Detection techniques
Lecture 1: dark matter

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GraSPA school
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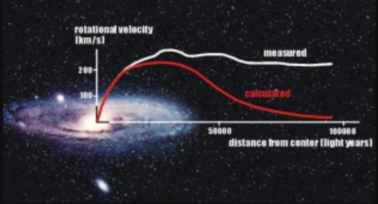
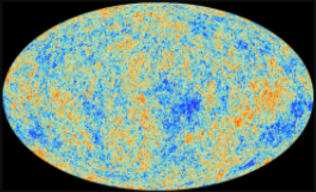
The 'invisible' particles

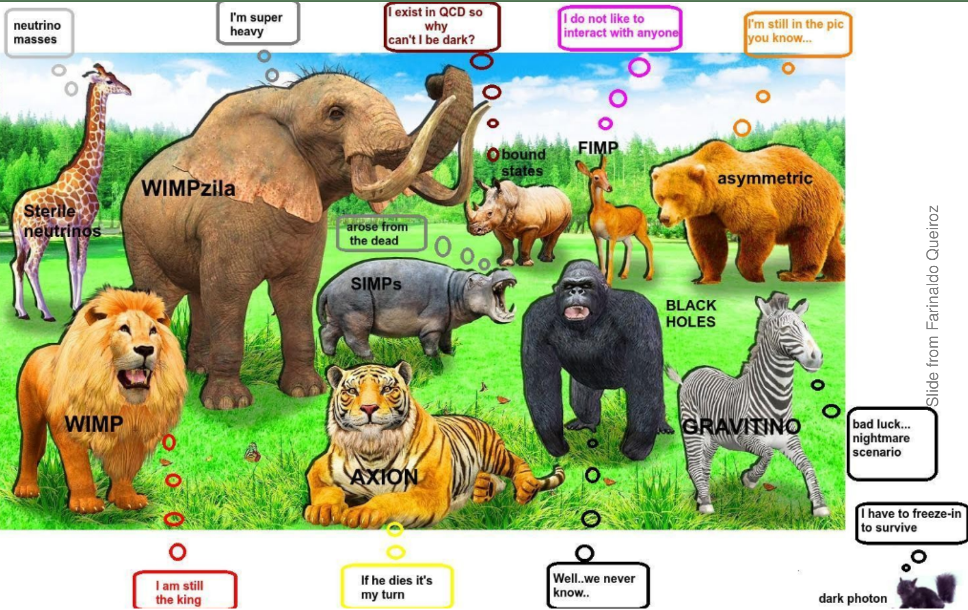
- Measurement of dark matter
  - Indications from Cosmology and Astronomy
  - No clear measurement yet
  - Goal: determine its mass and its interactions
- Neutrinophysics
  - Neutrino: well establised particle
  - Most parameters/properties measured
  - Neutrino astronomy possible



Consistent evidence for the existence of a new component in the Universe at different scales



What is the nature of dark matter?

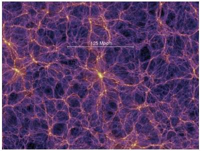


Slide from Farinaldo Queiroz

What is dark matter?

An elementary particle?

- Massive → explain gravitational effects
- Neutral → no EM interaction & Weakly interacting at most
- Stable or long-lived → not to have decayed by now
- Cold (moving non-relativistically) or warm → structure formation



In the standard model of particle physics:
Neutrino fulfil most
but it is a hot dark matter candidate

→ Models beyond SM typically predict NEW particles

How can we look for dark matter?

Production at LHC

$p + p \rightarrow \chi\bar{\chi} + X$

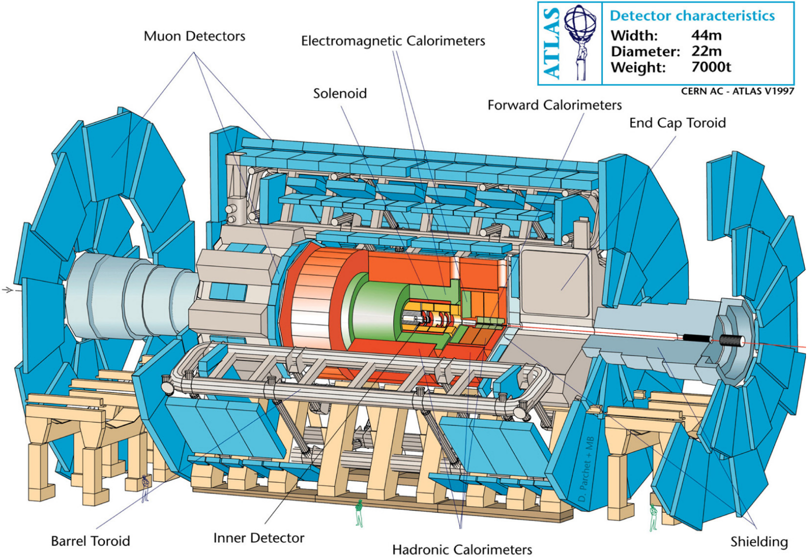
Direct detection

$\chi\, N \rightarrow \chi\, N$

Indirect detection

$\chi\bar{\chi} \rightarrow \gamma\gamma, q\bar{q}, \ldots$

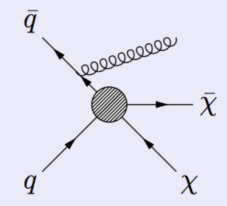
A collider detector ☺

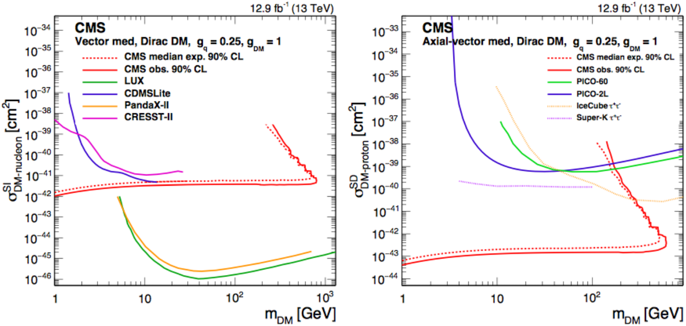


The ATLAS Detector

Dark matter searches at LHC

- Signatures: χ in cascades or $\chi\overline{\chi}$ accompanied by a mono-signature p + p $\rightarrow \chi\overline{\chi}$ + X
  - Large missing momentum from $\chi\overline{\chi}$
  - X can be a hadronic jet, a photon or a *W* or *Z* decaying hadronically
- Comparison of results with direct detection is model dependent





