Xenon Recovery from Used Nuclear Fuel

For Tests of Fundamental Physics

Regan Ross, June 23 2026

CAP Congress 2026

The Standard Model

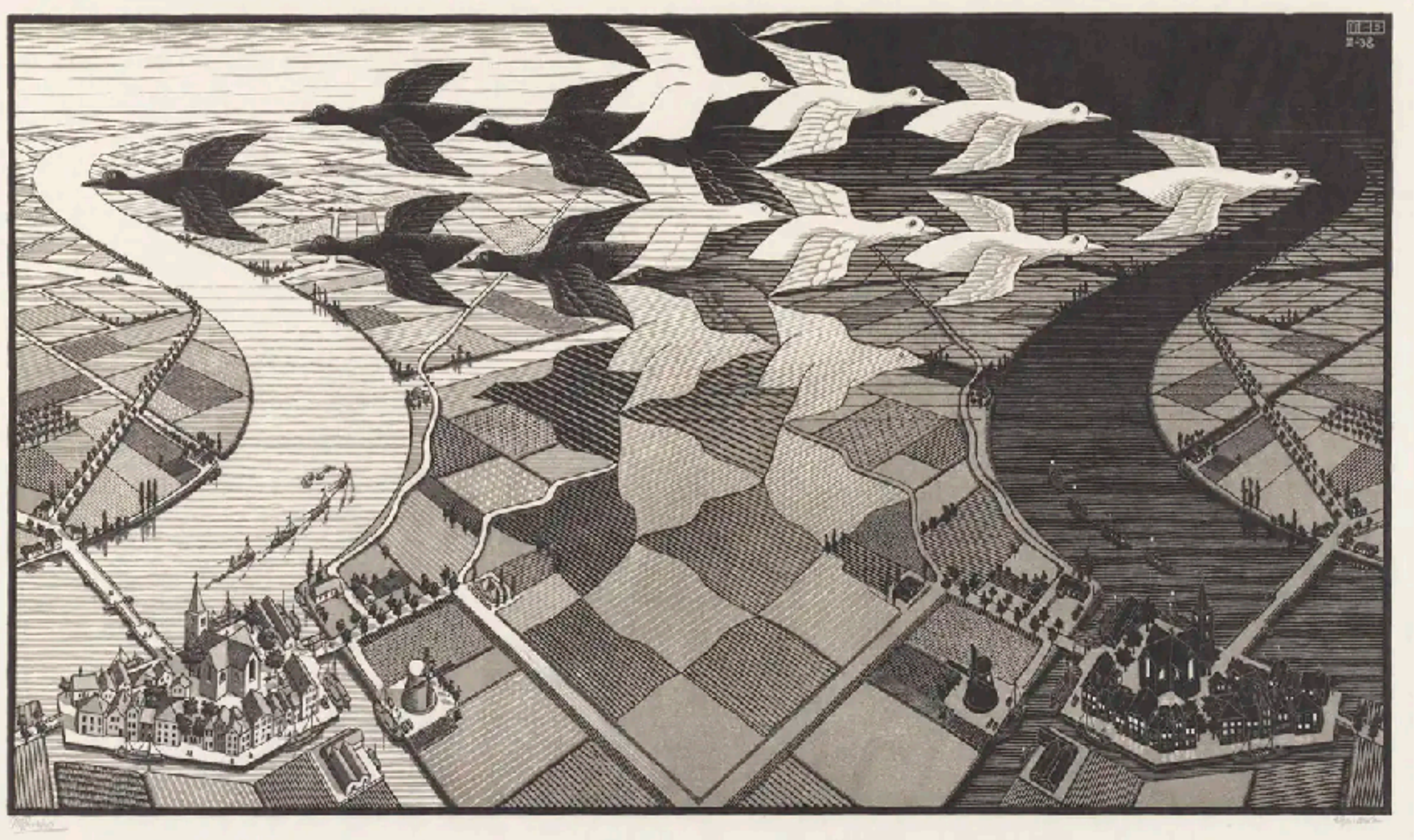
The SM has been extremely successful in describing particles and their interactions—even predicting the existence of new particles.

However, we know it is incomplete.

Baryon Asymmetry

Physics is symmetric under the interchange of particle and anti-particle

But we see only *matter*, not *antimatter* in the universe.



Dag und Nacht, M.C. Escher, 1938

Neutrino Masses

Neutrino masses are much smaller than other particle masses

The SM has little to say about their mass generation mechanism, their oscillatory nature, or their absolute mass scale

Le chant d'amour, R. Magritte, c. 1962

Neutrino Masses

Neutrino masses are much smaller than other particle masses

The SM has little to say about their mass generation mechanism, their oscillatory nature, or their absolute mass scale

Or their mass ordering

Ceci n'est pas un neutrino, R. Magritte, c. 2026 (AI)

Still life Reslicitando, R. Varo, 1963

Dark Matter

There is abundant evidence for celestial mass of an unknown nature:

Conflicting predicted and measured galactic rotation

Gravitational lensing (strong and weak)

Galaxy clustering dynamics

Cosmology and large scale structure formation in the universe

My advice is to go for the messes - that's where the action is.

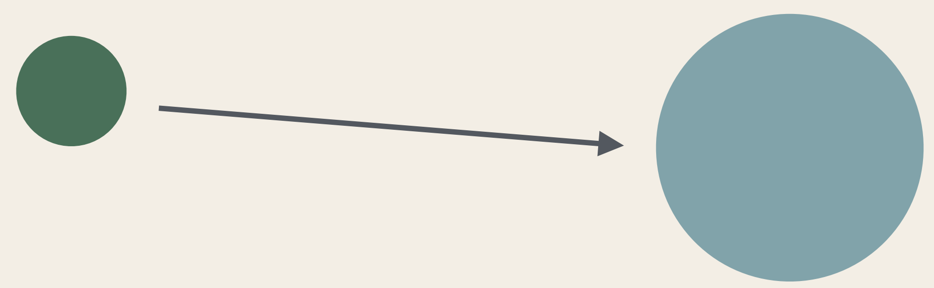
Steven Weinberg, McGill Science Convocation, 2003

The “Rare Event Search”

Searches for two kinds of hypothesized events:

