Dark matter and other rare event searches with DARWIN

darwin-observatory.org

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(for the DARWIN Consortium)

UCLA Dark matter
Los Angeles, February 19, 2016
DARWIN General Goals

• Build a dark matter detector capable of exploring the experimentally accessible parameter space for WIMP dark matter

• Base this detector on a TPC filled with Xe in its liquid form, a concept successfully proven by the ZEPLIN, XENON, LUX and PandaX programs

• Reach a low energy threshold and an ultra-low background before ER/NR discrimination, and probe a variety of other physics channels
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On a discriminating liquid-xenon detector for SUSY dark-matter observation

David B. Cline
DARWIN Science Goals

• **Probe WIMP-nucleon interactions for WIMP masses above ~5 GeV/c²**
  - via spin-independent, spin-dependent and inelastic interactions
  - probe even lower WIMP masses by using the charge signal alone

• Look for signatures of DM scattering off electrons

• Detect solar neutrinos: pp-neutrinos via nu-e scattering, ⁸B coherent nu scattering

• Search for the neutrinoless double beta decay in $^{136}$Xe

• Probe interaction of axions and axion-like particles, via the axio-electric effect

• Probe sterile neutrinos with masses in the > 10 keV range

• Probe bosonic SuperWIMPs via their absorption by Xe atoms
DARWIN TPC baseline concept

- 50 t LXe in total
- 40 t LXe in the TPC
- \( \sim 10^3 \) photosensors
- 2.6 m drift length
- 2.6 m diameter TPC
- PTFE reflectors, Cu field shaping rings
- Background: dominated by neutrinos

Components

- Radioactivity:
  - \(^{238}\text{U}\) < 10 mBq/PMT
  - \(^{228}\text{Th}\) \(\ll\) 0.5 mBq/PMT
  - \(^{226}\text{Ra}\) \(\ll\) 0.6 mBq/PMT
  - \(^{235}\text{U}\) \(\ll\) 0.3 mBq/PMT
  - \(^{60}\text{Co}\) \(\ll\) 0.8 mBq/PMT
  - \(^{40}\text{K}\) \(\ll\) 12 mBq/PMT

- XENON collaboration, arxiv:1503.07698

- High QE: \(\ll\) 35\% at 175 nm for a low energy threshold
- 90\% collection efficiency

- Gain average: \(\times 10^6\)

- 3-inch PMT, R11410-21
- 4-inch PMT
Backgrounds: nuclear recoils

- **Radiogenic** goal: $\sim 4 \times 10^{-5}$ events/(t y) in 30 t fiducial
  - active LS veto around cryostat under study
- **Cosmogenic** (MC: $7.3 \times 10^{-10}$ n/(cm$^2$ s) for $E_n > 10$ MeV)
  - <0.01 events/(t y) in XENON1T/nT shield
  - <<0.003 events/(t y) in 14 m diameter water shield
- **XENON1T muon veto performance must be improved by ~ a factor of 10** (conservative)
- Alternative: line the experimental hall with muon veto - possibility under study via MC

DARWIN in 14 m ø water Cherenkov shield

MC simulation for XENON1T
Backgrounds: electronic recoils

- Materials (cryostat, photosensors, TPC)
- $^{222}$Rn in LXe
- $^{85}$Kr in LXe ($^{nat}$Kr contains $2 \times 10^{-11}$ $^{85}$Kr)
- $^{136}$Xe double beta decay
- Solar neutrinos (mostly pp, $^{7}$Be)

Materials: strong self-shielding by dense LXe

<table>
<thead>
<tr>
<th>Channel</th>
<th>Before discr</th>
<th>After discr (99.98%)</th>
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<tbody>
<tr>
<td>$pp + ^{7}$Be neutrinos</td>
<td>95</td>
<td>0.488</td>
</tr>
<tr>
<td>Materials</td>
<td>1.4</td>
<td>0.007</td>
</tr>
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<td>$^{85}$Kr in LXe ($^{nat}$Kr)</td>
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<td>9.9</td>
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<td>$^{136}$Xe</td>
<td>56.1</td>
<td>0.036</td>
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1 t x yr exposure, 2-30 keVee
200 t x yr exposure, 4-50 keVnr, 30% acceptance
Backgrounds: electronic recoils

