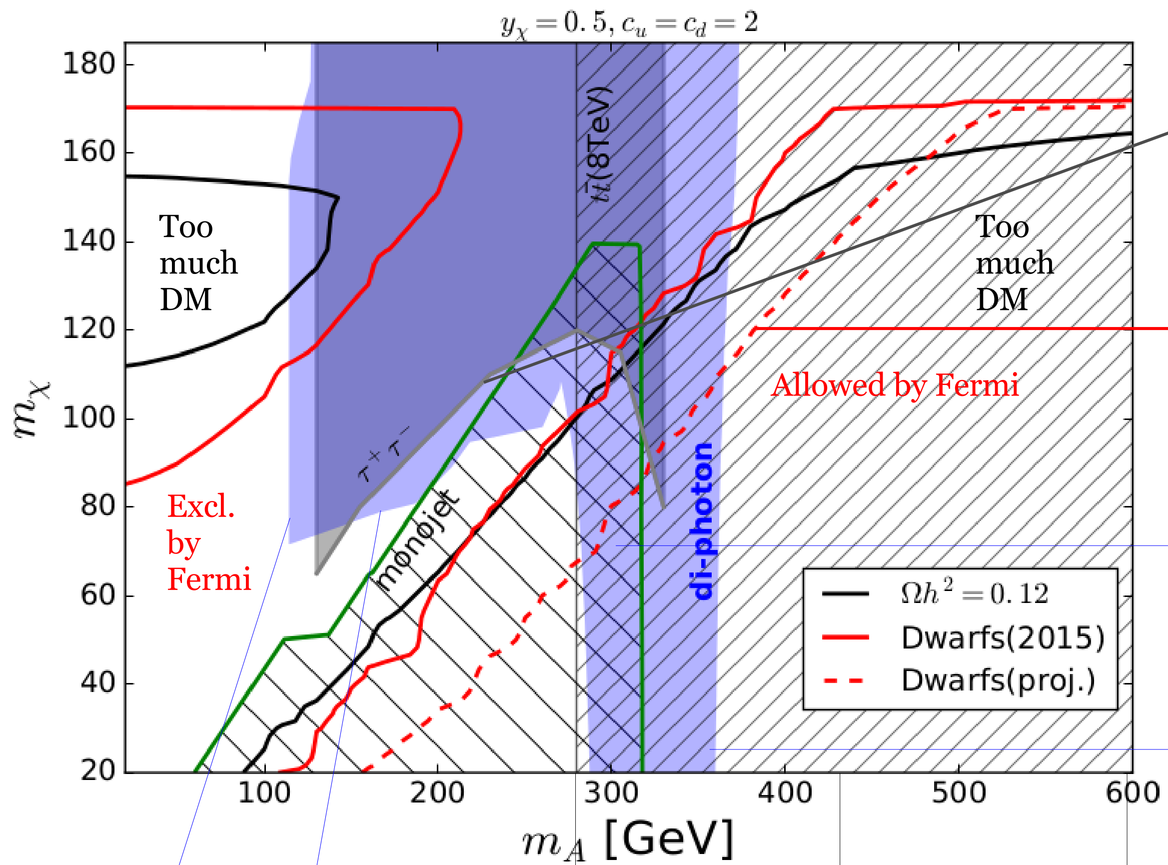
Results: fixed couplings – dark matter

Let's first fix the couplings and vary the masses



Results: fixed couplings – collider constraints

