Monte Carlo estimation of the XENON1T experiment electromagnetic and nuclear recoil background

Fabio Valerio Massoli

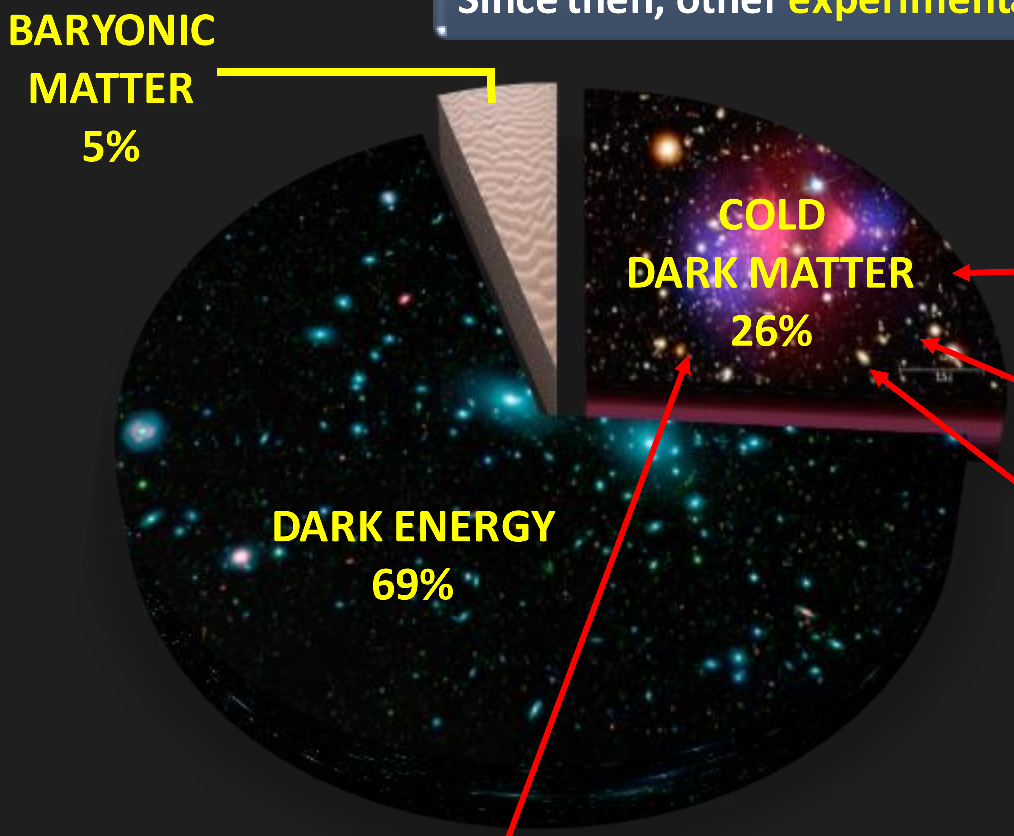
University of Bologna and INFN

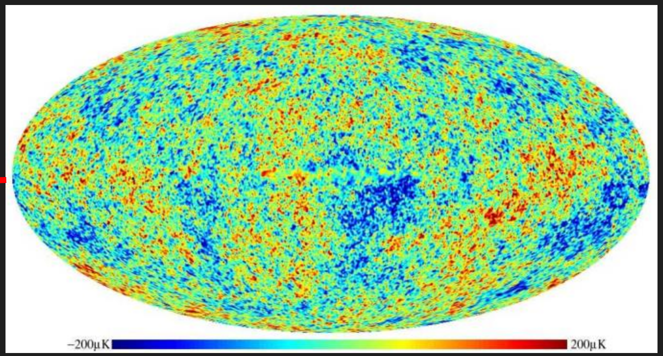
on behalf of the XENON Collaboration

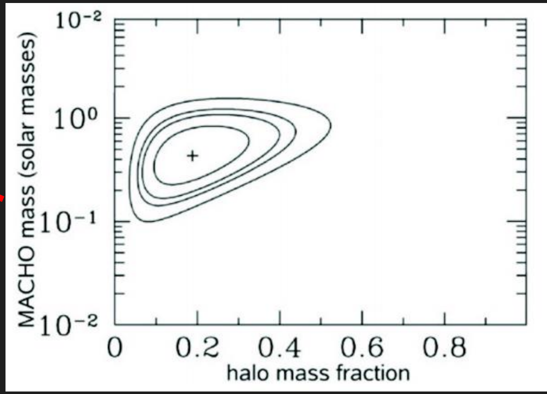
Stockholm Columbia RPI Nikhef Mainz UCSD Muenster MPIK Purdue Coimbra Subatech Bologna LNGS Torino Weizmann NYUAD Rice UCLA Bern Chicago

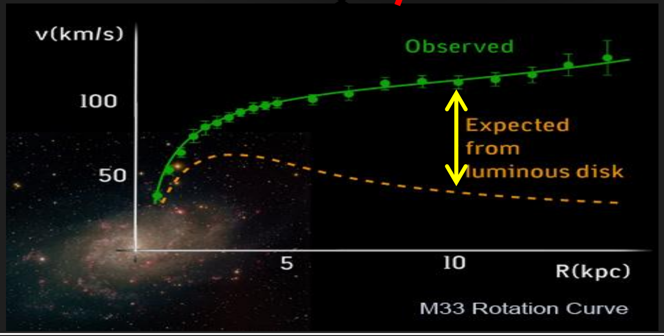
First evidences for DM come from the Zwicky studies on the Coma Cluster

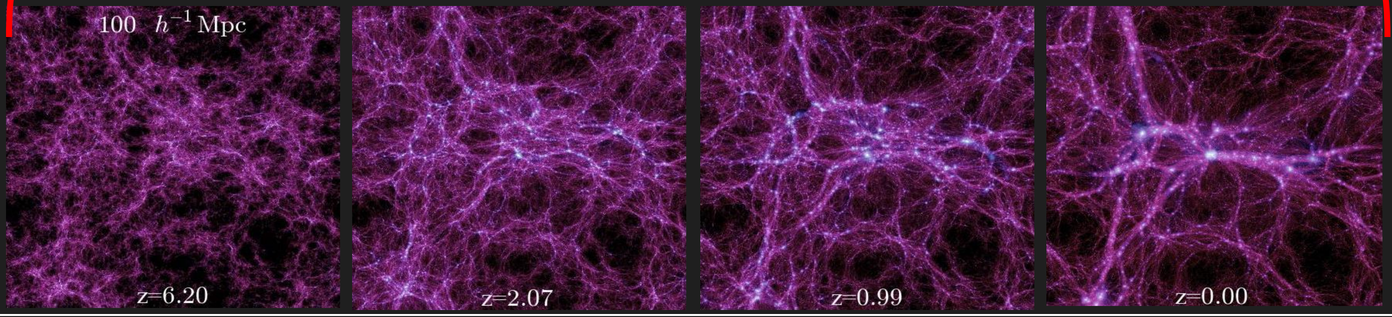
Since then, other **experimental observations** sustained the DM hypothesis:



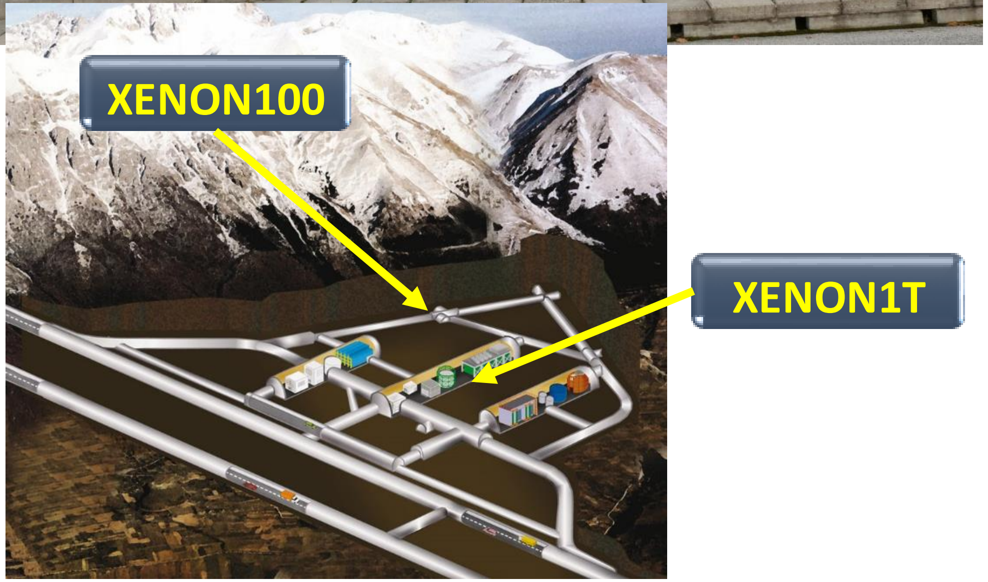






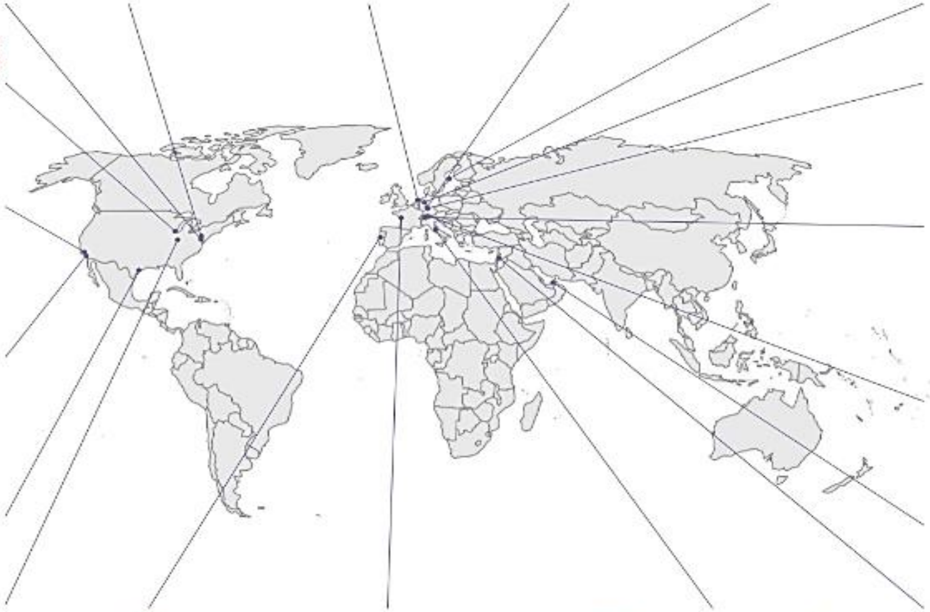


The XENON collaboration



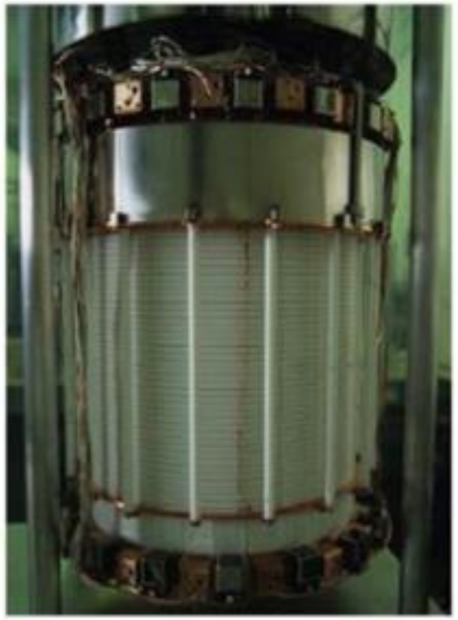
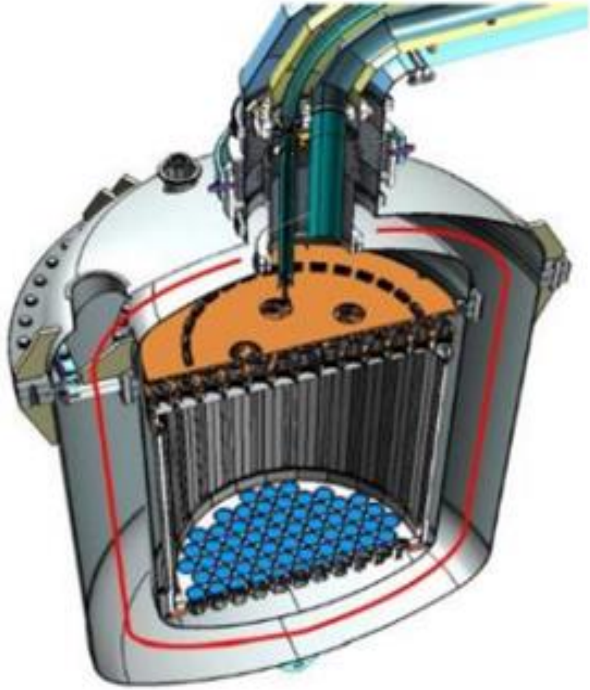
More than 100 scientists from 20 institutions

Columbia
RPI
Nikhef
Mainz
Stockholm
Muenster
Chicago
UCLA
UCSD
Rice
MPIK
Bern
Zurich
NYUAD

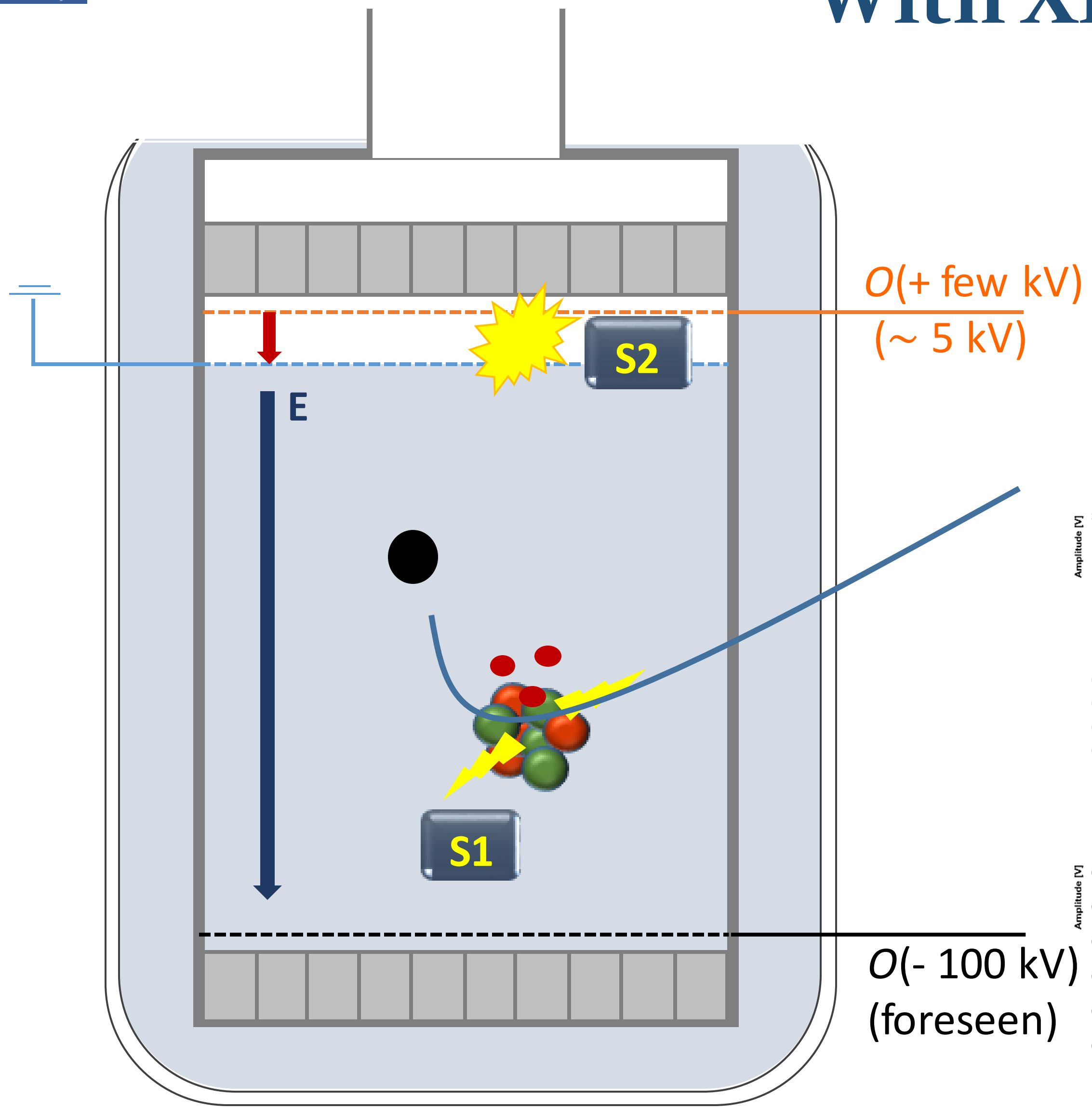


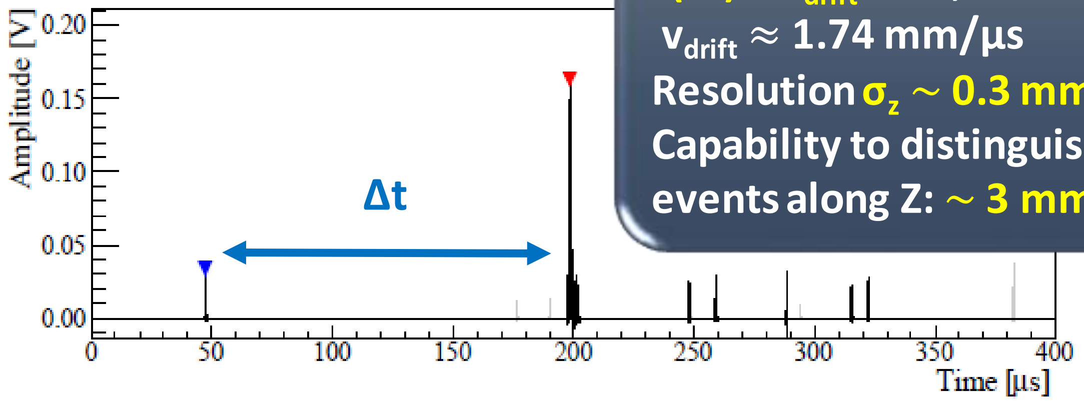
Purdue
Coimbra
Subatech
Bologna
LNGS
Torino
Weizmann

The XENON project

XENON10	XENON100	XENON1T	XENONnT
			
25 kg of LXe	161 kg of LXe	~ 3300 kg of LXe	~ 7000 kg of LXe
Result (2007):	Result (2012):	Projected (2017):	Projected (2022):
$\sigma_{SI} < 8.8 \times 10^{-44}\ cm^2$	$\sigma_{SI} < 2 \times 10^{-45}\ cm^2$	$\sigma_{SI} < 1.2 \times 10^{-47}\ cm^2$	$\sigma_{SI} < 2 \times 10^{-48}\ cm^2$

With XENON "eyes"



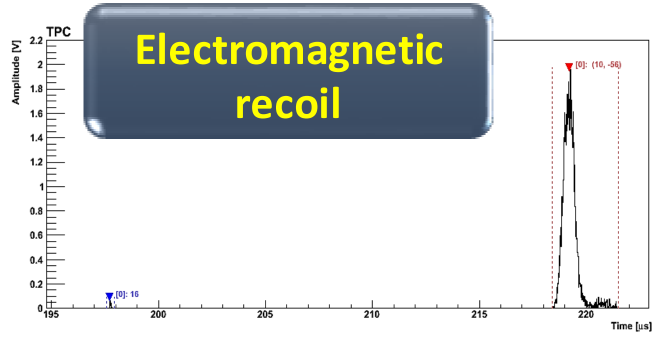


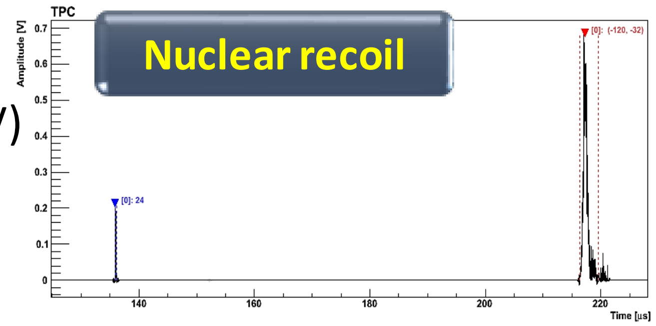
$z(dt) = v_{drift} \cdot \Delta t$;

