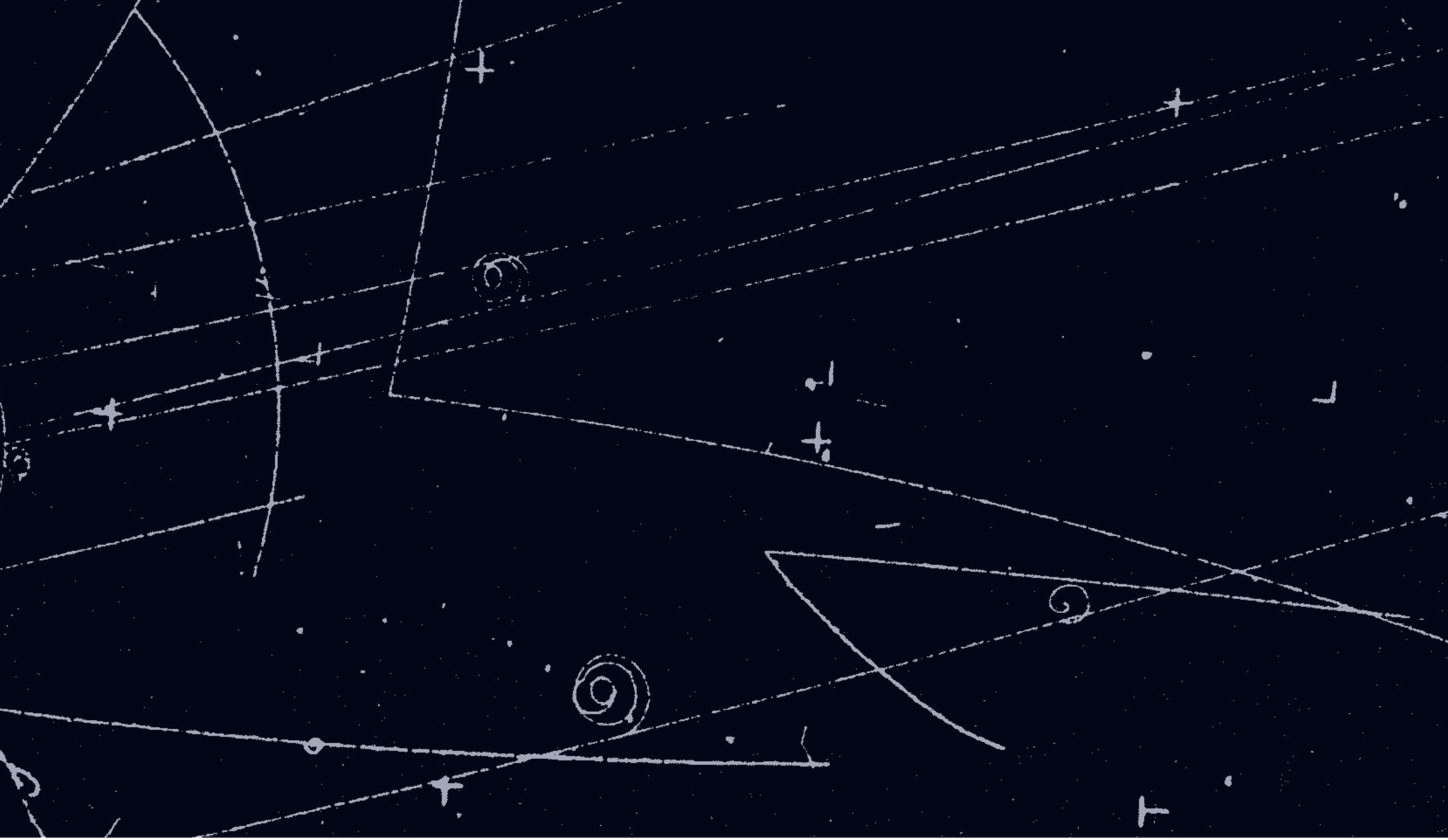


Accelerator based dark matter probes

Kate Pachal
TRIUMF

Introduction

We are here this week to talk about the future of high energy physics

That future has to center dark matter

Colliders have a vital role to play in the search for dark matter

I will focus on energy frontier machines & experiments (sorry IF)

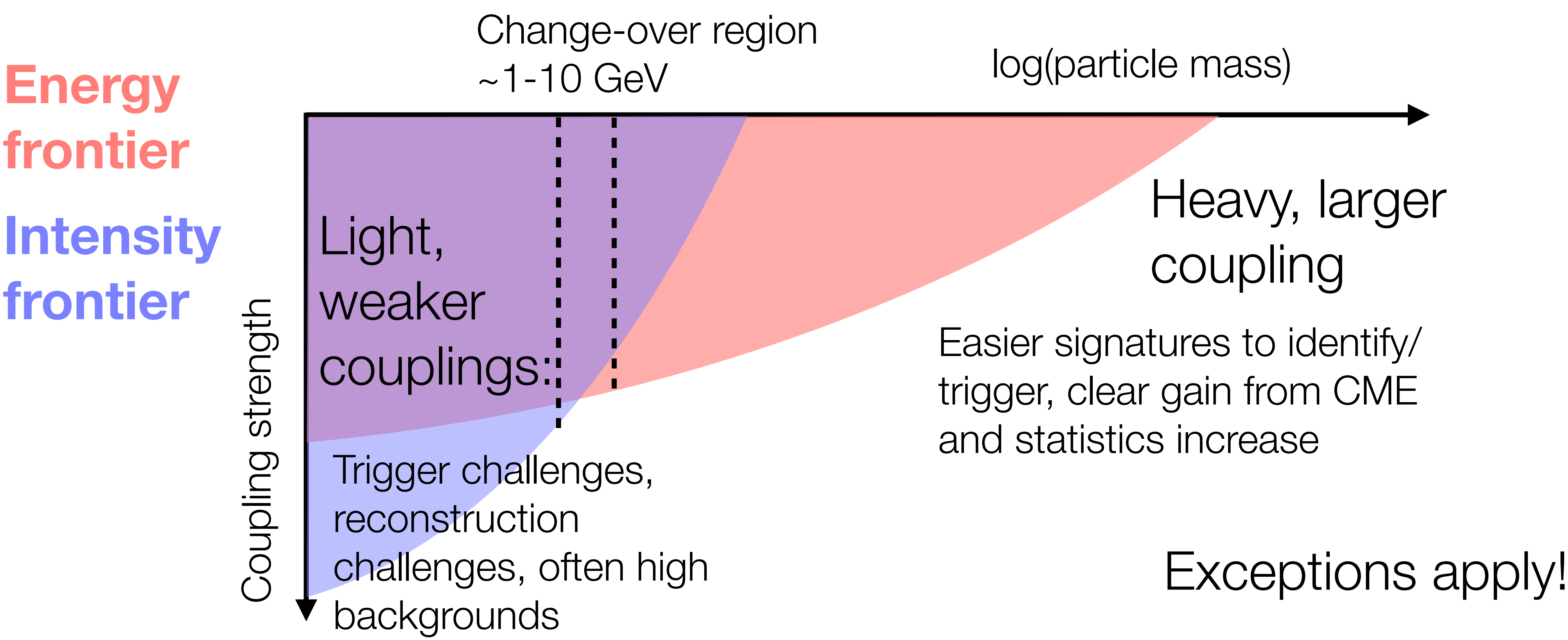
Today's agenda:

- What DM looks like at colliders
- What we are currently able to say about it
- What we could say about it with future colliders
- How we might think about framing this to the community

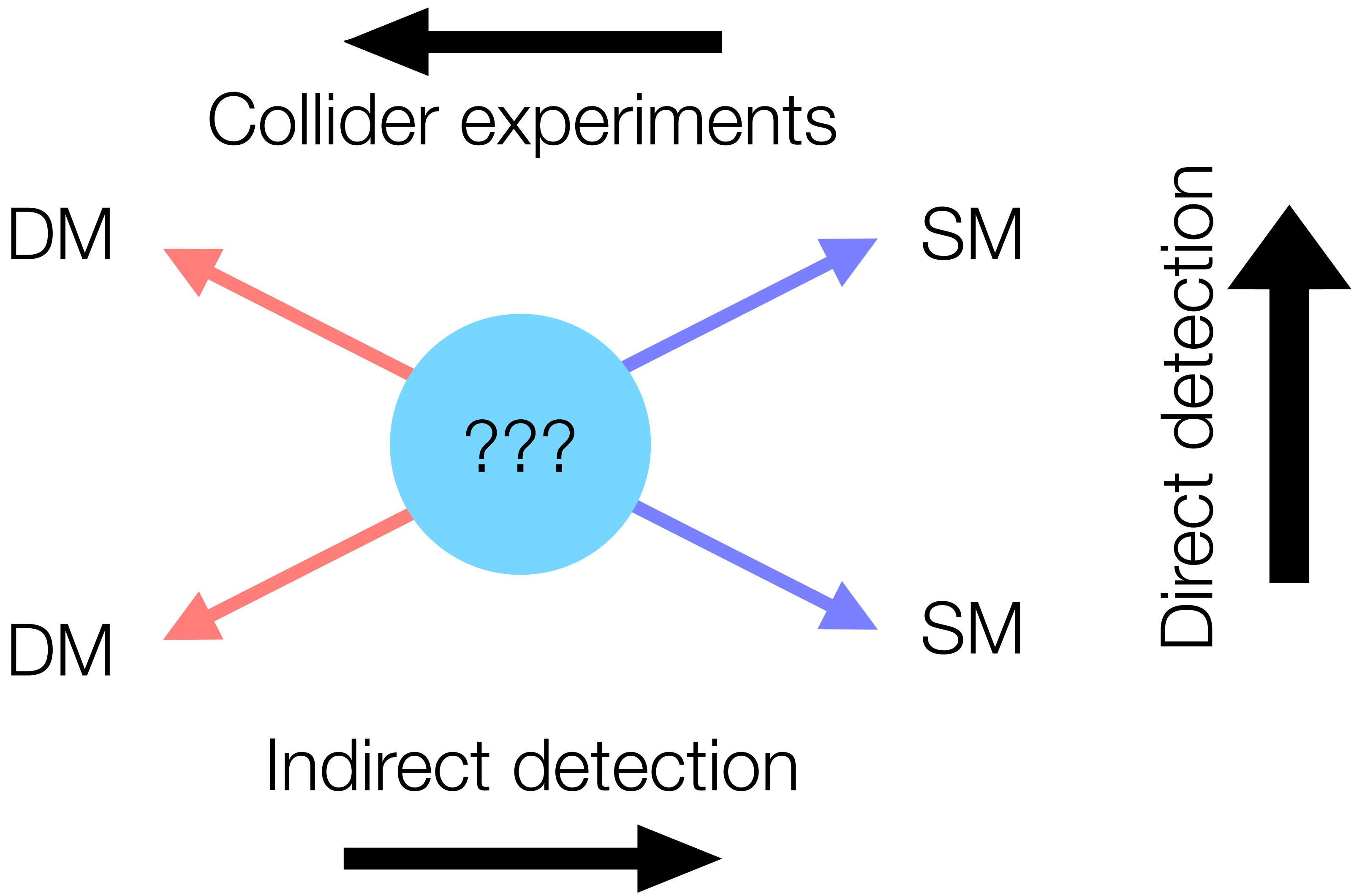
Medium-mass dark matter

Today, largely talking about cases with dark matter and/or associated new particles over ~ 1 GeV in mass

Does not mean “vanilla” WIMPs only! But light dark matter, and with it light mediators, are easier at intensity frontier experiments



Complementarity between DM experiments



Tired: all three approaches are probing the same thing (interchangeable)

Wired: different DM scenarios may be accessible to only one or two of the three approaches

Inspired: the future of the field needs all three to ensure success

Benchmarks

Dark matter models at the LHC

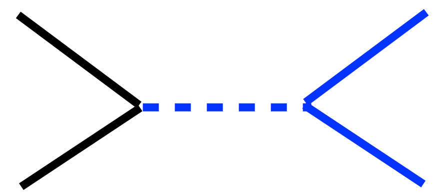
Standard Model: black
BSM: blue

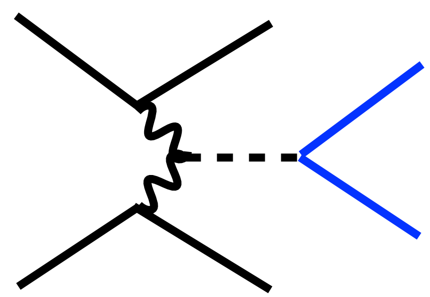
No EFTs

Mediator masses around energy scale of collider

Simplified models

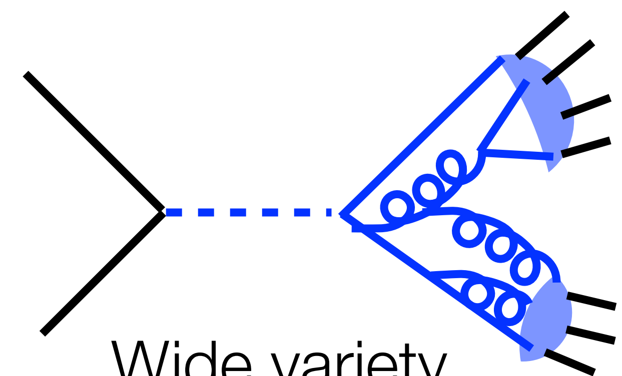
Spin-1 mediator, one DM particle





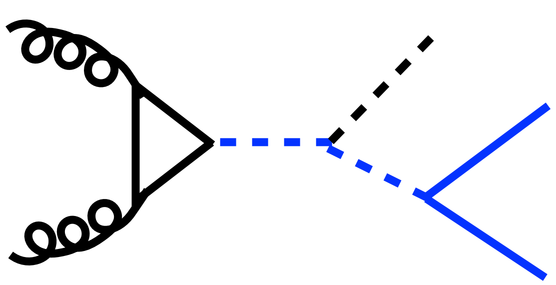
Simplified Higgs portal

Extended dark sectors



Wide variety

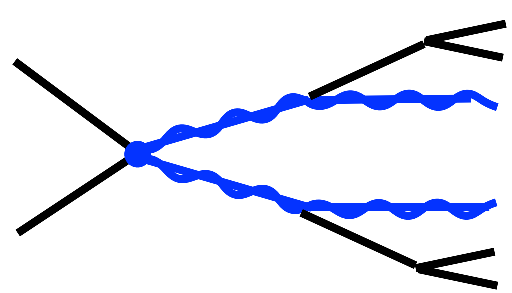
2HDM + pseudoscalar



Still simple, UV-complete pseudoscalar mediator model

SUSY scenarios

Cases with wino or higgsino-like LSP can give good DM candidates



Often simplified for practicality

Long-lived particles

Not a model; rather, a class of signatures emerging from many of the others

* speaking as an experimentalist

Pros and cons of different benchmarks*

Simplified models

Ease of comparison between analyses and experiments

Tractable parameter space to understand extent of coverage

Can lead to over-simplified view of what is “excluded” or uncovered

Complete/ complex models

Theoretically robust

Illuminate wide range of final states that are needed for thorough coverage of cases

Hard to form complete picture; hard to compare across contexts

No single answer. ATLAS & CMS lean on simplified models for comparisons; use complex models on analysis-by-analysis basis and for smaller comparison use cases

Relevance of relic densities

How much should we care about ensuring benchmarks are **compatible with relic density**?

Anything **up to $\Omega h^2 = 0.12$** is permitted; above that, get overproduction of dark matter relative to cosmological observation

Soft consensus in LHC experiments: know where the constraints are, but do not take them too seriously for simplified models

> Reasoning: goal of simplified models is to understand complementarity between channels and experiments, and identify gaps; theory is often too simple to be taken at face value anyway

However, relic density useful for setting **goal sensitivities**.

