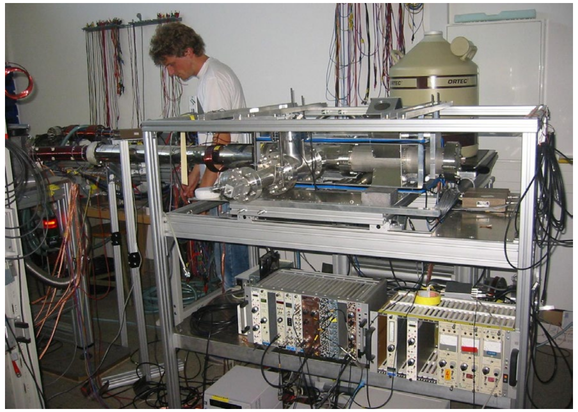
Low-Background Techniques

GRIDS 2026 Summer School

Thomas Brunner
McGill University
June 4, 2026

My Career Path



Studied Physics at the Technical University Munich (2001 – 2011)

- Undergraduate research project
- Diploma thesis (MSc equivalent)
  - Investigation of positronium formation on cold surfaces
- PhD project, stationed at TRIUMF, Vancouver
  - In-trap decay spectroscopy with the TITAN EBIT

Post doctoral research fellow at Stanford (2011 – 2015)

- EXO-200, nEXO, and Ba-tagging

Assistant professor at McGill (2015 – 2020)

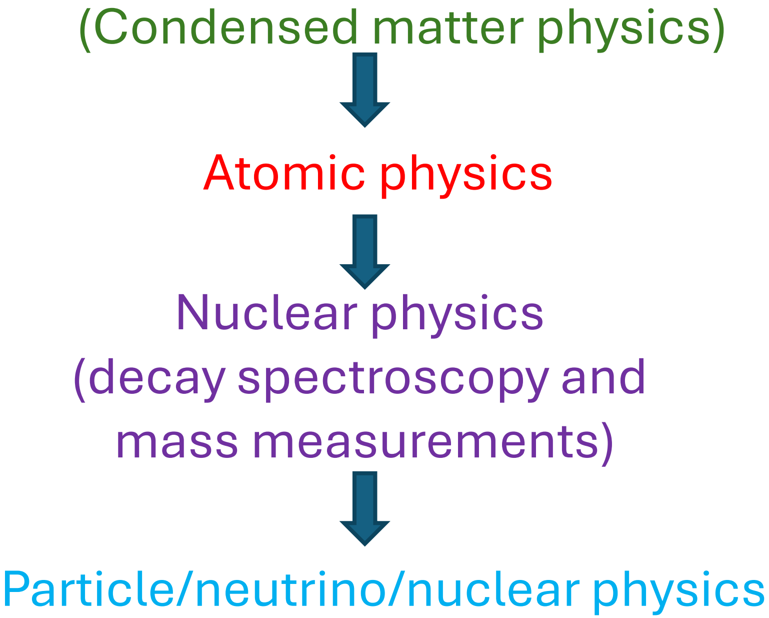
- EXO-200, nEXO, Ba-tagging, and in-trap decay spectroscopy

Associate professor at McGill (2020 – 2025)

- nEXO, Ba-tagging, and in-trap decay spectroscopy

Professor of Physics at McGill (2025 – now)

- XLZD, nEXO, Ba-tagging, and in-trap decay spectroscopy



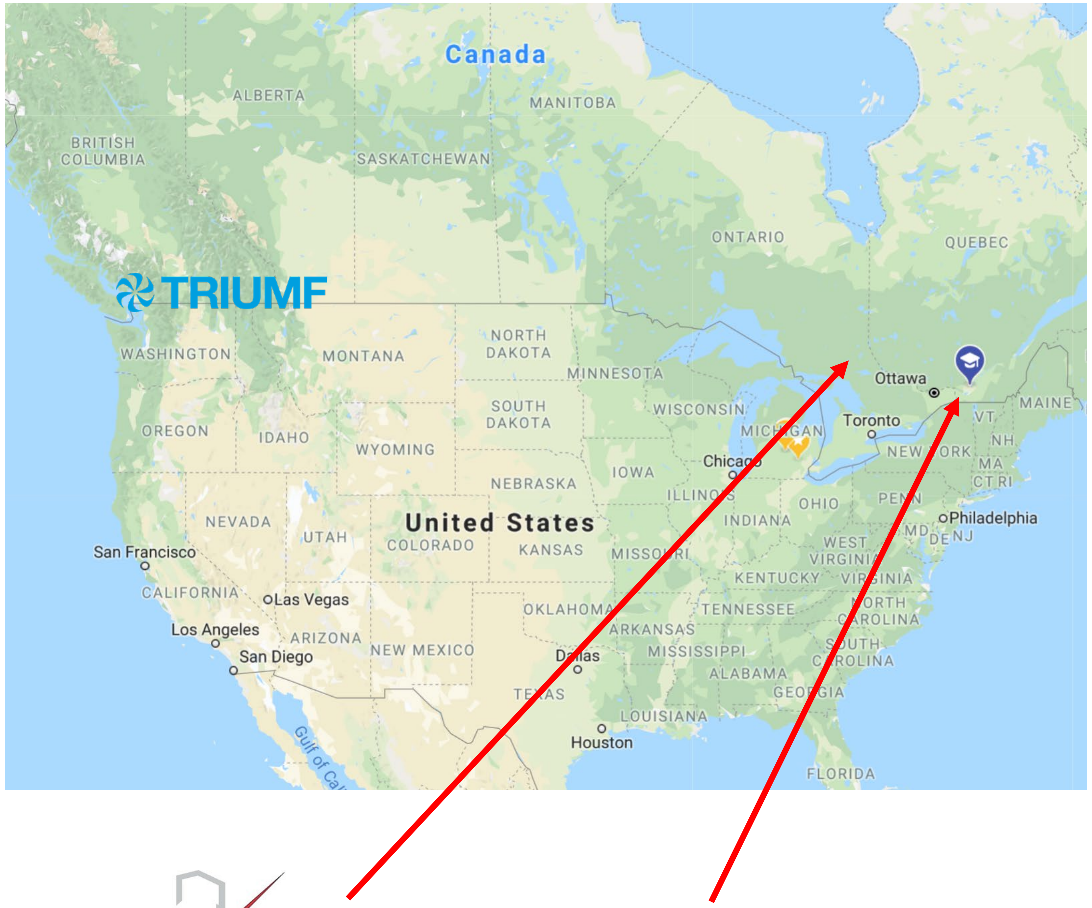
(Condensed matter physics)

Atomic physics

Nuclear physics
(decay spectroscopy and
mass measurements)

Particle/neutrino/nuclear physics

McGill University in Montreal



SNOLAB

McGill

Acknowledgement

- I use a lot of material from other sources, often without reference!
- I thank the following scientists for providing me with ideas and material:
  - Erica Caden
  - Jodi Cooley
  - Michelle Dolinski
  - Brian Lenardo
  - Hugh Lippincott
  - Brian Mong
  - David Moore
  - Andrea Pocar
  - ….

Fun facts

Neutrinos can come from….

Bananas

How many neutrinos are emitted by a banana each day?

Neutrinos can come from....

Bananas

About 1 million neutrinos per day are emitted from a banana.

Neutrinos can come from....

Sun

How many neutrinos from the sun pass our thumb's fingernail each second?

http://catalystyogi.com

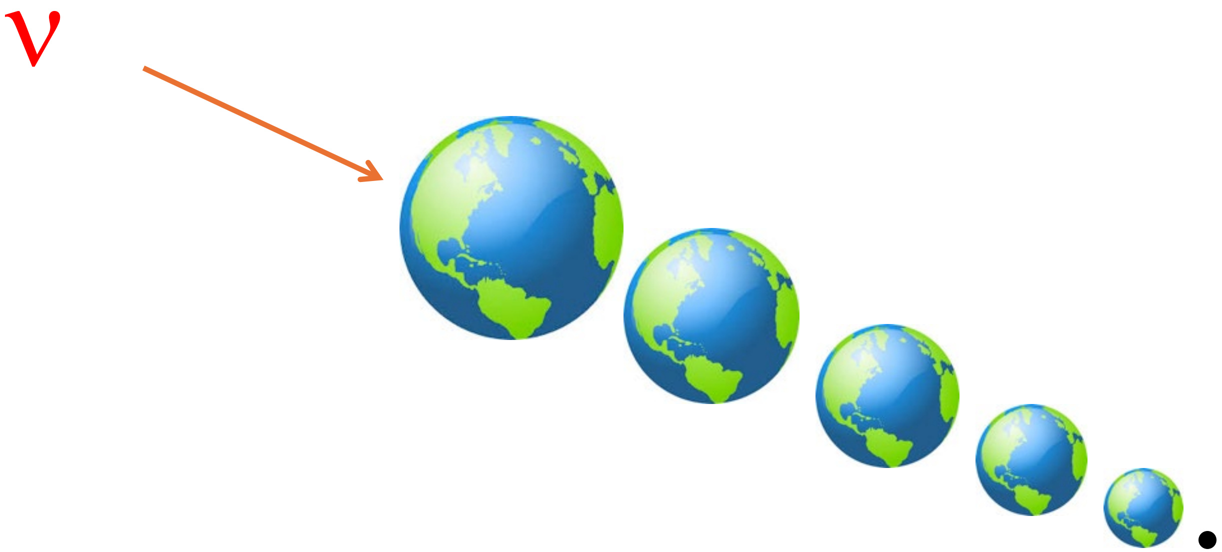
Neutrinos can come from....

Sun

50 billion = 50,000,000,000 neutrinos pass through your thumb nail every second

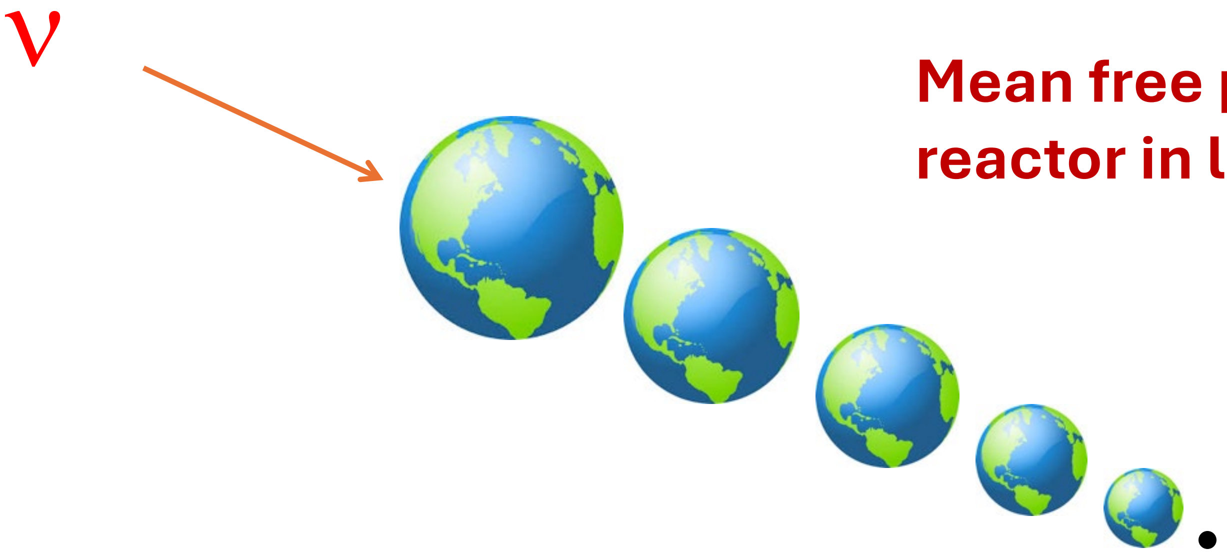
http://catalystyogi.com

Neutrino interactions are extremely weak.....



Through how many earths can neutrinos travel before interacting.

Neutrino interactions are extremely weak.....



Mean free path of neutrinos from a reactor in lead is ~ 0.3 light years !

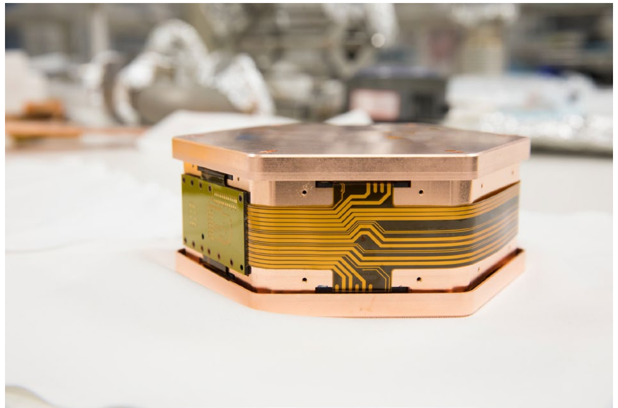
Neutrinos can travel through 10 billion earth before interacting.

... how do we shield against neutrinos?

What are low-background techniques? Why do we need them?

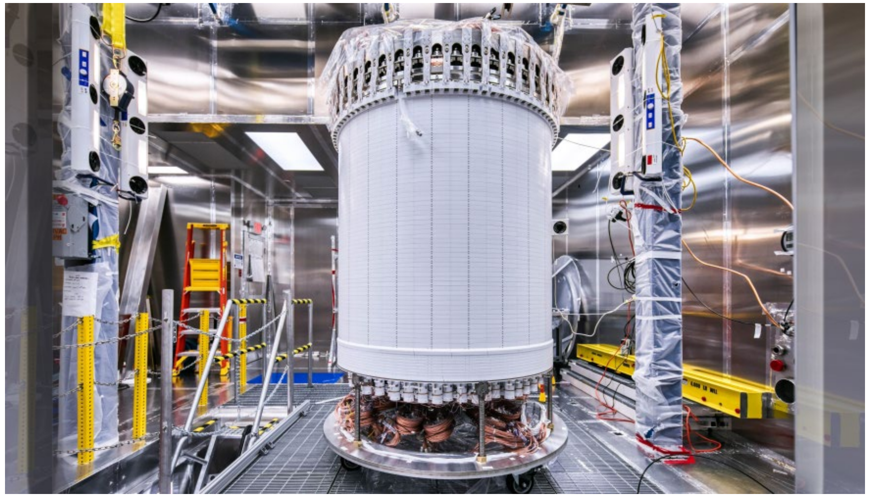
KATRIN

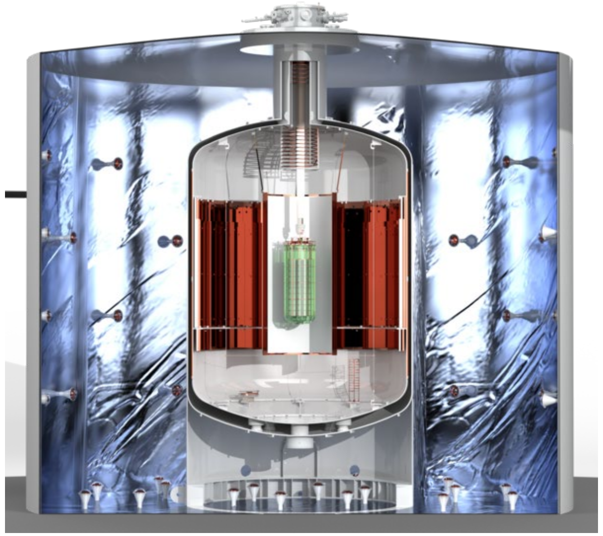
- Techniques to reduce backgrounds as much as possible/reasonable/affordable without significantly impacting signal sensitivity.
- Goal to discover signatures of events that are much rarer than (naturally occurring) backgrounds.



SuperCDMS

LZ

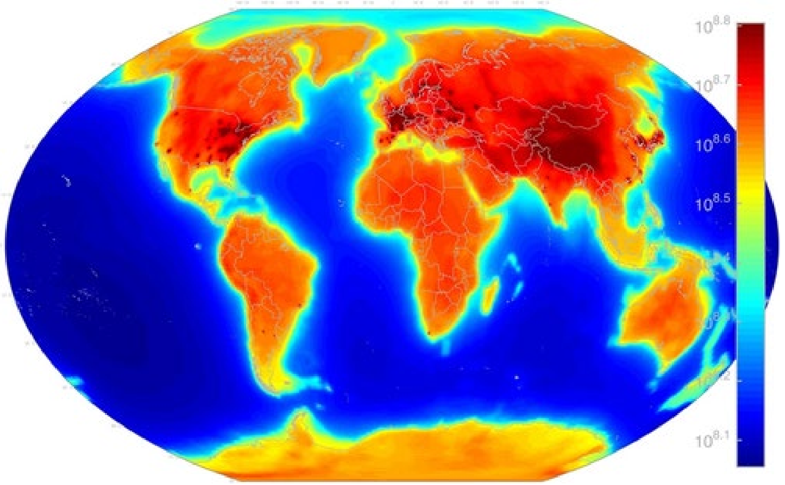




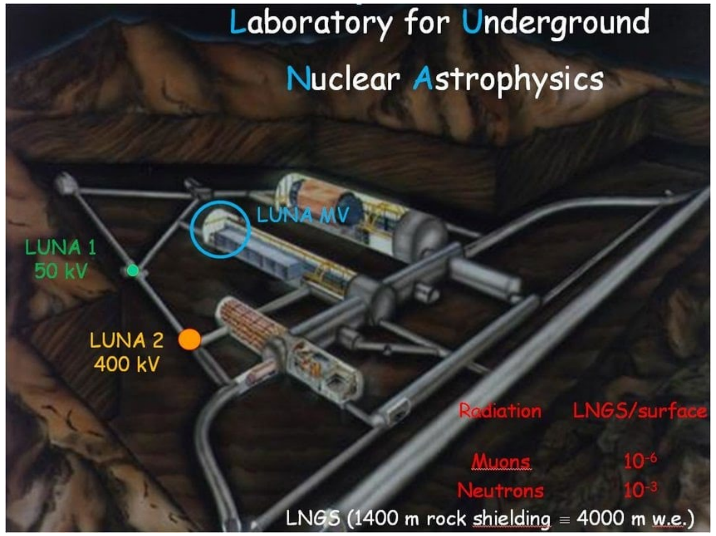
LEGEND-200

Physics Questions Requiring Low-Backgrounds

- Neutrino Physics
- Double Beta Decay
- Dark Matter
- Nuclear Astrophysics and Reactions
- Quantum Technology
- Rare Processes
- Geophysics
- Gravitational Waves
- General Relativity
- Underground Biology
- Nuclear Security
- Gamma Spectroscopy
- ....

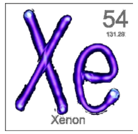


U-238/Th-232 antineutrino flux map




Felsenkeller Dresden

Physics Questions Requiring Low-Backgrounds



- Neutrino Physics
- Dark Matter
- **Double Beta Decay**
- Nuclear Astrophysics and Reactions
- Quantum Technology
- Rare Processes
- Geophysics
- Gravitational Waves
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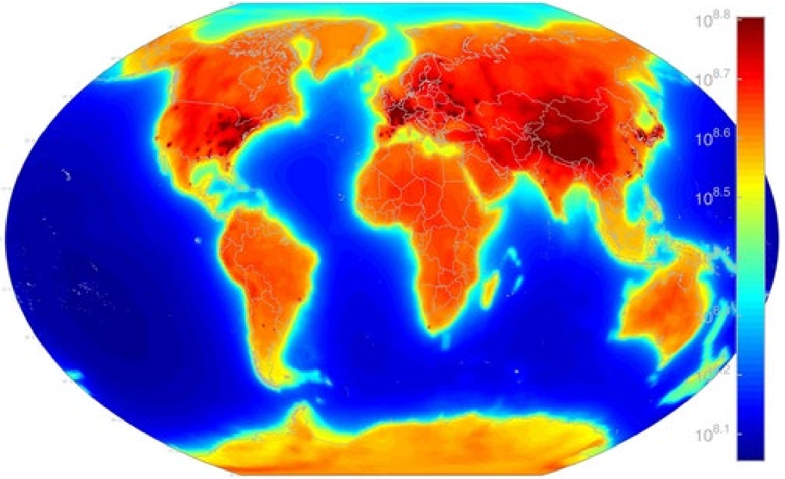
- Underground Biology
- Nuclear Security
- Gamma Spectroscopy
- …….



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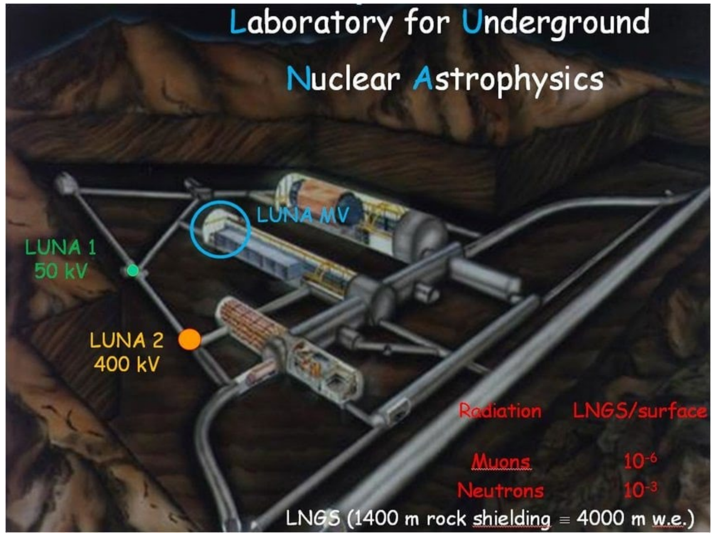
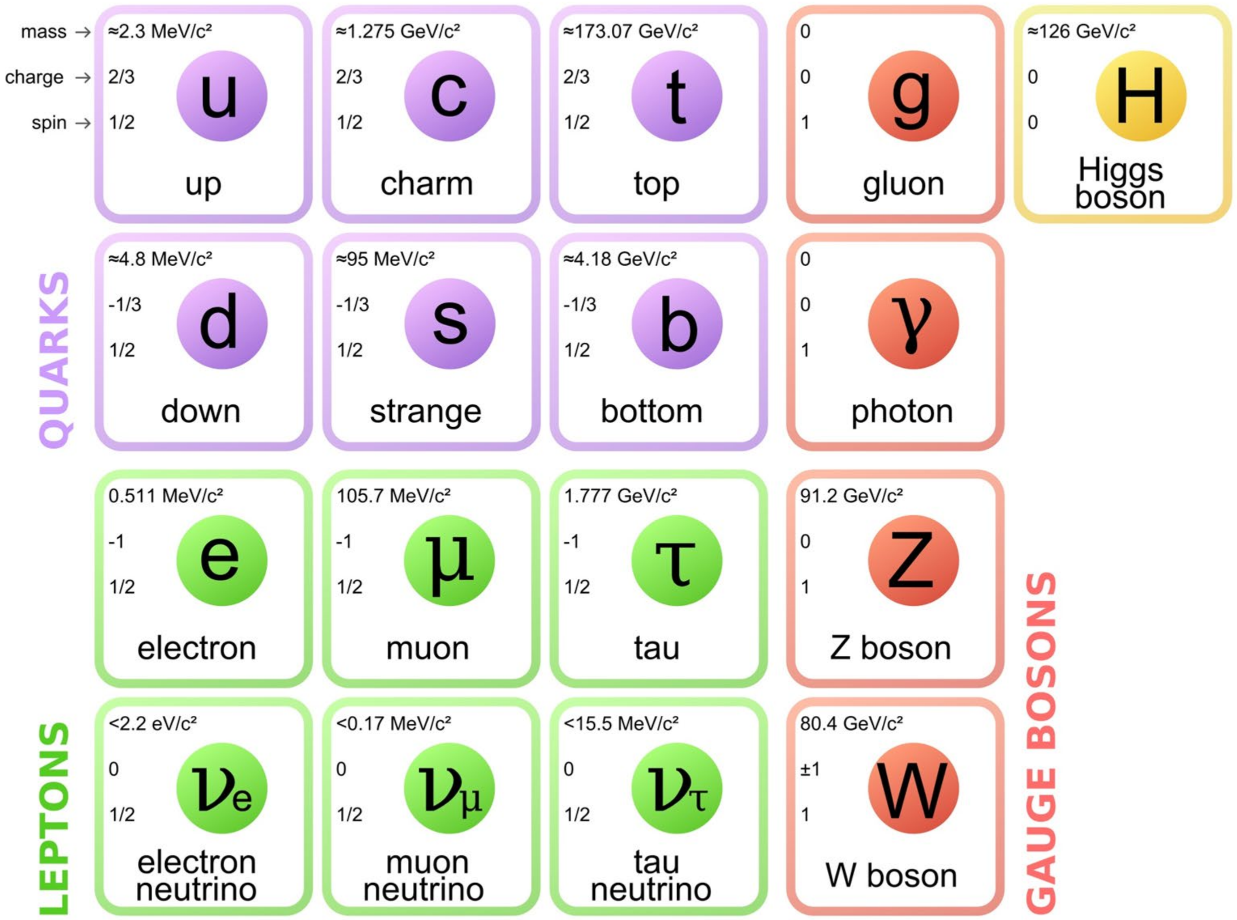



Felsenkeller Dresden

The Standard Model (SM)



mass → charge → spin →	≈2.3 MeV/c² 2/3 1/2 u up	≈1.275 GeV/c² 2/3 1/2 c charm	≈173.07 GeV/c² 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c² 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c² -1/3 1/2 d down	≈95 MeV/c² -1/3 1/2 s strange	≈4.18 GeV/c² -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c² -1 1/2 e electron	105.7 MeV/c² -1 1/2 μ muon	1.777 GeV/c² -1 1/2 τ tau	91.2 GeV/c² 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c² 0 1/2 ν_e electron neutrino	<0.17 MeV/c² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c² 0 1/2 ν_τ tau neutrino	80.4 GeV/c² ±1 1 W W boson	

- Defines fundamental particles, their symmetries, and their interactions
- Remarkable predictive power:

Electron magnetic moment:

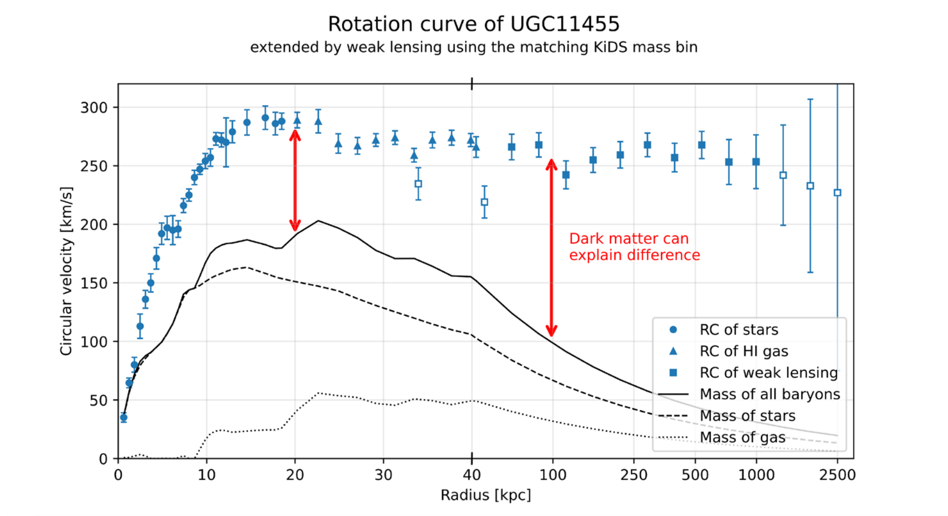
$$SM\ Prediction: -\mu_{e^-}/\mu_B = 1.001\,159\,652\,181\,61\,(024) \qquad [0.24\ \text{ppt}],$$

$$Measured: -\mu_{e^-}/\mu_B = 1.001\,159\,652\,180\,73\,(028) \qquad [0.28\ \text{ppt}],$$

G. Gabrielse et al., *Atoms* (2019)

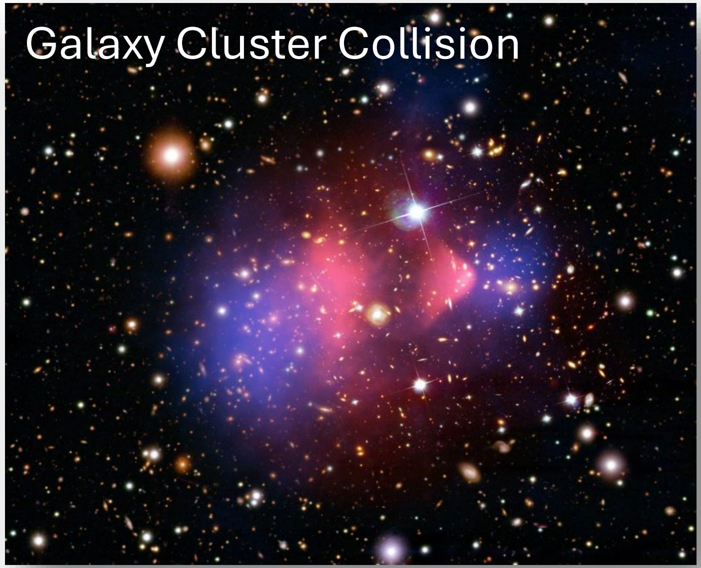
However, there are features of the universe that are not accounted for!

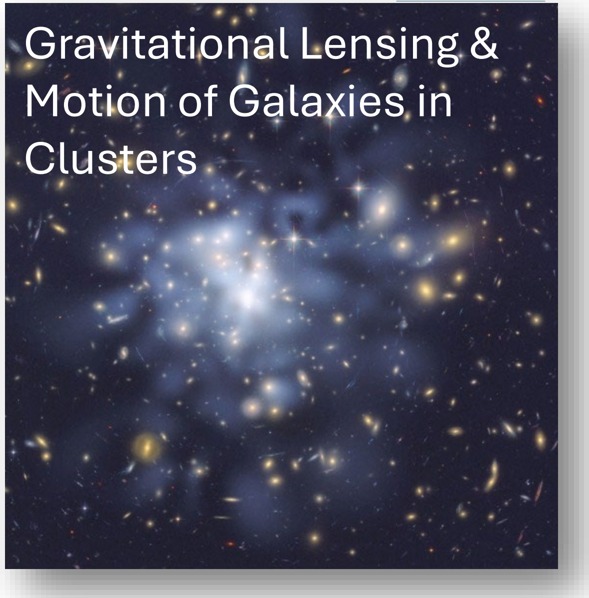
Dark Matter in a Nutshell

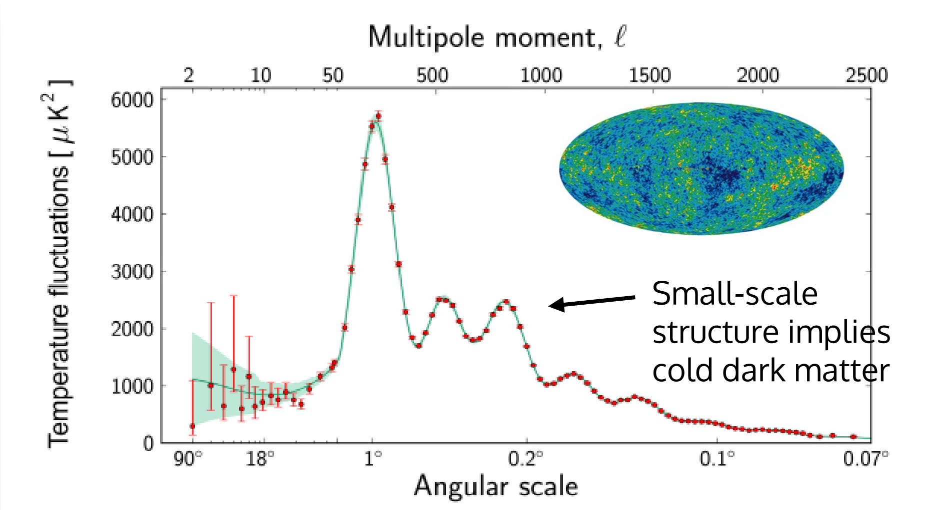


Source: https://en.wikipedia.org/wiki/Galaxy_rotation_curve

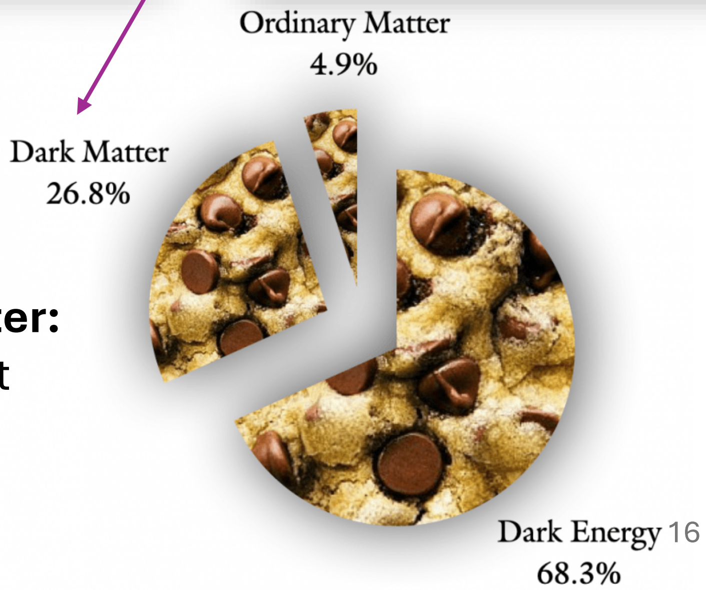
Source: NBC News







Source: ESA

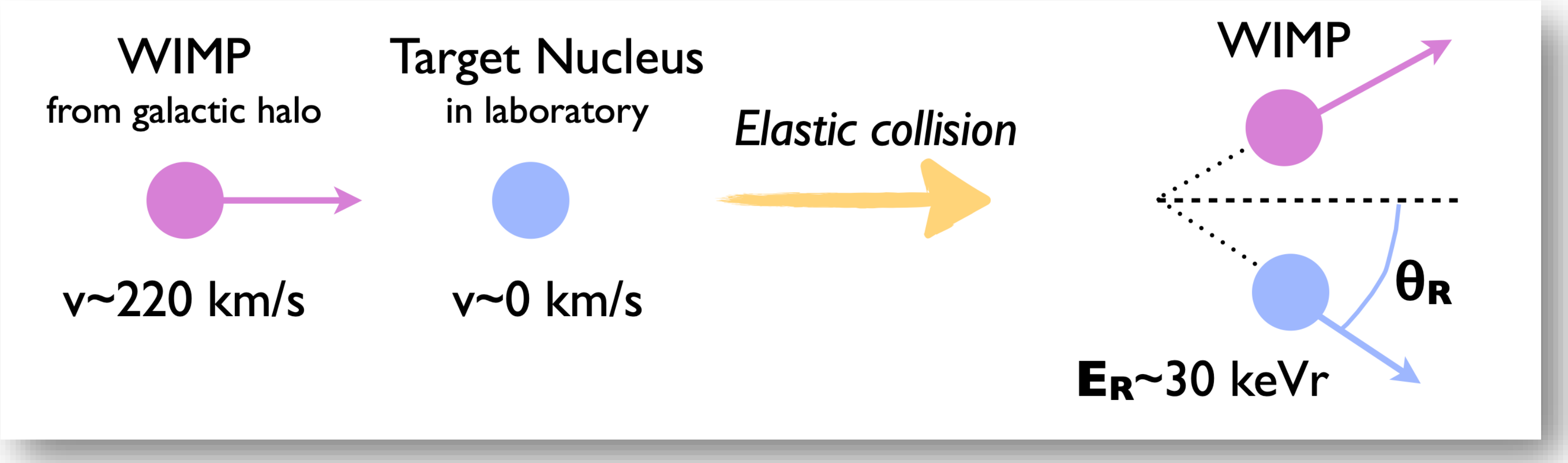


There must be some matter:

- Does not react with light (emit/absorb/reflect)
- Invisible to our tools – hence dark matter

WIMP Direct Detection

Assume that the dark matter is not only gravitationally interacting (WIMP).



