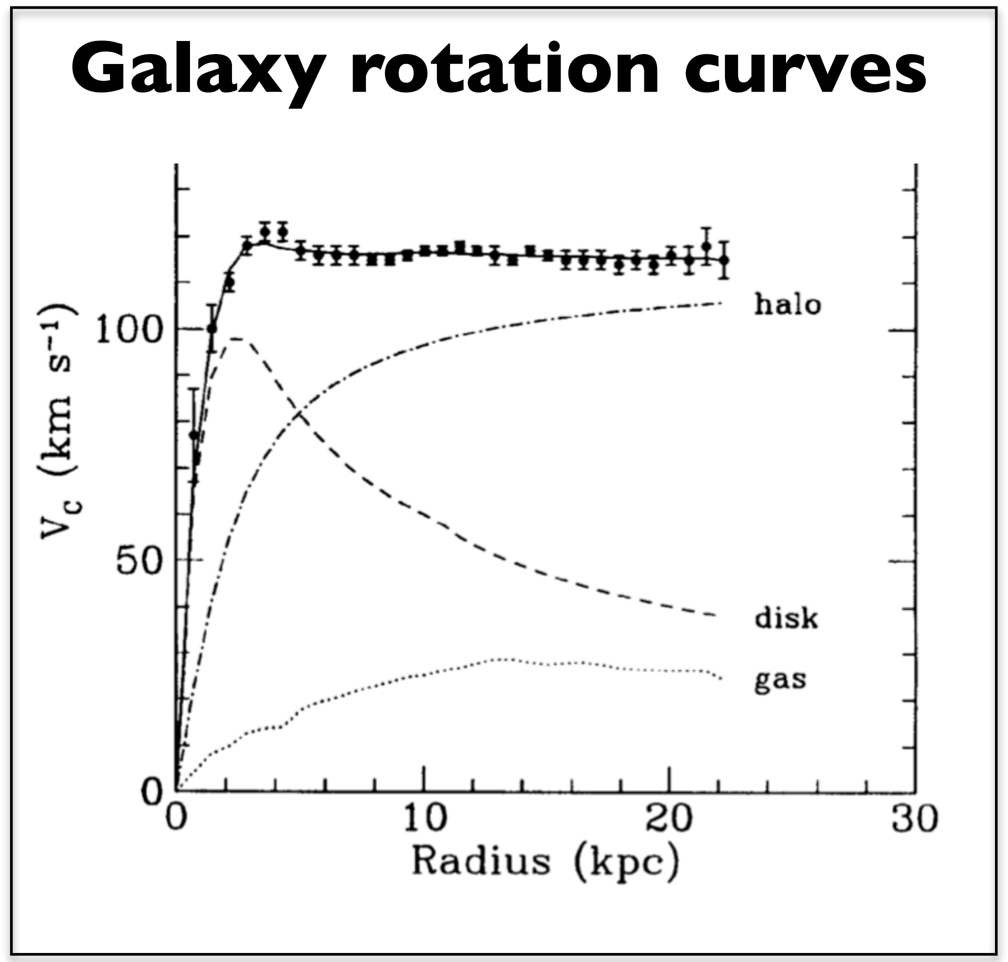
Dark matter: landscape and XLZD reach

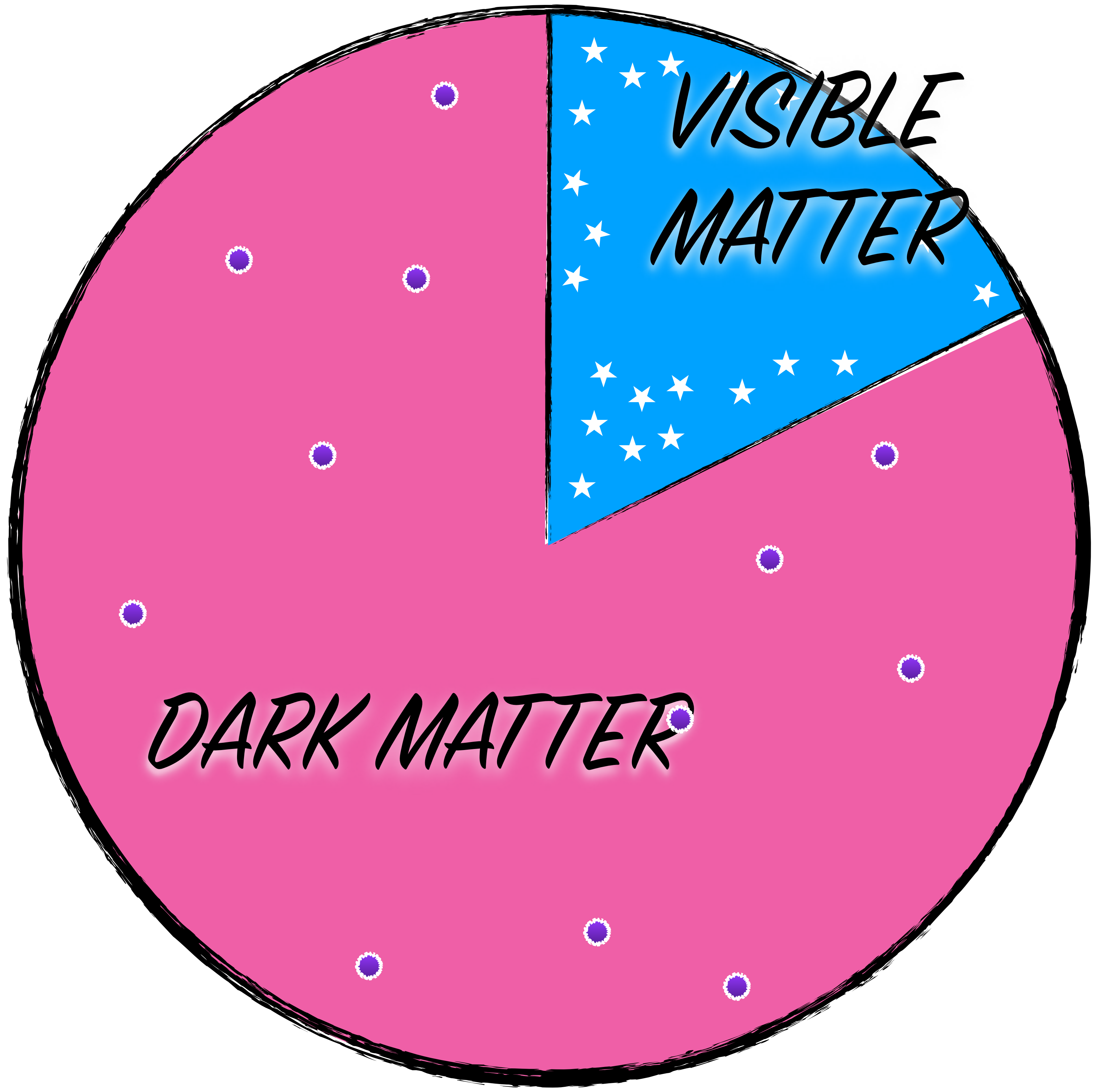
Christopher McCabe

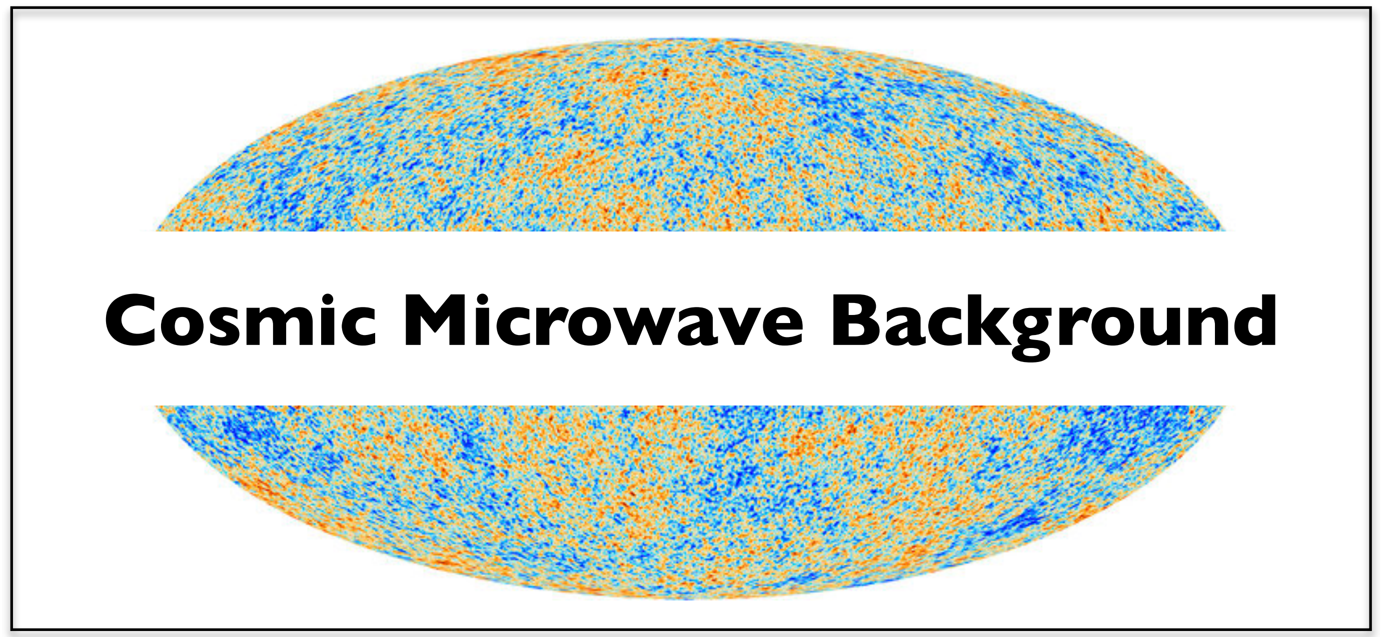
XLZD @ Boulby Open Community Meeting, Imperial, 4 July 2023

