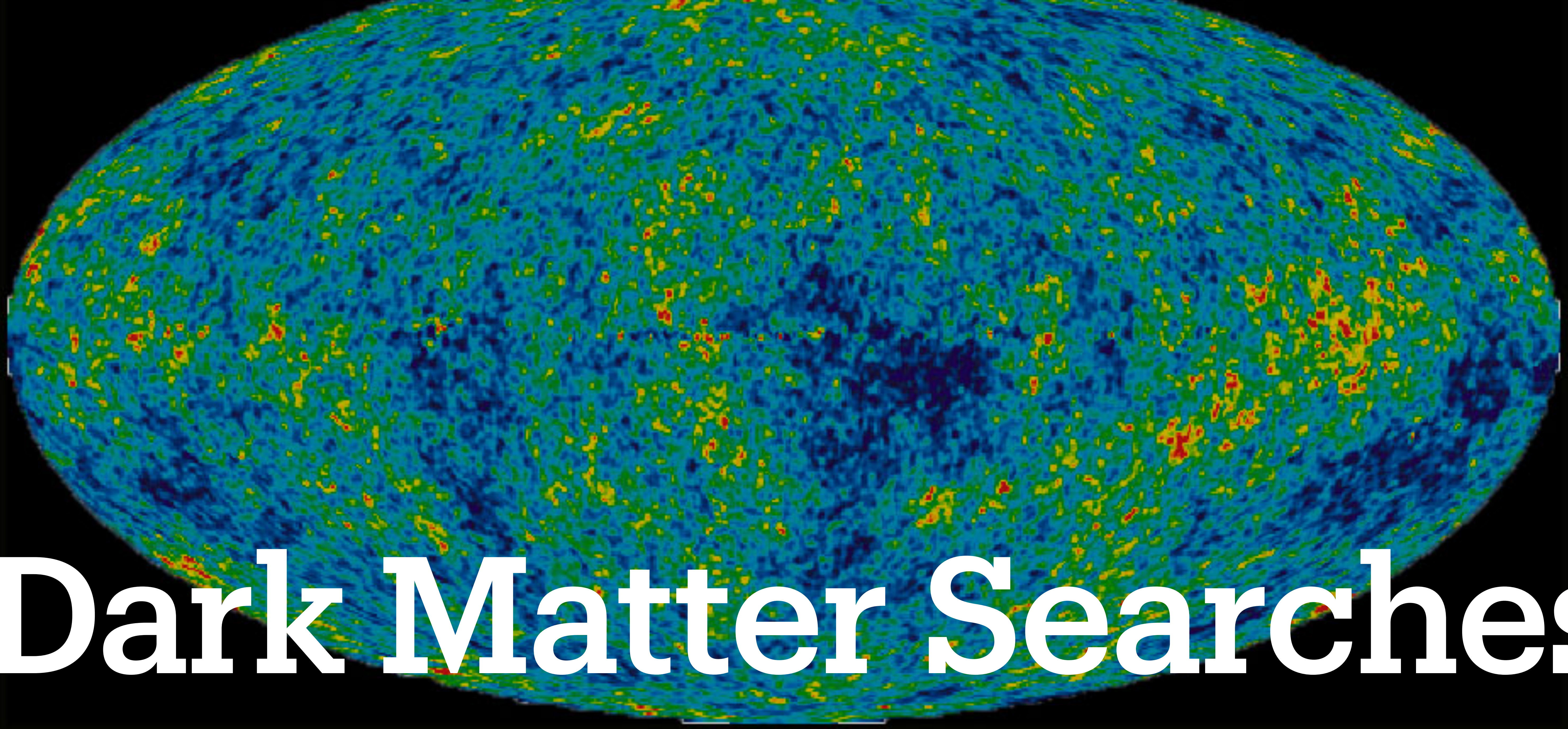
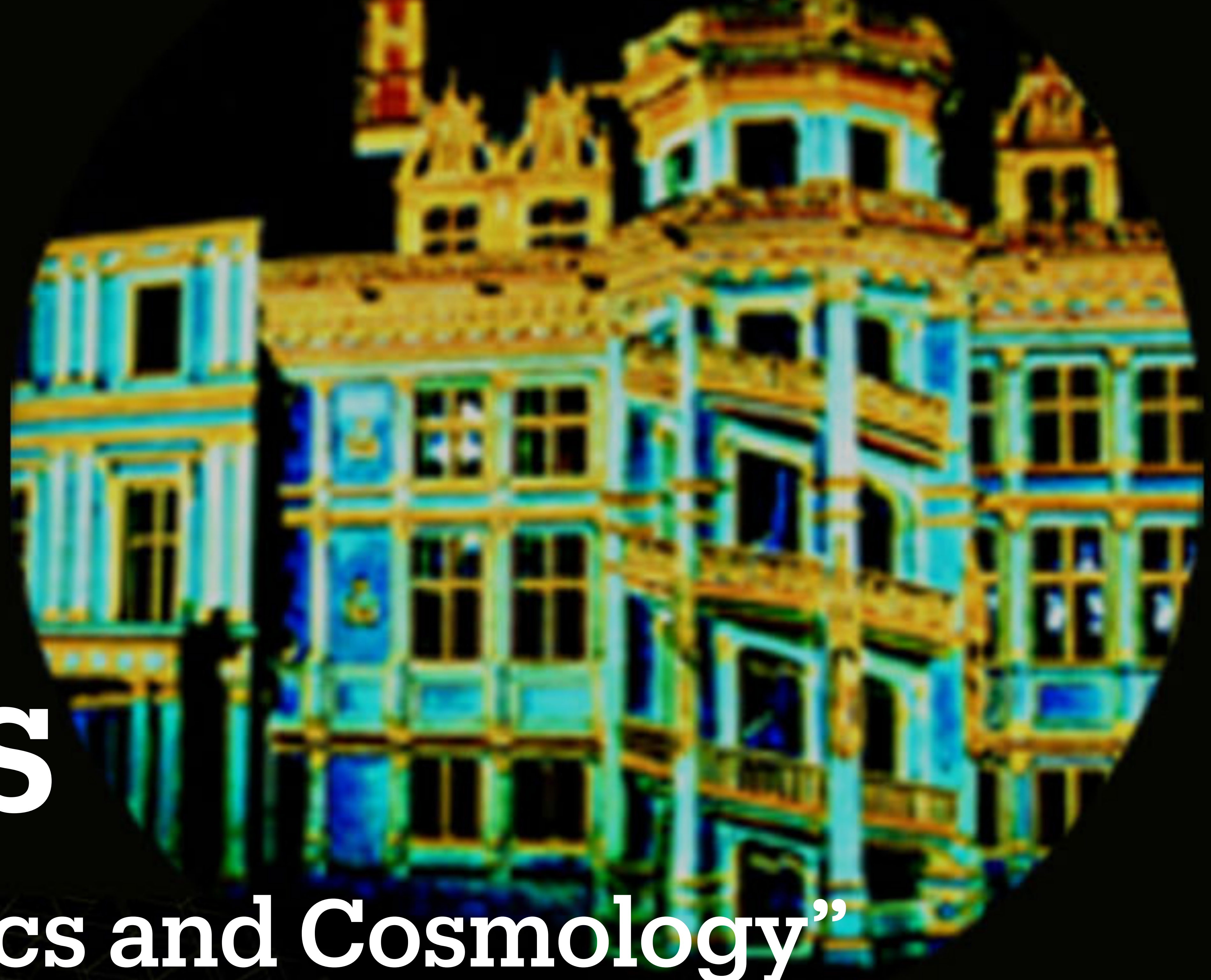
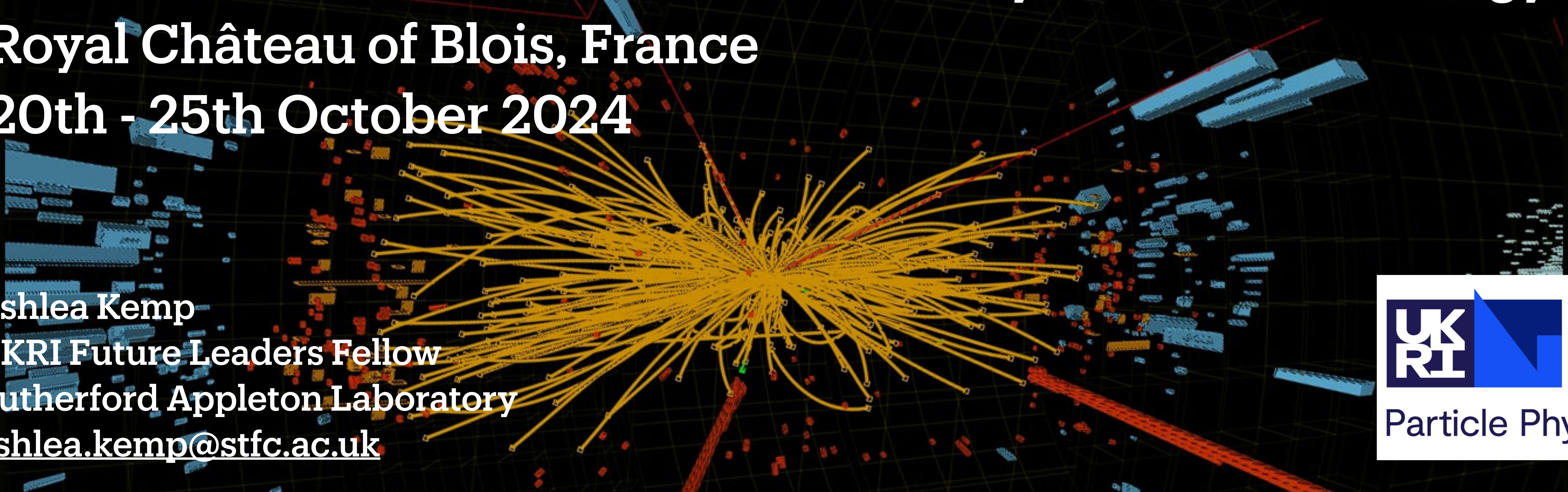




Dark Matter Searches

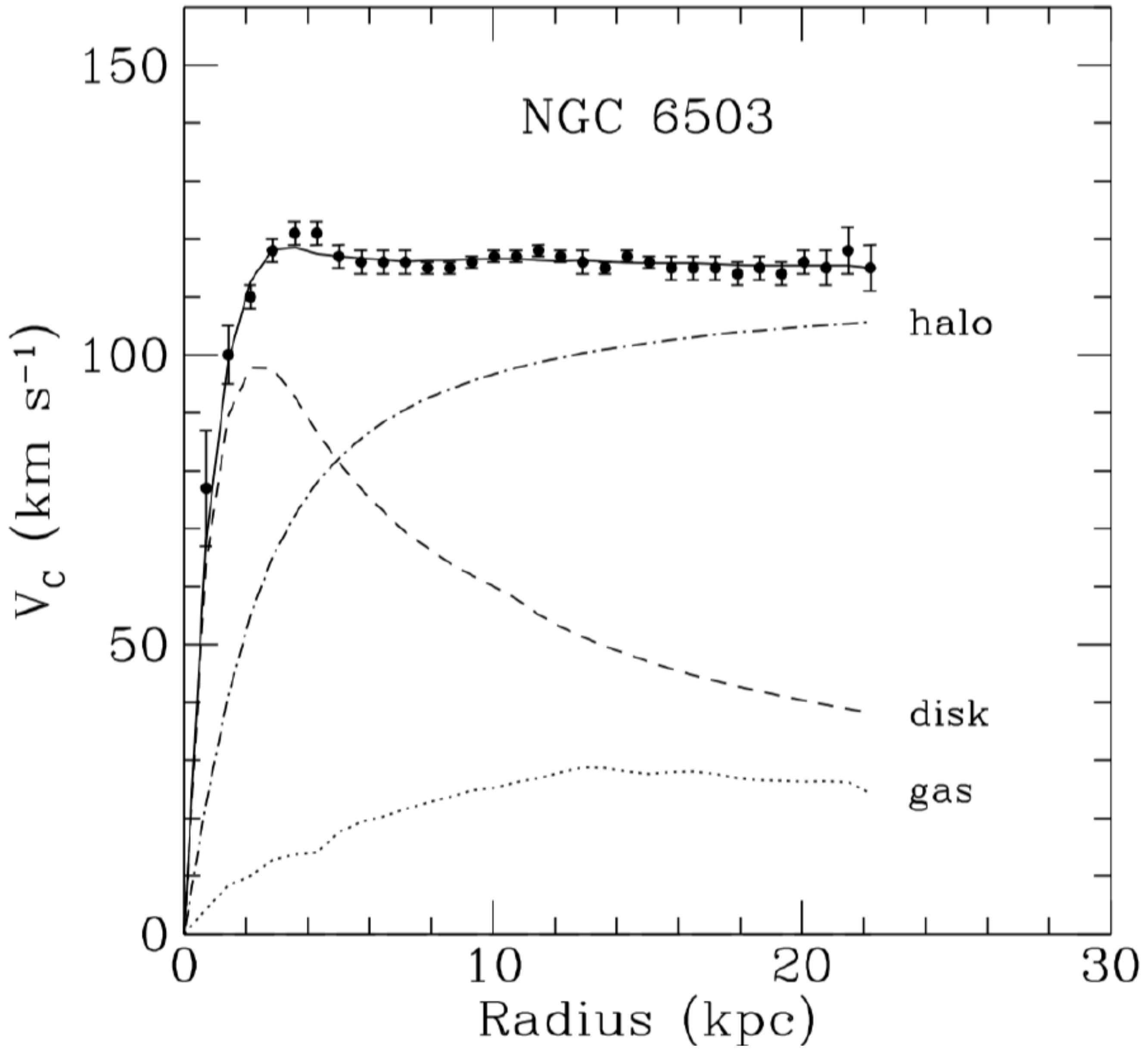
35th Rencontres de Blois on “Particle Physics and Cosmology”
Royal Château of Blois, France
20th - 25th October 2024

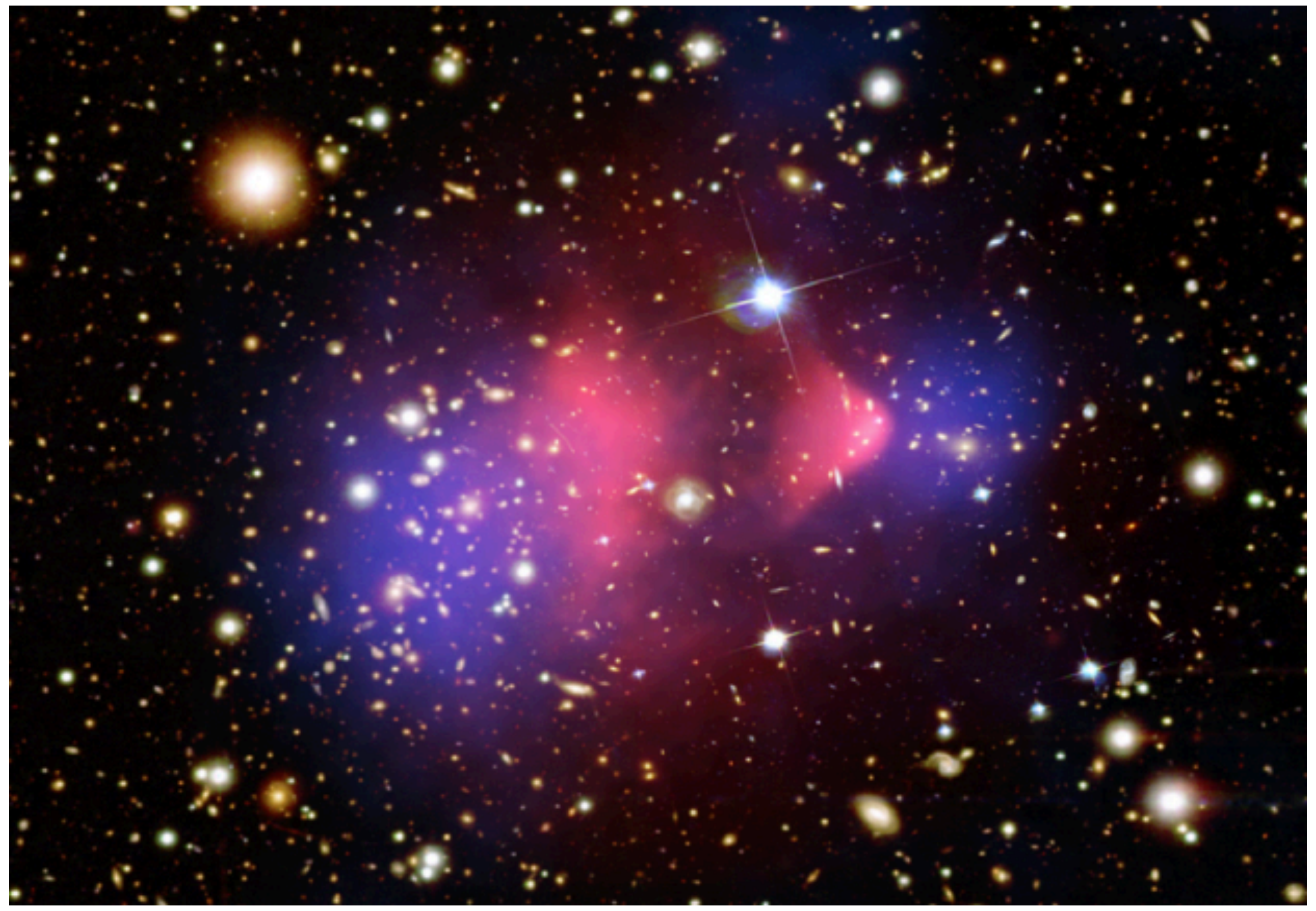


Ashlea Kemp
UKRI Future Leaders Fellow
Rutherford Appleton Laboratory
ashlea.kemp@stfc.ac.uk

UKRI Science and Technology Facilities Council
Particle Physics

Evidence for Dark Matter





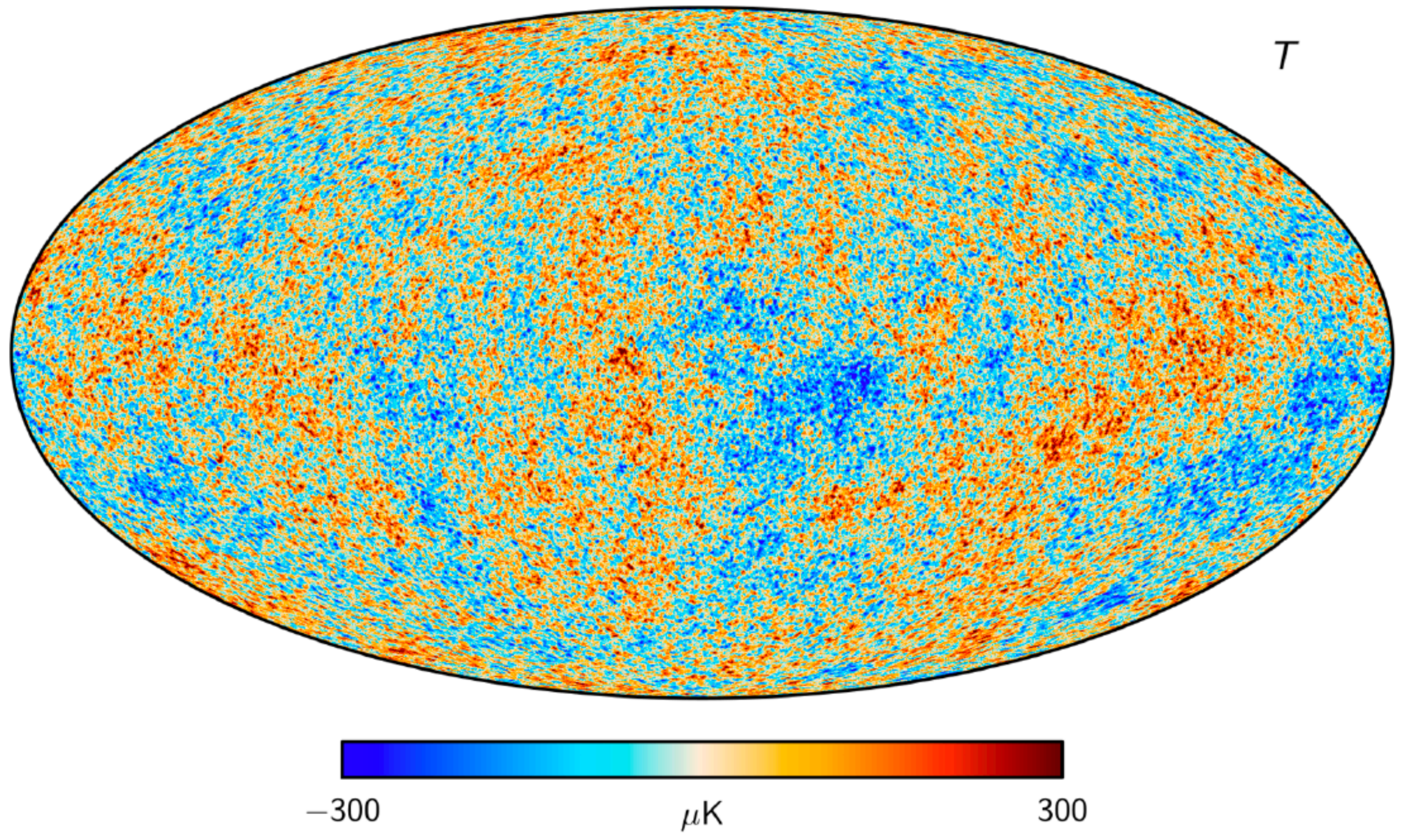
Clear evidence for dark matter (DM) on both galactic (←) and cosmological (→) scales.

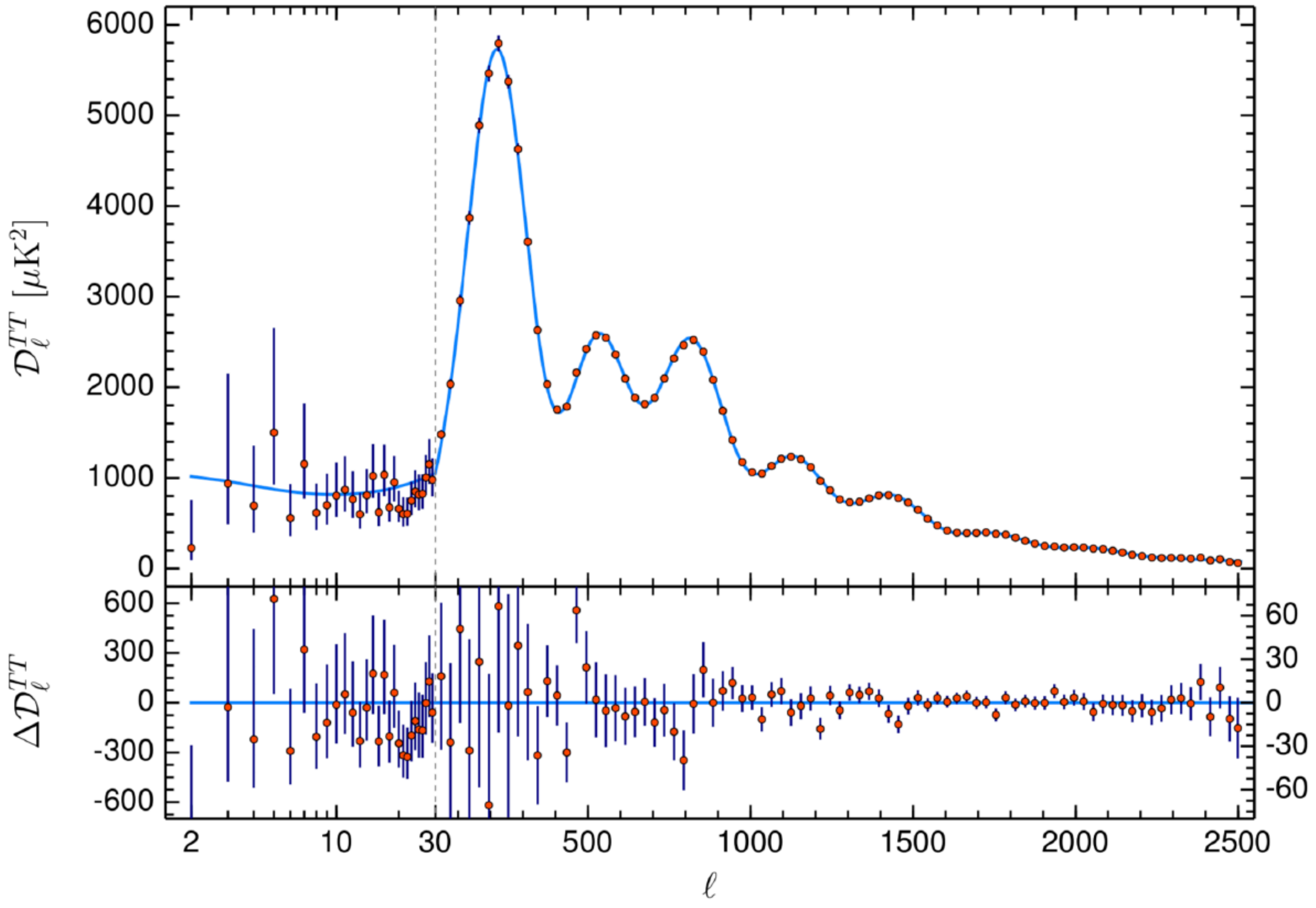
Galactic Rotation Curves: Flat velocity distribution implies non-luminous DM halo.

Bullet Cluster: Strong evidence for non-baryonic DM.

Cosmic Microwave Background: Temperature anisotropies of $\mathcal{O}(10^{-5})$ deduces (dark) matter-energy content of Universe.

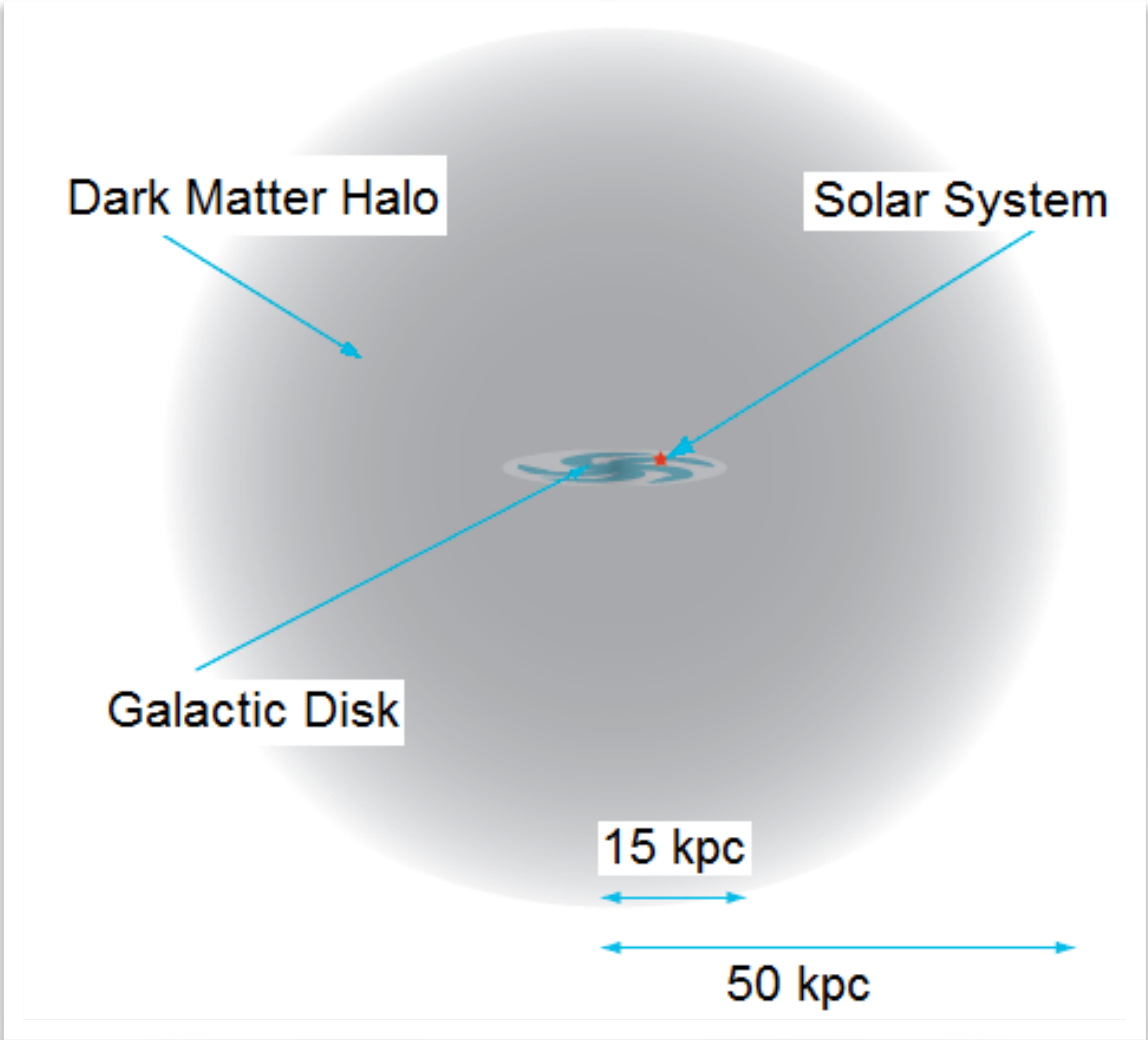
Large-Scale Structure: Cold DM predicts hierarchal evolution from gravitational interactions.





What *exactly* do we know about Dark Matter?

Spoiler: Not Much!



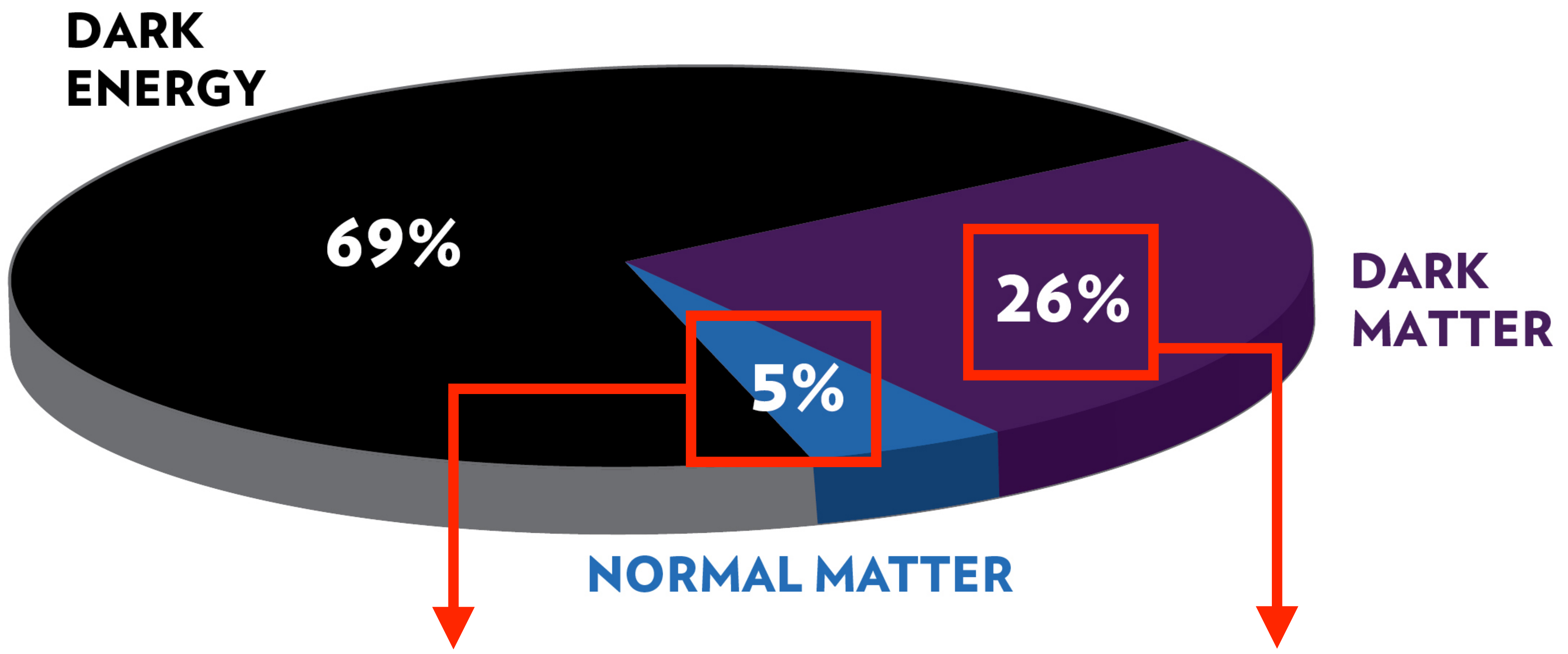
DM Halo Distribution, $M \propto r$

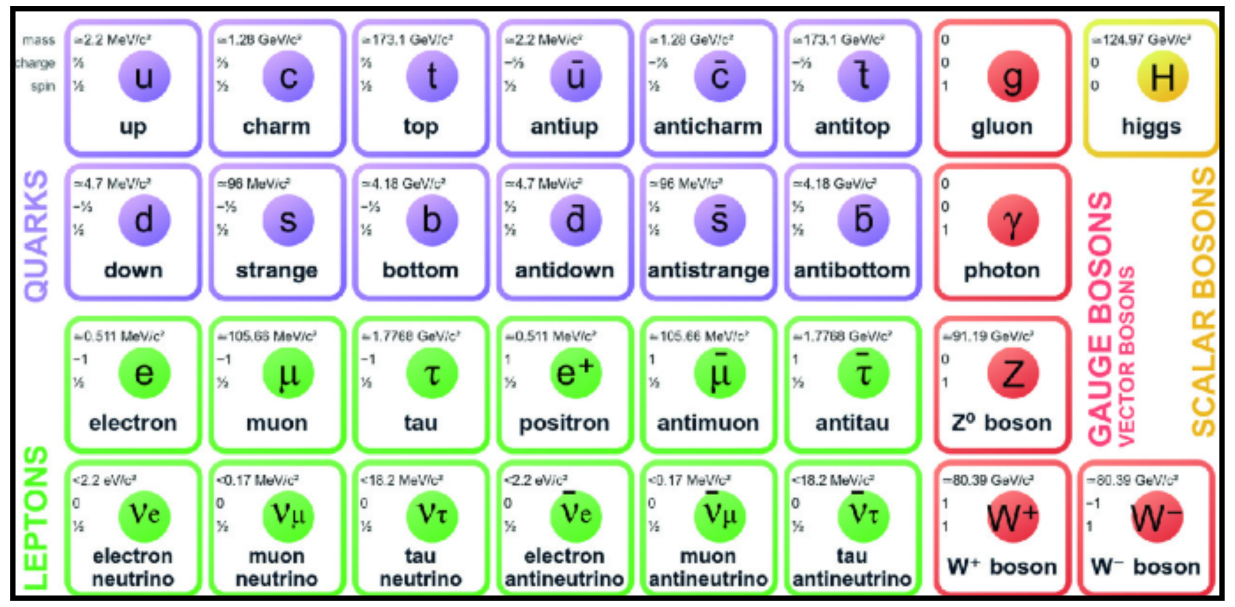
Optically dark: does not interact with EM force.

