Astrophysical searches for dark matter

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MAX-PLANCK-INSTITUT
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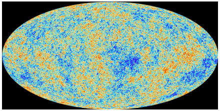
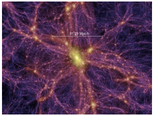
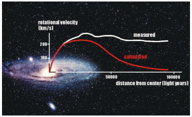
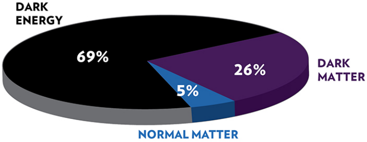
Image credit: NASA, ESA, ...

Dark matter in Cosmology and Astronomy

Overwhelming evidence for dark matter in our Universe

ΛCDM describes all observations very well

Previous talk by Gianfranco

BUT what is the nature of dark matter?

Well motivated theoretical approach:

WIMP

(**W**eakly **I**nteracting **M**assive **P**article)

Dark matter could be however non weakly-interacting or a completely different type of particle

How can we look for dark matter?

Indirect detection	Direct detection	Production at LHC
		
$\chi\overline{\chi} \to \gamma\gamma, q\overline{q}, \ldots$	$\chi\,\mathrm{N} \to \chi\,\mathrm{N}$	$\mathrm{p} + \mathrm{p} \to \chi\overline{\chi} + \mathrm{X}$

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

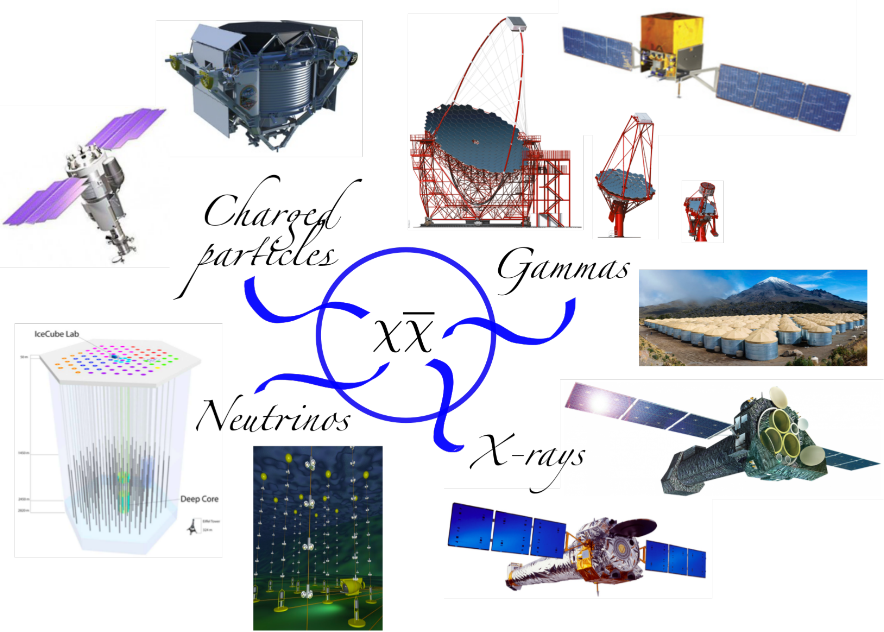
Expected particle flux:

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

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

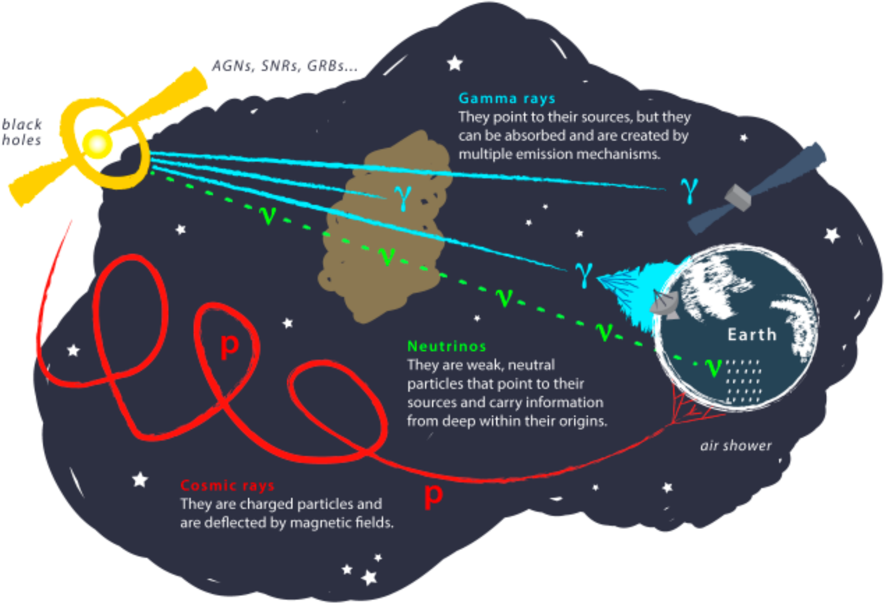
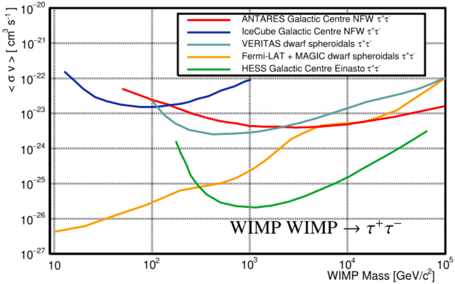
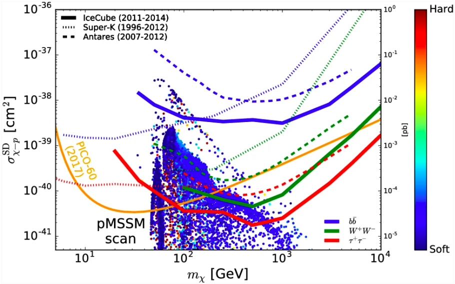


Figure credit: Juan Antonio Aguilar and Jamie Yang, IceCube/WIPAC

Indirect searches with ν's



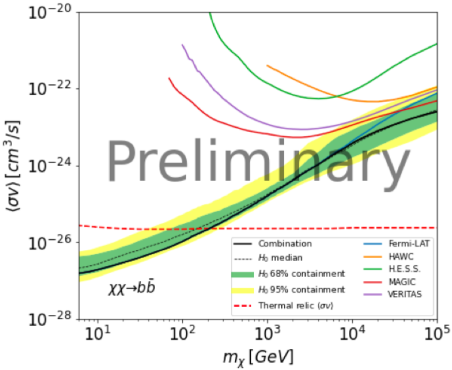
ANTARES galactic center search,
PLB 805, 135439 (2020)



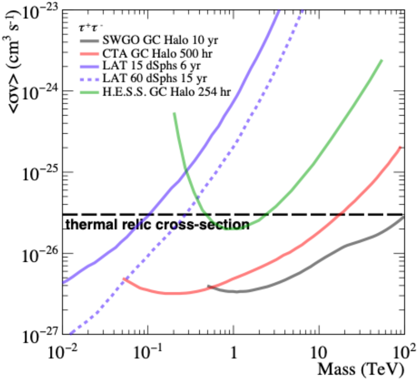
Neutrino limits on the spin-dependent
WIMP-proton cross section,
EPJC 78 (2018) 924

- Limits from ν-experiments on annihilation not yet competitive with $\gamma-$ray bounds
- Dark matter can be trapped in the Sun due to scattering consequent annihilation into GeV neutrinos
  → Competitive spin-dependent scattering constrains (compared with DD results)

Exclusion limits from γ searches



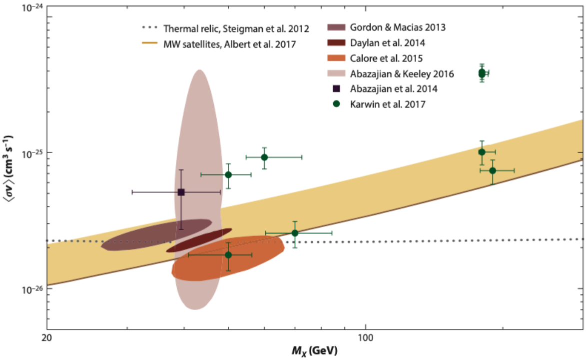
Combined limit of dwarf spheroidals from Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS, PoS ICRC2021 (2021) 528



Expected upper limit for SWGO and CTA observations of the GC halo, PoS ICRC2021 (2021) 555

- Dwarf spheroidal observations give best constrains in ~ $(1 - 100)$ 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 pulsars

