

The XENON Project: *present status* *and* *future prospects*

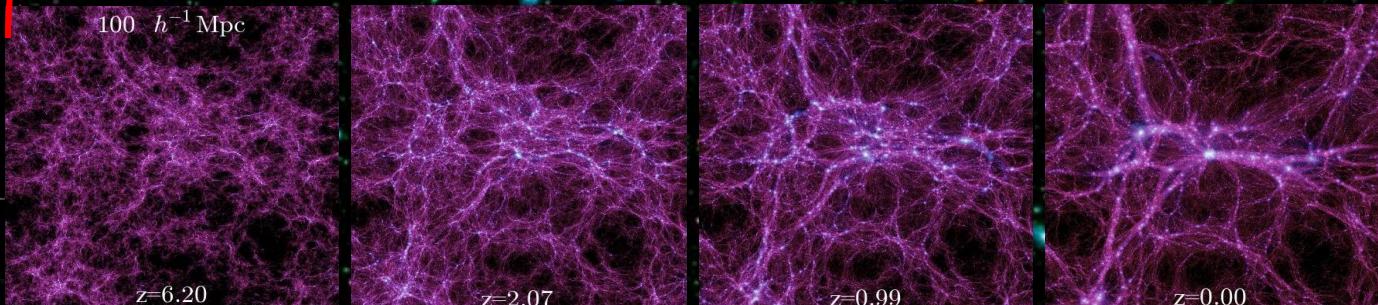
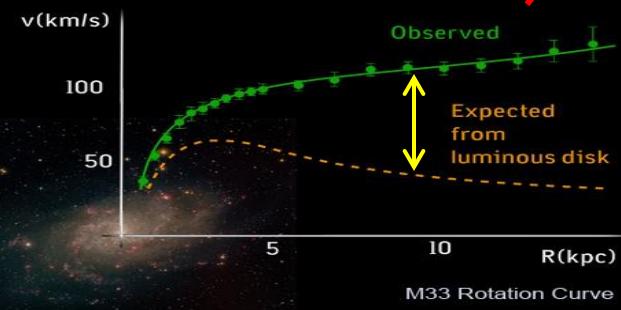
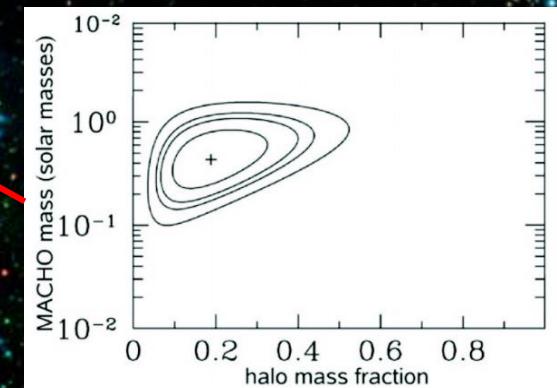
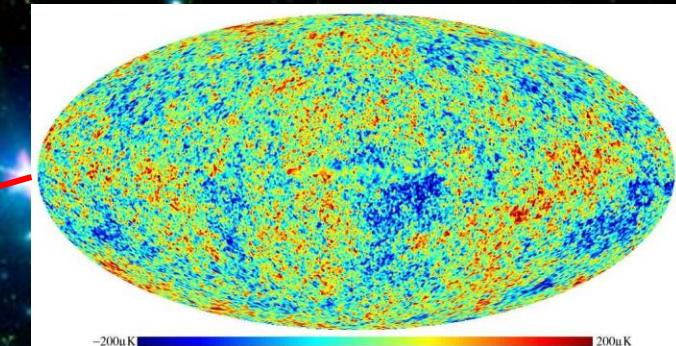
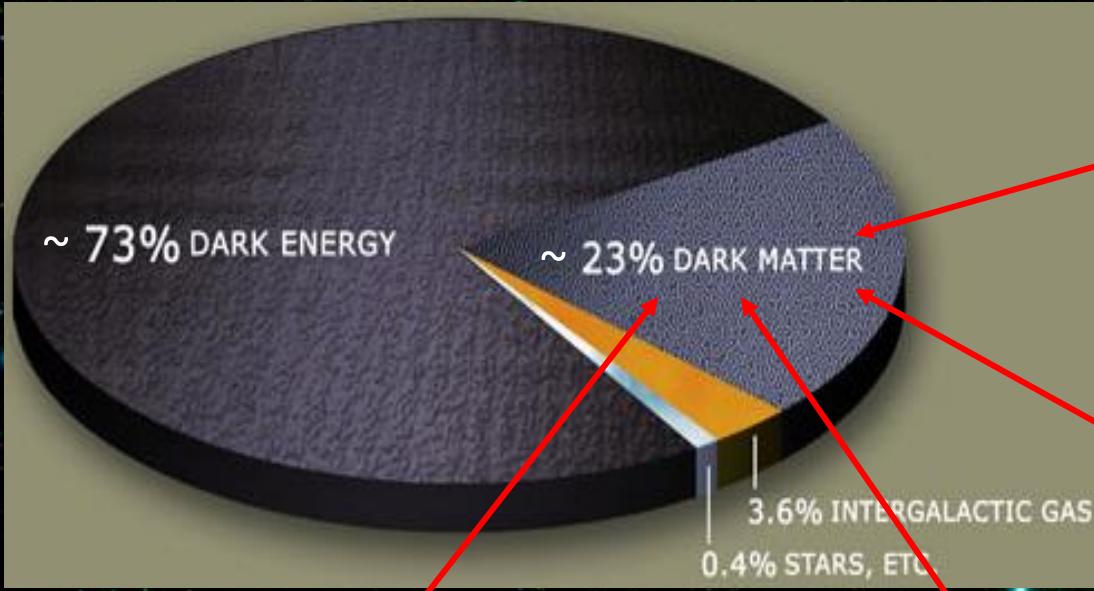


Fabio Valerio Massoli
University of Bologna and INFN
on behalf of the XENON Collaboration

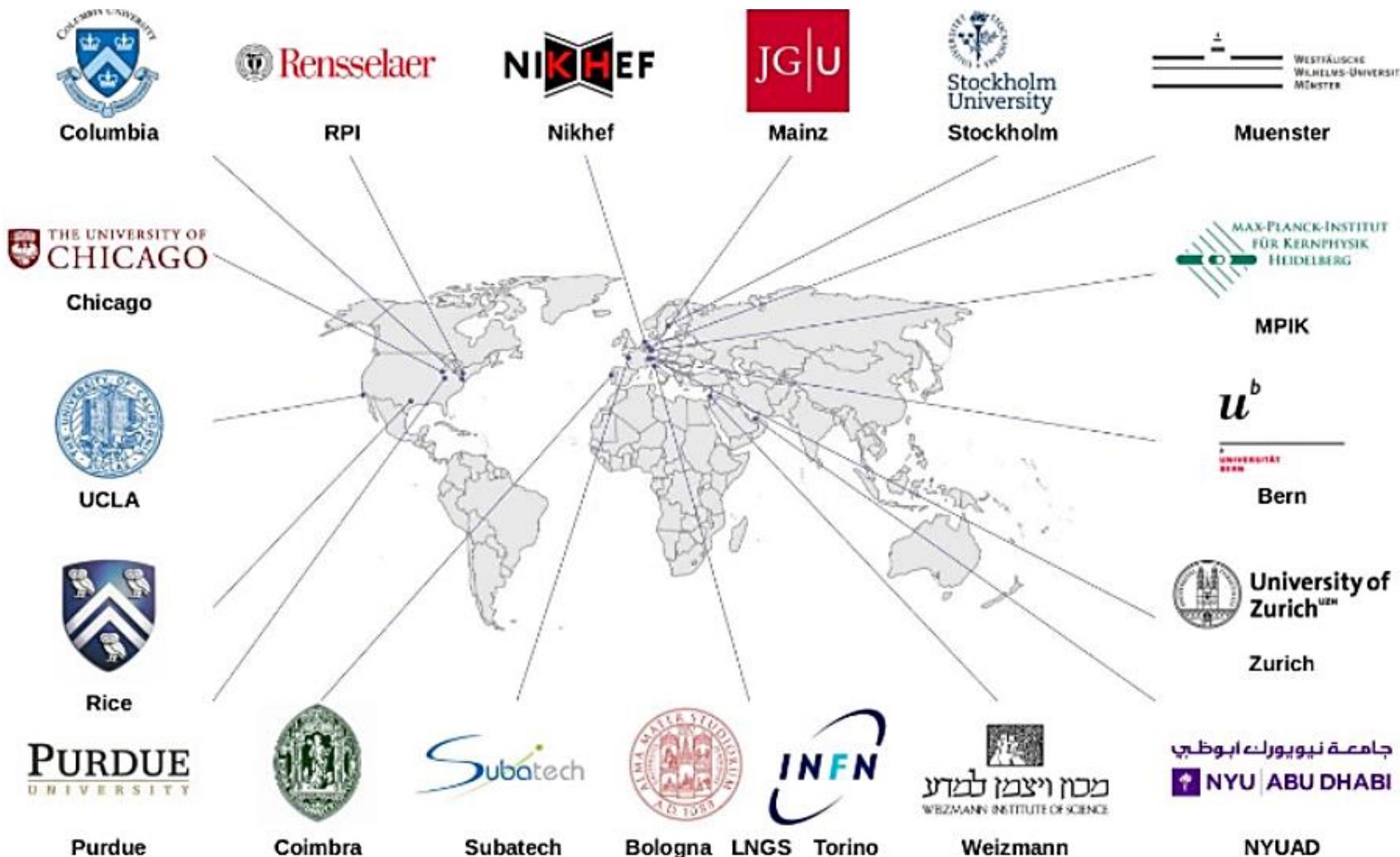


First evidences for DM come from the Zwicky studies on the Coma Cluster

Since then, other experimental observations sustained the DM hypothesis:



The XENON collaboration



The XENON project

XENON10



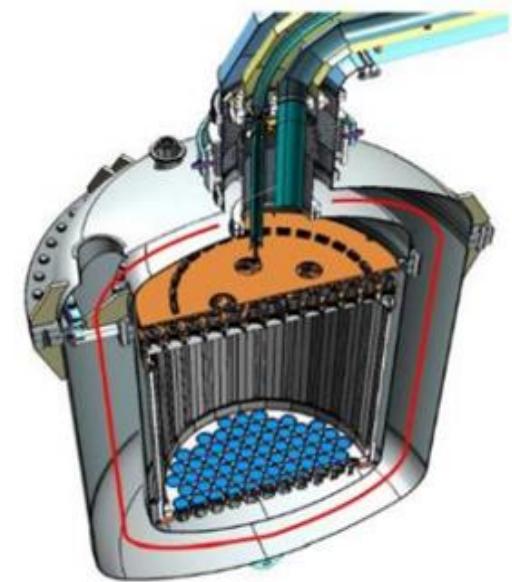
XENON100



XENON1T



XENONnT



25 kg of LXe

Result (2007):

$$\sigma_{SI} < 8.8 \times 10^{-44} \text{ cm}^2$$

161 kg of LXe

Result (2012):

$$\sigma_{SI} < 2 \times 10^{-45} \text{ cm}^2$$

~ 3300 kg of LXe

Projected (2017):

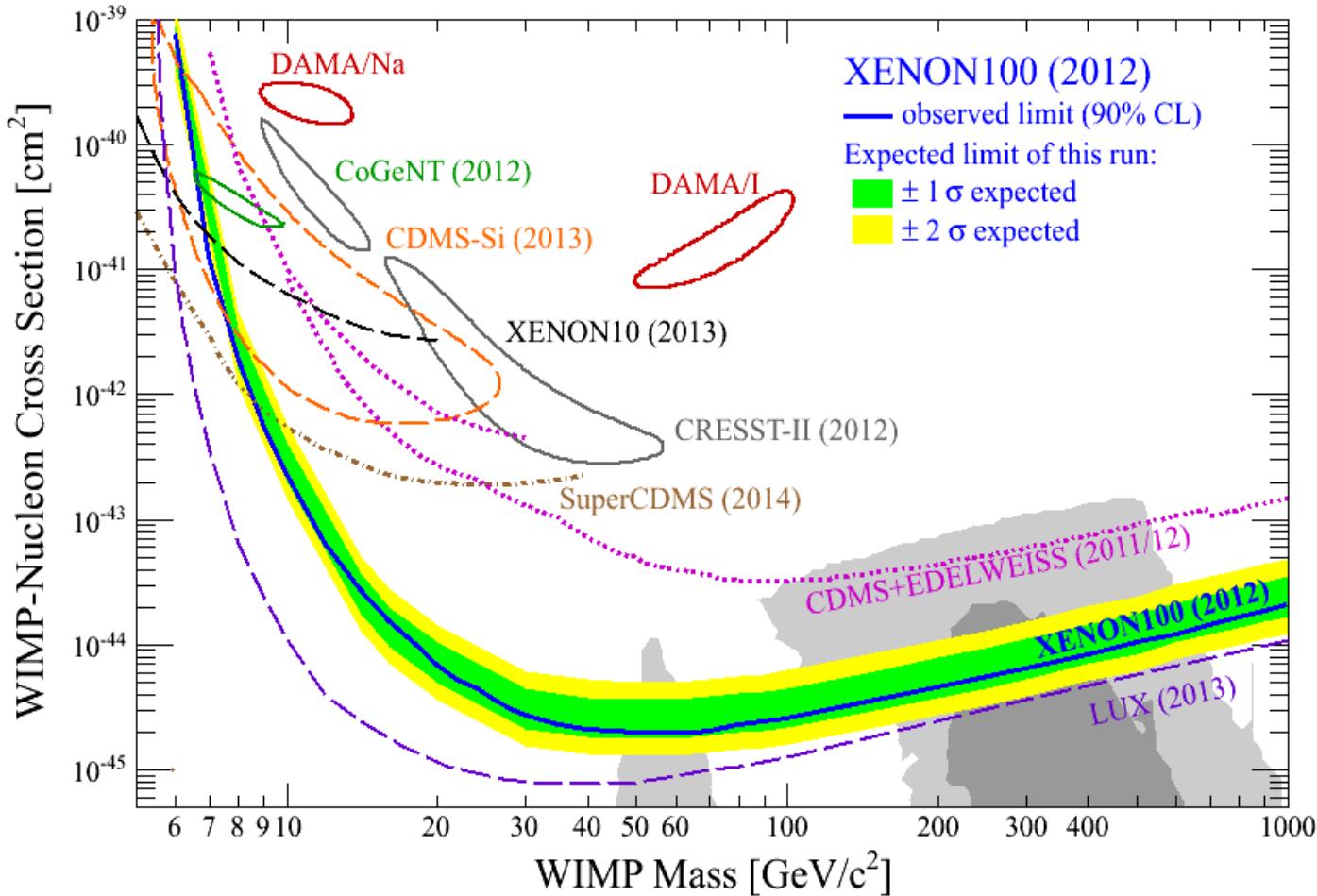
$$\sigma_{SI} < 1.2 \times 10^{-47} \text{ cm}^2$$

