# Direct Dark Matter Searches

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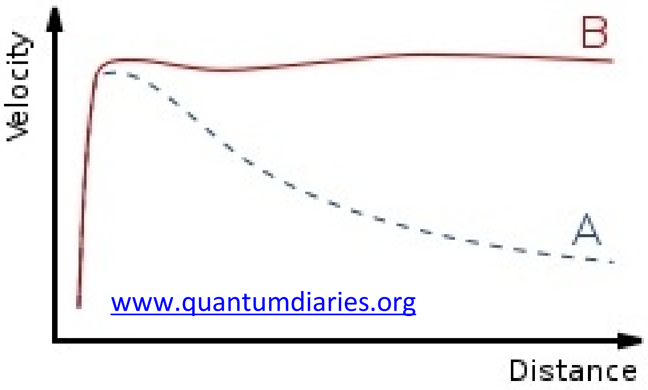
XXXIV Physics in Collision
Indiana University
September 20, 2014

# Evidence for Dark Matter

Galaxy rotation curves




The cosmic microwave background

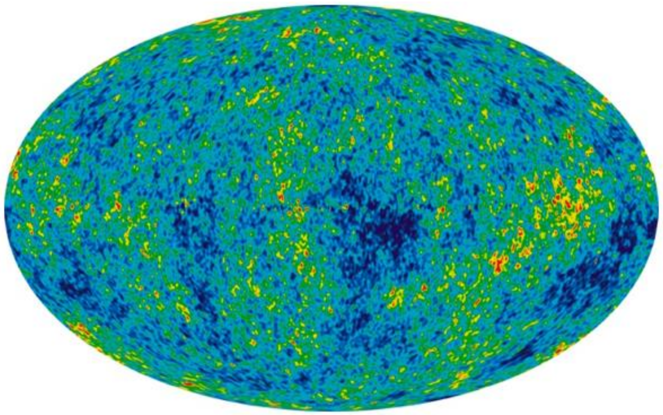


Image: ESA and the Planck collaboration

Gravitational lensing

Colley, Turner, Tyson, and NASA

- 27% of the energy composition of the universe
- Properties:
- Stable and electrically neutral
- Non-baryonic
- Non-relativistic, $v \sim 10^{-3}$
- Estimated local density: $0.3 \pm 0.1 \mathrm{GeV} \cdot \mathrm{cm}^{-3}$
- Candidates: WIMPs, axions, dark photons,...

# Composition of the Universe

The Higgs particle has been discovered, the last piece of the Standard Model.

But as successful as it has been, the Standard Model describes only 5% of the universe. The remaining 95% is in the form of dark energy and dark matter, whose fundamental nature is almost completely unknown.

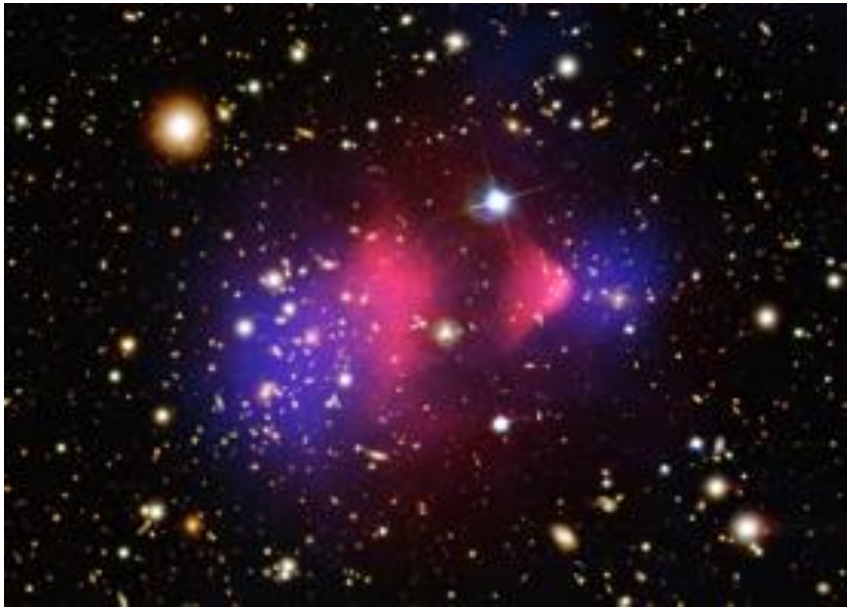
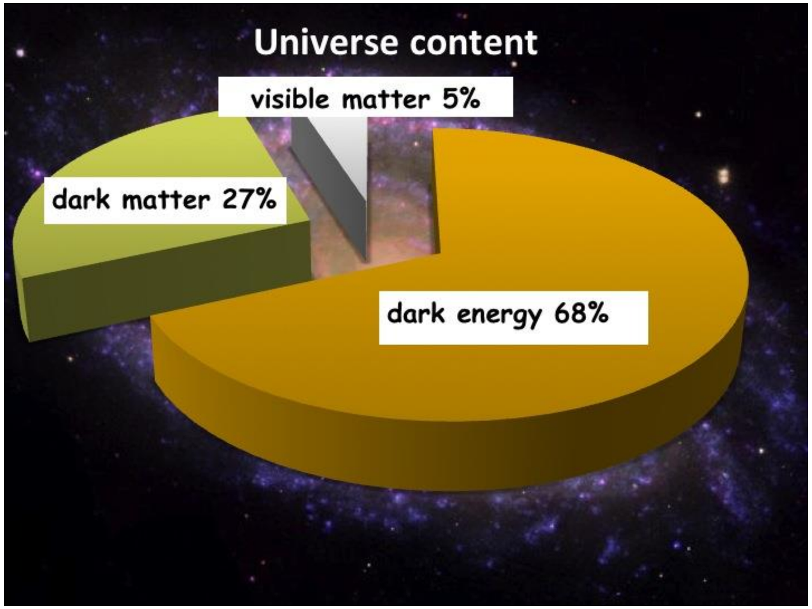


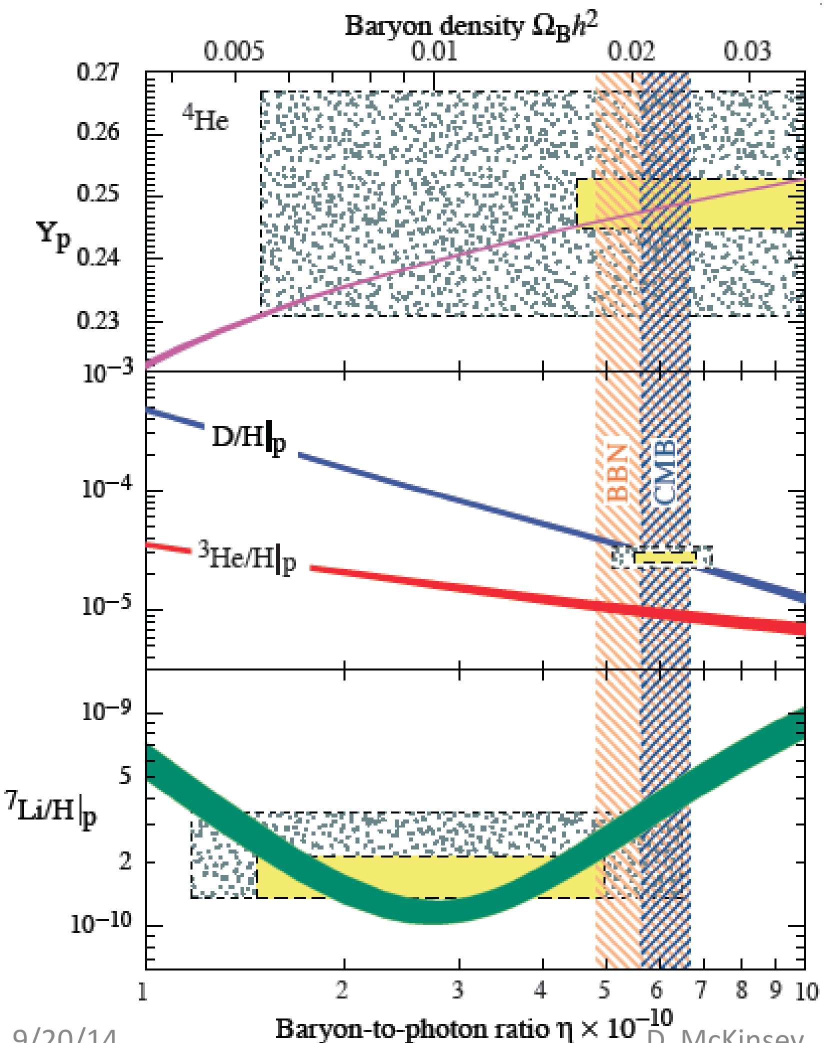
Image: X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

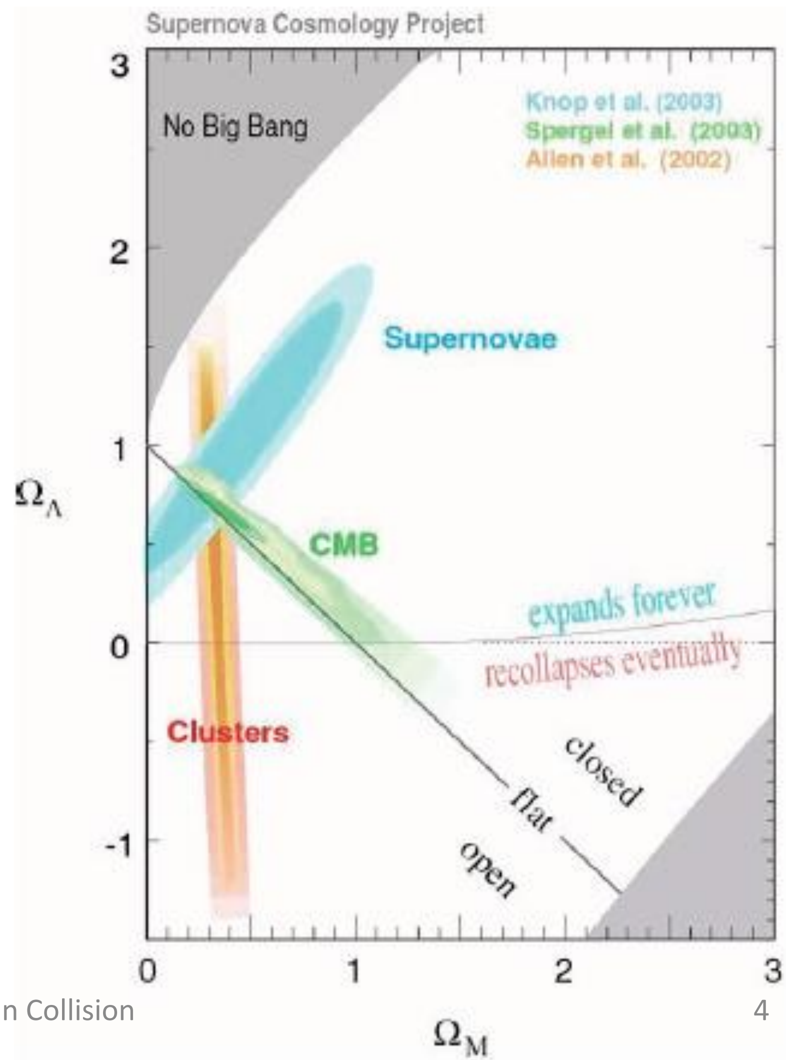



www.quantumdiaries.org

# Evidence for Dark Matter

Nucleosynthesis determines the density of baryons at early times; the amount of baryonic matter required is far smaller than the total quantity of matter.



# Weakly Interacting Massive Particles (WIMPs)

A new particle that only very weakly interacts with ordinary matter could form Cold Dark Matter

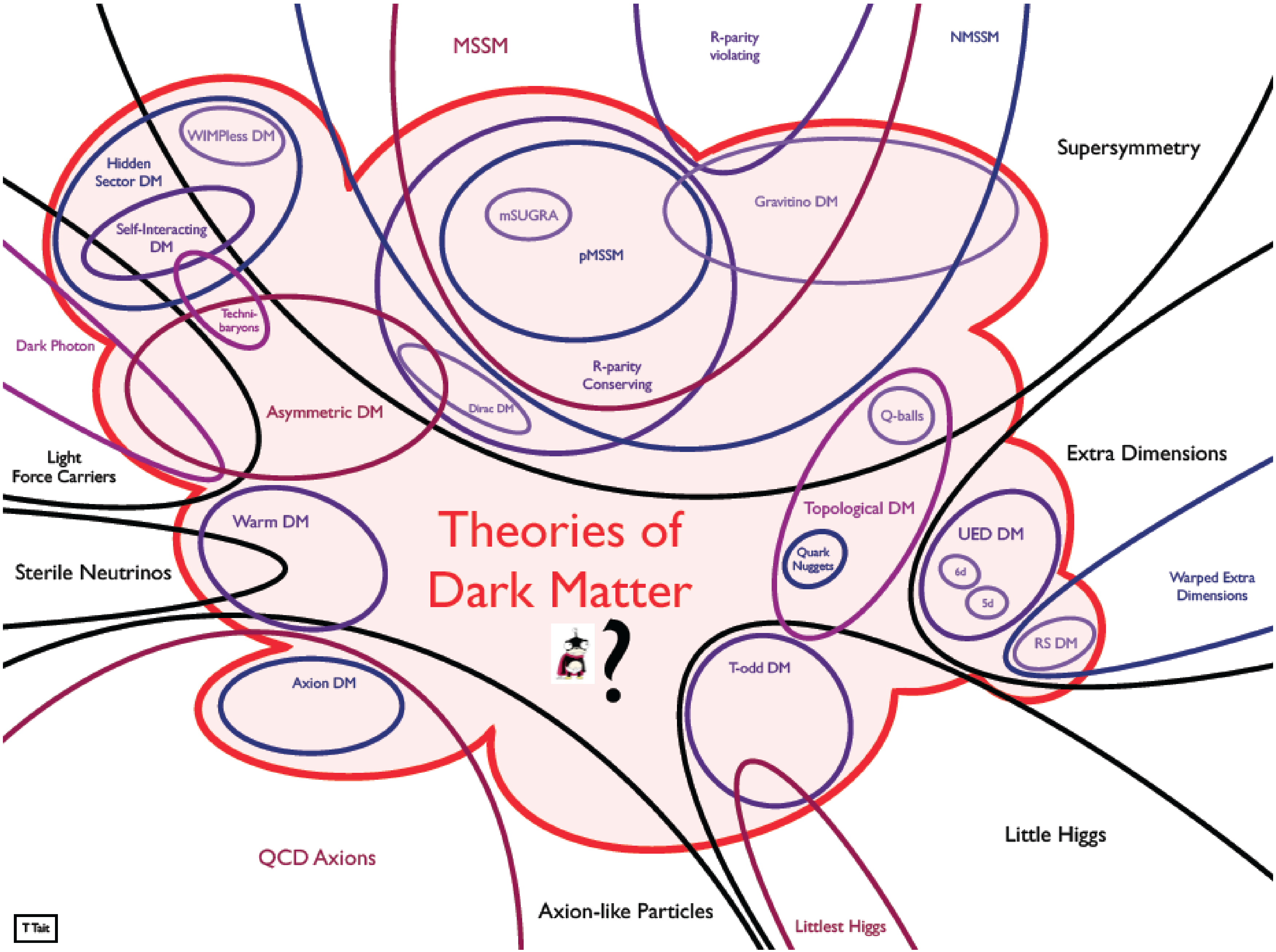
- Formed in massive amounts in the Big Bang.
- Non-relativistic freeze-out. Decouples from ordinary matter.
- Would exist today at densities of about $1000/m^3$.

Supersymmetry provides a natural candidate – the neutralino.

- Lowest mass superposition of photino, zino, higgsino
- Mass range from the proton mass to thousands of times the proton mass.
- Wide range of cross-sections with ordinary matter, from $10^{-40}$ to $10^{-50}$ $cm^2$.
- Charge neutral and stable!

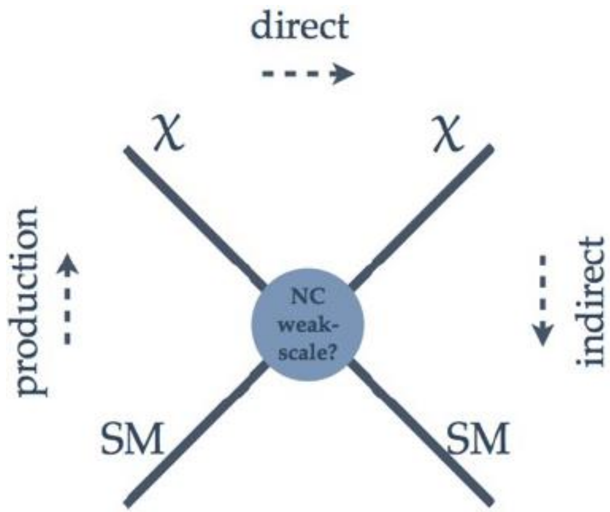
Universal Extra Dimensions: predicts stable Kaluza-Klein (KK) particles

- Similar direct detection properties as neutralino
- Distinguishable from neutralinos at accelerators

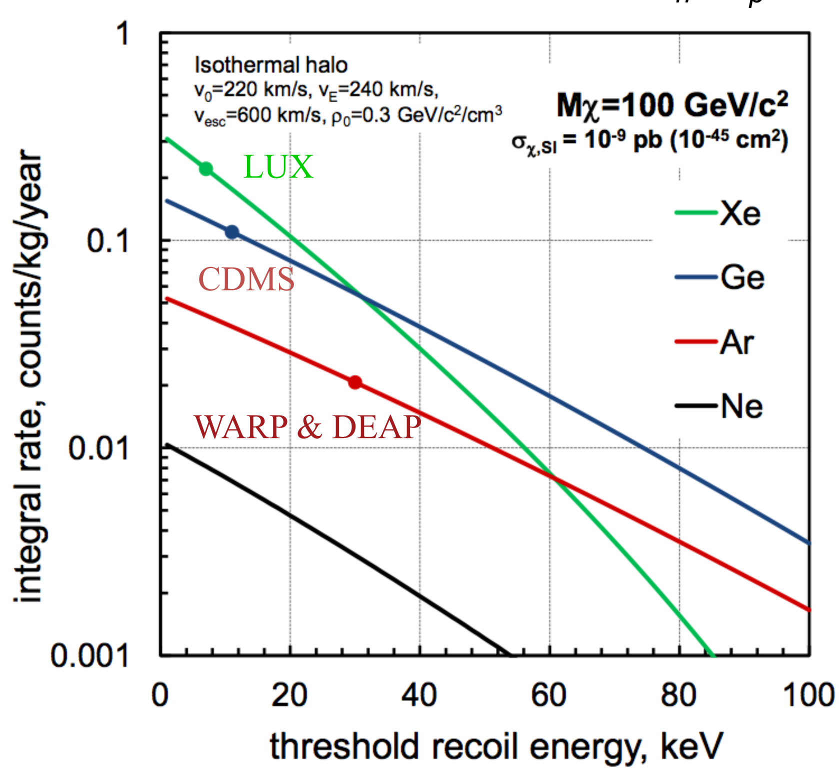

MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
R-parity Conserving
Dark Photon
Asymmetric DM
Dirac DM
Q-balls
Light Force Carriers
Extra Dimensions
Topological DM
Warm DM
Theories of Dark Matter
UED DM
Quark Nuggets
6d
5d
Sterile Neutrinos
Warped Extra Dimensions
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

# WIMP Direct Detection

Look for anomalous nuclear recoils in a low-background detector.
$R = N \rangle < \lceil v>$. From $<v>$ = 220 km/s, get order of 10 keV deposited.

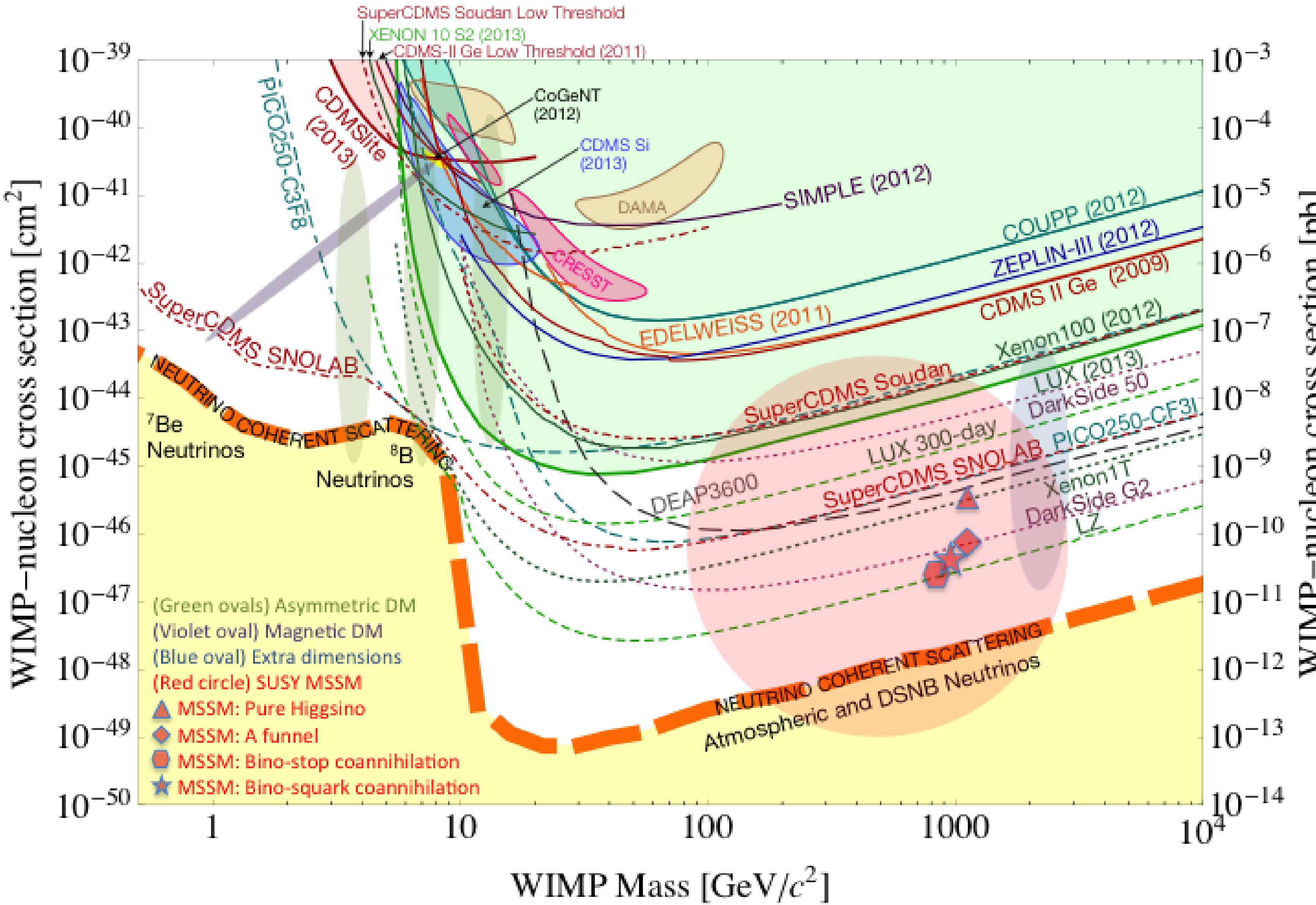


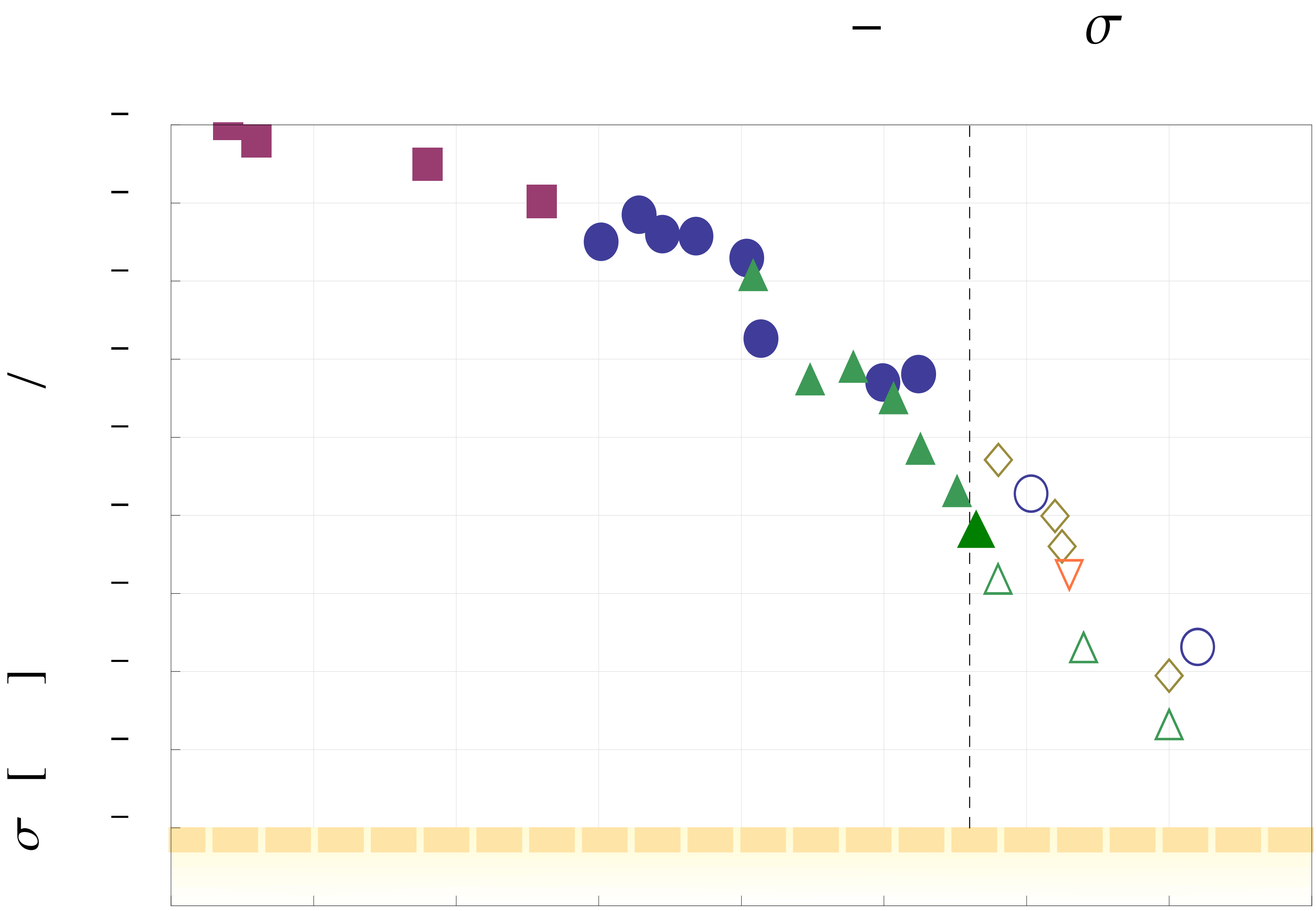

Spin-independent rates ($f_n = f_p$)



