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

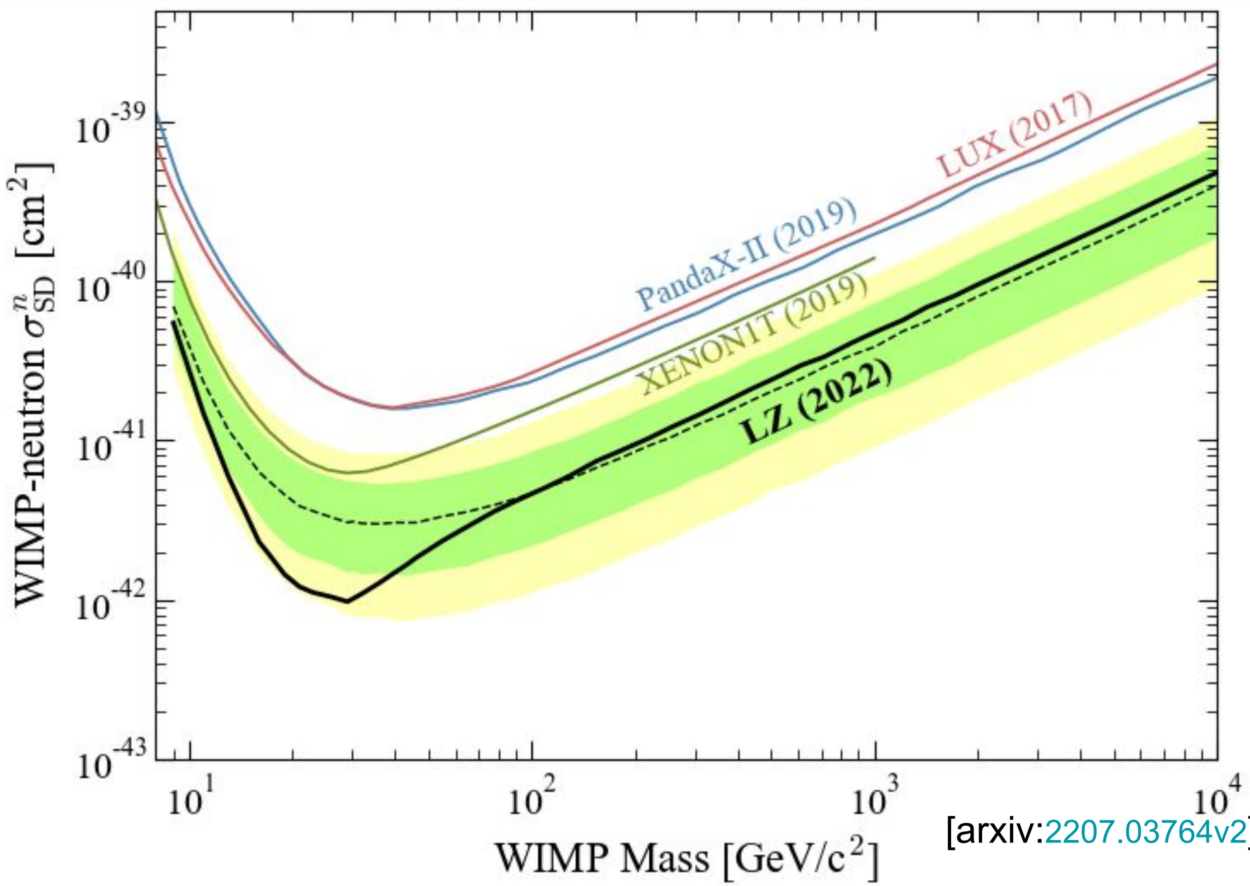
Alvine Kamaha (UCLA)

SURF User Association Annual General Meeting

October 24-26, 2022

Dark Matter (DM) Direct Detection: Status

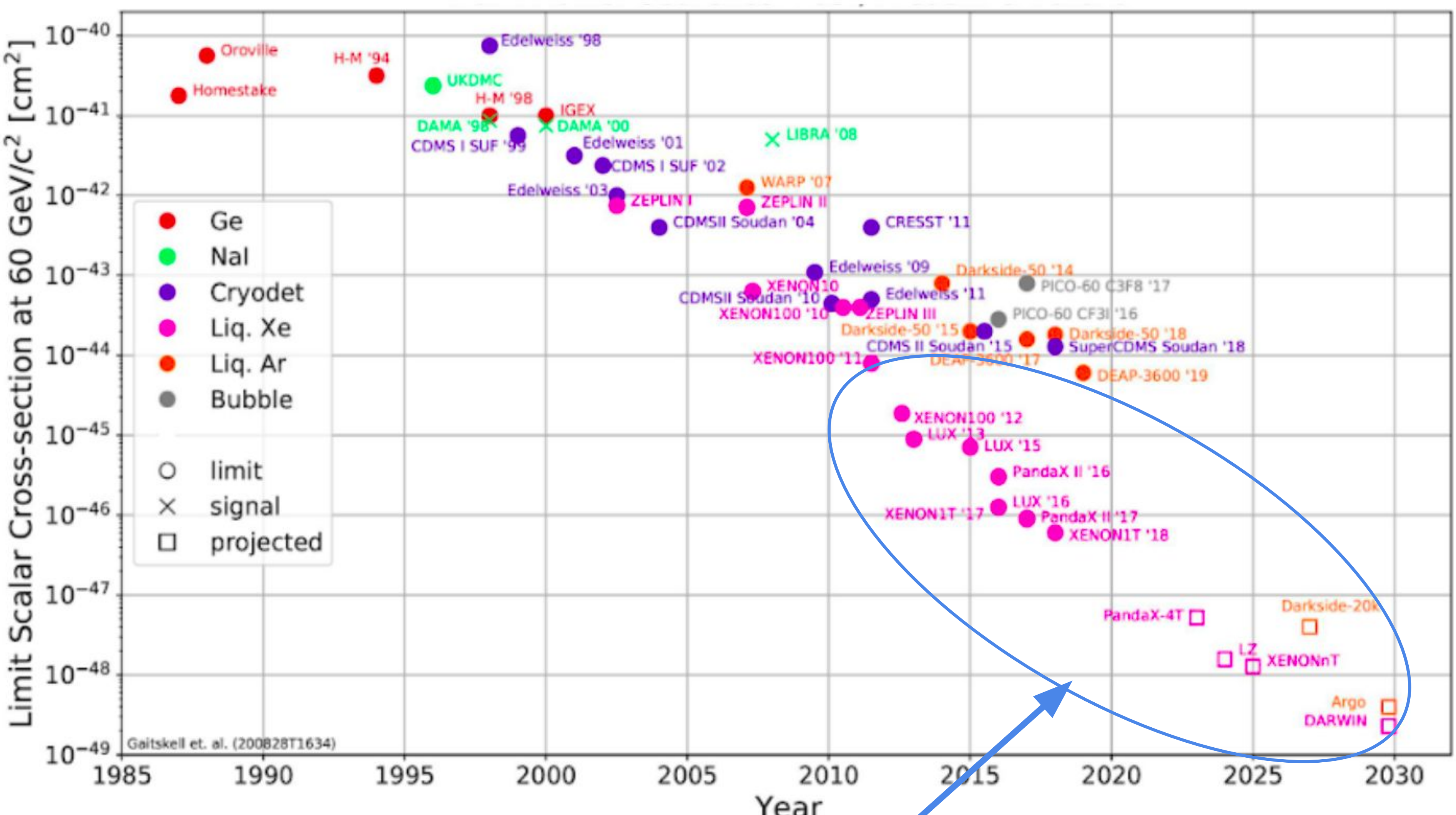
Fantastic first science **results by LZ** experiment **hosted at SURF** (*see talk by S. Shaw*) displaying the great potential of the LXe technology and what can be achieved with LZ in ~ 5years timeline



[arxiv:2207.03764v2]

