The XENON Dark Matter Program

• **Goal:** WIMP Dark Matter Search with a sensitivity of $\sim 10^{-48}$ cm$^2$

• **Strategy:** phased program with detectors of increasing fiducial target mass (from 10kg to 100kg to 1000kg) and decreasing overall background (XENON100 has achieved $5 \times 10^{-3}$ evts/kg/keVee/day before discrimination)

• **Detector:** LXe (sensitive to both scalar and axial coupling) two-phase XeTPC with simultaneous charge and light detection via PMTs. 3D-event imaging with millimeter spatial resolution. Low energy threshold ($\sim 6$ keVr)

• **Background Reduction and Signal Discrimination:** a) LXe self-shielding; b) Volume fiducialization; c) multiple-scatter events rejection; d) NR/ER discrimination via charge/light ratio

• **Status:** XENON100 continues to take data ($\sim 90$ live-days to-date); multiple analyses (solar axions, low-mass WIMPs, annual modulation..) being finalized with 225 live-days. Construction of XENON1T ongoing and on schedule. Science data taking expected in 2015
The phases of XENON

**Past: 2005-2007**

**XENON10**
15 kg active mass

\[ \sigma_{SI} < 8.8 \times 10^{-44} \text{ cm}^2 \text{ (2007)} \]

**Present: 2008-201?**

**XENON100**
62 kg active mass

\[ \sigma_{SI} < 2.0 \times 10^{-45} \text{ cm}^2 \text{ (2012)} \]

**Future: 2010-2017**

**XENON1T**
~ 2.2 ton active mass

\[ \sigma_{SI} \sim 2 \times 10^{-47} \text{ cm}^2 \text{ (proj.)} \]
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XENON @ Gran Sasso Lab

1.3 km rock
↓
3.1 km water equivalent shielding from cosmic rays
↓
factor $10^6$ reduction of muon flux
The Sensitivity of XENON1T

-goal: \( \sigma < 2 \times 10^{-47} \text{ cm}^2 \) for \( M_{\text{WIMP}} = 50 \text{ GeV} \) after 2t*year
Direct detection: progress over time

Factor ~ 10 every two years
DRIVEN BY XENON!

L. B., Physics of the Dark Universe 1, 94 (2012)
The XENON Collaboration

US led and NSF supported since start of project
~100 scientists from 15 institutions
The XENON Collaboration

Columbia, Nikhef, Mainz, Muenster, MPIK, Bern, UCLA, Zurich, Rice, Purdue, Coimbra, Subatech, Bologna LNGS Torino, Weizmann
Why Xe?

- **Scalability**: ton scale target at modest cost (~$1000/kg)
- **Xe nucleus (A~131)**: expect high rate for SI interactions if low energy threshold for NR
- ~50% odd isotopes (Xe-131 and Xe-129) for SD interactions
- **Intrinsically pure**: no long-lived radioactive isotopes; Kr/Xe can be reduced to ppt level
- **High Stopping Power** (Z = 54, 3gcm⁻³): active volume is self-shielding
- **Charge & Light**: highest yields among noble liquids. Simultaneously detected for NR discrimination
- **Background reduction**: by charge-to-light ratio and 3D-event localization in a TPC
Light and Charge depend on Particle $dE/dx$

Figure 2.9: Field dependence of relative ionization and scintillation yields of $\alpha$ particles, electronic recoils (ER), and nuclear recoils (NR) in LXe. Figure from Aprile et al. (2006b).