~ 7000 kg of LXe

Projected (2022):

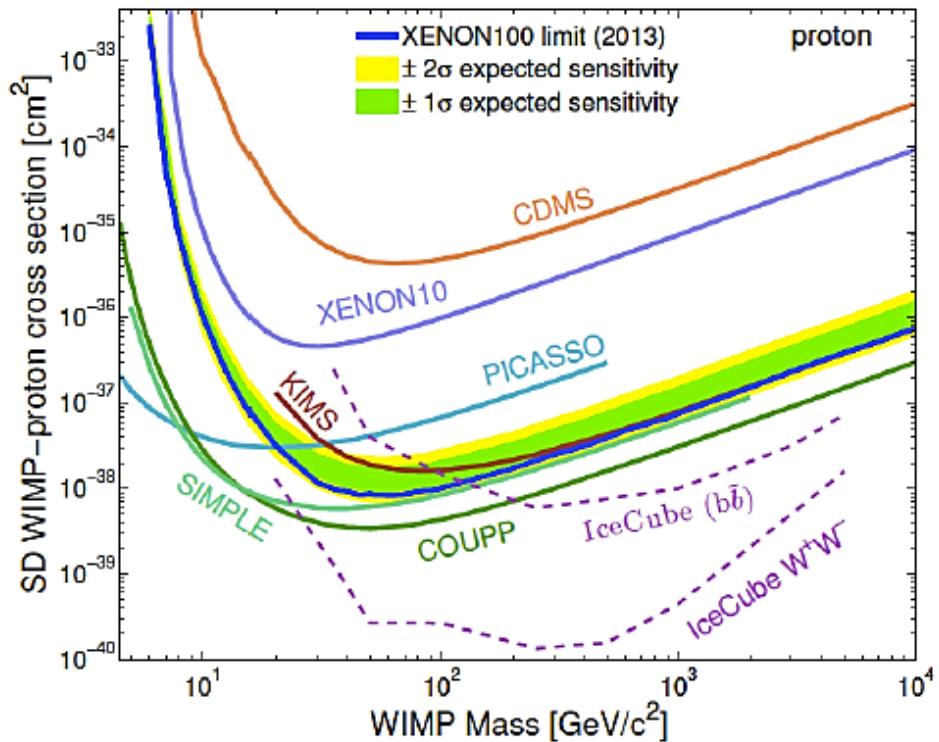
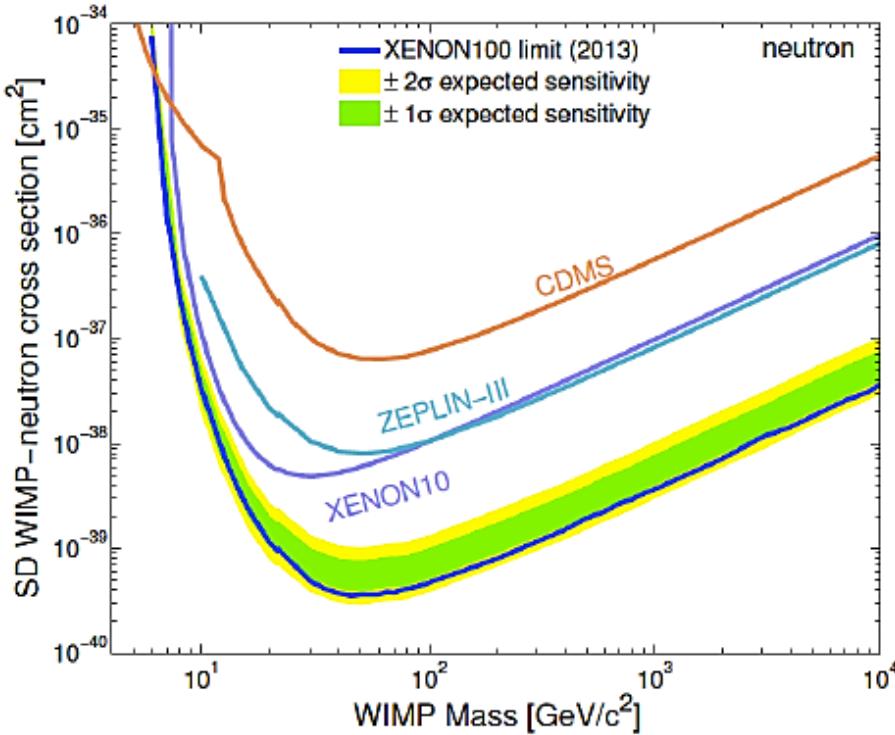
$$\sigma_{SI} < 2 \times 10^{-48} \text{ cm}^2$$

XENON100 SI results



In 2012, the collaboration released the results from XENON100 data acquired over 225 live-days, reaching a minimum for SI dark matter interaction cross section at $2.0 \times 10^{-45} \text{ cm}^2$ at $m_\chi = 55 \text{ GeV}/c^2$ (E. Aprile et al., Phys. Rev. Lett. 109, 181301 (2012))

XENON100 SD results

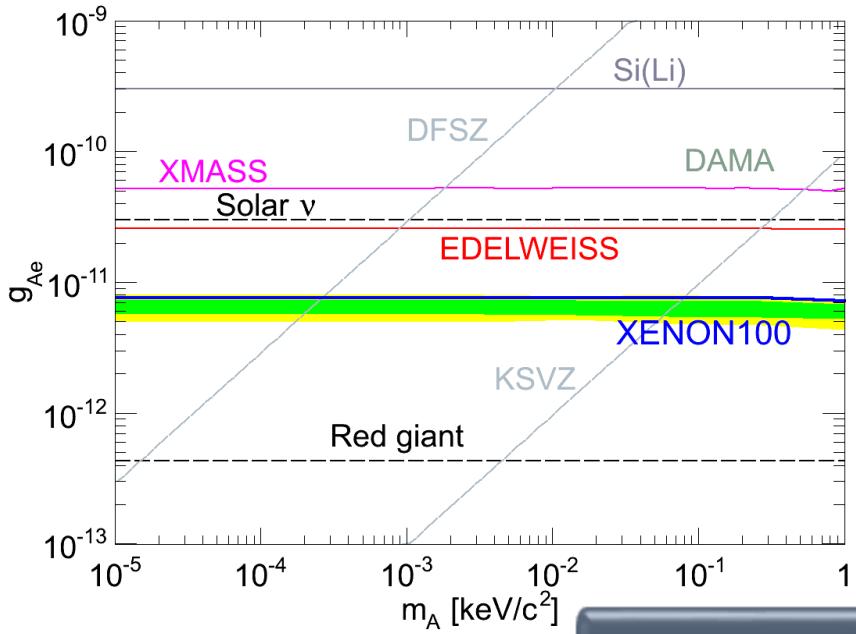


- ✓ 2 isotopes with nonzero spin: ^{129}Xe (26.2%) and ^{131}Xe (21.8%)
- ✓ Same data and event selection as SI search
- ✓ Nuclear physics from Menendez et al. were used (Menendez et al., Phys. Rev. D86, 103511 (2012))
- ✓ Best sensitivity for WIMP-neutron coupling: $\sigma_n < 3.5 \times 10^{-40} \text{ cm}^2$ for $m\chi = 45 \text{ GeV}/c^2$ (E. Aprile et al., Phys. Rev. Lett. 111, 021301 (2013))

XENON100 Solar Axions and ALPs results

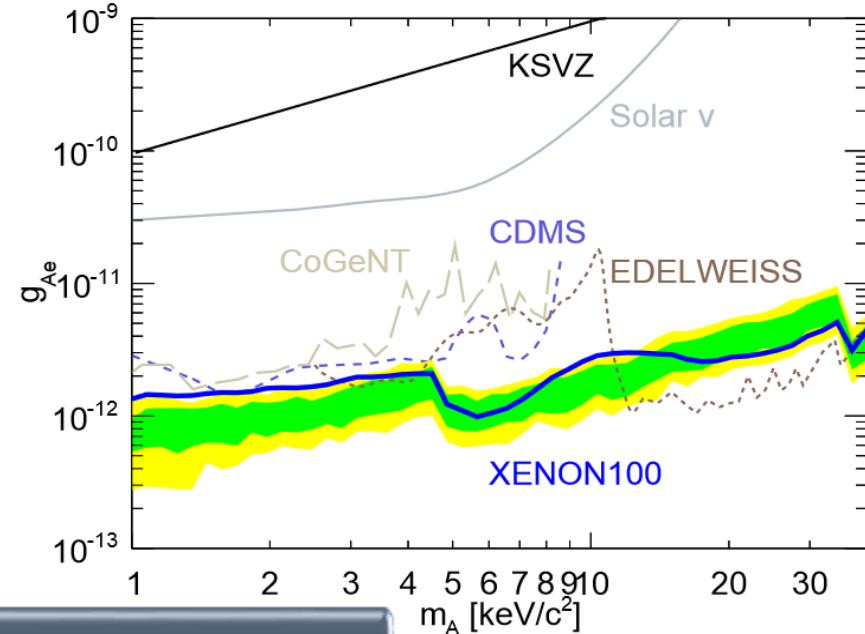


- Axions couple with electron via the axio-electric effect;
- use the same 225 days data as for WIMP search: look for electronic recoils;
- data is compatible with the background hypothesis;
- new upper limit on axion coupling to electrons: $g_{Ae} \leq 7.7 \cdot 10^{-12}$ (90% CL)



E. Aprile et al., Phys. Rev. D 90, 062009 (2014)

- ALPs couples to atomic electrons producing ERs;
- assuming ALPs constitute all of the galactic dark matter;
- data is compatible with the background hypothesis;
- best upper limit, in 5-10 keV/c^2 mass range, excluding an axion-electron coupling $g_{Ae} > 1 \cdot 10^{-12}$ (90% CL)



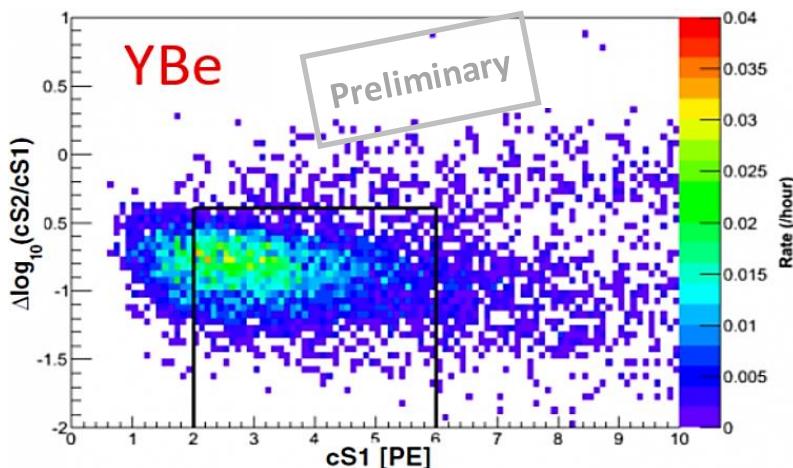
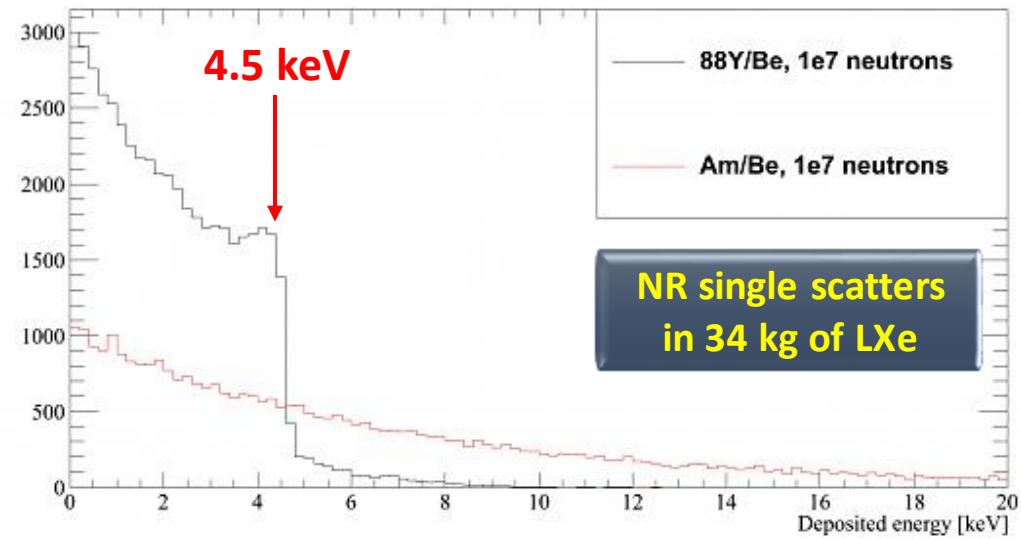
XENON100 current status

