Dark Matter and 0vbb physics program of XLZD

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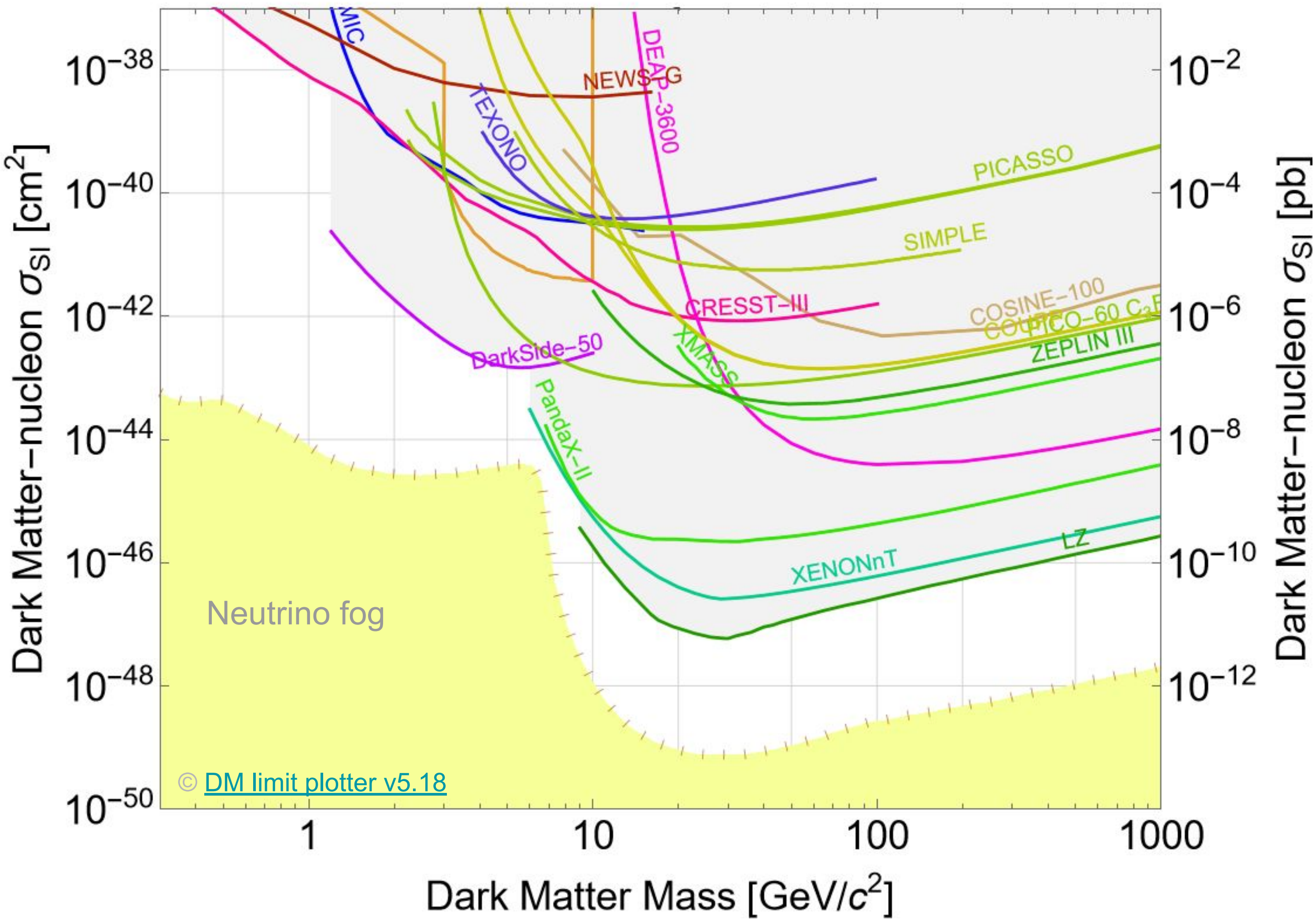
On behalf of the XLZD Consortium

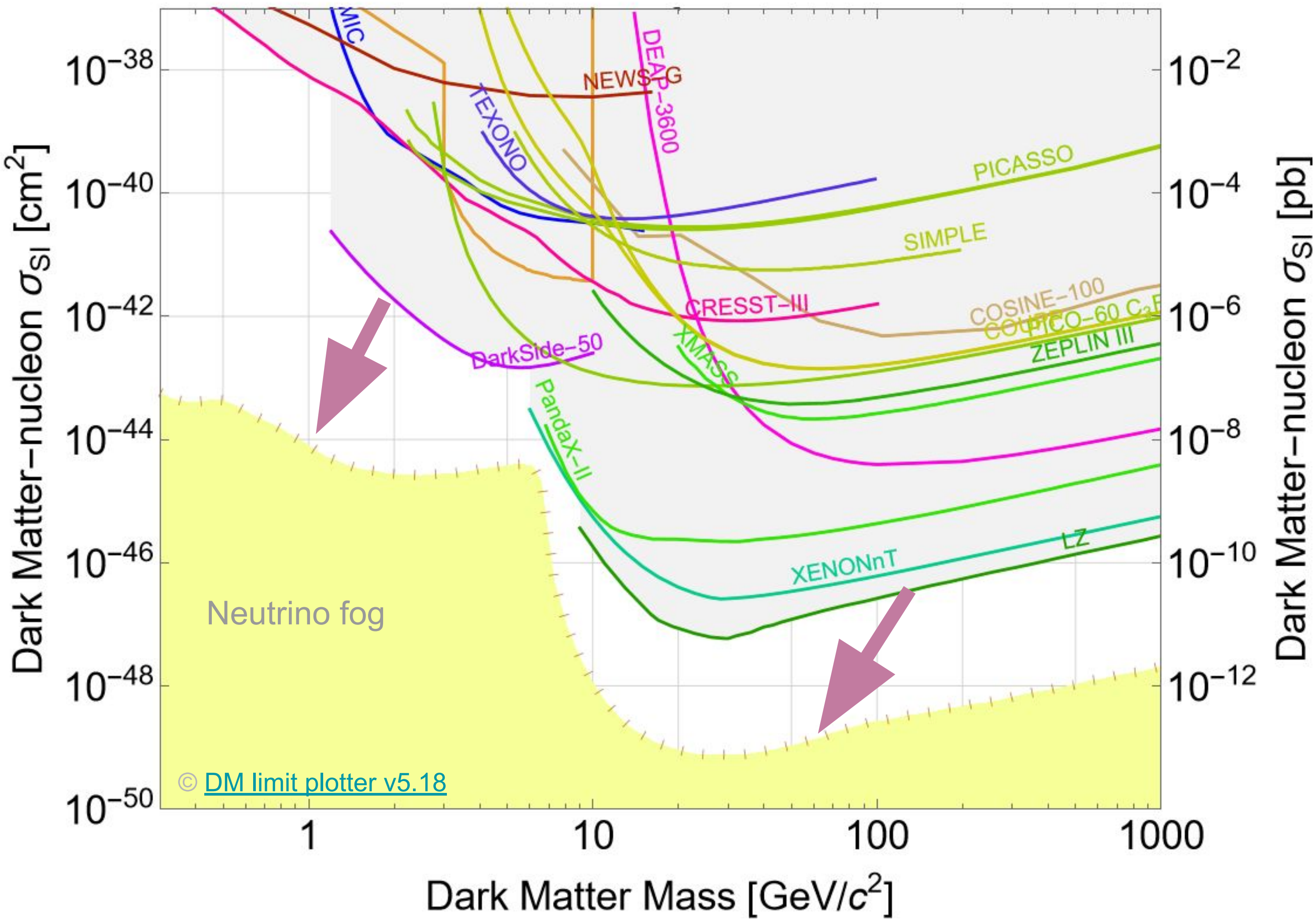
SLAC kTonne Xe Detectors Workshop
October 25-27, 2023

State of affairs in DM (WIMP) direct detection



Noble liquid detectors leading the field … for 15 years and counting!

