Dark matter searches using direct detection techniques and their future prospects

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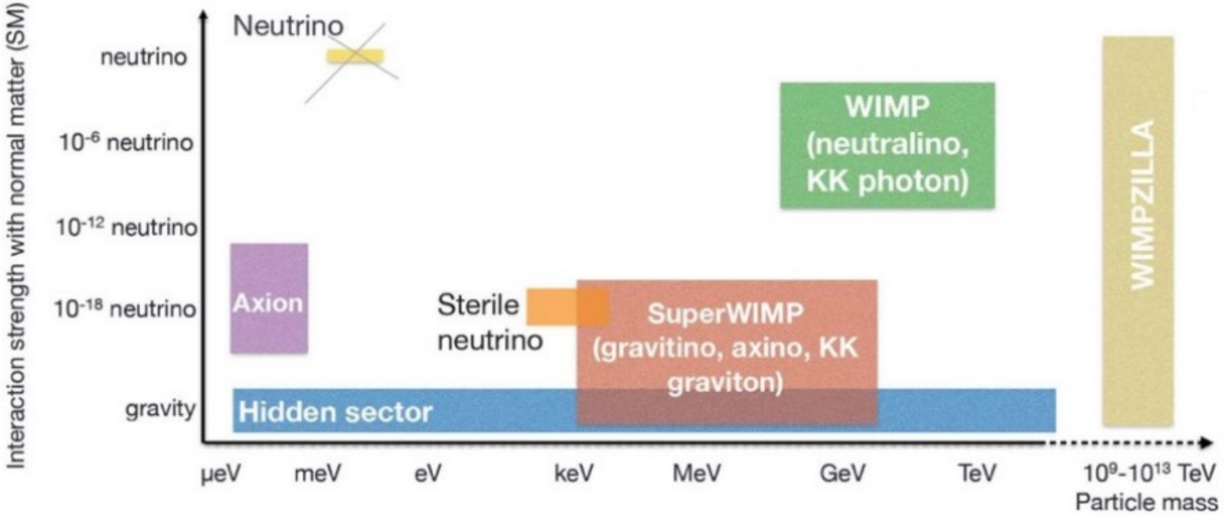
ICHEPAP2023
13 December, 2023

UCR PHYSICS & ASTRONOMY

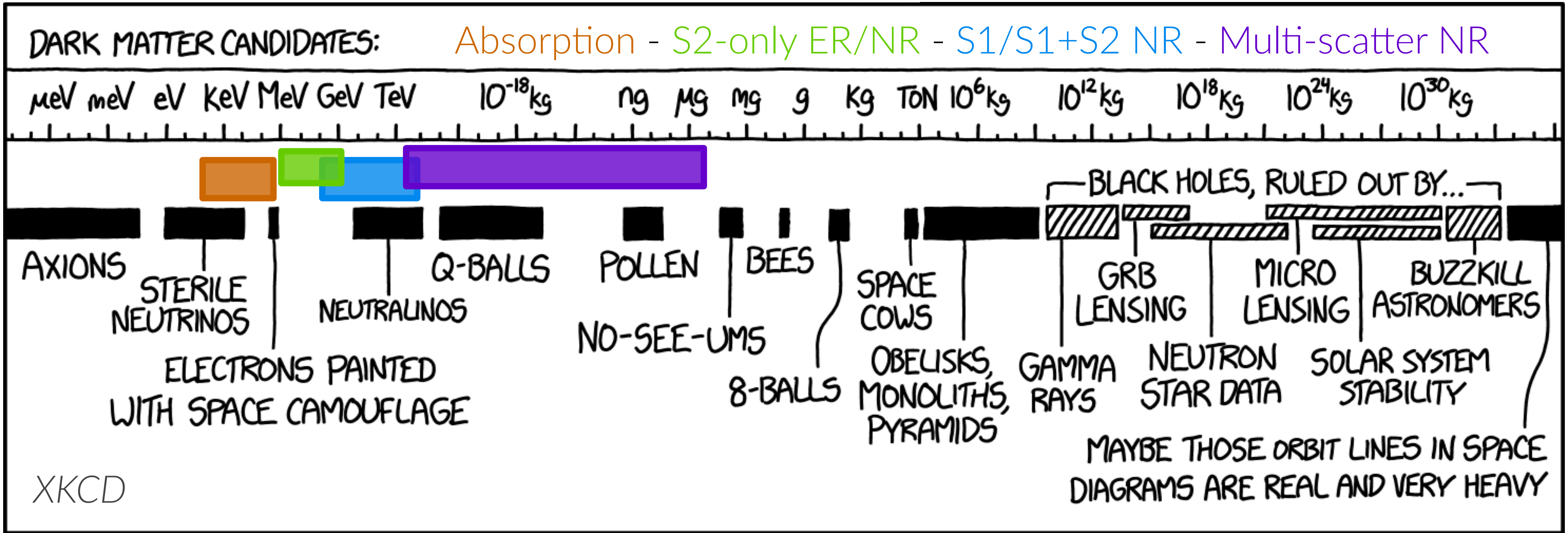
Bing AI, draw a picture of someone searching for dark matter



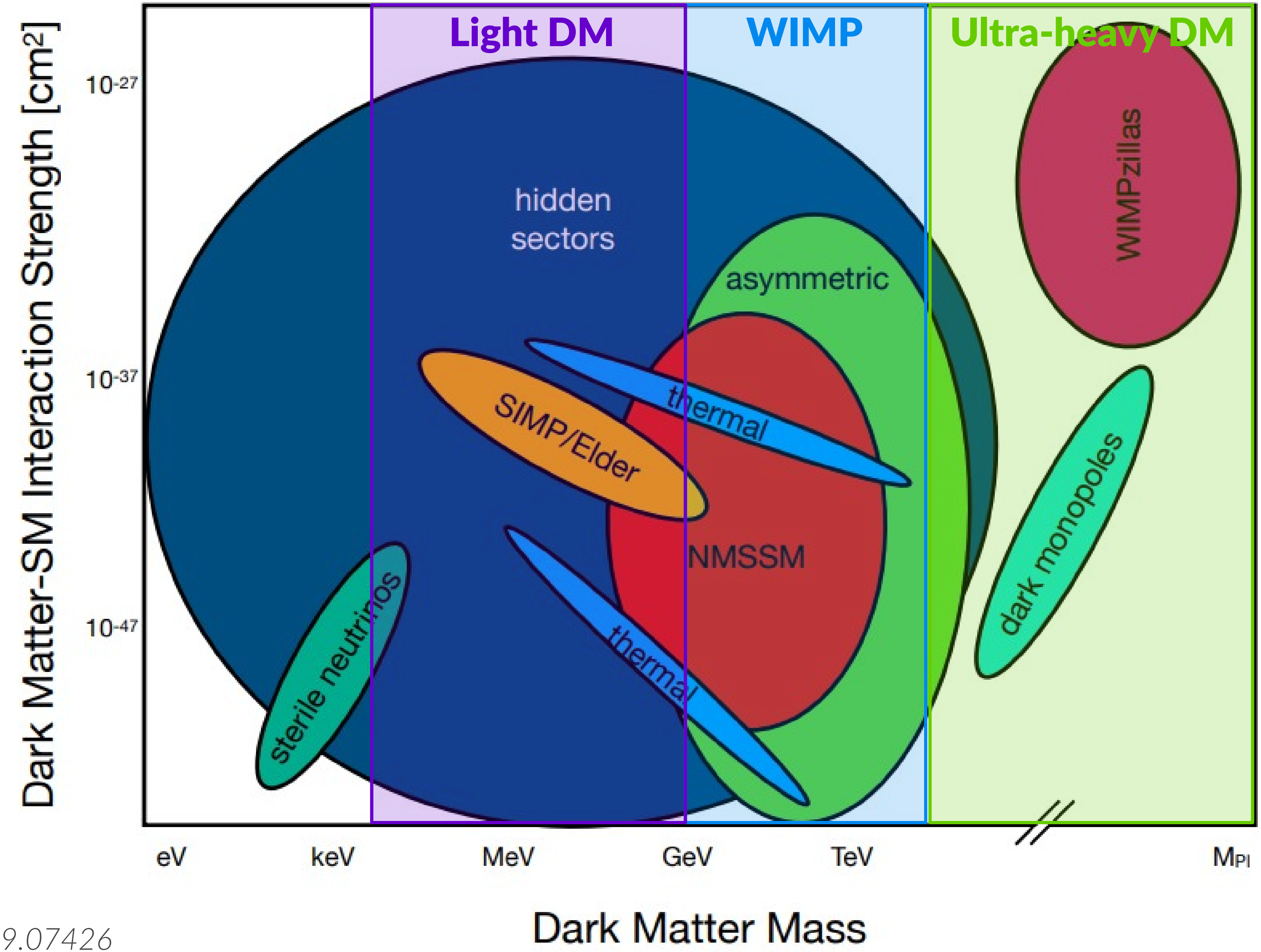
Focus on ~100 GeV-scale WIMP

Extend from sub-GeV to M_{planck}

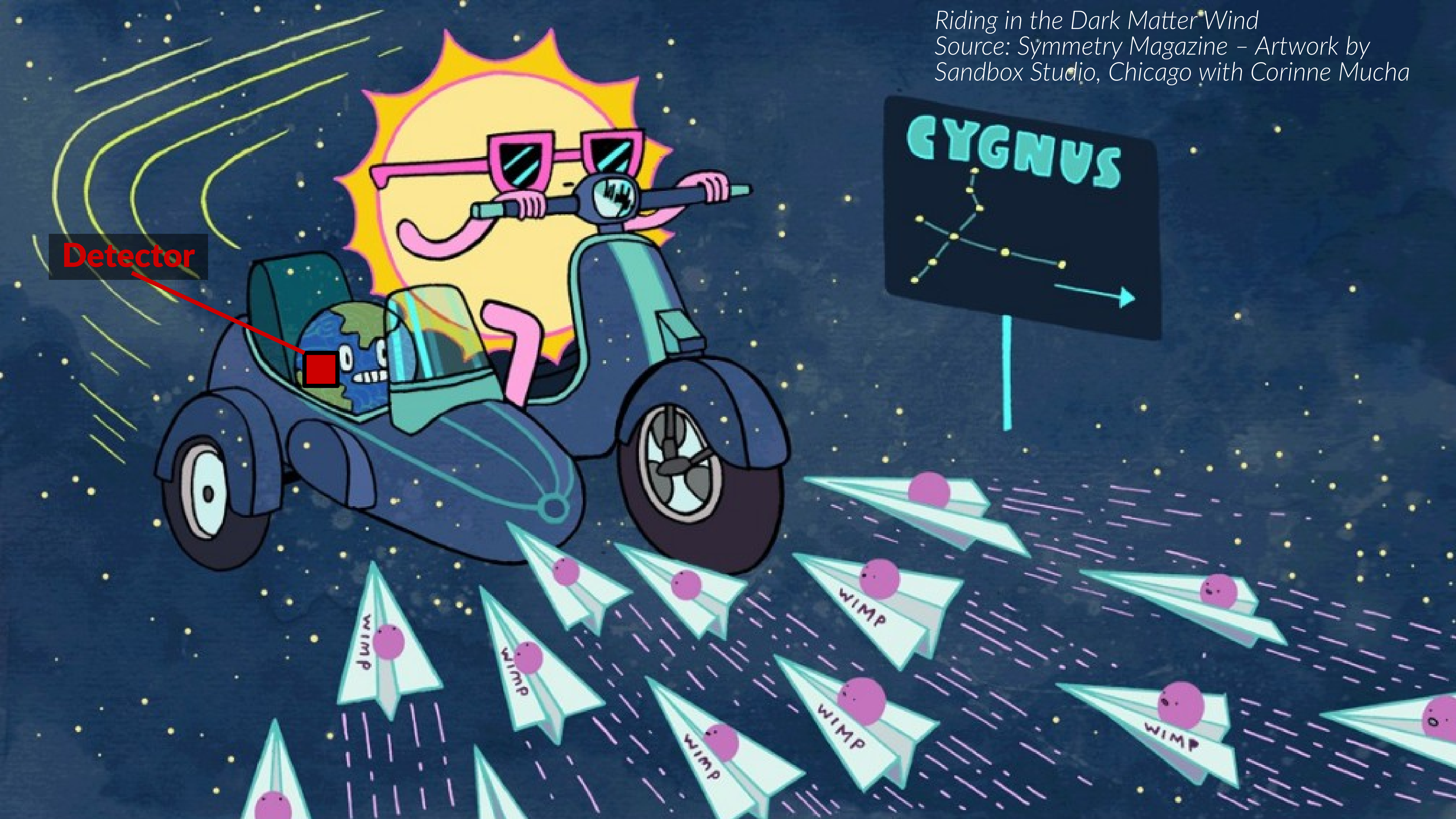
Axions/wave-like DM outside scope of this talk



XKCD



arXiv:2209.07426



Riding in the Dark Matter Wind
Source: Symmetry Magazine – Artwork by Sandbox Studio, Chicago with Corinne Mucha

What signals do we expect?

Number of DM events expected: μ_s = Exposure × $\int dE_R \cdot (dR/dE_R)$

Target density

Local DM density

DM-nucleus cross section

$$\boxed{\frac{dR}{dE_R}} = \frac{\boxed{\rho_T}}{\boxed{m_T}}\frac{\boxed{\rho_\chi}}{\boxed{m_\chi}}\boxed{\varepsilon(E_R)}\int_{v_{\min}}^{\infty} v\,\boxed{f_\chi^{\oplus}(\vec{v})}\boxed{\frac{d\sigma}{dE_R}}d^3\vec{v}$$

Differential scattering rate

Target nucleus mass

DM mass

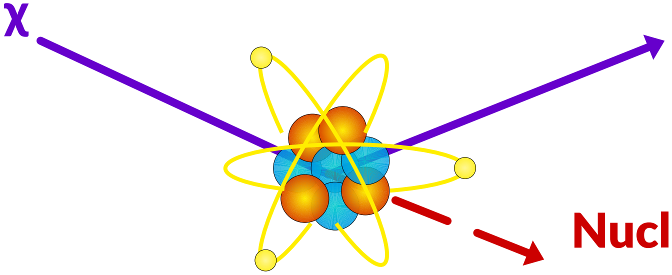
NR acceptance

DM velocity distribution

$$\boxed{\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu_p^2 v^2}F^2(q)A^2\sigma_p}$$

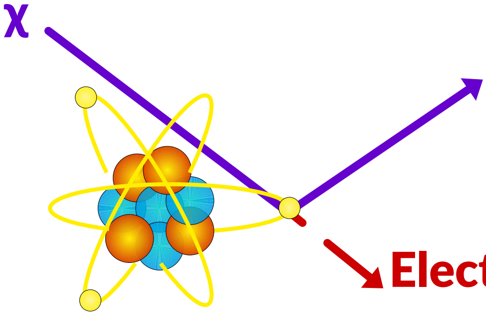
Encodes how DM interact with SM
Spin-independent? Spin-dependent?
Isospin violation?
Function depends on mediator

For the “standard WIMP” search…



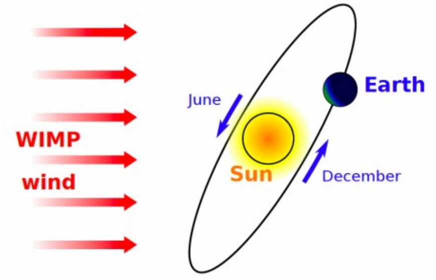
χ WIMP
neutron
α-particle
Neutrino CEvNS
…

Nuclear recoil

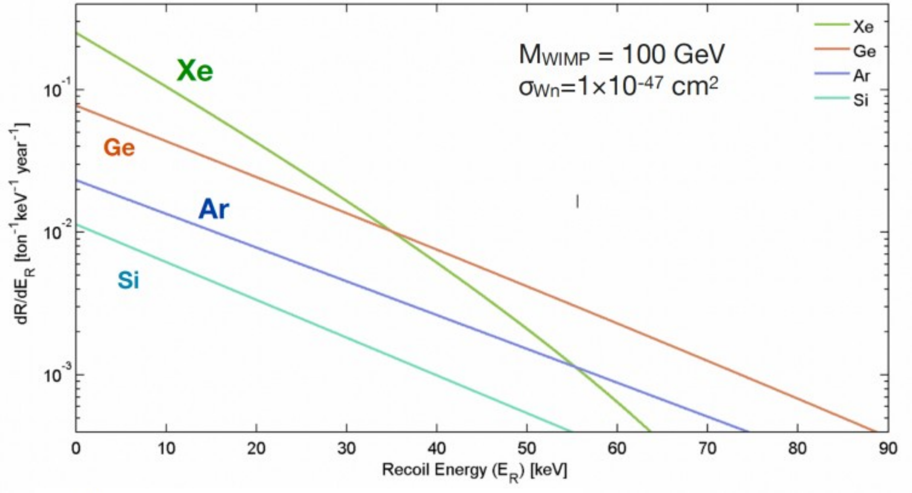


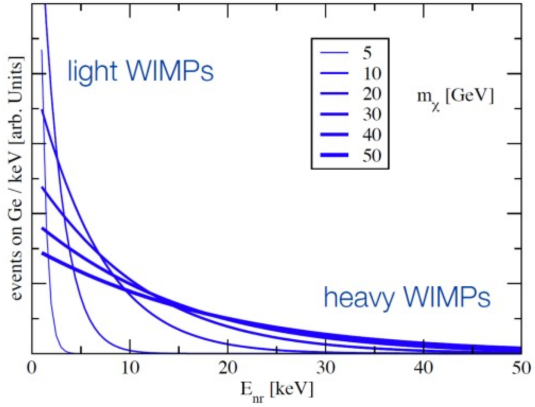
χ Light DM
γ-ray
β-particle
…

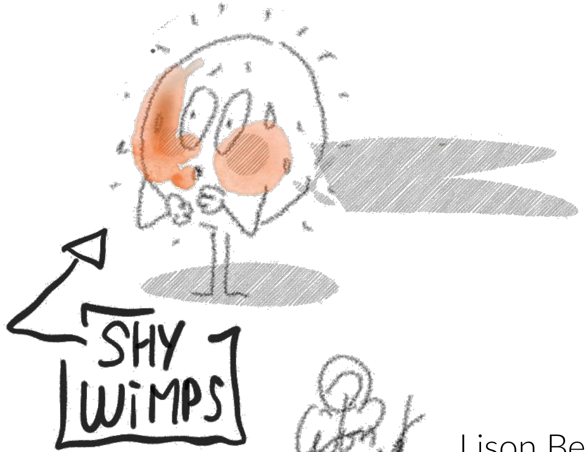
Electronic recoil



Motion of Earth relative to WIMP wind allows us to use **annual modulation** or **directionality** as a “smoking gun” signal