1. Low energy NR calibration with YBe

Maximum single-scatter recoil energy ~ 4.5 keV

Improve L_{eff} and Q_y measurements at low energies

Improve the understanding of detector at low energies

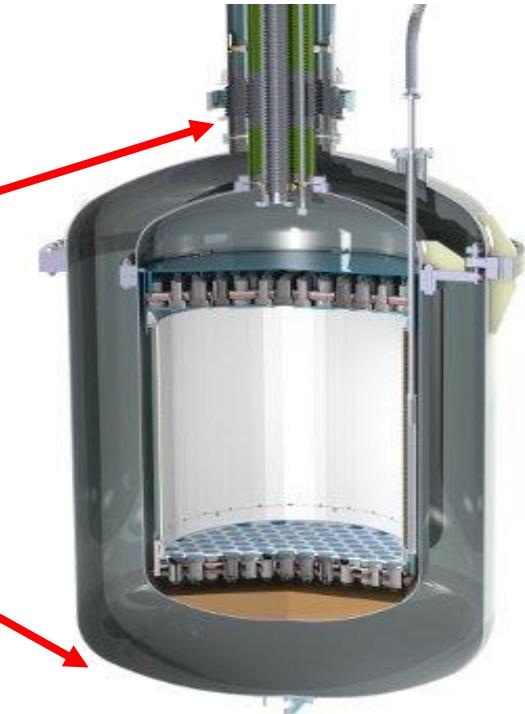
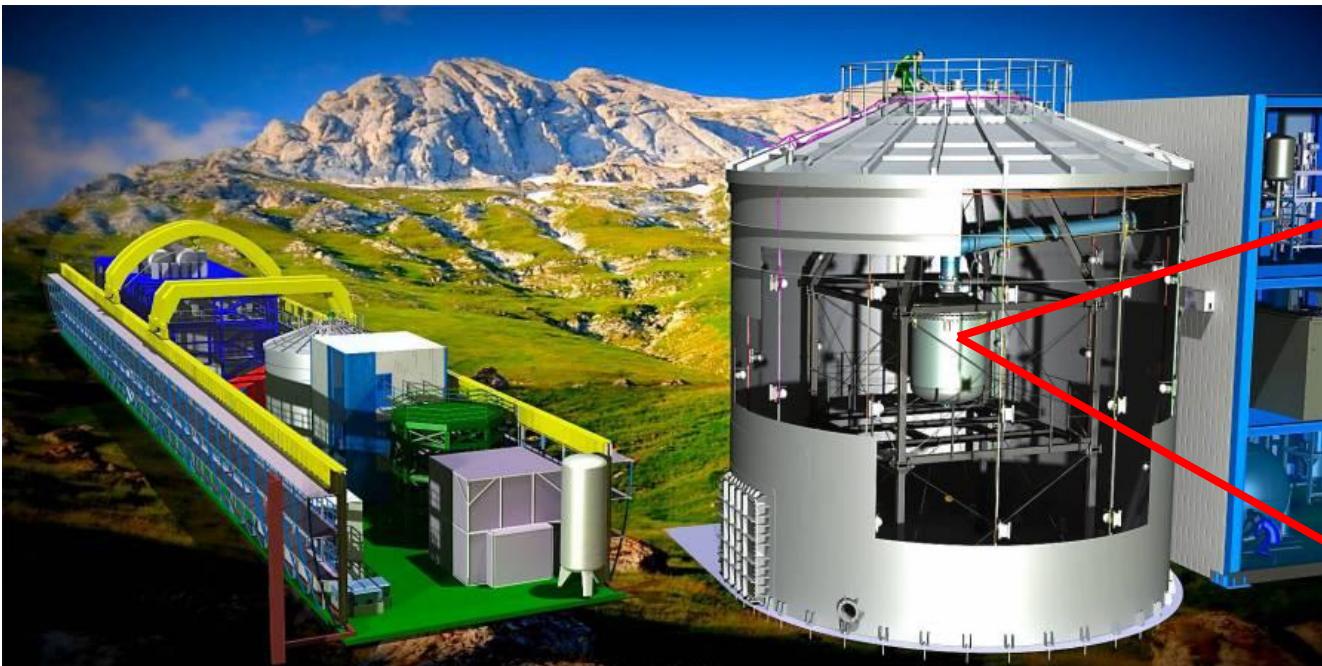


2. Results from a 150 days Dark Matter run in final stage of analysis

3. New calibration using ^{83m}Kr

4. Bench test for XENON1T: DAQ, calibrations (^{220}Rn), Rn distillation

The XENON1T experiment



- Total LXe mass: ~ 3.3 tonnes ➡ Total LXe active volume: 2 tonnes ➡ Fiducial volume: ~ 1 tonne;
- 248 3" PMTs Hamamatsu R11410-21, 35% average QE;
- a severe screening campaign has been faced to select materials with lowest radionuclide contamination level;
- field shaping rings produce a uniform drift field (0.5-1.0 kV/cm)
- $\mathcal{O}(10)$ kV/cm electrons extraction field

The XENON1T experiment: Muon Veto



The XENON1T detector is hosted inside a **Muon Veto Water Tank**

There is buffer of **water**, about **4 m**, around the detector

The **water** acts as a **passive shield** for cosmogenic neutrons **and** as an **active veto** for cosmic muons

84 high **QE** 8" **Hamamatsu R5912 PMTs** are used to **detect** the **muon Cherenkov light**

The MV allows for > 99.7% rejection power of **neutrons with a muon in the WT**

The MV allows for a > 71% rejection power of **neutrons without a muon in the WT**

The residual **muon-induced neutron background** is < 0.01 ev / (t · y)

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

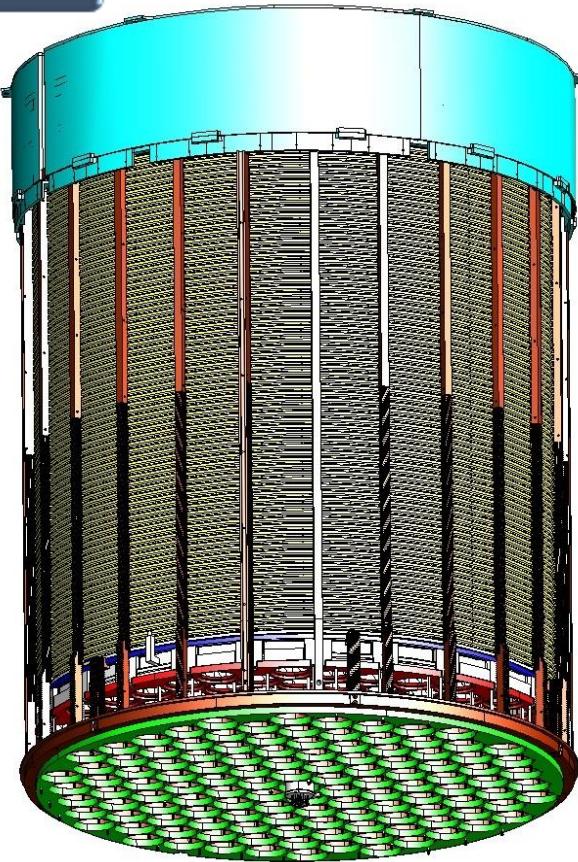
The XENON1T experiment: current status



The XENON1T background estimation

An overview of the whole TPC geometry

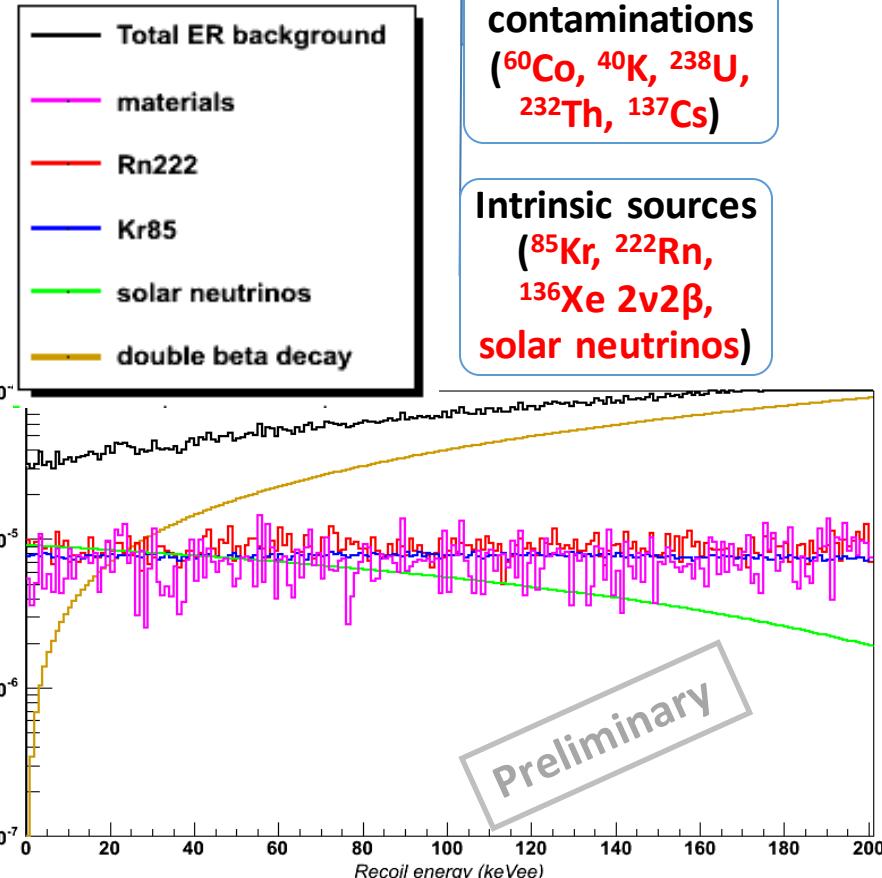
CAD drawings



MC implementation
(GEANT4)



The XENON1T background estimation



Electromagnetic background (ER)

Material contaminations
(^{60}Co , ^{40}K , ^{238}U ,
 ^{232}Th , ^{137}Cs)

Intrinsic sources
(^{85}Kr , ^{222}Rn ,
 ^{136}Xe 2v2 β ,
solar neutrinos)

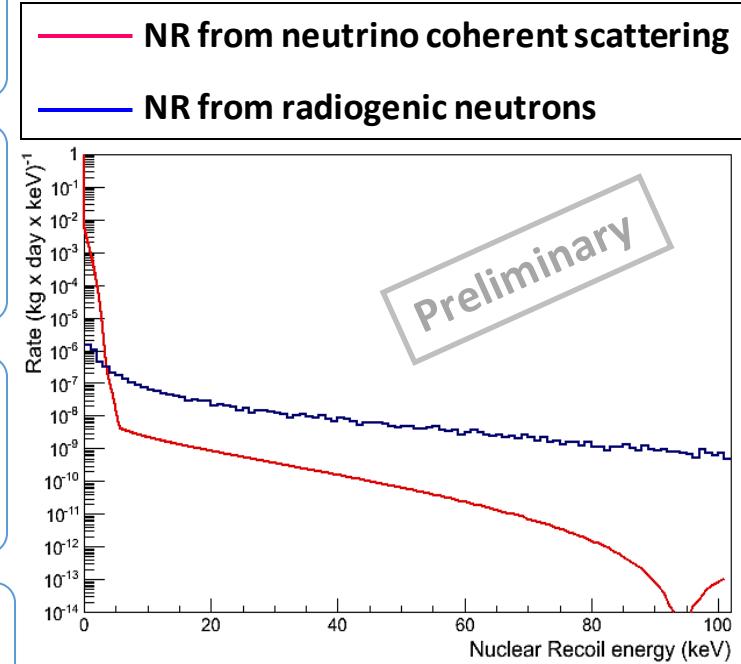
Nuclear background (NR)

Spontaneous fission (^{238}U)

(α , n) reactions
(^{238}U , ^{235}U , ^{232}Th)

