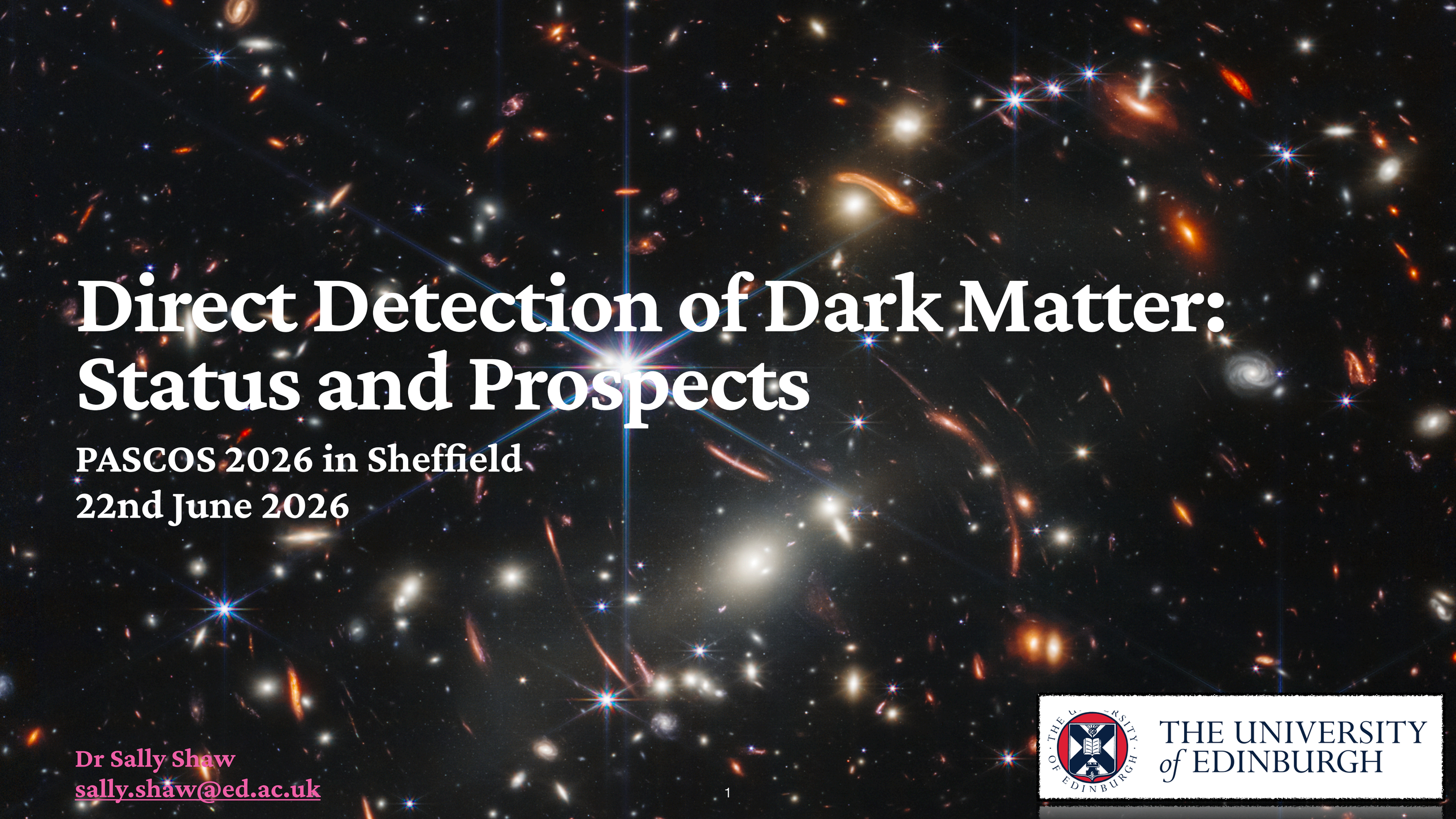
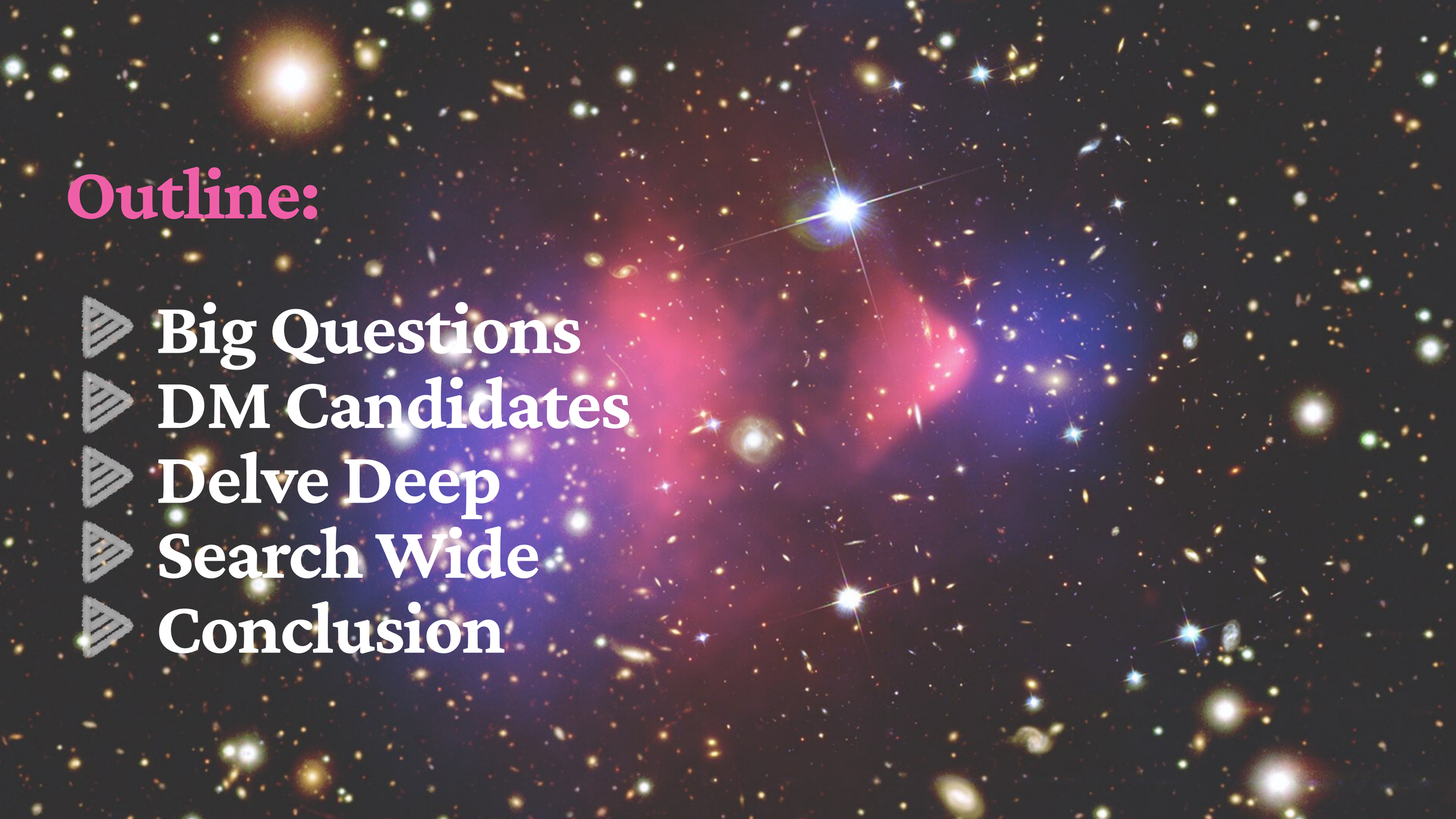


Direct Detection of Dark Matter: Status and Prospects

PASCOS 2026 in Sheffield
22nd June 2026

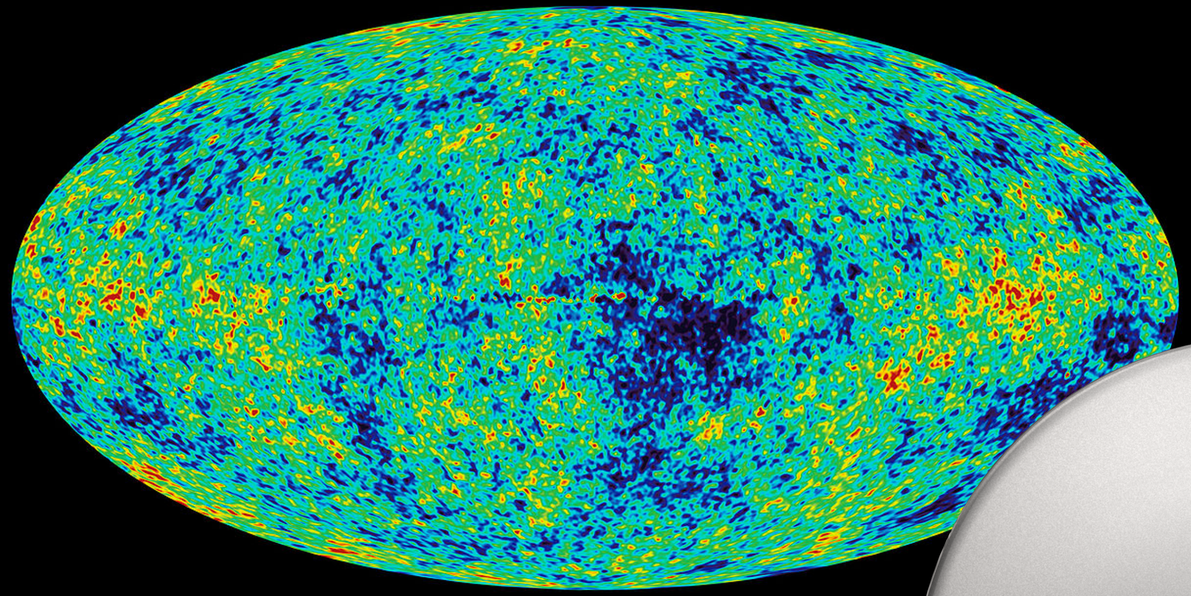
Dr Sally Shaw
sally.shaw@ed.ac.uk

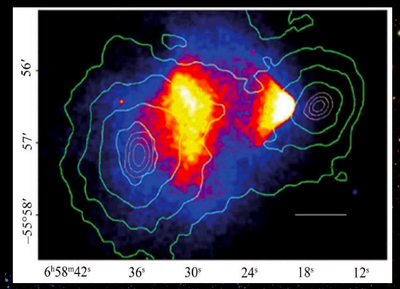
THE UNIVERSITY of EDINBURGH

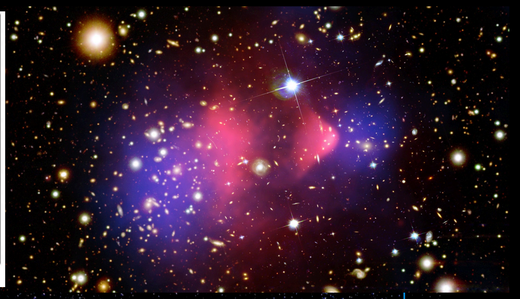


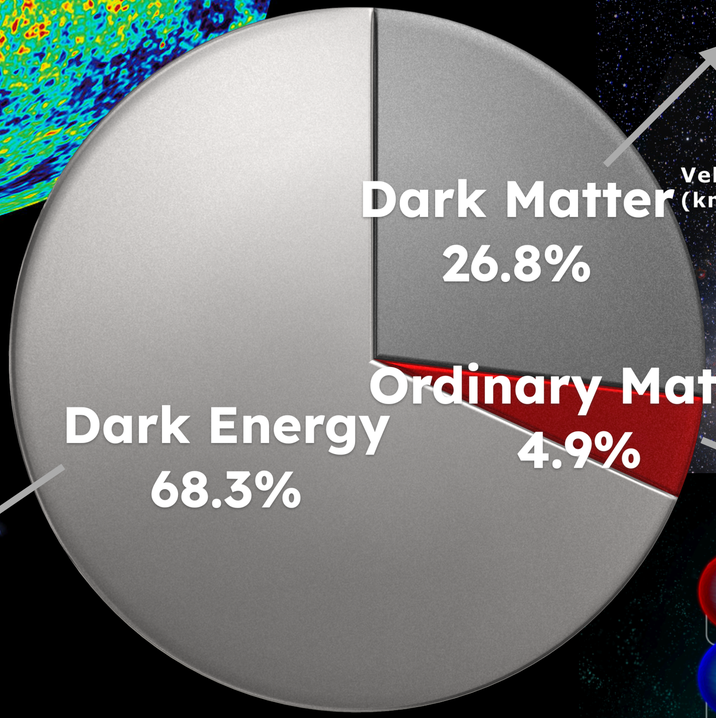
Outline:

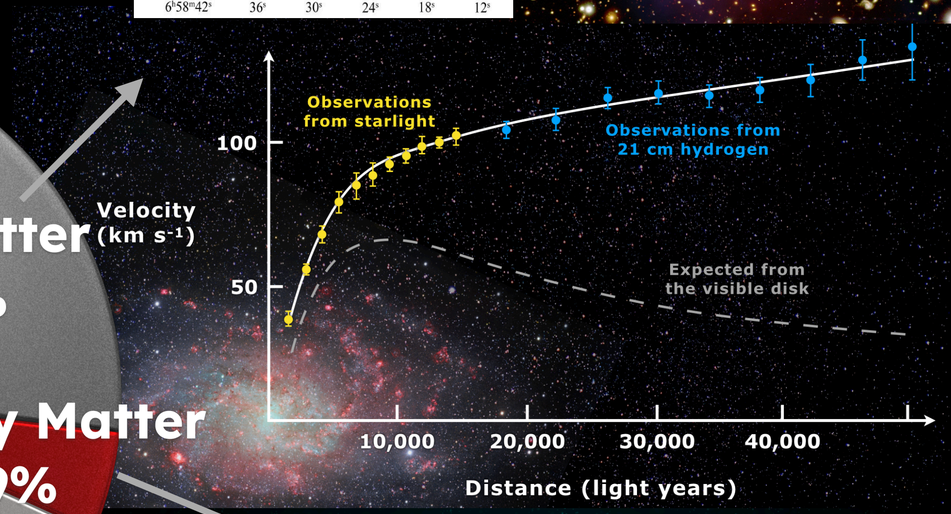
- Big Questions
- DM Candidates
- Delve Deep
- Search Wide
- Conclusion

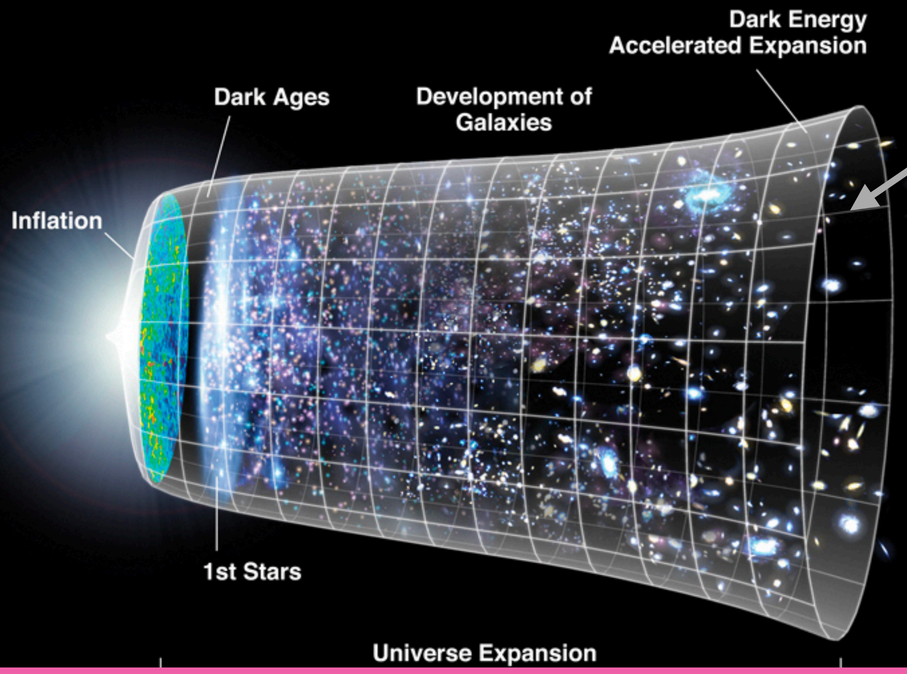


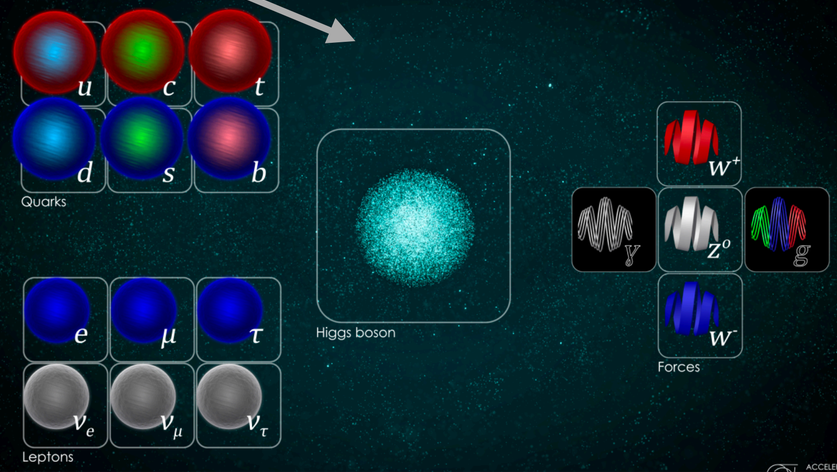












The Universe

★ Backup Slides

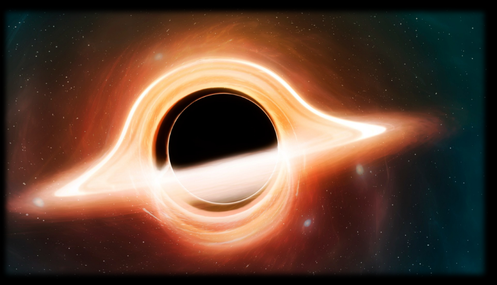
Dark Matter Big Questions

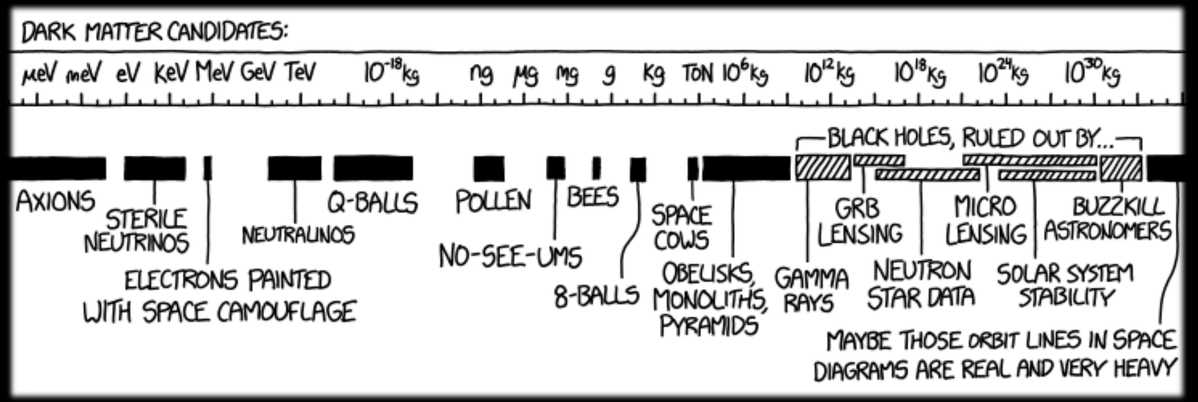
What is the nature of dark matter?

... that's kind of it.

