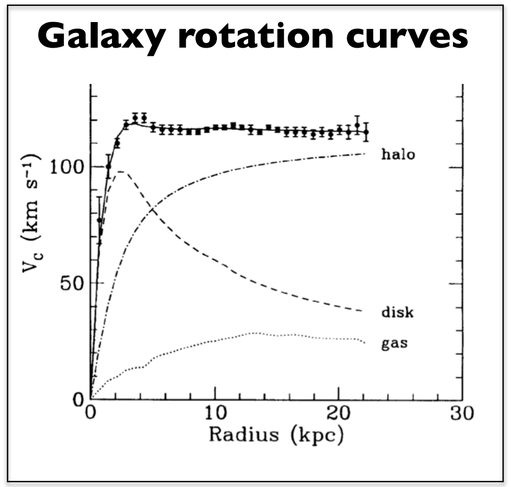
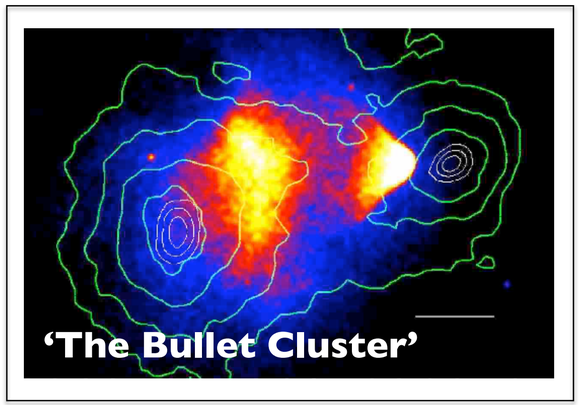
(Particle) dark matter theory

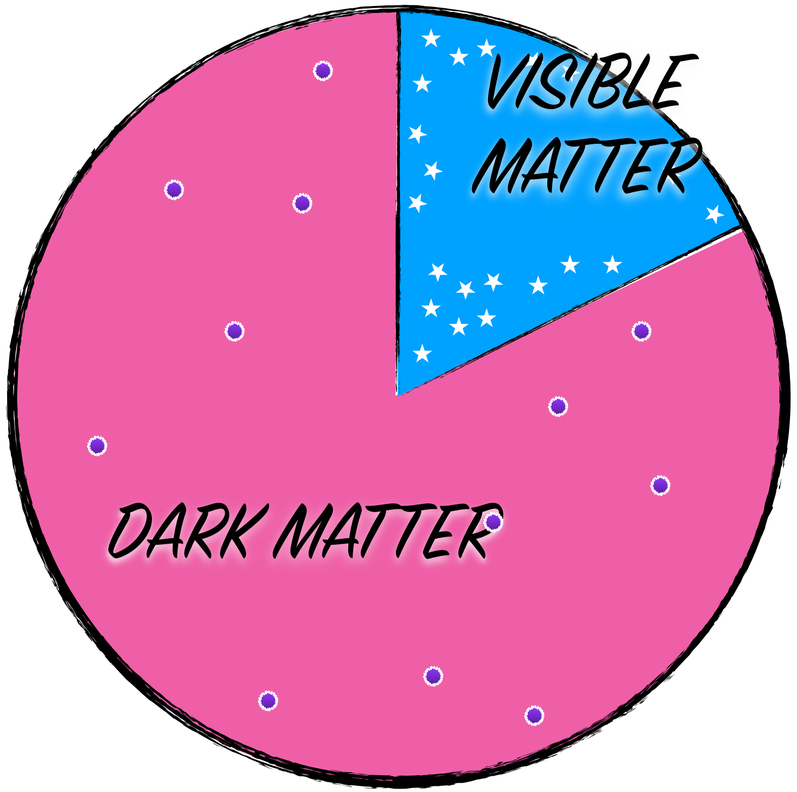
Christopher McCabe

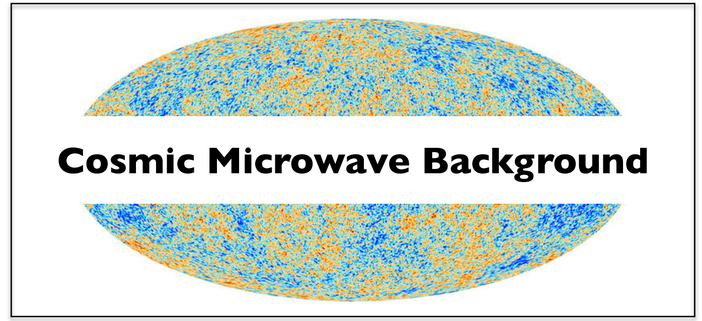
ECFA-UK Meeting, IPPP, 23 September 2024

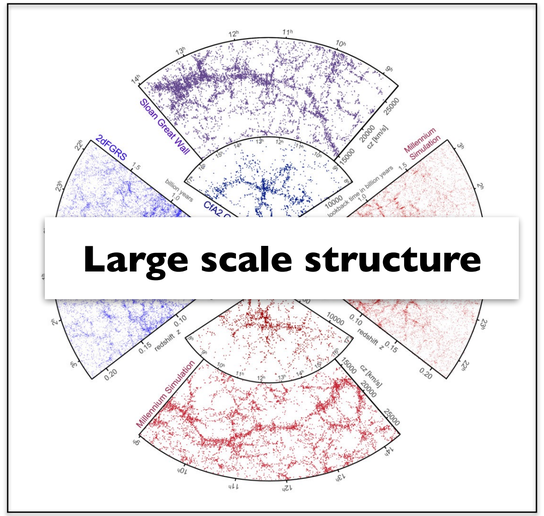
The problem *isn't discovering* dark matter…





