LARGE SCALE UNDERGROUND SCIENCE EXPERIMENTS

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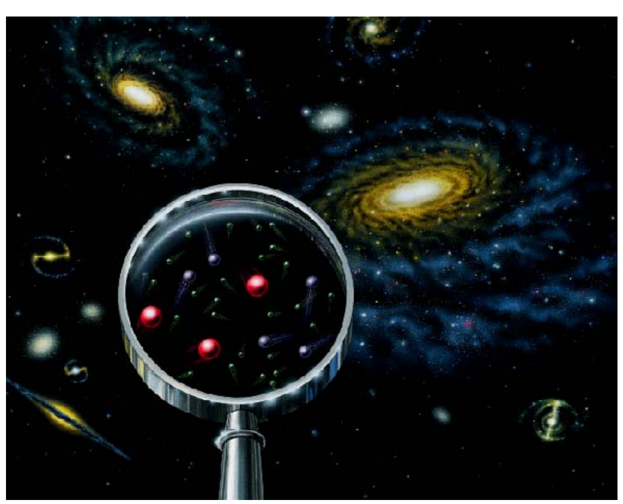
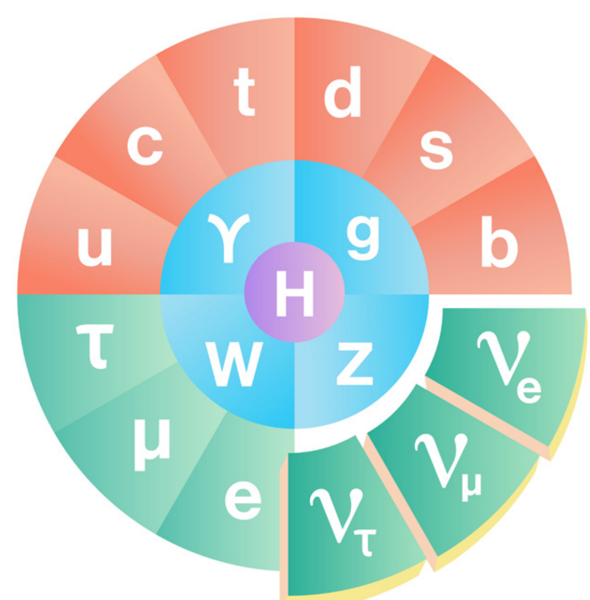
TWO MAJOR QUESTIONS IN ASTRO-PARTICLE PHYSICS

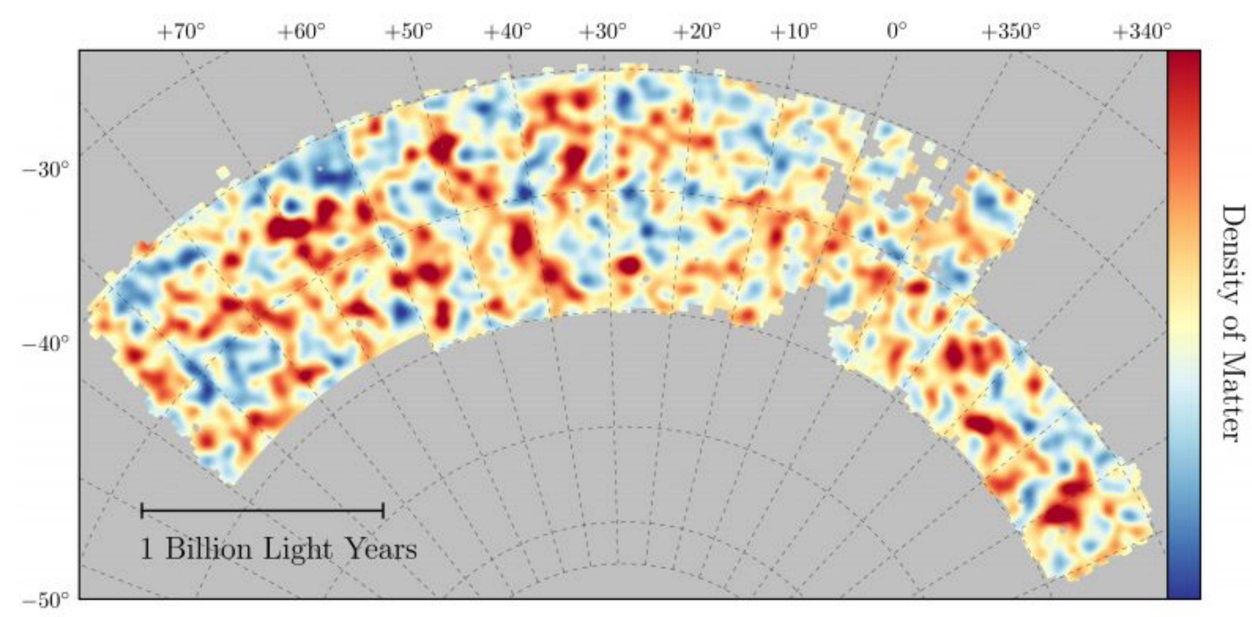
- What is the dark matter in our galaxy made of?
- What is the nature of neutrinos, and their mass?
    - To address these, we build large-scale, ultra-low background experiments, operated in underground laboratories





IN THE DARK…

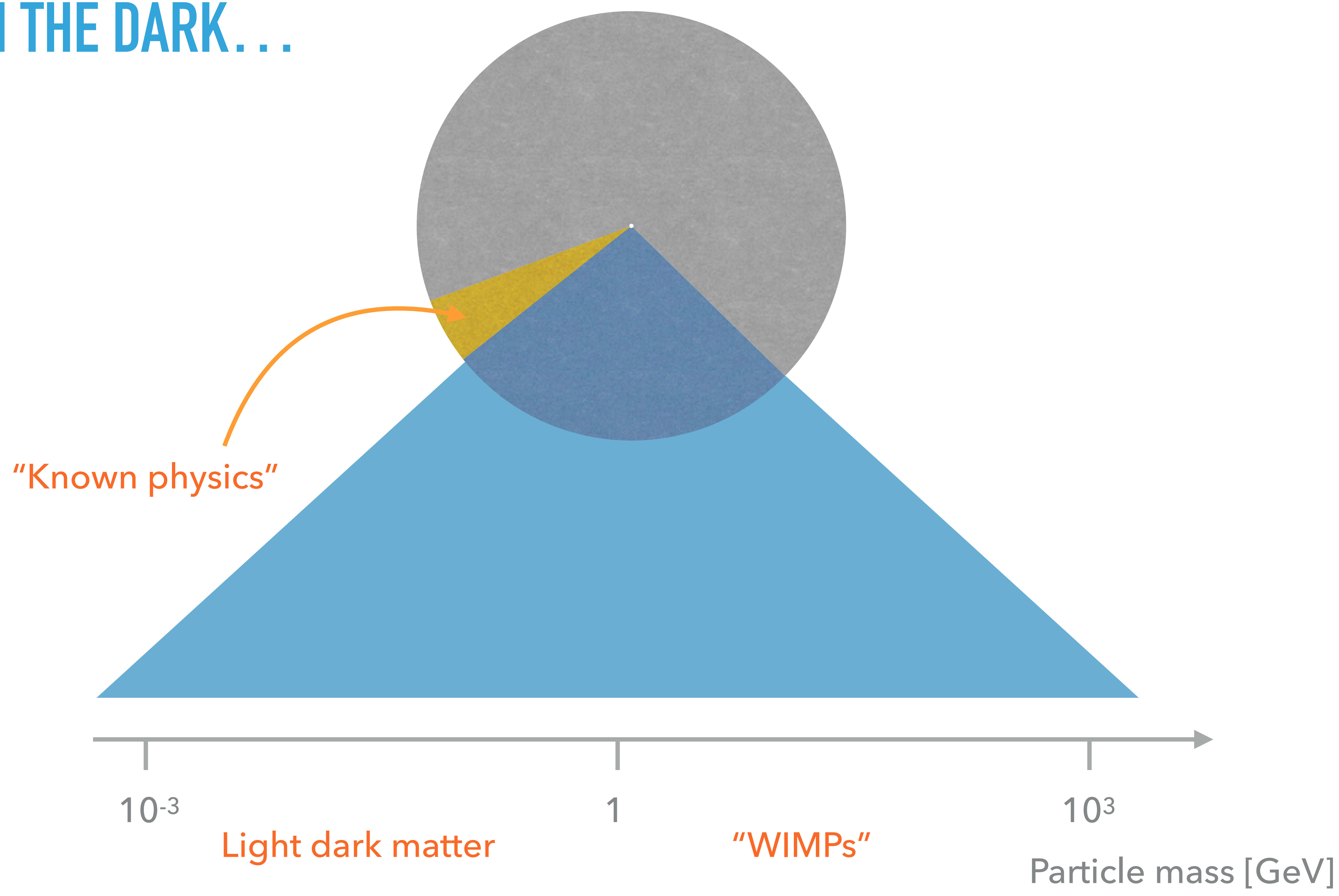
- The evidence for dark matter is overwhelming
  - Early and late cosmology (CMB, LSS)
  - Clusters of galaxies
  - Galactic rotation curves
  - Big Bang nucleosynthesis



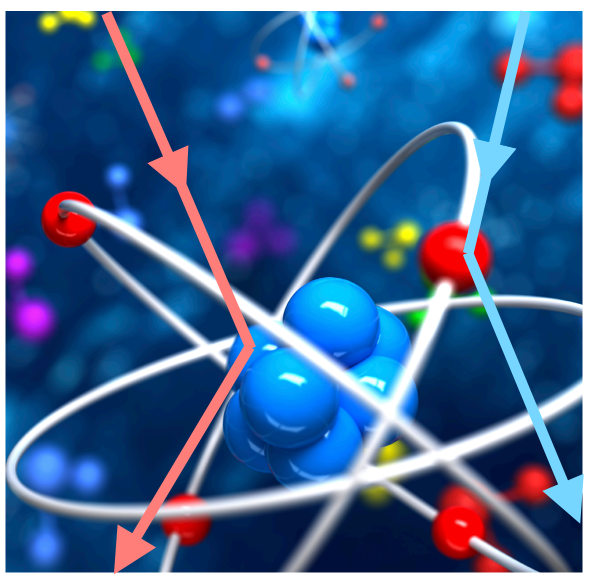
First DES dark matter results, 26×10^6 galaxies

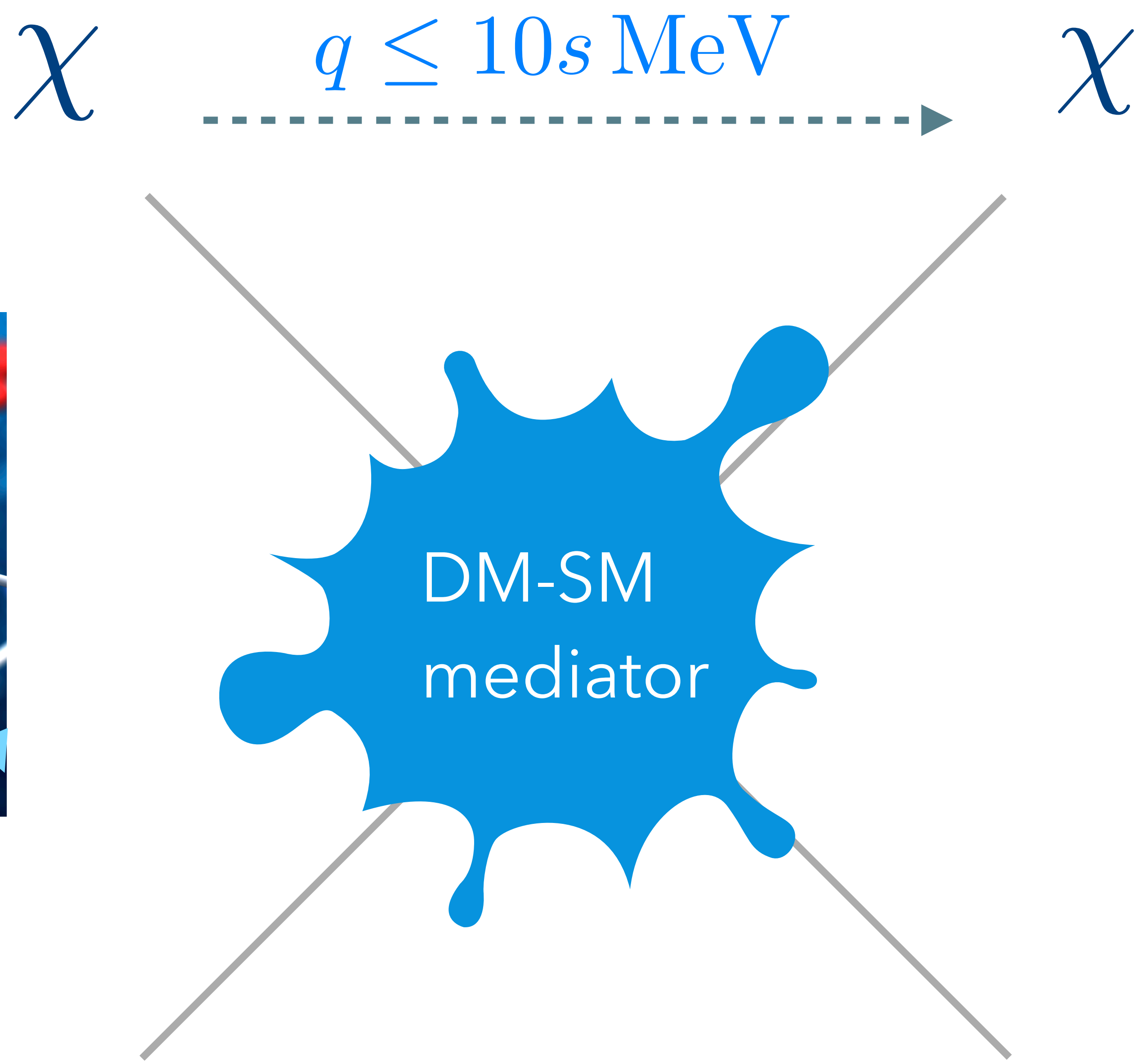
- But - no idea about its composition at the particle level

IN THE DARK…


"Known physics"
10-3
1
10³
Light dark matter
"WIMPs"
Particle mass [GeV]

HOW TO SEE IN THE DARK?





- collisions with electrons in the atomic shell, or absorption of light bosons via the so-called axio-electric effect
- Bremsstrahlung from polarised atoms; e- emission due to so-called Migdal effect

WHAT TO EXPECT IN AN EARTH-BOUND DETECTOR?

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv\, f(v)\, v \frac{d\sigma}{dE_R}$$

Detector physics

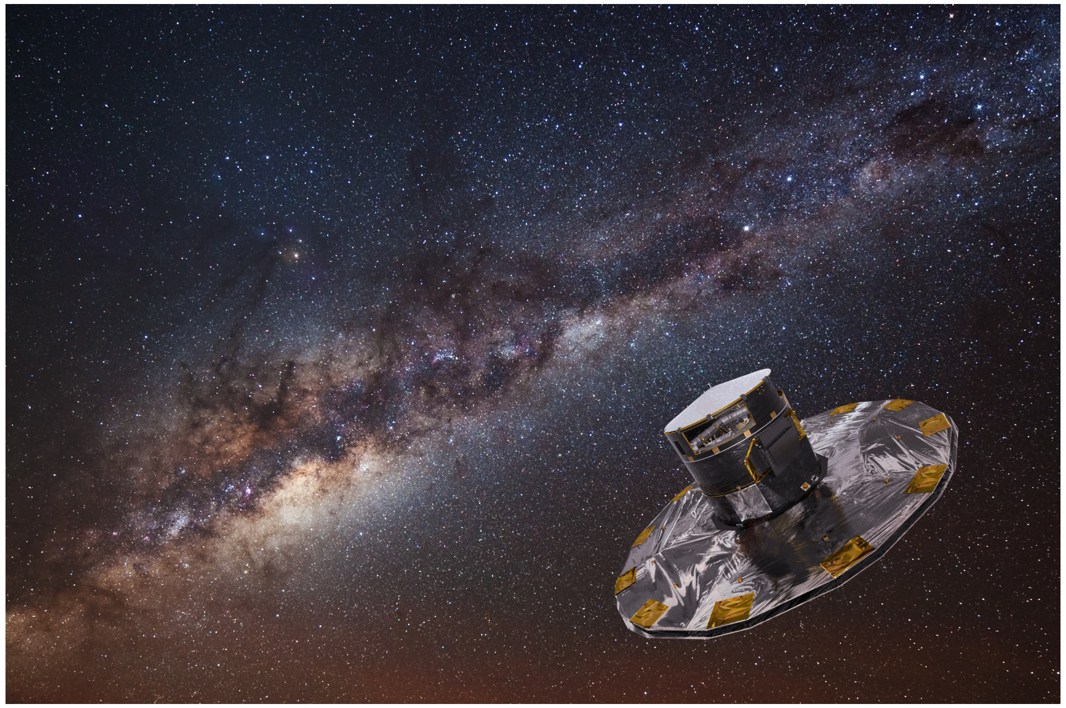
N_N, E_{th}

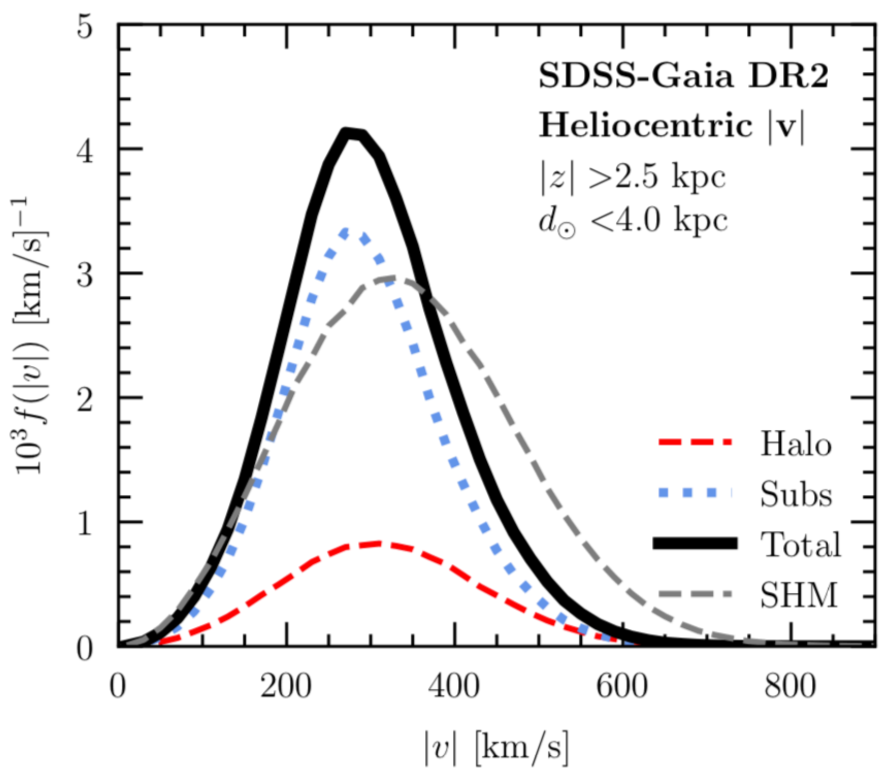
Particle/nuclear physics

$m_W, d\sigma/dE_R$

Astrophysics

$\rho_0, f(v)$





WHAT IS THE DM FLUX ON EARTH?