The XENON Detector: a 2-phase TPC

Discrimination of $e^{-}/\gamma$ and nuclear recoils: $(S2/S1)_{n,WIMP} < (S2/S1)_{e,\gamma}$ > 99% ER rejection

3D event position: drift time -> $z$ (<0.3mm); PMT pattern -> $x,y$ (<3mm)

**precise fiducial inner volume** (avoid BG in outer volume)

Discrimination of single/multiple scattering

**screening materials/purification of Xe** -> further background reduction
The XENON100 Detector

- 98 top array PMTs
- 80 bottom array PMTs
- 64 veto PMTs
- TPC

- 161kg Xe, 62kg target
- 30cm drift length
- Radio-purity → material screening
  - $^{85}$Kr → distillation column
  - $^{222}$Rn emanation → avoid/monitor
- Passive shielding: water, lead, PE, copper

R8520, QE>32% @175nm
Example of a low-energy event in XENON100

The maximum electron drift time at 0.53 kV/cm is 176 µs

S1 signal: ~ 100 photons
S2 signal: ~ 23 electrons

S1 signal: 5.14 photoelectrons
S2 signal: 459.7 photoelectrons

151 µs

- Delayed scintillation
- Secondary ionization
- Single electrons

Amplitude [V]

0 0.05 0.1 0.15 0.2

Time [µs]

0 50 100 150 200 250 300 350 400

Amplitude [V]

0 0.01 0.02 0.03 0.04 0.05 0.1 0.15 0.2

Time [µs]

46 46.5 47 47.5 48 48.5

Amplitude [V]

0 0.05 0.1 0.15 0.2

Time [µs]

196 198 200 202 204
Volume Fiducialization: power of a TPC

- 3D event imaging allows to select only central volume with lowest background exploiting LXe self-shielding
- Gammas from detector components and external sources stopped at edges
- Remaining background in fiducialized volume dominated by $^{85}$Kr and $^{222}$Rn in LXe

Optimization of fiducial volume with Monte Carlo: good background rejection efficiency $\leftrightarrow$ target mass
• MC simulations and background in good agreement
• Background very well understood in full energy range
• $5 \cdot 10^{-3}$ evts/kg/keV/d after the veto cut
→ achieved design goal of factor 100 lower than in XENON10! (and than any other search…)

PRD 83, 082001 (2011)
Results from XENON100: spin-independent

Best upper limit on WIMP-nucleon cross section: $2 \times 10^{-45}$ cm$^2$ at $M_W = 55$ GeV

XENON100

Results from XENON100: spin-dependent


$^{129}$Xe (spin-1/2) and $^{131}$Xe (spin-3/2), two isotopes with $J \neq 0$ and 26.2% and 21.8% abundance

$$\frac{d\sigma_{SD}(q)}{dq^2} = \frac{8G_F^2}{(2J + 1)v^2} S_A(q)$$

$$S_A(0) = \frac{(2J + 1)(J + 1)}{\pi J} [a_p \langle S_p \rangle + a_n \langle S_n \rangle]^2$$

Best sensitivity for neutron coupling: $3 \times 10^{-40} \text{ cm}^2$ at $M_W = 45 \text{ GeV}$
Energy Scale for Nuclear Recoils

Energy relation for $S1$

\[ E = \frac{S1}{L_y \cdot \mathcal{L}_{\text{eff}}(E)} \times \frac{1}{S_{\text{nr}}} \times S_{\text{ee}}. \]

**Light yield** of 122keV $\gamma$-rays

**Quenching-factor** of nuclear recoils

**Electric field** dependency

Energy relation for $S2$

\[ E = \frac{S2}{L_q \cdot Q_y(E)} \times \frac{1}{Q_y(E)} \]

**Secondary Amplification** of electron signals

**Charge yield** of nuclear recoils
Monte Carlo simulation of neutron data: PRD 88, 012006 (2013)

- Input AmBe spectrum (ISO 8529-1 standard). Analysis robust against variations of this spectrum
- Source strength measurement (PTB): (160 ± 4) n/s
- Complete Monte Carlo description of the detector including detector shield (water, lead, polyethylene and copper)
- $E_{dep}$ is converted to S1 and S2 including thresholds, resolutions and acceptances from data
Fit S2 channel - Determine Q_y

Step 1: Use $L_{\text{eff}}$ from direct measurements
→ reproduce S2 spectrum → obtain optimal $Q_y$

Step 2: Use obtained $Q_y$
→ reproduce S1 spectrum → obtain a new $L_{\text{eff}}$

Best fit for source strength: 159 n/s
↔ fits perfectly to PTB source measurement
Very satisfactory, absolute agreement of S1 data/MC comparison