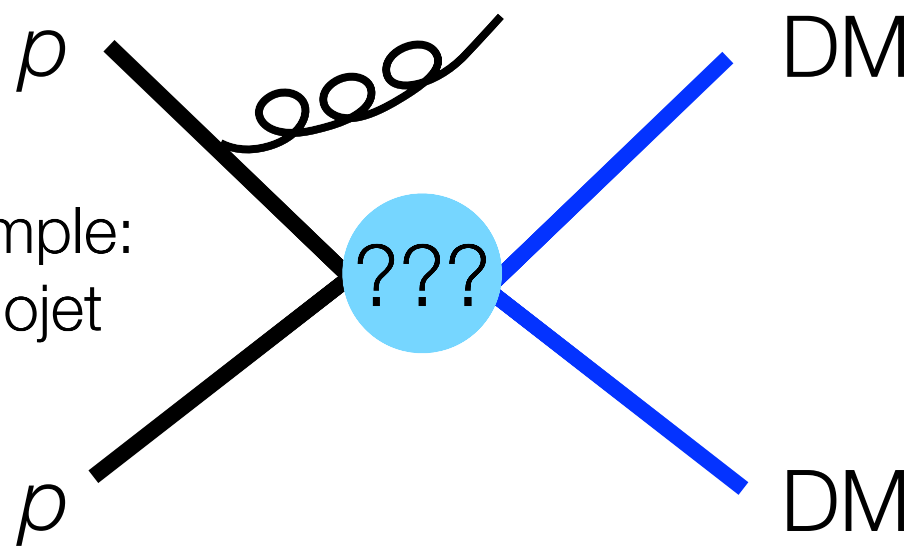
Could say a model is excluded once relic prediction reached

DM at the LHC

LHC signatures for DM searches

Most general: mono-X

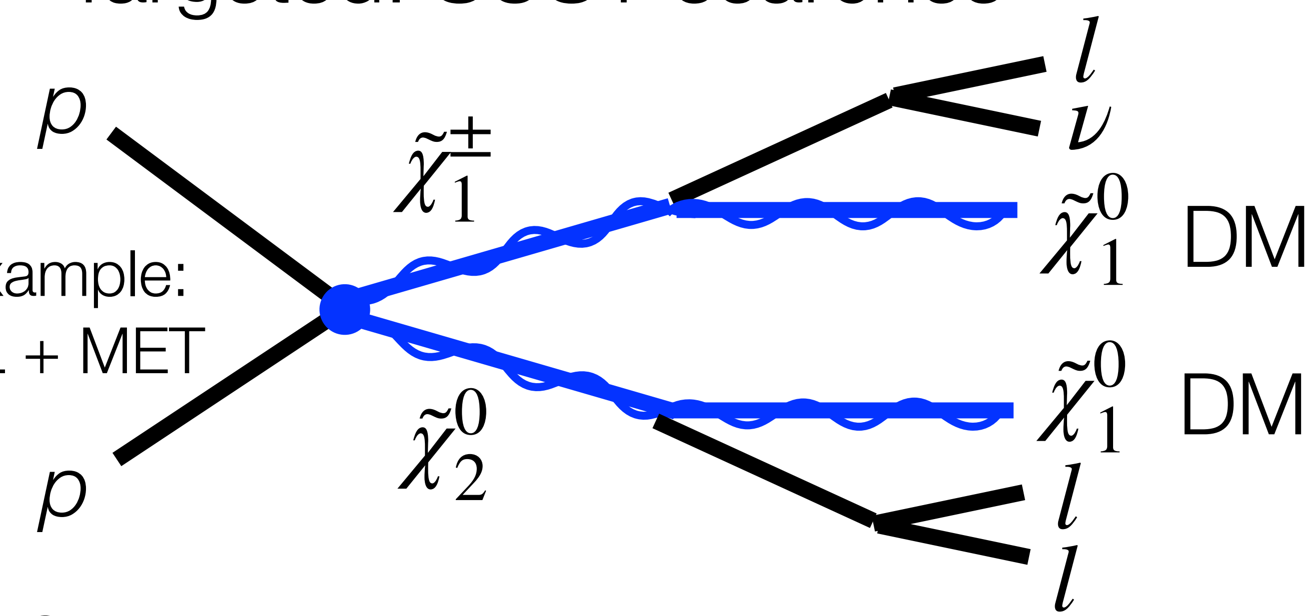
Example:
monojet



Model-independent; high backgrounds. ISR provides momentum, enabling missing energy reconstruction

Targeted: SUSY searches

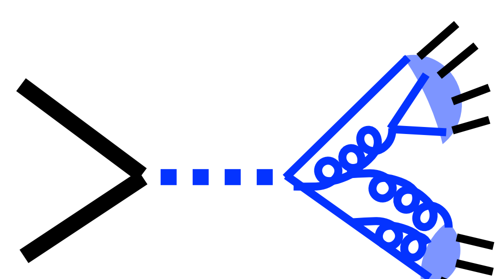
Example:
3L + MET



Generally complex final state allowing significant background suppression. MET remains key feature of selection

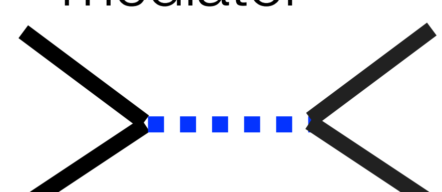
Non-MET-focused

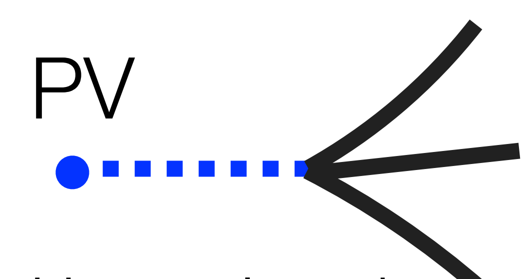
Various searches target models with dark matter implications, but that do not rely on MET in final state. Extended dark sectors, direct mediator searches, LLPs



QCD final states with distinctive features

SM decay of mediator





Unusual tracks or displaced energy deposits

Current status of LHC spin-1 simplified models

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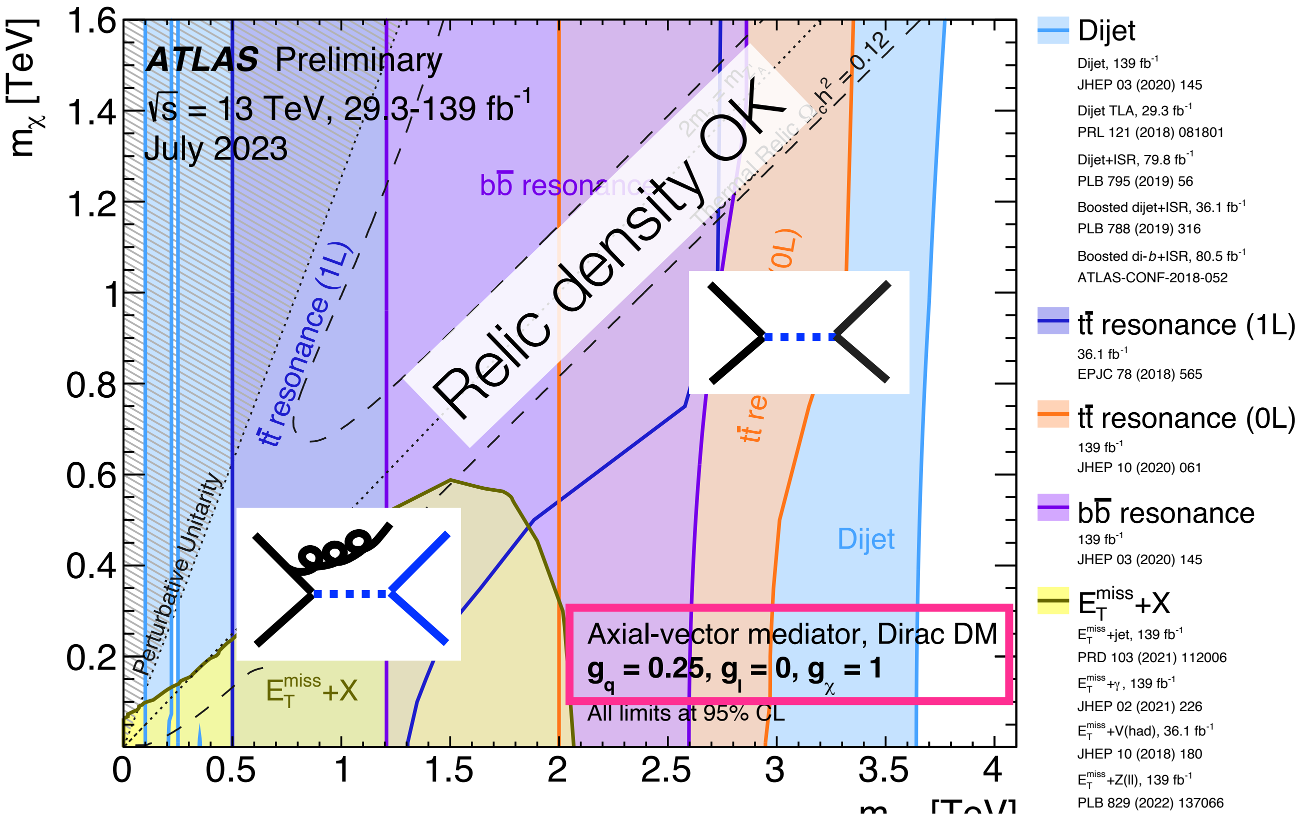
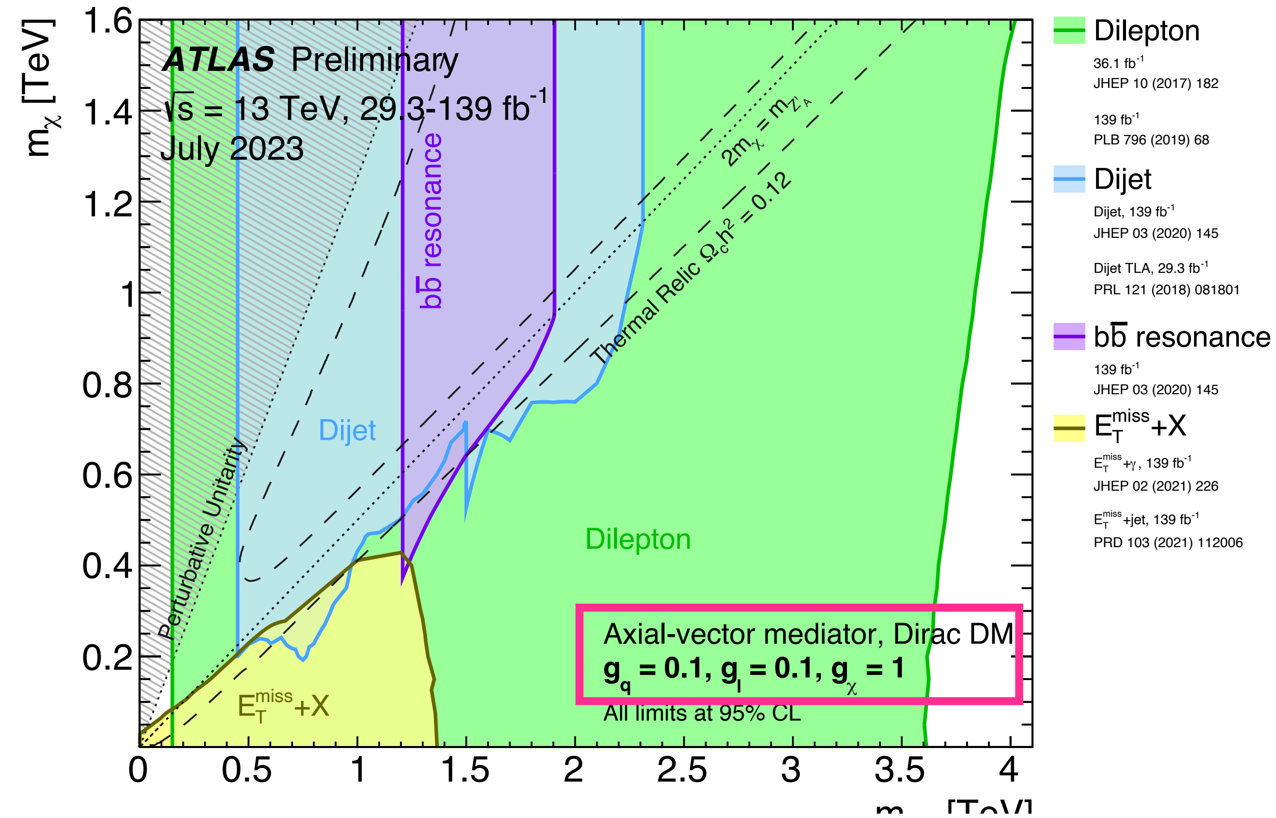
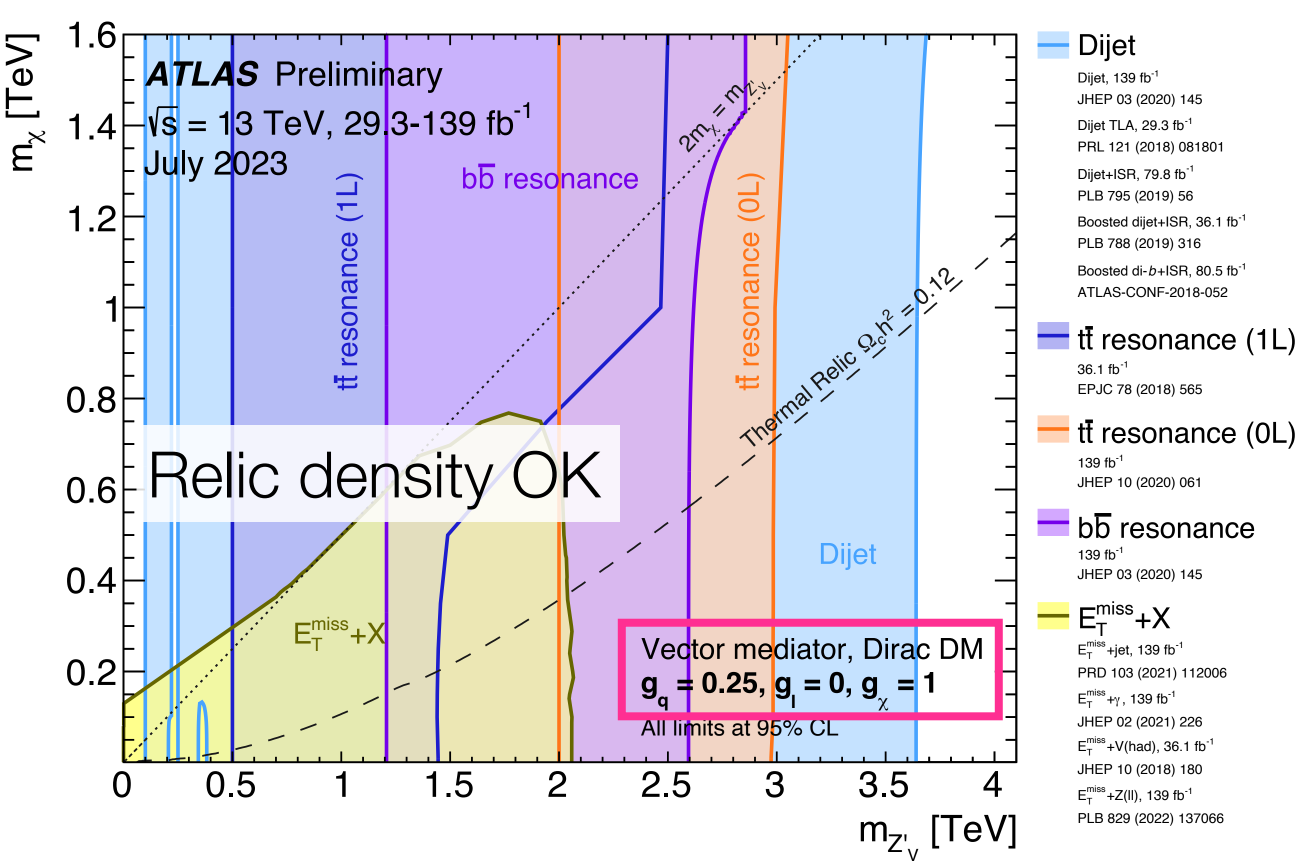
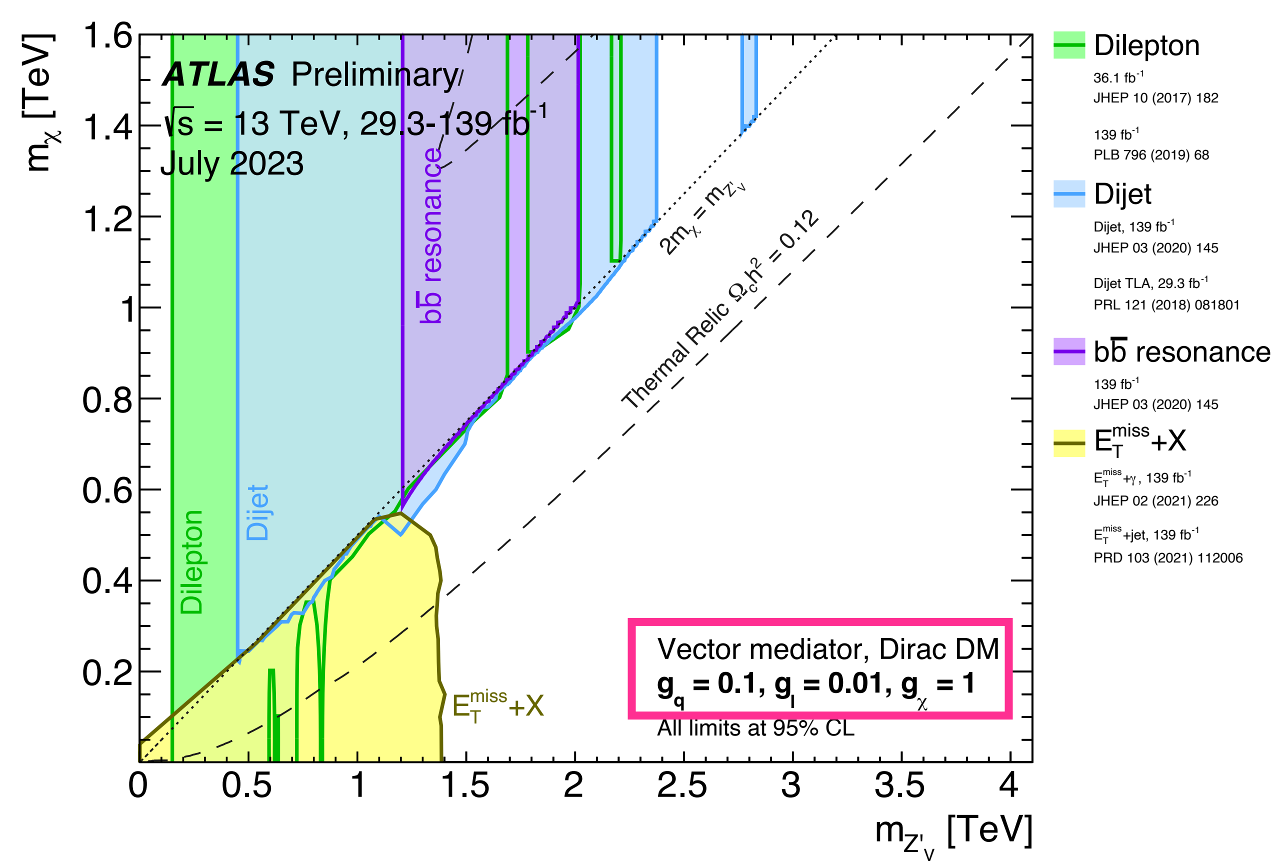