Figures from CMS, arXiv:1703.01651

Indirect detection: ingredients

- Where? → location
  - Galactic center (GC), galactic halo
  - Subhaloes, dwarf spheroidals (DSph), the Sun ..
- Into what? → particles produced (annihilation or decay)
  - $\chi\overline{\chi} \to \gamma\gamma, \gamma Z, \gamma H$
  - $\chi\overline{\chi} \to q\overline{q}, W^+W^-$ fragmentation into $\to e^+e^-, p\overline{p}, \nu$'s

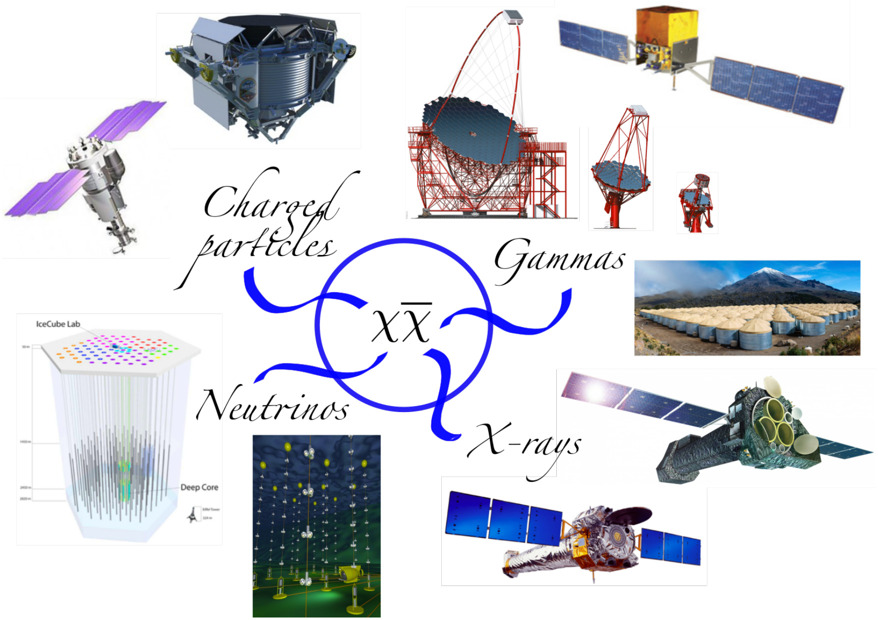
Expected particle flux:

$$\frac{d\Phi_p}{dE} = \frac{<\sigma_A v>}{4\pi 2 m_\chi^2} \cdot \frac{dN_p}{dE} \cdot J(\Delta\Omega), \qquad J(\Delta\Omega) = \int d\Omega \int \rho^2(\ell) d\ell$$

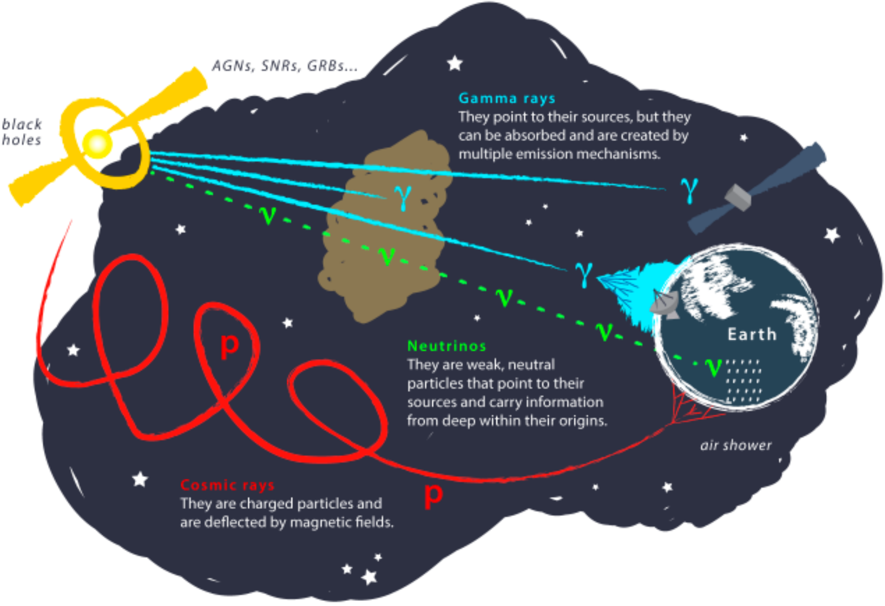
with ℓ the coordinate along the line of sight

- How measured? → detector technology
  - Satellites or balloons measuring charged particles, γ's or X-rays
  - Cherenkov telescopes and large neutrino observatories

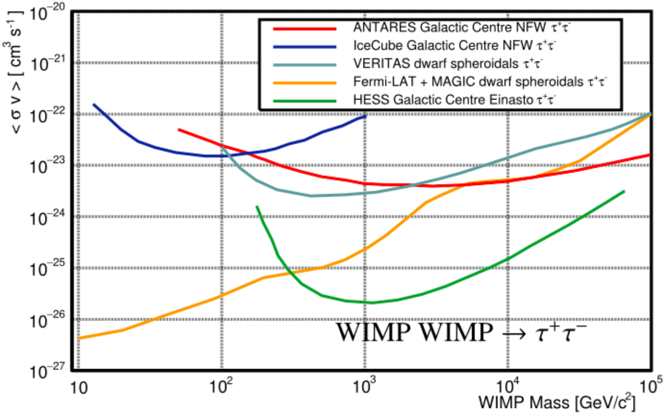
Technologies for indirect detection of dark matter



Indirect detection: particle propagation



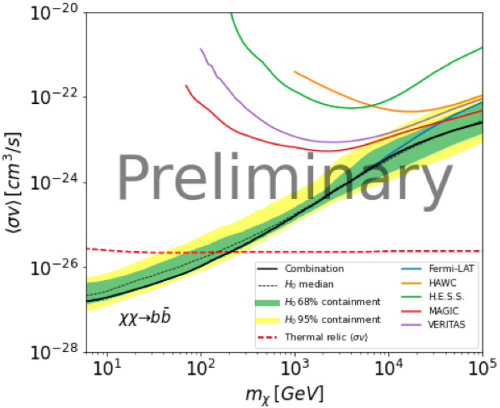
Indirect searches with ν's



ANTARES galactic center search, PLB 805, 135439 (2020)

- Limits from ν-experiments on annihilation not competitive with $\gamma-$ray bounds

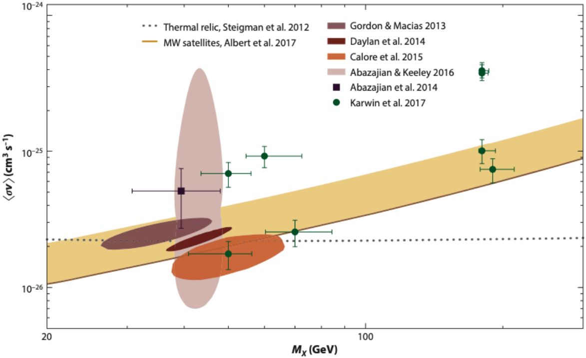
Exclusion limits from γ searches



Combined limit of dwarf spheroidals from Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS, PoS ICRC2021 (2021) 528