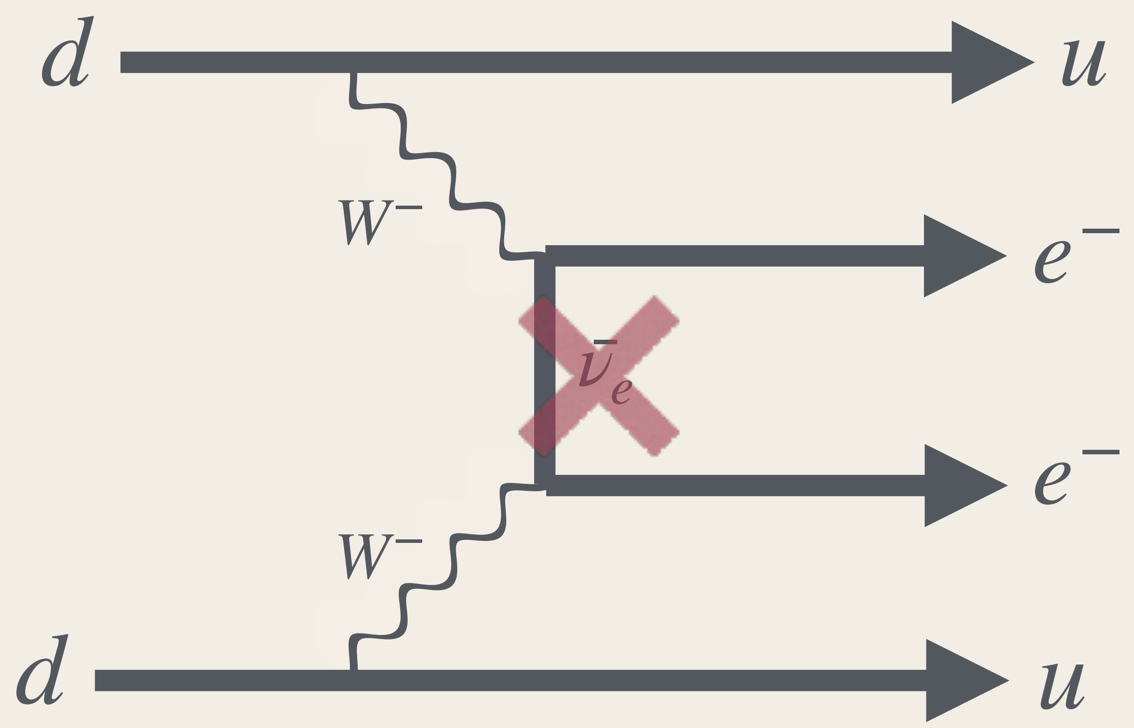
Dark matter - nuclear interaction

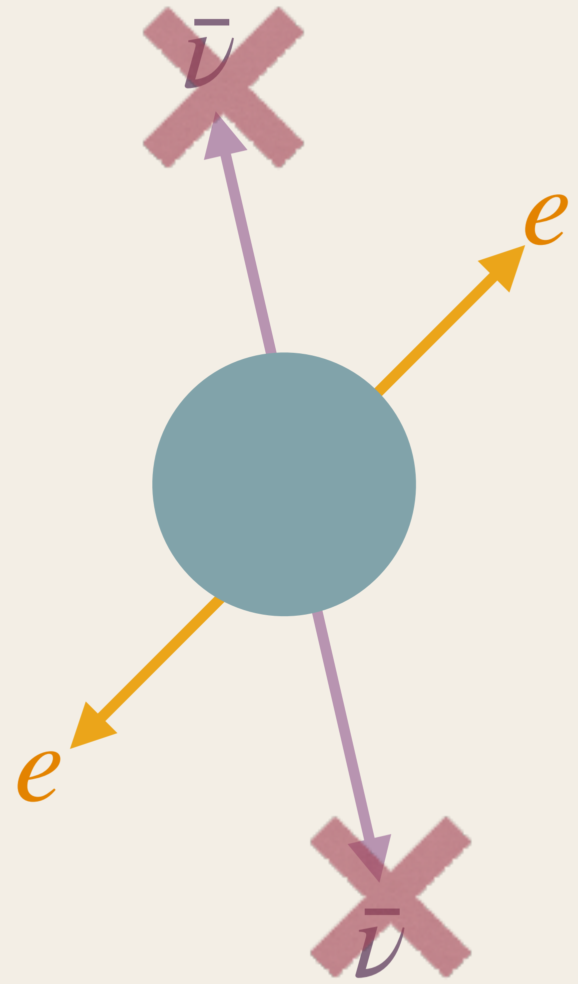
- DM scatters with nucleus
- Produces detectable signal
- Would establish particle nature of DM
- Establishes DM mass scale



Neutrinoless Double Beta Decay

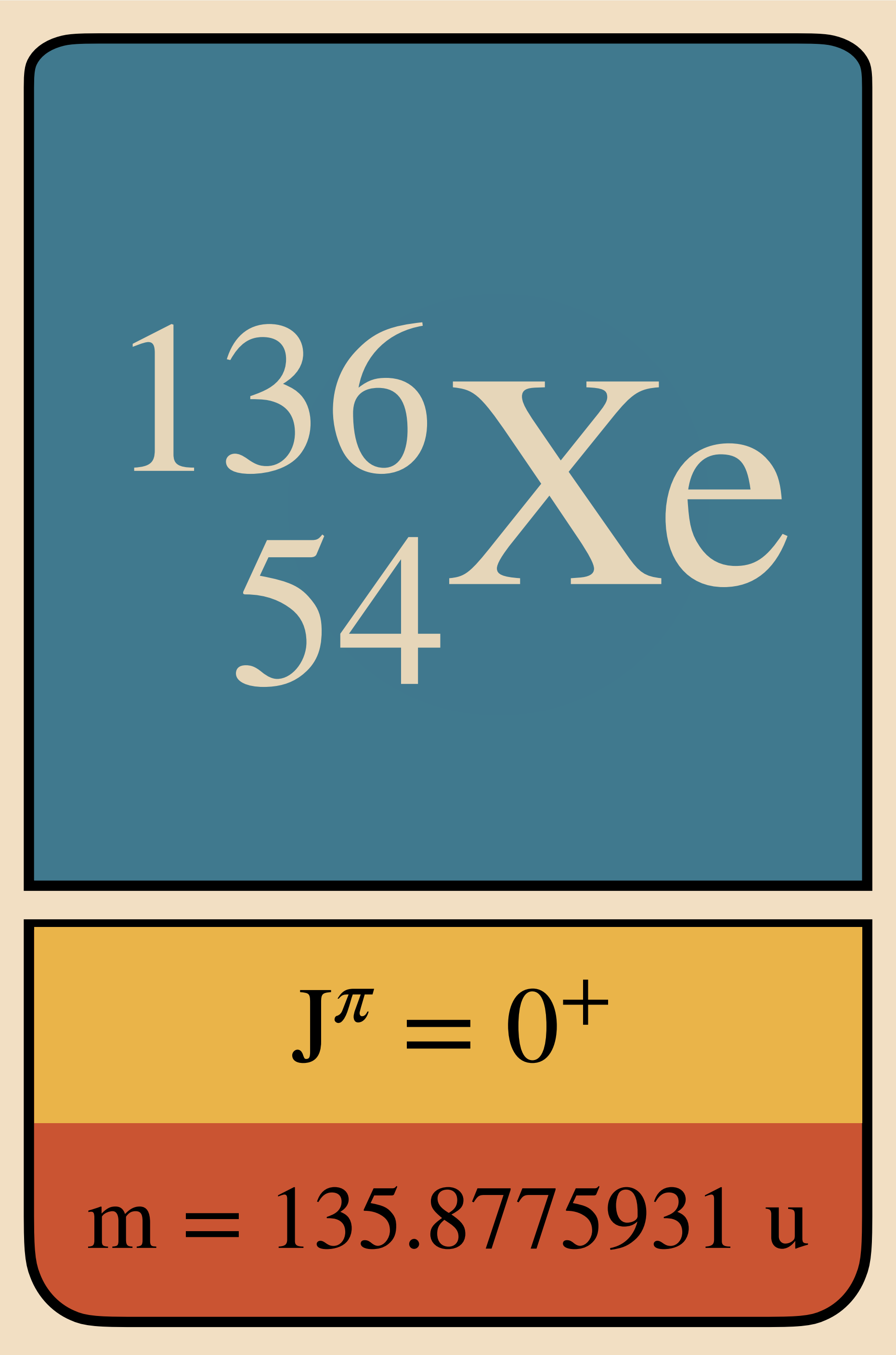
- Electrons emitted with equal and opposite momentum
- “Leptogenesis”
- Tells us about neutrinos





The Nucleus as a Laboratory

- Undergoes double beta decay
- Heavy nuclei are good for DM detection
- Strong scintillation and ionization signals possible
- Can be liquefied at ~ 165K
- Chemically inert
- *Comparatively* high natural abundance



