



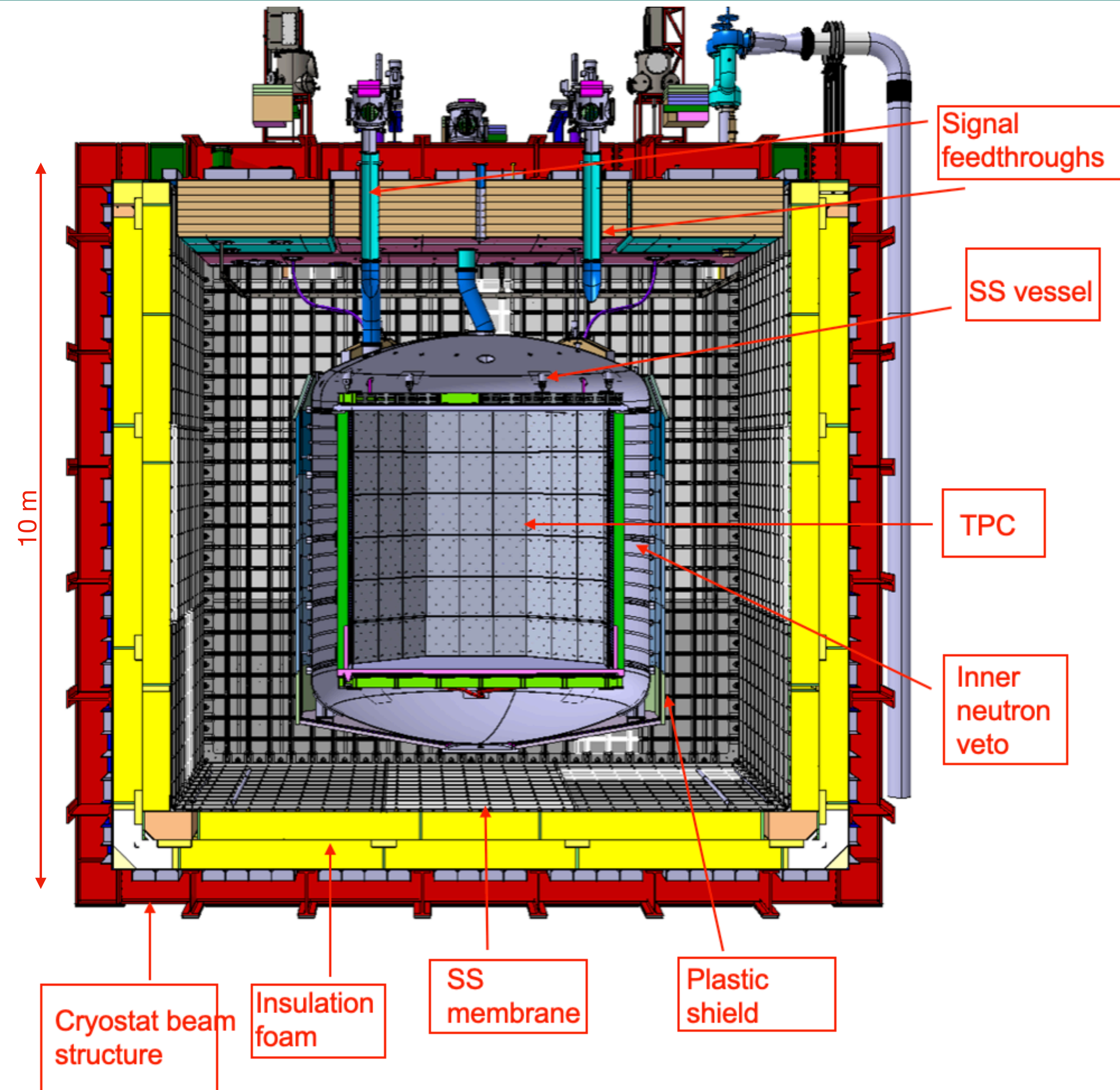
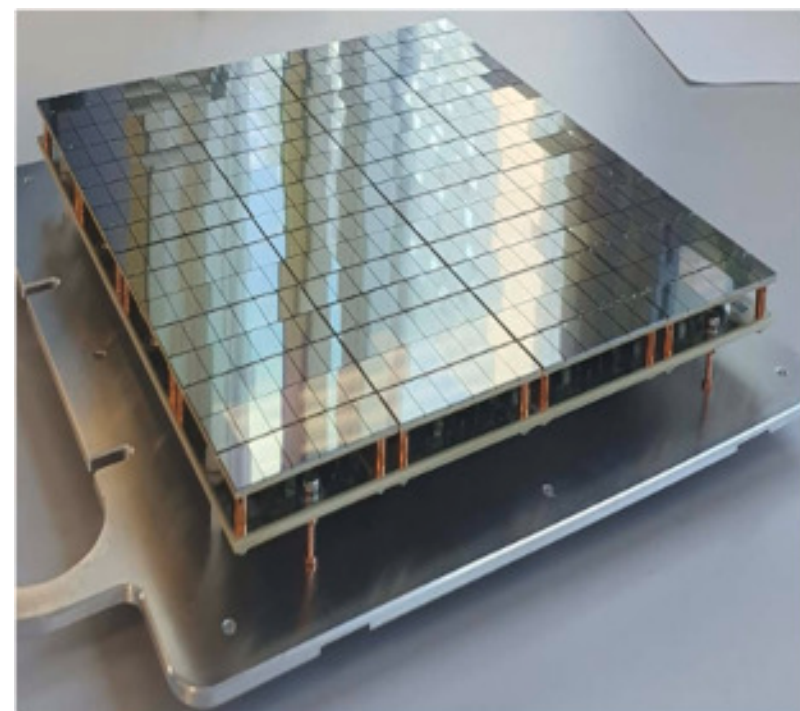
Status of DarkSide and prospects of $0\nu\beta\beta$ in large underground argon TPCs

P. Agnes, Gran Sasso Science Institute, L'Aquila (IT)
on behalf of the DS-20k Collaboration + Miguel Garcia
Peris, Benjamin Jones, Roxanne Guenette (UoM)

Second Workshop on Neutrinoless double beta decay
search in Xe - next-generation experiment

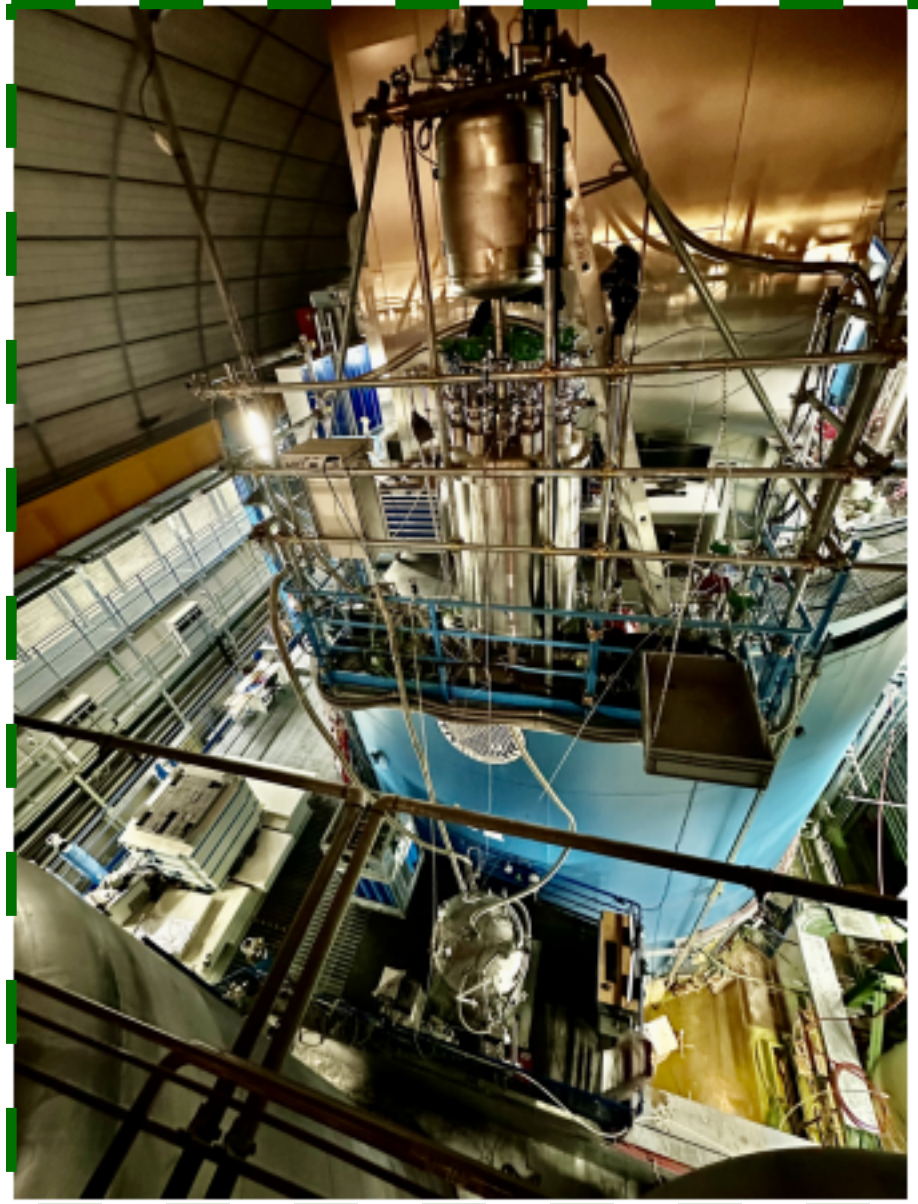
DarkSide-20k

- ❖ 3.5 m tall double-phase LAr TPC (51 t active) surrounded by 32 t Inner Veto. 3D vertex reconstruction with S1 (scintillation) and S2 (ionization)
- ❖ Builds upon 10^9 rejection of ER backgrounds (PSD).
- ❖ Hosted in a protoDUNE-like cryostat
- ❖ Needs 100 t of underground argon (UAr), extracted from underground in Colorado, US
- ❖ 25 m² of grouped arrays of custom-developed, low-noise, SiPMs
- ❖ TPB and PEN to shift scintillation light wavelength



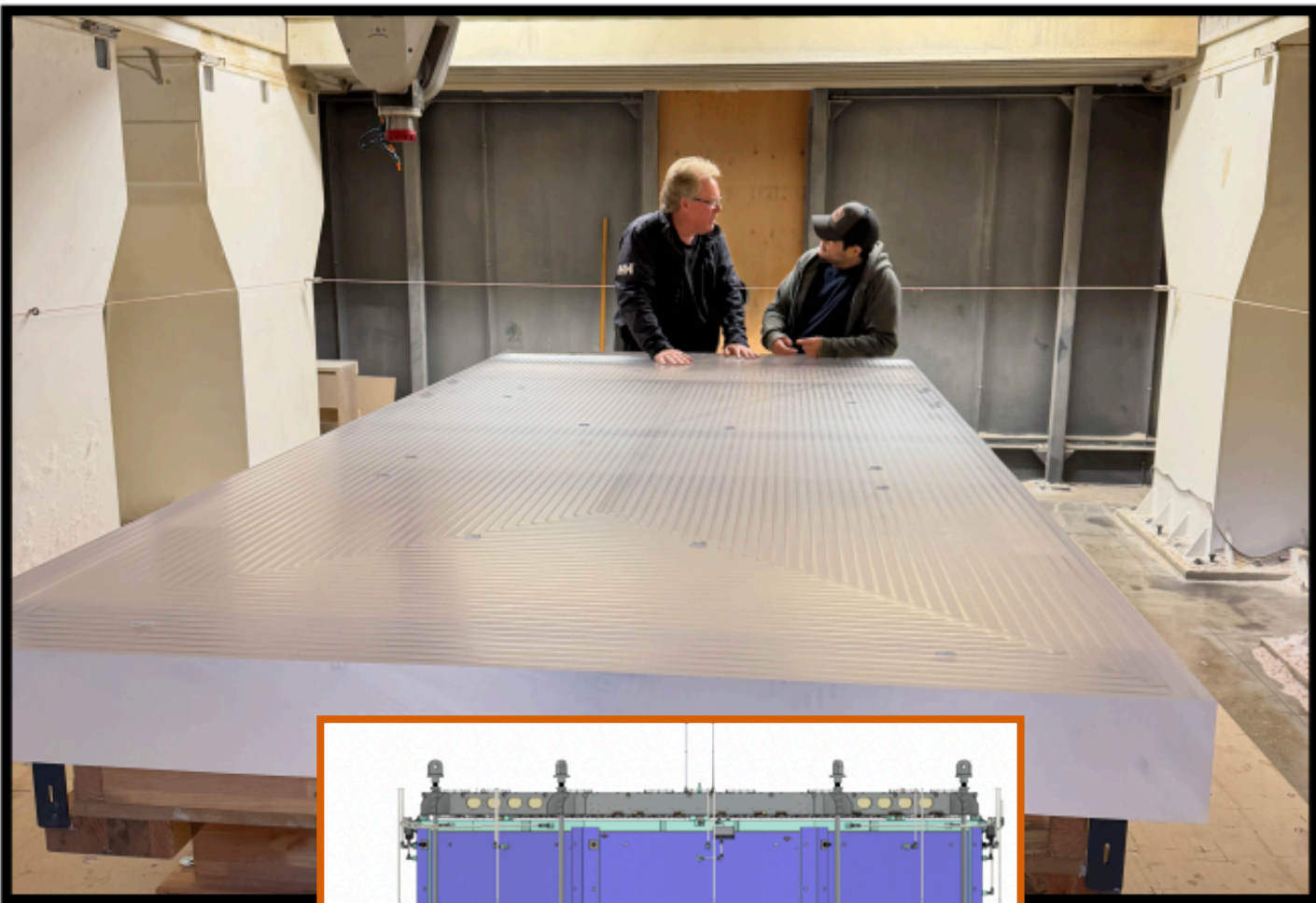
Construction underway at LNGS

Cryostat and cryogenics ready in Hall C at LNGS

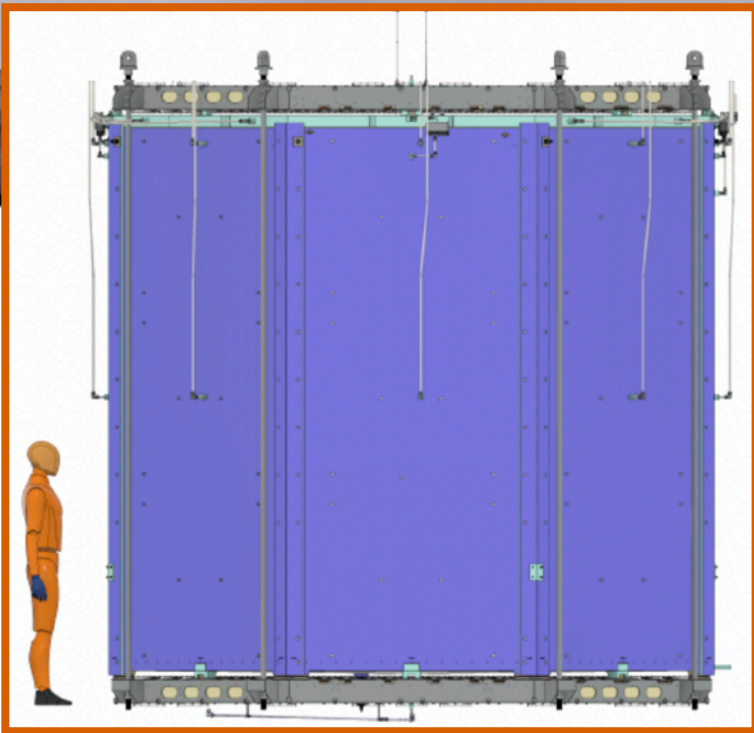
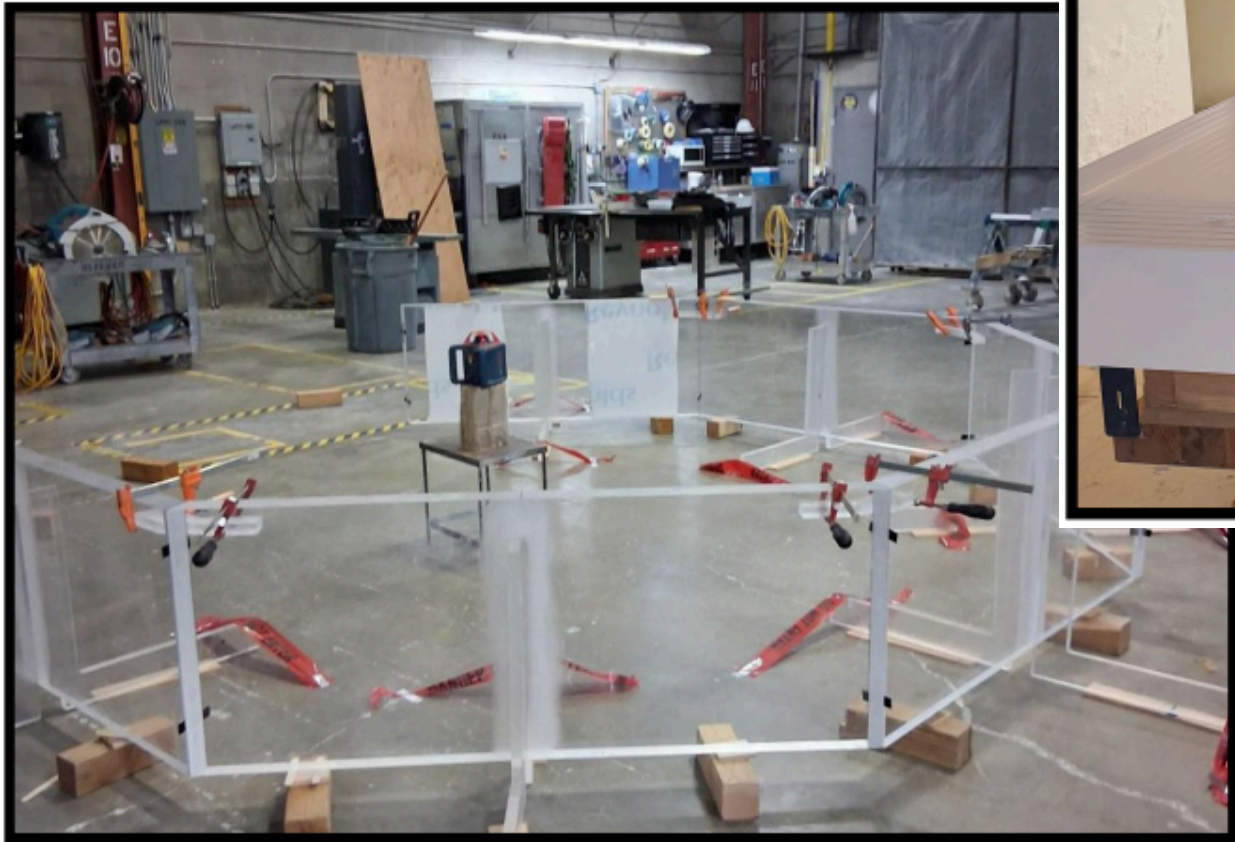


Main TPC barrel parts being assembled at U.of Alberta

DS-20k Barrel Panel Machining



To-Be-Bonded DS-20k Cathode

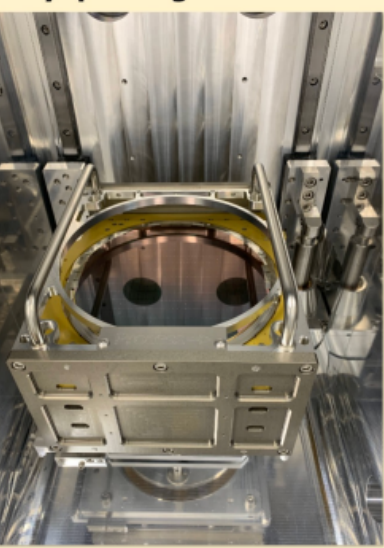


SiPM module assembly and testing exceeded 50%

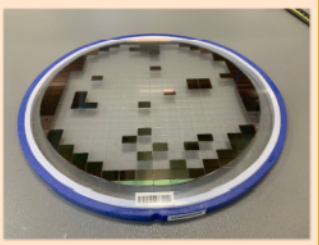
SiPM wafers from LFoundry



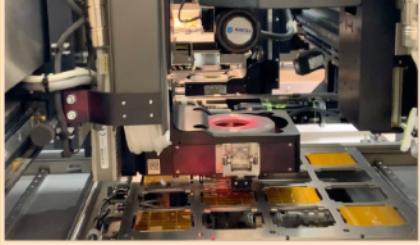
Cryoprobng Wafer Test



Dicing



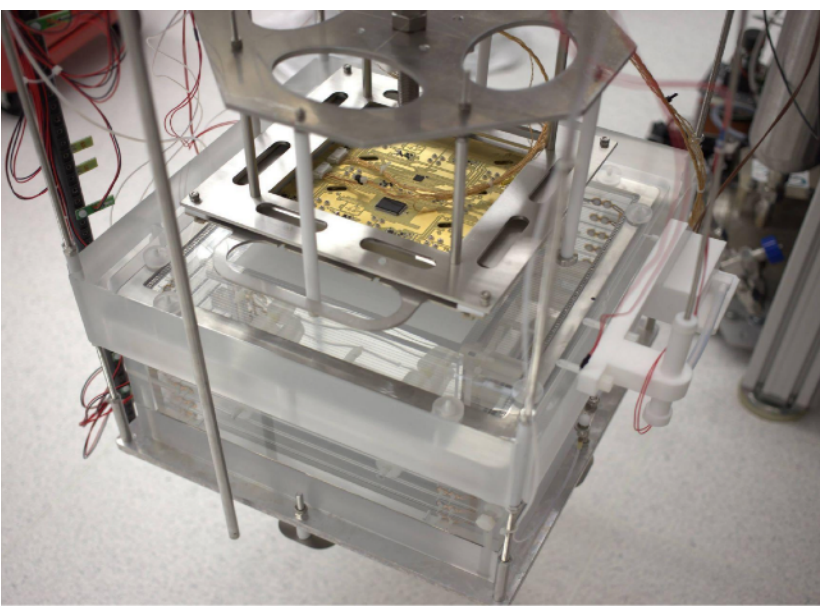
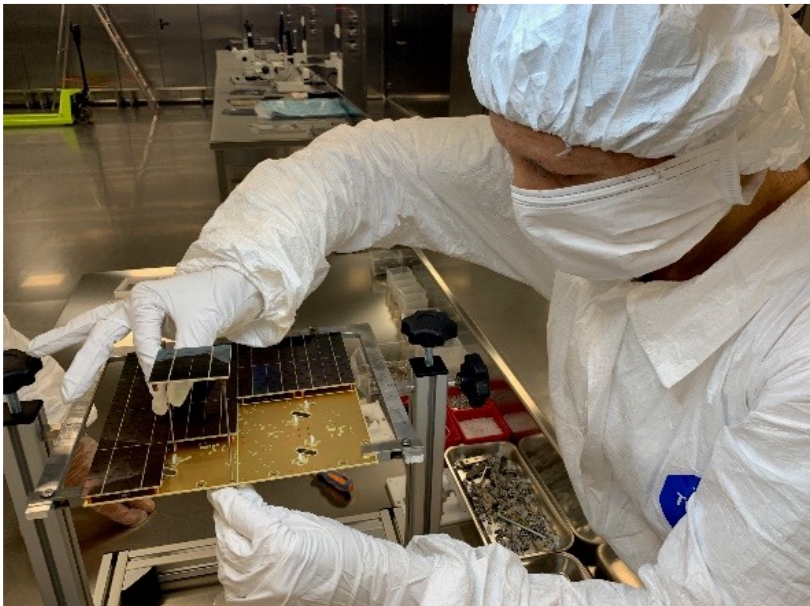
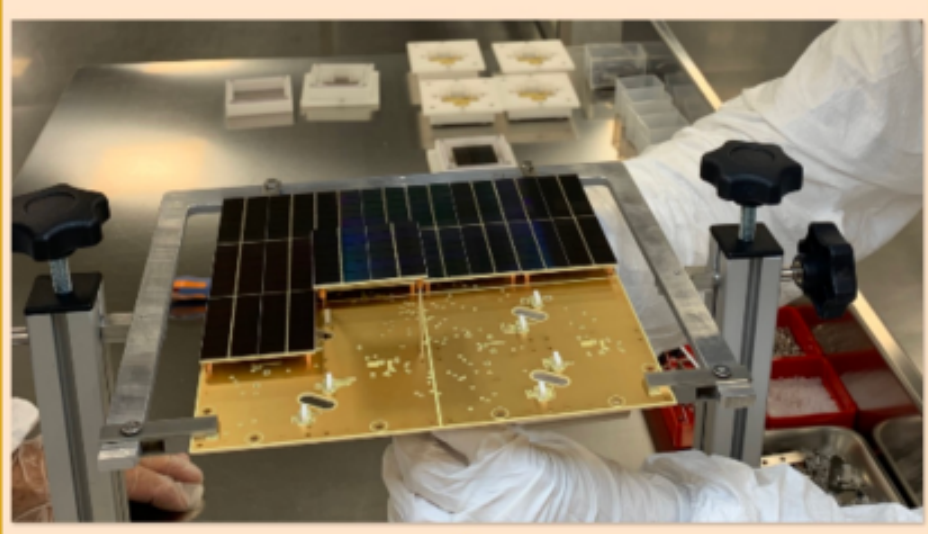
Flip-chip bonding