Looking into the future, beyond LZ & XENONnT



We want to probe the WIMP parameter space into the neutrino fog

XLZD: A Unified Xenon Community

- Consortium MOU signed in July 2021 by **X**ENONnT, **L**UX-**Z**EPLIN & **D**ARWIN

- Ongoing activities
  - Co-authored community white paper [arXiv:2203.02309](https://arxiv.org/abs/2203.02309)
  - Working groups: science, technical, siting
  - In-person meetings:
    - KIT in June 2022
    - UCLA April 2023

- Goal: operational in the ~2030s

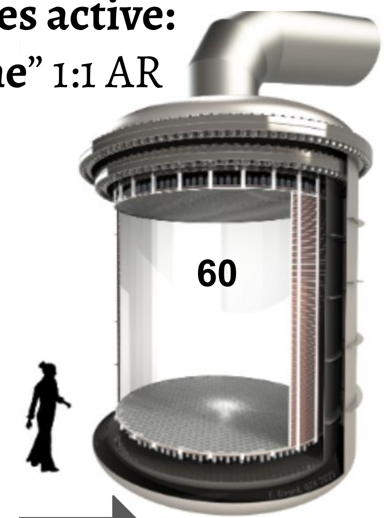
UCLA, 2023

KIT, 2022

XLZD: Detector Conceptual Design & Size

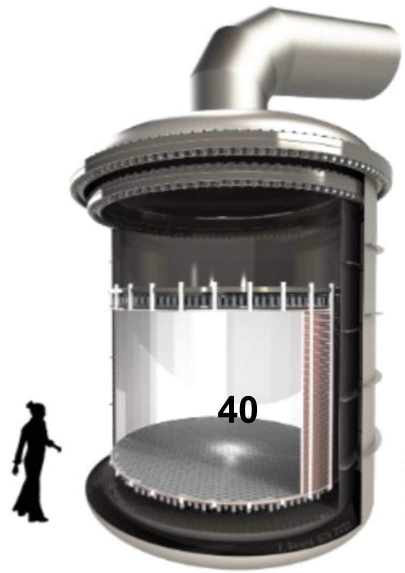
Technology of choice: dual-phase Xe-TPCs as progenitors LZ & XENONnT
Optimal size: ~x10 size LZ & XENONnT to search for WIMPs into the neutrino fog
Practical limit: depends on Xe procurement & other factors

60 tonnes active: "**baseline**" 1:1 AR (~3m)



Ongoing R&D to tackle detector infrastructure challenges → **See talk by Tom Shutt**

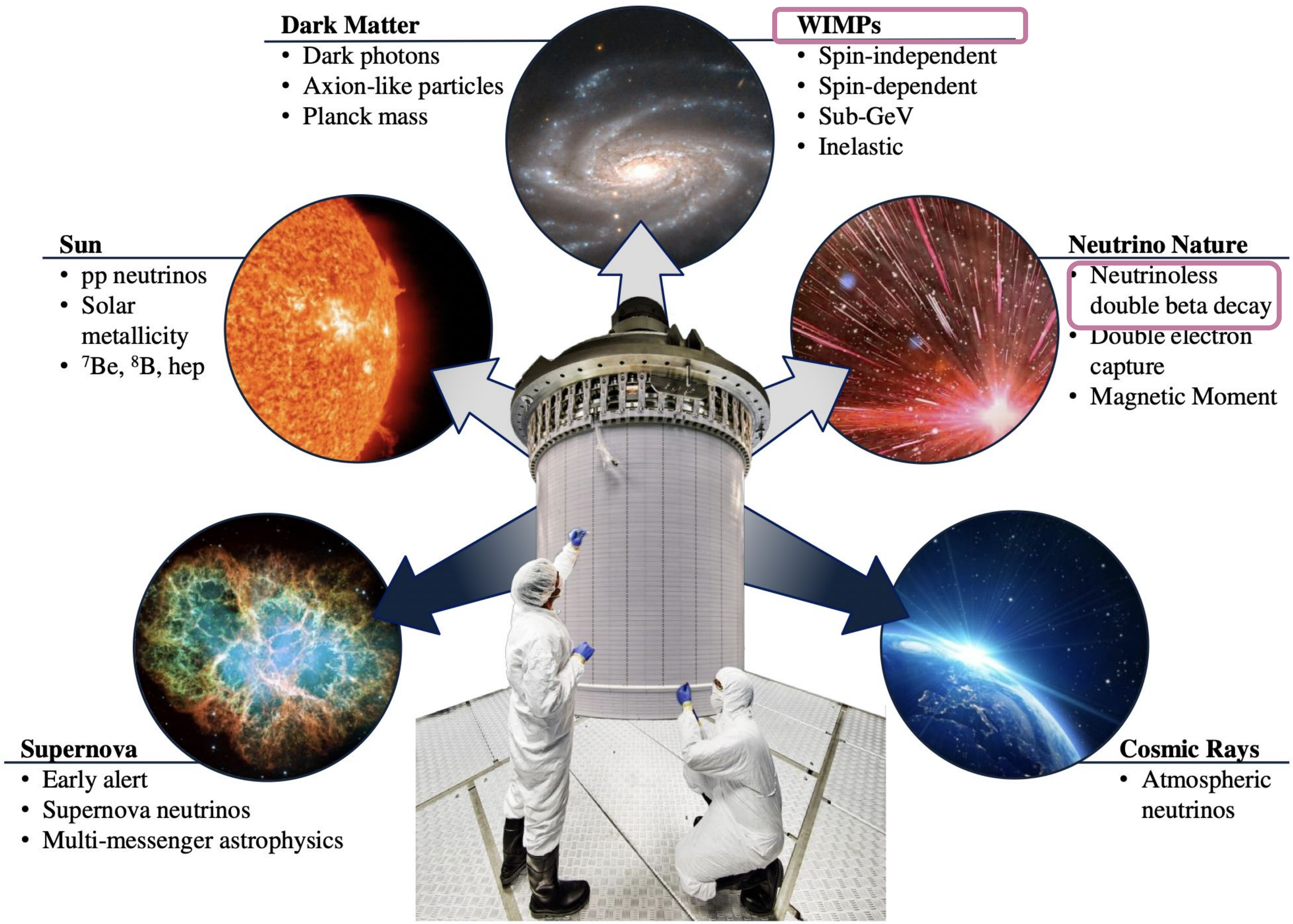
80 tonnes active: "**opportunity**" if Xe market favorable height>diameter



20-40 tonnes active: "slow Xe delivery rate" & early science height<diameter

AR: aspect ratio

XLZD: multi-physics searches



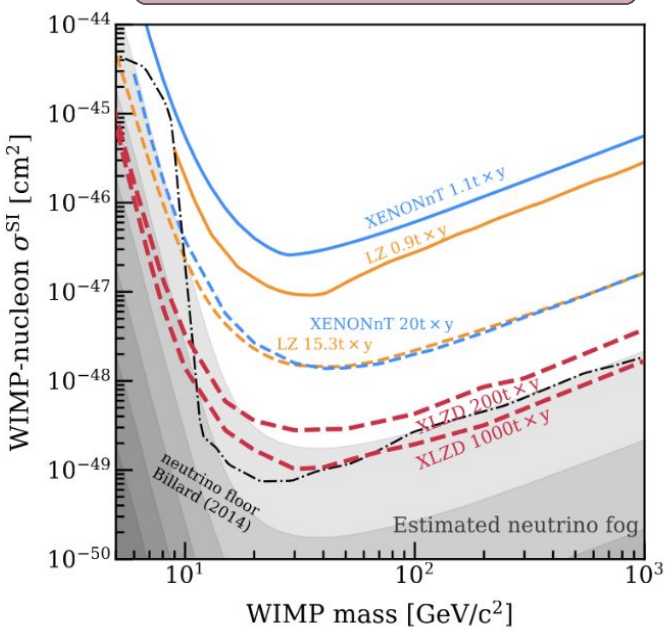
XLZD science case [arxiv 2203.02309]

DM Physics: Ultimate Search for WIMPs

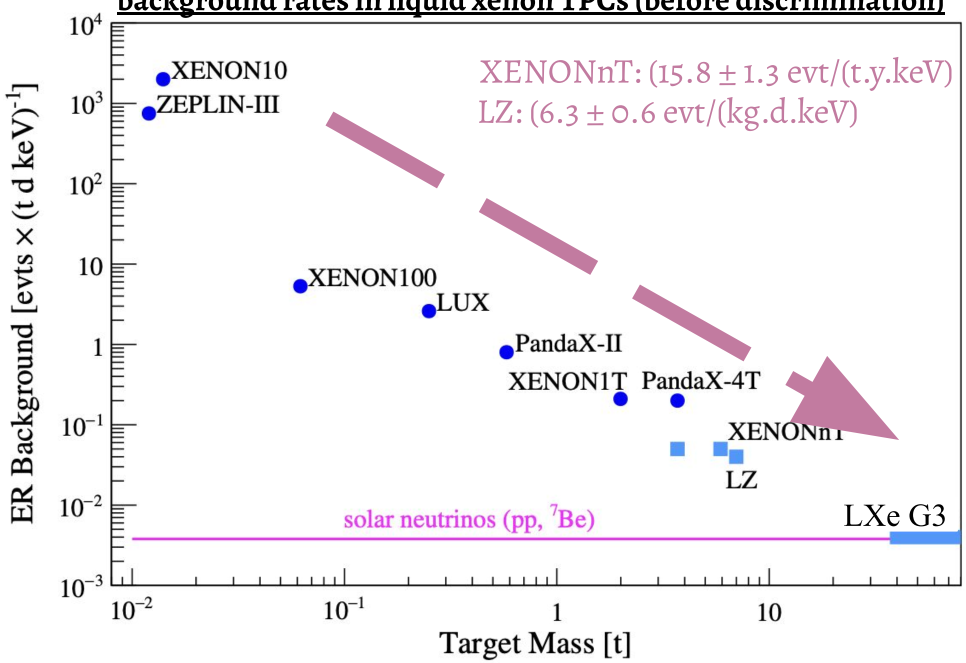
*limited by systematic

- XLZD will probe entire parameter space up to neutrino fog for $m\chi \geq 2$ Gev/c²
- Projected SI sensitivity (upper limit) for 200t×y and 1000* t×y exposure >10x current experiments. Assuming low but realistic bckg rate + 99.98% ER discrimination.

