

# A Next-Generation Liquid Xenon Observatory for Dark Matter & Neutrino Physics

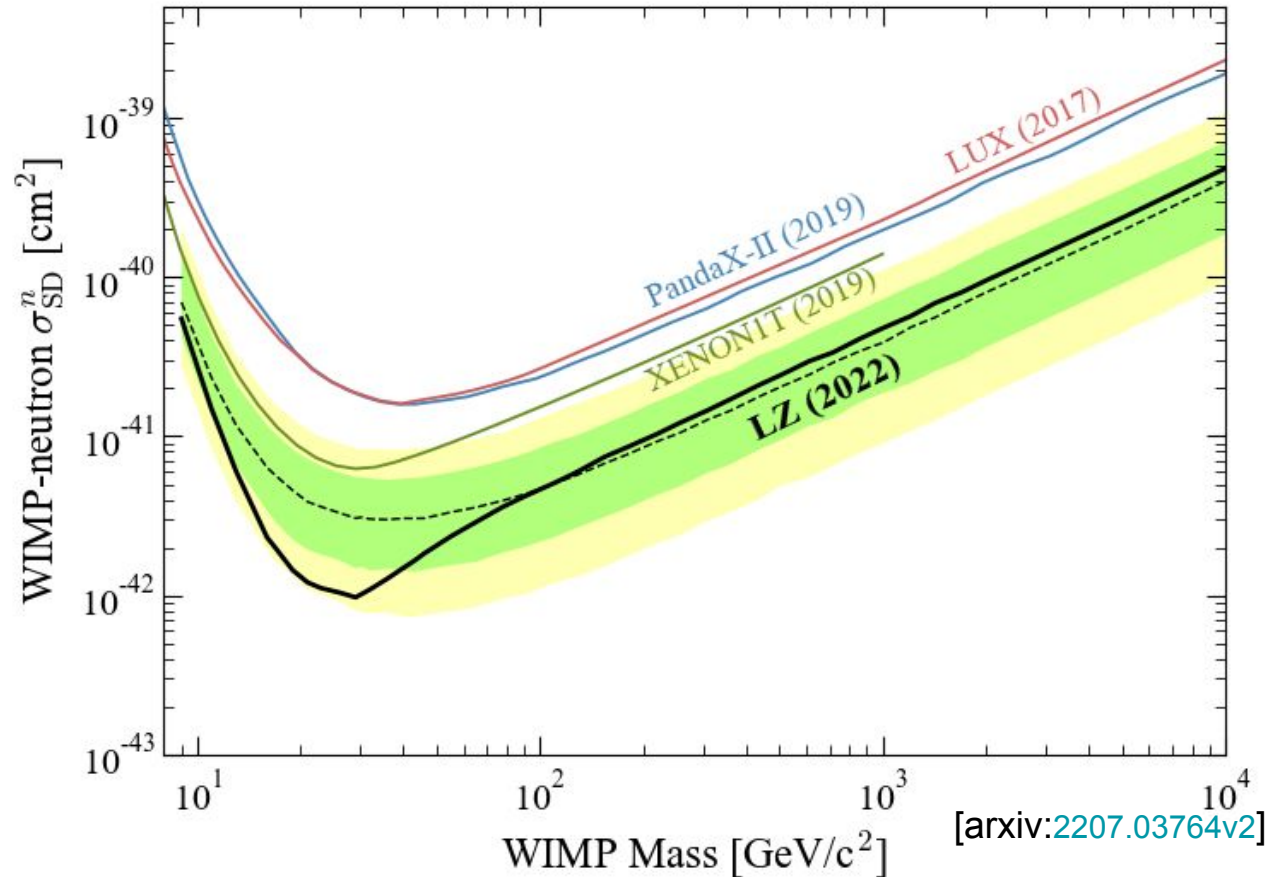


**Alvine Kamaha (UCLA)**

**SURF User Association Annual General Meeting  
October 24-26, 2022**

# Dark Matter (DM) Direct Detection: Status

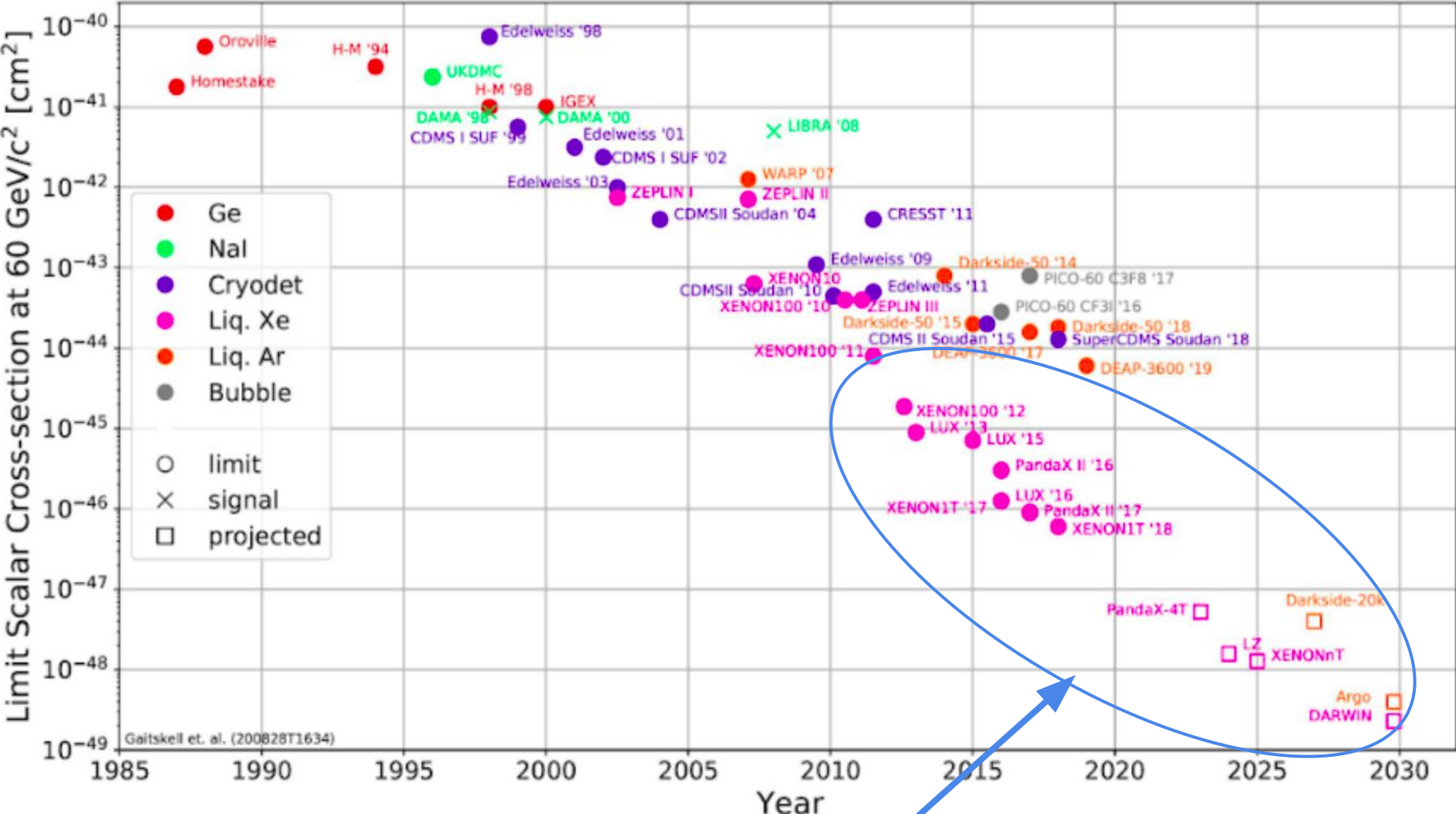
**Fantastic first science results by LZ** experiment **hosted at SURF** (see talk by S. Shaw) displaying the great potential of the LXe technology and what can be achieved with LZ in  $\sim 5$  years timeline



Noble liquid **Xenon detectors** (e.g **LZ**, **XENONnT**) lead the direct search for *high mass* WIMP dark matter particles