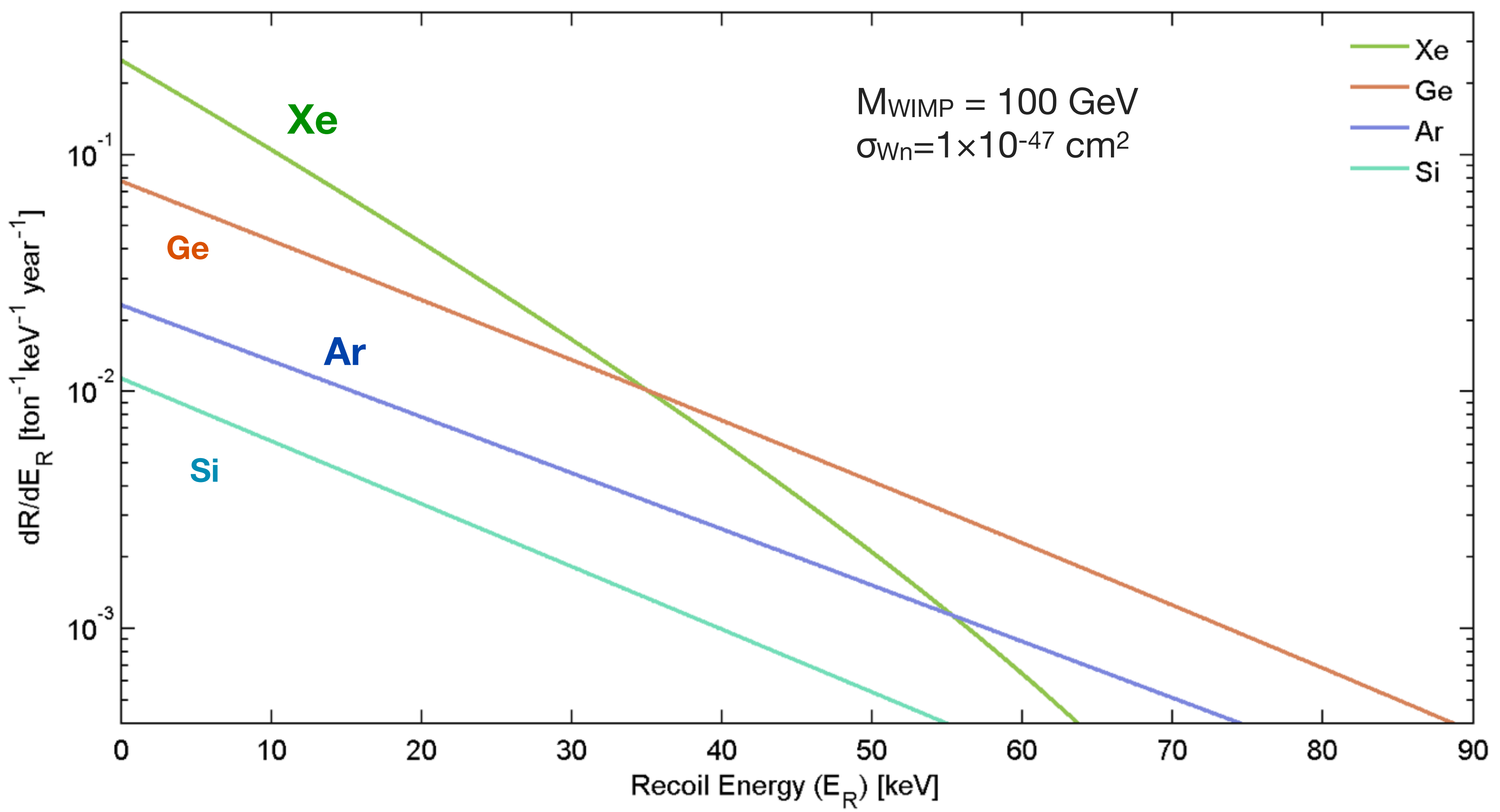
$$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV\,cm^{-3}} = 0.005 - 0.015\,\mathrm{M_\odot\,pc^{-3}}$$

Justin Read, Journal of Phys. G41 (2014) 063101

=> Flux on Earth: ~10^5 $cm^{-2}s^{-1}$ (M_W=100 GeV, for 0.3 GeV cm^{-3})

INTERACTION RATES

$$R \sim 0.13\ \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$



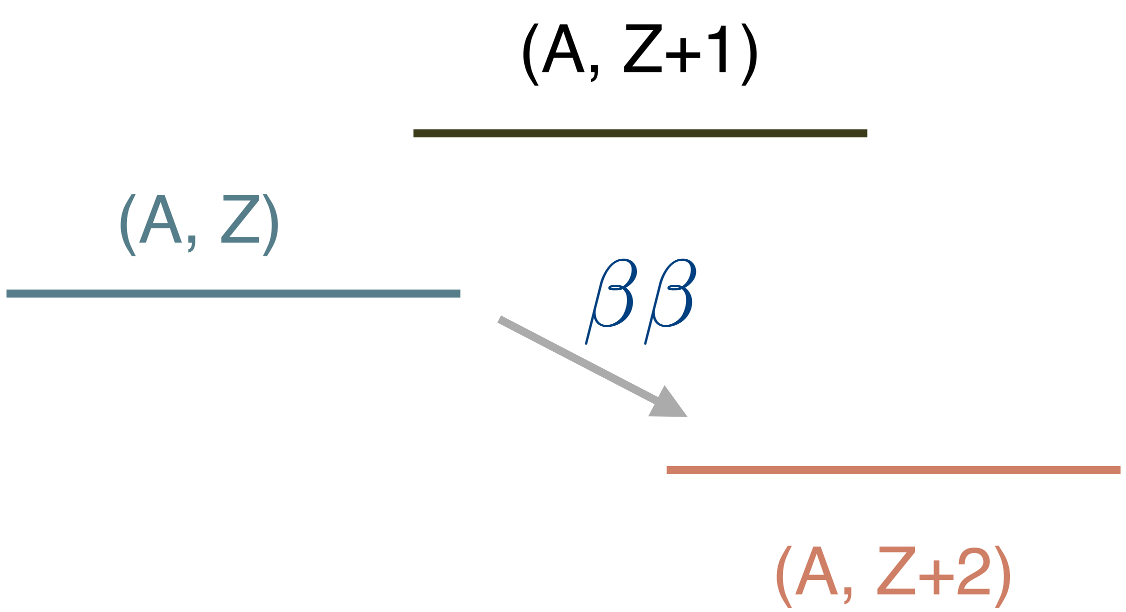
Nuclear recoil spectrum expected in a detector

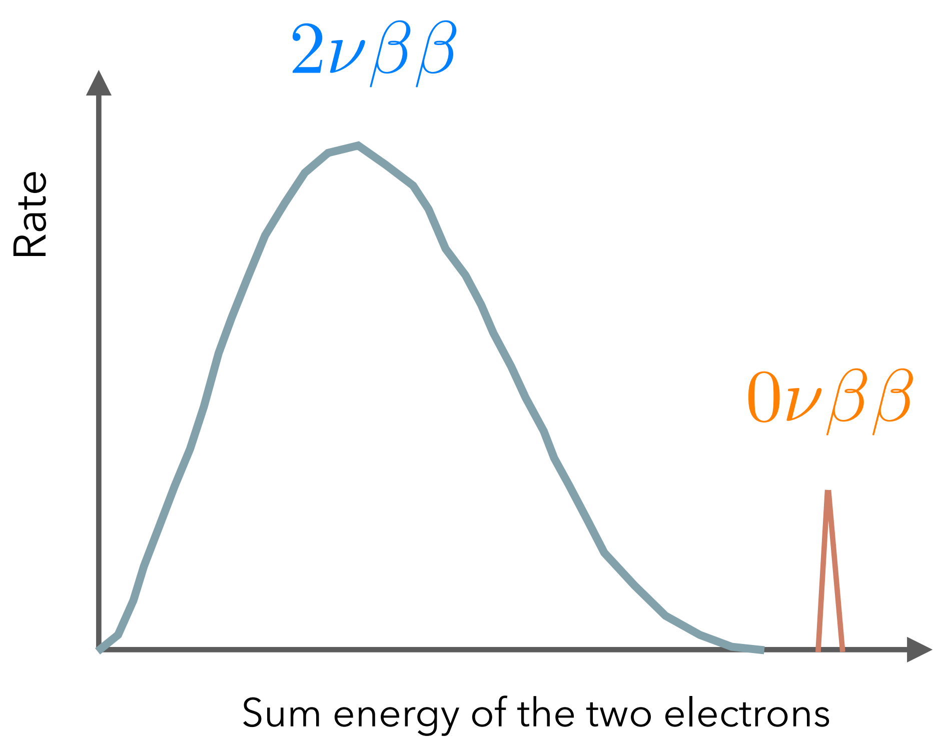
(SOME) OPEN QUESTIONS IN NEUTRINO PHYSICS

- What is the absolute mass of neutrinos?
- Are neutrinos their own antiparticles?
- These can be addressed with an extremely rare nuclear decay process: the double beta decay

THE DOUBLE BETA DECAY

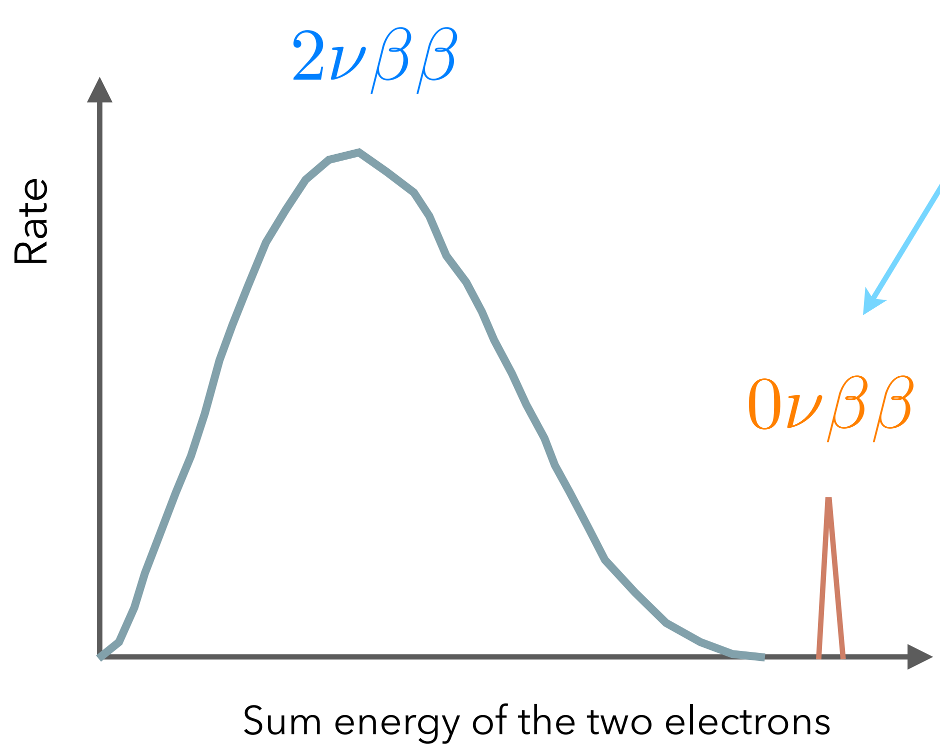
- Predicted by Maria-Goeppert Mayer in 1935
- The SM decay, with 2 neutrinos, was observed in 13 nuclei
- $T_{1/2} > 10^{18}$ y; ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U



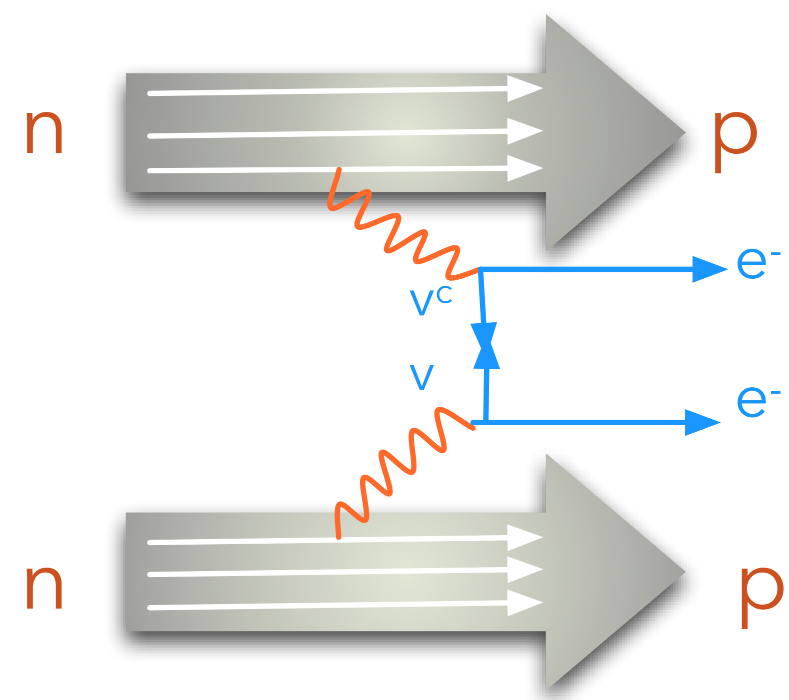


THE NEUTRINOLESS DOUBLE BETA DECAY

- Can only occur if neutrinos have mass and if they are their own anti-particles
- Expected signature: sharp peak at the Q-value of the decay



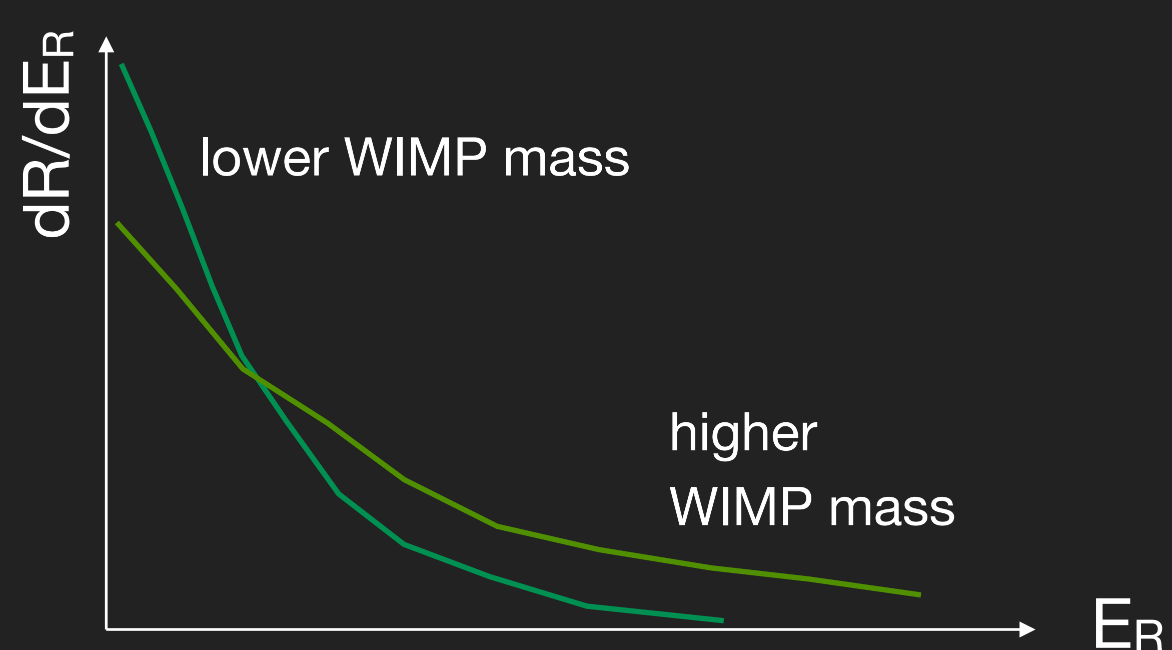
$$T_{1/2}^{0\nu\beta\beta} > 10^{24}\ \mathrm{y}$$

