Low Background Techniques

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Many thanks to Jodi Cooley & Hardy Simgen

Overview

I. The Name of the Game
II. Underground labs
III. Passive shielding
IV. Active shielding
V. Material Assay
VI. Fiducialization
VII. Liquid Purification
VIII. Discrimination
IX. Coincidence and Redundancy
X. Full Modeling

I. Low Background

Take Home:

- Sensitivity goes like $\frac{\text{Signal}}{\sqrt{\text{Background}}}$

Signal / √Background

Sensitivity goes like $\dfrac{\text{Signal}}{\sqrt{\text{Background}}}$

If you can, increase Signal.

Signal / √Background

Sensitivity goes like $\frac{\text{Signal}}{\sqrt{\text{Background}}}$

If you can, decrease Background: This lecture.

II. Underground Labs

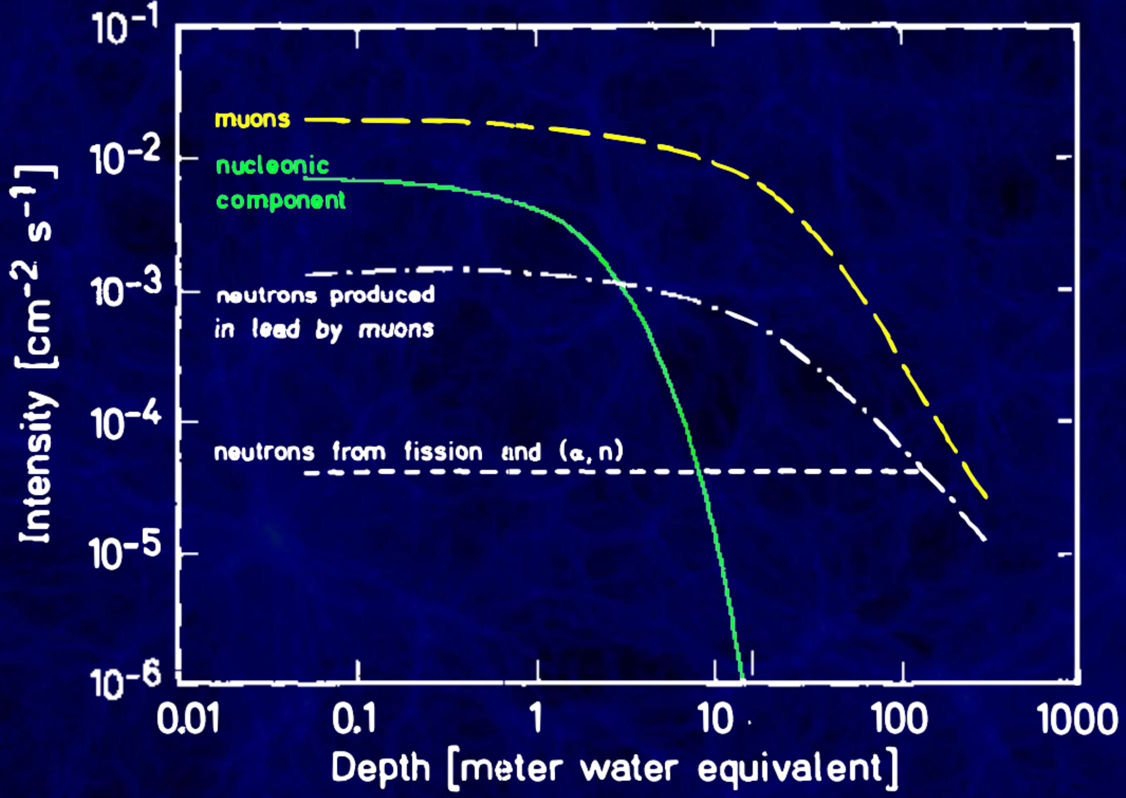
Take Home:

- Most background from cosmic rays
- Even shallow underground labs good
- Lots of deep labs to pick from


Auger

Cosmic Rays at Sea Level

species	flux / $m^{-2}\,s^{-1}$
muons	≈ 400
gammas	≈ 300
electrons, positrons	≈ 200
protons	≈ 6



Heusser 1995

Underground Labs

Nigel Smith UCLA 2018

Mine or Tunnel?

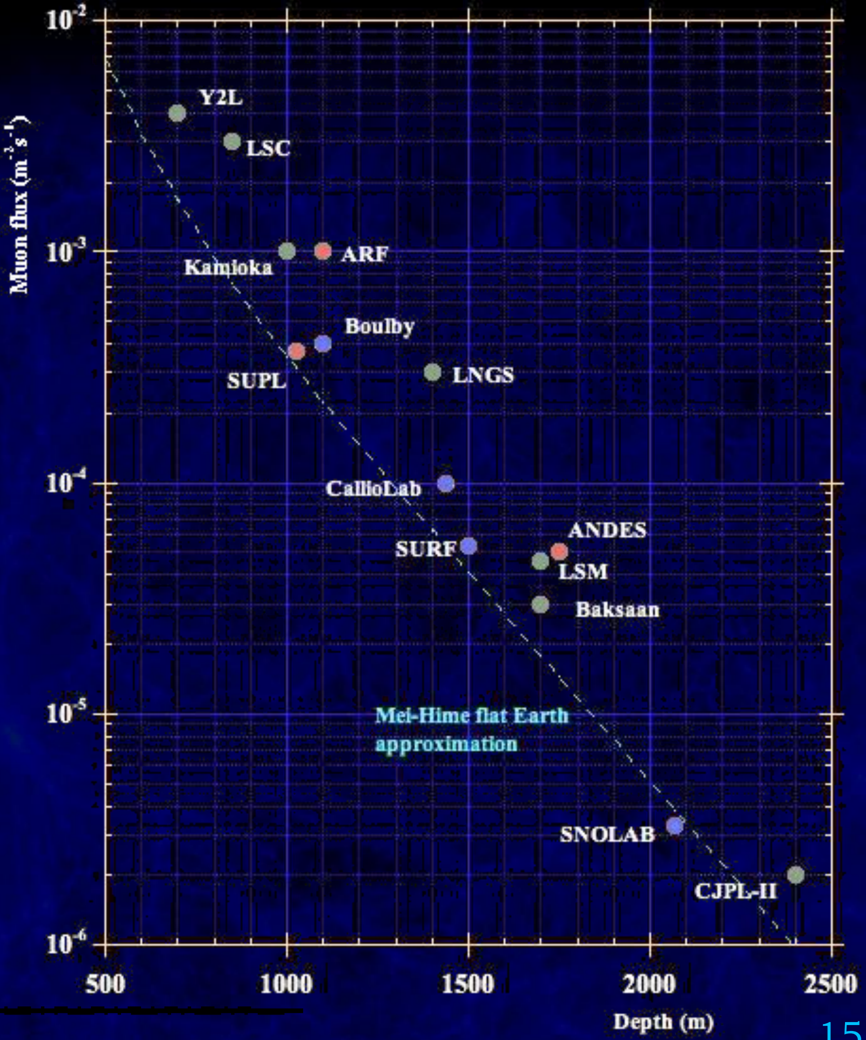

Gran Sasso mountain range
cable car
to ski resort
hiking path
lab
tunnel
Assergi
highway


I.N.F.N.
solo autorizzati

Overburden

Reduces cosmic ray
- flux (hadrons & muons)
- induced spallation products (mostly neutrons)

Muon flux depends on overburden, overburden profile, and seasonal effects

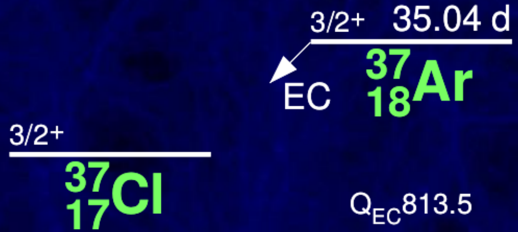


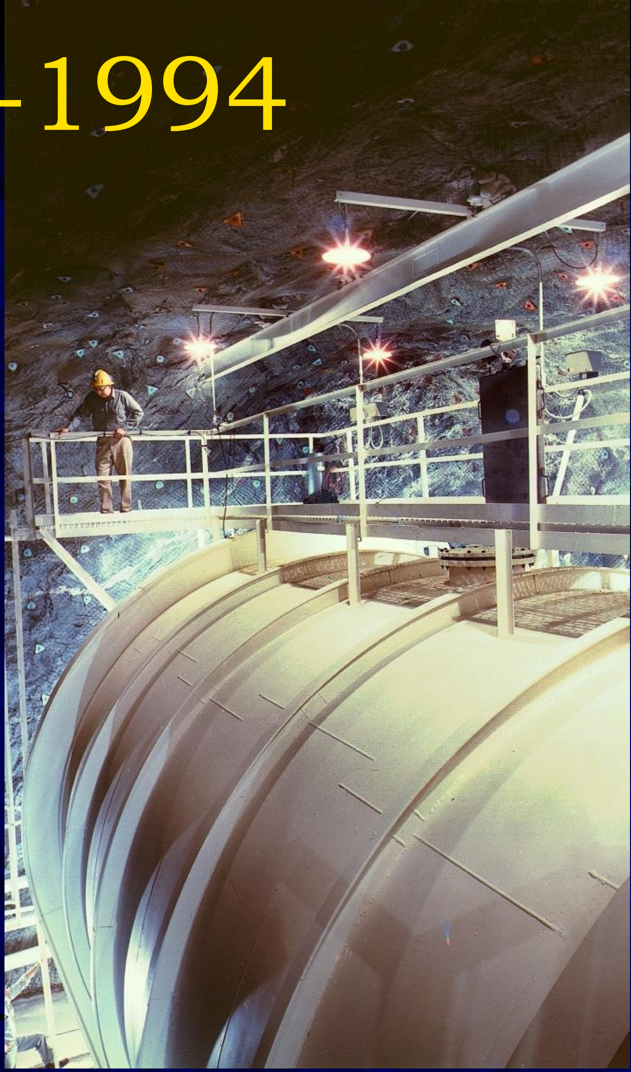
Nigel Smith UCLA 2018

Davis Experiment 1970-1994

615t perchlorethylene C_2Cl_4

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$





Proportional Counter

Cleveland+ 1998

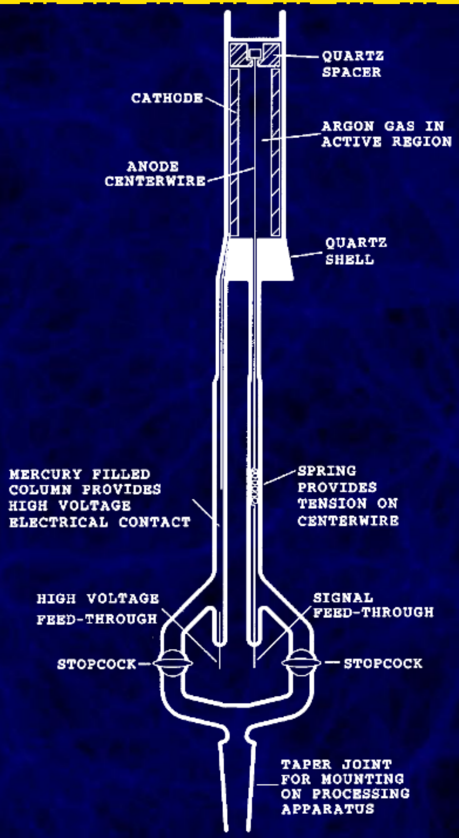
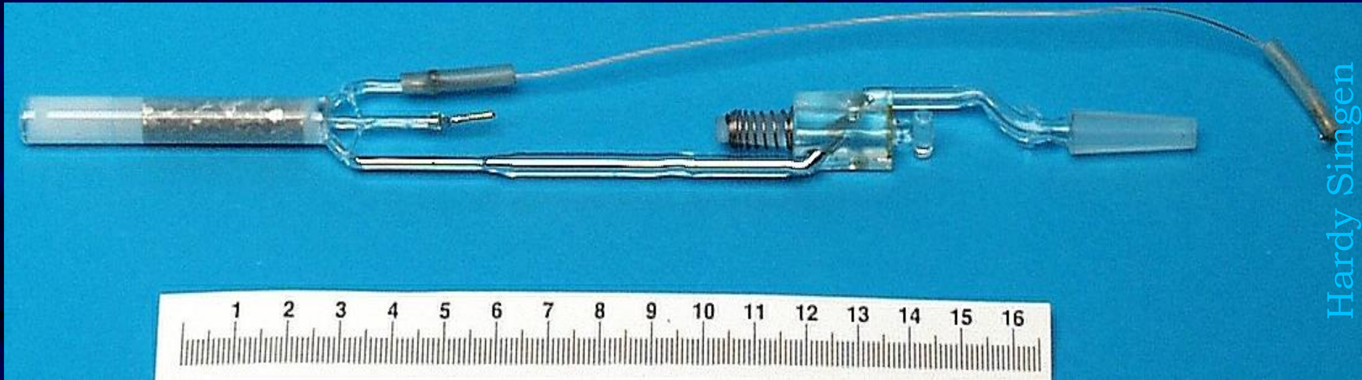


FIG. 7.—Proportional counter geometry. Sketch of the miniature proportional counters used to observe ^{37}Ar decays. Counters typically have an overall length of 20 cm, with an active region 30 mm long and 4.5 mm in diameter.



Hardy Simgen

III. Passive Shielding

Take Home:

- Pb simple against gammas
- PE simple against neutrons
- Concrete and Water cheap

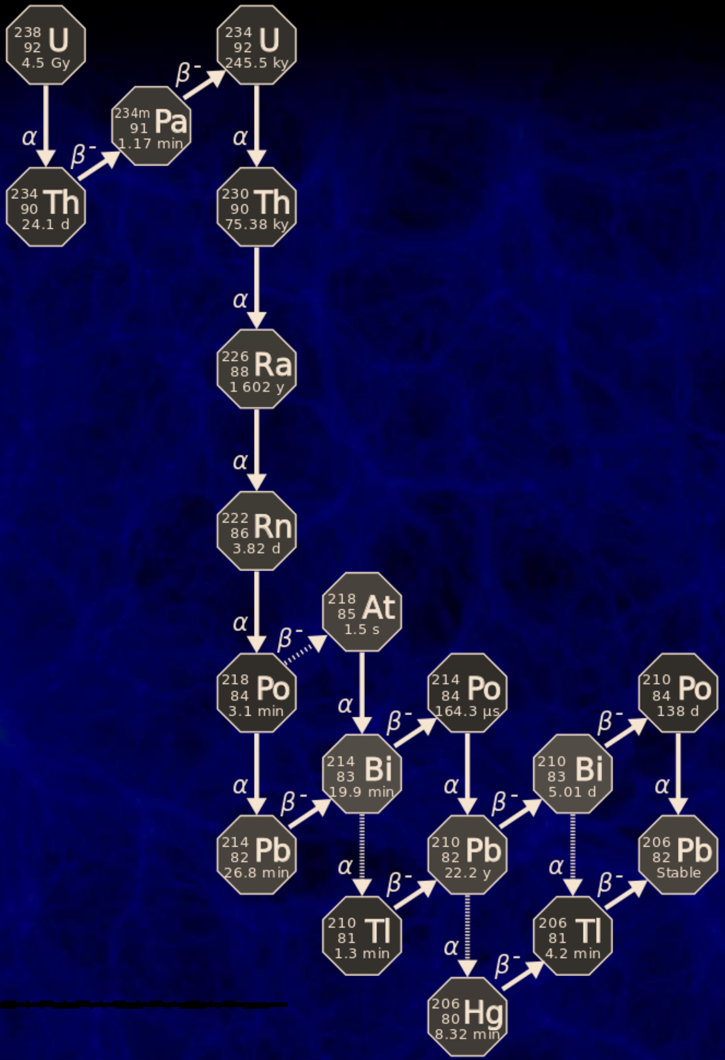
Radioactive Sources

- primordial
  e.g. ^{232}Th series, ^{238}U series, ^{40}K (5kBq/physicist)
- cosmic ray induced or spallation
  e.g. ^{11}C, ^{39}Ar
- anthropogenic
  e.g. ^{60}Co, ^{85}Kr, ^{90}Sr, ^{131}I
- plus the daughters
  e.g. ^{208}Tl, ^{222}Rn, …

Decay Chains

Never expect them to be in secular equilibrium!

A single isotope can give all kinds of α, β, γ



^{222}RnCrap

3.8235 d	$^{222}_{86}$Rn	α: 5.4895 (99.92)		γ: 511 (0.076)
	100 ↓ α	α: 4.986 (0.078)		
3.10 m	$^{218}_{84}$Po	α: 6.0024 (100)		
	0.020 99.980			
	β ↙ ↘ α			
1.6 s	$^{218}_{85}$At $^{214}_{82}$Pb	α: 6.694 (90)	β: 0.728 (42.2)	γ: 351.93 (35.1/37.6)
26.8 m	99.9 100		β: 0.670 (48.9)	γ: 295.22 (18.2/19.3)
	α ↘ ↙ β		β: 1.030 (6.3)	γ: 242.00 (7.12/7.43)
19.9 m	$^{214}_{83}$Bi	α: 5.452 (53.9)	β: 3.275 (18.2)	γ: 609.31 (44.6/46.1)
	0.021 99.979	α: 5.516 (39.2)	β: 1.542 (17.8)	γ: 1764.49 (15.1/15.4)
	α ↙ ↘ β		β: 1.508 (17.02)	γ: 1120.29 (14.7/15.1)
			β: 1.425 (8.18)	γ: 1238.11 (5.78/5.79)
			β: 1.894 (7.43)	γ: 2204.21 (4.98/5.08)
1.3 m	$^{210}_{81}$Tl $^{214}_{84}$Po	α: 7.6868 (99.99)		γ: 799.7 (0.0104)
164.3 μs	100 100		β: 4.209 (30)	γ: 799.7 (0.021)
	β ↘ ↙ α		β: 1.863 (24)	
22.3 y	$^{210}_{82}$Pb		β: 0.017 (80)	γ: 46.54 (4.25)
	100 ↓ β		β: 0.063 (20)	
5.013 d	$^{210}_{83}$Bi			
	100 ↓ β		β: 1.162 (99)	
138.376 d	$^{210}_{84}$Po	α: 5.3043 (99.99)		γ: 803.10 ($1.22*10^{-3}$)
	100 ↓ α			
stable	$^{206}_{82}$Pb			

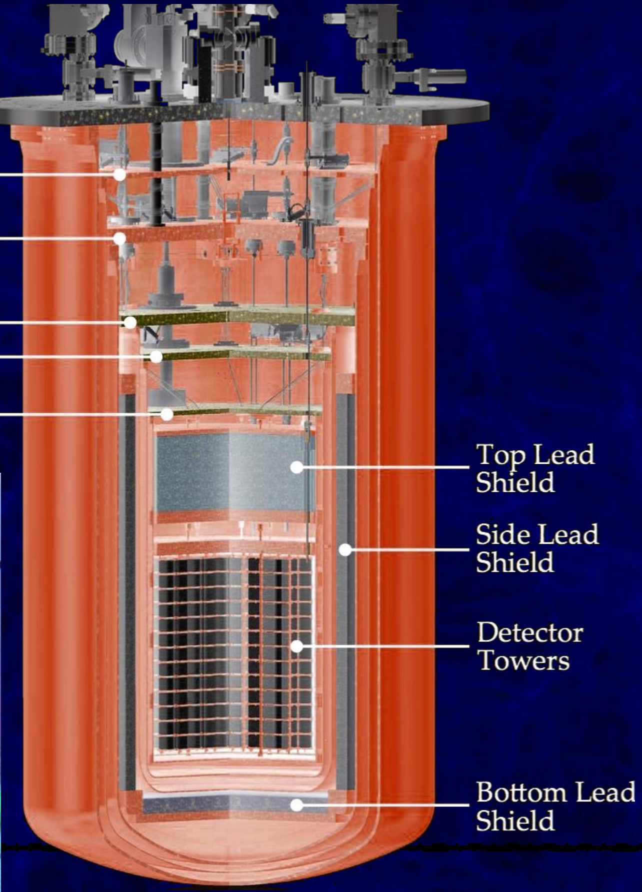
222RnCrap: Resulting Issues

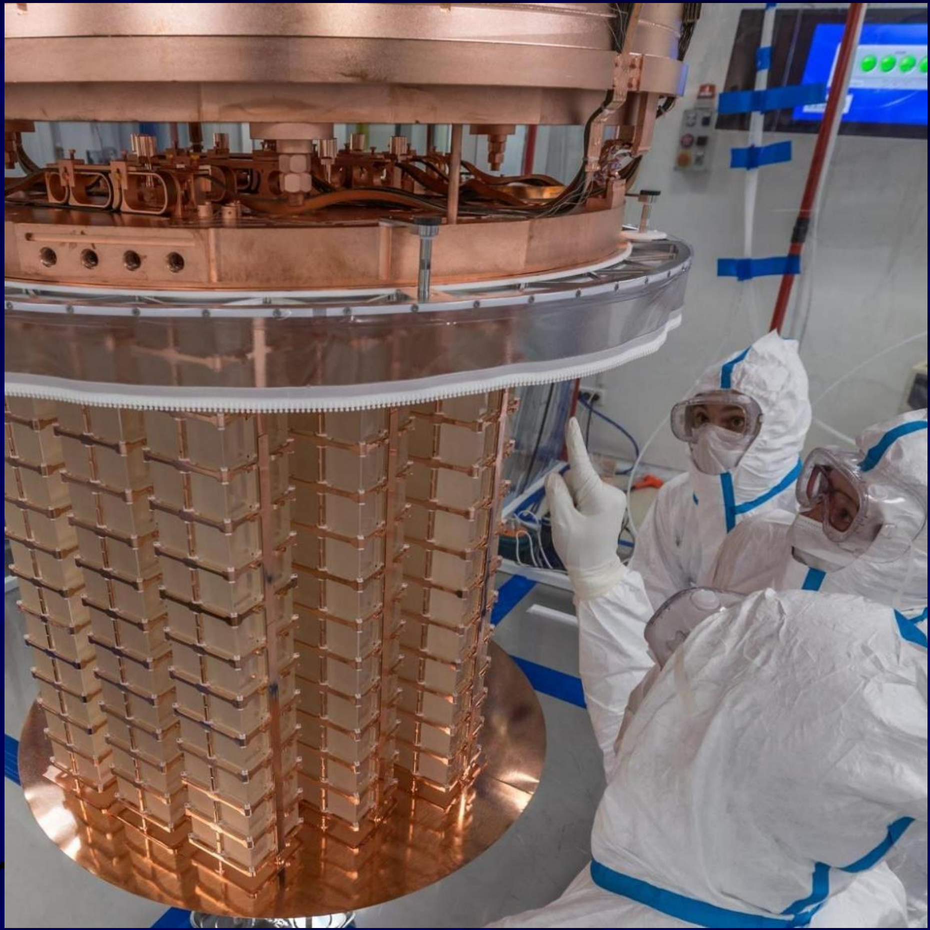
- Kamland: $^{13}C(\alpha,n)^{16}O$
- PICO: various alpha decays
- CDMS-II: low energy surface electrons from ^{210}Pb
- CRESST-II: degraded (low energy) ^{210}Pb recoils
- $0\nu\beta\beta$: various gamma lines
- Xenon TPCs: mis-reconstructed plated out decays