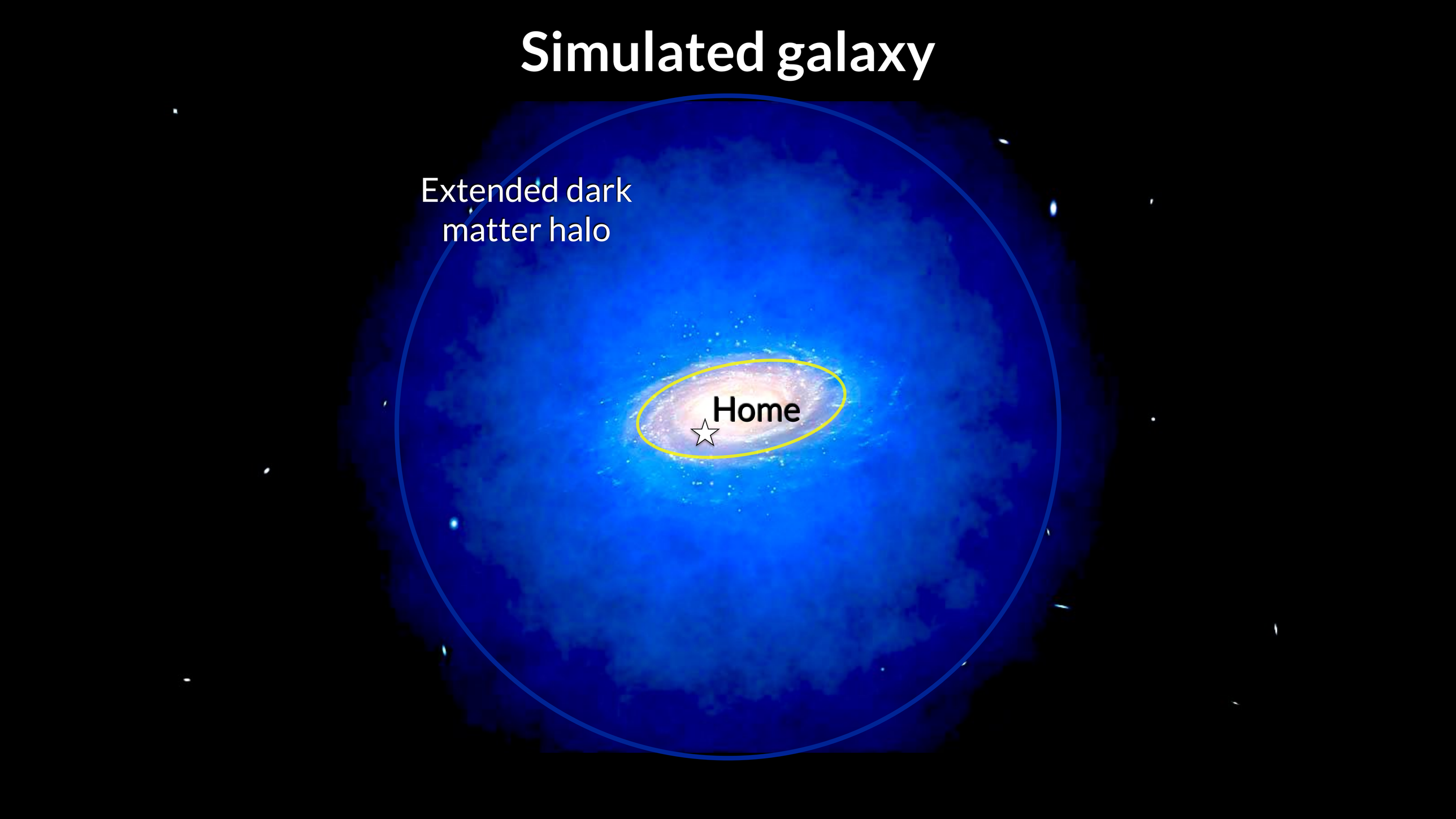




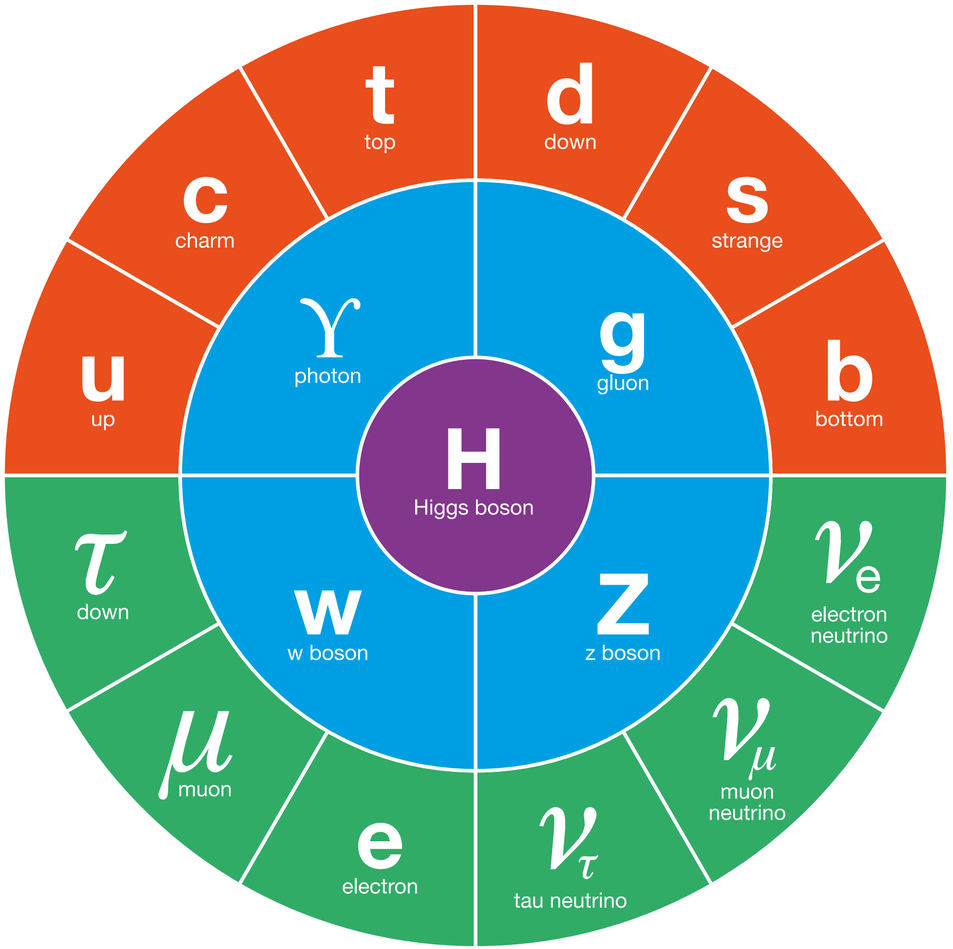


Existence of dark matter on astrophysical and cosmological scales is known and well characterised

Simulated galaxy



The problem is *characterising* dark matter...



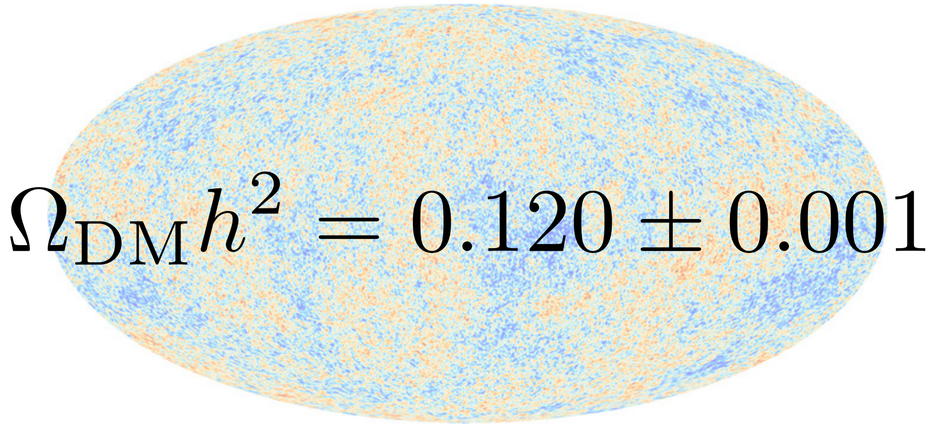
DM
dark matter

Dark Matter Particle (X^0)

X^0 mass: $m = ?$
X^0 spin: $J = ?$
X^0 parity: $P = ?$
X^0 lifetime: $\tau = ?$
X^0 interactions with normal matter?

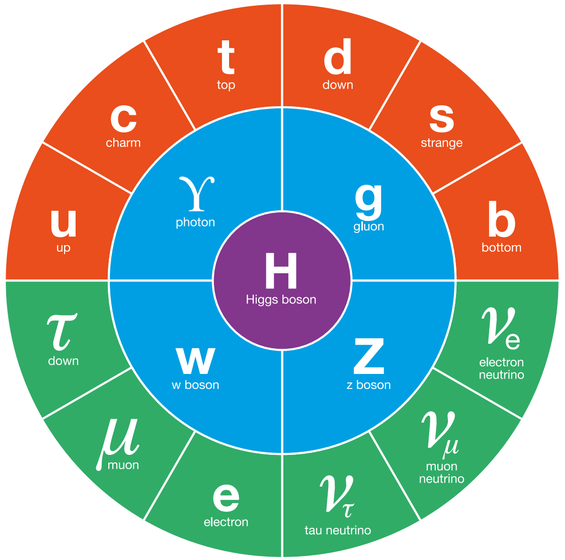
Cosmology and Particle Physics give clues