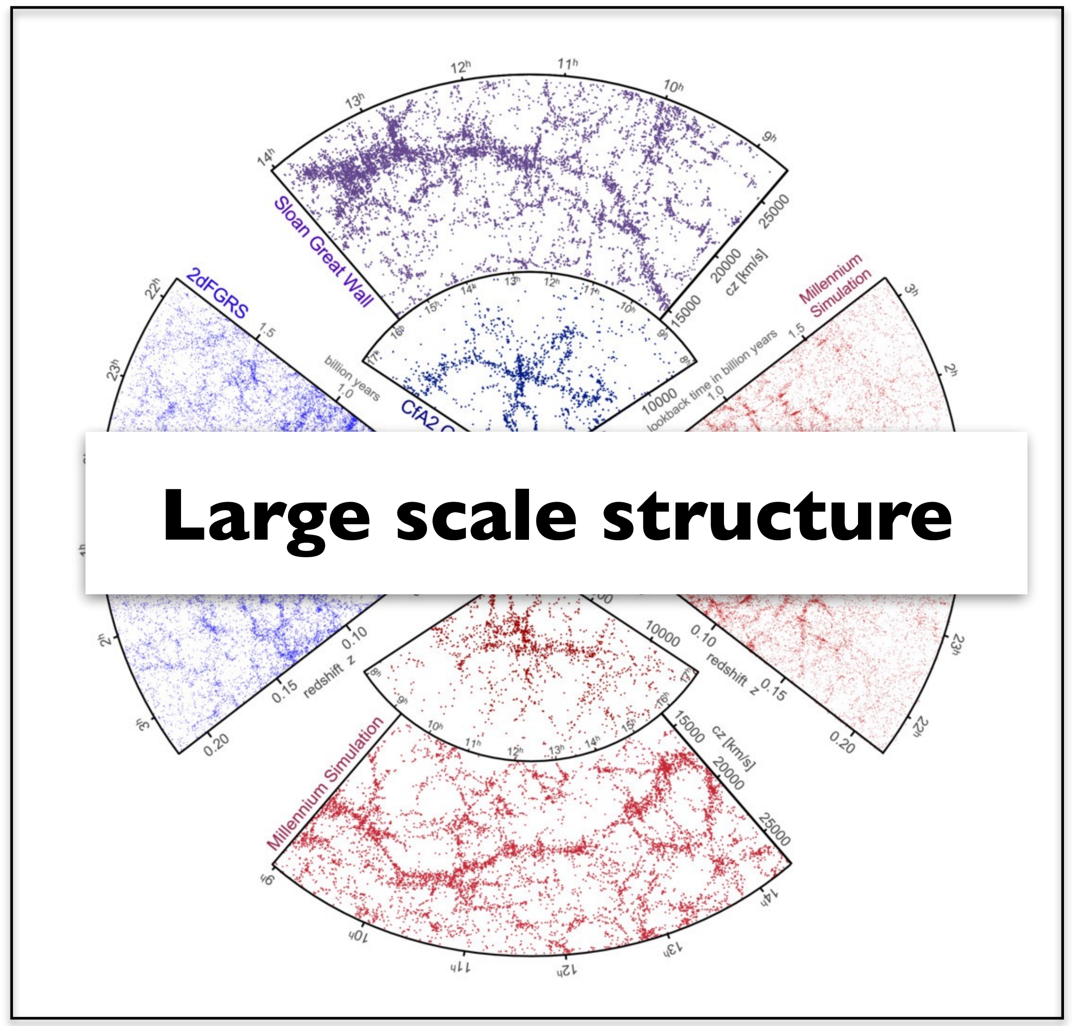
Dark matter landscape

Reminder: we have detected dark matter









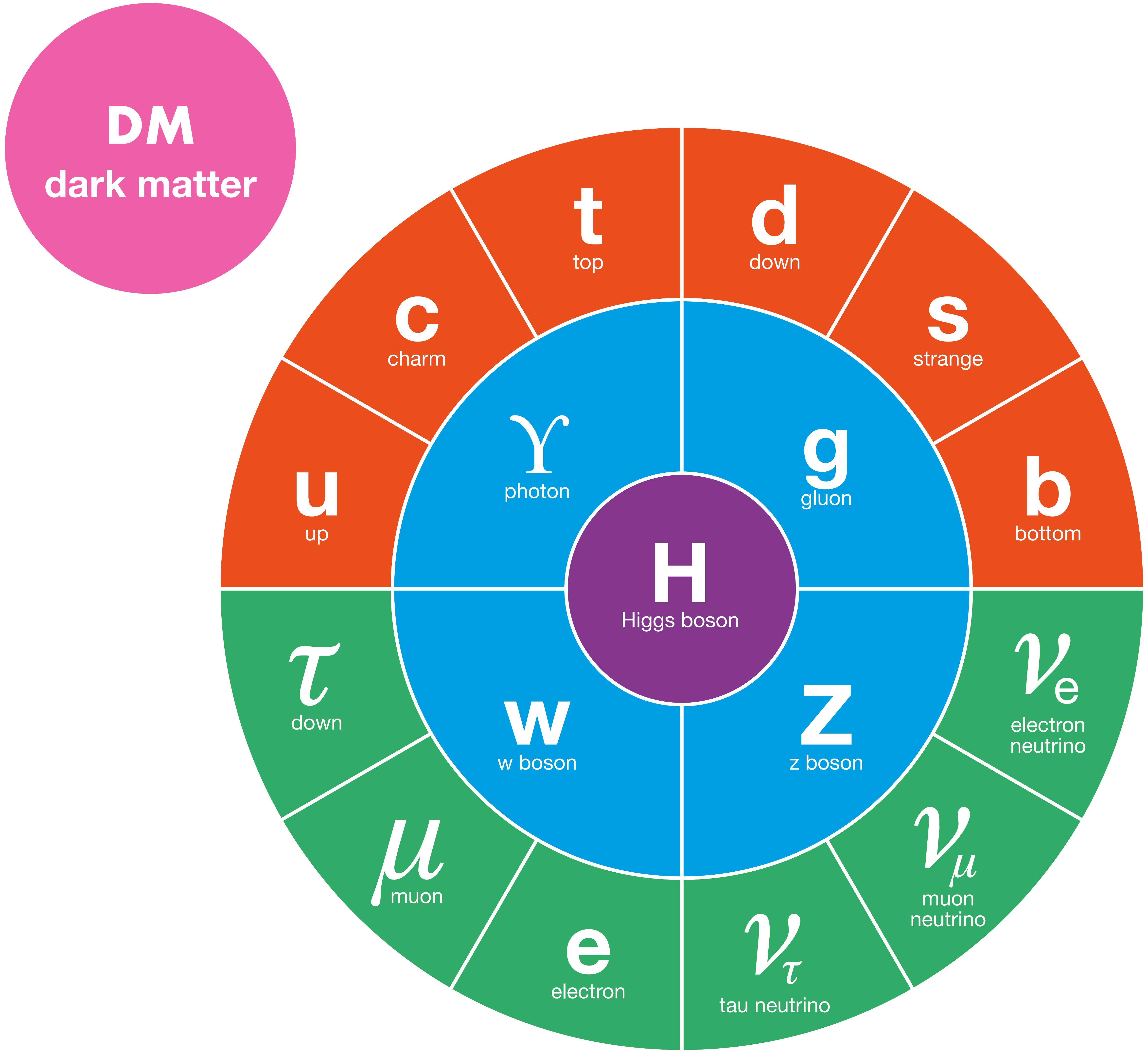
Existence of DM on astrophysical and cosmological scales is known and well characterised

Yet…

the microscopic nature of DM is almost completely unconstrained

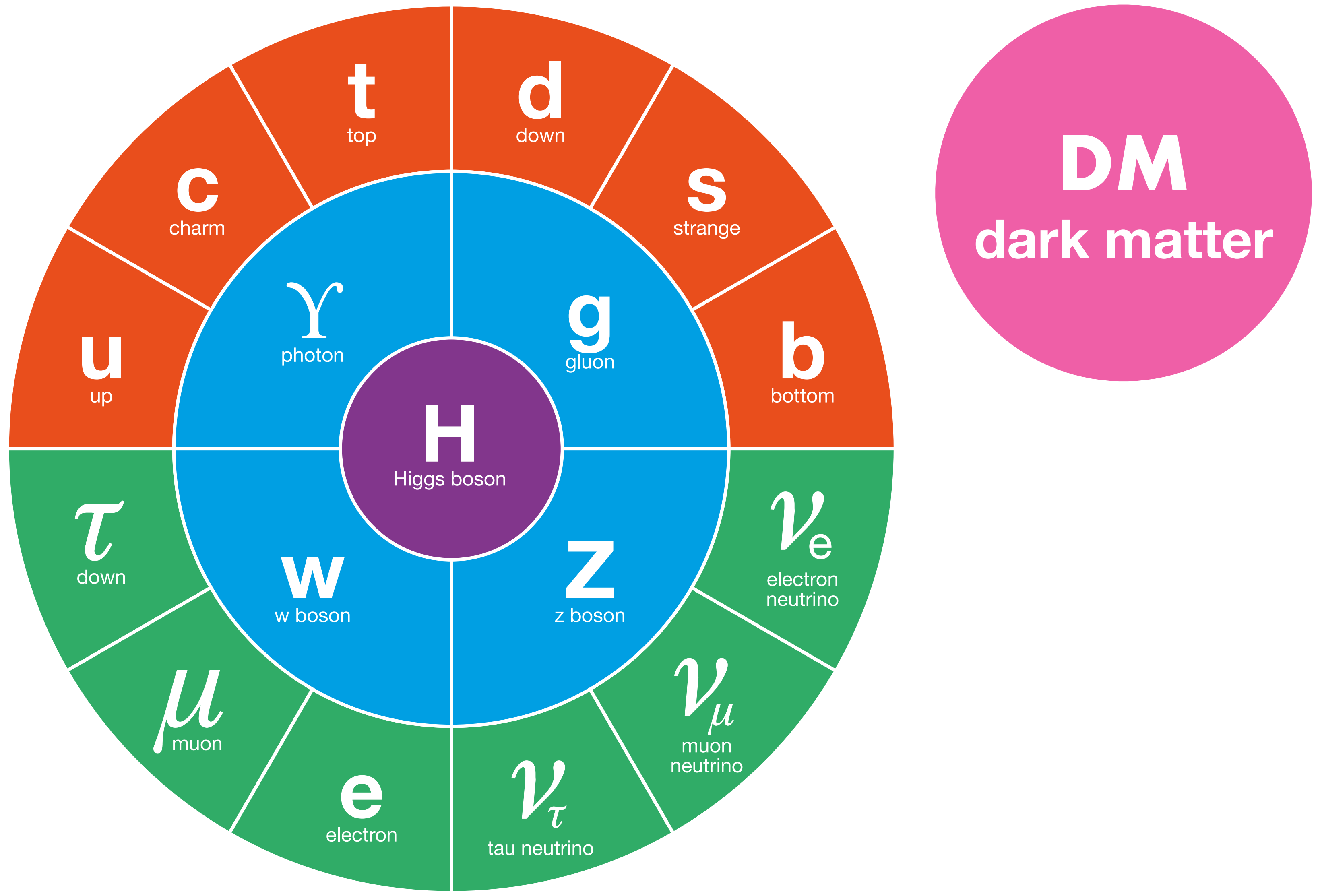
Dark Matter Particle (X^0)

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

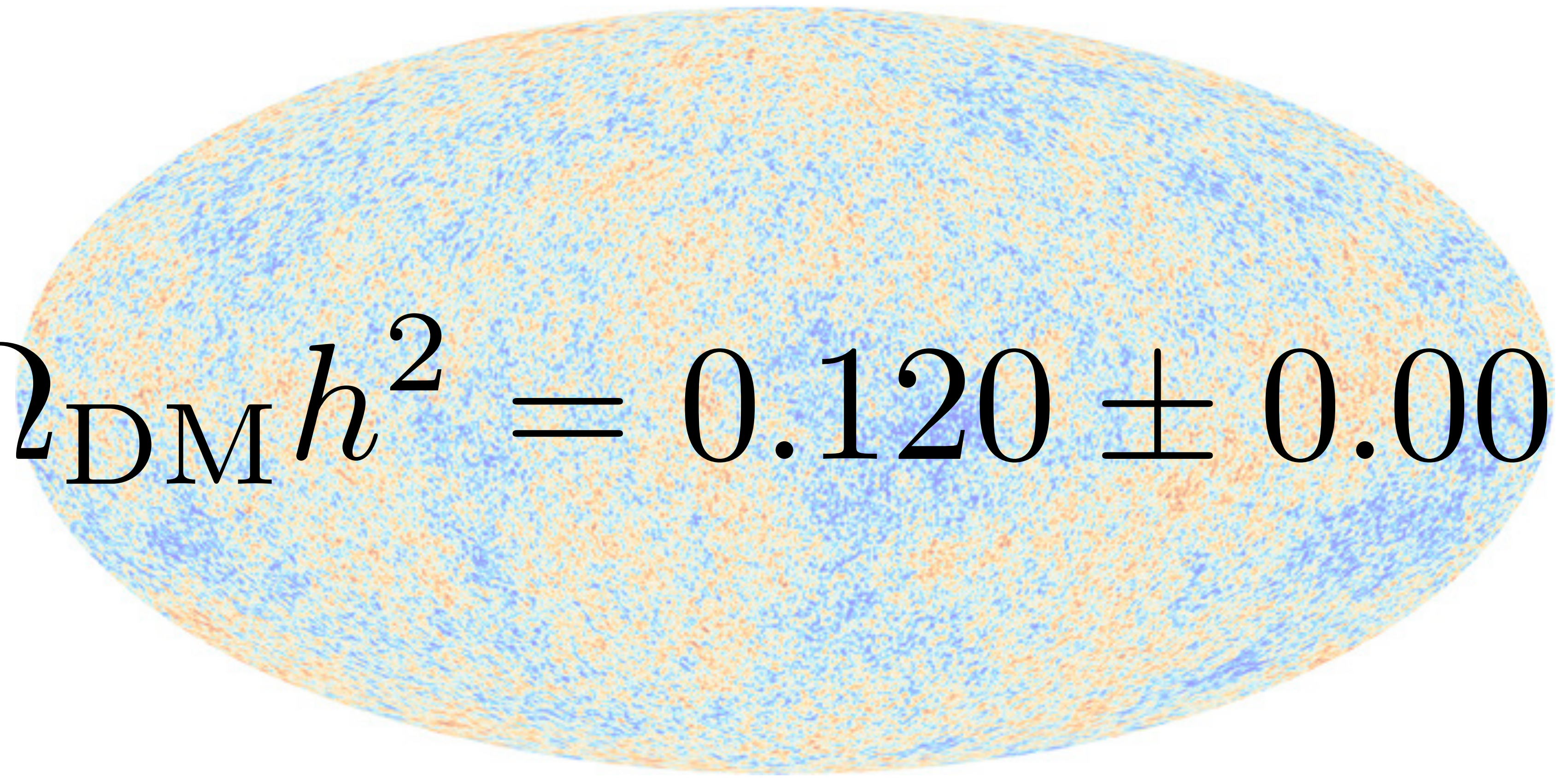


Why should DM interact with normal matter?

Particle Physics



Cosmology



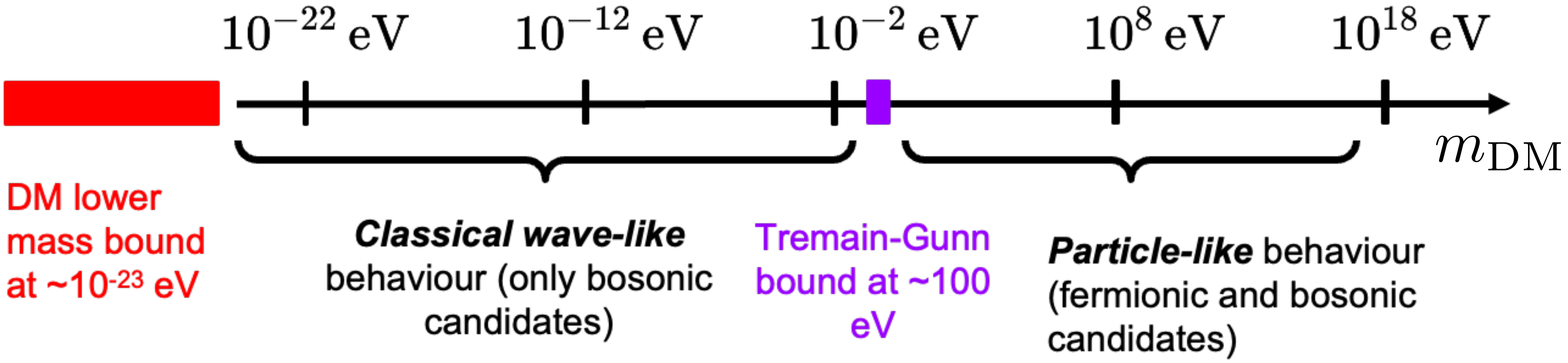
$$\Omega_{\rm DM} h^2 = 0.120 \pm 0.001$$

