University of Zurich[UZH]

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Dark matter, $0\nu\beta\beta$-decay, and neutrino physics with DARWIN

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Neutrino physics with multi-ton scale liquid xenon detectors
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Expected solar neutrino rates

● Solar neutrinos can be detected via elastic neutrino-electron scattering reaction: $\nu + e^- \rightarrow \nu + e^-$ (W or Z exchange for ν_e, and only neutral current reactions for other flavours)

→ test the main energy production mechanism in the Sun

● pp-neutrinos are produced in the proton fusion reaction:

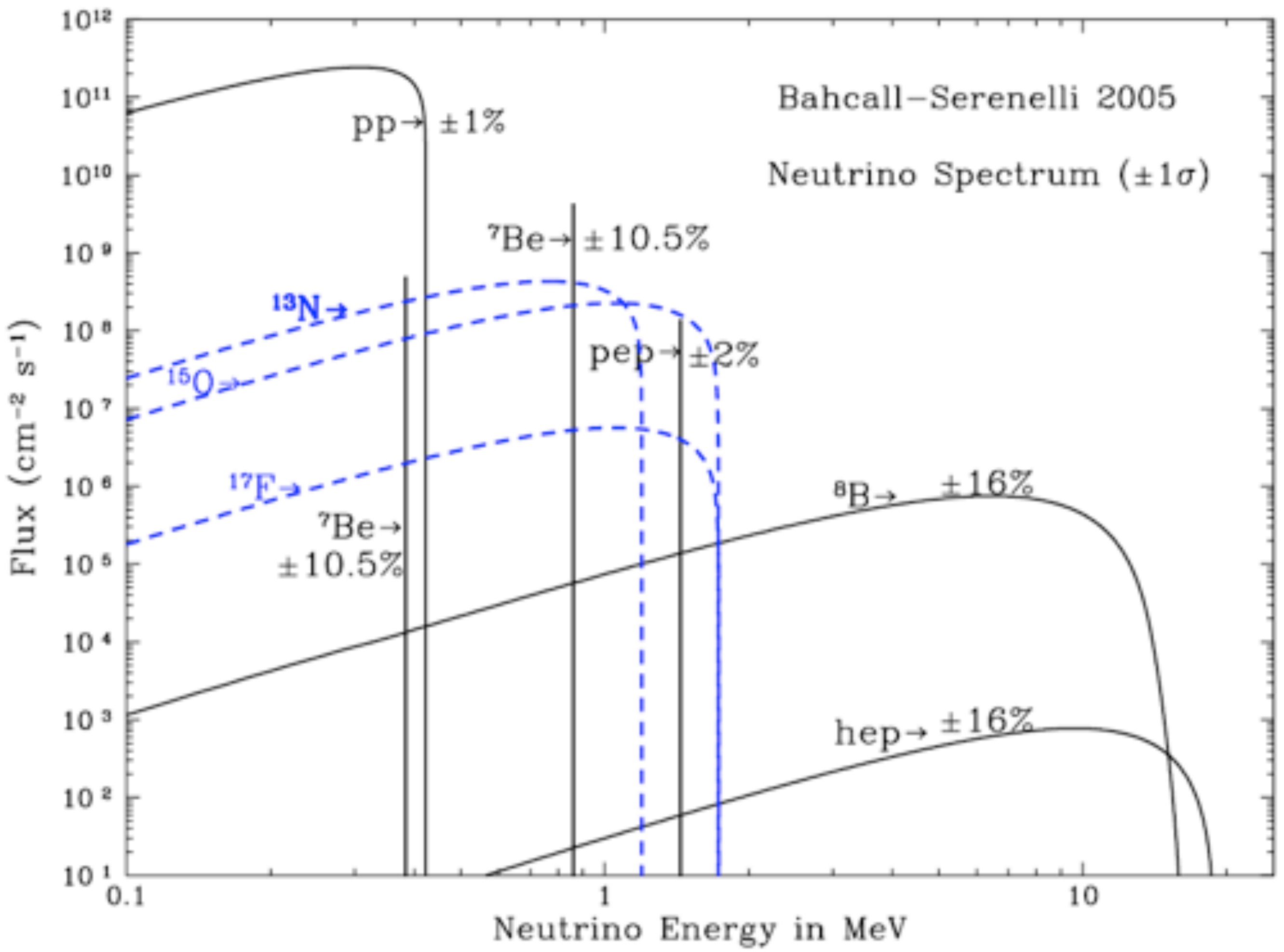
$$p + p \rightarrow {}^2H + e^+ + \nu_e$$

(endpoint at 420 keV)

● ^{7}Be-neutrinos are born in electron-capture:

$$^7Be + e^- \rightarrow {}^7Li + \nu_e$$

(10% 383 keV, 90% 862 keV)



Expected solar neutrino rates: Assumptions

- LXe target 18t; fiducial volume 14t → 3.47×10^{30} target electrons

- Scintillation light yield 46 photons/keV → energy threshold 2 $\mathrm{keV_{ee}}$

- Mean cross-sections for elastic neutrino-electron scattering:
  pp: $\sigma(\nu_e) = 11.6\times10^{-46}\ \mathrm{cm}^2$
  ^{7}Be: $\sigma(\nu_e) = 57.9\times10^{-46}\ \mathrm{cm}^2$

- Total neutrino fluxes:
  $\Phi(pp) = 5.94\times10^{10}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  $\Phi(^7Be) = 4.38\times10^{9}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

- Radial position resolution 15 mm; Z position resolution 3mm
  XENON100, 1” PMTs: 3 mm
  LUX, 2” PMTs: 5 mm → error on the FV calculation <0.1%
  XENON1T, 3” PMTs: 8 mm

- Energy resolution of the XENON100 detector (combined energy scale):

$$\frac{\sigma(E)}{E}[\%] = 0.9 + \frac{48.5}{\sqrt{E\ [\mathrm{keV}]}}$$

(~1% in the $0\nu\beta\beta$ region of interest)

Expected solar neutrino rates

- Neutrino spectral shape:

$$\frac{dN_\nu(E_\nu)}{dE_\nu} = A(Q + m_e - E_\nu)\left[(Q + m_e - E_\nu)^2 - m_e^2\right]^{\frac{1}{2}} E_\nu^2 F$$

Q – maximum neutrino energy, E_ν – initial neutrino energy, m_e – mass of the electron, F – correction factor (close to unity for the low-Z nuclei in the Sun), A – normalization factor

- Differential cross-section:

$$\frac{d\sigma(E_e, E_\nu)}{dE_e} = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2\left(1 - \frac{E_e}{E_\nu}\right)^2 - g_L g_R \frac{m_e}{E_e E_\nu}\right]$$

E_ν – kinetic energy of the final state electron, G_F – Fermi constant

$$g_L = \pm\frac{1}{2} + \sin^2\theta_W \qquad\qquad g_R = \sin^2\theta_W$$

Θ_W – Weinberg angle with $\sin^2\Theta_W = 0.231$; sign conventions for g_L is positive for ν_e, and negative for $\nu_{\mu,\tau}$

Expected solar neutrino rates

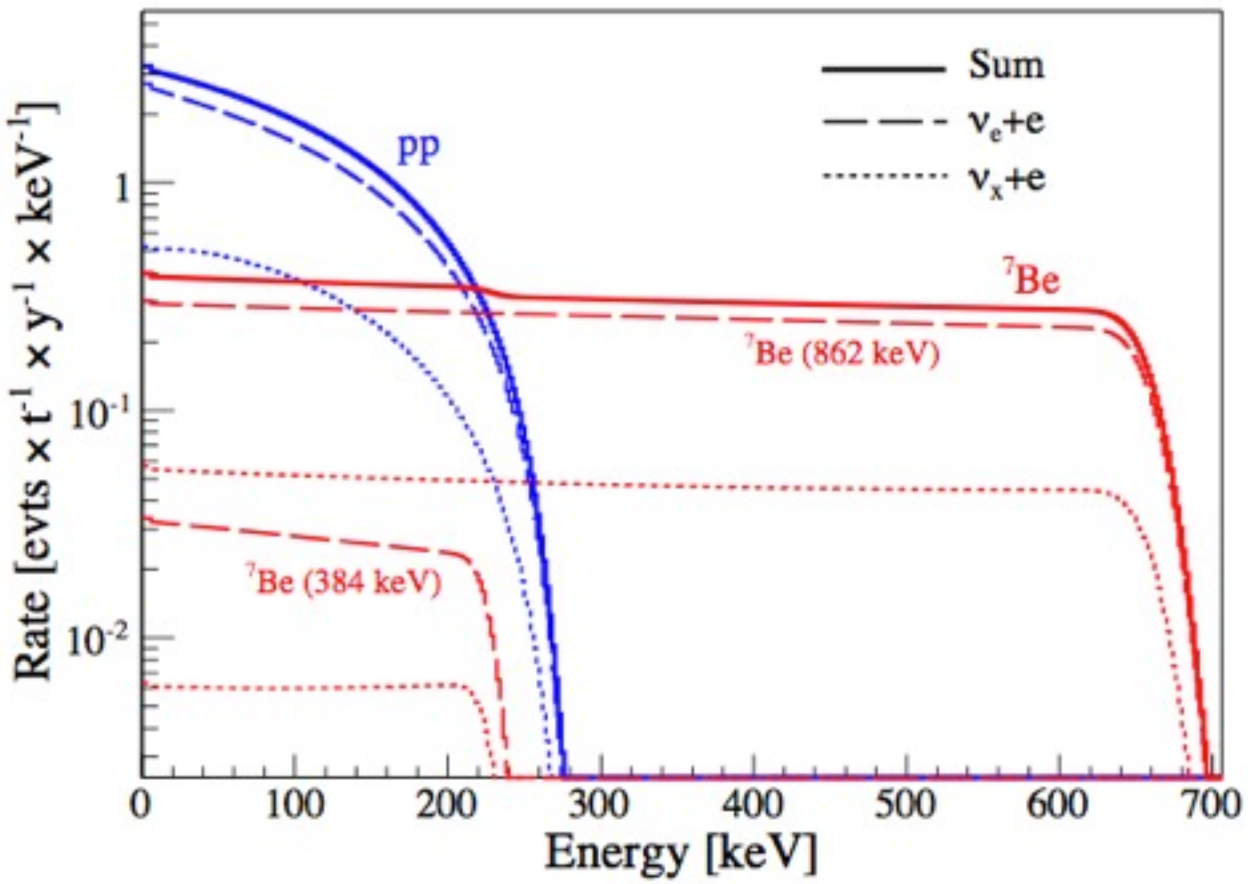
- Probability of neutrino arrival at the detector as electron neutrino