Spin Independent limits



We can also set Spin Dependent limits using odd Xe spin isotopes: ^{129}Xe (spin-½) and ^{131}Xe (spin-3/2)



[XENONnT Low ER search, PRL 129(2022) 161805]

[LZ Background determination: Phys. Rev. D 108, 012010]

XLZD science case [arxiv 2203.02309]

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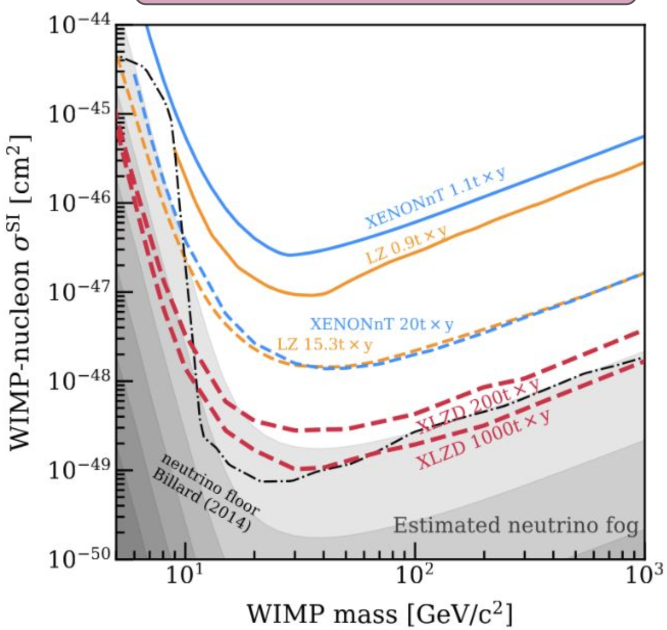
  - Discovery capability → WIMP spectroscopy

Spin Independent limits



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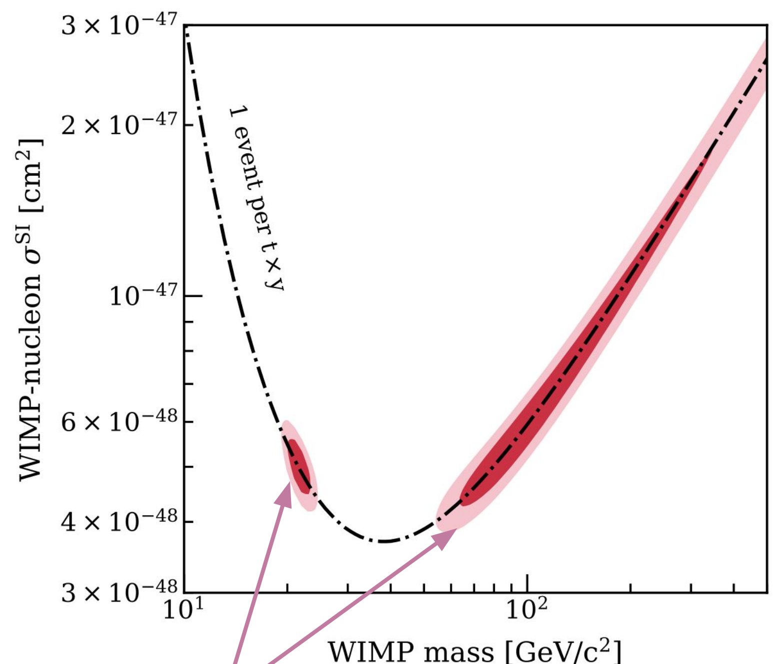
discovery potential & spectroscopy

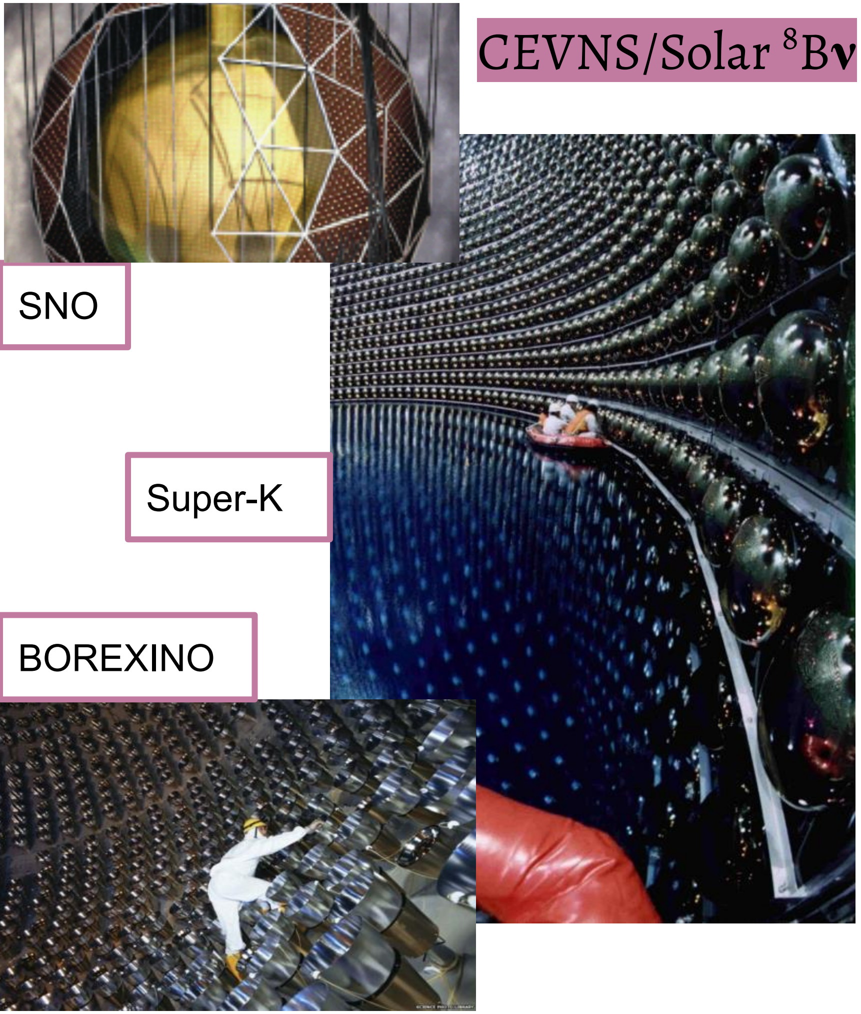


1σ (2σ) Confidence intervals for spin-independent WIMP signals at different masses

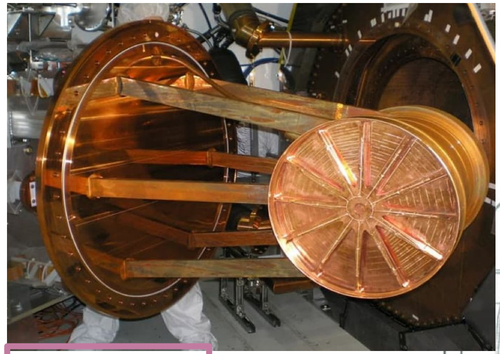
XLZD science case [arxiv 2203.02309]

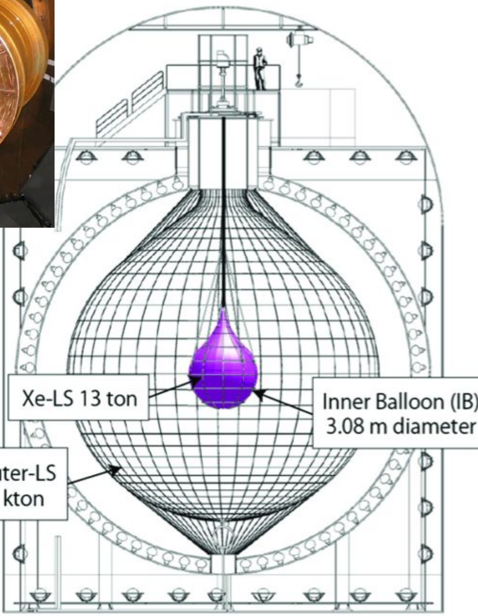
LXe Experiments can also go Neutrino, *for free* ...