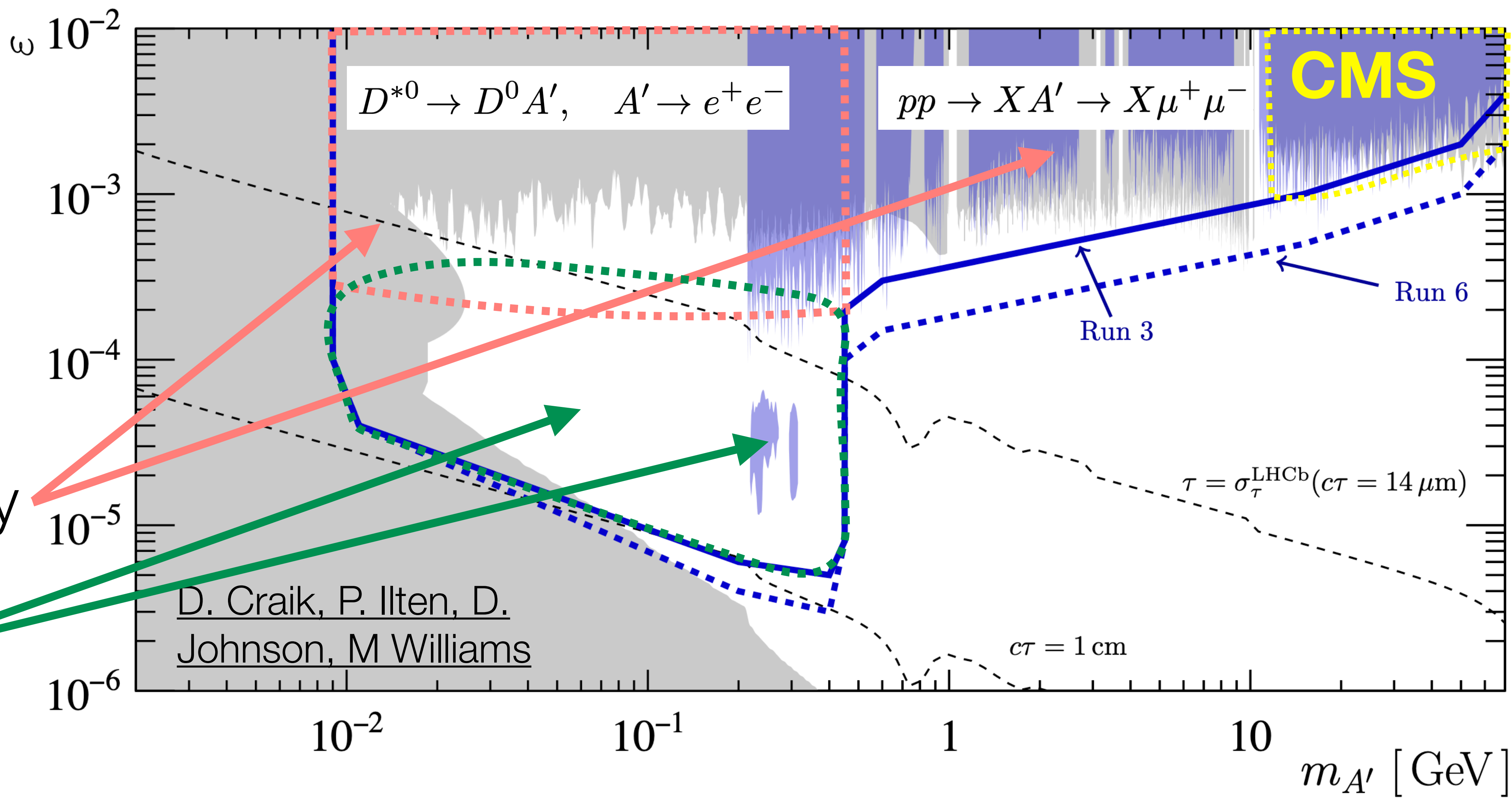
Dark photons at the LHC

Very popular spin-1 vector benchmark, especially with intensity frontier and physics beyond colliders community

LHCb is a powerhouse with Run 3 triggerless readout

Prompt decay

Displaced vertex



ATLAS & CMS can contribute at higher masses. Trigger poses a challenge. Simplified spin-1 limits translate fairly directly, but this is not currently a standard interpretation.

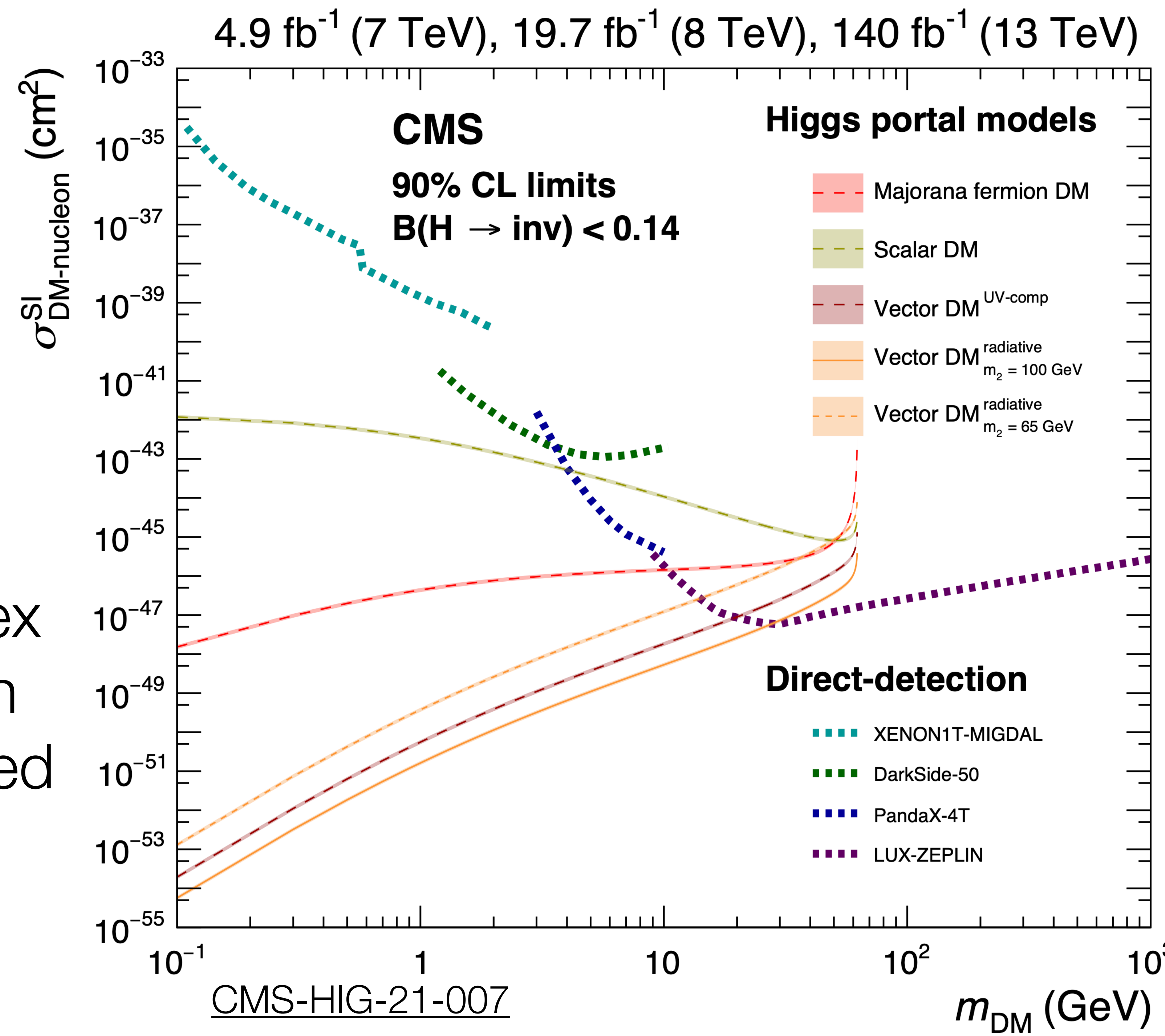
Higgs decays to dark matter

In Higgs portal models, the Higgs decays to DM, creating a MET signature

Possible UV-complete SM extension with just one DM particle if DM is a scalar

For vector DM, more complex scenario with dark Higgs can still be appropriately estimated via this EFT approach (ref.)

Current upper limits on $BR(h \to \text{inv}) \sim 0.11$ (ATLAS)



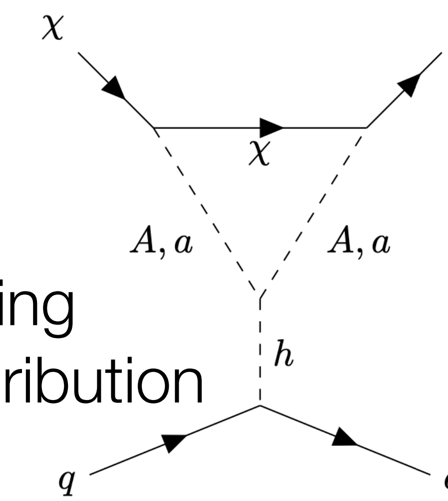
CMS-HIG-21-007

Model motivation from Arcadi, Djouadi, and Kado

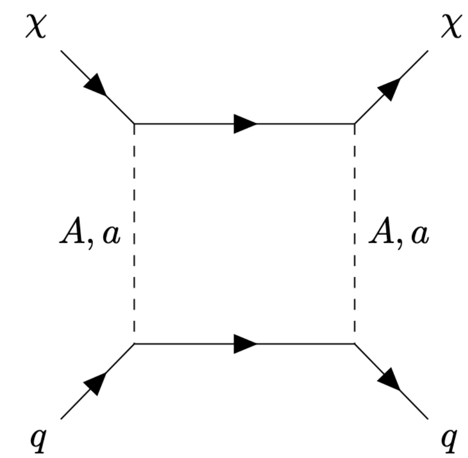
2HDM+a motivation and limits

DM with pseudoscalar mediator is a key LHC target because direct detection interactions are suppressed at tree level

