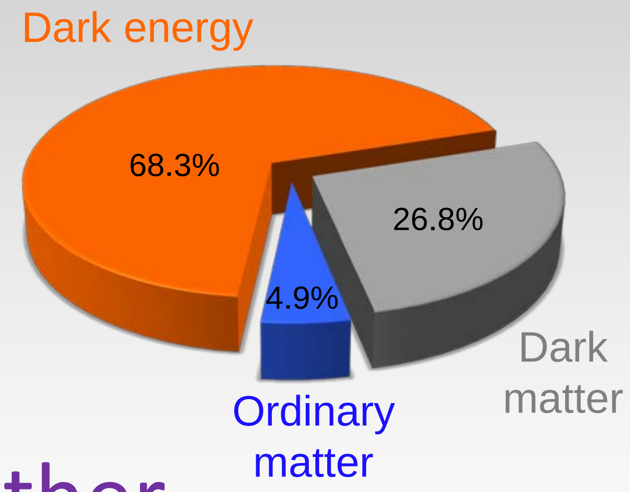
# "Shedding Light on The Dark Side of the Universe with LZ"


Wolfgang Lorenzon
University of Michigan

UNAM Nov 2017

# Don't let the bright lights fool you

# The DARK SIDE controls the UNIVERSE




**Dark Matter** holds it together

**Dark Energy** determines its destiny

# Big Questions

- What is our place in the Universe?
- What is it made of?
- How old is it?
- How has it developed?
- What is its ultimate fate?

# What Copernicus "Knew"*

- "First of all, we must note that the universe is spherical."

  *Elliptical orbits!*

- Motions are centered on the sun

  *Sun is at focus!*

- Uniform velocities

  *Equal areas in equal times!*

Nicolaus Copernicus (1473 – 1543)
the sun — rather than the Earth — is at the center of the solar system. This is considered among the most important landmarks in the history of modern science.

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*It ain't what you don't know, it's what you know that ain't so!

# What We "Know"*

- Cold dark matter holds the Universe together
  *we know nothing about it!*

- The Universe is dominated by a cosmological term
  (Dark Energy, cosmological constant, …)
  *we know less than nothing about it!*

→ The ultimate Copernican Revolution
  *95% of the Universe's mass/energy budget*
  *is unknown to us!*

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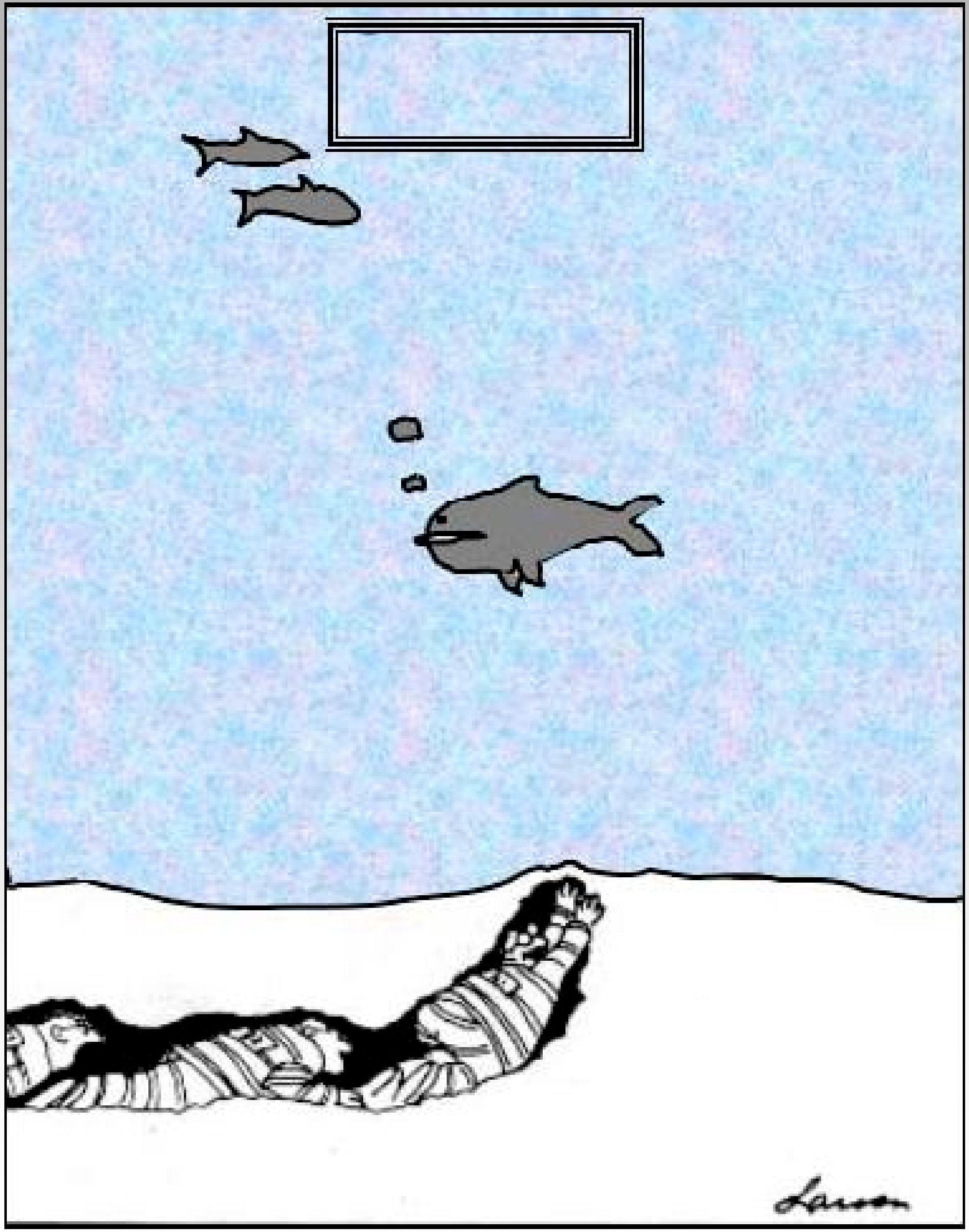
*It ain't what you don't know, it's what you know that ain't so!




**We're almost free, I just felt the first drops of rain**

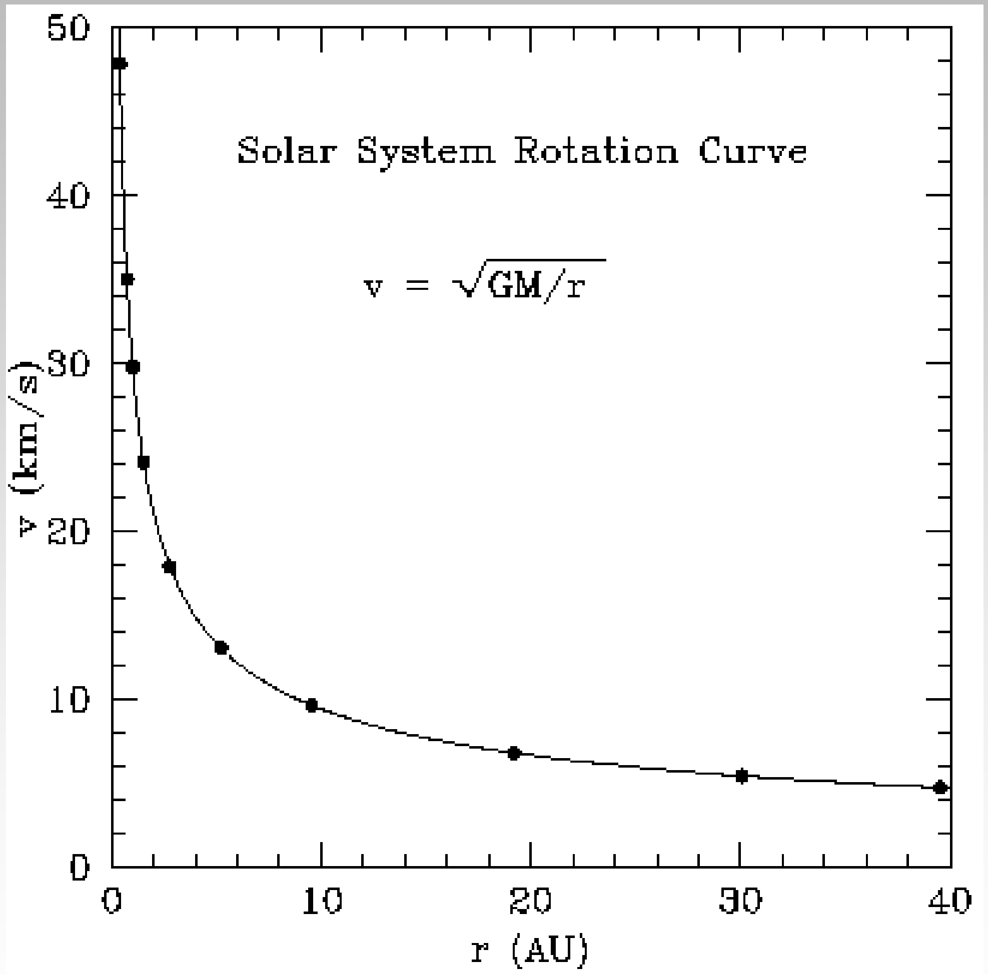
# The Mysterious DARK Matter

- Observations indicate that there is matter out there which does not emit, radiate, or absorb any kind of light
  - does not appear to interact with ordinary matter or itself at all except through gravity!

- One type of evidence for this is the way stars and gas in galaxies move …

# Solar System Rotation Curve

Average Speeds of the Planets

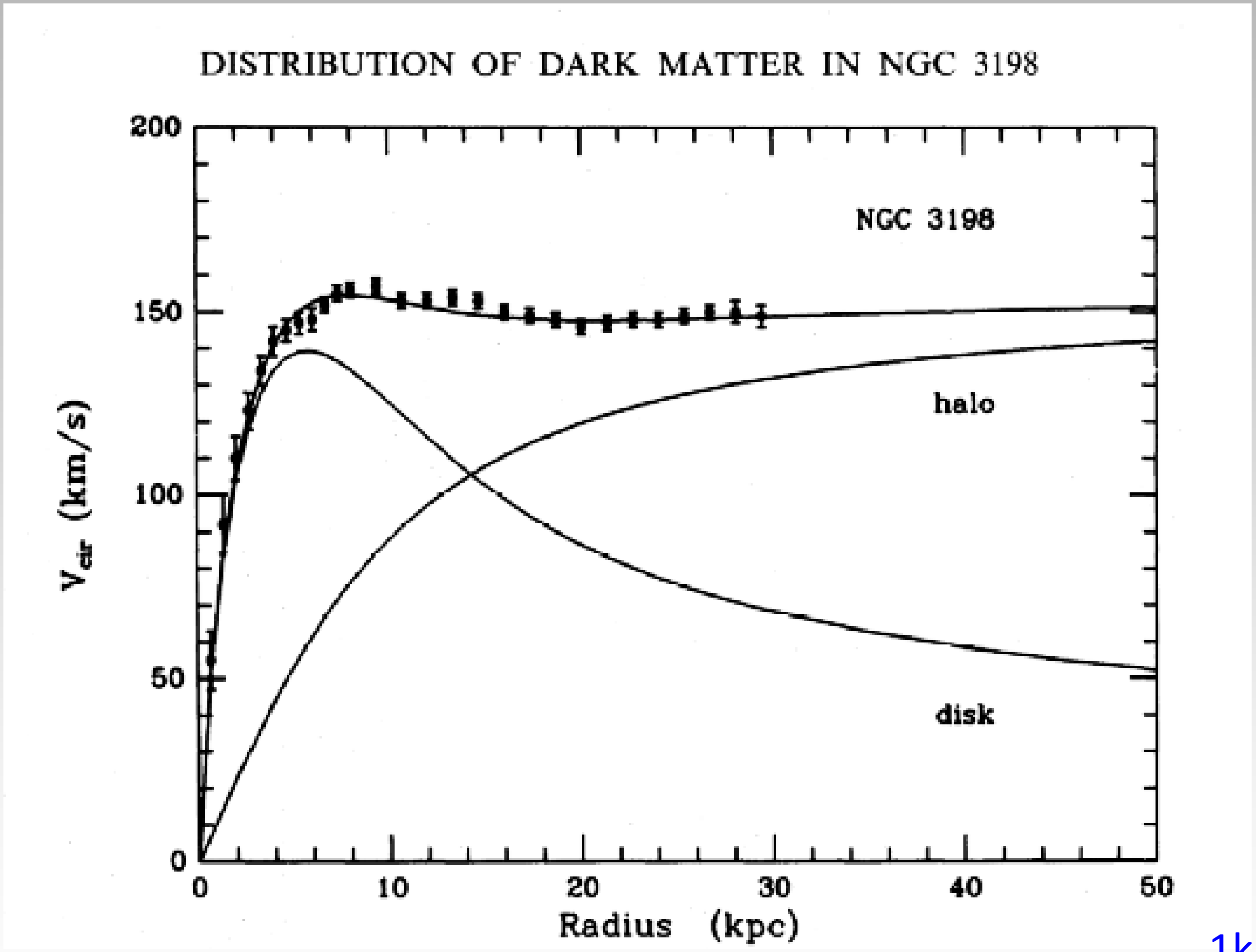



as you move out from the Sun, speeds of the planets drop

as expected:

$F_{gravitational} = F_{centripical}$
for planets to stay in orbit

# Rotation Curves of Galaxies



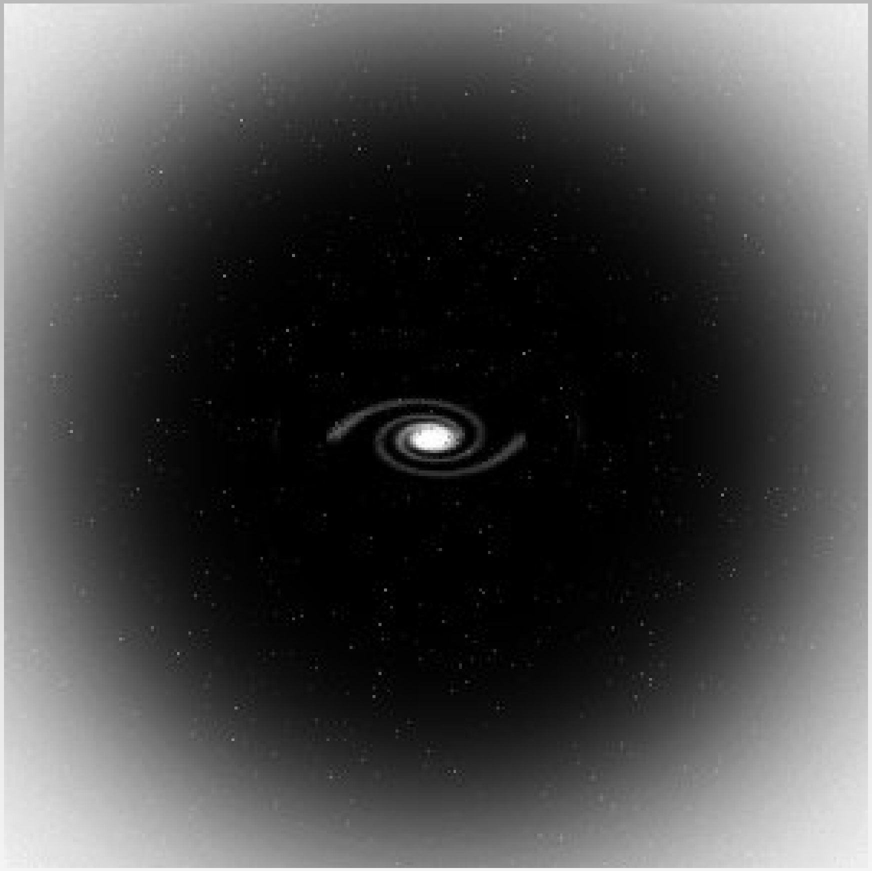

observed:
flat rotation
curve

expected
from stars

1kpc = 3,300 light years

95% of the mass in galaxies is made of an unknown dark matter component

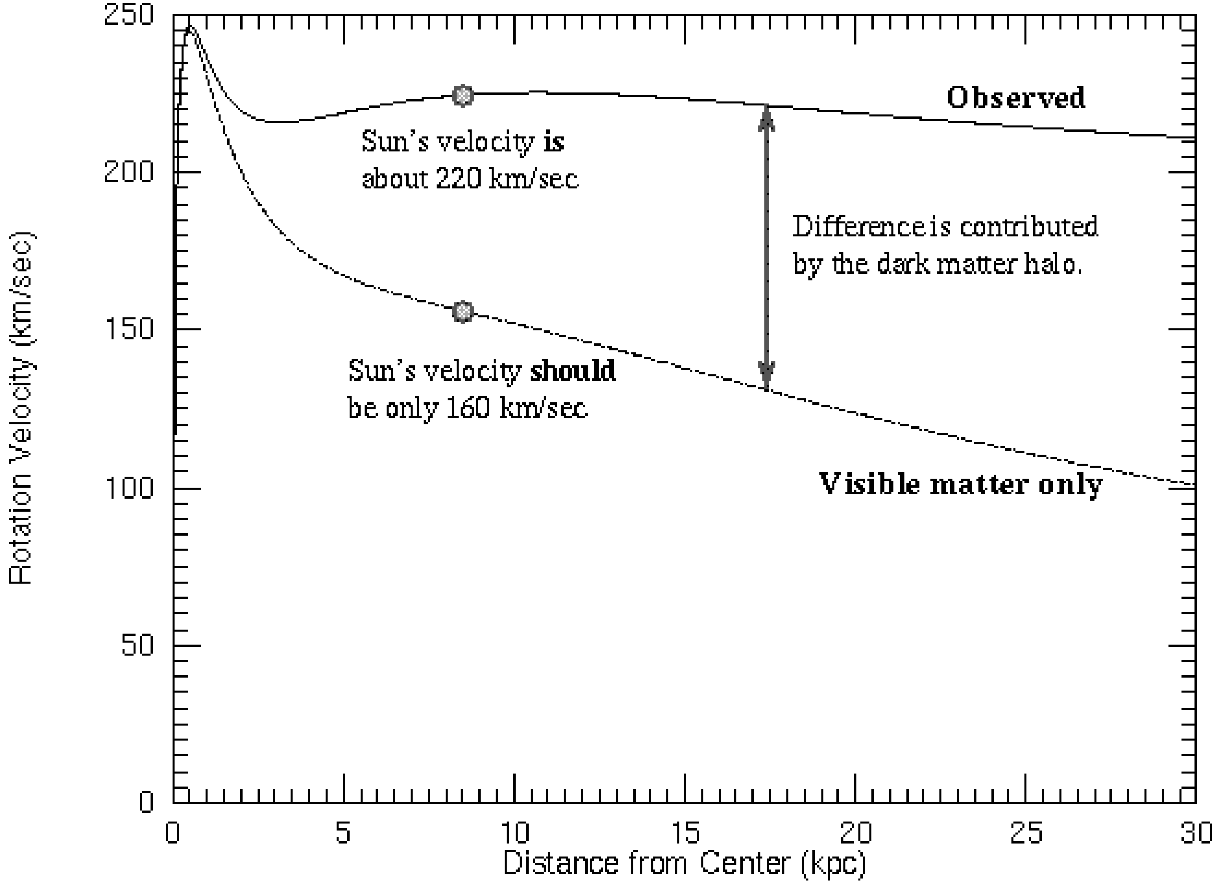
# Galaxies have Dark Matter Haloes



- dark matter local density: 0.32(0.02) GeV/cm$^3$

  *(inclusion of new LAMOST data, arXiv:1604.01216)*
- solar system is cycling the center of galaxy with an average speed of 220 km/s (annual modulation in earth movement)

# Sun's orbit is sped up by dark matter in the Milky Way

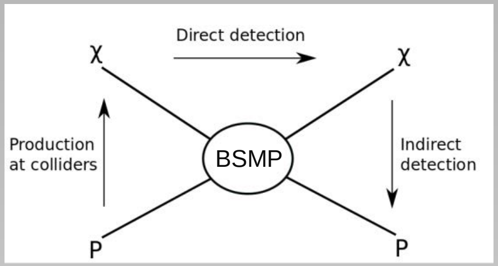



The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**

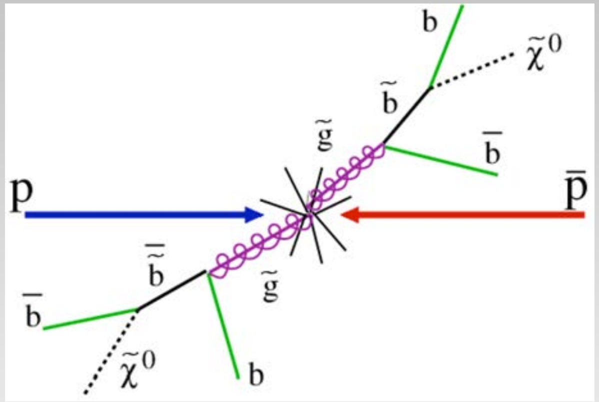
# What is Dark Matter?

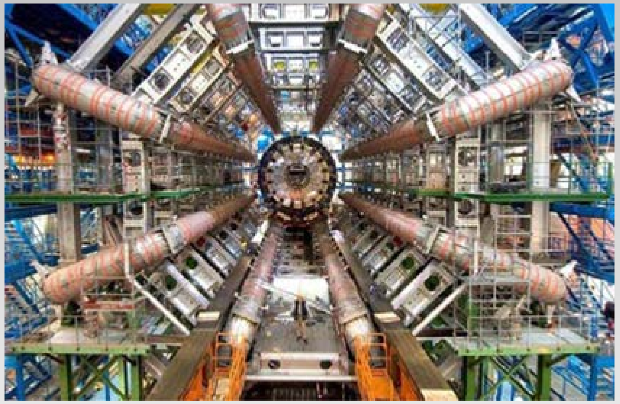
- Does not emit or absorb light in any wavelength
- Visible through gravitational effects only
  - but most models predict that Dark Matter should – on rare occasions – interact with ordinary matter
- Normal stuff that does not emit light?
  - brown dwarfs or planets, white dwarfs, neutron stars, black holes, dark galaxies and clusters of galaxies?
- Exotic particles?
  - “Hot” Dark Matter: neutrinos?
  - “Cold” Dark Matter: Weakly Interacting Massive Particles?
    WIMPs are about 100 times as heavy as protons
- Incorrect law of gravity?

# How does one detect a WIMP?

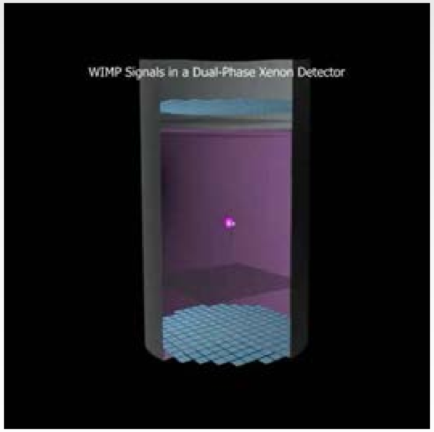



- Collider Search (production)



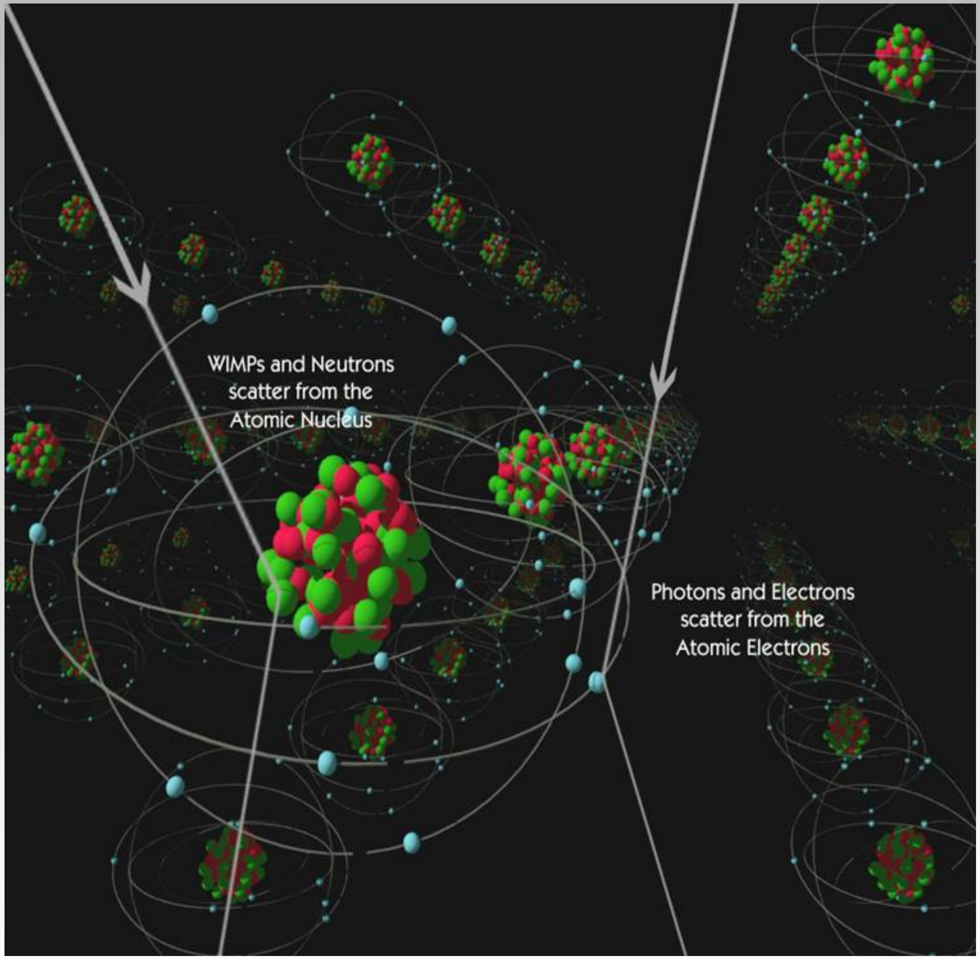



- Direct Search: waiting for dark matter reaction with detector material to happen




- Indirect Detection: of particles produced in dark matter annihilation

# WIMP – Direct Detection

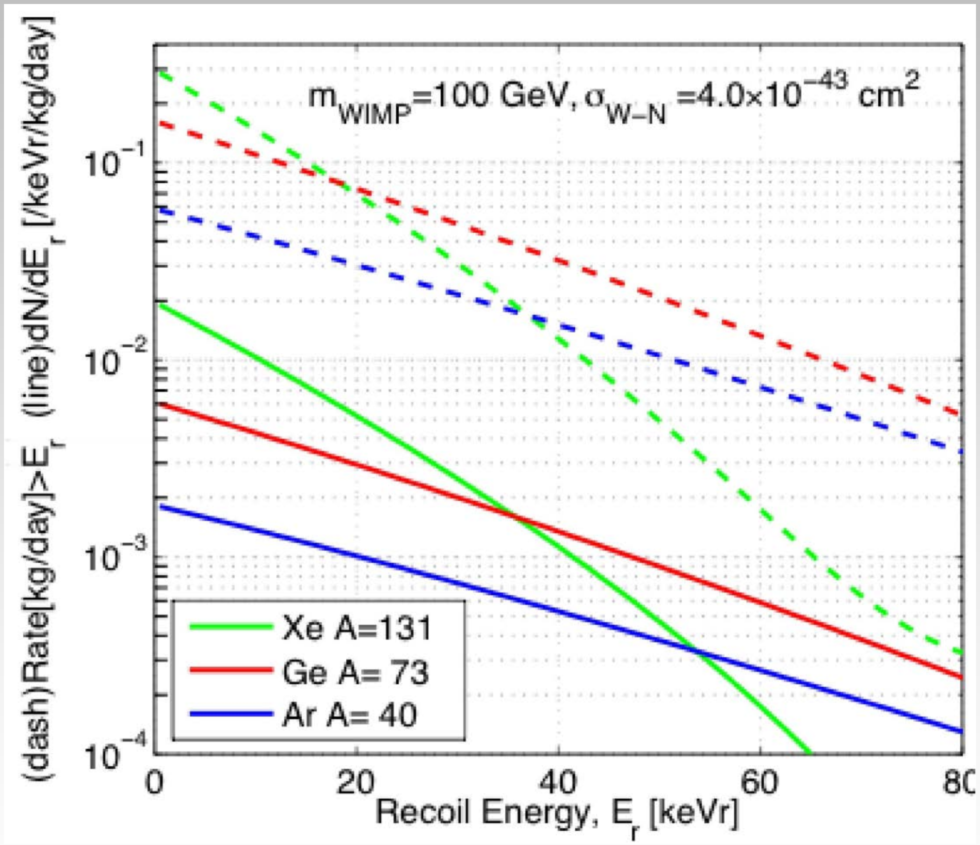



Credit: http://cdms.berkeley.edu

WIMP ↔ atomic nucleus in the detector, and detect its recoil (Goodman &Witten, 1985)

- Nuclear Recoil (NR): recoiling energy ≈10 keV
- Electron Recoil (ER): background (WIMP ER signal's energy hugely suppressed)

