Istituto Nazionale
di Fisica Nucleare

XENON
Dark Matter Project

Background and sensitivity predictions for XENON1T

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(on behalf of the XENON collaboration)

Feb 19th 2016, UCLA Dark Matter 2016

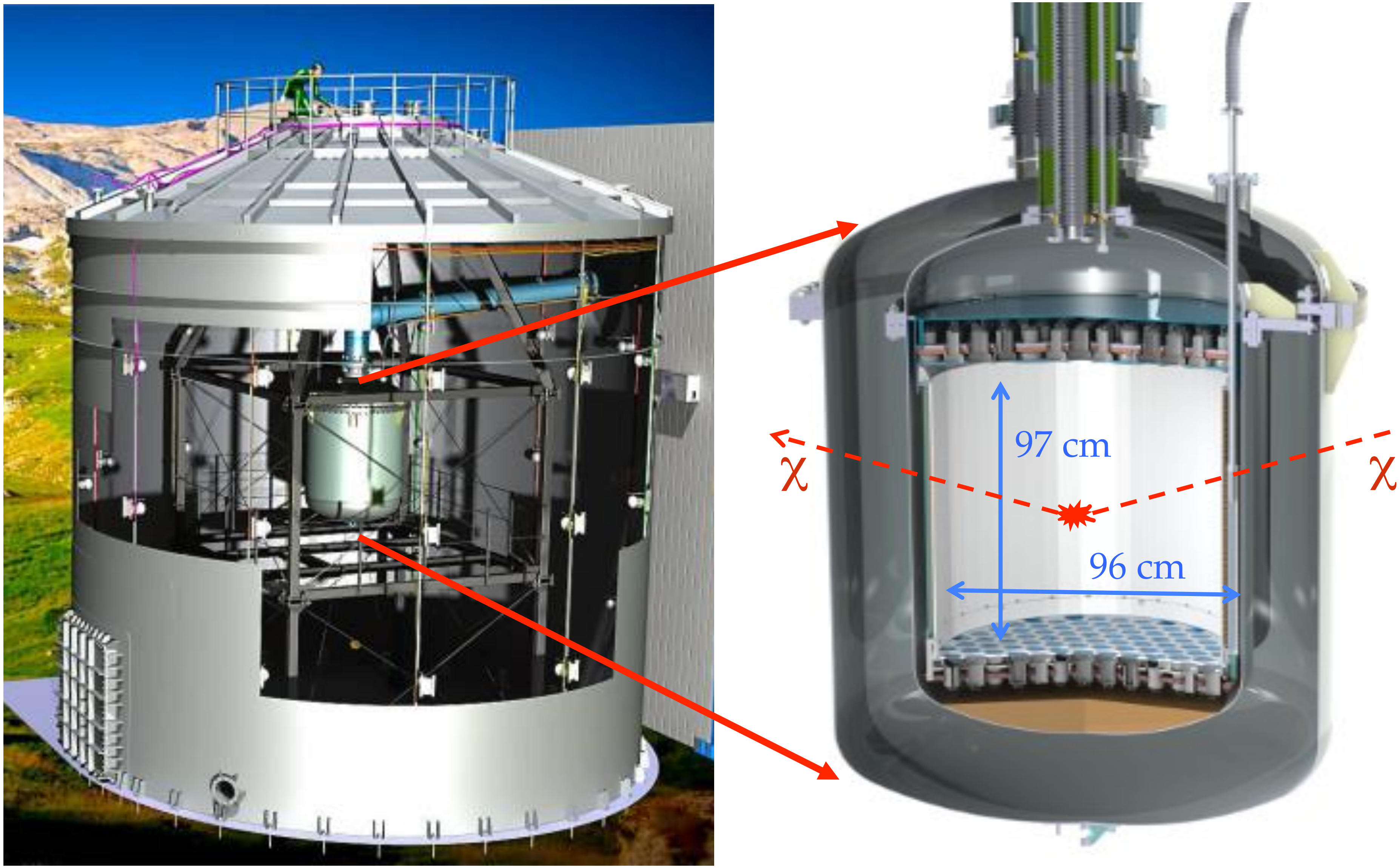
Outline

- Description of the detector;
- Prediction of the ER and NR backgrounds through a GEANT4 simulation of the experiment;
- Conversion of the energy released in the TPC by signal and background events into the S1 and S2 signals seen in the detector;
- Study the sensitivity to WIMP-nucleus spin-independent interactions.

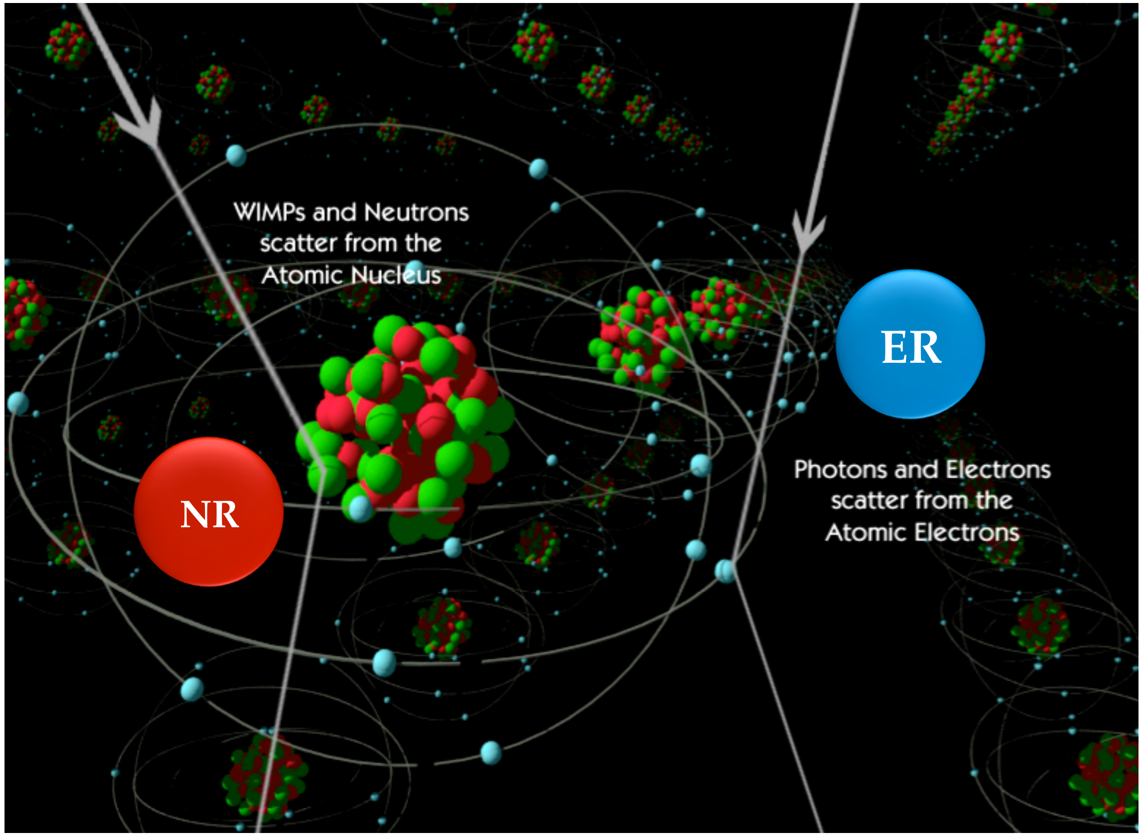
E. Aprile et al. (the XENON collaboration)
“Physics reach of the XENON1T dark matter experiment”,
arXiv:1512.07501,
submitted to JCAP

The XENON1T experiment

The XENON1T experiment



Main Backgrounds



Electron recoils (ER):

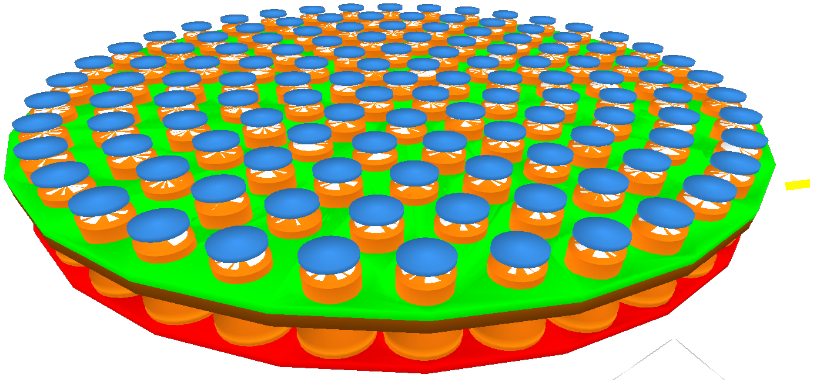
- low energy Compton scatters from the radioactive contaminants in the detector components: U and Th chains, ^{40}K, ^{60}Co, ^{137}Cs.
- Intrinsic contaminants: β decays of ^{222}Rn daughters, ^{85}Kr, ^{136}Xe.
- Elastic scattering of solar neutrinos off electrons.

Nuclear Recoils (NR):

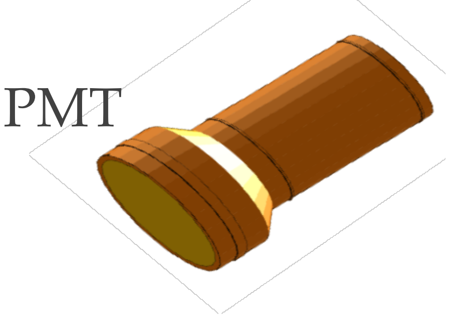
- Radiogenic neutrons: spontaneous fission and (α, n) reaction from the U and Th chains in the detector components.
- Muon-induced neutrons.
- Coherent scattering of neutrinos (mostly solar) off the Xe nuclei.