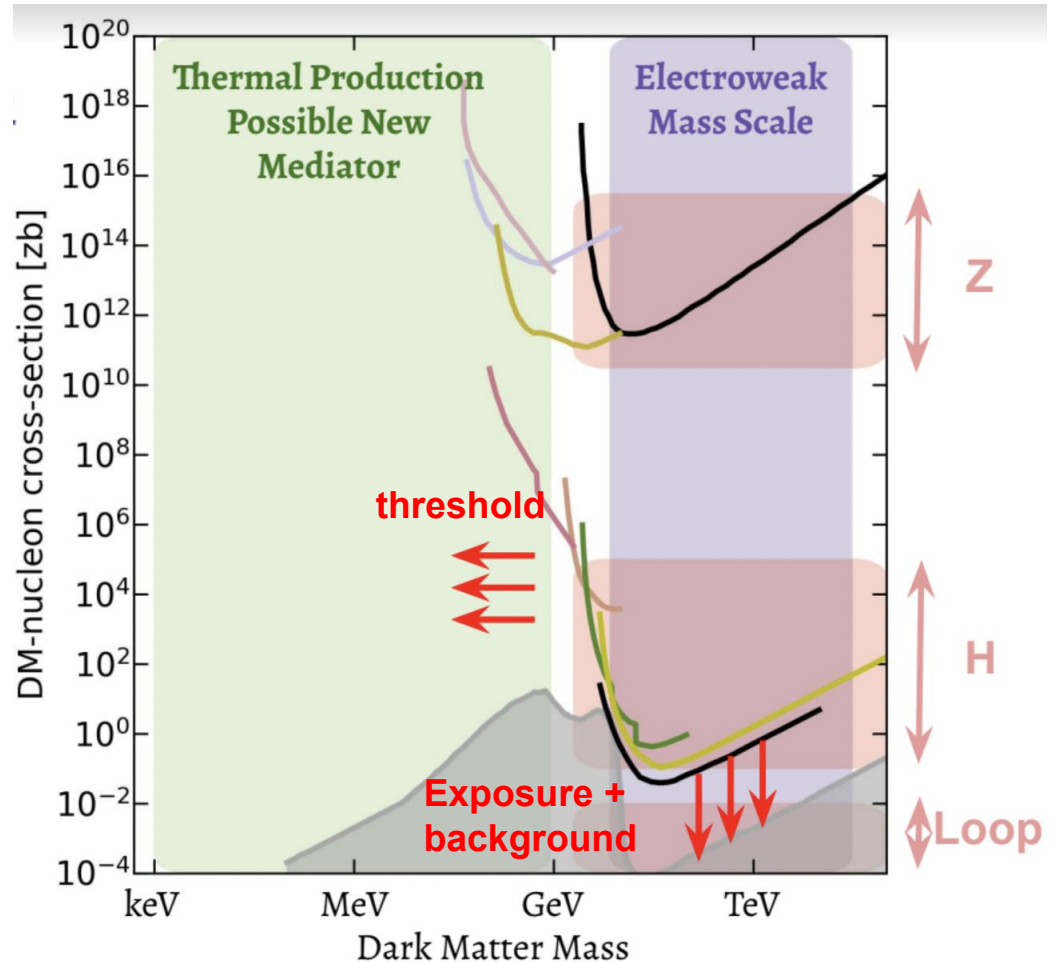
# DM Direct Detection: past, present & future



Dominated by dual-phase noble liquid detectors *at high mass since a decade* → very good **potential for discovery**

# Relevant Highlight from SNOWMASS'21

## Cosmic Frontier (CF1) Vision for dark matter over the next decade



Key message from the SNOWMASS'2021 particle physics community study:

**Delve Deep and look left**

# Relevant Highlight from SNOWMASS'21

We are going to need a **BIGGER** detector!

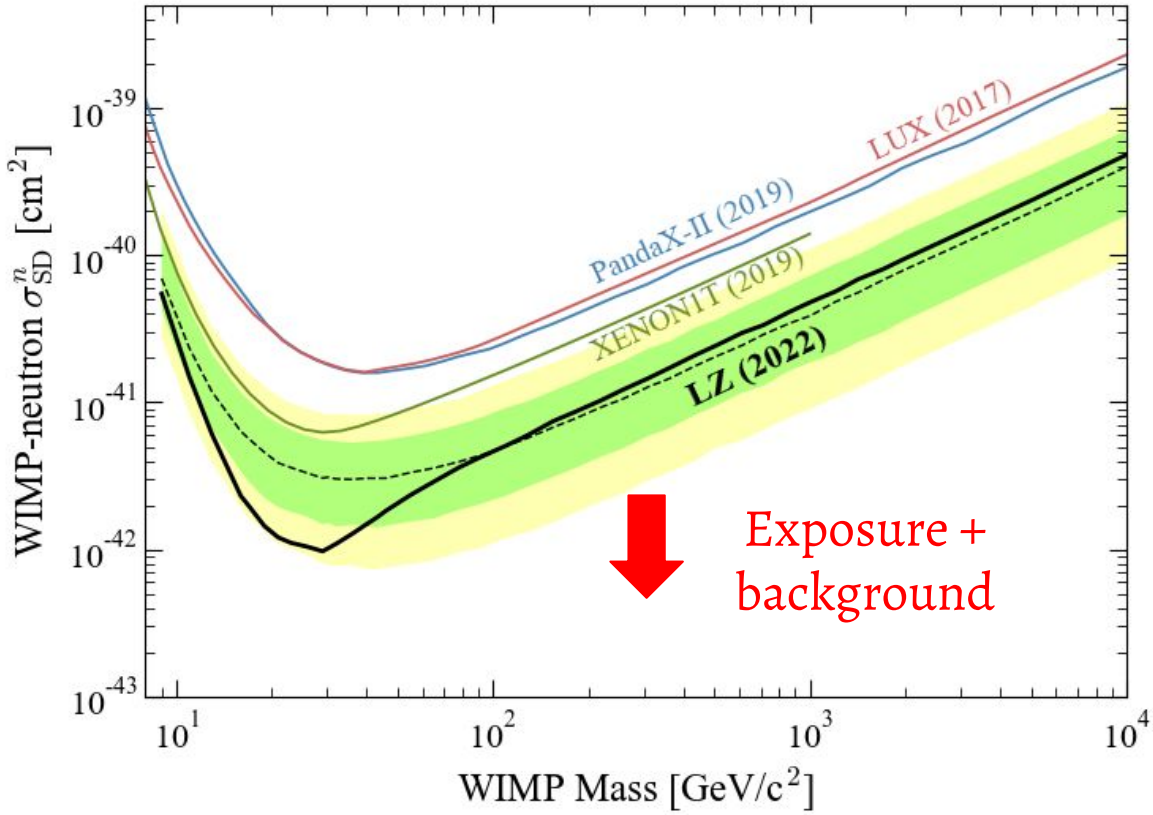


**Cosmic Frontier  
(CF1) Vision for  
dark matter over  
the next decade**

Key message from the S

**Delve Deep and look left**

# DM Direct Detection: Beyond LZ & XENONnT



**No DM discovery in LZ first results: → 2 scenarios:**

**Discovery (a few event candidates):**

→ higher stat needed for DM characterization

**No Discovery:**

→ Need to finish probing theo. WIMP parameter spaces

Need to build **bigger and smarter detector** in either case



# XLZD: A Unified Community

**Coming together** from the whole LXe community

Joint Whitepaper: **600 authors** from **141 institutions** across the globe

**Consortium** formed by **leading experiments** in the field  
**XENONnT/DARWIN & LZ**

Already **official** and **active**

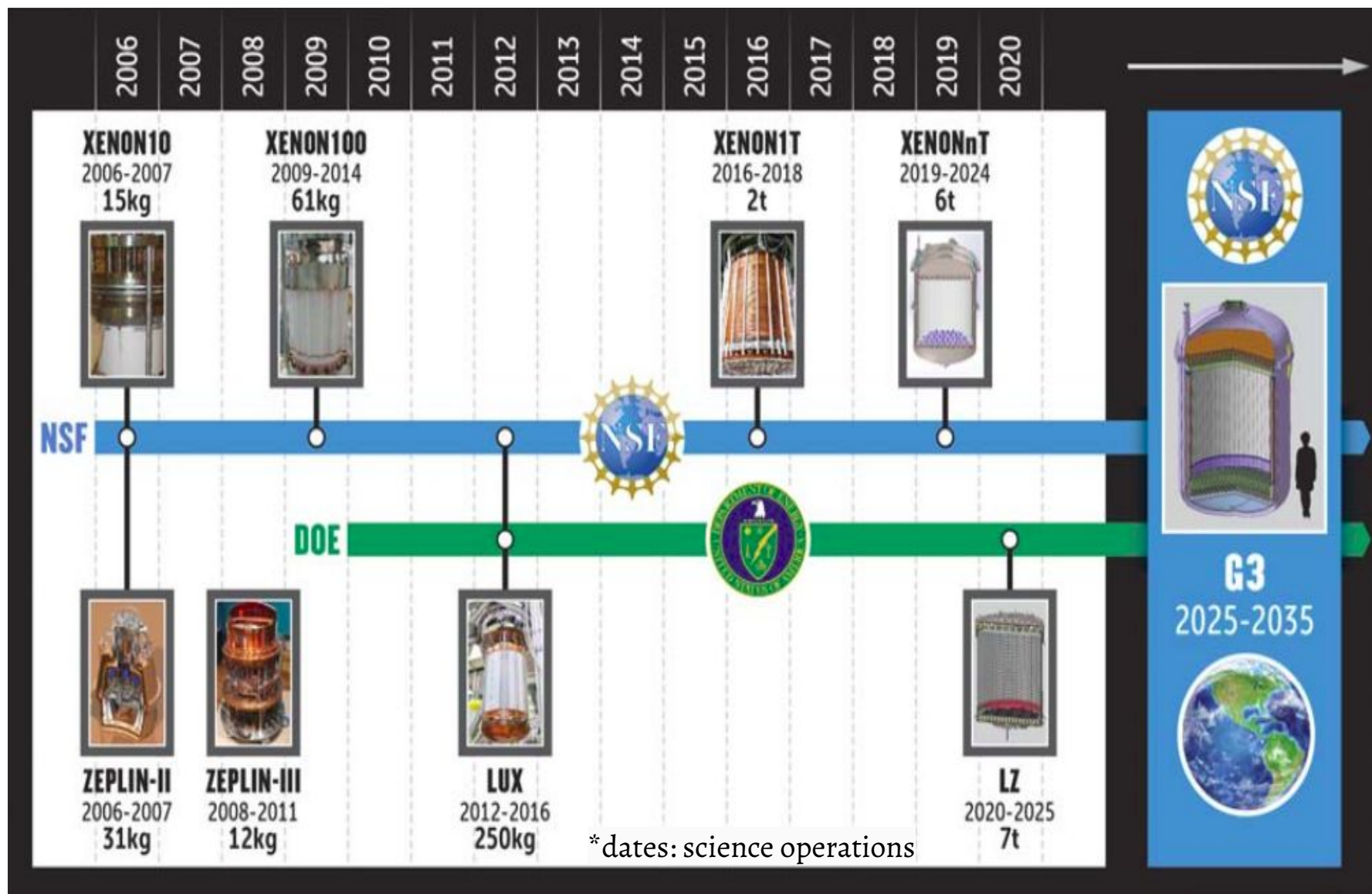
- First “collaboration” meeting in Europe in Summer 22
- Second “collaboration” meeting in US in Spring 23
- Weekly calls to discuss working group progress & status, etc ...