Lison Bernet – Moriond 2019
http://lisonbernet.ultra-book.com/

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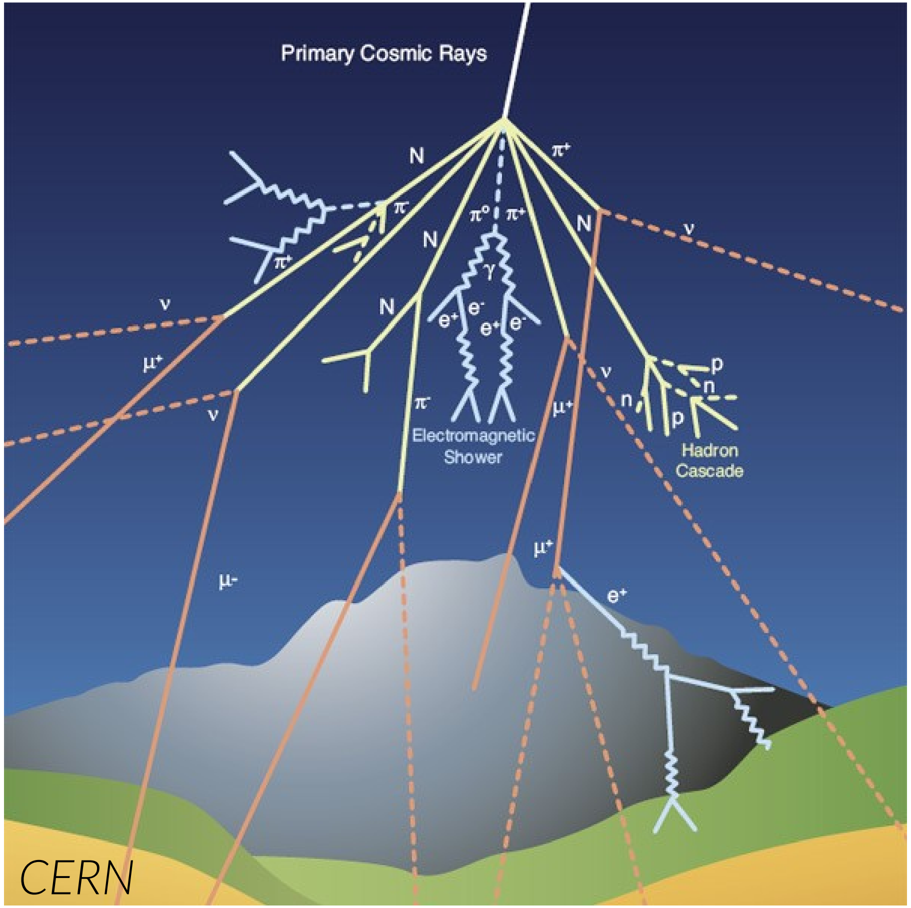
http://lisonbernet.ultra-book.com/

Background sources: Environmental

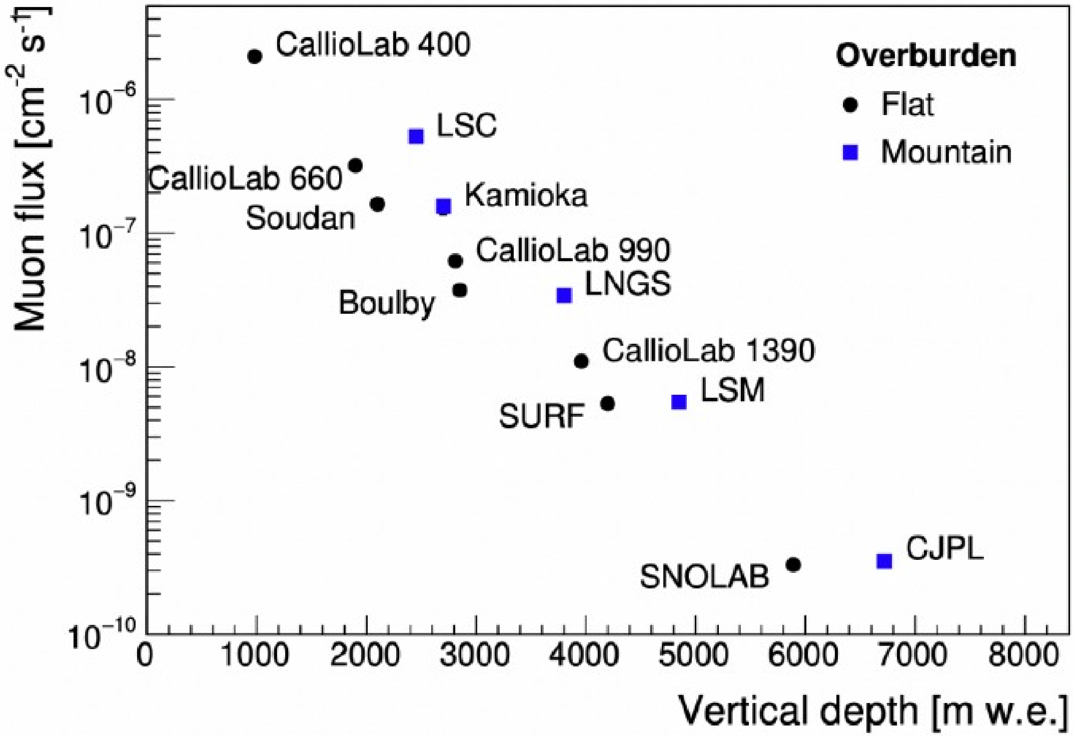


CERN

Above ground:

Material activation→Minimize exposure

High event rate→Go deep underground



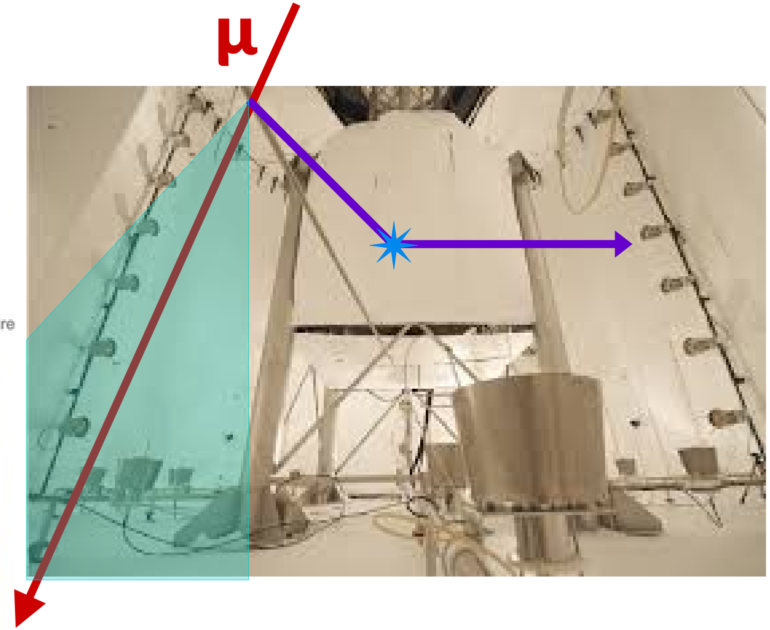
Background sources: Environmental

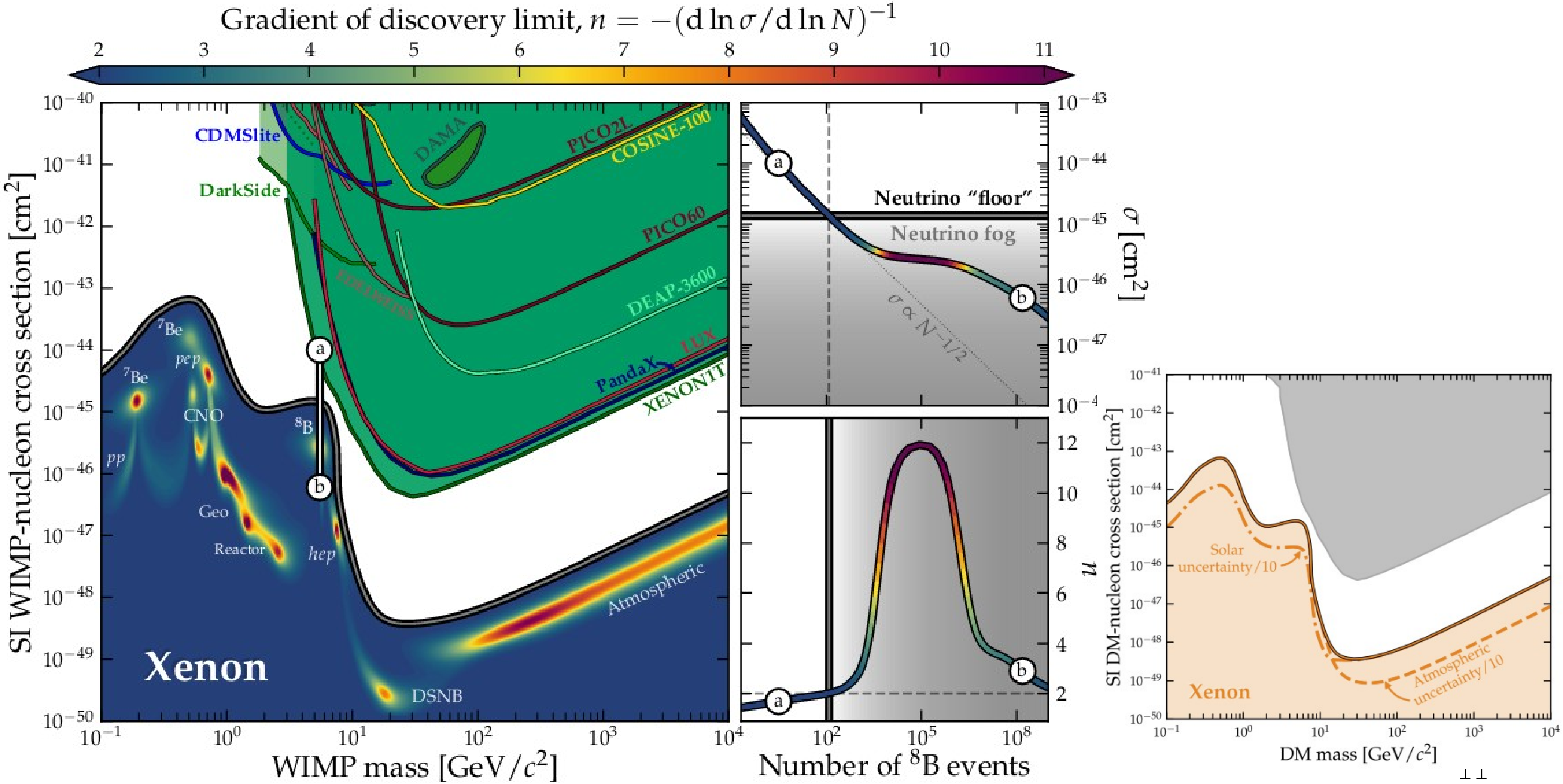
Underground ground:

Cosmogenic neutrons (e.g. muon spallation) → Muon veto

Atmospheric and solar neutrino CEvNS → Directionality? Annual modulation?

A. Ianni





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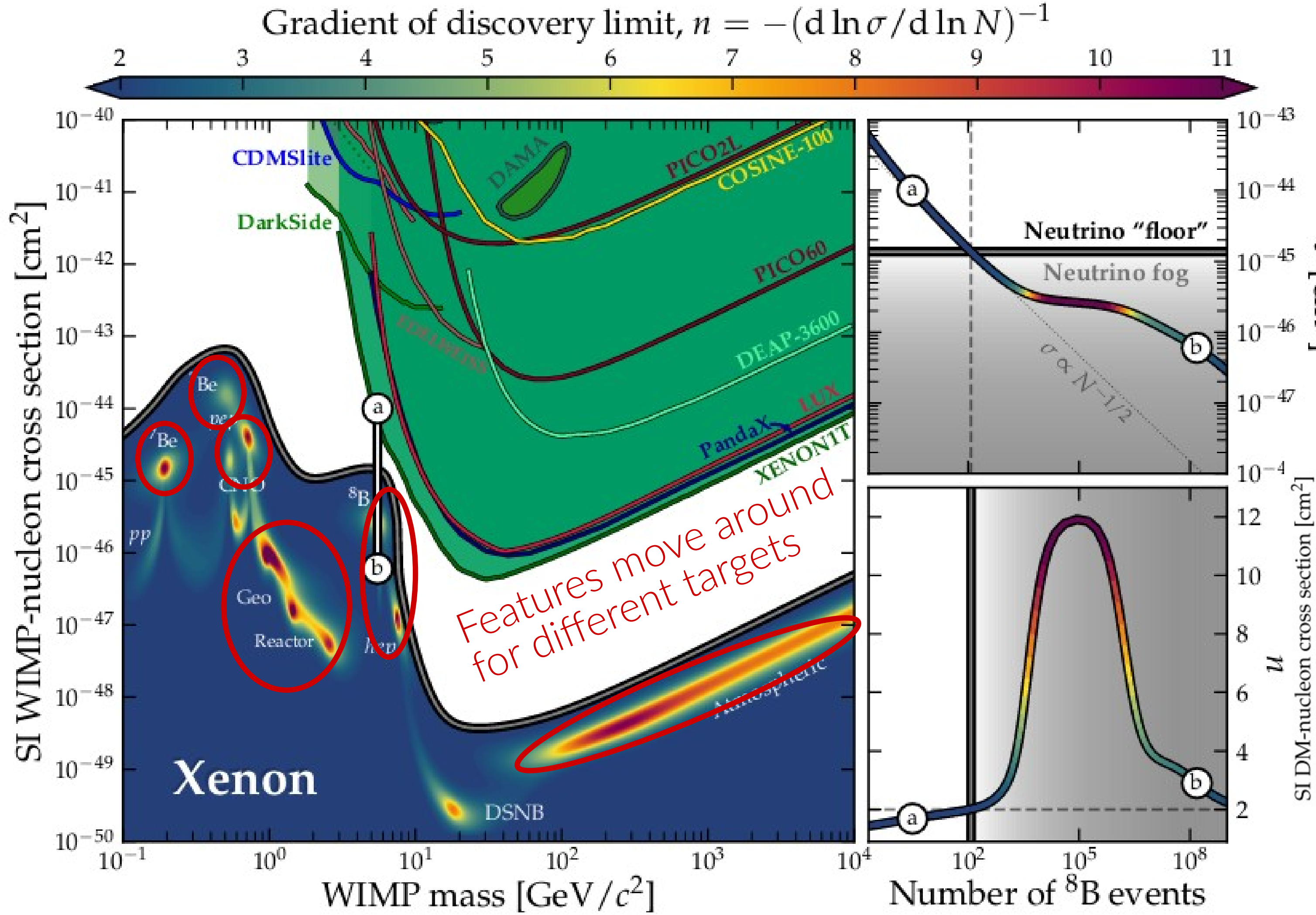
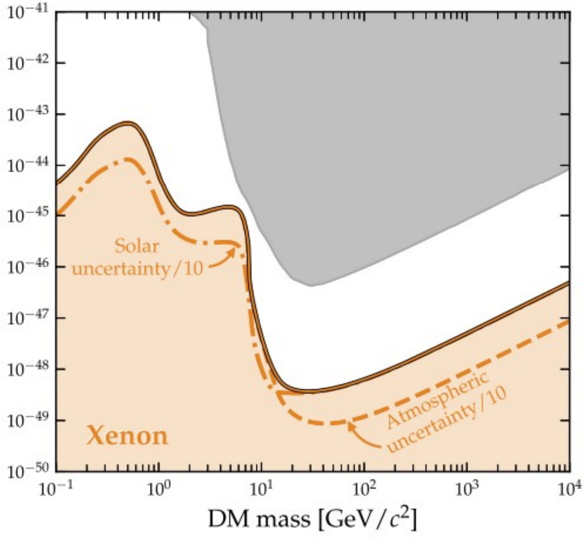
Target complementarity

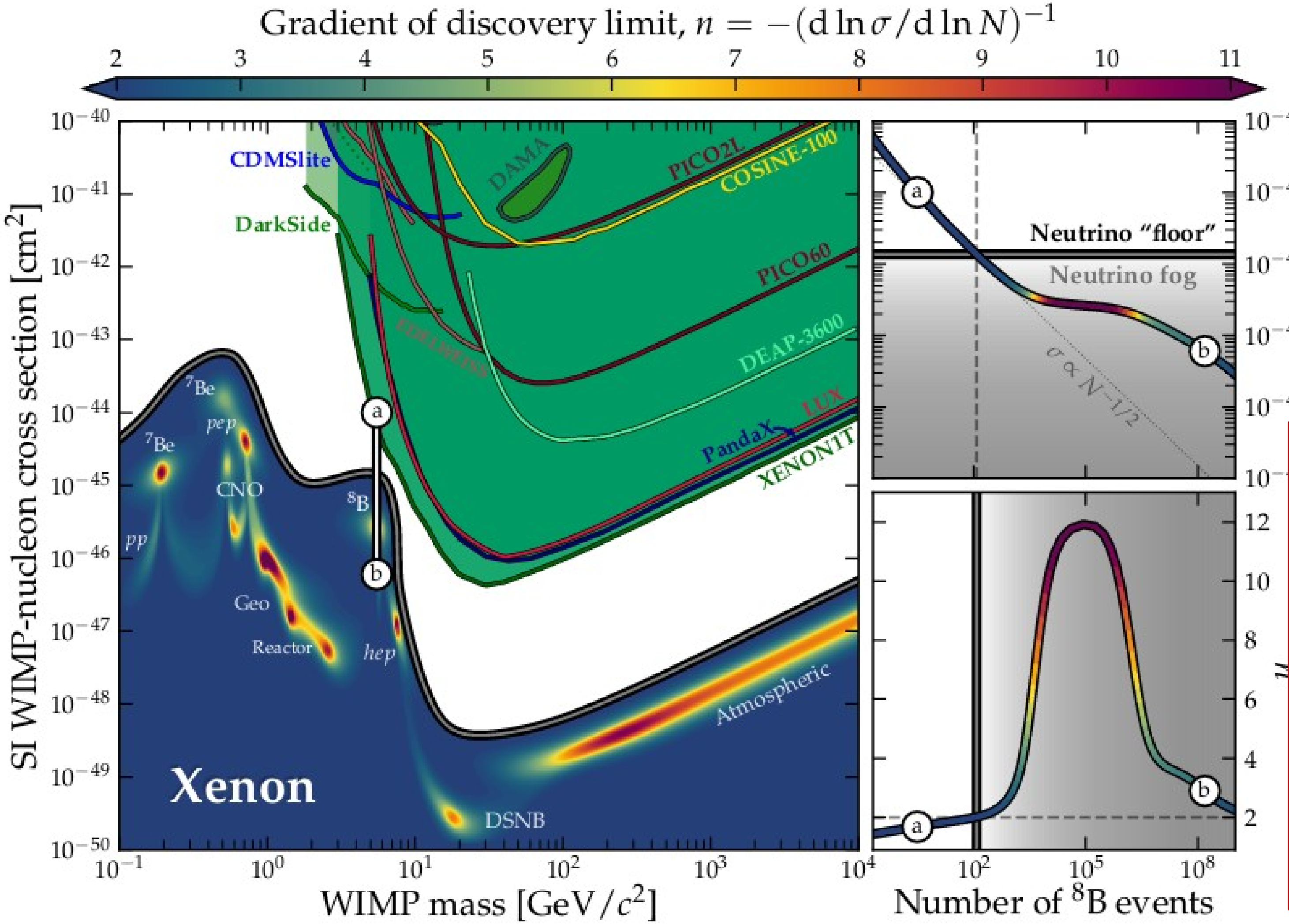


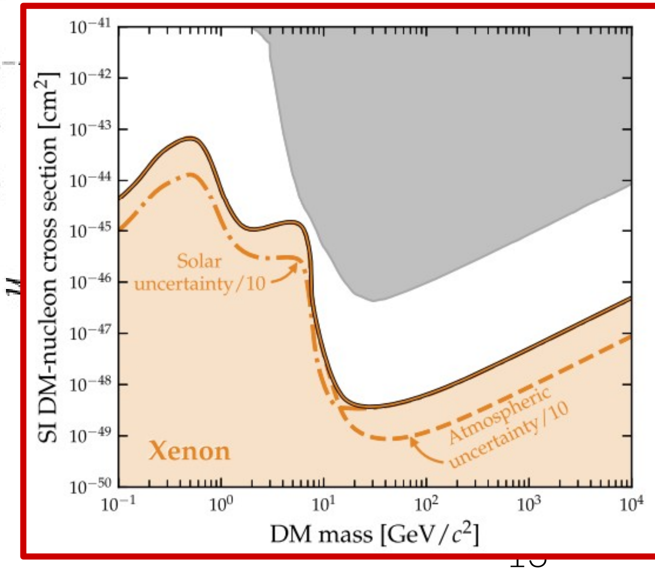
Features move around for different targets



Ciaran A. J. O'Hare Phys. Rev. Lett. 127, 251802

Improving v background uncertainties



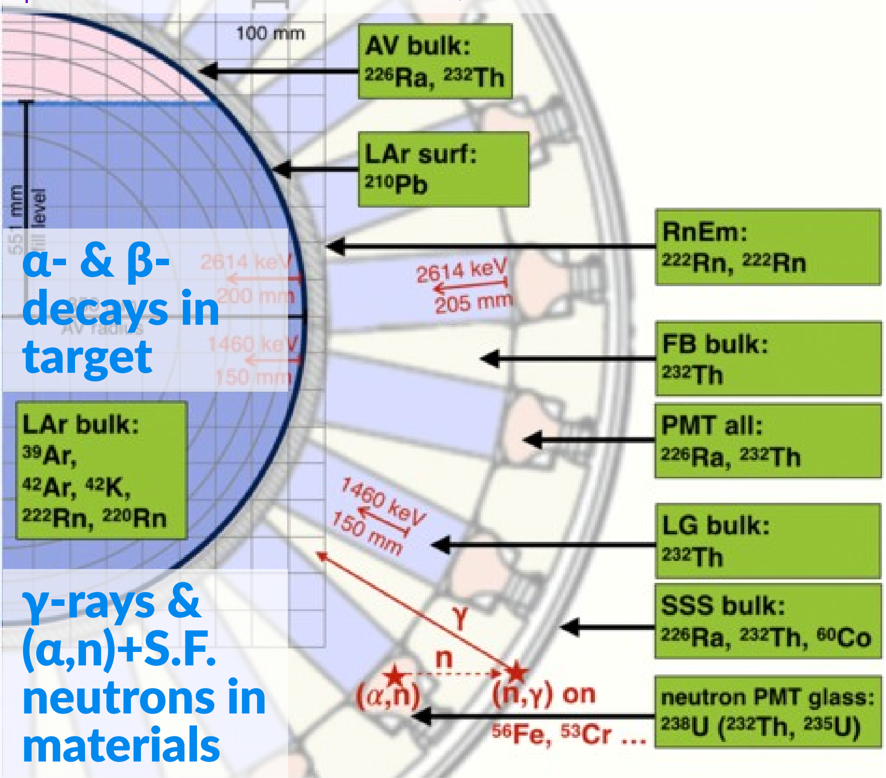


Ciaran A. J. O'Hare Phys. Rev. Lett. 127, 251802

Sources of background: Radiogenic

Trace ^{238}U, ^{232}Th, ^{234}U, ^{40}K, ^{60}Co, etc.