MC simulation in GEANT4

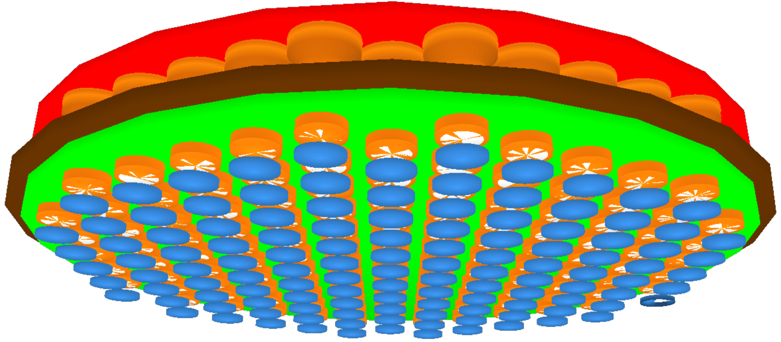
Top PMT array



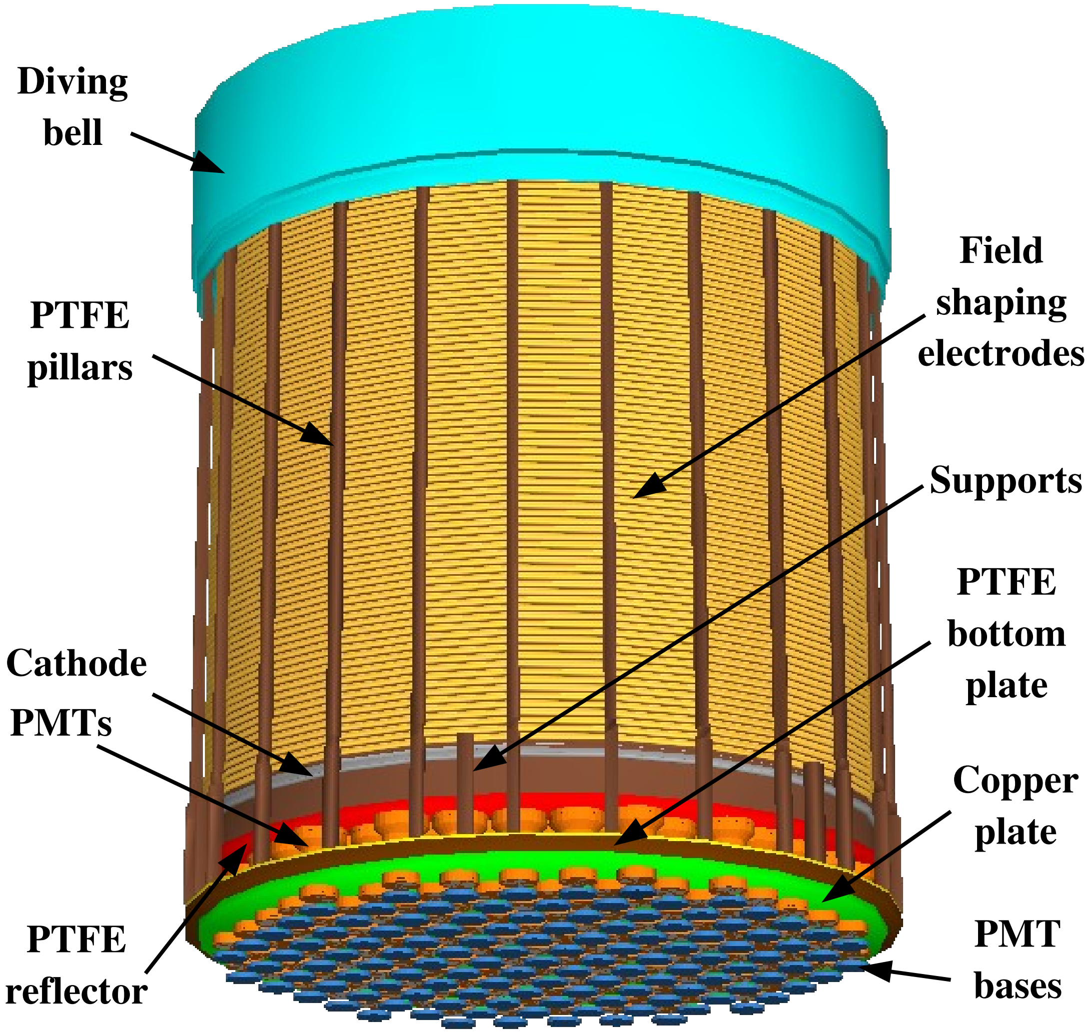
A single PMT



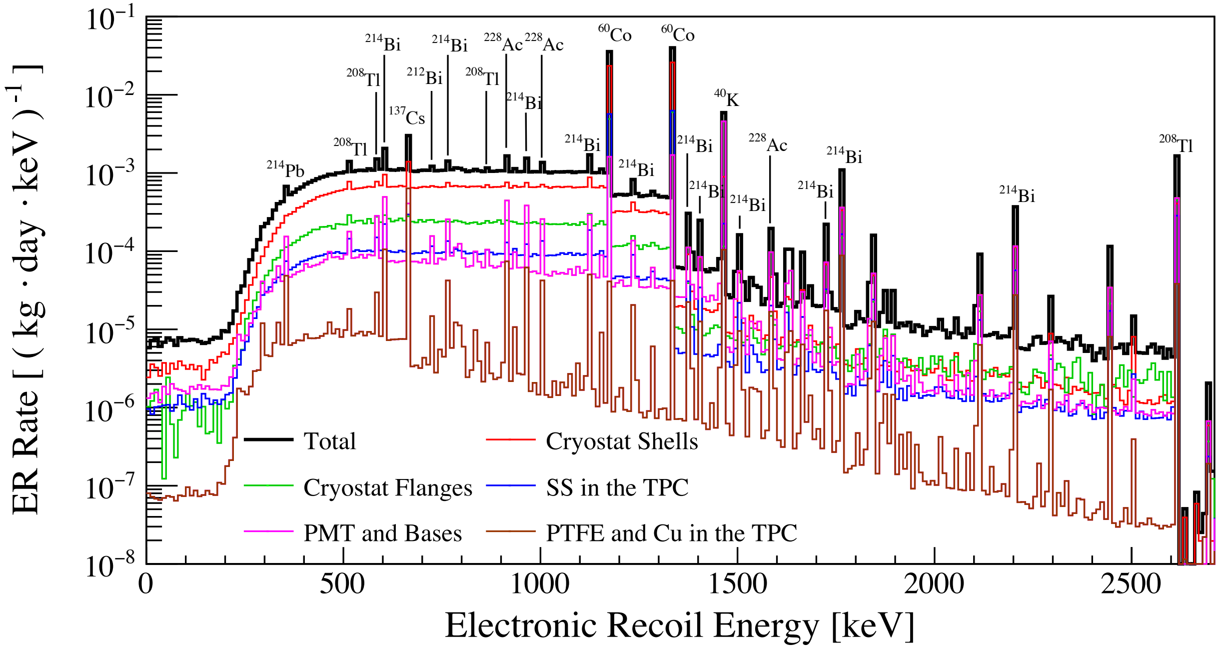
Bottom PMT array



The whole TPC

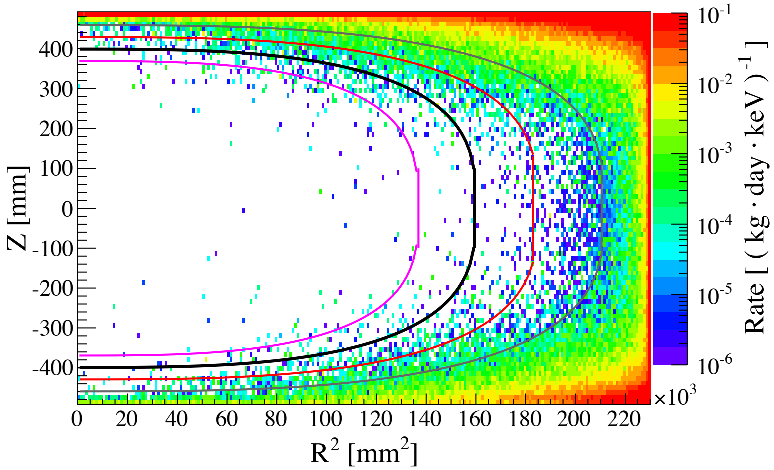


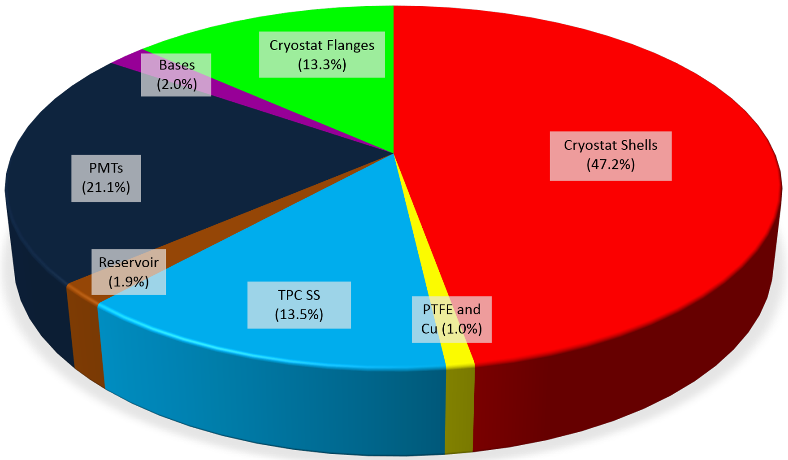
ER from the materials



Extensive screening campaign using gamma (Ge) and mass (ICP-MS) spectrometry.
Eur.Phys.J. C75 **(2015) 546**

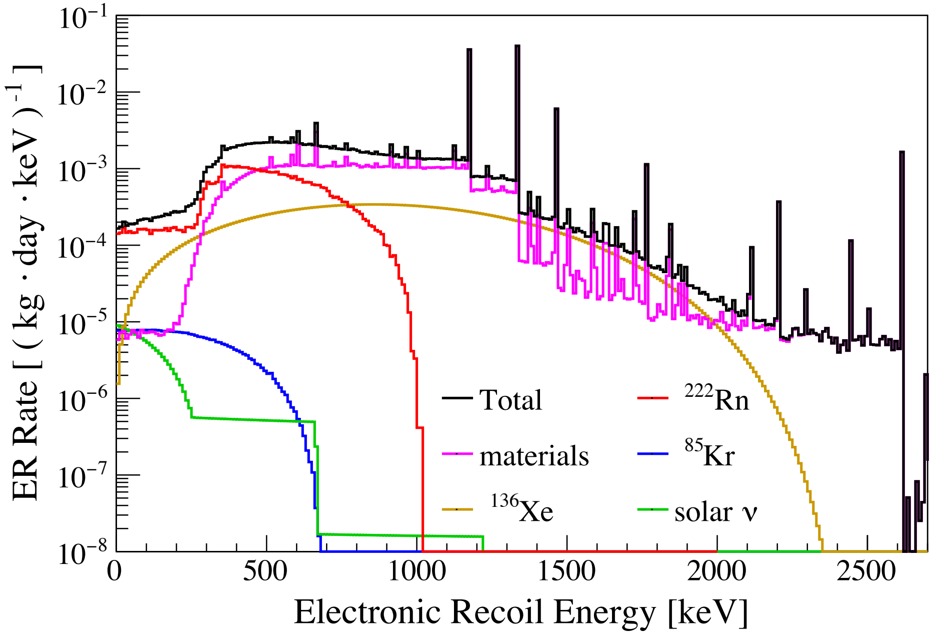
ER background
from the materials
in 1 t Fiducial Volume,
in [1, 12] keV:
7.3 10^{-6} (kg day keV)$^{-1}$

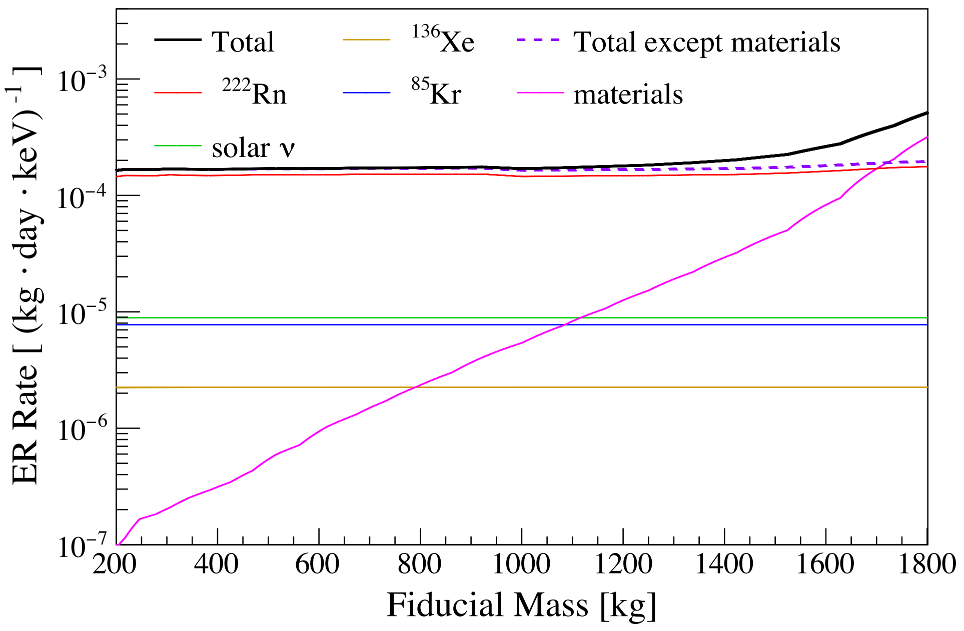




Total ER background

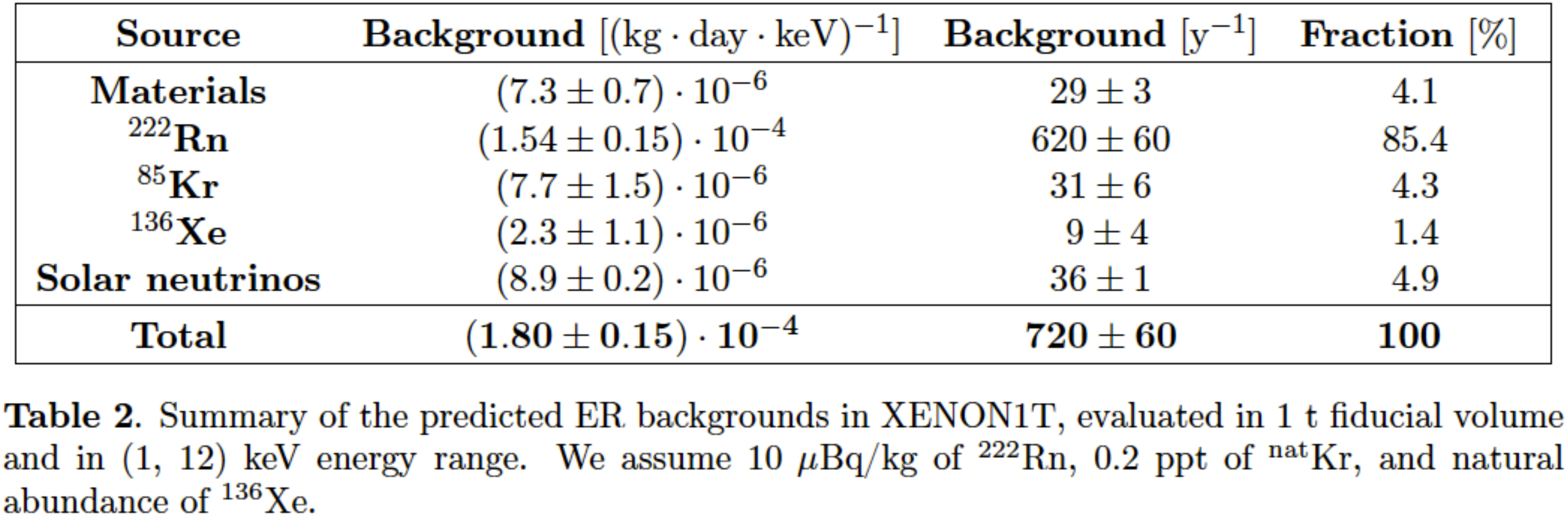
Assumptions on the intrinsic backgrounds:
0.2 ppt of ^{nat}Kr (already achieved in XENON1T distillation column tests),
10 μBq/kg of ^{222}Rn (conservative estimation based on Rn emanation meas.).





