Review of Xenon Detector Technologies

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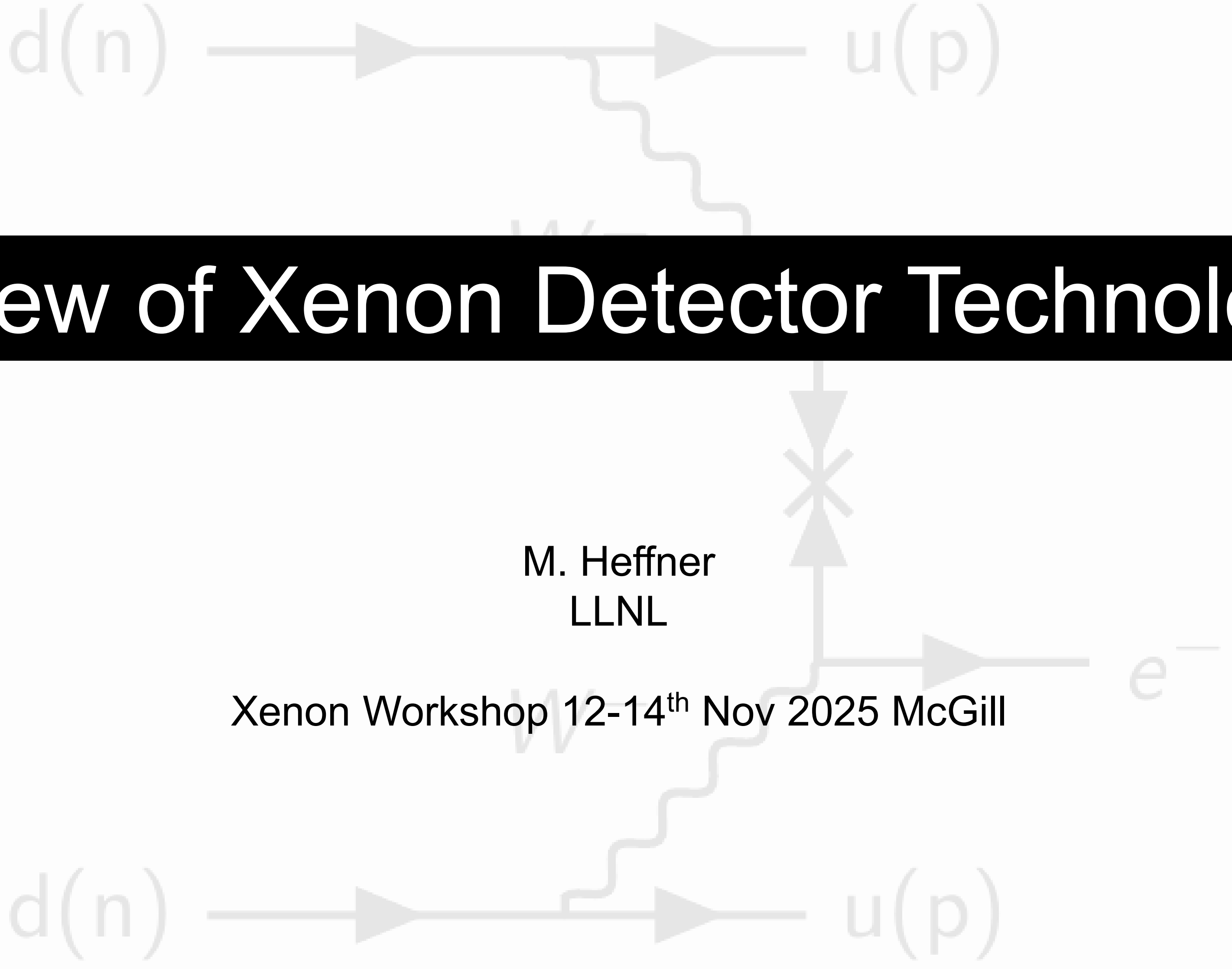
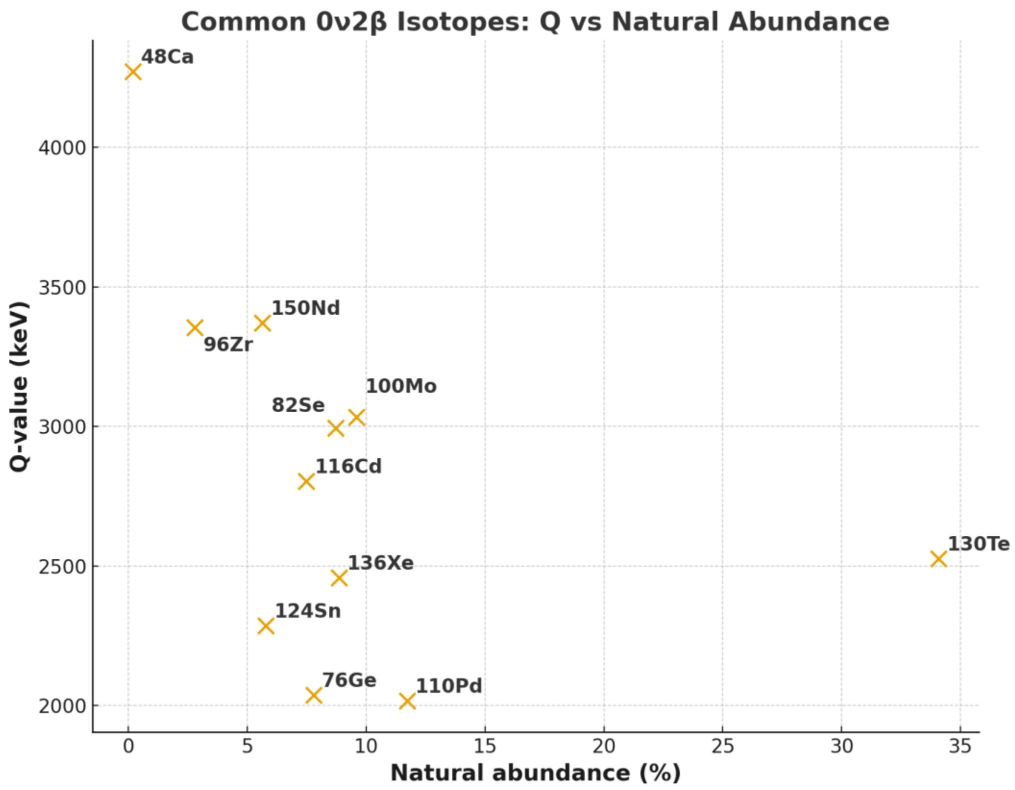
Xenon Workshop 12-14th Nov 2025 McGill