Muon-induced neutrons

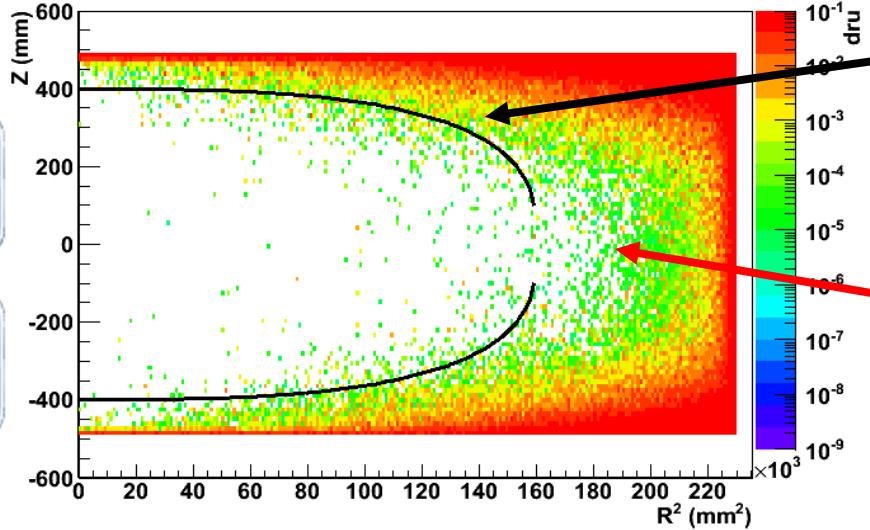
Neutrino coherent scatterings



The XENON1T ER background estimation

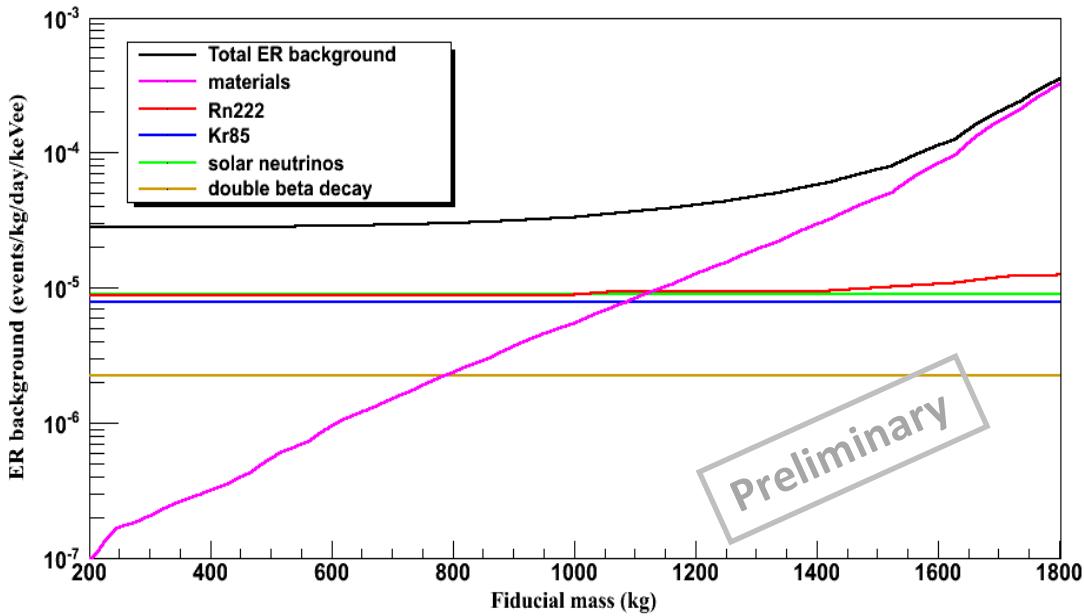
ER background is evaluated in the [2, 12] keV energy region

As reference, a fiducial volume (FV) of **1 tonne** is considered



1 tonne FV

Thanks to the **self-shielding ability** of the LXe, most of the ER from materials are outside the FV



Due to their nature, the intrinsic sources are **uniformly distributed** in the LXe volume

Their contribution to the ER background cannot be reduced through position cuts

The XENON1T NR background estimation

Radiogenic neutrons (MeV range) from ^{238}U S.F. and (α, n) reactions from α emitted along the decay chains of ^{238}U , ^{235}U and ^{232}Th

Cosmogenic neutrons (up to tens of GeV) from muon interactions with the rocks and detector materials. Thanks to the Muon Veto system of XENON1T their contribution to the NR background is $\lesssim 0.01 \text{ ev/y}$, i.e. negligible

Single elastic scatterings are indistinguishable from the WIMP signal

Fast neutrons (mean free path: tens of cm) can produce a single scatter into the LXe active volume

Neutrino coherent scattering can also give single scattering nuclear recoils that can mimic WIMP interactions.



The XENON1T background estimation results

ER background assuming a discrimination level, in the S2/S1 parameter, of 99.75%

NR background assuming an acceptance level, for nuclear recoils, of 40%

Source	Expected events ([2, 12] keV and 1 tonne-year)
materials	$0.07 \pm 10\%$
^{222}Rn ($1\mu\text{B}/\text{kg}$)	$0.08 \pm 20\%$
^{85}Kr	$0.07 \pm 20\%$
Solar neutrinos	$0.08 \pm 5\%$
^{136}Xe $2\nu 2\beta$ decay	$0.02 \pm 50\%$
Total	0.32 ± 0.03

Source	Expected events ([5, 50] keV and 1 tonne-year)
materials	$0.24 \pm 20\%$
Muon-induced neutrons	< 0.01
CNNS*	$0.01 \pm 20\%$
Total	0.26 ± 0.05

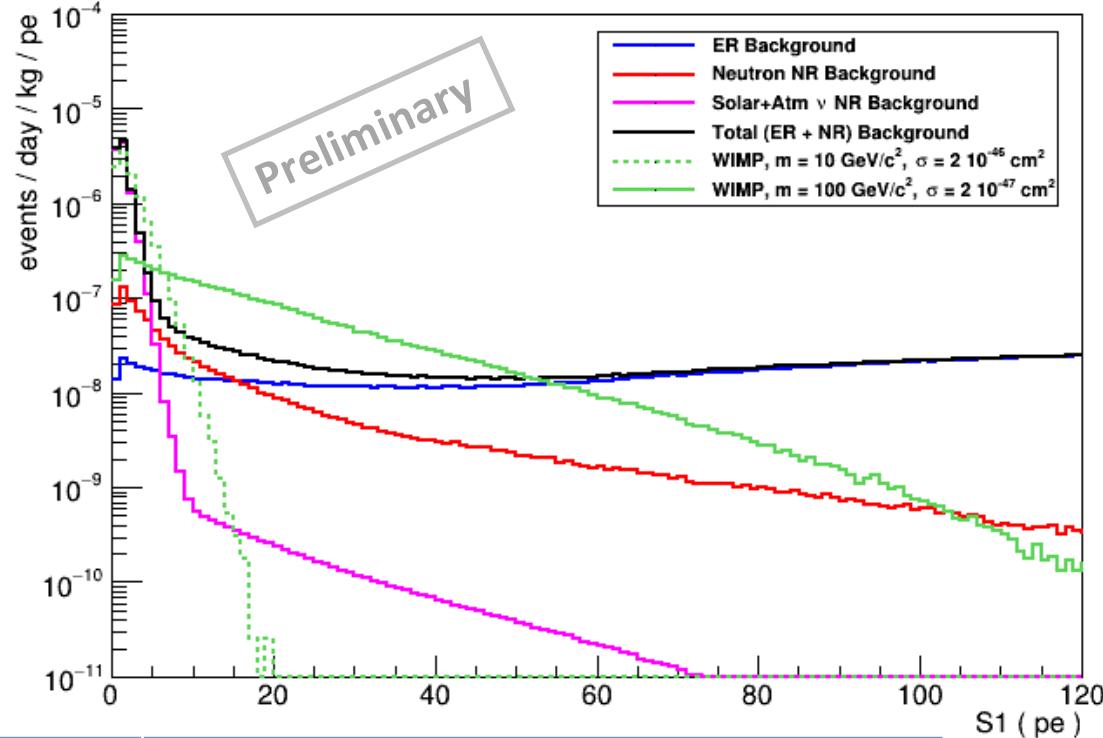
CNNS* given the very steep spectrum of NR from CNNS, its contribution must be evaluated after the conversion into S1, because of Poisson fluctuations above threshold

The XENON1T background estimation results

ER have been converted from energy to S1 signal through the use of the NEST toolkit

NR have been converted using the L_{eff} and the Q_y obtained via MC - data comparison (Phys. Rev. D88 (2013) 012006)

To convert the energy an averaged, over the whole TPC, value of LCE equal to 38% has been used



Source	Background in [3, 70] PE (ev. / ton / y)
ER (materials + intrinsic + solar ν)	0.32
NR from radiogenic neutrons	0.22
NR from neutrino coherent scattering	0.21
Total	0.75

The XENON1T sensitivity

The Profile Likelihood Method

E. Aprile et al., Phys. Rev. D 84, 052003 (2011)

$L(\mu_s, \hat{t})$: conditional maximized likelihood obtained by profiling out the nuisance parameter. Given a fixed value of μ_s to test, \hat{t} is the value of t which maximizes L

$L(\hat{\mu}_s, \hat{t})$: unconditional maximized likelihood obtained using both the maximum likelihood estimators (MLE) of μ_s and t

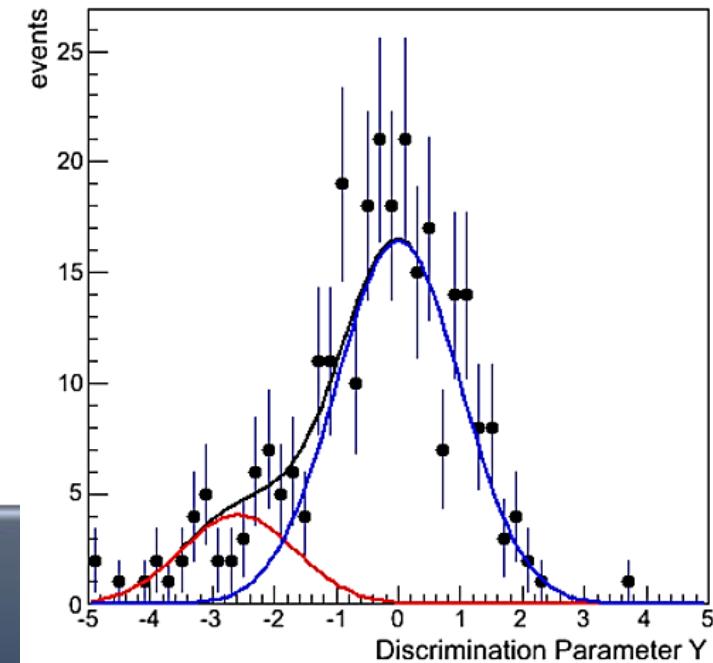
$$L(\mu_s, \mu_{bER}, \mu_{bNR}, t) = \frac{e^{-(\mu_s(t) + \mu_{bER} + \mu_{bNR}(t))} (\mu_s(t) + \mu_{bER} + \mu_{bNR}(t))^{n^{obs}}}{n^{obs}!}.$$

$$\prod_{i=1}^{n^{obs}} \left[\frac{\mu_s(t) f_s(S_{1i}) g_s(Y_i) + \mu_{bER} f_{bER}(S_{1i}) g_{bER}(Y_i) + \mu_{bNR}(t) f_{bNR}(S_{1i}) g_{bNR}(Y_i)}{\mu_s + \mu_{bER} + \mu_{bNR}(t)} \right] \cdot e^{-\frac{t^2}{2}}$$

The test statistic

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

We are looking only for upper limits



The XENON1T sensitivity

The t nuisance parameter

The parameter t is used to describe the uncertainty on the L_{eff} .

L_{eff} extrapolated down to 1 keV.

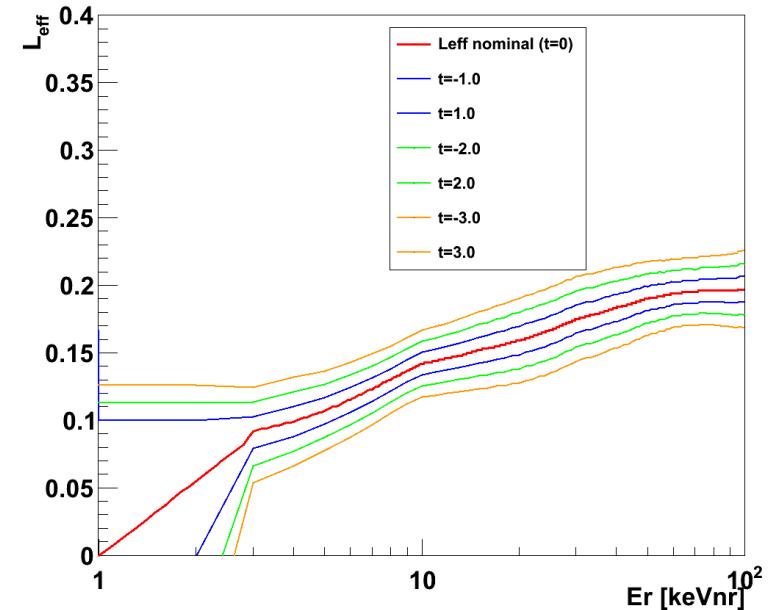
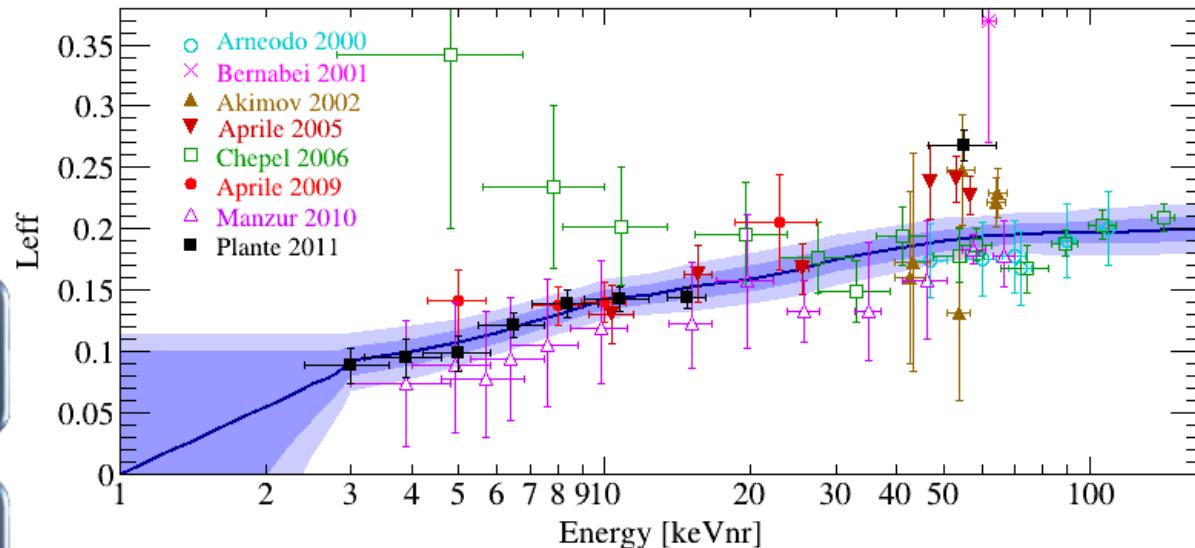
Both, signal and NR background are modeled for L_{eff} variation.

