University of Zurich[UZH]

PARTICLE PHYSICS IN LIQUID XENON DETECTORS

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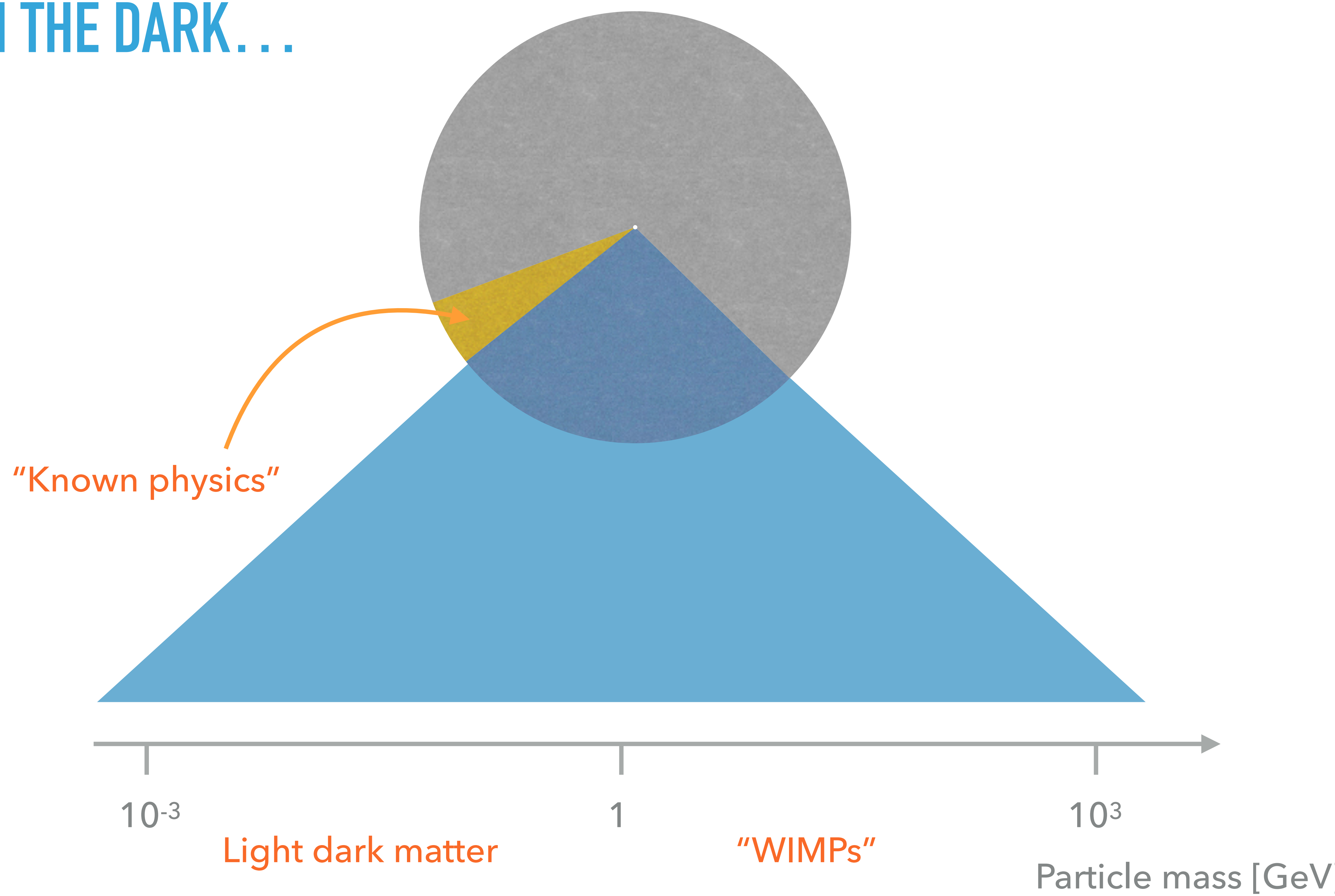
MASSIVE NEUTRINOS WORKSHOP
HERAEUS SEMINAR, PHYSIKZENTRUM BAD HONNEF
JULY 11, 2019

SOME KEY OPEN QUESTIONS IN PARTICLE PHYSICS

- The nature of dark matter
- Baryogenesis
- The strong CP problem
- The fermion mass spectrum and mixing
- The cosmological constant
- …
- Some of these can be addressed with liquid xenon detectors operated deep underground
- Demonstrated excellent sensitivities and scalability to large target masses

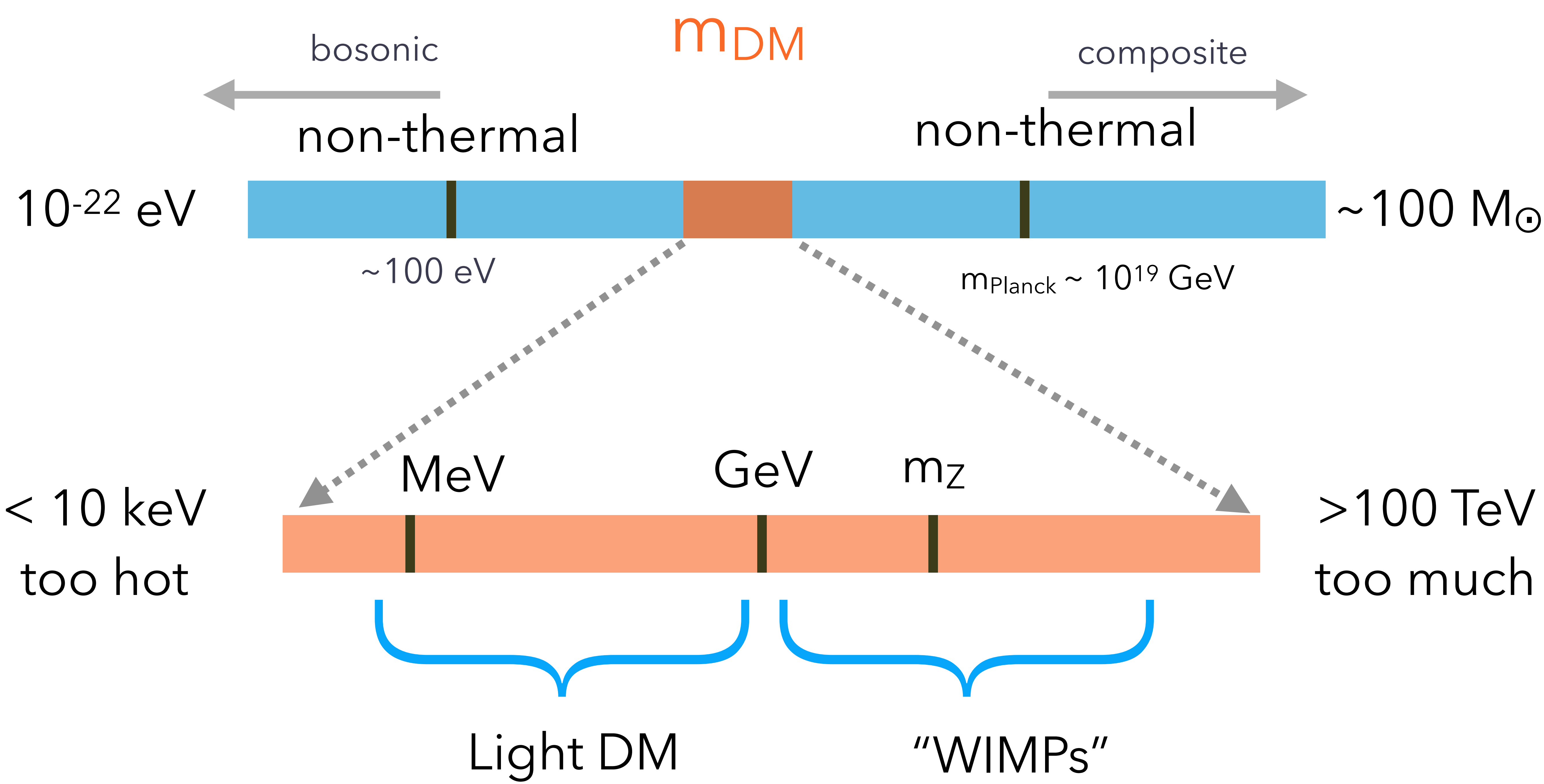
IN THE DARK…



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

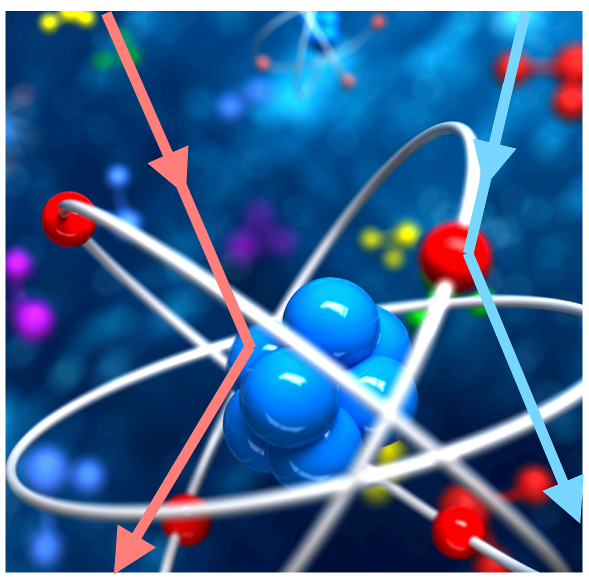
See also arXiv:1707.04591

DARK MATTER CANDIDATES



HOW TO SEE IN THE DARK?

χ $\xrightarrow{q \leq 10s\,\mathrm{MeV}}$ χ



DM-SM mediator

- 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

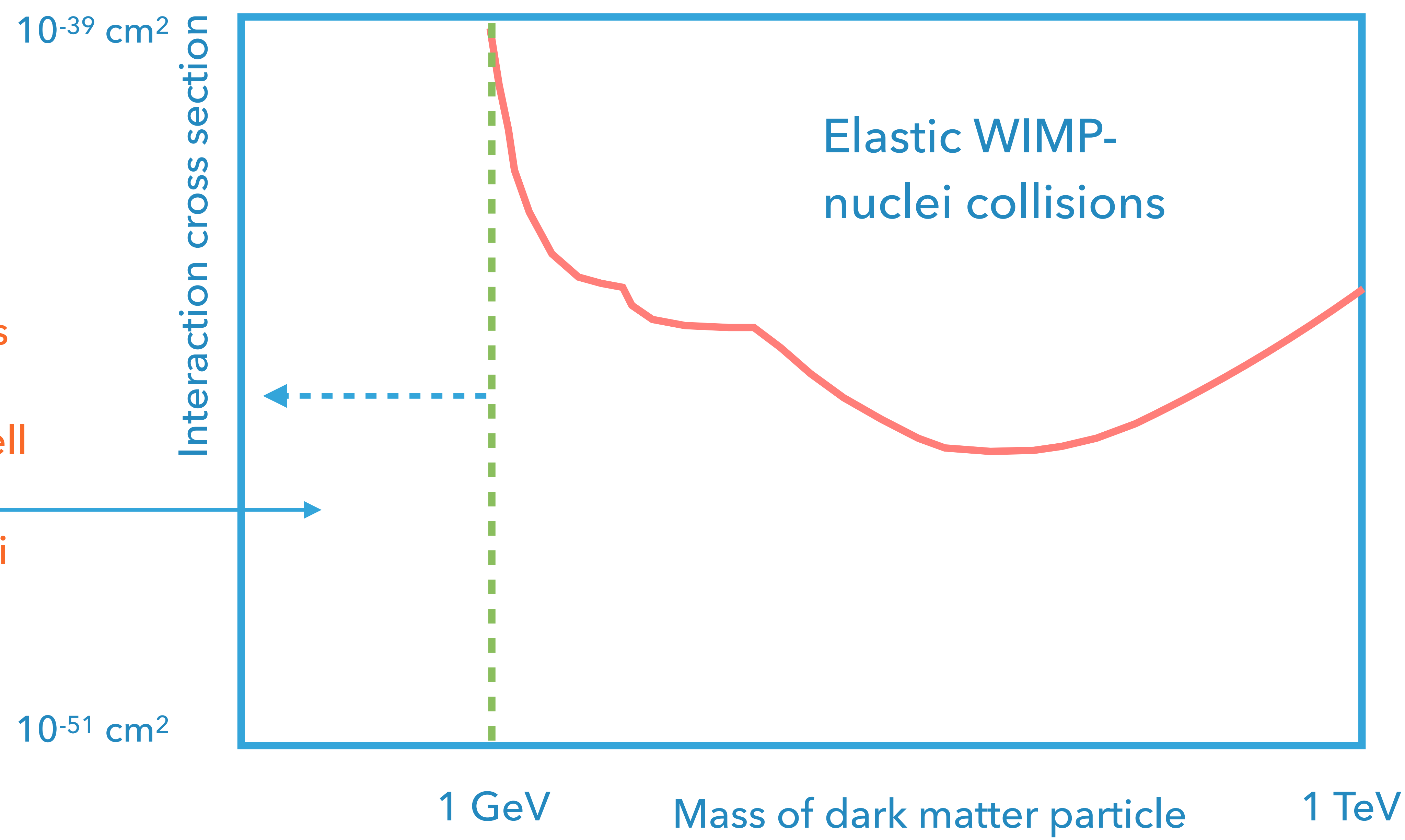
Standard Model states

Standard Model states

DARK MATTER PARTICLE INTERACTIONS

see R. Essig et al, 2018, and others

Electron recoils and additional signal from shell e⁻ from the recoiling nuclei



SCATTERING OFF ELECTRONS

Rouven Essig, KITP 2018

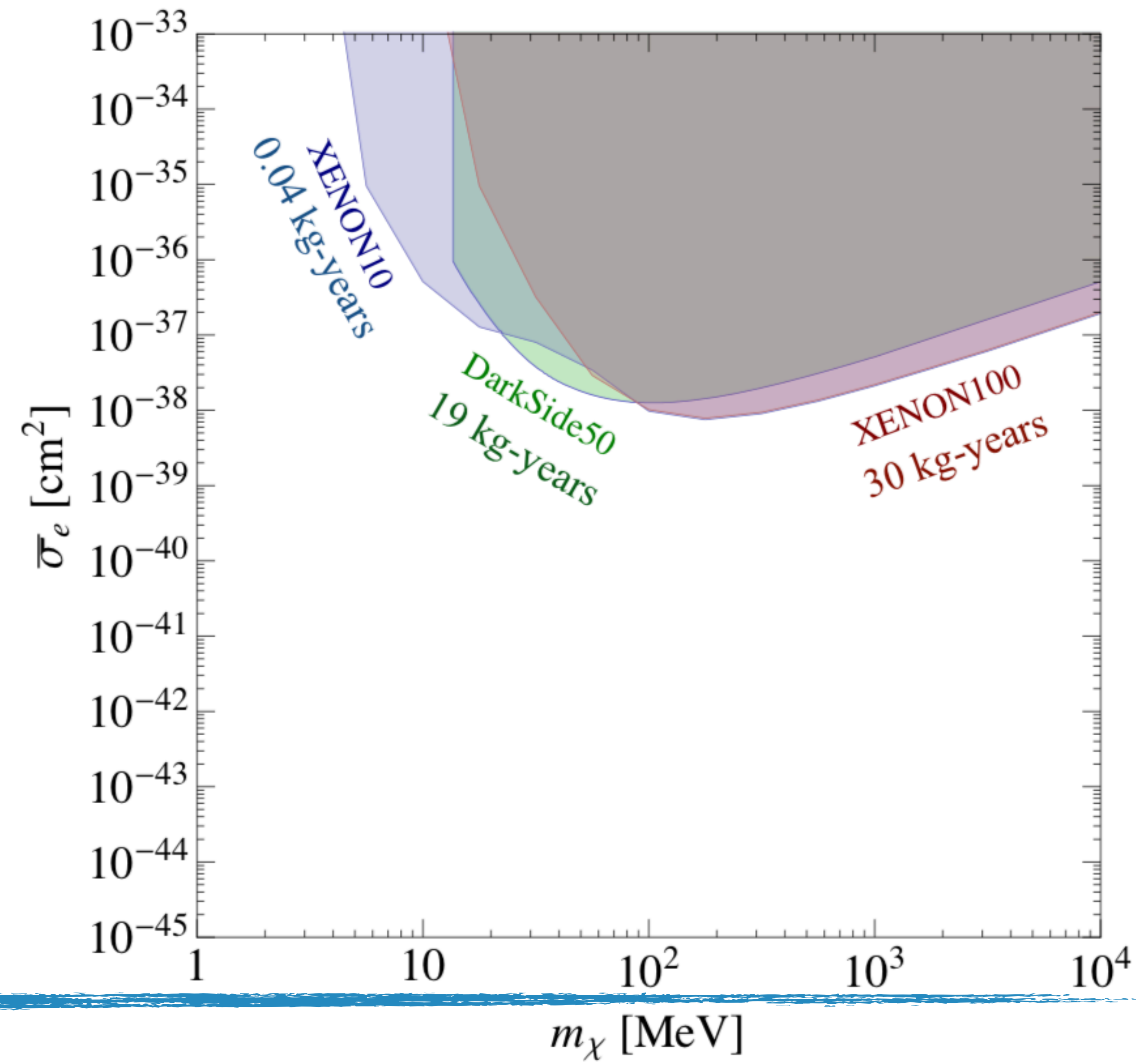
All the kinetic energy (e.g., 50 eV for a 100 MeV particle, v~10^{-3}c) can be transferred to the material

In general: ionisation, excitation, molecular dissociation

For a bound e^- with E_B, a DM mass of

$$m_\chi \geq 250\,\mathrm{keV} \times \mathrm{E_B}/1\,\mathrm{eV}$$

can be probed



1 keV 1 MeV

Recently: many new techniques to search for much lighter (sub-GeV) particles

see also "Cosmic visions", 1707.04591

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

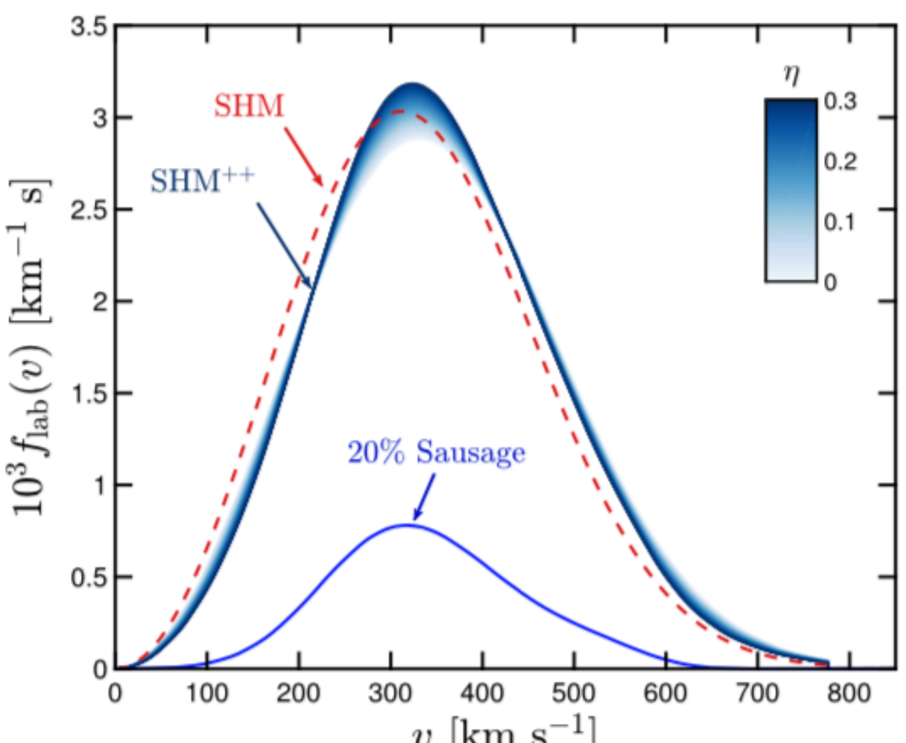
$m_W, d\sigma/dE_R$

Astrophysics

$\rho_0, f(v)$

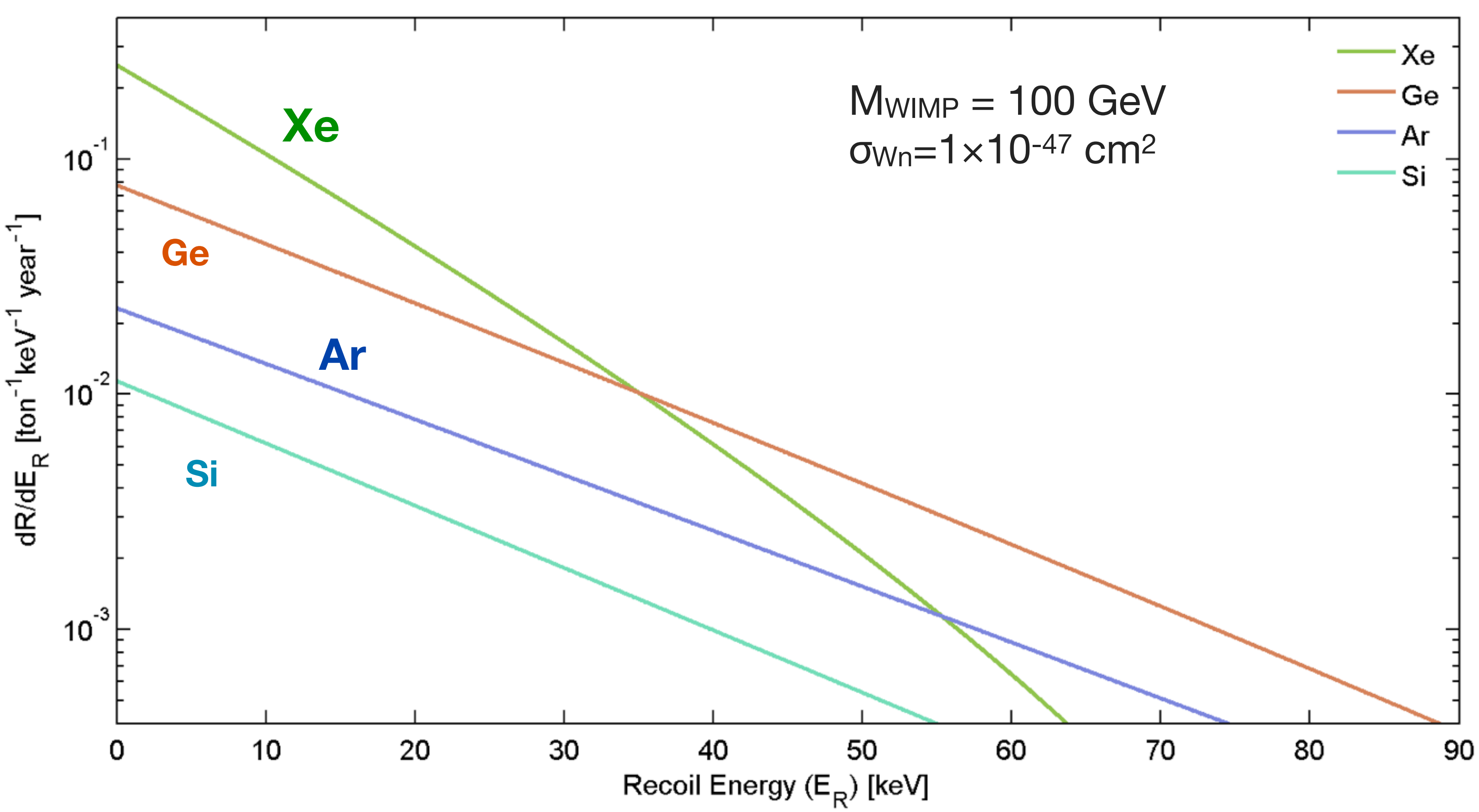
SHM	Local DM density	ρ_0	$0.3\ \mathrm{GeV\,cm^{-3}}$
	Circular rotation speed	v_0	$220\ \mathrm{km\,s^{-1}}$
	Escape speed	v_{esc}	$544\ \mathrm{km\,s^{-1}}$
	Velocity distribution	$f_R(\mathbf{v})$	Eq. (1)
SHM^{++}	Local DM density	ρ_0	$0.55 \pm 0.17\ \mathrm{GeV\,cm^{-3}}$
	Circular rotation speed	v_0	$233 \pm 3\ \mathrm{km\,s^{-1}}$
	Escape speed	v_{esc}	528^{+24}_{-25}
	Sausage anisotropy	β	0.9 ± 0.05
	Sausage fraction	η	0.2 ± 0.1
	Velocity distribution	$f(\mathbf{v})$	Eq. (3)