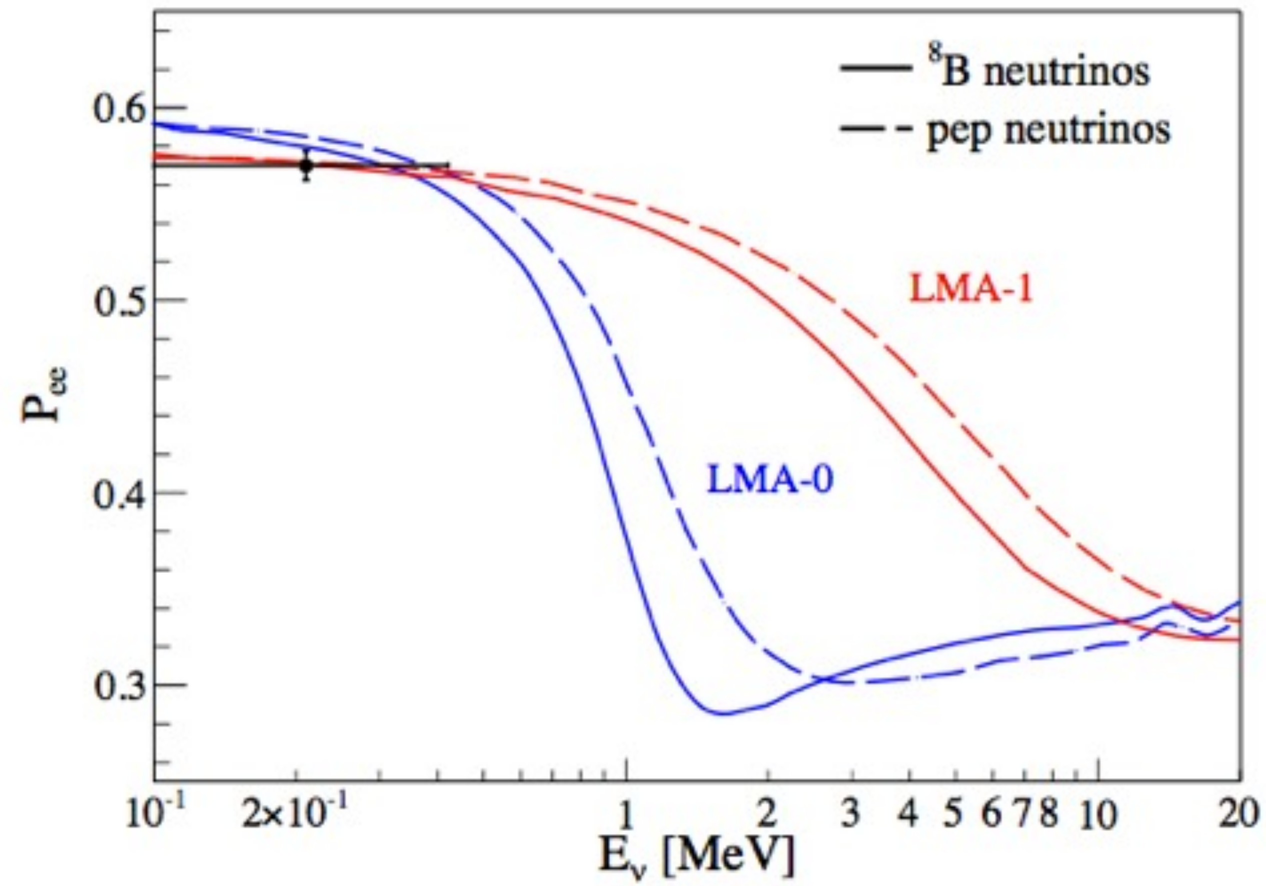
$$P_{ee} = \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2 2\theta_{12}\right) + \sin^4\theta_{13}$$

- Assuming mixing angles $\sin^2\Theta_{12} = 0.312$ and $\sin^2 2\Theta_{13} = 0.092$, electron-neutrino survival probability is $P_{ee} = 0.543$, and the overall rates
- Differential electron recoil spectrum

$$\frac{dN_e(E_e)}{dE_e} = N_0 \times t \times \sum_i^{flavours} \int dE_\nu \frac{d\phi_i(E_\nu)}{dE_\nu}\frac{d\sigma_i(E_e, E_\nu)}{dE_e}$$

N_0 – number of electrons in the target, t - measuring time





WIP-nucleon interaction rates

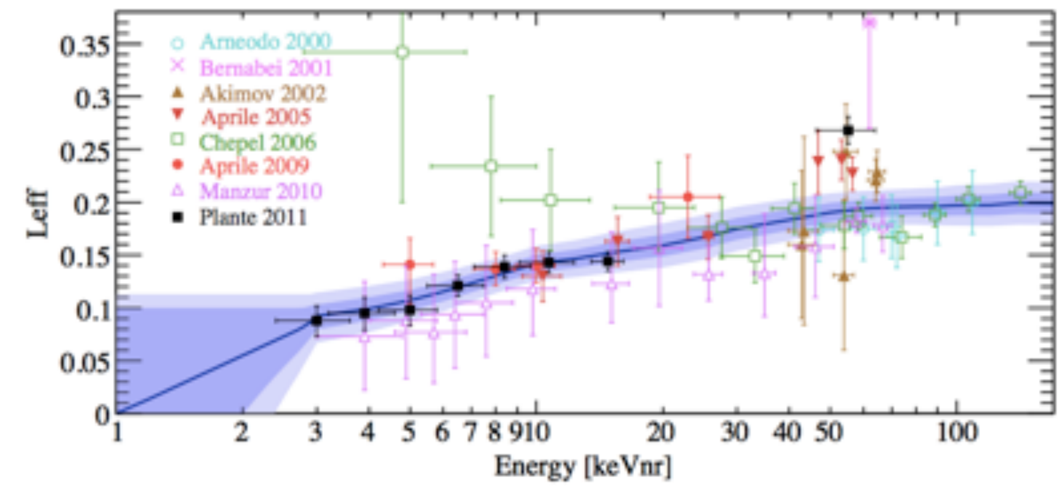
- Standard halo model: isothermal halo, local DM density 0.3 GeV/cm^3, circular velocity 220 km/h, escape velocity 544 km/s

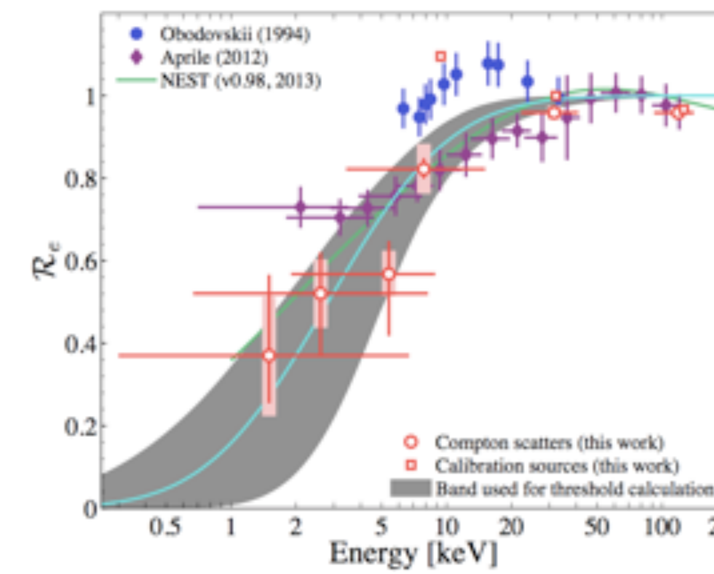
- M_1 = 100 GeV/c^2, $\sigma_1 = 10^{-47}$ cm^2
  M_2 = 40 GeV/c^2, $\sigma_2 = 10^{-47}$ cm^2

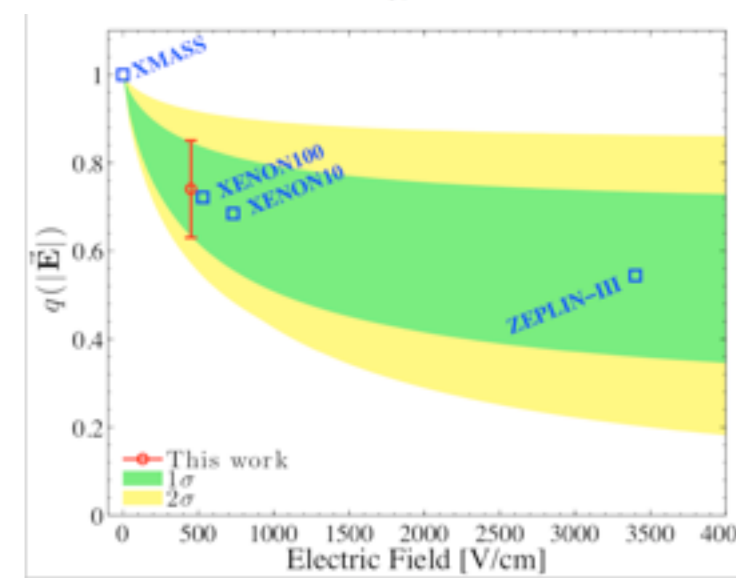
- Conversion from keV$_{ee}$ to keV$_{nr}$ using L_{eff}:
  2 keV$_{ee}$ → 6.6 keV$_{nr}$
  10 keV$_{ee}$ → 36.8 keV$_{nr}$