Let's first 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

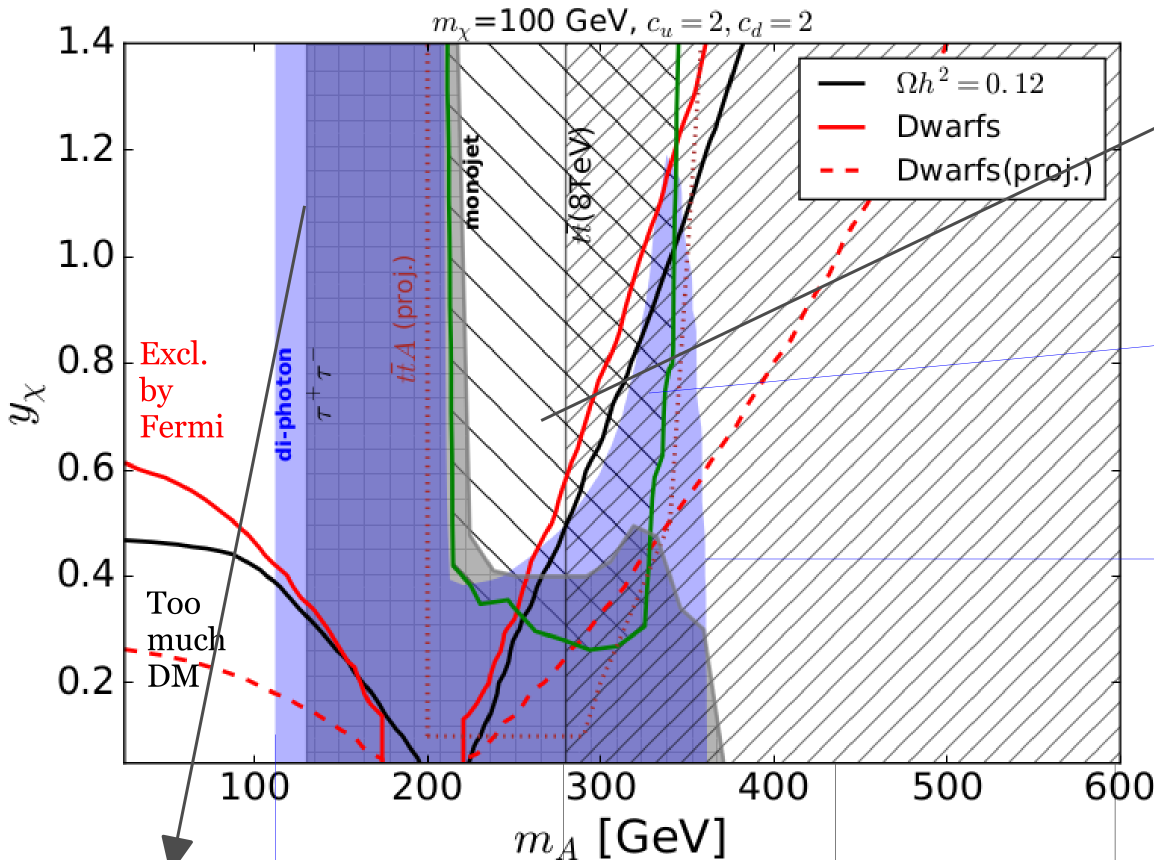
tt resonance searches @ 8 TeV

Diphoton BR suppressed + reduced LHC sensitivity

Dark matter searches are complementary!