Cosmology



$$\Omega_{\rm DM} h^2 = 0.120 \pm 0.001$$

Particle Physics



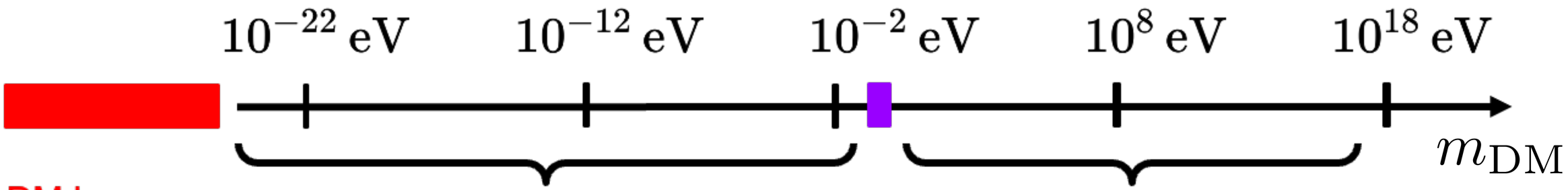
DM
dark matter

Explaining this value suggests dark and visible matter interactions are generic

&

Informs and limits the possible interactions

DM landscape: classifying by mass



DM lower mass bound at ~10^{-23} eV

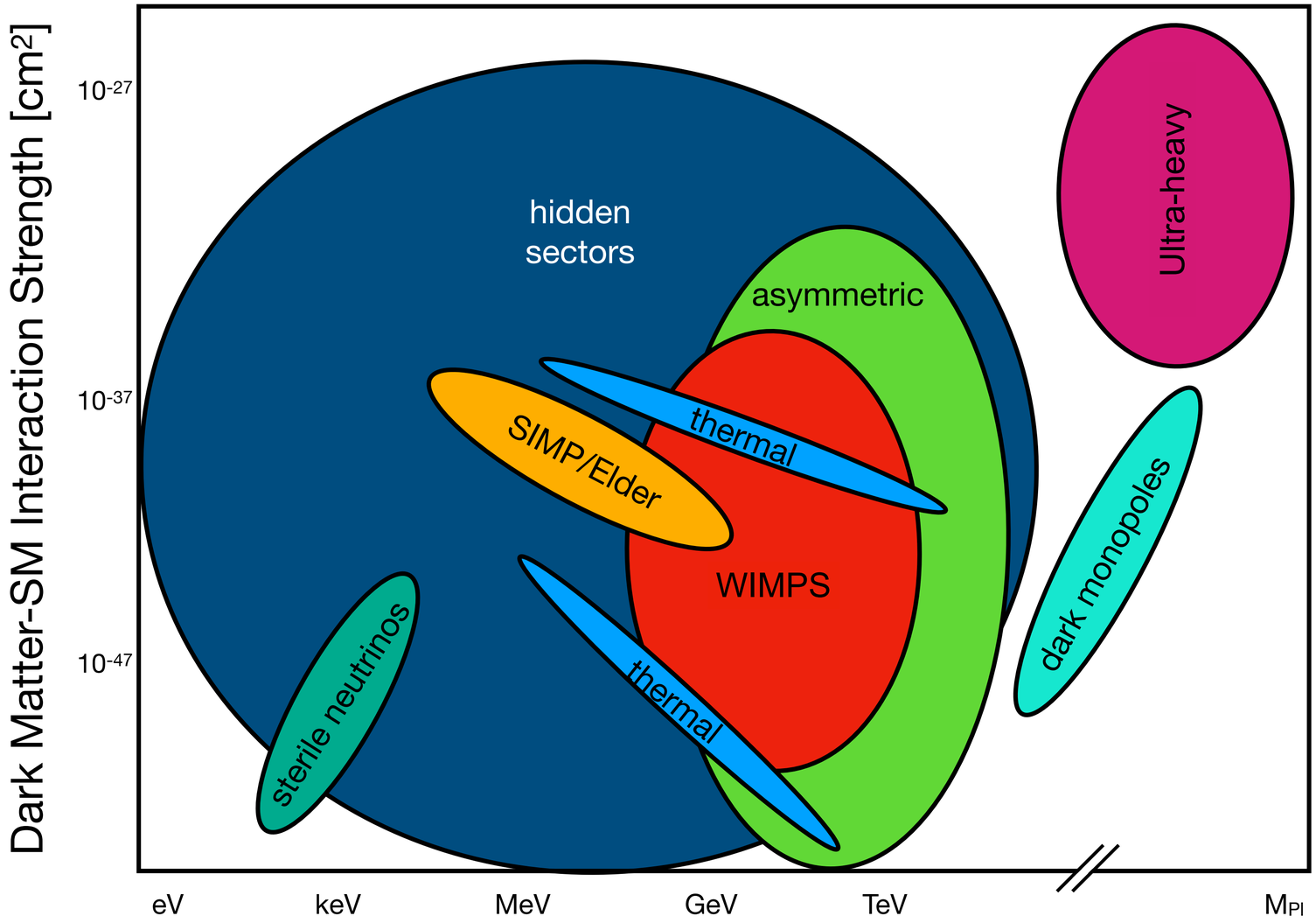
Classical wave-like behaviour (only bosonic candidates)

Tremain-Gunn bound at ~100 eV

Particle-like behaviour (fermionic and bosonic candidates)

This talk

Particle DM landscape: many possibilities



Cooley et al
arXiv:2209.07426

How can we make progress?

Cosmic Frontier's recommendation:

Delve deep (cover high priority targets e.g., WIMPs)

Search wide (explore as much DM parameter space as possible)

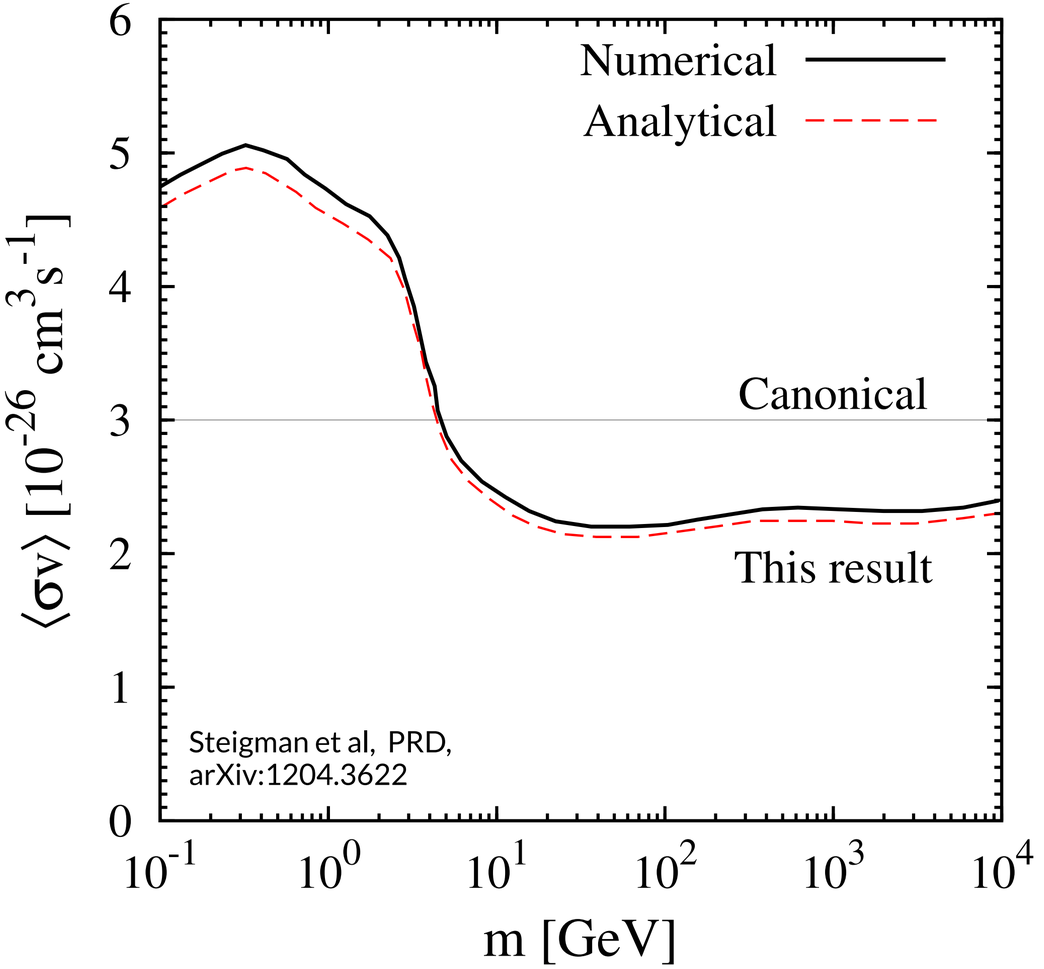
Cooley et al
arXiv:2209.07426

High priority target: WIMPs

'Delve deep'

- (Probably) the most studied DM candidate
- 'Natural' mechanism to produce the observed relic abundance '*WIMP-miracle*'
- One-to-one correspondence with a single particle physics input:

  Annihilation cross-section with SM particles
- Embedded in theories that alleviate the 'hierarchy problem' (SUSY, etc)
  - Idea of '*Natural WIMPs*' but '*Unnatural WIMPs*' also work

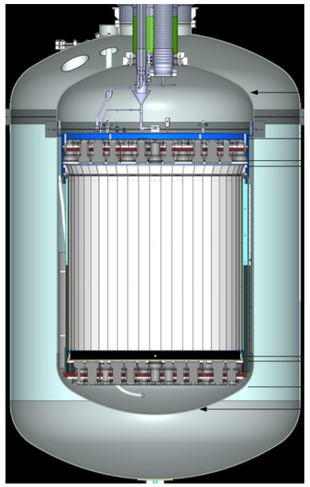


High priority target: WIMPs

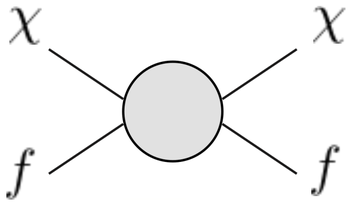
'Delve deep'

- The 'single particle physics' input focussed minds
- Produced many complementary searches:

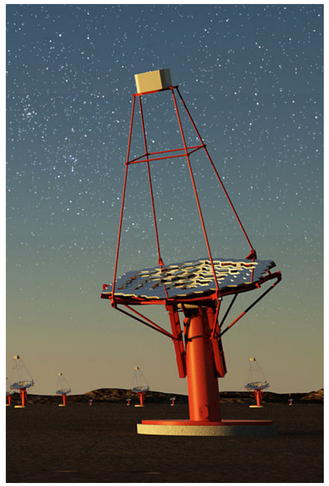
Direct detection



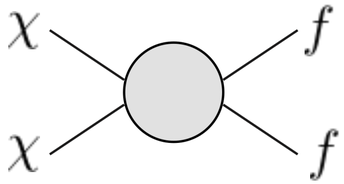
Shake it



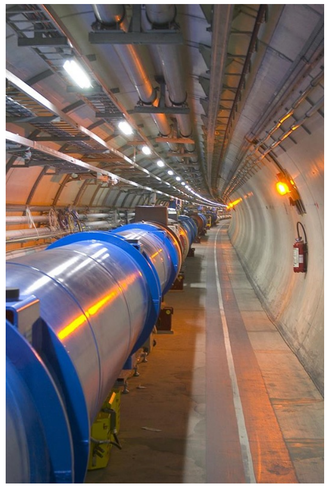
Indirect detection



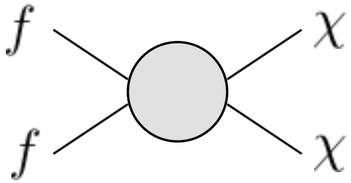
Break it



Collider



Make it



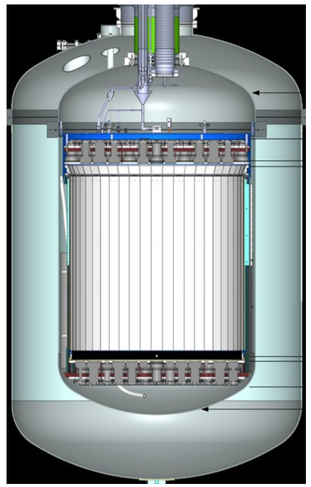
+ …

High priority target: WIMPs

'Delve deep'

- Also somewhat of an industry for theorists to probe models from many directions

Direct detection



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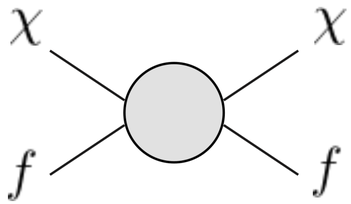
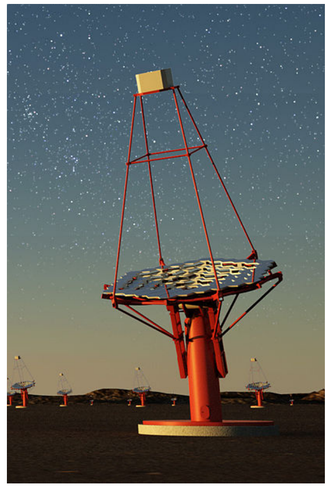


Indirect detection



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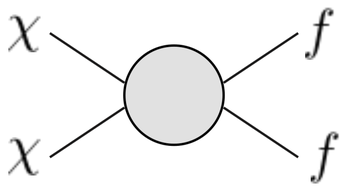
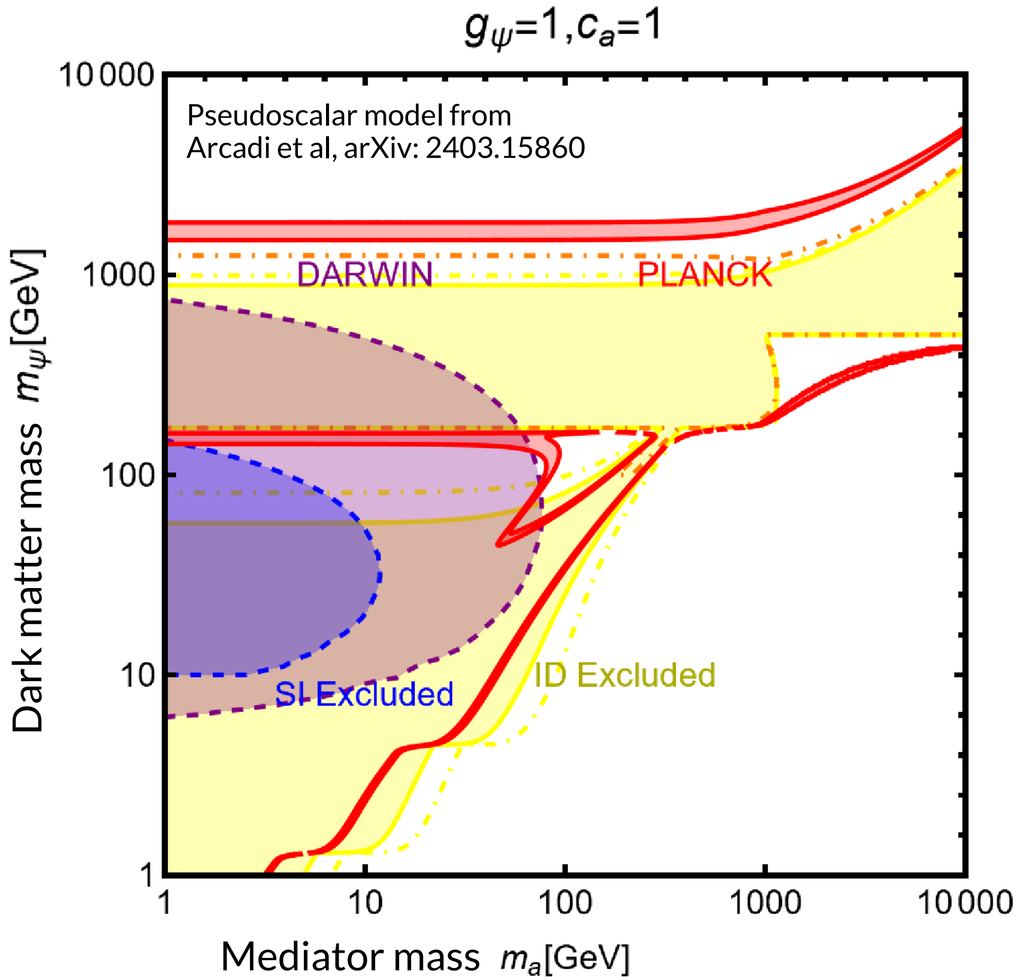
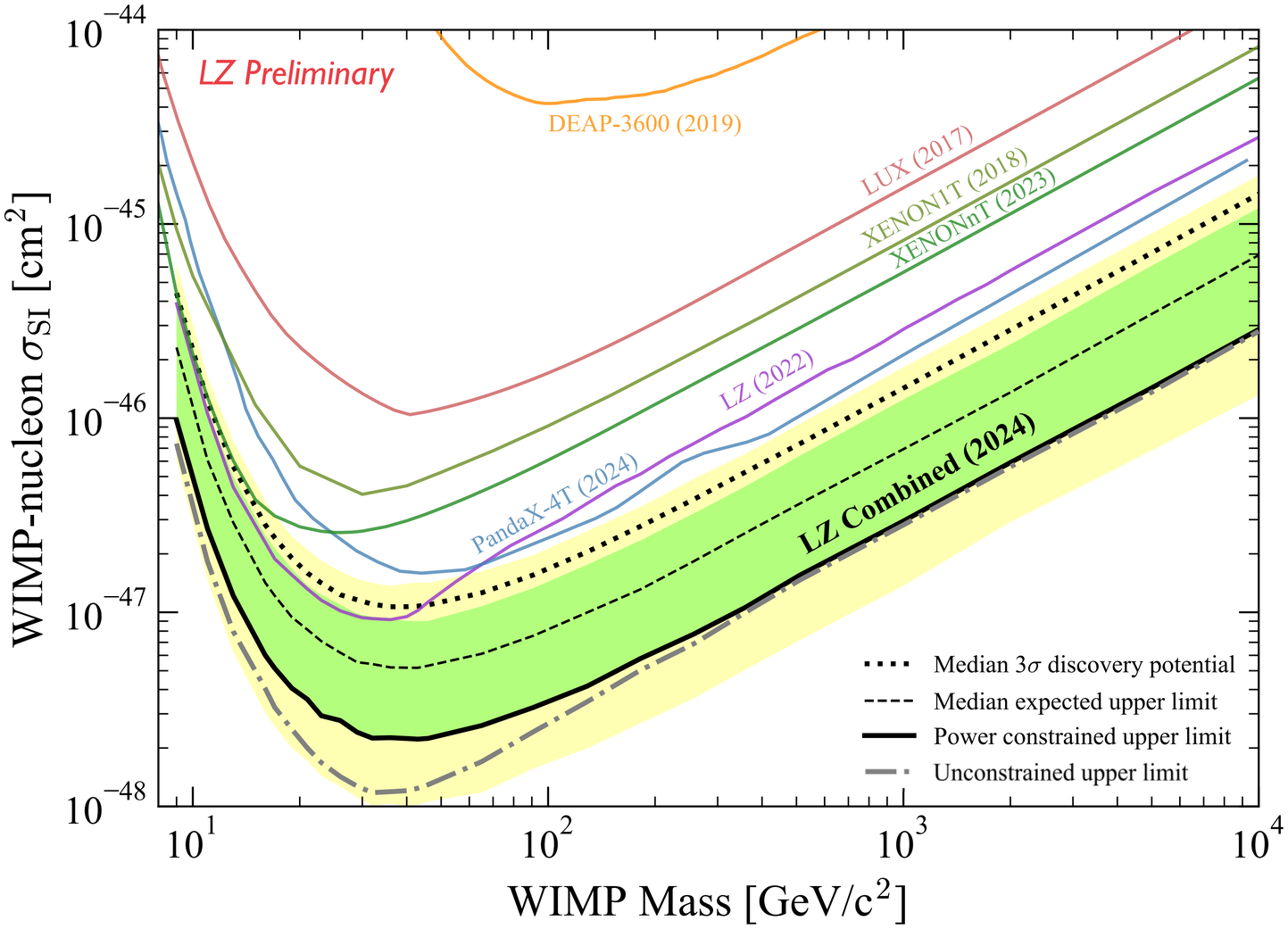




WIMPs: What has direct detection taught us so far?