- Apply Poisson fluctuations in the number of PE

- Convert to keV$_{ee}$ scale using measured light yield of low-energy electronic recoils at drift field ~0.5 kV/cm (in agreement with NEST prediction)

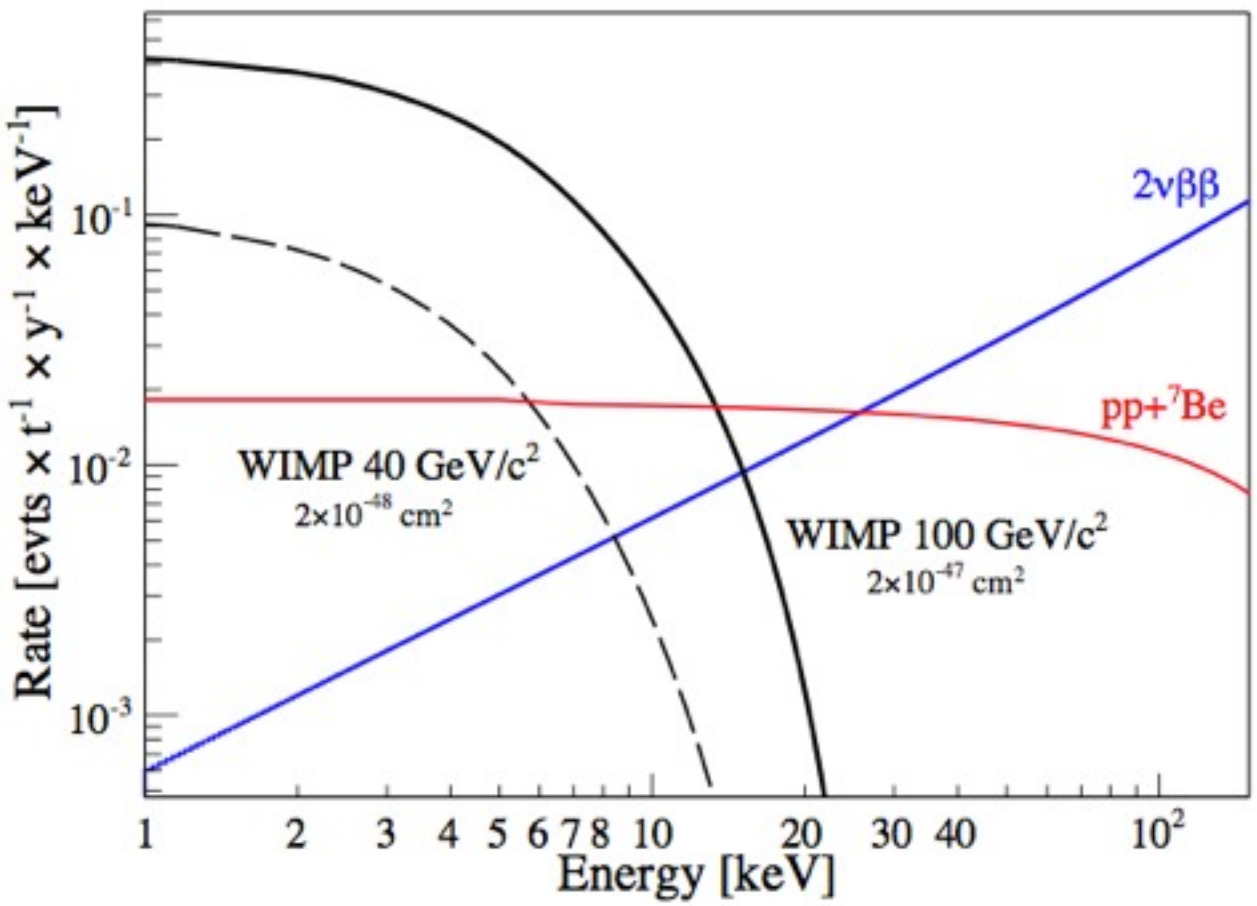


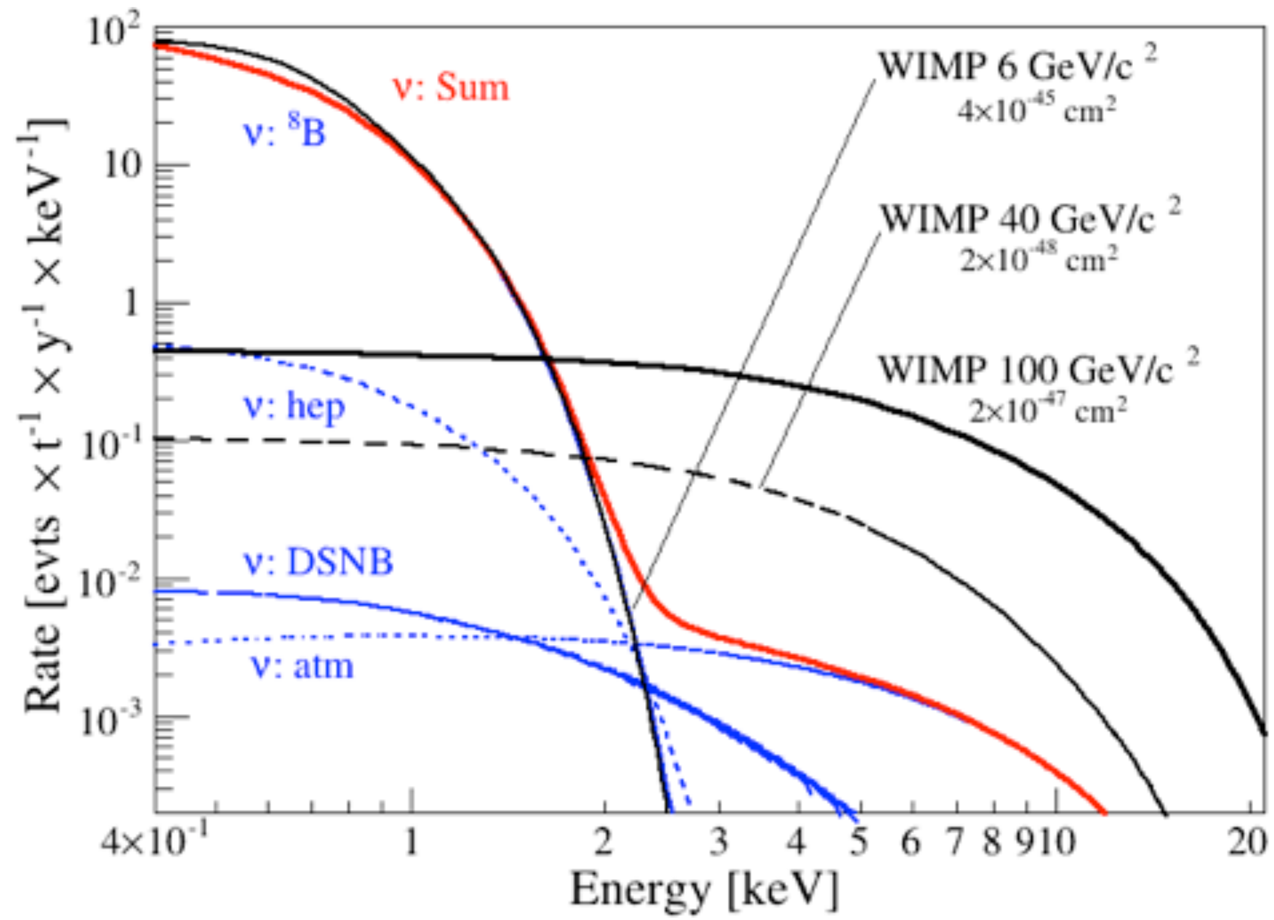




WIMP and neutrino sensitivity

- Assuming electronic recoil rejection 99.5%, nuclear recoil acceptance 50%





- Electronic recoil neutrino BG limits DM search channel (spin-independent WIMP-nucleon coupling) around cross-sections of 2×10^{-48} cm^2, dominated by interactions of pp-neutrinos

- Coherent neutrino-nucleus elastic scattering (mostly ^{8}B and hep neutrinos) affects the sensitivity to low-mass WIMPs

- Atmospheric and diffuse supernovae neutrinos become relevant at 10^{-48} cm^2

$0\nu\beta\beta$-decay of ^{136}Xe

- Natural xenon composition: abundance of ^{136}Xe is 8.9%
  $\rightarrow$ 534 kg of ^{136}Xe in the 6t target

- Region of interest for $0\nu\beta\beta$ is 3σ around the Q-value of ^{136}Xe
  2458.7±0.6 keV
  (2385 to 2533 keV)