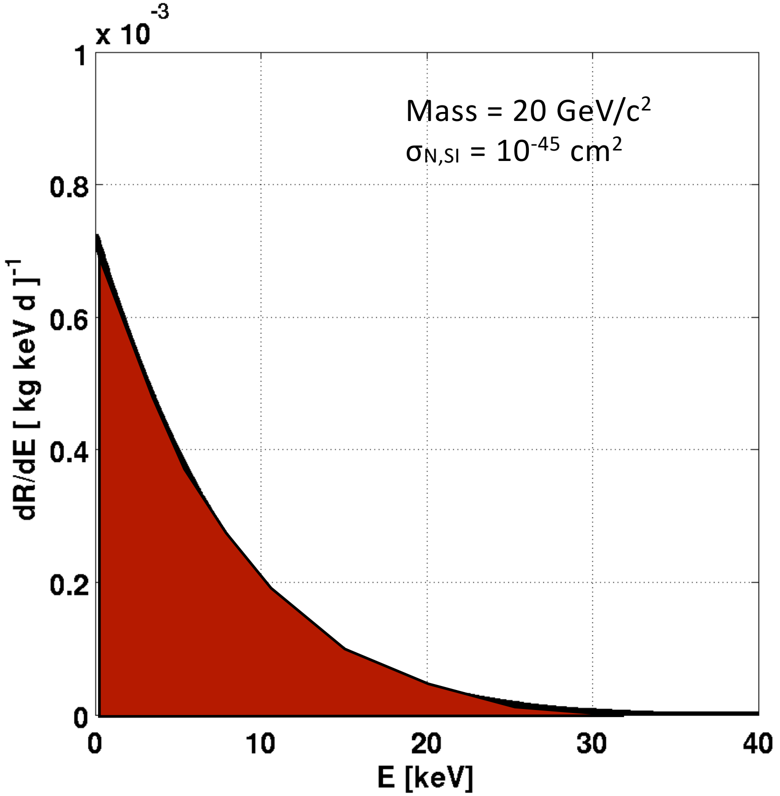
Elastic scatter of a **W**eakly **I**nteracting **M**assive **P**article (WIMP) off a nucleus

- Imparts a small amount of energy in a recoiling nucleus (order keV).
- Can occur via spin-dependent or spin-independent channels.
- Need to distinguish this event from the overwhelming number of background events → reduce backgrounds.

→ Need large exposure (target mass x observation time)

The Event Rates Are Extremely Low!

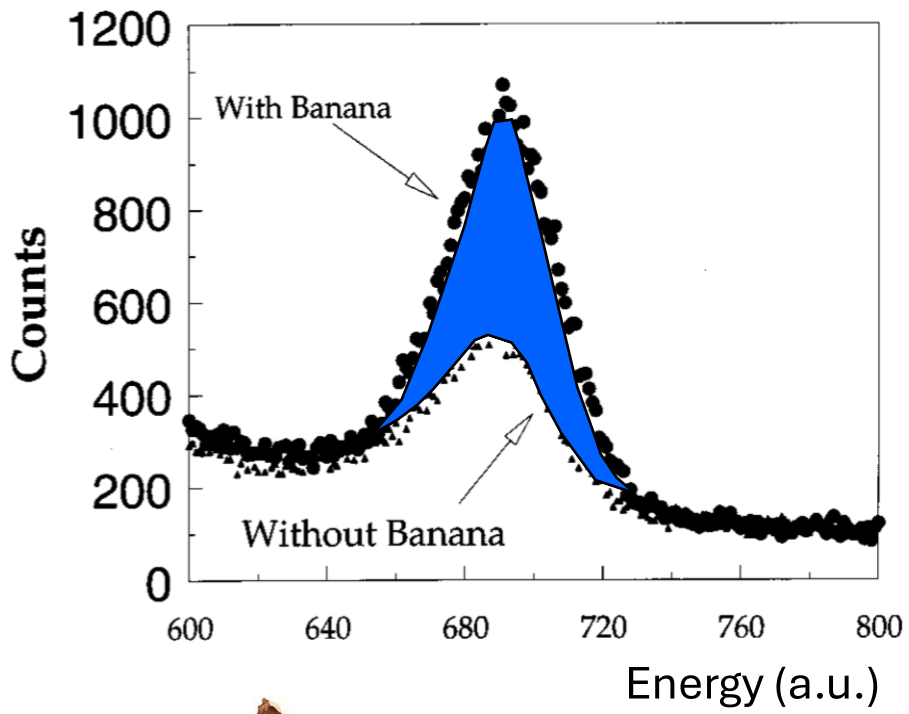
- Expected WIMP Spectrum



~1 event per kg per year (nuclear recoils)

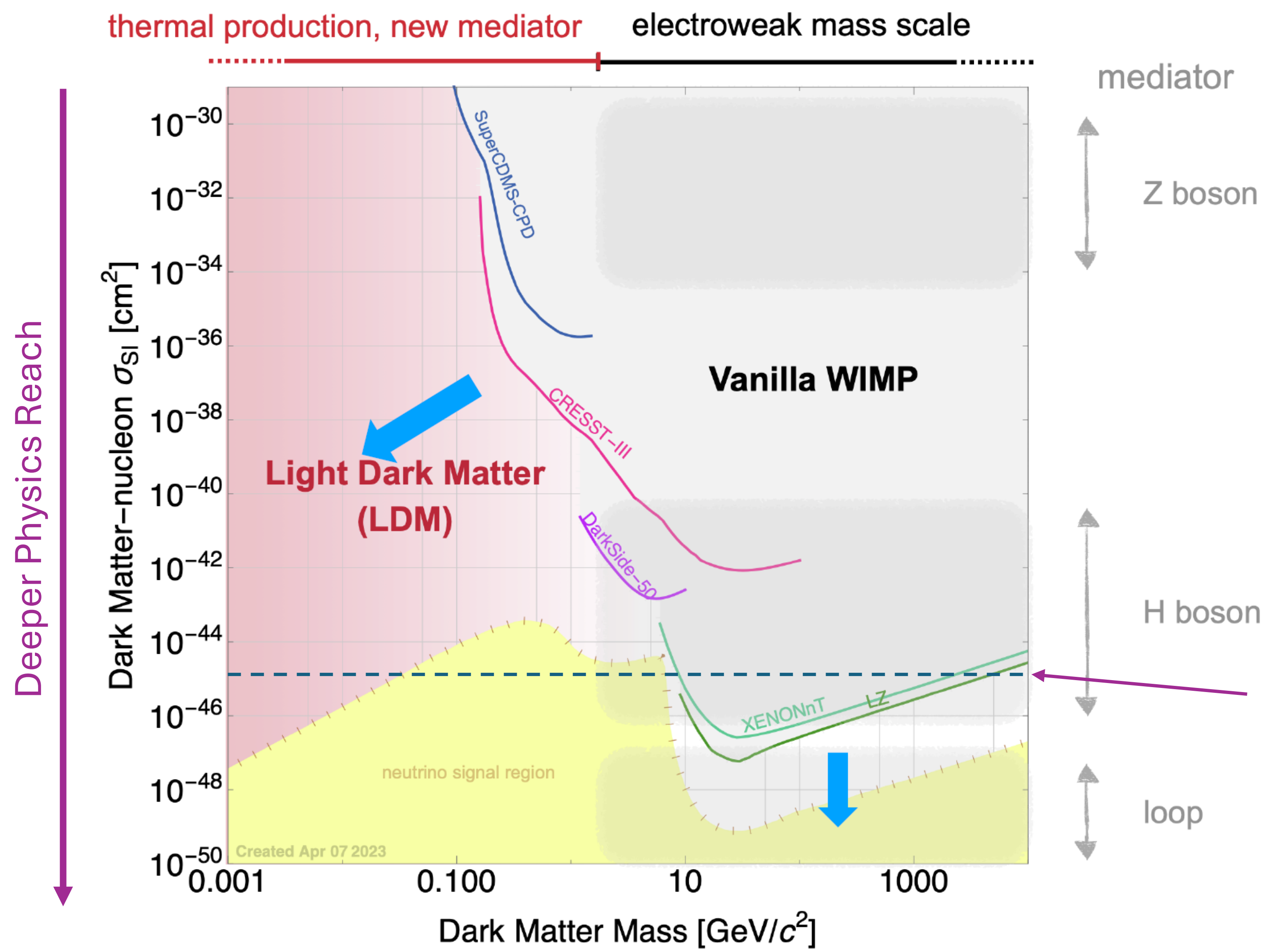
- Measured Banana Spectrum

Hoeling et al Am.J.Phys. 1999, 67, 440.



~10 decays/100g/s

Direct Detection Landscape



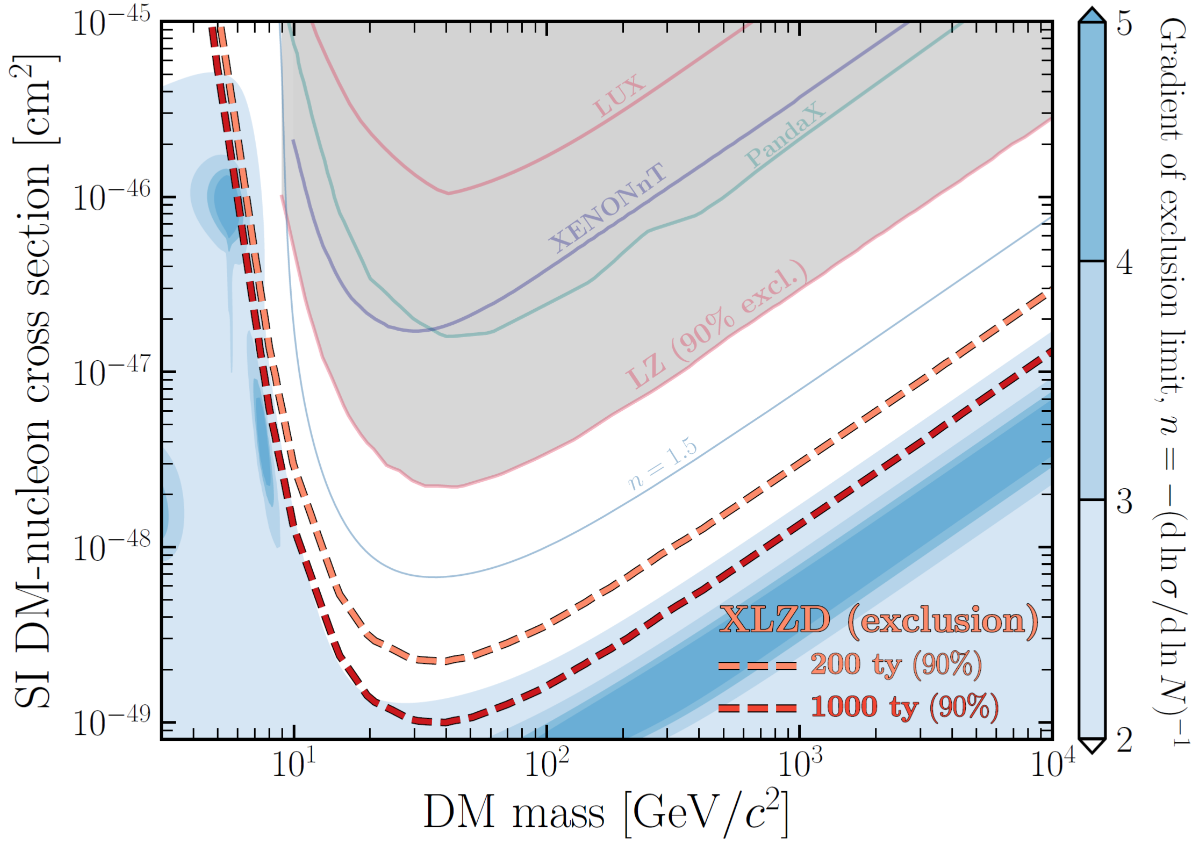
Cross section from previous slide

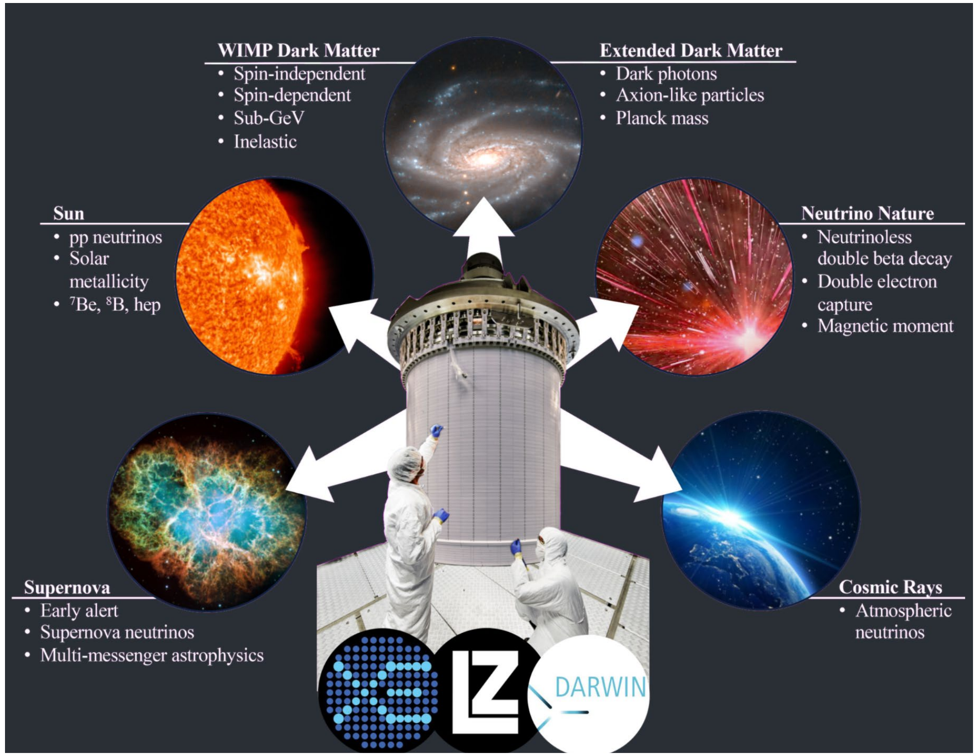
$\sigma_{SI} = 10^{-45}$ cm^2 , 20 GeV/c^2

~ 1 event/kg/year

Next-generation detectors need to be several orders of magnitude more sensitive!

Dark Matter: Where do we need to go?

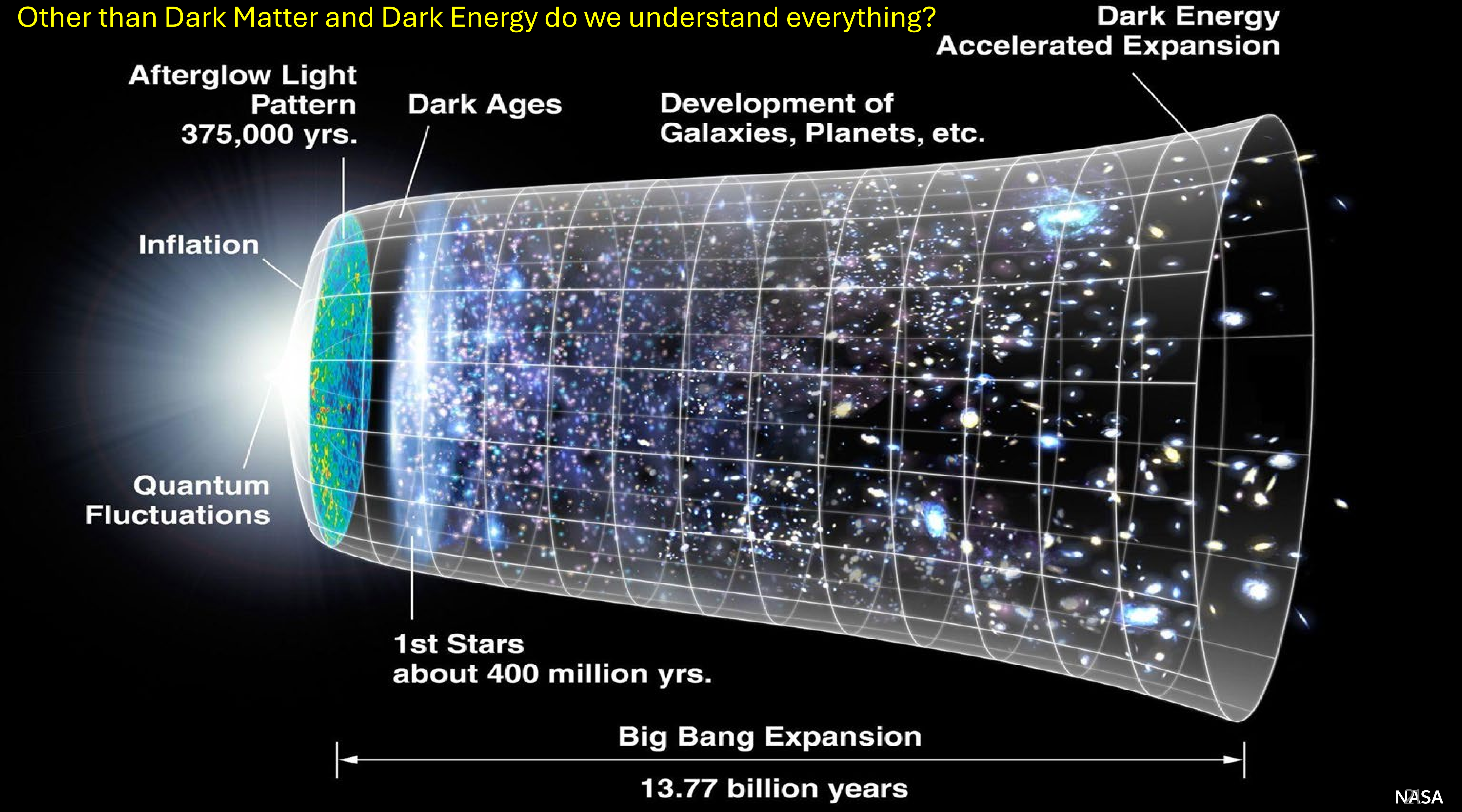




- 1000 T-year experiment has the potential to be the **ultimate WIMP dark matter** experiment.

→ Drives 60-80 T Xe target range.

Other than Dark Matter and Dark Energy do we understand everything?

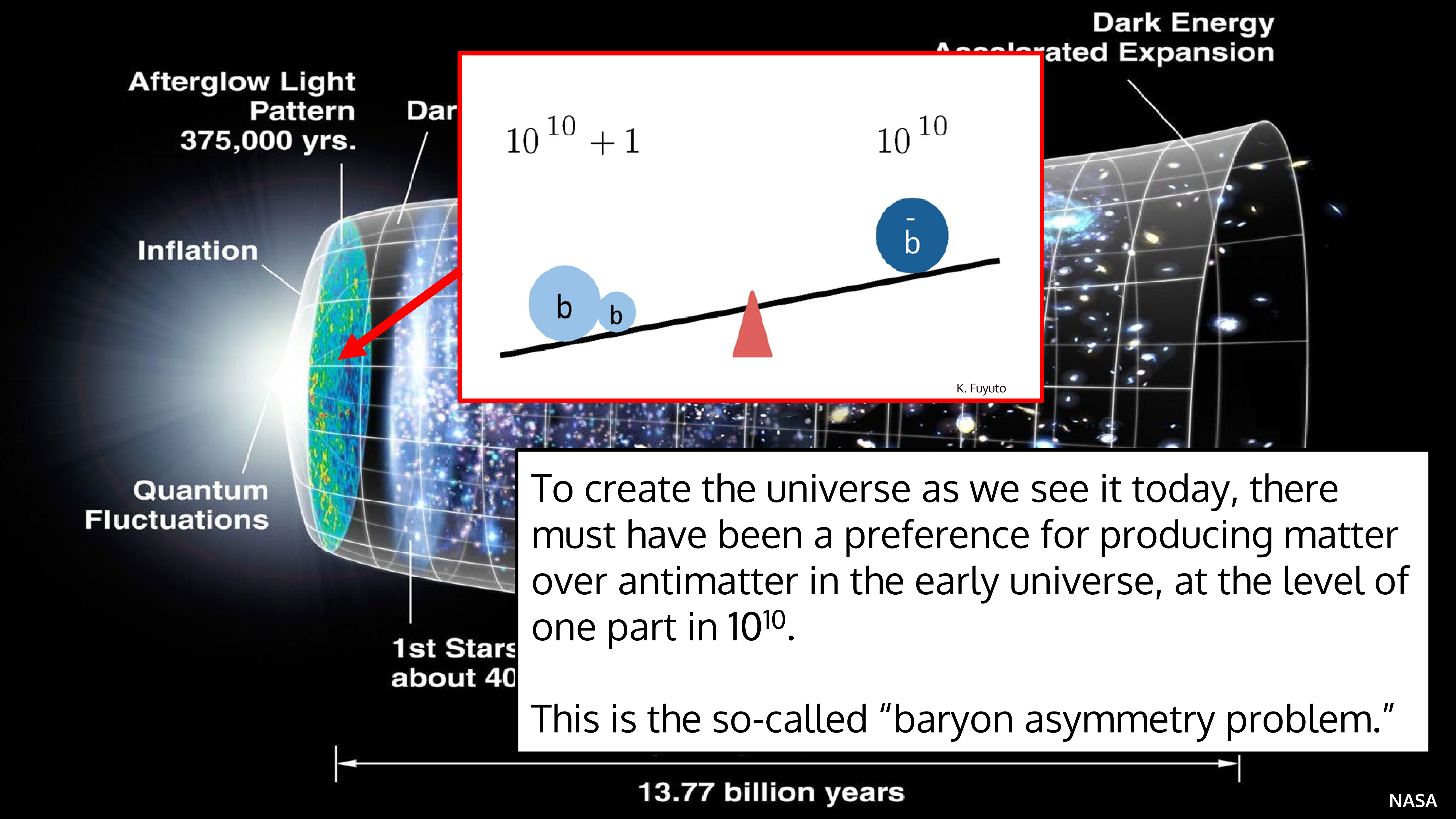


NASA

The universe is full of matter…

(and dark matter)

…but no antimatter?

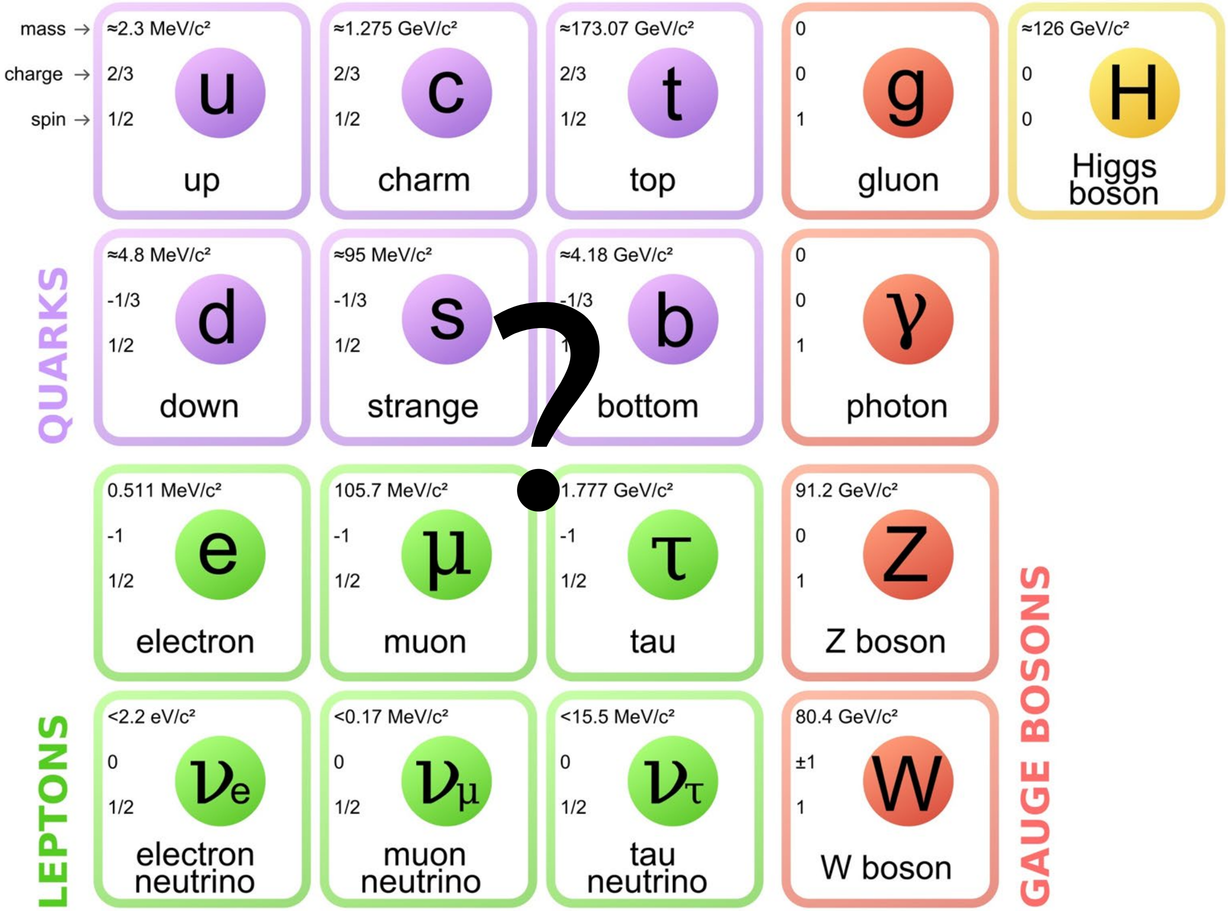


To create the universe as we see it today, there must have been a preference for producing matter over antimatter in the early universe, at the level of one part in 10^{10}.

This is the so-called “baryon asymmetry problem.”

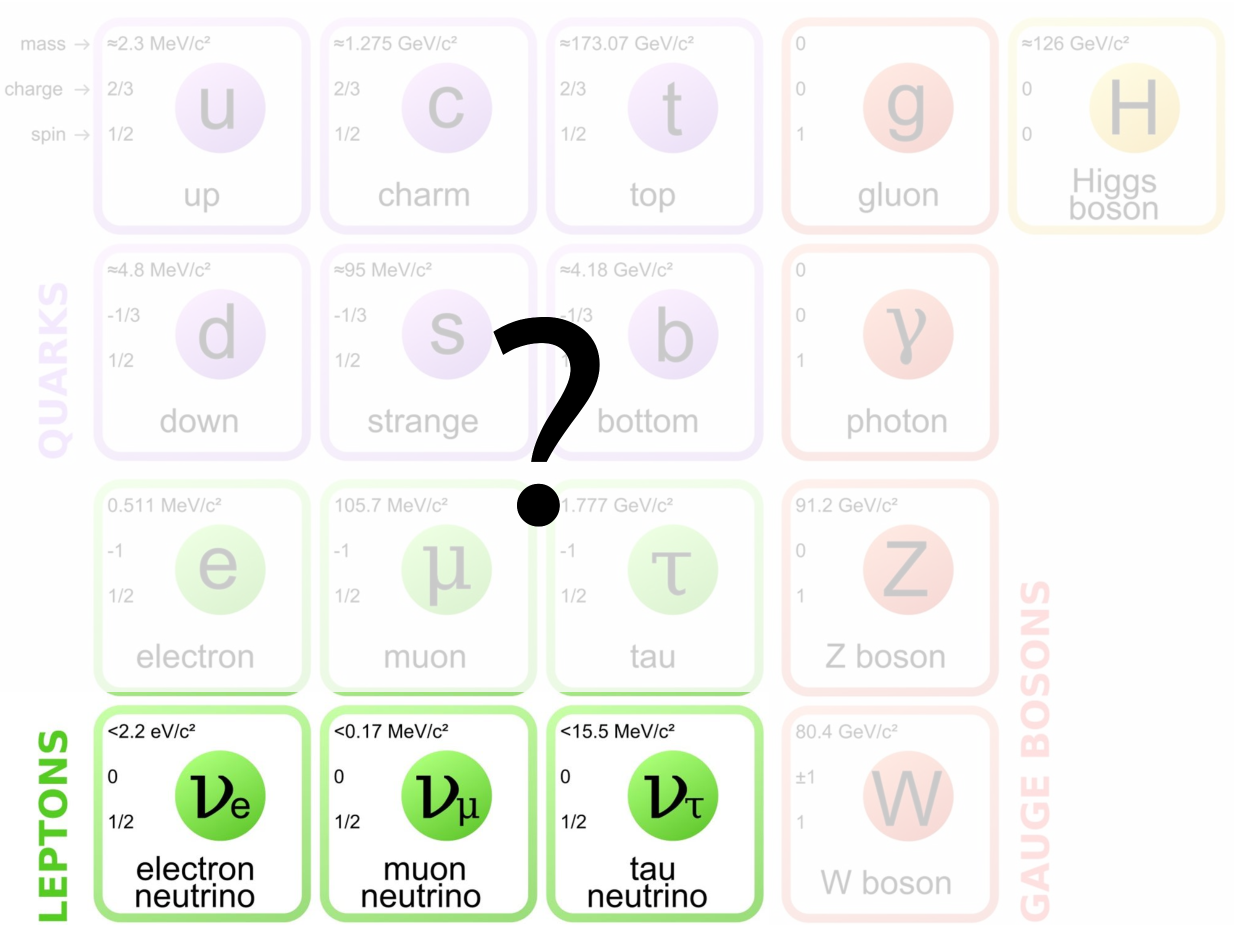
NASA

Where does the asymmetry come from?



We have not yet found interactions in the Standard Model which can produce this asymmetry.

Where does the asymmetry come from?



We have not yet found interactions in the Standard Model which can produce this asymmetry.

Neutrinos

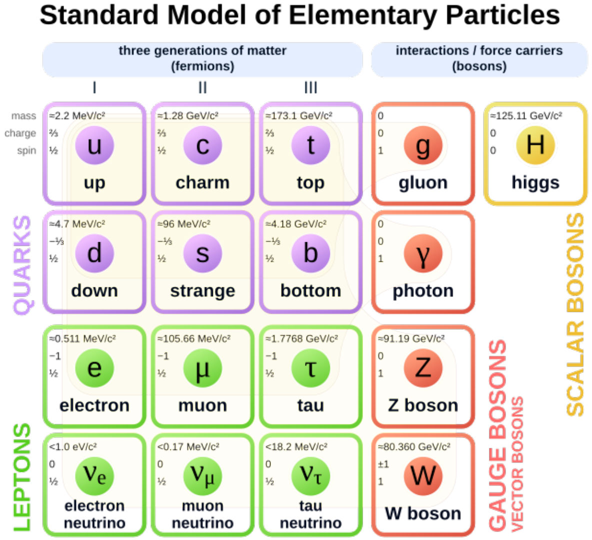
- Most abundant particle in the universe! (other than photons)
- Uncharged, three "flavors" (e, **μ**, **τ**)
- Interact only via the weak force
- Assumed to be massless in the Standard Model

- **But they don't quite fit!**

Neutrinos – Misfits of the Standard Model?

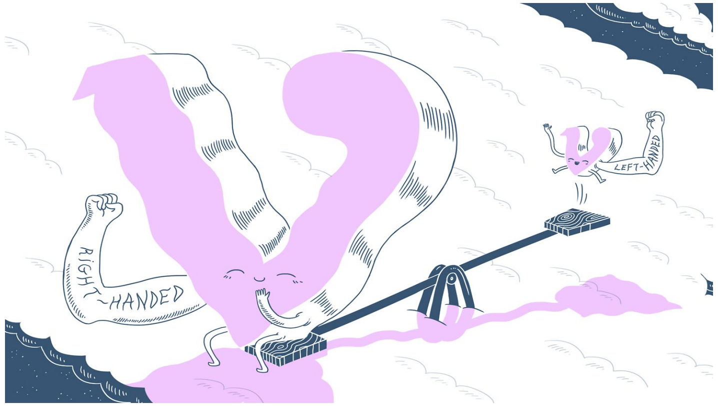
Mass Generation

Nature of the Neutrino (and origin of its mass) is not accounted for in the Standard Model.



New Physics

0νββ observation supports the See-Saw mechanism theory.



Why neutrino masses are not zero, but many orders of magnitude less than other fundamental particles?

neutral

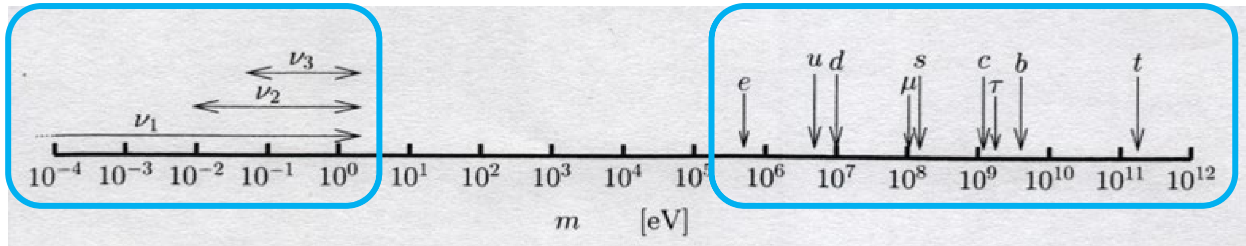
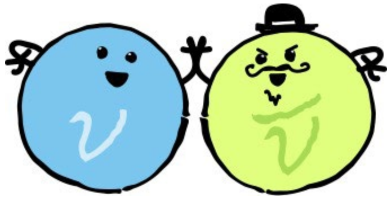


FIG. 14.1. Order of magnitude of the masses of leptons and quarks.

charged

Quantum Nature of Neutrino

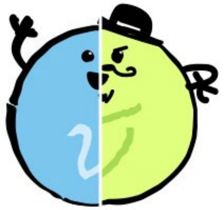
Theory 1: Neutrinos behave just like other matter particles and there are distinct matter and antimatter versions.



Neutrino **Antineutrino**

Paul Dirac

Theory 2: The neutrino and antineutrino are the same thing.



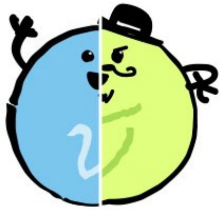
Ettore Majorana

Majorana Neutrinos

E. Majorana

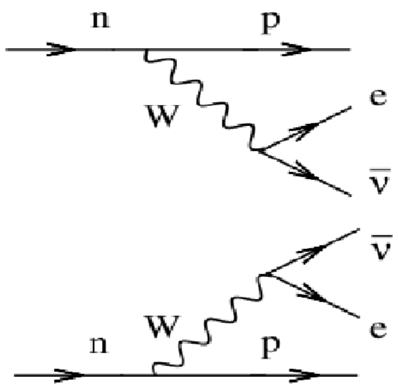
- Neutrino could be its own antiparticle
- [Nuovo Cimento 14, 171 (1937)]

$$\nu \equiv \bar{\nu}$$



Double Beta Decay

Maria Goeppert Mayer



Two neutrino double beta decay

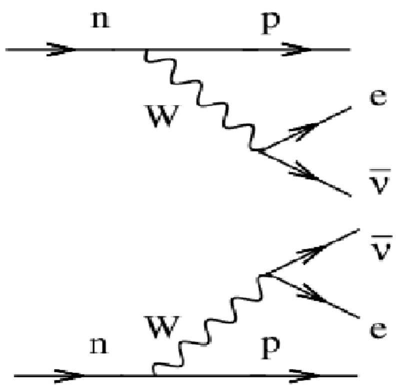
$$ {}^{136}_{54}Xe \rightarrow {}^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e $$

1935 Maria Goeppert Mayer first proposed the idea of two neutrino double beta decay [Phys.Rev 48 (1935) 512]

1987 first direct observation in ^{82}Se by M. Moe

Double Beta Decay

Maria Goeppert Mayer



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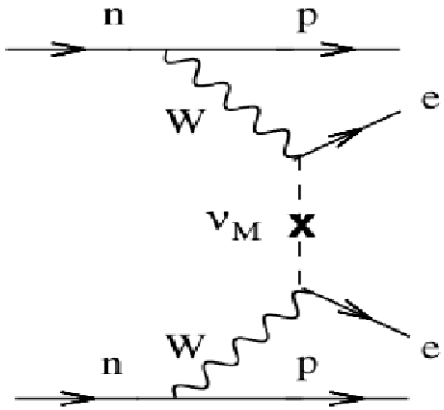
Wendell Fury



Matter-only creation process!