'Delve deep'



@~10^{-39} cm^2: *Z*-mediated (spin-independent) interactions: *excluded*

@~10^{-44} cm^2 and below: Higgs-mediated interactions: *putting pressure on this channel*

WIMPs: What has direct detection taught us so far?

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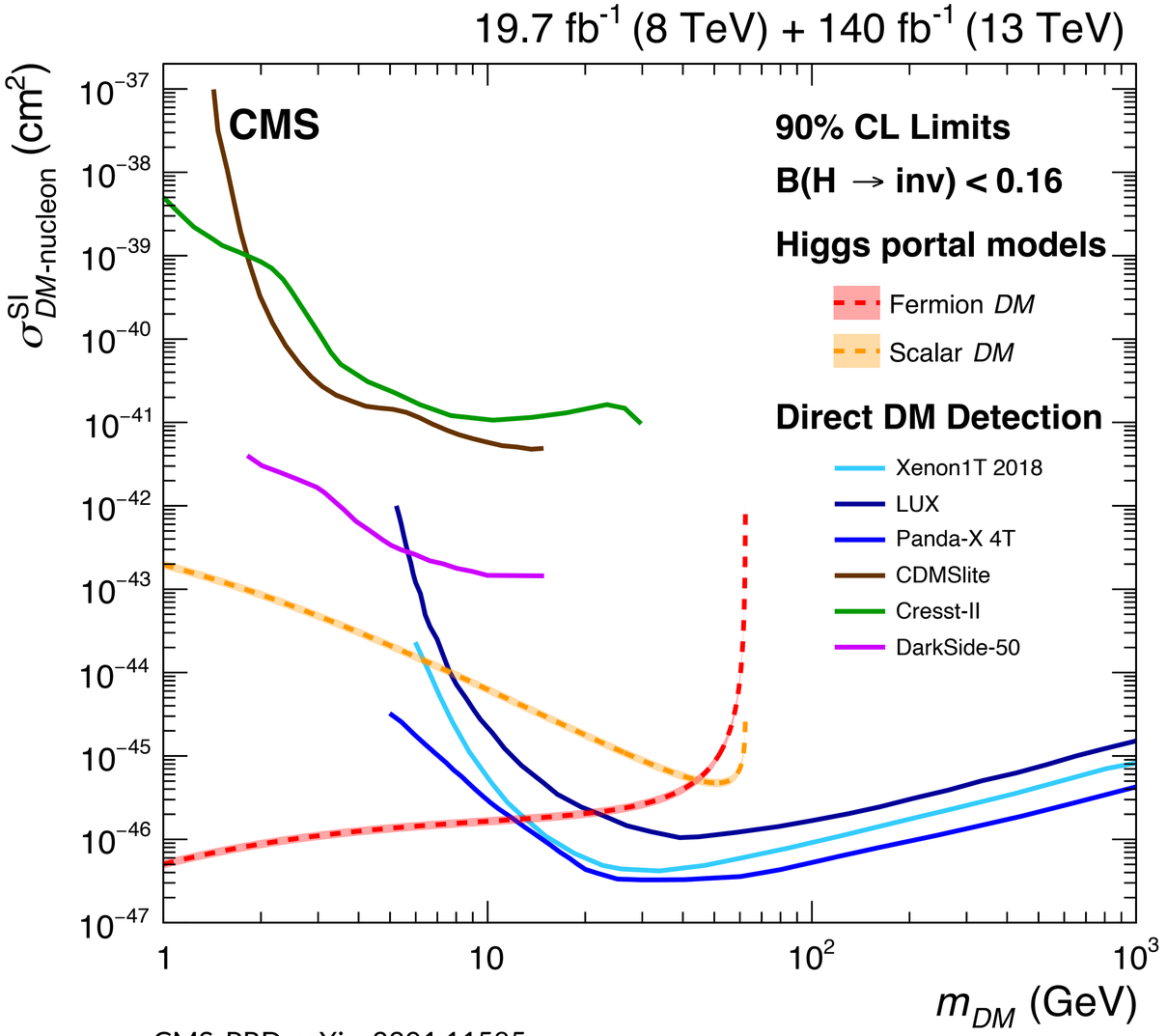


CMS, PRD, arXiv: 2201.11585

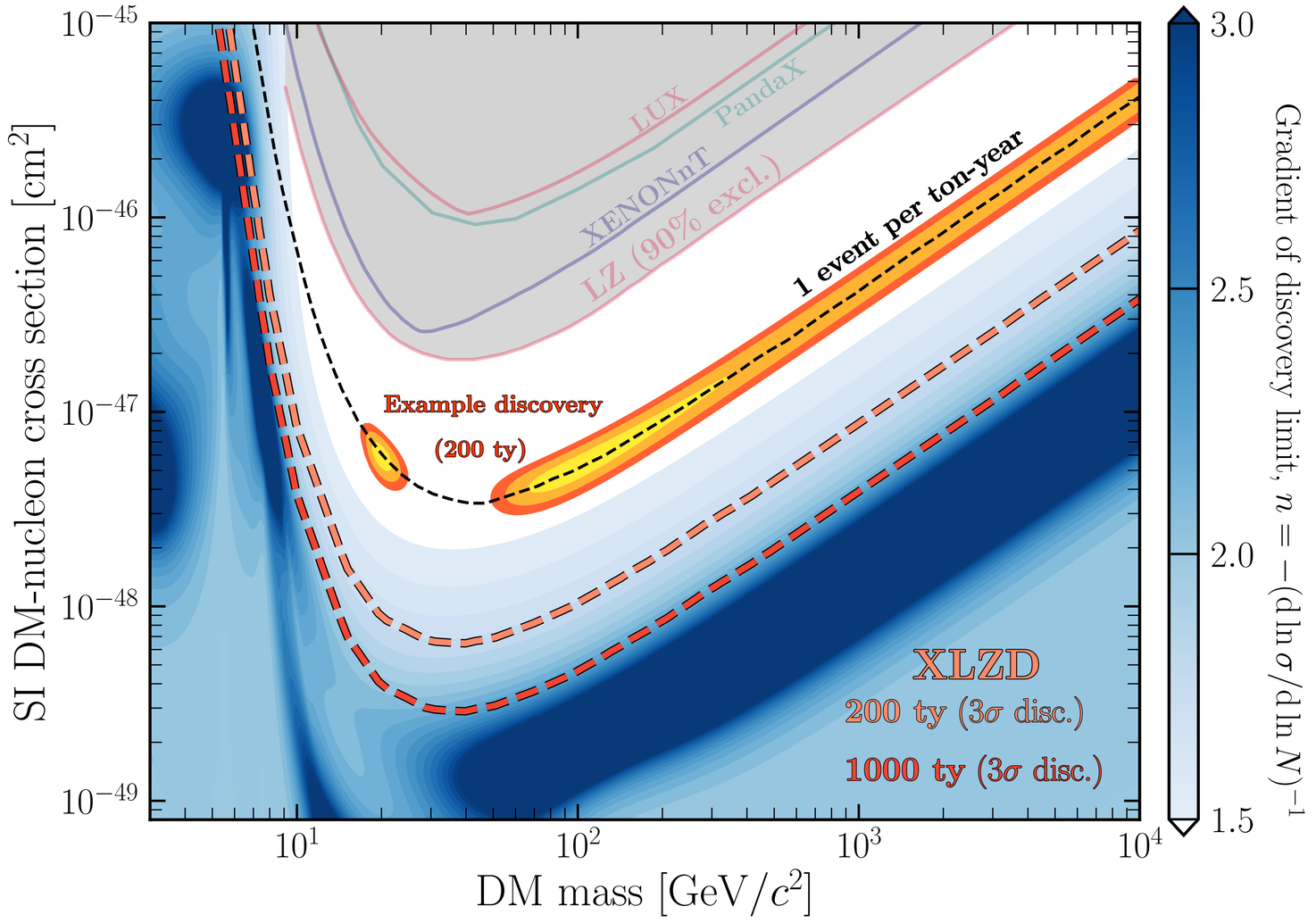
@~10^{-39} cm^2: *Z*-mediated (spin-independent) interactions: *excluded*

@~10^{-44} cm^2 and below: Higgs-mediated interactions: *putting pressure on this channel*

…and complementary to collider probes of the Higgs coupling

WIMPs: to come?