- Materials (cryostat, photosensors, TPC)
- $^{222}$Rn in LXe
- $^{nat}$Kr in LXe ($^{nat}$Kr contains $2 \times 10^{-11}$ $^{85}$Kr)
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WIMP physics with xenon nuclei

Probe WIMP-Xe interactions via:

- spin-independent elastic scattering: $^{124}$Xe, $^{126}$Xe, $^{128}$Xe, $^{129}$Xe, $^{130}$Xe, $^{131}$Xe, $^{132}$Xe (26.9%), $^{134}$Xe (10.4%), $^{136}$Xe (8.9%)
- spin-dependent elastic scattering: $^{129}$Xe (26.4%), $^{131}$Xe (21.2%)
- inelastic WIMP-$^{129}$Xe and WIMP-$^{131}$Xe scatters

\[ \chi + ^{129,131}\text{Xe} \rightarrow \chi + ^{129,131}\text{Xe}^* \rightarrow \chi + ^{129,131}\text{Xe} + \gamma \]

1 ns, 0.5 ns

40 keV, 80 keV

SI, elastic WIMP-nucleus
SD, elastic WIMP-nucleus
SD, inelastic WIMP-nucleus

M. Schumann et al., JCAP10 (2015) 016
WIMP physics: spectroscopy

- Capability to reconstruct the WIMP mass and cross section for various masses - here 20, 100, 500 GeV/c\(^2\) - and cross sections

Exposure: 200 t y

1 and 2 sigma credible regions after marginalising the posterior probability distribution over:

\[ v_{esc} = 544 \pm 40 \text{ km/s} \]
\[ v_0 = 220 \pm 20 \text{ km/s} \]
\[ \rho_X = 0.3 \pm 0.1 \text{ GeV/cm}^3 \]

Update: Newstead et al., PRD D 88, 076011 (2013)
WIMP physics: sensitivity for SI scattering

- $E = [3-70] \text{ pe} \sim [4-50] \text{ keV}_{nr}$

200 t y exposure, 99.98% discrimination, 30% NR acceptance, $LY = 8 \text{ pe/keV}$ at 122 keV

Note: “nu floor” = 3-sigma detection line at 500 CNNS events above 4 keV
**WIMP physics: complementarity with the LHC**

- Minimal simplified DM model with only 4 variables: $m_{DM}$, $M_{med}$, $g_{DM}$, $g_q$
- Here DM = Dirac fermion interacting with a vector or axial-vector mediator; equal-strength coupling to all active quark flavours

$$\sigma_{DD} \propto \frac{g_{DM}^2 g_q^2 \mu^2}{M_{med}^4}$$

![Spin independent vs Spin dependent](image)
Technical challenge: discrimination

- A level of 99.98% needs factor of 5 improvement w.r.t. XENON100
  - high light yield - R&D for high (4-pi) coverage with photosensors is ongoing; options are high QE PMTs, SiPMs and/or GPMs; single-phase TPC also under study
  - strong R&D program in place
  - high stats ER band calibrations - internal sources, for instance tritiated methane à la LUX; also $^{220}$Rn as in XENON1T

LUX Tritium calibration using CH$_3$T (inert)
Technical challenge: HV & drift field

- Electron drift length of 2.6 m, high purity, and uniform field at the 1% level
- HV to bias the cathode must be -130 to -260 kV to have a drift field of 0.5 - 1 kV/cm
  - build long (2.6 m) TPC demonstrator(s)
- Robust, and transparent grid or wire electrodes with 2.6 m diameter
- Challenge is to combine thin wires O(100 µm) to ensure high LCE
  - build shallow (2.6 m ø) TPC demonstrator(s)
- Very precise, 3D field simulations based on the BEM technique
Technical challenge: liquid target