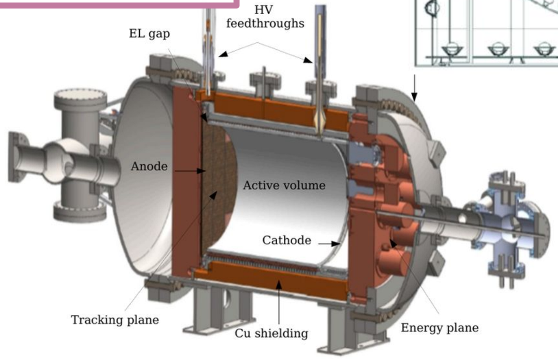
CEVNS/Solar $^{8}B\nu$



$0\nu\beta\beta$

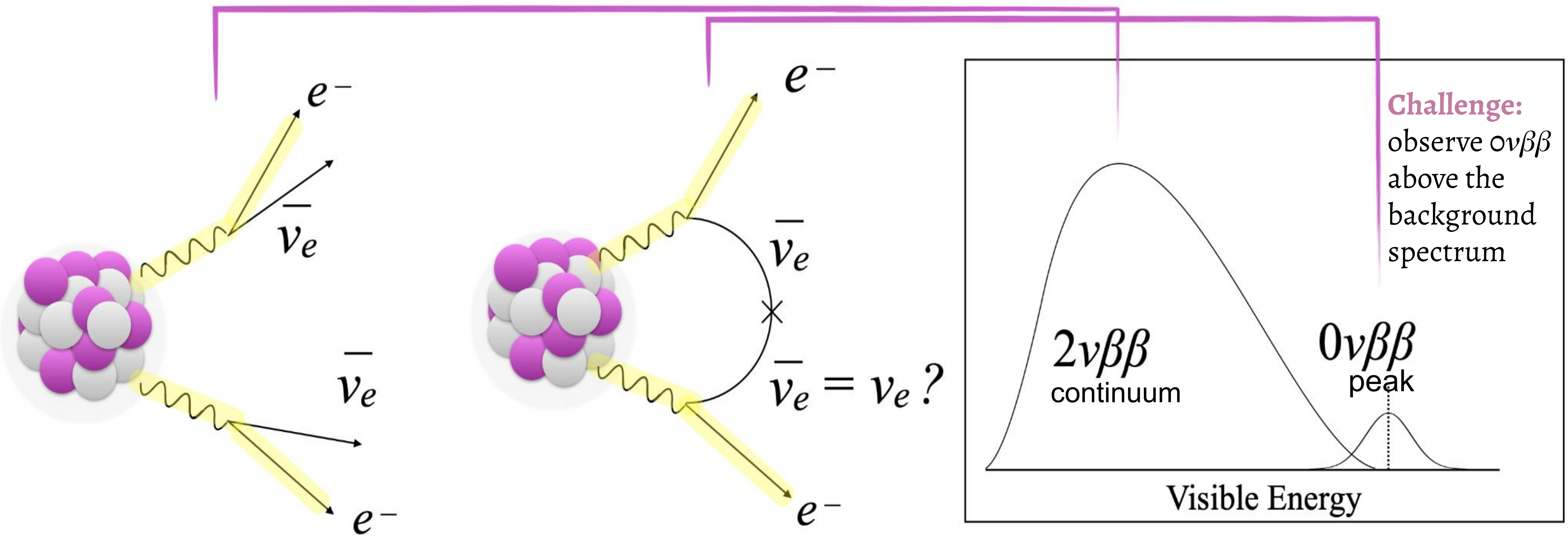






... and have complementary/competitive results to dedicated ν experiments!

ν Physics: neutrinoless double beta decay



Double beta decay (2νββ)

- Happens when a single β-decay is forbidden or suppressed
- $T_{1/2}$>2.3x10^{26} yr (KamLAND-Zen)
- Confirmed only in 14 isotopes (e.g ^{136}Xe)

Neutrinoless double beta decay (0νββ)

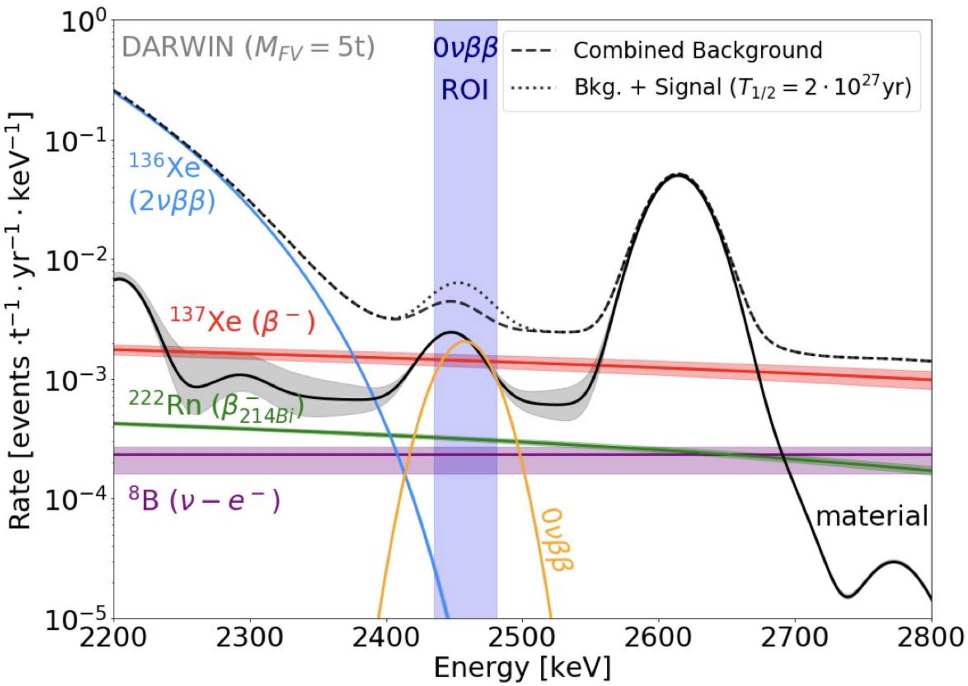
- BSM process. Can happen if **ν** are majorana
- Monoenergetic peak at the Q-value of 2νββ isotope
- Explain matter/antimatter asymmetry

ν Physics: 0νββ study in XLZD using ^{136}Xe

Illustration of a hypothetical 0νββ signal ($T_{1/2} = 2 \times 10^{27}$ yr) along with the predicted background spectrum around the 0νββ energy ROI for 5 tonnes FV

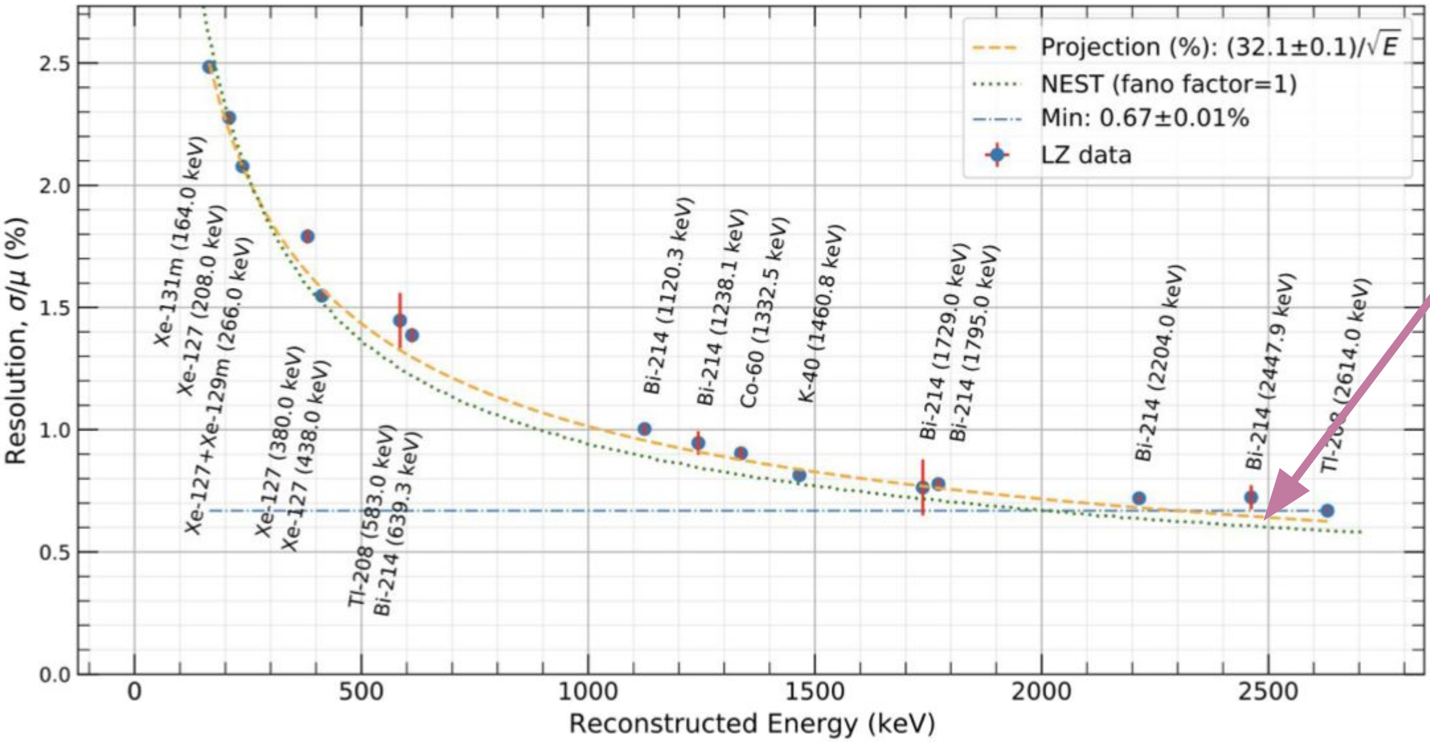
- High energy γ-ray from detector materials
- Uniformly distributed electron-induced signals
  - ^{136}Xe 2νββ-decay leakage into energy ROI
  - ^{8}B (ν-e$^-$) scatterings ← irreducible
  - ^{214}Bi (^{222}Rn progeny) β-decay leakage into energy ROI
  - ^{137}Xe (from ^{136}Xe activation by muons) β-decay leakage into energy ROI

