IFAE 2023

DARK MATTER DIRECT DETECTION

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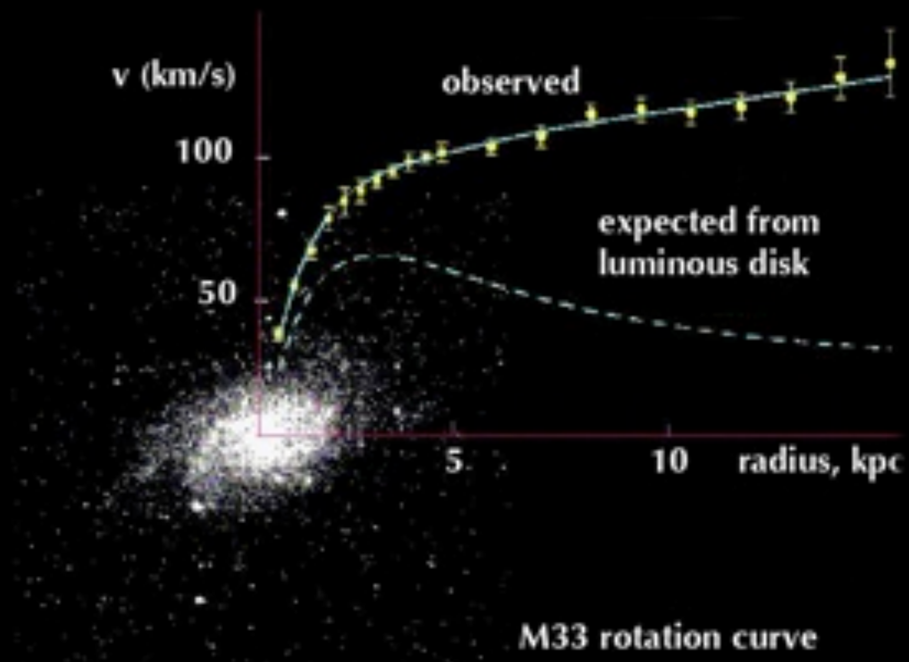
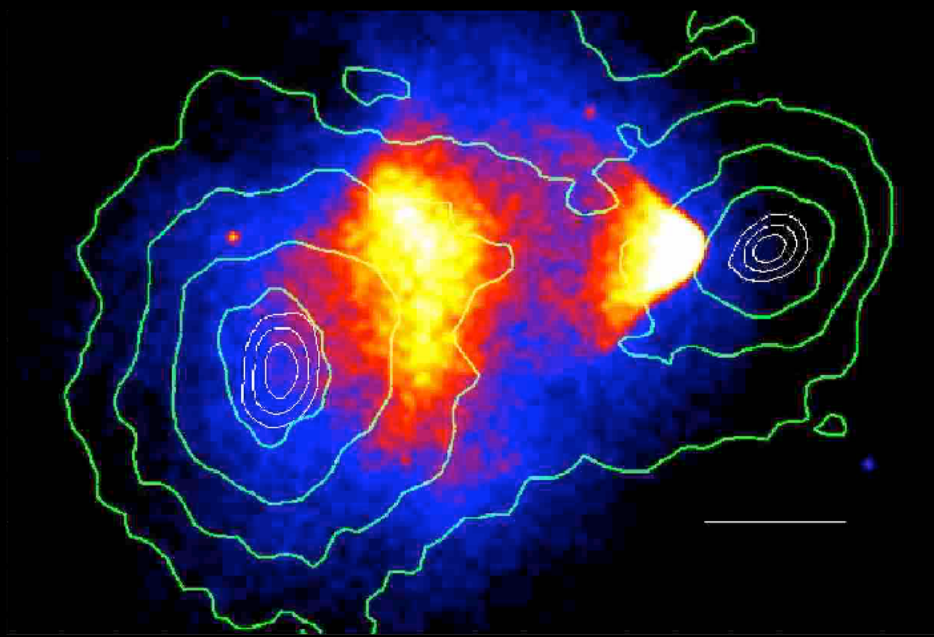
OBSERVATIONAL EVIDENCE FOR DM AT ALL SCALES

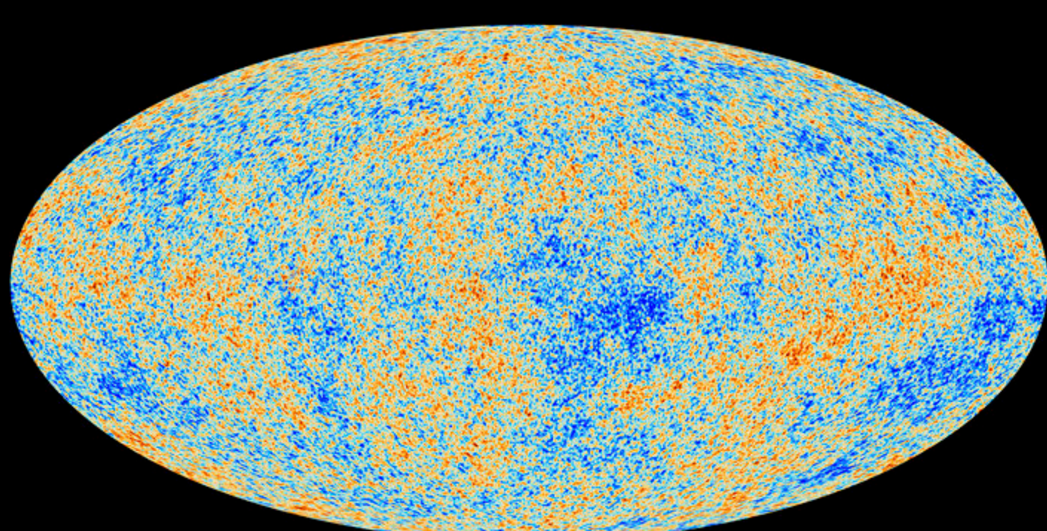
Galaxies

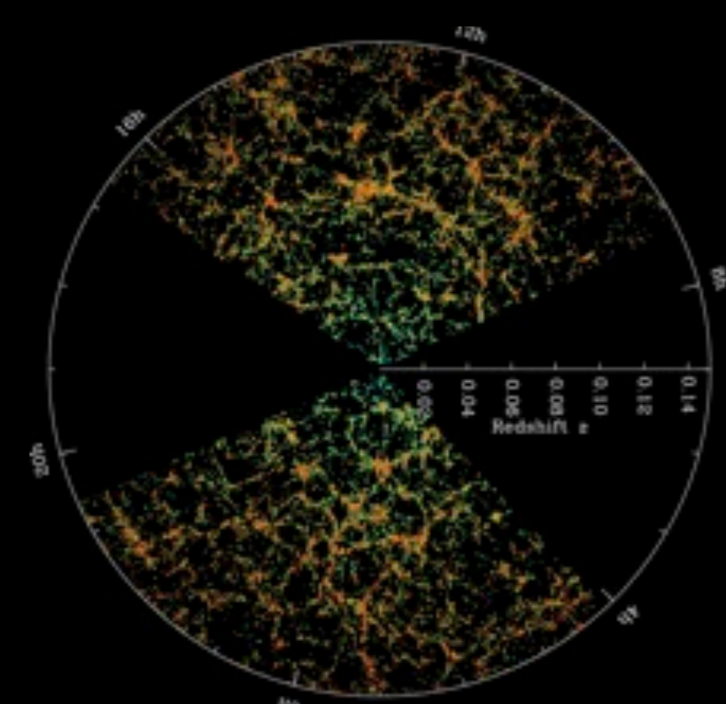




Galactic Clusters

CMB

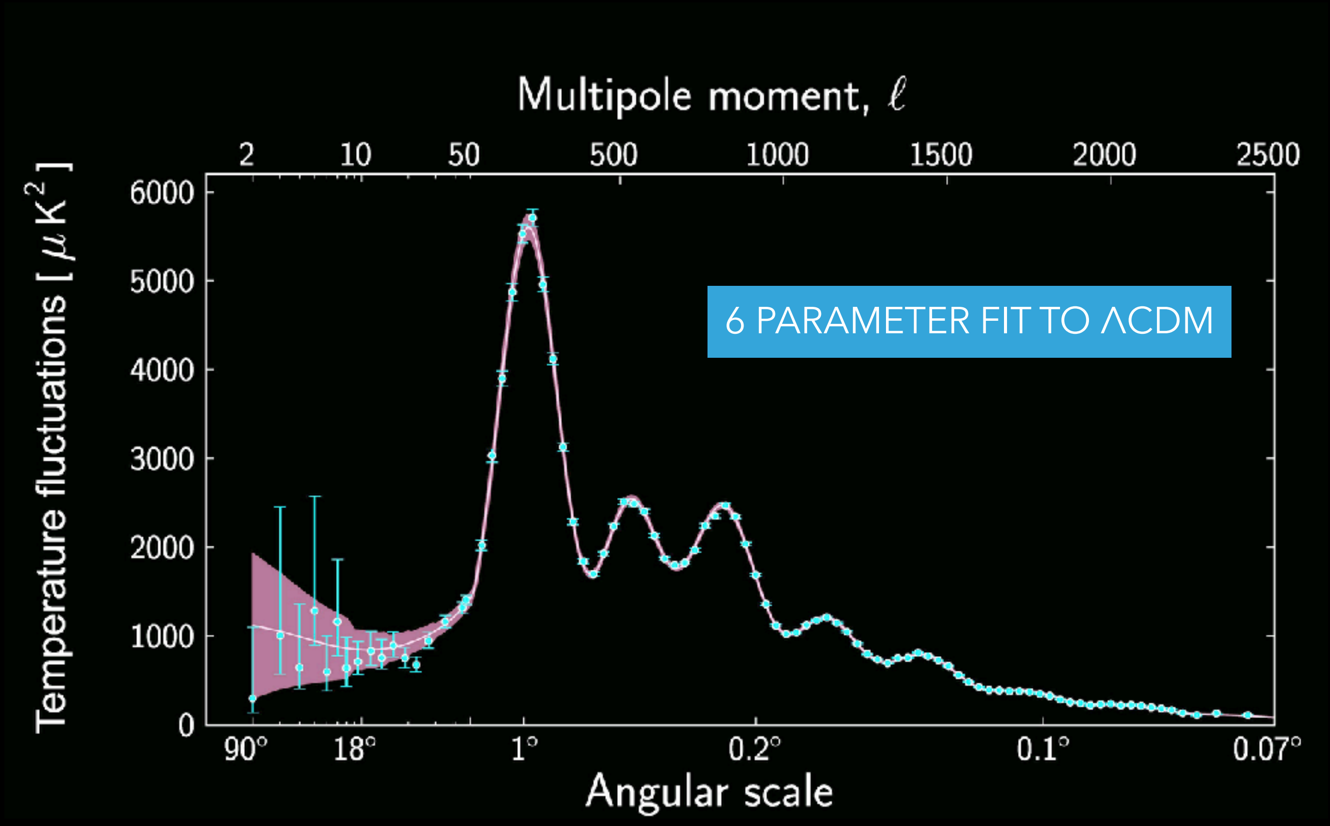


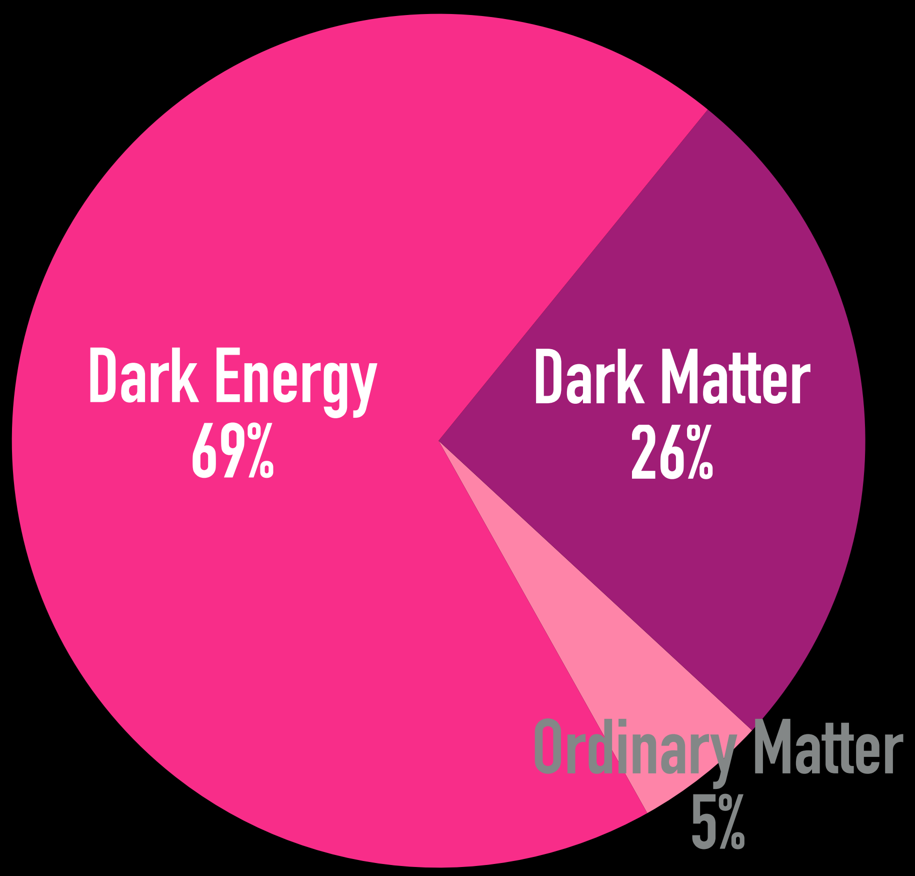


Structure

A DARK UNIVERSE

- ΛCDM Cosmological Model
  - $\Omega_b h^2 = 0.02237 \pm 0.00015$
  - $\Omega_M h^2 = 0.143 \pm 0.0011$
- 100σ difference between the baryon density and the matter density
- DM accounts for 85% of total matter in Universe

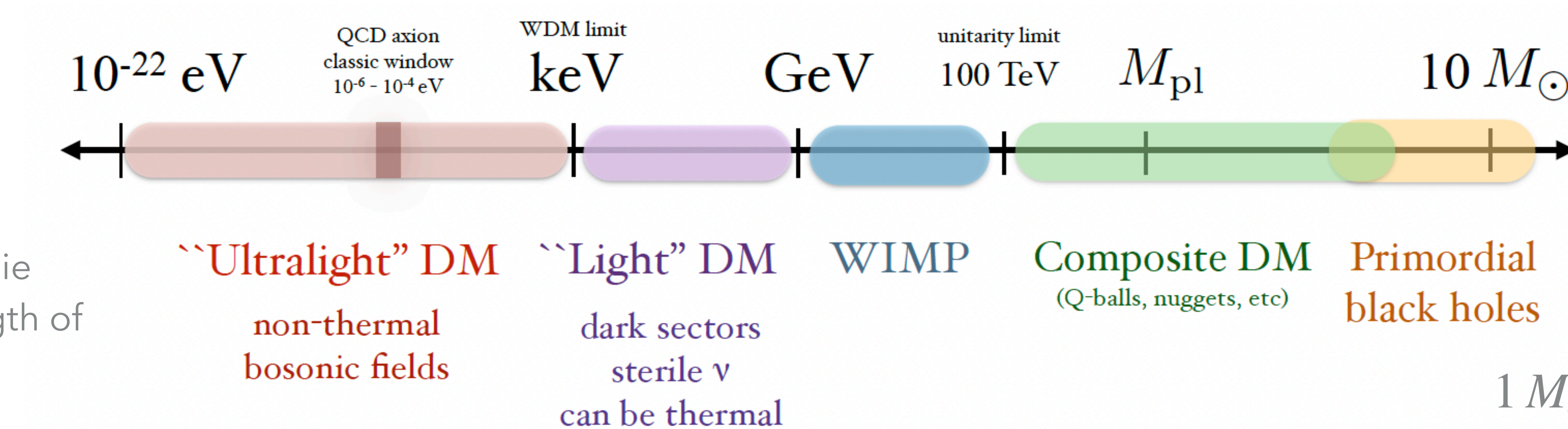




Planck Collaboration, Astron. Astrophys. 641, A1 (2020)

WHAT IS DARK MATTER?

A spectrum spanning 80 orders of magnitude



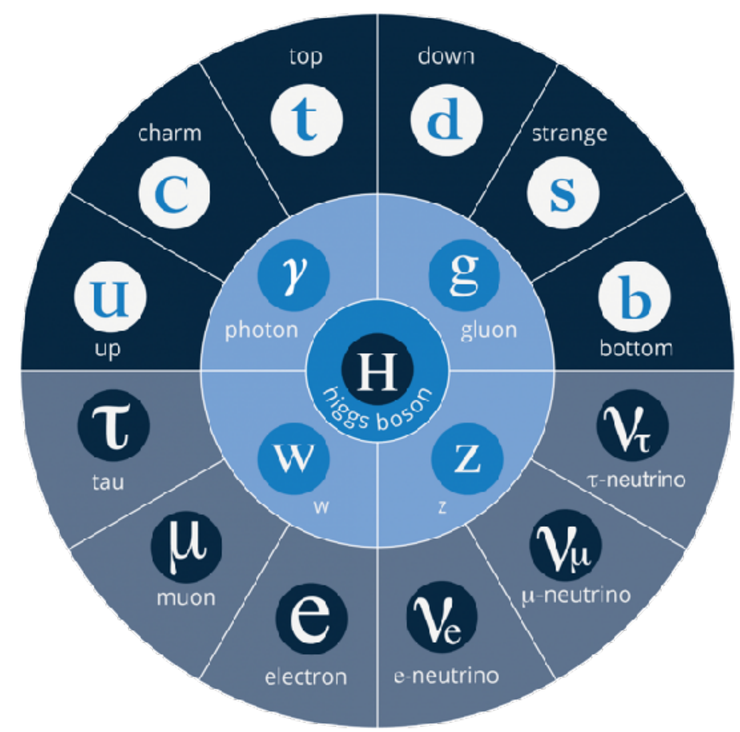
(de Broglie wavelength of galaxy)

$1\ M_\odot = 10^{57}$ GeV

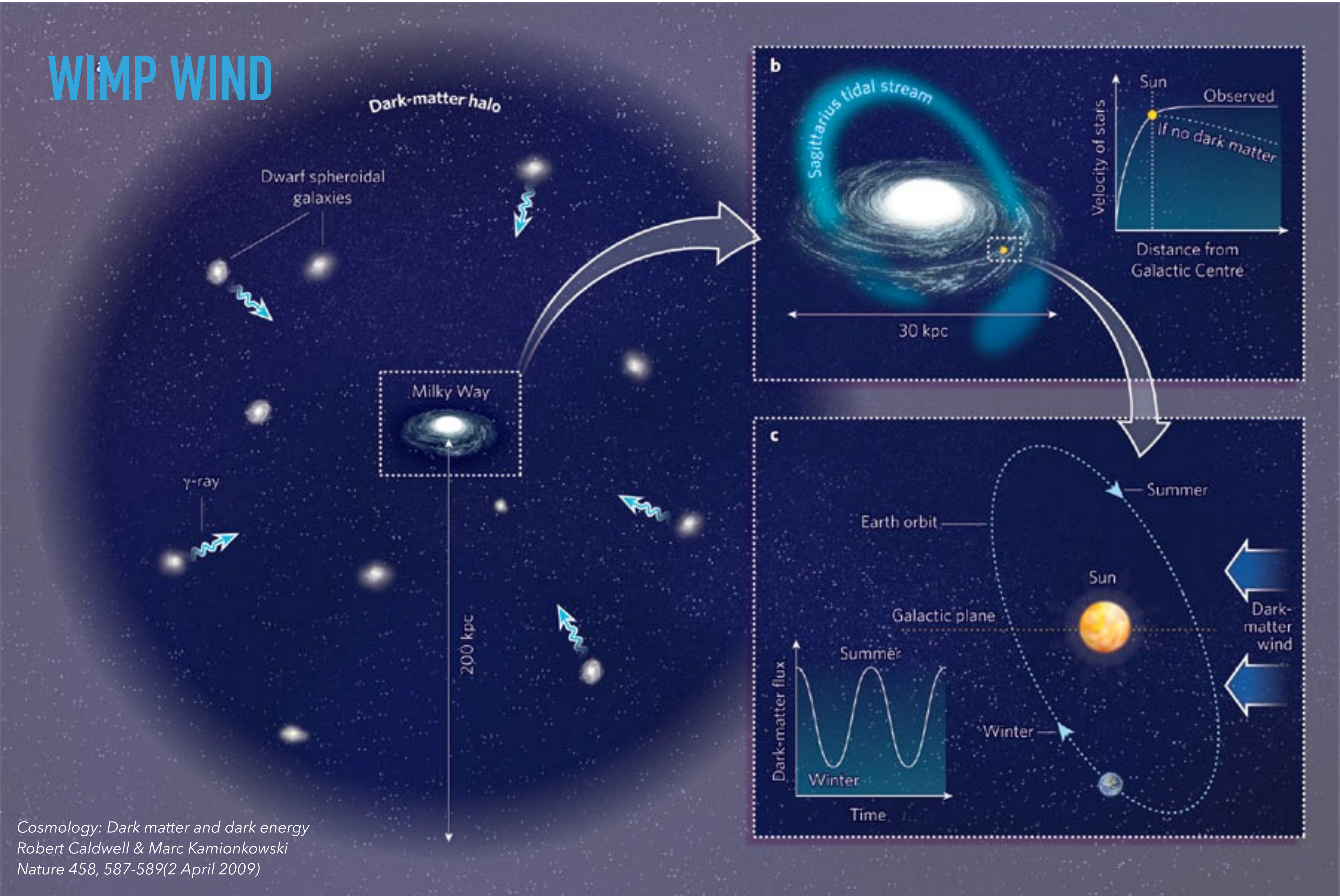
WIMP paradigm: a good place to start looking

The Minimal WIMP Model Basic Assumptions:

- Single particle that does not interact with itself
- Interacts weakly with Standard Model
- 2→2 annihilations primarily in s-wave
- Annihilations set thermal abundance today



WIMP WIND



Cosmology: Dark matter and dark energy
Robert Caldwell & Marc Kamionkowski
Nature 458, 587-589(2 April 2009)

WIMP WIND ON EARTH

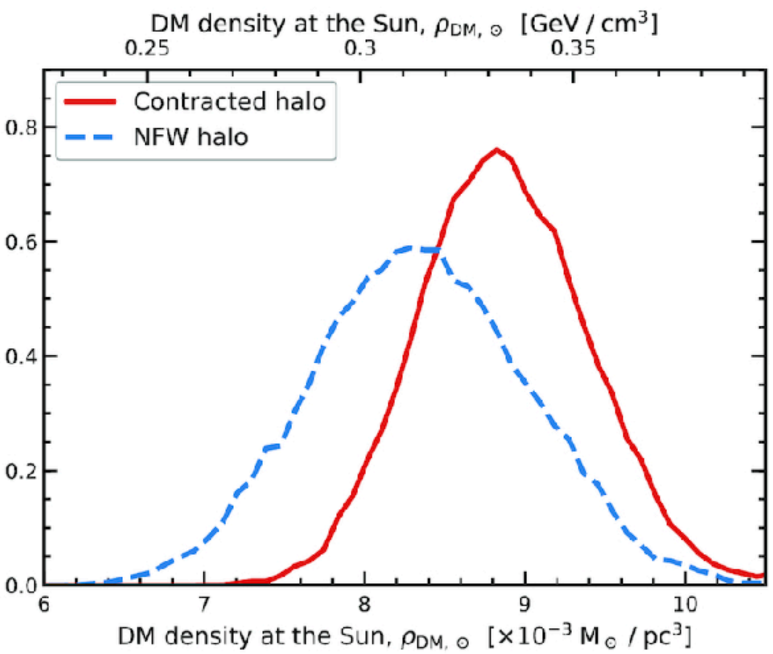
$$\Phi \simeq \frac{10^5}{\text{s cm}^2} \times \left(\frac{100\,\text{GeV}}{m_\chi}\right)$$

- Goodman & Witten (1985): “Detectability of certain dark matter candidates”

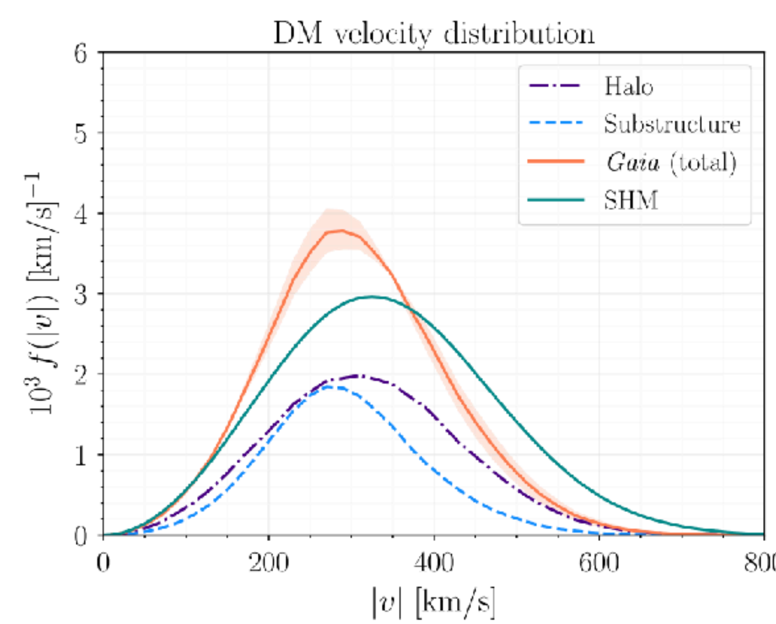
$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \times \int dv\, f(v)\, v\, \frac{d\sigma_\chi}{dE_R}$$