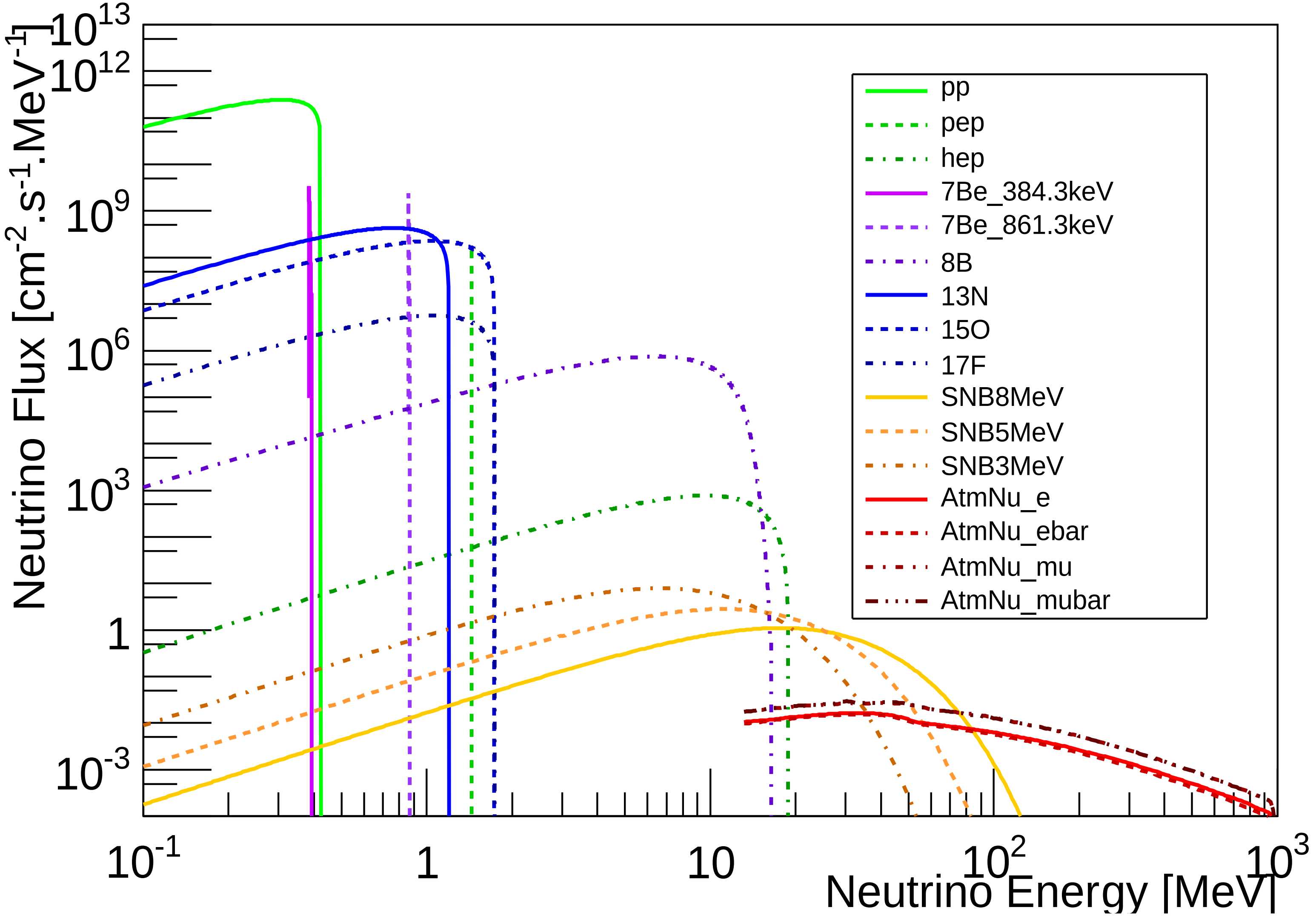

Requirements:
- Low radioactivity
- Low energy threshold
- Electron recoil rejection
- Scalability
- Deep underground lab

# Spin-Independent Limits



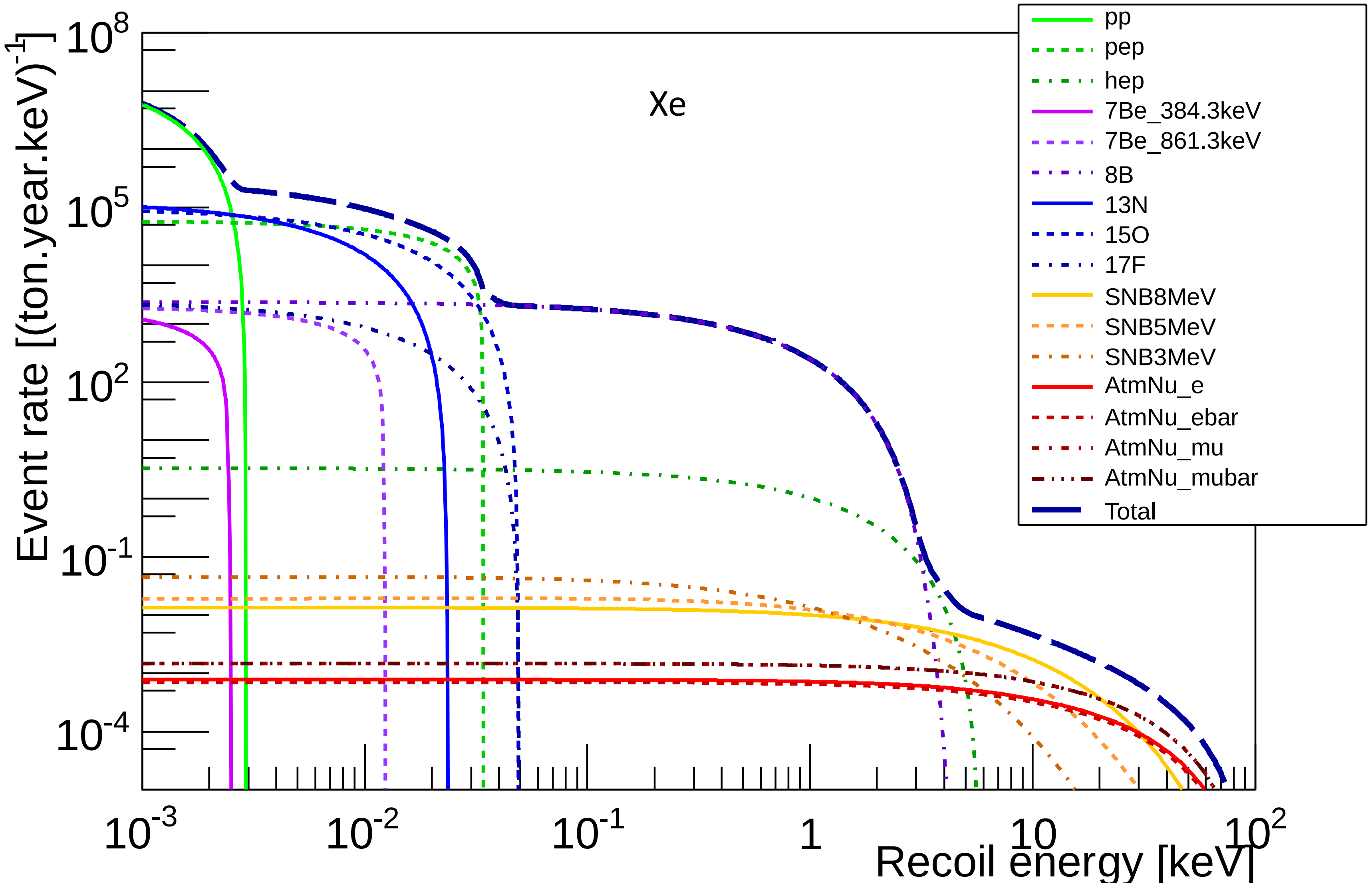


# Solar and atmospheric neutrino fluxes

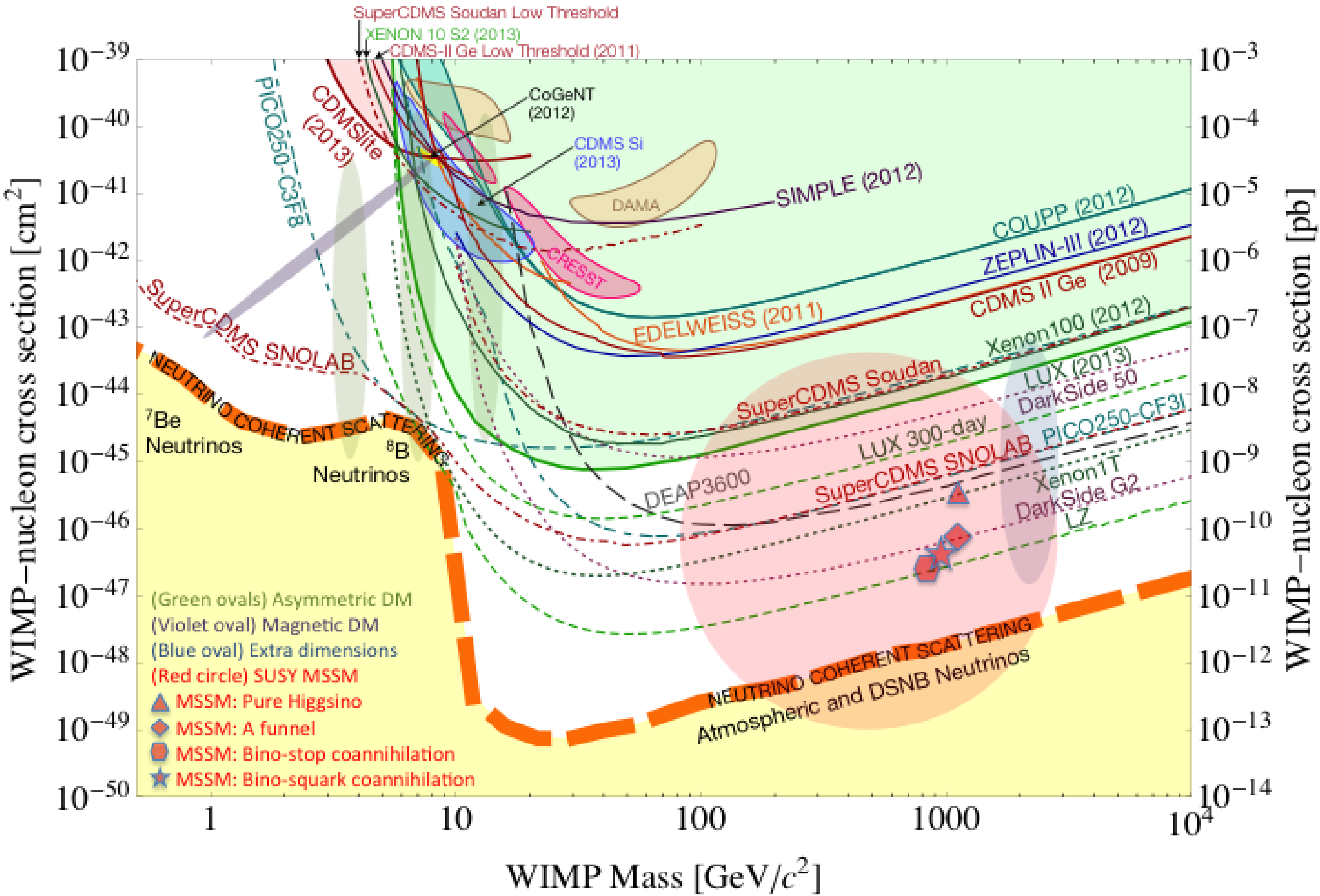


# Coherent neutrino-nucleus scattering events

(Billard, Strigari, and Figeroa-Feliciano, PRD 89, 023524 (2014)



# Spin-Independent Limits



# Effective Field Theory of Dark Matter Direction Detection

- Significant theory developments in direct detection, based on realization that nucleon velocities cannot in general be neglected, and that including momentum-dependent operators is more theoretically consistent than the standard Spin-Independent/Spin-Dependent formulation.
- Along with SI and SD, the effective WIMP-nucleon interaction also has Angular-Momentum-Dependent (LD) and Spin-and-Angular-Momentum-Dependent (LSD) responses. In addition, there are distinct responses from transverse and longitudinal spin-dependent responses.
- There can also be interference between operators, in addition to interference between neutron and proton response.
- If dark matter interactions are seen, then we will need multiple targets to map out the interaction physics. Also, a given target can have "blind spots", so multiple targets are needed to comprehensively search for WIMP interactions.
- See: J. Fan et al, arXiv:1008.1591, A. L. Fitzpatrick et al, arXiv:1203.3542, A. L. Fitzpatrick et al, arXiv:1211.2818, N. Anand et al, arXiv:1308.6288, N. Anand et al, arXiv:1405.6690.

# Nuclear form factors vary substantially by element

$$\frac{dN}{dE_R} \sim 5000\text{keV}^{-1}\left(\frac{\text{exposure}}{\text{kg}\cdot\text{day}}\right)\left(\frac{100\text{GeV}}{m_\chi}\right)^3 \mathcal{L}_{\text{int}}^2$$

Interaction terms

| | $S_n^2$ | $S_p^2$ | $L_n^2$ | $L_p^2$ | $(S_n \cdot L_n)^2$ | $(S_p \cdot L_p)^2$ |
|---|---|---|---|---|---|---|
| F | $8 \cdot 10^{-5}$ | 0.2 | 0.04 | 0.05 | 0.6 | 0.1 |
| Na | 0.0004 | 0.06 | 0.1 | 0.8 | 5.5 | 3.3 |
| Ge | 0.02 | $5 \cdot 10^{-6}$ | 1.1 | 0.003 | 35 | 100 |
| I | 0.004 | 0.07 | 0.4 | 2. | 100 | 500 |
| Xe | 0.02 | $2 \cdot 10^{-5}$ | 0.4 | 0.04 | 500 | 300 |

(from arxiv:1211.2828)

Xe has great LSD response!

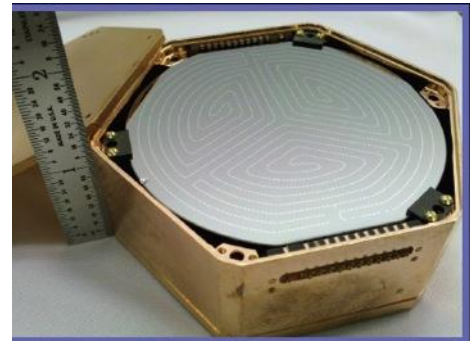
Over 50 proposed and existing experiments worldwide.
Summarized in SnowmassCF1 document: http://arxiv.org/abs/1310.8327
(Impossible to cover them all here)

| Experiment | Status | Target | Technique |
|---|---|---|---|
| **Cryogenic Solid State** | | | |
| SuperCDMS Soudan | Current | 9 kg Ge | Ionization, Phonons |
| SuperCDMS SNOLab | Planned | 200 kg Ge | Ionization, Phonons |
| SuperCDMS SNOLab | Planned | 400 kg Ge | Ionization, Phonons |
| Edelweiss | Current | 4 kg Ge | Ionization, Phonons |
| CRESST | Current | 10 kg CaWO4 | Scintillation, Phonons |
| EURECA | Planned | Ge; CaWO4 O(100-1000kg) | Ionization+Phonons; Scintillation+Phonons |
| CoGeNT | Current | 440 g Ge | Ionization |
| C-4 | Planned | 5.2 kg Ge | Ionization |
| TEXONO | Current | O(1kg)Ge | Ionization |
| CDEX | Current | O(1-10kg)Ge | Ionization |
| **Liquid Xenon** | | | |
| LUX | Current | 350 kg LXe | Ionization, Scintillation |
| LZ | Planned | 8000 kg LXe | Ionization, Scintillation |
| PandaX-1a | Current | 125 kg LXe | Ionization, Scintillation |
| PandaX-1b | Planned | 500 kg LXe | Ionization, Scintillation |
| PandaX-2 | Planned | 2400 kg LXe | Ionization, Scintillation |
| XENON100 | Current | 62 kg LXe | Ionization, Scintillation |
| XENON1T | Planned | 2500 kg LXe | Ionization, Scintillation |
| XENON10T | Planned | 20000 kg LXe | Ionization, Scintillation |
| XMASS-I | Current | 835 kg LXe | Scintillation |
| XMASS-1.5 | Planned | 5000 kg LXe | Scintillation |
| XMASS-II | Planned | 20000 kg LXe | Scintillation |
| **Liquid Argon** | | | |
| DarkSide-50 | Current | 50 kg LAr | Ionization, Scintillation |
| DarkSide-G2 | Planned | 5000 kg LAr | Ionization, Scintillation |
| ArDM | Current | 1 ton LAr | Ionization, Scintillation |
| MiniCLEAN | Current | 500 kg LAr/LNe | Scintillation |
| DEAP-3600 | Current | 3600 ton LAr | Scintillation |
| CLEAN | Planned | 40 ton LAr/LNe | Scintillation |

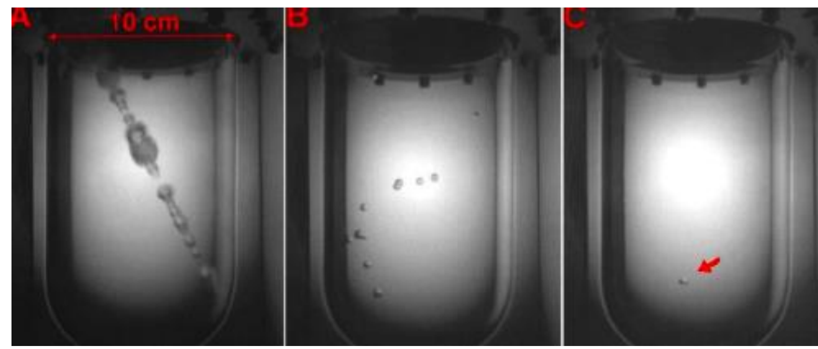
| | | | |
|---|---|---|---|
| **Crystal and Annual Modulation** | | | |
| DAMA/LIBRA | Current | NaI | Europe |
| ELEGANT | Current | NaI | Japan |
| DM-Ice17 | Current | 17 kg NaI(Tl) | Scintillation |
| DM-Ice | Planned | 250 kg NaI(Tl) | Scintillation |
| Princeton NaI | Planned | NaI | Scintillation |
| ANAIS | Planned | 250 kg NaI | Scintillation |
| CINDMS | Planned | 100 kg CsI(Na) | Scintillation |
| KIMS | Current | cesium iodide | Scintillation |
| **Superheated Liquids** | | | |
| COUPP-60 | Current | CF3I | Bubbles |
| COUPP-1T | Planned | CF3I | Bubbles |
| PICASSO | Current | C4F10 | Bubbles |
| Pico | Planned | 250 kg CF3I | Bubbles |
| SIMPLE Phase III | Current | 1-2 kg C2ClF5 | Bubbles |
| SIMPLE Phase IV | Planned | 1000 kg C2ClF5 | Bubbles |
| **Directional Detection** | | | |
| DRIFT-IId | Current | 139 g CS2, CS4 | Ionization |
| DRIFT-III | Planned | 10s of kg CS2, CS4 | Ionization |
| DMTPC | Current | CF4 gas | Ionization |
| D^3 | Planned | | Ionization |
| MIMAC | Planned | | Ionization |
| Newage | Planned | | Ionization |
| **New Ideas** | | | |
| Columnar recombination | Planned | Xe gas | Ionization, Scintillation |
| DAMIC | Current | Silicon | Ionization |
| Liquid He-4 | Planned | 1-100 kg LHe | Ionization, Scintillation, Rotons |
| DNA | Planned | Gold | Broken DNA bonds |
| Nuclear emulsions | Planned | few 10s of kg emulsion | silver grains and microscopy |

# WIMP Direct Detection Technologies

- Cryogenic detectors (CDMS, Edelweiss, CRESST): Excellent background rejection, low threshold and good energy resolution.



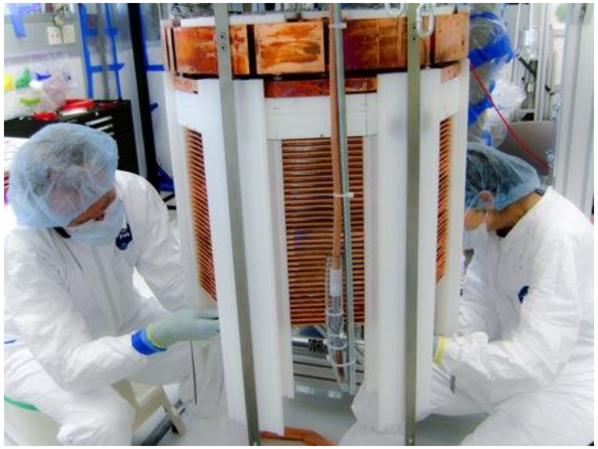
- Threshold detectors (COUPP, SIMPLE, PICASSO): Ultimate electron recoil rejection, inexpensive, easy to change target material for both SI and SD sensitivity.




- Single-phase LAr, LXe (DEAP, CLEAN, XMASS): Simple and relatively inexpensive per tonne, pulse-shape discrimination and self-shielding.

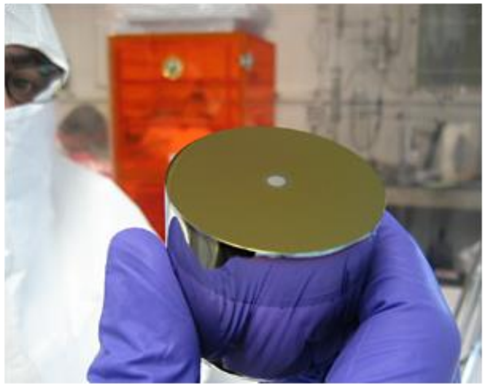
# WIMP Direct Detection Technologies

- Dual-phase Ar (DarkSide, ArDM): Excellent electron recoil rejection, position resolution.



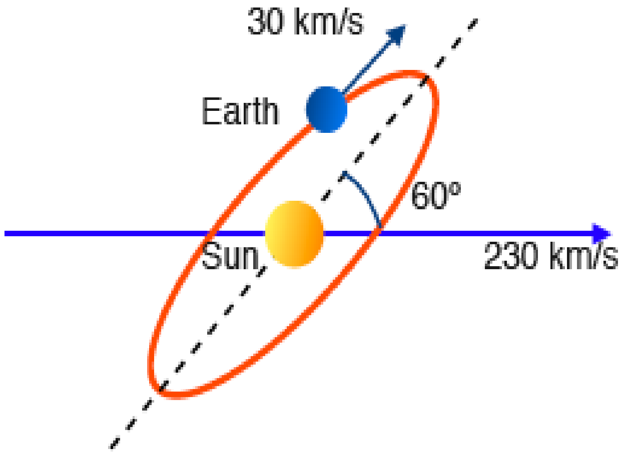
- Dual-phase Xe (XENON, LUX, Panda-X): Suitable target for both SI and SD, low energy threshold, excellent position resolution, self-shielding.

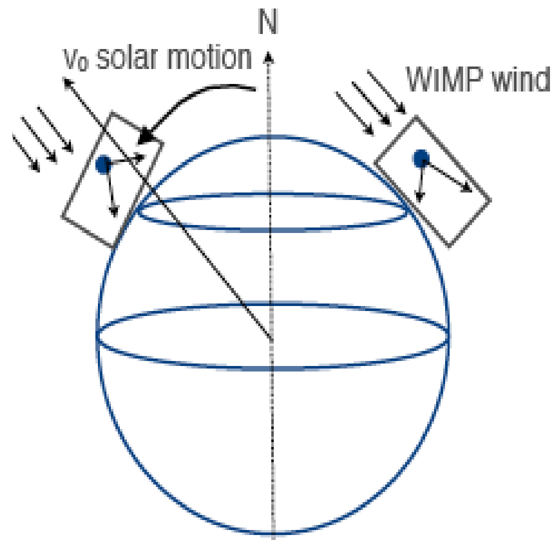
- Scintillating crystals (DAMA/LIBRA, KIMS, ANAIS, ELEGANT, DM-Ice): Annual modulation with large target mass.

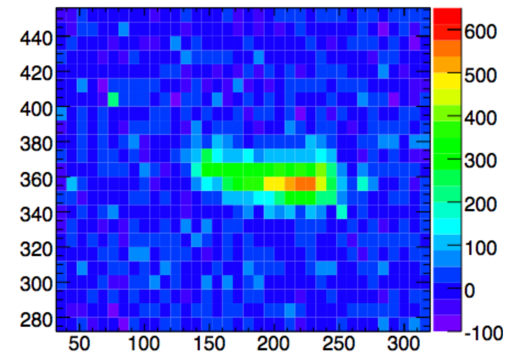


- Ionization detectors (CoGeNT, DAMIC): Very low energy threshold, good energy resolution.

# WIMP Directional Detectors
# (DRIFT, DMTPC, D^3, MIMAC, NEWAGE, NEXT/Osprey)



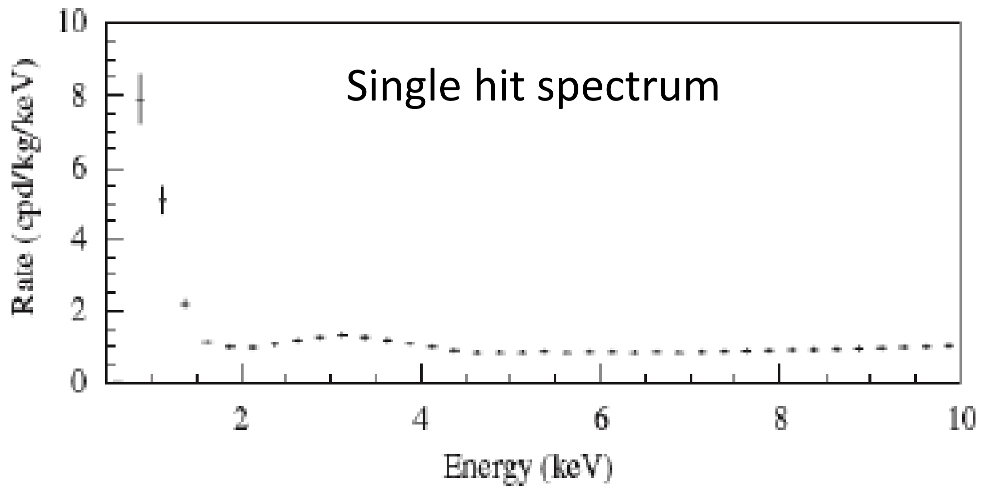

In the long run, directional detection will allow one to map out the velocity distribution of the dark matter in the galactic halo, and could serve as an important input to modeling of the detailed formation history and dynamics of the galaxy.