- Procurement, storage, cooling, high-speed purification of ~50 t of LXe
  - coordinate procurement among institutions, funding agencies and companies
- Storage: à la ReStoX, developed for XENON1T/nT, acts as a demonstrator
  - possible solution: a network of 7 interconnected ReStoX units, with a main storage directly connected to the cryostat
  - study a different mechanism for recovery, based on gravity (recuperation pipe below cryostat)

ReStoX: can store up to 7.6 t of xenon
Max heat leak: ~50 W
Technical challenge: backgrounds

- ER dominance by solar neutrinos needs:
  - low intrinsic levels of $^{85}$Kr and $^{222}$Rn
- $^{85}$Kr: 0.1 ppt $^{\text{nat}}$Kr (0.2 ppt $^{\text{nat}}$Kr => same background level as solar neutrinos)
  - 0.2 ppt is goal for XENON1T, factor 20 better than this already achieved by Münster group*:
    separation factor > 120000
- $^{222}$Rn: 0.1 µBq/kg (1 µBq/kg => same background level as solar neutrinos)
  - 10 µBq/kg is goal for XENON1T: control Rn levels with low-emanation materials & cryogenic distillation (use different vapour pressure), adsorption

*M. Murra, Münster: $^{\text{nat}}$Kr/Xe < 26e-15 = 26 ppq (90% CL); measured with MPIK RGMS system
Physics reach: solar neutrinos

\[ \nu + e^- \rightarrow \nu + e^- \]

- Rate of solar neutrinos > 2 keV
  \[ R_{pp} \approx 1.05 \text{ events/(t d)} \]
  \[ R_{7Be} \approx 0.51 \text{ events/(t d)} \]
- pp neutrinos (2-30 keV):
  - 2571 events/(30 t y)
- \(^7\)Be neutrinos (2-30 keV):
  - 321 events/(30 t y)
- \(^{220}\)Rn: 0.1 µBq/kg; \(^{nat}\)Kr: 0.1 ppt
- Reach ~ 1% precision after 3 years
Physics reach: double beta decay

- $^{136}\text{Xe}$: Q-value = 2458.7 ± 0.6 keV
- Fiducial mass 6 t $^{\text{nat}}\text{Xe}$
  - Sensitivity to 0nbb-decay of $^{136}\text{Xe}$:
    - $T_{1/2} > 5.6 \times 10^{26}$ yr (95% CL) in 30 t y
    - $T_{1/2} > 8.5 \times 10^{27}$ yr (95% CL) in 140 t y
- Assumptions:
  - $^{222}\text{Rn}$: 0.1 µBq/kg (~ 0.036 events/(t y))
  - ($^8\text{B}$ rate is ~ 0.036 events/(t y))
  - $\sigma/E = 1\%$ at Q-value
Physics reach: coherent neutrino scatters

- **Neutrino sources:**
  - $^8$B solar neutrinos
  - DSNB
  - Atmospheric neutrinos

- **Expected rates:**
  - 90 events/(t y) above 1 keVnr
  - $1.8 \times 10^{-2}$ events/(t y) above 4 keVnr

With an energy threshold of $\sim$1 keVnr, DARWIN would detect about 3000 CNNS events per year.
Physics reach: heavy sterile neutrinos

- Explore physics scenarios in which \( \nu \rightarrow e^- \) interactions are enhanced due to BSM processes:
  - new interactions between neutrinos and e\(^-\) mediated by a very light or massless particle (these would dominate the SM rates at low energies relevant for DD)
  - A: nu with magnetic moment of \( 0.32 \times 10^{-10} \mu^B \)
  - B, C, D: A’-mediated \( \nu \rightarrow e^- \) scattering (sterile neutrinos heavier than \(~ 10\) keV)
    - A’ is a new light gauge boson (“dark photon”) that has a small kinetic mixing with the photon

Harnik, Kopp, Machado, JCAP 07 (2012) 026
Possible location at LNGS

- Minimum water tank dimensions: 14 m diameter
- Space in Hall B (former ICARUS location)
- Or space in Hall C (Borexino shield or other), or Hall A
Estimated DARWIN timescale