Evans, O'Hare, McCabe, PRD99, 2019



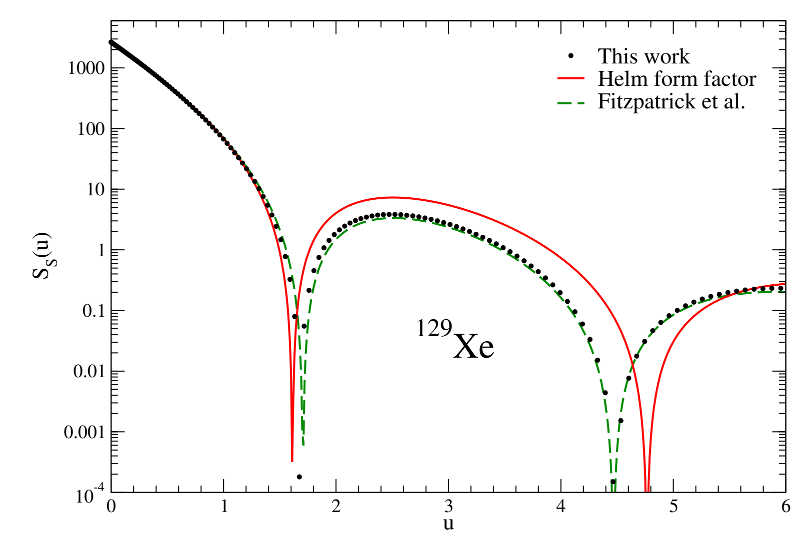
INTERACTION RATES

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

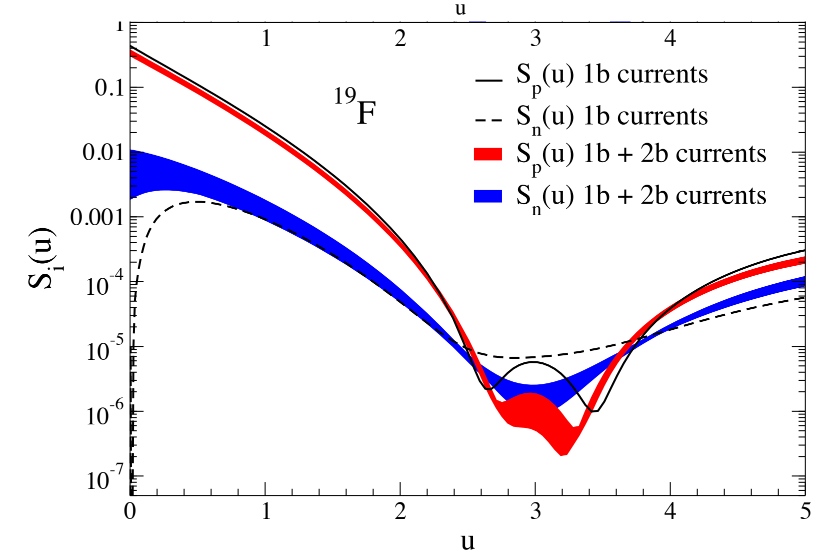


Spin-independent (SI) nuclear recoil spectrum

LB, Physics of the Dark Universe 2012



SI



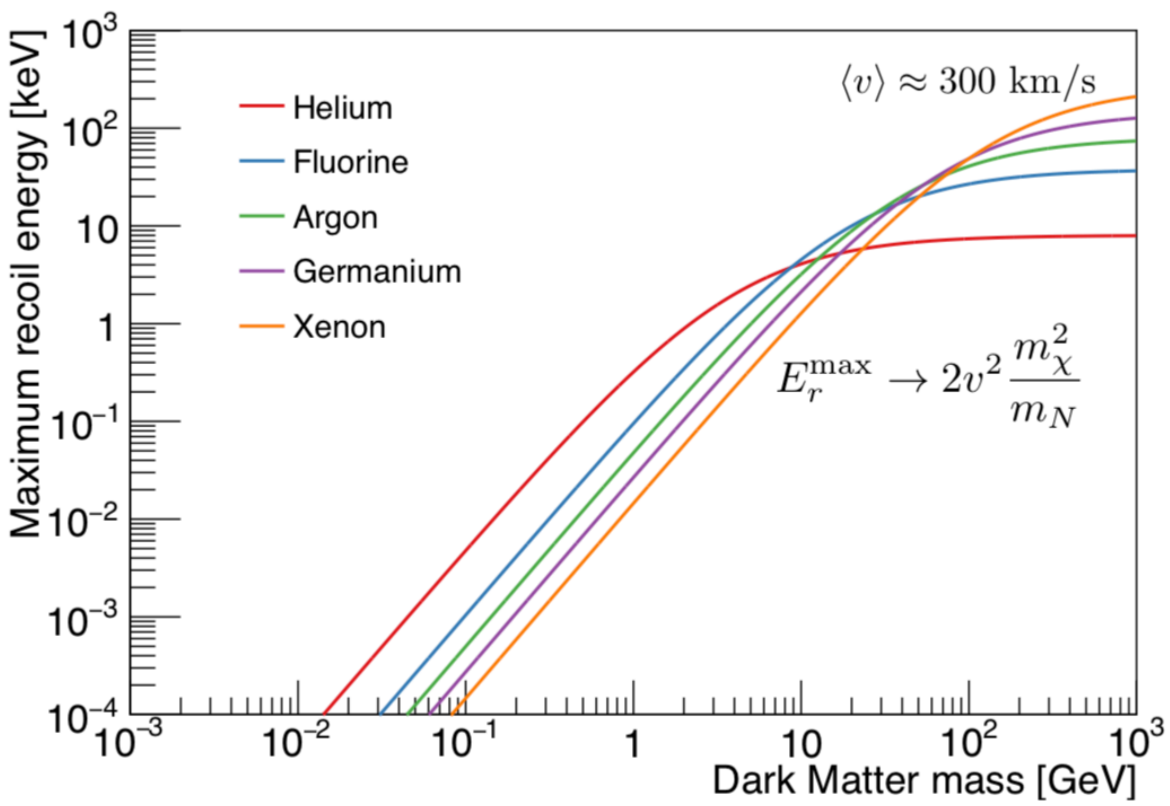
SD

A. Schwenk, J. Menendez et al

LOW-MASS DARK MATTER

- Once the mass of the dark matter particle is much smaller than the nuclear mass, the transfer of kinetic energy becomes very inefficient
- Thus, exploit *dark matter - electron scattering* R. Essig, J. Mardon, T. Volansky, PRD85, 2012

DM-nucleus scattering



+ electronic recoil

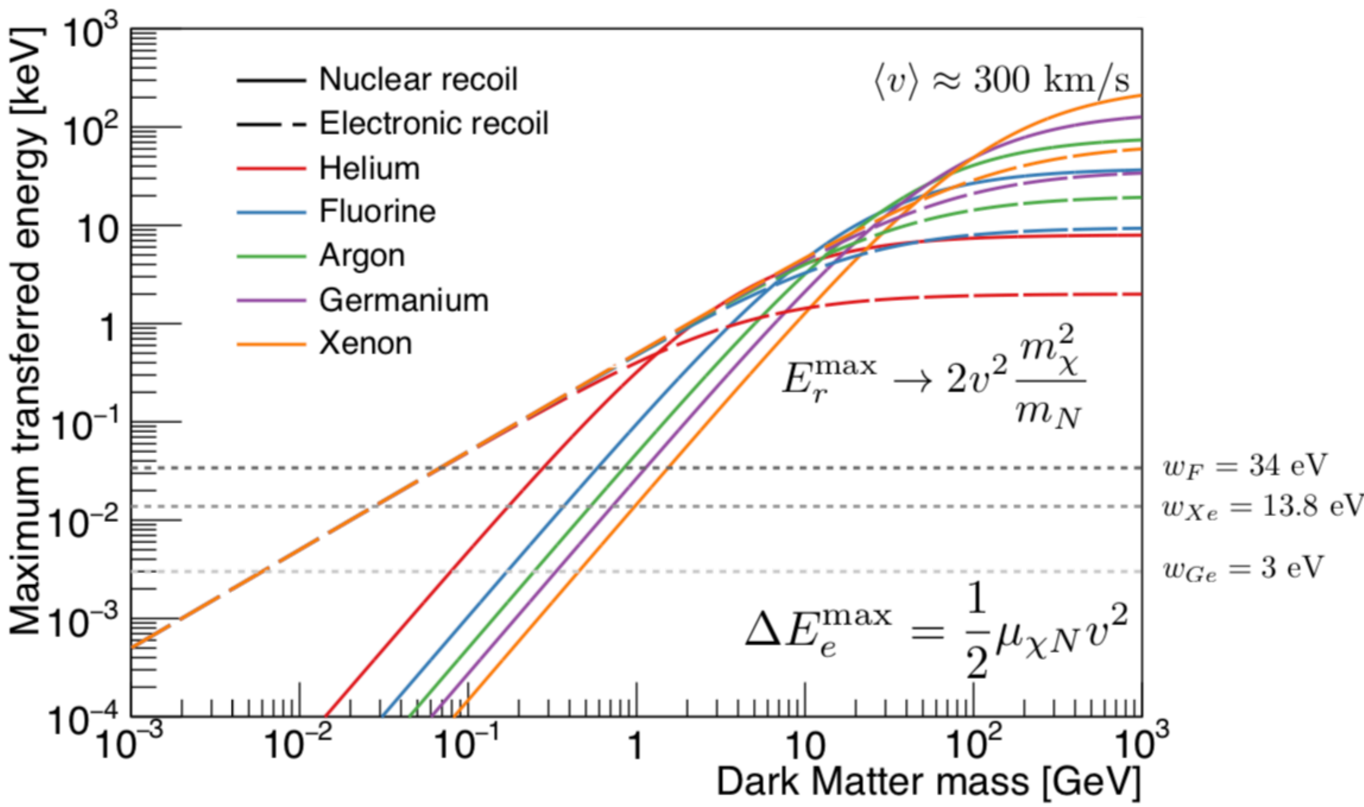
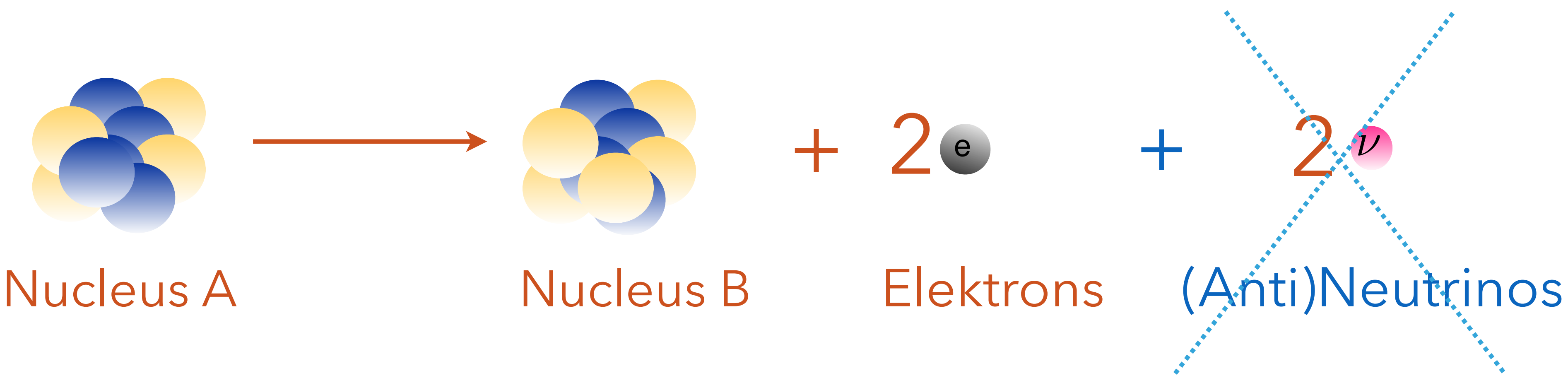


Fig. shown by Silvia Scorza, PPC2018, Zurich

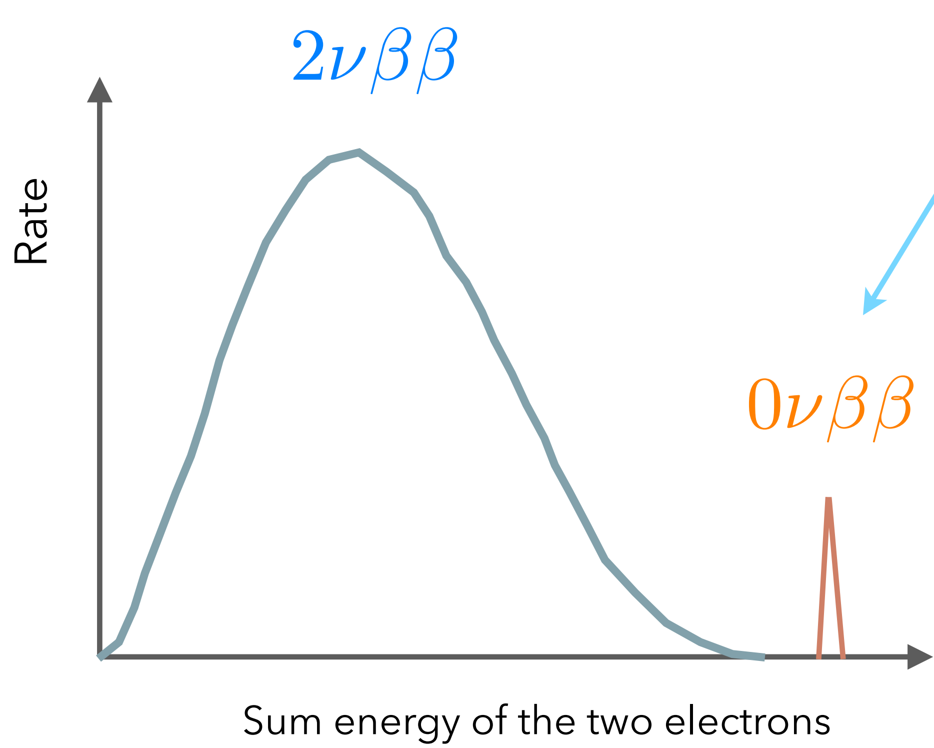
(SOME) OPEN QUESTIONS IN NEUTRINO PHYSICS

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

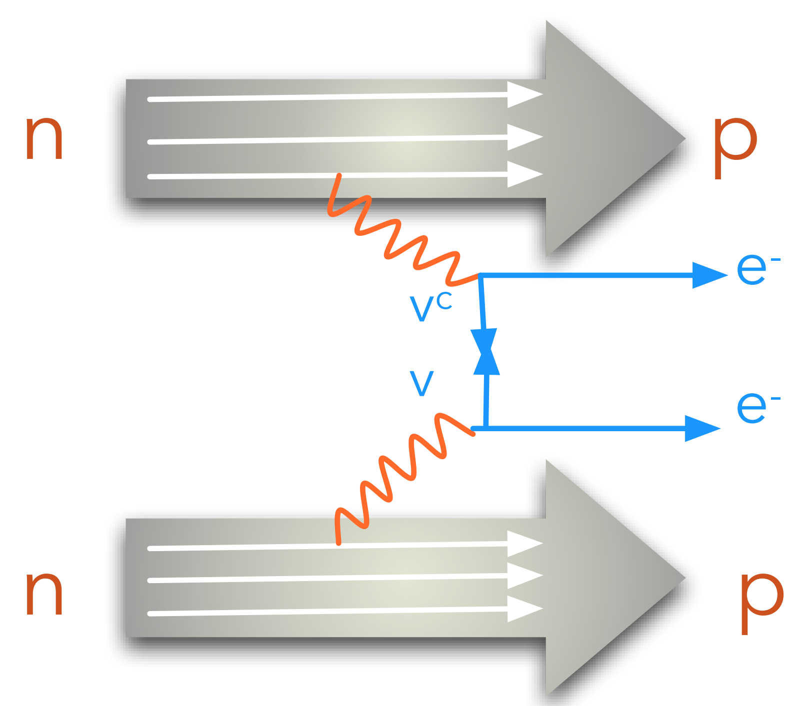


THE NEUTRINOLESS DOUBLE BETA DECAY

- 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

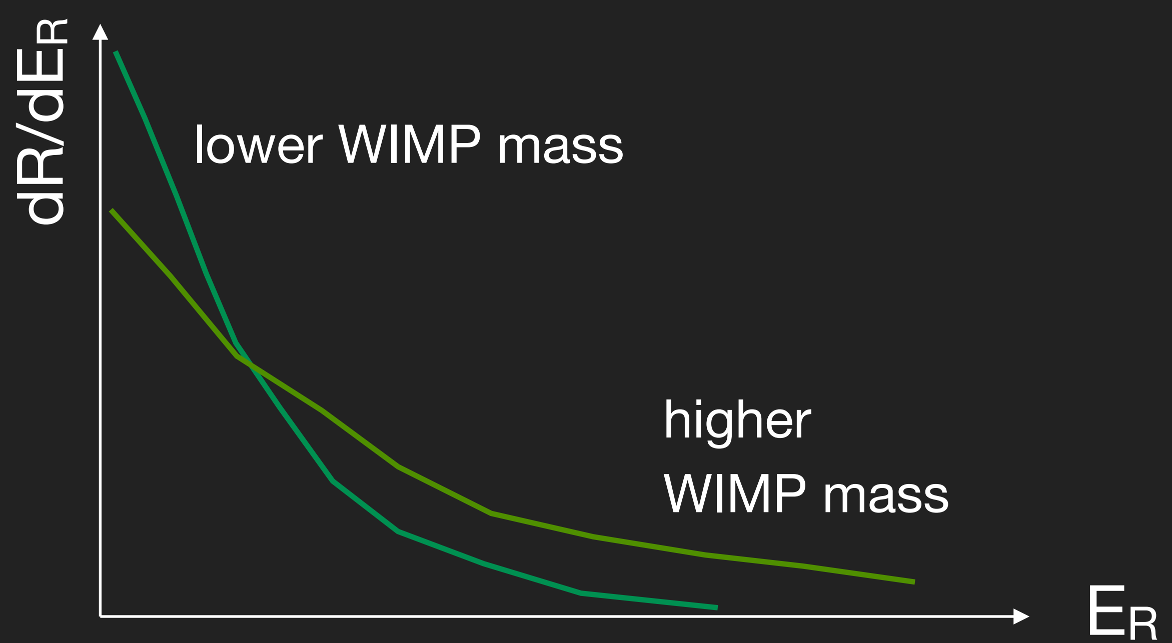


$$T_{1/2}^{0\nu\beta\beta} > 10^{24}\ \mathrm{y}$$

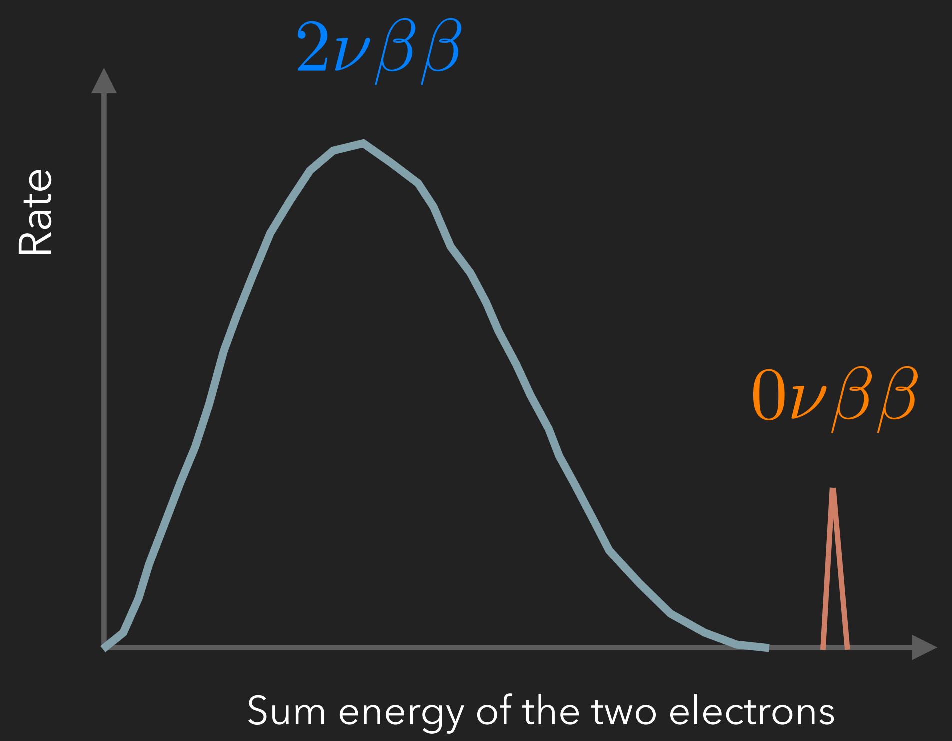


MAIN CHARACTERISTICS

- 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

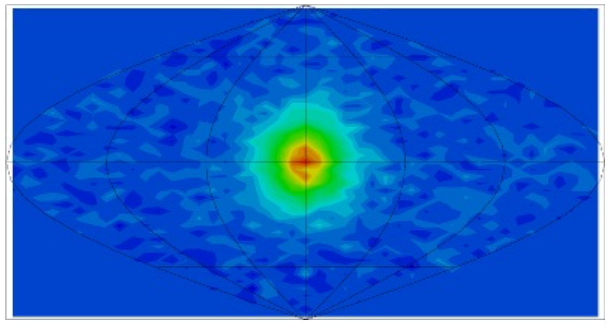
- Low energy thresholds
- Large detector masses
- Ultra-low backgrounds
- Excellent signals versus background discrimination