'Delve deep'



- XLZD (LXe): discovery machine for natural WIMPs down to the 'neutrino fog'
- Liquid Argon experiments also on track to cover similar parameter space

  (see dedicated talks)

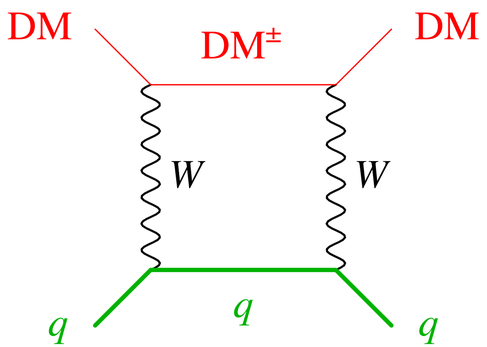
To come: non-natural WIMPs

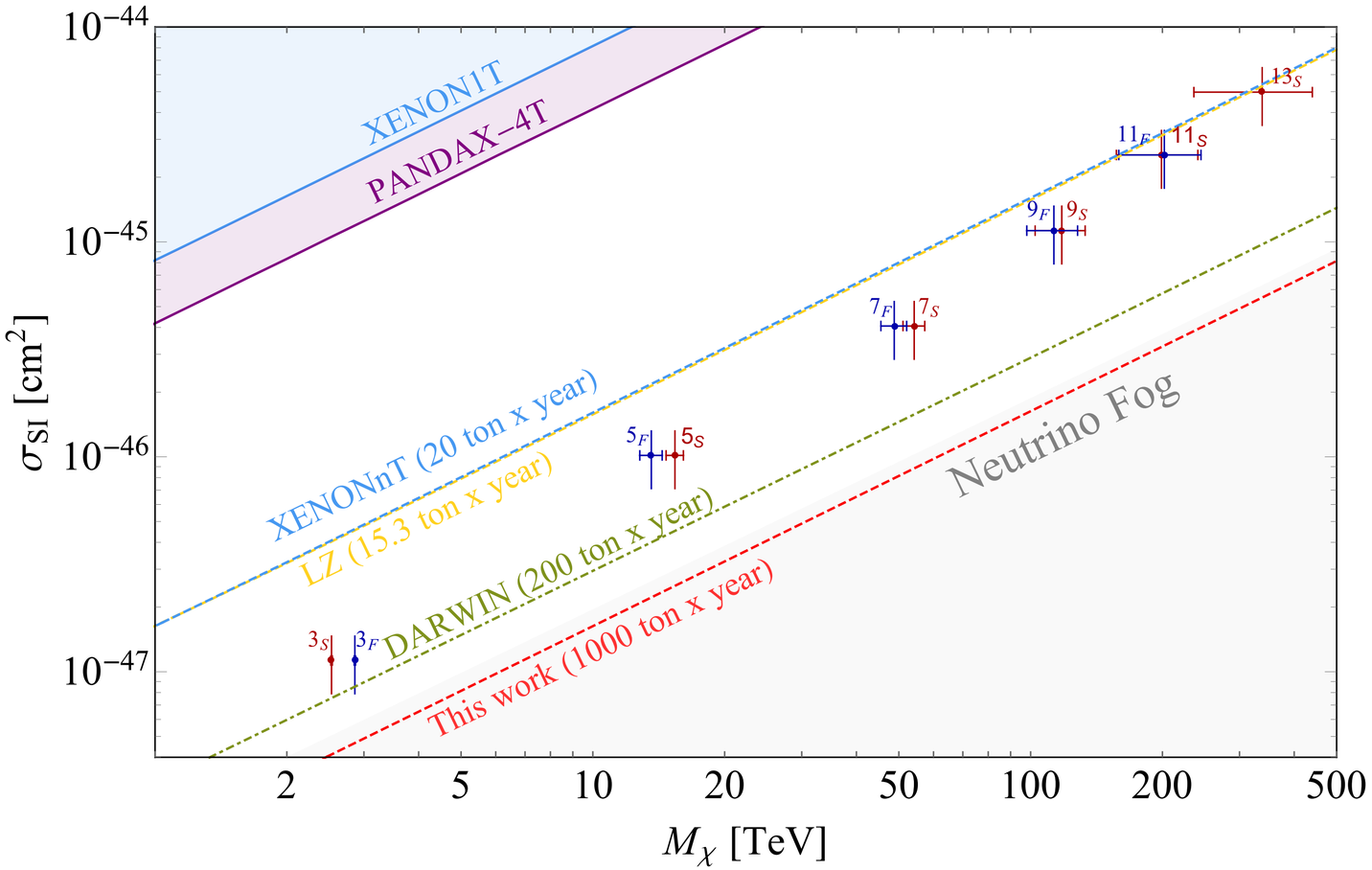
‘*Delve deep*’

- XLZD(ARWIN): will finally probe the ‘minimal dark matter’ family of models

  Cirelli et al, arXiv:0512090

- Minimal dark matter: introduce a stable, weakly interacting particle as part of an SU(2) multiplet





Aalbers, JPhyD
arXiv:2203.02309

Beyond Standard Model Mediators

'Search wide'

Isotopes with unpaired spin give sensitivity to interactions that couple to spin
[e.g, 129Xe and 131Xe isotopes @~50% abundance]

LXe-TPC

Can test a menagerie of dark matter interactions that arise through more exotic mediators

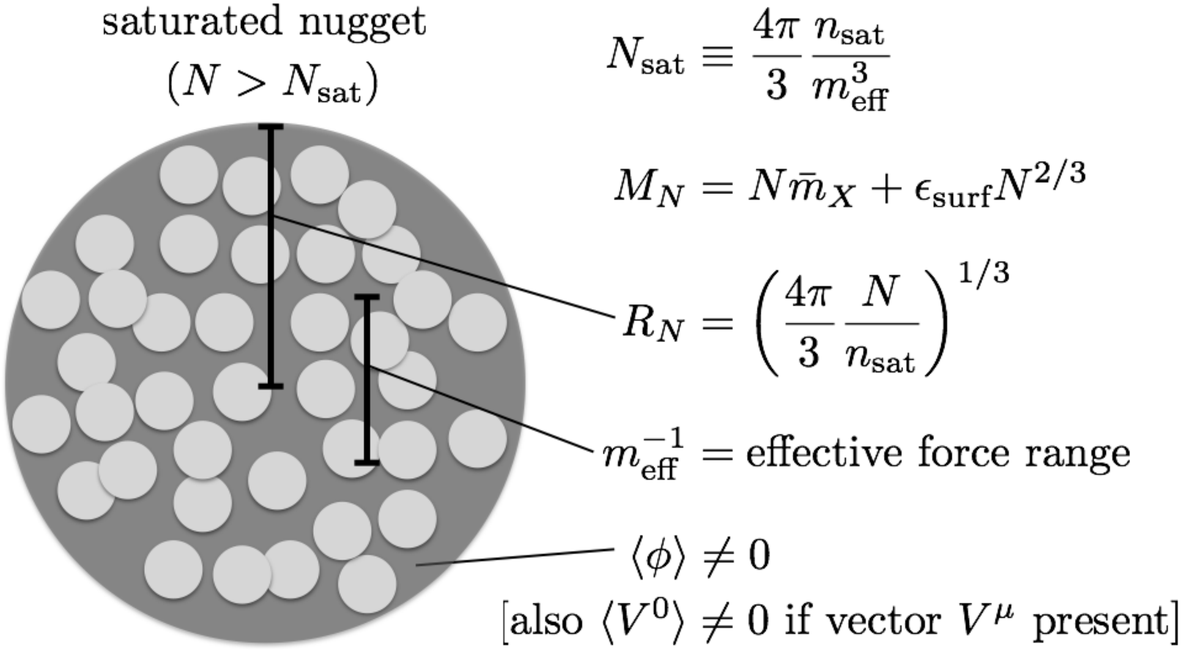
Type	Abbrev.	Operator ($\mathcal{O}$)	Dimension	Coherent enhancement	Coefficients
Magnetic Dipole	-	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	5	Partial	C_F
Electric Dipole	-	$\bar{\chi}\sigma^{\mu\nu}\chi \tilde{F}_{\mu\nu}$	5	Yes	$\tilde{C}_F$
Vector⊗Vector	VV	$\bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma_{\mu}q$	6	Yes	$C^{VV}_{u,d,s}$
Axial-vector⊗Vector	AV	$\bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma_{\mu}q$	6	Yes	$C^{AV}_{u,d}$
Tensor⊗Tensor	TT	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	6	Yes	$C^{TT}_{u,d,s}$
Pseudo-tensor⊗Tensor	$\widetilde{TT}$	$\bar{\chi}\sigma^{\mu\nu}i\gamma_5\chi\bar{q}\sigma_{\mu\nu}q$	6	Yes	$\tilde{C}^{TT}_{u,d,s}$
Scalar⊗Scalar	SS	$\bar{\chi}\chi m_q\bar{q}q$	7	Yes	$C^{SS}_{u,d,s}$
Scalar-gluon	S_g	$\alpha_s\bar{\chi}\chi G^a_{\mu\nu}G^{\mu\nu}_a$	7	Yes	C^{S}_{g}
Pseudo-scalar - gluon	$\tilde{S}_g$	$\alpha_s\bar{\chi}i\gamma_5\chi G^a_{\mu\nu}G^{\mu\nu}_a$	7	Yes	$\tilde{C}^{S}_{g}$
Pseudo-scalar⊗Scalar	PS	$\bar{\chi}i\gamma_5\chi m_q\bar{q}q$	7	Yes	$C^{PS}_{u,d,s}$
Spin-2	-	$\bar{\chi}\gamma_{\mu}i\partial_{\nu}\chi\bar{\theta}^{\mu\nu}_{q(g)}$	8	Yes	$C^{(2)}_{u,d,s,g}$
Axial-vector⊗Axial-vector	AA	$\bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma_{\mu}\gamma_5q$	6	No	$C^{AA}_{u,d,s}$