^{222}Rn (mainly from ^{214}Pb β-decay) is the most relevant source of ER background in most of the TPC.

Total ER background

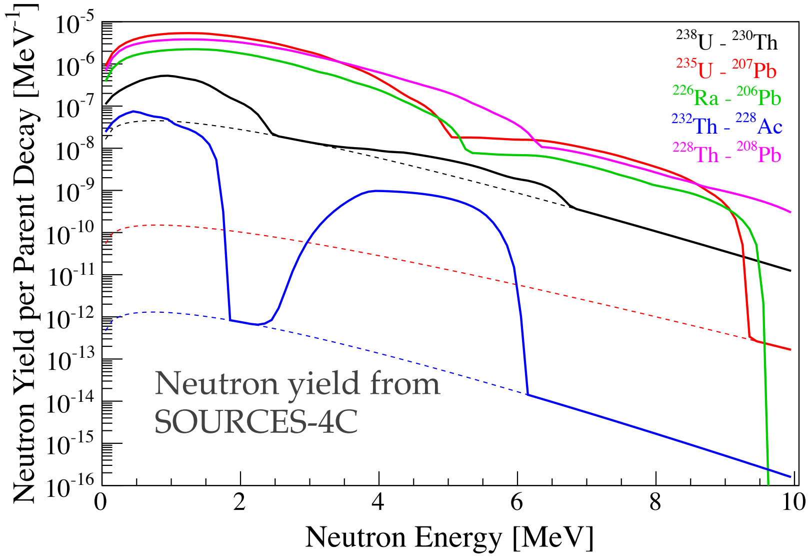


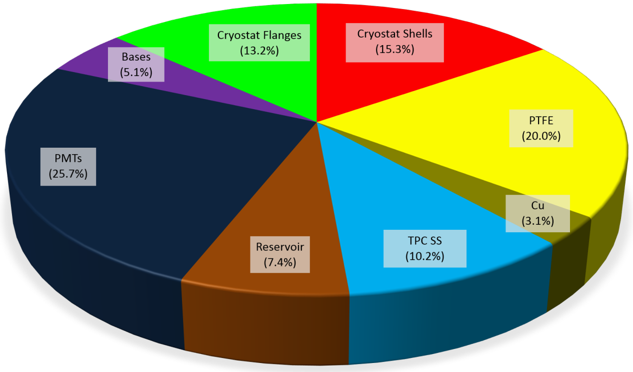
Source	Background $[(\mathrm{kg}\cdot\mathrm{day}\cdot\mathrm{keV})^{-1}]$	Background $[\mathrm{y}^{-1}]$	Fraction [%]
Materials	$(7.3 \pm 0.7) \cdot 10^{-6}$	29 ± 3	4.1
^{222}Rn	$(1.54 \pm 0.15) \cdot 10^{-4}$	620 ± 60	85.4
^{85}Kr	$(7.7 \pm 1.5) \cdot 10^{-6}$	31 ± 6	4.3
^{136}Xe	$(2.3 \pm 1.1) \cdot 10^{-6}$	9 ± 4	1.4
Solar neutrinos	$(8.9 \pm 0.2) \cdot 10^{-6}$	36 ± 1	4.9
Total	$\mathbf{(1.80 \pm 0.15) \cdot 10^{-4}}$	$\mathbf{720 \pm 60}$	**100**

Table 2. Summary of the predicted ER backgrounds in XENON1T, evaluated in 1 t fiducial volume and in (1, 12) keV energy range. We assume 10 μBq/kg of ^{222}Rn, 0.2 ppt of $^{\mathrm{nat}}$Kr, and natural abundance of ^{136}Xe.

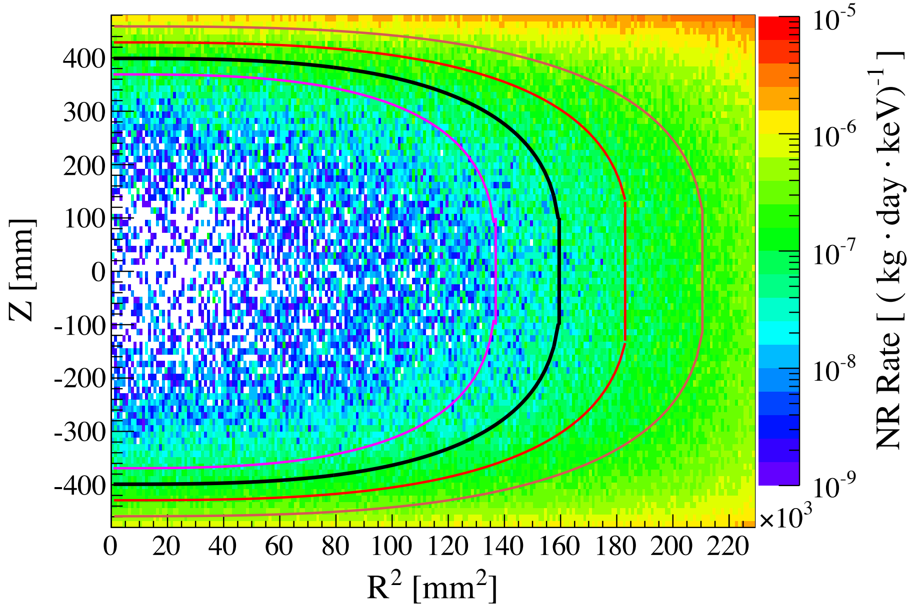
- The numbers above are before any ER/NR discrimination.
- In 1 t FV, the background from the material is at the same level as the one from solar neutrinos and from Kr

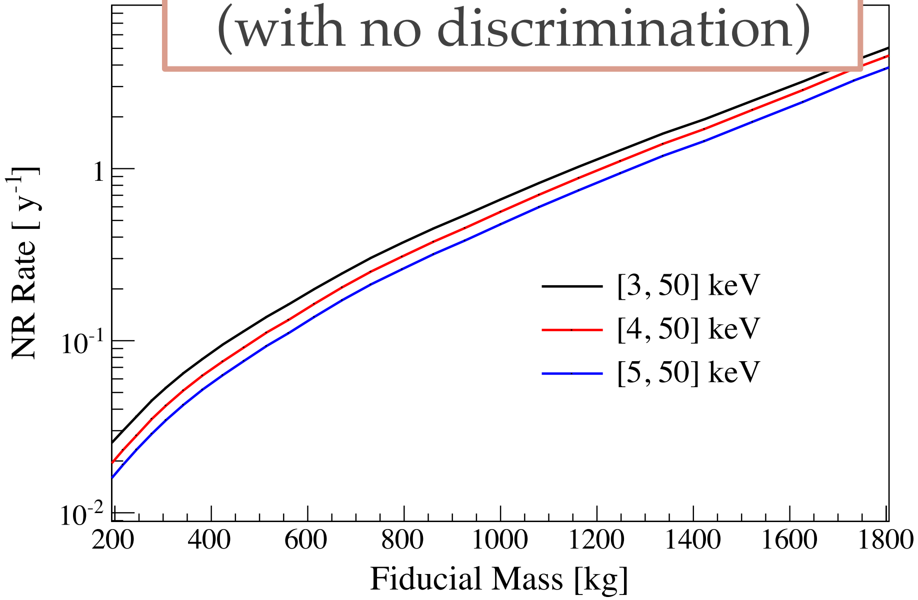
NR from radiogenic neutrons



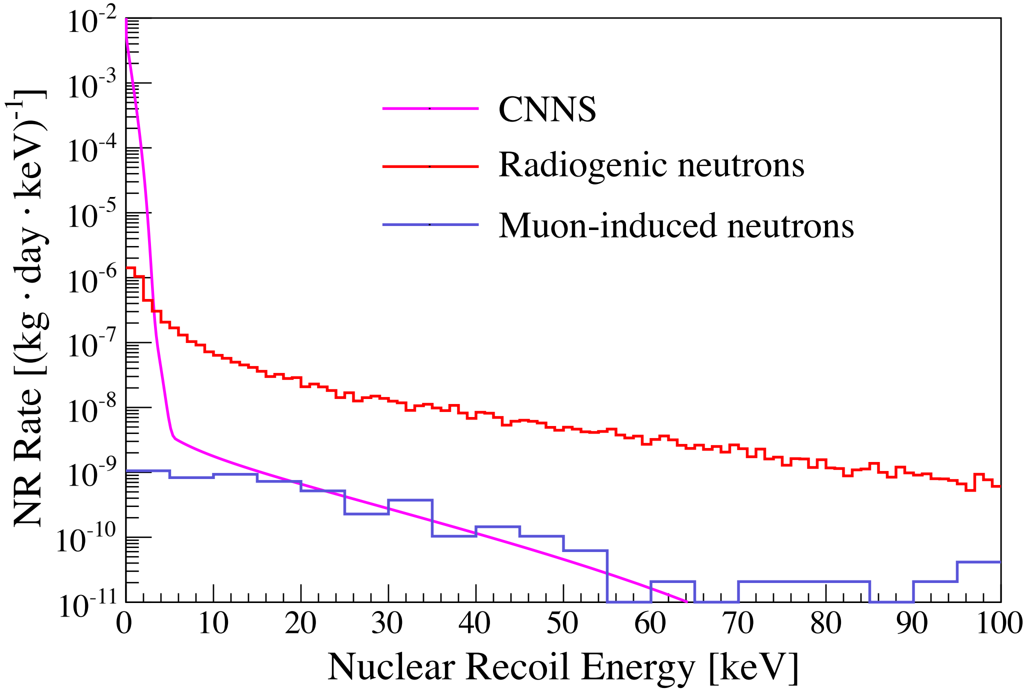


In 1t FV, [4, 50] keV:
0.6 events / y
(with no discrimination)





Total NR background



Single Scatter, 1 t Fiducial Volume,
[4, 50] keVr, 100% NR acceptance

Source	Background (ev/y)
Radiogenic neutrons	0.6 ± 20%
Muon-induced neutrons	< 0.01 (muon veto ON)
CNNS	0.02 ± 20%
Total NR	**0.62 ± 0.12**

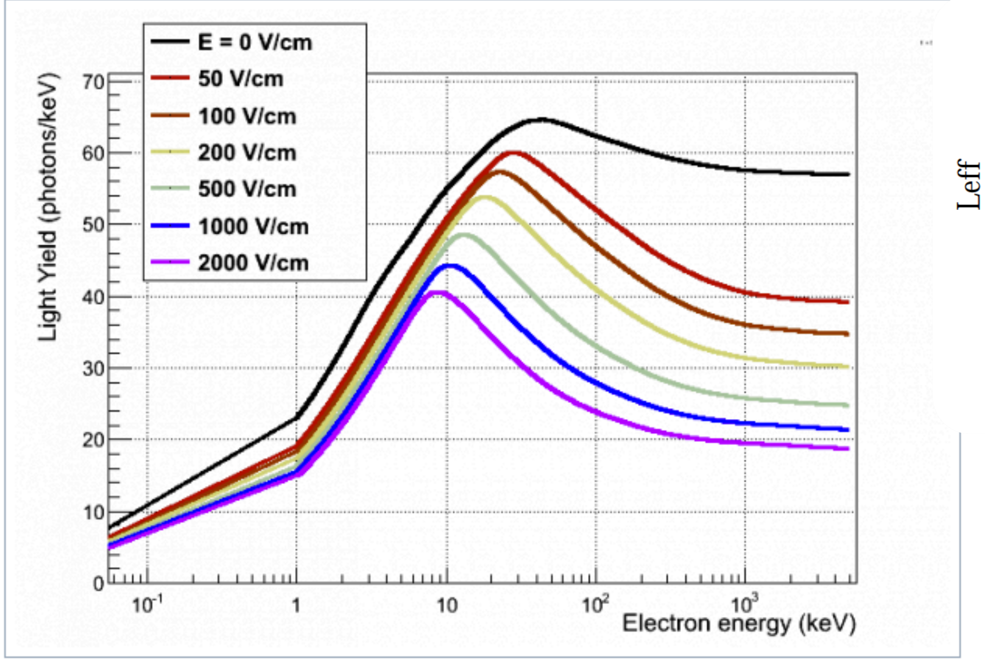
Given the very steep spectrum of NR from CNNS, its contribution will become more relevant after the conversion into the S1, S2 signals, considering the detector response and energy resolution.