[G3Xe science case, **arxiv** 2203.02309]



$0\nu\beta\beta$ Sensitivity driver: Energy Resolution

[LZ energy resolution, JINST 18 (2023) C04007]
[Xenon1T energy resolution, European Phys C, 80]



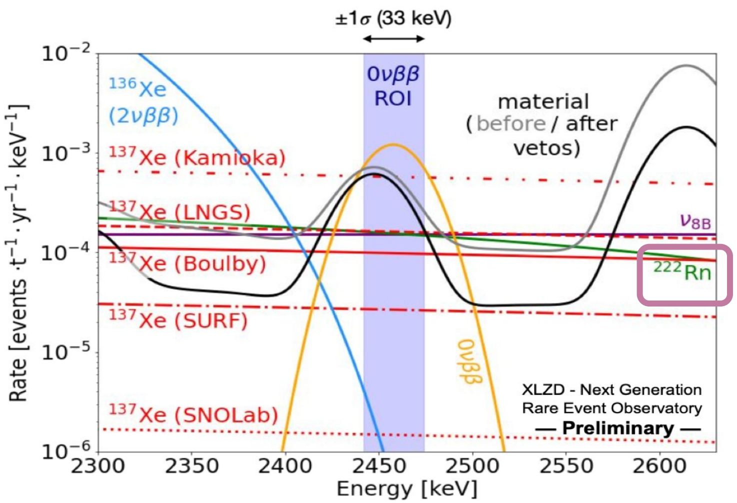
LZ demonstrated **0.67%** energy resolution at $Q(^{136}Xe)$=2458 kev

XLZD assumes energy resolution of **0.65%** $Q_{\beta\beta}$ (baseline) and **0.6%** $Q_{\beta\beta}$ (optimistic)

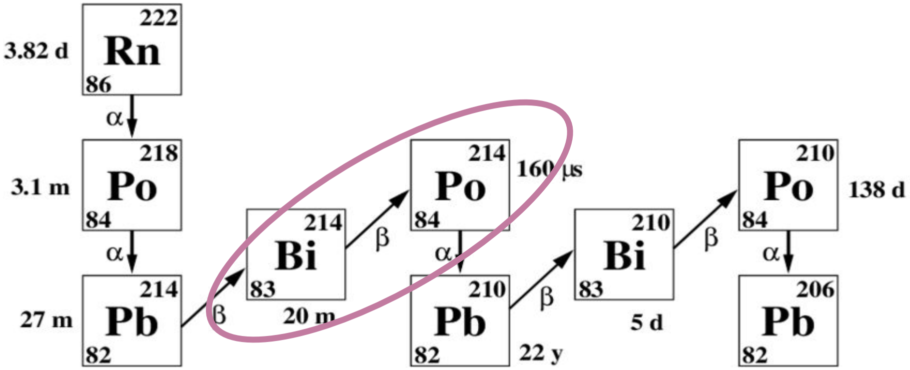
- Achievable based on LZ unprecedented result & XENON1T prior result
- Enables to potentially **suppress** ^{136}Xe $2\nu\beta\beta$-decay **spectrum leakage** into $0\nu\beta\beta$ energy ROI

$0\nu\beta\beta$ Sensitivity driver: Intrinsic ^{222}Rn Background

- Emanate from internal TPC surfaces, Uniform across detector volume
- Progeny ^{214}Bi (Q_β=3270 keV BR=19.7%) $\Rightarrow$mostly flat spectra in energy ROI



- XLZD assumes **^{222}Rn level of 0.1 μBq/kg** for baseline & optimistic scenarios
  - **XENONnT** ^{222}Rn level down to **0.8 μBq/kg** due to an inline high-flow radon removal system



XLZD will build a larger system + cryogenic material screening + novel surface treatment techniques $\Rightarrow$ anticipating **~x10 reduction**

- Also assume additional tagging of ^{214}Po α-decay which allows ^{214}Bi vetoing at **99.95%** (baseline) and **99.99%** (optimistic scenario)

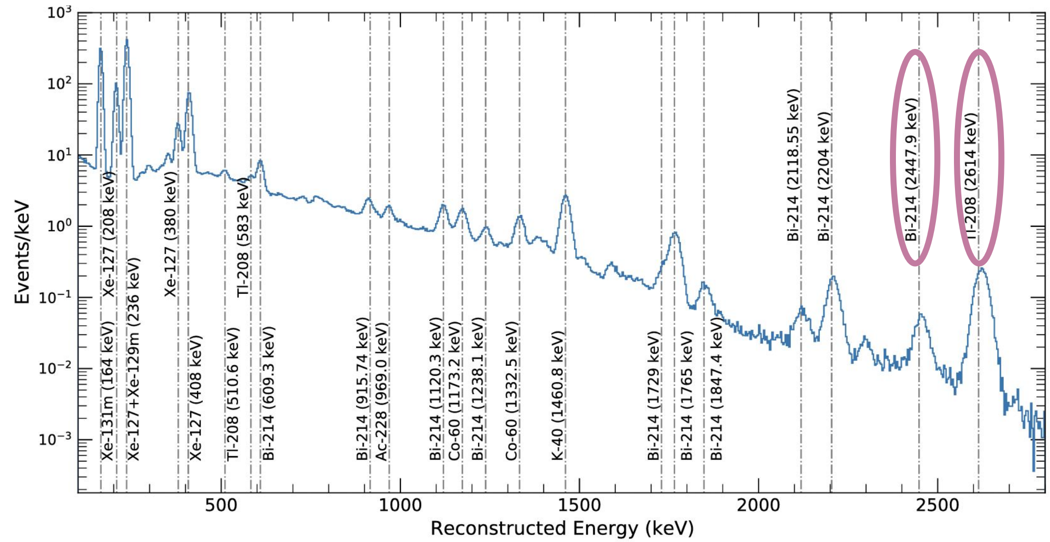
$0\nu\beta\beta$ Sensitivity driver: γ Backgrounds

Backgrounds of concern are high energy γ from detector materials near TPC (*)

- ^{208}Tl from ^{232}Th chain (2615 keV)
- ^{214}Bi γ from ^{238}U chain (2447 keV)

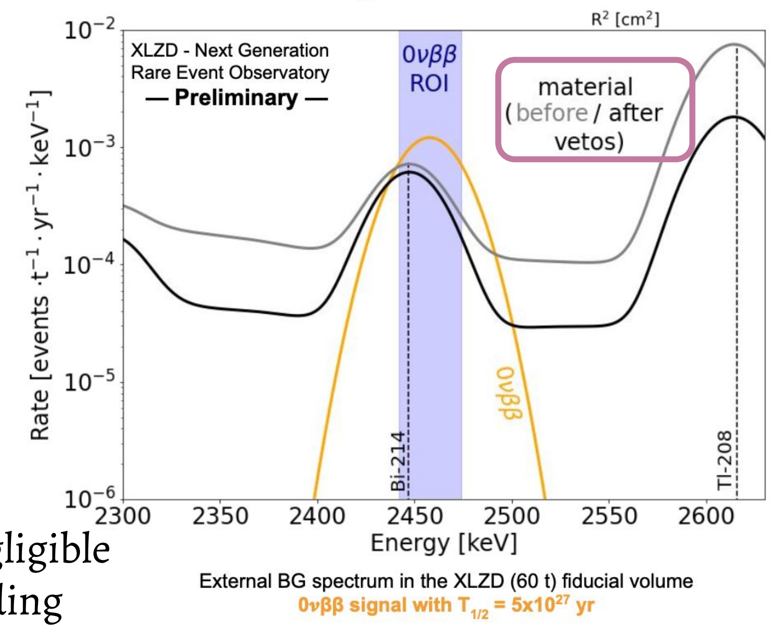
Stringent screening & radioactive control program during detector construction phase demonstrated by LZ (& XENONnT) **is crucial and is assumed in baseline scenario**

[LZ ER energy spectrum in 0.1-2.8 MeV range, JINST 18 (2023) C04007]



Vetoing

Instrumented **xenon skin** + OD volumes (as in LZ) enable to tag & reject coincident gammas or Compton scatters from ^{208}Tl mainly (2615 keV) leading to >80% reduction overall (70% reduction skin alone) for ^{208}Tl



(*) cavern **γ** is assumed negligible due to ~12m of water shielding

$0\nu\beta\beta$ Sensitivity driver: γ Backgrounds

Backgrounds of concern are high energy *γ* from detector materials near TPC (*)