Informs and limits the possible interactions

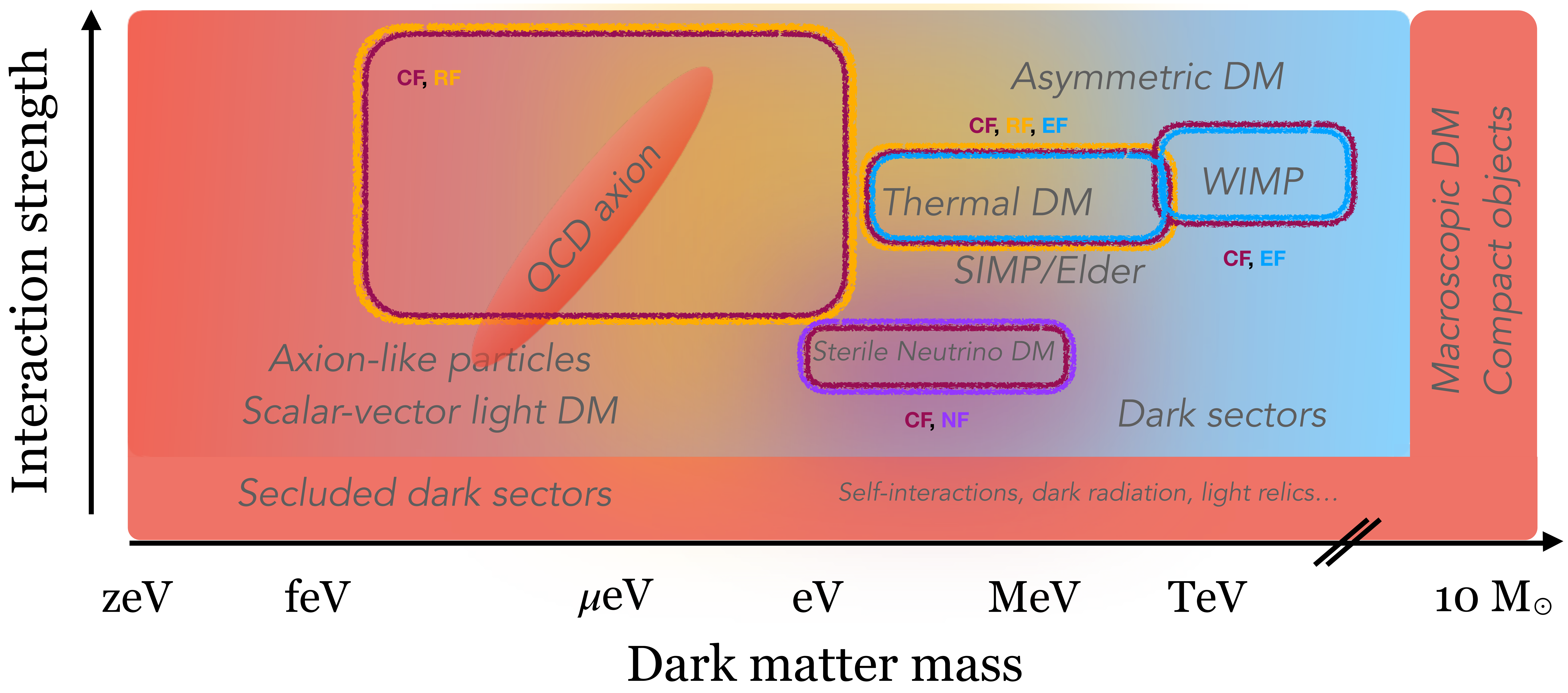
&

Explaining this value suggests dark and visible matter interactions are generic

DM landscape: classifying by mass



DM landscape: classifying by mass and interaction



Boveia et al, arXiv:2211.07027

DM landscape: classifying with clever people's 'mind-map'

Bertone, Tait, Nature
arXiv:1810.01668

How can we make progress?

Aim: *determine DM mass and interaction cross section*

(or, experimentally exclude the broadest accessible ranges of both quantities)

Approach: search for direct interaction of DM with a terrestrial detector

Cosmic Frontier's recommendation:

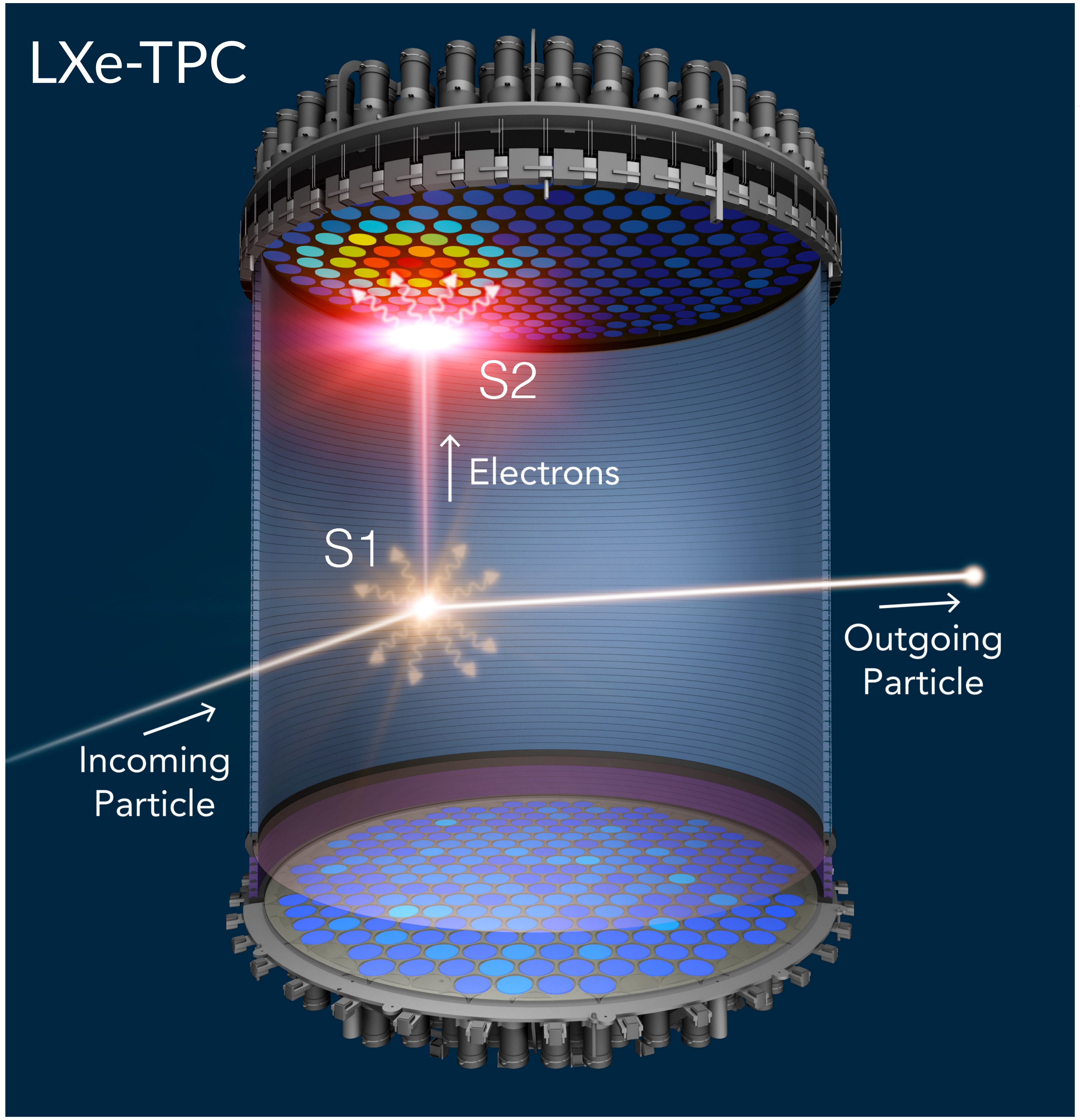
Delve deep (cover high priority targets e.g., WIMPs)

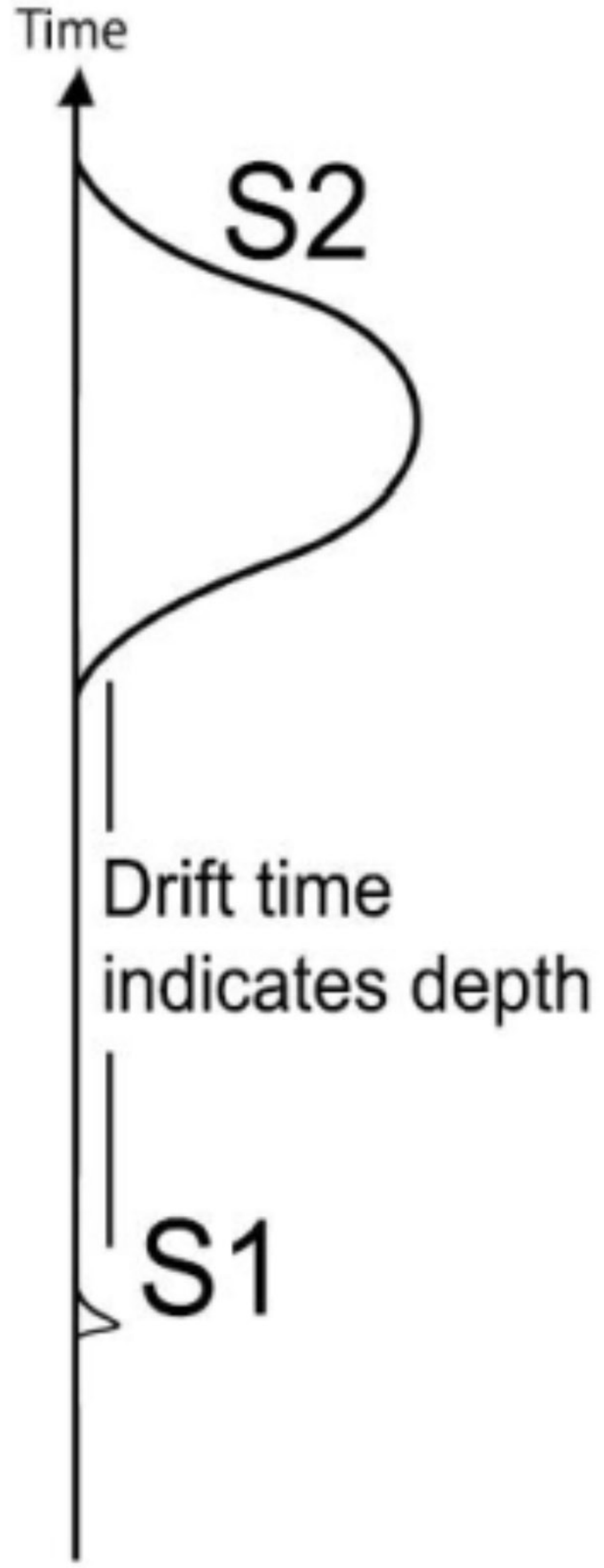
Search wide (explore as much DM parameter space as possible)