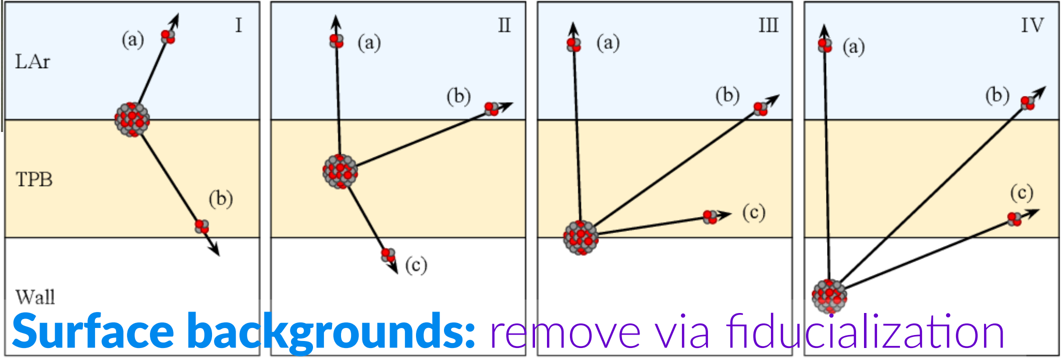
Remove via mutliple scatter cuts, particle identification, fiducial cuts…



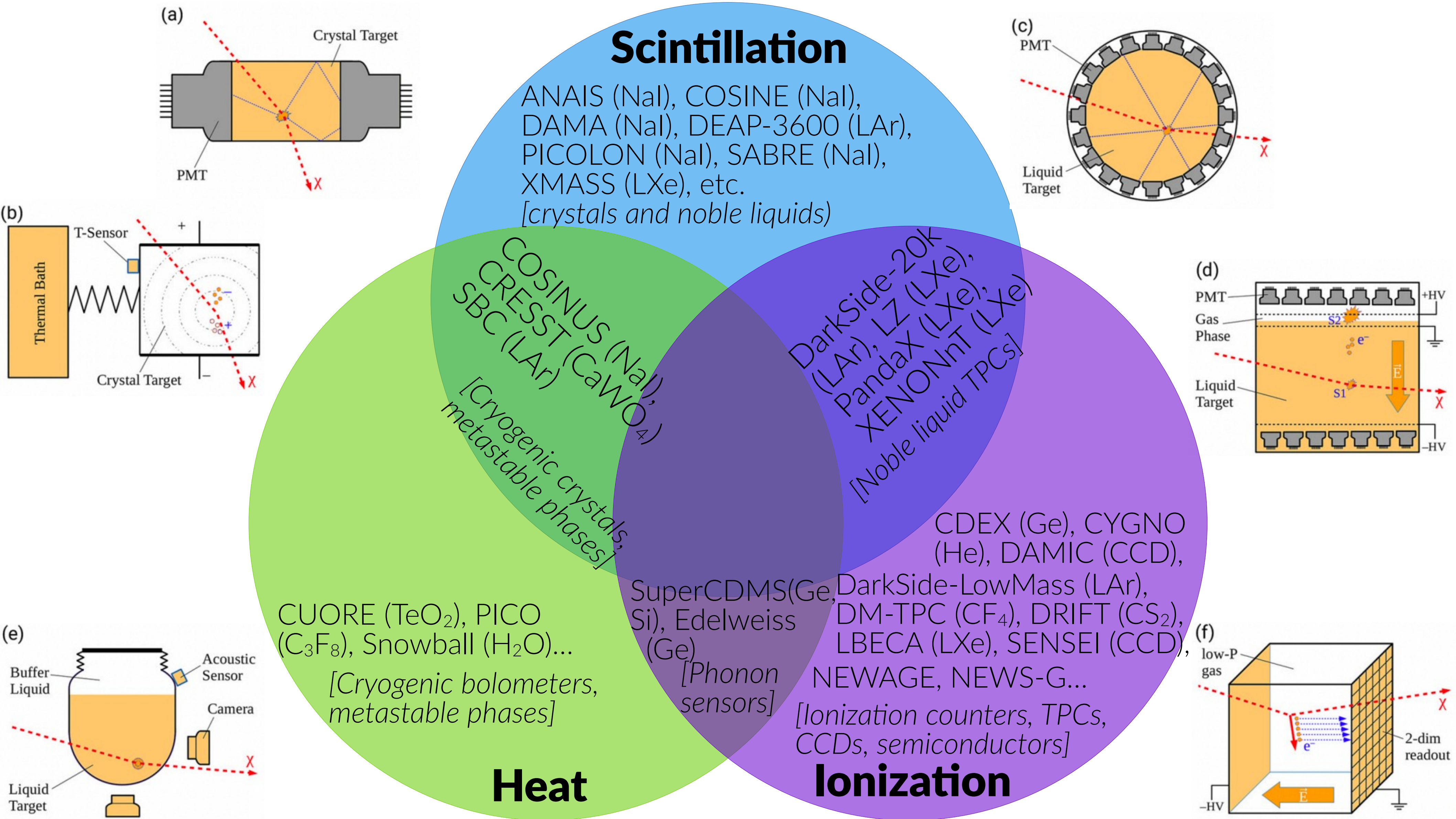
α- & β- decays in target

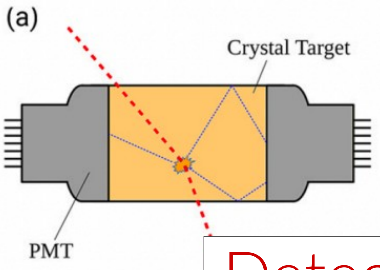
γ-rays & (α,n)+S.F. neutrons in materials

SNOLAB radio-assay facility



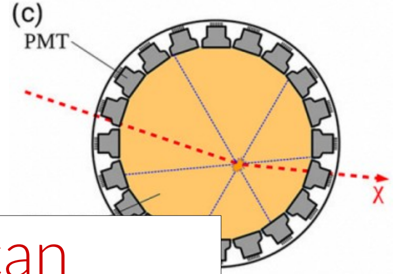
Surface backgrounds: remove via fiducialization


Scintillation
ANAIS (NaI), COSINE (NaI), DAMA (NaI), DEAP-3600 (LAr), PICOLON (NaI), SABRE (NaI), XMASS (LXe), etc.
[crystals and noble liquids]
COSINUS (NaI), CRESST ($CaWO_4$), SBC (LAr)
[Cryogenic crystals, metastable phases]
DarkSide-20K (LAr), LZ (LXe), PandaX (LXe), XENONnT (LXe)
[Noble liquid TPCs]
CUORE (TeO_2), PICO (C_3F_8), Snowball (H_2O)...
[Cryogenic bolometers, metastable phases]
Heat
SuperCDMS(Ge, Si), Edelweiss (Ge)
[Phonon sensors]
CDEX (Ge), CYGNO (He), DAMIC (CCD), DarkSide-LowMass (LAr), DM-TPC (CF_4), DRIFT (CS_2), LBECA (LXe), SENSEI (CCD), NEWAGE, NEWS-G...
[Ionization counters, TPCs, CCDs, semiconductors]
Ionization
(a)
Crystal Target
PMT
X
(b)
Thermal Bath
T-Sensor
+
−
Crystal Target
X
(c)
PMT
Liquid Target
X
(d)
PMT
+HV
Gas Phase
S2
e^-
$\vec{E}$
Liquid Target
S1
X
−HV
(e)
Buffer Liquid
Acoustic Sensor
Camera
Liquid Target
X
(f)
low-P gas
e^-
X
2-dim readout
$\vec{E}$
−HV

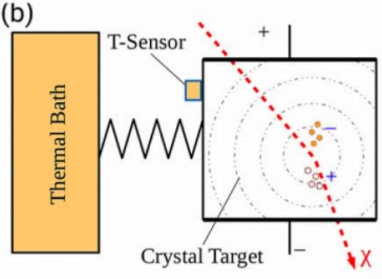


Scintillation

ANAIS (NaI), COSINE (NaI),
DAMA (NaI), DEAP-3600 (LAr),
PICOLON (NaI), SABRE (NaI),

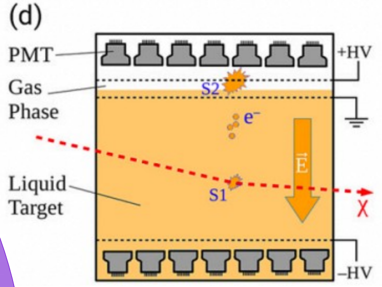


Detectors that utilize two channels can compare both in order to achieve particle identification, often at the cost of a higher energy threshold



(NaI),
(CaWO$_4$)
CA (CaWO$_4$),
(LAr)
[Cryogenic crystals, metastable phases]

D
(LAr
Panda
XENON
[Noble liquid TPCs



CDEX (Ge), CoGeNT (Ge), DAMIC (CCDs), DarkSide-LowMass (LAr), DM-TPC (CF$_4$), DRIFT (CS$_2$), LBECA (LXe), NEWAGE, NEWS-G…

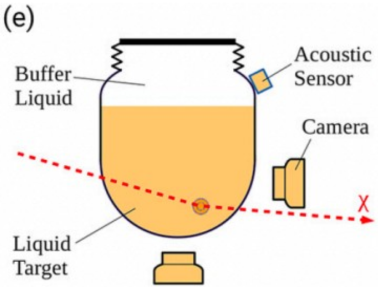
SuperCDMS(Ge, Si), Edelweiss (Ge)
[Phonon sensors]

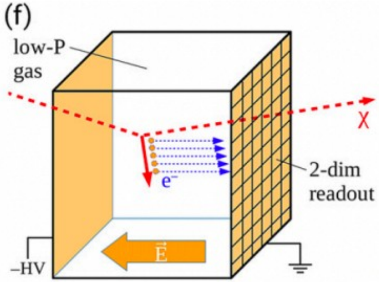
CUORE (TeO$_2$), PICO (CCl$_2$F$_2$), Snowball (H$_2$O)…
[Cryogenic bolometers, metastable phases]

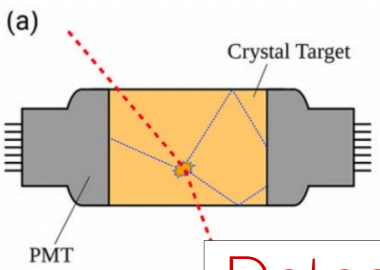
[Ionization counters, TPCs, CCDs, semiconductors]

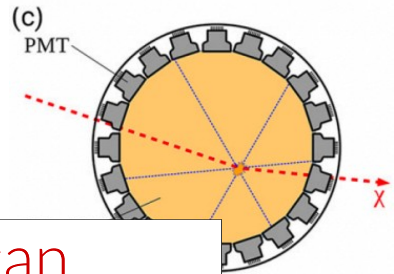
Heat

Ionization



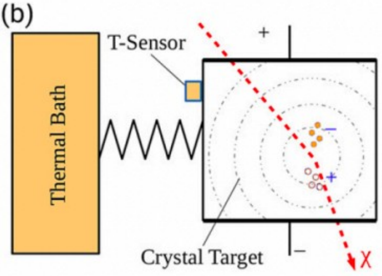






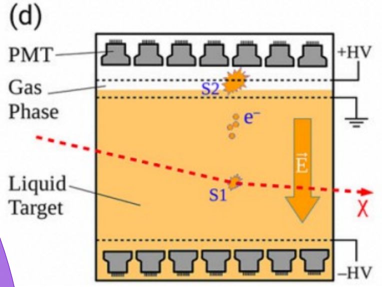
Scintillation

ANAIS (NaI), COSINE (NaI), DAMA (NaI), DEAP-3600 (LAr), PICOLON (NaI), SABRE (NaI),



Detectors that utilize two channels can compare both in order to achieve particle identification, often at the cost of a higher energy threshold

Sensitivity to lighter dark matter candidates requires detectors that produce detectable quanta via lower-energy processes – e.g. superconductors, superfluid helium



eNT

Ds),

SuperCDMS(Ge, Si), Edelweiss (Ge)

[Phonon sensors]

DarkSide-LowMass (LAr), DM-TPC (CF_4), DRIFT (CS_2), LBECA (LXe), TEXONO (Ge), NEWS-G…

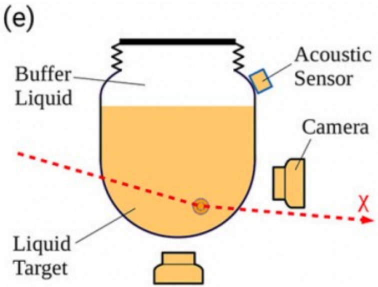
[Ionization counters, TPCs, CCDs, semiconductors]

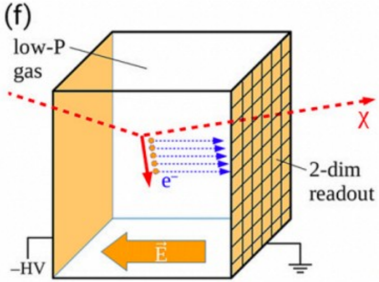
Ionization

CUORE (TeO_2), PICO (CCl_2F_2), Snowball (H_2O)…

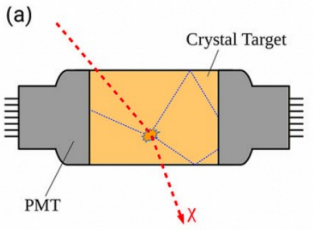
[Cryogenic bolometers, metastable phases]

Heat





NaI(Tl) annual modulation searches



DAMA/LIBRA (LNGS, Italy): 250 kg NaI(Tl) crystals over 20 yrs. Modulation seen at 13.4σ in 1–6 keV

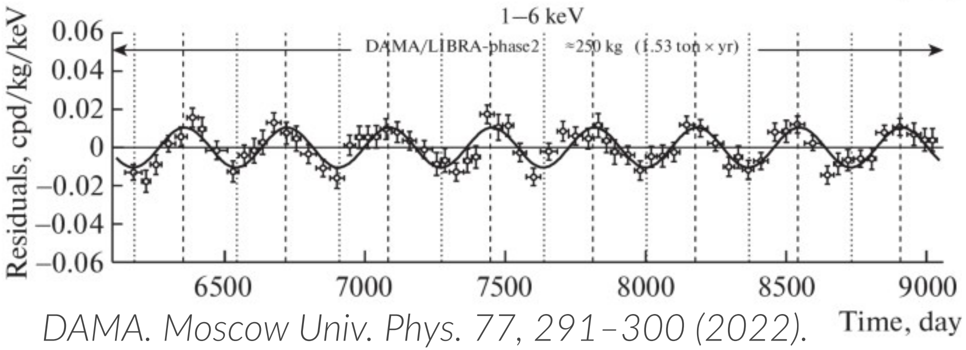
ANAIS 112 (Canfranc, Spain): 113 kg NaI(Tl), in 5 yrs. Incompatible w/ DAMA at 3.3σ in 1–6 keV.

COSINE 100 (Yangyang, South Korea): 61.3 kg NaI(Tl) in liquid scintillator veto over 2.8 yrs. No modulation evidence, best-fit amplitude: 0.0067±0.0042 cts/(day·kg·keV) in 1–6 keV. Growing 200 kg of crystals for COSINE 200

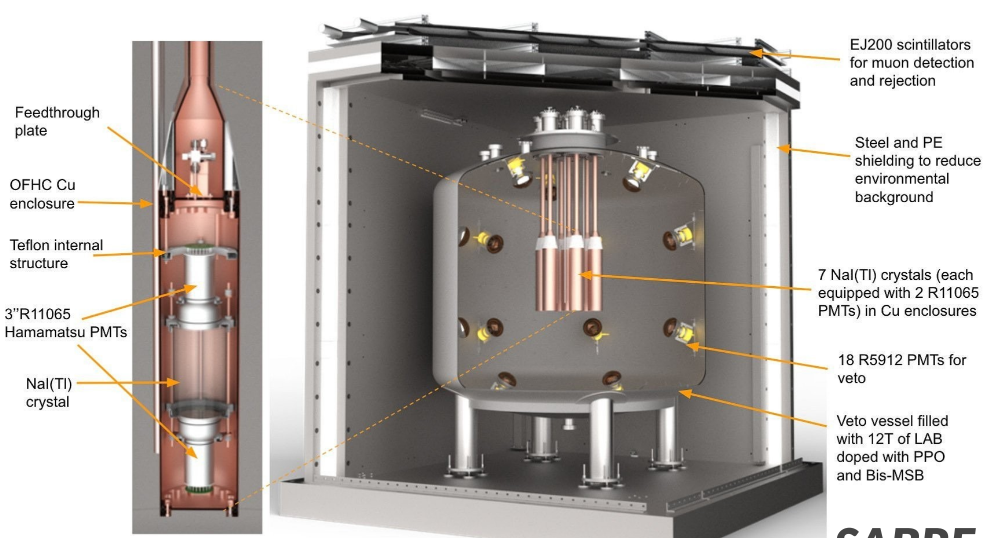
SABRE (LNGS, Italy + SUPL, Australia): Prototype at LNGS w/ ultra-pure NaI(Tl) underway. Compare modulation in N+S hemispheres controls seasonal effects. Radiopurity competitive w/ DAMA

PICOLON (Kamioka, Japan): NaI(Tl) in prep, to be submerged in Kamland scintillator

COSINUS (LNGS, Italy): Cryogenic NaI(Tl) scintillator+bolometer, in prep. Will use light+heat to discriminate electronic and nuclear recoils

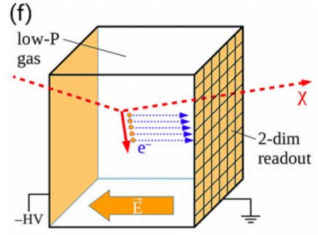


DAMA. Moscow Univ. Phys. 77, 291–300 (2022).