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

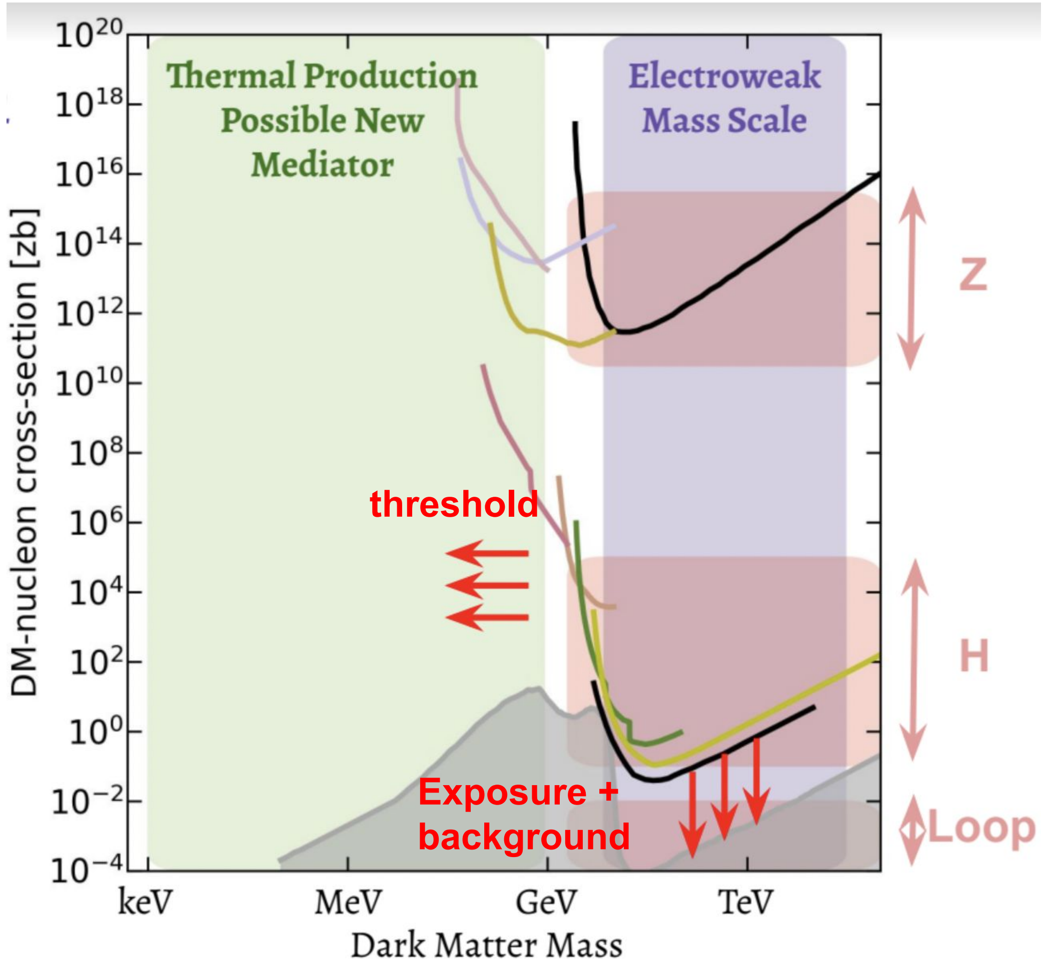
DM Direct Detection: past, present & future