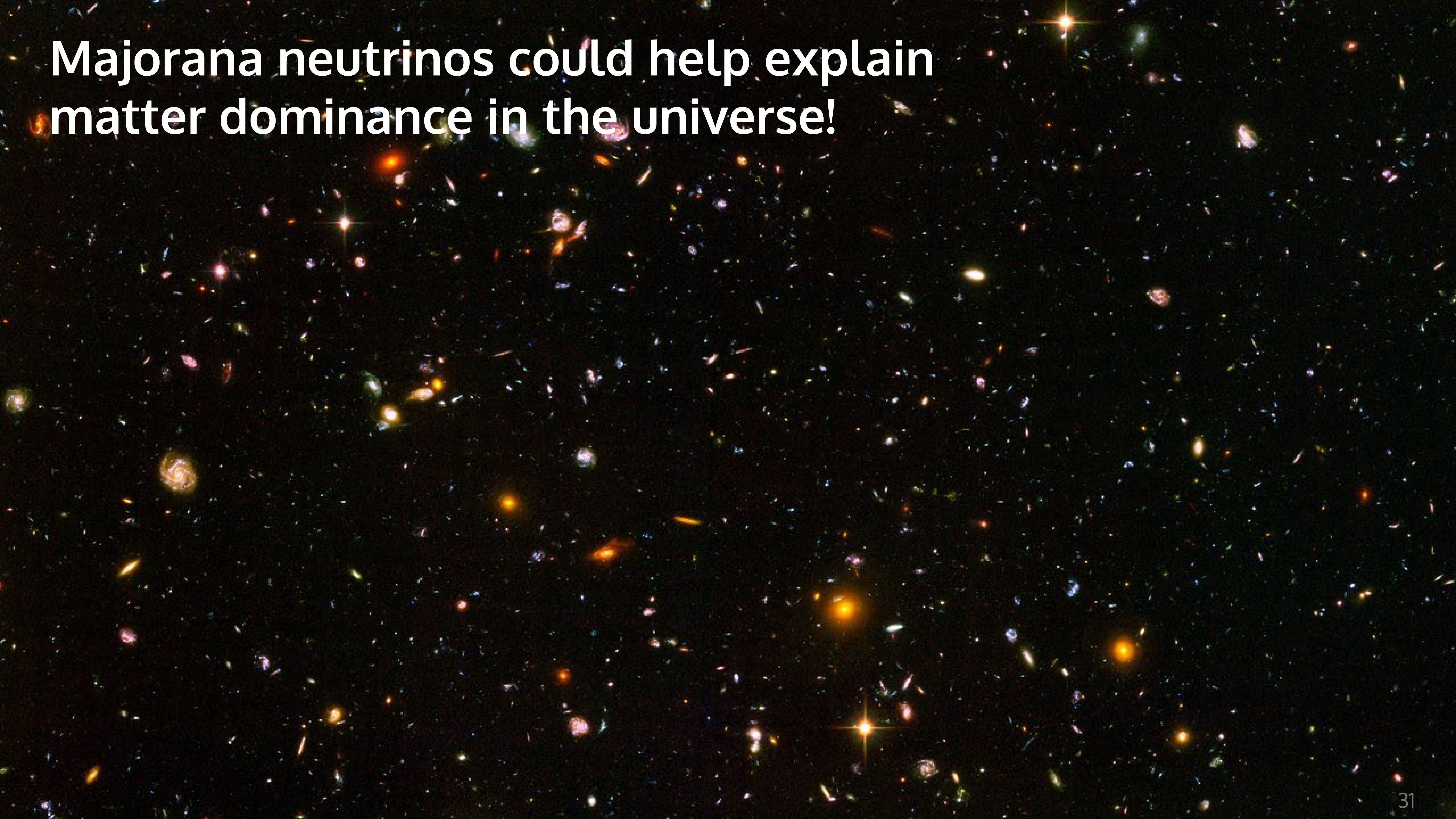
Neutrinoless double beta decay

$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-}$$

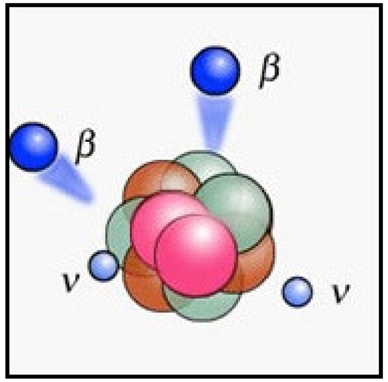
1937 Ettore Majorana proposed the theory of Majorana fermions

1939 Wendell Furry proposed neutrinoless double beta decay [Phys. Rev. **56**, 1184 (1939)]

Majorana neutrinos could help explain matter dominance in the universe!

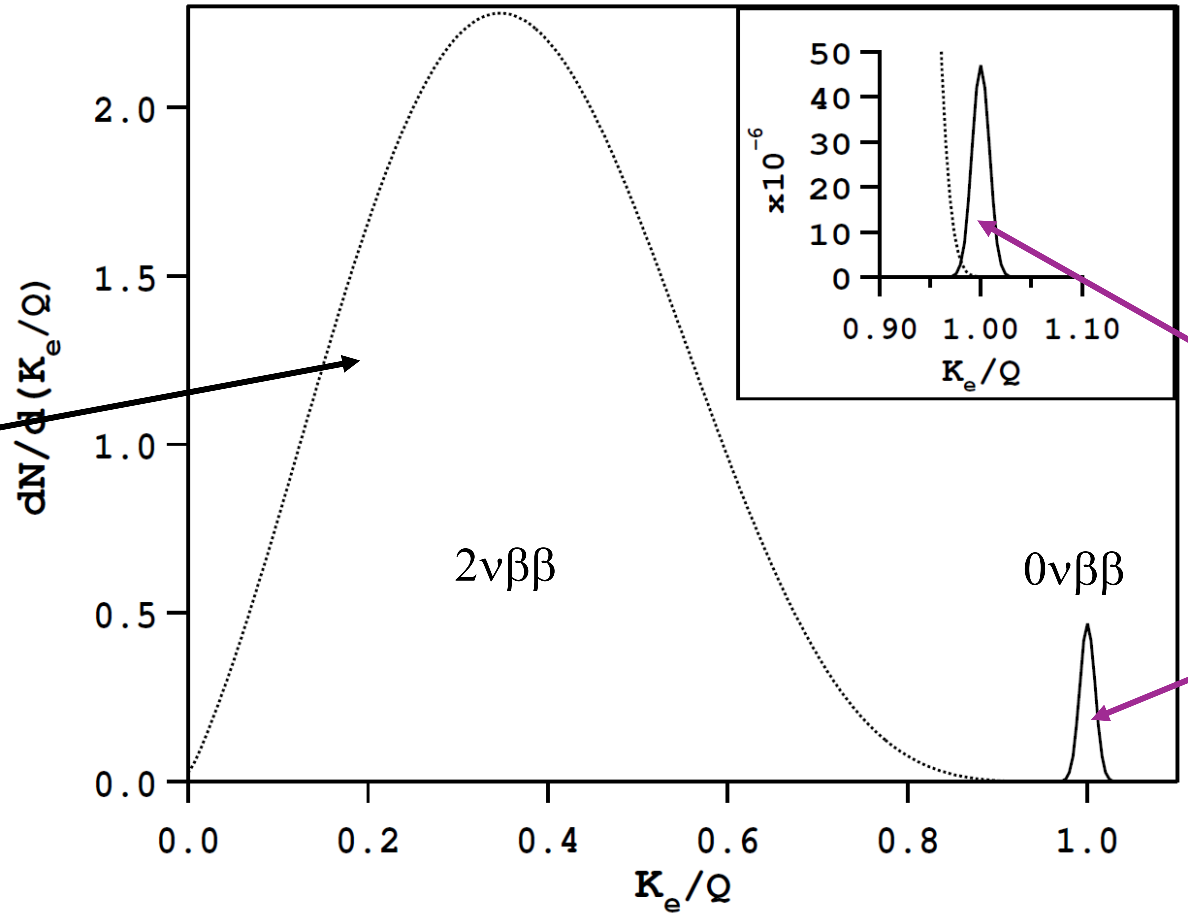


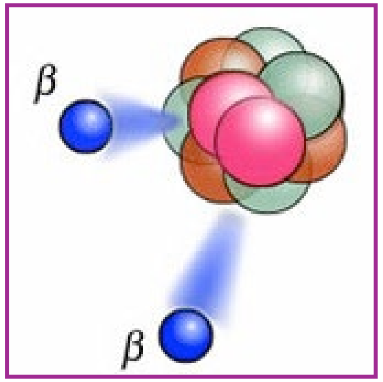
Double Beta Decay - 0νββ only for Majorana ν!



2νββ spectrum
(normalized to 1)

[arXiv:hep-ph/0611243]





0νββ peak
(normalized to 10^{-6})

0νββ peak
(normalized to 10^{-2})

2νββ
$T_{1/2} \approx 10^{20}$ y

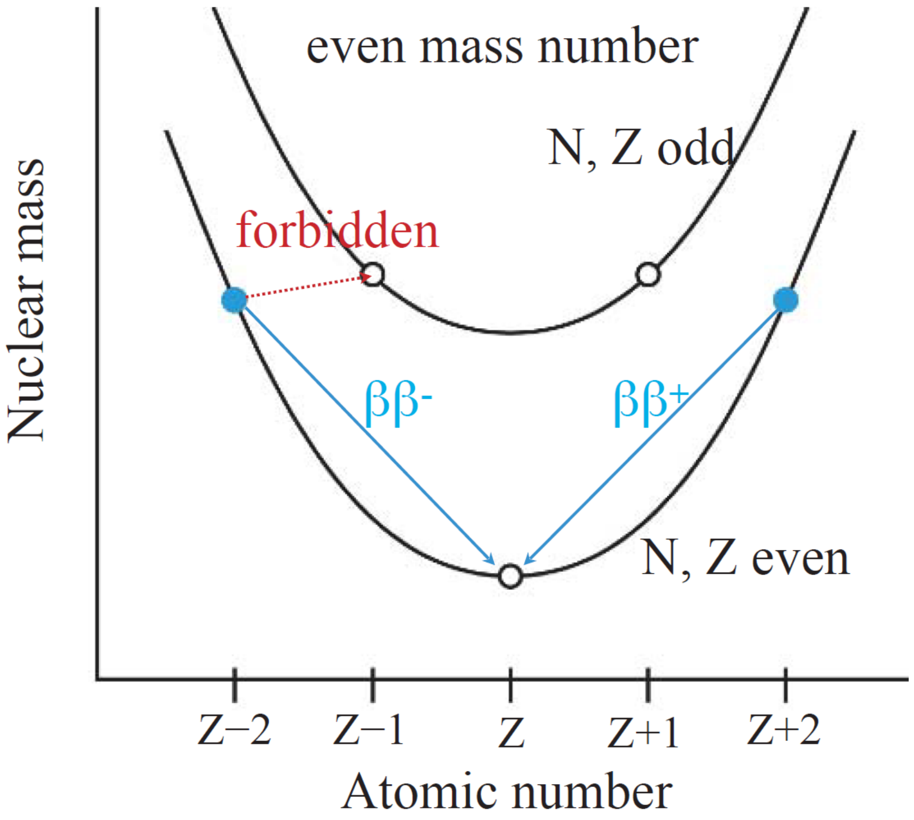
0νββ
$T_{1/2} > 10^{25\text{-}26}$ y

0νββ not observed yet!

Double Beta Decay

- Second-order weak nuclear process
- First-order beta decay is forbidden energetically or by spin → ββ is detectable

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e$$



Drives Technology

Defines ROI & BGND Constraints

Drives Cost

	ββ-decay nuclei with Q > 2 MeV	**Q (MeV)**	**Abund. (%)**
	^{48}Ca → ^{48}Ti	**4.271**	**0.187**
GERDA, MJD, LEGEND	**^{76}Ge → ^{76}Se**	**2.040**	**7.8**
	^{82}Se → ^{82}Kr	**2.995**	**9.2**
	^{96}Zr → ^{96}Ru	**3.350**	**2.8**
CUPID	**^{100}Mo → ^{100}Ru**	**3.034**	**9.7**
	^{110}Pd → ^{110}Cd	**2.013**	**11.8**
	^{116}Cd → ^{116}Sn	**2.802**	**7.5**
	^{124}Sn → ^{124}Te	**2.228**	**5.8**
CUORE, SNO+	**^{130}Te → ^{130}Xe**	**2.528**	**34.2**
EXO-200, nEXO, KamLAND ZEN, NEXT	**^{136}Xe → ^{136}Ba**	**2.479**	**8.9**
	^{150}Nd → ^{150}Sm	**3.367**	**5.6**

Quo Vadis 0νββ Search? ... it’s complicated.

Current Limit

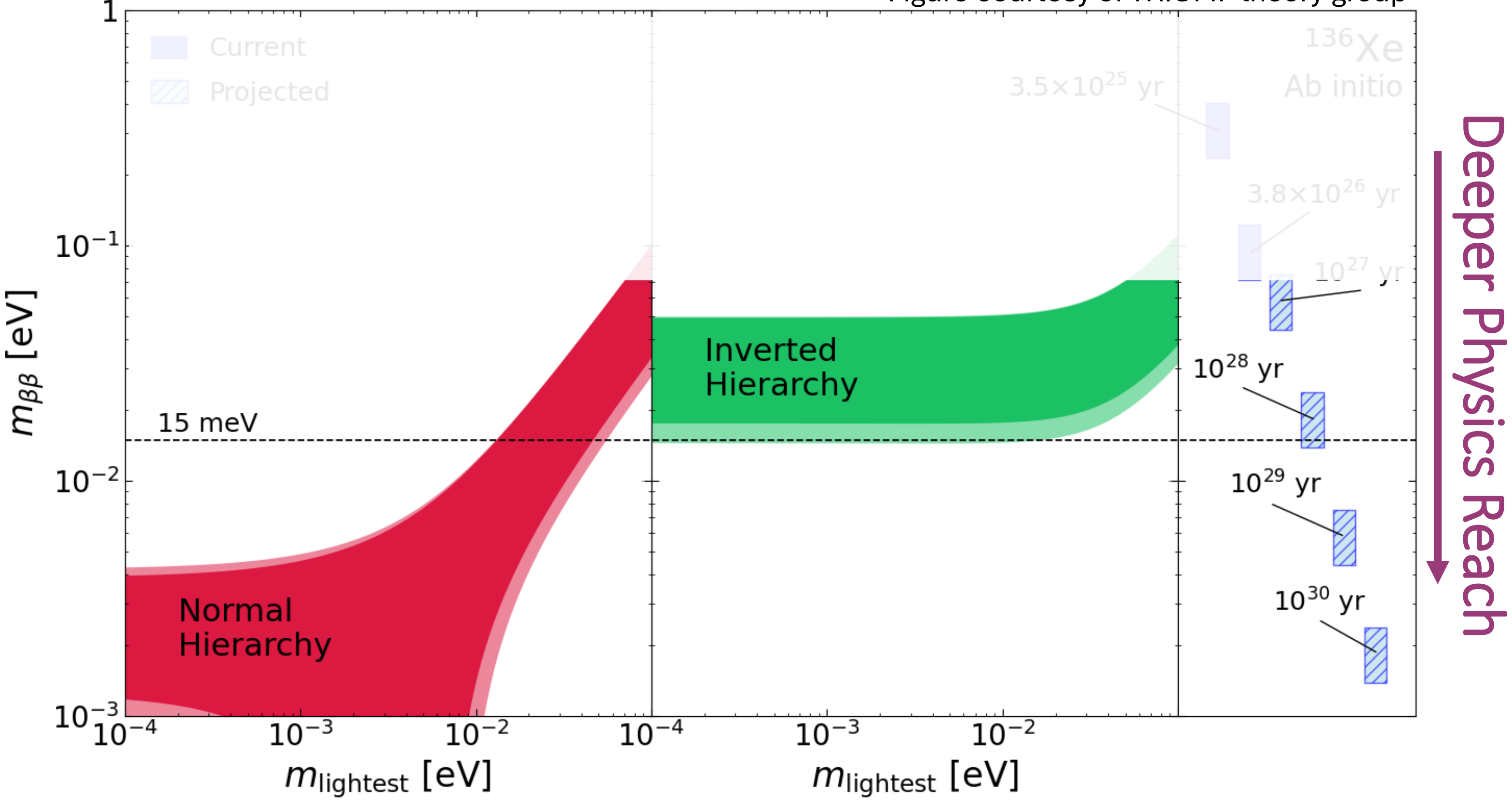
Next-Generation

We know how to do this technically,
but funding unclear

Ultimate Experiment?

The ultimate goal in 0νββ of ~1 meV

Figure courtesy of TRIUMF theory group



$$\left(T^{0\nu}_{1/2}\right)^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} g_A^4 |M^{0\nu}|^2$$

Phase space factor

Axial coupling, $g_A = 1.27$

NME

Disclaimer: Effective Majorana mass $\langle m_{\beta\beta}\rangle$ is an effective, albeit imperfect, metric to compare physics reach between isotopes and experiments.

Aside: Reminder of Radioactive Decay

- Activity [decays/time] is a measure of the decay rate of a radionuclide.

$$A = \frac{dN}{dt} = \lambda N$$

λ = *decay constant*
N = total number of radioactive atoms

- The decay constant is the probability that a radioactive atom will decay.

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

- The number of atoms of the radioisotope present is given by

$$N = \frac{Avogadro's\ Number}{atomic\ mass\ of\ the\ radionuclide} \times mass\ of\ the\ radionuclide$$

- Abundance refers to the relative portions of stable isotopes of an element.

Strategy to reach 10^{28} years: More Isotope

- Ultimately, even a background free experiment is limited by exposure, i.e., by the number of atoms.

$$\frac{dN}{dt} = \frac{\ln(2)}{T_{1/2}} N = 0.693\ \frac{N}{T_{1/2}}$$

^{136}Xe Rate at 10^{28} years:
~0.3 decays/tonne/yr

Mass required for 1 decay/year (average)

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

^{nat}Xe [T]
3.7
37
367
3679

XLZD scale $^{nat.}$Xe

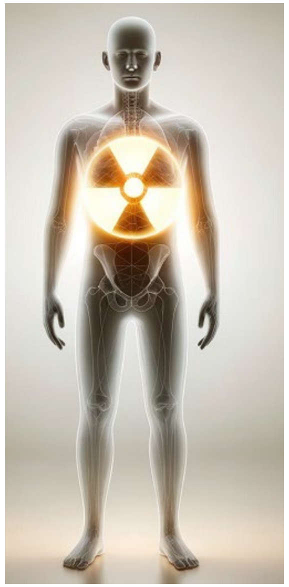
~10 decays/100g/s

So how do we do low-background experiments?

Reminder:

Event rate of interest ~1/O(detector volume)/year

~10 decays/100g/s



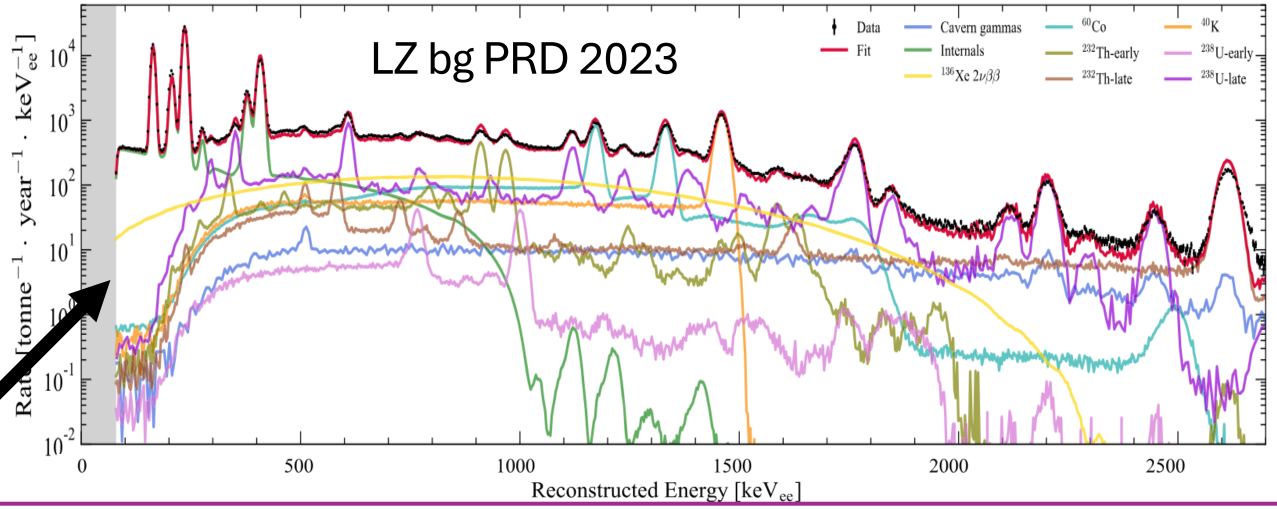
~4-5 kdecays/75kg/s

Optimized for Different Energy Scales!

WIMP-like DM searches optimize against

- Neutrons
- Low-energy X-rays, some βs

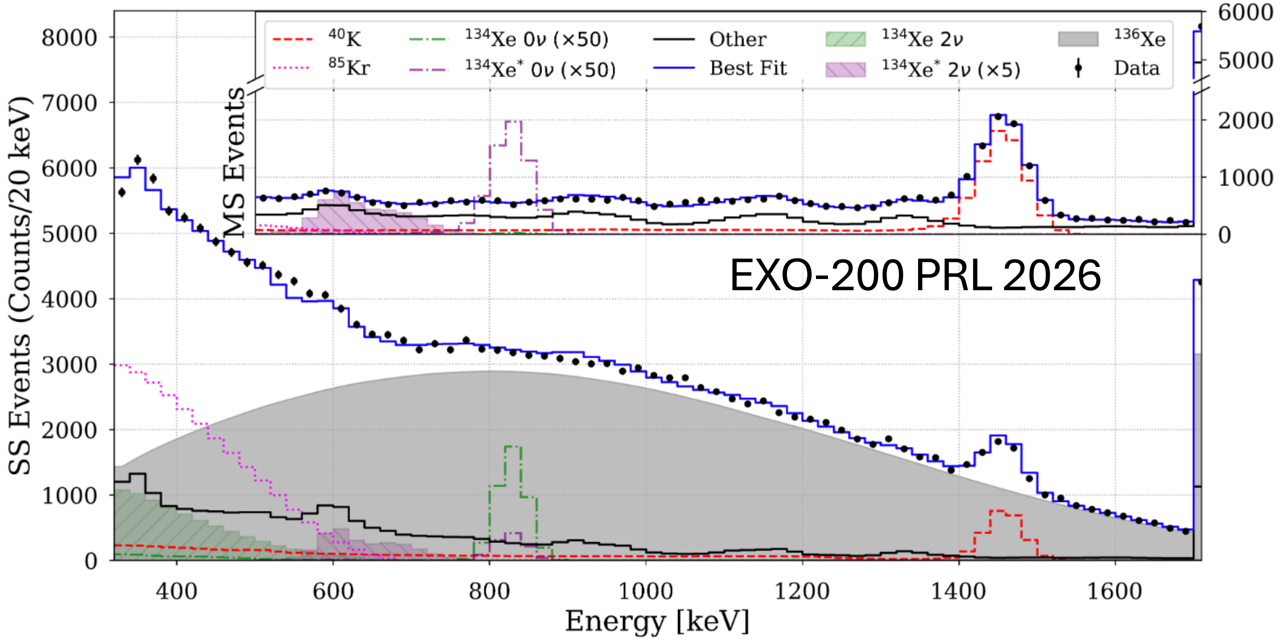
Higher energy searches come with deep fiducial selection



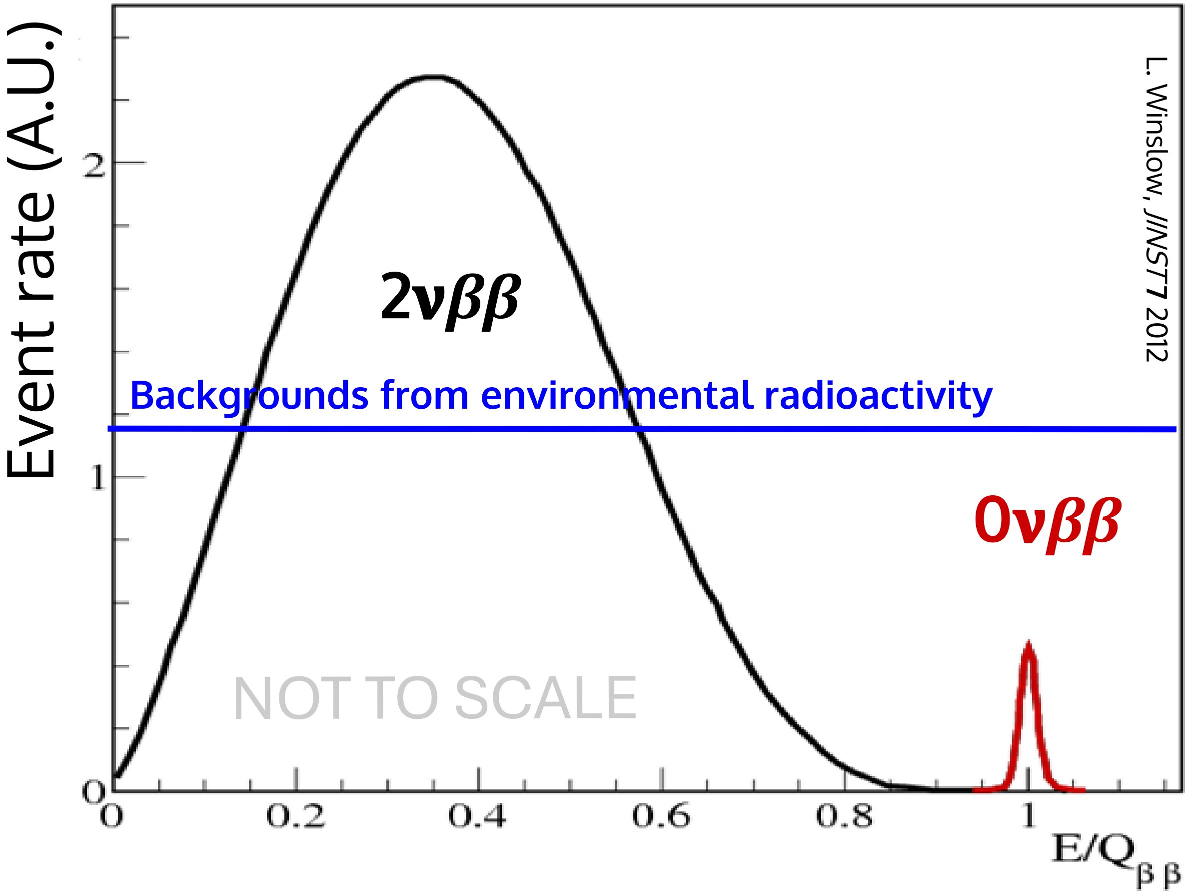
OK here!

0νββ decay searches optimize against MeV gamma rays (and betas)

- long-lived decay chains, neutron capture, activation products
- Tl-208, Bi-214, Co-60, (K-40)
- (n,γ) on Cu, F, Xe;



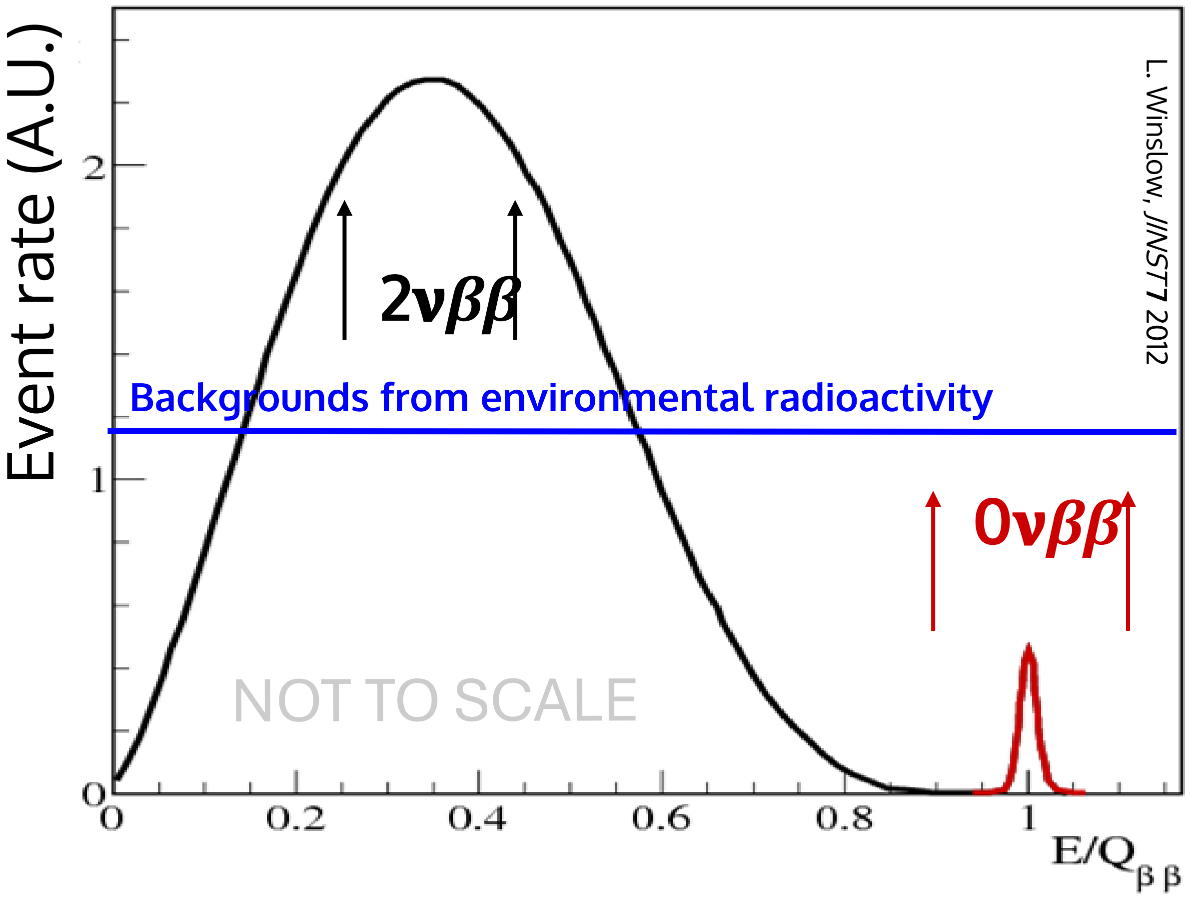
Optimizing a 0νββ search



L. Winslow, *JINST* 7 2012

What drives the sensitivity of a 0νββ search experiment?

Optimizing a 0νββ search

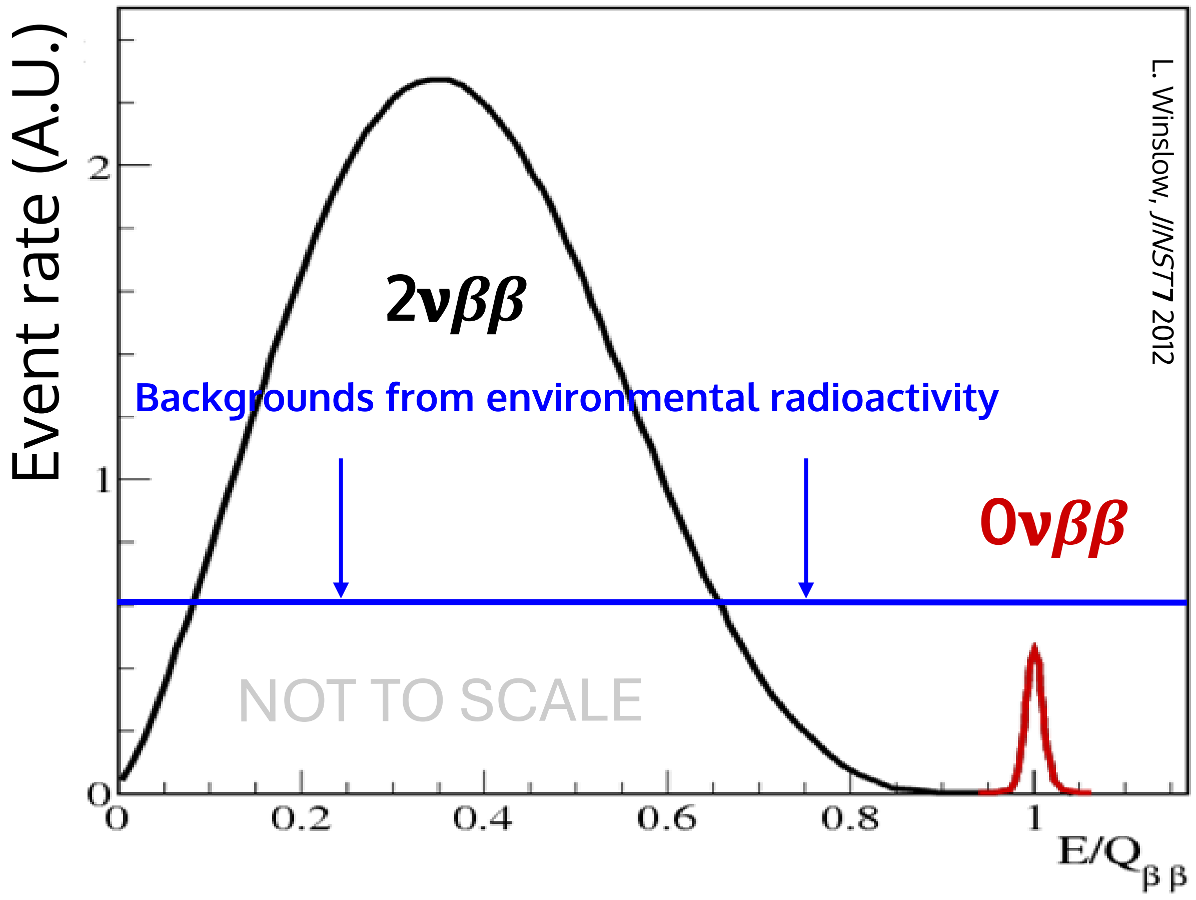


What drives the sensitivity of a 0νββ search experiment?

1. A lot of the **ββ** isotope

→ Remember from previous slide:
- current generation: order 100s kg
- next-generation: order tonne

Optimizing a 0νββ search

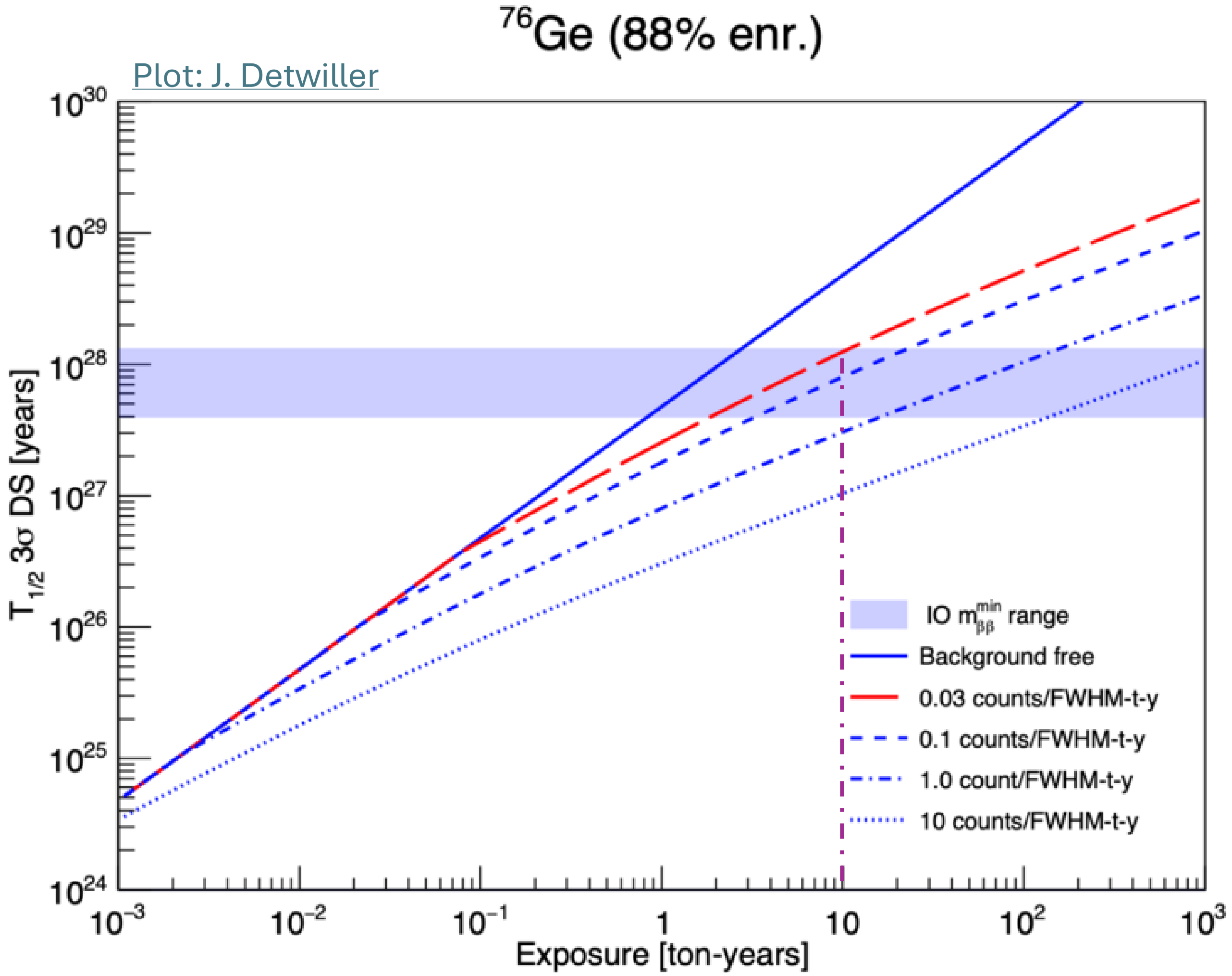


L. Winslow, *JINST* 7 2012

What drives the sensitivity of a 0νββ search experiment?