Gravitationally bound to our galaxy, ρ = 0.3 GeV/cm$^{3.}$

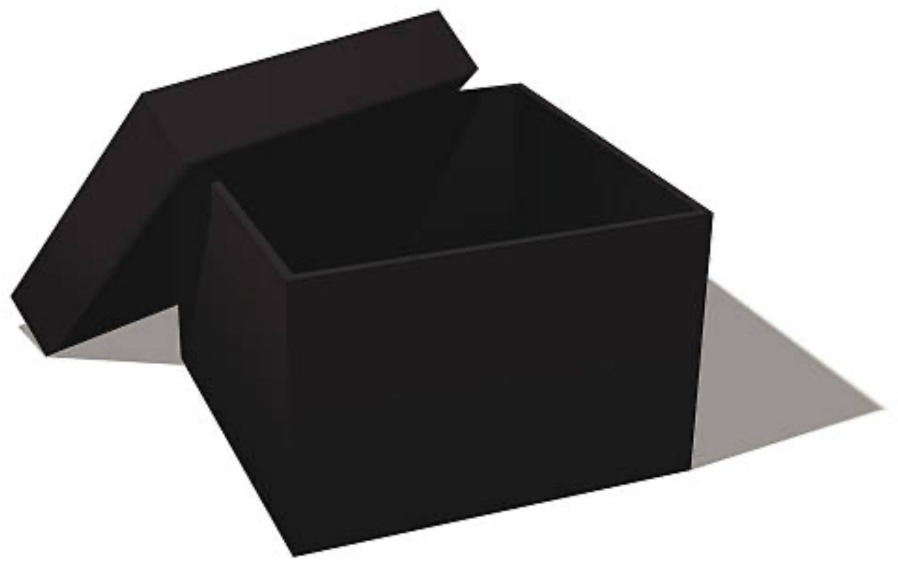
Extremely weakly interacting.

Comprises ~25% of Universe; 5x more abundant than normal matter!



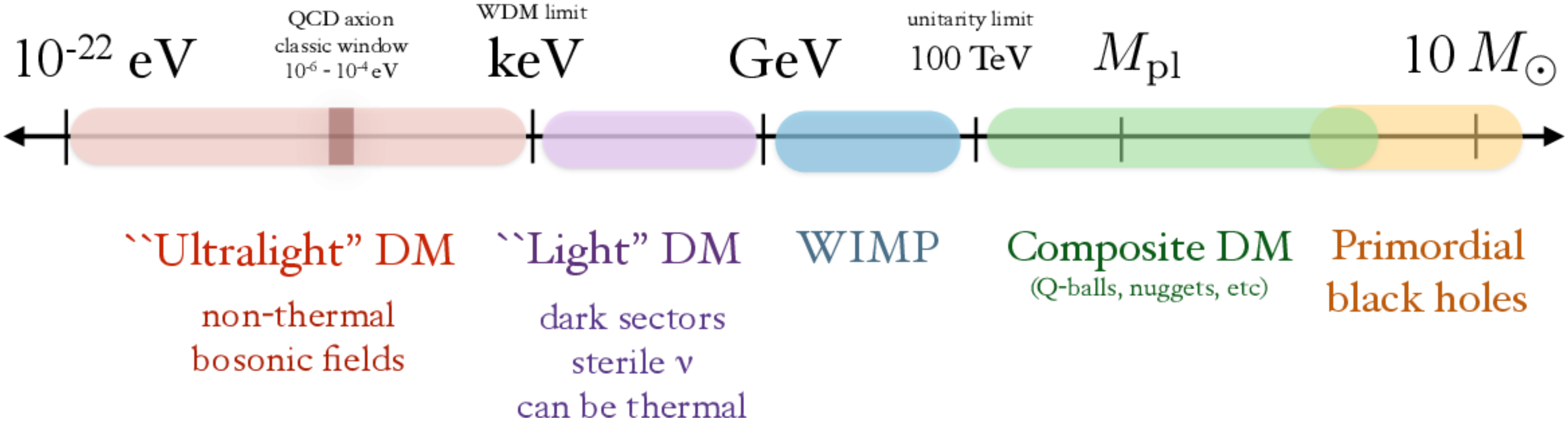


mass charge spin	≈2.2 MeV/c² ⅔ ½ u up	≈1.28 GeV/c² ⅔ ½ c charm	≈173.1 GeV/c² ⅔ ½ t top	≈2.2 MeV/c² −⅔ ½ $\bar{u}$ antiup	≈1.28 GeV/c² −⅔ ½ $\bar{c}$ anticharm	≈173.1 GeV/c² −⅔ ½ $\bar{t}$ antitop	0 0 1 g gluon	≈124.97 GeV/c² 0 0 H higgs
QUARKS	≈4.7 MeV/c² −⅓ ½ d down	≈96 MeV/c² −⅓ ½ s strange	≈4.18 GeV/c² −⅓ ½ b bottom	≈4.7 MeV/c² ⅓ ½ $\bar{d}$ antidown	≈96 MeV/c² ⅓ ½ $\bar{s}$ antistrange	≈4.18 GeV/c² ⅓ ½ $\bar{b}$ antibottom	0 0 1 γ photon	GAUGE BOSONS VECTOR BOSONS SCALAR BOSONS
	≈0.511 MeV/c² −1 ½ e electron	≈105.66 MeV/c² −1 ½ μ muon	≈1.7768 GeV/c² −1 ½ τ tau	≈0.511 MeV/c² 1 ½ e^+ positron	≈105.66 MeV/c² 1 ½ $\bar{\mu}$ antimuon	≈1.7768 GeV/c² 1 ½ $\bar{\tau}$ antitau	≈91.19 GeV/c² 0 1 Z Z^0 boson	
LEPTONS	<2.2 eV/c² 0 ½ ν_e electron neutrino	<0.17 MeV/c² 0 ½ ν_μ muon neutrino	<18.2 MeV/c² 0 ½ ν_τ tau neutrino	<2.2 eV/c² 0 ½ $\bar{\nu}_e$ electron antineutrino	<0.17 MeV/c² 0 ½ $\bar{\nu}_\mu$ muon antineutrino	<18.2 MeV/c² 0 ½ $\bar{\nu}_\tau$ tau antineutrino	≈80.39 GeV/c² 1 1 W^+ W^+ boson	≈80.39 GeV/c² −1 1 W^- W^- boson



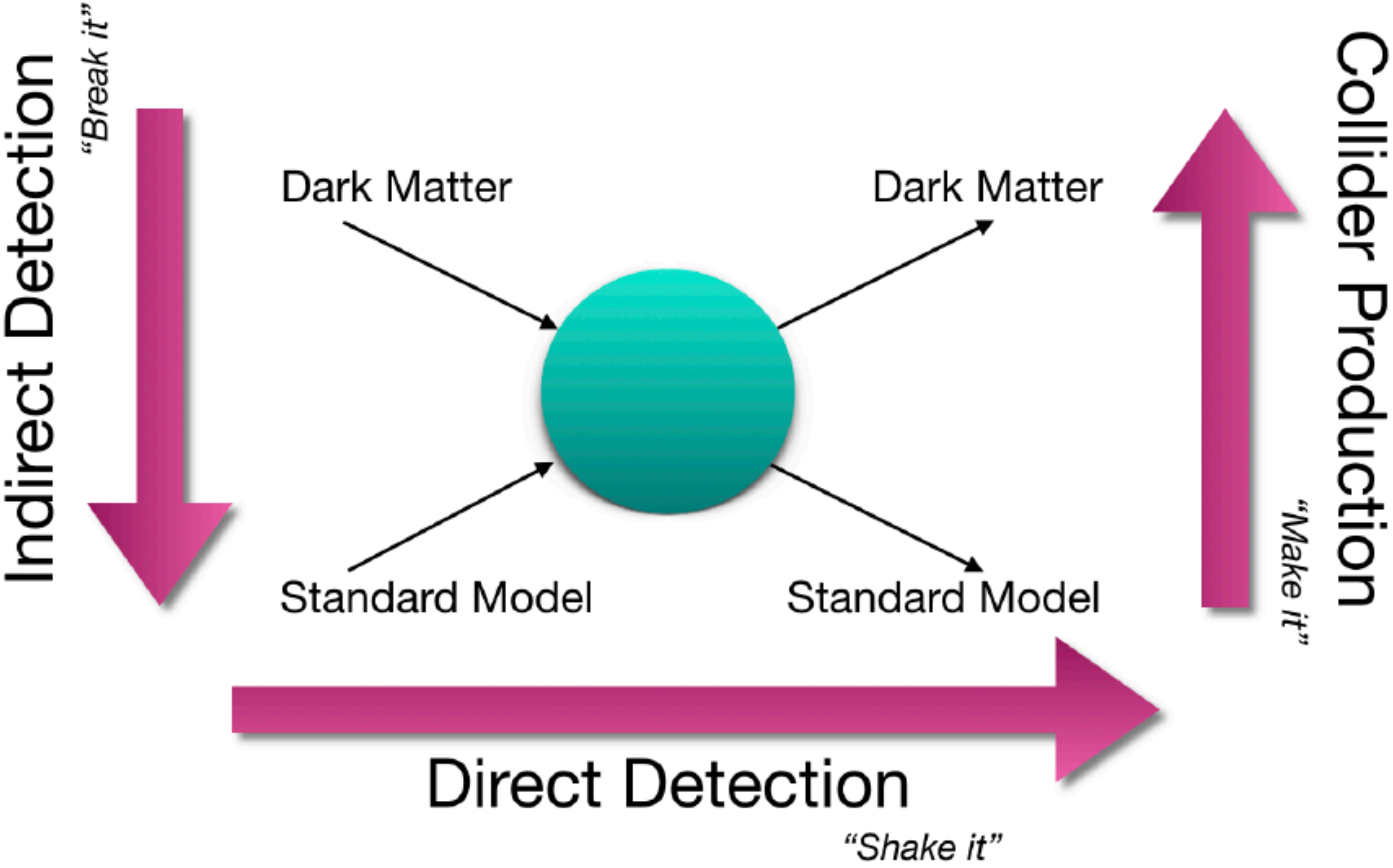
The Challenge

Dark Matter can span over 80 orders of magnitude!



Lin, Tongyan. "TASI lectures on dark matter models and direct detection." arXiv preprint arXiv:1904.07915 4 (2019).

An Experimentalist's View



Indirect Detection

"Break it"

Dark Matter

Dark Matter

Standard Model

Standard Model

Collider Production

"Make it"

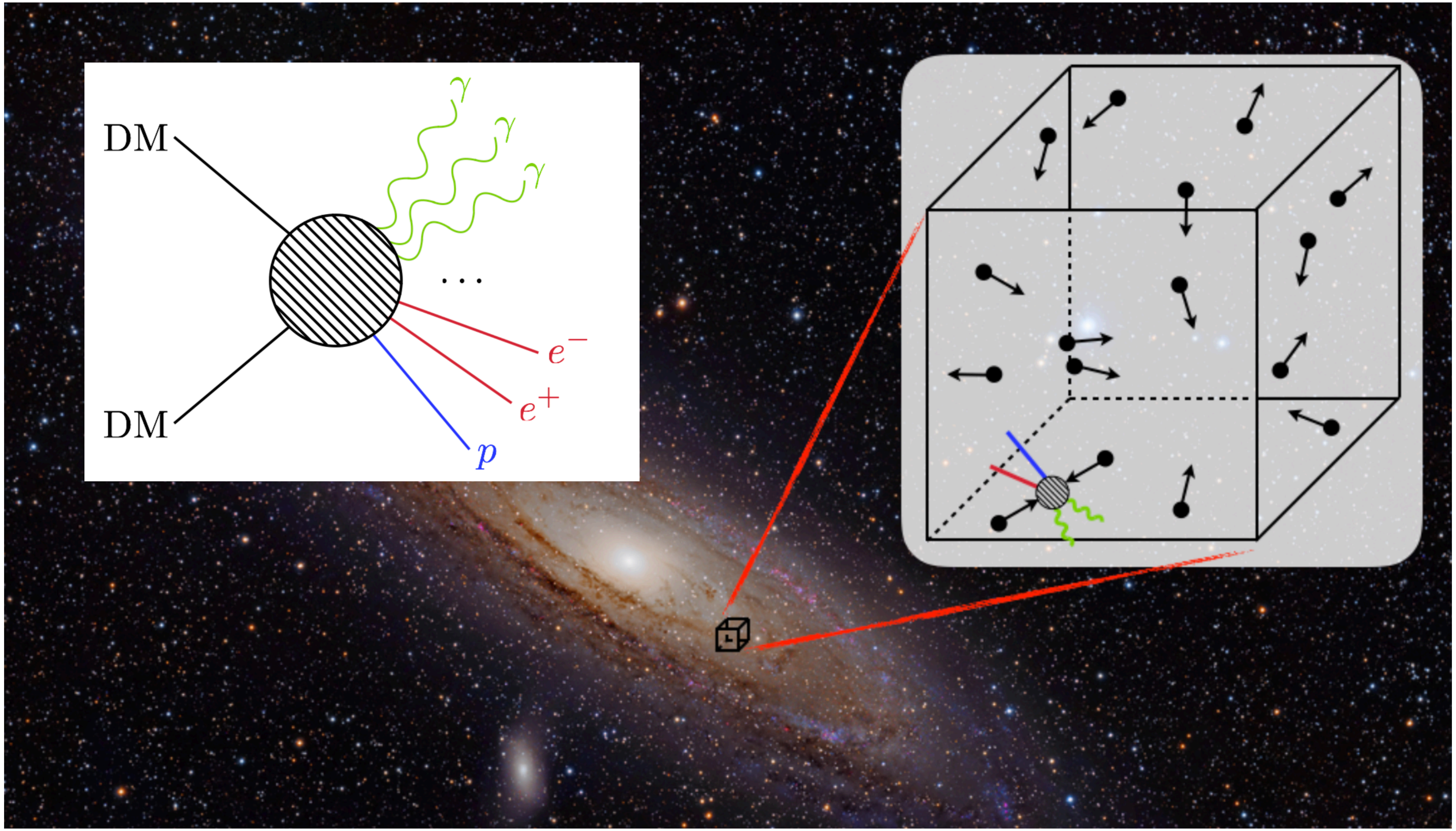
Direct Detection

"Shake it"

An Experimentalist's View

Indirect Detection

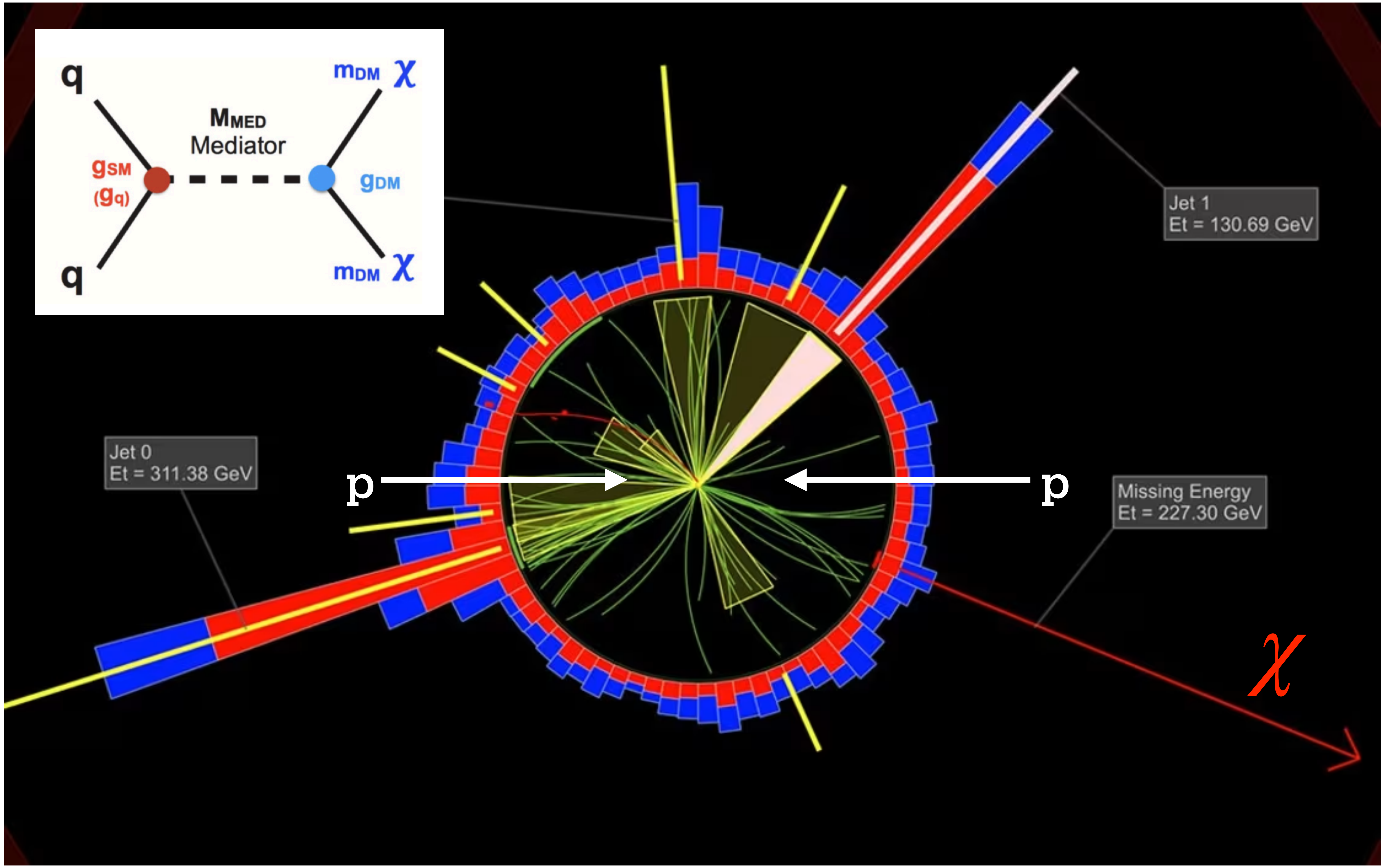
"Break it"



Anomalous flux of γ, ν, cosmic-rays from DM-DM annihilations gravitationally accumulated in heavy cosmological objects.

https://nickrodd.com/research.html

An Experimentalist's View



Collider Production

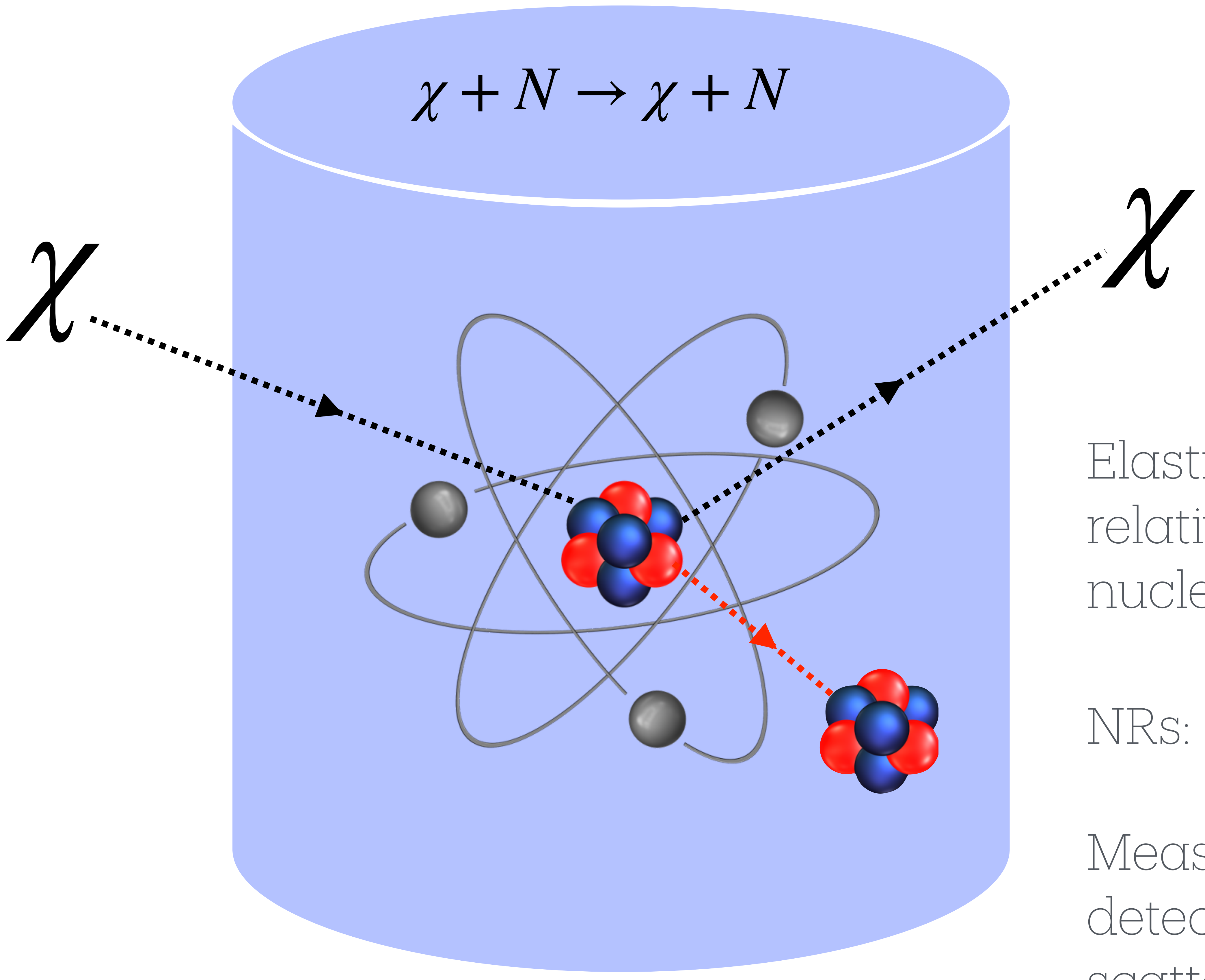
"Make it"

Missing transverse energy associated with DM produced via

$$p + p \to \chi + \chi.$$

https://www.nbcnews.com/sciencemain/whats-dark-matter-find-out-about-new-frontiers-physics-2d11692139

An Experimentalist's View

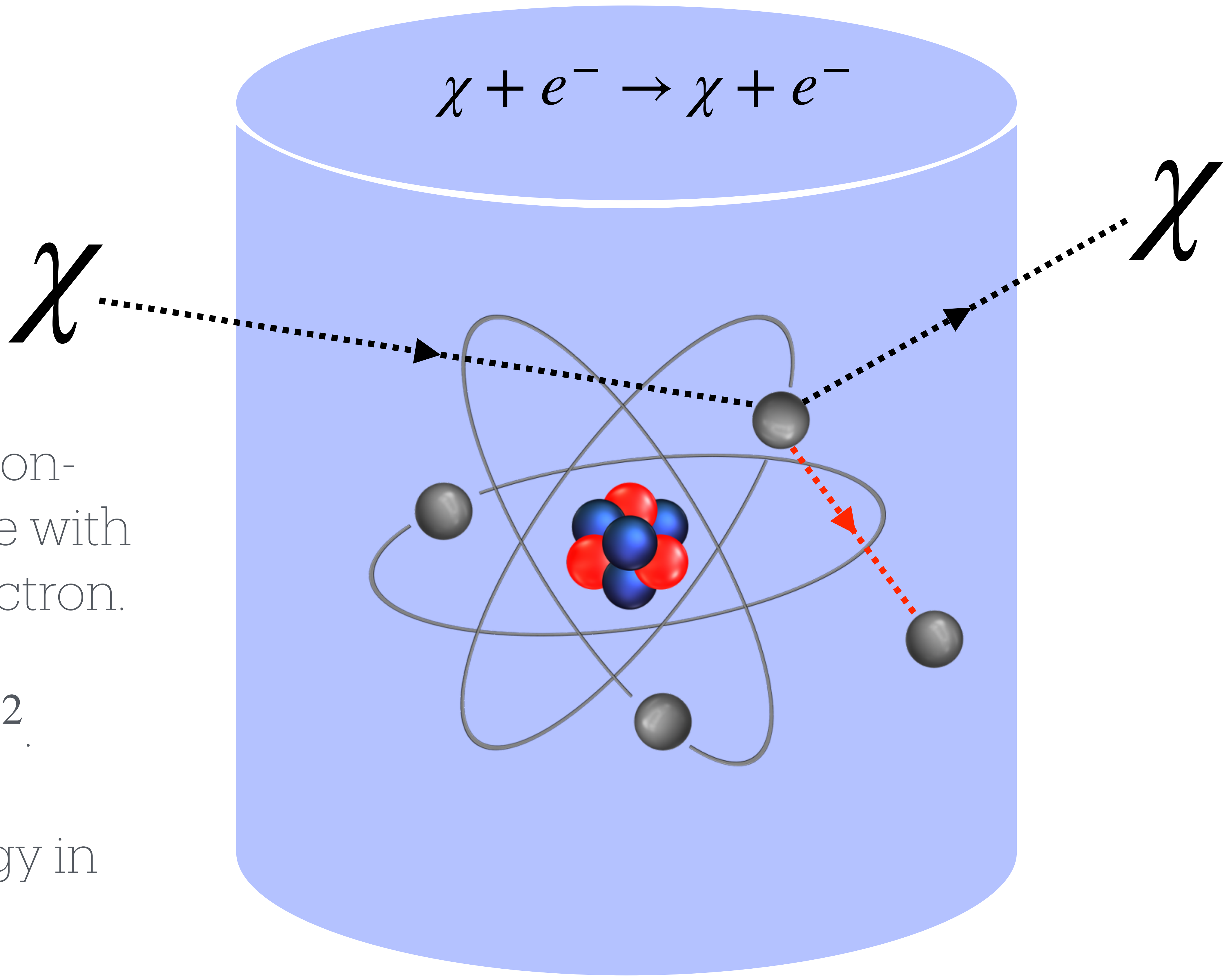


Nuclear Recoil (NR)

Elastic scattering of non-relativistic DM particle with nucleus or atomic electron.

NRs: Coherent, $\sigma \propto A^2$.

Measure NR/ER energy in detector to infer DM scattering interaction.



Electron Recoil (ER)

Direct Detection

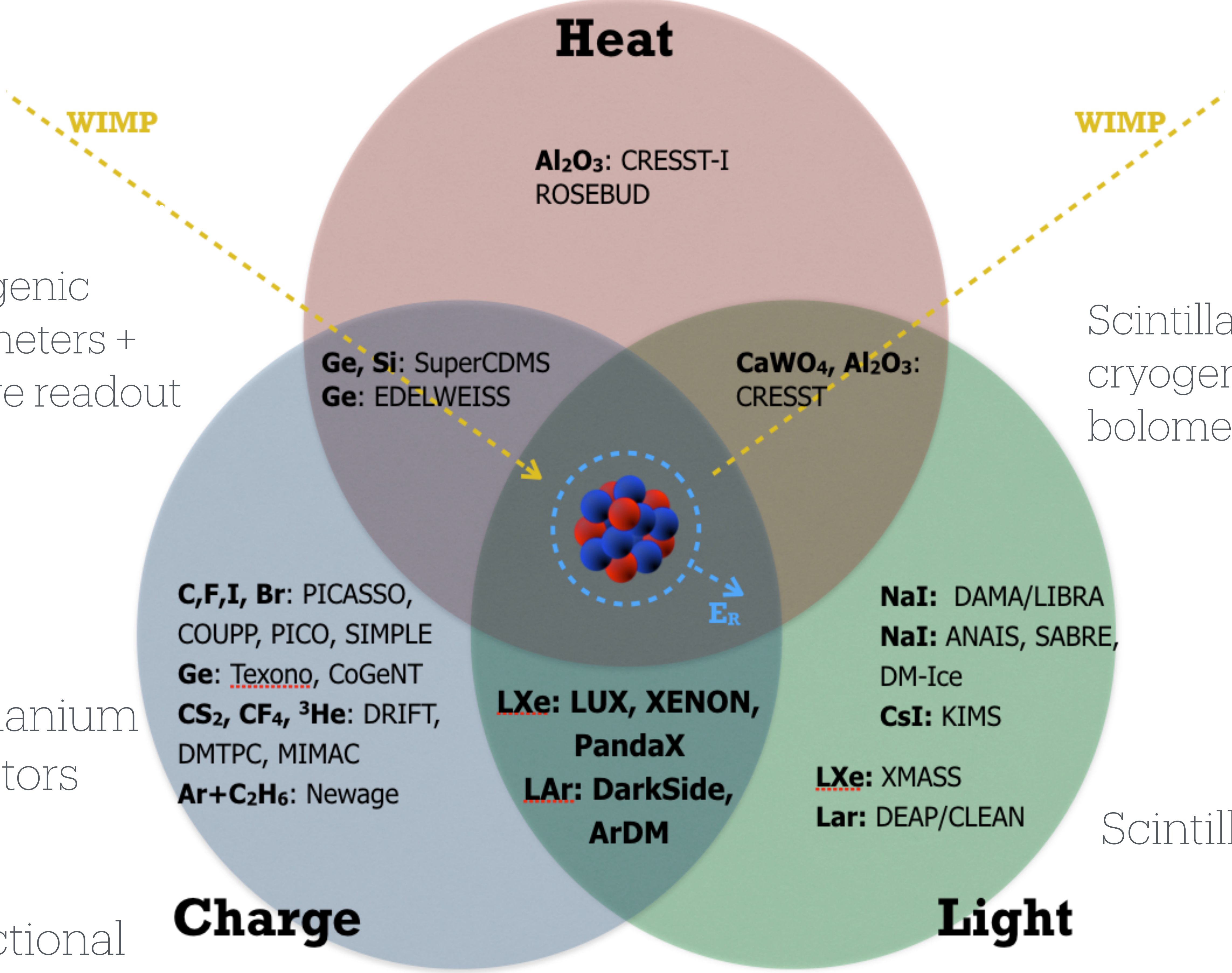
"Shake it"

Direct Detection

Technologies

$E_{\text{Thr,Heat}} \sim \mathcal{O}(10's\ \text{eV})$

Potential to reach meV



Cryogenic bolometers

Superheated liquids

Cryogenic bolometers + charge readout

Scintillating cryogenic bolometers

Germanium detectors

Scintillating crystals

Directional detectors

Liquid noble-gas dual-phase time projection chambers

Liquid noble-gas detectors

$E_{\text{Thr,Q}} \sim \mathcal{O}(10\ \text{eV})$

Potential to reach eV

$E_{\text{Thr},\gamma} \sim \mathcal{O}(\text{keV})$

Potential to reach 10 eV

Courtesy of J. Monroe (ICHEP '24)

Direct Detection

Technologies

Cryogenic
bolometers

Superheated
liquids

$E_{\text{Thr,Heat}} \sim \mathcal{O}(10's\ \text{eV})$

Potential to reach meV

Heat

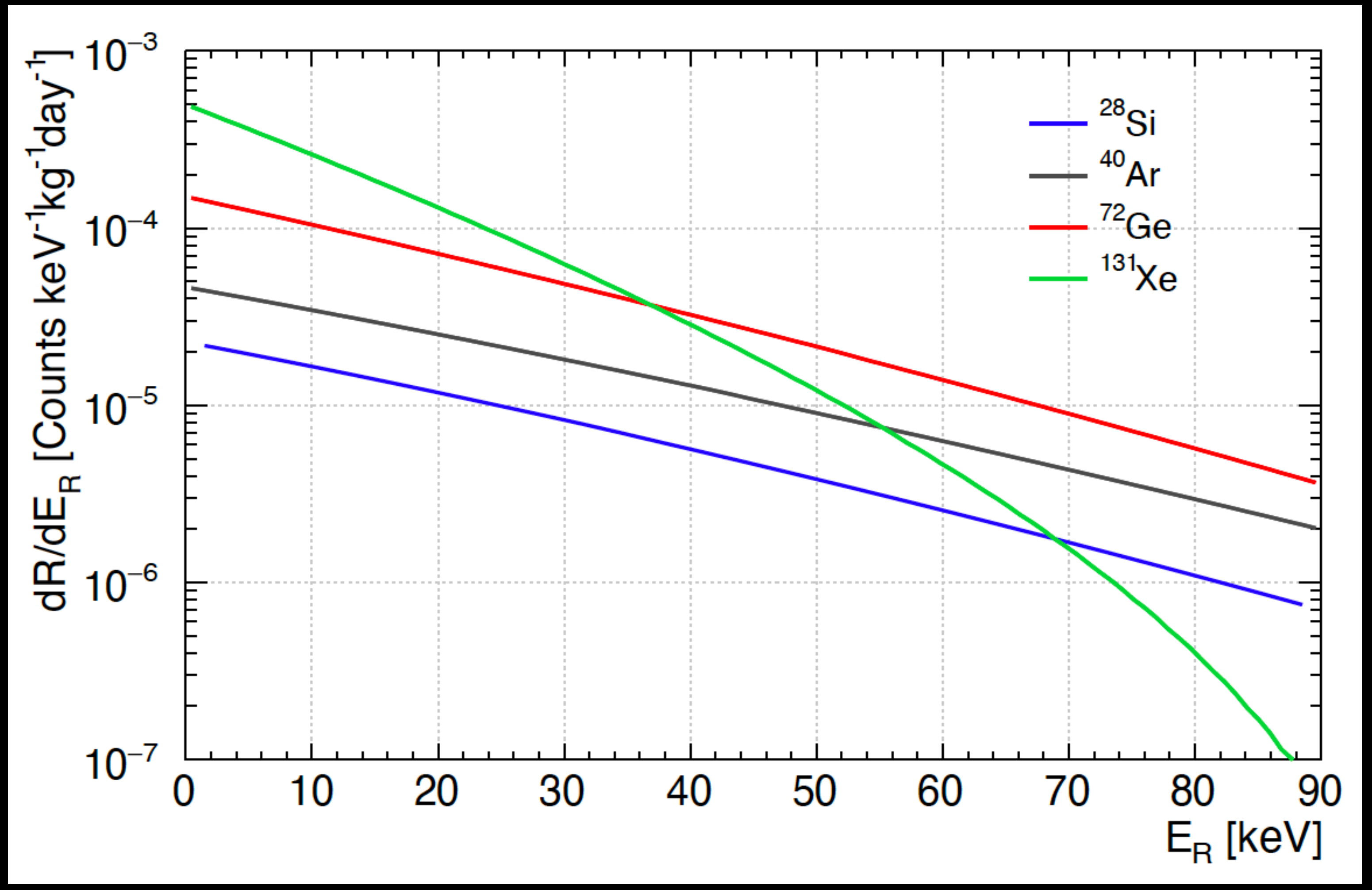
Choice of which targets/technique(s) to use is based on compromise between achieving:

1) Lowest energy threshold.