But, in more detail:

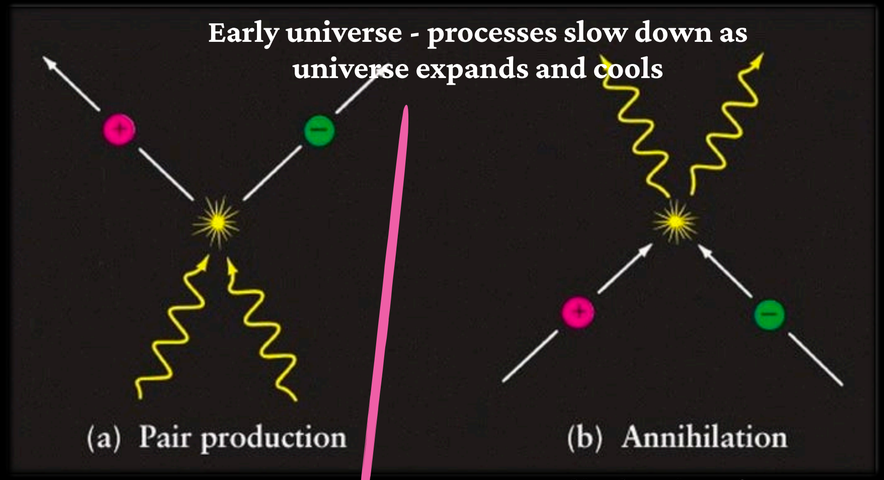
- Is it a particle?
- What are its properties?
- How does it interact?
- Is there one particle or many (a dark sector)?
- How does it explain astrophysical observations?

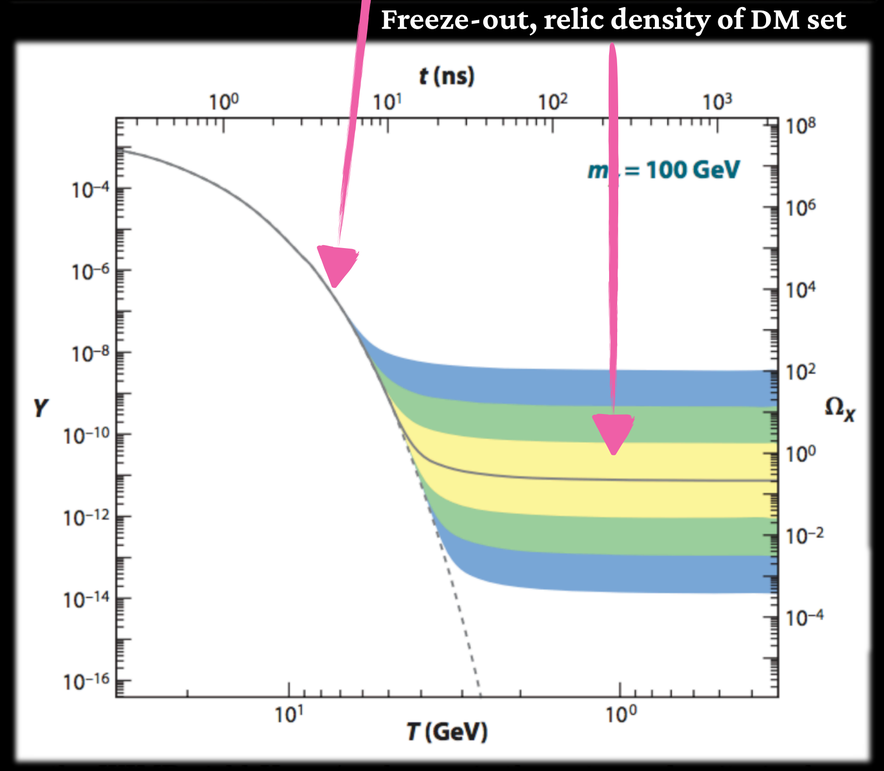




Particle Dark Matter

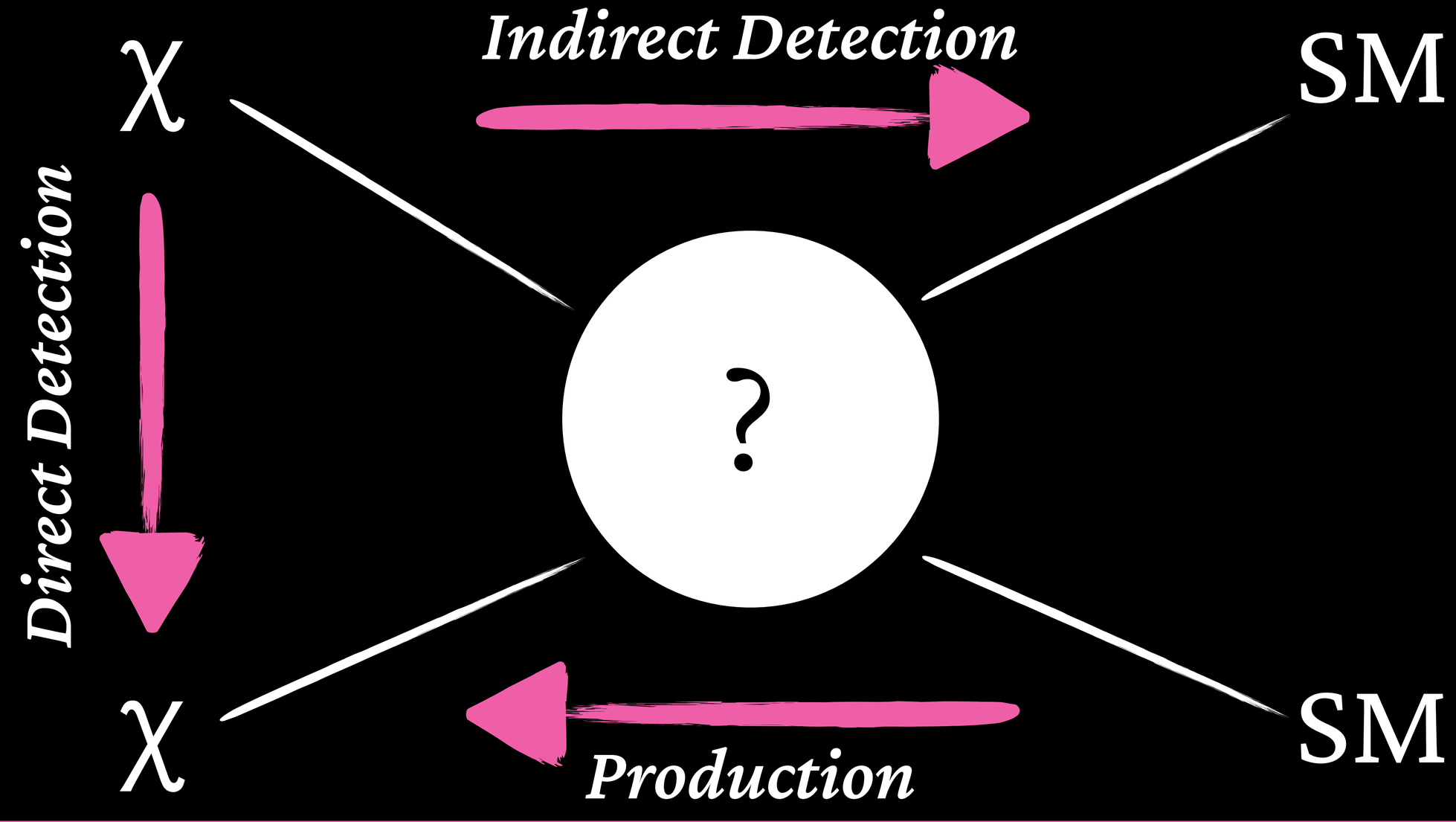
- Leading cosmology model is **ΛCDM.**
  - CDM = cold dark matter, has to be **non-baryonic, neutral, stable** (or τ >> age of universe).
- Theoretically well-motivated is the Weakly Interacting Massive Particle (WIMP).
  - ***WIMP miracle:*** measured relic abundance of DM → annihilation cross section O(weak interaction)
  - WIMPs expected to couple to the SM: *WIMP-nucleon scattering*
  - Lightest supersymmetric particle (LSP) from Supersymmetric models is an ideal candidate (e.g. neutralino)





3 ways to detect dark matter particles

Enabling discovery with a multi-faceted approach



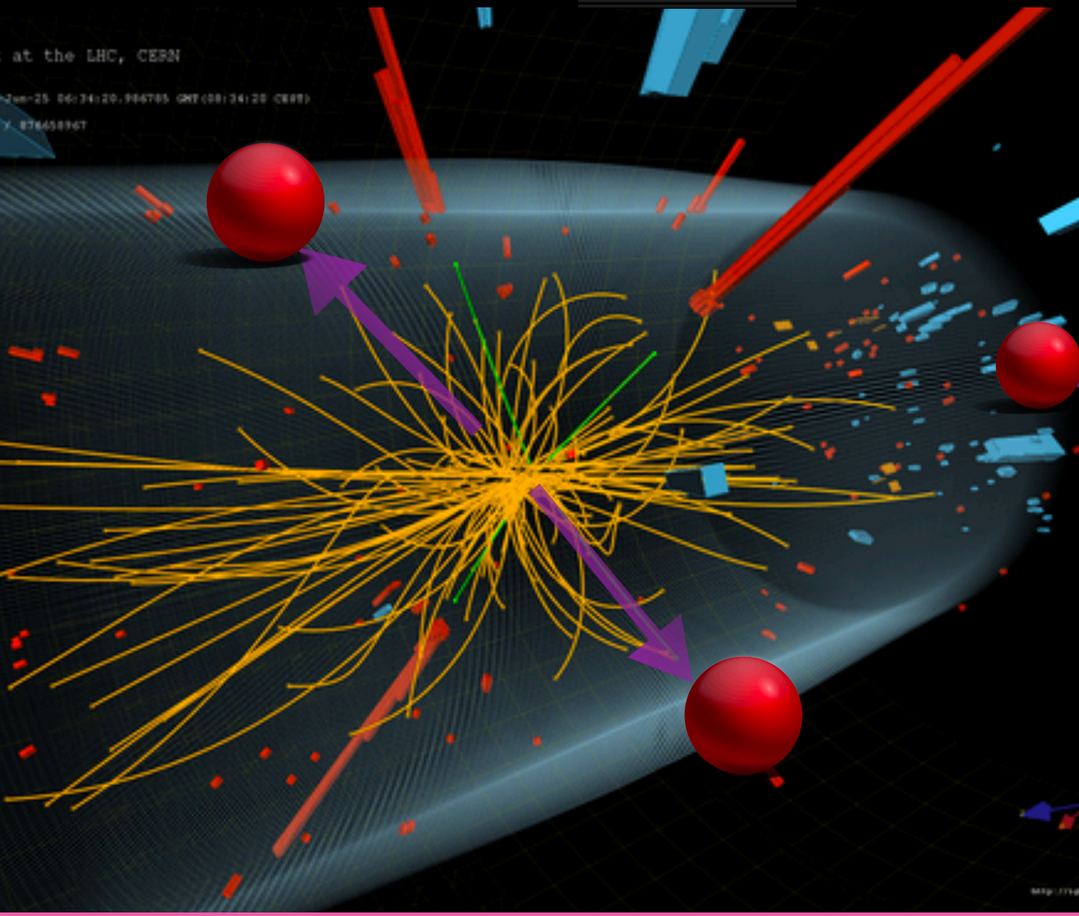
3 ways to detect dark matter particles

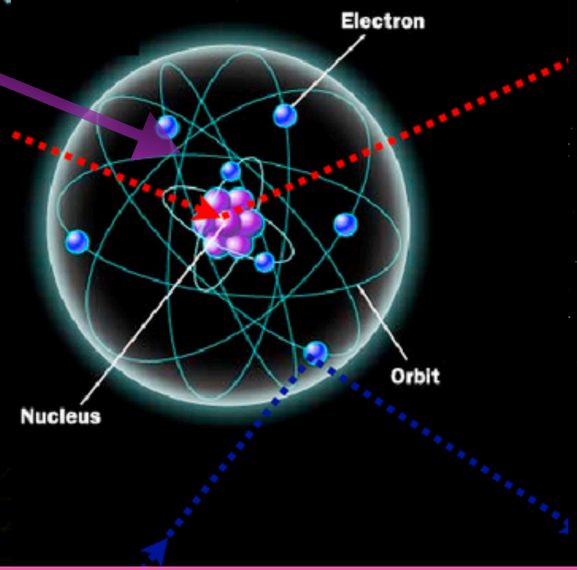
Enabling discovery with a multi-faceted approach

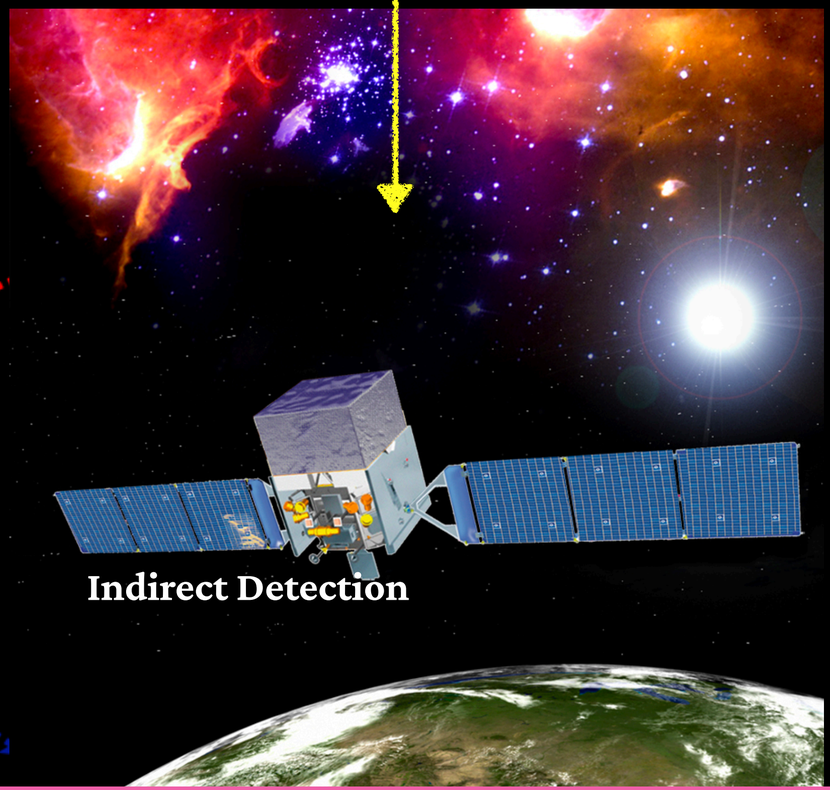
MAKE IT

SHAKE IT

BREAK IT



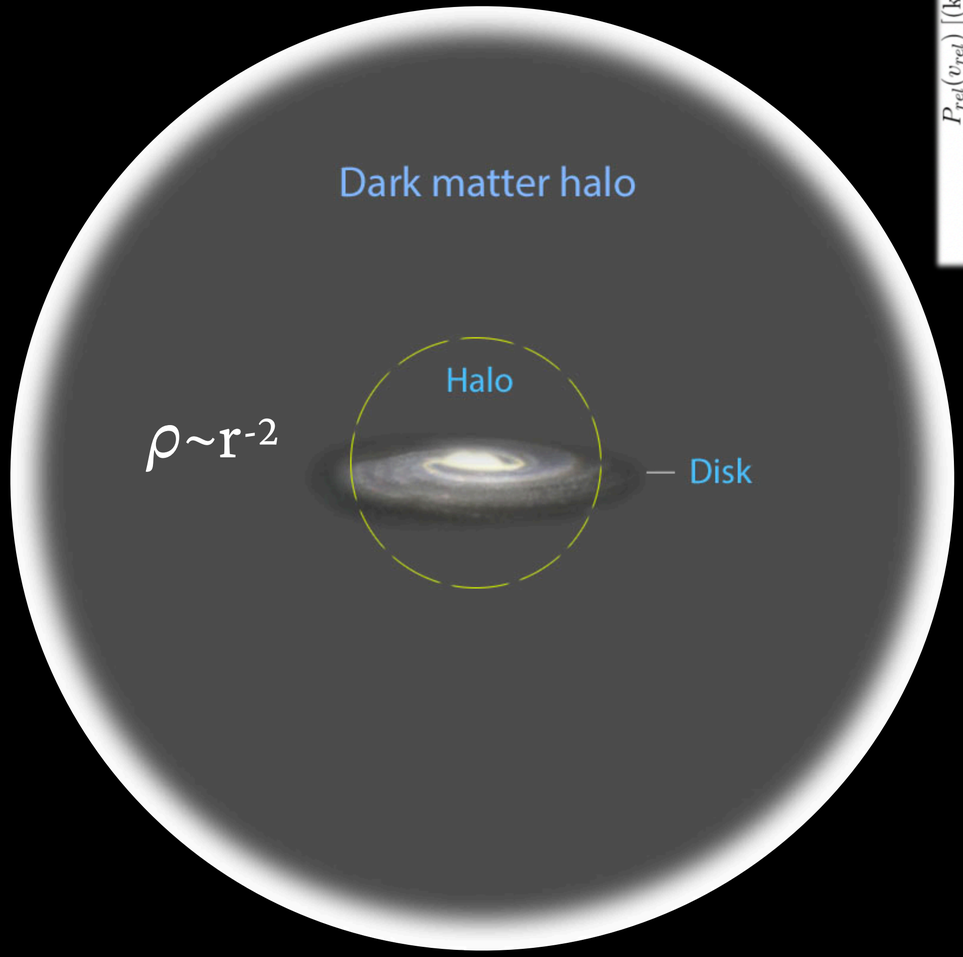


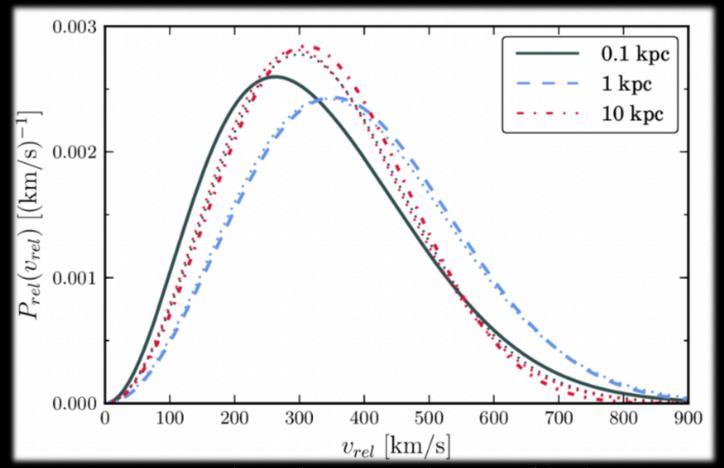


Indirect Detection

Direct Detection

Dark matter exists in a **halo** extending far beyond the visible boundaries of the galaxy





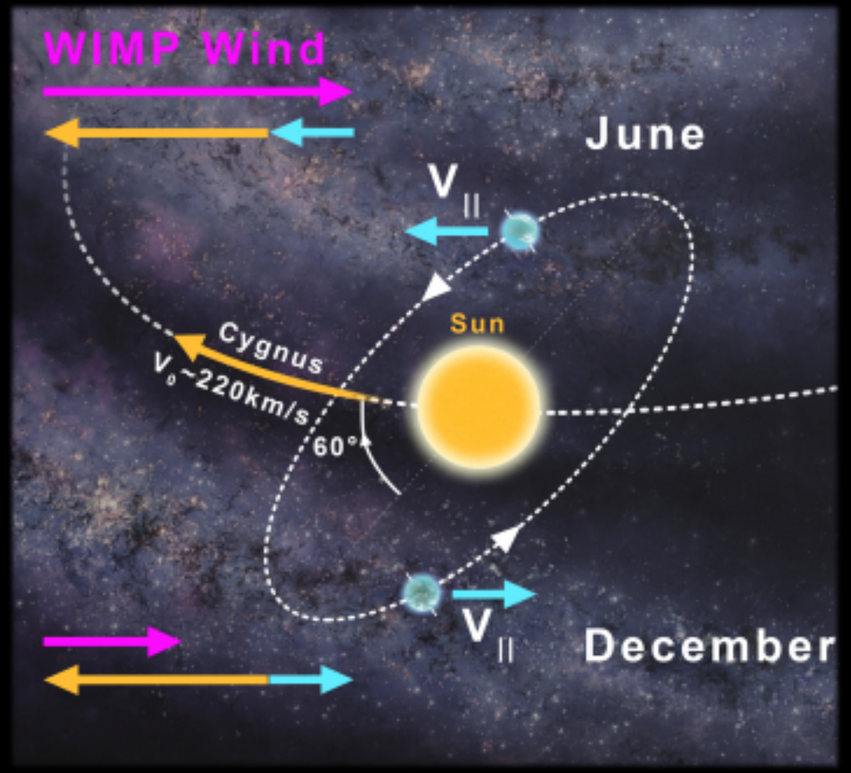
Francesc Ferrer and Daniel R. Hunter, *The impact of the phase-space density on the indirect detection of dark matter*, JCAP09(2013)005