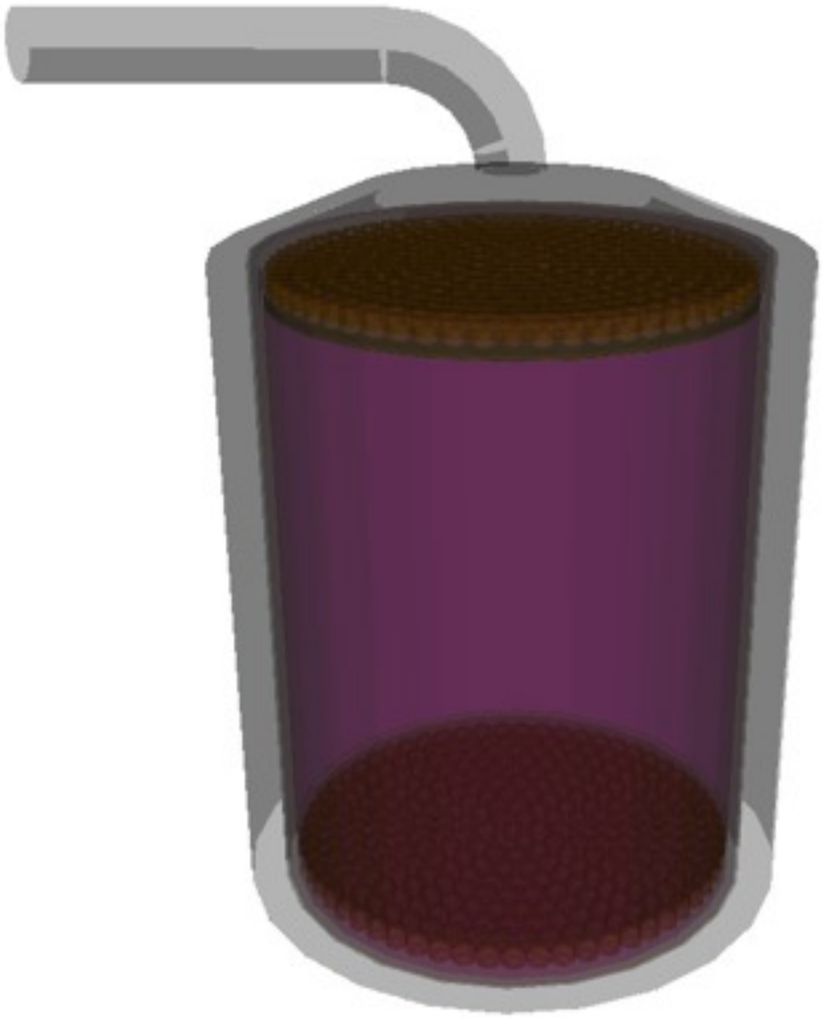
- Energy resolution in ROI is 1%

- Spectral shape parametrization with

$$dN/dE = E_{Xe} \times (E_0 - E_{Xe})^5 \times (E_{Xe}^4 + 10 \cdot E_{Xe}^3 + 40 \cdot E_{Xe}^2 + 60 \cdot E_{Xe} + 30)$$

$$(E_0 = QXe/m_{e-}c^2; \quad E_{Xe} = E/m_{e-}c^2)$$

Background from radioactivity in the construction materials



- The best results from XENON100 and XENON1T screening campaigns have been selected

- The modeled photosensors are 2.8”, and might be a QUPID or Hamamatsu R11410 PMT

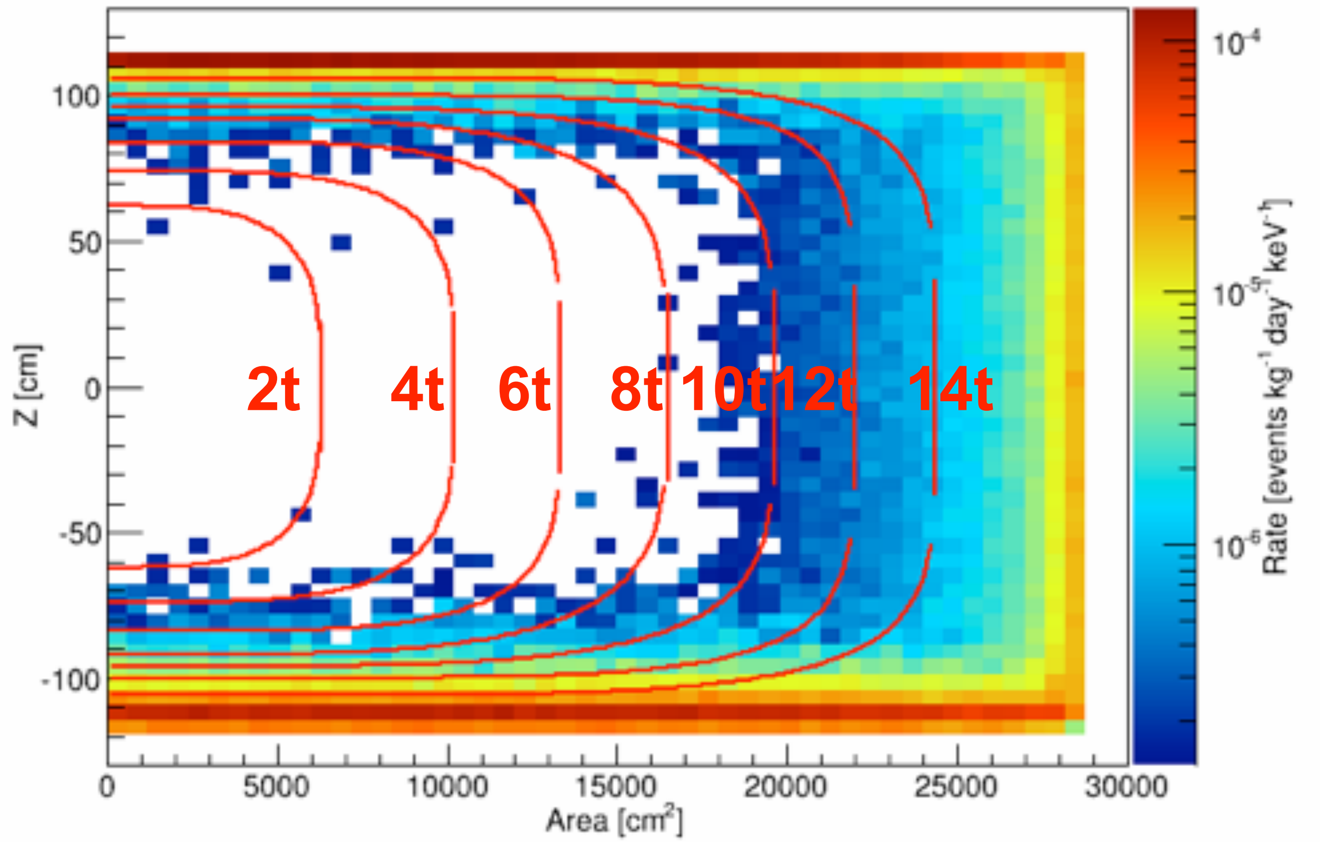
- Intrinsic contamination:
  0.1 ppt of ^{nat}Kr,   0.1µBq/kg of ^{222}Rn

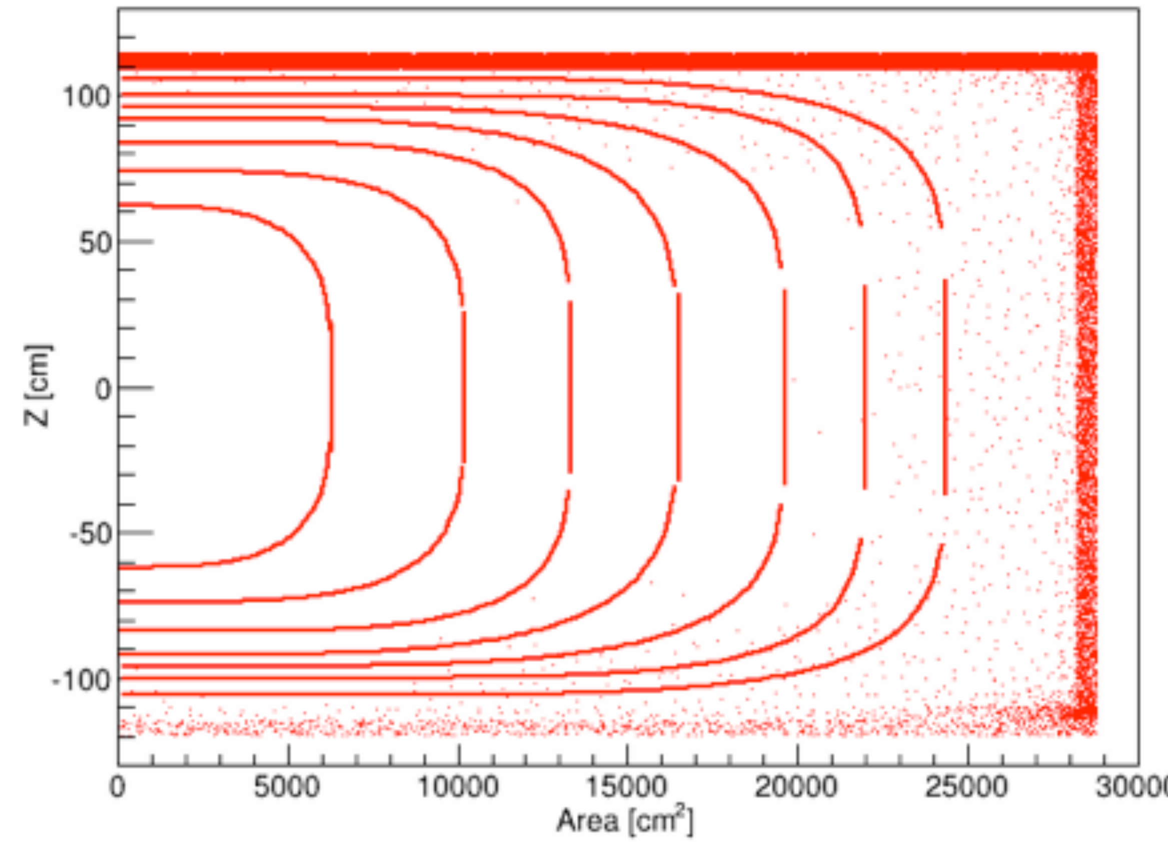
  XENON100: (1.0±0.2) ppt of krypton
  EXO-200: (3.7±0.4) ppt of radon