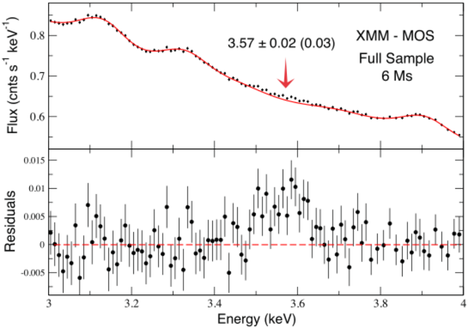
X-ray searches and the 3.5 keV line

- 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

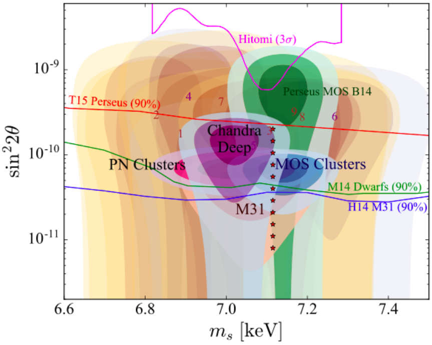
  Present in several nearby galaxies and galaxy clusters

  but not found in large statistic searches (Dessert et al. 2018 & Foster et al. 2021)

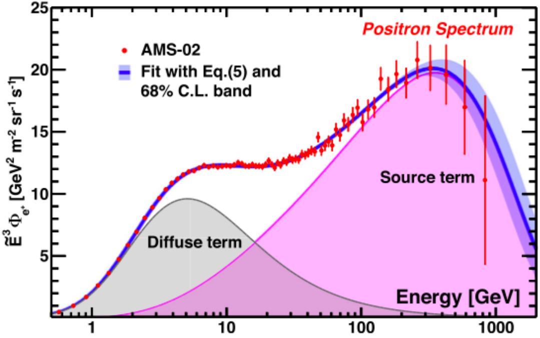
Bulbul et al. 1402.2301 (and Jeltema et al. 1408.1699)



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

Indirect detection summary

Variety of objects of interest & searches

with stringent limits touching into the thermal relic cross section

Please look at the talks on the parallel sessions on Friday

Several signals being discussed since years

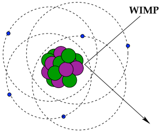
- unclear origin: dark matter?

  or an astrophysical background?

- further studies/data will help to clarify

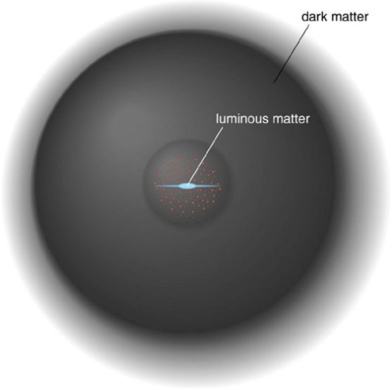
What does direct detection tell us?

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

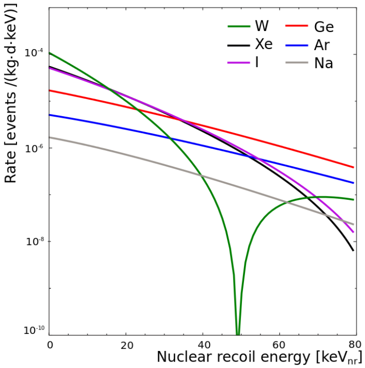
Parameters of interest:

- m_χ = WIMP mass (~ 100 GeV)
- σ = WIMP-nucleus elastic scattering cross section (SD or SI)

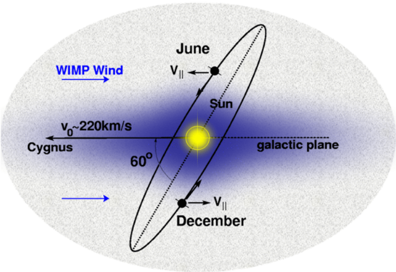
Detector requirements and signatures

- Large detector mass (grams up to several tonnes)
- Low energy threshold ~ few keV's or sub-keV
- Very low background and/or background discrimination (from γ's, e^-'s, neutrons and ν's!)