Dark matter follows a **velocity distribution** within the halo (in the Galactic frame) with a maximum velocity of v_{esc}

In Earth's frame, see an **annual modulation.** DM has a higher relative v in June than Dec

→ more likely to be above threshold

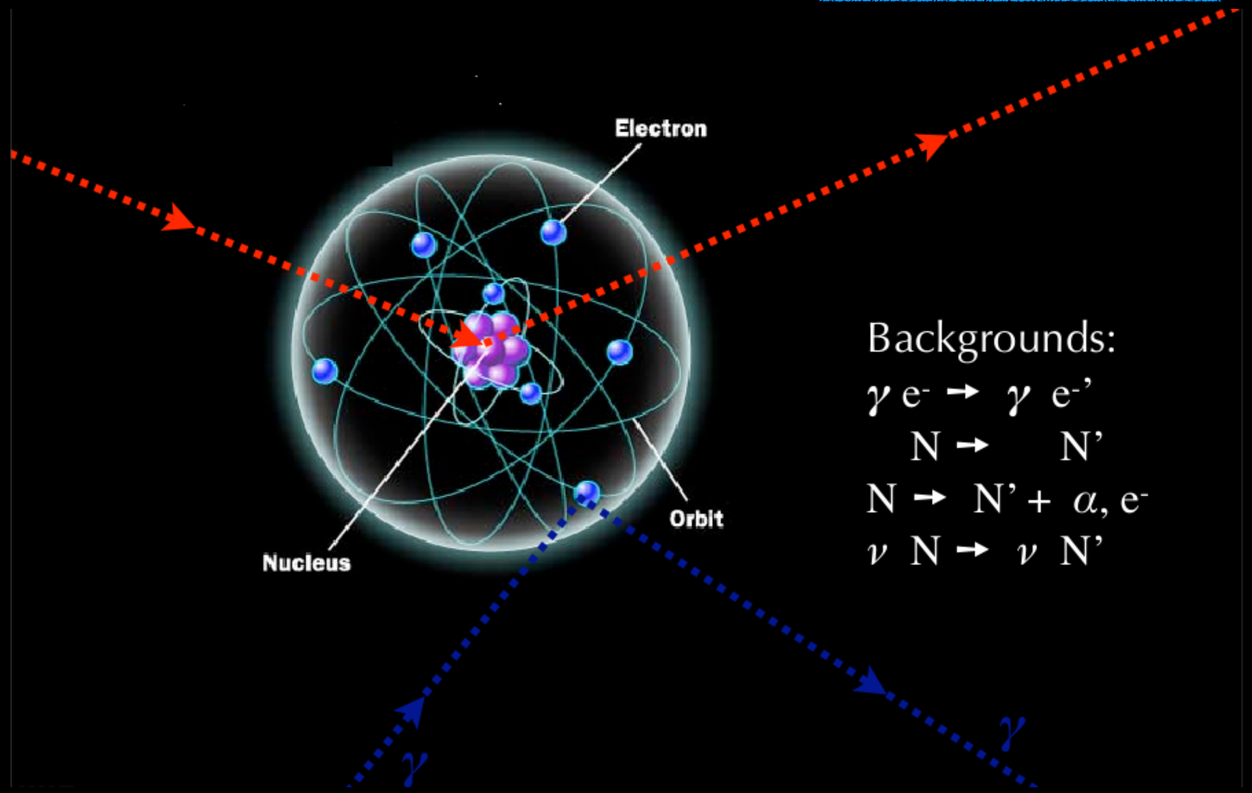
→ peak rate in June, minimum in Dec



Direct Detection

detector exposure | **particle + nuclear physics** | **astrophysics**

$$\frac{dN}{dE_R} = \epsilon \frac{\rho}{2m_\chi \mu_{\chi N}} \sigma_0 F^2(E_R) \int_{v_{min}} \frac{f(\bar{v})}{v} d^3v$$



Backgrounds:

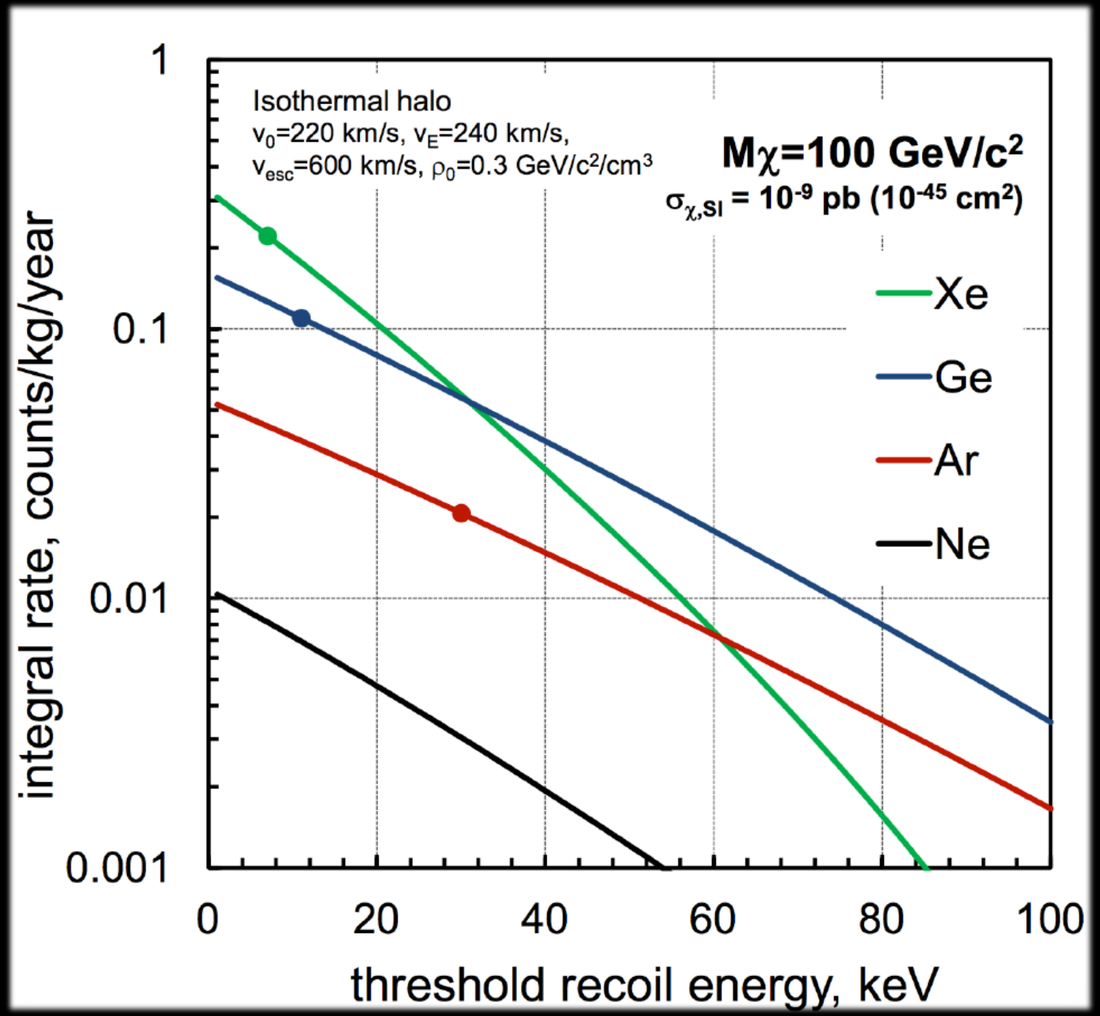
γ e$^-$ → γ e$^-$'

N → N'

N → N' + α, e$^-$

ν N → ν N'

DM ν translated to recoil energy in DM-scattering, get an **exponentially falling rate** → threshold very important



V. Chepel and H. Araujo, *Liquid noble gas detectors for low energy particle physics*, Journal of Instrumentation 8(04), R04001 (2013)

WIMP Dark Matter

An undergrad student I taught:

*"Given this paper 'Supersymmetric Dark Matter' by Jungman, Kamionkowski and Griest is **older than me,** I'm wondering if the current state of the field is one that still favours WIMPs as one of the main focuses of detection efforts."*

WIMP Dark Matter

"Given th *ungman,*
Kamionk *dering if*
the curre *IMPs as*

FORBES > INNOVATION > SCIENCE

The 'WIMP Miracle' Hope For Dark Matter Is Dead

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group ⓘ

Follow

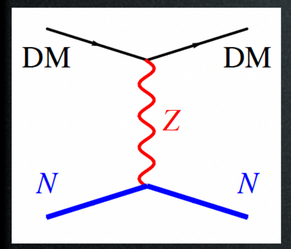
Feb 22, 2019, 02:00am EST

WIMP Dark Matter

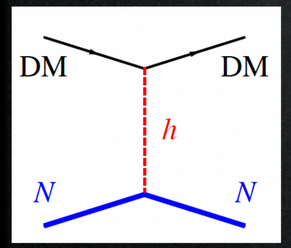
Simplest models ruled out but WIMP models survive through more complex diagrams & effective field theories

Dark Matter candidates circa 2026: the WIMPs and beyond the WIMPs
Marco Cirelli - IDM 2026

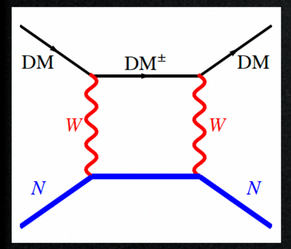
SM weak scale SI interactions



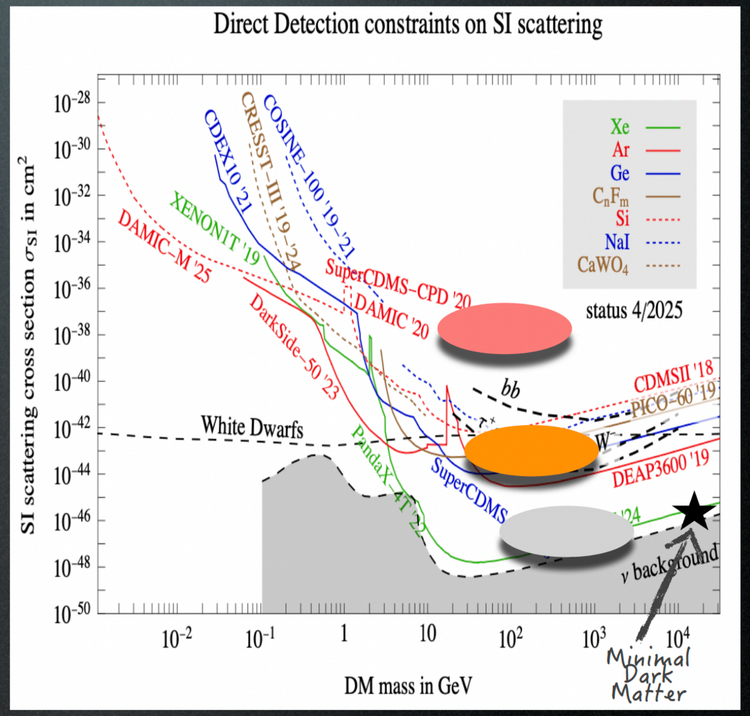
tree level, vector



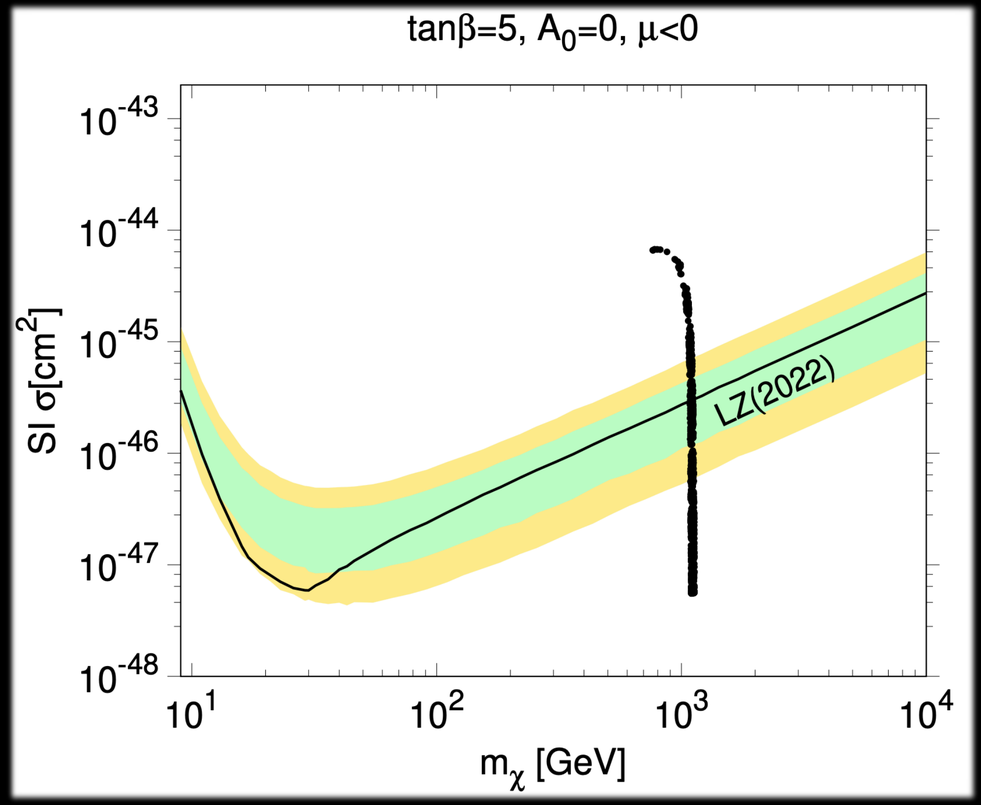
tree level, scalar



one loop



M. Cirelli, A. Strumia, J. Zupan 'Dark Matter', 2406.01705



"Most of the surviving CMSSM parameter space features a **Higgsino-like dark matter particle** with a **mass ~1000–1100 GeV**, which could best be probed with future direct searches for dark matter scattering."

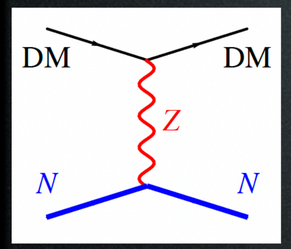
The CMSSM Survives Planck, the LHC, LUX-ZEPLIN, Fermi-LAT, H.E.S.S. and IceCube
Ellis, Olive, Spanos, Stamou
arXiv:2210.16337

WIMP Dark Matter

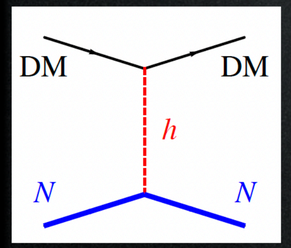
Simplest models ruled out but WIMP models survive through more complex

Dark Matter candidates cir
Mar

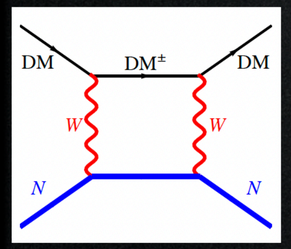
SM weak sc



tree level, vector

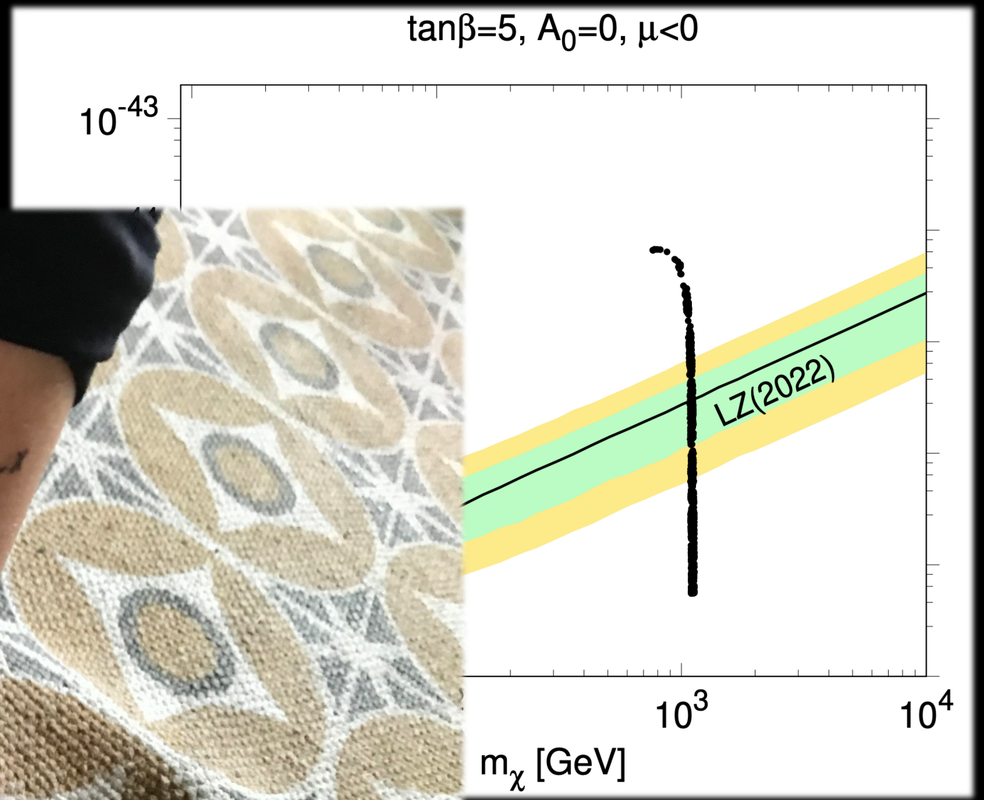


tree level, scalar



one loop

M. Cirelli, A. Strumia, J. Zupan 'Dark Matter', 2406.01705



CMSSM parameter space
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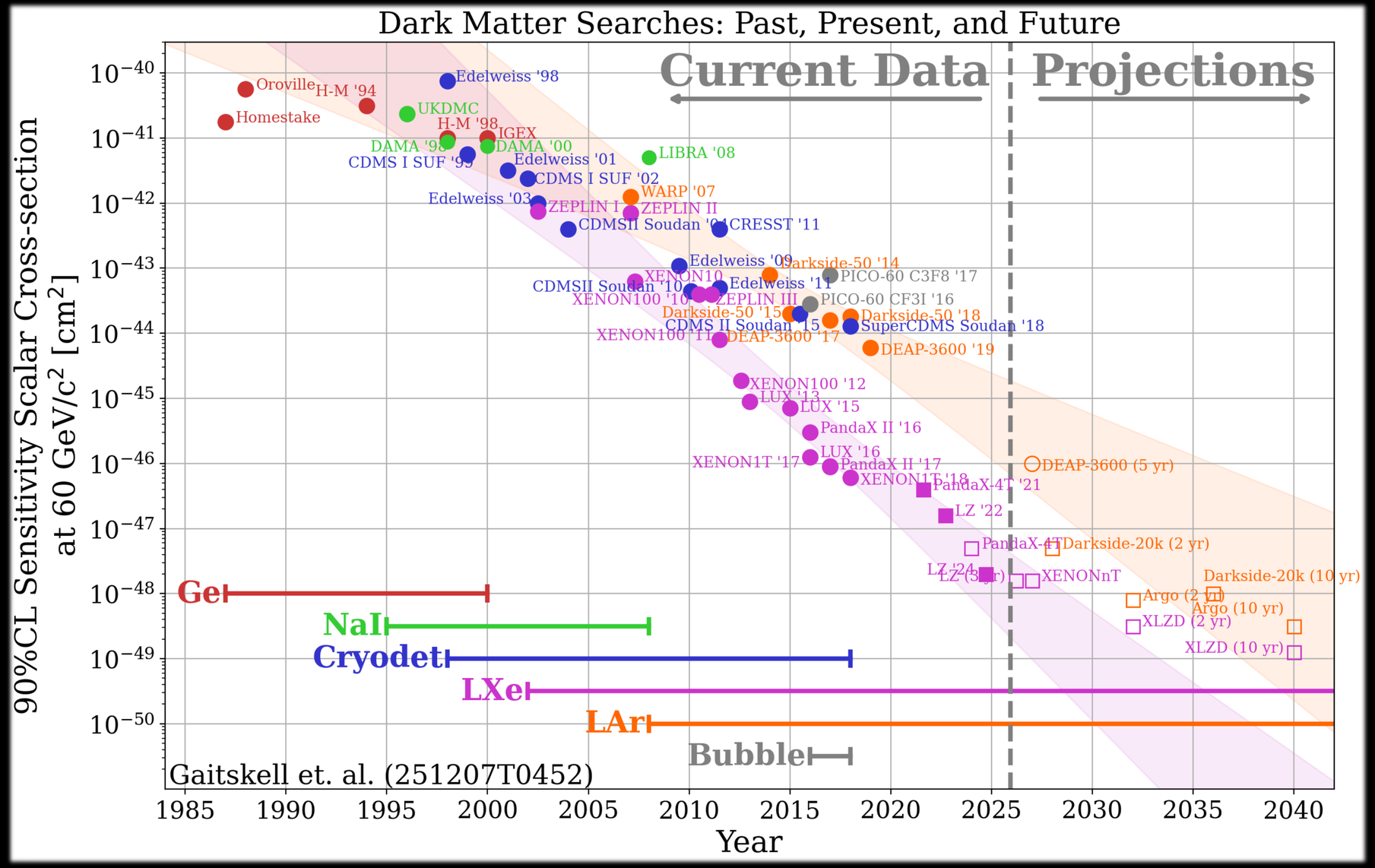
scattering."