Implied best-fit $L_{\text{eff}}$ consistent with direct measurements

Confirmation of robust $L_{\text{eff}}$ description down to 3keV nuclear recoil energy
XENON100 New Exposure (2013)

- Lowered Kr/Xe contamination to ppt level to demonstrate capability for XENON1T
- Performed new AmBe calibration and confirmed excellent agreement with MC study
- Detector parameters are stable and performance excellent
- Primary goal is to take another full year of data and possibly more years to study annual modulation. R&D work at Columbia & Zurich continue to measure the ER energy scale
Calibration with an YBe source

- Monoenergetic neutron from (gamma, n) reaction from an YBe source with ~150keV
- Only very low energy depositions (<6KeVnr hard threshold)
- Provides a direct way of observing in a controlled setup the binomial distribution of light signals and a signal similar to the expected for low mass WIMPs
Ongoing Analyses with XENON100 Data

- Low WIMP mass analysis using only S2 signals
- Limits on axions and ALPs
- Studies of the annual modulation of the electronic recoil signals
Annual Modulation Analysis

- Dark matter data acquired over three different periods spanning almost three years (data taking still ongoing)

- Study modulation of electron recoils data using different tools:
  - Unbinned profile likelihood analysis
  - Lomb Scargle periodogram
Annual modulation analysis

- Detector operating in very stable conditions in the selected periods
- Variations in all slow control parameters below the 1% level
- No significant correlations between event rate and any of the SC parameters
Annual modulation analysis

- Experiments in small detectors to find the equivalence between detected light and energy deposition for electronic recoils in LXe

(see poster on low energy measurements with electric field by Luke Goetzke)
S2 only analysis

- The XENON100 detector is able to identify single electrons with very high efficiency thanks to the high proportional scintillation yield (16pe/e-)
- While the trigger efficiency is low for single electrons, it becomes 100% for signals with about 8 electrons
**S2 only analysis**

- WIMPs with mass of a few GeV may produce very low energy nuclear recoils which in XENON100 can be detected via the ionization signal without an associated light signal, due to the better efficiency to detect electrons. Also $\text{Leff}$ drops rapidly with decreasing energy, and uncertainty on $\text{Leff}$ becomes relevant.

- WIMPs with mass of $\sim 500$ MeV can interact with atomic electrons ejecting them. These can also be detected via S2 only signals in XENON100.

- The rate of few electron signals is used to study low mass WIMPs, improving the XENON10 limits and constraining some of the reported detections.

- We will also study the annual modulation of these signals to further improve the sensitivity to these low energy interactions.
• The analysis of the XENON100 AmBe data has provided an indirect measurement of the $Q_y$ value for nuclear recoils down to low energies that will be useful to interpret the measured rate in terms of WIMP interactions.

• A detailed study has been performed to identify production mechanisms of single electrons in the XENON100 detector.
Axion and ALP Searches

- Axions and Axion Like Particles (ALPs) can interact with atomic electrons via the axioelectric effect (analog to the photoelectric effect)

- An axion interacting in XENON100 would produce an electronic recoil with energy equal to the axion mass minus the binding energy of the electron.

- The expected event rate is a combination of the axion flux, cross section and the photoelectric cross section for the xenon
Axion and ALP searches

- Astrophysical models provide expected flux for solar axions (continuum spectrum) and galactic (monoenergetic) axions, which can be used to predict the expected rate in XENON100.