More radical ideas: ultra-heavy dark matter

'Search wide'

- Hidden sectors enrich the possibilities for dark matter
- Consider dark particles that self interact through an attractive force:

  particles may bind together to form large composite states
- Composite size on the strength and range of the force, and on the presence or absence of bottlenecks



McCullough et al, arXiv: 1406.2276
Wise et al, arXiv:1411.1772
Hardy et al, arXiv:1411.3739
Zurek et al, arXiv:1707.02313
+ many, many more

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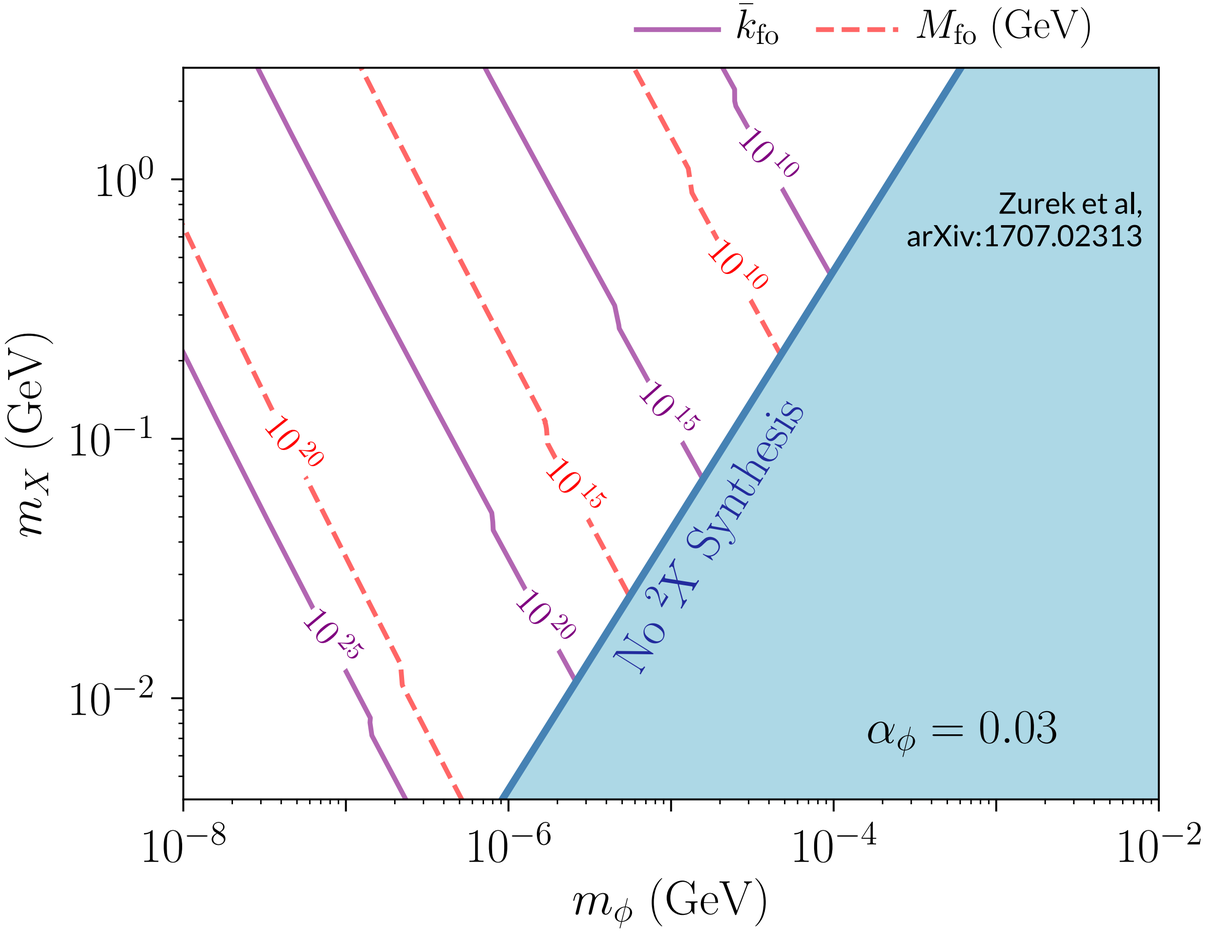

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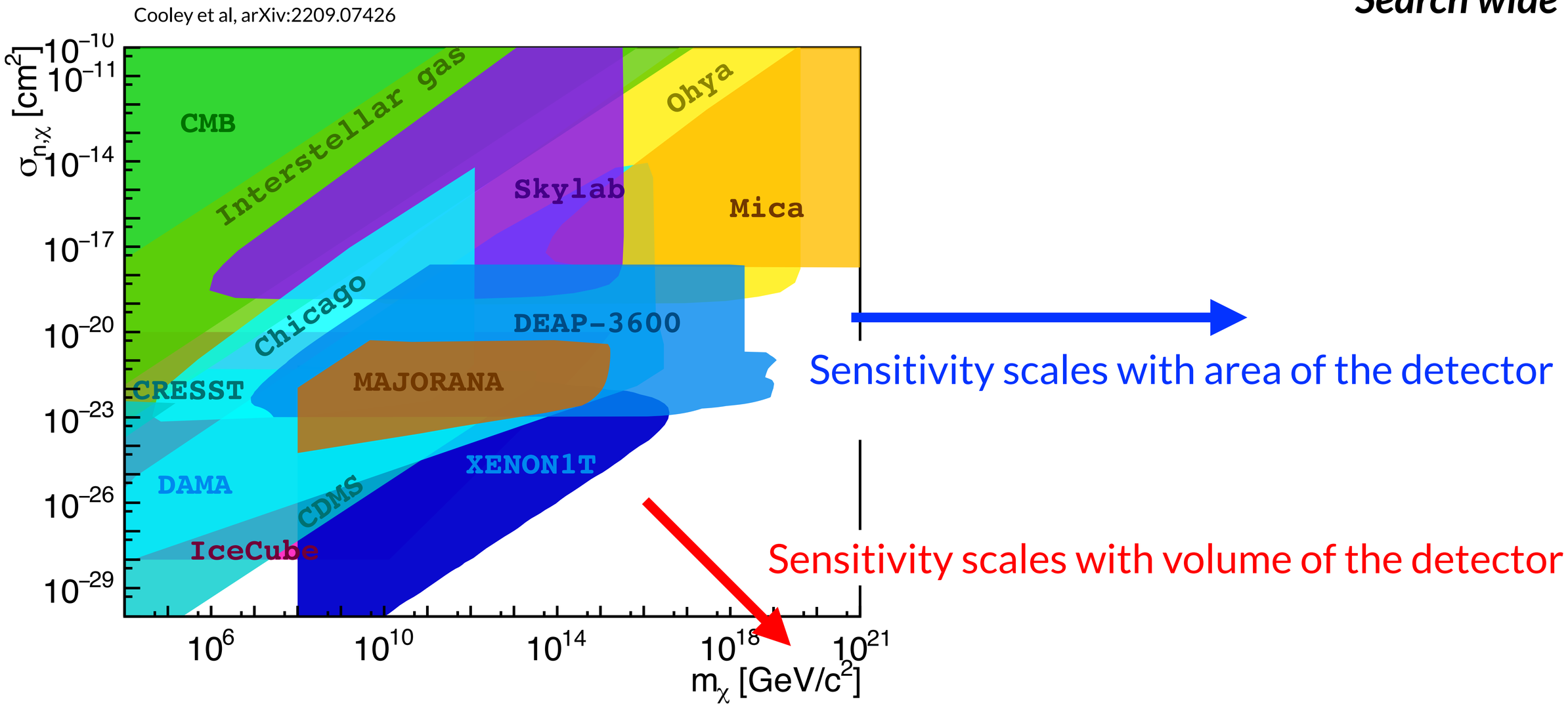
Direct searches for Planck scale candidates

