The XENON Program Highlights

Christopher Tunnell (Rice University)

On behalf of the XENON collaboration

@AstroTunnell @XENON1T

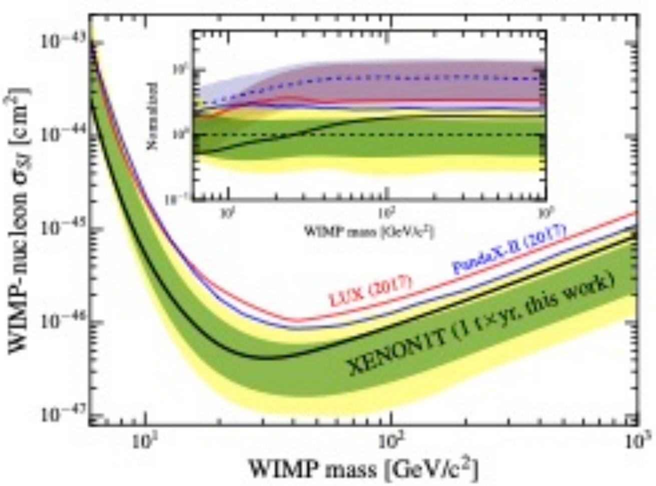
The XENON Program Highlights

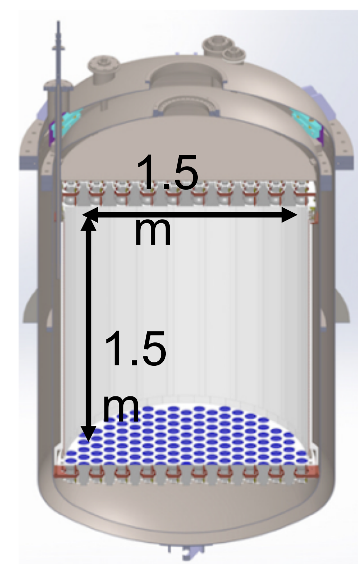
Three parts of talk

1T WIMP Search

1T's 4.4σ excess

nT Future

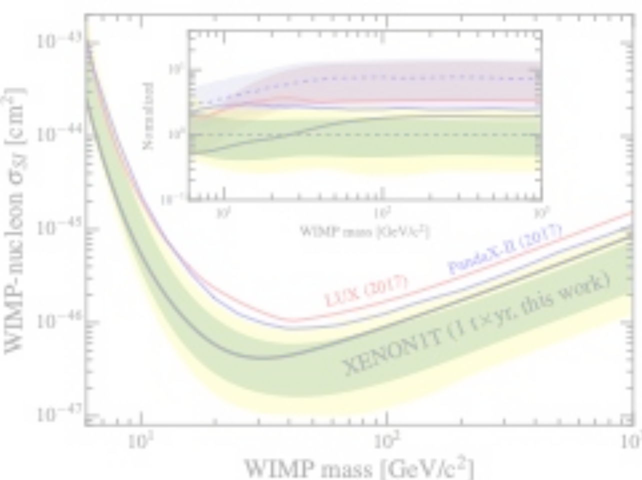




The XENON Program Highlights

But first: what is XENON?

1T WIMP Search



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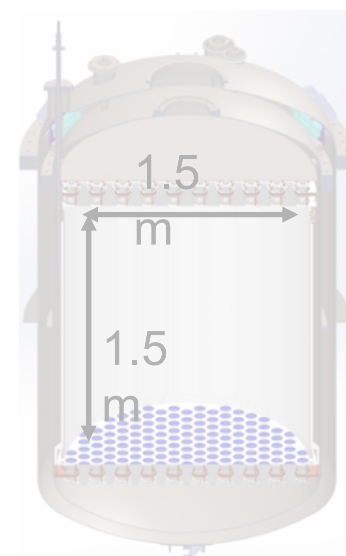


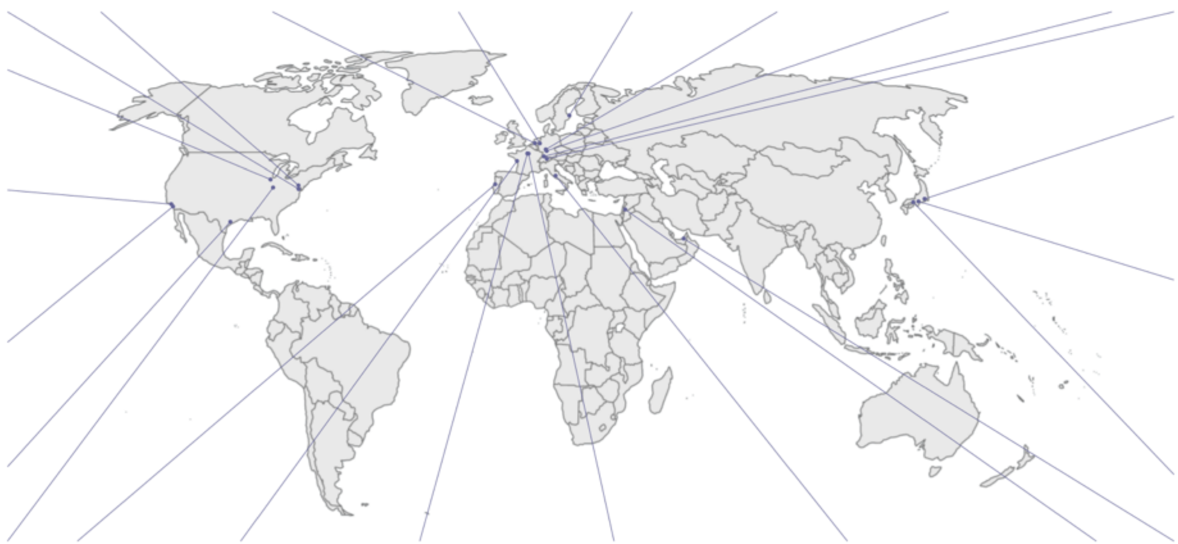
Map of collaborations

XENON

Columbia · RPI · Nikhef · Muenster · Stockholm · Mainz · MPIK, Heidelberg · Freiburg · Zurich