SABRE

Gaseous TPCs and directionality



Due to the lower density of gaseous TPCs, ionization tracks from nuclear and electronic recoils are long enough to be measured, allowing directionality to be inferred. Track density and electron diffusion can inform particle identification. Directionality can help suppress neutrino backgrounds.

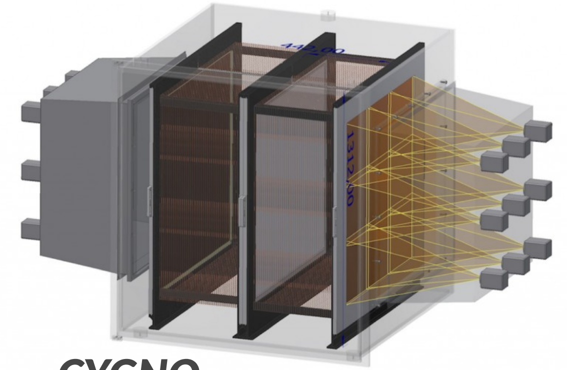
CYGNO (LNGS, Italy): 1 m^3 He demo. being prepared. Will follow w/ 30-100 m^3 detector

DM-TPC (MIT, USA): 150 g CF_4 low-pressure TPC, in R&D and prototyping phase

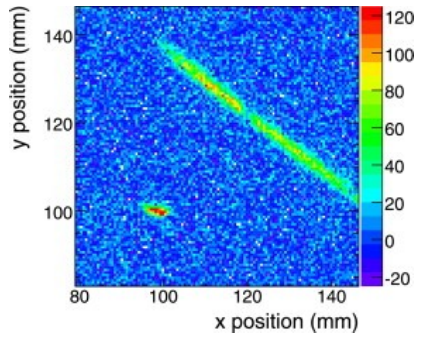
DRIFT-IId (Boulby, UK): 24 g of CS_2, CF_4, or O_2. Successfully demonstrated, plans to scale up

NEWAGE (Kamioka, Japan): 10 g off CF_4. Successfully demonstrated, plans to scale up

NEWS-G (SNOLAB, Canada): 283 g of Ne+CH_4 (and others) Spherical Proportional Counters; low-threshold, non-directional DM search

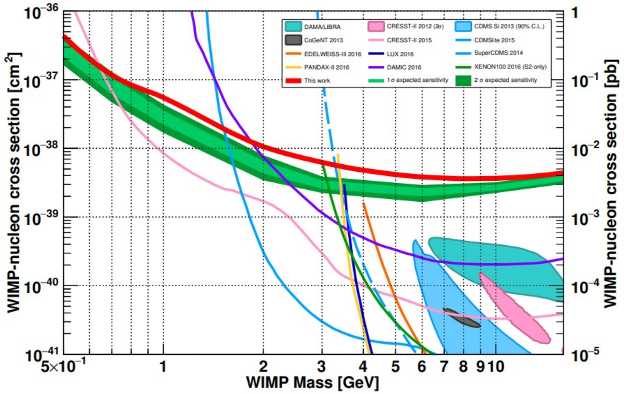


CYGNO



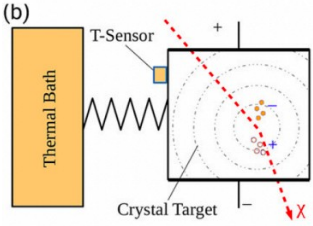
DMTPC. Phys Lett B 695 1–4 (2011); 124–129

NEWS-G



NEWS-G. Astropart Phys 97 (2018):54–62

Cryogenic crystals, semiconductors



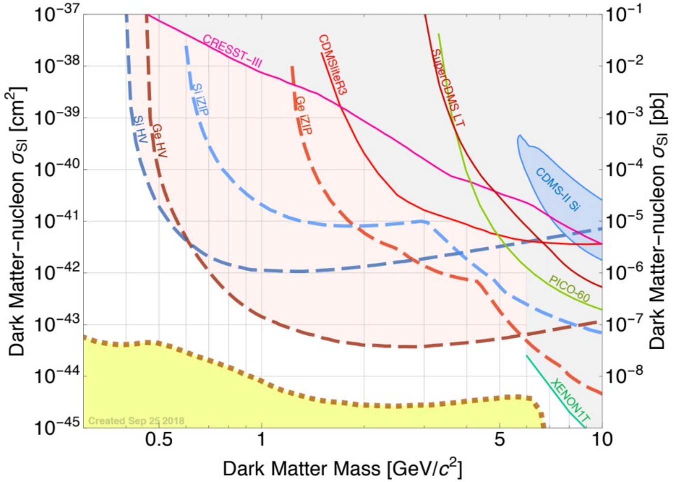
Low-energy cryogenic detectors using silicon and germanium targets for bolometers. These targets typically scintillate or produce detectable ionization charges, allowing them to achieve particle identification and low energy thresholds

SuperCDMS (SNOLAB, Canada): 36 kg Ge and Si phonon and ionization detectors (iZip & HV)

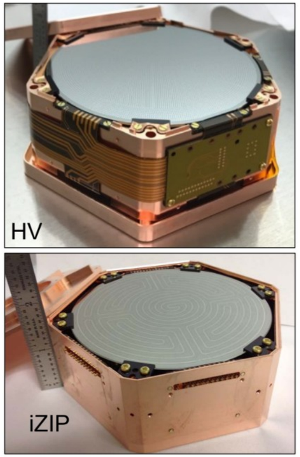
CDEX-10 (CJPL, China): 10 kg p-type point contact HPGe ionization detectors, collecting data

CRESST-III (LNGS, Italy): 23.6 g $CaWO_4$ crystal scintillating bolometers

EDELWEISS-III (LSM, France): 21 kg Fully Inter-Digitized (FID) Ge bolometer w/ ionization readout

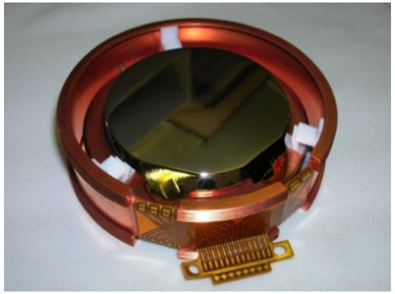


SuperCDMS. TAUP 2015



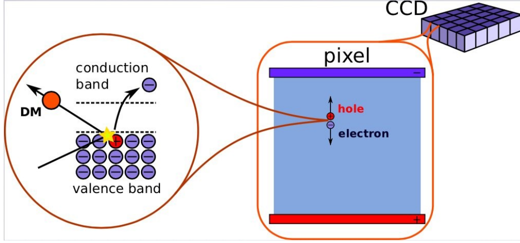
SuperCDMS

CRESST



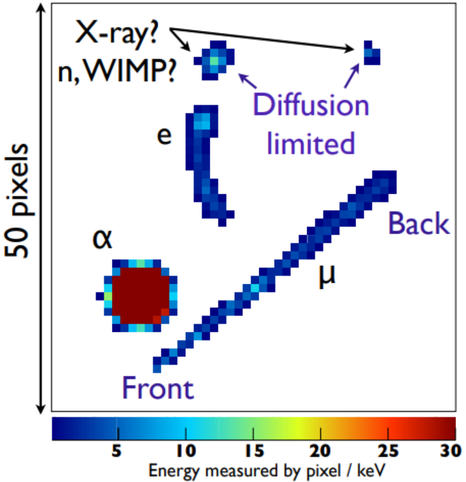
EDELWEISS bolometer

CCD-based detectors

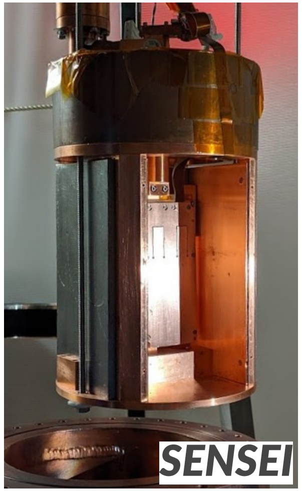


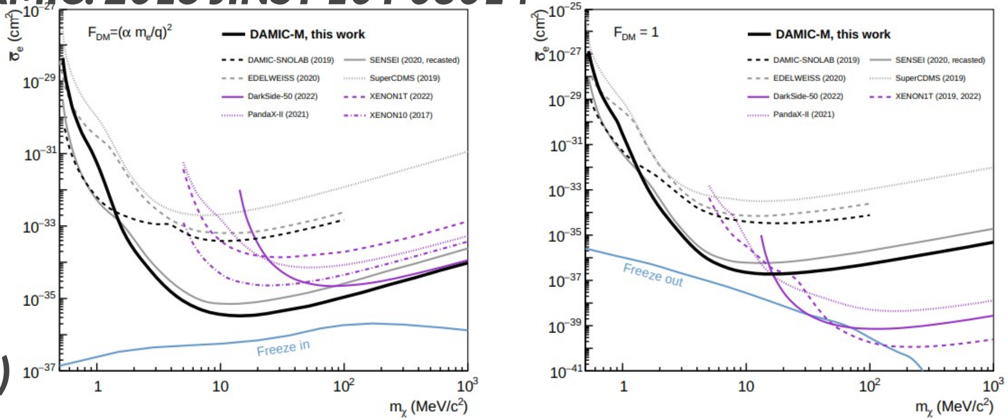
Charge-coupled devices (CCDs) can record the ionization track of a recoiling particle, allowing for particle identification and low-threshold searches for electron-coupled DM

- **DAMIC-M LBC** (LSM, France): 18 g CCDs. First search performed. Plans to scale to 700 g
- **SENSEI** (Fermilab, USA): 2 g high-resistivity skipper-CCDs with reduced noise. Plans to scale to 100 g at SNOLAB
- **OSCURA** (LNGS, Italy): 10 kg skipper-CCDs, in R&D and plannign phase



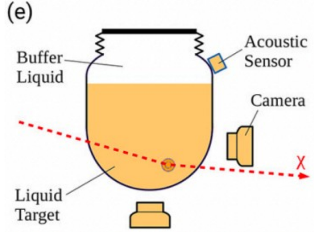
DAMIC. 2015 JINST 10 P08014





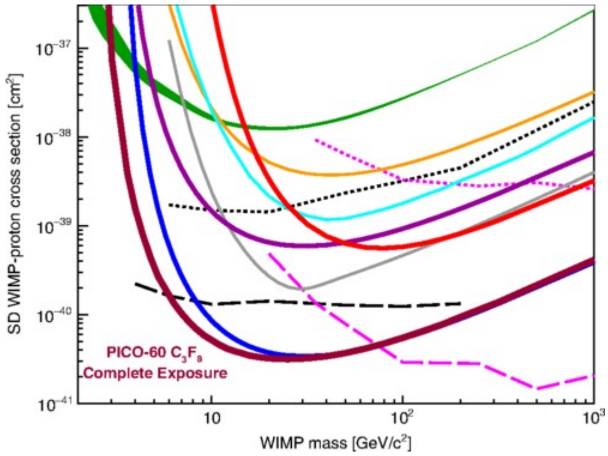
DAMIC. PRL 130, 171003 (2023)

Phase-change detectors



By superheating/cooling the target to the edge of a phase transition, heat generated by a nuclear recoil can nucleate a bubble without backgrounds from electronic recoils

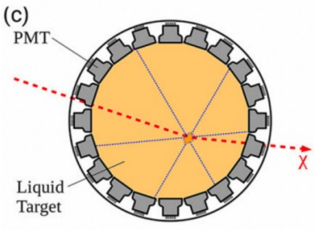
- **PICO-40L** (SNOLAB, Canada): 57 kg of C_3F_8 (freeon) in a bubble chamber, currently being commissioned. Focus on spin-dependent DM
- **SBC-LAr10** (SNOLAB, Canada): 10 kg xe-doped LAr bubble chamber using scintillation to veto high-energy nuclear recoils (α's, neutrons) with a 100 eV threshold. Prototype being commissioned
- **SNOWBALL:** a future supercooled water-target detector, forming ice after DM scatters on ^{1}H. Currently in R&D phase



PICO. Phys. Rev. D 100, 022001 (2019)

SBC – arXiv:2207.12400

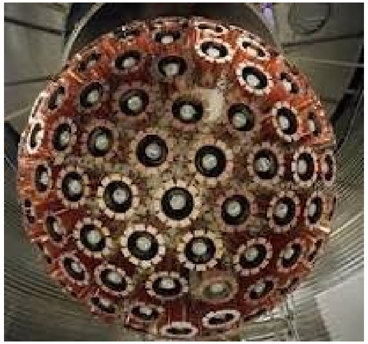
Noble liquid scintillators

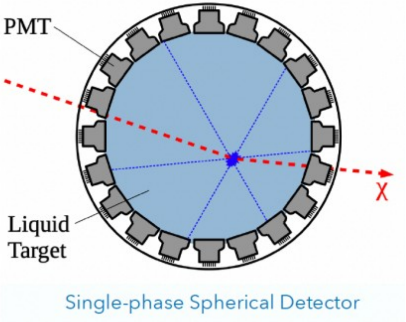


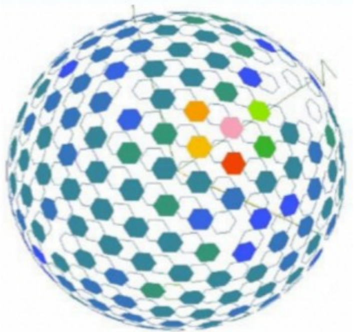
Noble liquids (e.g. LAr and LXe) are readily scaled to large sizes and scintillate very efficiently, making them well-suited for tonne-scale detectors and larger, and can be made extremely radio- and chemically pure

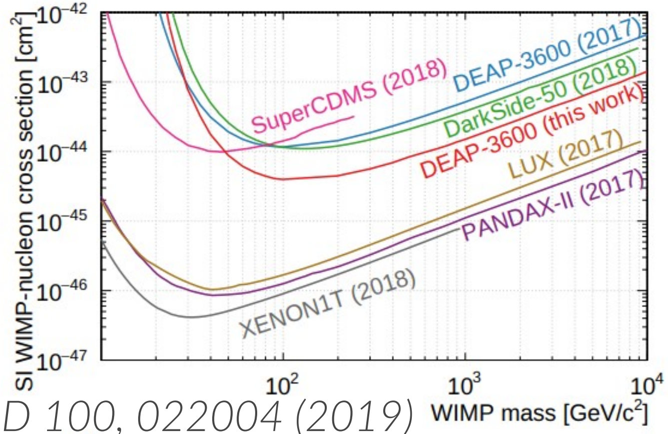
DEAP-3600 (SNOLAB, Canada): 3.3 tonnes of LAr, currently offline for upgrades. Electronic recoil background suppression by ~10^{10} using pulse shape discrimination

XMASS-I (Kamioka, Japan): 800 kg of LXe, completed operations in 2019

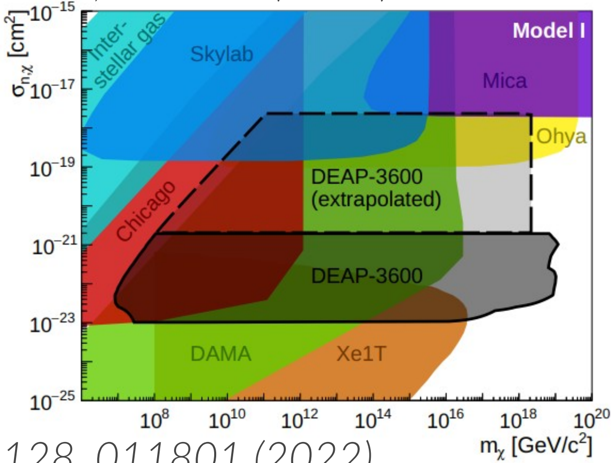






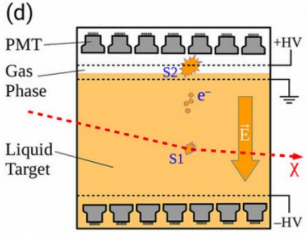


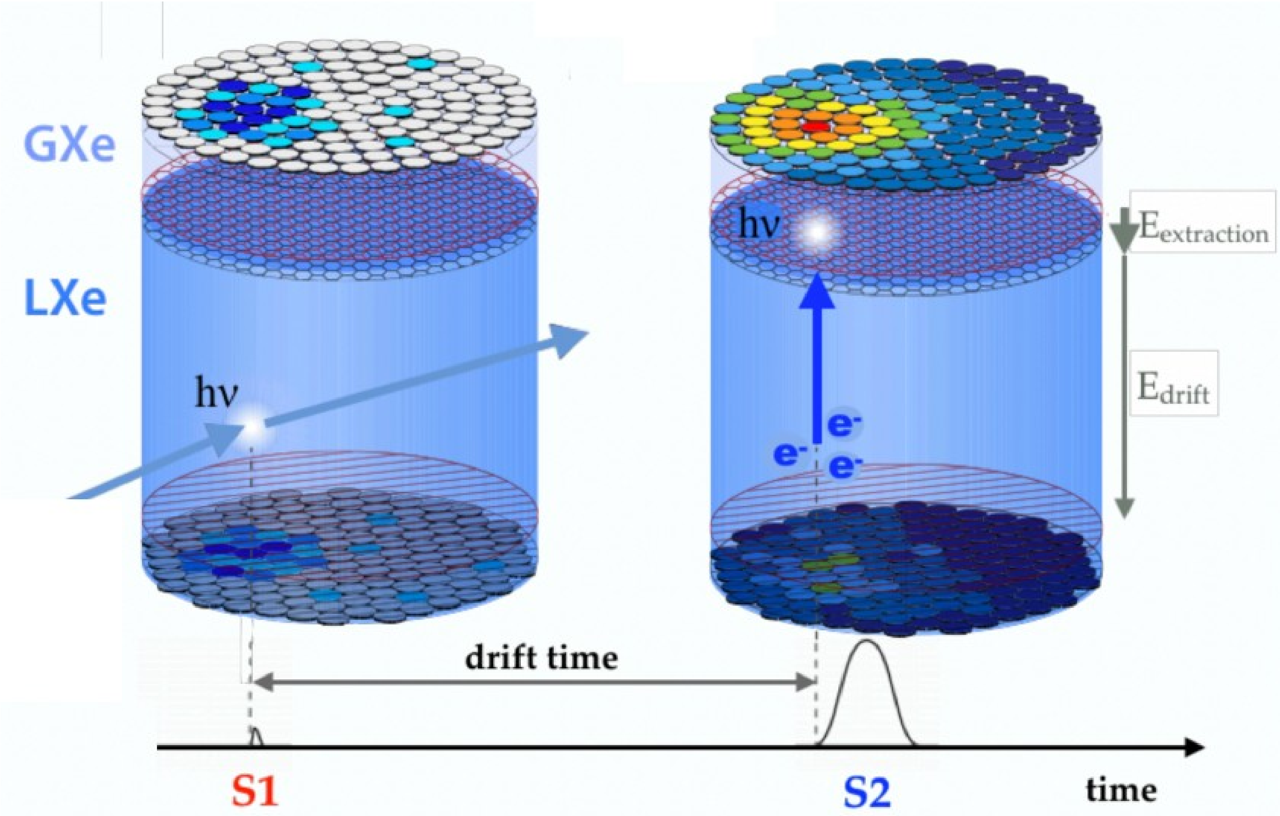
DEAP. PRD 100, 022004 (2019)