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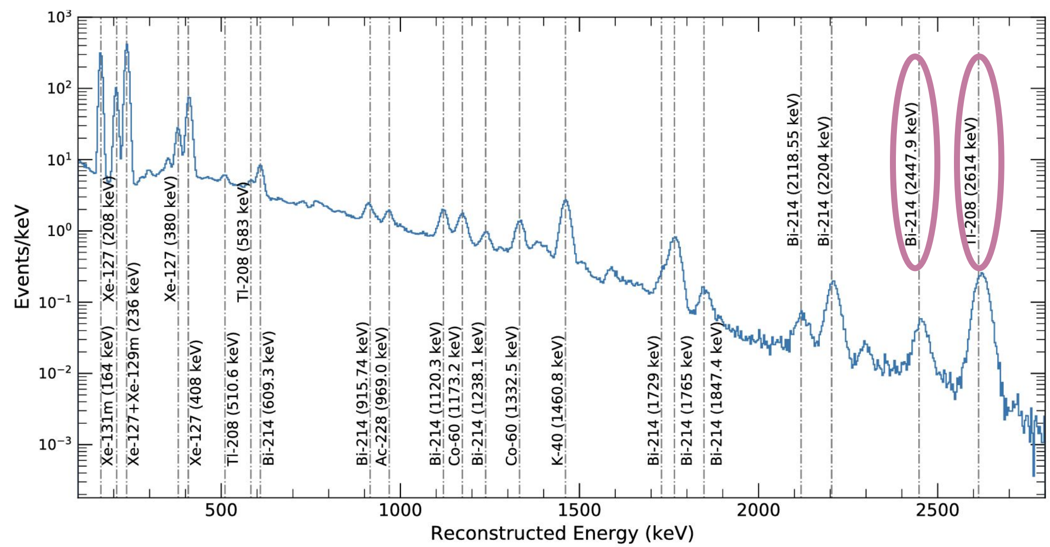

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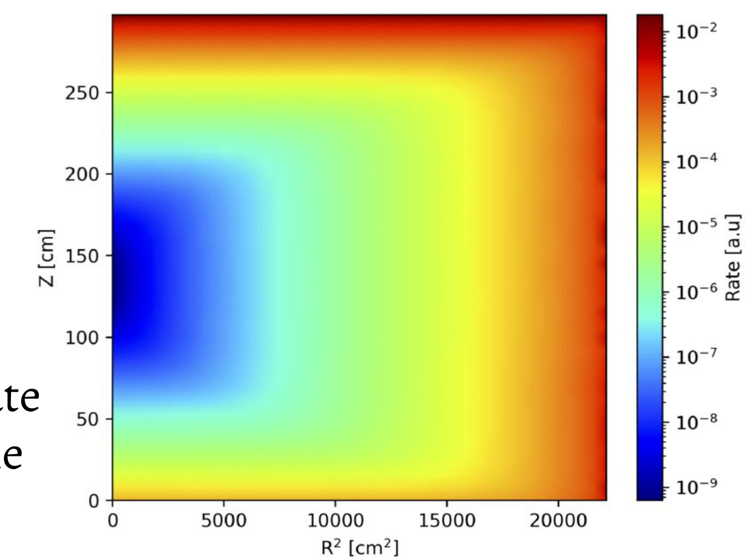
Fiducialization

- **^{214}Bi** becomes the **main bckg from detector material ⇒ficucialization**

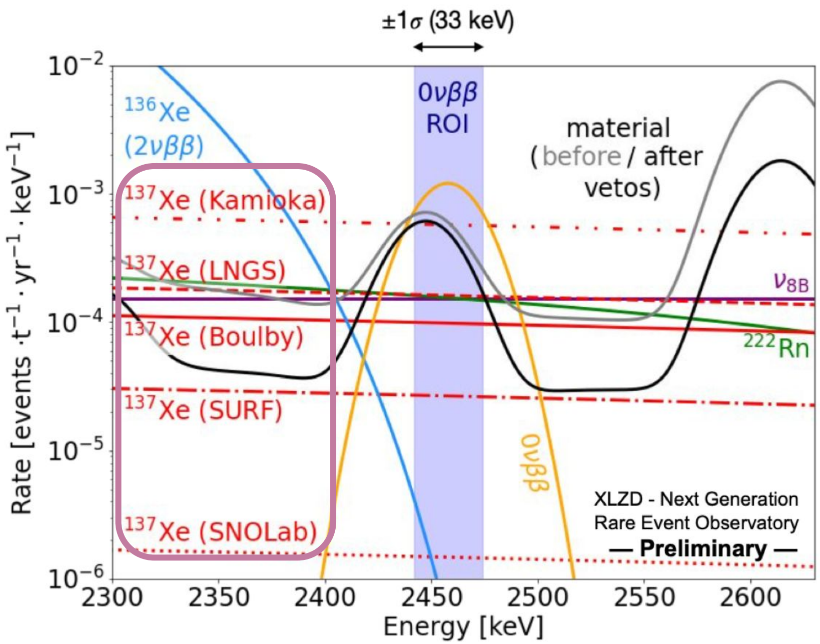
Example of ^{214}Bi ***γ*** SS bckg rate in the ROI for 60t active



Because of Xe self-shielding rate in the central region << rate at surface → use to optimize the 0νbb FV & sensitivity

$0\nu\beta\beta$ Sensitivity driver: Cosmogenic Activation

- Main concern: ^{137}Xe (β-decay with Q=4173 keV, T1/2=3.82 min)
  - Produced by muon-induced neutrons capture on ^{136}Xe
- **Lab depth dependent (*)**
  - Estimates from 5 UG labs being evaluated as potential host
  - Different depths → different cosmogenic neutrons→ Impact on ^{137}Xe background
  - Assume **rate at LNGS** (baseline) and **rate at SURF** (optimistic)



Total bckg + signal (assumes $T_{1/2}$=5x10^{27} yr) spectra

Site	Depth [m]	Depth [m w.e.]	μ flux [/m²/d]	^{137}Xe rate [/t/yr]	SS ROI rate [ev/t/yr/keV]
SNOLAB	2070	5890	<0.3	0.007	1.29×10^{-6}
SURF	1490	4300	4.6	0.142	2.72×10^{-5}
Boulby	1300	3330	14.6	0.404	7.73×10^{-5}
LNGS	1400	3800	29.7	0.822	1.57×10^{-4}
Kamioka	1000	2700	128	3.54	6.78×10^{-4}

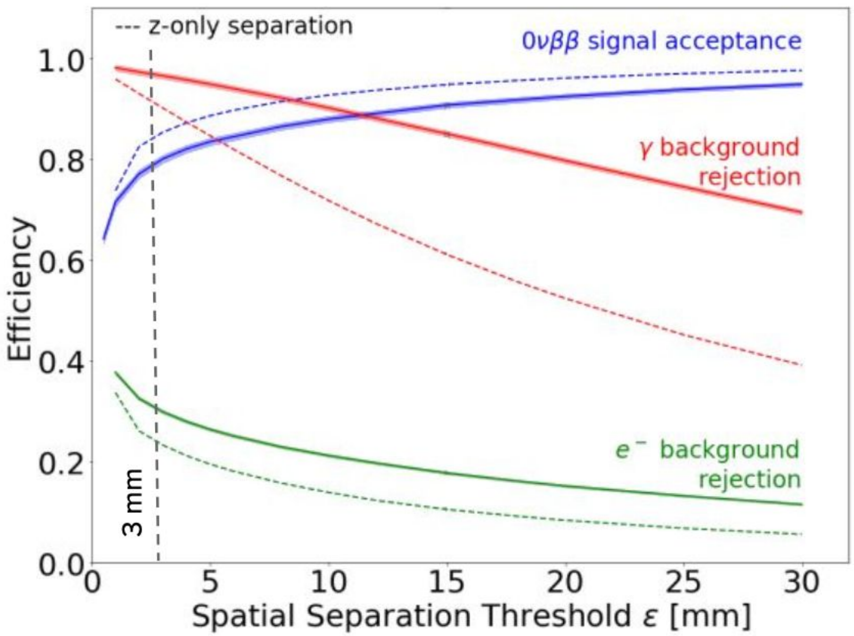
(*) Assuming radiogenic neutron activation is negligible via the use of local neutron shielding and xenon buffer volumes for ^{137}Xe to decay before the TPC

Further bckg reduction: MS vs SS discrimination

MS vs SS discrimination

- 0νbb will appear as single scatter
- MS vs SS discrimination enable to reduce γ and single electron (producing bremsstrahlung) backgrounds
- XZLD uses **3 mm** (baseline) or **2 mm** (progressive) for the vertical separation threshold, realistic.