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**

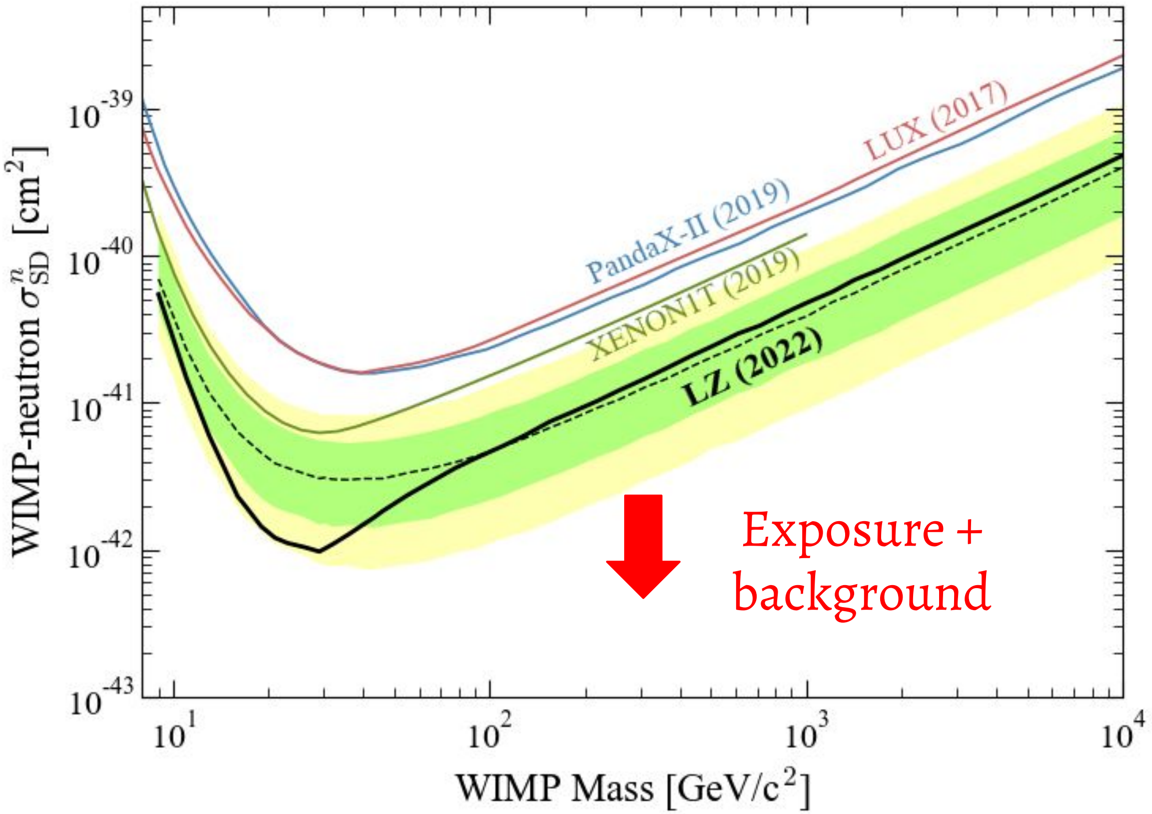
Relevant Highlight from SNOWMASS'21

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**

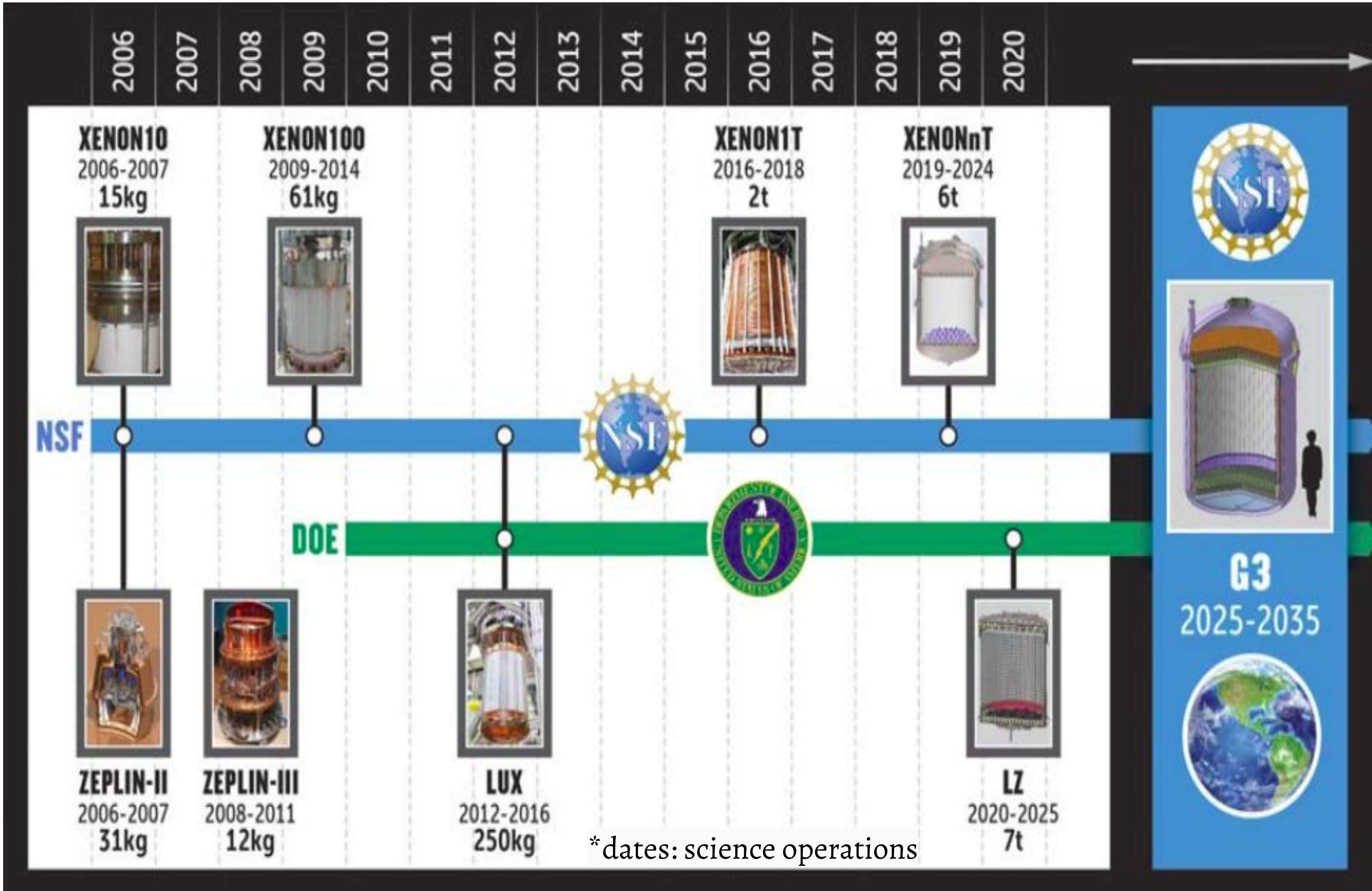
Already **official** and **active**

- 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 Karlrushe, Germany (June 2022)

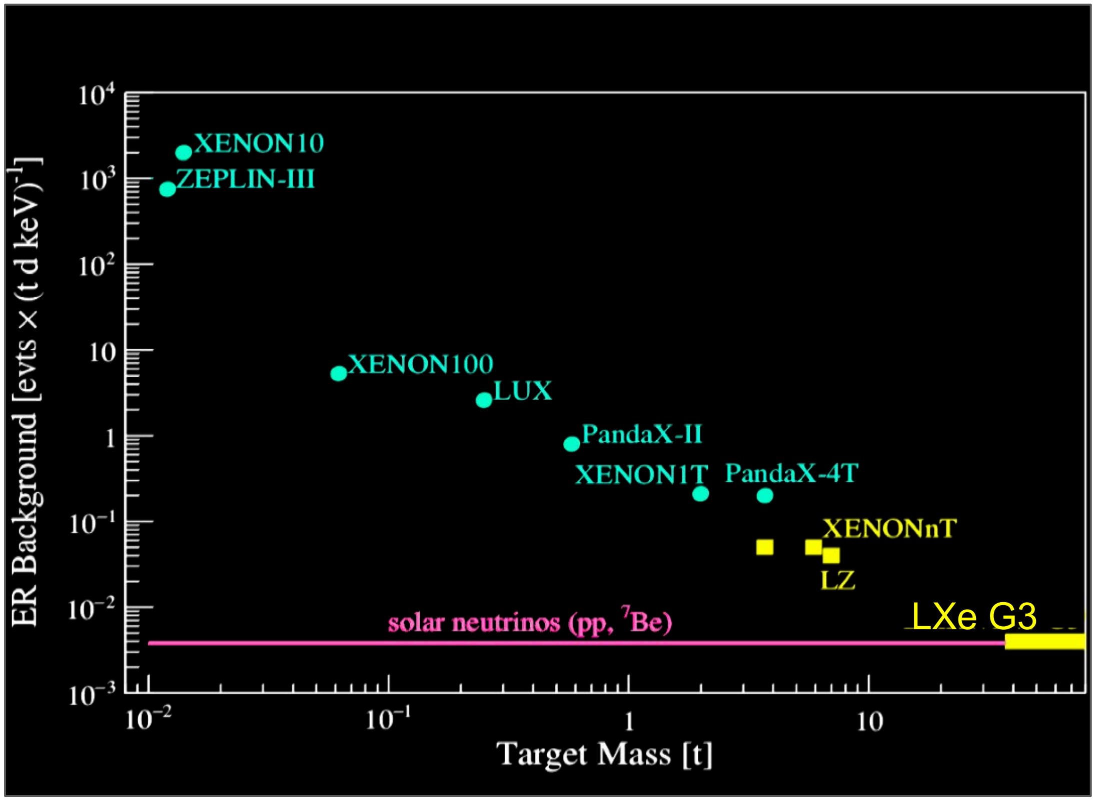
XLZD: funding in US

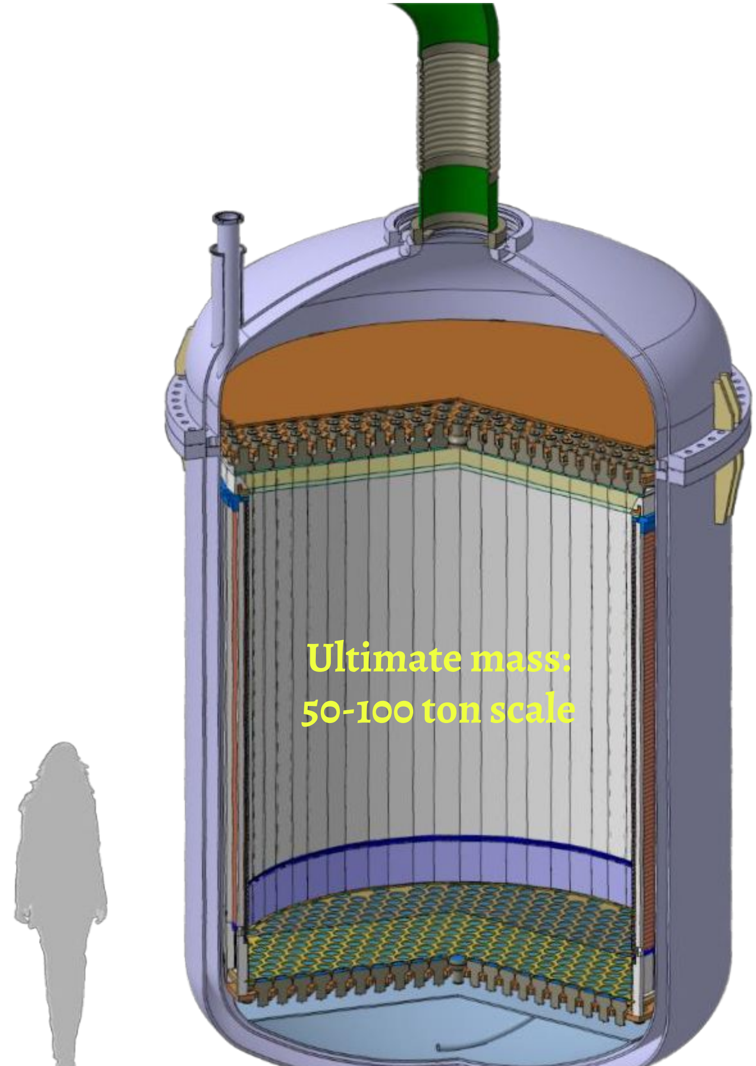
Note: M€ invested through various grants in Europe



