DARWIN: Towards the ultimate Dark Matter Detector

Manfred Lindner

on behalf of the Collaboration
**DARWIN = XENON + more groups**

The XENON program at Gran Sasso, Italy (3600 mwe)

<table>
<thead>
<tr>
<th>XENON10</th>
<th>XENON100</th>
<th>XENON1T &amp; XENONnT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total mass</strong></td>
<td>25 kg</td>
<td>161 kg</td>
</tr>
<tr>
<td><strong>Drift length</strong></td>
<td>15 cm</td>
<td>30 cm</td>
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<tr>
<td>$\sigma_{SI}$ limit (@50 GeV/c^2)</td>
<td>$8.8 \times 10^{-44}$ cm^2</td>
<td>$1.1 \times 10^{-45}$ cm^2</td>
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**See talks by:** E. Aprile, K. Ni, L. Grandi

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See talks by: E. Aprile, K. Ni, L. Grandi

XENONnT being prepared while XENON1T runs switching gears
Scaling Considerations

direct light signal → S1 drift of electrons → S2
→ excellent 3D position → fiducialization
→ cut backgrounds from ‘dirty’ surfaces

- S2/S1: ER > NR; pulse height & shape, ...

Nuclear Recoil
\[ \chi / n \]

Electronic Recoil
\[ \gamma / \beta \]

- technological challenges
  - longer drift length → increased HV
  - handling more Xe gas
    → cryogenics, distillation, safety
  - engineering
    - ...

ultra low backgrounds
- underground laboratory
- adequate \( \mu \)-veto, n-shielding
- extremely radio-pure materials
- Rn emanation, outgassing
- very clean Xe gas
  * Kr & Rn reduction & analytics
  * electron life-time
- MC simulations
Two main questions:
1) can a bigger version be realized in principle?
   ➔ phased program with reasonable technology steps
2) is it worth the effort?
   ➔ important connections & consider the risks
The Challenges towards DARWIN

Technology: Bigger...
- Longer drift length $\leftrightarrow$ HV
- Diameter $\leftrightarrow$ TPC electrodes
- Increased mass $\leftrightarrow$ cryogenics, LXe purification, safe storage
- Detector response $\leftrightarrow$ calibration & required corrections
- More or bigger photo-sensors $\leftrightarrow$ LY, QE, long term stability

Low Background: Sufficient S/B...
- Cosmogenic backgrounds $\rightarrow$ go deep enough, add $\mu$-veto, n-veto
- Fiducialization $\leftrightarrow$
- Detector materials
  - radio-pure detector components, surfaces, $\gamma$‘s, neutrons from ($\alpha$,n)
  - clean cryo-liquid $\leftrightarrow$ e-driftlength, avoid $^{222}$Rn, $^{85}$Kr, ...
  - techniques to select clean materials ($\gamma$ and Rn screening)
  - techniques to monitor LXe purity at required level
- Active background suppression $\leftrightarrow$ distillation
- The neutrino floor... and $2\nu\beta\beta$

Often mixed requirements: E.g. PMTs, Rn reduction, ...
Pushing the Sensitivity

assumptions are easy
➔ must demonstrate low background

DARWIN

baseline …?
+ cost
+ personnel

XENON1T

XENONnT

reached, Jan 2017

Baseline
1 µBq/kg $^{222}\text{Rn}$
0.02 ppt of $^{87}\text{Kr}/\text{Xe}$

Calendar Year

• γ screening facilities of XENON:
  • Several screening stations
    @MPIK underground lab (1mBq/kg)
  • GEMSE @Freiburg (100 µBq/kg)
  • UZH: GATOR @LNGS (100µBq/kg)
  • GIOVE @MPIK @15mwe
    (\(^{226}\)Ra: 70µBq/kg, \(^{228}\)Ra: 110µBq/kg, \(^{228}\)Th 50µBq/kg)
  • MPIK-GEMPIs @LNGS (10µBq/kg)