The L_{eff} curves are obtained as follows:

$$L_{eff}(t) = L_{eff}(\text{median}) + t \cdot \Delta L_{eff}(-1\sigma) \quad t < 0$$

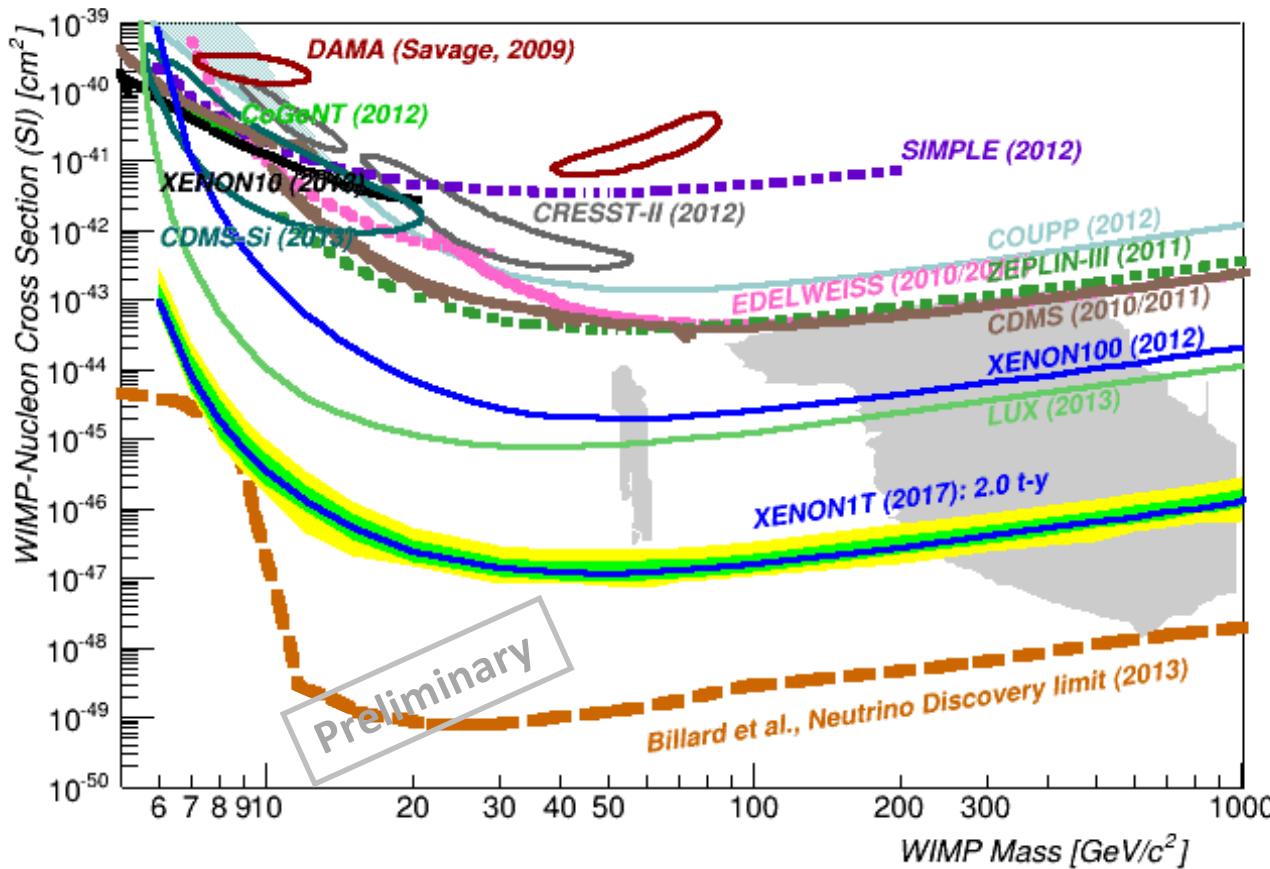
$$L_{eff}(t) = L_{eff}(\text{median}) + t \cdot \Delta L_{eff}(+1\sigma) \quad t > 0$$

ΔL_{eff} : distance between $L_{eff}(\text{median})$ and its boundaries at $\pm 1\sigma$



The XENON1T sensitivity

XENON1T sensitivity, 90% CL, with CLs

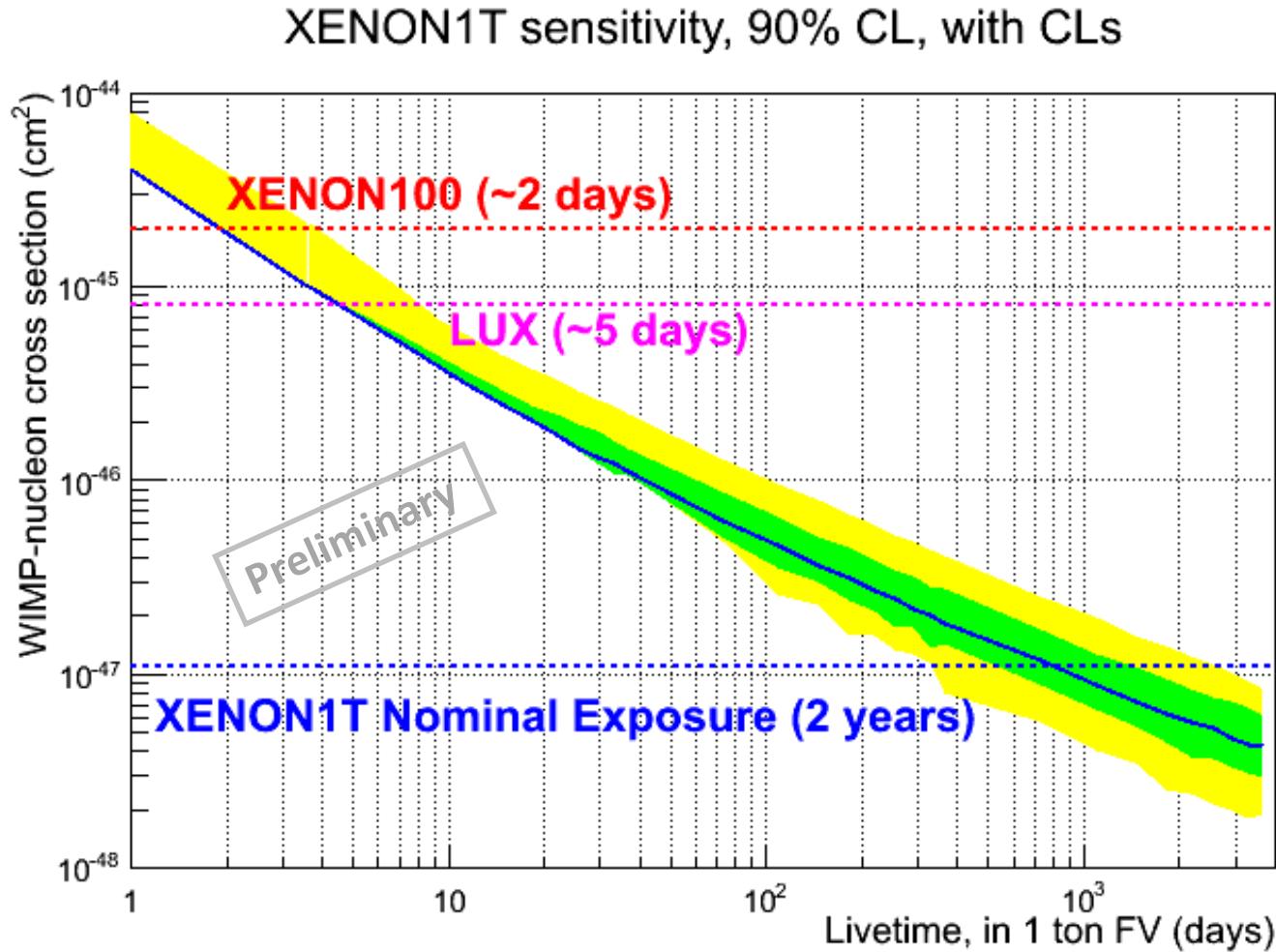


With an **exposure of 2 t*y**, XENON1T will reach a **minimum** for the **sensitivity** at:

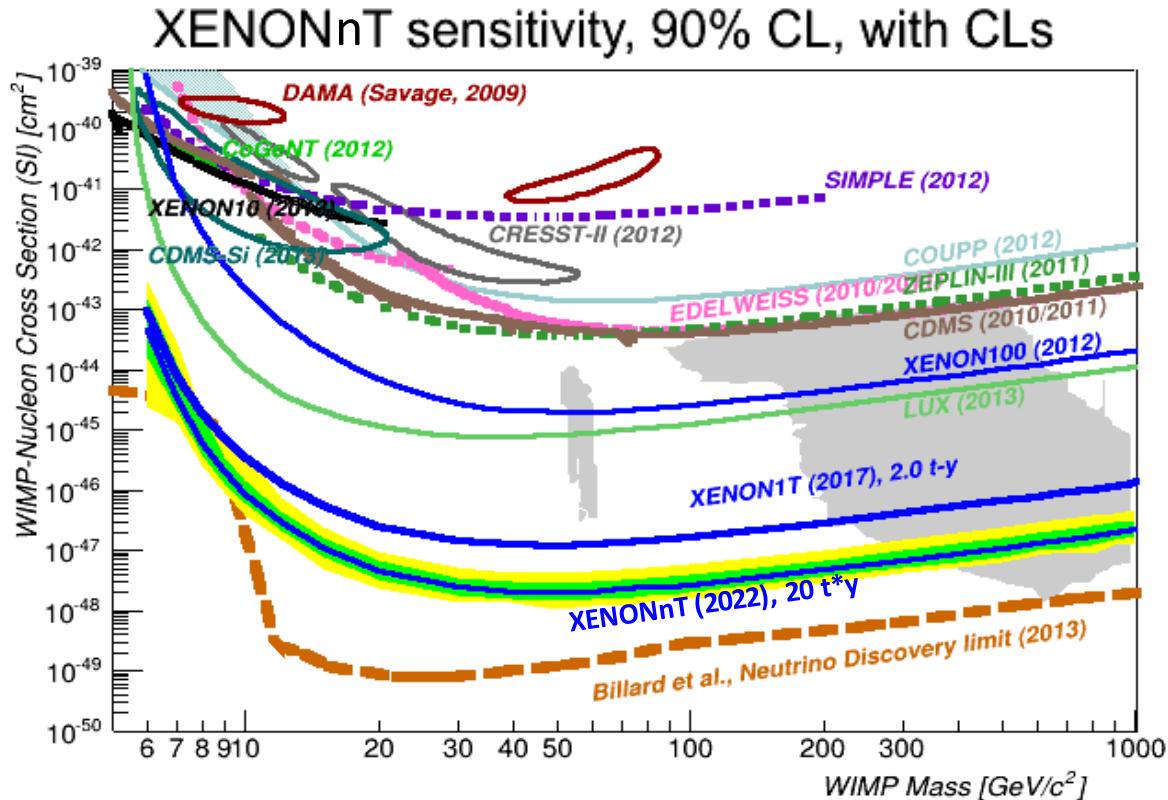
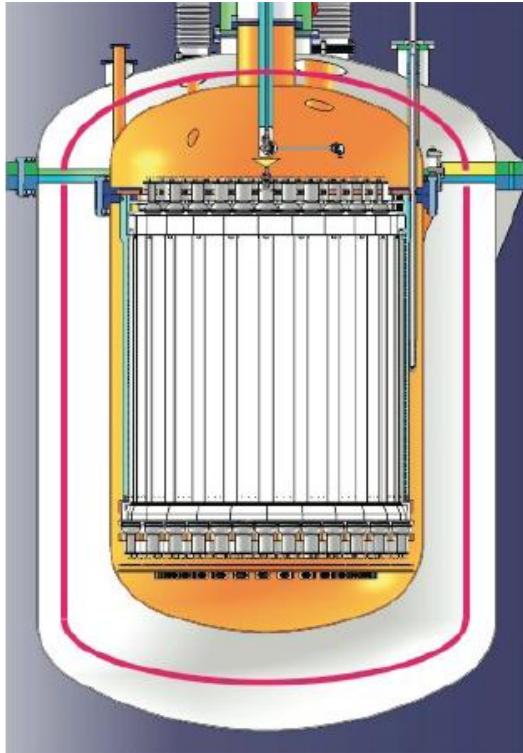
$$\sigma = 1.2 \cdot 10^{-47} \text{ cm}^2 \text{ for a WIMP mass of } 50 \text{ GeV}/c^2$$

The XENON1T sensitivity

Sensitivity, as a function of the time, considering a WIMP mass of $50 \text{ GeV}/c^2$