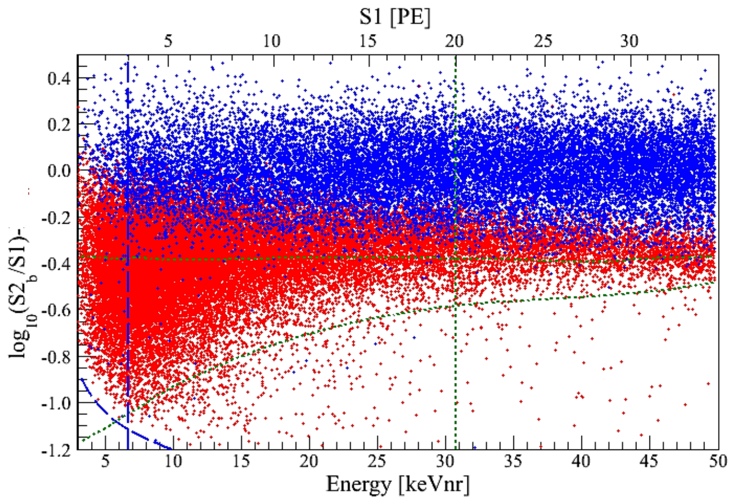
$v_{drift} \approx 1.74$ mm/μs

Resolution $\sigma_z \sim 0.3$ mm

Capability to distinguish two events along Z: ~ 3 mm







The XENON1T experiment

Few main **characteristics:**

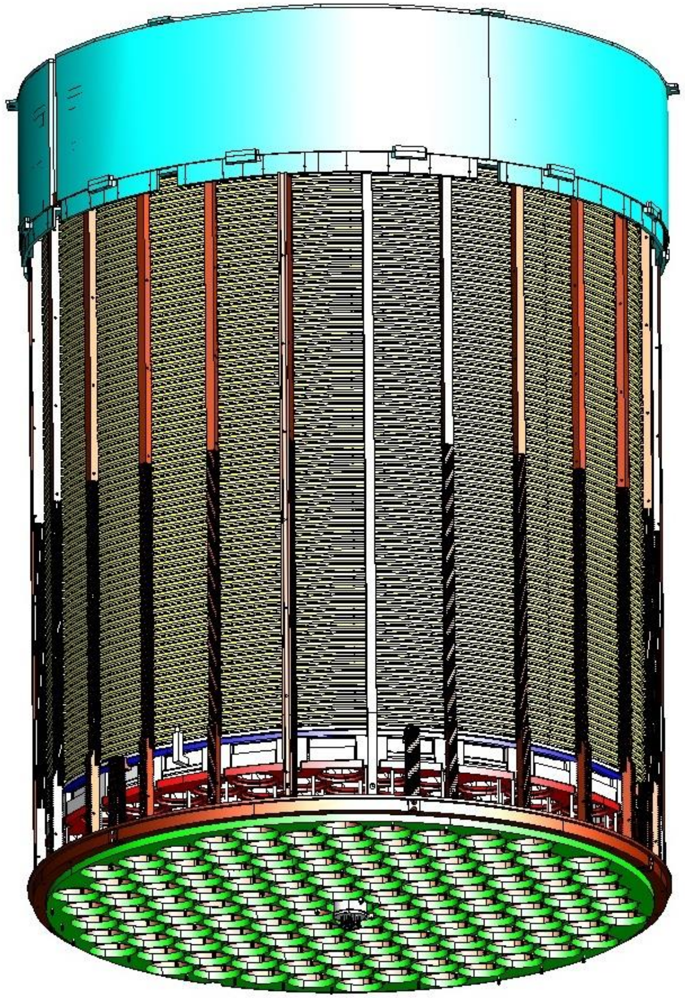
- **Total LXe mass: ~ 3.3 tonnes** ➡ Total LXe **active volume: 2 tonnes** ➡ **Fiducial volume: ~ 1 tonne;**
- **248 3" PMTs** Hamamatsu R11410-21, **35% average QE**;
- field shaping rings produce a **uniform drift field** (0.5 - 1.0 kV/cm)
- $\mathcal{O}$(10 kV/cm) electrons **extraction field**

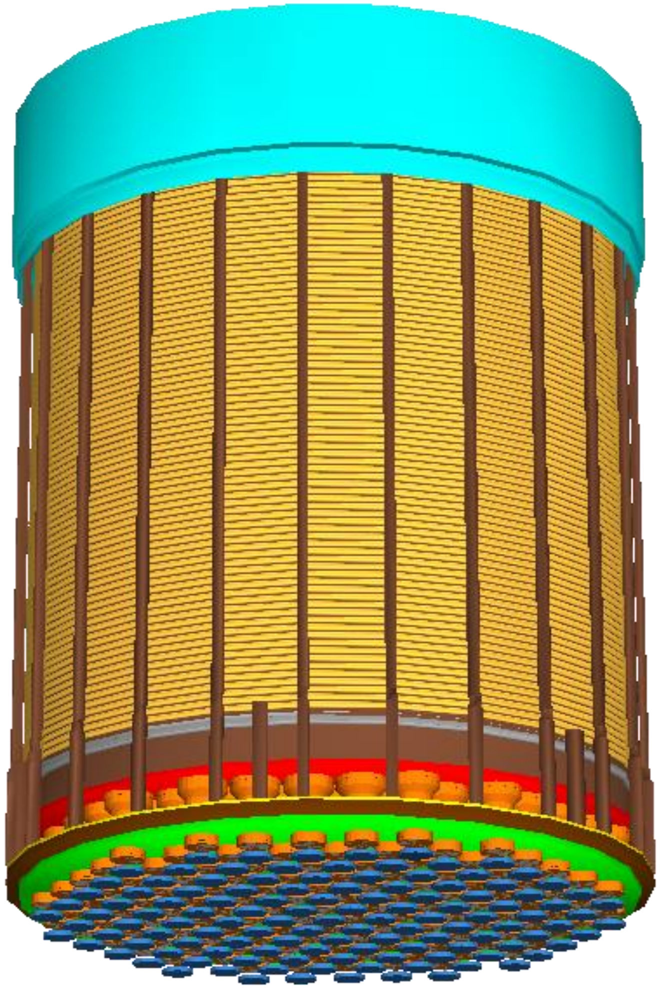
The XENON1T experiment: current status

STEP 1: construct detector geometry

An overview of the whole TPC geometry

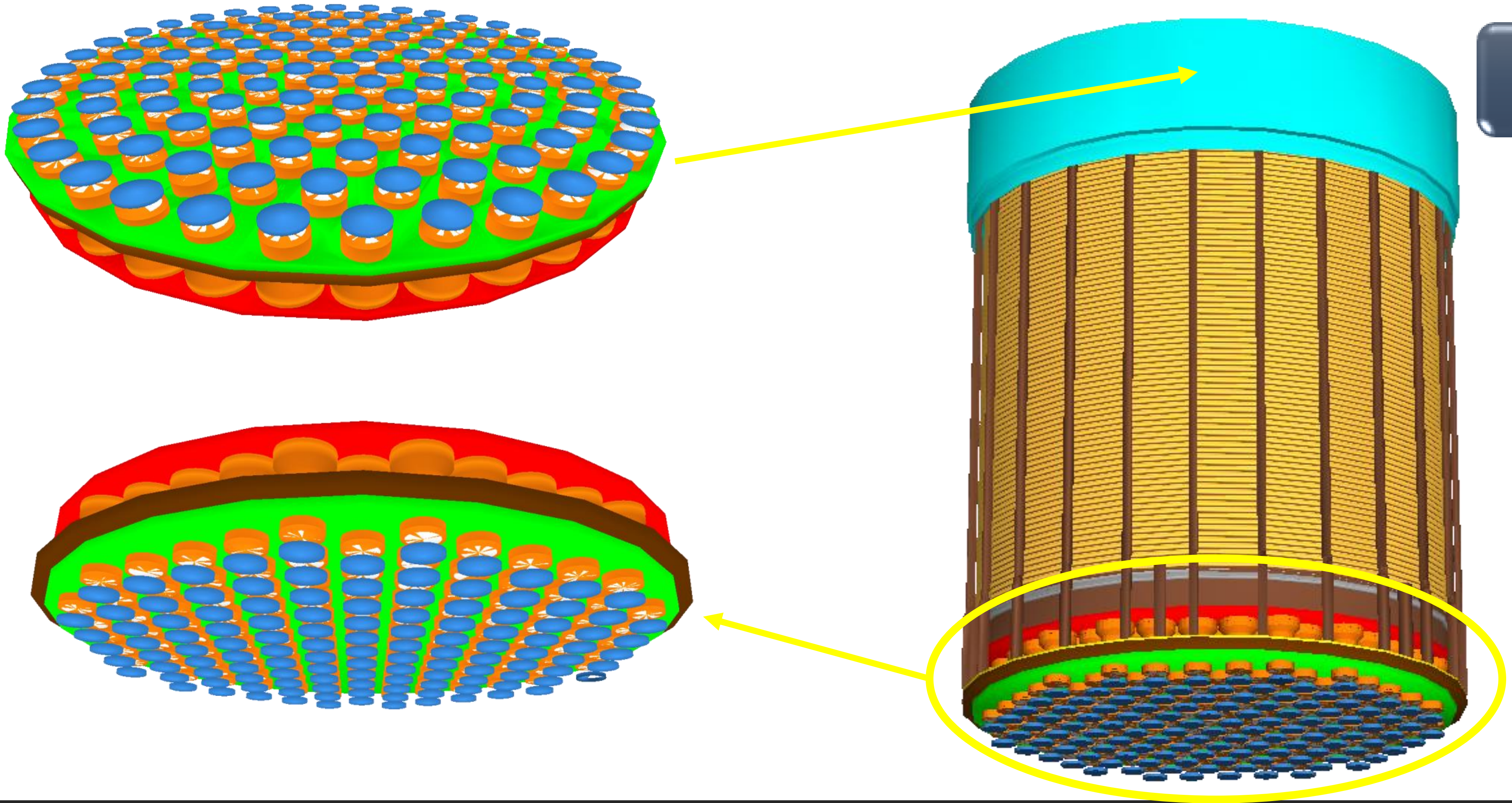
CAD drawings





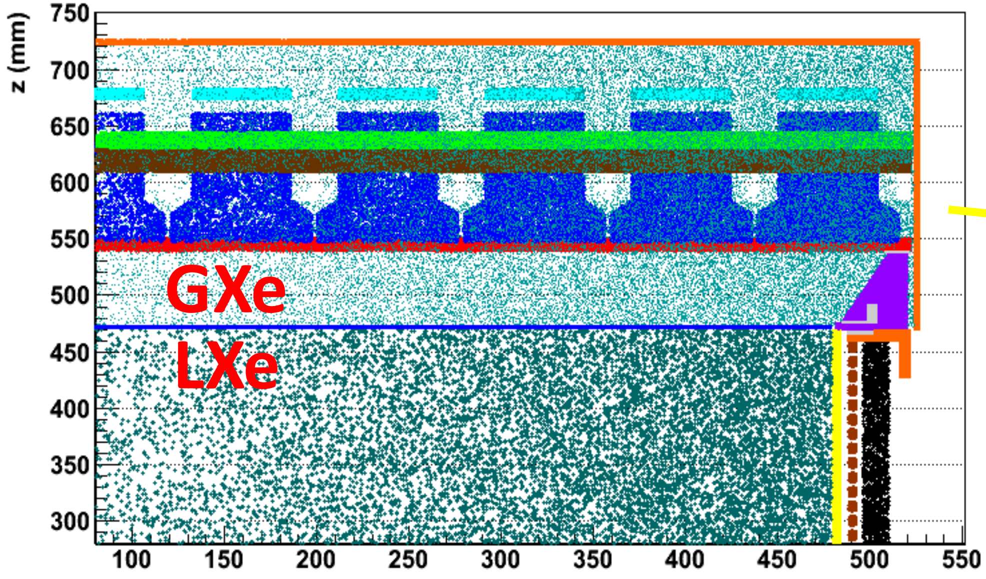
MC implementation (GEANT4)