Light & charge emission model

ER: NEST model

M. Szydagis et al., JINST 6 (2011) P10002, [arXiv:1106.1613]

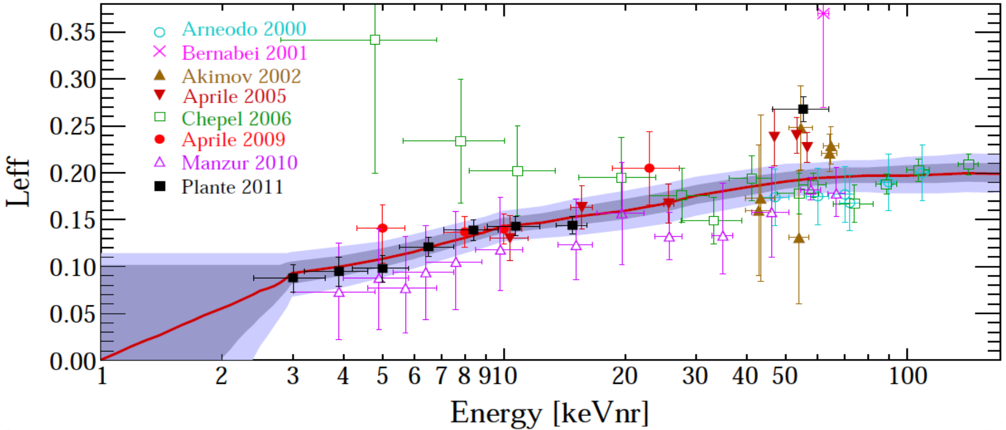
Fig. 1: Light Yield of the electron recoils

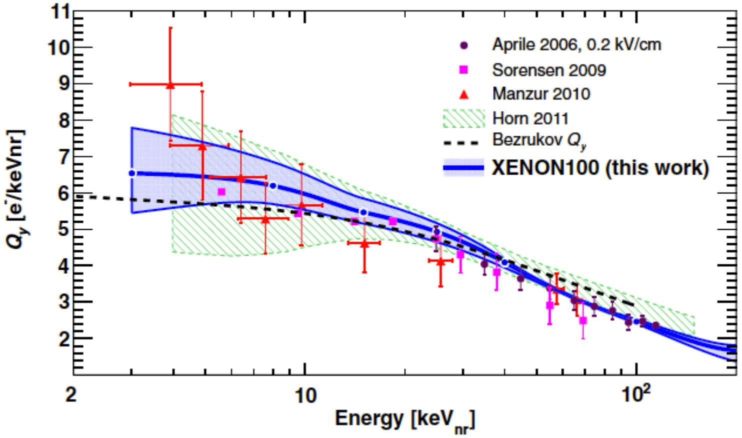


NEST is based at low energies on the direct measurement at Columbia and Zurich:
Phys. Rev. D 86, 112004 (2012)
Phys. Rev. D 87, 115015 (2013)

NR: direct measurements of L_{eff}, Q_y measured by XENON100

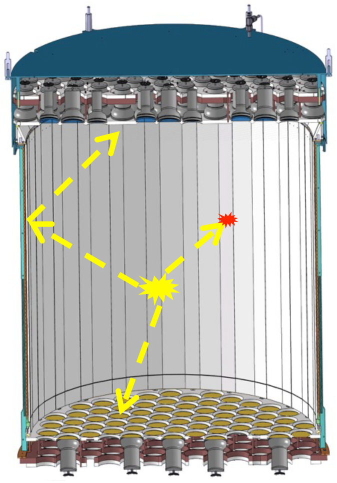
E. Aprile et al., Phys.Rev.D88 **(2013)** **012006**, [arXiv:1304.1427]





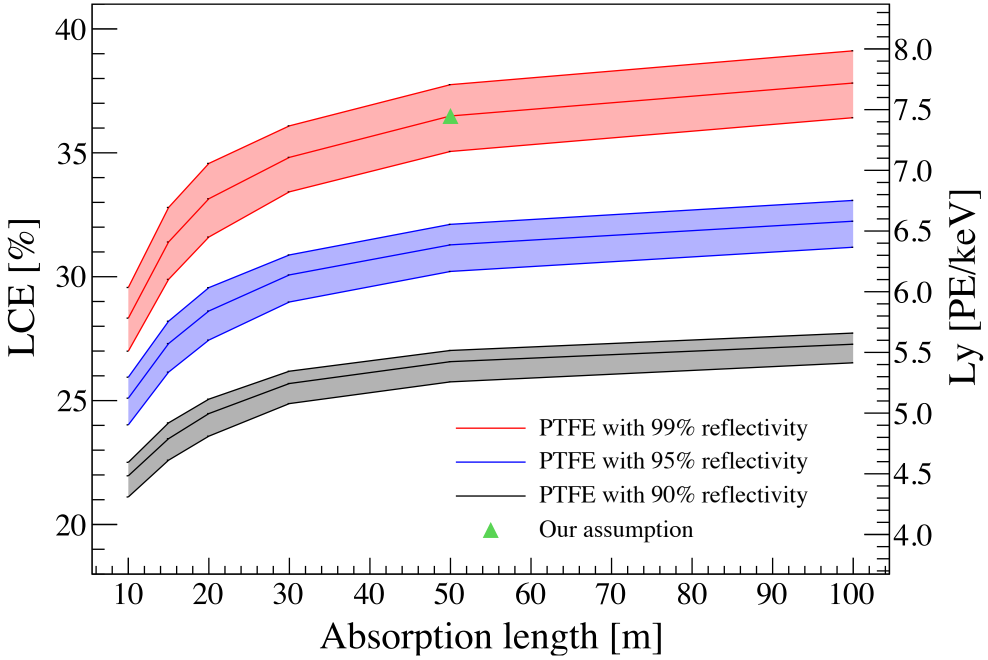
Light Collection Efficiency

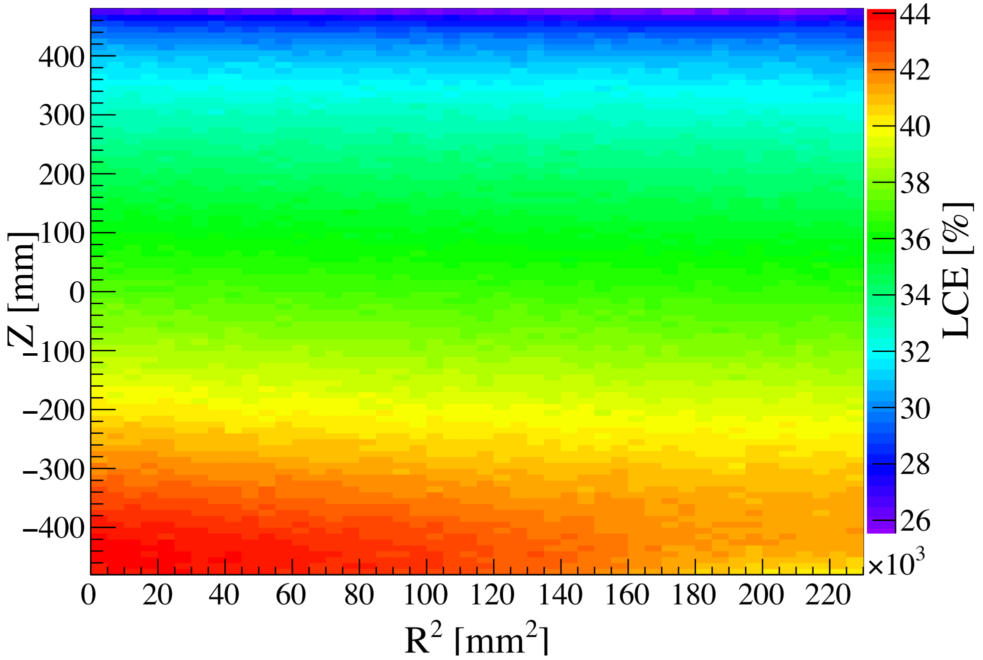
We generate optical photons uniformly inside the TPC, and follow their propagation inside it with all the reflections, refractions, absorptions, etc.



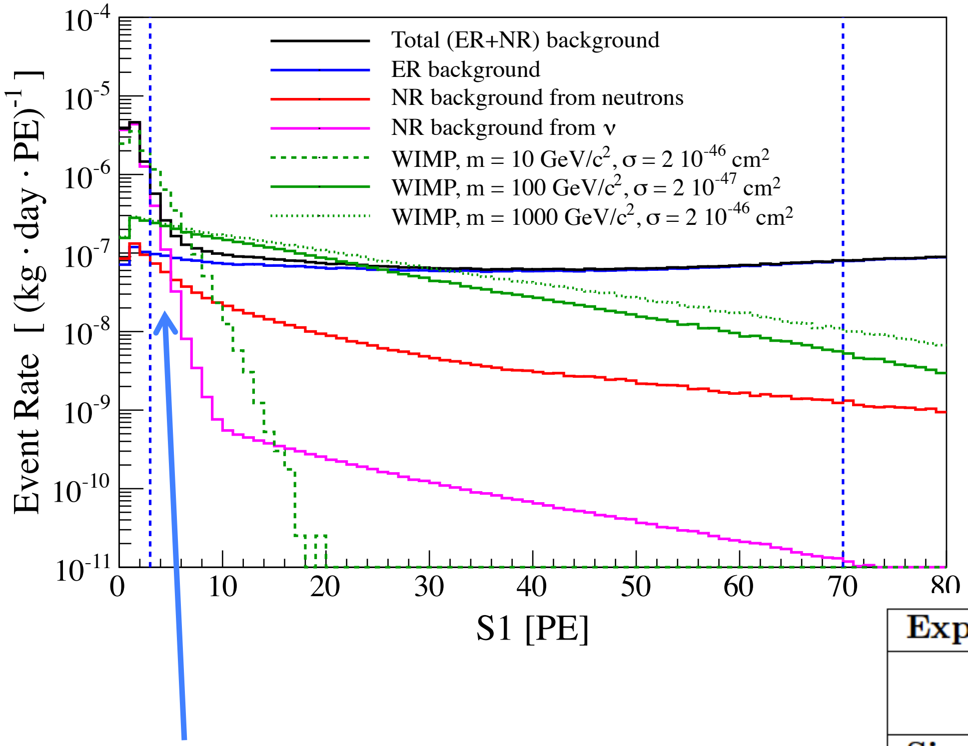
	Configuration 1	
Top screening mesh	94.5%	Mesh
Anode	92.9%	Mesh
Gate	92.9%	Mesh
Cathode	96%	Wires
Bottom screening mesh	94.5%	Mesh
Ly at 0 field with 99% PTFE	7.694 pe/keV	
Ly at 500 V/cm	4.6 PE/keV	

@122 keV





Signal and backgrounds in S1



- Electric field in the TPC: 500 V/cm
- Lower threshold of the region of interest: 3 PE (lowest one used so far by XENON100)
- Higher end: 70 PE, corresponding on average to 50 keVr (include >90% of NR spectrum for 100 GeV WIMP)
- S2 > 8 electrons

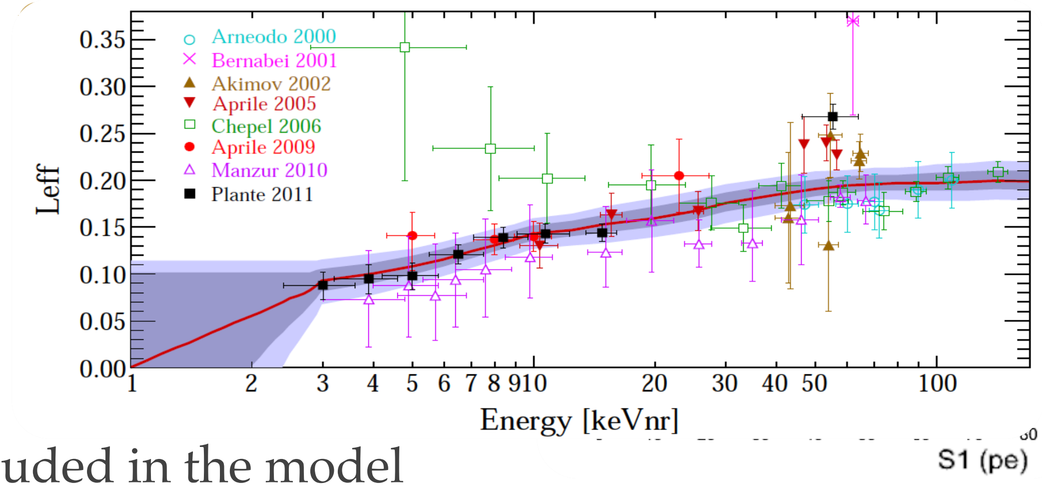
ER background is the most relevant one, apart from the low S1 region where CNNS becomes dominant.

