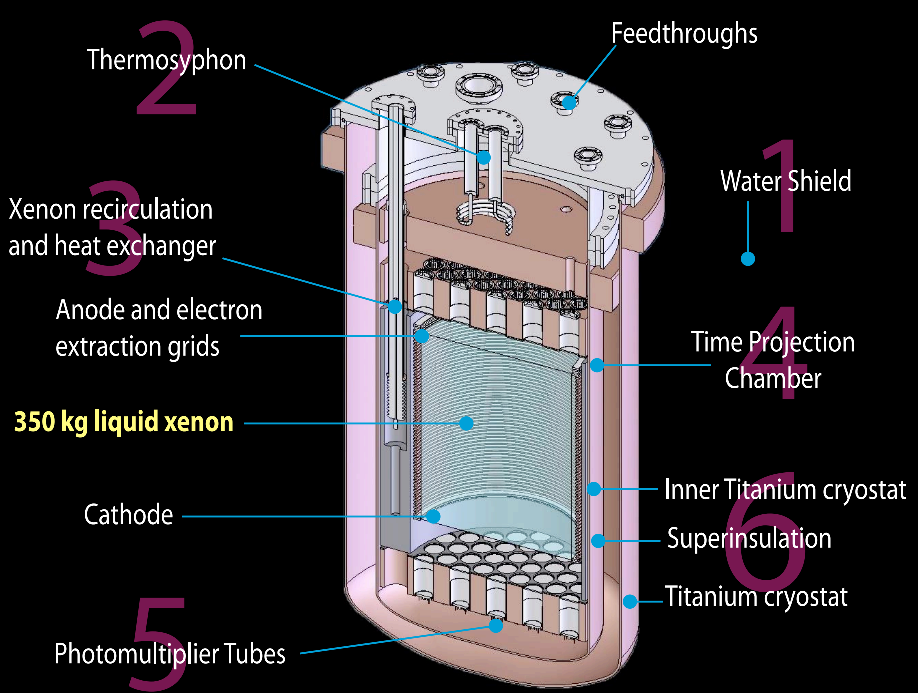
LUX: A Liquid Xenon Dark Matter Detector



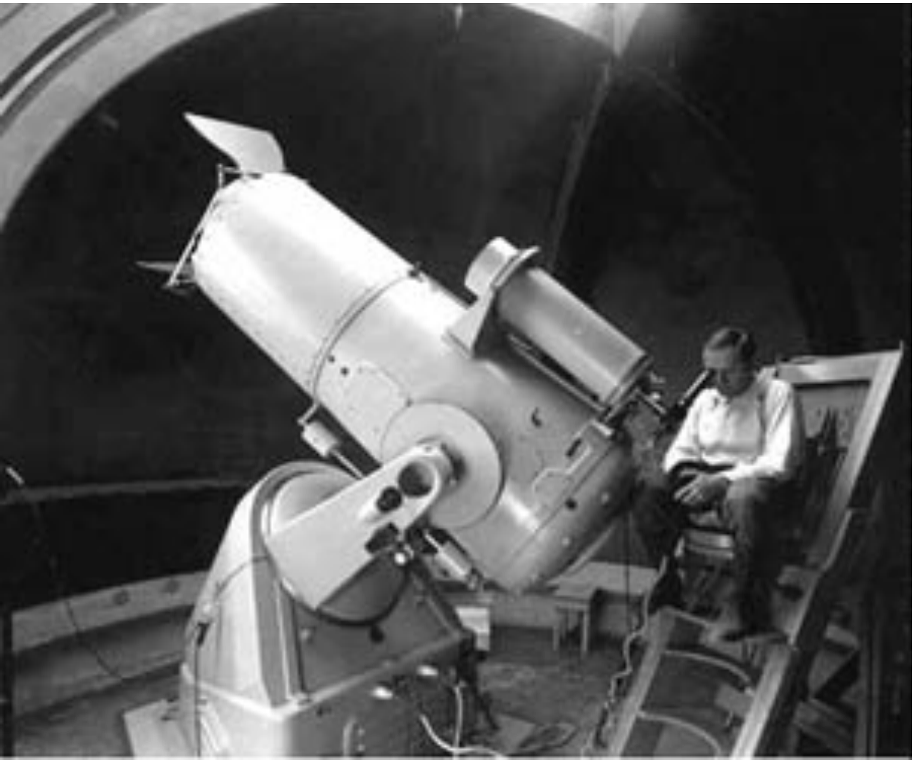
Masahiro Morii
Harvard University

KEK Physics Seminar

Evidences of Dark Matter

Original claim was made by Fritz Zwicky (1933)

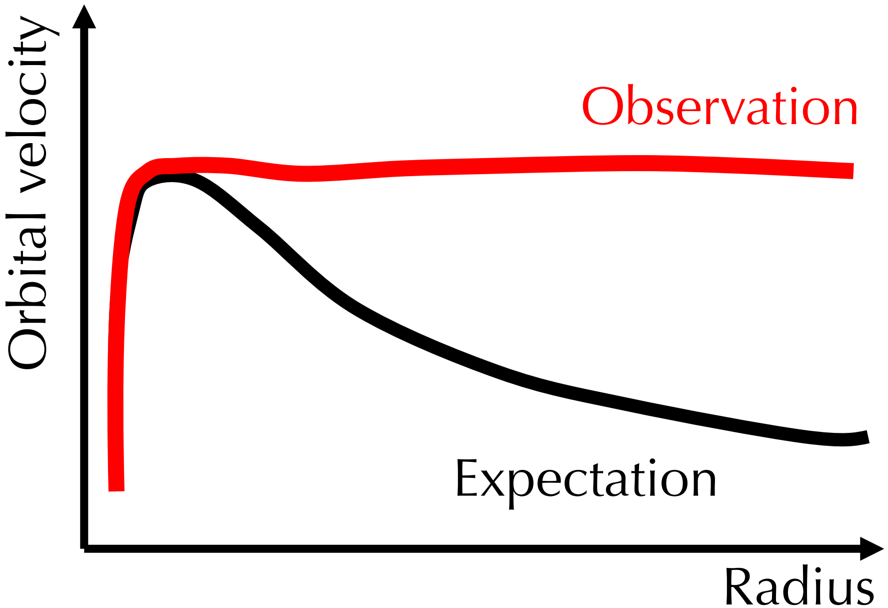
- Measured line-of-sight velocities of the galaxies in the Coma cluster
- Inferred the total mass of the cluster to be 100x larger than that of the luminous matter component
- Explanation: substantial amount of non-luminous matter must exist



Rotational Curve

Vera Rubin *et al*. (1979) measured orbital velocity vs. radius of spiral galaxies

- If the mass distribution ≈ luminosity distribution, i.e. concentrated at the center, $v(r)$ should drop as $1/\sqrt{r}$ at large r



Observation disagrees

- Large amount of matter (which does not emit light) is distributed far away from the center

Bullet Cluster

Two colliding clusters of galaxies are observed in three ways:

- Optical telescope sees the stars
- X-ray sees hot interstellar gases (shown in red)
- Gravitational lensing sees the mass distribution (shown in blue)

Different components suffer different effects in the collision

- Hot gases interact electro-magnetically, and thus strongly decelerated
- Stars suffer smaller disturbances
- Mass dist. appears to pass through without being disturbed

Astronomy to Particle Physics

Existence of Dark Matter is established from its gravitational effects

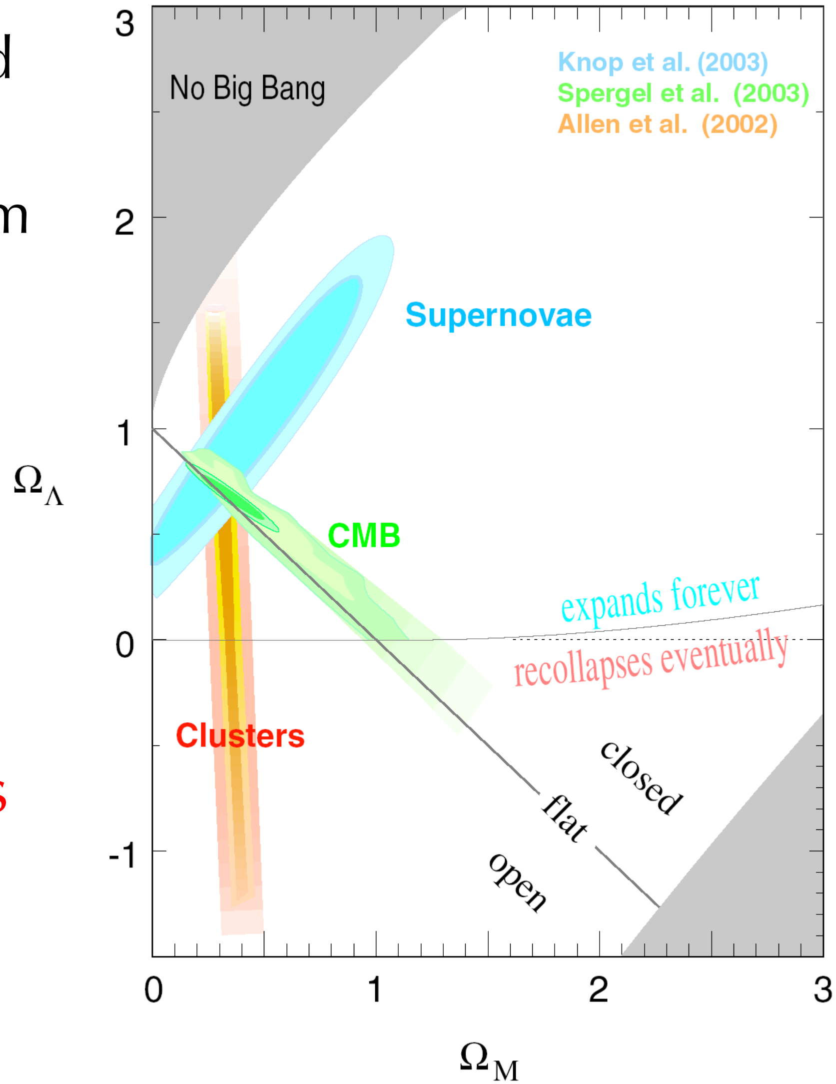
Amount of Dark Matter is inferred from astronomical data

- ~23% of the energy of the Universe
- Local density 0.3 GeV/cm^3

Identity of Dark Matter is unknown

- Majority must be cold (i.e. non-relativistic) and non-baryonic
- They are not a part of the Standard Model