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

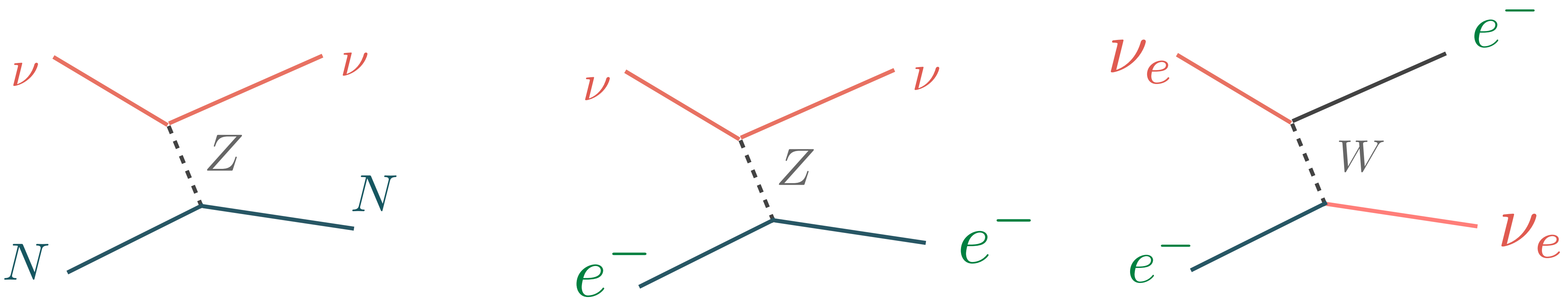
- Excellent energy resolution
- Large detector masses
- Ultra-low backgrounds
- Excellent signals versus background discrimination

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

BACKGROUNDS

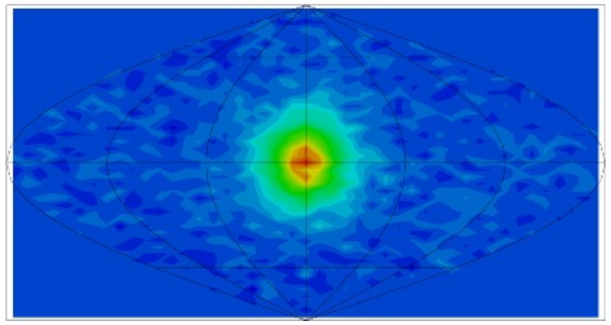


- In the ideal case: below the expected signal
  - Muons & associated showers; cosmogenic activation of detector materials
  - Natural (^{228}U, ^{232}Th, ^{40}K), anthropogenic (^{85}Kr, ^{137}Cs) and other (^{60}Co, ^{42}Ar, etc) radioactivity: γ, e^-, n, α
  - Ultimately: neutrinos (+ $2\nu\beta\beta$-decays,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



COHERENT, Science, August 3, 2017

BACKGROUNDS



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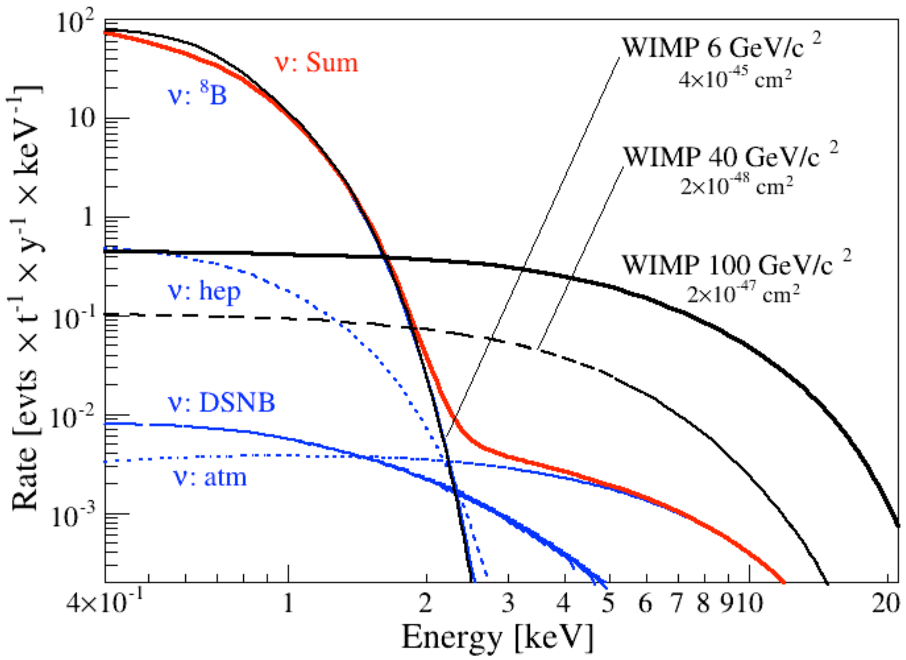
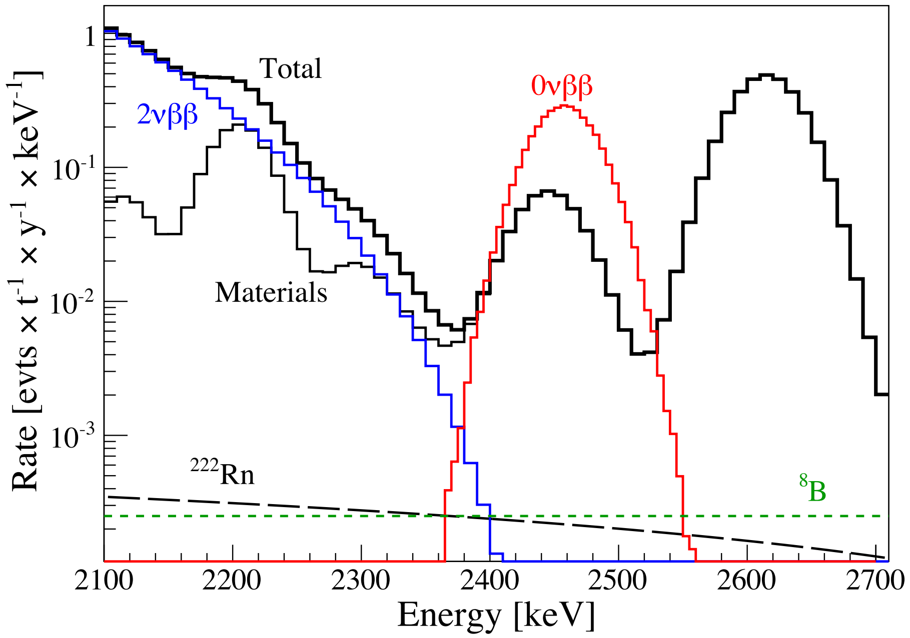
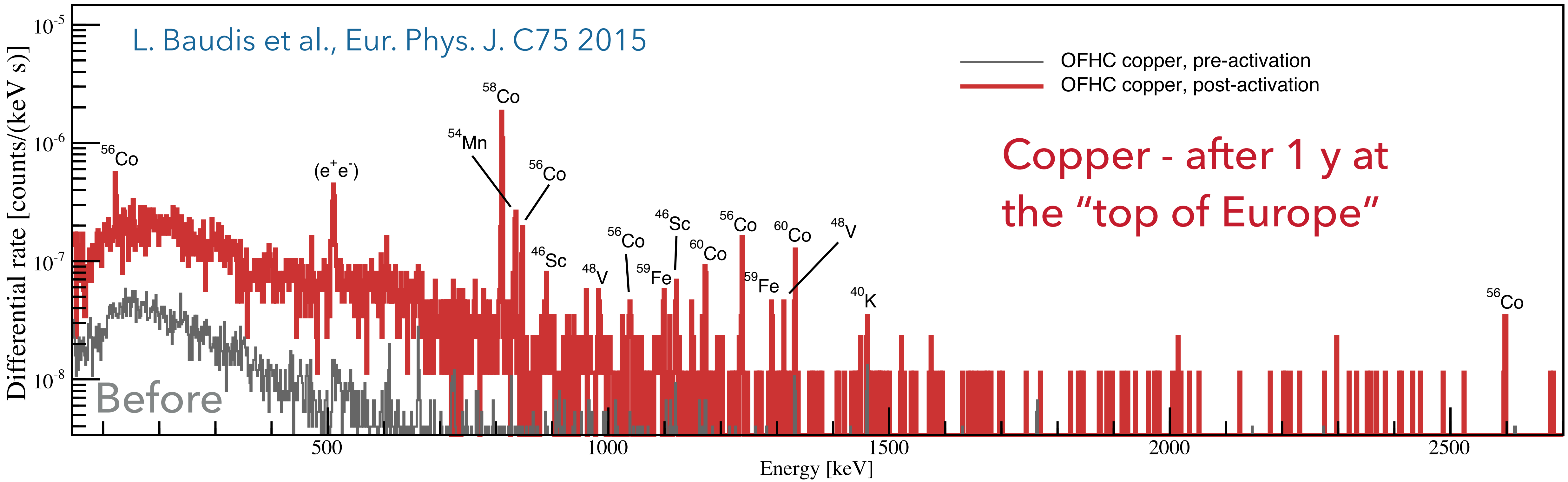




LB et al., JCAP01 (2014) 044

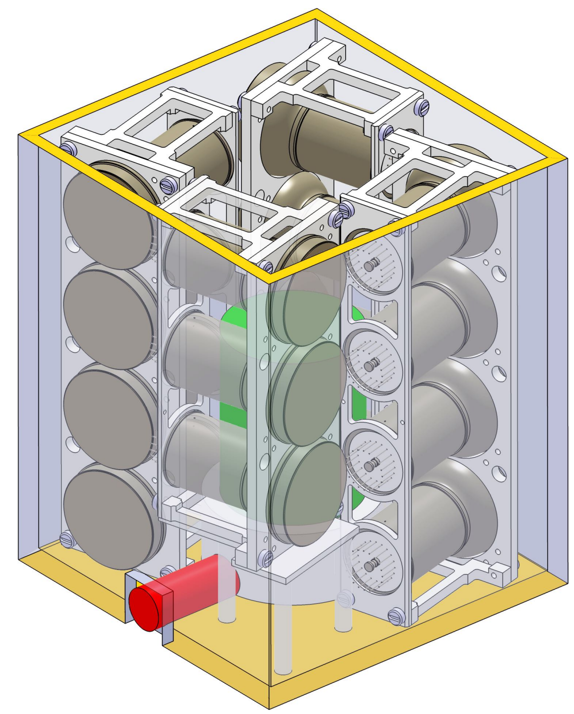
AVOID EXPOSURE TO COSMIC RAYS

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



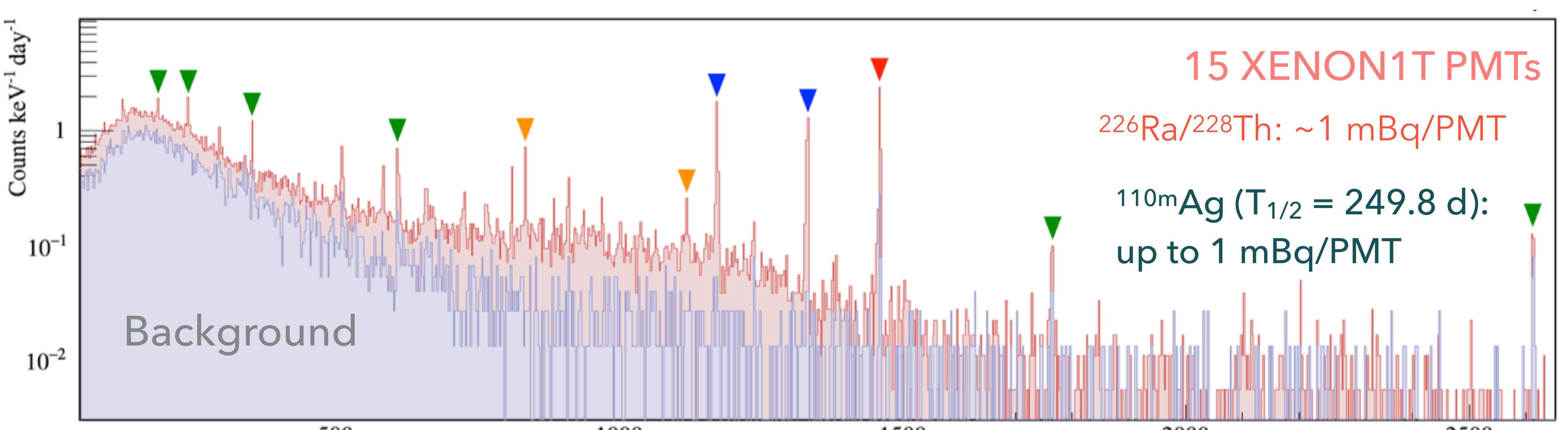
MATERIAL SCREENING AND SELECTION

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



Gator HPGe detector at LNGS

L. Baudis et al., JINST 6, 2011



XENON collaboration, EPJ-C 75 (2015) 11

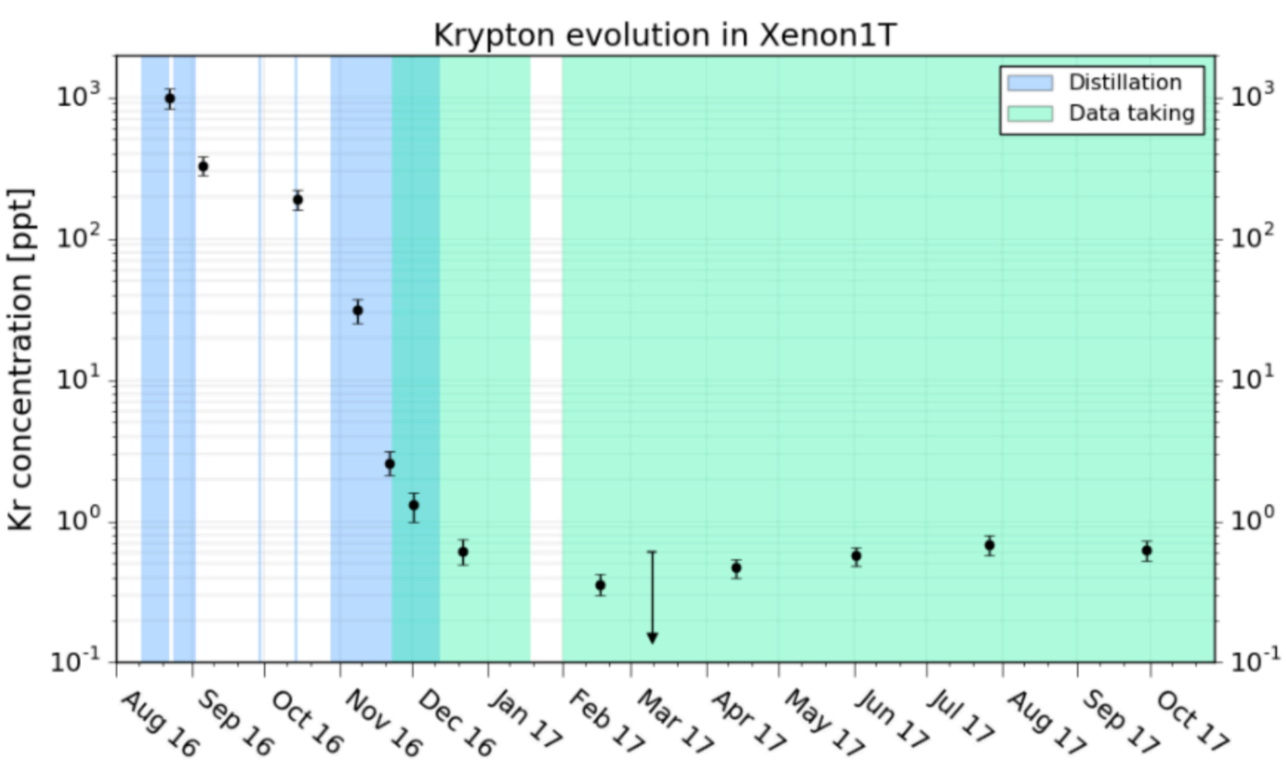
XENON collaboration, EPJ-C 77 (2017) 5

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)



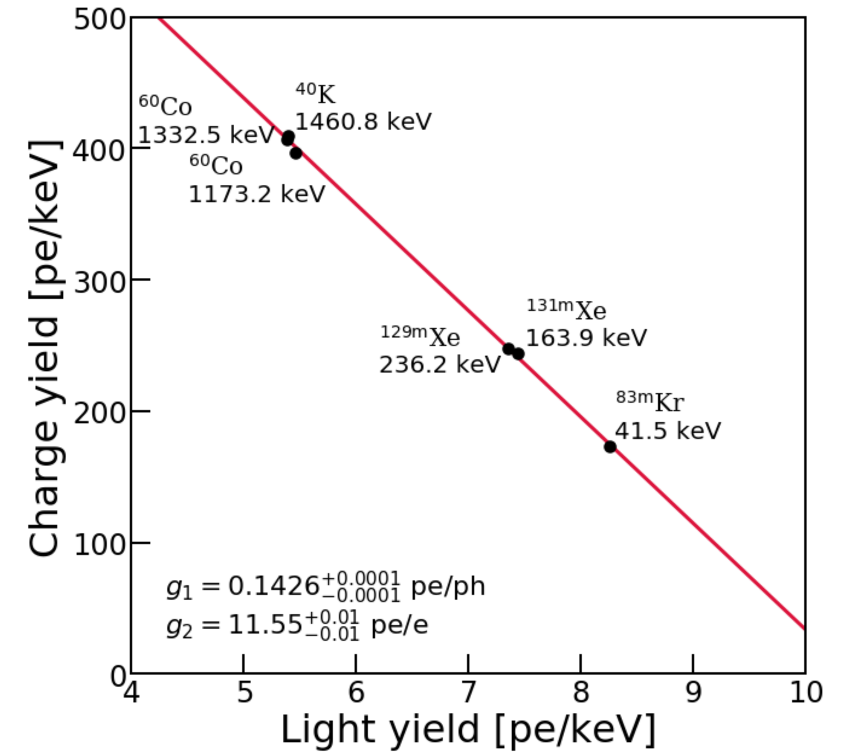
Evolution of Kr/Xe [ppt, mol/mol] level during online distillation

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

ENERGY RESOLUTION

- Anti-correlation between light (S1) and charge (S2)
- Energy scale uses linear combination of S1 and S2
- Photon gain: g_1 (pe/photon), electron gain: g_2 (pe/electron)

$$\frac{S2}{E} = \frac{g_2}{W} - \frac{g_2}{g_1}\frac{S1}{E}$$

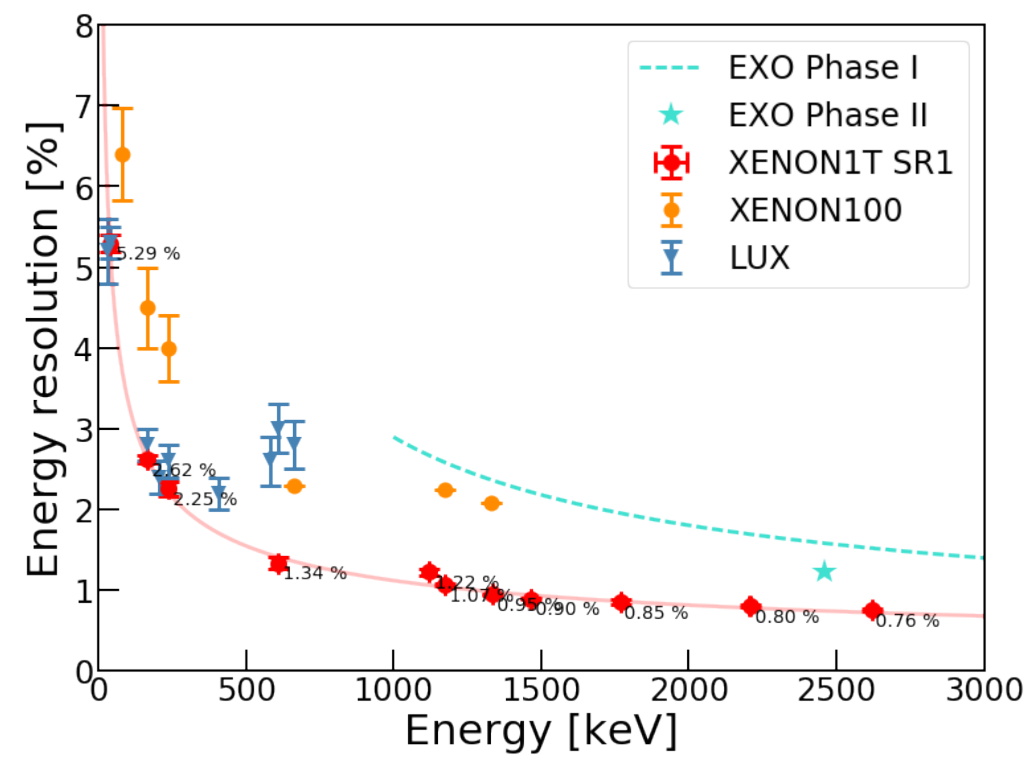


$$E = (n_{ph} + n_e) \cdot W = \left(\frac{S_1}{g_1} + \frac{S_2}{g_2}\right) \cdot W$$

W-value = 13.7 eV

Example for XENON1T:

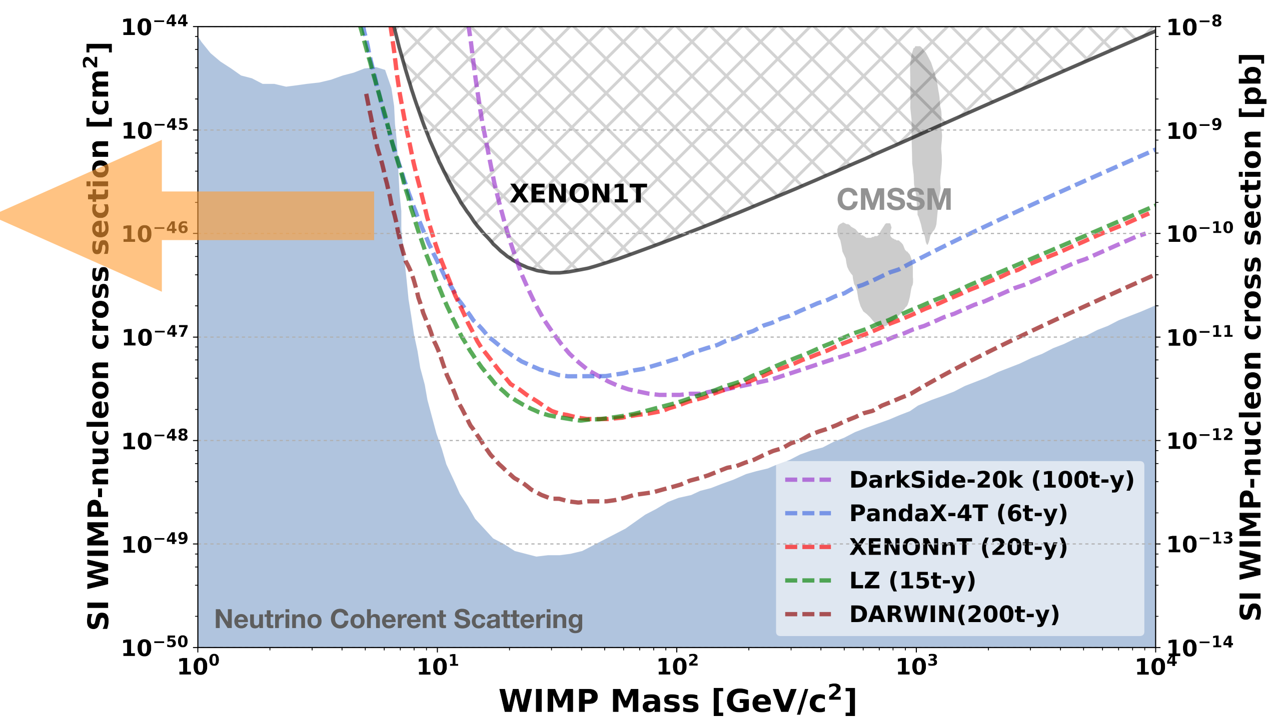
0.8% relative energy resolution (σ/E) around 2.5 MeV



EXPERIMENTAL STATUS: OVERVIEW

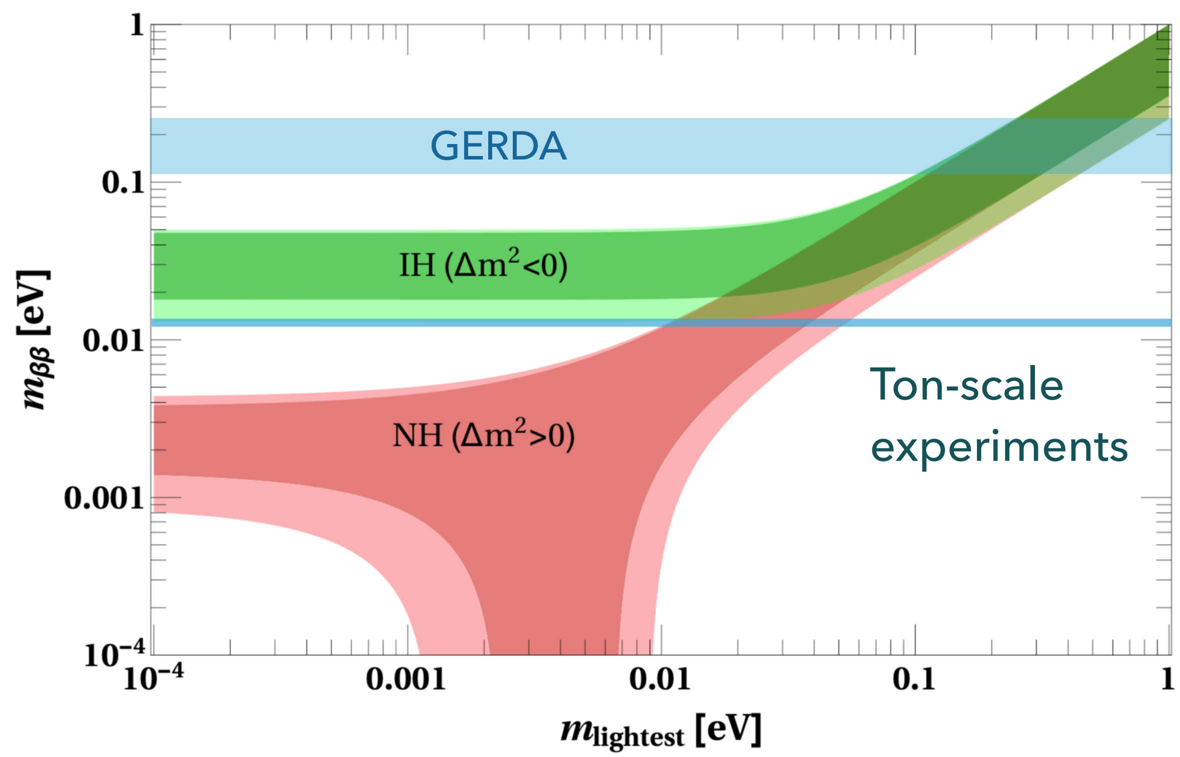
- No evidence for dark matter particles
- Probing scattering cross sections (on nucleons) of a few x 10^{-47} cm^2

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



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

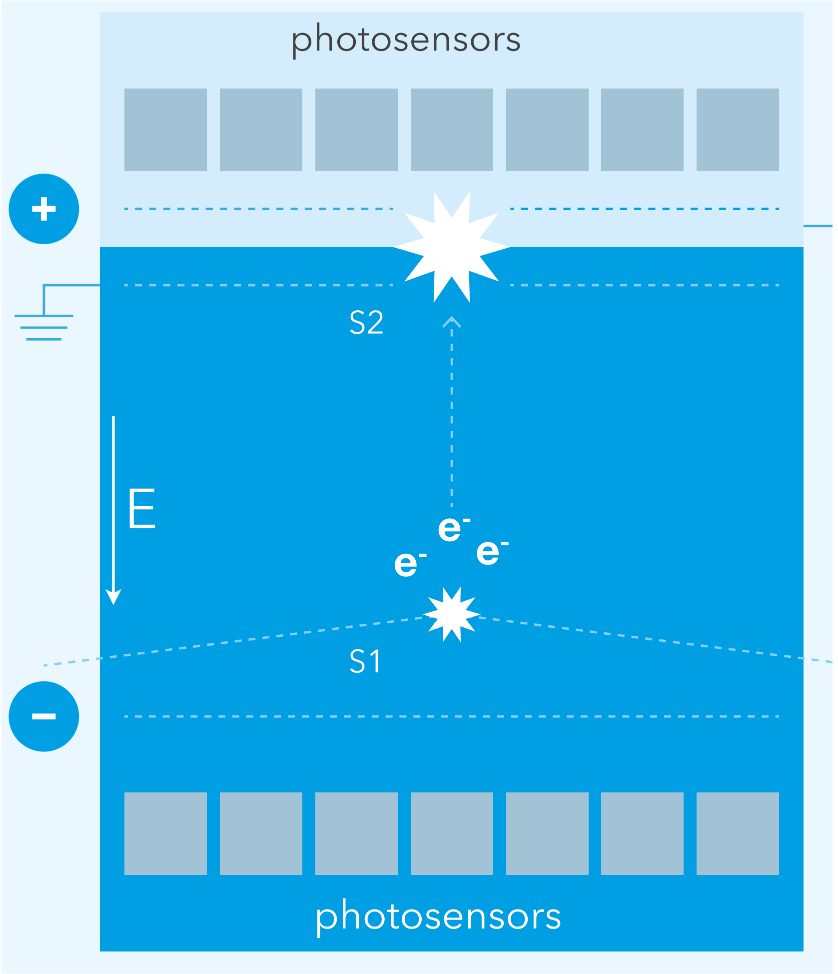
$$m_{\beta\beta} < 0.11 - 0.26\,\mathrm{eV}\ (90\%\mathrm{C.L.})$$



LIQUEFIED XENON

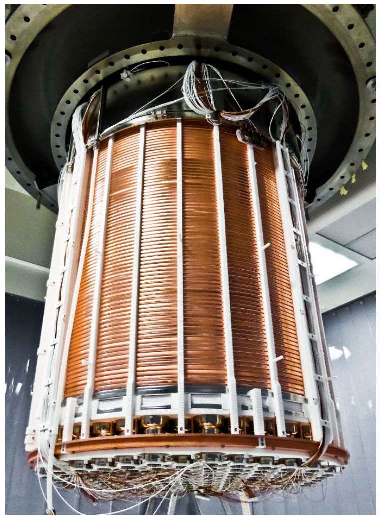
- Single and two-phase Xe detectors
- Time projection chambers:
  - 3D position resolution via *light (S1)* & *charge (S2)* -> fiducialisation
  - S2/S1 ->particle ID
  - Single versus multiple interactions

Example: 2-phase Xe TPC



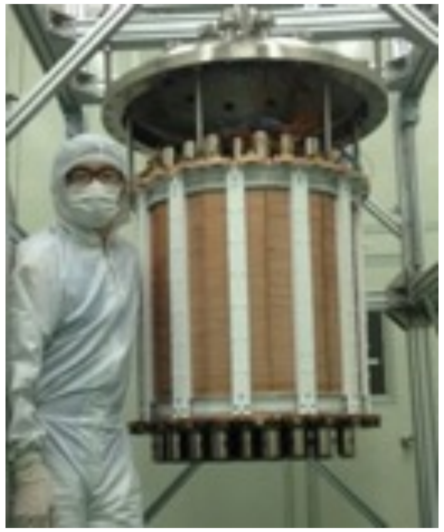
XMASS

XENON1T

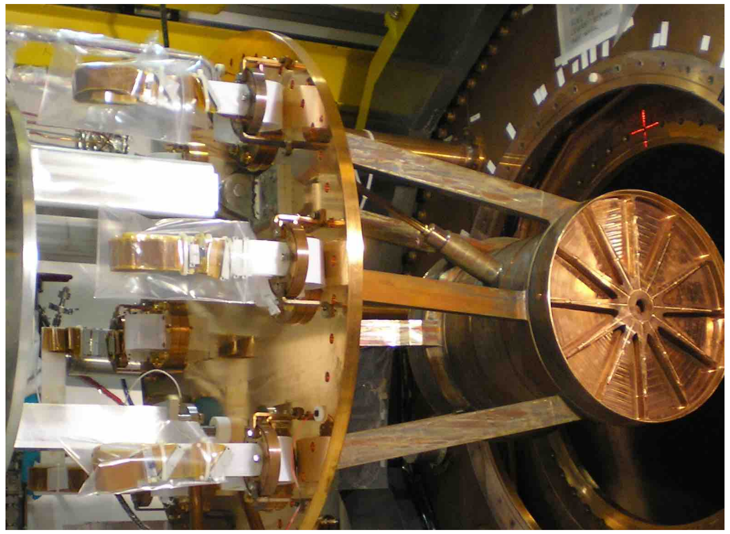


LUX

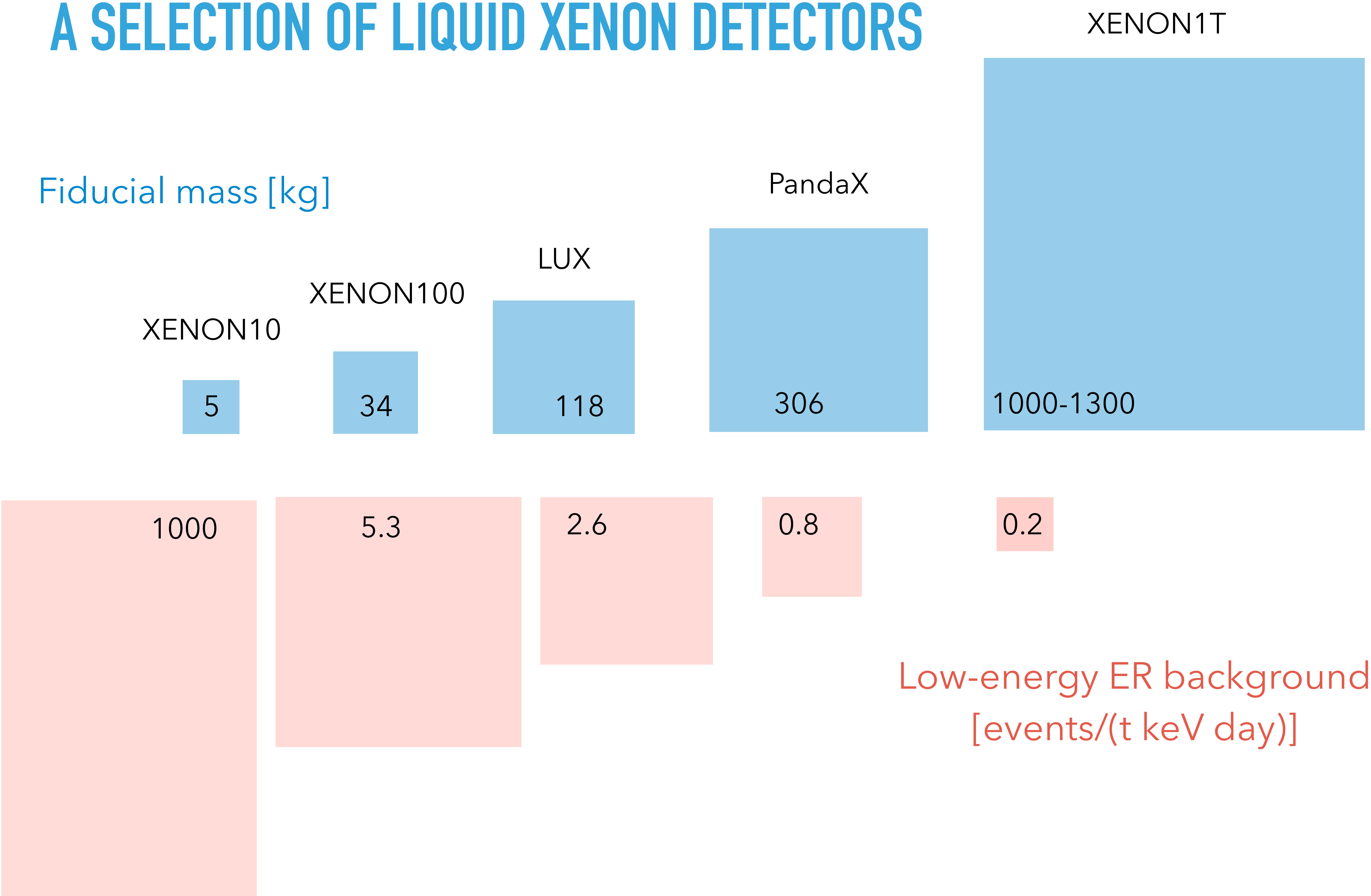
PandaX-II



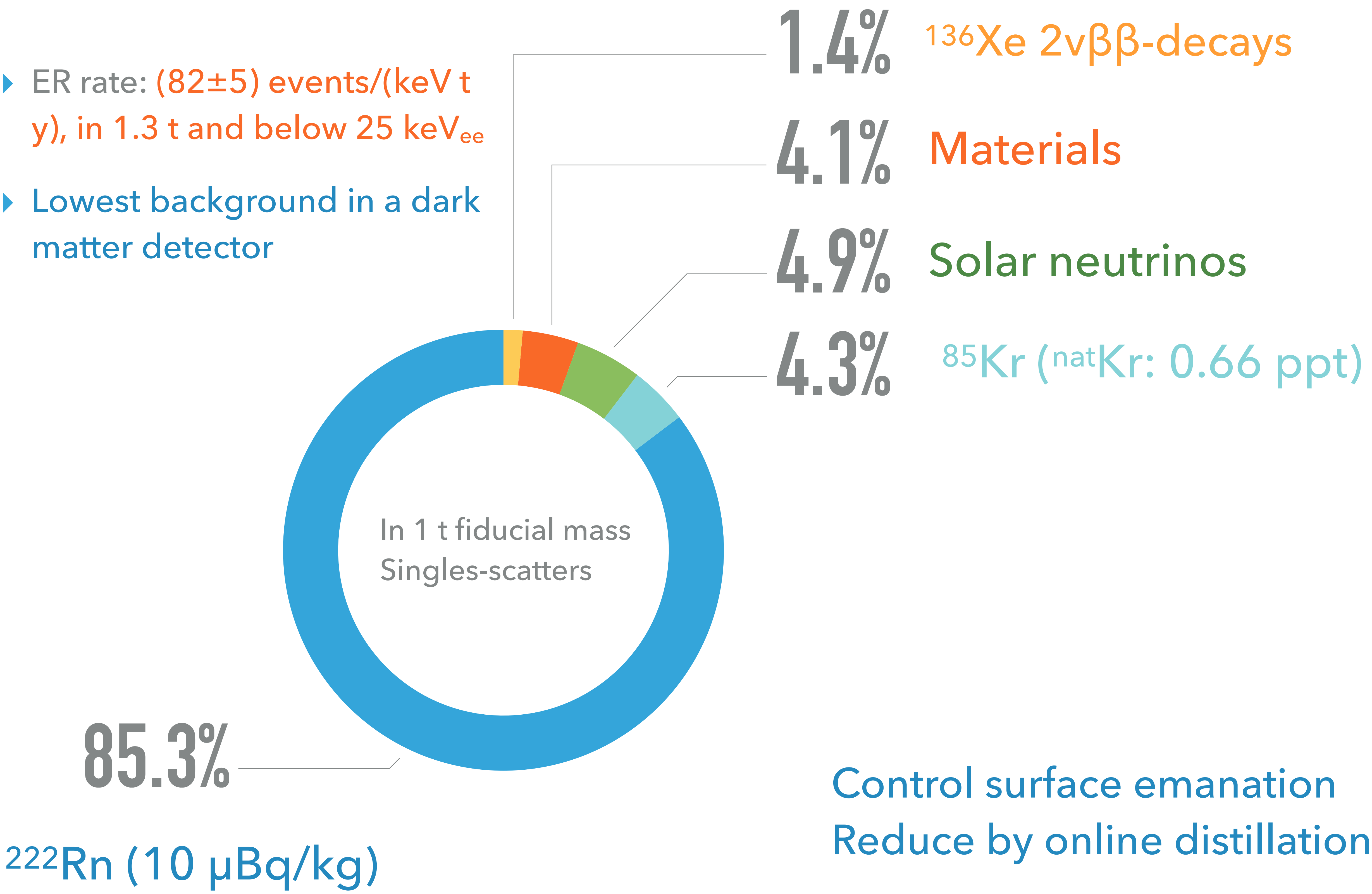
EXO-200



A SELECTION OF LIQUID XENON DETECTORS

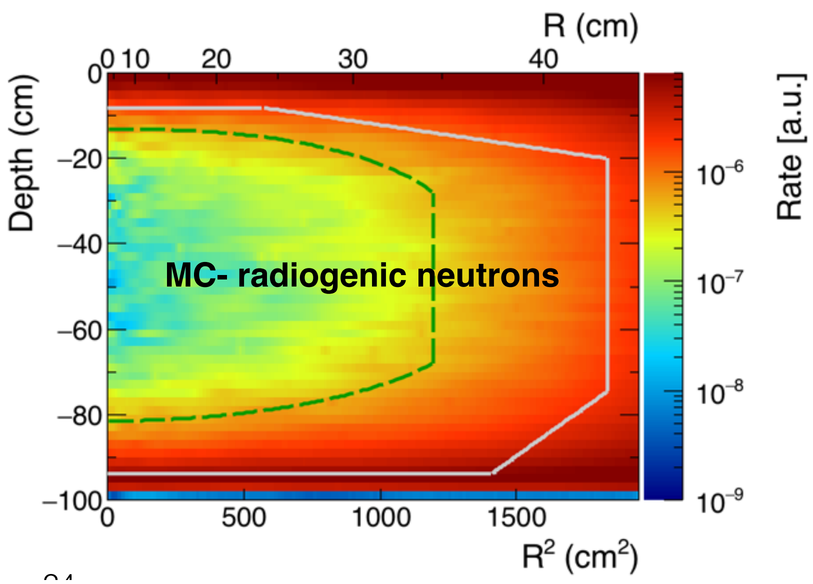


- ER rate: (82±5) events/(keV t y), in 1.3 t and below 25 keV_{ee}
- Lowest background in a dark matter detector