*XLZD Meeting in Karlsruhe, Germany (June 2022)*

# XLZD: funding in US

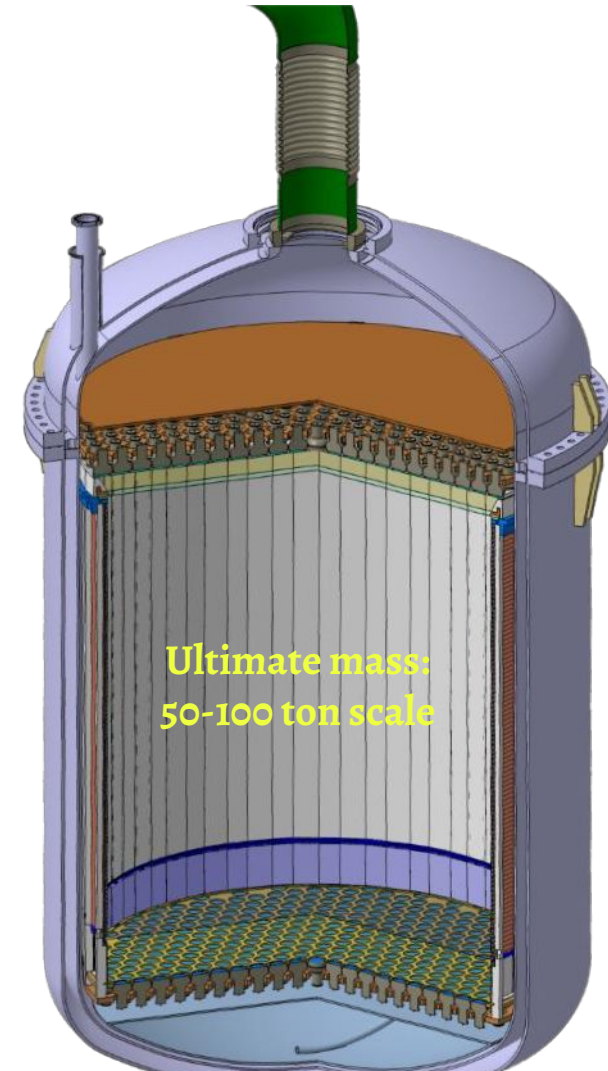
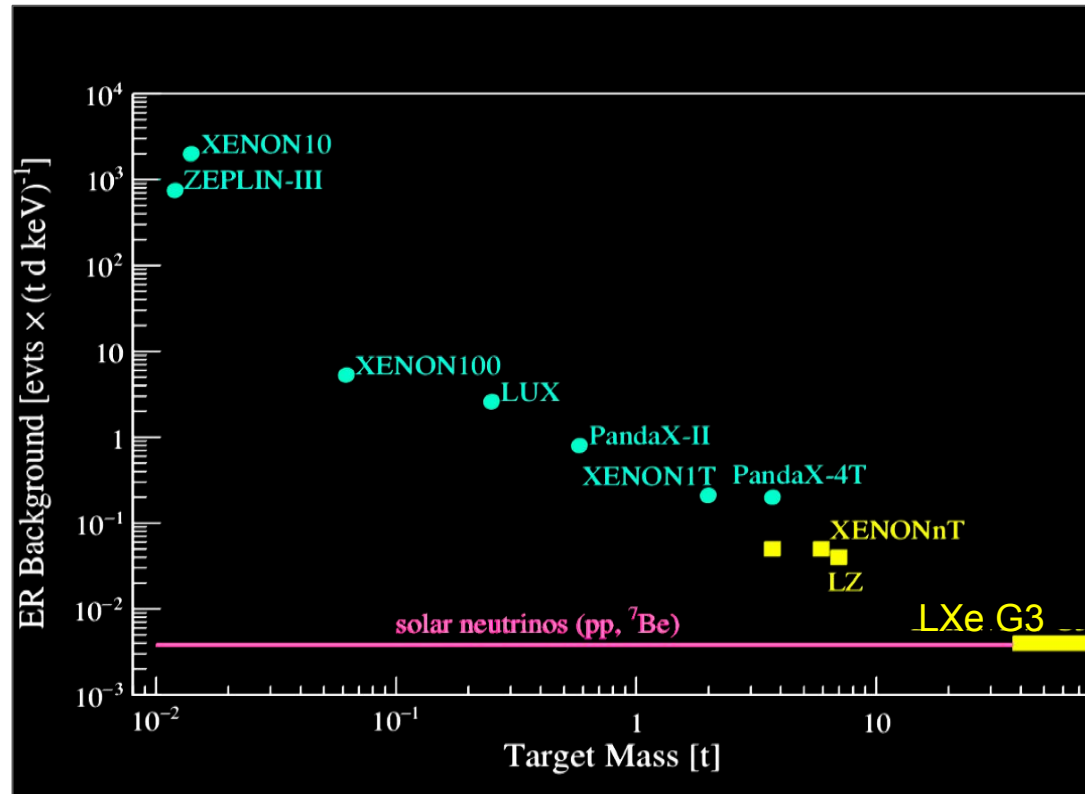
Note: M€ invested through various grants in Europe





# XLZD: the ultimate WIMP detector & beyond

- Optimal scale-up of the existing LXe technology down to the neutrino “fog”

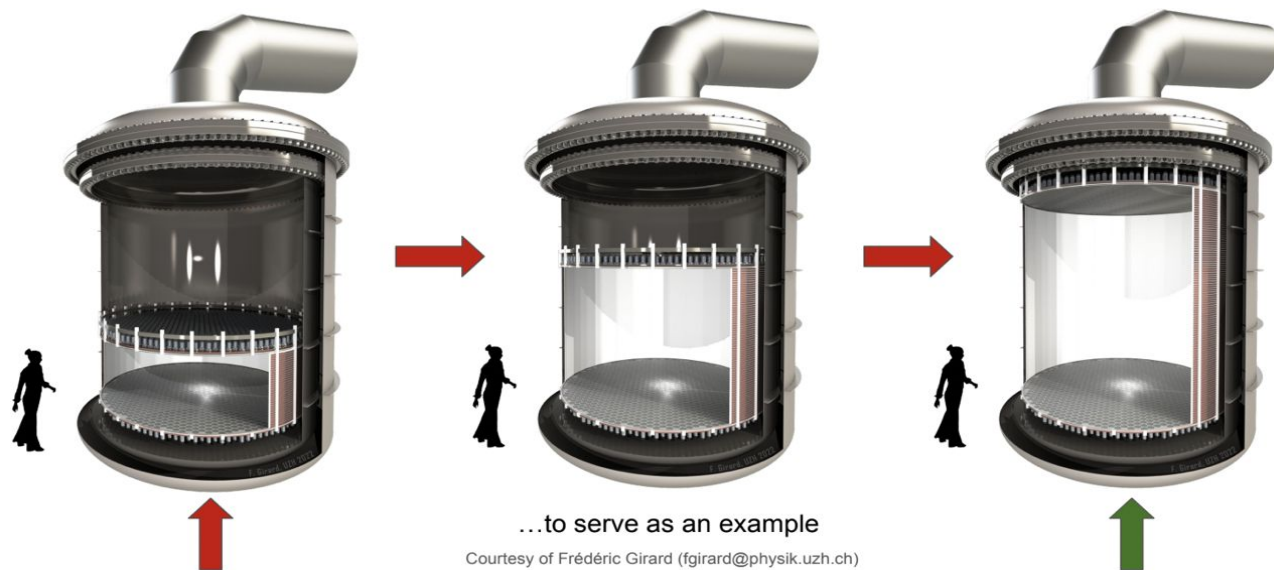


[XENONnT/LZ/DARWIN \(a.k.a XLZD\) detector](#)

- Start after LZ & XENONnT
  - Science Ops - late 2020's
- **Various R&D** currently ongoing in several institutions