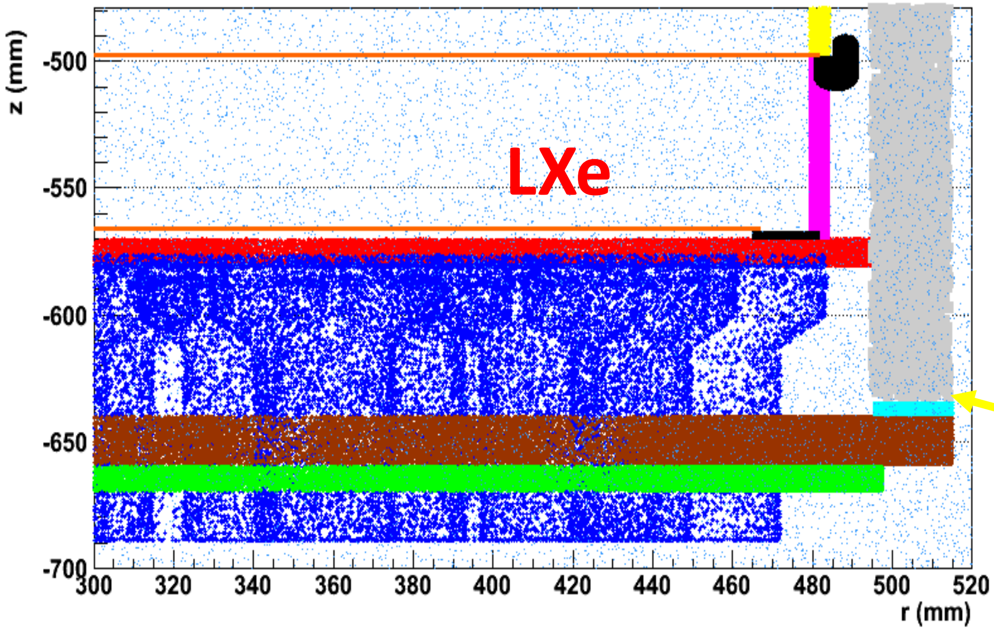
STEP 1: construct detector geometry

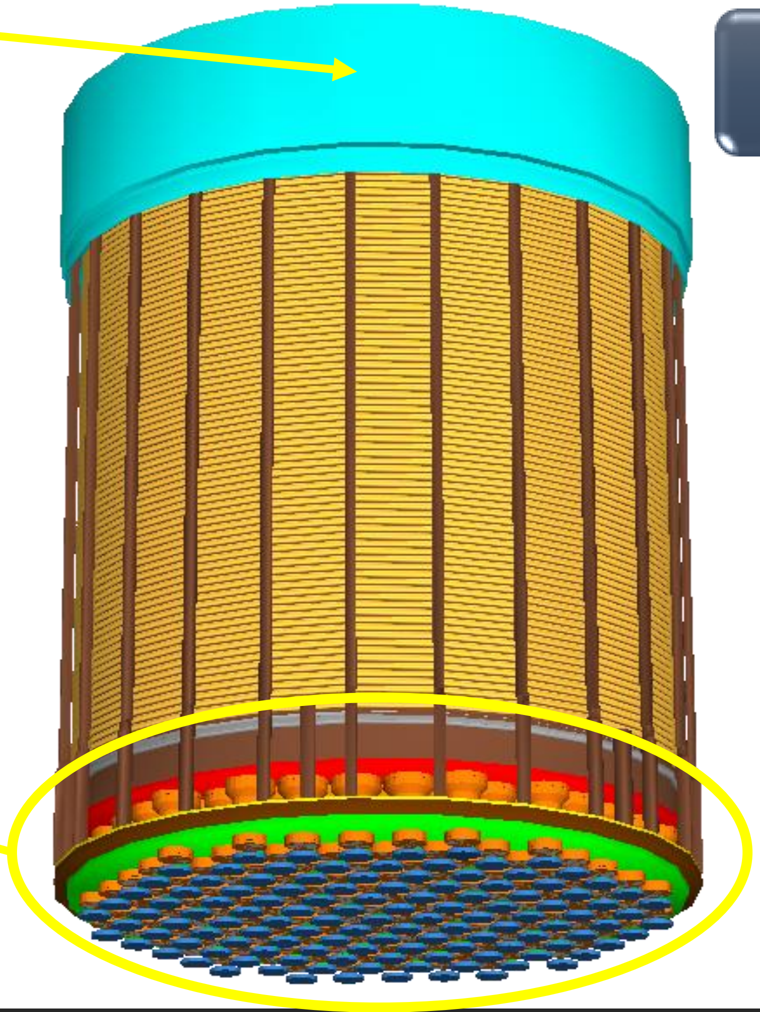


MC implementation
(GEANT4)

STEP 1: construct detector geometry







MC implementation (GEANT4)

STEP 2: identify background sources

- **Electromagnetic background (ER)**
  - Decays from material contaminations
  - Intrinsic sources
- **Nuclear background (NR)**
  - Spontaneous fission
  - Muon-induced neutrons
  - (α, n) reactions
  - Neutrino coherent scatterings

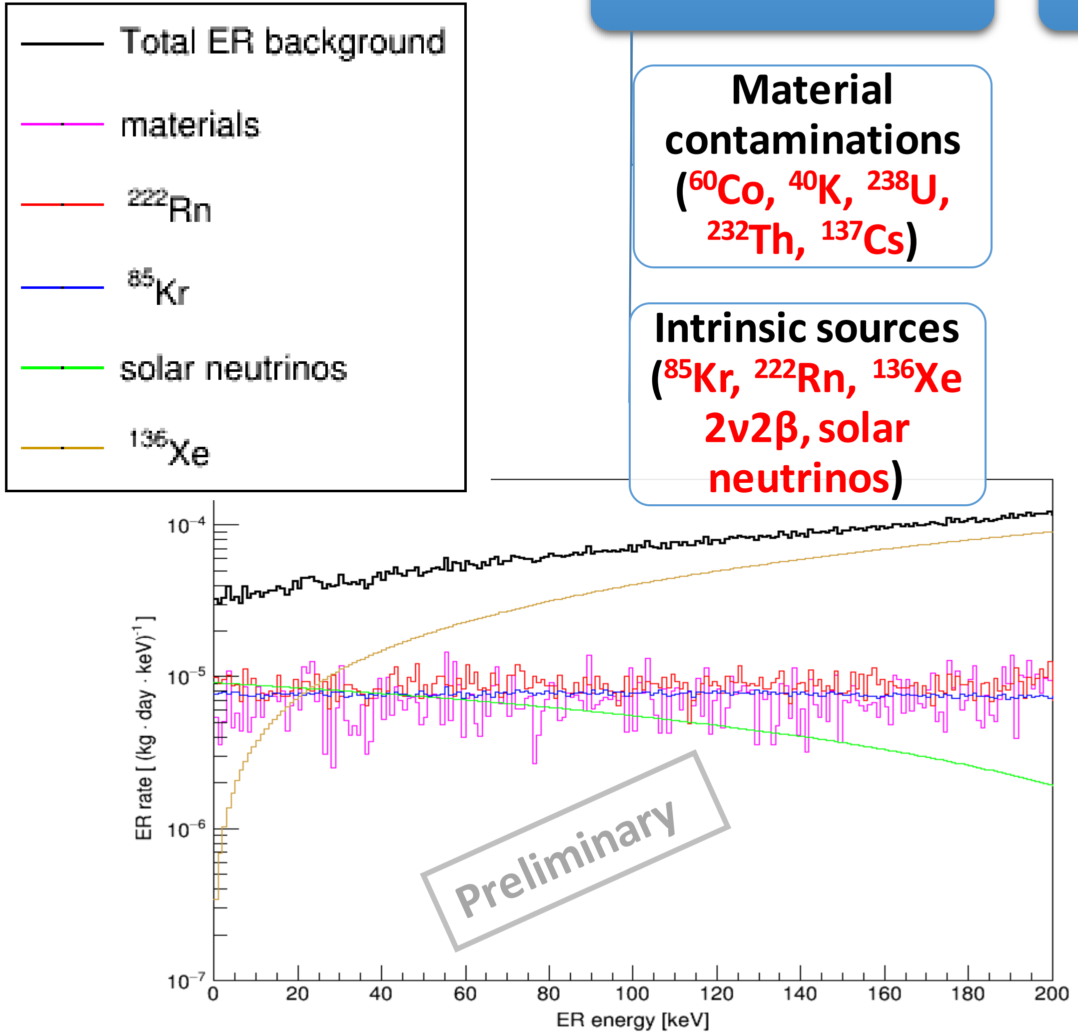
STEP 3: run the simulation & analyze the output