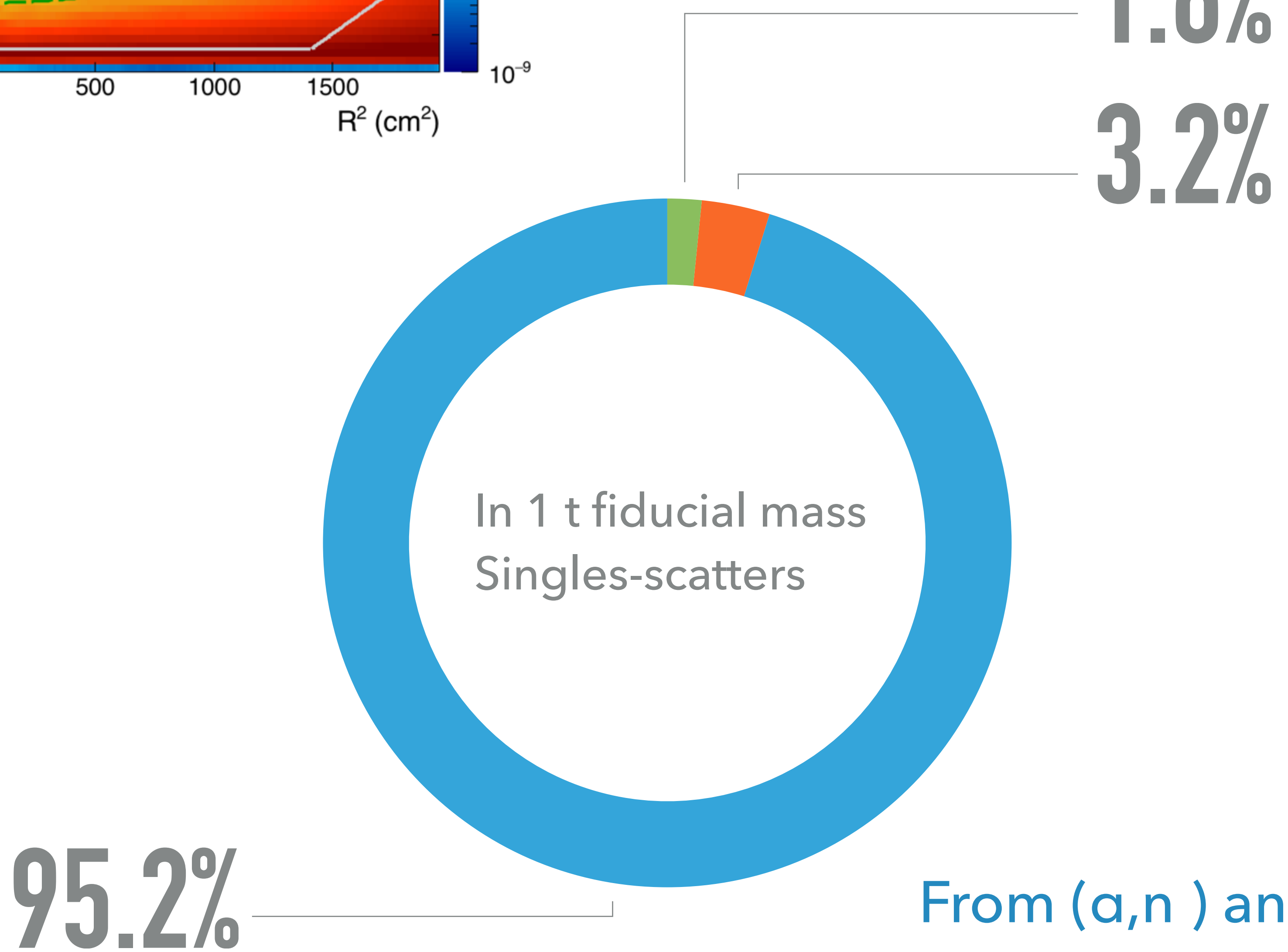


Control surface emanation
Reduce by online distillation

EXAMPLE XENON1T: NUCLEAR RECOIL BACKGROUNDS



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



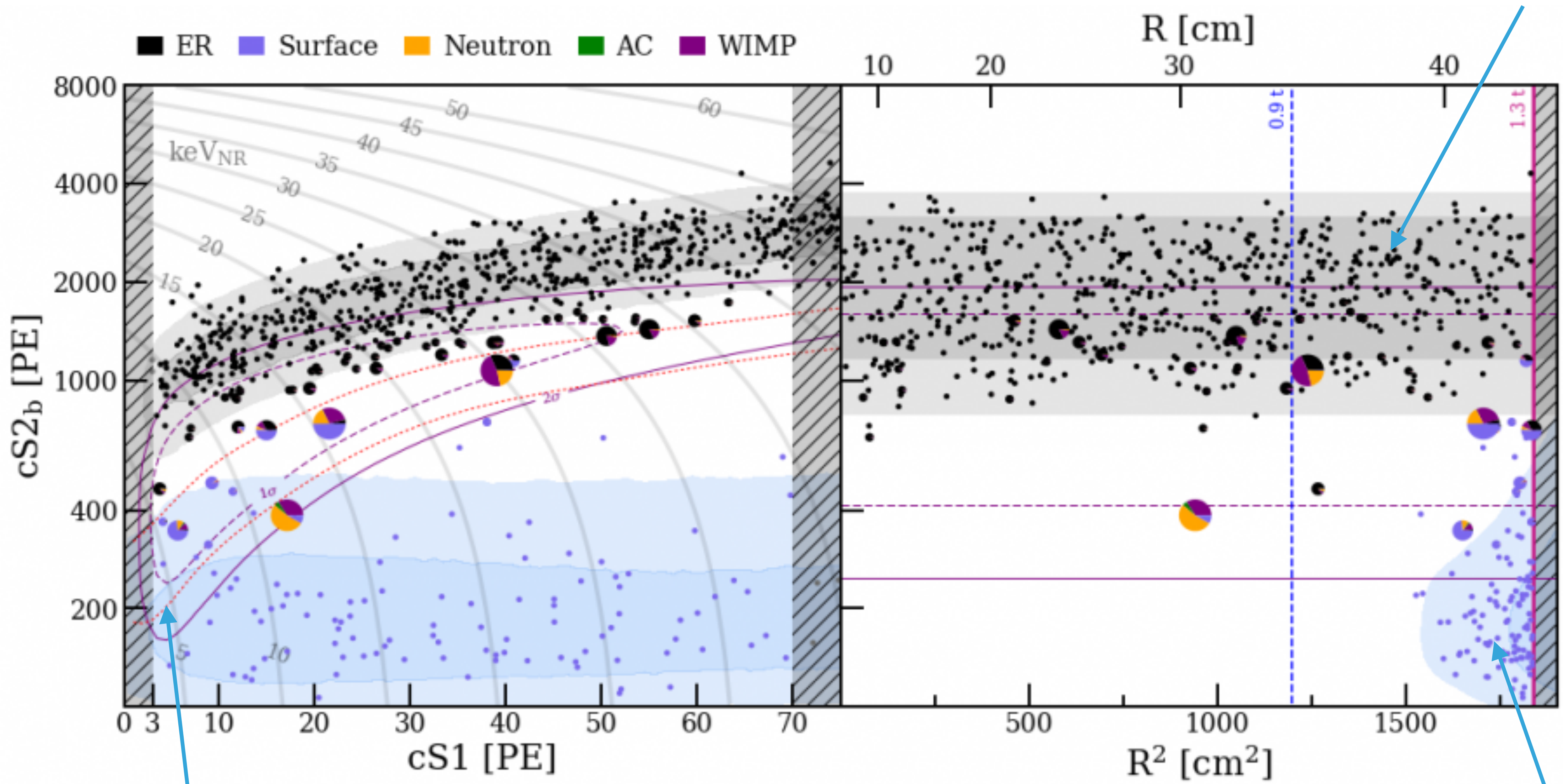
Coherent neutrino-nucleus scattering from ^{8}B neutrinos; irreducible, but relevant at low (<1 keV) energies

Radiogenic neutrons

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

EVENTS IN THE WIMP REGION-OF-INTEREST

ER component



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

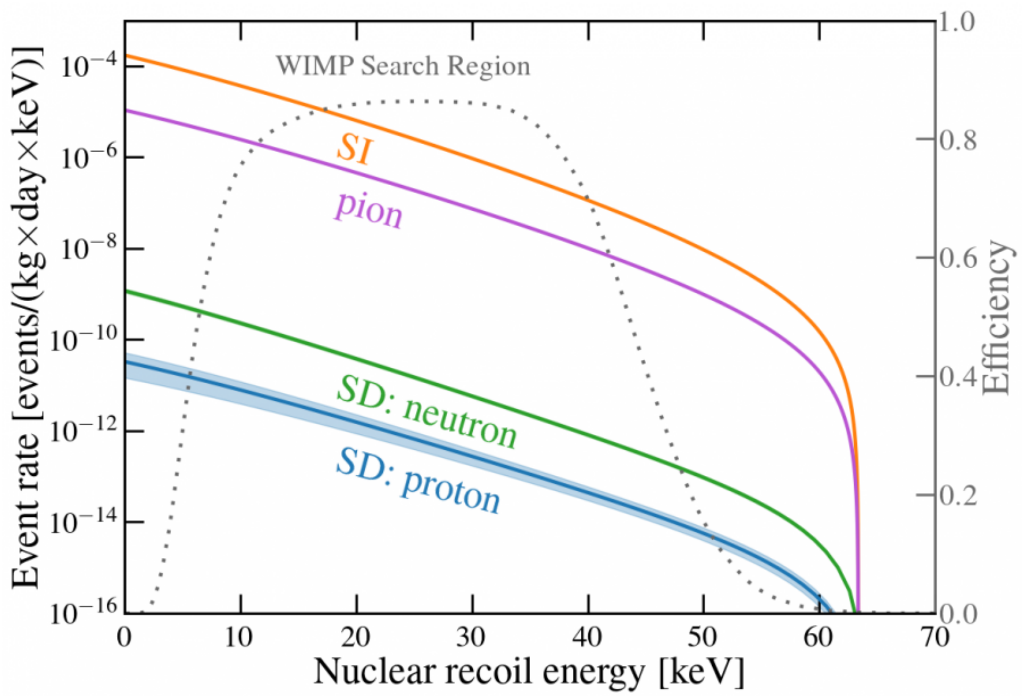
Surface component

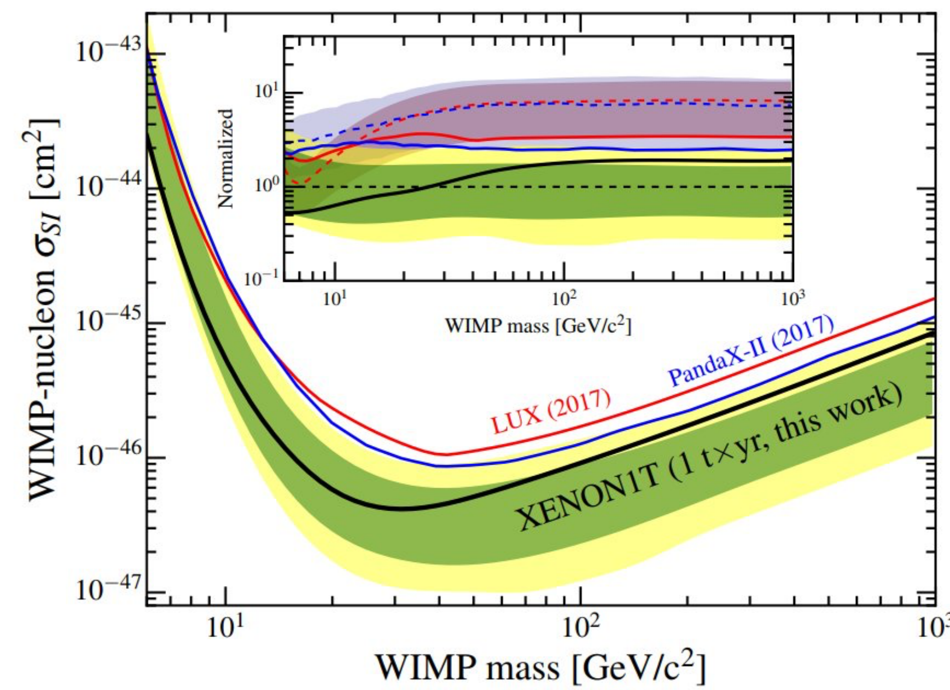
WIMP SEARCHES

XENON collaboration, PRL 122, 2019

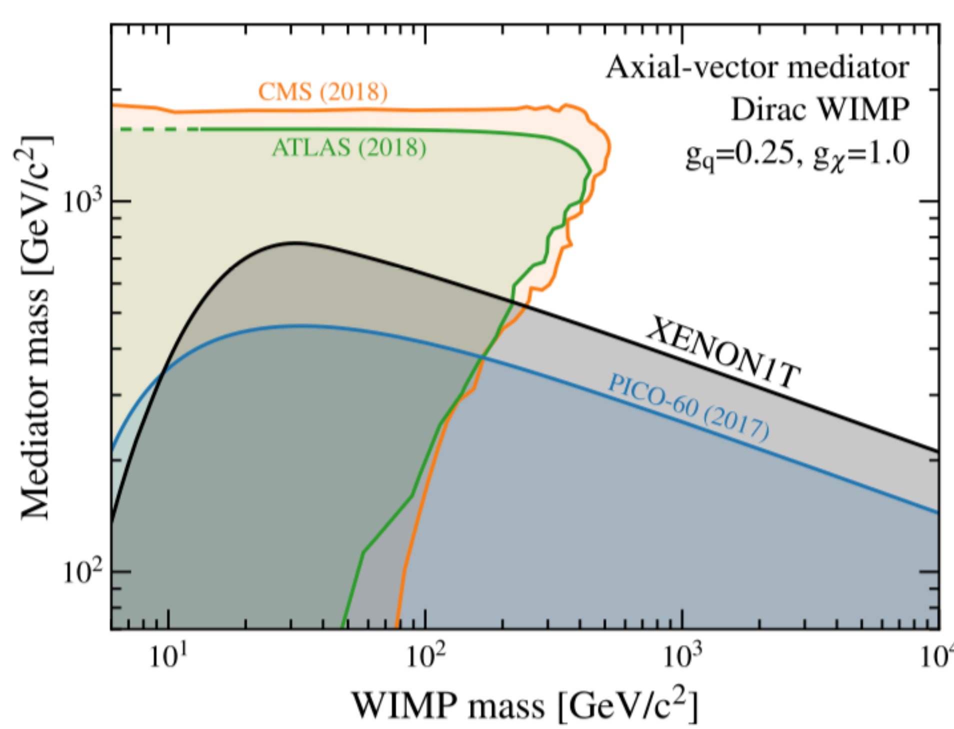
30 GeV WIMP, σ=1x10^{-45} cm^2

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





Axial-vector mediator and a Dirac WIMP, with fixed mediator-quark and mediator-WIMP coupling



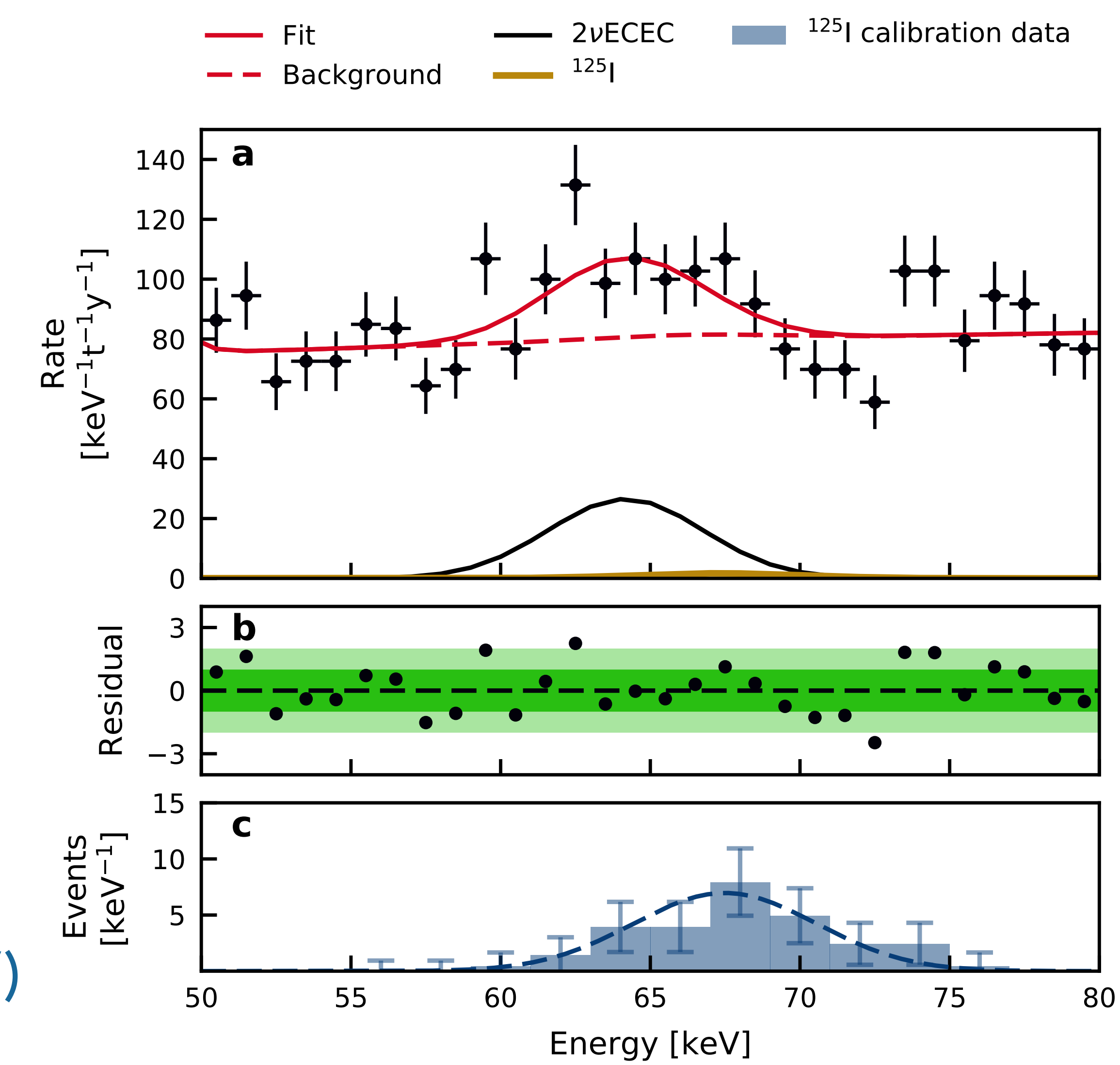
XENON collaboration, PRL 122, 2019

See posters by A. Fieguth and C. Wittweg

DOUBLE ELECTRON CAPTURE

$$^{124}\mathrm{Xe} + 2\mathrm{e}^- \rightarrow \; ^{124}\mathrm{Te} + 2\nu_e$$

- ^{124}Xe in ^{nat}Xe: 0.095%
- 1 t ^{nat}Xe ≈ 1 kg ^{124}Xe
- Total observed energy: 64.33 keV (2 x K-shell binding energy; Q-value = 2.86 MeV)
- Blind analysis: (56-72) keV region masked
- Number of signal events: (126±29), expected background from ^{125}I: (9±7) events (at 67.5 keV)



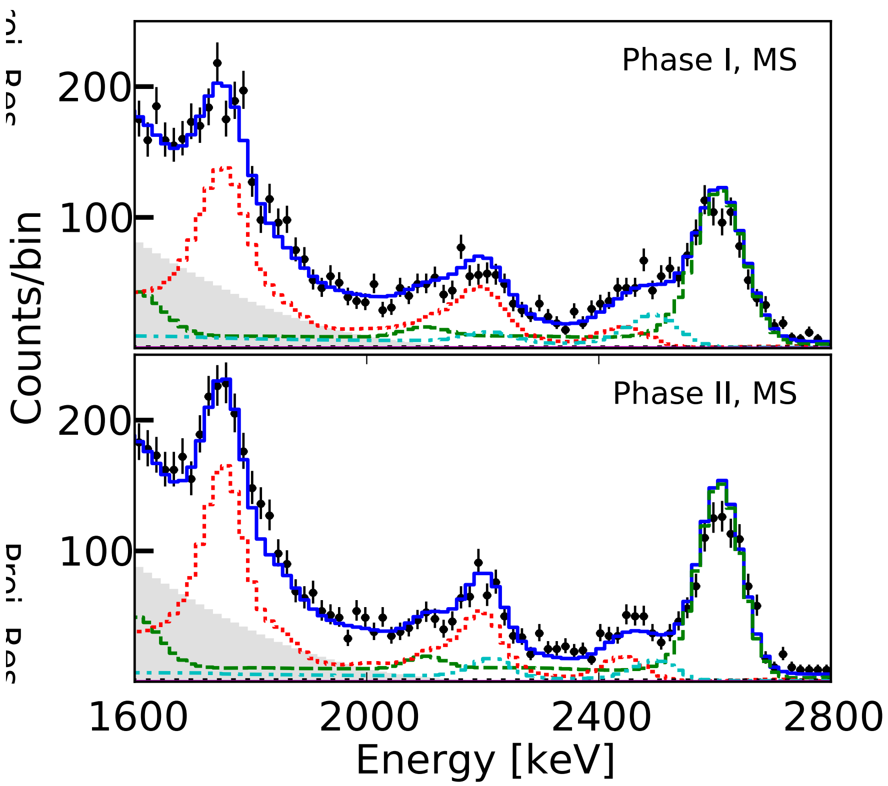
$$T_{1/2} = (1.8 \pm 0.5_{\mathrm{stat}} \pm 0.1_{\mathrm{sys}}) \times 10^{22}\ \mathrm{y}$$

XENON collaboration, Nature 568, April 25, 2019

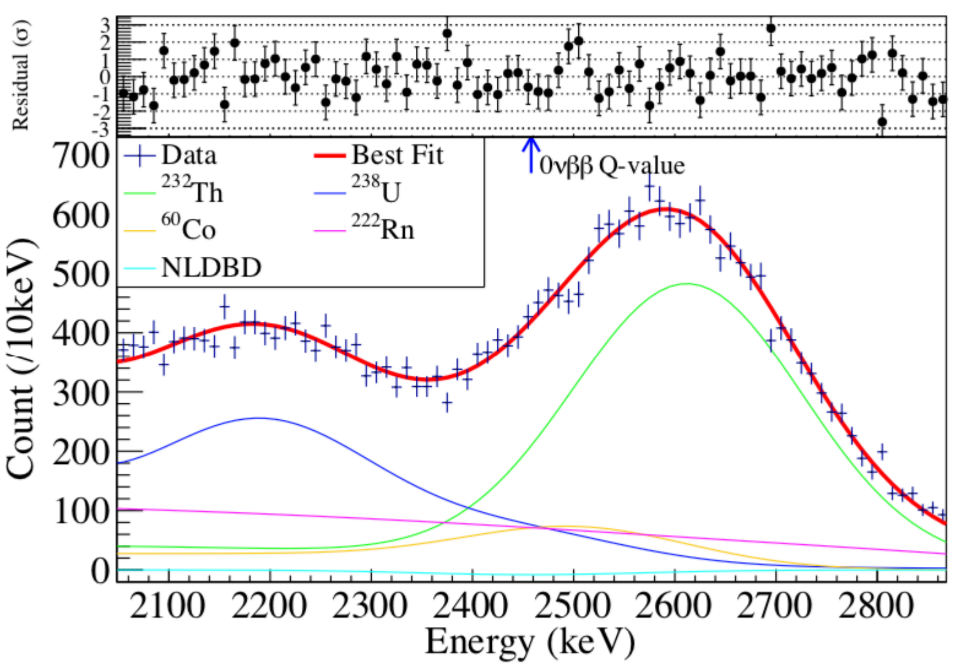
NEUTRINOLESS DOUBLE BETA DECAY OF 136-XE