Solid Shielding, e.g. Majorana

Matt Kapust

Archeological Lead: CUORE

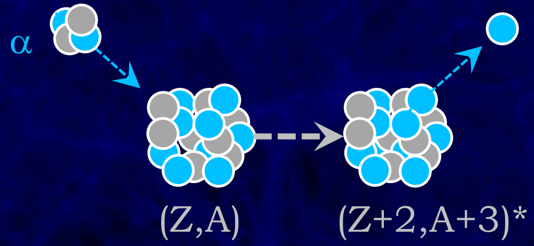




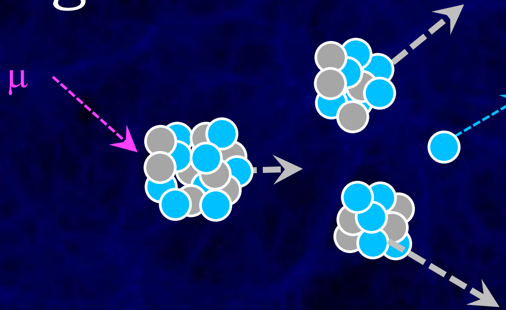
Neutrons

Sources

radiogenic: α,n



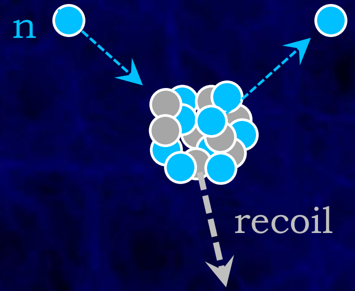
cosmogenic



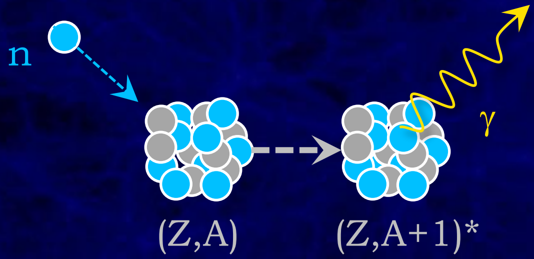
or spontaneous fission, e.g. ^{235}U

Backgrounds

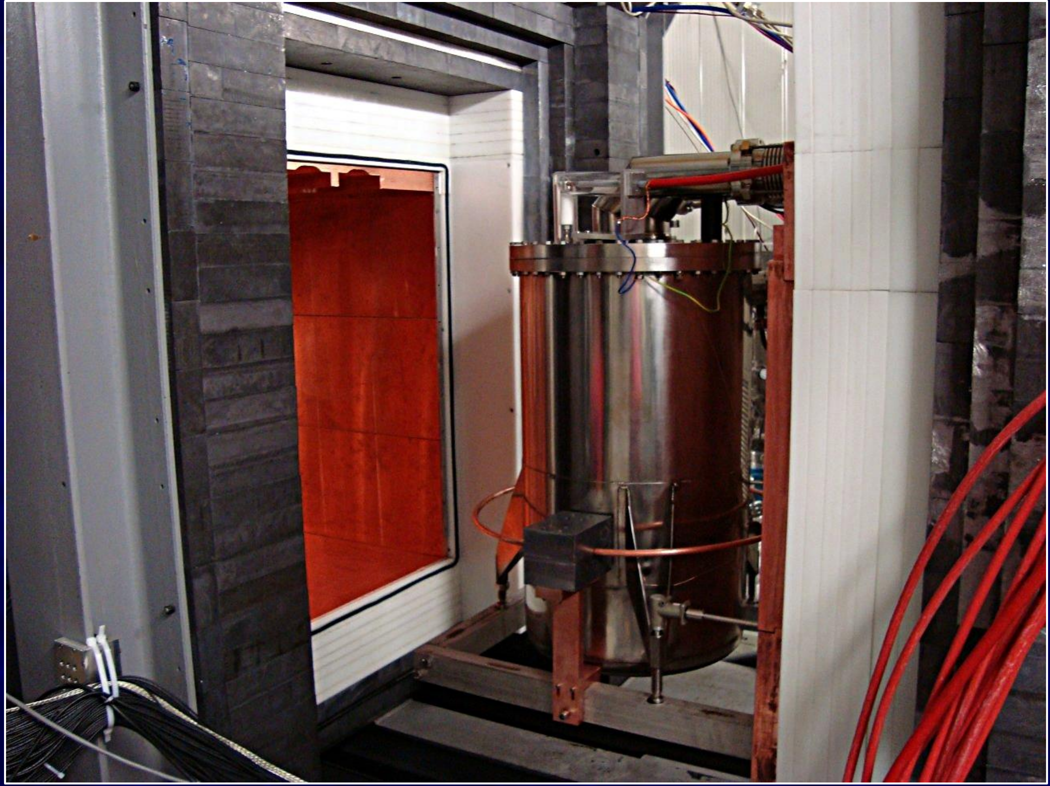
elastic scatter:



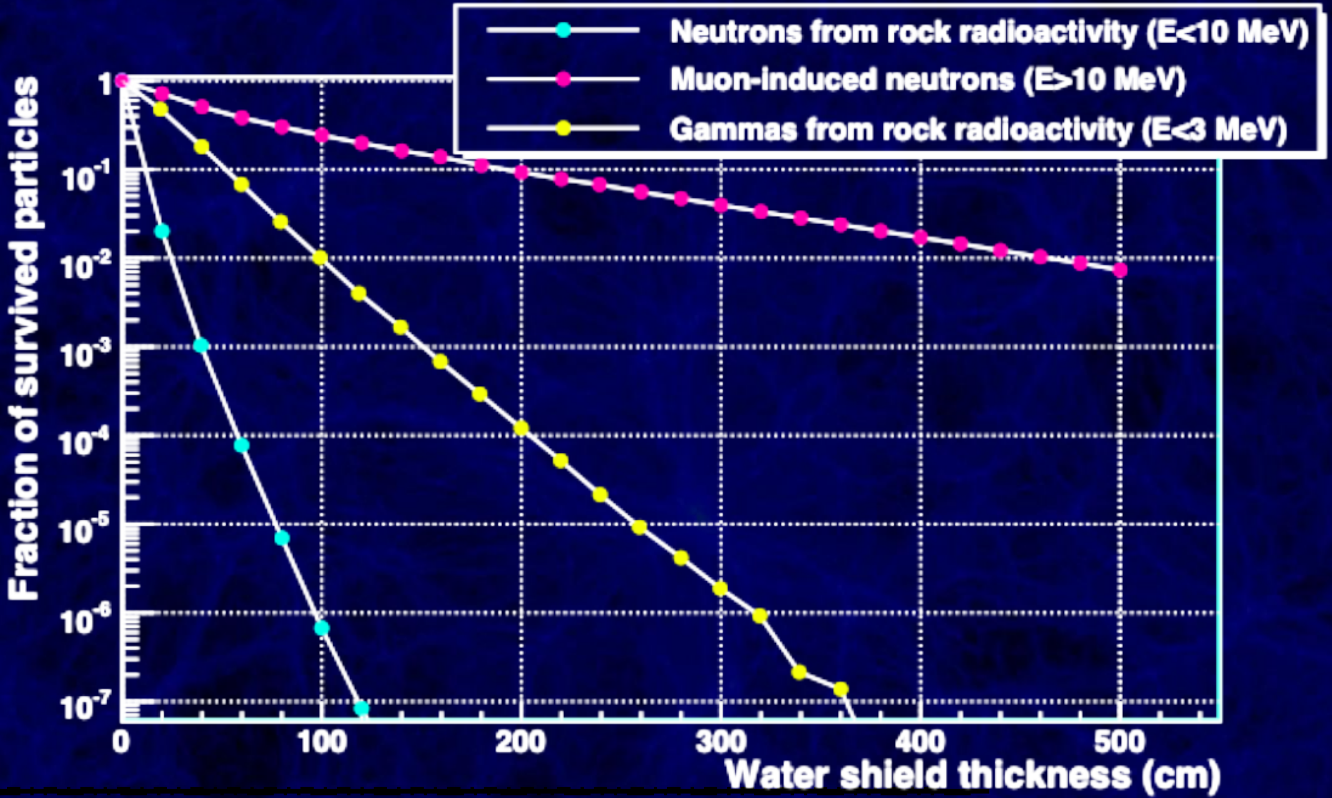
capture:



Solid Shielding, e.g. XENON100



Or simply use water



Marco Selvi

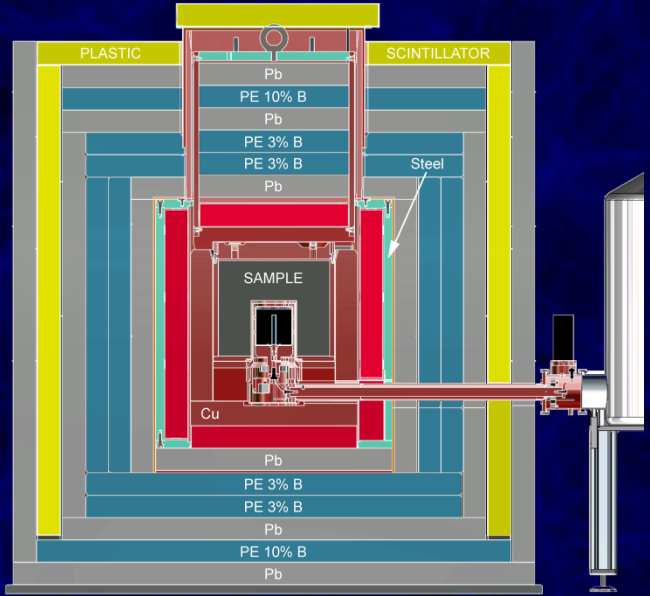
IV. Vetos

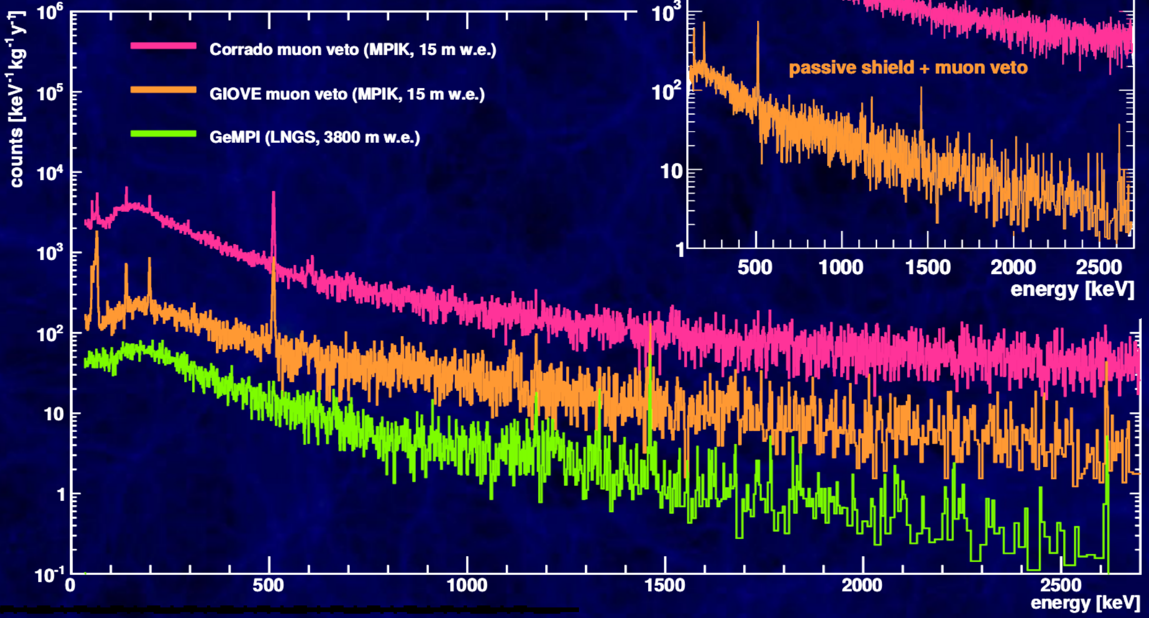
Take Home:

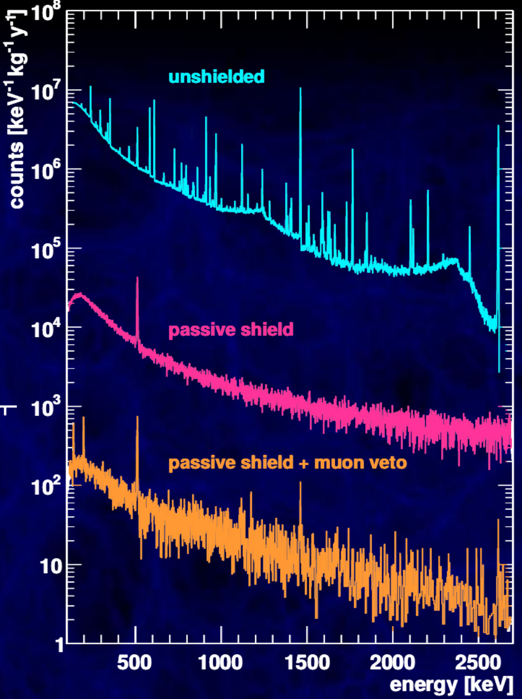
- Create Virtual Depth
- Reduce coincident backgrounds

Virtual Depth

Gerd Heusser TAUP2015



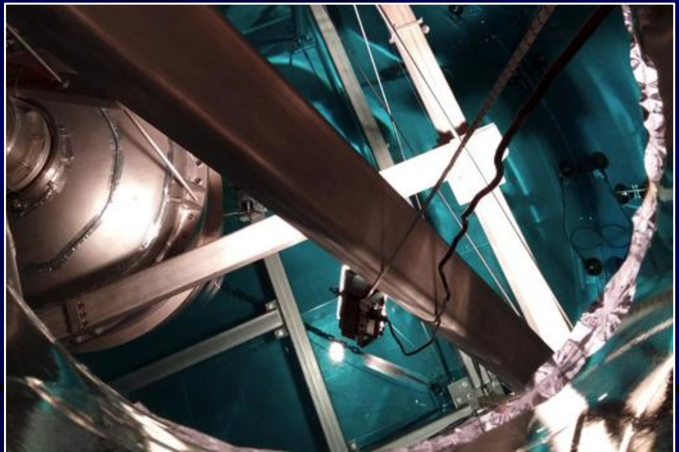




μ Veto, e.g. XENON1T

10m tall, 9.6m∅
700t high purity water

Passive shield against γ & n
Active shield against μ:
water Cherenkov muon veto

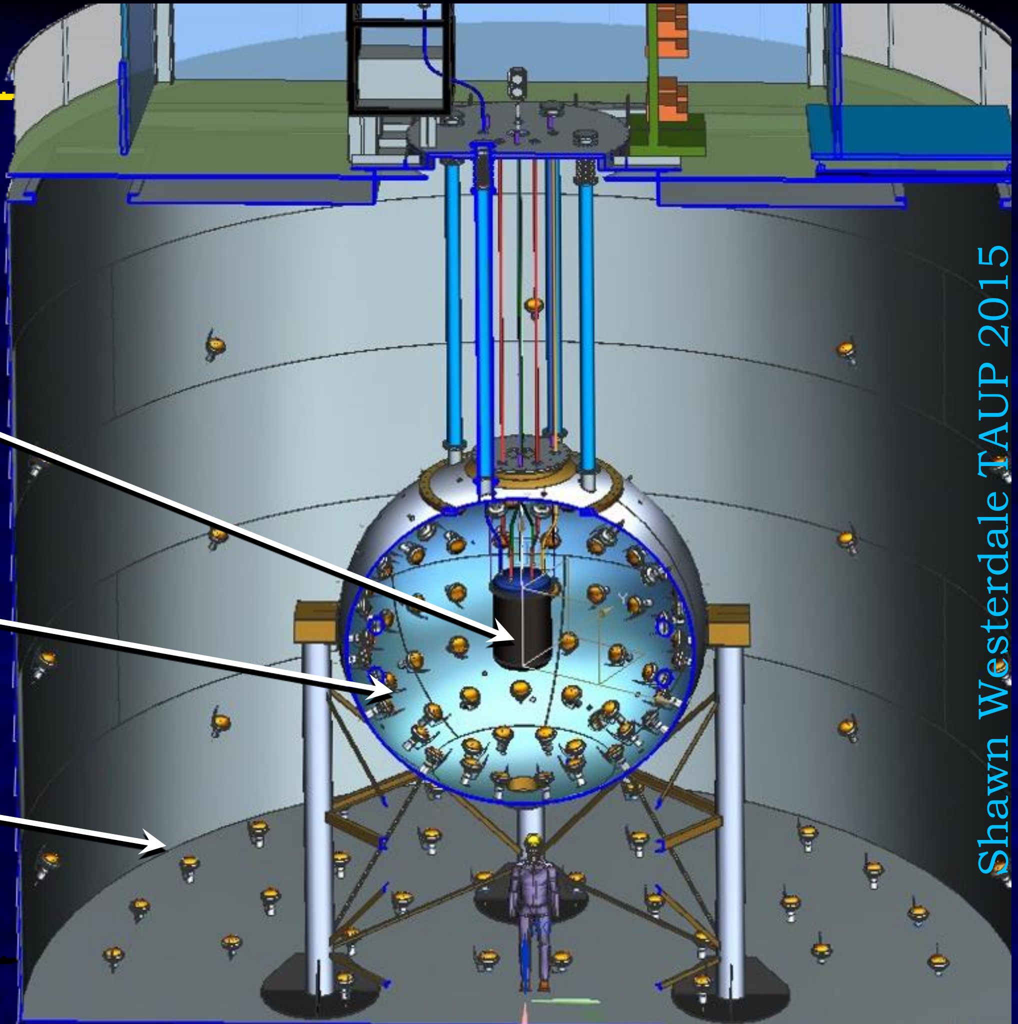


DarkSide

Argon target

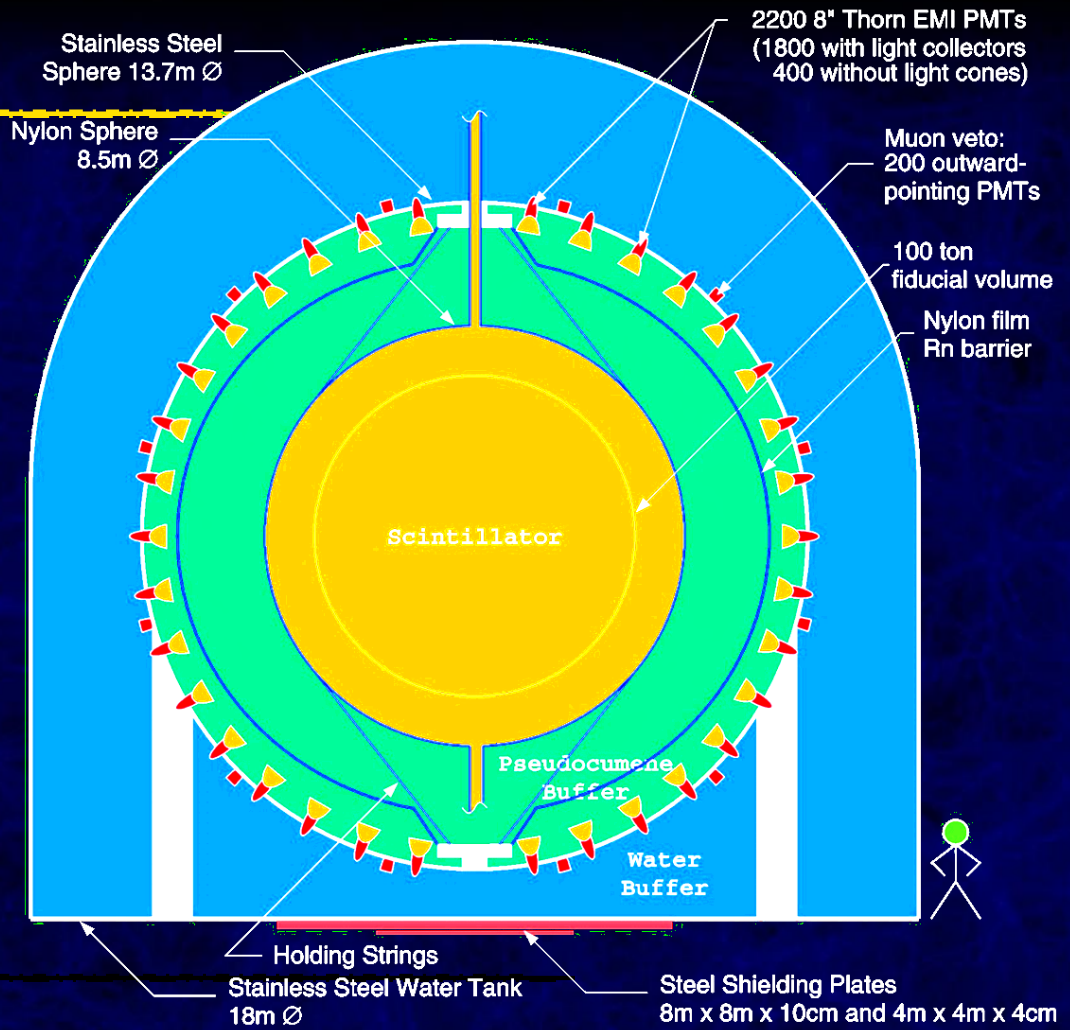
Liquid scintillator veto
pseudocumene plus boron