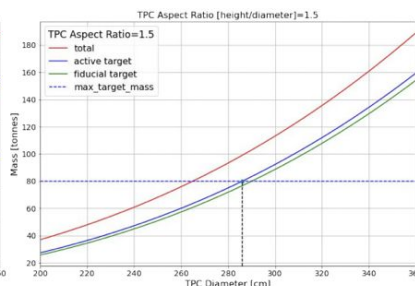
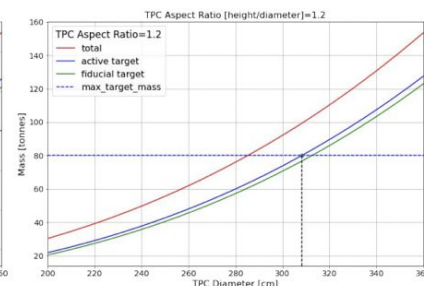
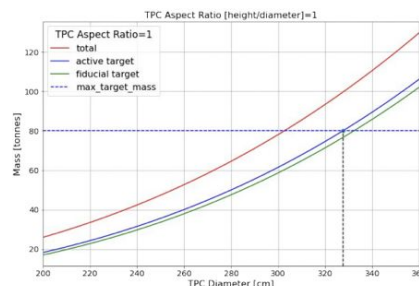
# XLZD R&D: Detector Conceptual Design & Size

Stage approach  
VS  
Monolithic approach



...to serve as an example

Courtesy of Frédéric Girard (fgirard@physik.uzh.ch)



**AR = 1**

- TPC Act. Mass = **40 tonnes**:  
→ TPC  $\varnothing$ =259 cm & drift=259 cm
- TPC Act. Mass = **60 tonnes**:  
→ TPC  $\varnothing$ =297 cm & drift=297 cm
- TPC Act. Mass = **80 tonnes**:  
→ TPC  $\varnothing$ =327 cm & drift=327 cm

**AR = 1.2**

- TPC Act. Mass = **40 tonnes**:  
→ TPC  $\varnothing$ =244 cm & drift=292 cm
- TPC Act. Mass = **60 tonnes**:  
→ TPC  $\varnothing$ =280 cm & drift=336 cm
- TPC Act. Mass = **80 tonnes**:  
→ TPC  $\varnothing$ =308 cm & drift=369 cm

**AR = 1.5**

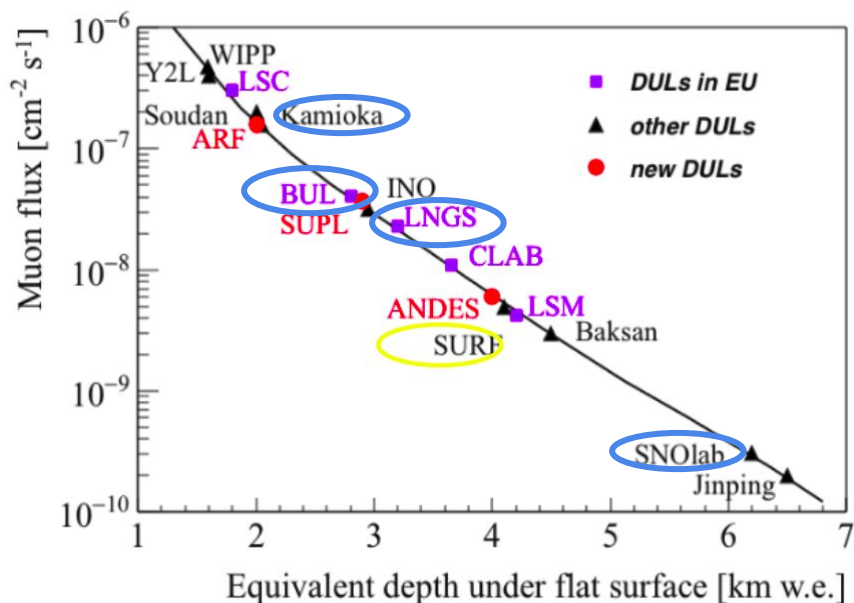
- TPC Act. Mass = **40 tonnes**:  
→ TPC  $\varnothing$ =227 cm & drift=340 cm
- TPC Act. Mass = **60 tonnes**:  
→ TPC  $\varnothing$ =259 cm & drift=388 cm
- TPC Act. Mass = **80 tonnes**:  
→ TPC  $\varnothing$ =286 cm & drift=429 cm

In either approach, optimum size is **~ 100 tones** in volume (linear dimensions **~3 meter**) → *huge detector!*

**Pancake (AR <1) vs Oval (AR >1)**

AR: Aspect Ratio

# XLZD: Siting



- 5 sites are being evaluated for XLZD (SURF, KAMIOKA, BOULBY, SNOLAB & LNGS)
  - Well known sites which demonstrated good supporting capabilities (SC) to carry out the science goals of state-of-the-art rare event search experiments.
- A next generation G3 detector like XLZD (~**3 meter** scale) will require **additional SC**: significant staging space and underground fabrication capabilities (e.g. larger and lower RRCR) than what currently exist in most of these facilities.
  - Required **cavity ~20 to 25 meters in diameter**: Gran Sasso (exist), Boulby (new construction), SURF (new construction or shared with LBNF)
  - UG access is generally a challenge and should be carefully planned



# XLZD: Siting @ SURF

- **Great support** during LZ construction @ SAL, UG transport & daily LZ operation
  - Surface lab (class 100 CR  $54\text{m}^2$ ,  $240\text{m}^3$ )
  - **But LZ underground site small for XLZD** & U/G Rn concentration too high ( $300\text{-}350\text{ Bq/m}^3$ )  $\Rightarrow$  mitigation strategies will be required.

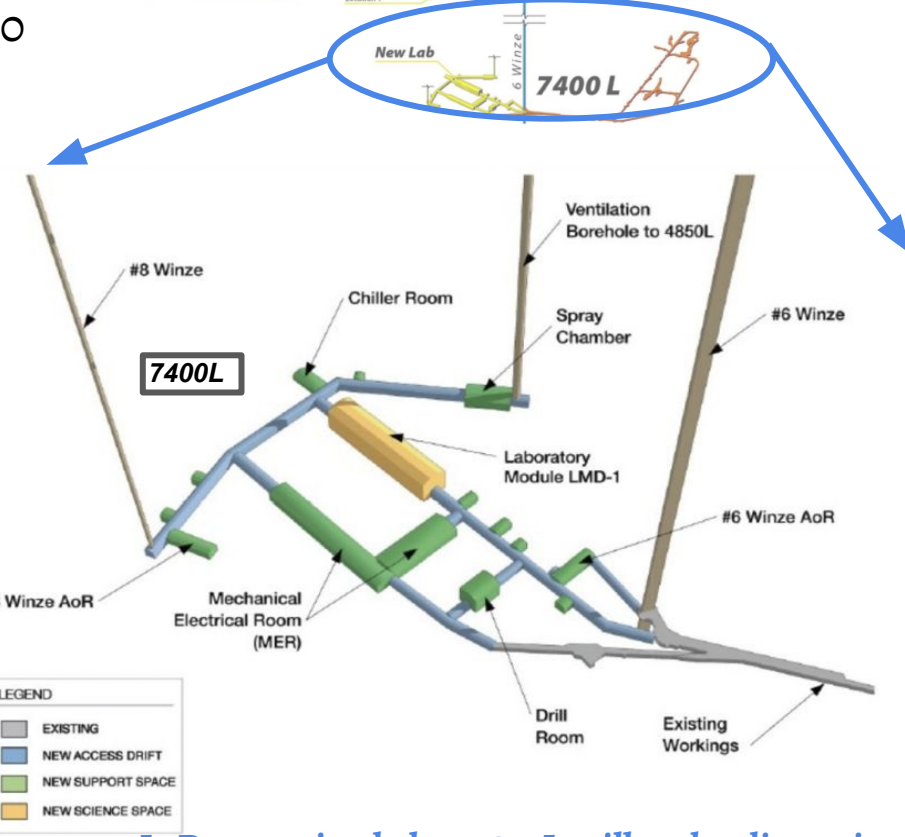
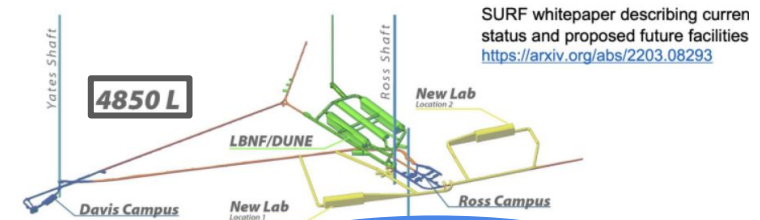
$\Rightarrow$  **New space** needed, options:

- New lab module @ 4850L ( $50\text{-}100\text{m} \times 20\text{m} \times 28\text{m}$ ) through LBNF?
- New lab module @ 7400L - under discussion?