# DAMA

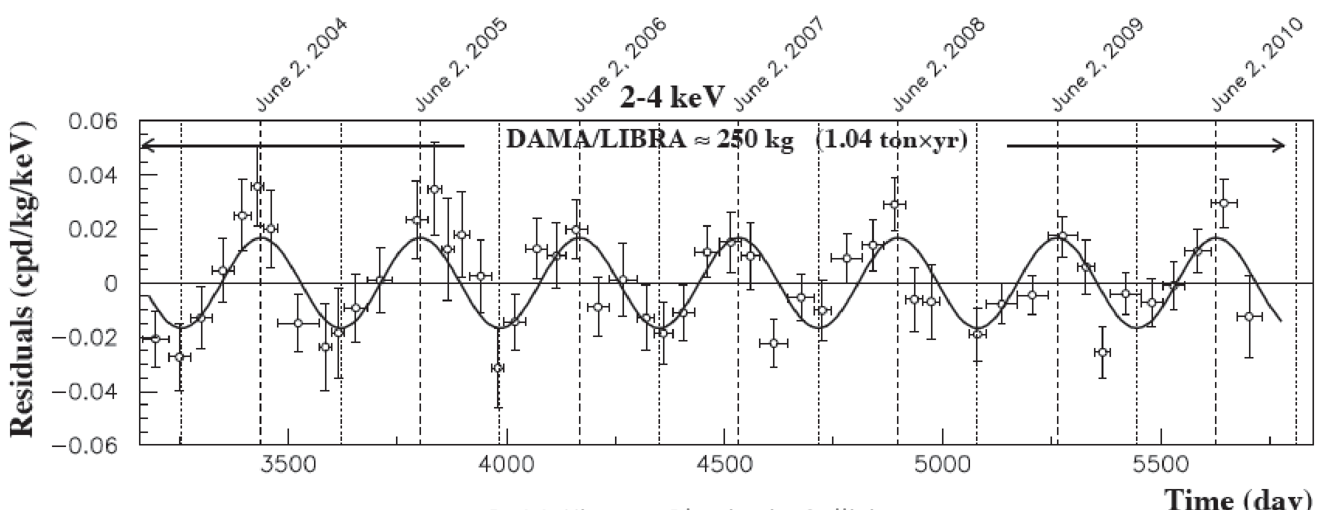
Array of NaI detectors, with PMT readout
DAMA/NaI: 100 kg of NaI(Tl)
DAMA/LIBRA: 250 kg of NaI(Tl)

Annual modulation of 2-6 keV single hits, with 9.3 sigma significance, attributed to variation of the
Earth rotates around the Sun.

No modulation at higher energies
No modulation of multiple hit events




New runs: DAMA has been operating with high-QE phototubes since Dec 2010.



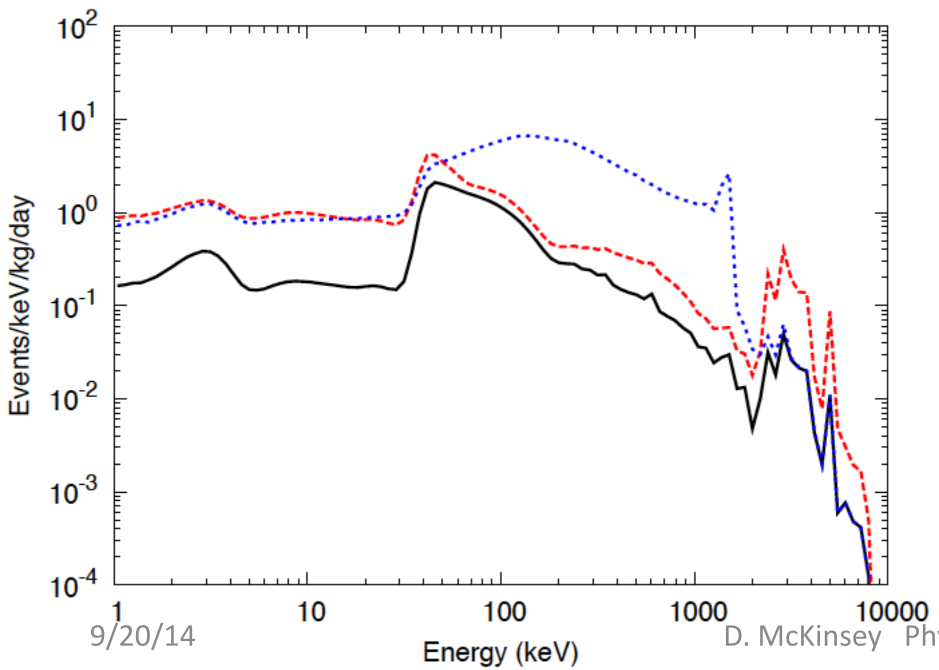
# DAMA background studies

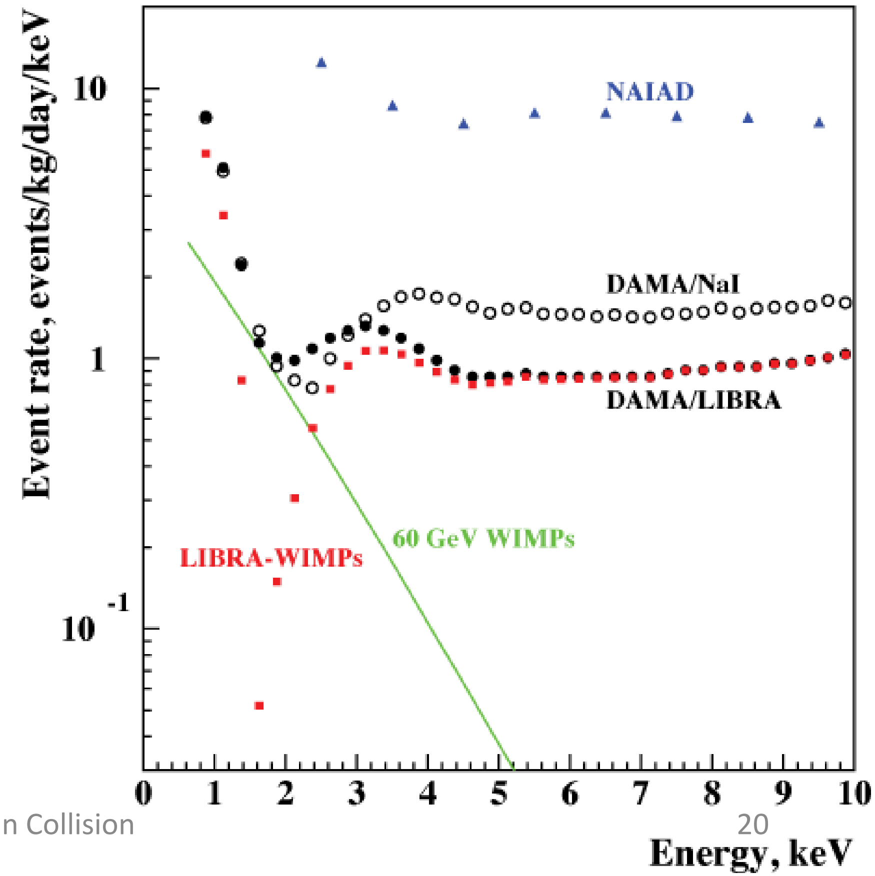
Annual modulation is an unexplained mystery.

Subtracting WIMP spectrum from measured spectrum predicts a minimum in background spectrum from 1.5 – 2 keV. This is difficult to obtain from background simulations.

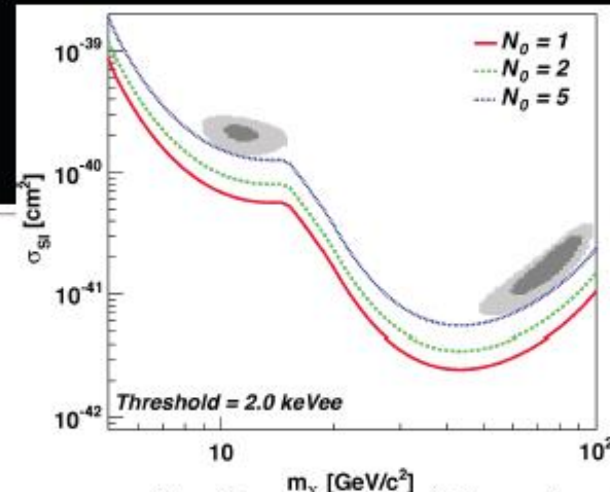
Little room for continuous, non-modulated part of WIMP signal when backgrounds are included. See Kudryavtsev et al, *Astroparticle Phys.*, **33** (2010) 91-96

Simulated background spectra



# DM-ICE Phases



Cherwinka *et al.* Astropart. Phys. 35 (2012)

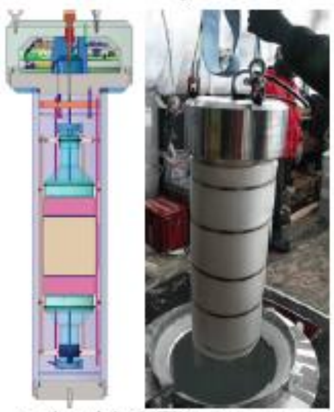
**Goal:**

Unambiguously test DAMA claim

- Exclusion within 500 kg*yr

**Experimental Phases:**

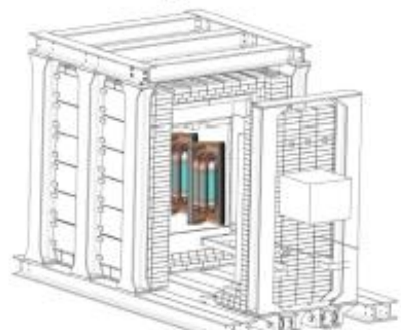
**DM-ICE17**



17 kg NaI(Tl) at 2450 m under South Pole ice

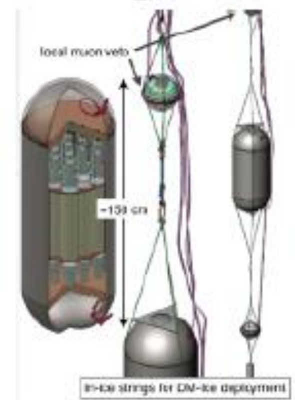
Operating since 2011

**DM-ICE250 North**



2x125 kg NaI(Tl) modules at underground lab

**DM-ICE250 South**




Same detectors deployed at South Pole (as necessary)

# Annual Modulation Dark Matter Searches with NaI Detectors

| | | | | |
|---|---|---|---|---|
| **Northern Hemisphere** | Gran Sasso<br>**DAMA/Libra**<br>250kg<br>running | Gran Sasso<br>**SaBRE**<br>R&D | Canfranc<br>**ANAIS**<br>250 kg<br>starting in 2014? | **PICO-LON**<br>**KIMS**<br>etc… |
| **Southern Hemisphere** | South Pole<br>**DM-Ice**<br>17 kg running<br>R&D for 250 kg | | | ice rock |

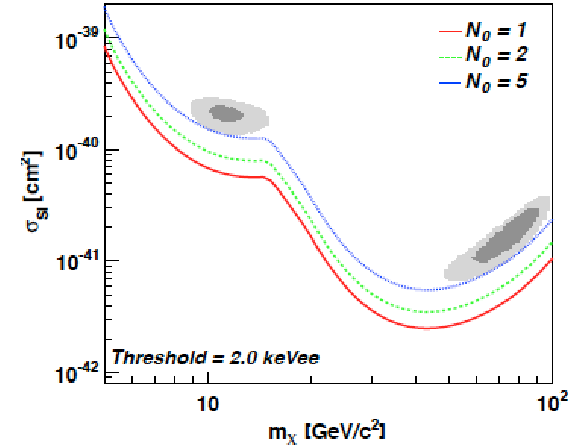
Several Groups conducting ultra-pure crystal with several vendors to go to the full scale

**DM-Ice:**

- NaI dark matter search in an entirely different environment
- South Pole offers:
  - Ultra-clean and ultra-stable environment
  - Seasonal variation unambiguously different from dark matter modulation
  - IceCube offers muon monitoring and veto as well as experience
  - NSF-run South Pole Station for logistical support

# Physics Program for DM-Ice

**Directly test DAMA's assertion that the observed annual modulation is due to dark matter & understand its origin**




**500 kg•years**
(2 - 4 keV) with 1, 2, and 5 dru background (DAMA has ~1 dru)

- probes longest-standing dark matter claim
- NaI(Tl) target
- aims to understand origin of DAMA's signal
- only experiment with access to both Northern & Southern Hemispheres

A Phased Experimental Program

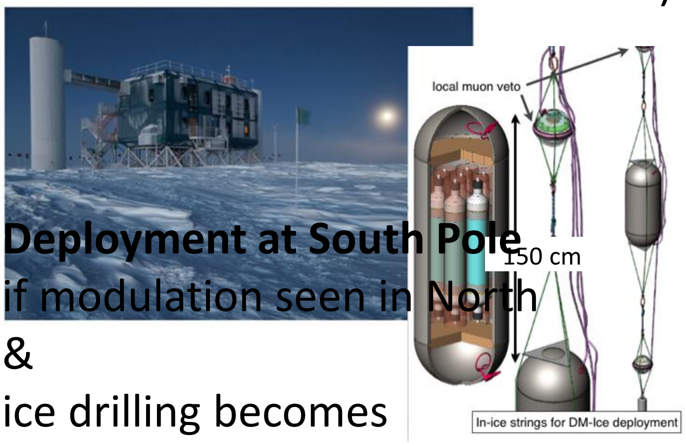
DM-Ice17

**Operating since 2011**
17 kg of NaI(Tl) at 2450m depth at South Pole

DM-Ice 250 North

**Northern Hemisphere Run**
portable 250 kg NaI(Tl) detector,
first deployment in the Northern Hemisphere

DM-Ice 250 South




**Deployment at South Pole**
if modulation seen in North
&
ice drilling becomes available

Astropart.Phys. 35 (2012) 749-754

# New Low-Background NaI(Tl) Crystals

Development of NaI(Tl) detectors with Alpha Spectra, Inc (ASI) in CO, USA

Three groups work with Alpha Spectra: DM-Ice, ANAIS, KIMS.

Communication and sharing of R&D results

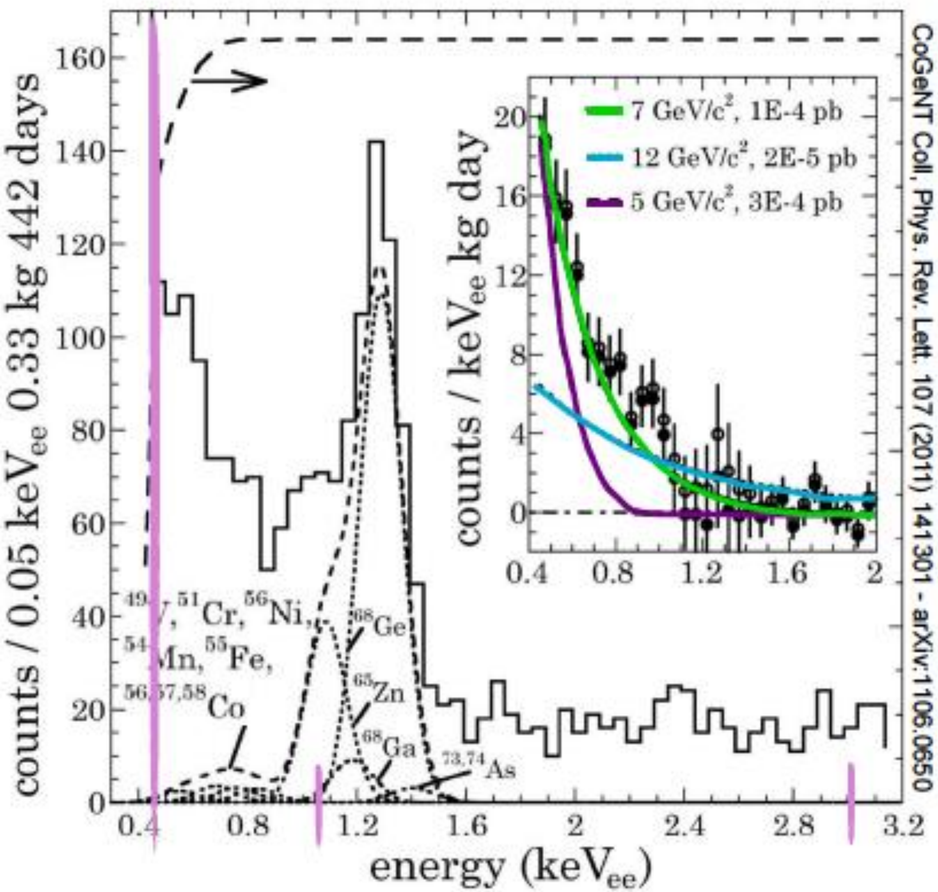
- 2 x 18 kg crystals from Alpha Spectra are at Fermilab MINOS near hall for testing.

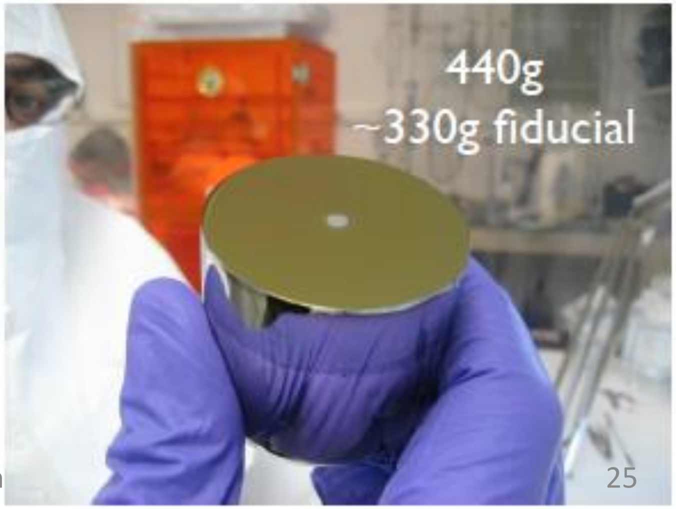
- If these crystals confirm specifications, total of 250 kg can be grown and encapsulated as detectors at ASI in less than 12 months.

Backgrounds are within acceptable levels for an experiment with 2 counts/day/keV/kg.
Sufficient to test the DAMA signal at > 5σ with 3 years of data.

# CoGeNT

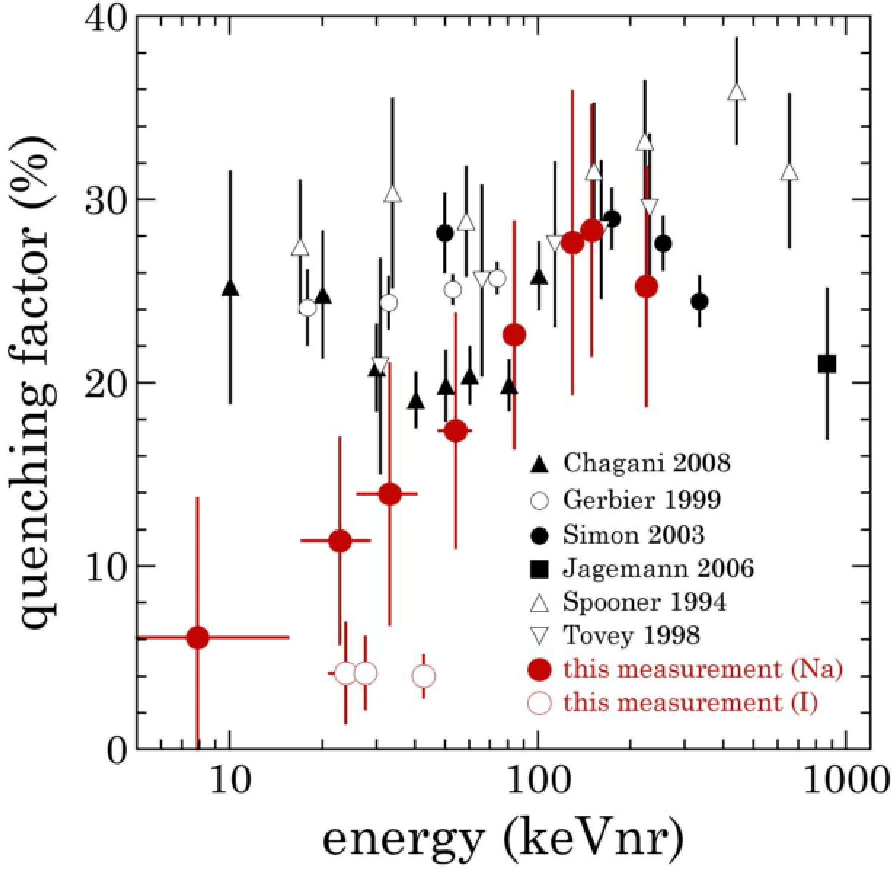
Technology: P-type, point contact Germanium detectors

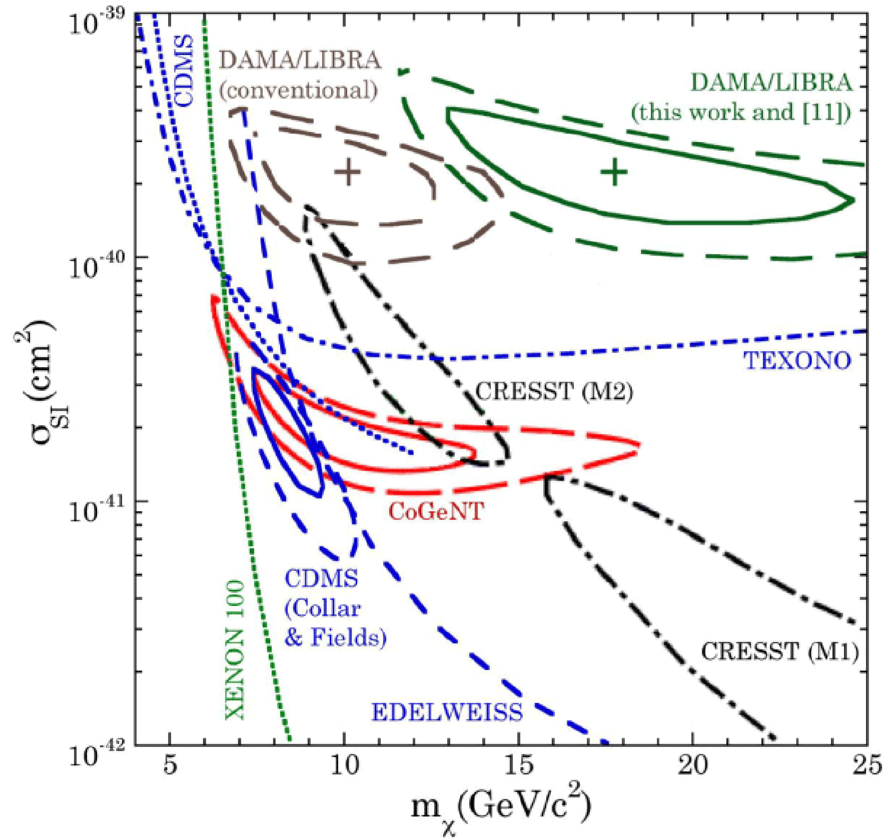


# NaI quenching factor

How much scintillation light is produced by nuclear recoils, relative to electron recoils
New measurement: J. Collar, arXiv:1302.0796, arXiv:1303.2686
Hard to see how DAMA could be consistent with CoGeNT anomaly