DEAP. PRL 128, 011801 (2022)

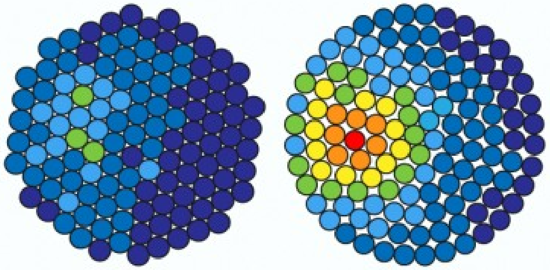
Dual-phase noble liquid TPCs





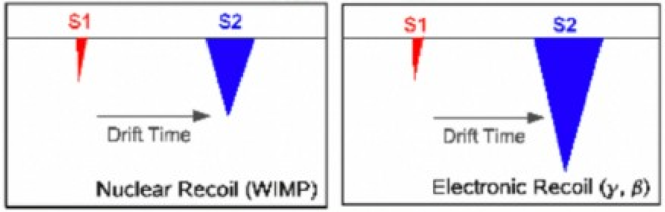
S1
Primary Scintillation

S2
Ionization (Secondary Scintillation)



Position reconstruction (fiducialization)

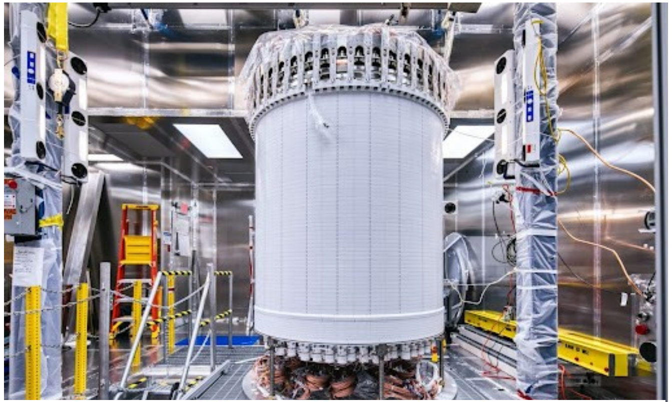
$$\frac{S2}{S1}_{NR} < \frac{S2}{S1}_{ER}$$

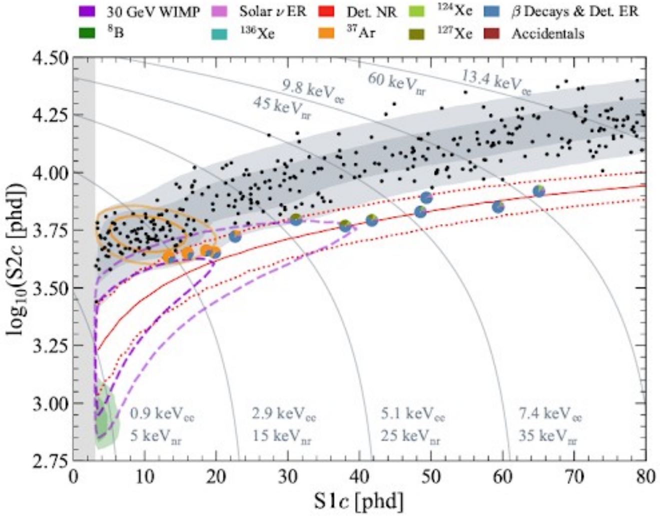


Particle discrimination

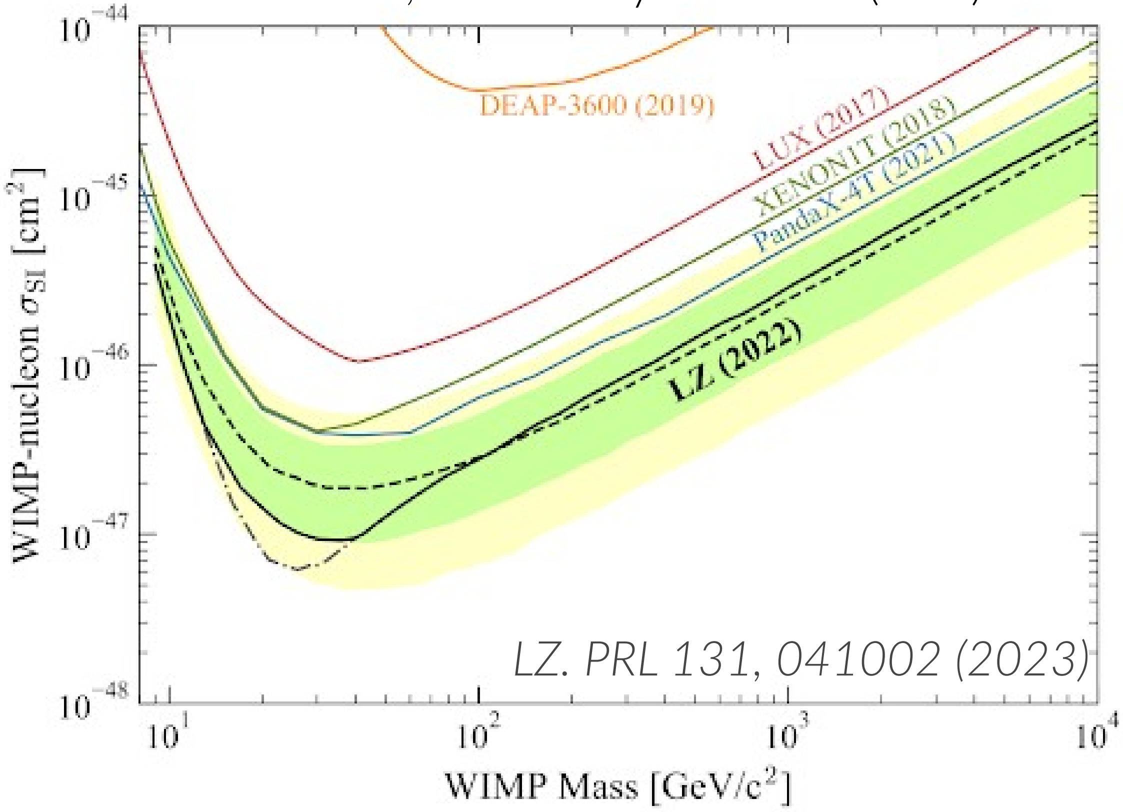
Slide from B. Bottino – ICPPA 2022

LXe TPCs: LZ





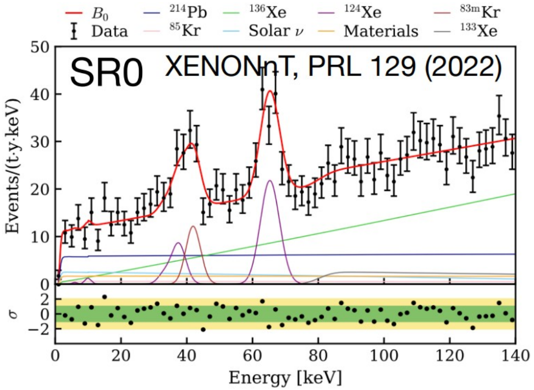
7 tonnes, 60 live days at SURF (USA)

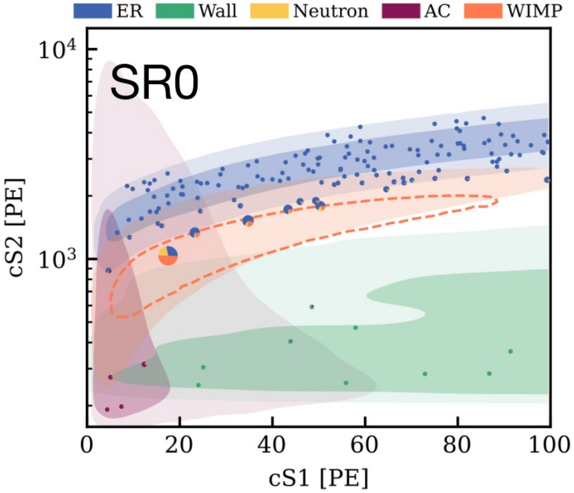


LZ. PRL 131, 041002 (2023)

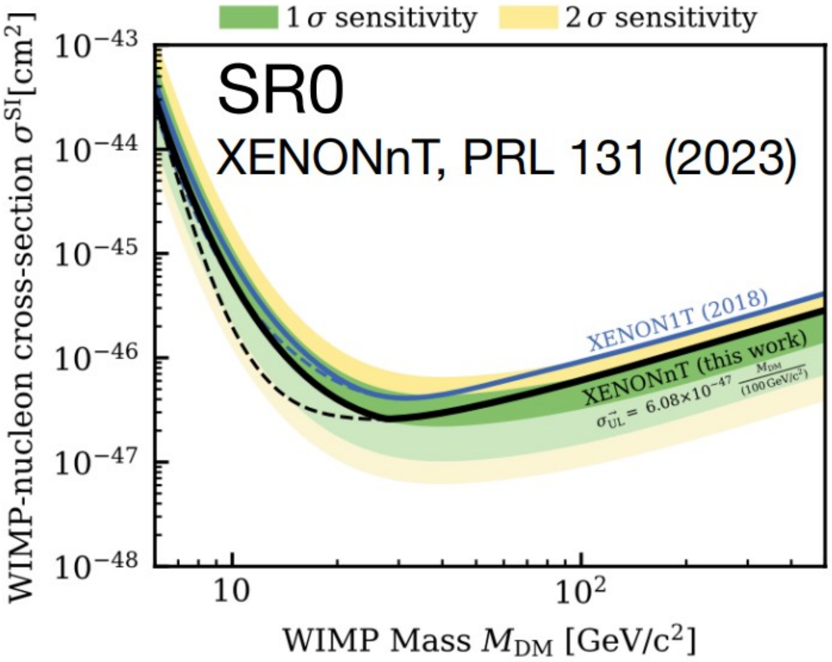
Also sensitive to 0νββ, solar neutrino CEνNS. Planned run thru 2028

LXe TPCs: XENONnT



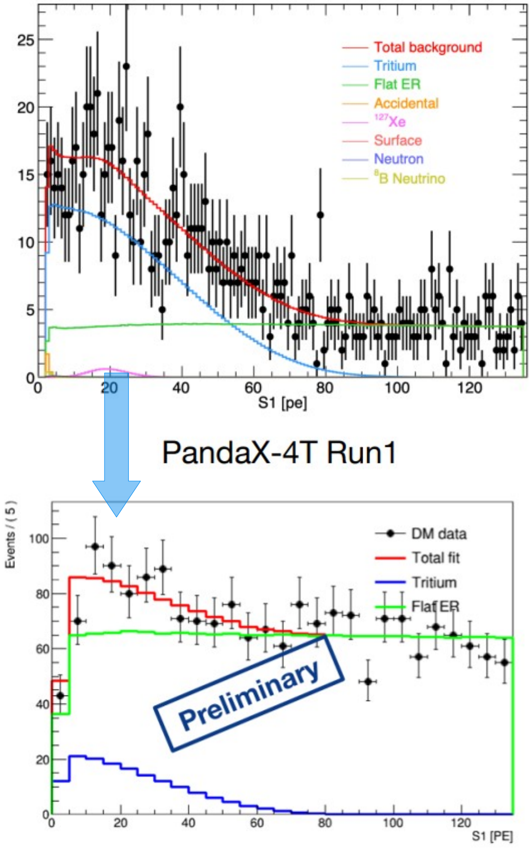


6 tonnes, 91 days at LNGS (Italy)



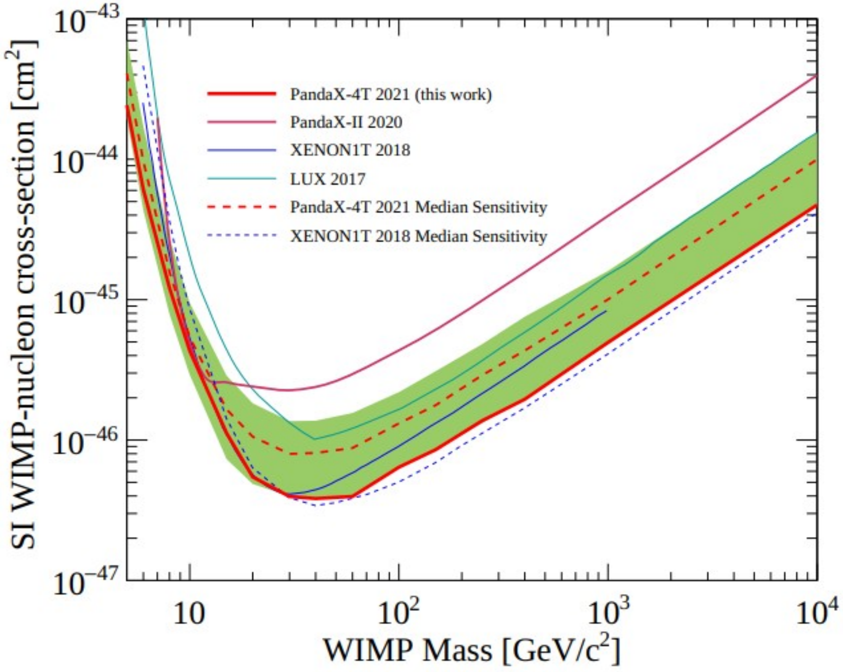
LXe TPCs: PandaX

PandaX-4T Run0 (PRL 2021)



PandaX-4T Run1

2.7 tonnes, 86 days at CJPL (China)

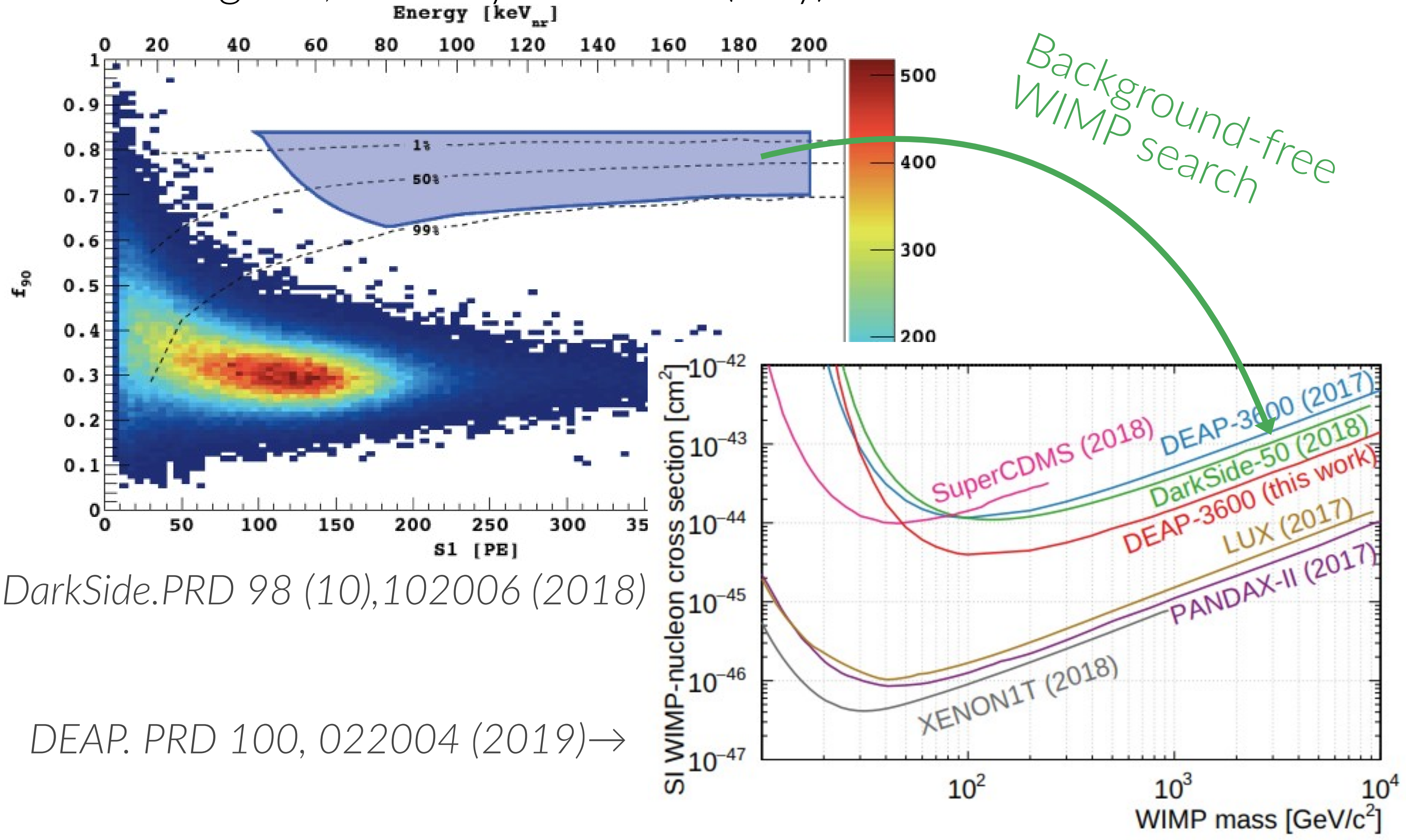


Run0: 3.0±0.3 cts/day
Run1: 0.4±0.1 cts/day

Detector upgrades
Plan to resume end of 2023

LAr TPCs: DarkSide-50

50 kg LAr, 532 days at LNGS (Italy).