Dark Matter is a particle physics problem as much as it is an astronomy problem



WIMP Dark Matter

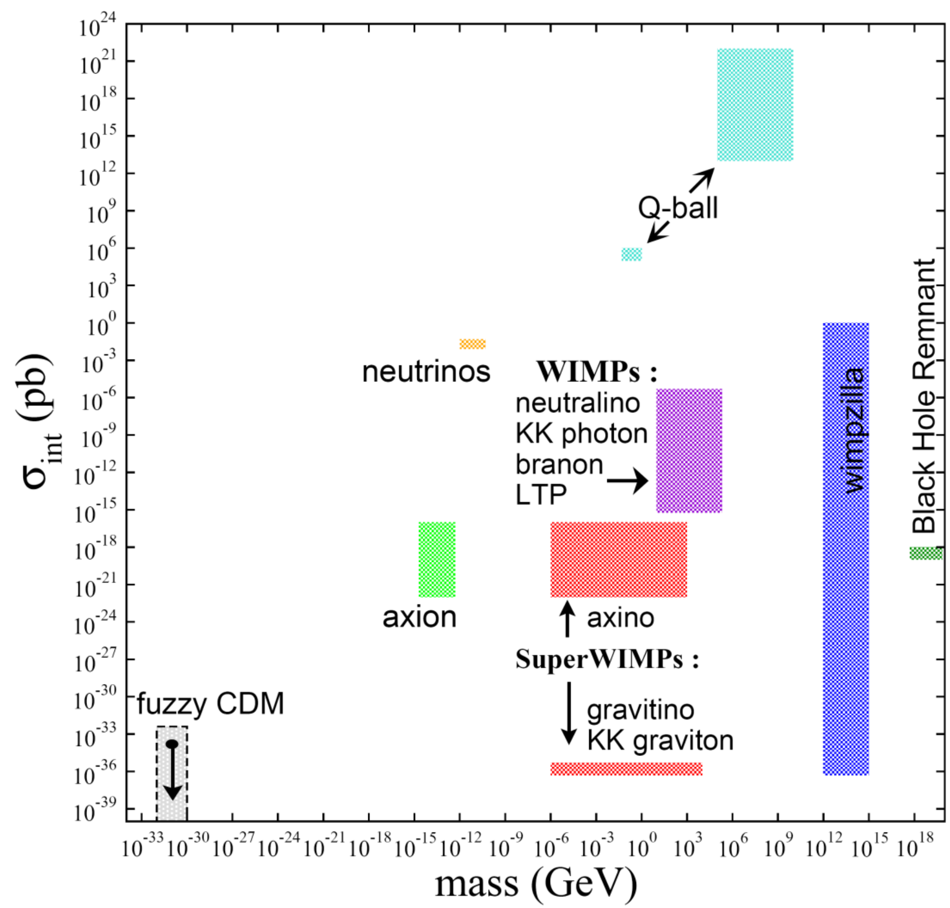
No shortage of candidates, but…

WIMPs (Weakly Interacting Massive Particles) are the front runners

- ~100 GeV new particles with Weak (and gravitational) interactions
- Such a particle would naturally have the right thermal relic density

Many theories beyond the SM predict WIMPs

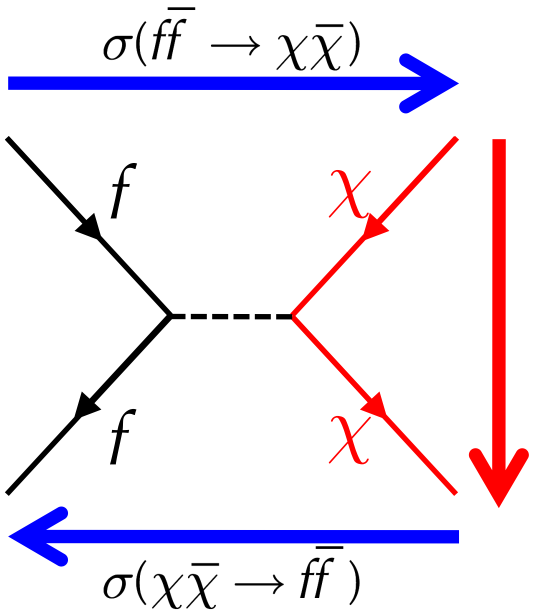
- Attempting to solve the hierarchy problem often results in new stable particles at the Weak scale
- Example: SUSY with R-parity and the **L**ightest **S**upersymmetric **P**article



WIMP Hunting

Going beyond gravity, three ways to detect WIMPs

- WIMP pair production at the hadron colliders



$\sigma(\chi f \rightarrow \chi f)$

- Direct detection: WIMP scattering off a nucleus in the detector

- Observe radiation from WIMP pair annihilation

Cross sections are related, and constrained by the relic abundance

- Predictions are model dependent

Direct Detection Limits

Best limits on the WIMP-nucleor cross section are ~4×10^{-44} cm^2

- CDMS II : Ge (and Si) crystals at 10 mK, 612 kg-day exposure

➔ < 3.8×10^{-44} cm^2 at 70 GeV

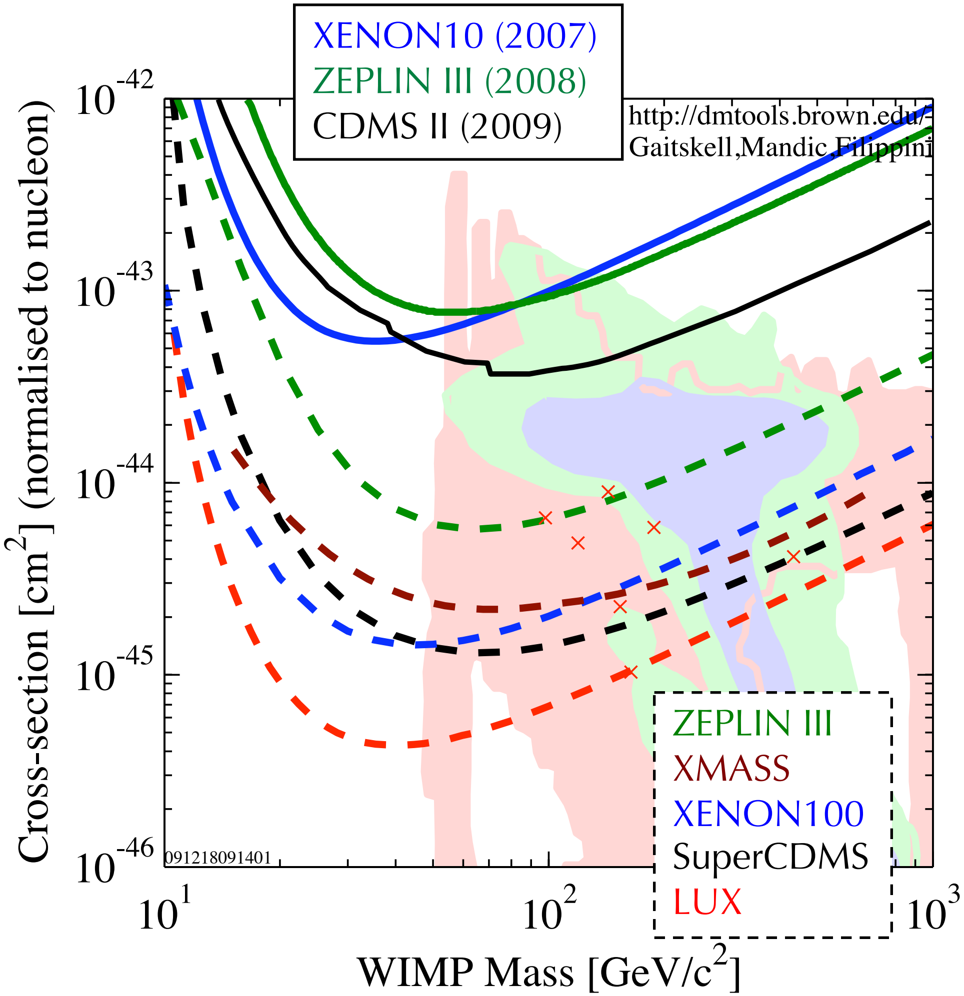
- XENON10 : liquid Xe, 316 kg-day

➔ < 5.6×10^{-44} cm^2 at 30 GeV

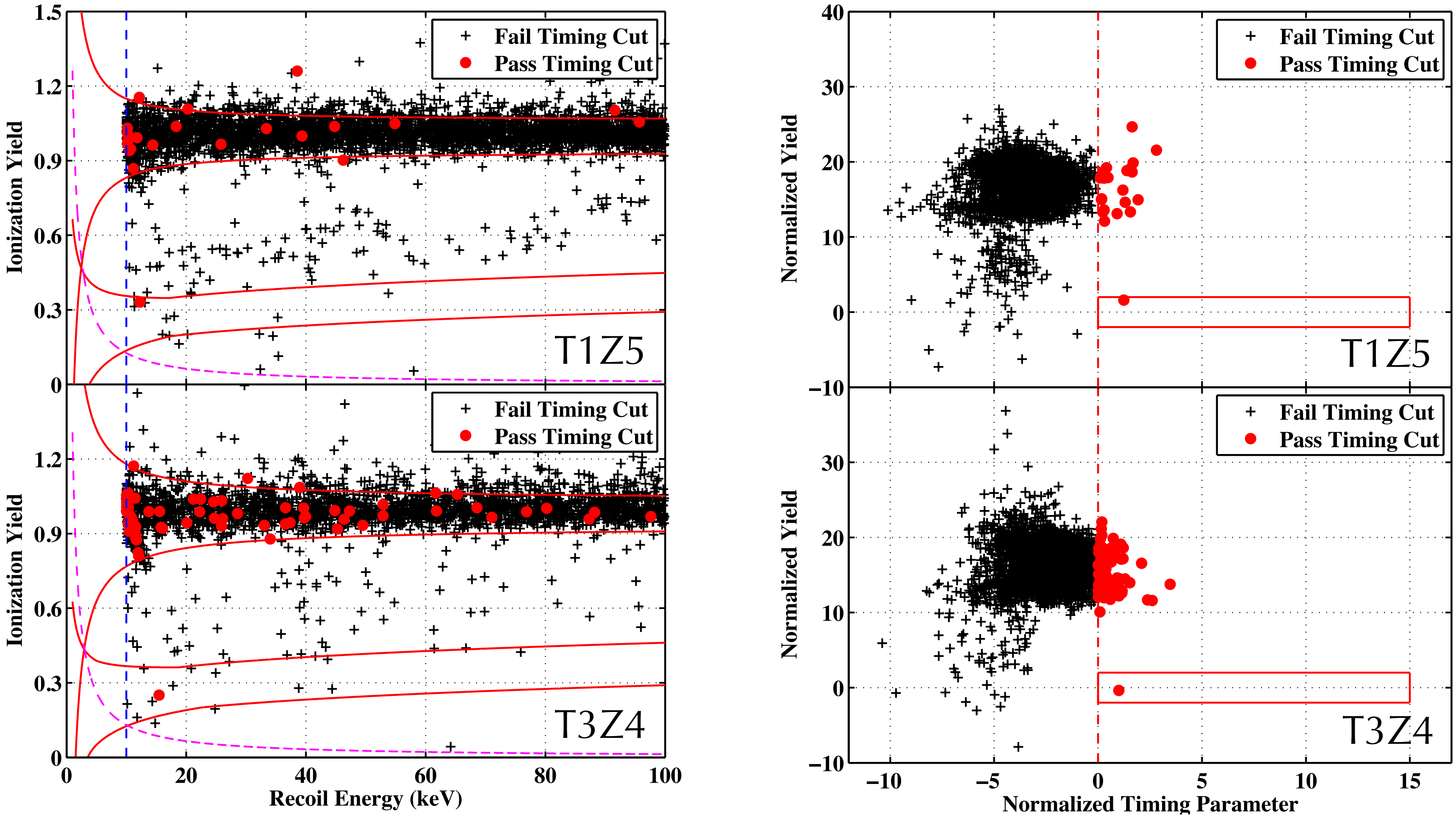
SUSY models predict the cross sections around 10^{-44} cm^2