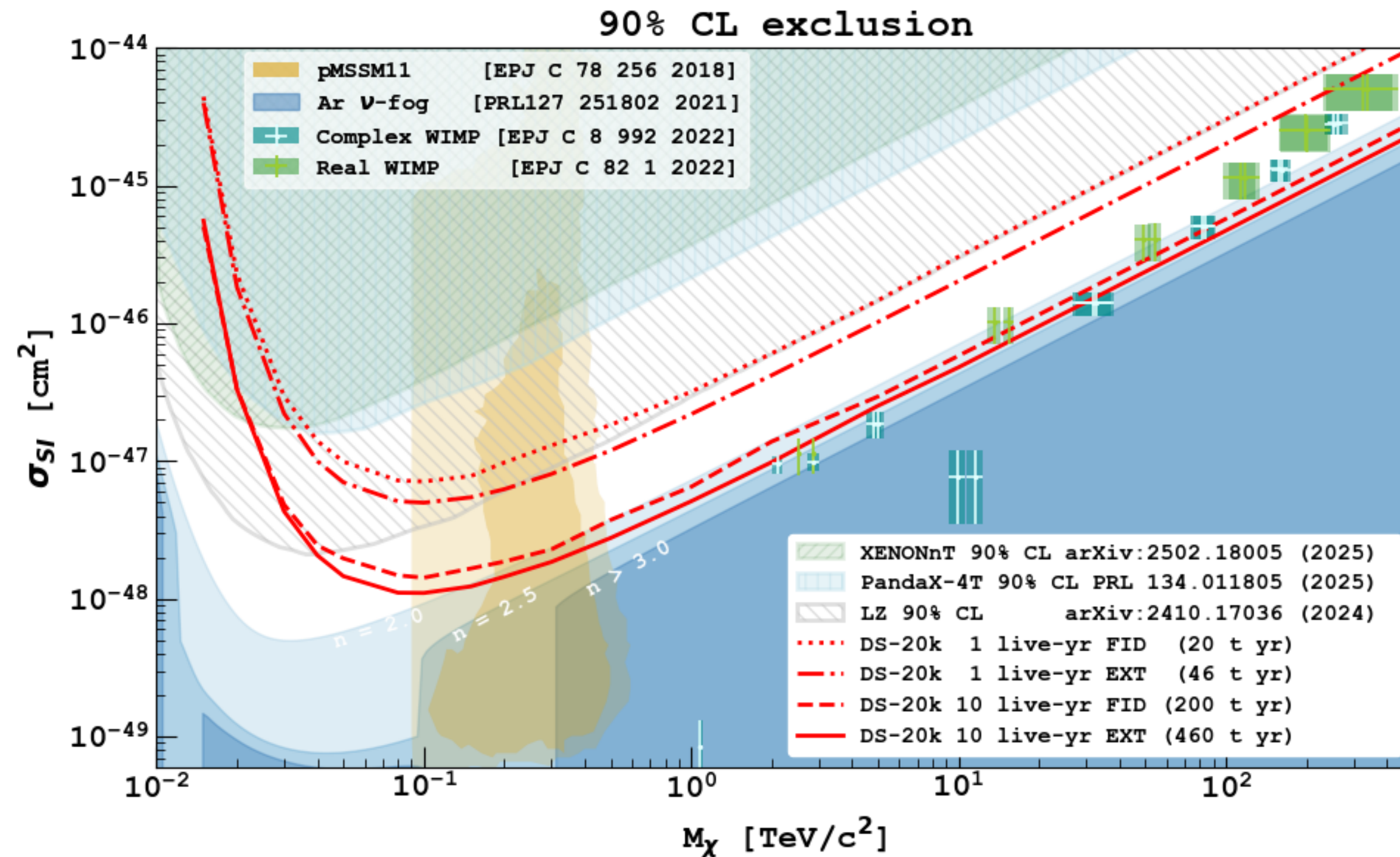
QR-code engraving



TPC PDU Assembly

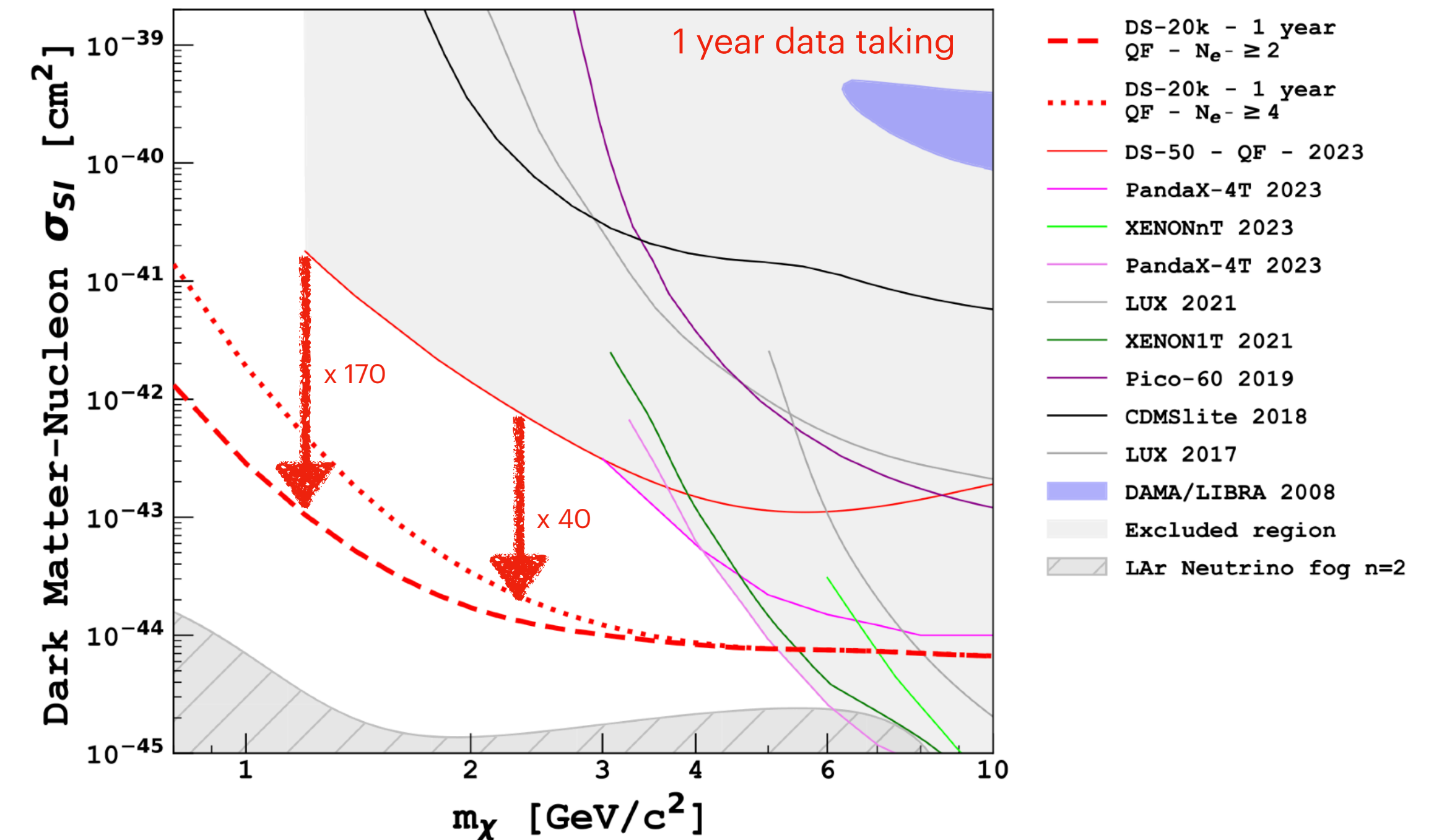


Primary physics goals



High-mass WIMP search, projecting exclusion
at $1 \times 10^{-48} \text{ cm}^2$ at $100 \text{ GeV}/c^2$

Data taking starting in 2029, 10+ yrs projected



Improving current constraints for
GeV-scale WIMPs by 100x

None of this is the topic of this talk

Topic of this talk

DarkSide + collaborators from colleagues from University of Manchester invited to explore the idea of loading LXe (^{136}Xe) in **DarkSide-20k**, to enable sensitivity to $0\nu\beta\beta$

1) potential limitations of current experiment design

2) detector resolution and backgrounds, to estimate potential sensitivity with current layout

CAVEATS

- most of the open questions on feasibility can not be answered without some dedicated R&D
- in any case meant to be a future perspective, priority is for WIMP search with pure UAr (starting 2029)

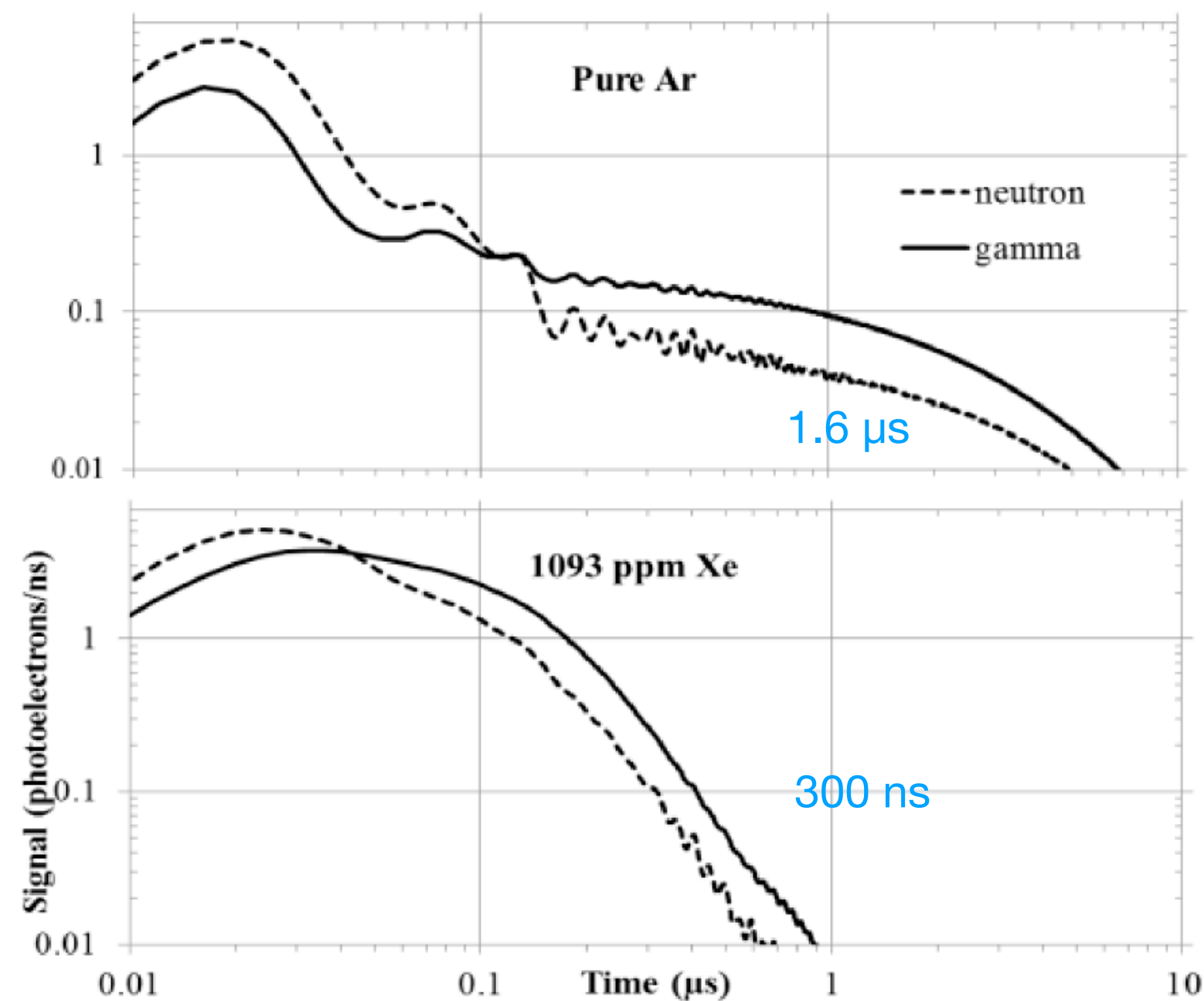
Xe-loaded liquid argon

Widespread interested in the community (DarkSide [ref], DUNE [ref], DRD2 [ref], various R&D[ref, ref, ref, ref])

Doping implies energy transfer

from Ar_2^* (128 nm) to Ar^*Xe^* (150) and Xe_2^* (175 nm)

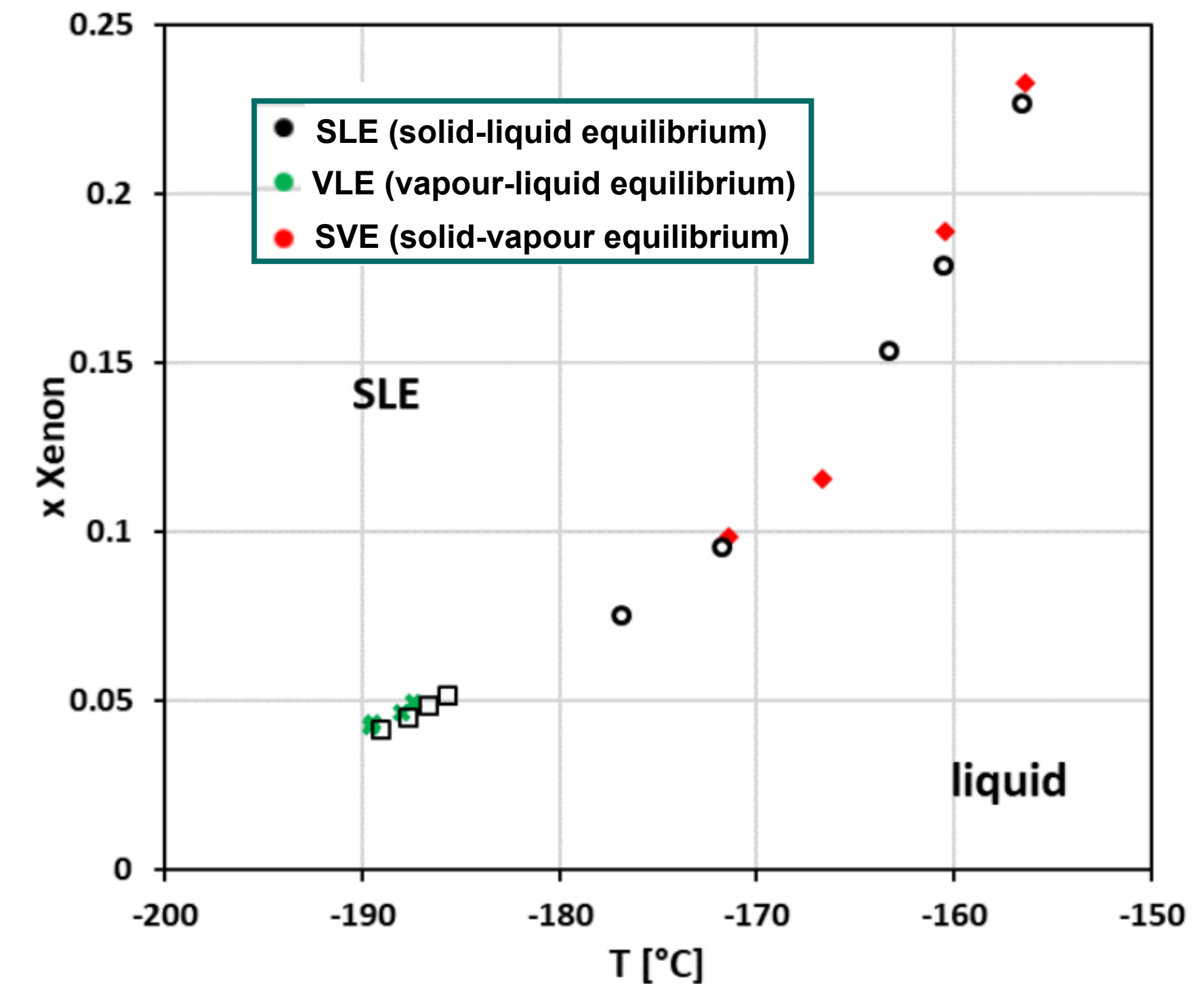
- efficient shift of scintillation wavelength from 10 ppm
- ~20% increase in scintillation light yield from 10 to $\sim 10^3$ ppm
- ~10% ionization charge at $> 10^3$ ppm
- overall faster scintillation pulse, at the **cost** of **discrimination**



Wahl et al, 2014, up to 1000 ppm mass fr. [ref]

Thermodynamic limit is 4-5% molar fraction

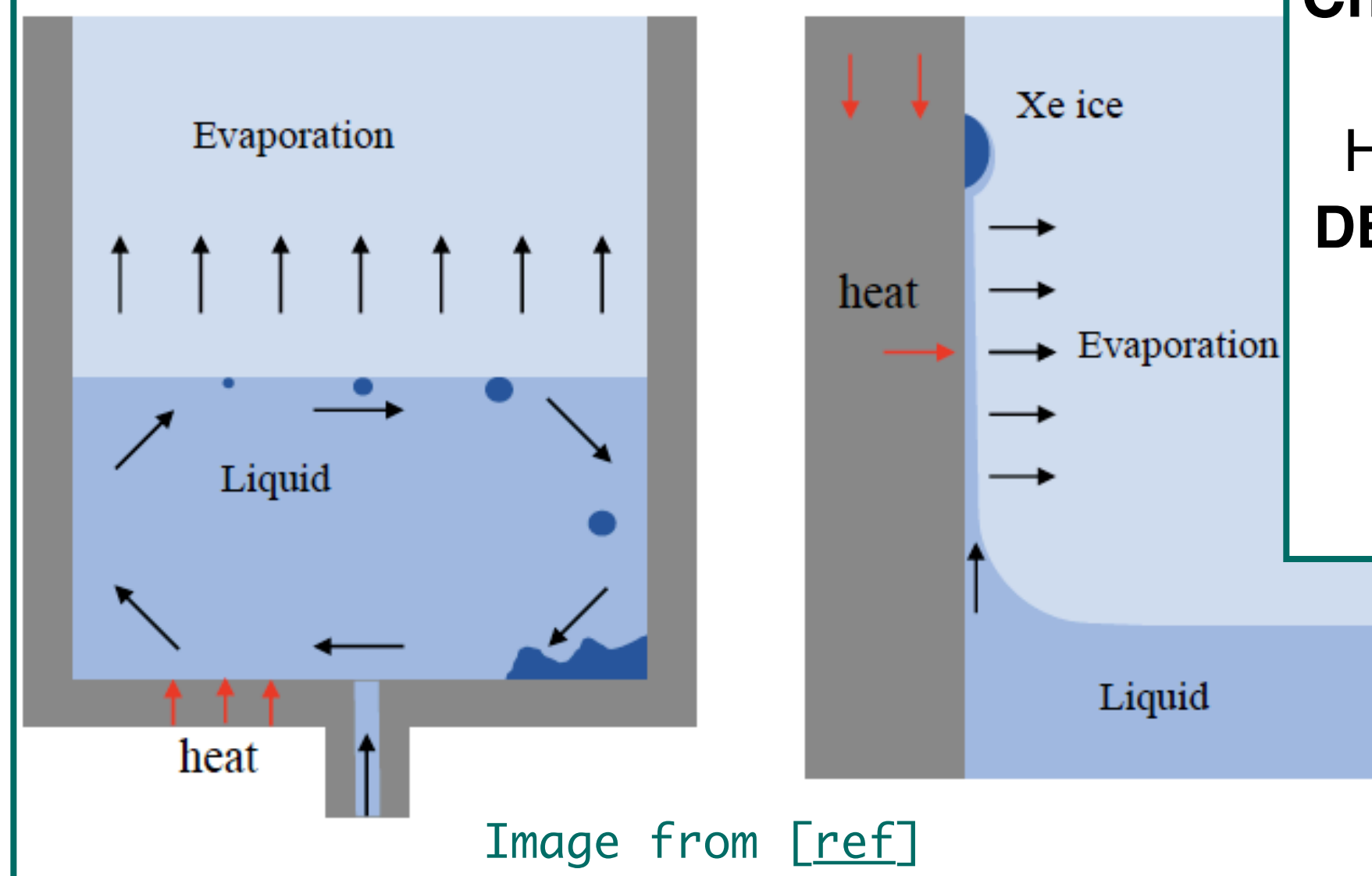
- Dedicated setup at *École des Mines* (X-Art)
- Dedicated setups (CHILLAX [ref]) operated continuously at 2%