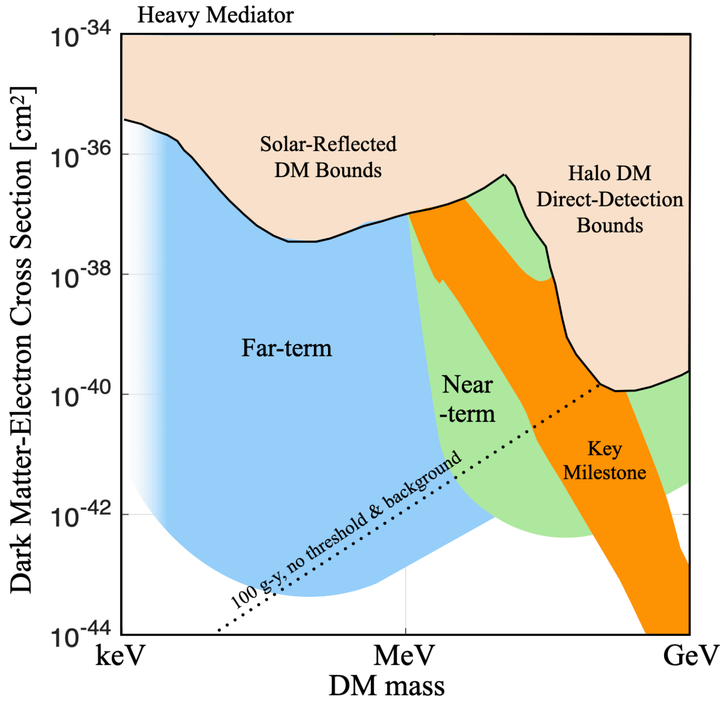
'Search wide'

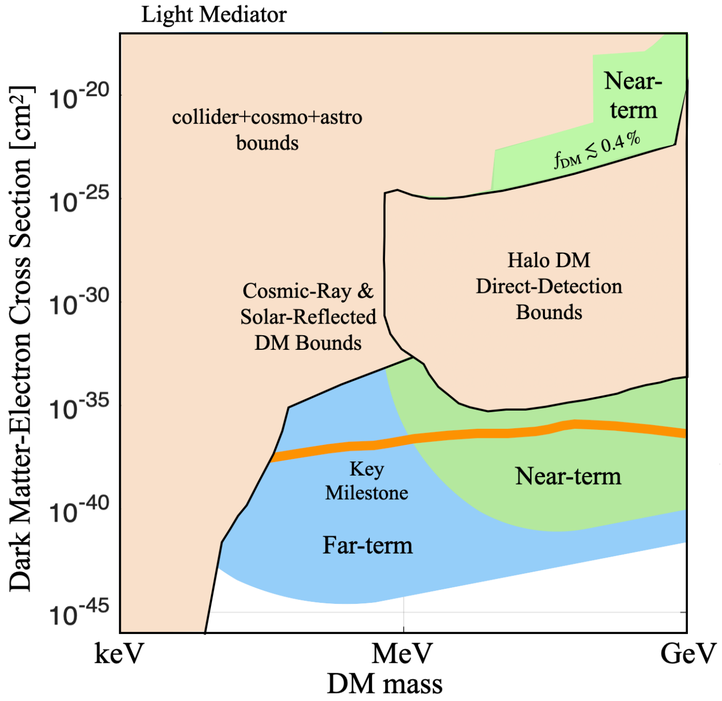


Landscape of sub-GeV dark matter

'Search wide'

- Hidden sectors enrich the possibilities for sub-GeV dark matter
- Relic density from:
  - variations on the WIMP mechanism afforded by portal interactions (SIMP, ELDER, …)
  - Freeze-in mechanism
- Exciting developments using existing detectors and proposing new technologies





Essig et al
arXiv: 2203.08297

Landscape of sub-GeV dark matter

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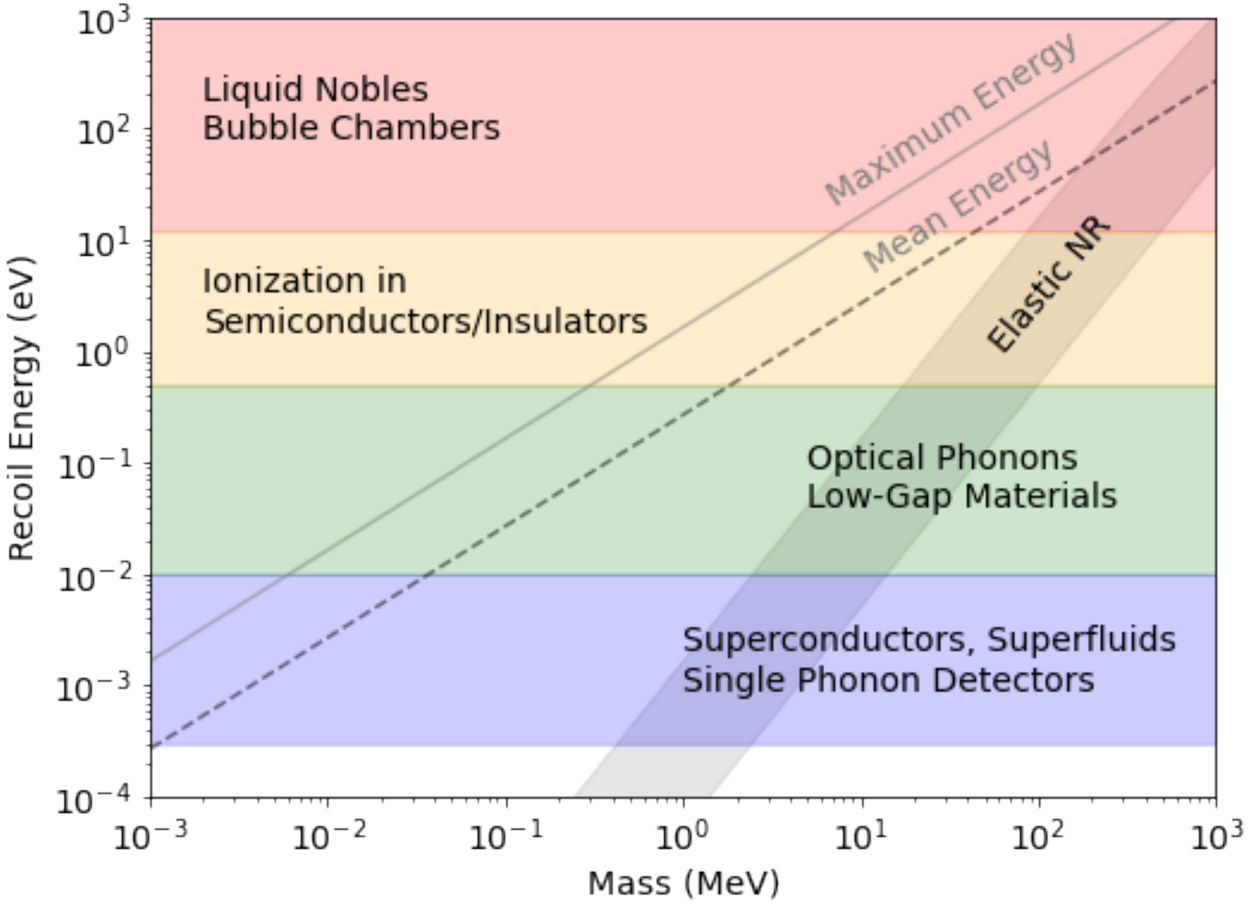
See talks tomorrow morning



Essig et al
arXiv: 2203.08297

Summary

The search for particle dark matter continues unabated…

Current strategy adopted by the international community summarised as
‘***delve deep and search wide***’

Direct detection searches allow for the test of the full mass range of *particle* dark matter:

- Now: in the regime where experiments are probing Higgs-DM interactions
- Future: definitively probes ‘natural-WIMPs’ to the neutrino floor, start to probe minimal DM models (loop-induced interactions)
- Testing richer hidden sector extensions with candidates from the keV to Planck scale

As we will hear: UK activities are at the forefront of the field with proposals for ‘broadband’ searches (LZ, DarkSide, XLZD) and more focussed searches (DarkSPHERE, SOLAIRE, UltraDark…)