Detector component	Material	Mass [unit]	Specific activity [mBq/unit] $^{228}Th/^{226}Ra/^{40}K/^{60}Co$
Outer cryostat	Copper	2150 kg	0.02/0.07/0.023/0.008
Inner cryostat	Copper	1737 kg	0.02/0.07/0.023/0.008
Electrodes, bell	Copper	113 kg	0.02/0.07/0.023/0.008
TPC	Teflon	313.6 kg	0.2/0.05/0.59/0.01
Photosensors	Quartz	1050 pieces	0.28/3.2/0.39/6.0/0.15
Total (instrumented) volume	LXe	21.4 (18) t	0.1 ppt ^{nat}Kr, 0.1 μBq/kg ^{222}Rn

Background reduction with fiducial volume and multi-site cuts

- 3D position reconstruction – fiducialization of the LXe target
- Z coordinate from delay time between S1 and S2
  → resolution ~3mm (typical S2 width 2μs, electron drift velocity 1.5 mm/μs)
- XY resolution of about 8 mm can be achieved with 3 inch phototubes
  → not considered for multiple scatter rejection
  (probability to have such an event is already low)

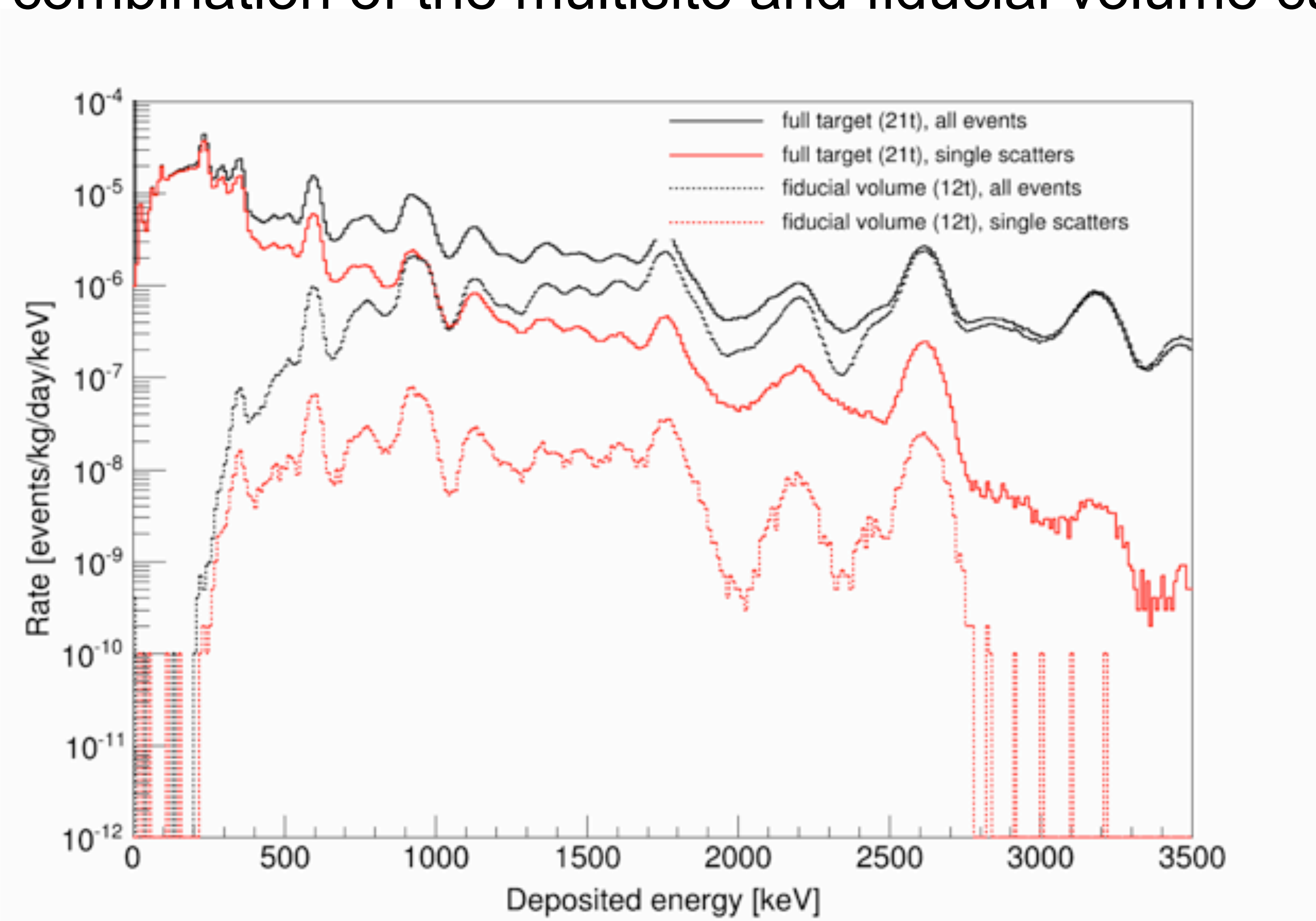


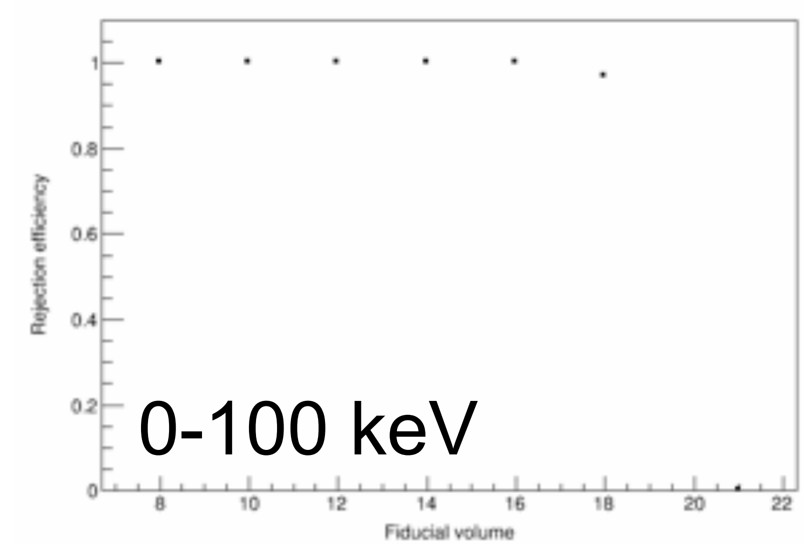


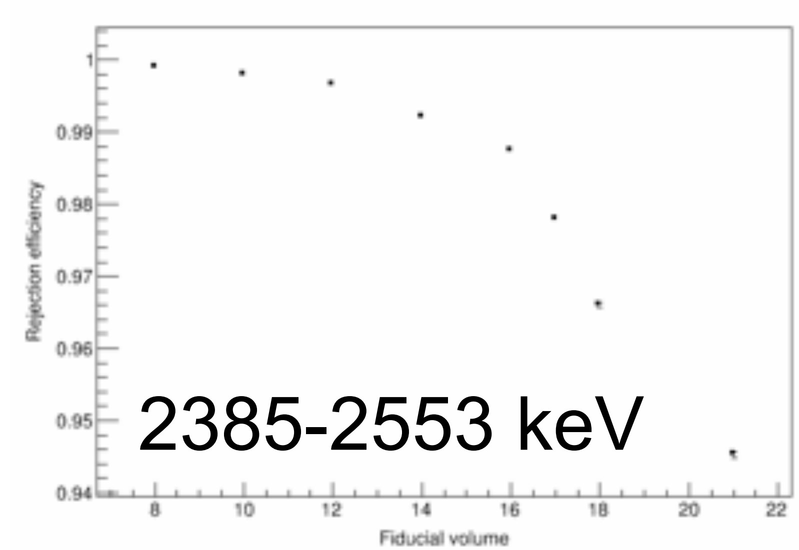
Background reduction with fiducial volume and multi-site cuts

● Due to the geometry of the detector (large outer edge surface area), it is likely for a particle to scatter only once and leave the active volume. Instead, when an interaction happens in the center of the target, the remaining xenon acts as an active veto for multiple scattering events

● Rejection of the multiple scattering events has to be calculated with the combination of the multisite and fiducial volume cuts (>99.5%)