2010 - 2013
First R&D phase, Aspera funded
June 2013: Aspera final report

2014 - 2019
R&D and design study
2018: CDR/TDR

2019 - 2021
Engineering studies
2019-20: demonstrators at home institutions
2021: construction/integration at LNGS

2022 - 2032
Construction, commissioning, science run
2022: construction/integration at LNGS
2023: commissioning
2024: physics runs start
The DARWIN Consortium

23 groups from 9 countries
12th Patras Workshop on Axions, WIMPs and WISPs

20-24 June 2016
Jeju Island, South Korea

Scientific Programme
- The physics case for WIMPs, Axions, WISPs
- Direct and indirect searches for
- Dark Matter and Dark Energy
- Direct and indirect searches for Axions, WISPs
- Signals from astrophysical sources
- Review of collider experiments
- New theoretical developments

Organizing committee:
Yannis K. Semertzidis (Chair, CAPP/IBS & KAIST), Vassilis Anastassopoulos (University of Patras), Laura Baudis (University of Zurich), Joerg Jaeckel (University of Heidelberg), Axel Lindner (DESY), Andreas Ringwald (DESY), Marc Schumann (AEC Bern), Konstantin Zioutas (University of Patras & CERN)

Local organizing committee:
Yannis K. Semertzidis (Chair), Dominika Konikowska (Contact person), Woohyun Chung, Yooji Jiang, SooKyoung Jung, Young-im Kim, ByungRok Ko, Soohyung Lee, Yujung Lee, Ka Young Oh, Eleni Petrakou, SungWoo Youn

Contact: capp@ibs.re.kr

http://axion-wimp.desy.de

Important dates:
04 April 2016 Deadline for abstract submission
20 April 2016 Announcement for decisions on submitted contributions
25 April 2016 Deadline for early registration
20 May 2016 Deadline for late registration

Sponsors: AEC Bern, CERN, DESY, European Research Council, Institute for Basic Science of South Korea (IBS), KAIST, U. Patras, U. Zaragoza, U. Zurich
End
The DARWIN Consortium

23 groups from 9 countries
Physics reach: bosonic SuperWIMPs

• Bosonic, light, super weakly interacting cold dark matter (mass in the 10-100 keV range)

• Scattering cross section is many orders of magnitude below the weak-scale cross section, but such particles could be absorbed in LXe and produce a detectable signal

• Signature: a line at the rest mass of the boson

\[
\sigma_{\text{abs}} \nu \approx \sigma_{\text{photo}} (\omega = m_a) c \approx \frac{3 m_a^2}{4 \pi \alpha f_a^2}
\]

\[
R \approx \frac{1.2 \times 10^{19}}{A} g_{\text{ee}}^2 \frac{m_a}{\text{keV}} \frac{\sigma_{\text{photo}}}{b} \frac{\text{kg}^{-1}}{\text{d}^{-1}}
\]

\[
g_{\text{ee}} = \frac{2 m_e}{f_a}
\]

\[
R \approx \frac{4 \times 10^{23}}{A} \frac{\alpha}{\alpha'} \frac{\text{keV}}{m_V} \frac{\sigma_{\text{photo}}}{b} \frac{\text{kg}^{-1}}{\text{d}^{-1}}
\]

M. Pospelov, A. Ritz, M. Voloshin, PRD 78, 2008
Physics reach: solar axions

Look for solar axions via their couplings to electrons, $g_{Ae}$, through the axio-electric effect

$$\sigma_{Ae} = \sigma_{pe}(E_A) \frac{g_{Ae}^2}{\beta_A} \frac{3E_A^2}{16\pi\alpha_{em}m_e^2} \left(1 - \frac{\beta_A^{2/3}}{3}\right)$$

$$\phi_A \propto g_{Ae}^2 \implies R \propto g_{Ae}^4$$

- XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs
- **Factor of ~10 improvement with DARWIN**

---

$E_{\text{kin}} = 200$ keV, $m_A < 1$ keV/c$^2$

$g_{Ae} = 2 \times 10^{-11}$

$\sigma_{pe}$ (Events/PE)