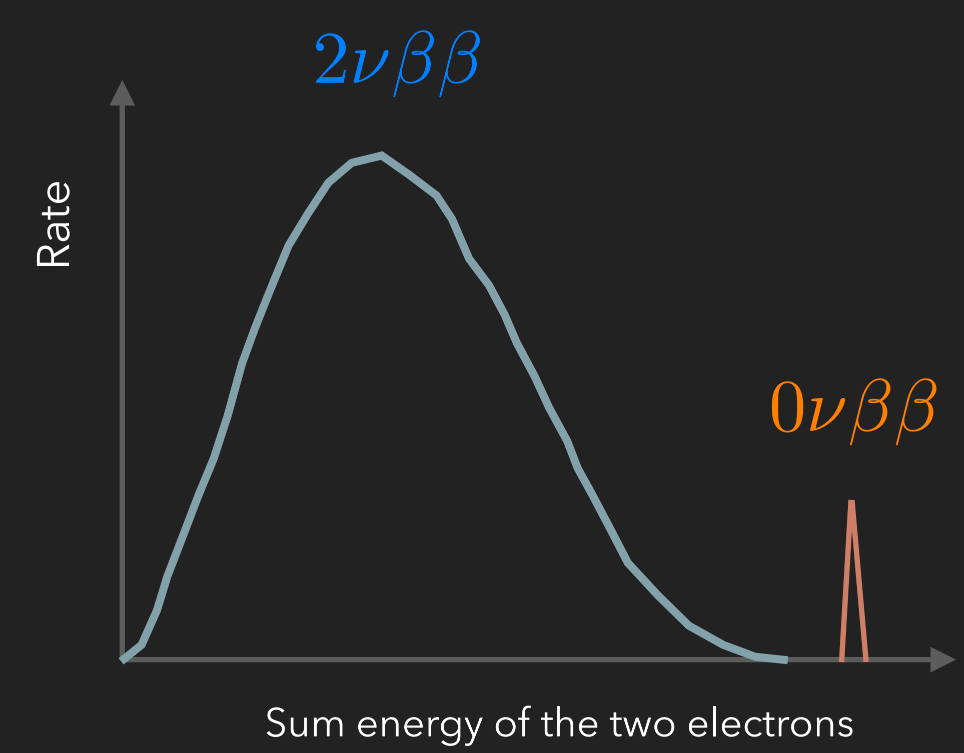


MAIN CHARACTERISTICS

- Nuclear recoils: keV-energies
- Featureless recoil spectrum
- Very low event rates: < 0.1/(kg x year)

- Q-value: MeV-scale
- Peak at the Q-value
- Very low event rates: <0.1/(kg x year)





MAIN EXPERIMENTAL REQUIREMENTS

- Low energy thresholds
- Large detector masses
- Ultra-low backgrounds
- Excellent signals versus background discrimination

$$R \propto N \frac{\rho_0}{m_\chi} \sigma_{\chi N} \langle v \rangle$$

- Excellent energy resolution
- Large detector masses
- Ultra-low backgrounds
- Excellent signals versus background discrimination

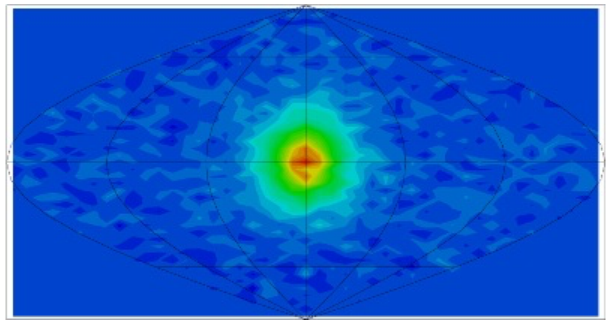
$$T^{0\nu}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

EMPLOYED NUCLEI

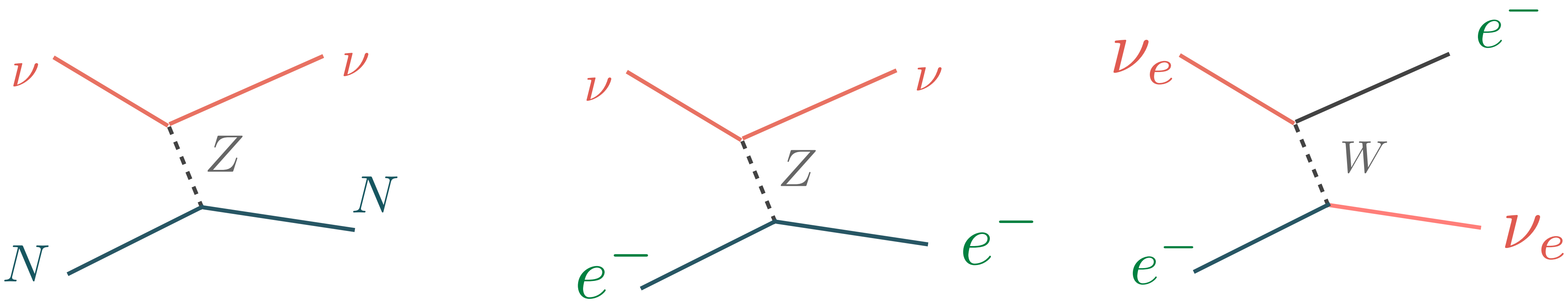
Nucleus	Spin	Abund [%]
^{19}F	$1/2^+$	100
^{23}Na	$3/2^+$	100
^{27}Al	$5/2^+$	100
^{29}Si	$1/2^+$	4.7
^{73}Ge	$9/2^+$	7.76
^{127}I	$5/2^+$	100
^{129}Xe	$1/2^+$	26.4
^{131}Xe	$3/2^+$	21.2
^{40}Ar	–	99.6
^{70}Ge, ^{72}Ge, ^{74}Ge, ^{76}Ge	–	
^{124}Xe,^{126}Xe,^{128}Xe, ^{130}Xe, ^{132}Xe, ^{134}Xe,^{136}Xe	–	

Candidate*	Q [MeV]	Abund [%]
^{48}Ca -> ^{48}Ti	4.271	0.187
^{76}Ge -> ^{76}Se	2.040	7.8
^{82}Se -> ^{82}Kr	2.995	9.2
^{96}Zr -> ^{96}Mo	3.350	2.8
^{100}Mo -> ^{100}Ru	3.034	9.6
^{110}Pd -> ^{110}Cd	2.013	11.8
^{116}Cd -> ^{116}Sn	2.802	7.5
^{124}Sn -> ^{124}Te	2.228	5.64
^{130}Te -> ^{130}Xe	2.530	34.5
^{136}Xe -> ^{136}Ba	2.479	8.9
^{150}Nd -> ^{150}Sm	3.367	5.6

BACKGROUNDS



- In the ideal case: below the expected signal
  - Muons & associated showers; cosmogenic activation of detector materials
  - Natural (^{228}U, ^{232}Th, ^{40}K), anthropogenic (^{85}Kr, ^{137}Cs) and other (^{60}Co, ^{42}Ar, etc) radioactivity: $\gamma,\ e^-,\ n,\ \alpha$
  - Ultimately: neutrinos (+ $2\nu\beta\beta$-decays, depending on the energy resolution)



COHERENT, Science, August 3, 2017

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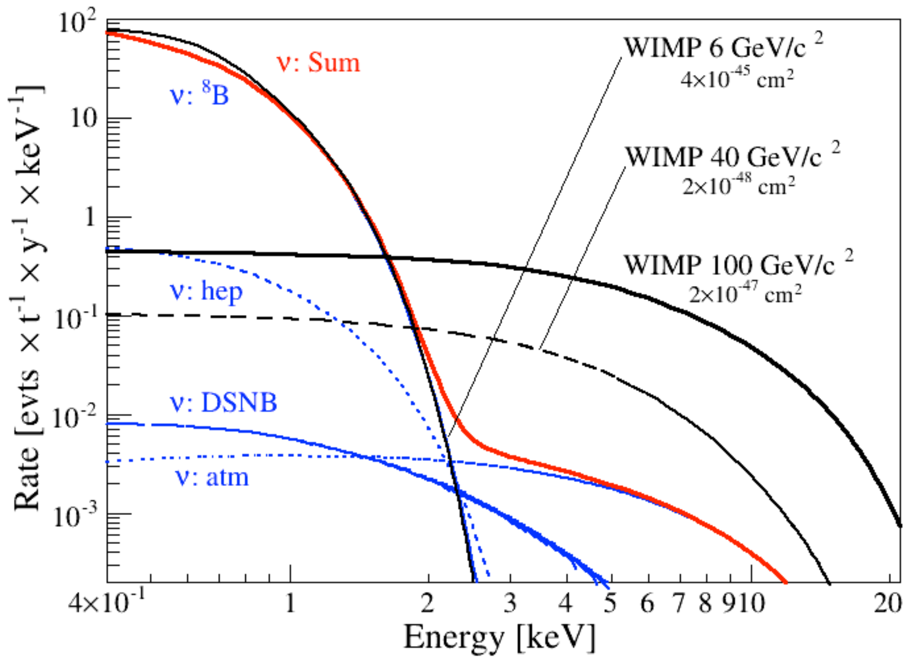
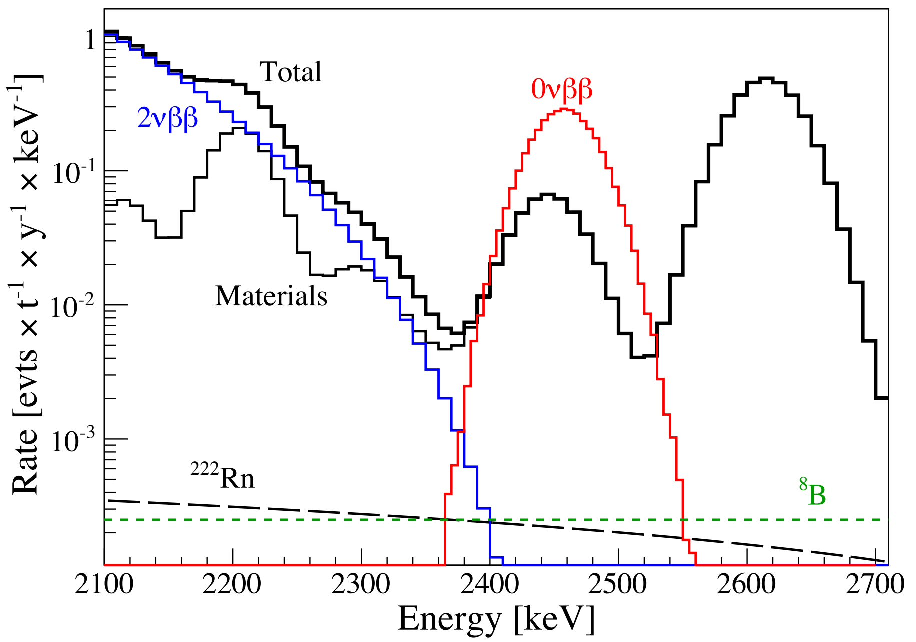
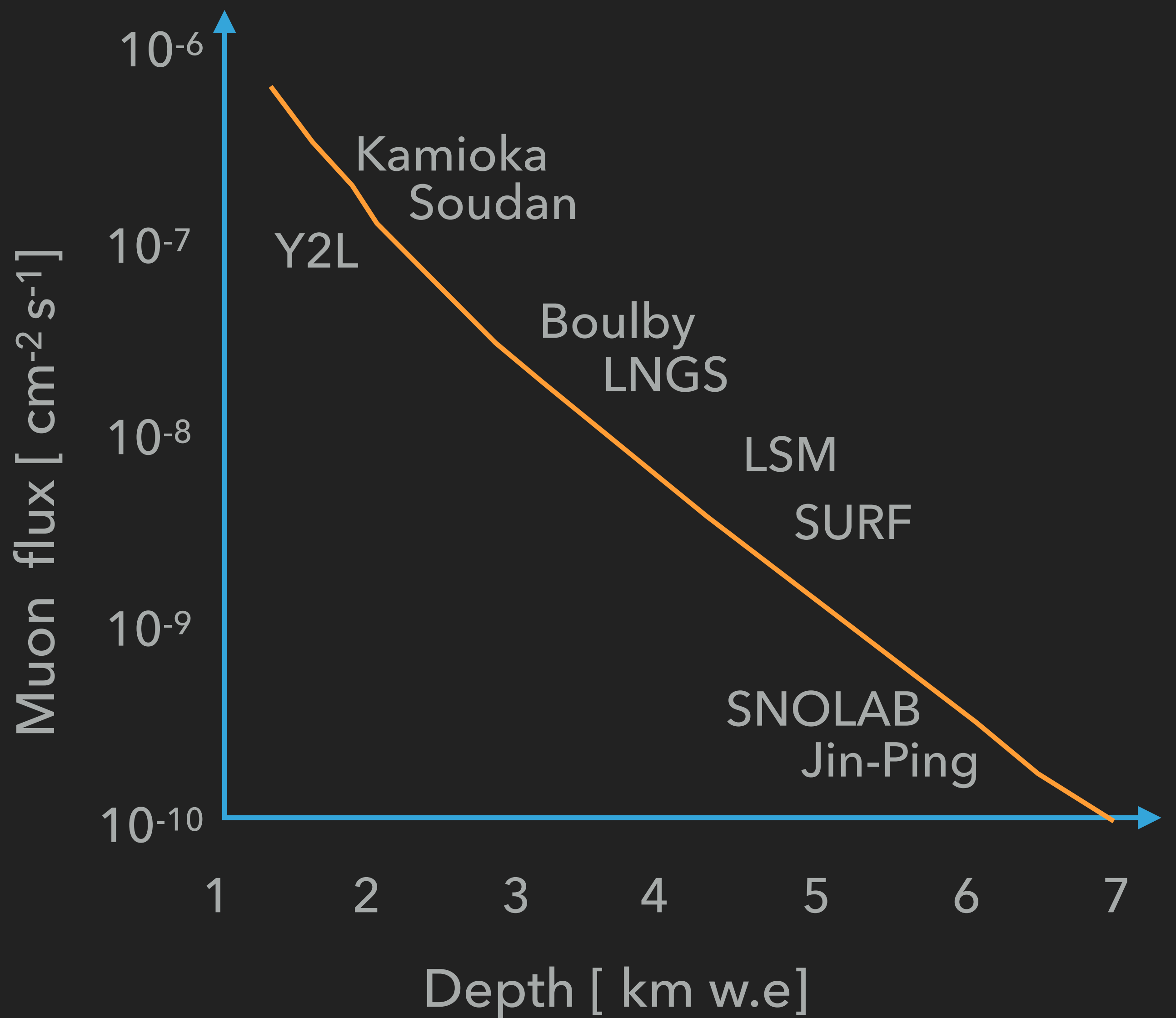


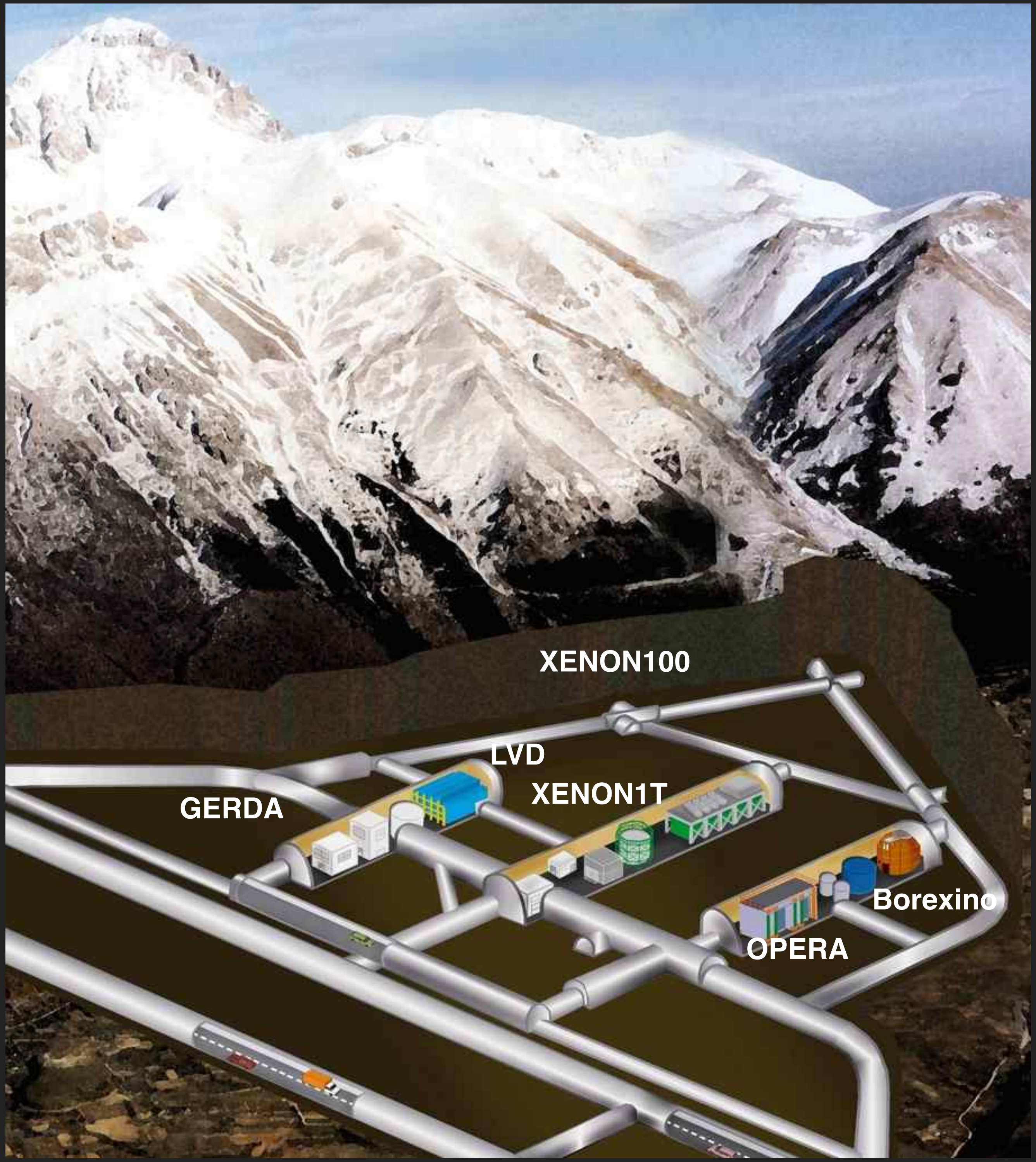


LB et al., JCAP01 (2014) 044

GO UNDERGROUND

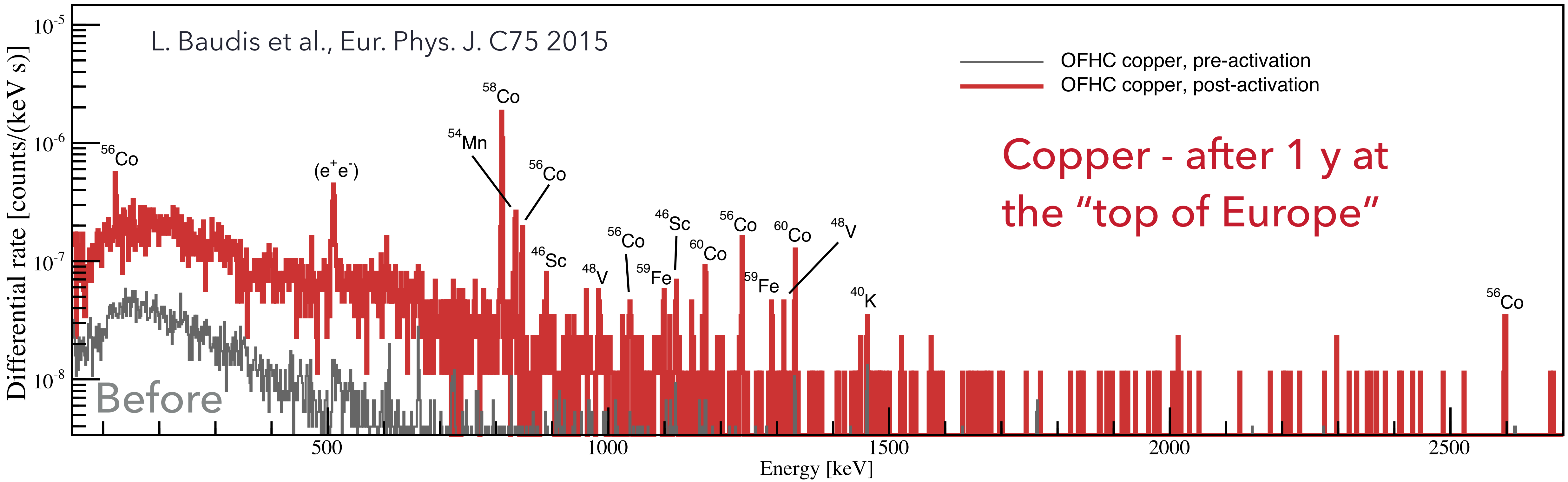
- Network of underground laboratories





AVOID EXPOSURE TO COSMIC RAYS

- Spallation reactions can produce long-lived isotopes
- Activate and compare with predictions (Activia, Cosmo, etc)