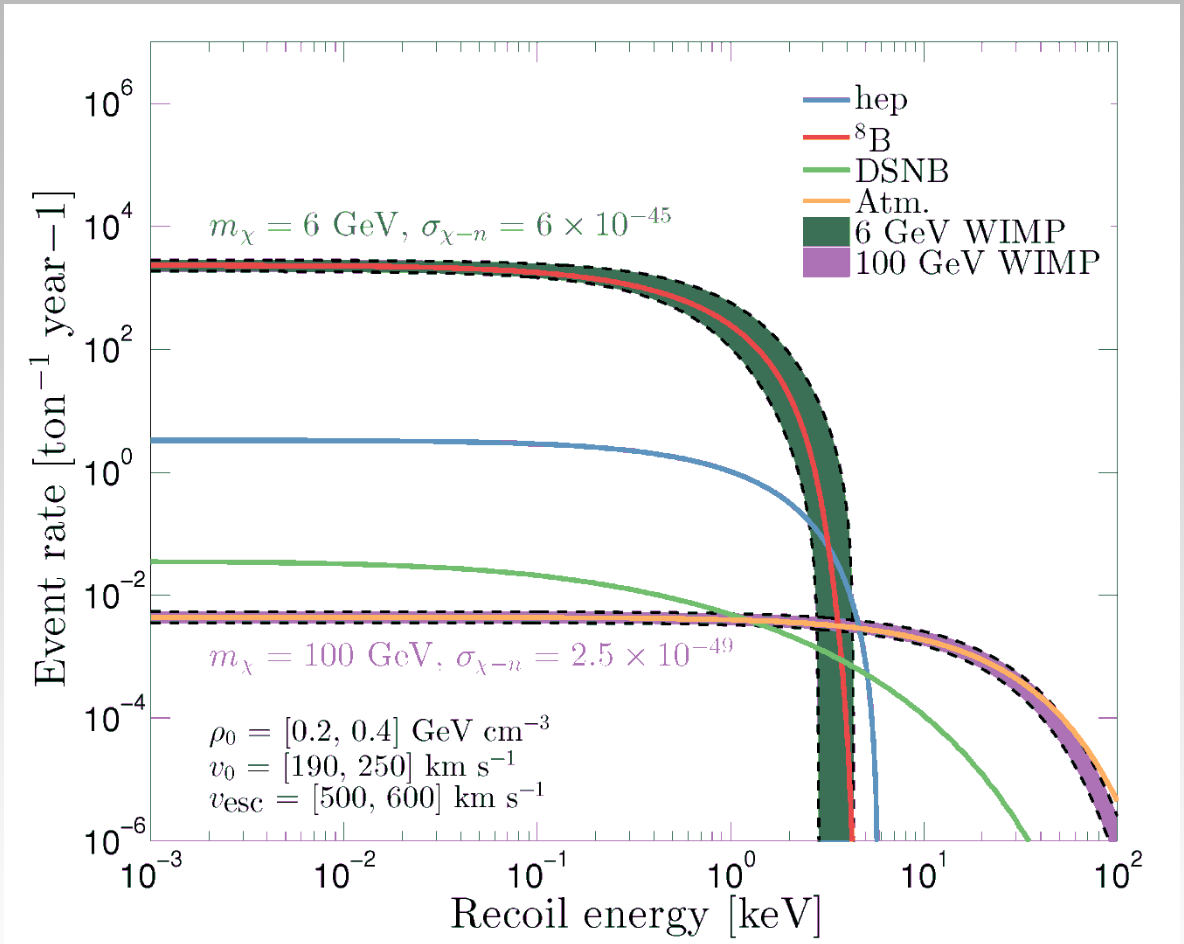
# Elastic Recoil Spectrum




Gaitskell, Ann. Rev. Nucl. Part. Sci., 54 (2004) 315

- Spin-independent (SI): coherent scattering on all nucleons ($A^2$ enhancement)
- Note: spin-dependent effect can be viewed as scattering with outer unpaired nucleon. No luxury of $A^2$ enhancement

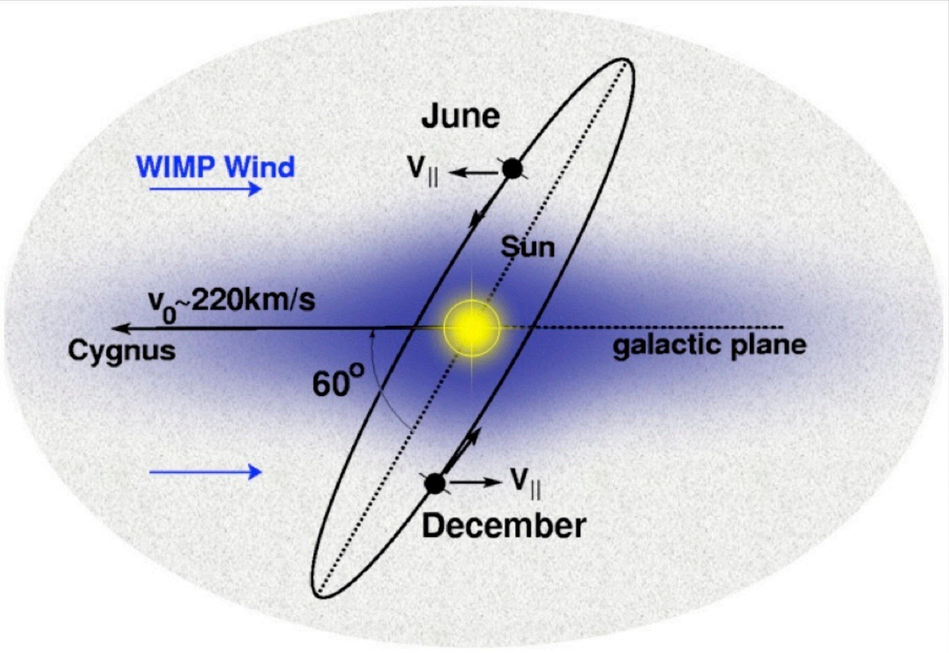
# Neutrino "Floor"




O'Hare, Phys. Rev. D 94, 063527 (2016)

- Energy threshold ↓ => mass DM↓
- neutrinos present an irreducible background to WIMP searches
- ideas do exist how to go beyond this "floor" (directional, annual modulation, etc)
- but pragmatic issue is still how to get there

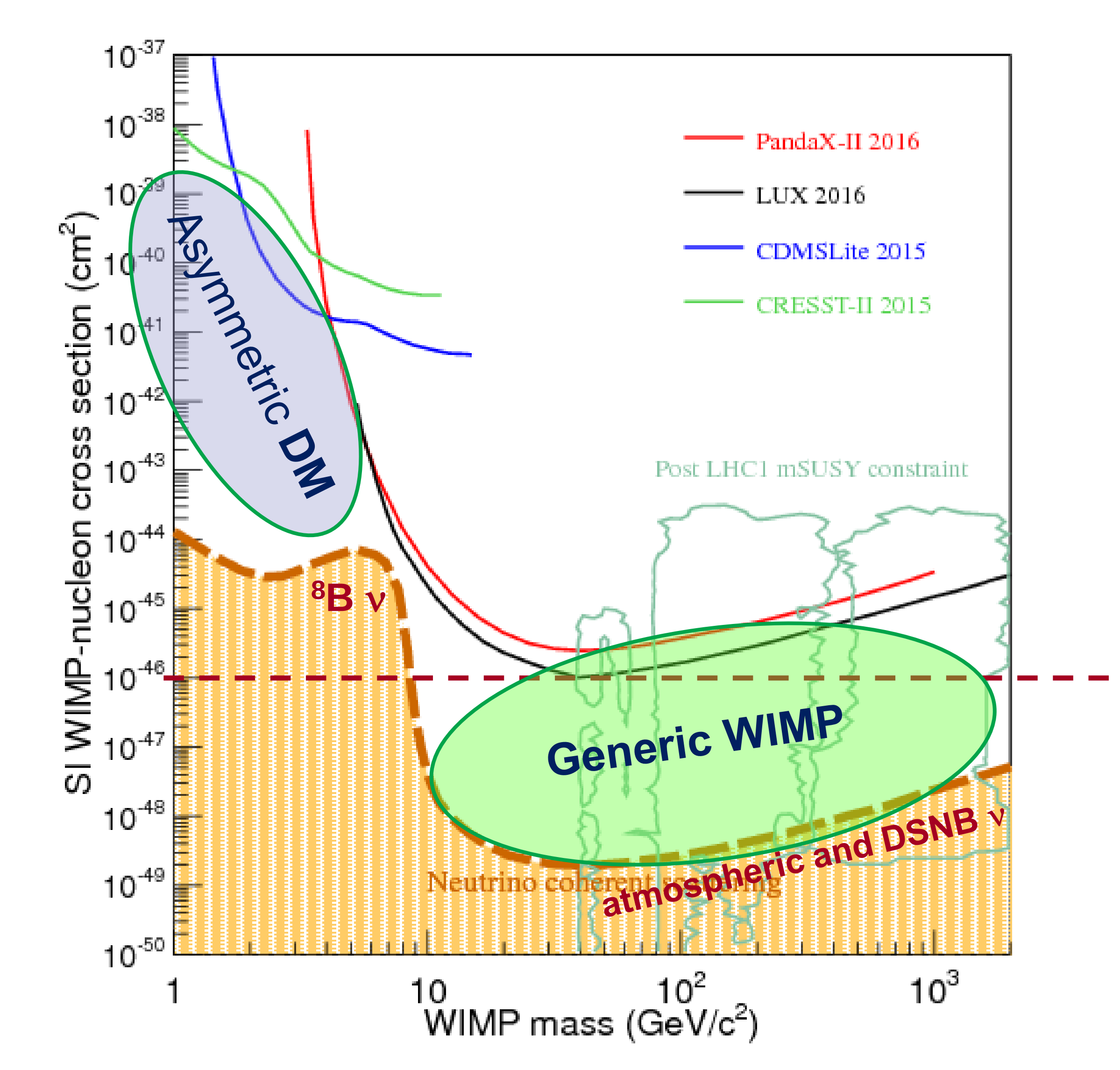
# Annual Modulation, Directionality




Credit: https://www.hep.ucl.ac.uk/darkMatter/

- Annual modulation of the WIMP signal arises because the velocity of a DM detector through the WIMP halo changes as the Earth moves around the sun
- Seasonal variations of the velocity: ±30 km/s => ±5% modulation effects (subtle)

# Available Hiding Space for DM



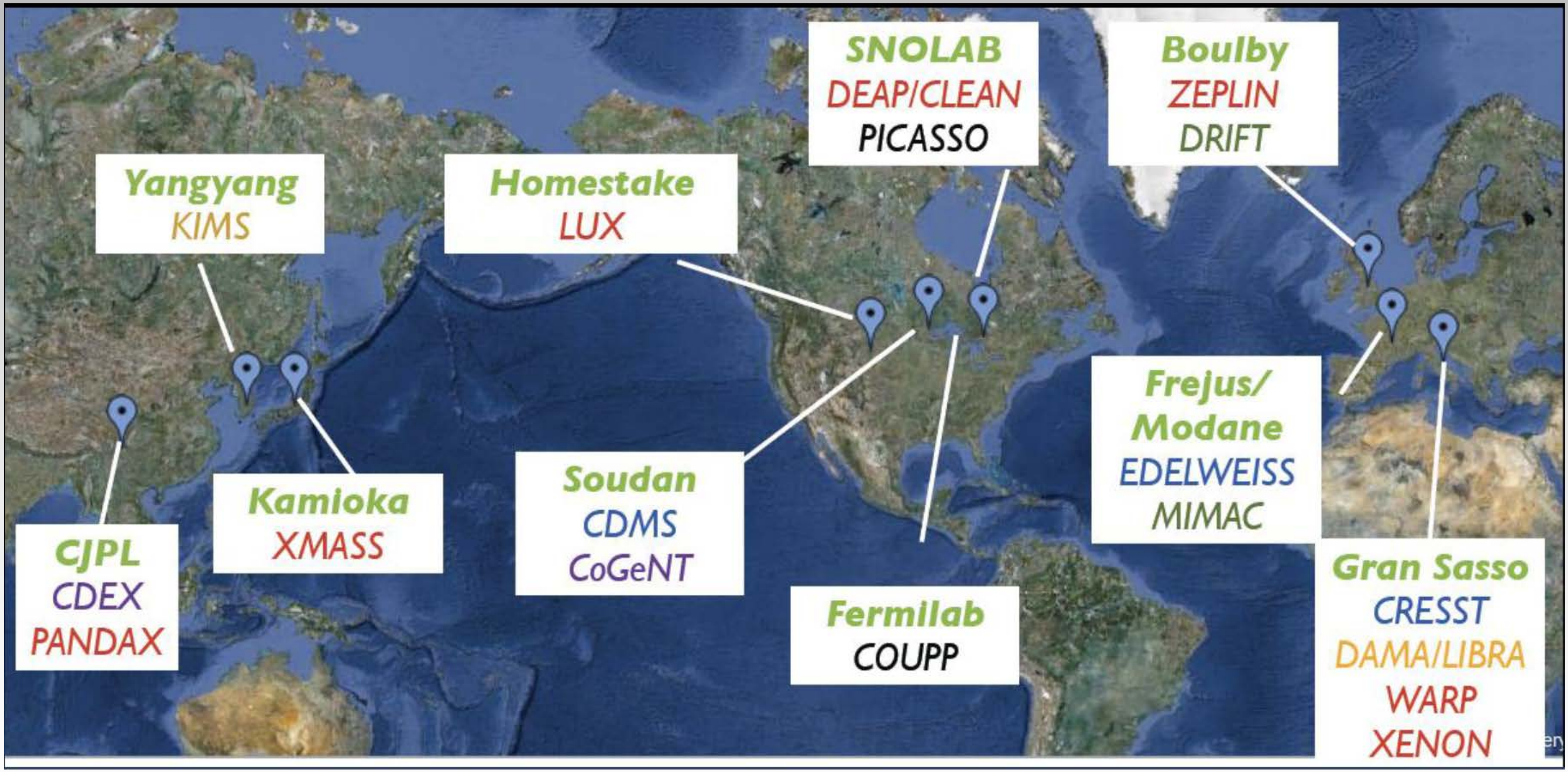

Nature Physics 13, 212 (2017)

a few events/100kg/year

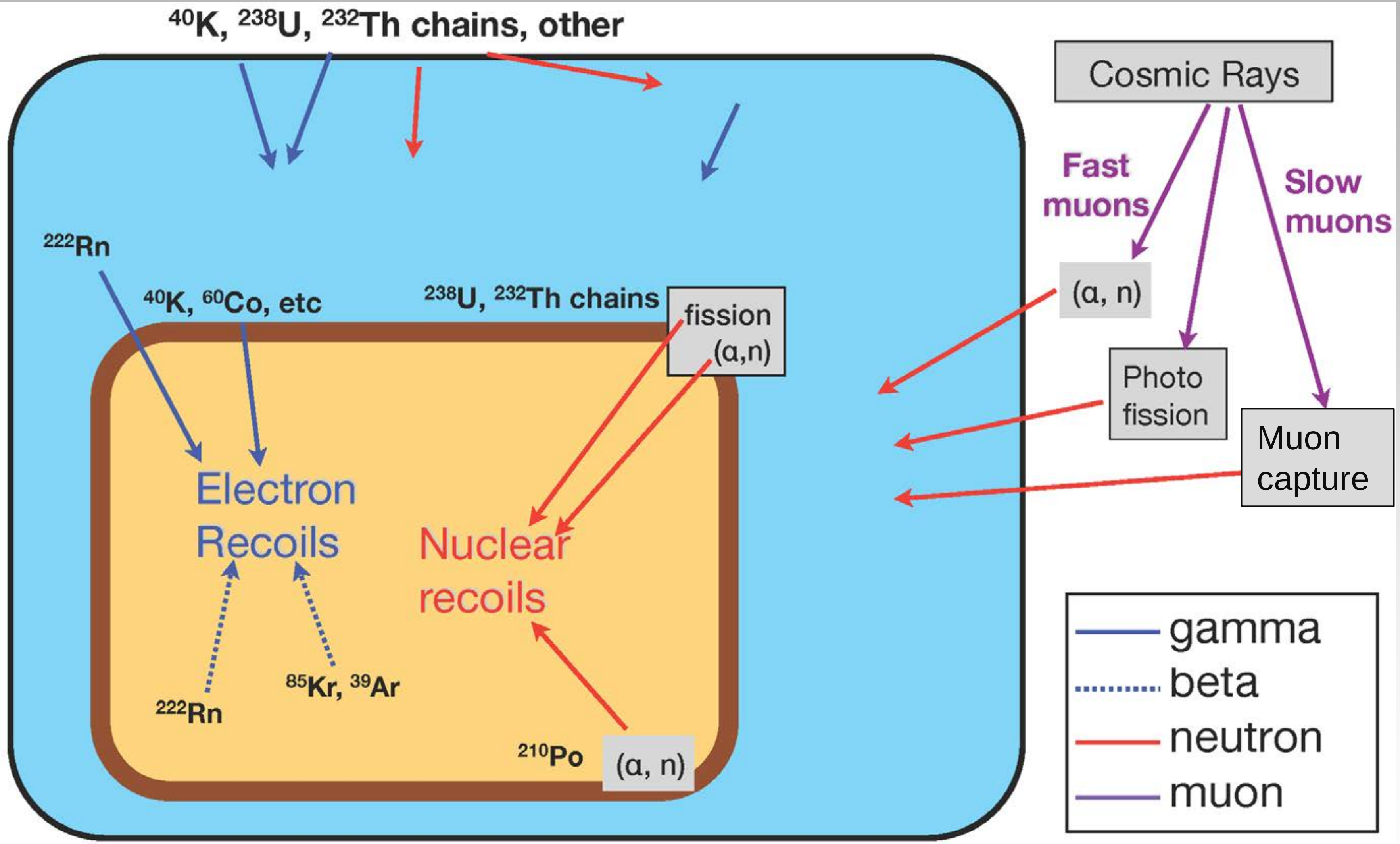
2 directions (G2):