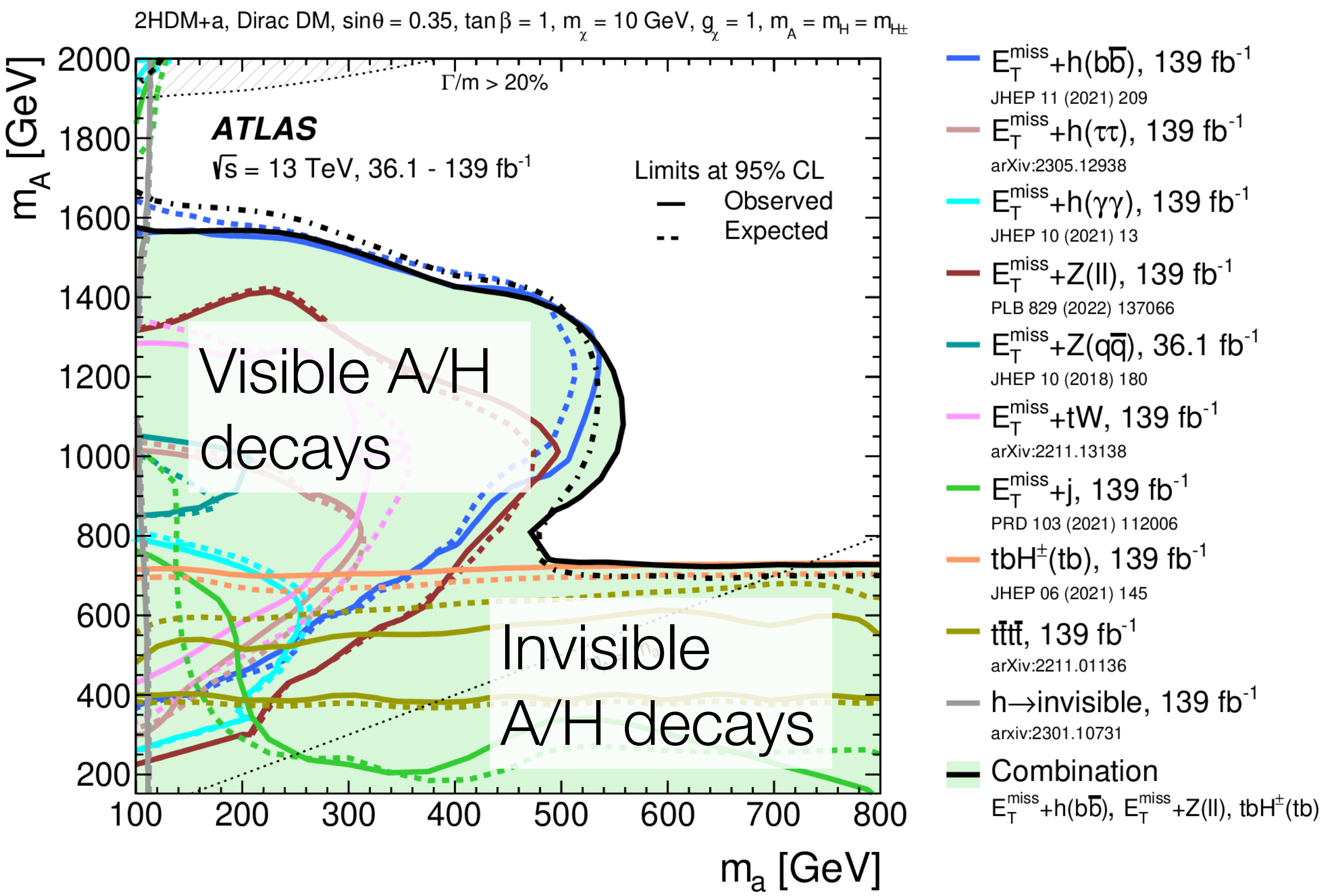
DD leading contribution

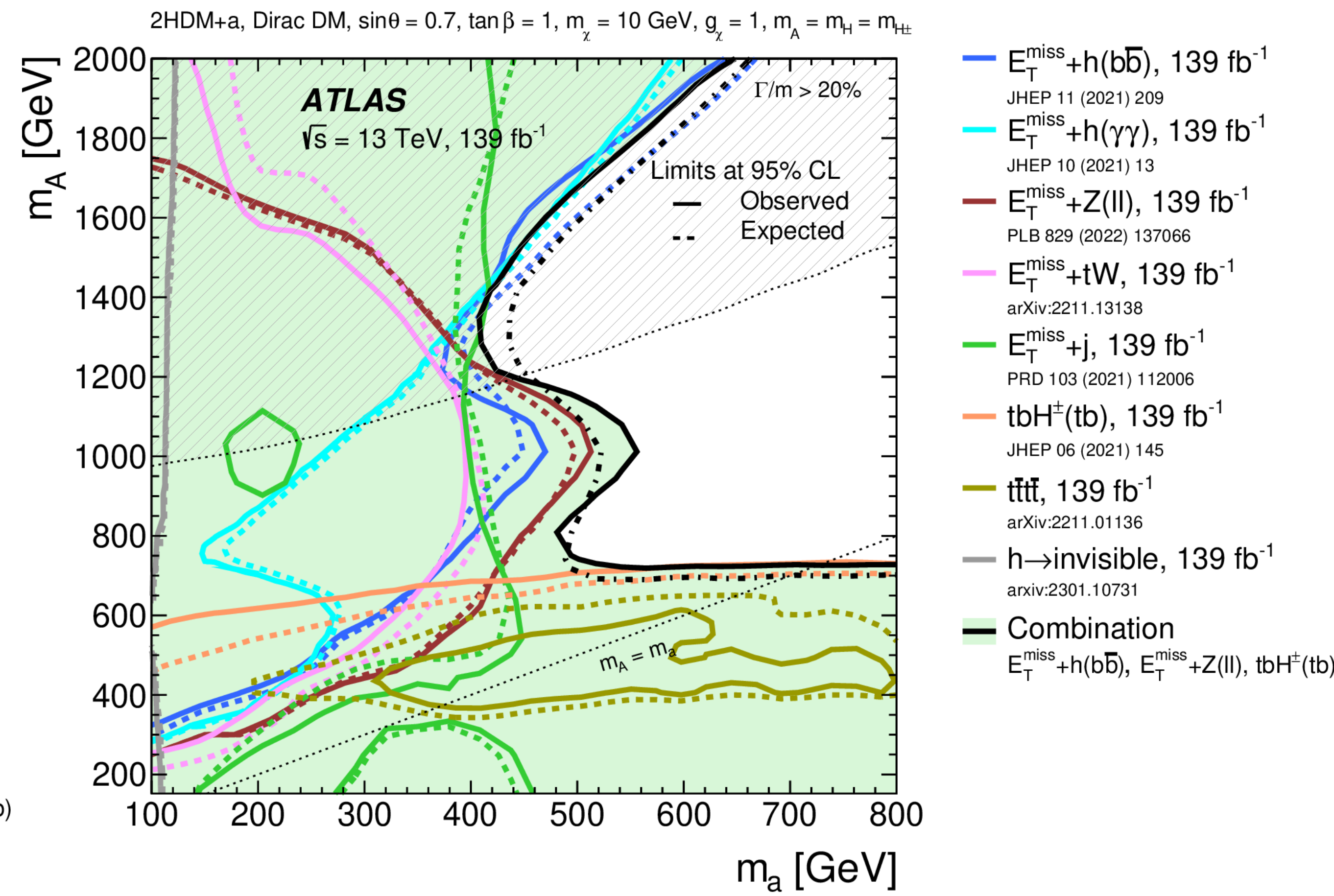


LHC DM working group



Additional DD box diagrams





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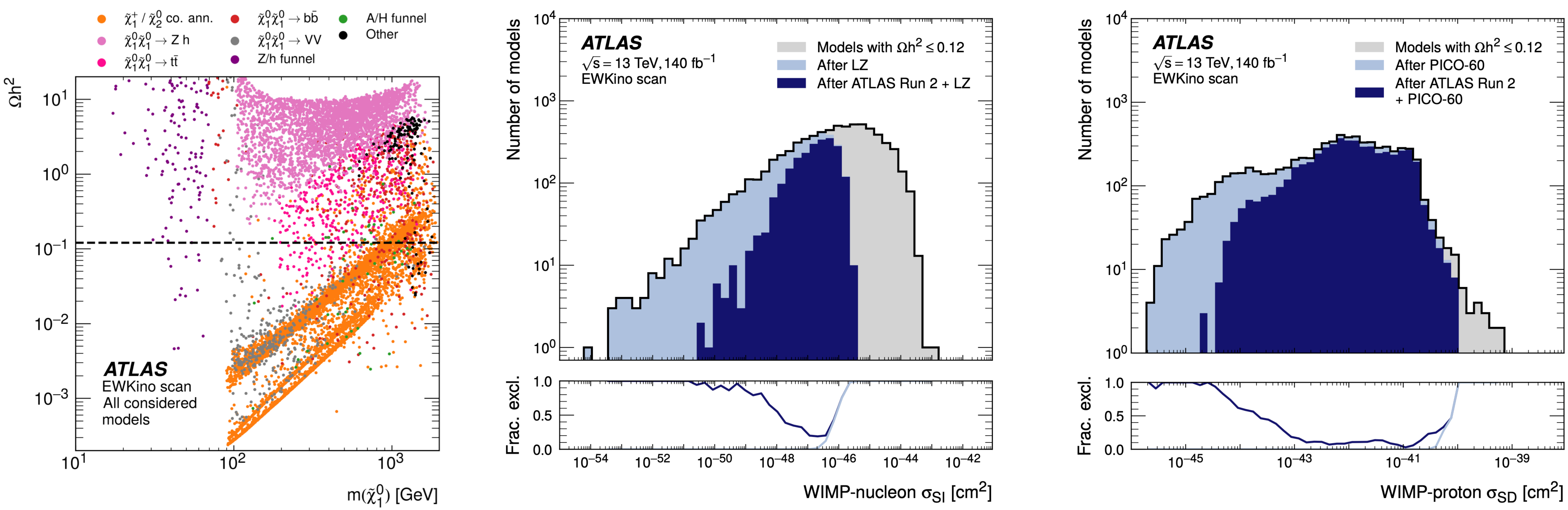
The state of SUSY dark matter

Let's look at pMSSM scan of DM candidates ATLAS CERN-EP-2024-021

Co-annihilation with small mass splitting from wino/higgsino-like $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ to LSP gives most of the viable candidates explored here

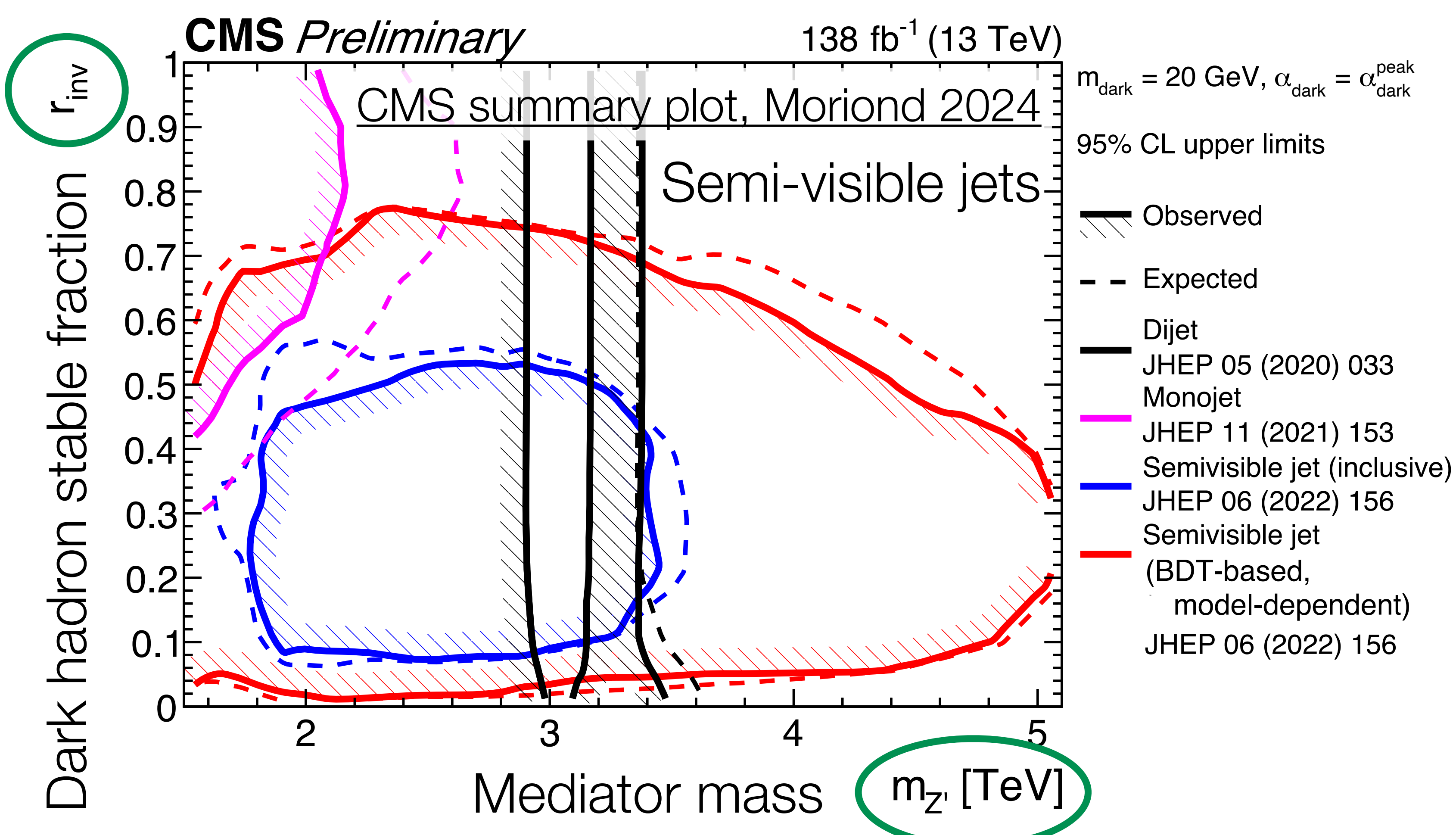


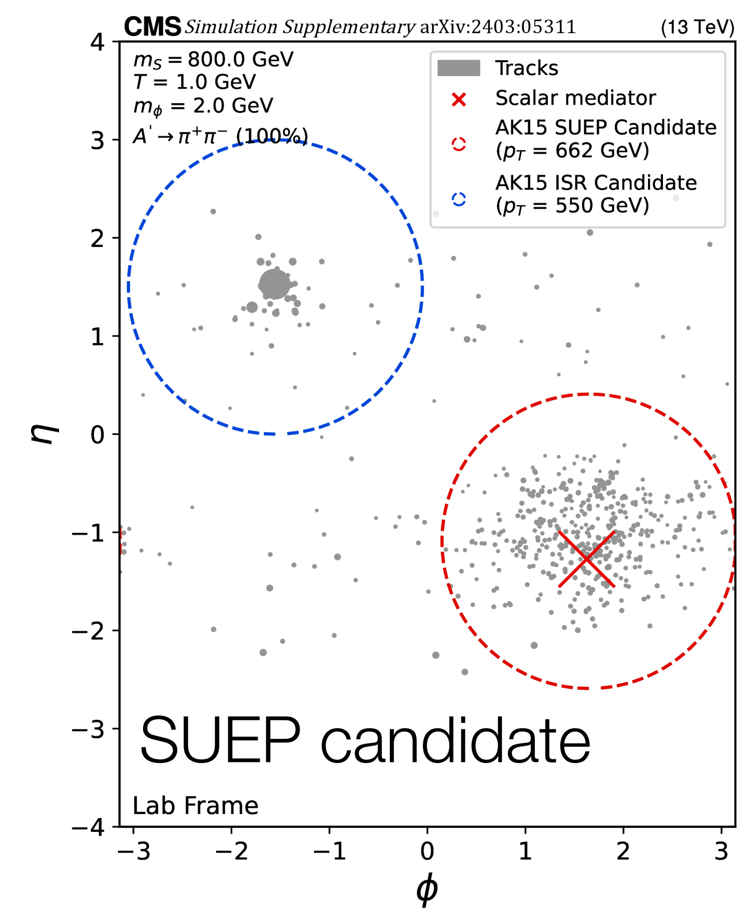
Can see 1) there is considerable space left for SUSY DM candidates in hard-to-reach electroweak signatures, and 2) there is good complementarity between LHC and direct detection reach

Extended dark sectors: growing area of interest

Assume numerous additional particles, one of which could provide stable DM candidate

Dark QCD & related give signatures with "weird jets": containing displaced vertices, high fraction of invisible particles, etc depending on model details. Other cases give no jets at all (e.g. SUEPs)