- ρ_χ galactic dark matter halo local density
- v relative velocity wrt terrestrial detector
- σ_χ elastic scattering off target nuclei

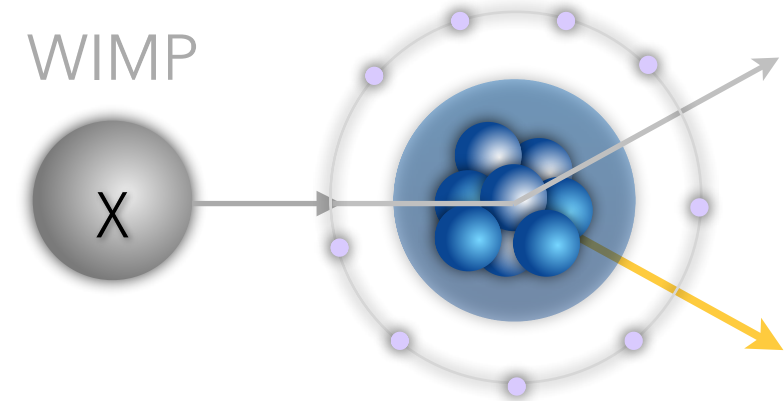
M. Cautun et al, MNRAS 2020



Buch et al, PRD101, 2020



WIMP-NUCLEON SCATTERING



- Non-relativistic scattering
  $v/c \simeq 10^{-3}$

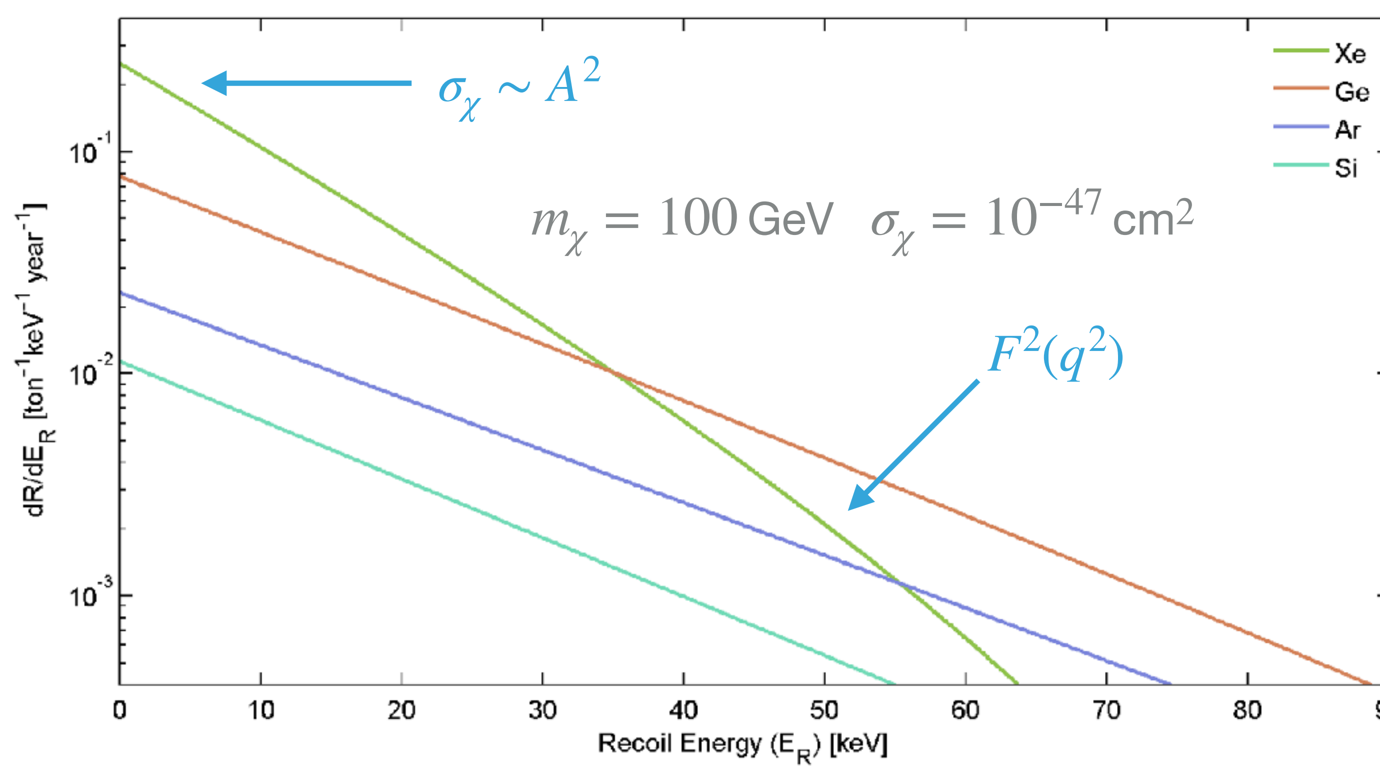
$$E_0 = \frac{1}{2} m_\chi v^2; \quad r = \frac{4 m_\chi m_N}{(m_\chi + m_N)^2}$$

$$E_R = E_0 r \frac{(1 - \cos\theta)}{2}$$

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} \exp\left(-\frac{E_R}{E_0 r}\right) \times [S(E_R) F^2(q^2) I$$

$F^2(q^2)$ Form factor
$S(E_R)$ seasonal modulation
I Interaction type

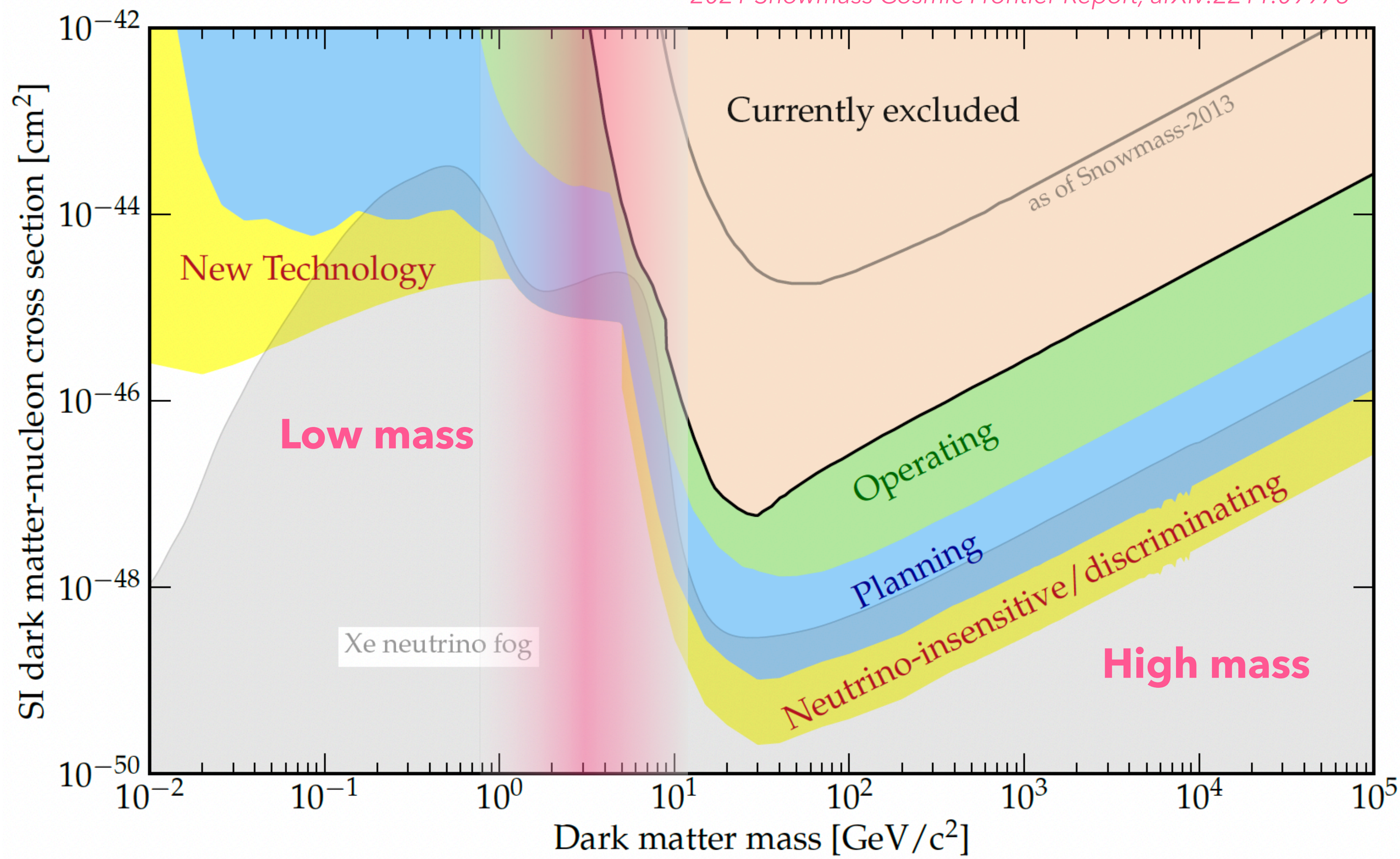
- Contact interaction independent of momentum exchange (nucleus as a particle, with charge and spin)
  - ➡ standard SI/SD description
  - ➡ nuclear form factors generally included



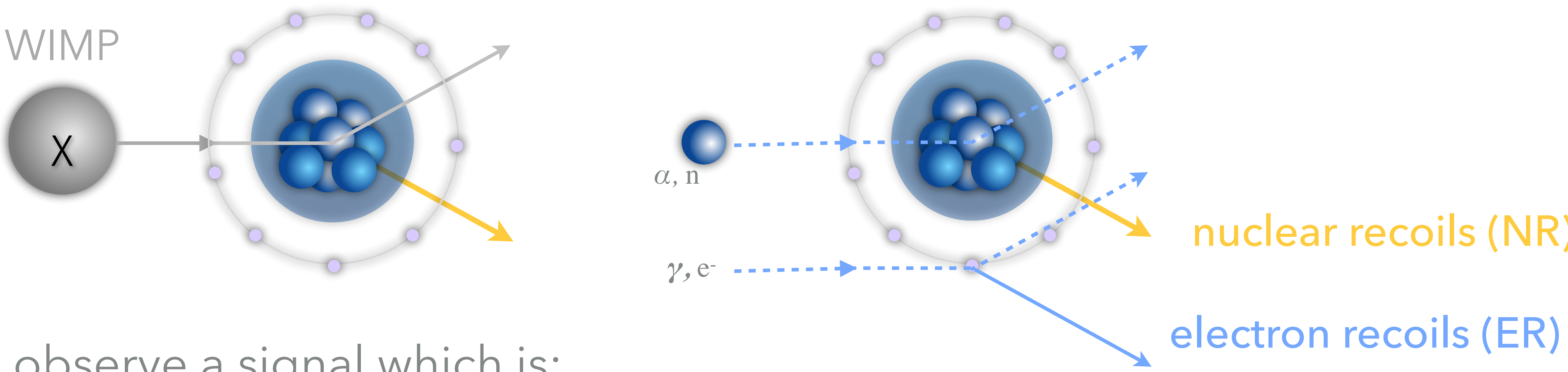
WIMP NUCLEON SI INTERACTION EXCLUSION LIMITS LANSCAPE

- To improve sensitivity:
  - larger exposure M × T and lower background
- To extend sensitivity at low mass WIMPs:
  - lower energy threshold
- Minimum of the curve:
  - depends on target nuclei

2021 Snowmass Cosmic Frontier Report, arXiv:2211.09978

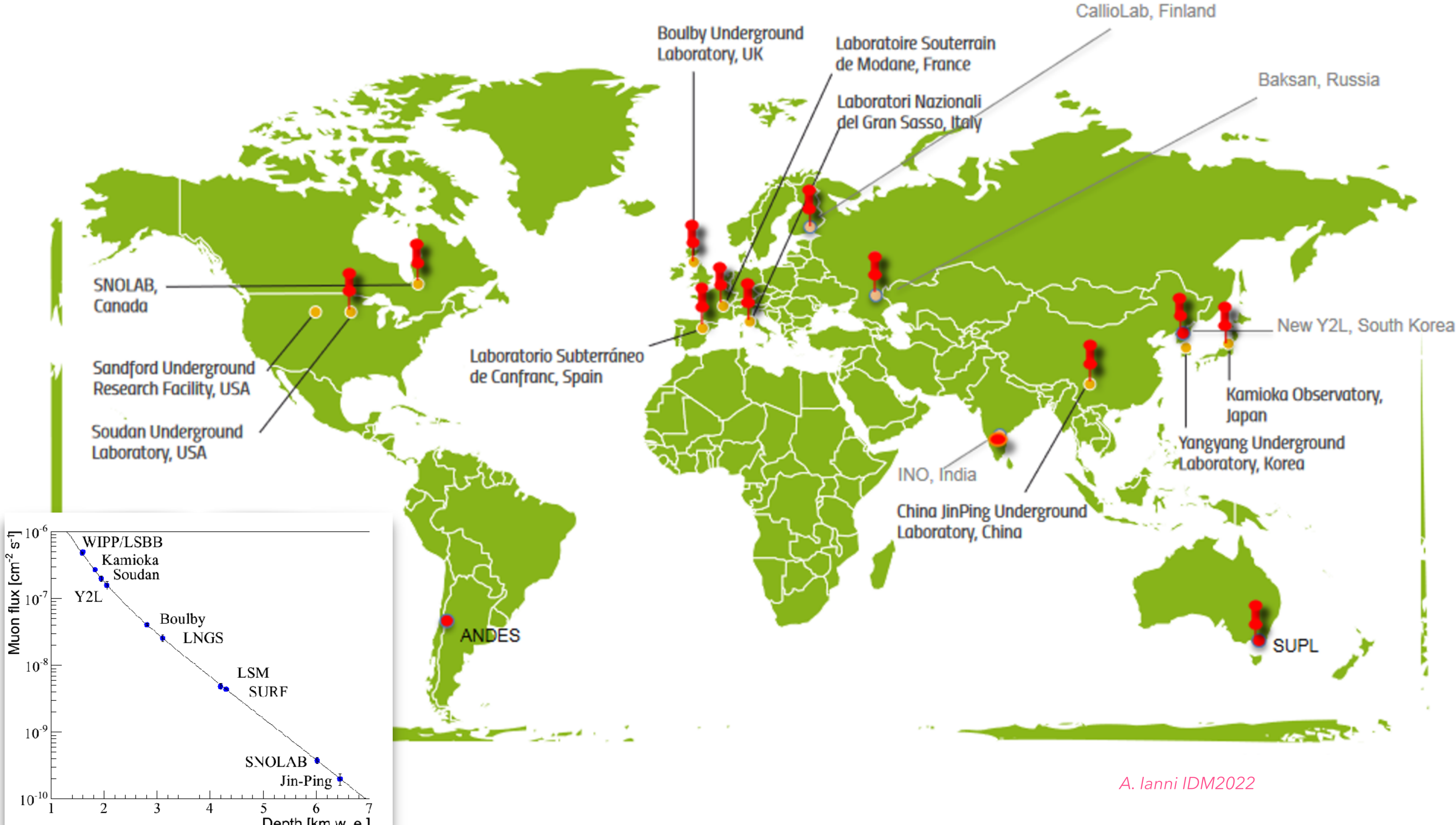


EXPERIMENTAL CHALLENGE



- To observe a signal which is:
  - very small: low recoil energies < 100 keV
  - very rare: <1 event/(kg y) at low masses and < 1 event/(t y) at high masses
  - buried in backgrounds with > 10^6 higher rates:
    - Muon-induced neutrons: NRs
    - Cosmogenic activation of materials/targets: ERs
    - Radioactivity of detector materials: NRs and ERs
    - Target intrinsic isotopes: ERs

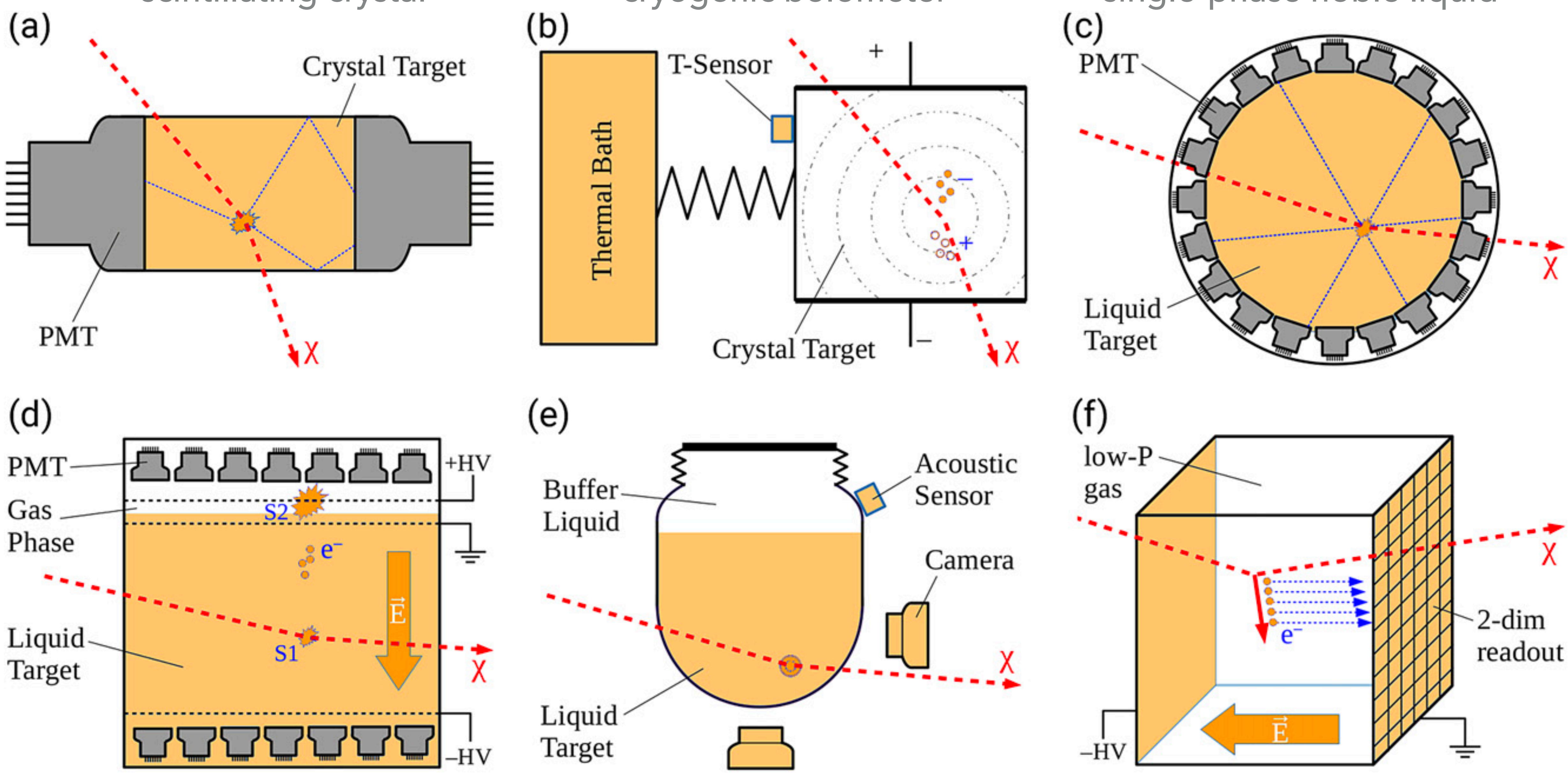
DEEP UNDERGROUND LABORATORIES



A. Ianni IDM2022

DETECTOR TECHNOLOGIES

scintillating crystal — cryogenic bolometer — single-phase noble liquid

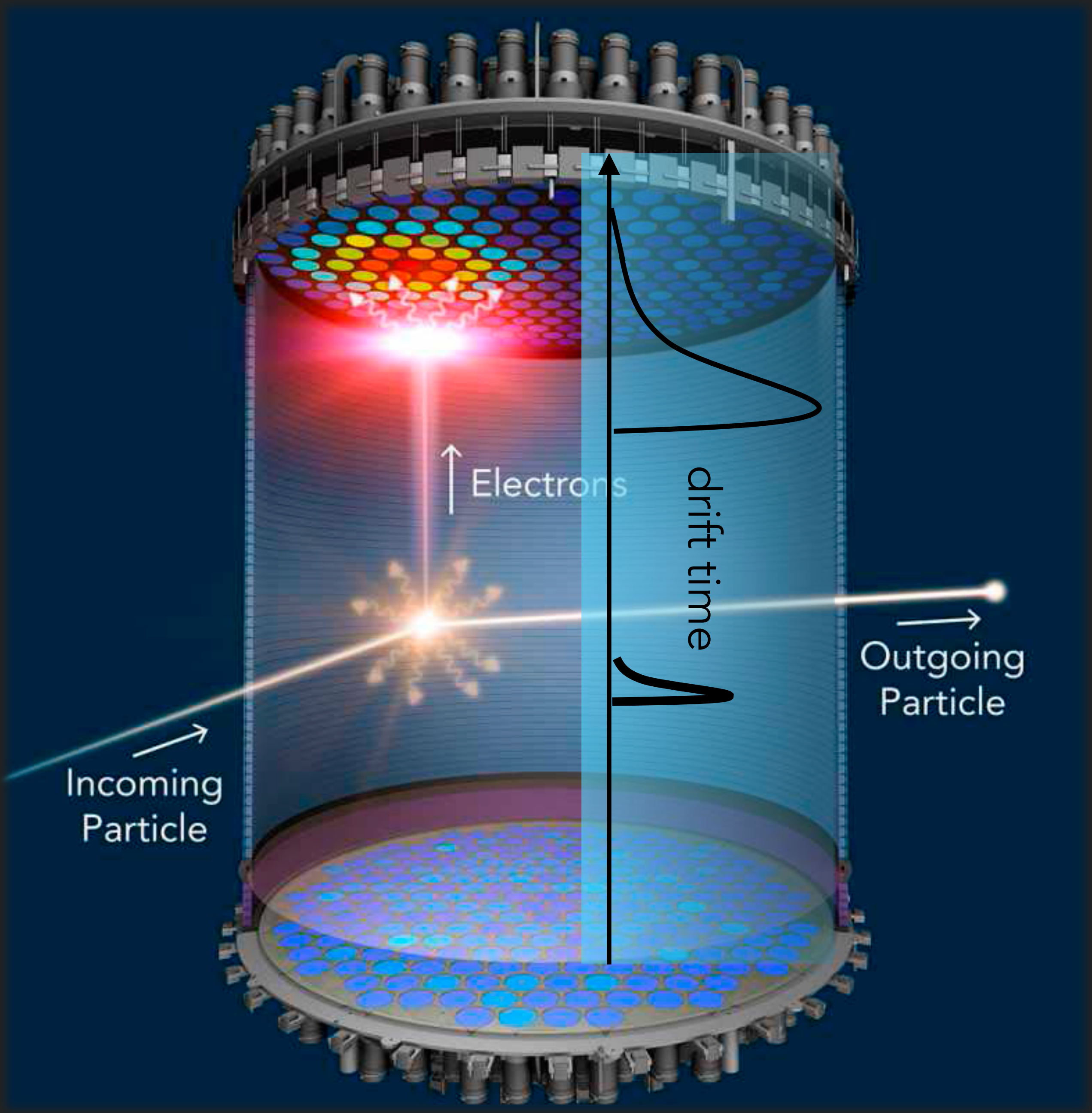


dual-phase noble liquid TPC — bubble chamber — directional detector

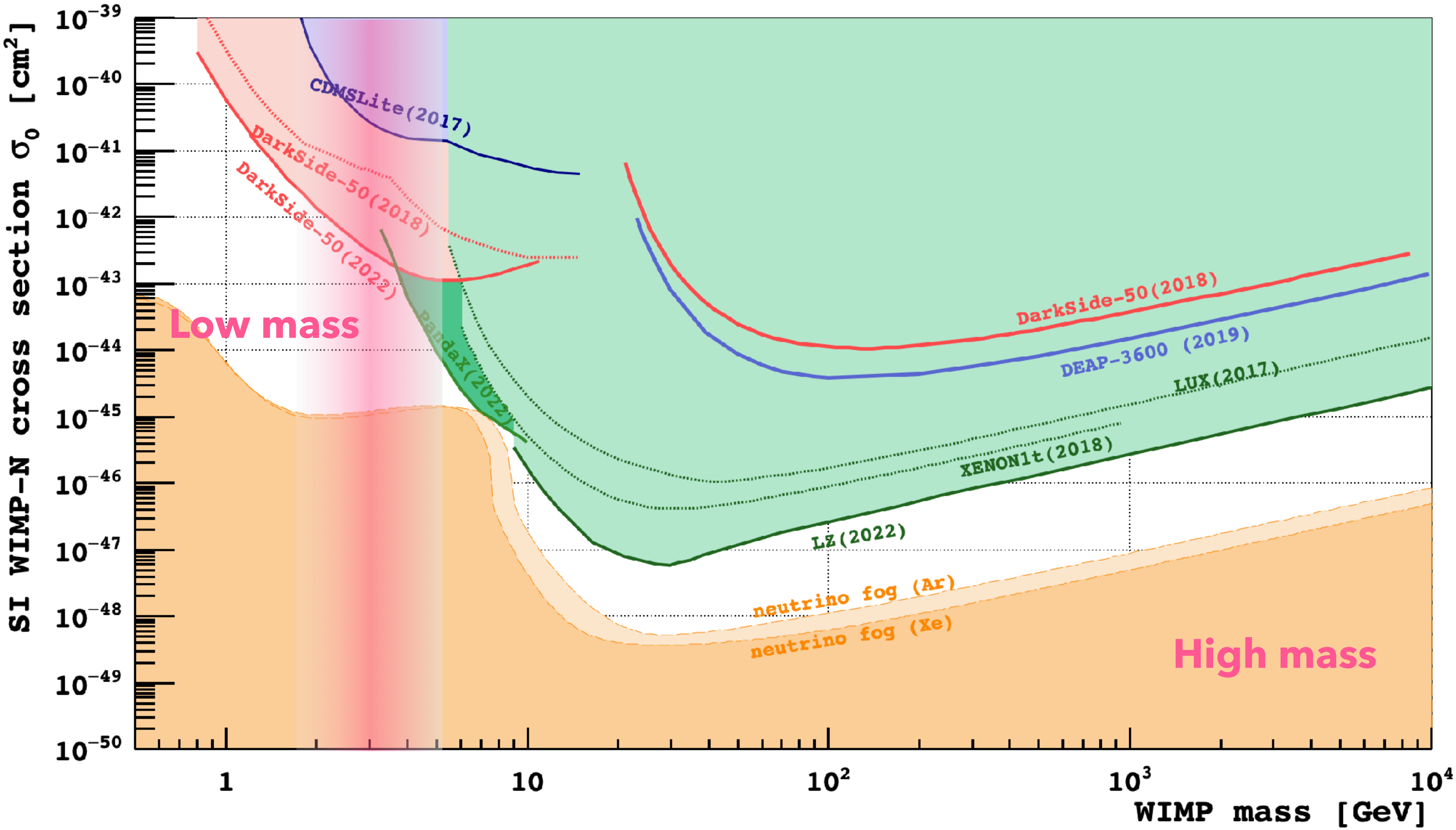
APPEC DM Report, Rep. Prog. Phys. 85 (2022) 056201