- Dwarf spheroidal observations give best constrains in $\sim (1 - 100)$ GeV
- Galactic center by HESS (and HAWC) most sensitive at TeV energies

γ searches: galactic center excess



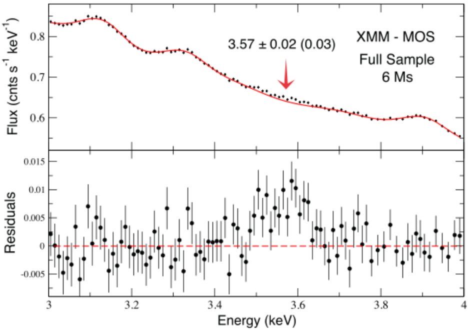
Figures from S. Murgia, Annu. Rev. Nucl. Part. Sci. (2020) 70:455

- Excess of γ-rays at the Galactic Center
- Signal consistent with a dark matter particle with a mass of ~ 50 GeV
- Other interpretations possible: millisecond pulsar emission

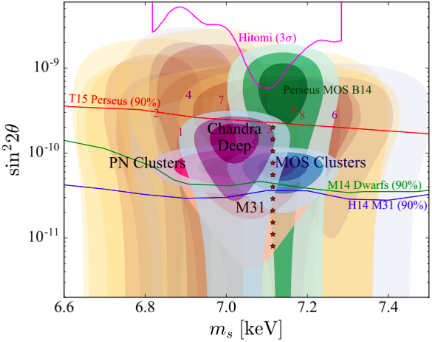
X-ray searches and the 3.5 keV line

- Search for monoenergetic signals from decaying dark matter, e.g. sterile neutrino $\chi \rightarrow \nu_\ell \gamma$
- X-ray line at 3.5 keV in the XMM-Newton and Chandra satellites
  Present in several nearby galaxies and galaxy clusters
  but not found in large statistic searches (Dessert et al. 2018 & Foster et al. 2021)

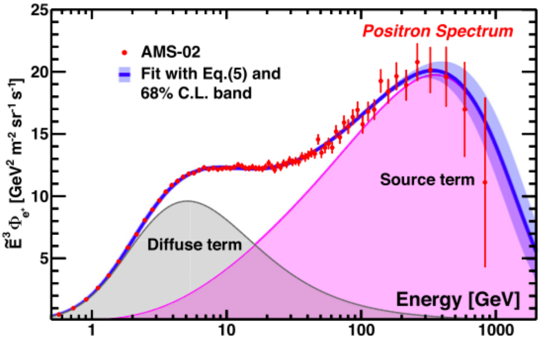
Bulbul et al. 1402.2301 (and Jeltema et al. 1408.1699)



Abazajian (2017) arXiv:1705.01837



Charged particles: positron excess

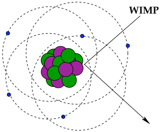


Positron flux in AMS, Phys. Rept. 894 (2021) 1

- Positron excess observed by PAMELA in 2008
- Confirmed by AMS-02 and measured at higher energies
- Unclear origin of source term:
  dark matter annihilation or local pulsars

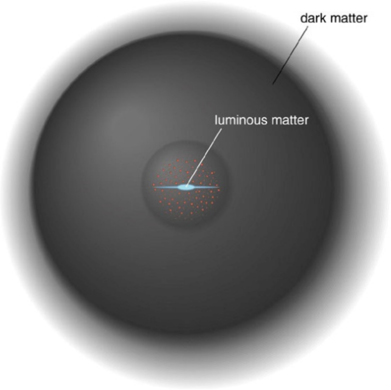
→ Interesting upcoming searches with antinuclei in GAPS

Direct detection: 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
- $f(\mathbf{v},t)$ = WIMP velocity distribution

Parameters of interest:

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

The standard halo model

Isotropic, isothermal sphere with a Maxwellian velocity distribution

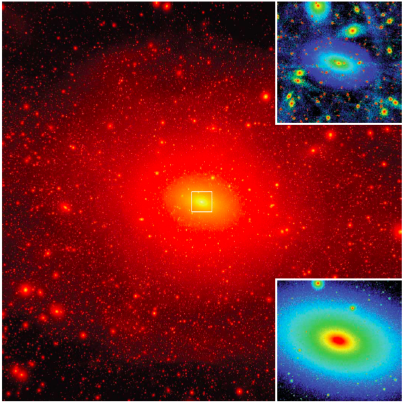
$$f(v) = N \cdot \exp\left(\frac{-3|v|^2}{2\sigma^2}\right)$$

Local density $\rho_0 = 0.3\,\text{GeV/cm}^3 = 0.008\,M_\odot/pc^3 = 5 \cdot 10^{-23}\,\text{g/cm}^3$
determined via mass modelling of the Milky Way

About 1 WIMP in a coffee cup (assuming $m_\chi \sim 100\,\text{GeV}/c^2$)

Circular velocity $v_c = 220\,\text{km/s}$ & Escape velocity $v_{esc} = 544\,\text{km/s}$

Dark matter distribution



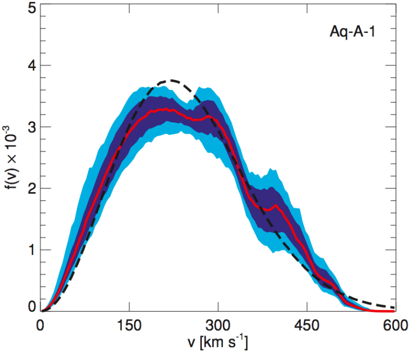
Via Lactea II projected dark matter density map of a galaxy with the mass of the Milky Way, J. Diemand *et al.*, Nature 454 (2008)

Density profile:

- Sub-structure is predicted
- Profile dependent on baryonic history

Rates depend on the velocity distribution:

- Standard model: isotropic Maxwellian
- Simulations: triaxial and with non-smooth $|v|$



Velocity modulus distribution a simulated halo (Acquarius). Vogelsberger *et al.*, Mon. Not. R. Astron. Soc. **395** (2009) 797

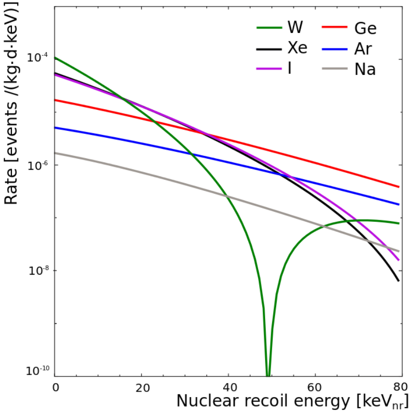
Detector requirements and signatures

- Requirements for a dark matter detector
  - Large detector mass
  - Low energy threshold ~ sub-keV to few keV's
  - Very low background and/or background discrimination
  - Long term stability