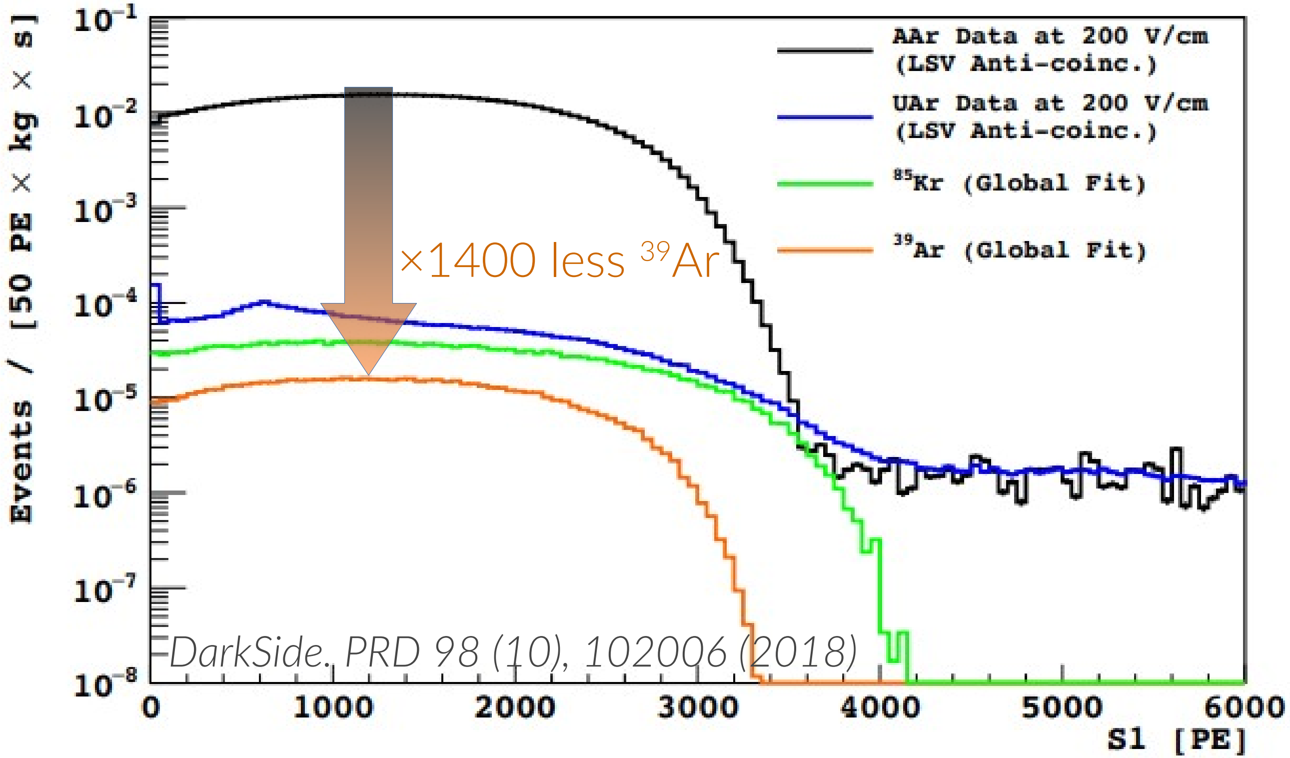
Background-free WIMP search

DarkSide.PRD 98 (10),102006 (2018)

DEAP. PRD 100, 022004 (2019)→

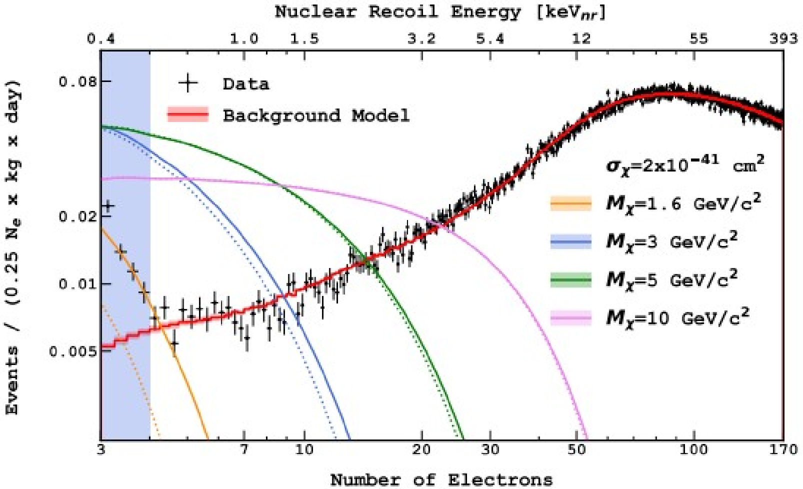
LAr TPCs: DarkSide-50

Pioneered use of low-radioactivity underground argon (UAr)

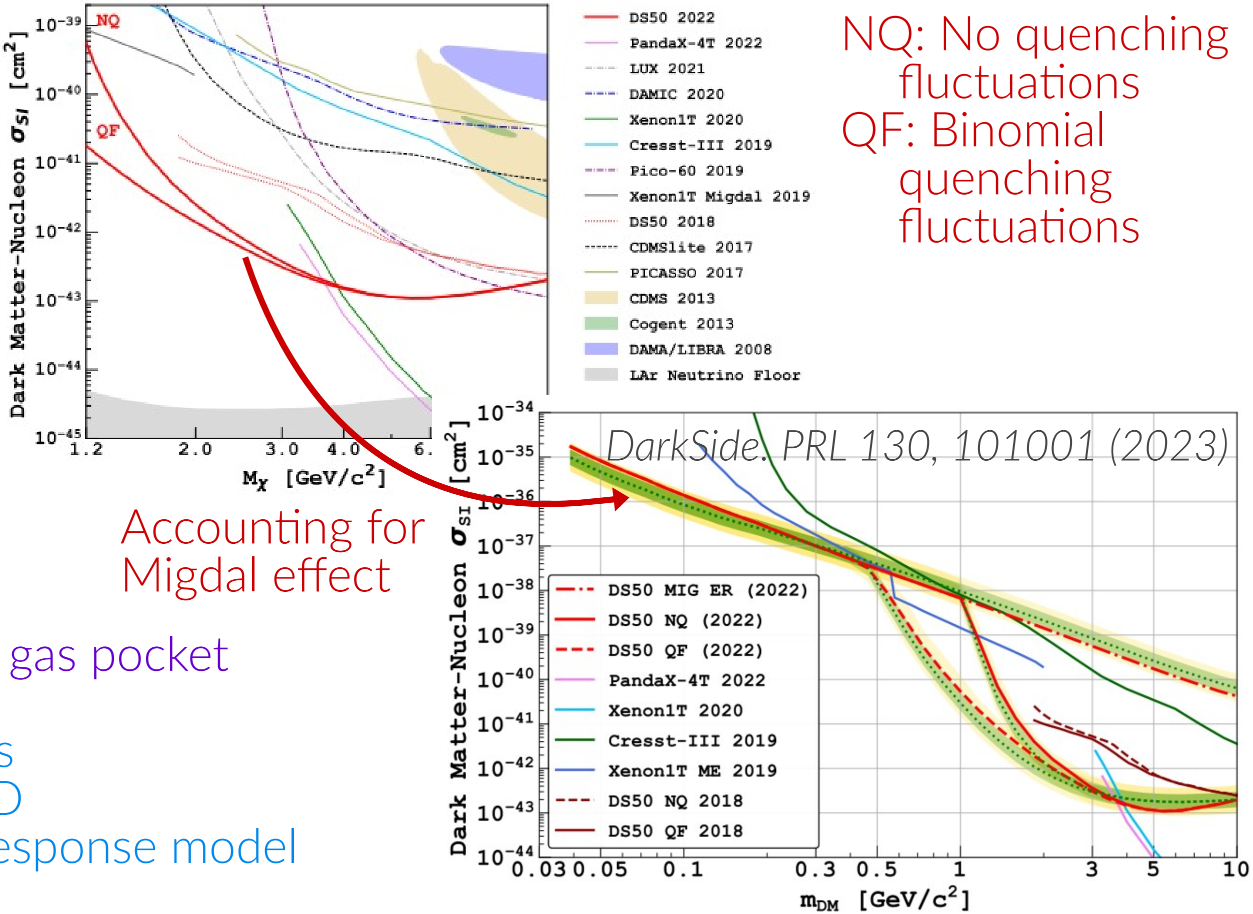


DarkSide, PRD 98 (10), 102006 (2018)

LAr TPCs: DarkSide-50, S2-only



DarkSide. PRD 107, 063001 (2023)



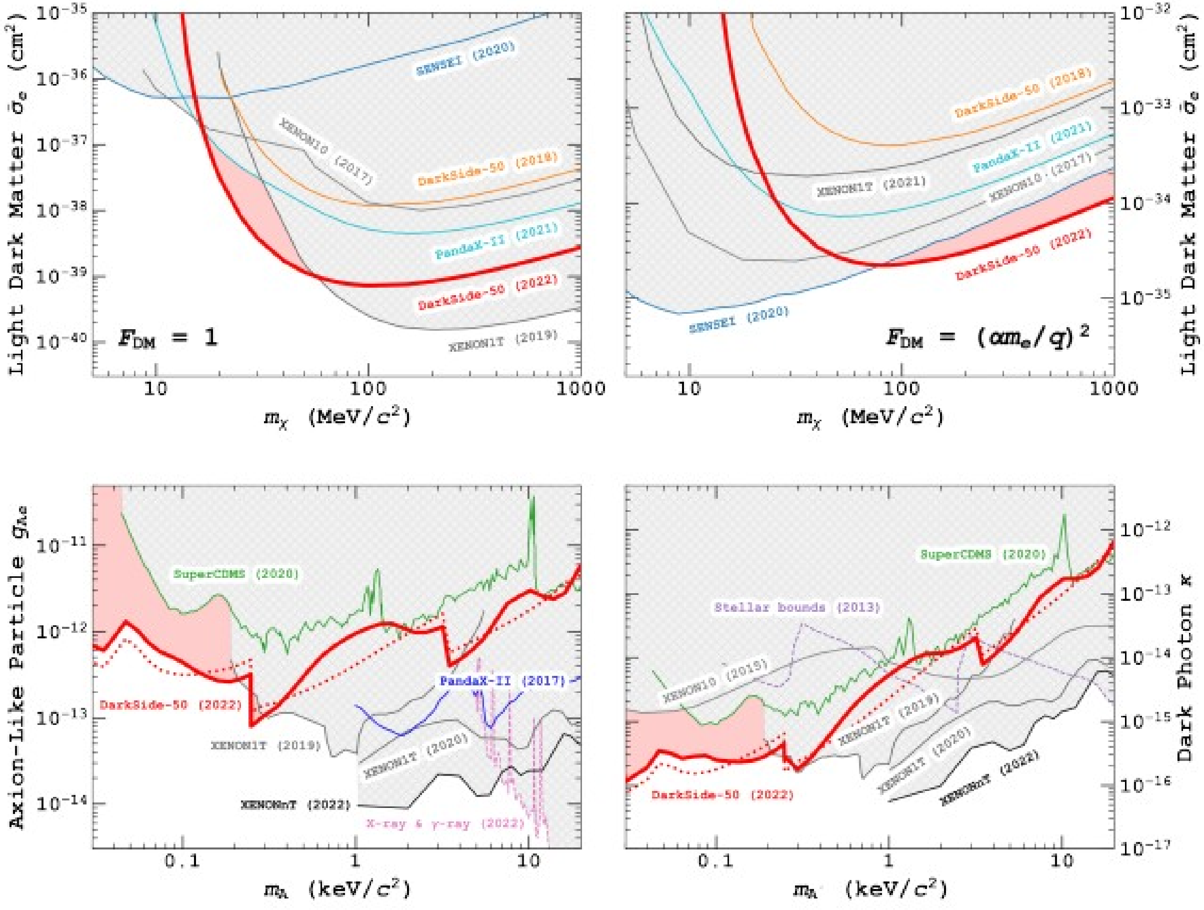
DarkSide. PRL 130, 101001 (2023)

Accounting for Migdal effect

NQ: No quenching fluctuations
QF: Binomial quenching fluctuations

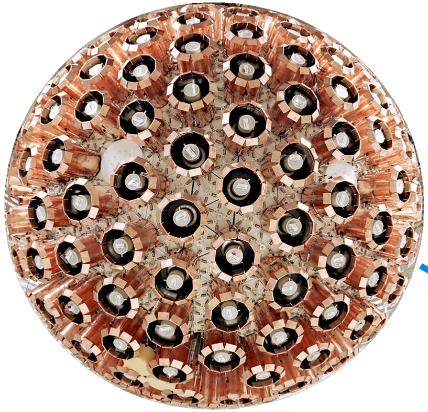
S2 reaches lower energy than S1, due to gas pocket amplification
Benefit from high purity and light nucleus
Threshold set by spurious e$^-$ → Need R&D
Planning ex situ calibrations to validate response model

LAr TPCs: DarkSide-50, S2-only



DarkSide.130, 101002 (2023)

Global Argon Dark Matter Collaboration

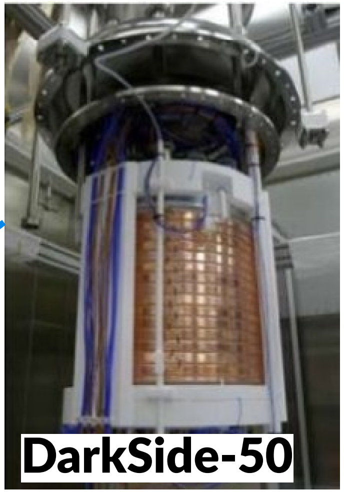


DEAP-3600

ArDM

Y. Wang

DarkSide-20k: Under construction at LNGS
50 tonnes of UAr in a 30 tonne UAr + Gd-PMMA neutron veto, in a 650 tonne AAr outer muon veto
Planned exposure: 200 t×yr



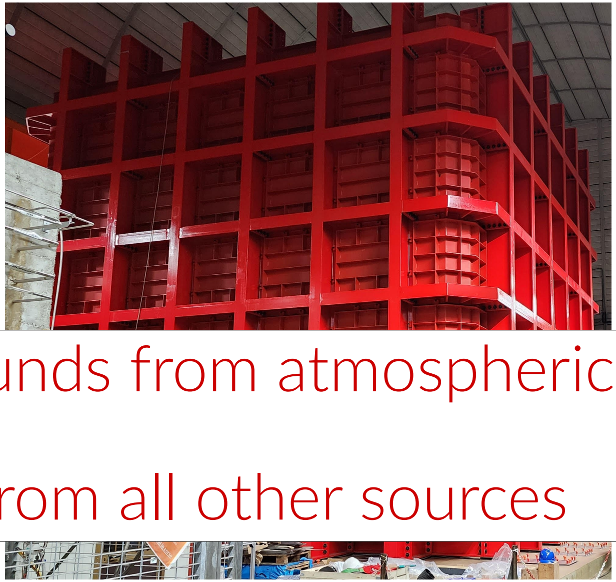
DarkSide-50

MiniCLEAN

Global Argon Dark Matter Collaboration

DEAP-3

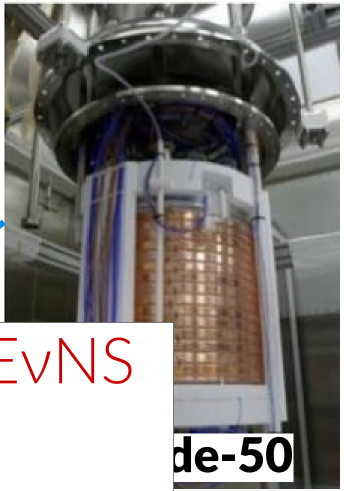
ArDM



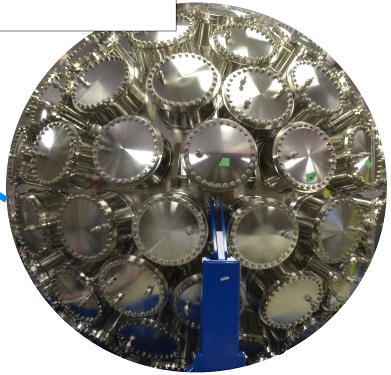
Expect 3 backgrounds from atmospheric neutrino CEvNS

<<1 background from all other sources

DarkSide-20k: Under construction at LNGS
50 tonnes of UAr in a 30 tonne UAr + Gd-PMMA neutron veto, in a 650 tonne AAr outer muon veto
Planned exposure: 200 t×yr

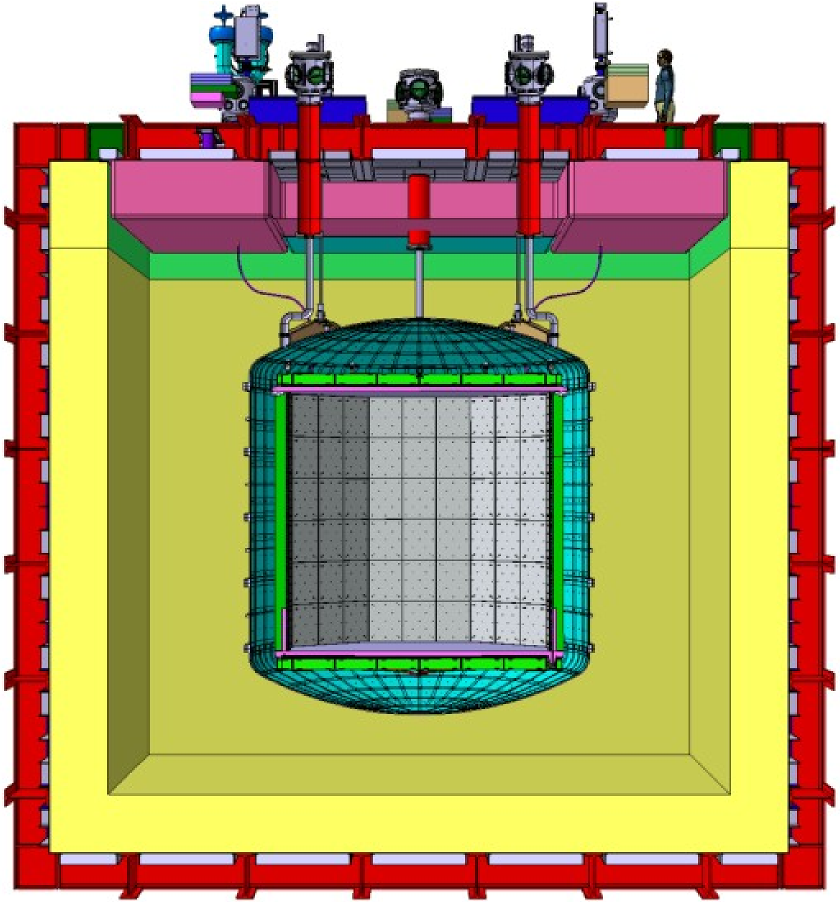


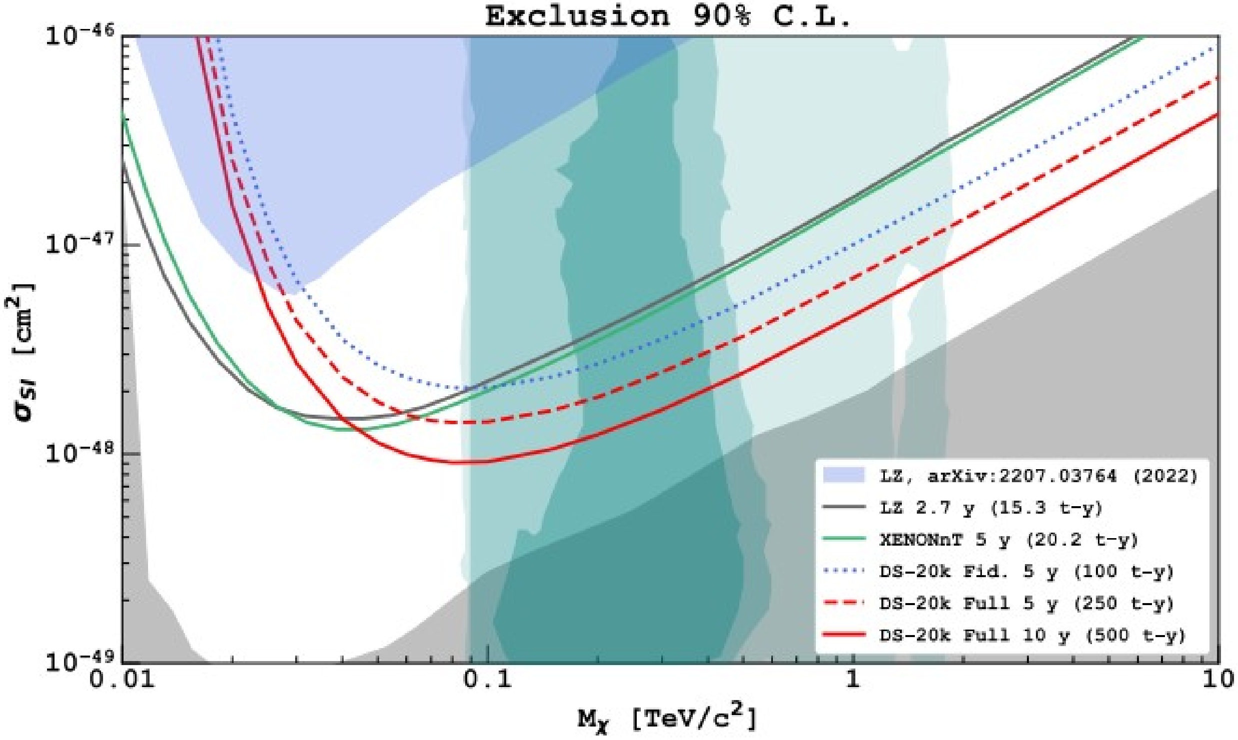
de-50



MiniCLEAN

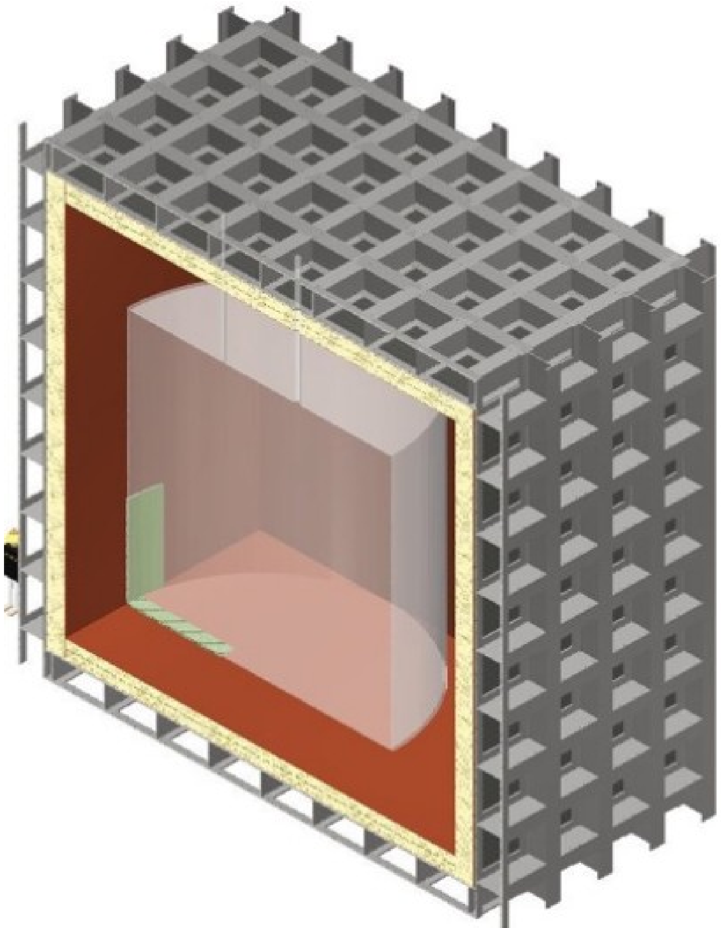
DarkSide-20k





To be followed by Argo at SNOLAB, which will reach the neutrino fog with a 3000 t×yr exposure