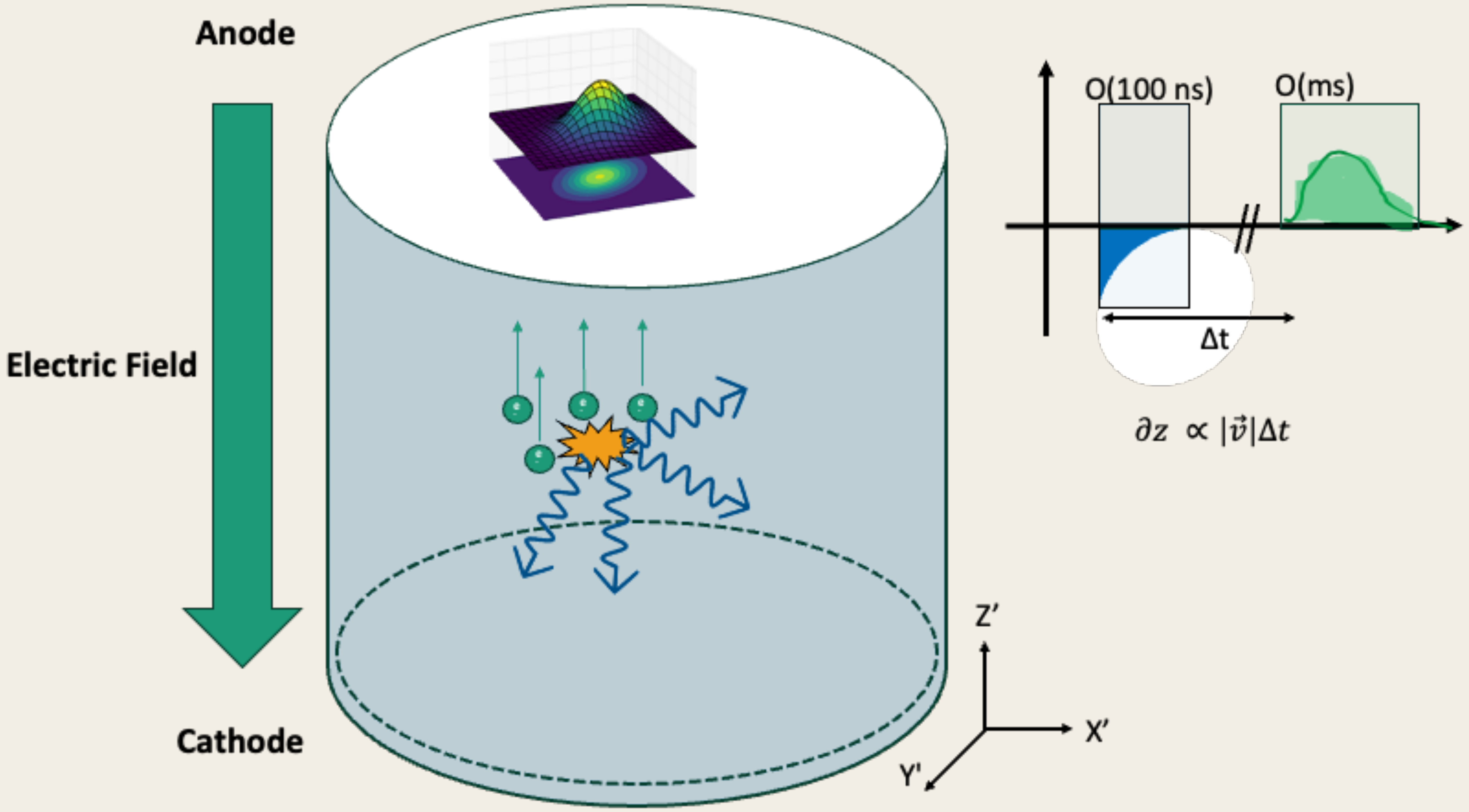
Xenon Time Projection Chambers

For 0νββ and Dark Matter Searches

- Xenon time projection chambers (TPCs) have been continuously improving for over 2 decades

- They leverage xenon's favourable properties to detect light, charge, event position and topology.

- Event parameters and self-shielding provides background discrimination



D. Gallacher

0νββ Candidate Isotopes

should meet the following criteria:

- High natural abundance; large N
- Fine energy resolution; small ΔE
- Few intrinsic backgrounds; small B
- Easily discernible 0νββ signal
- Feasible to work with

$$T_{1/2}^{0\nu} \leq \frac{\epsilon \ln 2 \sqrt{Nt}}{\sqrt{B\Delta E}}$$

0νββ Candidate Isotopes

should meet the following criteria:

$$T_{1/2}^{0\nu} \propto \sqrt{Nt}$$

Xenon-Based Experiments

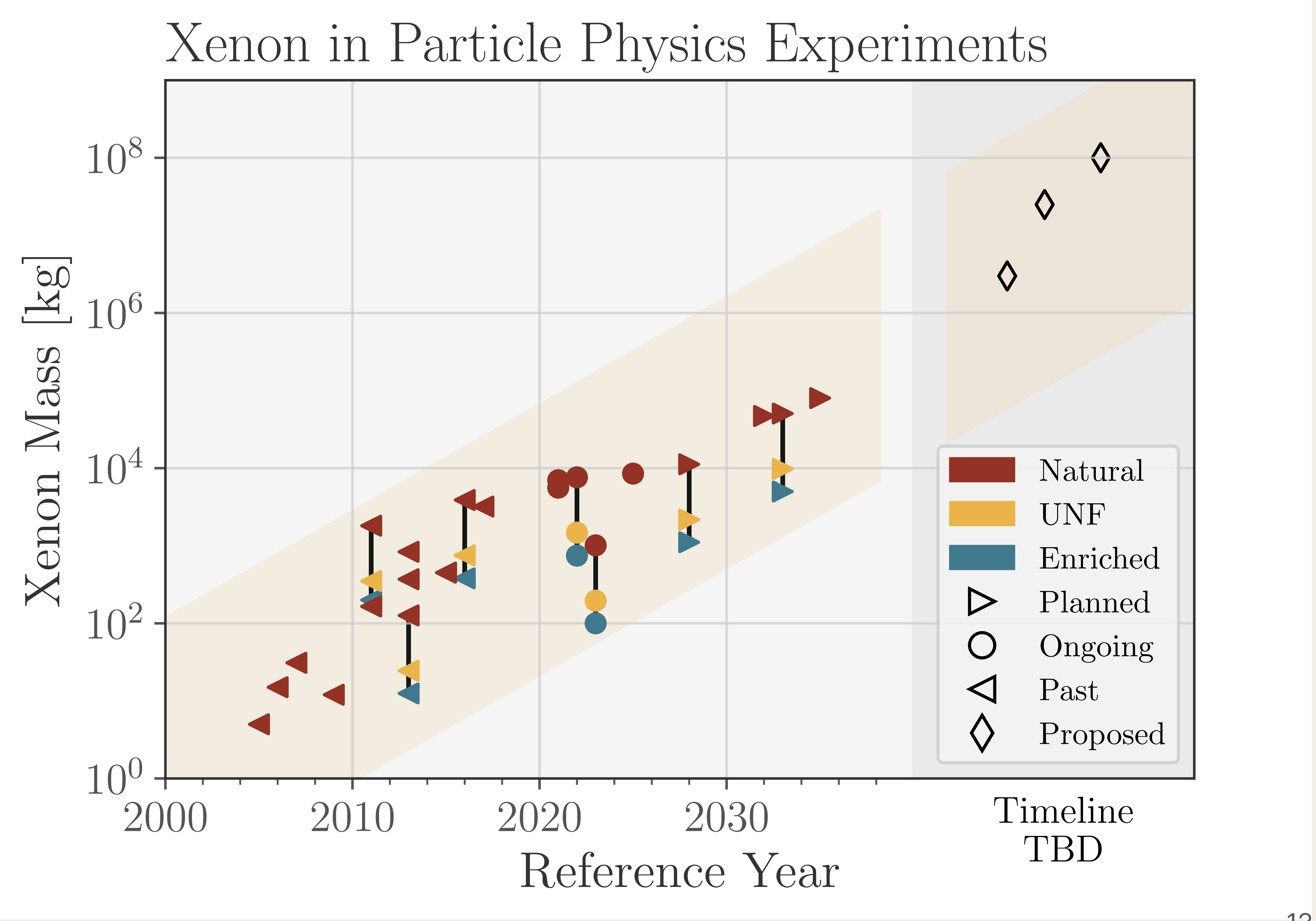
For 0νββ and Dark Matter Searches

There is evident increasing demand for xenon for WIMP dark matter search experiments and 0νββ searches.

Sensitivity scales with mass!