Water Cherenkov detector



Shawn Westerdale TAUP 2015

BOREXINO



Stainless Steel
Sphere 13.7m ∅
Nylon Sphere
8.5m ∅
2200 8" Thorn EMI PMTs
(1800 with light collectors
400 without light cones)
Muon veto:
200 outward-
pointing PMTs
100 ton
fiducial volume
Nylon film
Rn barrier
Scintillator
Pseudocumene
Buffer
Water
Buffer
Holding Strings
Stainless Steel Water Tank
18m ∅
Steel Shielding Plates
8m x 8m x 10cm and 4m x 4m x 4cm

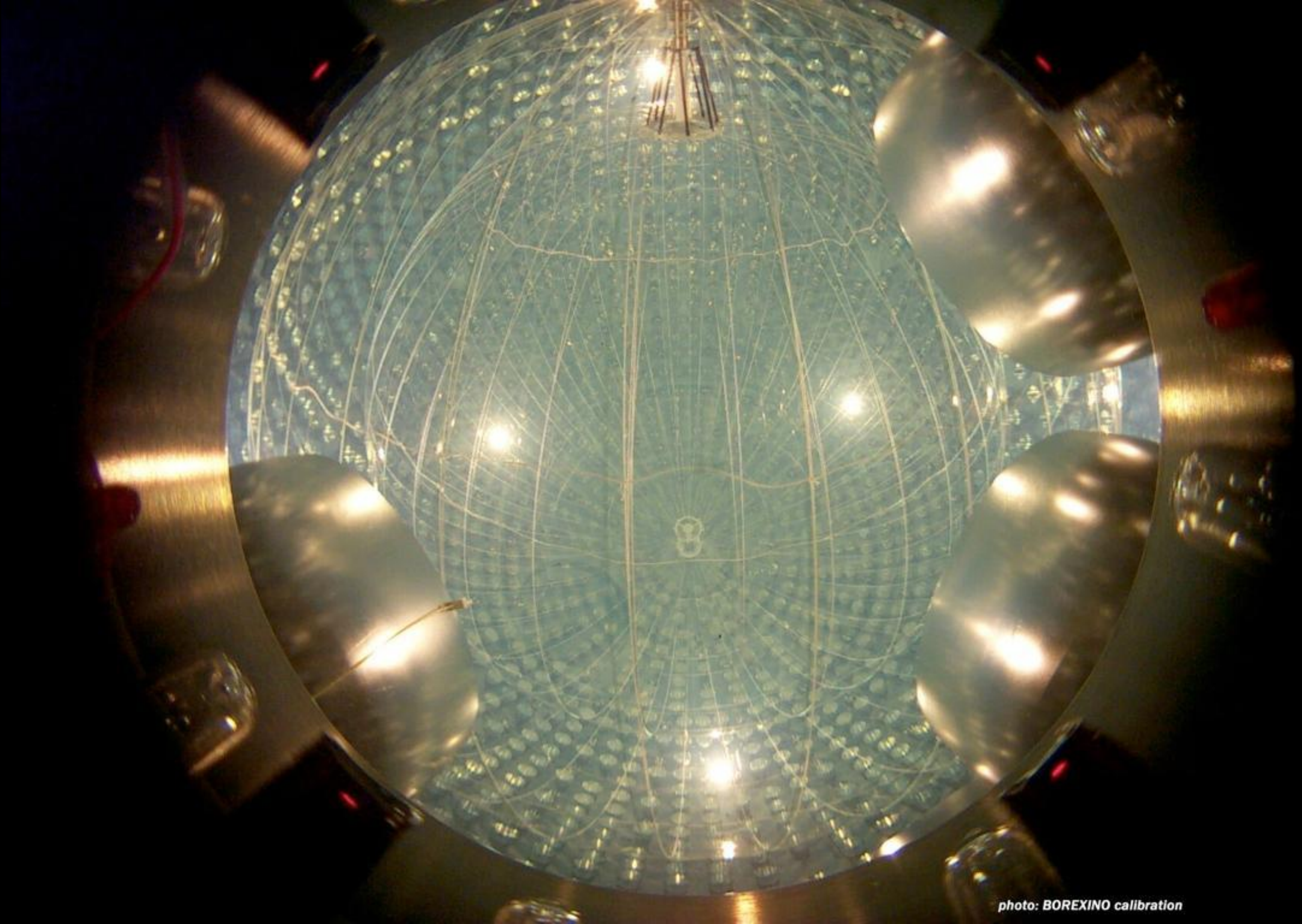


photo: BOREXINO calibration

V. Material Selection

Take Home:

- Be careful what you build from.
- Screen everything.

Requirements

e.g. BOREXINO:

$^{14}C/^{12}C < 10^{-18}$

$^{nat}K < 10^{-14}$ g/g (^{40}K)

^{nat}Ar < 70 vol-ppb (^{39}Ar)

^{nat}Kr < 0.1 vol-ppt (^{85}Kr)

e.g. GERDA:

cryostat stainless <5mBq/kg ^{228}Th

detector holder PTFE <100μBq/kg ^{228}Th

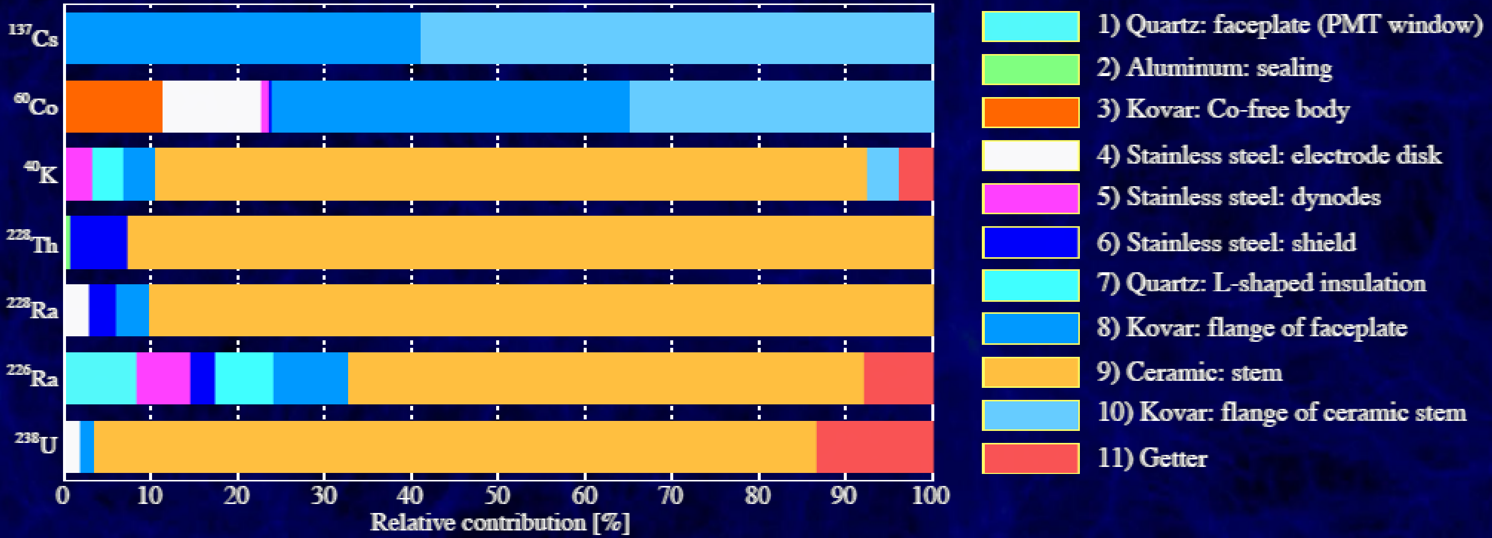
shield argon <1μBq/m^3 (STP) ^{222}Rn

Laborious yet Heroic Efforts

Hand-machine every nut and bolt

Work with suppliers

XENON 1503.07698

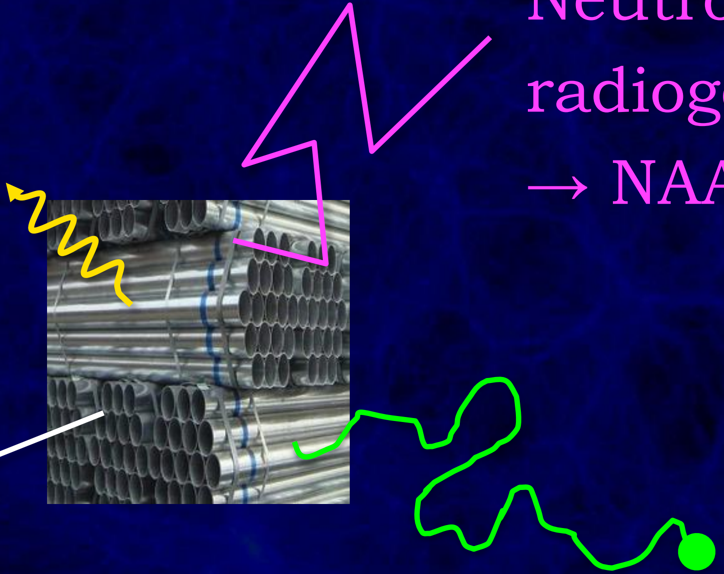


But little research into clean ores

Assay Techniques

Gamma emission
Pb, Bi, Tl, K, Co, …
→ HPGe spectroscopy

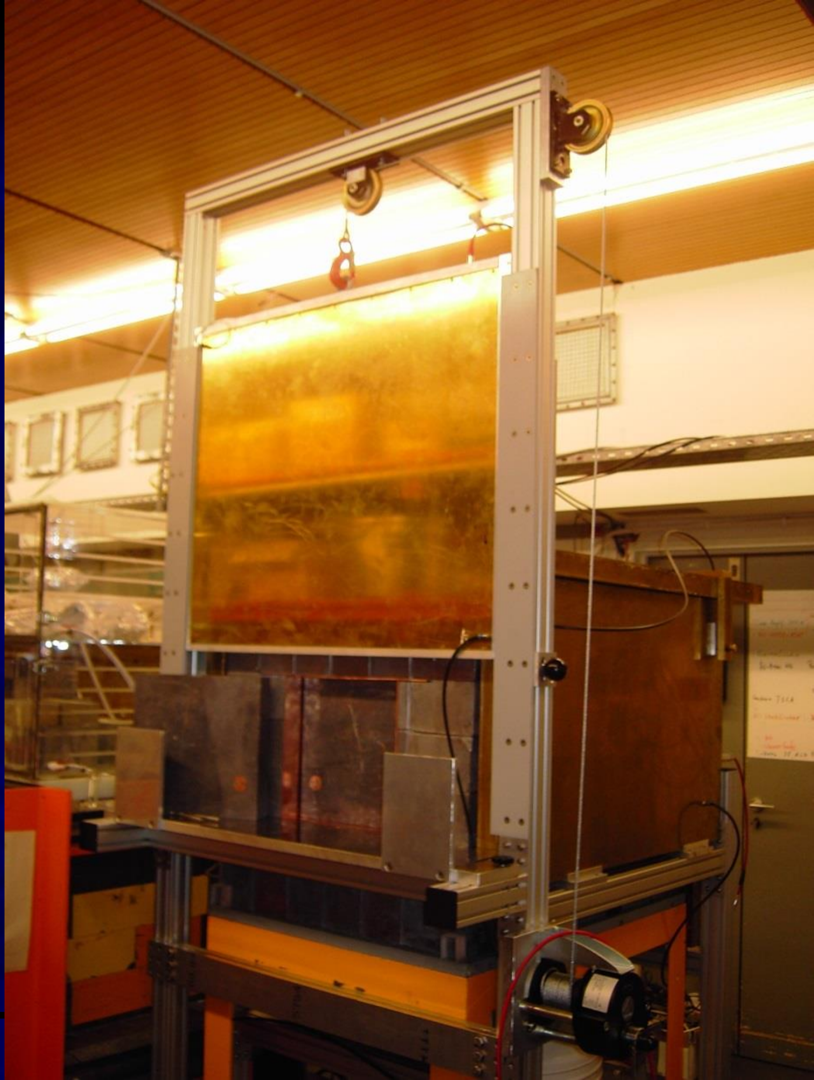
Neutron emission
radiogenic (U/Th)
→ NAA / ICPMS



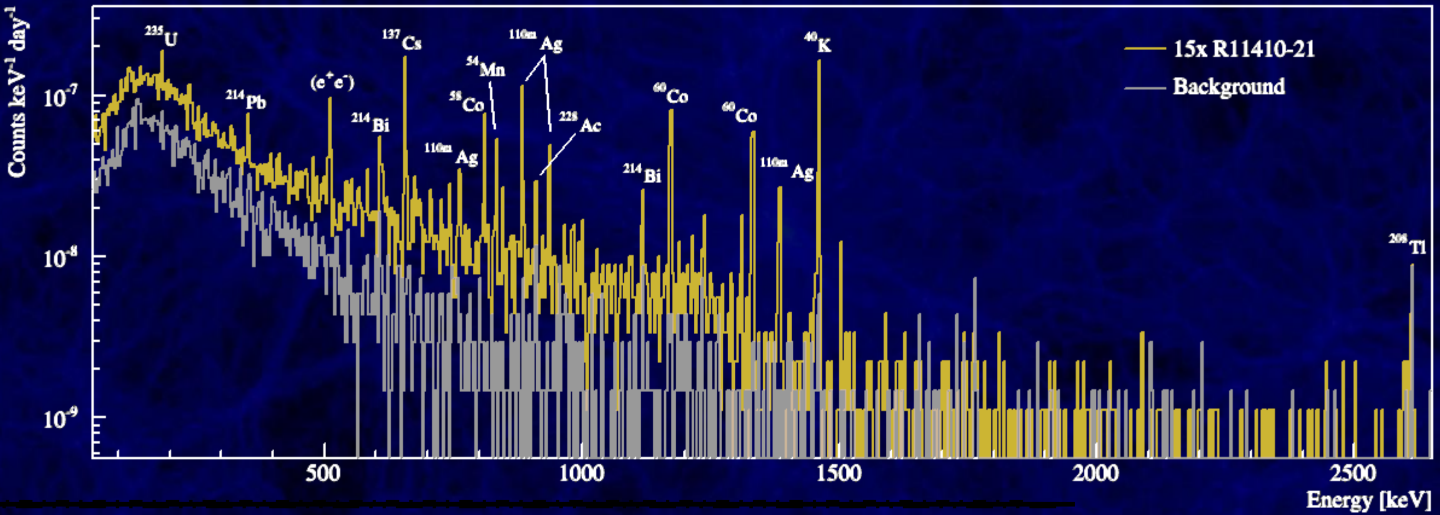
Alpha Spectrometry,
XIA, Beta Cage

Radon outgassing
^{222}Rn (^{226}Ra), ^{220}Rn (^{224}Ra)
→ Radon emanation systems

HPGe Screening

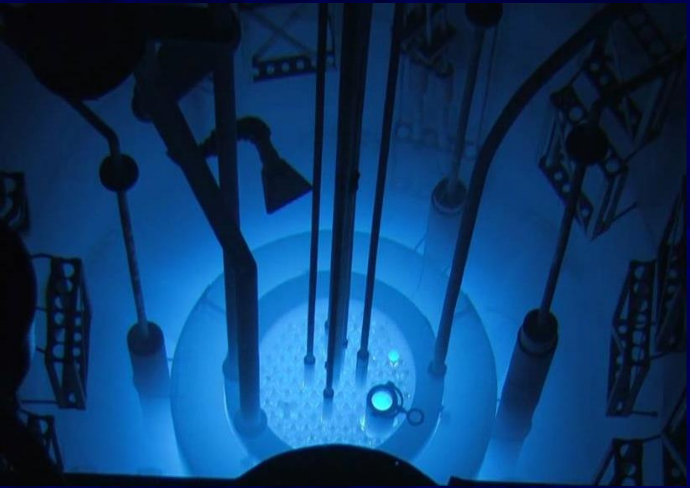


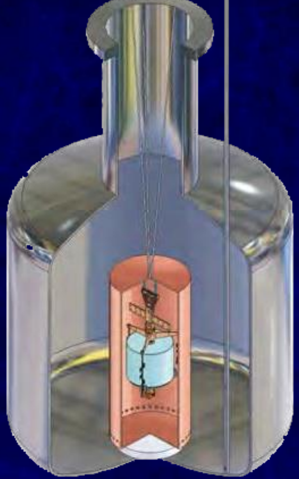
Example: Hamamatsu R11410

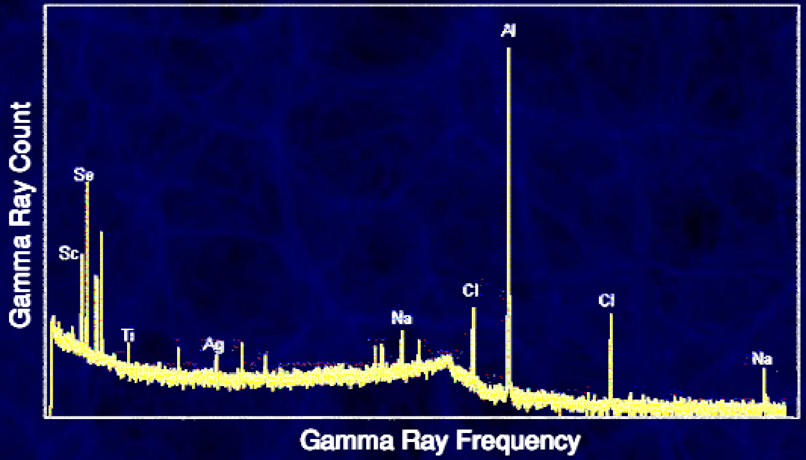


XENON 1503.07698

Neutron Activation Analysis







Tessa Johnson

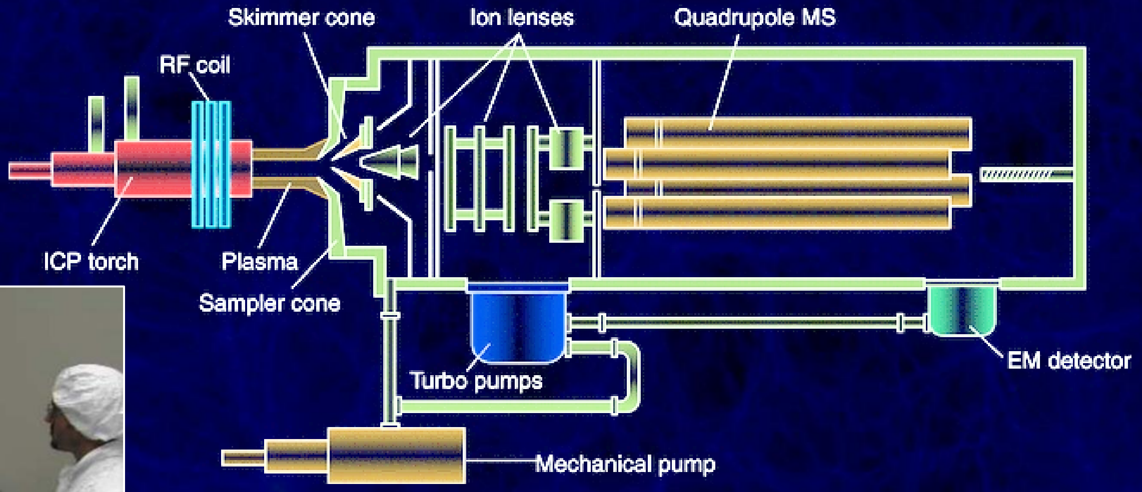
$^{238}U(n,\gamma)^{239}U \xrightarrow{(t_{1/2}=24m)} {}^{239}Np \xrightarrow{(t_{1/2}=2.4d)}$ [103,106,228,278] keV γ's

$^{232}Th(n,\gamma)^{233}Th \xrightarrow{(t_{1/2}=22m)} {}^{233}Pa \xrightarrow{(t_{1/2}=27d)}$ [300,312] keV γ's

$^{41}K(n,\gamma)^{42}K \xrightarrow{(t_{1/2}=12h)}$ 1524 keV γ, ^{40}K from natural abundance

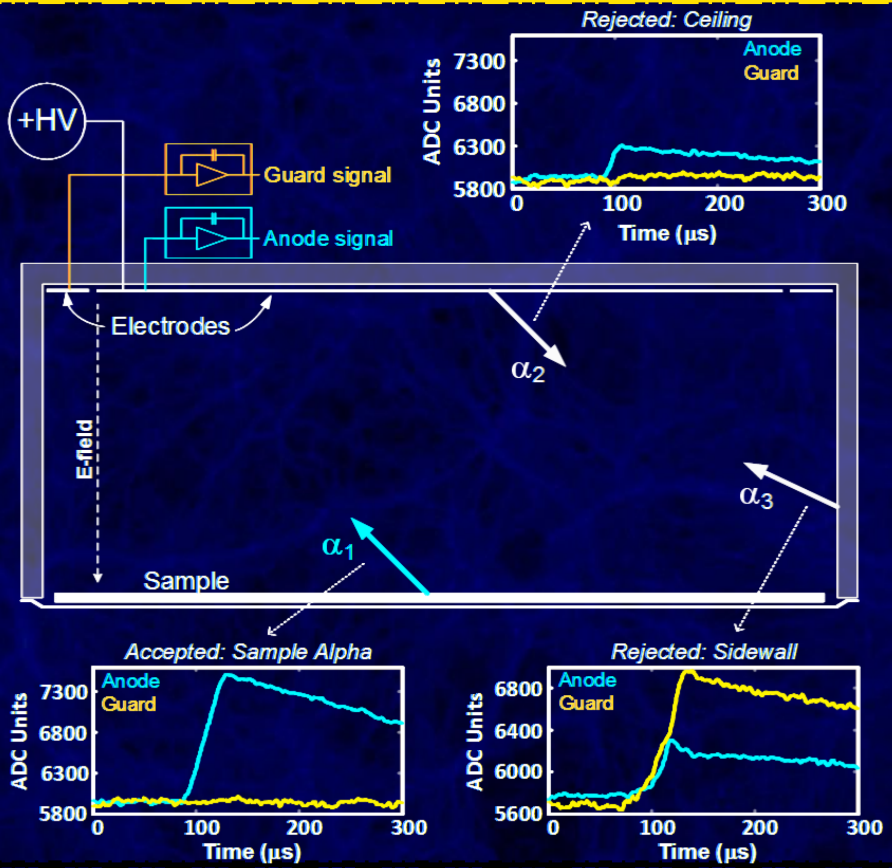
ICPMS

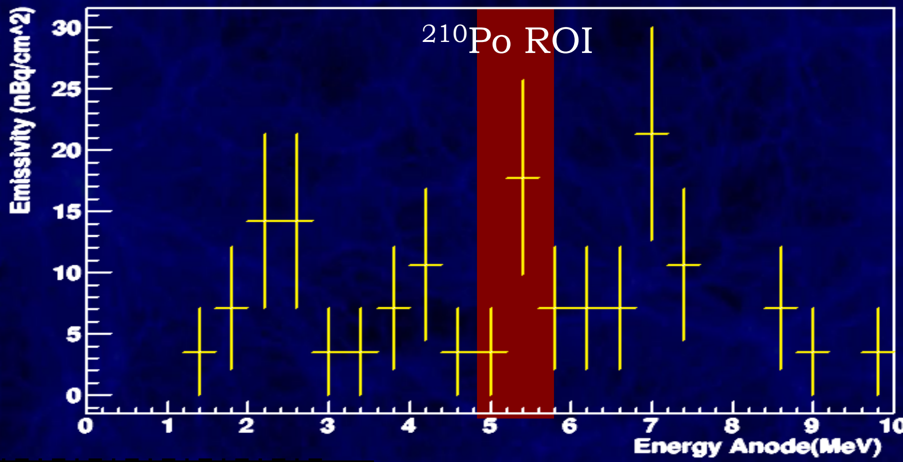
Ionize material, accelerate plasma in mass spectrometer