Expectation values of events in XENON1T, in 2 t·y exposure

	No discrimination	99.75% ER discrimination
Signal (μ_s)		
6 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-45}$ cm^2)	0.68	0.27
10 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-46}$ cm^2)	4.65	1.86
100 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-47}$ cm^2)	7.13	2.85
1 TeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-46}$ cm^2)	8.85	3.54
Background		
Total ER (μ_{bER})	1300	3.25
NR from neutrons	1.10	0.44
NR from CNNS	1.18	0.47
Total NR (μ_{bNR})	2.28	0.91

Statistical model

- 2D statistical model:
  S1 and discrimination.
- Profile Likelihood method, exclusion test statistic, with CLs (Eur. Phys. J. C71 (2011) 1554).



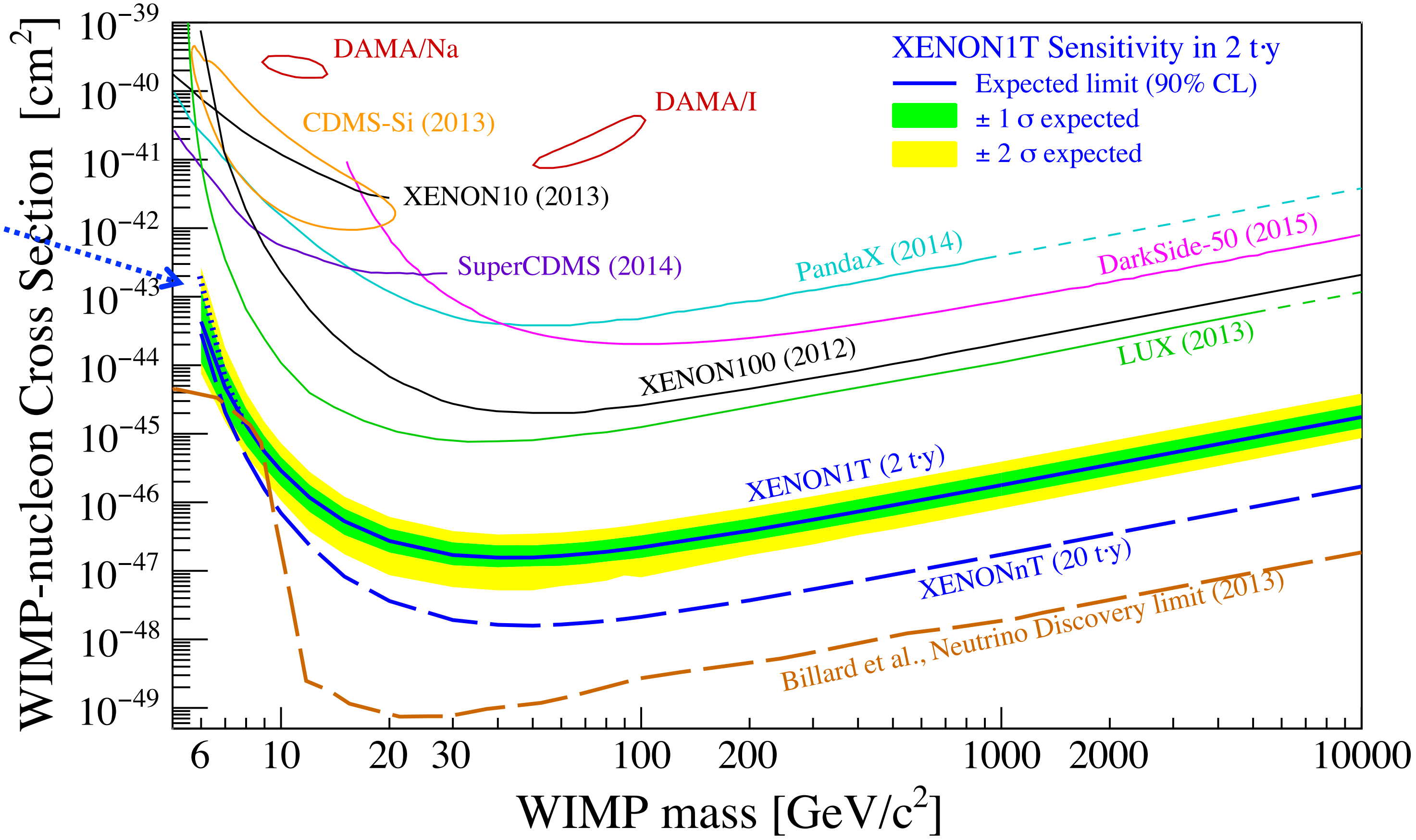
- Systematic uncertainties are included in the model as nuisance parameters, and profiled out.

$$-2\ln L(\mu_s,t) = 2\left[\mu_s(t)+\mu_{bER}+\mu_{bNR}(t)\right] - 2\sum_{i=1}^{N_{obs}}\left[\mu_s(t)\,f_s(S1_i)\,g_{NR}(Y_i)\right.$$
$$\left. + \mu_{bER}\,f_{bER}(S1_i)\,g_{ER}(Y_i) + \mu_{bNR}(t)\,f_{bNR}(S1_i)\,g_{NR}(Y_i)\right] + t^2$$

- The most relevant uncertainty is related to $\mathcal{L}_{eff}$, which rules the light output of nuclear recoils in LXe. Thus it affects, in a correlated way, both the WIMP signal and the NR backgrounds.
  We consider also other systematics: Q_y, and the overall uncertainty on ER and NR background (assumed 10% and 20%, respectively).
- We study the sensitivity bands via generation of MC toy experiments.

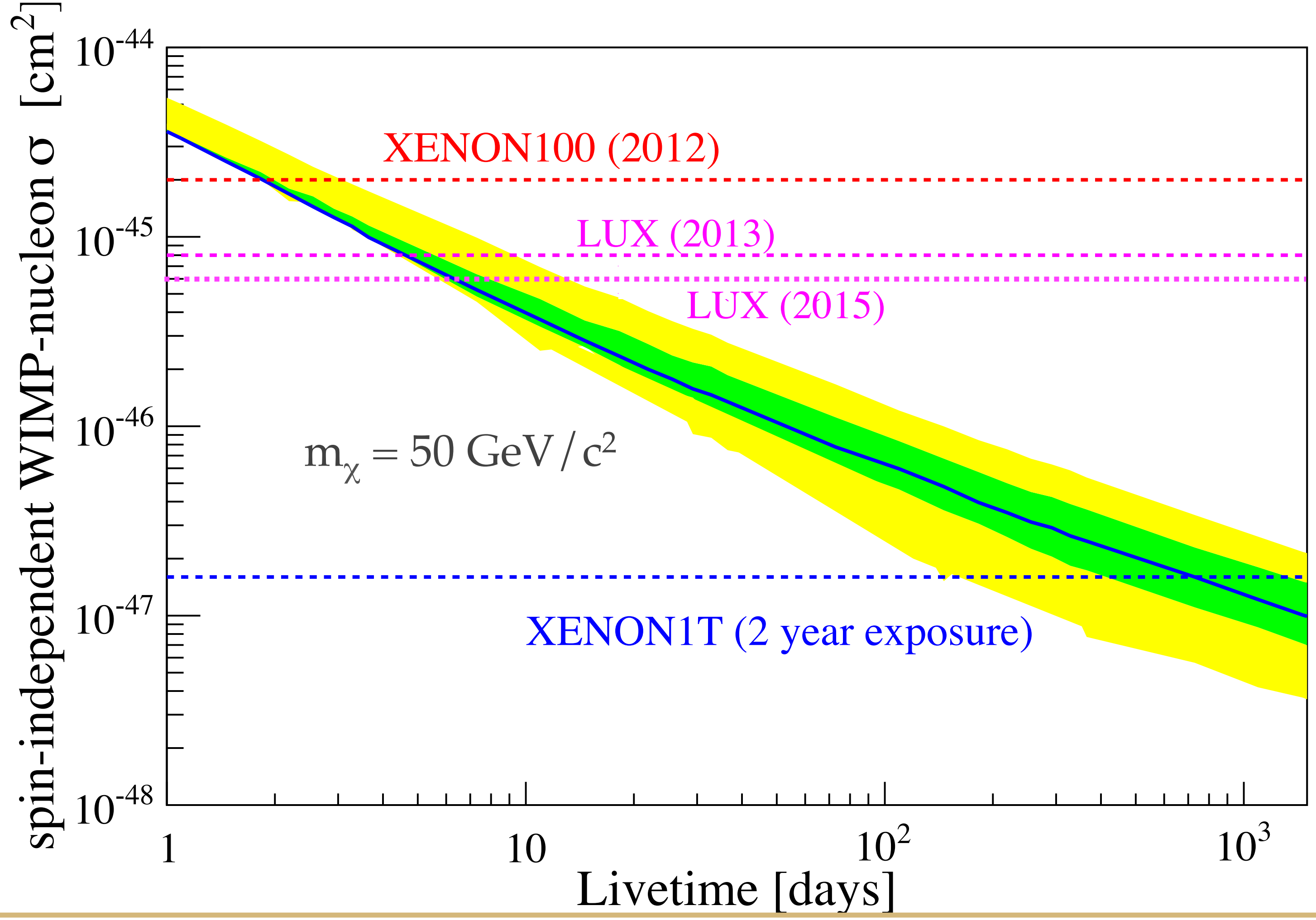
XENON1T sensitivity

Dotted blue line shows the XENON1T sensitivity assuming a cutoff below 3 keV



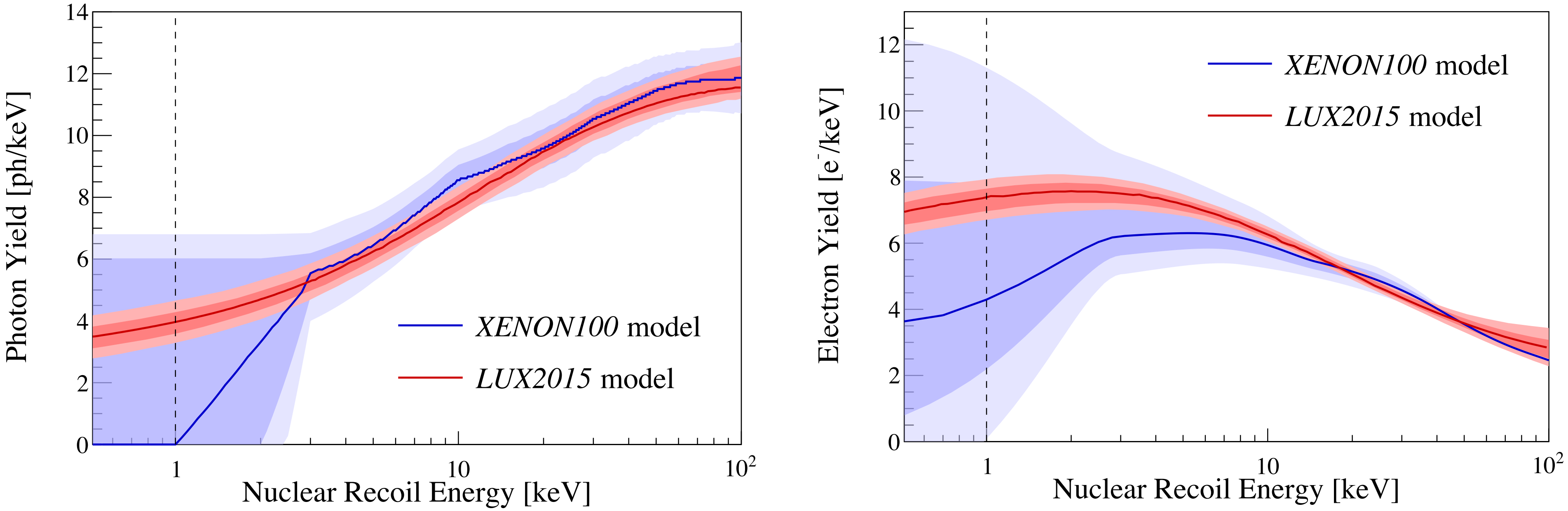
With a 2 t y exposure, with XENON1T we'll reach a sensitivity to spin-independent WIMP-nucleon interactions of $1.6\ 10^{-47}$ cm^2 for a 50 GeV/c^2 WIMP.