LARGE EXPOSURE: NOBLE LIQUID TPC

- dual-phase Time Projection Chambers with multi-tonne liquid Xe, Ar targets
- read out primary scintillation: "S1" + proportional gas scintillation from drifted electrons: "S2"
- 3D position reconstruction:
  - time difference between S1 and S2 gives Z position (few mm resolution)
  - pattern of S2 light gives XY position (~1cm resolution)
- background identification + passive suppression
- zeptobarn (10^{-45} cm^2) to yoctobarn (10^{-48} cm^2) sensitivity to WIMP dark matter

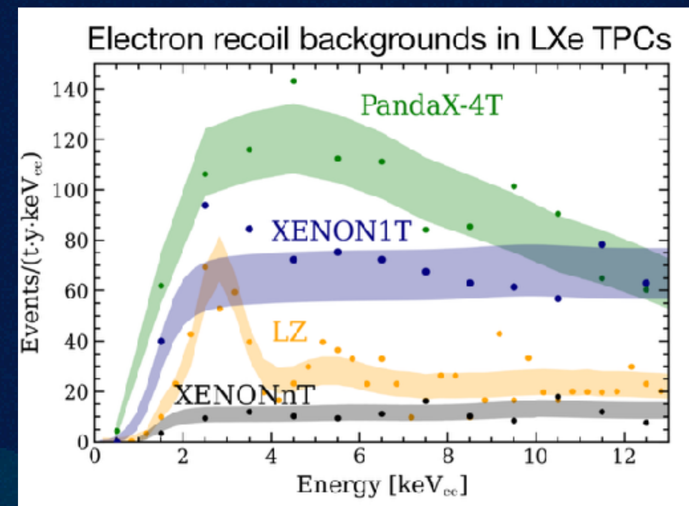


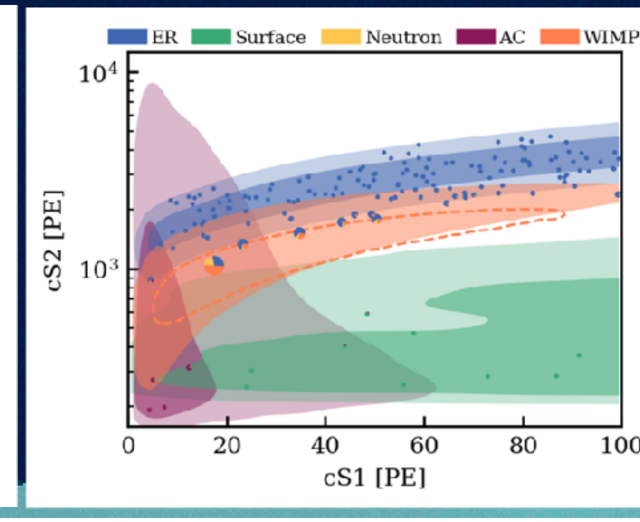
SENSITIVE TO A BROAD RANGE OF WIMP MASSES



XENON DETECTORS

LZ: best limit for high WIMP masses
XENON: lowest background from ER





XENON:2303.14729

2010

10 kg **XENON 10** (LNGS)

ZEPLIN II (Boulby)

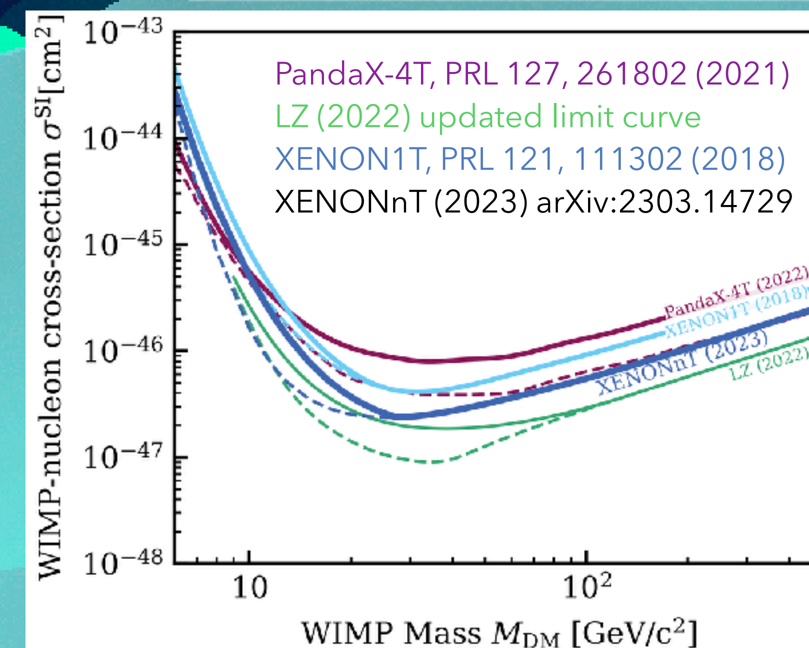
ZEPLIN III (Boulby)

XENON 100 (LNGS)

100 kg

LUX (250 kg, SURF),

PANDA-X (500 kg, CJPL)



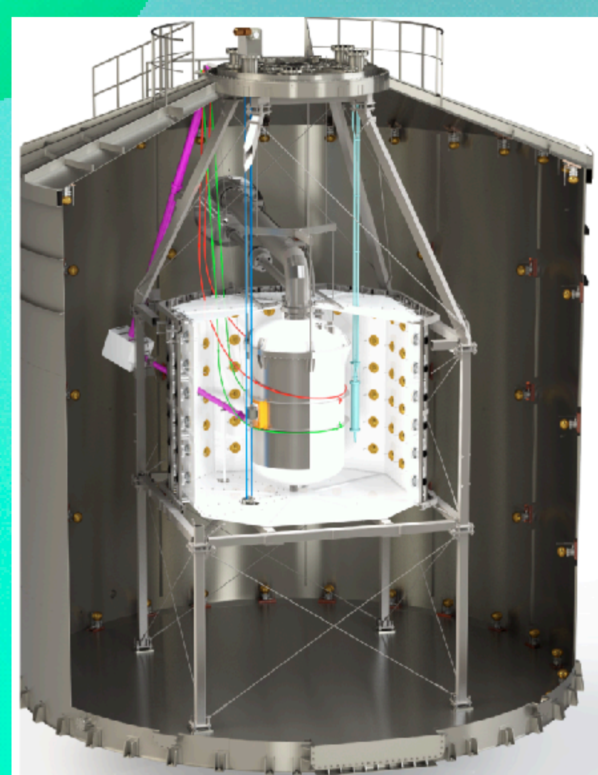
E. Aprile UCLA DM2023

2015

XMASS (0.8t, Kamioka)

1000 kg

XENON 1T (1t, LNGS)



PandaX-4:(4t, CJPL)

XLZD Consortium formed

2020

XENONnT: (6t, LNGS)

LZ: (7t, SURF)

10000 kg

DARWIN, PandaX-xT: 50 t

arXiv:2203.02309v1

Credits: Jocelyn Monroe, ESPP, Granada 2019

ARGON DETECTORS

LAr high mass: background discrimination

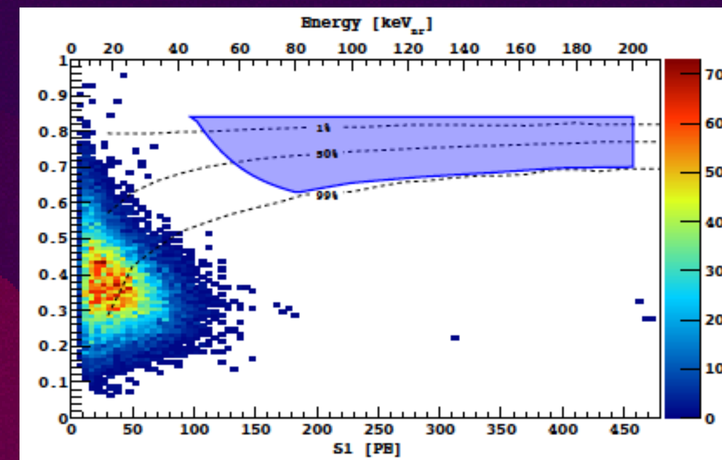
2010

10 kg

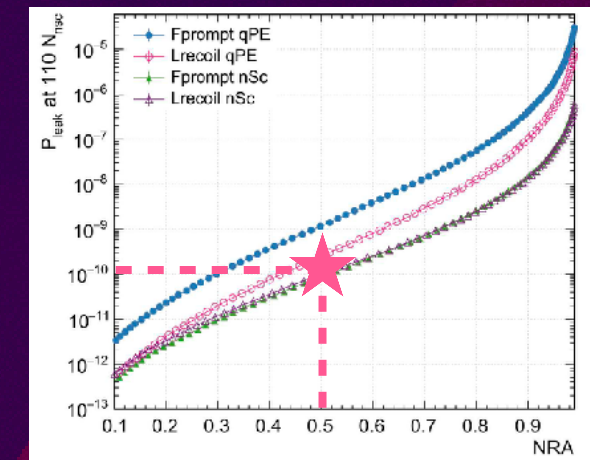
DarkSide-50
(50 kg, LNGS)

ArDM
(1t, LSC)

100 kg



Phys. Rev. D 98, 102006 (2018)



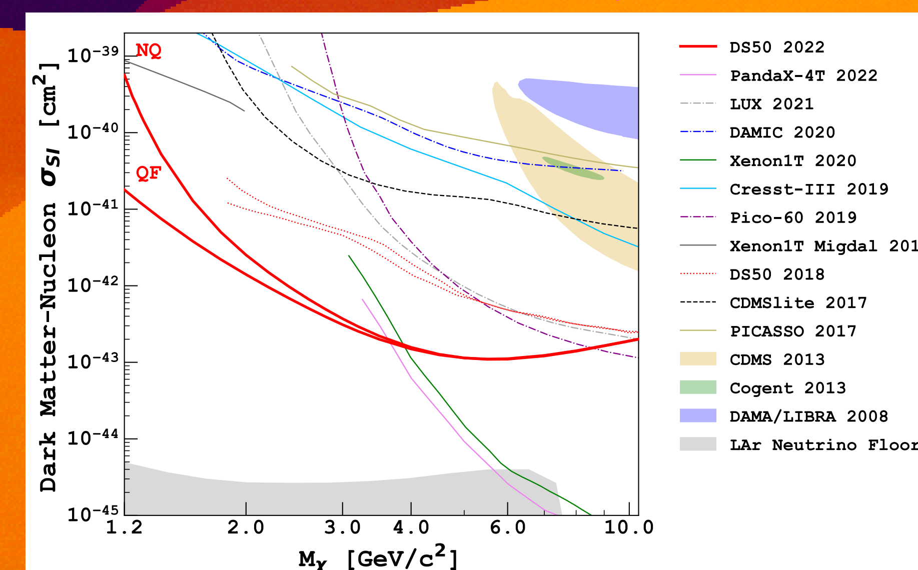
Eur. Phys. J. C 81, 823 (2021)

DS50 low mass: leading SI limit at 1.2-3.6 GeV/c^2

1000 kg

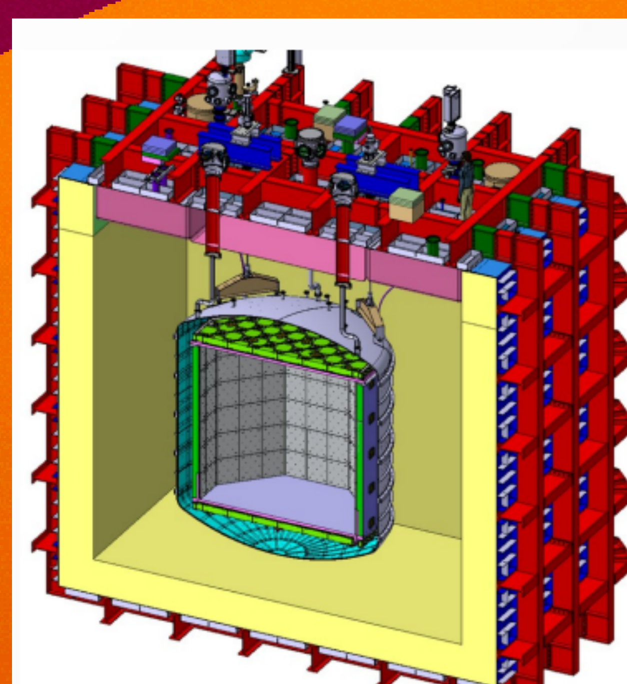
2015

DEAP-3600
(3.6t, SNOLAB)



10000 kg

Phys. Rev. D 107, 063001 (2023)



Global Argon Dark Matter Collaboration formed

2020

DarkSide-20k
(50t, LNGS)

100000 kg

ARGO: 400 t, SNOLAB

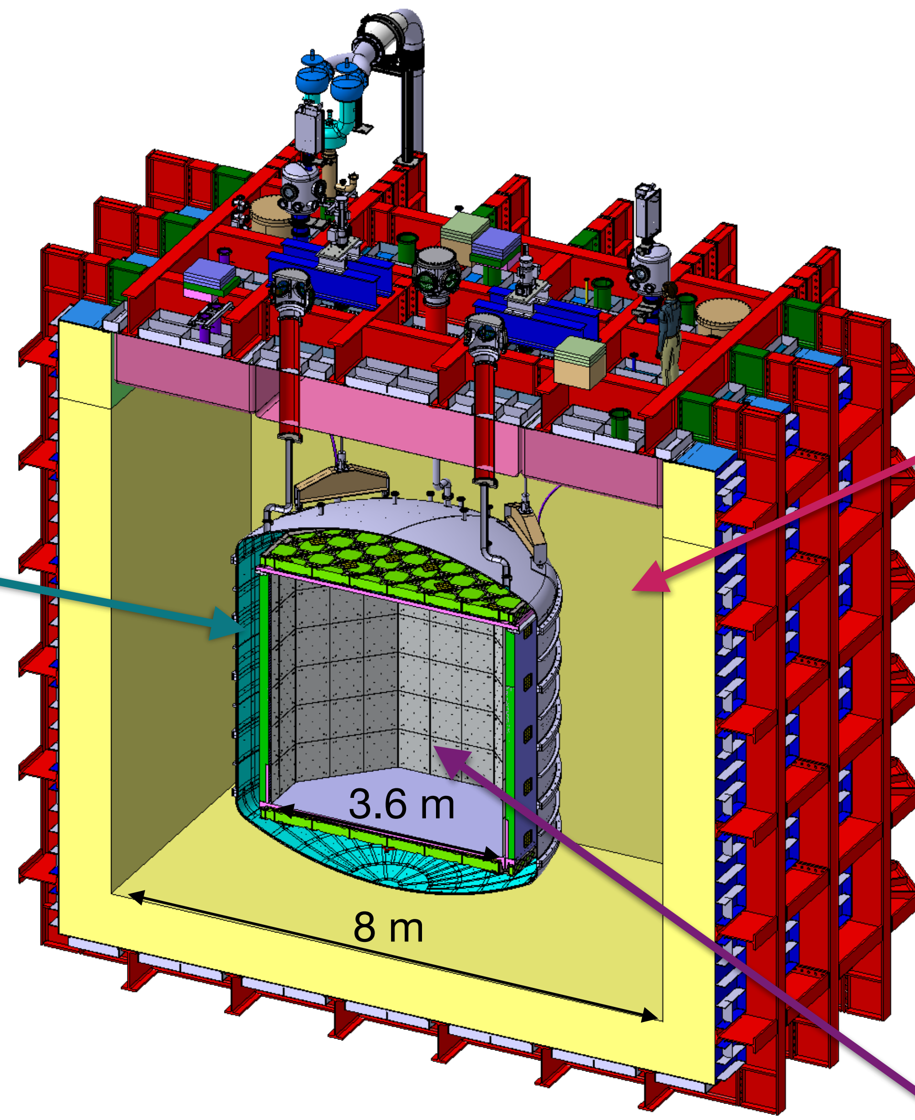
Credits: Jocelyn Monroe, ESPP, Granada 2019

THE DARKSIDE-20K DETECTOR

Inner Veto

Radiogenic n's

12-ton underground LAr



Outer Veto

Cosmic μ's and showers

600-ton atmospheric LAr

TPC

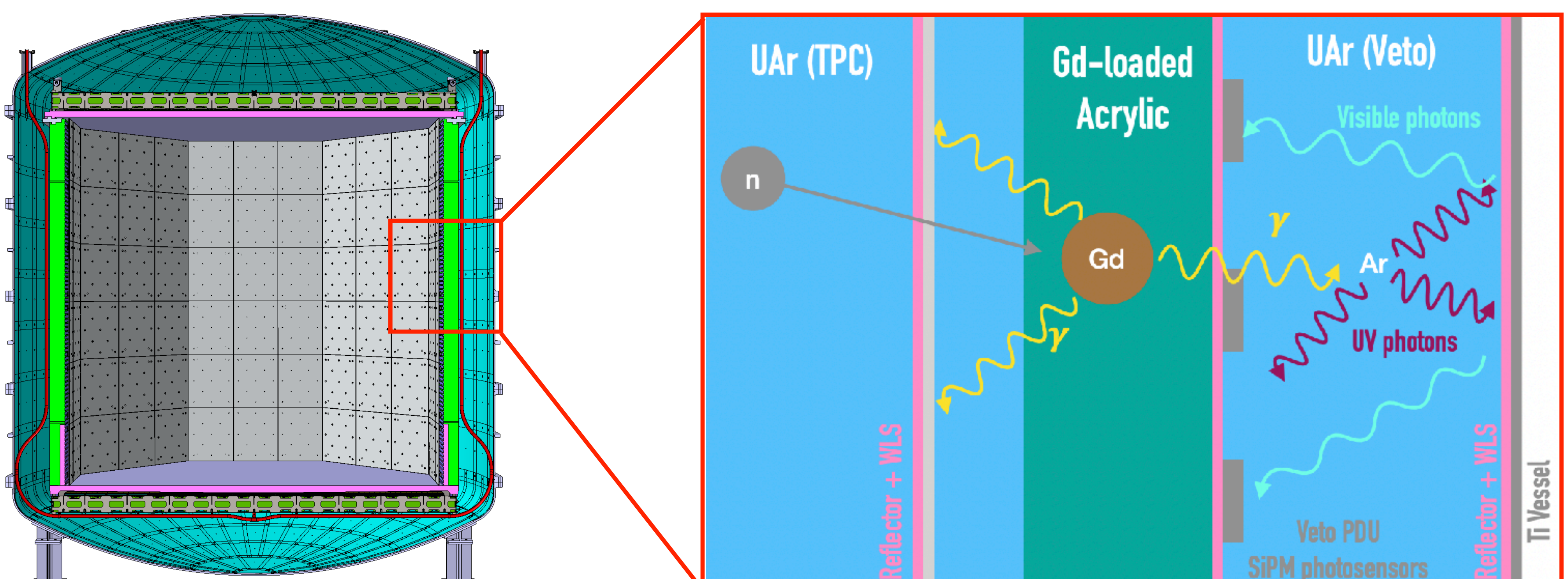
Dark matter detector

50-ton underground LAr/GAr

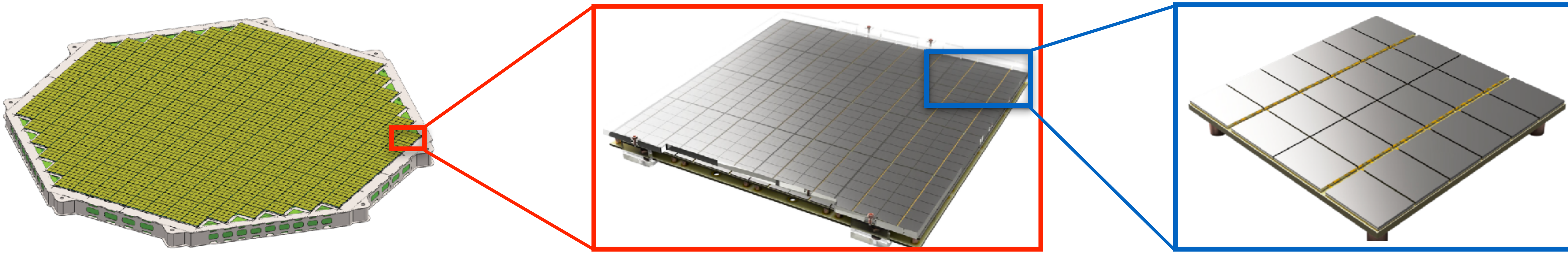
(20-ton fiducial mass)

NEUTRON TAGGING VIA Gd-LOADED ACRYLIC

- γ-rays (<8MeV) from n capture by Gd
- n-tagging efficiency ~90%
- R&D finished and production started



LOW RADIOACTIVITY, HIGH EFFICIENCY SiPM PHOTOSENSORS

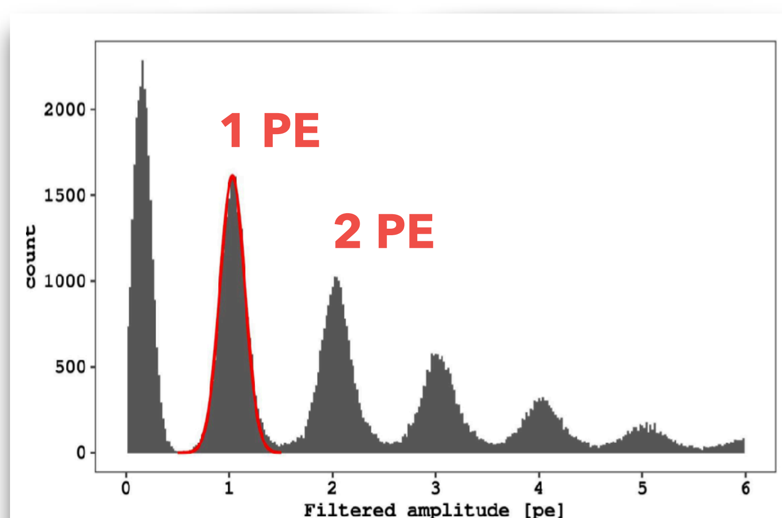


TPC optical plane ($\sim 21\ \mathrm{m}^2$)
525 PDUs

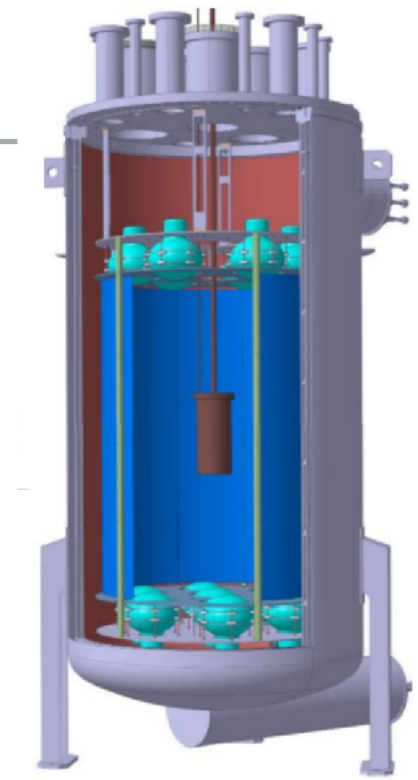
Photo Detection Unit
16 tiles arranged into 4 channels

Tile / photo-detector module
24 SiPMs + signal amplifier

- Wafer delivery from LFoundry started in 2022
- Packaging and assembly for TPC sensors: **Nuova Officina Assergi** (NOA), about to start operations
- Packaging and assembly for Veto sensors: RAL and Liverpool, UK
- Several test facilities to qualify production: Naples, Liverpool, Edinburgh, AstroCent



LOW RADIOACTIVITY ARGON: URANIA & ARIA



1) UAr extraction at the URANIA plant.