X-Art [ref, ref]

Challenges for cryogenic system, loading and purification

Instabilities



Challenges outside the cryostat:

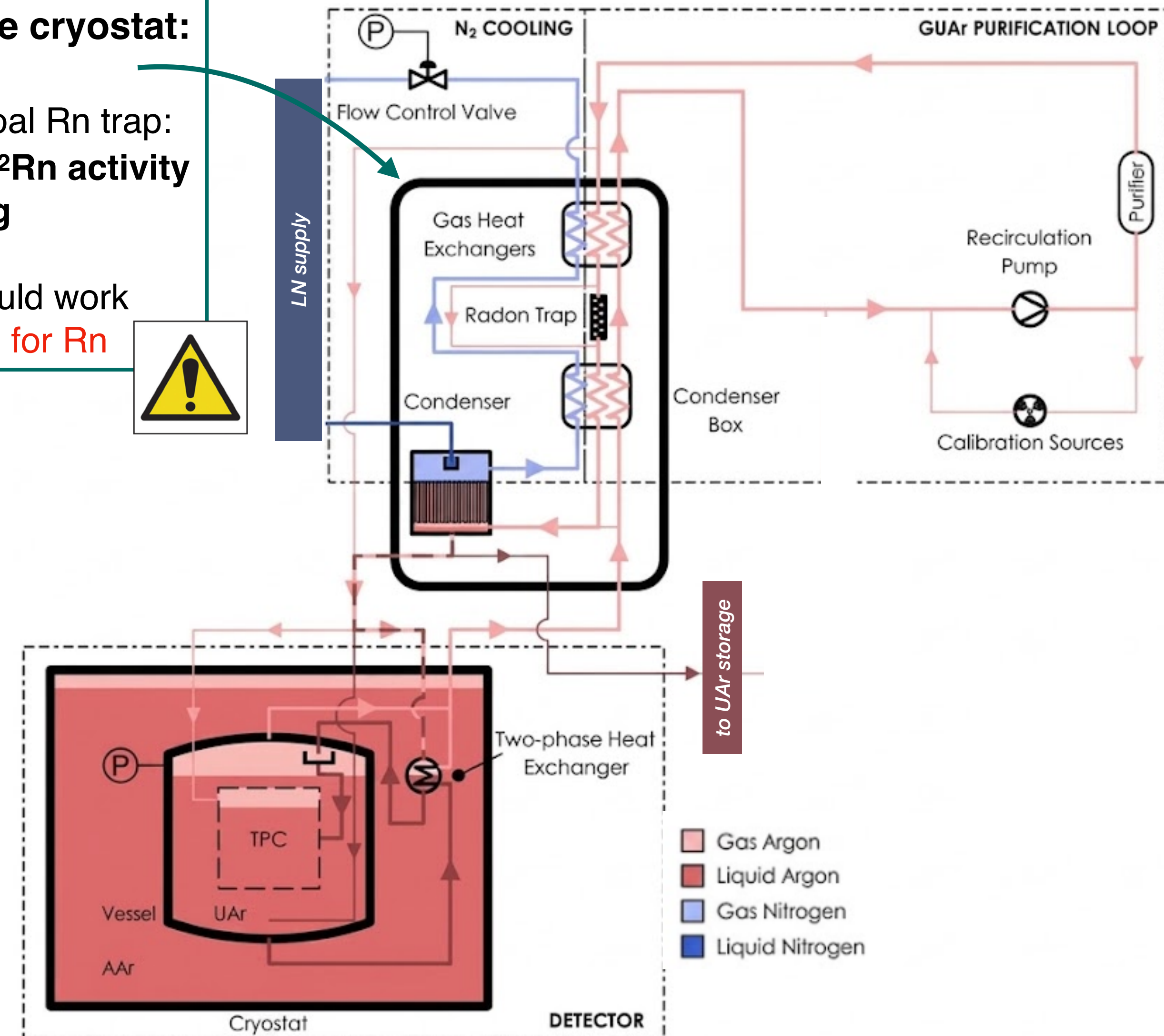
Hot-getter + cold charcoal Rn trap:
DEAP-3600 achieved ^{222}Rn activity of 0.2 uBq/kg

but charcoal trap would work effectively for Xe as for Rn



Challenges inside the cryostat:

operation in a AAr bath limits heat exchanges in the vicinity of the TPC, however: **risk of freezing at liquid/gas interfaces** (ullage, gas pocket, heat exchanger, photodetectors)



DarkSide-20k cryogenic system [ref]

Detector resolution

Full optics G4 **simulations** of pure-LAr TPC predict LY at **~10 PE/keV** at null field (20% higher than DS-50)

Tunable EL gain, baseline of 20 PE/e-

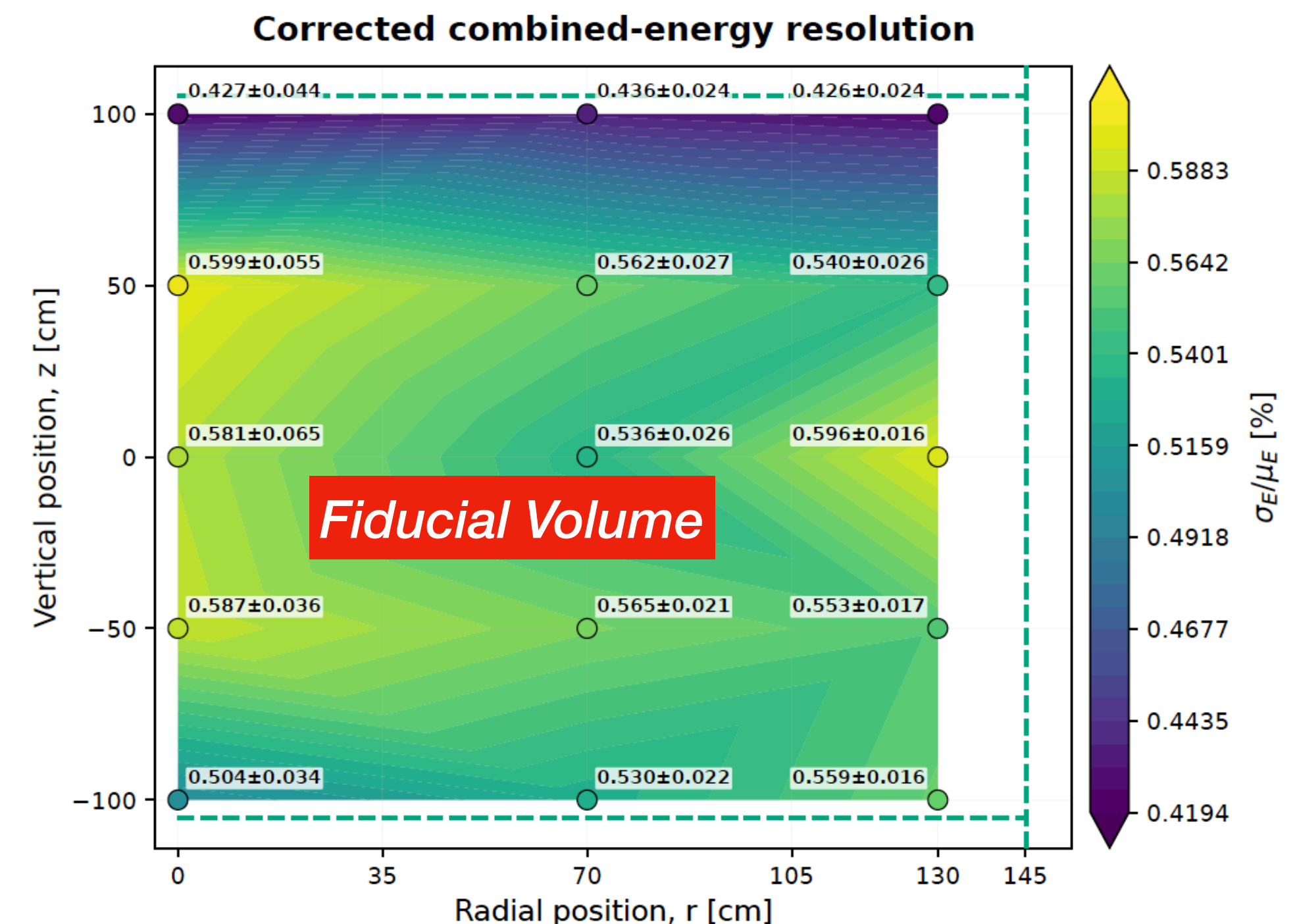
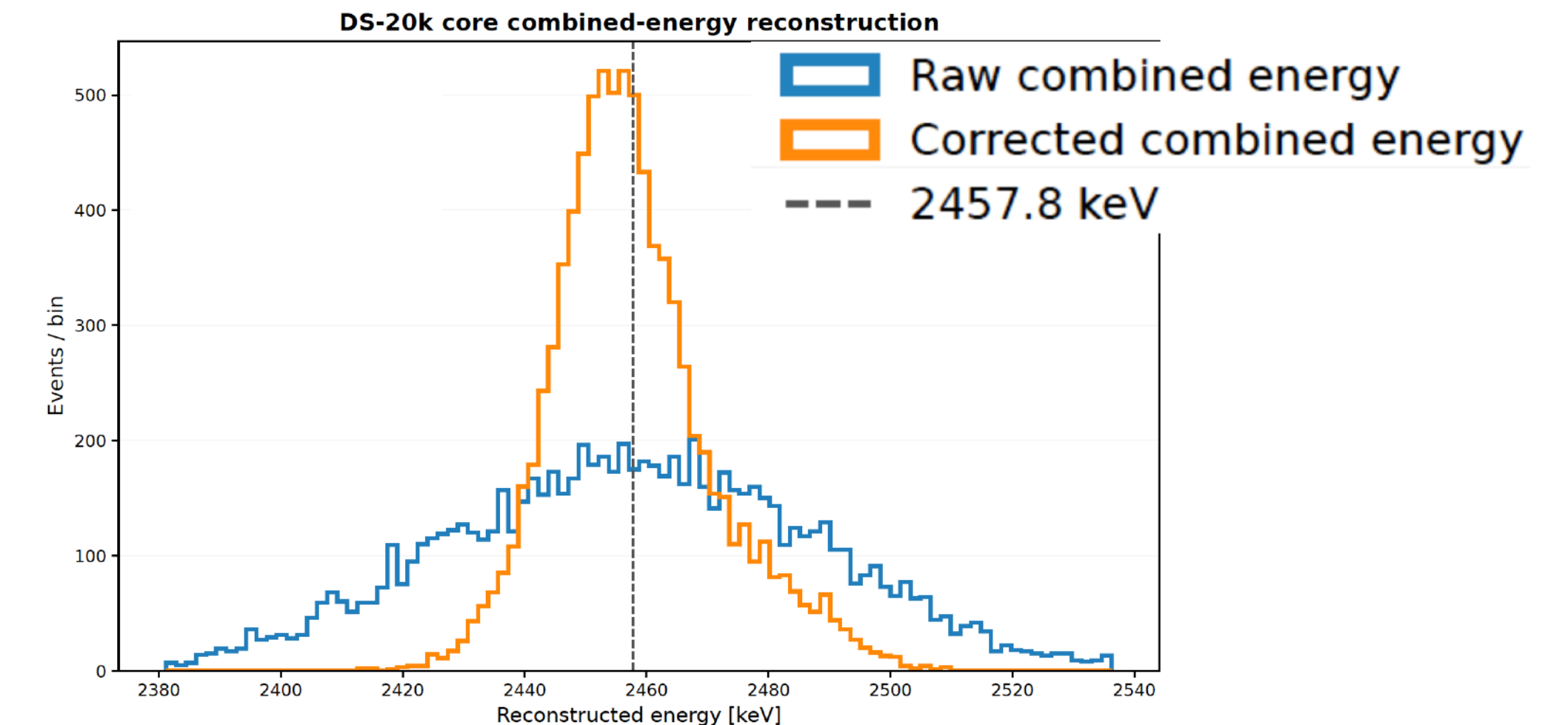
Working on implementation of updated time response profiles for S1 and S2. Test electronics/DAQ chains in simulation with collaborative tools

- linearity of S1 charge reconstruction up to 100's of PE per channel occupancy
- little impact of S2 saturation

Preliminary result (single 2.45 MeV electrons uniformly spread in the FV):

(S1-only, null field) $\sigma / \mu = \mathbf{1.2\%}$

(S1-S2 combined, E field) $\sigma / \mu = <1\%$



Assumptions so far and next slides

1) Assume **4% (molar) loading** of LXe in DarkSide-20k

=> **12 t of LXe** in the circulation loop (designed for 100 t of UAr)

2) In the following, refer to **highly enriched LXe**

==> 100% isotopic composition of ^{136}Xe

3) Assume **LAr response**

=> **1.2%** energy resolution at endpoint of $2\nu\beta\beta$ (100 keV ROI)

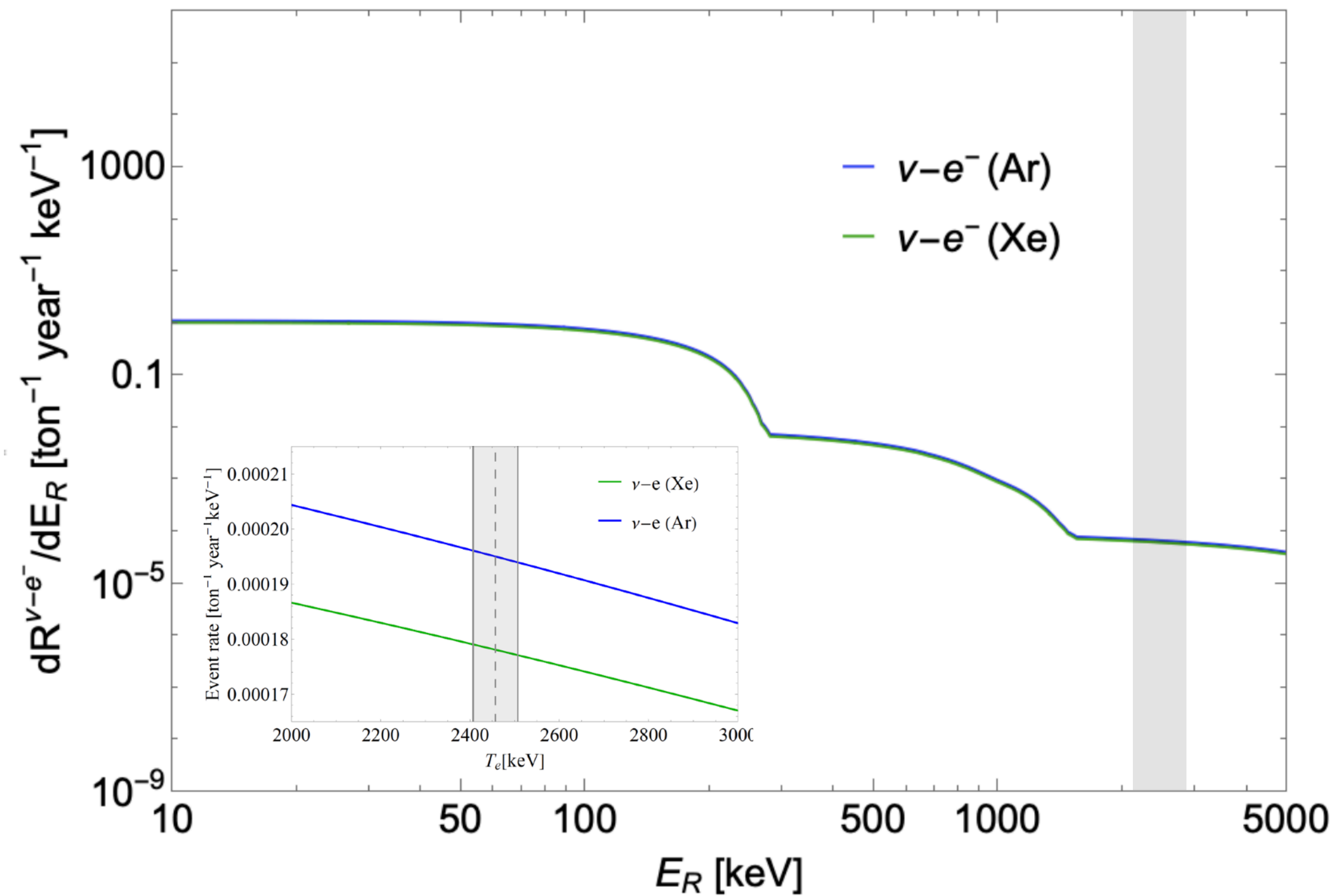
4) Backgrounds

- Solar neutrinos
- β and γ from detector materials, Rn chain and n captures
- Tail of $2\nu\beta\beta$
- Cosmogenics (^{137}Xe , ^{38}Cl , ^{39}Cl)

5) Sensitivity

Solar neutrinos, tail of the $2\nu\beta\beta$

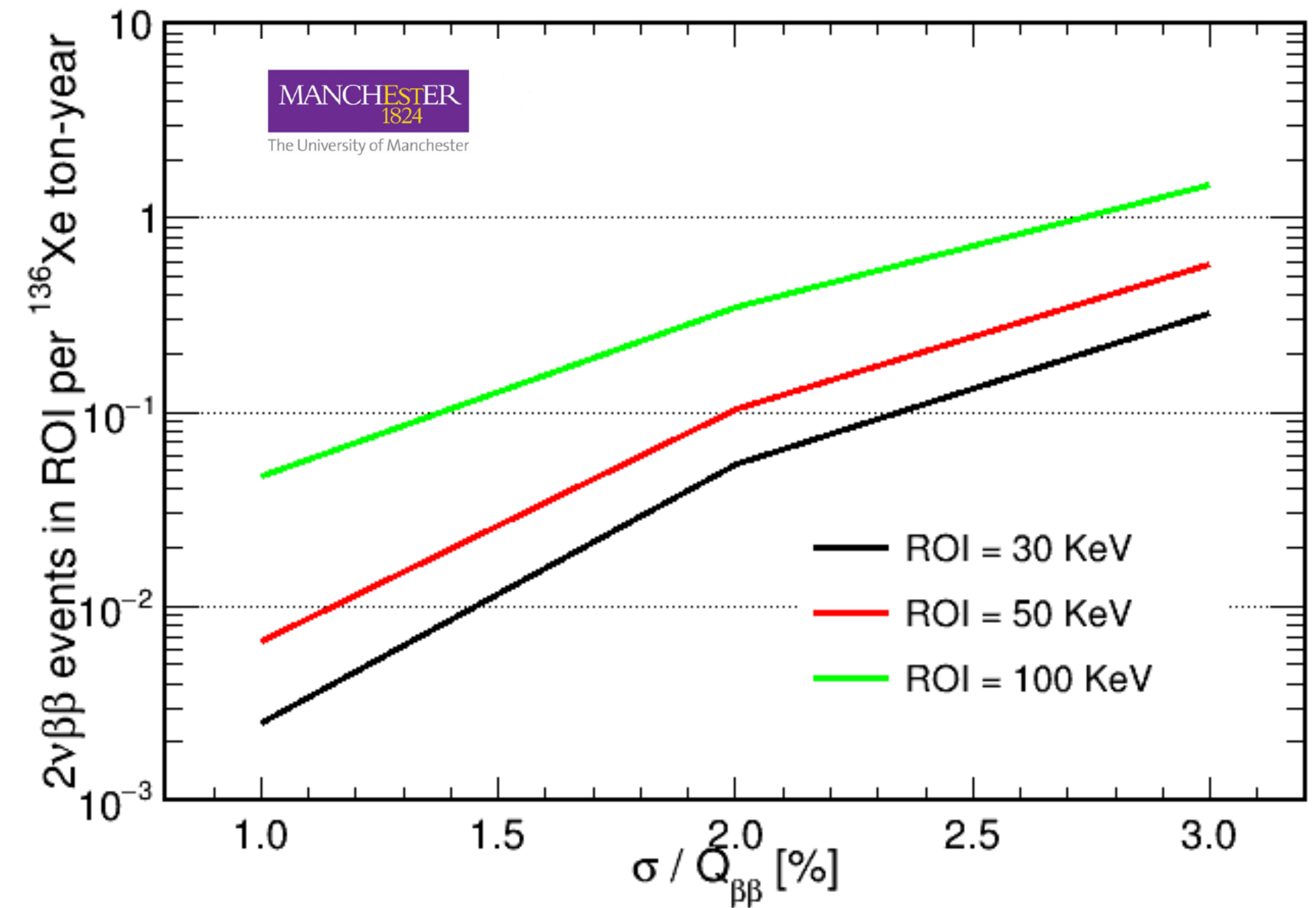
Solar neutrinos



$1.95 \times 10^{-4} /t_{\text{Ar}}/\text{yr}/\text{keV}$ in LAr
 $1.78 \times 10^{-4} /t_{\text{Xe}}/\text{yr}/\text{keV}$ in LXe