Why Xenon?

<u>Xenon</u>:

- High Density
- Good Self-shielding
- Excellent scintillation and ionization properties
- Non toxic
- Commercially produced
- Good electron drift properties (easy to clean)
- Competitive Q and abundance
- Large noble gas TPCs already demonstrated at scale
- Scaleable to 10^{30} yr sensitivity
- The only gas or liquid of the 11 $0\nu2\beta$ isotopes with Q>2MeV
- ...



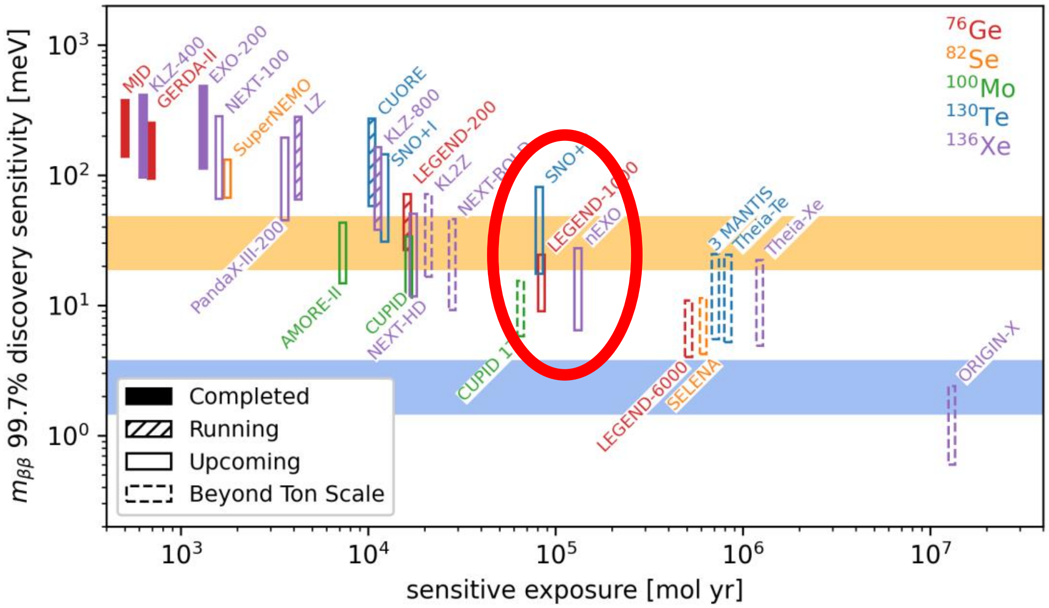
<u>Issues for Xenon:</u>

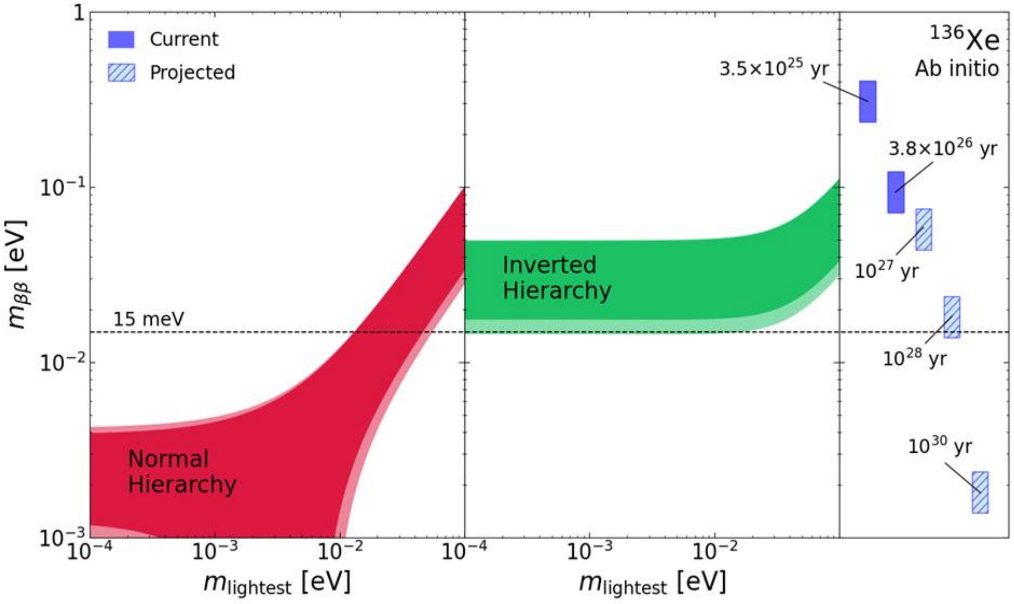
- Cost of the xenon
- Close ^{214}Bi line (~10keV away)

Why Xenon? (Plausible scaling to 10^{30})

Detector technology			Isotope acquisition	External backgrounds	Internal backgrounds	Energy resolution ($2\nu\beta\beta$)	Isotope mass fraction (solar ν)	Detector technology maturity (kton scale)
Segmented detectors								
	HPGe		?	✗	?	✓	✓/?	✗
	Bolometers		✓/?	✗	?	✓	✓/?	✗
	Tracking/CCDs	Se based	✓	?/✗	?	✓	✓	✗
Monolithic detectors								
	Liquid scintillator	Te doped	✓	✓	?	✗	✗	✓
		Xe doped	✗	✓	✓	✗	✗	✓
	TPCs	Gas Xe	✗	✓	✓	✓	✓	✓/?
		Liquid Xe	✗	✓	✓	✓	✓/?	✓
		Xe doped Ar	✗	✓	✗/?	✗/?	✗	✓
		SeF_6 (ion drift)	✓	✓	?	?	✓/?	✗

Why Target >10^{28} Year Sensitivity?