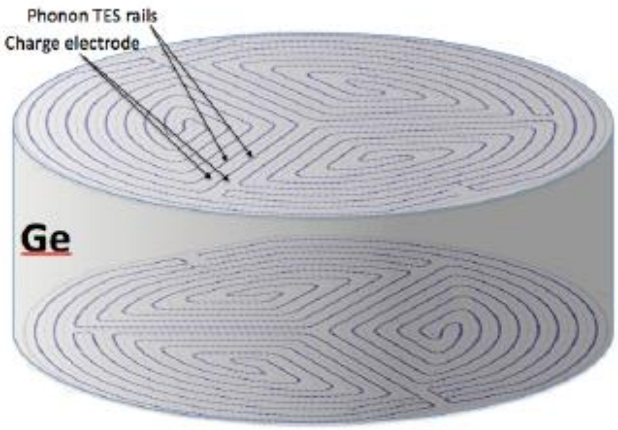


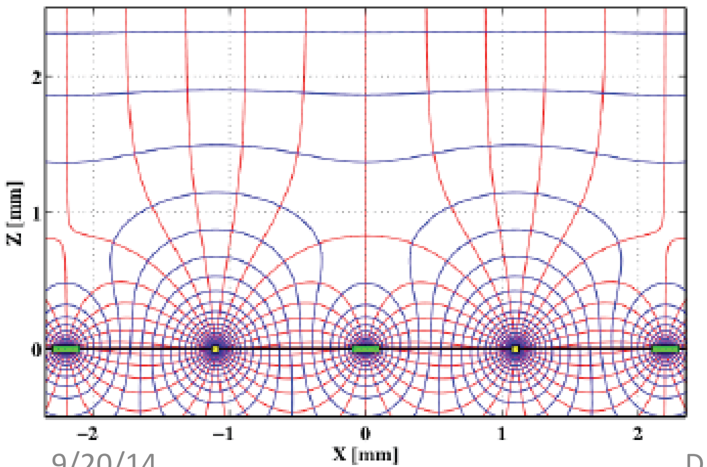



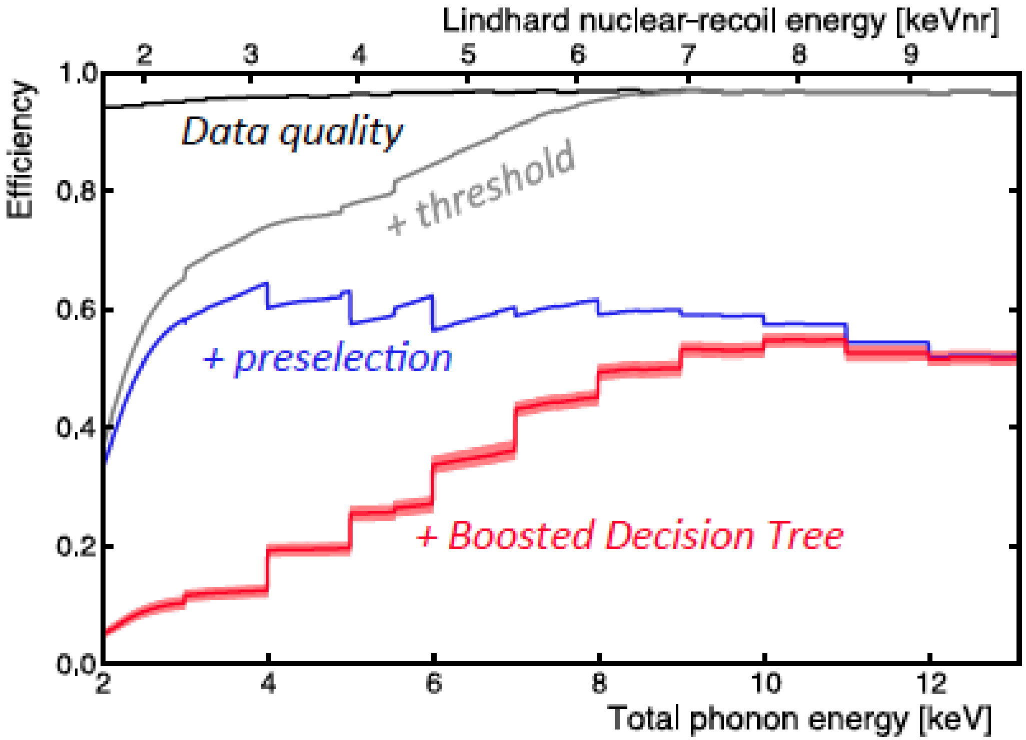
# SuperCDMS

New iZip detectors have interleaved z-sensitive ionization and phonon sensors on both faces
Charge near the surface of the detector is collected on only one side
Charge in the bulk is collected on both faces
15 iZIPs are in the Soudan infrastructure built for CDMS-II

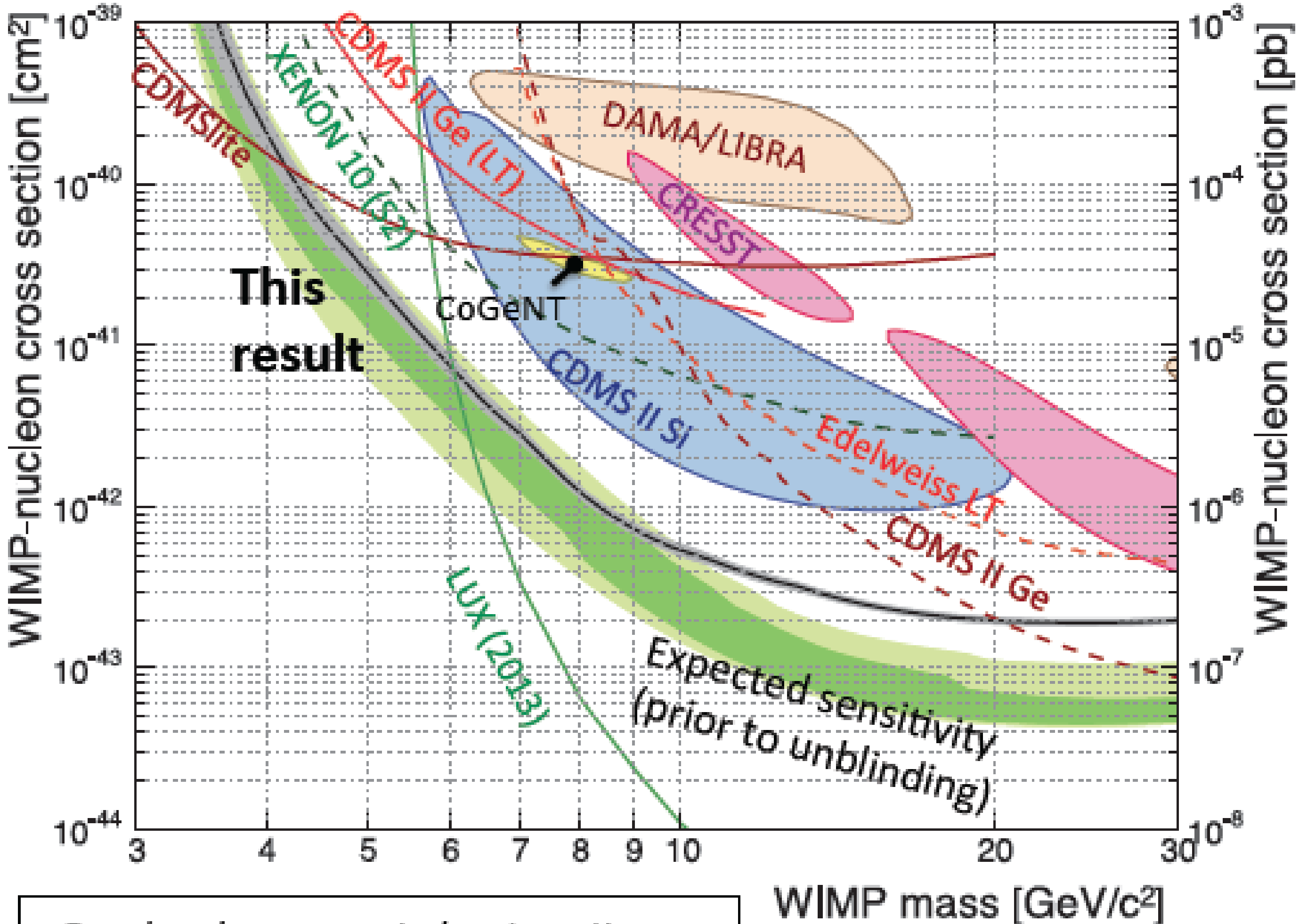
Lauren Hsu, UCLA Dark Matter 2014



# New SuperCDMS Results




*Gray bands: propagated systematic unc. from fiducial volume + nuclear recoil energy scale + trigger efficiency*

L. Hsu

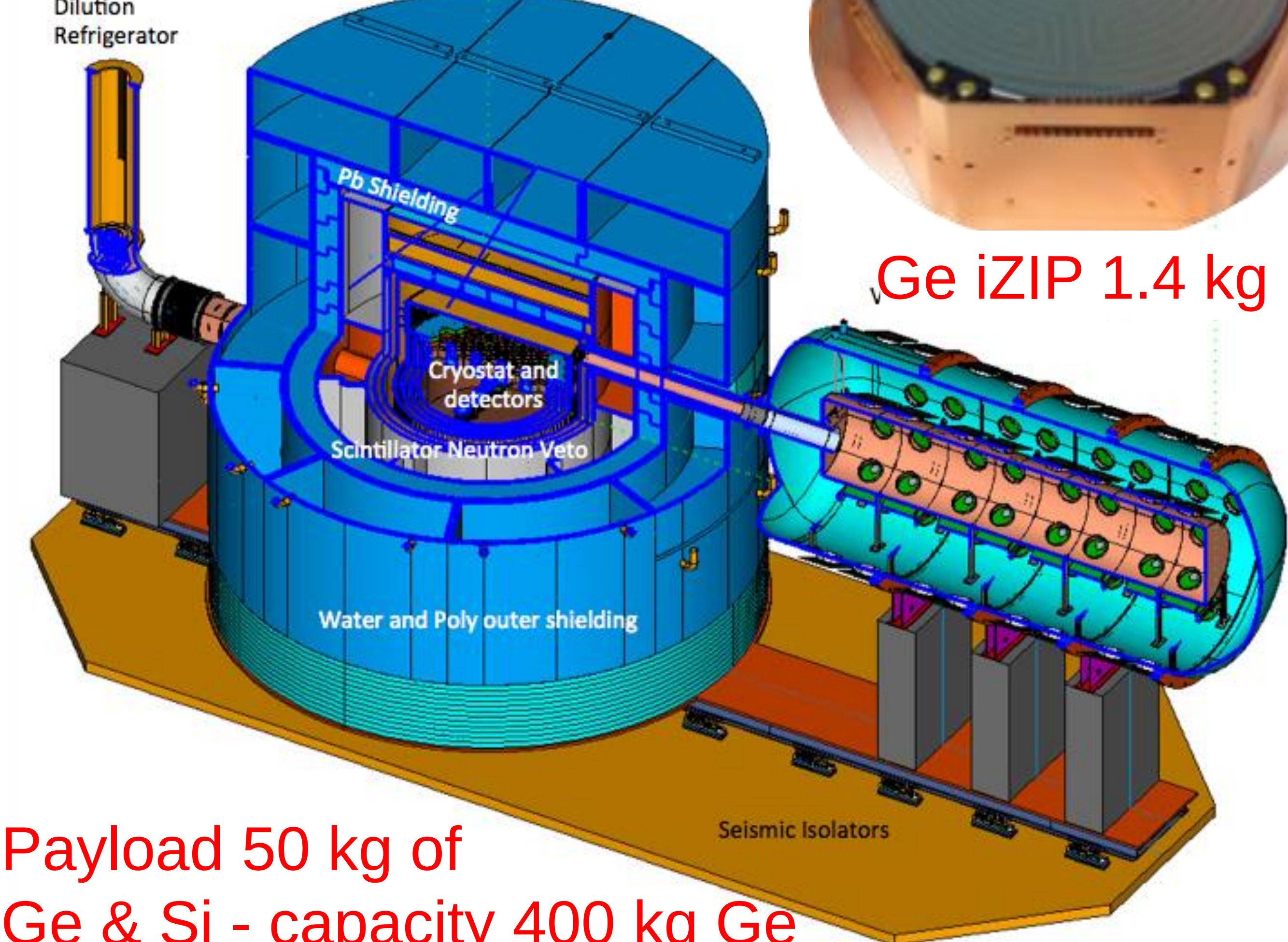
UCLA February 2014

# What is SuperCDMS SNOLAB?

- Next-generation direct detection experiment designed for minimum WIMP-nucleon cross section sensitivity < 1E-46 cm^2 at 60 GeV but optimized for world-class light mass (< 30 GeV) WIMP sensitivity
- Essential parameters:
  - 50 kg Ge target mass composed of 100mm x 33mm iZIP detectors (considering Si as well)
  - Cryogenics system designed for up to 400 kg of detectors at <40 mK (probably 20-30 mK)
  - Active and passive shielding to achieve < 0.1 event background in 4 years of operation
  - Location at 6000 mwe depth in SNOLAB ladder lab

# SuperCDMS SNOLAB Experiment

- SNOLAB 6010 mwe




Ge iZIP 1.4 kg

Payload 50 kg of
Ge & Si - capacity 400 kg Ge

Ge Tower 8.4 kg

# The Noble Liquid Revolution

Noble liquids are relatively inexpensive, easy to obtain, and dense.

Easily purified

- low reactivity
- impurities freeze out
- low surface binding
- purification easiest for lighter noble liquids

Ionization electrons may be drifted through the heavier noble liquids

Very high scintillation yields

- noble liquids do not absorb their own scintillation
- 30,000 to 40,000 photons/MeV
- modest quenching factors for nuclear recoils

Easy construction of large, homogeneous detectors

# Liquified Noble Gases: Basic Properties

Dense and homogeneous
Do not attach electrons, heavier noble gases give high electron mobility
Easy to purify (especially lighter noble gases)
Inert, not flammable, very good dielectrics
Bright scintillators

| | Liquid density (g/cc) | Boiling point at 1 bar (K) | Electron mobility ($cm^2$/Vs) | Scintillation wavelength (nm) | Scintillation yield (photons/MeV) | Long-lived radioactive isotopes | Triplet molecule lifetime ($\mu$s) |
|---|---|---|---|---|---|---|---|
| LHe | 0.145 | 4.2 | low | 80 | 19,000 | none | 13,000,000 |
| LNe | 1.2 | 27.1 | low | 78 | 30,000 | none | 15 |
| LAr | 1.4 | 87.3 | 400 | 125 | 40,000 | $^{39}$Ar, $^{42}$Ar | 1.6 |
| LKr | 2.4 | 120 | 1200 | 150 | 25,000 | $^{81}$Kr, $^{85}$Kr | 0.09 |
| LXe | 3.0 | 165 | 2200 | 175 | 42,000 | $^{136}$Xe | 0.03 |

# Self-Shielding

In early 2000's, neutrino experiments (Super-K, SNO, KamLAND, Borexino) have demonstrated that extremely low background levels may be achieved by using an ultrapure liquid, surrounded by photomultipliers, with the outer part of the detector Shielding the inner part from radioactivity.

A realization: Liquefied noble gases may be used in the same way, with high light yields (like organic scintillator) but without the carbon-14. Such experiments may reach low enough energy thresholds to search for dark matter interactions. Noble liquids may be purified to an exceptional degree. Helium, neon, and xenon are radiopure.

First conceptions:
CLEAN (McKinsey and Doyle, arXiv:astro-ph/9907314,
McKinsey and Coakley, arXiv:astro-ph/0402007)
XMASS, Y. Suzuki, arXiv:hep-ph/0008296.

**Much skepticism at the time: Can such detectors really have low enough internal backgrounds, low enough energy threshold, good enough position reconstruction?**

**In the years since, small, precise, clever detectors → Big, just smart enough detectors.**

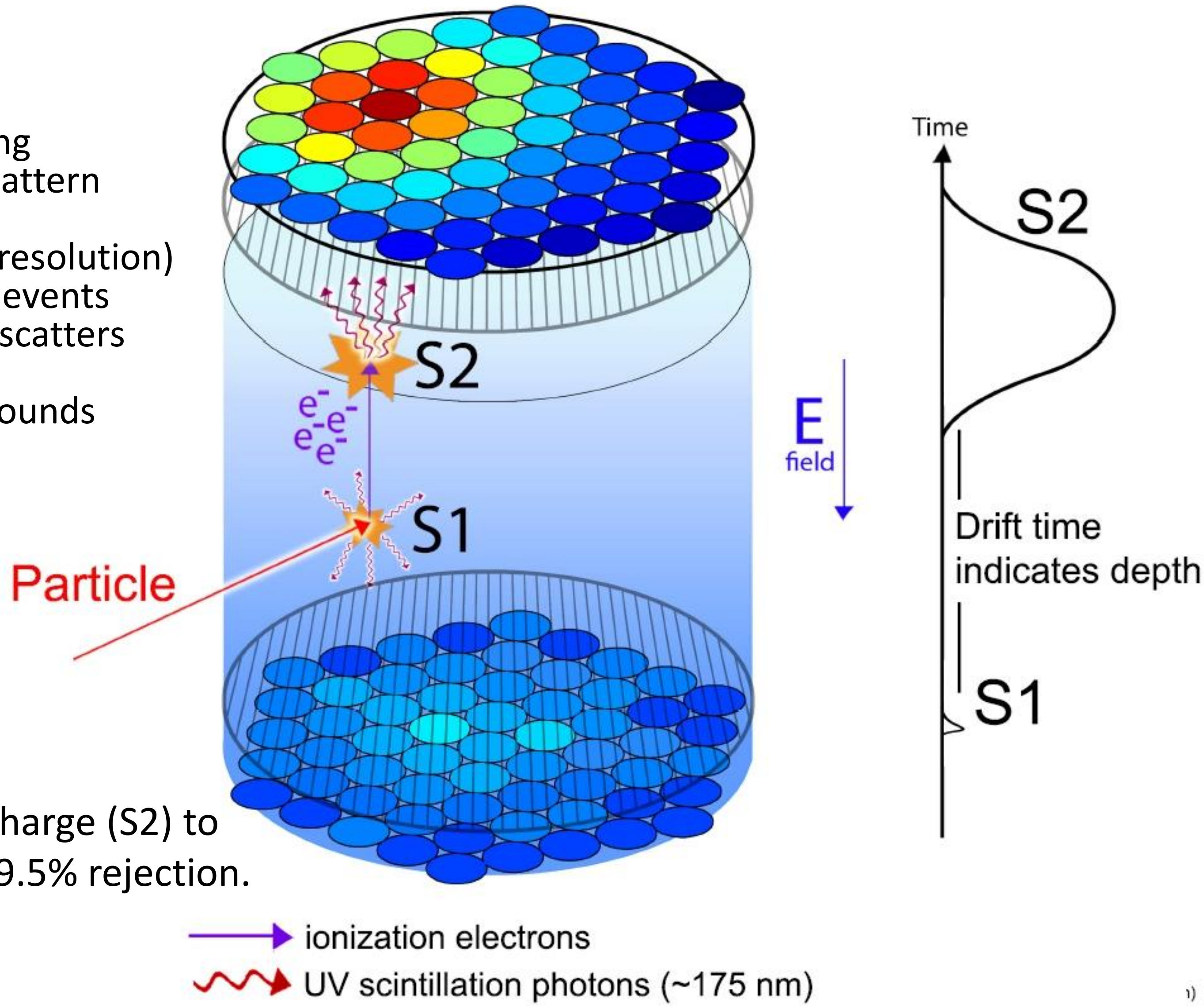
# Two-phase Xenon WIMP Detectors

Z position from S1 – S2 timing
X-Y positions from S2 light pattern

Excellent 3D imaging (~mm resolution)
- eliminates edge events
- rejects multiple scatters

Gamma ray, neutron backgrounds reduced by self-shielding

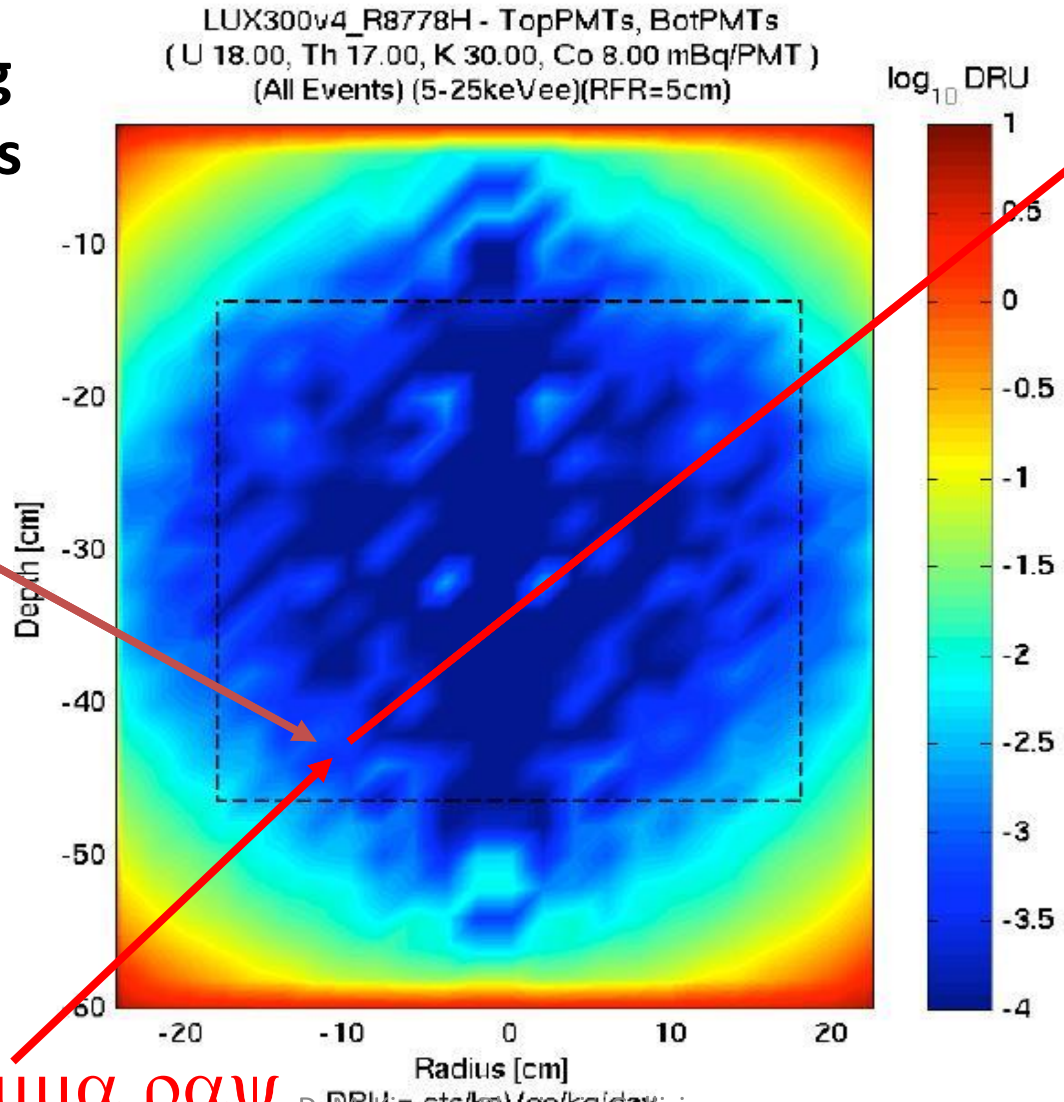
Reject gammas, betas by charge (S2) to light (S1) ratio.  Expect > 99.5% rejection.



# Kinematics alone provides strong rejection

**Self-shielding is what makes LUX work**

~ keV deposition




Must cross full volume without interacting again

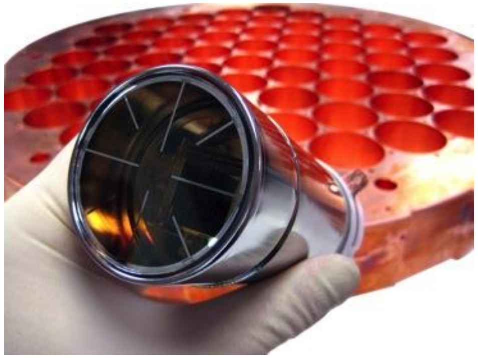
~ MeV γαμμα ραψ

# Light Collection in Liquid Xenon

A key development: cryogenic PMTs with fused silica windows

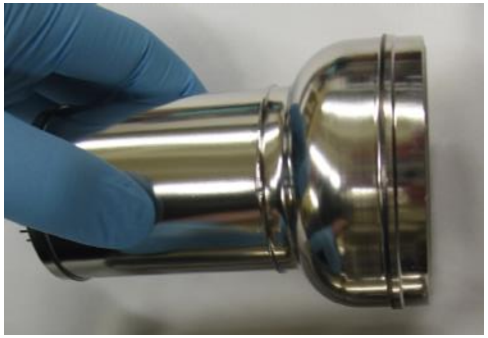
- PMT window passes 178 nm light
- No need for wavelength shifter
- 28-35% quantum efficiency
- Very low radioactivity

R8778 (5 cm round)



(5 cm hexagonal)

R11410 (8 cm round)

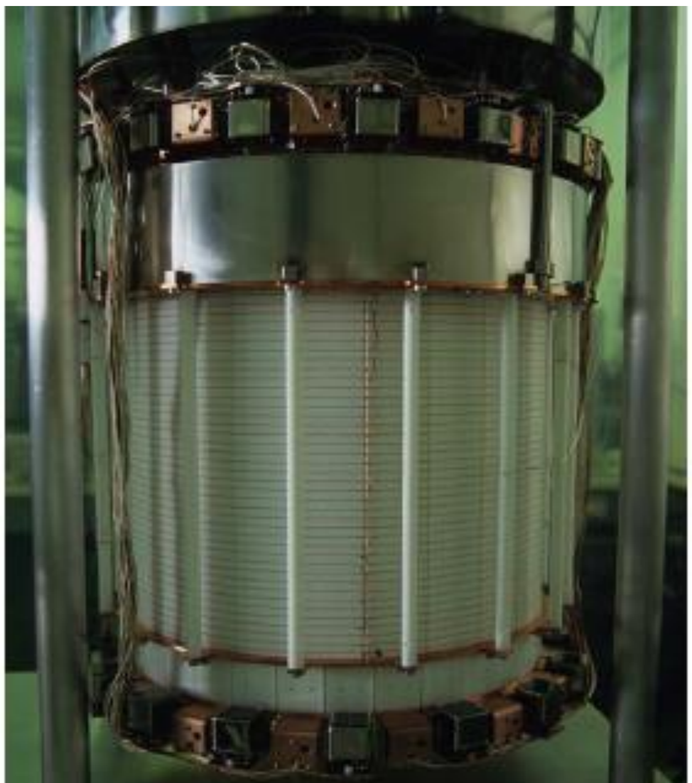


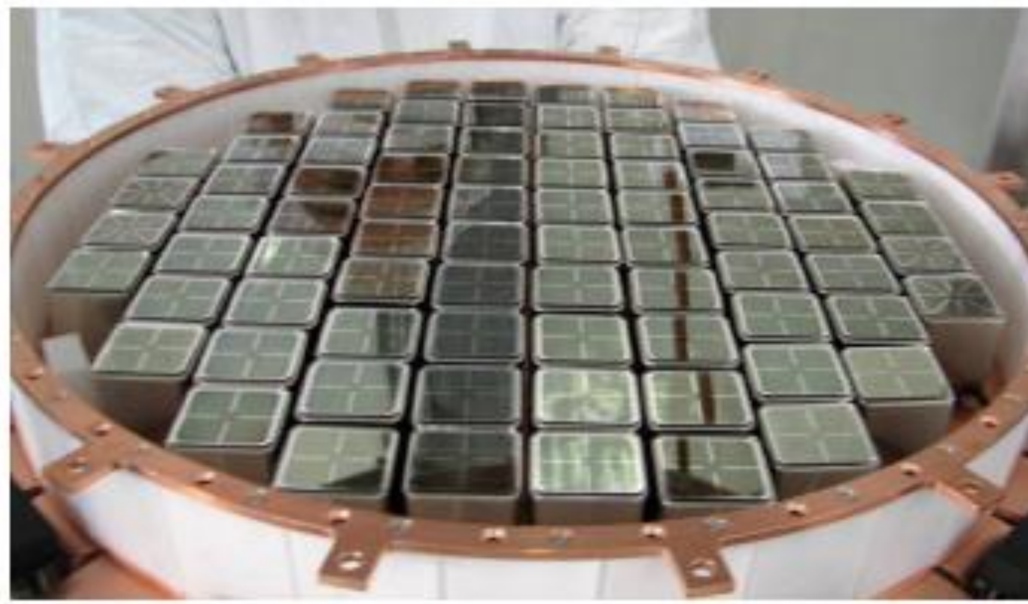
Another key development: Teflon (PTFE) is found to be extremely reflective (> 95%) to LXe scintillation