Stefano Nisi

Surface Alpha Screening

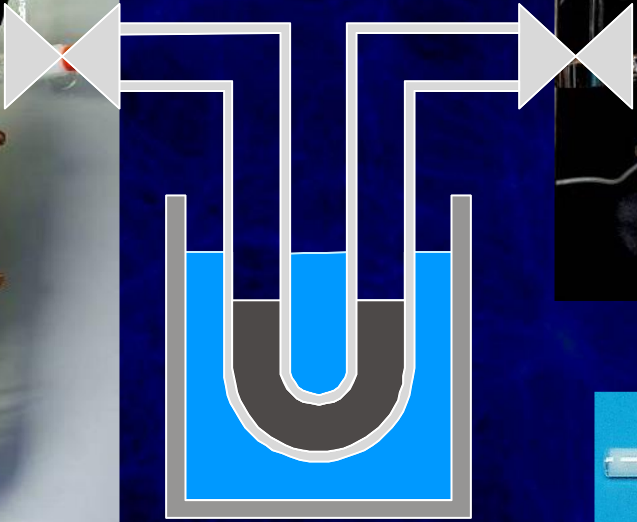


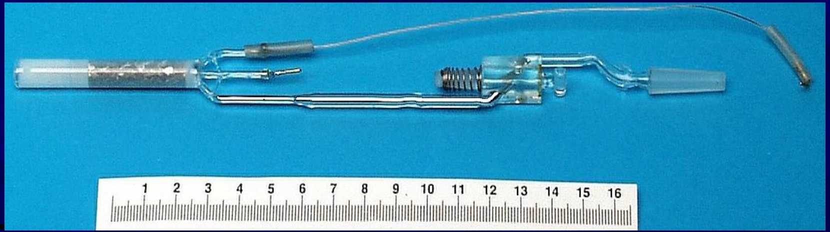


Jodi Cooley

Radon Emanation

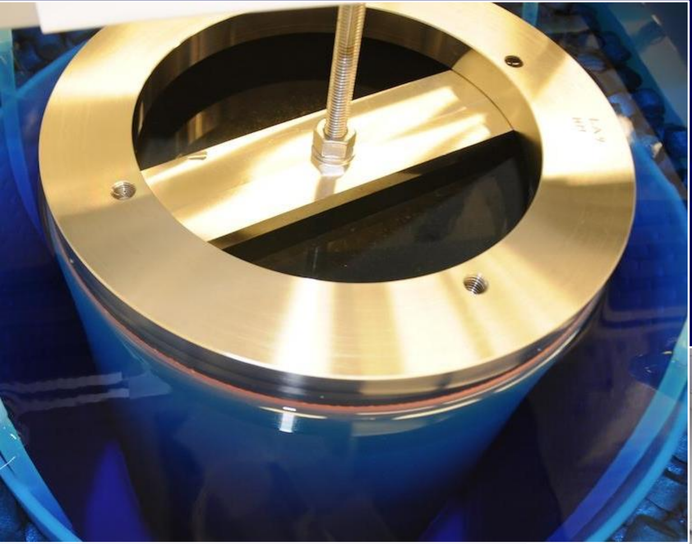
Hardy Simgen



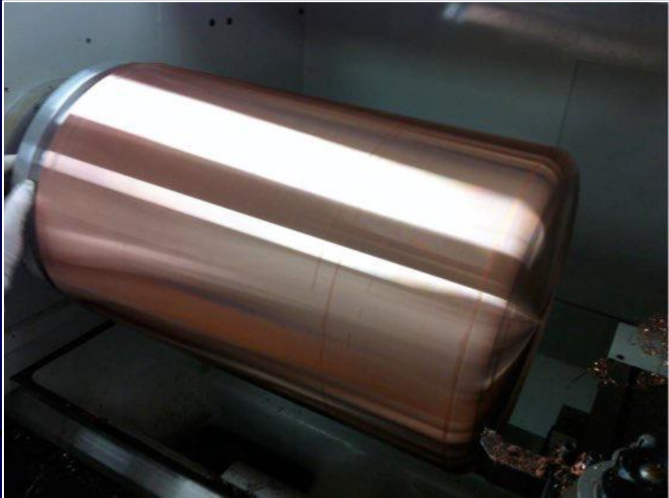


Cu Electroforming (PNNL)

MAJORANA: electrodeposit Cu onto mold underground



via Jodi COoley



U&Th chains
<0.1μBq/kg

Community Database

radiopurity.org

Community Material Assay Database

Search | Submit | Settings | About

copper

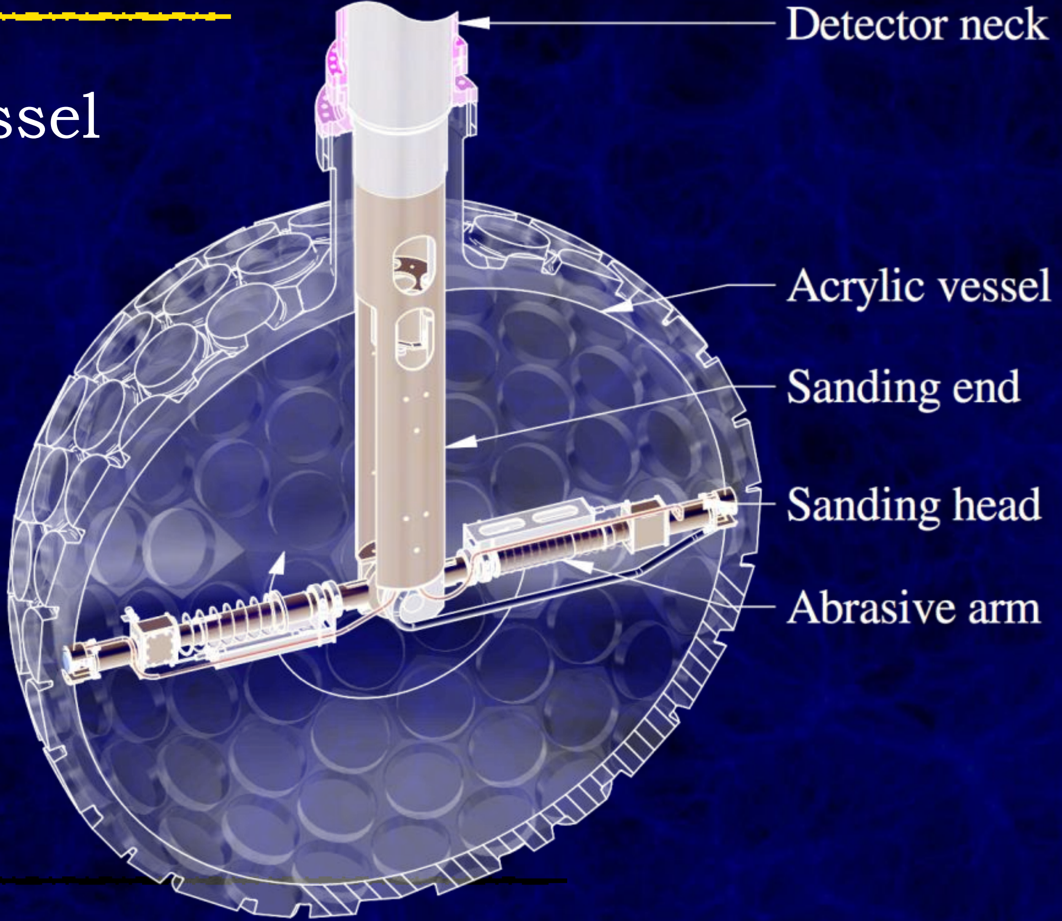
EXO (2008)	**Copper, OFRP, Norddeutsche Affinerie**	Th	< 2.4 ppt	U	< 2.9 ppt	...
EXO (2008)	**Copper tubing, Metallica SA**	Th	< 2 ppt	U	< 1.5 ppt	
ILIAS ROSEBUD	**Copper, OFHC**	...				
XENON100 (2011)	**Copper, Norddeutsche Affinerie**	Th-228	21() muBq/kg	U-238	70() muBq/kg	...
XENON100 (2011)	**Copper, Norddeutsche Affiinerie**	Th-228	< 0.33 mBq/kg	U-238	< 11 mBq/kg	...
EXO (2008)	**Copper gasket, Serto**	Th	6.9() ppt	U	12.6() ppt	...
EXO (2008)	**Copper wire, McMaster-Carr**	Th	< 77 ppt	U	< 270 ppt	...

http://radiopurity.org & NIM A 839 (2016) 6

Reduce Surface Contamination

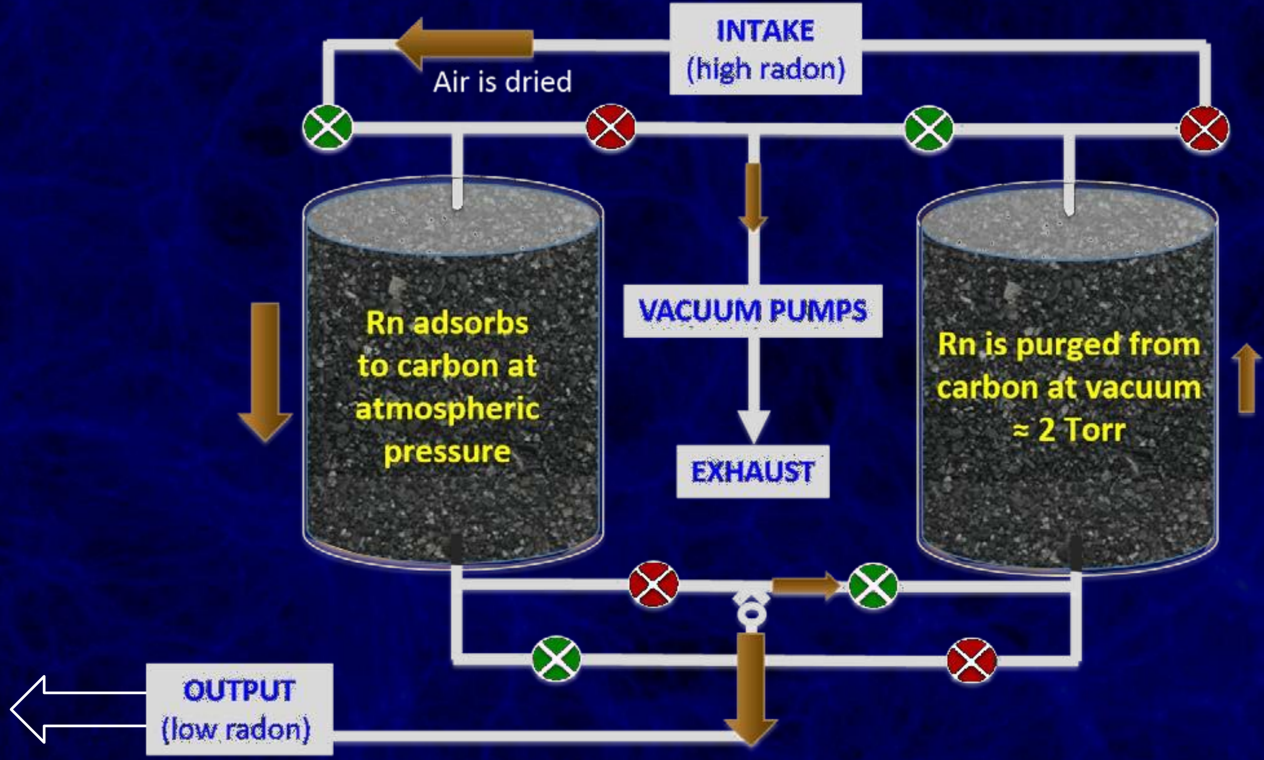
DEAP3600: Acrylic vessel

Resurfacer:
remove 500μm,
reduced Rn
by factor 2000



Radon Free Air, e.g. @SNOLab

Lab Air ~130 Bq/m^3



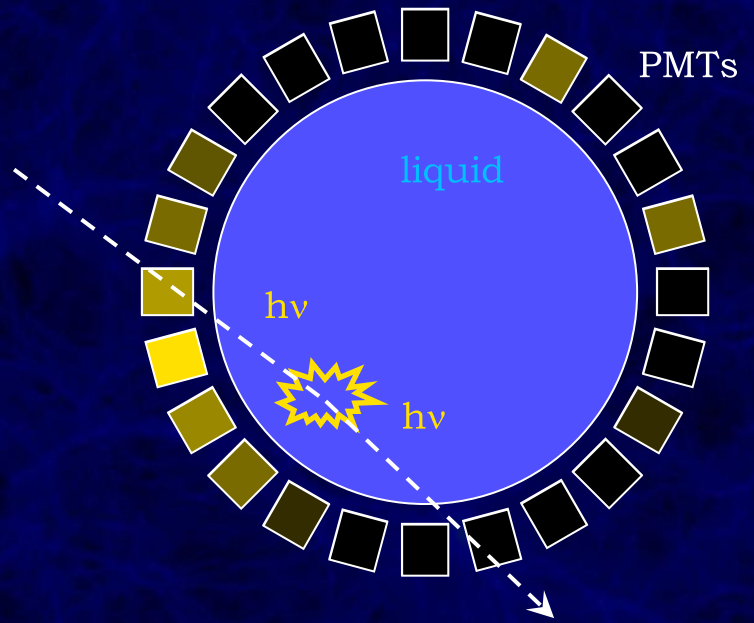
Radon-mitigated air
<0.1 Bq/m^3
to radon-free cleanroom

VI. Fiducialization

Take Home:

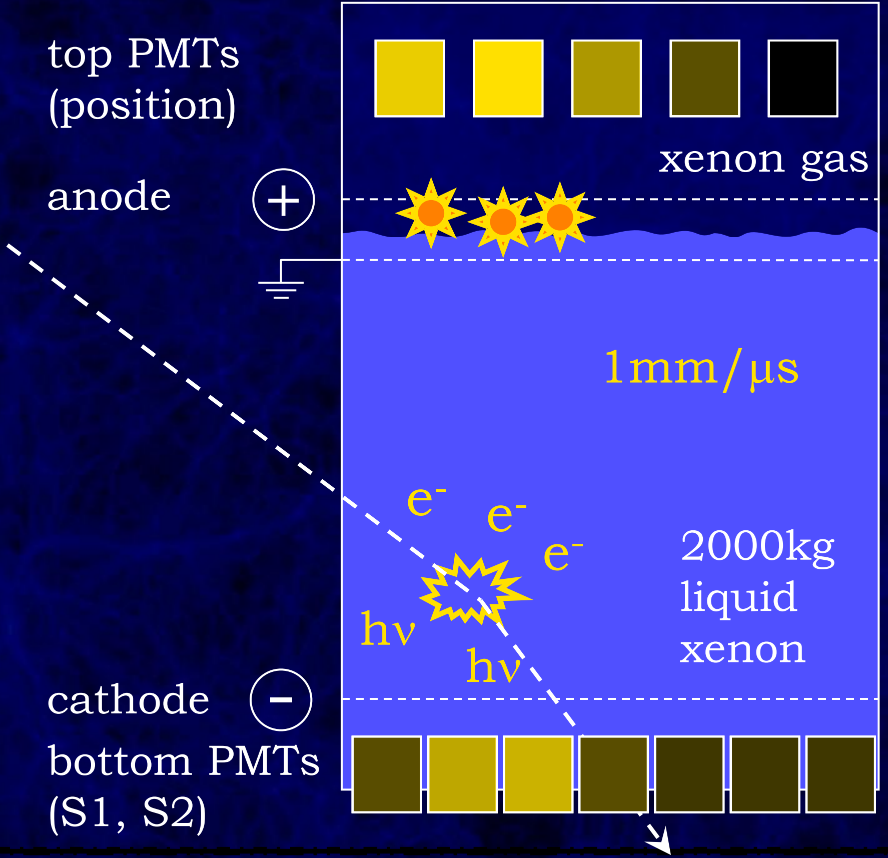
- Surfaces are bad, bulk is good

Single Phase, e.g. DEAP3600

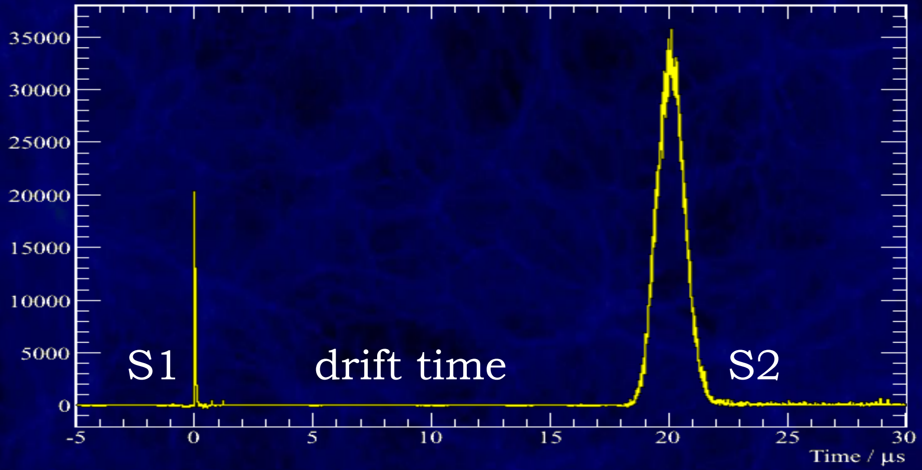


Vertex position from scintillation (S1) hit pattern
Worked great for ν experiments

Dual-Phase TPC: e.g. XENON1T

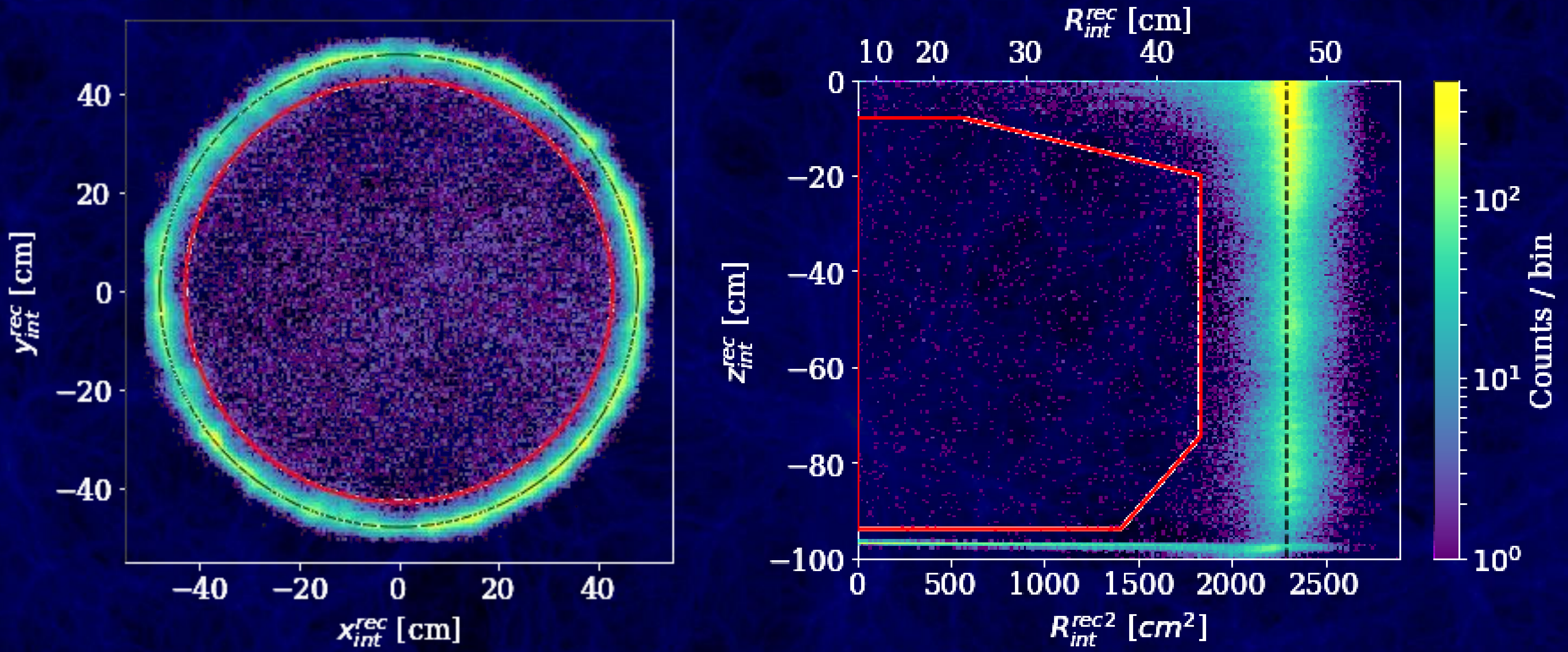


3D position information
S2 hit pattern: $\delta r < 2\,\mathrm{cm}$
drift time: $\delta z < 500\,\mu\mathrm{m}$