…and Build the Experiment ASAP





- LEGEND-1000 and Cupid have projects now for the equivalent of ~10^{28} yr
  - Sets the minimum standard for new projects to be relevant.
- KamLAND-Zen is making progress toward 10^{27} yr.
- Activity in China also adds time pressure.

What is required to get 10^{28} yr?

Radioactive Decay

$$\frac{dN}{dt} = \frac{ln(2)}{T_{1/2}} N$$

Half life(yr)	Events/tonne/yr*
10^{26}	30
10^{27}	3
10^{28}	0.3
10^{29}	0.03
10^{30}	0.003

*for xenon

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Mass required for 1 decay/year

Half life [yr]	Atoms	^{76}Ge [t]	^{100}Mo [t]	^{130}Te [t]	^{136}Xe [t]
10^{27} years	1.4x10^{27}	0.18	0.24	0.31	0.32
10^{28} years	1.4x10^{28}	1.82	2.4	3.11	3.26
10^{29} years	1.4x10^{29}	18.2	24	31.1	32.6
10^{30} years	1.4x10^{30}	182	240	311	326

Xenon detectors

Detector Type	Phase	Example Experiments
Gas TPC	Gas	NEXT, PandaX-III, Gotthard
Liquid TPC (single-phase)	Liquid	XMASS, EXO-200
Dual-phase TPC	Liquid/Gas	XENON, LUX, LZ, PandaX
Xe-doped Liquid Scintillator	Liquid	KamLAND-Zen
Wire Chamber / Proportional Counter	Gas	RXTE, X-ray astronomy
Ar–Xe Mixtures	Liquid	R&D
Solid Xenon	Solid	R&D
Negative-ion / Digital TPC	Gas	R&D

