Dark matter direct detection experiments

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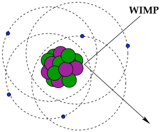
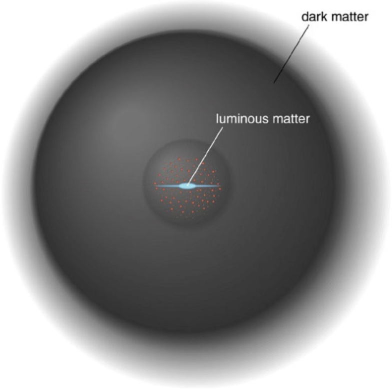
30th International Symposium on Lepton Photon Interactions at High Energies

Dark matter in the Milky Way



$E_R \sim \mathcal{O}(10\,\mathrm{keV})$

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\, \mathrm{d}^3 v$$



Astrophysical parameters:

- ρ_0 = local density of the dark matter in the Milky Way

  'Standard' value: $\rho_\chi \simeq 0.3\,\mathrm{GeV/cm^3}$
- $f(\mathbf{v},t)$ = WIMP velocity distribution, $\langle v \rangle \sim 220\,\mathrm{km/s}$

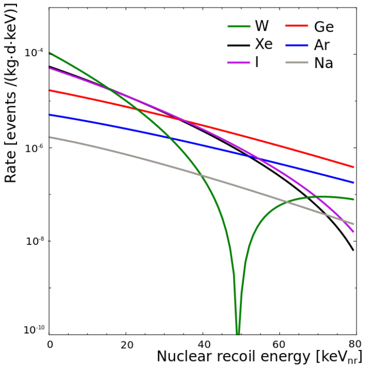
Parameters of interest:

- m_χ = WIMP mass ($\sim 100\,\mathrm{GeV}$)
- σ = WIMP-nucleus elastic scattering cross section (SD or SI)

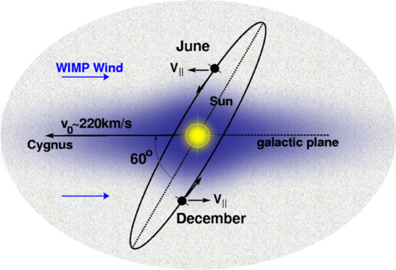
Detector requirements and signatures

- Large detector mass (grams up to several tonnes)
- Low energy threshold ~ few keV's or sub-keV
- Very low background and/or background discrimination

J. Phys. G: 43 (2016) 1 & arXiv:1509.08767



- Other signatures of dark matter
  - Annual modulated rate
  - Directional dependance

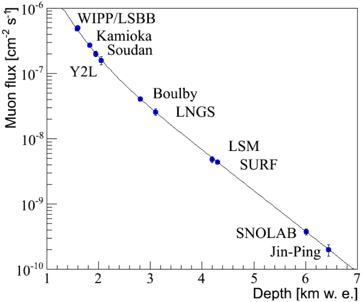


Backgrounds and reduction strategies

- External γ's from natural radioactivity:
  - Material screening & selection $+$ Shielding

- External neutrons: muon-induced, (α, n) and from fission reactions
  - Go underground!
  - Neutron shielding
  - material selection for low U and Th concentrations

  $+$ Neutrinos from the Sun, atmospheric and from supernovae



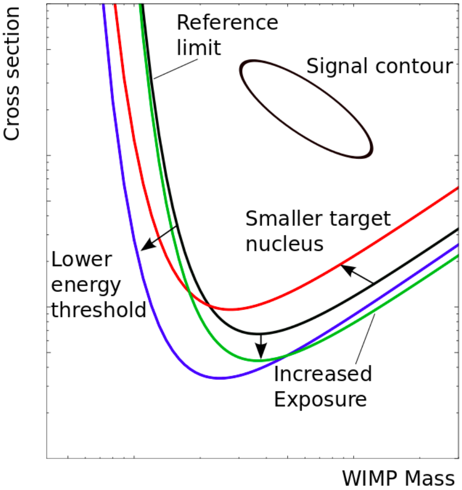
J. Phys. G: 43 (2016) 1 & arXiv:1509.08767

- Internal backgrounds:
  - Liquids/gases: Rn-emanation from surrounding materials
  - Solids: surface events from α- or β-decays
  - Cosmogenic activation important for all

Result of a direct detection experiment

→ Statistical significance of signal over expected background?