- Smaller cross sections are possible, but less favored by other particle-physics experimental data

Next generation of experiments are aiming for $\sigma_{\chi N} \sim 10^{-45}$ cm^2



CDMS II Events



Z. Ahmed *et al.*, CDMS Collaboration, arXiv:0912.3592

Experimental Challenges

Signal is elastic $\chi N \to \chi N$ with small recoil energy E_N ~10 keV

- Not much of an experimental signature to reject background

Background sources include

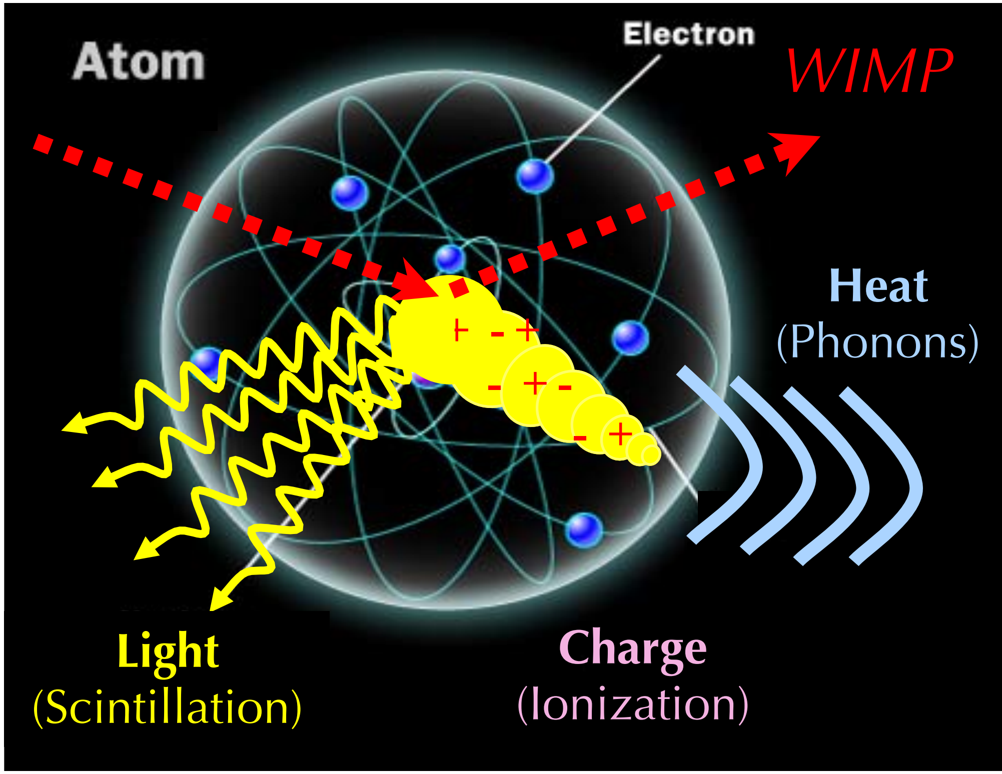
- $N \to N' + \alpha$ or e^-
- $\gamma e \to \gamma e$
- $nN \to nN$
- $\nu N \to \nu N$

To combat the backgrounds

- Screen everything for radiopurity
- Use multiple signatures ➔
- Go deep underground

Cross sections are small

- Need large detector mass
- But what?



Liquid Xenon

WIMP-nucleus cross section $\propto A^2$

- de Broglie wavelength ~ nuclear radius

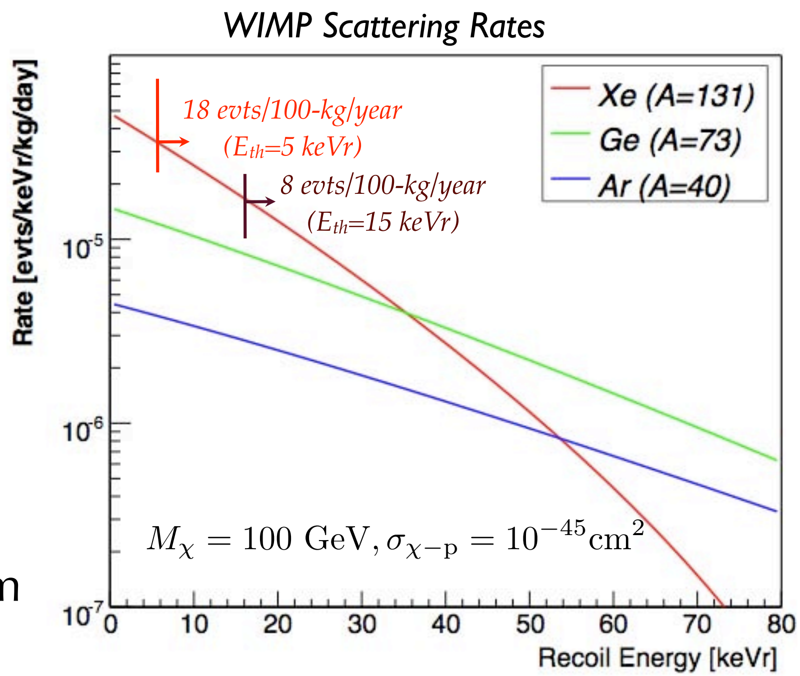
Xe (A = 131.3) gives high signal rate

- 100 kg-year exposure can probe 10^{-45} cm^2

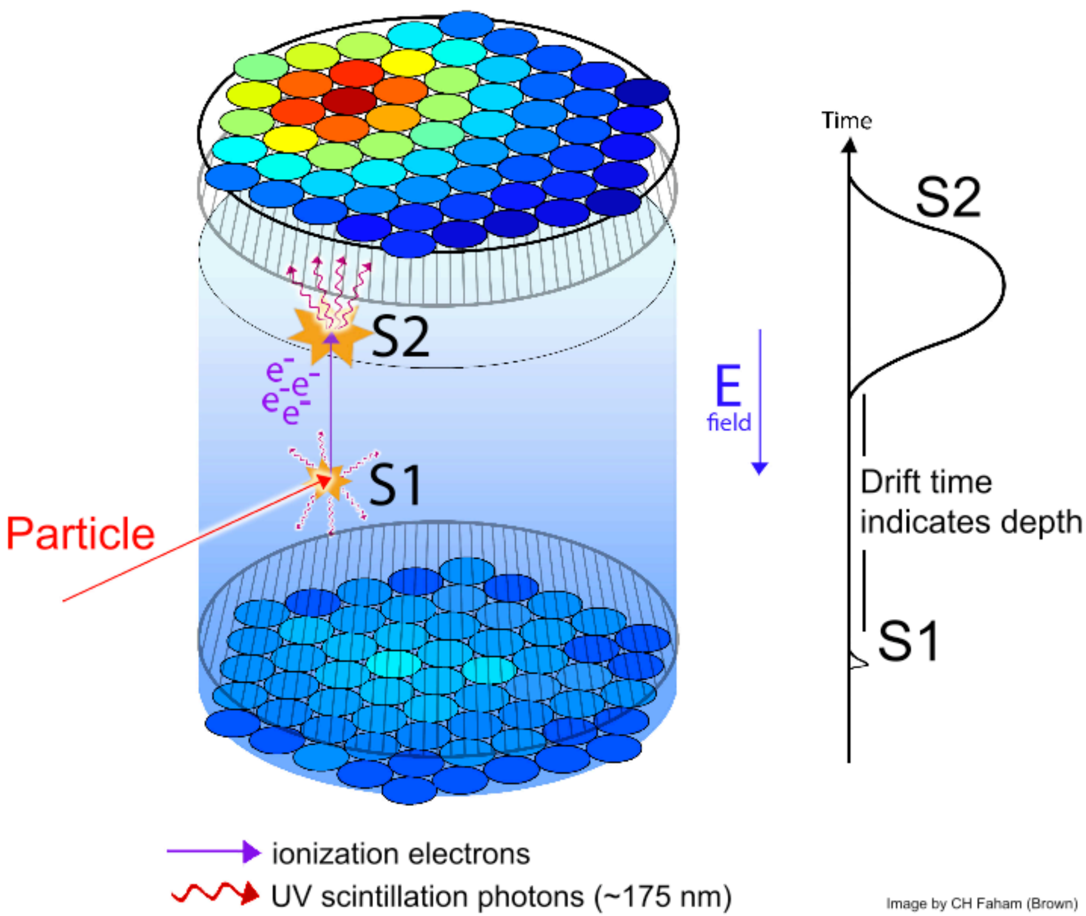
Key liquid Xe properties

- High density: 3 g/cm^3
- High boiling point: 165K
- Good scintillator: 42 photons/keV at 175 nm
- High ionization yield: W = 15.6 eV
- As a liquid, it can be circulated and purified
- No long-lived radioactive isotopes
  - ^{85}Kr must be removed by charcoal chromatography