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



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



Overview of WIMP searches

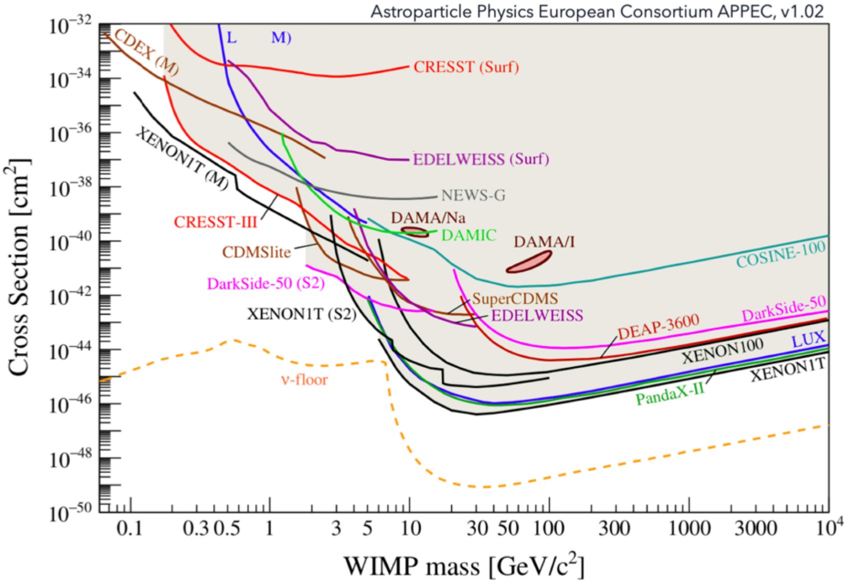
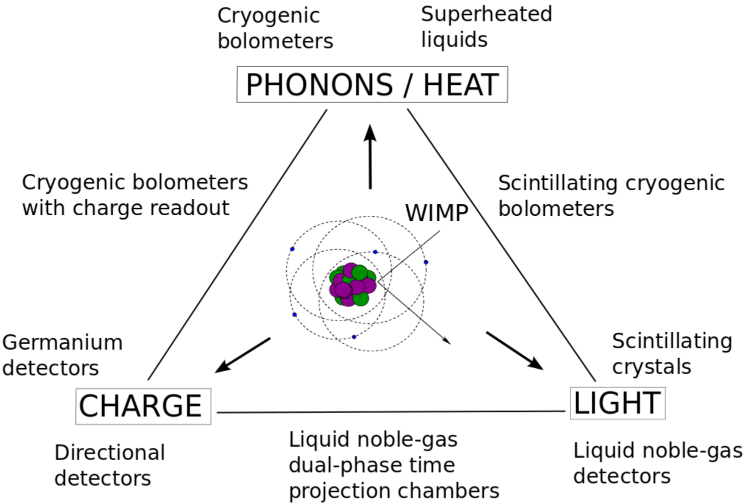


Figure modified from Rept. Prog. Phys. 85 (2022) 5, 056201

Direct detection experiments

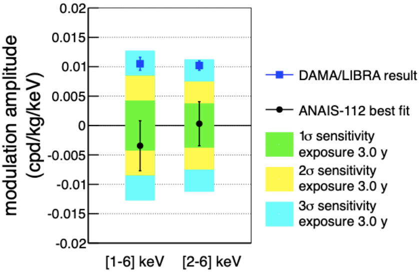


J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

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 $13.7\,\sigma$

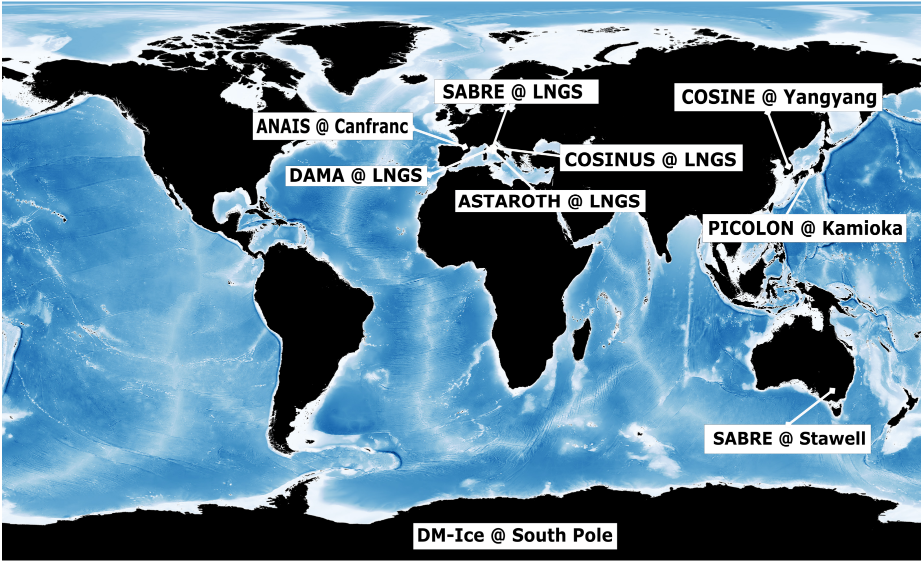
ANAIS, PRD 103 (2021) 102005 & arXiv:2103.01175