2) Largest exposure.

3) Best particle identification.

4) Lowest background contamination.



$E_{\text{Thr,Q}} \sim \mathcal{O}($

Potential to reach eV

Directional
detectors

Liquid noble-gas
dual-phase time
projection chambers

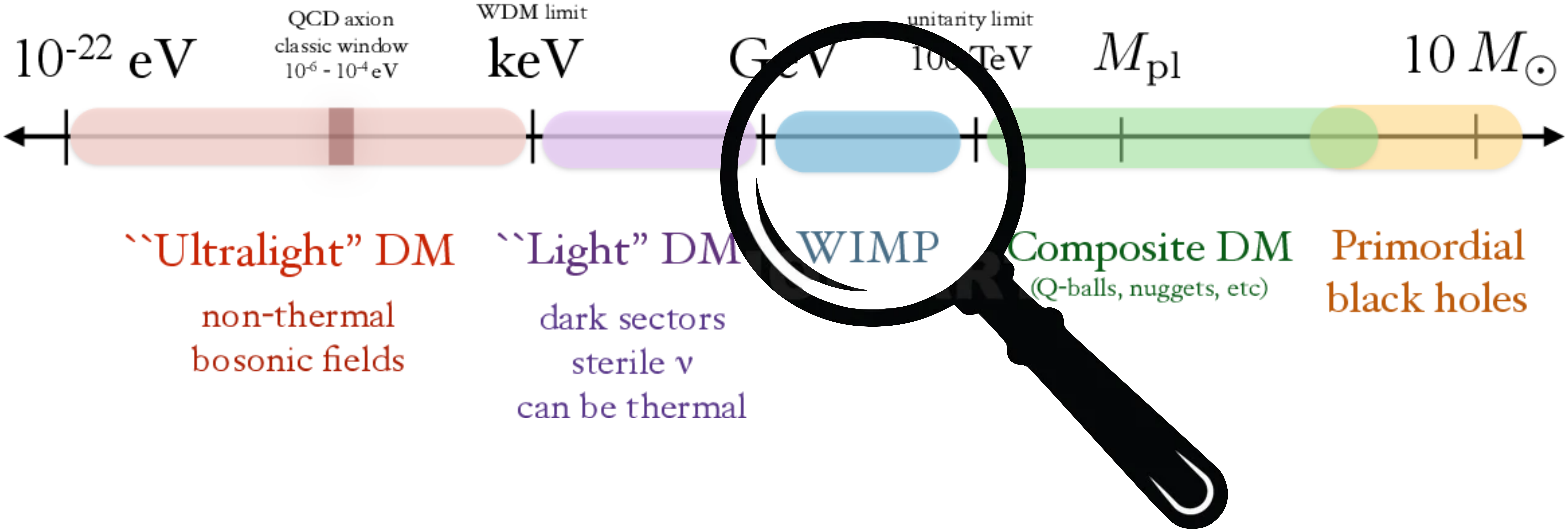
Liquid noble-gas
detectors

$E_{\text{Thr},\gamma} \sim \mathcal{O}(\text{keV})$

Potential to reach 10 eV

Courtesy of J. Monroe (ICHEP '24)

Weakly Interacting Massive Particles



WIMP Search Overview

Pushing Unchartered Territory

local WIMP density

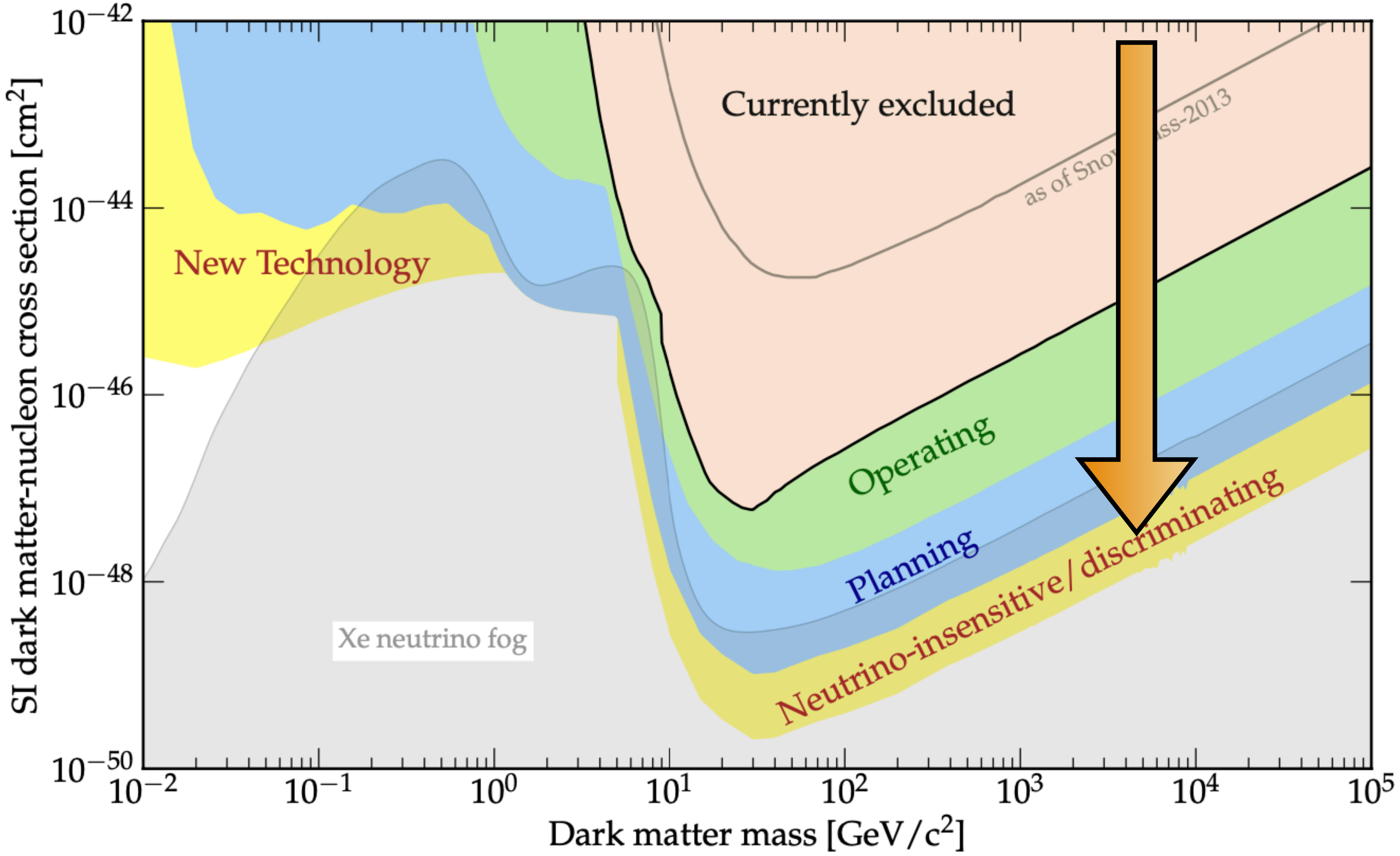
WIMP-nucleon scattering cross section

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_N m_\chi}\int_{v_{min}}^{\infty} v f(v)\frac{d\sigma_{\chi N}}{dE_R}dv$$

nucleus mass

WIMP mass

WIMP speed distribution in detector frame



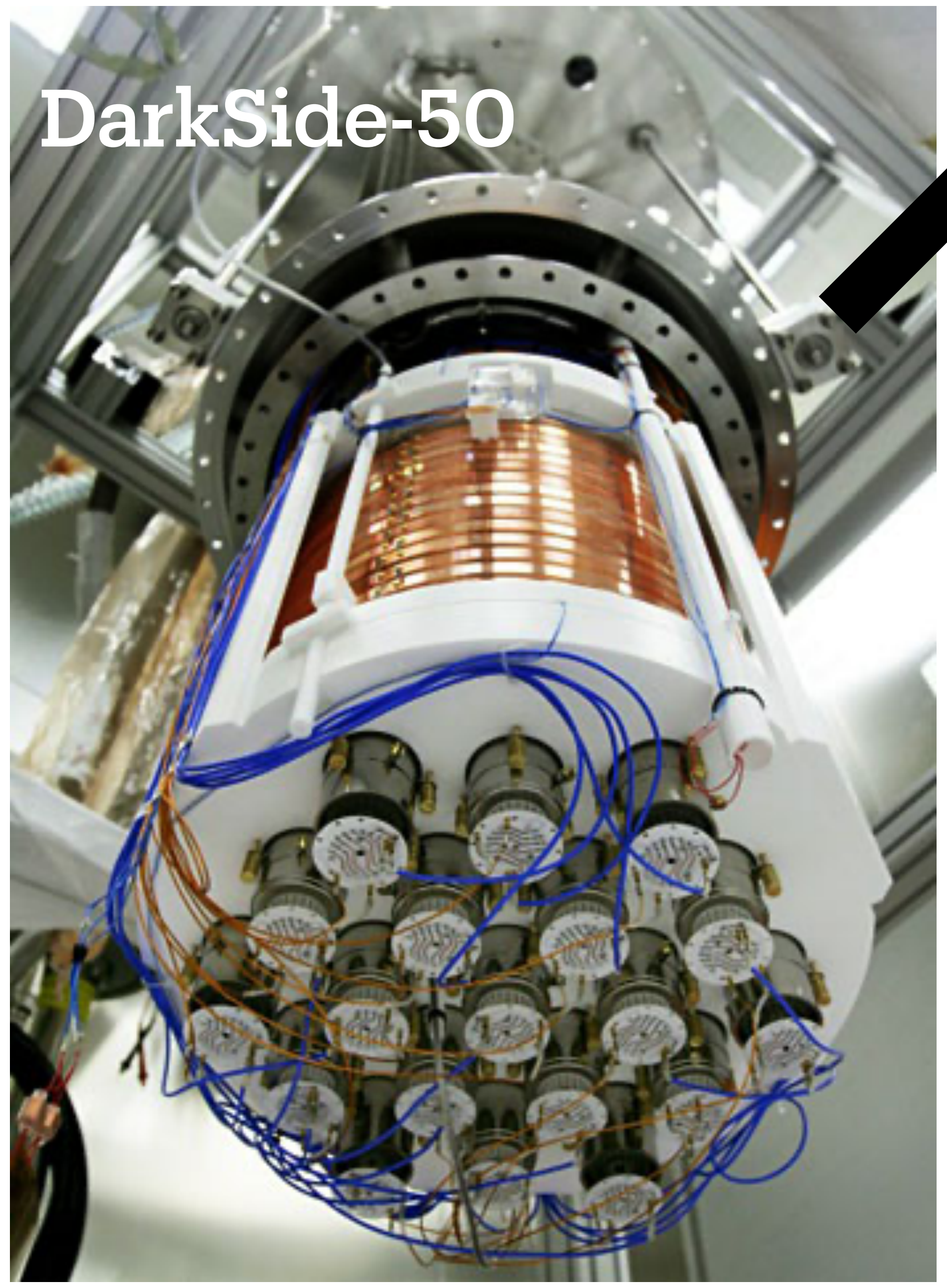
Expect <1 signal event per year!

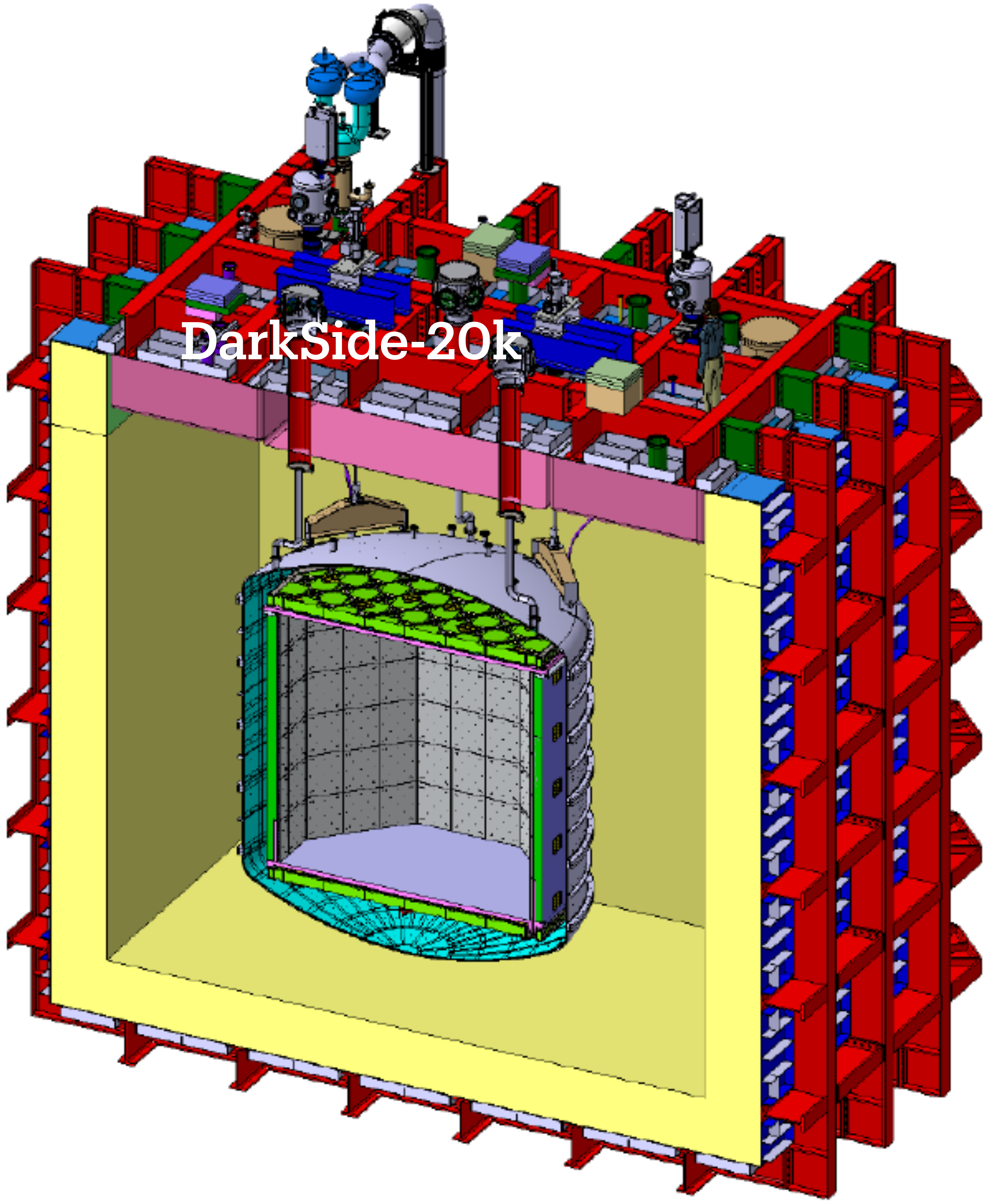
Snowmass Cosmic Frontier Report, arXiv:2211.09978

WIMP Search Overview

Pushing Unchartered Territory

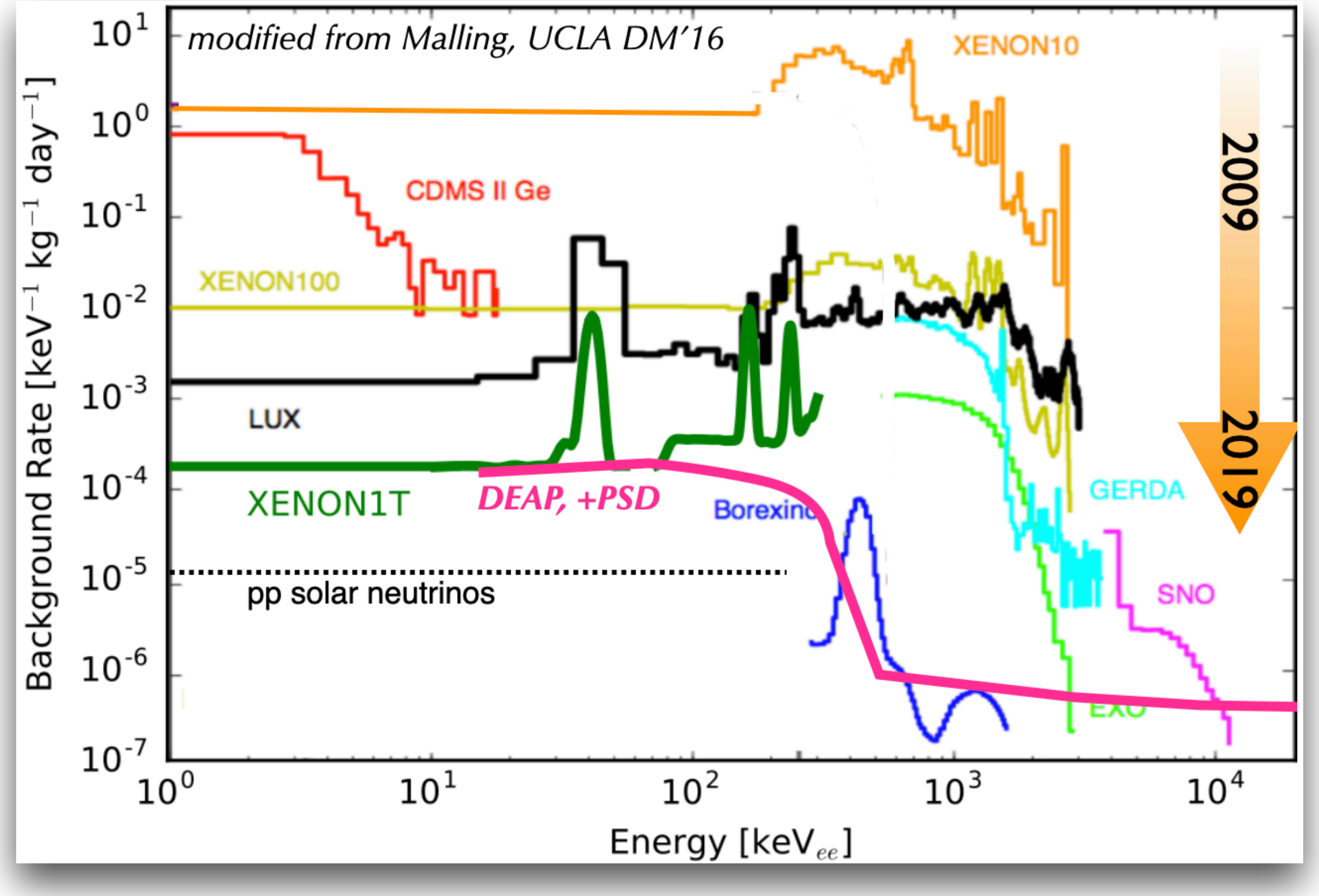
1) Larger Detectors
- Operate them for longer!





DarkSide-50 → DarkSide-20k: x1000 increase in target volume.

2) Background Mitigation
- Material Control/Radioassay
- Particle ID (Bkgd Discrimination)



Courtesy of J. Monroe (ICHEP '24)

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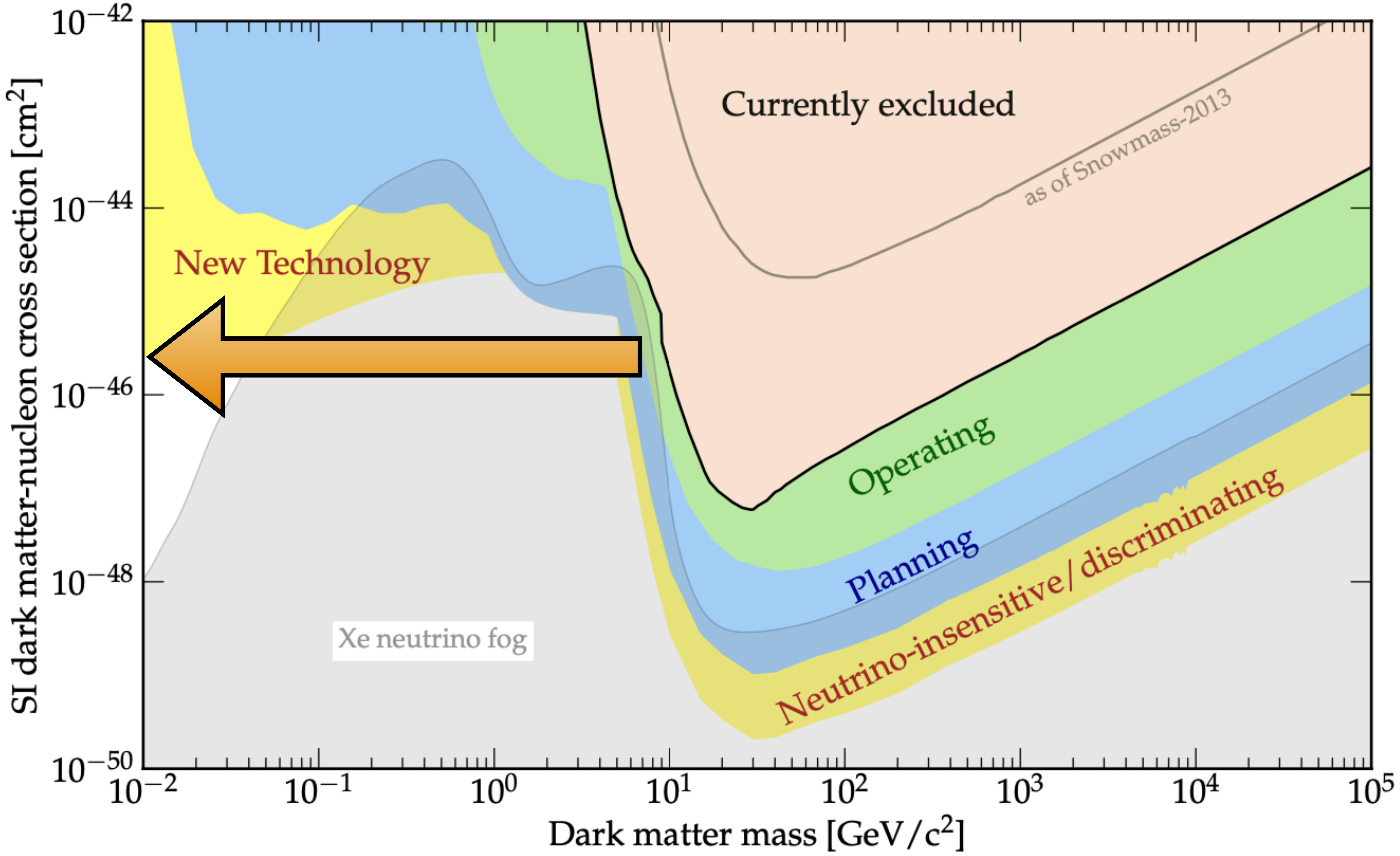
nucleus mass

WIMP mass

WIMP speed distribution in detector frame



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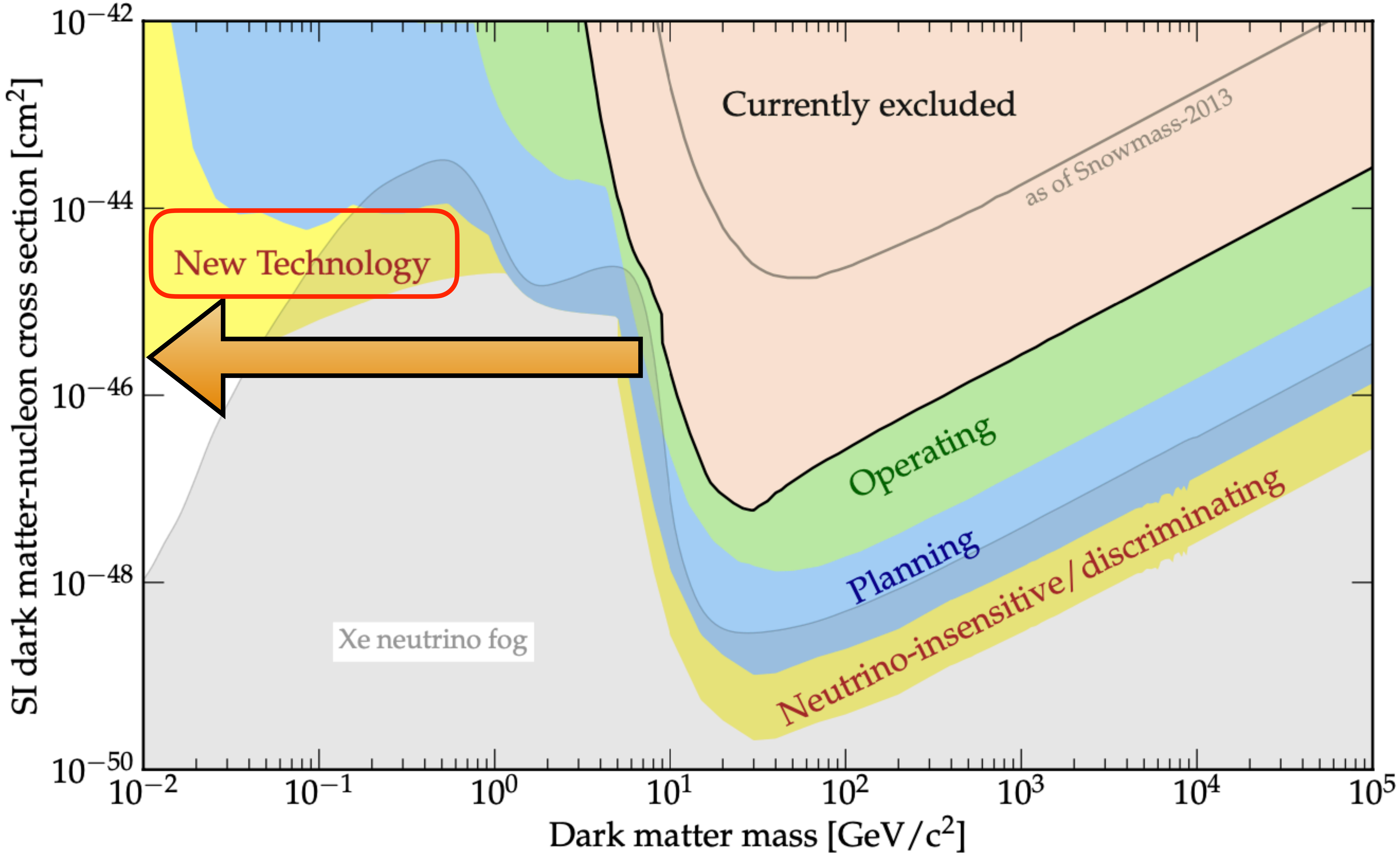
WIMP speed distribution in detector frame



Expect <1 signal event per year!

Snowmass Cosmic Frontier Report, arXiv:2211.09978

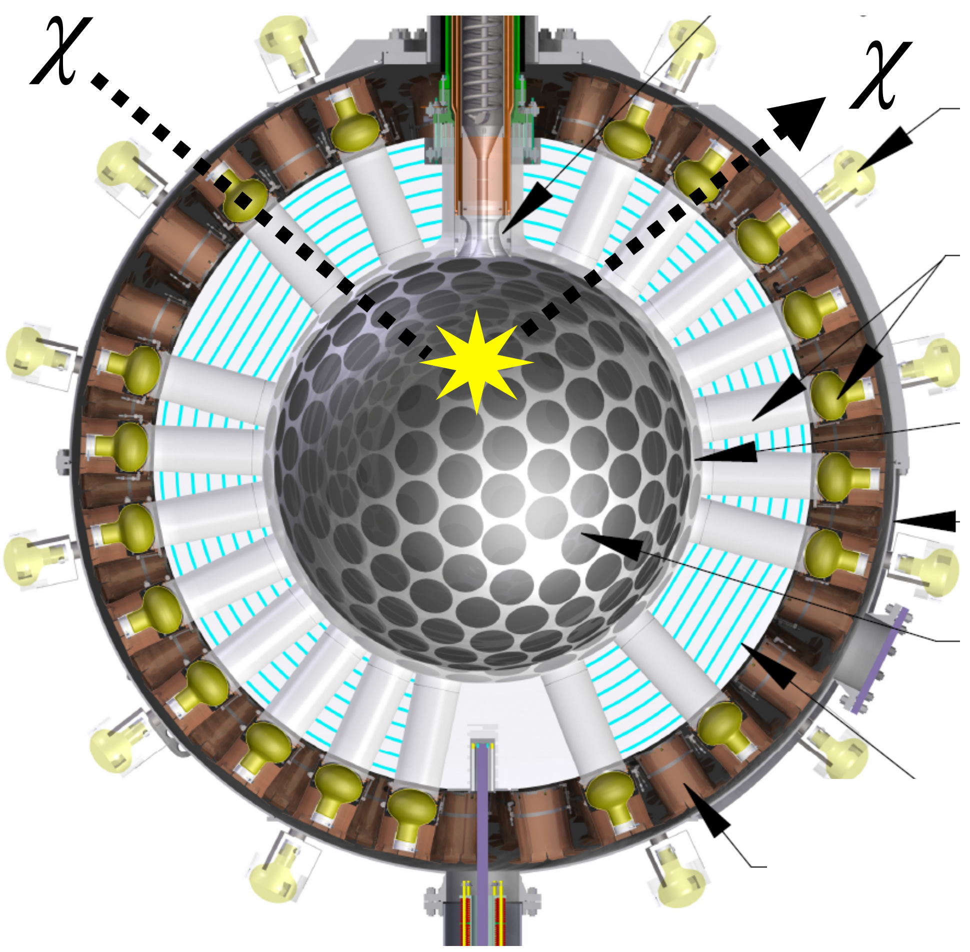
High Mass WIMP Searches

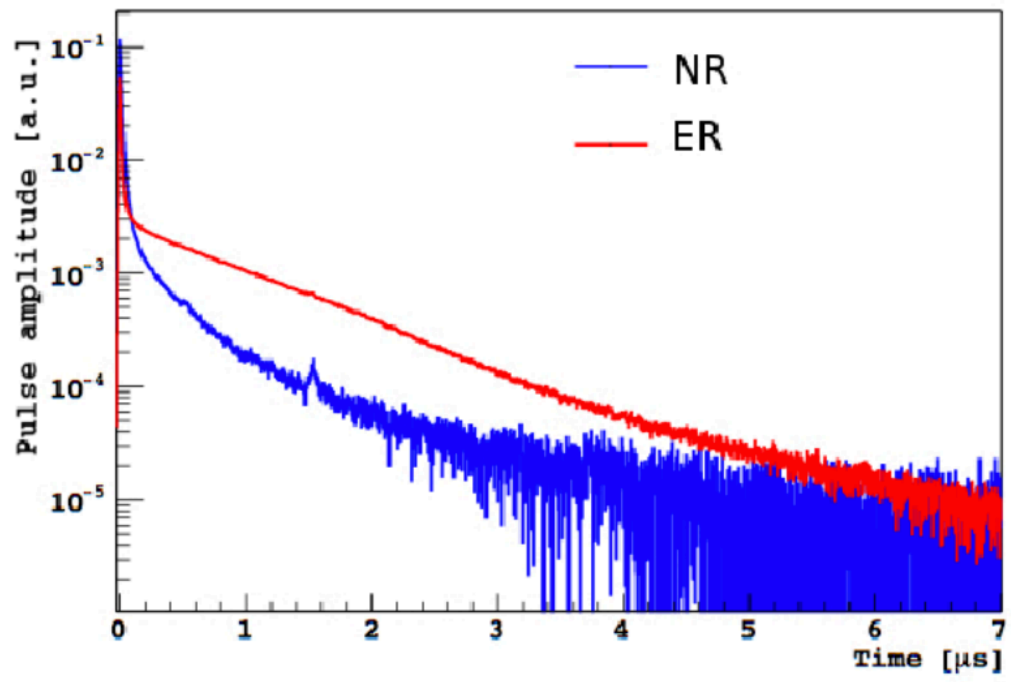
Liquid noble detectors lead constraints.