1. A lot of the **ββ** isotope
2. Ultra-low backgrounds
    1) Shielding
    2) Characterize the Background
    3) Material Selection & Purification
    4) Material Handling

Impact of backgrounds on 0νββ sensitivity



Plot: J. Detwiller

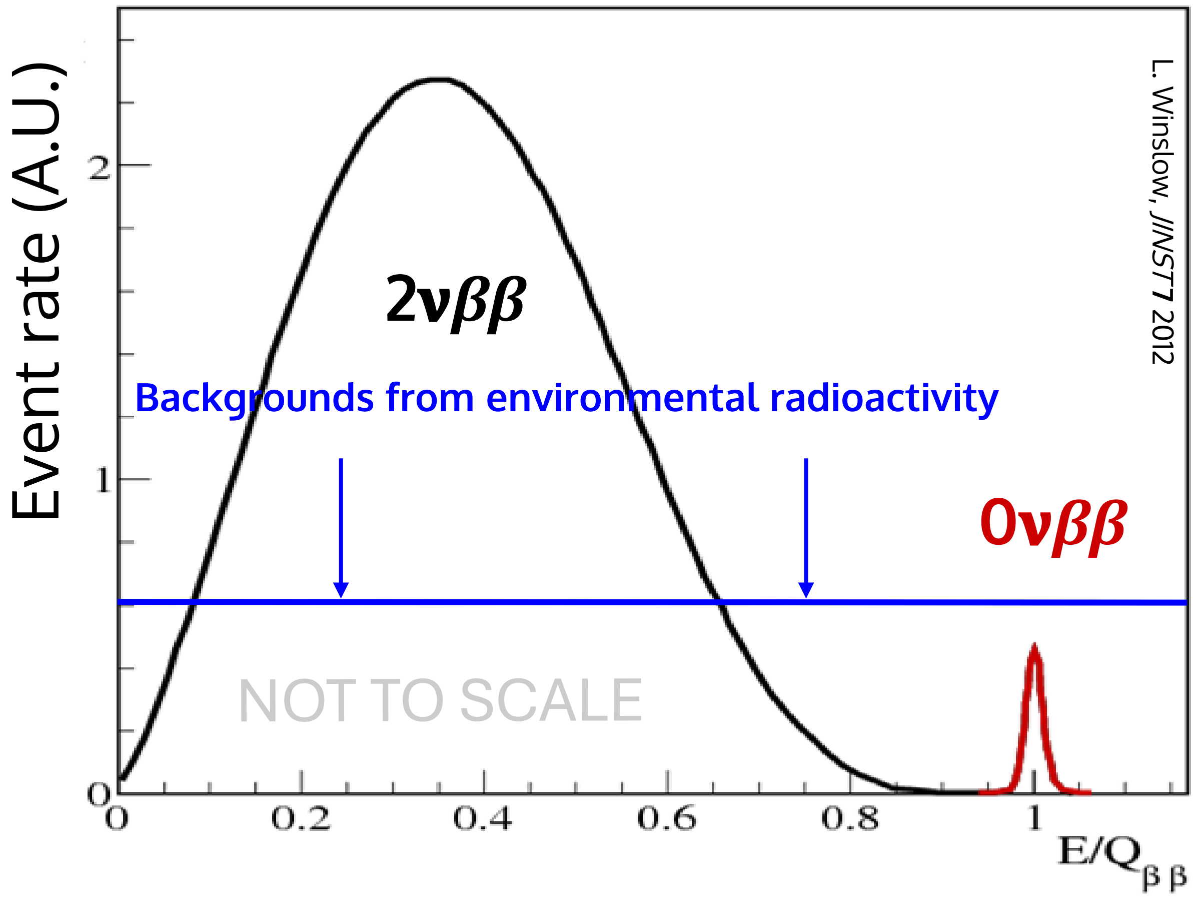
More Rare

Deeper Physics Reach

More Exposure (mass x observation time)

Exposure and physics goal drive background requirements!

Optimizing a 0νββ search

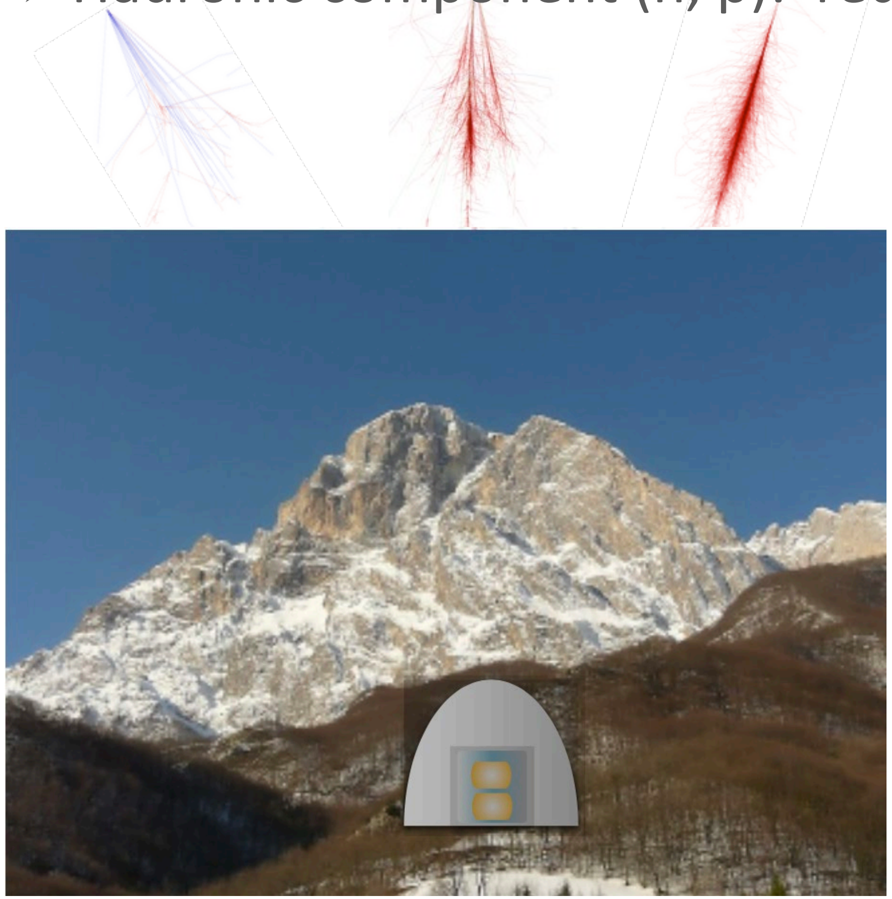


What drives the sensitivity of a 0νββ search experiment?

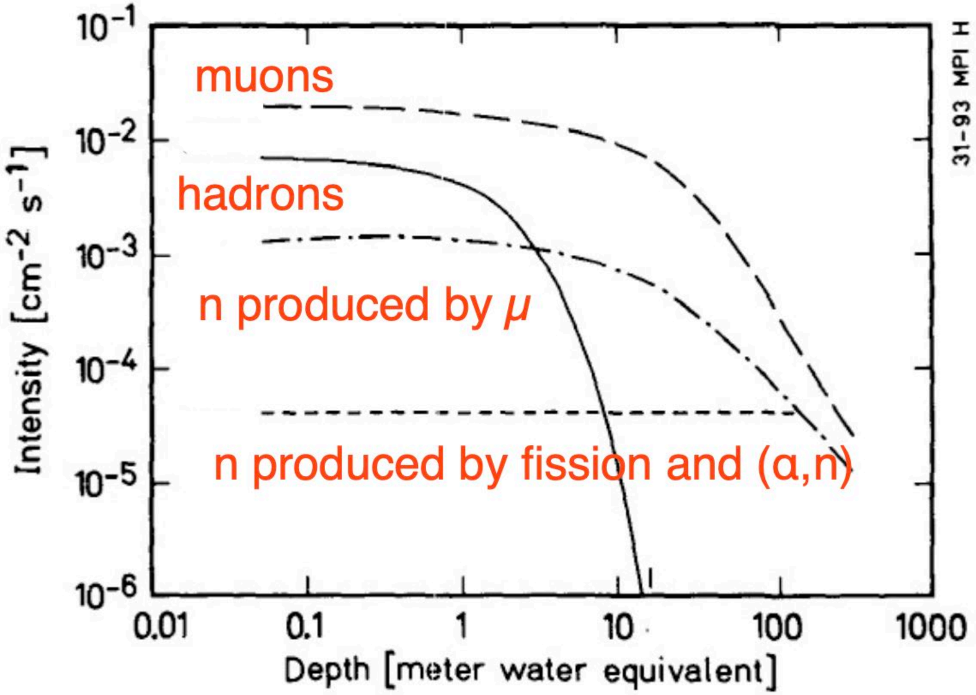
1. A lot of the **ββ** isotope
2. Ultra-low backgrounds
    1) **Shielding**
    2) Characterize the Background
    3) Material Selection & Purification
    4) Material Handling

Cosmic Ray Induced Backgrounds

- ➢Cosmic rays and secondary/tertiary particles can be problematic!
- ➢Hadronic component (n, p): reduced by a few meters water equivalent (m.w.e.).

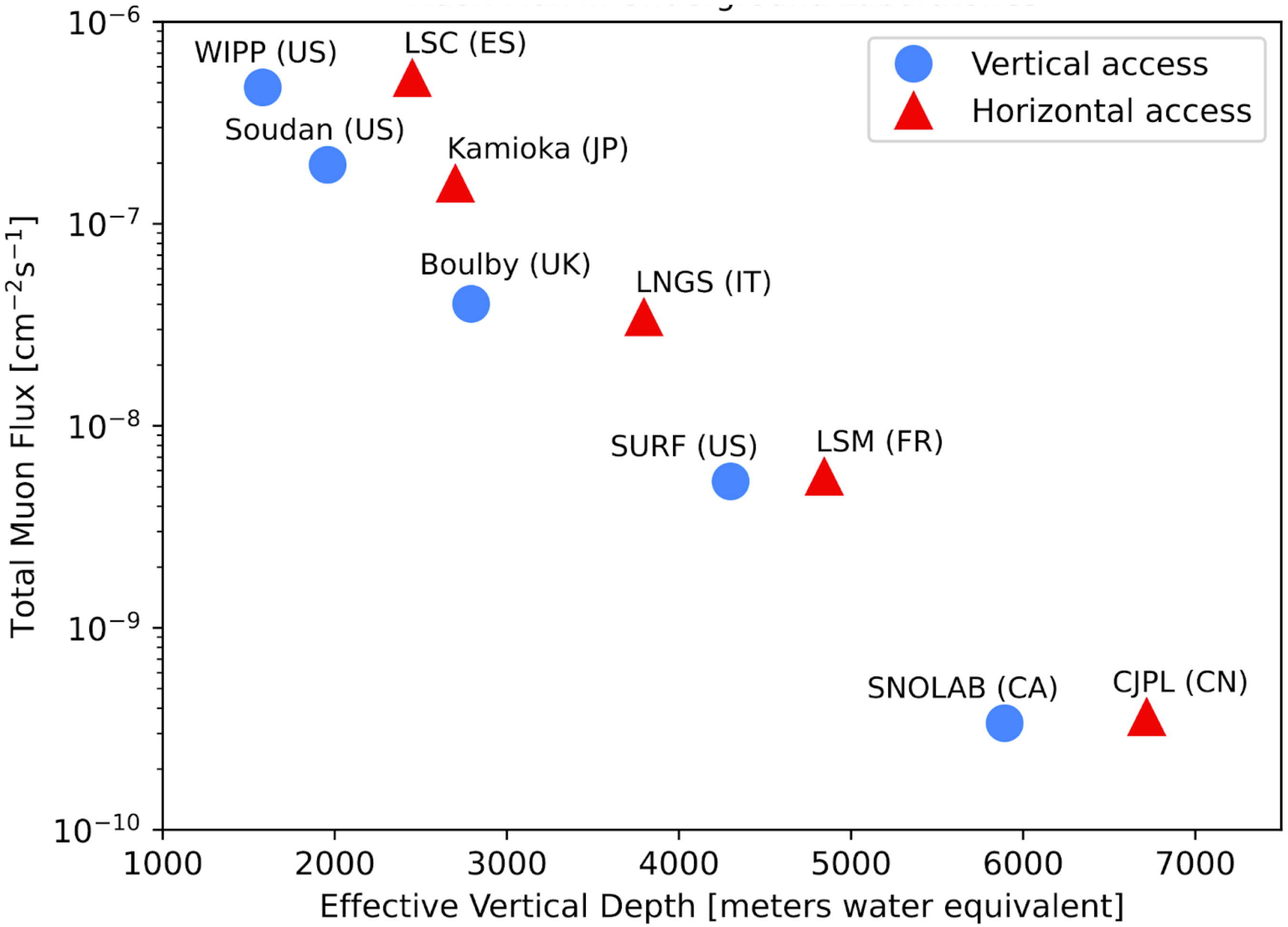


Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth
Gerd Heusser, 1995



Muon shielding

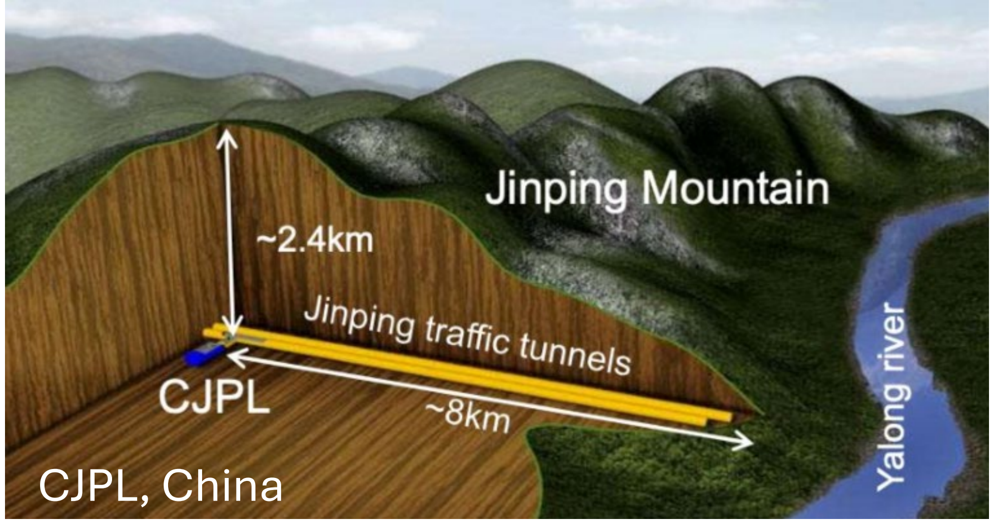
sea level: 10^9 μ/m^2/y
1 μ/cm^2/min
0.0167 1 μ/cm^2/s

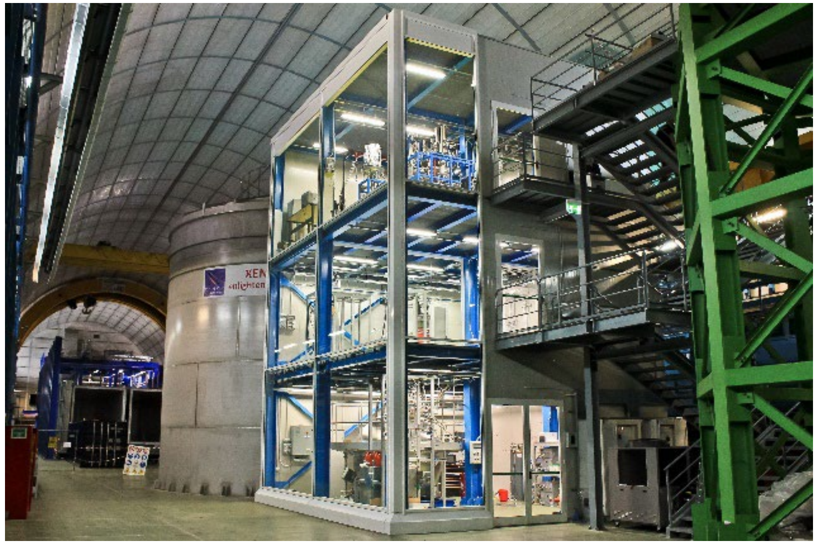


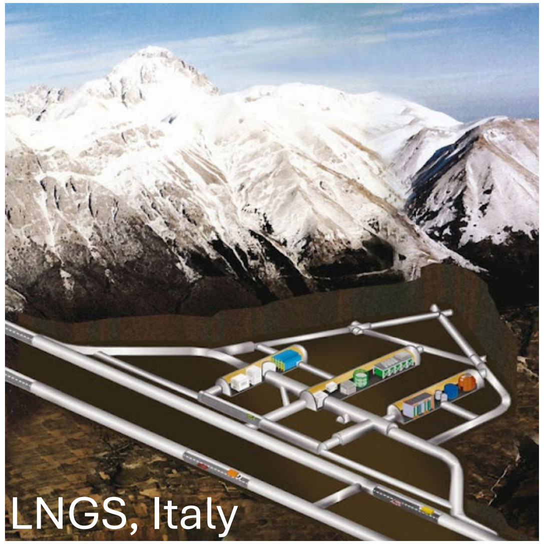
Up to ~ 7 orders of magnitude reduction

Courtesy E. Caden, adapted from: Zi-yi Guo et al 2021 Chinese Phys. C 45 025001

Horizontal Access (examples)

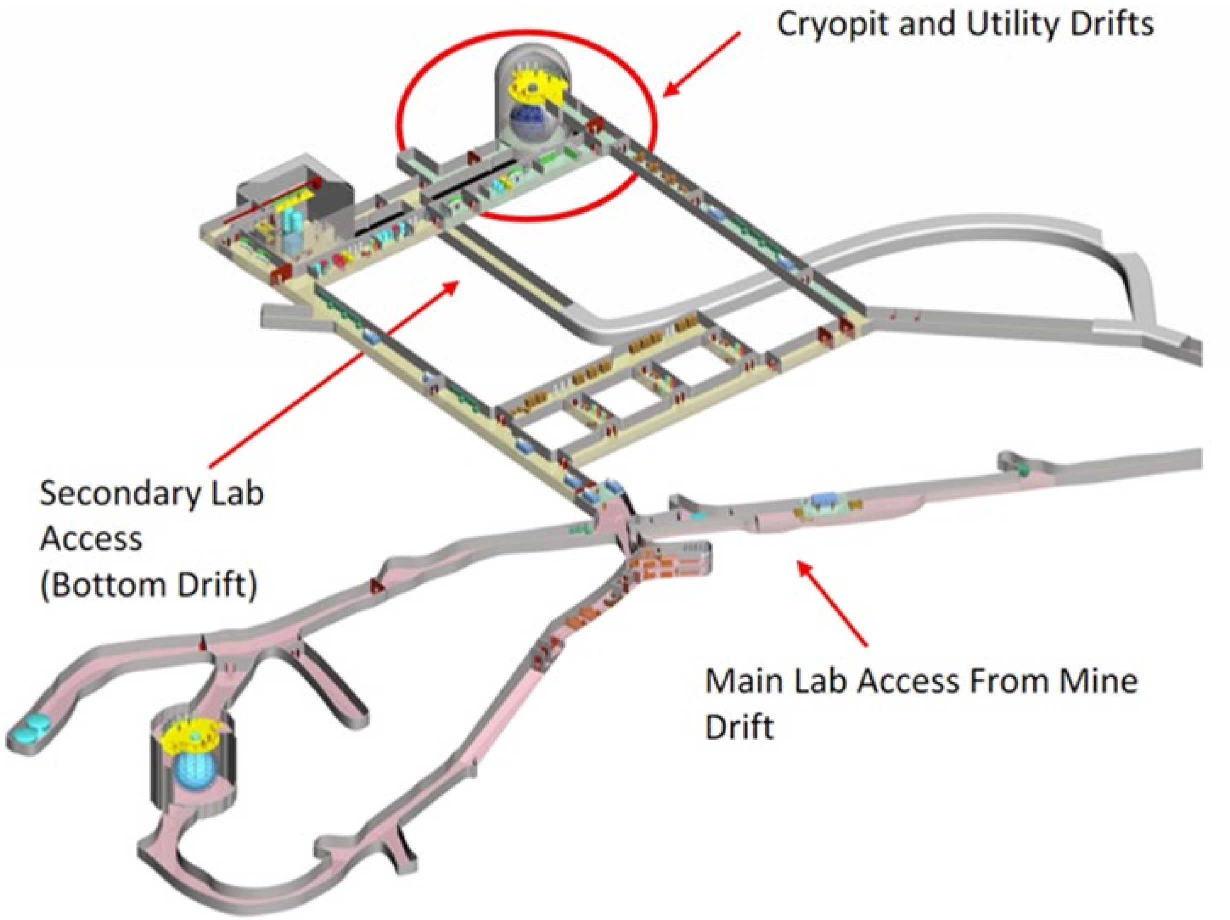


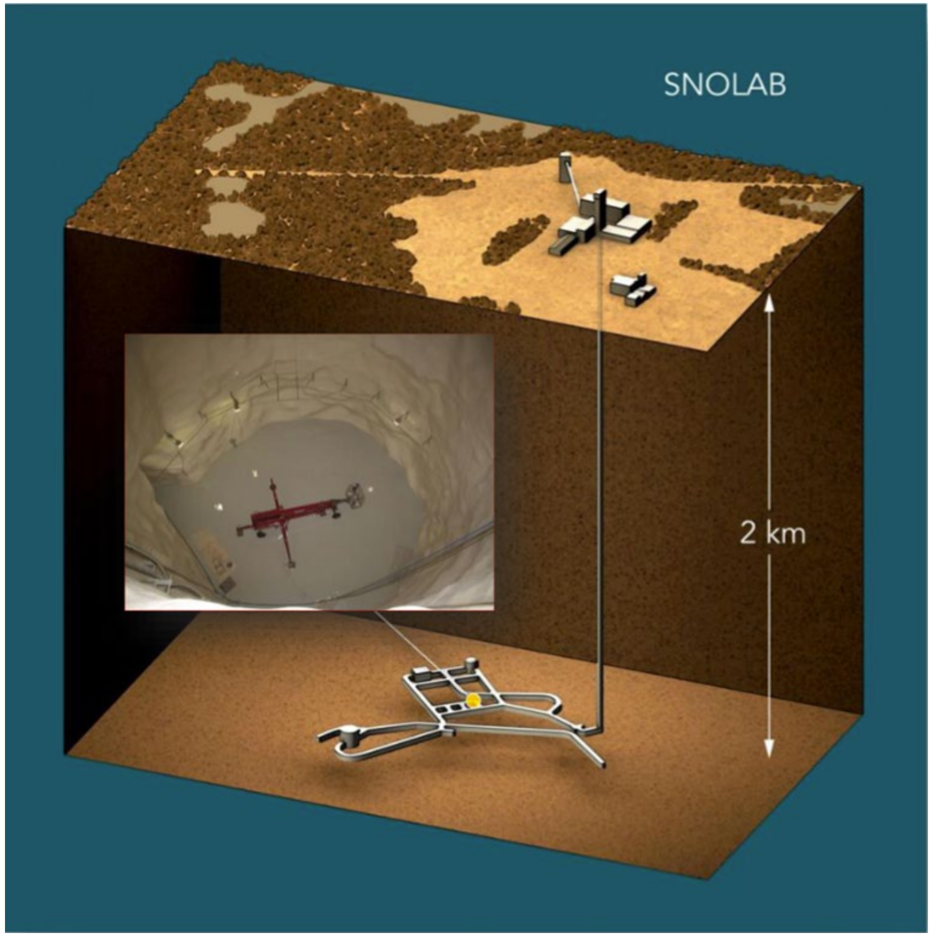




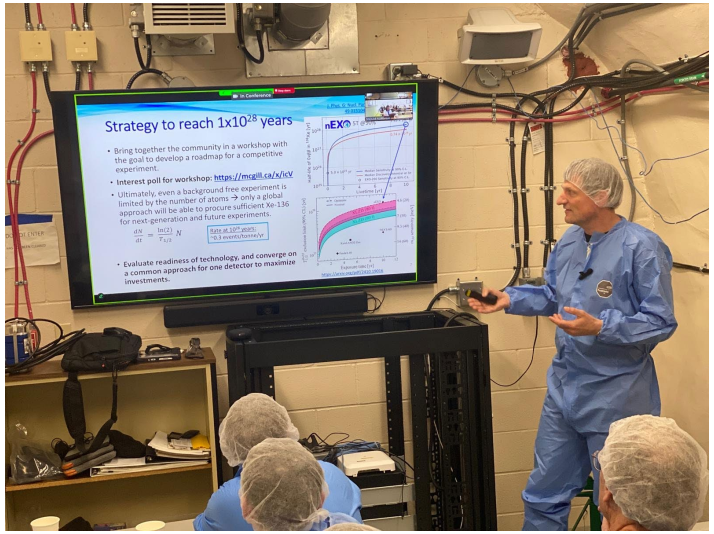
Vertical Access – SNOLAB, Canada

The facility is situated at the 6800 level, approximately 2 km below the surface, and is accessed via a cage elevator followed by a 1.5 km walk to the laboratory entrance.





Impressions from SNOLAB



Strategy to reach 1x10^{28} years

- Bring together the community in a workshop with the goal to develop a roadmap for a competitive experiment.
- **Interest poll for workshop: https://mcgill.ca/x/icV**
- Ultimately, even a background free experiment is limited by the number of atoms → only a global approach will be able to procure sufficient Xe-136 for next-generation and future experiments.

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

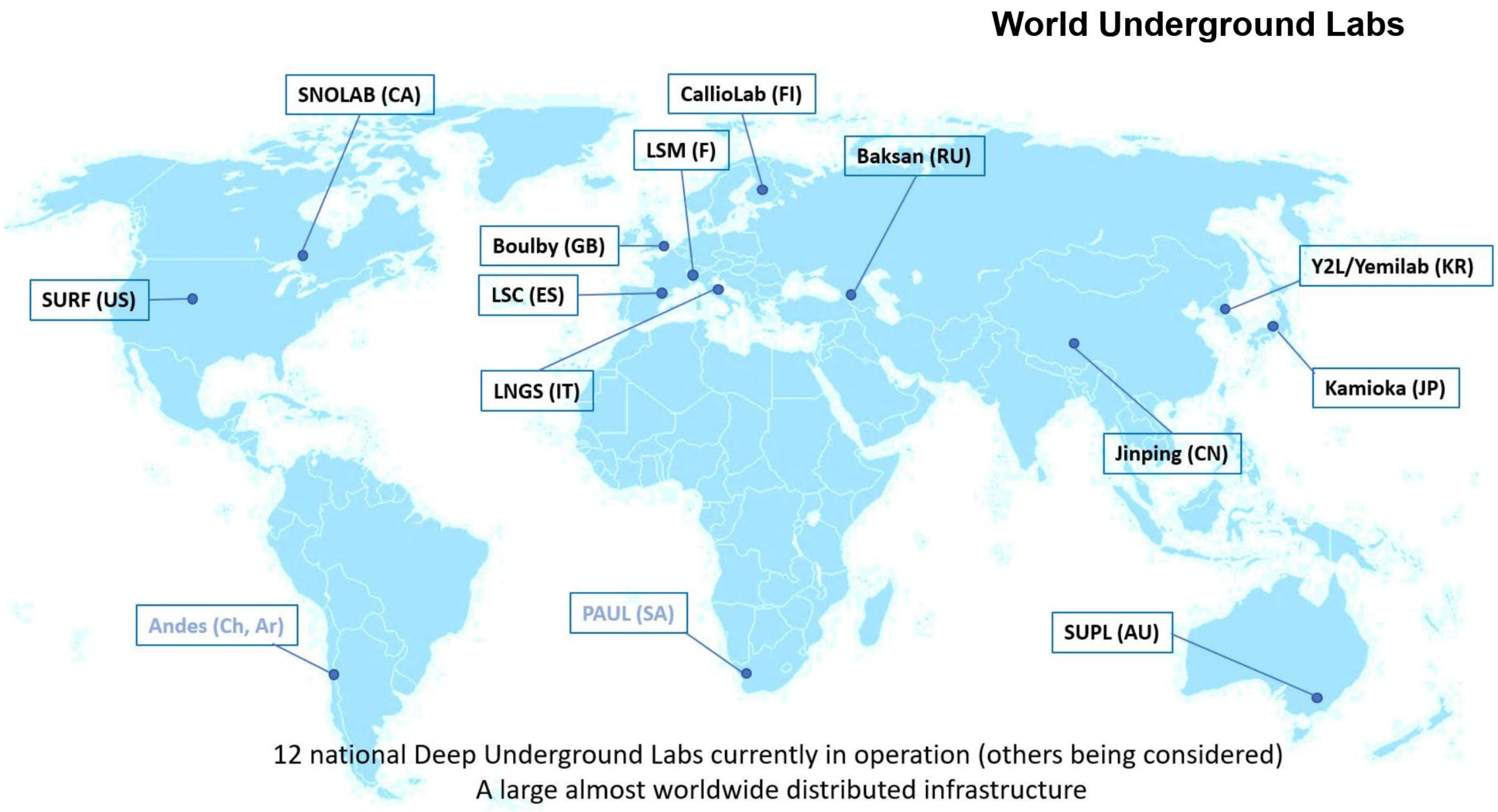
Rate at 10^{28} years:
~0.3 events/tonne/yr

- **Evaluate readiness of technology, and converge on a common approach for one detector to maximize investments.**

J. Phys. G: Nucl. Par 49 015104

https://arxiv.org/pdf/2410.19016

Underground labs

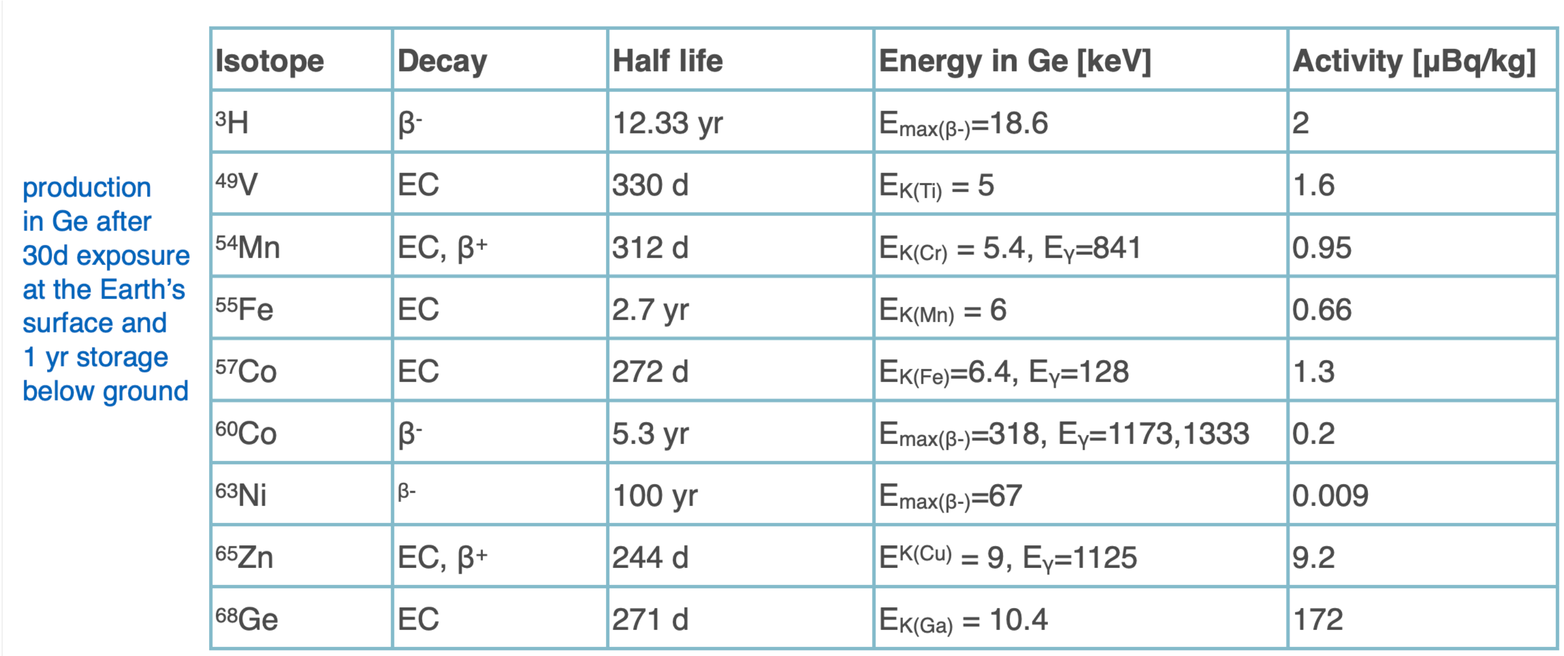


12 national Deep Underground Labs currently in operation (others being considered)
A large almost worldwide distributed infrastructure

Figure courtesy of S. Paling, TAUP 2025

Activation of Detector Materials

- Activation of a detector or materials close to the detector during production or transportation at Earth’s surface is another concern.
  - CR spectrum varies with geomagnetic latitude and the flux varies with height above Earth.
  - Cross section for production of isotopes — not all are measured
- Production is dominated by (n, x) reactions (95%) and (p, x) reactions (5%)

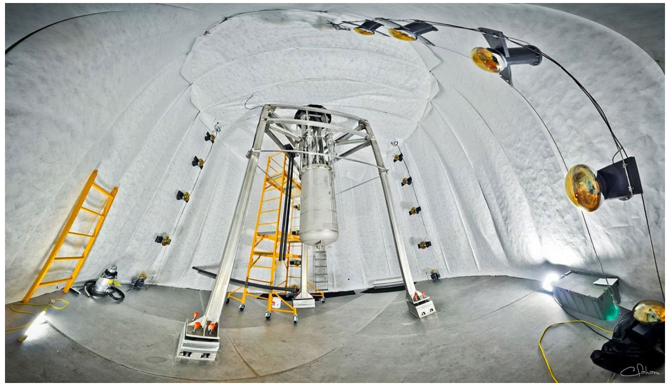


production in Ge after 30d exposure at the Earth’s surface and 1 yr storage below ground

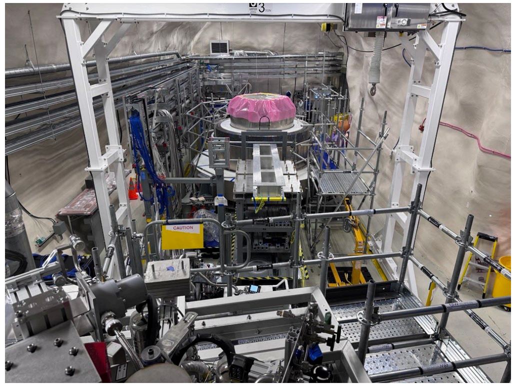
Isotope	Decay	Half life	Energy in Ge [keV]	Activity [μBq/kg]
^{3}H	β^-	12.33 yr	$E_{max(\beta-)}=18.6$	2
^{49}V	EC	330 d	$E_{K(Ti)} = 5$	1.6
^{54}Mn	EC, β^+	312 d	$E_{K(Cr)} = 5.4$, $E_\gamma=841$	0.95
^{55}Fe	EC	2.7 yr	$E_{K(Mn)} = 6$	0.66
^{57}Co	EC	272 d	$E_{K(Fe)}=6.4$, $E_\gamma=128$	1.3
^{60}Co	β^-	5.3 yr	$E_{max(\beta-)}=318$, $E_\gamma=1173,1333$	0.2
^{63}Ni	β^-	100 yr	$E_{max(\beta-)}=67$	0.009
^{65}Zn	EC, β^+	244 d	$E^{K(Cu)} = 9$, $E_\gamma=1125$	9.2
^{68}Ge	EC	271 d	$E_{K(Ga)} = 10.4$	172

David Radford with LEGEND crystal

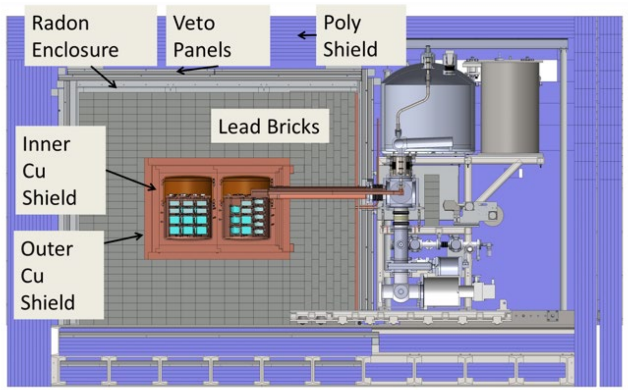
Environmental Backgrounds



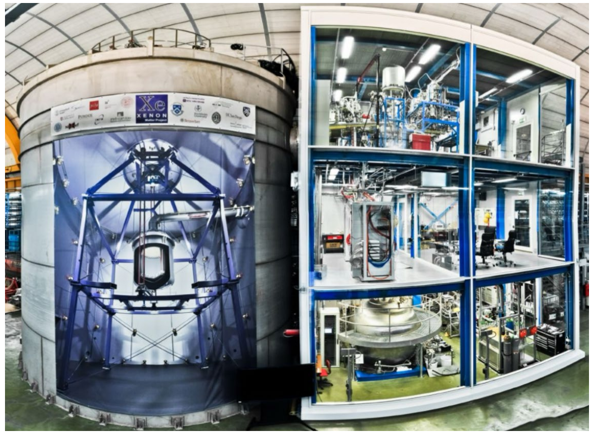
LUX/LZ Muon Veto



SuperCDMS SNOLAB Passive Shield



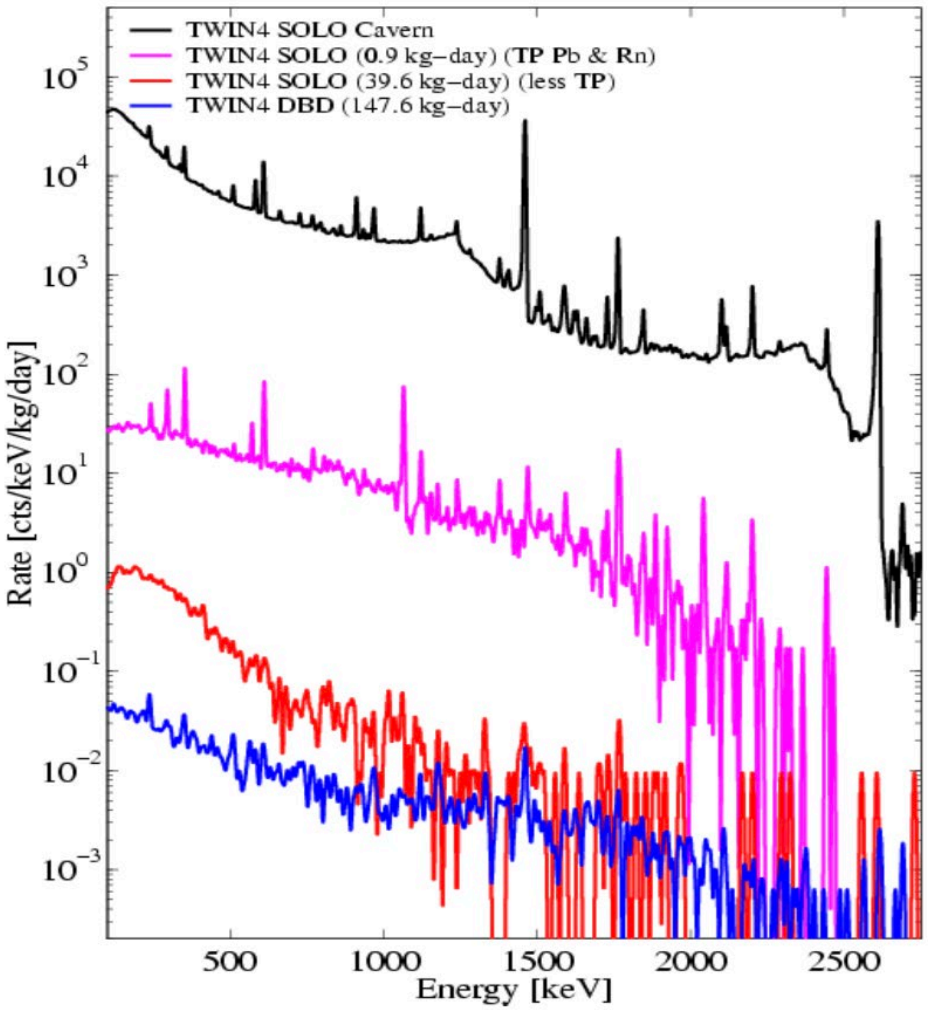
Majorana Demonstrator Passive Shield



XENON1T water shield & infrastructure

- A combination of high-Z and low-Z materials are employed to diminish the neutron and gamma fluxes.
  - Lead, polyethelyne, copper
- Nitrogen purge of shield structures to reduce backgrounds induced by airborne radon decays
- Large water shields
  - passively reduce environmental radioactivity and muon-induced neutrons
  - can reduce underground fluxes of gamma and radiogenic fluxes by a factor of ~10^6 by employing a 1 - 3 m water shield
- Active muon vetos using doped scintillator (ie boron) can be used to identify events related to both cosmogenic and radiogenic neutrons.