- EXO-200: BI ≈ 2 x 10^{-3} $kg^{-1}y^{-1}$ keV^{-1}, 234.1 kg y ^{136}Xe exposure, σ/E =1.15%, $T_{1/2}$ > 3.5 x 10^{25} y (90% CL)
- PandaX-II: BI ≈ 0.16 $kg^{-1}y^{-1}$ keV^{-1}, 242 kg y (22.2 kg y ^{136}Xe) exposure, σ/E = 4.2%; $T_{1/2}$ > 2.4 x 10^{23} y (90% CL)
- XENON1T: analysis in progress, σ/E ≈ 0.8%

EXO-200, arXiv: 1906.02723



PandaX-II, arXiv: 1906.11457



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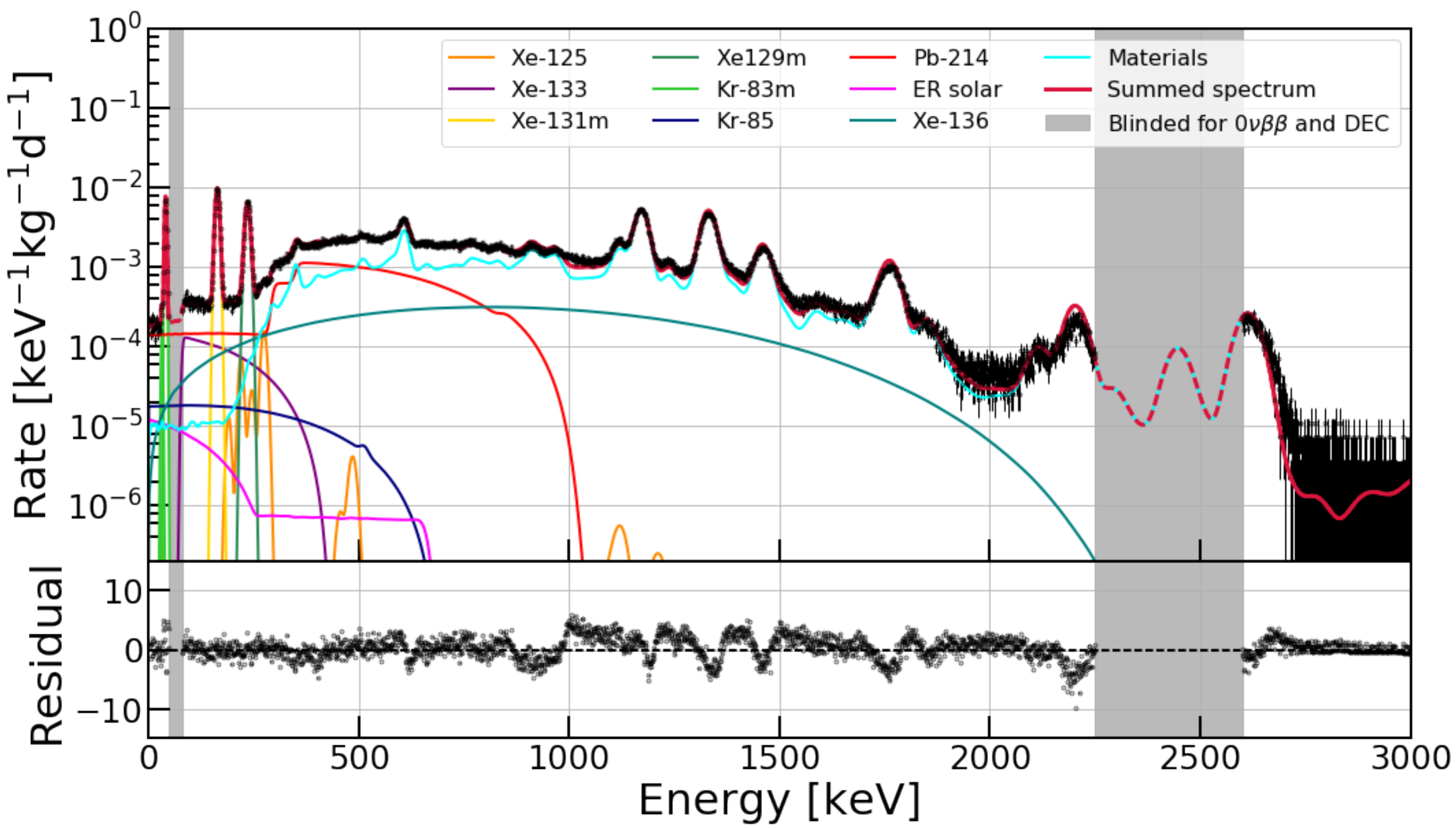
- PandaX-II: BI ≈ 0.16 $kg^{-1}y^{-1}$ keV^{-1}, 242 kg y (22.2 kg y ^{136}Xe) exposure, σ/E = 4.2%; $T_{1/2}$ > 2.4 x 10^{23} y (90% CL)
- XENON1T: analysis in progress, σ/E ≈ 0.8%

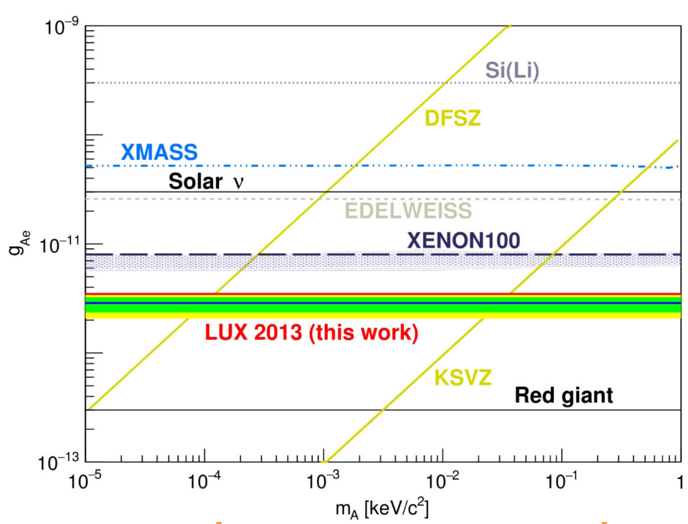


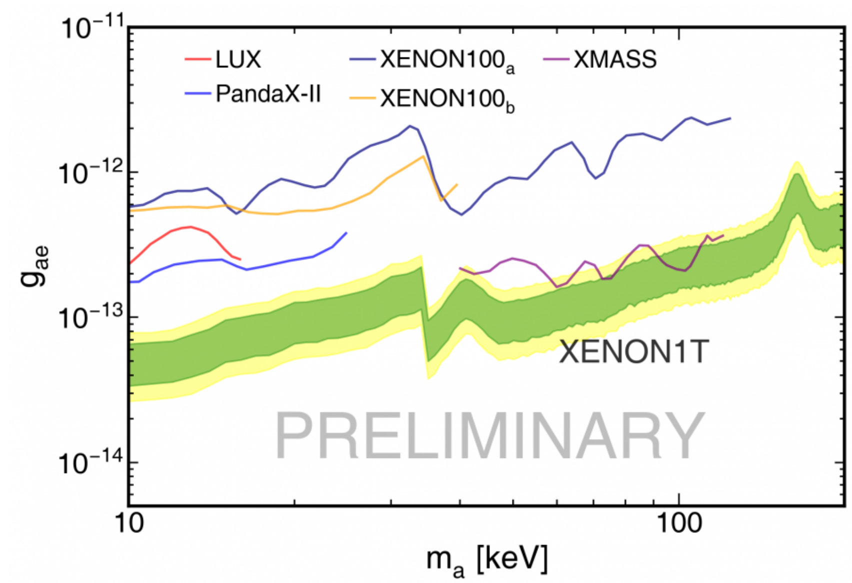
XENON1T energy spectrum matching up to 3 MeV, preliminary

AXIONS, AXION-LIKE PARTICLES AND DARK PHOTONS

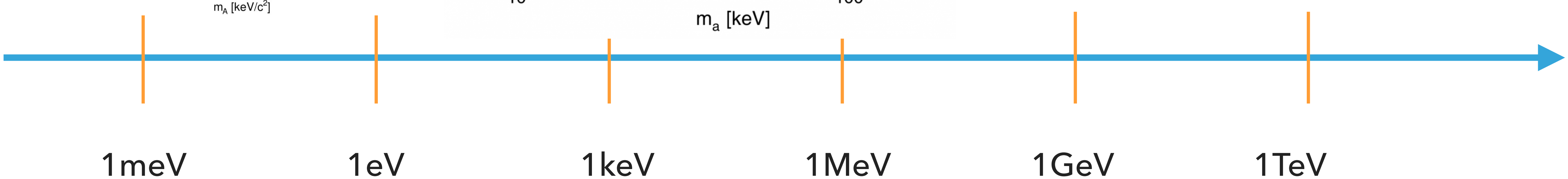
- Absorption via axio-electric effect; peak at particle mass

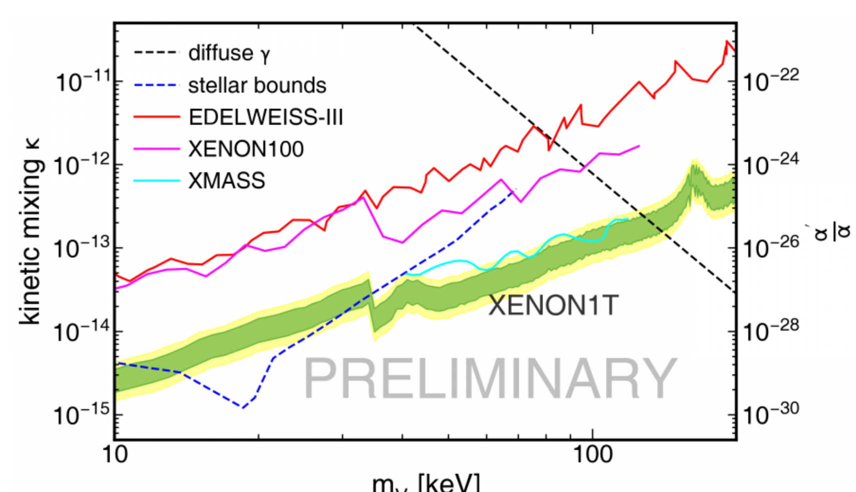
Solar axions, LUX PRL 118, 2017





$$R \simeq \frac{4\times10^{23}}{A}\frac{\alpha'}{\alpha}\left(\frac{\mathrm{keV}}{m_v}\right)\left(\frac{\sigma_{pe}}{\mathrm{b}}\right)\mathrm{kg}^{-1}\mathrm{d}^{-1}$$





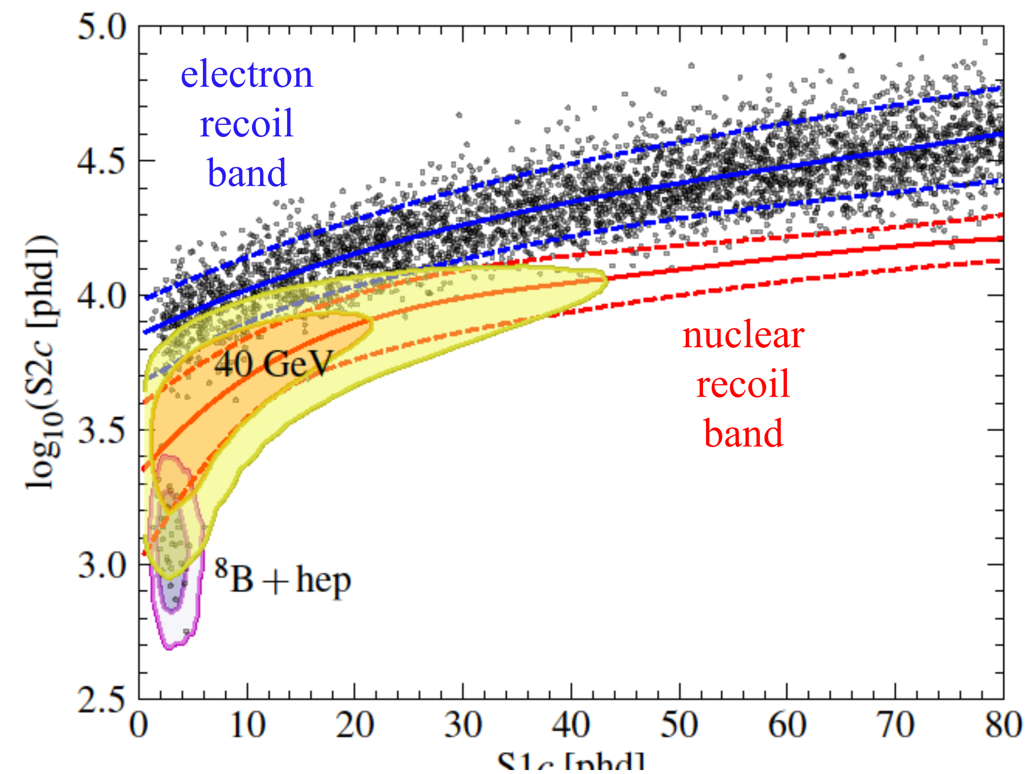
$$R \simeq \frac{1.29\times10^{19}}{A}g_{ae}^2\left(\frac{m_a}{\mathrm{keV}}\right)\left(\frac{\sigma_{pe}}{\mathrm{b}}\right)\mathrm{kg}^{-1}\mathrm{d}^{-1}$$

Rates assume ρ_0=0.3 GeV/cm^3

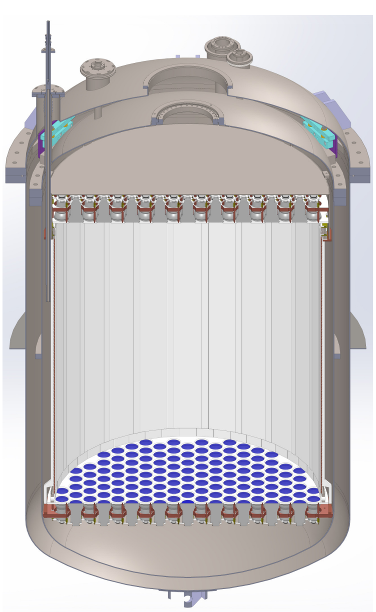
LIQUEFIED XENON

- In construction:
  - LUX-ZEPLIN, XENONnT, PandaX-4t
- Planned or design and R&D stage
  - nEXO (5 t ^{enr}Xe), DARWIN (50 t LXe)

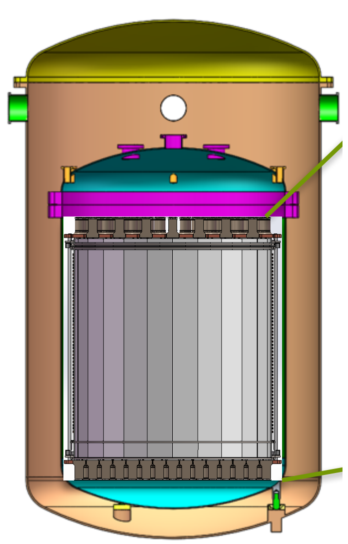
LZ: 40 GeV WIMP, 1000 days, 5.6 t fiducial



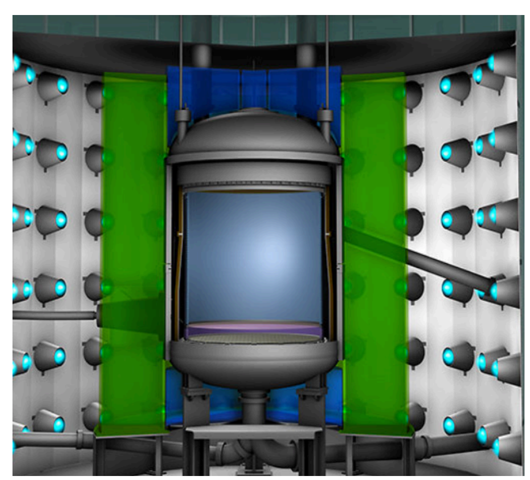
See talk by G. Gratta



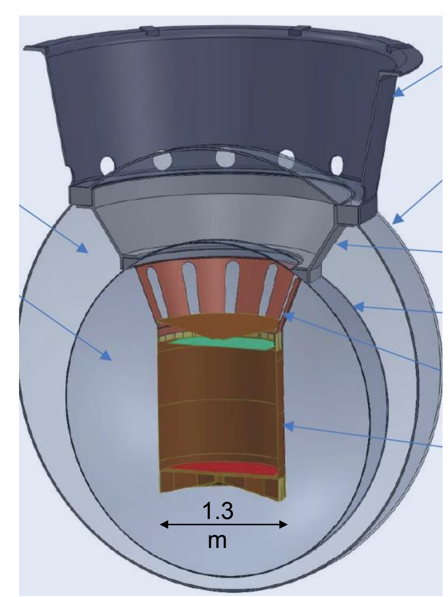
XENONnT: 8t LXe
Data taking 2020



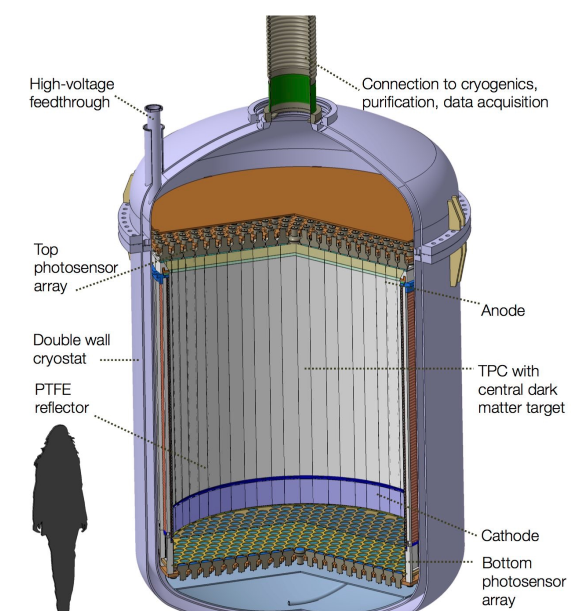
PandaX-4t LXe
Data taking 2019



LUX-ZEPLIN: 8 t LXe
Data taking 2020



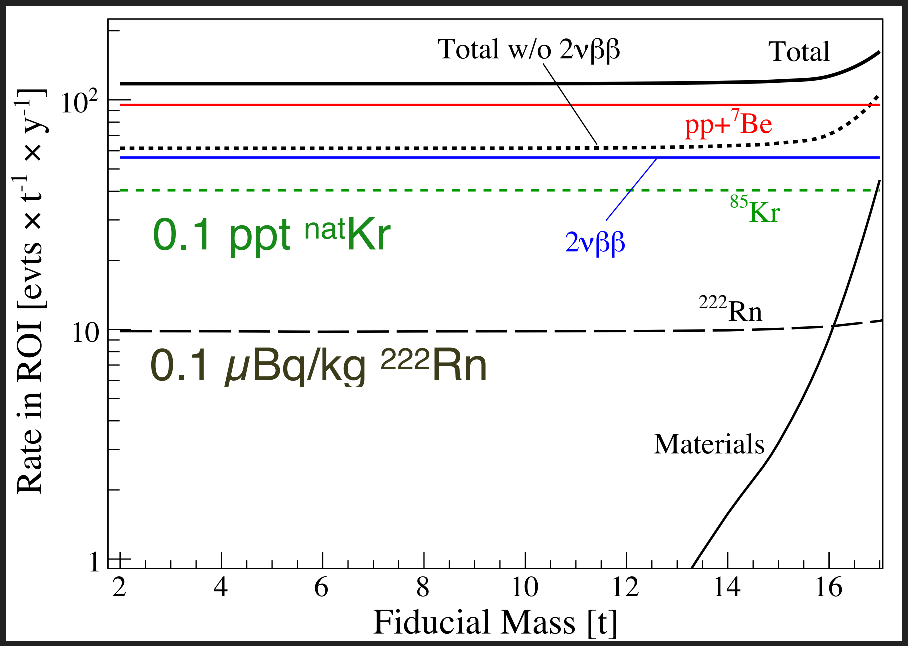
nEXO: 5 t ^{136}LXe
Data taking ~202?