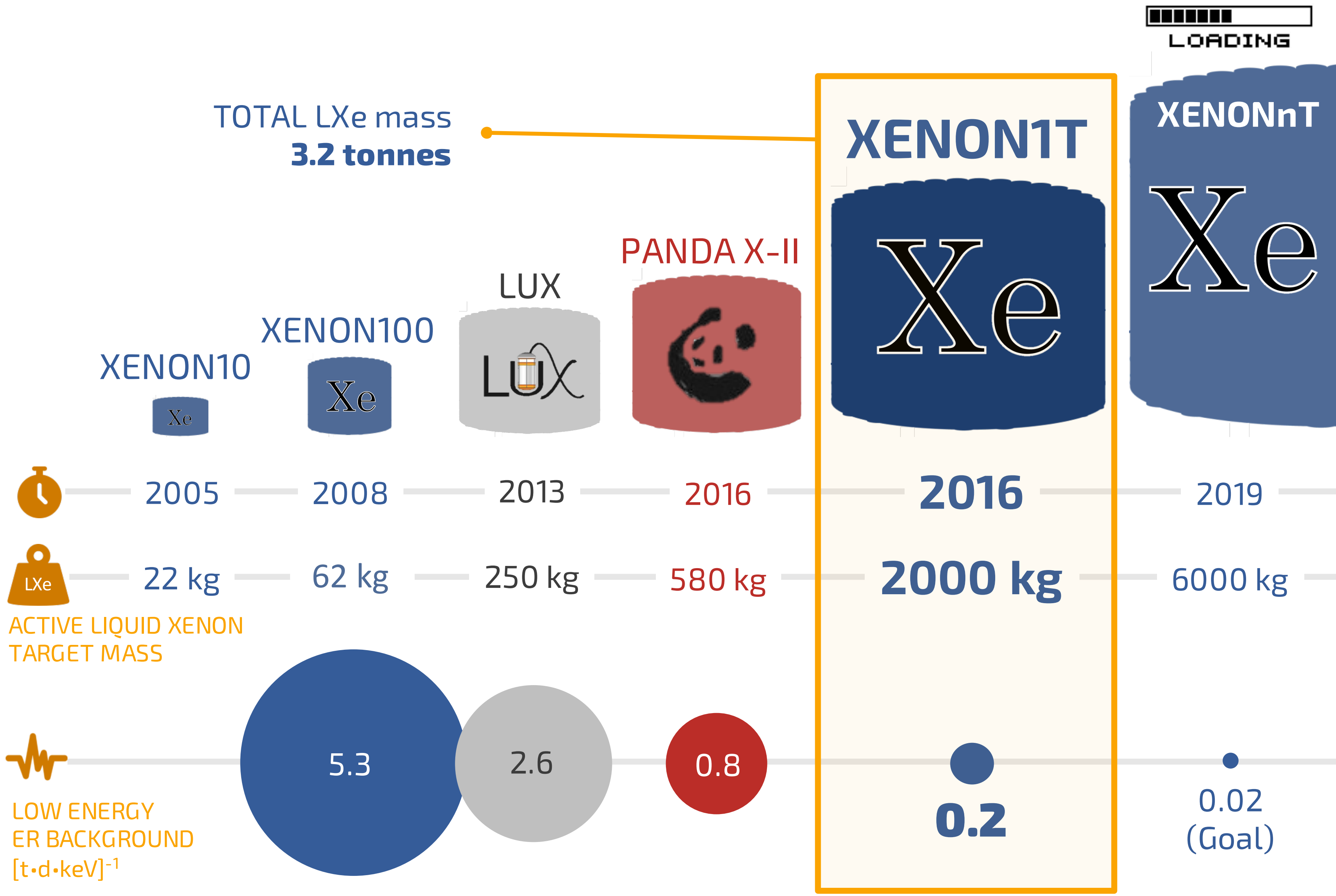
Chicago · UCLA · UCSD · Rice · Purdue

Tokyo · Nagoya · Kobe · NYUAD



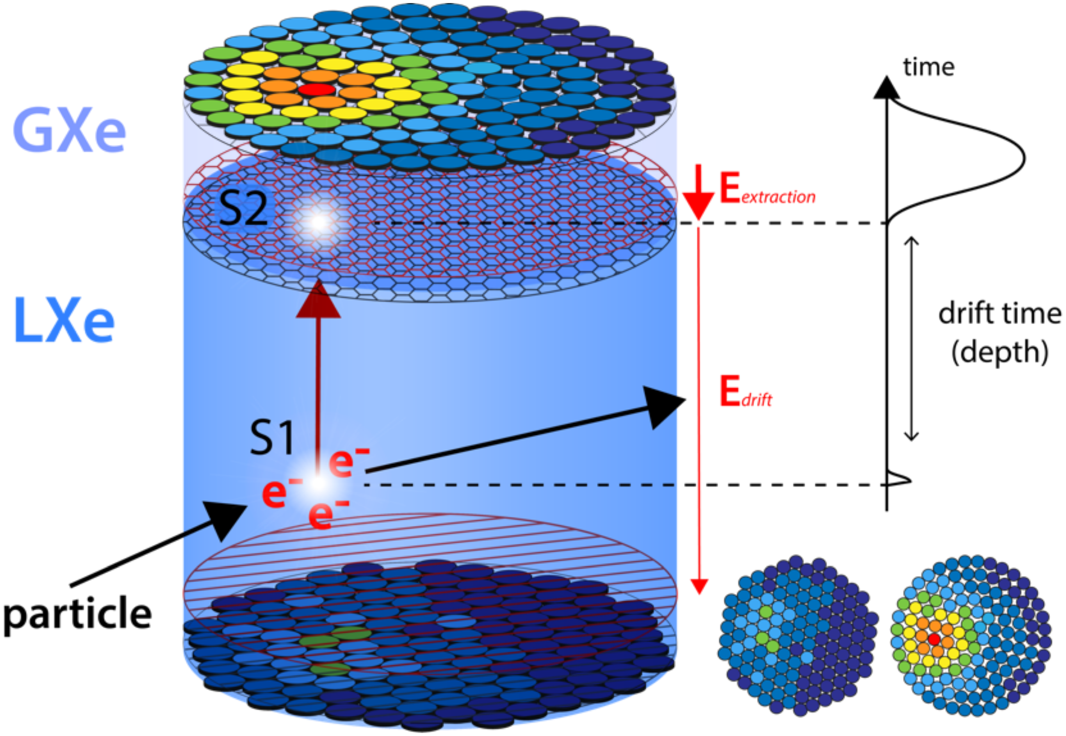
Coimbra · Subatech · LPNHE · LAL · Bologna · LNGS · Torino · Napoli · Weizmann

Xenon two-phase detectors



Detection Principle same as before

Q: What do scuba diver and time-projection chamber have in common?



Answer:
Flashlight = Scintillation photons S1
Bubbles = Ionization electrons S2

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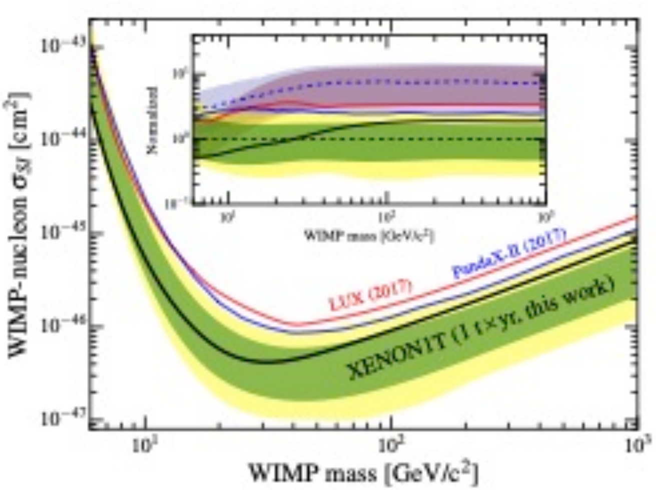

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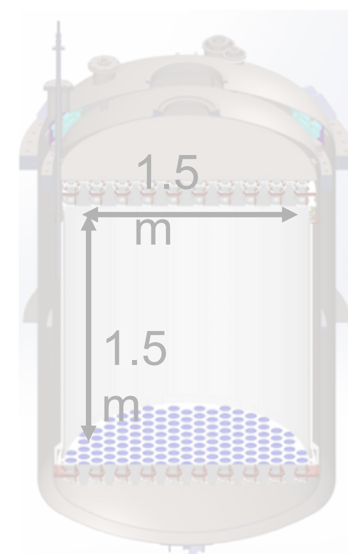
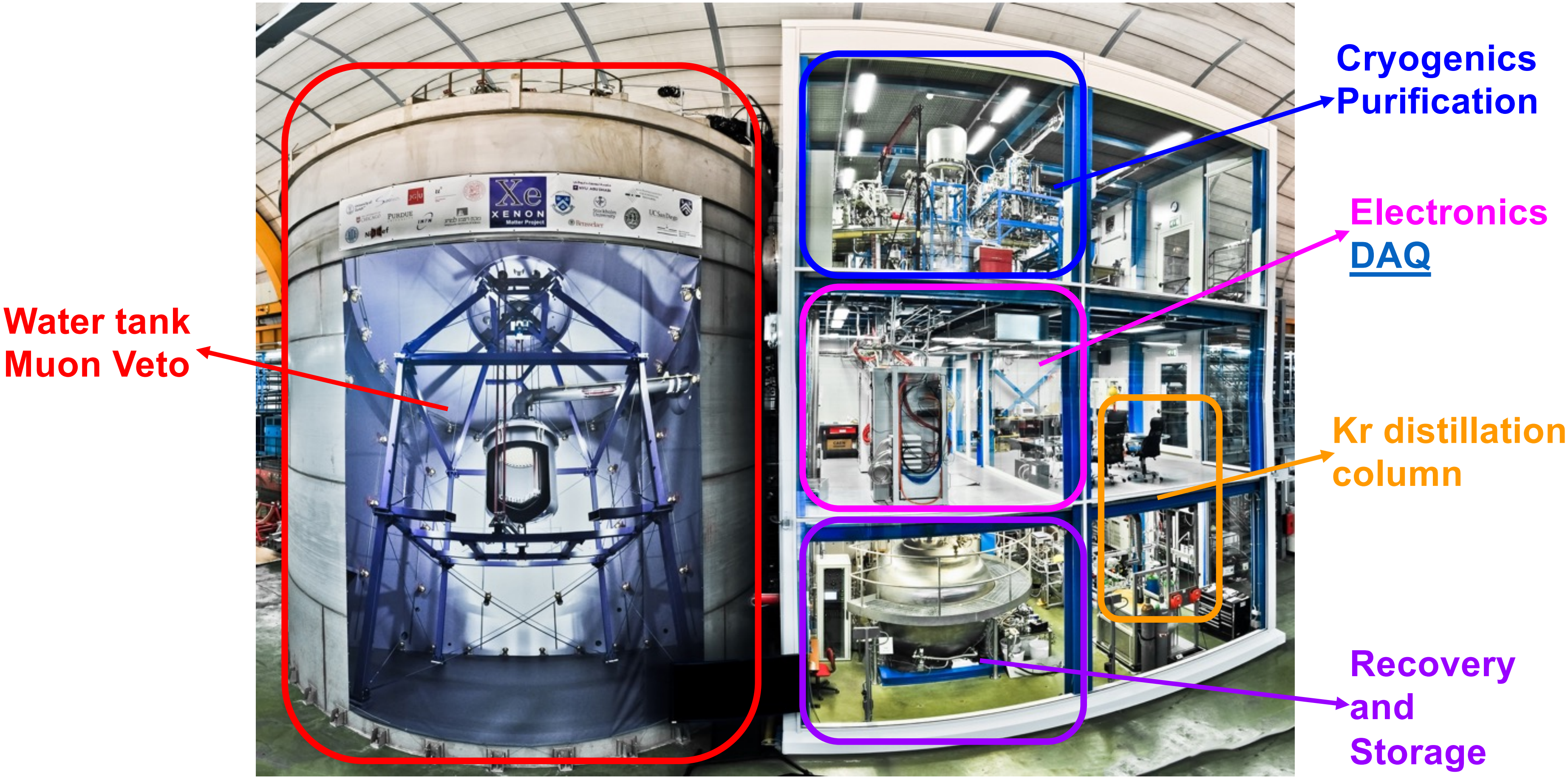
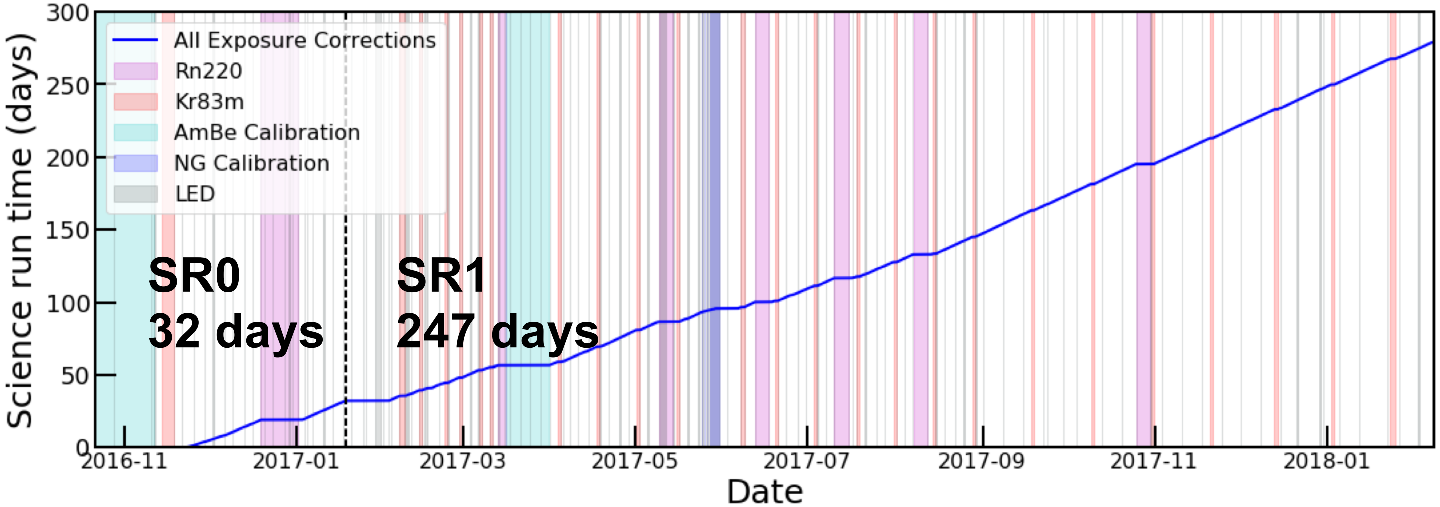


XENON1T



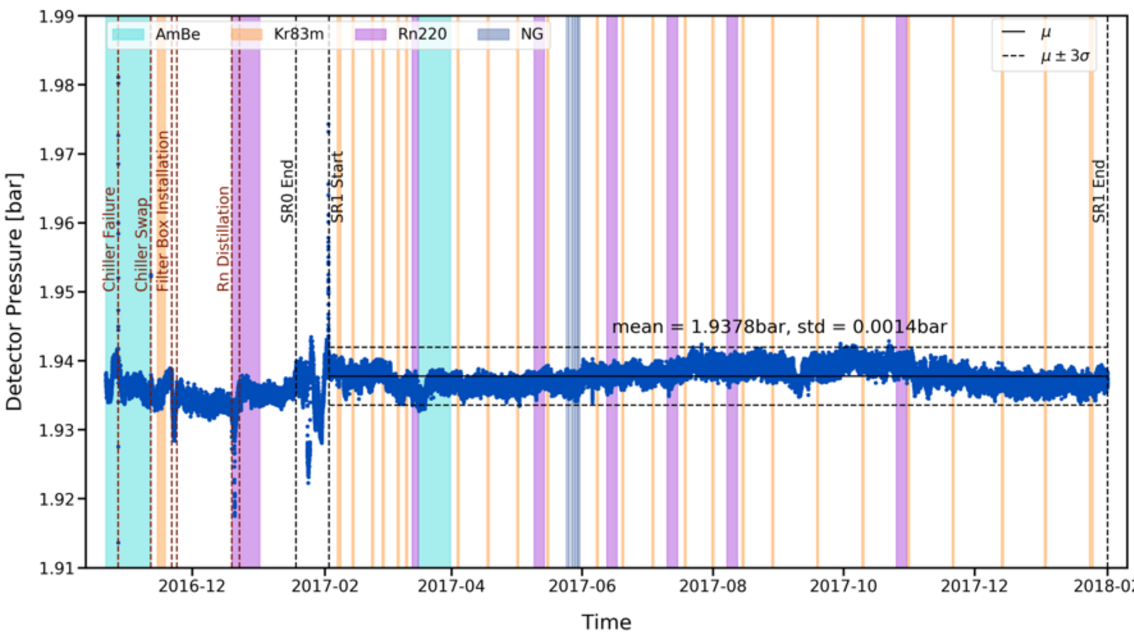
Aprile et al. Eur. Phys. J. C (2017) 77: 881.