Leakage of the $2\nu\beta\beta$ tail

Based on implementation of full decay generator



$< 7 \times 10^{-2} /t_{\text{Xe}}/\text{yr}$ in LXe
 $< 9 \times 10^{-3} t_{\text{mix}}/\text{yr}$ in mixture at 4% loading

Internal sources

— ^{39}Ar , ^{85}Kr , ^{42}Ar (^{42}K) not an issue

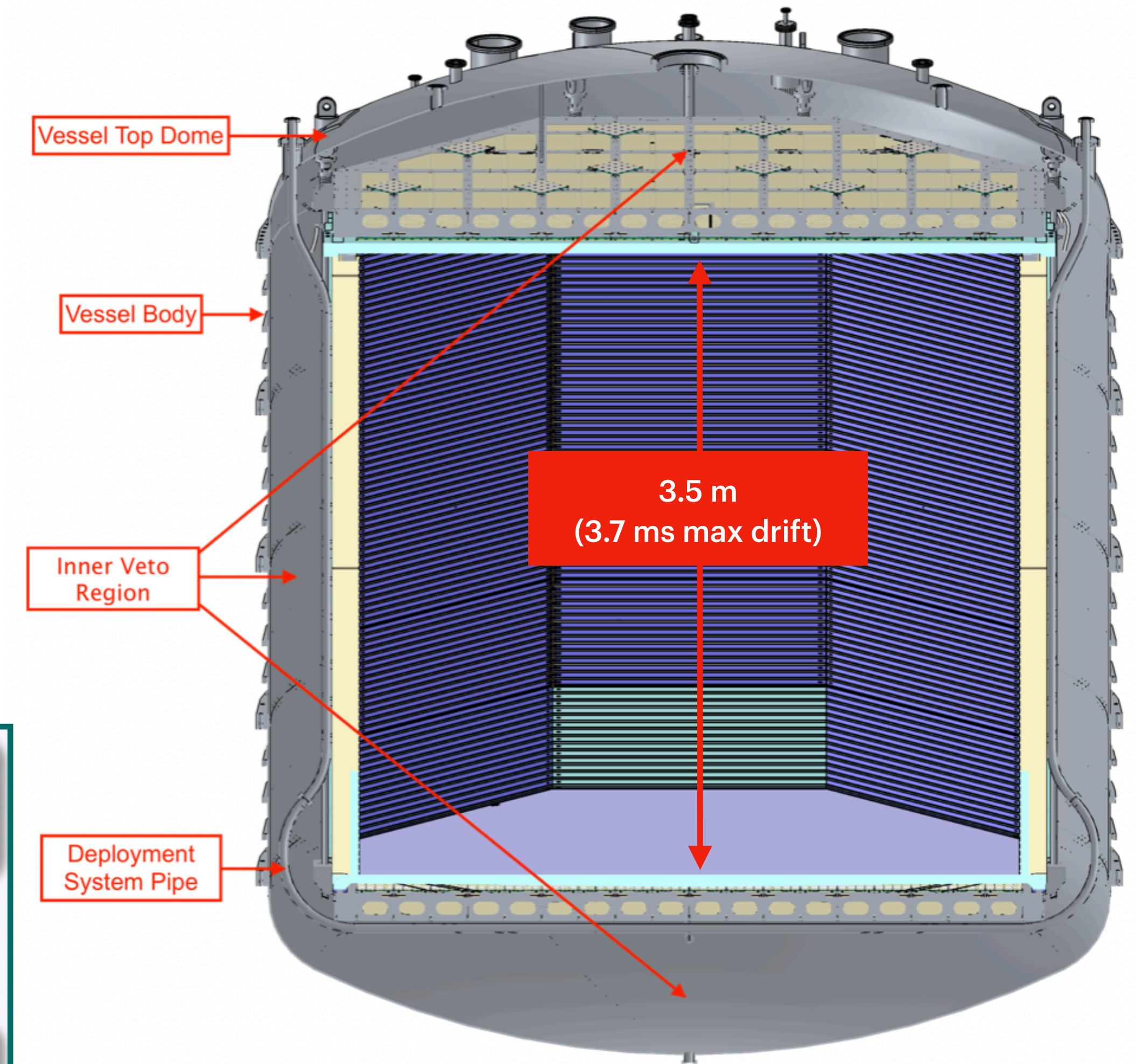
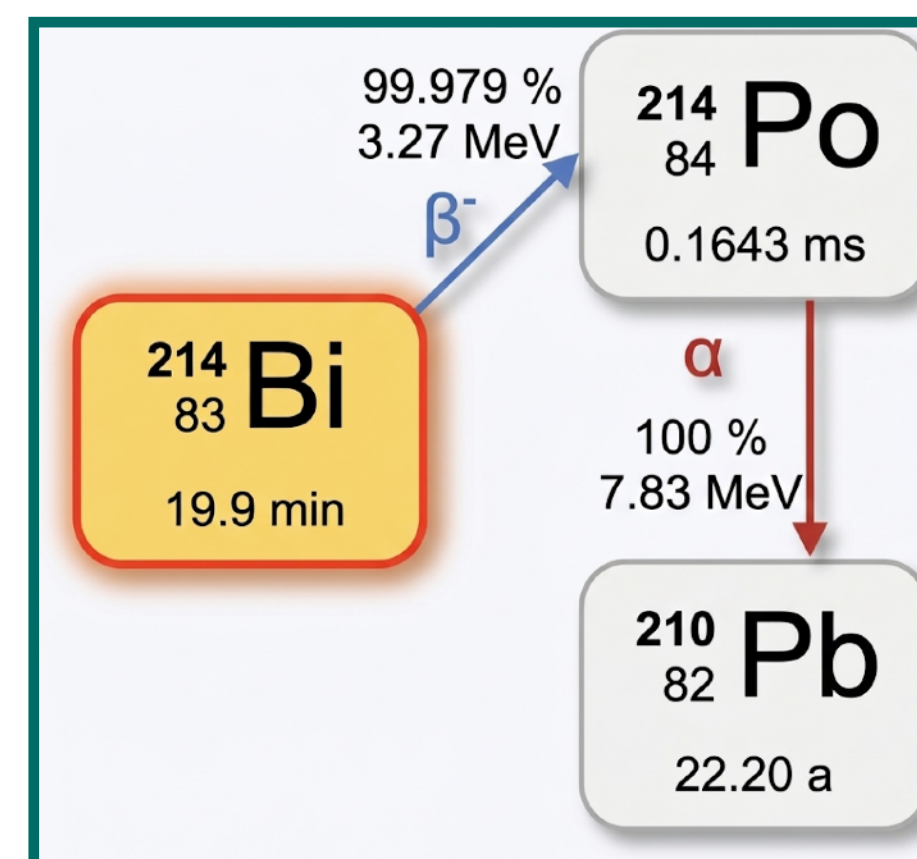
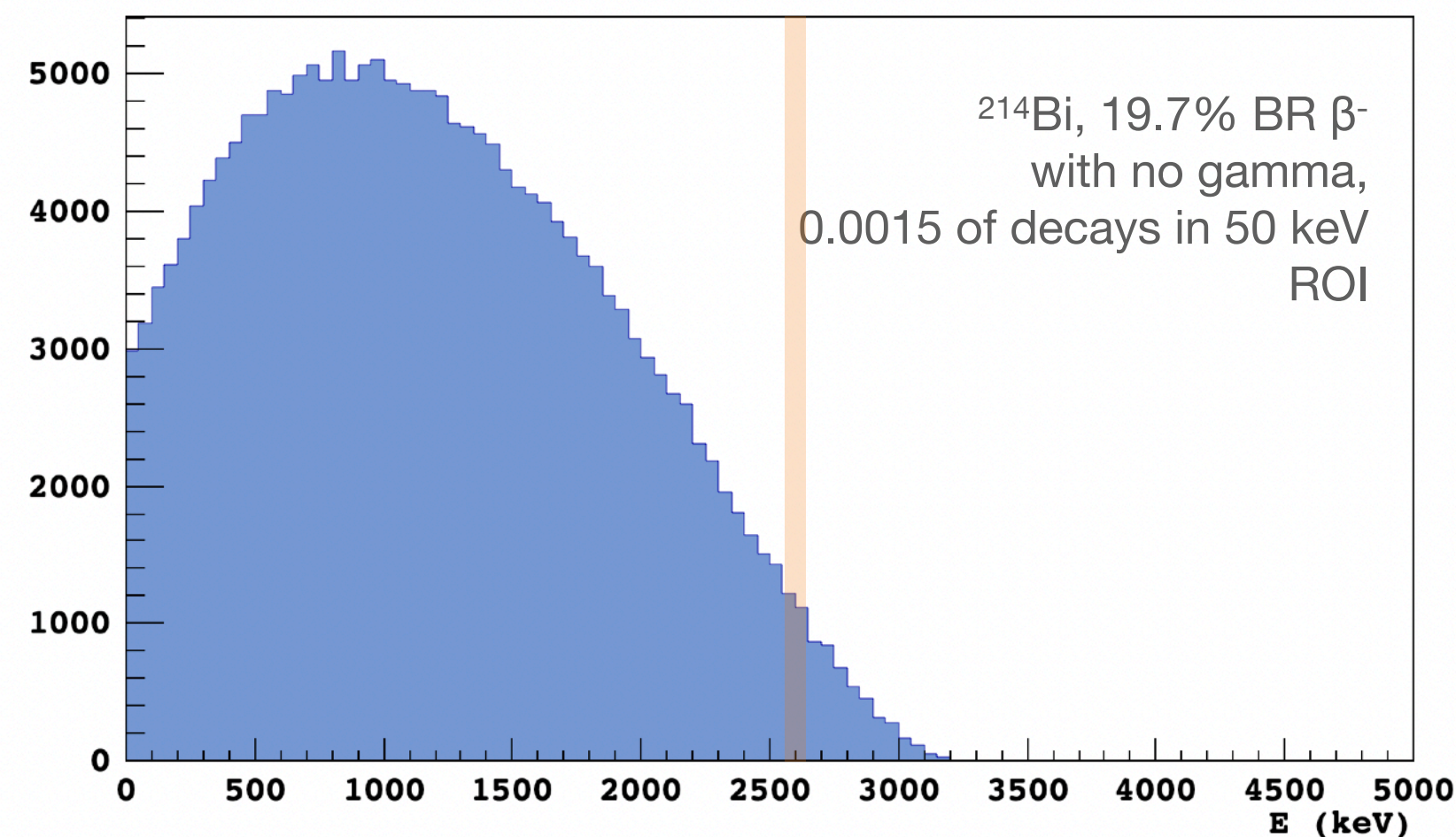
^{42}Ar production UG is negligible (2 decays/t/yr)

— ^{222}Rn induces possible background due to ^{214}Bi

^{214}Bi can be tagged thanks to Bi-Po coincidence ($\tau_{1/2} = 164 \mu\text{s}$) with very high efficiency. **Assume 99.9% efficiency of Bi-Po tagging**, even if **in principle this can be higher** (DarkSide-20k acquires data in trigger-less mode, i.e. with no fixed-width acquisition window)

. DEAP-3600 reached **0.2 uBq/kg** but **this yet to be proven in Xe-doped LAr**

Assuming 10x worse than DEAP, 99.9% tagging: 2×10^{-3} /t/yr/keV



Cosmogenics

FLUKA simulation of muon flux in Hall C at LNGS with up to date detector geometry (0.2 years lifetime), used to estimate production rate of potential backgrounds in ROI

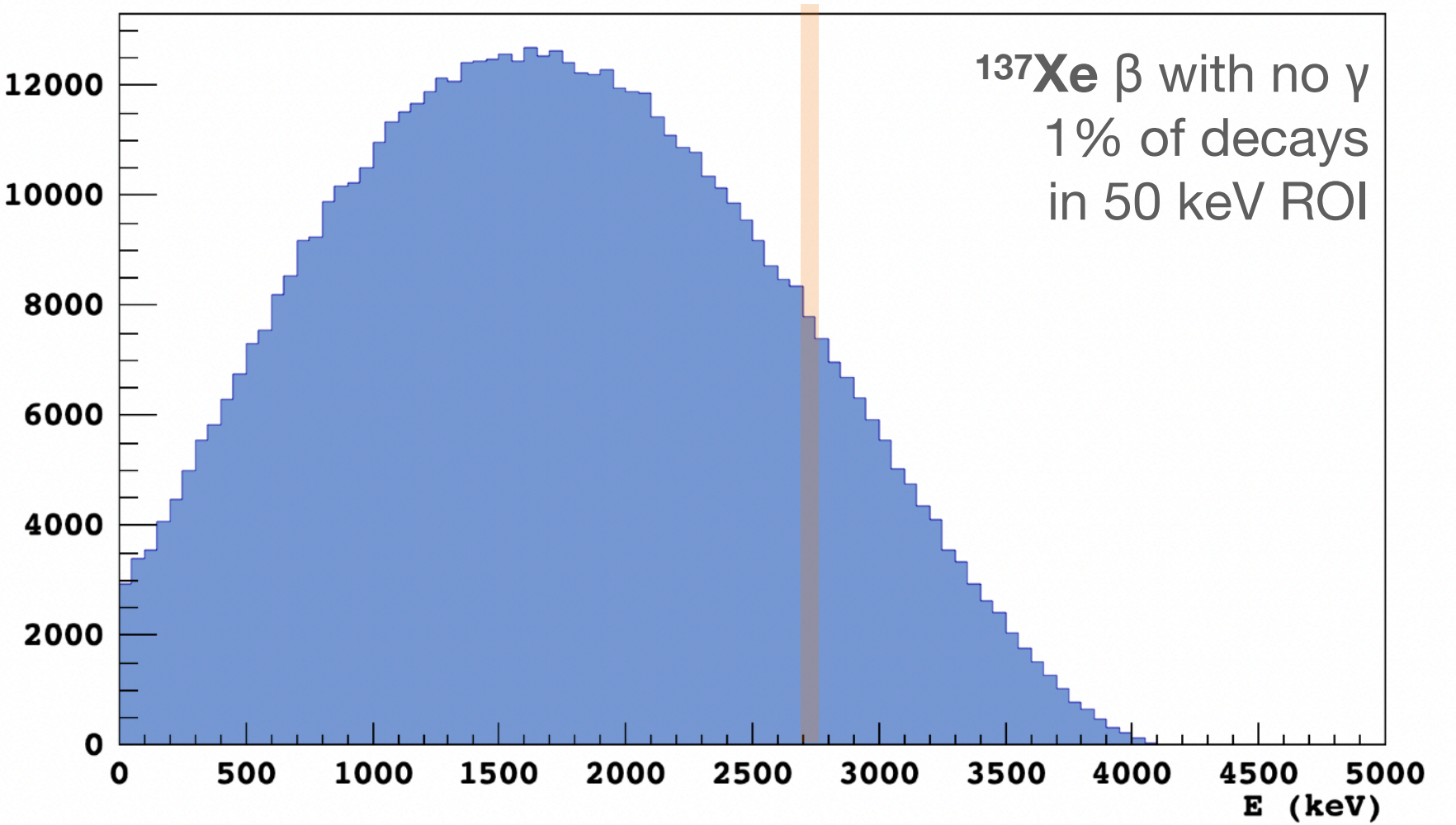
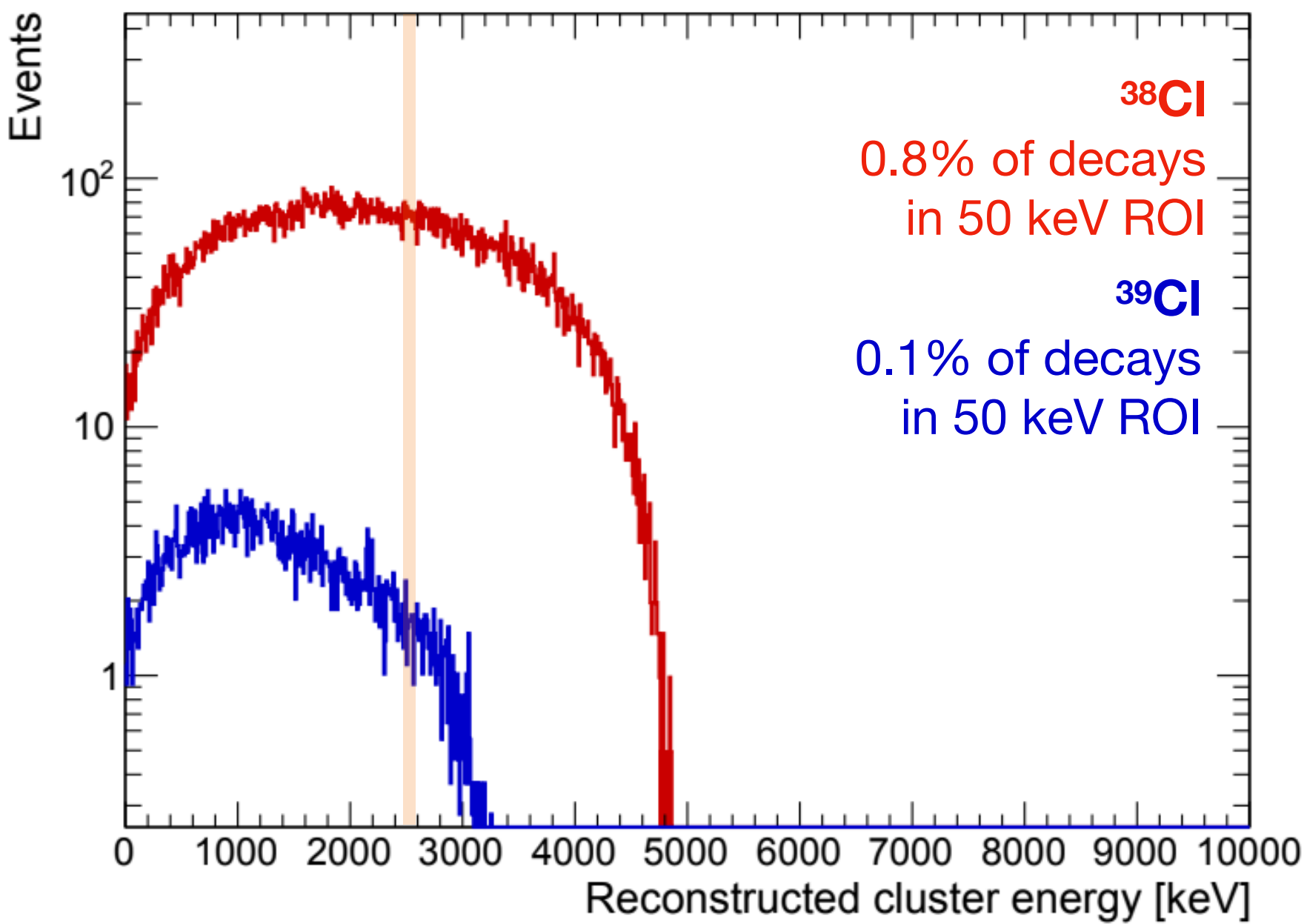
Dominant backgrounds are ^{38}Cl , ^{39}Cl (μ capture and spallation in LAr) and ^{137}Xe (neutron capture on ^{136}Xe)

Sample	^{38}Cl (/ t _{Ar} /yr)	^{39}Cl (/ t _{Ar} /yr)	^{137}Xe (/ t _{136Xe} / yr)	Comments
This work	18 ± 2	38 ± 4	56 ± 6	3800 m.w.e. $\Phi = 3.4 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ < μ energy> = 270 GeV
LEGEND (LNGS) [ref]	~20	~20		Preliminary (conference paper)
DUNE (SURF) [ref]	4 x 6 = 24	5.5 x 6 = 33		4300 m.w.e. $\Phi = 5.6 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ < μ energy> = 280 GeV
DARWIN (LNGS) [ref]			0.8 / 0.089 = 9.0	Using natXe, scaling by isotopic abundance
Scaled from nEXO [ref]			2.2 x 90= 198	Using enriched ^{136}Xe , scaling by μ flux ($\Phi = 3.7 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$)

$^{137}\text{Xe}:$
 $^{38}\text{Cl}:$
 $^{39}\text{Cl}:$

$1.3 \pm 0.1 \times 10^{-3}$
 $2.5 \pm 0.3 \times 10^{-3}$
 $6.7 \pm 0.7 \times 10^{-4}$

$/ t_{\text{mix}} / \text{yr} / \text{keV}$
 $/ t_{\text{mix}} / \text{yr} / \text{keV}$
 $/ t_{\text{mix}} / \text{yr} / \text{keV}$



