Direct Detection of Dark Matter

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DM AP Dark Matter Astroparticle Physics

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Vulcano, May 23, 2018

Content

Introduction

- I do not need to convince you about the presence of Dark Matter in the Universe
- The dark matter puzzle remains fundamental: dark matter is matter - it leads to the formation of structure and galaxies in our universe
- We have a standard model of CDM, from “precision cosmology” (CMB, LSS): however...

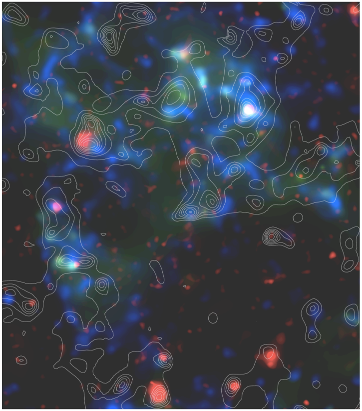

Figure: Large scale distribution of dark matter, probed through gravitational lensing
HST COSMOS survey; Nature 445 (2007), 268

Introduction
The need for Dark Matter

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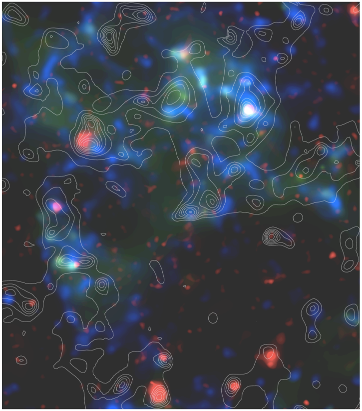
- measurement $\neq$ understanding



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$\sim$ 85% of matter in the universe is of unknown nature

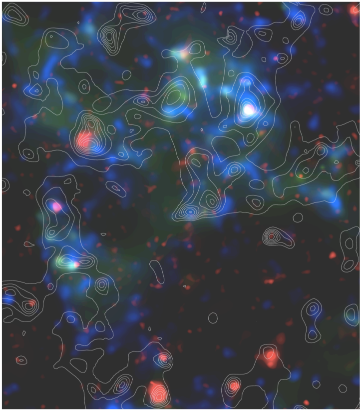

Figure: Large scale distribution of dark matter, probed through gravitational lensing
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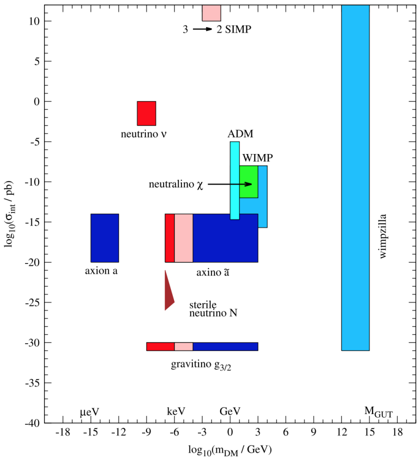
- This question needs an elaborated answer with many inputs:
  - Exists today and is there since the early Universe
  - Constraints from astrophysics and searches for new particles
  - Massive (gravitation)
  - Long-lived (Big Bang relic)
  - Electrically neutral (No colour charge, no electric charge, no strong self-interaction, i.e. dark)
  - Non-baryonic (BBN)
  - Collisionless (Bullet cluster)
  - Cold, i.e. dissipationless and negligible “free-streaming” effect (Structure formation)
- We know what DM can’t be: can’t be made of standard model particles!

Introduction
Particle Dark Matter

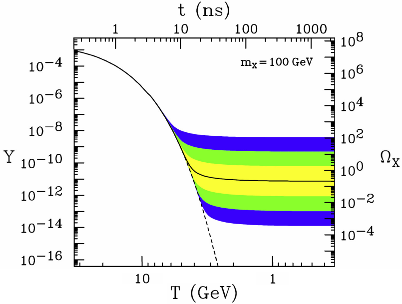
- very many candidates
- masses and interaction strength span over a lot of orders of magnitudes
- but we prefer one specific class: Weakly Interacting Massive Particles (WIMPs)

H. Baer et al. / Physics Reports 555 (2015) 1–60



DM particles might have been produced as “thermal relic” of the Big Bang.

Feng, J., Ann. Rev. Astron. Astrophys. 48: 495, 2010



DM particles might have been produced as "thermal relic" of the Big Bang.