The XENON1T upgrade: XENONnT



The **outer vessel of XENON1T is able to host the XENONnT detector**

ER and NR backgrounds from materials assumed negligible in the fiducial volume

An exposure of 20 t*y has been considered

Conclusion

- ✓ In 2012, XENON100 published its best results reaching a sensitivity to cross section of

$$\sigma = 2 \cdot 10^{-45} \text{ cm}^2 \text{ at (90\% CL, } m_\chi = 55 \text{ GeV/})$$

- ✓ Results from a 150 days Dark Matter run in final stage of analysis.
- ✓ In [3,70] PE, assuming a discrimination level for ER of 99.75% and a 40% acceptance for NR, the XENON1T total background in 1 tonne FV is:

$$(0.75 \pm 0.06) \text{ ev/(t*y)}$$

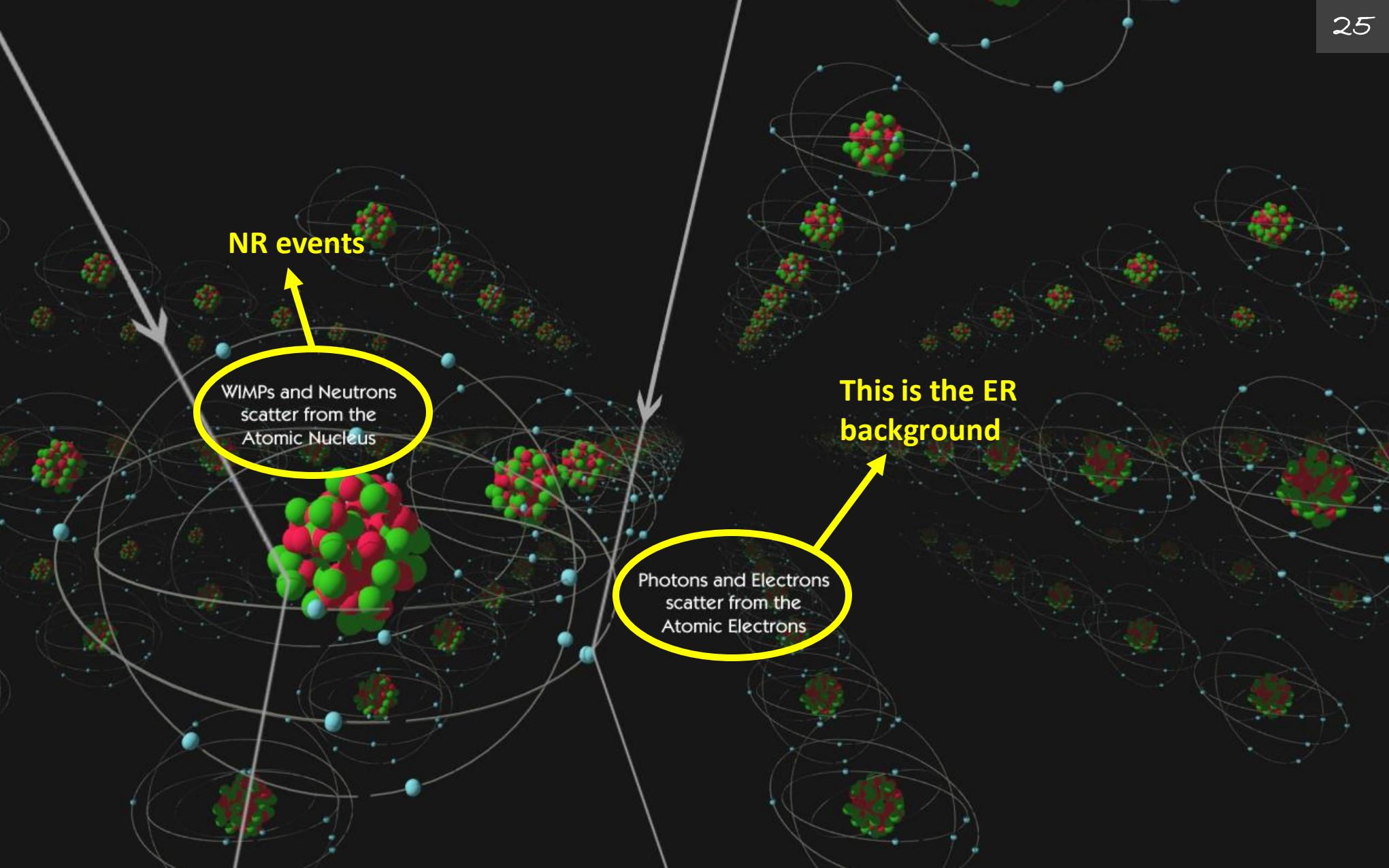
- ✓ With an exposure of 2 t*y, the XENON1T experiment will be sensitive to WIMP-nucleon scattering cross section of

$$\sigma = 1.2 \cdot 10^{-47} \text{ cm}^2 \text{ (90\% CL, } m_\chi = 50 \text{ GeV/c}^2)$$

- ✓ The upgrade of XENON1T, XENONnT, will be able to go even below such limits reaching sensitivities, assuming an exposure of 20 t*y, as low as

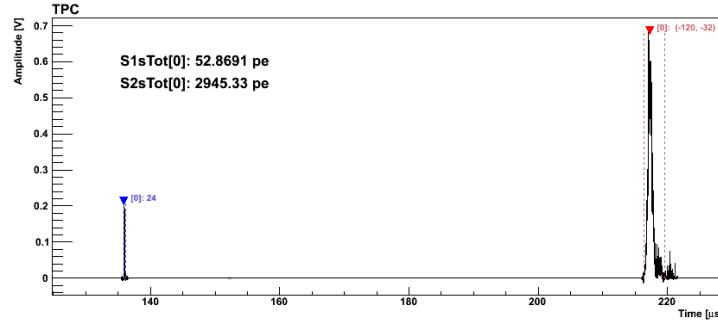
$$\sigma = 2 \cdot 10^{-48} \text{ cm}^2 \text{ (90\% CL, } m_\chi = 50 \text{ GeV/c}^2)$$