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Advantages of the TPC types

Gas

- No Cryogenics
- Excellent Energy resolution
- Long tracks for topology
- Tune-able cherenkov discrimination
- Easier staging
- Current 0v2B limit:
  - 5.5-13x10^23yr

Liquid

- Self-shielding
- Project most advanced
- Current 0v2B limit:
  - 5.6x10^25 yr EXO-200

Dual-phase

- Self-shielding
- Low energy threshold
- Other physics (DM, etc)
- Current 0v2B limit:
  - 2.1x10^24 PandaX-4T

Any of these could in principle reach 10^{28} yr sensitivity

Proposal #1

Decide on one detector for the whole xenon TPC community.

- **Advantages**: Substantial cost savings, aligned community would be very effective with sponsor(s)
- **Problem**: Which technology? There are many details and each scientist has different intuition about what path to take (technically and politically) and even differences in goals.

I think this would get us a 10^{28} yr result the fastest, but can we do it?

How to Make Progress…

- While we consider proposal #1, what can we do to work in that direction, or at a minimum not destructively interfere?
- Is there any *significant* disadvantage to work more closely as a xenon community?
  - Workshops
  - Shared technical projects and resources
  - …

Proposal #2 (not mutually exclusive)

Form a consortium (or similar) to make it easier to work together on projects.

- **Advantages**: Maybe lower cost a bit, leverage the entire community, show funding agencies that we are serious and can work together.
- **Disadvantages**: Collaborations letting go of some control, possible irreconcilable differences in goals, requires lots of communication, may not be stable against a few disruptive folks, <u>likely to be the slowest path</u> after not working together at all, etc...

Some Ideas of Common Interest

- **Xenon Acquisition** (both natural and enriched)
- High Voltage Testing and Research in Xenon
- Co-locating experiments to share hardware
- Staged experiments using the same shielding
- Radioassay
- Improved photon sensors and electronics
- Improved microphysics
- Common simulation and sensitivity assessment tools
- DAQ and controls

Xenon Acquisition

Slide from Thomas

Challenge Xe Procurement (in tonnes)

* extrapolated

	Experiment	Natural Xe req.		Xe enriched at 90%
0νββ	nEXO	**51 t***	←	5 t
0νββ	NEXT-HD	**10 t***	←	1 t
0νββ	NEXT-HDMM	51 t – 101 t	←	5 t - 10 t
DM/ Multi purpose	XLZD	60 t active **(78 t)**		
DM/ Multi purpose	XLZD	80 t active (100 t*)		
DM/ Multi purpose	PandaX-xT	43 t active **(56 t*)**		
	Total Xe req.	**202 t**		

Experiment	Natural Xe		Enriched Xe
EXO-200	**1.8 t**	←	~200 kg (@80%)
NEXT-100	**1.1 t**	←	~100 kg (@90%
KamLAND-Zen	**7.7 t**	←	~750 kg
XENONnT	**~10 t**		
LZ	**~10 t**		
PandaX-xT	**~20 t**		
Total Xe av.	**50.6 t**		

Crude assumptions (on entire slide!):

- Proposed next-generation experiments will require ~200 t of ^{nat}Xe by ~2035.
- Experiments hold 51 t equivalent ^{nat}Xe (40 t ^{nat}Xe and 1 t ^{136}Xe @90%).
- Global xenon production is estimated to be between 50
- Assumption: Order of 5 t/yr of Xe plausibly procurable w

Largest single cost (after labor)
$1.2 - $4 per gram as of 2024
Enrichment $10 - $15 per gram

Xenon Acquisition

- China has made a big impact on the availability Perhaps this solves the interference in the market to some degree, but that needs to be looked at more carefully.
- How can we share the xenon? Discussed at kilotonne workshop and informally between experiments.
- **Proposal #3** : *Develop a community plan for xenon acquisition.*

Conclusion

- We have the xenon TPC technology in hand to make some really great advance on important physics.
- The costs presented by the fragmented community appear to be a significant impediment.
- Perhaps we should think about a different path:
  - P1: Decide on one detector for the whole xenon TPC community.
  - P2: *Form a consortium (or similar) to make it easier to work together on projects.*
  - *P3: Develop a community plan for xenon acquisition.*
  - *P4 - Pn: ….Other ideas from this workshop*

END

Signals in Xenon relevant to 0n2b

- Scintillation Light
- Charge
- Phonons
- Cherenkov
- Ba ion detection
- Electroluminesce

Readout Technologies

- Charge collection electrodes (pad, wires, etc)
- Townsend avilanche on to electrode
- PMT/ SiPM
- GEMs/ Micromegas