- Initially: Universe dense and hot and particles are in thermal equilibrium $\chi\chi \leftrightarrows q\bar{q}$
- When $T \lesssim m_\chi \longrightarrow$ Boltzmann suppression $\Upsilon \sim e^{-m_\chi/T}$ $\chi\chi \overset{\not\leftarrow}{\rightarrow} q\bar{q}$
- Υ would drop to zero if the Universe was only cooling, but it is expanding $\longrightarrow$ the probability for DM particle to meet becomes very low ("thermal relic"): $\chi\chi \overset{\not\leftarrow}{\not\rightarrow} q\bar{q}$

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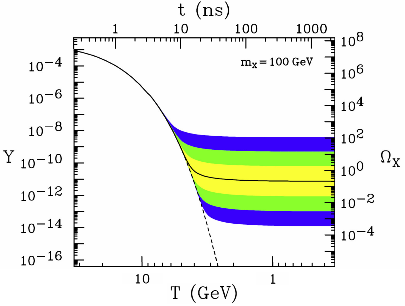

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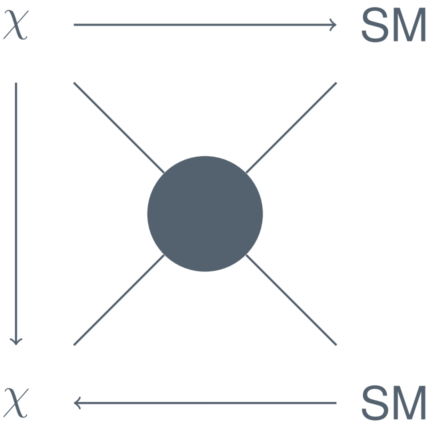
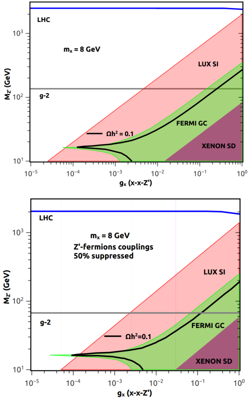
$$\Omega_{DM} \approx \frac{10^{-26} cm^{-3} s^{-1}}{\langle \sigma\nu \rangle} \approx 0.27$$

$$\langle \sigma\nu \rangle_{\sim Weak} \approx \frac{\alpha^2}{m_{DM}^2} \approx 10^{-25}$$

Detection of WIMPs
The complementary approaches





Viable versus excluded regions of the parameter space can be defined combining the different approaches to rule (or not) out theoretical models
In this example:

Alves, A. et al. Phys. Rev. D 92, 083004 (2015)

WIMPs direct detection approach

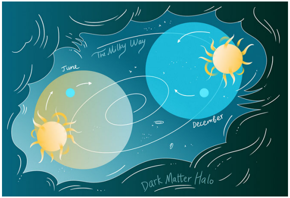
Direct WIMP searches
On earth

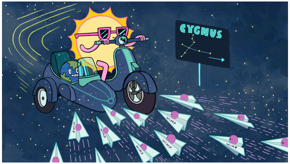
WIMPs interactions:

- nuclear recoils
- scatter once (if at all!) (uniformly throughout detector volume)

The idea:

- Our galaxy is immersed in a WIMP halo
- WIMPs in such halo have a certain velocity distribution
- The Sun moves at a speed of 232 km/s around galactic centre
- The Earth moves around the Sun with a speed of 30 km/s
- Annual flux modulation (~ 3% effect, most events close to threshold)
- Diurnal direction modulation (larger effect ~ 30%, requires direction sensitivity, e.g. low-pressure gas target)





Place detector on Earth
WIMPs interact ($\sigma \lesssim 10^{-46}$ cm^2) with the nucleus inducing a NUCLEAR RECOIL of energy:

$$E_R = \frac{q^2}{2m_N} = \frac{\mu^2 \nu^2}{m_N}(1 - cos\theta)$$

- q = momentum transfer
- m_N = target nucleus mass
- μ = reduced mass
- ν = mean WIMP-velocity on respect to the target
- θ = scattering angle in the center of mass

Observables: E_R and θ

In a standard scenario, the differential rate spectrum of a WIMP on a (under)ground based detector is:

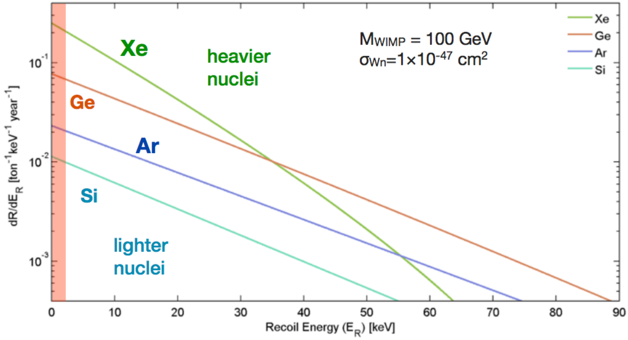
$$\frac{dN}{dE_R} \sim \frac{\rho_o}{2m_\chi \mu}\left[\sigma^{SI} F_{SI}^2 + \sigma^{SD} F_S^2\right] \int_{v_{min}}^{v_{esc}} \frac{\hat{\boldsymbol{f}}_{lab}(\hat{\boldsymbol{v}}, t)}{v} d^3 v$$