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

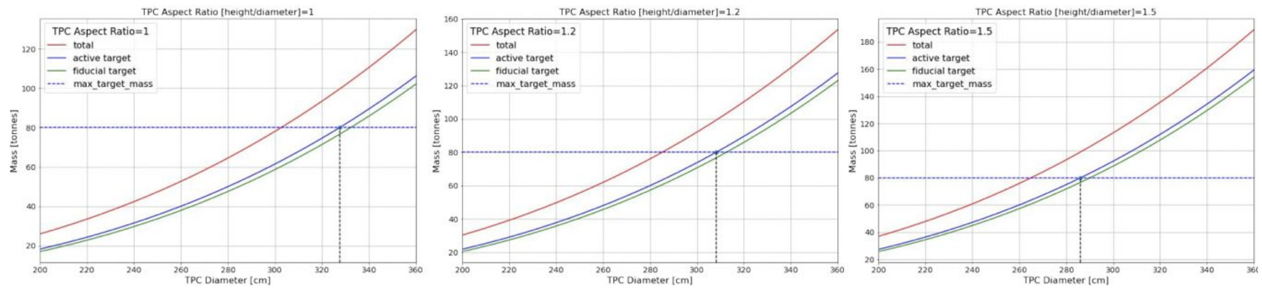
XLZD R&D: Detector Conceptual Design & Size

Stage approach
vs
Monolithic approach

...to serve as an example

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

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

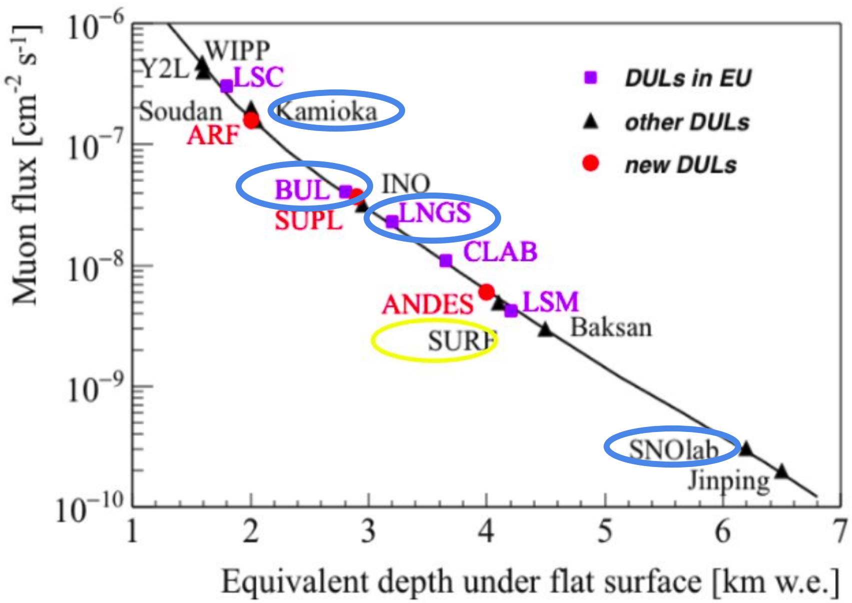


AR =1	AR =1.2	AR =1.5
• TPC Act. Mass = **40 tonnes**: → TPC ∅=259 cm & drift=259 cm	• TPC Act. Mass = **40 tonnes**: → TPC ∅=244 cm & drift=292 cm	• TPC Act. Mass = **40 tonnes**: → TPC ∅=227 cm & drift=340 cm
• TPC Act. Mass = **60 tonnes**: → TPC ∅=297 cm & drift=297 cm	• TPC Act. Mass = **60 tonnes**: → TPC ∅=280 cm & drift=336 cm	• TPC Act. Mass = **60 tonnes**: → TPC ∅=259 cm & drift=388 cm
• TPC Act. Mass = **80 tonnes**: → TPC ∅=327 cm & drift=327 cm	• TPC Act. Mass = **80 tonnes**: → TPC ∅=308 cm & drift=369 cm	• TPC Act. Mass = **80 tonnes**: → TPC ∅=286 cm & drift=429 cm

AR: Aspect Ratio

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

XLZD: Siting



Sanford Underground Research Facility
South Dakota Science and Technology Authority

SNOLAB

UKRI Science and Technology Facilities Council
Boulby Underground Laboratory

KAMIOKA OBSERVATORY

INFN LABORATORI NAZIONALI DEL GRAN SASSO

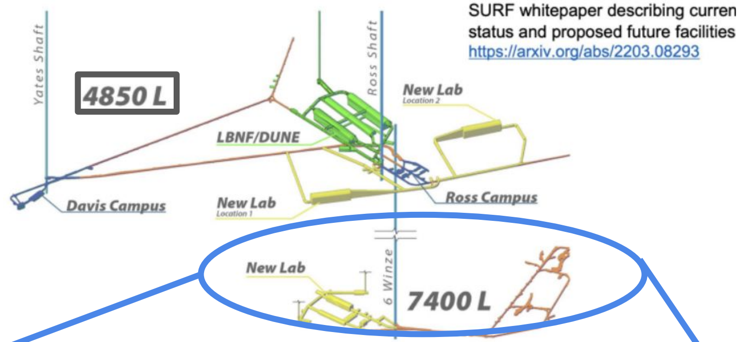
- 5 sites are being evaluated for XLZD (SURF, KAMIOKA, BOULBY, SNOLAB & LNGS)
  - Well known sites which demonstrated good supporting capabilities (SC) to carry out the science goals of state-of-the-art rare event search experiments.
- A next generation G3 detector like XLZD (~**3 meter** scale) will 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

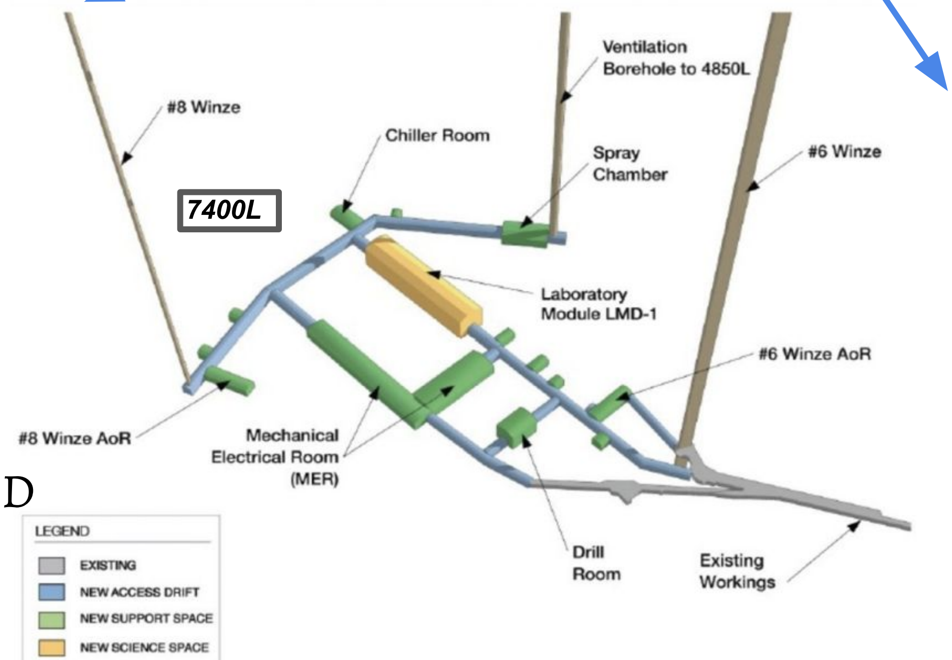
XLZD: Siting @ SURF

- **Great support** during **LZ** construction @ SAL, UG transport & daily LZ operation
  - Surface lab (class 100 CR 54m², 240 m³)
  - **But LZ underground site small for XLZD** & U/G Rn concentration too high (300-350 Bq/m³) ⇒ mitigation strategies will be required.