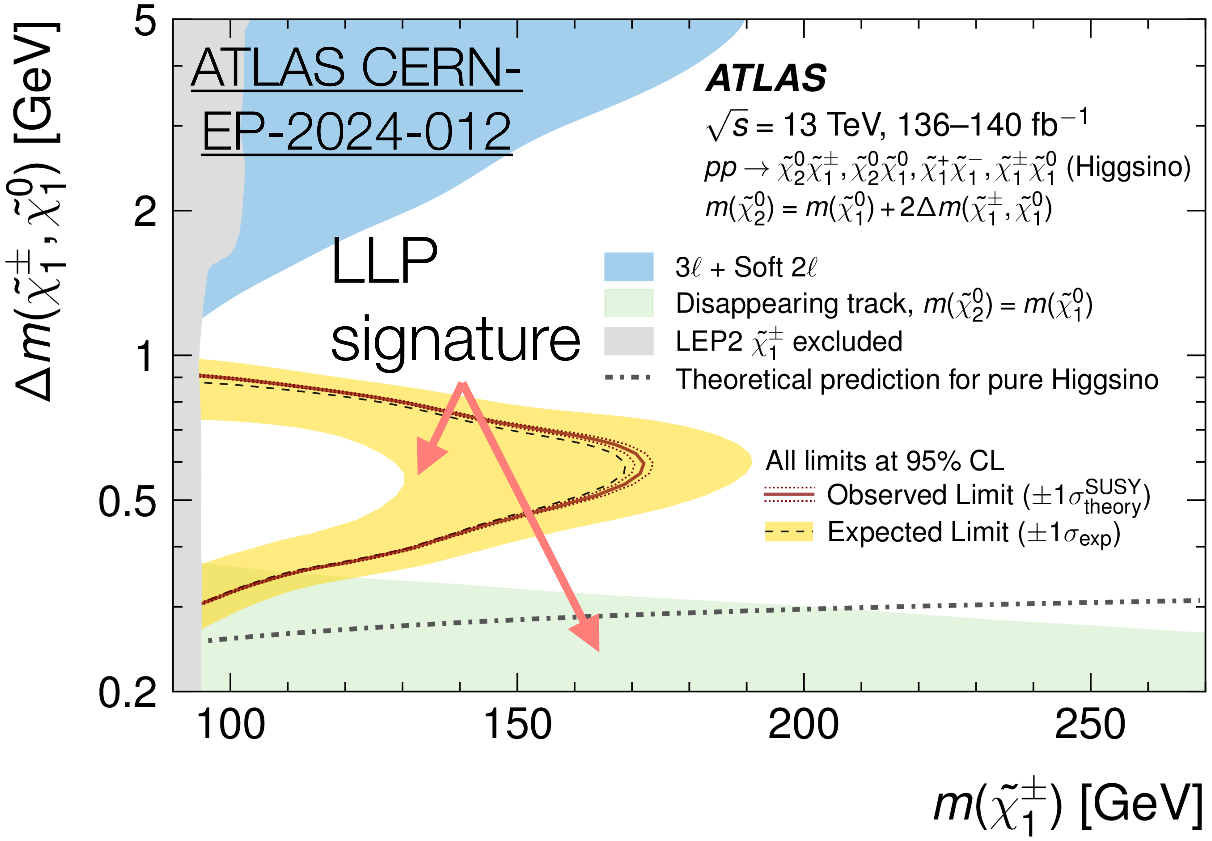


CMS EXO-23-002

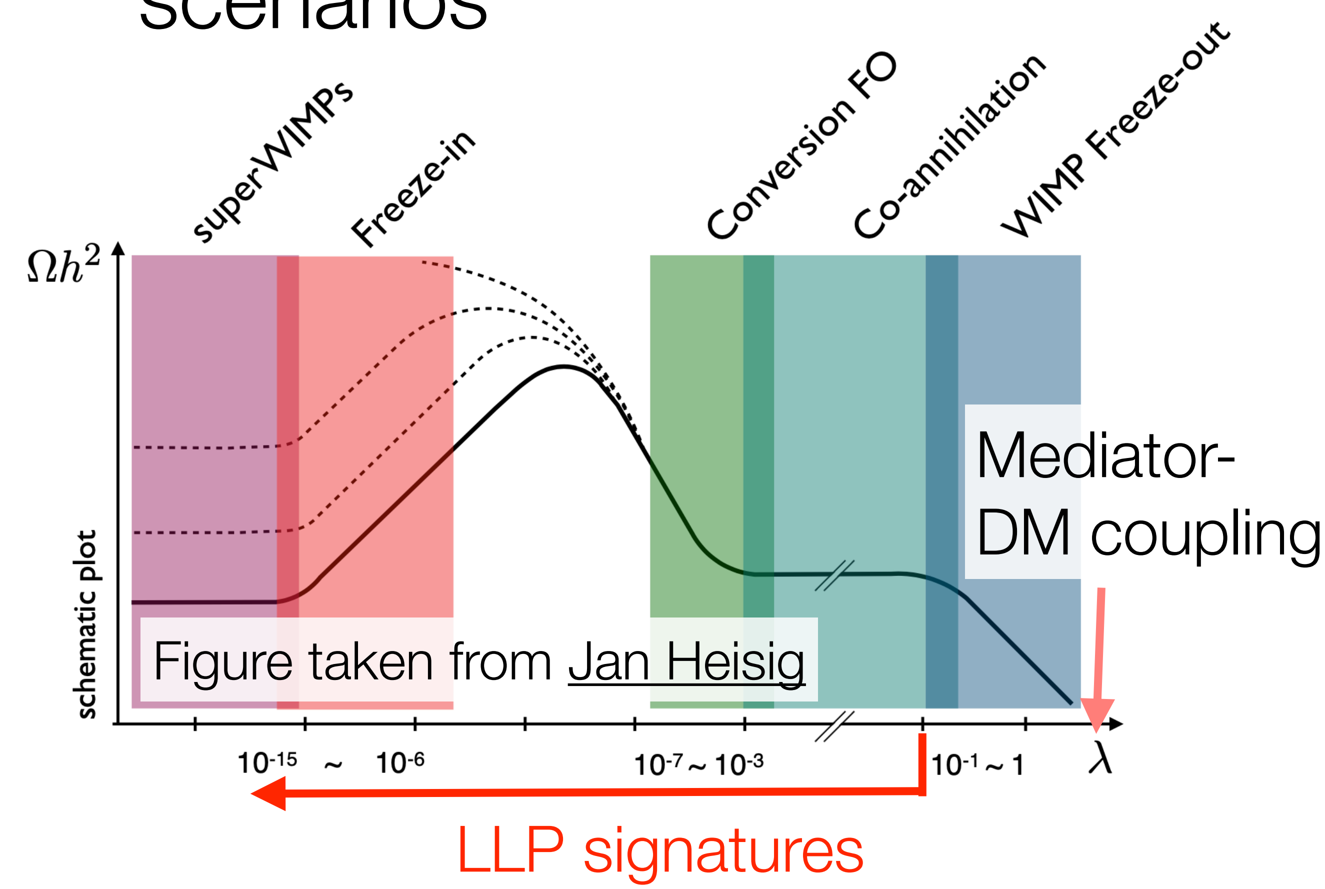
Long-lived particle searches

Saw one case already: displaced decays in dark photons with small ε. Other important examples:

Models with very small mass splittings, e.g. Higgsino DM



Freeze-in dark matter scenarios



Can get LLPs from small mass splittings or small couplings, and turn up frequently in asymmetric, freeze-in, & SUSY DM

DM at HL-LHC and future colliders

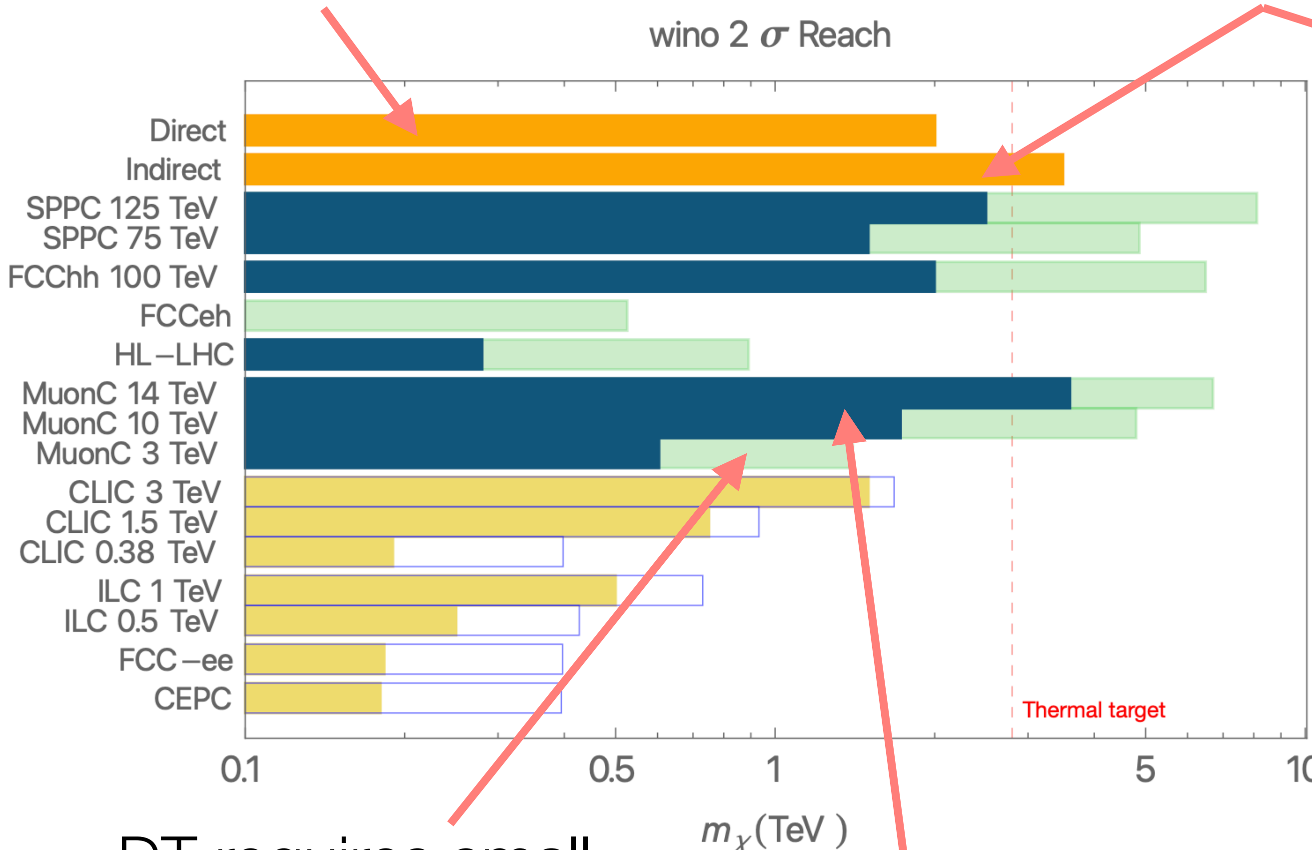
Opportunities at future colliders: SUSY DM

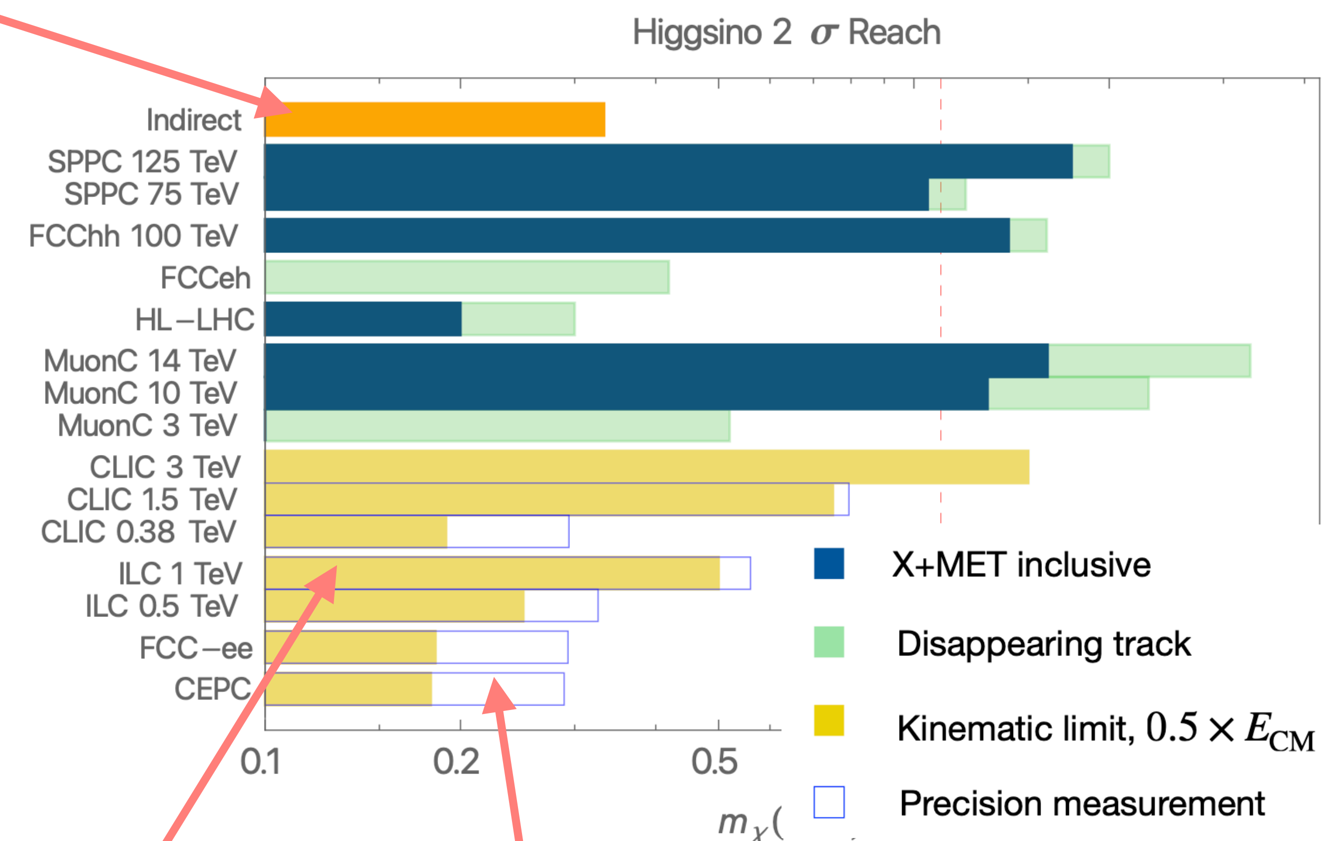
Minimal EW multiplet scenario: SM gauge couplings fix interactions so mass is only free parameter and thermal DM predictions simple.

DARWIN (50T) projection

FERMI & H.E.S.S.

DD below neutrino fog





DT requires small mass splittings

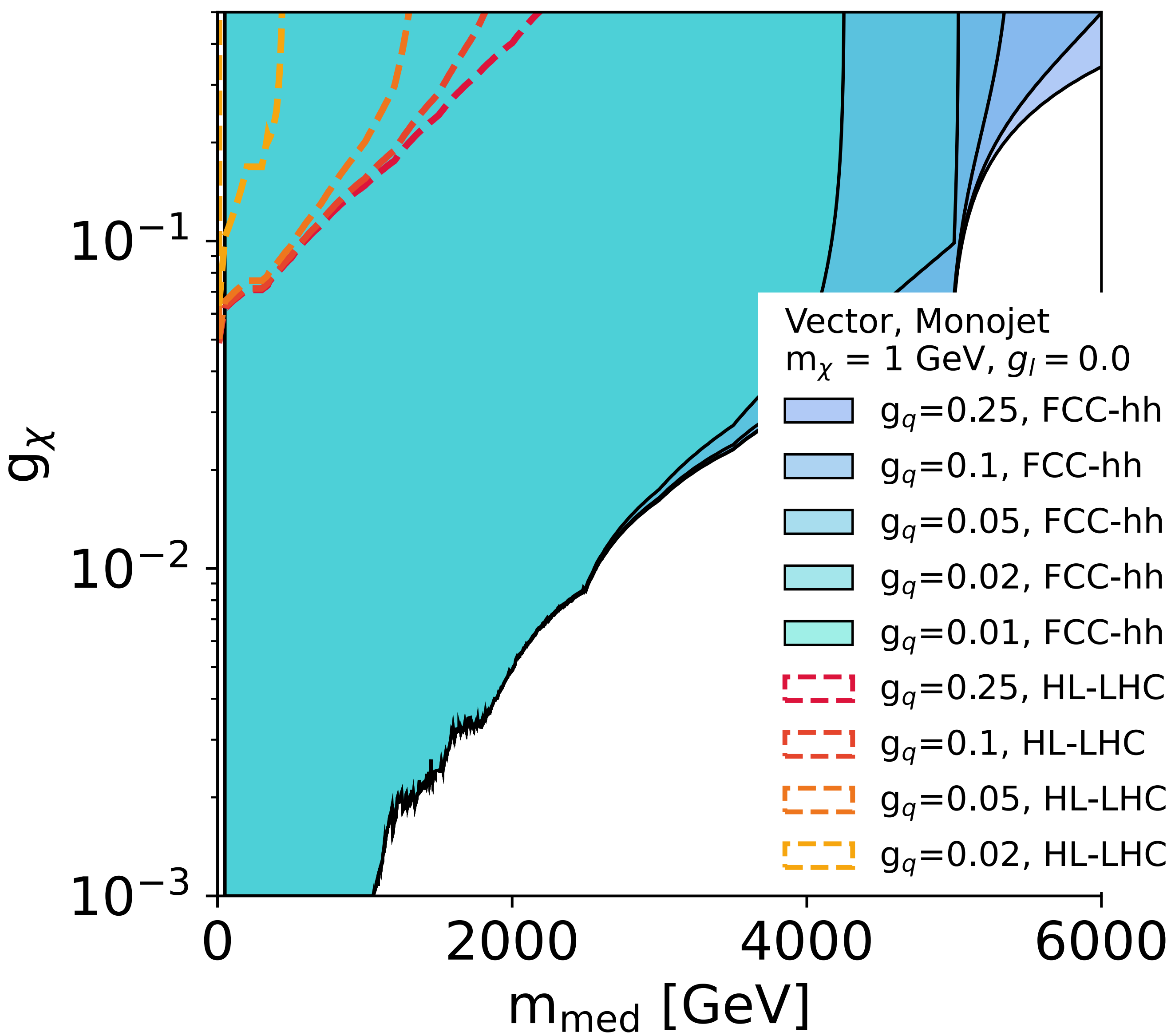
More general for other scenarios

Optimistic?