Cost: $1000/kg



Two-Phase Xe Detector



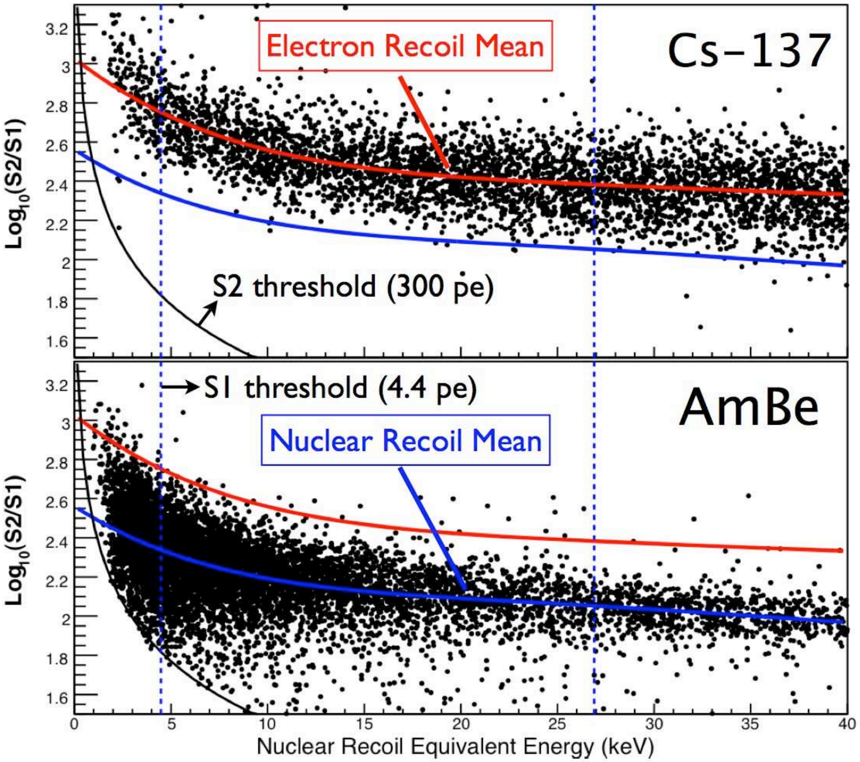
PMTs collect prompt (S1) and proportional (S2) light

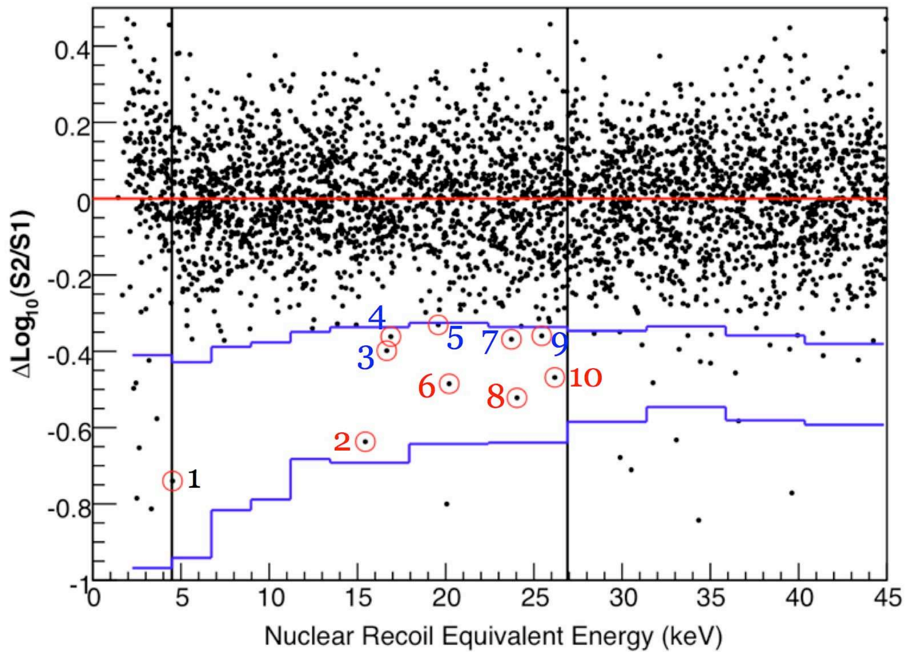
- S1-S2 delay → Drift length
- S2 light pattern → Horizontal location

S2/S1 ratio differs markedly between electron and nuclear recoils

- Nuclear recoils have higher ionization density → higher recombination probability → higher S1 yield
- >98.5% rejection of EM backgrounds

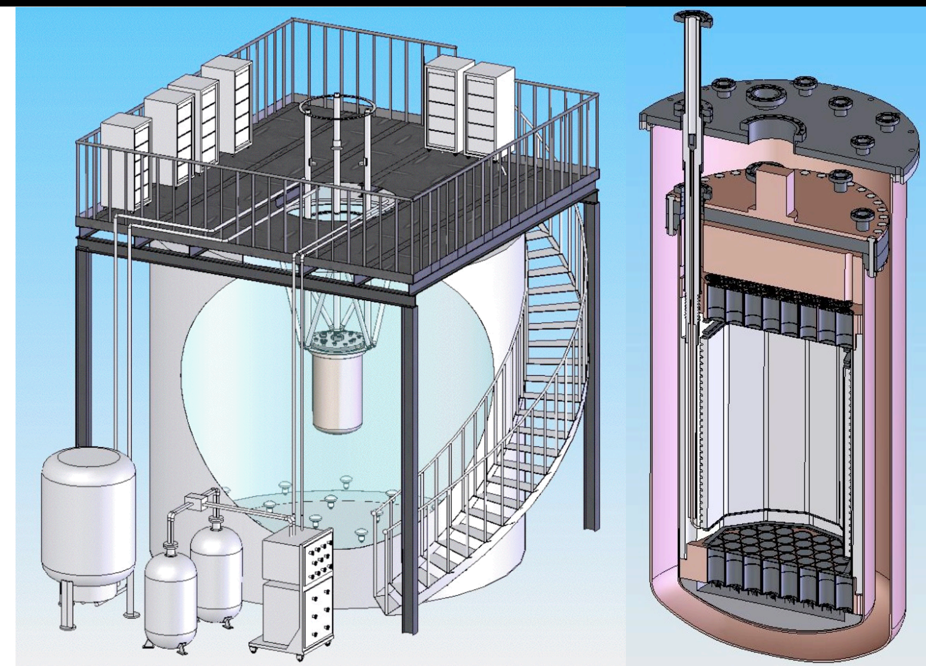
S2/S1 Ratio





- XENON10 calibration data show clean discrimination between electron and nuclear recoils
- log(S2/S1) normalized to the electron recoil data is used to select the signal candidates

Scaling Up



Liquid Xe experiments scale well

- Readout $\propto$ (volume)$^{2/3}$
- Good self shielding: X_0 = 2.77 cm

	XENON10	LUX
Total Xe	22 kg	350 kg
Fiducial	5.4 kg	100 kg
Live time	58.6 days	100 days
Location	Gran Sasso	Homestake

L technology to achieve <1 bkgd.

- Xe purification system has a ×100 capacity (300 kg/day)
- Ultra-low activity Ti vacuum vessel replaces SS + Cu
- PMTs have lower activity (9/3 mBq of U/Th per tube) and higher QE (27%)
- 183 m^3 purified water tank shields the detector from neutrons

Xenon Purification System

Purification of liquid xenon is crucial:

- Light-absorbing impurities → scintillation light is lost
- Electronegative impurities → electrons are lost during the drift

Gas-phase recirculation system through heated getter

- Evaporate liquid Xe → purify Xe gas → re-condense
- Used successfully in XENON10 and ZEPLIN II

Size of LUX demands larger flow rate → higher cooling power

- 300 kg recirculation per day = 200W = 100 litre of liquid N_2 per day

Heat-exchanger system reduces the cooling power by 96%

- Demonstrated 400 kg/day throughput at 18W
- cf. XENON10 system did 40 kg/day at ~30W

^{85}Kr is removed by chromatography through a charcoal column

- Bolozdynya *et al.*, NIM A579, 50-53 (2007)

Energy Threshold

Energy threshold is determined by the S1 light yield

- Different for electron vs. nuclear recoil

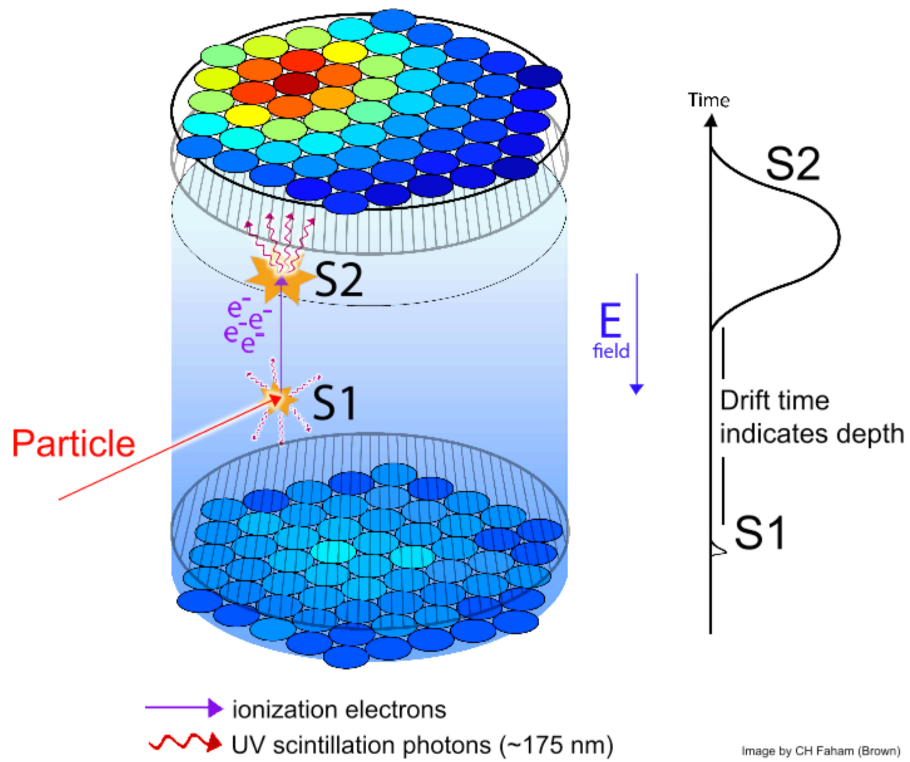
XENON10 performance:

- S1 light yield =1 phe/keVnr
- Analysis cut = 4.5 keVnr
- PMT was R8520 (1″ sq., QE = 14%)

LUX differs only slightly

- PMT is R8778 (2″ dia., QE = 27%)
  → Less coverage, better QE
- Bottom grid is more transparent
- Expect 1 phe/keVnr