$\phi_A \propto g_{Ae}^2 \implies R \propto g_{Ae}^4$

- DFSZ
- KSVZ
- XMASS
- EDELWEISS
- Si(Li)
- XMASS
- EDELWEISS
- XMASS
- EDELWEISS
- Si(Li)

XENON, Phys. Rev. D 90, 062009 (2014)
Physics reach: galactic axion-like particles (ALPs)

Look for ALPs via their couplings to electrons, $g_{Ae}$, through the axio-electric effect

Expect line feature at ALP mass

assume $\rho_{dm} = 0.3$ GeV/cm$^3$

$$\phi_A = c\beta_A \times \frac{\rho_{dm}}{m_A}$$

$$R \propto g_{Ae}^2$$

• XEON100: based on 224.6 live days x 34 kg exposure; using the electronic-recoil spectrum, and measured light yield for low-energy ERs

• Factor of $\sim 100$ improvement with DARWIN
Physics reach: low WIMP masses

- Achieve a lower energy threshold for NRs if the energy is measured by the S2 signal ($e^-$), with ~ 20-25 PE per extracted $e^-$ in the gas phase.

- **XENON10**: threshold of $E_{nr} \sim 1$ keV reached.

- **XENON100**: analysis ongoing.

- Loss of S2/S1 discrimination: sensitivity reduction by ~ factor 100, compared to higher WIMP masses; acceptable because at low WIMP masses the solar neutrinos will dominate the NR rate.

- **LUX (APS2015)**: ionization signal absolutely measured below 1 keVnr.
Technical challenge: discrimination

• **Best value in LXe by ZEPLIN-III, 99.987%**

• **LUX: 99.9% - 99% (at 50% NR acceptance)**

• **K. Ni: ER power > 10^5 at 50% acceptance**

  • weak dependance on field strength, but field uniformity crucial

<table>
<thead>
<tr>
<th></th>
<th>Field (kV/cm)</th>
<th>Light yield (pe/keVee, for 122 keV at zero field)</th>
<th>Energy ROI (keVnr)</th>
<th>NR acceptance</th>
<th>ER rejection power</th>
</tr>
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<tr>
<td>ZEPLIN-II</td>
<td>1.0</td>
<td>1.1</td>
<td>14-58</td>
<td>50%</td>
<td>98.5%</td>
</tr>
<tr>
<td>XENON10</td>
<td>0.73</td>
<td>5.4</td>
<td>4.5~26.9</td>
<td>45%~49%</td>
<td>99.9~99.3%</td>
</tr>
<tr>
<td>ZEPLIN-III</td>
<td>3.4</td>
<td>3.1-4.2</td>
<td>7-35</td>
<td>~50%</td>
<td>99.987%</td>
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<td>XENON100</td>
<td>0.53</td>
<td>3.8</td>
<td>6.6-43.3</td>
<td>60%~20%</td>
<td>99.75%</td>
</tr>
<tr>
<td>LUX</td>
<td>0.18</td>
<td>8.8</td>
<td>3-27</td>
<td>50%</td>
<td>99.9~99%</td>
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Energy resolution

S1 resolution of 5 keVnr versus light yield

S2 resolution of 5 keVnr versus e-lifetime
ER backgrounds: XENON1T/nT & DARWIN-LXe

• ER background before discrimination, in [2-12] keVee

• XENON1T: ~ 128 events/(t y)
  • materials + 0.2 ppt Kr + 1µBq/kg Rn + solar nu + 2nbb

• XENONnT: ~ 109 events/(t y)
  • 0.2 ppt Kr + 1µBq/kg Rn + solar nu + 2nbb

• DARWIN: ~ 35 events/(t y)
  • 0.1 ppt Kr + 0.1µBq/kg Rn
  • solar neutrino dominated
Technical challenges: light yield

MC simulation for a 2 m tall and 2 m diameter LXe TPC with XENON1T grids

Light yield for 122 keV, E = 0

PDE = photon detection efficiency
(for photons hitting the GPM window)

- PTFE reflectivity = 95%
- Rayleigh scattering length = 30 cm
- XENON1T PMTs and meshes
- 90% transparent field cage