⇒ **New space** needed, options:

- New lab module @ 4850L (50-100m x 20m x 28 m) through LBNF?
- New lab module @7400L - under discussion?





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

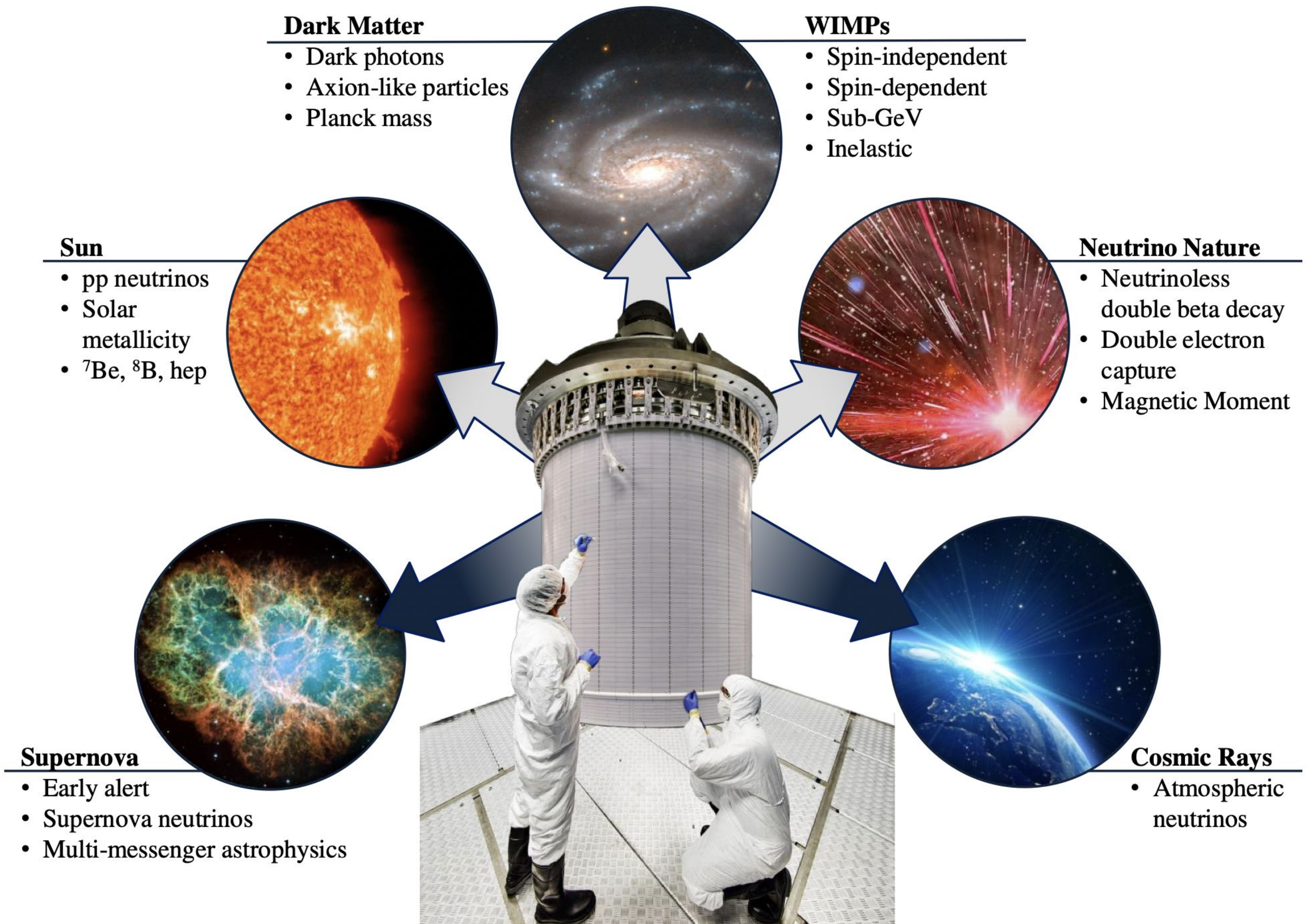
- **Cosmic ray shielding and environmental backgrounds** @4850L/4300 mwe meet XLZD requirements
  - (NIM A 638, (2011) 63-66)
  - (Astropart.Phys. 116 (2020) 102391, NIM A 812, (2016) 1-6)
- Need to think about *pesky* neutrino beam

XLZD: the ultimate WIMP detector & beyond

A rich science program discussed **on 77 pages [arxiv 2203.02309]**

Not only dark matter!

XLZD: A Rare Event Observatory

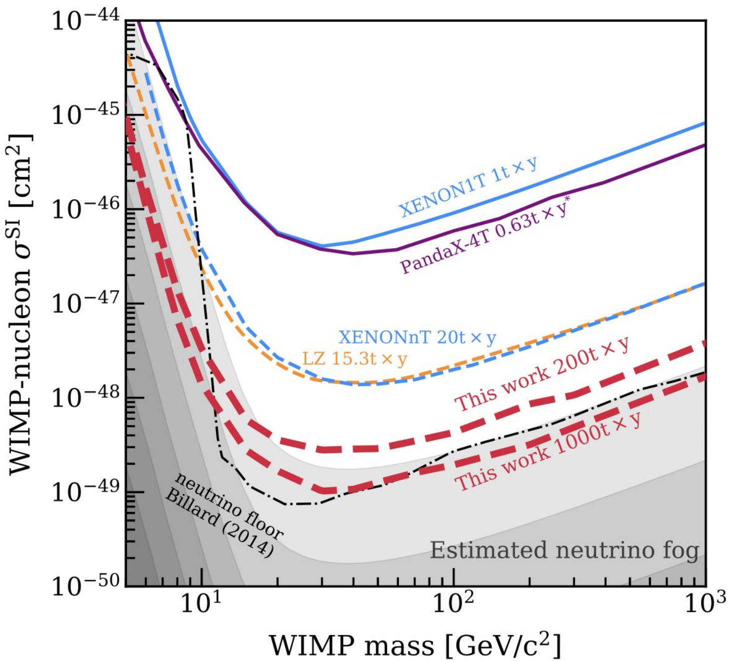


XLZD science case [arxiv 2203.02309]

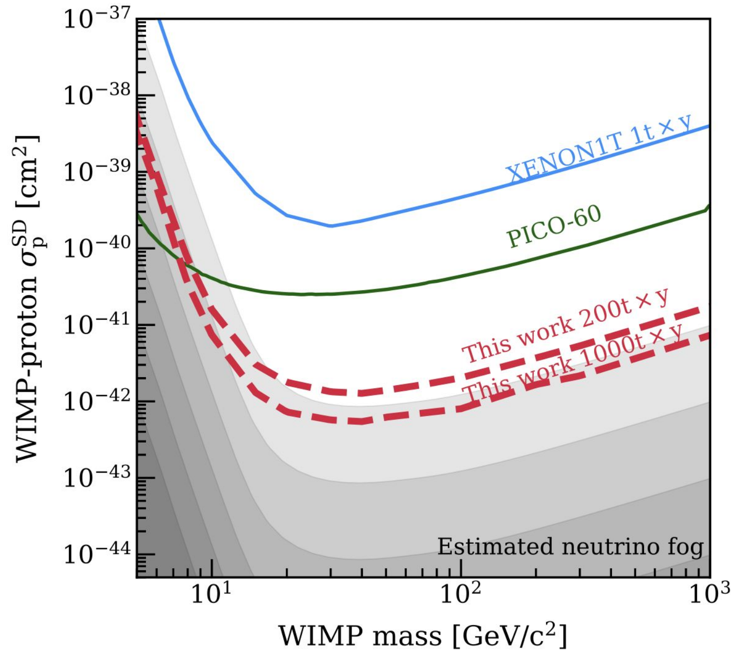
DM Physics: XLZD WIMP Sensitivity

- Projected sensitivity (upper limit) for 200t×y and 1000 t×y exposure
- Will probe entire parameter region for mχ ~ 2 Gev/c² until ~neutrino ~~floor~~fog
  - Likelihood analysis
  - 99.98% ER rejection @ 30% NR acceptance