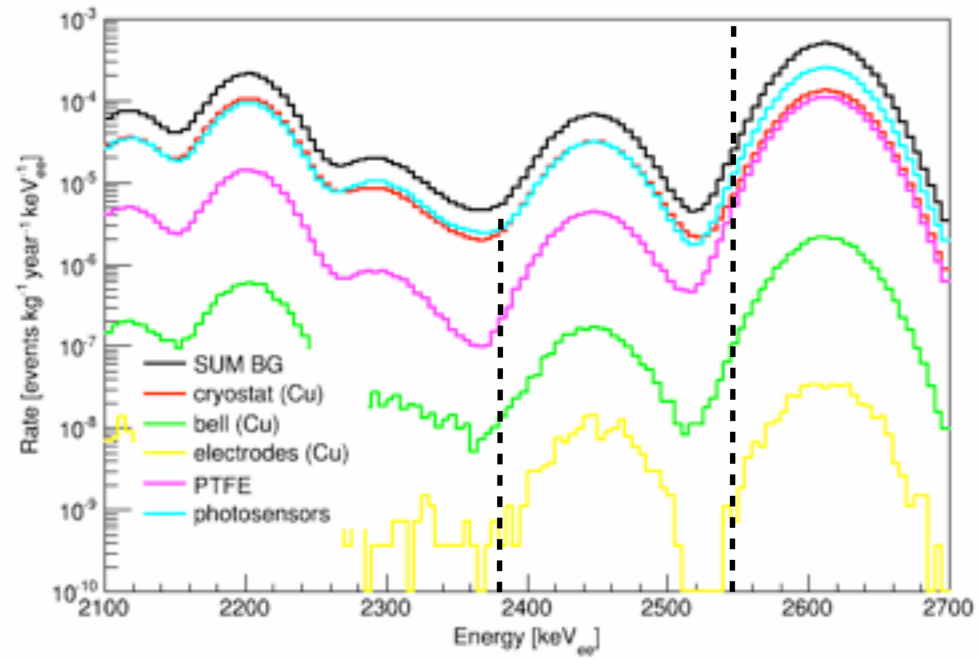


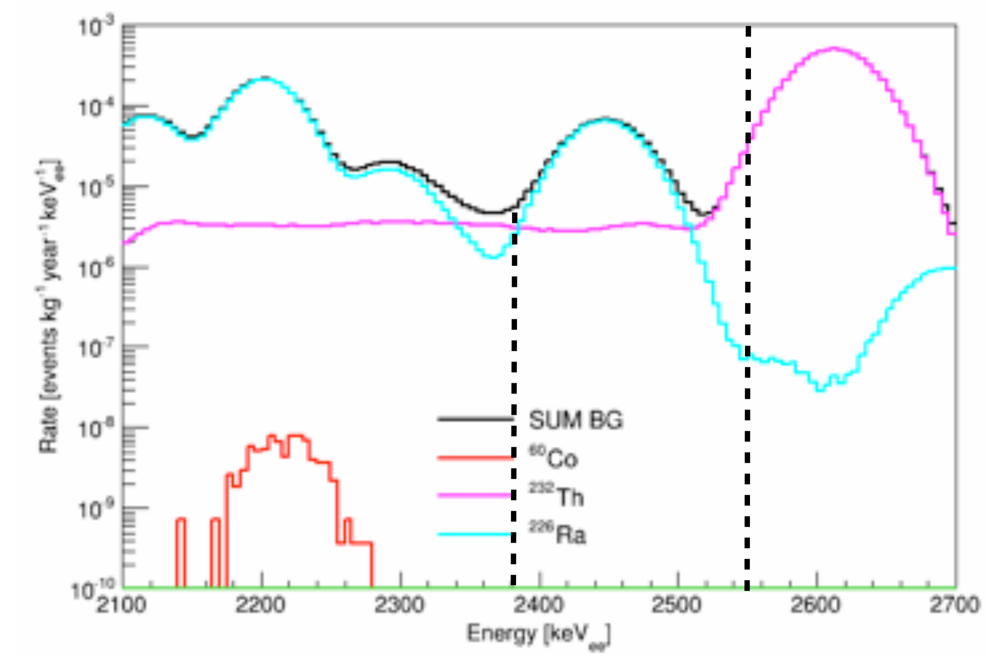




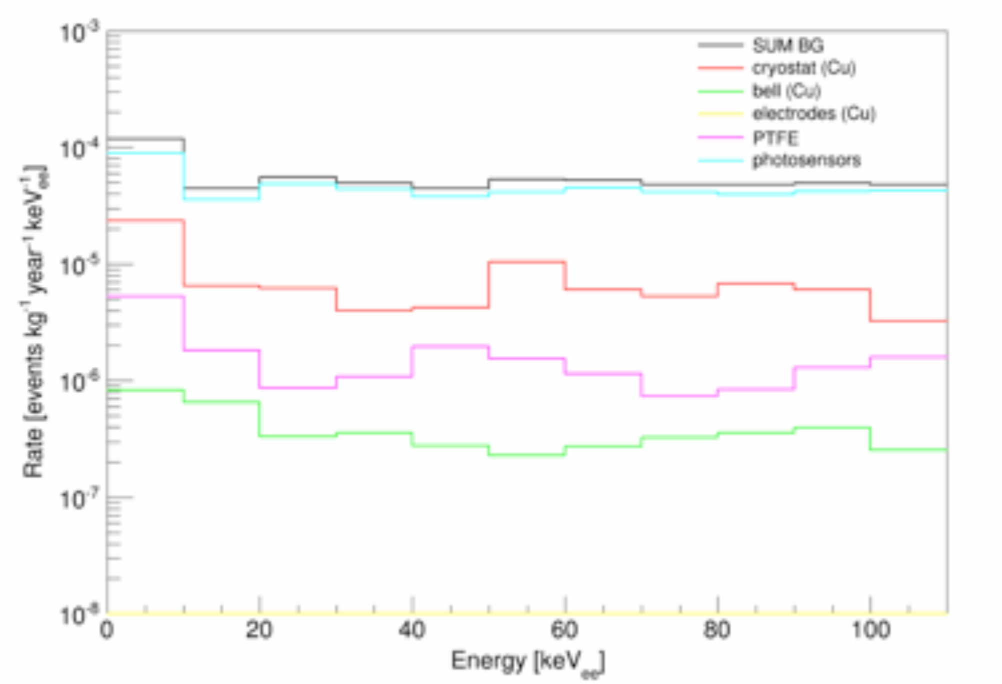
Background from radioactivity in the construction materials

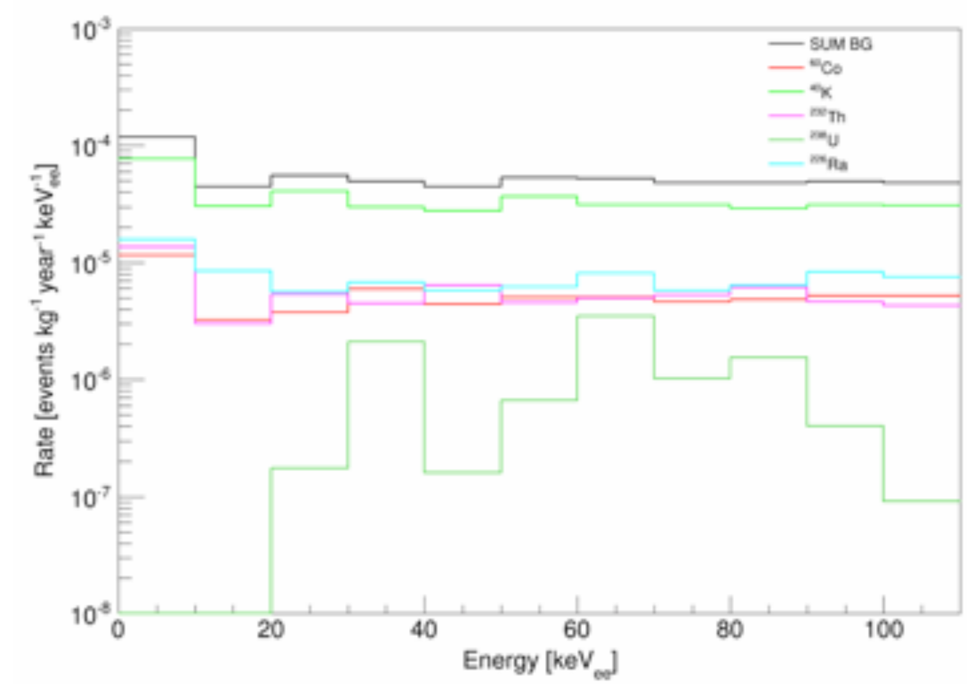
- In the 0νββ-search energy region BG is dominated by decays from ^{226}Ra chain in the cryostat. 2nd largest contribution comes from the photosensors





- Background in the WIMP-search energy range (materials only) is dominated by ^{40}K in the photosensors, followed by the cryostat, TPC and diving bell





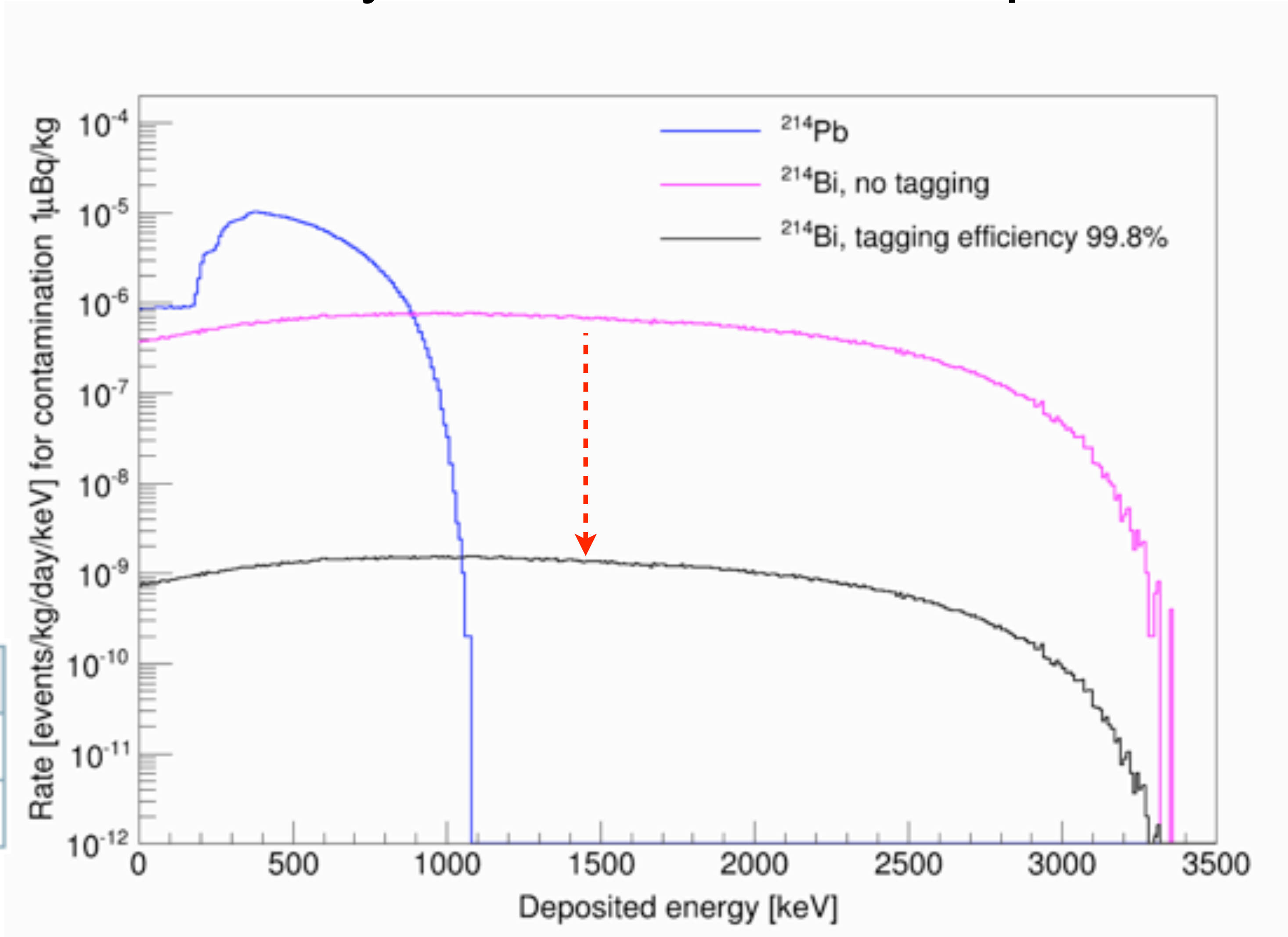
Background from intrinsic contamination with radon