Argo: The ultimate LAr detector to push into the neutrino fog

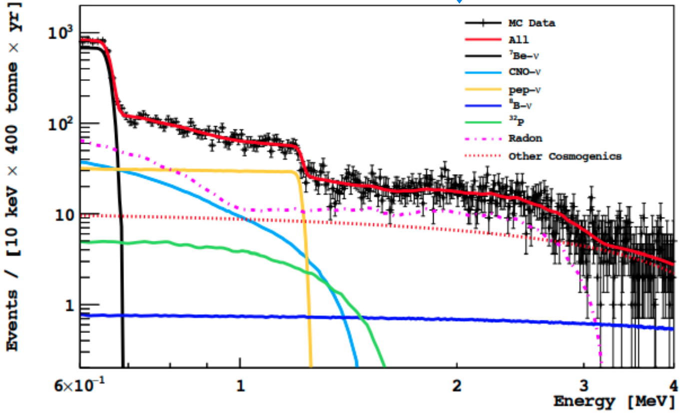


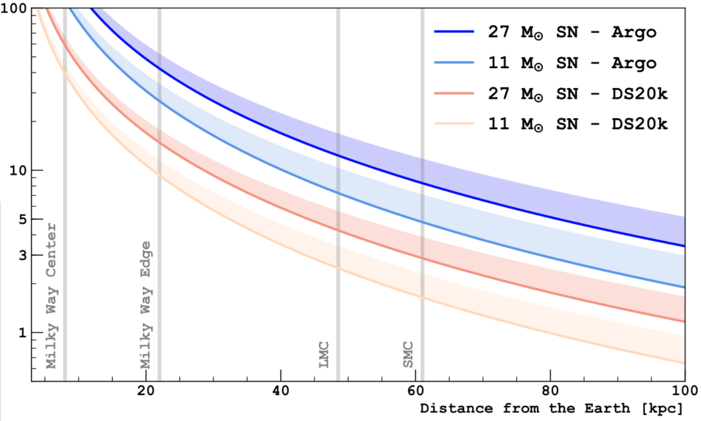
Timeline: Early 2030’s at SNOLAB

Mass: ~300 tonnes

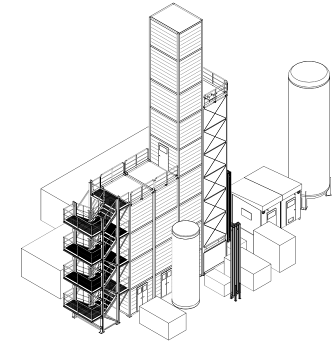
Rich broader physics program:

- Supernova neutrino sensitivity to CEvNS & ^{40}Ar(ν_e,e$^-$)^{40}K*
- Solar neutrino physics





UAr: Low radioactivity argon

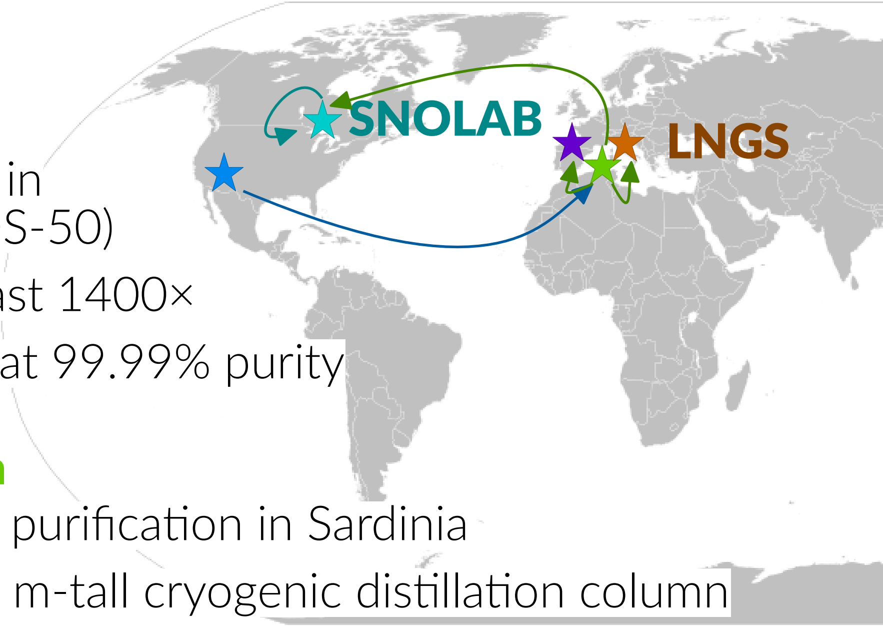


Urania

UAr extraction plant in Colorado (same as DS-50)

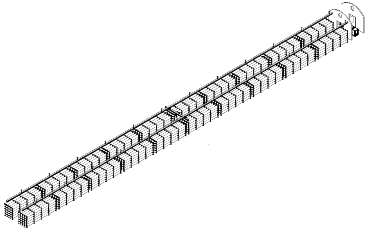
^{39}Ar reduction: at least 1400×

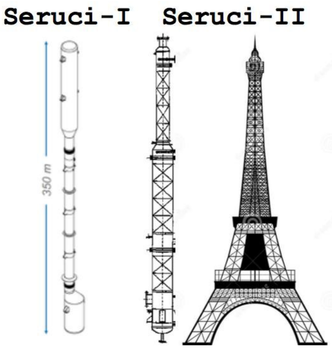
Extract: 250 kg/day at 99.99% purity



ARGUS

Long-term UAr storage at SNOLAB





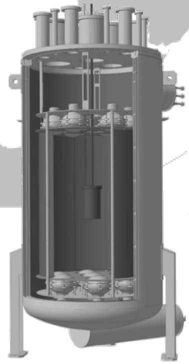
Aria

UAr purification in Sardinia

350 m-tall cryogenic distillation column

Chem. purification: 10^3× reduction at O(1 tonne/day)

^{39}Ar depletion: 10× reduction at O(10 kg/day)



DArT in ArDM

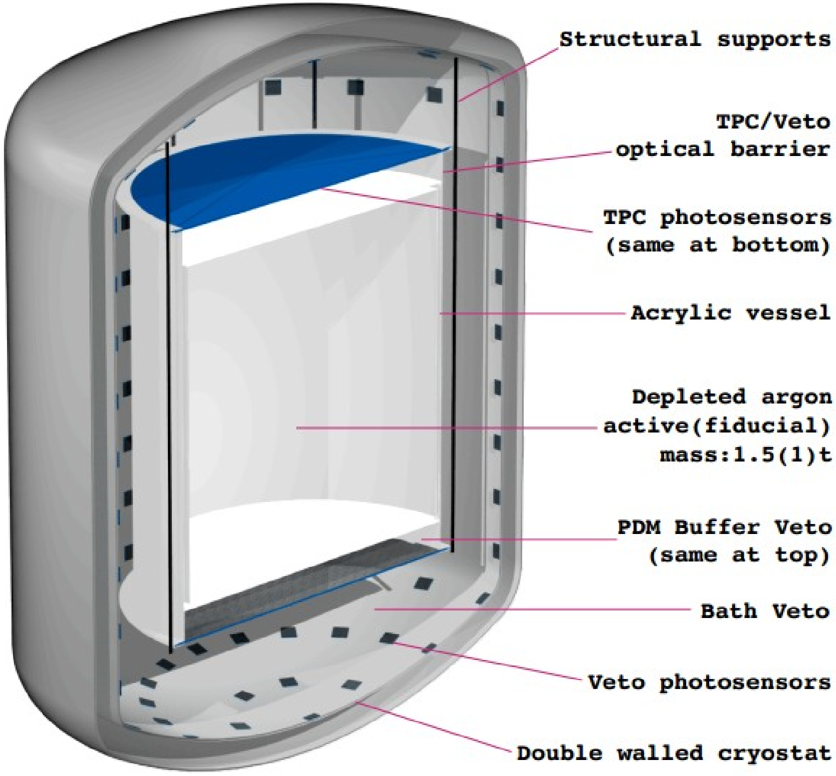
Small-batch ^{39}Ar assay facility in Canfranc Lab, Spain

Sensitivity: depletion factor U.L. of 6×10^4 at 90% C.L. in 1 week of counting time

DarkSide Collaboration. "Separating ^{39}Ar from ^{40}Ar by cryogenic distillation with Aria for dark matter searches". Eur.Phys.J.C 81, 359 (2021)
DarkSide Collaboration. "Measurement of isotopic separation of argon with the prototype of the cryogenic distillation plant Aria for dark matter searches". Eur. Phys. J. C 83, 453 (2023)

DarkSide Collaboration. "Design and construction of a new detector to measure ultra-low radioactive-isotope contamination of argon". JINST 15 P02024 (2020)

DarkSide-LowMass: Optimized for S2-only analyses



Active (fiducial) mass: 1.5 (1) tonnes underground argon

Better 1e$^-$ resolution: Stronger electroluminescence field and more uniform extraction grid using tense wire grid

Additional ^{39}Ar depletion: 10–100× relative to DS-50 w/ Urania improvements and isotopic purification in Aria

Decreased γ activity: Low-radioactivity SiPMs and stainless steel from DS-20k, ultrapure acrylic from DEAP

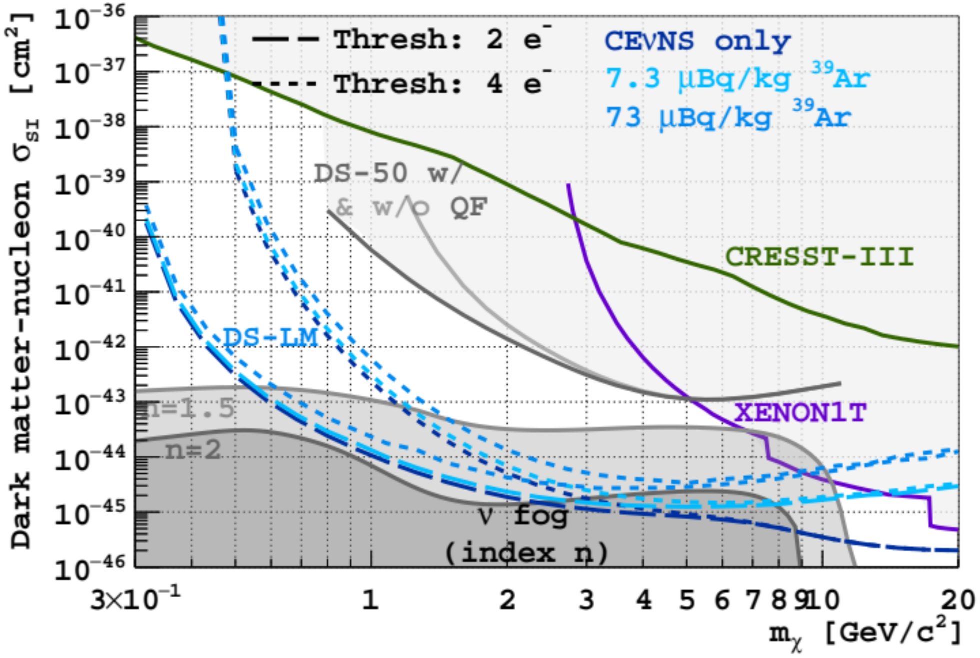
Two-fold γ veto: Additional 10× suppression of γ backgrounds with PDM buffer veto and bath veto, which tag γ's coming from the two dominant sources (photoelectronics and cryostat) *en route* to TPC

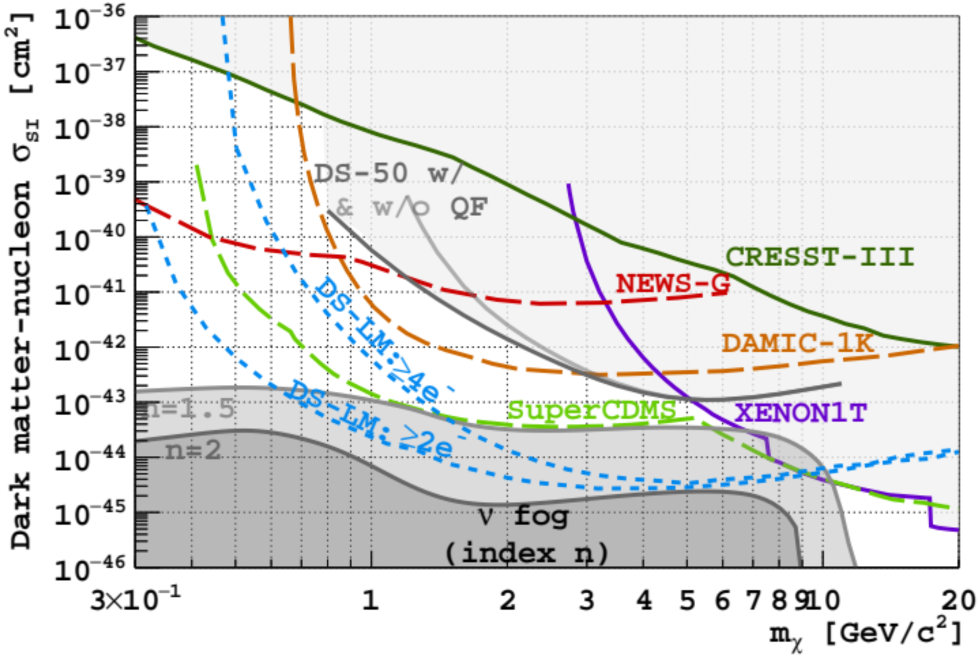
Lower spurious e$^-$ background rate: Through improved argon purity, and targeted removal of most important impurities, pending ongoing R&D

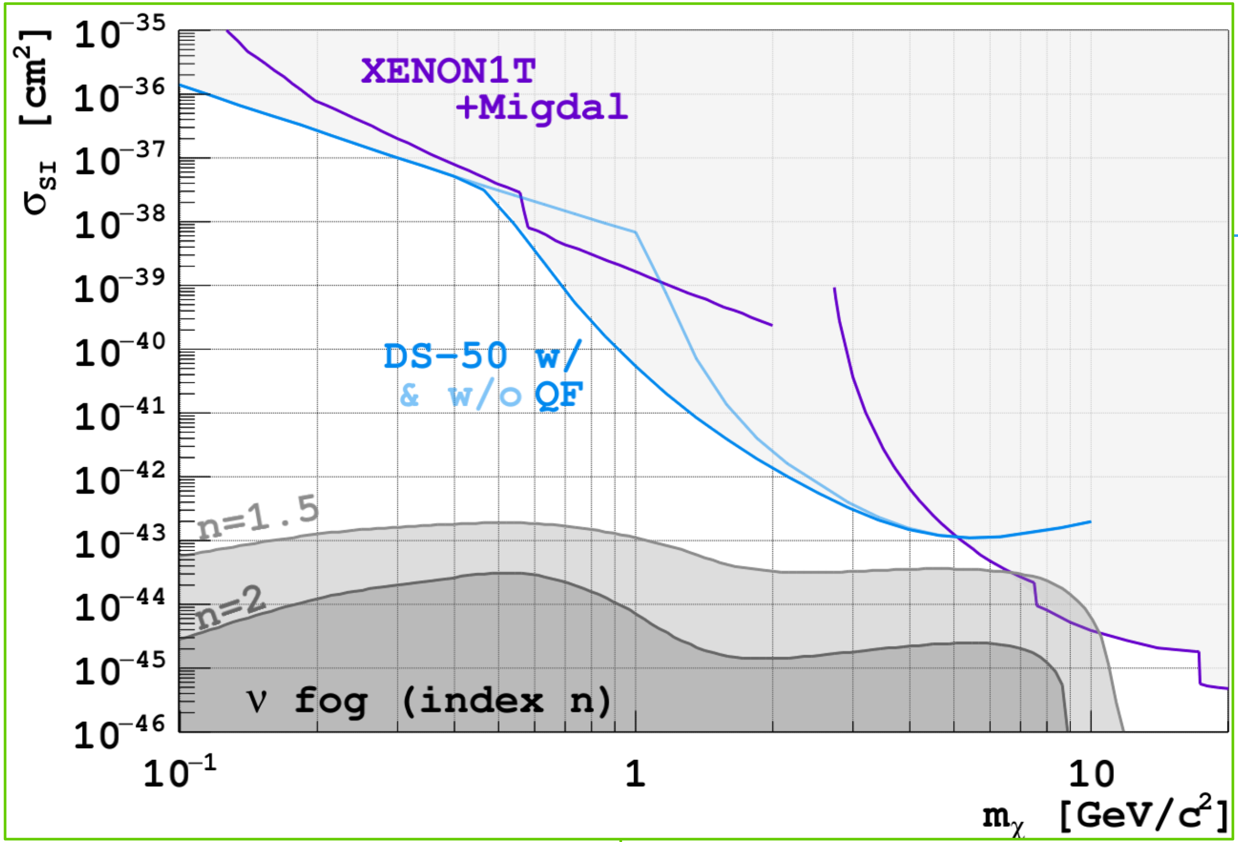
Cryostat immersed in water tank (not shown)

