Direct Detection of Dark Matter and XENONnT

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Overview

- What is Dark Matter (DM)?
- What is DM Direct Detection?
- How to directly detect DM?
- The XENON way of detecting DM
- Upgrading XENON1T to XENONnT
- Beyond XENONnT: Completing the XMASS physics program
Dark Matter is what:
- holds galaxy clusters together
- holds galaxies together
- shaped the Universe: BAO
- bred the fuel for stars: BBN
- explains the CMB measurements
- keeps theorists puzzled
- keeps experimentalists busy: LHC, (in-)direct detection
What we know:

**Dark Matter (DM) gravitates**, and is:

- long lived: still around, since the Big Bang
- neutral: dark
- collisionless: bullet cluster
- non-relativistic: heavy and cold (freeze out)
  - light and axionic (misalignment)

What we hope for:

... that it also *interacts* with OUR baryonic world in some way 
OTHER than gravitationally ...

If – and only if – it does can we *maybe* “see” or even probe Dark Matter.
Theoretical “”””Guidance?

What to do depends on who you ask, who your “favorite” theorist is 😞😞😞
How to look for dark matter:

- **Collider search**: Check LHC data for new particles that fit the bill.

- **Direct detection**: Build background-free detectors and publish every event.

- **Indirect detection**: Find SM particle excesses from DM aggregations.

- **Self-interaction**: DM particles interacting with themselves?
DM Direct Detection Signals?

Most persistent: DAMA/Libra annual modulation (1805.10486: 12.9σ)

Notes:
- CoGeNT now <2σ
- CDMS-Si 3σ, but:
  - not observed in Ge
- DAMA/Libra:
  - tension with others!

worldwide NaI(Tl) verification efforts:
- ANAIS (Canfranc, Spain)
- Cosine (Yangyang, Korea)
- DM-Ice (Antarctica)
- Sabre (LNGS, Italy)

graphic from: 1209.3339
Direct Detection Technologies

ionization (electrons)

DRIFT, DM-TPC, DAMIC
PICO, MIMAC, NEWAGE
CoGeNT

CDMS EDELWEISS

XENON LUX/LZ
PandaX DarkSide
ArDM

DAMA/Libra
XMASS DEAP
COSINE ANAIS
Sabre

scintillation (photons)

heat (phonons)

CRESST

COUPP PICASSO

superheated fluids (bubbles)
Why (Liquid) Xenon?

- high mass number
- no long-lived radioactive isotope
- high density (liquid): 3g/cm³
- 48% odd isotopes (natural)
- ββ candidate
- good scintillation yield

→ high SI cross section
→ no intrinsic background
→ self-shielding
→ SD cross section

$^{136}$Xe $\rightarrow$ $^{136}$Ba + 2e⁻ + 2.48MeV
~ 46ph/keV

SI cross-section:

$\sigma_0 = A^2 \frac{\mu_I^2}{\mu_P^2} \sigma_{\chi-p}$
The XENON Collaboration

@LNGS: April 2019 Technical Meeting

155 scientists from 27 institutions
The next step in the **XENON program**: dual phase liquid xenon detectors for

- the discovery of dark matter particle interactions
- a precision measurement of pp-solar neutrinos
- the observation of SN explosions through coherent scattering
- the search for double beta decay ($^{136}$Xe)

→ the goals are the same as they were for single phase XMASS!

**XENON timeline**: (3rd line: total Xe / length of drift)

<table>
<thead>
<tr>
<th>XENON10</th>
<th>XENON100</th>
<th>XENON1T</th>
<th>XENONnT</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 kg / 15 cm</td>
<td>161 kg / 30 cm</td>
<td>3.2 t / 100 cm</td>
<td>8 t / 150 cm</td>
</tr>
<tr>
<td>$10^{-43}$ cm$^2$</td>
<td>$10^{-45}$ cm$^2$</td>
<td>$4*10^{-47}$ cm$^2$</td>
<td>$2*10^{-48}$ cm$^2$</td>
</tr>
</tbody>
</table>
Dual Phase TPC Advantages

- discriminates nuclear/electron recoil $\geq 5$ keV
- better fiducialization:
- S2 amplification $\rightarrow$ low threshold
Background is the **Enemy!**

XENON1T matched BG spectrum at low energies:

\[ ^{222}\text{Rn} \rightarrow ^{214}\text{Pb} \]

**... and is retreating, but not beaten.**

Low-energy ER background

[ events / (tonne keV day) ]
pictures above of XENON1T: → proven infrastructure in place → upgrade !!!

some guy crouching
Hall B: XENON1T → XENONnT

XENON1T:
(current holder of heavy WIMP world bragging rights)

infrastructure and sub-systems proven in action !!! 
→ ready, upgrade, go...

the upgrades are underway:
- larger, cleaner TPC
- Xe liquid phase purification
- continuous Rn distillation
- add a neutron veto

(underlined: w/Kamioka expertise)
TPC & Cryostat

- **2.0 → 5.9 tonne active LXe volume**
  \[ \varnothing 133 \text{ cm}, 148 \text{ cm drift} \]

- **494 PMTs** (3” Hamamatsu R11410-21)
  \[ 127 \rightarrow 253 \text{ in gas}, 121 \rightarrow 241 \text{ in liquid} \]

- **200 V/cm drift field** (design)

**挑战：**
- no charge-up
- metal

**场形变：**
- 双重场形变阵列
- 金属

**场配置：**
- 实验 + 模拟
- PTFE: 场形变
- Cu 线后方：场形变
- 避免电荷累积

**质量验证：**
- TPC 电极上的线验证
New: Liquid Phase Purification

**electronegative contaminants:**
- limit the electron lifetime $\rightarrow$ limit S2 for long drift
- continually re-supplied from detector materials...
  $\rightarrow$ *need to be removed continually!*