Results: fixed SM couplings and DM mass – S1

Next, we fix m_χ = 100 GeV and study our three benchmarks for the SM couplings



Inv. decays dominate

Form-factor enhancement

tt decays dominate

+ ttA projections will probe the same region as monojets

No ττ results available

tt cross section measurements @ 8 TeV

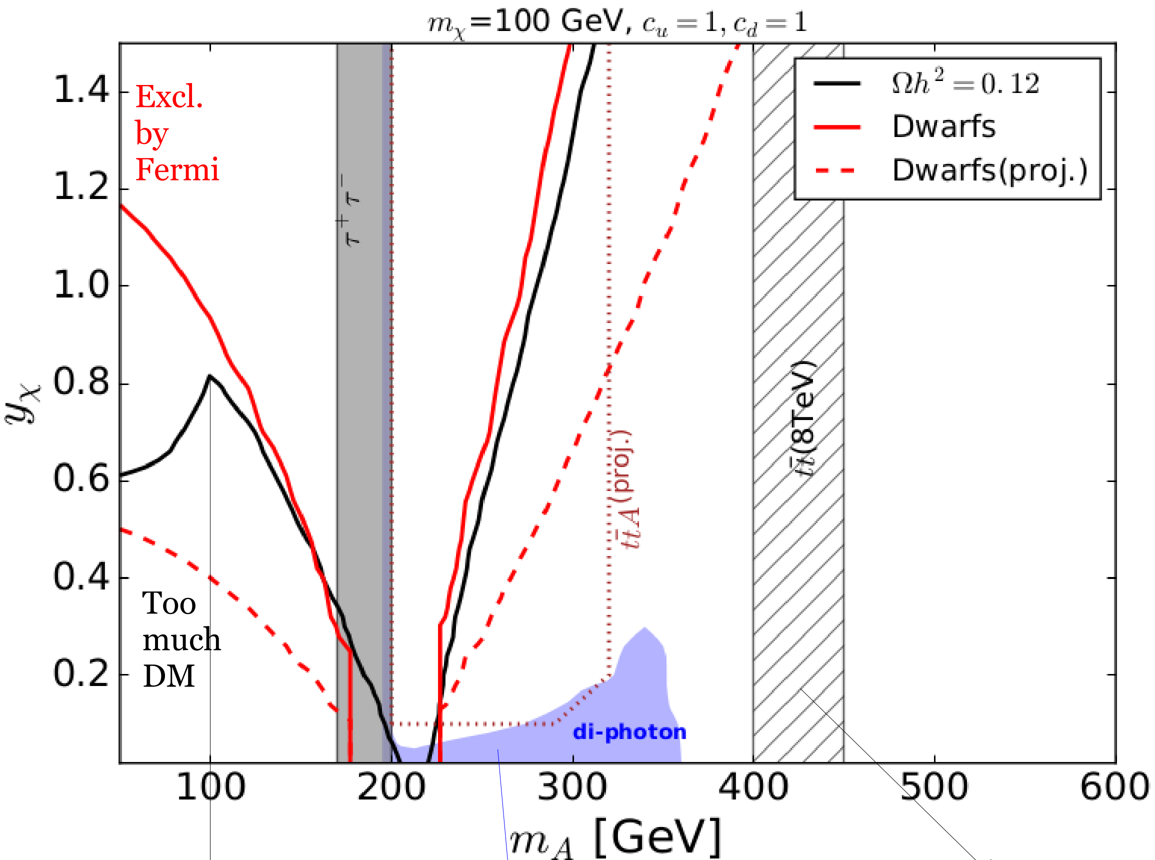
tt resonance searches @ 8 TeV

Only m_χ < 130 GeV allowed and will be probed by Fermi

Diphoton BR suppressed + reduced LHC sensitivity

Results: fixed SM couplings and DM mass – S2

Reducing the SM couplings the LHC constraints get substantially relaxed



· Monojet searches only exclude small mass range around mχ ~ 200 GeV for large couplings, result not shown.

· ttA prospects better in this respect.

· Best perspectives with Fermi-LAT.