Environmental Backgrounds



Ge detector underground, no shield

Ge detector underground, Pb shield and purge for Rn

- A combination of high-Z and low-Z materials are employed to diminish the neutron and gamma fluxes.
  - Lead, polyethelyne, copper
- Nitrogen purge of shield structures to reduce backgrounds induced by airborne radon decays
- Large water shields
  - passively reduce environmental radioactivity and muon-induced neutrons
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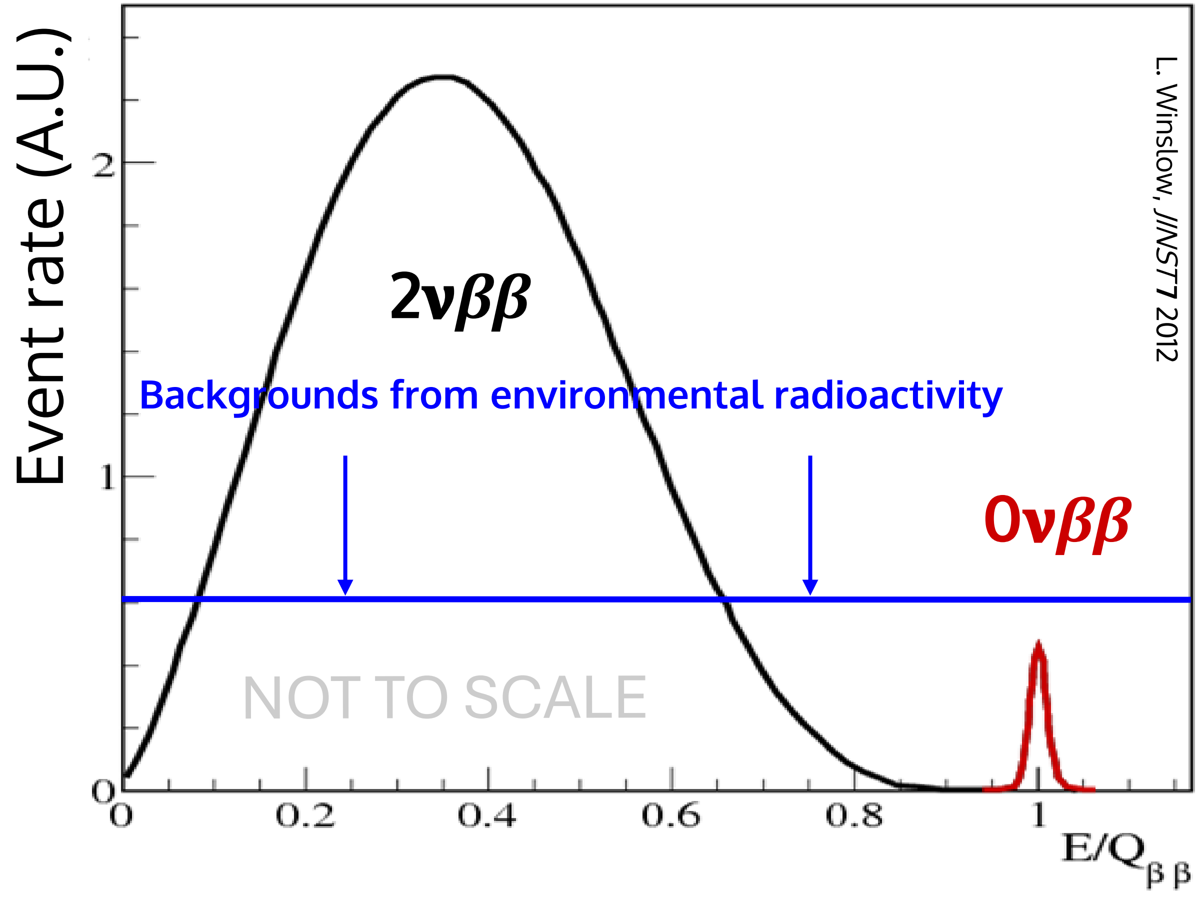
- Active muon vetos using doped scintillator (ie boron) can be used to identify events related to both cosmogenic and radiogenic neutrons.

Optimizing a 0νββ search



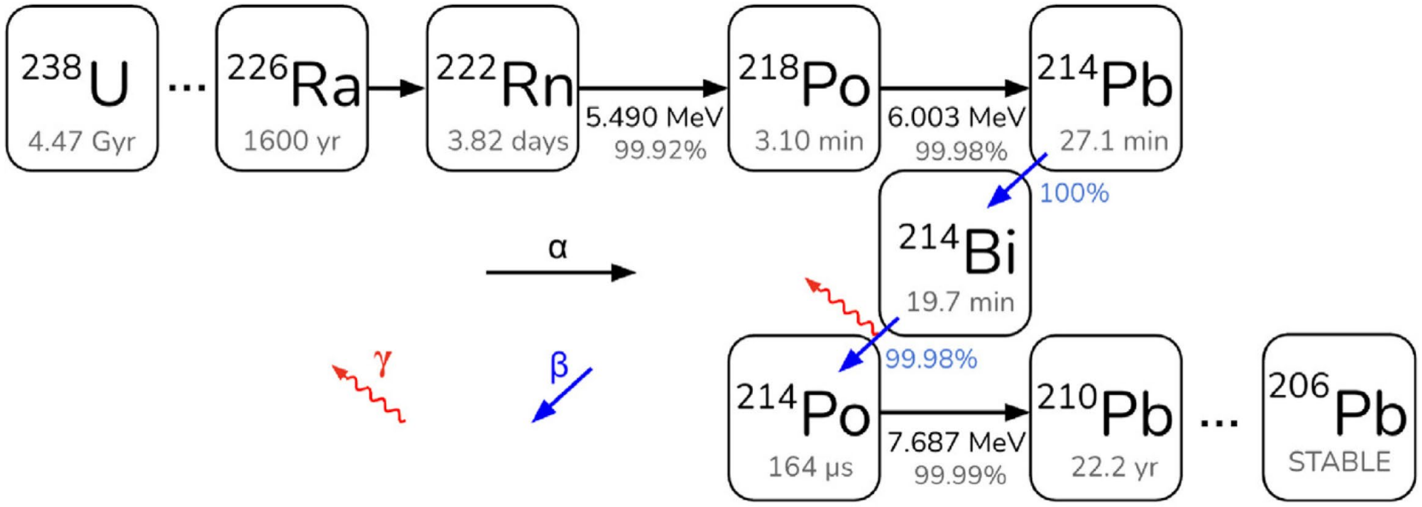
L. Winslow, *JINST7* 2012

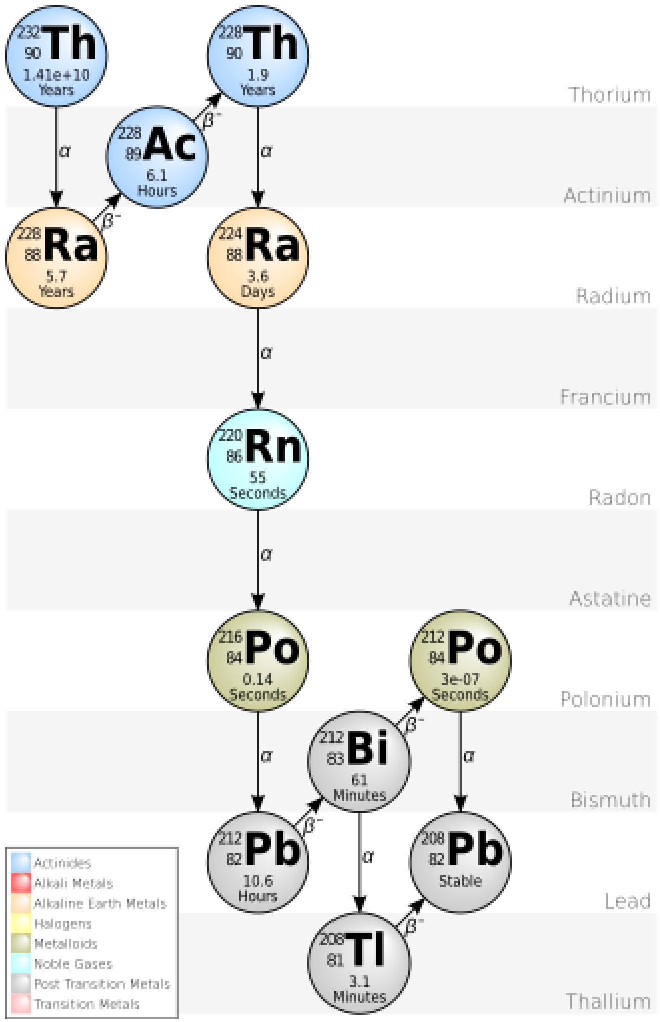
What drives the sensitivity of a 0νββ search experiment?

1. A lot of the **ββ** isotope
2. Ultra-low backgrounds
    1) Shielding
    2) **Characterize the Background**
    3) Material Selection & Purification
    4) Material Handling

Internal Radioactivity

- ^{238}U, ^{238}Th, ^{40}K, ^{137}Cs, ^{60}Co, ^{39}Ar, ^{85}Kr, ... decays in the detector target, materials surrounding the target medium and shield
- A number of methods are employed to characterize materials before using them as detector components.
- In most cases, looking for materials at levels of < 1 ppb.

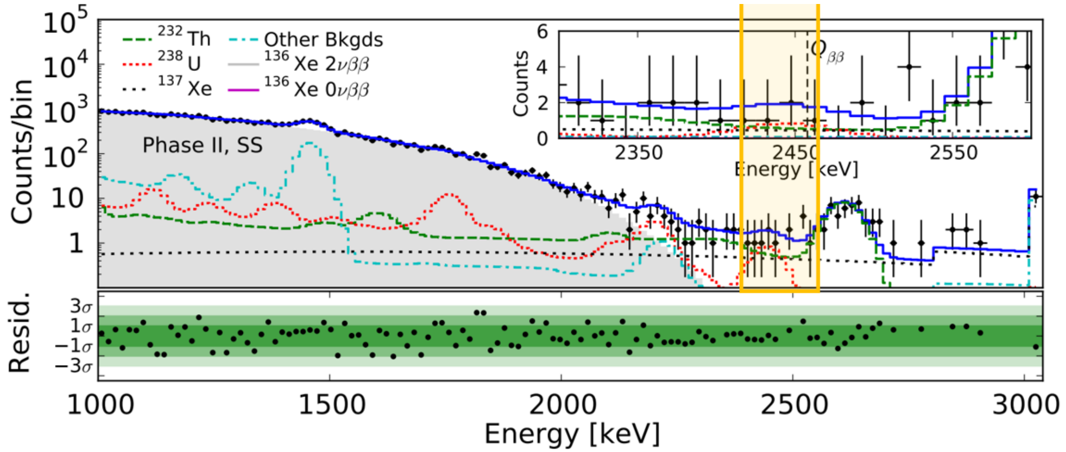




Backgrounds in order of impact

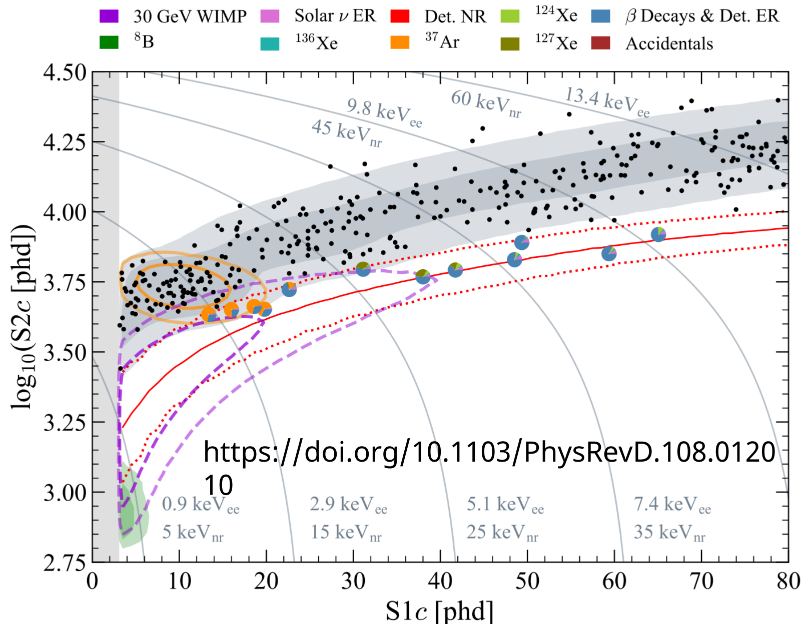
0νββ in ^{136}Xe ($Q_{\beta\beta}$=2457 keV)

1) ^{214}Bi (γ, 2448 keV, 1.5%)
2) ^{208}Tl (γ, 2614 keV, 100%)
3) ^{137}Xe (β – 4173 keV)
4) ^{60}Co (γγ 1173+1332 keV)
5) …



WIMPS in LXe

1) ^{214}Pb (β – 12% “naked beta”)
2) ^{85}Kr (β – 99% “naked beta”)
3) ν-ER
4) …



https://doi.org/10.1103/PhysRevD.108.012010

Backgrounds in order of impact

$0\nu\beta\beta$ in ^{136}Xe ($Q_{\beta\beta}$=2457 keV)

1) ^{214}Bi (γ, 2448 keV, 1.5%)
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4) ^{60}Co ($\gamma\gamma$ 1173+1332 keV)
5) …

WIMPS in LXe

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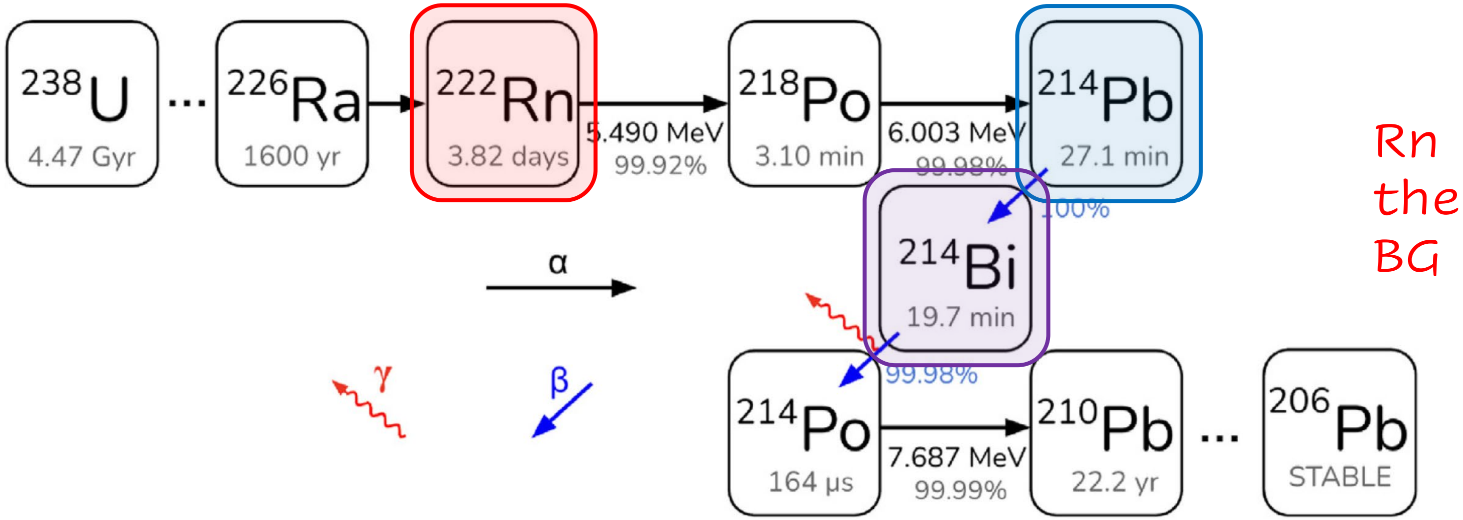
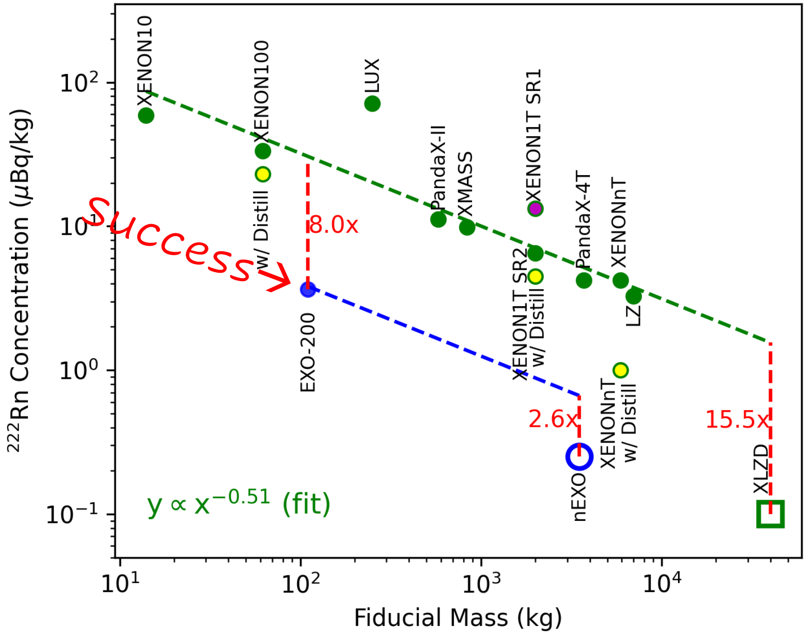
4) …



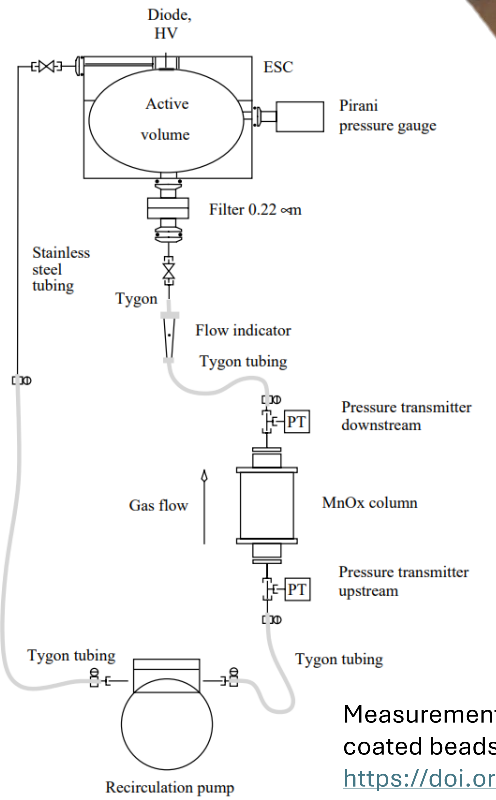
Rn is expected to be the largest source of BG in nEXO and XLZD

EXO-200 Rn Assay Program

- EXO-200 Rn assays done at SNOLAB
  - Achieved ~ 600uBq activity assaying most suspicious components & rejected some bad ones!



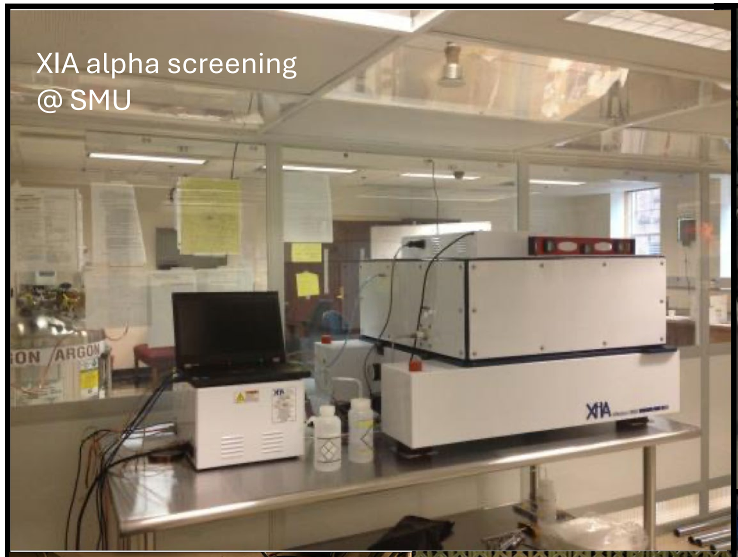
- Instruments built for SNO
  - Used to ^{226}Ra assay water

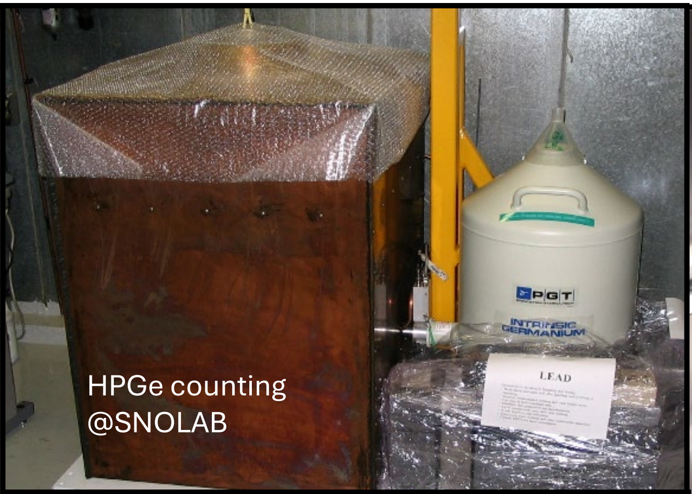


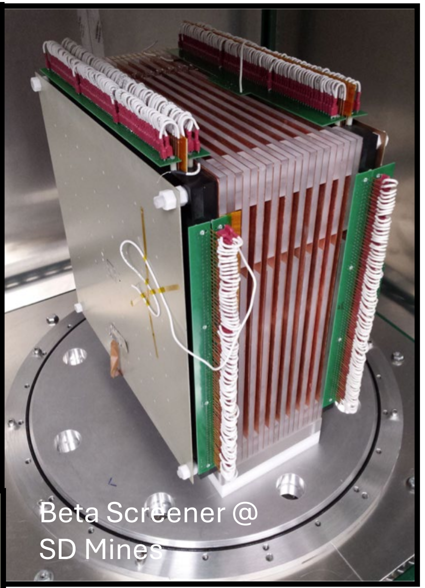
1) MnOx beads collect Ra from water in purification loop
2) Measure MnOx column w/ ESC
3) Rn emanation relates to Ra:H2O

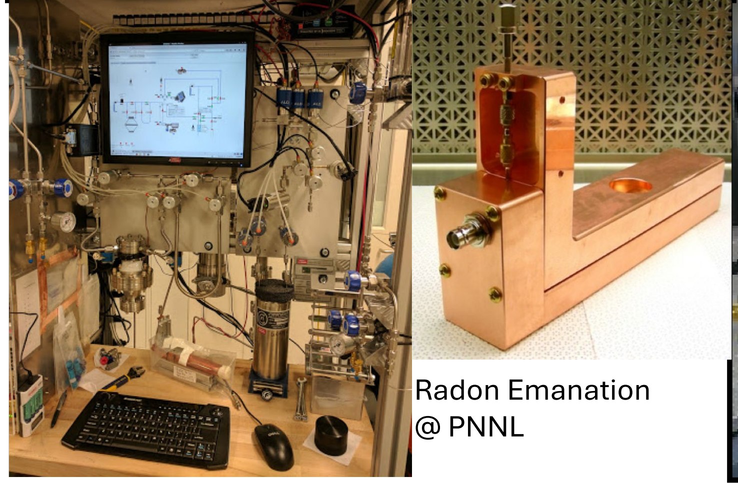
Measurement of radium concentration in water with Mn-coated beads at the Sudbury Neutrino Observatory
https://doi.org/10.1016/S0168-9002(03)00616-8

Radioassaying Tools


XIA alpha screening
@ SMU


HPGe counting
@SNOLAB


Beta Screener @
SD Mines


Radon Emanation
@ PNNL


ICPMS @LNGS

Your tool of choice depends on:

- Required sensitivity
- Radiation of interest
- Material to study
- Resources
- ….

In most cases, looking for materials at levels of < 1 ppb.

Many other Options

Technique	Sensitivity
Radon Emanation	0.1-10 µBq/kg (Ra)
Immersion Whole Body Counters	10^{-13}-10^{-14} g/g (U/Th)
ICPMS (Inductively Coupled Plasma Mass Spectrometry)	ppt to ppt (U/Th/K)
SIMS/GDMS (Secondary Ion & Glow Discharge Mass Spectroscopy)	1 ppb (SIMS) 10-100ppt (GDMS)
AMS (Accelerator Mass Sepctroscopy)	< 1 ppt
Neutron Activation Analysis	100 pg (U), 10 ng (K)

Workhorse in 0νββ detector development

How Well Can We Do with Ge?

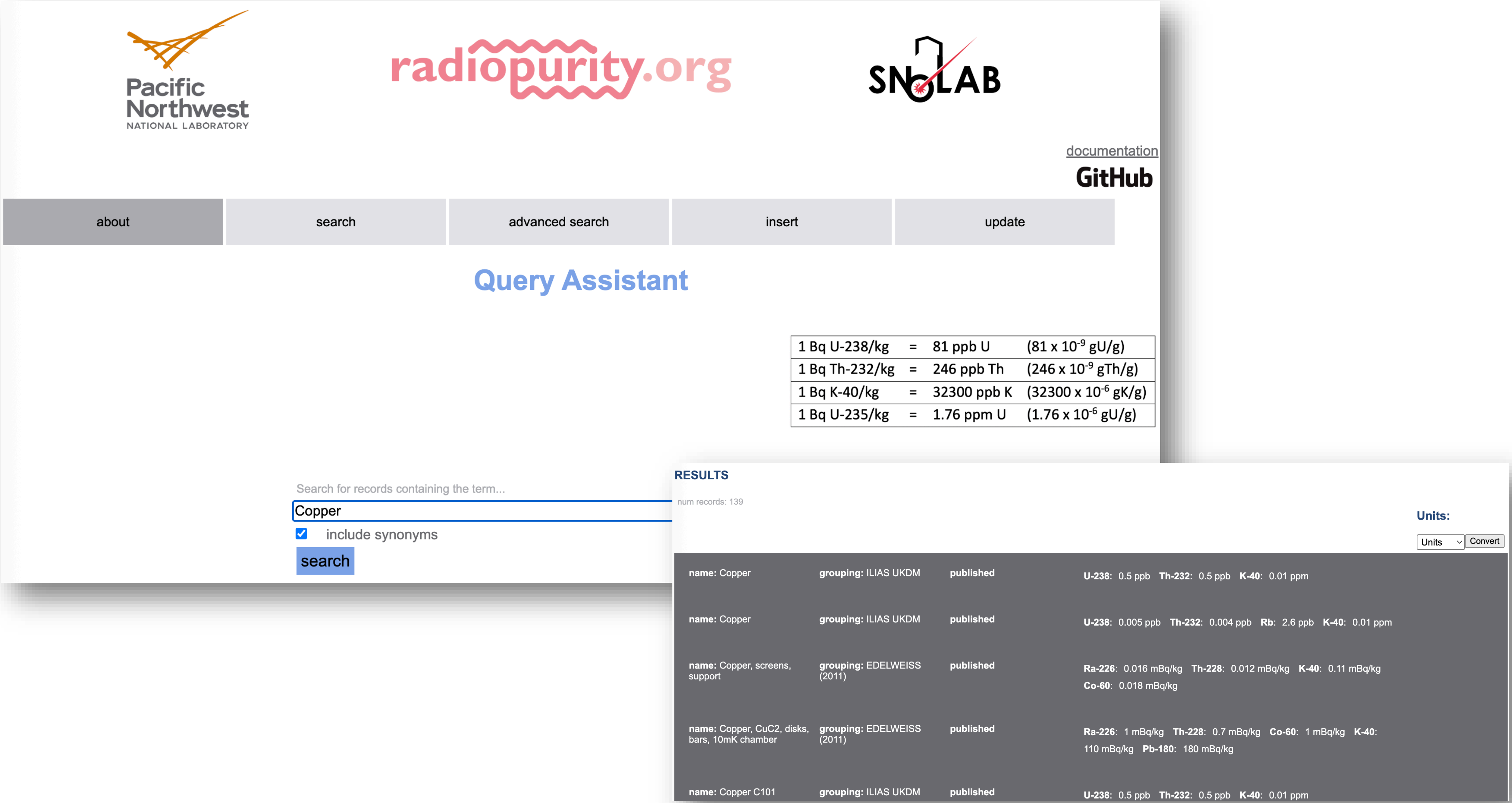
Augmented Commercial Systems:
Commercially purchased High-Purity Ge detector is placed in a custom designed shield (Pb, copper, neutron moderation and capture materials, active cosmic ray veto, underground location)

Fully Custom Systems:
In addition to a custom shield, a custom cryostat design with attention to design of and placement of electronics to minimize background sources (U/Th/K).

HPGe Counting:

Isotope/Chain	Standard Size (ppb) | (mBq/kg)		Large Size & Long Count (ppb)
^{238}U	~0.1	~1.0	0.009
^{232}Th	~0.3	~1.5	0.02
^{40}K	~700	~21	87
^{238}U	0.001	0.12	
^{232}Th	0.001	0.004	
^{40}K	1	0.031	

Global Community Assaying Effort!



Query Assistant

1 Bq U-238/kg	=	81 ppb U	(81×10^{-9} gU/g)
1 Bq Th-232/kg	=	246 ppb Th	(246×10^{-9} gTh/g)
1 Bq K-40/kg	=	32300 ppb K	(32300×10^{-6} gK/g)
1 Bq U-235/kg	=	1.76 ppm U	(1.76×10^{-6} gU/g)

Search for records containing the term...