- improve sensitivity at large mass
- improve sensitivity at small mass

# A "DARK MATTER RUSH"



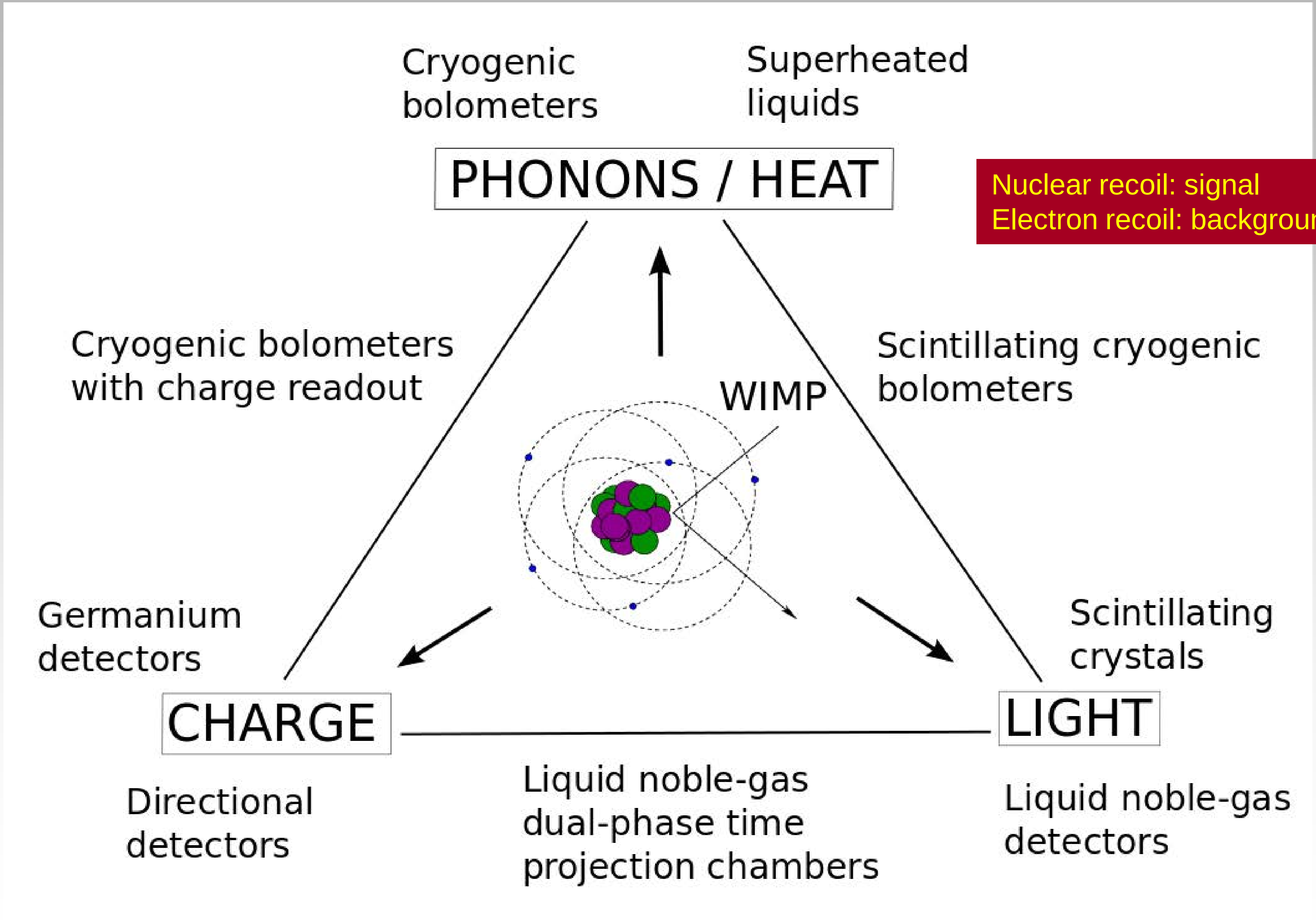
# Backgrounds: Internal & External




Credit: Tom Shutt (SLAC)

Note: ambient backgrounds are ≈$10^{11}$x DM rate

# DM Detection Techniques




Nuclear recoil: signal
Electron recoil: background

# Cryogenic Low Threshold Detectors

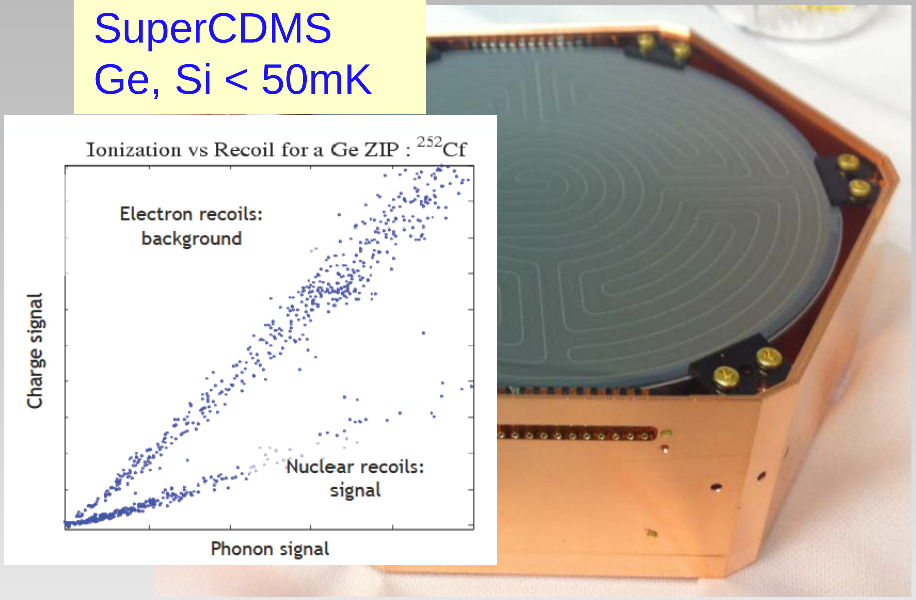
| **Cost per kg** | **Very high*** |
|---|---|
| Difficulty in target scaling | Moderate: build arrays |
| Radioactive isotope | Ge/Si can be very pure |
| Position reconstruction ability | iZIP: yes via interdigitated electrodes<br>Surface/volume available via PSD |
| Self shielding | Moderate: not monolithic, surface background important |
| ER background suppression | Excellent if phonon and ionization detection $10^{-6}$ |
| RoI | Low mass WIMPs |

* difficult to give $/kg due to significant cost on processing/fabrication.

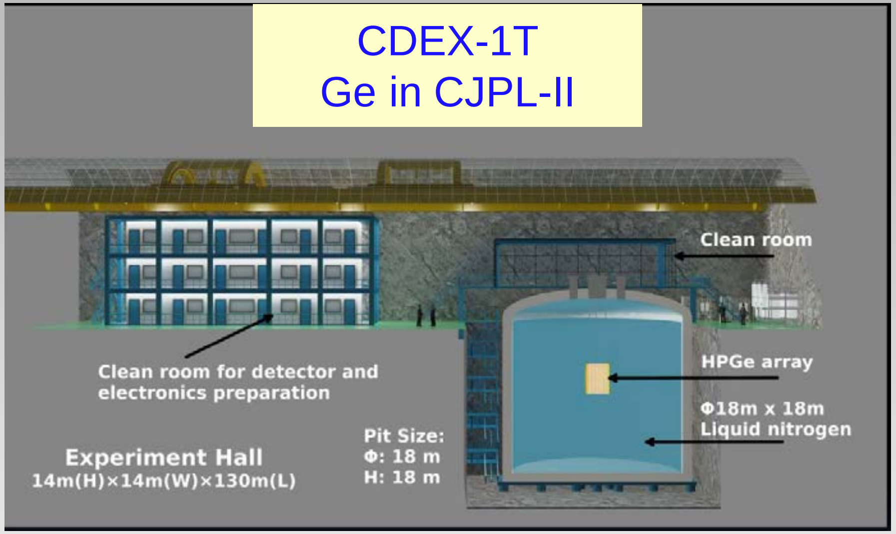
Credit: J. Liu, EPS 2017

# Cryogenic Detector Program

SuperCDMS
Ge, Si < 50mK

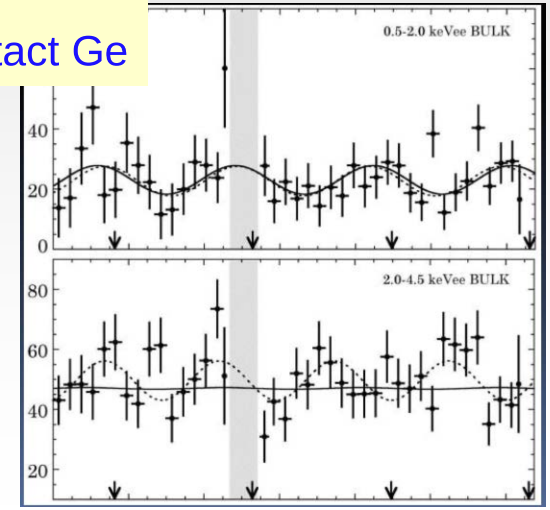



CDEX-1T
Ge in CJPL-II

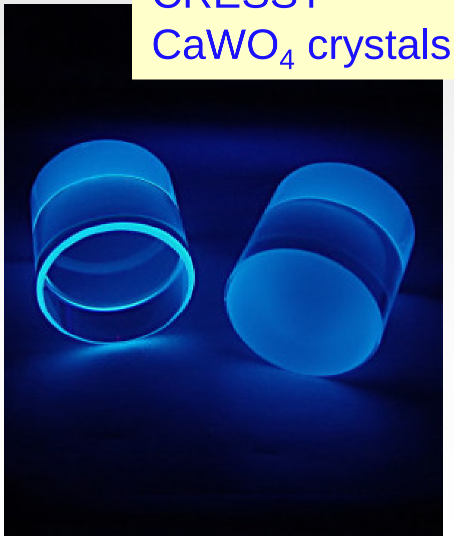



GoGeNT
point-contact Ge

Annual modulation signal

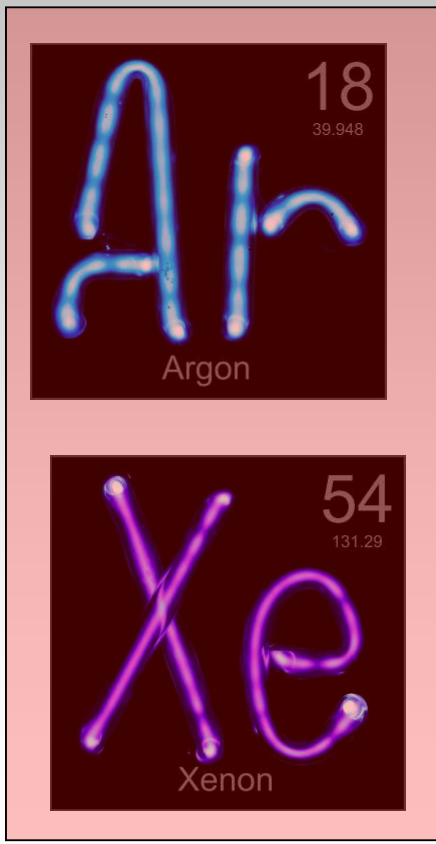



CRESST
$CaWO_4$ crystals (10 mK)



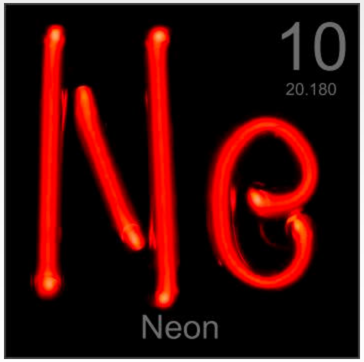
# Liquid Noble Detectors

- scalable to large mass
- good detector media: scintillation + charge
- pure, hence radiopure*