- **Cosmic ray shielding and environmental backgrounds @ 4850L/4300 mwe meet XLZD requirements**

- (NIM A 638, (2011) 63-66)
- (Astropart. Phys. 116 (2020) 102391, NIM A 812, (2016) 1-6)

- Need to think about *pesky* neutrino beam



**7400L - Deep option below 4850L still under discussion. Offers x20 reduction in muons compared to other sites**

# XLZD: the ultimate WIMP detector & beyond

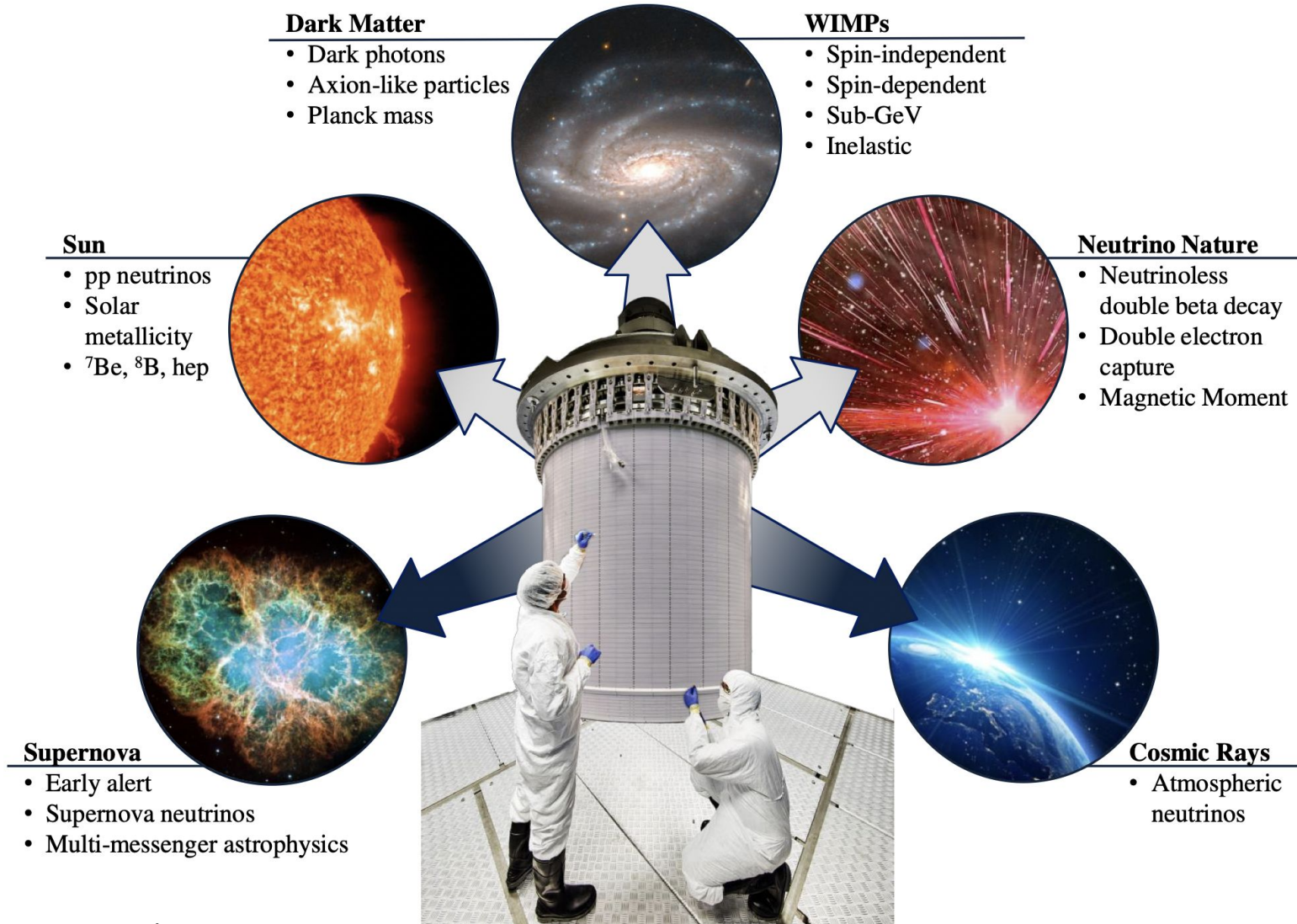
A rich science program discussed on 77 pages

[[arxiv 2203.02309](https://arxiv.org/abs/2203.02309)]

- I. Introduction
    - A. An Observatory for Rare Events
    - B. Evidence for Dark Matter
    - C. Dark Matter Direct Detection
    - D. An Evolution of Scales
    - E. The Liquid Xenon Time Projection Chamber
    - F. Xenon as a Detector Medium
  - II. Dark Matter WIMPs
    - A. WIMP Direct Detection
    - B. WIMP Sensitivity Projections: Method
    - C. Spin-Independent WIMPs
    - D. Spin-Dependent Scattering
    - E. Effective Field Theory
      - 1. Nonrelativistic Effective Field Theory
      - 2. Chiral Effective Field Theory
      - 3. WIMP-Pion Coupling
      - 4. Three-Flavor EFT and the UV
    - F. Nuclear Structure Factors
    - G. Inelastic Scattering
    - H. Discriminating Between WIMP-Nucleus Responses
      - I. Scattering at High Momentum Transfer
      - J. Simplified Models
    - K. Electroweak Multiplet Dark Matter
    - L. Implications for Supersymmetry
    - M. Inelastic Dark Matter
    - N. Self-Interacting Dark Matter
    - O. Leptophilic Interactions
    - P. Modulation Searches
    - Q. Confronting the Neutrino Fog
  - III. Broadening the Dark Matter Reach
    - A. Double Photoelectron Emission
    - B. Charge-Only Analysis
    - C. General Dark Matter-Induced Atomic Responses
    - D. Migdal Effect and Bremsstrahlung
    - E. Hydrogen Doping
    - F. Upscattered Dark Matter
    - G. Dark Matter Annihilation Products
    - H. FIMPs and Super-WIMPs
      - 1. Dark Photons
      - 2. Axions and Axion-Like Particles
      - 3. Solar Axions, Dark Matter, and Baryon Asymmetry
    - I. Asymmetric Dark Matter
    - J. Composite Dark Matter
    - K. Mirror Dark Matter
    - L. Luminous Dark Matter
    - M. Magnetic Inelastic Dark Matter
    - N. Dark Matter around the Planck Mass
  - IV. Double Beta Processes
    - A. Neutrinoless Double Beta Decay of  $^{136}\text{Xe}$
  - V. Neutrinos for Astrophysics
    - A. Neutrino Interactions
      - 1. Coherent Elastic Neutrino-Nucleus Scattering
      - 2. Electroweak Interaction
    - B. Solar Neutrinos
      - 1. Boron-8 Solar Neutrinos (NR)
      - 2. Hep Solar Neutrinos (NR)
      - 3. pp Solar Neutrinos (ER)
      - 4. CNO Neutrinos (ER)
      - 5. Neutrino Capture on Xenon-131 and Xenon-136
    - C. Atmospheric Neutrinos (NR)
    - D. Supernova Neutrinos (NR)
      - 1. Galactic Supernova Neutrinos
      - 2. Pre-Supernova Neutrinos
      - 3. Supernova Early Warning System
      - 4. Diffuse Supernova Neutrinos
    - E. Terrestrial Antineutrinos (ER)
    - F. Other Neutrino Physics
      - 1. Measuring the Weinberg Angle
      - 2. Electron-Type Neutrino Survival Probability
      - 3. Searching for New Physics of Neutrinos
  - B. Double Electron Capture on  $^{124}\text{Xe}$
  - C. Other Double-Beta Processes
- VI. Additional Physics Channels
  - A. Solar Axions
  - B. Neutrino Dipole Moments and Light Mediators
  - C. Fractionally Charged Particles
  - D. Nucleon Decay
  - E. Short-Baseline Oscillations
- VII. Background Considerations
  - A. Underground Laboratories
  - B. Fiducialization
  - C. Material Selection
  - D. Intrinsic Background Mitigation
  - E. Isolated Light and Charge Signals and Accidental Coincidences
  - F. Monte-Carlo Simulation of Backgrounds
    - 1. Background Model
    - 2. Generation of S1 and S2 Signals
  - G. Discrimination
- VIII. Complementarity with Other Experimental Efforts
  - A. Crossing Symmetry for Freeze-Out Relic Particles
  - B. Dark Matter at Colliders
  - C. Indirect Dark Matter Searches
  - D. Measurements of Standard Model Parameters
  - E. Other Direct Dark Matter Searches
    - 1. Solid State Detectors
    - 2. Liquid Target Detectors
  - F. Neutrinoless Double Beta Decay Experiments
  - G. CE $\nu$ NS Experiments
  - H. Solar Neutrino Experiments
    - I. Gravitational Wave Searches
    - J. Xenon in Medical Physics
  - K. Liquid Xenon TPCs for Nuclear Security
  - L. Data-Intensive and Computational Sciences
- IX. Research Community Priority
  - A. Dark Matter
  - B. Neutrinoless Double Beta Decay
  - C. Neutrinos
- X. Summary
- XI. Acknowledgements
- References