Spin Independent couplings



Spin Dependent couplings (p-only)



200 t×y: $\sigma<2.5\times10^{-49}$ @ 40GeV/c²   excellent complementarity to LHC searches

XLZD science case [arxiv 2203.02309]

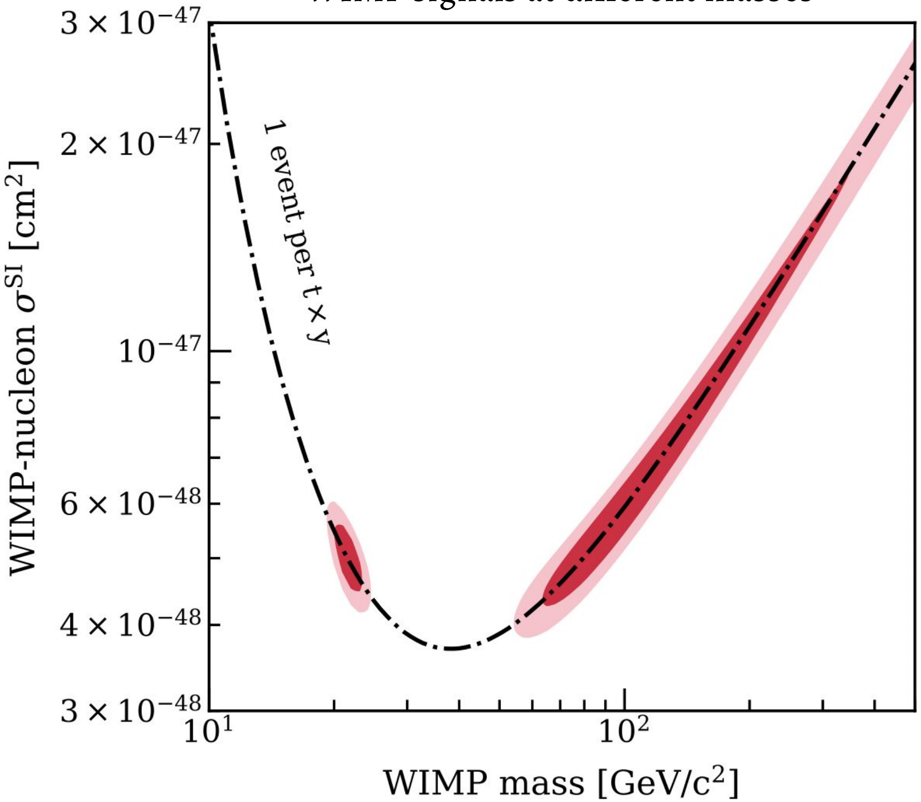
DM Physics: XLZD WIMP Spectroscopy

- Capability to reconstruct the WIMP mass & cross section (SI) for various masses below 500 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 t×y
Reconstruction:
m_χ =20, 100 GeV/c^2

Confidence intervals for spin-independent WIMP signals at different masses



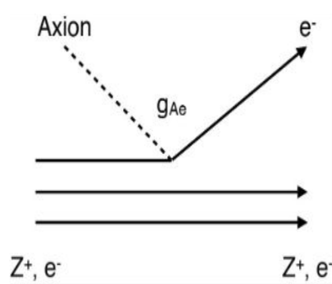
XLZD science case [arxiv 2203.02309]

DM Physics: Solar axions & galactic ALPs

- 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

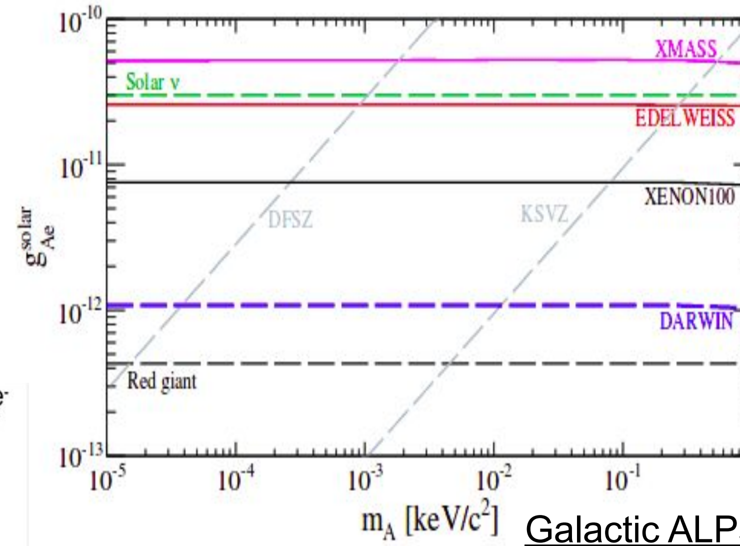
- Solar axions & ALPs couple to xenon via axio-electric effect (ER)
  → Ionize a xenon atom



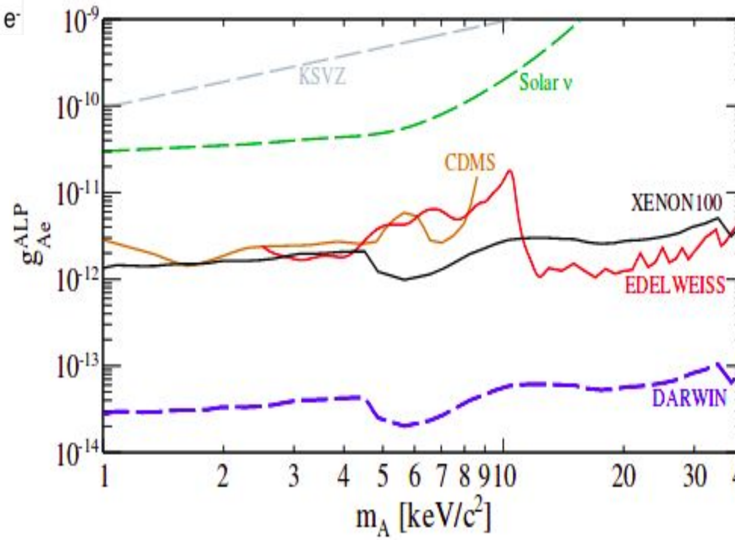
- Expect mono-energetic peak at axion mass
- Sensitivity to solar axions
  - ~ X10 improvement relative to Xenon100

- Sensitivity to galactic ALPs
  - ~X100 improvement relative to XENON100
  - $$g_{Ae}^{\text{solar}} \propto (MT)^{-1/8}$$
    $$g_{Ae}^{\text{ALP}} \propto (MT)^{-1/4}$$