ANAIS using NaI crystals @Canfranc:

- DAMA modulation disfavoured
  at $3.3\,\sigma$ for [1-6] keV
  at $2.6\,\sigma$ for [2-6] keV
- Experiment continuously taking data

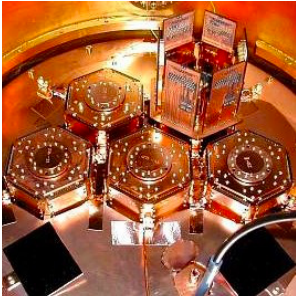
Tests of annual modulation with NaI



Bolometer experiments


CRESST experiment


EDELWEISS experiment

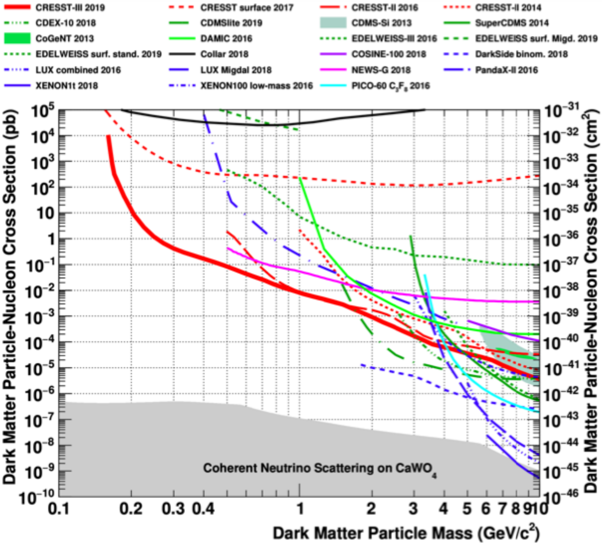

Super-CDMS experiment

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

  CRESST, PRD 100 (2019) 102002 (E_{th} = 30 eV) → New data release @iDM in the next weeks!
- CDMS/EDELWEISS: germanium bolometers

  CDMS-Lite, PRD 99 (2019) 062001 (E_{th} = 70 eV)

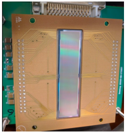
Results from cryogenic bolometers



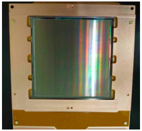
CRESST Coll., Phys. Rev. D 100, 102002 (2019)

New SuperCDMS HVeV result with 0.93 g silicon crystal with $E_{th} \sim 10$ eV missing in this figure PRD 105, 112006 (2022)

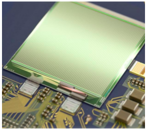
Low threshold searches with CCDs



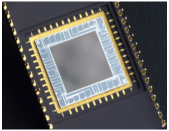
SENSEI
PRL 125 (2020) 171802



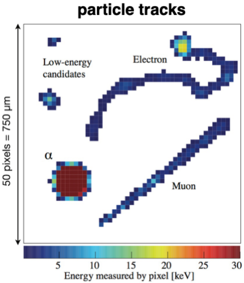
DAMIC
PRL 123, 181802 (2019)



DANAE
EPJC 77 (2017) 12, 905



DMSQUARE
N. Avalos@TAUP2021

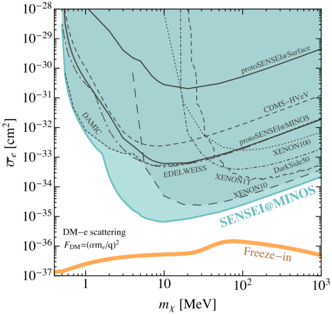


From Nuria Castelló-Mor @ICHEP2022 (DAMIC)