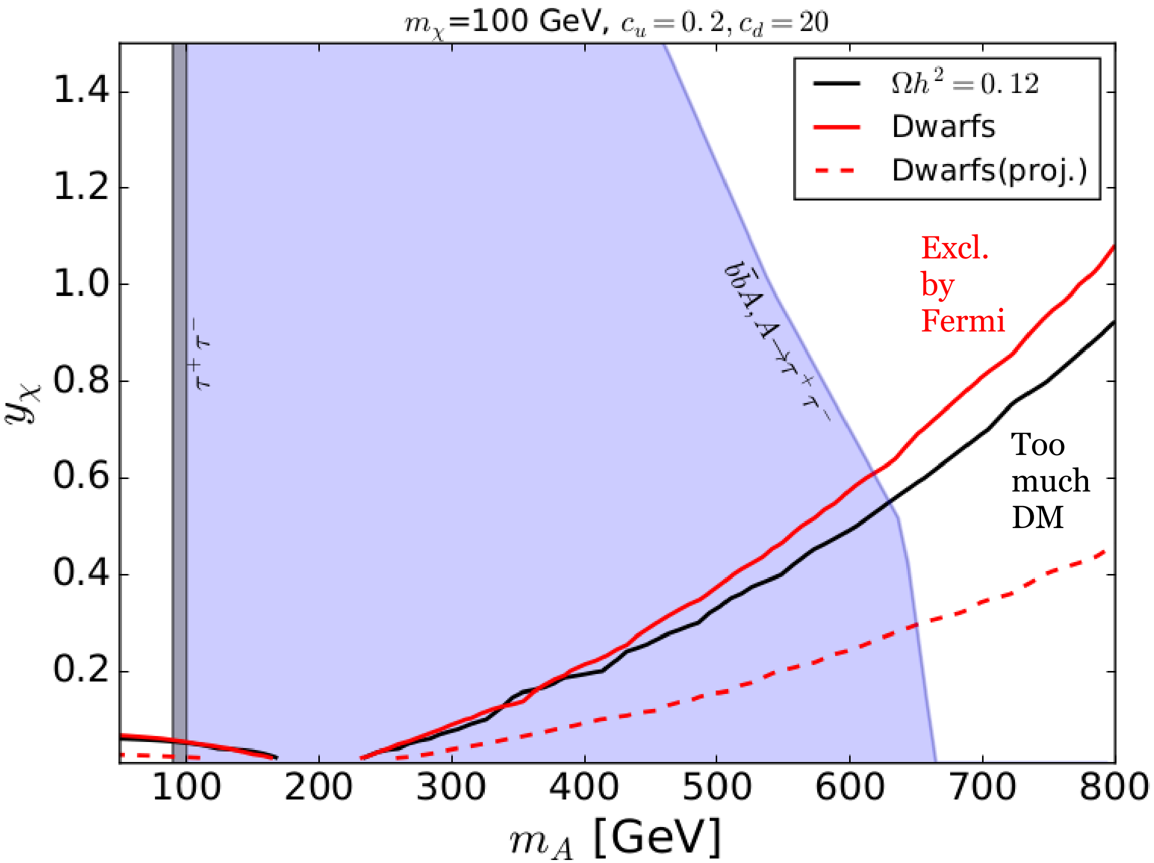
· $\chi\chi \to AA$ opens up

tt resonance searches @ 8 TeV

Diphoton behaviour understood as before

Results: fixed SM couplings and DM mass – S3

Finally, we consider out "bottom-dominated" scenario



· top-related constraints vanish.

· But bottom-related ones shine!

· Additional constraints (albeit already excluded by $bbA, A \to \tau\tau$) can be obtained from $bbA, A \to$ inv, for $m_A \sim$ 200 – 300 GeV and large DM coupling.

· Once again, Fermi-LAT will probe almost the entire parameter space after 15 years of data acquisition.

What would happen in a UV-complete model?

Arguably, the previous picture is a bit oversimplified. Generalisations of these results are model-dependent. Two simple UV embeddings of this picture:

i) If DM is a SM singlet, a singlet+2HDM scalar sector.

e.g. M. Bauer, Haisch, Kahlhoefer, arXiv:1701.07427

ii) If we wish to keep the scalar sector minimal, a bino-higgsino-like DM candidate.

e.g. S. Banerjee *et. al.*, arXiv:1603.07387,
A. Bharucha, F. Brümmer, R. Ruffault, arXiv:1703.00370

What should we expect?

· Opening up additional (“hadronic”) DM annihilation channels would shift the Planck and Fermi results in the same direction → The allowed parameter space regions should remain narrow (modulo coannihilations).

· Some coupling to the CP-even scalars should be present, so direct detection could also become relevant.

· tt constraints should hold, although their interplay with Planck would get modified.

· Additional (model-dependent) constraints should become relevant.

Summary and outlook

· We have computed a set of complete, state-of-the art constraints on pseudoscalar-mediated dark matter models for m_A around the weak scale. The models turn out to be either very constrained or will be probed within the next few years.

· Planck, direct/indirect detection and collider constraints are complementary. The latter are also complementary amongst *themselves*.

· One of the handicaps we encountered: LHC results for low-mass resonance searches are not available/do not exist. We believe that useful constraints can be obtained from these searches and we hope the collaborations will provide them (esp. $\gamma\gamma/\tau\tau$).

e.g. A. Mariotti *et. al.*, arXiv:1710.01743

· As a long-term project, it would be interesting to compare UV-complete generalisations of this framework.

This would be *a lot* of work!