Solar axions

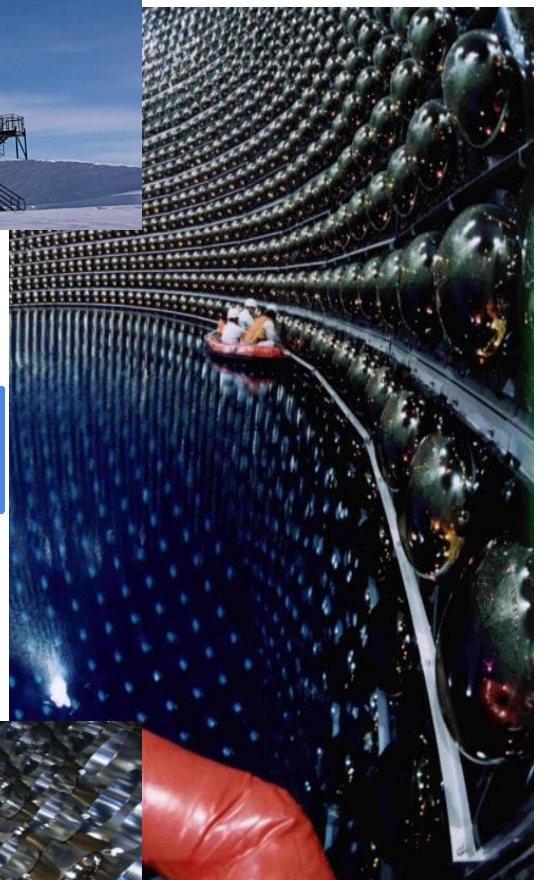


Galactic ALPs



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

IceCube, 1km³, 1Gt

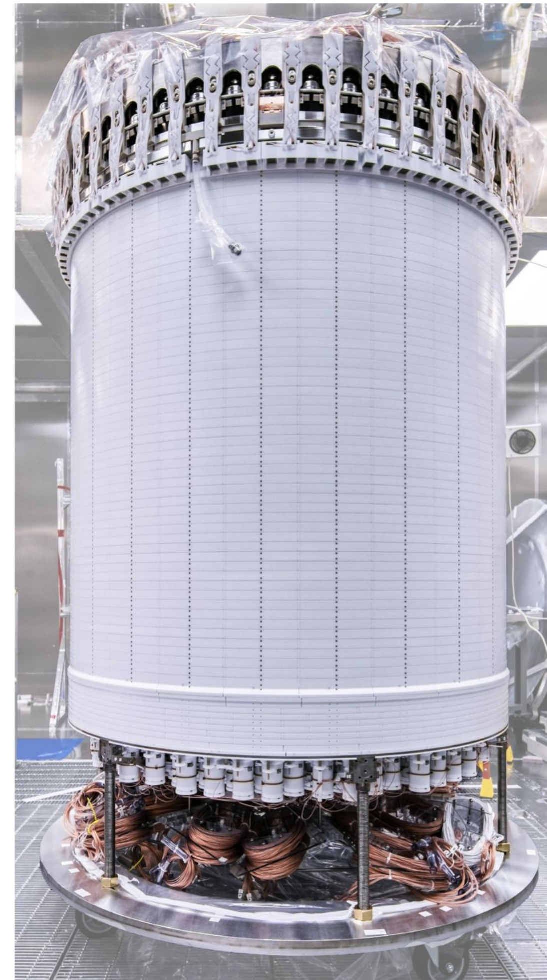


Super-K, 40m, 50kt

BOREXINO, 17m, 280t

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

$$\boldsymbol{\sigma} \propto A^2$$



LZ, 1.5m, 10t

LXe Experiments can also go Neutrino!!!

Coherent Elastic Scattering

For both **WIMPs** & **solar/supernova ν**

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

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

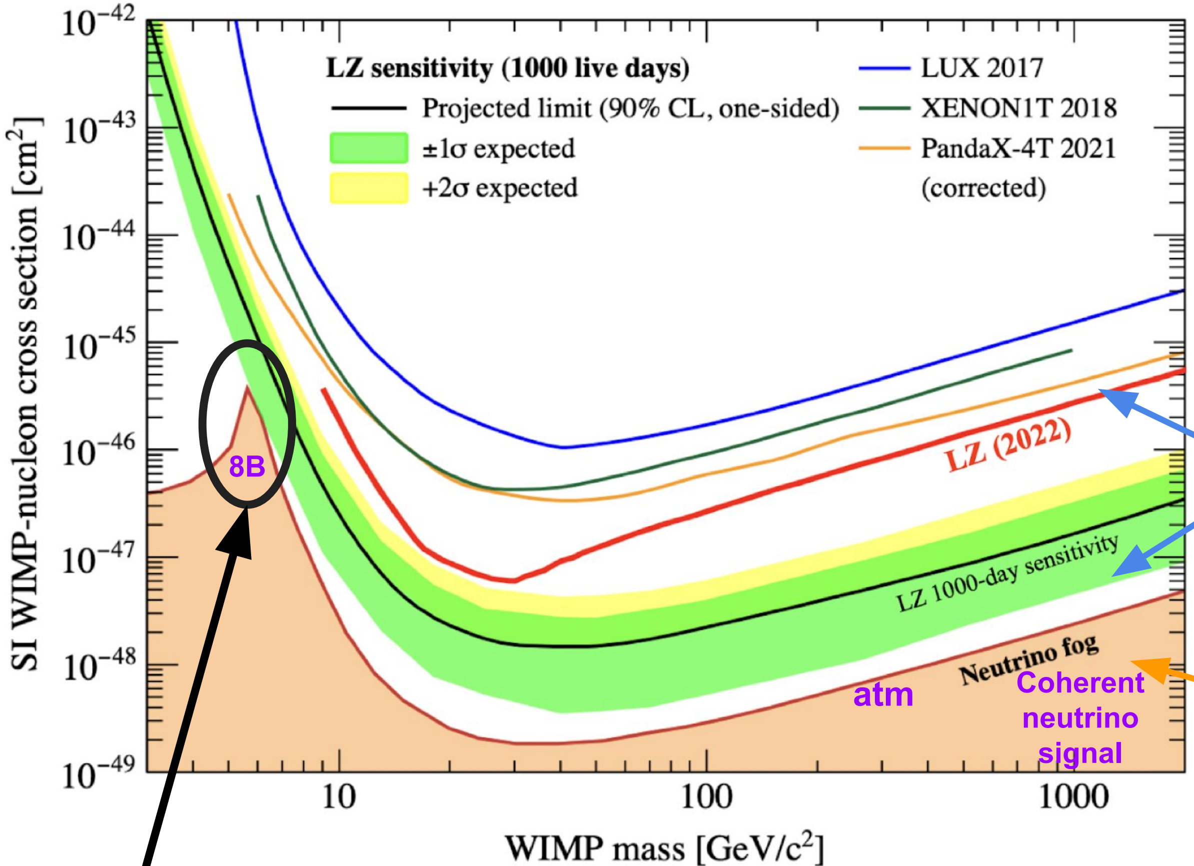
Recoil degenerate in transferred momentum *p*

→ for some parameter space, **WIMPs** and **neutrinos** indistinguishable: **“neutrino fog”**

LXe Experiments can also go Neutrino!!!