We assume 5 keVnr for estimating our physics reach



Radioactivity Control

γ-ray background must be moderately low

- Suppressed by self shielding and S1/S2 ratio

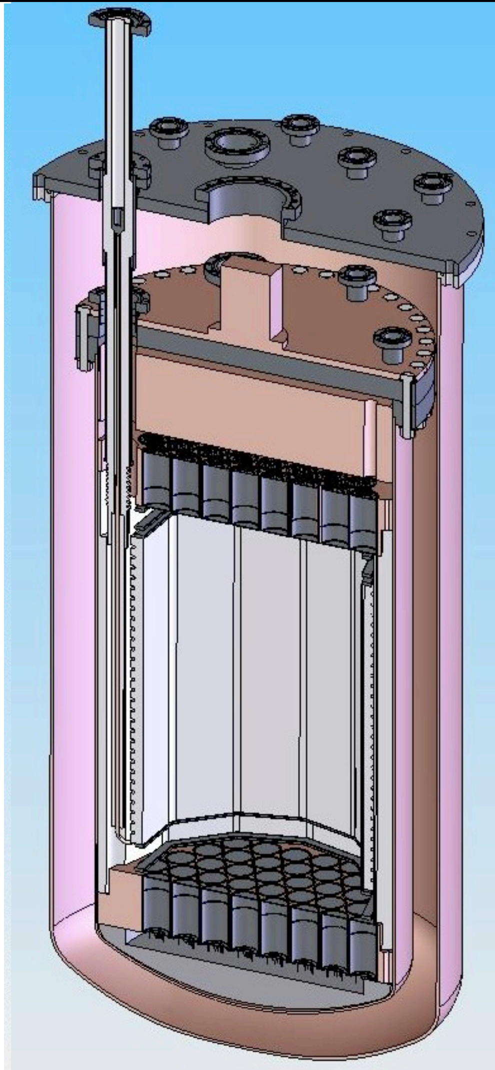
PMTs have been screened for radioactivity

- <9/3 mBq of U/Th per tube

Vacuum vessel uses high-purity titanium

- XENON10 used SS combined with Cu shielding
- Ti has low U/Th/K content and mechanically strong
- Top flanges are made of SS
- Cu shielding between the flange and the top PMTs

All internal components are screened, and kept in clean rooms to avoid Rn exposure



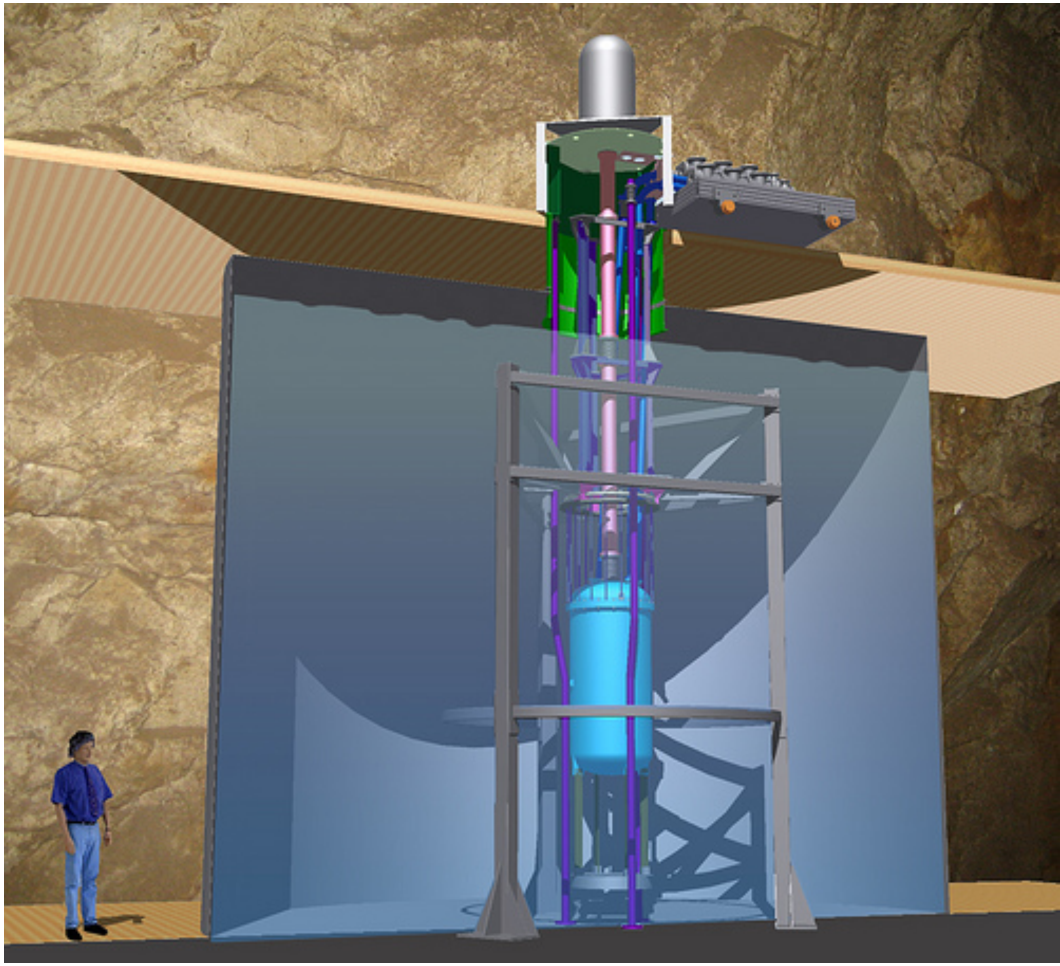
Water Shield

Detector is suspended inside a 183 m^3 purified water tank

- Fast neutrons generated in the rocks by cosmic rays are efficiently absorbed

PMTs inside the water tank will veto cosmic rays passing through the water

- Minor component of the electron-recoil background

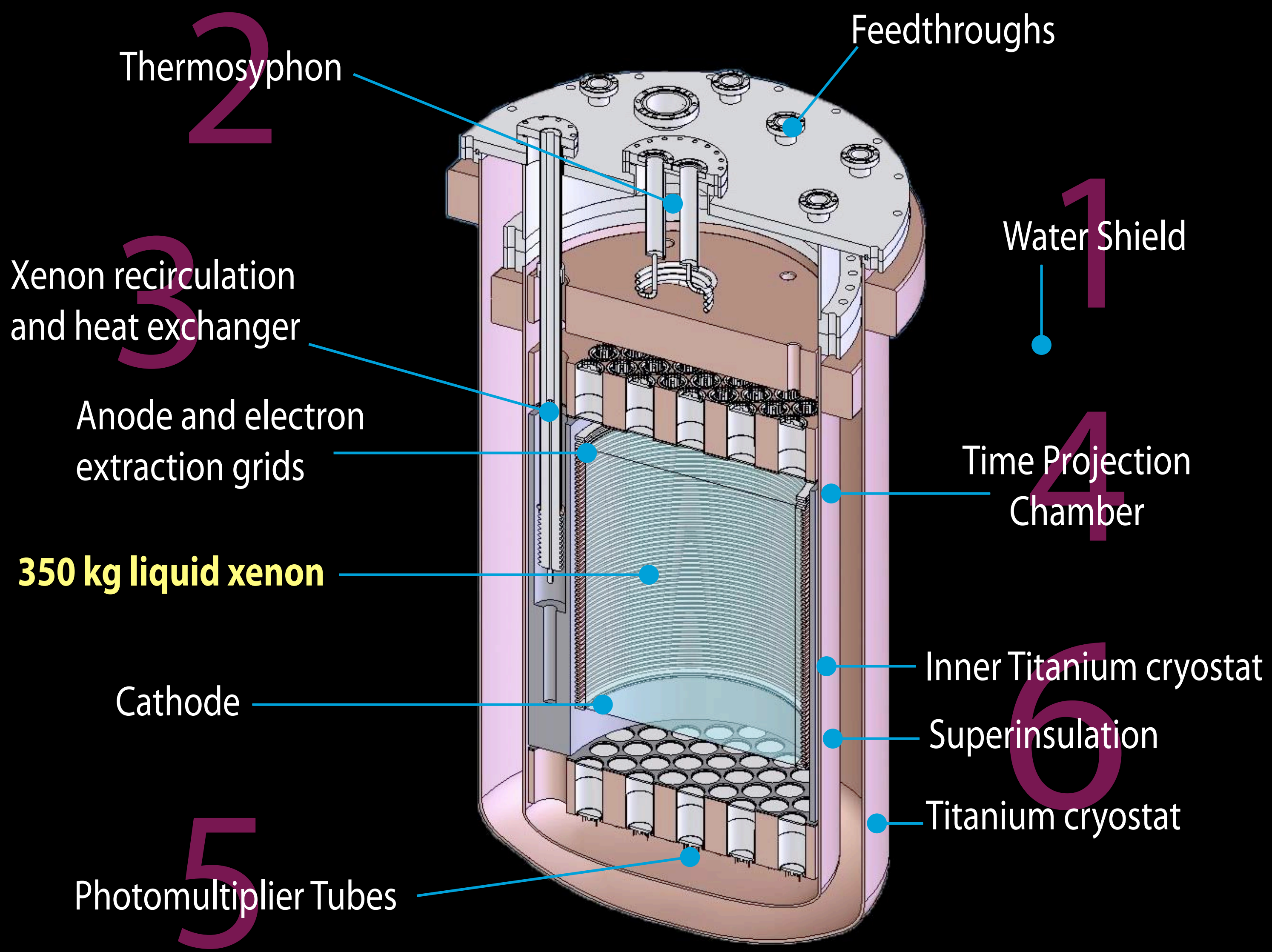


LUX Collaboration

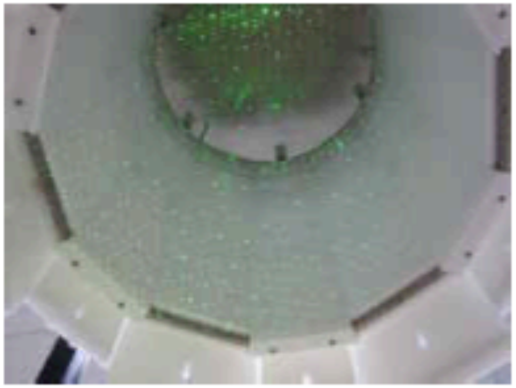
Brown, Case Western, LBNL, Harvard, LLNL, Maryland, Texas A&M, UC Davis, Rochester, South Dakota, Yale