LHC, LUX-ZEPLIN, Fermi-LAT, H.E.S.S.
d IceCube
e, Spanos, Stamou
arXiv:2210.16337

WIMP-Nucleon Cross Section Evolution

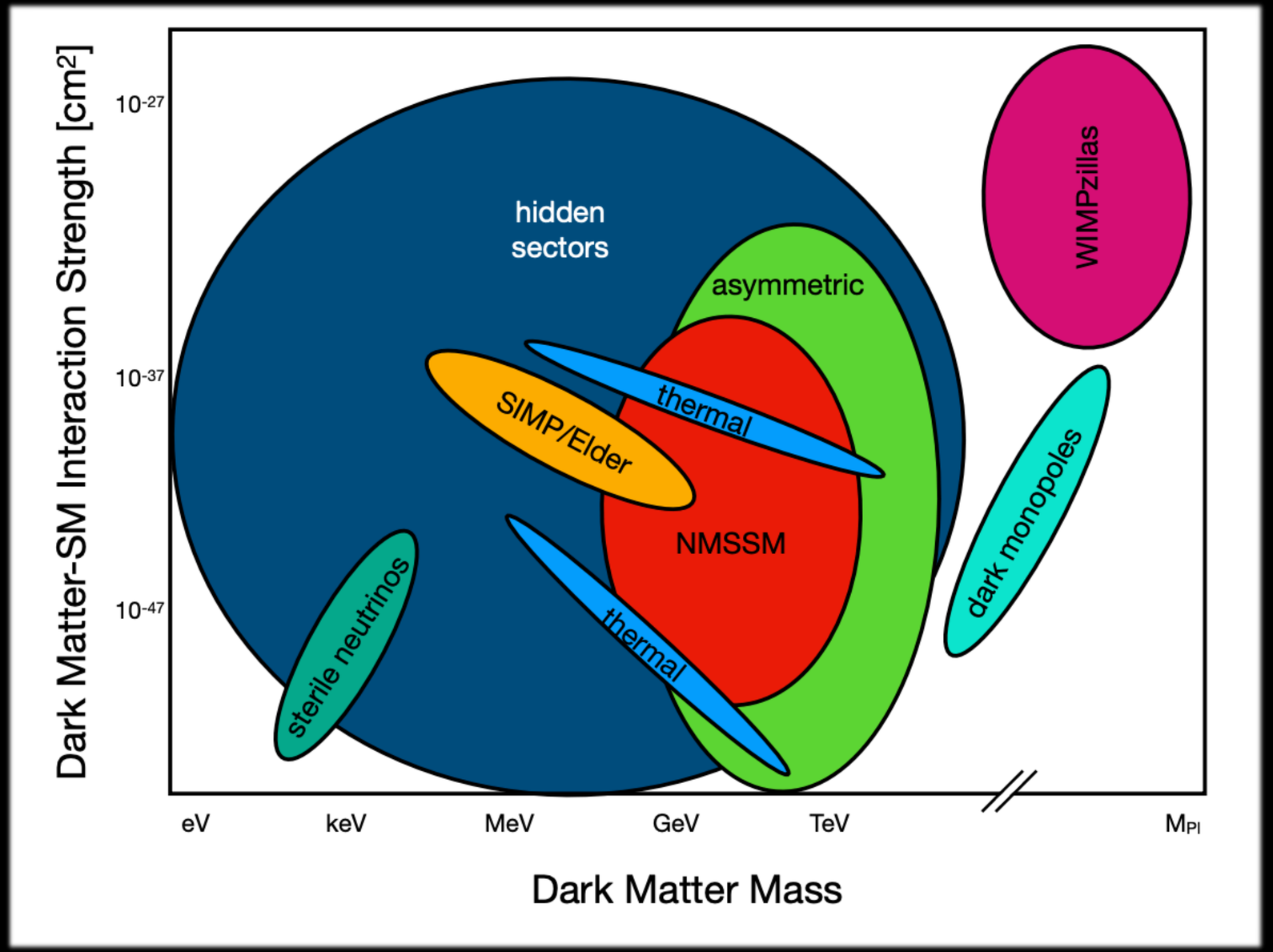


R.J.Gaitskell, "Direct Detection of Dark Matter", Annu. Rev. Nucl. and Part. Sci. 54 (2004) 315-359 (updated by R.J. Gaitskell et al., Private Communication, 2025)

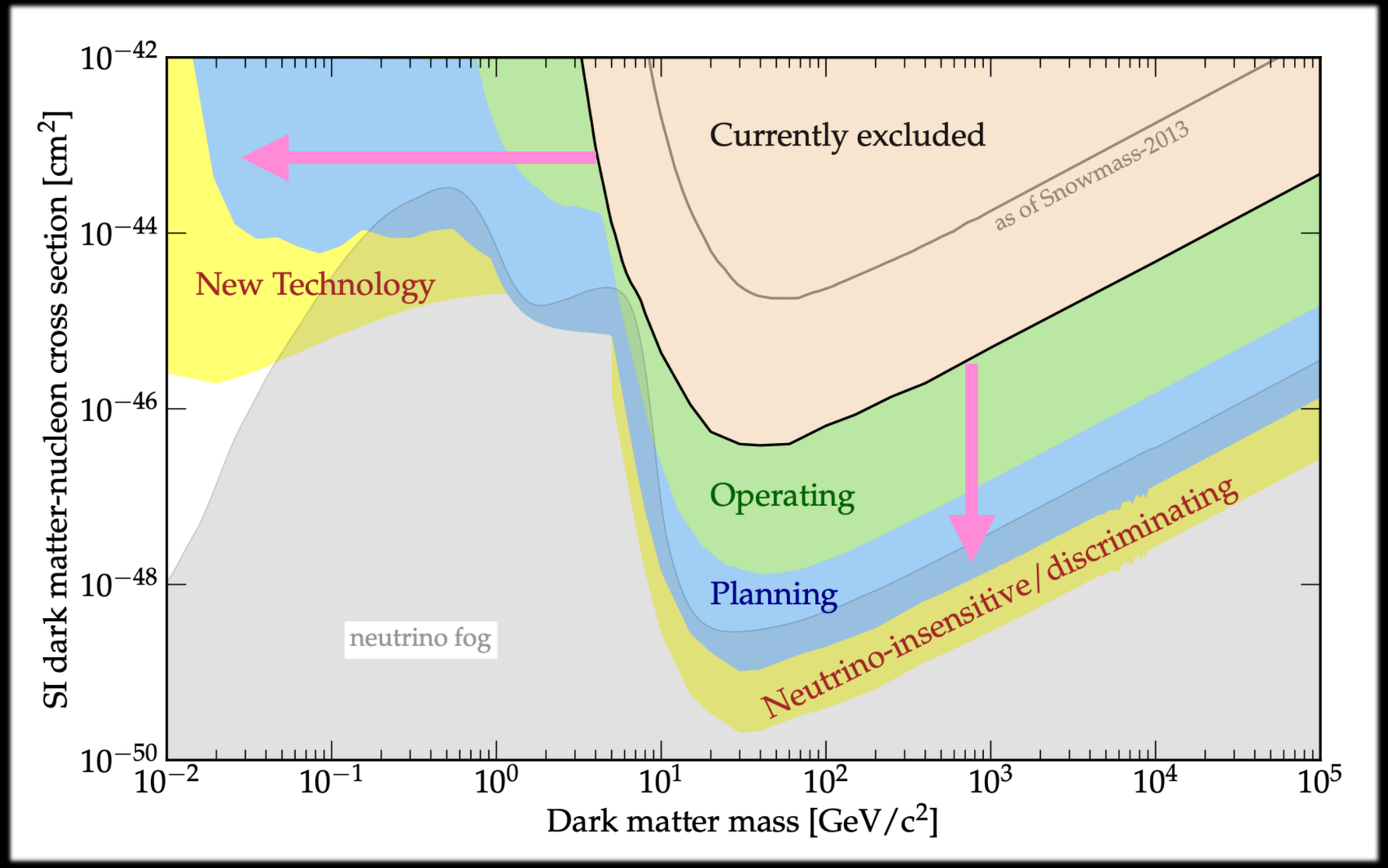
Dark Matter Candidates

- Many, many candidates beyond “vanilla WIMPs”...
- Experiments to detect DM have an enormous range of masses to cover
- Current experiments are **not sensitive** to many candidates at either ends of the mass range
- Need to “***delve deep and search wide***”

Report of the Topical Group on Particle Dark Matter for Snowmass 2021
arXiv:2209.07426

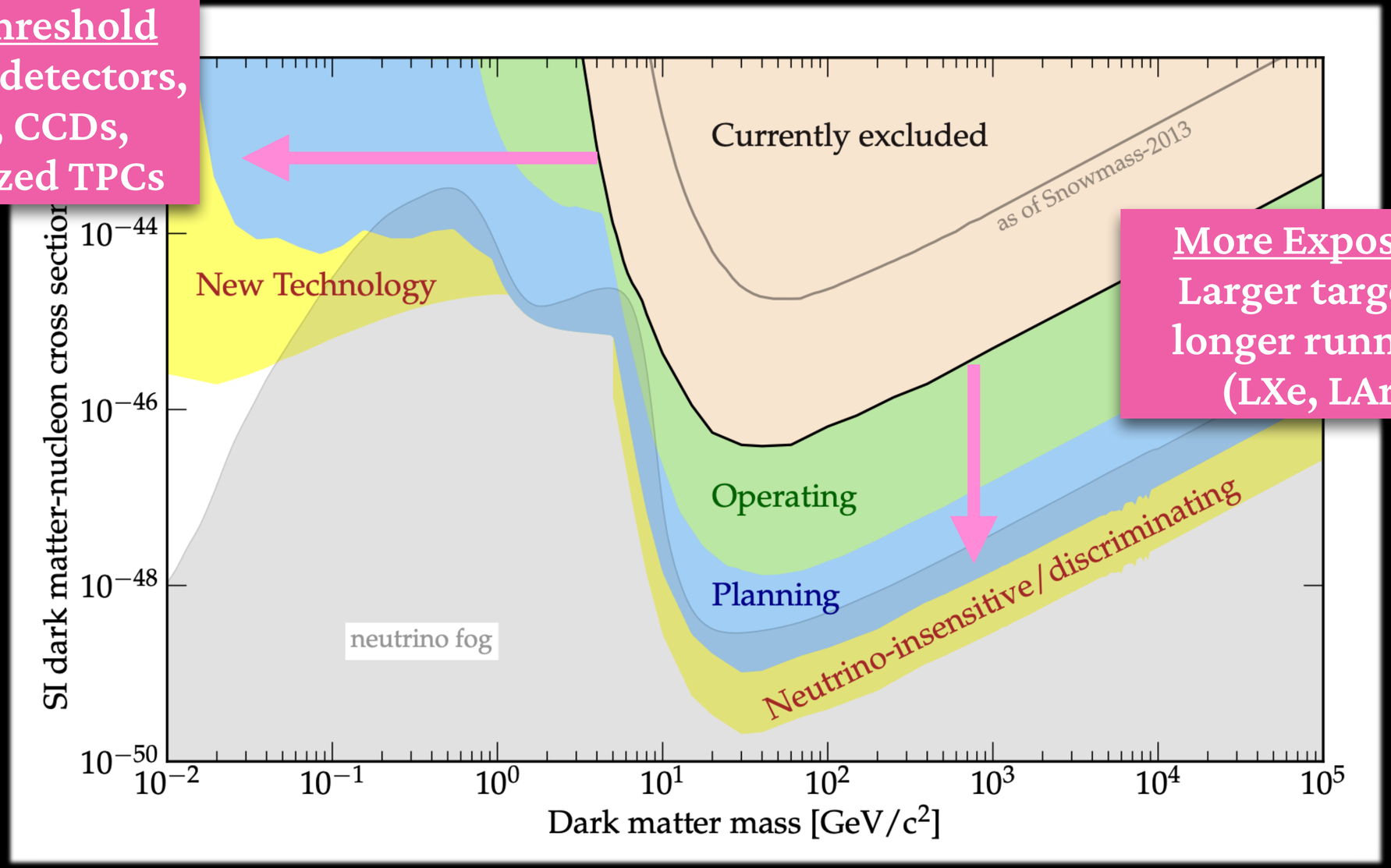


Delve Deep & Search Wide



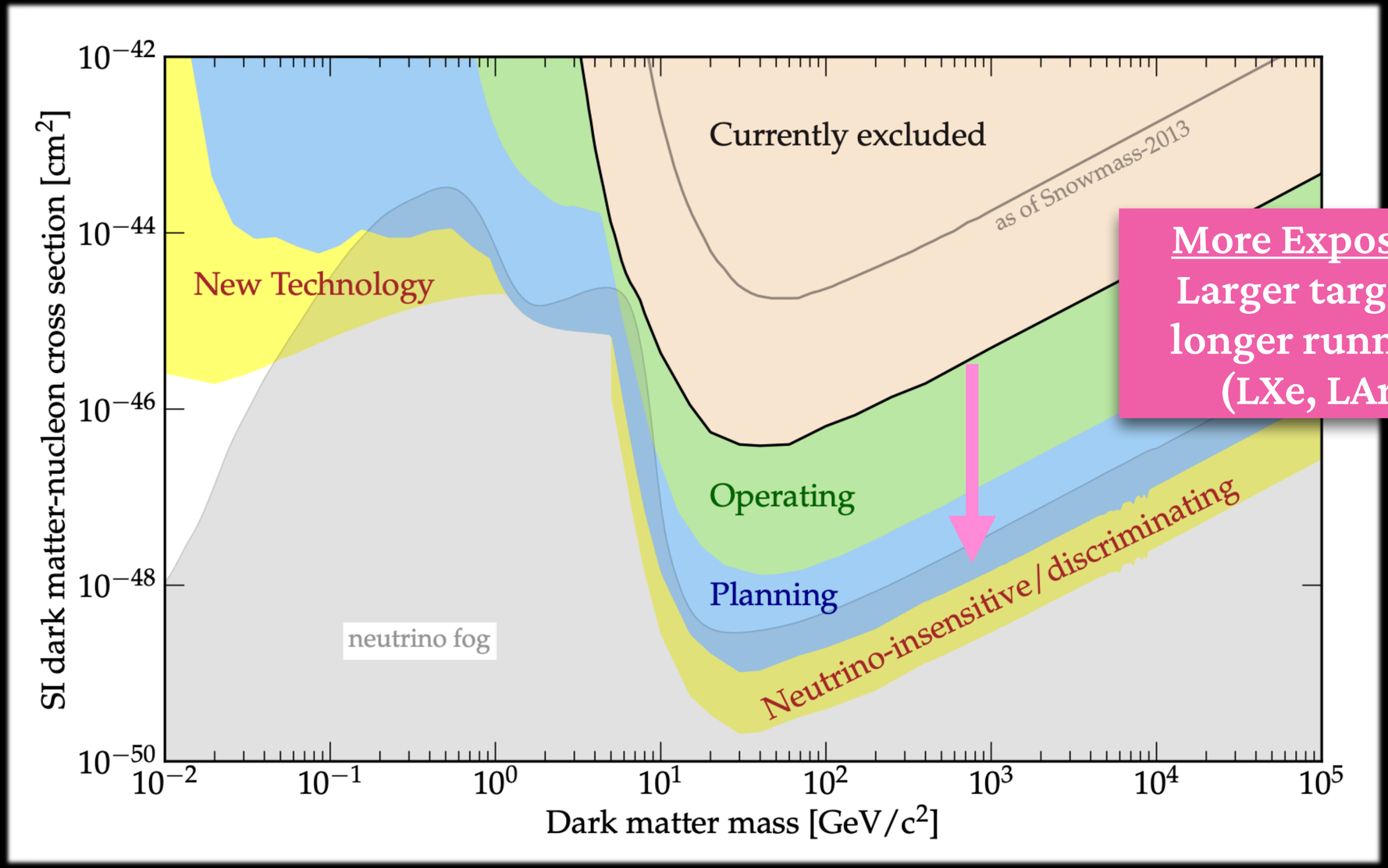
Delve Deep & Search Wide

Low Threshold
Phonon detectors, SPCs, CCDs, optimized TPCs



More Exposure
Larger targets, longer running (LXe, LAr)

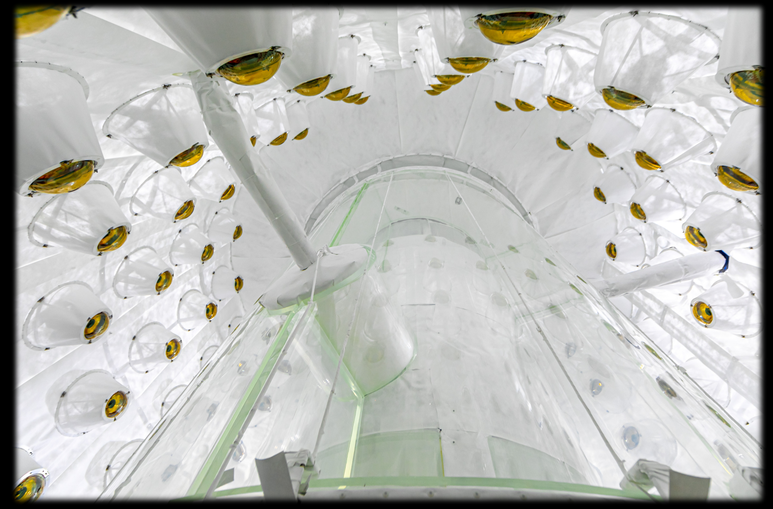
Delve Deep

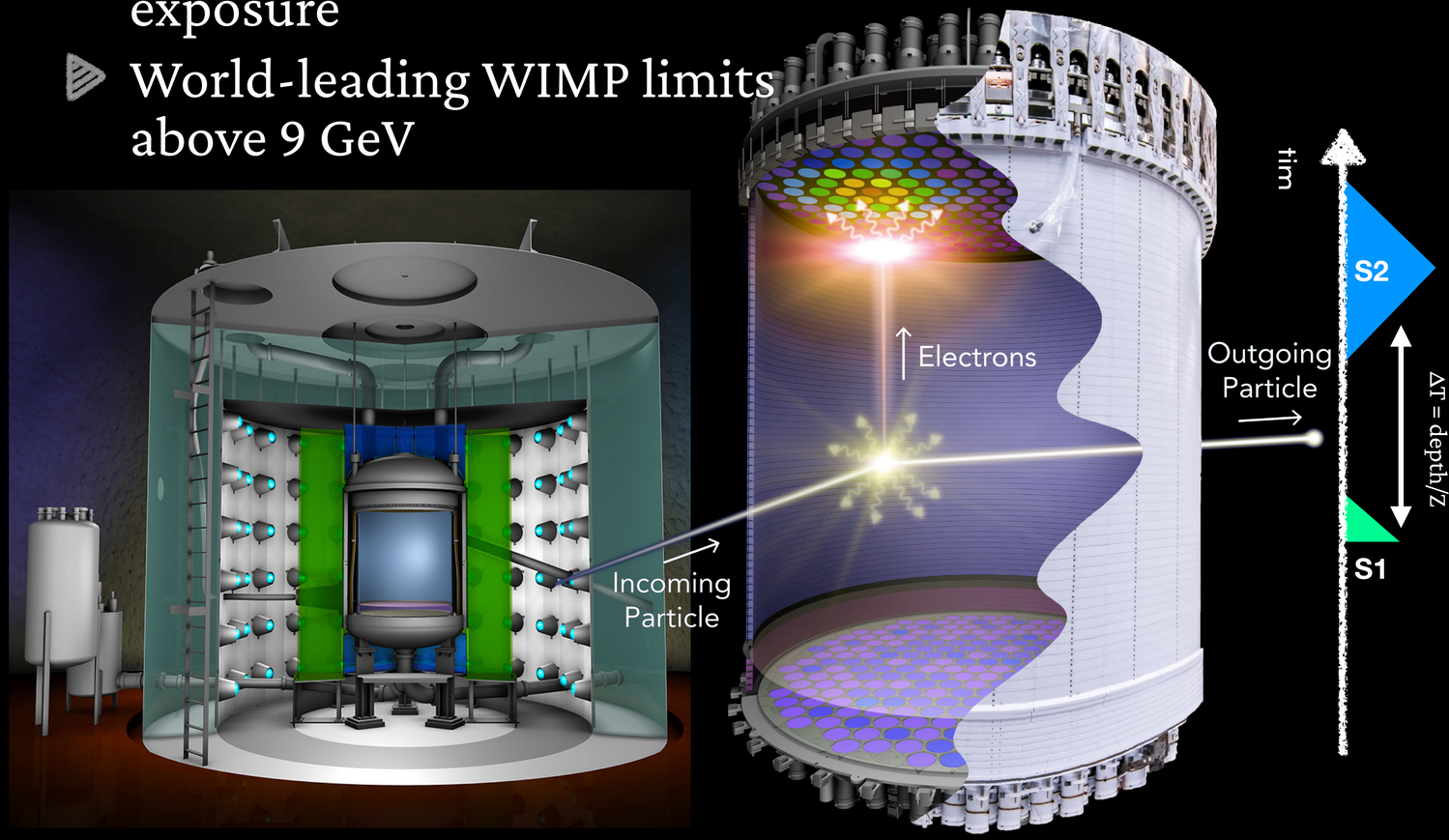


More Exposure
Larger targets, longer running (LXe, LAr)