J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767



- Positive signal
  - Region in σ_χ versus m_χ
- Zero signal
  - Exclusion of a parameter region

o Low WIMP masses: detector threshold matters

o Minimum of the curve: depends on target nuclei

o High WIMP masses: exposure matters $\epsilon = m \times t$

Overview of WIMP searches

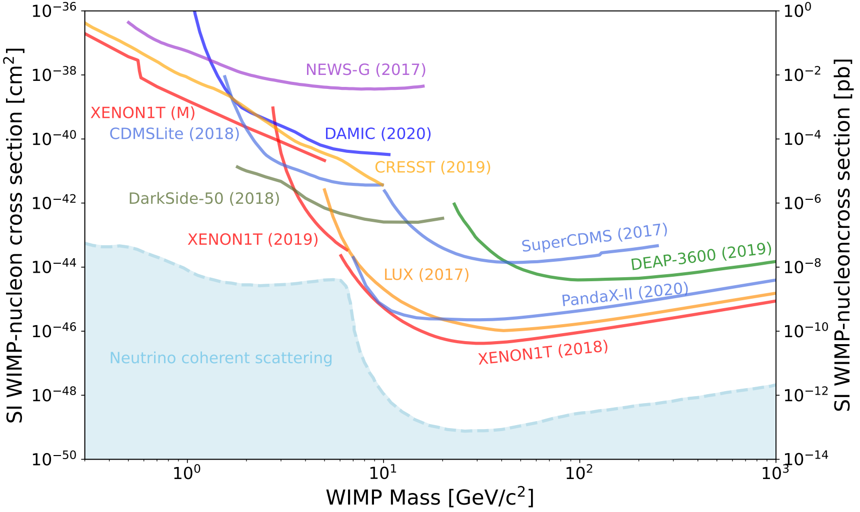
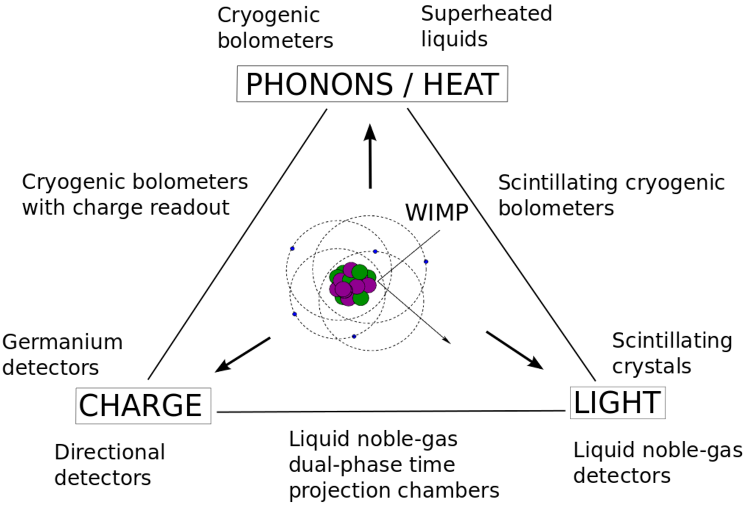


Figure updated from PDG, Prog. Theor. Exp. Phys. 2020 (2020) 083C01

Direct detection experiments



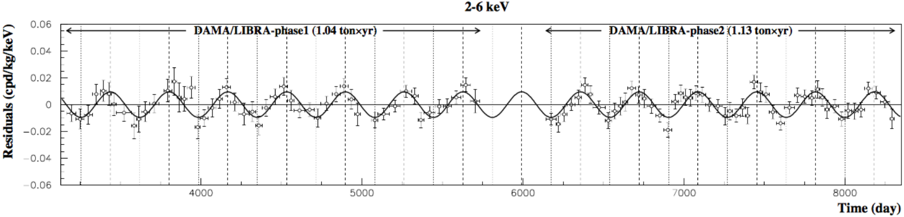
J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

This talk will discuss a selection of experiments

DAMA annual modulation

- Ultra radio-pure NaI crystals @LNGS
- Annual modulation of the background rate in the energy region $(2-6)$ keV
- Last results (2018): signal at $12.9\,\sigma$

Nucl. Phys. At. Energy 19 (2018) 307



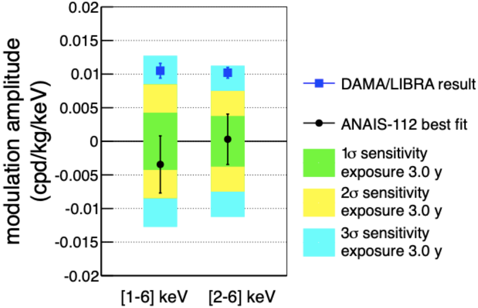
→ New results July 2021: $13.7\,\sigma$ significance @EPS-HEP conference by P. Belli