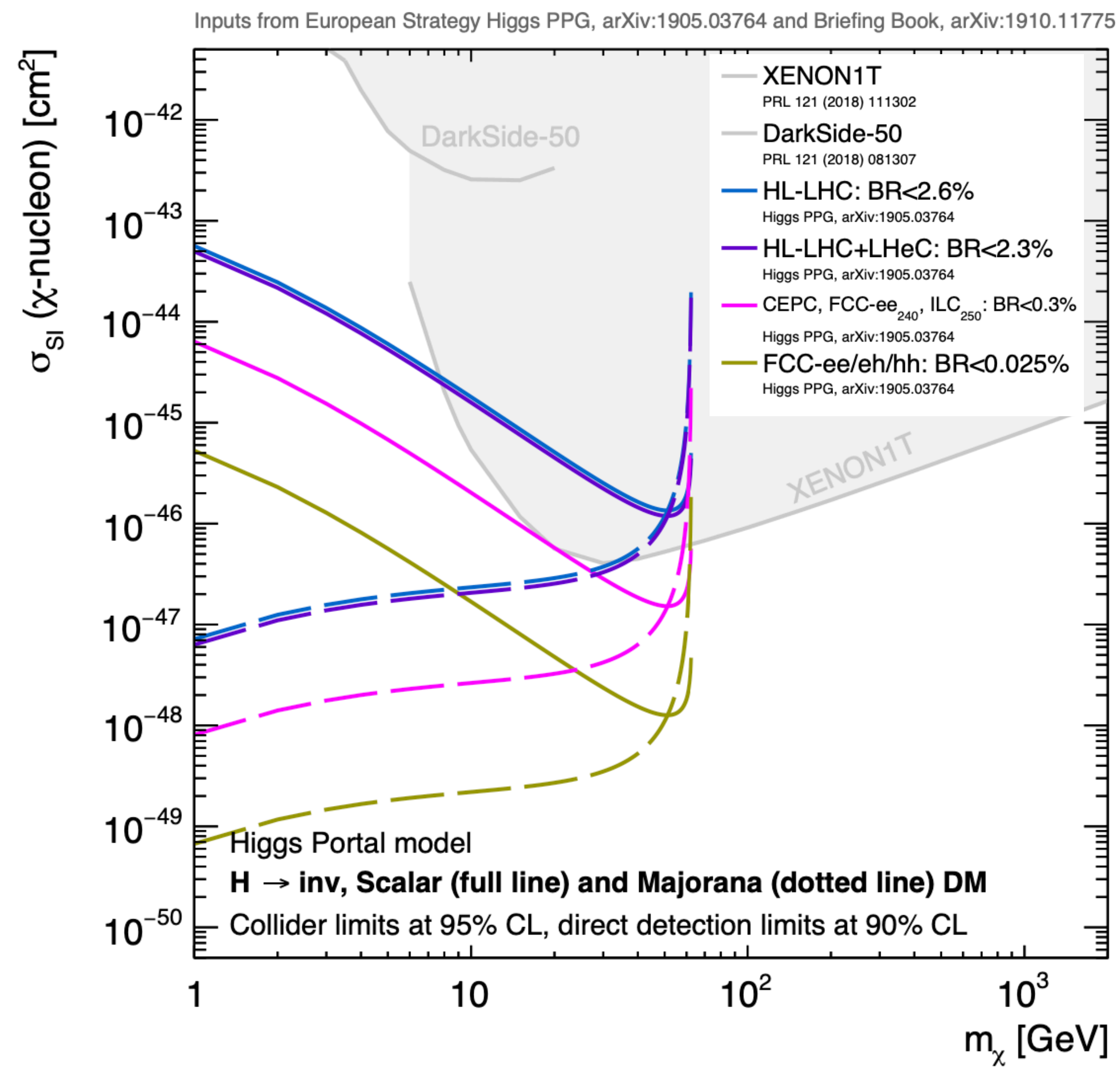
EW measurements set indirect but strong constraints

Reaching thermal target is not easy, but possible at some colliders

Opportunities at future colliders: non-SUSY DM



Spin-1 vector mediator: monojet sensitivity to DM coupling



Higgs portal: $H \to \mathbf{inv}$ sensitivity compared to current DD

Parasitic experiments at future colliders

Future colliders have possibilities beyond collision point detectors

Dedicated LLP experiments

Valuable when LLP signature is trigger limited

Limited use at e+e- machines but useful at hadron & probably muon machines

Different signatures can favour forward (FASER-esque) vs off-axis far detectors

Beam dump experiments

Missing energy/mass experiments not possible at EF machines

Could probably do a re-scattering experiment here but I've not seen it talked about

Visible decay searches are well suited and could be added to future colliders (examples 1, 2)

Discussing complementarity

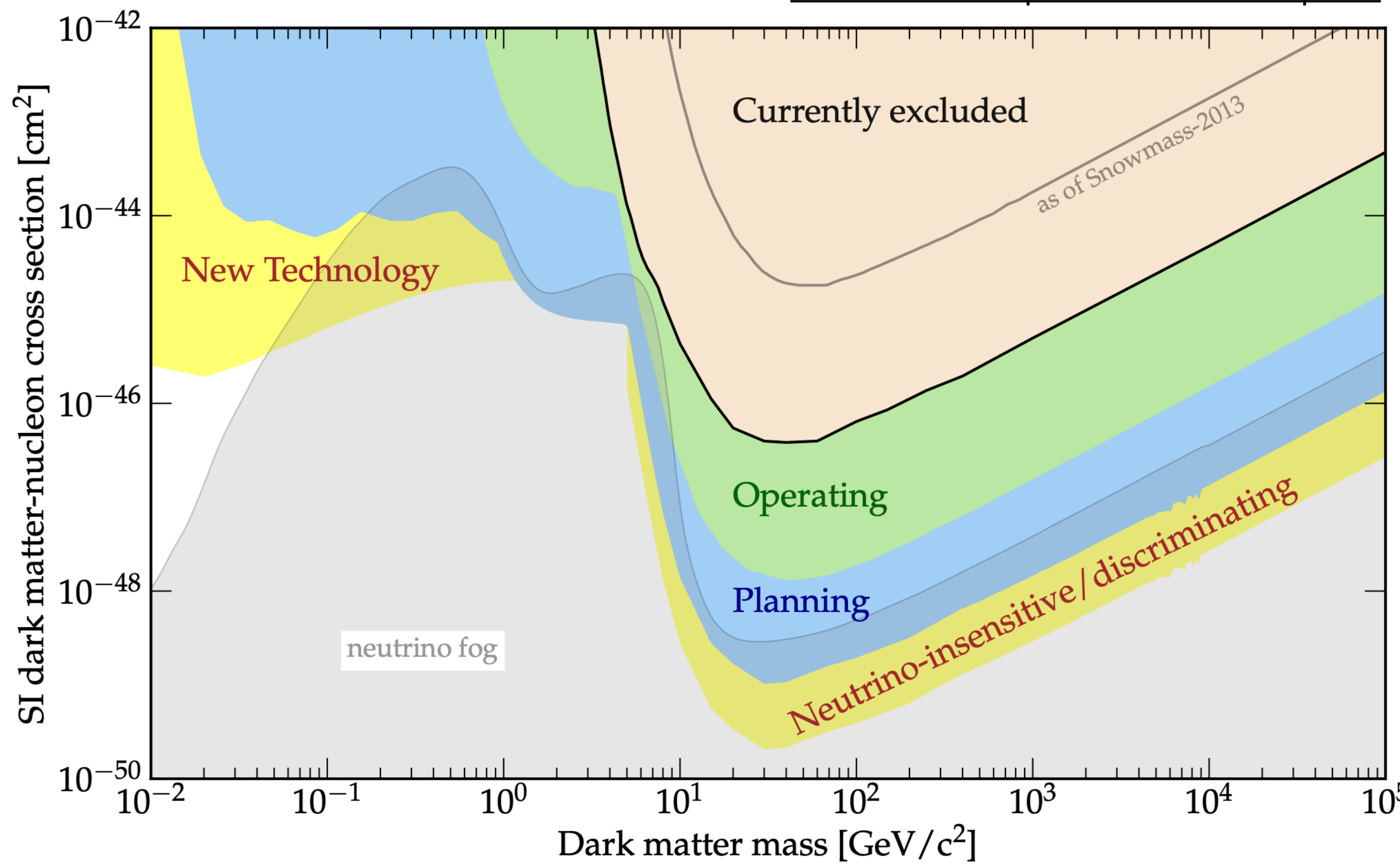
Mentioned earlier that we need to highlight complementary areas of strength between DD, ID, and future colliders

This will be key to building the field we want to see

Often easier said than done.

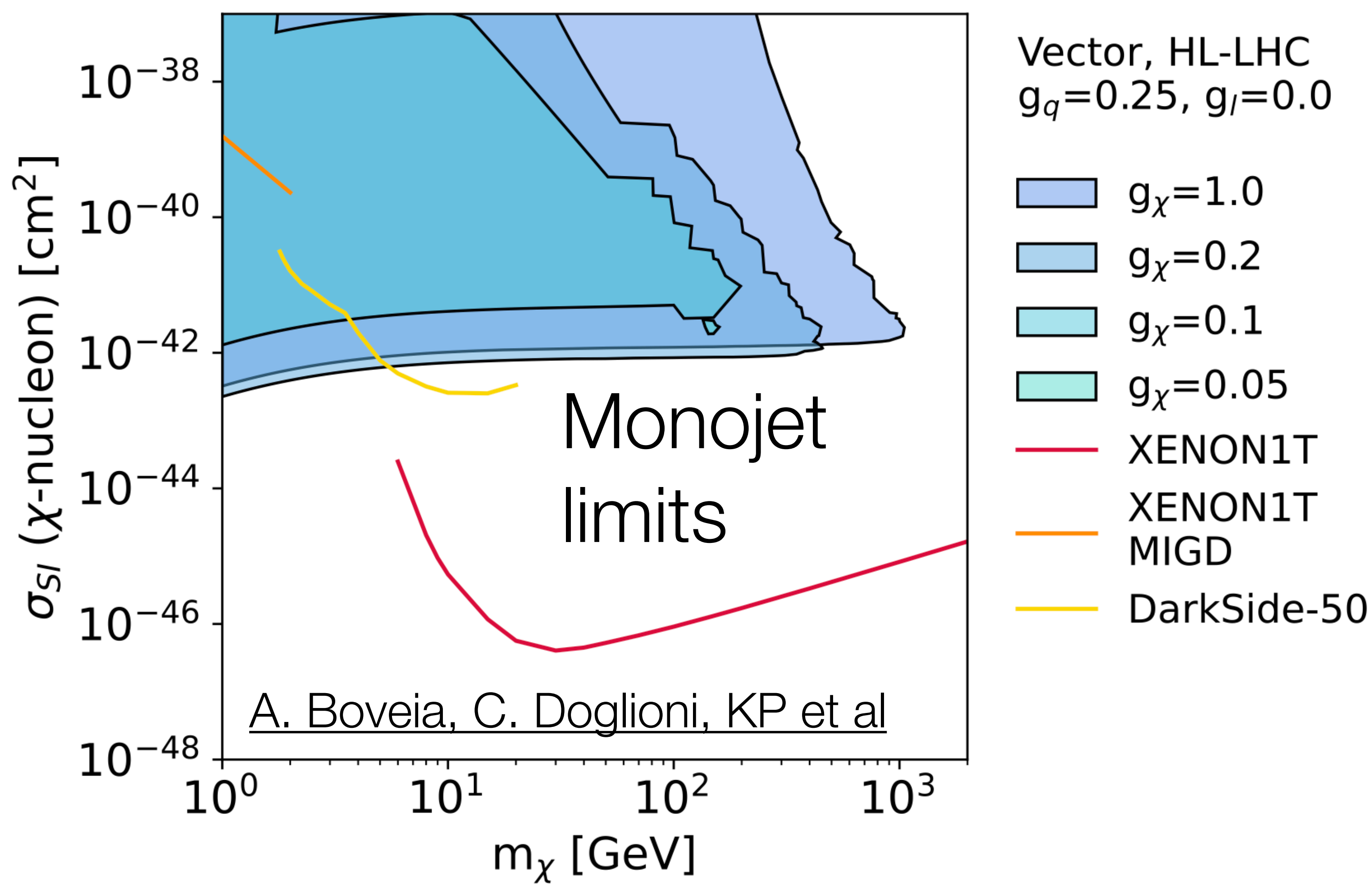
DD limits can use EFT; EF searches require model assumptions. Reducing problem dimensions to 2D plane usually needs extra assumptions