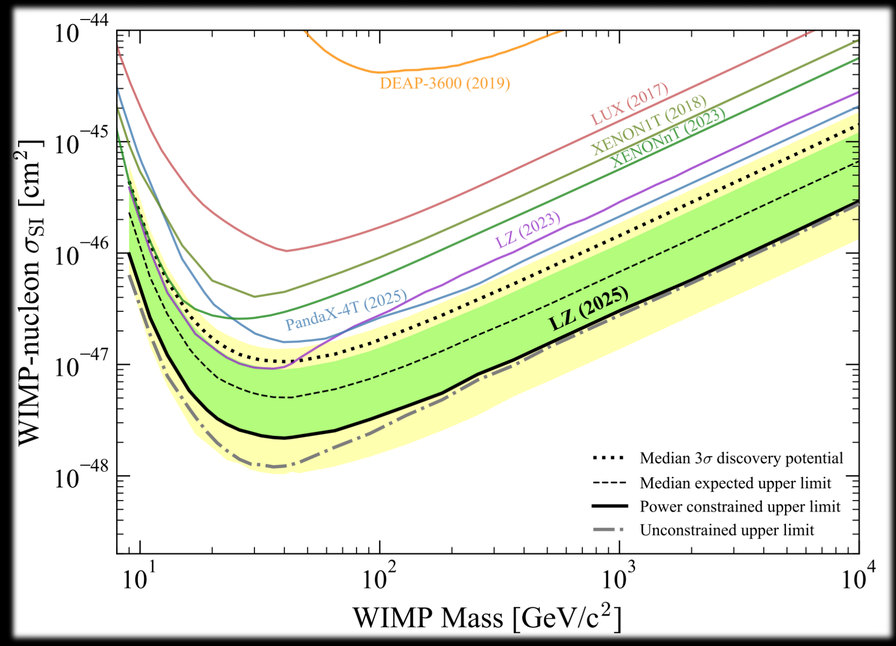
LZ

- Dual-phase **LXe TPC**, 7T target at Sanford Underground Research Facility (SURF) in South Dakota
- 17T GdLS Outer Detector & 2T instrumented LXe skin
- Operating since 2021, 2025 results used 4.2 tonne-year exposure
- World-leading WIMP limits above 9 GeV





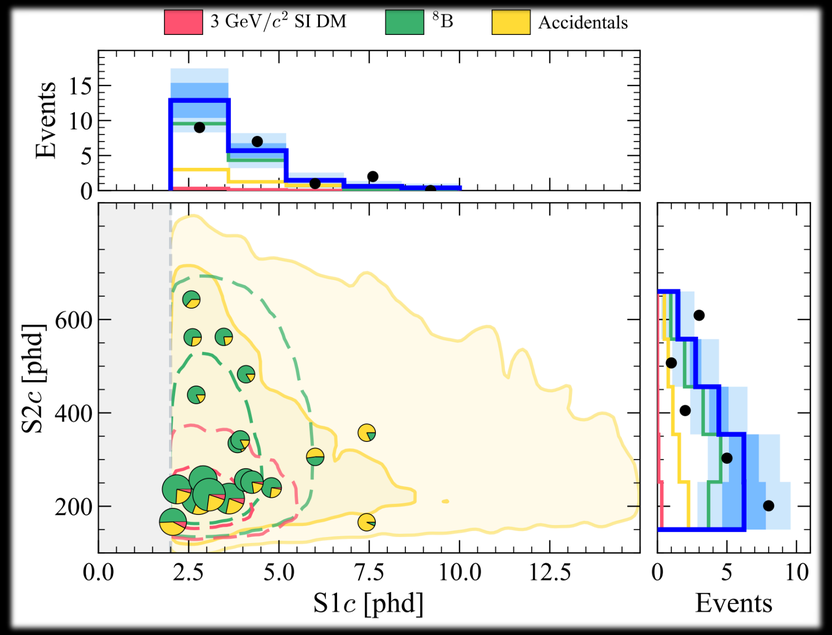
Dark Matter Search Results from 4.2 Tonne-Years of Exposure of the LUX-ZEPLIN (LZ) Experiment
J. Aalbers et al, Phys. Rev. Lett. ***135****, 011802 (2025)*

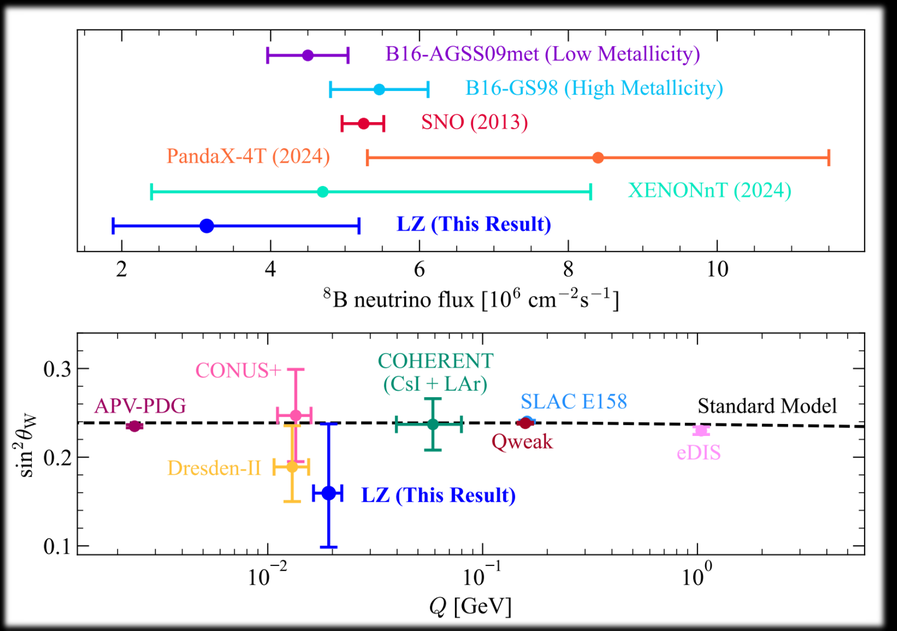


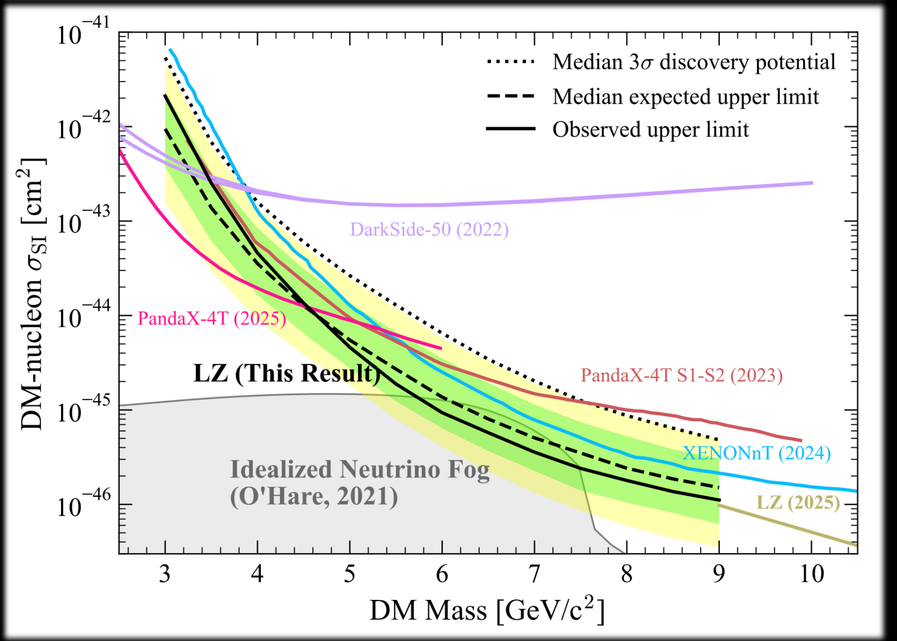
LZ

- New results focus on low energy region of interest **1-6 keVee**
- First evidence **(4.5σ)** of **coherent neutrino-nuclear scattering (CEνNS) on Xe** from **Boron-8** solar neutrinos
- New low mass constraints between 3 - 9 GeV
- LZ continues to operate and take data towards a 1000 day dataset by end of 2027

Searches for Light Dark Matter and Evidence of Coherent Elastic Neutrino-Nucleus Scattering of Solar Neutrinos with the LZ Experiment
D.S. Akerib et al, aeXiv:2512.08065

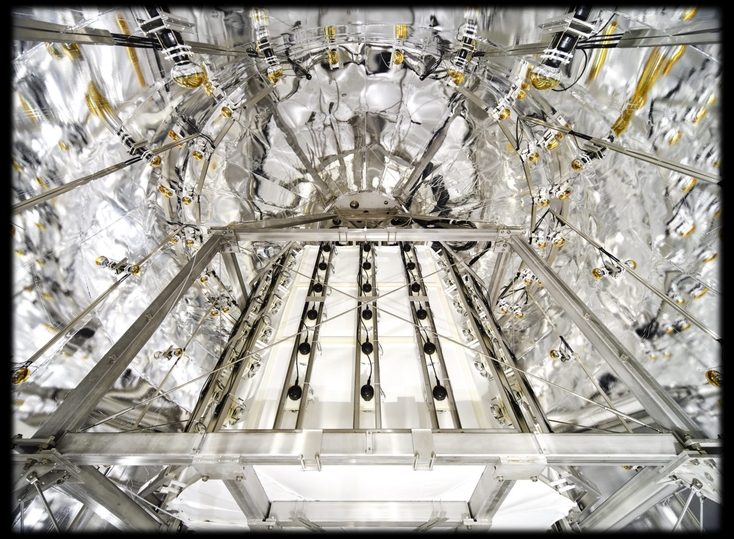


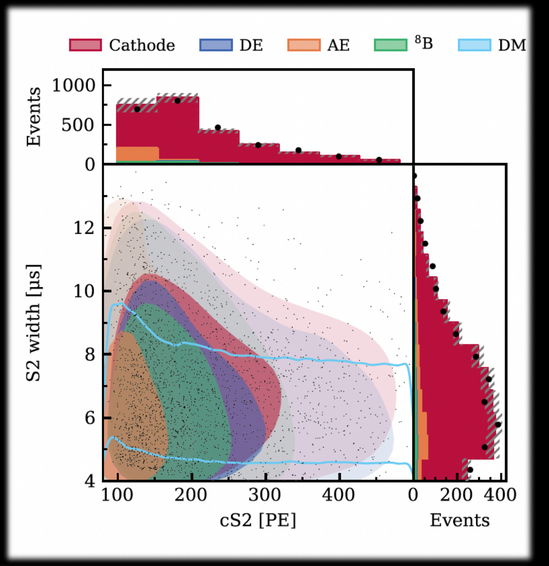


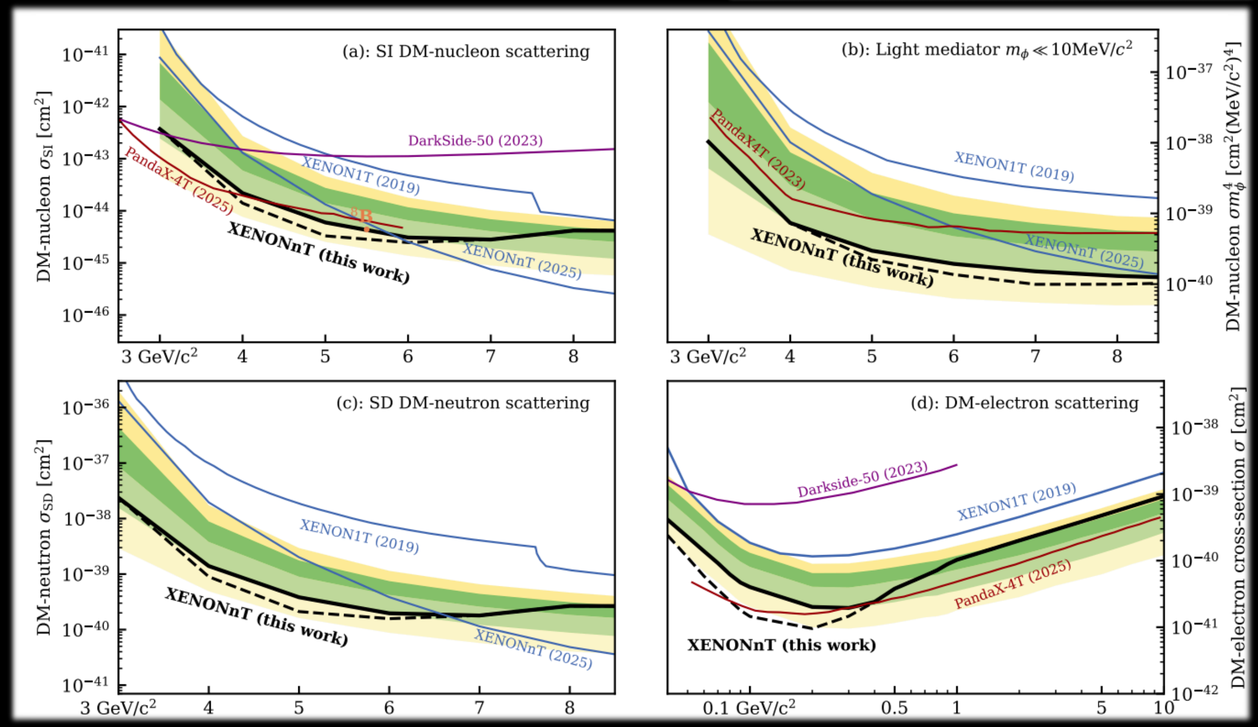


XENONnT

- Dual-phase LXe TPC, 5.9 T active located at LNGS
- Gd-water neutron veto
- Recent results include an ionisation-only search (“S2-only”) & constraints on light DM
- **Machine learning** techniques used to remove backgrounds from delayed electrons, accidental electrons and Pb-210 on cathode





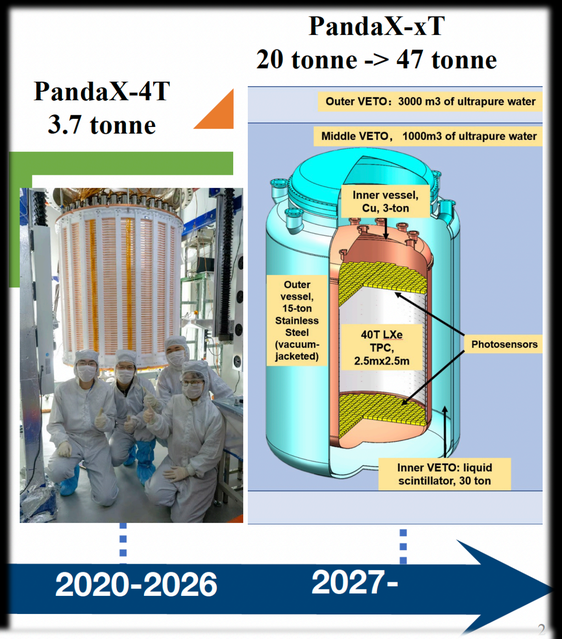


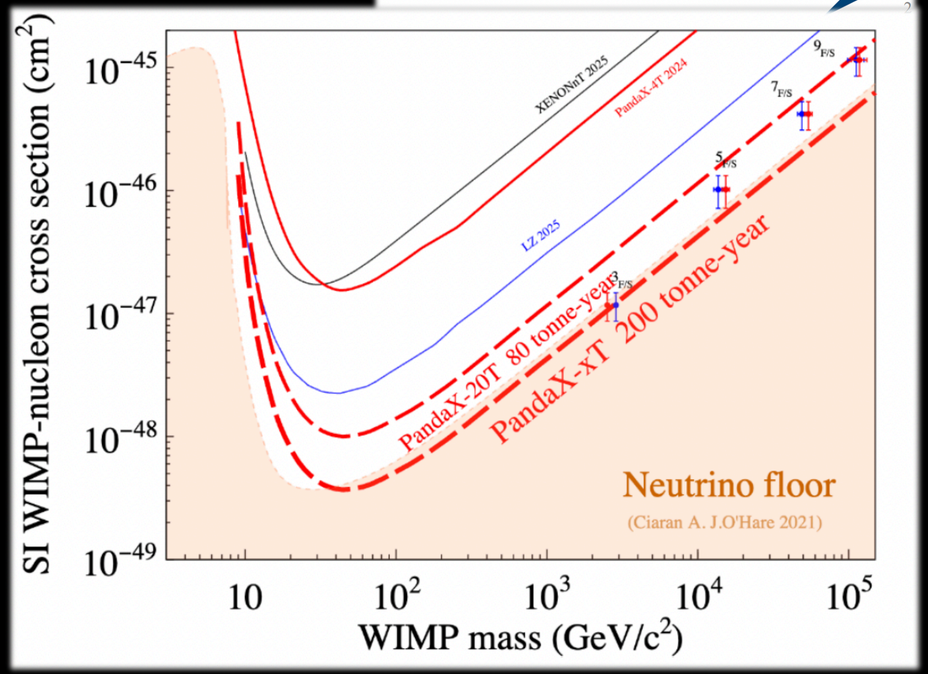
Light Dark Matter Search with 7.8 Tonne-Year of Ionization-Only Data in XENONnT
Aprile, E. et al, arXiv:2601.11296

PandaX

- **PandaX-4T** has completed its full physics program
  - ~700 live days collected
  - Calibration techniques tested (DD/DT pulsed neutrons, Ar37)
- **PandaX-20T** fully funded, all Xe acquired
  - Staged plan, eventually 47-tonne Xe with 40-tonne sensitive volume
  - Cold LS veto outside Cu vessel
- Timeline:
  - 2026: 4T decommissioning
  - 2027: 20T installation & commissioning
  - 2028: 20T physics operation

PandaX-20T: the next generation xenon detector for dark matter and neutrino searches
Xiang Xiao, IDM 2026