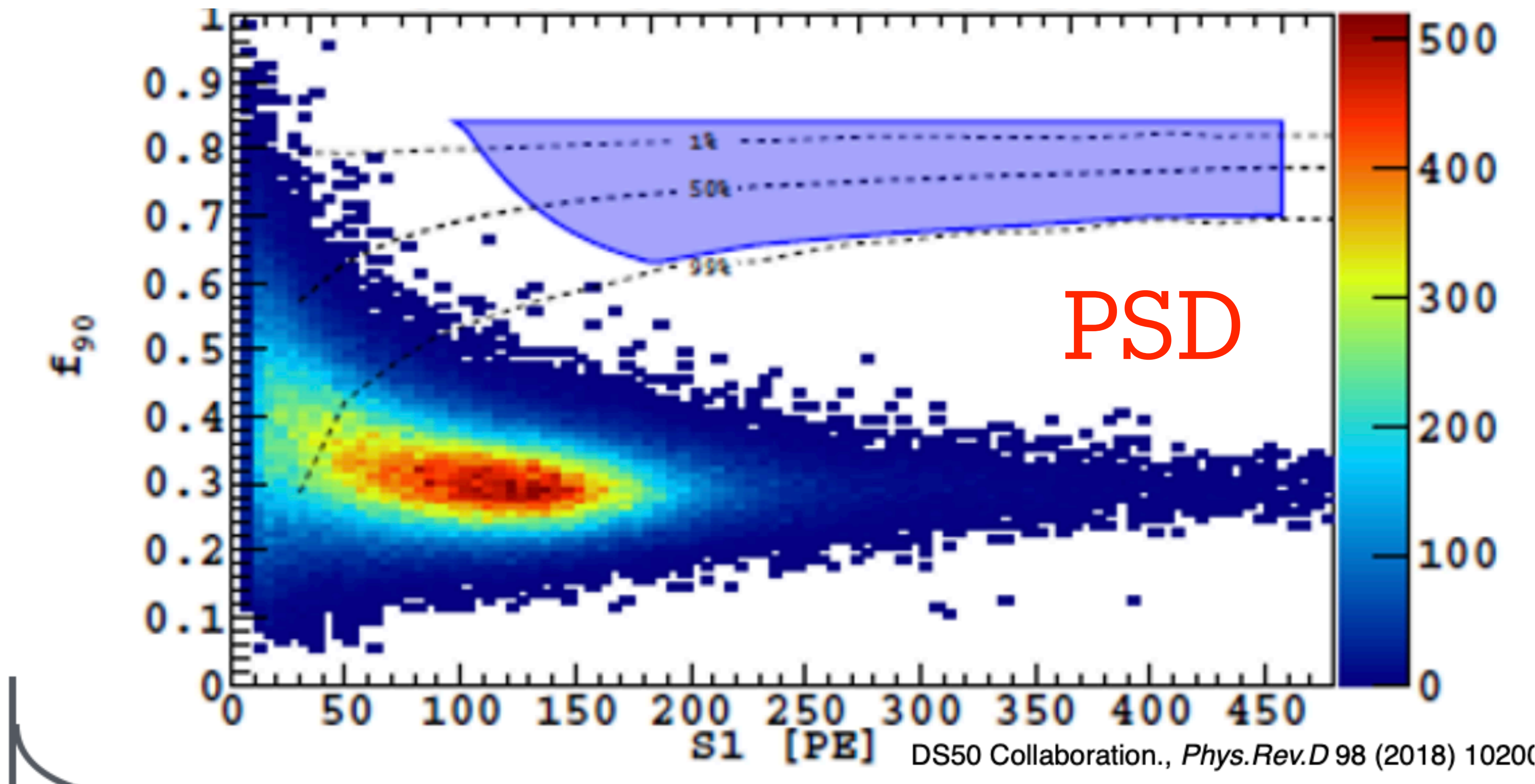
DEAP-3600: Single-Phase Liquid Argon → Scintillation signal (S1) only.

Dual-Phase Time Projection Chambers (TPCs) [Liquid & Gas] → Scintillation (S1) and Ionisation (S2) signal; better position reconstruction.

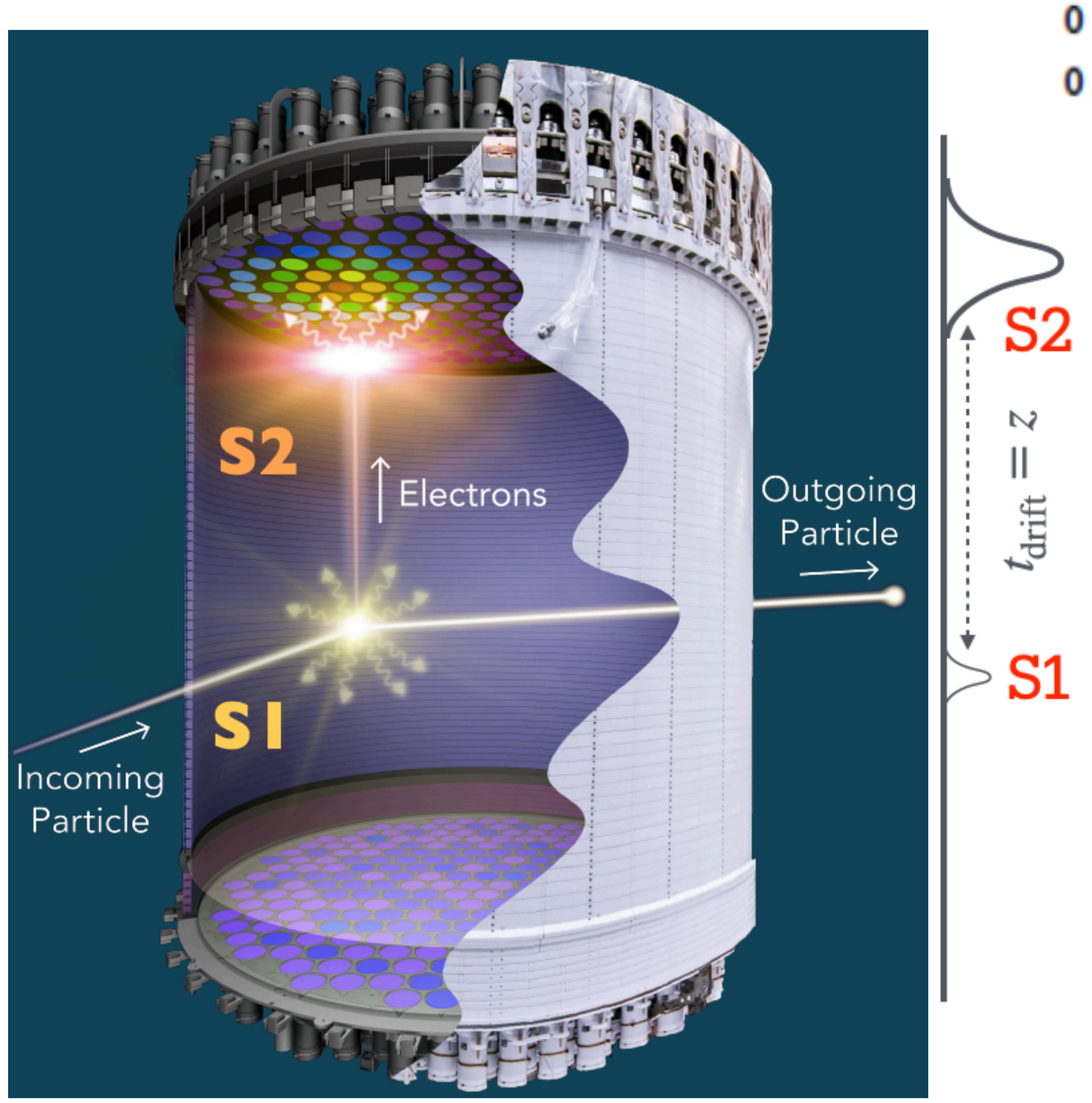
- Xenon: PandaX, XENON-1T, LZ
    - Lower intrinsic radioactivity; enhanced A^2 boost factor (spin-independent).
- Argon: DarkSide-50 (DarkSide-20k)
    - Strong NR/ER discrimination power from Pulse Shape Discrimination (PSD), more scalable.

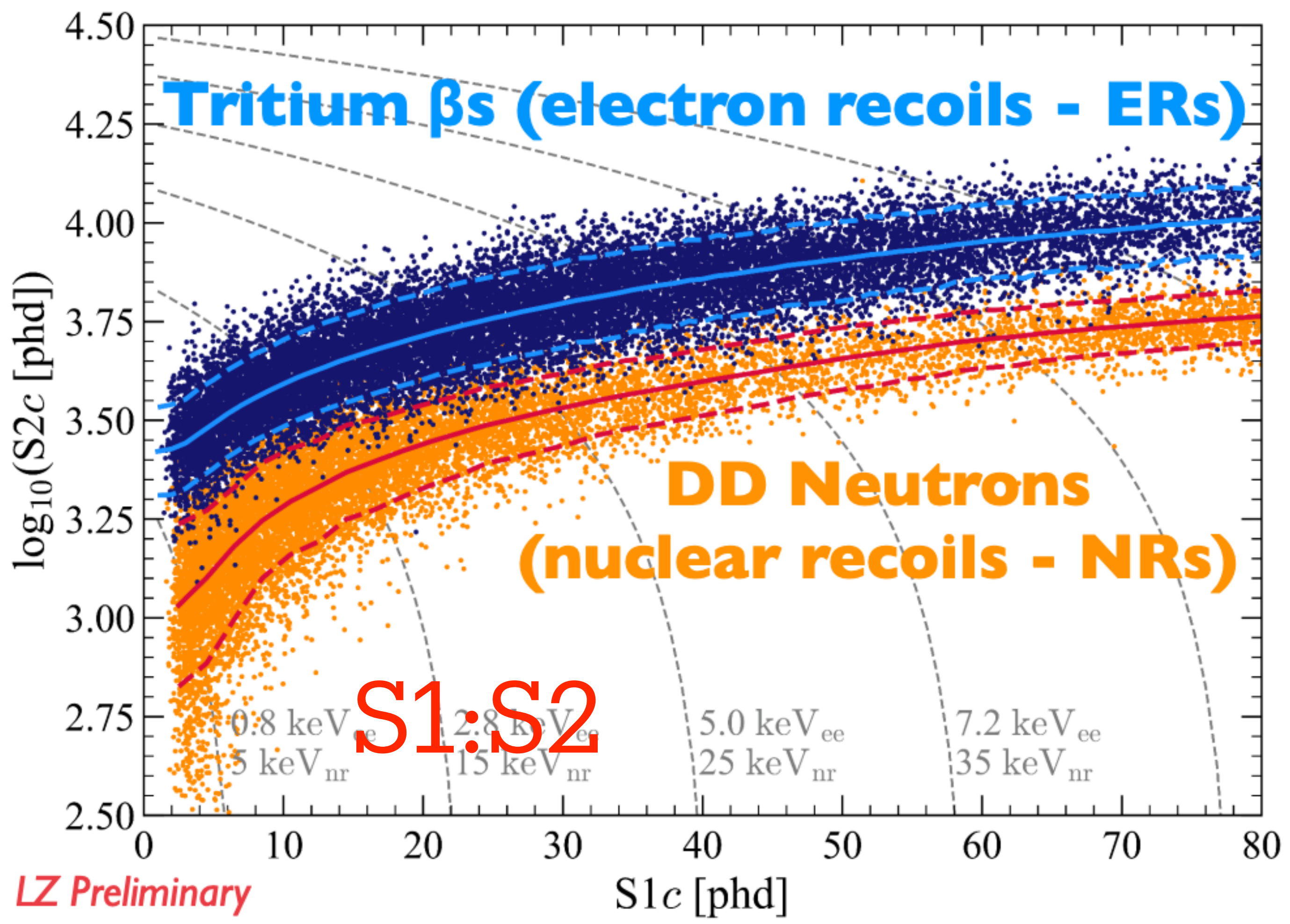






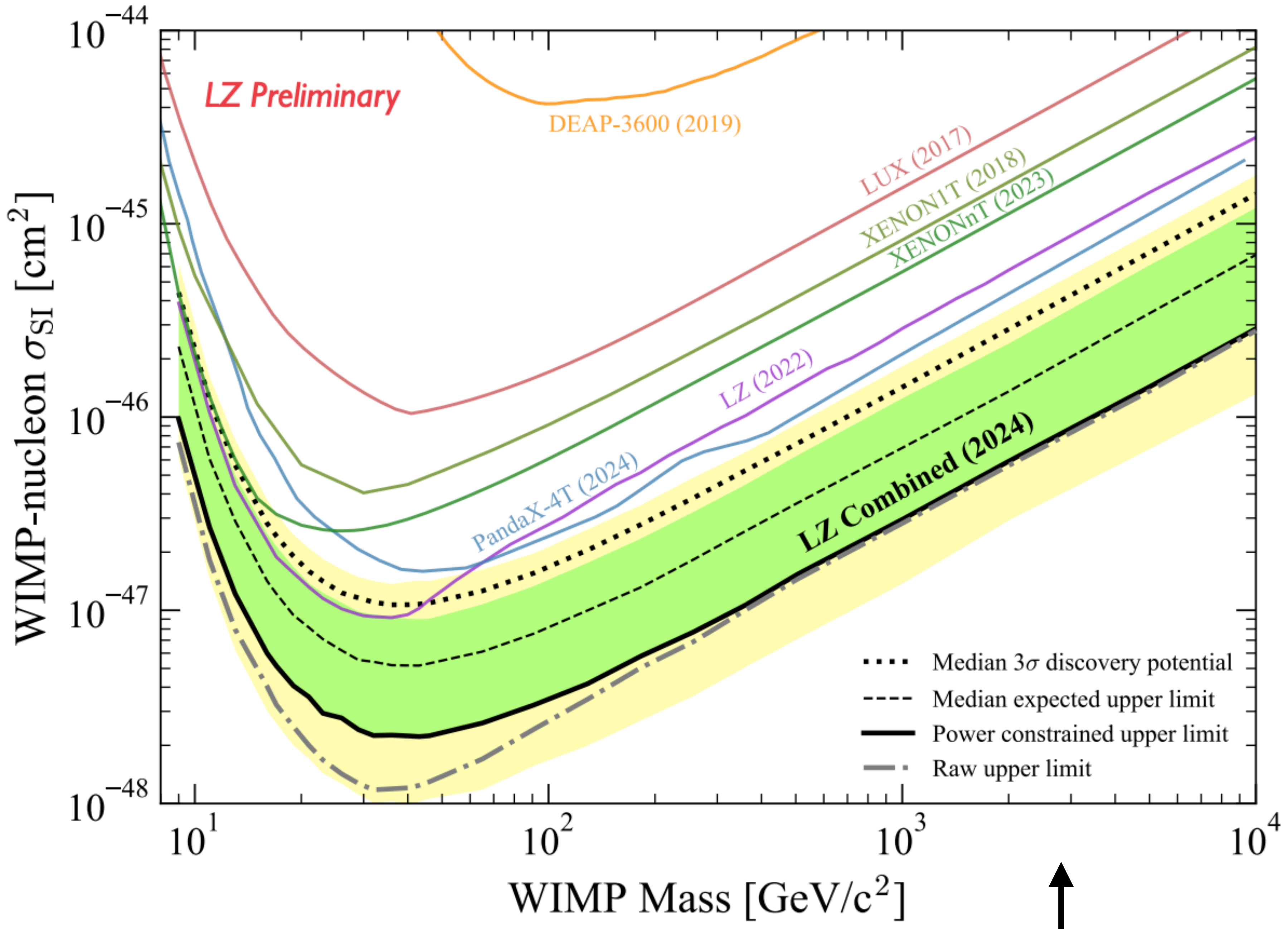
DS50 Collaboration., *Phys.Rev.D* 98 (2018) 10200





Courtesy of A. Cottle (ECFA '24)

High Mass WIMP Searches

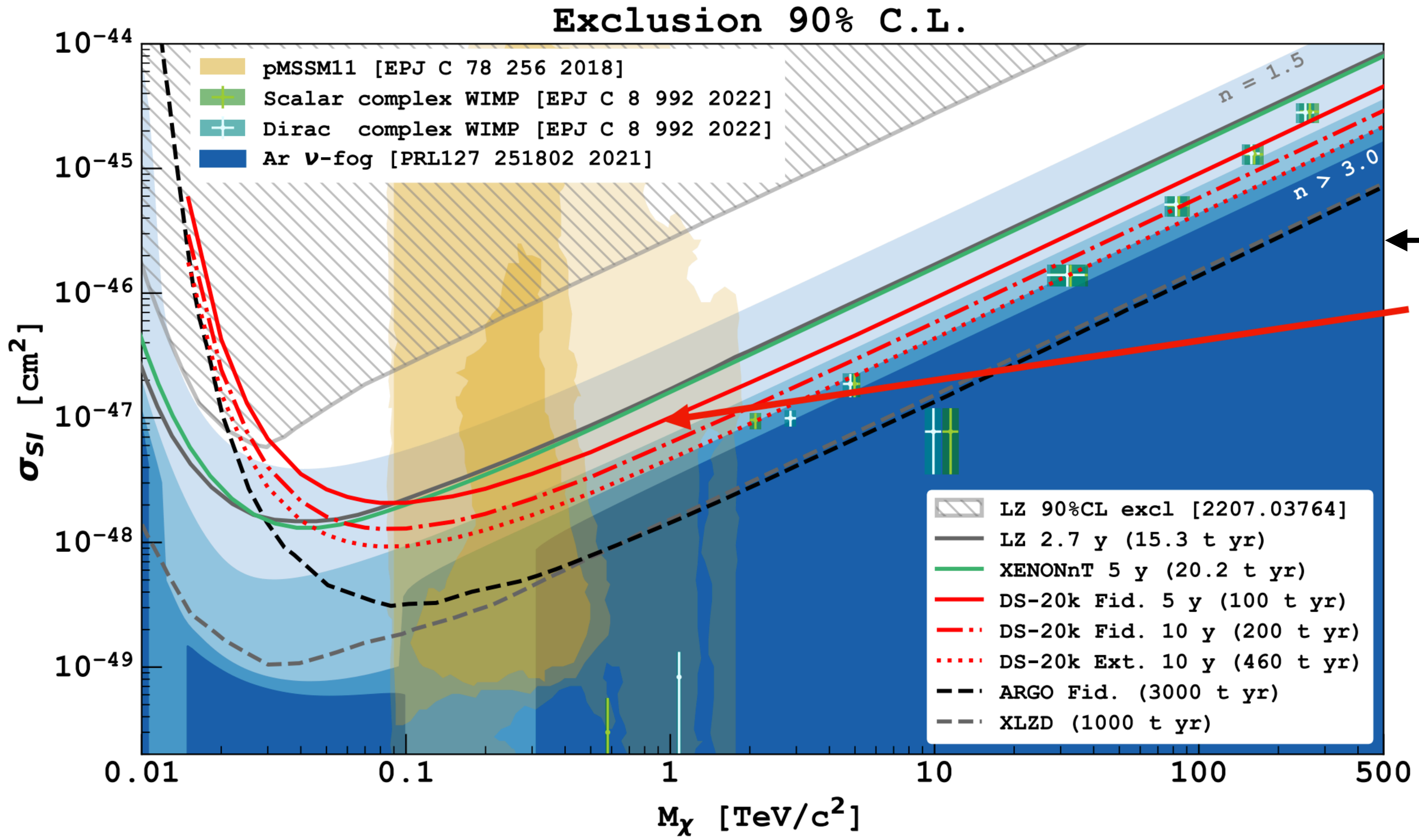


Leading limits on SI-WIMP interactions from LZ (7 tonne LXe).

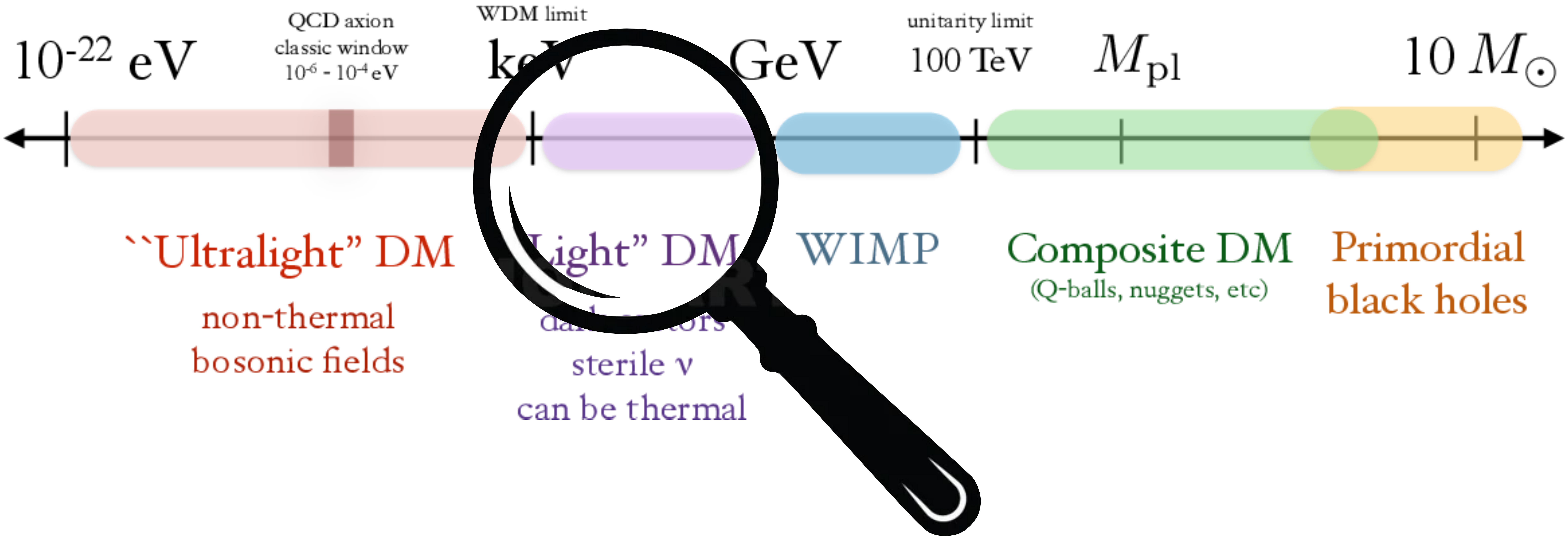
- Next generation LXe experiment: XLZD (40-60 tonnes)

Global Argon Dark Matter Collaboration (GADMC) formed in 2017: 400+ people across 14 countries.

- DarkSide-20k (50 tonnes LAr) currently being constructed at LNGS; SI-WIMP sensitivity projection down to ν floor! **[See D. Santone's talk].**

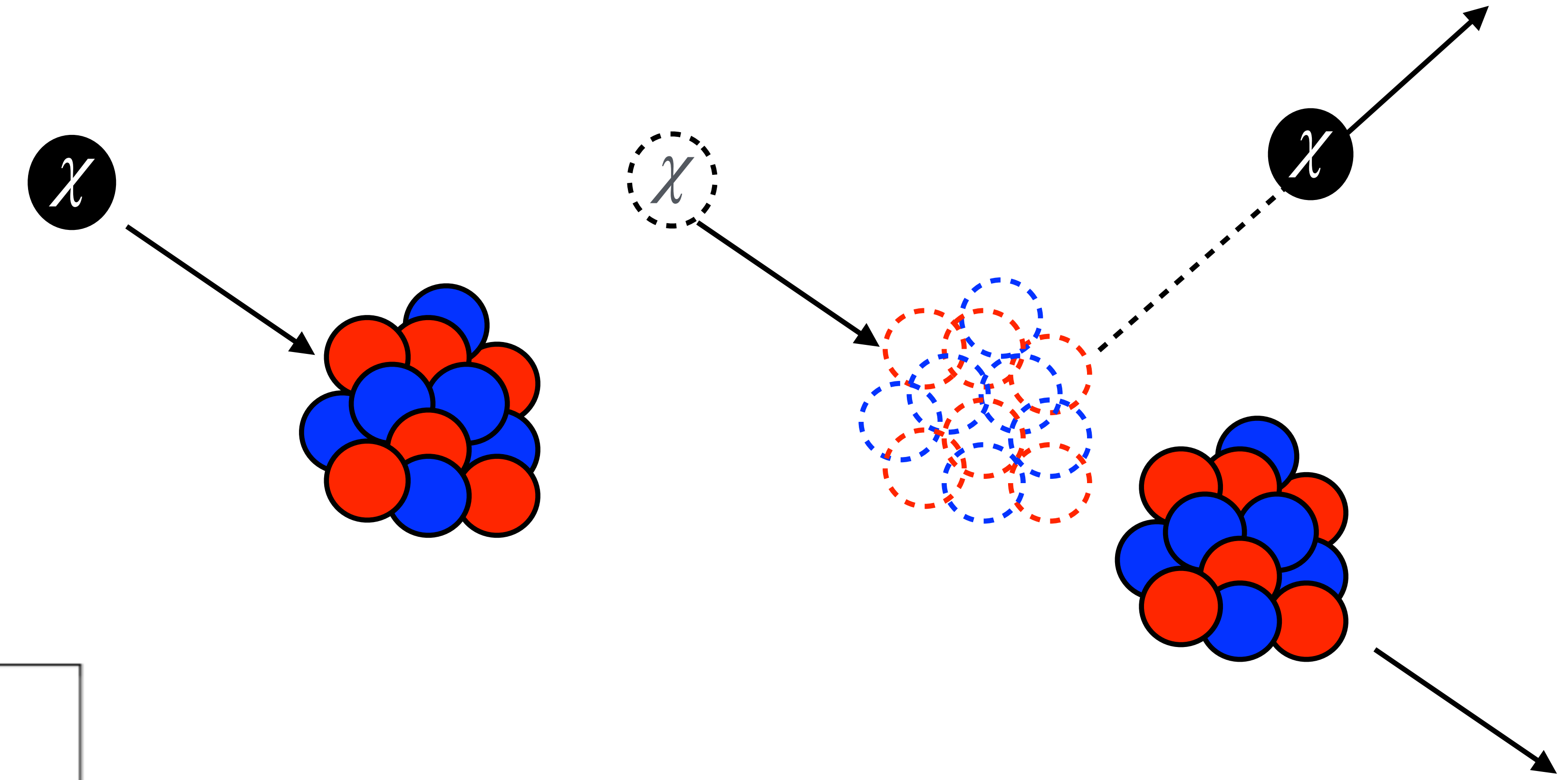


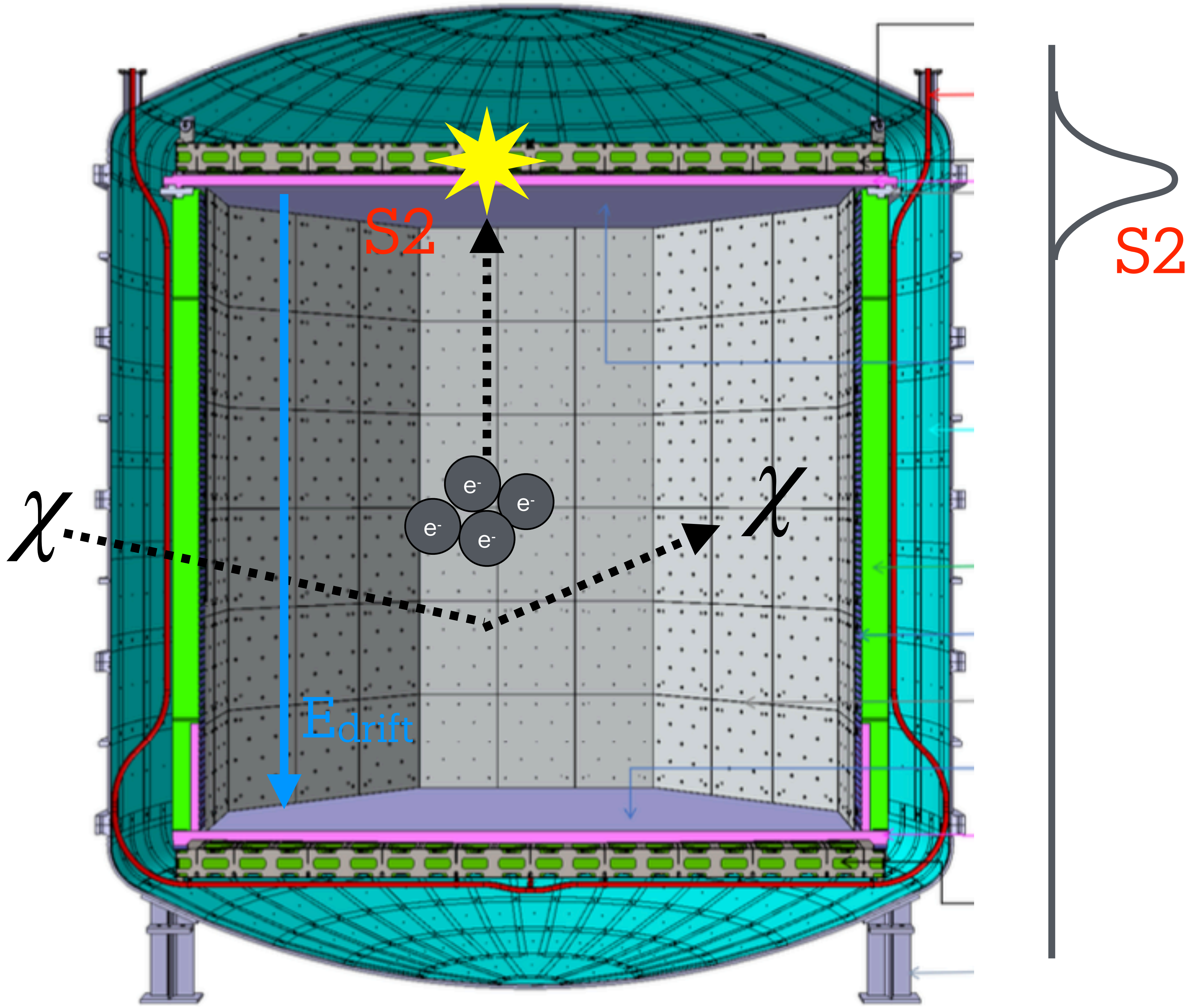
“Light” Dark Matter

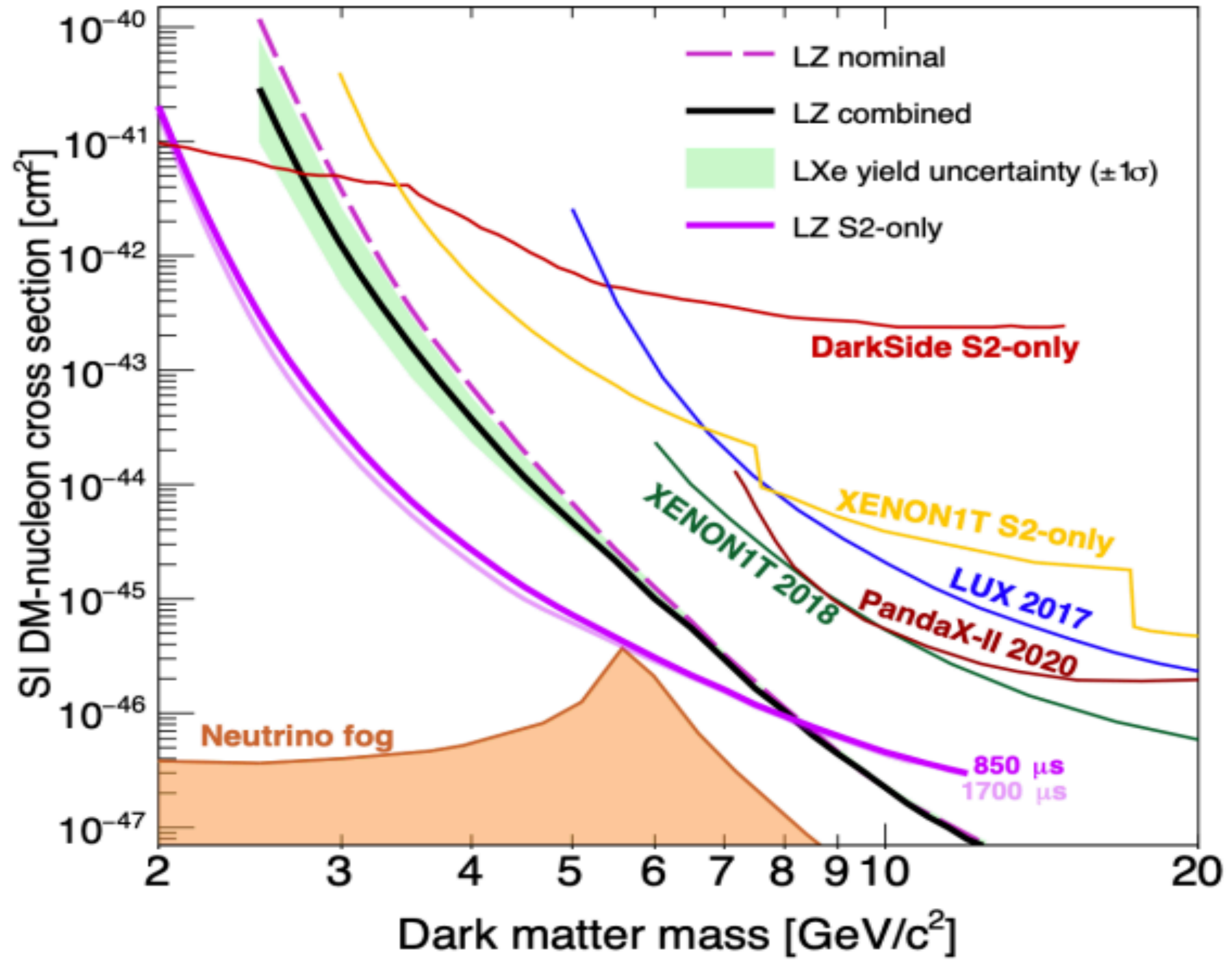


Low-Mass WIMP Searches

Liquid Nobles: Dual-phase TPC technology can exploit ionisation signal (S2) only to reach sub-keV recoil energy thresholds.