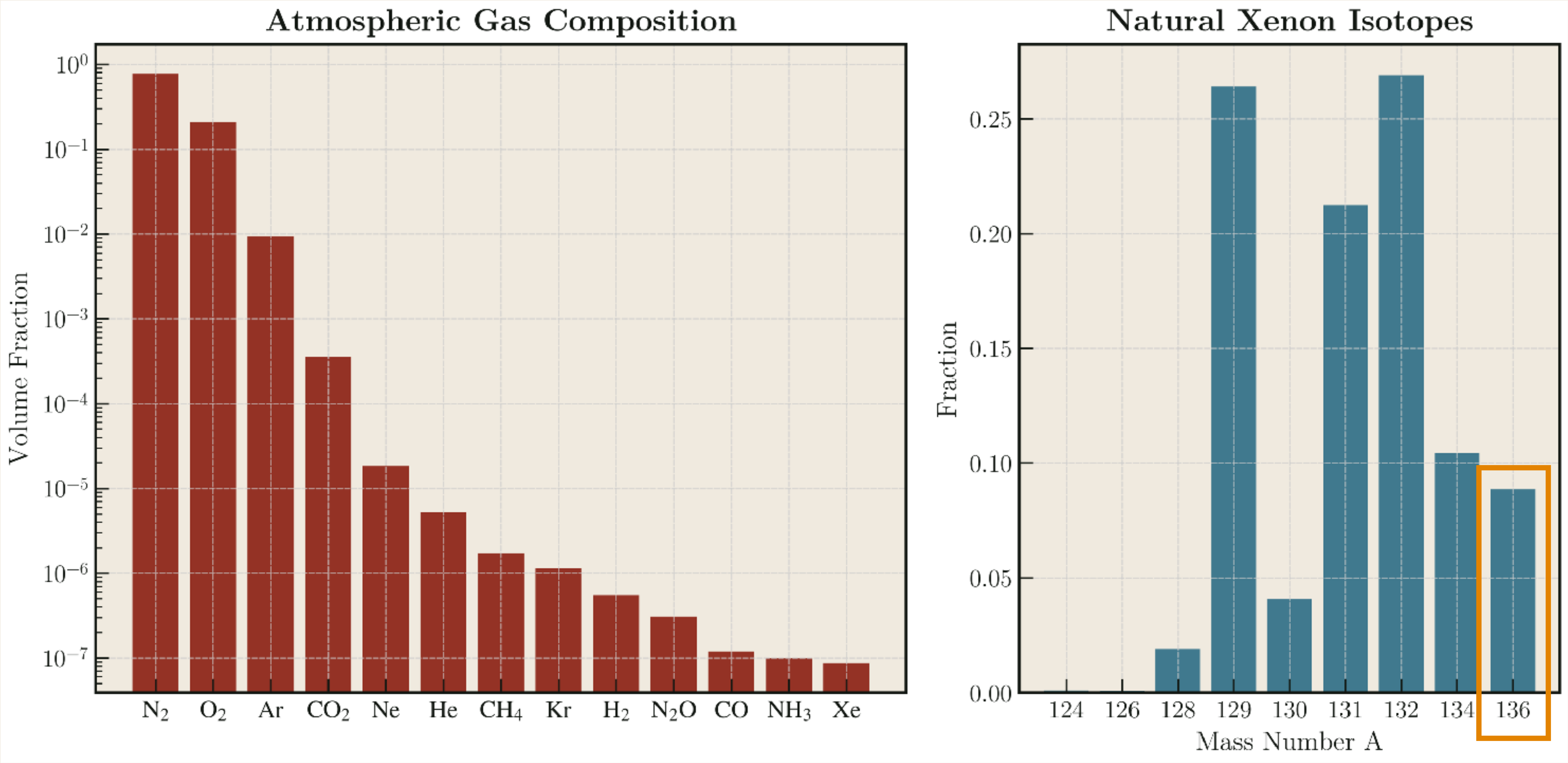
Xenon is becoming the single greatest expenditure!

At ≈ \$5/g, tonne scale experiments can cost \$5M to \$50M / tonne !

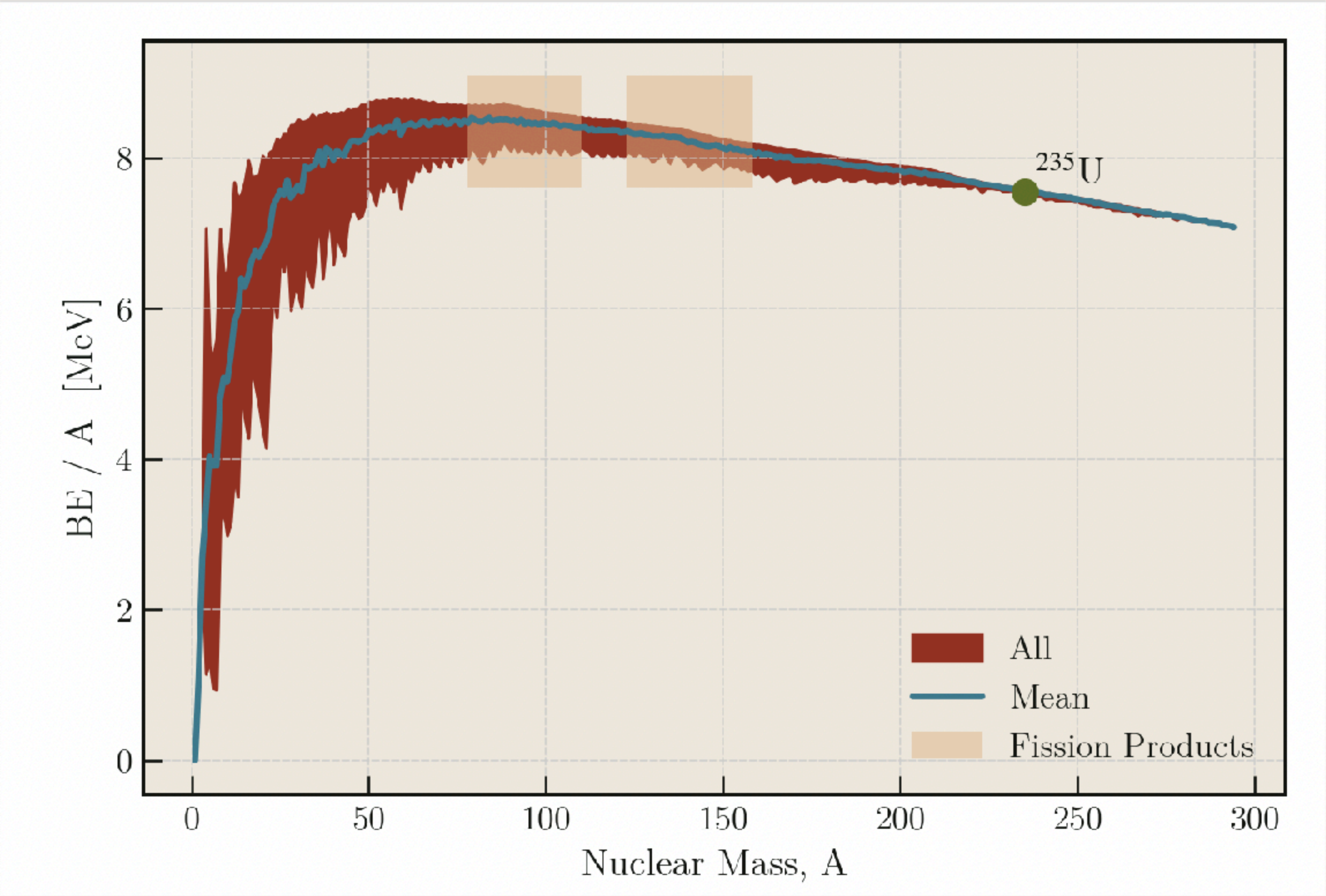


Atmospheric Abundance of Xe

Dilute, but unlimited.



Fission
(of ^{235}U)