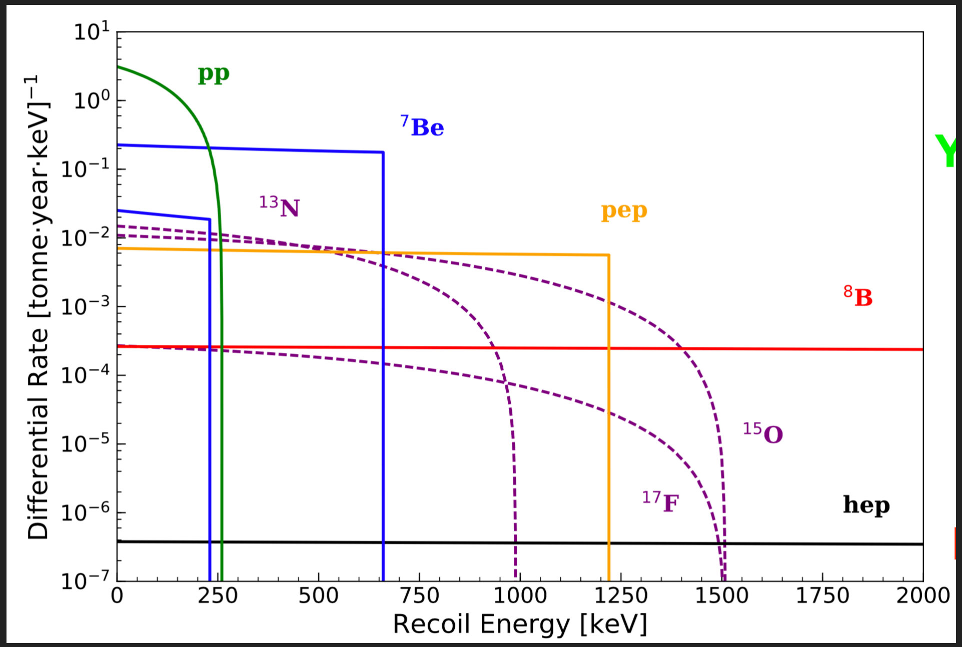


DARWIN: 50 t LXe
Data taking ~2026

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 & material selection
- ^{nat}Kr in LXe (contains 2 x 10^{-11} ^{85}Kr): 0.1 ppt -> already achieved
- ^{136}Xe double beta decay -> search for 0vββ-decay
- Solar neutrinos (pp, ^{7}Be): will dominate -> but interesting physics channel

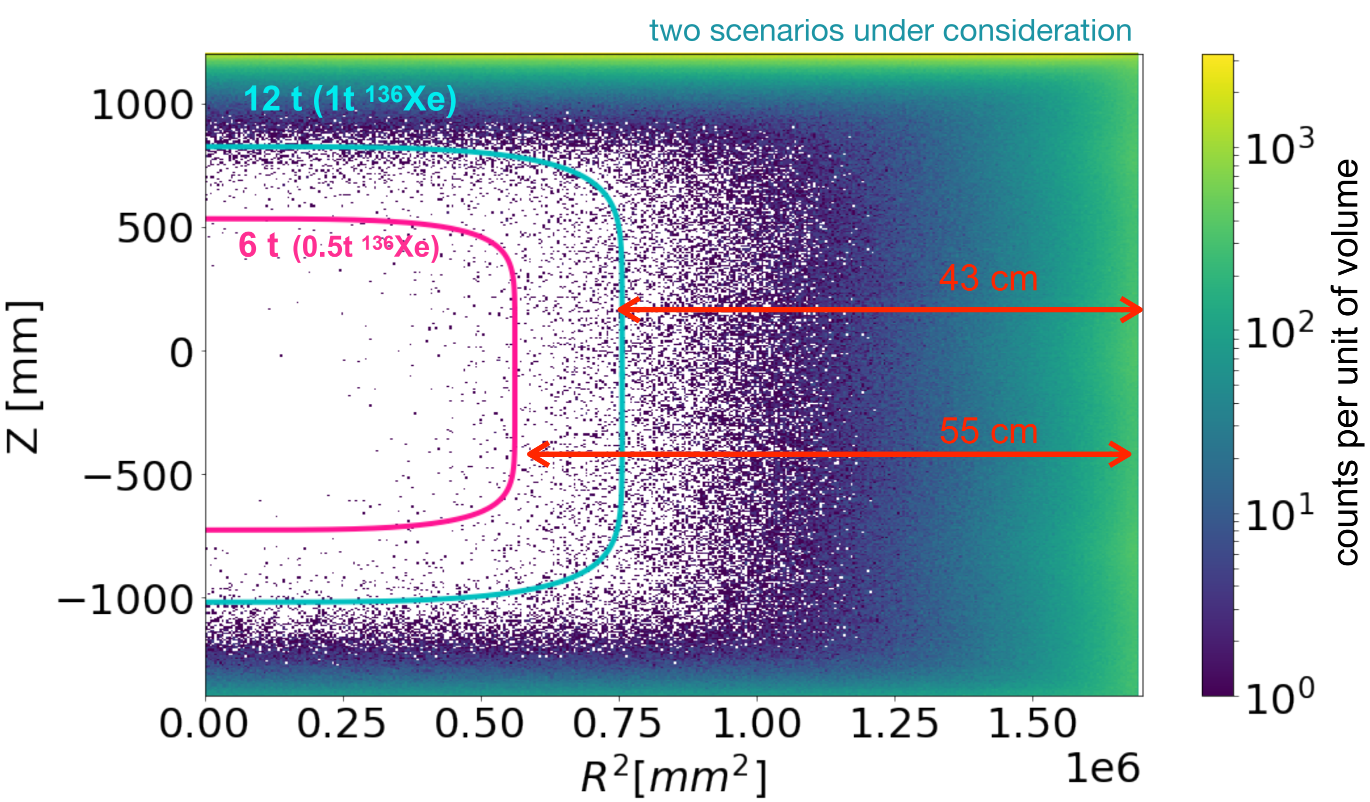




DARWIN: BACKGROUND FROM MATERIALS

- Detailed Geant4 simulations of ER backgrounds (in baseline design)
- 2 toy scenarios: 12 t and 6 ton fiducial mass

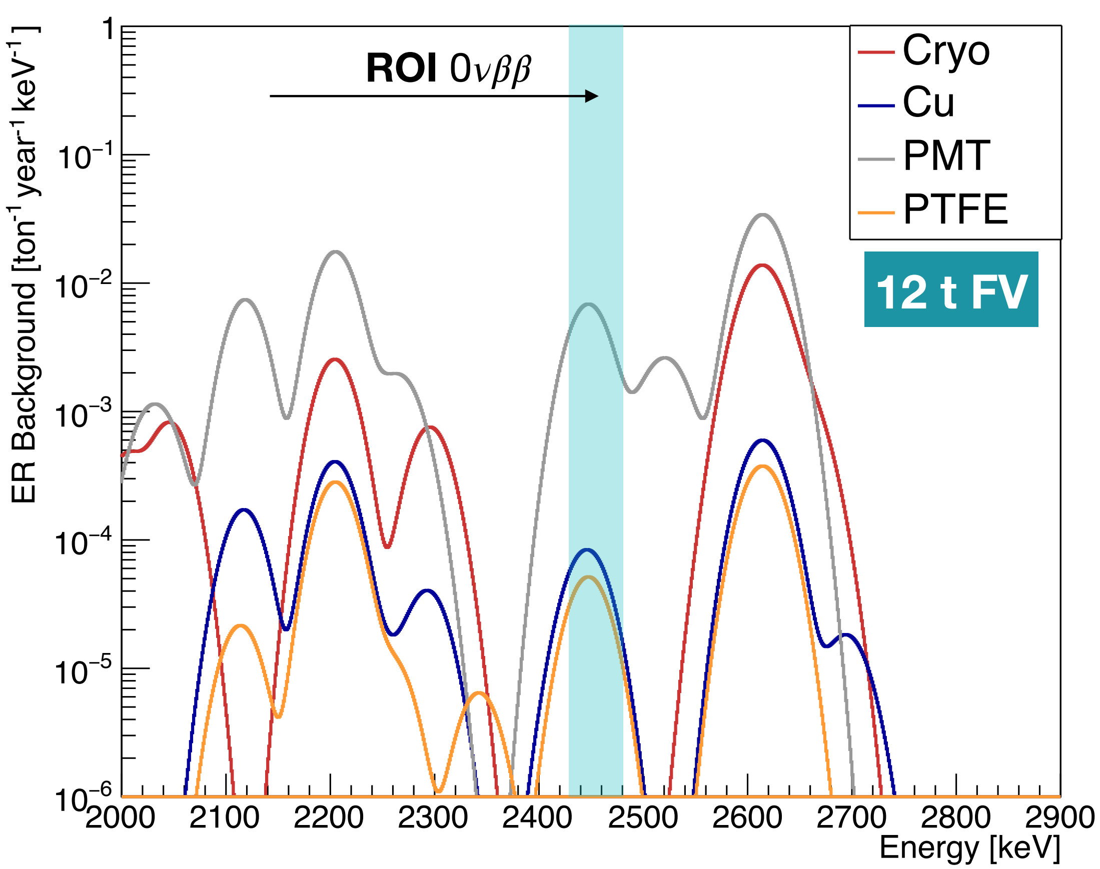
Element	Material	Mass
Outer Cryostat	Ti	3038 kg
Inner Cryostat	Ti	2093 kg
Bottom Pressure Vessel	Ti	375 kg
LXe instrumented Target	LXe	39342 kg
LXe Buffer outside the TPC	LXe	8955 kg
LXe around Pressure Vessel	LXe	273 kg
GXe in top dome + TPC top	GXe	27 kg
TPC Reflector (3mm thickness)	PTFE	146 kg
Structural support Pillars (24 units)	PTFE	84 kg
Top Frames for Anode + Gate	Ti	139 kg
Cathode Frame	Ti	50 kg
Bottom Screening Frame	Ti	20 kg
Field Shaping Rings (92 units)	Cooper	678 kg
Photosensor Arrays (2 disks)	PMT	343 kg



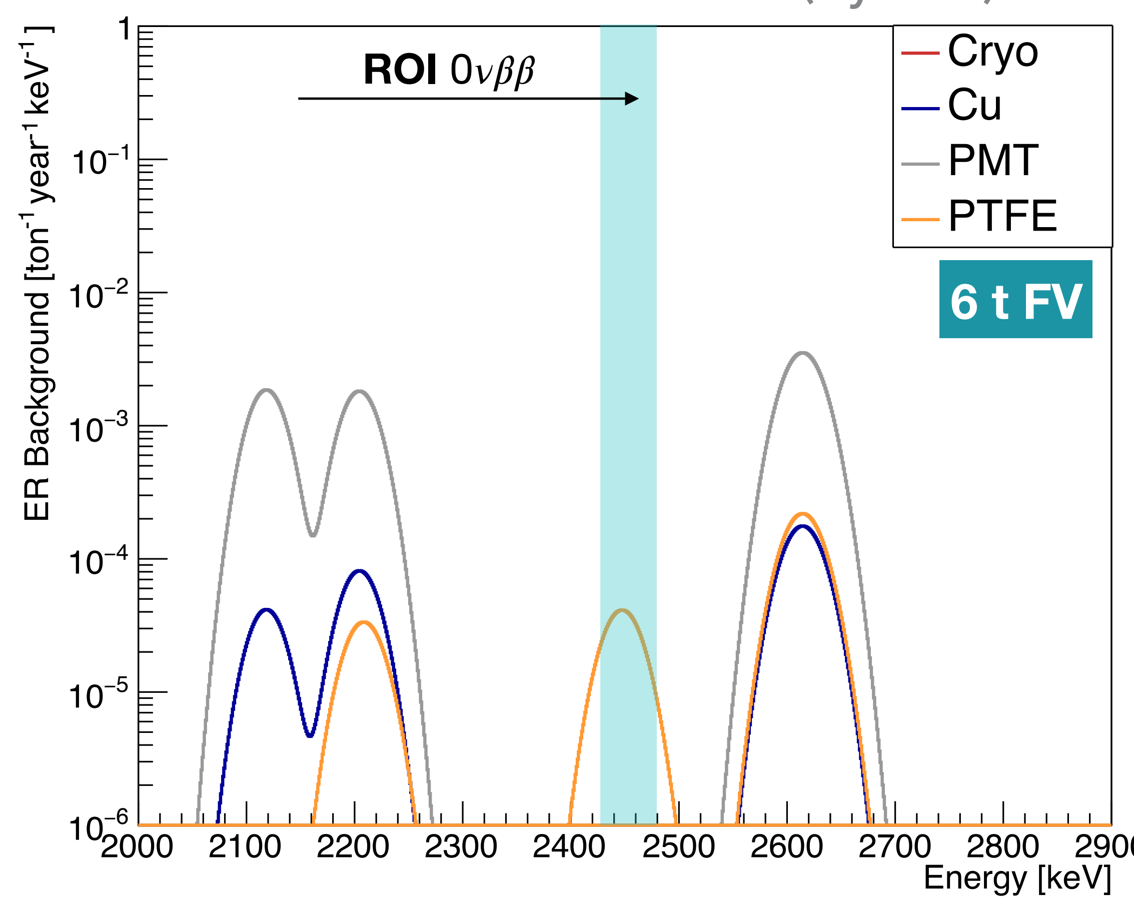
DARWIN: BACKGROUND FROM MATERIALS

- Detailed Geant4 simulations of ER backgrounds (in baseline design)
- 2 toy scenarios: 12 t and 6 ton fiducial mass

5.2×10^{-3} event in ROI/(t y keV)



3.3×10^{-5} event in ROI/(t y keV)

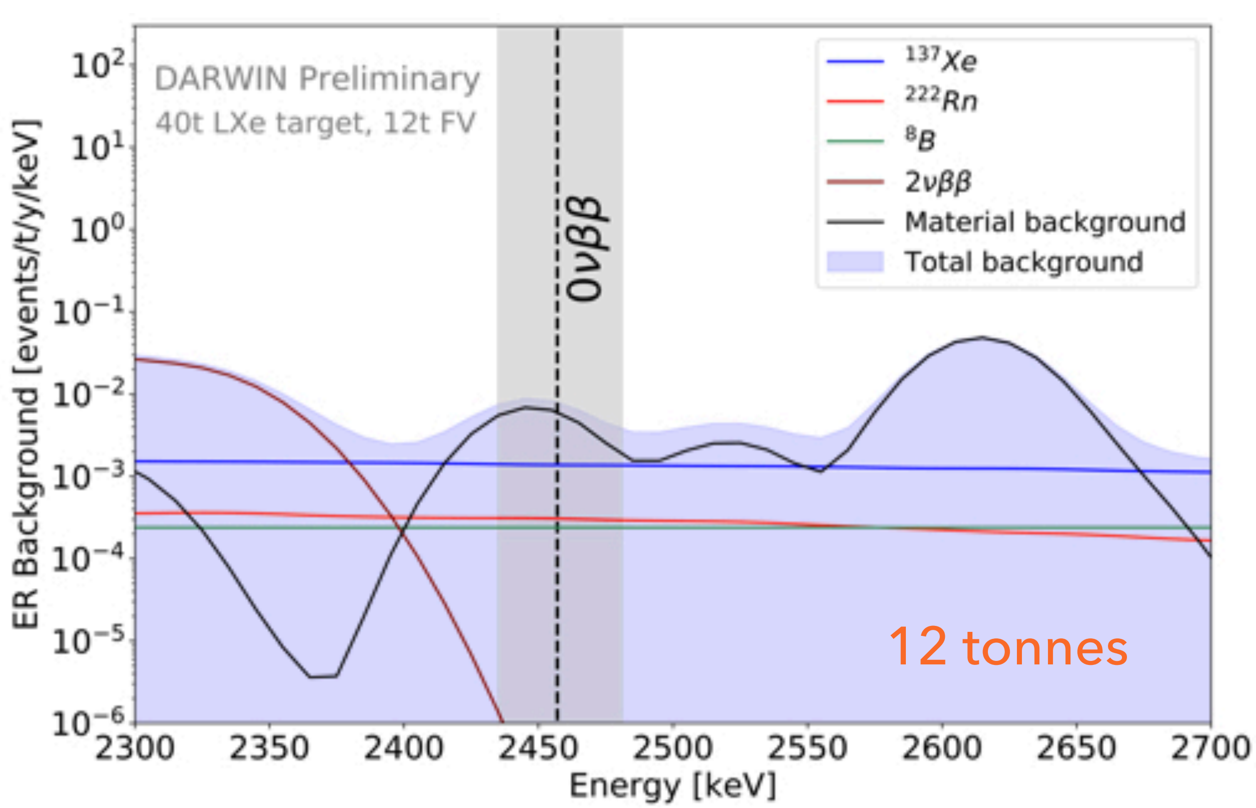


ROI: Q-value ± FWHM/2 = (2435-2481) keV

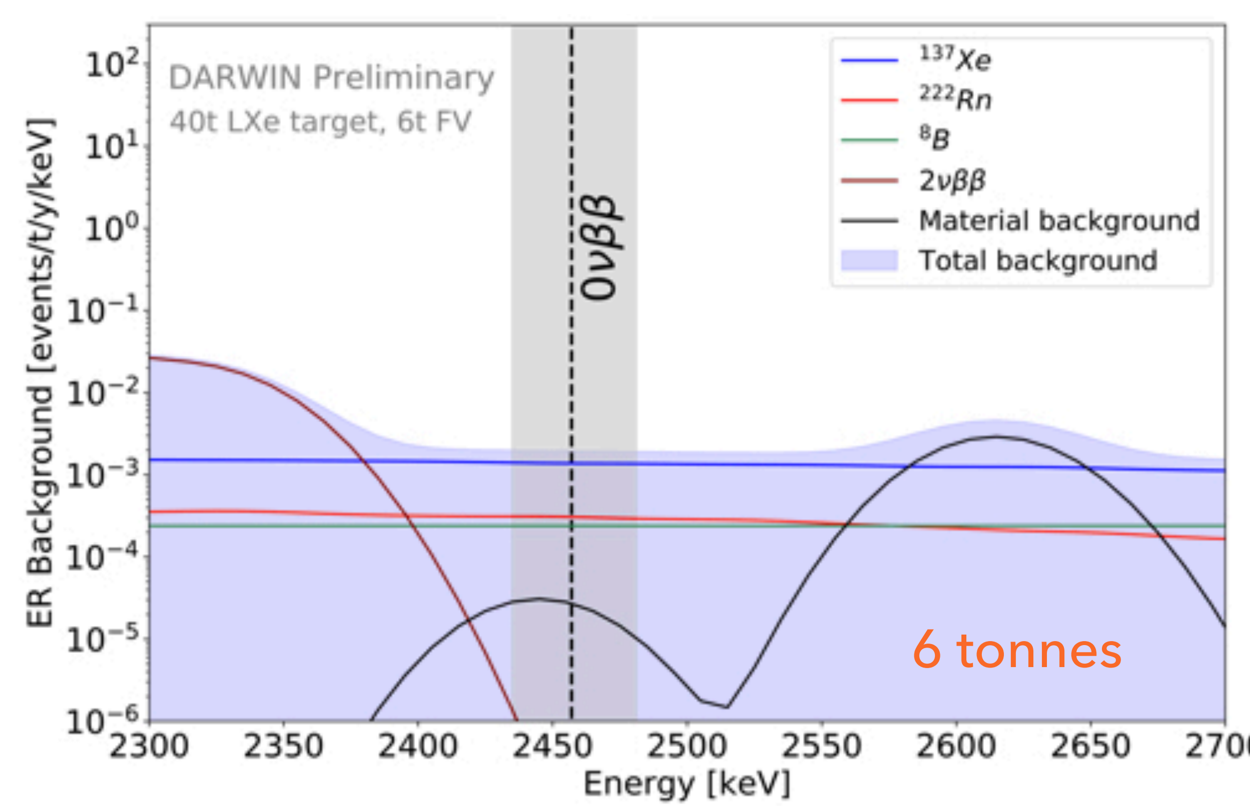
DARWIN: INTRINSIC BACKGROUNDS

- Intrinsic backgrounds: ^{137}Xe, ^{222}Rn, ^{8}B
- ^{137}Xe: β-decay with Q=4173 keV, $T_{1/2}$=3.82 min (via n-capture on ^{136}Xe)

7 x 10^{-3} events in ROI/(t y keV)



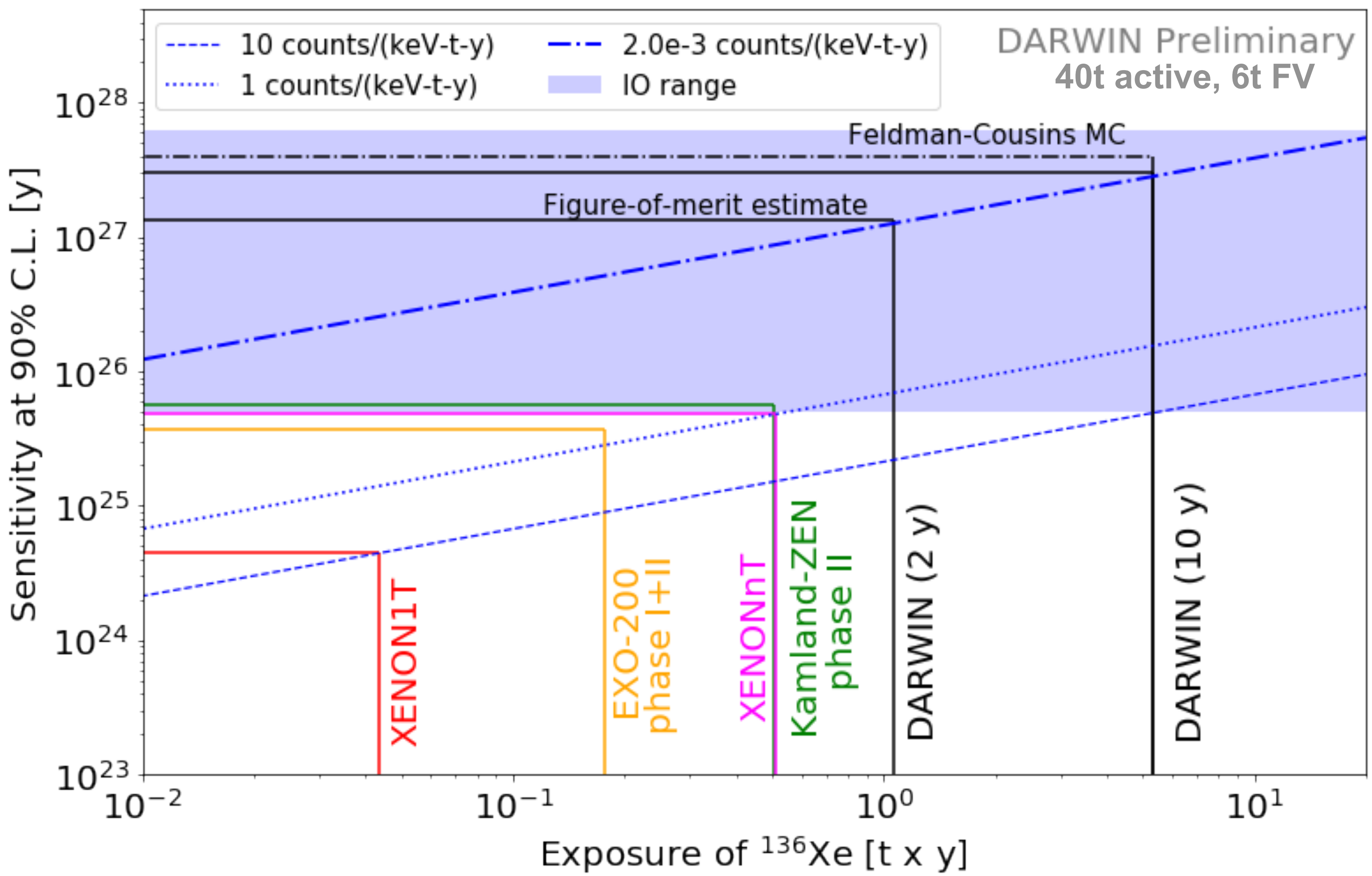
2 x 10^{-3} events in ROI/(t y keV)



ROI: Q-value ± FWHM/2 = (2435-2481) keV

DARWIN: SENSITIVITY (PRELIMINARY)

- Figure-of-merit and FC approach
- Fiducial volume not optimised + more detailed ^{137}Xe study + SiPMs for photonsensors



$$T_{1/2}^{0\nu} = \ln 2 \frac{\epsilon f_{roi} \alpha N_A}{1.64 M_{Xe}} \frac{\sqrt{Mt}}{\sqrt{B \Delta E}}$$