- Funded by DOE & NSF

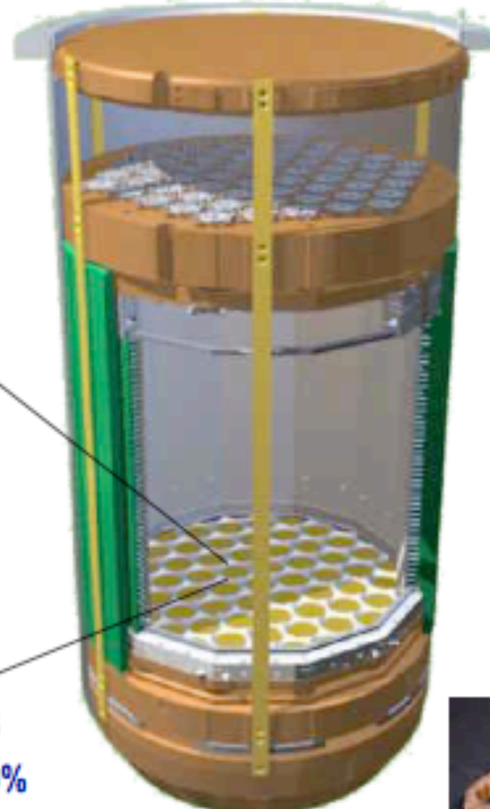
LUX Detector



Detector Internals



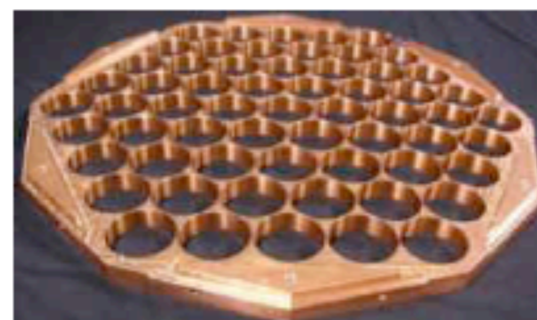
- HV Grids in place and tested



- Dodecagonal field cage + PTFE reflector panels

- 122 2" PMT R8778
  - 175 nm, QE > ~30%
  - U/Th ~9/3 mBq/PMT
  - All tested in LUX 0.1 program

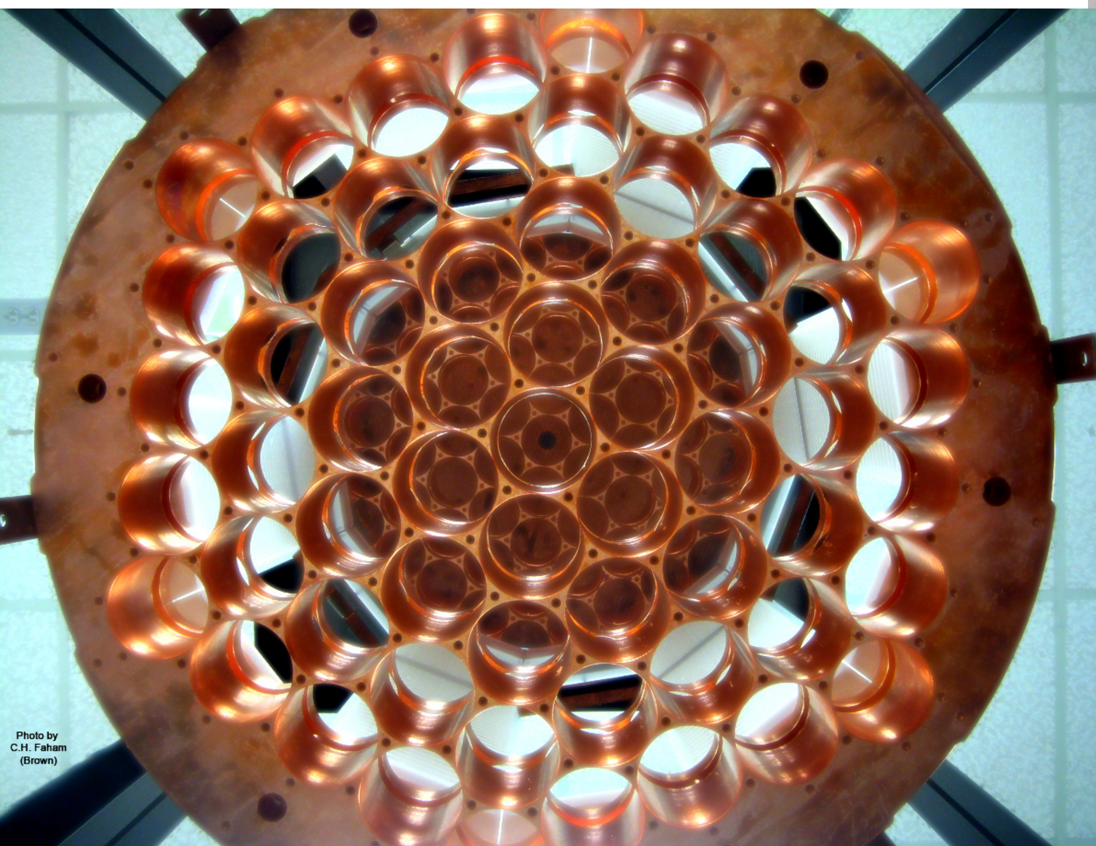
Assembly taking place at Texas A&M since early 2009

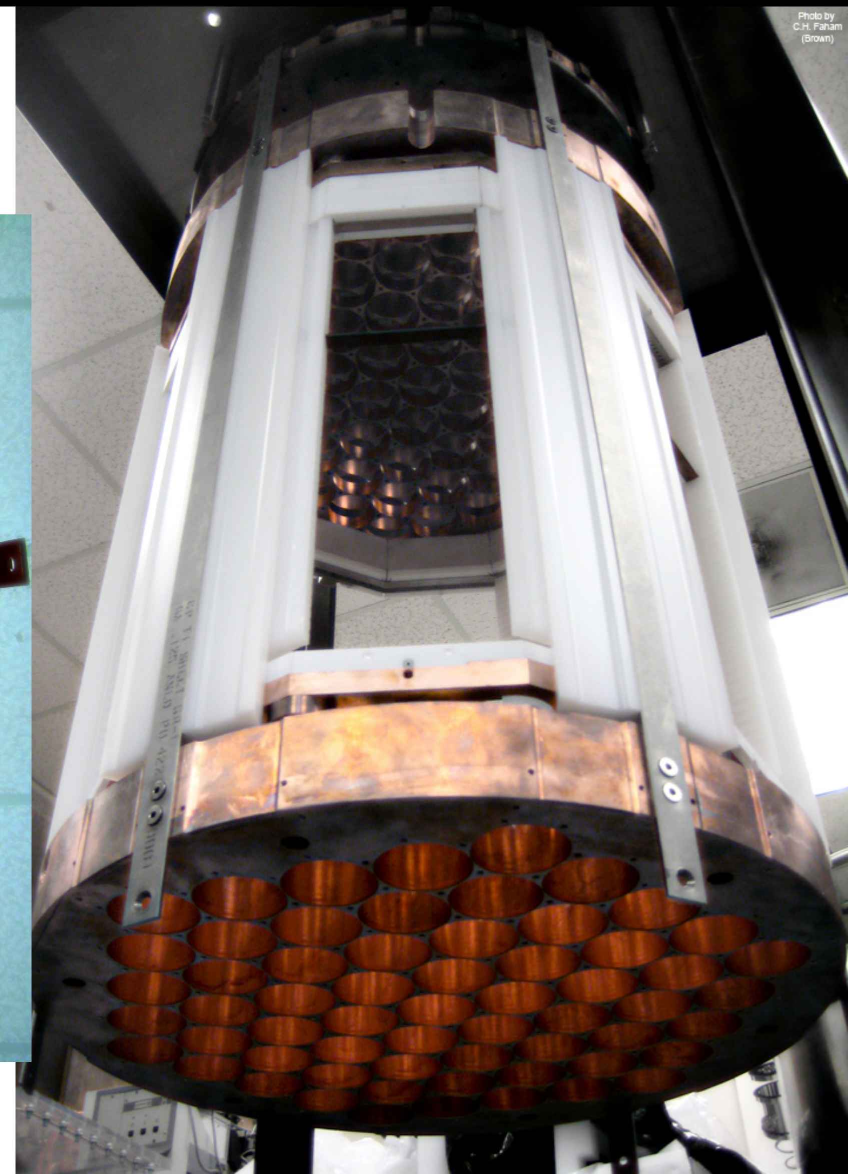


- Copper PMT holding plate

Internal Assembly

Assembly in progress at Texas A&M since early 2009





LUX0.1

Prototype LUX operating on surface at Case Western Reserve University

Includes all LUX components:

- Cryogenics
- Recirculation and purification
- Slow control and safety systems
- PMTs and HV
- Readout electronics
- Data acquisition
- Analysis software