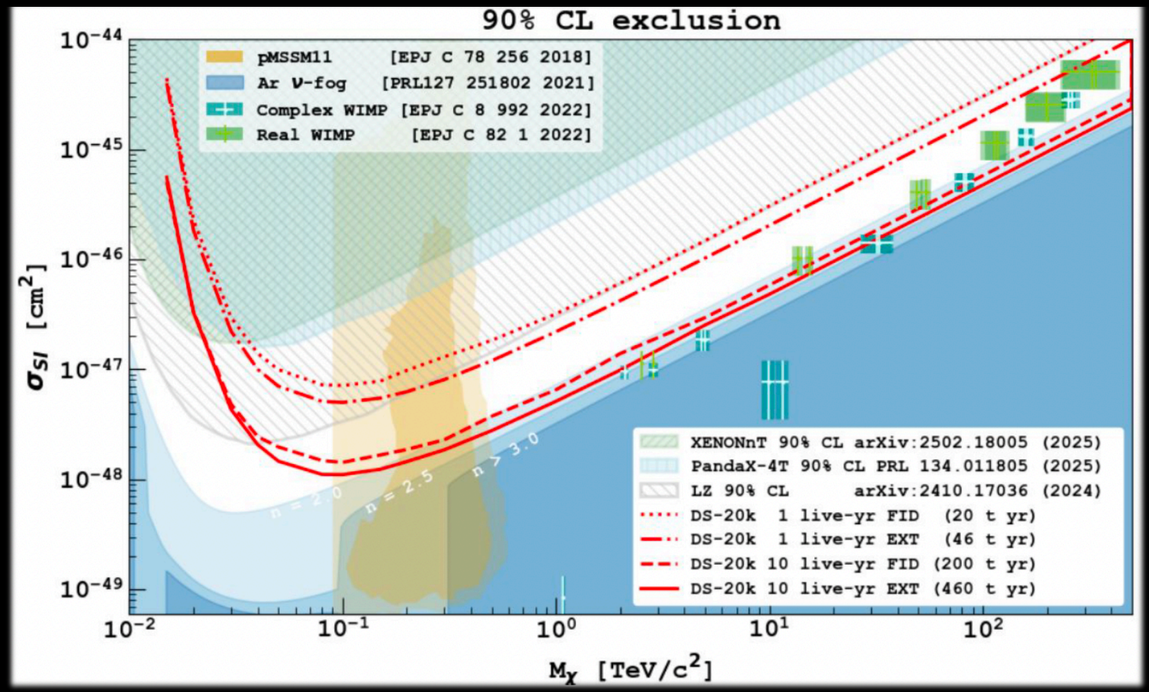




DarkSide-20K

Status of the DarkSide-20k experiment
Vicente Pesudo, IDM 2026

- Dual-phase underground Argon (UAr) TPC
  - UAr inner veto, atm. Ar outer veto
  - Argon lighter than LXe - **lower threshold**, pulse shape discrimination for ER/NR in addition to S1/S2
- **DarkSide-20k** construction at Gran Sasso Laboratory (LNGS) advanced
  - Cryostat and internal crane installed
  - Underground Ar cryogenics system to be upgraded by the end of the summer
- Detector will be ready for filling end of 2028

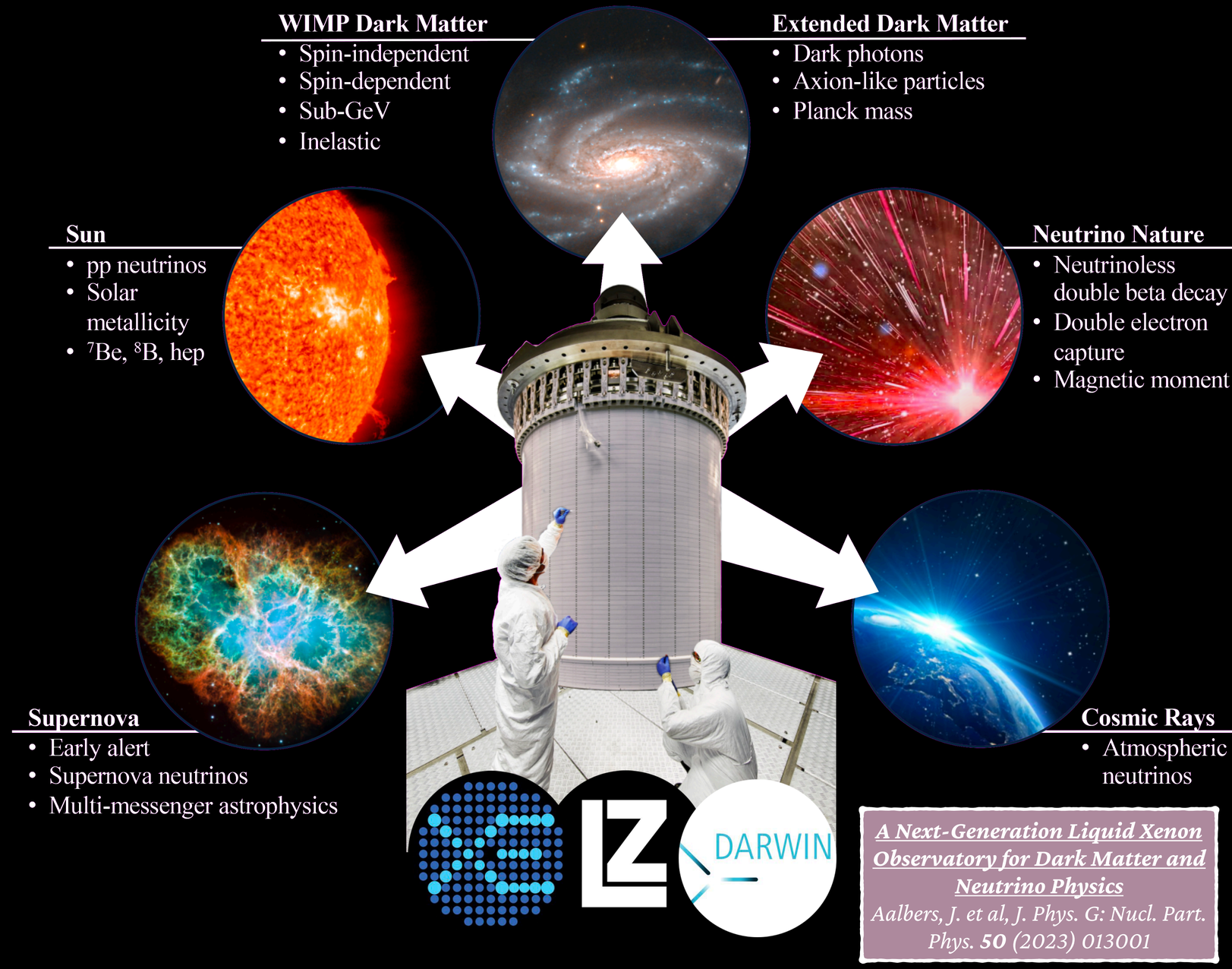


XLZD

XENON, DARWIN and LZ have joined forces to build a 40T-80T LXe TPC.

Science drivers:

- The **ultimate probe of WIMPs** down to the neutrino fog
- A **competitive and economic** search for neutrinoless double-beta decay
- Measurements of multiple astrophysical neutrino signals

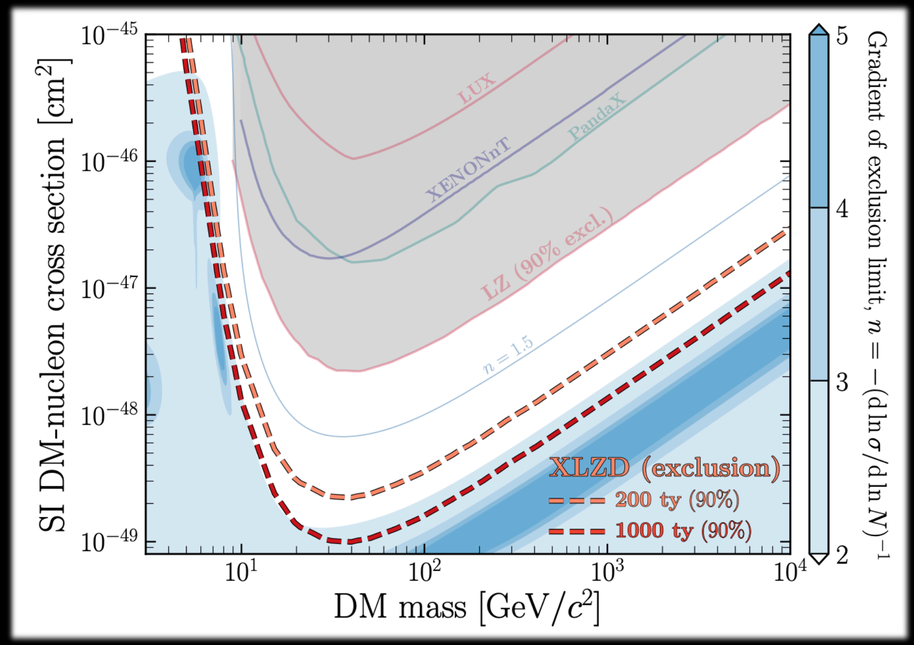


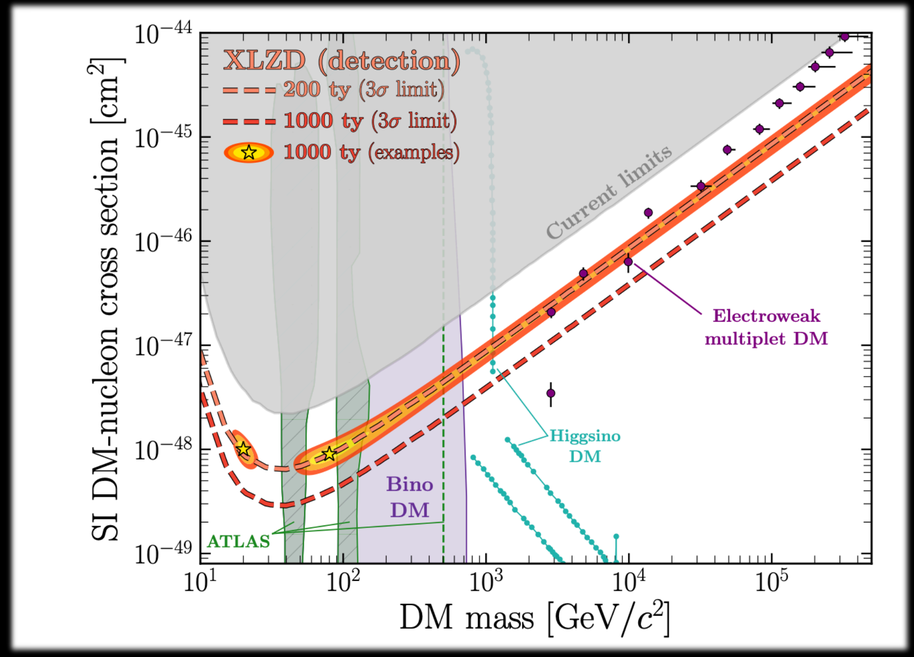
A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics
Aalbers, J. et al, J. Phys. G: Nucl. Part. Phys. ***50*** *(2023) 013001*

XLZD

- Despite P5 recommendation in 2023, in Dec 2025 DOE HEP announces deferring of G3DM until early 2030's due to funding constraints
- International partners working towards **CDR** for **early 2027**
- 11 Canadian institutions recently joined XLZD
- Technical evaluation of 4 sites to complete in the coming months: **Boulby** (UK), **LNGS** (Italy), **SURF** (USA), **SNOLAB** (Canada)
- XLZD planned to be the d**efinitive search for medium to high WIMP masses** - 3σ discovery potential at SI cross section of 3×10^{-49} cm^2 at 40 GeV

The XLZD Design Book: Towards the Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics
Aalbers, J. et al, Eur. Phys. J. C (2025) 85: 1192





Annual Modulation

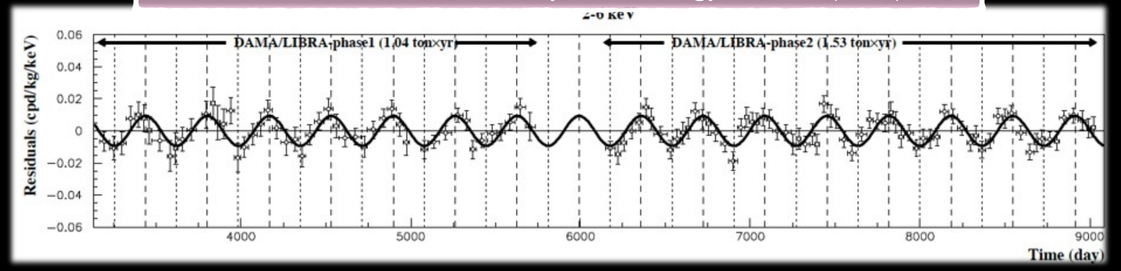
DAMA/LIBRA claim 13.7σ annual modulation signal in 2-6 keV window in NaI(Tl) target.

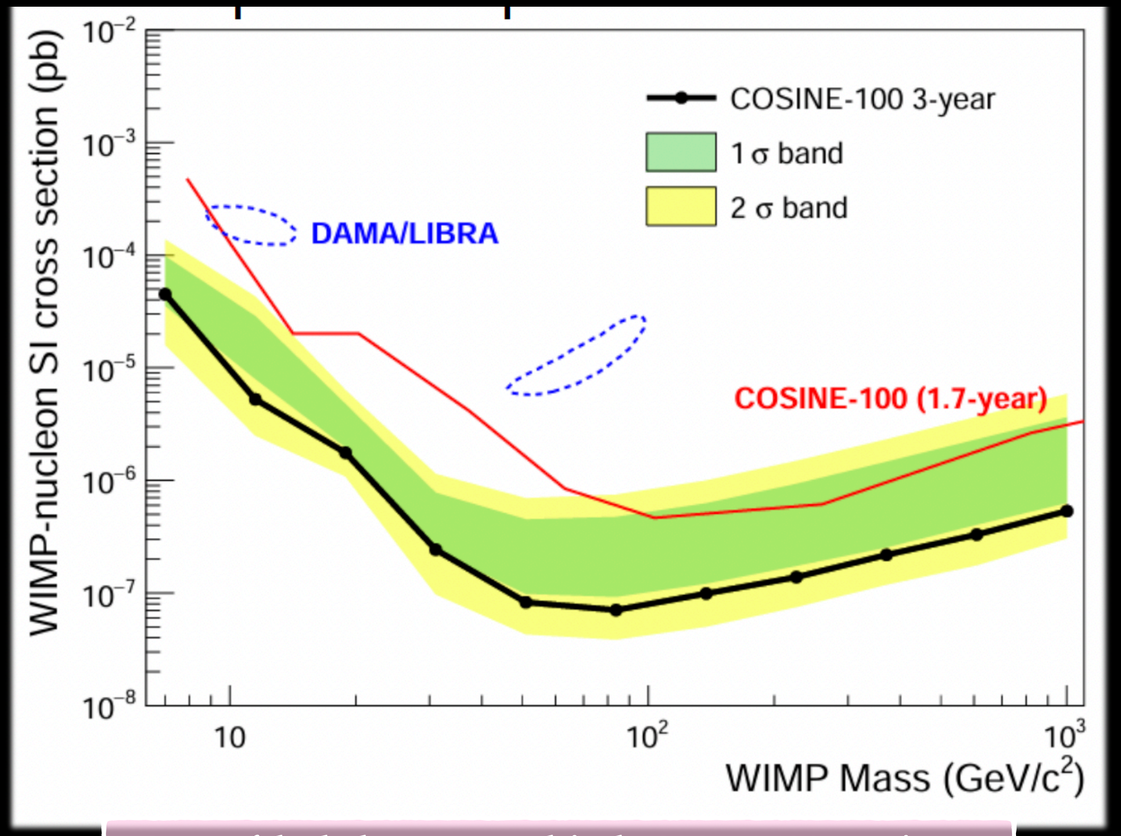
Suite of experiments running to test this in the same and different targets, N/S hemisphere, different vetos etc.

COSINE-100 recent results with same target, NaI(Tl):

- 6-year data modulation analysis ruled out DAMA/LIBRA's claim with 3.25$\boldsymbol{\sigma}$.
- Combined data with ANAIS-112 also disfavors the DAMA/LIBRA signal with 4.7$\boldsymbol{\sigma}$.
- 3-year data event selection lowered threshold to 0.7 keV; SI limit excludes the DAMA/LIBRA contours

Further results from DAMA/LIBRA–phase2 and perspectives
R. Bernabei et al., Nucl. Phys. At. Energy 22, 329 (2021)

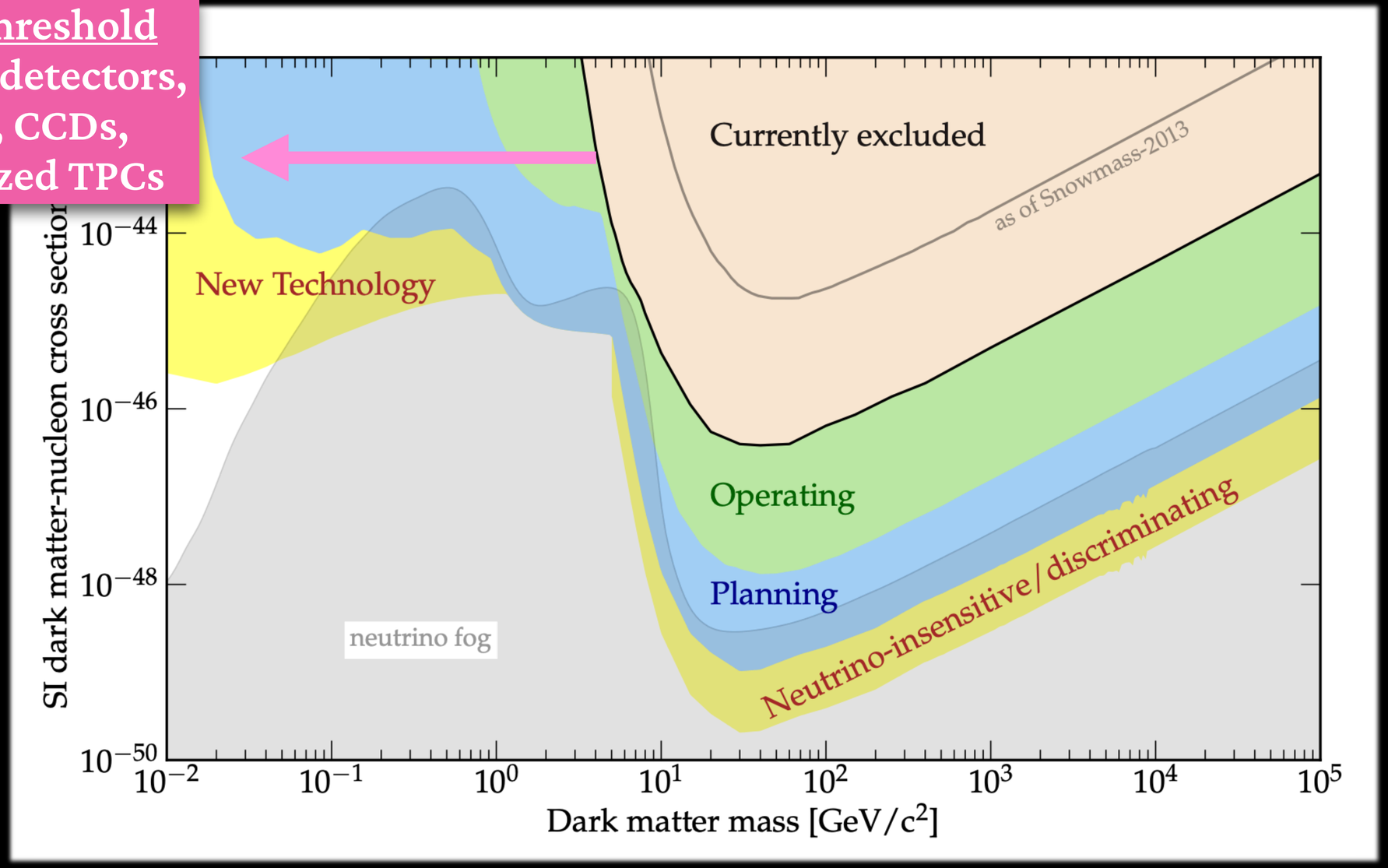




Status of the dark matter search in the COSINE-100 experiment
Jinyoung Kim- IDM 2026