- Reflectivity in gaseous Xe is much lower ~ 50%, so this is mysterious
- Internal reflection at PTFE-LXe interface?
- Allows efficient light collection in two-phase Xe, without floating PMTs at high voltage

# XENON100

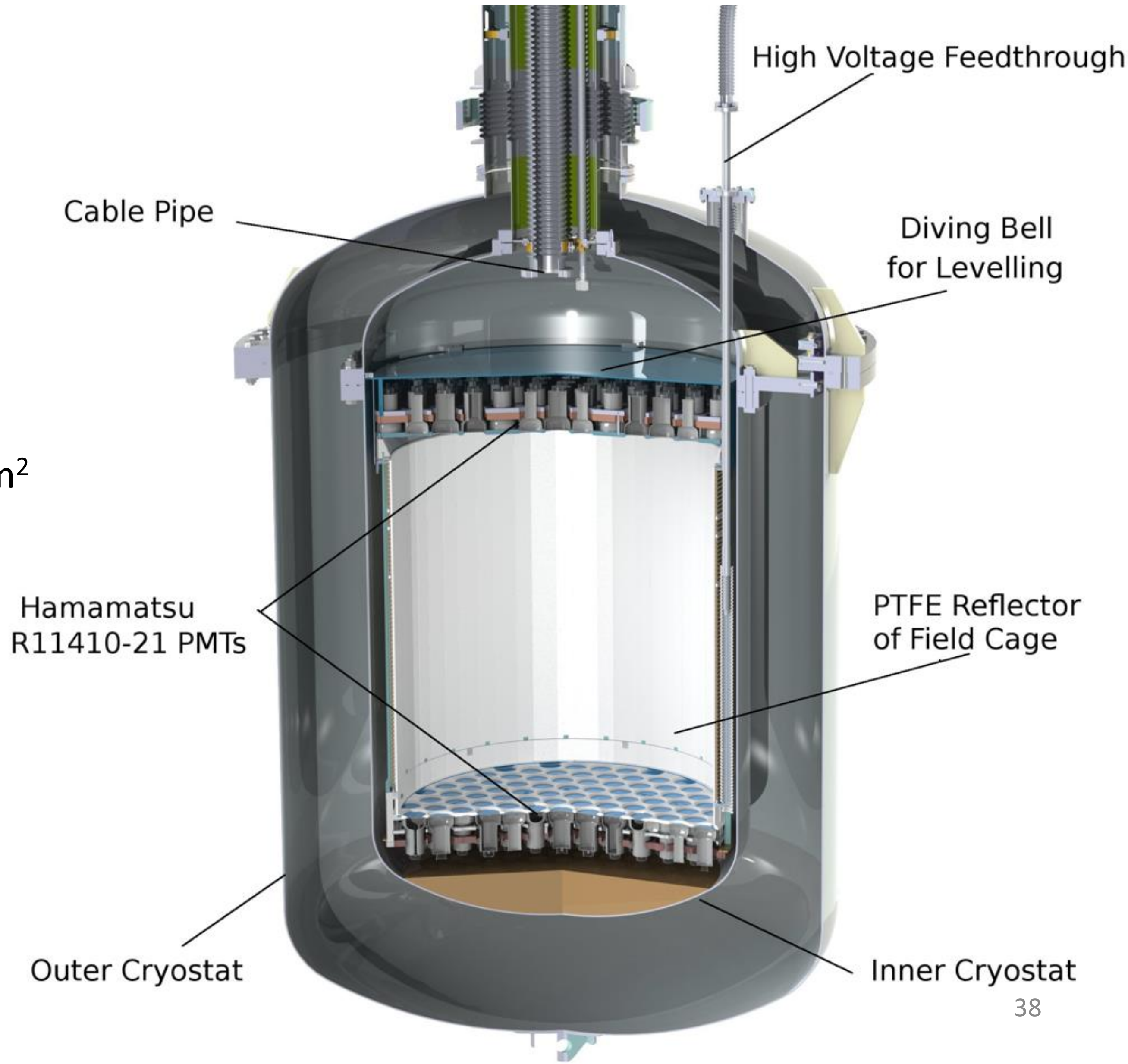
- Two-phase Xe detector with 62 kg active target, 34 kg fiducial mass
- 242 1-inch square PMTs: 1 mBq (U/Th) and ~30% QE
- Multilayer passive shield (Cu, Poly, Pb+Water)
- Background rate of 5.3e-3 events/keV/kg/day after veto cut, before discrimination
- 19 ppt of Kr contamination
- Next step: XENON1T, with sensitivity at 2e-47 $cm^2$ at 50 GeV in 2017.





# XENON1T

- 1 m-drift TPC
- 3.3 tonnes of LXe
- Water shielding
- Science goal: 2 x $10^{-47}$ $cm^2$
- Operational in 2015

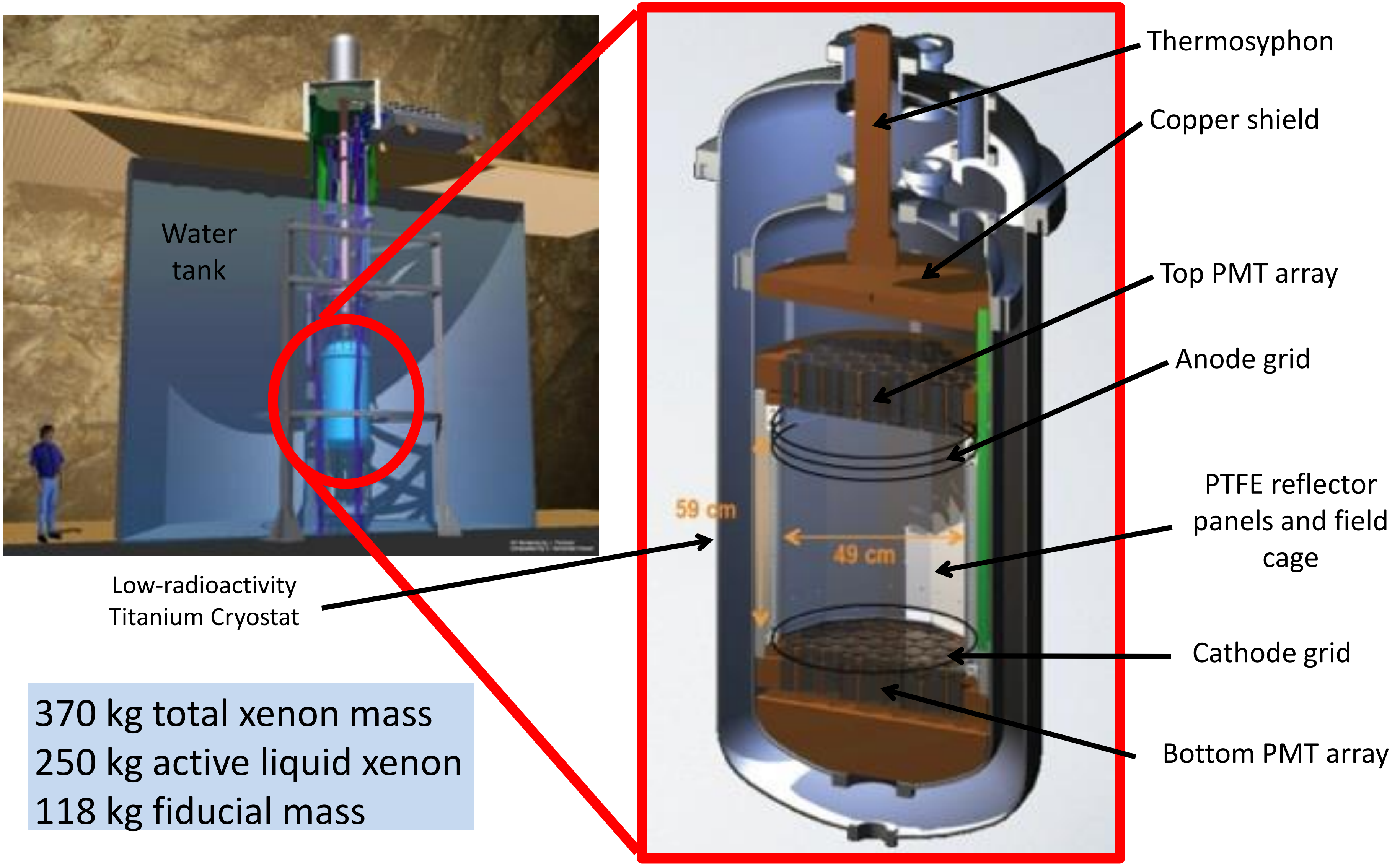


# ystems


Xe
XENON
Matter Project
XENON1
enlightening the

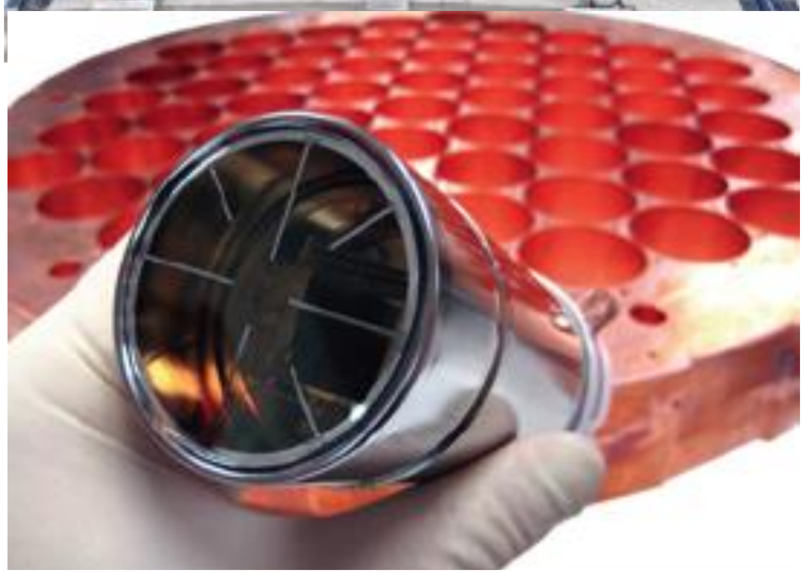

Cryogenic and Purification
Electronics and DAQ
ReStoX and Kr-Colum

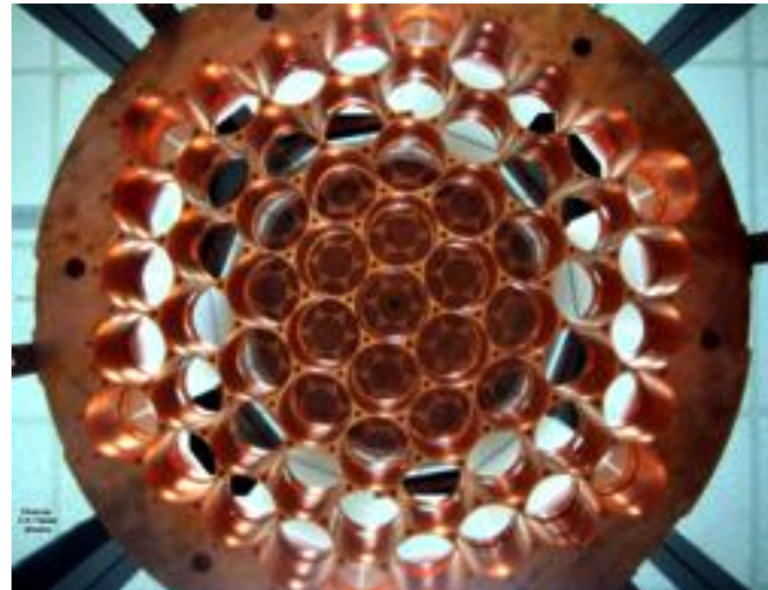
# The LUX Detector

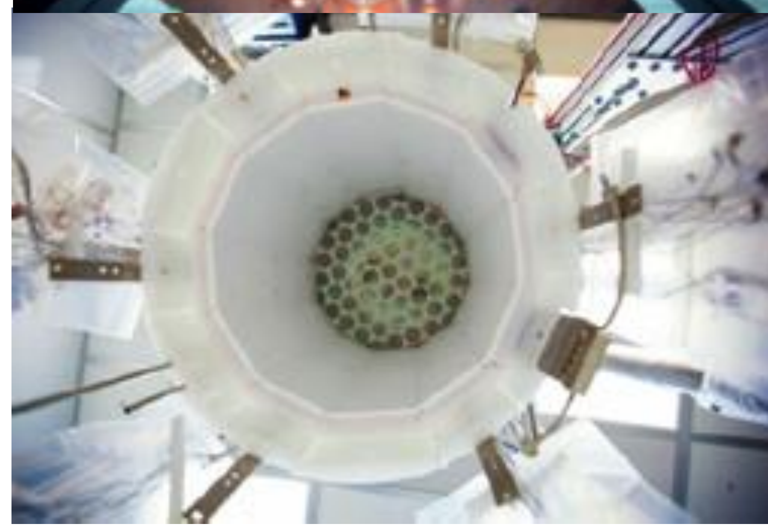



370 kg total xenon mass
250 kg active liquid xenon
118 kg fiducial mass

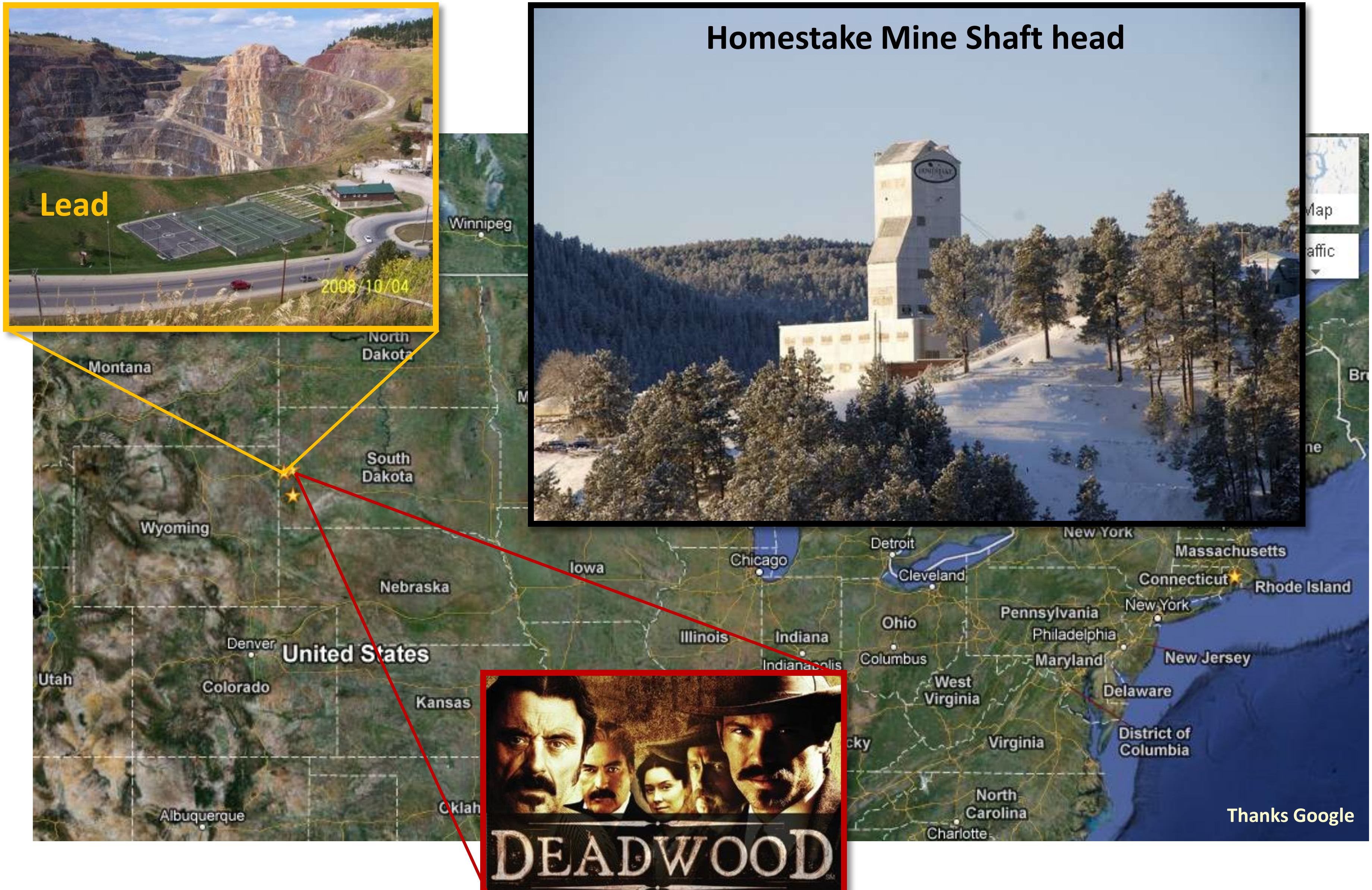
# LUX – the Instrument







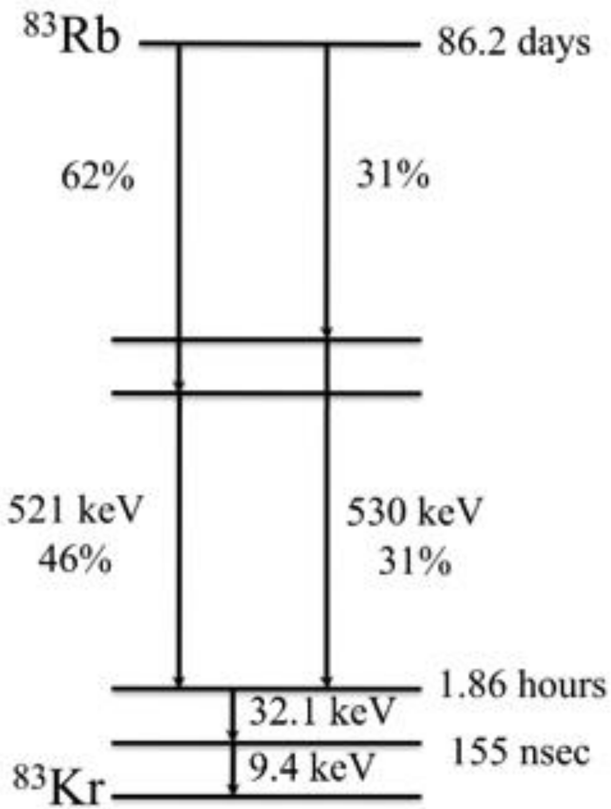
# The Sanford Underground Research Facility



LUX installed in its water tank shield, a mile underground at SURF

# Kr-83m Calibration

- Rb-83 produces Kr-83m when it decays; this krypton gas can then be flushed into the LUX gas system to calibrate the detector as a function of position.
- Provides reliable, efficient, homogeneous calibration of both S1 and S2 signals, which then decays away in a few hours, restoring low-background operation.
- See L. Kastens et al, PRC **80**, 045809 (2009) and JINST **5**, P05006 (2010); Manalaysay et al, PRD **81**, 073303 (2010).

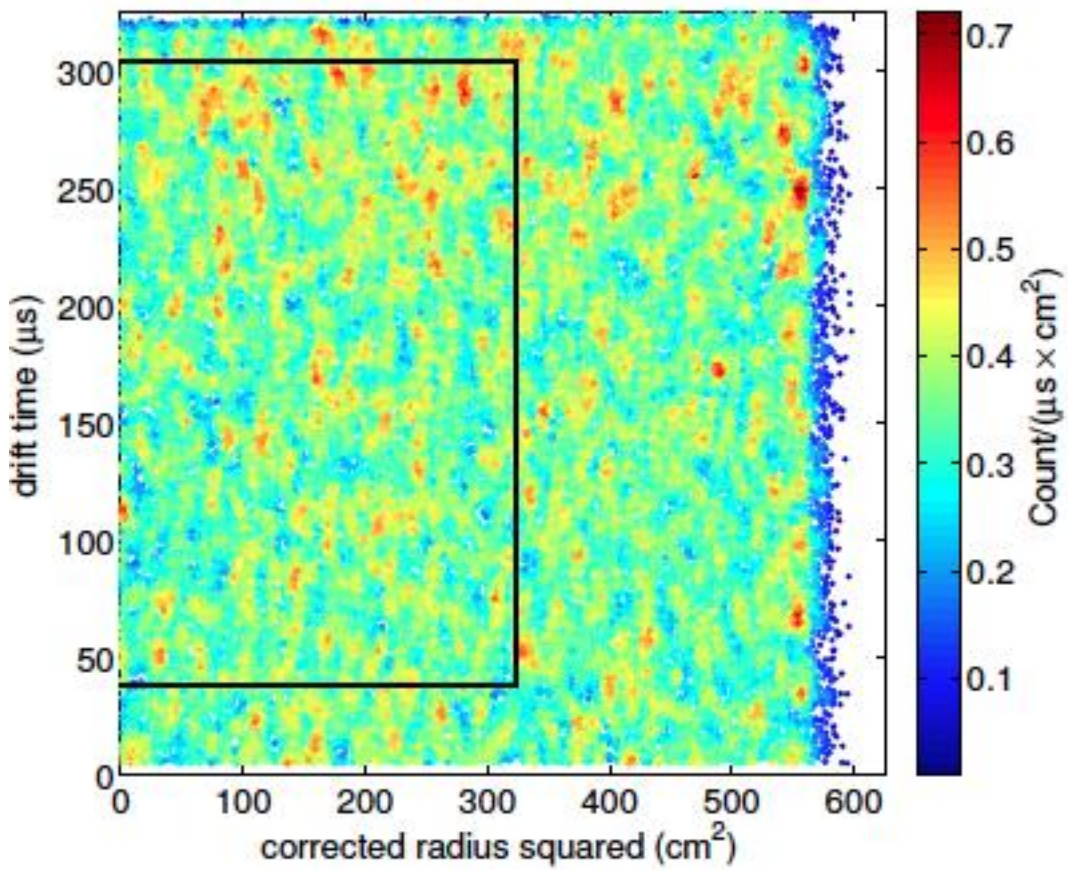



Kr-83m source (Rb-83 coated on charcoal, within xenon gas plumbing)

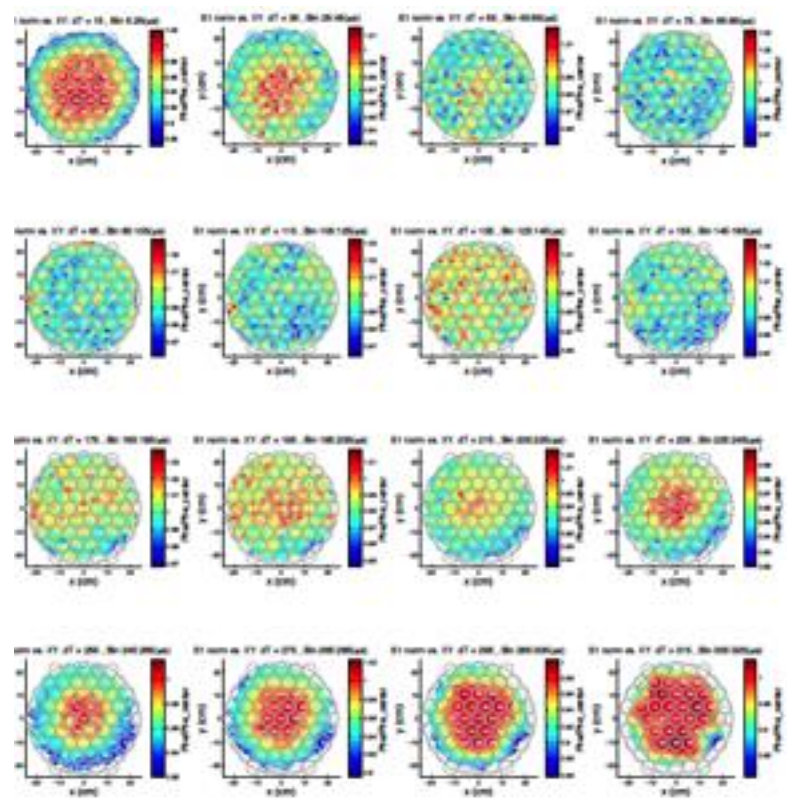
# Kr-83m Calibration

- Over 1 million Kr-83m events, spread uniformly through the detector

Fiducial volume determination




Position-based S1 corrections

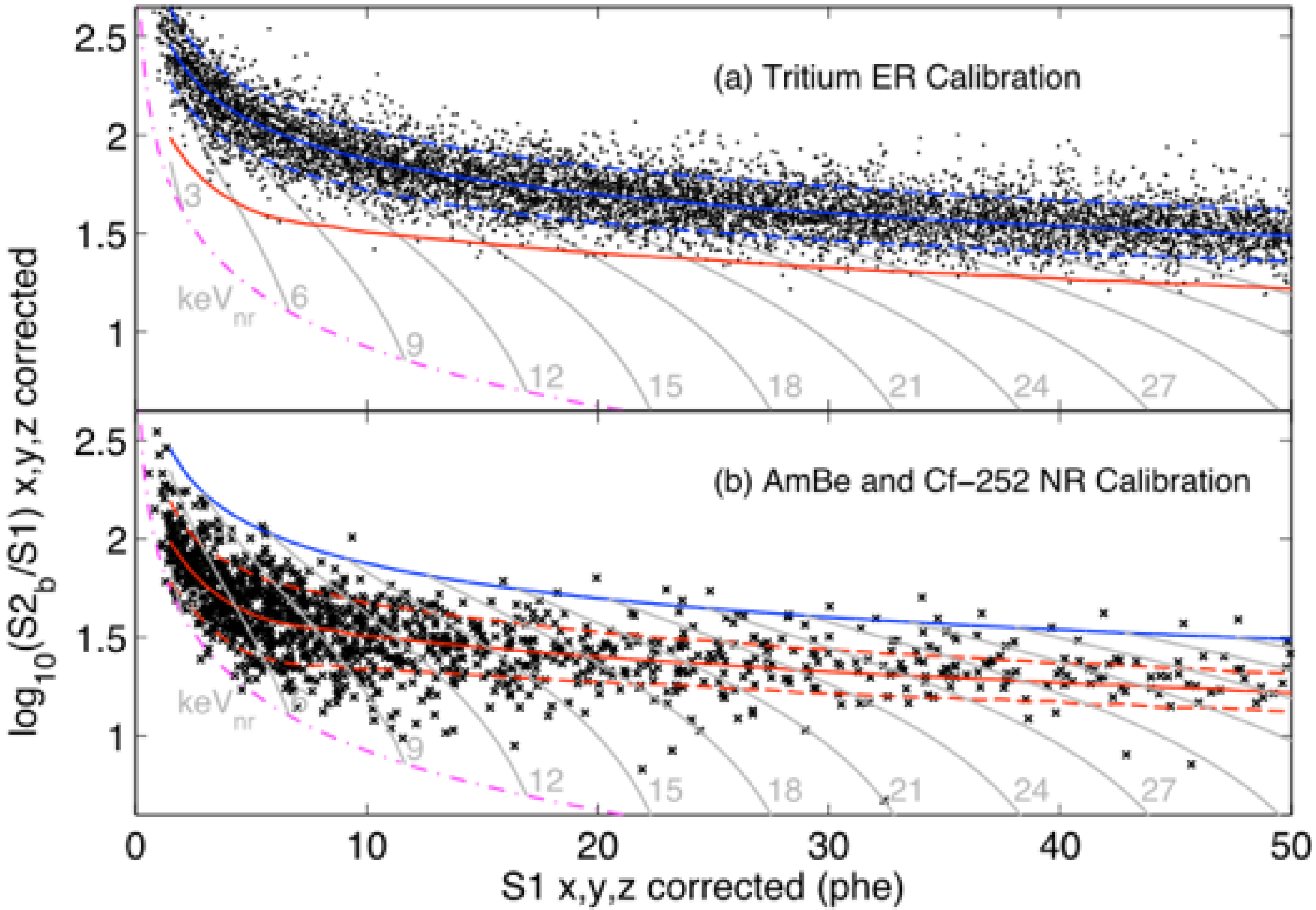


# Tritiated Methane Calibration

- LUX uses tritiated methane, doped into the detector, to accurately calibrate the efficiency of background rejection.
- This beta source (endpoint energy 18 keV) allows electron recoil S2/S1 band calibration with unprecedented accuracy
- The tritiated methane is then fully removed by circulating the xenon through the getter
- Parametrization of the  electron recoil band from the high-statistics tritiated methane data is then used to characterize the background model.