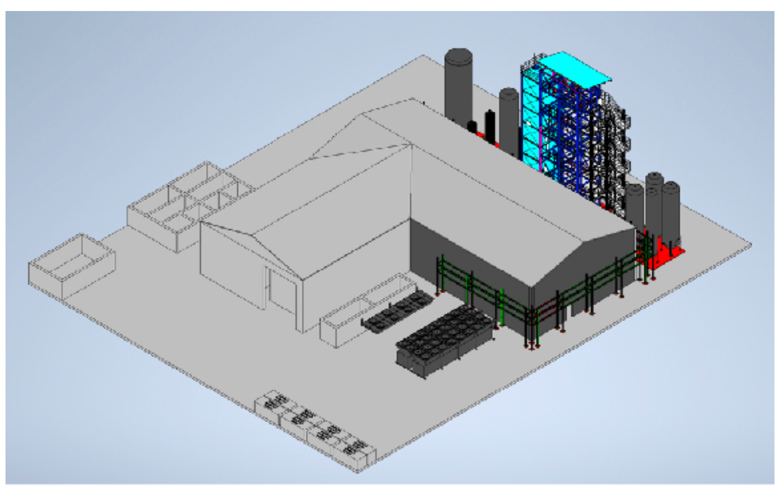
^{39}Ar (β-decay) suppressed by $\sim 10^3$ in underground CO_2 reservoir in Cortez, Colorado

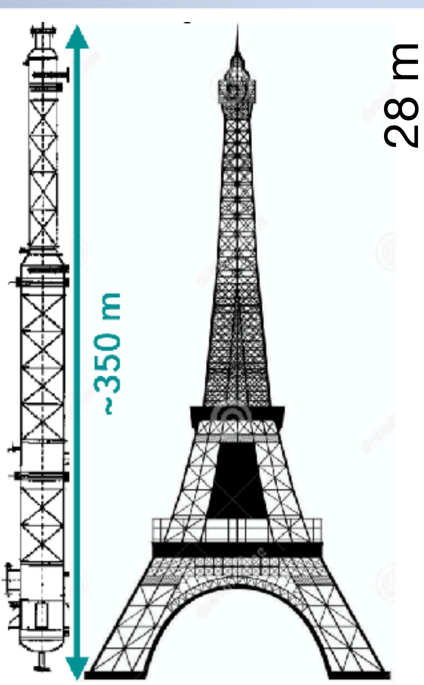
UAr extraction rate: 250-330 kg/day

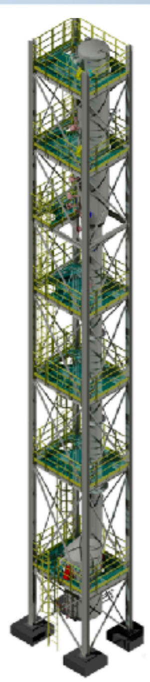
Expected argon purity at outlet: 99.99%

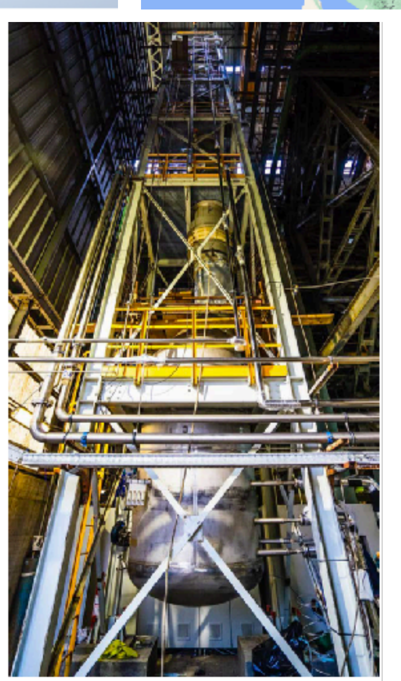
3) Qualification at Canfranc, DArT in ArDM

A single-phase LAr detector with active volume ~1L, capable of measuring UAr to AAr ^{39}Ar depletion factors of the order of 1000 with 10% precision in weeks









Eur. Phys. J. C (2021) 81:359

2) Cryogenic distillation at the ARIA facility

Installed in the shaft of a coal mine

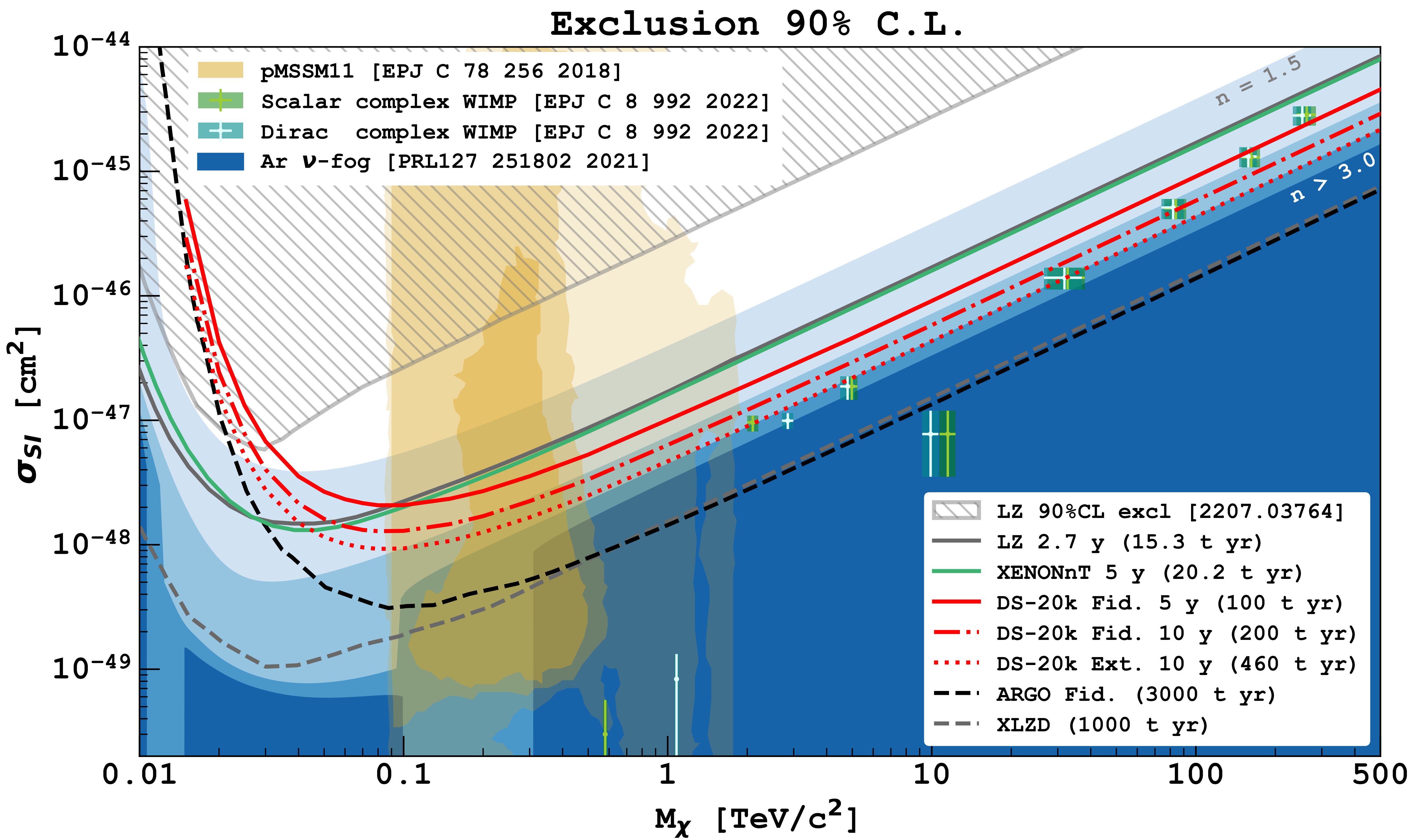
Chemical purification rate: 1 t/day

First module operated according to specs with nitrogen

Run completed with Ar at the end of 2020: results to be published soon

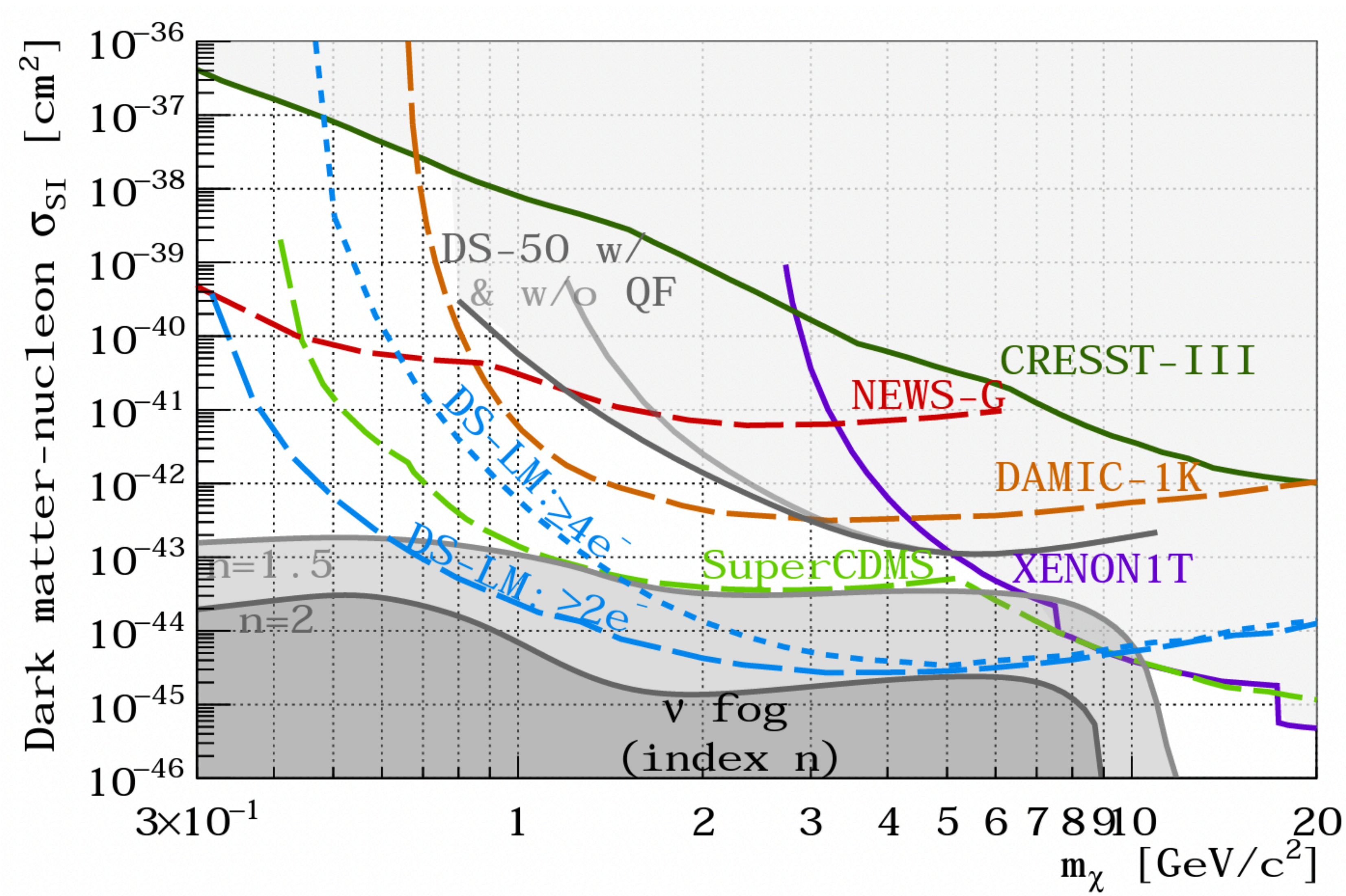
Full assembly about to start

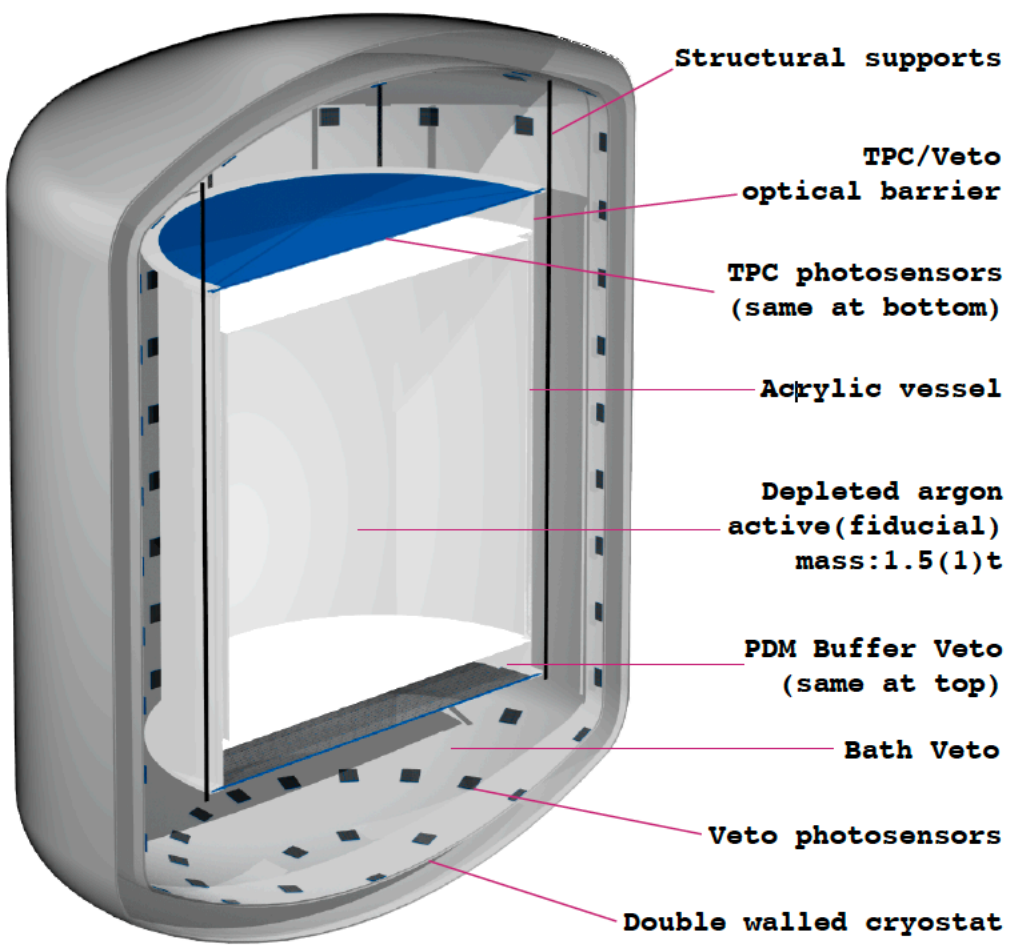
HIGH MASS WIMP SI INTERACTION EXCLUSION LIMITS PROSPECTS



LOW MASS WIMP SI INTERACTION EXCLUSION LIMITS PROSPECTS

Sensitivity projection for a 1 ton-year exposure dualphase LAr TPC optimized for light dark matter searches through the ionization channel

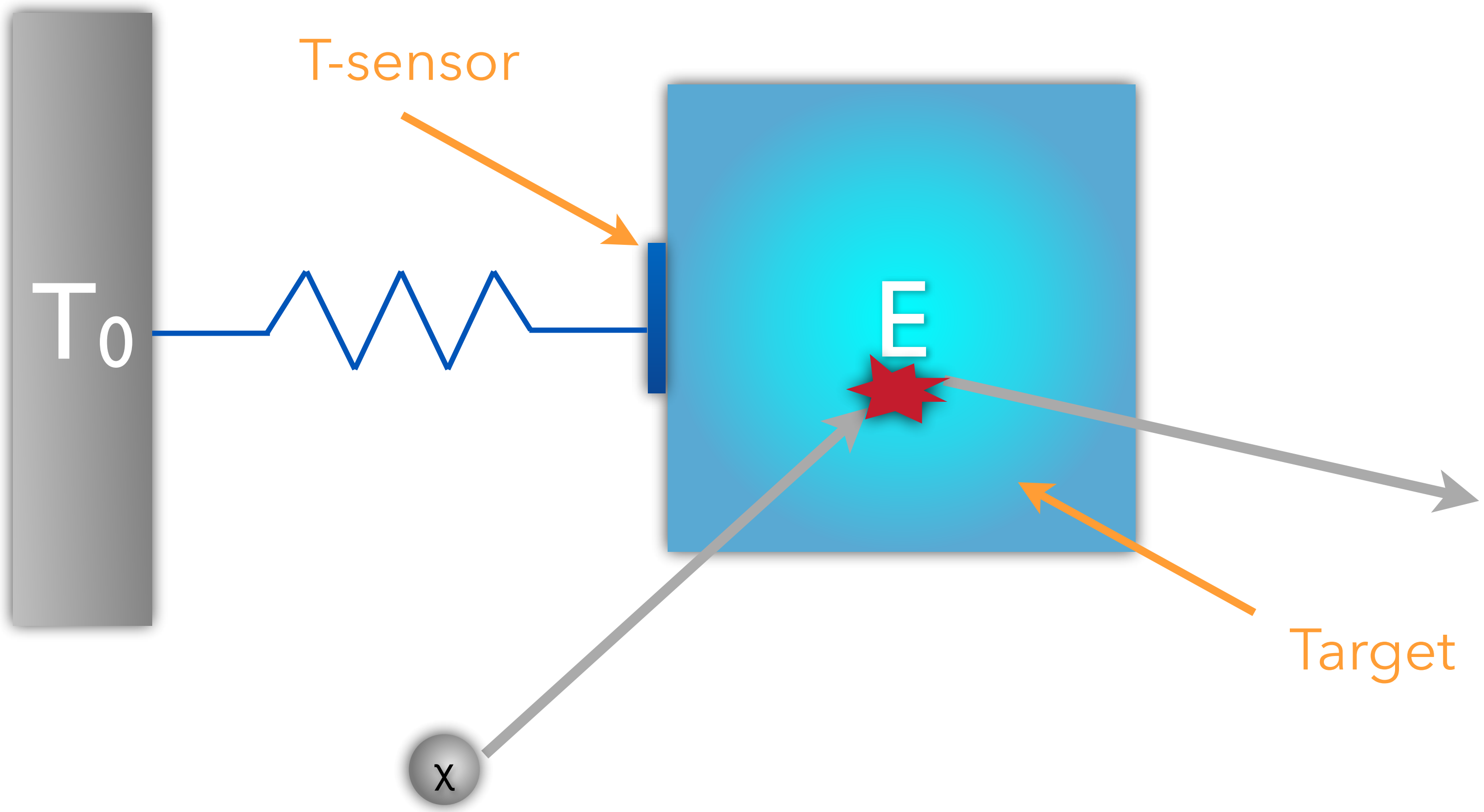


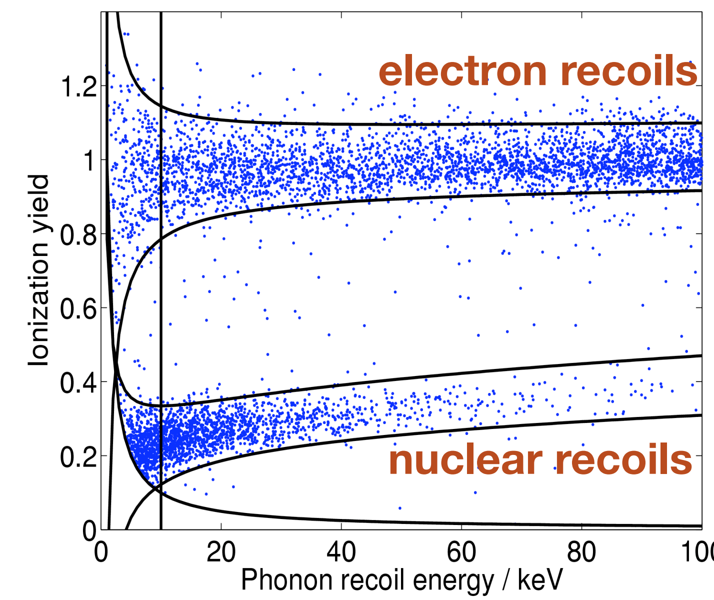


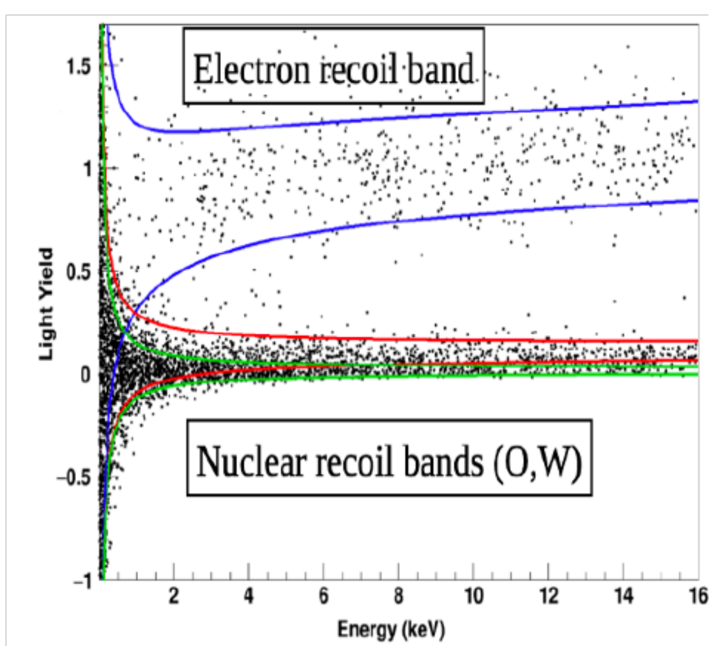
arXiv:2209.01177

LOW THRESHOLD: BOLOMETERS

CHARGE & PHONONS:	SUPERCDMS EDELWEISS
LIGHT & PHONONS:	CRESST COSINUS





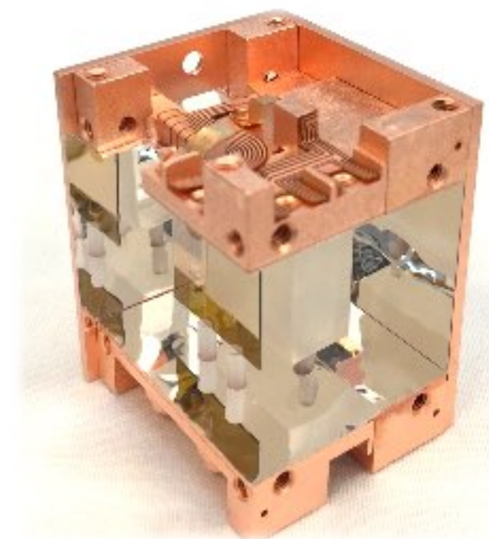


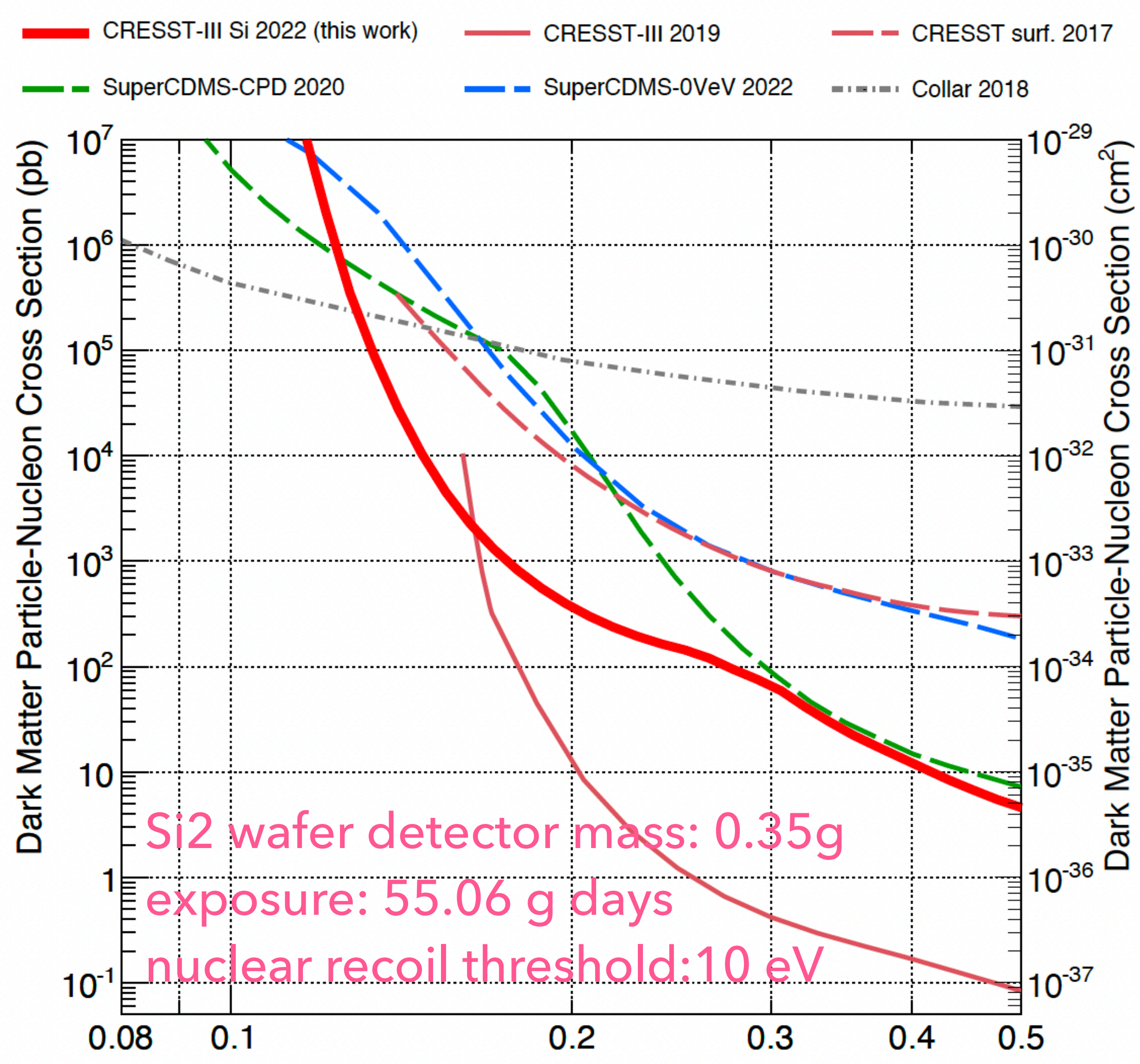
E deposition → temperature rise ΔT ~ μK → requires detectors at mK