XLZD science case [arxiv 2203.02309]

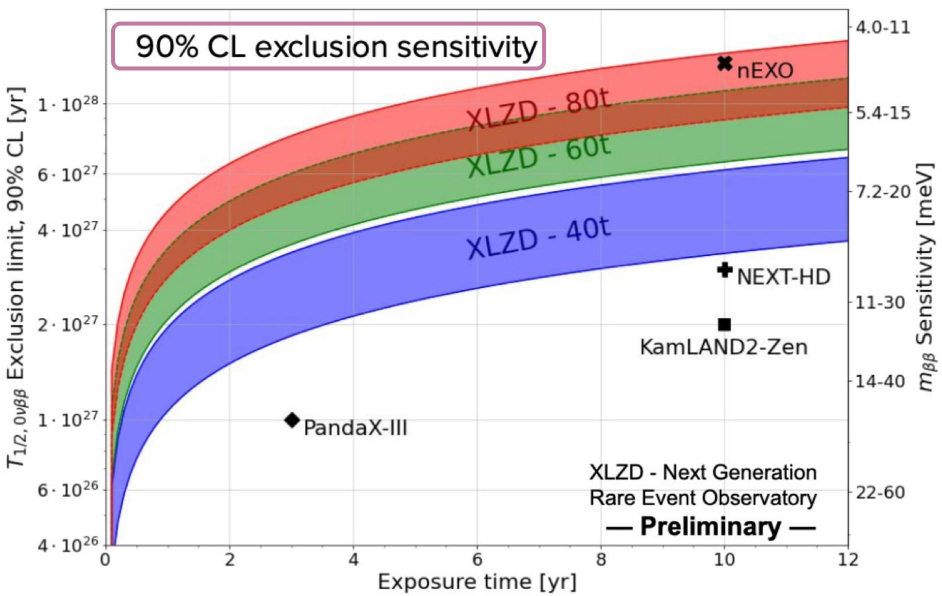


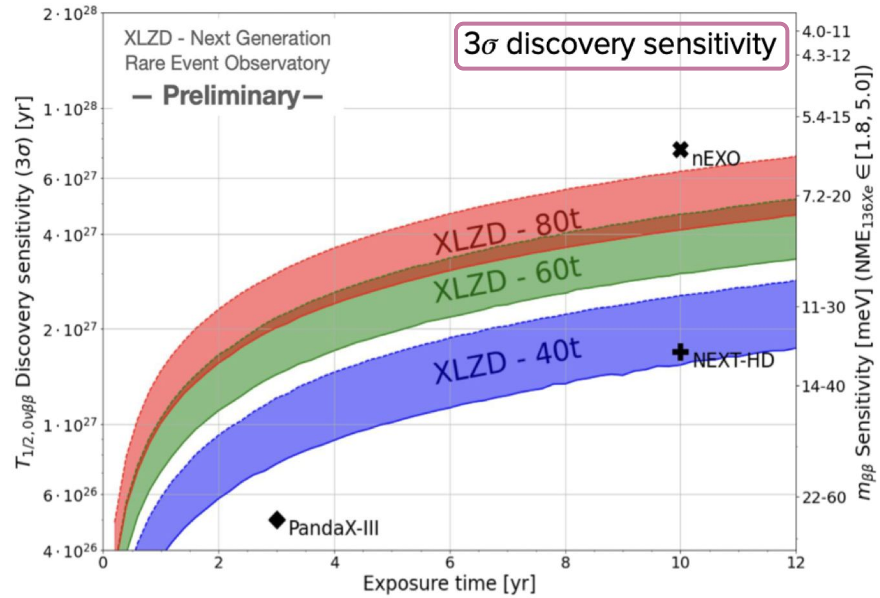
Efficiency of $0\nu\beta\beta$ signal acceptance and background rejection as a function of the minimum distance for individual reconstruction of energy depositions

ν Physics: projected $0\nu\beta\beta$ sensitivity using ^{136}Xe

Natural abundance of ^{136}Xe is 8.9% $\Rightarrow$
(no enrichment)

- 5.3 tonnes in 60 tonnes active (**baseline**)
  6 (7) tonnes FV $\Rightarrow$ 0.6 tonnes ^{136}Xe (progressive)
- 3.5 tonnes in 40 tonnes active (**risk mitigation**)
  9 (12) tonnes FV $\Rightarrow$ 1.1 tonnes ^{136}Xe (progressive)
- 7.1 tonnes in 80 tonnes active (**optimistic**)
  15 (18) tonnes FV $\Rightarrow$ 1.6 tonnes ^{136}Xe (progressive)





Lower (upper) bounds correspond to baseline (optimistic) scenario

ν Physics: Measuring Majorana neutrino mass

The effective majorana mass can be obtained by measuring the 0$\nu\beta\beta$ half-life

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\,|\mathcal{M}^{0\nu}|^2\,\frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

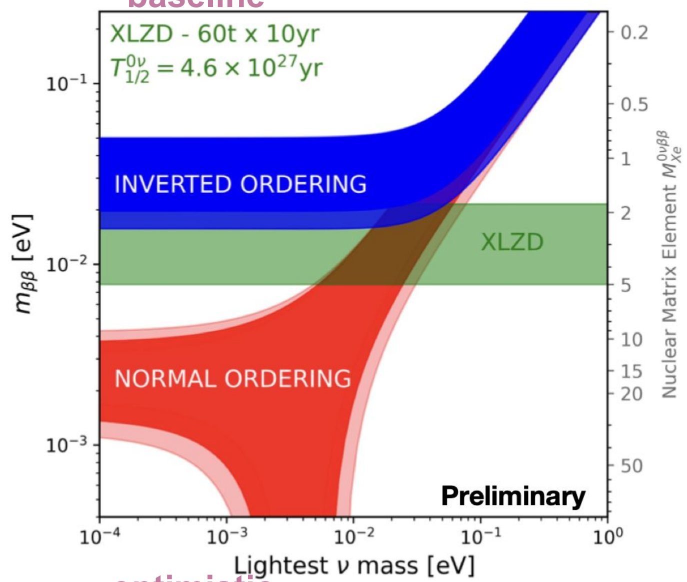
$G^{0\nu}$: Phase space factor

$|M^{0\nu}|^2$: nuclear matrix element

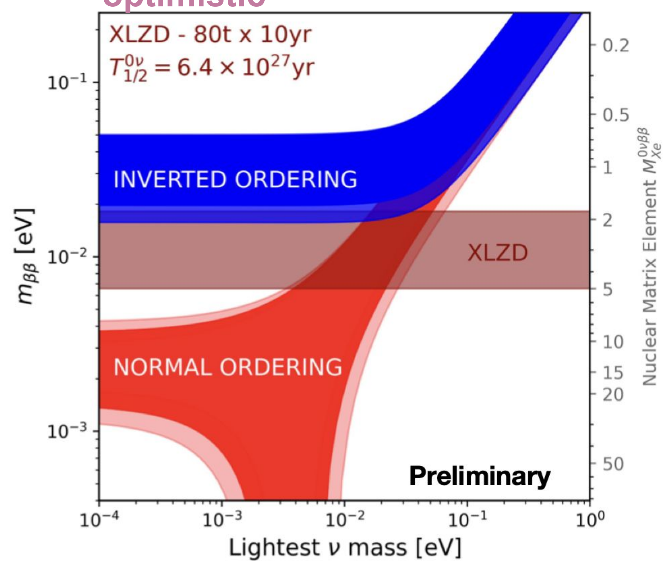
$|m_{\beta\beta}| = |\sum_i U_{ei}^2 m_i|$: effective Majorana mass

(*) subject to uncertainties in the nuclear matrix element

baseline



optimistic



Conclusion

- **Xe TPCs** are leading the high mass WIMP search **since 2007** - and **have consistently delivered on design sensitivity (e.g. LZ & XENONnT)**

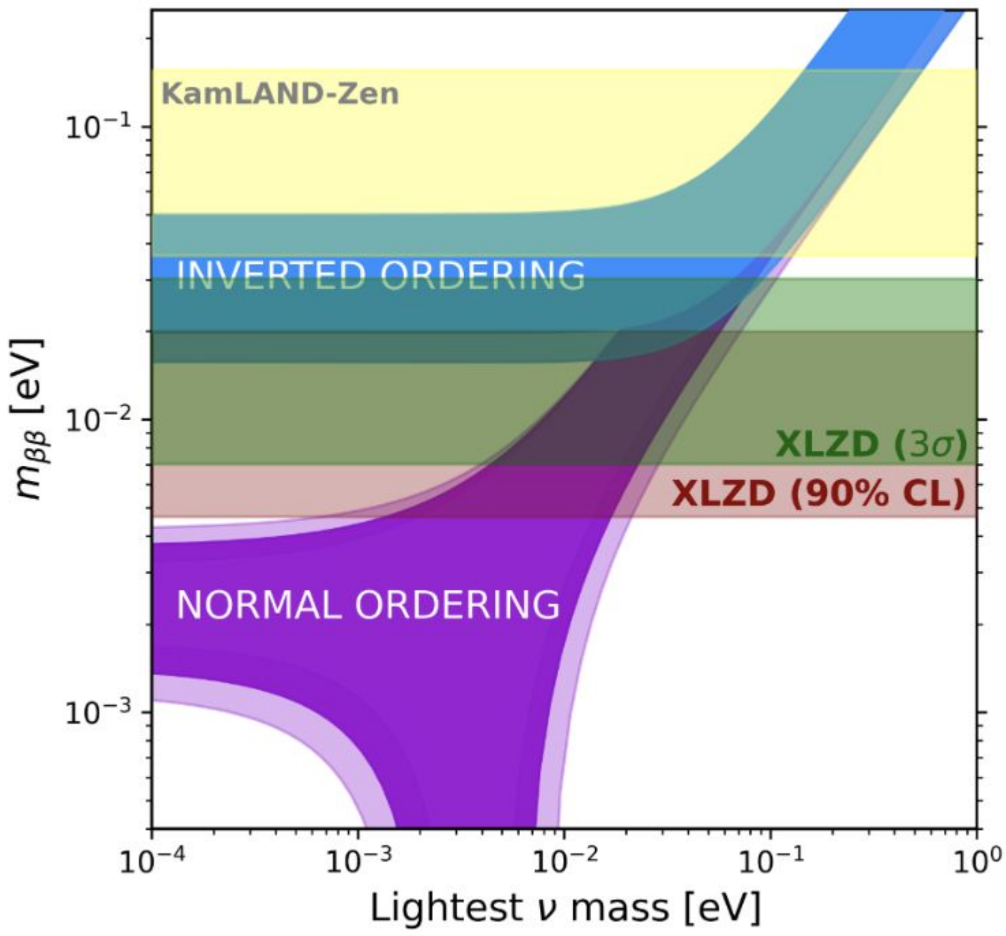
- LZ, XENONnT & DARWIN have **joined forces** to build the next generation (G3) of Xe-TPC dark matter detector: **massive** & ultra **low background** detector with a **broad science program in dark matter and neutrino physics**.