- Possible signatures of dark matter
  - Spectral shape of the recoil spectrum
  - Annual modulated rate
  - Directional dependance

Signatures: spectral shape

$$\frac{dR}{dE}(E) \approx \left(\frac{dR}{dE}\right)_0 F^2(E) \exp\left(-\frac{E}{E_c}\right)$$

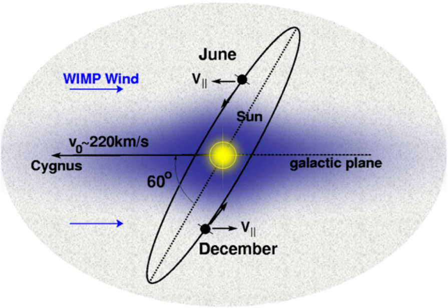


J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

Event rates as function of nuclear recoil energy for different target materials

Signatures: Annual modulation

$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E) \cdot \cos\left(\frac{2\pi(t-t_0)}{T}\right)$$



- Earth rotation around the Sun
- Relative speed of DM particles larger in summer
- Larger number of nuclear recoils above threshold in summer

Signatures: directionality

$$\frac{dR}{dE\ d\cos\gamma} \propto \exp\left[\frac{-[(v_E + v_\odot)\cos\gamma - v_{min}]^2}{v_c^2}\right]$$

γ: NR direction relative to the mean direction of solar motion

v_E and $v_\odot$: the Earth and Sun motions

$v_c = \sqrt{3/2 v_\odot}$: halo circular velocity

- Nuclear recoil direction has an angular dependence
- Mostly low-pressure gases used for directional searches

Directionality visualisation

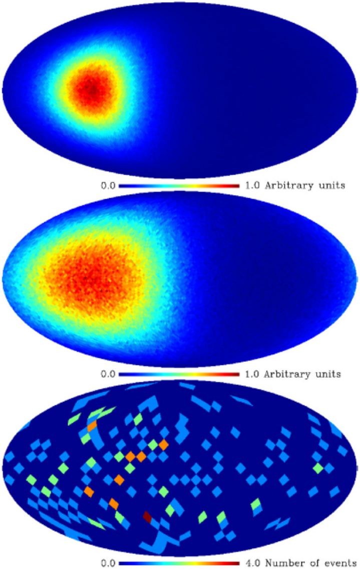


Figure from J. Billard *et al.* 2010

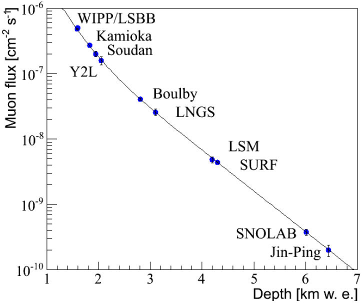
- WIMP flux in the case of an isothermal spherical halo
- WIMP-induced recoil distribution
- A typical simulated measurement:
  100 WIMP recoils and
  100 background events
  (low angular resolution)

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!
  - Shield: passive (polyethylene) or active (water/scintillator vetoes)
  - material selection for low U and Th concentrations

  \+ Neutrinos from the Sun, atmospheric and from supernovae



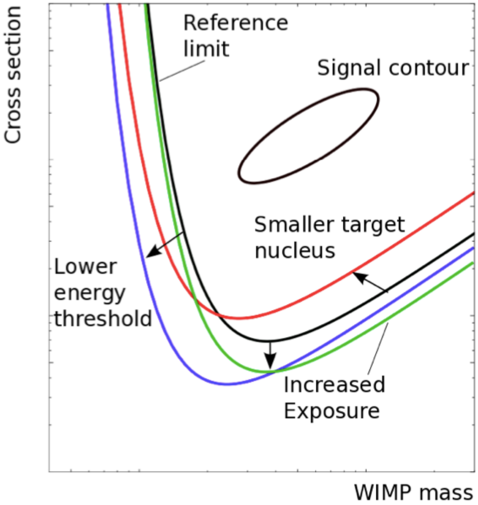
J. Phys. G: 43 (2016) 1 & arXiv:1509.08767

- 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

  - Low WIMP masses: detector threshold matters
  - Minimum of the curve: depends on target nuclei
  - High WIMP masses: exposure matters $\epsilon = m \times t$

Overview of WIMP searches

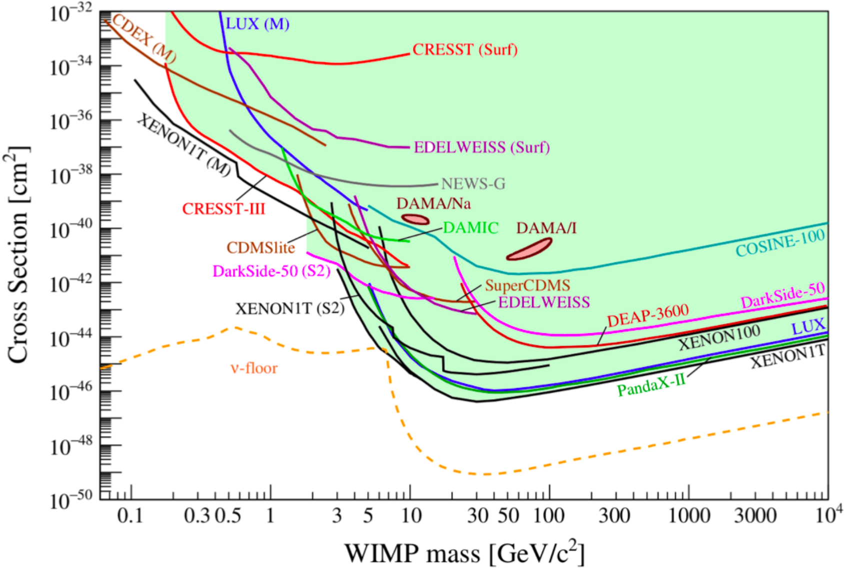
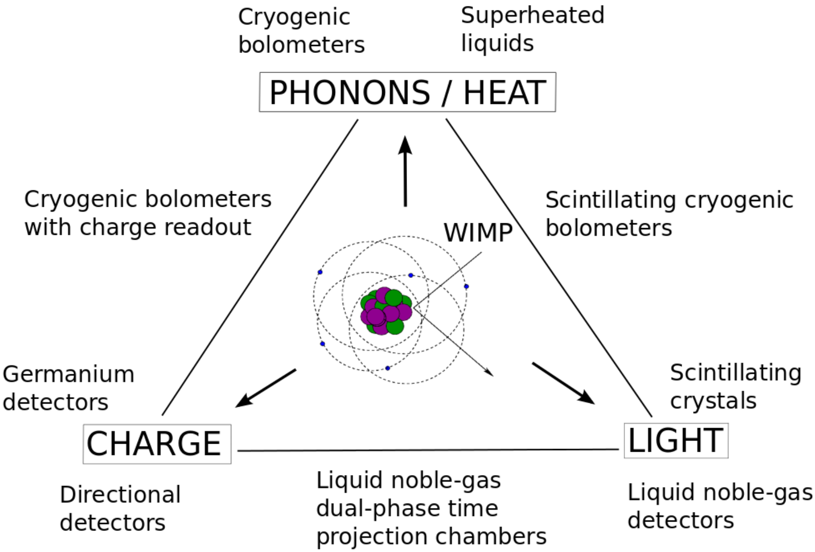