- Sub-keV (< 100 eV) energy thresholds & background discrimination
- Crystals: Ge, Si, $CaWO_4$, NaI
- T-sensors:
  - superconductor thermistors (highly doped superconductor): NTD Ge → **EDELWEISS**
  - superconducting transition sensors (thin films of SC biased near middle of normal/SC transition): TES → **CDMS, CRESST, COSINUS**

CRESST @LNGS

- Sub-GeV WIMP mass sensitivity
- **CRESST-III** run 07/2016 - 02/2018
  - Target crystal mass: 23.6g
  - Gross exposure (before cuts): 5.7 kg days
  - Nuclear recoil threshold: 30 eV
- Low Energy Excess, still being investigated
  - LEE observed "everywhere", in particular in cryogenic experiments → one single common origin considered unlikely, stress from crystal, sensor or holding.
- Recent results in the ~100 MeV range for the DM mass and for both SI (Si, CaWO4) and SD (LiAlO2) interactions
- Moving ahead to increase the exposure to consolidate the capability of light DM detection





arXiv:2212.12513v1

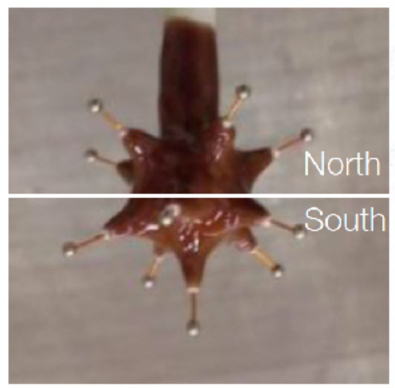
LOW THRESHOLD: SPC & CCD

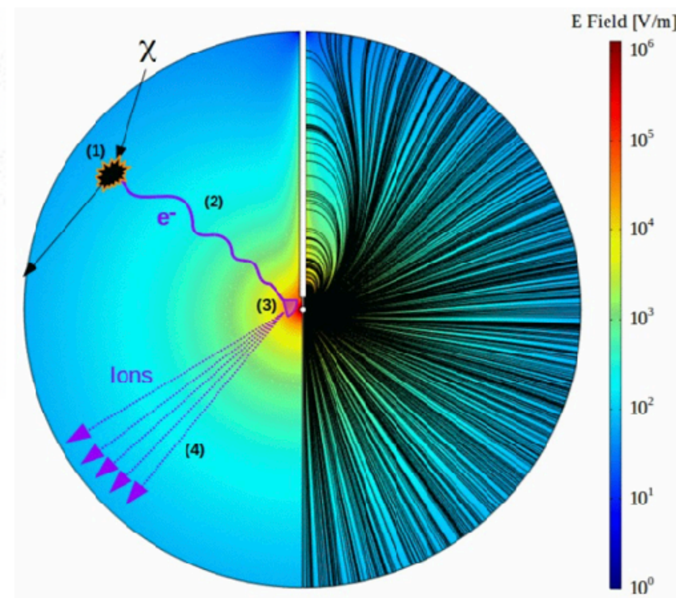
- **SPC**: spherical proportional counter, light targets (H, He, Ne), pulse shape discrimination against surface events, low energy threshold (very low capacitance)
- **Skipper CCDs**: low ionization energy, low noise, and particle tracks for background reduction, particle ID (DAMIC-M, SENSEI)

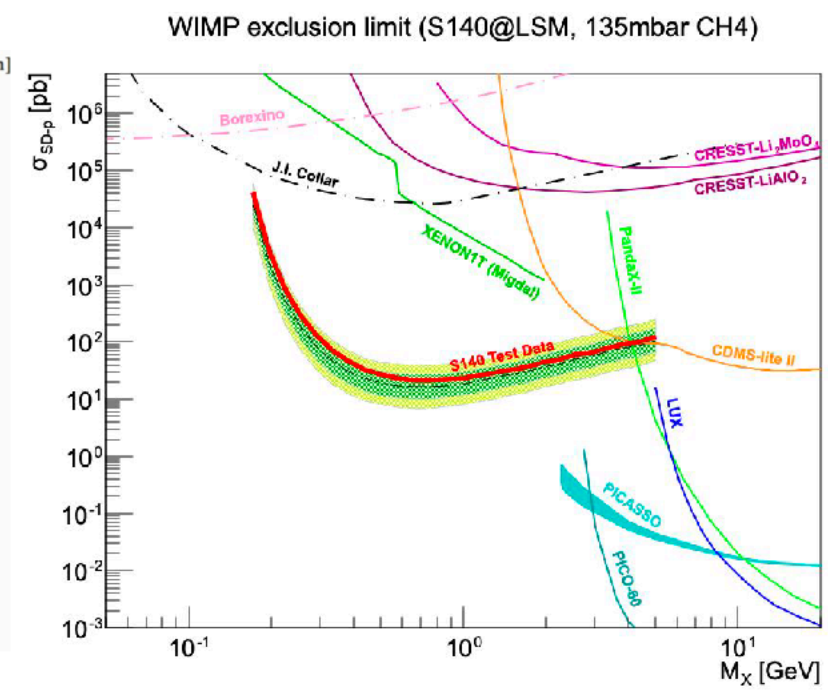
NEWSG @LSM

140 cm diameter copper sphere

135 mbar of pure CH4 (110 g)

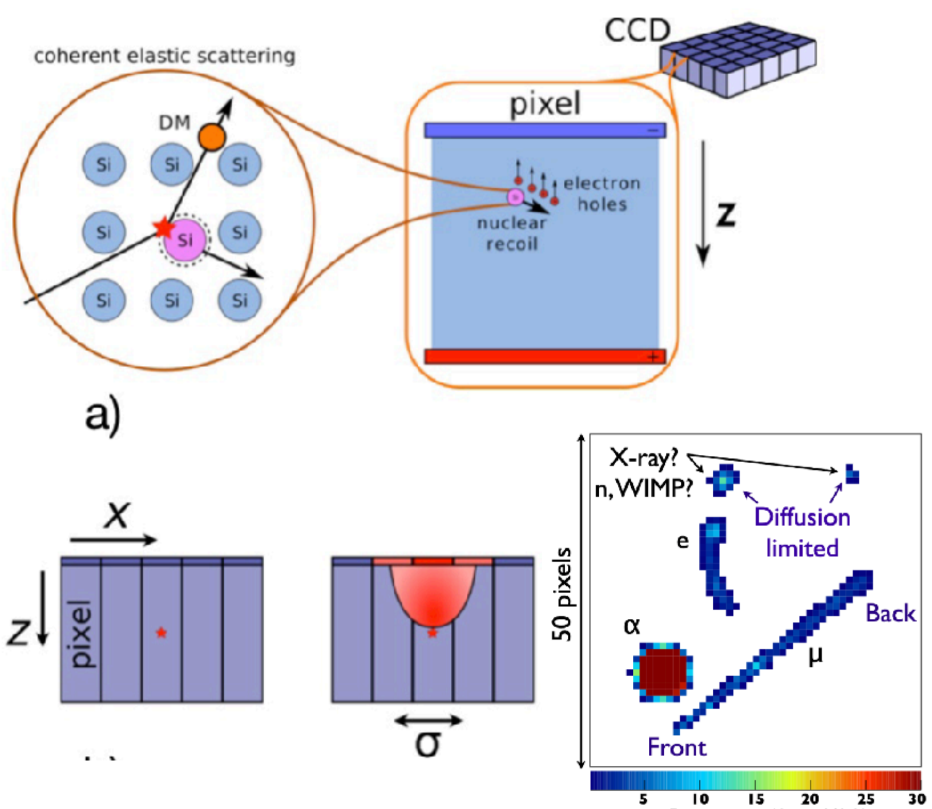


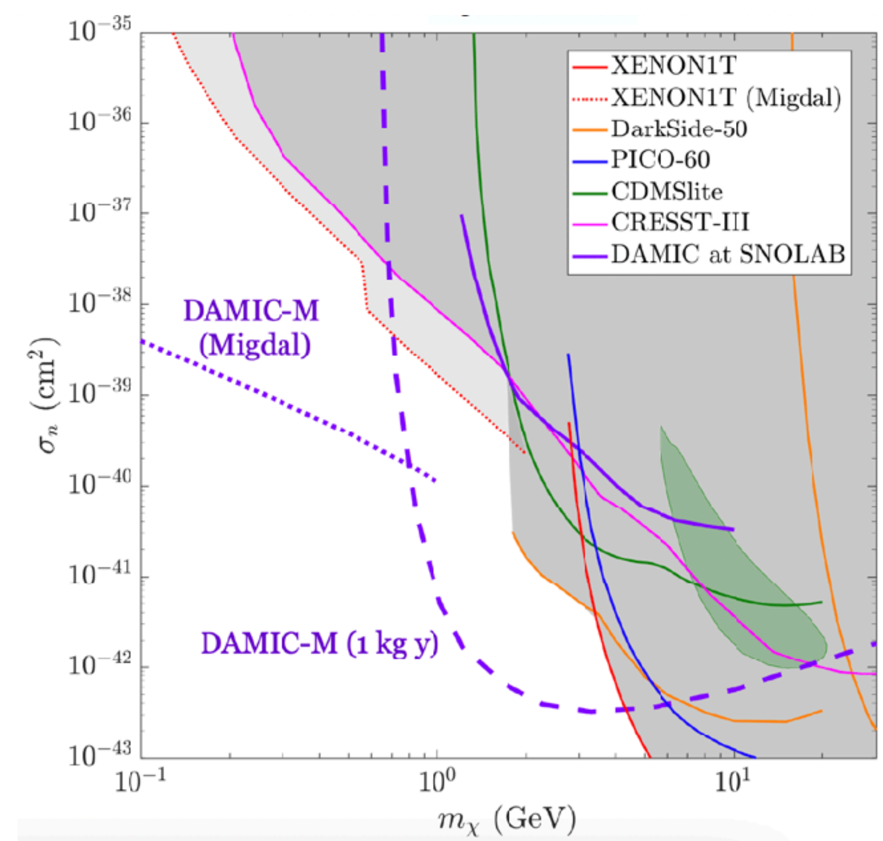




D. Durnford UCLA DM 2023

DAMIC-M @LSM





J-P.Zopounidis UCLA DM 2023

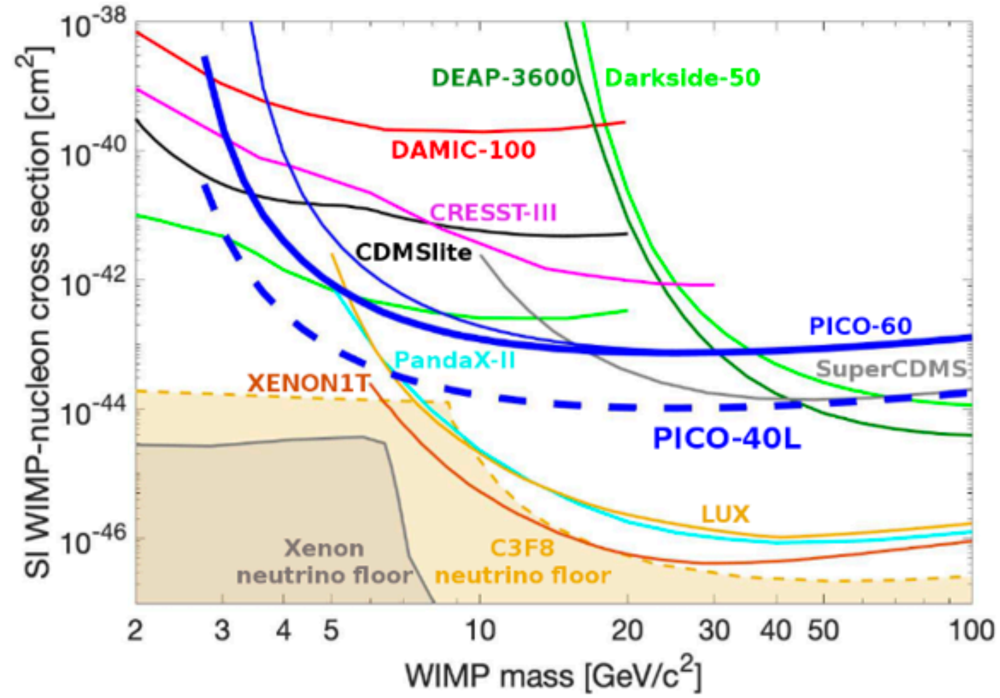
THRESHOLD DETECTORS

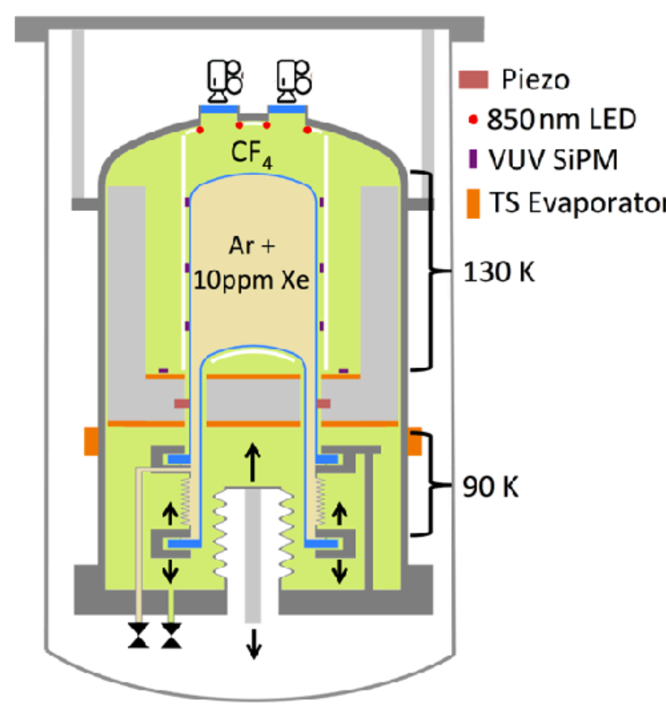
Quasi background-free detection of sub-keV nuclear recoils:

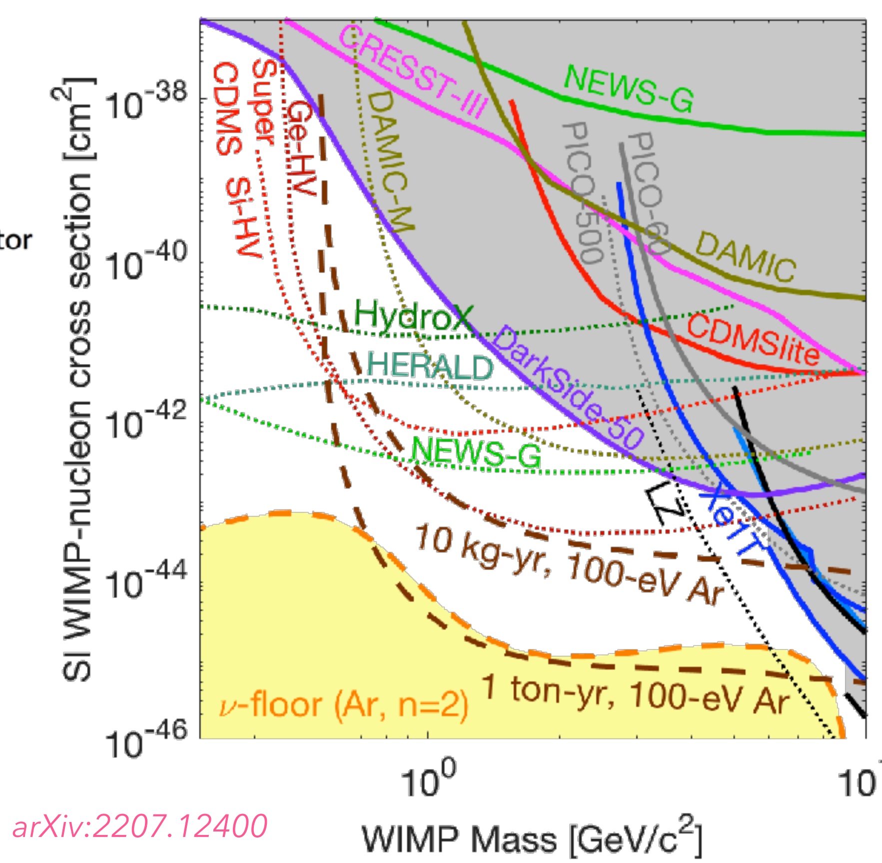
- Nucleation depends on NR threshold and target fluid:
  - Freon-based chambers ER-blind @ ~3 keV
  - Liquid-noble chambers ER-blind @ < 500 eV, (target 100 eV)

- **PICO** (SNOLAB): superheated freon target, camera + acoustic readout, background rejection based on topology O(10^{-2})
  - **PICO-60** SD WIMP-p best limit with 60 kg C_3F_8 target
  - **PICO-40L** new design running
  - **PICO-500** planned
- **SBC** (SNOLAB): Scintillating Bubble Chamber, superheated 10 kg Xe-doped LAr, cooled to 130 K, piezoelectric sensors + cameras readout + SiPMs for scintillation signal
  - **SBC-LAr10** demonstrator @Fermilab running in 2024, radio pure detector gearing up for first DM search @SNOLAB

Phys. Rev. D 100, 082006 (2019)



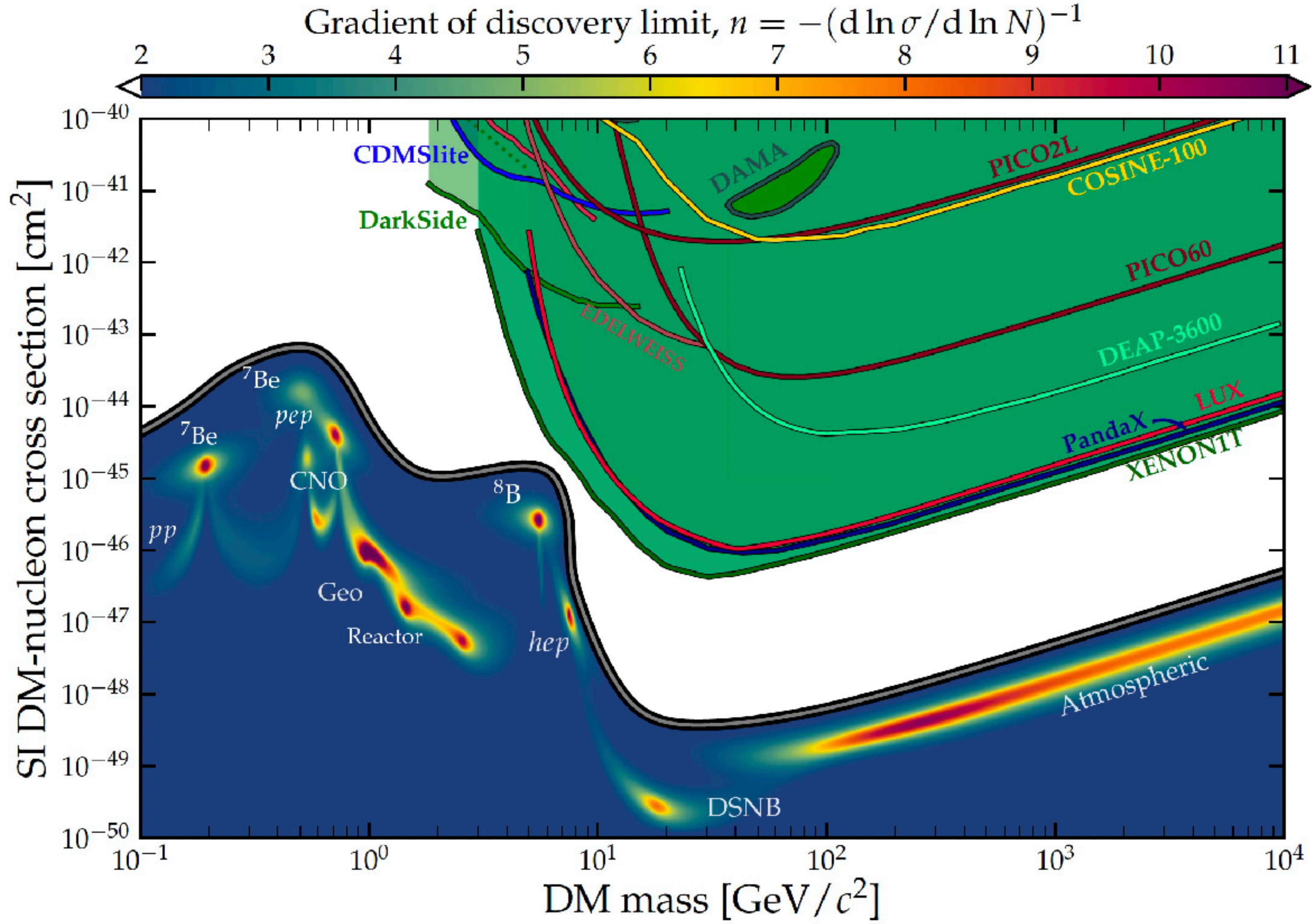




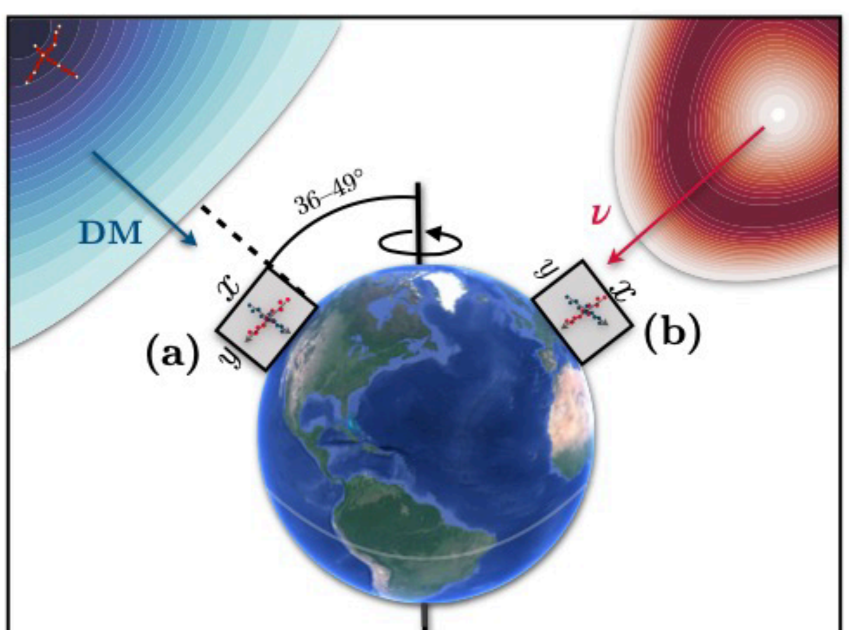
arXiv:2207.12400

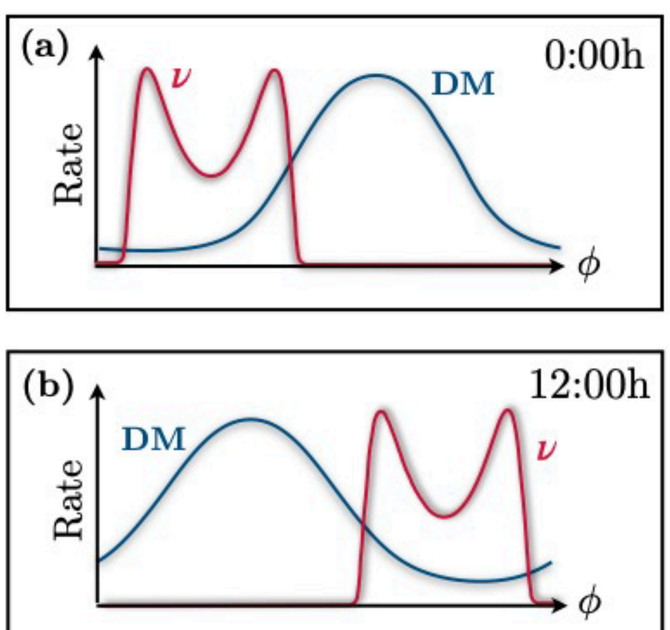
DIRECTIONALITY: THROUGH THE NEUTRINO FOG

