Status of direct WIMP Dark Matter search

Marcello messina
Columbia University

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Evidence for Dark Matter

• Astrophysical Observations

All consistent with ~25% dark matter (give or take).

Possible candidates: WIMPs
Collisions of invisibles particles with atomic nuclei

Direct detection principle
Scattering of a WIMP with an atomic nucleus

Momentum transfer ~ few tens of MeV

Energy deposited in the detector ~ few keV - tens of keV

\[ E_R = \frac{q^2}{2m_N} < 30 \text{ keV} \]

\[ v/c \sim 0.75 \times 10^{-3} \]

Direct detection principle
Observables: Rate

Event rate in a terrestrial detector

Detector physics  Particle/nuclear physics  Astrophysics

\[ R \sim N_N \times \frac{\rho_0}{m_W} \times \langle v \rangle \times \sigma \]

\( N_N, E_{th} \)

\( m_W, d\sigma/dE_R \)

\( \rho_0, f(v) \)

\[ M_{\text{WIMP}} = 100 \text{ GeV} \]

\[ \sigma_{\text{Wn}} = 1 \times 10^{-47} \text{ cm}^2 \]

CMSSM, \( \mu > 0 \)

Posterior pdf

Log Priors

BayesFITS (2014)
Scattering cross section on nuclei

• In general, interactions leading to WIMP-nucleus scattering are parameterized as:
  
  • **scalar interactions** (coupling to WIMP mass, from scalar, vector, tensor part of L)
  
  \[ \sigma_{SI} \sim \frac{\mu^2}{m^2_\chi} \left[ Z f_p + (A - Z) f_n \right]^2 \]

  f_p, f_n: scalar 4-fermion couplings to p and n

  => nuclei with large A favorable (but nuclear form factor corrections)

  • **spin-spin interactions** (coupling to the nuclear spin J_N, from axial-vector part of L)

  \[ \sigma_{SD} \sim \mu^2 \frac{J_N + 1}{J_N} \left( a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2 \]

  a_p, a_n: effective couplings to p and n; \langle S_p \rangle and \langle S_n \rangle expectation values of the p and n spins within the nucleus

  => nuclei with non-zero angular momentum (corrections due to spin structure functions)
Observables: rate modulations

The soft WIMP wind

- Rate and shape of nuclear recoil spectrum depend on target material
- Motion of the Earth causes:
  - annual event rate modulation: June - December asymmetry ~ 2-10%
  - sidereal directional modulation: asymmetry ~20-100% in forward-backward event rate

D. Spergel, PRD 36, 1988

Drukier, Freese, Spergel, PRD 33, 1986
Background Suppression: the holy grail

Avoid Backgrounds

**Shielding**
- deep underground location
- large shield (Pb, water, poly)
- active veto ($\mu$, coincidence)
- self shielding $\rightarrow$ fiducialization

**Select radiopure materials**

Use knowledge about expected WIMP signal

**WIMPs interact only once**
- $\rightarrow$ single scatter selection
- requires some position resolution

**WIMPs interact with target nuclei**
- $\rightarrow$ nuclear recoils
- exploit different $dE/dx$ from signal and background

Examples:
- scintillation pulse shape
- charge/light ratio
- ionization yield
WIMPs Direct Detection Experiments

- Crystals (NaI, Ge, Si)
- Cryogenic Detectors
- Liquid Noble Gases

- SuperCDMS
- EDELWEISS

- Charge
- CRESST-I
- CUORE
- CRESST

- Phonons

- Light
- XENON, LUX/LZ
- ArDM, Panda-X
- Darkside, DARWIN

- Tracking:
  - DRIFT, DMTPC
  - MIMAC, NEWAGE

- Superheated Liquids:
  - COUPP
  - PICASSO
  - SIMPLE

- DEAP-3600, CLEAN
- DAMA, KIMS
- XMASS, DM-Ice,
- ANAIS, SABRE

- CoGeNT
- CDEX
- Texono
- Malbek
- DAMIC
The WIMP landscape

As a final calculation, we have mapped out the WIMP landscape. To cover this large WIMP mass region, the exposure required to get 100 neutrino background events. For heavier WIMPs, the potential of WIMPs in direct detection experiments due to the neutrino background events is 2,150 ton-years. Given these exposures were increased to obtain 500 neutrino events.

Combining better knowledge of the neutrino background, annual modulation, and/or large directional detection experiments. WIMP-nucleon cross sections of $10^{-45}$ to $10^{-47}$ cm$^2$ are shown not to be from WIMPs, the dominant neutrino components are labeled. Progress beyond this line would require very large exposures, lower systematic uncertainties, and/or large directional detection experiments.