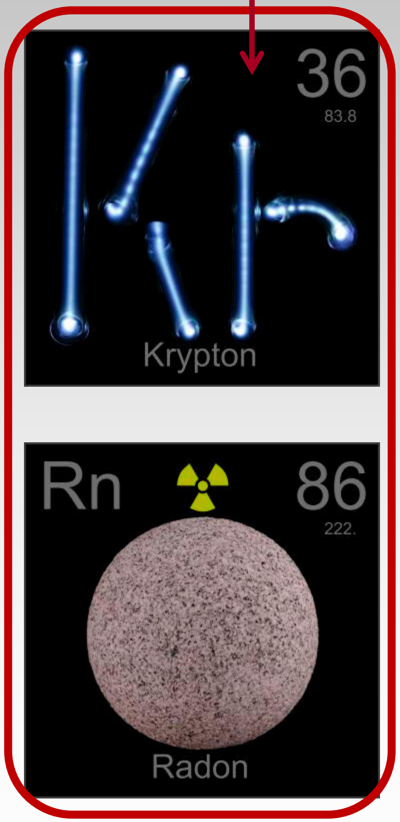




light WIMPs



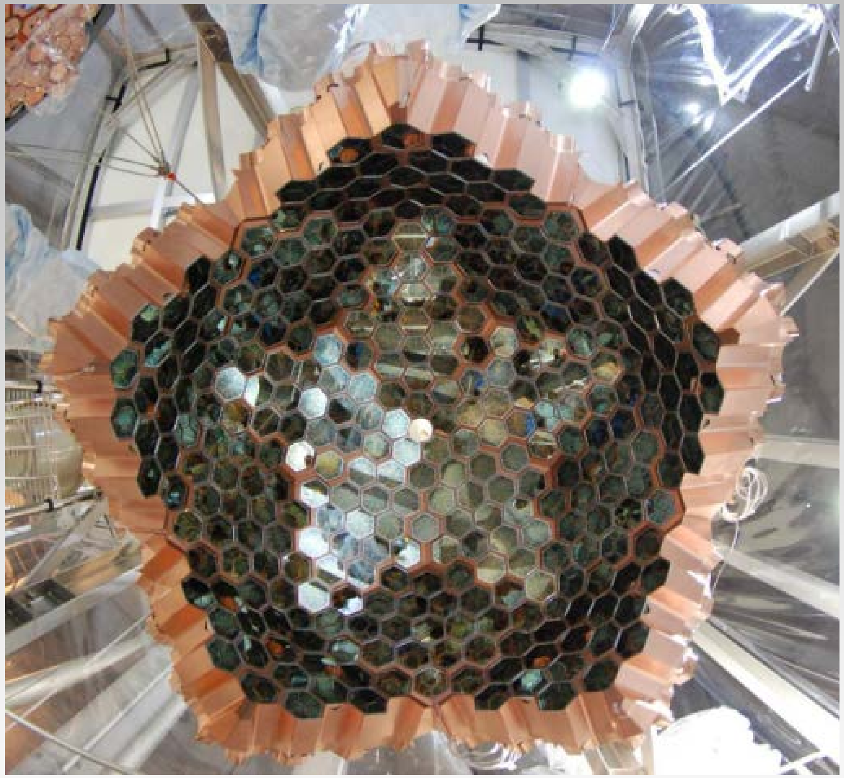

1 MBq/kg




Credit: http://periodictable.com/

*except when not: $^{39}$Ar, $^{85}$Kr

# Single-Phase / Dual-Phase

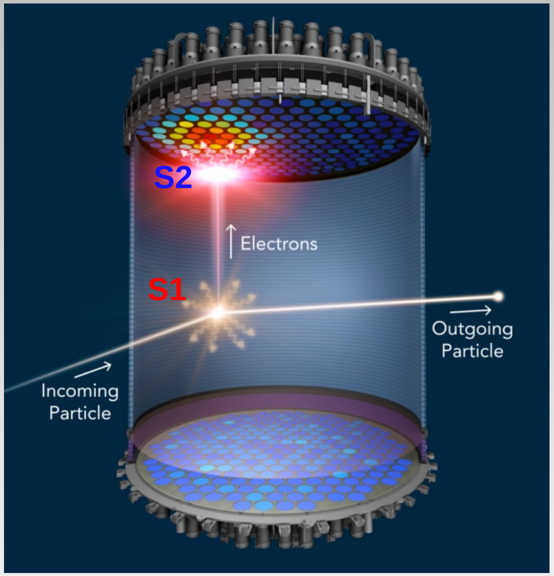


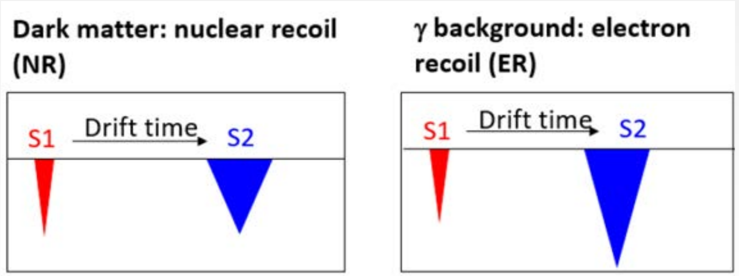
4π scintillation:

→ very high light collection

Time-Projection-Chamber (TPC):

→ 3-dim position information




$(S2/S1)_{NR} << (S2/S1)_{ER}$

# Liquid Argon Detectors

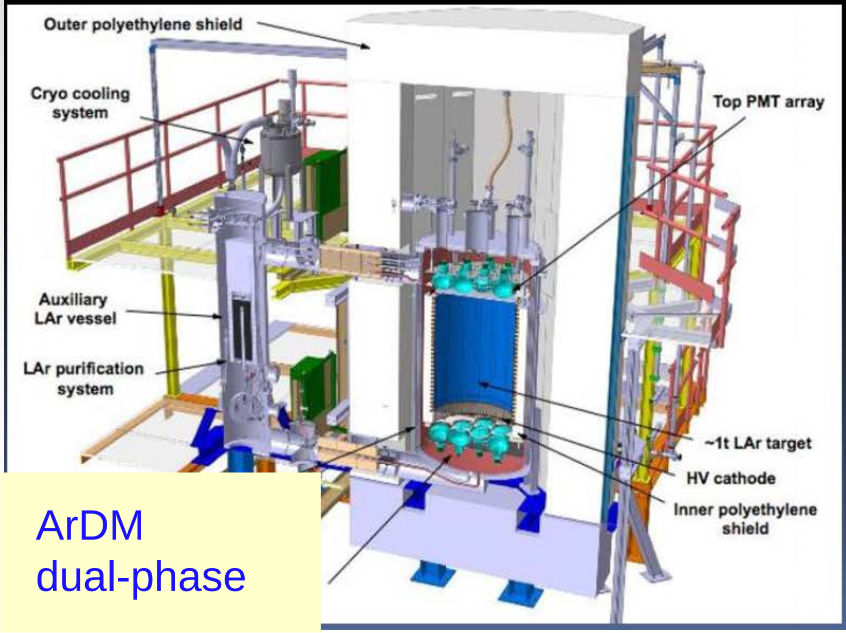
| | |
|---|---|
| **Cost per kg** | **cheap** |
| Difficulty in scaling | Easy (monolithic detector) |
| Radioactive isotope | $^{39}Ar$ (1Bq/kg) except using underground Ar (UAr) |
| Position reconstruction ability | TPC: excellent (few mm)<br>Single-phase: yes (cm) |
| Self shielding | Good |
| ER background suppression | Excellent via PSD ($10^{-8}$), additional in TPC |
| Energy threshold | High (needed for PSD) |

Credit: J. Liu, EPS 2017

# Liquid Argon Program


DEAP 3600
single-phase

Mini-Clean
single-phase




ArDM
dual-phase

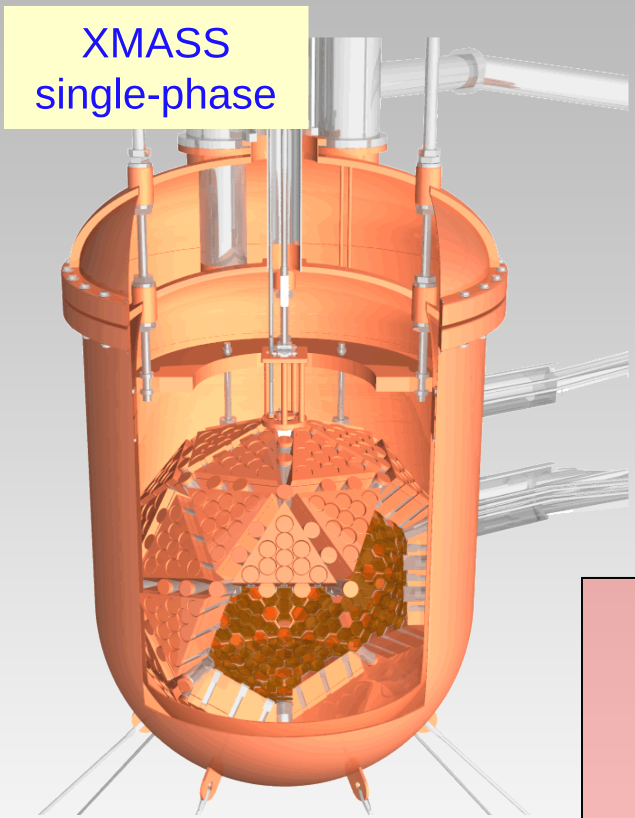
DarkSide-50
dual-phase

# Liquid Xenon Detectors

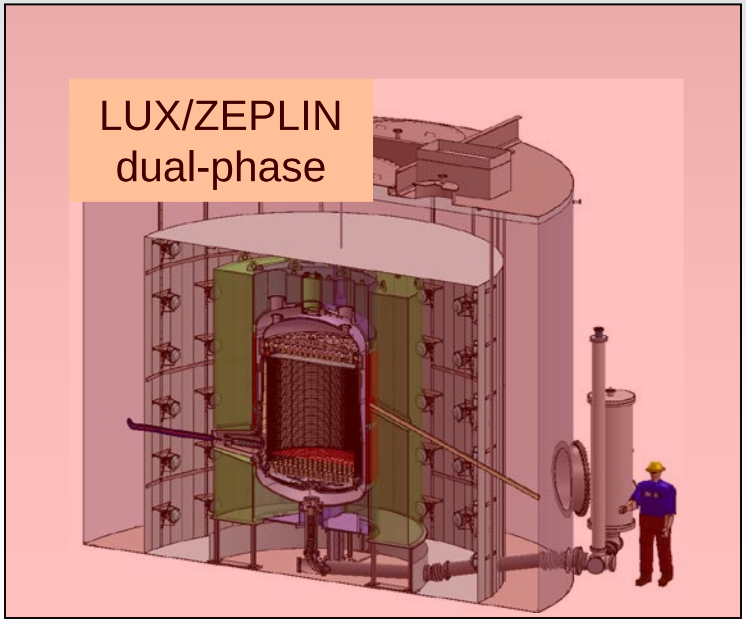
| | |
|---|---|
| **Cost per kg** | **High: ~$1500/kg (material only)** |
| Difficulty in scaling | Easy: monolithic |
| Radioactive isotope | Very pure except $^{136}Xe$, other than short lived cosmogenic isotopes |
| Position reconstruction ability | TPC: excellent (few mm)<br>Single phase: ~cm |
| Self shielding | Excellent |
| ER background suppression | TPC: good with charge/light ratio 0.5%<br>Single phase: moderate with PSD |
| RoI | Medium to high mass WIMPs |

Credit: J. Liu, EPS 2017

# Liquid Xenon Program








# The LZ Collaboration

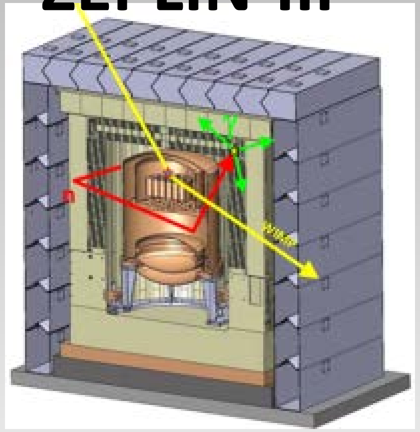
March 2017

**36 institutions; about 250 scientists, engineers, and technicians**

1) Center for Underground Physics (South Korea)
2) LIP Coimbra (Portugal)
3) MEPhI (Russia)
4) Imperial College London (UK)
5) STFC Rutherford Appleton Lab (UK)
6) University College London (UK)
7) University of Bristol (UK)
8) University of Edinburgh (UK)
9) University of Liverpool (UK)
10) University of Oxford (UK)
11) University of Sheffield (UK)
12) Black Hill State University (US)
13) Brookhaven National Lab (US)
14) Brown University (US)
15) Fermi National Accelerator Lab (US)
16) Lawrence Berkeley National Lab (US)
17) Lawrence Livermore National Lab (US)
18) Northwestern University (US)
19) Pennsylvania State University (US)
20) SLAC National Accelerator Lab (US)
21) South Dakota School of Mines and Technology (US)
22) South Dakota Science and Technology Authority (US)
23) Texas A&M University (US)
24) University at Albany (US)
25) University of Alabama (US)
26) University of California, Berkeley (US)
27) University of California, Davis (US)
28) University of California, Santa Barbara (US)
29) University of Maryland (US)
30) University of Massachusetts (US)
31) University of Michigan (US)
32) University of Rochester (US)
33) University of South Dakota (US)
34) University of Wisconsin – Madison (US)
35) Washington University in St. Louis (US)
36) Yale University (US)

# LZ = LUX + ZEPLIN

## ZEPLIN-III

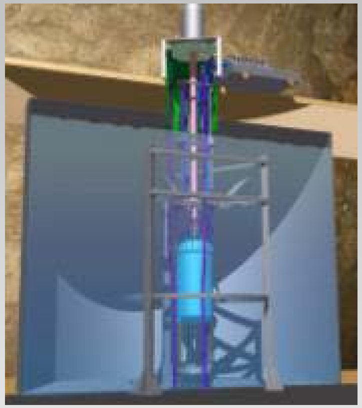



6 kg LXe fid

ZEPLIN pioneered WIMP-search with 2-phase Xe
$3.9 \times 10^{-44}$ cm$^2$

+

## LUX

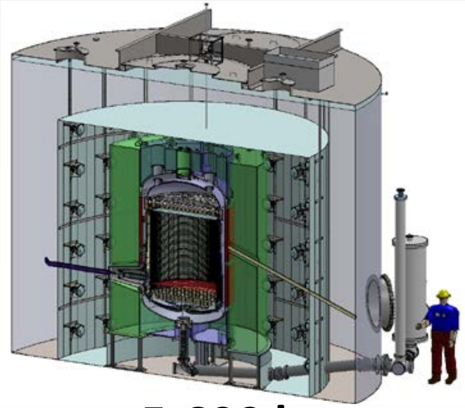


100 kg

$1.1 \times 10^{-46}$ cm$^2$ at 50 GeV/c$^2$ (decommissioned in early 2017)

## LZ

→



5,600 kg

Scale-up using demonstrated technology and experience for low-risk but aggressive program:

- internal background-free strategy
- some infrastructure inherited from LUX
- **LZ expected sensitivity: $2.3 \times 10^{-48}$ cm$^2$ with 3-yr run**