Figure from Rept. Prog. Phys. 85 (2022) 5, 056201

Direct detection experiments



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

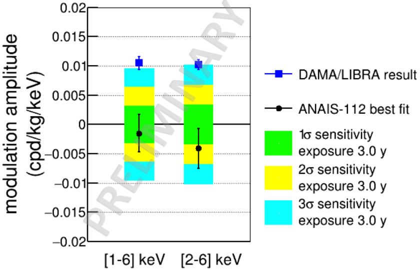
Scintillating crystals

- Mostly NaI (Tl) and CsI (Tl) used in dark matter searches
- Arrays of several crystals at room temperature
  → simple operation, important for long-term stability
- No particle discrimination
  → Low radioactivity of the target material
  → Rejection of multiple scatters in different crystals

Annual modulation signature

- DAMA experiment @LNGS
  using ultra radio-pure NaI crystals
- Annual modulation of the background rate in the energy region $(2-6)$ keV
- Last results (2021): signal at $13.7\,\sigma$

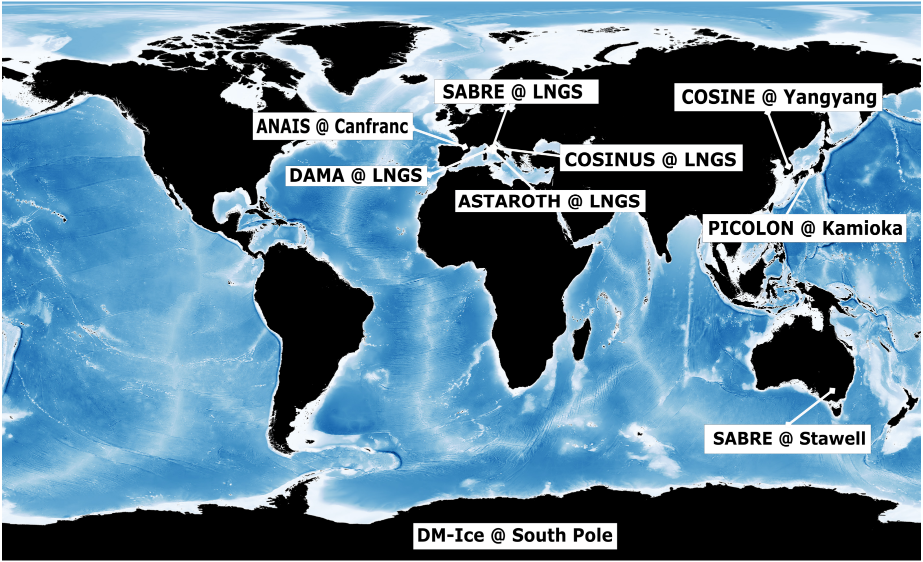
ANAIS, improved from PRD 103 (2021) 102005
Talk @ UCLA2023 by María Martínez



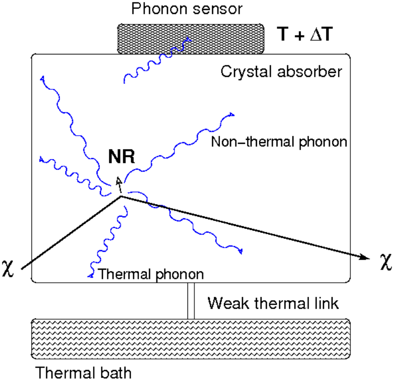
ANAIS using NaI crystals @Canfranc:

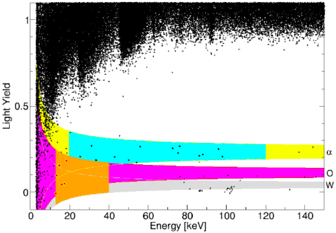
- DAMA modulation disfavoured
  at $3.8\,\sigma$ for [1-6] keV
  at $4.2\,\sigma$ for [2-6] keV
- Experiment continuously taking data

Tests of annual modulation with NaI



Cryogenic bolometers





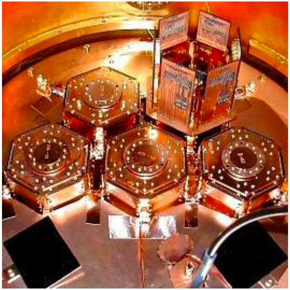
- Crystals at (10 – 100) mK
- Temperature rise:
  $\Delta T = E/C(T)$
  E.g. Ge at 20 mK, $\Delta T = 20\,\mu$K for few keV recoil
- Measurements of ΔT
  NTD: neutron transmutation-doped Ge sensors
  TES: Transition edge sensors
- Discrimination: combination with light or charge read-out
- Large separation of electronic and nuclear recoil bands

Example from CRESST, EPJC 72 (2012) 1971

Bolometer experiments

CRESST experiment

EDELWEISS experiment



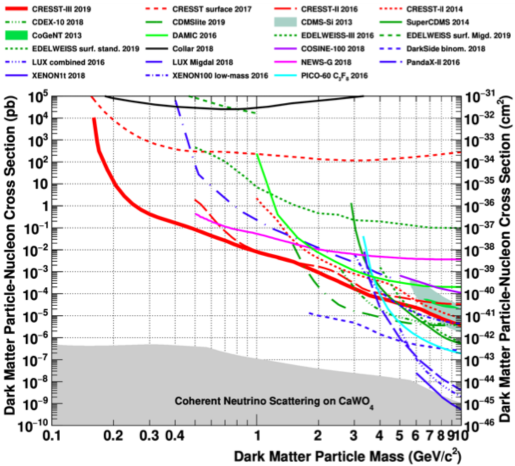
CDMS experiment

- Excellent sensitivities (low m_χ) due to their low energy thresholds
- CRESST: scintillating bolometer ($CaWO_4$)

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

  CDMS-Lite, PRD 99 (2019) 062001 (E_{th} = 70 eV)
- COSINUS: NaI target, new in the game!