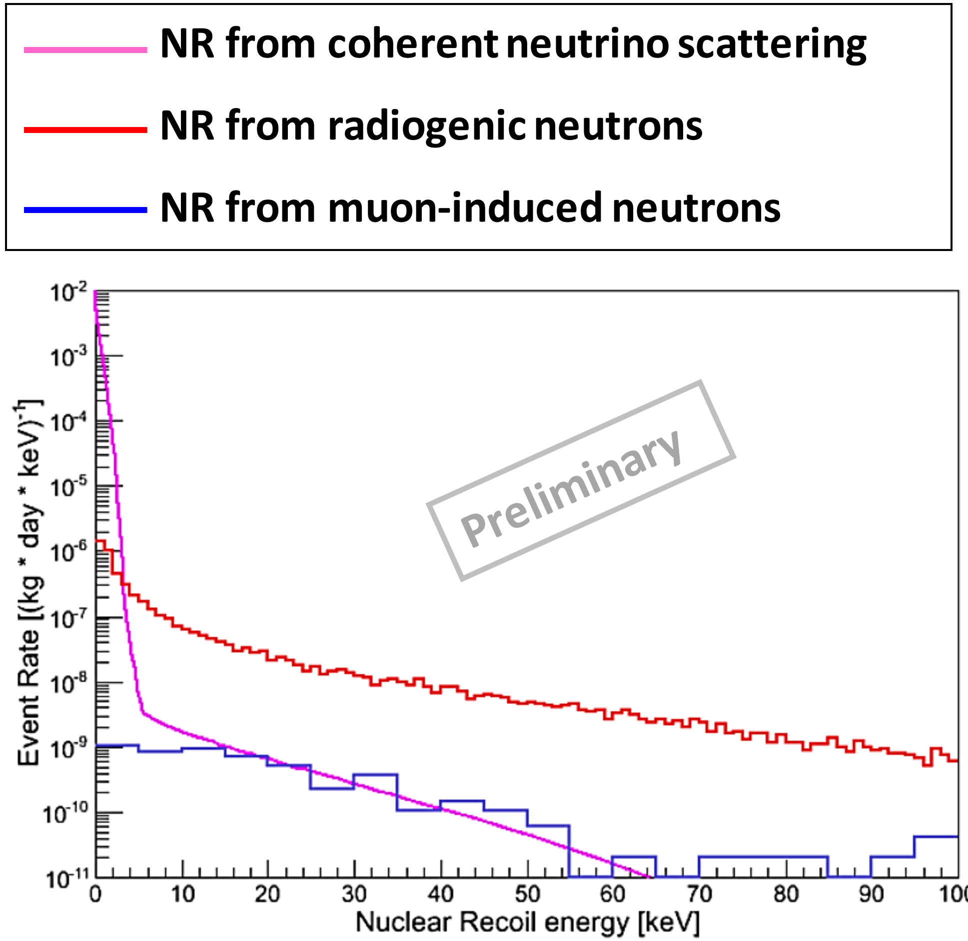
Electromagnetic background (ER)

- **Material contaminations** (^{60}Co, ^{40}K, ^{238}U, ^{232}Th, ^{137}Cs)
- **Intrinsic sources** (^{85}Kr, ^{222}Rn, ^{136}Xe $2\nu2\beta$, solar neutrinos)

Nuclear background (NR)

- **Spontaneous fission** (^{238}U)
- **(α, n) reactions** (^{238}U, ^{235}U, ^{232}Th)
- **Muon-induced neutrons**
- **Neutrino coherent scatterings**

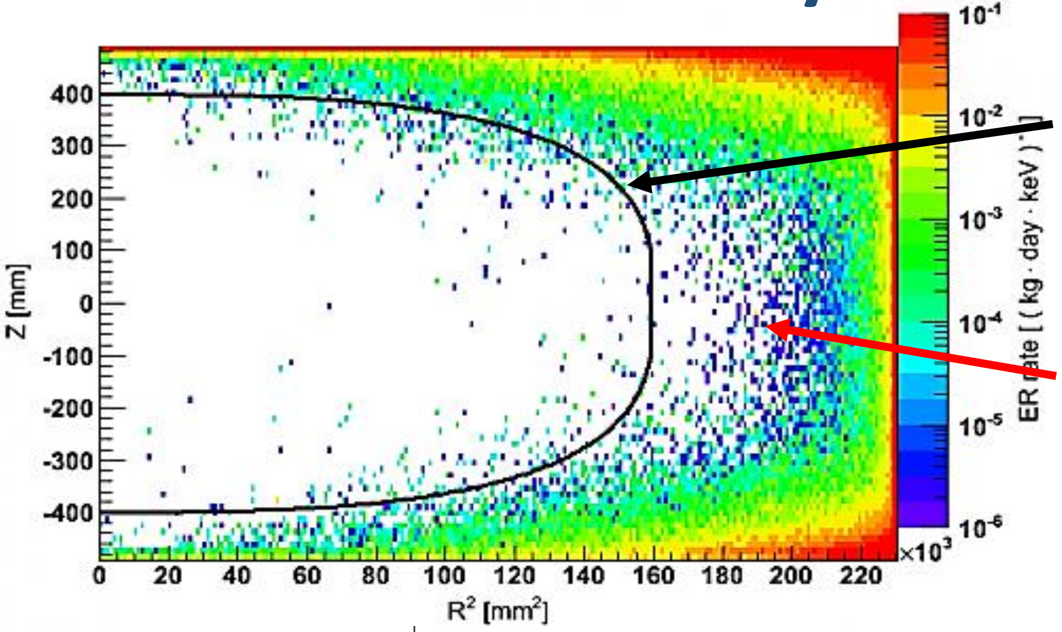




STEP 3: run the simulation & anaylize the output

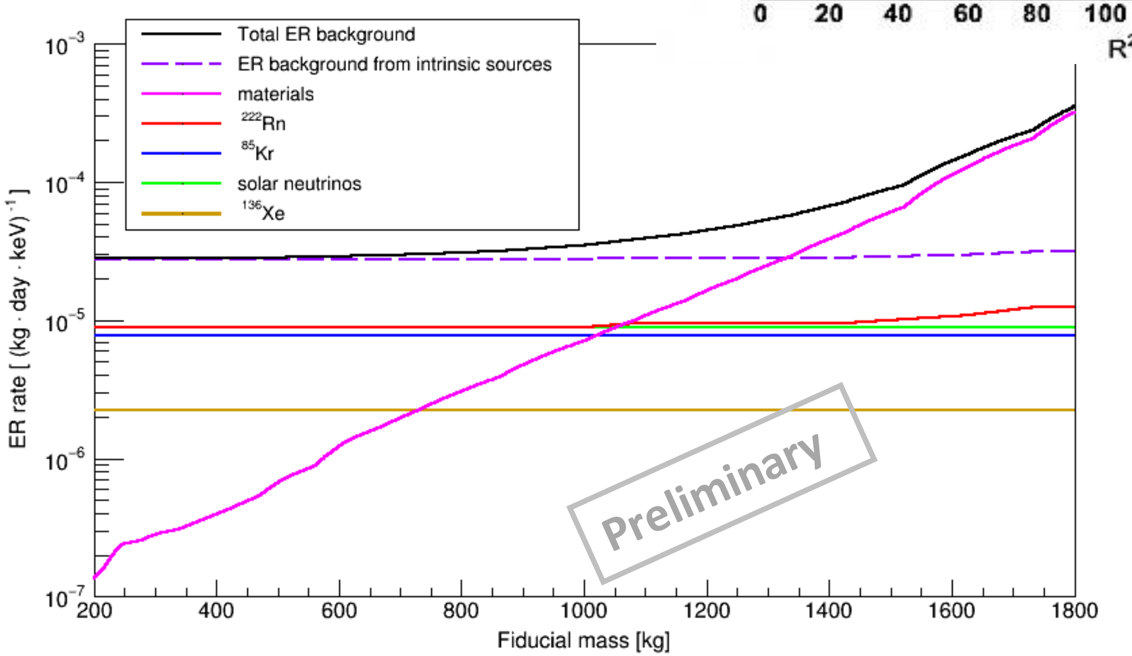
ER background is evaluated in the **[2, 12] keV** energy region

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**



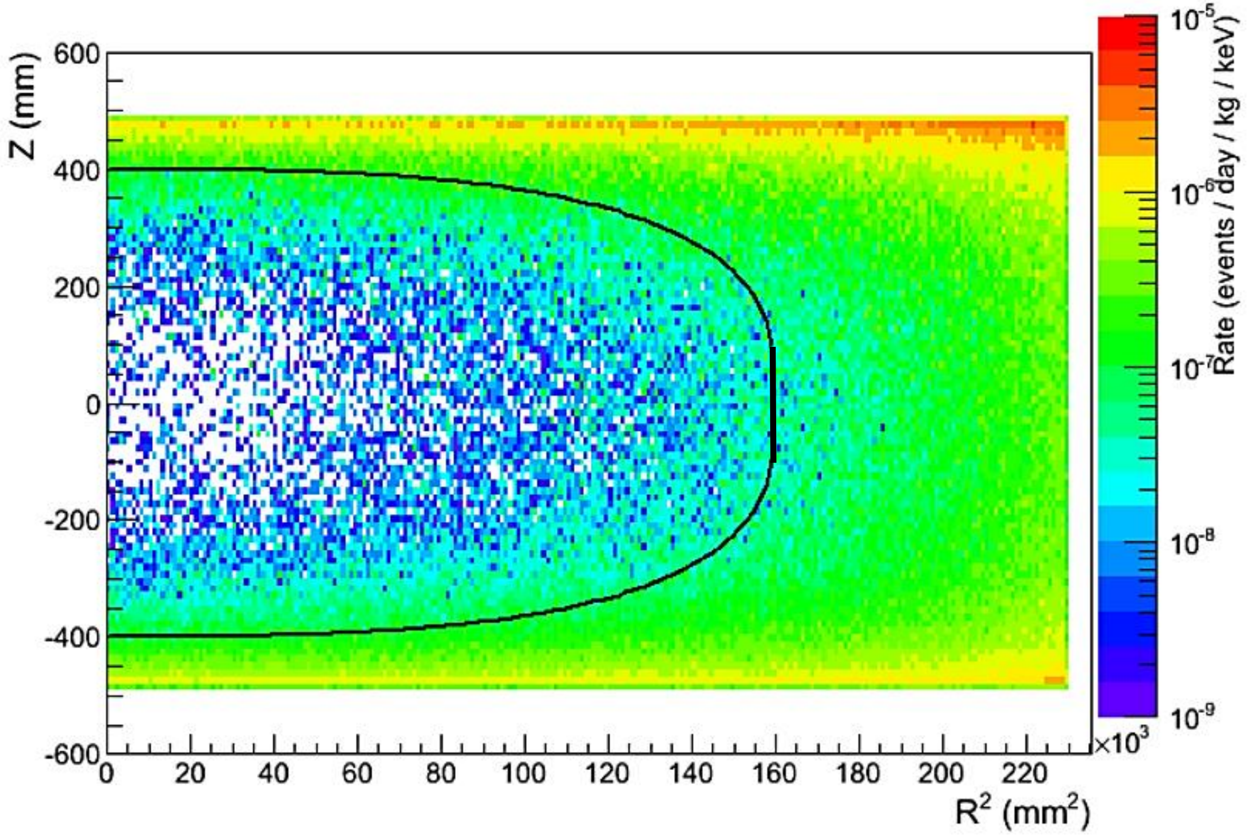
Due to their nature, the intrinsic sources are **uniformly distributed** in the LXe volume