# Electron Recoil and Nuclear Recoil Bands

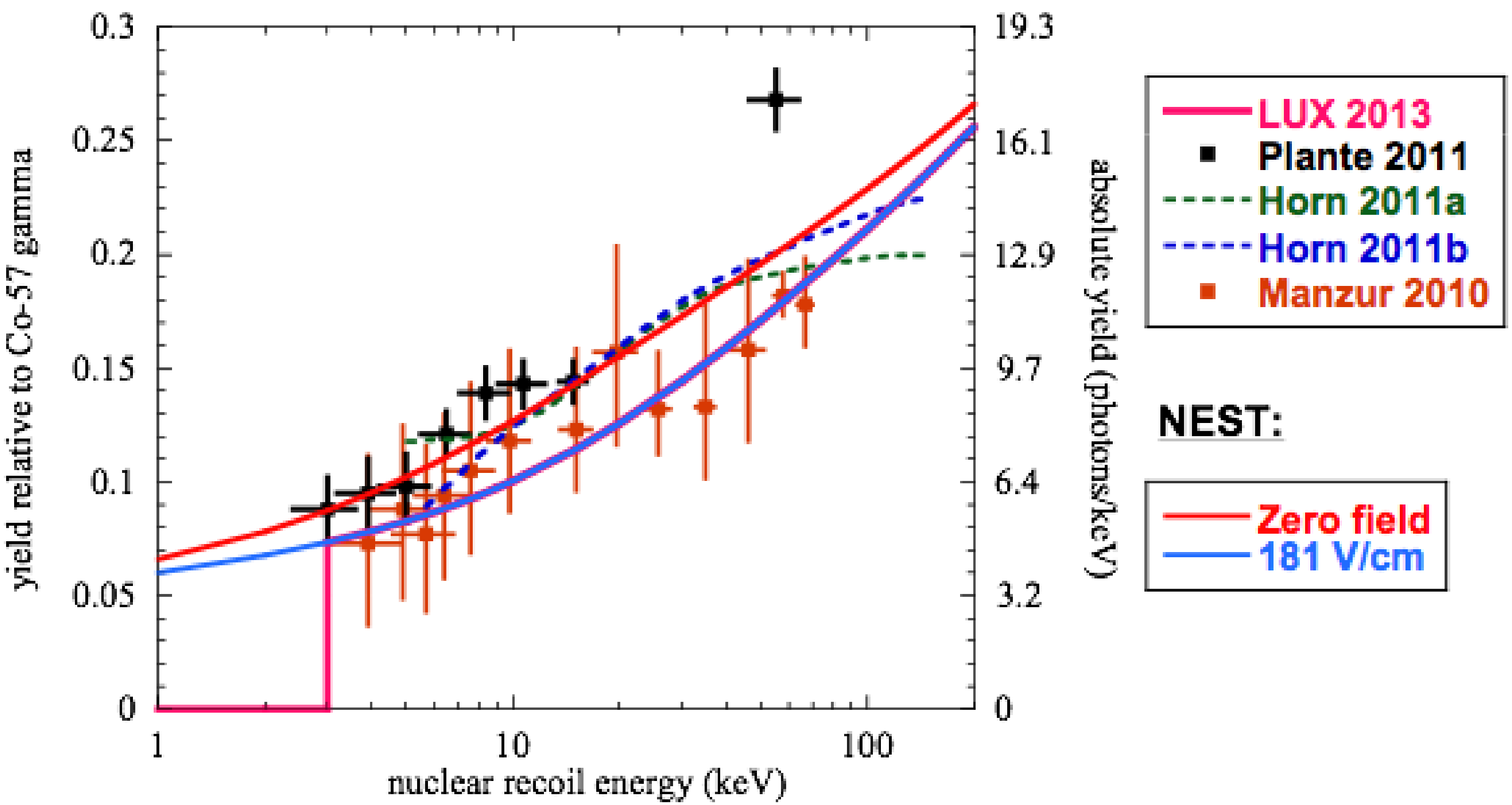
Tritium provides very high statistics electron recoil calibration (200 events/phe)
Neutron calibration is consistent with NEST + simulations



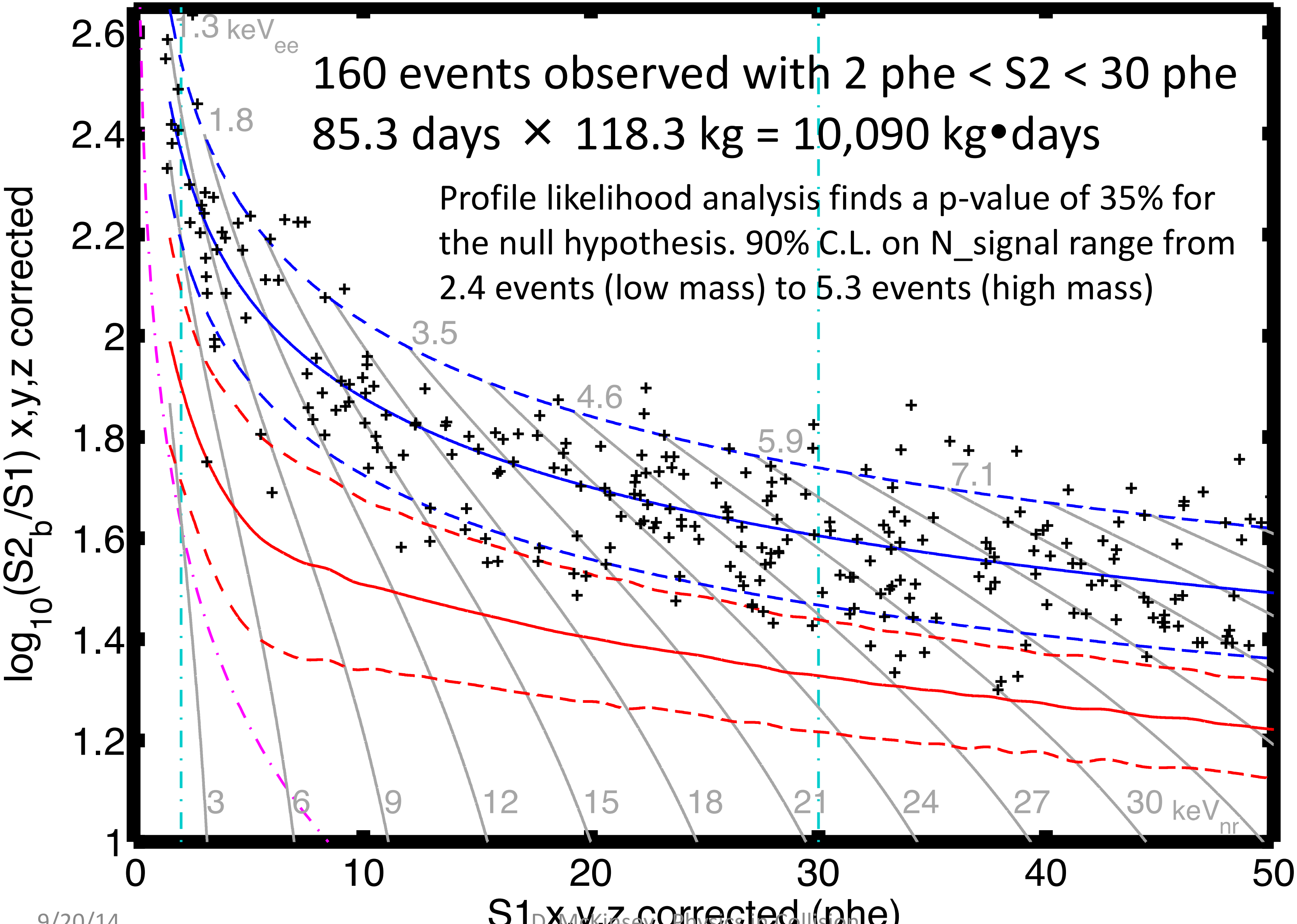

Gray contours indicate constant energies using a S1-S2 combined energy scale

# Light and Charge Yields in LUX

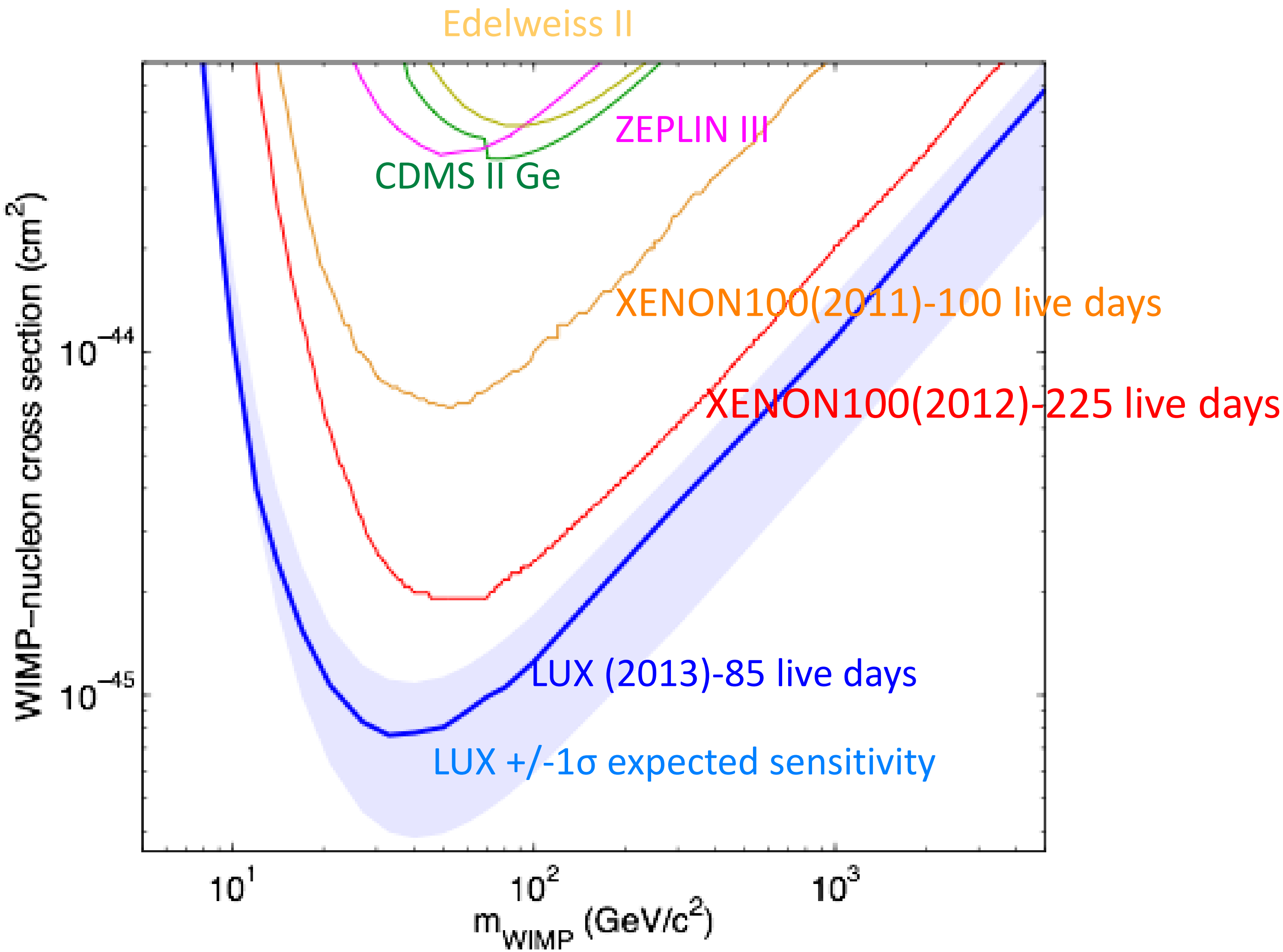
- Modeled Using Noble Element Simulation Technique (NEST).
- NEST based on canon of existing experimental data.
- **Artificial cutoff in light and charge yields assumed below 3 keVnr, to be conservative**.
- Includes predicted electric field quenching of light signal, to 77-82% of the zero field light yield