Global Argon Dark Matter Collaboration *Phys. Rev. D 107, 112006 (2023)*

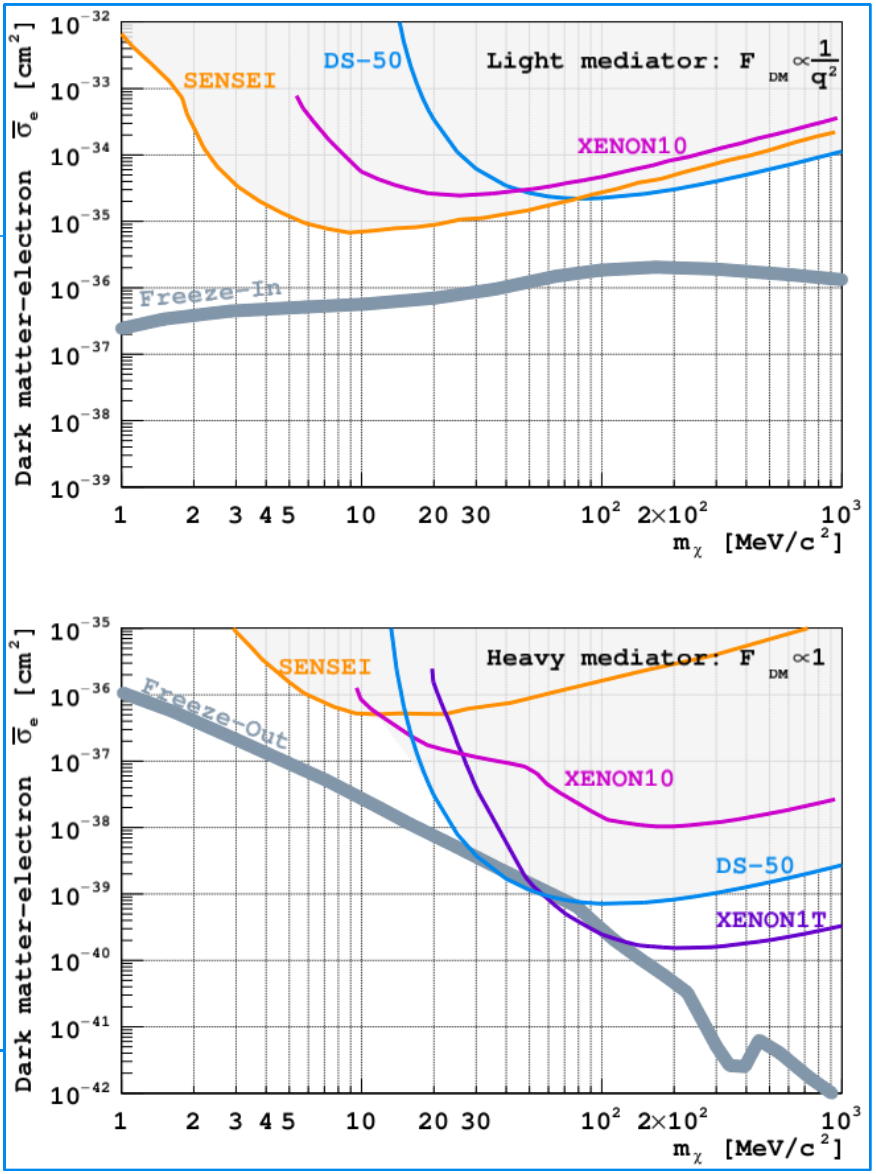
DarkSide-LowMass: Sensitivity to the ν fog in 1 tonne year exposure



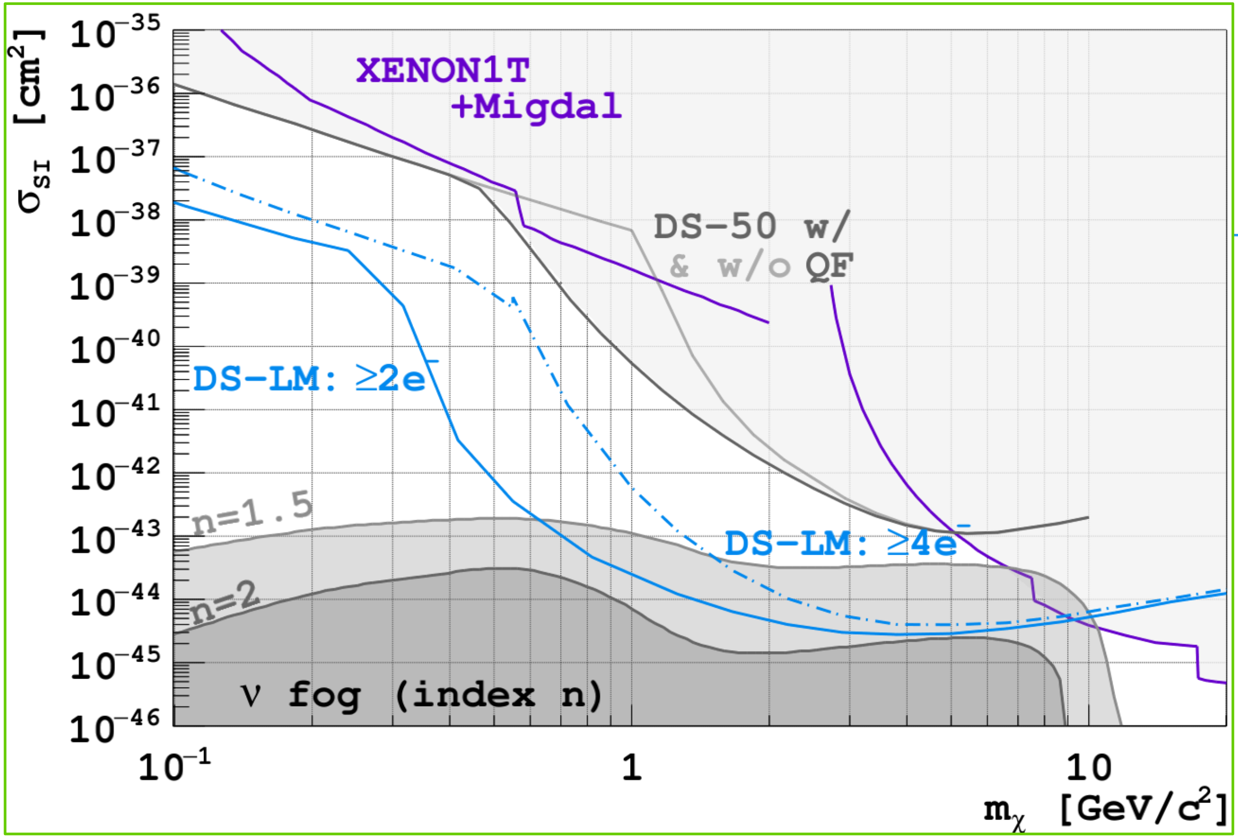


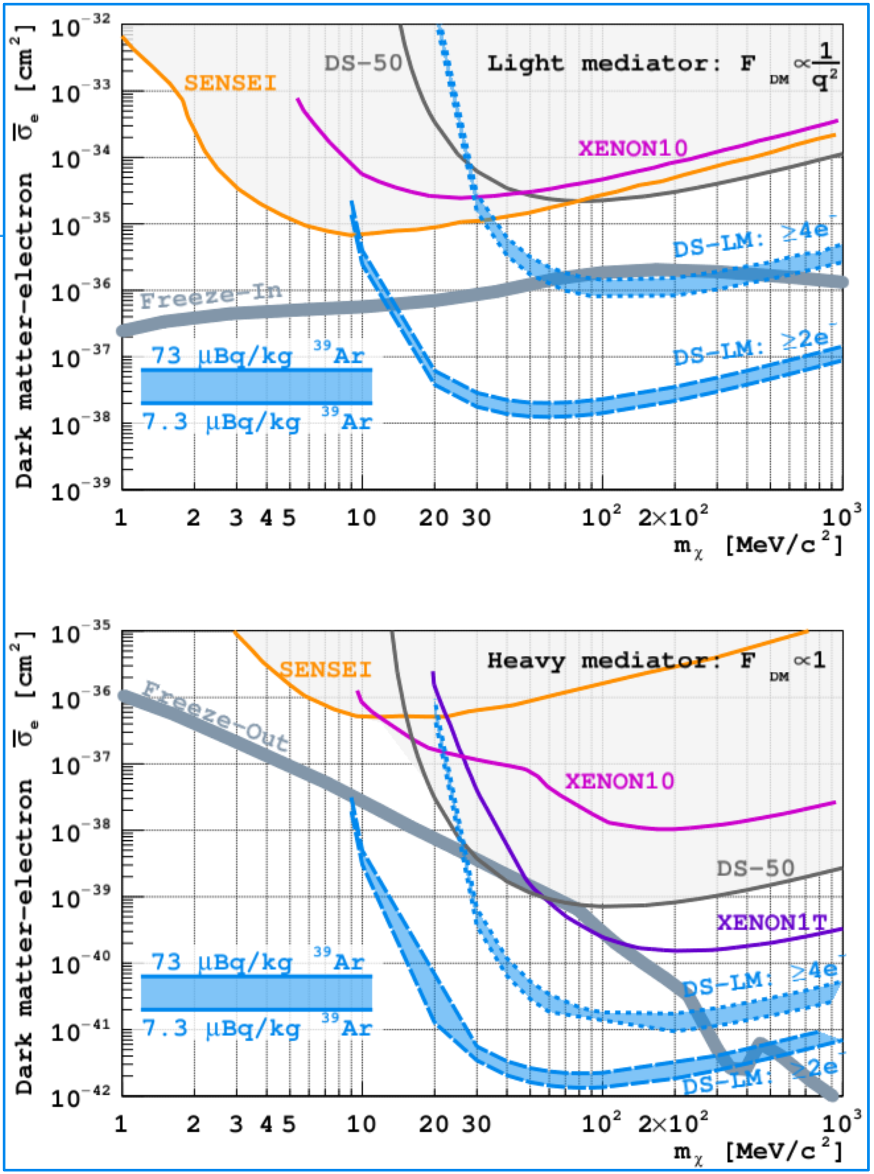


DarkSide Collaboration. "Search for dark matter-nucleon interactions via Migdal effect with DarkSide-50". arXiv:2207.11967 (2022)



DarkSide Collaboration. "Search for dark matter particle interactions with electron final states with DarkSide-50". arXiv:2207.11968 (2022)

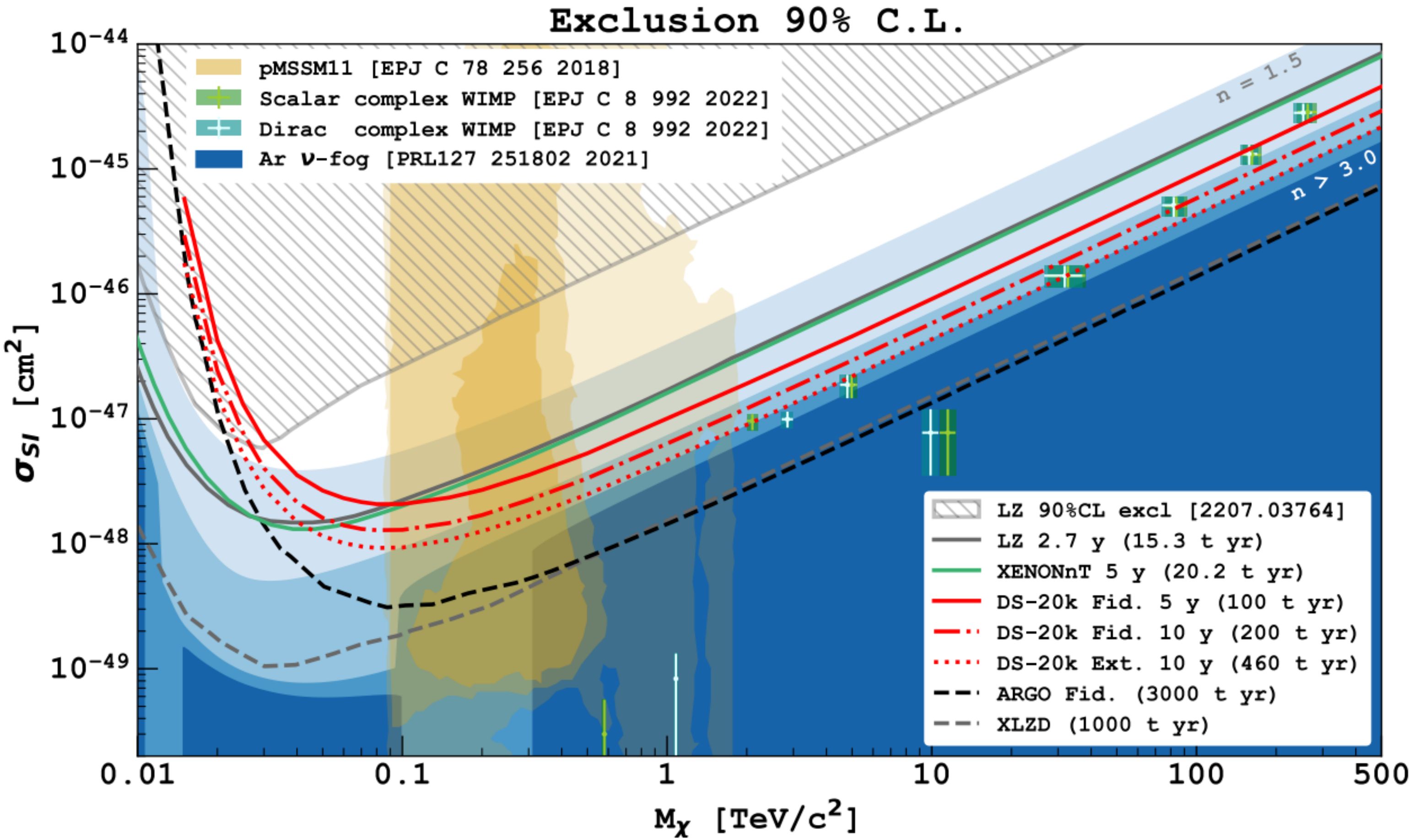




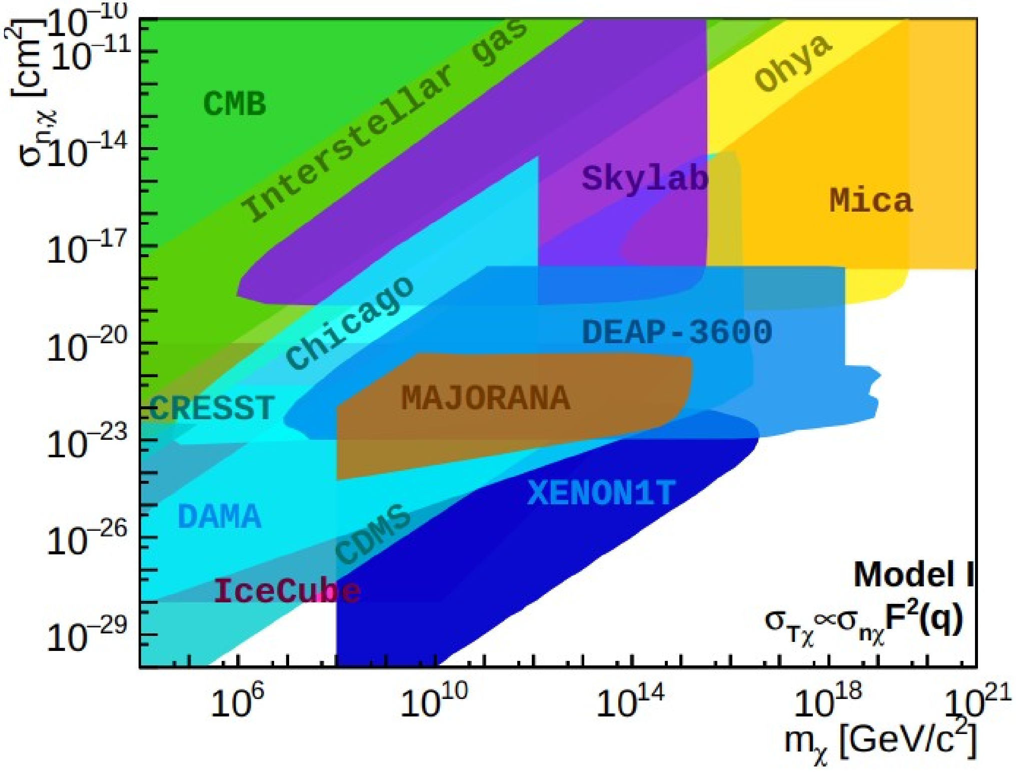
Nuclear couplings: Sensitivity to GeV-scale candidates down into the neutrino fog

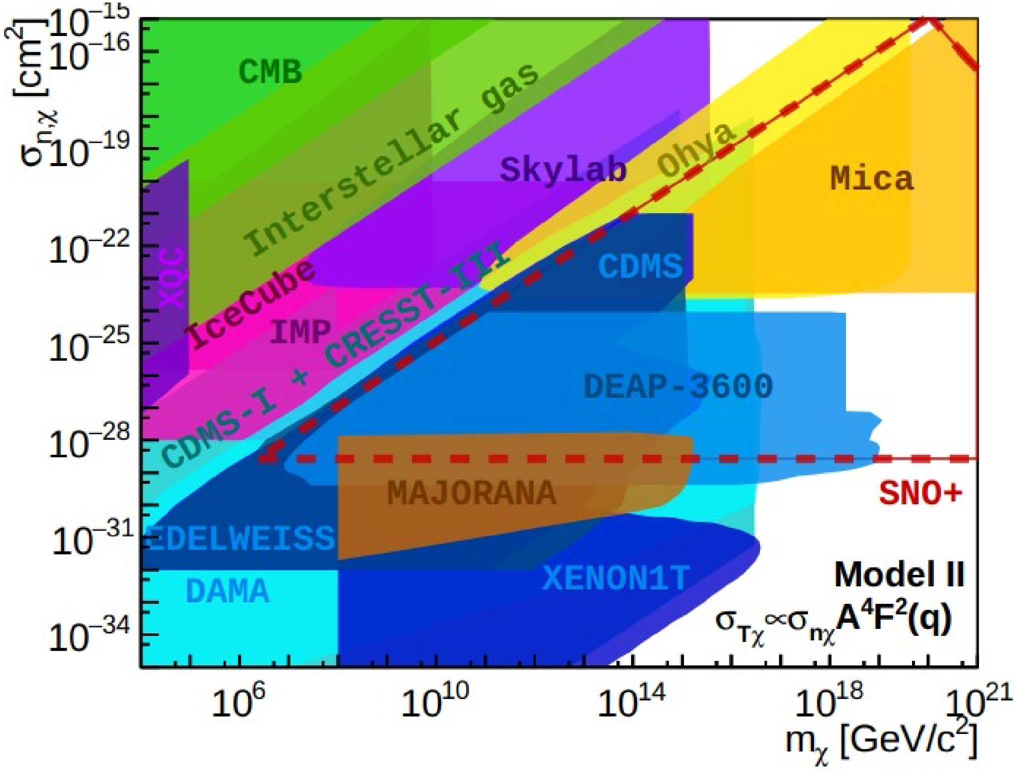
Electronic couplings: Sensitivity to sub-GeV candidates covering cross sections that explain the relic abundance in freeze-in and freeze-out production mechanisms

Current and future heavy DM searches



Ultra-heavy dark matter searches





arXiv:2203.06508

Current and upcoming technology is paving the way for a wide range of exciting direct detection searches for dark matter from masses spanning the keV to Planck scale

Future detectors will use a ride range of technologies with far-reaching possibilities

Beyond searches for dark matter, these detectors will be powerful neutrino detectors, with sensitivity to supernova, solar, and reactor neutrinos

END