Data taking



278.8 days

1 ton-year exposure

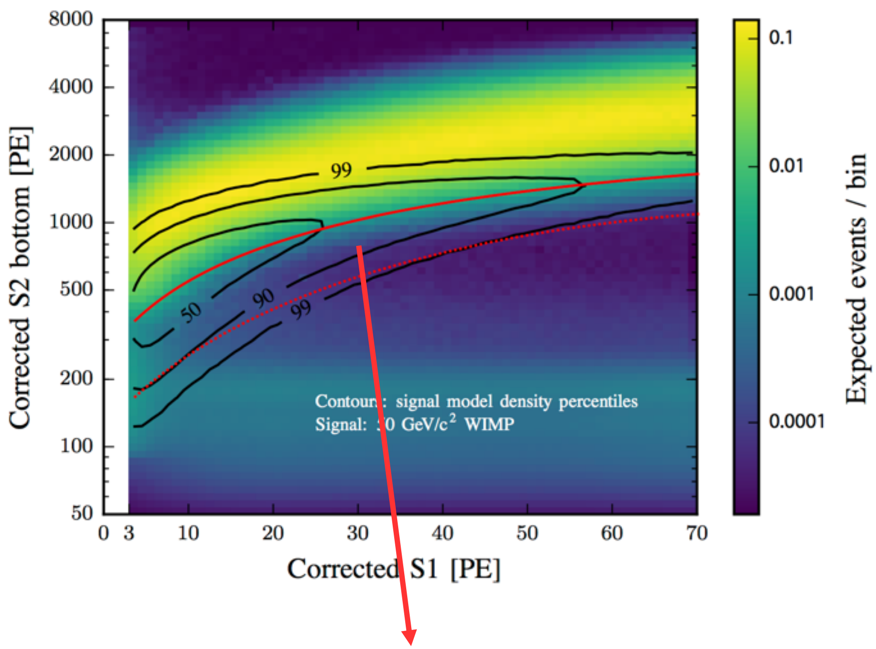


stable

arXiv:1906.04717

Background predictions

ROI corresponds in average to
[4.9, 40.9] keV_{nr} ([1.4, 10.6] keV_{ee})



NR reference region

50% NR acceptance with 99.75% ER rejection

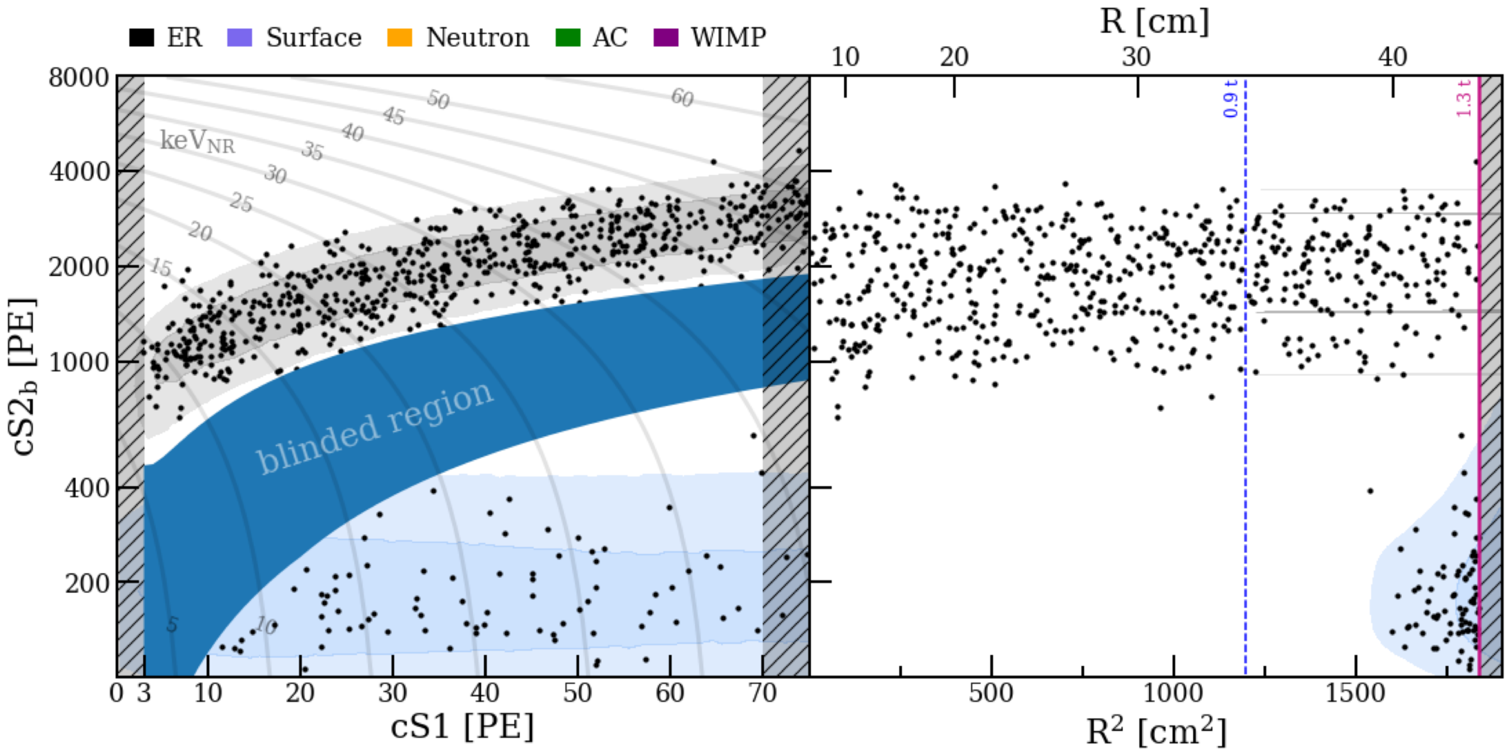
Background model in 4 dimensions:
S1, S2, R, Z

Mass (ton)	1.3	1.3	0.9
($cS1$, $cS2_b$)	Full	Reference	Reference
ER	627 ± 18	1.62 ± 0.30	1.12 ± 0.21
Neutron	1.43 ± 0.66	0.77 ± 0.35	0.41 ± 0.19
CEνNS	0.05 ± 0.01	0.03 ± 0.01	0.02
AC	$0.47^{+0.27}_{-0.00}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$
Surface	106 ± 8	4.84 ± 0.40	0.02
Total BG	735 ± 20	7.36 ± 0.61	1.62 ± 0.28

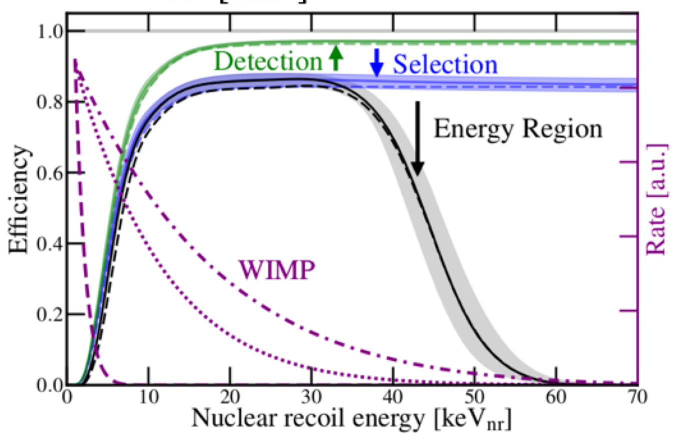
Statistical inference in 1.3 t fiducial volume and full (S1, S2) space