Cooley et al
arXiv:2209.07426

Dark matter landscape in the context of XLZD

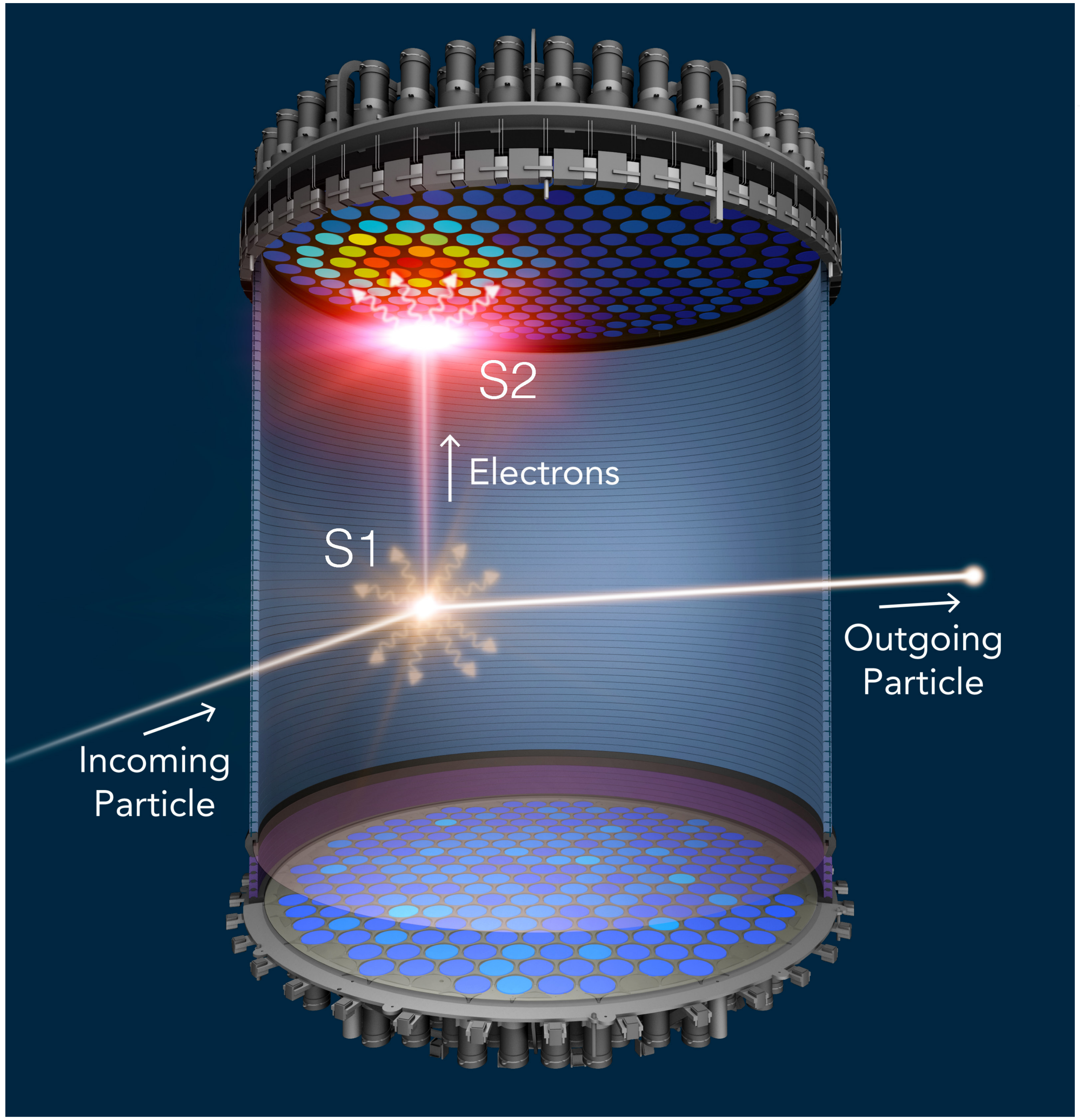
XLZD detection principle



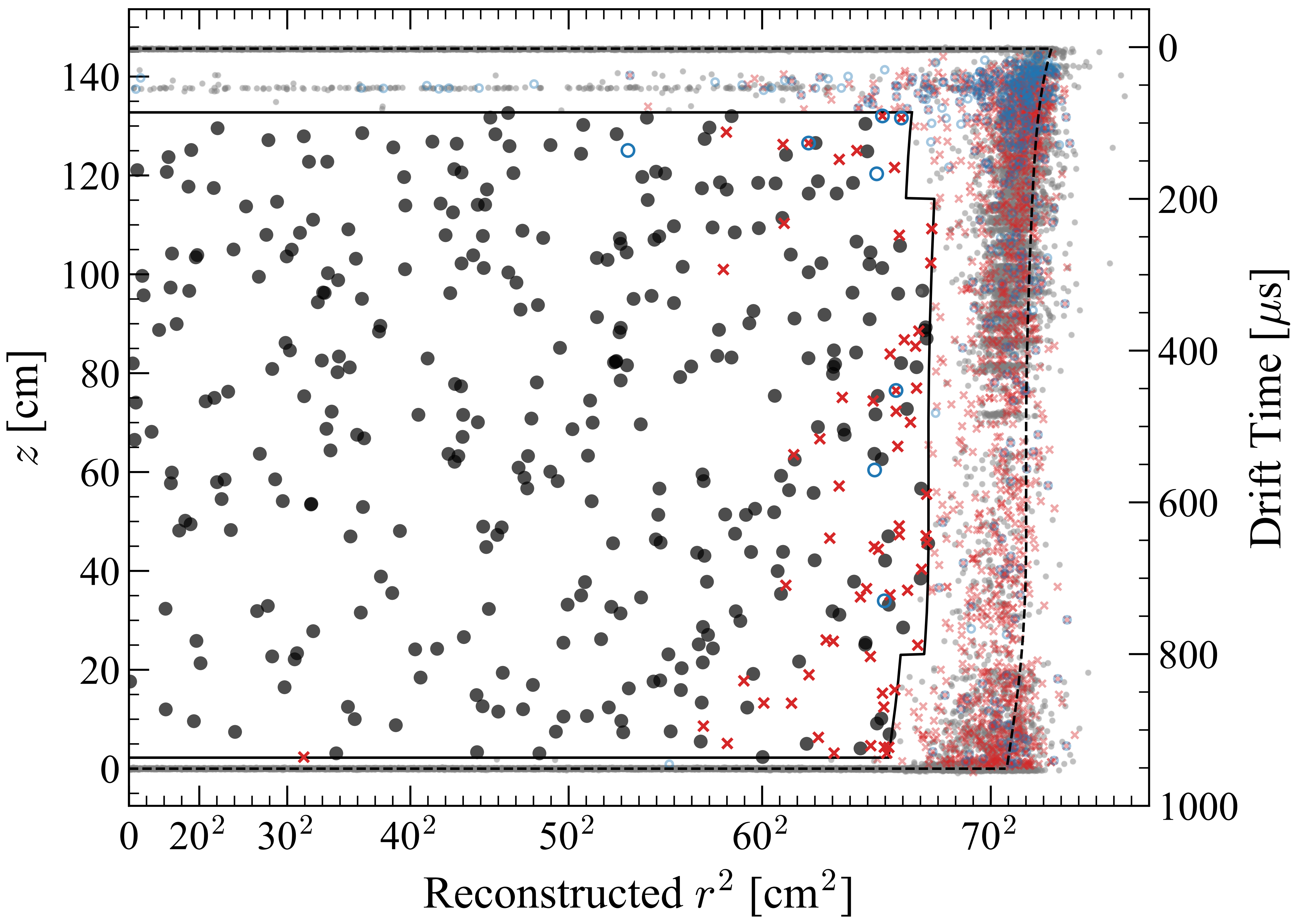


XLZD detection principle

LZ, PRL, arXiv:2207.03764

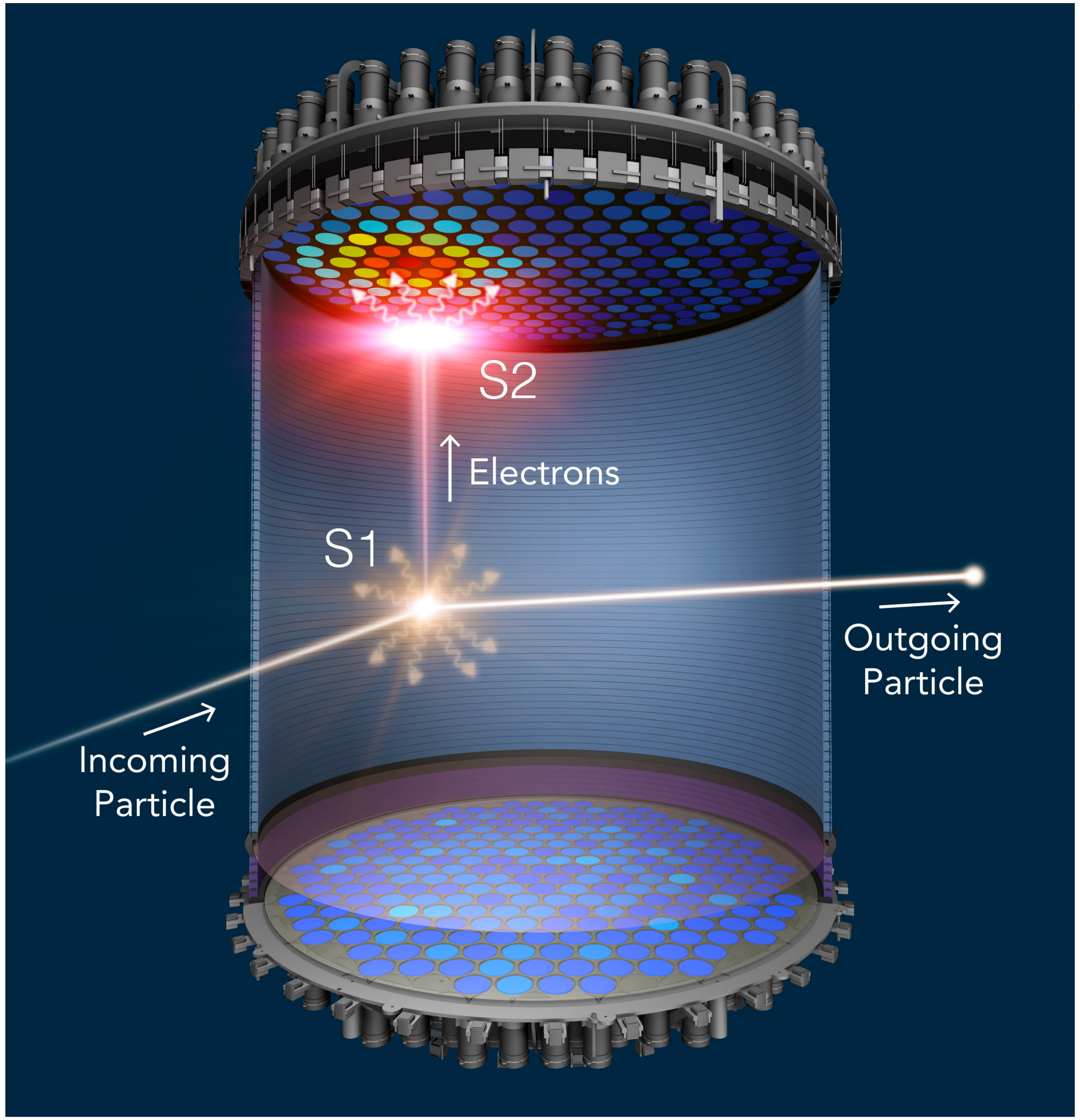


3D reconstruction of interaction position:

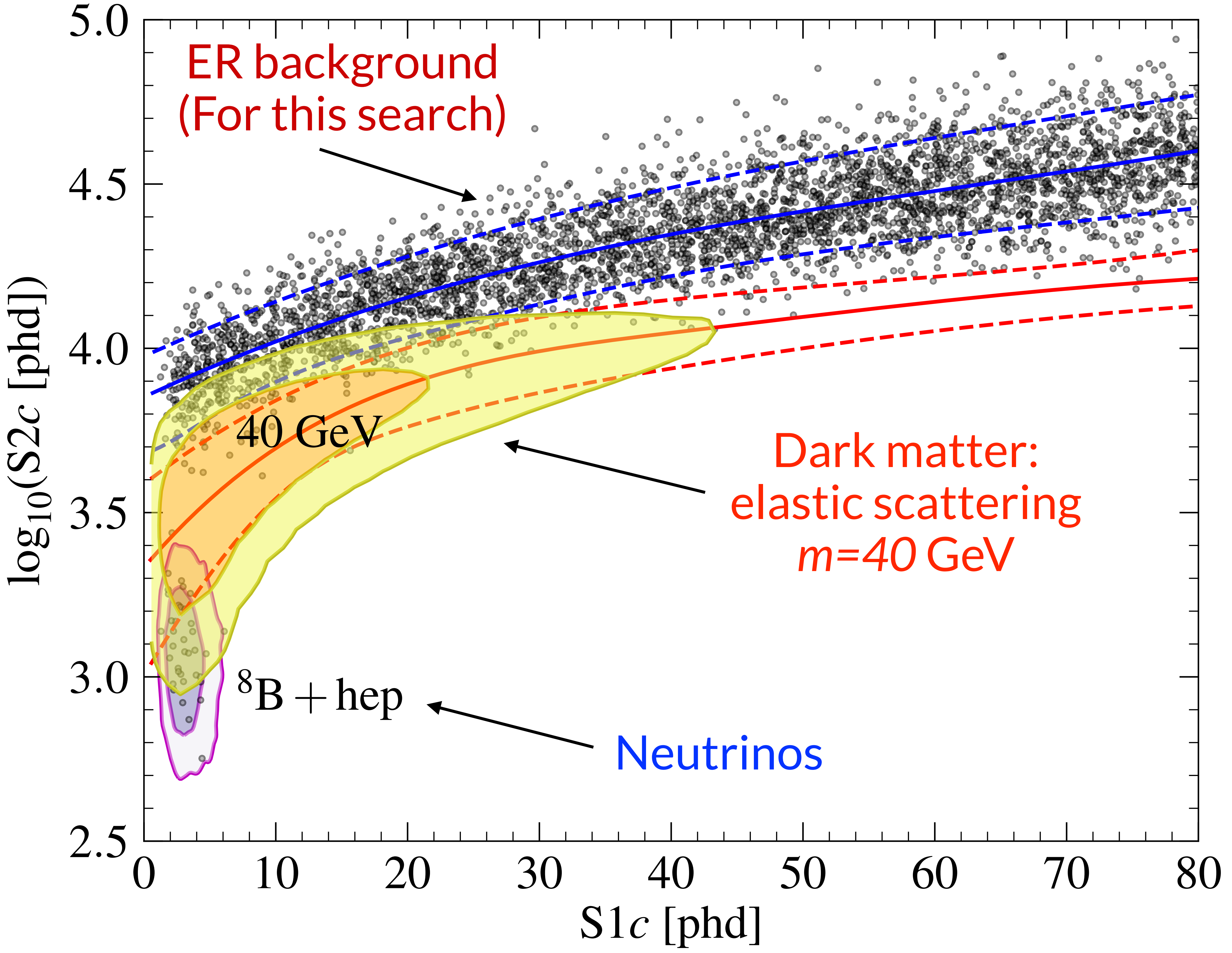


Can exploit Xe self-shielding to search in quietest parts of the detector

XLZD detection principle

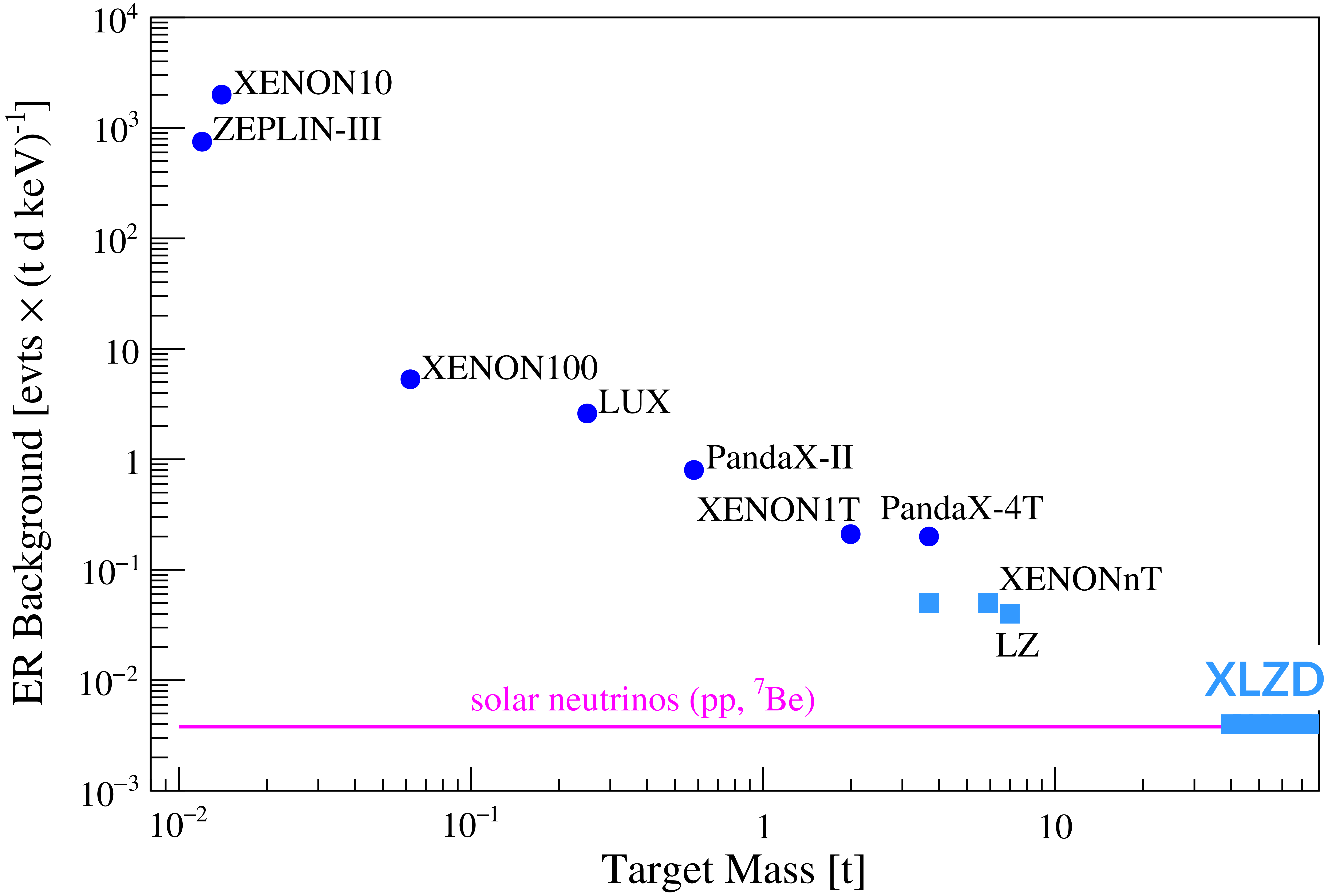


Discrimination between different interactions



LZ, PRD
arXiv:1802.06039

Why can XLZD improve on previous experiments?