Where:

- m_χ, σ^{SI} and σ^{SD} (WIMP mass, WIMP-nucleon spin-independe and spin-dependent interaction cross-sections respectively) are the interesting quantities
- ρ_o ($0.2 - 0.56$ GeV cm^{-3}) is the local (i.e. at the Solar radius) dark matter density, and $\hat{\boldsymbol{f}}_{lab}(\hat{\boldsymbol{v}}, t)$) is the lab frame WIMP velocity distribution (Astrophysic input)
- F_{SI}^2 and F_{SD}^2 are the spin independent/spin dependent nuclear form factor (Detector related)

Integrate over WIMP velocity distribution; in general assumed to be of Maxwell-Boltzmann type, which so far is a pretty good approximation

How do all these things look all together?



Corresponds to 1 event/ton/year!!

Need many orders of magnitude reduction from a tonne scale detector at sea level

Direct WIMP searches

The backgrounds

With current limit on cross sections $\sigma \sim 10^{-46}$ cm^2 (~ 10 event/ton/year):

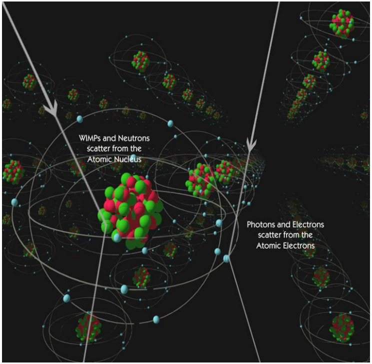
- without background: **Sensitivity ~ M × t**
- with background: **Sensitivity** $\sim\sqrt{M \times t}$ until limited by systematics

Nature:

Mainly α, β, γ,n,μ

Sources

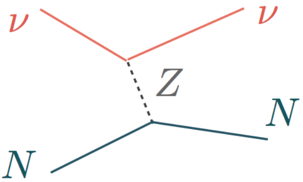
- Artificially produced radionuclides (^{85}Kr, ^{137}Cs) - γ−ray
- Cosmogenic radionuclides (60Co) - mostly γ-ray
- Natural primordial radionuclides (^{238}U, ^{232}Th, 40K) - γ-rays and neutrons
- Cosmic muons - neutrons

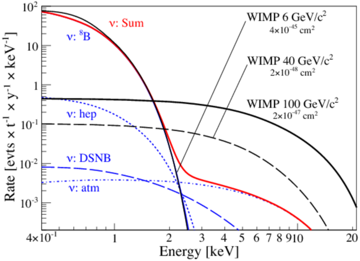


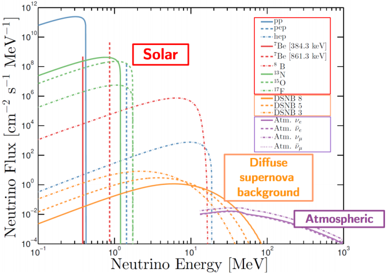
Direct WIMP searches

The “ultimate” background

Ultimately coherent neutrino-nucleus scattering (solar, atmospheric and supernovae neutrinos) will be the limiting factor



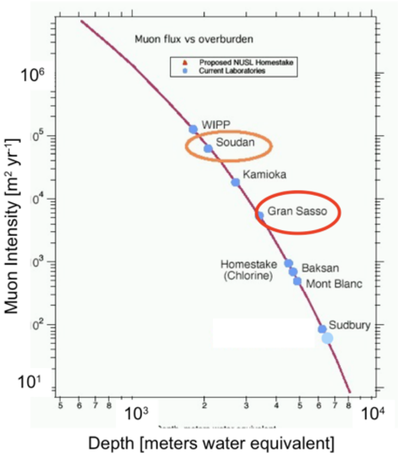




Direct WIMP searches

Underground to reduce backgrounds

- Move detector underground (reduce μ)
- Shield (actively and/or passively) detector from environmental radioactivity (reduce α, β, γ,n,μ)
- Select detector construction materials
- Big detector with multiple scattering identification allow further background reduction
- Use event positioning (if possible) for sensitive medium self shielding and/or surface events rejection
- Use other methods to reject the main background, i.e. β and γ from real signal



Direct WIMP searches

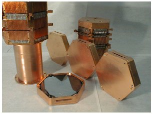
Where Underground?