Backup slides

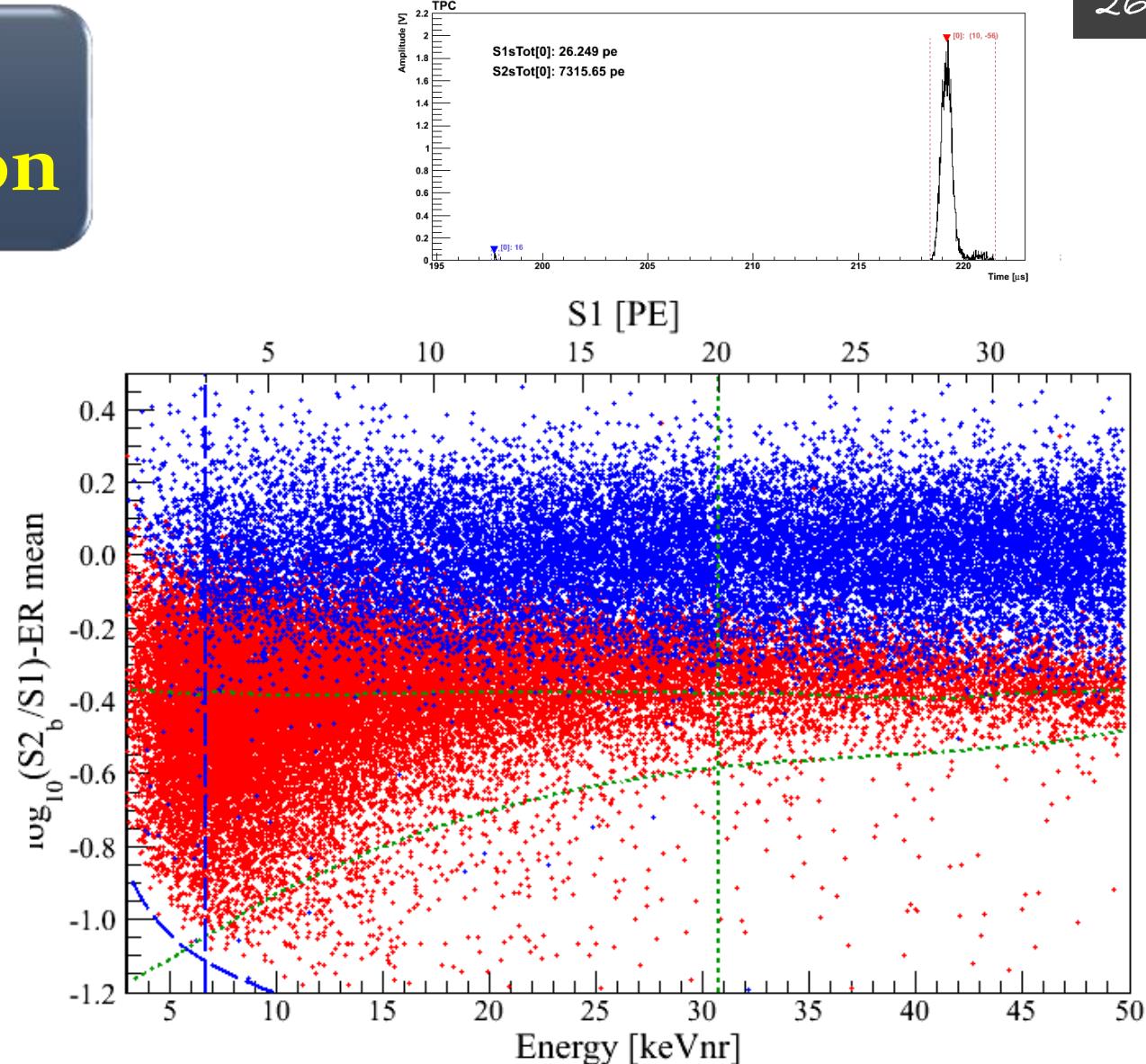


Particle discrimination

Electromagnetic recoil band

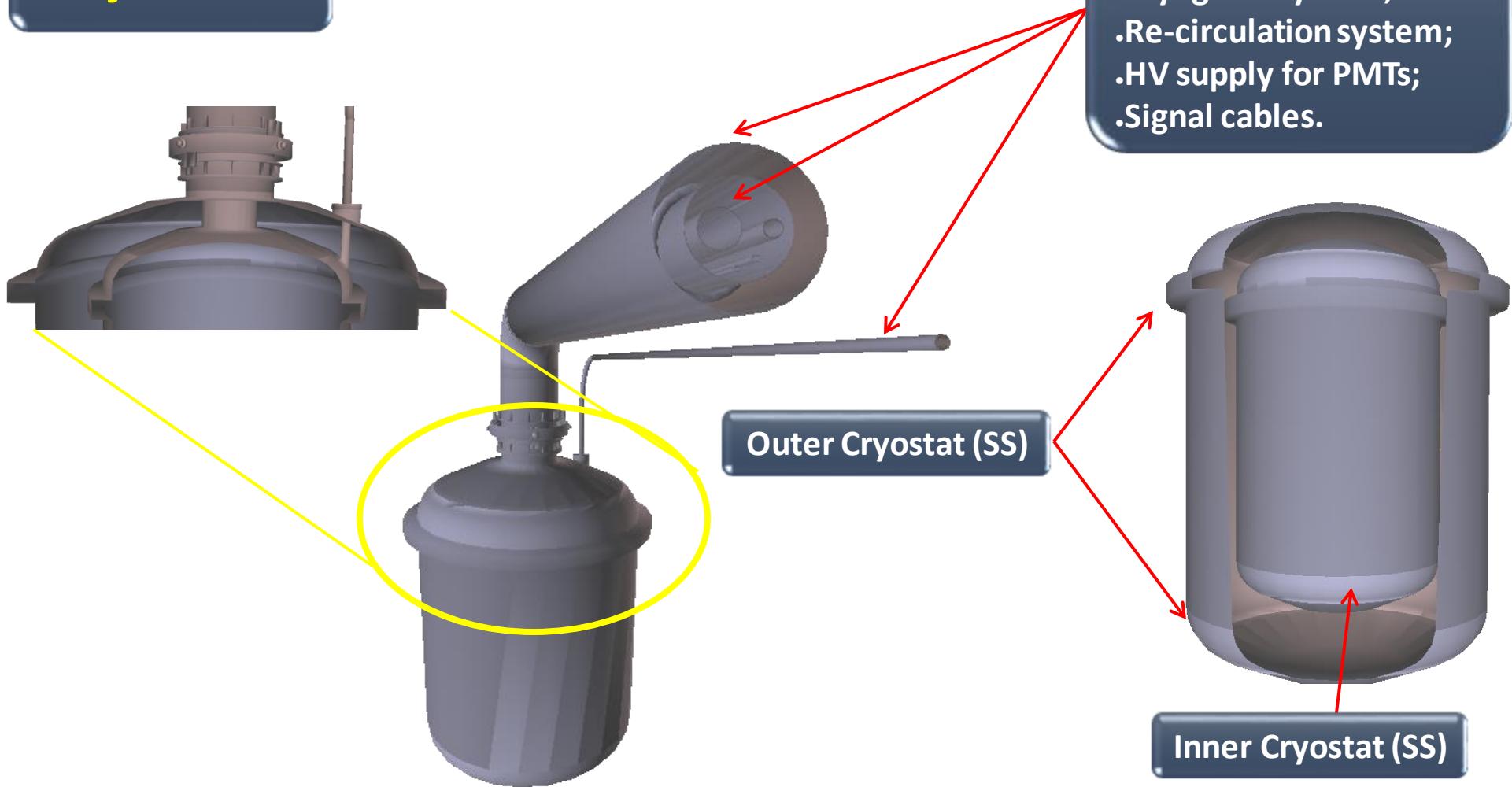


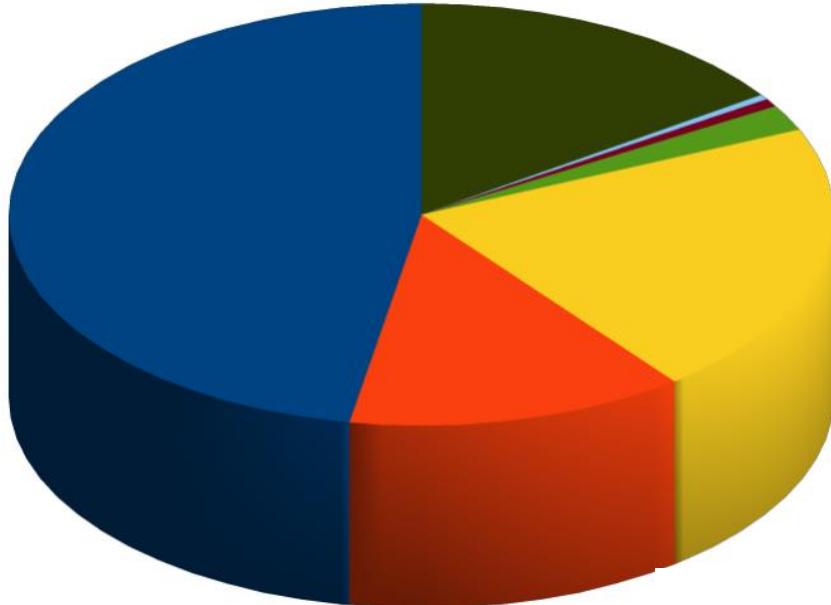
Nuclear recoil band



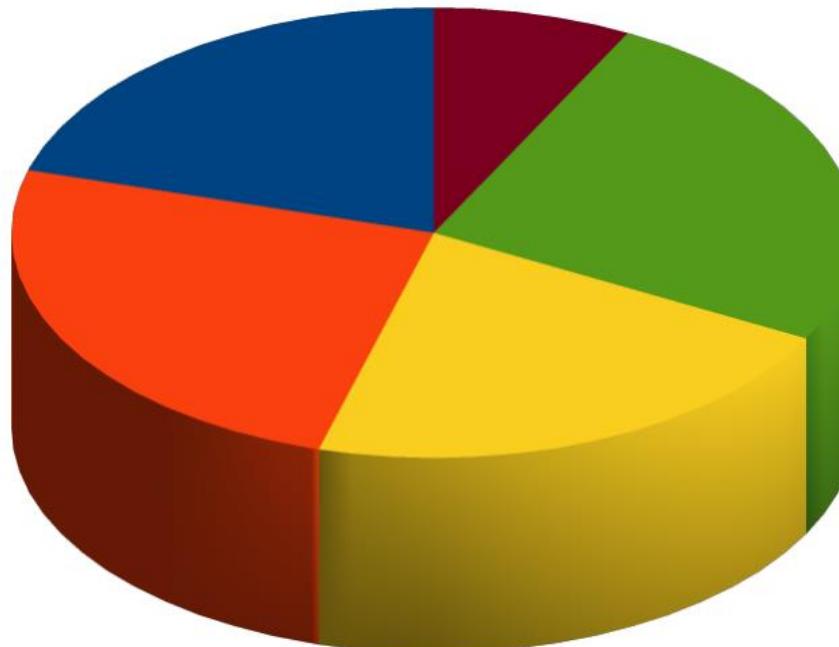
GEANT4 simulation of XENON1T

Cryostats



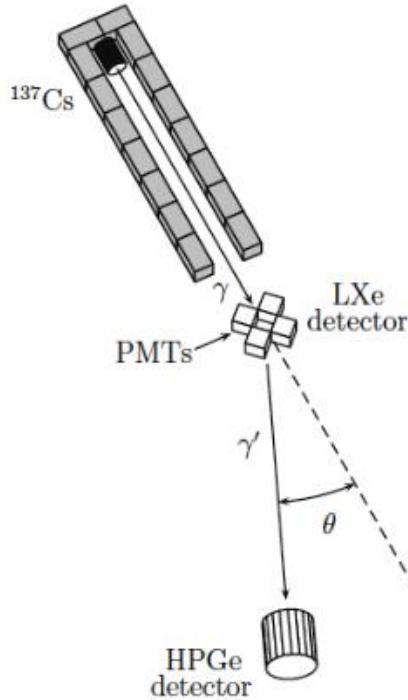


- Cryostat shells
- Cryostat flanges
- PMTs
- PMT bases
- PTFE components
- Cu components
- SS components



- Materials
- 222Rn
- 85Kr
- solar neutrinos
- 2v2 β

ER energy scale



External ^{137}Cs γ source and ^{83m}Kr e^- internal source

$$E_{ER} = E_\gamma - E_{\gamma'} = E_\gamma - \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2} (1 - \cos \theta)}$$

The results are given as efficiency with respect to the 32.1 keV transition of the ^{83m}Kr

$$E_{ER}(\text{keV}_{ee}) = \frac{S_1}{L_{y,ER}(32.1 \text{ keV})} \frac{1}{R_e} \frac{1}{Q(E)}$$

$L_{y,ER}(32.1 \text{ keV}) = 3.76 \text{ PE/keV}$ (XENON100 light yield at 32.1 keV and zero field);

R_e : scintillation efficiency relative to the 32.1 keV transition of ^{83m}Kr at zero electric field;

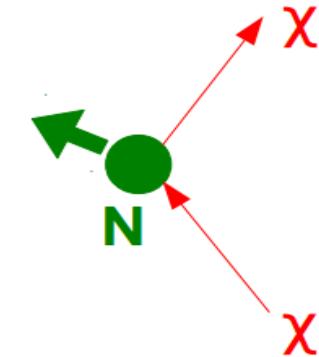
$Q(E)$: quenching factor for a non-zero electric field

Different response to electromagnetic and nuclear recoils: the \mathcal{L}_{eff}

ER: a particle that interacts with the atomic electrons loses energy and produces excitation and ionization, both named **electronic excitation**. The energy loss under this process defines the **electronic stopping power**. This is the measurable signal.

NR: part of the energy given to the nucleus is spent to **atomic motion**, i.e. not measurable signal.

To reconstruct the energy lost in ER and NR it is necessary to take into account their **different scintillation properties**



$$\mathcal{L}_{eff}(E_R) = \frac{L_{y,nr}(E_R)}{L_{y,er}(E_{er} = 122 \text{ keV})}$$

scintillation yield of the nuclear recoil

scintillation yield of electronic recoils from photoabsorbed 122 keV γ rays from a ^{57}Co source at zero field

$$E_R \approx 2 E_n \frac{m_n}{m_n + m_{Xe}} (1 - \cos \theta)$$

Experimentally it is defined the **relative scintillation efficiency**, \mathcal{L}_{eff} , for NR

$$E_R(\text{keV}_r) = \frac{S_1}{L_{y,er}(122 \text{ keV})} \frac{1}{\mathcal{L}_{eff}} S_{nr}$$

$$S_{ee} = 0.58 \quad \left. \right\} S_{ee(nr)} \text{ is the quenching due to the drift field}$$

$$S_{nr} = 0.95$$

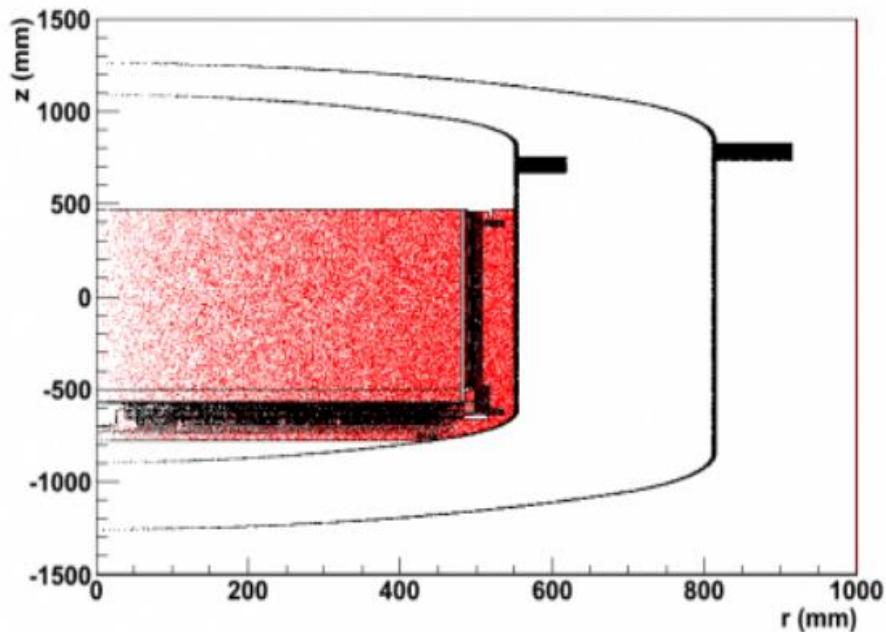
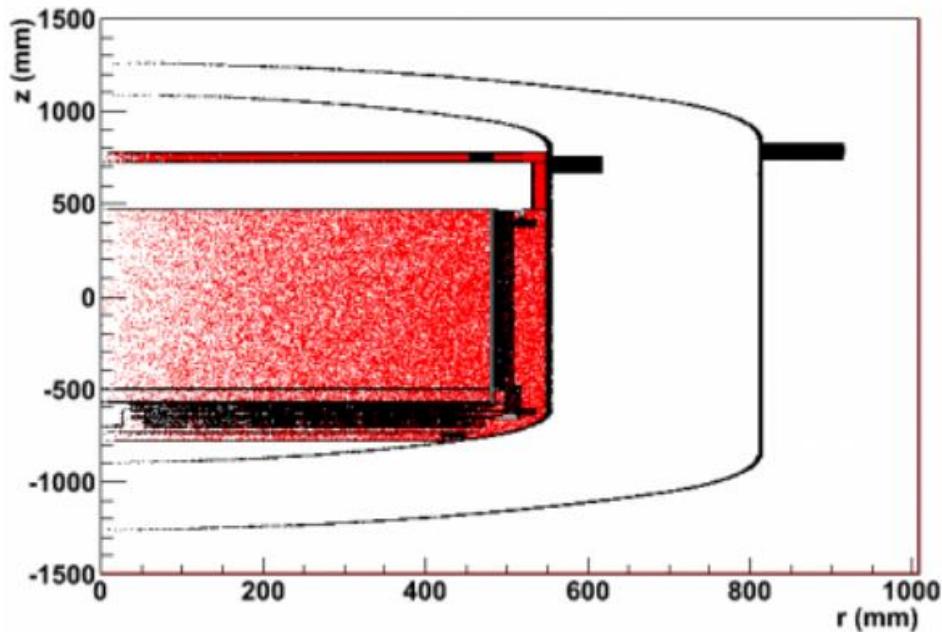
GEANT4 simulation of XENON1T

Diving bell

The option w/o bell have been considered

Option with the bell

Option without the bell

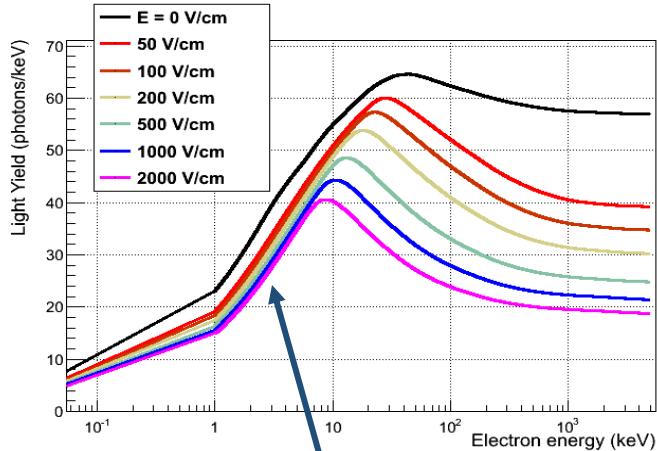


How to sum ER and NR?