Bigger target mass:

Rare events occur more frequently

Lower background:

Rarer events can be observed over background

High priority target: WIMPs

- WIMPs, historically, are the most studied DM candidate
- Advantages:
  - ‘naturally’ produced with the right relic abundance
  - Embedded in theories that alleviate the ‘hierarchy problem’ (SUSY, etc)
- Idea of ‘*Natural WIMPs*’

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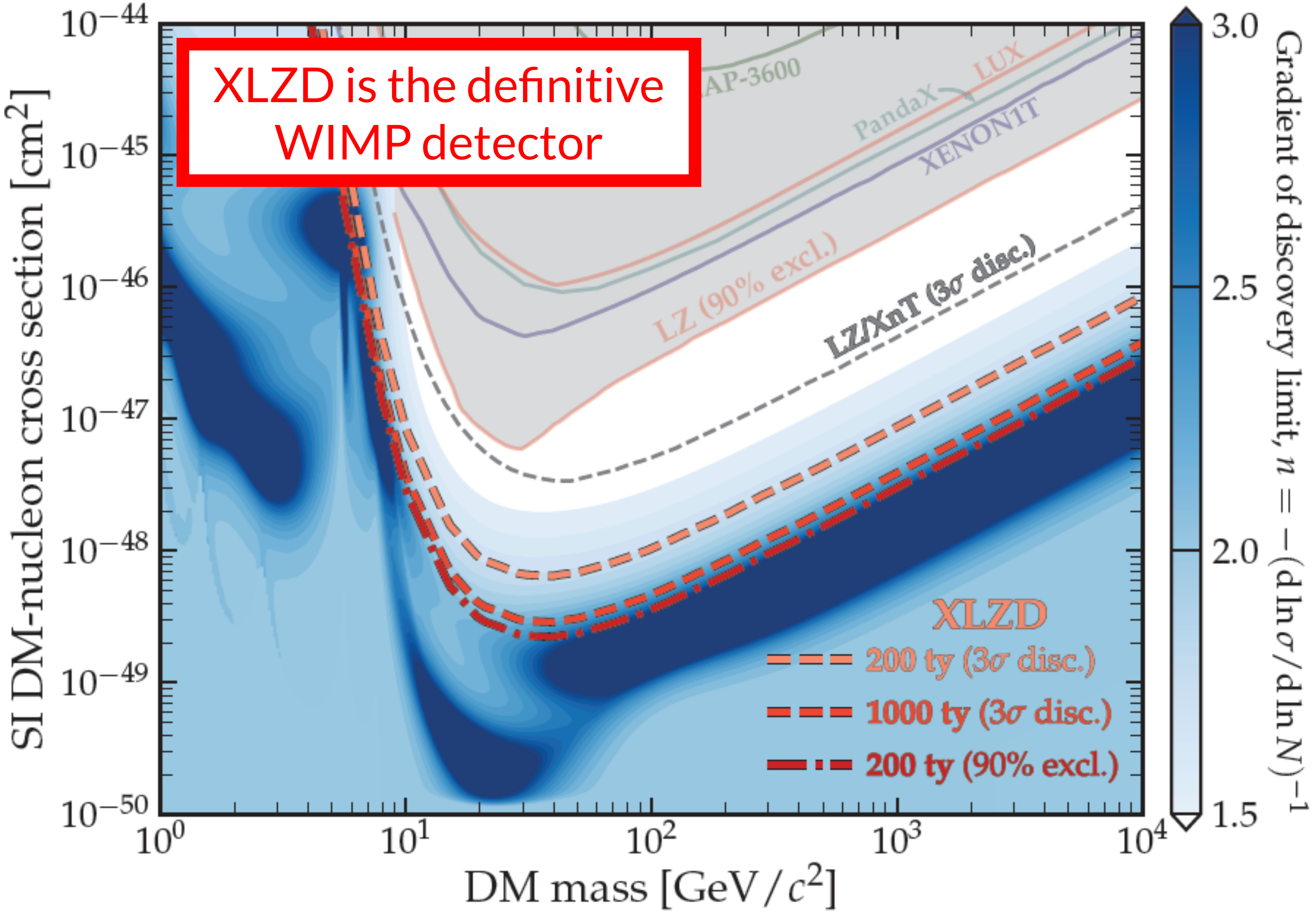
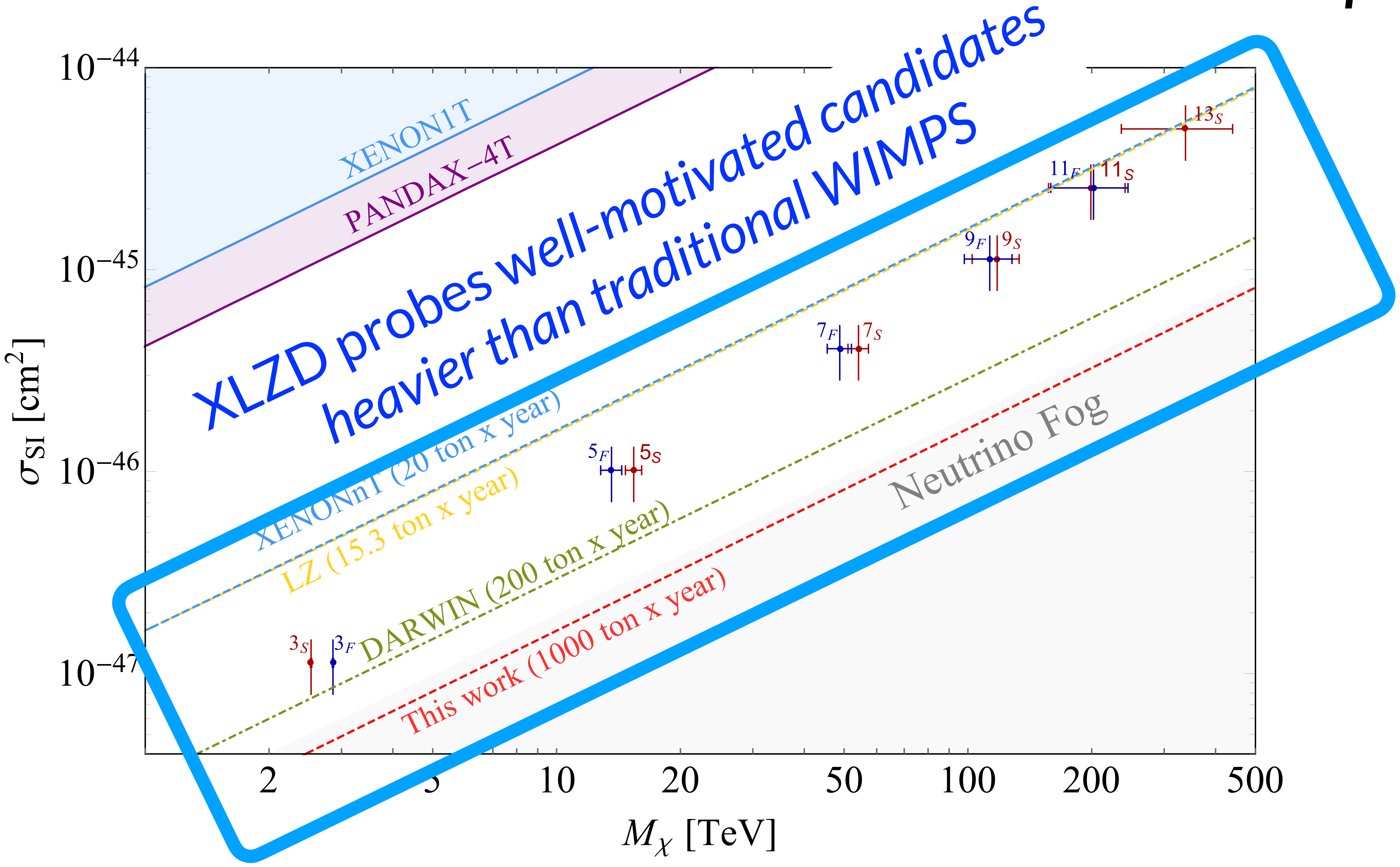


Non-natural WIMPs: heavier candidates

- WIMPs, historically, are the most studied DM candidate
- Advantages:
  - ‘naturally’ produced with the right relic abundance
  - ~~Embedded in theories that alleviate the ‘hierarchy problem’ (SUSY, etc)~~
- Link to hierarchy problem not needed for DM
  - Idea of ‘*non-natural WIMPs*’

‘Delve deep’