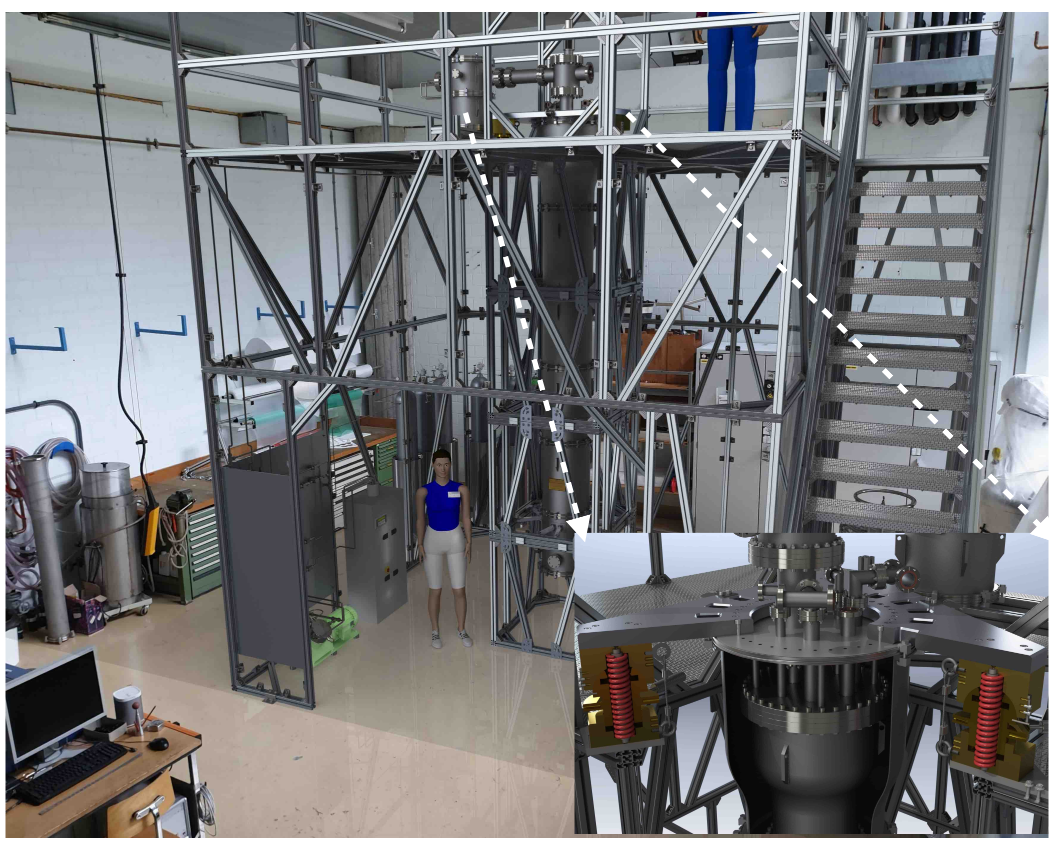
Fid. Mass [t]	Half-life sensitivity [y] at 90 C.L. 2 years	10 years
All background sources		
6	1.3×10^{27}	3.0×10^{27}
12	1.0×10^{27}	2.3×10^{27}
Irreducible ^{8}B background only		
6	3.3×10^{27}	7.5×10^{27}
12	4.7×10^{27}	1.06×10^{28}

DARWIN R&D EXAMPLES

European Research Council
Established by the European Commission

- Detector, Xe target, background mitigation, photosensors, etc
- Two large-scale demonstrators (z & x-y) supported by ERC grants
- Stay tuned: @DarwinObserv

Universität Zürich[UZH]



Test e^- drift over 2.6 m (purification high-voltage)

UNI FREIBURG

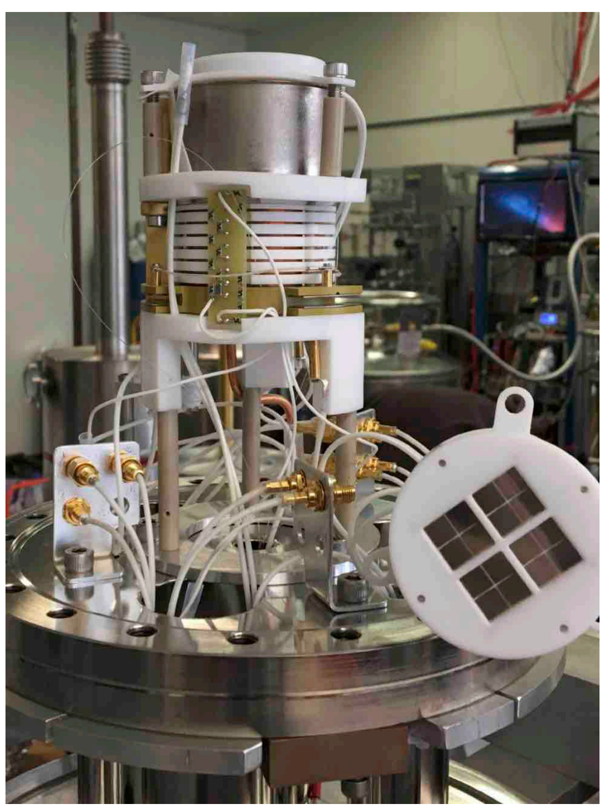
Test electrodes and homogeneity of extraction field

DARWIN R&D EXAMPLES

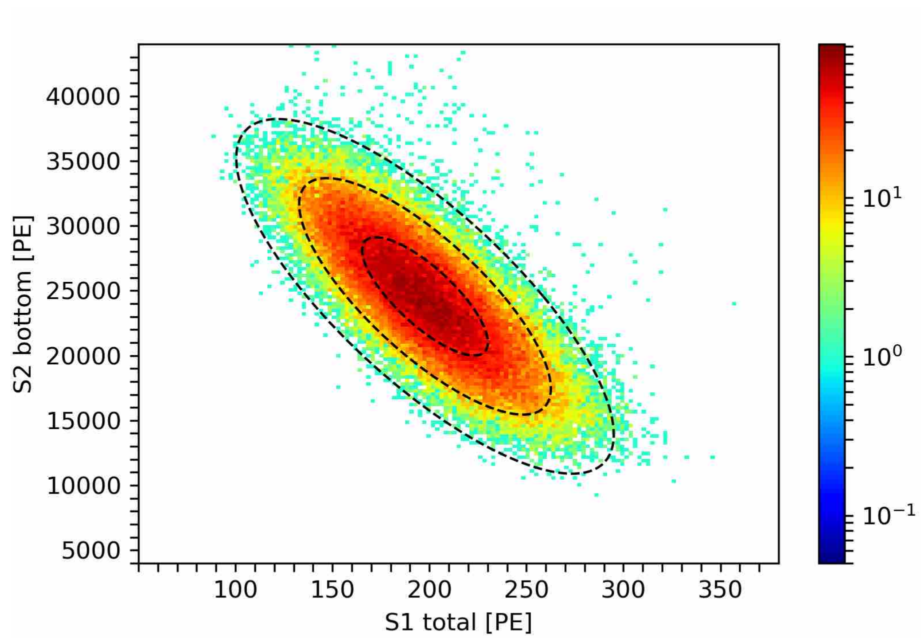
European Research Council
Established by the European Commission

- Photosensors: test SiPM arrays as PMT replacements
- First Xe-TPC with SiPM in top array; characterisation with ^{37}Ar source ongoing

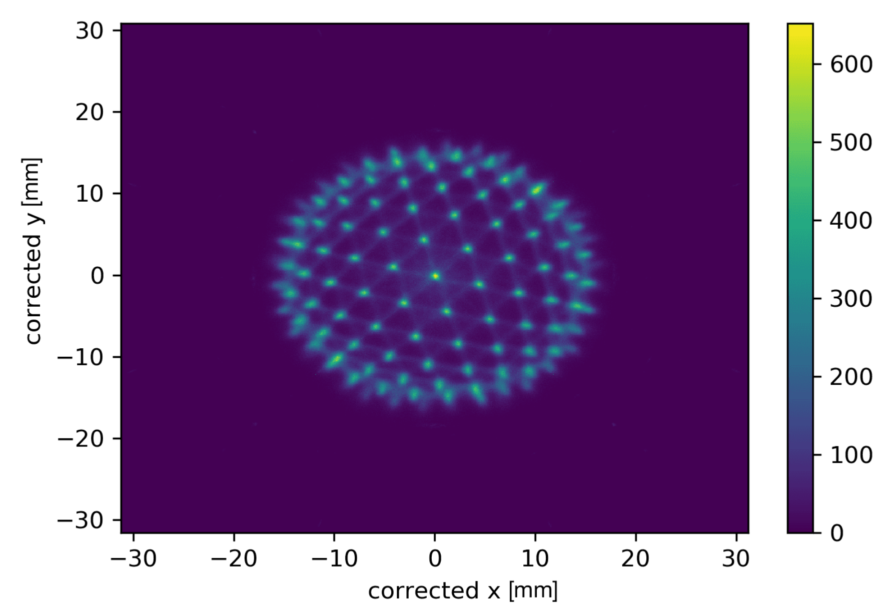
Characterisation with ^{83m}Kr source



Upgrade of Xurich-II (LB et al., EPJ- C 78, 2018)



S2-S1 anti-correlation for the 32.1 keV line

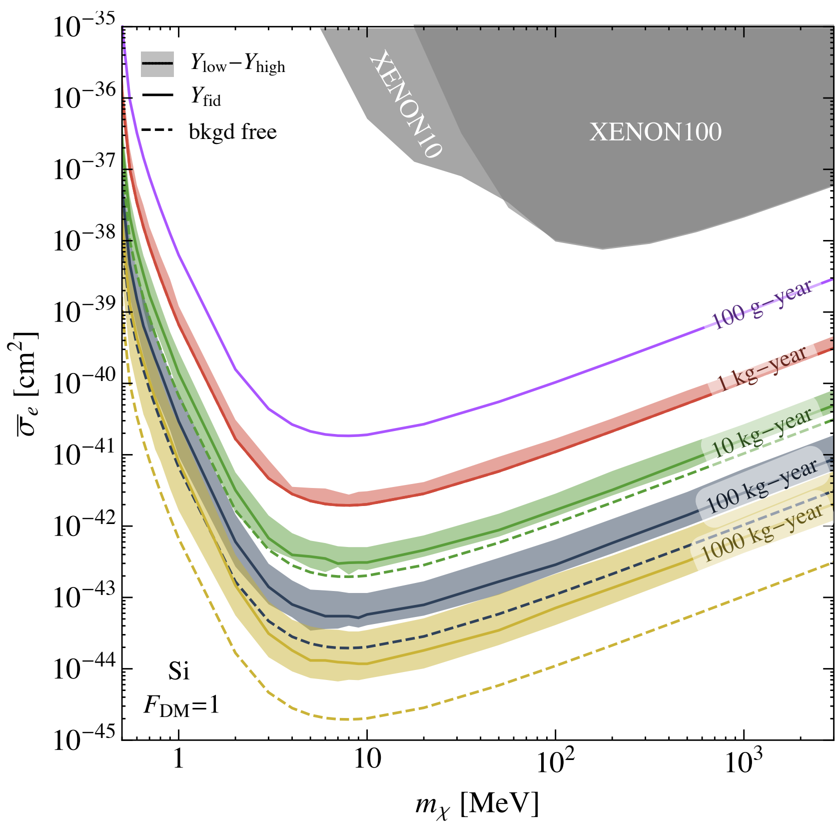


x-y position reconstruction

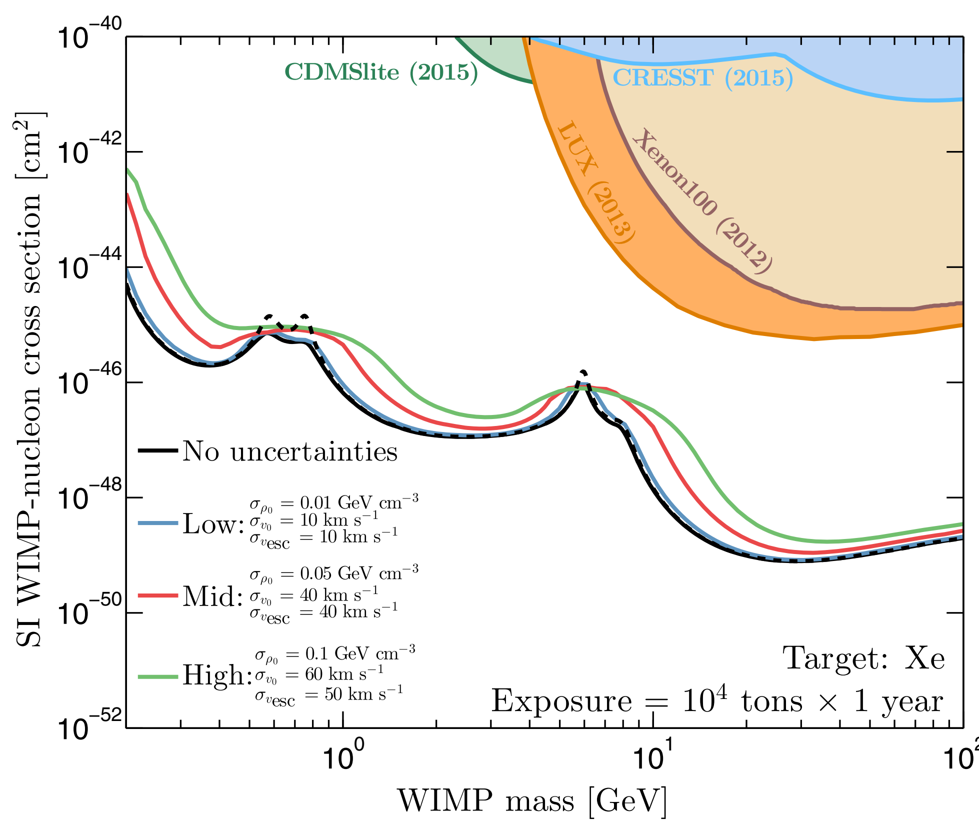
NEUTRINO BACKGROUNDS FOR DM SEARCHES

- Low mass region: limit at ~ 0.1- 10 kg year (target dependent)
- High mass region: limit at ~ 10 ktonne year
- But: annual modulation, directionality, momentum dependance, inelastic DM-nucleus scatters, etc

Discovery limits (2-σ) for various ionisation efficiencies Y, solar ν background only



DM-electron scatters (R. Essig et al, PRD97, 2018)



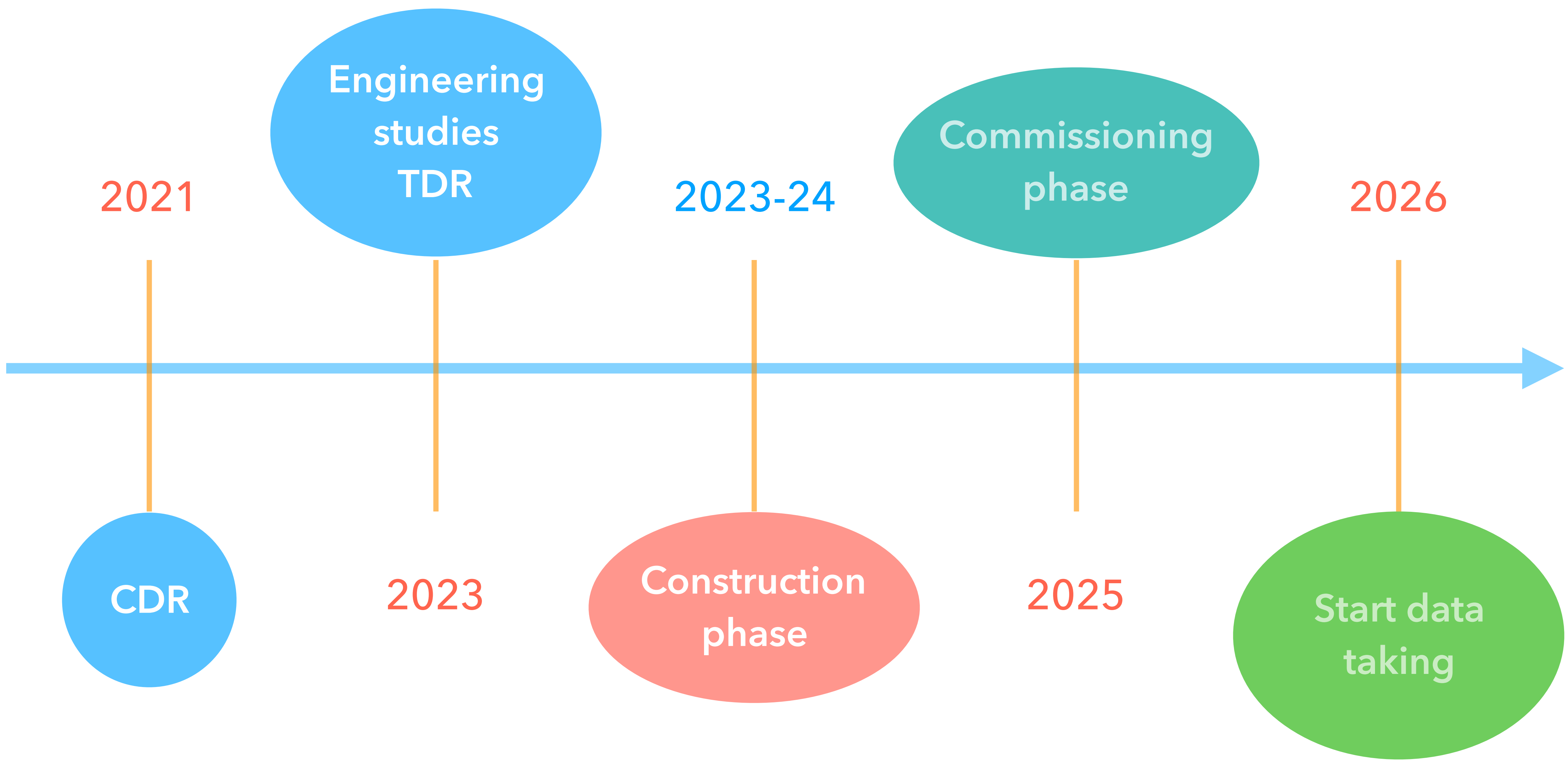
DM-nucleus scatters (C.A.J. O'Hare, PRD94, 2016)

CONCLUSIONS

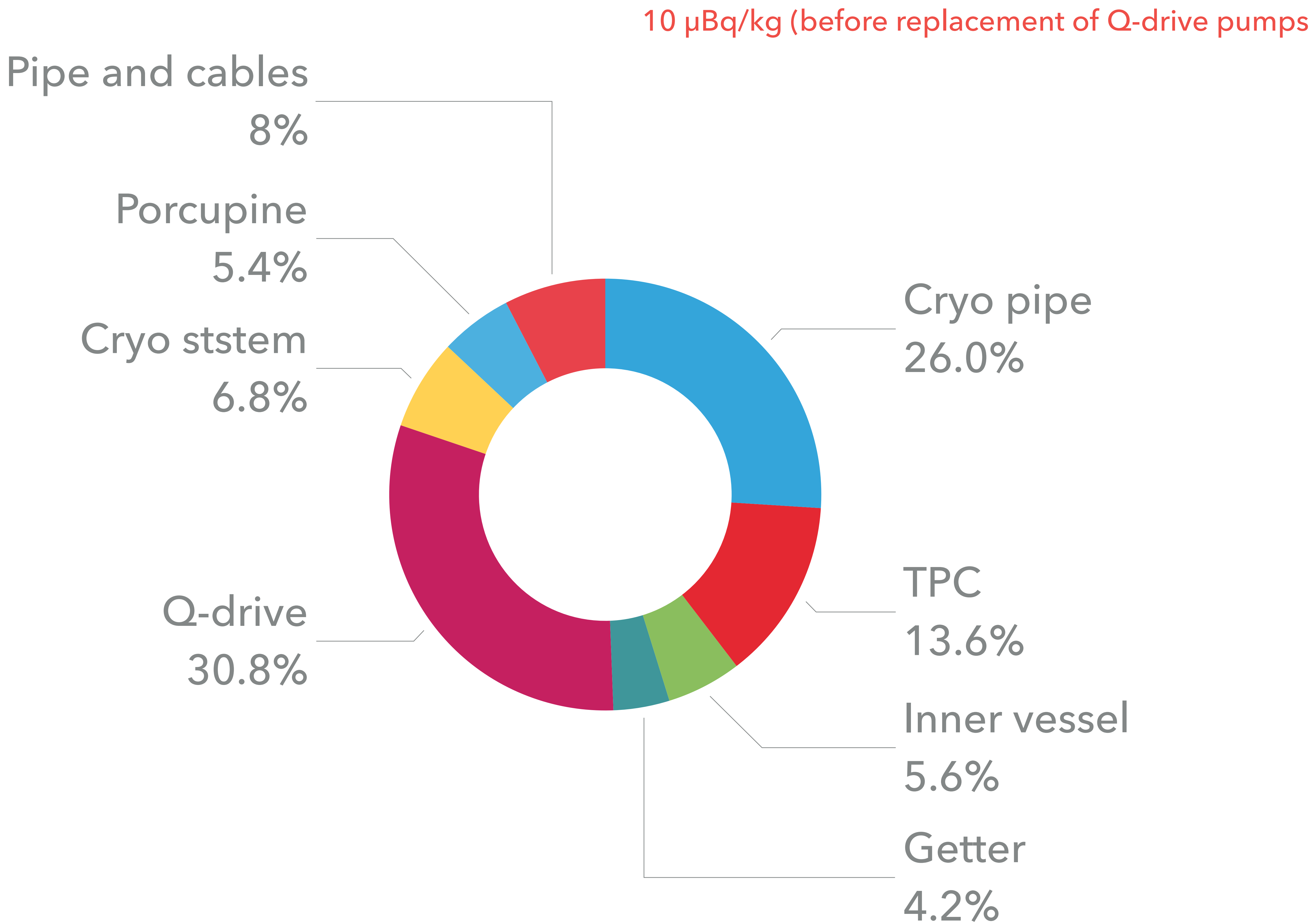
- Experiments using liquefied Xe: excellent sensitivities in particle/astroparticle physics
- Due to very low expected event rates, we need:
  - Large detector masses, ultra-low backgrounds (material radio-assay & Rn reduction remain crucial)
  - Very good energy resolutions, low energy thresholds
- 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 in particles physics (neutrinos, $0\nu\beta\beta$, axion/ALPs, dark photons, WIMPs, etc)
- Eventually limited by neutrino interactions (but also new physics opportunities!)

THE END

DARWIN TIMESCALE



RADON BUDGET IN XENON1T



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