Search Wide

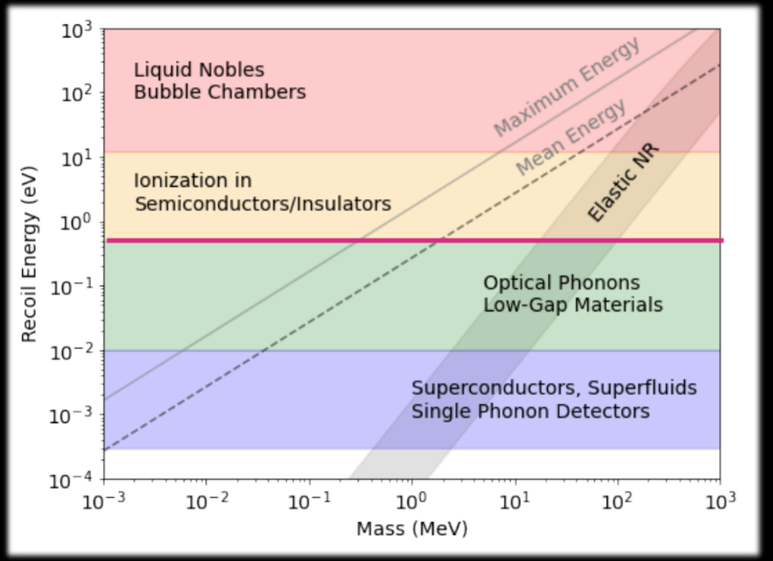
Low Threshold
Phonon detectors, SPCs, CCDs, optimized TPCs

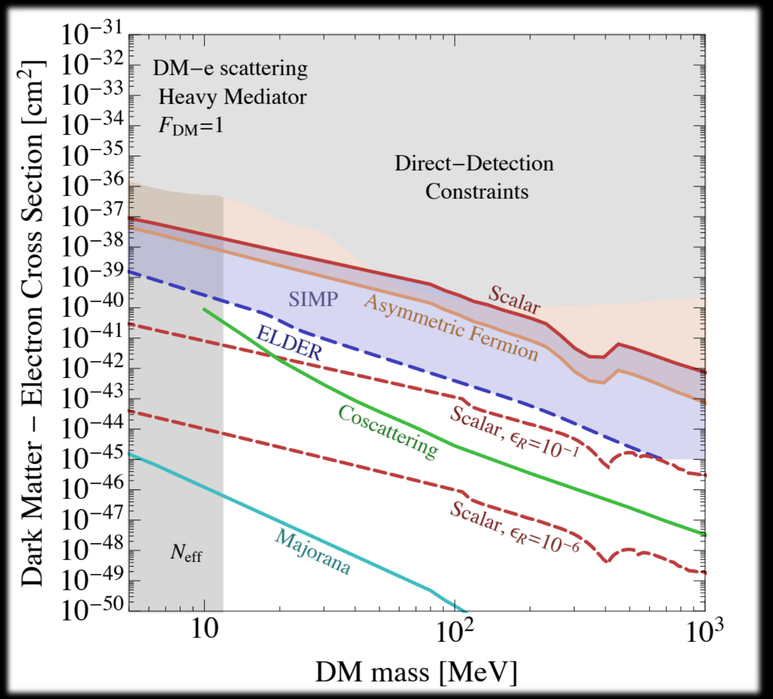


Low Mass DM

"The landscape of low-threshold dark matter direct detection in the next decade" Snowmass2021 Cosmic Frontier
arXiv:2203.08297

- Light (< 1 GeV) DM invokes **technological challenges** for detection
- Interaction is mix of DM-nucleus, scattering DM-e scattering and both depending on model
- Need **different technology** - lots of small scale experiments currently probing the low mass regime & proposals for upgrades for larger experiments e.g. H-doping in LZ (HydroX)



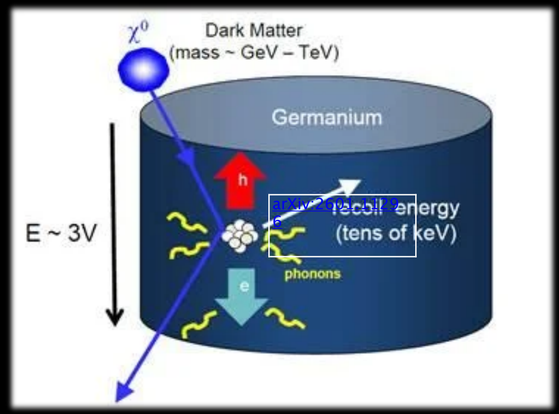


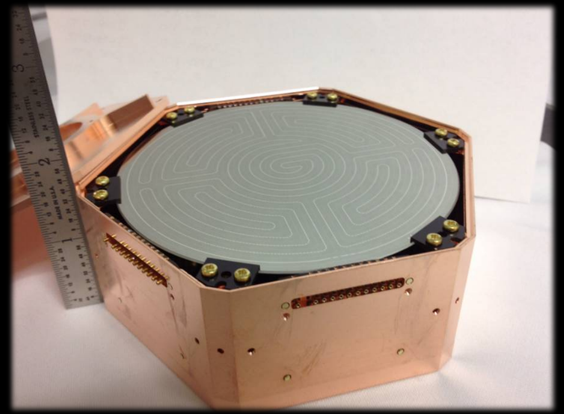
This is by no means an exhaustive list of light DM candidates....

Candidate	Light WIMPs	Solar Axion	ALPs	Sterile ν	Hidden Photons
Mass	sub-GeV	μeV - meV	10^{-11} - 10^{3} eV	keV	1 keV - 10 GeV
Detection Methods	ionisation-only searches, phonons, Migdal effect, doping of LXe with light elements	Axio-electric effect (ER spectrum), conversion to γ in microwave cavities	Axio-electric effect (mono energetic ER), conversion to γ in microwave cavities	Decay to ν through active/ sterile mixing	Dark photo-electric effect, decay products

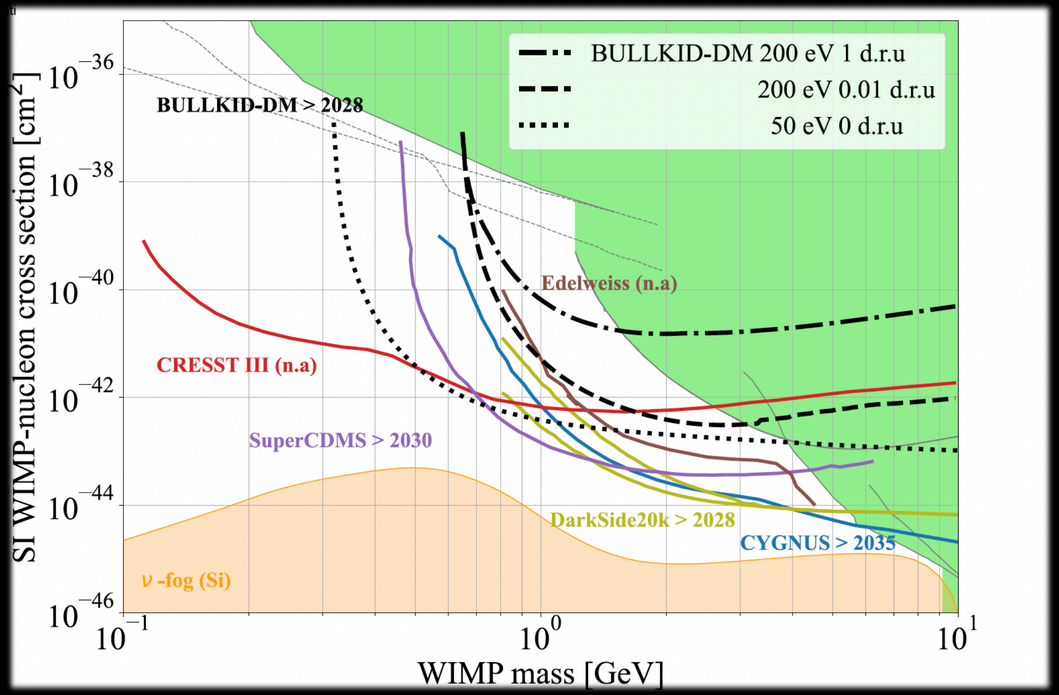
Cryogenic Detectors

- SNOLAB: **SuperCDMS**
  - Target materials: Si (0.6 kg), Ge (1.4 kg)
  - Two types of detector: Interleaved Z-sensitive Ionization and Phonon (iZIP) & High Voltage
  - First pulses Jan 15, 2026 !
- LNGS: **CRESST-III**, **BULLKID-DM**, **COSINUS**
  - CREST-III: Targets - CaWO4, Si, LiAlO2, Al2O3 (sapphire) and Si-On-Sapphire (SOS)
  - BULLKID: 800g Si
  - COSINUS: 34g NaI, cold DAMA check, taking data 2026-2027
- LSM: **TESSERACT**
  - Ge/Si and superfluid He targets, TES-based sensors (QETs). Operations 2029-2031





"Direct searches for light dark matter with cryogenic experiments and the low-energy excess"
Belina Von Krosigk , IDM 2026

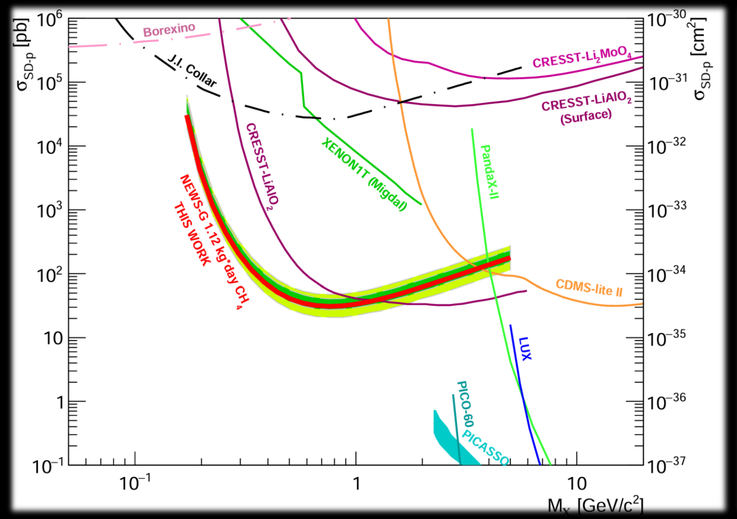


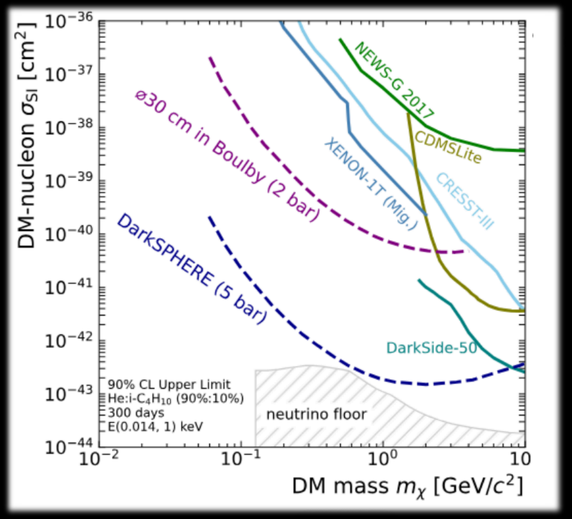
Spherical Proportional Counters

NEWS-G: Sub-GeV DM detection with **Spherical Proportional Counters**

- Detects ionisation electrons drifted to an anode
- Easy to swap target gas - check different nuclei
- NEWS-G @ LSM recently set strongest constraints on spin-dependent WIMP-proton (directly on H) cross-section in the 0.18 – 1.2 GeV range
  - SNOLAB run with Ne-CH4, CH4 and He-CH4 - analysis underway
  - Next: DarkSphere - 300cm, potentially at Boulby

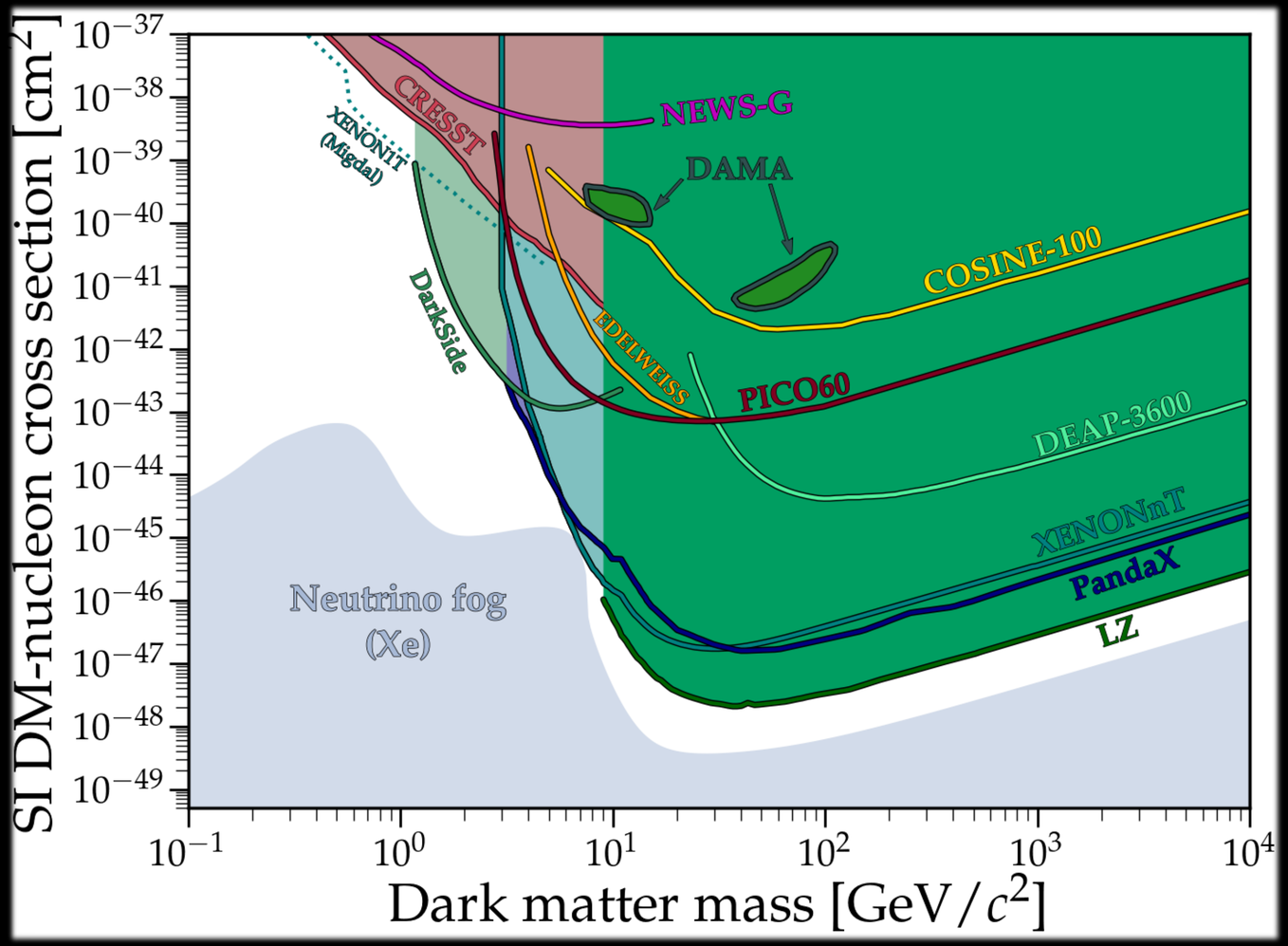
"Searching for light dark matter with DarkSPHERE"
L. Milligan, IDM 2026



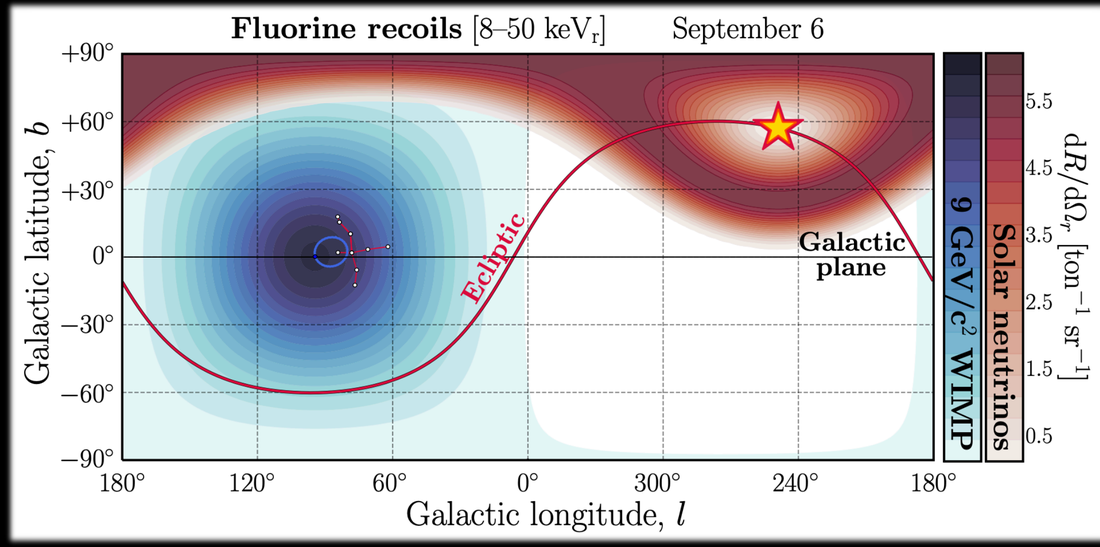


Directional Detection

Direct DM experiments ARE now detecting CEνNS from astrophysics neutrinos - will limit DM sensitivity



**The neutrino fog is defined to be the regime for which $n > 2$, with the neutrino "floor" being the largest cross section for each mass where this transition occurs*



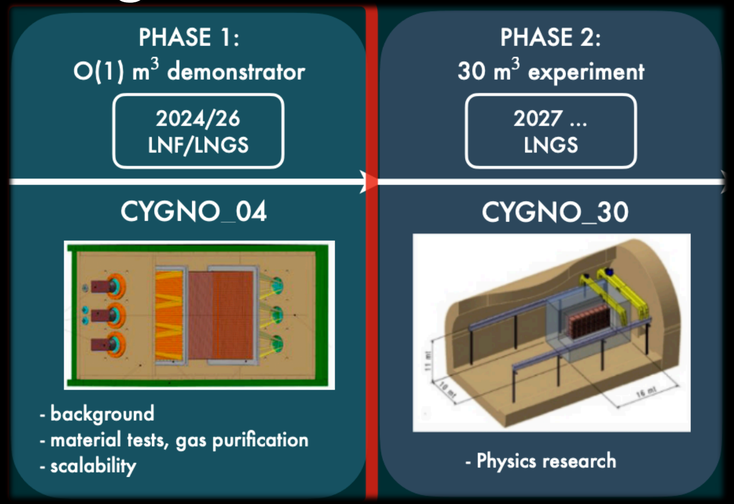
Directionality allows clear discrimination of neutrinos (position tracks the sun) from DM (always from Cygnus)