WIMP interpretation in contradiction with many other results

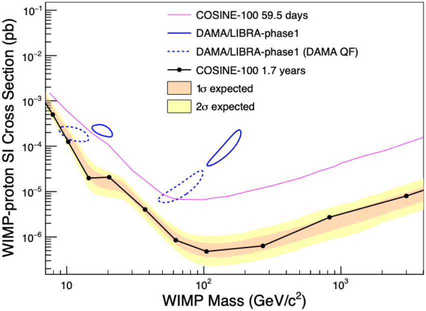
Worldwide effort to verify/refute this result

Recent results from ANAIS & COSINE-100

ANAIS, PRD 103 (2021) 102005 & arXiv:2103.01175



COSINE-100, Sci.Adv. 7 (2021) 46 & arXiv:2104.03537



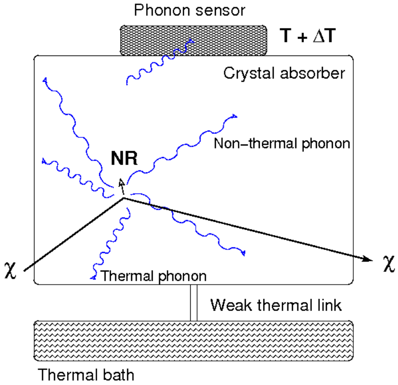
ANAIS @Canfranc:

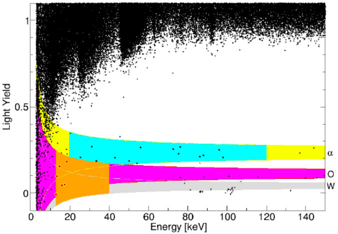
- DAMA modulation disfavoured
  at 3.3 σ for [1-6] keV
  at 2.6 σ for [2-6] keV
- Sensitivity above 3 σ within 2022

COSINE-100 @Yangyang:

- DAMA SI signal excluded
- Modulation analysis compatible with both DAMA and no modulation

Cryogenic bolometers





- Crystals at $(10-100)\,\text{mK}$
- Temperature rise: $\Delta T = E/C(T)$

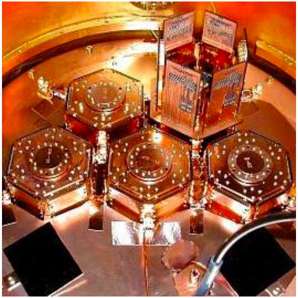
  E.g. Ge at 20 mK, $\Delta T = 20\,\mu\text{K}$ for few keV recoil
- Measurements of ΔT with NTD or TES
- Discrimination: combination with light or charge read-out
- Large separation of electronic and nuclear recoil bands

Example from CRESST, EPJC 72 (2012) 1971

Bolometer experiments

CRESST experiment

EDELWEISS experiment



Super-CDMS experiment

- Excellent sensitivities (low m_χ) due to their low energy thresholds
- CRESST: scintillating bolometer

  CRESST, PRD 100 (2019) 102002 (E_{th} = 30 eV)
- CDMS/EDELWEISS: germanium bolometers

  CDMS-Lite, PRD 99 (2019) 062001 (E_{th} = 70 eV)
- New CDMS HVeV 0.93 g silicon crystal with E_{th} = 9.2 eV V. Novati @TAUP2021

Results from cryogenic bolometers

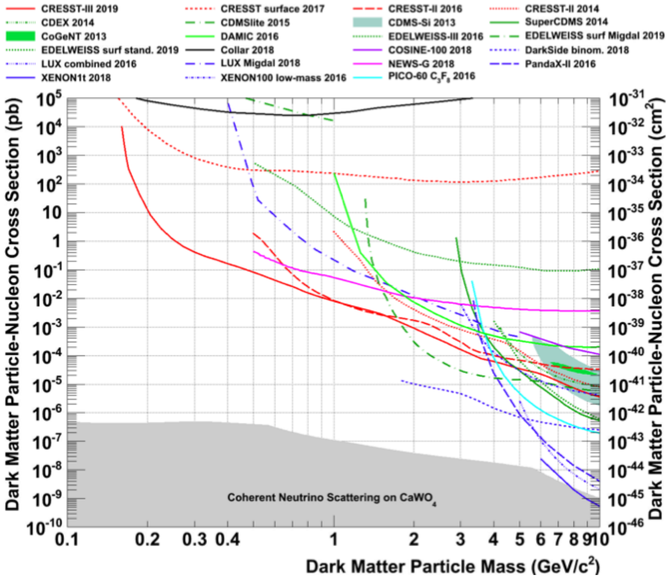
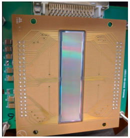