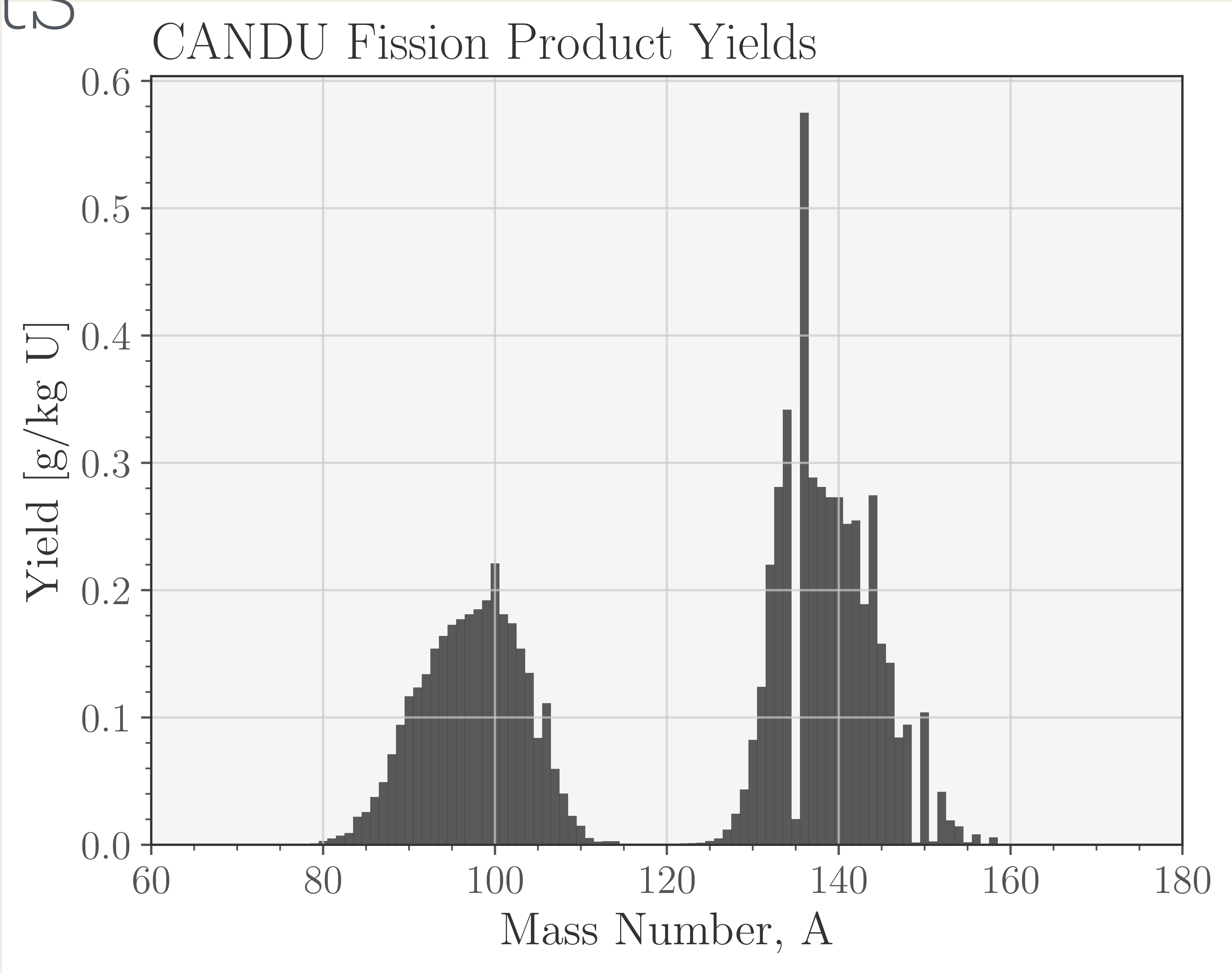


Fission Products

Burnup of 685 GJ/kg U

One year cooled.

CANDU = CANadian Deuterium Uranium



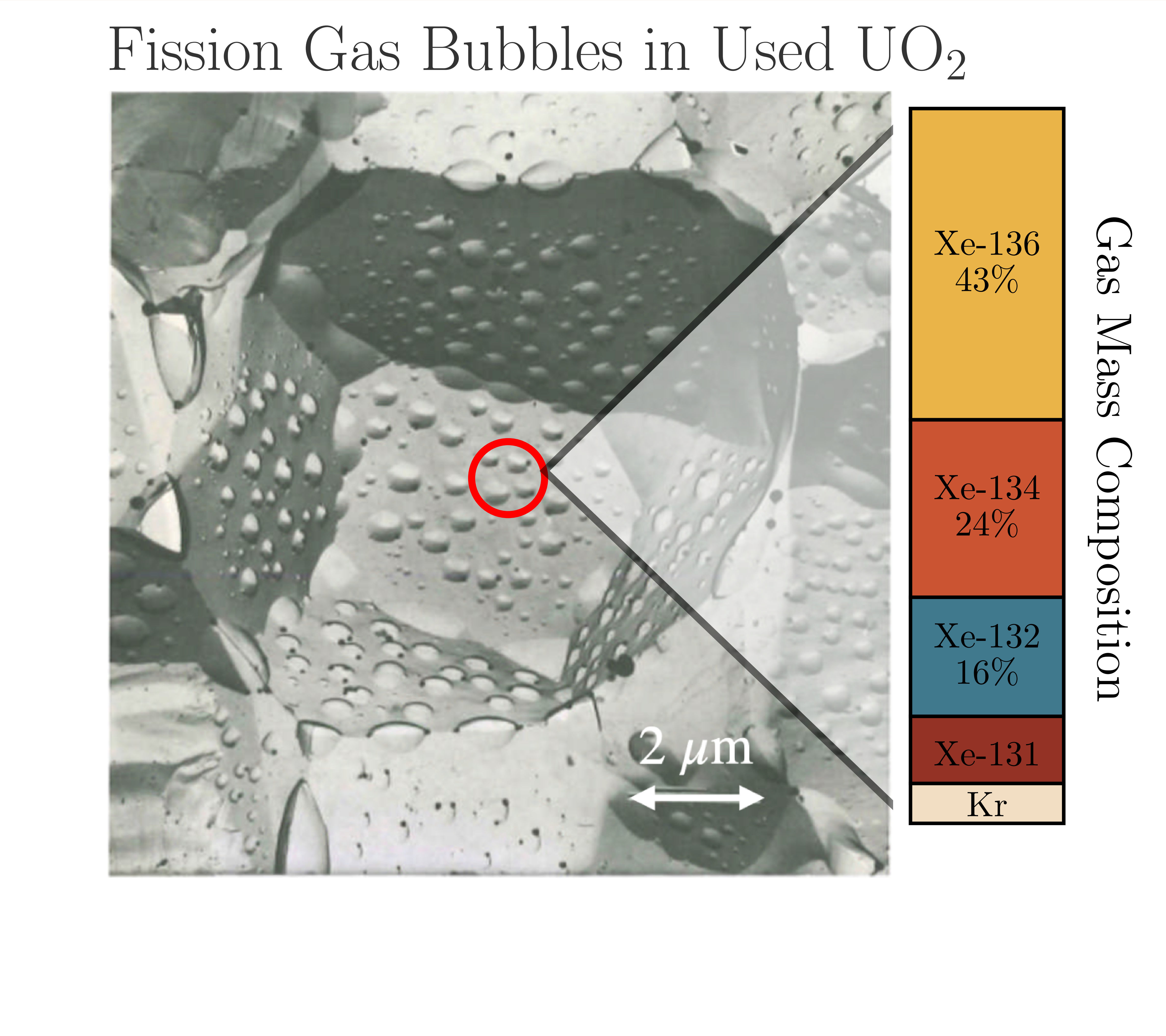
Simulated yields from CANIGEN & ORIGEN codes.

Xenon from Used Nuclear Fuel

An untapped source

Bubbles of Kr and Xenon are trapped in the UO_2 fuel after burn-up. They accumulate at grain boundaries in the metal.

~ 1.5 g of Xenon per kg of U metal



How much is there?