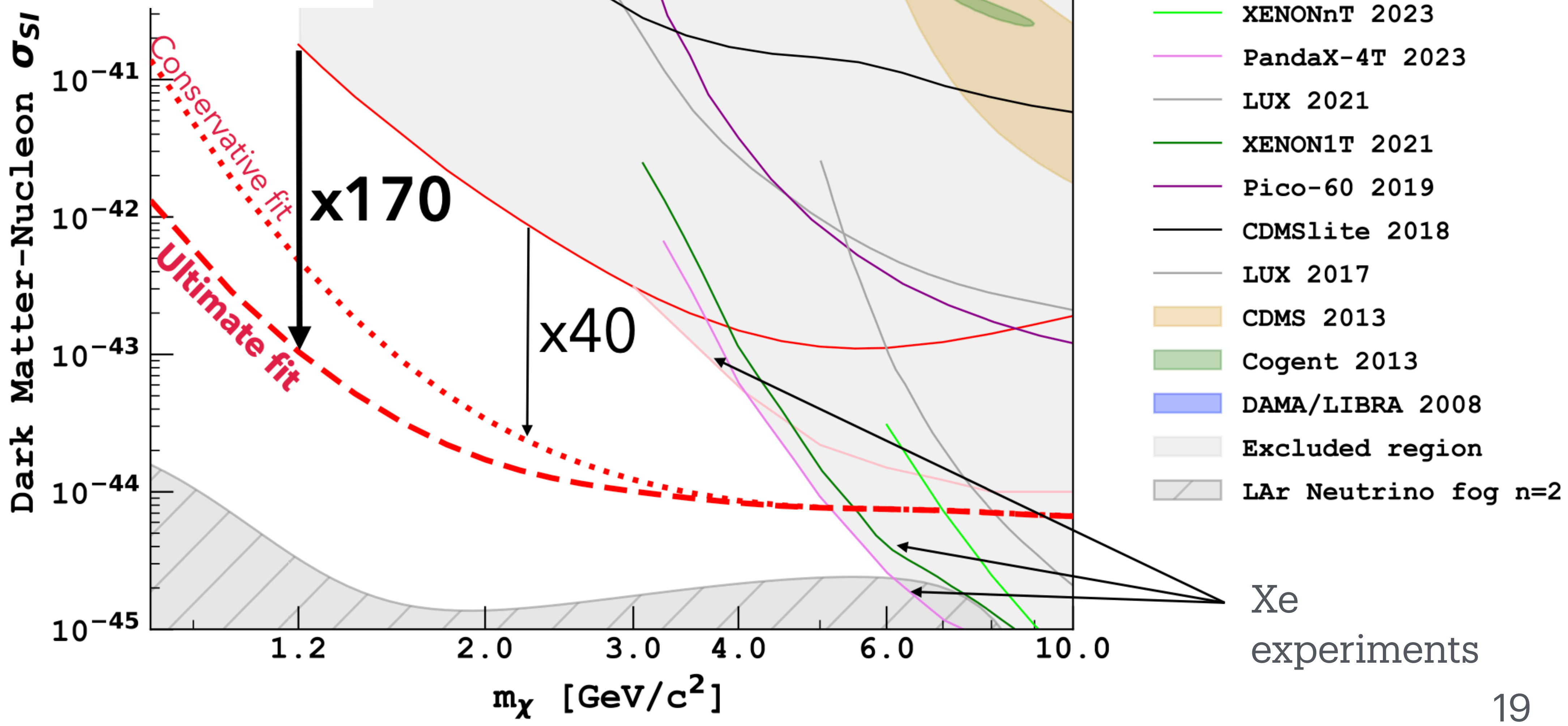




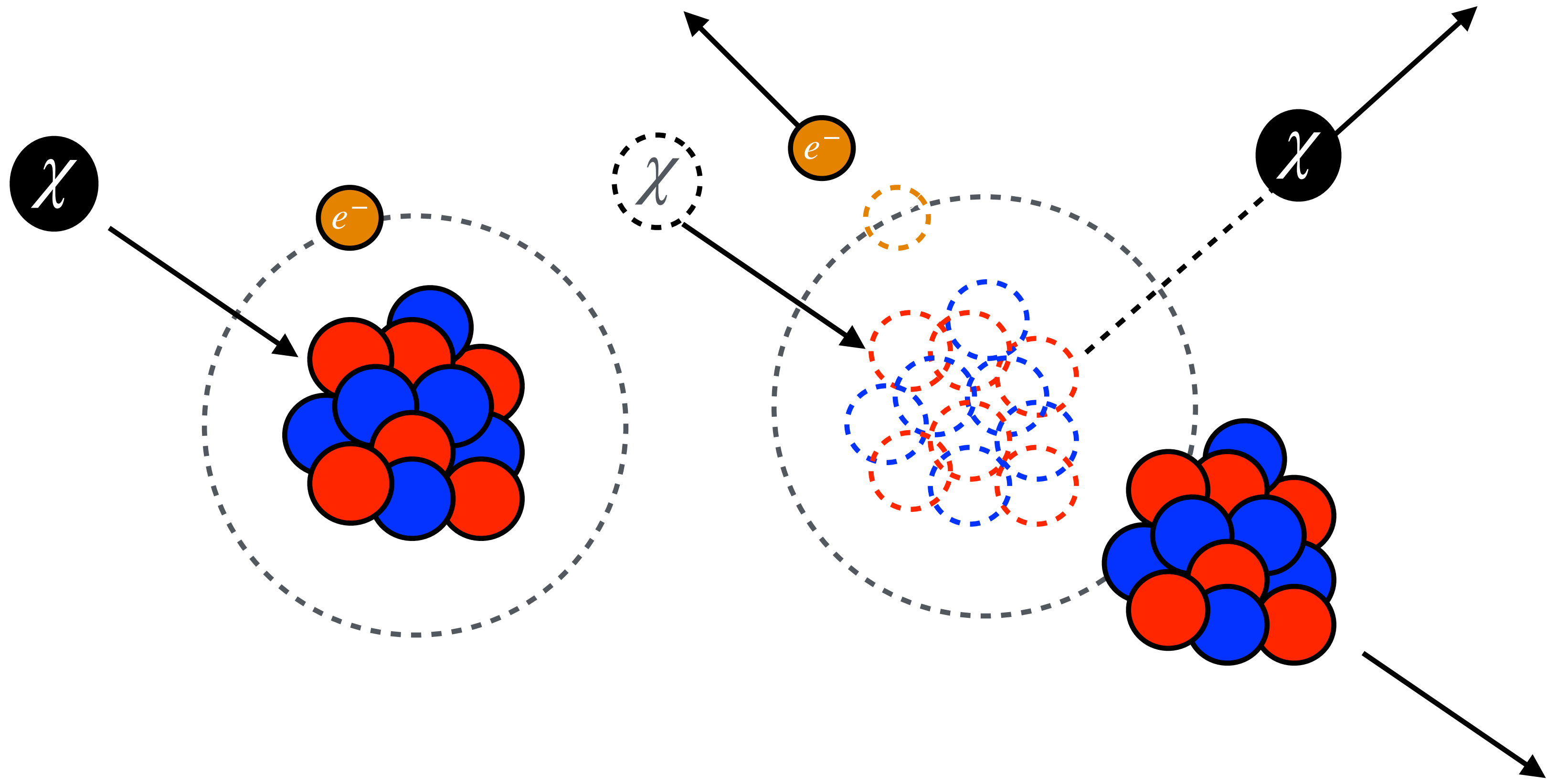


Akerib, D. S., et al. "Enhancing the sensitivity of the LUX-ZEPLIN (LZ) dark matter experiment to low energy signals." arXiv preprint arXiv:2101.08753 (2021).

Acerbi, F., et al. "DarkSide-20k sensitivity to light dark matter particles." arXiv preprint arXiv:2407.05813 (2024).



Low-Mass WIMP Searches



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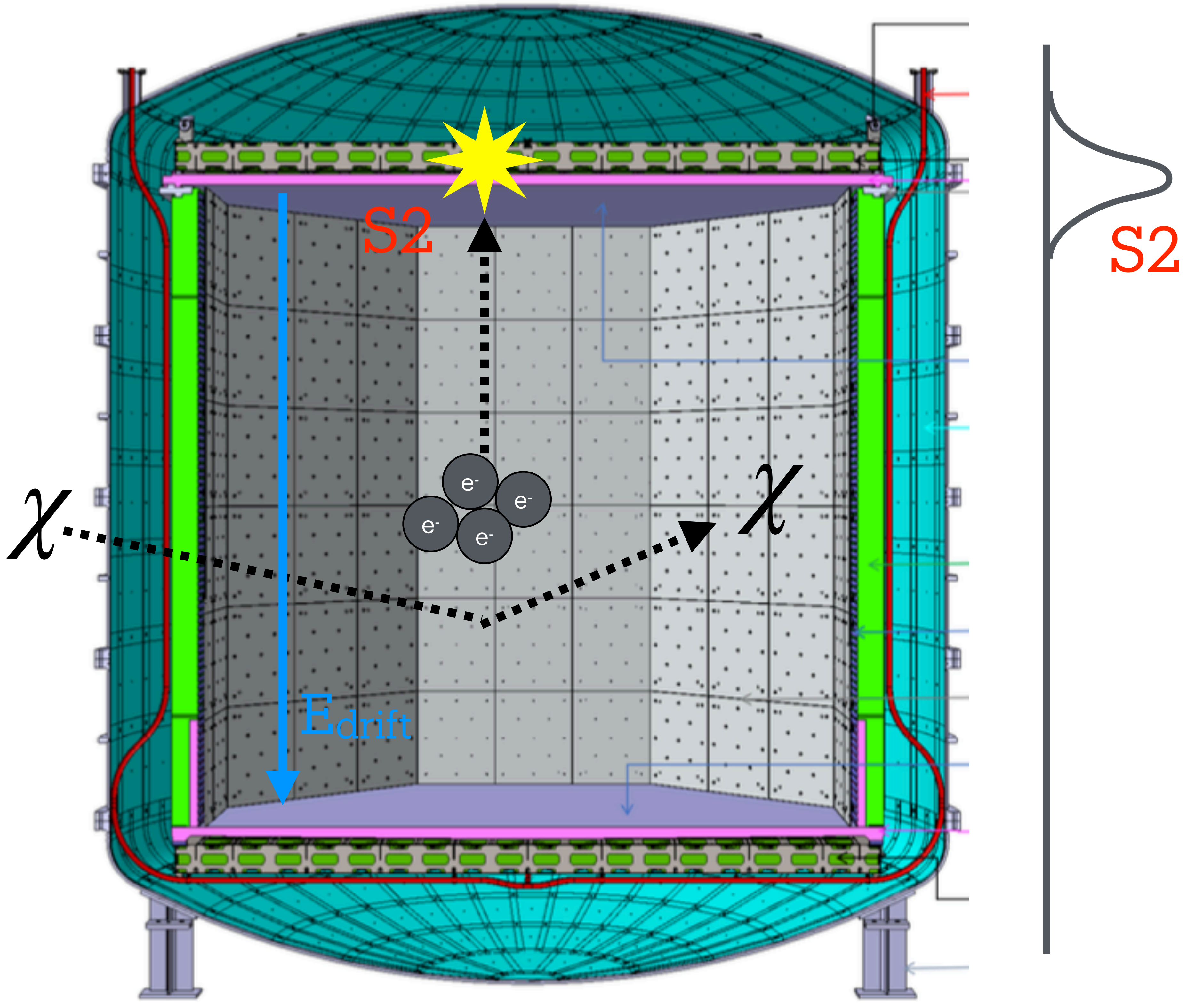
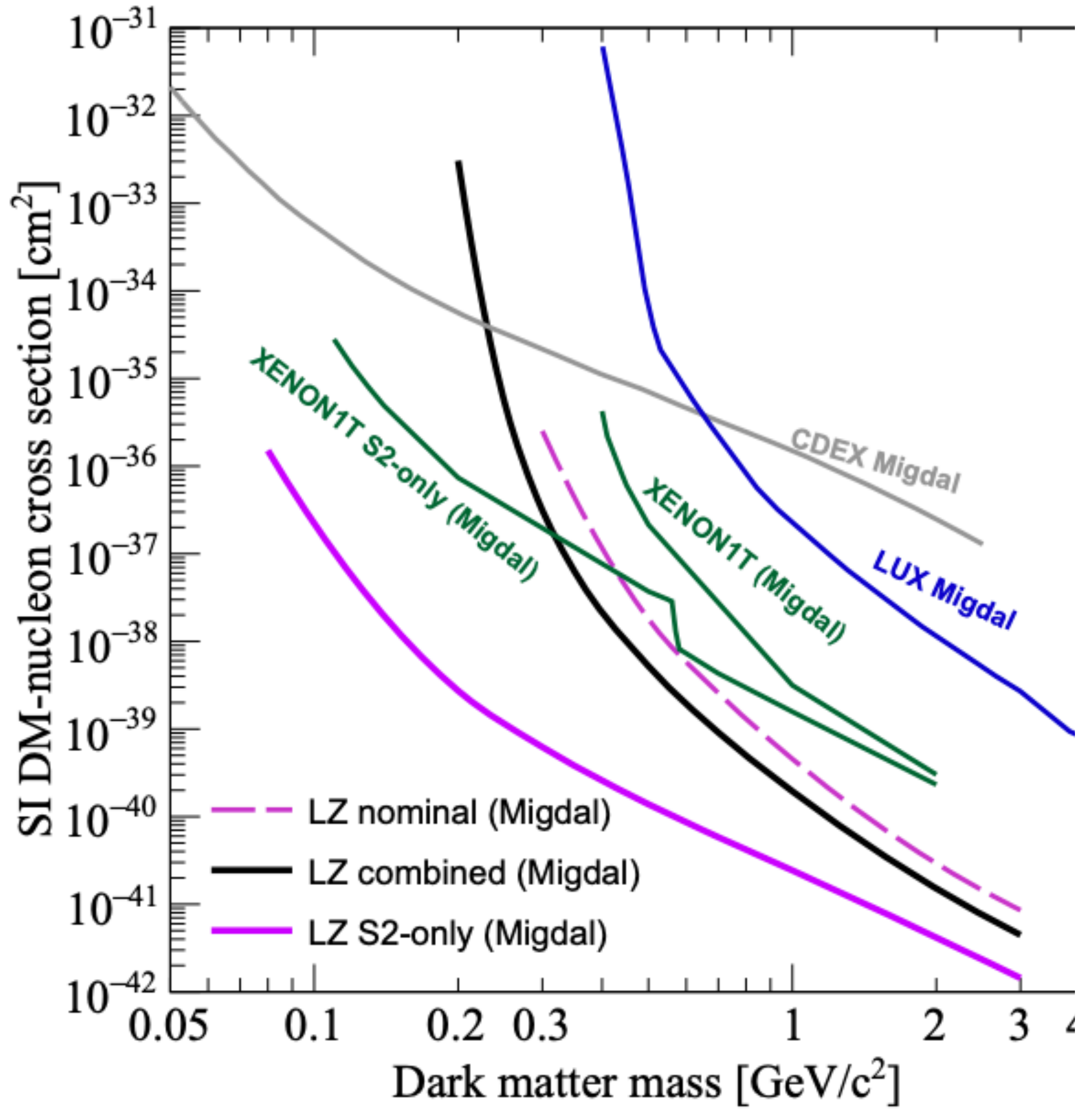
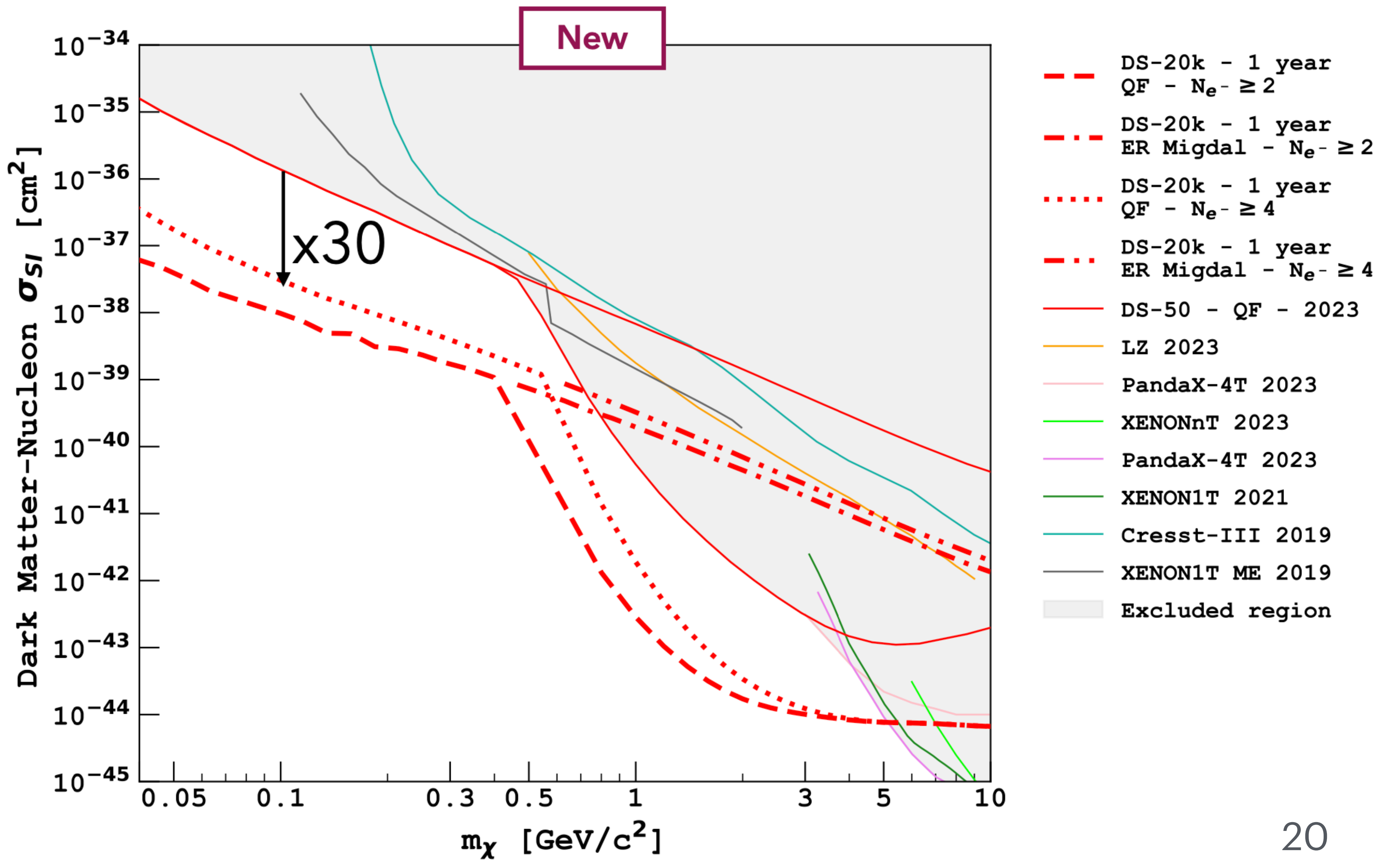


Migdal Effect: Surrounding electron cloud accelerated after NR, releases de-excitation ionisation.

- Additional ionisation signal means even lower energy threshold!





** Same citations as previous slides*

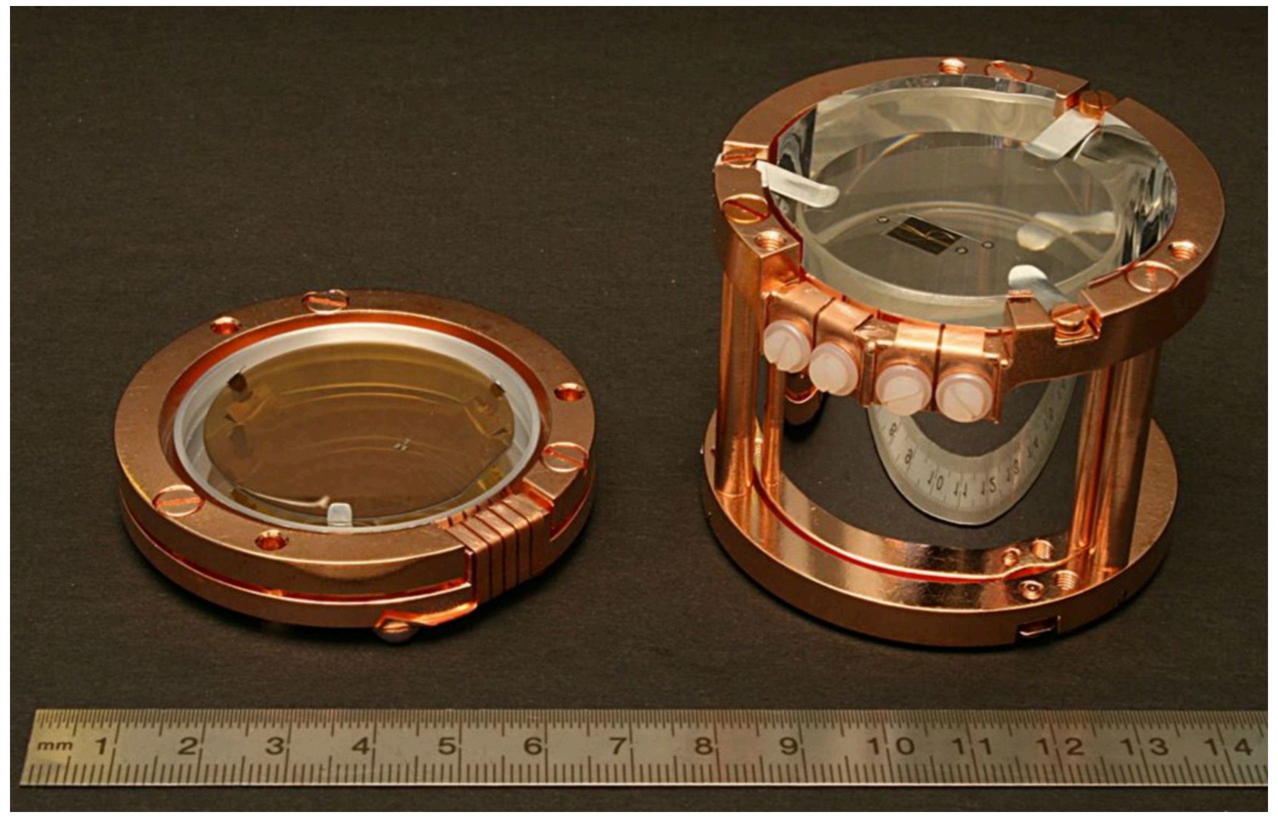
Low-Mass WIMP Searches

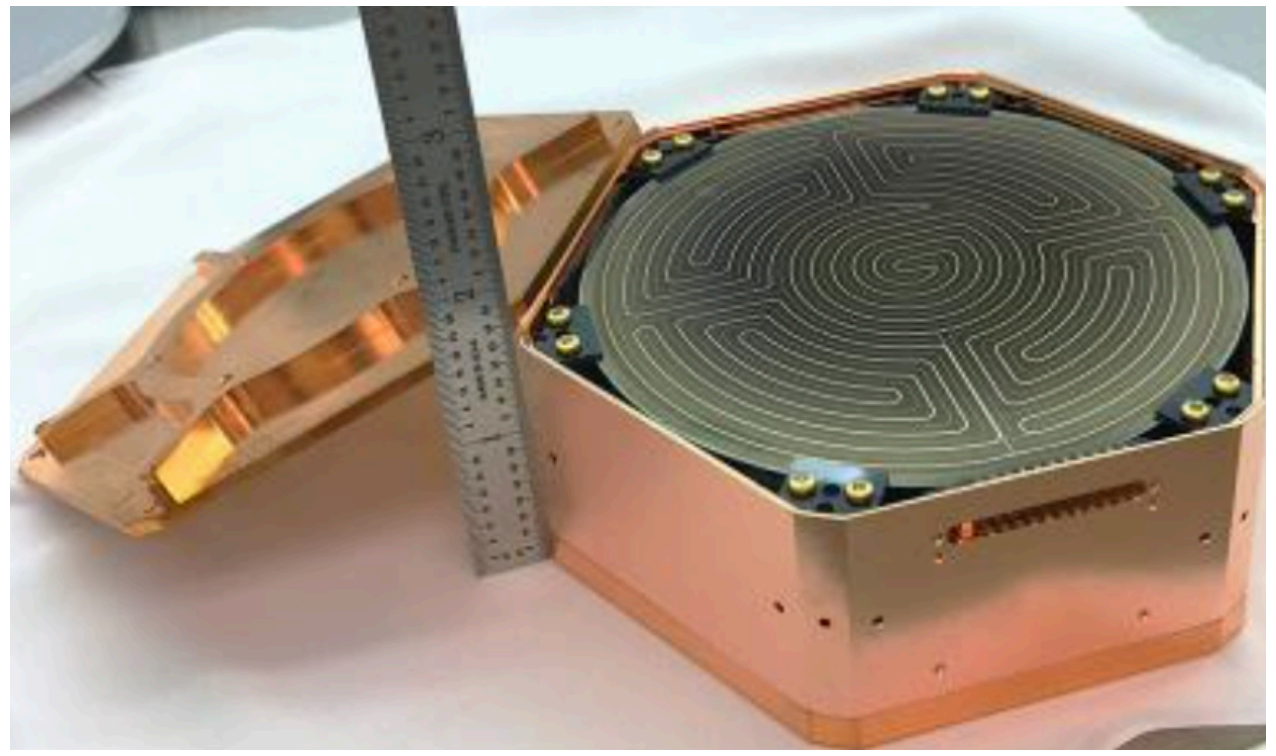
Low-mass cryogenic experiments have potential to reach meV recoil energy thresholds: opportunity to explore brand new parameter space!

- Limited by readout technology.

Scintillating Crystals

- Al_2O_3, $CaWO_4$ (CRESST)
- Recoil energy from heat, particle ID from heat/scintillation ratio.



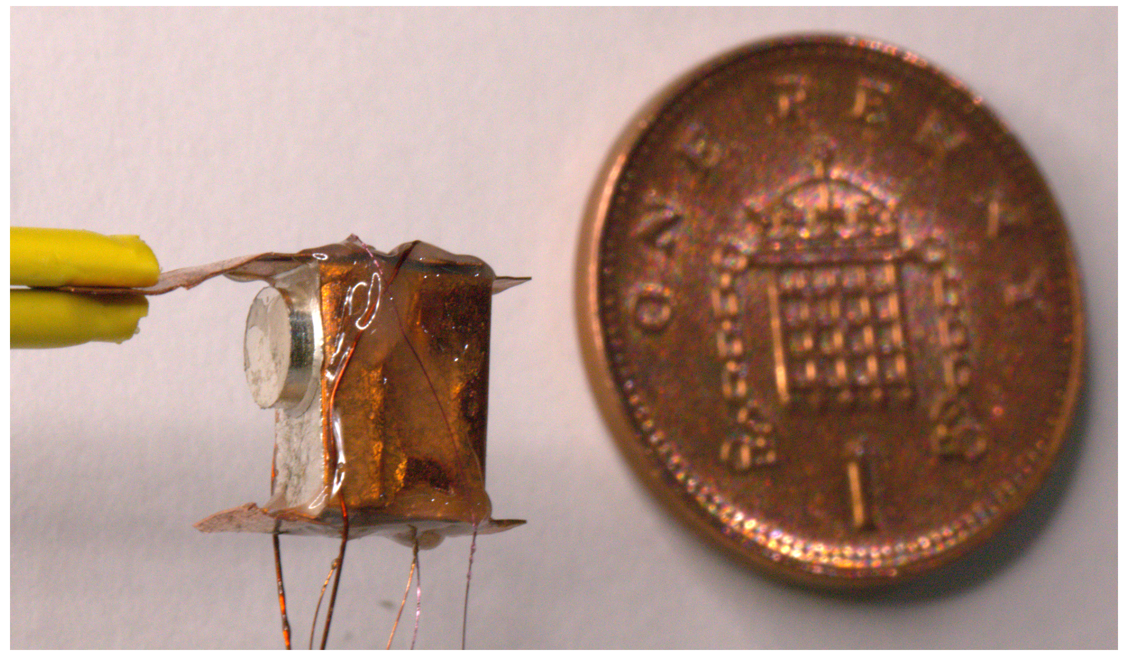


Semiconductors

- Ge, Si detectors (EDELWEISS, SuperCDMS)
- Recoil energy from heat, particle ID from heat/ionisation ratio.

Superfluid Helium Bolometers

- He-4 (HeRALD) or He-3 (QUEST-DMC).
- Recoil energy from quasiparticles (heat), particle ID from quasiparticle/scintillation ratio.



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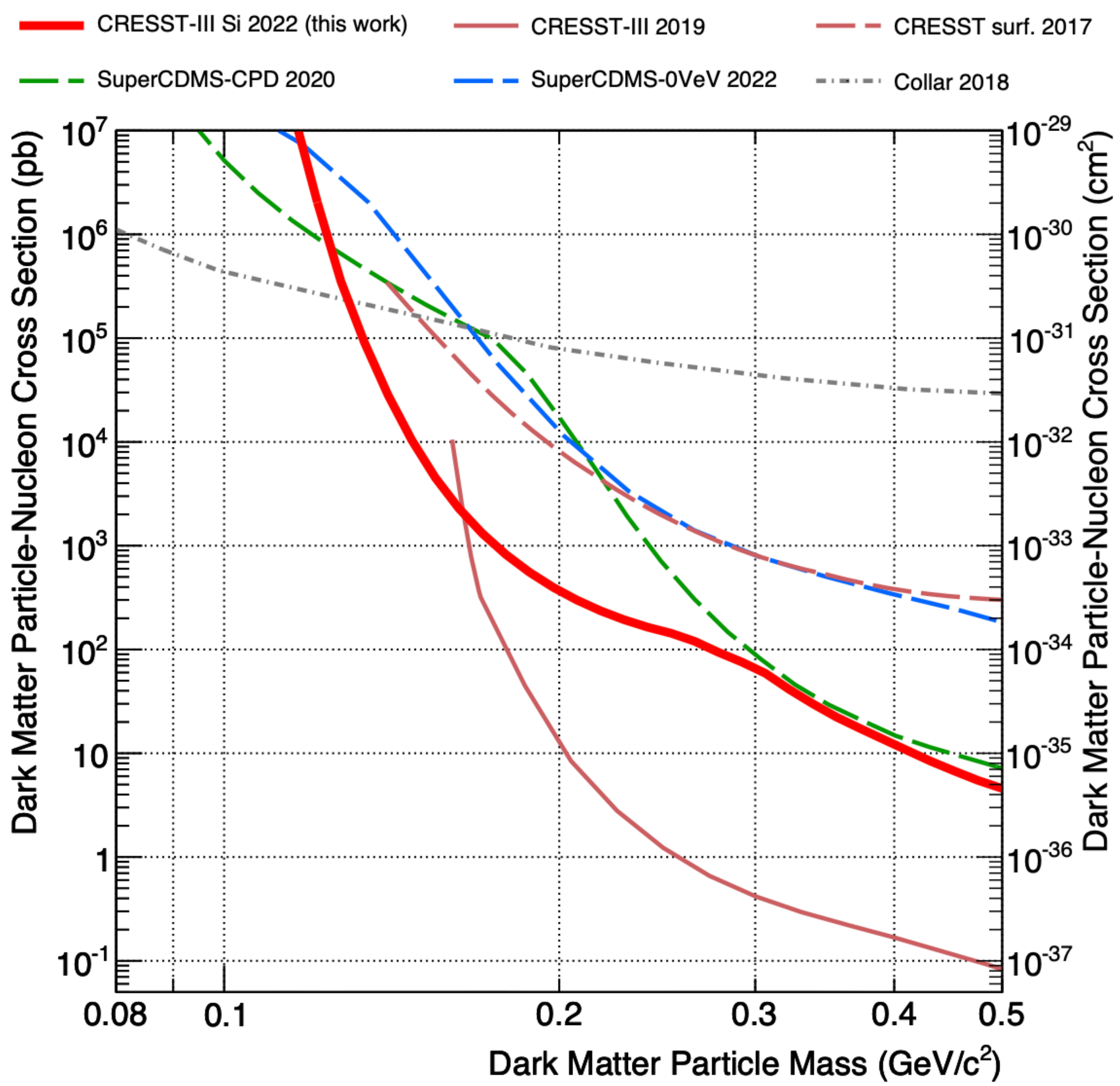
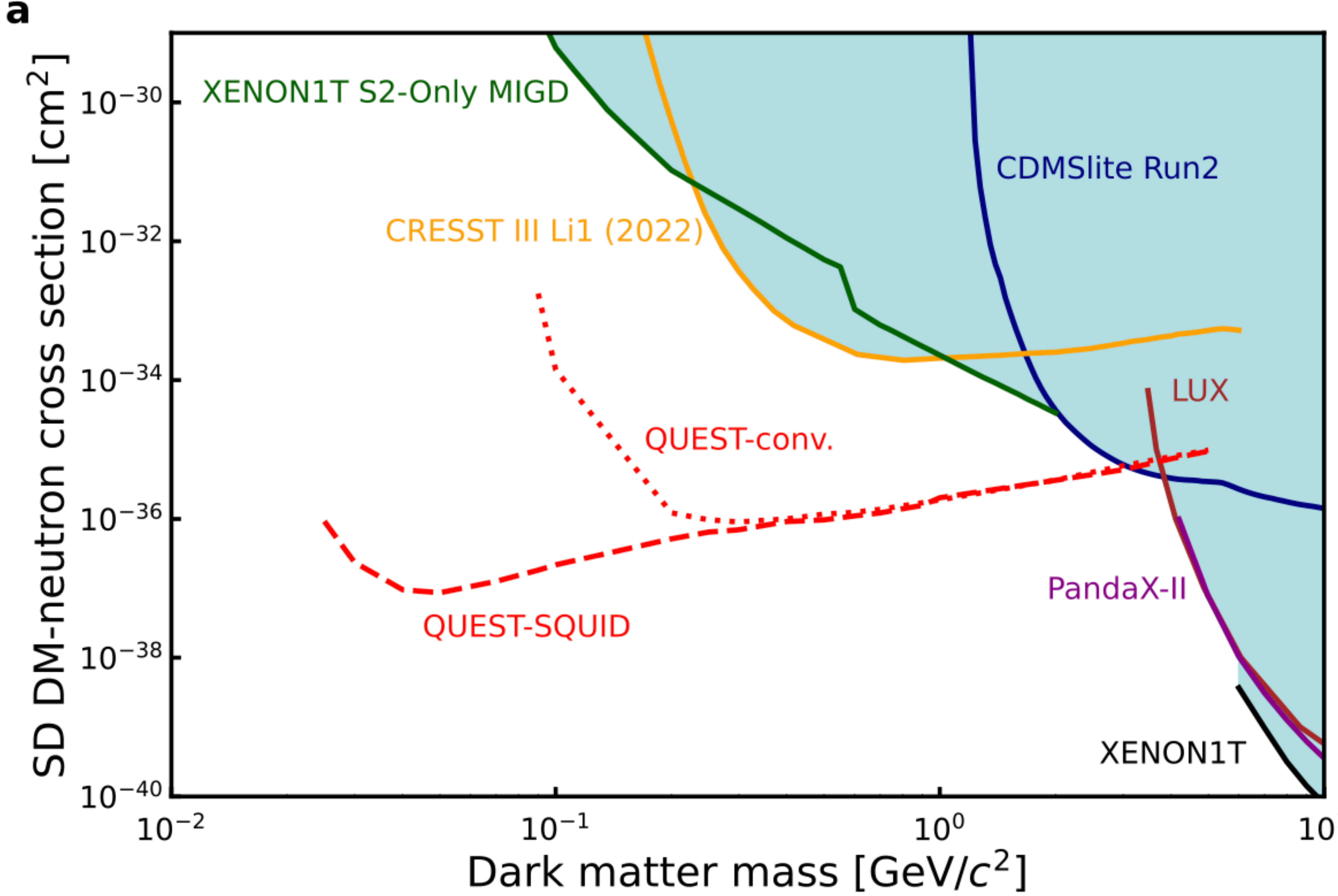


Spin-independent (←) and spin-dependent (→) interactions can be probed using different targets.