*Not only dark matter!*

# XLZD: A Rare Event Observatory

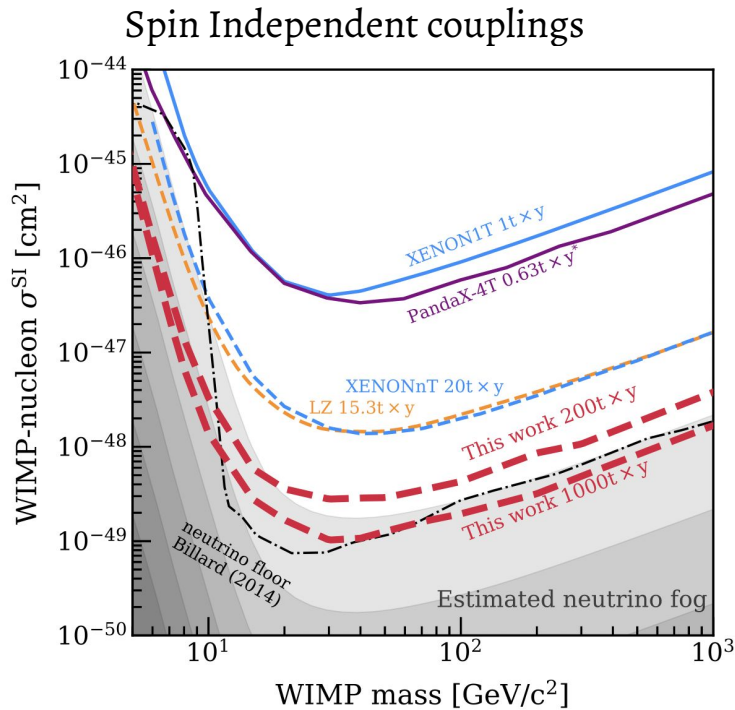


XLZD science case [[arxiv 2203.02309](https://arxiv.org/abs/2203.02309)]

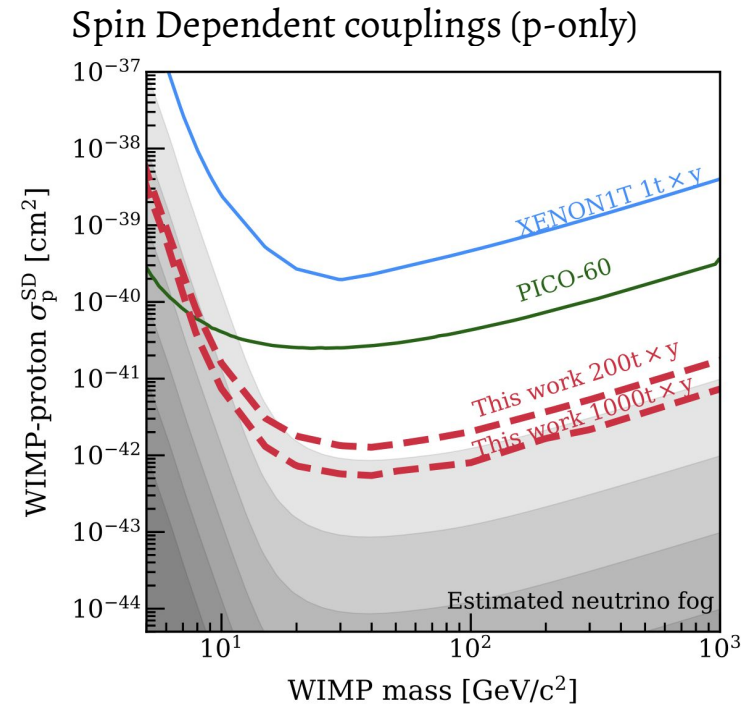


# DM Physics: XLZD WIMP Sensitivity

- Projected sensitivity (upper limit) for 200t×y and 1000 t×y exposure
- Will probe entire parameter region for  $m_\chi \sim 2 \text{ GeV}/c^2$  until ~neutrino floor fog
  - Likelihood analysis
  - **99.98% ER rejection @ 30% NR acceptance**



200 t×y:  $\sigma < 2.5 \times 10^{-49} \text{ @ } 40 \text{ GeV}/c^2$



excellent complementarity to LHC

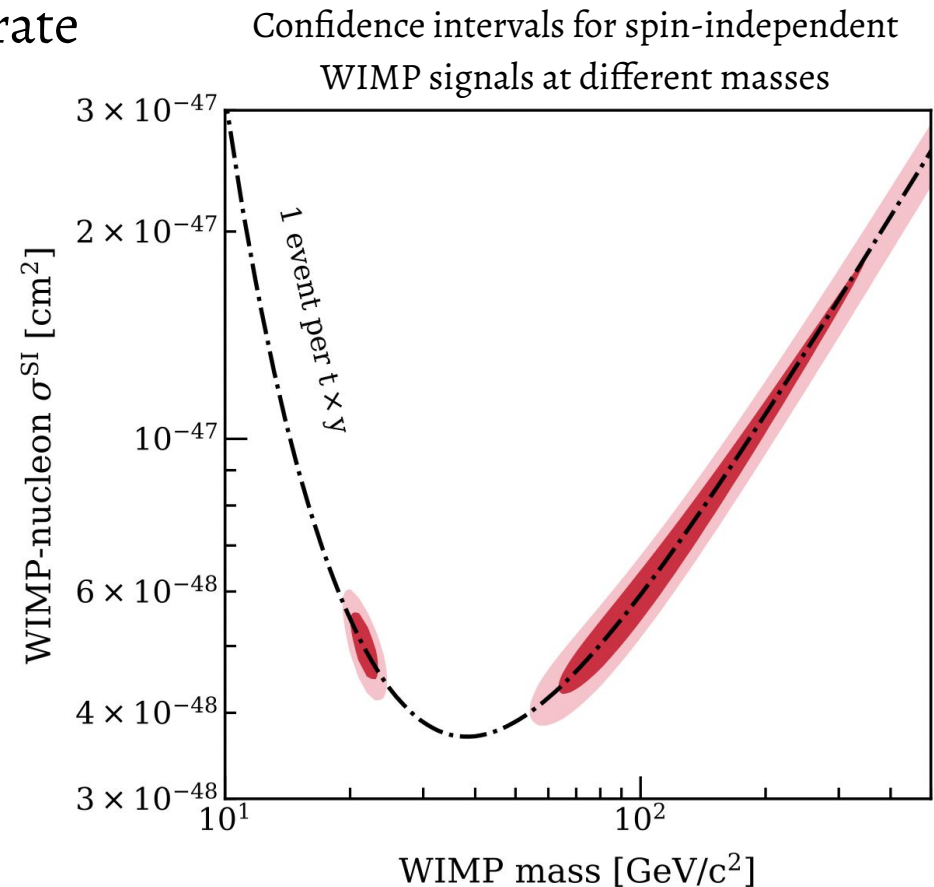
# DM Physics: XLZD WIMP Spectroscopy

- Capability to reconstruct the WIMP mass & cross section ( $\sigma^{\text{SI}}$ ) for various masses below  $500 \text{ GeV}/c^2$ 
  - Possibility to constraint WIMP astrophysical parameters
- Width & length of contours demonstrate how well WIMP parameters can be reconstructed in XLZD

**Exposure:**  $1000 \text{ t} \times \text{y}$

**Reconstruction:**

$m_\chi = 20, 100 \text{ GeV}/c^2$



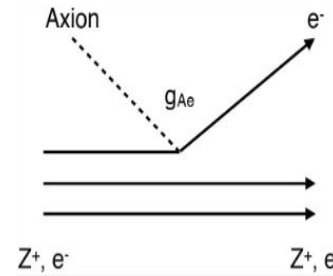
# DM Physics: Solar axions & galactic ALPs

## Solar axions

- Axions: hypothetical particles postulated to solve the strong CP problem
  - Does not represent majority of dark matter but well motivated candidates

- ALPs: generalization of the axion concept without addressing the strong CP problem

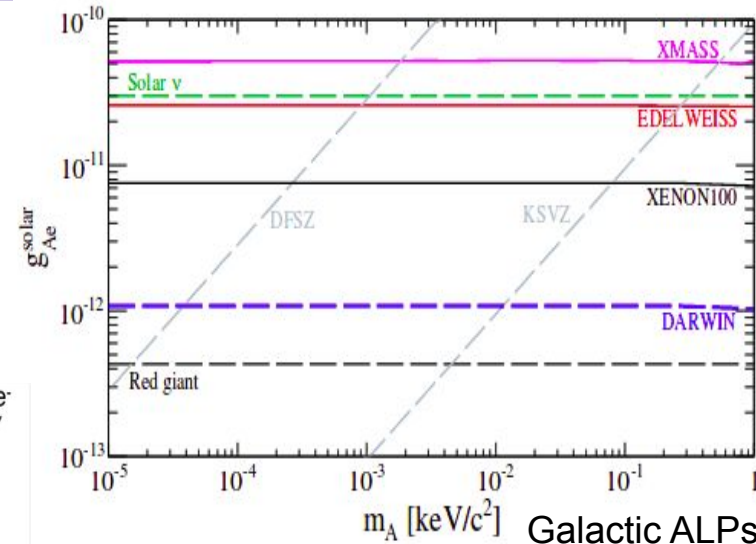
- Solar axions & ALPs couple to xenon via axio-electric effect (ER)
  - Ionize a xenon atom