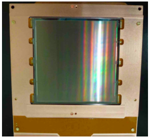
Figure from CRESST, Phys.Rev.D 100 (2019) 102002 & arXiv:1904.00498

Low threshold searches with CCDs



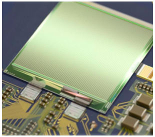
SENSEI

PRL 125 (2020) 171802



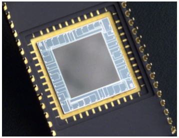
DAMIC

PRL 123, 181802 (2019)



DANAE

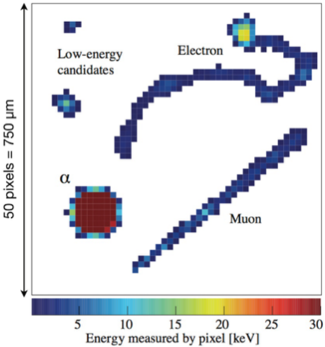
EPJC 77 (2017) 12, 905



DMSQUARE

N. Avalos@TAUP2021

particle tracks

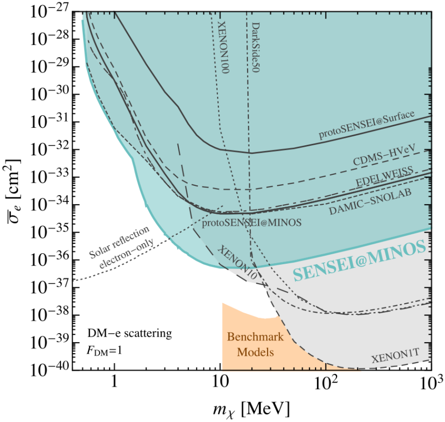


- Gram-scale silicon detectors with $E_{th} \sim 50\,\mathrm{eV}_{ee}$
- 3D reconstruction of tracks possible
- Test of DM-electron scattering below to 1 MeV DM mass

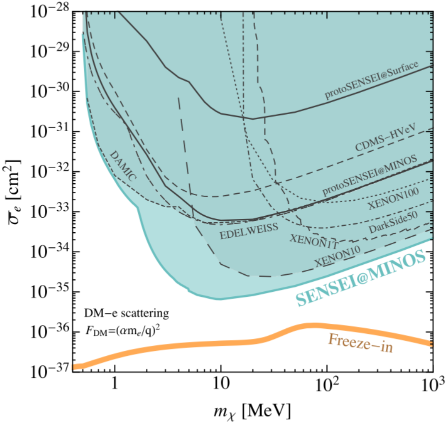
  & test of low WIMP masses

Figure from D. Norcini @TAUP2021 (Status of DAMIC)

Overview dark-matter scattering off electrons



DM-electron scattering (heavy mediator)



DM-electron scattering (light mediator)

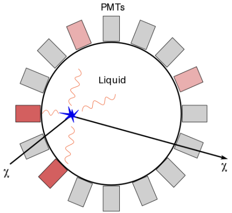
Figures from SENSEI, Phys. Rev. Lett. 125 (2020) 171802

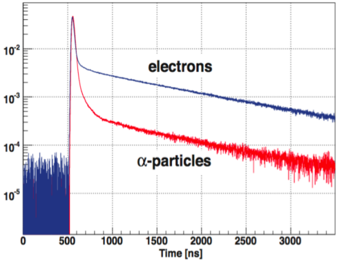
Advantages of liquid noble gases

- Large masses and homogeneous targets (LNe, LAr & LXe)
- 3D position reconstruction → fiducialization

Single phase (liquid) -type of detector:

- High light yield using 4π photosensor coverage
- Pulse shape discrimination (PSD) from scintillation





Scintillation decay constants of LAr by ArDM

- Very different singlet and triplet lifetimes in argon & neon
- Relative amplitudes depend on particle type → discrimination

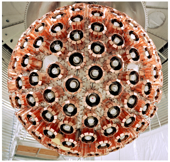
10^{-8} by DEAP-I above 25 keV$_{ee}$ (50% acceptance)