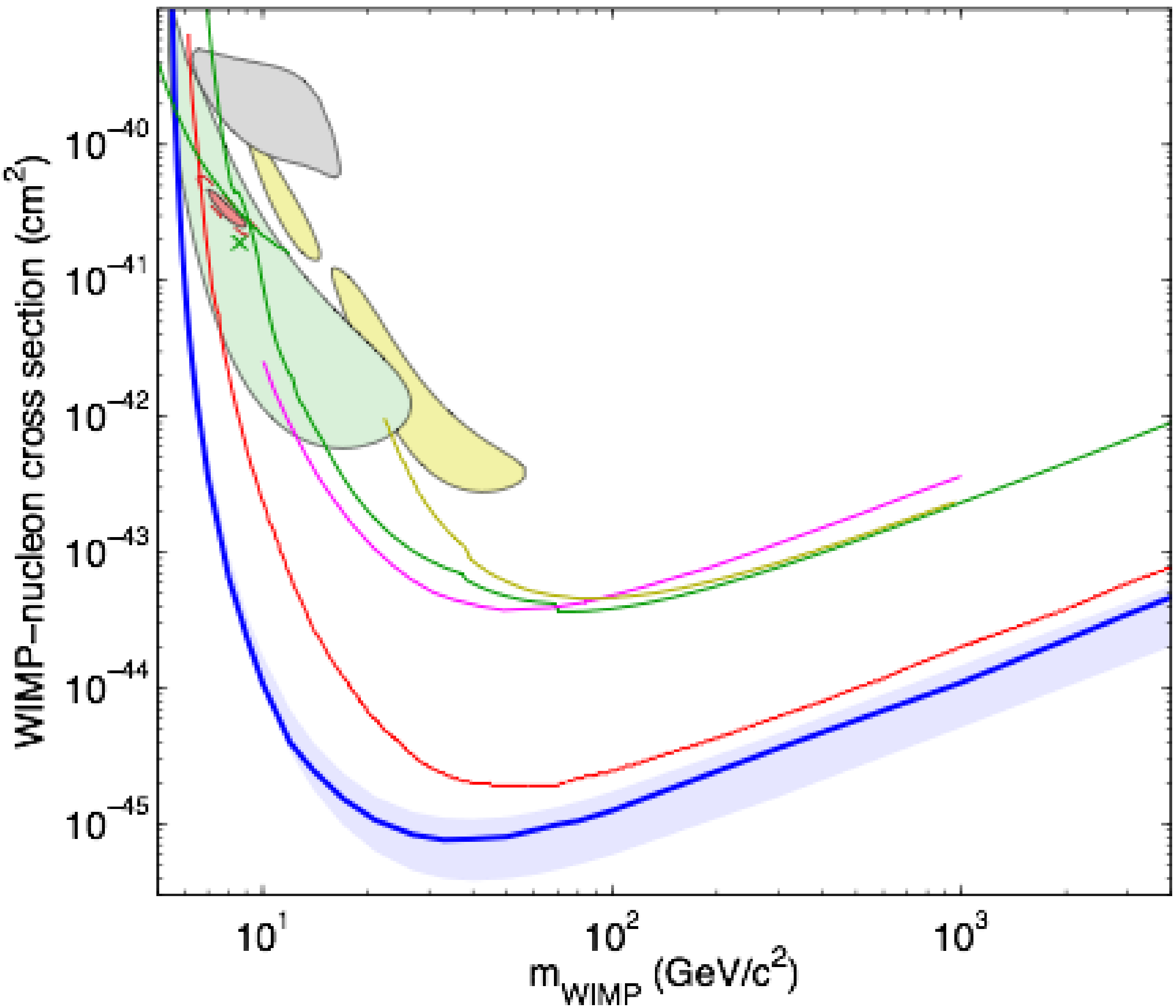
# LUX WIMP search data



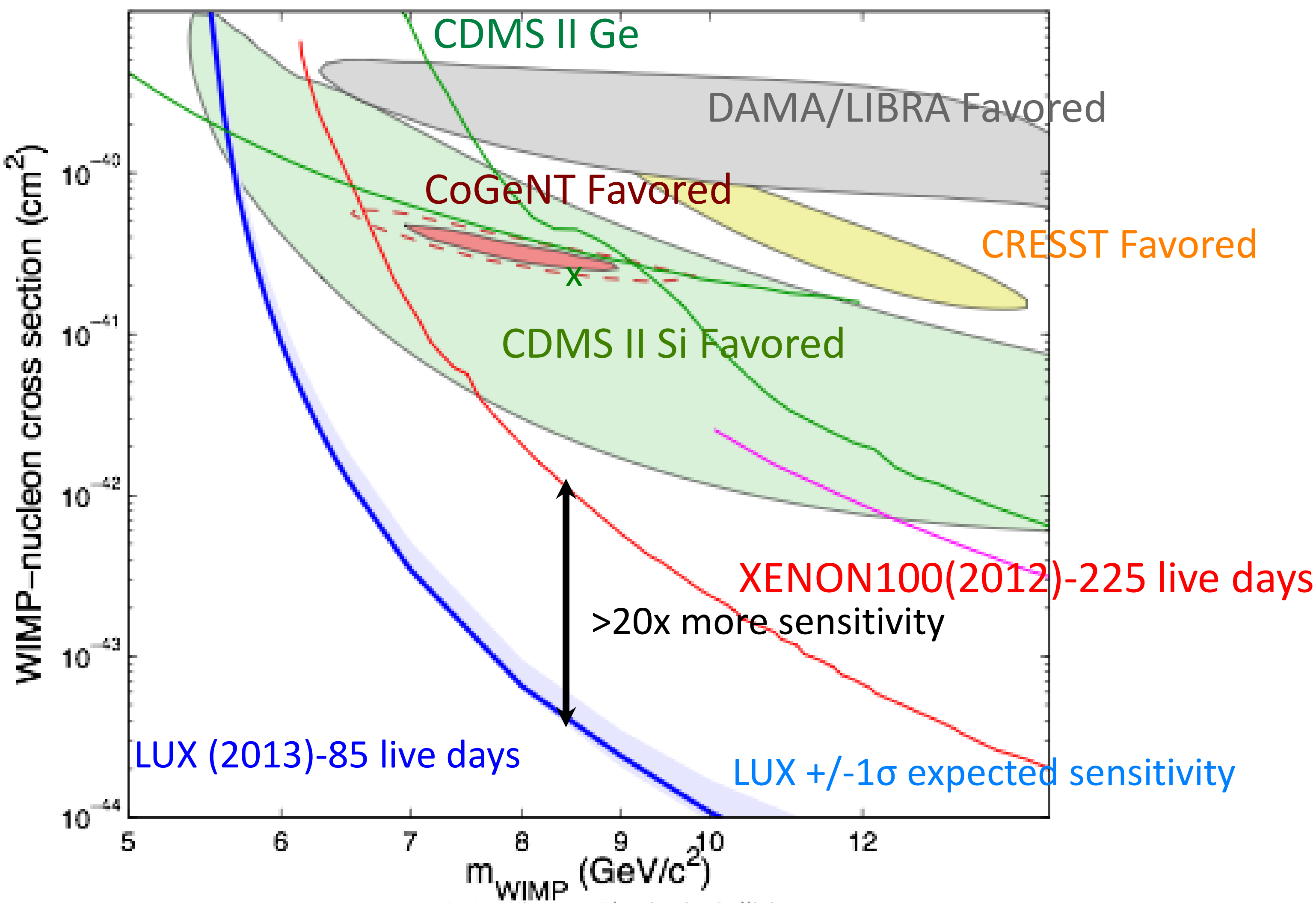
# Spin Independent Sensitivity Plots



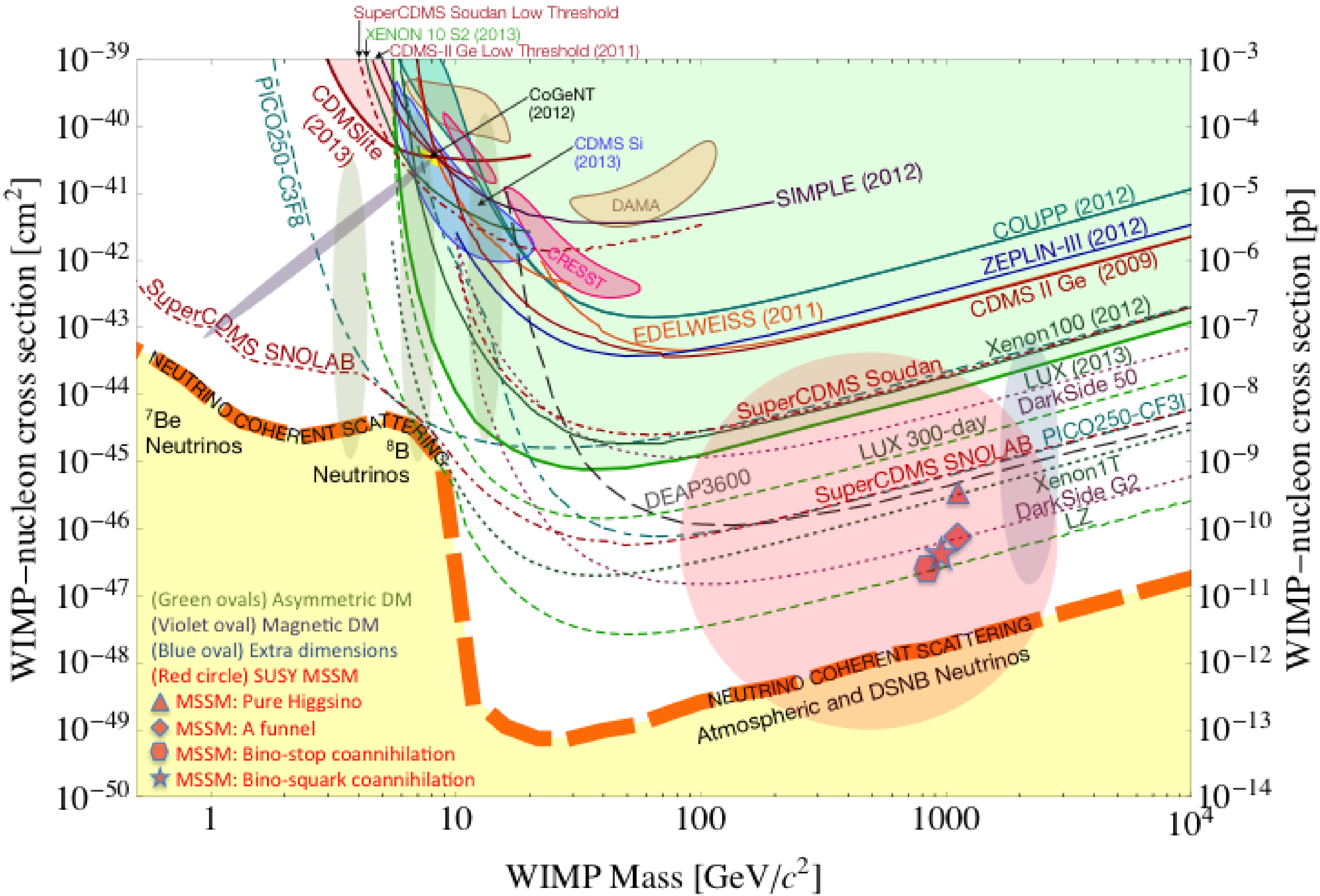
# Spin Independent Sensitivity Plots



# Low Mass WIMPs - Fully excluded by LUX

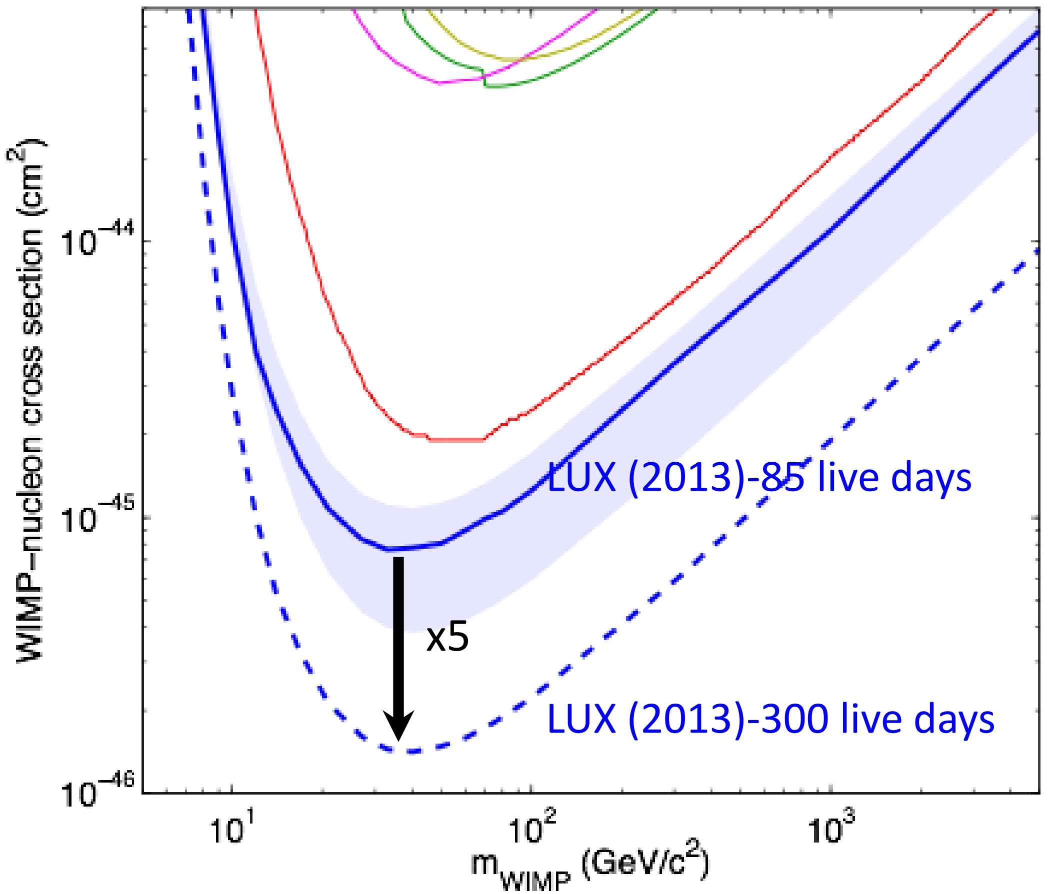


# Spin-Independent Limits

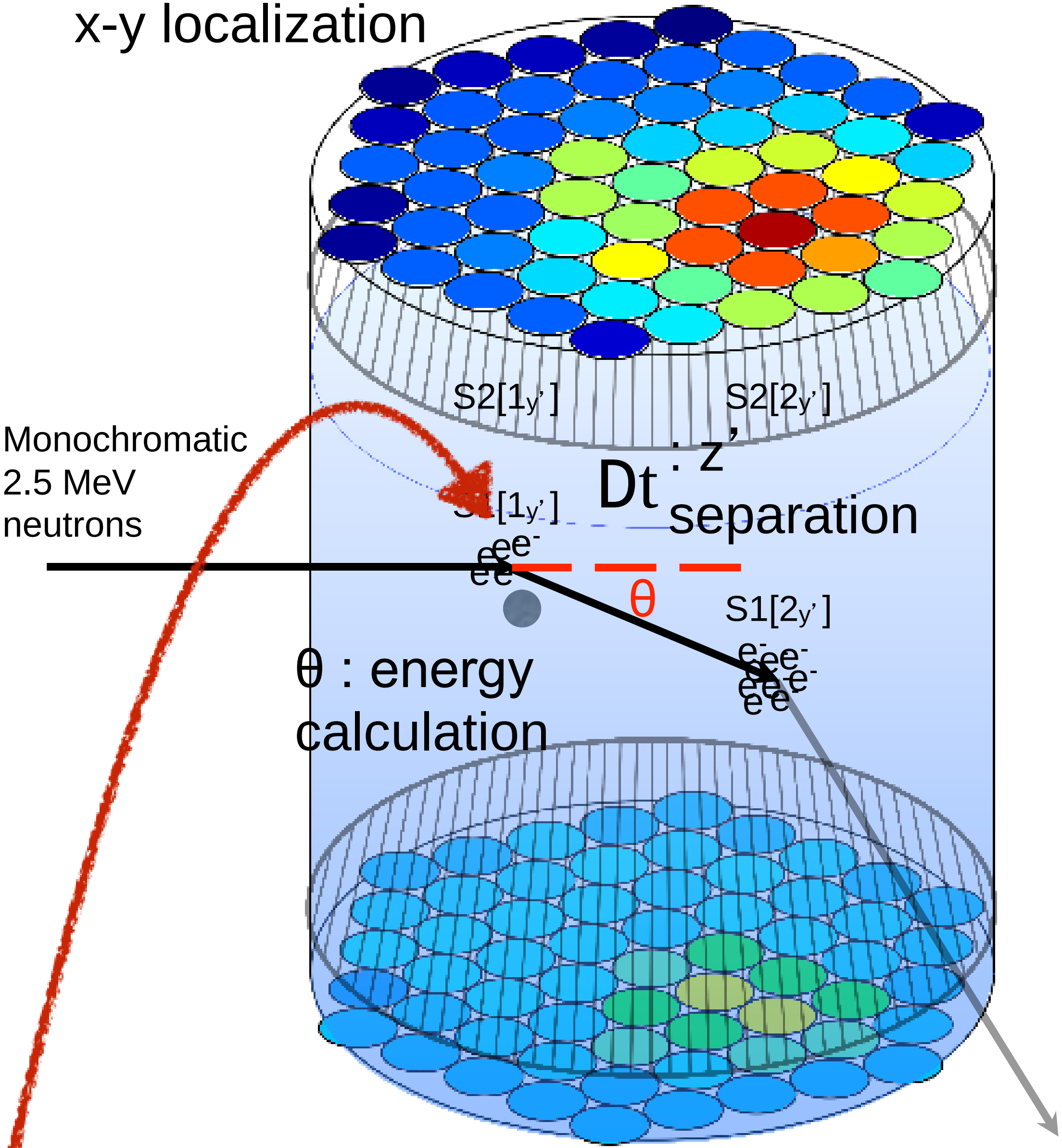


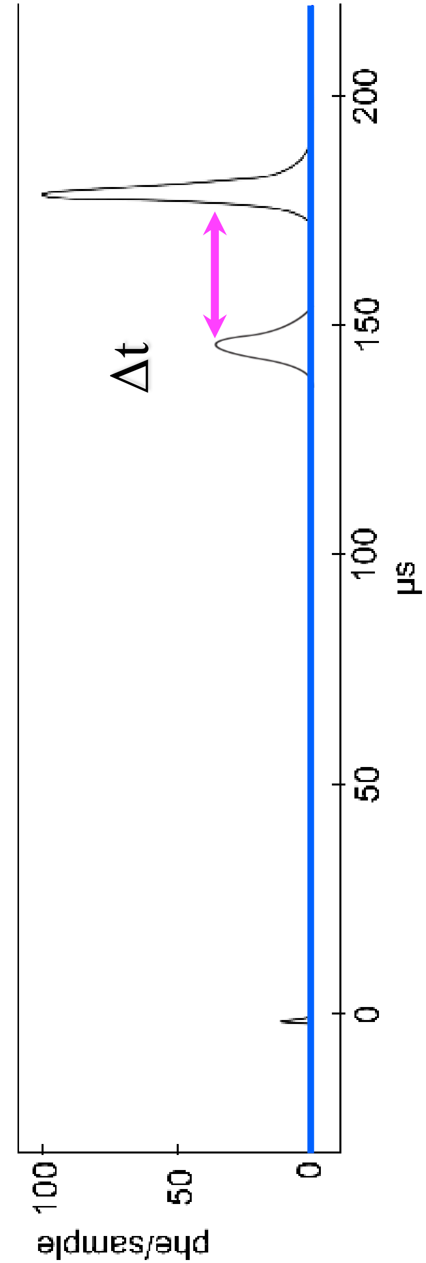
# Projected LUX 300 day WIMP Search Run

- We intend to run LUX for a new run of 300 days in 2014/15
  - Extending sensitivity by another factor 5
  - Even though LUX sees no WIMP-like events in the current run, it is still quite possible to discover a signal when extending the reach
  - LUX does not exclude LUX
- WIMPs remain our favored quarry
- LZ 20x increase in target mass
  - If approved plans to be deployed in Davis Lab in 2016+



top hit pattern:
x-y localization

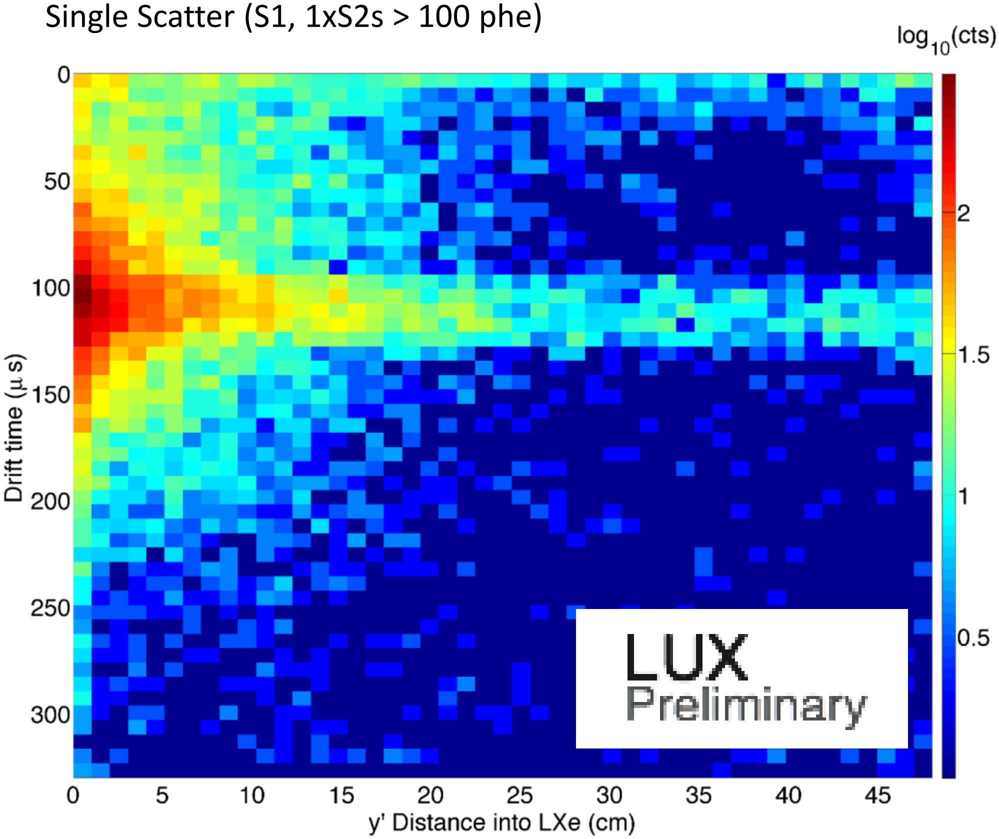



$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

# Neutron Conduit Installed in the LUX Water Tank - Fall 2012

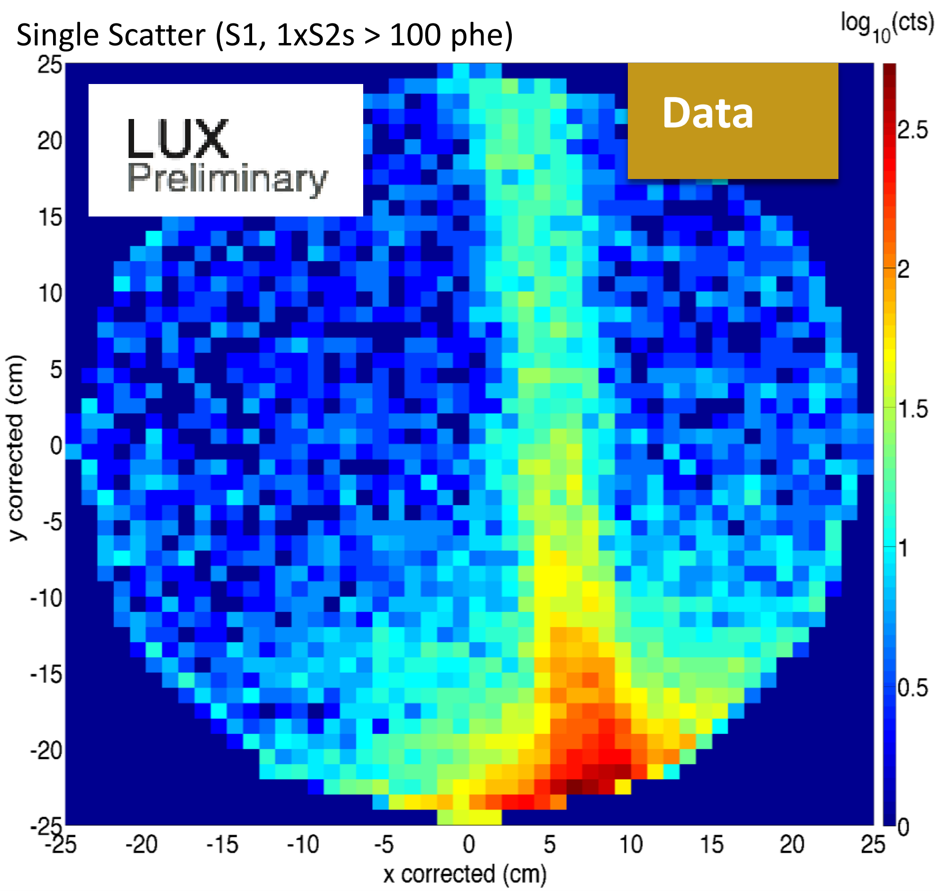
# Adelphi DD108 Neutron Generator Installed Outside LUX Water Tank - Fall 2013

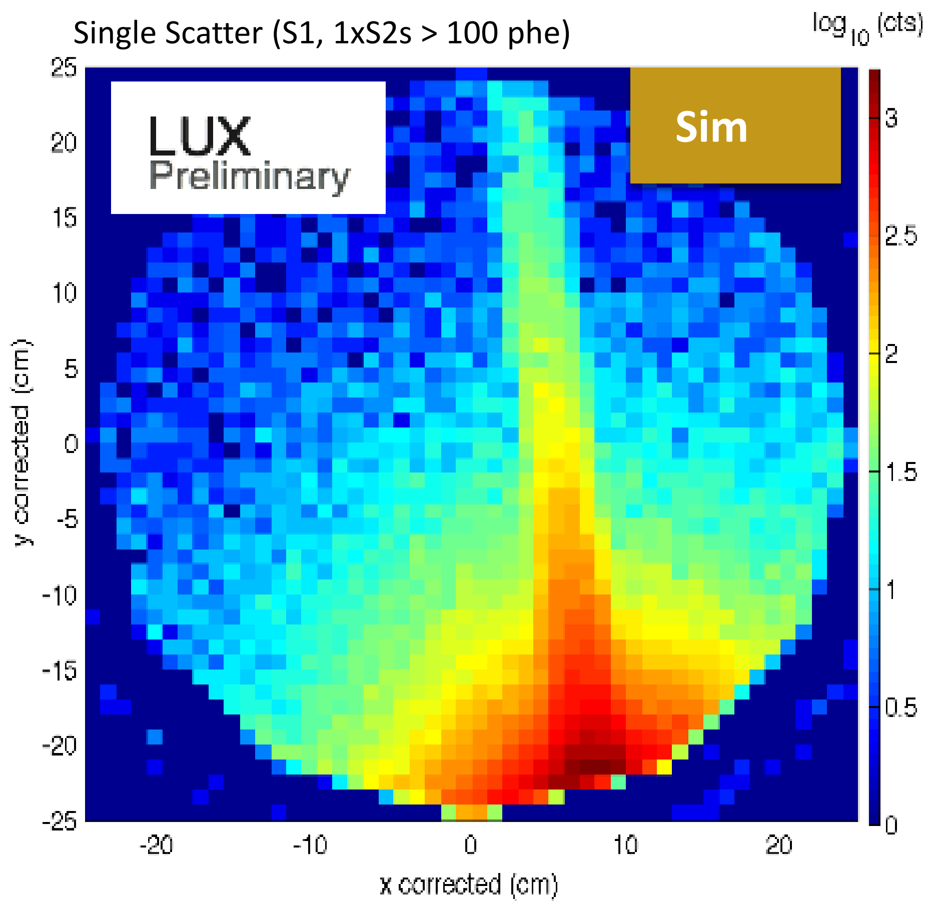



- Neutron generator/beam pipe assembly aligned 15.5 cm below liquid level in LUX active region to maximize usable single / double scatters
- Beam leveled to ~1 degree
- 105.5 live hours of neutron tube data used for analysis

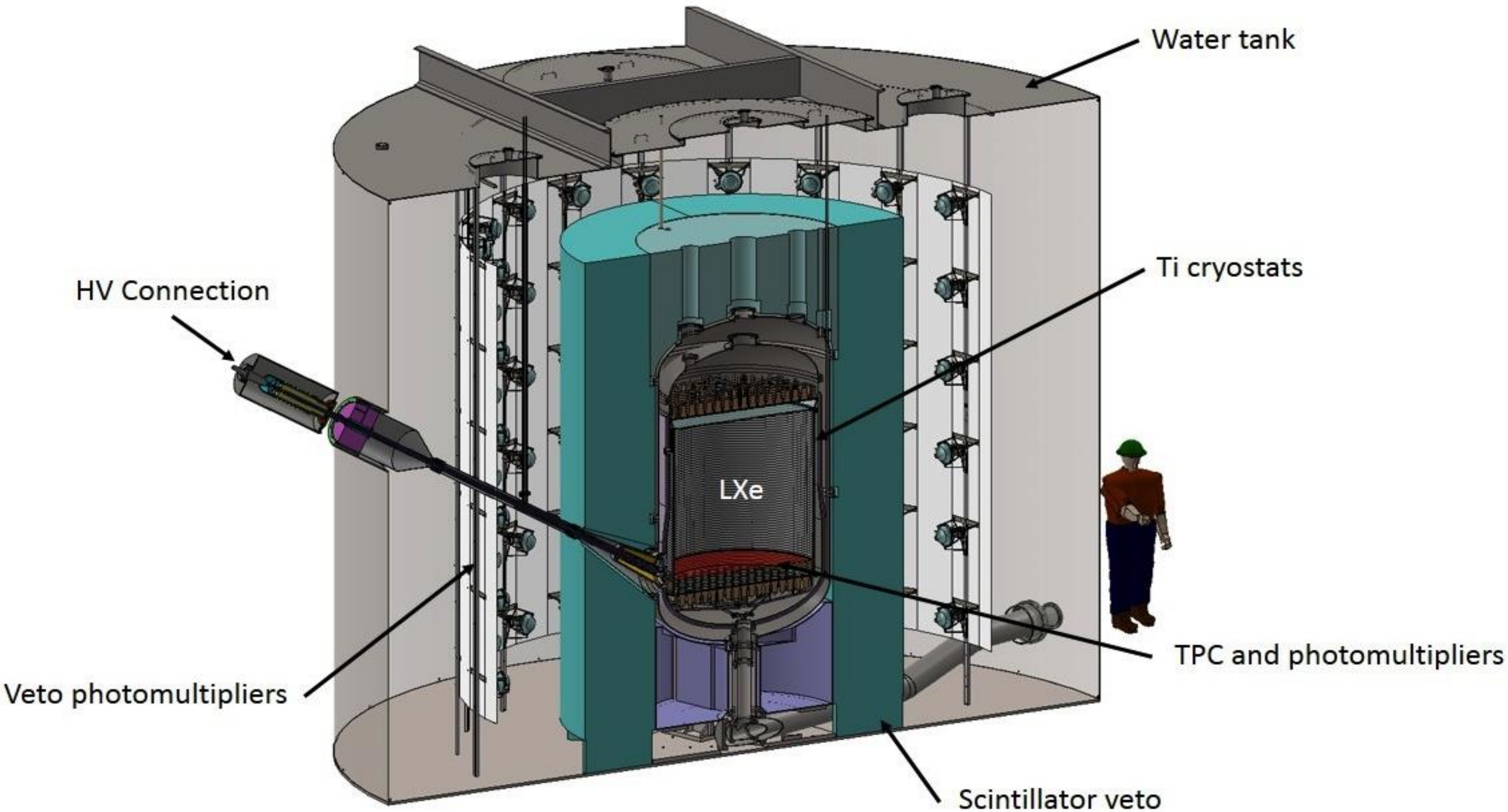
# Reconstructed Neutron Beam Event X-Y Positions

Complete Geant4 LUXSim + NEST simulation of D-D neutron calibration

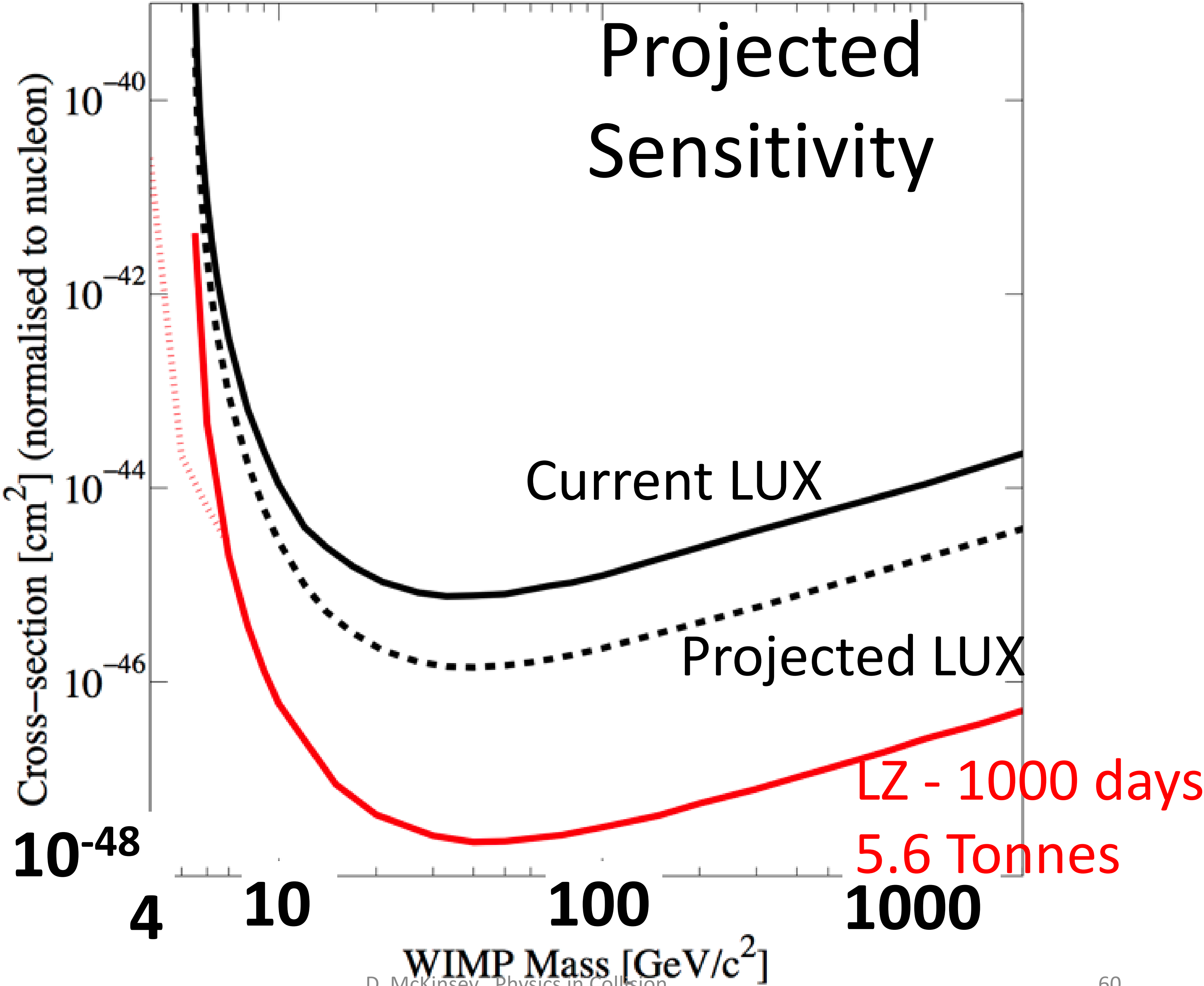


# LUX – ZEPLIN (LZ)

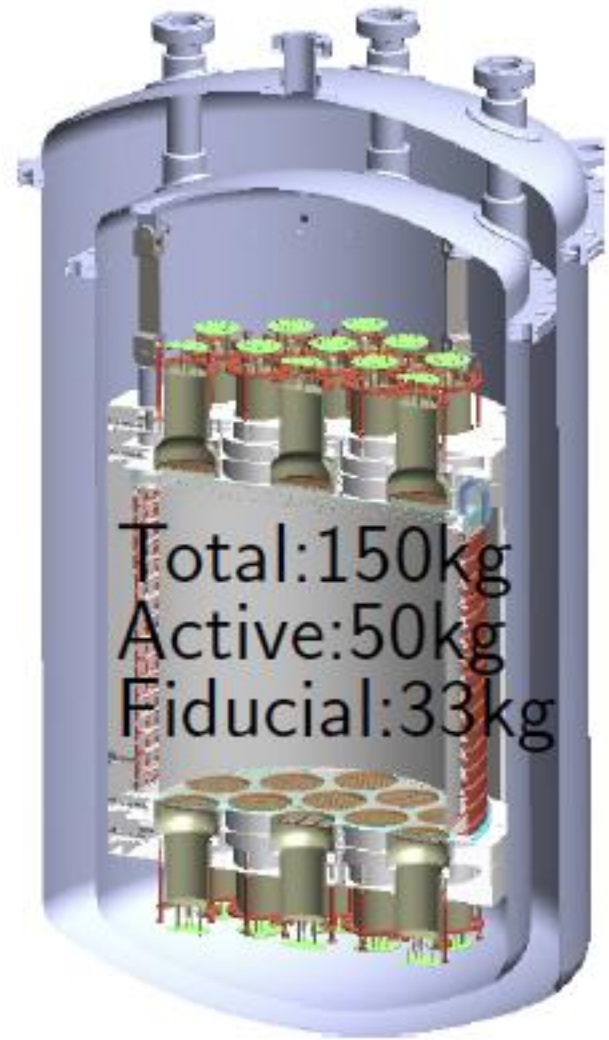



7 tonnes of LXe inside dual – phase TPC.
Scintillator veto substantially increases background rejection and characterization.
Located in water tank (same as LUX) at Sanford Underground Research Facility, Lead, SD.
Chosen as one of the G2 dark matter experiments; "First Dark" in ~ 2017.