- XLZD will be the **ultimate WIMP detector** to probe WIMP dark matter parameter space into the neutrino fog.

- **Without enrichment** in ^{136}Xe, XLZD can do **competitive/complementary** search with respect to dedicated $0\nu\beta\beta$ experiments. We welcome collaboration, advice, and engagement with $0\nu\beta\beta$ experts!

Backup

ν Physics: Measuring Majorana neutrino mass

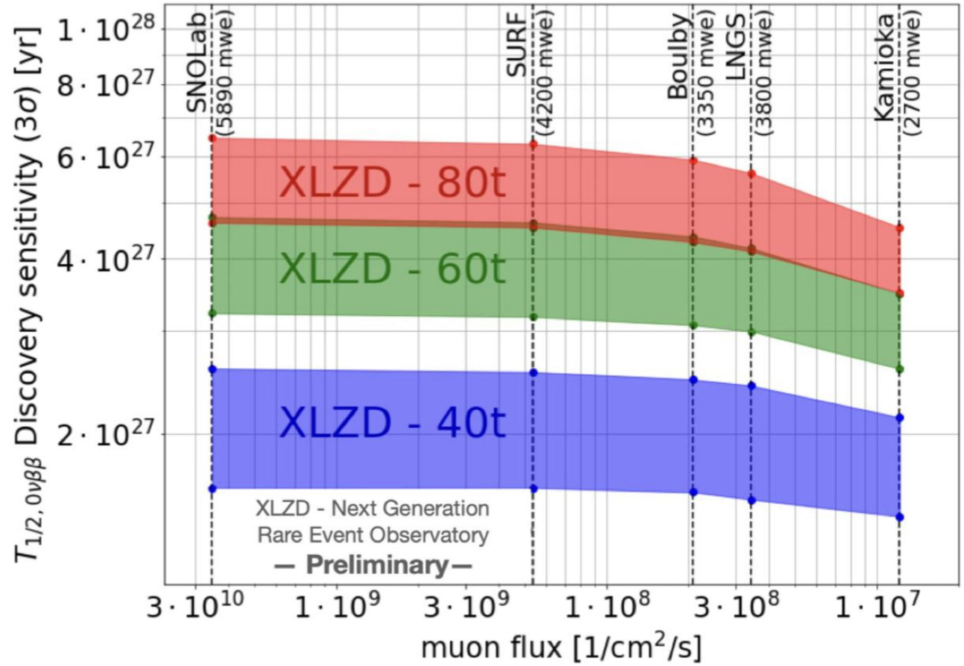


XLZD limit after 10 years of exposure at optimistic scenario (80 tonnes).
Current best limit from KamLAND-Zen is also shown

XLZD Laboratory location

Impact on laboratory depth on 0vbb sensitivity

Science considerations such as the impact of the laboratory backgrounds on science (e.g. *0νββ* sensitivity) is fed into the siting decision process. but final outcome depends on many other considerations above XLZD-ers



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

ν Physics: XLZD 0νββ sensitivity drivers

Parameter	Scenario Baseline	Progressive
^{222}Rn concentration [μBq/kg]	0.1	
BiPo tagging eff. [%]	99.95	99.99
External γ BG [% LZ]	30	10
Installation site	LNGS	SURF
Energy resolution [%]	0.65	0.60
SS/MS vert. sep. [mm]	3	2

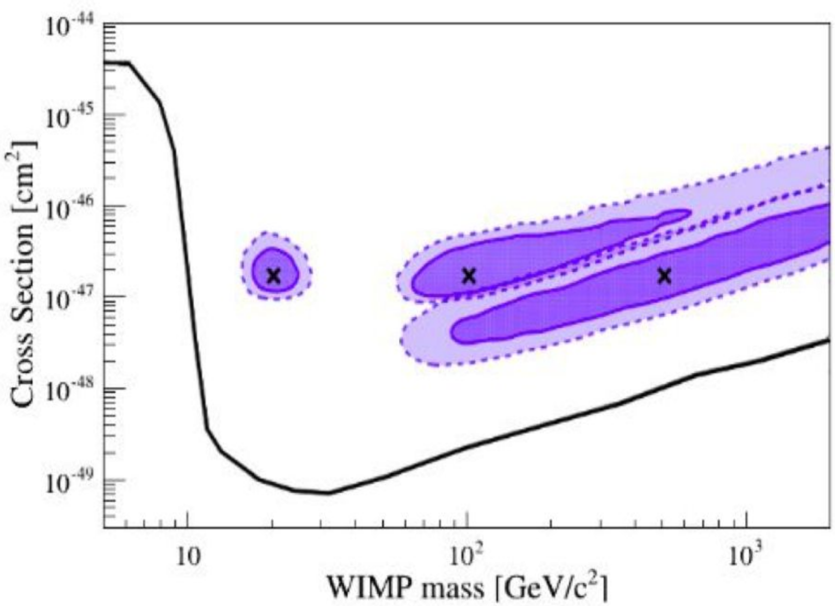
1.) instrumented target mass
2.) external background and 222-Rn contamination
3.) laboratory depth → muon flux
4.) energy resolution and SS/MS discrimination

stronger impact ↓ smaller impact

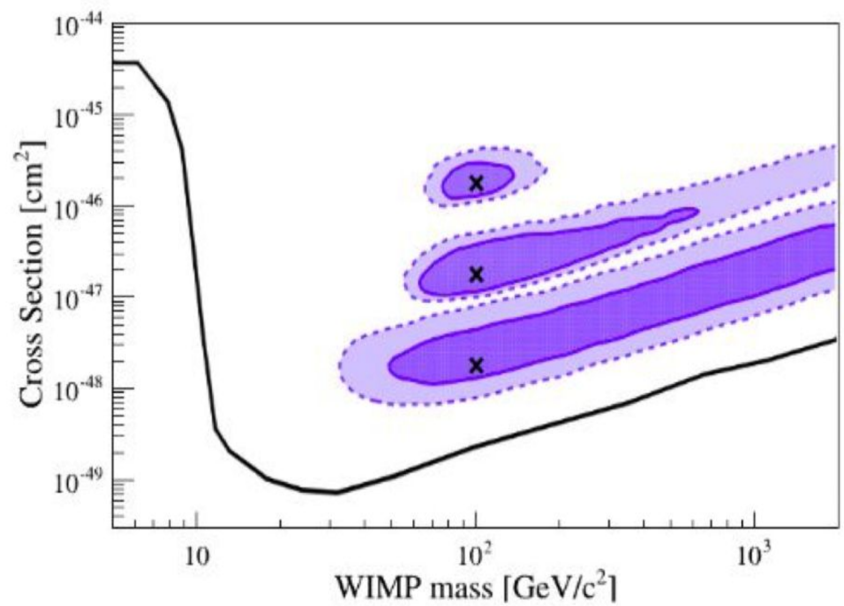
DM Physics: WIMP Spectroscopy

- Capability to reconstruct the WIMP mass & cross section (SI) for various masses below 500 GeV/c^2
  - Possibility to constraint WIMP astrophysical parameters
- Results shown for DARWIN, ~~G3Xe~~ XLZD will be better
- Width & length of contours demonstrate how well WIMP parameters can be reconstructed in DARWIN

Exposure: 200 ty
Reconstruction:
mχ =20, 100, 500 GeV/c^2
and σ = 2 x 10^{-47}cm^2



Exposure: 200 ty
Reconstruction:
mχ = 100 GeV/c^2
and σ = 2 x 10^{-47}, 2 x 10^{-47}, 2 x 10^{-47}cm^2



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A Kamaha, COSSURF 2019