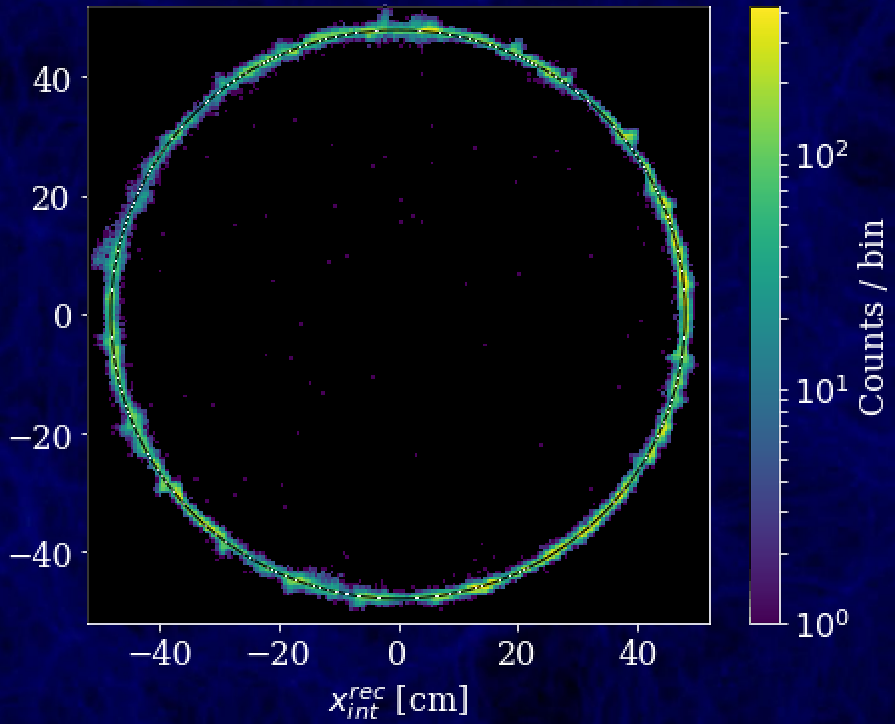
Self-Shielding in Xenon

Reduce background with exp(-diameter/λ_γ)

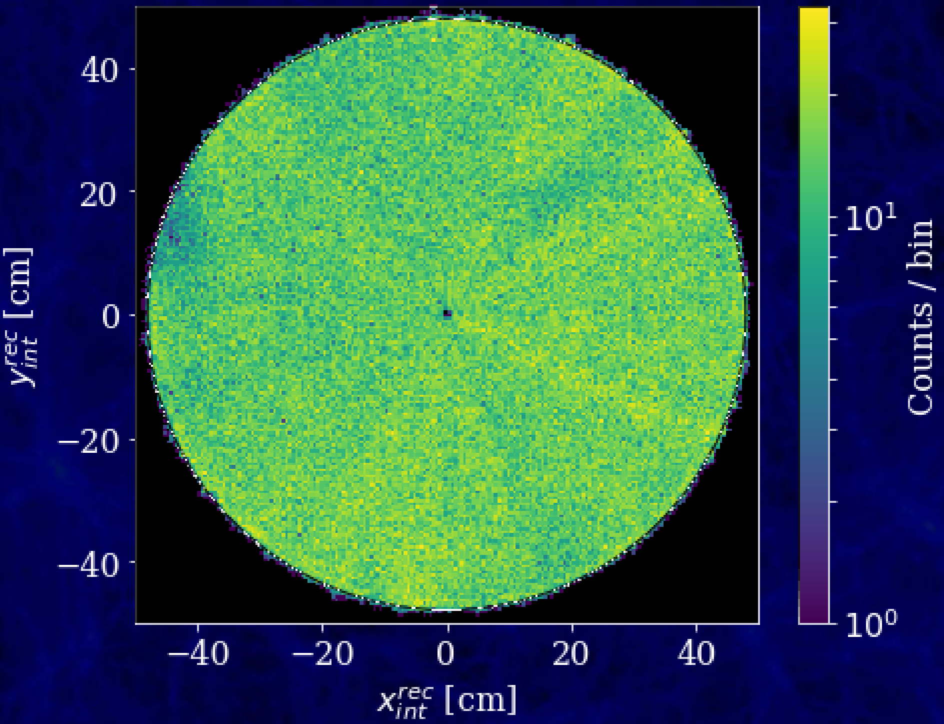


XENON1T Background Examples

^{210}Po: at wall, as expected



^{218}Po: uniform, as expected



VII. Liquid Purification

Take Home:

- Adsorption filters
- Distillation techniques

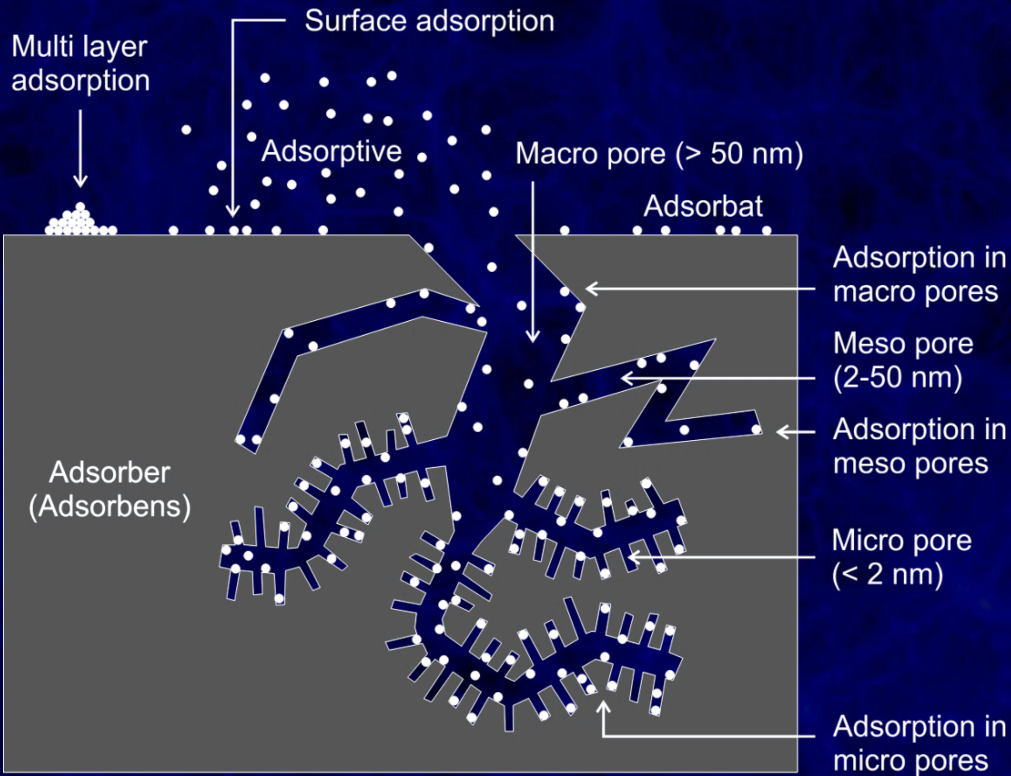
Adsorption

Great for

- All kinds of purifications
- Rn free air

Fails if

- binding energies too similar (Ar/N_2, O_2/N_2)
- carrier gas stronger bound than contamination (Kr in Xe)
- adsorber emanates more than adsorbs (Rn)

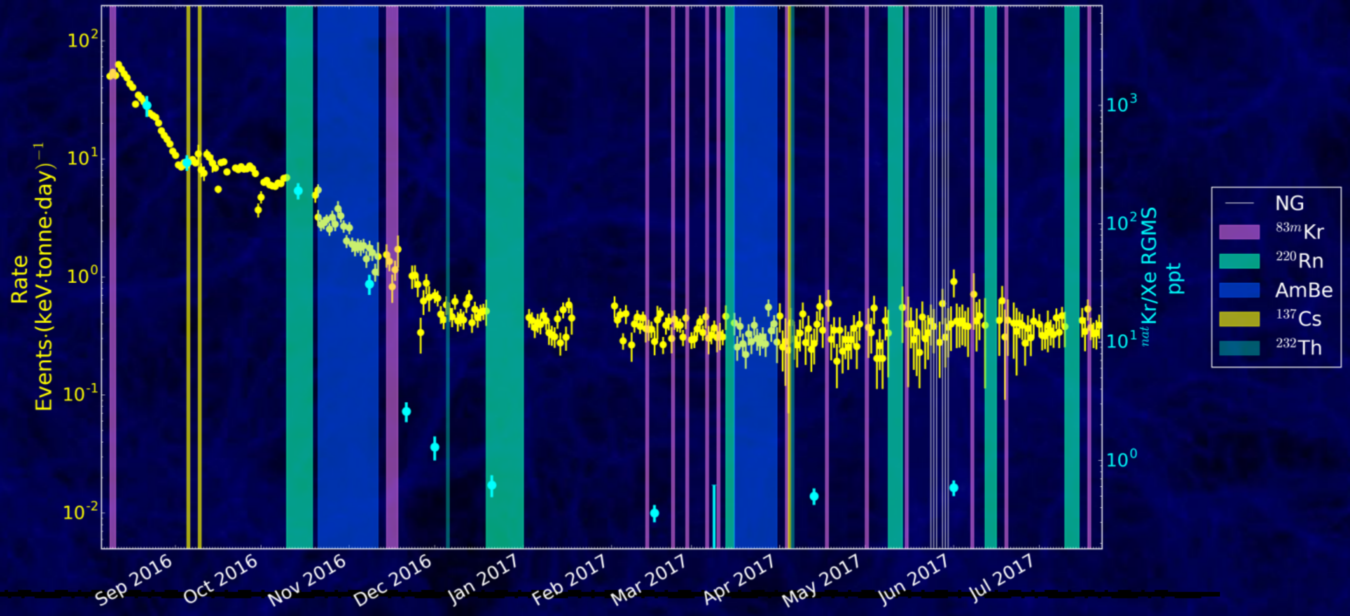


Kr Distillation (^{85}Kr)

Commercial Xe: >10 ppb Kr/Xe

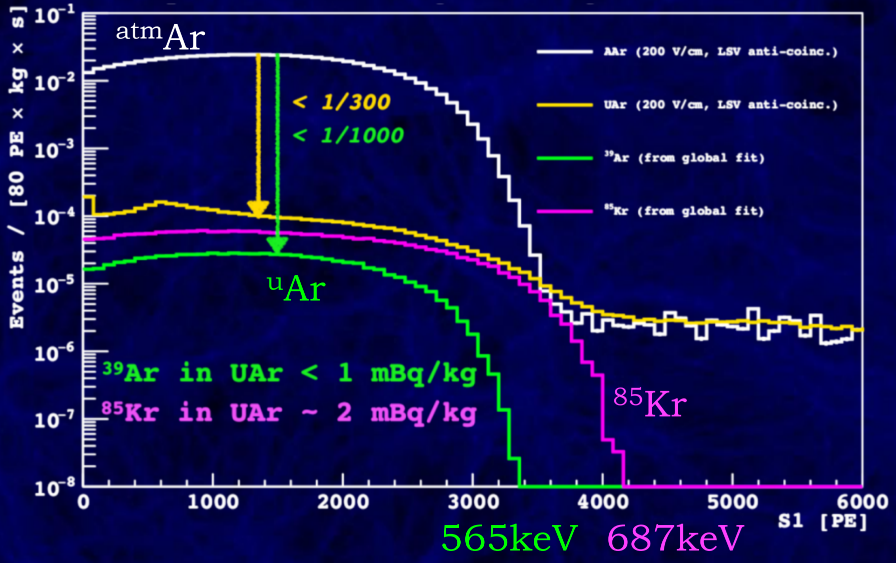
XENON1T requirement 0.2 ppt

5.5 m distillation column, 6.5 kg/h throughput



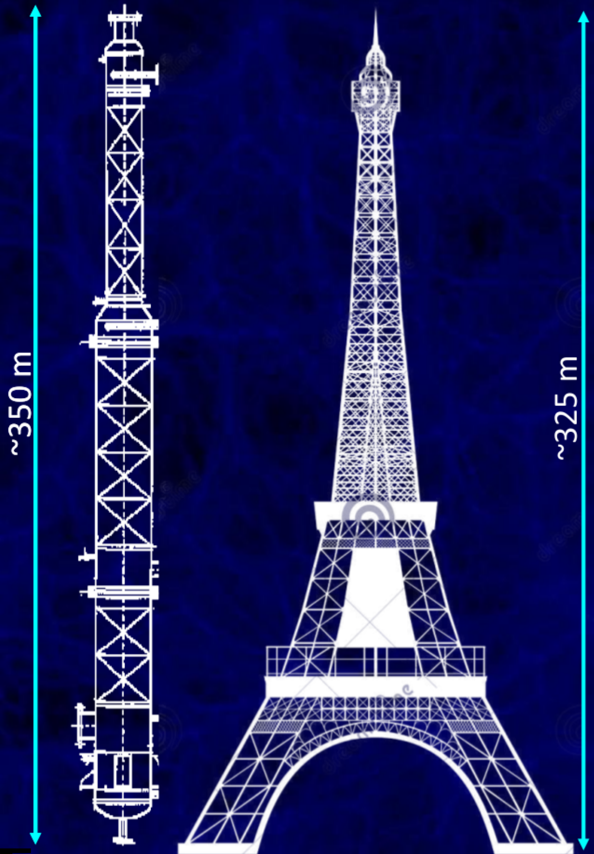
Isotopic Separation for DarkSide

- ^{atm}Ar contains too much $_{39}Ar$
- $^{underground}Ar$ from CO_2 well better:



DarkSide 1510.00702

- "Aria" column for isotopic separation



Andrew Renshaw UCLA 2018

Putting all together, e.g. LZ

Intrinsic Contamination Backgrounds	Mass (kg)	Composite	U early (mBq/kg)	U late (mBq/kg)	Th early (mBq/kg)	Th late (mBq/kg)	Co60 (mBq/kg)	K40 (mBq/kg)	n/yr (inc. S.F. rej.)	ER (cts)	NR (cts) (w/ SF rej.)
Upper PMT Structure	46.7	Y	5.32	0.80	1.08	0.72	0.03	3.81	5.23	0.14	0.001
Lower PMT Structure	71.7	Y	2.62	0.24	0.41	0.30	0.00	1.33	6.57	0.08	0.001
R11410 3" PMTs	91.9	Y	71.63	3.20	3.12	2.99	2.91	15.41	81.83	1.47	0.013
R11410 PMT Bases *	2.8	Y	369.62	75.87	38.91	33.07	0.97	50.58	25.25	0.37	0.003
R8778 2" PMTs	6.1	Y	138.02	59.39	16.93	16.90	16.25	412.67	52.98	0.13	0.008
R8520 Skin 1" PMTs	2.1	Y	62.17	5.29	4.91	4.85	24.44	336.60	53.71	0.02	0.008
R8520 Skin PMT Bases *	0.2	Y	212.95	108.46	42.19	37.62	2.23	123.61	3.62	0.00	0.000
PMT Cabling	62.5	Y	5.81	7.05	1.24	1.62	0.01	6.30	0.75	0.88	0.000
TPC PTFE	184.0	N	0.02	0.02	0.03	0.03	0.00	0.12	22.54	0.06	0.008
Grid Wires	0.18	N	1.20	0.27	0.33	0.49	1.60	0.40	0.00	0.00	0.000
Grid Holders	92.3	Y	2.86	0.83	0.94	0.82	1.42	2.82	20.71	0.97	0.008
Field Shaping Rings	82.5	Y	5.49	1.14	0.72	0.65	0.00	2.00	41.04	0.98	0.016
TPC Sensors	4.45	Y	21.17	5.04	1.87	1.56	1.36	9.36	4.96	0.02	0.000
TPC Thermometers	0.57	Y	26.57	11.84	5.57	4.31	0.99	462.60	1.79	0.06	0.000
Xe Recirculation Tubing	15.1	Y	0.79	0.18	0.23	0.33	1.05	0.30	0.64	0.00	0.000
HV Conduits and Cables	137.7	Y	3.6	2.3	0.6	0.8	1.4	2.5	26.5	0.05	0.006
HX and PMT Conduits	199.6	Y	3.36	0.48	0.48	0.58	1.24	1.47	5.23	0.05	0.001
Cryostat Vessel	2705.0	Y	1.69	0.11	0.40	0.40	0.18	0.54	159.44	0.94	0.017
Cryostat Seals	33.7	Y	75.29	27.56	3.50	5.93	9.76	140.80	127.08	0.54	0.006
Cryostat Insulation	13.8	Y	85.84	36.55	11.44	9.15	3.40	78.87	35.33	0.48	0.004
Cryostat Teflon Liner	26.0	N	0.02	0.02	0.03	0.03	0.00	0.12	3.18	0.00	0.000
Outer Detector Tanks	4299.3	Y	3.28	0.60	0.54	0.57	0.03	4.78	200.65	0.96	0.002
Liquid Scintillator	17640.3	Y	0.01	0.01	0.01	0.01	0.00	0.00	14.28	0.03	0.000
Outer Detector PMTs	204.7	Y	570	470	395	388	0.00	534	7 587	0.01	0.000
Outer Detector PMT Supports	770.0	N	12.35	12.35	4.07	4.07	9.62	9.29	258.83	0.00	0.000
Subtotal (Detector Components)										**8.01**	**0.101**
222Rn (1.63 µBq/kg)										588	-
220Rn (0.08 µBq/kg)										99	-
natKr (0.015 ppt g/g)										24.5	-
natAr (0.45 ppb g/g)										2.47	-
210Bi (0.1 µBq/kg)										40.0	-
Laboratory and Cosmogenics										4.3	0.06
Fixed Surface Contamination										0.19	0.39
Subtotal (Non-ν counts)										**787**	**0.55**
Physics Backgrounds											
136Xe 2νββ										67	0
Astrophysical ν counts (pp+7Be+13N)										255	0
Astrophysical ν counts (8B)										0	0**
Astrophysical ν counts (Hep)										0	0.21
Astrophysical ν counts (diffuse supernova)										0	0.05
Astrophysical ν counts (atmospheric)										0	0.46
Subtotal (Physics backgrounds)										322	0.72
Total										1,090	1.27
Total (with 99.5% ER discrimination, 50% NR efficiency)										5.44	0.63
										6.08	

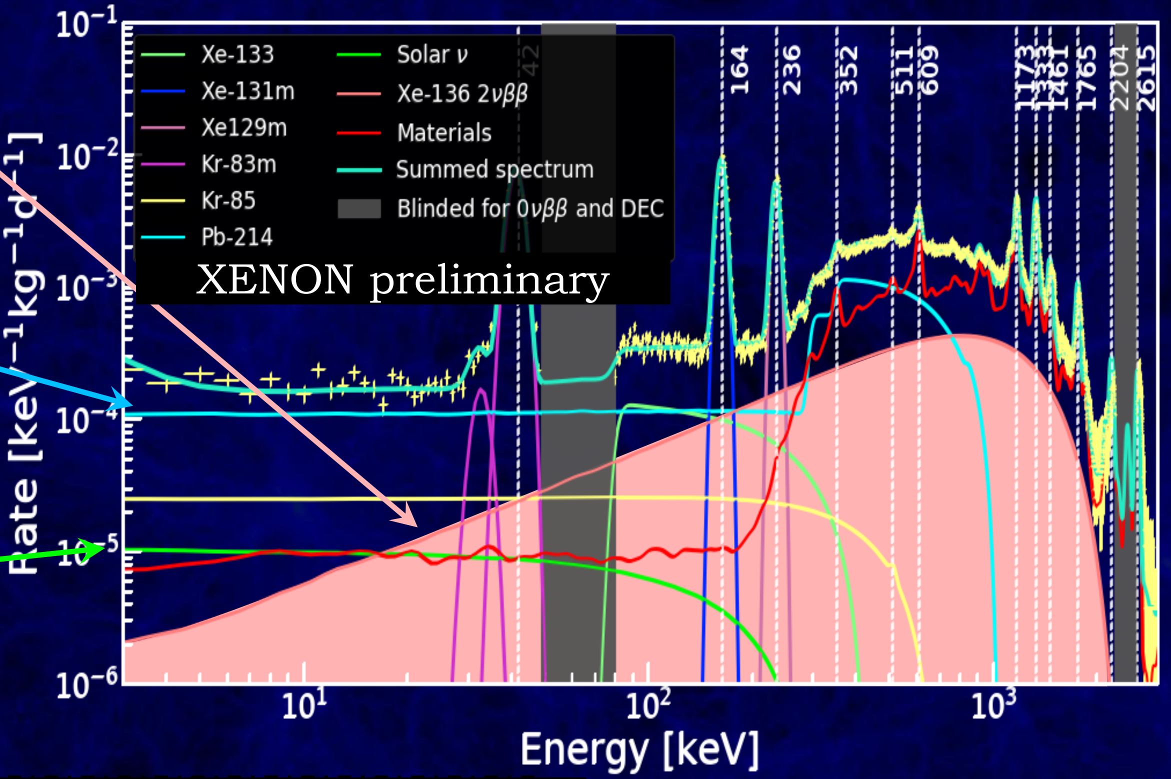
Kimberly Palladino, TAUP 2017

XENON1T Background Spectrum

overall, 2ν2β important ($t_{1/2}$~10^{21} years!)