Needs for conversion from energy to S₁ and S₂ signals

ER

$$N_{quanta} = \text{Gauss}(73 \cdot E, \sqrt{73 \cdot E \cdot F})$$



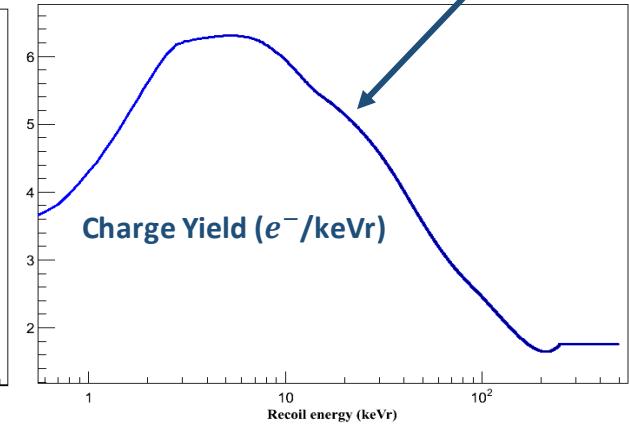
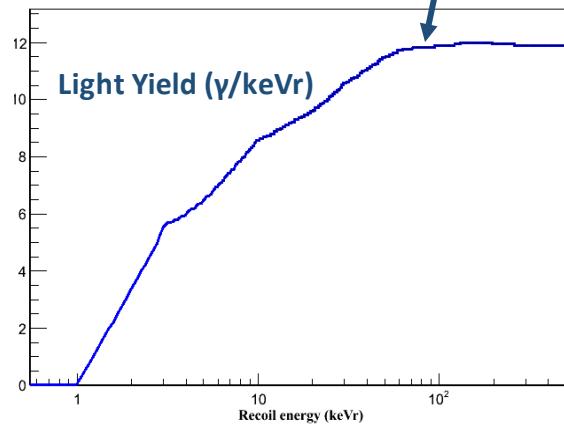
$$f_{light} = \langle N_{phot} \rangle / N_{quanta}$$

$$N_{phot} = \text{Binomial}(N_{quanta}, f_{light})$$

$$N_{e^-} = N_{quanta} - N_{phot}$$

NR

$$\langle N_{phot} \rangle = E \cdot \underline{\mathcal{L}_{eff}(E)} \cdot Ph^{122 \text{ keV}_{ee}} \cdot S_{NR}, \quad \langle N_{e^-} \rangle = E \cdot Q_y(E)$$



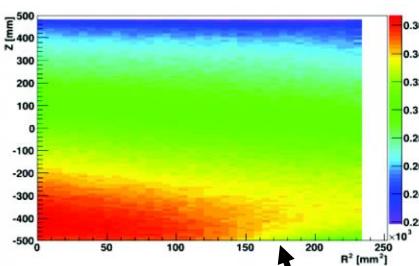
$$\langle N_{quanta} \rangle = \langle N_{phot} \rangle + \langle N_{e^-} \rangle$$

$$N_{quanta} = \text{Gauss}(\langle N_{quanta} \rangle, \sigma = \sqrt{\langle N_{quanta} \rangle \cdot F}).$$

$$N_{phot} = \text{Binomial}(N_{quanta}, \langle N_{phot} \rangle / \langle N_{e^-} \rangle)$$

$$N_{e^-} = N_{quanta} - N_{phot}.$$

S1 and S2 signals



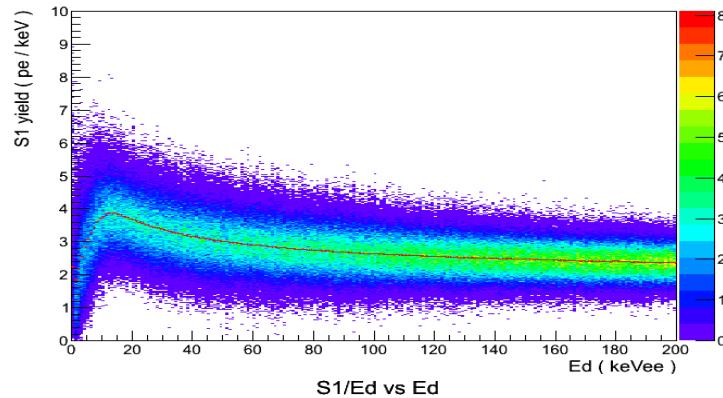
$$DE = LCE \cdot QE \cdot CE$$

$$DP = \text{Binomial}(N_{phot}, DE)$$

$$S1 = \text{Gauss}(DP, 0.5 \cdot \sqrt{DP})$$

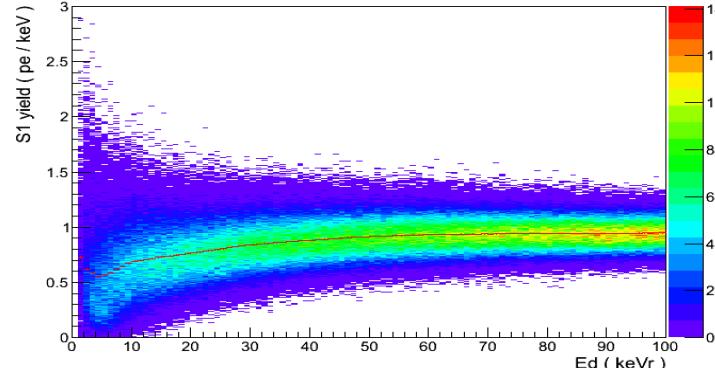
S1/Ed vs Ed

ER



S1/Ed vs Ed

NR



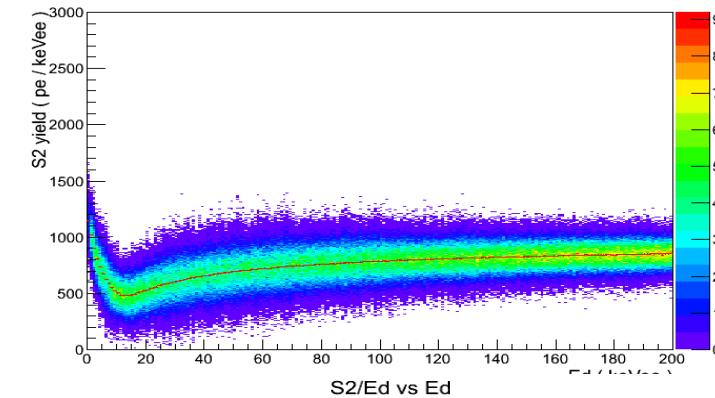
S1/Ed vs Ed

$$Prob = e^{-t/e_{life}}$$

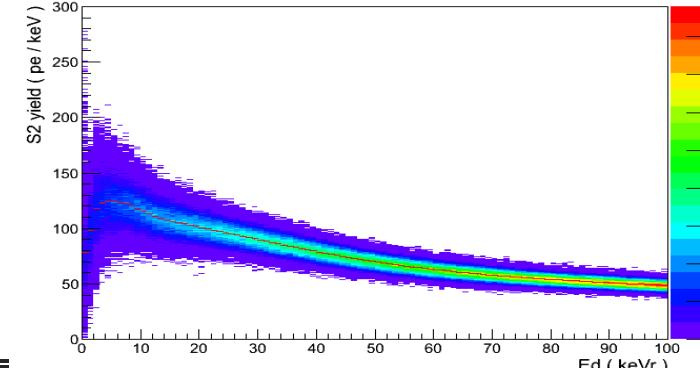
Impossibile visualizzare l'immagine.

$$S2 = \text{Gauss}(N_{e^-}^{surv} \cdot 20, 7 \cdot \sqrt{N_{e^-}^{surv}})$$

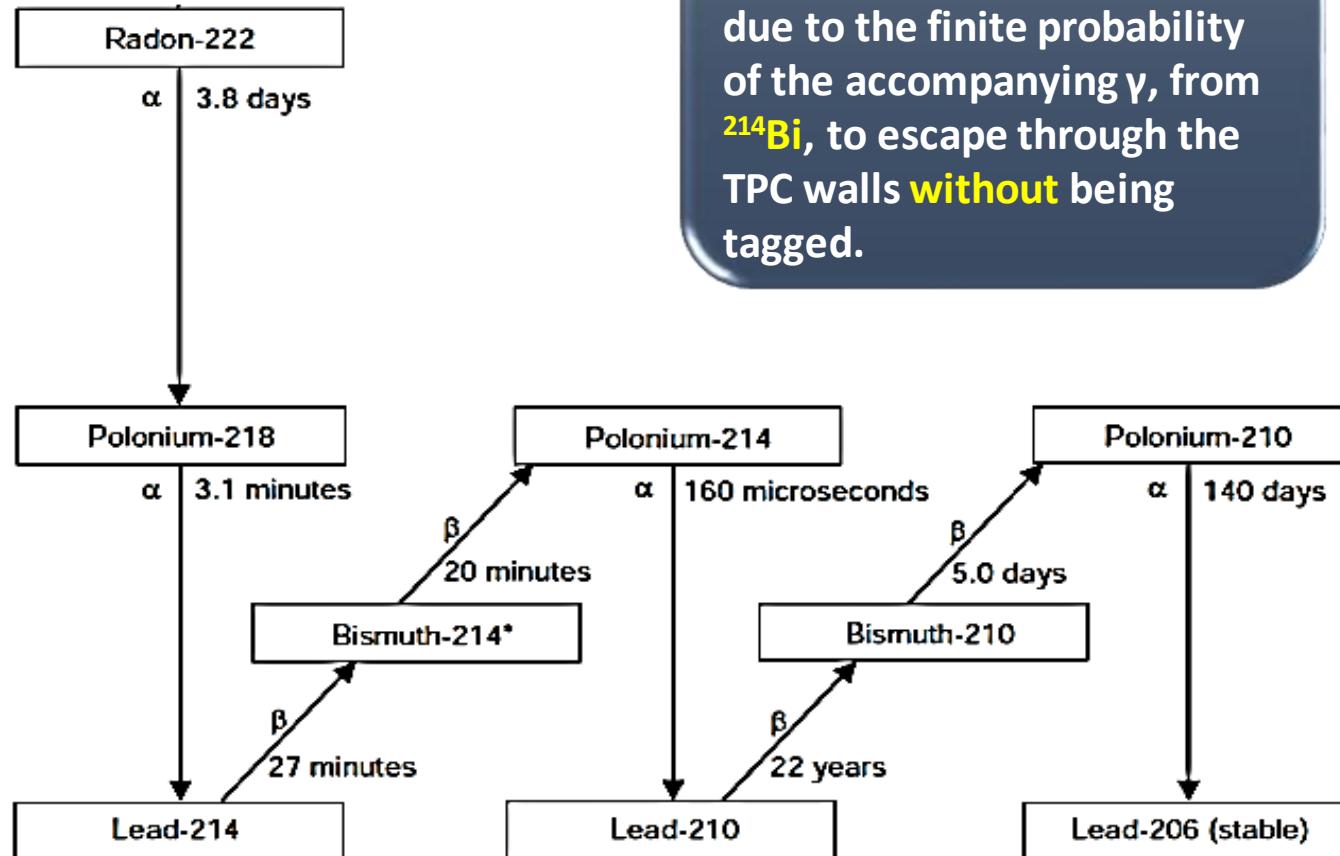
S2/Ed vs Ed



S2/Ed vs Ed



S2/Ed vs Ed



The slightly rise of the ^{222}Rn at higher fiducial masses is due to the finite probability of the accompanying γ , from ^{214}Bi , to escape through the TPC walls without being tagged.

The XENON1T experiment: Muon Veto



The XENON1T detector is hosted inside a **Muon Veto Water Tank**

There is buffer of **water**, about **4 m**, around the detector

The **water** acts as a **passive shield** for cosmogenic neutrons ($\sim 7.3 \cdot 10^{-10} n/(cm^2 s)$) and as an **active veto** for cosmic muons ($\sim 3.31 \cdot 10^{-8} \mu/(cm^2 s)$)

84 high QE **8"** Hamamatsu R5912 PMTs are used to **detect** the **muon Cherenkov light**

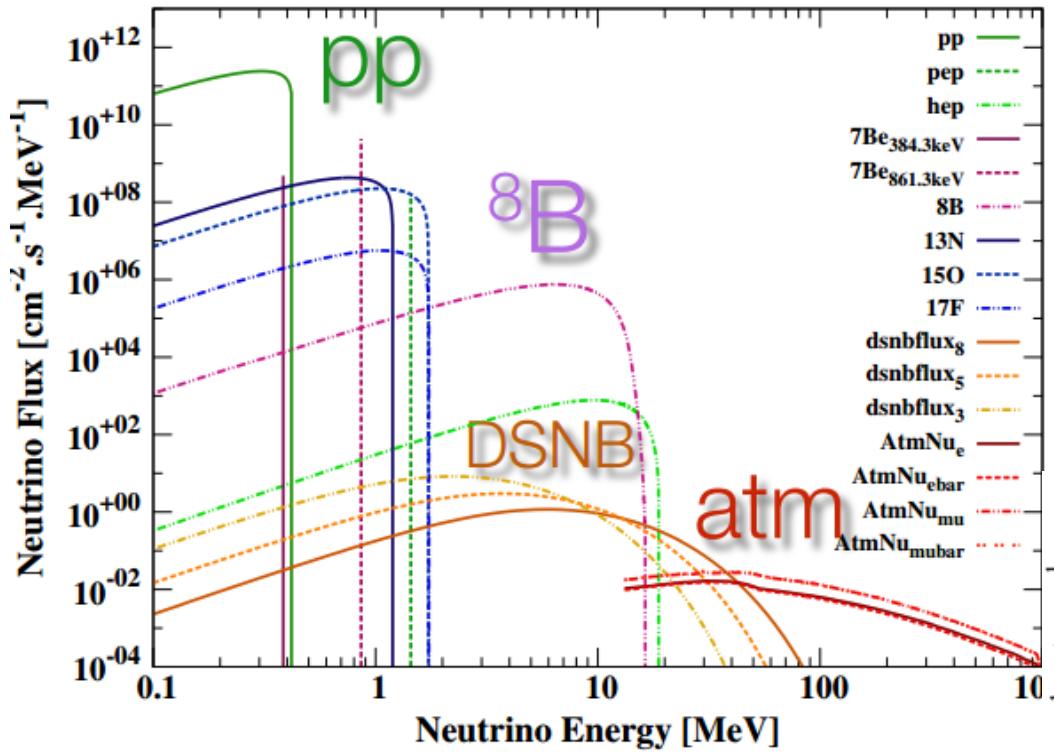
The MV allows for **> 99.7% rejection power** of **neutrons with a muon in the WT**

The MV allows for a **> 71% rejection power** of **neutrons without a muon in the WT**

The residual **muon-induced neutron background** is **< 0.01 ev / (t · y)**

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

The neutrino background



NR from ${}^8\text{B}$ solar neutrinos (nucleus coherent scattering): below $\sim 4 \cdot 10^{-45} \text{ cm}^2$

NR from atmospheric and DSNB neutrinos (nucleus coherent scattering): below $\sim 10^{-49} \text{ cm}^2$