M. G. Boulay *et al.*, arXiv:0904.2930

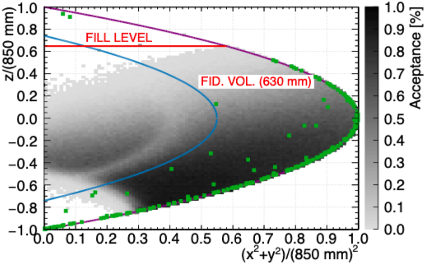
Single phase detectors

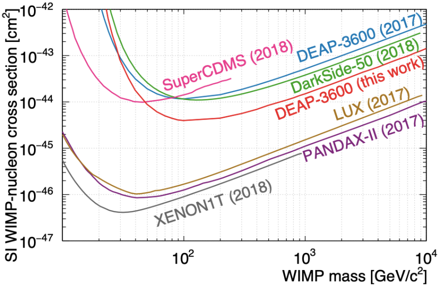
DEAP - LAr detector at SNOLAB, Canada

Dark matter **E**xperiment with **A**rgon and **P**ulse shape discrimination



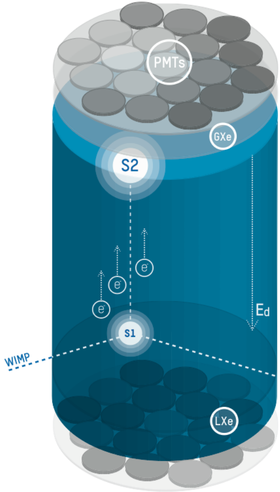
- 3 600 kg total mass & 3 280 kg fiducial volume
- Results of 231 d DEAP, PRD 100 (2019) 022004
- Most competitive liquid argon results





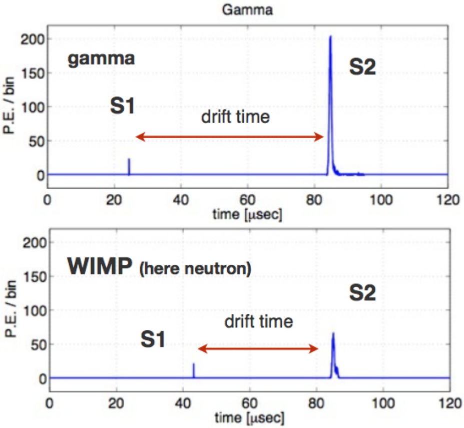
From Jan. 2018 to Mar. 2020: blind data taking → analysis on-going!

Two phase noble gas TPC



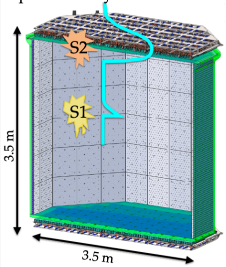
- Scintillation signal (S1)
- Charges drift to the liquid-gas surface
- Proportional signal (S2)

→ Electron- /nuclear recoil discrimination



- Position resolution
  → XY from PMT pattern
  → Z from drift time

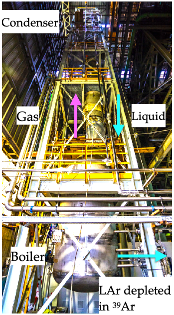
The DarkSide experiment



- DarkSide-50 run @LNGS with 50 kg mass
  DarkSide, PRD 98 (2018) 102006 & PRL 121 (2018) 8, 081307
- DarkSide-20K: new global LAr collaboration
  - 50 t total target mass
  - TPC inside a sealed acrylic vessel
  - SiPM for light read-out (~ 19 m^2)

- Underground Ar from URANIA plant (Colorado)
  Depletion factor (in ^{39}Ar) measurement @Canfranc
  Shipment to distillation in ARIA @Sardinia
- Aiming at high mass dark-matter search
  ROI (20 – 200) keV_{nr} → operation in 2025