- 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



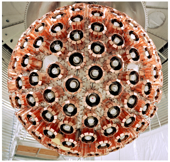
DM-e⁻ scattering (light mediator)
SENSEI, PRL 125 (2020) 171802

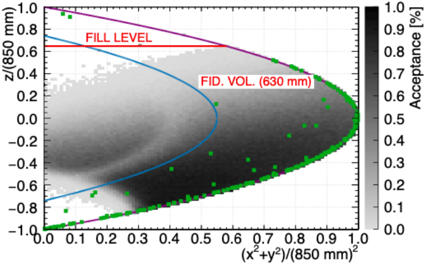
The DEAP single phase LAr detector

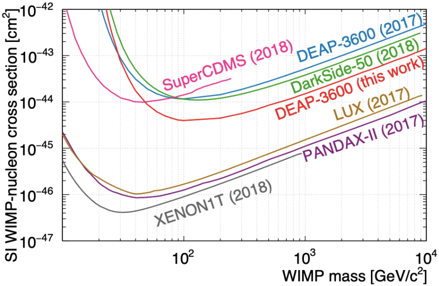
DEAP - LAr detector at SNOLAB, Canada

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

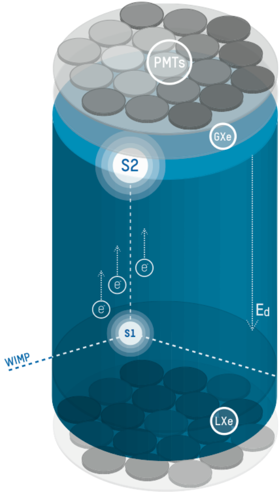






From Jan. 2018 to Mar. 2020: blinded data → analysis on-going

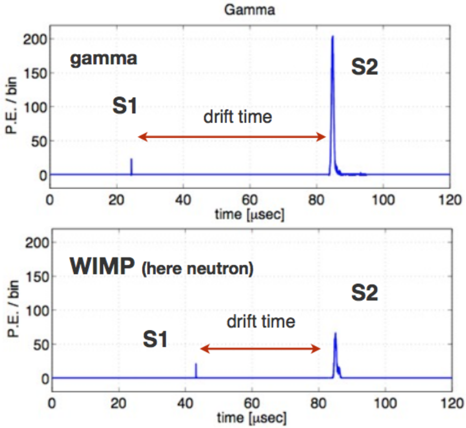
Two phase noble gas TPC



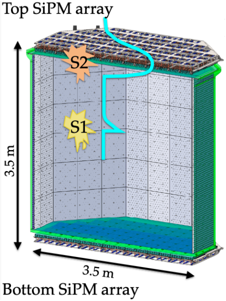
- Position resolution
  → XY from PMT pattern
  → Z from drift time

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

→ Electron- /nuclear recoil discrimination



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 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

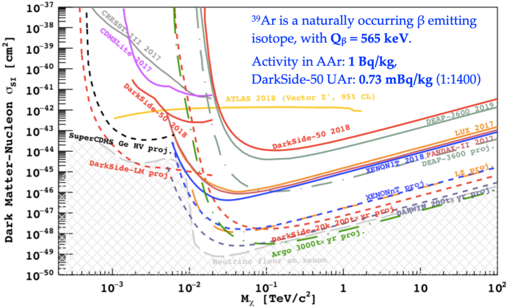
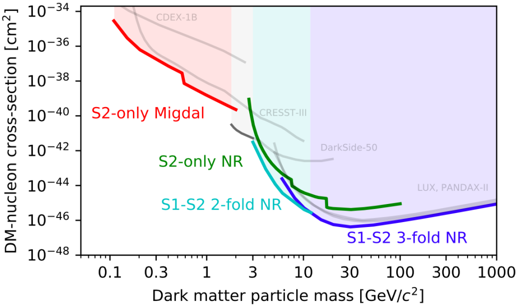
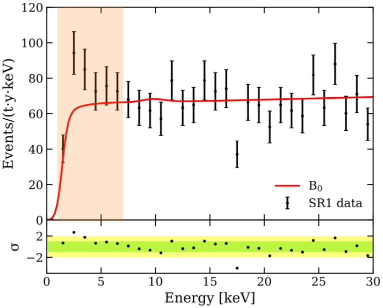