# Sanford Underground Research Facility


Davis Cavern 1480 m
(4200 mwe)
LZ in LUX Water Tank
South Dakota, USA

**LZ Here**

# Scale up ≈ 50 in Fiducial Mass

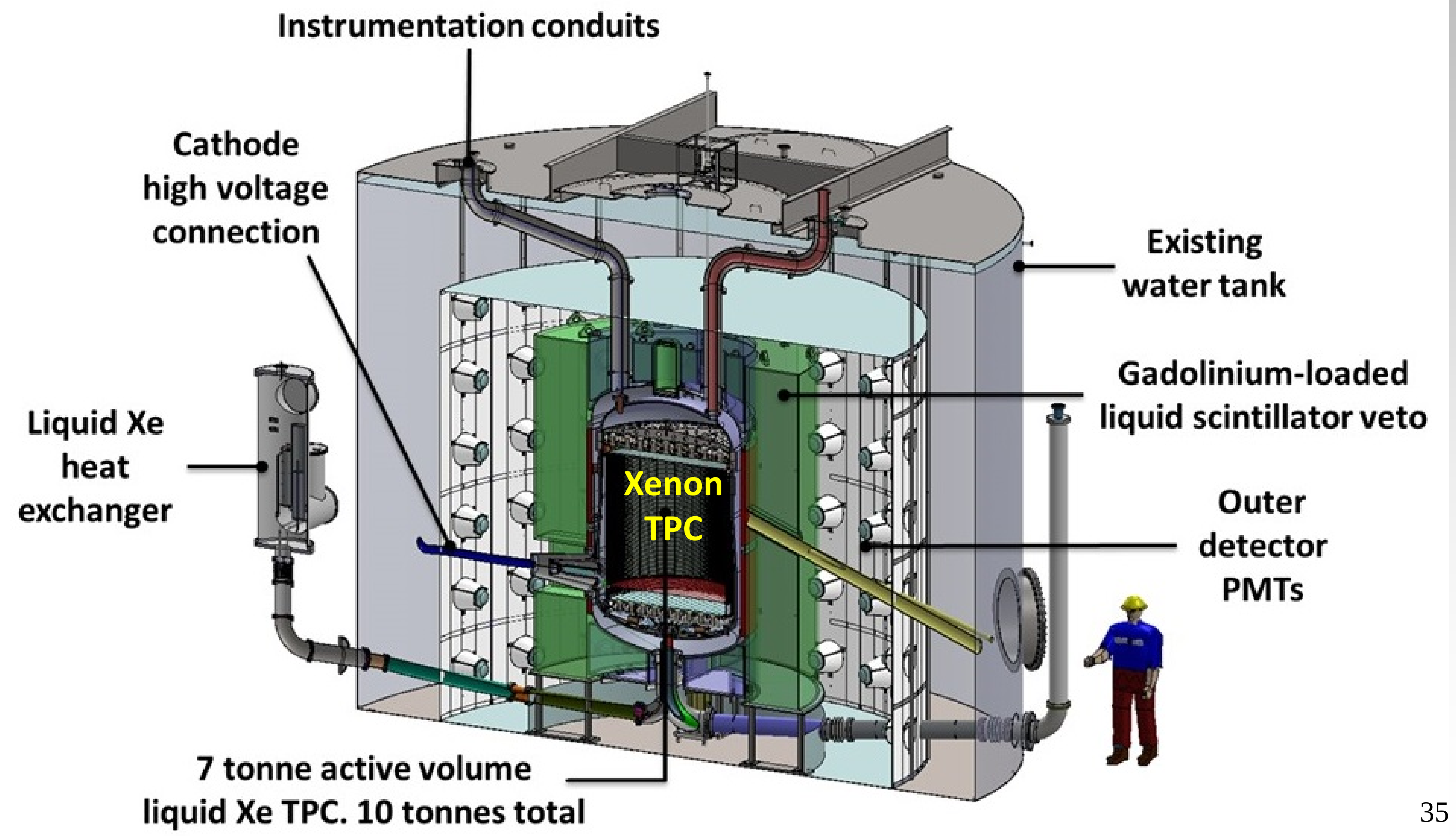
**LZ**

**Total mass – 10 T**
**WIMP Active Mass – 7 T**
**WIMP Fiducial Mass – 5.6 T**

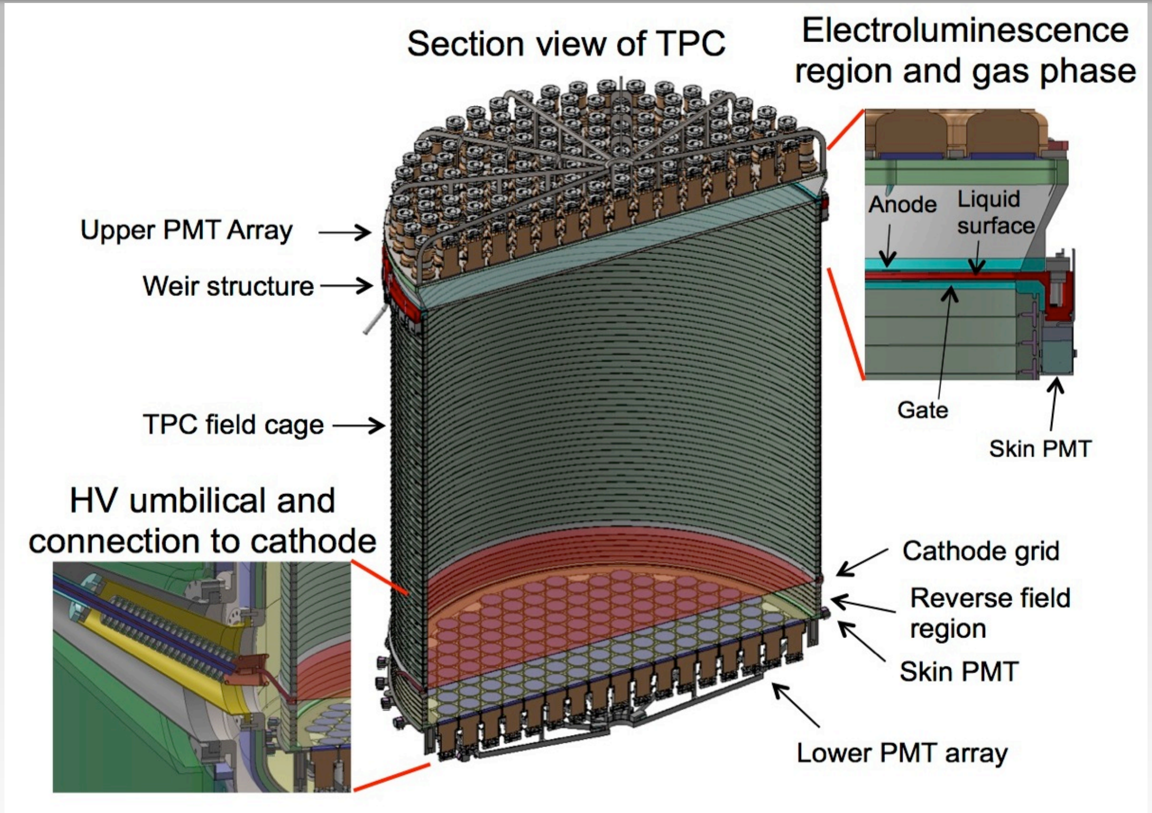
**LUX**

+ maintain background-free, low-energy response

# LZ Detector Overview



# Dual-phase liquid xenon TPC



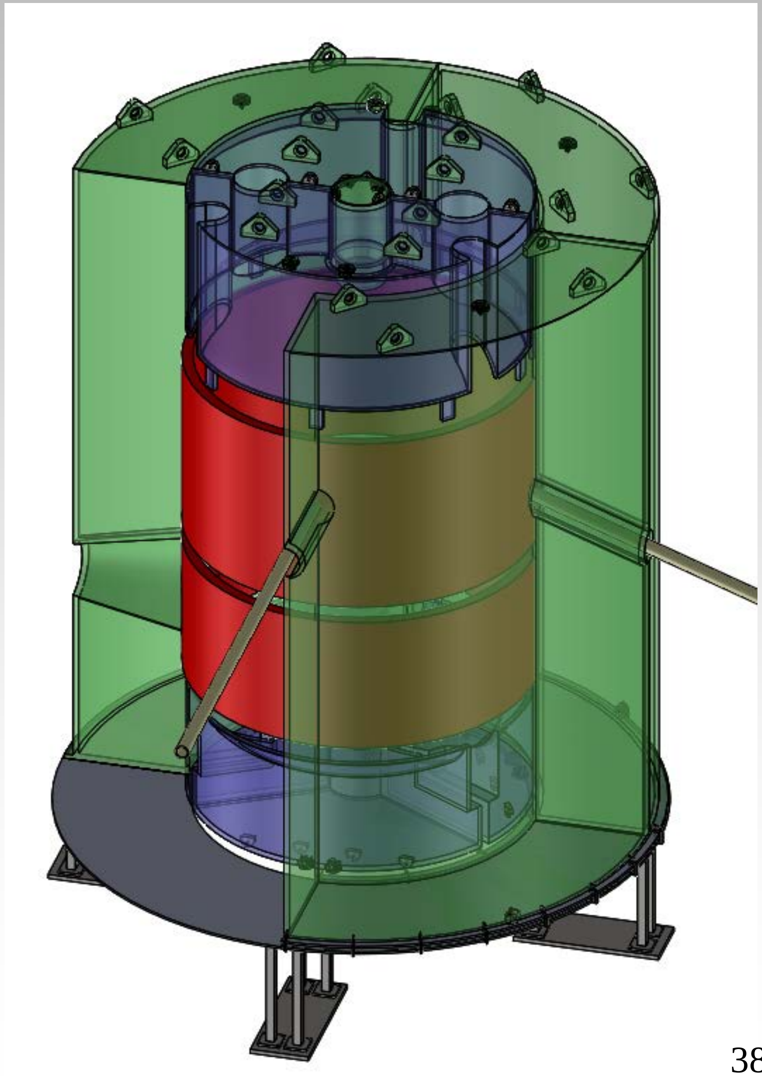

- 7 T active LXe mass, 146 cm diameter, 146 cm length
- 488 PMTs (247 top, 241 bot) 3” R11410 PMTs (activity ~mBq; high QE)
- TPC lined with high-reflectivity PTFE ($R_{PTFE} \geq 95\%$)
- instrumented “Skin” region optically separated from TPC (180 PMT)

# Background Reduction: key design points

- Photomultipliers of ultra-low natural radioactivity
- Low background titanium cryostat
- LUX water shield and an added Gadolinium-loaded liquid scintillator active veto
- Instrumented “skin” region of peripheral xenon as another veto system
- Radon suppression during construction, assembly and operations
- Ultra-low levels of Kr in Xe

# The Outer Detector (OD)

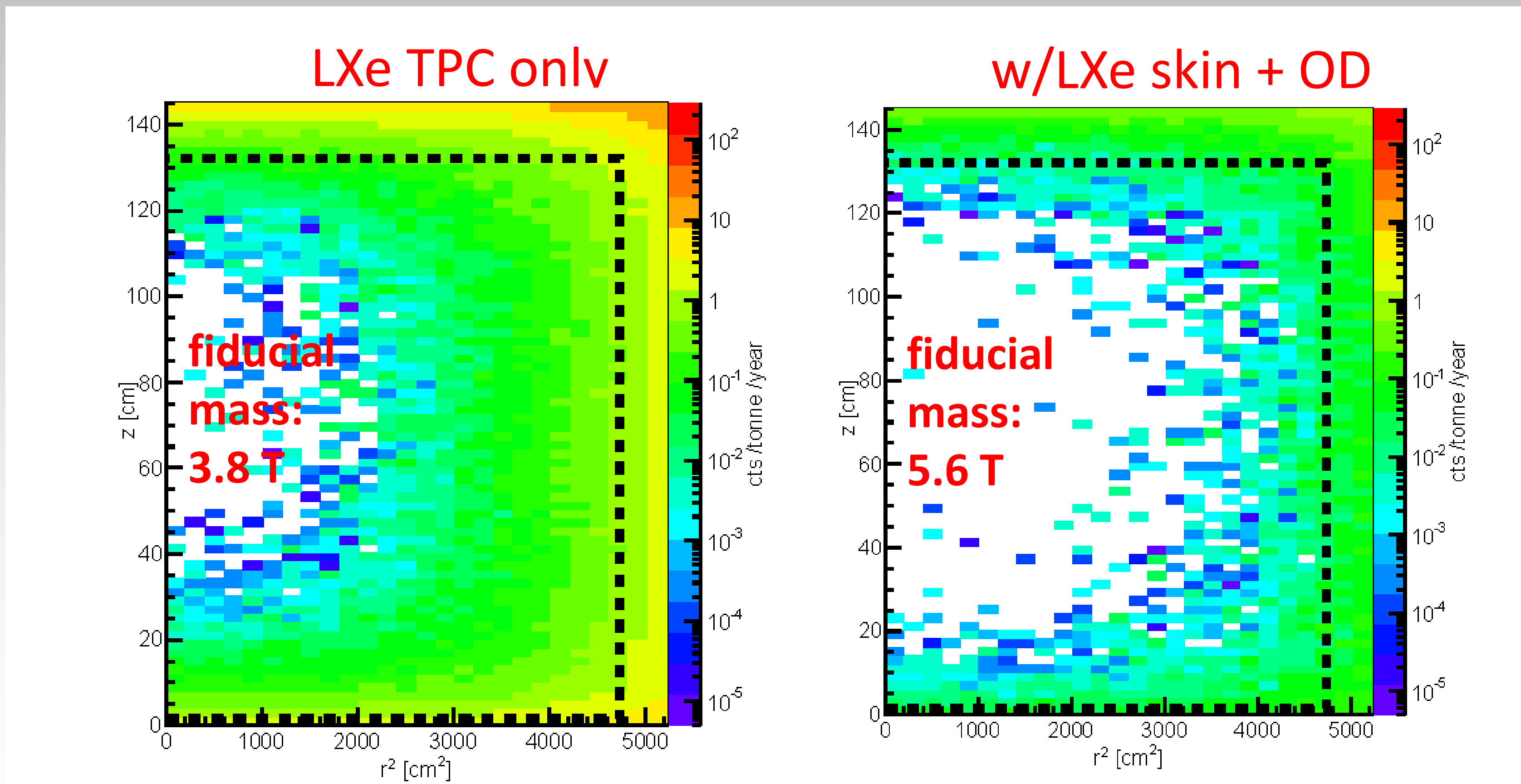
- Essential to utilize most Xe, maximize fiducial volume
- Hermetic measurement of penetrating backgrounds
- Segmented tanks – installation constraints (shaft, water tank)
- 60 cm thick, 21.5 T of Gadolinium-loaded LAB* liquid scintillator, OK underground
- 97% efficiency for neutrons
- Daya Bay legacy, scintillator & tanks (and people)



* Linear AlkylBenzene

# Powerful Background Rejection

Simulated single NR scatter in TPC before/after Skin+OD vetoes




- Increases effective fiducial mass from 3.8 T → 5.6 T
- Internal backgrounds now dominate

# Background Control

- Assay and assess all candidate detector materials and components with many dedicated screening facilities prior to adoption

- Assay techniques:
  - gamma spectroscopy
  - mass spectroscopy
  - neutron activation analysis(NAA)
  - radon emanation counting
  - alpha spectroscopy

*Detector components*

*Xenon contaminants*

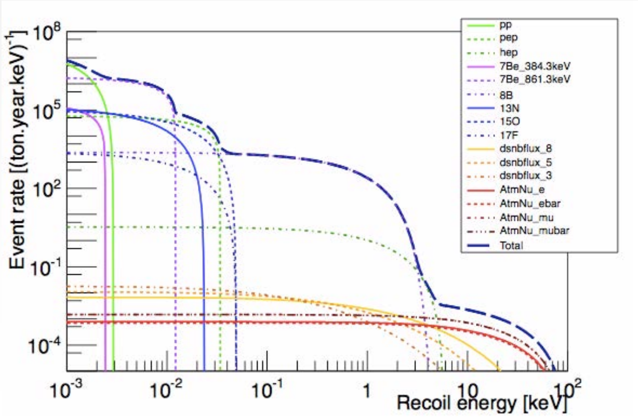
*Environment, cosmogenic, surface contamination*