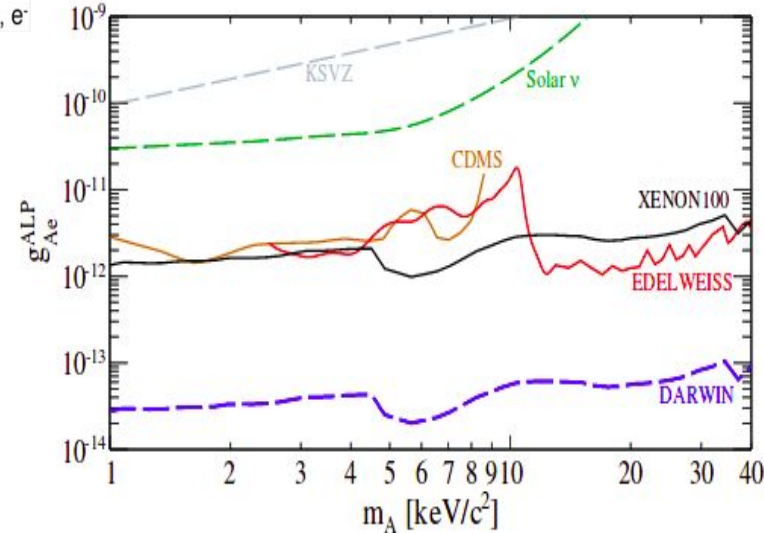
- Expect mono-energetic peak at axion mass
- Sensitivity to solar axions
  - ~ X10 improvement relative to Xenon100
- Sensitivity to galactic ALPs
  - ~X100 improvement relative to XENON100

$$g_{Ae}^{\text{solar}} \propto (MT)^{-1/8}$$

$$g_{Ae}^{\text{ALP}} \propto (MT)^{-1/4}$$



## Galactic ALPs





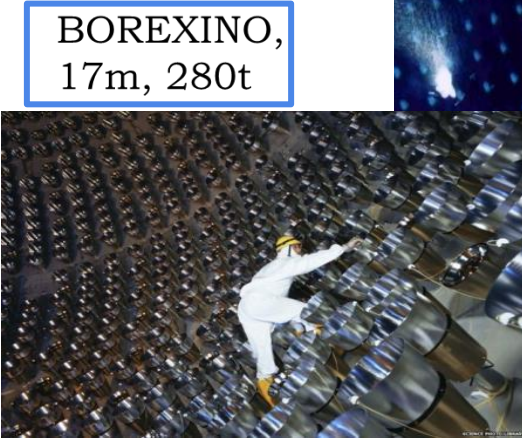
# LXe Experiments can also go Neutrino, *for free!!!*



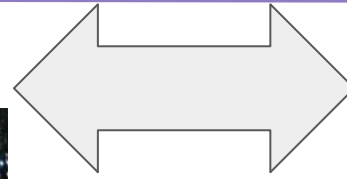
IceCube,  
1km<sup>3</sup>, 1Gt



Super-K,  
40m, 50kt



BOREXINO,  
17m, 280t



Low (keV)  
energies:  
Coherent  
Elastic  
Neutrino-  
Nucleus  
scattering  
(CEVNS)

$$\sigma \propto A^2$$



LZ, 1.5m, 10t

# LXe Experiments can also go Neutrino!!!

## Coherent Elastic Scattering

For both **WIMPs** & **solar/supernova  $\nu$**

$$\frac{\lambda_{\text{deBroglie}}}{2\pi} = \frac{\hbar}{p} \sim \frac{197\text{MeV fm}}{100\text{GeV } 10^{-3}c} \sim \frac{197\text{MeV fm}}{10\text{MeV}} > r_{\text{nucleus}}$$

→ interact with entire nucleus:  $\sigma \propto A^2$

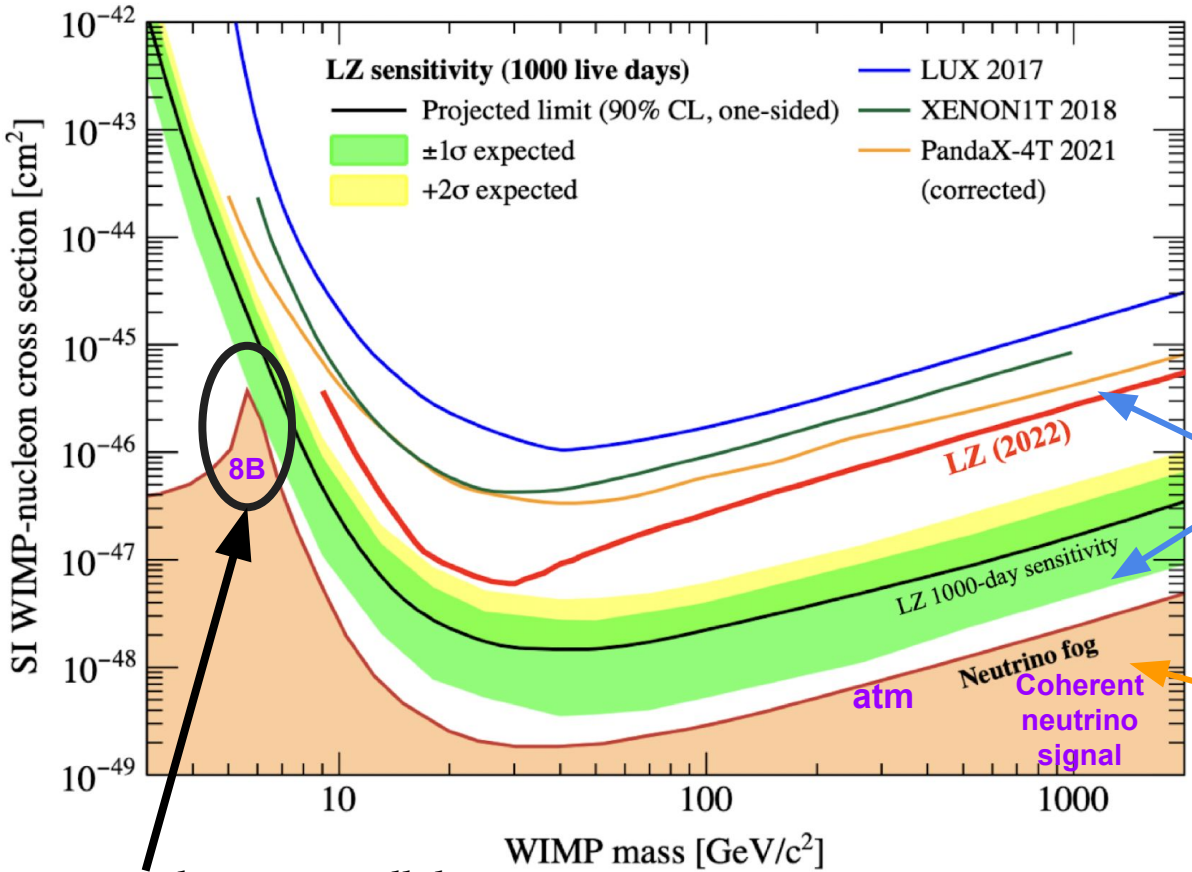
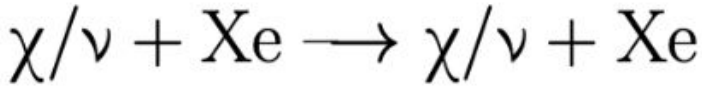
Recoil degenerate in transferred momentum  $p$

→ for some parameter space, **WIMPs** and **neutrinos** indistinguishable:

**“neutrino fog”**

# LXe Experiments can also go Neutrino!!!

## Coherent Elastic Scattering



Simple scattering kinematics: degenerate in momentum

heavy WIMP,  $v \sim 10^{-3}c$

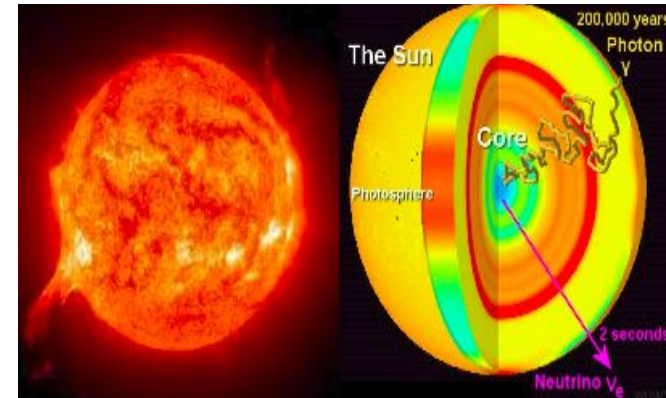
Coherent Neutrino-Nucleus Scattering light  $n, v \sim c$