^{222}Rn the usual challenge

some sensitivity at low energies to pp solar ν

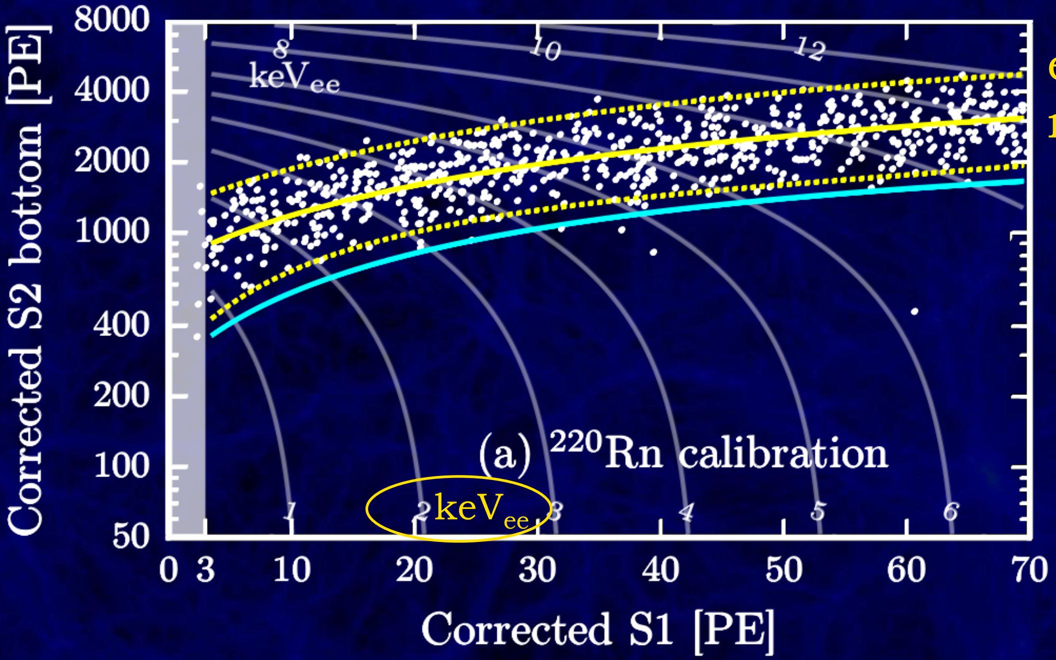


VIII. Discrimination

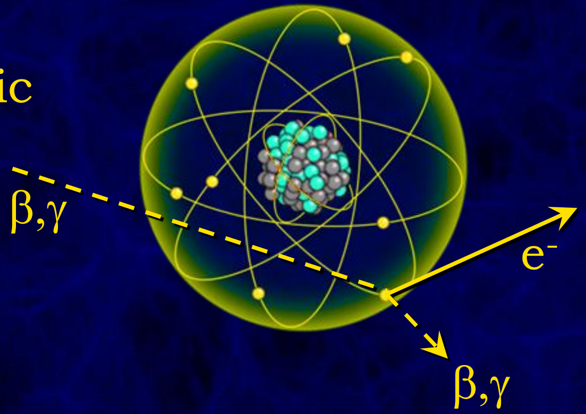
Take Home:

- You should be able to tell signal from at least some background

ER/NR Discrimination (SR0)

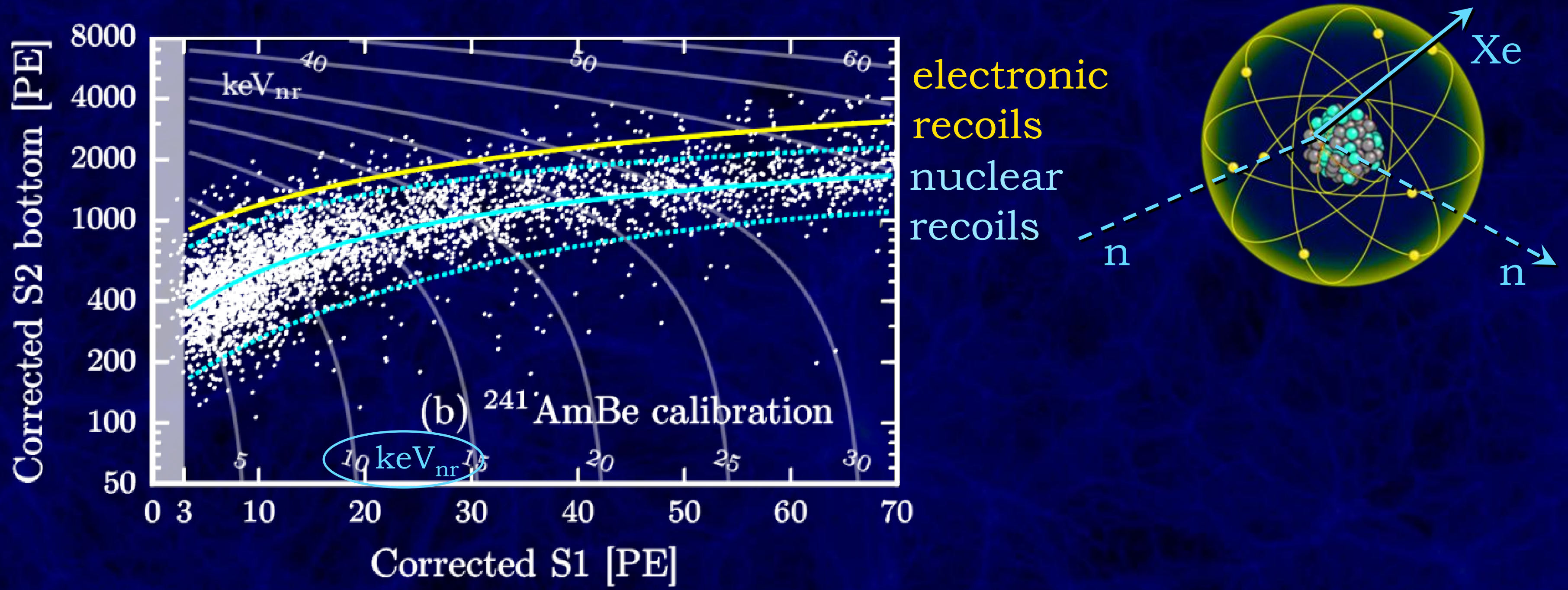


electronic recoils



XENON 1705.06655

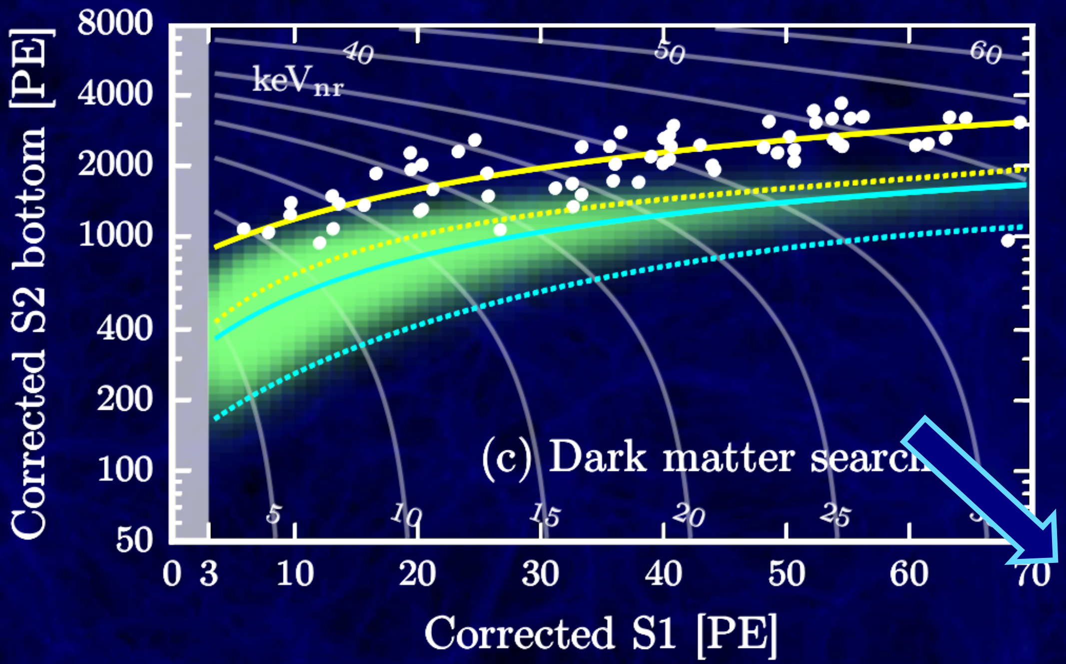
ER/NR Discrimination (SR0)



XENON 1705.06655

Dark Matter Search (SR0)

First science data, 34 live days:

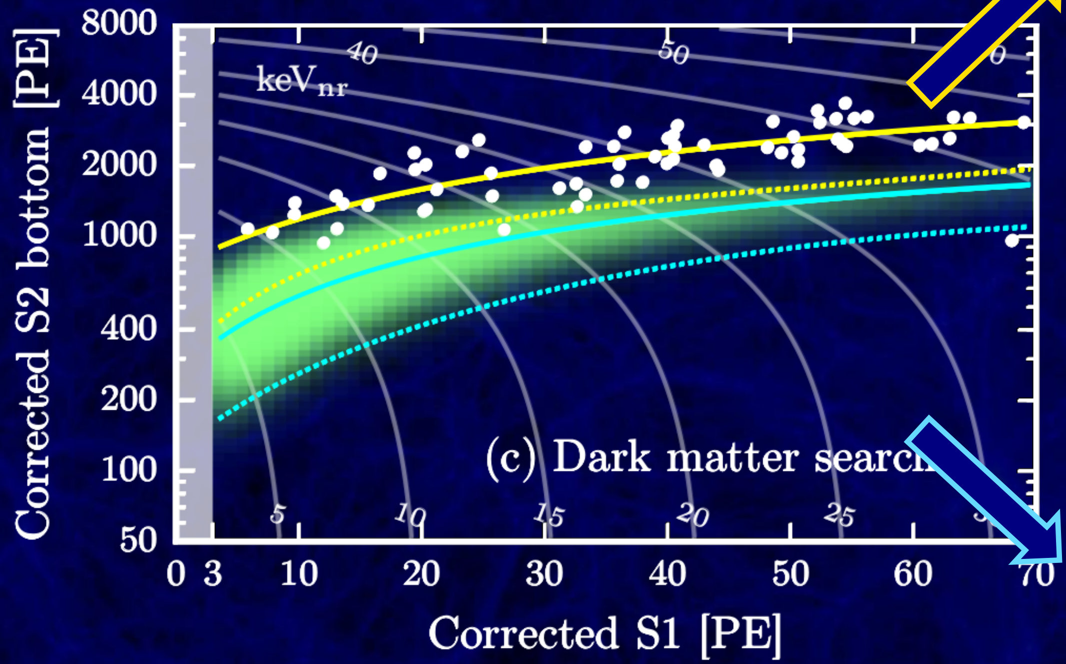


- WIMPs, SI & SD!
- iDM and other EFT
- GeV DM

XENON 1705.06655

Ample Science from "Background"

First science data, 34 live days:



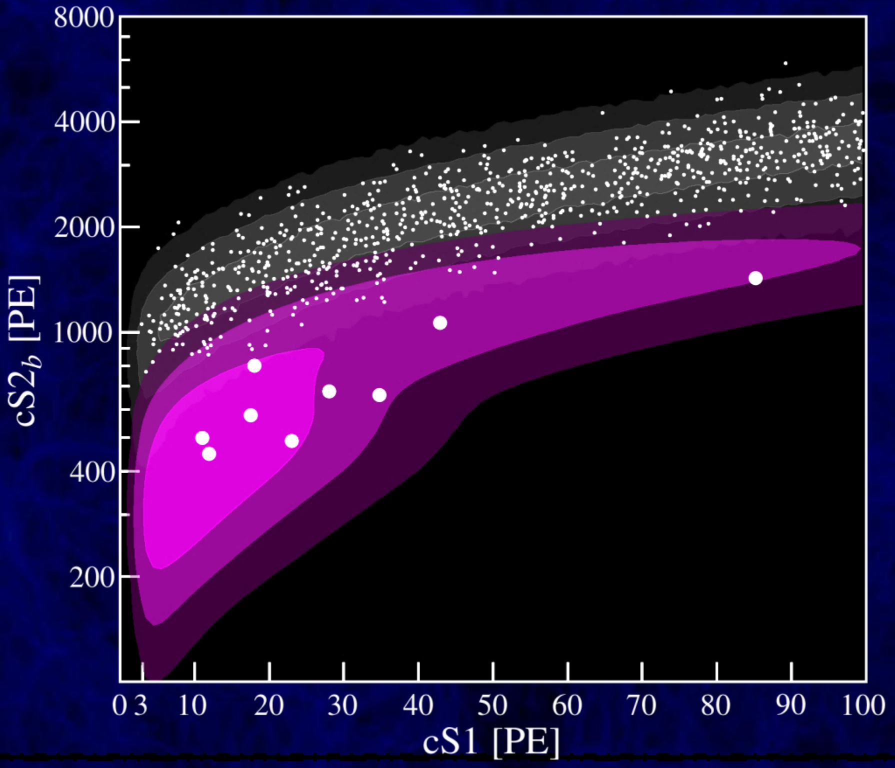
- leptophilic/axial-vector WIMPs, MeV DM
- Migdal & Bremsstrahlung
- inelastic scatter, miDM
- ALPs, dark photons, SuperWIMPs, solar axions, luminous DM, mirror DM
- sterile ν
- DEC on ^{124}Xe

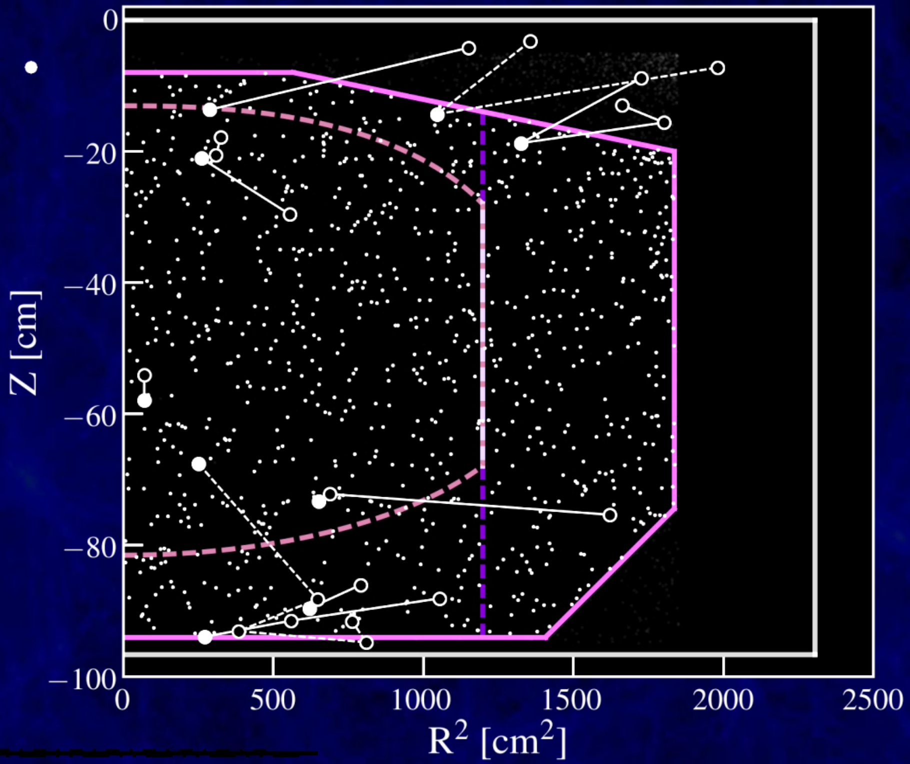
- WIMPs, SI & SD!
- iDM and other EFT
- GeV DM

too many XENON100 references to list here

Distinguish Neutrons: Multiplicity

Neutrons look different from WIMPs!



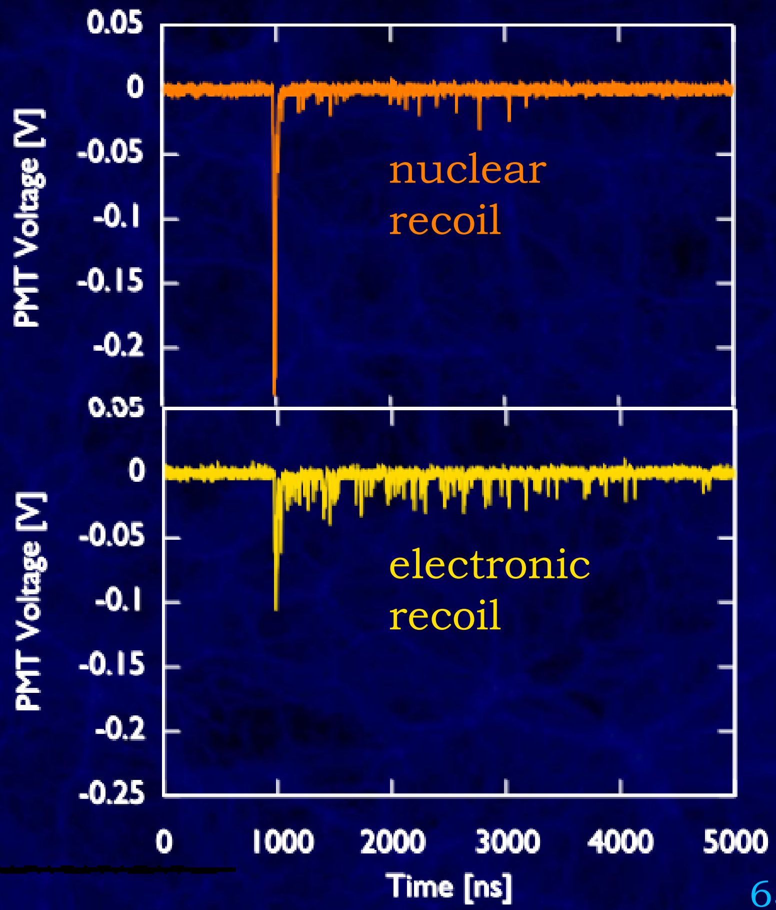


Argon: Pulse Shape Discrimination

Ar_2^* dimer
singlet state decays with 6ns,
triplet state with 1.5µs.
e.g. in DEAP3600:

Excellent performance:
$>10^6$: 1 discrimination

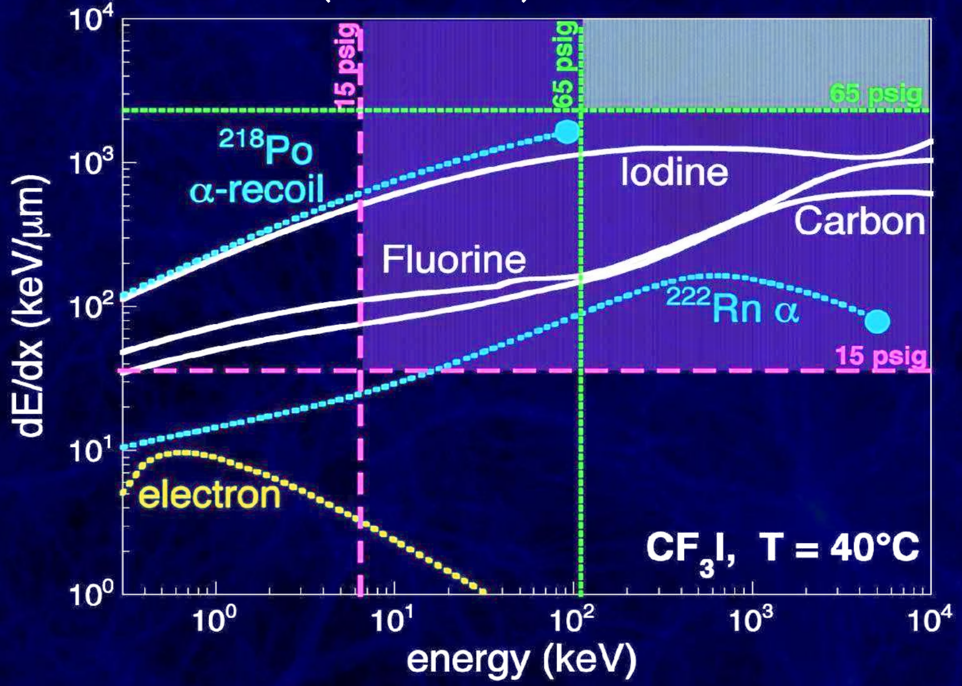
But high energy threshold
~ 40 keV_{nr} (DarkSide-50)



Berta Beltran TAUP2015

Bubble chambers, e.g. PICO@SNOLAB

Detector blind ($<10^{-10}$) to ER!



H. Lippincott TAUP2013

(+Acoustic alpha-NR discrimination)

IX. Coincidence & Redundancy

Take Home:

- Coincidence extremely powerful to fight accidental backgrounds
- Redundancy required to overcome unexpected backgrounds

Cowan & Reines 1956

Discover $\bar{\nu}_e$ via $\bar{\nu}_e + p \to n + e^+$
in triple coincidence:
two 511keV & delayed n capture

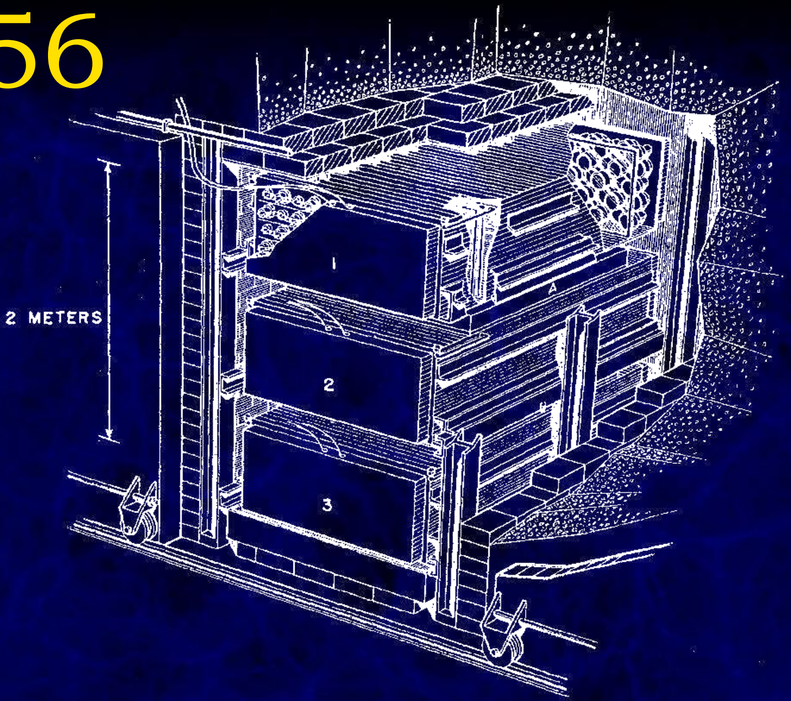
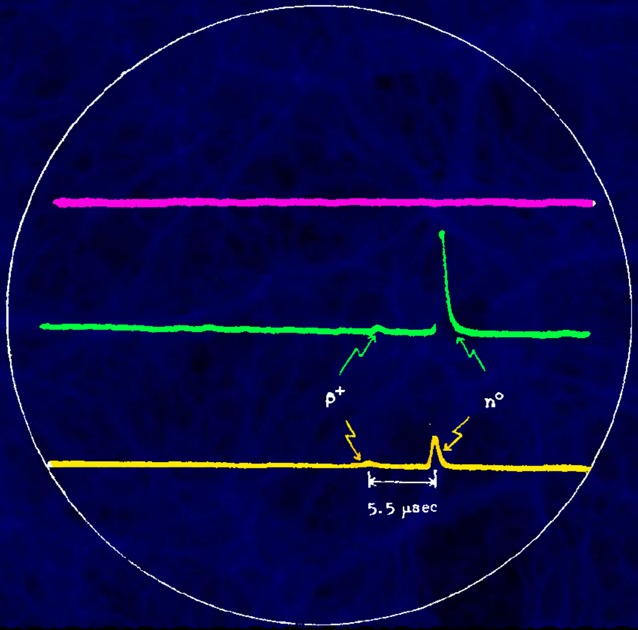


FIG. 2. Sketch of detectors inside their lead shield. The detector tanks marked 1, 2, and 3 contained liquid scintillator solution which was viewed in each tank by 110 5-in. photomultiplier tubes. The white tanks contained the water-cadmium chloride target, and in this picture are some 28 cm deep. These were later replaced by 7.5-cm deep polystyrene tanks, and detectors 1 and 2 were lowered correspondingly. A drip tank, not shown here, was later set underneath tank 3 in the event of a leak. Because of the weight it was necessary to move the lead doors with a hydraulic system.