- From ^{222}Rn decay chain, only ^{214}Pb and ^{214}Bi undergo β-decay.
- Isotopes after ^{210}Pb are not considered due to it's long mean lifetime and slow buildup
- Positively charged ions after decay drift in the electric field to the cathode
- Decays of ^{214}Bi can be identified by tagging the coincidence with ^{214}Po α-decay ($T_{1/2}$ = 164 μs)
- Two scintillation peaks can be separated if they are at least 300 ns apart

Waveform length	Efficiency
(0.3 – 200) us	57.83 %
(0.3 – 1) ms	98.56 %
(0.3 – 2) ms	99.85 %
(0.3 – 10) ms	99.87 %

Isotope	GEANT4.9.5	LBNL	NNDC	Table of Isotopes
Pb214	6.2	6.3	11.0	9.3
Bi214	18.2	18.2	19.1	19.9

→ possible increase in predicted BG by a factor of ~2



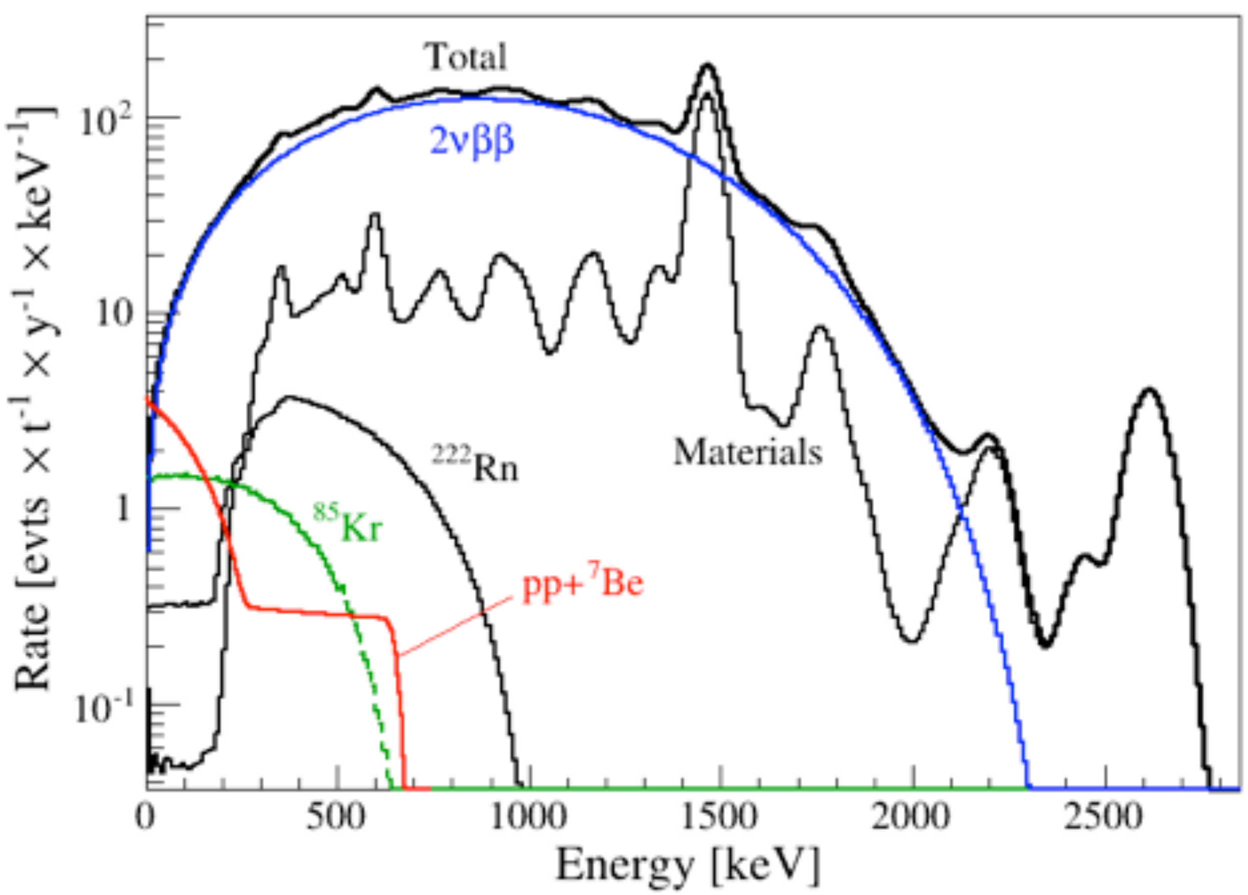
Background in low energy region. Neutrino and WIMP detection

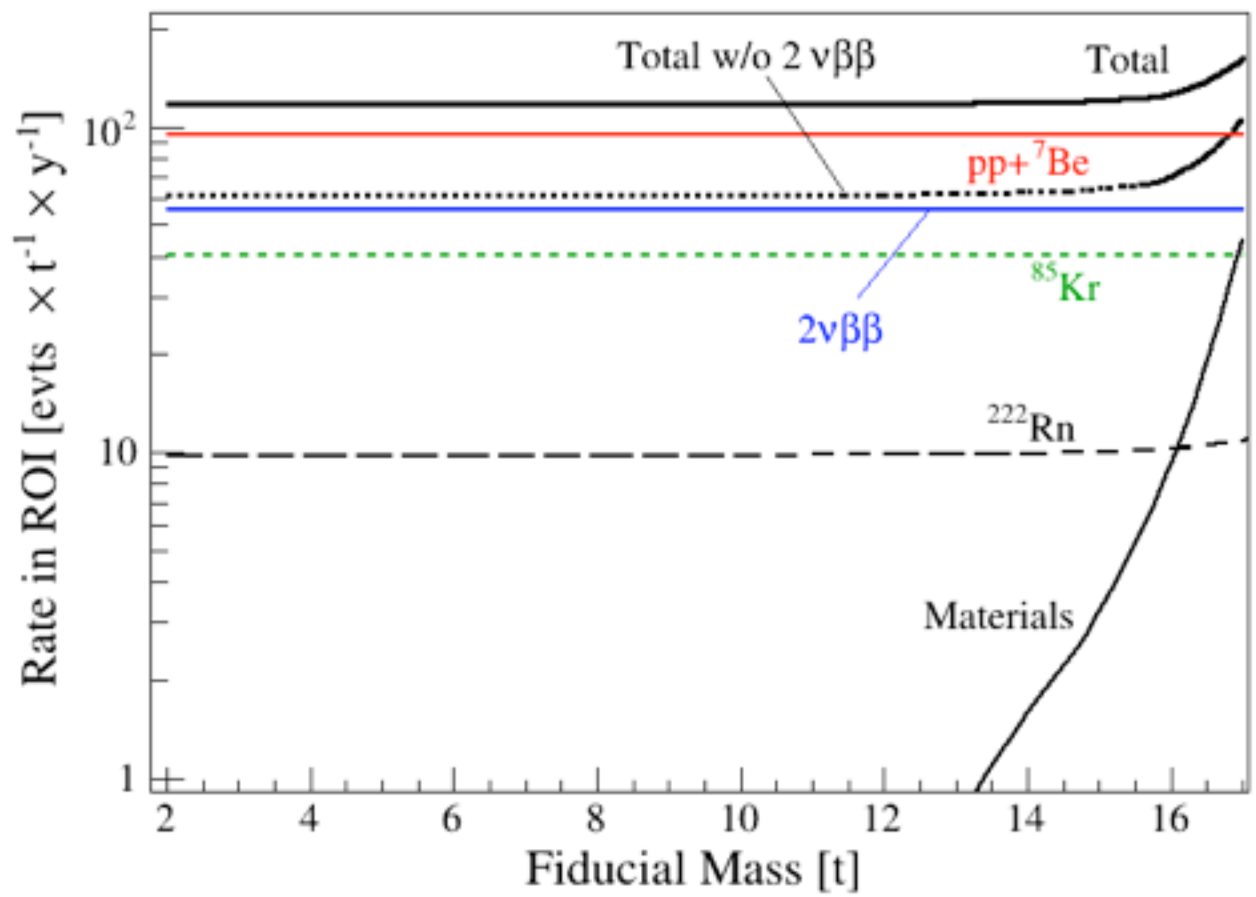
- The total background at low energies is dominated by 2νββ-decays of ^{136}Xe ($T_{1/2} = 2.11\times10^{21}$ years, as measured by EXO-200), followed by krypton

- Chose 14t of LXe in the central detector region

- Energy range for neutrino measurement up to 30 keV_{ee} (intersect with ^{136}Xe 2νββ curve)