Phys. Rev. D **99**, 112009

Spin Independent WIMP result

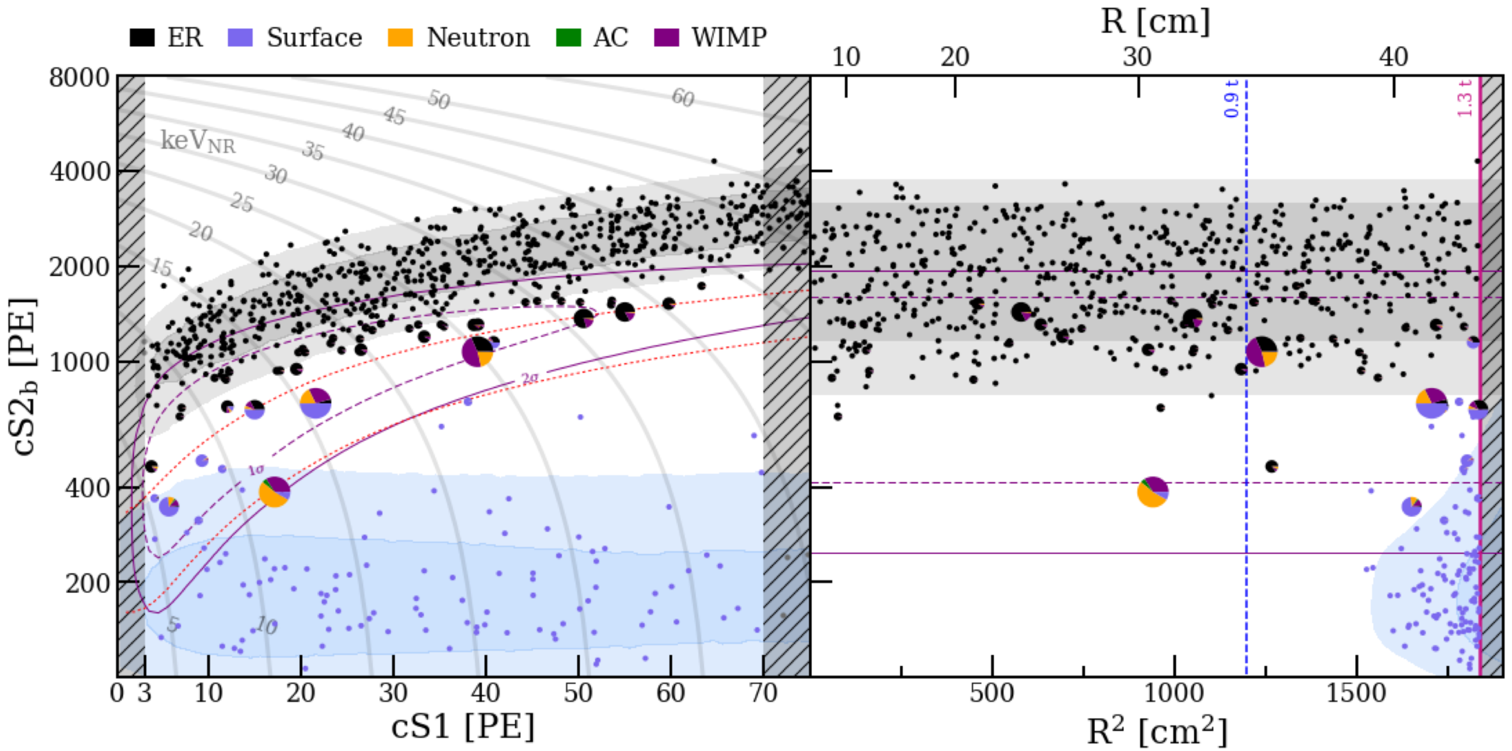


All selection criteria were defined before unblinding



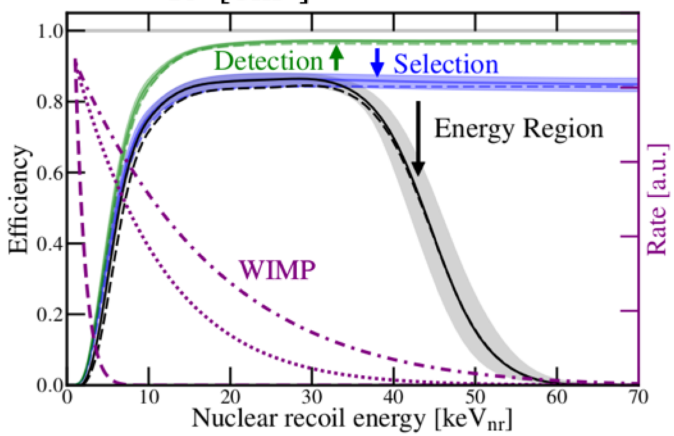
Phys. Rev. D **99**, 112009

SI-WIMP result



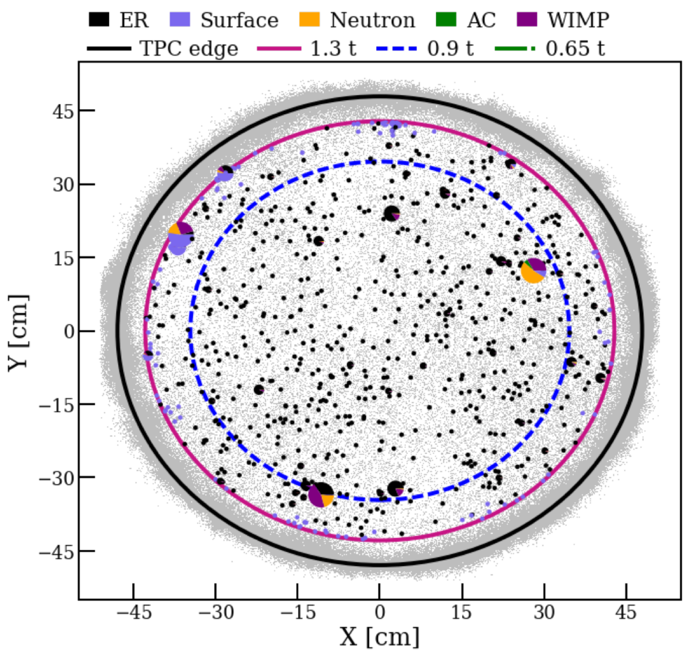
Events that pass all cuts are shown

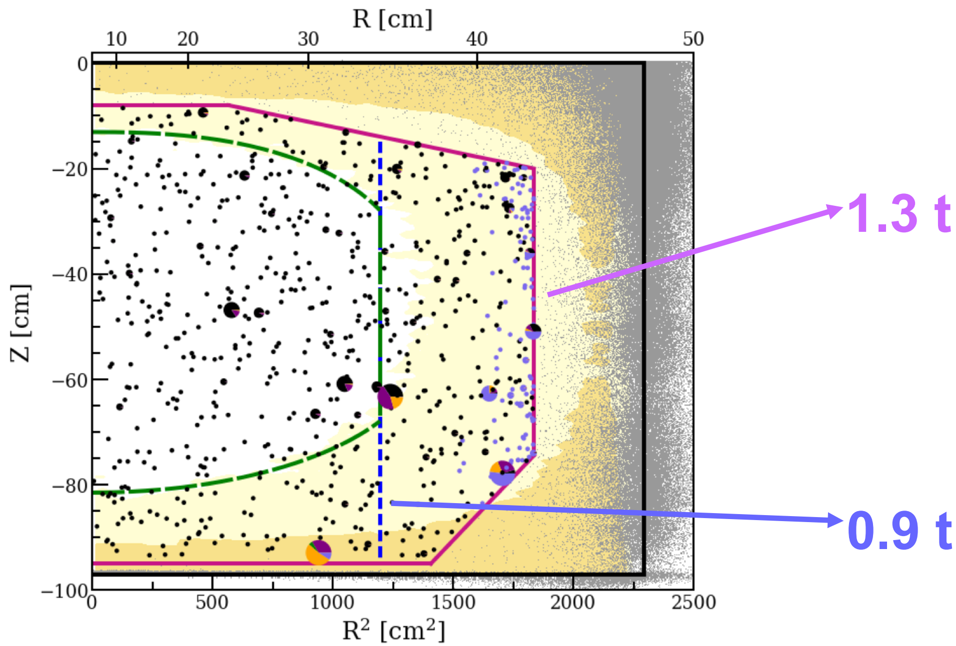
They are shown as pie charts representing the best-fit probabilities of the background and signal (200 GeV WIMP) components at each event



Phys. Rev. D **99**, 112009

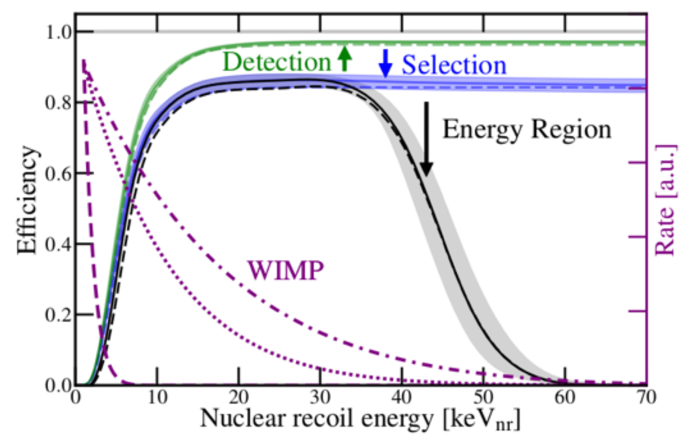
SI-WIMP result





Performed unbinned profile likelihood, model uncertainties included as nuisance parameters

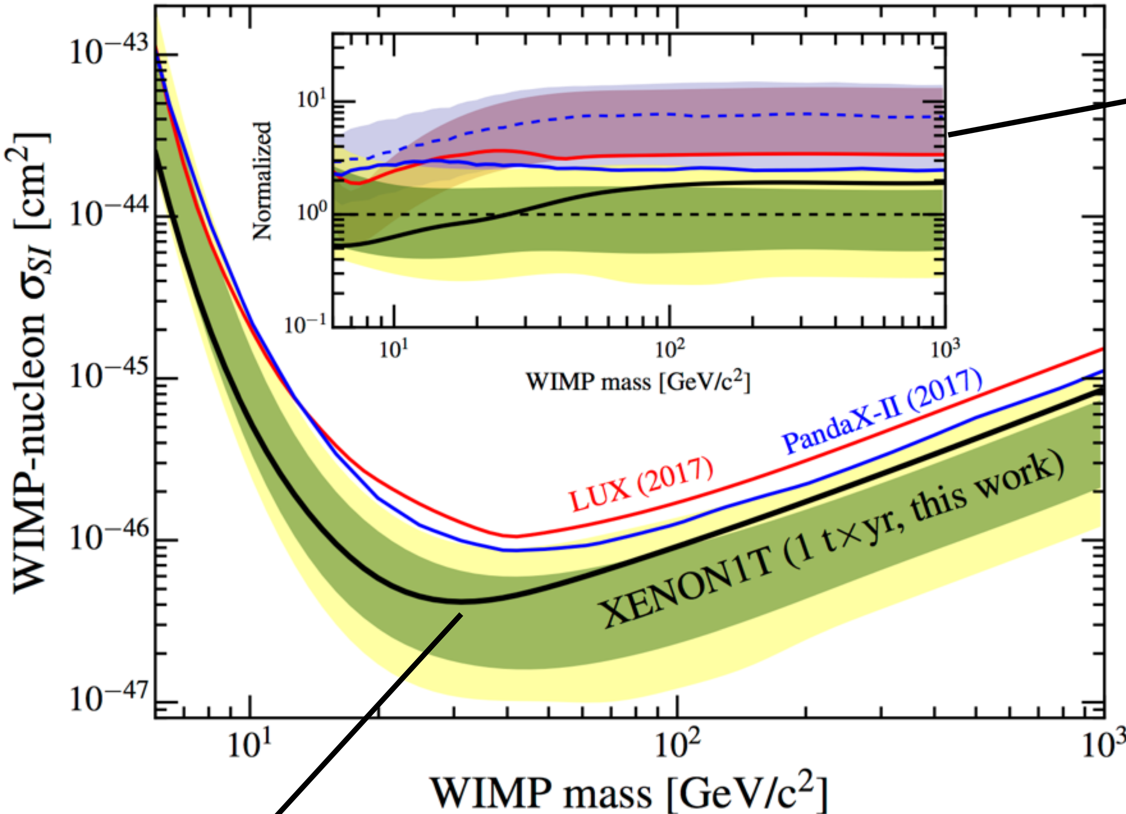
Maximum radius of 1.3 t fiducial volume set by surface event contribution.