Direct Detection Limits
Ciaran O'Hare

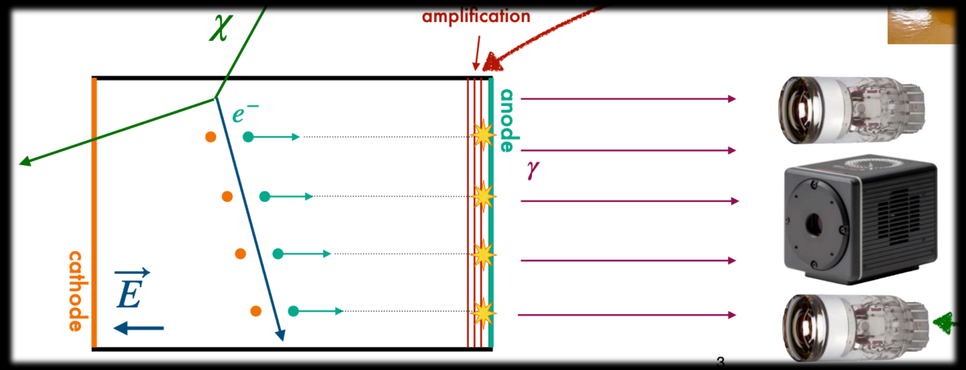
CYGNUS

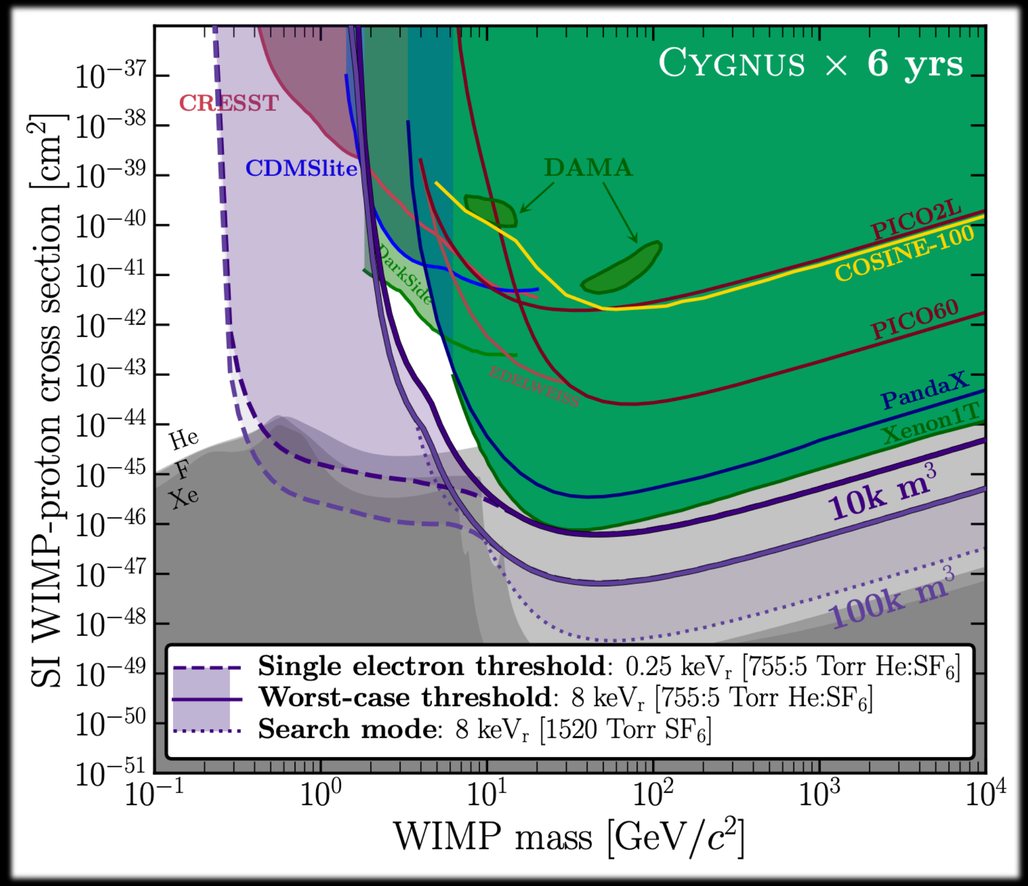
- Long term CYGNUS Vision: **Multi-site Galactic Recoil Observatory** with directional sensitivity to WIMPs and neutrinos using low-density gas TPCs. Targeting low-mass WIMP region (~10 keV) with directionality
- Prototyping in various stages across the world

e.g. CYGNO-04 at LNGS - 0.4m³ demonstrator



Commissioning and design of the CYGNO-04 detector at LNGS
S. Piacentini, IDM 2026



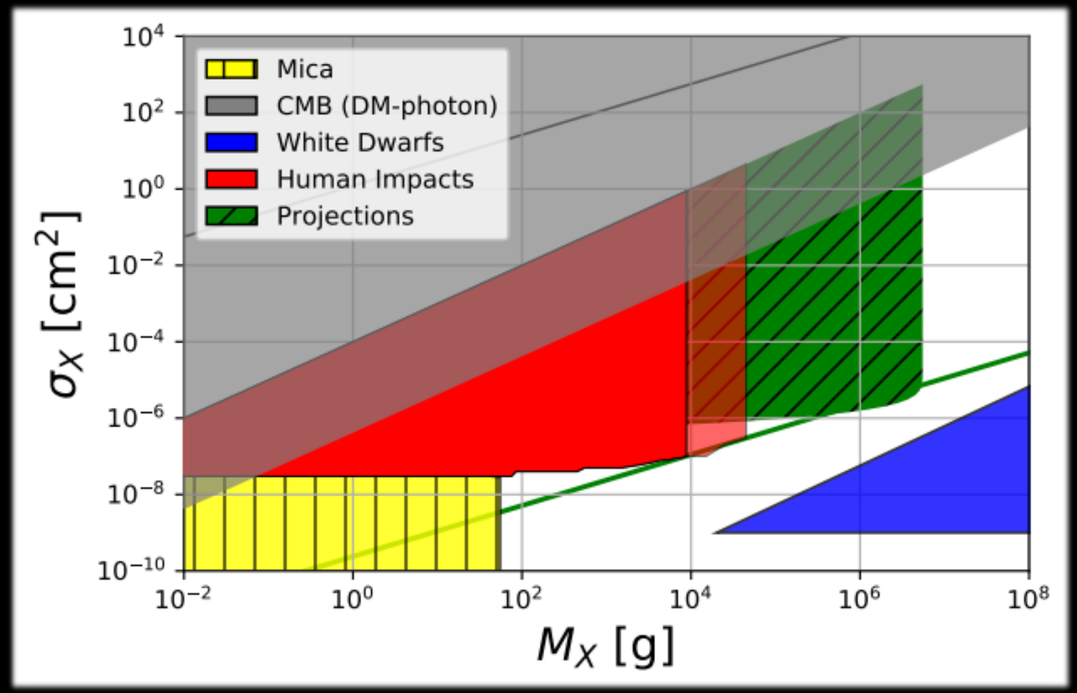


Honourable Mentions

Widening the search through novel ideas!

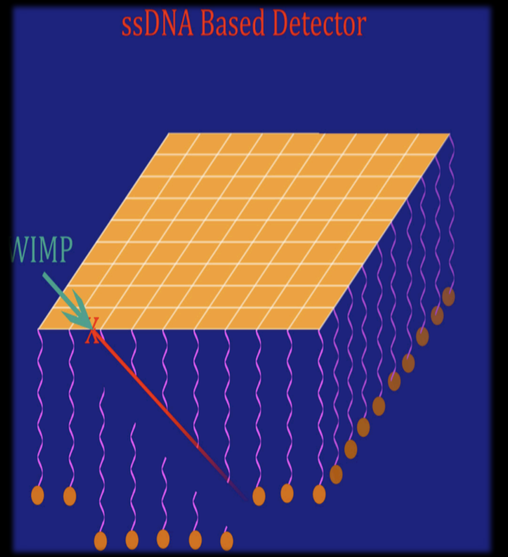
Death by dark matter

Death and Serious Injury from Dark Matter
J. S. Sidhu, R. Scherrer and G. Starkman
*Phys. Let. B, **803**, 135300, (2020)*



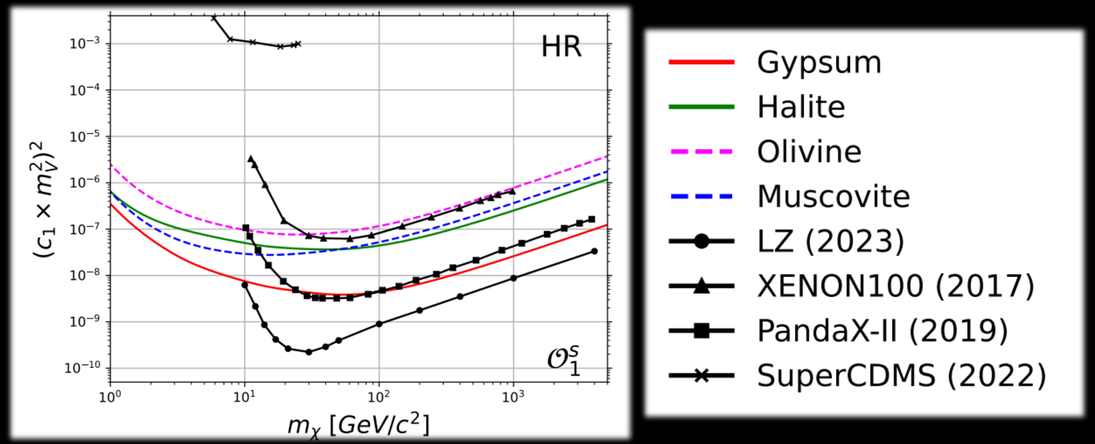
DNA detectors

New Dark Matter Detectors using DNA or RNA for Nanometer Tracking
A. Drukier et al
arXiv:1206.6809

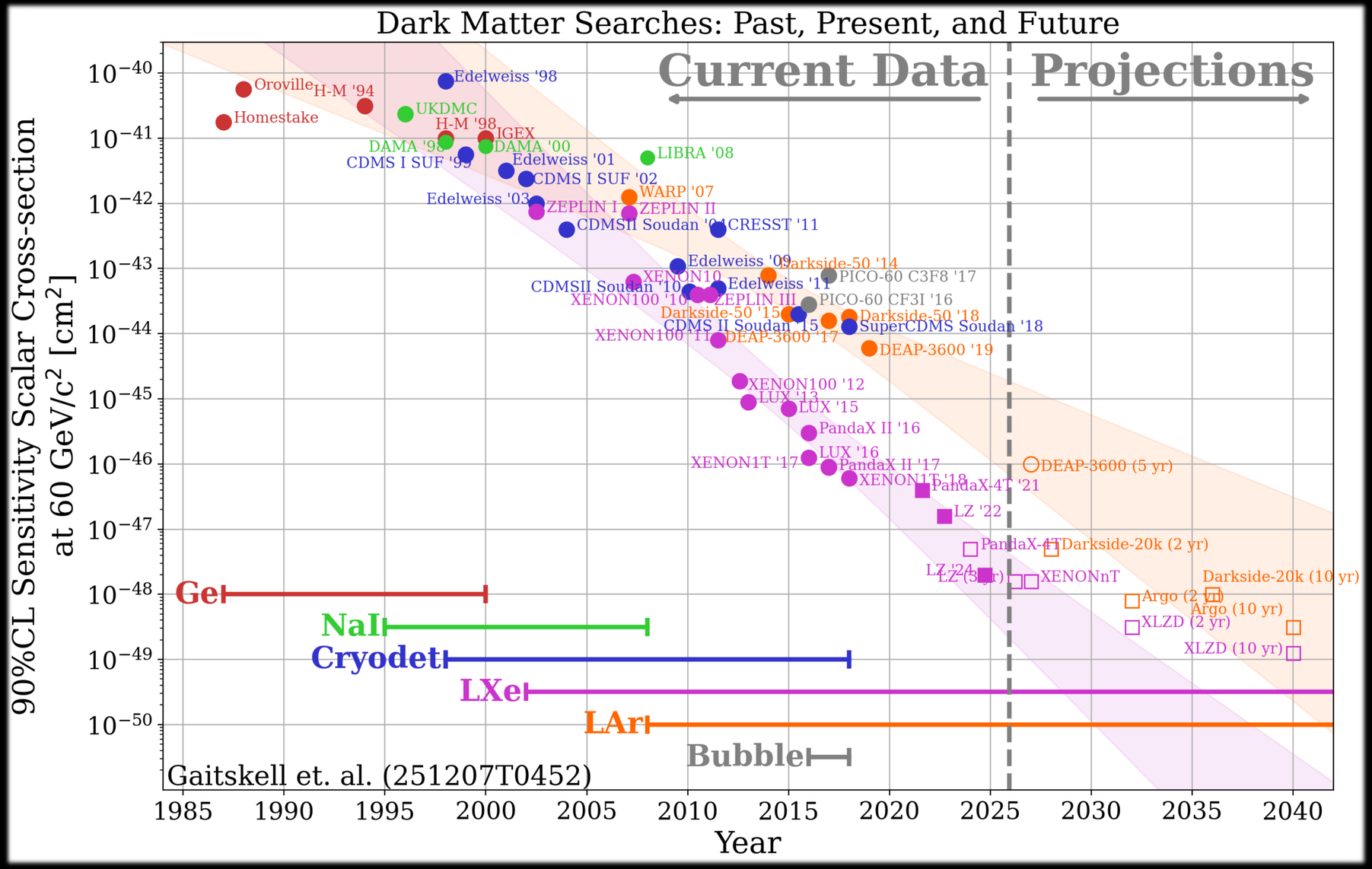


Paleodetectors

Projected Sensitivity of Paleo-Detectors to Dark Matter Effective Interactions with Nuclei
D. P. Theodosopoulos, et al
*Phys. Rev. D **113**, 123044 (2026)*



Conclusions

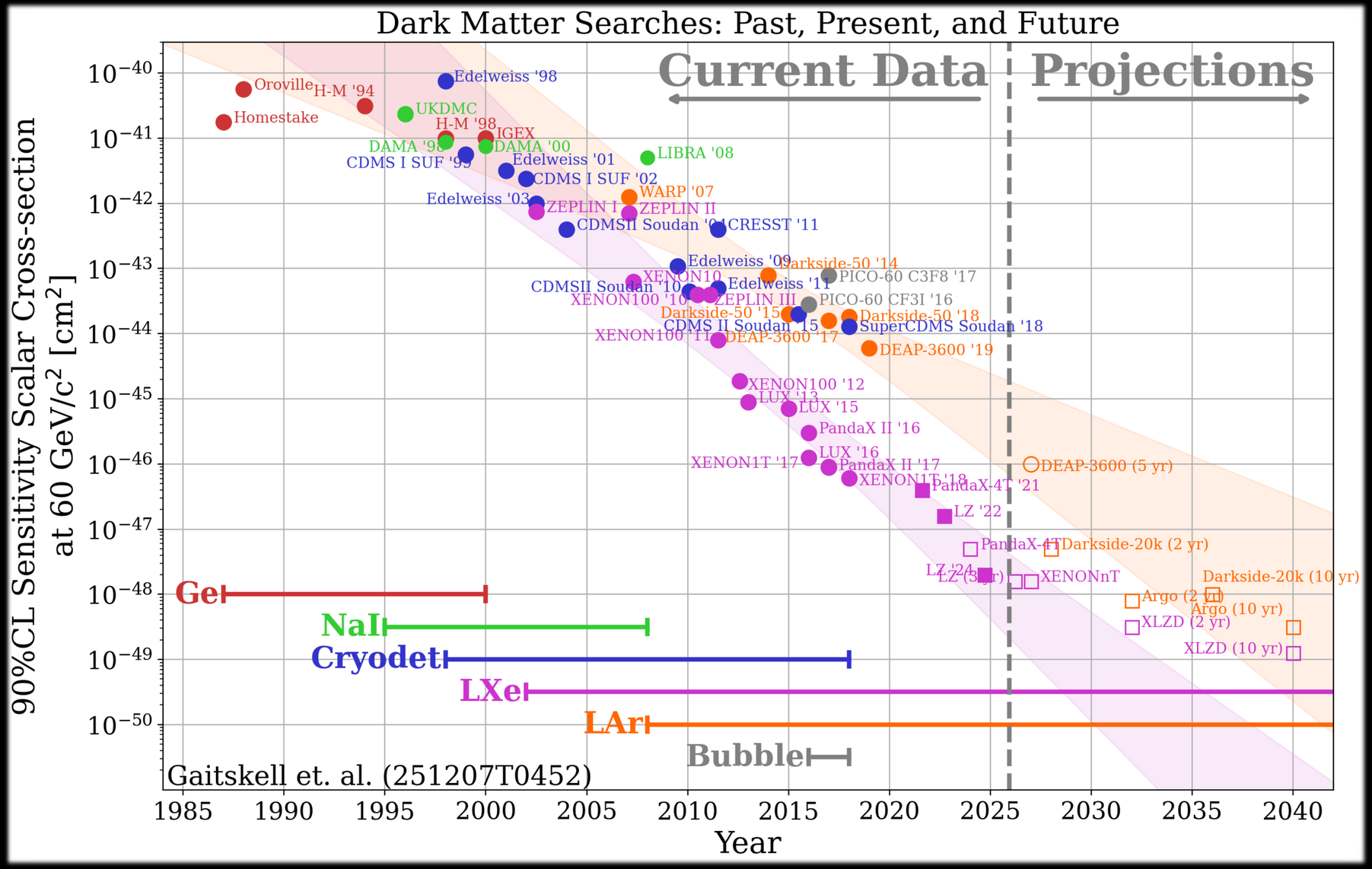


R.J.Gaitskell, "Direct Detection of Dark Matter", Annu. Rev. Nucl. and Part. Sci. 54 (2004) 315-359 (updated by R.J. Gaitskell et al., Private Communication, 2025)

Conclusions

Zeptobarn

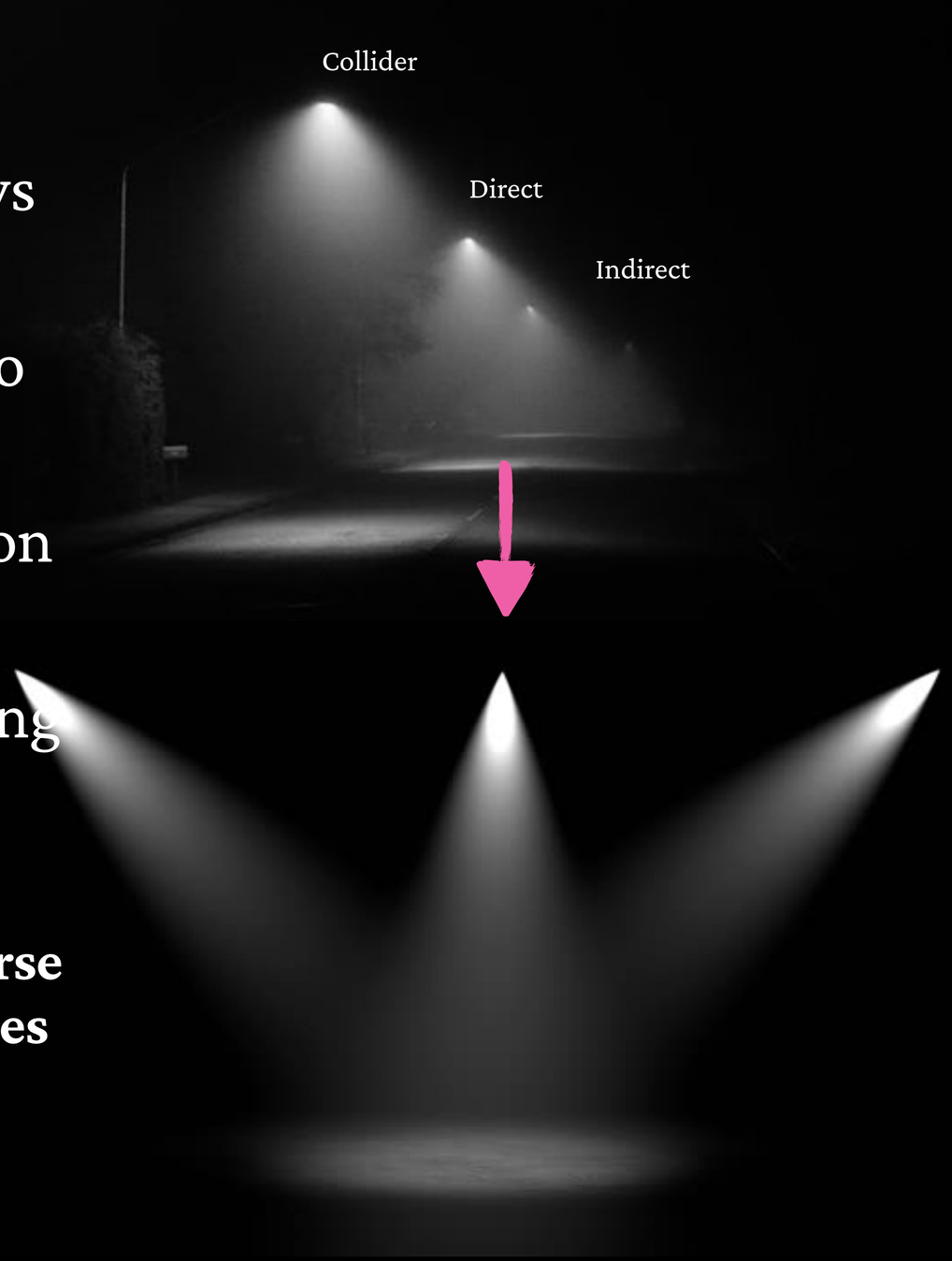
Yoctobarn



R.J.Gaitskell, "Direct Detection of Dark Matter", Annu. Rev. Nucl. and Part. Sci. 54 (2004) 315-359 (updated by R.J. Gaitskell et al., Private Communication, 2025)

Conclusions

- The search for dark matter continues, and grows broader...
- Interesting era is beginning - we have started to measure the **neutrino fog**
  - This eventually limits standard direct detection techniques
- Dual focus on increasing exposure and increasing low mass sensitivity **- delve deep and search wide**
  - Multiple targets in Direct searches can probe a **diverse set of DM models** and **wide range of DM properties**
- Still chance for **DM discovery** with running and planned experiments - stay tuned!



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