Background from detector materials

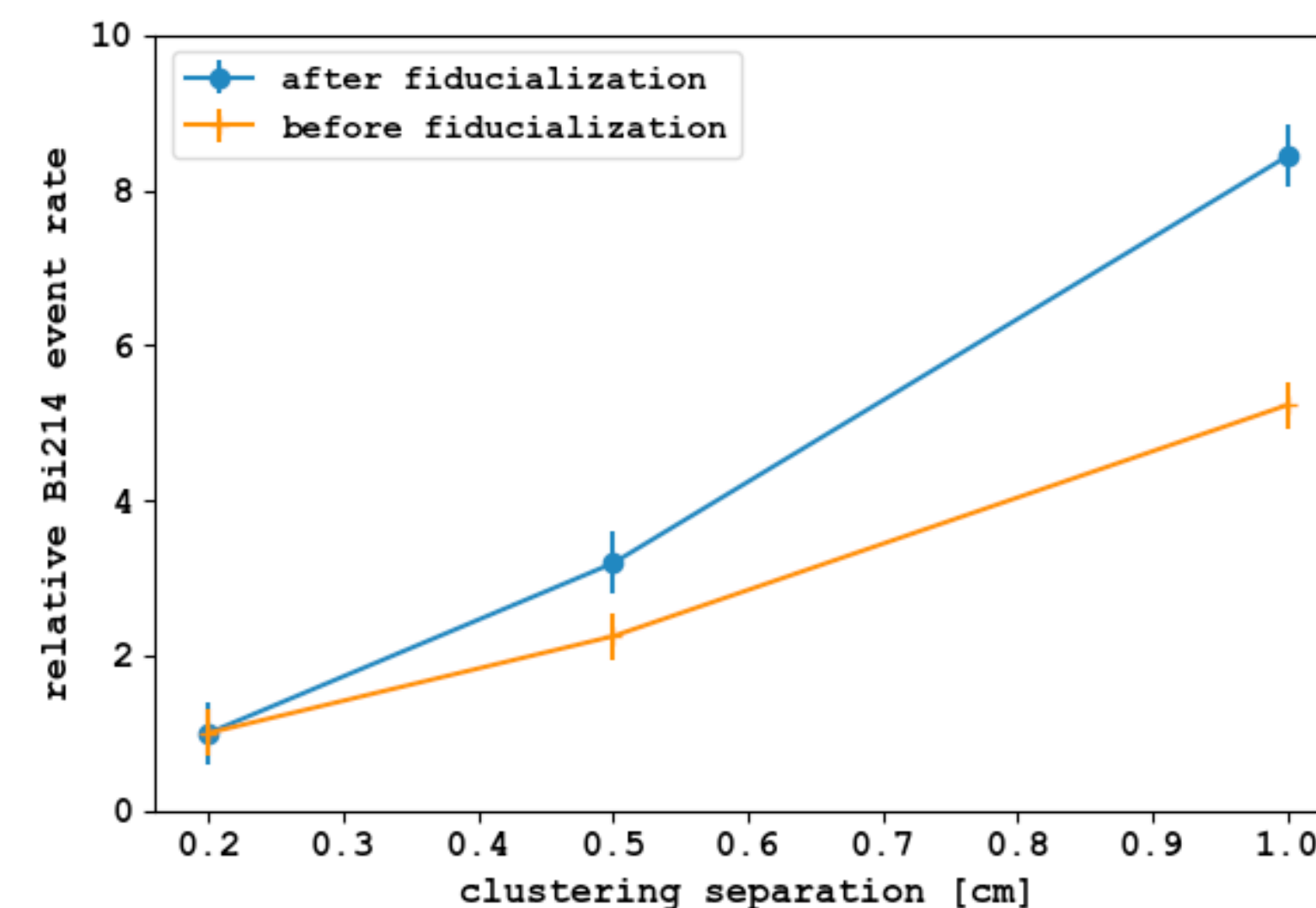
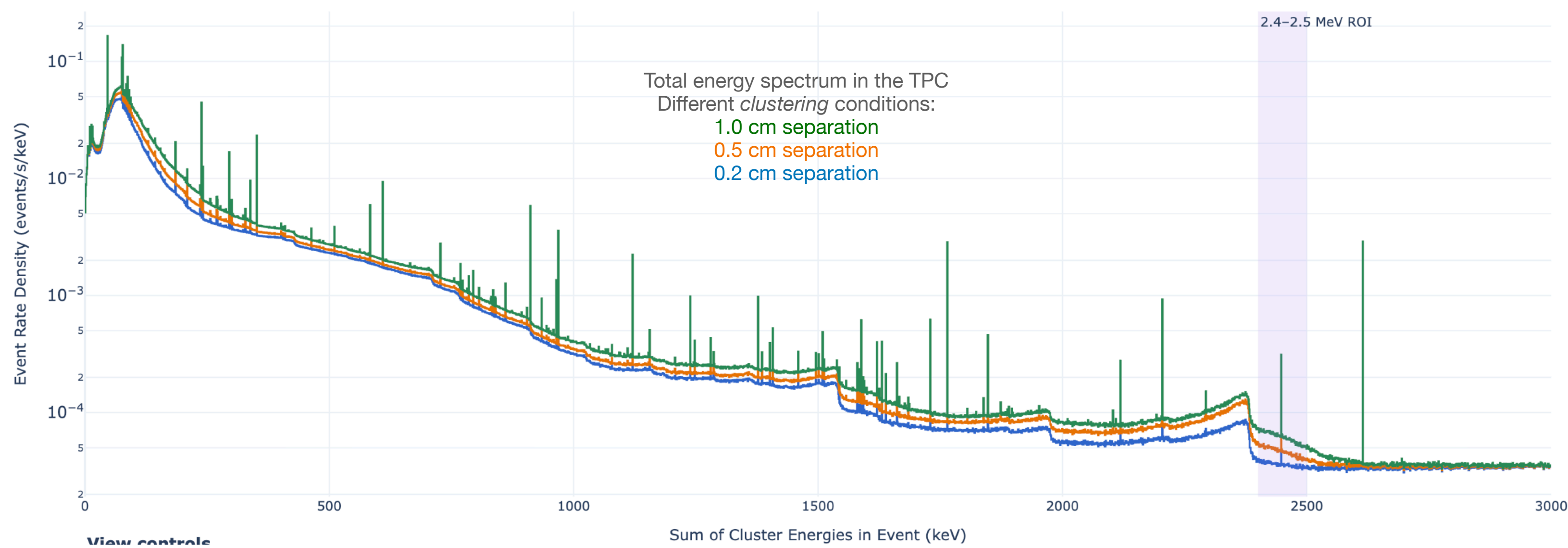
G4 simulation of full gamma background model from materials

Material screening result database is pretty complete

Started from a matrix of **81 combinations** of decay chains and locations, narrowed down to just a few (which can generate single scatters in ROI and in FV): ^{214}Bi (2.45 MeV, ~1.5% BR) and ^{208}Tl (2.6 MeV)

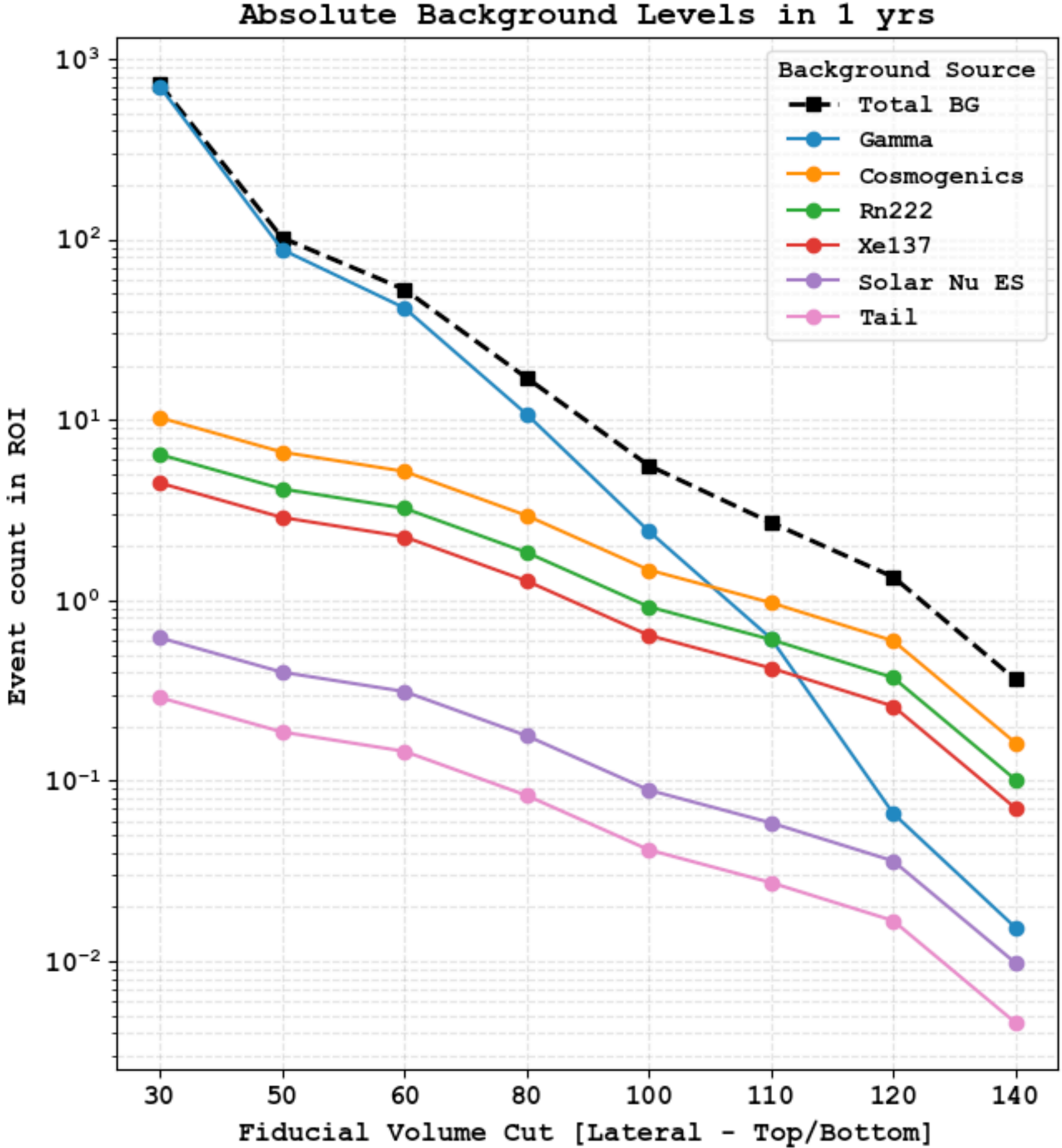
Event rate in ROI is dominated by unresolved Compton + photoelectric by ^{214}Bi γ -rays from the SiPM photodetectors

The result is very sensitive to the assumed capability of the detector to resolve them, which is approximated by grouping nearby energy deposits within a conservatively large vertical distance: **1 cm**

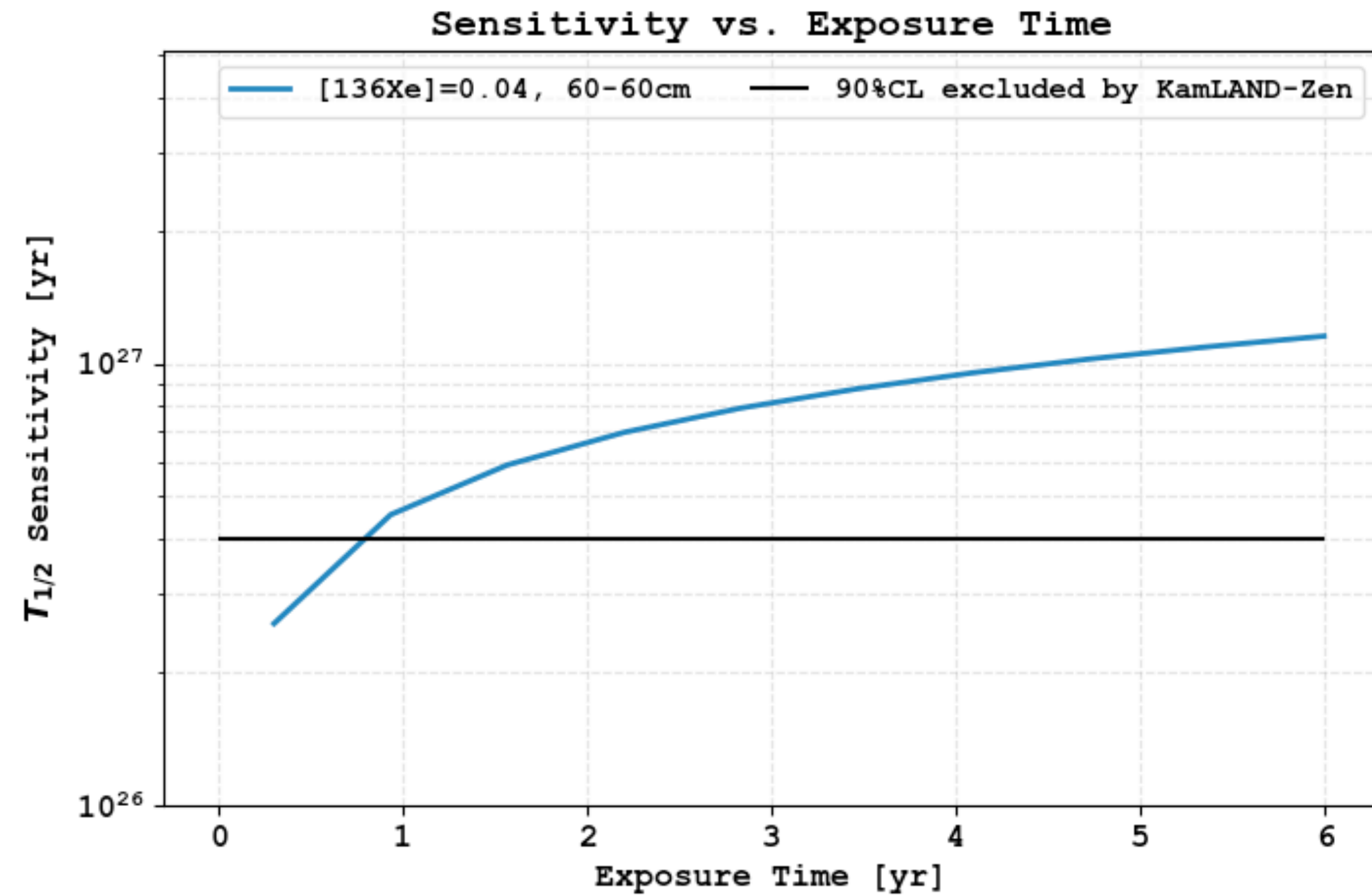


Reference scenario

	Source	Events/t _{mix} / yr in 100 keV ROI 30-30 cm (30 t _{mix} FV)	Events/t _{mix} / yr in 100 keV ROI 50-50 cm (19 t _{mix} FV)	Events/t _{mix} / yr in 100 keV ROI 80-80 cm (8.4 t _{mix} FV)	Comments / uncertainties
	Gammas	24.5	4.75	1.31	Full bg model, assuming 1 cm clustering. Uncertainties on bg
Flat in ROI	Cosmogenics (³⁸ Cl, ³⁹ Cl)	0.32 ± 0.04			This work
	Rn progeny	0.2			10x worse than DEAP-3600 (i.e. 2 uBq/kg), and 99.9%
	¹³⁷ Xe	0.13 ± 0.01			This work
	Solar neutrinos	0.02			Irreducible
	¹³⁶ Xe 2νββ tail	< 0.009			
	Neutron captures	< 0.01			



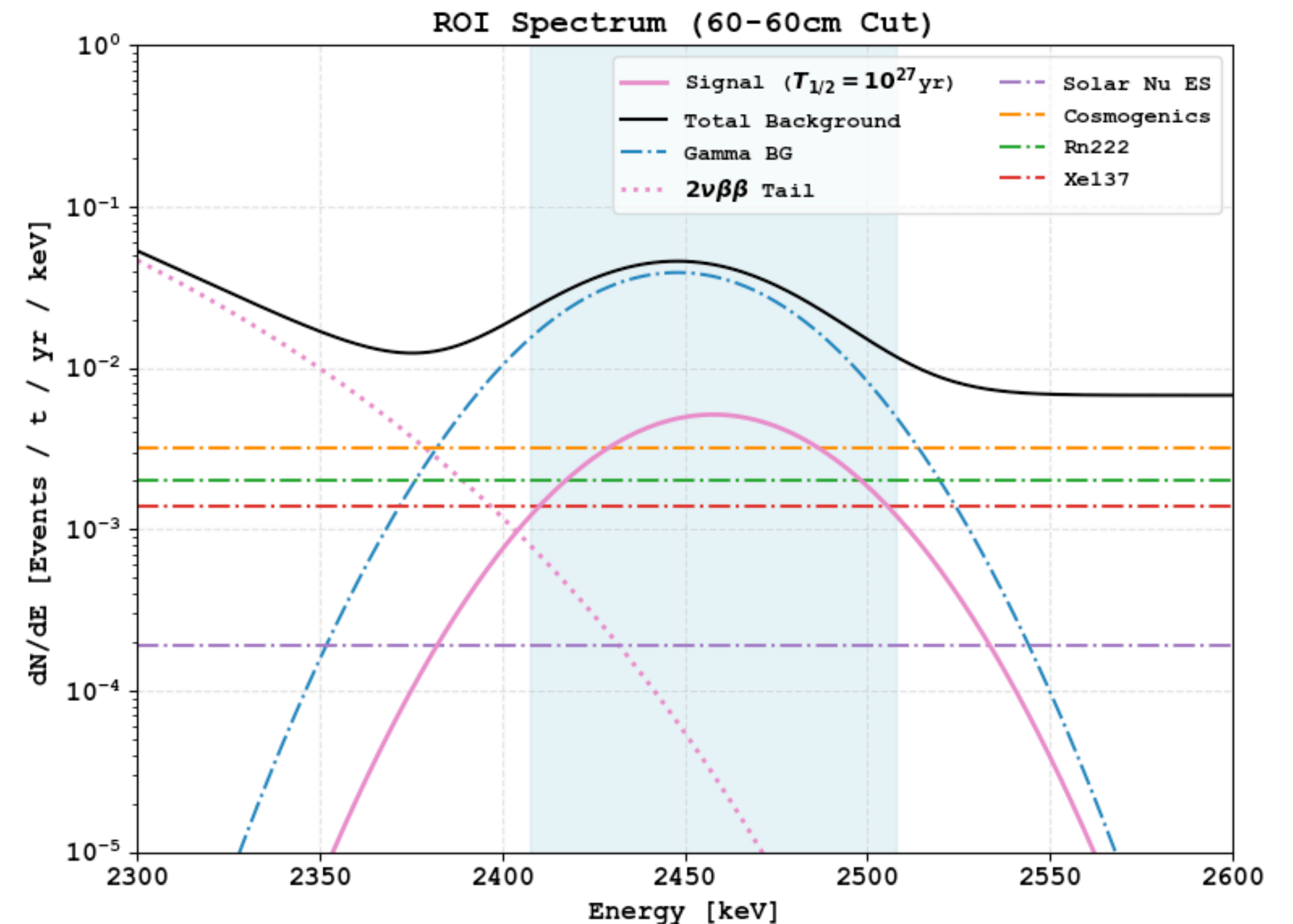
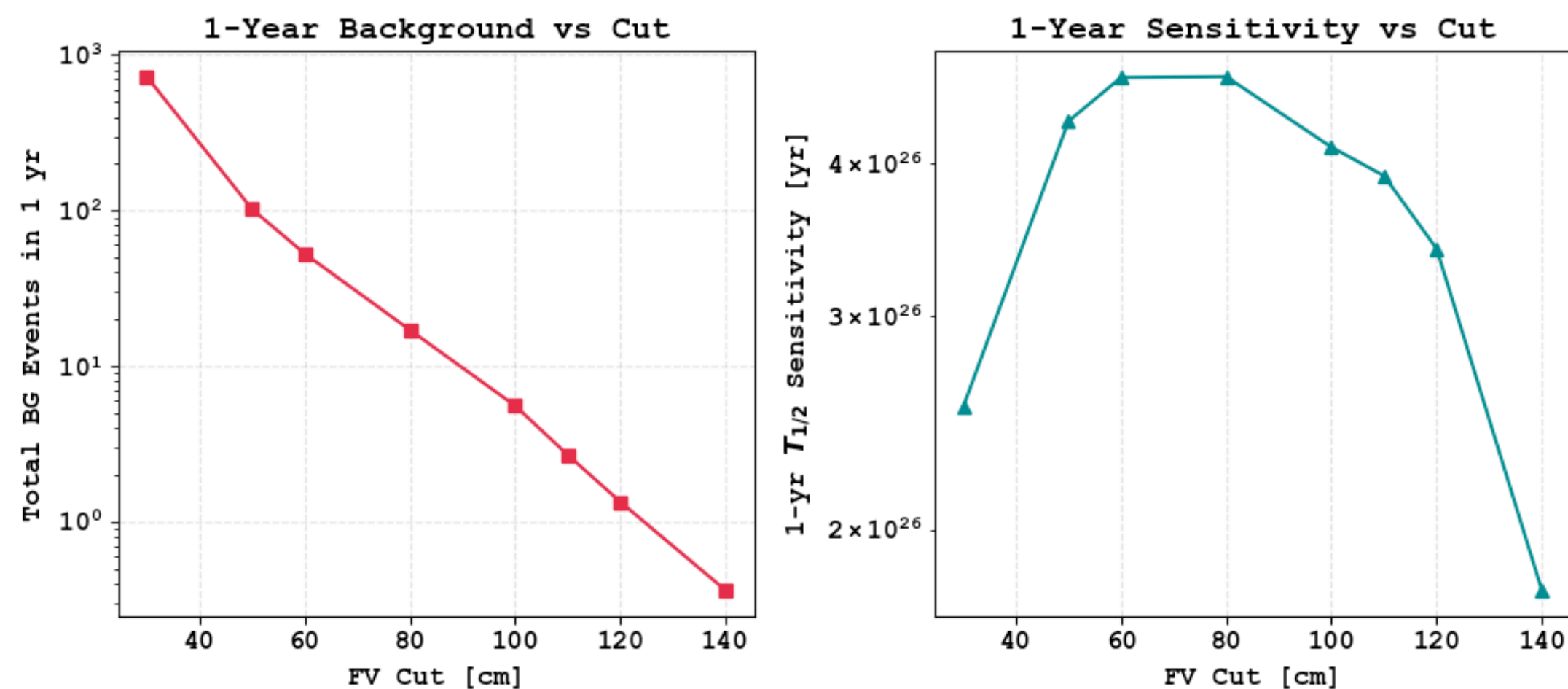
Reference scenario