Sensitivity to brand new parameter space!

[See P. Franchini's talk].



Angloher, G., et al. "Results on sub-GeV dark matter from a 10 eV threshold CRESST-III silicon detector." Physical Review D 107.12 (2023): 122003.

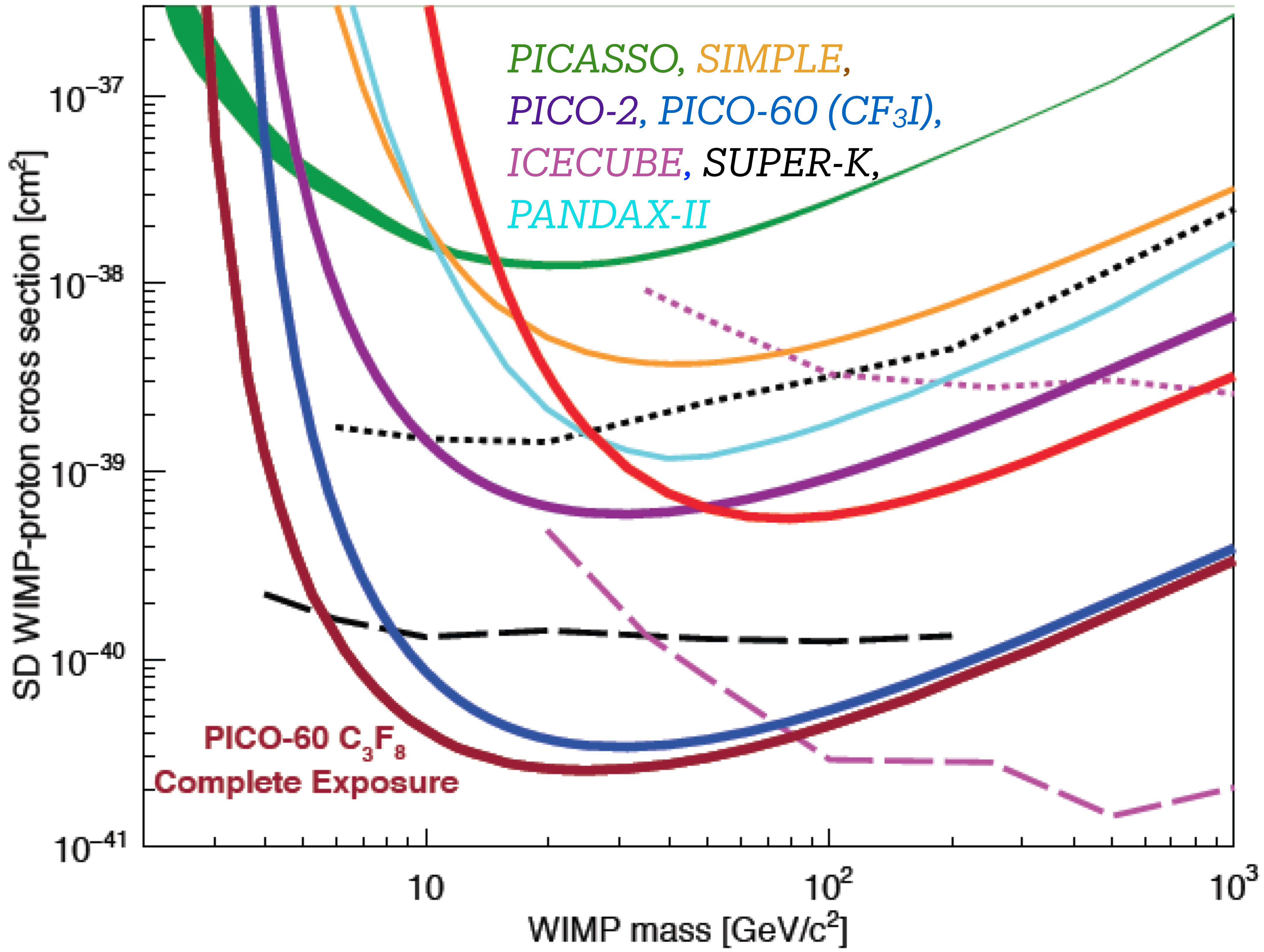
QUEST-DMC collaboration, et al. "QUEST-DMC superfluid 3 He detector for sub-GeV dark matter." The European Physical Journal C 84.3 (2024): 248.

Complementarity: Indirect Detection

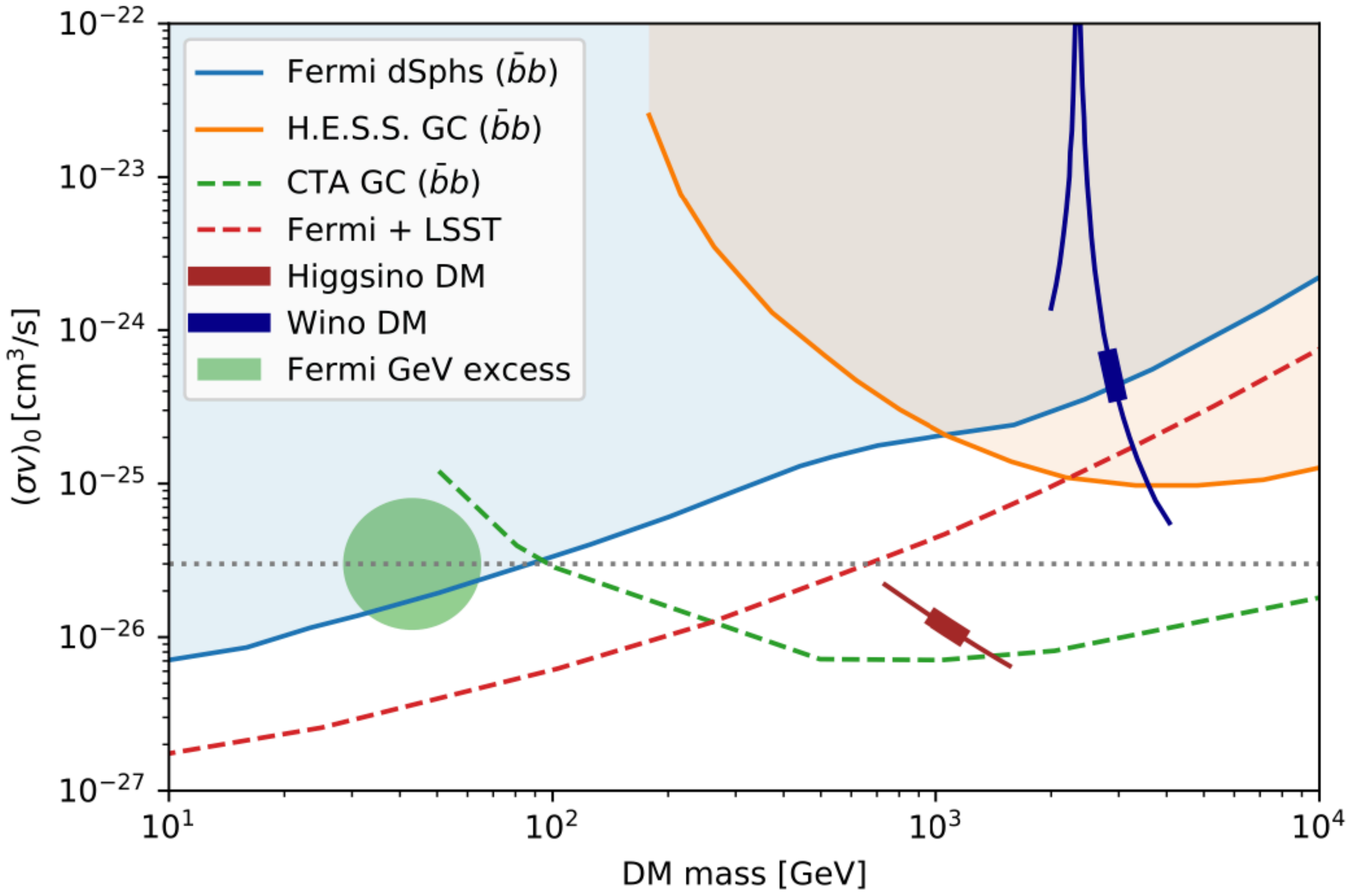
Ellis et al.,"European Strategy for Particle Physics Preparatory Group: Physics Briefing Book." arXiv preprint arXiv:1910.11775 (2019).

Leading constraints at high mass: WIMP trapping in the Sun.

- WIMP-p scattering + capture in the Sun.
- Annihilation signatures in neutrino telescopes.



Courtesy of J. Monroe (ICHEP '24)



Gamma-ray observations of dwarf spheroidal galaxies → Constraints on DM self-annihilation cross section.

- 'Fermi GeV excess': DM signal?

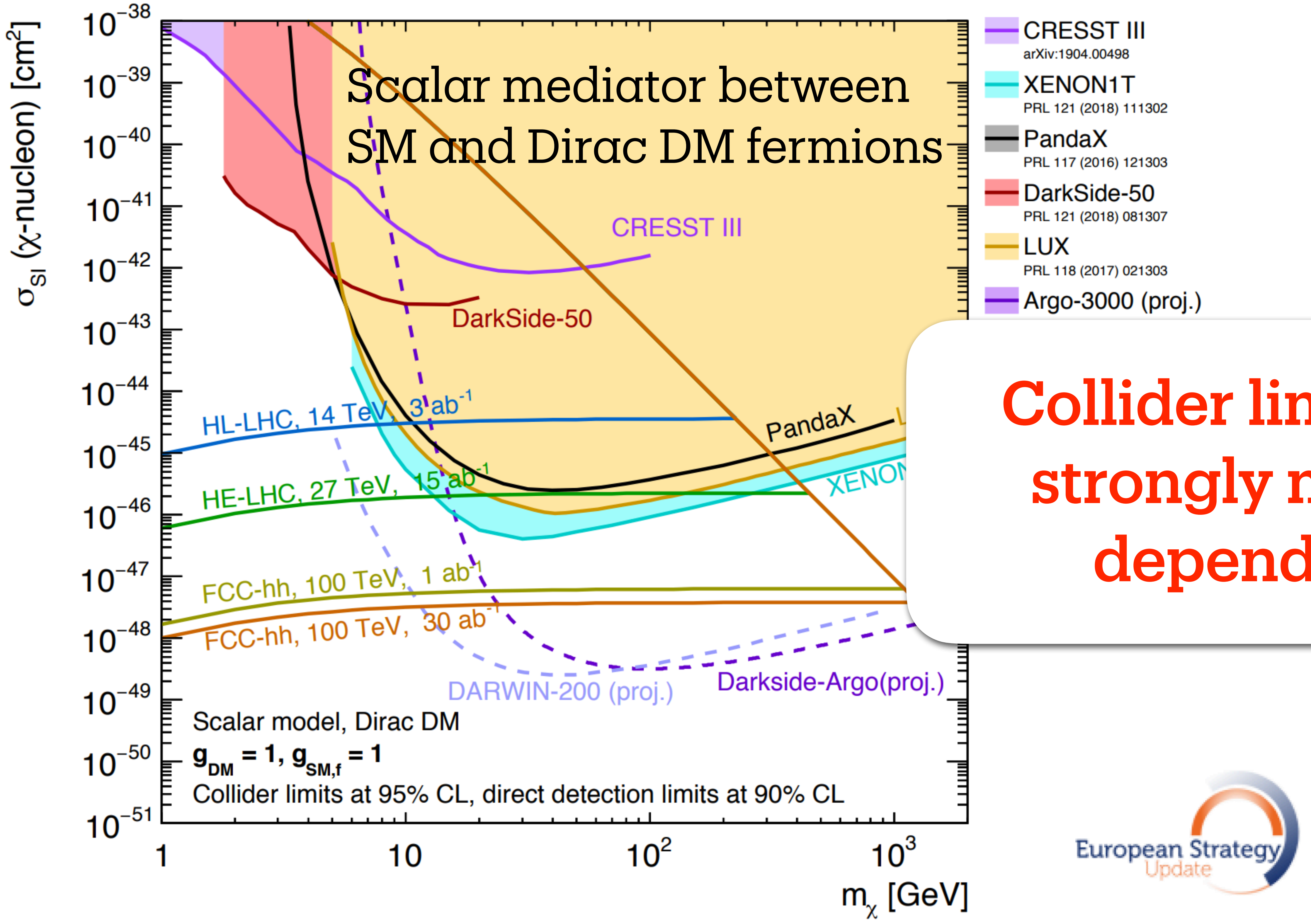
Astrophysical interpretations of the excess probed with upcoming radio observations, while collider experiments probe dark matter origin.

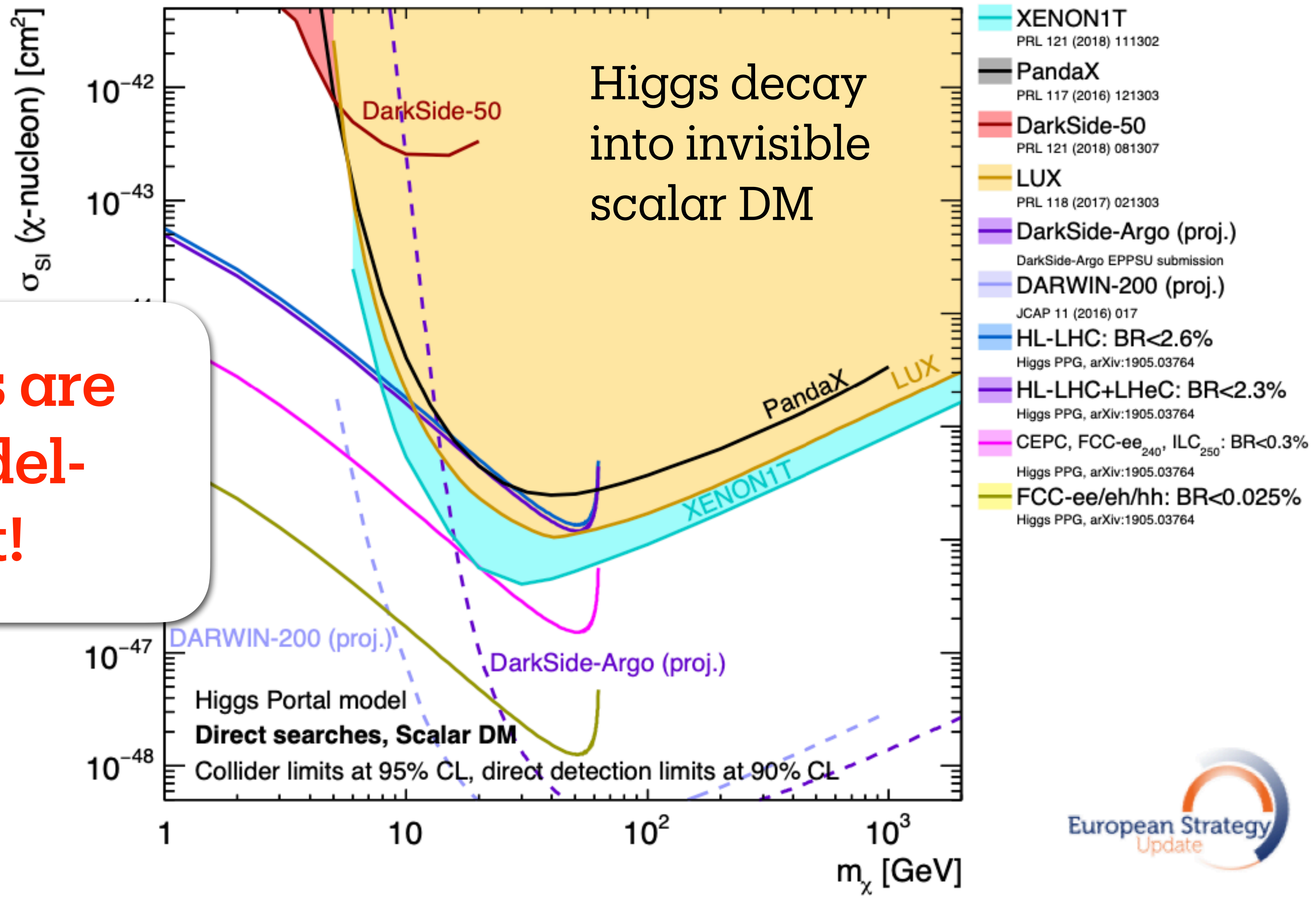
Complementarity: Collider Searches

Colliders probe *what* the dark matter particle is (no assumptions made on thermal history of DM)

- Limits on branching ratios → cross-section vs mass (direct detection).

Happy region of overlap where accelerators can confirm direct detection discovery (and vice versa!)

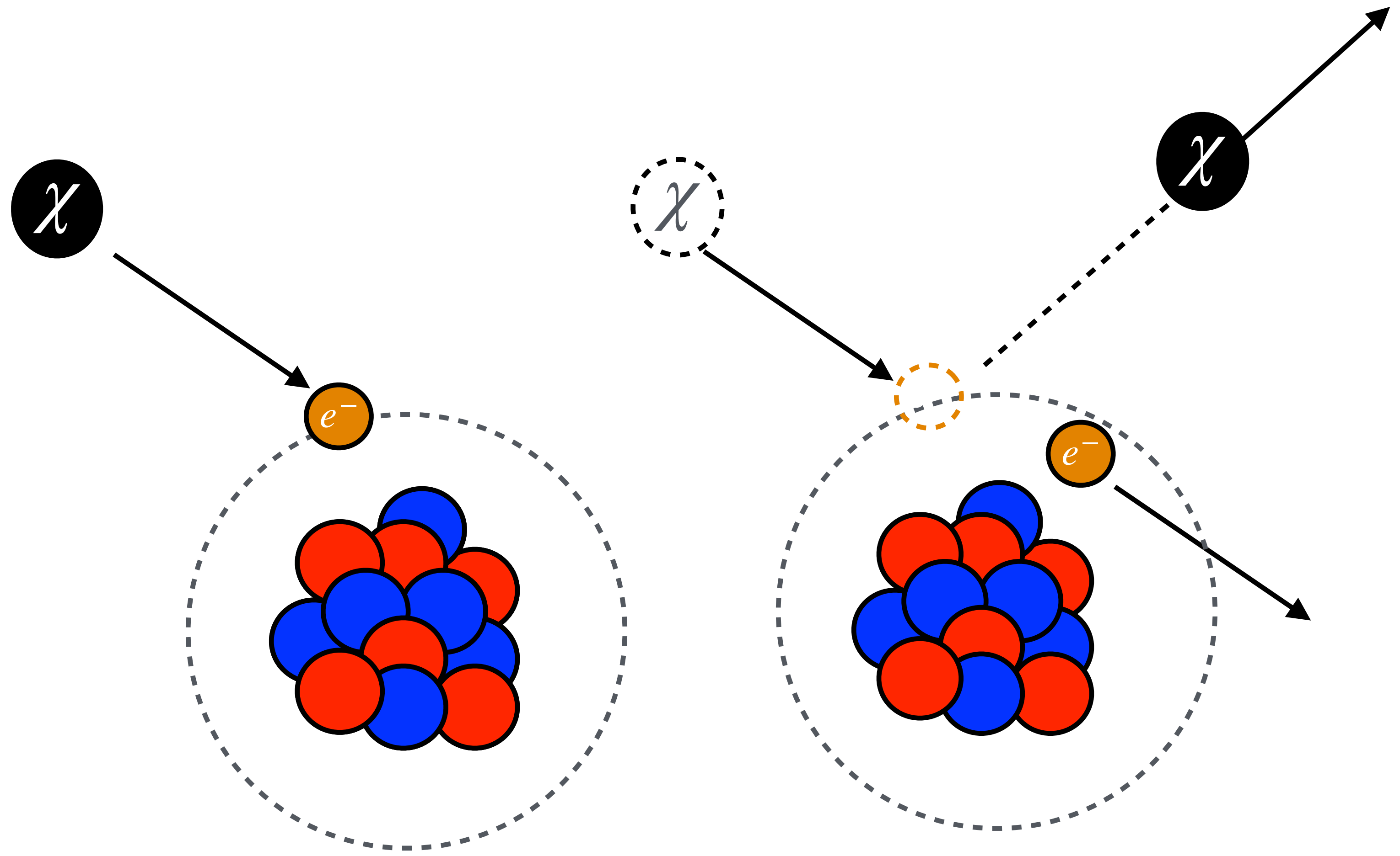




Collider limits are strongly model-dependent!

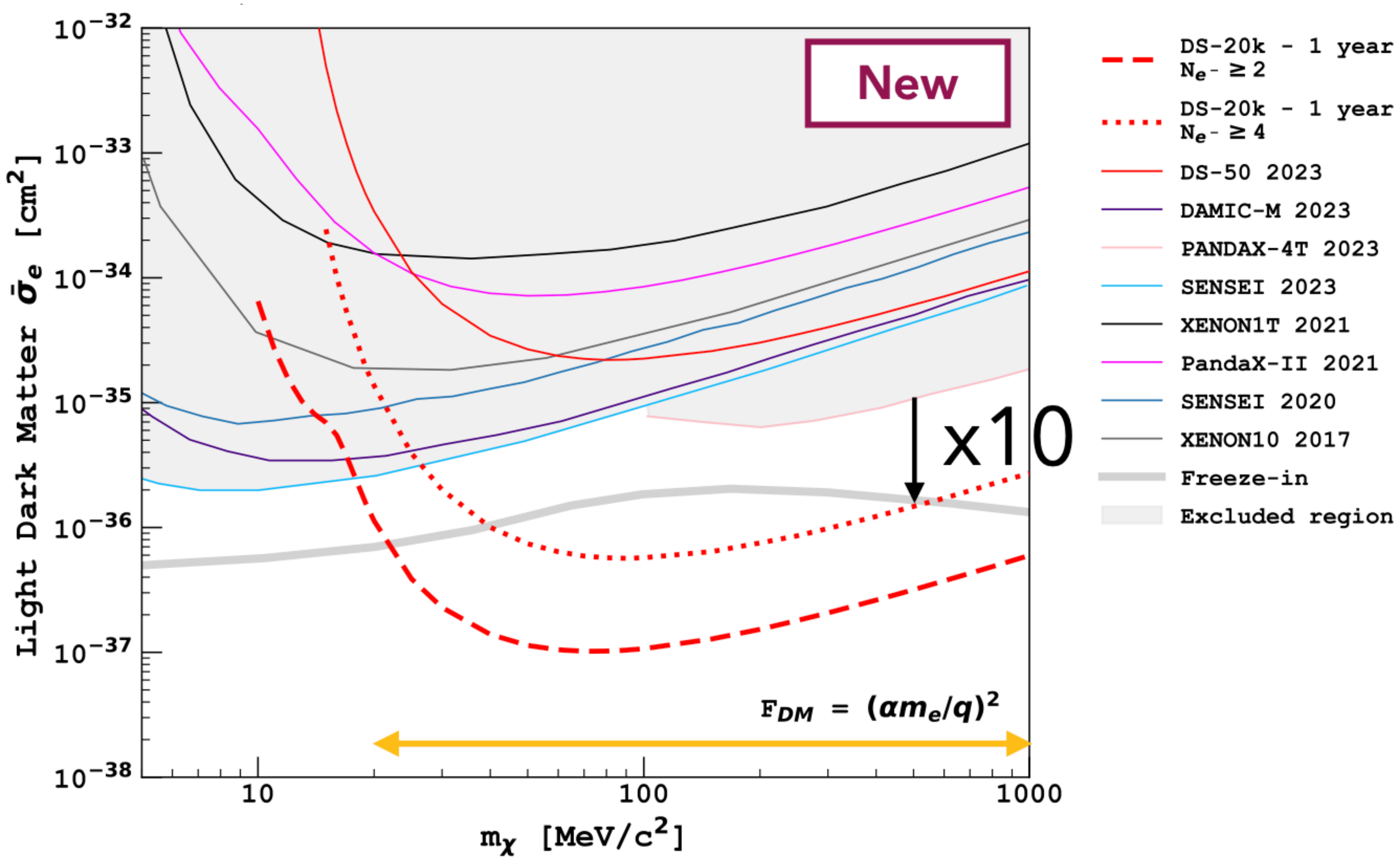
Ellis et al. "European Strategy for Particle Physics Preparatory Group: Physics Briefing Book." arXiv preprint arXiv:1910.11775 (2019).

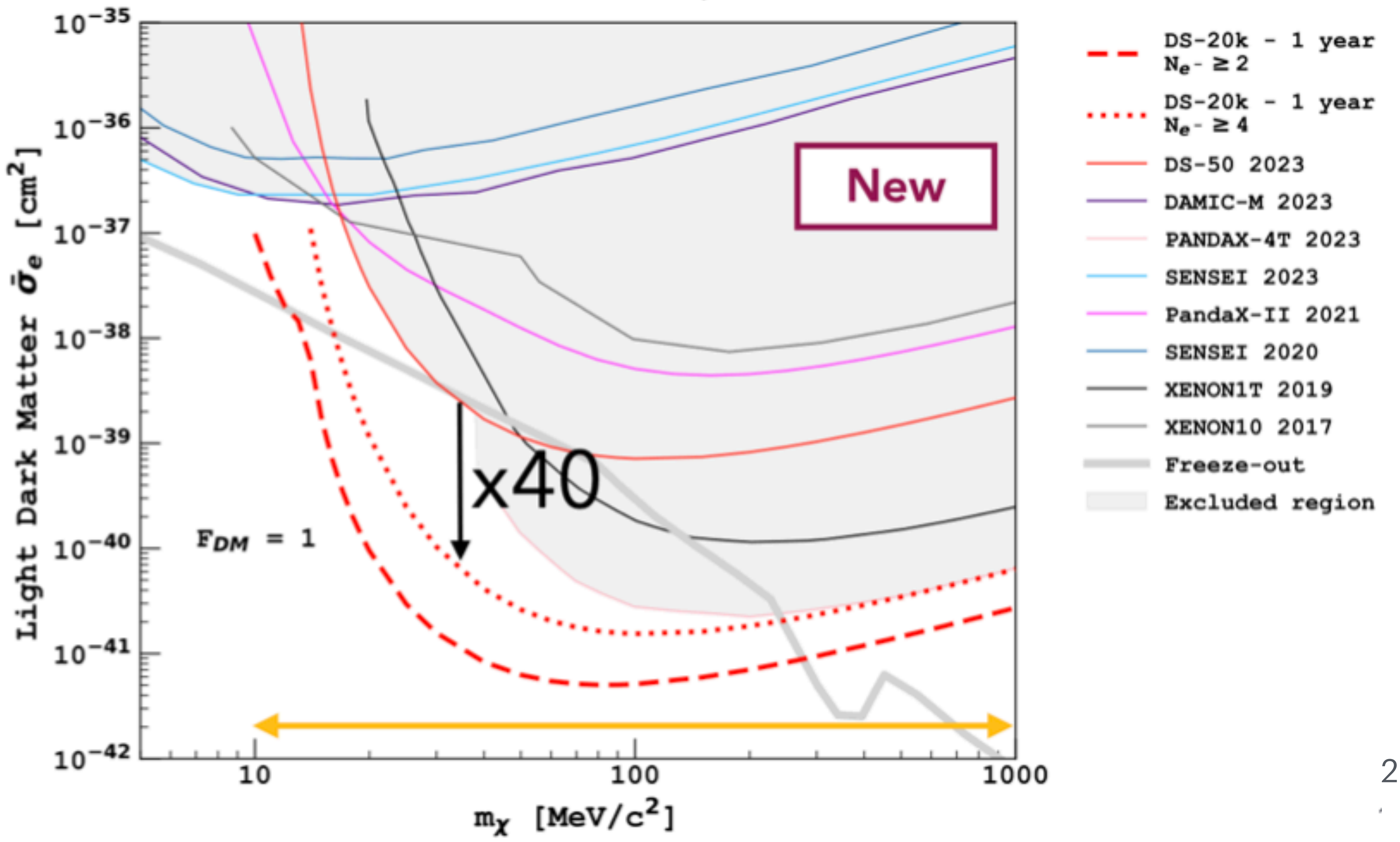
Beyond the WIMP Paradigm



Elastic scattering off atomic electrons: interaction of sub-GeV DM fermion/scalar boson via vector mediator.

Mediator can be light $(m_{\text{med}} \ll m_\chi)$ or heavy $(m_{\text{med}} \gg m_\chi)$.

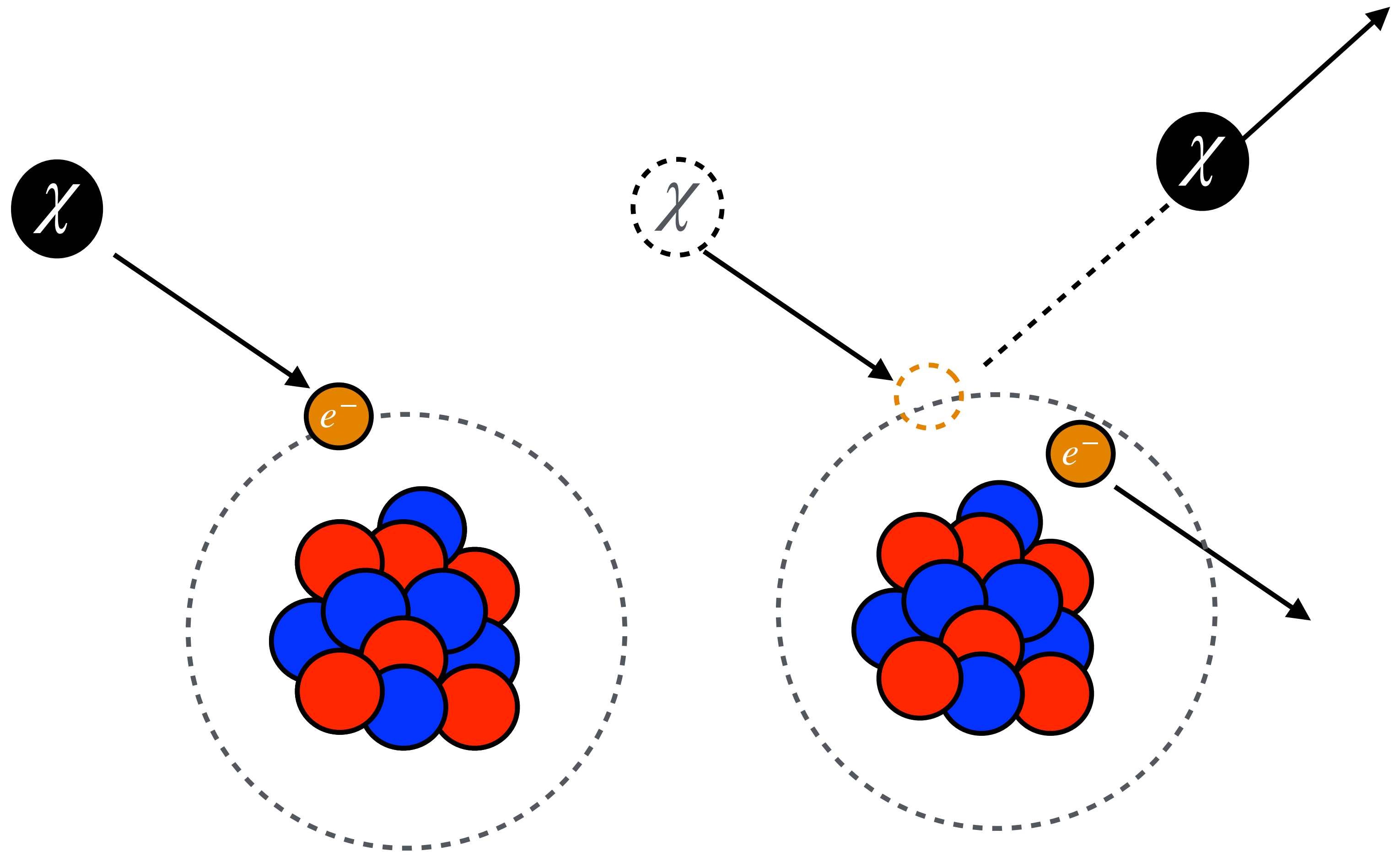




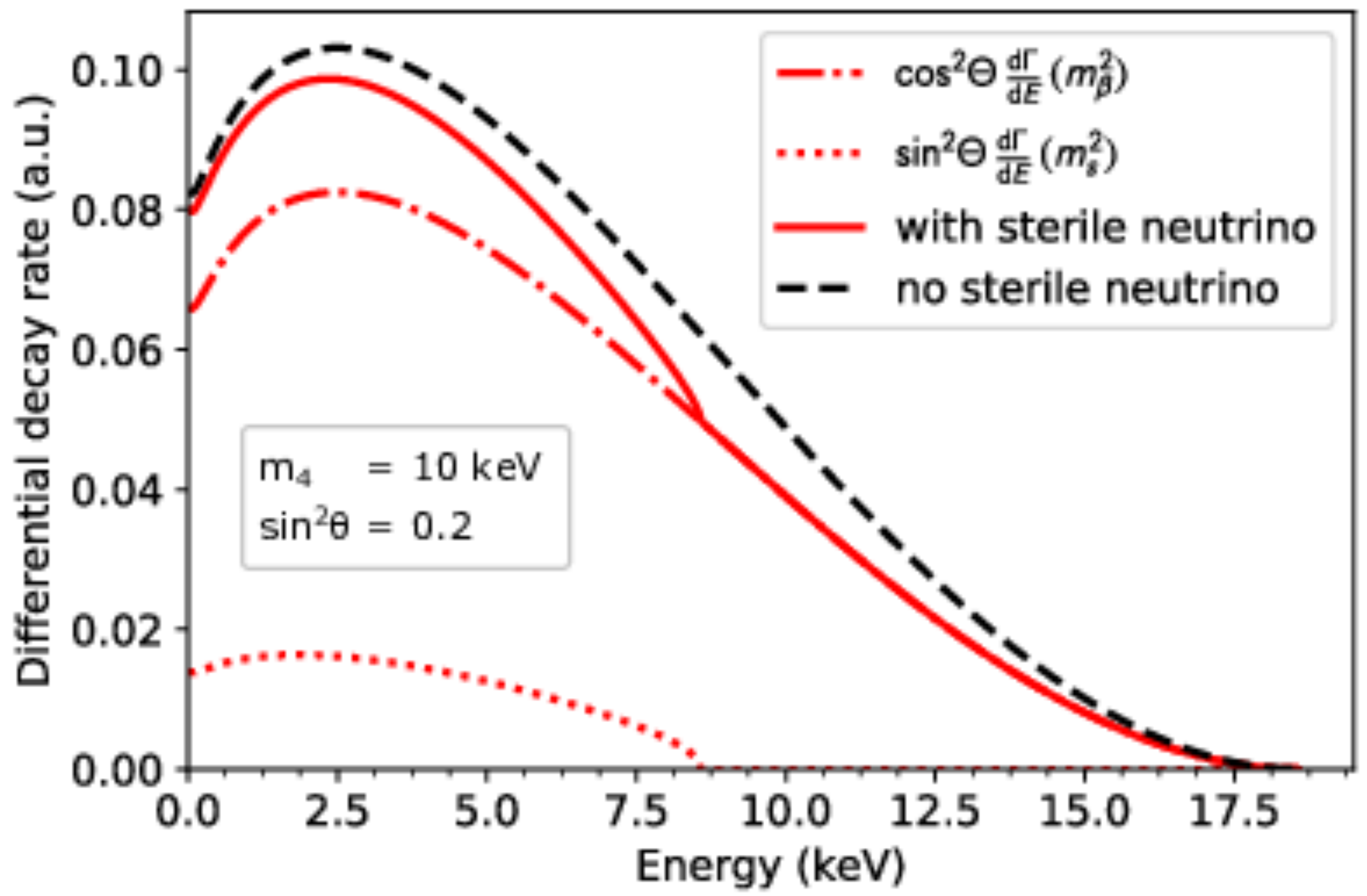
Acerbi, F., et al. "DarkSide-20k sensitivity to light dark matter particles." arXiv preprint arXiv:2407.05813 (2024).