- Gamma source calibration data used to predict the expected XENON100 background.
XENON1T

- 1m drift TPC with ~3.5 ton LXe
- Water shield as Cherenkov Muon Veto
- ER background < 5 x 10^{-5} DRU
- Kr/Xe < 0.5 ppt & Rn/Xe < 1 μBq/kg
- Project approved and funded
- 50% of project costs covered by NSF
- Design of major systems completed
- Construction in Hall B ongoing
Water Tank: 10 m High; 9.6 m diameter
A cylindrical water tank with a minimum buffer of 4-5 m, equipped with PMTs to detect muons through Cherenkov light. External dimensions: diameter 10 m, height 10 m.
XENON1T Background Suppression

Requirement: < 1 event in the full exposure

**External γ’s:**
- suppression via self-shielding ($\rho_{LXe} \sim 3g/cm^3$)
- material screening and selection

**Internal BGs ($^{222}$Rn and $^{85}$Kr)**
- cryogenic distillation column (Kr)
  - < 1 ppt Kr/Xe achieved in XENON100
- online Rn removal by Rn tower

**Neutrons**
- muon veto and material selection
- low U and Th contaminations
  $\rightarrow$ low $\alpha$ and $(\alpha,n)$ production

Example: Development of low radioactivity PMTs with Hamamatsu
$<$1mBq/PMT in U and Th

Background rejection power:
>$99.5\%$ neutrons with a $\mu$
tagged in the veto $\rightarrow$ muon-induced n-back:
0.01/ year $\rightarrow$ negligible
Kr Reduction and Measurement

- Goal is to reduce Kr/Xe to < 0.5 ppt
- after last distillation XENON100: (0.97 ± 0.19) ppt ⇒ less than 0.04 mDRU from $^{85}$Kr
- 5m distillation column with 3kg/hr @ $10^4$ separation (3m version built and under testing)
- two analysis tools developed by Collaboration to measure Kr/Xe at ppt level

RGMS (arXiv:1308.4806)

The Columbia Atom Trap

- Transition between $5^3D_3$ and $5^3P_2$
- $^{40}$Ar to avoid contamination by Kr
  - $\lambda_{^{40}Ar} = 811.7542$ nm, $\lambda_{^{84}Kr} = 811.5132$ nm
- Achieved by a single diode laser

Single atom detection
The XENON1T Detector
PMTs

- 300 Hamamatsu R11410-21
- XENON1T version: high QE (average 36% @ 178nm) and low radioactivity (< 1mBq/PMT in U/Th)
- all PMTs screened and tested at room temperature (DC rate, HV scan, after-pulsing, transit time,)
- repeated cool-down at <2K/min
A facility built at Columbia Nevis Lab to demonstrate:

- high speed (~100 SLPM) Xe circulation and purification on short time scale
- long electron lifetime for 1 m drift in a 2-phase TPC (a vertical slice of XENON1T)
- high voltage (~100 kV) with custom-made low radioactivity feedthroughs
- performance of R11410-21 PMTs in LXe and with field
Xe: Storage & Recovery

- Vacuum-insulated, LN-cooled, high-pressure (70 bar) SS sphere
- store > 6 tons of Xe in gas or liquid phase under high purity conditions
- fast (hours) recovery of Xe from detector in case of emergency
SUMMARY

• XENON100 is still leading the search for DM direct detection, thanks to the large target mass, ultra-low background, and 3D imaging capability. Other LXe-based searches using larger target mass (LUX and XMASS) expected to improve on XENON100’s result. By how much depends on the background’s level reached by these experiments. In comparison, LAr-based experiments, long thought to be easier to realize, have lagged behind but should soon start to deliver thanks to advances in key technologies and improved design (DarkSide50).

• XENON100 has achieved its original sensitivity goal of $2 \times 10^{-45}$ cm$^2$ for SI interactions, thanks to the extremely low background achieved. Results on SD interactions are the best reported to-date, for $n$-coupling. Results on several other searches are to be released soon. XENON100 continues to take data, after the further reduction in intrinsic Kr-background which has been measured to be at 1 ppt level. Focus is going to be on annual modulation.

• XENON1T construction at LNGS is advancing rapidly. The project’s schedule is on track and data taking still expected to start in 2015. It will be the first G2 experiment (ton scale) worldwide. Largely based on proven technologies and on demonstrated new concepts. With 100 x less background than XENON100, it should achieve sensitivity of $2 \times 10^{-47}$ cm$^2$. By replacing the TPC with one of larger mass (~6ton) another order of magnitude in sensitivity will be possible with the same experimental infrastructures built for XENON1T.