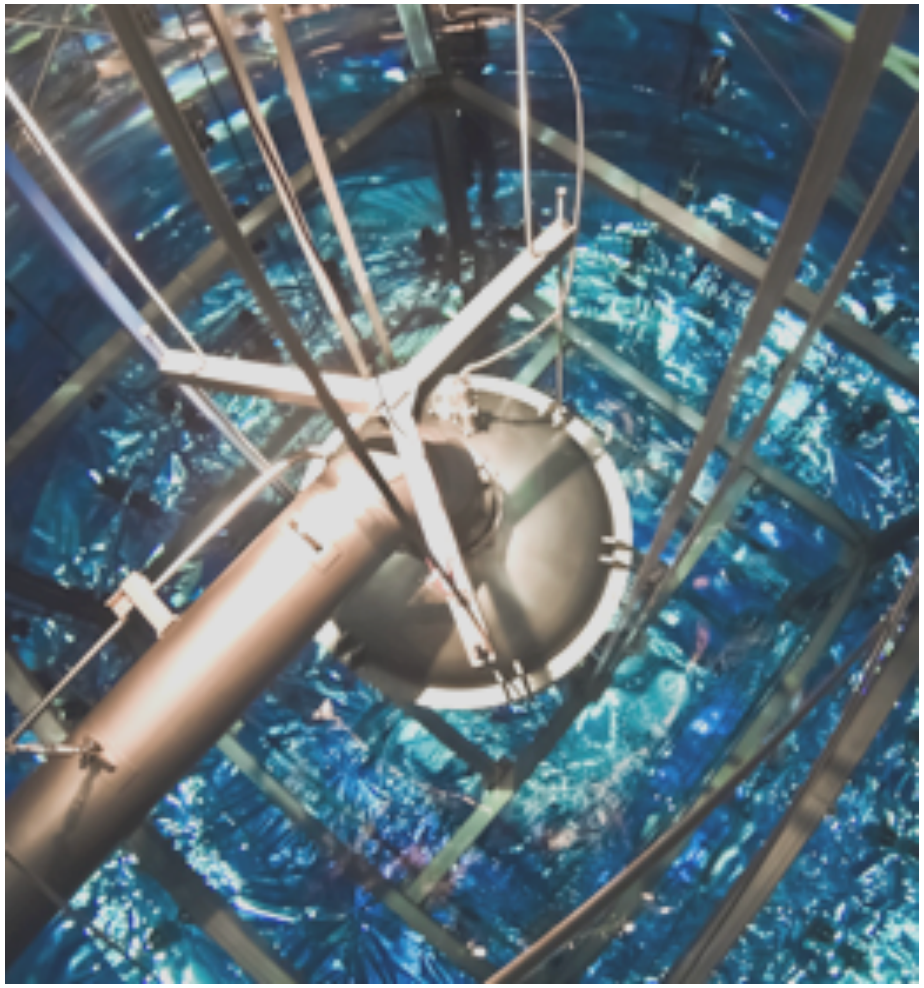


SHIELD, SHIELD, SMARTER SHIELD

XENON10

XENON100

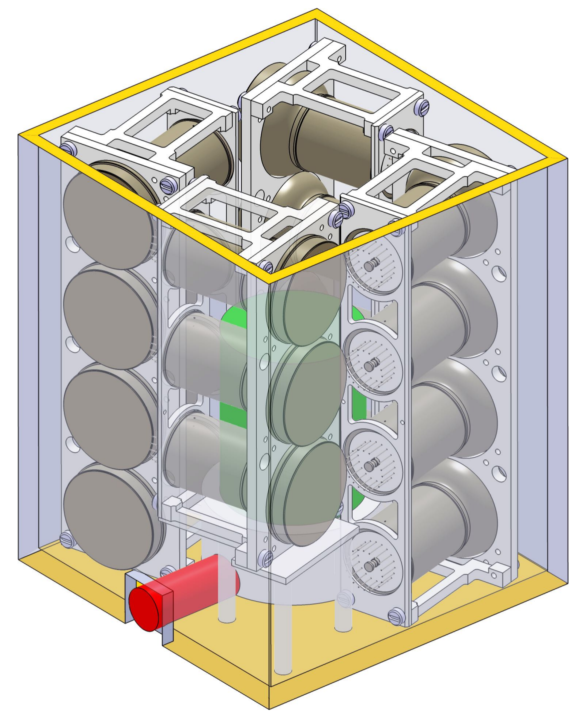
XENON1T



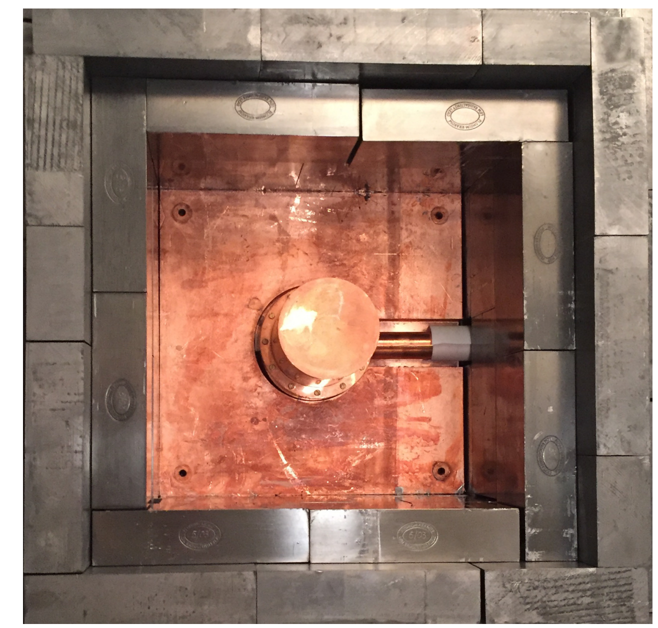
Example: 3 generations of xenon dark matter experiments

MATERIAL SCREENING AND SELECTION

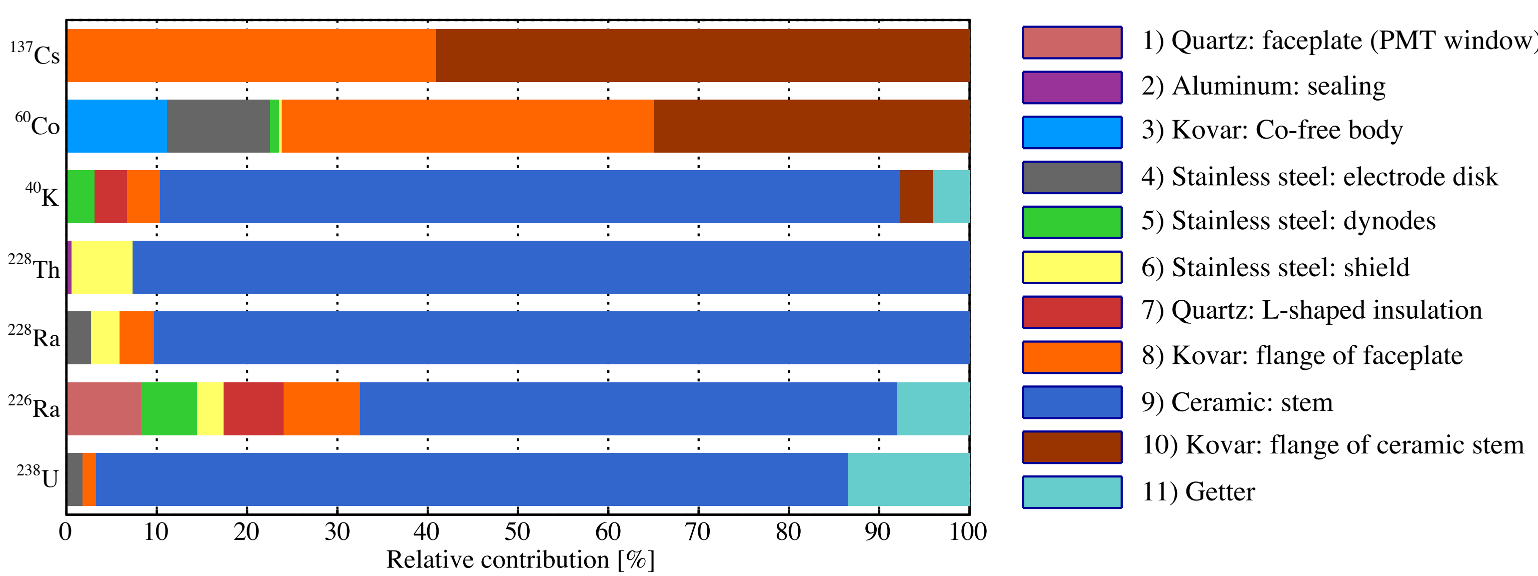
- Ultra-low background, HPGe detectors
- Mass spectroscopy
- Rn emanation facilities



Gator HPGe detector at LNGS



L. Baudis et al., JINST 6, 2011

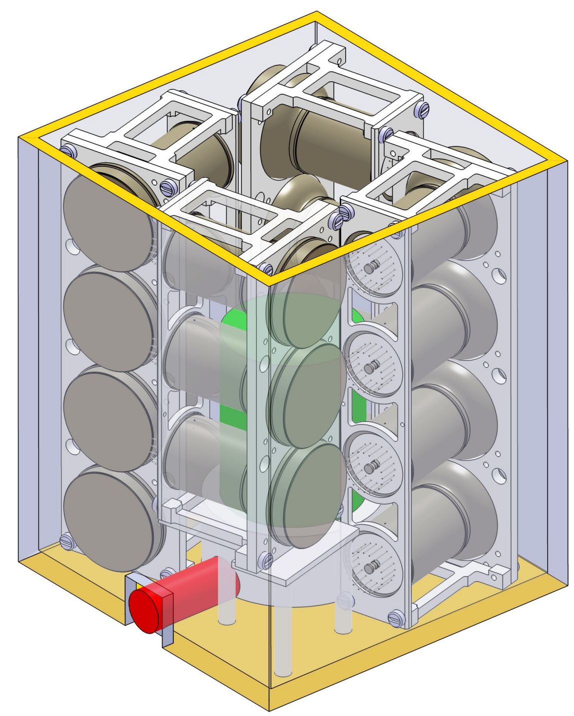


First: screening & selection of all photosensor materials

Second: screening of final products

MATERIAL SCREENING AND SELECTION

- Ultra-low background, HPGe detectors
- Mass spectroscopy
- Rn emanation facilities



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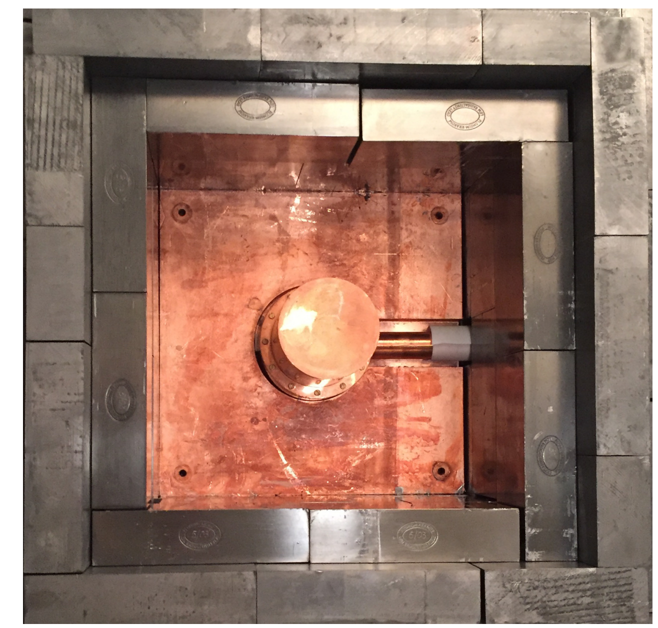

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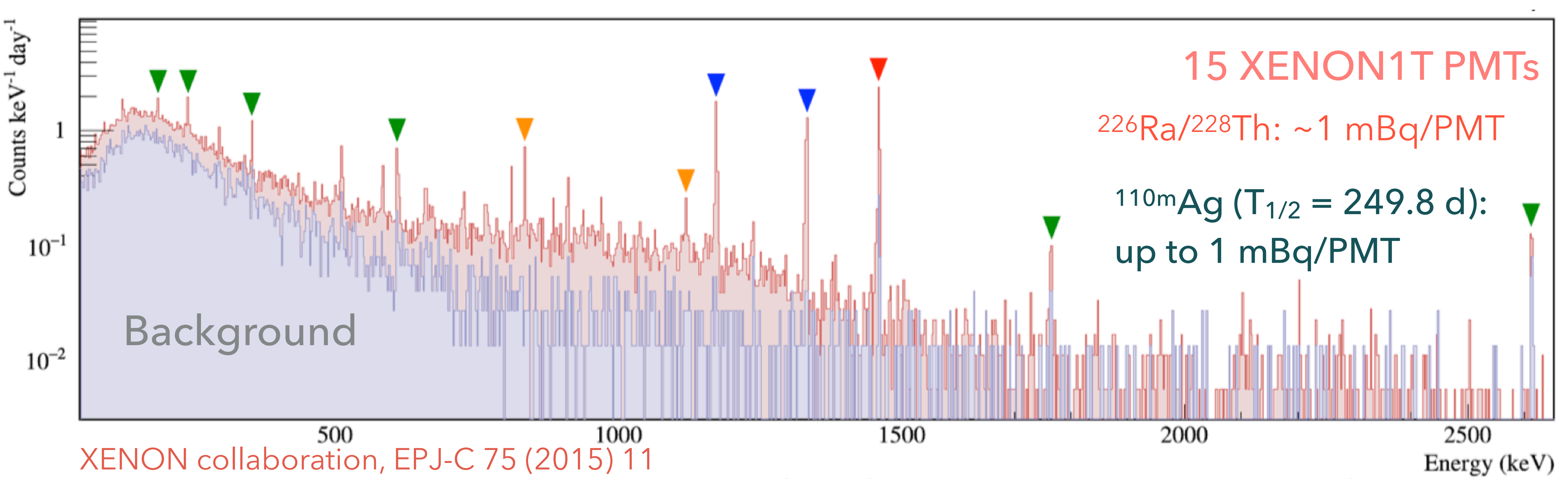