- Directional detectors can separate neutrino and DM signals
- n remains <2 even in the neutrino fog
- fog becomes a positive: a source of guaranteed signal in DM experiment!



arXiv:2109.03116

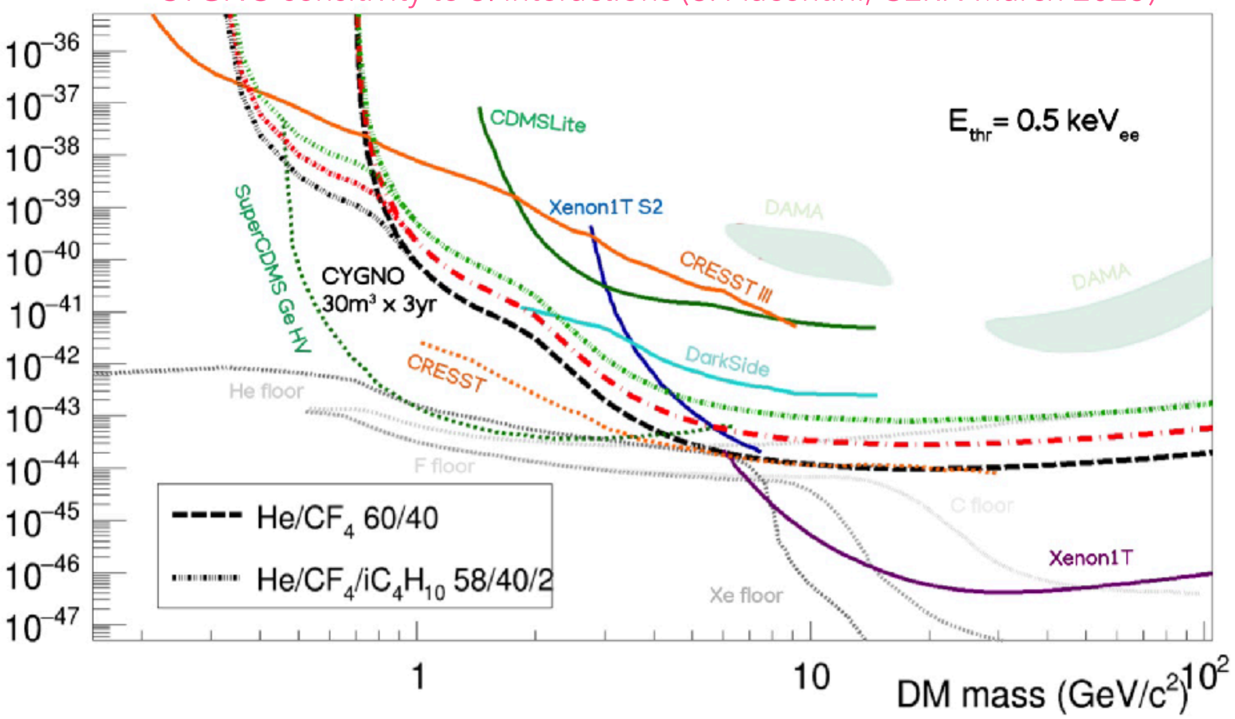




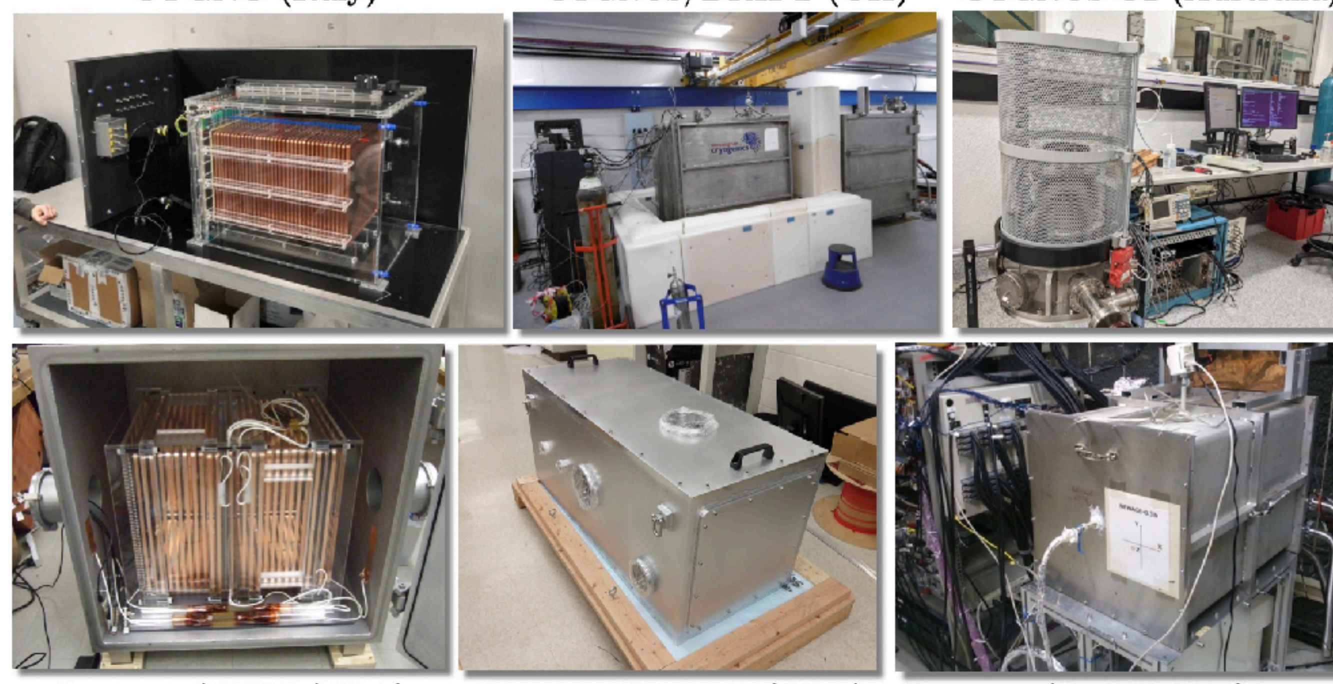
DIRECTIONALITY: THROUGH THE NEUTRINO FOG

- Mature technology: gaseous TPC with different readouts ➟ **CYGNUS (10-1000 m³)**

CYGNO sensitivity to SI interactions (S. Piacentini, CERN March 2023)

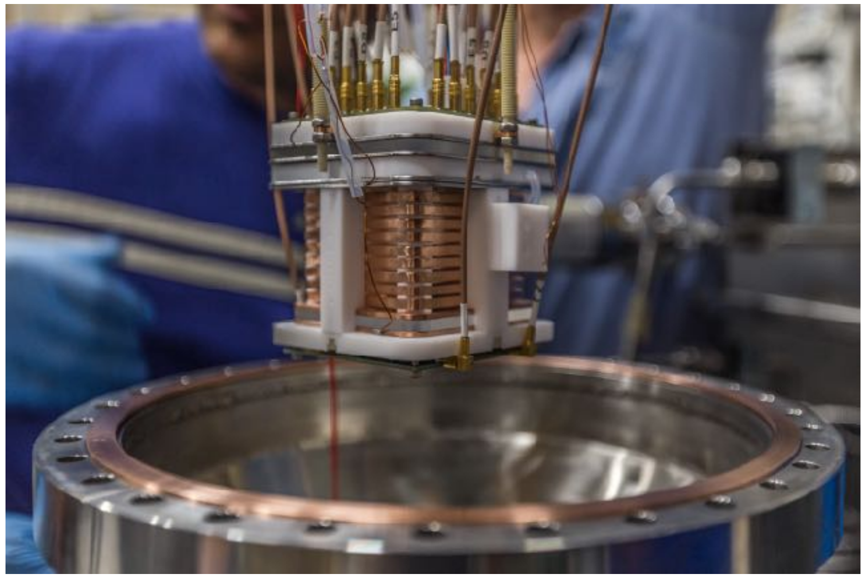


CYGNO (Italy) | CYGNUS/DRIFT (UK) | CYGNUS-Oz (Australia)

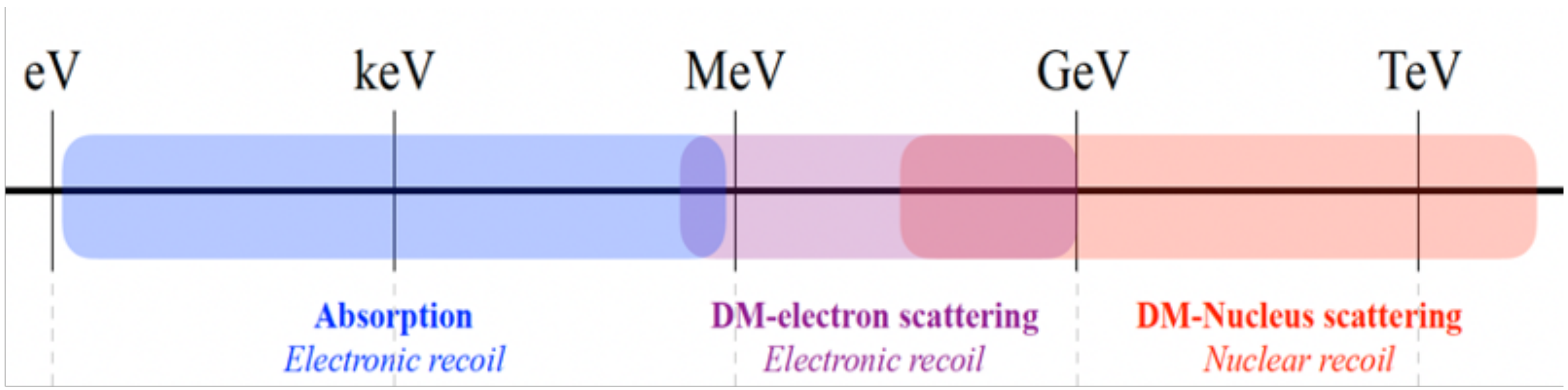


CYGNUS/UNM (USA) | CYGNUS-HD 40 L (USA) | CYGNUS/NEWAGE (Japan)

- R&D on several other techniques:
  - **NEWSdm** Nanometric track direction measurement in nuclear emulsions (exploit resonant light scattering using polarised light)
  - **RED** Columnar Recombination in liquid argon TPC
  - **PTOLEMY** Graphene target (nanoribbon or nanotubes)

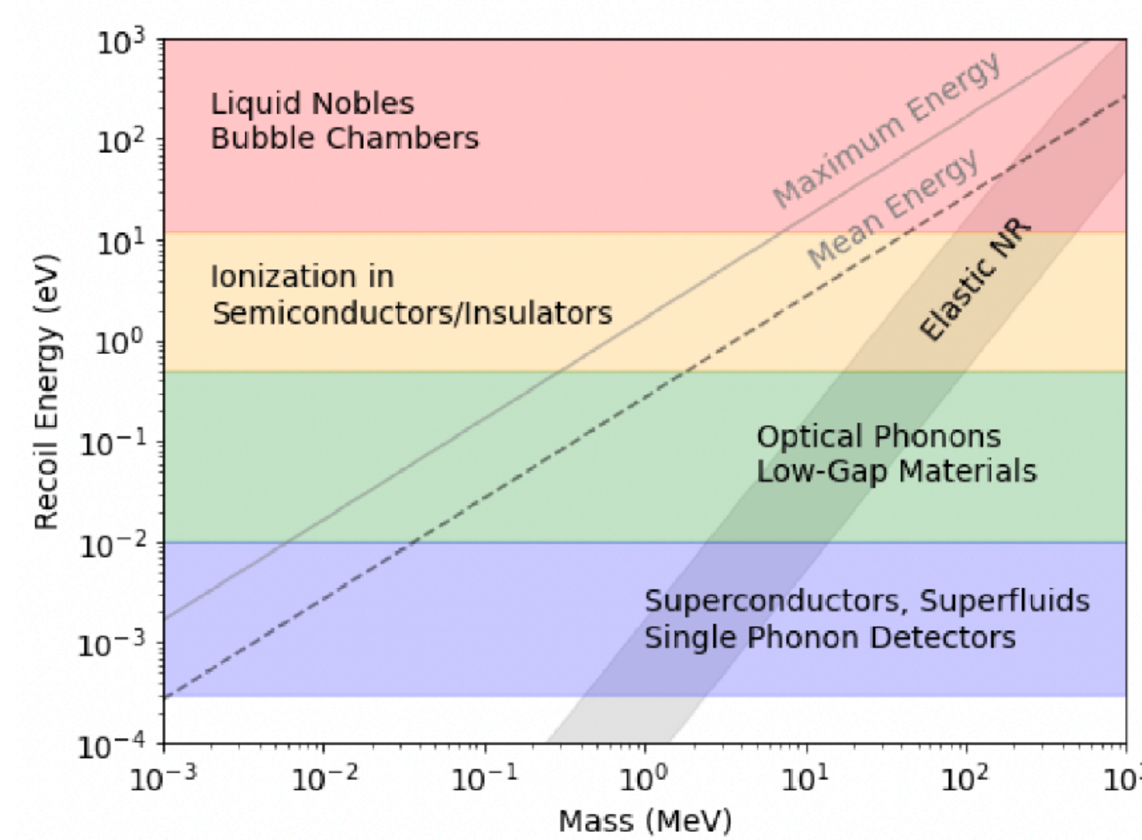


LIGHT DARK MATTER (SUB-GEV)



- DM mass kinematically accessible through inelastic interactions extracting substantial fraction of the DM kinetic energy:
  - DM-N scattering w/ Migdal
  - DM-e scattering
  - DM scattering w/ collective modes (e.g. phonons, magnons)

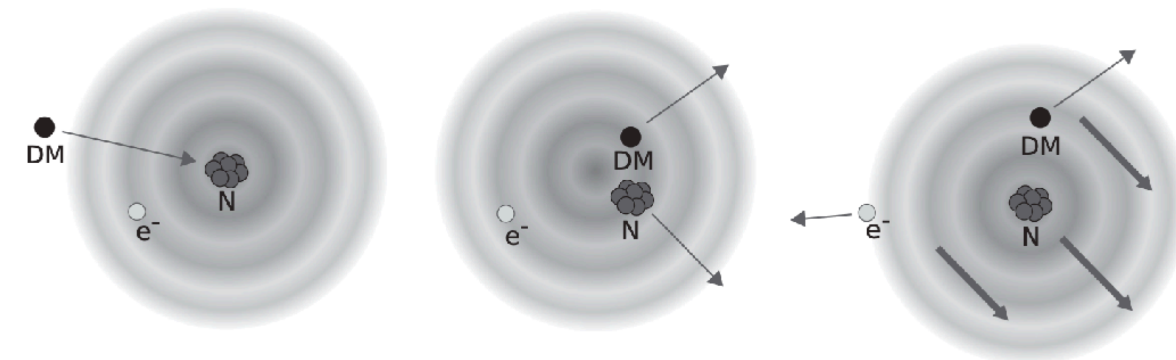
$$E_{\text{kin}} = \frac{1}{2} m_{\text{DM}} v_{\text{DM}}^2 \sim 1 \text{ eV} \left(\frac{m_{\text{DM}}}{1 \text{ MeV}} \right)$$



arXiv:2203.08297

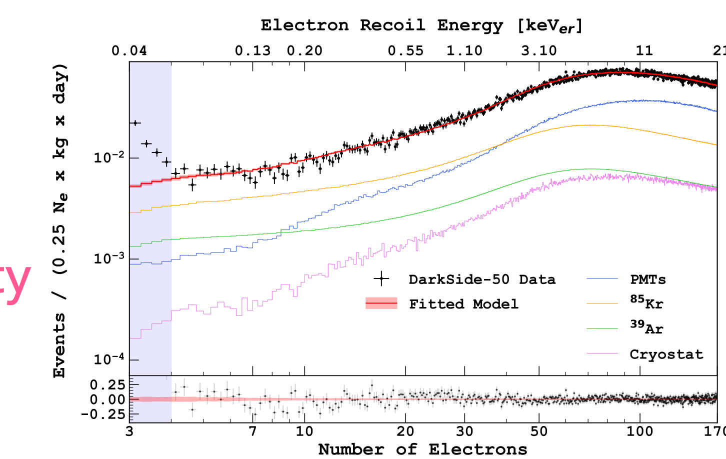
Ibe, et al, JHEP 03 (2018) 194

DM–N SCATTERING w/ MIGDAL

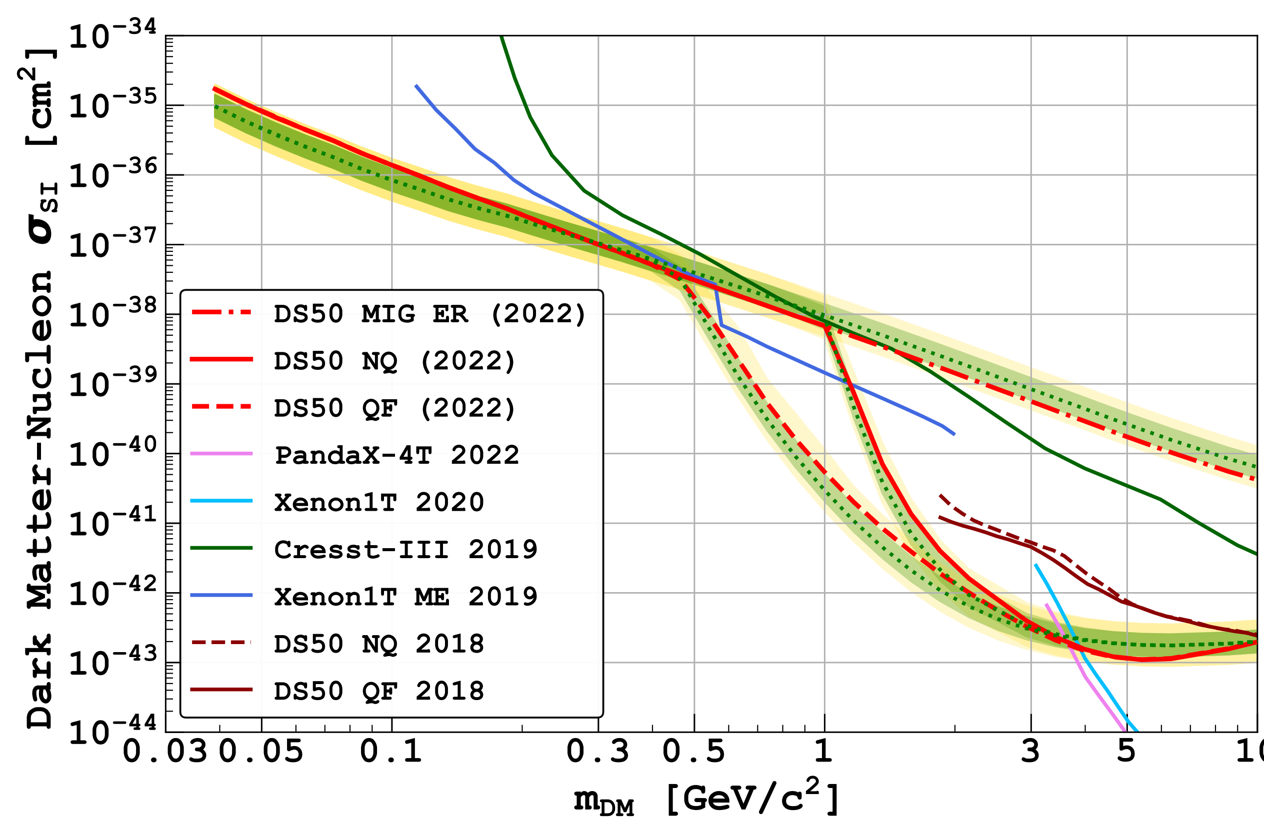


- Interactions between a neutral particle and a nucleus may result in atomic excitation or ionization
- Migdal atomic relaxation can lead to keV electron recoil (ER) energy for sub-keV nuclear recoils (NRs)
- Potential enhancement of low-mass dark matter sensitivity has been explored
  - LUX, PRL 122 131301 (2019)
  - XENON1T, PRL 123 241803 (2019), PRD 106 022001 (2022)
  - DarkSide50, PRL 130 101001 (2023)
  - EDELWEISS, PRD 106 062004 (2022)
  - CDEX-1B, PRL 123 161301 (2019)
  - SuperCDMS, arXiv: 2203.02594
  - and more …
- This effect has not been definitively verified
  - MIGDAL @LLNL: 14.1MeV neutrons on LXe

Analysis based on ionization significantly enhances the sensitivity in sub-GeV region



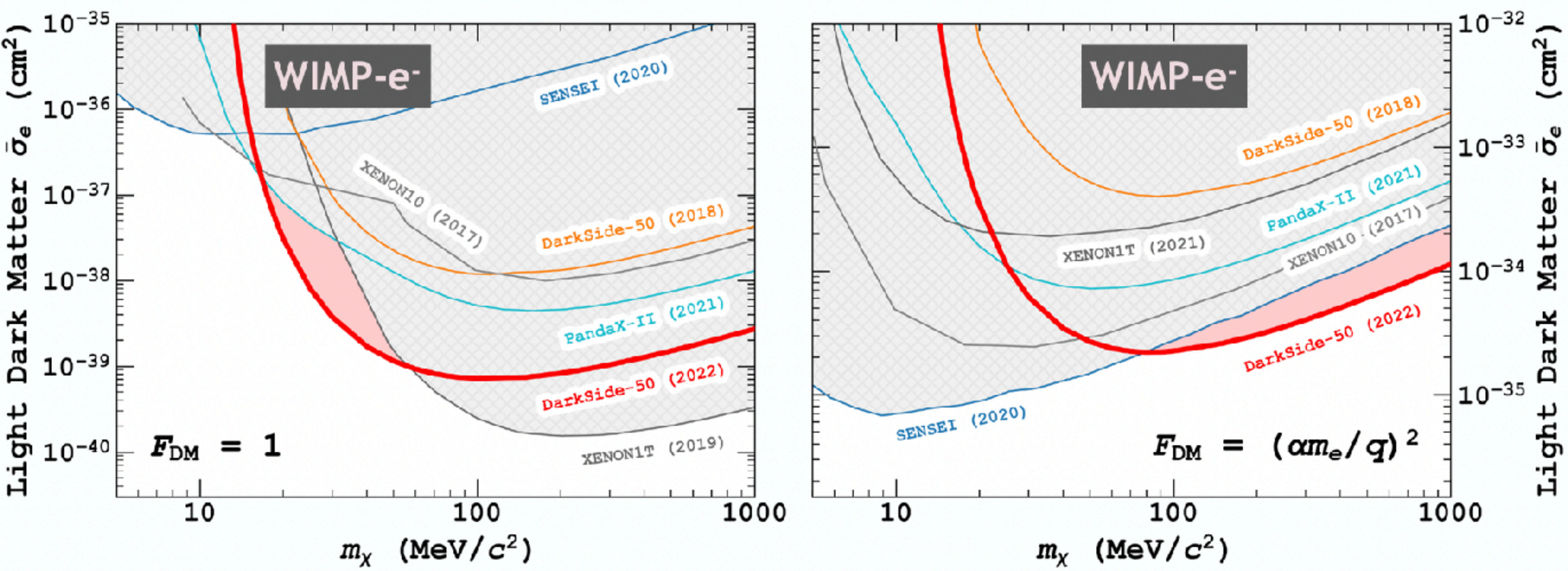
Phys. Rev. D 107, 063001 (2023)