Sensitivity VS time



In less than 10 days we can reach the sensitivity of the currently running experiments

LUX2015 emission model



With the recent LUX measurement (arXiv:1512.03506):

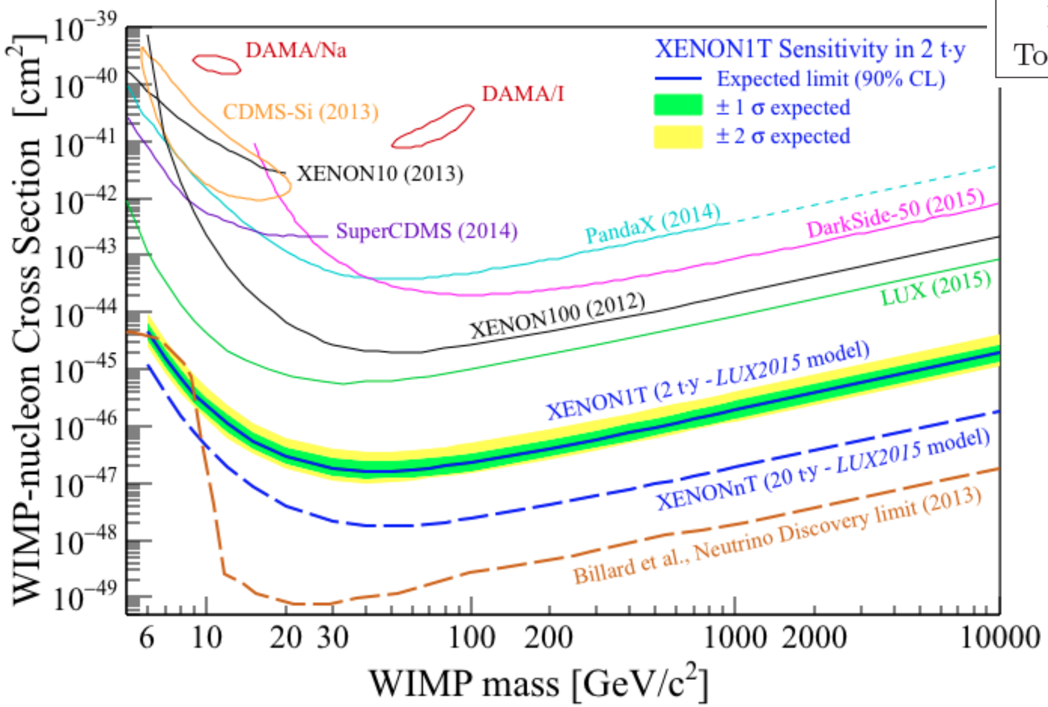
- Larger photon and electron yield, in particular at low energy (below 3 keV),
- Much smaller systematic uncertainties.

XENON1T sensitivity

Assuming the *LUX2015* emission model

Expectation values of events in XENON1T, in 2 t·y exposure

	XENON100 model	*LUX2015* model
Signal (μ_s)		
6 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-45}$ cm^2)	0.68	2.72
10 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-46}$ cm^2)	4.65	5.96
100 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-47}$ cm^2)	7.13	7.13
1 TeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-46}$ cm^2)	8.85	8.85
Background		
Total ER (μ_{bER})	1300	1300
NR from neutrons	1.10	1.13
NR from CNNS	1.18	5.36
Total NR (μ_{bNR})	2.28	6.49



Potential to detect CNNS from solar neutrinos.

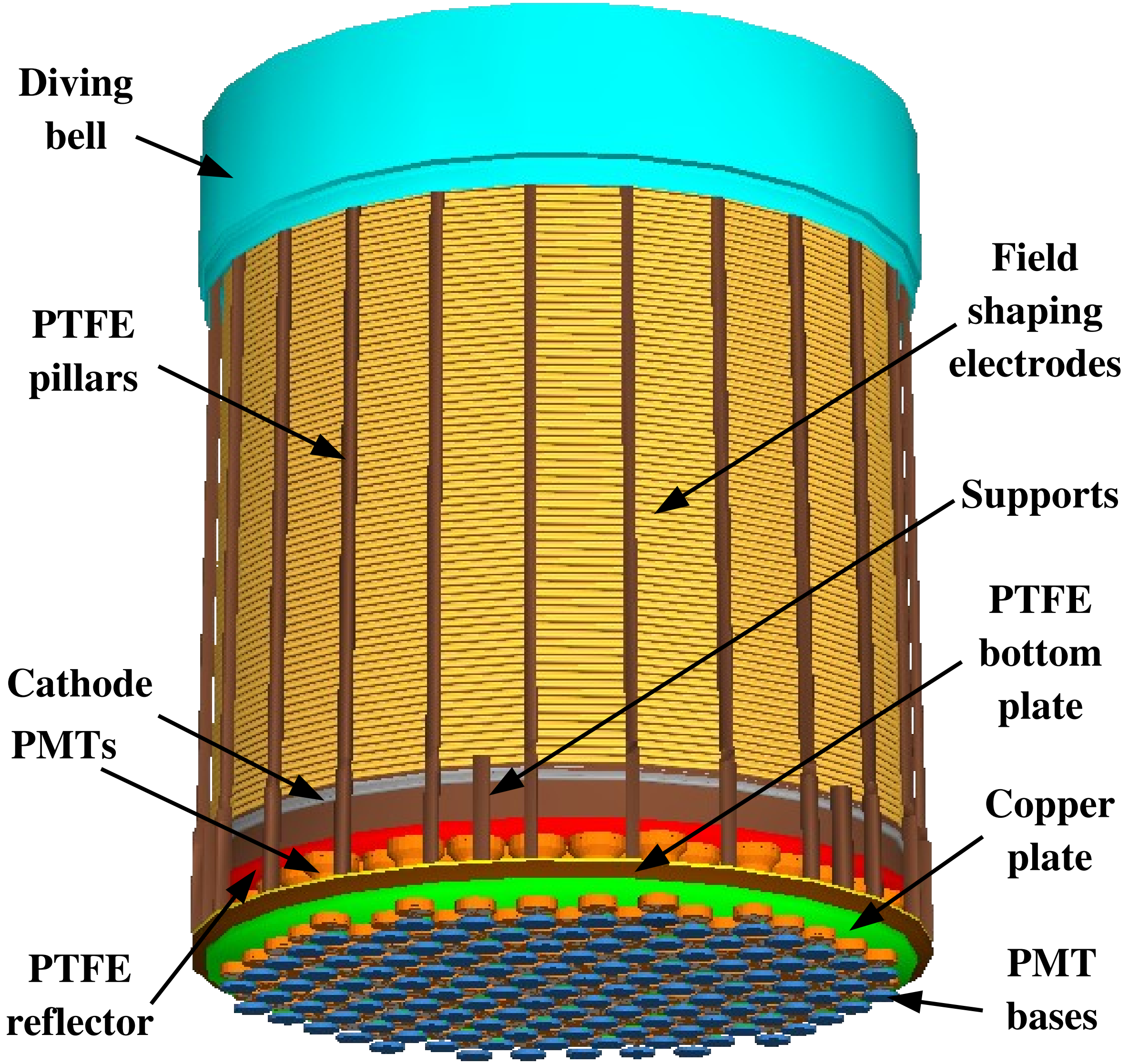
Significant improvement in sensitivity to WIMPs at low masses, below 10 GeV/c^2.

Summary & Conclusions

- ER and NR backgrounds from the detector materials are reduced to a subdominant level in the inner 1 t FV.
- The most relevant background comes from ^{222}Rn in LXe, (assuming a uniform contamination of 10 μBq/kg). Total ER background: $1.8\ 10^{-4}$ (kg day keV)$^{-1}$.
- With a 2 t y exposure, with XENON1T we'll reach a sensitivity to spin-independent WIMP-nucleon interaction of $1.6\ 10^{-47}$ cm^2 for a 50 GeV/c^2 WIMP.
- Good potential to detect for the first time coherent scattering of neutrinos from the Sun, in particular assuming the *LUX2015* emission model. Improved sensitivity at low mass WIMPs too.

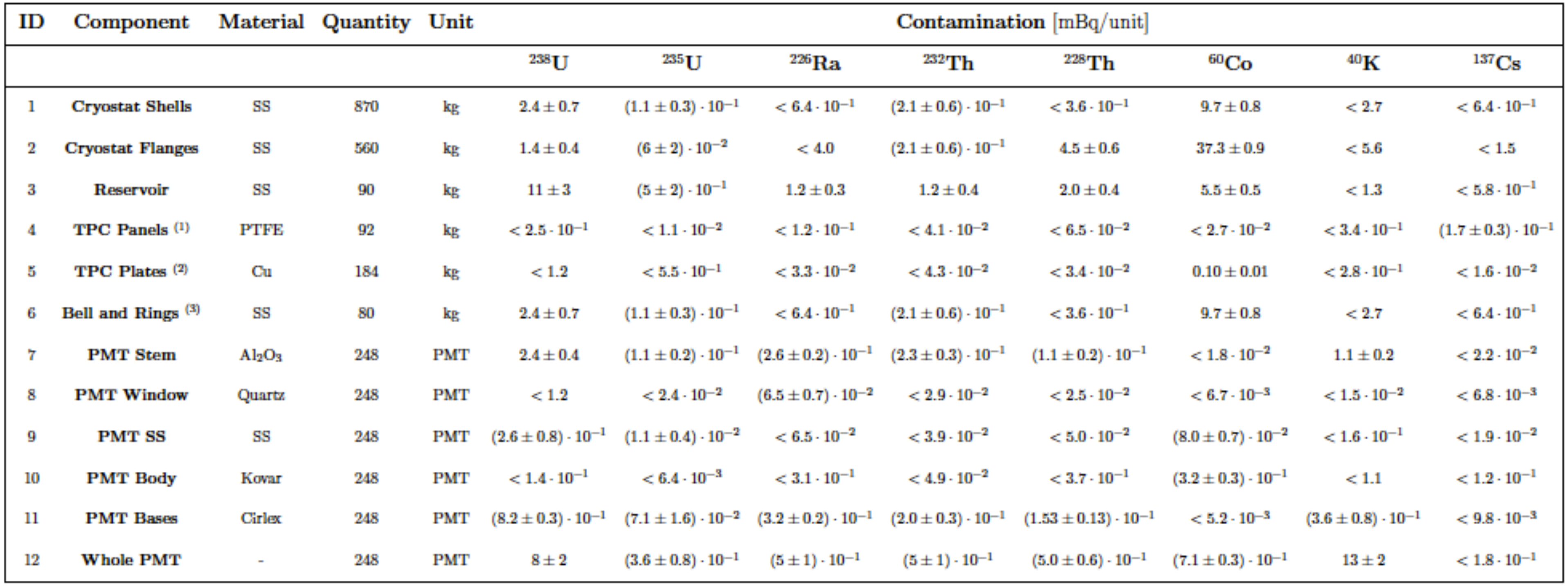
Backups

MC simulation in GEANT4



ER from the materials

Extensive screening campaign using Ge gamma spectrometry and mass spectrometry (ICP-MS)