E. Pantic @TAUP 2021 conference



Beyond DarkSide-20K

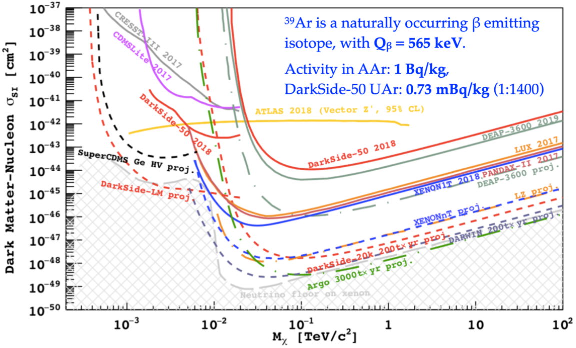
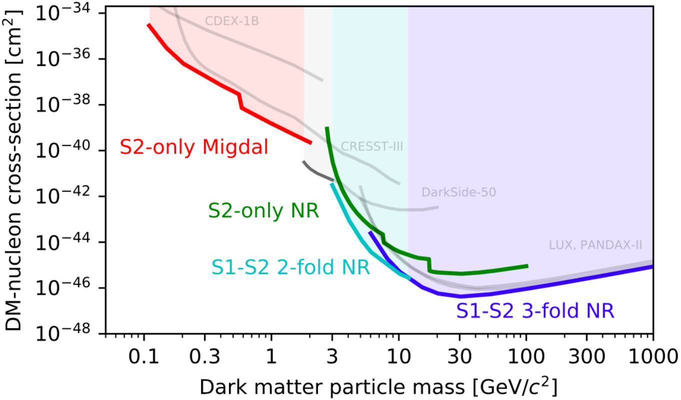


Figure from W. M. Bonivento @Canfranc SC 2021

- ARGO@SNOLAB (conceptual study)
  - Reach atmospheric neutrino floor with ~ 360 t (fiducial) UAr
  - Single- or dual-phase detector with photodetectors (~ 100 m^2)
- DarkSide-LowMass (conceptual study)
  - Reach solar neutrino floor with ~ 1 t (fiducial) in 1 y
  - Depleted underground argon & ionization channel only

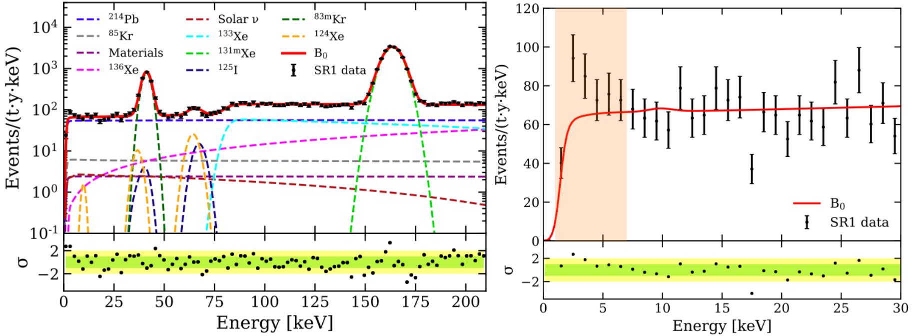
XENON1T results



XENON1T, PRL121 (2018) 111302, PRL123 (2019) 241803, PRL123 (2019) 251801, PRL126 (2021) 091301

- XENON1T operated at LNGS from 2016 to 2019
- Best upper limits for WIMP masses above 3 GeV/c^2
- Migdal result: depends on the experimental confirmation of this effect

Interesting signal

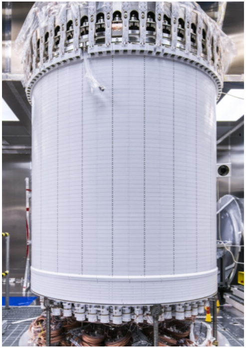


XENON1T, Phys. Rev. D 102 (2020) 072004 & arXiv: 2006.09721

Excess of events in (1-7) keV in the background region

- $\sim 3.3\,\sigma$ statistical significance
- A lot of excitement (> 350 citations since June 2020)
- Unclear origin: Tritium? or Axion signal? or something else?

Next generation: LZ, PandaX-4T and XENONnT



LZ:

- 7 T target mass
- Currently commissioning

PANDAX-4T:

- 4 T target mass
- First data released in July 2021

XENONnT:

- 6 T target mass
- Currently taking data

→ A race to measure WIMPs down to $\sigma \sim 10^{-48}\,\mathrm{cm}^2$

Released data from current LXe detectors

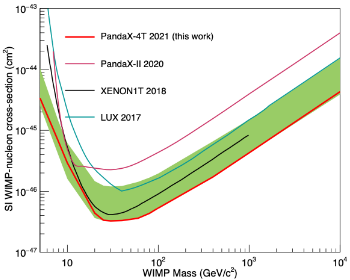


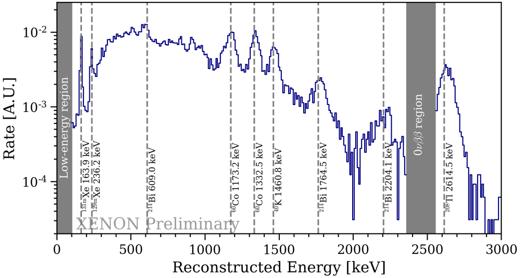
Figure from arXiv:2107.13438

- First results of PandaX-4T@CJPL (non blind analysis)
- Contamination with ^{3}H