Phys. Rev. D **99**, 112009

SI-WIMP result

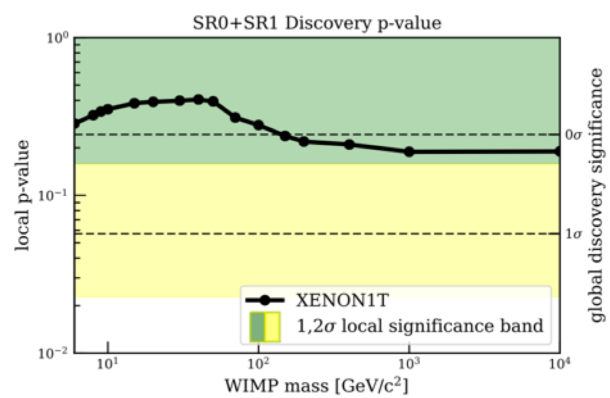
E. Aprile et al., Phys. Rev. Lett. 121, 111302 (2018)



Median sensitivity 7 times better than previous experiments

σ_{SI}<4.1*10^{-47} cm^2 (90% C.L.) @ 30 GeV/c^2

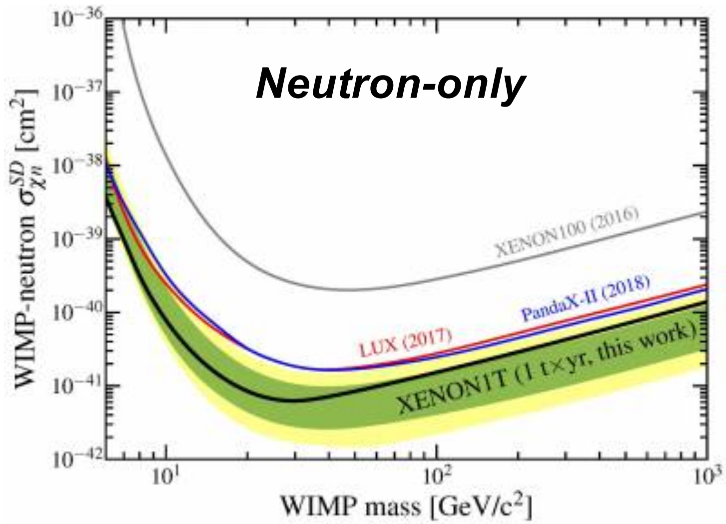
No significant excess (>3σ) in the 1.3 tons fiducial volume at any WIMP mass

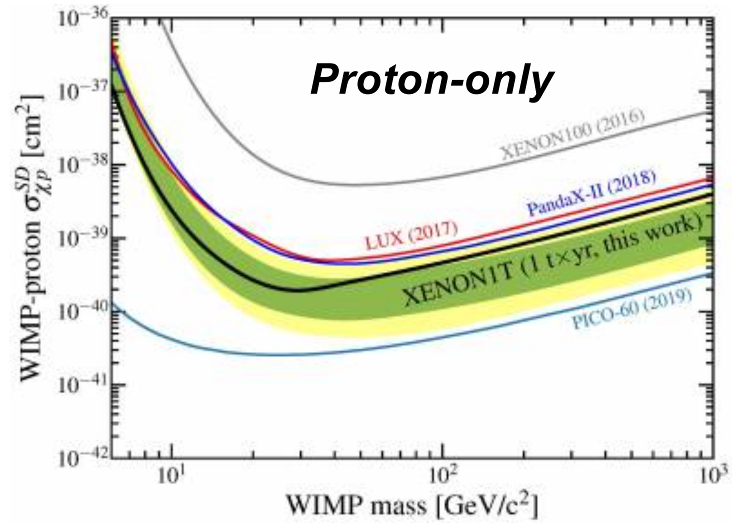


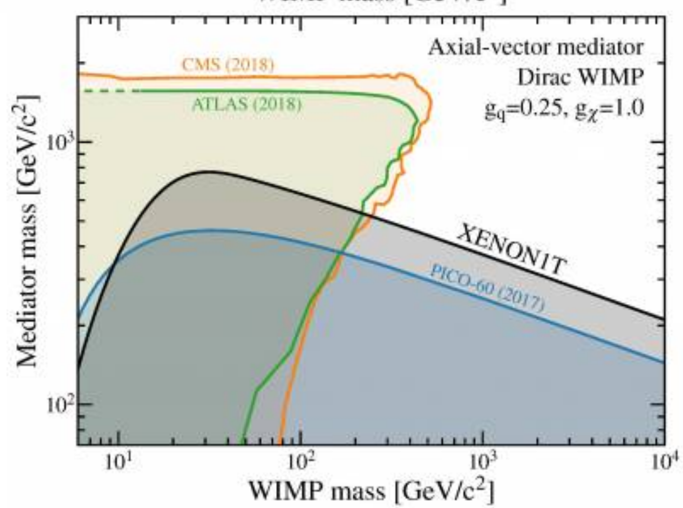
Phys. Rev. D **99**, 112009

SD-WIMP result

E. Aprile et al., Phys. Rev. Lett. 122, 141301 (2019)







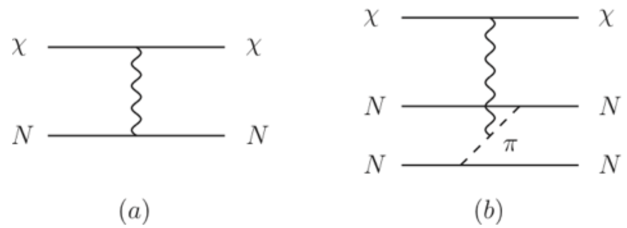
Same event selection criteria for a SD search

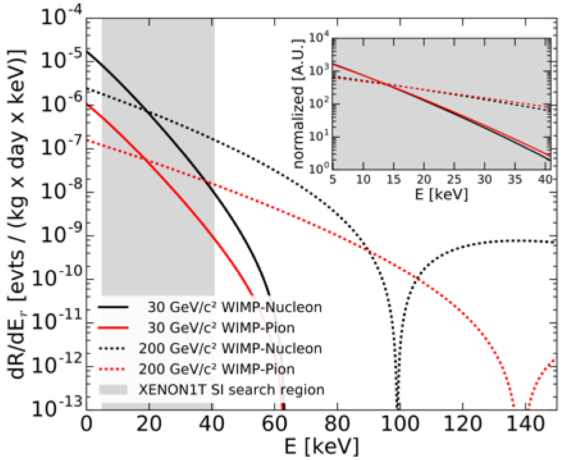
Most stringent limit on WIMP-neutron scattering cross section

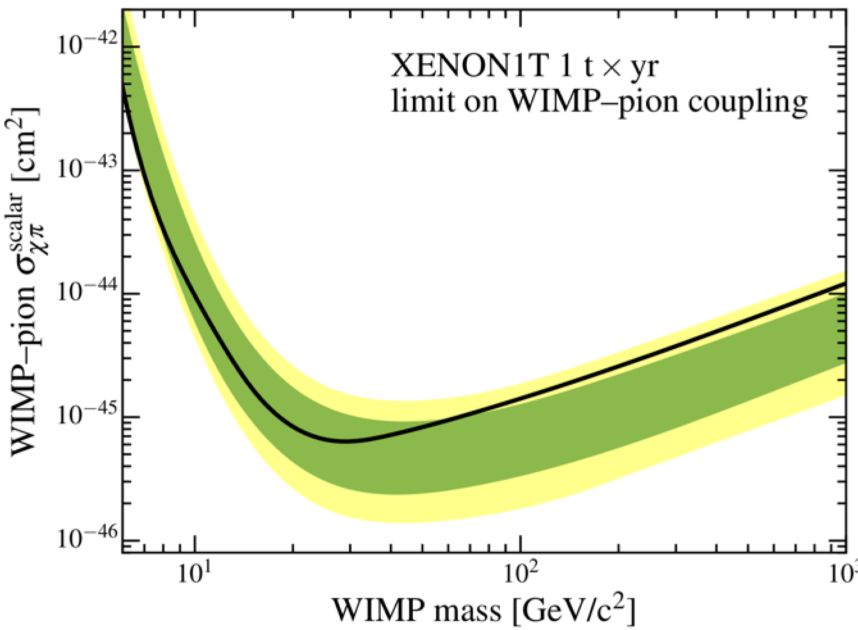
Opens up experimental comparisons (left example). Note optimistic g_X=1 assumption.

WIMP-Pion coupling

E. Aprile et al., Phys. Rev. Lett. 122, 071301 (2019)







Coupling of WIMP with virtual pion-current between two nucleons

Same falling exponential differential recoil spectrum as WIMP-nucleon interaction

Limit setting as in SI analysis

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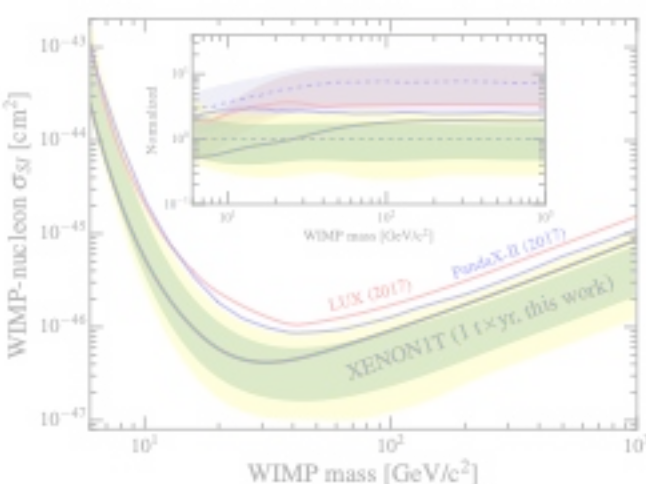