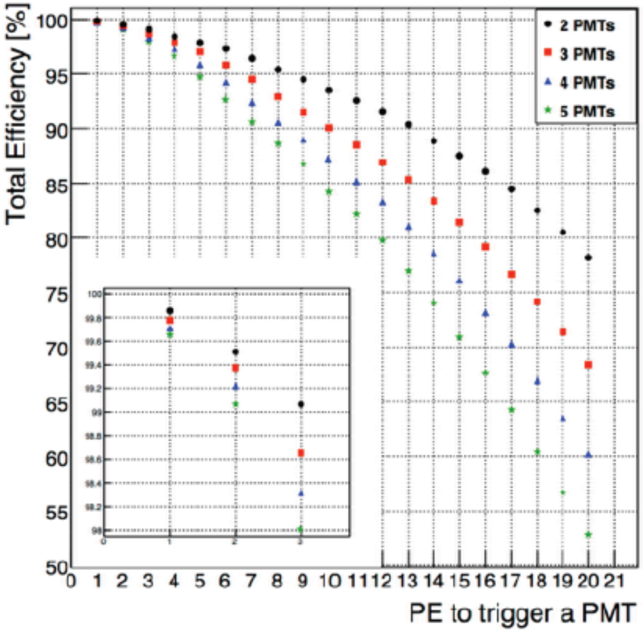
ID	Component	Material	Quantity	Unit	Contamination [mBq/unit]							
					^{238}U	^{235}U	^{226}Ra	^{232}Th	^{228}Th	^{60}Co	^{40}K	^{137}Cs
1	**Cryostat Shells**	SS	870	kg	2.4 ± 0.7	$(1.1 \pm 0.3) \cdot 10^{-1}$	$< 6.4 \cdot 10^{-1}$	$(2.1 \pm 0.6) \cdot 10^{-1}$	$< 3.6 \cdot 10^{-1}$	9.7 ± 0.8	< 2.7	$< 6.4 \cdot 10^{-1}$
2	**Cryostat Flanges**	SS	560	kg	1.4 ± 0.4	$(6 \pm 2) \cdot 10^{-2}$	< 4.0	$(2.1 \pm 0.6) \cdot 10^{-1}$	4.5 ± 0.6	37.3 ± 0.9	< 5.6	< 1.5
3	**Reservoir**	SS	90	kg	11 ± 3	$(5 \pm 2) \cdot 10^{-1}$	1.2 ± 0.3	1.2 ± 0.4	2.0 ± 0.4	5.5 ± 0.5	< 1.3	$< 5.8 \cdot 10^{-1}$
4	**TPC Panels** (1)	PTFE	92	kg	$< 2.5 \cdot 10^{-1}$	$< 1.1 \cdot 10^{-2}$	$< 1.2 \cdot 10^{-1}$	$< 4.1 \cdot 10^{-2}$	$< 6.5 \cdot 10^{-2}$	$< 2.7 \cdot 10^{-2}$	$< 3.4 \cdot 10^{-1}$	$(1.7 \pm 0.3) \cdot 10^{-1}$
5	**TPC Plates** (2)	Cu	184	kg	< 1.2	$< 5.5 \cdot 10^{-1}$	$< 3.3 \cdot 10^{-2}$	$< 4.3 \cdot 10^{-2}$	$< 3.4 \cdot 10^{-2}$	0.10 ± 0.01	$< 2.8 \cdot 10^{-1}$	$< 1.6 \cdot 10^{-2}$
6	**Bell and Rings** (3)	SS	80	kg	2.4 ± 0.7	$(1.1 \pm 0.3) \cdot 10^{-1}$	$< 6.4 \cdot 10^{-1}$	$(2.1 \pm 0.6) \cdot 10^{-1}$	$< 3.6 \cdot 10^{-1}$	9.7 ± 0.8	< 2.7	$< 6.4 \cdot 10^{-1}$
7	**PMT Stem**	Al_2O_3	248	PMT	2.4 ± 0.4	$(1.1 \pm 0.2) \cdot 10^{-1}$	$(2.6 \pm 0.2) \cdot 10^{-1}$	$(2.3 \pm 0.3) \cdot 10^{-1}$	$(1.1 \pm 0.2) \cdot 10^{-1}$	$< 1.8 \cdot 10^{-2}$	1.1 ± 0.2	$< 2.2 \cdot 10^{-2}$
8	**PMT Window**	Quartz	248	PMT	< 1.2	$< 2.4 \cdot 10^{-2}$	$(6.5 \pm 0.7) \cdot 10^{-2}$	$< 2.9 \cdot 10^{-2}$	$< 2.5 \cdot 10^{-2}$	$< 6.7 \cdot 10^{-3}$	$< 1.5 \cdot 10^{-2}$	$< 6.8 \cdot 10^{-3}$
9	**PMT SS**	SS	248	PMT	$(2.6 \pm 0.8) \cdot 10^{-1}$	$(1.1 \pm 0.4) \cdot 10^{-2}$	$< 6.5 \cdot 10^{-2}$	$< 3.9 \cdot 10^{-2}$	$< 5.0 \cdot 10^{-2}$	$(8.0 \pm 0.7) \cdot 10^{-2}$	$< 1.6 \cdot 10^{-1}$	$< 1.9 \cdot 10^{-2}$
10	**PMT Body**	Kovar	248	PMT	$< 1.4 \cdot 10^{-1}$	$< 6.4 \cdot 10^{-3}$	$< 3.1 \cdot 10^{-1}$	$< 4.9 \cdot 10^{-2}$	$< 3.7 \cdot 10^{-1}$	$(3.2 \pm 0.3) \cdot 10^{-1}$	< 1.1	$< 1.2 \cdot 10^{-1}$
11	**PMT Bases**	Cirlex	248	PMT	$(8.2 \pm 0.3) \cdot 10^{-1}$	$(7.1 \pm 1.6) \cdot 10^{-2}$	$(3.2 \pm 0.2) \cdot 10^{-1}$	$(2.0 \pm 0.3) \cdot 10^{-1}$	$(1.53 \pm 0.13) \cdot 10^{-1}$	$< 5.2 \cdot 10^{-3}$	$(3.6 \pm 0.8) \cdot 10^{-1}$	$< 9.8 \cdot 10^{-3}$
12	**Whole PMT**	-	248	PMT	8 ± 2	$(3.6 \pm 0.8) \cdot 10^{-1}$	$(5 \pm 1) \cdot 10^{-1}$	$(5 \pm 1) \cdot 10^{-1}$	$(5.0 \pm 0.6) \cdot 10^{-1}$	$(7.1 \pm 0.3) \cdot 10^{-1}$	13 ± 2	$< 1.8 \cdot 10^{-1}$

Screening of PMTs: E. Aprile et al., Eur.Phys.J. C75 **(2015) 546,** [arXiv:1503.07698]
Dedicated paper on screening of XENON1T materials in preparation

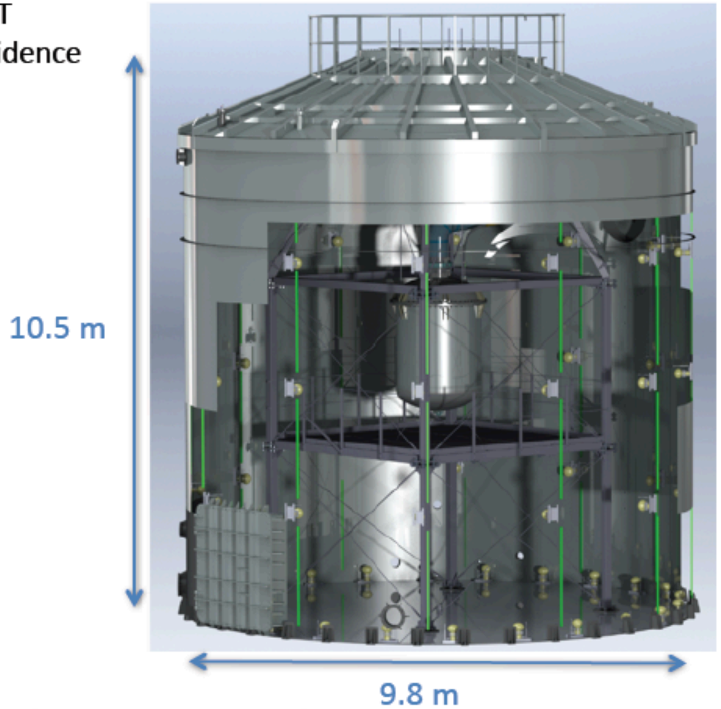
NR from μ-induced n

Negligible, thanks to the water shield and Cherenkov muon veto surrounding the detector

- Stainless steel tank with 700 m³ of demineralized water
- 84 high QE PMTs (8”) sensitive to Cherenkov light
- Internal surfaces covered with reflector film
- Efficiency in tagging muon events depends on PMT threshold and required number of PMT hits in coincidence



E. Aprile et al., JINST 9 P11006 (2014)



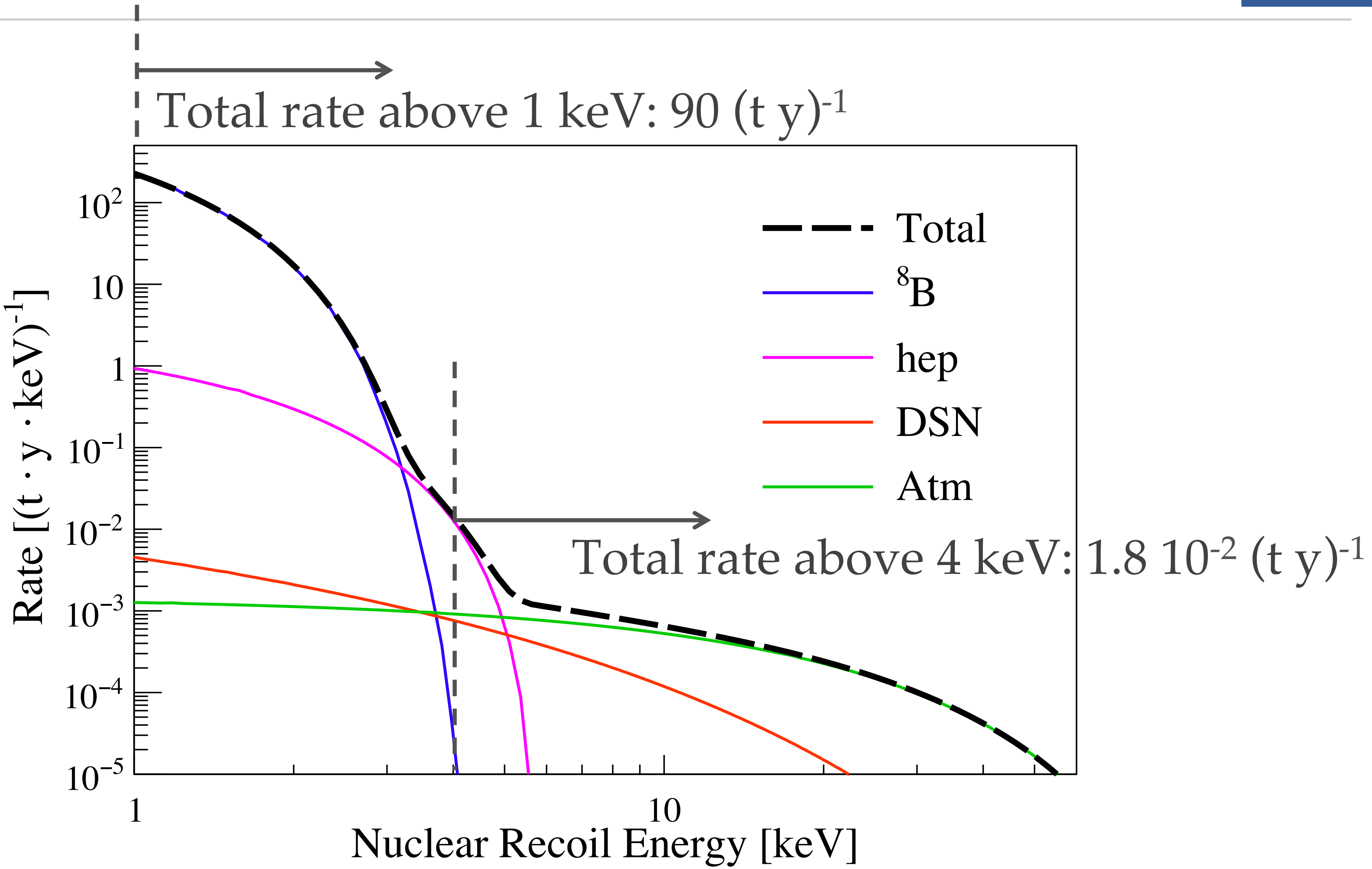
Expected efficiency in tagging muon induced neutrons (Monte Carlo studies):

➢ **>99.7%** for muons traversing the water tank (1/3 of muon events)

➢ **> 71.4%** for muons interacting in rock only (2/3 of muon events)

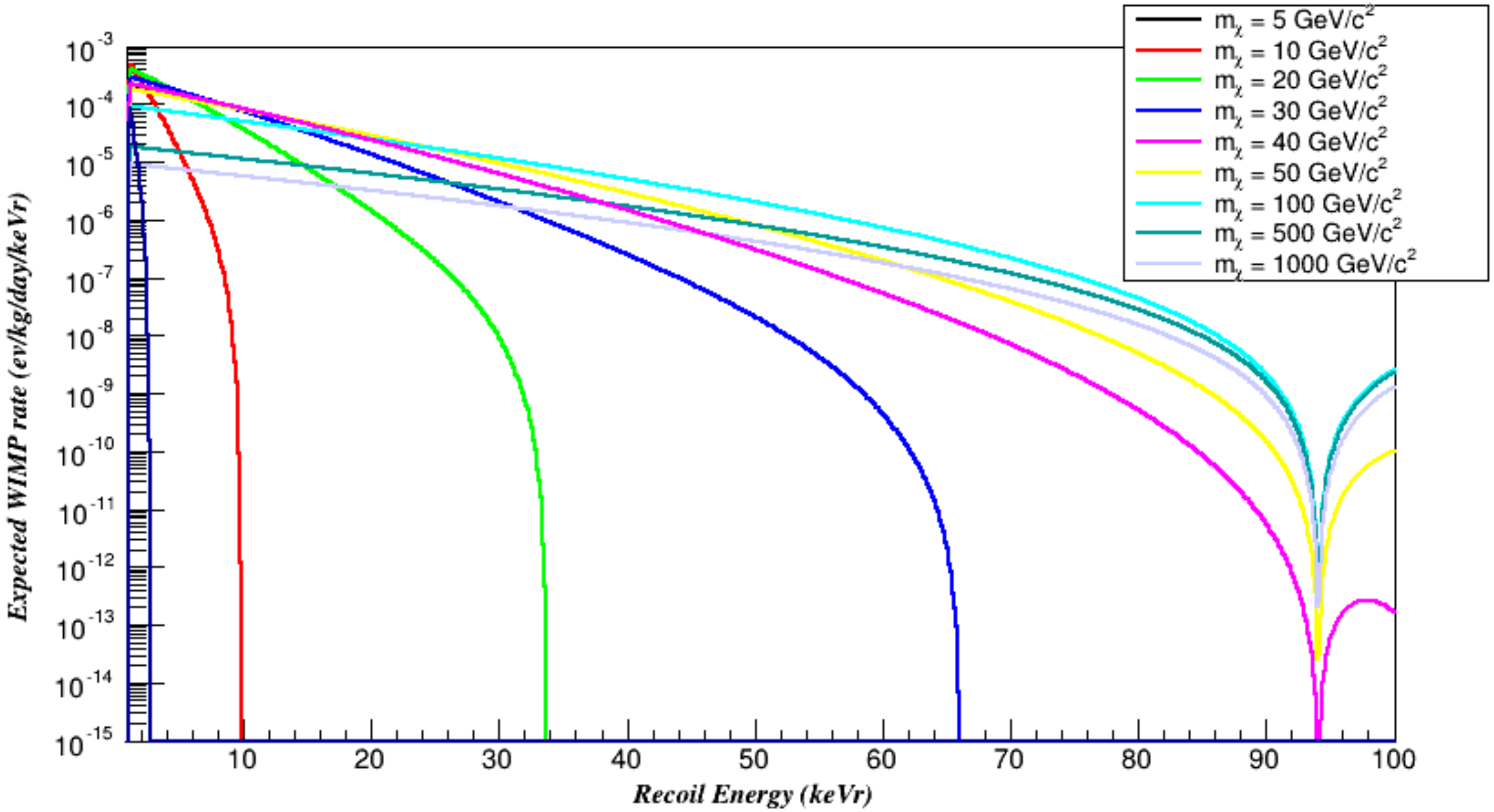
Induced neutron background in 1 ton fiducial volume < 0.01 y^{-1}