Beyond the WIMP Paradigm

Mertens, Susanne, et al. "A novel detector system for KATRIN to search for keV-scale sterile neutrinos." Journal of Physics G: Nuclear and Particle Physics 46.6 (2019): 065203.

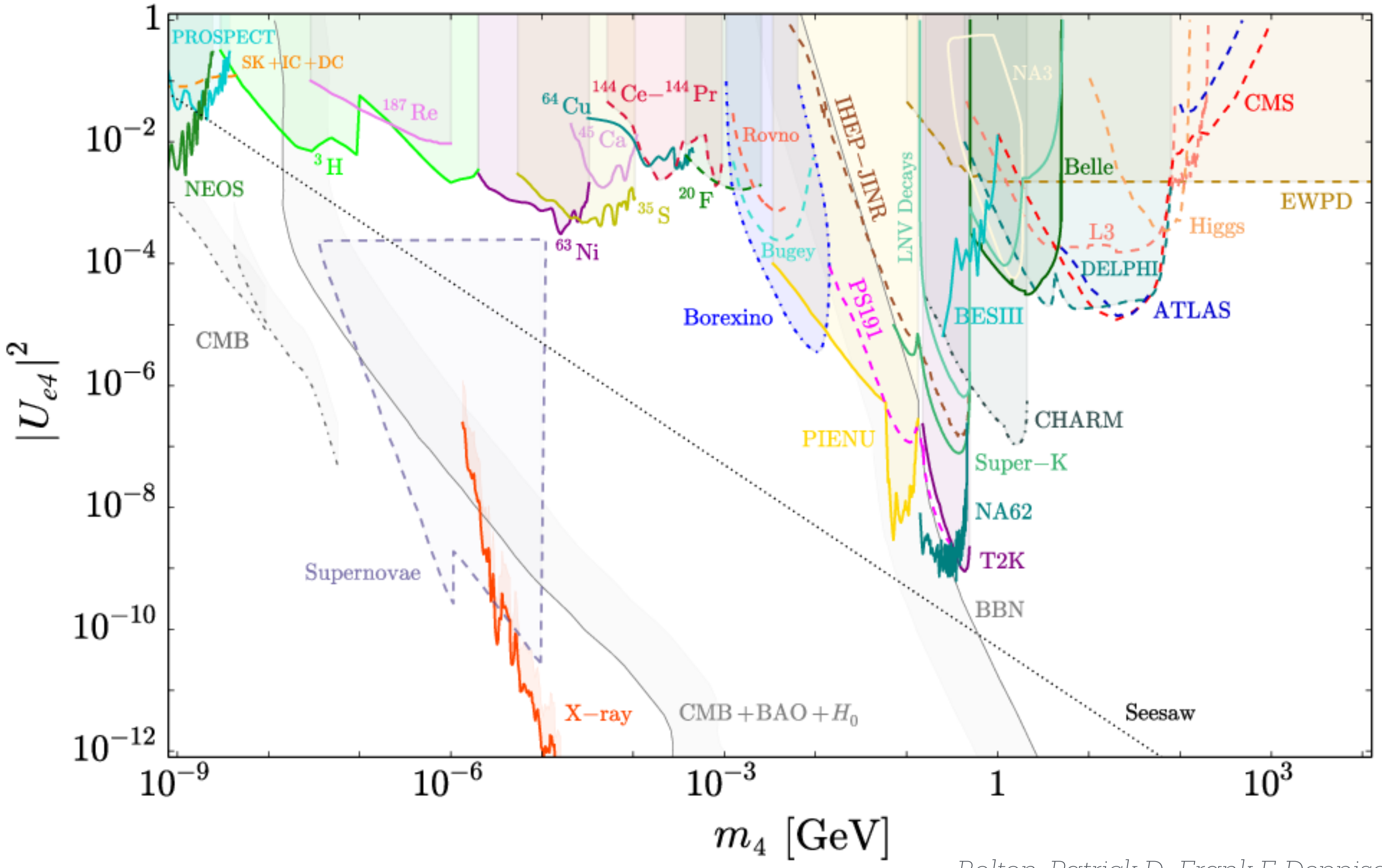


Constraints on $|U_{e4}|^2$ from beta decay: energy spectrum modified by sterile neutrino mixing.



Warm DM inelastic scatters off atomic electrons: sterile ν!

Sterile ν mixing with an active ν state by an angle $|U_{e4}|^2$ could inelastically scatter off a bound electron.

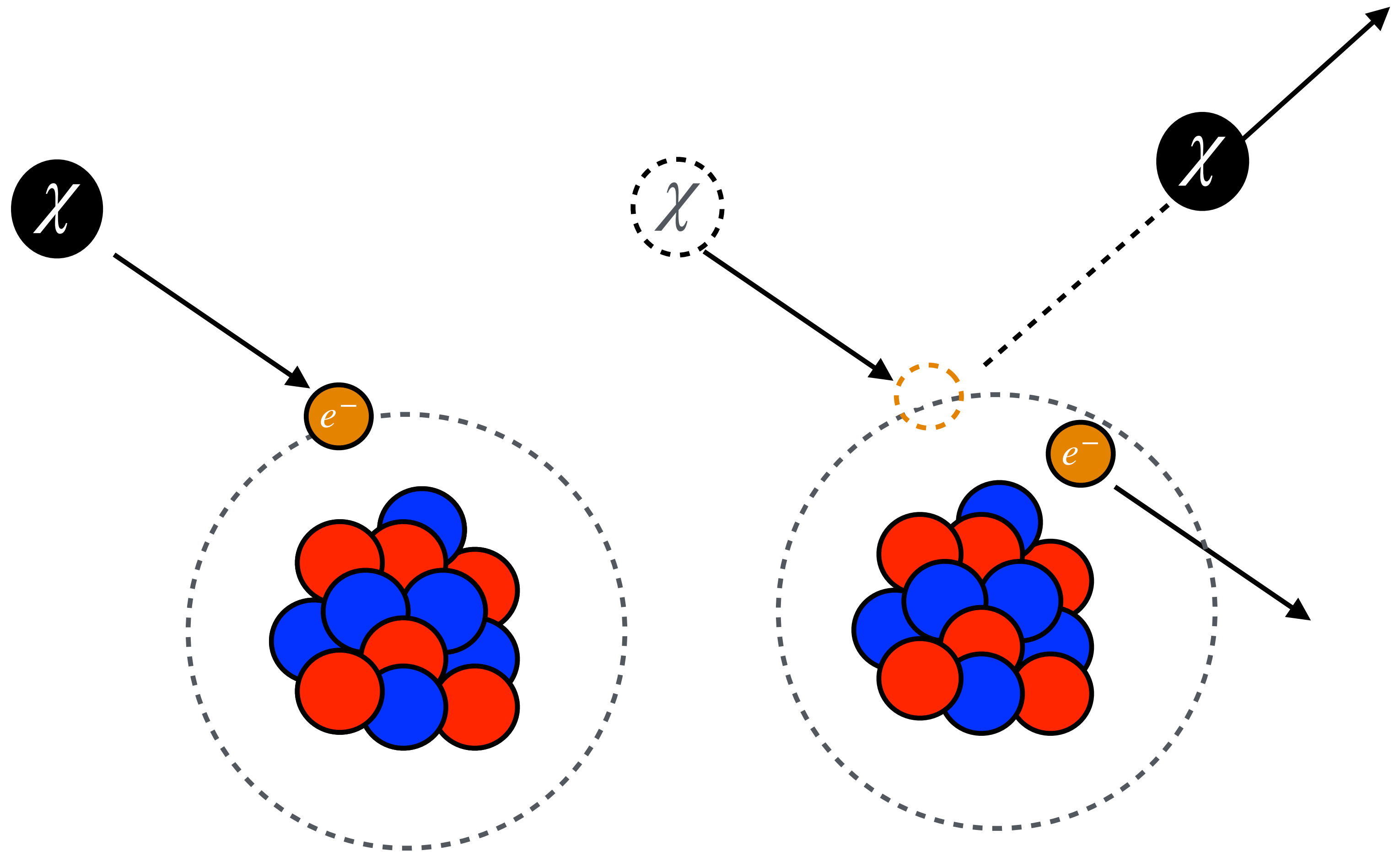


Bolton, Patrick D., Frank F. Deppisch, P. S. Dev. "Neutrinoless double beta decay versus other probes of heavy sterile neutrinos." Journal of HEP 2020.3 (2020): 1-56.

Indirect detection: X-ray energy spectrum strongly constrains $|U_{e4}|^2$

Beyond the WIMP Paradigm

Mertens, Susanne, et al. "A novel detector system for KATRIN to search for keV-scale sterile neutrinos." Journal of Physics G: Nuclear and Particle Physics 46.6 (2019): 065203.



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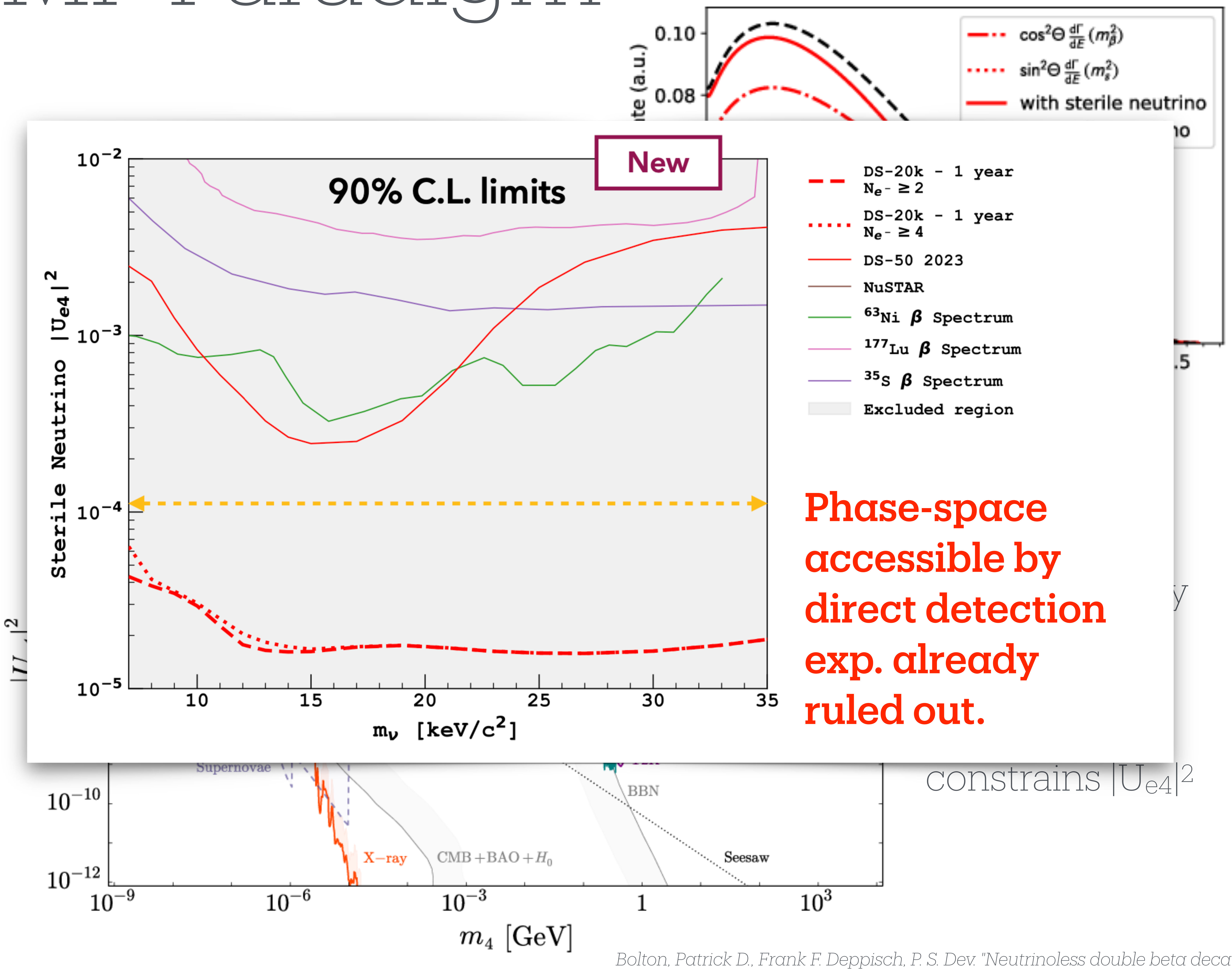
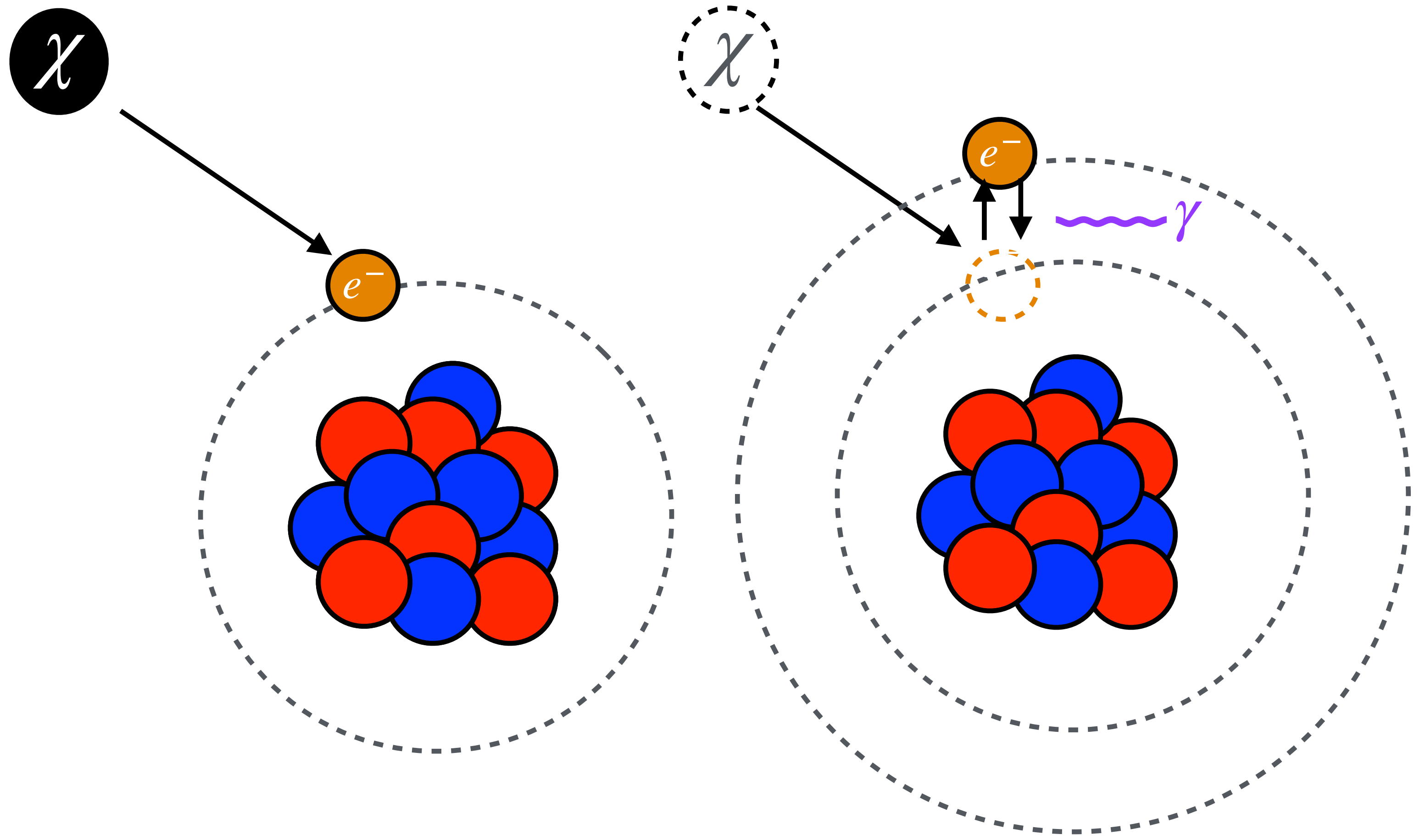


Phase-space accessible by direct detection exp. already ruled out.

constrains $|U_{e4}|^2$

Bolton, Patrick D., Frank F. Deppisch, P. S. Dev. "Neutrinoless double beta decay versus other probes of heavy sterile neutrinos." Journal of HEP 2020.3 (2020): 1-56.

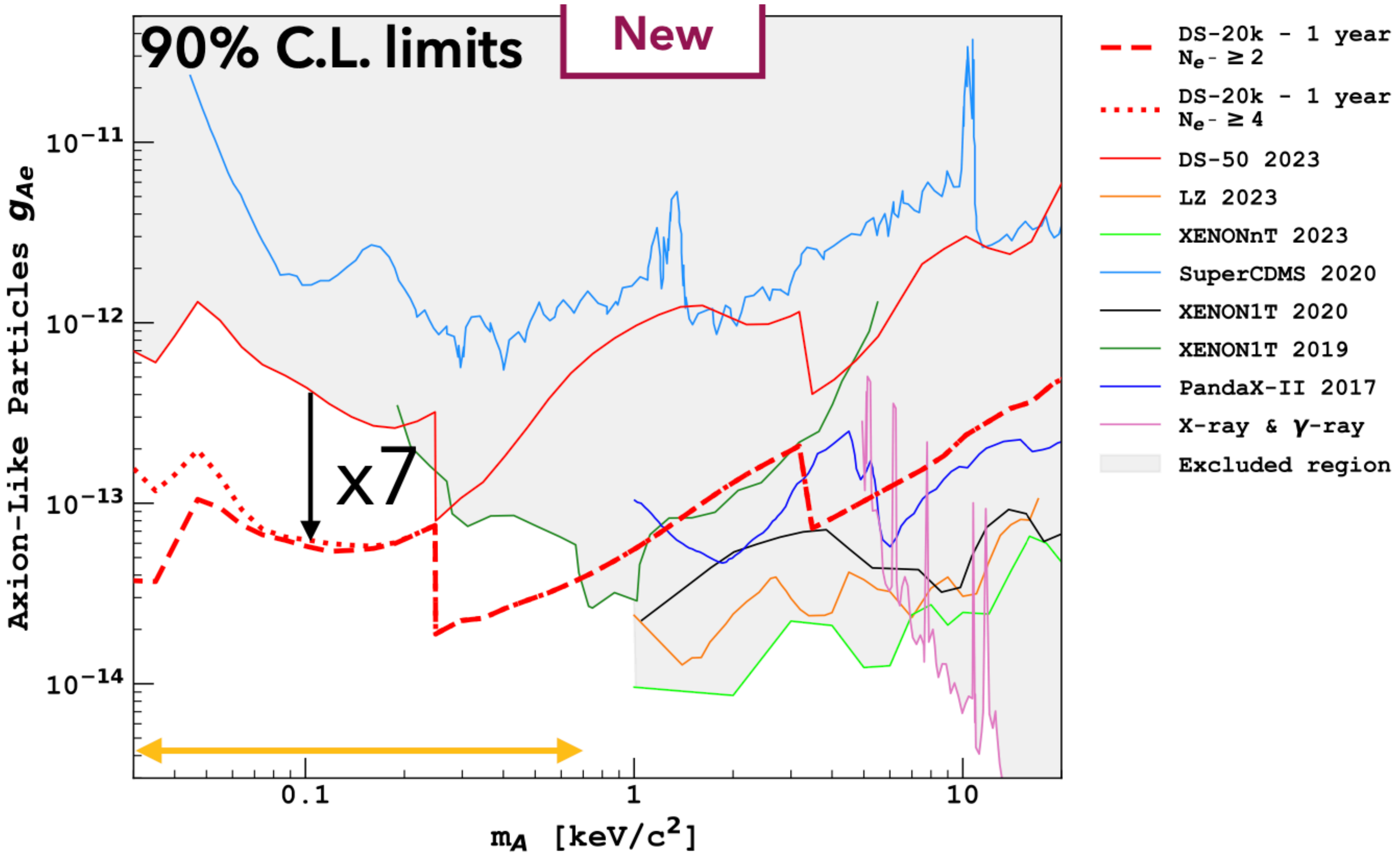
Beyond the WIMP Paradigm

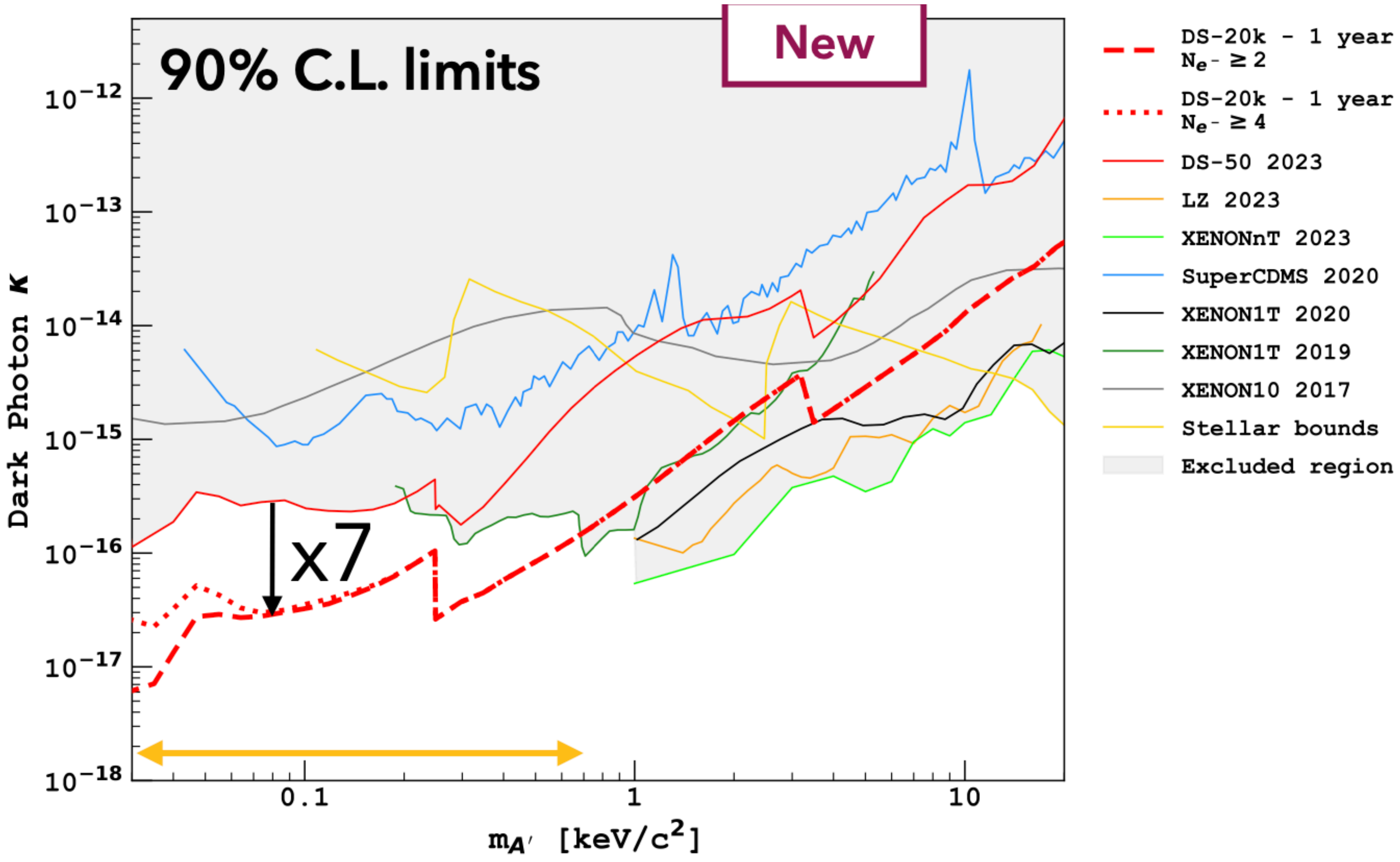


Absorption by atomic electrons: “dark” photons (DPs) via kinetic mixing, axion-like particles (ALPs) via axioelectic effect.

- Perform “bump hunt”: mono-energetic peak centred at m_χ (smeared by detector resolution).

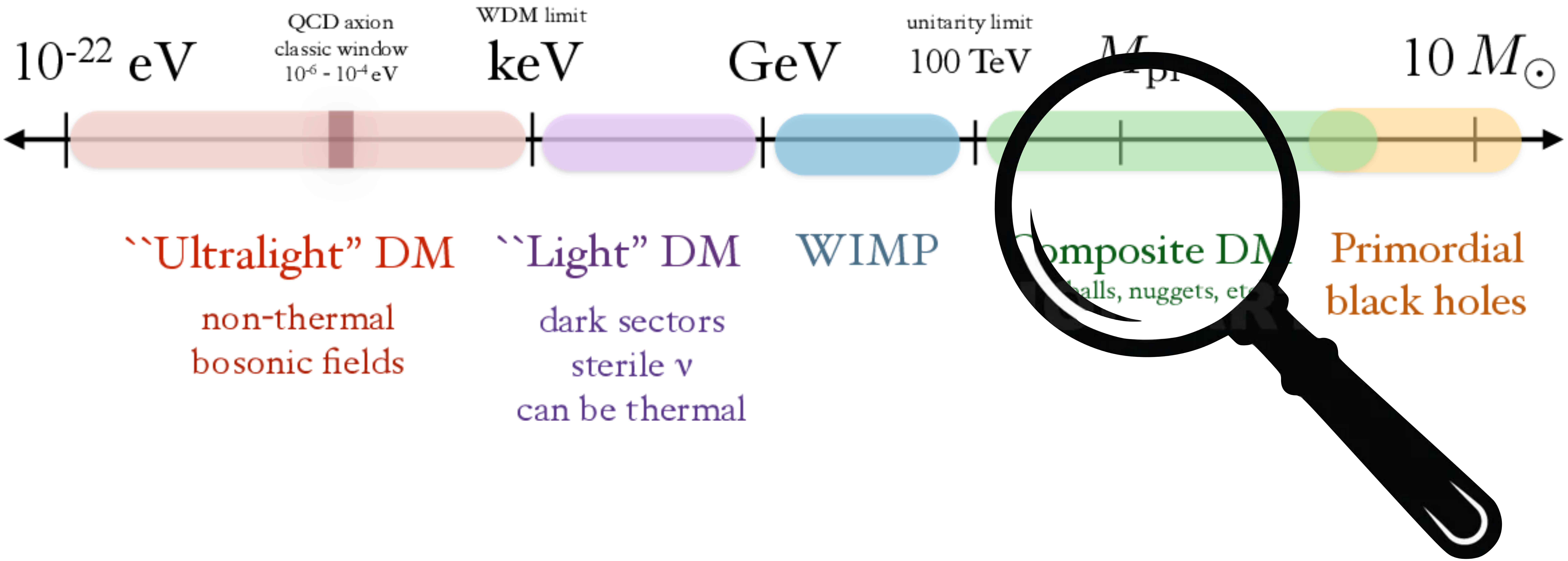
Set constraints on ALP-e^- coupling g_{Ae} or DP kinetic mixing strength κ.





Acerbi, F., et al. "DarkSide-20k sensitivity to light dark matter particles." arXiv preprint arXiv:2407.05813 (2024).

Very Heavy Dark Matter



10^{-22} eV

QCD axion
classic window
10^{-6} - 10^{-4} eV

WDM limit
keV

GeV

unitarity limit
100 TeV

M_{pl}

10 $M_{\odot}$

``Ultralight" DM

non-thermal
bosonic fields

``Light" DM

dark sectors
sterile ν
can be thermal

WIMP

omposite DM

alls, nuggets, et

Primordial
black holes

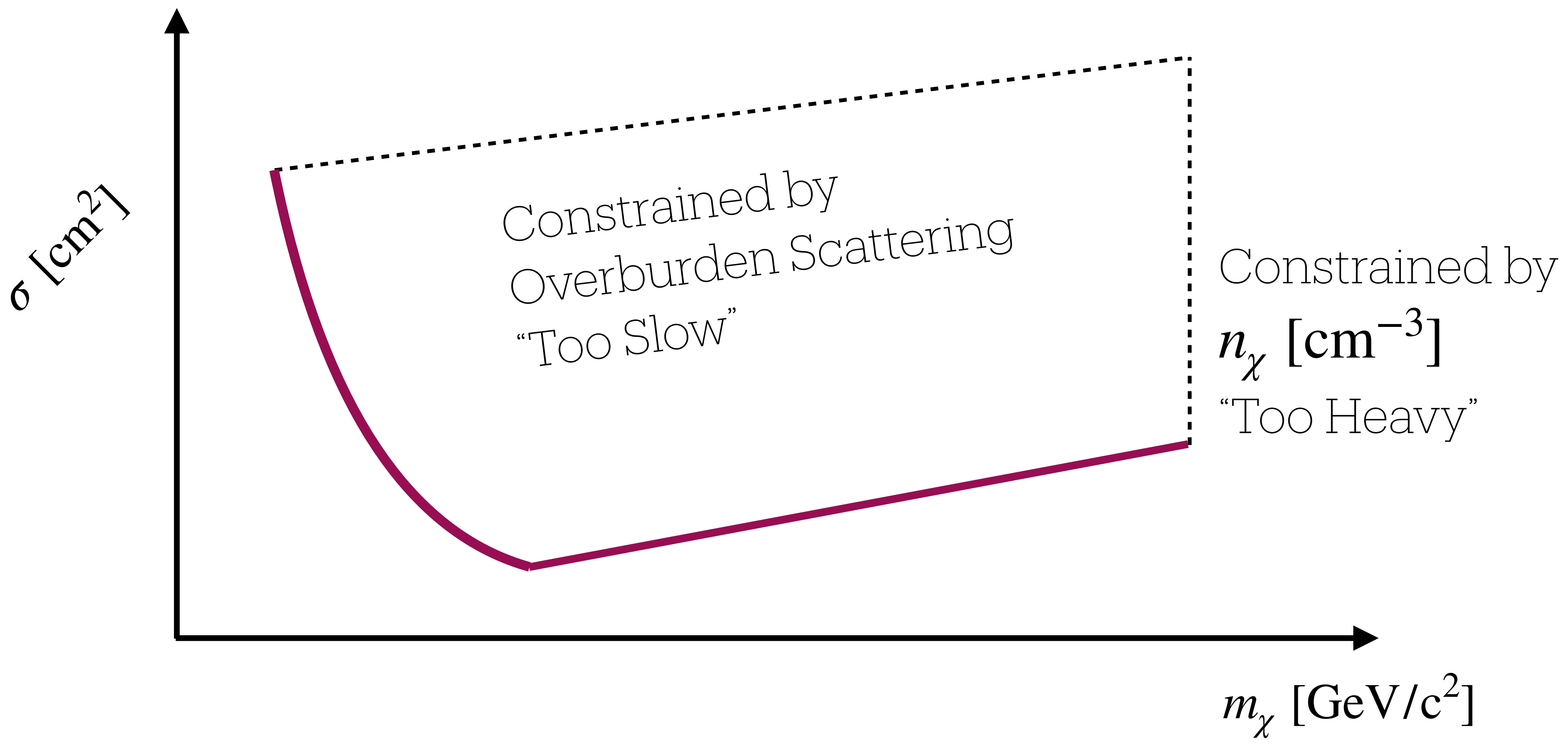
Planck-Scale Mass Searches

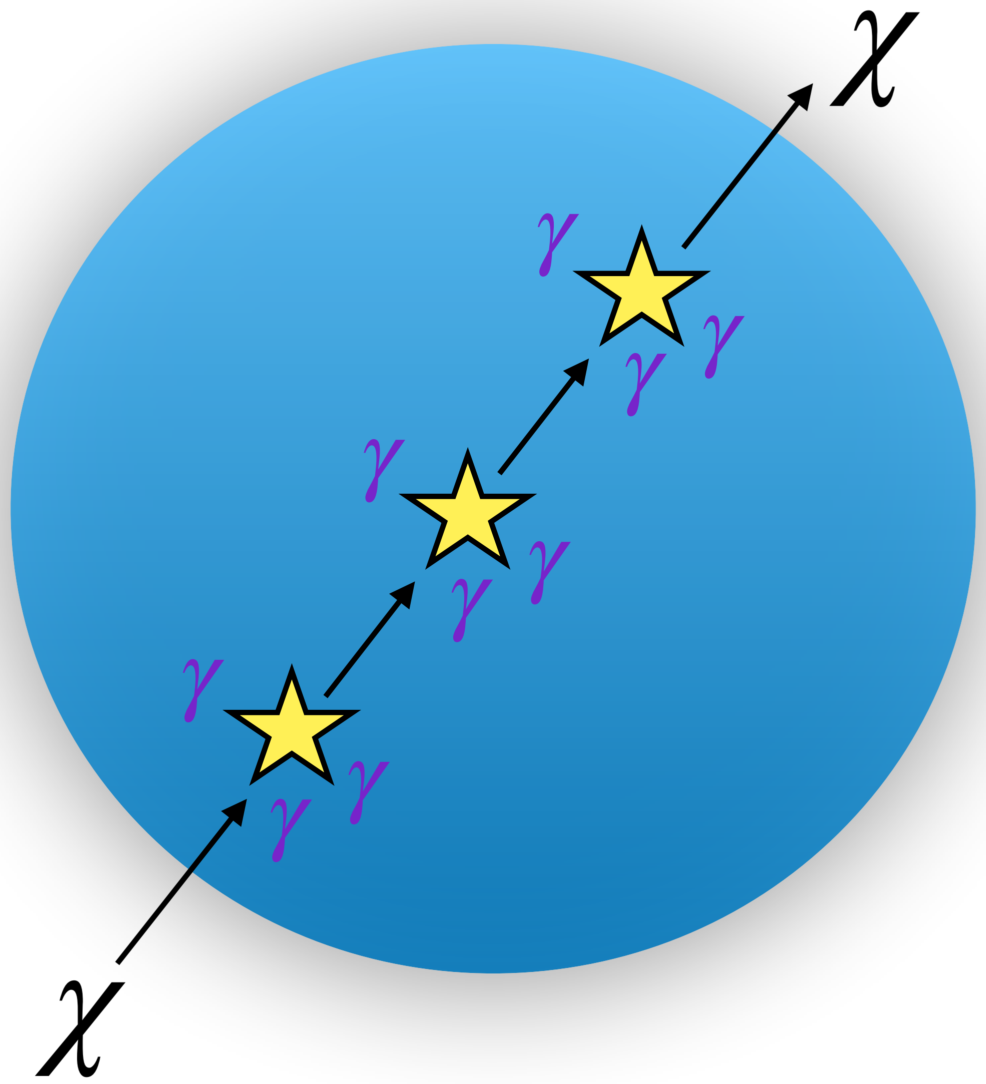
Produced non-thermally through GUTs, primordial black hole radiation, or extended thermal production in a dark sector.