Figure from the DarkSide collaboration

XENON1T results



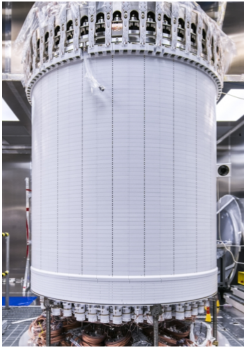
XENON1T, publications from 2018 to 2021



XENON1T, PRD 102 (2020) 072004

- XENON1T operated at LNGS from 2016 to 2019 providing several world leading results in the last years
  – Migdal result: depends on the experimental confirmation of this effect
- **Excess of events in (1-7) keV** in the background (ER) region
  → Unclear origin: XENONnT data will clarify very soon

Current generation: LZ, PandaX-4T and XENONnT



LZ:

- 7 T target mass
- First data released last Thursday!

PANDAX-4T:

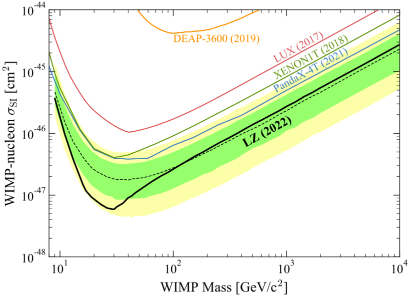
- 4 T target mass
- First data released in July 2021

XENONnT:

- 6 T target mass
- First data about to be released!

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

LZ results from last Thursday & XLZD

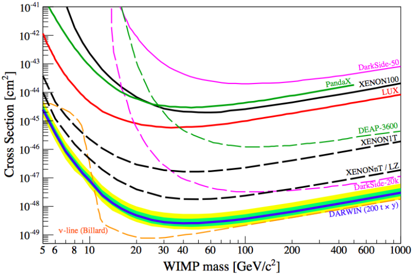


LZ, arXiv:2207.xxxx

- SR1: 5.5 t and 60 days
- Currently best exclusion limit

- XLZD: XENON, LZ and DARWIN together

  Common paper with physics case: arXiv:2203.02309



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

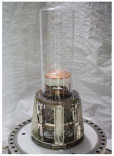
DARWIN, XENON + LUX ZEPLIN meeting in Karlsruhe, July 2022

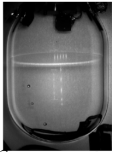
Other detectors and technologies being developed ...

... but not discussed in this talk

Superheated fluid detectors

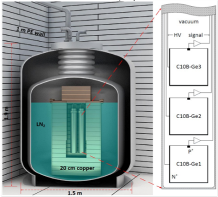
PICO



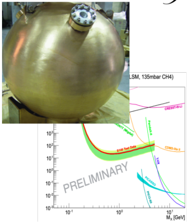


Best for spin-dependent

CDEX, germanium

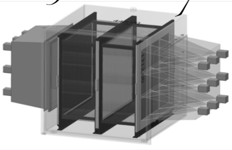


NEWS-G

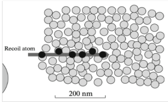


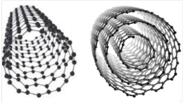
Directional experiments

CYGNO, low pressure gas



NEWSdm, emulsion





ANDROMeDa, nanotubes

Others ...

Please look at the talks on the parallel sessions on Saturday

Summary

Direct & indirect searches are quickly progressing covering a large DM range in mass and cross section

Exploring WIMPs but also light DM, ALPs, dark photons ...

Current signals/excesses are not confirmed or have alternative explanations

We hope for a dark matter discovery soon, ideally in various detectors/searches!

THANK YOU!

Backup: Cross sections for WIMP elastic scattering

- Spin-independent interactions: coupling to nuclear mass

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

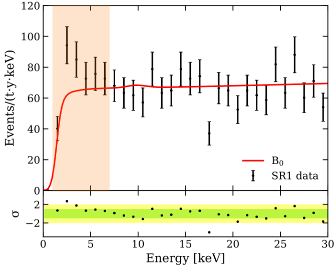
- Spin-dependent interactions: coupling to nuclear spin

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

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

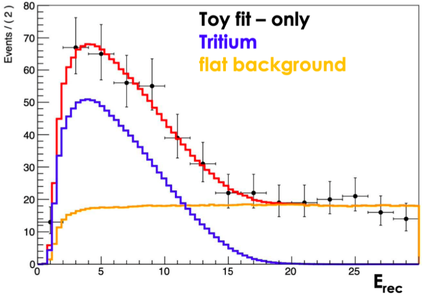
$a_{p,n}$: effective couplings to p and n