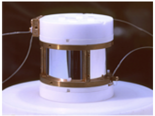
Direct WIMP searches

Background suppression techniques

SIMPLE
PICO
CUORE

Heat





E_R

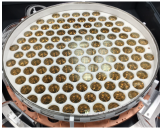
CRESST
COSINUS

Ionization

Scintillation

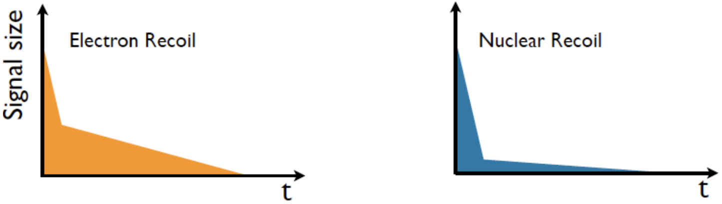
CDEX, Malbek
DAMIC, NEWS gas
CoGENT, DRIFT
DMTPC, MIMAC
NEWS, NEWAGE

DEAP-3600, CLEAN
DAMA, KIMS, XMASS,
COSINE, ANAIS, SABRE

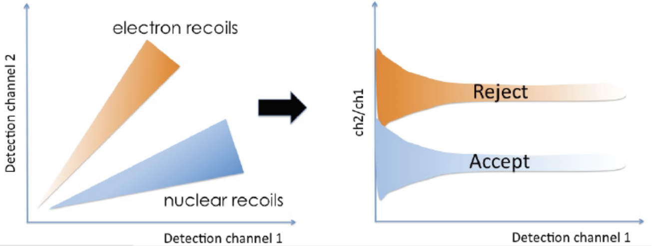


XENON, LUX/LZ, Panda-X
DARWIN, DarkSide, ArDM

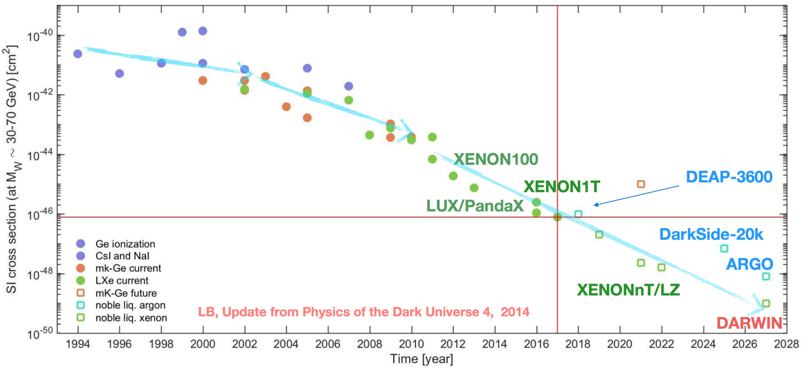
Pulse shape discrimination (Scintillation)



Use the combined two signals in order to do “particle ID”



Direct WIMP searches
Sensitivity improvement

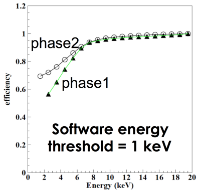


A biased selection of WIMP search experiments

Direct WIMP searches

Long standing controversial signal: DAMA/Libra

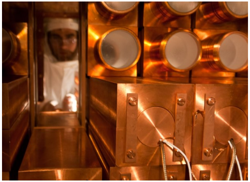
Properties of the detector (upgrade, **DAMA/LIBRA-Phase2**):

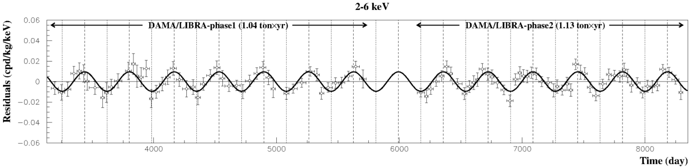


- Higher light yield: 6-10 phe/keV;
- 1 keV software energy threshold
- Combined runs (1&2): 2.17 ton $\times$ yr, 11.9σ **C.L.**)

DAMA might see electronic recoils, Examples:

Axial-vector couplings:
Kopp et al., PRD 80, 083502 (2009),
Changet al., PRD 90, 015011 (2014)
Bell et al., PRD 90, 035027 (2014)
Mirror dark matter:
Foot, Int.J.Mod.Phys. A29, 1430013 (2014)
Luminous dark matter:
Feldstein et al., PRD 82, 075019 (2010)