XENON collaboration, EPJ-C 75 (2015) 11

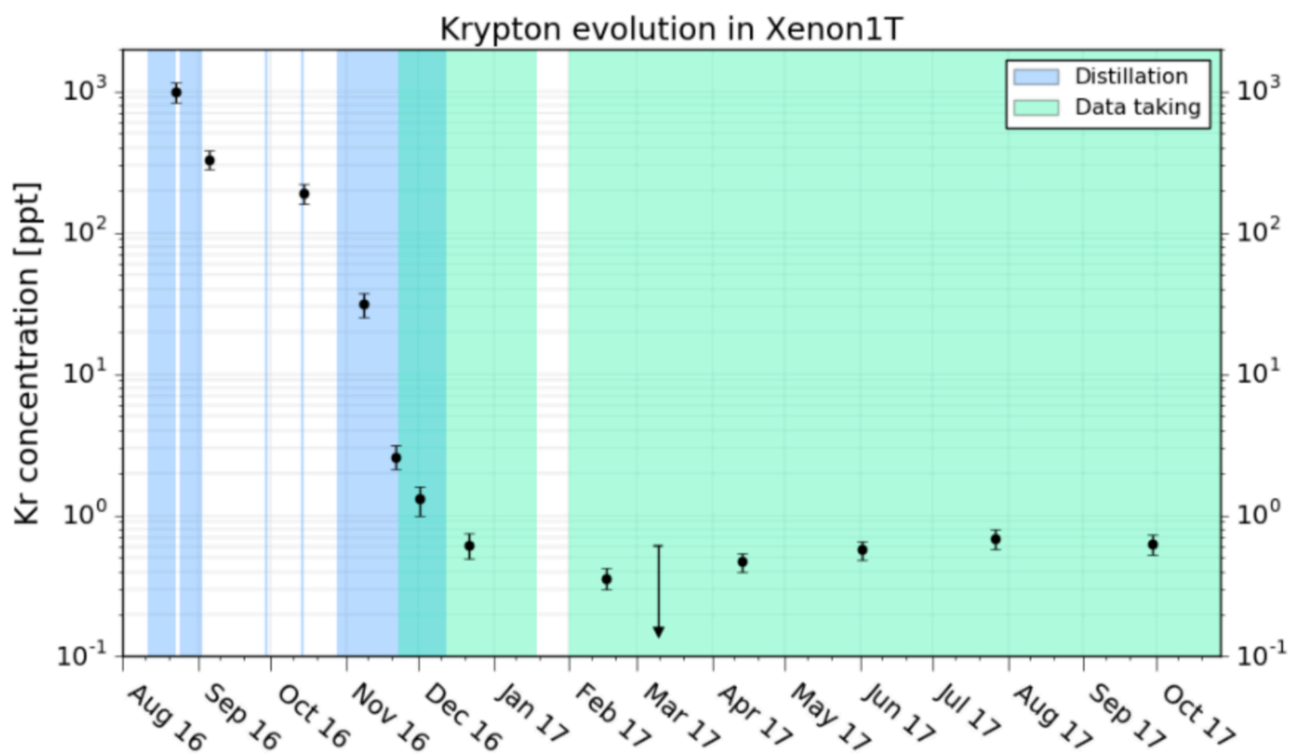
XENON collaboration, EPJ-C 77 (2017) 5

A KRYPTON DISTILLATION COLUMN

- Commercial Xe: 1 ppm - 10 ppb ^{nat}Kr
- ^{85}Kr: $T_{1/2}$ = 10.8 y, Q-value = 687 keV; $^{85}Kr/^{nat}Kr$ 2 x10^{-11} mol/mol
- Dark matter Xe detector sensitivity demands < 0.1 ppt ^{nat}Kr
- Solution: 5.5 m distillation column, 6.5 kg/h output; factor > 6.4. x 10^5 separation down to < 48 ppq (= 10^{-15} mol/mol)

As measured by RGMS + Gas Chromatography with 8 ppq detection limit

(EPJ-C 74, 2014)

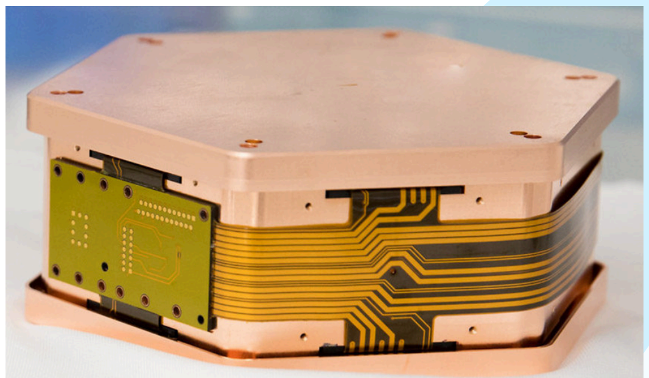


Evolution of Kr/Xe [ppt, mol/mol] level during online distillation

For Rn removal: XENON collaboration, EPJ-C 77 (2017) 6

Heat

CRESST



Nuclear recoil energy

EDELWEISS
SuperCDMS

Charge

Light

LXe: XMASS
LAr: DEAP-3600
CsI: KIMS
NaI: ANAIS
DAMA/LIBRA, COSINE, SABRE

C_3F_8, CF_3I: PICO
Ge: CDEX
Si: DAMIC, SENSEI
CF_4: DRIFT, DMTPC, MIMAC, Newage, NEWS

XENON, LZ
DARWIN,
DarkSide,
PandaX

(not a complete list)

Heat

CUORE
CUPID

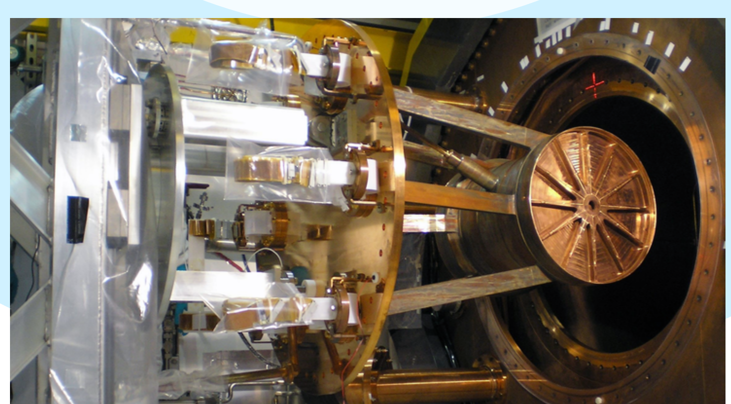
Energy of the two electrons

Charge

GERDA
MAJORANA
LEGEND
SuperNEMO

Light

KamlandZEN
SNO+



nEXO, NEXT
DARWIN

(not a complete list)

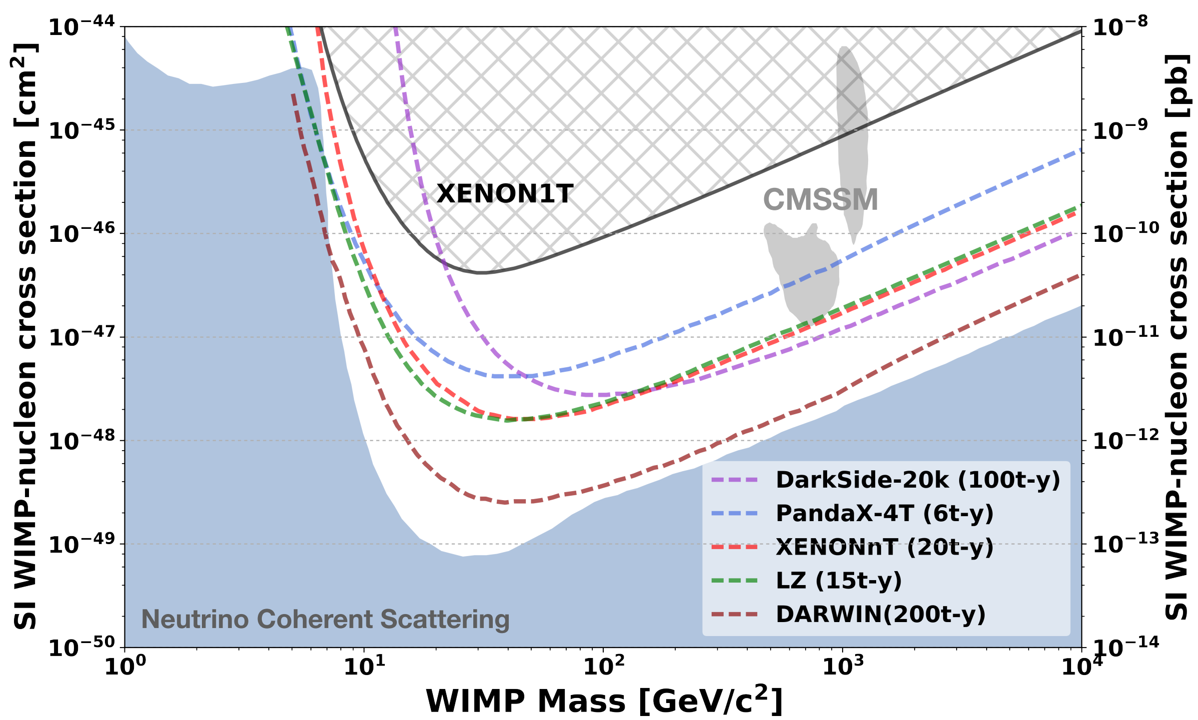
EXPERIMENTAL STATUS: OVERVIEW

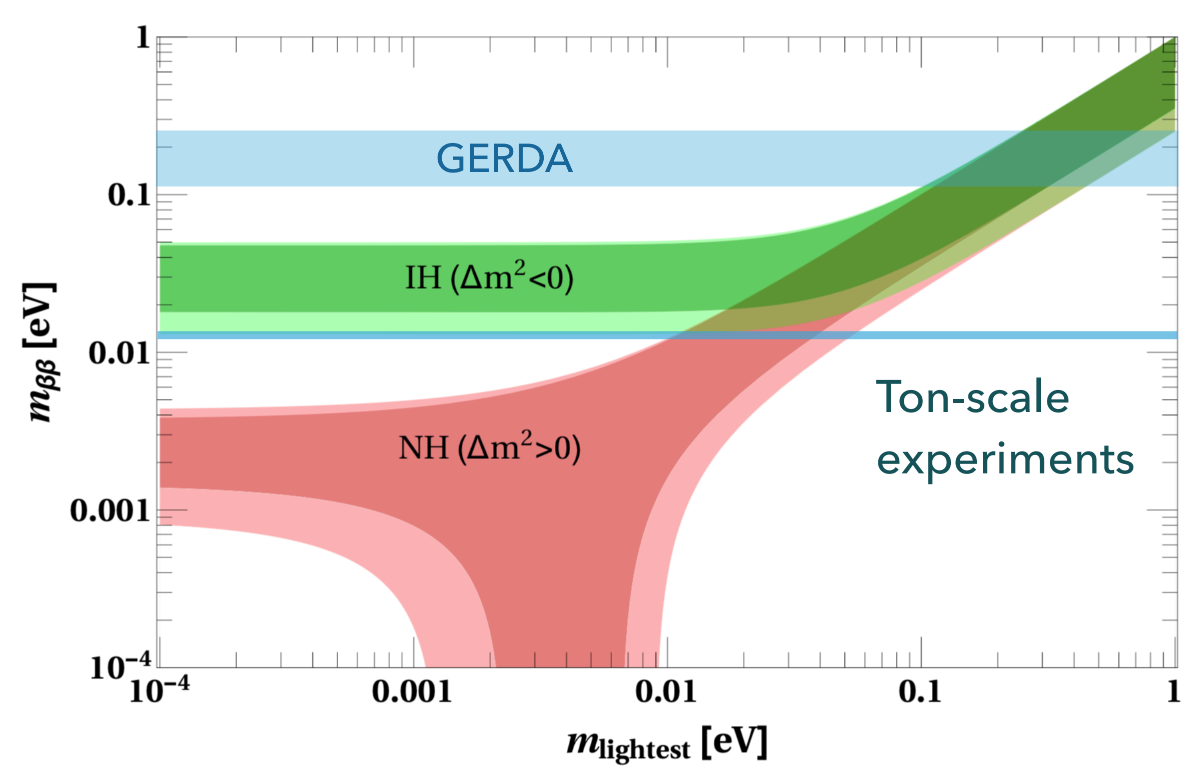
- No evidence for dark matter particles
- Probing scattering cross sections (on nucleons) of a few x 10^{-47} cm^2

- No evidence for the neutrino less double beta decay
- Probing half-lives up to 1.2 x 10^{26} yr

$$\sigma_{\rm SI} < 4.1 \times 10^{-47} {\rm cm}^2 \text{ at } 30\,{\rm GeV/c^2}$$

$$m_{\beta\beta} < 0.11 - 0.26\,{\rm eV}\ (90\%{\rm C.L.})$$



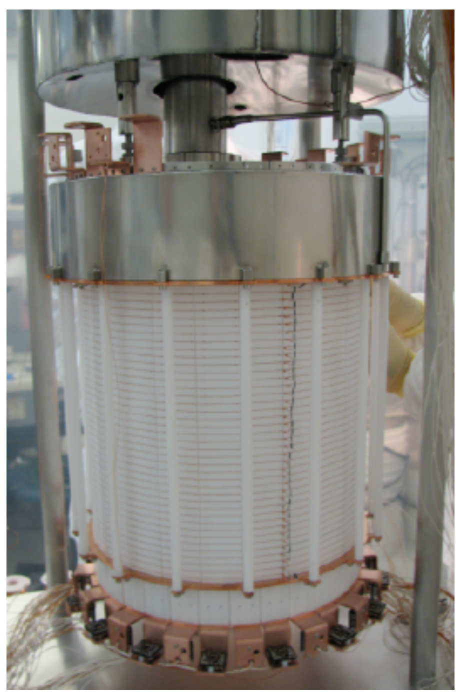


WE NEED LARGER DETECTORS WITH LOWER BACKGROUNDS

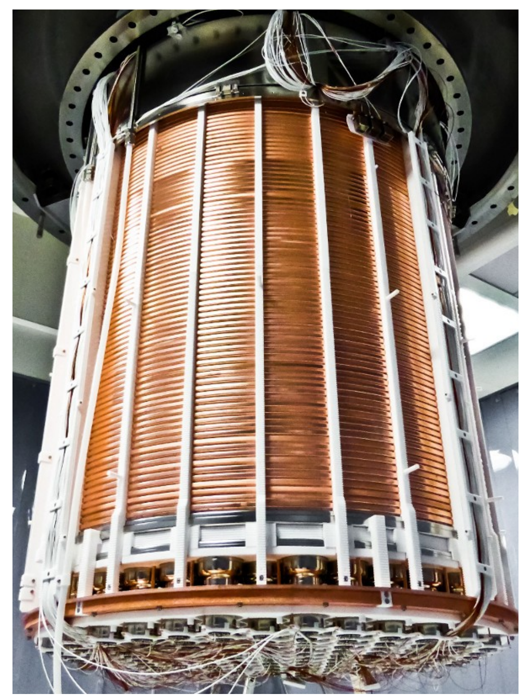
THE XENON&DARWIN PROJECTS

XENON10

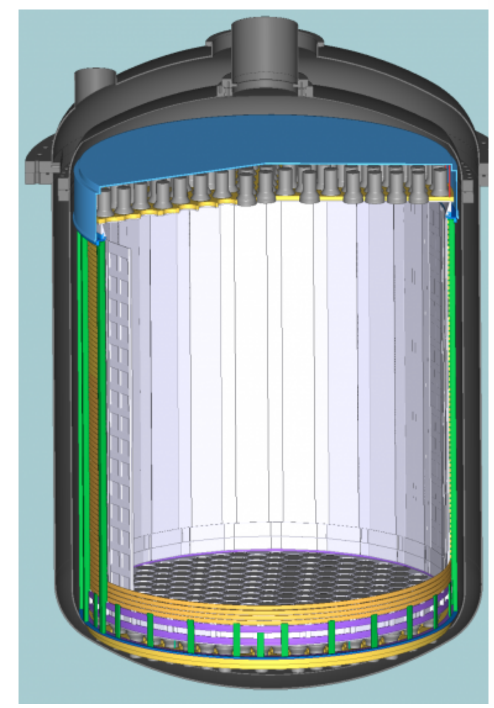
XENON100



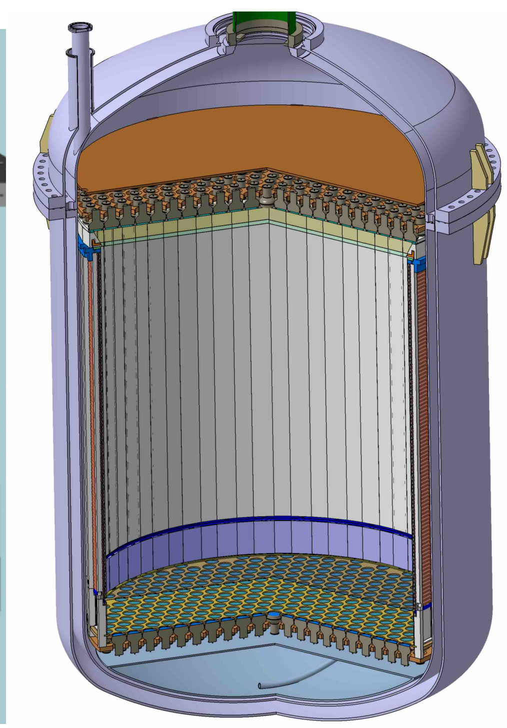
XENON1T



XENONnT

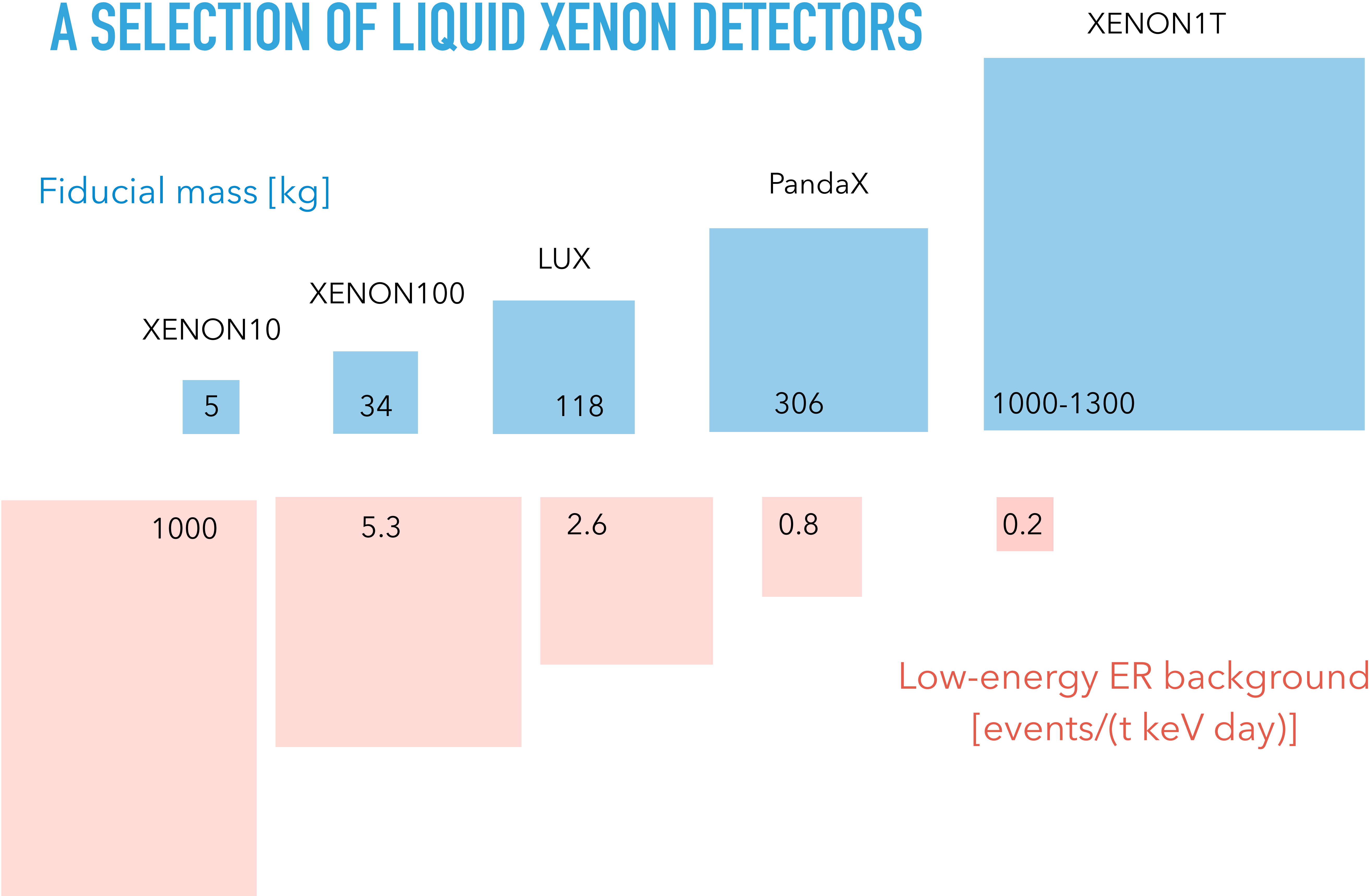


DARWIN



2005-2007	2008-2016	2012-2018	2019-2023	2020+
15 kg	161 kg	3200 kg	8200 kg	50 tonnes
$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	$\sim 10^{-47}$ cm^2	$\sim 10^{-48}$ cm^2	$\sim 10^{-49}$ cm^2