→ very powerful
γ screening capabilities
(capacity, sensitivity)
of XENON + others

→ + ICPMS, …
Example: Radio-pure PMTs for XENON1T

Hamamatsu
R11410-21
3”, 248 pcs

- careful material selection,
- screening of materials
- screening of final PMTs
< 1mBq/PMT in U/Th

Intensive cooperation:
- improvements & optimization
- radio-purity

- extensive testing at room temperature and cold
high QE: 35% @ 175nm
stability, tightness,…
30% single PE resolution

JINST 12 P01024 (2017)

⇌ electronic recoil BG from materials

JCAP 04 (2016) 027
unstable $^{85}\text{Kr}$ in air $\rightarrow$ impurity in Xenon gas
- active removal by distillation
- control by precise measurements

Kr measurements:
- with gas chromatography
- Rare Gas Mass Spectroscopy (RGMS @MPIK)
  $\rightarrow$ measure $^{nat}\text{Kr}$ to ppt level
  $\rightarrow$ extrapolate: $^{85}\text{Kr}$ from atmospheric abundance
  $\rightarrow$ RGMS down to ppq level

- $^{84}\text{Kr}$ measurement with atomic trap (ATTA @ Columbia U)
  $\rightarrow$ measurement of $^{84}\text{Kr}$ to ppt level
  $\rightarrow$ extrapolate: $^{85}\text{Kr}$ from atmospheric abundance
  $\rightarrow$ atom trap operational and efficient for Ar*
Krypton Removal by cryogenic Distillation

- commercial Xenon contains 1 ppm – 10 ppb of Kr
- $^{85}\text{Kr}$ is unstable

- goal: reduce Kr to sub ppt
- XENON100 achieved (19 ± 1) ppt

XENON1T distillation column (Münster):
- through-put up to 6.5 kg/hr
- separation factor > 6.4 $10^5$
- final Kr/Xe < 1 ppt
- capable to obtain an output concentration < 48 ppq


- also operated for Rn removal
- already factor 2 below the 100ppq goal of DARWIN
Radon screening facilities of XENON:

$^{222}$Rn emanation technique
- based on MPIK gas counting systems
- few atoms/probe
- large samples $\leftrightarrow$ absolute sensitivity
- some established numbers:
  - Nylon (Borexino) < 1$\mu$Bq/m$^2$
  - Copper (Gerda): 2$\mu$Bq/m$^2$
  - Stainless steel (Borexino): 5$\mu$Bq/m$^2$
  - Titanium: $(100 \pm 30)$ $\mu$Bq/m$^2$

Auto-Ema: New automatized Rn screening facility @MPIK $\Rightarrow$ many samples

$\Rightarrow$ Thousands of past and new $\gamma$ and Rn screening results in a materials data base @MPIK

$\Rightarrow$ In addition: cleanliness procedures (production, treatment, dust, storage, …)
Rn removal by cryogenic Distillation


- $^{nat}$Kr/Xe < 360 ± 60 ppq
- $^{222}$Rn 10 µBq/kg target concentration
- lowest background level of all LXe exps.
- DARWIN goal for $^{222}$Rn: 0.1 µBq/kg ➔ another factor 100

XENON1T Rn budget well understood

- Kr level measured precisely by RGMS
- DARWIN goal for $^{222}$Rn: 0.1 µBq/kg ➔ another factor 100
DARWIN Conceptual Design

- **Baseline:** 50t LXe
- **40t LXe TPC, aim at 200 t*yr**
- **TPC dimension 2.6m x 2.6m**
- ~1800 * 3” PMTs (or ~1000 4” PMTs)
- **Low-background cryostat**
- **PTFE reflector panels**
- **Copper E-field shaping rings**
- **Water Cherenkov shield (~14m diameter)**
- **Liquid scintillator neutron veto under study**
- **Possible location LNGS**
- **aim at sensitivity of a few 10^{−49} cm^2, limited by irreducible ν-backgrounds**
- **R&D and initial design now**
- **Timescale: after XENONnT**
- **Cost effective:**
  - use existing Xe gas; buy more & re-sell
  - no enrichment (also faster)