Threshold & atomic mass

Detector size x time matter

COHERENT NEUTRINO SCATTERING

Atmospheric and DSNB Neutrinos

$^{7}\text{Be}$ Neutrinos

$^{8}\text{B}$ Neutrinos

The WIMP landscape

10^{-37} \quad 10^{-39} \quad 10^{-38} \quad 10^{-39} \quad 10^{-40} \quad 10^{-41} \quad 10^{-42} \quad 10^{-43} \quad 10^{-44} \quad 10^{-45} \quad 10^{-46} \quad 10^{-47} \quad 10^{-48} \quad 10^{-49} \quad 10^{-50}

WIMP–nucleon cross section [cm$^2$]

10^{-37} \quad 10^{-39} \quad 10^{-38} \quad 10^{-39} \quad 10^{-40} \quad 10^{-41} \quad 10^{-42} \quad 10^{-43} \quad 10^{-44} \quad 10^{-45} \quad 10^{-46} \quad 10^{-47} \quad 10^{-48} \quad 10^{-49} \quad 10^{-50}

WIMP Mass [GeV/c$^2$]

10^{-1} \quad 10^{-2} \quad 10^{-3} \quad 10^{-4} \quad 10^{-5} \quad 10^{-6} \quad 10^{-7} \quad 10^{-8} \quad 10^{-9} \quad 10^{-10} \quad 10^{-11} \quad 10^{-12} \quad 10^{-13} \quad 10^{-14}

WIMP–nucleon cross section [pb]
DAMA/Libra experiment

233 kg of pure NaI crystals readout by PMTs with a screen of concrete, polipropilene, Pb and Cu

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2σ C.L.
Direct evidence for dark matter particles? The DAMA signal seems incompatible with other experiments (Billard et al. 2013, Snowmass 2013, LUX 2013, CDMSlite 2015).

- Spin-independent interactions
- Standard halo model

DAMA signal

Gondolo, IDM 2016
DAMA Incompatible with Other Experiments

XENON100 Results: Spin-Dependent Interactions


World-best limit for neutron coupling:

\( \sigma_n < 3.0 \times 10^{-40} \text{ cm}^2 \) at 45 GeV/c

Aprile et al (XENON100) 2013

Spin-dependent interactions

Amole et al (PICO) 2015

ATLAS and CMS (WIMP production at the LHC)

IceCube and SuperK (high-energy neutrinos from the Sun)

Gondolo, IDM 2016
XENON100 excludes leptophilic models

- Dark matter particles interacting with $e^-$
  
  1. No evidence for a signal
  
  2. Exclude various leptophilic models as explanation for DAMA/LIBRA

Upcoming NaI Projects to directly test DAMA

**SABRE @ LNGS**
Sodium-iodine with Active Background REjection

*Strategy:*
- lower background: better crystals, PMTs
- liquid scintillator veto against $^{40}\text{K}$ (factor 10)
- lower threshold (PMTs directly coupled to NaI)
- Eliminate seasonal effects: North (LNGS) and South Hemisphere (Australia: Stawell Underground Physics Laboratory)

*Status:* tests with 2.5 kg crystal ongoing and the 5 kg crystal is growing

**Predecessors:**
- DM-Ice: 17 kg 2 Crystals of 8.5 kg NaI @ South Pole
- KIMS: 12 CsI crystals for 104.4 kg @ Y2L, Korea

**COSINE-100 (DM-Ice + KIMS) @Yangyang**

107 kg of NaI pure Crystal, LS veto and Pb shield - commissioning

**ANAIS @ Canfranc**
113 kg in Pb shield
→ start of data taking soon
→ background 2-3x DAMA (no veto)
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Expected Sensitivity for COSINE-100 in 5 y

COSINE-100 (DM-Ice + KIMS) @ Yangyang
110 kg of NaI pure Crystal, LS veto and Pb shield - commissioning
ANAIS @ Canfranc
113 kg in Pb shield
→ start of data taking soon
→ background 2-3x DAMA (no veto)
Cryogenic micro-calorimeter at $T \sim \text{mK}$

- Detect a temperature increase after a particle interacts in an absorber

\[ \Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}} \]
\[ \tau = \frac{C(T)}{G(T)} \]

For more details see L. Gastaldo talks on Friday-morning session
**EDELWEISS** - **SuperCDMS** - **CRESST**: the race for the low WIMP mass region

**SuperCDMS @ SNOLAB**
read phonons and charges from Ge and Si crystals
- aim for 50 kg-scale experiment (cryostat can accommodate 400 kg)
  - low threshold → focus on 1-10 GeV/c² mass range
- Improvements: deeper lab, better materials, better shield, improved resolution, upgraded electronics, active neutron veto?
- 100 x 33.3 mm ZIPs (1.4 kg Ge, 0.6 kg Si) → fabrication protocol established