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

STEP 3: run the simulation & anaylize the output

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



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 ev/y, i.e. negligible

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

STEP 4: estimate the background (before conversion)

ER background assuming ER/NR **discrimination level** of **99.75%**

Source	Expecetd events ([2, 12] keV and 1 tonne-year)
materials	$0.07 \pm 10\%$
^{222}Rn (1μB/kg)	$0.08 \pm 20\%$
^{85}Kr	$0.07 \pm 20\%$
$\nu_{\odot}$	$0.08 \pm 2\%$
^{136}Xe	$0.02 \pm 50\%$
Total	**0.32 ± 0.03**

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

Source	Expecetd events ([5, 50] keVr and 1 tonne-year)
materials	$0.22 \pm 20\%$
Muon-induced neutrons	< 0.01
CNNS*	$0.01 \pm 20\%$
Total	**0.23 ± 0.04**

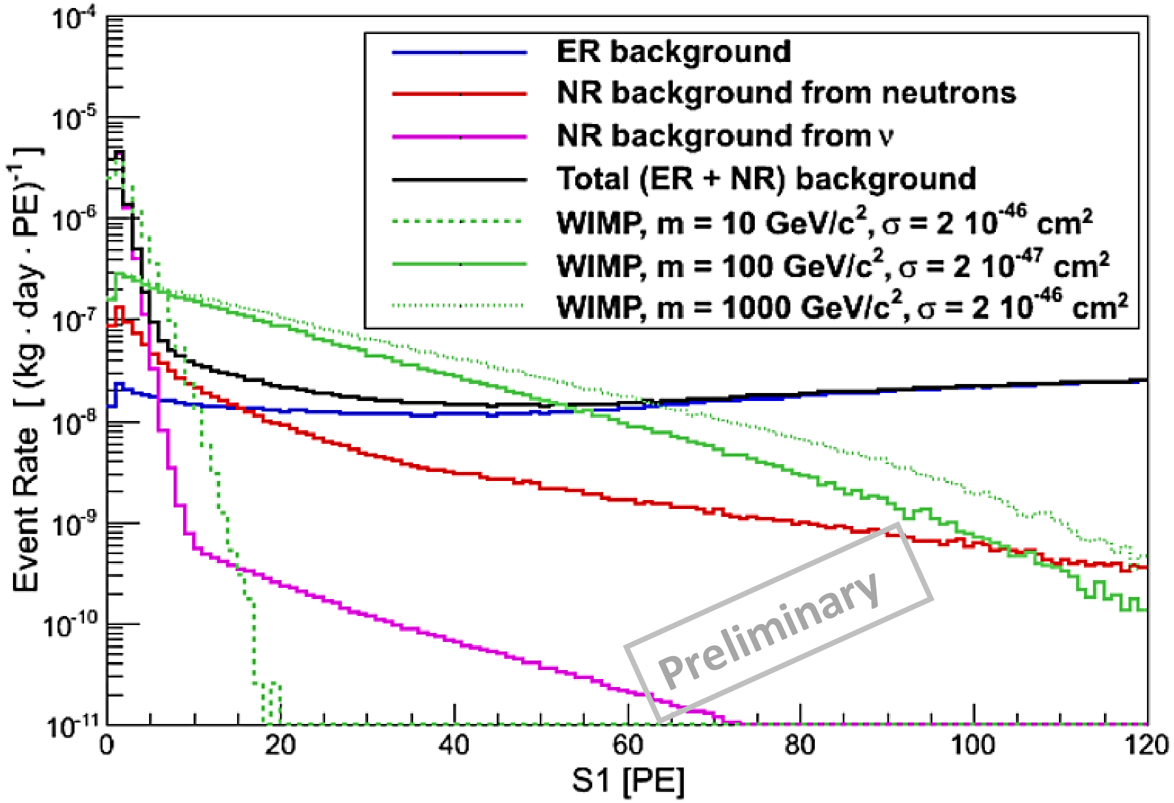
CNNS* given the very steep spectrum of NR from **CNNS**, its **contribution** must be **evaluated after the conversion** into **S1**, because of Poisson fluctuations above threshold

STEP 4: estimate the background (after conversion)

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)

We assumed 99.75% ER/NR discrimination and 40% NR acceptance



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	0.23
Total	**0.77**

Conclusion

- in [5, 50] keVr and in 1 tonne fiducial volume the main contributions to the NR background comes from radiogenic neutrons from detector materials and from CNNS
- given the very steep spectrum of NR from CNNS, its background contribution must be evaluated after the conversion into S1, because of Poisson fluctuations above threshold
- thanks to the use of the Muon Veto, the background contribution of muon-induced neutrons is $\lesssim$ 0.01 ev/y, i.e. negligible
- in [2, 12] keV and in 1 tonne fiducial volume the main contributions to the ER background come from ^{222}Rn, solar neutrinos and ^{85}Kr
- in [2, 12] keV and for fiducial volumes larger than 1400 kg, the background from detector materials becomes dominant
- in the energy range [20, 300] keV, in 1 tonne fiducial volume, the $2\nu2\beta$ decay of the ^{136}Xe becomes dominant while above 300 keV, the detector materials give the highest contribution
- in [3,70] PE, assuming a discrimination level for ER of 99.75% and a 40% acceptance for NR, the XENON1T background in 1 tonne FV is:

$$(0.55 \pm 0.05)\ \mathrm{ev/(t^*y)}$$

- in [3,70] PE, the XENON1T background from CNNS, in 1 tonne FV, is:

$$(0.23 \pm 0.05)\ \mathrm{ev/(t^*y)}$$

Xe XENON Dark Matter Project

Conclusion

- ✓ in [5, 50] keVr and in 1 tonne fiducial volume the main contributions … round comes from radiogenic neutrons from detector materials and from CN…
- ✓ thanks to the use of the Muon Veto, the background co… trons is ≲ 0.01 ev/y, i.e. negligible
- ✓ given the very steep spectrum of NR from C… uated after the conversion into S1, because o…
- ✓ in [2, 12] keV and in 1 tonne fid… ckground come from ^{222}Rn, solar neutrin…
- ✓ in [2, 12] keV and f… ground from detector materials becomes do…
- ✓ in th… ume, the 2ν2β decay of the ^{136}Xe becomes … rials give the highest contribution
- ✓ … vel for ER of 99.75% and a 40% acceptance for NR, the … is:

$$(0.55 \pm 0.05)\ \mathrm{ev/(t^{*}y)}$$

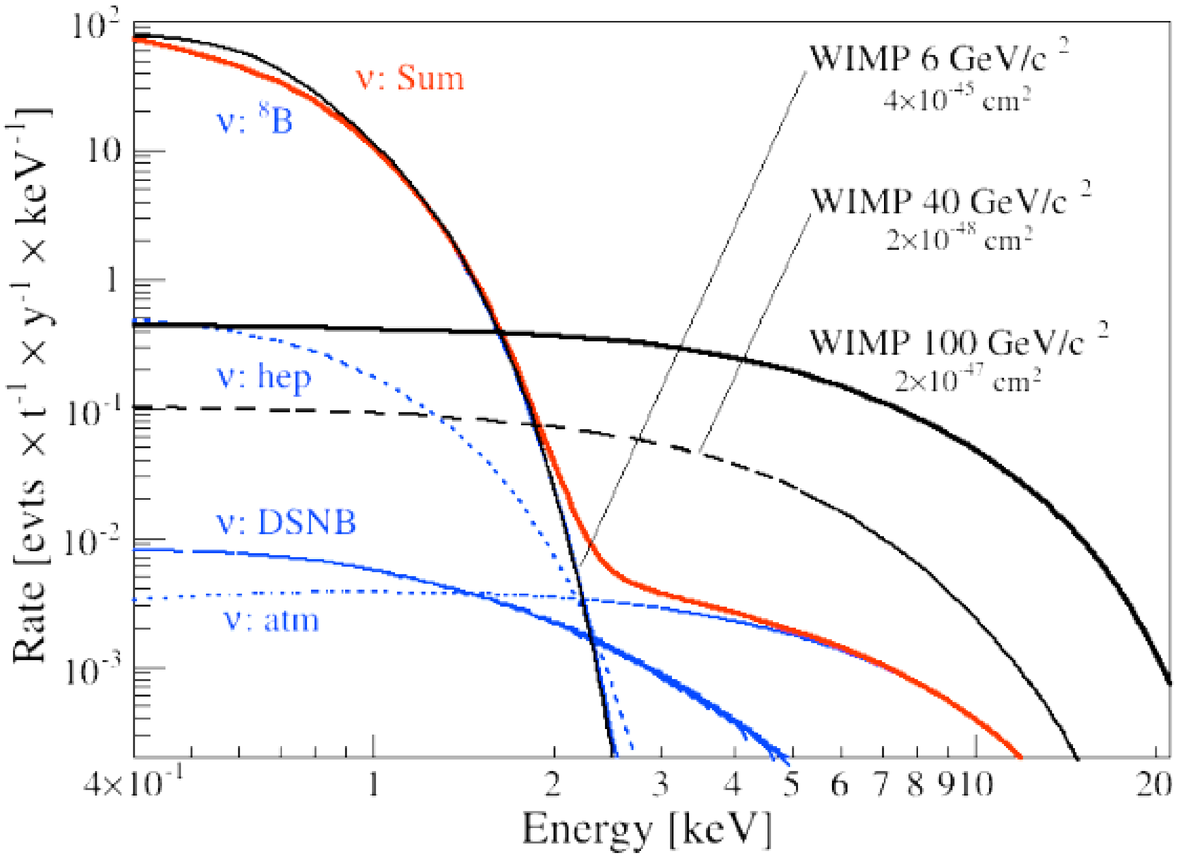
- ✓ in [… NON1T background from CNNS, in 1 tonne FV, is:

$$(0.23 \pm 0.05)\ \mathrm{ev/(t^{*}y)}$$

Thank you!!!