NR from CNNS (Coherent neutrino-nucleus scattering)


Total rate above 1 keV: 90 (t y)$^{-1}$

Total rate above 4 keV: 1.8 10^{-2} (t y)$^{-1}$

WIMP signal



Halo model: v_0 = 220 km/s, v_{Sun} = 250 km/s,
v_{esc} = 544 km/s, ρ=0.3 GeV/cm^3

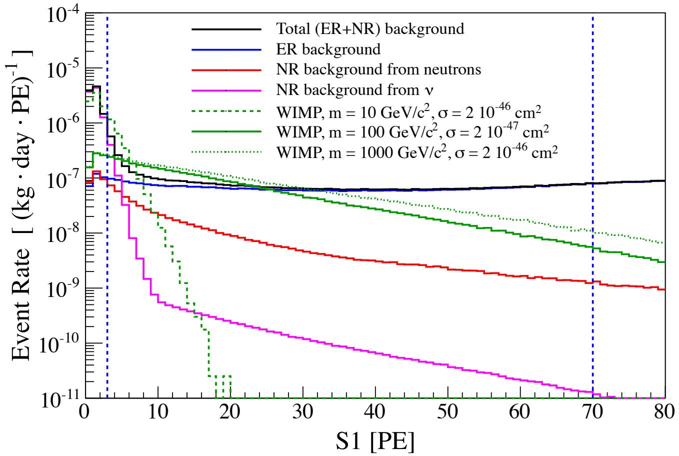
2d statistical model

S1 distributions

Recoil energy spectra **converted into S1 distributions** (n° PE detected) through

- **Light Yield L_Y** (n° γ produced/keV)
- **Charge Yield Q_Y** (n° e^- produced/keV)
- **Detector performance** (**LCE**, PMTs **QE** and **CE**)

- 2 t·y exposure
- **m_χ=100 GeV/c²**
- **μ_s=50** (enhanced)
- **μ_{bER}=1300**
- **μ_{bNR}=2.3**



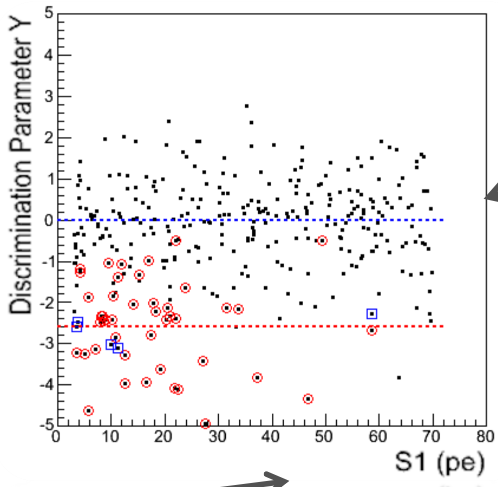
Y distributions

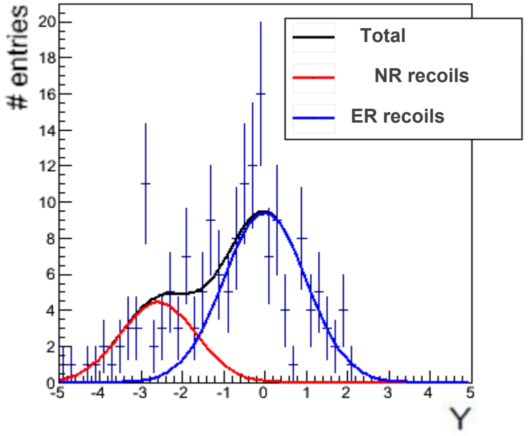
Y is an idealized version of the **discrimination parameter** **$\log_{10}$(S2/S1)**

- ER events *Gauss(0,1)*
- NR events *Gauss(-2.58,0.92)*

These distributions reproduce the XENON100 **ER/NR discrimination** and **NR acceptance** performance

NO discrimination cut on ER events (full data set used)

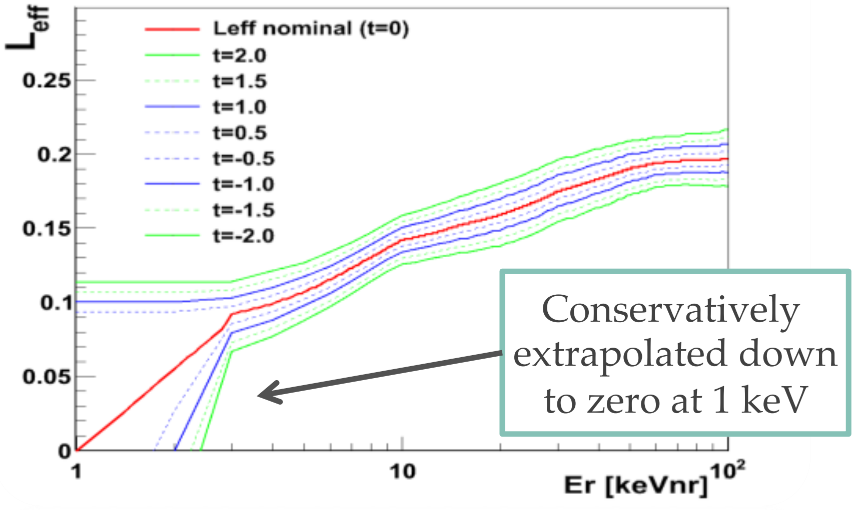




▪ **ER Background** events
□ **NR Background** events
○ (NR) **Signal** events

Systematic uncertainty on $\mathcal{L}_{\text{eff}}$

- The **RELATIVE SCINTILLATION EFFICIENCY** $\mathcal{L}_{\text{eff}}$ rules the light output of nuclear recoils in Xenon
- $\mathcal{L}_{\text{eff}}$ is the major **systematic uncertainty** for XENON1T; no direct experimental measurements below 3 keV.



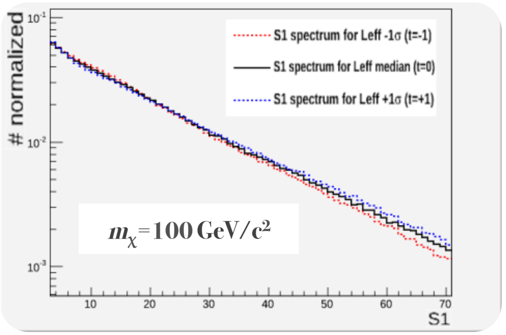
Conservatively extrapolated down to zero at 1 keV

Parameterization of the uncertainty on $\mathcal{L}_{eff}$

Gaussian nuisance parameter ***t***

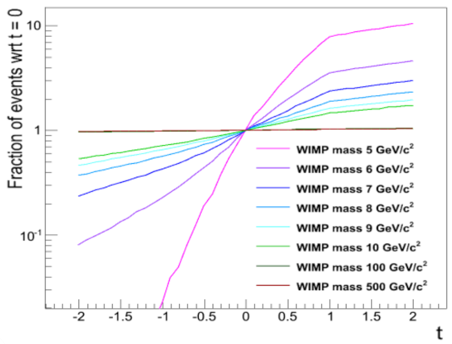
$$\mathcal{L}_{eff} = \begin{cases} \mathcal{L}_{eff}(\text{median}) + t \cdot \Delta\mathcal{L}_{eff}(+1\sigma) & \text{if } t \geq 0 \\ \mathcal{L}_{eff}(\text{median}) + t \cdot \Delta\mathcal{L}_{eff}(-1\sigma) & \text{if } t < 0 \end{cases}$$

IMPACT OF $\mathcal{L}_{eff}$ VARIATIONS



S1 SPECTRAL SHAPES of signal and backgrounds change very slightly under different $\mathcal{L}_{eff}$

⟹ **We keep fixed the shape of S1 spectra**



NUMBER of EXPECTED EVENTS in [3,70] PE

CNNS neutrinos behave like 6 GeV/c² WIMP

Neutrons behave like 30 GeV/c² WIMP

The **number of expected events** from **CNNS** and **low mass WIMPs** is highly affected by L_{eff} variations

⟹ $\mu_s = \mu_s(t)$ and $\mu_{bNR} = \mu_{bNR}(t)$

Profile likelihood method

Likelihood function
(unbinned, extended)
Parameter of interest $\boldsymbol{\mu_s}$

$$-2\ln L(\mu_s,t) = 2\left[\mu_s(t)+\mu_{bER}+\mu_{bNR}(t)\right] - 2\sum_{i=1}^{N_{obs}}\left[\mu_s(t)\,f_s(S1_i)\,g_{NR}(Y_i) + \mu_{bER}\,f_{bER}(S1_i)\,g_{ER}(Y_i) + \mu_{bNR}(t)\,f_{bNR}(S1_i)\,g_{NR}(Y_i)\right] + t^2$$

The uncertainty on $\mathcal{L}_{\mathrm{eff}}$, affecting both WIMP signal and NR background in a correlated way, is included in the likelihood as a nuisance parameter and profiled out.

Exclusion test statistic

Profile Likelihood ratio

$L(\mu_s, \hat{\hat{t}})$ is the *conditional* maximized likelihood

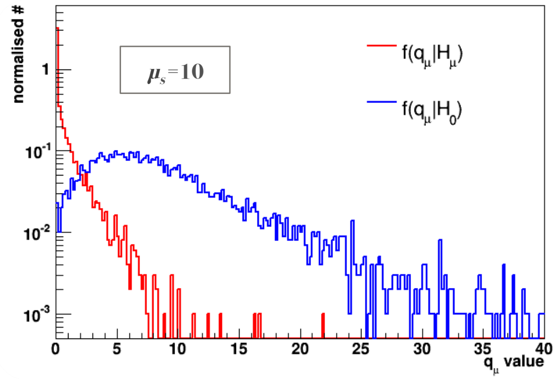
$L(\hat{\mu}_s, \hat{t})$ is the *unconditional* maximized likelihood

$$q_\mu = \begin{cases} -2\ln\frac{L(\mu_s,\hat{\hat{t}})}{L(\hat{\mu}_s,\hat{t})} & \text{if } \hat{\mu}_s \le \hat{\mu}_s \\ 0 & \text{if } \hat{\mu}_s > \hat{\mu}_s \end{cases}$$

Compute test statistic P.D.F.

$f(q_\mu|H_\mu)$ under **signal hypothesis H_μ**

$f(q_\mu|H_0)$ under **bkg-only hypothesis H_0**



Run hypotheses tests

- Generated **10^4 MC toy experiments** under $\boldsymbol{H_0}$
- **Rejection test** of each signal hypothesis $\boldsymbol{H_\mu}$ (different μ_s) using ***med[q_μ/H_μ]*** as observed test statistic $\boldsymbol{q_\mu^{obs}}$
- The **significance** of each test is given by the ***p-value***

$$p'_s = \frac{\int_{q_\mu^{obs}}^{\infty} f(q_\mu|0)\,\mathrm{d}q_\mu}{\int_{q_\mu^{obs}}^{\infty} f(q_\mu|\mu)\,\mathrm{d}q_\mu}$$

Modified p-value
$\mathrm{CL_s}$ method