Coherent Elastic Scattering

$$\chi/\nu + Xe \longrightarrow \chi/\nu + Xe$$



Simple scattering kinematics: degenerate in momentum

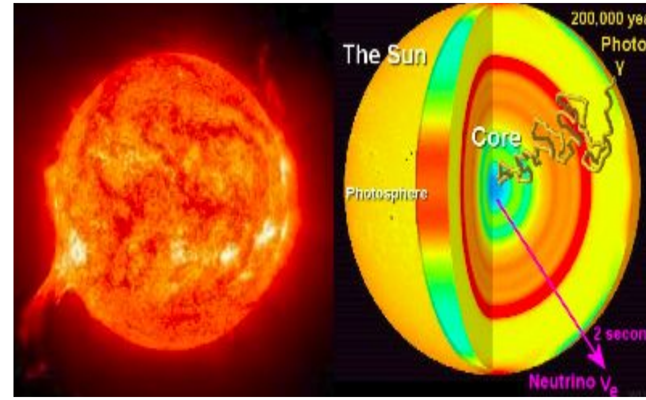
heavy WIMP, $v \sim 10^{-3}c$

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

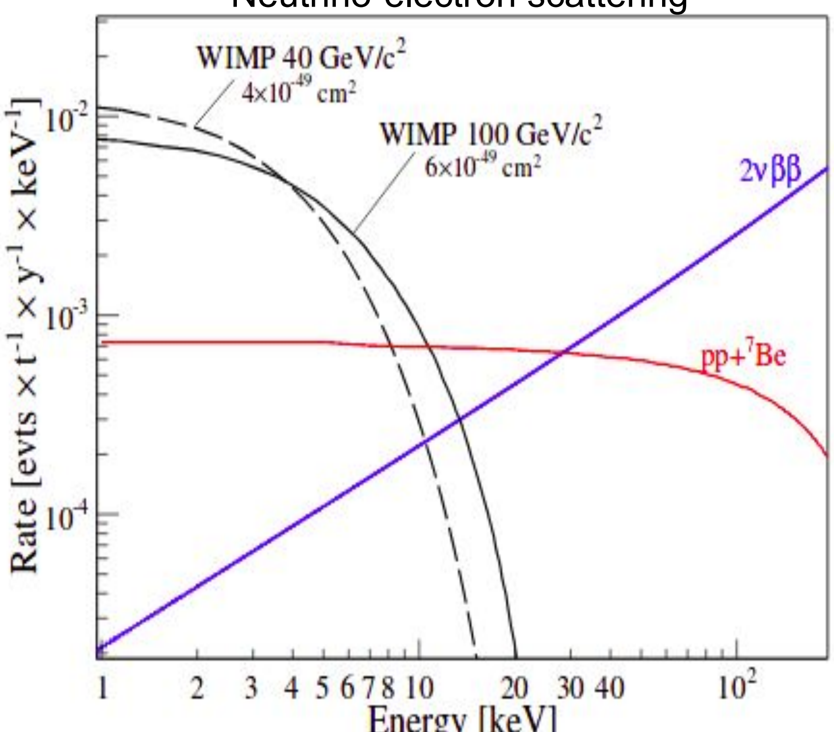
Large LXe detectors will detect 8B CE**ν**NS signals

ν Physics: Low Energy solar neutrinos

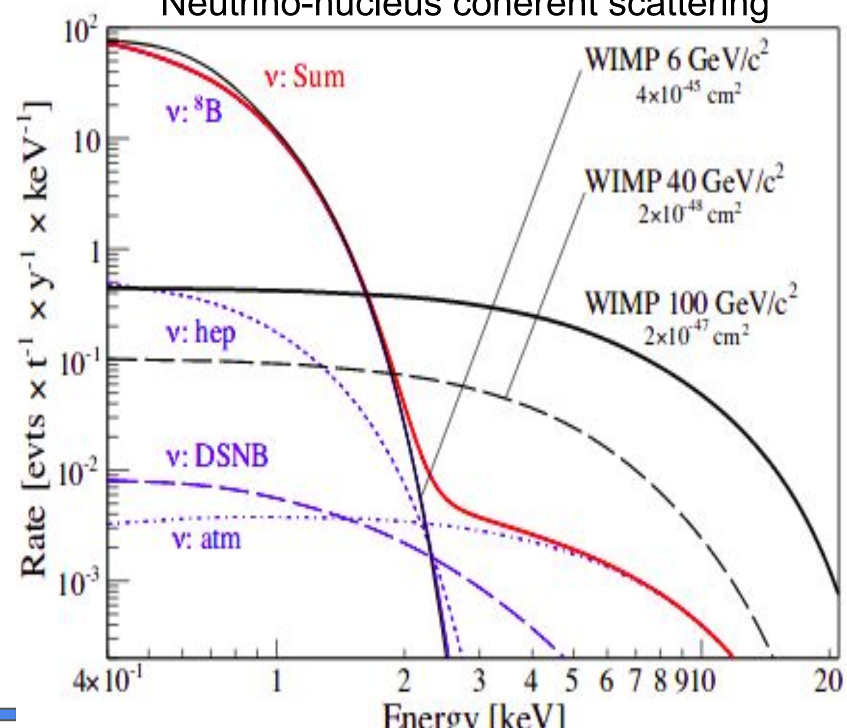
- Low E solar neutrinos, **pp** & 7Be, **8B**, CNO
  - Vast majority of solar neutrinos, help to **understand & improve solar models** (eg solar metallicity & luminosity)
  - Very low energetic, hard to detect
- **Prominent backgrounds for WIMP searches**
  - Neutrino-electron scattering (ER channel)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



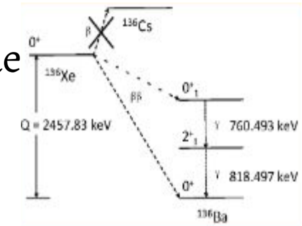
Neutrino-electron scattering



Neutrino-nucleus coherent scattering



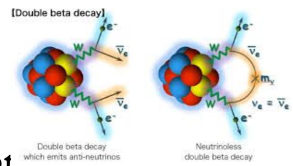
ν Physics: Neutrinoless double beta decay



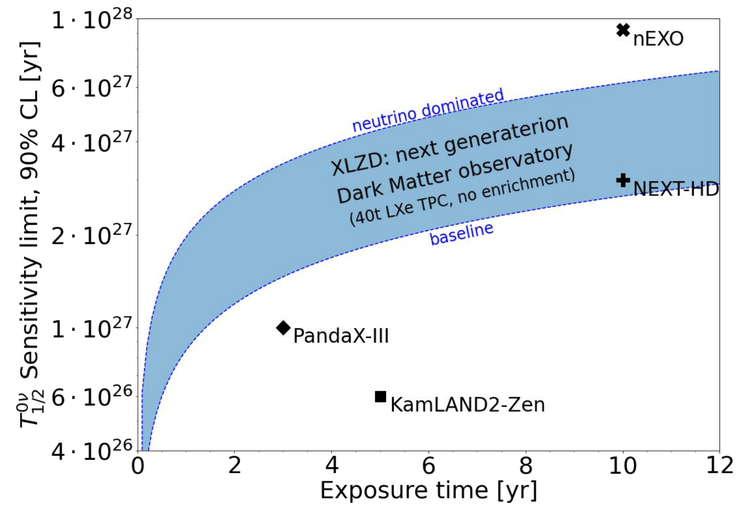
- Monoenergetic single event site at Q value of the decay
- Measured half life not cross-section

Motivation:

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



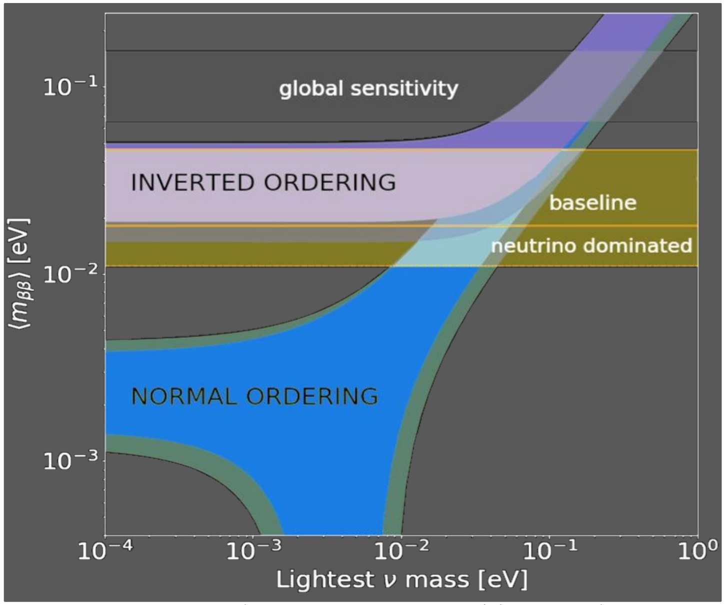
Sensitivity to Xe-136 ovbb half life vs exposure



- 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 0vbb** 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: $T_{1/2} = 5.6\times10^{26}$ year with σ/E ~1% at $Q_{\beta\beta}$



potentially probe entire inverted hierarchy

[arxiv:2003.13407]

Conclusion: Take home messages

- **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.