Projected Sensitivity
Current LUX
Projected LUX
LZ - 1000 days
5.6 Tonnes
Cross–section [cm$^2$] (normalised to nucleon)
10$^{-40}$
10$^{-42}$
10$^{-44}$
10$^{-46}$
10$^{-48}$
4
10
100
1000
WIMP Mass [GeV/c$^2$]

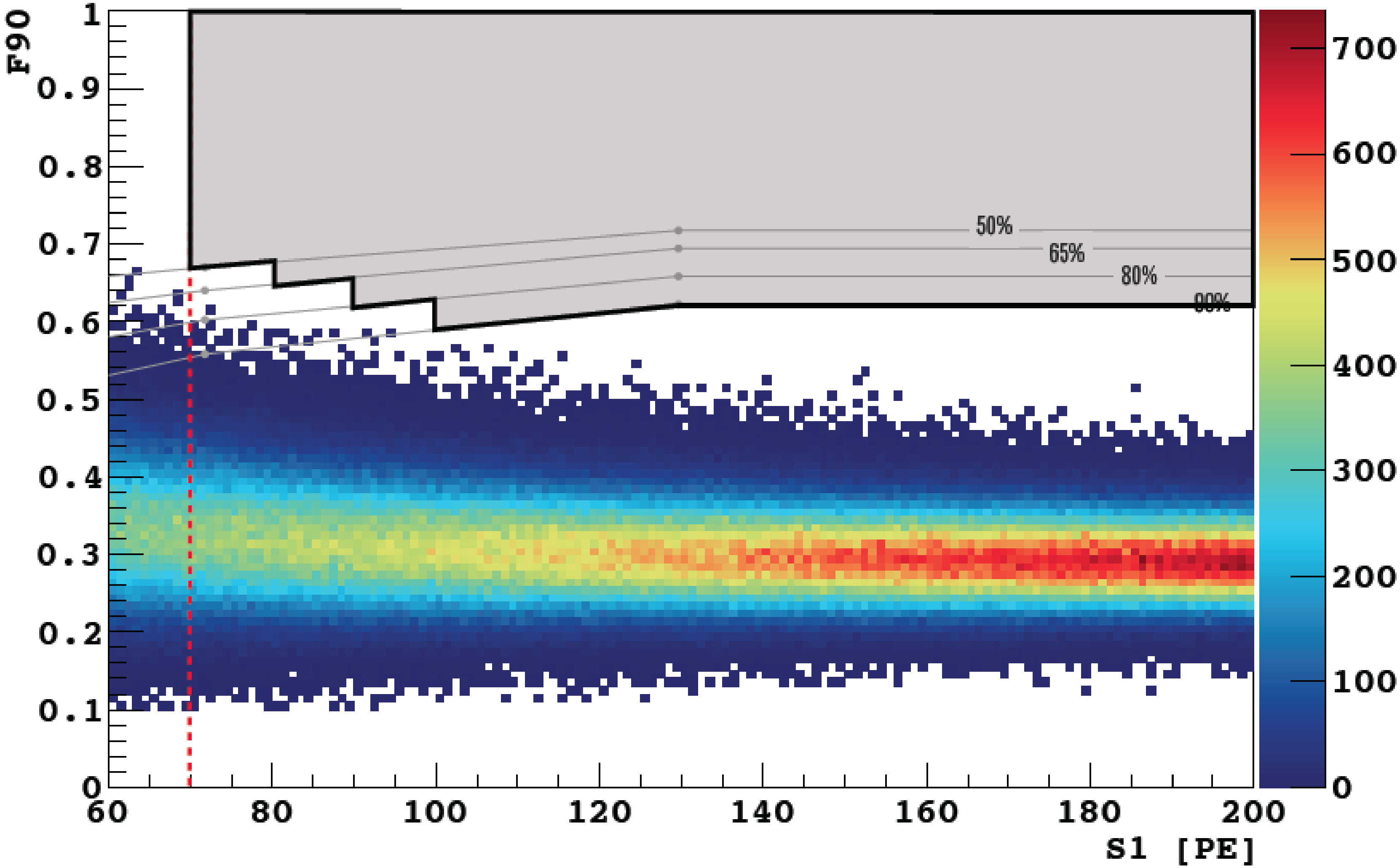
# DarkSide-50

- A two-phase Argon detector.
- Funded by NSF, DOE, INFN.
- Uses both pulse shape and S2/S1 discrimination to reduce electron recoil backgrounds.
- Underground Ar, with $^{39}$Ar reduced by factor > 100. Production at 0.5 kg/day.
- Located in Gran Sasso
- Projected sensitivity ~ 1 x $10^{-45}$ cm$^2$ at 100 GeV after 3 years live time.

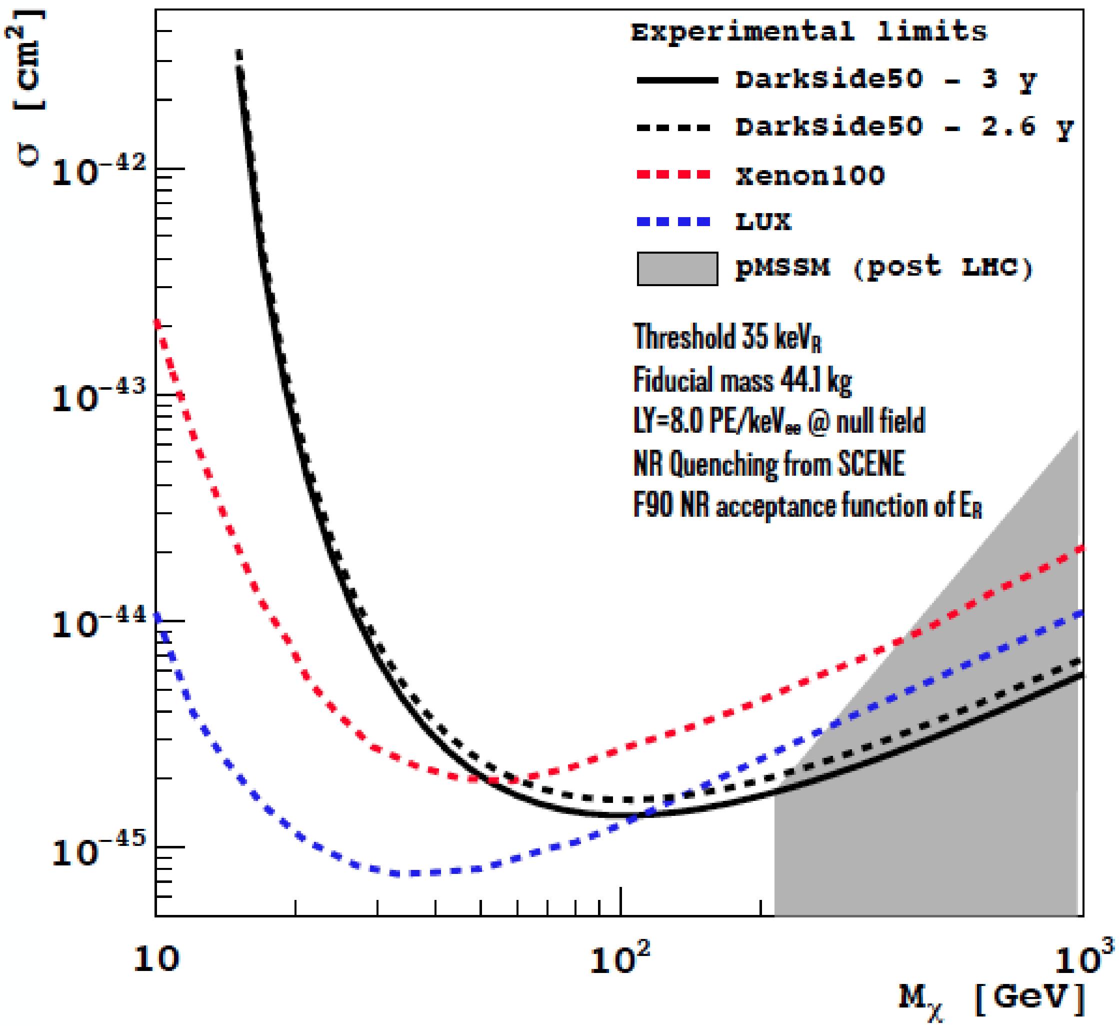


# First Data from DarkSide-50 (280 kg days)

Slide from L. Grandi, UCLA Dark Matter 2014



# DarkSide-50 Projected Sensitivity



# DEAP-3600 Dark Matter Search at SNOLAB

**Project Overview**

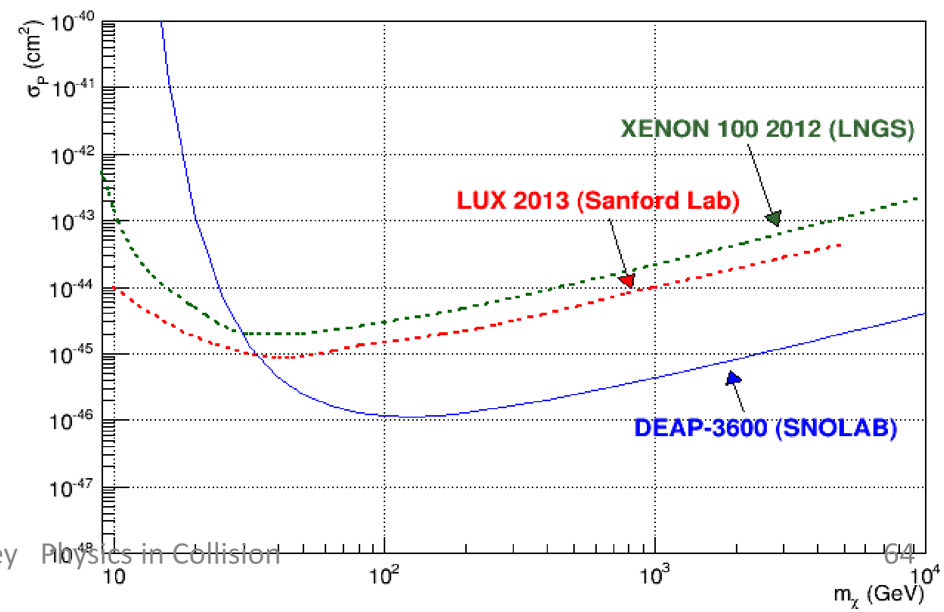
3.6 tonne liquid argon target in
85-cm radius ultraclean acrylic vessel,
255 8-inch HQE PMTs

1 tonne fiducial mass designed for
< 0.2 background events/year

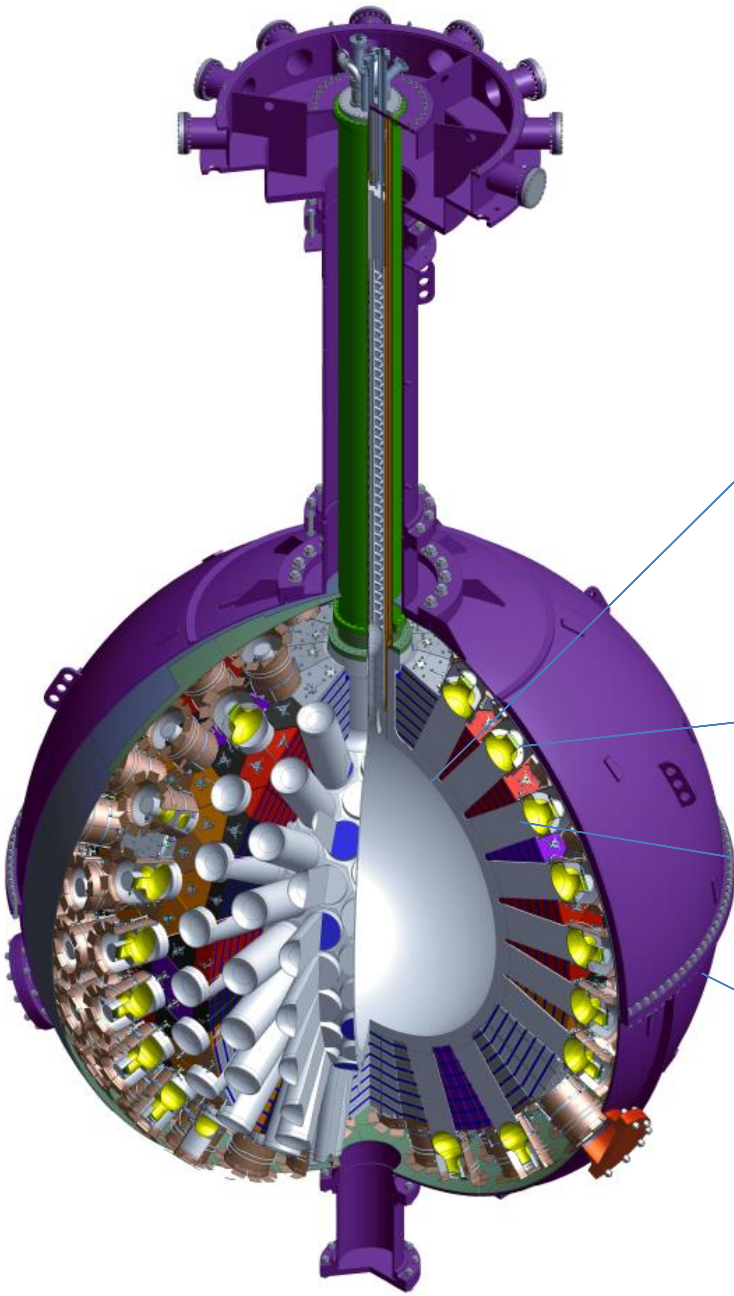
$10^{-46}$ $cm^2$ sensitivity for 100-GeV WIMP
with 3-year exposure
with 15 $keV_{ee}$ (60 $keV_r$) threshold

**Project Timeline**

| | |
|---|---|
| Turn-on PMT systems | Oct 2014 |
| Argon gas runs and in-situ background measurements, commissioning | Fall 2014 |
| Physics Data start | Early 2015 |



# DEAP-3600 Detector



3600 kg argon target
(1000 kg fiducial)
in sealed ultraclean
Acrylic Vessel

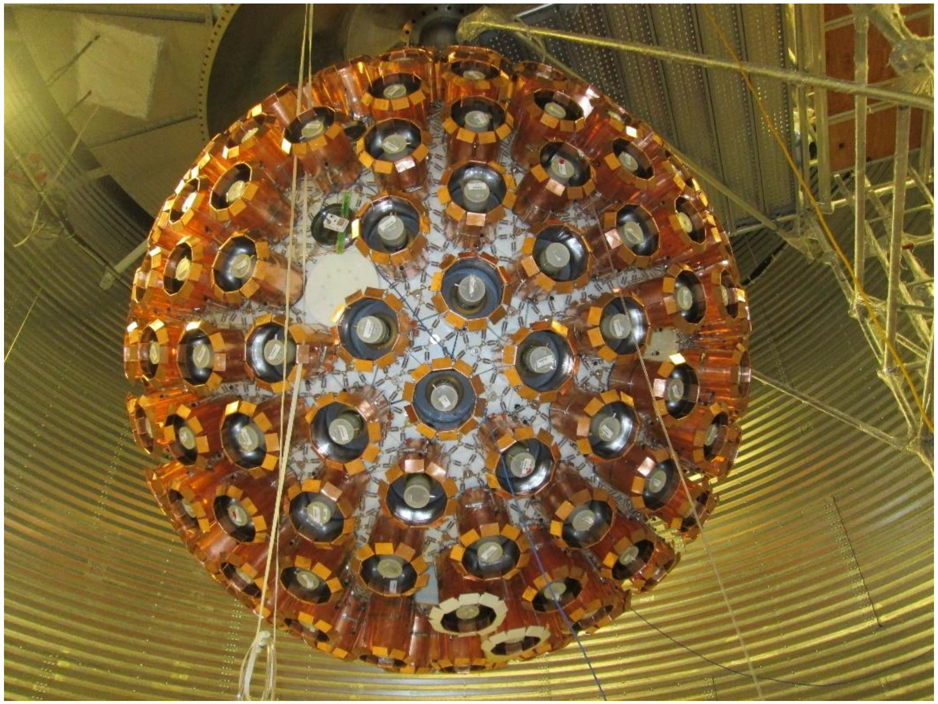
Vessel is "resurfaced"
in-situ to remove
deposited Rn daughters
after construction

255 Hamamatsu
R5912 HQE PMTs 8-inch
(32% QE, 75% coverage)

50 cm light guides +
PE shielding provide neutron
moderation

Steel Shell immersed in 8 m
water shield at SNOLAB

# DEAP-3600 Detector at SNOLAB

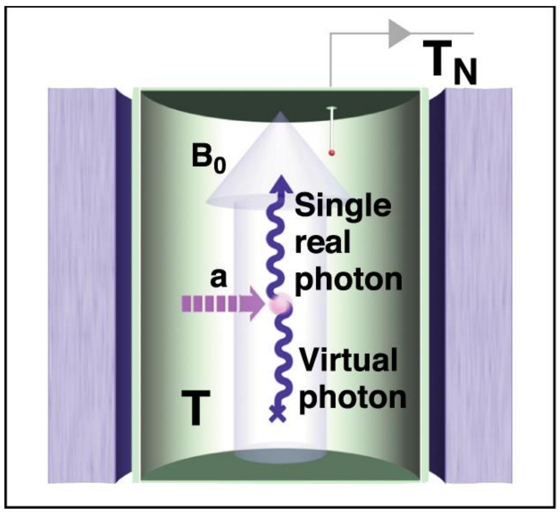


Completed inner detector
255 8” R5912HQE PMTs
installed in shield tank

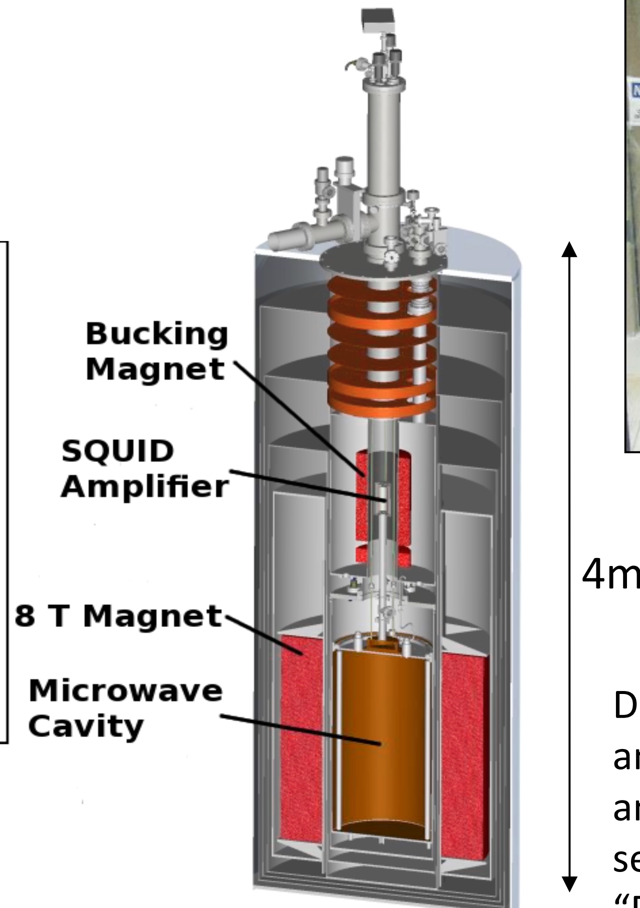
Steel Containment Sphere
in 8m diameter water shield tank

# ADMX: Principle of Operation

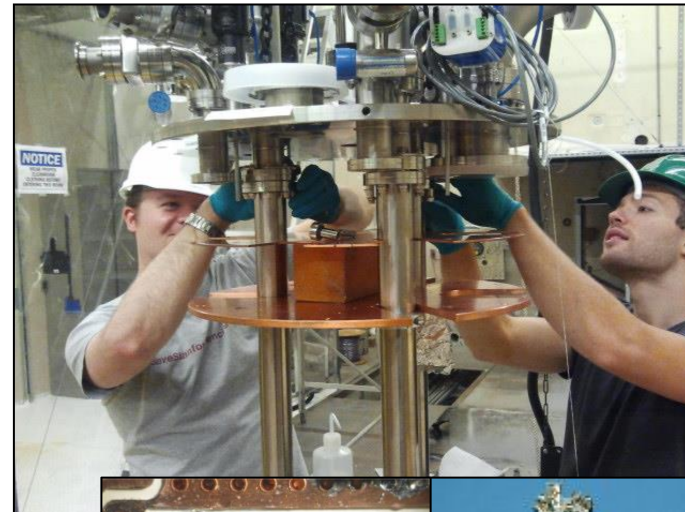
Halo axions convert into microwave photons inside a RF cavity threaded by a strong magnetic field

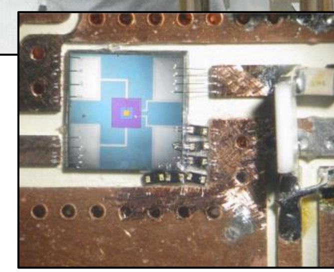



ADMX is sensitive to sub-yoctowatts of microwave power




New ADMX experiment insert fabricated and being assembled

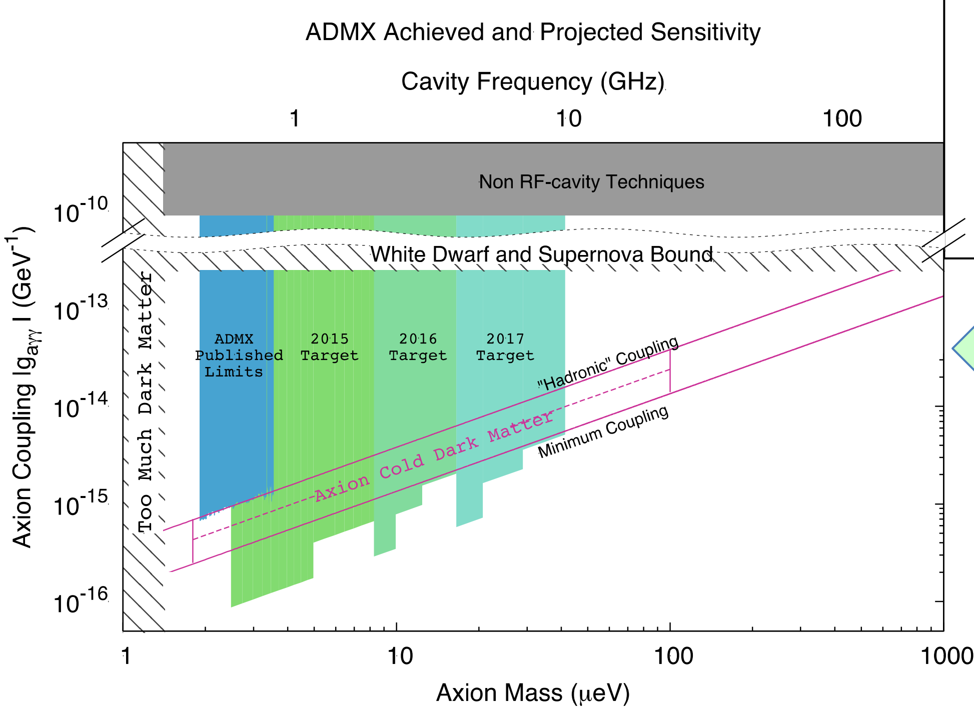


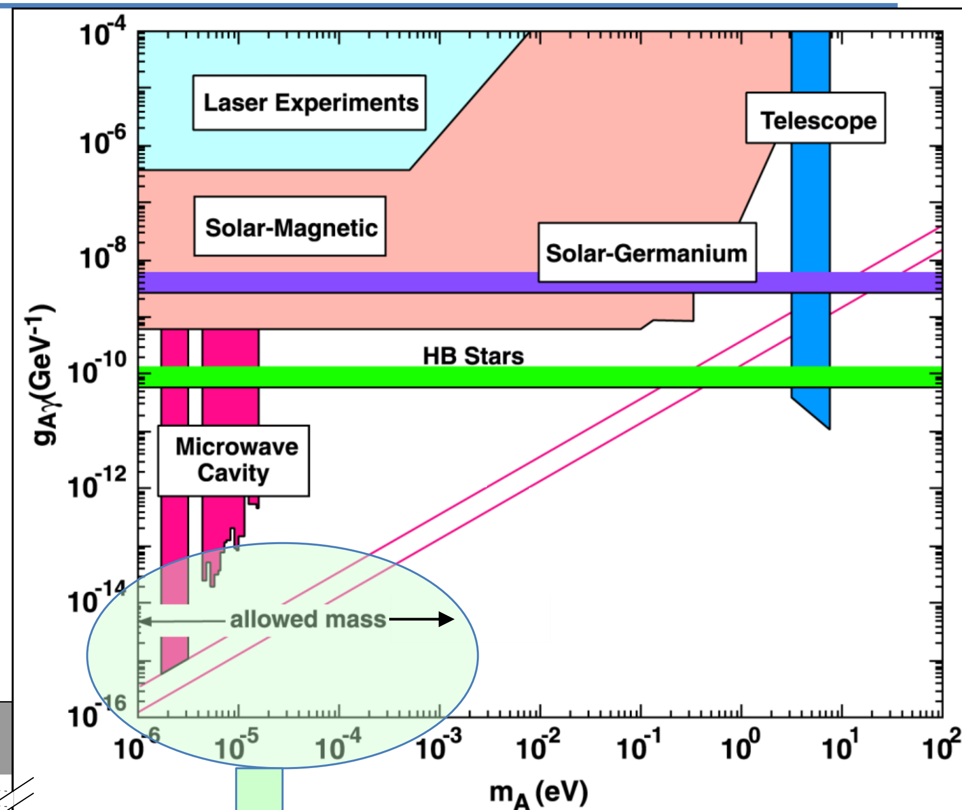


Dilution refrigerator and quantum-limited amplifiers provide sensitivity for the ADMX “Definitive Search”

# ADMX: The "Definitive" Search for QCD Dark-Matter Axions

The dilution refrigerator in ADMX significantly speeds the dark-matter search, so that …




… ADMX has the sensitivity to either detect the dark-matter QCD axion or reject this hypothesis at high confidence.

# Summary

- The hunt continues for dark matter interactions. Dark matter continues to be our best, most unambiguous evidence for physics beyond the Standard Model.
- New, significant developments in theory of dark matter interactions. For experiments, the basic figures of merit remain the same: low background and low energy threshold.
- After CDMS and LUX limits, the low-mass “hints” are disfavored as WIMP signals. Science is happening!
- It is still possible that dark matter particles are just out of reach, waiting to be detected by the next round of experiments.