→ no check of XENON1T excess possible

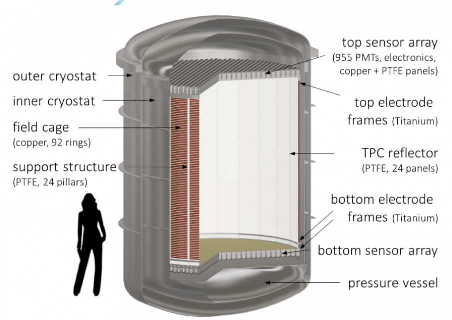
- Rn level at 4.2 μBq/kg similar to XENON1T

- XENONnT @LNGS, first performance data
- Background goal in reach (Rn ~ 1.7 μBq/kg)
- Test low ER excess

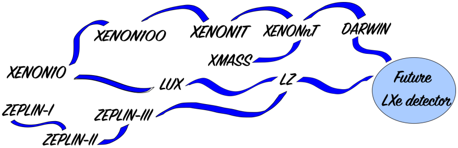


DARWIN: the ultimate WIMP detector

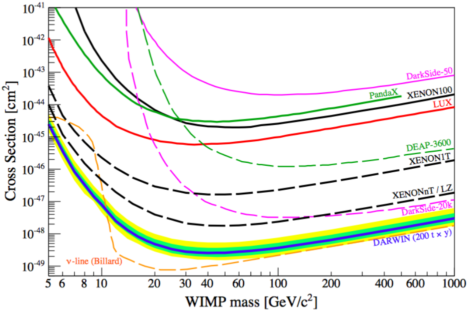
dark matter wimp search in noble liquids
DARWIN



50 t LXe total (40 t in the TPC)



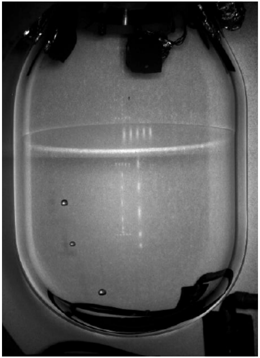
- Goal: measure WIMP properties / ultimate cross-section sensitivity
- Additional physics channels:
  - Solar & supernova ν's
  - CEνNS, proton decay, DEC & neutrinoless $\beta\beta$-decay ...



DARWIN, JCAP 1611 (2016) no.11, 017, arXiv:1606.07001

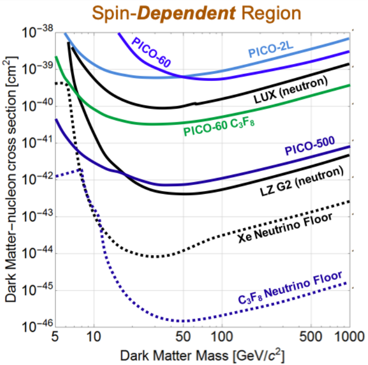
Superheated fluid detectors

COUPP experiment



- Energy depositions > E_{th} → expanding bubble detected with cameras + piezo-acoustic sensors

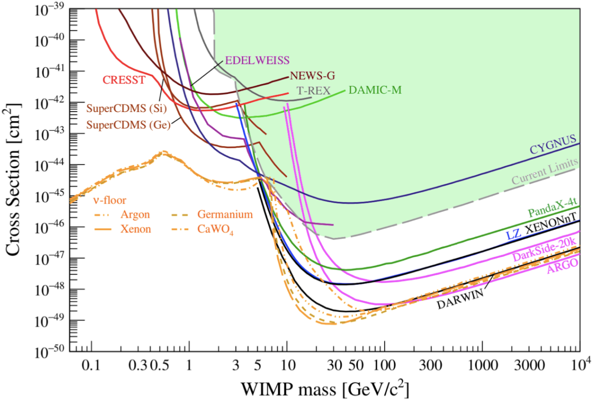
- A bubble chamber filled with superheated fluid (C_3F_8) in meta-stable state
- Great sensitivity to spin-dependent σ



- PICO-500: detector to be installed in the miniCLEAN space @SNOLAB

  (TDR planned for early 2022)

Looking at the future



Sensitivity projections from the APPEC report, J. Billard et al., (2021) arXiv:2104.07634

- DD covers a large range in mass and cross section
- Exploring WIMPs but also light DM, ALPs, dark photons ...
- We hope for a dark matter discovery ideally in various detectors!