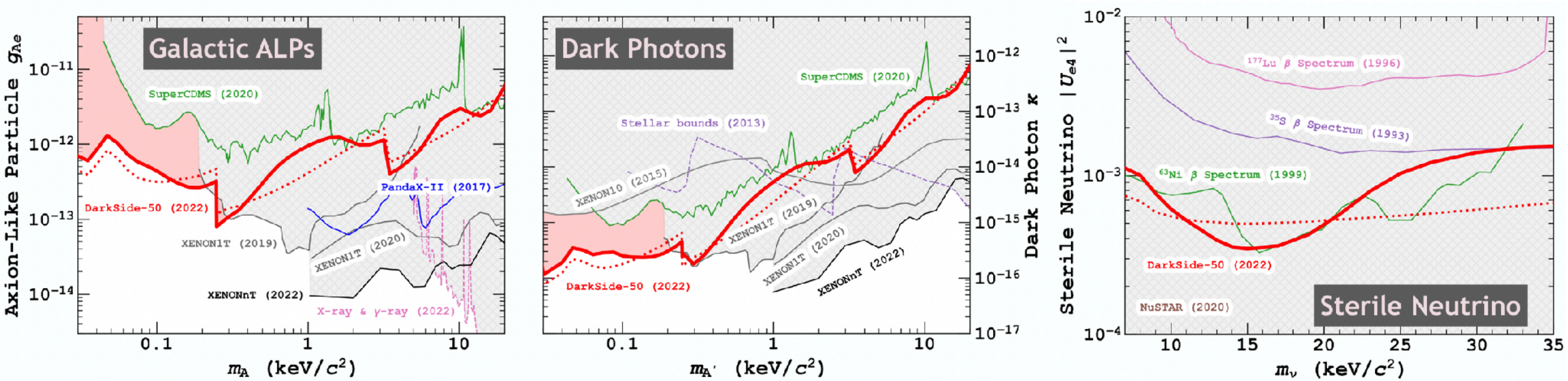
PRL 130, 101001 (2023)

DM-e SCATTERING

Light DM interactions with final state electrons



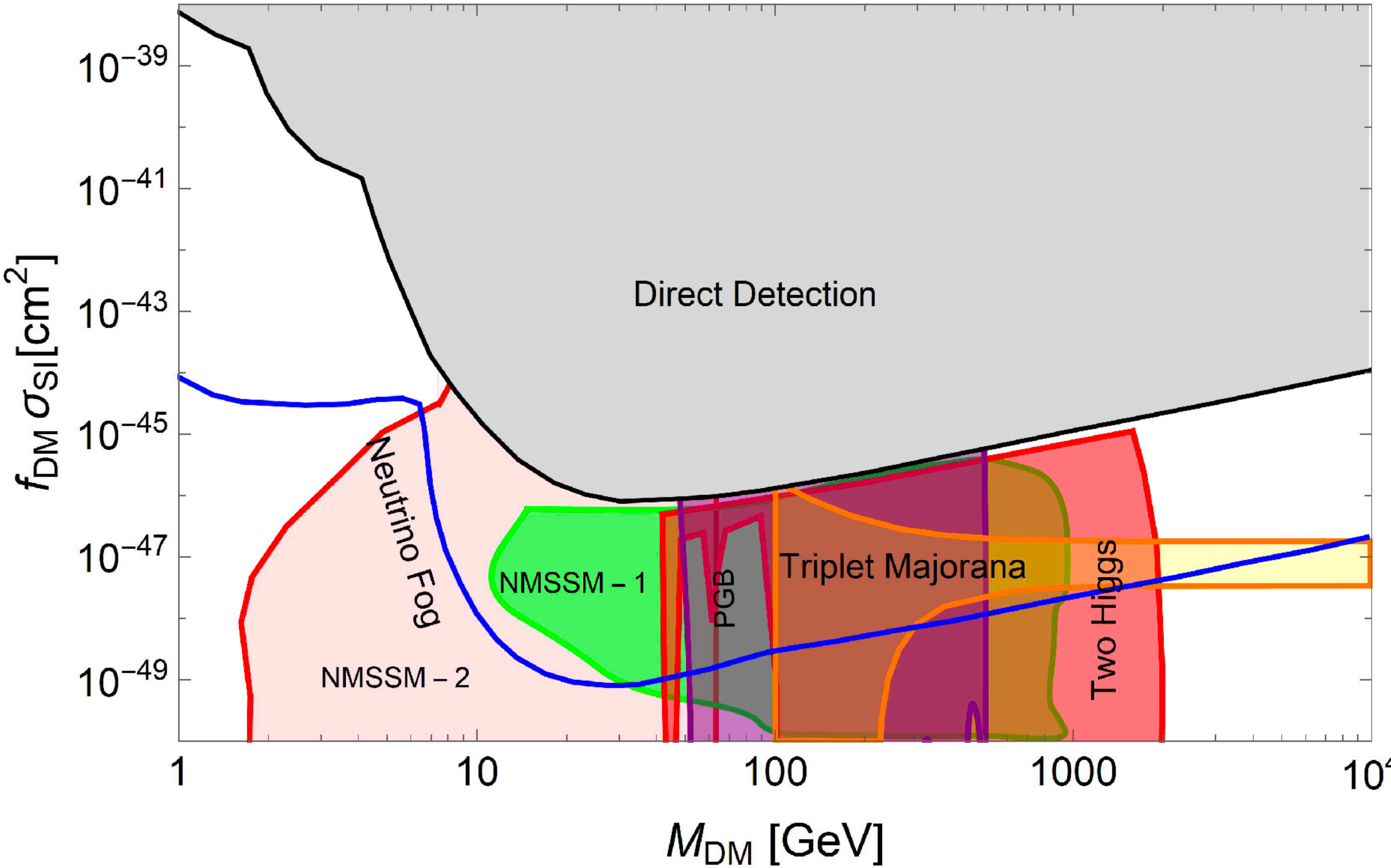
- light DM-electron scattering
- absorption of bosonic DM (axion-like particles and dark photons)
- sterile neutrino-electron scattering



PRL 130, 101002 (2023)

WHAT NEXT?

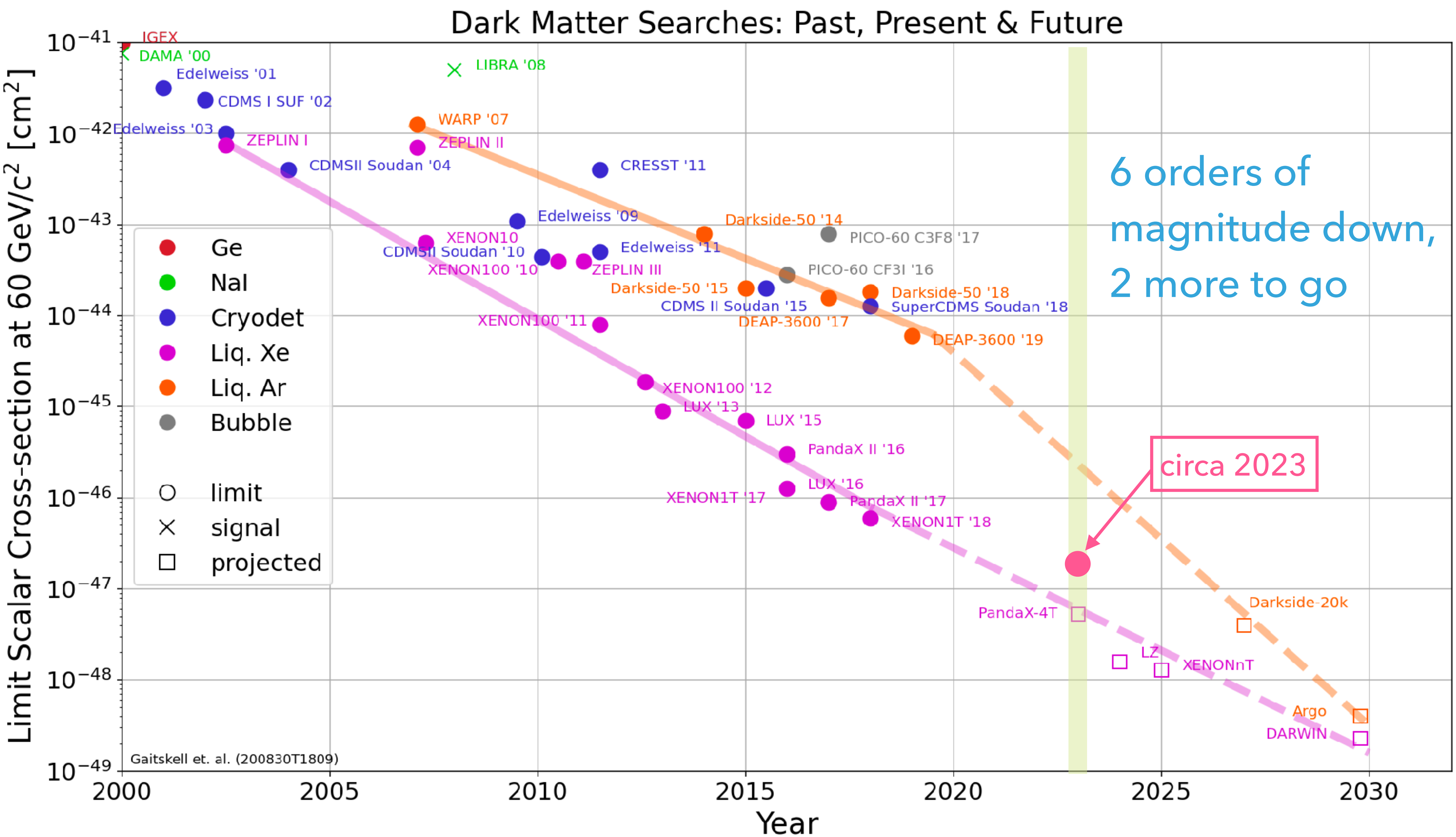
predictions for SI scattering cross sections (in plots of DM-proton cross section versus DM mass) for visible sector models



arXiv:2203.08084

WIMP SEARCH TIMELINE

Take as reference spin-independent cross section upper limits at 60 GeV WIMP mass



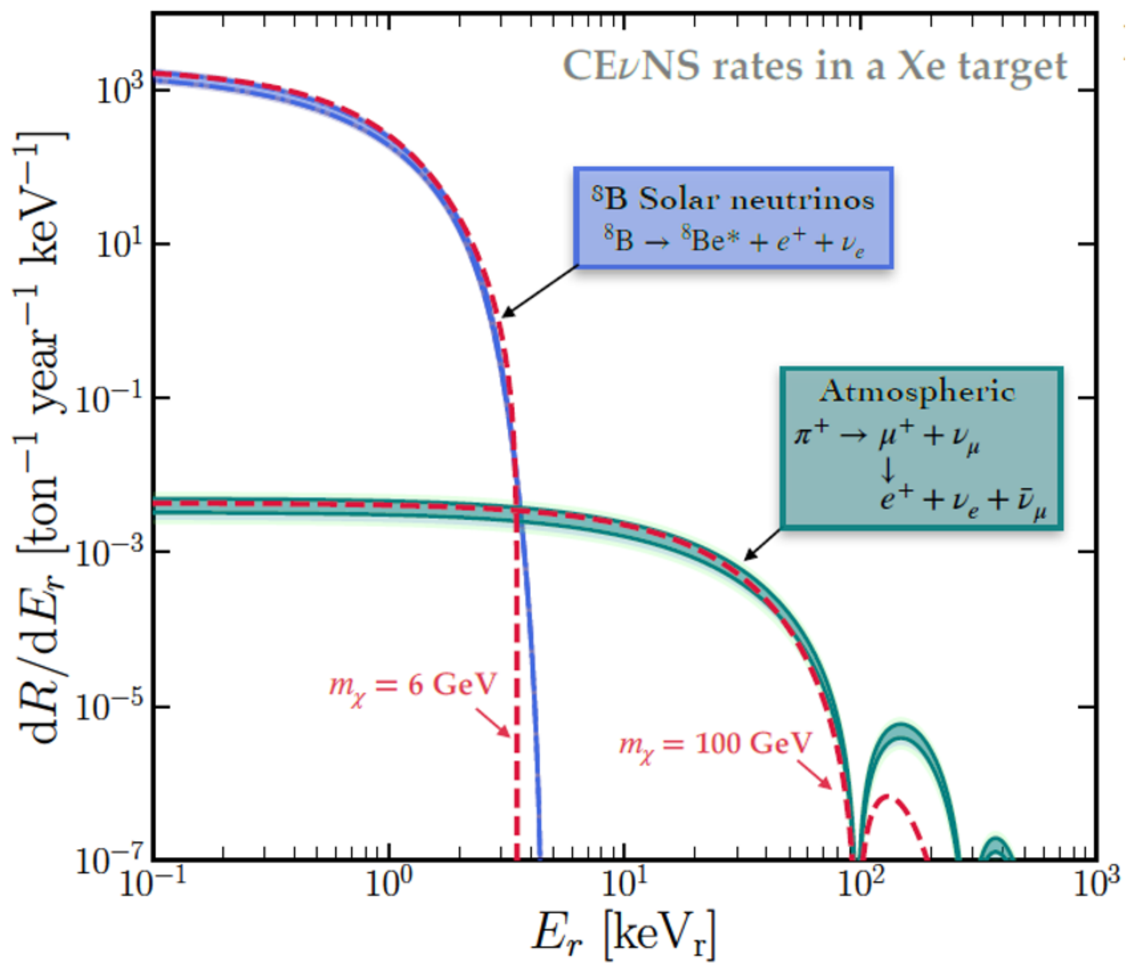
SUMMARY & OUTLOOK

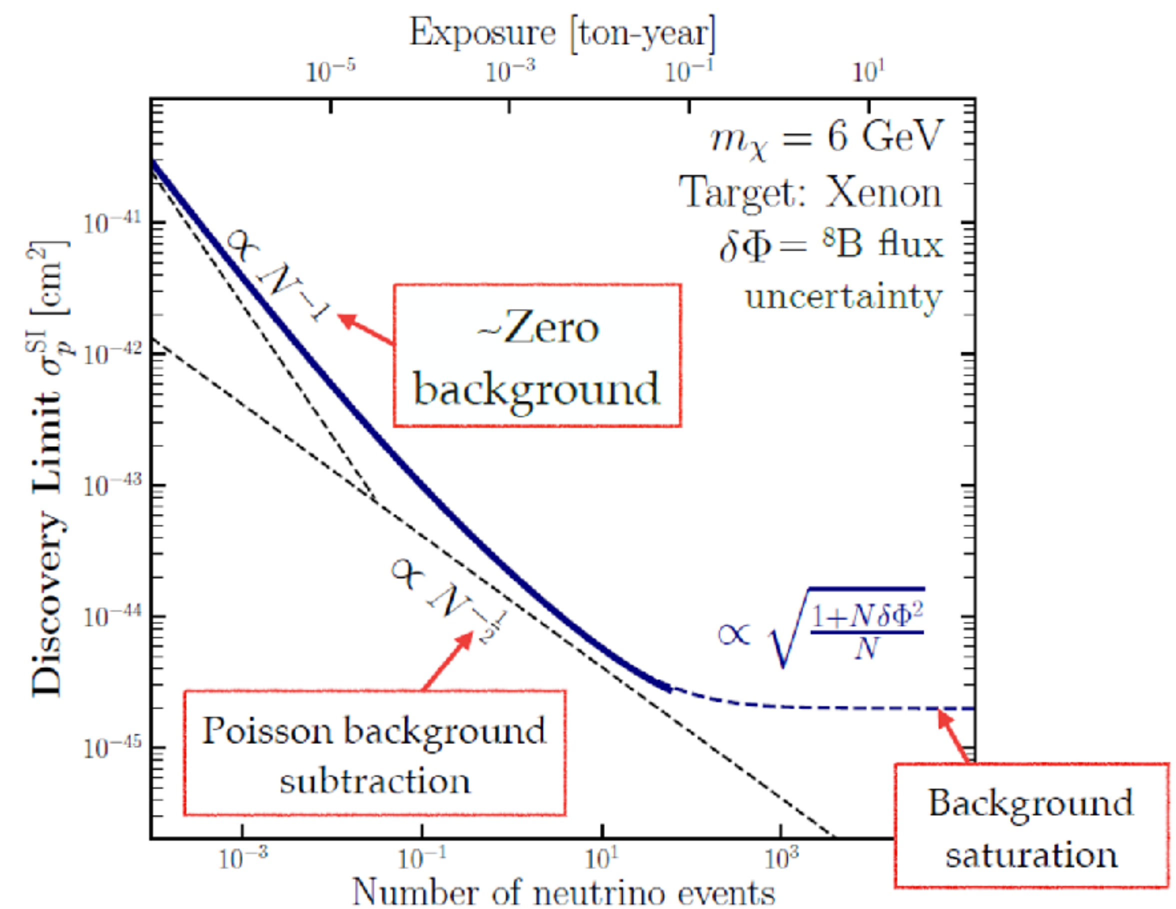
- Direct dark matter detection experiments need to explore everywhere
- WIMP still main paradigm: a variety of detector technologies in place to reach ν fog, add directional sensitivity to clear it
- Light DM probed via scattering to 1 MeV (and via absorption to ~eV), and possibly much lower
- *Ultra Light DM: a wealth of dedicated initiatives probing sub-eV masses (not covered here…)*

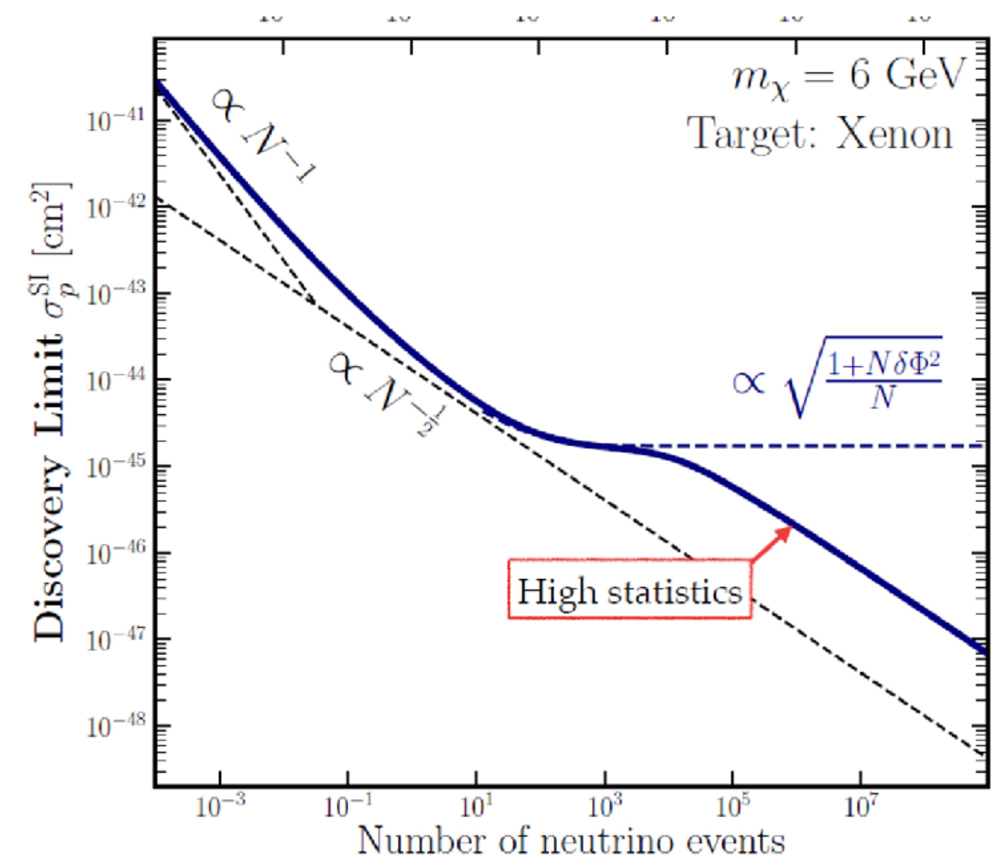
ADDITIONAL SLIDES

IRREDUCIBLE BACKGROUND: NEUTRINOS

C. O'Hare, IDM 2022





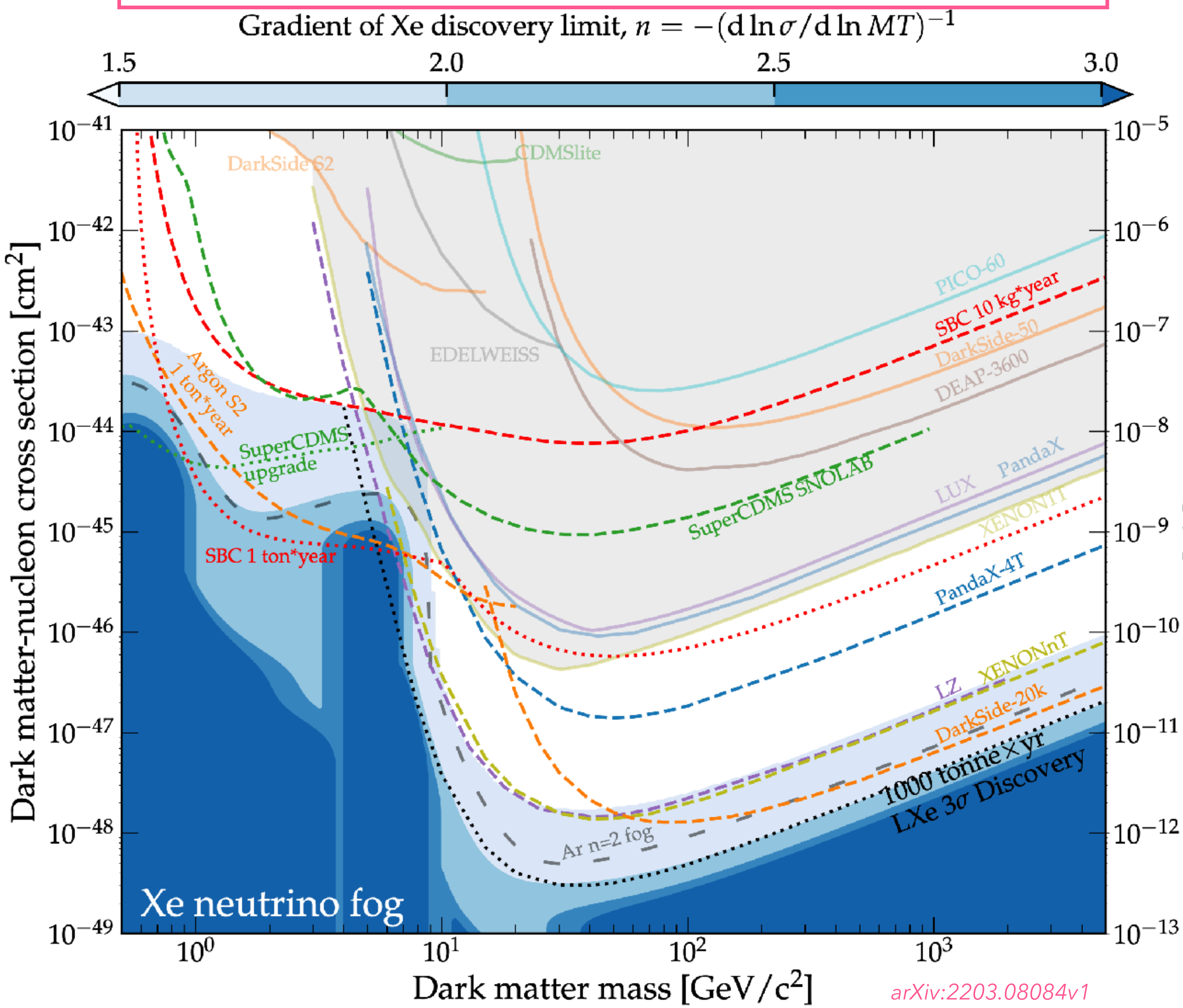


- Coherent nuclear recoils from several astrophysical sources (Sun, atmosphere, and diffuse Supernovae)
- DM/CEvNS signals not identical → with high statistics, an experiment can overcome background uncertainty using spectral information

NEUTRINO FOG

- Neutrino floor from CEvNS not a hard limit on direct detection sensitivity, rather a gradual penalty that can be overcome to some extent.
- To clear the fog:
  - increase exposures
  - have multiple target nuclei
  - improve neutrino flux measurements
  - use signatures

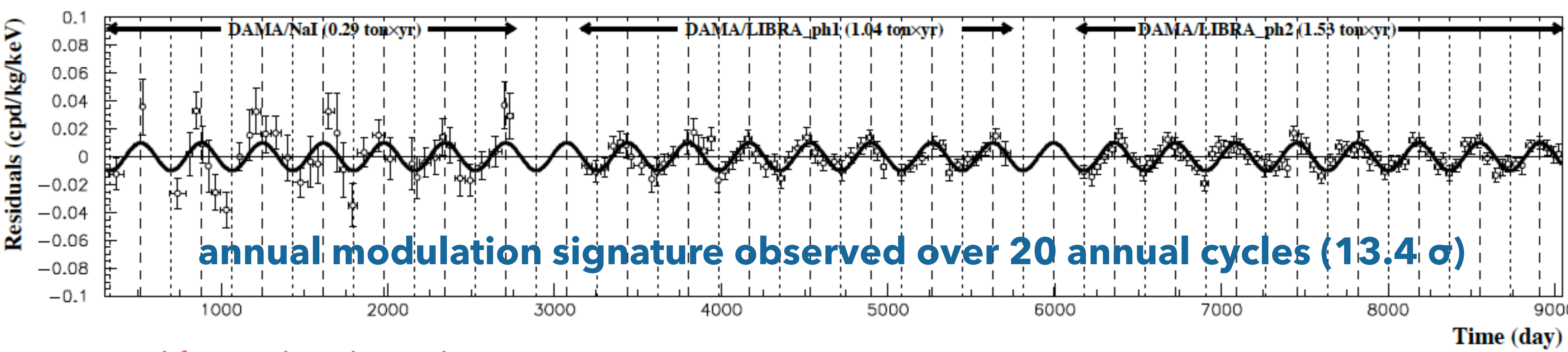
The n index quantifies the diminishing gain in increasing exposure when limited by neutrinos:
reducing the sensitivity by a factor of 10 requires increasing the exposure by at least 10^n



arXiv:2203.08084v1

DAMA MODULATION SIGNAL

- Standard Halo Model predicted modulation A~0.02-0.1, t_0=152.5 days
- **DAMA/NaI + DAMA/LIBRA-phase1 + phase2:**
  - 2.86 t × yr (2 – 6 keV)
  - $A = (0.00996 \pm 0.00074)$ cpd/kg/keV χ^2/dof $= 130/155$