Copper

☑ include synonyms

search

RESULTS

num records: 139

name: Copper **grouping:** ILIAS UKDM **published** **U-238**: 0.5 ppb **Th-232**: 0.5 ppb **K-40**: 0.01 ppm

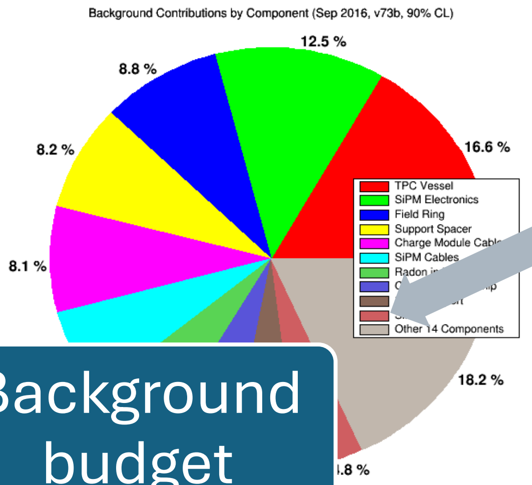
name: Copper **grouping:** ILIAS UKDM **published** **U-238**: 0.005 ppb **Th-232**: 0.004 ppb **Rb**: 2.6 ppb **K-40**: 0.01 ppm

name: Copper, screens, support **grouping:** EDELWEISS (2011) **published** **Ra-226**: 0.016 mBq/kg **Th-228**: 0.012 mBq/kg **K-40**: 0.11 mBq/kg **Co-60**: 0.018 mBq/kg

name: Copper, CuC2, disks, bars, 10mK chamber **grouping:** EDELWEISS (2011) **published** **Ra-226**: 1 mBq/kg **Th-228**: 0.7 mBq/kg **Co-60**: 1 mBq/kg **K-40**: 110 mBq/kg **Pb-180**: 180 mBq/kg

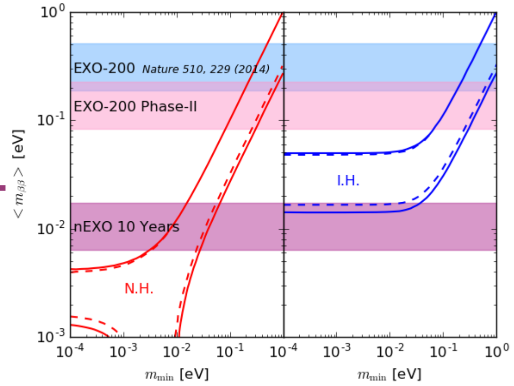
name: Copper C101 **grouping:** ILIAS UKDM **published** **U-238**: 0.5 ppb **Th-232**: 0.5 ppb **K-40**: 0.01 ppm

Iterative Design Process



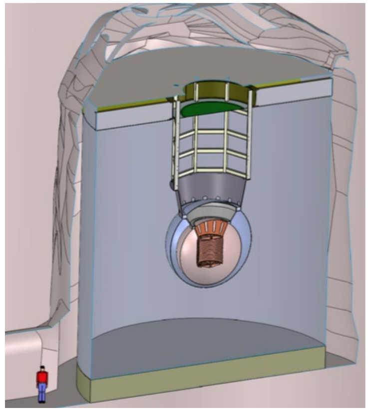
Background budget

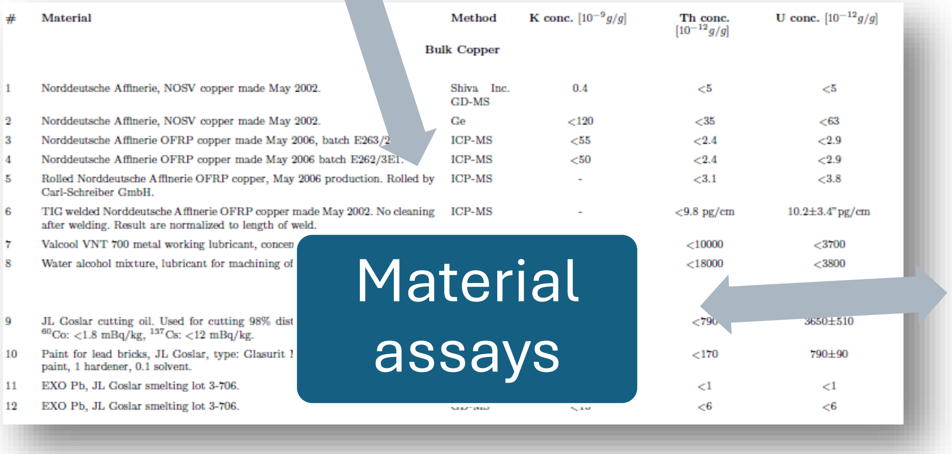
Physics sensitivity



Need to provide assays with enough resolution to give feedback to design

Detector design

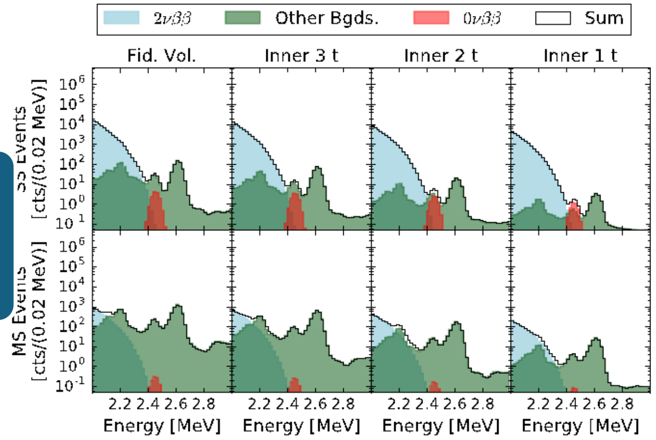




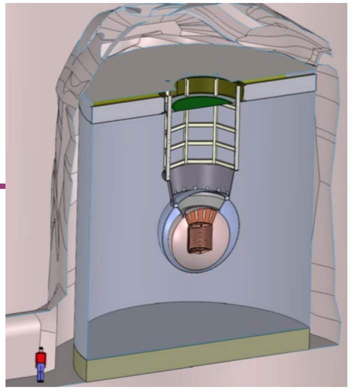
#	Material	Method	K conc. $[10^{-9} g/g]$	Th conc. $[10^{-12} g/g]$	U conc. $[10^{-12} g/g]$
		Bulk Copper			
1	Norddeutsche Affinerie, NOSV copper made May 2002.	Shiva Inc. GD-MS	0.4	<5	<5
2	Norddeutsche Affinerie, NOSV copper made May 2002.	Ge	<120	<35	<63
3	Norddeutsche Affinerie OFRP copper made May 2006, batch E263/2	ICP-MS	<55	<2.4	<2.9
4	Norddeutsche Affinerie OFRP copper made May 2006 batch E262/3E1.	ICP-MS	<50	<2.4	<2.9
5	Rolled Norddeutsche Affinerie OFRP copper, May 2006 production. Rolled by Carl-Schreiber GmbH.	ICP-MS	-	<3.1	<3.8
6	TIG welded Norddeutsche Affinerie OFRP copper made May 2002. No cleaning after welding. Result are normalized to length of weld.	ICP-MS	-	<9.8 pg/cm	10.2±3.4" pg/cm
7	Valcool VNT 700 metal working lubricant, concen			<10000	<3700
8	Water alcohol mixture, lubricant for machining of			<18000	<3800
9	JL Goslar cutting oil. Used for cutting 98% dist ^{60}Co: <1.8 mBq/kg, ^{137}Cs: <12 mBq/kg.			<79	3650±510
10	Paint for lead bricks, JL Goslar, type: Glasurit paint, 1 hardener, 0.1 solvent.			<170	790±90
11	EXO Pb, JL Goslar smelting lot 3-706.			<1	<1
12	EXO Pb, JL Goslar smelting lot 3-706.			<6	<6

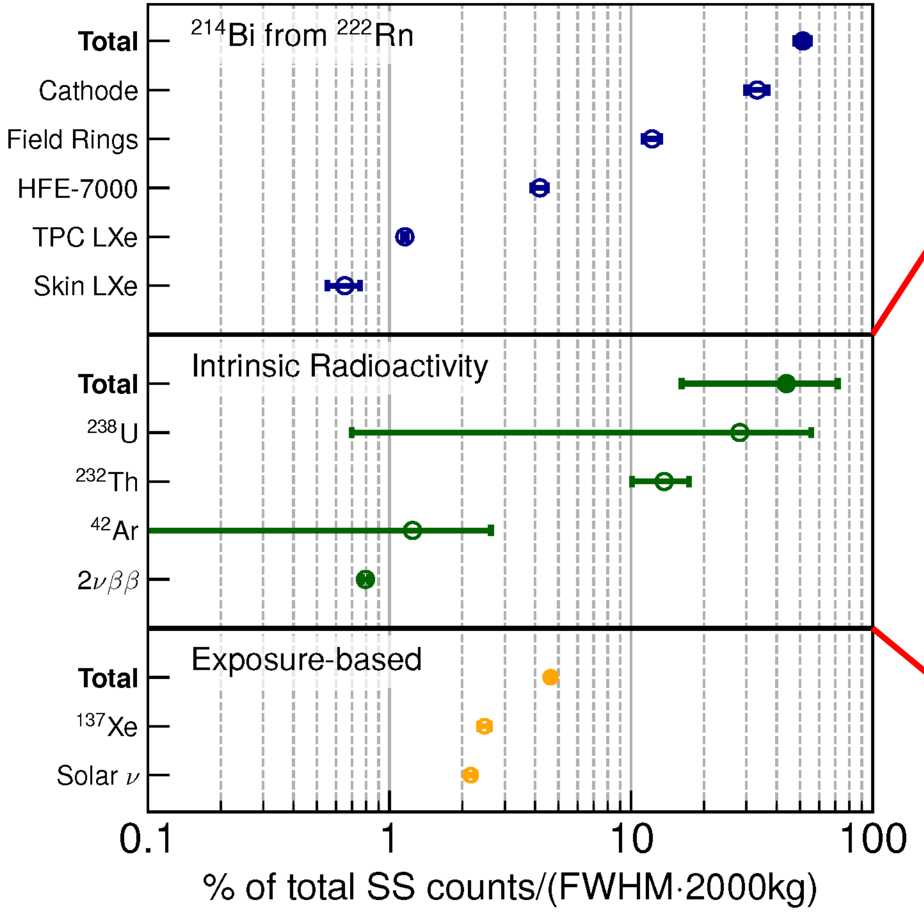
Material assays

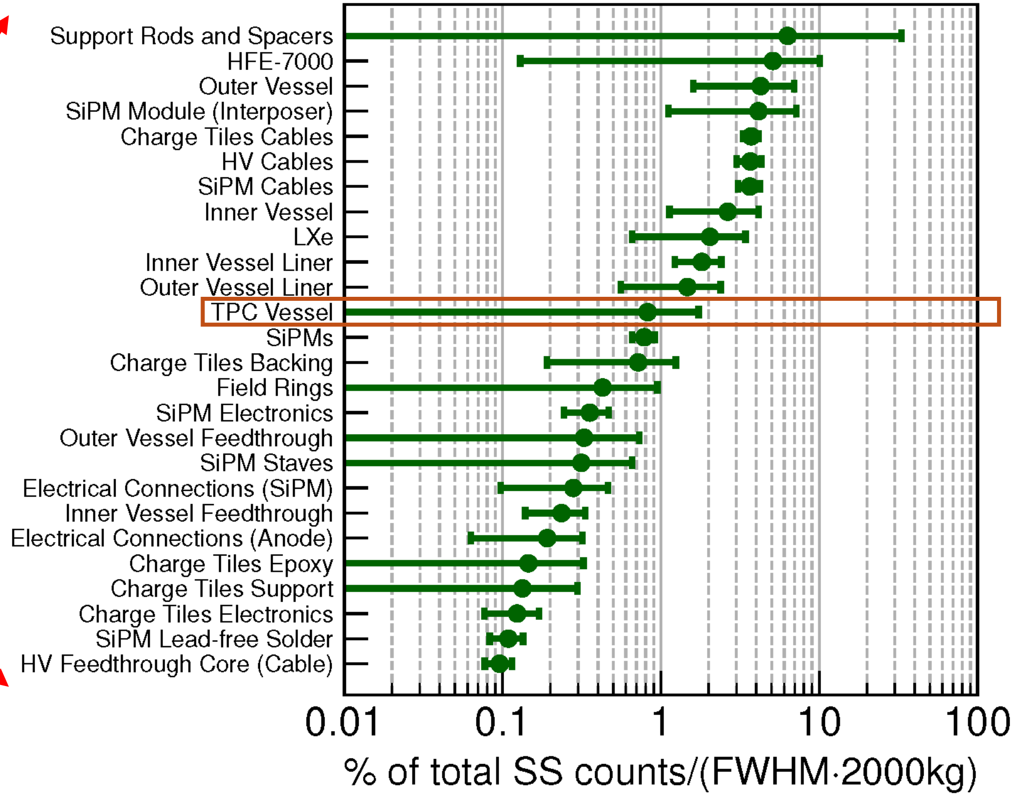
Monte Carlo simulations



nEXO detector concept well optimized



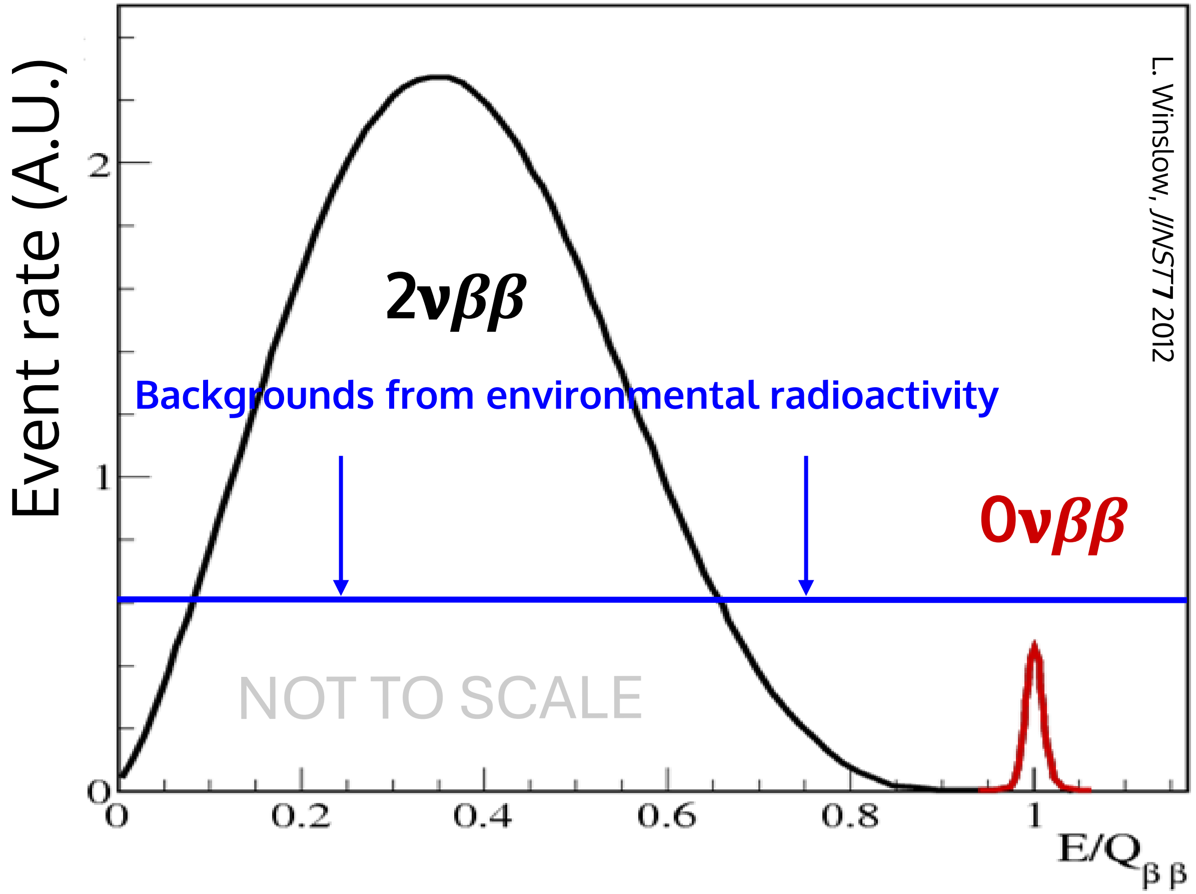




TPC vessel Cu was largest BGND contributor in nEXO 2017 sensitivity study
→ EF copper

No detector component dominates the background.

Optimizing a 0νββ search

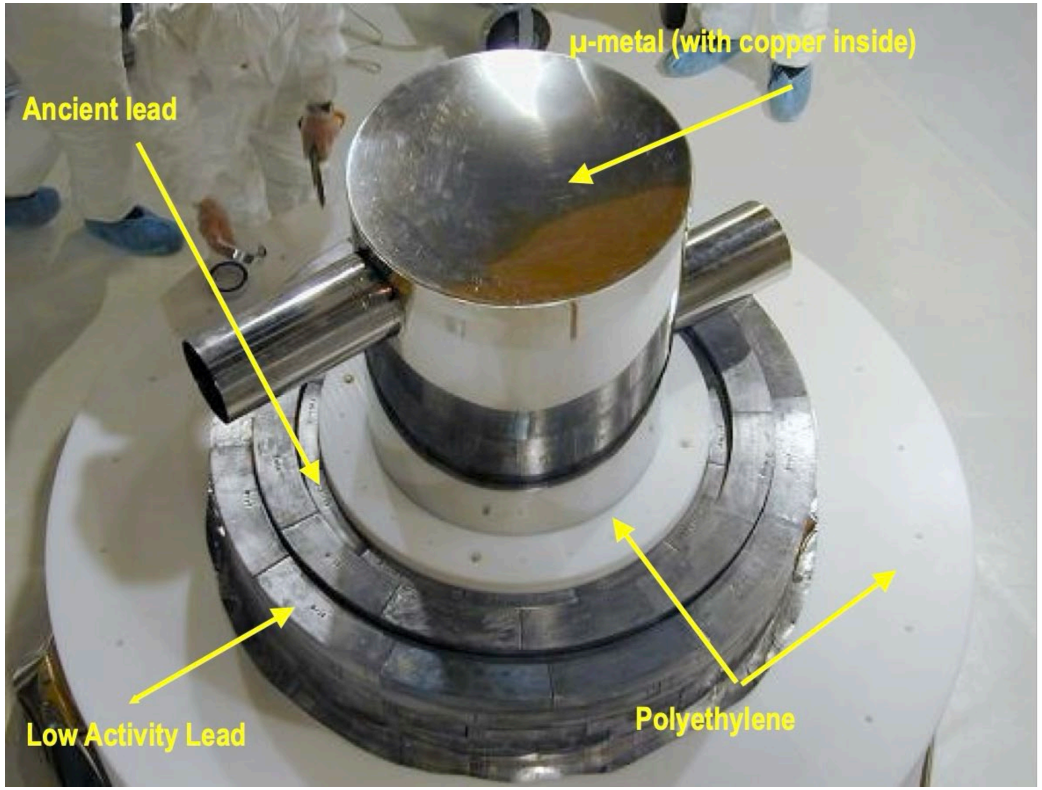


L. Winslow, *JINST7* 2012

What drives the sensitivity of a 0νββ search experiment?

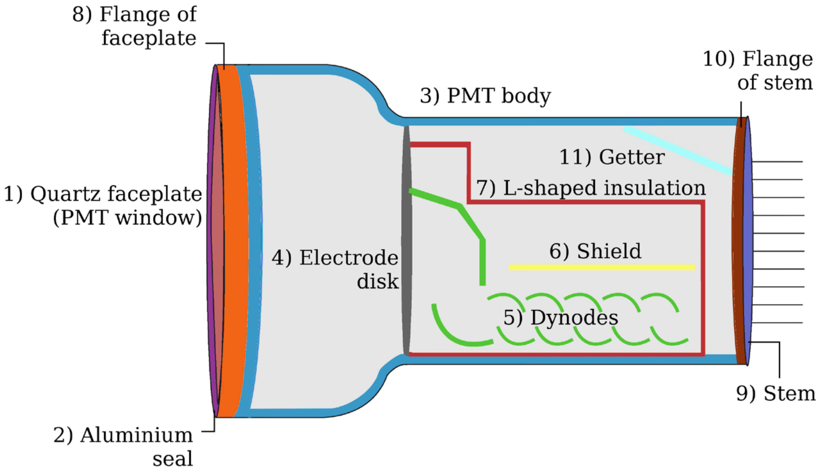
1. A lot of the **ββ** isotope
2. Ultra-low backgrounds
    1) Shielding
    2) Characterize the Background
    3) **Material Selection & Purification**
    4) Material Handling

Use Cleanest Materials Possible



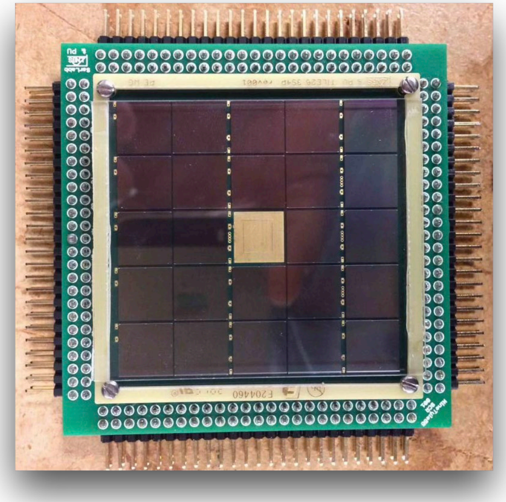
Shield made from Low Activity and Ancient Lead
(SuperCDMS Soudan)

Development of Low Radioactivity PMTs (XENON1T)



arXiv:1503.07698

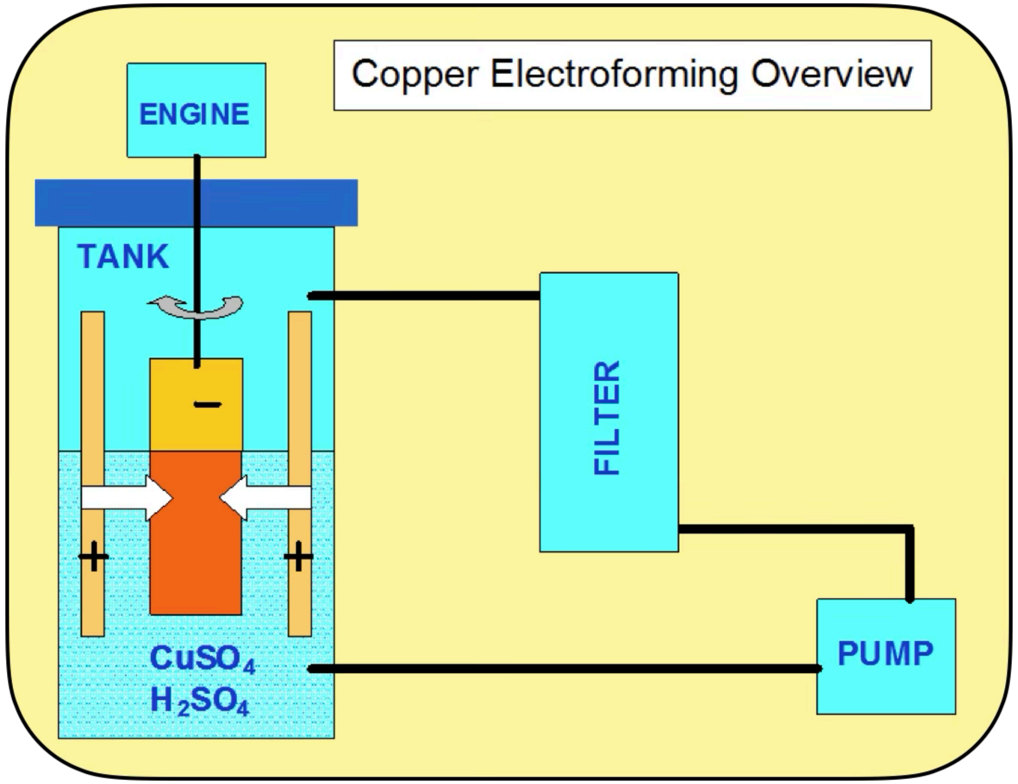
SiPMs replace PMTs
(Darkside)



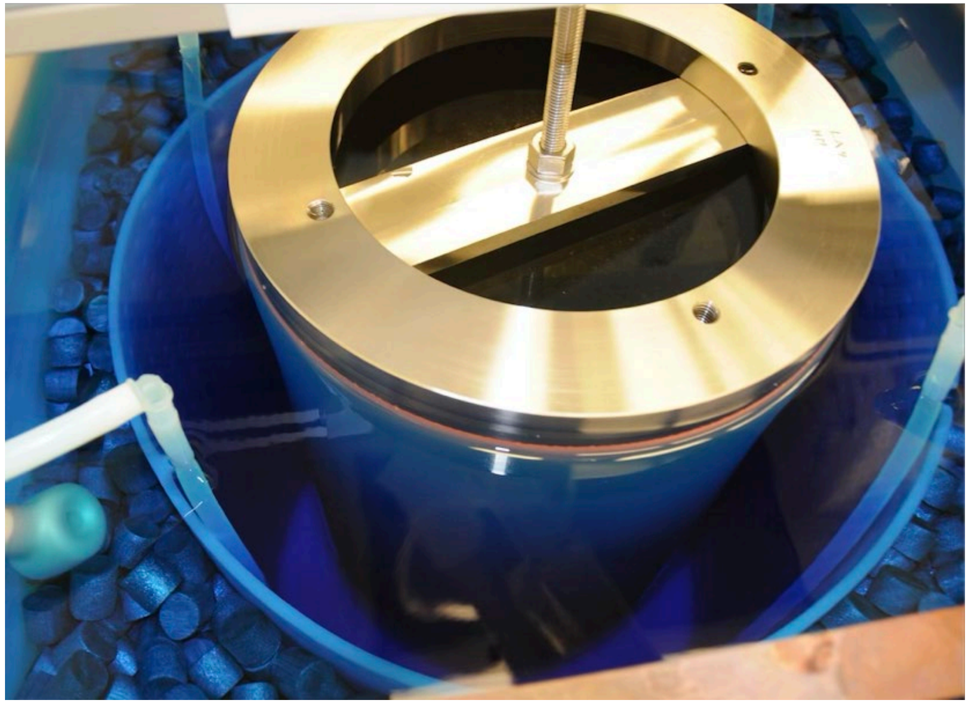
arXiv: 1706.04220

Make what you cannot find

Electroforming is a method of producing pieces by the deposition of a metal onto a mold, which is subsequently removed.



Electroforming of copper at PNNL

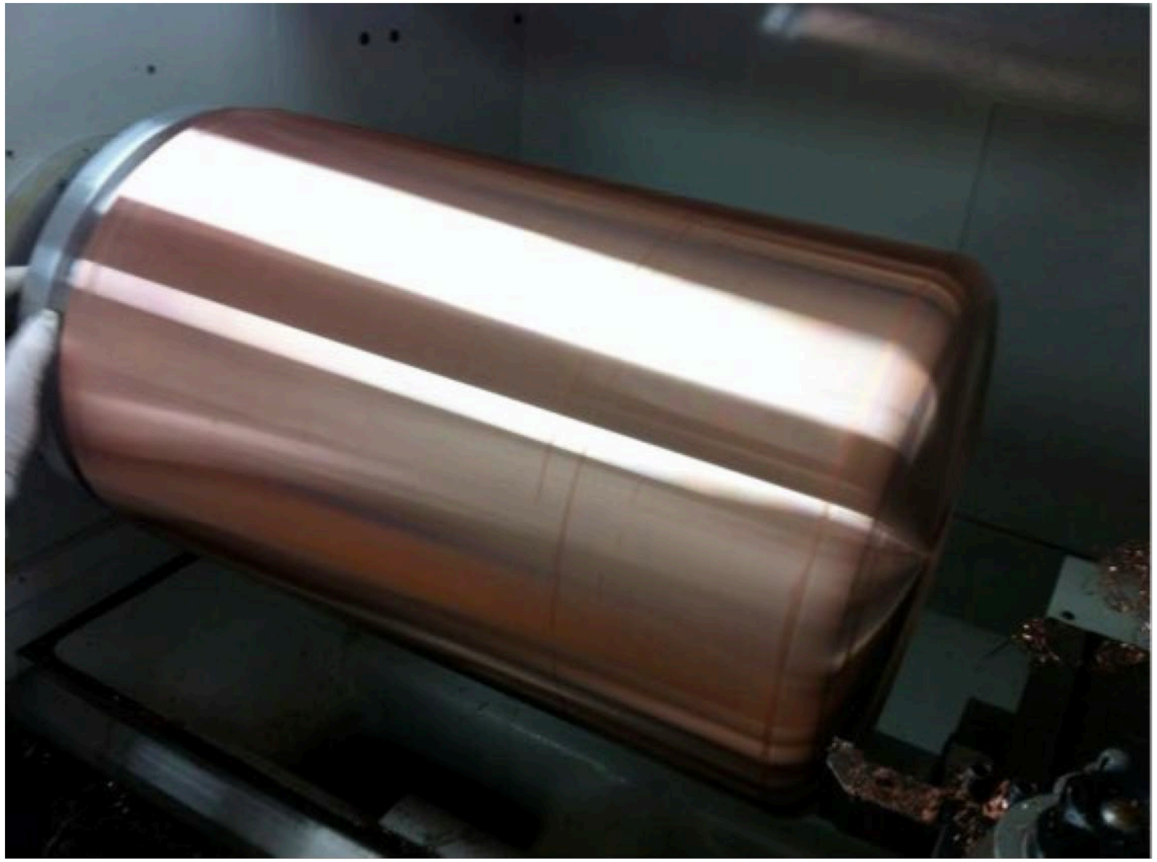


Th decay chain (ave) ≤ 0.1 μBq/kg
U decay chain (ave) ≤ 0.1 μBq/kg

Electroforming developed at PNNL

Electroforming Baths

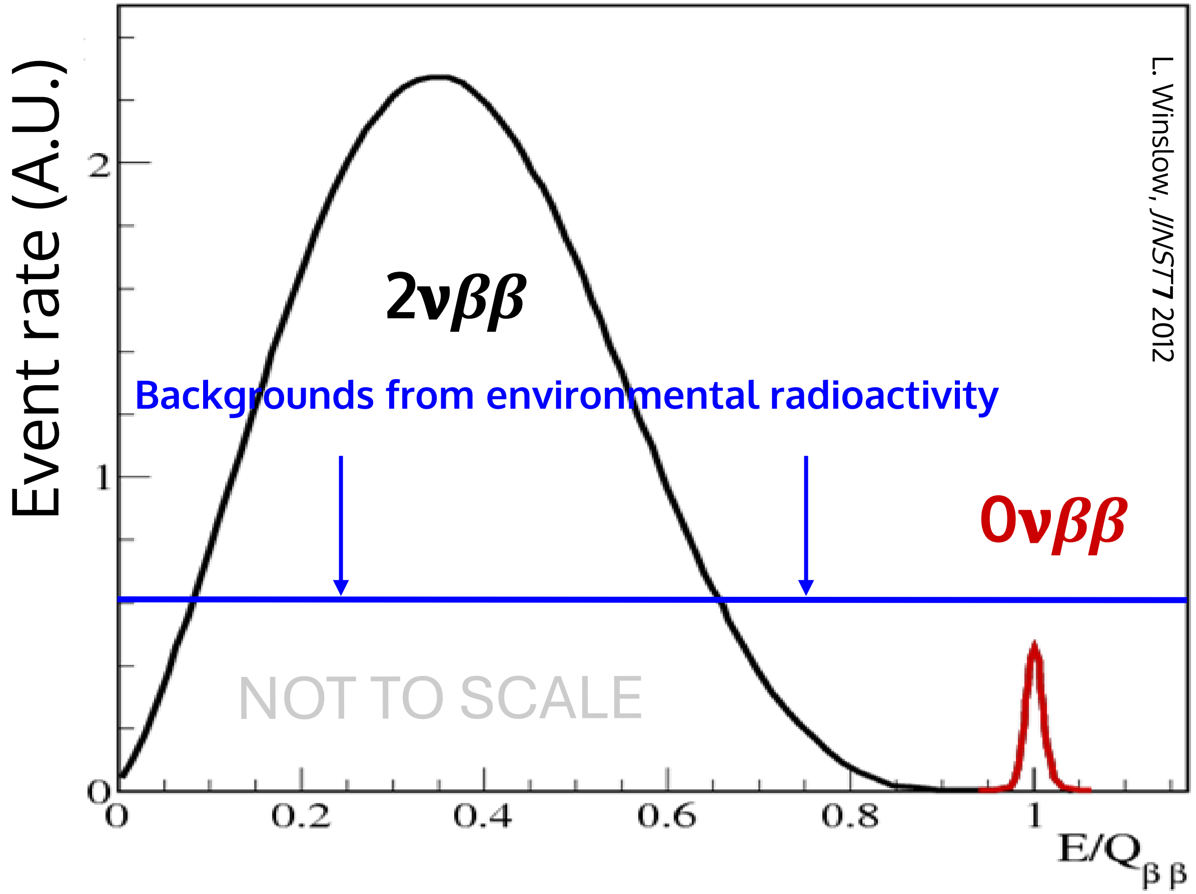
Inspection of Mandrels



Electroformed copper after turning on lathe.

R&D program under way to establish technology at SNOLAB

Optimizing a 0νββ search



L. Winslow, *JINST7* 2012

What drives the sensitivity of a 0νββ search experiment?

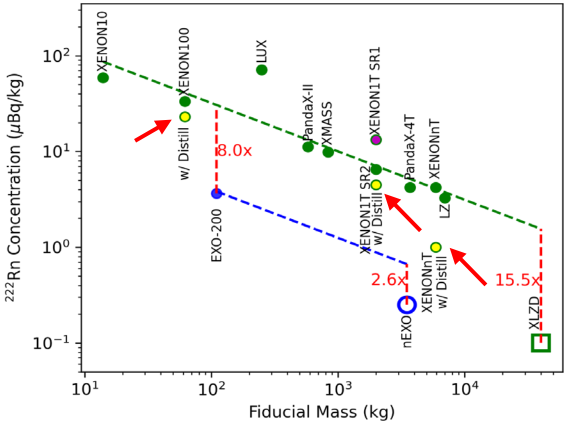
1. A lot of the **ββ** isotope
2. Ultra-low backgrounds
    1) Shielding
    2) Characterize the Background
    3) Material Selection & **Purification**
    4) Material Handling

Xe:Rn Distillation

Pioneered by XENON Collaboration

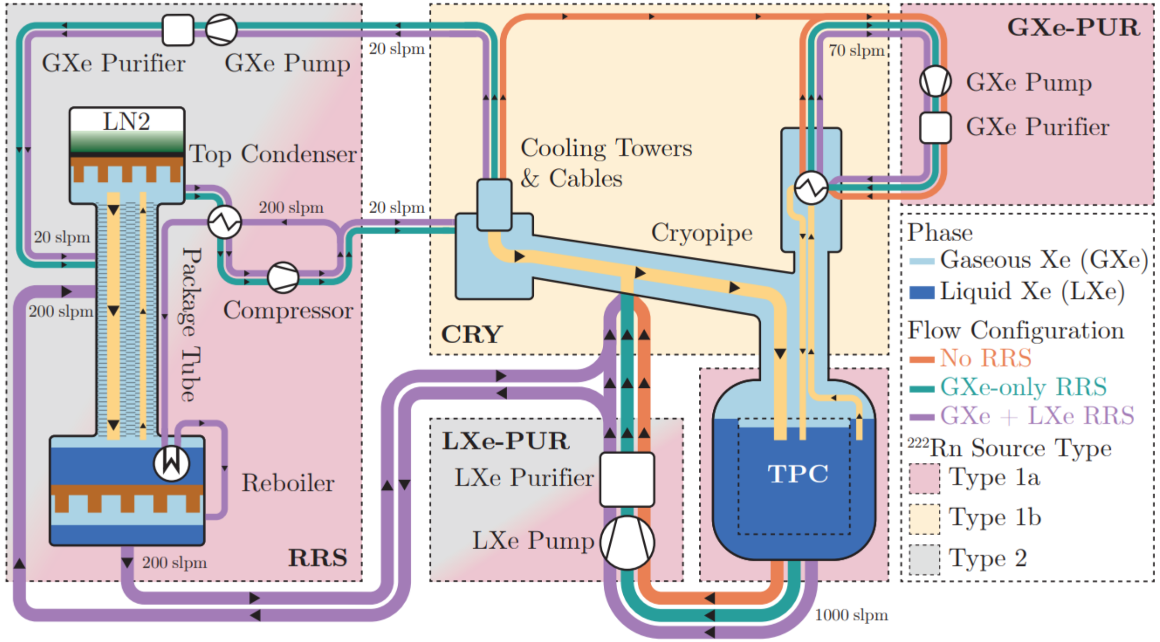
Removes Rn from:

- Inline sources: 100%
- Mixed sources: $N_{Rn} \approx \frac{k_M}{(\lambda_{\text{Rn}}+f)}$
  - k_M = Mixed emanation rate
  - λ_{Rn}=Rn decay constant ($2e^{-6}s^{-1}$)
  - f = Xe turnover rate ($\sim \lambda_{Rn}$)

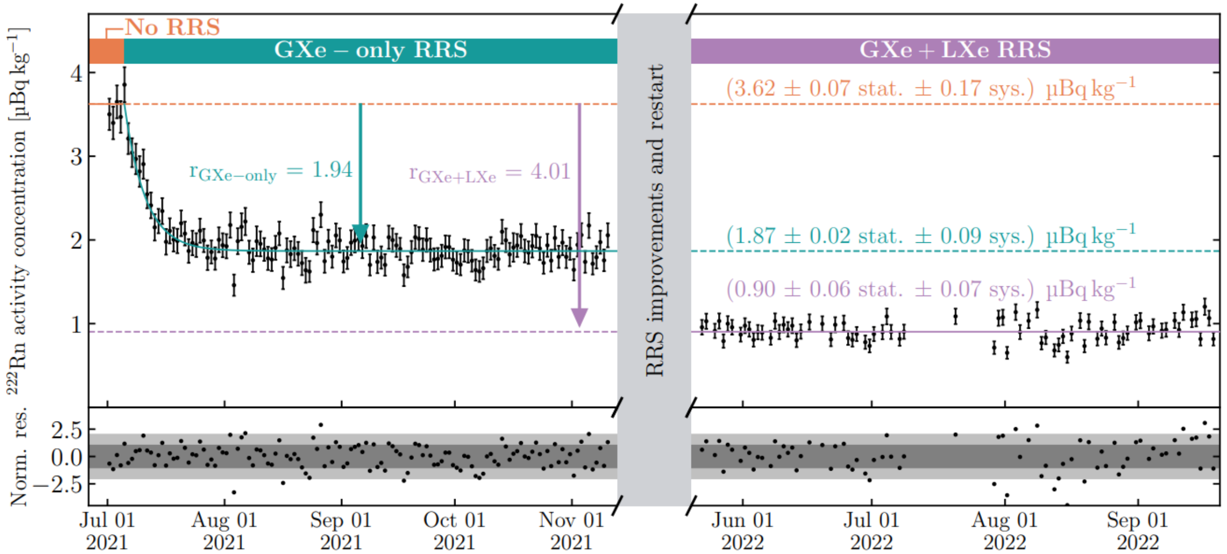


Effective!