*Physics backgrounds*

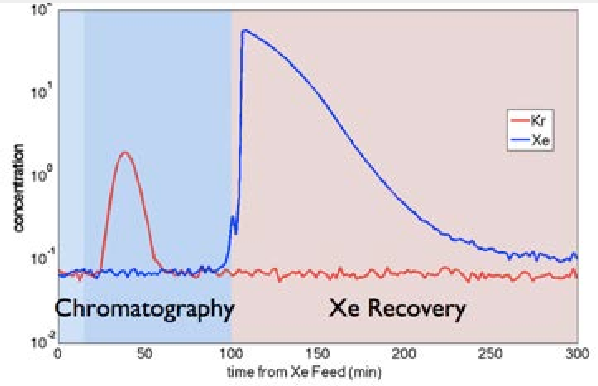
| Intrinsic Contamination Backgrounds | Mass (kg) | U early (mBq/kg) | U late (mBq/kg) | Th early (mBq/kg) | Th late (mBq/kg) | Co60 (mBq/kg) | K40 (mBq/kg) | ER (cts) | NR (cts) (w/ SF rej.) |
|---|---|---|---|---|---|---|---|---|---|
| Upper PMT Structure | 46.7 | 5.25 | 0.80 | 1.07 | 0.72 | 0.03 | 3.77 | 0.14 | 0.001 |
| Lower PMT Structure | 71.7 | 2.69 | 0.24 | 0.42 | 0.30 | 0.00 | 1.36 | 0.08 | 0.001 |
| R11410 3" PMTs | 91.9 | 71.63 | 3.20 | 3.12 | 2.99 | 2.82 | 15.41 | 1.46 | 0.013 |
| R11410 PMT Bases | 2.8 | 287.74 | 75.80 | 28.36 | 27.93 | 1.43 | 69.39 | 0.36 | 0.004 |
| R8778 2" PMTs | 6.1 | 137.50 | 59.38 | 16.88 | 16.88 | 16.25 | 412.50 | 0.13 | 0.008 |
| R8520 Skin 1" PMTs | 2.2 | 60.50 | 5.19 | 4.75 | 4.75 | 24.20 | 332.76 | 0.02 | 0.001 |
| R8520 Skin PMT Bases | 0.2 | 212.95 | 108.46 | 42.19 | 37.62 | 2.23 | 123.61 | 0.00 | 0.000 |
| PMT Cabling | 104.2 | 30.13 | 1.55 | 3.32 | 3.15 | 0.65 | 33.12 | 1.45 | 0.001 |
| TPC PTFE | 184.0 | 0.02 | 0.02 | 0.03 | 0.03 | 0.00 | 0.12 | 0.06 | 0.008 |
| Grid Wires | 0.18 | 1.20 | 0.27 | 0.33 | 0.49 | 1.60 | 0.40 | 0.00 | 0.000 |
| Grid Holders | 92.3 | 2.86 | 0.83 | 0.94 | 0.82 | 1.42 | 2.82 | 0.97 | 0.008 |
| Field Shaping Rings | 92.5 | 5.49 | 0.13 | 0.32 | 0.26 | 0.00 | 0.71 | 0.27 | 0.004 |
| TPC Sensors | 1.32 | 22.40 | 8.94 | 11.38 | 9.57 | 0.35 | 19.44 | 0.01 | 0.002 |
| TPC Thermometers | 0.08 | 335.50 | 90.46 | 38.48 | 25.02 | 7.26 | 3,359 | 0.06 | 0.000 |
| Xe Recirculation Tubing | 15.1 | 0.79 | 0.18 | 0.23 | 0.33 | 1.05 | 0.30 | 0.00 | 0.000 |
| HV Conduits and Cables | 137.7 | 2.0 | 2.0 | 0.4 | 0.6 | 1.4 | 1.2 | 0.04 | 0.001 |
| HX and PMT Conduits | 199.6 | 3.36 | 0.48 | 0.48 | 0.58 | 1.24 | 1.47 | 0.05 | 0.001 |
| Cryostat Vessel | 2409.6 | 1.70 | 0.14 | 0.30 | 0.25 | 0.10 | 0.64 | 0.72 | 0.014 |
| Cryostat Seals | 33.7 | 73.91 | 26.22 | 3.22 | 4.24 | 10.03 | 69.12 | 0.45 | 0.002 |
| Cryostat Insulation | 23.8 | 18.91 | 18.91 | 3.45 | 3.45 | 1.97 | 51.65 | 0.43 | 0.007 |
| Cryostat Teflon Liner | 26.0 | 0.02 | 0.02 | 0.03 | 0.03 | 0.00 | 0.12 | 0.00 | 0.000 |
| Outer Detector Tanks | 3199.3 | 0.16 | 0.39 | 0.02 | 0.06 | 0.04 | 5.36 | 0.45 | 0.001 |
| Liquid Scintillator | 17640.3 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.03 | 0.000 |
| Outer Detector PMTs | 204.7 | 570 | 470 | 395 | 388 | 0.00 | 534 | 0.01 | 0.000 |
| Outer Detector PMT Supports | 770.0 | 12.35 | 12.35 | 4.07 | 4.07 | 9.62 | 9.29 | 0.00 | 0.000 |
| **Subtotal (Detector Components)** | | | | | | | | **7.18** | **0.077** |
| 222Rn (1.65 μBq/kg) | | | | | | | | 597 | - |
| 220Rn (0.08 μBq/kg) | | | | | | | | 101 | - |
| natKr (0.015 ppt g/g) | | | | | | | | 24.5 | - |
| natAr (0.45 ppb g/g) | | | | | | | | 2.47 | - |
| 210Bi (0.1 μBq/kg) | | | | | | | | 40.0 | - |
| Laboratory and Cosmogenics | | | | | | | | 4.3 | 0.06 |
| Fixed Surface Contamination | | | | | | | | 0.19 | 0.37 |
| **Subtotal (Non-ν counts)** | | | | | | | | **776** | **0.50** |
| Physics Backgrounds | | | | | | | | | |
| 136Xe 2νββ | | | | | | | | 67 | 0 |
| Astrophysical ν counts (pp+7Be+13N) | | | | | | | | 255 | 0 |
| Astrophysical ν counts (8B) | | | | | | | | 0 | 0 |
| Astrophysical ν counts (Hep) | | | | | | | | 0 | 0.21 |
| Astrophysical ν counts (diffuse supernova) | | | | | | | | 0 | 0.05 |
| Astrophysical ν counts (atmospheric) | | | | | | | | 0 | 0.46 |
| Subtotal (Physics backgrounds) | | | | | | | | 322 | 0.72 |
| Total | | | | | | | | [illegible] | [illegible] |
| Total (with 99.5% ER discrimination, 50% NR efficiency) | | | | | | | | [illegible] | [illegible] |
| | | | | | | | | 6.10 | |

# Internal Backgrounds

- Rn (and Kr) dominant internal background sources
- Rn:
  - Emanates from most materials
  - 13.4 mBq requirement, 1.3 mBq goal (active region)
    - Rn removal system at UMich
  - Four measurement systems with ~0.1 mBq sensitivity
  - Main assembly laboratory at SURF will have reduced radon air system
- Kr:
  - Remove $^{85}$Kr to <15 ppq using gas chromatography
- Neutrino-induced backgrounds

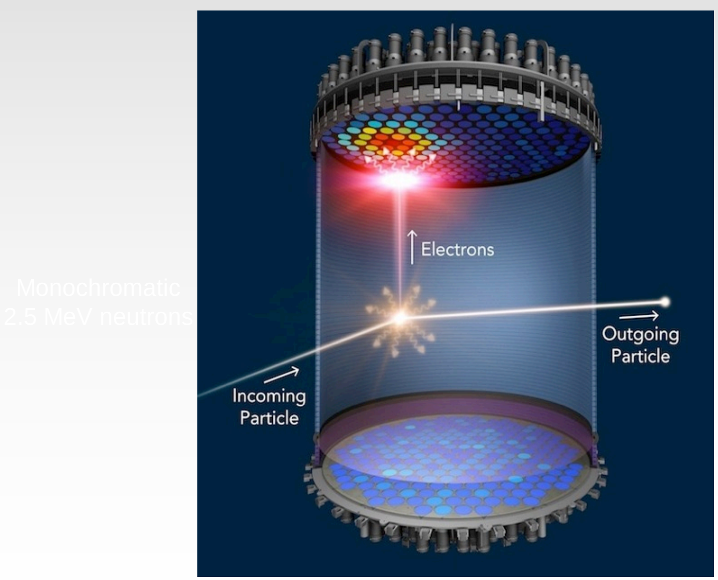

Chromatography from column



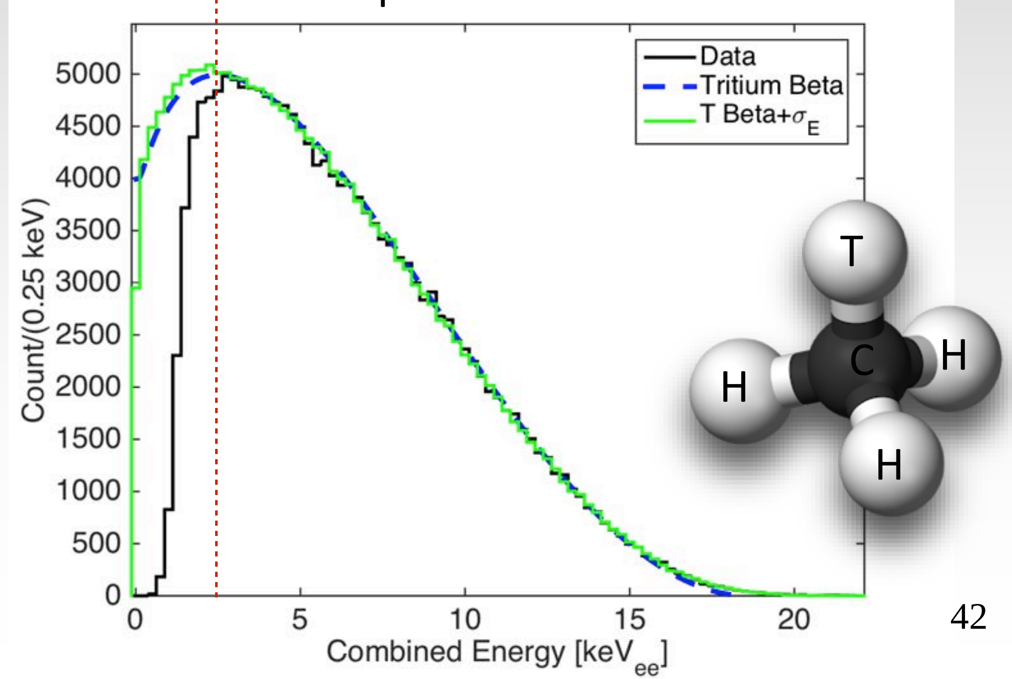
# Calibrations

- Expand upon successful LUX program (and other experience)
- DD Neutron Generator (Nuclear Recoils)
- Tritiated Methane (Electron Recoils)
- Movable photon sources e.g. tubes penetrating cryostat
- Additional sources e.g. YBe source for low energy (Nuclear Recoils)