Backup slides

STEP 2: identify background sources



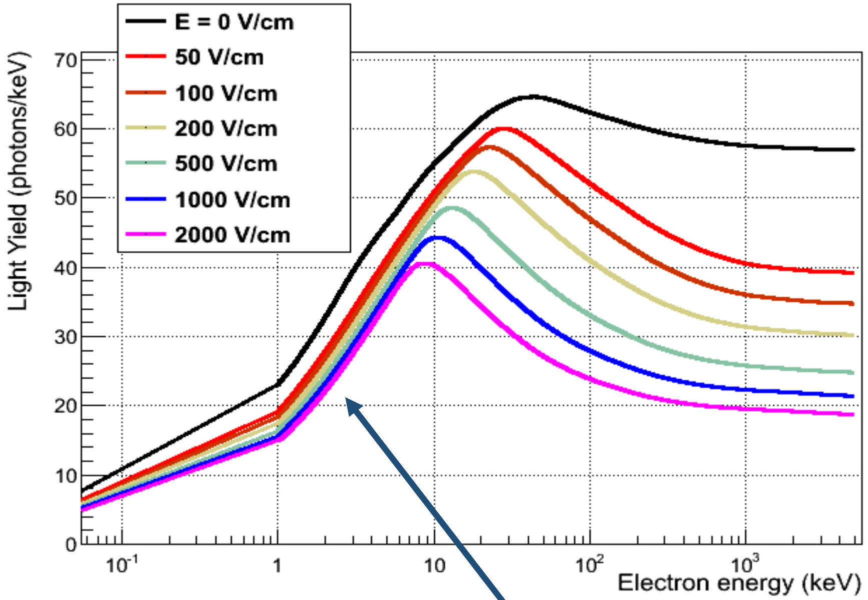
NR from ^{8}B solar neutrinos (nucleus coherent scattering): below $\sim 4 \cdot 10^{-45} cm^2$

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

STEP 4: estimate the background

ER

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



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

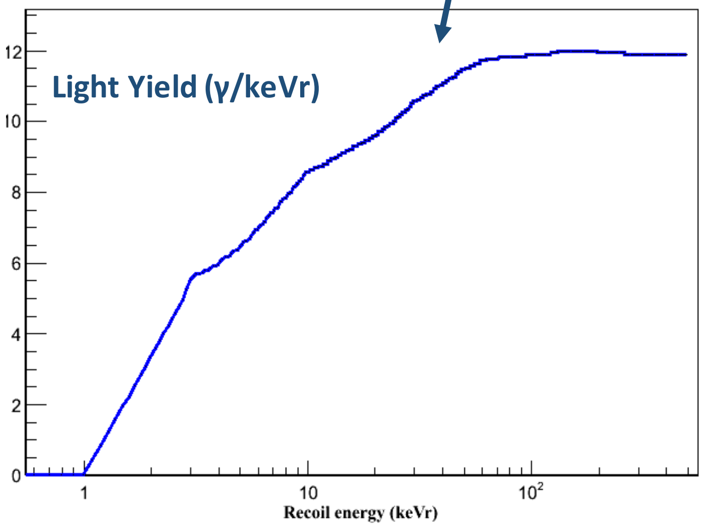
$$N_{phot} = \text{Binomial}(N_{quanta},\ f_{light})$$

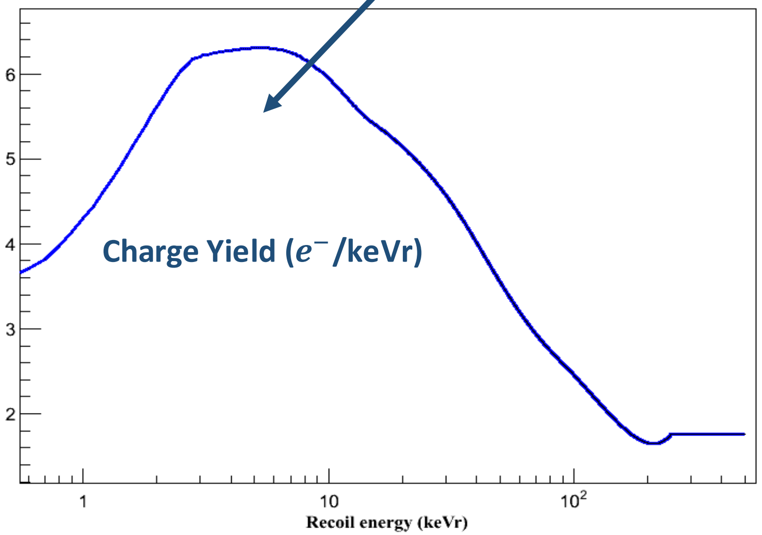
$$N_{e^-} = N_{quanta} - N_{phot}$$

NR

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

$$\langle N_{e^-} \rangle = E \cdot Q_y(E)$$





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

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

$$N_{phot} = Binomial(N_{quanta},\ \langle N_{phot} \rangle / \langle N_{quanta} \rangle)$$

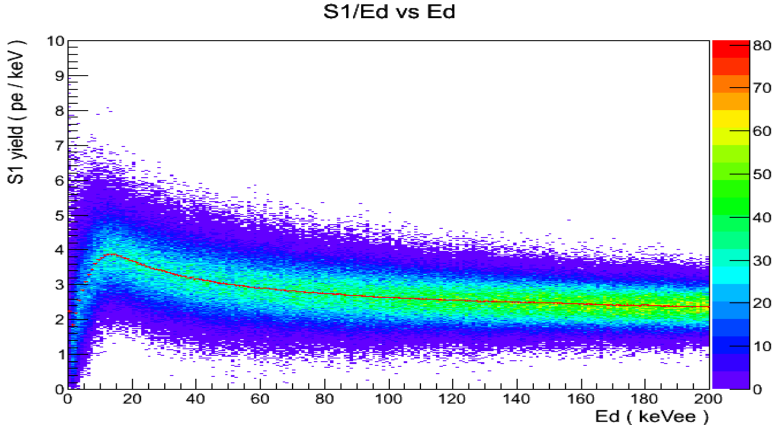
$$N_{e^-} = N_{quanta} - N_{phot}.$$

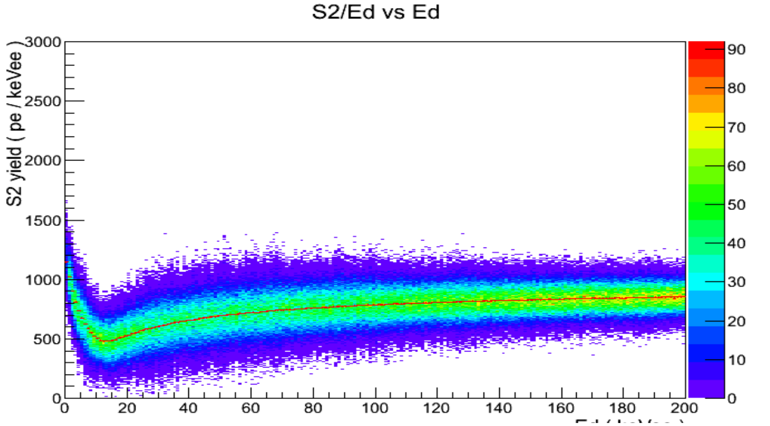
STEP 4: estimate the background

$$DE = LCE \cdot QE \cdot CE$$
$$DP = \mathrm{Binomial}(N_{phot},\ DE)$$
$$S1 = \mathrm{Gauss}(DP,\ 0.4 \cdot \sqrt{DP})$$

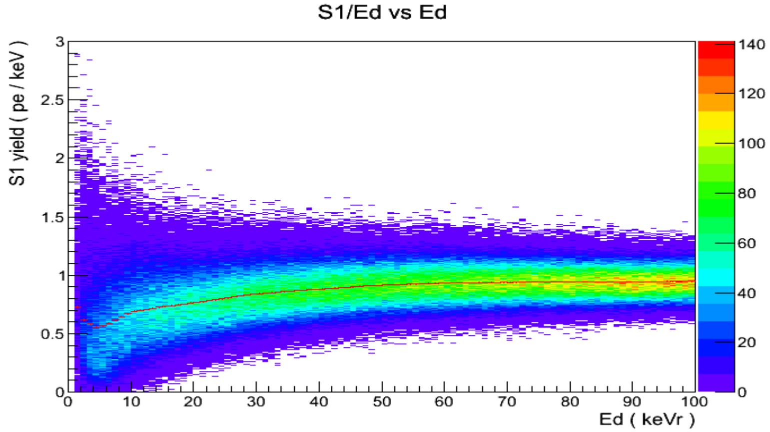
$$Prob = e^{-t/e_{life}},$$
$$N_{e^-}^{surv} = \mathrm{Binomial}(N_{e^-},\ Prob)$$
$$S2 = \mathrm{Gauss}(N_{e^-}^{surv} \cdot 20,\ 7 \cdot \sqrt{N_{e^-}^{surv}})$$