2016-20: construction
2020: begin data taking

**EDELWEISS @ LSM**: arXiv:1603.05120
read phonons and charges from Ge crystals
2016: largest (20 kg) Ge array in operation
2017: 350 kg×d in HV mode to optimize 1-10 GeV sensitivity

Future: ton scale together with CDMS (EURECA)

**CRESST II @ LNGS**:  
read phonons and scintillation light from CaWO₄
successful background reduction;
data taking 2013-2015, 52 kg×d
2016: lowest thresh 300 eVnr
Record sensitivity below 1.7 GeV WIMP mass
Upcoming projects: CRESST-III

**Goal:** lower threshold to $100 \text{ eV}_{nr}$

→ smaller crystals of best background quality (250 g → 24 g)
→ all-scintillating detector design
  all material surrounding the detectors is scintillating → avoid partial energy depositions
→ improv

**Status:**
- Prototype already exceeds design goal: 50 eV$_{nr}$ threshold
- first 4 modules were mounted in February 2016
- cool-down soon
Upcoming projects: CRESST-III

Goal: lower threshold to 100 eV

- smaller crystals of best background quality (250 g → 24 g)
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  - avoid partial energy depositions
  - improve signal-to-noise

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● first 4 modules were mounted in February 2016
● cool-down soon

Phase 1
• 50 kg-days 1 year of running with 10 small modules

arXiv:1503.08065
The High Mass Region: noble liquid experiments continue to lead the race
Noble Liquid Detectors

- Detect either light only or simultaneously light and charge signals produced by a particle interaction in the sensitive liquid target
Noble Liquid Detector Concepts

Single Phase Detector

Dual Phase Detector

- PMT
- gas
- liquid target

pos HV

neg HV

E

Amplitude vs. Time

S1

Amplitude vs. Time

S1

S2
DEAP @ SNOLAB: DEAP-3600 - Ready for Physics Run!

- Single phase LAr, 3.6 tonne (1 tonne fiducial).
- Spherical ultra-pure acrylic vessel (AV).
- 255 HQ Hamamatsu PMTs, coupled via acrylic light guides.
- Foam and polyethylene provide further shielding.
- 3 um layer of wavelength shifter (TPB) converts 128 nm scintillation light into the visible range.
- AV enclosed inside Steel Shell, immersed in 403 m³ water tank with 45 veto PMTs.

L. Roszkowski et al., JHEP 1408 (2014) 067
DEAP @ SNOLAB: DEAP-3600 - Ready for Physics Run!

- Dual phase TPC with 46 kg 39Ar-depleted LAr (1400 background reduction factor) inside 30 tons LS neutron veto inside a 1000 tons water Cherenkov muon veto.
- 1st result from 2616 kg d with UAr -> no event in search region. Still taking data.
- Proposed DS20k under funding review. Large R&D effort on SiPMs and other technologies. Construction of the very large distillation facility (350 m column) placed inside a coal mine (Seruci, Sardinia) has started.
XMASS @ Kamioka: present and future

- XMASS -1: spherical Cu vessel with 830 kg LXe viewed by 642 PMTs (photocathode coverage >62%)
- 14 PE/keV but no possibility to reject NRs; position reconstruction/ self-shielding /water Cherenkov muon veto
- Still taking data - R&D on PSD - new dome-shaped PMT development for XMASS 1.5 (1000 PMTs)
- Sensitivity Goal: \( \sim 10^{-47} \text{ cm}^2 \) @ 50 GeV in 3-5 y
Dual Phase TPC Experiments: present and future
LXeTPCs: 50-500 kg scale

XENON100 @ LNGS
- 62 kg LXe,
- reached WIMP science goal
- inelastic DM, spin-dependent, modulation, axions, light WIMP, Bosonic Super WIMPs,..
- still running as test facility for XENON1T/nT

LUX @ SURF
NIM A 704, 111 (2013)
- latest result from 332 days presented at IDM2016
- 250 kg LXe
- published first limit in 2013
- in 2013 - best world limit
- reanalysis published in 2016
- will be removed by 2017

PandaX-II @ CJPL
arXiv:1602.06563
- at present largest LXe TPC
- still taking data
- new SS cryostat
  → lower radioactivity
- TPC: 60cm×60cm,
  500 kg target

New result from 98.7 days:
- Best upper limit:
  - $2.5 \times 10^{-46} \text{ cm}^2$ at 40 GeV
arXiv:1607.07400v1
LUX new result: awaiting paper