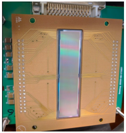
Results from cryogenic bolometers



CRESST Coll., Phys. Rev. D 100, 102002 (2019)

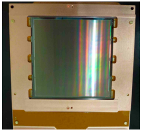
→ Excess of low energy events present in CRESST and several other experiments - detector effect being investigated (EXCESS workshop series)

Low threshold searches with CCDs



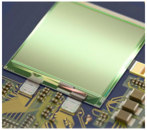
SENSEI

PRL 125 (2020) 171802



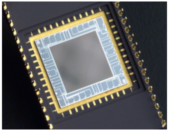
DAMIC

PRL 123, 181802 (2019)



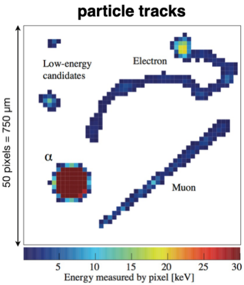
DANAE

EPJC 77 (2017) 12, 905



DMSQUARE

N. Avalos@TAUP2021

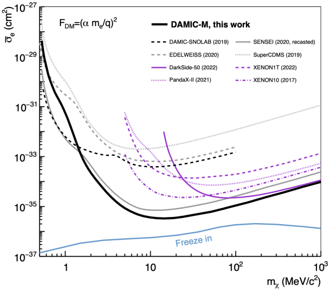


From Nuria Castelló-Mor @ICHEP2022 (DAMIC)

- Gram-scale Si detectors with $E_{th} \sim 50\,\mathrm{eV}_{ee}$
- 3D track reconstruction
- Test of DM-e^- scattering below to 1 MeV DM mass

  & low mass WIMPs tests

→ Future: OSCURA, a 10 kg detector by SENSEI & DAMIC



DM-e^- scattering (light mediator)
DAMIC, arXiv:2302.02372

Advantages of liquid noble gases for DM searches

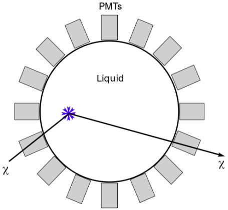
- Large masses and homegeneous targets (LNe, LAr & LXe)
  Two detector concepts: single & double phase
- 3D position reconstruction → fiducialization
- Transparent to their own scintillation light

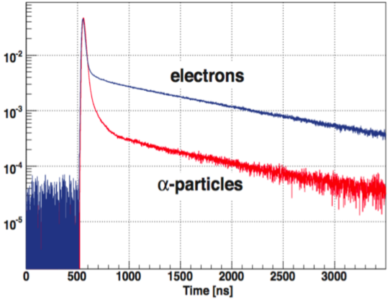
	LNe	LAr	LXe
Z (A)	10 (20)	18 (40)	54 (131)
Density [g/cm^3]	1.2	1.4	3.0
Scintillation λ	78 nm	125 nm	178 nm
BP [K] at 1 atm	27	87	165
Ionization [e$^-$/keV]*	46	42	64
Scintillation [γ/keV]*	7	40	46

* for electronic recoils

Single phase (liquid) detectors

- High light yield using 4π photosensor coverage
- Position resolution in the cm range
- Pulse shape discrimination (PSD) from scintillation





Scintillation decay constants of argon measured by ArDM

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

DEAP-I obtained 10^{-8} discrimination in LAr above 25 keV$_{ee}$ (50% acceptance)

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

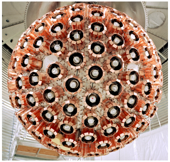
→ PSD less powerful in LXe: similar decay constants XMASS, NIM. A659 (2011) 161

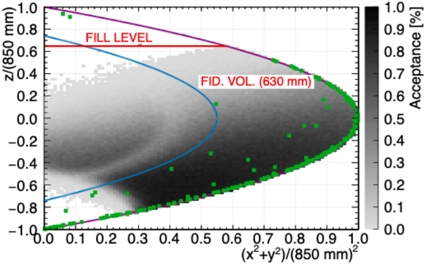
The DEAP single phase LAr detector

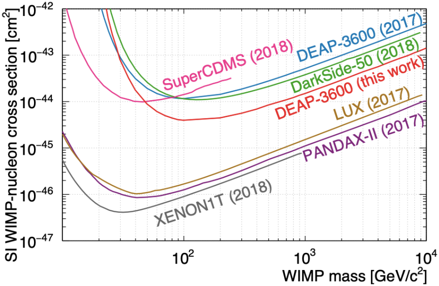
DEAP - LAr detector at SNOLAB, Canada

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

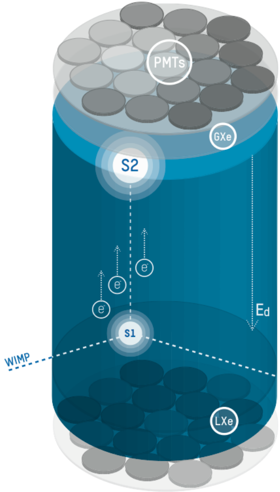






From Jan. 2018 to Mar. 2020: blinded data → results soon!

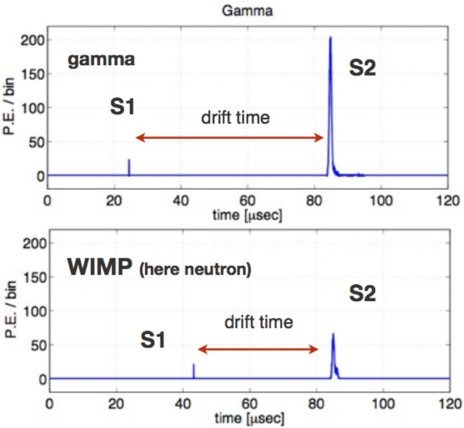
Two phase noble gas TPC



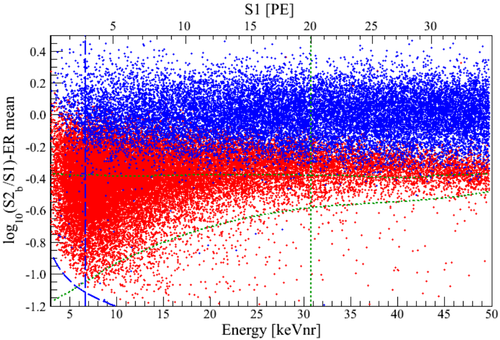
- Drift field
- Electronegative purity
- Position resolution

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

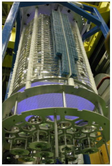
→ Electron- /nuclear recoil discrimination