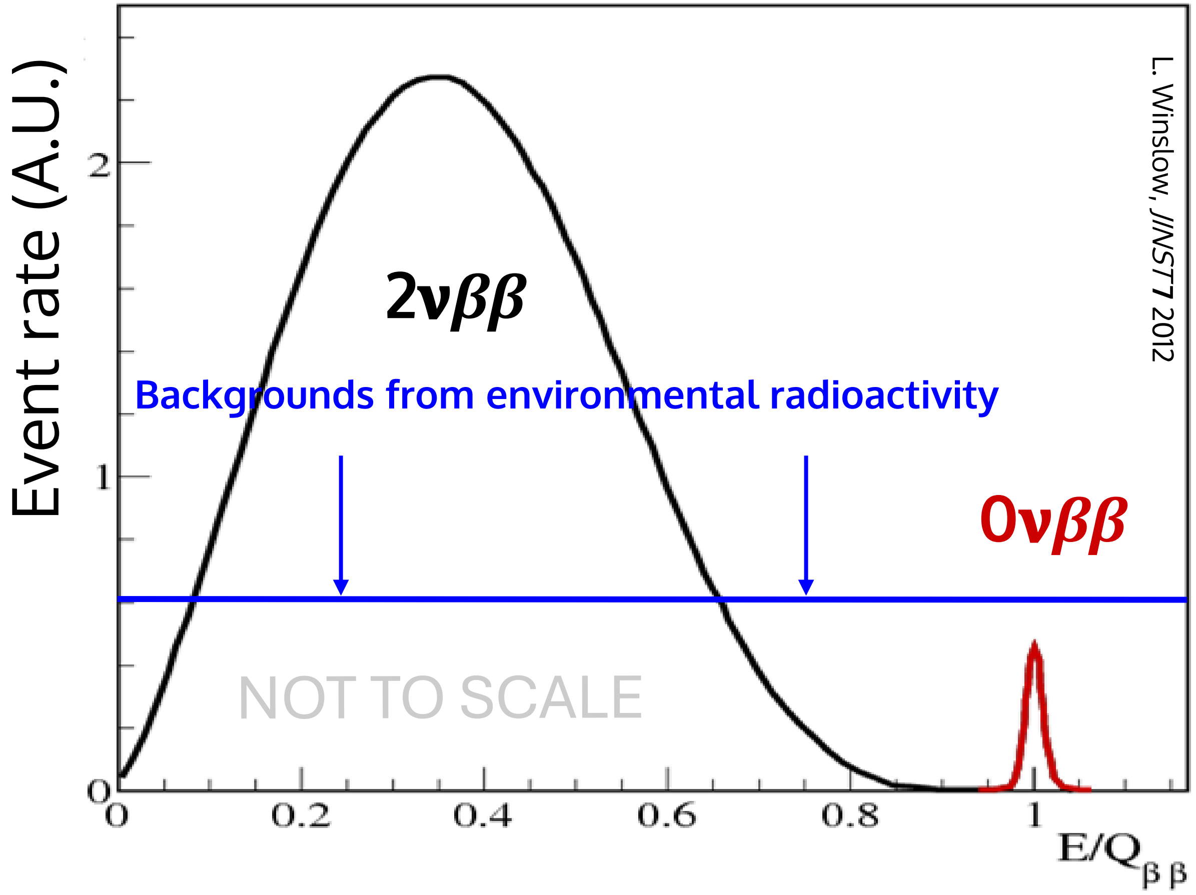
XENONnT distillation system



https://arxiv.org/abs/2502.04209



Optimizing a 0νββ search

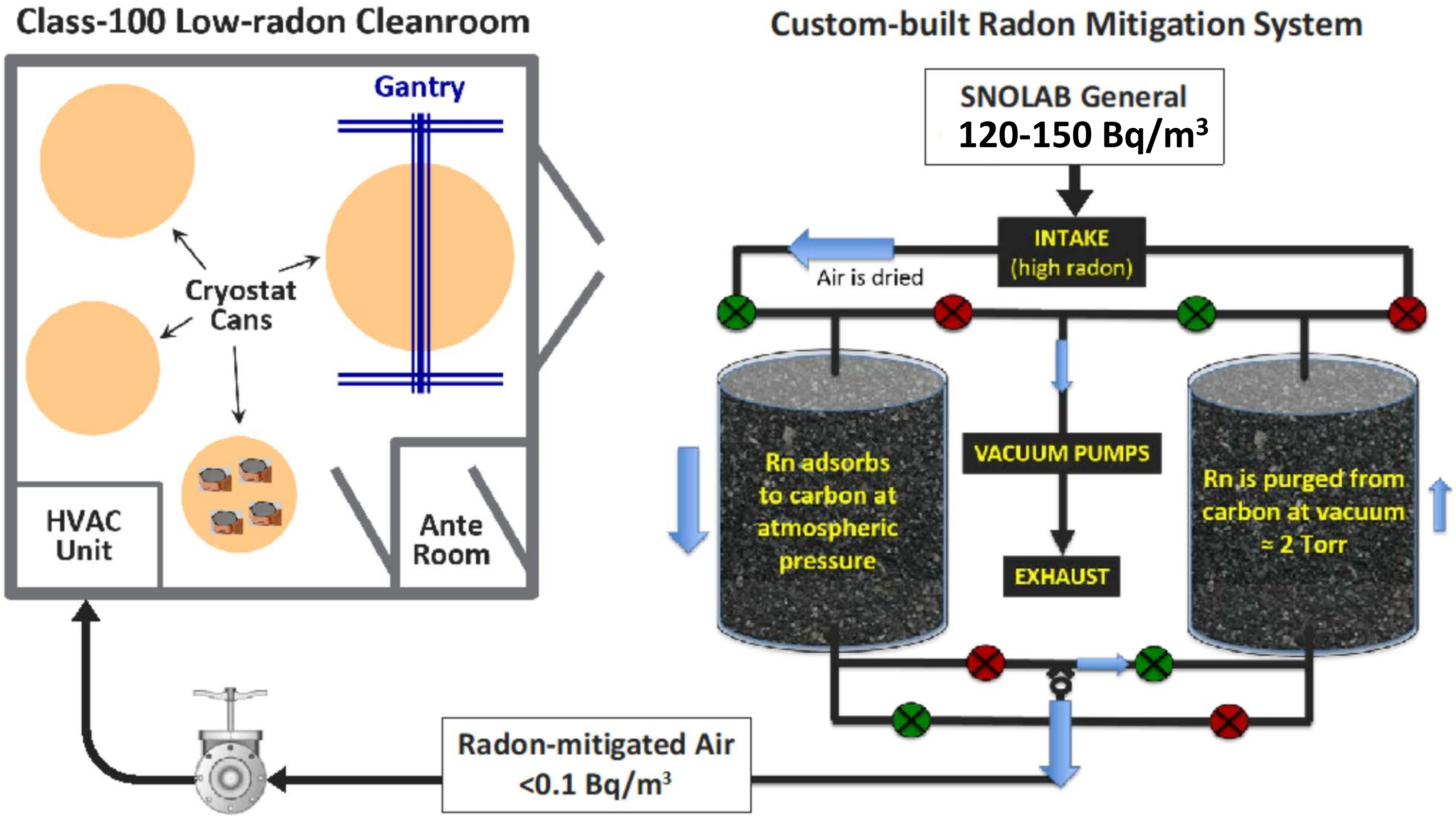


L. Winslow, *JINST7* 2012

What drives the sensitivity of a 0νββ search experiment?

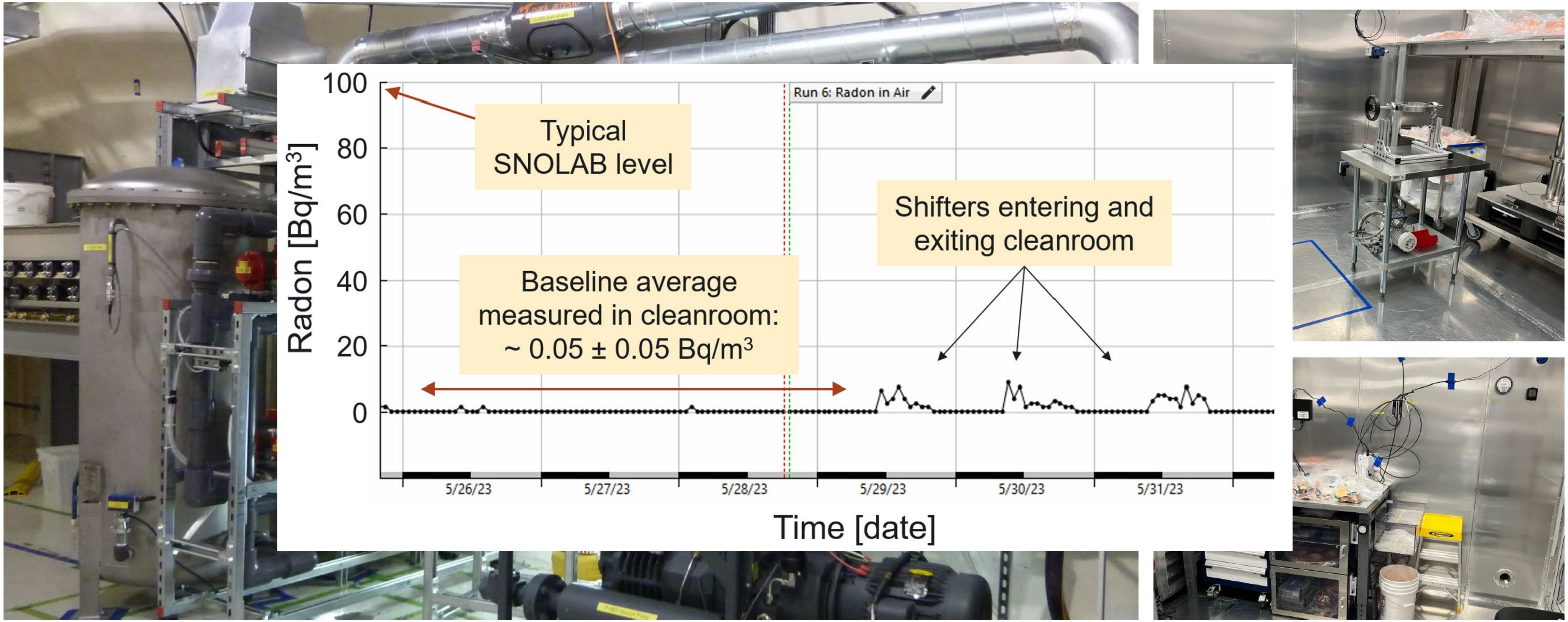
1. A lot of the **ββ** isotope
2. Ultra-low backgrounds
    1) Shielding
    2) Characterize the Background
    3) Material Selection & Purification
    4) **Material Handling**

Low Radon Cleanroom @ SNOLAB



Vacuum Swing Absorption (VSB)

VSA Radon System at SNOLAB



Typical SNOLAB level

Baseline average measured in cleanroom: ~ 0.05 ± 0.05 Bq/m^3

Shifters entering and exiting cleanroom

Clean Room and Material Handling Requirements

Surface etching removes surface contamination.

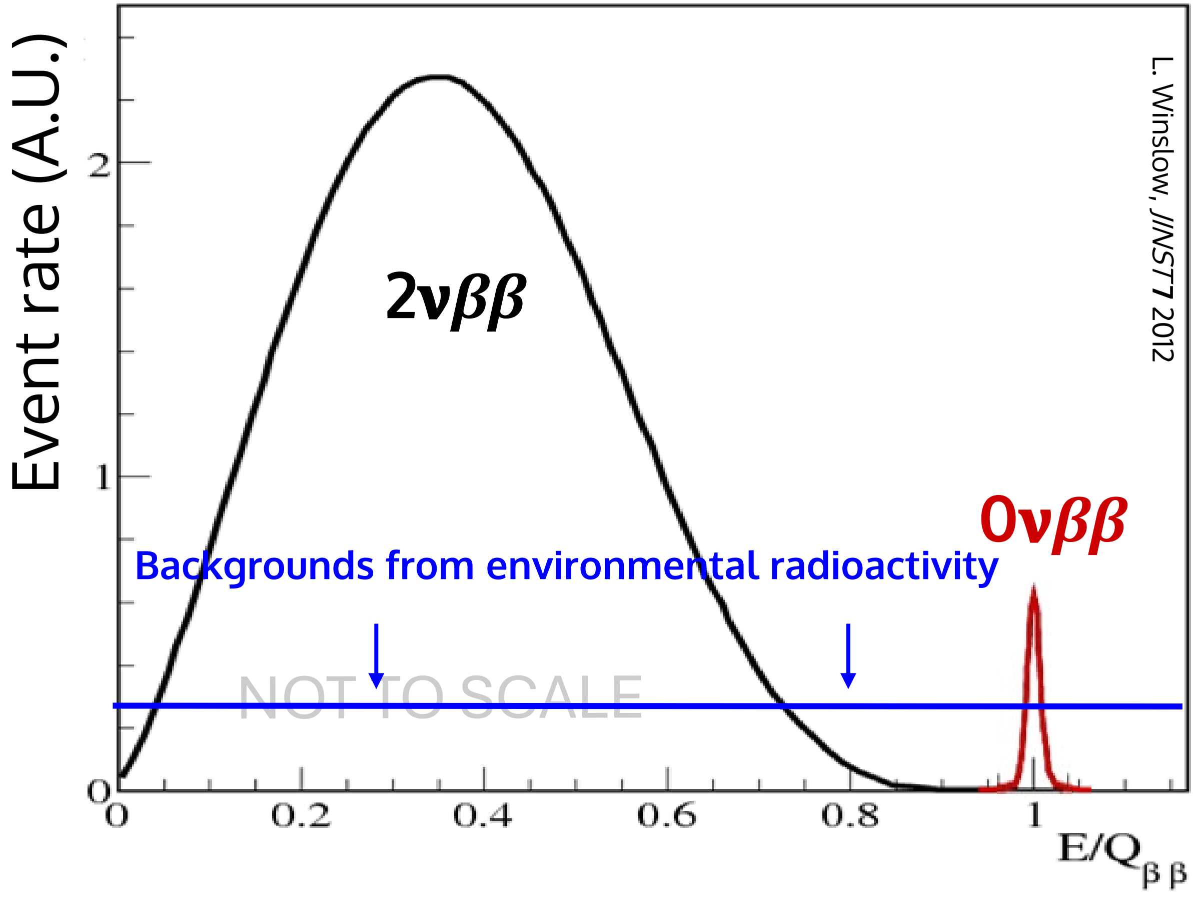
N_2 purge storage to prevent alpha plate out.

LZ dark matter experiment

This cryostat will house 7 tons of liquid xenon

Tight cleanliness requirements for fabrication and assembly → gets more challenging for large experiments.

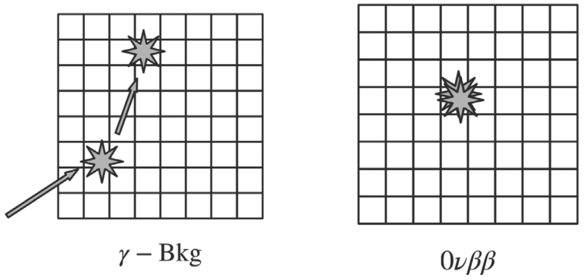
Optimizing a 0νββ search

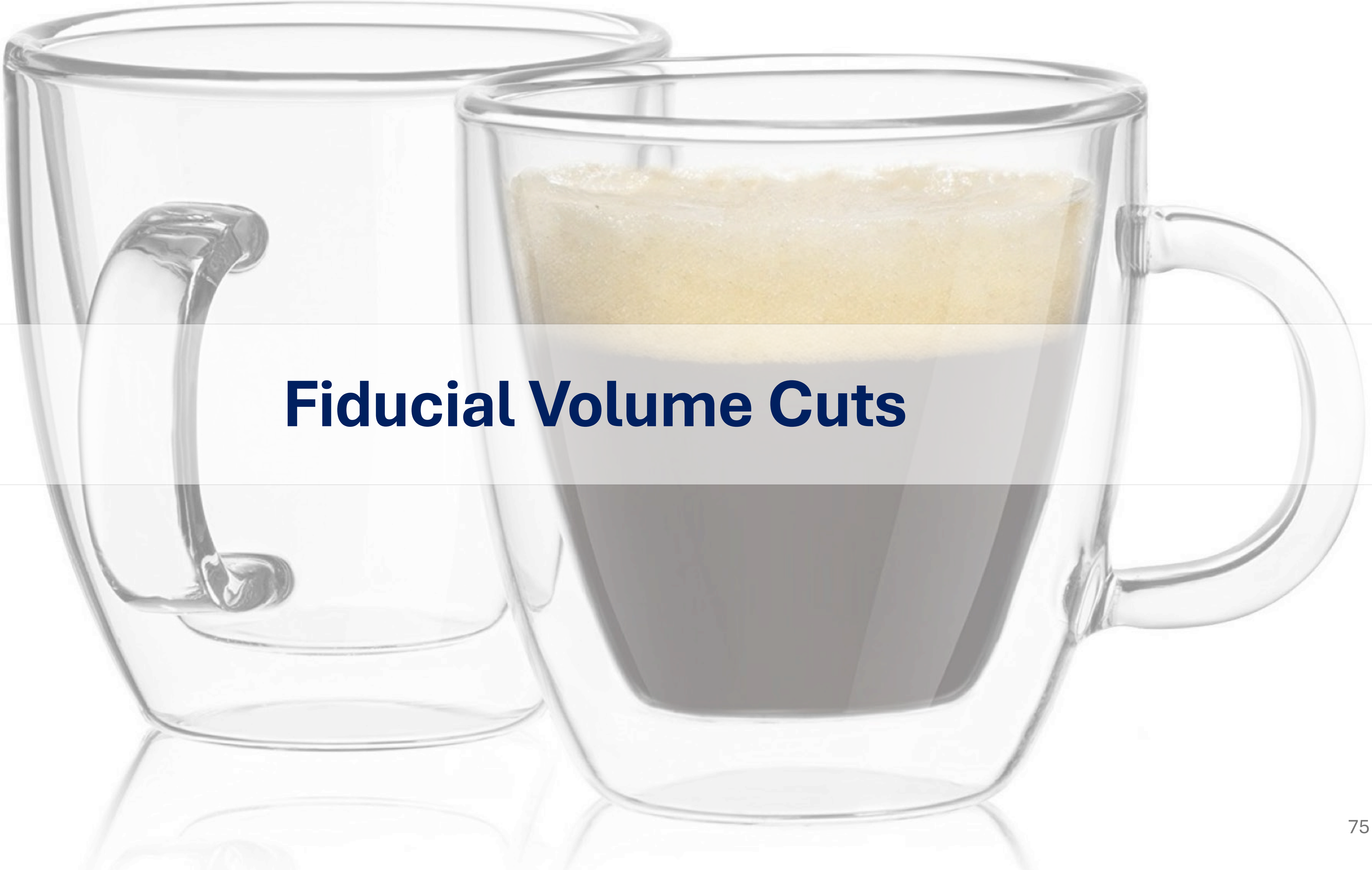


L. Winslow, *JINST* 7 2012

What drives the sensitivity of a 0νββ search experiment?

1. A lot of the **ββ** isotope
2. Ultra-low backgrounds
3. Good energy resolution (not covered)
4. **Signal/background discrimination capabilities**

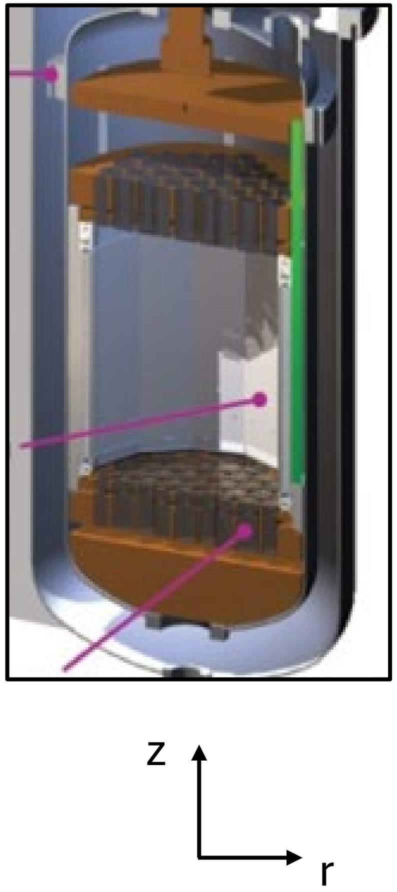


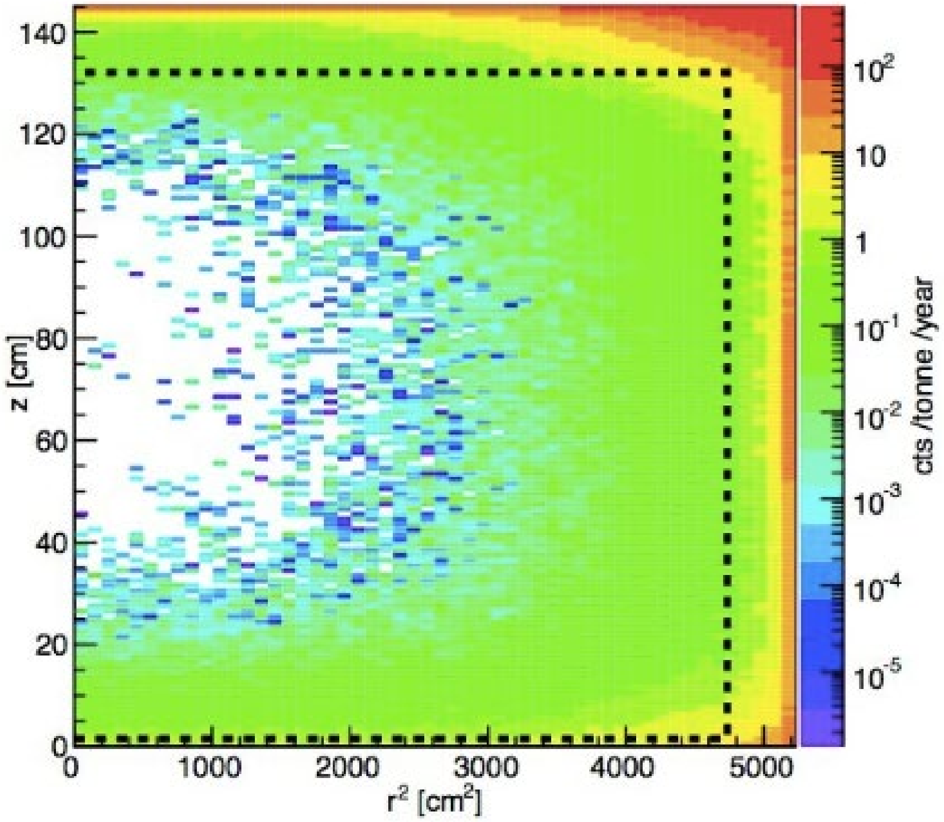


Fiducial Volume Cuts

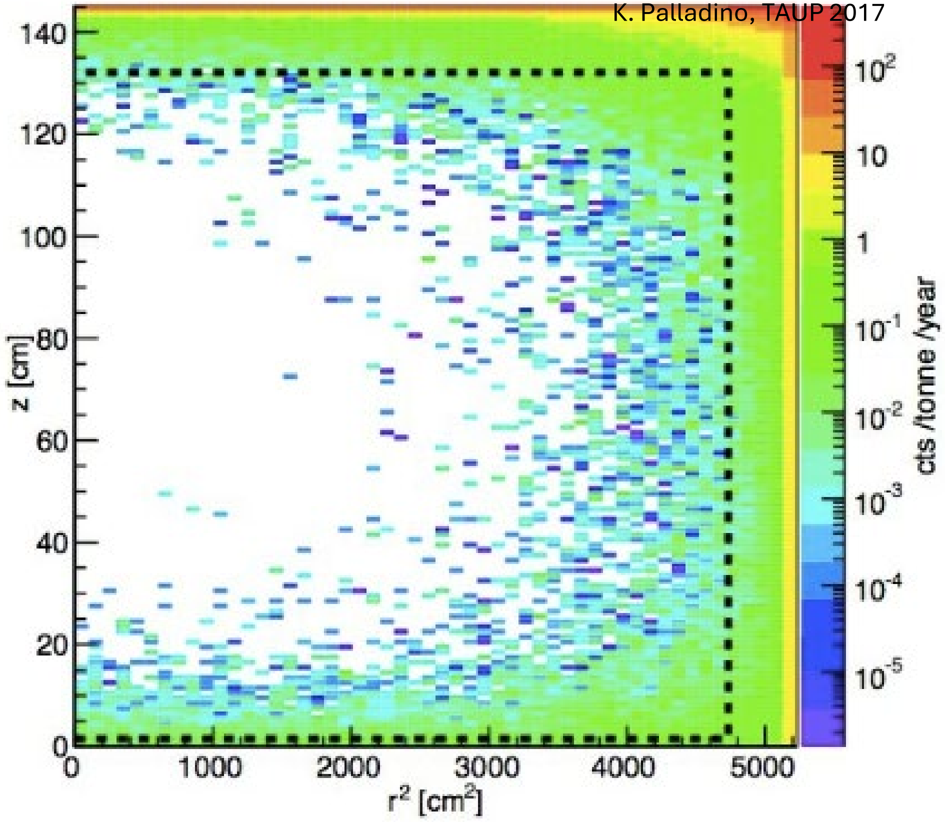
Self Shielding Properties

Example: LZ Dark Matter Experiment



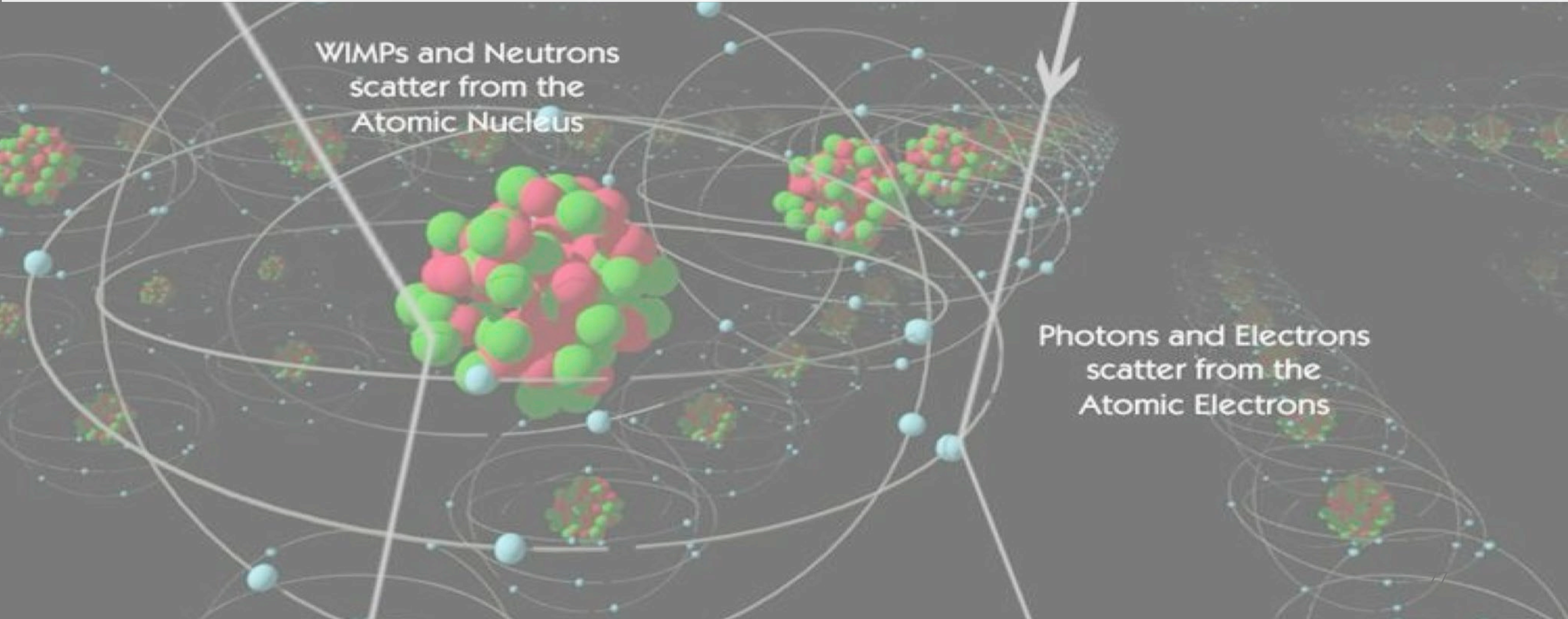


LXe TPC only
3.8 T fiducial mass


K. Palladino, TAUP 2017

LXe TPC + Skin + OD
5.6 T fiducial mass

Discrimination of Backgrounds



Event Signatures: Particle Dependent

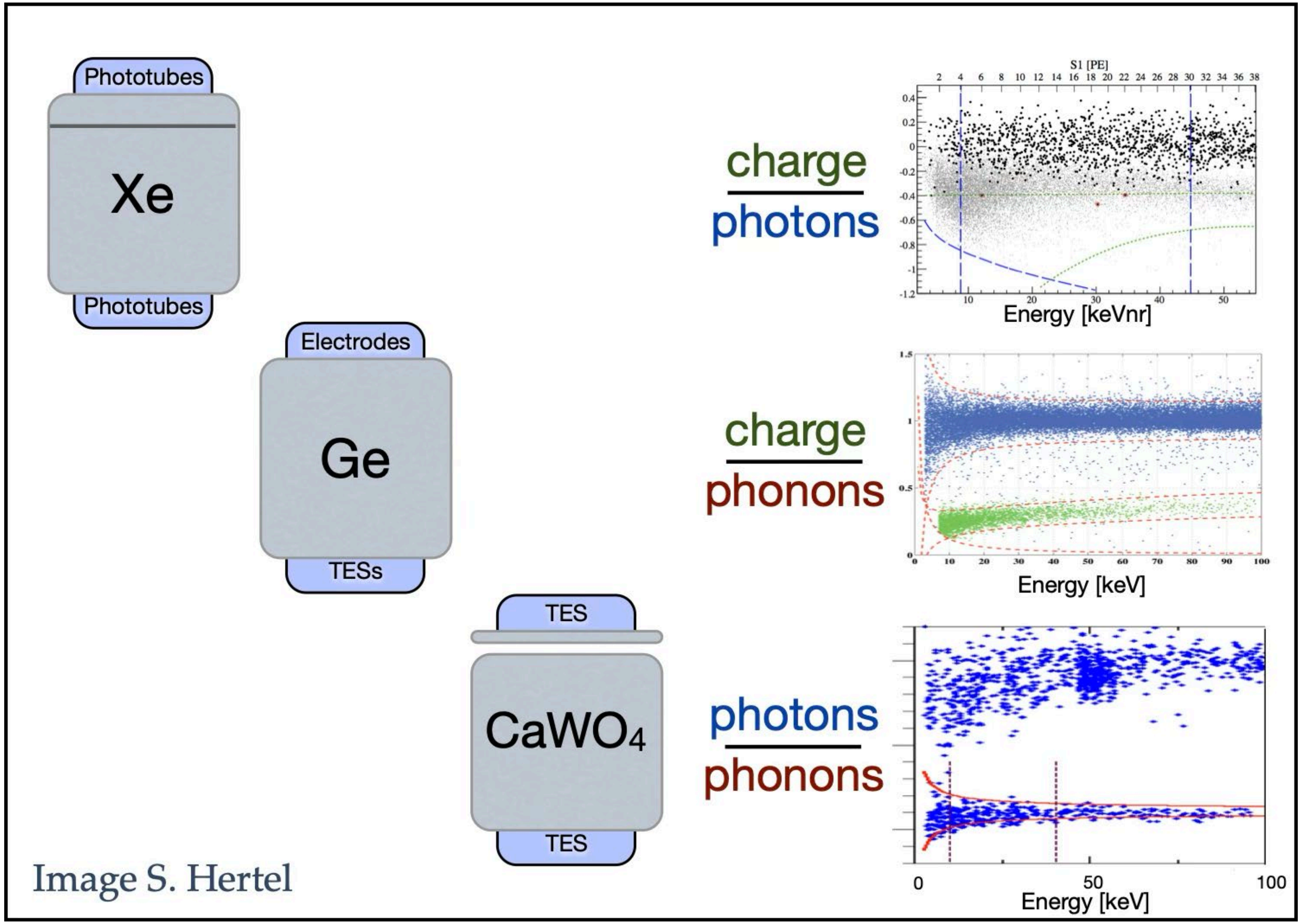
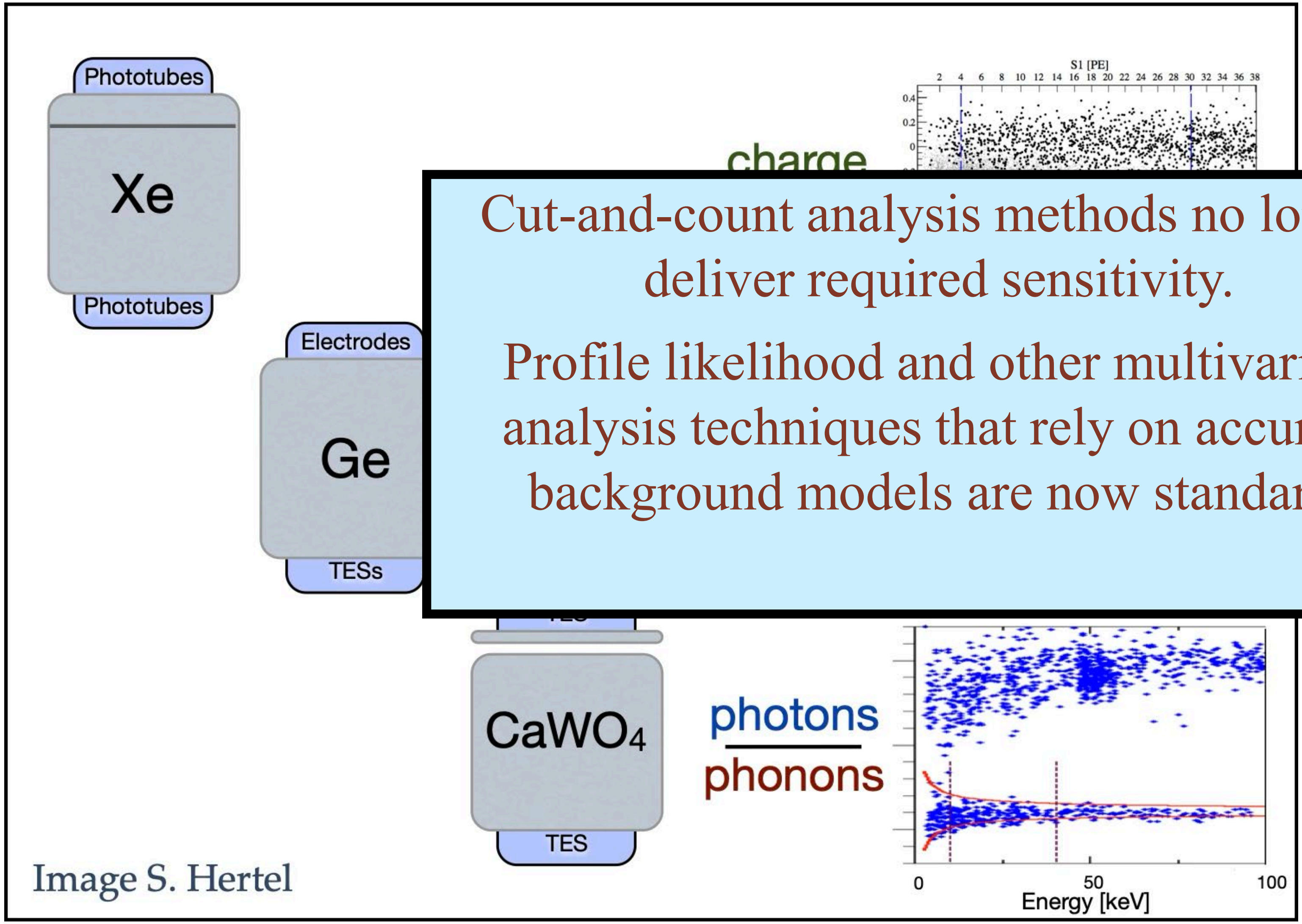


Image S. Hertel

Ratio of energy deposition in various readout channel depends on particle depositing energy

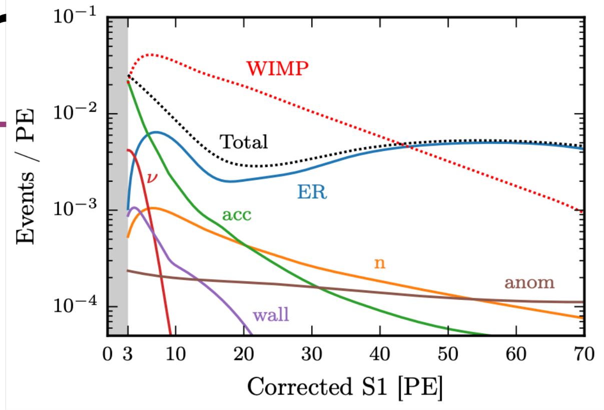
Event Signatures: Particle Depender

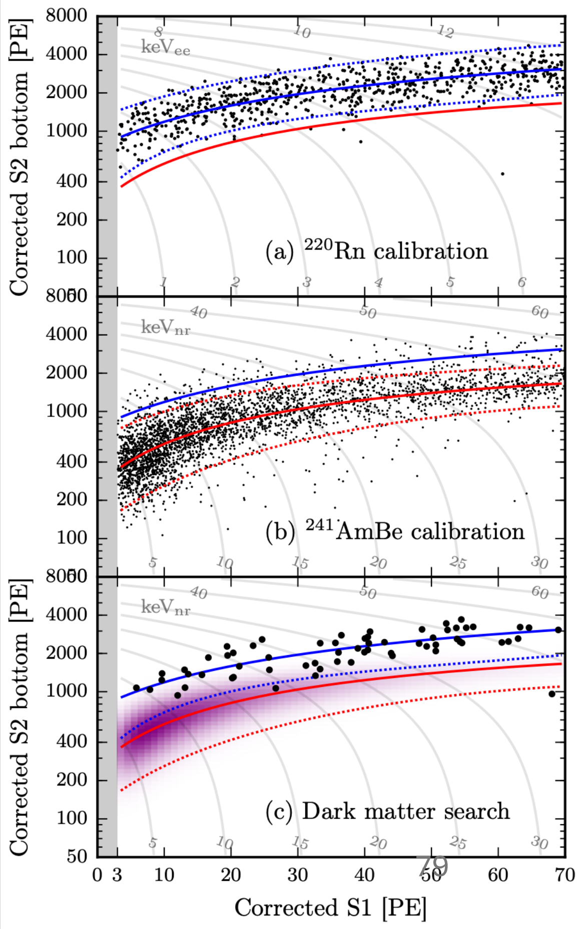


Cut-and-count analysis methods no longer deliver required sensitivity.