Direct WIMP searches

NaI projects to test DAMA

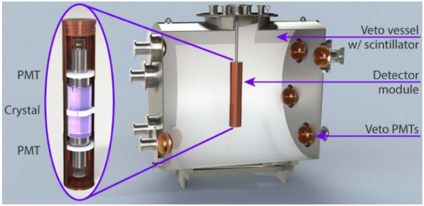
aim at testing the DAMA claim using the same target/detector
→ main challenges: crystal purity, low threshold, target mass

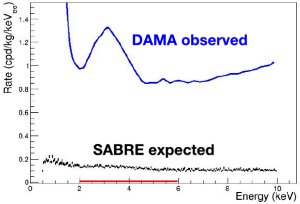
SABRE *P. Urquio (COSMO 2016)*

*S*odium-iodine with *A*ctive *B*ackground *RE*jection

Strategy:

- lower background: better crystals ✓, PMTs
- liquid scintillator veto against ^{40}K (factor 10)
- lower threshold (PMTs directly coupled to NaI)
- North (LNGS) and South (Australia)
- *Status*: tests with 5 kg crystals ongoing at LNGS





DM-Ice: 17 kg @ South Pole
arxiv:1602.05939

COSINE = KIMS+DM-Ice
~100 kg @ Yangyang → start soon

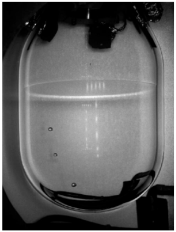
ANAIS: 112 kg @ Canfranc
→ background ~2-3x DAMA

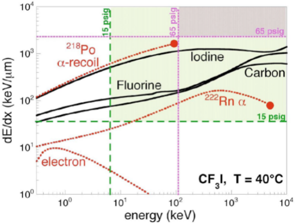
COSINUS R&D: *EPJ C 76, 441 (2016)*
NaI with bolometric+light readout

by M. Schumann

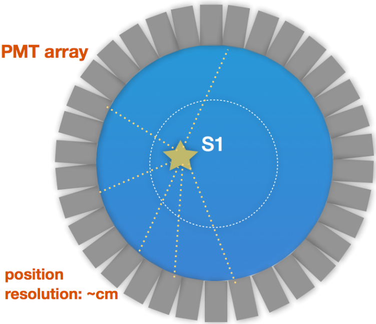
Direct WIMP searches
Superheated liquid detectors

- Superheat detector in a metastable state
- An energy deposit can destroy a metastable state and generate bubbles
  - Tune P and T to be sensitive only to nuclear recoils
  - α-particles can be acoustically discriminated
- All experiments use Fluorine, containing ^{19}F that has a good sensitivity to SD interactions
- COUPP (CF_3I), PICASSO (C_4F_{10}), SIMPLE (C_2ClF_5), PICO (fusion of PICASSO and COUPP)
- Very recently PICO has published the most stringent limit on SD coupling to protons
  - 52 kg of C_3F_8,
  - 1167-kg-day exposure at a 3.3-keV thermodynamic threshold
  - $\sigma \sim 3.4 \times 10^{-41}$ cm² for a 30-GeV c^{-2} WIMP mass





Direct WIMP searches
Liquid noble gases

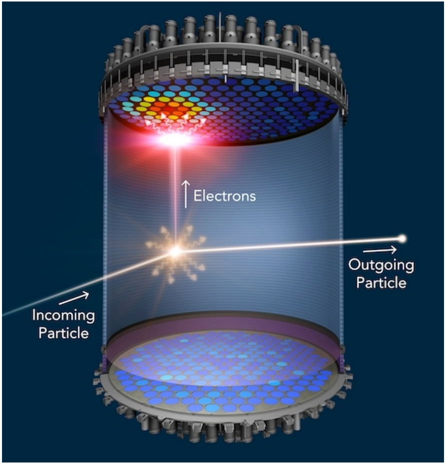


XMASS at Kamioka:

835 kg LXe (100 kg fiducial), single-phase, 642 PMTs
new run since fall 2013
several results

DEAP at SNOLab:

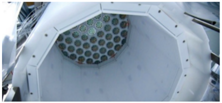
3600 kg LAr (1t fiducial)
single-phase detector
in commissioning
dark matter run in 2016



Some important characteristics of LXe (and LAr) when operated at cryogenic temperature

- Good self-shielding (Xe), homogeneous
- Easily scalable to large mass Good scintillators
- If used in 2-phase TPC mode: both ionization and scintillation can be used for discrimination 3D positioning for "fiducialization"