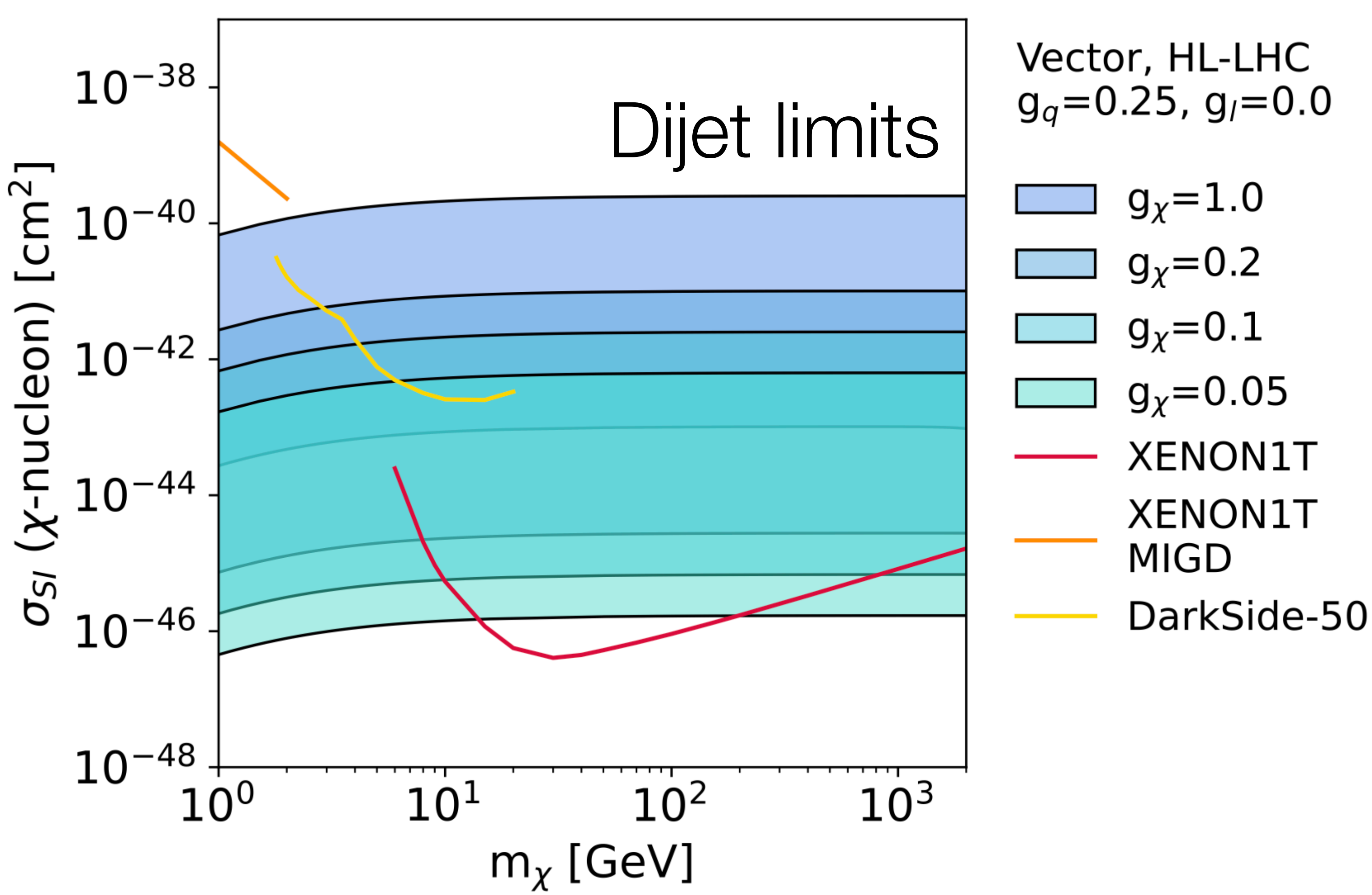
Snowmass particle DM report



Show example I know best: LHC DMWG spin-1 simplified model

Must reduce 4-5 free parameters (m_{med}, m_χ, g_{SM}, g_χ) to 2





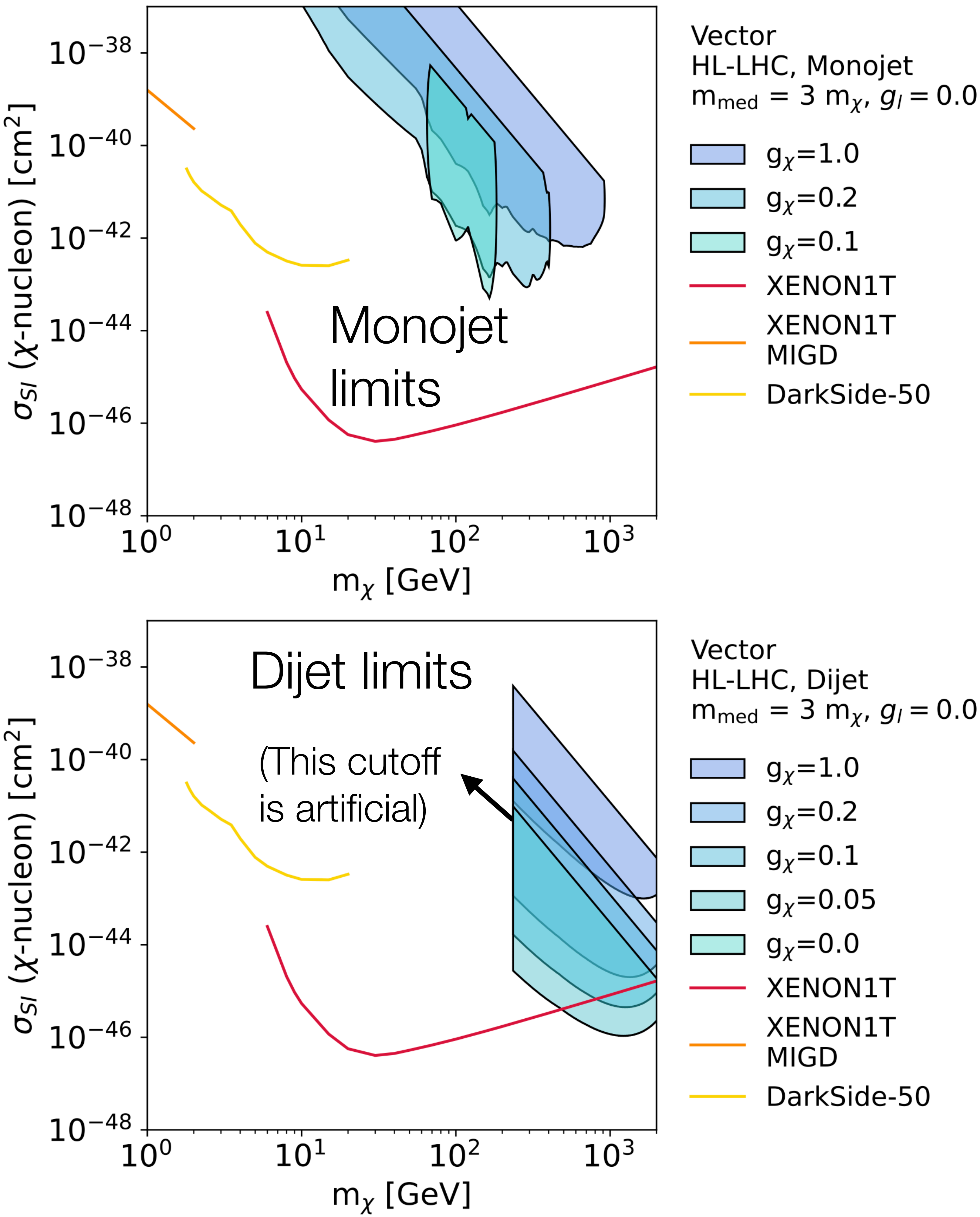
These are the type of projections we usually show from ATLAS and CMS

Couplings take explicit values

Mediator mass absorbed into y axis variable

Implication: no constraint on mediator mass

Points with strong collider limits have high mediator mass to DM mass ratio



Same concept, different projection into two dimensions

Now ratio between mediators is fixed and g_q is absorbed into y axis

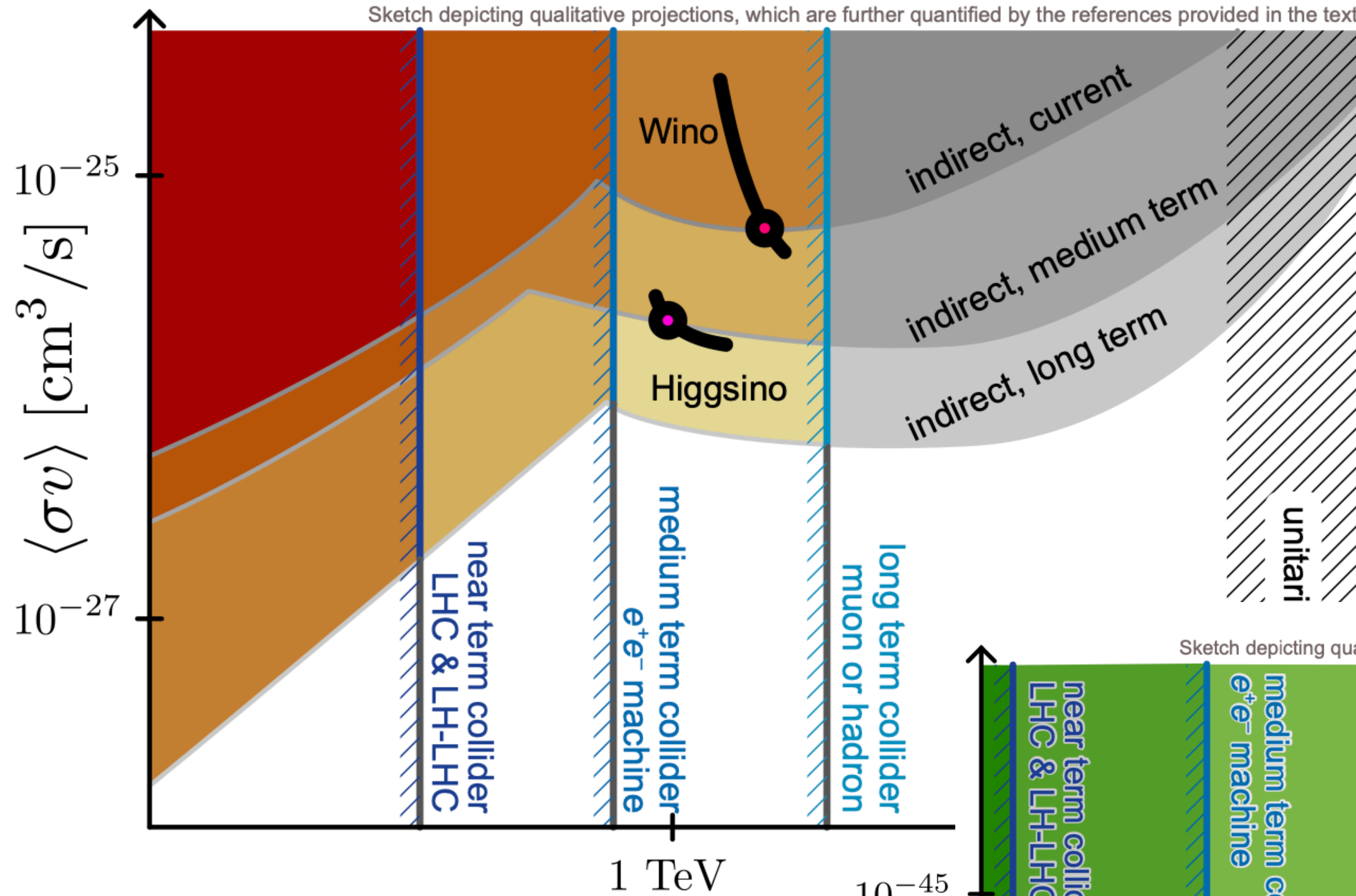
Colliders have unique strengths in accessing heavy mediators

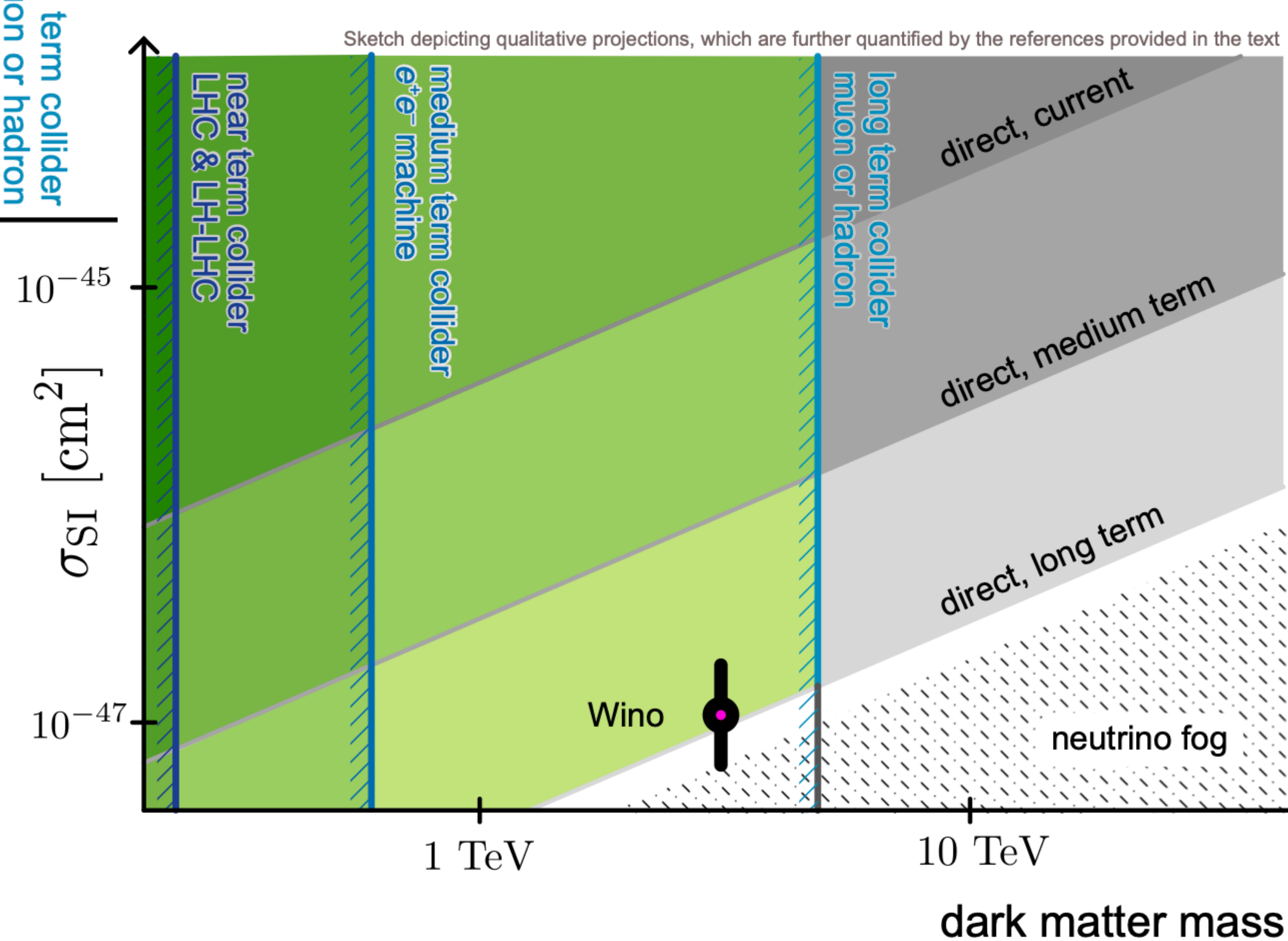
Direct detection has unique strengths in accessing small couplings

Must present both for complete picture

A few sketches from Snowmass dark matter complementarity report

arXiv:2210.01770





Wino & Higgsino DM candidate sensitivity vs mass for indirect and direct detection and future colliders

Conclusion

Conclusion

Dark matter searches at colliders are complicated, take many forms, and are still not fully explored

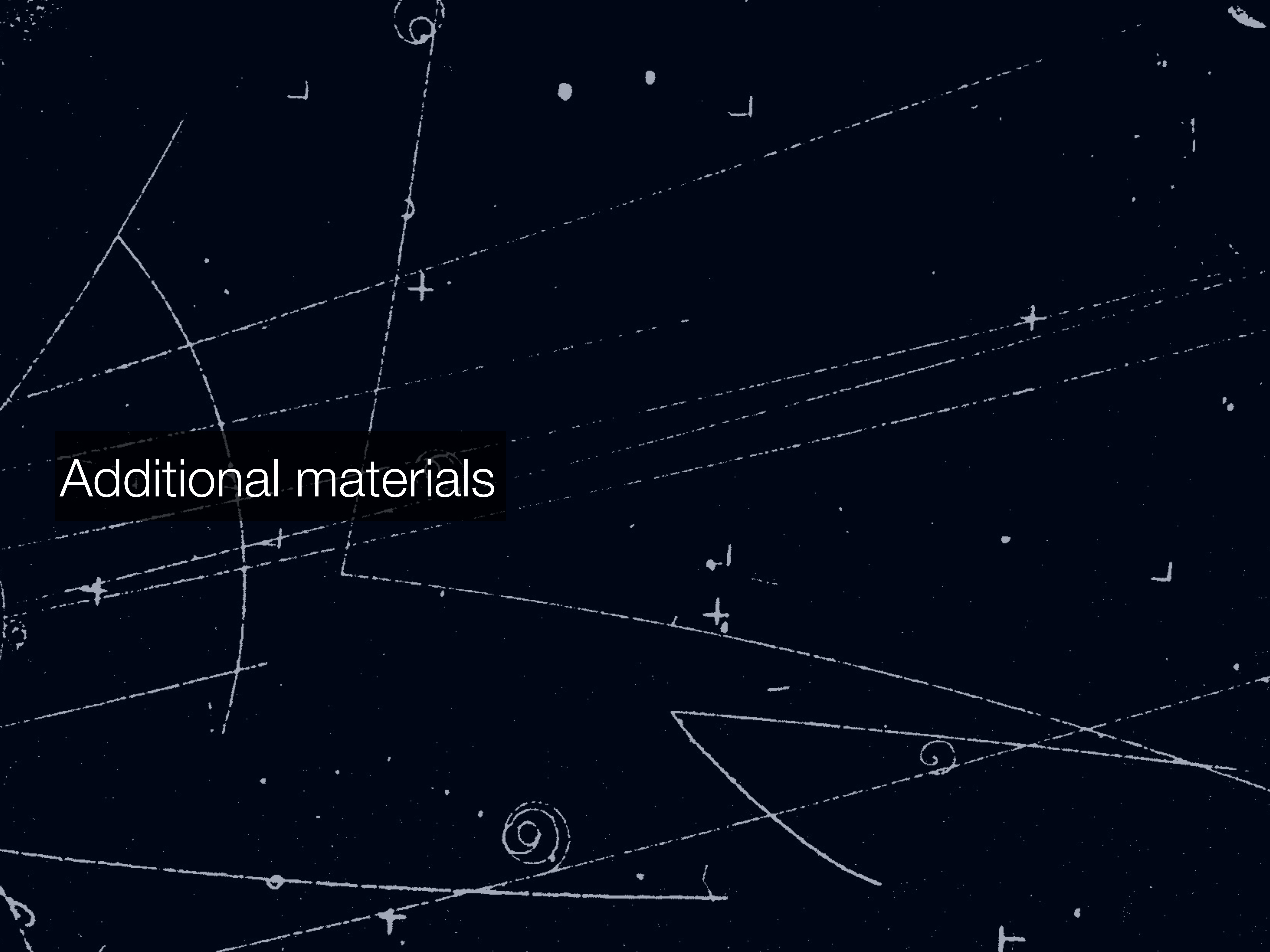
We rely on theory community to help us guide this work