An untapped source

3.3 million used CANDU fuel bundles

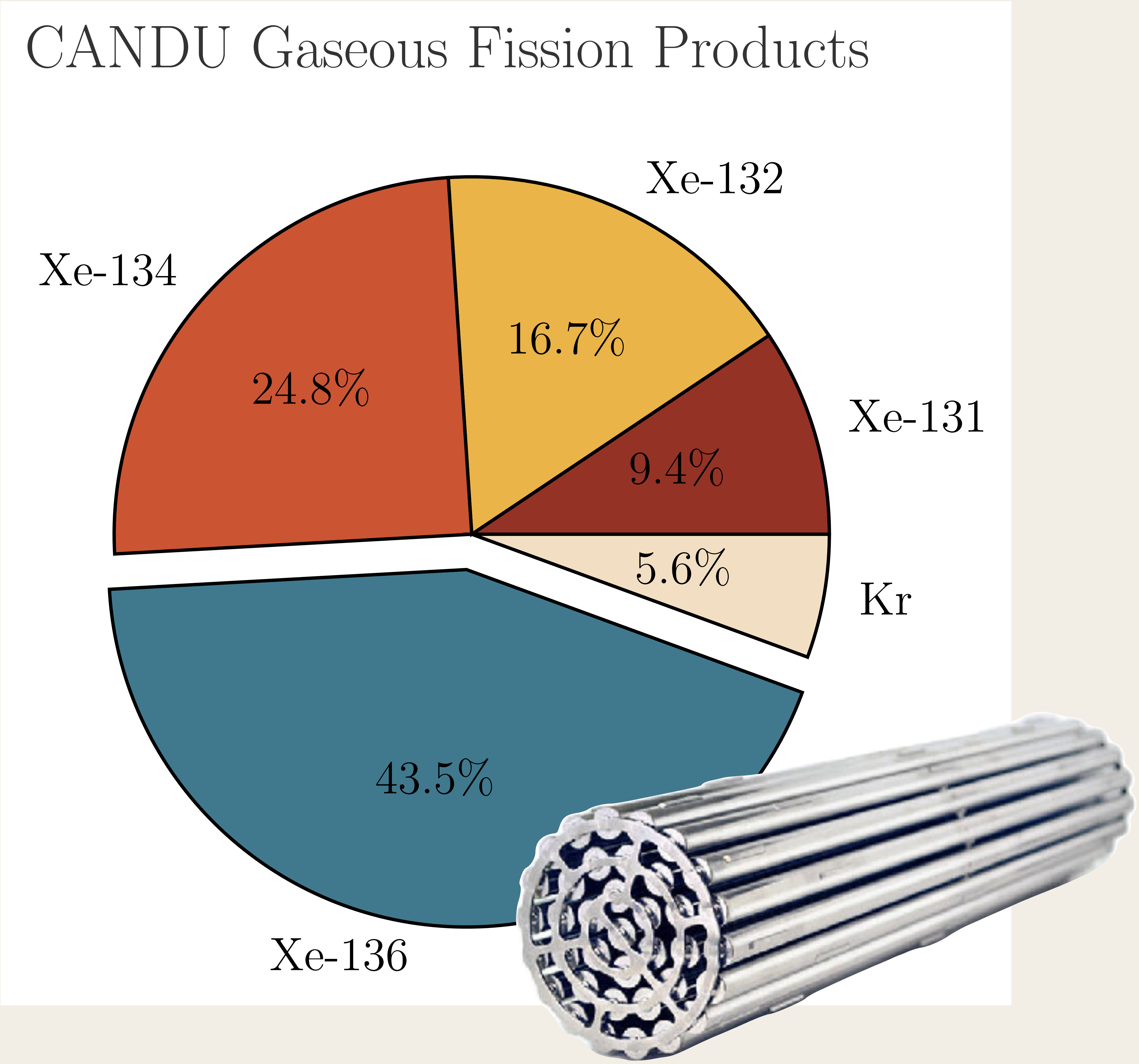
64.260 kt of heavy metal (t-HM)

80 t of xenon ⟶ 36 t of Xe-136

Inventory will **double** by reactor expiration.

Xenon-136 present at about 560 ppm.

14,000 times more concentrated
than atmospheric xenon.

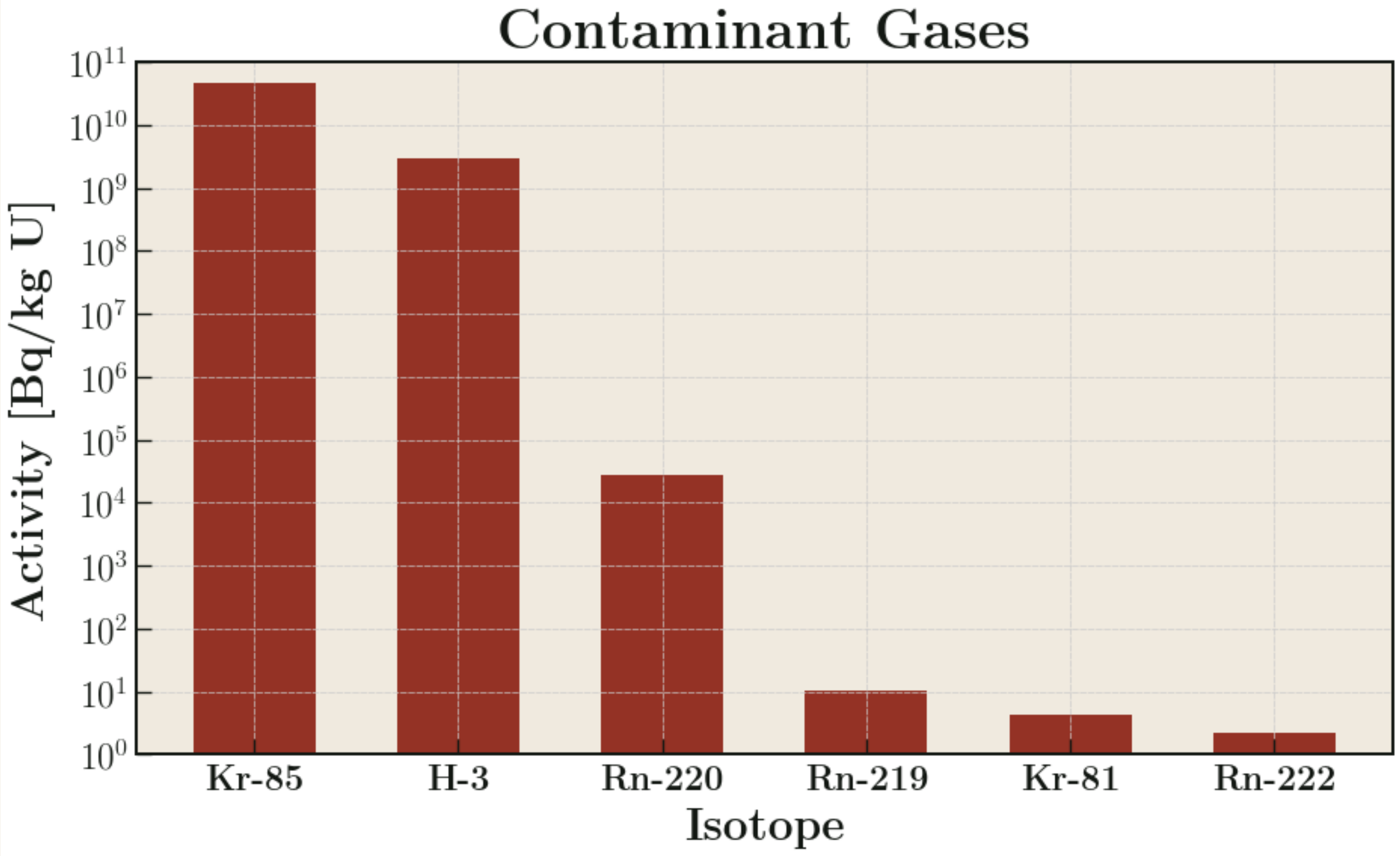


What else is there?

Isotope	Bq/kg U *	$T_{1/2}$	Mode	E (keV)	g/kg U *
^{3}H	2.96e+09	12.32 y	β^-	19	8.27e-06
^{81}Kr	4.26e+00	2.29e+05 y	EC	–	5.45e-09
^{85}Kr	4.55e+10	10.76 y	β^-	687	3.13e-03
^{129m}Xe	0.00e+00	8.9 d	IT	236	3.51e-07
^{131m}Xe	0.00e+00	11.8 d	IT	164	0.00
^{133}Xe	0.00e+00	5.25 d	β^- / γ	427 / 81	0.00
^{219}Rn	1.04e+01	3.96 s	α	6946	2.15e-20
^{220}Rn	2.70e+04	55.6 s	α	6405	7.92e-16
^{222}Rn	2.18e+00	3.82 d	α	5590	3.82e-16

* after 10 years of cooldown

Potential Background Sources



Demonstrable Purification Ability

- **Kr** Removal with Cryogenic Distillation, XENON Collaboration, arXiv:1612.04284
    - Down to < 30 ppq
- **Rn** Removal down to Solar ν Level, XENONnT Collaboration arXiv:2502.04209
    - Down to $< 1\mu$Bq / kg
- **Rn** Removal (from argon) with Silver Zeolites, Dunford et al., arXiv:2505.07979
    - Using novel adsorbents

Operational Challenges

Neglecting bureaucratic friction

- Maximum ~ 1g Xe / element (37 per bundle)
- Fuel elements (pellets) are designed to HOLD gases
- Dangerous (dose rates of 10s to 100s of Sv/hr)
- Experimentation must be done in hot cells

(Pre-irradiation ;)

Operational Challenges

- Hot cells are expensive (~$1000/hr)