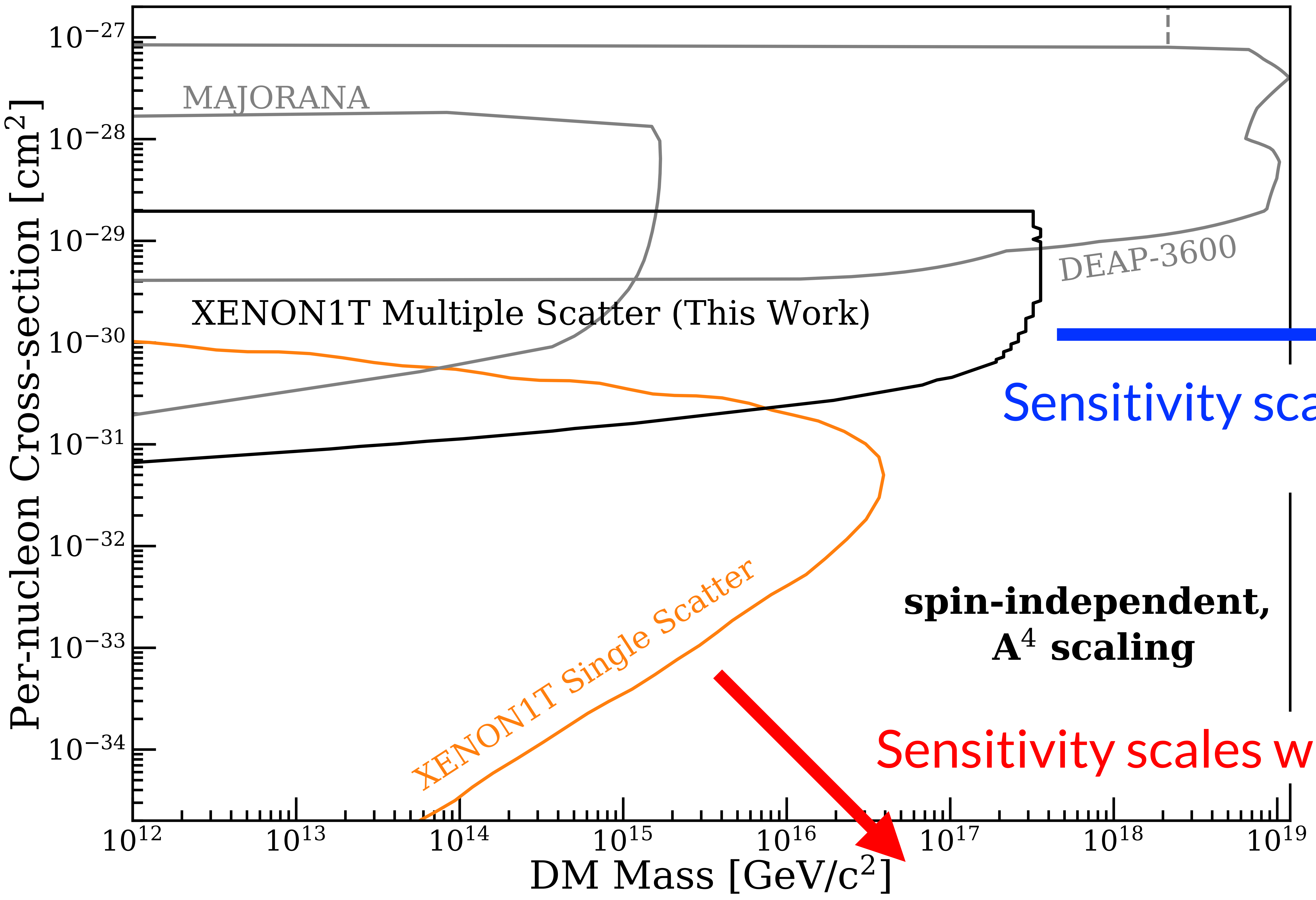


Aalbers, JPhyD
arXiv:2203.02309

Even heavier candidates: towards the Planck scale

XENON, PRL, arXiv:2304.10931

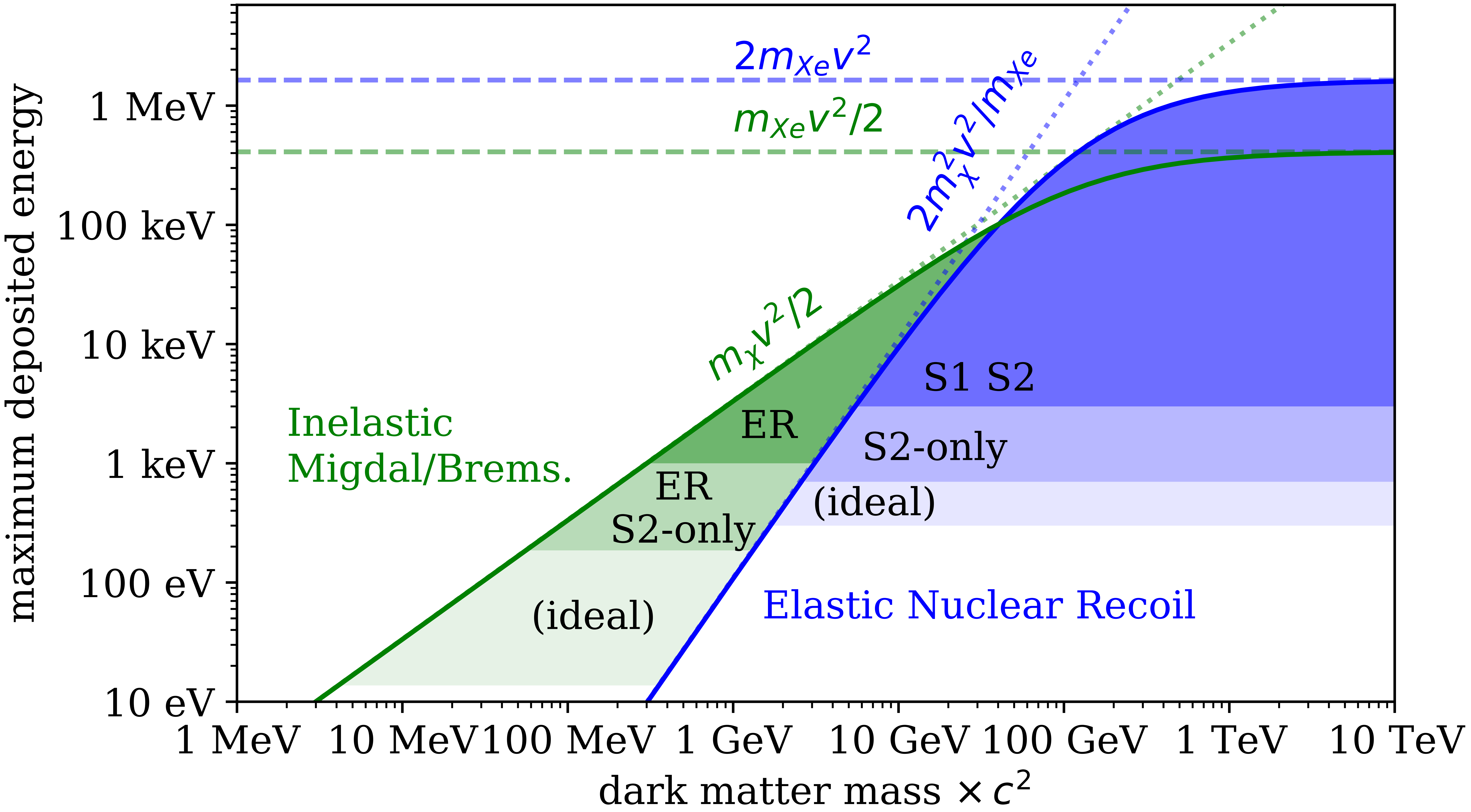
'Search wide'



Sensitivity scales with area of the detector

Sensitivity scales with volume of the detector

Non-natural WIMPs: towards lighter DM candidates



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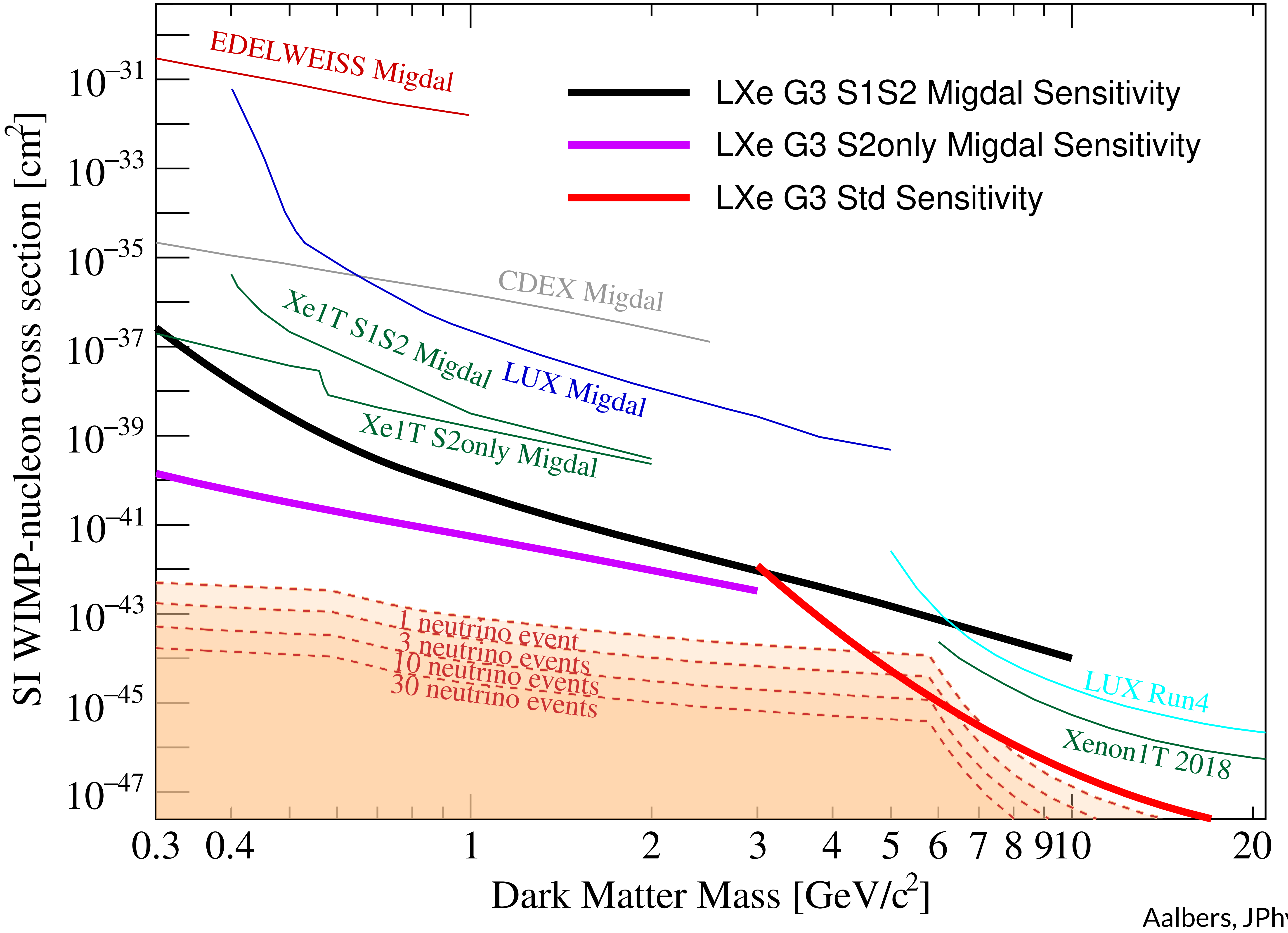
Non-natural WIMPs: towards lighter DM candidates

'Search wide'

'**Migdal effect**':
electrons and the nucleus are coupled in atoms so perturbations of the nucleus can induce electronic transitions

Allows XLZD to prove the sub-GeV window

(Several activities ongoing to gain a better understanding of the effect)



Aalbers, JPhyD
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XLZD: multi-target detector

Xenon naturally contains several isotopes with sizeable abundance (>~5%)

‘Odd neutron isotopes’ (129Xe and 131Xe) give sensitivity to interactions that couple to spin
[136Xe for neutrinoless double-beta decay]

LXe-TPC

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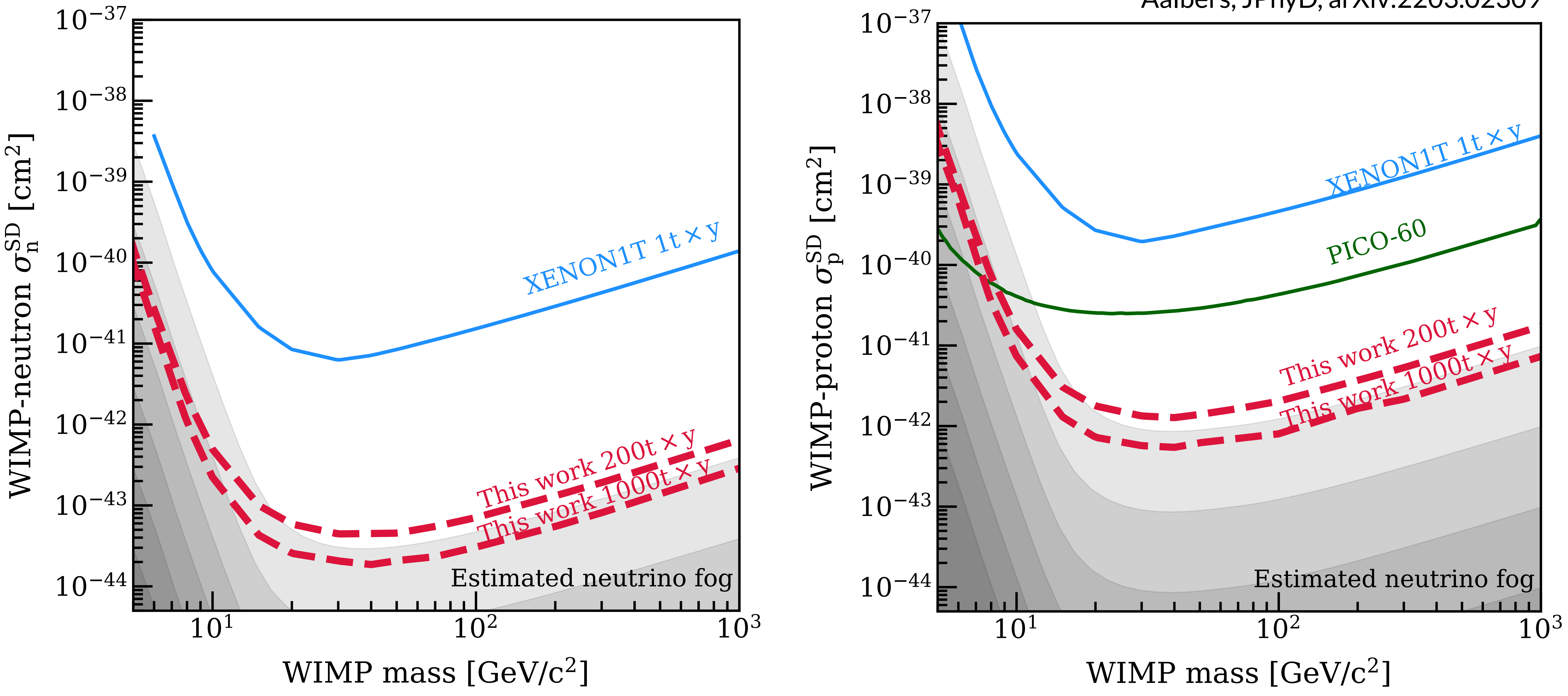

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'Odd neutron isotopes' (129Xe and 131Xe) give sensitivity to interactions that couple to spin
[136Xe for neutrinoless double-beta decay]

LXe-TPC

Can test a menagerie of dark matter interactions

Type	Abbrev.	Operator ($\mathcal{Q}$)	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	$\bar\chi\gamma^\mu\gamma_5\chi\bar q\gamma_\mu\gamma_5 q$	6	No	$C^{AA}_{u,d,s}$

XLZD: beyond elastic scattering

'Search wide'

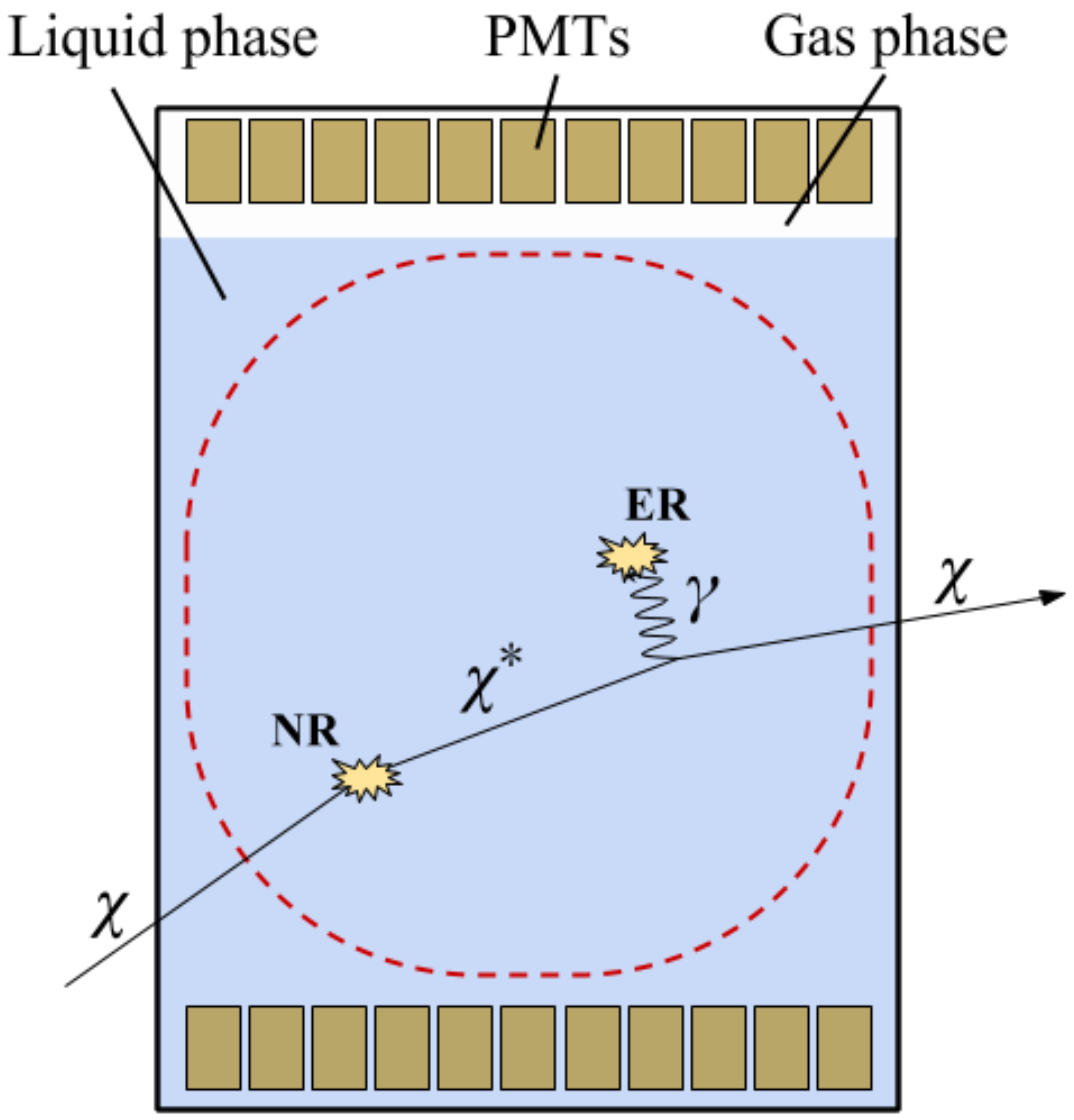
Multiple DM candidates have been proposed with sub-structure