DD neutron calibration

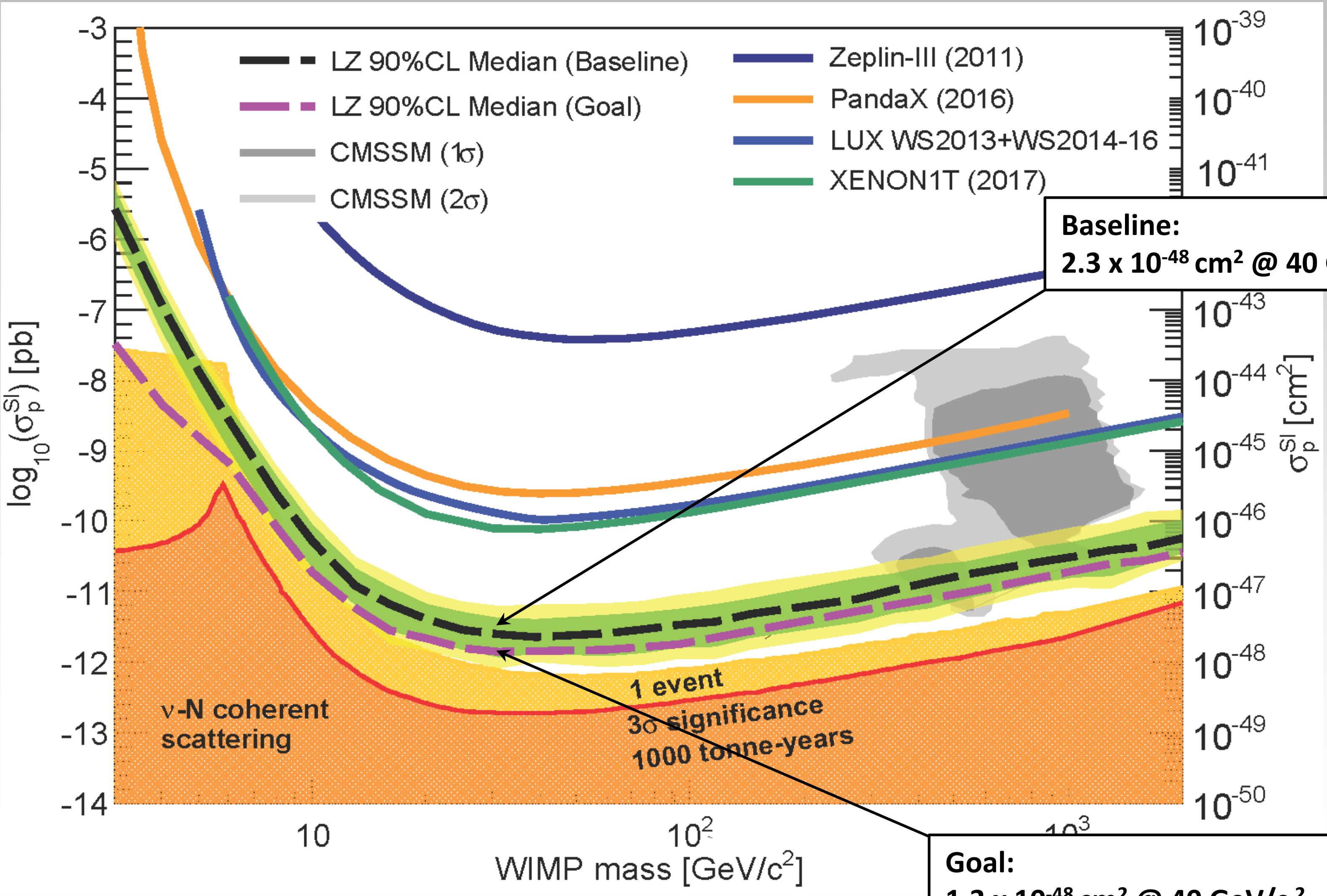



Tritium Beta Spectrum Measured in LUX



# Projected LZ Sensitivity – Spin Independent

**(5.6 T fiducial, 1000 live-days)**

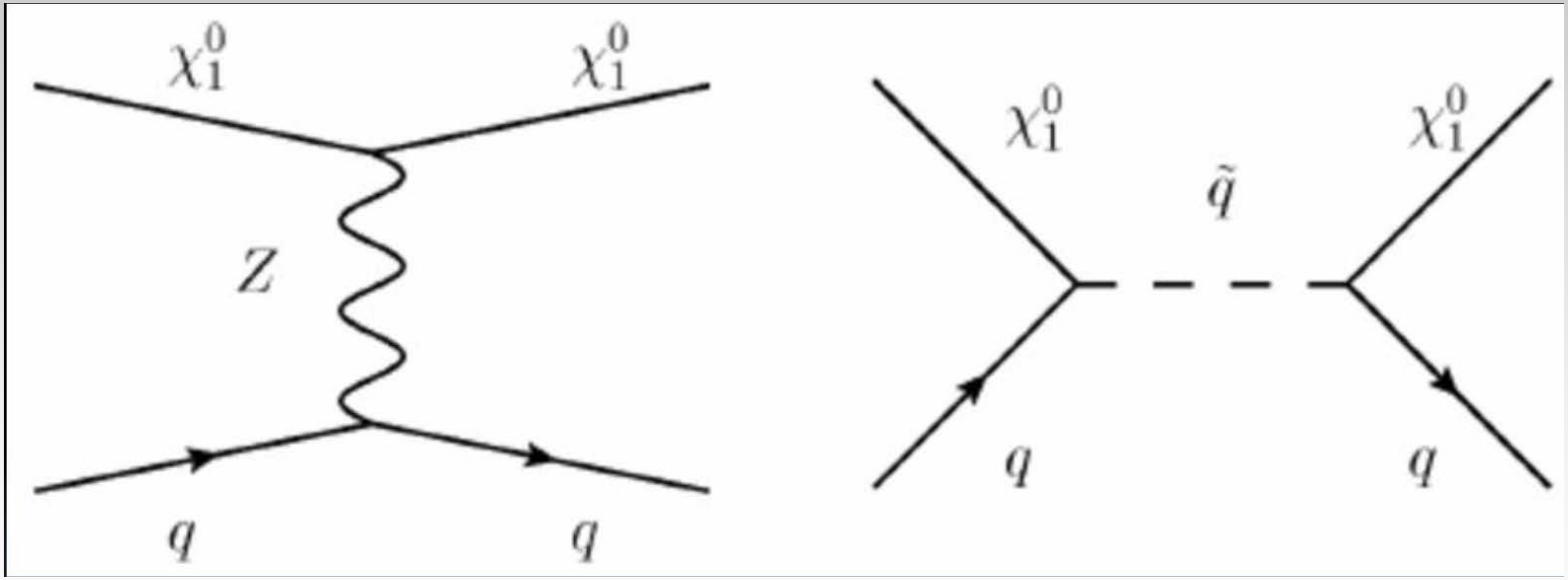



**Baseline:**
**2.3 x 10^-48 cm² @ 40 GeV/c ²**

**Goal:**
**1.3 x 10^-48 cm² @ 40 GeV/c ²**

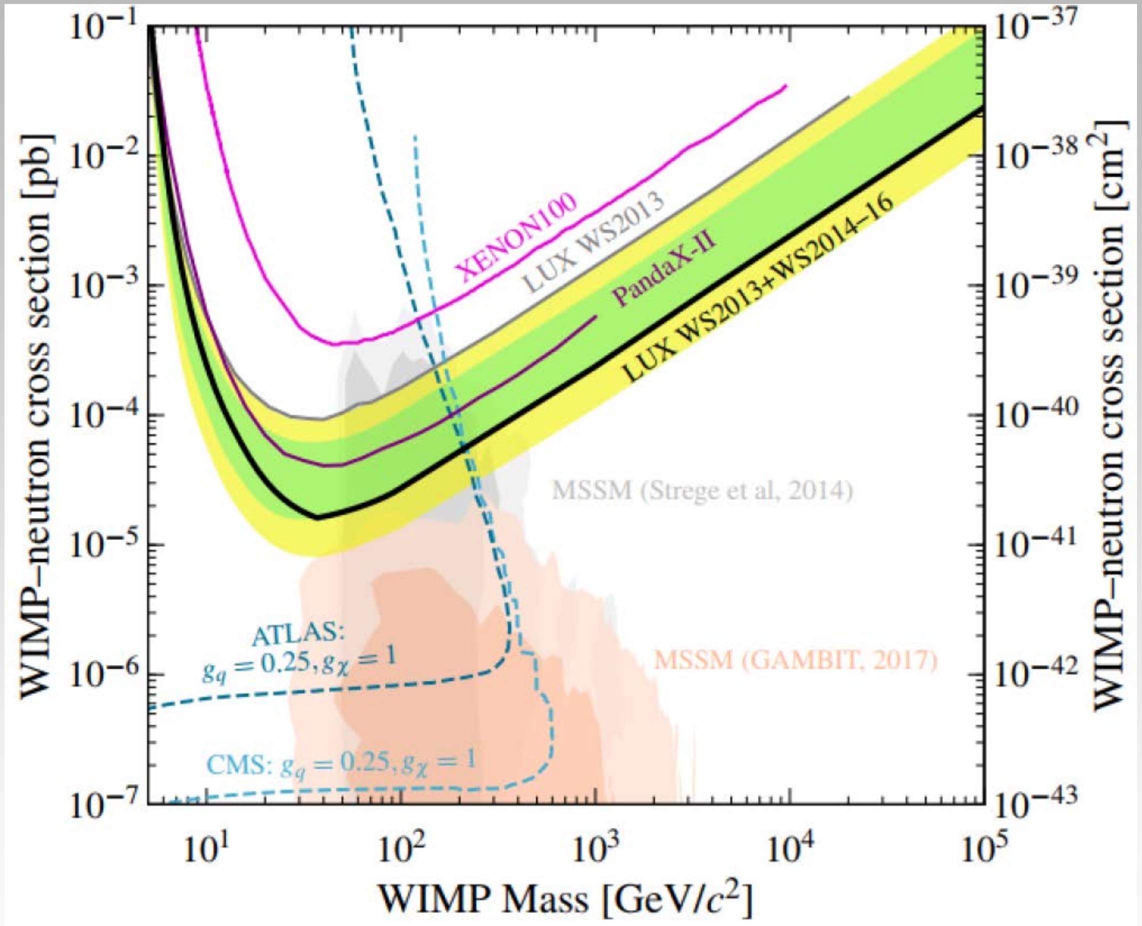
# Spin-dependent Interaction

- Natural to expect if WIMP has spin:



# $^{129}$Xe and $^{131}$Xe: SD χ–n coupling

Phys. Rev. Lett. 118, 251302 (2017)

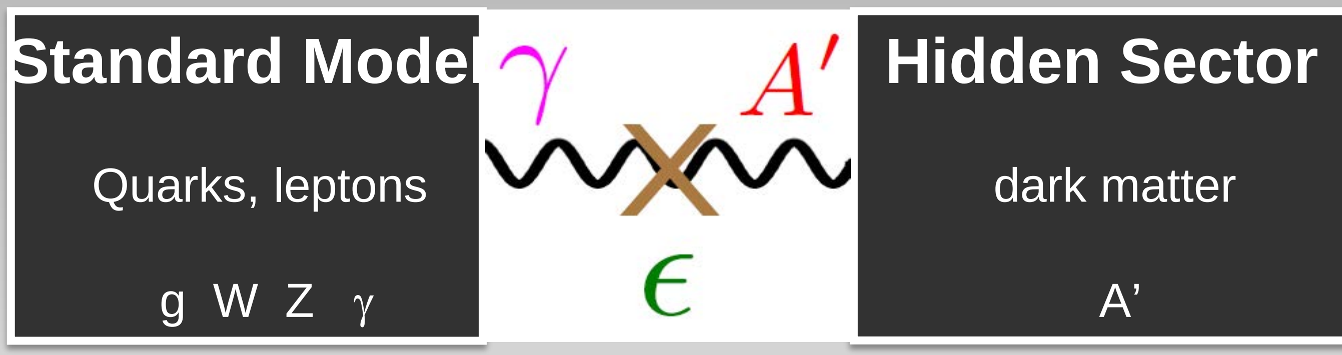



- LUX full exposure limit: 1.6x10$^{-41}$ cm$^2$ @35 GeV/c$^2$
- Collider search complementary for lower mass

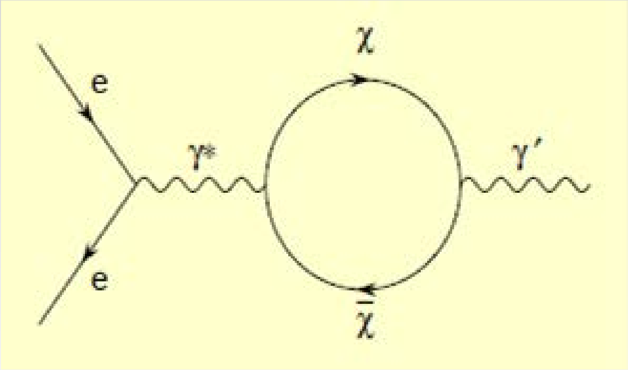
# The Future: Reaching ν floor + beyond

- At high WIMP mass:
  - DARWIN: the ultimate WIMP detector (50 ton LXe mass)
  - DarkSide-20K (20 ton UAr @ LNGS)→ ARGO/DEAP-nT (1kton-year @ ??)
    - crucial technologies: low rad. UAr and SiPMs
- At low WIMP mass:
  - SuperCDMS (Soudan → SNOLAB)
    - reduce background, phonon resolution to 10 eV
  - Liquid He
    - Energy threshold 10 meV
- Other avenues (ie, rejecting the WIMP hypothesis)
  - Warm Dark Matter (go to much lower mass)
  - Axion-like particles (matter-antimatter asymmetry in universe)
  - Dark Photons as Dark Matter
    - DM does not interact with know particles at all, but exists in a hidden sector

# Exploring Dark Matter with Dark Photons




- Dark sector could interact with the standard model sector via a hidden gauge boson (A’ or “dark photon” or “para photon” or “hidden photon”)
- Dark photons can provide a portal into the dark sector
- Dark photons could couple to standard model matter with $\alpha' = \alpha\varepsilon^2$

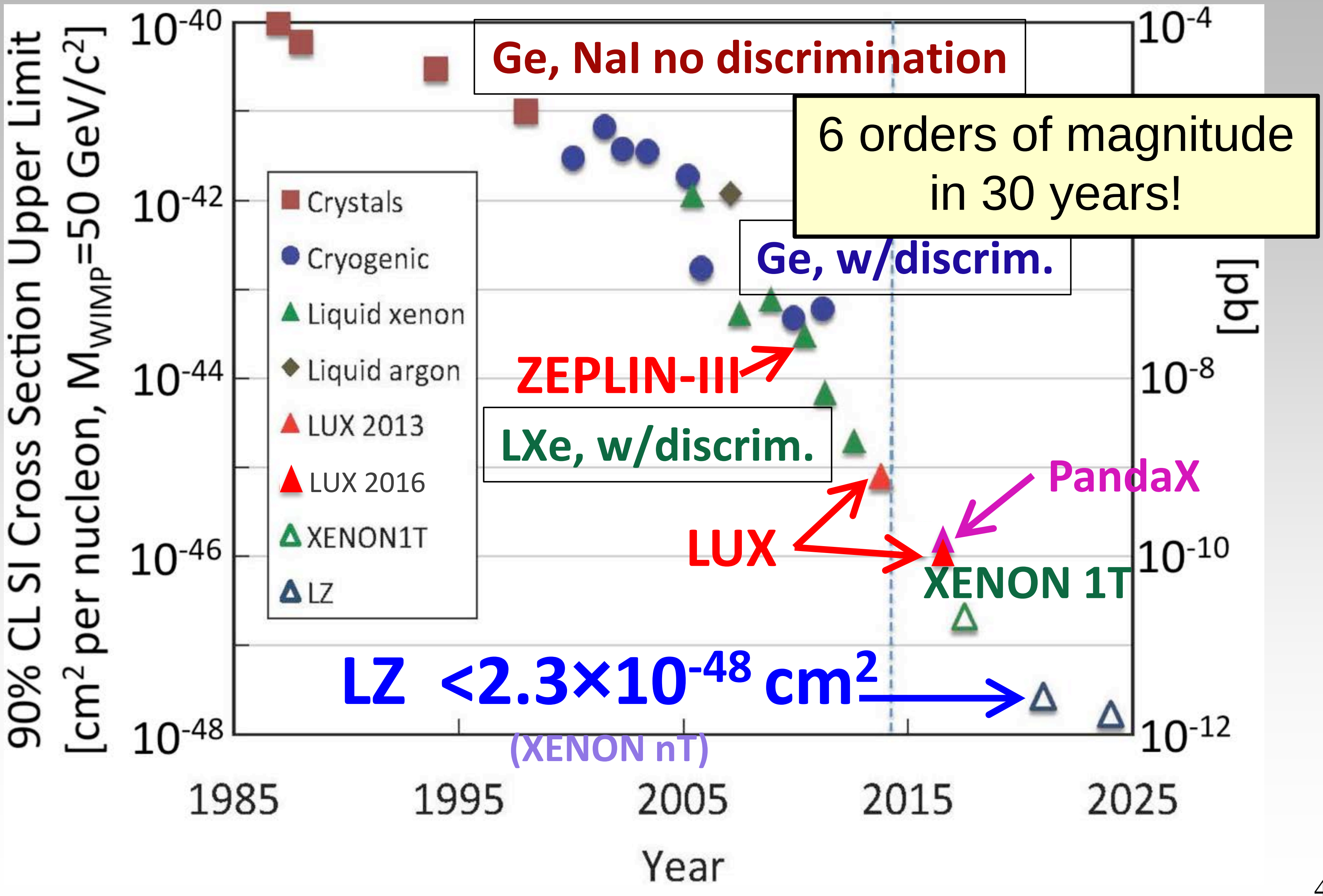



A’ produced via a loop mechanism

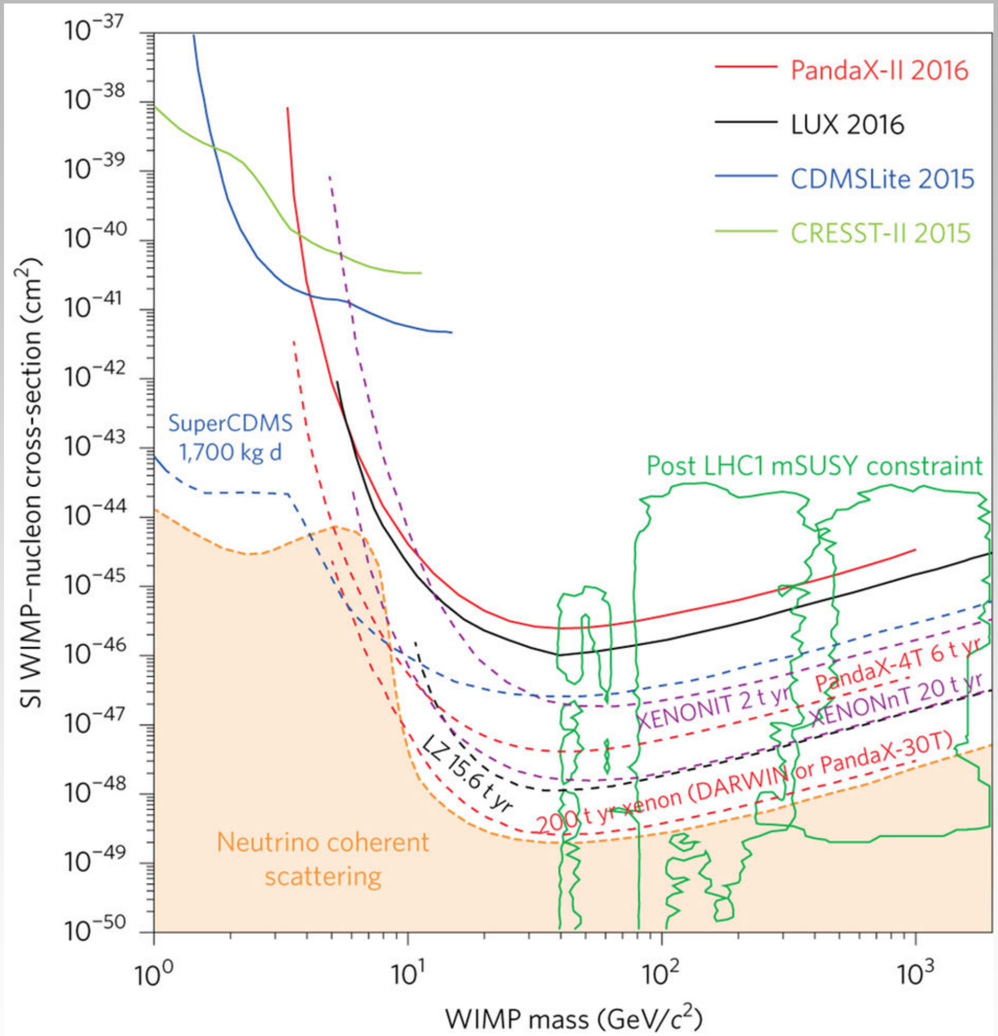
B. Holdom, PLB **166** (1986) 196
J. D. Bjorken et al, PRD **80** (2009) 075018

$\varepsilon \sim 10^{-2}$ to $10^{-8}$ from loops of heavy particles

# Faster than Moore



# Discovery Just around the corner?




- In next 5 years, several Generation-2 experiments will turn on and have new results
- Stronger interplay between collider/indirect/direct experiments and the theory community

# Thank You