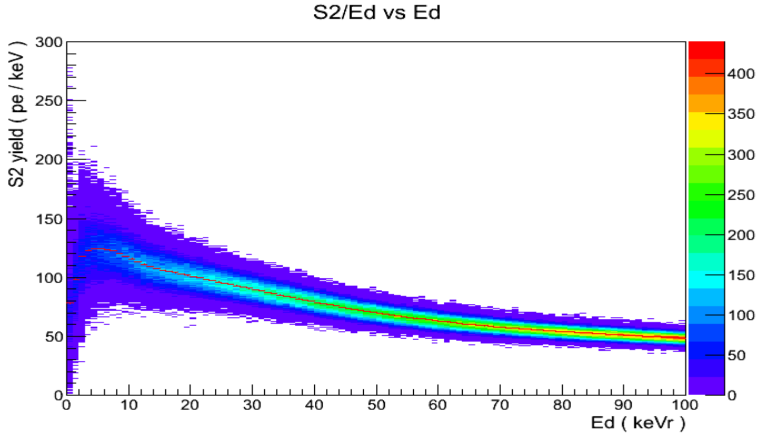
ER





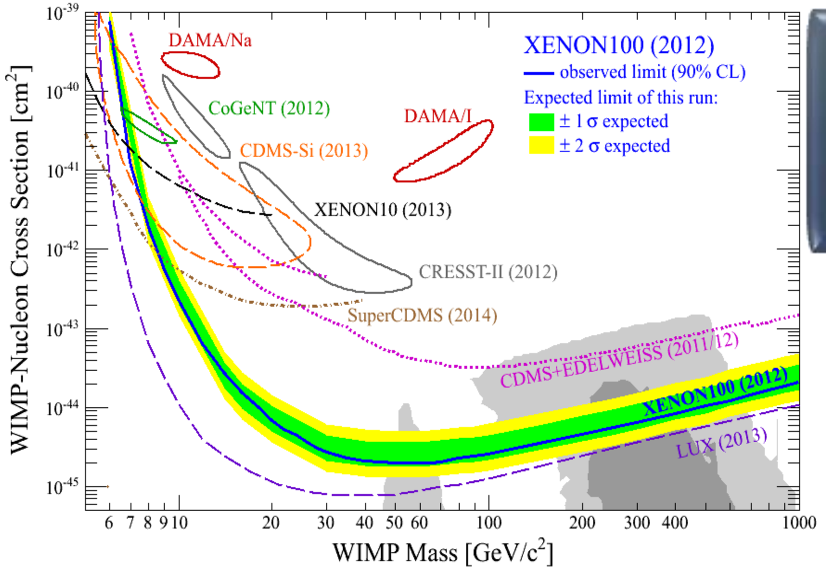
NR





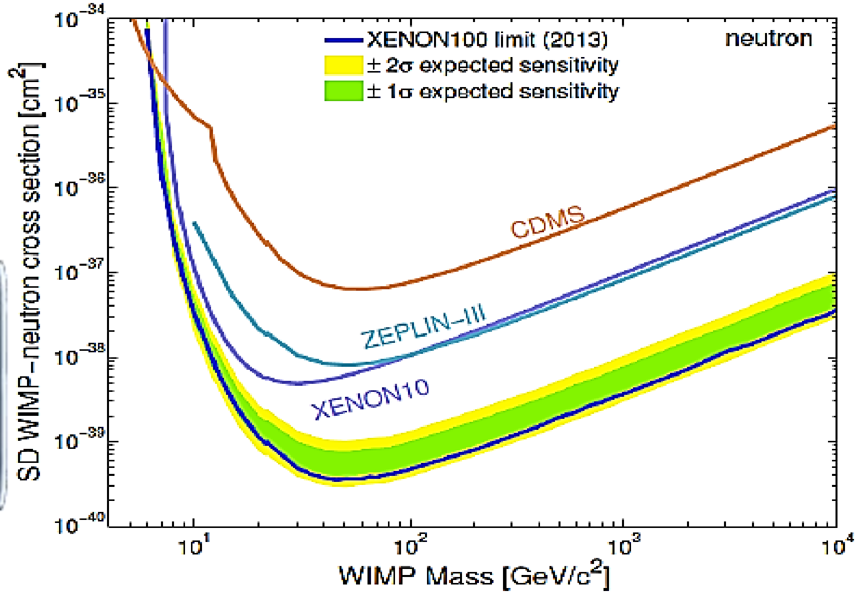
XENON Dark Matter Project

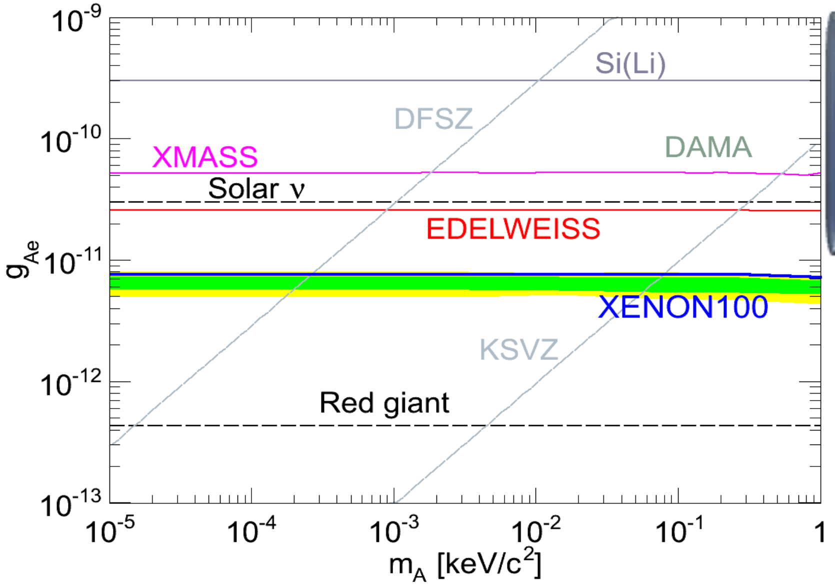
XENON100 RUN10 results (2012 - 2014)



WIMP SI coupling:
$\sigma \leq 2.0 \times 10^{-45}$ cm^2 (90% CL)
E. Aprile et al., Phys. Rev. Lett. 109, 181301 (2012)

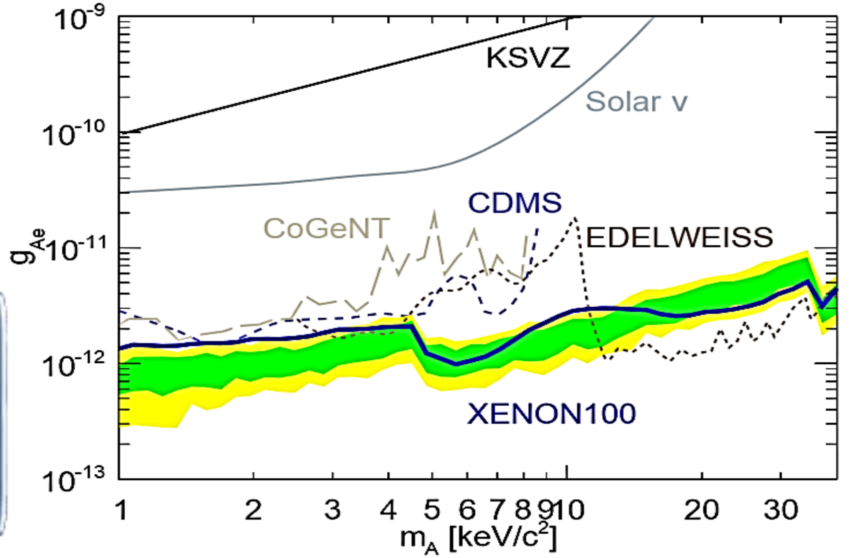
WIMP SD coupling:
$\sigma_n \leq 3.5 \times 10^{-40}$ cm^2 (90%CL)
E. Aprile et al., Phys. Rev. Lett. 111, 021301 (2013)





AXION - electron coupling:
$g_{Ae} \leq 7.7 \cdot 10^{-12}$ (90% CL)
E. Aprile et al., Phys. Rev. D 90, 062009 (2014)

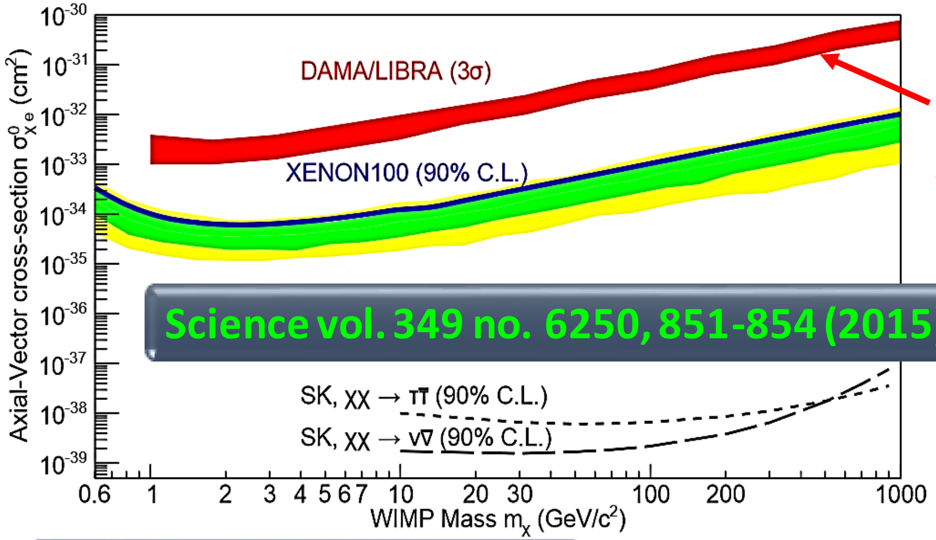
ALPs - electron coupling:
$g_{Ae} \leq 1 \cdot 10^{-12}$ (90% CL)
E. Aprile et al., Phys. Rev. D 90, 062009 (2014)



XENON100 latest results (2015)

DAMA/LIBRA experiment observes annual modulation interpretable as due to leptophilic DM particles

From XENON100 data (PL), it is excluded DM coupling to electrons, through axial-vector interactions, with $\sigma \geq 6 \cdot 10^{-35}$ cm² for WIMP masses above 2 GeV/c²



DAMA/LIBRA allowed region

Science vol. 349 no. 6250, 851-854 (2015)

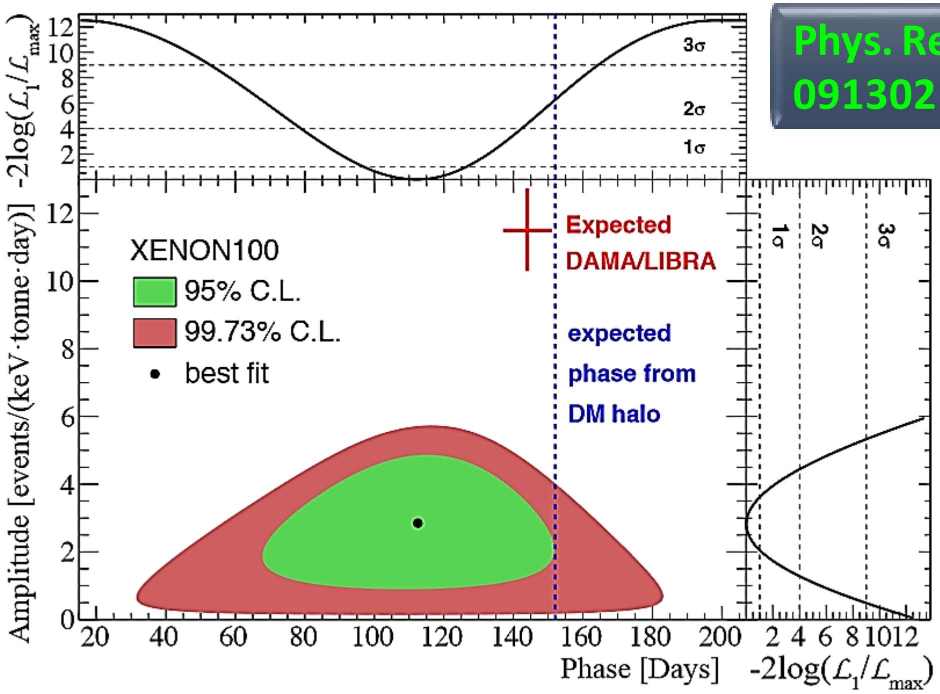
From the integral of the recoil spectrum, different DM models can be excluded as explanation of the DAMA/LIBRA modulation signal

MODEL	EXCLUSION (σ)
A - V	4.4
Mirror DM	3.6
Luminous DM	4.6

Unbinned PL analysis of ER data testing periodic signal hypotheses against null hypothesis (A=0)

Fixing a period of 1 year:

- Standard DM halo phase is disfavored by 2.5σ
- Assuming A - V coupling of WIMPs to electrons, DAMA/LIBRA annual modulation is excluded at 4.8 σ



Phys. Rev. Lett. 115, 091302 (2015)