Cowan & Reines 1956

Discover $\bar{\nu}_e$ via $\bar{\nu}_e + p \to n + e^+$
in triple coincidence:
two 511keV & delayed n capture



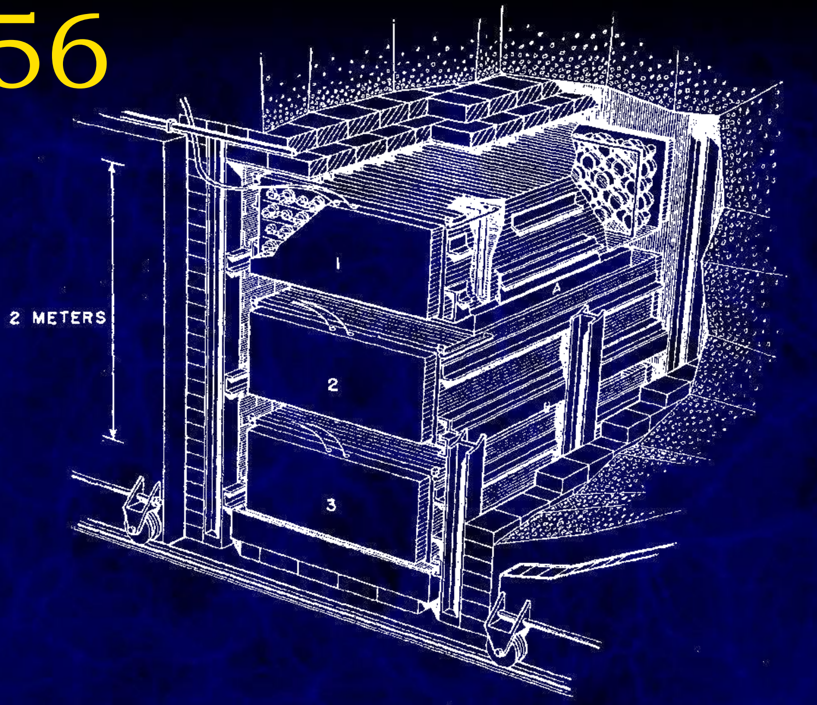
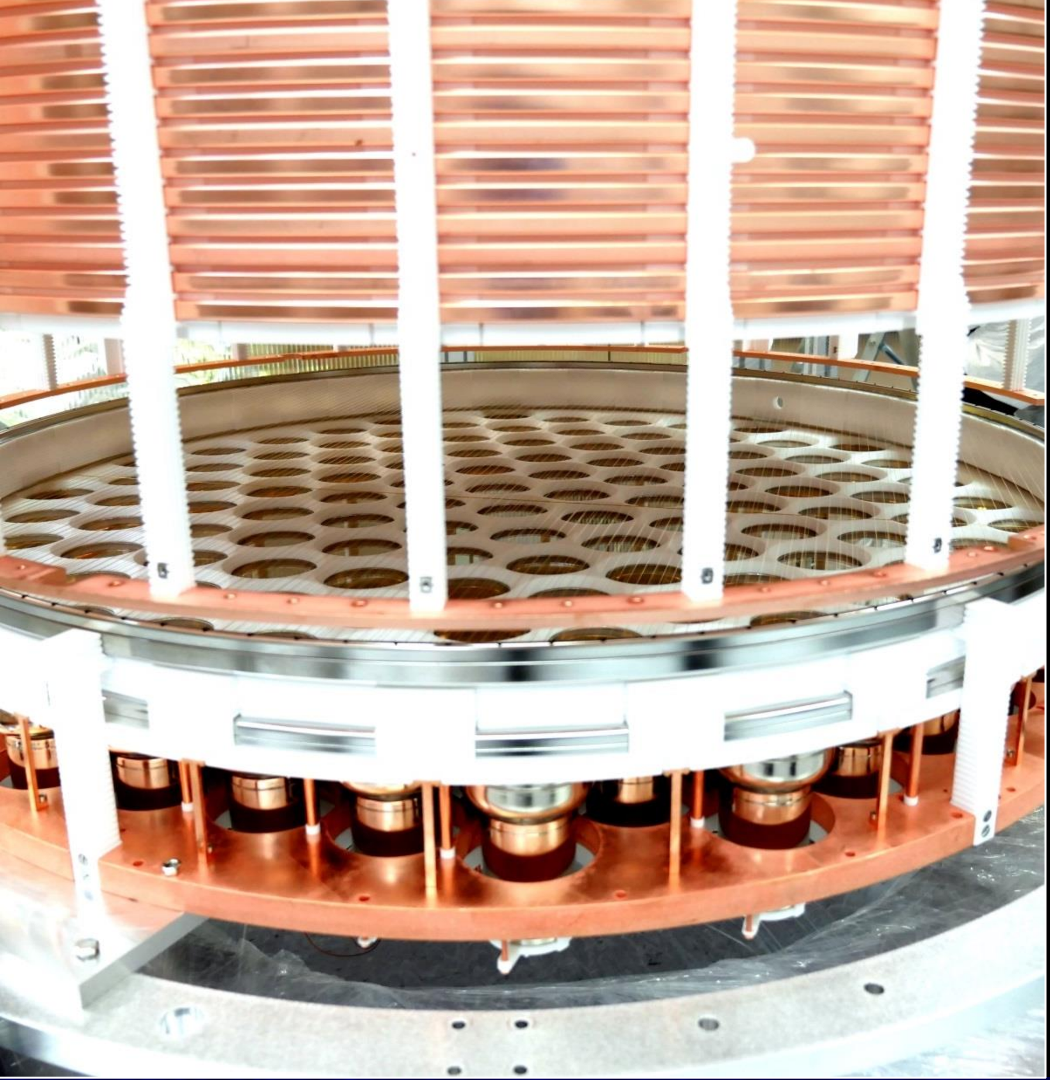
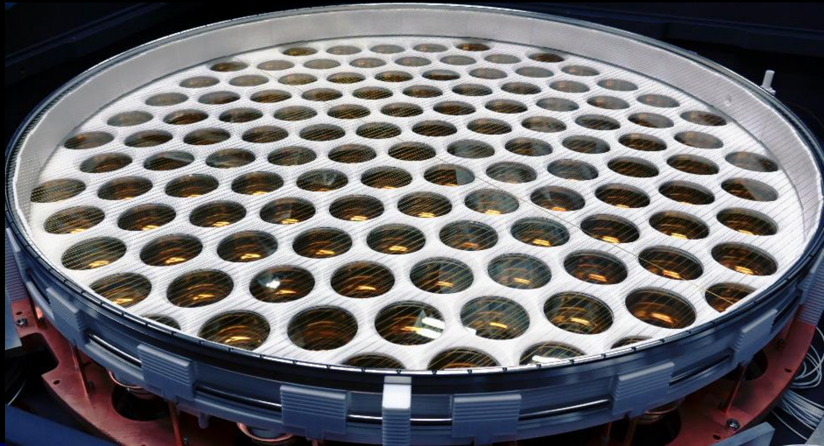


FIG. 2. Sketch of detectors inside their lead shield. The detector tanks marked 1, 2, and 3 contained liquid scintillator solution which was viewed in each tank by 110 5-in. photomultiplier tubes. The white tanks contained the water-cadmium chloride target, and in this picture are some 28 cm deep. These were later replaced by 7.5-cm deep polystyrene tanks, and detectors 1 and 2 were lowered correspondingly. A drip tank, not shown here, was later set underneath tank 3 in the event of a leak. Because of the weight it was necessary to move the lead doors with a hydraulic system.

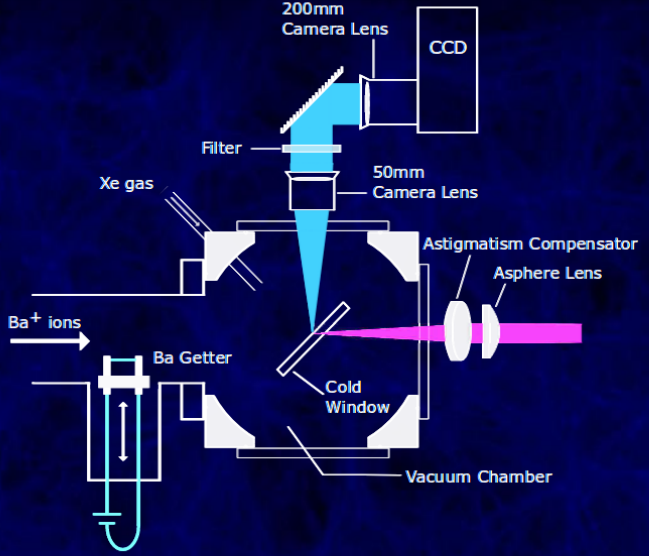


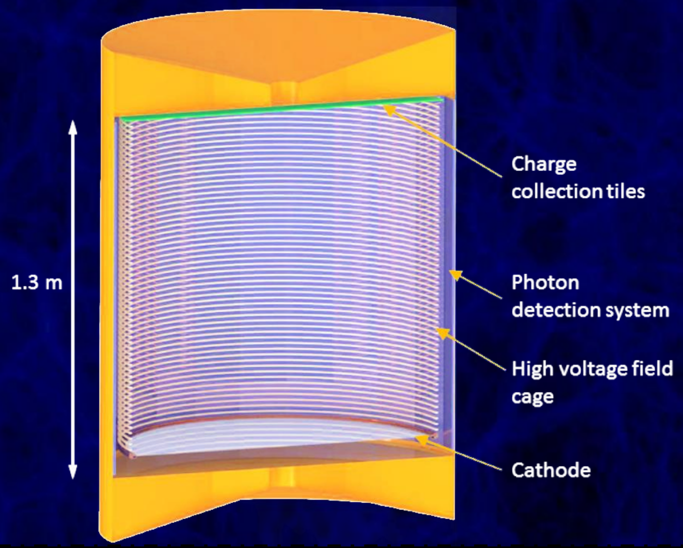


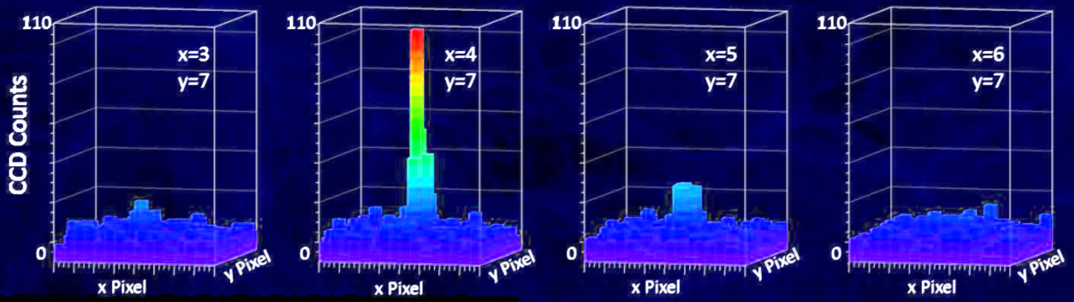
Ba Tagging in nEXO

Add coincidence to $0\nu\beta\beta$ signal:

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







nEXO 1806.10694.

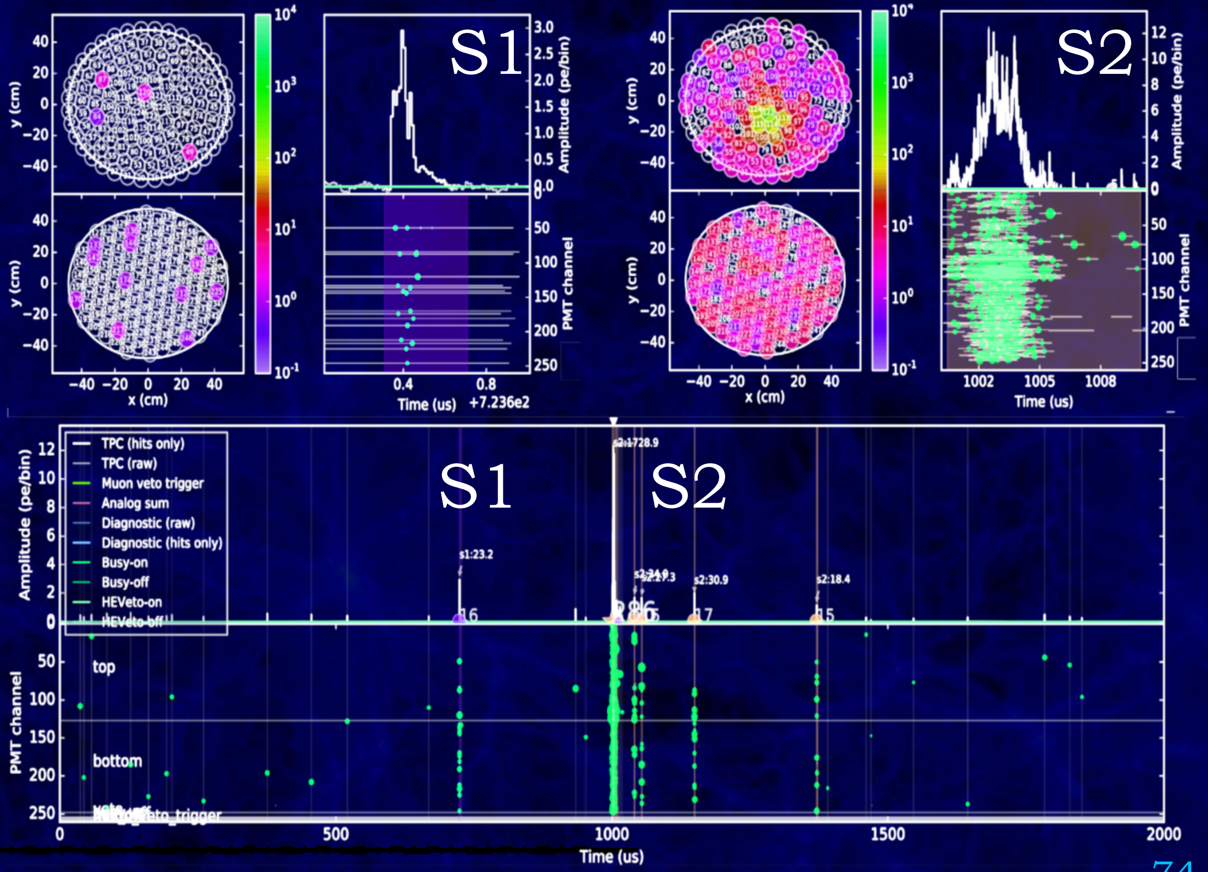
Sensitivity Limitations

No recent dark matter search was limited by a priori known radioactive backgrounds.
Instead: detector artefacts

The Secret of Success

Redundant event information: can fight detector artefacts

(collect ~2.5MB per event)



Topologies

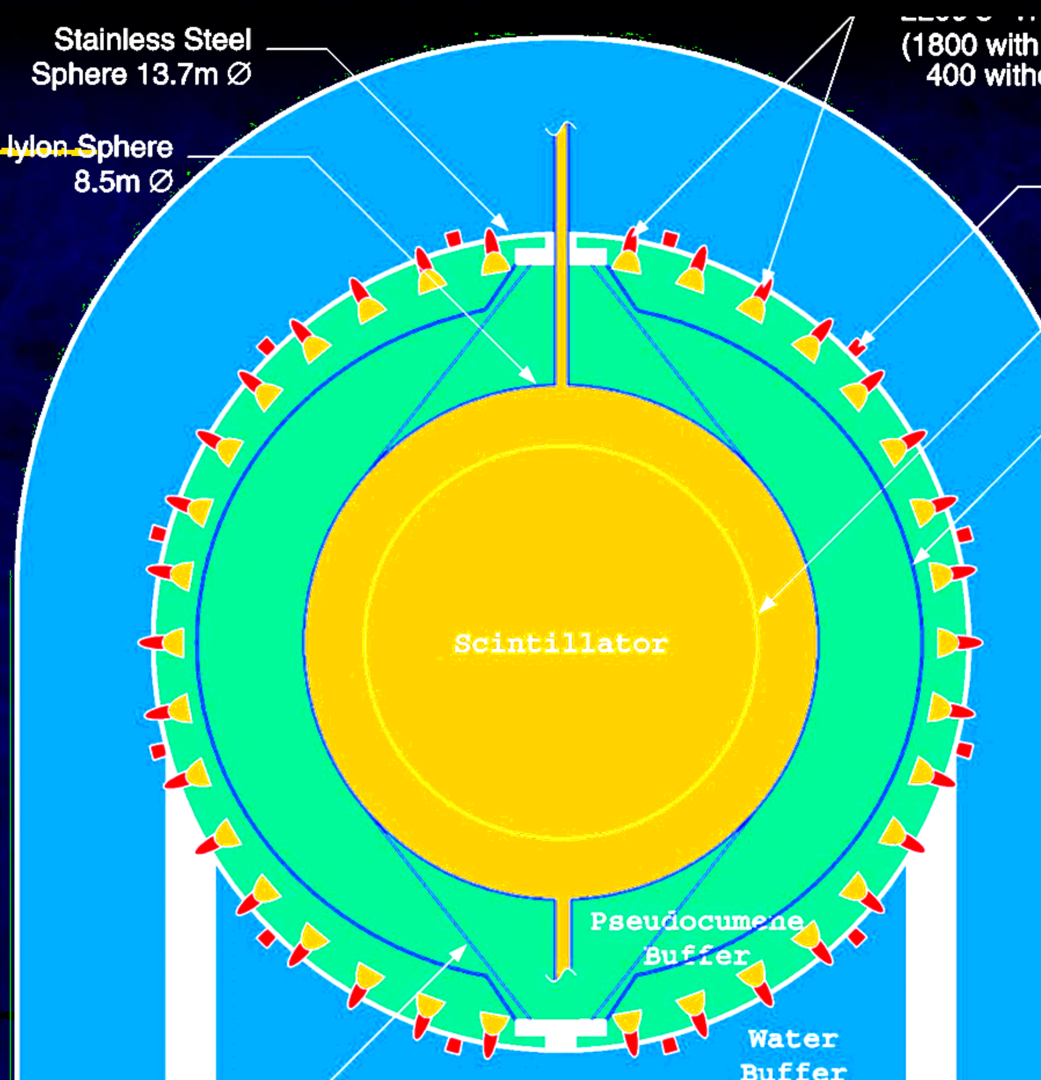
$\mu + {}^{12}C \rightarrow \mu + n + {}^{11}C$

(250μs)

capture
2.2MeV

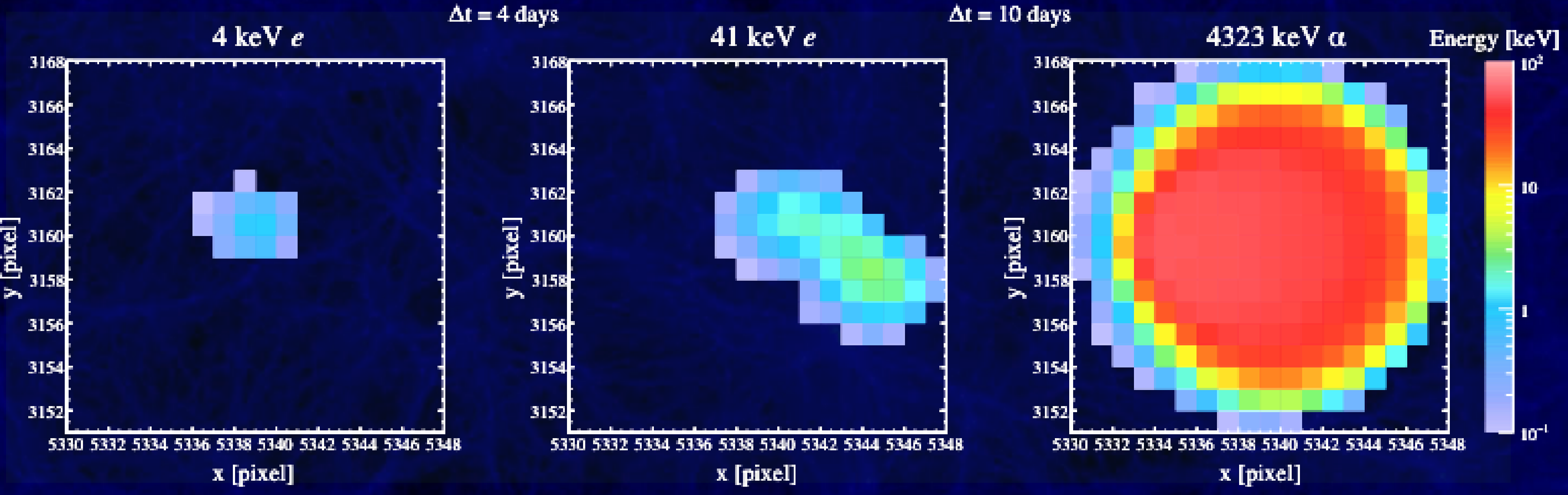
$(t_{1/2}=20\text{min})$

${}^{11}B + e^{+} + \nu_e$



Topologies with DAMIC CCD

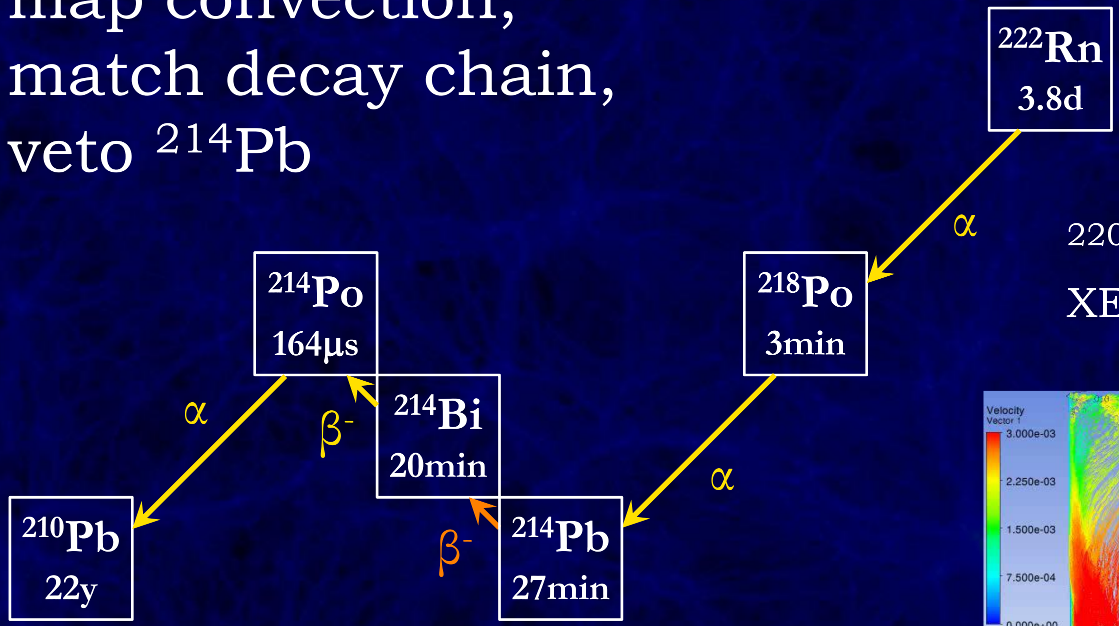
$$^{210}\mathrm{Pb} \xrightarrow{(t_{1/2}=22y)} \beta + {}^{210}\mathrm{Bi} \xrightarrow{(t_{1/2}=5d)} \beta + {}^{210}\mathrm{Po} \xrightarrow{(t_{1/2}=138d)} \alpha$$