Testing the low energy excess in XENON1T

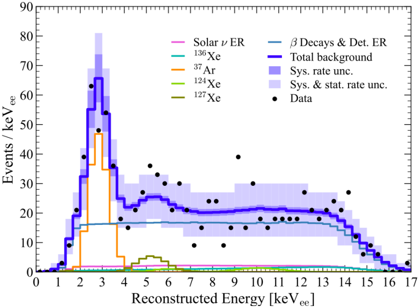


XENON1T, PRD 102 (2020) 072004

- XENON1T excess in (1-7) keV
- PandaX spectrum dominated by tritium
- LZ spectrum dominated by ^{37}Ar
- XENONnT essential to clarify the excess
  → data release very soon!

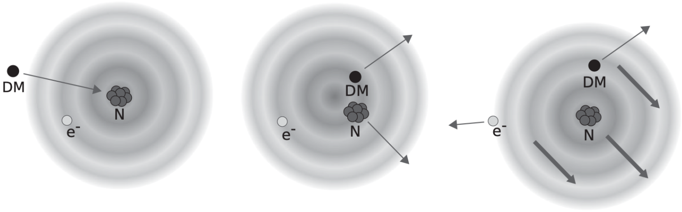


PandaX, talk by Qing Lin @ICHEP2022



LZ coll., recent results 07/2022

Low-mass WIMP searches using the Migdal effect

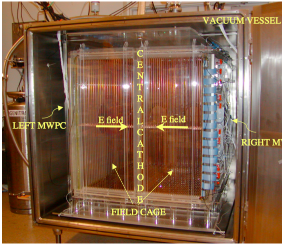


Scheme from Dolan et al., PRL 121 (2018)101801

- 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

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



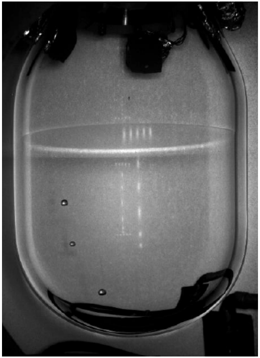
- DRIFT @Boulby - m^3 experiment: important technology milestone
  DRIFT, Phys. Dark Univ. 9-10 (2015) 1 & Astropart.Phys. 91 (2017) 65
- Operation of a 'large-scale' experiment

- **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

Superheated fluid detectors

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

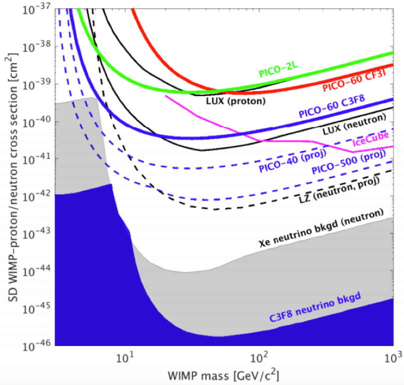


Figure from Eric Vázquez Jáuregui @ICHEP2022

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

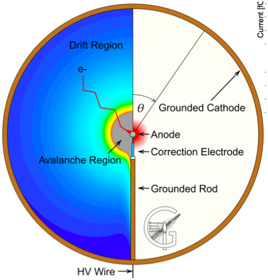
NEWS-G experiment

- Metallic vessel filled with a noble gas mixture
- Single anode in the middle
- Low energy threshold ~ (10 – 15) eV
- Low-A target atoms increases sensitivity to low-mass WIMPs

- New sphere of 140 cm ∅ filled with $CH4$
- Operated in LSM, 10 d of data → SD results

- Commissioning just finished at SNOLAB
- Data taking starting now

Talk K. Nikolopoulos @ICHEP2022

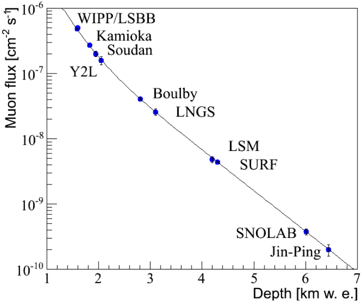


Backgrounds and reduction strategies

- 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: radioactive isotopes, Rn-emanation
  - Solids: surface events from α- or β-decays
  - Cosmogenic activation important for all