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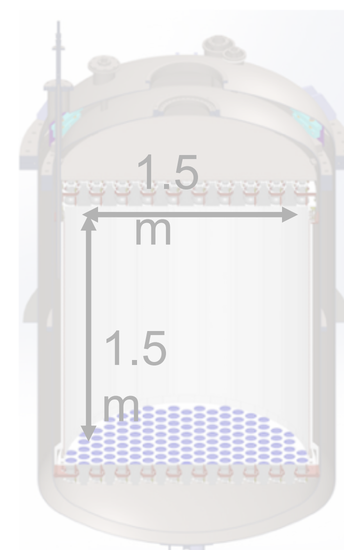
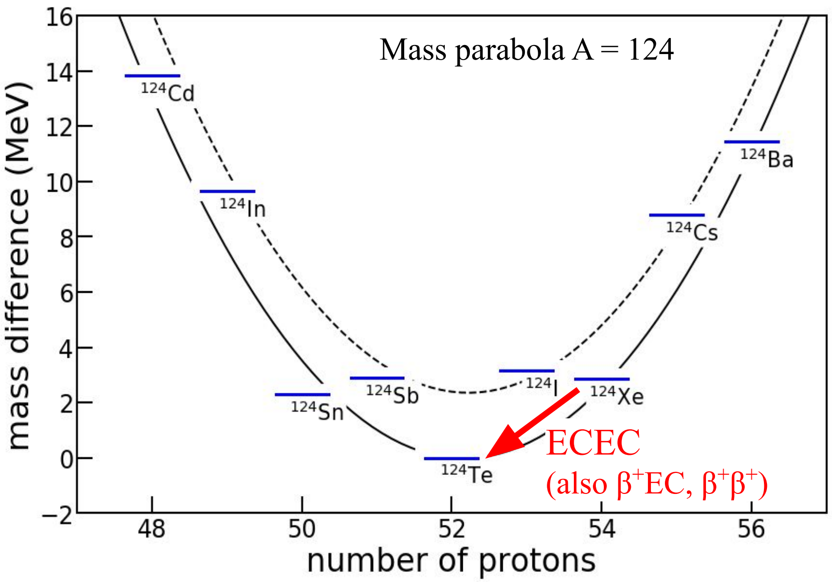
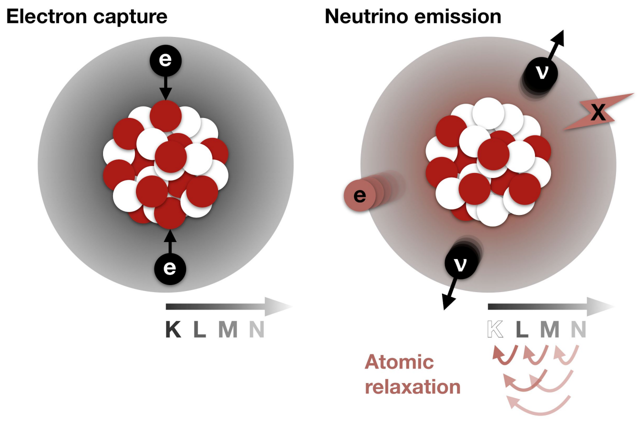


What is 2-Neutrino Double-Electron Capture (2νDEC)





$$^{124}Xe + 2e^- \rightarrow {}^{124}Te + 2\nu_e \quad (Q_{DEC} = 2857 \text{ keV})$$

- Nucleus captures two atomic shell electrons
- Recoil of nucleus O(10 eV) negligible
- Observe X-rays and Auger electrons
  - double K-shell capture: **E_{DEC} = 64.3 keV**

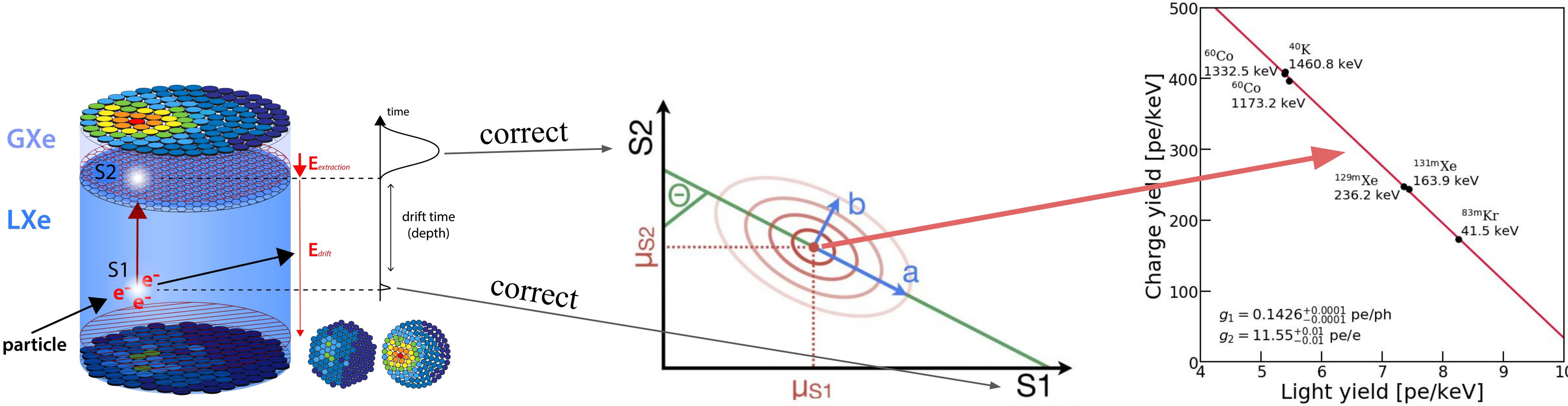
Why look for 2νDEC in ^{124}Xe?

Rare event search: Liquid xenon (LXe) as detection medium

Because we can.

- Isotopic abundance of ^{124}Xe: $\eta_{124Xe} \approx 0.1\%$
  ➜ **~ 1.5 kg of ^{124}Xe target mass** (1.5 t total)
- Good energy resolution < 5%
- Low background < 10^{-3} cts keV^{-1} kg^{-1} day^{-1}
- Live time > 100 days

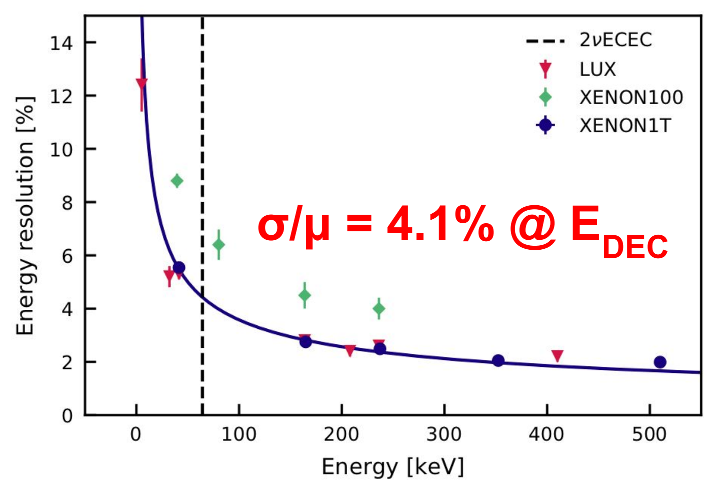
Energy scale determination



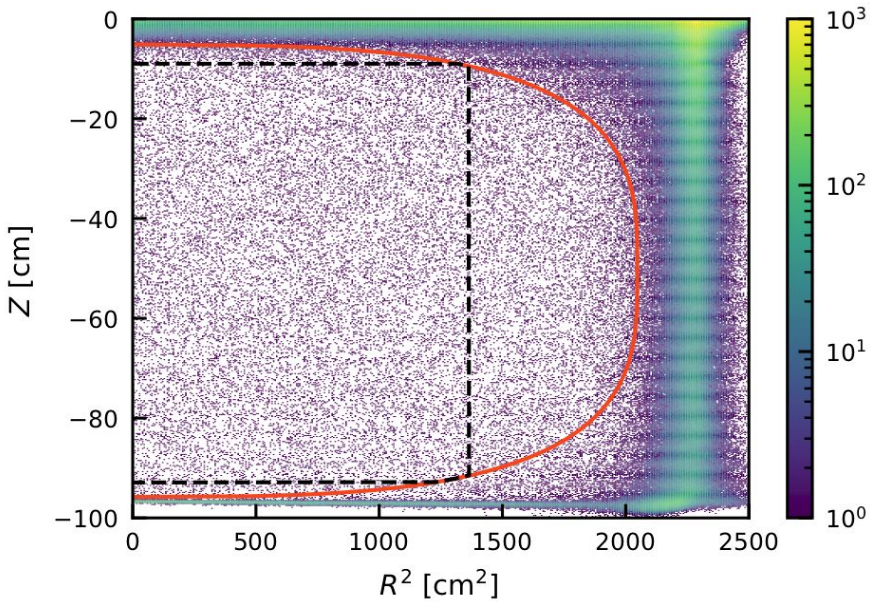
Combined Energy Scale (CES):

$$E = (N_{ph} + N_e) \times W$$
$$= (S1/g_1 + S2/g_2) \times W$$

(average energy to generate measurable quanta in LXe: W = 13.7 eV)



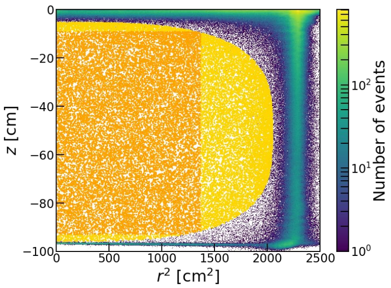
Exposure and Fiducial Volume (FV)

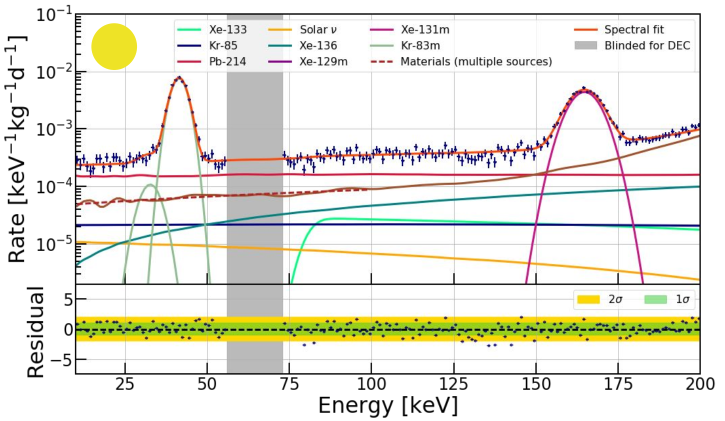


Optimize sensitivity $\propto$ $\text{mass}_{FV} \times (N_{Bg})^{-½}$
(in energy range [80, 140] keV)

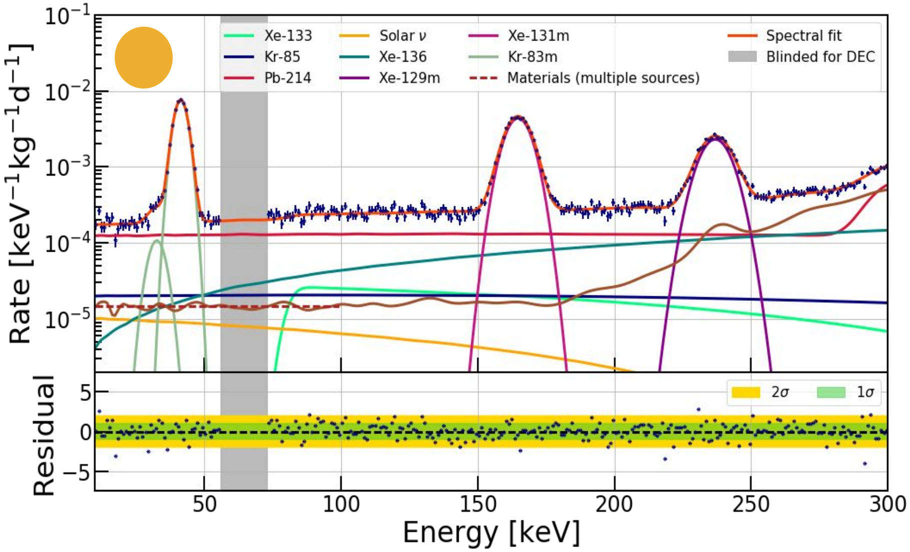
- 1.5 t FV (red)
- 1.0 t inner / 0.5 t outer (dashed black)
- In-situ abundance measurement:
  $^{124}\text{Xe}/^{nat}\text{Xe} = (9.94 \pm 0.14_{stat} \pm 0.15_{sys})\times10^{-4}$
  ➜ $\mathbf{m_{124Xe} = 1.49}$ **kg**
- **177.7 days** total live time