Backup: Cross sections for WIMP elastic scattering

- Spin-independent interactions: coupling to nuclear mass

$\sigma_{SI} = \frac{m_N^2}{4\pi(m_\chi + m_N)^2} \cdot [Z \cdot f_p + (A - Z) \cdot f_n]^2$, $\quad f_{p,n}$: eff. couplings to p and n

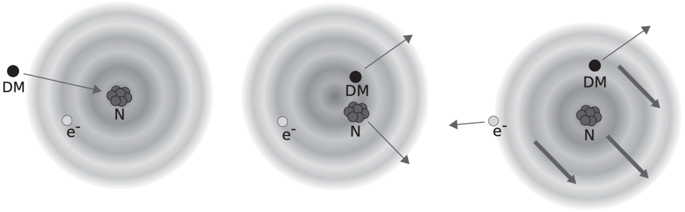
- Spin-dependent interactions: coupling to nuclear spin

$\sigma_{SD} = \frac{32}{\pi} \cdot G_F \cdot \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \cdot \frac{J_N + 1}{J_N} \cdot [a_p \langle S_p \rangle + a_n \langle S_n \rangle]^2$

$\langle S_{p,n} \rangle$: expectation of the spin content of the p, n in the target nuclei

$a_{p,n}$: effective couplings to p and n

Low-mass WIMP searches using the Migdal effect

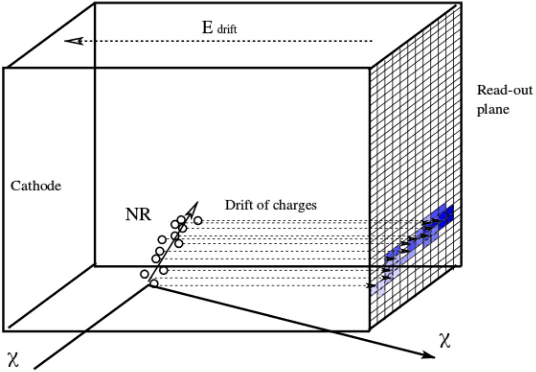


Scheme from Dolan et al., PRL 121 (2018)101801

- Sudden acceleration of a nucleus can lead to excitation or ionization of the shell electrons Ibe et al., JHEP 03 (2018) 194
- Yet no experimental evidence of this effect!
- Two strategies being followed:
  - MIGDAL collaboration: ER+NR vertex in a low pressure gaseous detector
  - Nakamura et al.: two clusters (NR + X-ray) in position sensitive gaseous detector Nakamura et al., (2020) arXiv:2009.05939

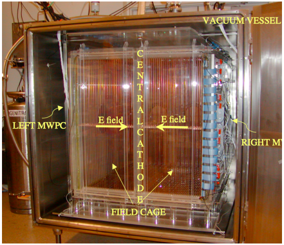
Directional searches

- In solids or liquids, several keV recoil is below 100 nm
- But for a low pressure-gas, $P < 100$ Torr, the range is $\sim (1-2)$ mm
- Most projects use low pressure TPCs with CF_4 (^{19}F) as target
  → Challenge: measure ~ mm tracks in cubic meter volumes



Directional searches

→ Not competitive with liquids or solids at the moment but important confirmation in case of a WIMP detection



- DRIFT @Boulby - m^3 experiment: important technology milestone
  DRIFT, Phys. Dark Univ. 9-10 (2015) 1 & Astropart.Phys. 91 (2017) 65
- Operation of a 'large-scale' experiment

- **CYGNUS**: international proto-collaboration to measure DM and CEνNS of solar ν's exploring directionality & particle identification
  CYGNUS (2020) arXiv:2008.12587
- Including previous efforts from DRIFT, MIMAC, DMTPC, NEWAGE & new developments like CYGNO

Note also the directional searches with nuclear emulsion detectors, A. Goloratiuk @TAUP2021

NEWS-G experiment

NEWS-G, Astropart.Phys. 97 (2018) 54

- Metallic vessel filled with a noble gas mixture
- Single anode in the middle
- Low energy threshold ~ 10 eV
- Low-A target atoms increases sensitivity to low-mass WIMPs

- New sphere of 140 cm ∅ filled with CH_4
- Operated in LSM, 12 d of data being analysed
- Construction finished at SNOLAB in August 2021
- First light seen!

Talks of D. Durnford & K. Nikolopoulos @TAUP2021