Simple minded exclusion, not based on a fit,
little optimization of the ROI

$$T_{1/2}^{0\nu} = \ln 2 \frac{N_A \mathcal{E}}{M_{\text{Xe}} S(B)}$$

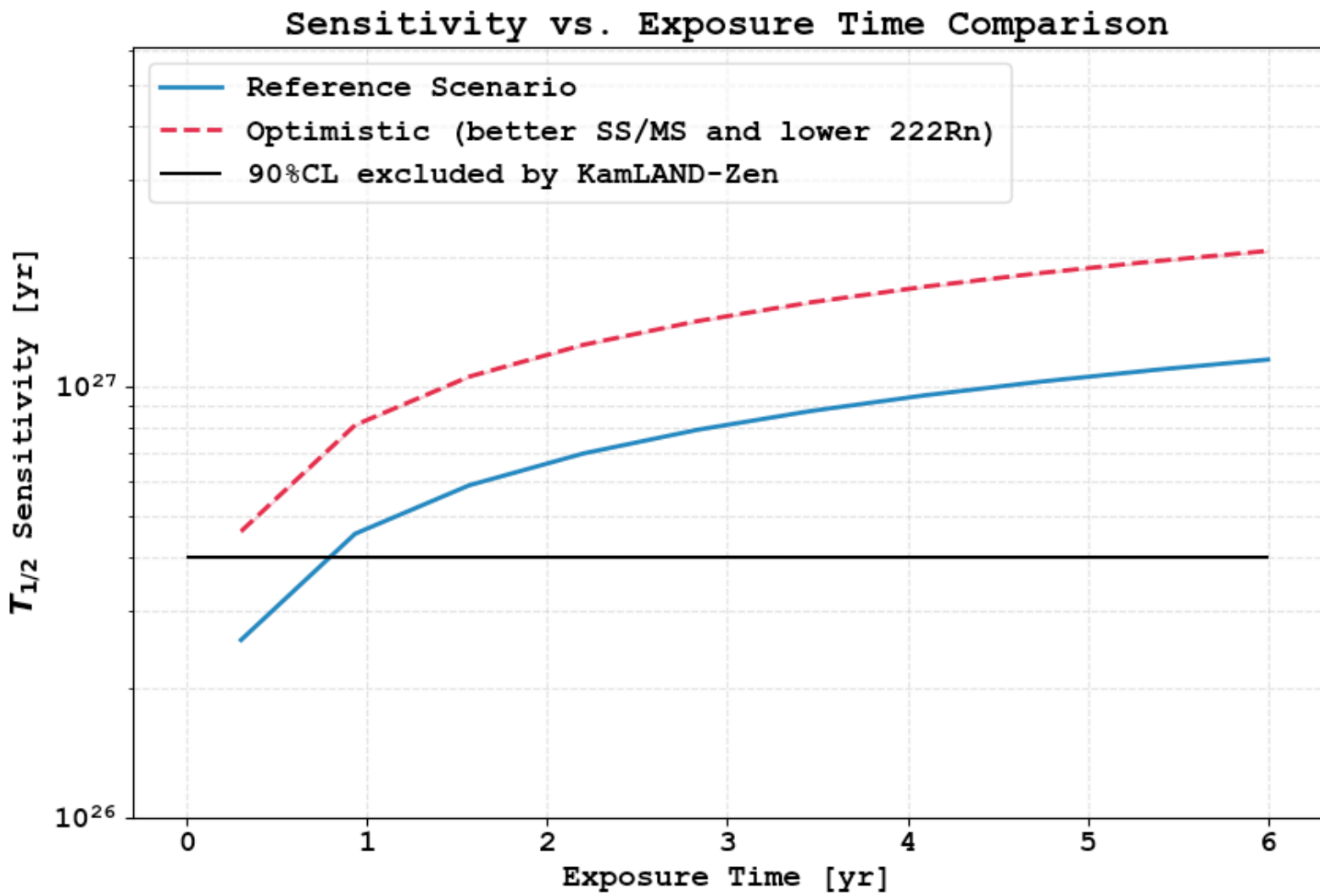
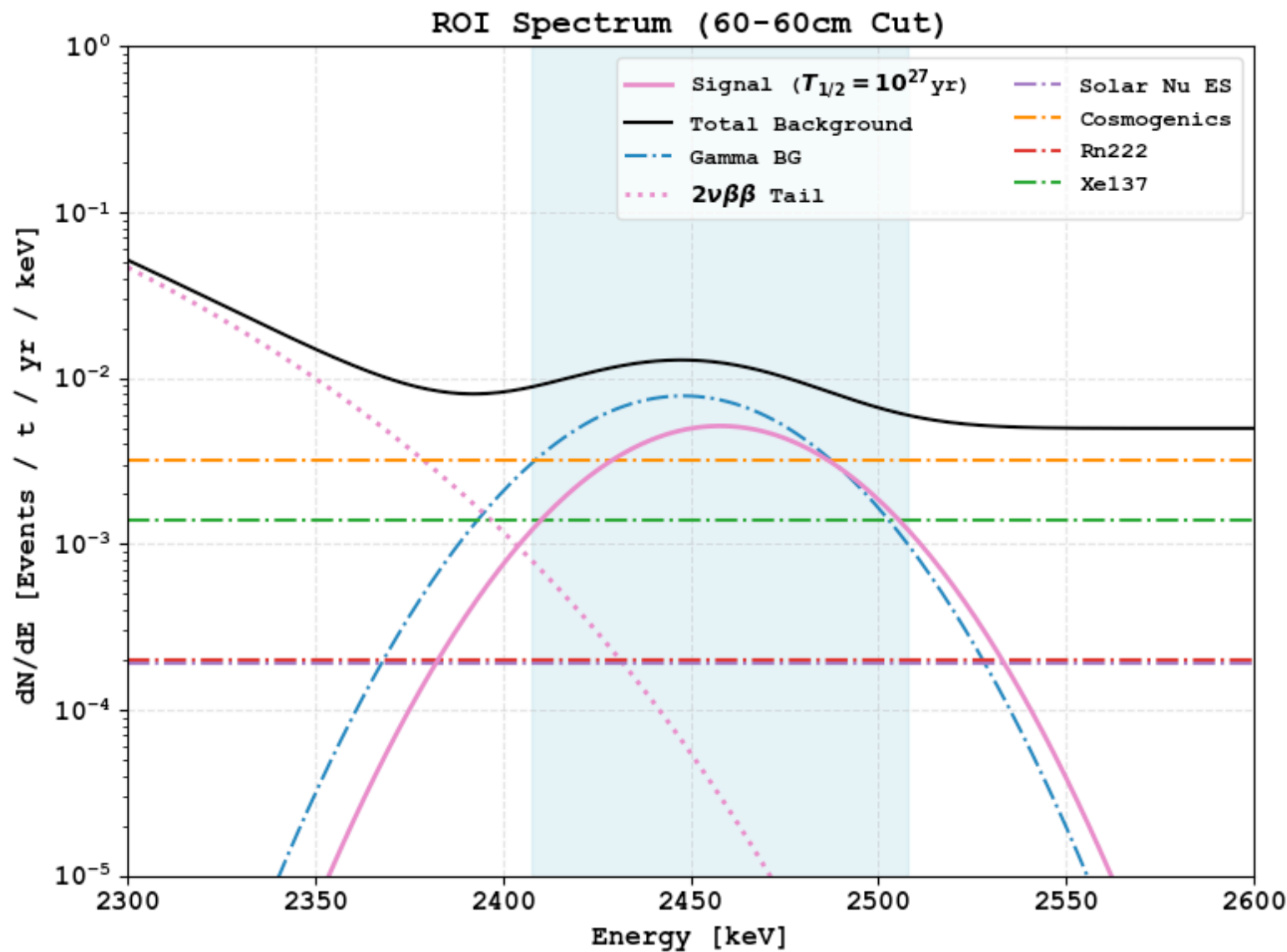
N_A Avogadro's constant
 M_{Xe} molar mass of Xe
 E exposure
 $S_{90\%CL}(B) = 1.64 \sqrt{B}$



Optimistic configuration

Source	Events/ t_{mix} / yr in 100 keV ROI 30-30 cm (30 t_{mix} FV)	Events/ t_{mix} / yr in 100 keV ROI 50-50 cm (19 t_{mix} FV)	Events/ t_{mix} / yr in 100 keV ROI 80-80 cm (8.4 t_{mix} FV)	Factor wrt to baseline scenario	Comments / uncertainties
Gammas	4.9	0.95	0.26	0.2x	Full bg model, 5x better MS resolution capability
Cosmogenics (^{38}Cl , ^{39}Cl)	0.32 ± 0.04			1x	From this work
^{137}Xe	0.13 ± 0.01			1x	
Rn progeny	0.02			0.1x	As achieved in DEAP-3600 and same 99.9% tagging
Solar neutrinos	0.02			1x	
^{136}Xe $2\nu\beta\beta$ tail	< 0.009			1x	
Neutron captures	< 0.01			1x	

Gamma bg at same level as cosmogenics: factor of 2x improvement



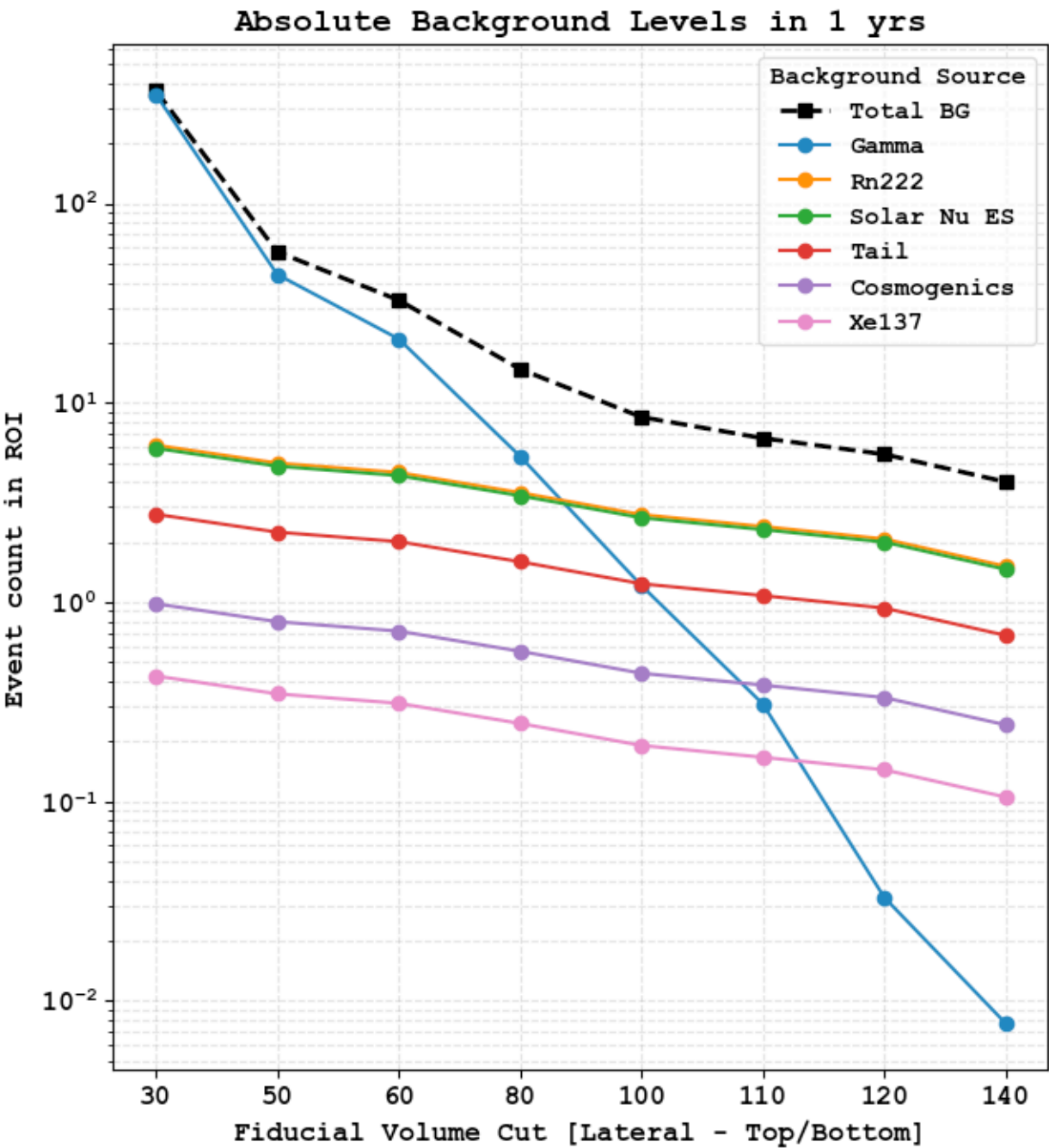
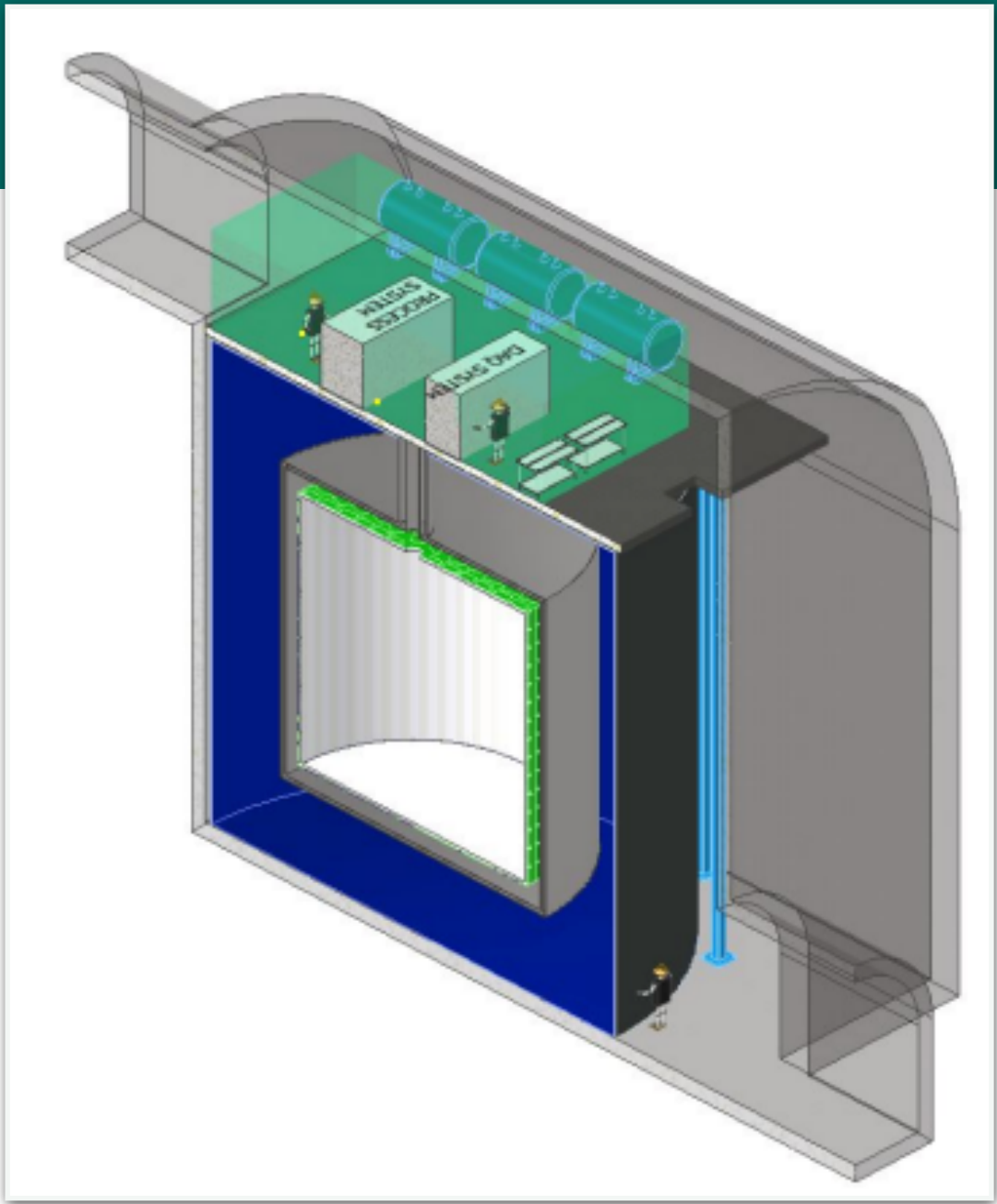
The ARGO scenario

- ◆ Assuming 400 t active mass detector [ref], 5 m tall, installed at **SNOLab (100x smaller μ flux)**
- ◆ Same material radioactivity scaled by surface and detector energy resolution at 2.5 MeV (1.2%)

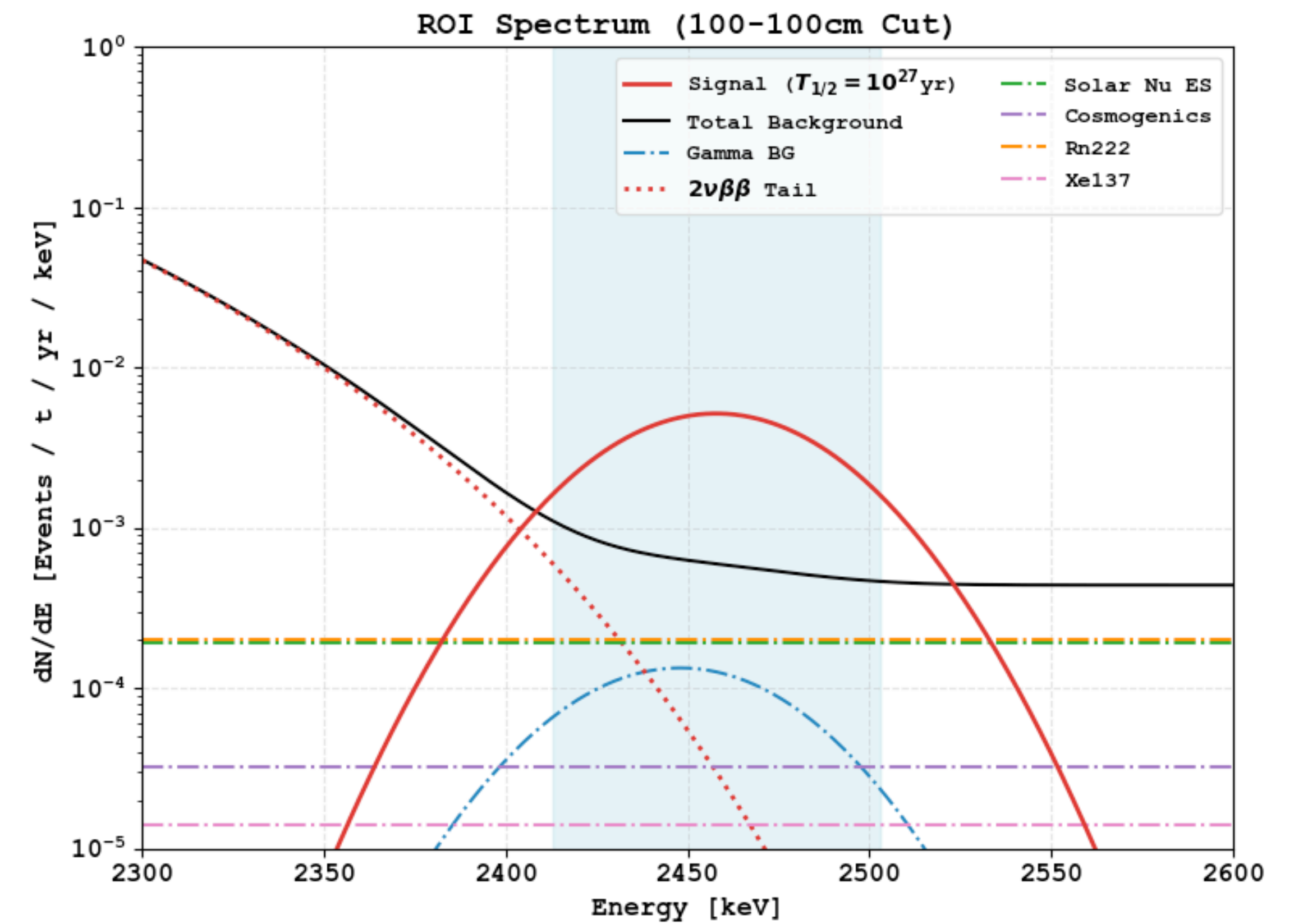
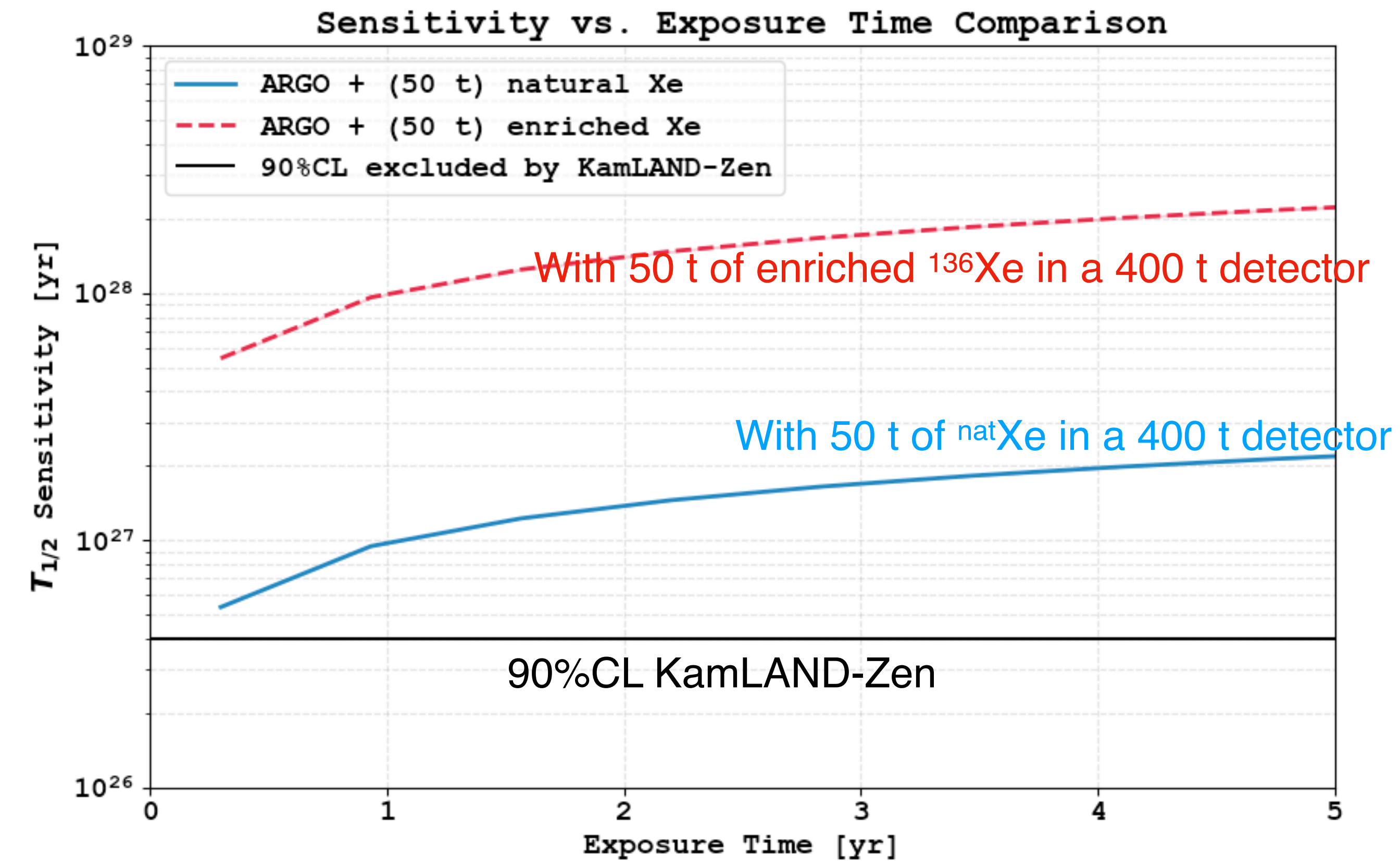
Source	Events/ t_{mix}/yr in 100 keV ROI 30-30 cm (300 t_{mix} FV)	Events/ t_{mix}/yr in 100 keV ROI 50-50 cm (250 t_{mix} FV)	Events/ t_{mix}/yr in 100 keV ROI 80-80 cm (180 t_{mix} FV)	Events/ t_{mix}/yr in 100 keV ROI 120-120 cm (100 t_{mix} FV)	Factor wrt to baseline scenario	Comments / uncertainties
Gammas	11.4	1.71	0.29	0.003	5x	Same material activity, scaled by detector surface, 10x MS/SS
Solar neutrinos	0.02 *				1x	Irreducible **
Rn progeny	0.02				0.1x	As in DEAP-3600
^{136}Xe $2\nu\beta\beta$ tail	0.01				1x	
Cosmogenics (^{38}Cl , ^{39}Cl)	0.003				0.01x	This work
^{137}Xe	0.001				0.01x	Rate for nEXO