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[www.darwin-observatory.org](http://www.darwin-observatory.org)
The DARWIN Collaboration

France:
- Subatech
- LAL
- LPNHE

Germany:
- University of Münster
- MPIK, Heidelberg
- University of Freiburg
- KIT, Karlsruhe
- University of Mainz
- TU Dresden
- Heidelberg University

Great Britain:
- Imperial College London

Italy:
- INFN, Sezione LNGS
- INFN, Sezione di Bologna

Israel:
- Weizmann Institute of Science

The Netherlands:
- Nikhef, Amsterdam

Portugal:
- University of Coimbra

Sweden:
- Stockholm University

Switzerland:
- University of Zürich

USA:
- Columbia University
- UCLA
- Arizona State University
- Purdue University
- Rice University
- UCSD
- University of Chicago
- Rensselaer Polytechnic Institute

Abu Dhabi:
- New York University Abu Dhabi

- seed funding
- 2 approved ERC grants
- ExIn application
Spin Independent (SI) WIMP Interaction

tests much of the generic WIMP space of models

- a declining WIMP case w/o discovery?
- solar neutrino signal & CNNS: 200 t*yr
Neutrino Physics with DARWIN

- Coherent Neutrino-Nucleus Scattering (CNNS)
  200 t\*yr → ca. 200 (25) events for > 3 (4) keV_{NR}

- Low energy solar neutrino signal: pp, \(^7\)Be
  ~1% statistical uncertainty for 100 t\*yr → solar models & \(\nu\) properties

real-time measurement of the solar neutrino flux:
→ 7.2 events/day from pp
→ 0.9 events/day from \(^7\)Be

- Supernova neutrinos:
  → 5\(\sigma\) sensitivity for a 27M\(\odot\) SN progenitor at 10 kpc (~700 events)
  → flavor-insensitive neutrino energy measurement

JCAP 01, 044 (2014)
Axions and ALPS

- measurement via axio-electric effect (ER channel)
- expect mono-energetic peak at the particle mass
- moderate sensitivity to axions (weak dependence of the coupling on the exposure: $g_{Ae}^{\text{sol}} \propto (MT)^{-1/8}$)
- sensitivity to ALPs two orders of magnitude better than current limits
- dominant backgrounds: solar neutrinos and $2\nu\beta\beta$ of $^{136}\text{Xe}$
0νββ with $^{136}$Xe

8.9% natural abundance

$\Rightarrow$ 3.5 t $^{136}$Xe in 40t without enrichment!

$Q_{\beta\beta} = (2458.7 \pm 0.6)$ keV

Assume:
- 6t fiducial
- energy resolution at $Q_{\beta\beta} \sim 1%$

$\begin{align*}
8.9\% \text{ natural abundance} \\
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\end{align*}$

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Assume:
- 6t fiducial
- energy resolution at $Q_{\beta\beta} \sim 1%$

Sensitivity @ 95% CL:
- 30 t*yr $\Rightarrow T_{1/2} > 5.6 \times 10^{26}$ yr
- 140 t*yr $\Rightarrow T_{1/2} > 8.5 \times 10^{27}$ yr

**IMPORTANT:** DARWIN might become a powerful, cost effective and time-wise competitive 0νββ experiment (no enrichment!)
Conclusions

Fast upgrade of XENON1T to XENONnT (mostly existing infrastructure)

- end of 2018

- low-background technology at the next level seems feasible
- all other required technological improvements should be possible

- detector scaling to the projected limits
- exciting prospects for DARWIN:
  - ‘ultimate’ discovery machine for WIMPs
  - added value: new physics topics
    - solar neutrinos
    - supernova neutrinos
    - coherent neutrino scattering
    - axions & ALPs
    - double beta decay: $0_{\text{nbb}}$