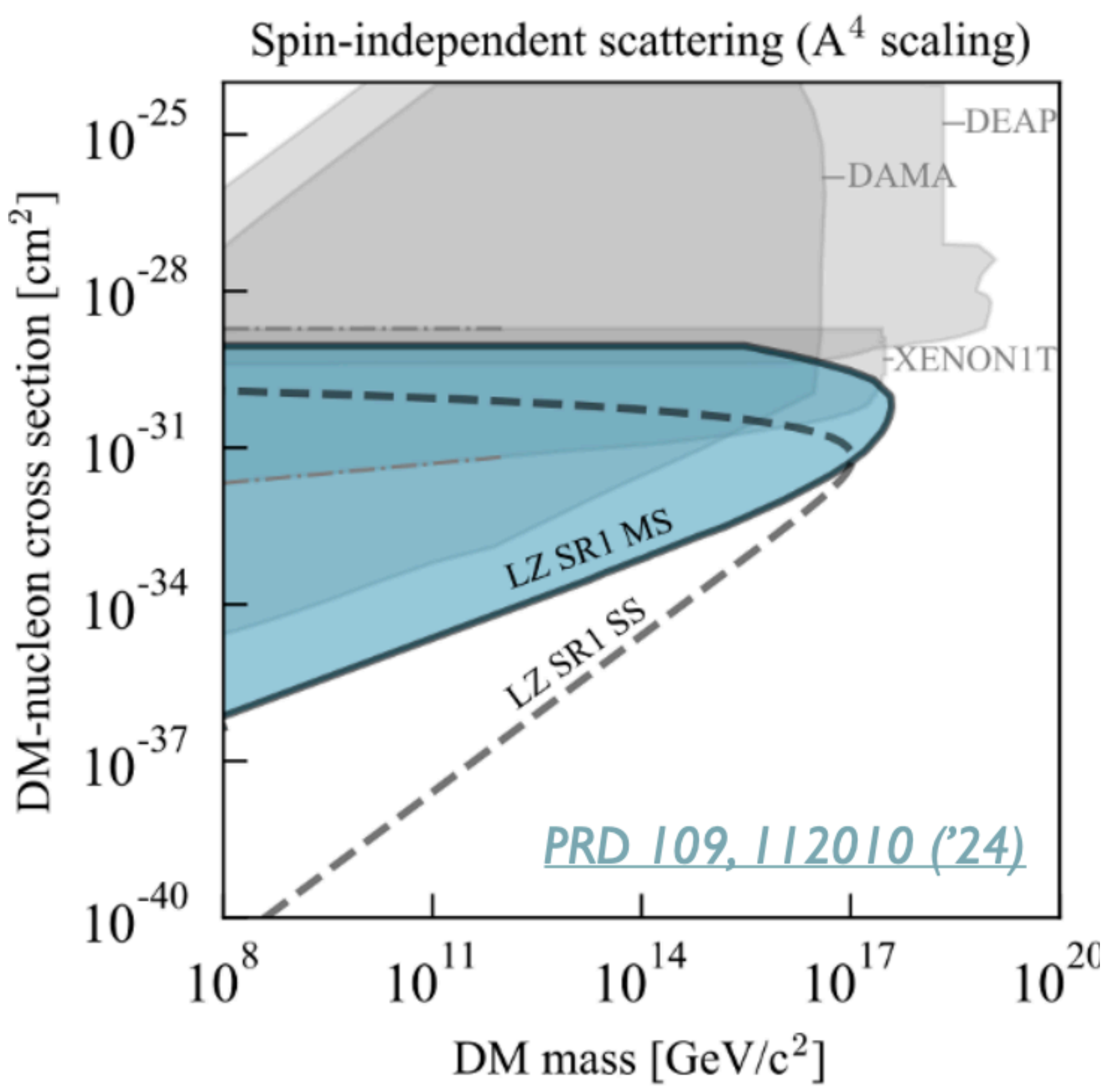
Has high enough mass to scatter multiple times as it traverses a detector: multiple co-linear NRs.

Optimal target: large detector area normal to DM flux and large "thickness":

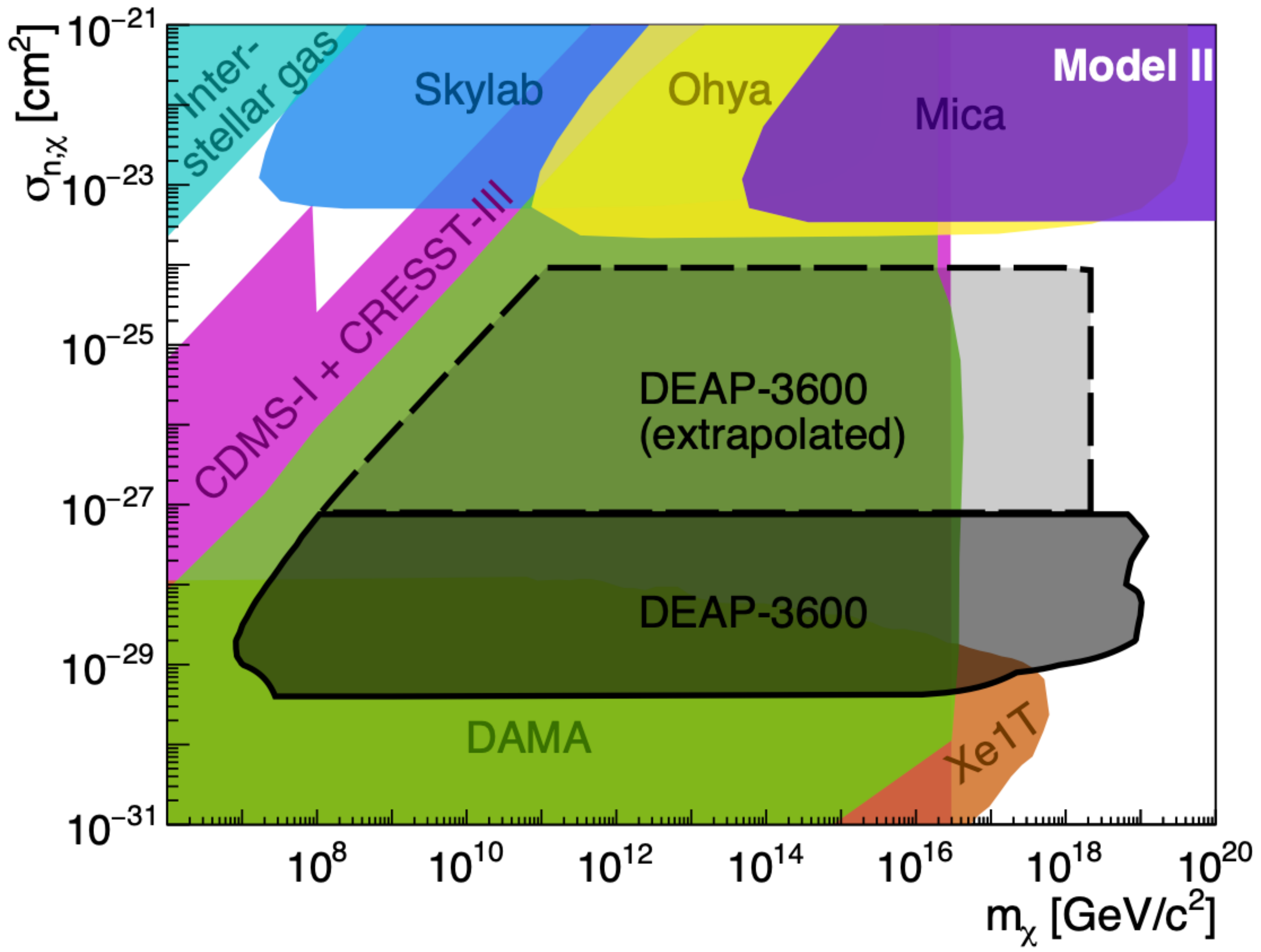
- First direct detection constraints from DEAP-3600, followed by LZ.





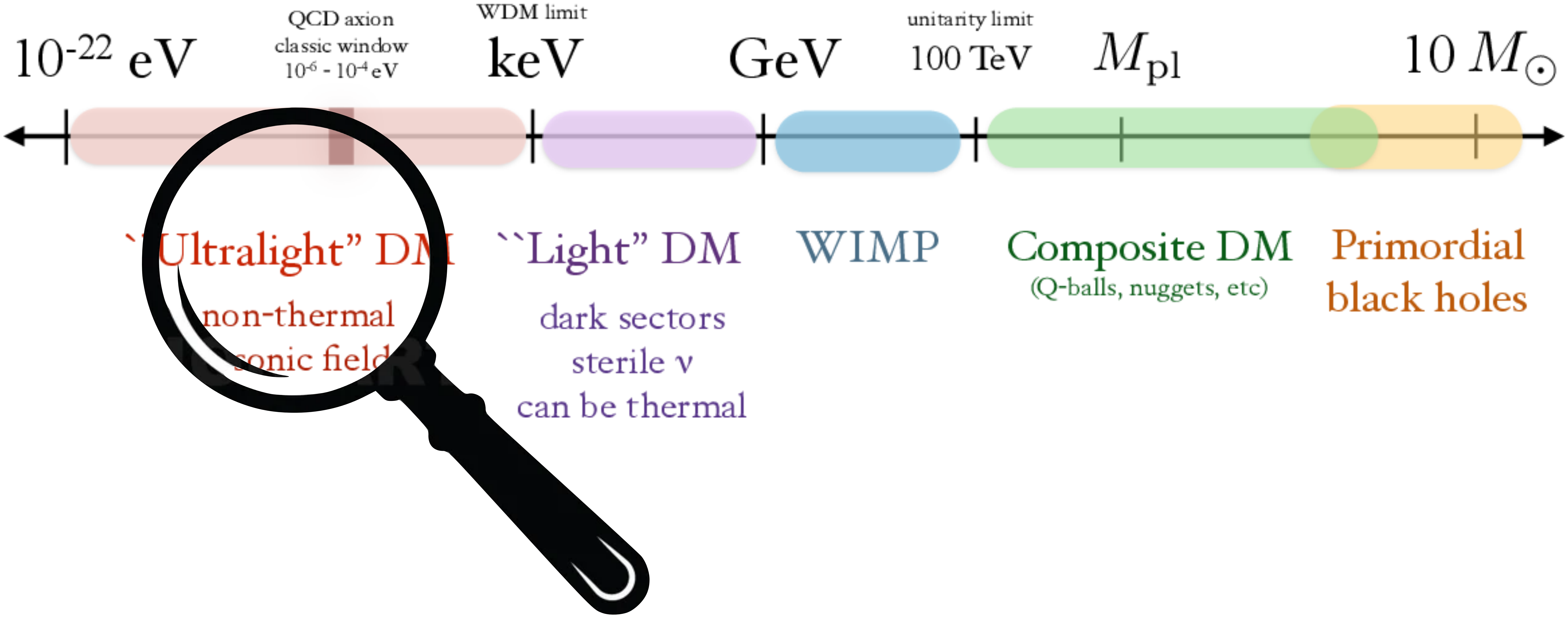


PRD 109, 112010 ('24)



Adhikari, P., et al. "First direct detection constraints on Planck-scale mass dark matter with multiple-scatter signatures using the DEAP-3600 detector." Physical Review Letters 128.1 (2022): 011801

Axions as Dark Matter



10^{-22} eV

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classic window
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``Ultralight" DM
non-thermal
bosonic field

``Light" DM
dark sectors
sterile ν
can be thermal

WIMP

Composite DM
(Q-balls, nuggets, etc)

Primordial
black holes

Axion Searches

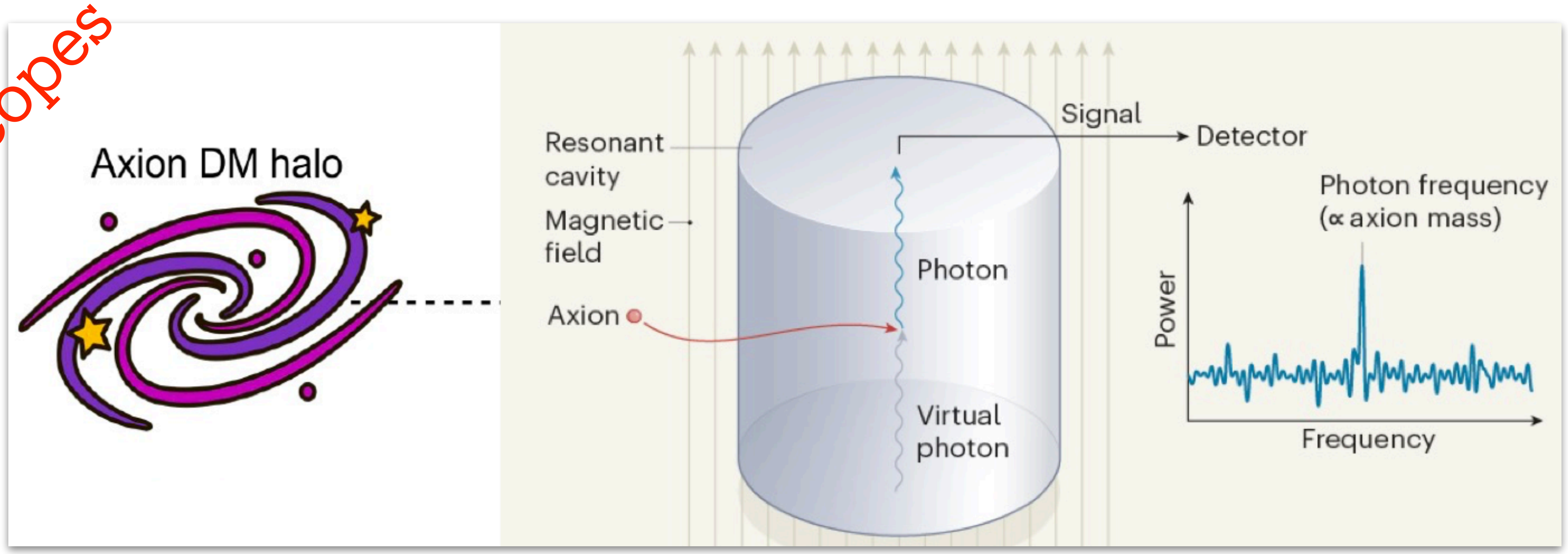
Motivated to solve strong CP problem.

Detect weak conversion of axions into microwave photons in the presence of a strong $\vec{B}$ field.

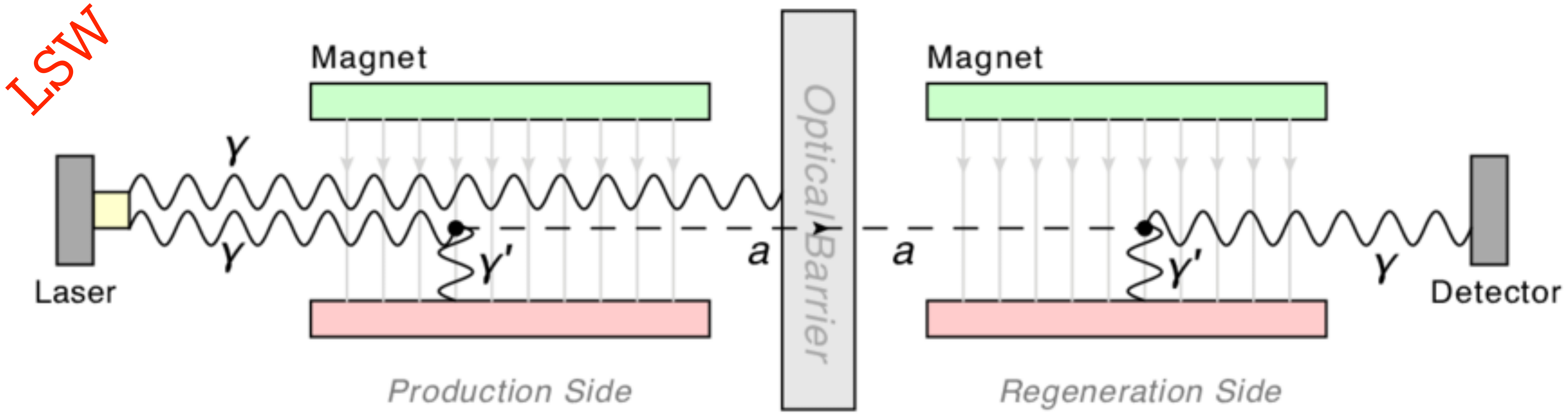
Detectors:

- Haloscopes (relic axions).
- Light-shining-through walls (lab axions).
- Helioscopes (solar axions).

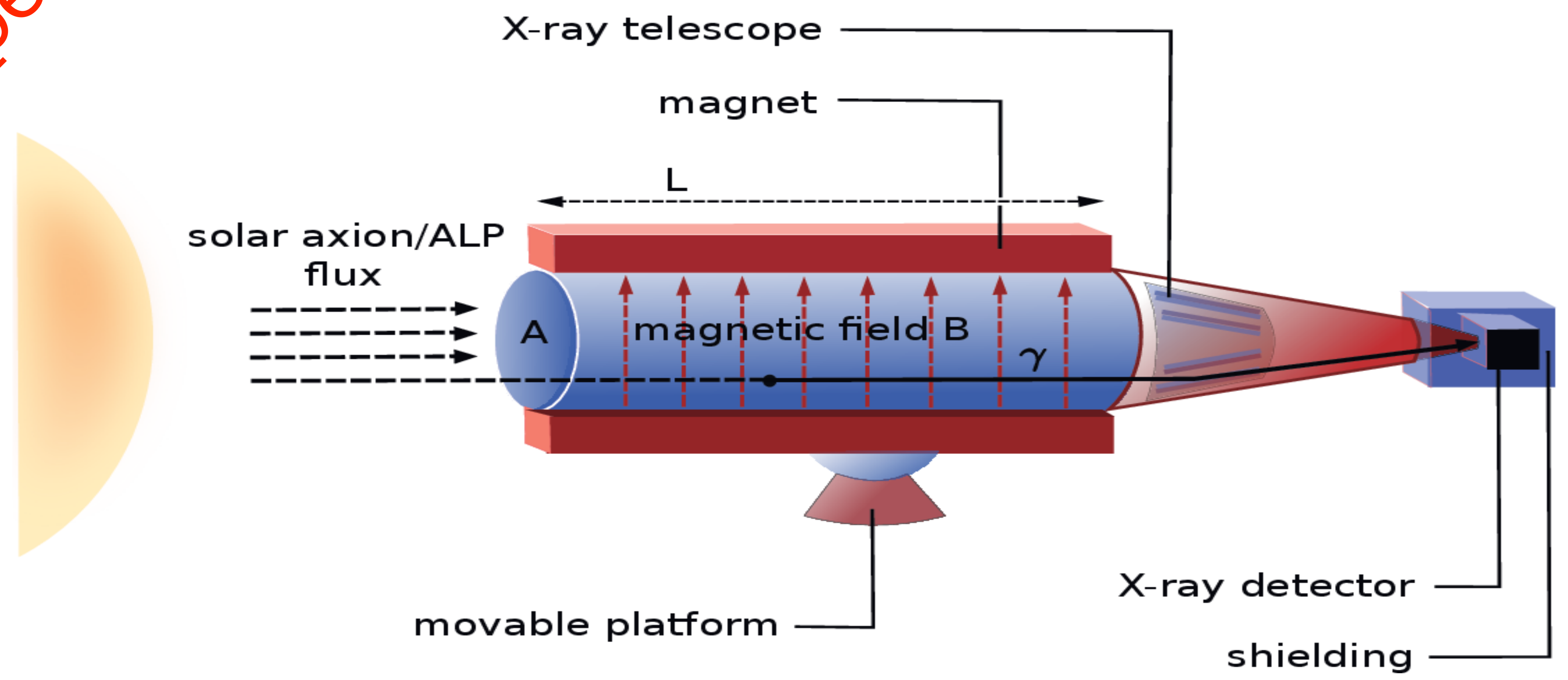
Haloscopes



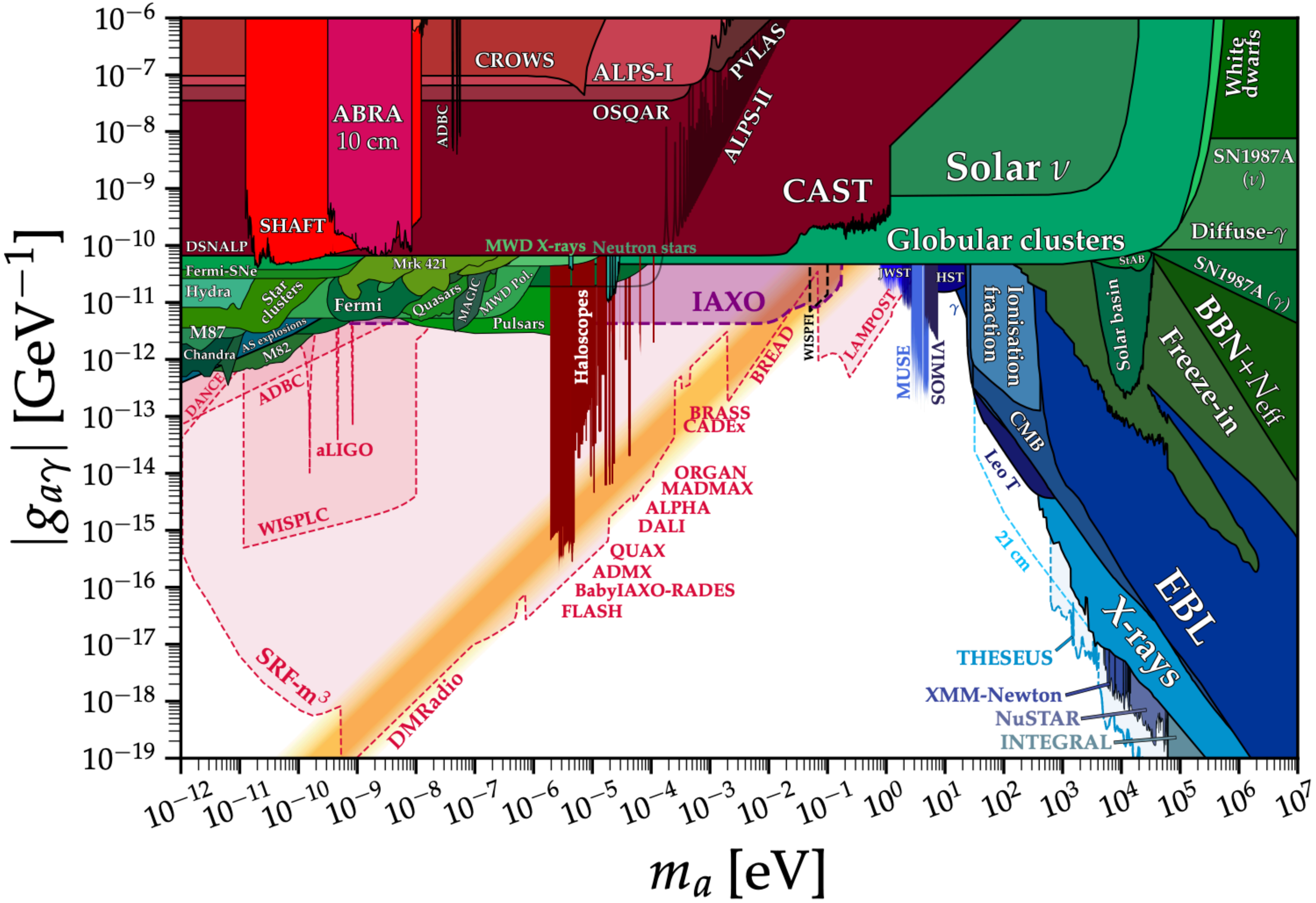
LSW



Helioscopes



Axion Searches



Many constraints on axion-photon coupling strength $g_{a\gamma}$.

- Strong overlap with quantum sensor development.

Courtesy of J. Monroe (ICHEP '24)

Conclusions

No concrete dark matter signals yet, however thanks to technology advances, direct detection searches are firmly in discovery mode!

From axions to very heavy dark matter: we are exploring dark matter candidates spanning ~40 orders of magnitude!

Liquid noble detectors lead the charge in high mass WIMP searches and will reach neutrino floor within the next decade.

- Complementarity with high energy frontier.

Cryogenic experiments provide best opportunity to observe low mass (sub-GeV) WIMPs and dark matter candidates beyond WIMP paradigm.

- New (quantum) technologies continue to drive down energy thresholds to sub-eV level: probing brand new parameter space!

Back-Up

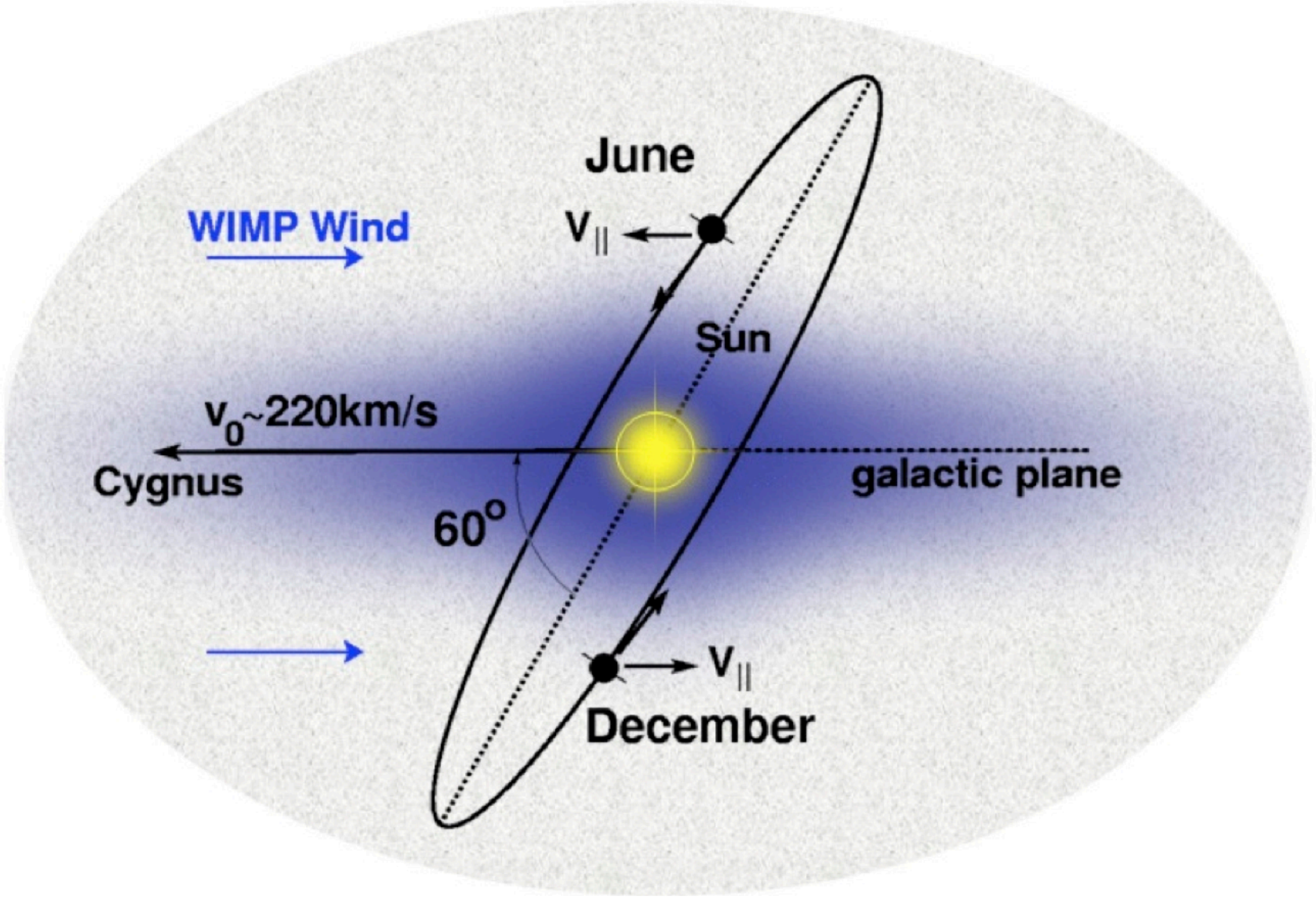
Modulation Signals

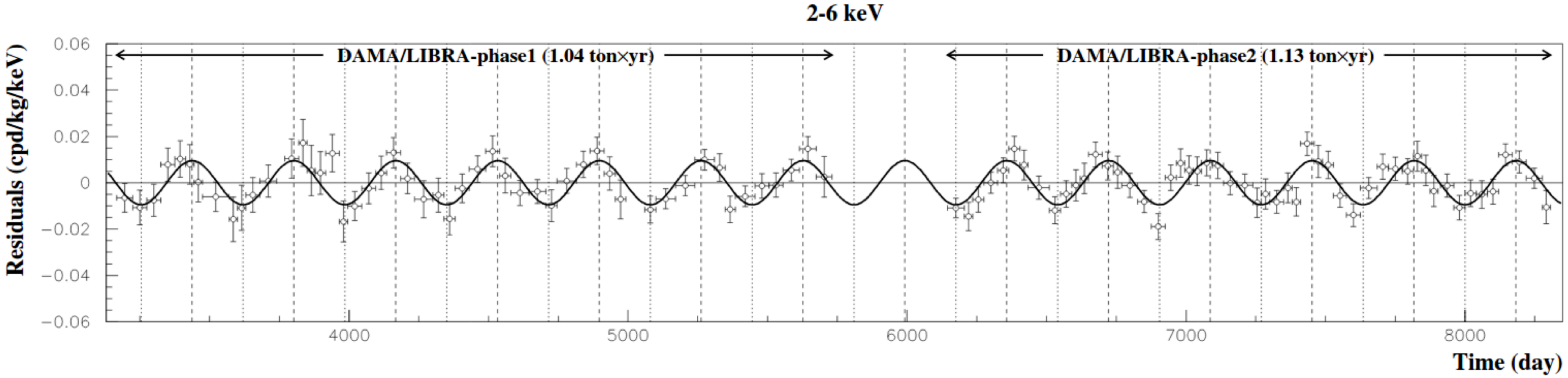
Sun moves through the Milky Way with a velocity of about v_S ~ 220 km/s: boost of dark matter velocity distribution in the laboratory frame,

- "WIMP Wind" coming from the direction of Cygnus.

The Earth moves around the Sun with a velocity of about v_E ~ 30 km/s, increasing the boost in summer and decreasing it in winter.

- Larger WIMP flux in summer compared to winter (~15% effect)





DAMA: Observes modulation, but not consistent with what is expected for DM-n scattering...