A SELECTION OF LIQUID XENON DETECTORS



XENON collaboration, EPJ-C 77 (2017) 12

XENON1T AT THE GRAN SASSO LABORATORY

Water tank and Cherenkov muon veto

Cryostat and support structure for TPC

Time projection chamber

Cryogenics pipe (cables, xenon)

Cryogenics and purification

Data acquisition and slow control

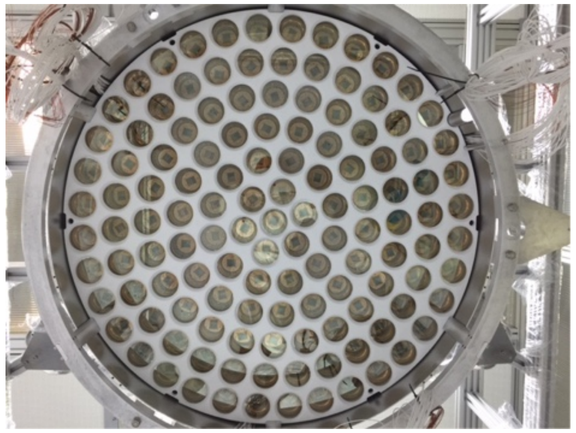
Xenon storage, handling and Kr removal via cryogenic distillation

THE XENON1T TPC IN THE CLEANROOM AT LNGS

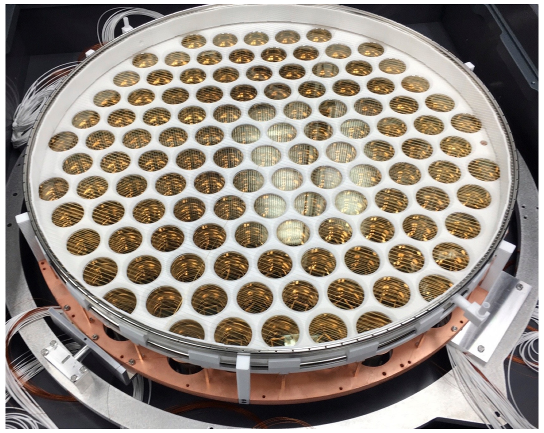
THE TIME PROJECTION CHAMBER

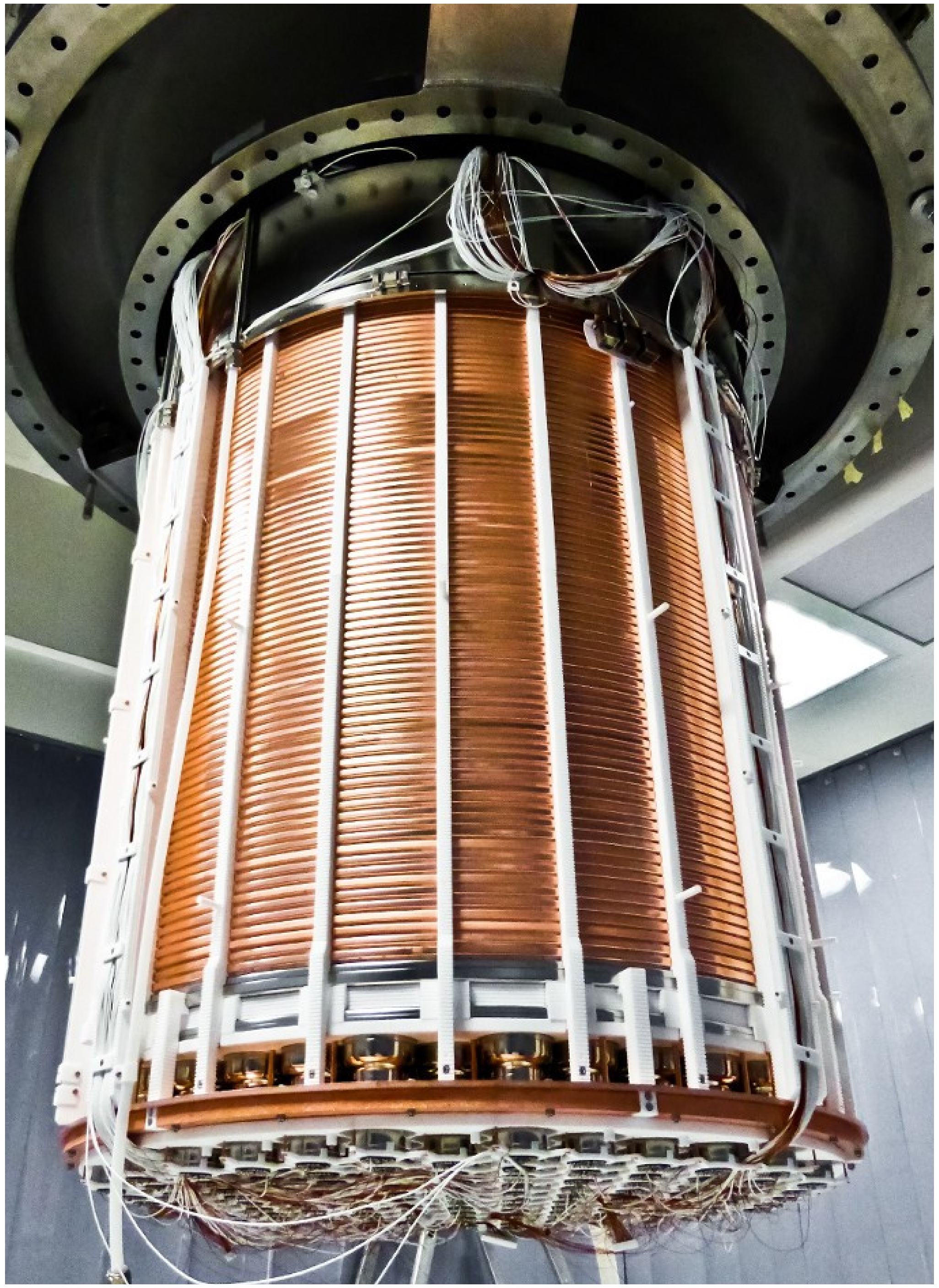
- 3.2 t LXe in total, 2 t in the TPC
- 97 cm drift, 96 cm diameter
- 248 3-inch PMTs
- 74 Cu field shaping rings, 5 electrodes, 4 level meters

127 PMTs top array



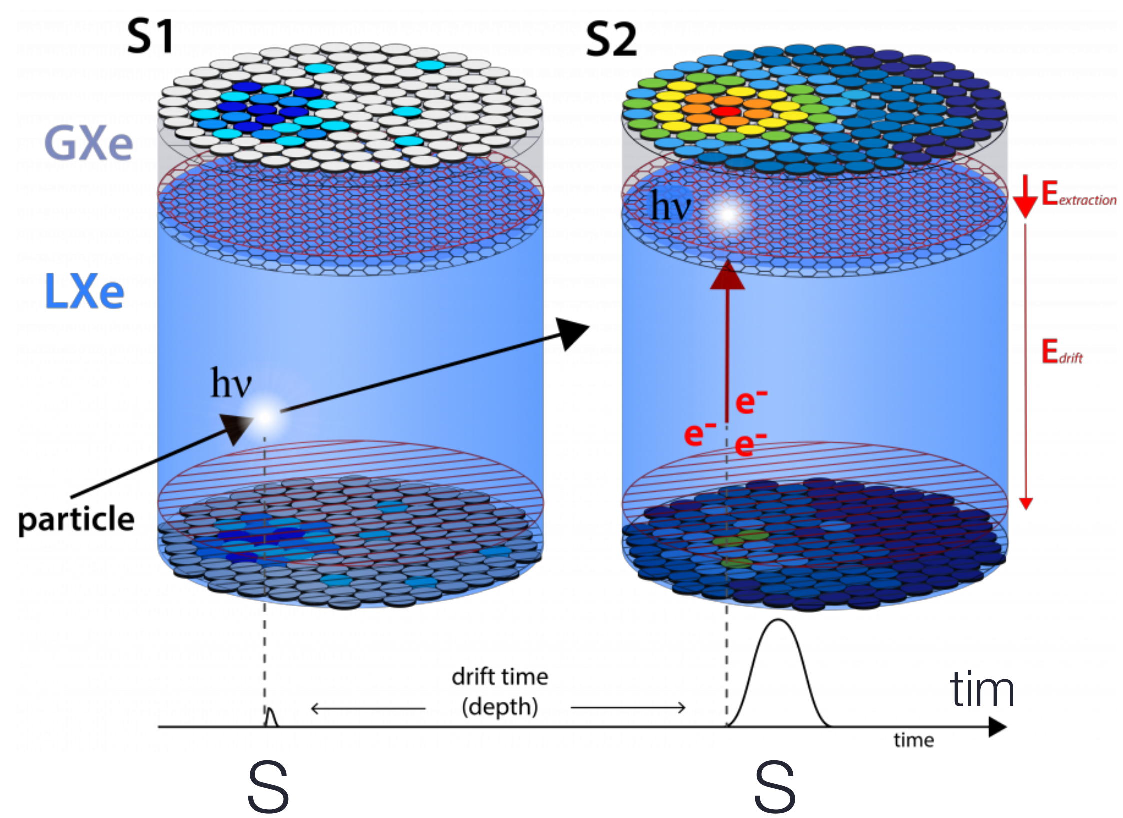
121 PMTs bottom array



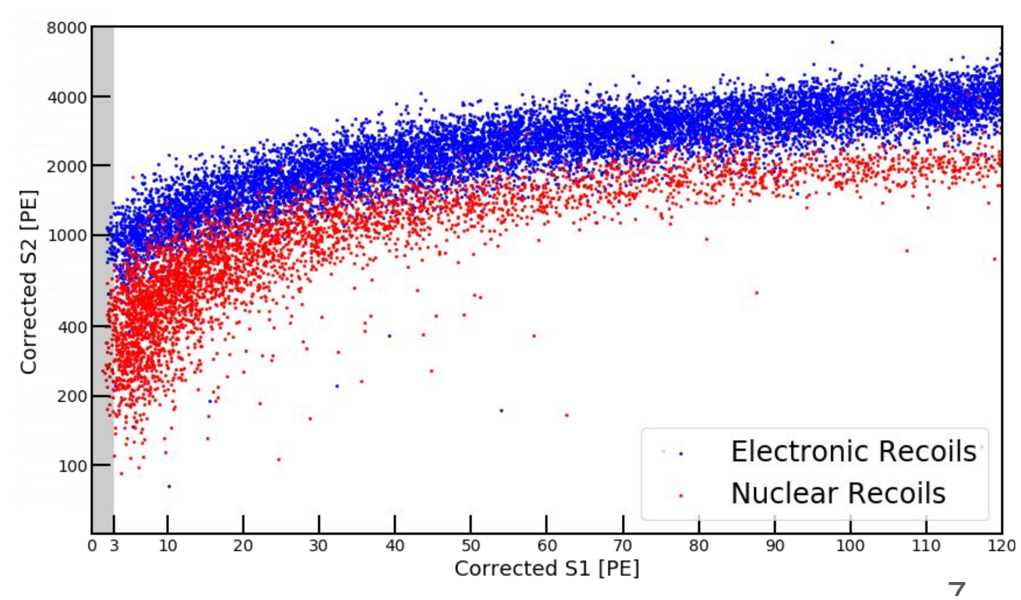


ELECTRONIC AND NUCLEAR RECOILS

- 3D position resolution via light (S1) and charge (S2) signals
- S2/S1 depends on particle ID
- Fiducialisation
- Single versus multiple interactions



Electronic recoils (interactions with electronic shell)



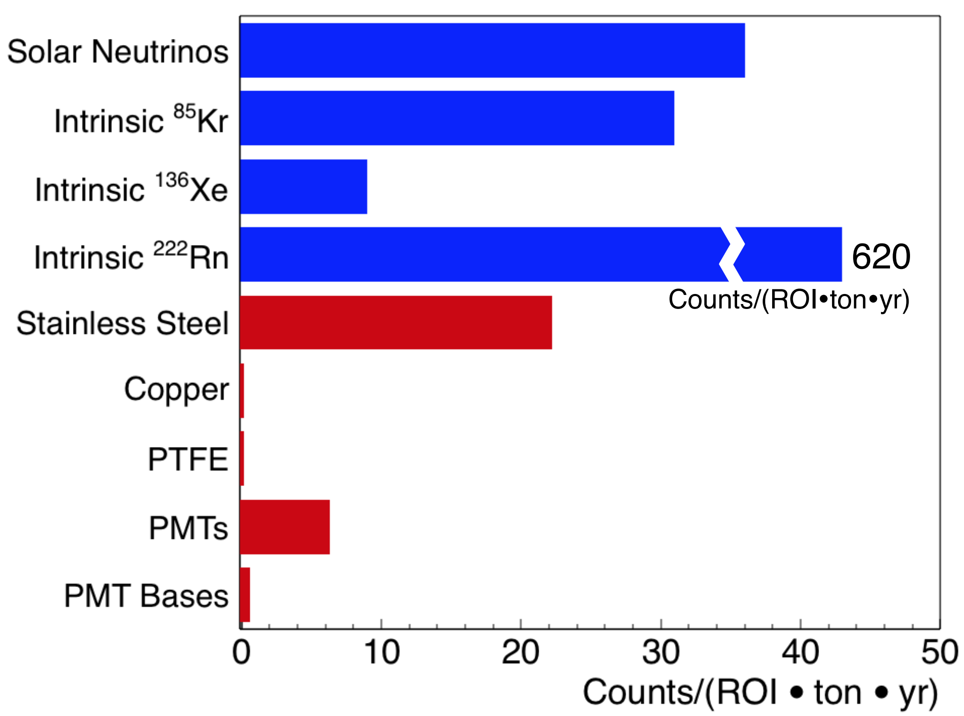
Nuclear recoils (interactions with atomic nuclei)