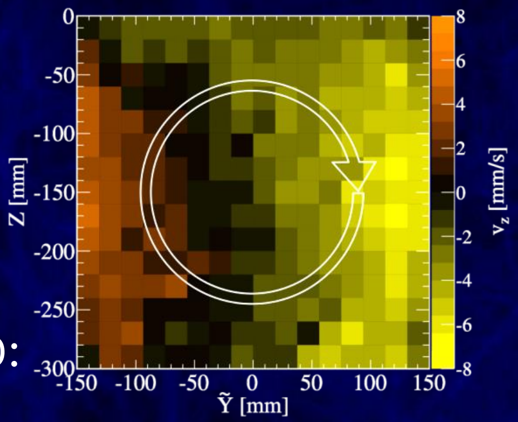
Alvaro Chavarria UCLA 2018

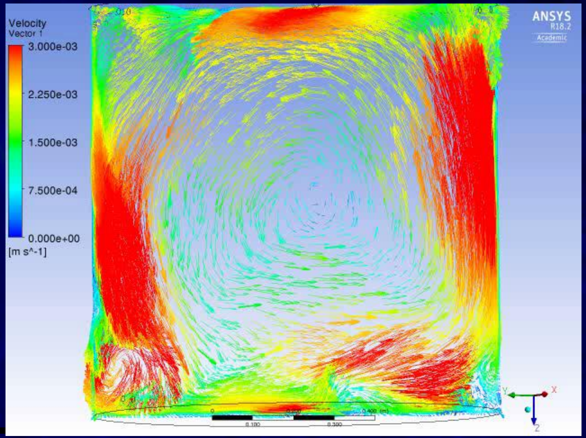
XENON1T: ^{222}Rn Veto

map convection,
match decay chain,
veto ^{214}Pb



^{220}Rn in XENON100:





XENON1T Simulation

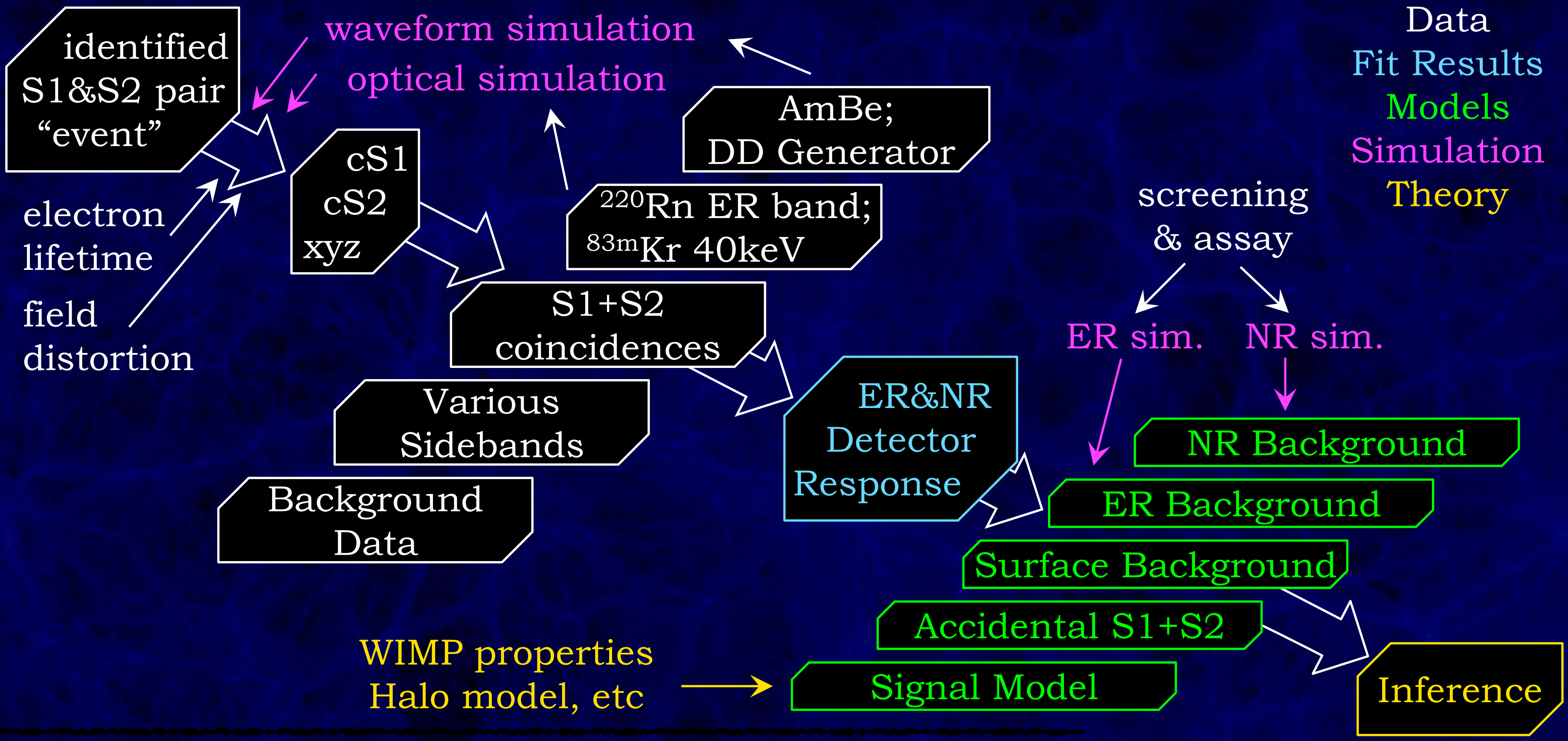
XENON 1611.03585

X. Full Modeling

Take Home:

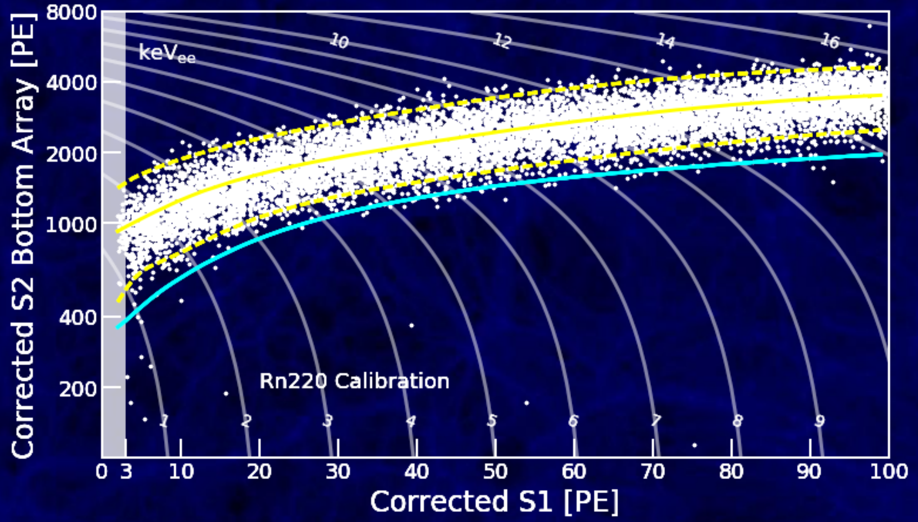
- Modeling your background is better than just cutting them

XENON1T Analysis, Simplified

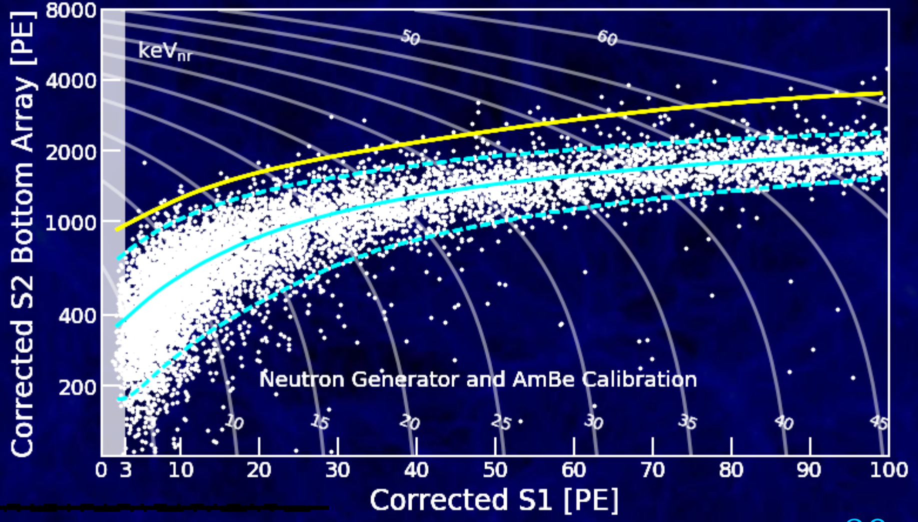


ER & NR Band calibration

ER: ^{220}Rn

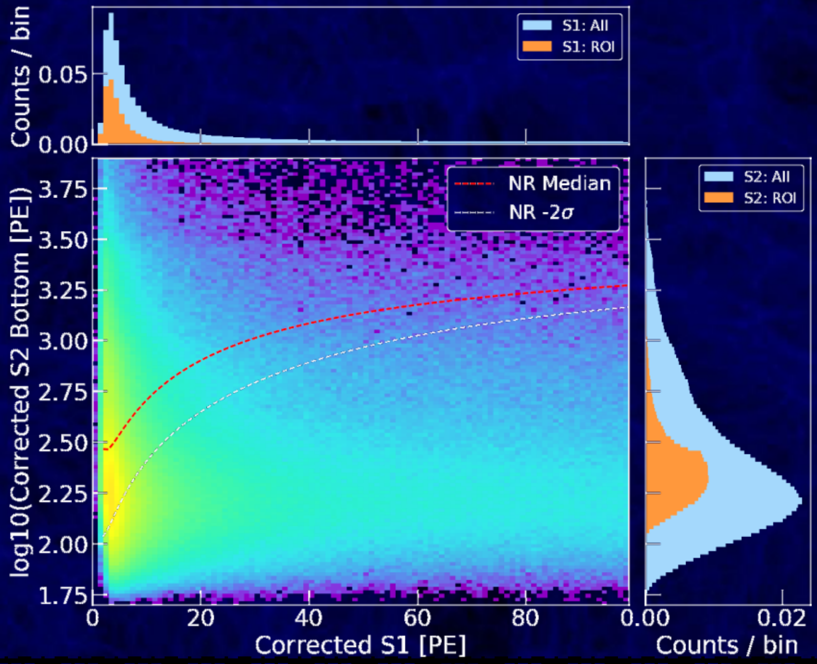


NR: DD generator
& $^{241}AmBe$

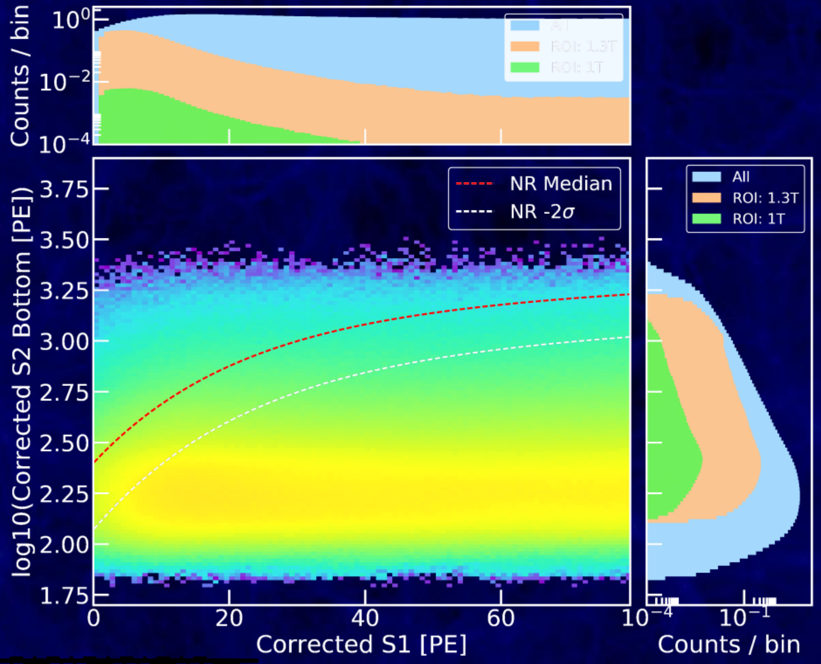


Background Models

Accidental coincidences:
Pairs of random S1 & S2s



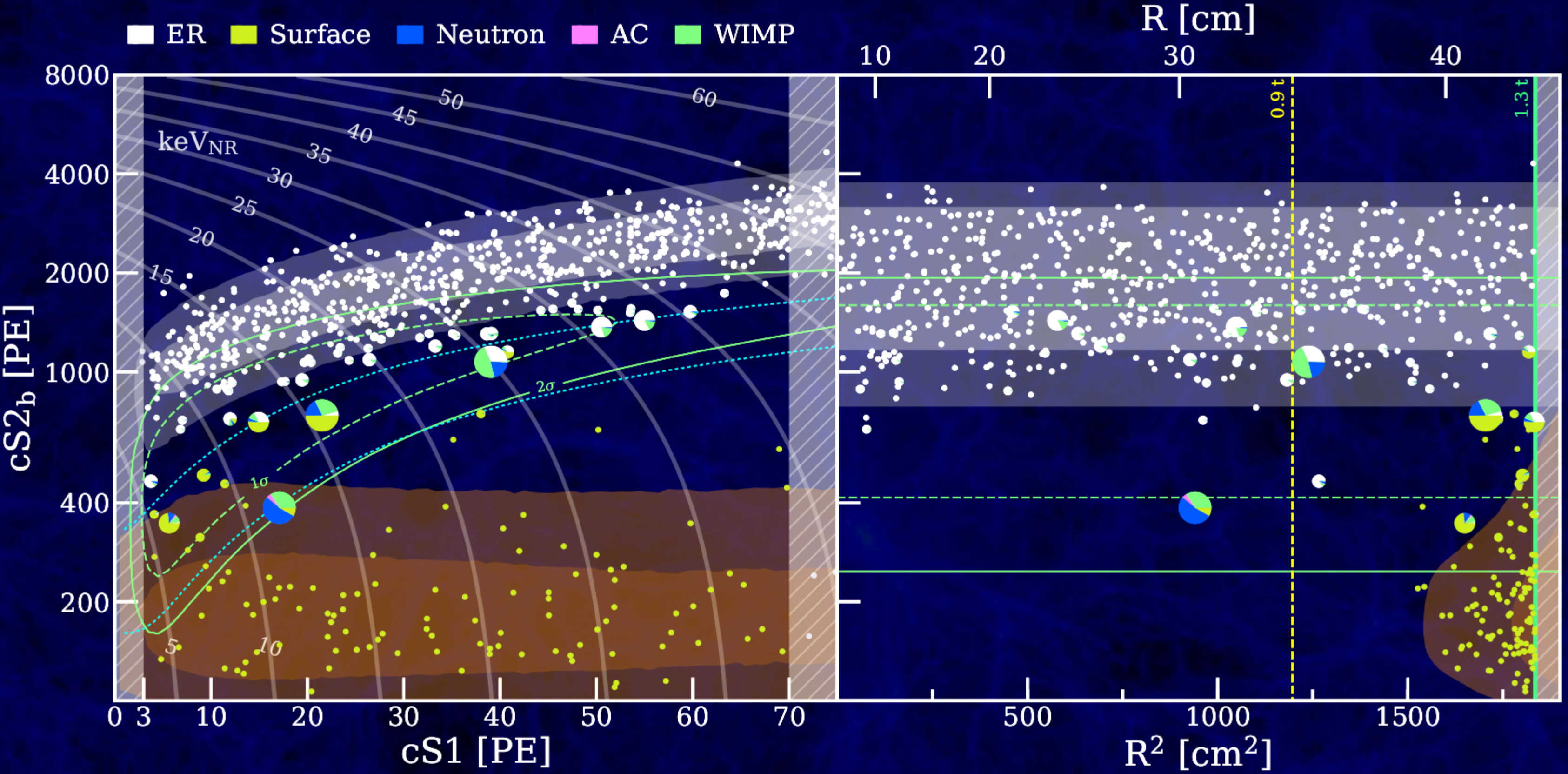
Wall background:
Tails of events on Teflon



Blinding & Salting

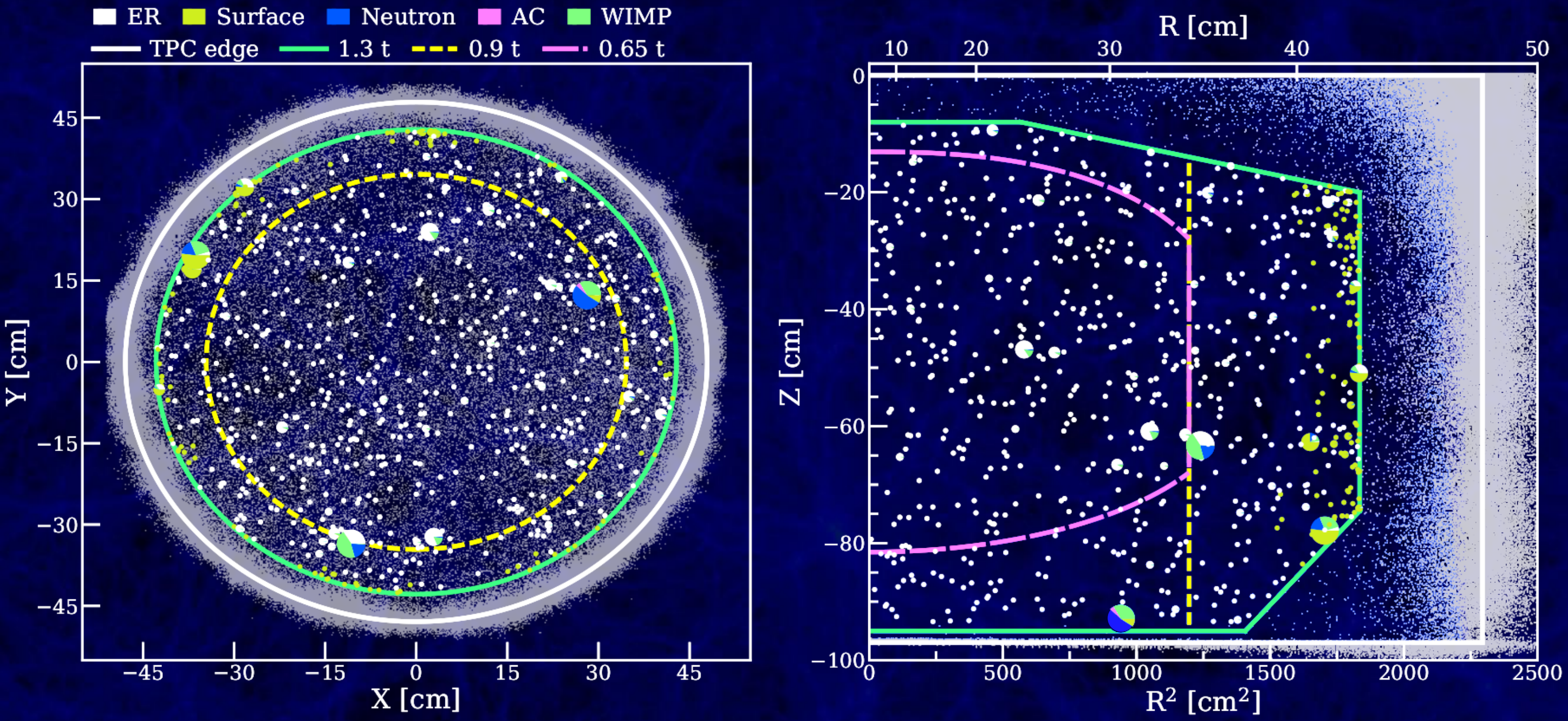
Remember medicine? Design your bias out of the analysis

XENON1T Science Run 1



XENON 1805.12562

XENON1T Science Run 1



XENON 1805.12562

XI. Taking it Further

Take Home:

- Incredibly versatile technologies
- Lots to be creative with