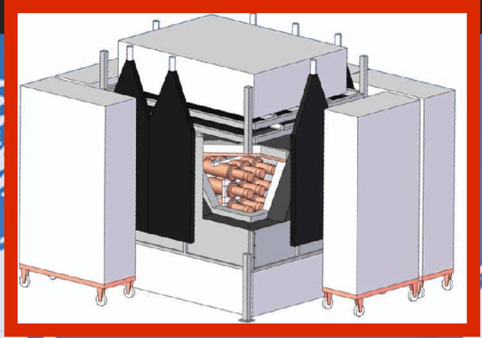
No signal from other direct detection experiments

ANAIS-112 (LSC) & COSINE-100 (Y2L) offer direct test, no clear observation of modulation

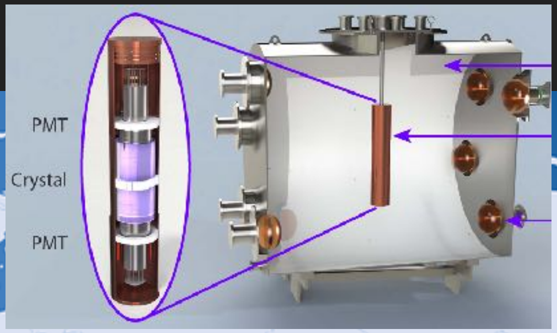
DAMA/LIBRA–phase2-empowered running with lower software energy threshold of 0.5 keV

MODEL INDEPENDENT CHECK

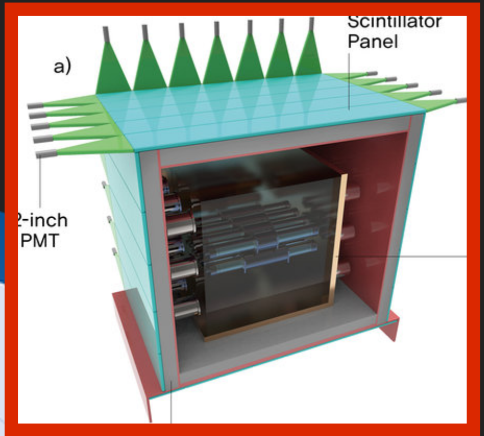
ANAIS-112



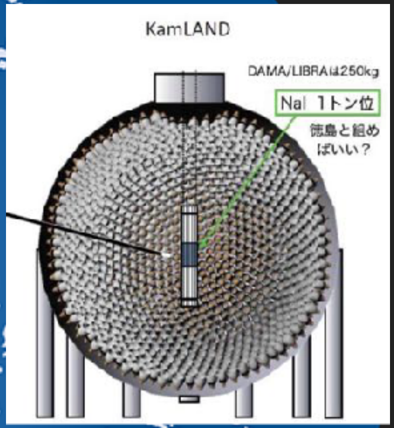
SABRE NORTH



COSINE-100

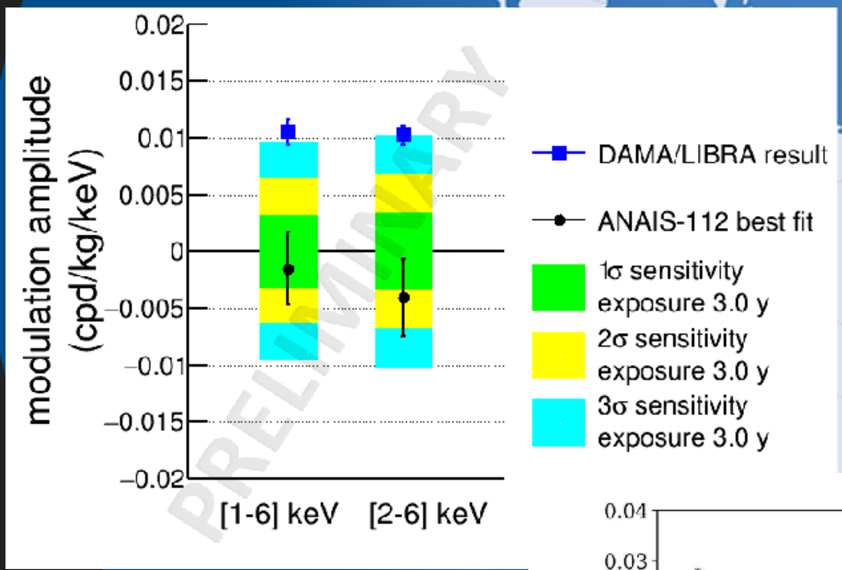


PICOLON

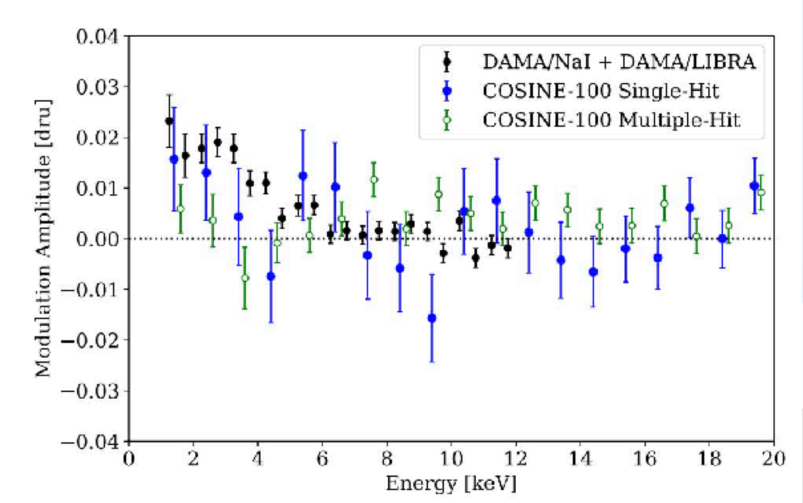


COSINUS

TAKING DATA



ANAIS-112, UCLA DM 2023

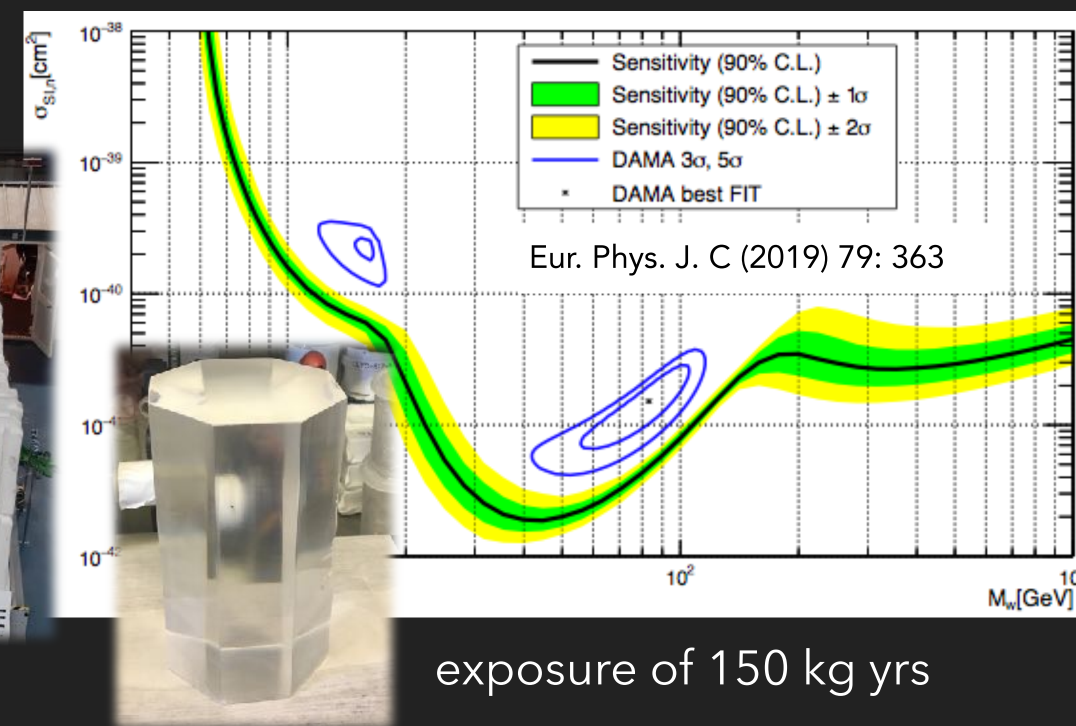


COSINE-100, Phys. Rev. D. 106, 052005

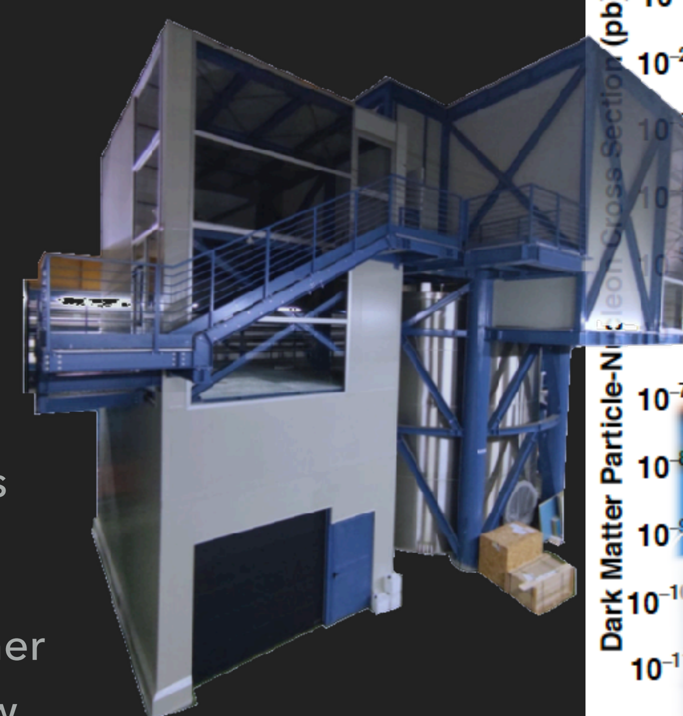
SABRE SOUTH

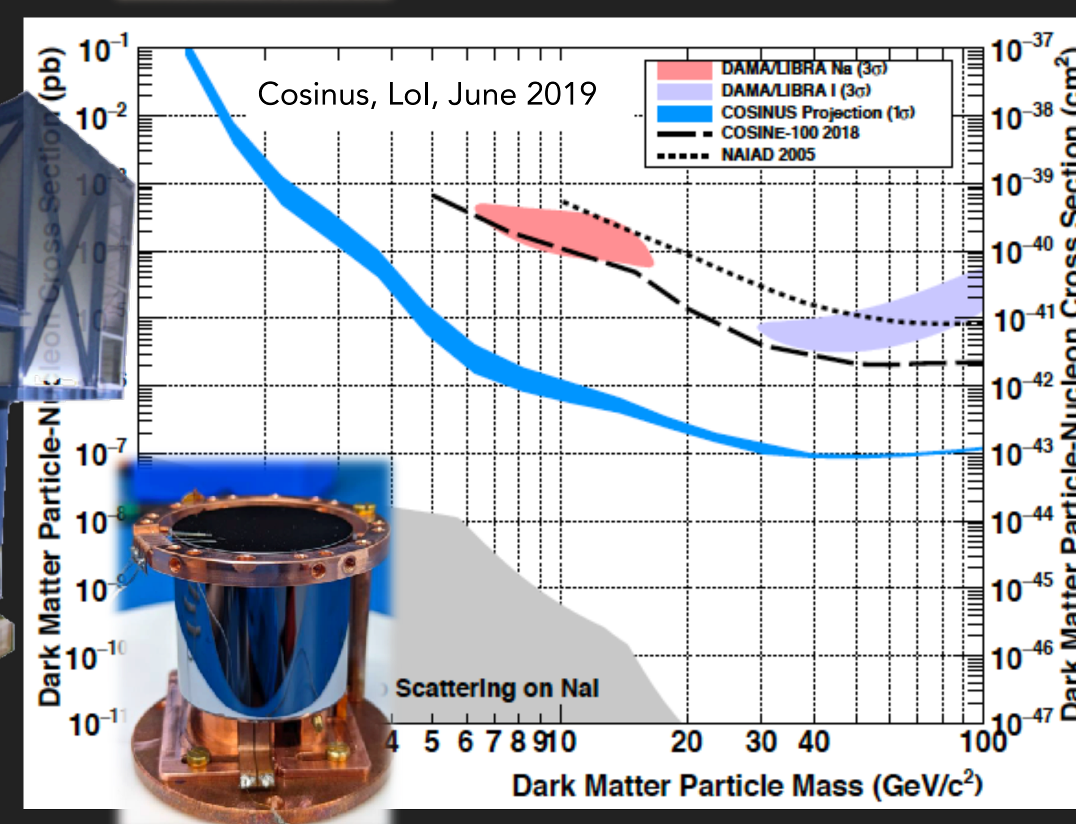
MODULATION PERSPECTIVE (@LNGS)

- **SABRE**
  - Development of ultra-high purity NaI(Tl) crystals (3-5 kg, 0.1-0.3 dru in the ROI)
    - PoP at LNGS exploited successfully ^{40}K tagging with sensitivity at the level of 1ppb
  - Two sites: LNGS in Northern and SUPL in Southern hemisphere
    - Passive shielding (North) + active veto (South)
- **COSINUS**
  - NaI detectors operated as cryogenic calorimeters
  - dual readout of heat and scintillation light
  - construction phase, several prototypes, mass 60g → 110g
  - COSINUS-1π: $\mathcal{O}$(100 kg days) to know whether DAMA sees a nuclear recoil signal or not (low threshold essential)



exposure of 150 kg yrs



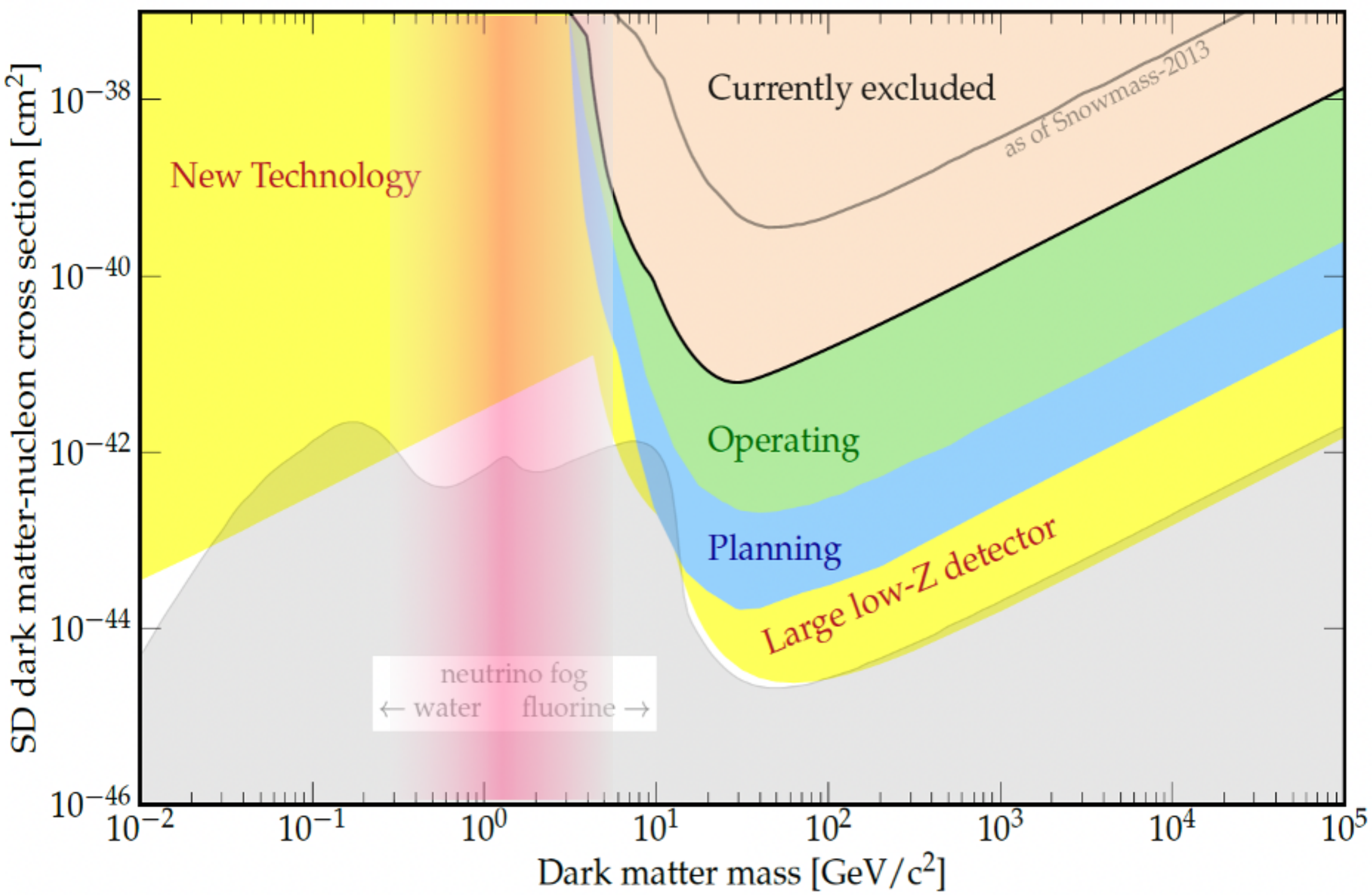


exposure of 100 kg days

WIMP NUCLEON SD INTERACTION EXCLUSION LIMITS LANSCAPE

- Spin-dependent phase space is wide-open at lower masses but technology to probe deep at 10 – 100 GeV/c^2 is well-developed
  - **PICO** superheated bubble chambers Freon (C_3F_8) probe proton coupling
  - **LXe TPC** detectors cover n-coupling, but the xenon neutrino fog is decades higher than the fluorine neutrino fog
  - **EDELWEISS, SuperCDMS** n-coupling at lower masses **CRESST** is exploring new SD crystals with Lithium
  - New technology could be a liquid/solid phase change detector like supercooled H_2O

2021 Snowmass Cosmic Frontier Report, arXiv:2211.09978



WIMP–NUCLEON SCATTERING IN NREFT

- More general description by non-relativistic effective field theory
- expansion parameters: $v/c \simeq 10^{-3}$ and $|\vec{q}|/m_M$
- $|\vec{q}| \simeq O(10 - 100\,\mathrm{MeV})$ is the momentum exchange
- m_M is some large scale involved (DM mass, nucleus mass, or a heavy mediator mass)

relativistic interactions constructed as bilinear products of the available scalar and four-vector amplitudes (20 effective Lagrangians)

j	$\mathcal{L}^j_{\mathrm{int}}$	Nonrelativistic reduction	$\sum_i c_i \mathcal{O}_i$	P/T
1	$\bar\chi\chi\bar N N$	$1_\chi 1_N$	$\mathcal{O}_1$	E/E
2	$i\bar\chi\chi\bar N\gamma^5 N$	$i\frac{\vec q}{m_N}\cdot\vec S_N$	$\mathcal{O}_{10}$	O/O
3	$i\bar\chi\gamma^5\chi\bar N N$	$-i\frac{\vec q}{m_\chi}\cdot\vec S_\chi$	$-\frac{m_N}{m_\chi}\mathcal{O}_{11}$	O/O
4	$\bar\chi\gamma^5\chi\bar N\gamma^5 N$	$-\frac{\vec q}{m_\chi}\cdot\vec S_\chi\frac{\vec q}{m_N}\cdot\vec S_N$	$-\frac{m_N}{m_\chi}\mathcal{O}_6$	E/E
5	$\bar\chi\gamma^\mu\chi\bar N\gamma_\mu N$	$1_\chi 1_N$	$\mathcal{O}_1$	E/E
6	$\bar\chi\gamma^\mu\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$\frac{\vec q^{\,2}}{2m_N m_M}1_\chi 1_N + 2(\frac{\vec q}{m_\chi}\times\vec S_\chi + i\vec v^\perp)\cdot(\frac{\vec q}{m_M}\times\vec S_N)$	$\frac{\vec q^{\,2}}{2m_N m_M}\mathcal{O}_1 - 2\frac{m_N}{m_M}\mathcal{O}_3 + 2\frac{m_N^2}{m_M m_\chi}(\frac{\vec q^{\,2}}{m_N^2}\mathcal{O}_4 - \mathcal{O}_6)$	E/E
7	$\bar\chi\gamma^\mu\chi\bar N\gamma_\mu\gamma^5 N$	$-2\vec S_N\cdot\vec v^\perp + \frac{2}{m_\chi}i\vec S_\chi\cdot(\vec S_N\times\vec q)$	$-2\mathcal{O}_7 + 2\frac{m_N}{m_\chi}\mathcal{O}_9$	O/E
8	$i\bar\chi\gamma^\mu\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$2i\frac{\vec q}{m_M}\cdot\vec S_N$	$2\frac{m_N}{m_M}\mathcal{O}_{10}$	O/O
9	$\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar N\gamma_\mu N$	$-\frac{\vec q^{\,2}}{2m_\chi m_M}1_\chi 1_N - 2(\frac{\vec q}{m_N}\times\vec S_N + i\vec v^\perp)\cdot(\frac{\vec q}{m_M}\times\vec S_\chi)$	$-\frac{\vec q^{\,2}}{2m_\chi m_M}\mathcal{O}_1 + \frac{2m_N}{m_M}\mathcal{O}_5 - 2\frac{m_N}{m_M}(\frac{\vec q^{\,2}}{m_N^2}\mathcal{O}_4 - \mathcal{O}_6)$	E/E
10	$\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$4(\frac{\vec q}{m_M}\times\vec S_\chi)\cdot(\frac{\vec q}{m_M}\times\vec S_N)$	$4(\frac{\vec q^{\,2}}{m_M^2}\mathcal{O}_4 - \frac{m_N^2}{m_M^2}\mathcal{O}_6)$	E/E
11	$\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar N\gamma^\mu\gamma^5 N$	$4i(\frac{\vec q}{m_M}\times\vec S_\chi)\cdot\vec S_N$	$4\frac{m_N}{m_M}\mathcal{O}_9$	O/E
12	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$-[i\frac{\vec q^{\,2}}{m_\chi m_M} - 4\vec v^\perp\cdot(\frac{\vec q}{m_M}\times\vec S_\chi)]\frac{\vec q}{m_M}\cdot\vec S_N$	$-\frac{m_N}{m_\chi}\frac{\vec q^{\,2}}{m_M^2}\mathcal{O}_{10} - 4\frac{\vec q^{\,2}}{m_M^2}\mathcal{O}_{12} - 4\frac{m_N^2}{m_M^2}\mathcal{O}_{15}$	O/O
13	$\bar\chi\gamma^\mu\gamma^5\chi\bar N\gamma_\mu N$	$2\vec v^\perp\cdot\vec S_\chi + 2i\vec S_\chi\cdot(\vec S_N\times\frac{\vec q}{m_N})$	$2\mathcal{O}_8 + 2\mathcal{O}_9$	O/E
14	$\bar\chi\gamma^\mu\gamma^5\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$4i\vec S_\chi\cdot(\frac{\vec q}{m_M}\times\vec S_N)$	$-4\frac{m_N}{m_M}\mathcal{O}_9$	O/E
15	$\bar\chi\gamma^\mu\gamma^5\chi\bar N\gamma^\mu\gamma^5 N$	$-4\vec S_\chi\cdot\vec S_N$	$-4\mathcal{O}_4$	E/E
16	$i\bar\chi\gamma^\mu\gamma^5\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$4i\vec v^\perp\cdot\vec S_\chi\frac{\vec q}{m_M}\cdot\vec S_N$	$4\frac{m_N}{m_M}\mathcal{O}_{13}$	E/O
17	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\gamma^5\chi\bar N\gamma_\mu N$	$2i\frac{\vec q}{m_M}\cdot\vec S_\chi$	$2\frac{m_N}{m_M}\mathcal{O}_{11}$	O/O
18	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\gamma^5\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$\frac{\vec q}{m_M}\cdot\vec S_\chi[i\frac{\vec q^{\,2}}{m_N m_M} - 4\vec v^\perp\cdot(\frac{\vec q}{m_M}\times\vec S_N)]$	$\frac{\vec q^{\,2}}{m_M^2}\mathcal{O}_{11} + 4\frac{m_N^2}{m_M^2}\mathcal{O}_{15}$	O/O
19	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\gamma^5\chi\bar N\gamma_\mu\gamma^5 N$	$-4i\frac{\vec q}{m_M}\cdot\vec S_\chi\vec v_\perp\cdot\vec S_N$	$-4\frac{m_N}{m_M}\mathcal{O}_{14}$	E/O
20	$i\bar\chi i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\gamma^5\chi\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$4\frac{\vec q}{m_M}\cdot\vec S_\chi\frac{\vec q}{m_M}\cdot\vec S_N$	$4\frac{m_N^2}{m_M^2}\mathcal{O}_6$	E/E

PHYSICAL REVIEW C 89, 065501 (2014)