XENON collaboration: JCAP 1604 (2016) 04

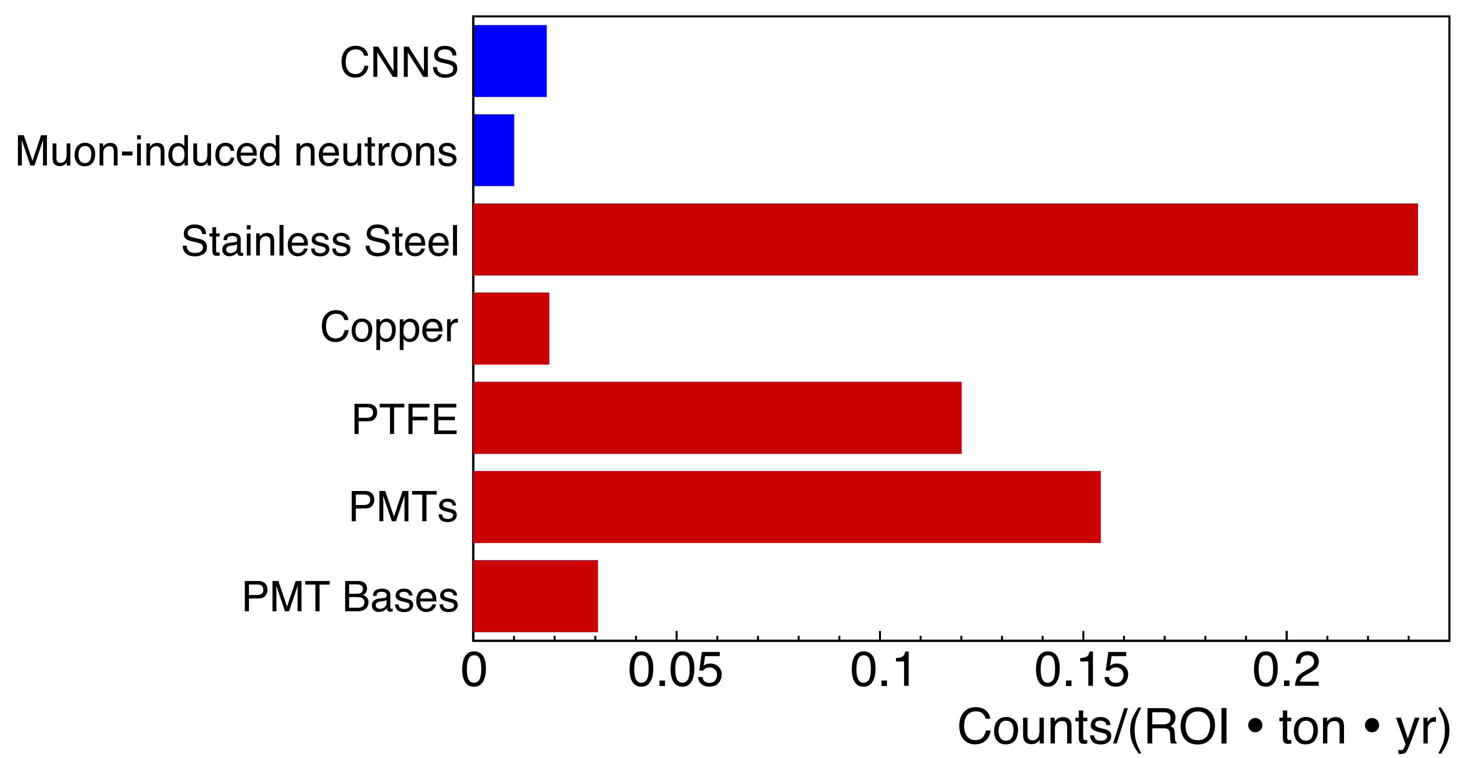
BACKGROUND PREDICTIONS

- Based on material screening & selection
- Electronic and nuclear recoils in 1 t fiducial, 1-12 keV_{ee} and 4-50 keV_{nr}

Electronic recoils



Nuclear recoils

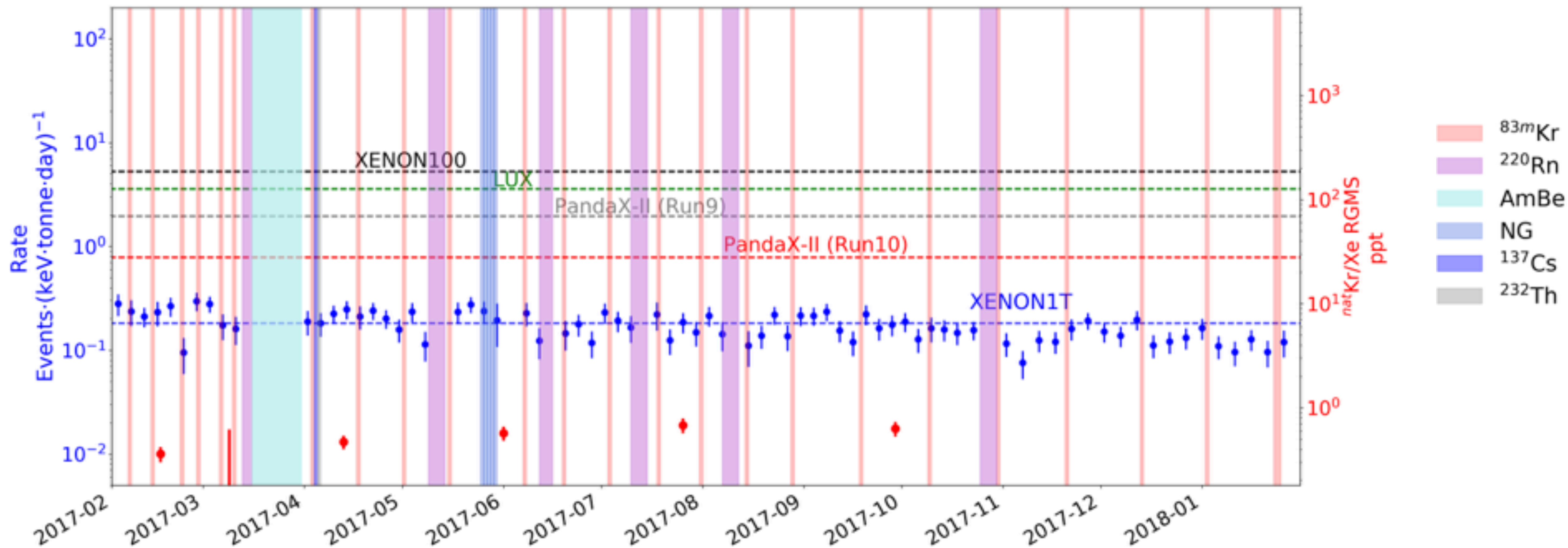


Intrinsic and neutrinos + materials

BACKGROUND PREDICTIONS AND DATA

- ER rate: (82±5) events/(keV t y), in 1.3 t and below 25 keV_{ee}
- Lowest background in a dark matter detector

^{nat}Kr: ~0.45 ppt ; ^{222}Rn: ~ 10 μBq/kg

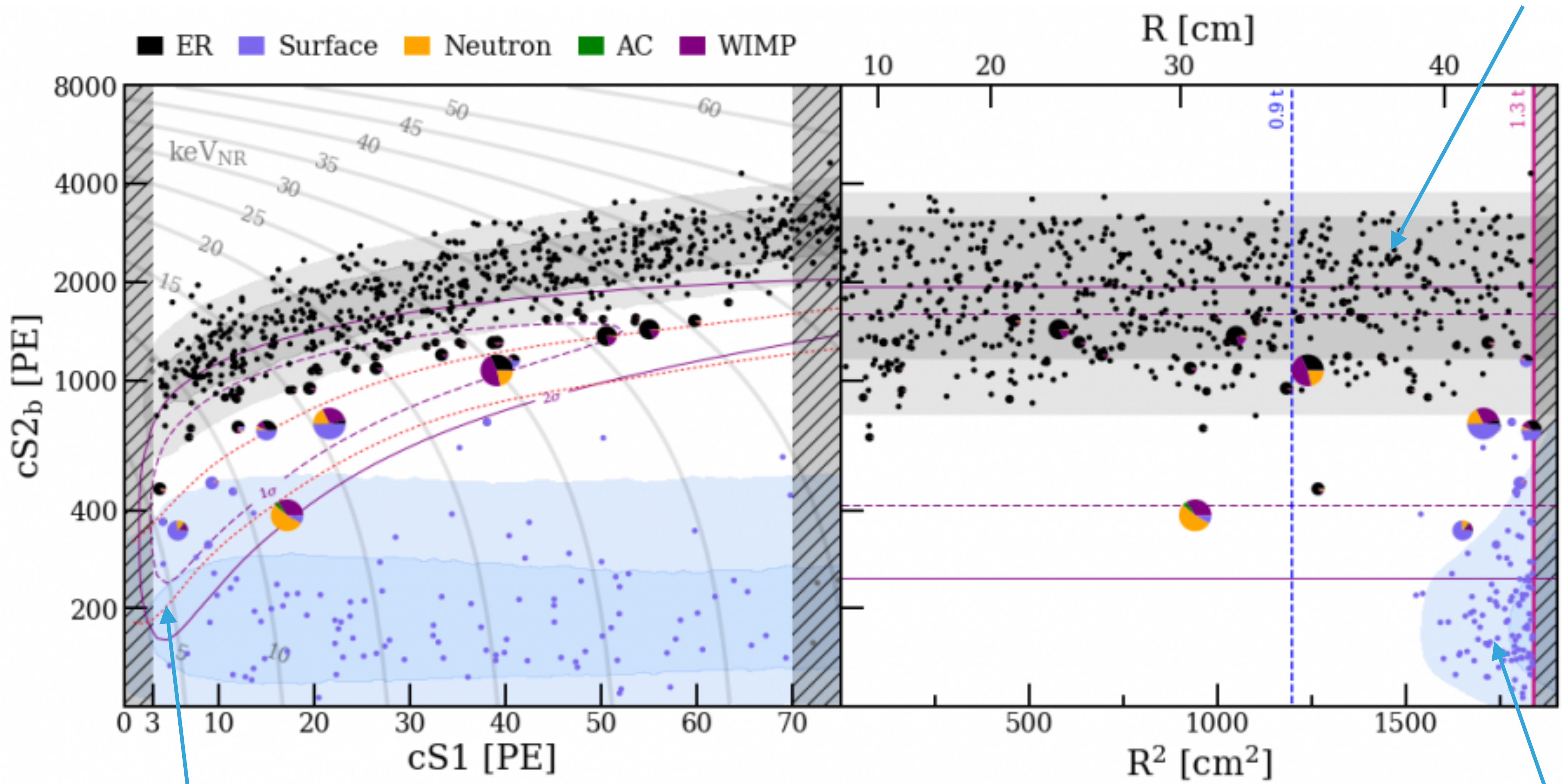


^{222}Rn: 85.4%, ^{85}Kr: 4.3%, solar ν: 4.9%, materials: 4.1%, ^{136}Xe: 1.4%

XENON Collab., PRL 121 (2018)

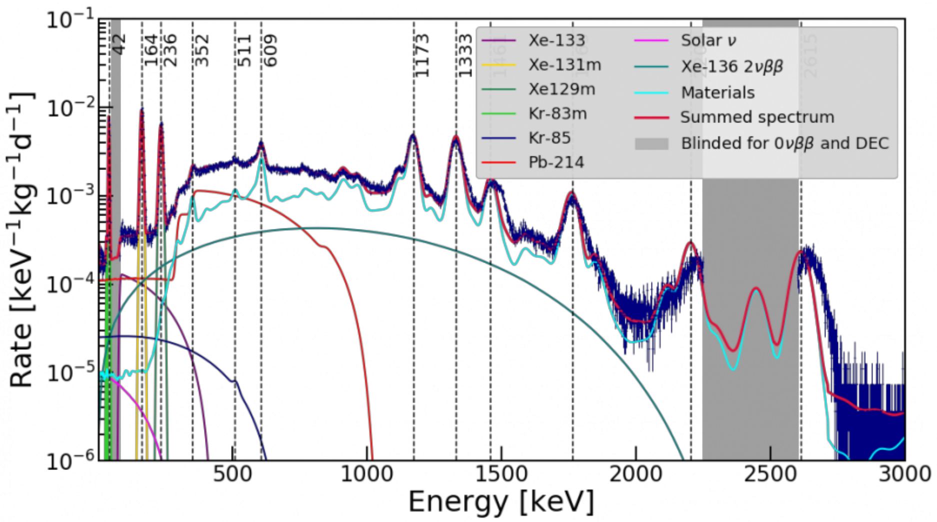
EVENTS IN THE WIMP REGION-OF-INTEREST

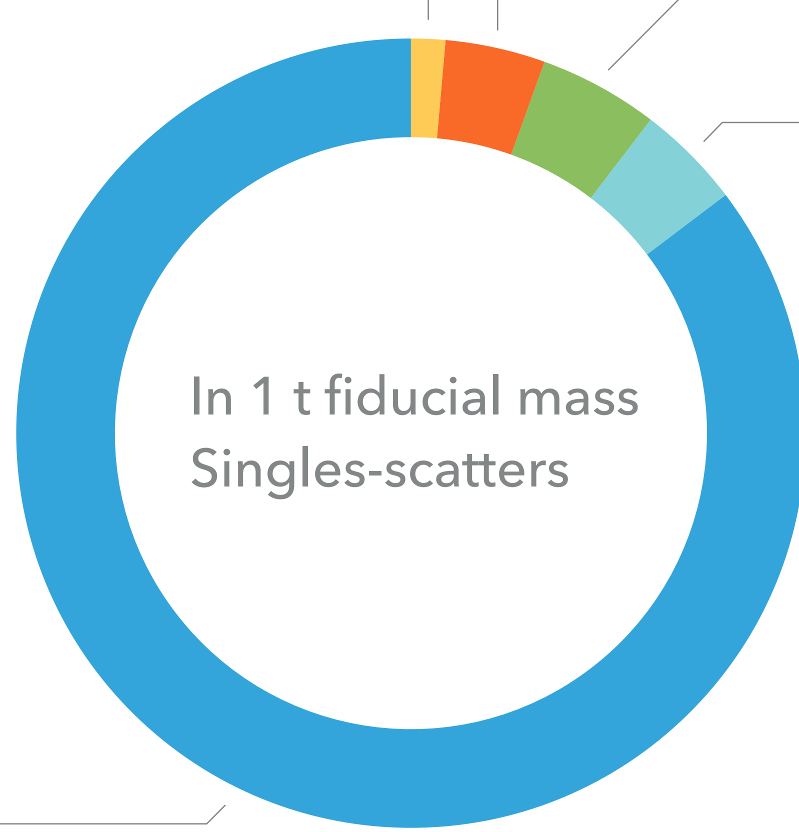
ER component



1-σ and 2-σ percentile of 200 GeV WIMP component

Surface component

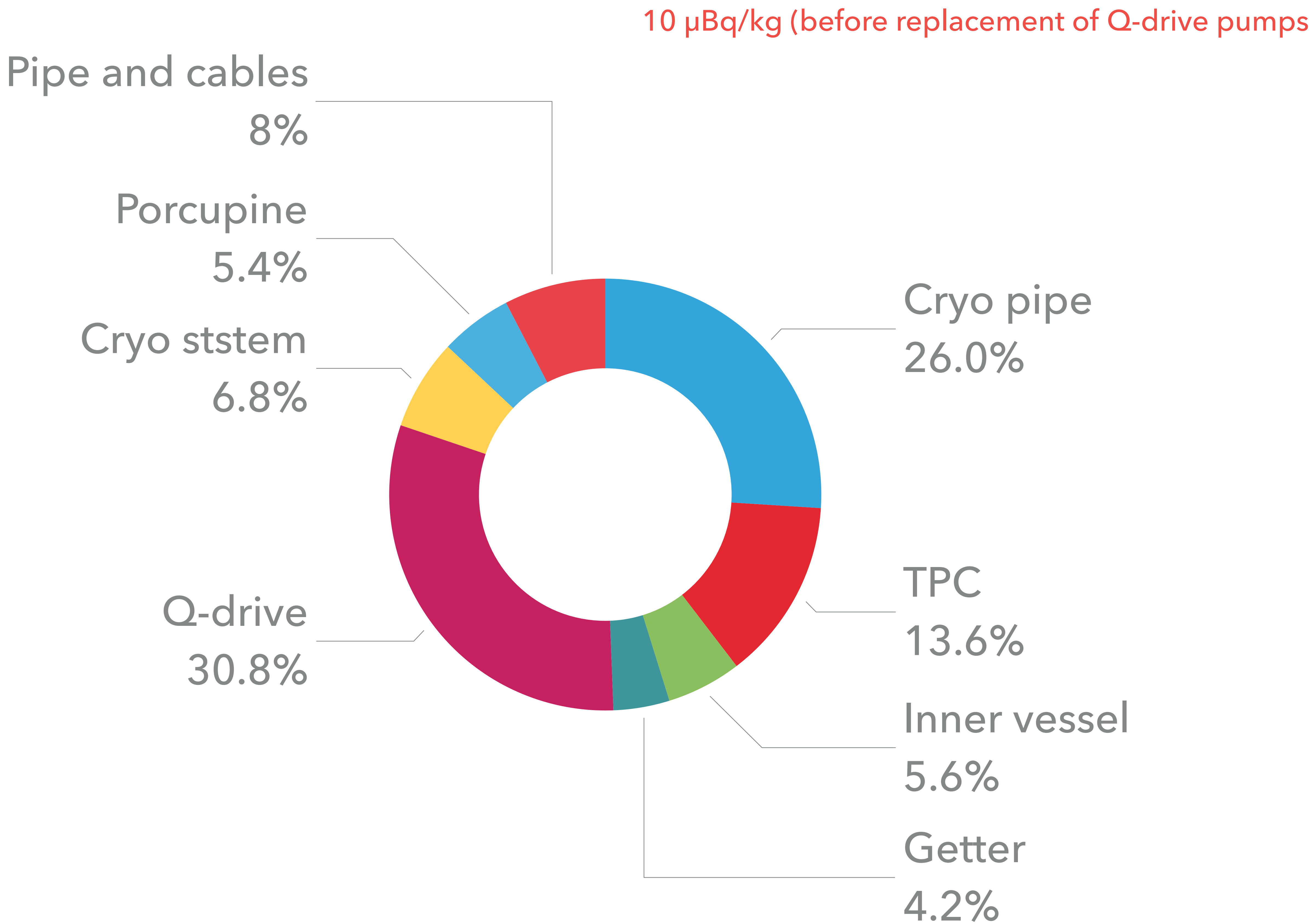




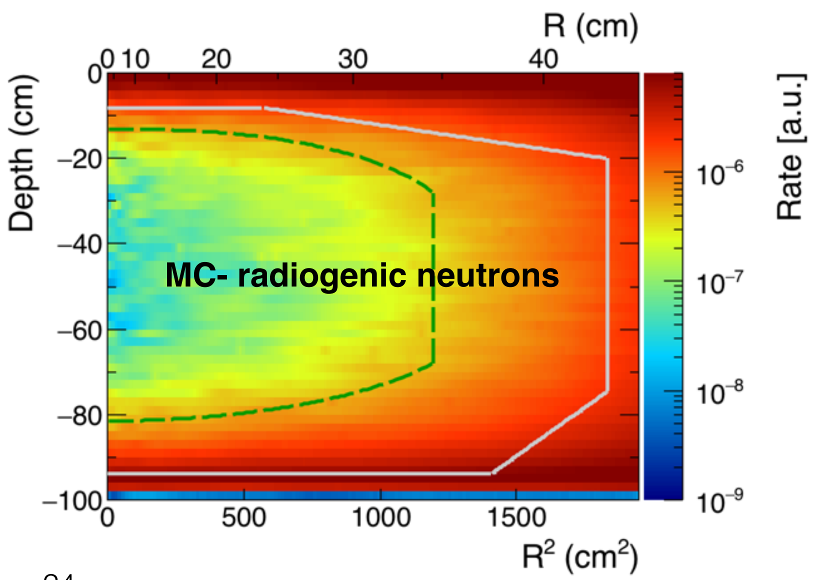
^{222}Rn (10 μBq/kg)