- Brazil bands show the 1- and 2-sigma range of expected sensitivities, based on random BG-only experiments.
- **Factor of 4 improvement** over the previous LUX result in the high WIMP masses
- Minimum exclusion of $2.2 \times 10^{-46} \text{ cm}^2$ at 50 GeV
From LUX to LZ @ SURF

- Scale LUX by 40 in Fiducial
- New detector with 7 ton active LXe
- Aimed at 5.6 ton FV with combination of active LXe and LS veto
- Use same water shield of LUX
- Extensive screening campaign and MC simulations

**Timeline:**
- 2017/18: prepare for surface / UG assembly at SURF
- 2019: start UG installation
- 2020: start operation by end of the year
- 2025+ : plan 5+ years of operation

**Sensitivity Goal (1000 live days):**

- $3 \times 10^{-48} \text{ cm}^2 \text{ at } 40 \text{ GeV}$
XENON10 
15 cm drift TPC - 25 kg 
$\sim 10^{-43}$ cm$^2$

XENON100 
30 cm drift TPC - 161 kg 
$\sim 10^{-45}$ cm$^2$

XENON1T/XENONnT 
100 cm drift TPC - 3500 kg/7000 kg 
$\sim 10^{-47}$ cm$^2$ / $10^{-48}$ cm$^2$
The XENON1T Experiment
The XENON1T Experiment
The XENON1T Experiment

- **Science goal**: 100 x more sensitive than XENON100
- **Target/Detector**: 3.5 ton of Xe/ dual-phase TPC with 250 high QE - low radioactivity PMTs.
- **Shielding**: water Cherenkov muon veto.
- **Cryogenic Plants**: Xe cooling/purification/distillation/storage systems designed to handle up to 10 ton of Xe. Upgrade to a larger detector (*XENONnT*) planned for 2018
- **Status**: All systems successfully tested. Commissioning of detector ongoing. First science run this Fall.
- **Sensitivity Goal**: $2 \times 10^{-47} \text{ cm}^2 \text{ @ 50 GeV in 2ty}$
The XENON1T experiment: inner detector

- 127 3” sensors top
- 121 3” sensors
- 1 ton fiducial
- 3 t total @180K

The TPC

TPC installation underground

PMT arrays
XENON1T Commissioning: TPC filled with LXe and now shielded by water!
XENON1T Commissioning
e-lifetime and TPC performance rapidly improving -
- Kr-distillation started- getting ready for WIMPs time!!

150 µs
Expected sensitivity of XENON1T and XENONnT
DarkSide @ LNGS: present and future

- Dual phase TPC with 46 kg 39Ar-depleted LAr (1400 background reduction factor) inside 30 tons LS neutron veto inside a 1000 tons water Cherenkov muon veto
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- Proposed DS20k. TDR in preparation. Large R&D effort on SiPMs and other technologies. Construction of the very large distillation facility (350 m column) placed inside a coal mine (Seruci, Sardinia) has started.

arXiv:1510.12345
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One additional technology which is quite unique: the Bubble Chamber
PICO Bubble Chambers @ SNOLAB

- Chamber filled with a superheated fluid in meta-stable state
- Detection principle: when particle deposits energy > Eth in radius < r0 a bubble expansion take place
- Acoustic Discrimination: alpha deposits energy over tens of microns; NRs deposit energy over tens of nanometer
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PICO 60 (now) and PICO 500 (future ~2018)

- the largest (36.8 kg target of CF3I) in operation (SNOLAB), made with radio pure synthetic quartz. Run I: world leading SD proton sensitivity for WIMP> 25GeV
- Anomalous background correlated with time of expansion has been identified as bubble nucleation on the vessel surface
- Run II of PICO 60: new 45 L target with lower threshold (C3F8); new water system, new vessel and geometry; new online filtration system; water shield filled in July; FIRST BUBBLE observed on Aug 1, 2016 (C. Krauss ICHEP 2016)

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Conclusions

Cold dark matter is a explanation for many cosmological & astrophysical observations

It could be made of WIMPs - thermal relics from an early phase of our Universe

So far, no convincing evidence of a dark matter particle was found

However, DAMA/LIBRA experiment is claiming an observation of an annual modulation since long time.

Excellent prospects for discovery and clarification

New experiments, based on NaI technology, are getting ready to run in view of clarifying once and for all the nature of the DAMA/LIBRA longstanding annual modulation. Better late than never.

Direct detection: increase in WIMP sensitivity by 2 orders of magnitude in the next few years

reach neutrino background (measure neutrino-nucleus coherent scattering!) this/next decade

high complementarity with indirect & LHC searches