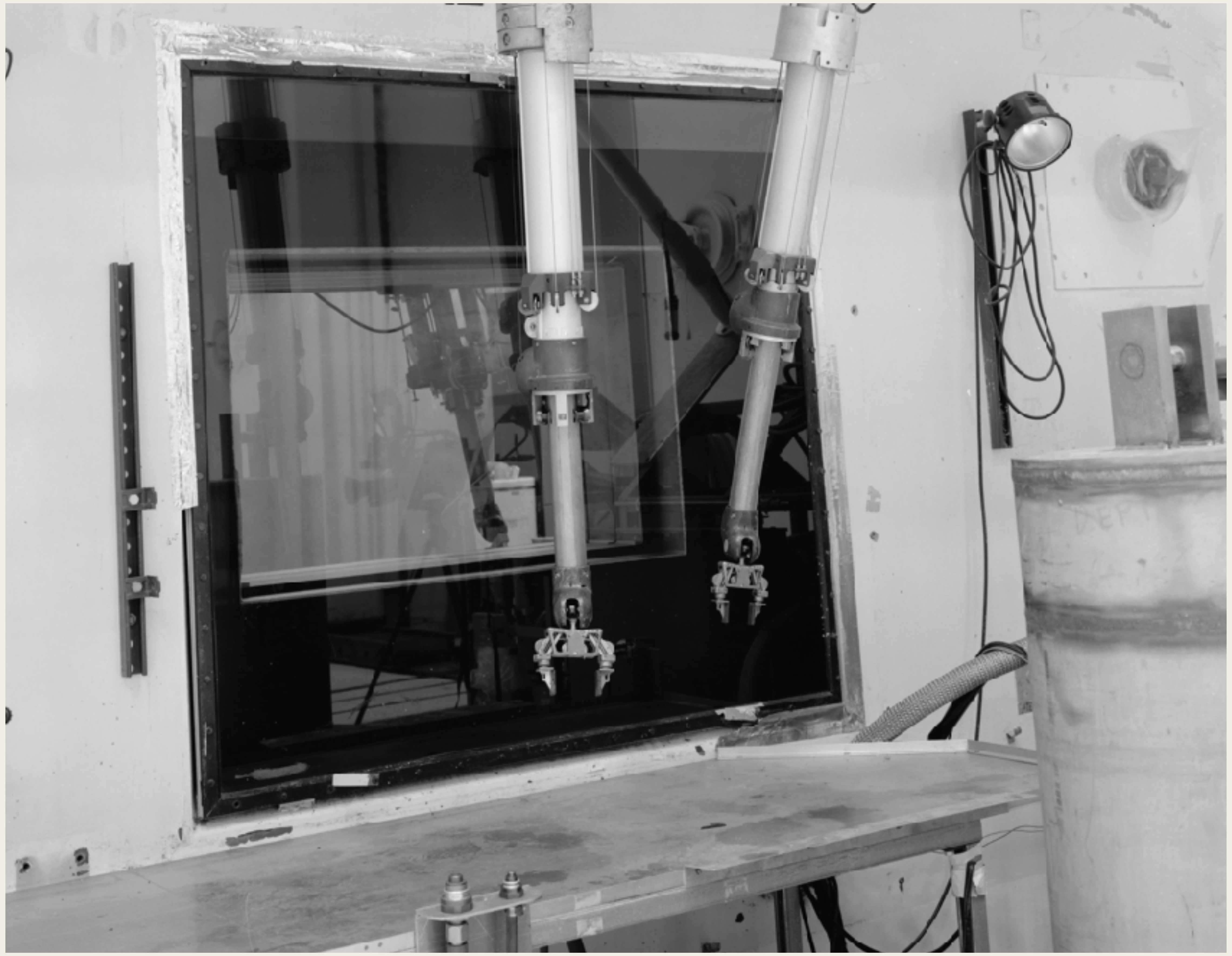
- Instruments in hot cells must be operated by “manipulators”

- Apparatus must be built accordingly

Hot cell at CNL

Operational Challenges

Hot cell at CNL



Hot cell at Nevada Test Site

Operational Challenges

UNF Transportation Cask (DOE)

A CNL Visit

(no photos allowed)

- Extensive facilities for analysis & fuel QA
- Focus on reactor engineering
  (as opposed to basic research)
- Not opposed to collaboration
- Do not have a (real) supply of UNF

CNL on the Ottawa River

Conclusion

Where do we go from here?

Remarks

- Maybe one can dodge the red tape by avoiding chemical dissolution
- The most plausible route is to build a parasitic process on top of *reprocessing*
- Maybe this is worth exploring without the burden of creating a new supply, but merely promoting new science & collaboration

Questions

- What apparatus are available elsewhere?
- Can we construct a lab-scale demonstrator? Is it worth trying?
- Who can help?
- Can discuss collaborating with La Hague?
- Can this grow to support tonne-scale experiments?

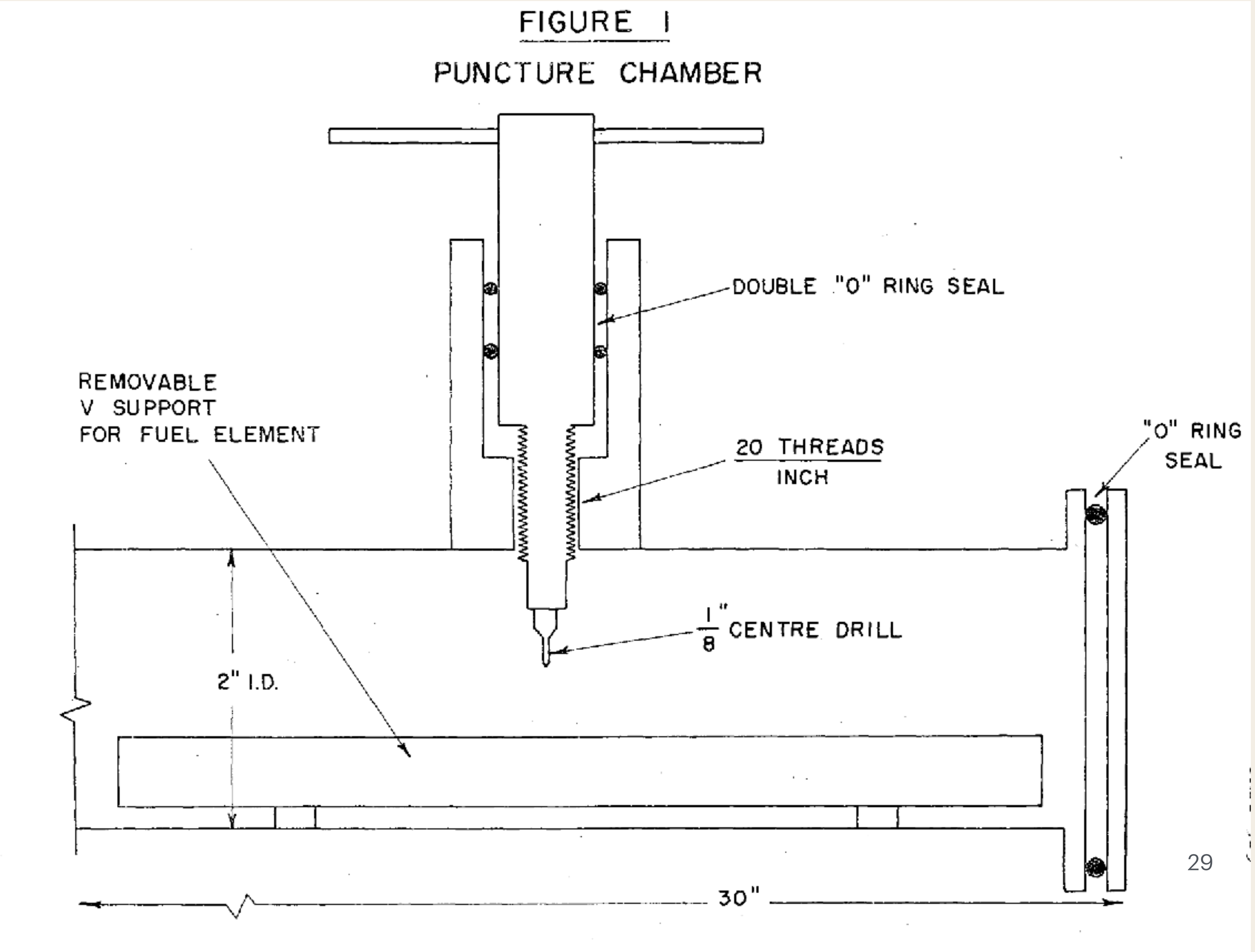
Thank you!

Contact:

Regan Ross, **regan.ross@mail.mcgill.ca**

Previous Work at CNL

Great. Dated, but great.