Control surface emanation
Reduce by online distillation

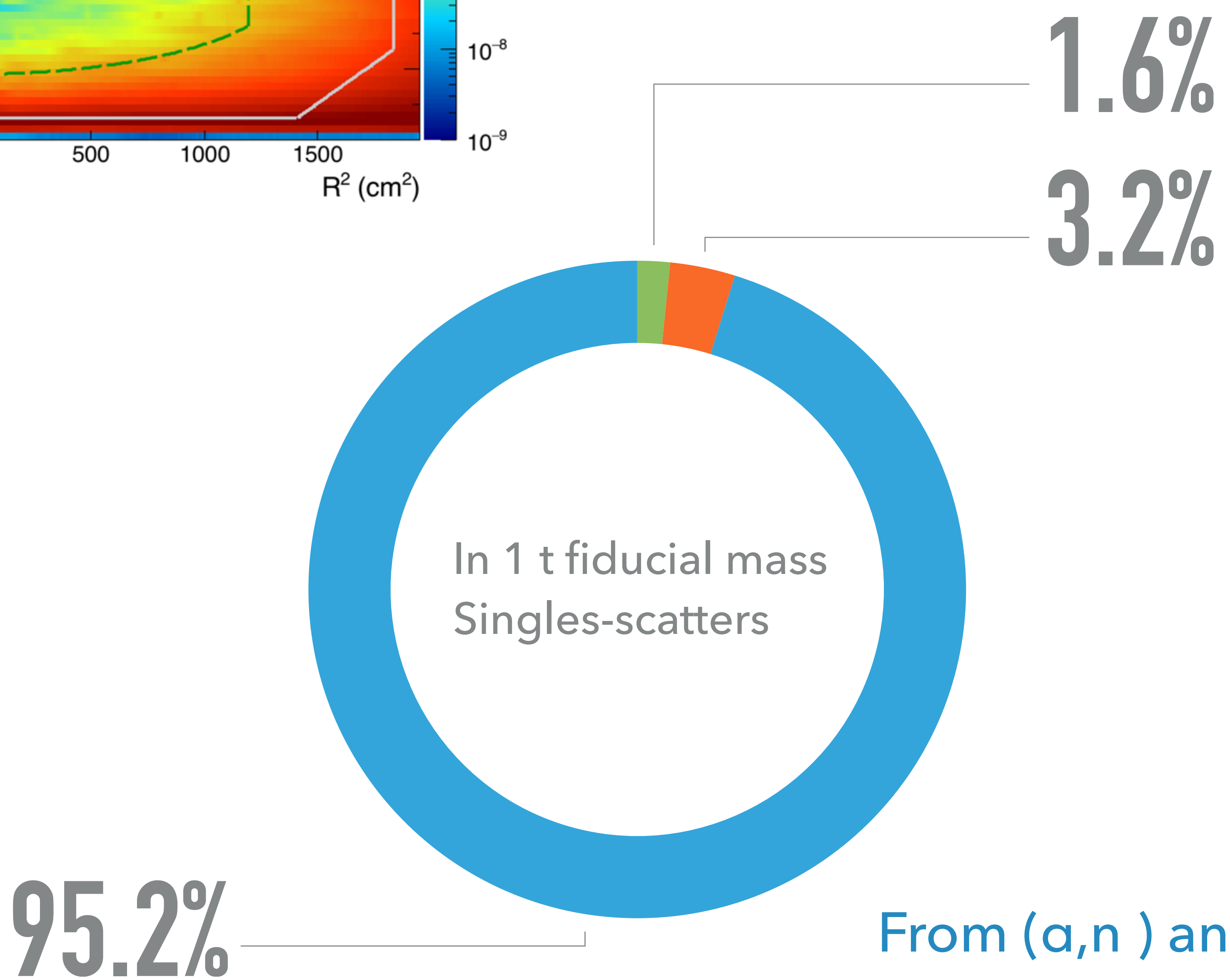
RADON BUDGET IN XENON1T



NUCLEAR RECOIL BACKGROUNDS



Cosmogenic neutrons (muon induced neutrons); rock overburden, water Cherenkov shield (here upper limit)



Coherent neutrino-nucleus scattering from ^{8}B neutrinos; irreducible, but relevant at low (<1 keV) energies

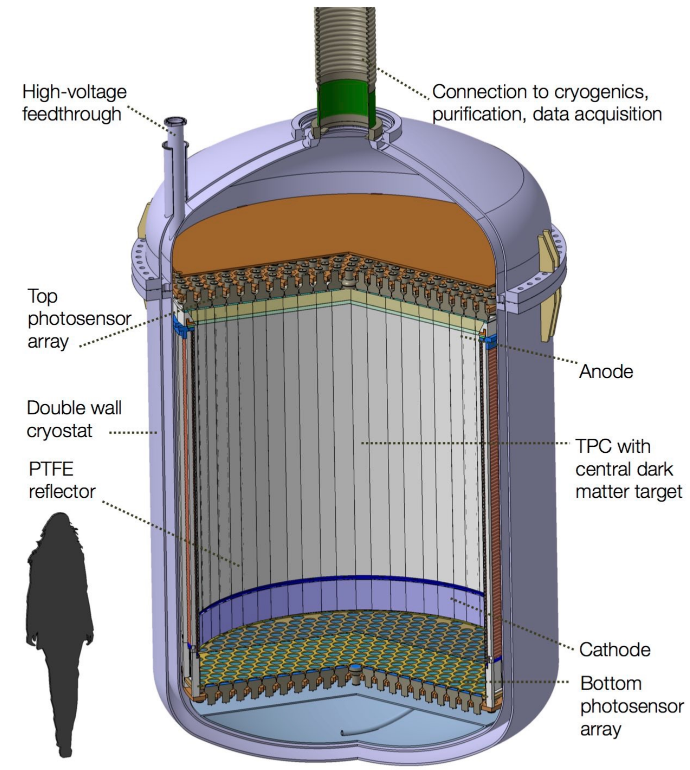
Radiogenic neutrons

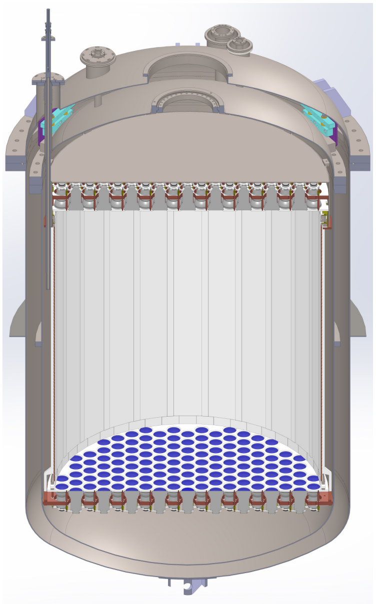
From (α,n) and SF reactions; material selection; single versus multiple-scatters

LIQUEFIED NOBLE GASES

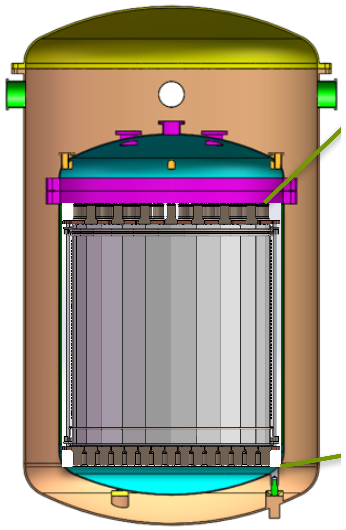
- In construction:
  - LUX-ZEPLIN, XENONnT, DarkSide-20k, PandaX-4t
- Planned (design and R&D stage)
  - DARWIN (50 t LXe), ARGO (300 t LAr)

DARWIN: 50 t LXe
Data taking ~2026

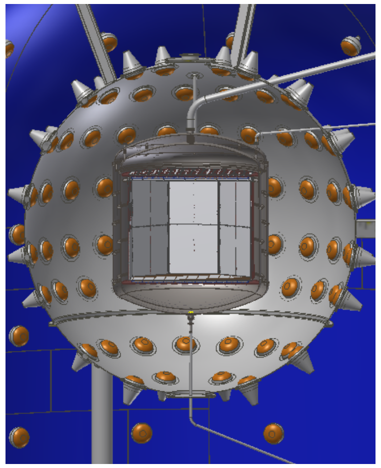




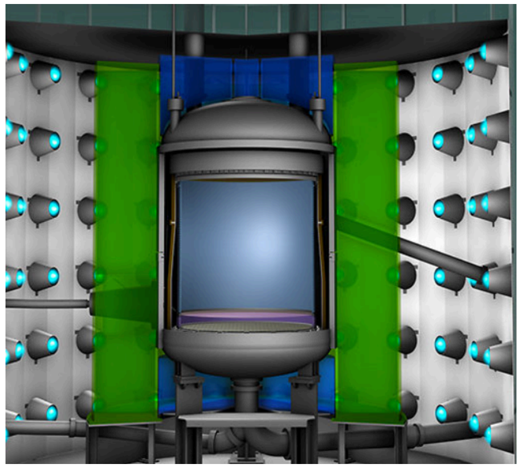
XENONnT: 8t LXe
Data taking 2020



PandaX-4t LXe
Data taking 2019



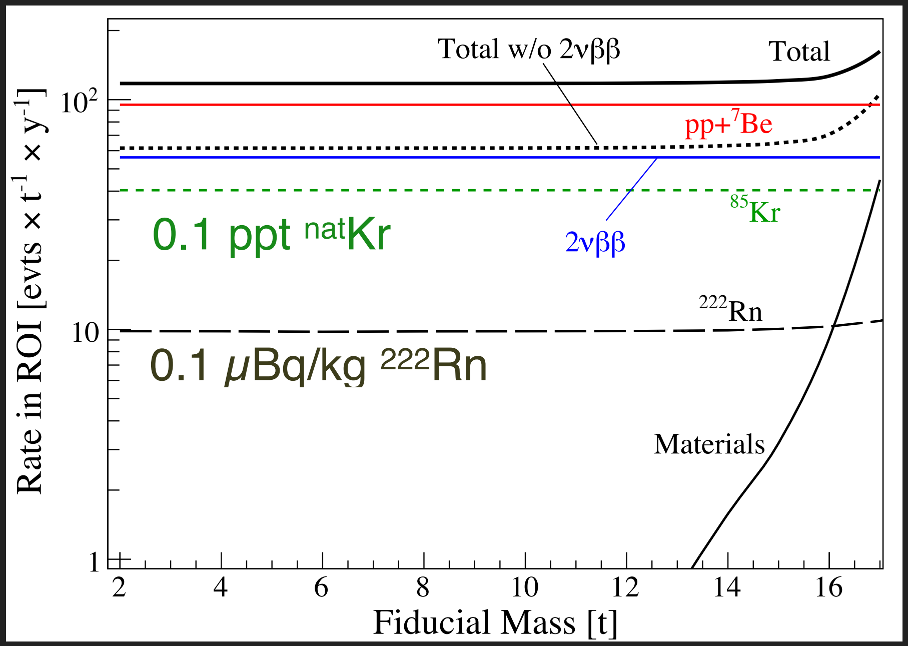
DarkSide: 20 t LAr
Data taking 2021

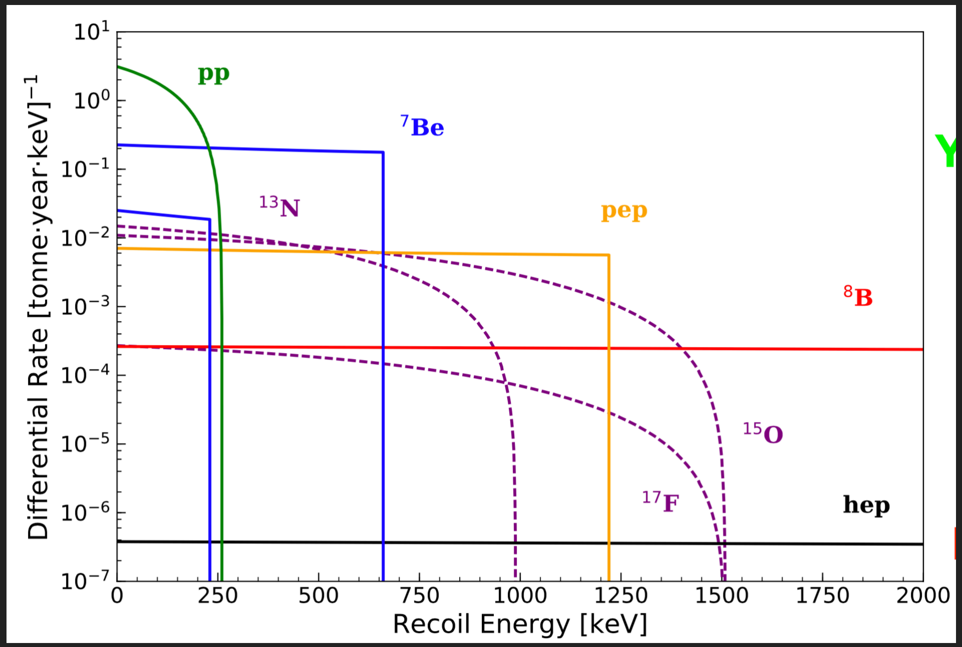


LUX-ZEPLIN: 8 t LXe
Data taking 2020

REQUIREMENTS FOR MULTI-TON, NEXT-GENERATION EXPERIMENTS

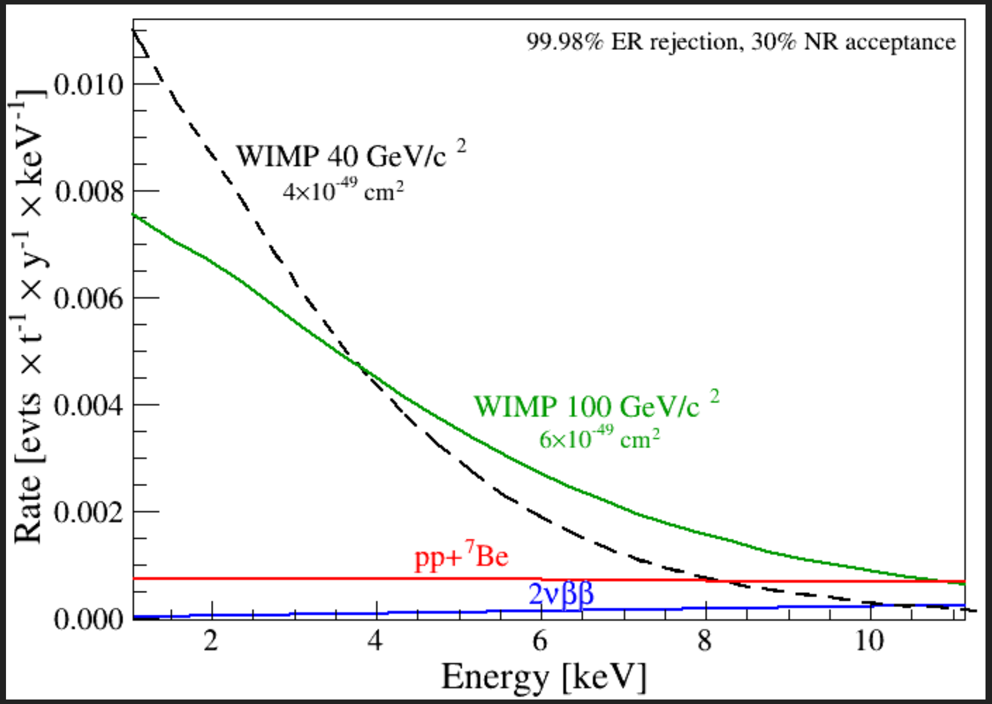
- Materials (cryostat, photosensors, TPC, etc): strong self-shielding by dense LXe
- ^{222}Rn in LXe: 0.1 µBq/kg -> via cryogenic distillation column
- ^{nat}Kr in LXe (contains 2 x 10^{-11} ^{85}Kr): 0.1 ppt -> already achieved
- ^{136}Xe double beta decay -> search for 0nbb-decay!
- Solar neutrinos (pp, ^{7}Be): will dominate -> but interesting physics channel





REQUIREMENTS FOR MULTI-TON, NEXT-GENERATION EXPERIMENTS

- Materials (cryostat, photosensors, TPC, etc): neutrons from (alpha,n) reactions
- Cosmogenic (<0.003 events/(t y) in 14 m water Cherenkov shield
- ^{8}B neutrinos: coherent nu-nucleus scattering)
- ^{222}Rn in LXe, ^{nat}Kr in LXe, ^{136}Xe, pp, ^{7}Be neutrinos



Channel	Before discr	After discr (99.98%)
pp + ^{7}Be neutrinos	**95**	**0.488**
Materials	1.4	0.007
^{85}Kr in LXe (0.1 ppt ^{nat}Kr)	40.4	0.192
^{222}Rn in LXe (0.1 μBq/kg)	9.9	0.047
^{136}Xe	56.1	0.036

CONCLUSIONS

- Large-scale underground experiments share many common features
- Due to very low expected event rates:
  - Large detector masses, ultra-low background goals
  - Material radio-assay (and radon emanation measurements) and selection remains crucial
- In general: dark matter detectors are optimised at keV energy scales, double beta decay detectors at MeV-scale energies
  - Can we do both? Ideally, large detectors with sensitivity to search for a variety of signals
- Eventually limited by neutrino interactions (but also new physics opportunities!)

OF COURSE, "THE PROBABILITY OF SUCCESS IS DIFFICULT TO ESTIMATE, BUT IF WE NEVER SEARCH, THE CHANCE OF SUCCESS IS ZERO"

G. Cocconi & P. Morrison, Nature, 1959

THE END