- WIMP ROI up to 2–10 keV_{ee}V. + electronic recoil rejection 99.5%





Background in low energy region. Neutrino and WIMP detection

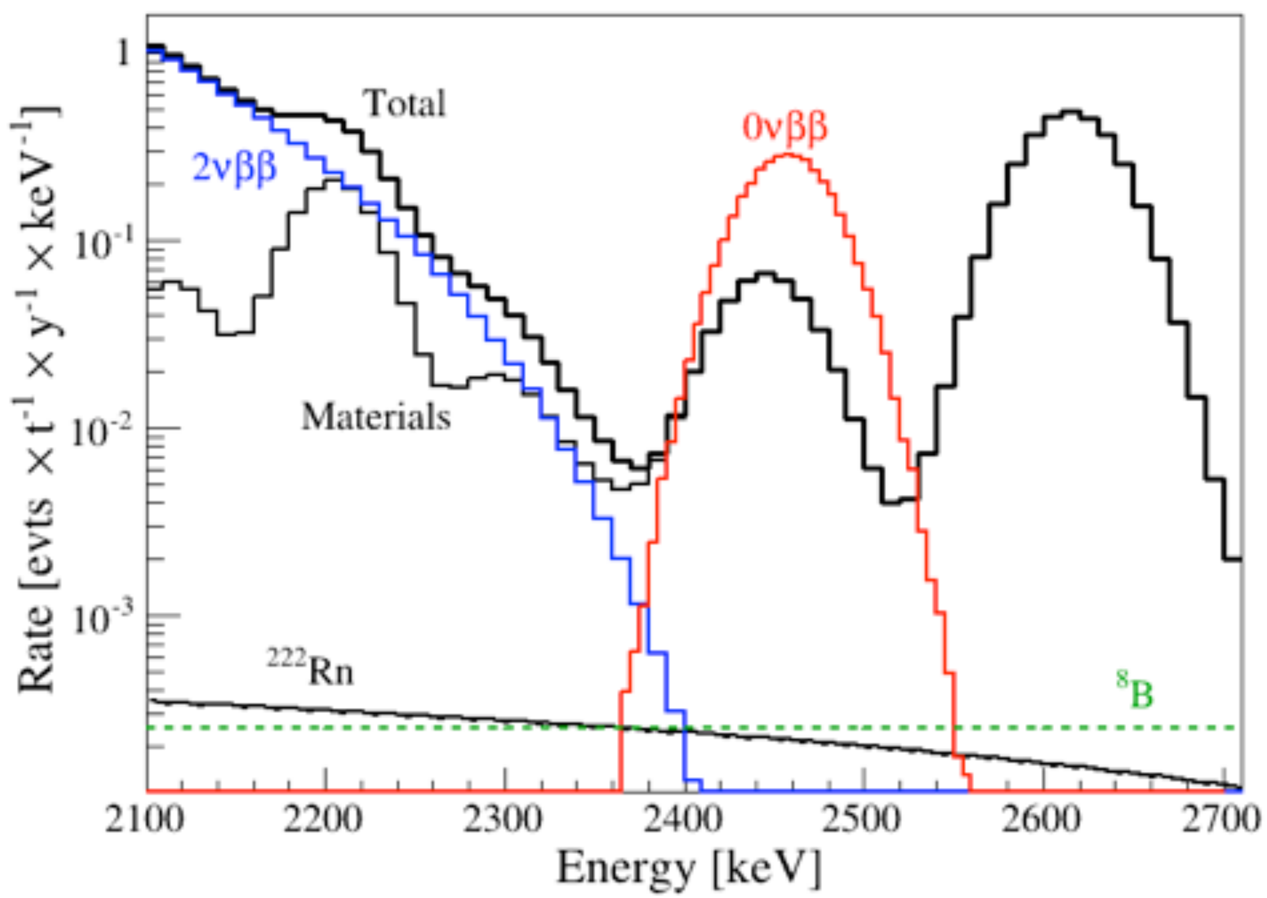
- Fiducial mass 14t
- For WIMP-search, ER rejection 99.5%, NR acceptance 50%

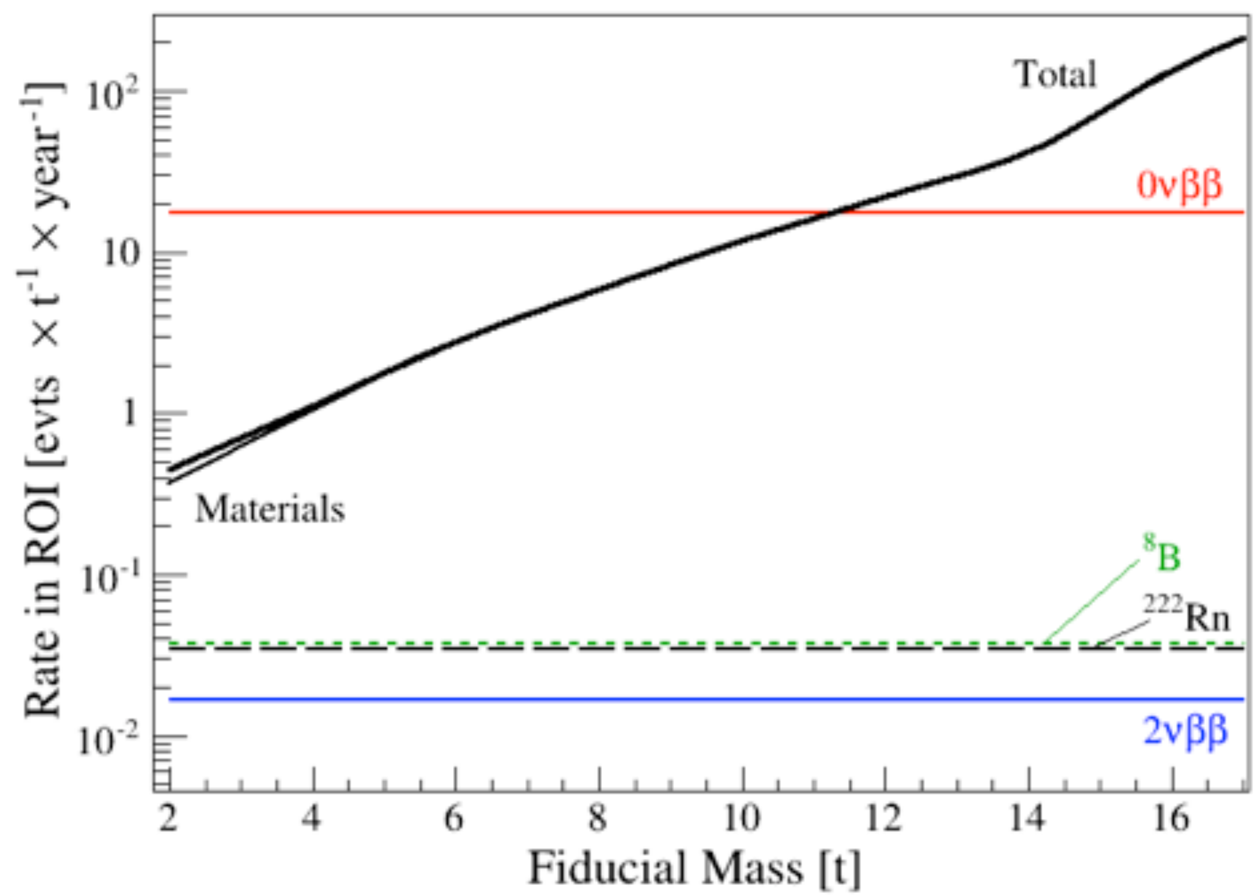
Physics channel	Low-energy ν measurement	Dark matter search
Energy range	2–30 keV	2–10 keV
Assumptions	No ER/NR discrimination	99.5% ER rejection 50% NR acceptance
Rate	Events/(14 t·y)	Events/(14 t·y)
Solar pp neutrinos	1180	1.75
Solar ^{7}Be neutrinos	151	0.25
100 GeV/c^2 WIMP, 2×10^{-47}cm^2	42	19
40 GeV/c^2 WIMP, 2×10^{-48}cm^2	5.2	2.5
Coherent ν scattering	0.98	0.45
Detector components	19	0.03
^{85}Kr in LXe (0.1 ppt of ^{nat}Kr)	565	0.82
^{222}Rn in LXe (0.1 μBq/kg)	139	0.20
^{136}Xe ($2\nu\beta\beta$)	785	0.41

Background for ^{136}Xe 0νββ-decay search

- Fiducial mass 6t
- BG dominated by ^{226}Ra sub-chain decays (^{214}Bi) in the cryostat and photosensors
- Assuming:
  $T_{1/2}(0\nu\beta\beta) = 1.6\times10^{25}$ years
  $T_{1/2}(2\nu\beta\beta) = 2.11\times10^{21}$ years

	Events/(6 t y)
Energy range	2385–2533 keV
Signal events	106
Detector components	27
^{222}Rn in LXe (0.1μBq/kg)	0.21
^{8}B (ν-e scattering)	0.22
^{136}Xe ($2\nu\beta\beta$)	0.14





Summary

● Integrated pp-neutrino rate in 2–30 keV after 5 years run (with 14t fiducial mass) is 5900 events

→ statistical uncertainty of the measured flux ~1%

→ limiting background for WIMP-search channel (WIMP-nucleon cross-sections below $\sim 2\times10^{-48}$ cm^2 and WIMP masses around 50 GeV/c^2, assuming ER rejection of 99.5%)

● Nuclear recoils from coherent scattering of solar neutrinos will limit the sensitivity to WIMP masses below 6 GeV/c^2 to cross-sections above $\sim 5\times10^{-45}$ cm^2

● Half-life sensitivity to $0\nu\beta\beta$-decay of ^{136}Xe after 5 years of data (6t fiducial mass) is 3.6×10^{26} years