There remains plenty of non-excluded space for cosmologically motivated particle dark matter above the ~GeV scale

There are also areas of DM phase space that only colliders can probe, just as there are areas that only direct or indirect detection experiments can probe

Complementarity, DM discovery potential, and the potential to exclude values aligning with cosmological observations should be thoroughly understood and included in future collider proposals

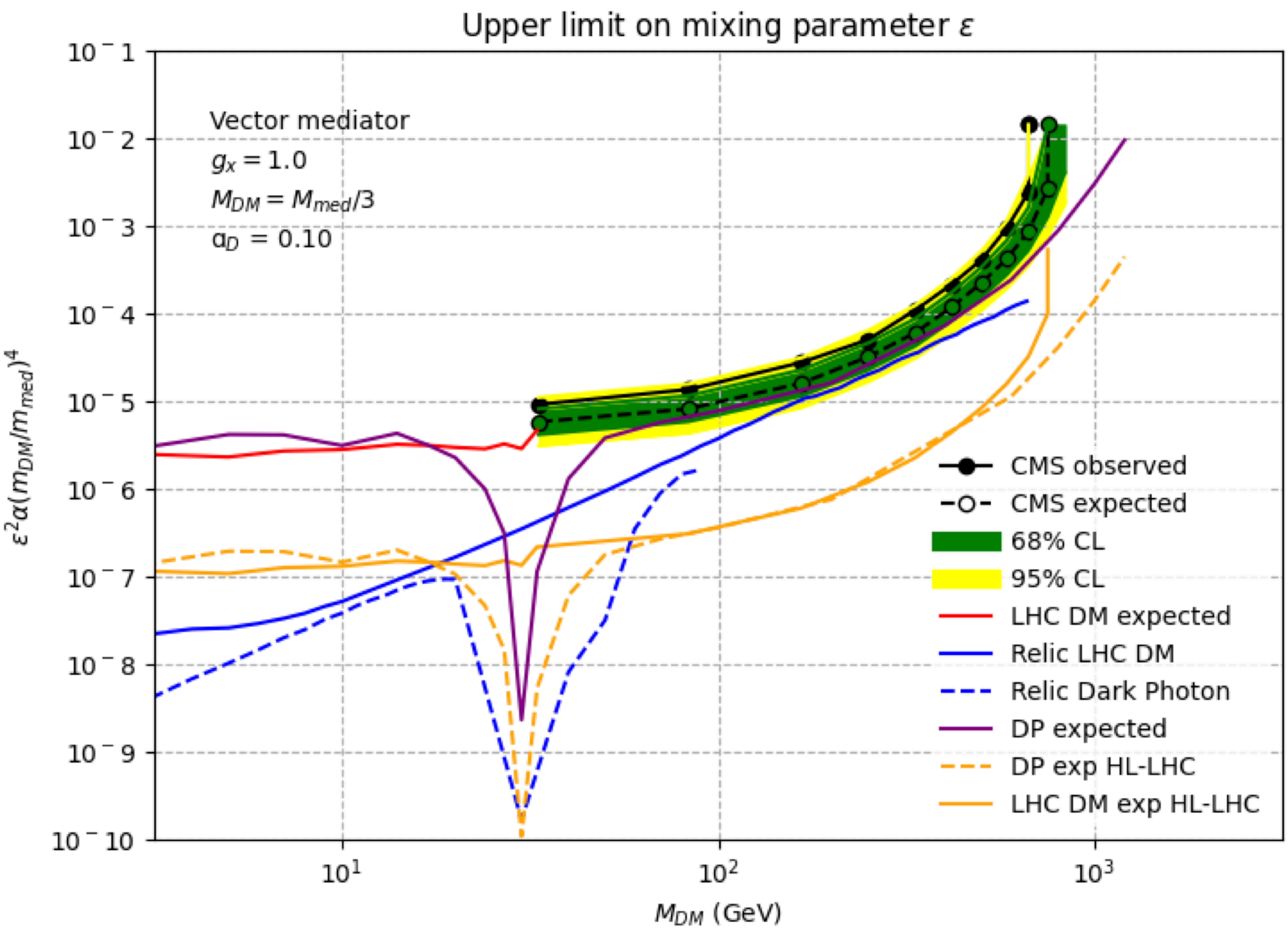
Additional materials



References

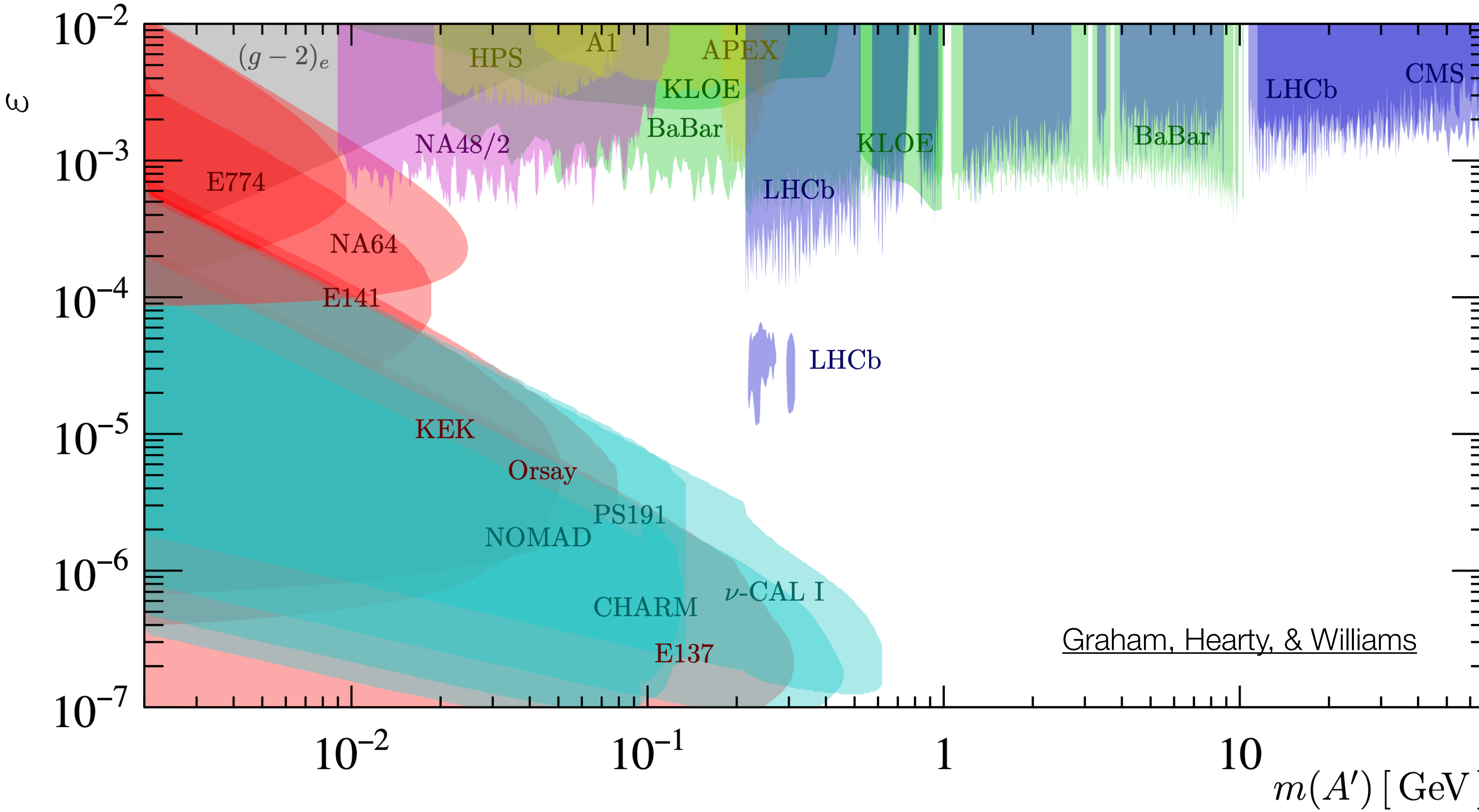
- LHC simplified models (s-channel mediators) arXiv:1507.00966
- LHC 2HDM+a model: arXiv:1810.09420
- Notes on Higgs portal: arXiv:2001.10750, arXiv:1903.03616
- Snowmass BSM topical group report arXiv:2209.13128
- Snowmass particle dark matter topical group report arXiv:2209.07426
- Snowmass DM complementarity report: arXiv:2210.01770
- Spin-1 projection comparisons for HL-LHC and FCC arXiv:2206.03456
- European Strategy briefing document: cds link

Comparison between true dark photon model and LHC simplified Z' mediator model, demonstrating good agreement above Z peak



A. Boveia, C. Doglioni, P. Harris, KP, et al

Current limits on visible dark photon decays, by experiment



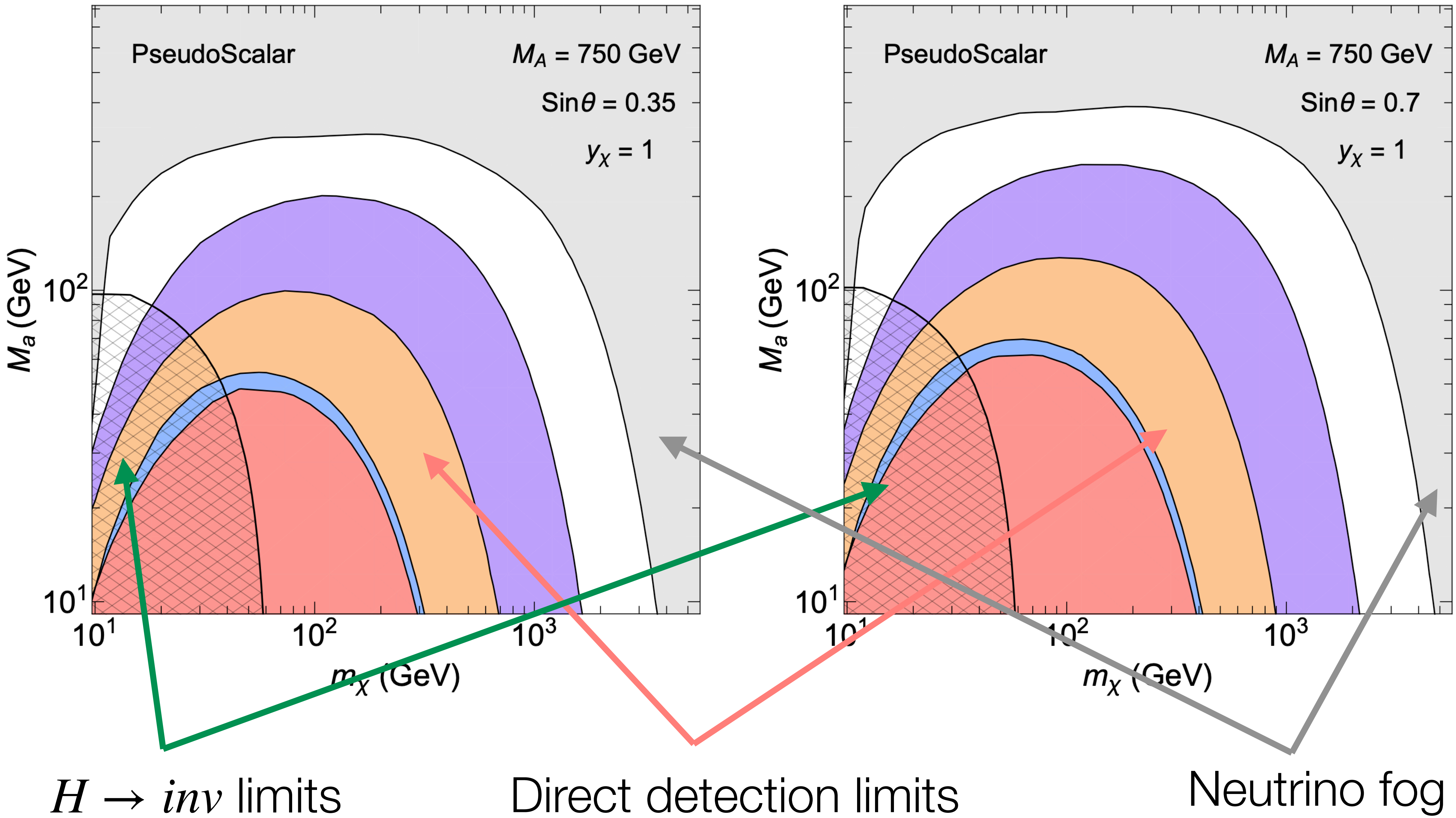
2HDM+a model and parameter choice description

The model considered here is the 2HDM+a model suggested by the LHC DM Working Group, which is the simplest gauge-invariant and renormalizable ultraviolet completion of the simplified pseudoscalar model initially recommended by the LHC DM Forum, which only contained the DM candidate and the mediator. This model is a type-II two-Higgs-doublet (2HDM) model to which an additional pseudoscalar *a* and a fermionic DM candidate χ are added. After electroweak symmetry breaking, the 2HDM contains five Higgs bosons: a lighter CP-even boson, h, a heavier CP-even boson, H, a CP-odd boson, A, and two charged bosons, $H\pm$. While the phenomenology of the model would be determined by 14 free parameters, some benchmark choices are made in order to match *h* with the observed SM Higgs boson, to ensure the stability of the Higgs potential, or to evade electroweak precision measurement constraints. In the end, the benchmarks are defined by five parameters: the mass of the heavy Higgs bosons, which are taken to be degenerate, $m_A = m_H = m_{H\pm}$; the mass of the pseudoscalar mediator, m_A; the mass of the DM particle, m_χ; the mixing angle θ between the two CP-odd states a and A; and the ratio of the vacuum expectation values of the two Higgs doublets, tan β.

ATLAS EXOT-2023-14

Shape of direct detection exclusions in 2HDM+a model, M_a vs m_χ plane. Requires fixing of other three parameters

LHC Dark Matter Working Group



How spin-1 simplified model to DD plane conversion works

For details, see this talk

$$\sigma_{\mathrm{SI}} \simeq 6.9 \times 10^{-41}\ \mathrm{cm}^2 \cdot \left(\frac{g_q g_{\mathrm{DM}}}{0.25}\right)^2 \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\mathrm{GeV}}\right)^2$$

1 variable

3 variables

Fix two and the other one becomes the thing that changes as σ_{SI} changes.

Implications and consequences can be very different, but can also be somewhat opaque when just looking at final 2D plot.