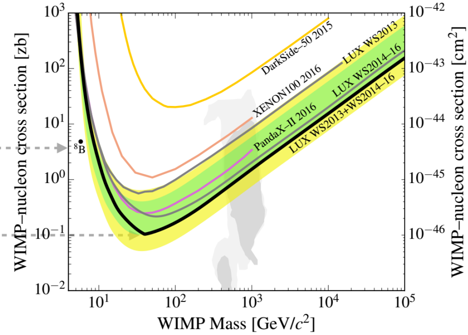
LUX: no evidence



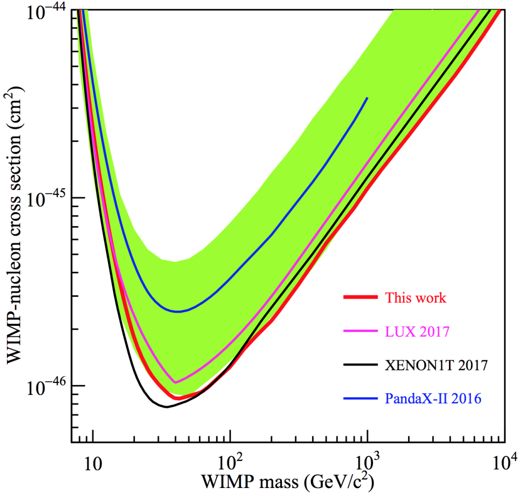
LUX collaboration, PRL 116, 161301 and arXiv:1608.07648
PandaX collaboration: PRL, August 2016

Expected events from ^{8}B neutrinos

Minimum at 0.1 zb



Panda-X: Phys. Rev. Lett. 119, 181302 Results from 77.1 live days of



PandaX-II

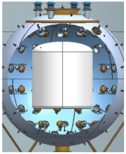
Direct WIMP searches

Liquid noble gases 5

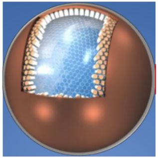
New and future noble liquid detectors:

- Taking science data: XENON1T (3.3 t LXe) at Gran Sasso
- Approved LXe: LUX-ZEPLIN 7t, XENONnT 7t
- Proposed LAr: DarkSide-20k, DEAP-50T; Proposed LXe: XMASS 5
- Design & R&D: DARWIN 50 t LXe; ARGO 300 t LAr, DEAP-50T LAr

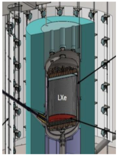
XENONnT: 7t LXe



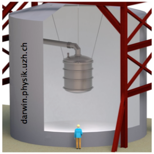
DarkSide: 20 t LAr



XMASS: 5t LXe



LZ: 7t LXe

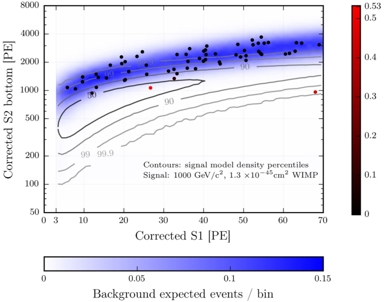


DARWIN: 50 t LXe

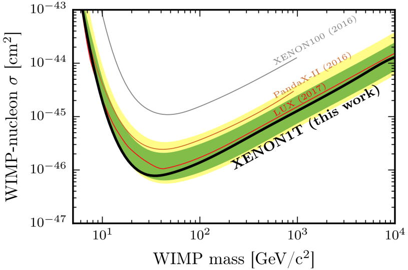
XENON1T

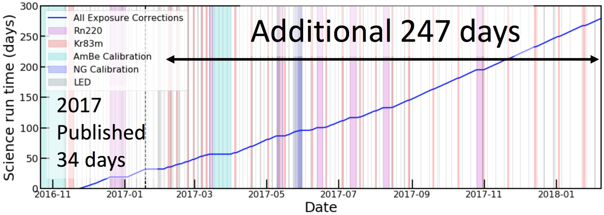
- Total (active) LXe mass: 3.3 t (2 t), 1 m electron drift, 248 3-inch PMTs in two arrays
- Background goal: 100 x lower than XENON100 ~ $5x10^{-2}$ events/(t d keV)