Large LXe detectors will detect 8B CE $\nu$ NS signals

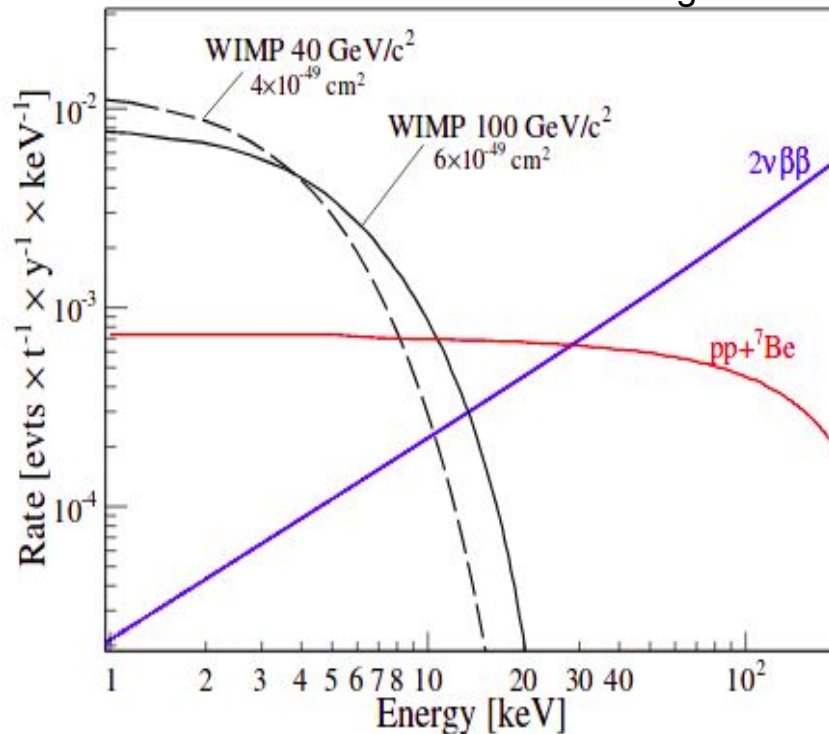


# $\nu$ Physics: Low Energy solar neutrinos

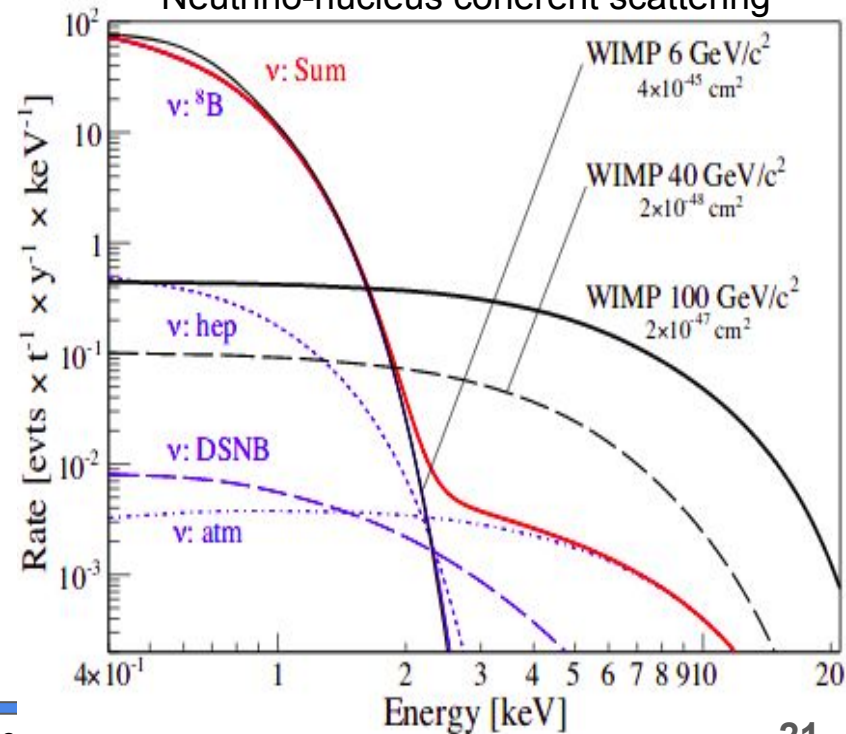
- Low E solar neutrinos, **pp** &  ${}^7\text{Be}$ , **8B**, CNO
  - Vast majority of solar neutrinos, help to **understand & improve solar models** (eg solar metallicity & luminosity)
  - Very low energetic, hard to detect
- **Prominent backgrounds for WIMP searches**
  - Neutrino-electron scattering (ER channel)
  - **Neutrino nucleus coherent scattering** (NR channel)



Neutrino-electron scattering



Neutrino-nucleus coherent scattering

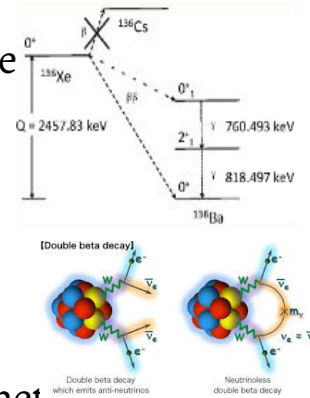


# $\nu$ Physics: Neutrinoless double beta decay

- Monoenergetic single event site at  $Q$  value of the decay
- Measured half life not cross-section

## Motivation:

- ⇒ Discovery of Majorana particles
- ⇒ Discovery of lepton number violation
- ⇒ Discovery of violation of conservation of net difference between lepton number and baryon number



- Current best limits set by EXO-200 & KamLAND-Zen using ~100's kg of Xe-136

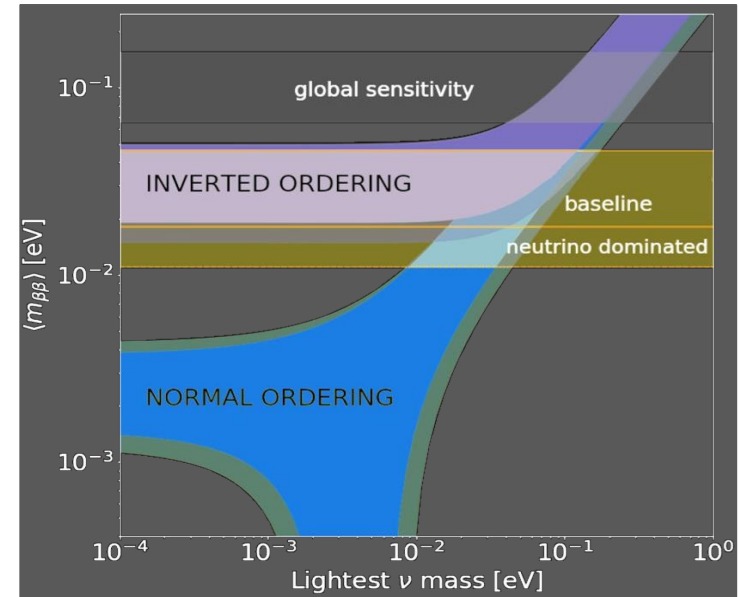
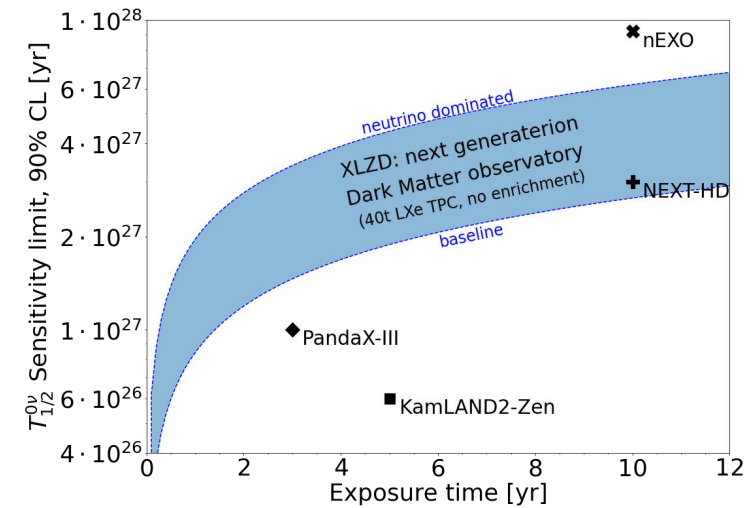
- **No Xe-136 enrichment needed for G3 LXe to set competitive limit to  $\nu\nu\beta\beta$  future ton-scale experiments** →

- Xe-136 abundance in natural xenon : 8.9%  
→ XLZD 40 tons of Xe has 3.6 tons of Xe-136

- Sensitivity:  $T_{1/2} = 5.6 \times 10^{26}$  year with  $\sigma/E \sim 1\%$  at  $Q_{\beta\beta}$

[arxiv:2003.13407]

## Sensitivity to Xe-136 $\nu\nu\beta\beta$ half life vs exposure



potentially probe entire inverted hierarchy

# Conclusion: Take home messages

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- **LXe TPCs** have led high mass WIMP searches **since 2007** - and **have consistently delivered on design sensitivity (e.g. LZ)**
- **Leading experiments** in the dark matter field (LZ & XENONnT /DARWIN) which utilizes this technology **joined forces** to build the next generation (G3) of dark matter detector.
- **LZ & XENONnT/DARWIN** are actively working together on central questions for this new detector which will **address numerous scientific questions** in addition to probing dark matter nature.
- From our early design studies we are confident that a **20m cavity is suitable for a G3 experiment** such as **XLZD**. **This suggests new space at SURF will be needed.** We are confident that the **cosmic ray shielding** and environmental **backgrounds** of the **4850 L meet the background requirements** for a LXe G3 experiment.