Allows for inelastic scattering of DM with nuclei

Rich phenomenology of signals: higher energy signals; mixed nuclear recoil and electronic recoil signals

Larger TPC allows for larger DM lifetimes to be probed

[WIMPs can also excite the xenon nucleus: could be used as a secondary discovery channel]

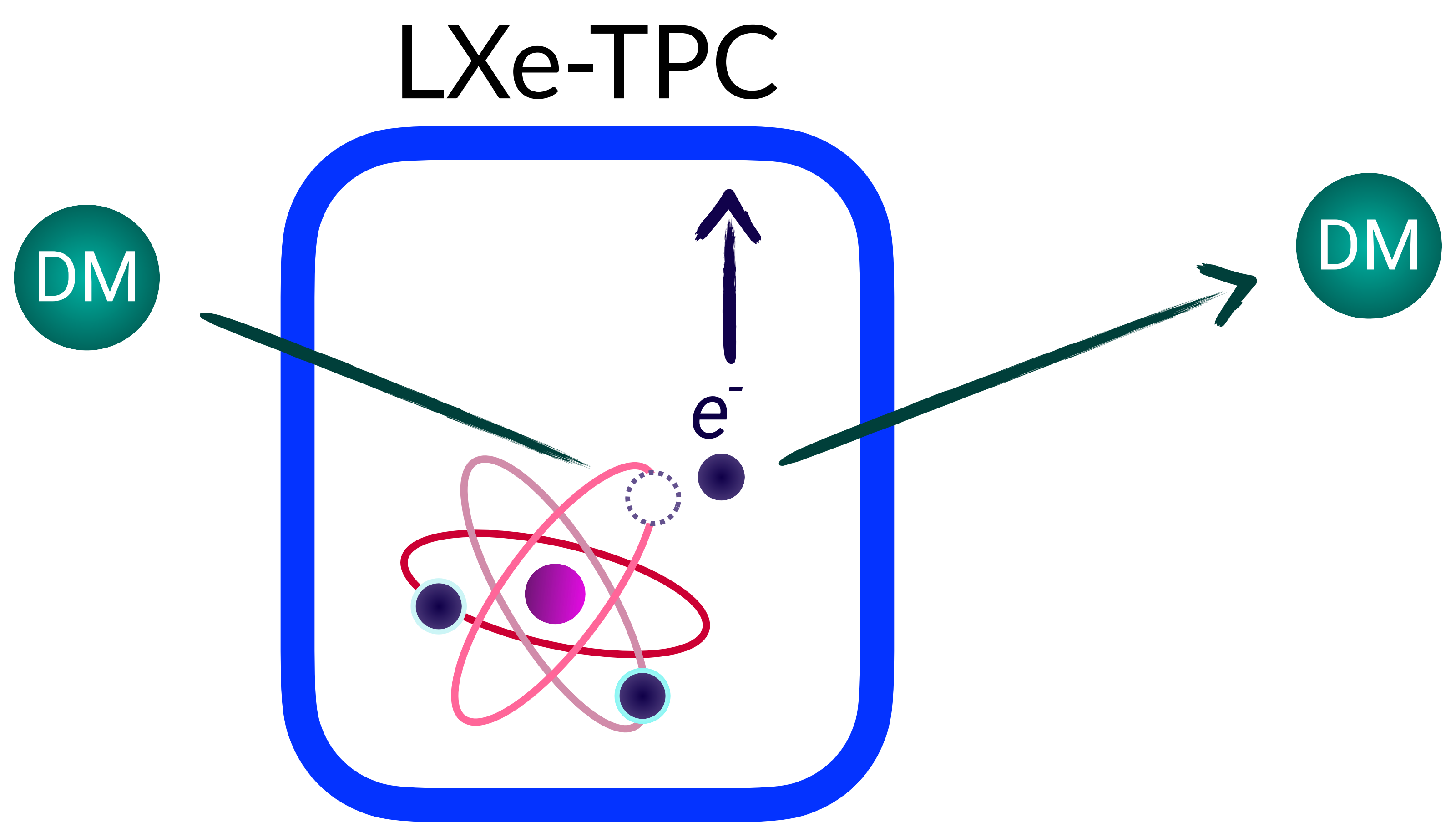


XENON, JCAP, arXiv:1704.05804

Broadening the search: charge only signals

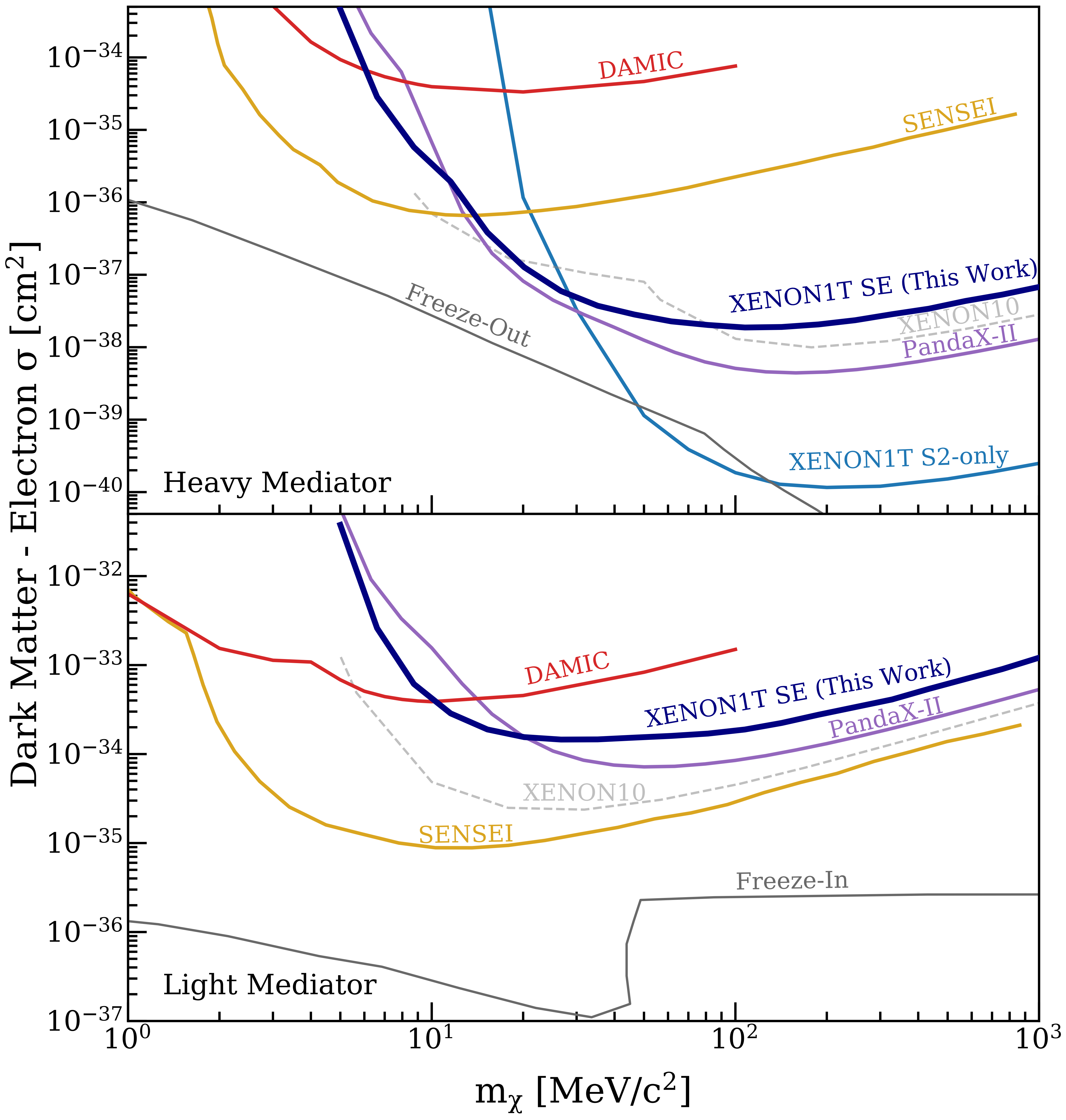
'Search wide'

Much recent activity exploring the sub-GeV window with ionisation signals, giving DM sensitivity down to ~10 MeV



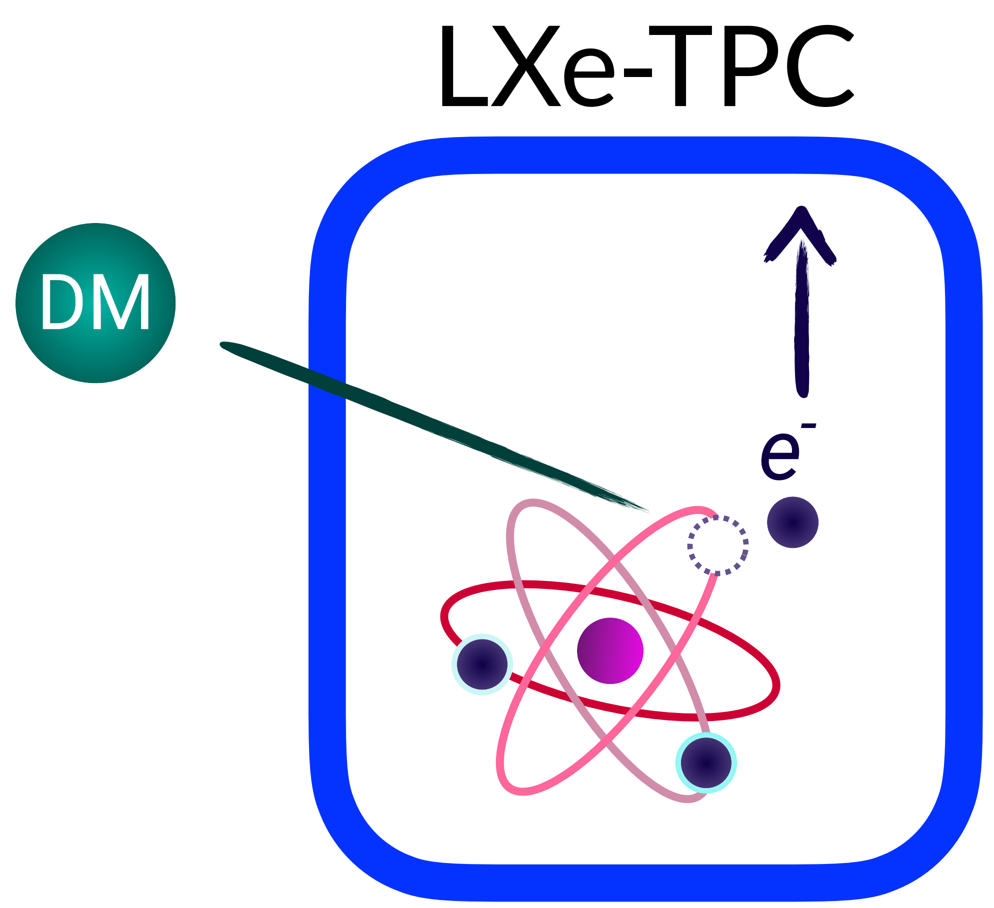
Larger TPC allows for:

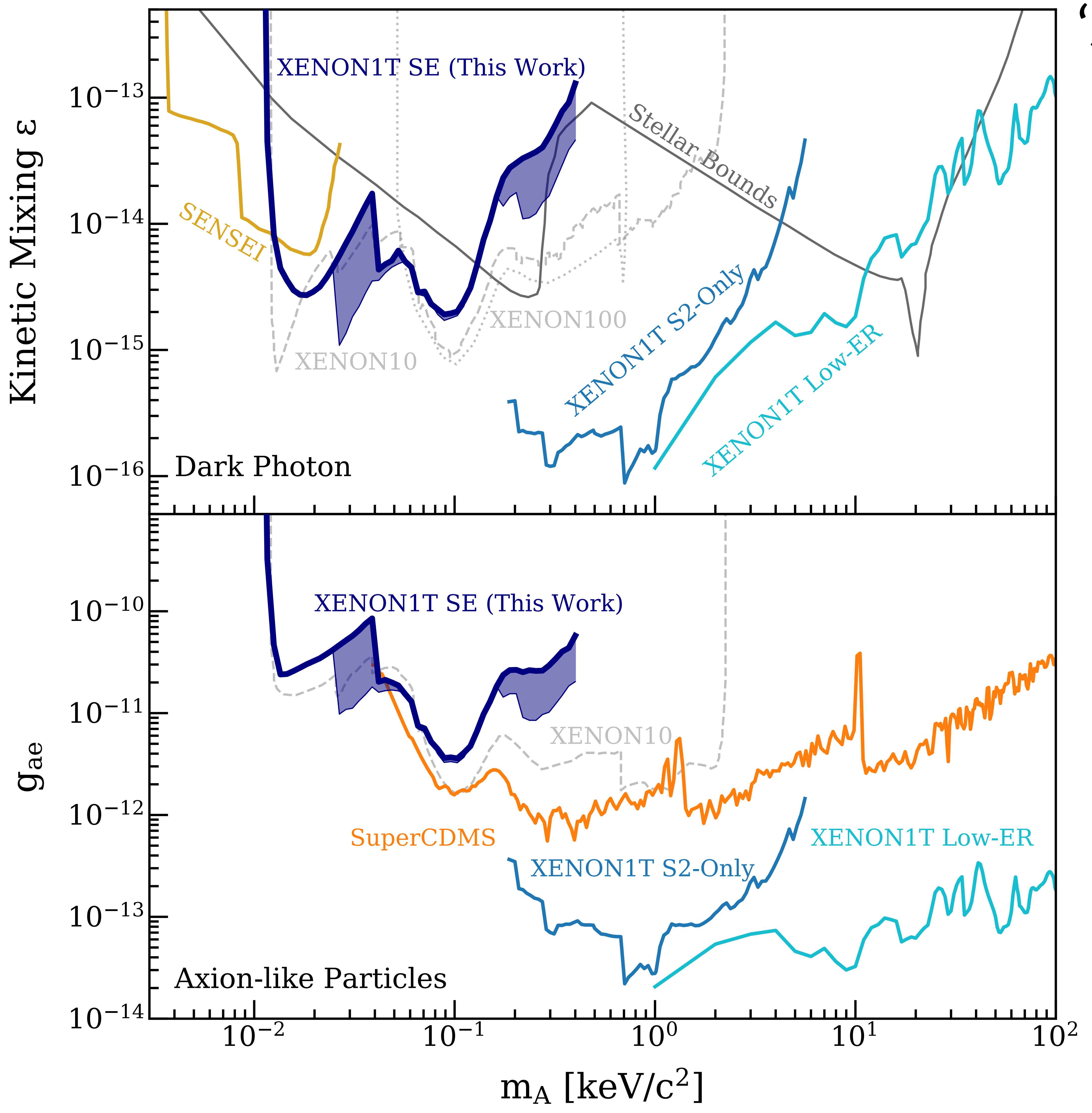
- improved identification of S2s from the bottom of the detector
- decrease in Xe contamination from the relative scaling of volume and surface area



Broadening the search: charge only signals

DM absorption (bosons) gives DM sensitivity down to ~10 eV



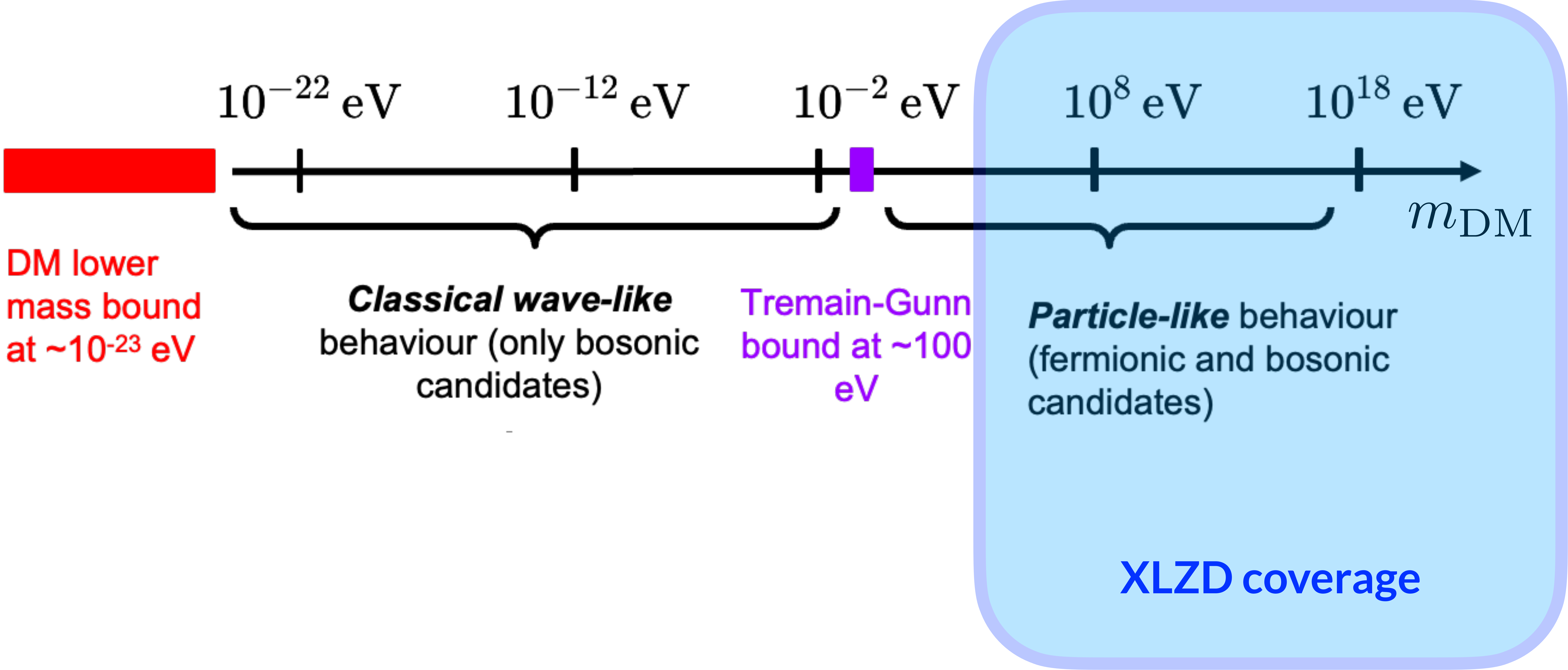


'Search wide'

Larger TPC and lower background rates will improve sensitivity

Allows XLZD to probe down to the particle DM/ wave DM boundary (~few eV)

Summary: what does XLZD do?



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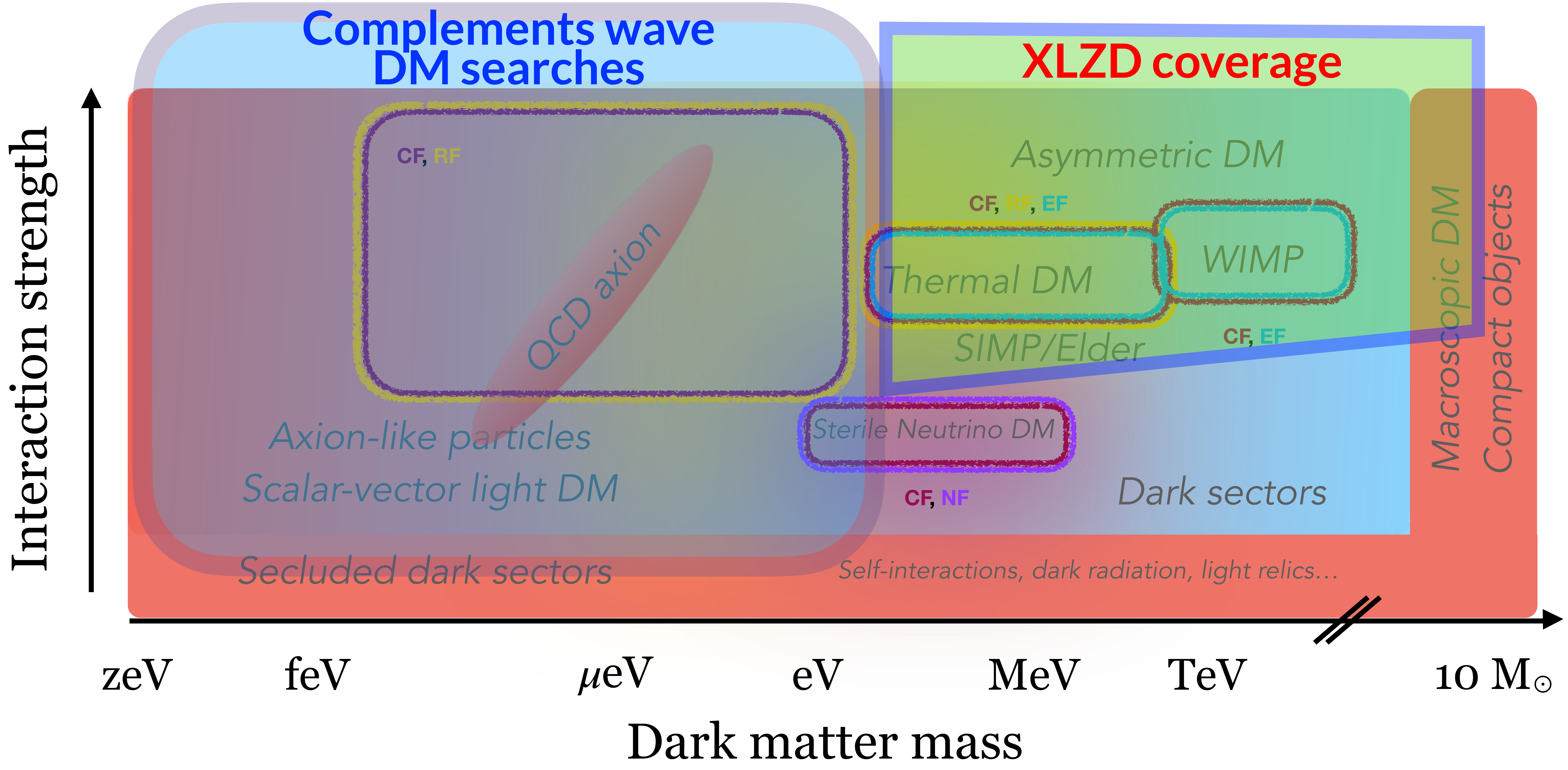

Boveia et al, arXiv:2211.07027

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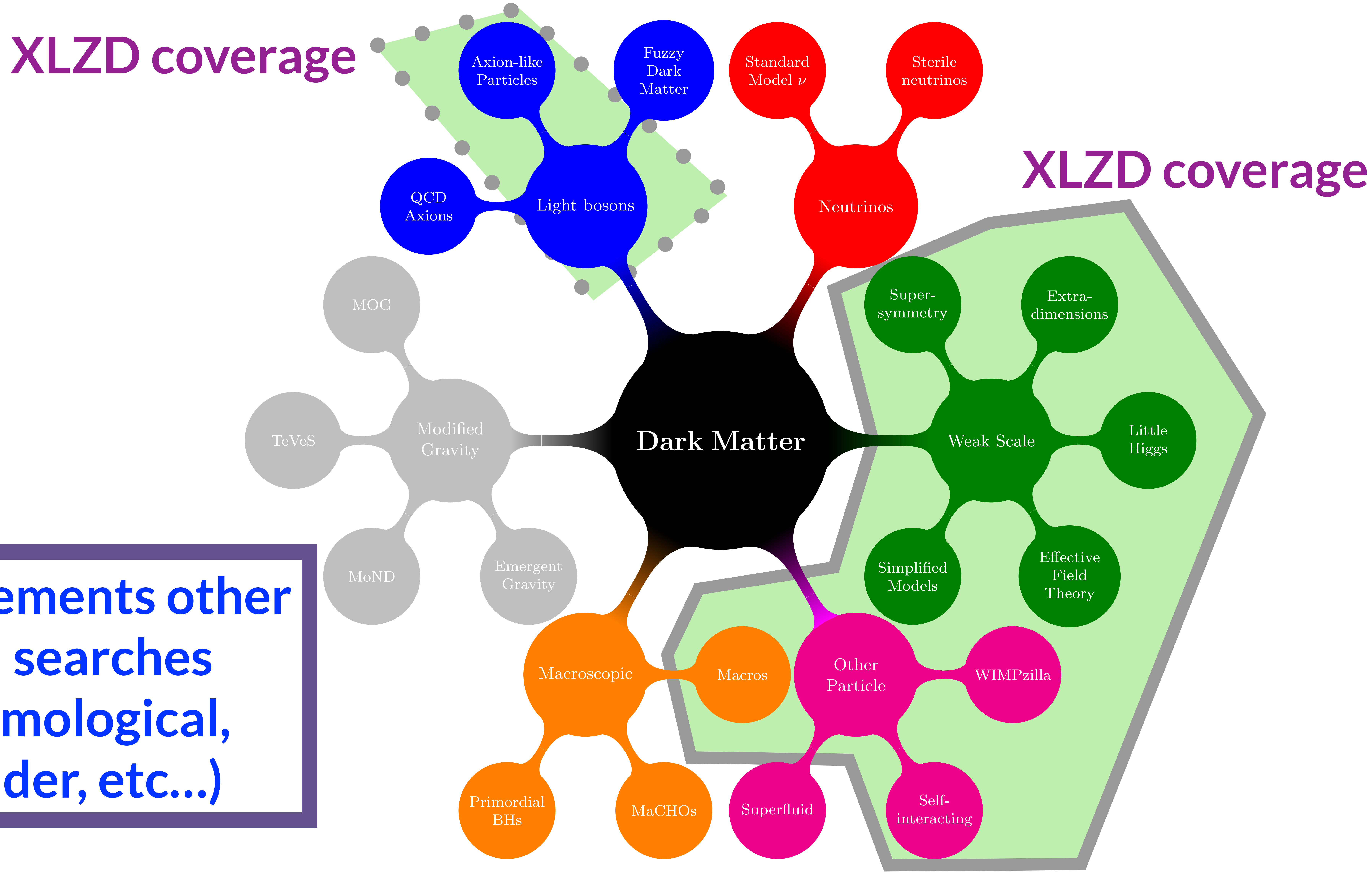

Complements other DM searches (Cosmological, collider, etc...)

Bertone, Tait, Nature
arXiv:1810.01668

Summary

The search for dark matter continues…
Current strategy adopted by the community summarised with ‘***delve deep and search wide***’

In this context, XLZD is the definitive broadband, multi-purpose particle dark matter detector

XLZD definitively probes ‘natural-WIMPs’ to the neutrino floor, and gives sensitivity to candidates up to the Planck mass and down to eV scale

Remarkably, candidates across the full mass range of *particle* dark matter can be tested