XENON1T: first science run, 34 live days, ~ 1 ton fiducial volume



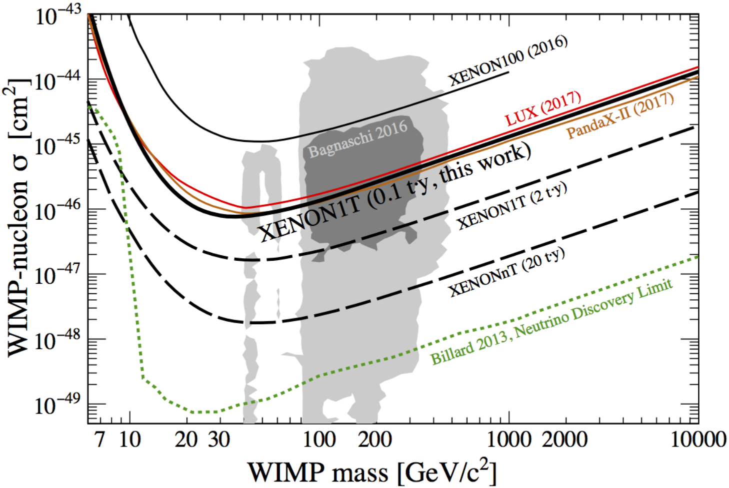
Phys. Rev. Lett. **119**, 181301, 2017





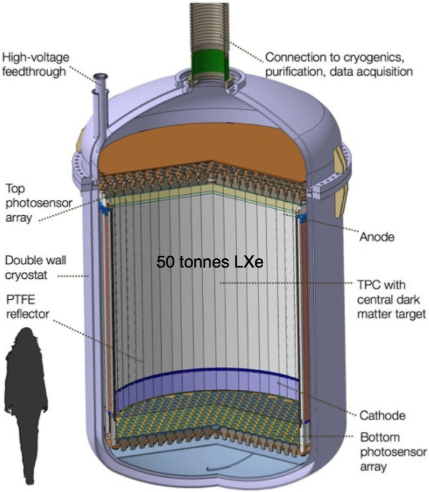
Direct WIMP searches

Current status



Direct WIMP searches

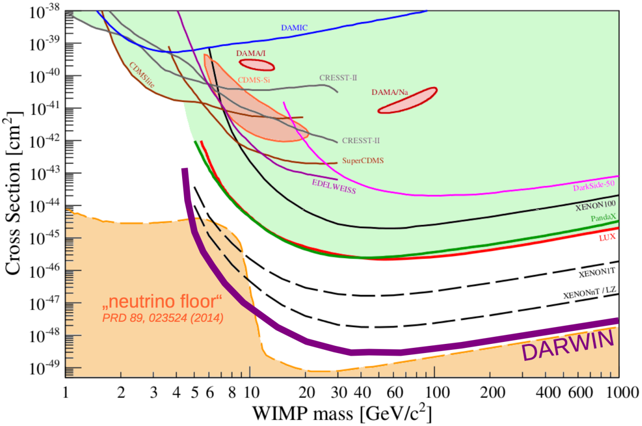
DARWIN: the ultimate WIMP Detector?



Ultimate LXe TPC at LNGS

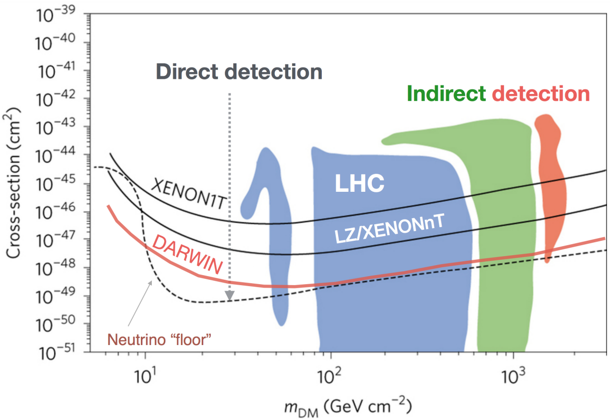
- 50 t (40 t) LXe in total (in the TPC)
- ~ 10^3 photosensors
- 2.6 m drift length, 2.6 m diameter TPC
- **Background: dominated by neutrinos**
- WIMP spectroscopy, and *lots of non-WIMP science:*
  - axion/ALP searches
  - solar pp neutrinos (<1% precision)
  - ^{8}B and SN neutrinos (CNNS)
  - $0\nu\beta\beta$-decay of ^{136}Xe

Direct WIMP searches
DARWIN: the ultimate WIMP Detector?



Direct WIMP searches

Direct, Indirect and collider



Beyond the WIMP paradigm

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- Absence of DM interaction with SM? $\longrightarrow$ New force...
- Question:

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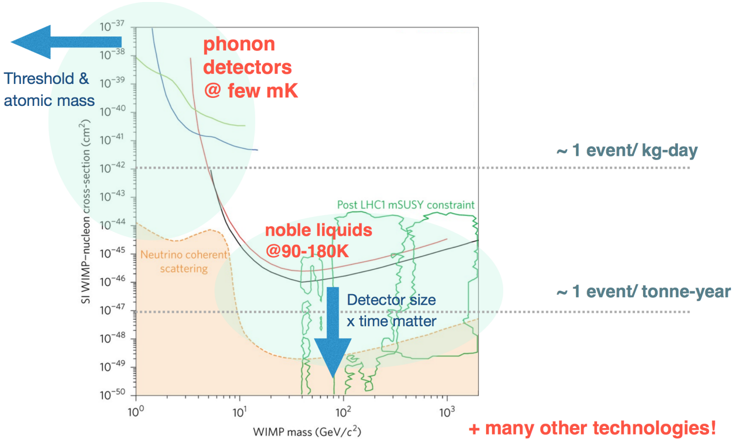
    - cosmological motivations (DM abundance)
  - several "*portal*" interaction between HSDM and SM are allowed (generated by radiative corrections)

Beyond the WIMP paradigm

Strategies



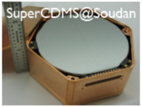
+ many other technologies!

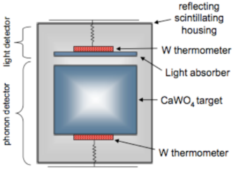
by L. Baudis

Light DM searches
Solid state cryogenic detectors

BOLOMETERS

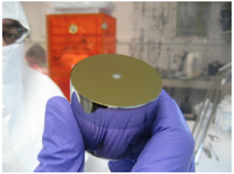
- Sub-K temperatures
- < 1 keV energy threshold (CRESST lowest ~300 eV_{nr})
- Excellent energy resolution
- Phonon signal combination with light (CRESST) or charge (EDELWEISS and CDMS) for background rejection



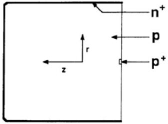


TRADITIONAL HPGE

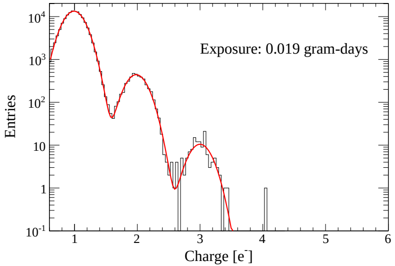
- Sub-keV energy threshold
- No background rejection
- Position sensitivity for surface events rejection
- CoGeNT, TEXONO



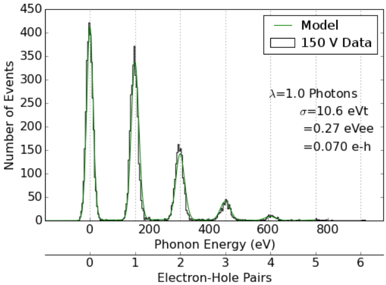
P-type Point Contact (PPC)



Light DM searches
Single electron sensitivity



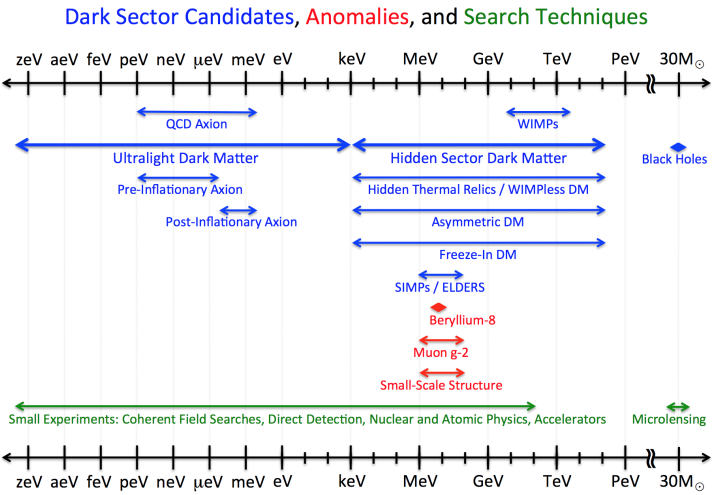
SENSEI - arXiv:1804.00088



SuperCDMS - arXiv:1804.10697

Light DM searches

Solid state cryogenic detectors



US Cosmic vision: New Ideas in Dark Matter 2017 – arXiv:1707.04591

Conclusions

... and perspective

- Cold dark matter is (still) a viable paradigm that explains all cosmological & astrophysical observations
- It could be made WIMPs - thermal relics from an early phase of our Universe
  - this hypothesis is testable: direct detection, indirect detection, accelerators
  - so far, no convincing detection of a dark matter particle in the laboratory
- But liquid xenon experiments offer excellent prospects for discovery
- increase in WIMP sensitivity by 2 – 3 orders of magnitude in the next decade
- reach neutrino background (measure neutrino-nucleus coherent scattering from solar/atm/SN neutrinos!) this & next decade