XENON up to 1T, XMASS, ... so far all used *hot* zirconium getters
$\rightarrow$ gas phase: too slow

**liquid purification:** (installed at XENONnT)

we have an 80% – 90% efficient Cu adsorbant
Continuous Rn Distillation

Rn sources in XENON1T:

- TPC (4.8 ± 2.2) mBq: 13.6%
- Inner vessel (2.0 ± 0.3) mBq: 5.6%
- Getters (1.5 ± 0.1) mBq: 4.2%
- 250 mm cryogenic pipe (9.2 ± 1.0) mBq: 26.0%
- 100 mm pipe + cables (2.7 ± 0.2) mBq: 7.6%
- Porcupine (1.9 ± 0.2) mBq: 5.4%
- Cryogenic system (2.4 ± 0.3) mBq: 6.8%

1st done in Xe100:

Type 2 sources of gas system:
- Pump 1, auxiliary emanation source + $k_2$

Qdrive pumps (10.9 ± 1.7) mBq replaced !!!

all a part of liquid purification

new XnT distillation column target: 1 µBq/kg

214Pb: low energy β-decay in 222Rn decay chain
→ BG in WIMP search region

Rn sources in XENON1T:

- 214Pb: low energy β-decay in 222Rn decay chain
- BG in WIMP search region

$\frac{F_{e^-}}{N(t)} \cdot k_1$
XnT Neutron Veto: à la Japonaise

put Gd into SK to tag antineutrinos:

Mark Vagins (K-IPMU) & John Beacom (Ohio)
PRL 93 (2004) 171101 (sketch by Mark)

EGADS: technology demonstration
→ SK-Gd starts JP-FY 2019 !!!

200-ton Water Cherenkov Detector
(240 50-cm PMT’s)

11/2011

15-ton Gadolinium Pre-treatment Mixing Tank

Selective Water+Gd Filtration System

Light @ 15 meters and Gd conc. in the 200-ton EGADS tank

After two and a half years at full Gd loading, during stable operations EGADS water transparency remains within the SK ultrapure range.

No detectable loss of Gd after more than 650 complete turnovers.

Slide credit: Mark Vagins

2019.06.04
Kai Martens, Kavli IPMU, @JHW2019
Neutron Veto for XENONnT

different optimization from EGADS/SK-Gd: low coverage (PMT = RI...), high efficiency

99% reflective

n-tagging efficiency estimate:
- 65% w/pure water
- 85% w/0.2% Gd loading

→ < 1 n in 20 t×y

ongoing @ LNGS: nVeto PMT testing
XENONnT Sensitivity Projection

a discovery experiment is being built at LNGS:

– using the cumulative experience of:
  ► many individual people !!!
  ► three successful generations of XENON detectors !!!
  ► XMASS
  ► Kamioka Gd efforts
  ► EGADS and SK-Gd
  ► lab staff at LNGS and Kamioka

– setting out to detect dark matter:
  ► heavy WIMPs
  ► nimble Axions
  ► YOUR favorite?
  ► anything that leaves a discernible trace...

Hisano 2015:
example of a next-to-leading order QCD cross-section calculation for wino-DM

Please see Shingo Kazama's talk on XENON1T results later today!
After XENONnT, LZ, PandaX-4T

30 tonnes fiducial volume means **50 tonnes of Xe** ~ yearly world production
→ 40 tonnes in TPC, 200 tonne*year exposure

continue the LXe experimental program:  
- dark matter (spectroscopy???)
- solar neutrinos
- $0\nu\beta\beta$
- SN neutrino detection

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**best environment needed:**
- overburden
- cleanliness
- access

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![Graph showing muon flux and WIMP mass](image)
G3 LXe Experiment: The Vision

still pushing the WIMP DM boundary – or measuring WIMP DM spectrum?

**solar neutrinos:**
- measure ER spectrum of pp- and $^7$Be neutrinos
- **CEνNS** for $^8$B neutrinos (+ direct SN neutrinos...) ← ER suppression

Q: $^{136}$Xe enrichment ($\rightarrow \beta\beta$ ER background...) ???
(heard of someone dreaming of a 1km high distillation column...)

40 tonnes natural Xe = 4.4 tonnes of $^{136}$Xe

case study (for live development project): DARWIN → JCAP 11, 017 (2016)
0νββ with 30 tonne LXe Detector

IH region of effective Majorana mass will be covered.

special HE readout to improve energy resolution at endpoint.

high sensitivity to half live due to high $^{136}$Xe mass.

The effort is being organized from now:
- G3C consortium here in Japan
- DARWIN mainly in Europa:
  preliminary timeline: TDR by 2024, construction 2024/25, data 2025–35
- PandaX XY (?)
  → can Japan/Kamioka play a role? Do we want to?  
  (I DO !)

HK starts 20XY → water shielded high pressure Xe TPC inside SK tank ???
Outlook

– we, the Japanese groups, are playing an important role, and contribute important knowledge and technology in XENONnT

– XENONnT and its competitors are built as discovery machines: push deep into the $10^{-48}$ cm$^2$ scale for WIMP SI interactions

– this physics program of both XENON and XMASS will be realized by one world-wide G3 liquid xenon detector consortium

– personal remark:
  
  Hall-C (ICRR) and Lab-1 (Kavli-IPMU) are a unique asset:
  – underground cleanroom environment with screening facilities
  – operational **800 ton water shield** and up to X 1ns FADC ch.
  – timely: national: **G3C** (G3 consortium)
  – operational worldwide: Kamioka Observatory: effort to “internationalize”
  – timely: national: LXe effort needs testbed
  – operational worldwide: what do YOU see:

  mere coincidence, or a chance to take a central role and leadership ?!?