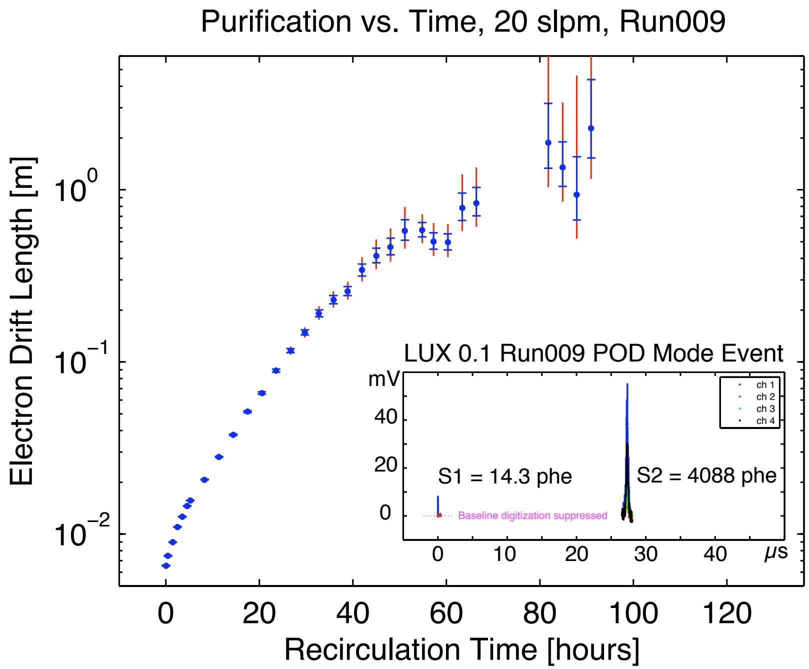
60 kg of liquid Xe viewed by 4 PMTs

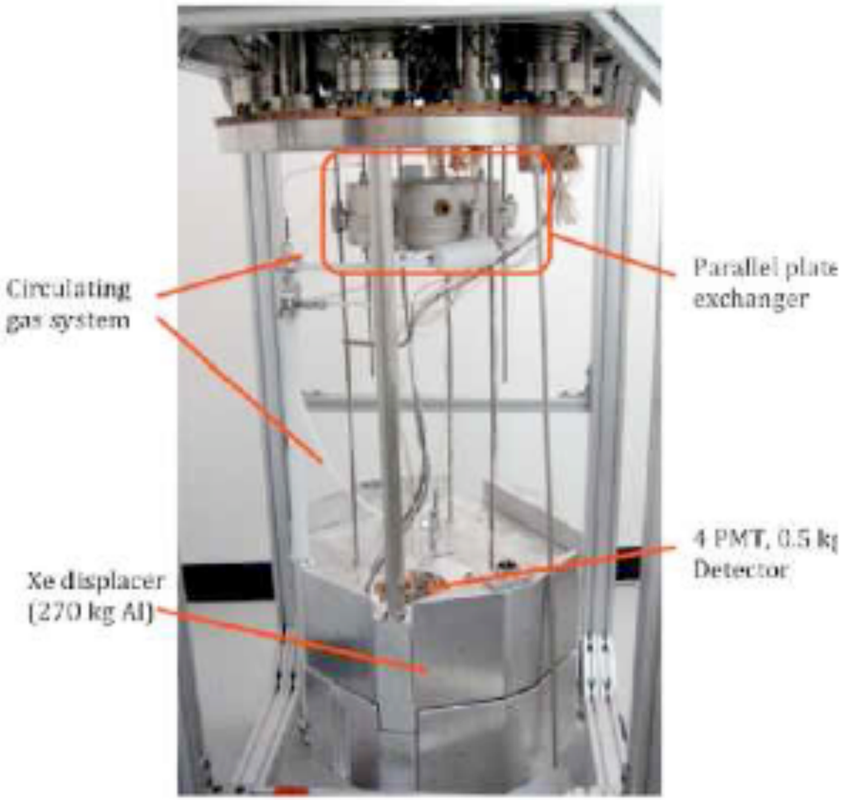
- Active region is ~5 cm tall

Xenon Purification System

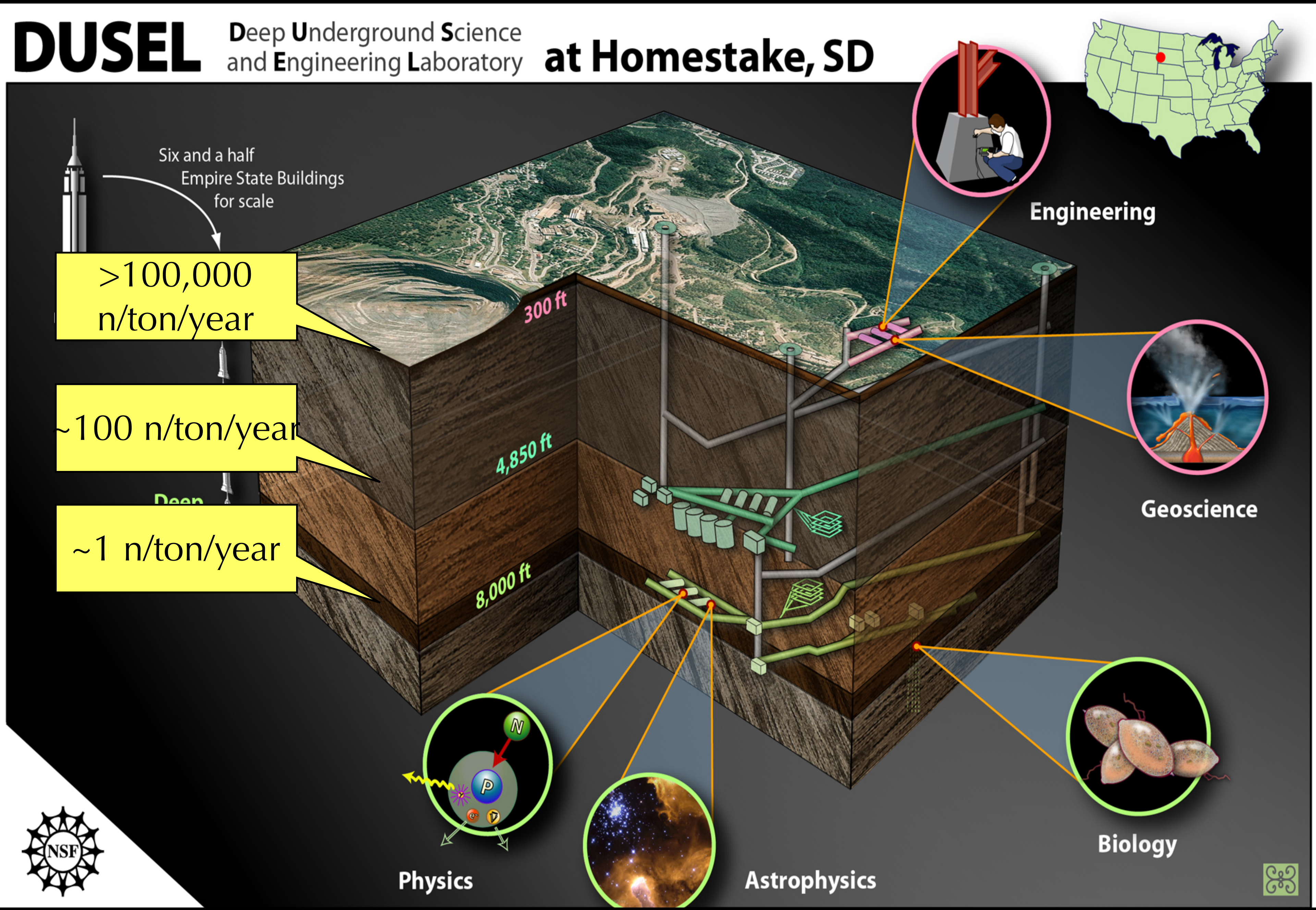
Operating on LUX0.1 containing 60 kg Xe

- 9 hour purification time constant
- Electron drift length >2m in 80 hours





- NB: internal surface area of LUX0.1 is identical to the full-scale LUX


DUSEL
Deep Underground Science
and Engineering Laboratory
at Homestake, SD
Six and a half
Empire State Buildings
for scale
>100,000
n/ton/year
~100 n/ton/year
~1 n/ton/year
300 ft
4,850 ft
8,000 ft
Engineering
Geoscience
Biology
Physics
Astrophysics
N
P
NSF

Sanford Laboratory

Feasibility demonstration prior to DUSEL

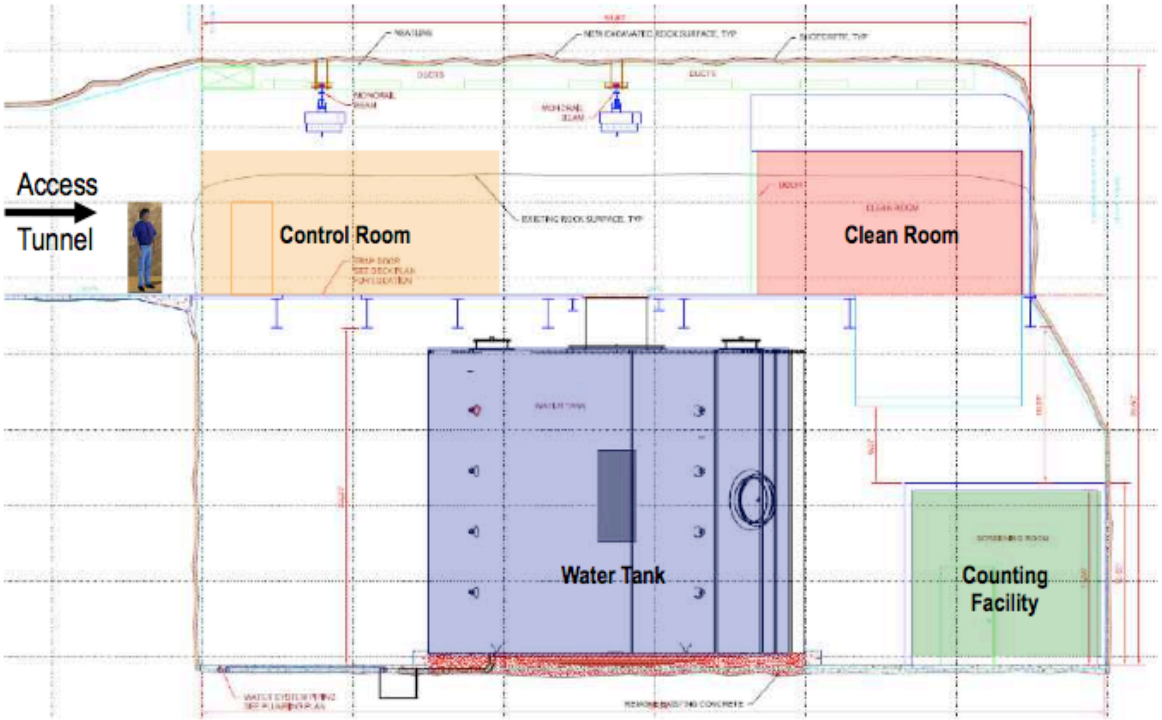
- $70M of $100M comes from a private donor

4,850 ft level (Davis Lab) outfitted for science programs

- LUX and Majorana are the initial occupants

Cavern will be ready in May 2010

- Two-storey 55′x30′x32′ space for LUX detector + clean room, control room, counting facility



Davis Lab 1964/2009

Surface Facility

Full scale LUX assembled and deployed in a surface building

- Building ready for occupancy as of November 30
- Exact duplicate of the underground layout except for the smaller (3 m) water tank

Detector integration in Jan-Feb followed by surface operation with 350 kg liquid Xe

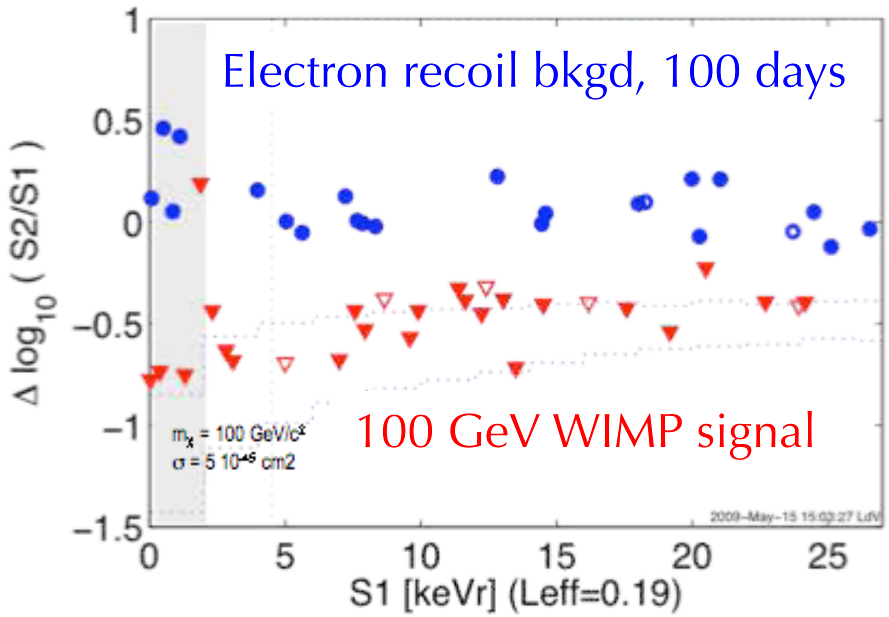
- Detector will be moved as-is when the 4850L lab is ready