* while signal scales with mass of Xe, the neutrino background scales with total mass

** irreducible for a given detector resolution which determines the ROI width



The ARGO scenario



Conclusions

◆ This is not a complete feasibility study. **Most of the questions regarding the operation of the DS20k with a significant Xe loading are still open.** These include (but are not limited to):

how avoid instabilities in the detector while achieving stable recirculation
efficiency of ^{222}Rn removal system (need for R&D)
the uncertainty on the energy response in ionisation and scintillation
impact of a faster signal time profile (now assumed as the pure LAr ones)

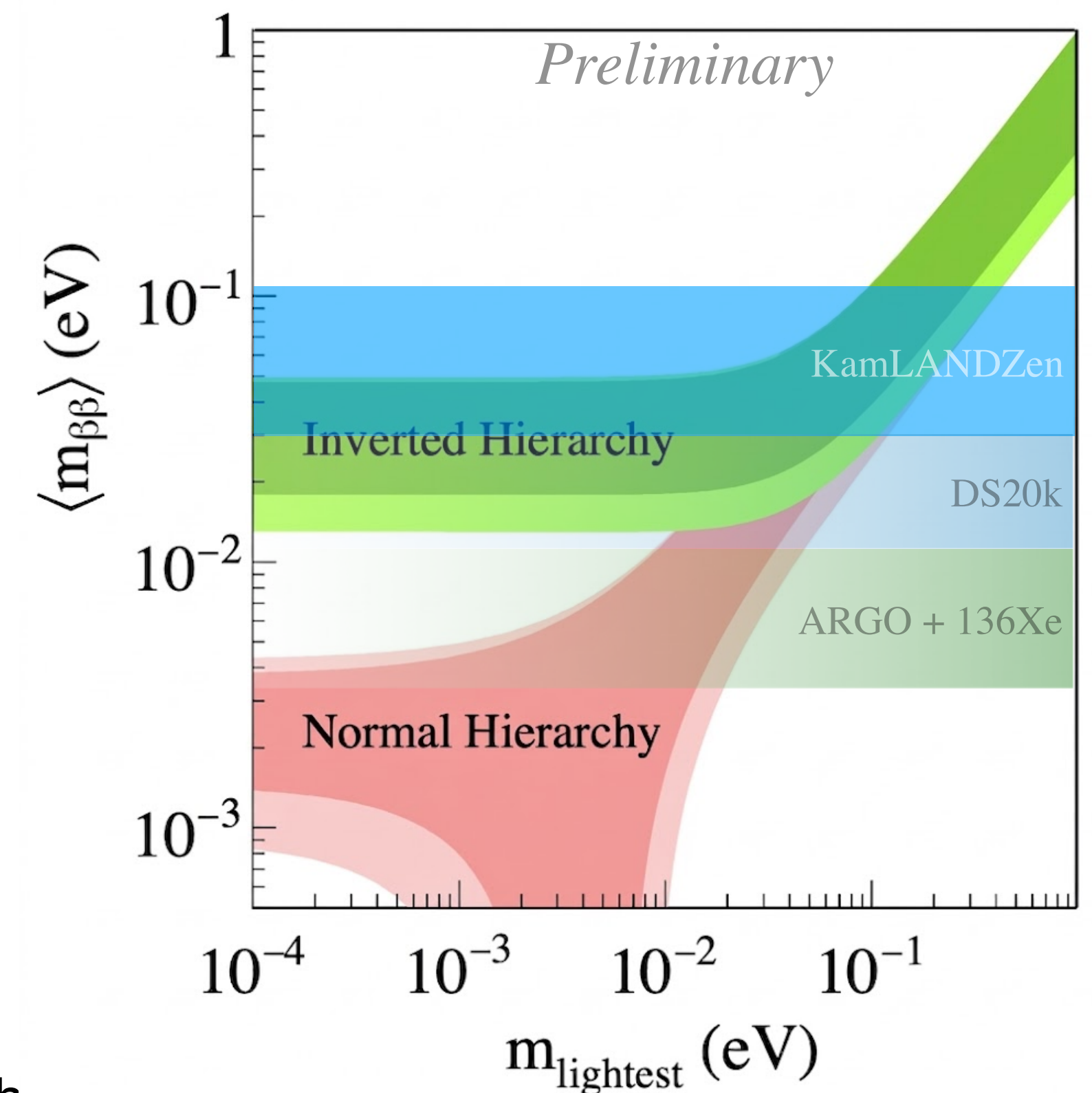
...

However, a very interesting exercise

◆ DS20k, not optimized, limited by γ -rays from ^{214}Bi , in particular from the photosensors (based on **realistic** background budget)

◆ ARGO at SNOLAB can suppress all backgrounds below solar neutrinos (event rate per unit mass is similar LAr and LXe)

◆ The ARGO platform may offer in the future (2040) the infrastructure to run a heavily LXe-doped LAr detector with **sensitivity to $m_{\beta\beta}$ beyond 10**. Incremental loading scenarios worth investigating



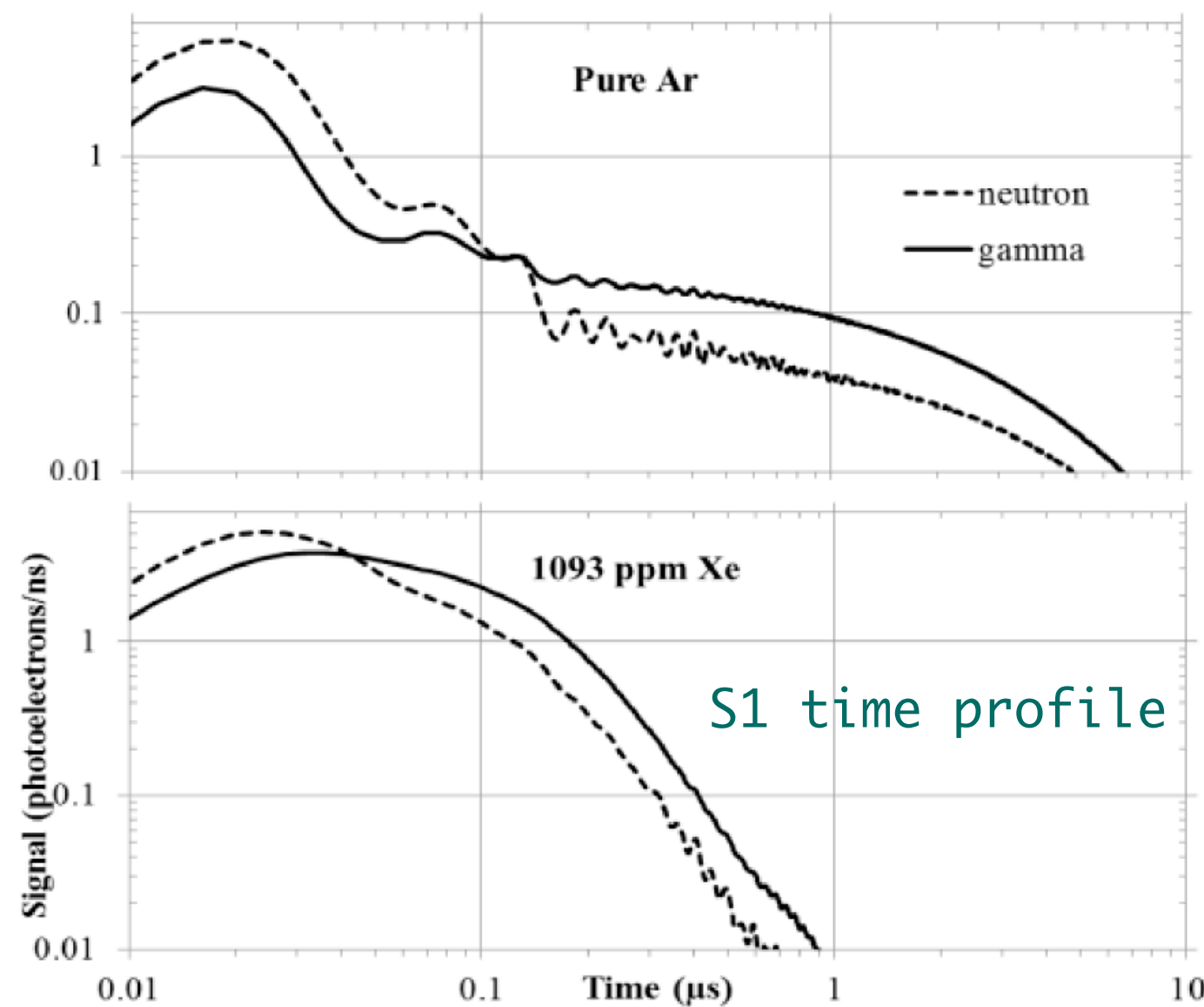
BACKUP

Scintillation and ionization yields

Doping implies energy transfer Ar_2^* (128 nm) to Ar^*Xe^* (150) and Xe_2^* (175 nm)

- ❖ **Scintillation yield:** ==> increase in the collected light signal (after TPB) up to ~20% at 2000 ppm
==> slower signal rise time but faster overall pulse (1500 ns → 300 ns)
- ❖ **Ionization yield:** ==> 10% increase in collected charge (smaller average ionization W)
- ❖ **Electroluminescence gain:** ==> time profile of EL pulse is still dominated by LAr τ_{slow} (3.2 μs), possible 1.4x increase of g2

Full implementation still in progress



Wahl et al, 2014, up to 1000 ppm [ref]

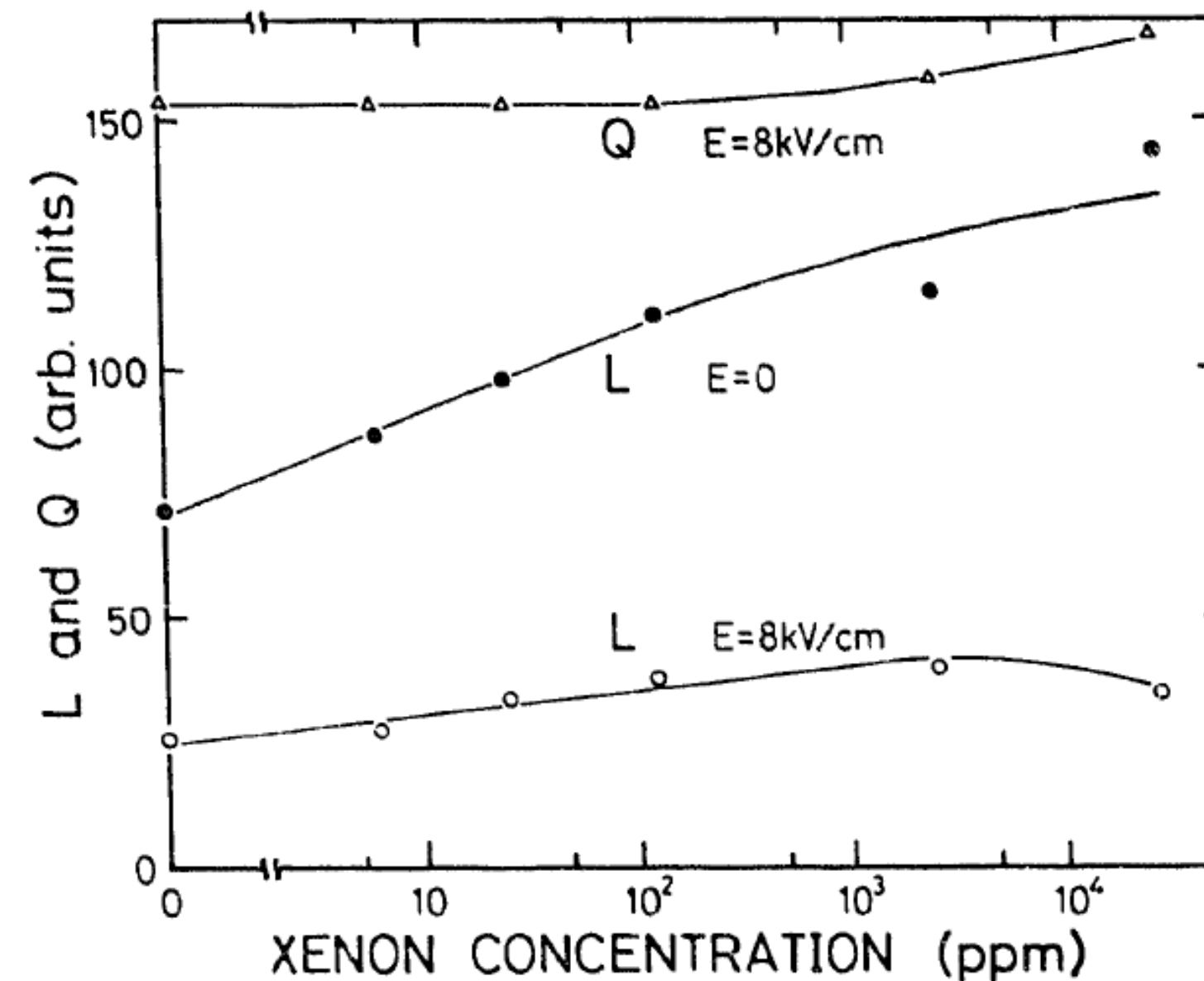
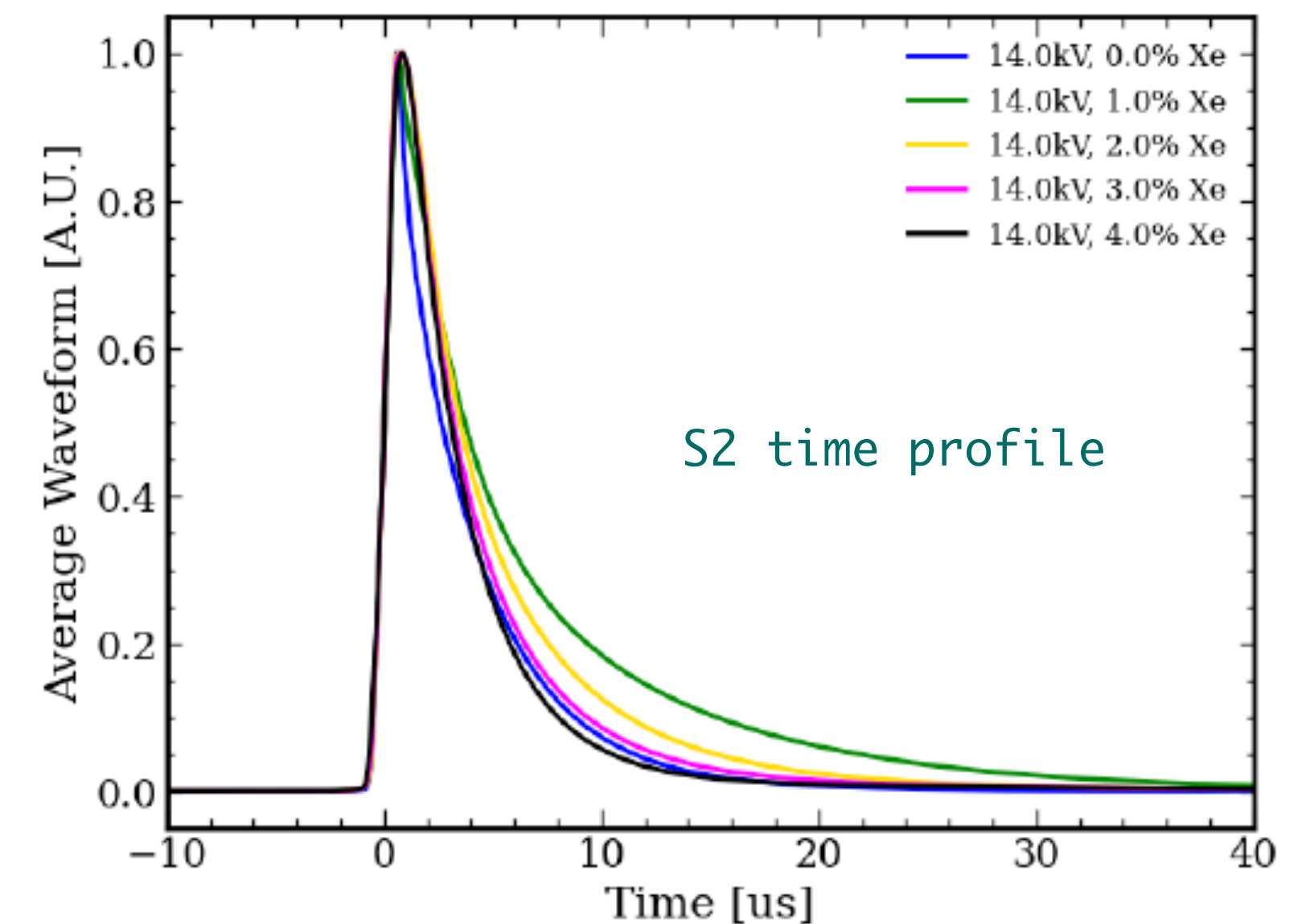


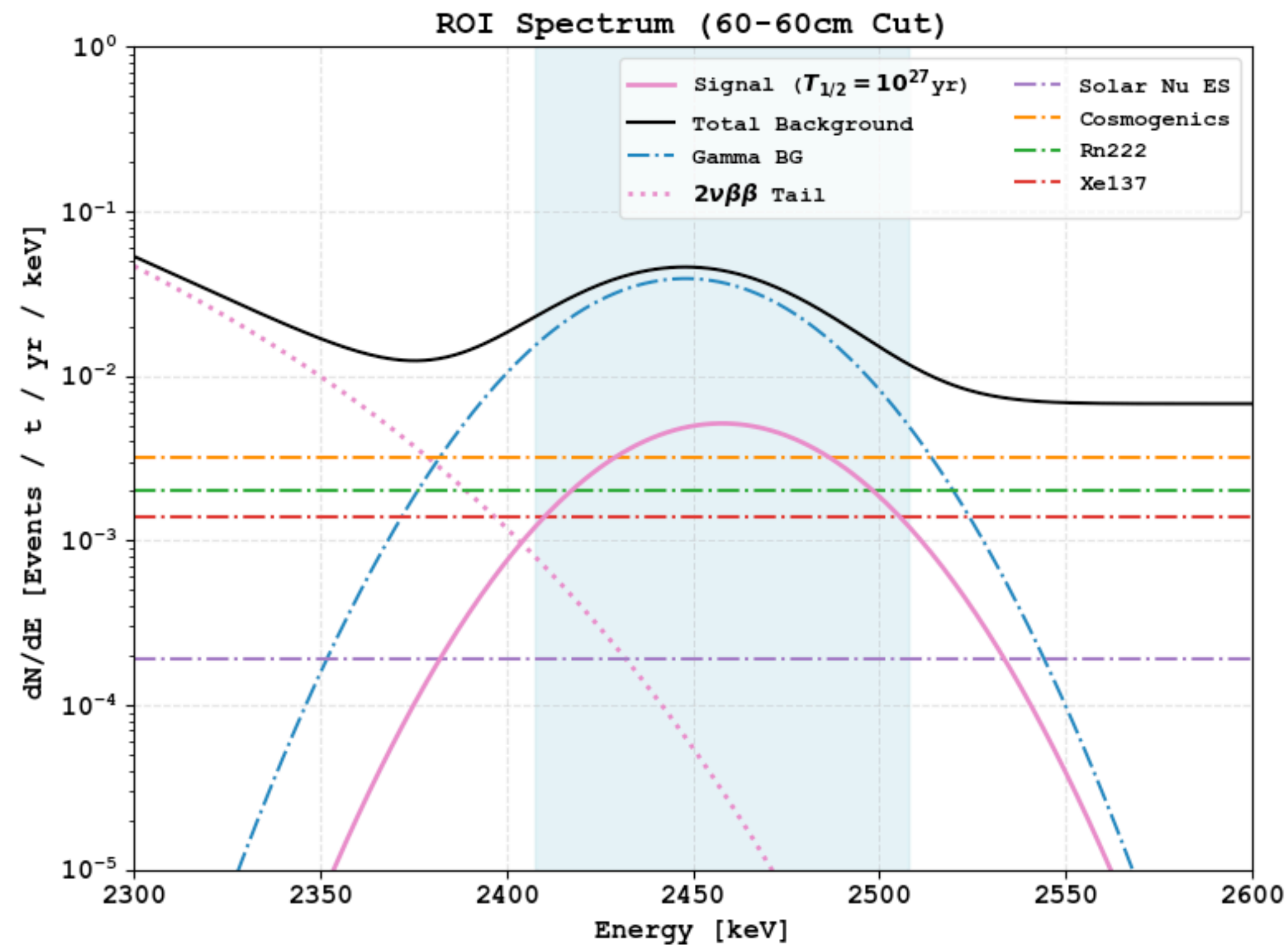
Fig. 2. The variation of the collected charge and the light output at the applied electric field of 8 kV/cm and the light output without the applied electric field in xenon-doped liquid argon as a function of xenon concentration.