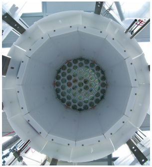


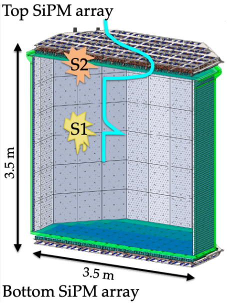
Double phase LAr & LXe experiments



Signal and background regions from the XENON100 detector







- 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 an acrylic vessel
  - SiPM for light read-out (~ 19 m^2)

- Aiming at high mass dark-matter search

  ROI (20 – 200) keV_{nr}
  → filling with underground argon planned for 2026

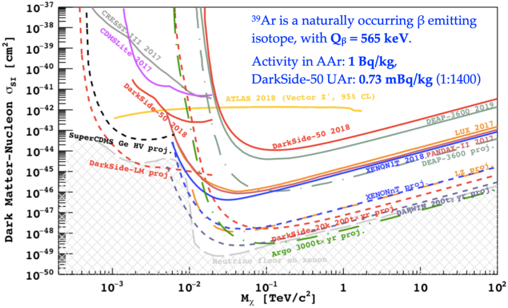
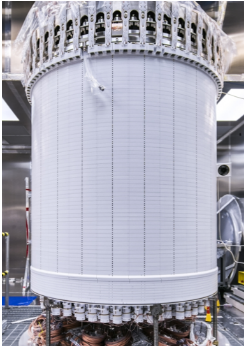


Figure from the DarkSide collaboration

Current generation: LZ, PandaX-4T and XENONnT



LZ:

- 7 T target mass

PANDAX-4T:

- 4 T target mass

XENONnT:

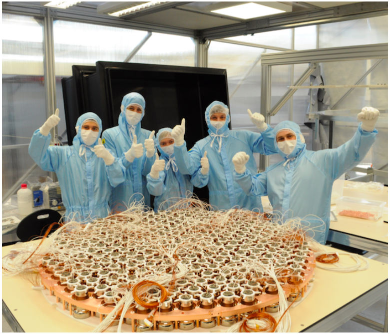
- 6 T target mass

All running and collecting data!

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

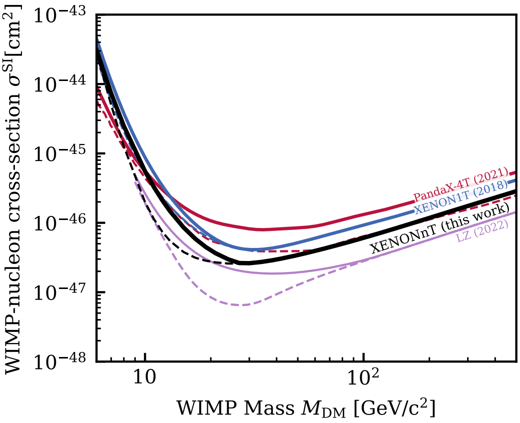
XENONnT

TPC: 1.5 m long und 1.5 m ∅
5.9 t liquid xenon in the detector
(8.5 t total mass)



- Assembled and commissioned during 2020
- First science run in 2021: SR0 with 1.16 tonne-years
- 3× larger target mass
- 5× less background

WIMP spin-independent result



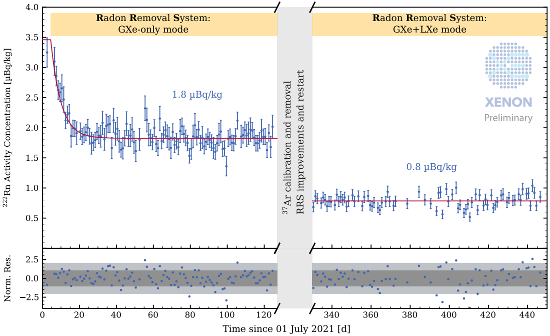
XENONnT, accepted in PRL, arXiv:2303.14729

Comparison of recent LXe experimental results applying the same conservative power-constrained method for the limit setting

→ Next steps: more data to reach the final sensitivity of $\sim 2 \times 10^{-48}$ cm^2

Radon background

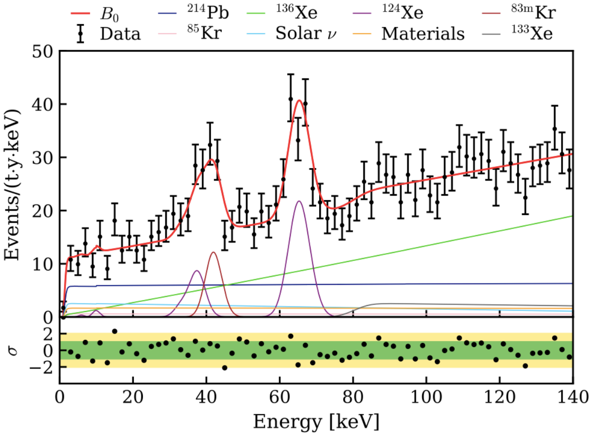
Dominating background in XENONnT & other LXe experiments
→ Extensive radon screening campaigns @MPIK



- SR0: distillation in gas mode → 1.8 μBq/kg
- Lowest radon level ever achieved in a LXe experiment!

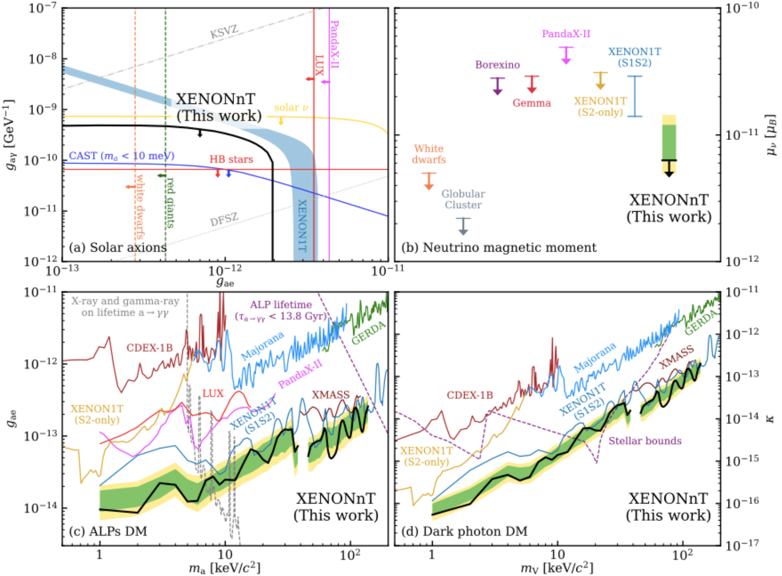
- SR1: distillation in liquid mode → 0.8 μBq/kg
- Radon background at the level of solar neutrino background!