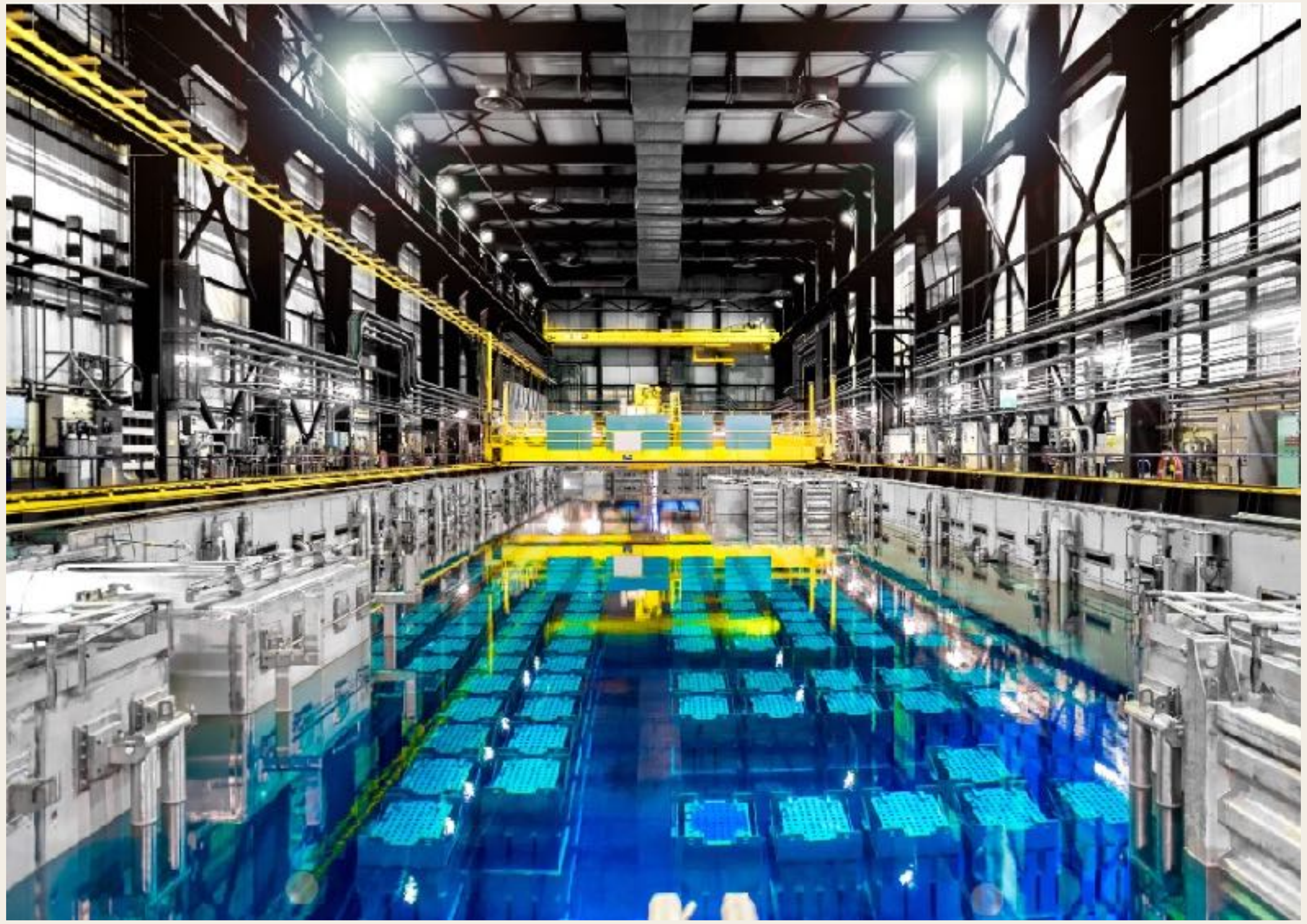
Puncture chamber from Morgan et al., 1960.

Still in use today!

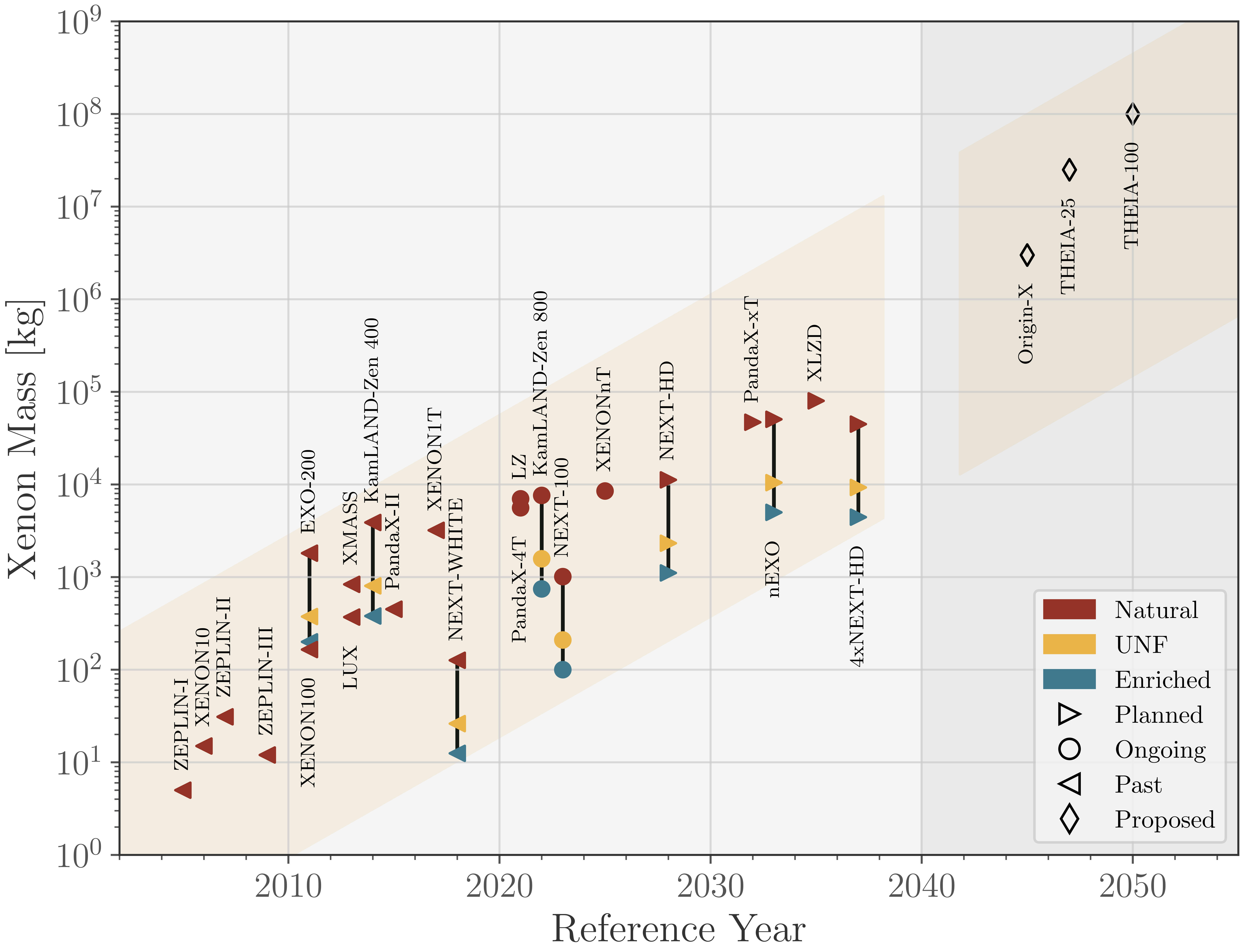
PUREX Process

The current *standard*

- UNF fully dissolved in acid
- Metals precipitated out (U, Pu)
- Gases are generally vented (all of them)
- Gases feasibly captured and purified?



UNF storage at La Hague, France.



Xenon Mass [kg]
Reference Year
2010
2020
2030
2040
2050
ZEPLIN-I
XENON10
ZEPLIN-II
ZEPLIN-III
XENON100
EXO-200
LUX
XMASS
KamLAND-Zen 400
PandaX-II
XENON1T
NEXT-WHITE
PandaX-4T
LZ
KamLAND-Zen 800
NEXT-100
XENONnT
NEXT-HD
PandaX-xT
nEXO
XLZD
4xNEXT-HD
Origin-X
THEIA-25
THEIA-100
Natural
UNF
Enriched
Planned
Ongoing
Past
Proposed