Suzuki et al, 1993, up to 1900 ppm [ref]

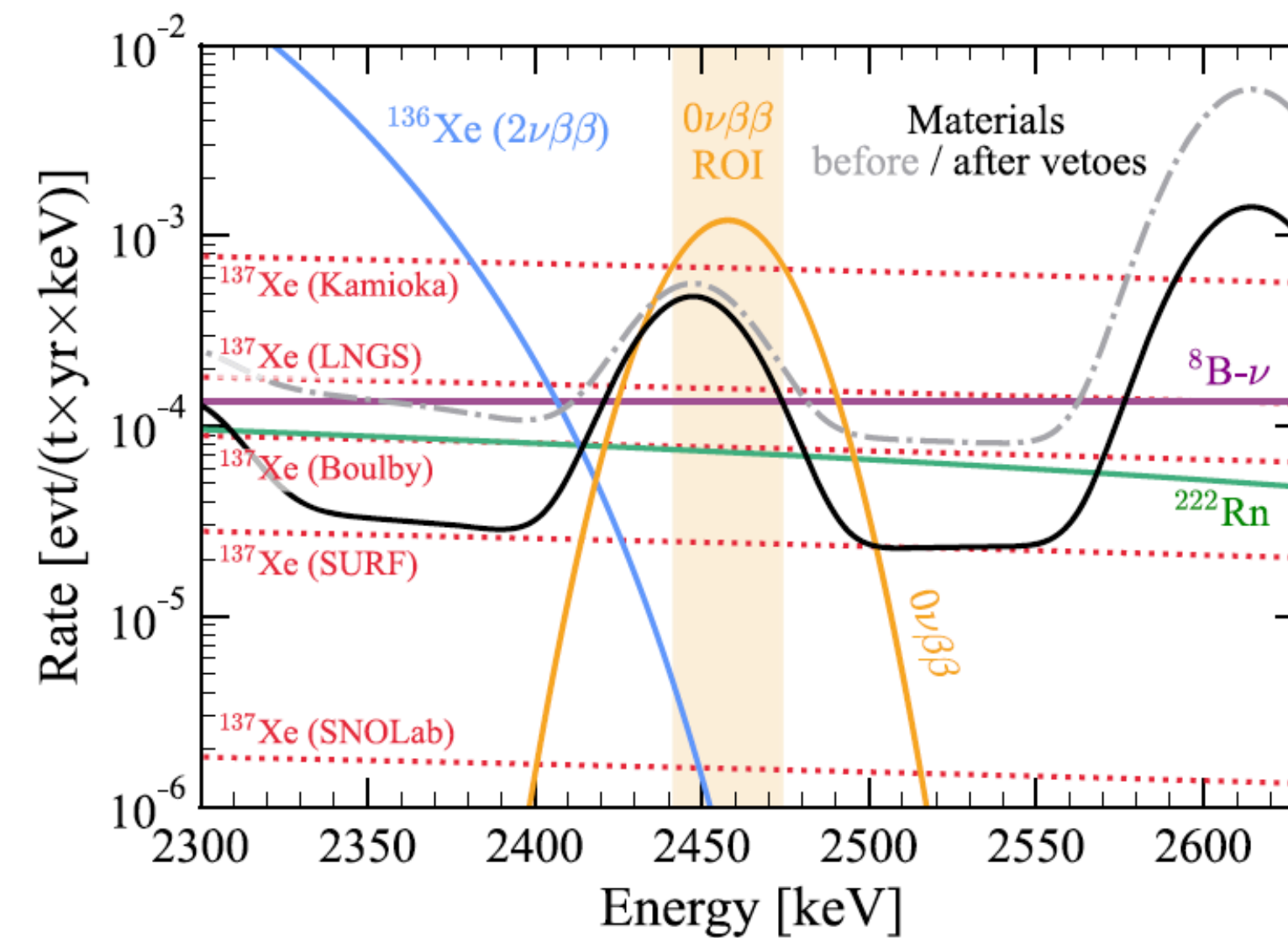
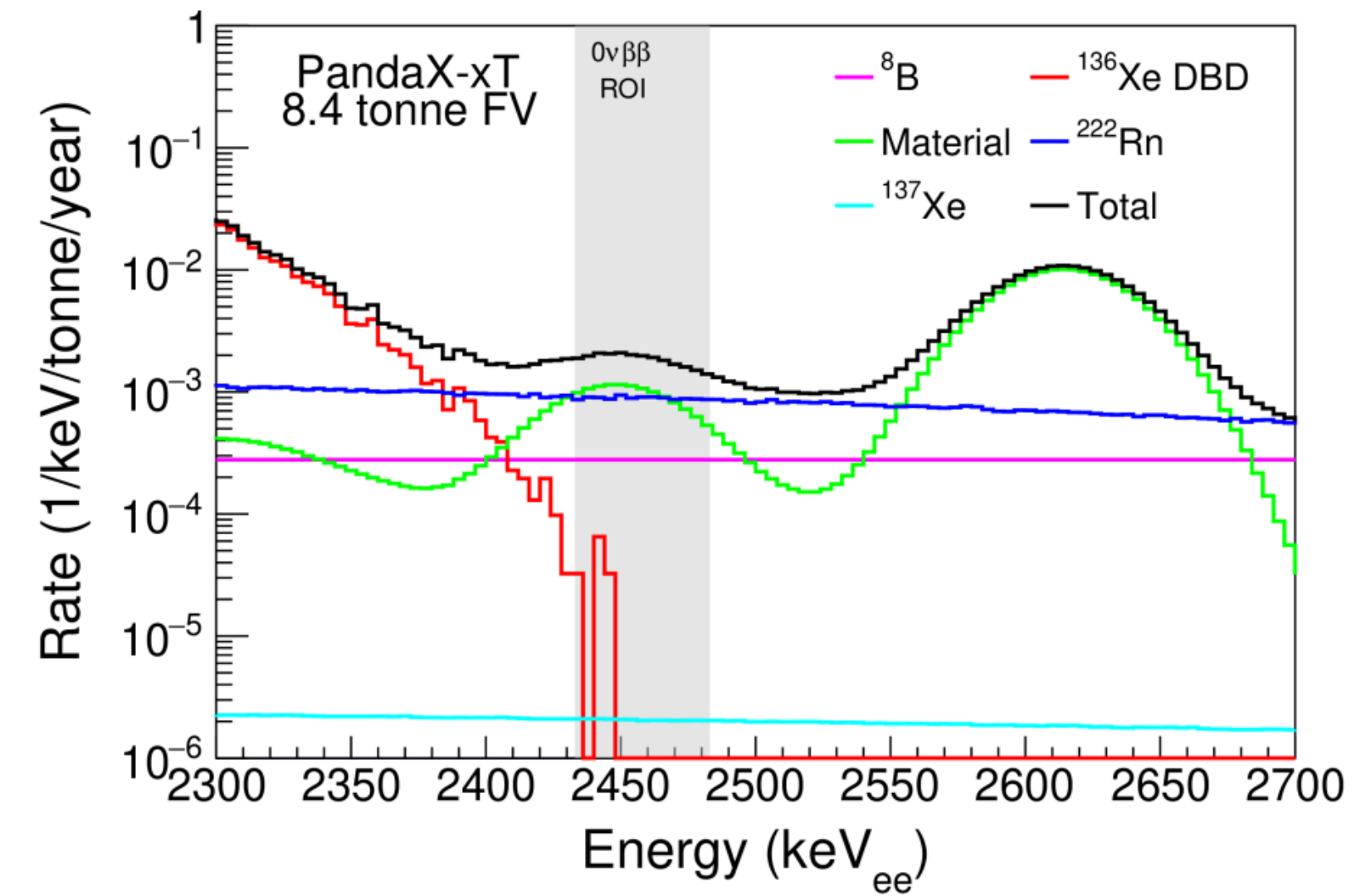


Kingston et al, up to 4000 ppm [ref] - g2

ROI Xe-based experiments



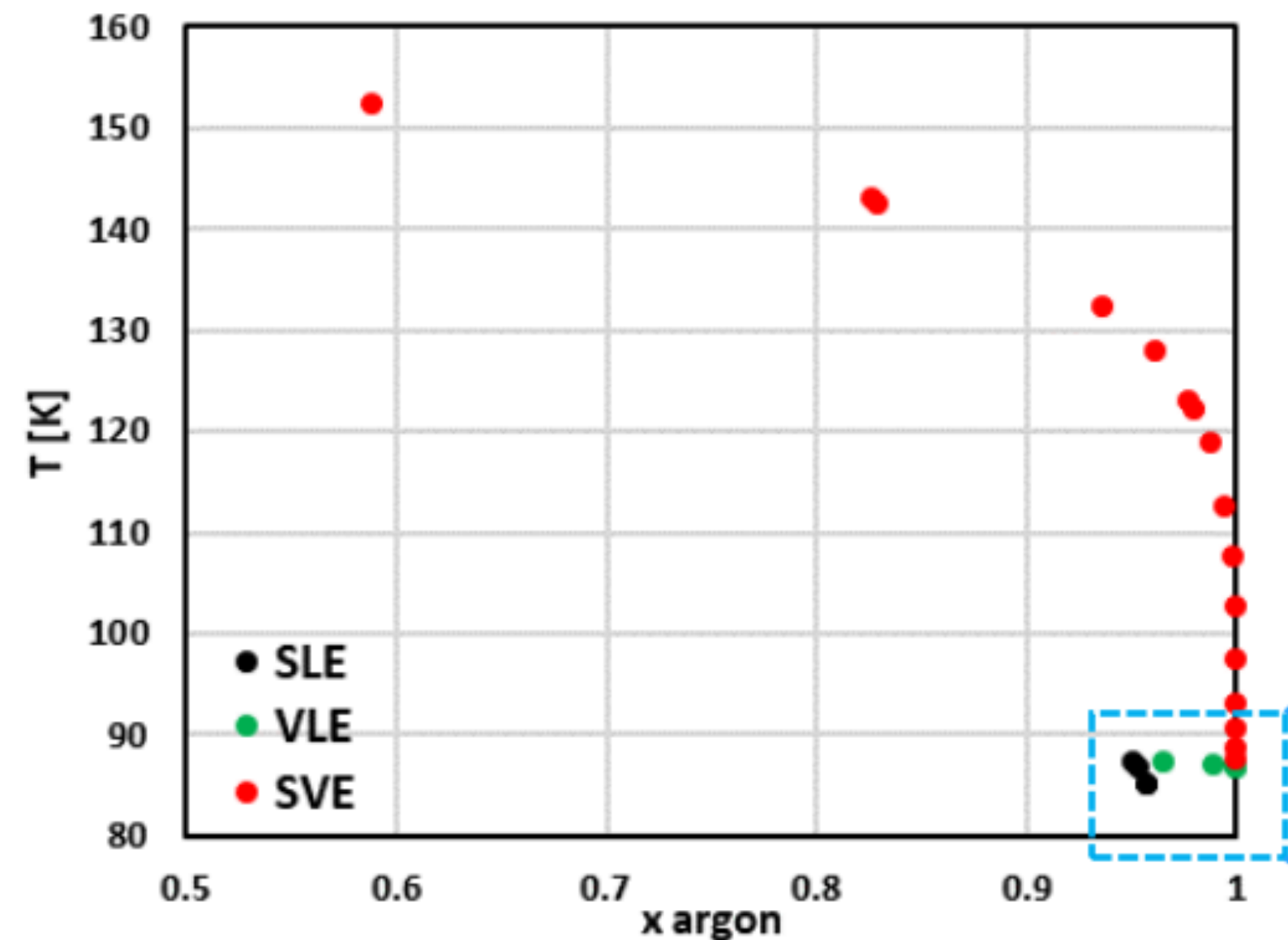
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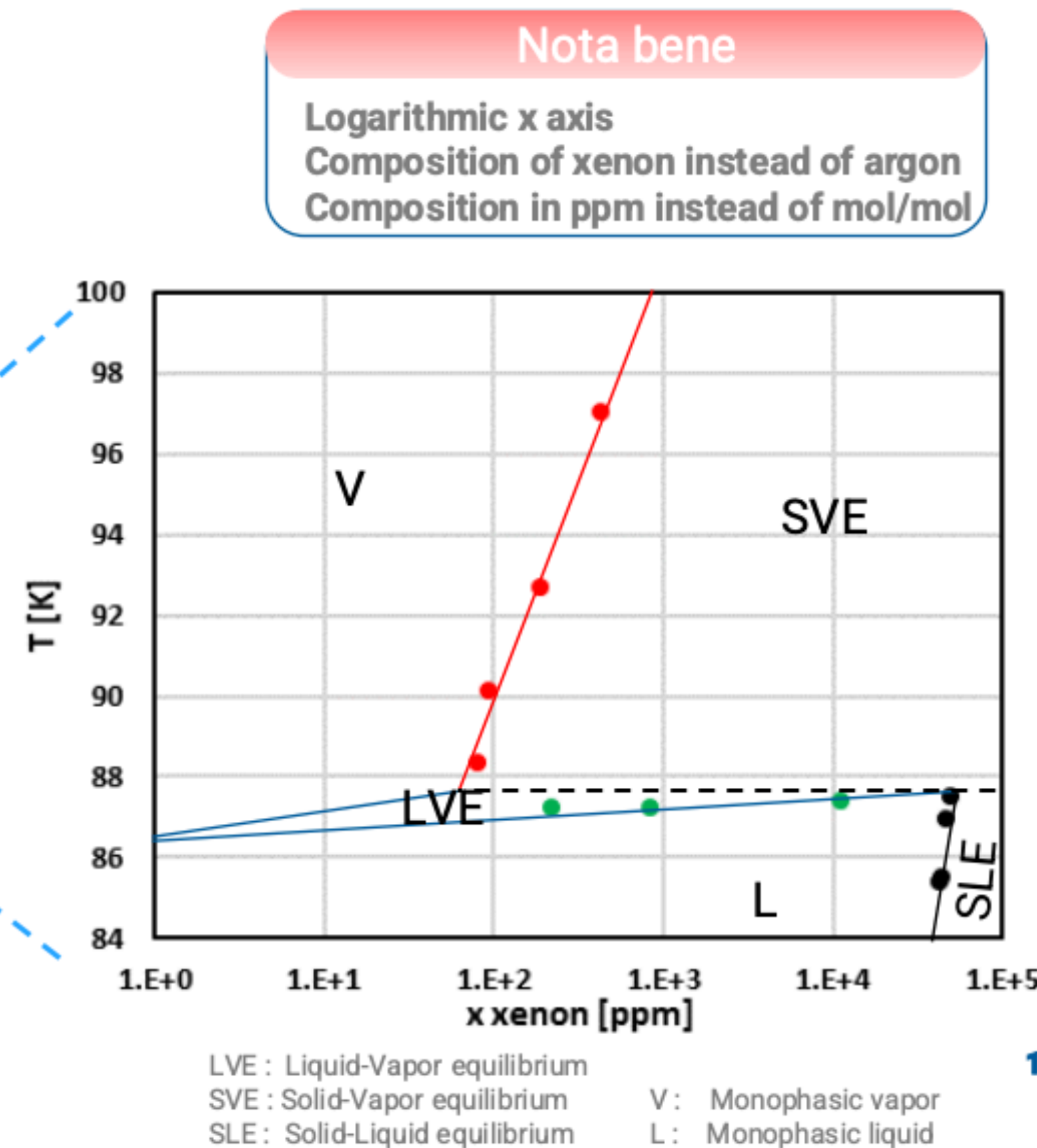
J. Phys. G: Nucl. Part. Phys. 52 (2025) 045102

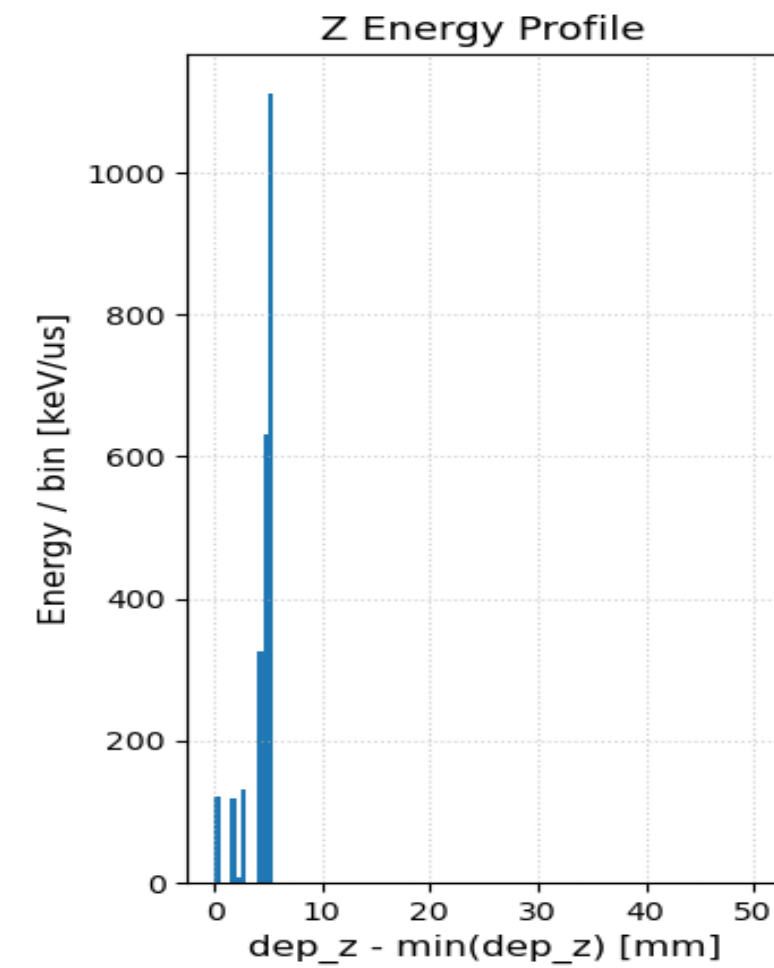
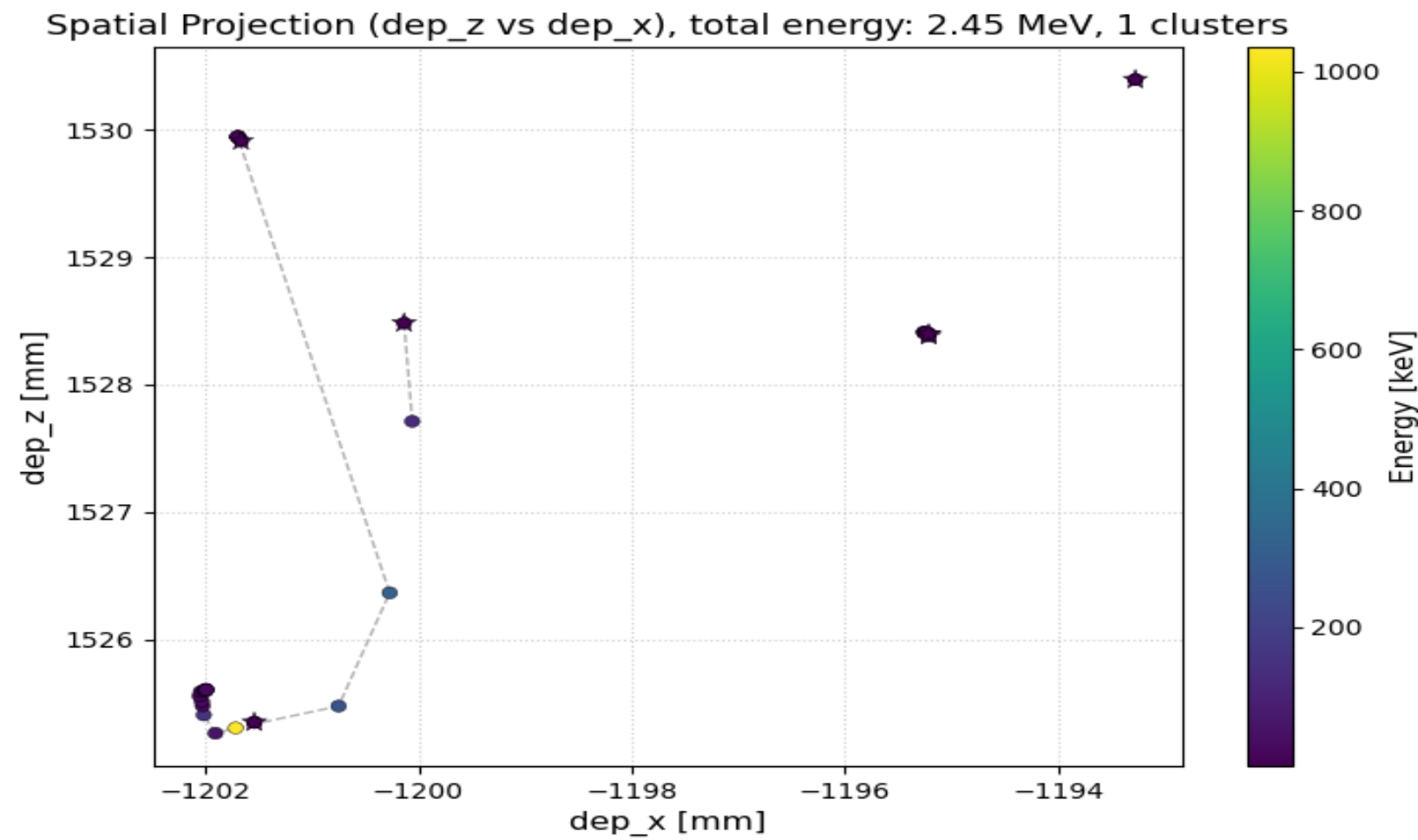
Experimental results

Global Temperature-composition diagram of xenon+argon system at 1 bar



- The solubility of solid xenon in liquid argon is of about 5%
- The solubility of solid xenon in vapor argon is lower than 100 ppm





The main bg topology is:

2.45 MeV γ penetrates in the TPC, travelling 10's cm (attenuation is ~ 15 cm).

Makes a first Compton depositing most of its energy

The surviving low energy γ ($< \text{few } 100\text{'s keV}$) travels a short distance before being converted (photoelectric effect)

It is likely that the event is quite compact, but the typical size of the reconstructed cloud of energy deposits appears to be larger than the typical size of a $\beta\beta 0\nu$ event.

I think it is not unreasonable to imagine that a smarter pulse finder would be able to separate the two interactions