SR0 electronic-recoil science data



- Spectrum still dominated by ^{214}Pb at low energies
- Above 40 keV, 2nd order weak processes dominate:
  - → Double electron capture 2νECEC of ^{124}Xe ($t_{1/2} = 2.23 \times 10^{21}$ y)
  - → Double beta decay $2\nu\beta\beta$ of ^{136}Xe ($t_{1/2} = 1.1 \times 10^{22}$ y)

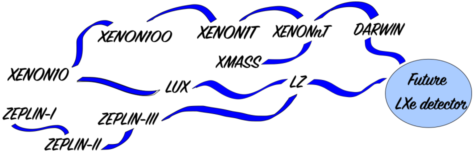
Constrains on physics models

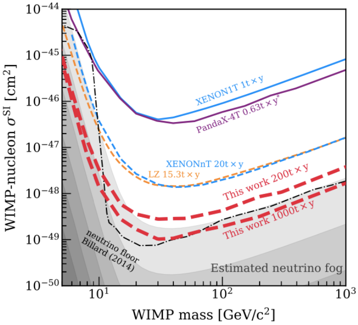


XENONnT, PRL 129 (2022) 161805 & arXiv:2207.11330

XLZD consortium

XENON, LUX ZEPLIN & DARWIN meeting in Karlsruhe, July 2022





XLZD:
XENON, LZ and DARWIN together

Common paper with physics case: arXiv:2203.02309

Cross sections for WIMP elastic scattering

- Spin-independent interactions: coupling to nuclear mass

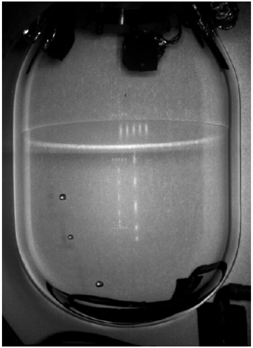
$$\sigma_{SI} = \frac{m_N^2}{4\pi(m_\chi + m_N)^2} \cdot [Z \cdot f_p + (A - Z) \cdot f_n]^2, \quad f_{p,n}\text{: eff. couplings to } p \text{ and } n$$

- 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

COUPP experiment



- Energy depositions > E_{th} → expanding bubble detected with cameras + piezo-acoustic sensors
- Bubble chamber with C_3F_8 superheated fluid

- Great sensitivity to spin-dependent σ

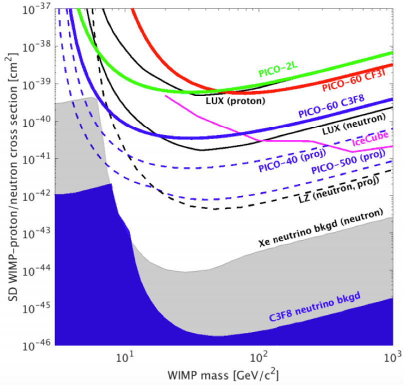
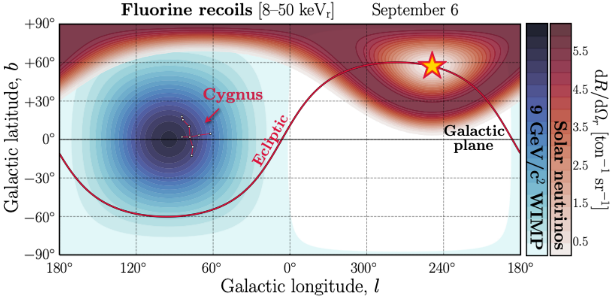
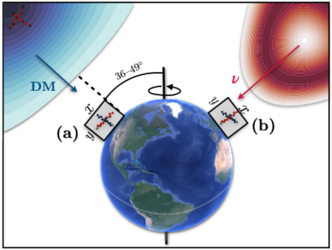


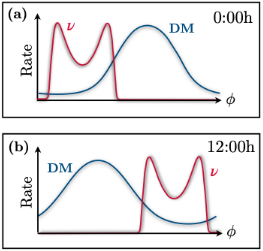
Figure from Eric Vázquez Jáuregui @ICHEP2022

- PICO40L: about to take data @SNOLAB
- PICO-500: ton-scale experiment to be installed in the miniCLEAN space @SNOLAB on 2023-2024

Distinguish dark matter from neutrinos



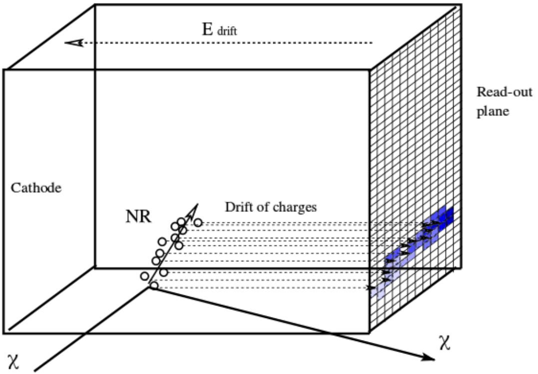




Vahsen et al., Ann. Rev. Nucl. Part. Sci. 71 (2021) 189-224 & arXiv:2102.04596

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 at the moment with liquids or solids but important confirmation in case of a WIMP detection

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

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

Slide from S. Vahsen UCLA 2023

Summary of dark matter searches

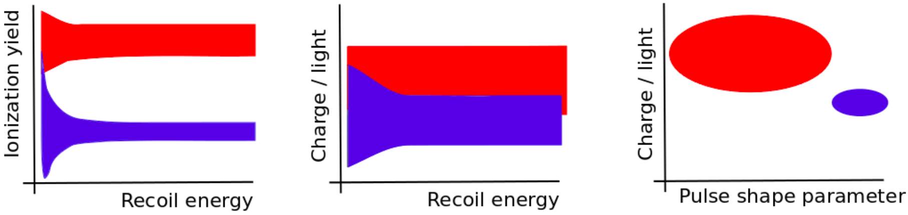
- LHC is producing very stringent results for the production of dark matter particles
- Exciting signal hints have appeared in indirect detection
  $\rightarrow$ but astrophysical explanations also exist for the observed features
- Large improvement of sensitivity in direct detection
  LXe technology is most sensitive at WIMP masses above $\sim 5\,\text{GeV}$
  Below this mass cryogenic bolometers have best results
- We hope for a dark matter discovery in various detectors and ideally via different searches!

Detector calibration

Purposes of detector calibration:

- Data stability:
  monitoring of detector parameters (amplification of signals, slow control parameters, ..) and of the related electronics
- Determination of energy scale:
  detector signals are photoelectrons, charges or heat
  $\rightarrow$ need to convert to keV$_{nr}$
- Determination of signal and background regions:
  description of nuclear and electronic recoil regions

Detector calibration: signal and background



- Discrimination in a cryogenic germanium detector (left)
  No surface events included!
- Discrimination in a liquid xenon detector (middle)
- Discrimination in a liquid argon detector (right)
  Two parameters available for discrimination