Profile likelihood and other multivariate analysis techniques that rely on accurate background models are now standard.

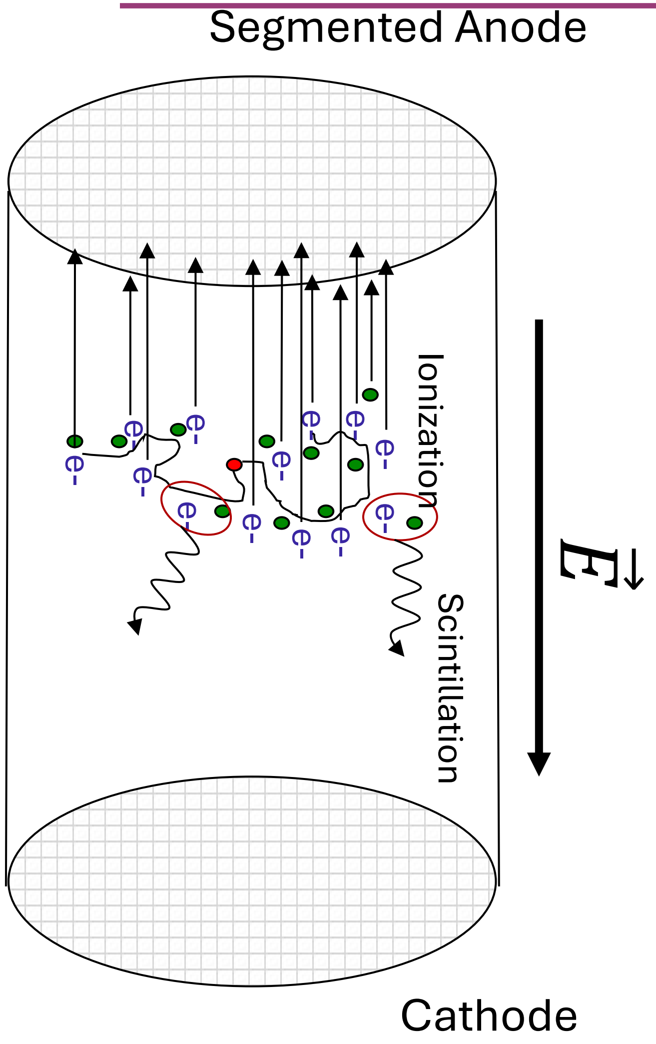
Image S. Hertel



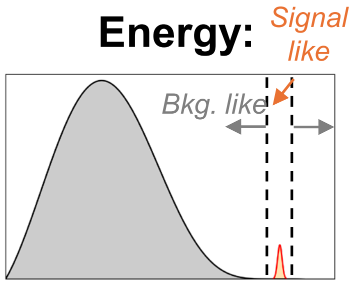


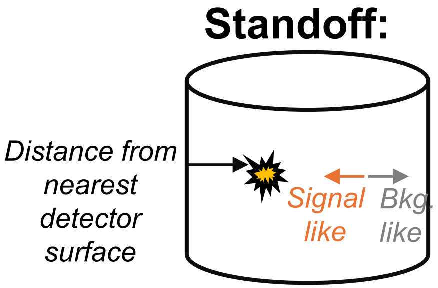
PRL 119.181301

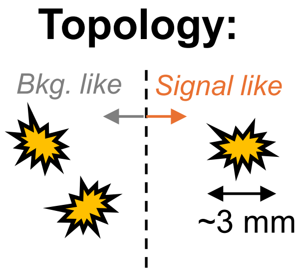
nEXO Signal and Background



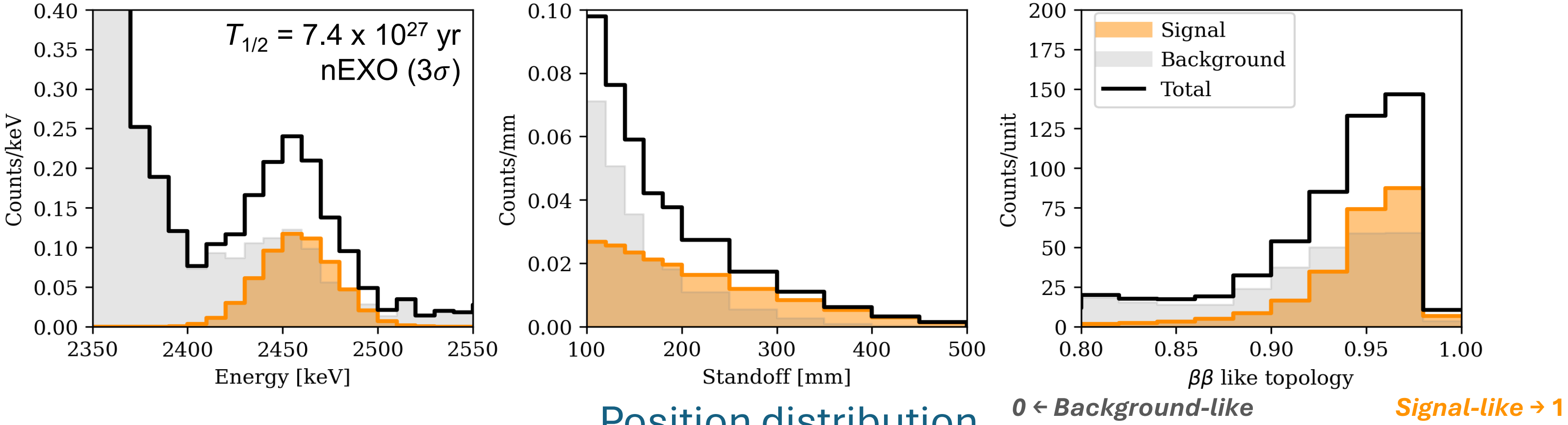
nEXO measures multiple parameters for each event to be able to robustly identify a 0νββ signal







1D projections of simulated nEXO signal and backgrounds:

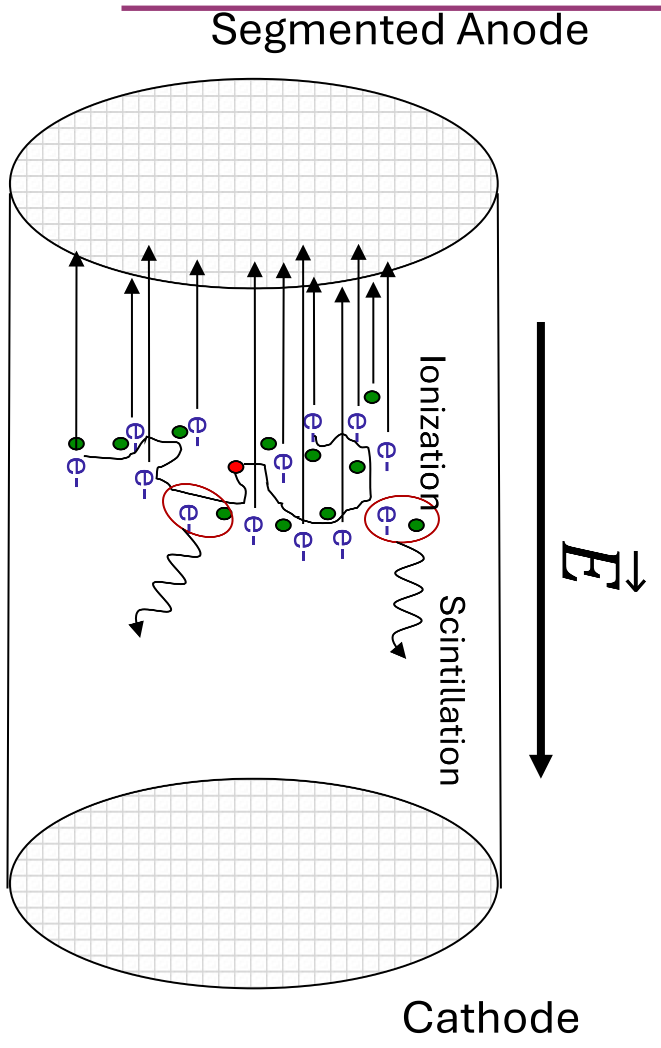


Energy from combined scintillation/ionization

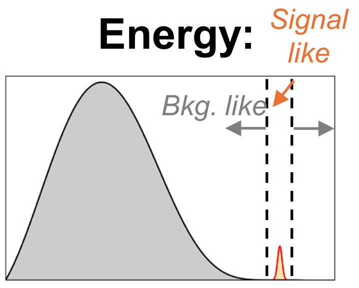
Position distribution from 3D event reconstruction

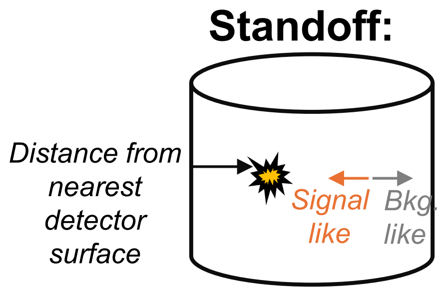
Topology, e.g., single-site or multi-site

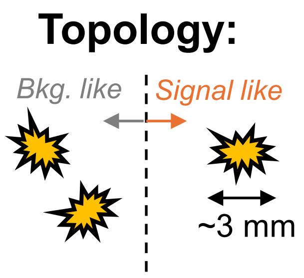
nEXO Signal and Background



nEXO measures multiple parameters for each event to be able to robustly identify a 0νββ signal







1D projections of simulated nEXO signal and backgrounds:

3x 1D projections help understanding things but they miss a great deal of information!

Energy from combined scintillation/ionization

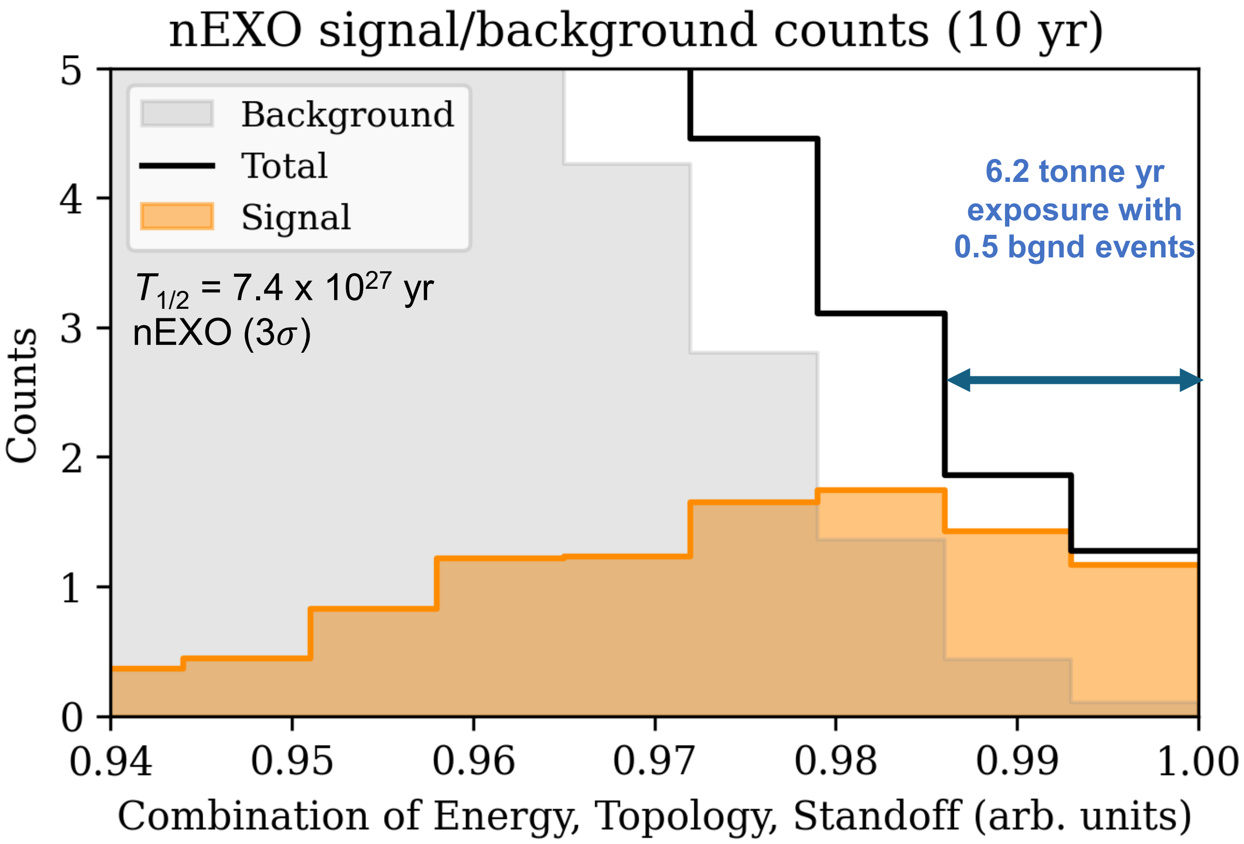
Position distribution from 3D event reconstruction

Topology, e.g., single-site or multi-site

nEXO Signal and Background

- Likelihood fit allows optimal weighting between signal and background combining energy, topology, and standoff over full 3D parameter space
- For clarity, we arrange the 3D bins into 1D, ordered by signal-to-background ratio.

Combine energy, topology, and standoff (preserving correlations)



6.2 tonne yr exposure with 0.5 bgnd events

0 ← Background-like

Signal-like → 1

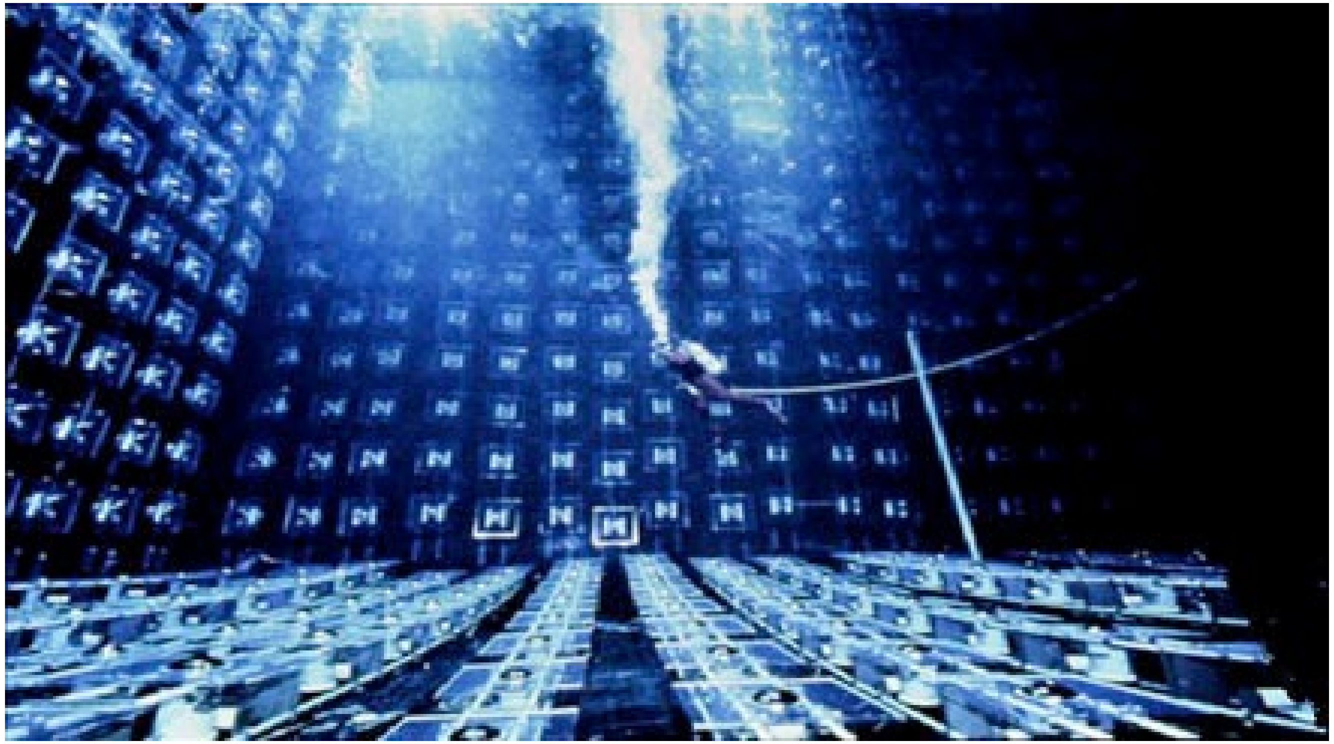
➔ nEXO is a "background-free" experiment

When Backgrounds become Signals

Can you think of an experiment where backgrounds became signals?

Large Water Cerenkov Detectors

Kamioka Nucleon Decay Experiment

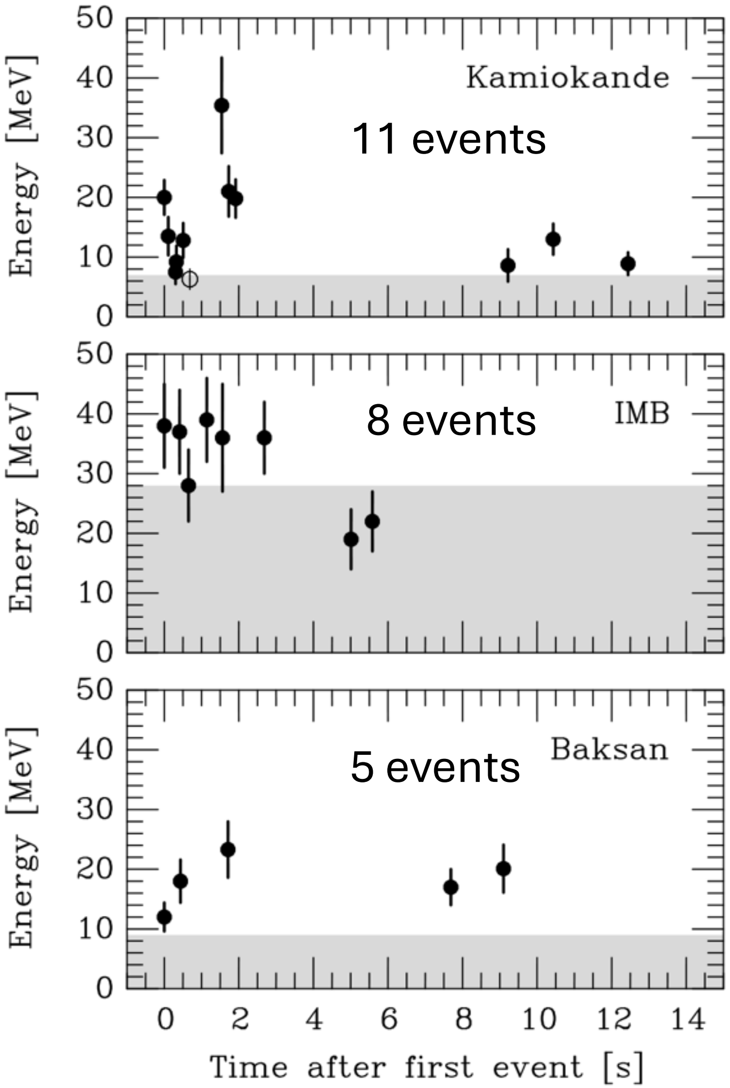


The Irvine Michigan Brookhaven Proton Decay Detector

3,000 t water
1983 start operation

- **Failed to see proton decay.**
- **Can be used to detect neutrinos.**
- **Confirms the solar deficit.**

Supernovae



G. Raffelt, Ann. Rev. Nucl. Part. Sci. 49 (1999)

Heavy elements are synthesized in Supernovae explosions

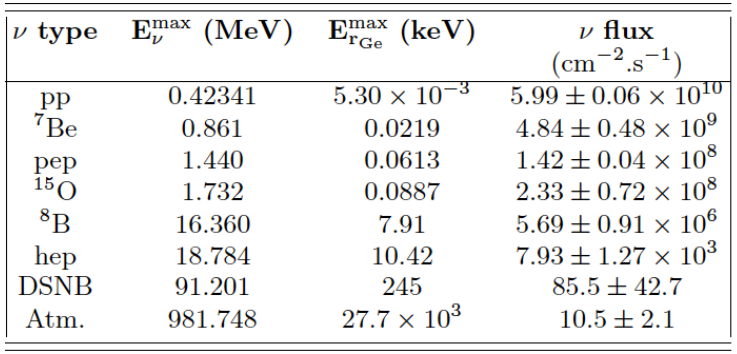
Most energy from the supernovae explosion are carried away by neutrinos

Luck event in 1987

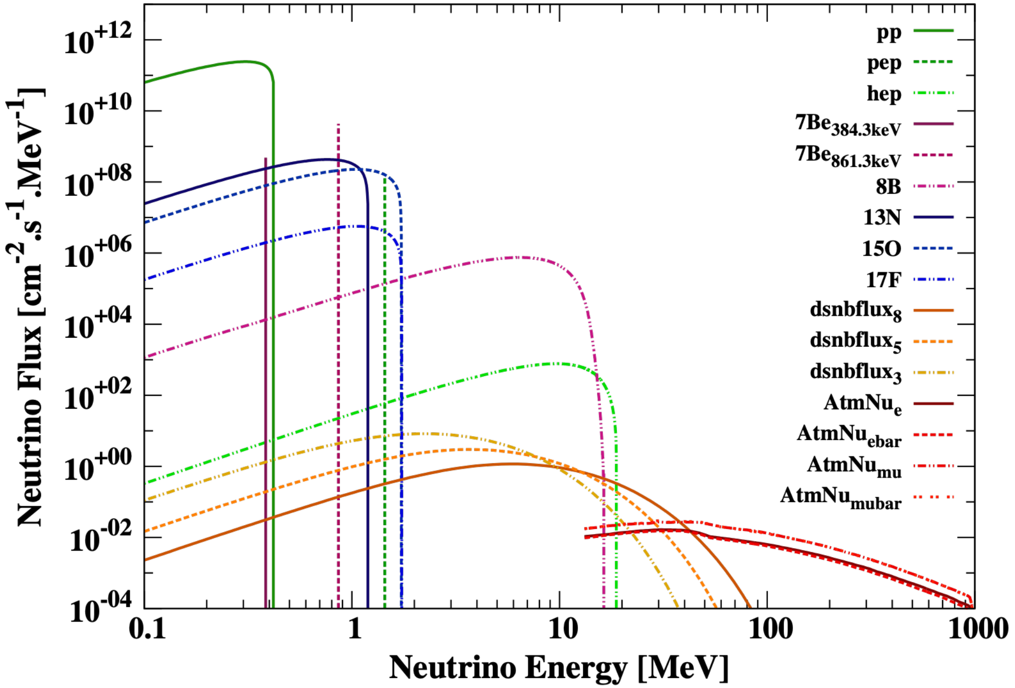
Always be Ready!

When Backgrounds become Signals

- Solar pp-neutrinos
  - low energies, high fluxes
  - contribute to the ER background via ν-e scattering at a level of 10 - 25 event/ton/year at low energies
- Neutrino-induced NR can not be distinguished from WIMP signals (^{8}B solar neutrinos)
  - ~10^3 events/ton/year for heavy targets
- Atmospheric Neutrinos and Diffuse Supernovae Neutrinos
  - ~1-5 events per (100 ton x year)



ν type	E_ν^{max} (MeV)	E_{rGe}^{max} (keV)	ν flux ($cm^{-2}.s^{-1}$)
pp	0.42341	5.30×10^{-3}	$5.99 \pm 0.06 \times 10^{10}$
^{7}Be	0.861	0.0219	$4.84 \pm 0.48 \times 10^{9}$
pep	1.440	0.0613	$1.42 \pm 0.04 \times 10^{8}$
^{15}O	1.732	0.0887	$2.33 \pm 0.72 \times 10^{8}$
^{8}B	16.360	7.91	$5.69 \pm 0.91 \times 10^{6}$
hep	18.784	10.42	$7.93 \pm 1.27 \times 10^{3}$
DSNB	91.201	245	85.5 ± 42.7
Atm.	981.748	27.7×10^{3}	10.5 ± 2.1

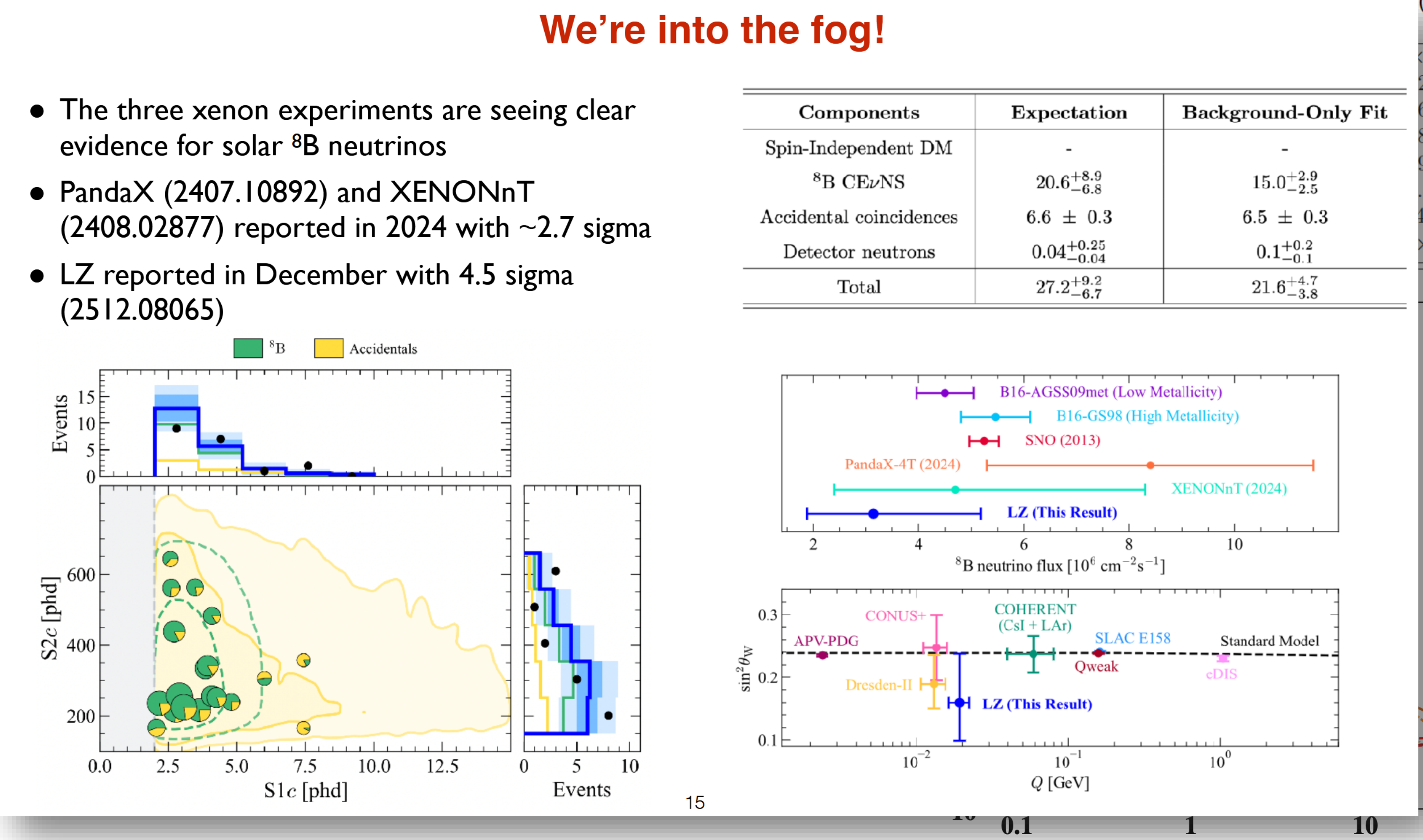


When Backgrounds become Signals

- Solar
  - low
  - con sca at l
- Neutri disting solar r
  - ~10
- Atmos Super
  - ~1-

	(keV)	ν flux $(\mathrm{cm}^{-2}.\mathrm{s}^{-1})$
	10^{-3}	$5.99 \pm 0.06 \times 10^{10}$
	219	$4.84 \pm 0.48 \times 10^{9}$
	613	$1.42 \pm 0.04 \times 10^{8}$
	887	$2.33 \pm 0.72 \times 10^{8}$
	91	$5.69 \pm 0.91 \times 10^{6}$
	.42	$7.93 \pm 1.27 \times 10^{3}$
	45	85.5 ± 42.7
	$\times 10^{3}$	10.5 ± 2.1

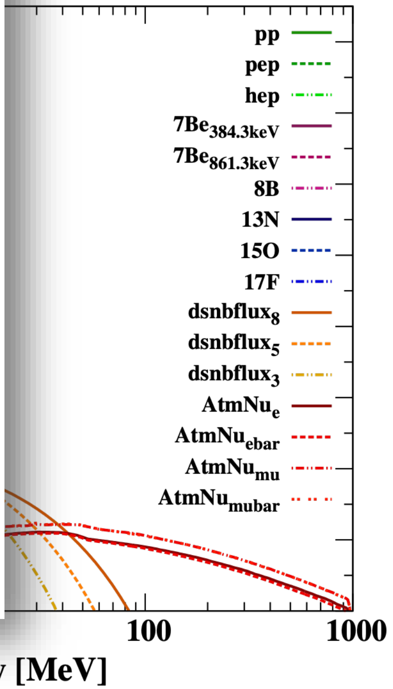
Lippincott, SNOLAB user meeting 2026



We're into the fog!

- The three xenon experiments are seeing clear evidence for solar ^{8}B neutrinos
- PandaX (2407.10892) and XENONnT (2408.02877) reported in 2024 with ~2.7 sigma
- LZ reported in December with 4.5 sigma (2512.08065)

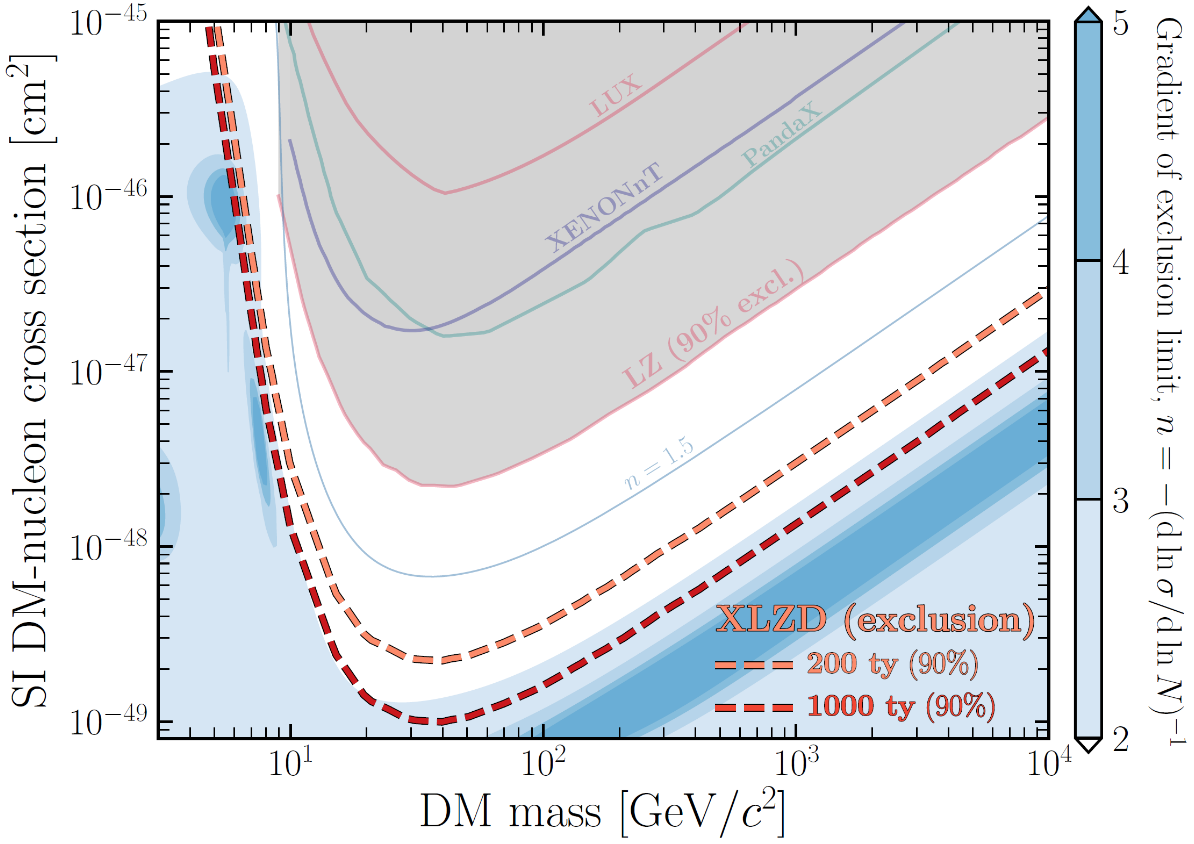
Components	Expectation	Background-Only Fit
Spin-Independent DM	-	-
^{8}B CEνNS	$20.6^{+8.9}_{-6.8}$	$15.0^{+2.9}_{-2.5}$
Accidental coincidences	6.6 ± 0.3	6.5 ± 0.3
Detector neutrons	$0.04^{+0.25}_{-0.04}$	$0.1^{+0.2}_{-0.1}$
Total	$27.2^{+9.2}_{-6.7}$	$21.6^{+4.7}_{-3.8}$

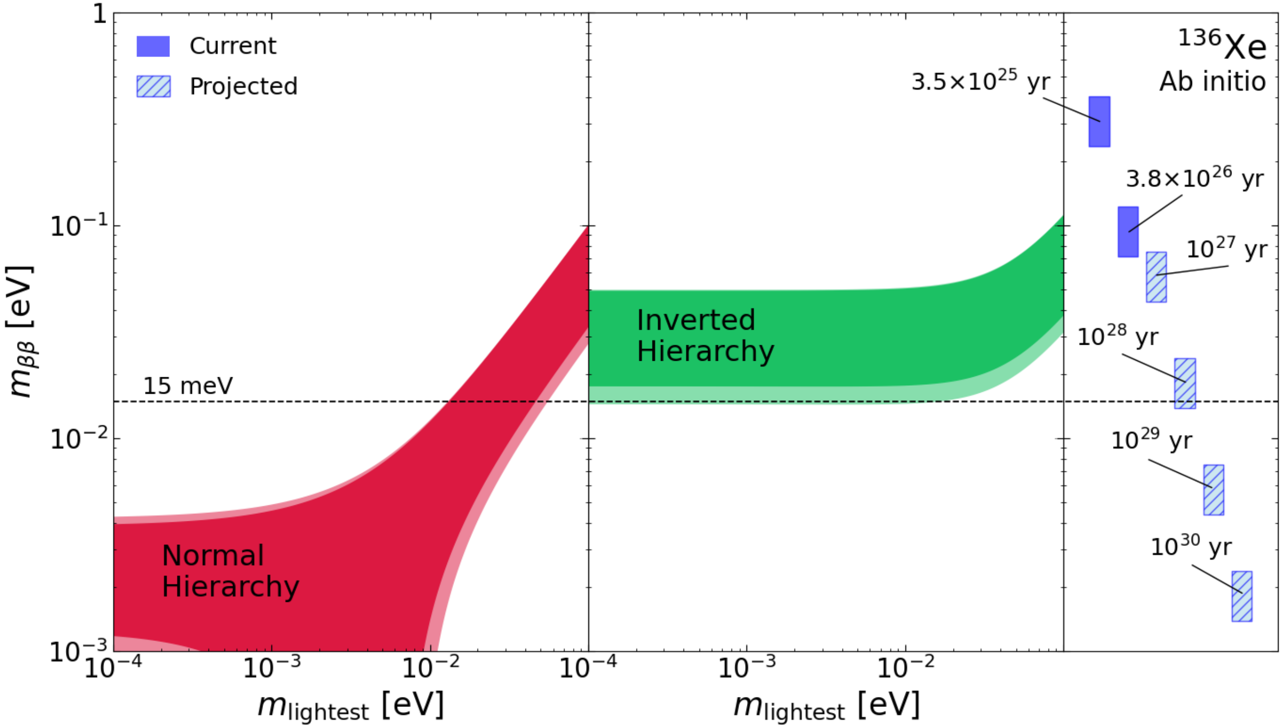


Concluding thoughts

- Rare-event searches are pushing the limits of our understanding of the Universe.
- These searches require unprecedented low levels of backgrounds to maximize their scientific reach.
- A suite of low-background techniques has been developed to measure and mitigate sources of backgrounds.
- A global effort is ongoing to further improve low-background techniques.
- **Knowing your backgrounds is crucial for the success of rare event searches.**

An Exciting Future!





Thank you for your attention!