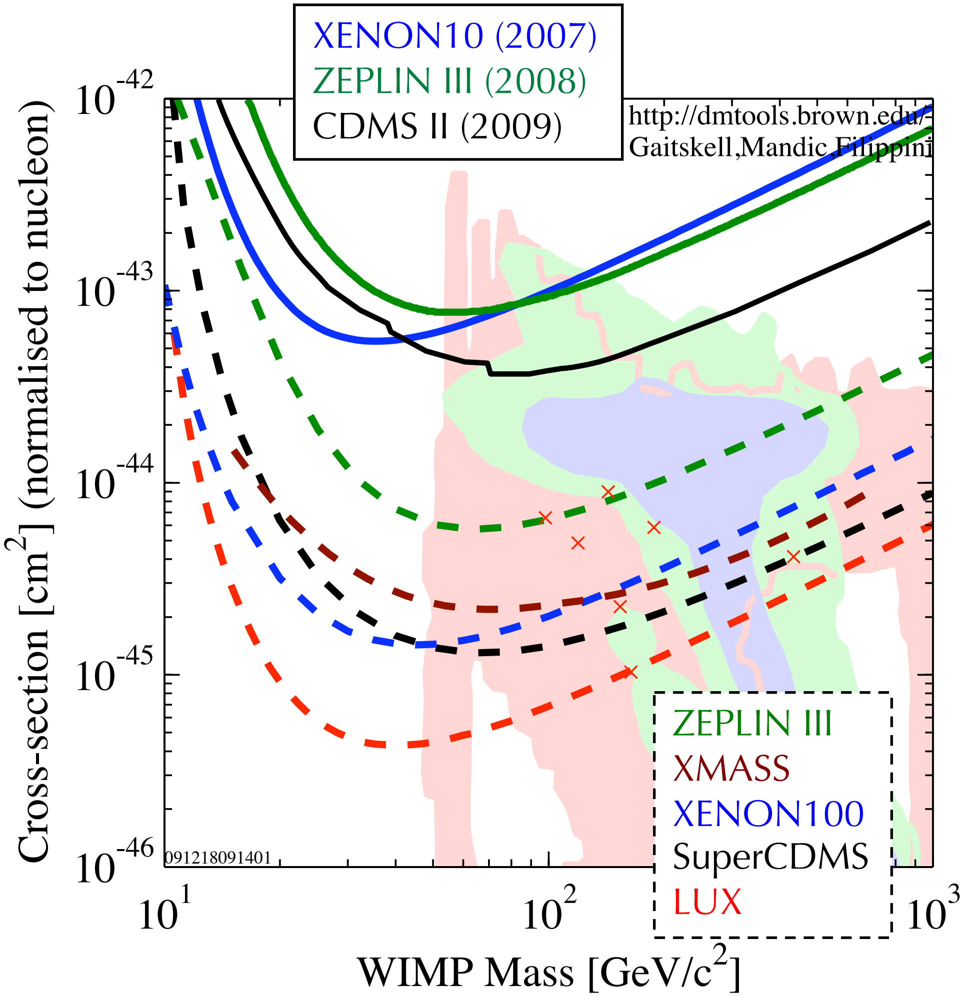
LUX Sensitivity

Will reach $\sigma_{\chi p} = 5\times10^{-46}$ cm^2 in 100 live days

- 50-to-100-fold improvement over the existing limit

If $\sigma_{\chi p} = 5\times10^{-45}$ cm^2 and $m_\chi = 100$ GeV, we will see:





Scaling Up Beyond LUX

How far can we scale the liquid Xe detector technology?

- Size isn't an issue — 3 tonne of liquid Xe is just 1 m^3
- Self-shielding improves with size — γ-ray background less important

Xe procurement: $1M/tonne

- World production is 45 tonne/year

Must keep the backgrounds low

- Instrumental radioactivity limits the fiducial volume
  - Develop 3″ PMTs with <1/1 mBq U/Th per tube
  - Control Rn contamination during the assembly
- Radioactivity inside Xe dominated by ^{85}Kr ➔ Bump up the purification system
- Cosmogonic neutrons ➔ Active shielding

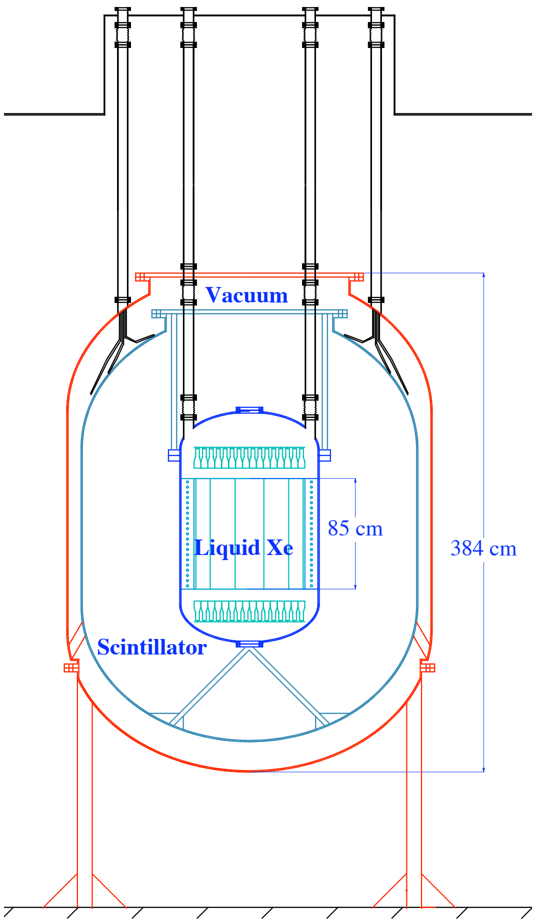
Ultimate limit: neutrino-nucleus coherent scattering @ 20 tonne

- Due to ^{8}B solar, atmospheric, and supernova neutrinos
- Fundamental limit of direct WIMP searches

LZS/LZD Projects

LZS (Sanford) = LUX scaled up to 1500 kg (1200 kg fiducial)

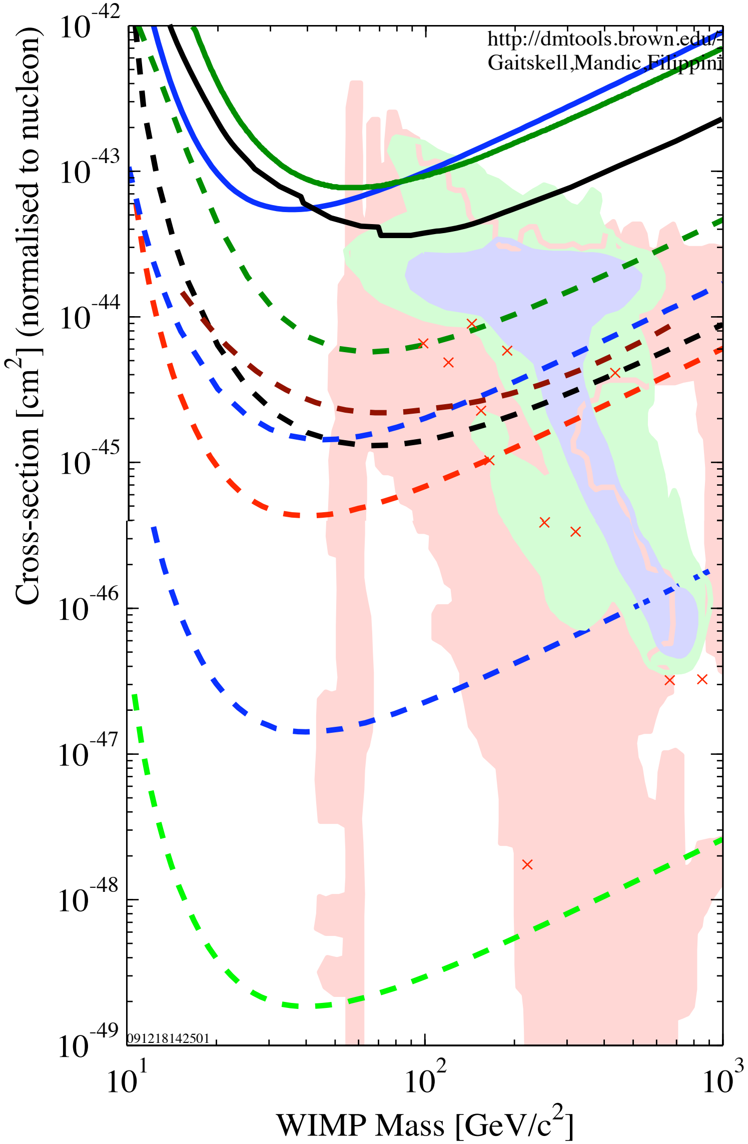
- Joint collaboration of LUX and ZEPLIN-III
- LUX infrastructure designed to accommodate LZ
- Liquid scintillator veto surrounds the detector to reduce cosmogenic neutron background and forward Compton scattering background
- Proposed for construction in 2010–2011 followed by 2012–2013 operation
- $\sigma_{\chi N} = 2\text{x}10^{-47}\ \text{cm}^2$ in 2 years



LZD (DUSEL) = 20 tonne concept

- 2 m diameter x 2 m height
- Construction 2013–2015, operation 2016–2019
- $\sigma_{\chi N} = 2\text{x}10^{-49}\ \text{cm}^2$ in 3 years

LZS/LZD Sensitivity



LUX: 100 kg x 300 days (2010–2011)

LZS: 1,200 kg x 500 days (2012–2013)

LZD: 13,500 kg x 1000 days (2016–2019)

Summary and Prospect

Dark Matter is a cosmology problem seeking a particle physics solution

- Evidences point to WIMPs waiting to be discovered
- Theoretical models suggest $\sigma_{\chi N} \approx 10^{-44}$–$10^{-45}$ cm^2

LUX experiment will use proven liquid Xe technology to reach $\sigma_{\chi N} = 5 \times 10^{-46}$ cm^2

- Covers 2-orders of magnitude of the theoretically favored region
- Dark Matter search run will start in 2010

LZS/LZD will push the sensitivity to $<10^{-48}$ cm^2 by 2019

We may know what Dark Matter is within this decade