Background Model





- XENON1T MC:
  - physical processes (Geant4)
  - detector specific response
- MC spectra matched to measured data
  - simultaneously in both volumes (orange/yellow)
  - including all known backgrounds
  - linear interpolation of material backgrounds (below 100 keV)
  - 27 fit parameters in total



^{125}I Background

(1) artificial activation during calibration campaigns
(DD-fusion neutron generator and/or ^{241}AmBe source)

(2) (radiogenic) activation outside the water shield
by environmental thermal neutrons.

$$^{124}\mathrm{Xe} + n \rightarrow {}^{125}\mathrm{Xe} + \gamma$$

capture of thermal neutrons

$$^{125}\mathrm{Xe} \xrightarrow[EC]{16.9\,\mathrm{h}} {}^{125}\mathrm{I}^* + \nu_e$$

$$^{125}\mathrm{I}^* \xrightarrow{<1\,\mathrm{ns}} {}^{125}\mathrm{I} + \gamma + X$$

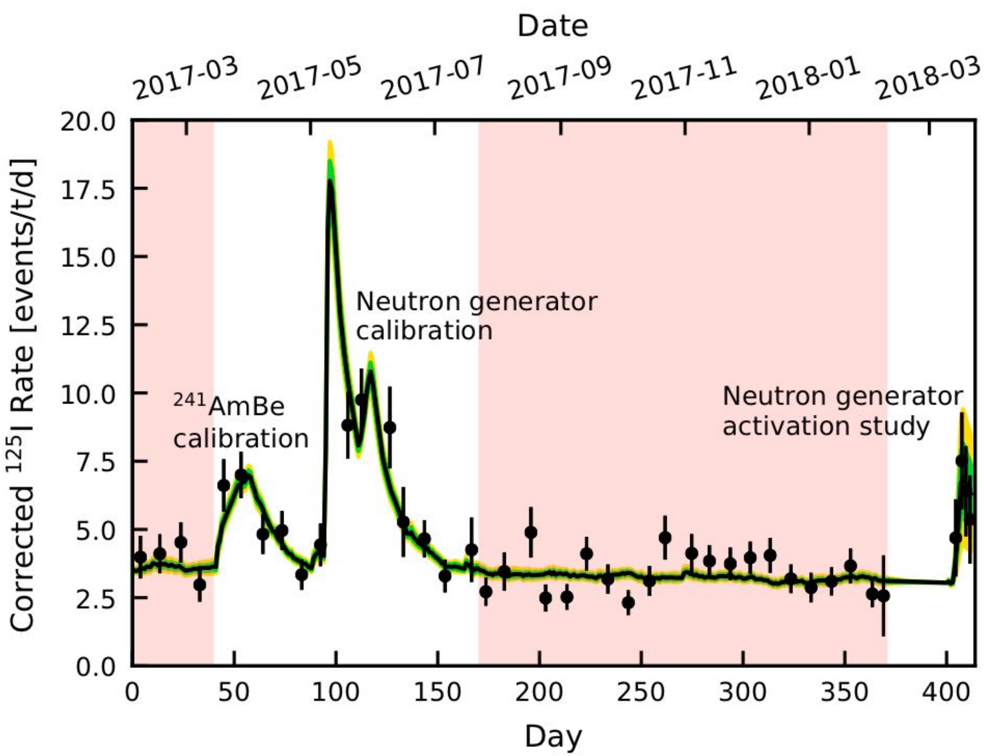
→ tag/model background
(Lines at 222 keV and 277 keV)

$$^{125}\mathrm{I} \xrightarrow[EC]{59.4\,\mathrm{d}} {}^{125}\mathrm{Te}^* + \nu_e$$

$$^{125}\mathrm{Te}^* \xrightarrow{1.48\,\mathrm{ns}} {}^{125}\mathrm{Te} + \gamma + X$$

→ Gaussian line at 67.3 keV

^{125}I Background



$$^{124}\mathrm{Xe} + n \rightarrow {}^{125}\mathrm{Xe} + \gamma$$

$$^{125}\mathrm{Xe} \xrightarrow[EC]{16.9\,\mathrm{h}} {}^{125}\mathrm{I}^{*} + \nu_e$$

$$^{125}\mathrm{I}^{*} \xrightarrow{<1\,\mathrm{ns}} {}^{125}\mathrm{I} + \gamma + X$$

$$^{125}\mathrm{I} \xrightarrow[EC]{59.4\,\mathrm{d}} {}^{125}\mathrm{Te}^{*} + \nu_e$$

$$^{125}\mathrm{Te}^{*} \xrightarrow{1.48\,\mathrm{ns}} {}^{125}\mathrm{Te} + \gamma + X$$

Artificial (DD, AmBe) ^{125}I:
Fit ^{125}Xe model to ^{125}I data

➔ $\tau_{eff} = (9.1 \pm 2.6)$ d

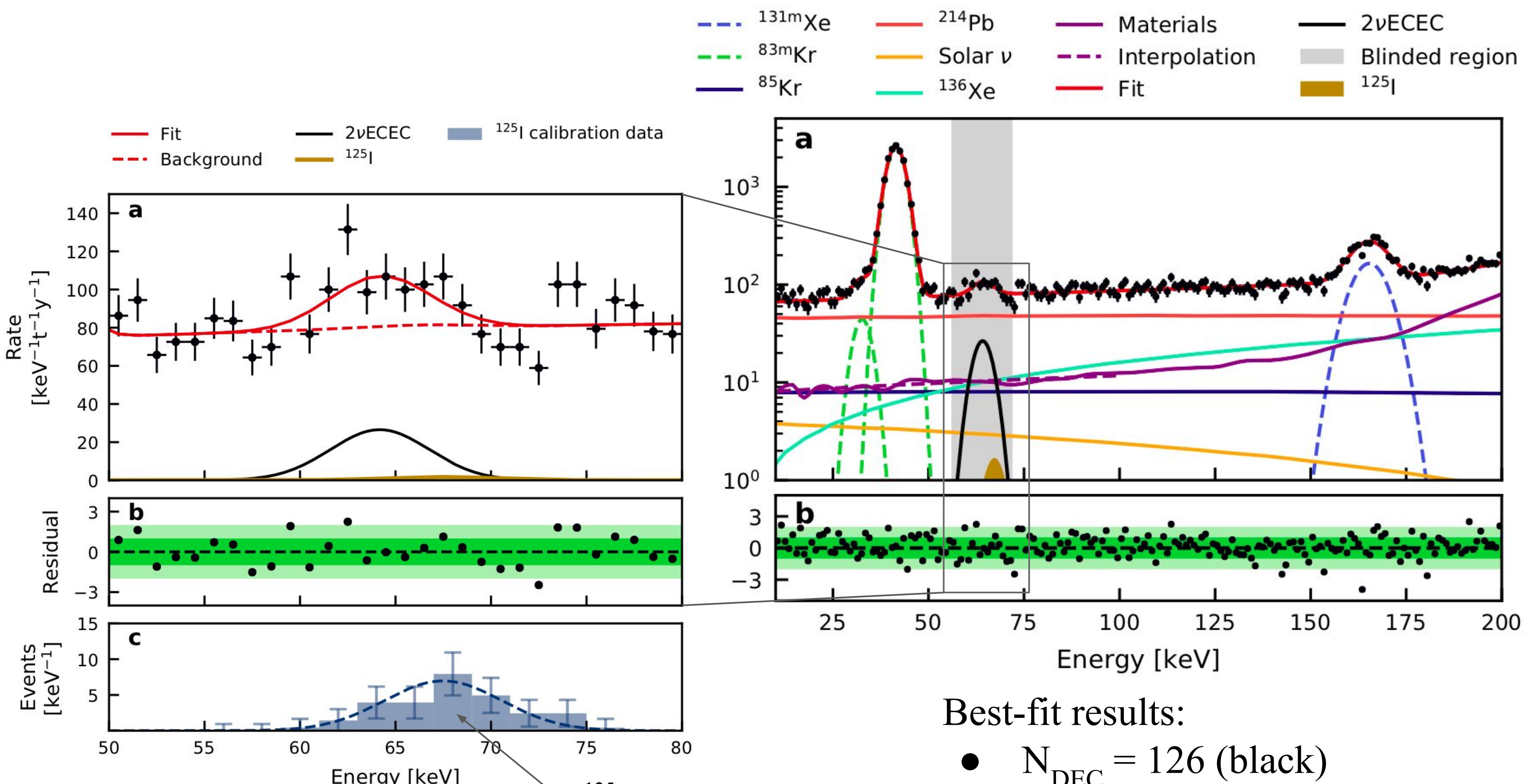
➔ $N_{125\text{-I,art}} = (6 \pm 6)$ events

Radiogenic ^{125}I:
(measured neutron flux, 5kg Xe outside water tank):

➔ $N_{125\text{-I,rad}} = (4 \pm 3)$ events

➔ **$N_{125\text{-I,tot}} = (10 \pm 7)$ events**

Results

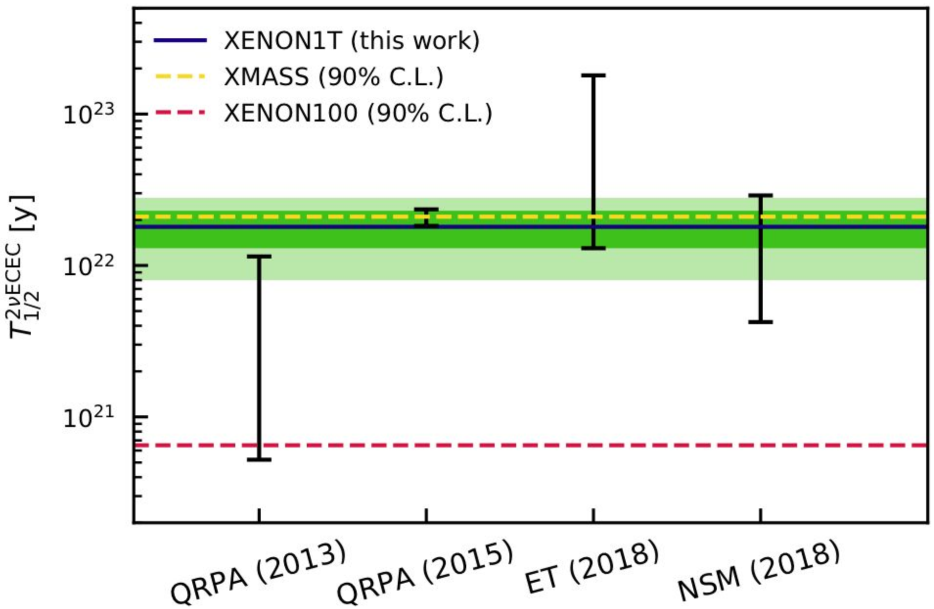


^{125}I during/after neutron calibrations

Best-fit results:

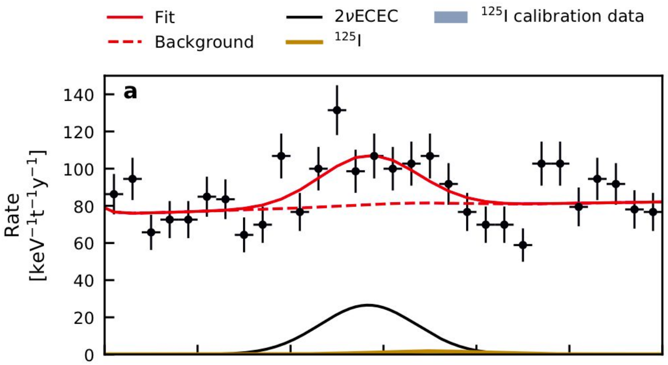
- N_{DEC} = 126 (black)
- N_{125I} = 9 (gold)

Results



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

E. Aprile et al., Nature 568 (2019), no.7753, 532535



$$T_{1/2}^{2\nu \mathrm{ECEC}} = \ln 2 \frac{\epsilon \eta N_A m t}{M_{\mathrm{Xe}} N_{2\nu \mathrm{ECEC}}}$$

Cut acceptance

$\varepsilon = 0.967 \pm 0.007_{stat} \pm 0.033_{sys}$

^{124}Xe abundance

$\eta = (9.94 \pm 0.14_{stat} \pm 0.15_{sys}) \times 10^{-4}$

^{nat}Xe target mass

$m = (1502 \pm 9_{sys})$ kg

Longest half life directly measured!

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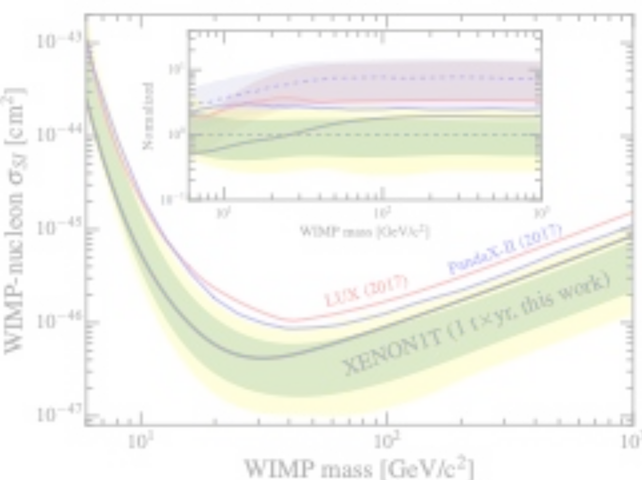

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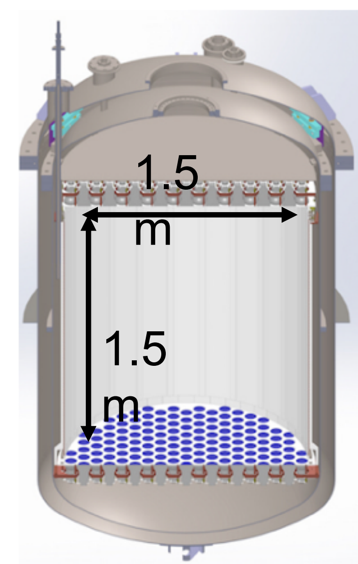
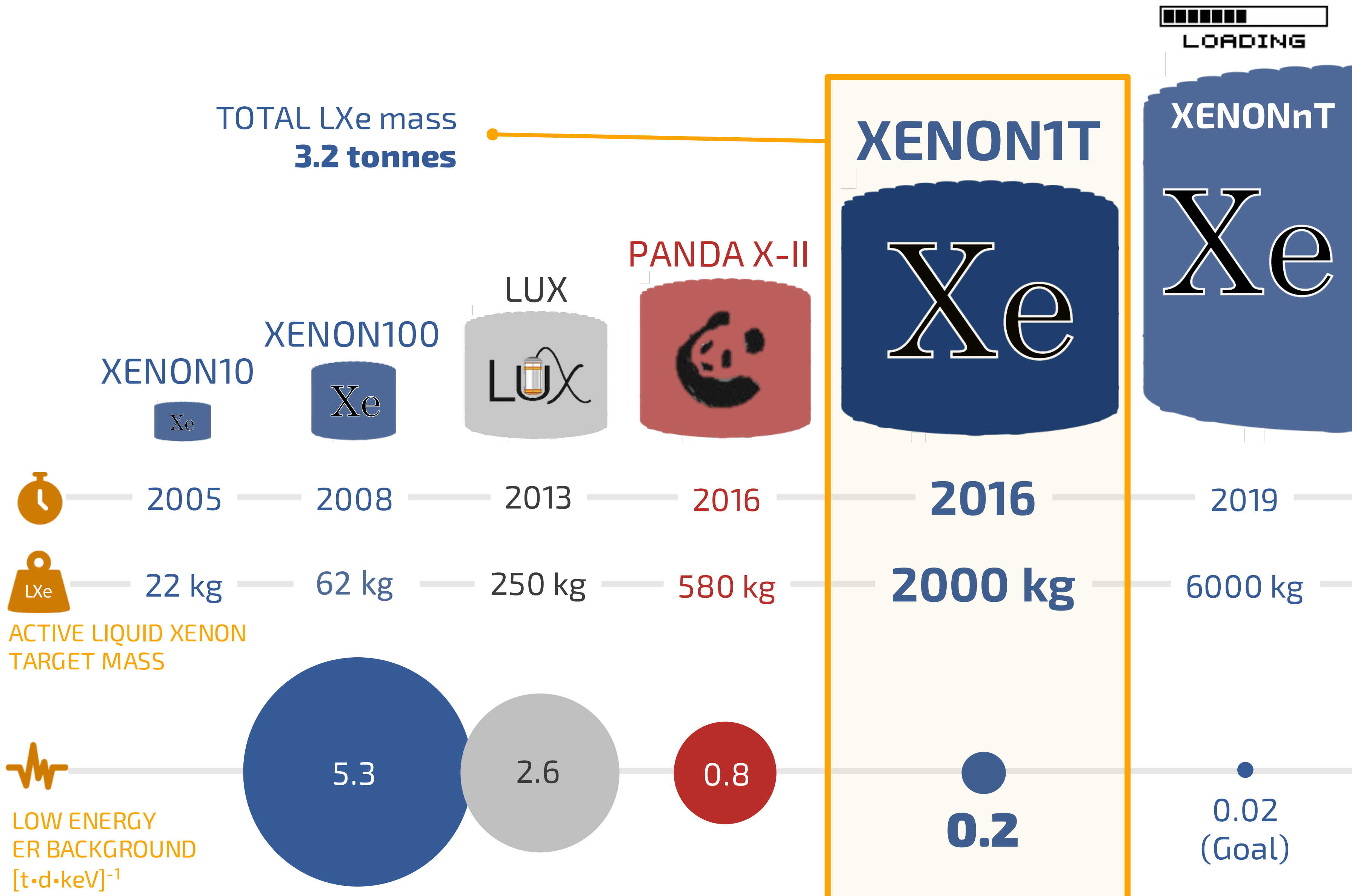
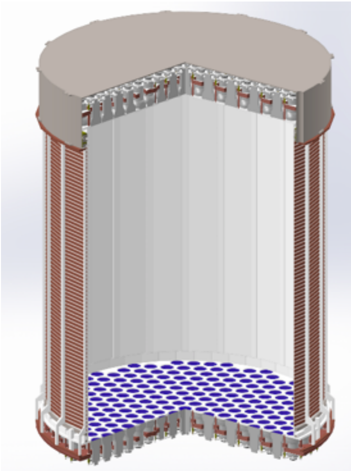


Xenon two-phase detectors



XENONnT



NEW TPC

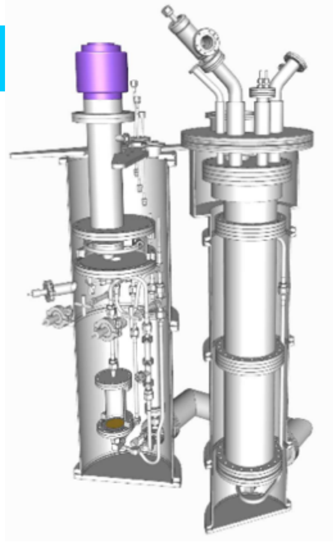
494 PMTs

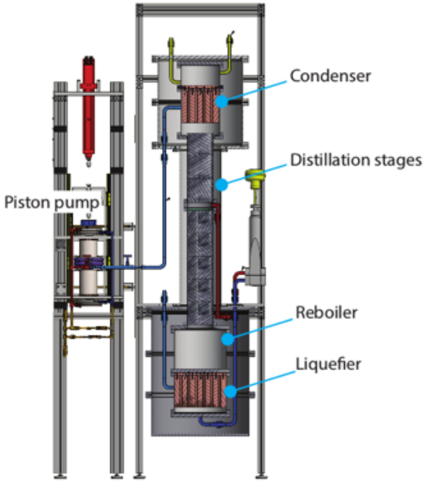
1.5 m height
1.3 m diameter

LXE PURIFICATION

Much faster purification speed

Possible to purify the 8 t of Xe in a reasonable time





RADON DISTILLATION COLUMN

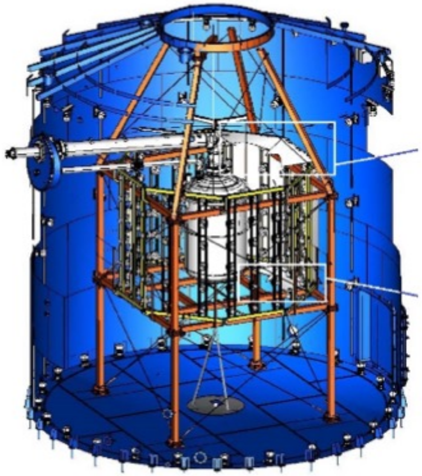
Goal 1 μBq/kg Rn contamination

Rn distillation already tested in XENON1T

NEUTRON VETO

0.2% Gd-doped water

120 additional PMTs around cryostat



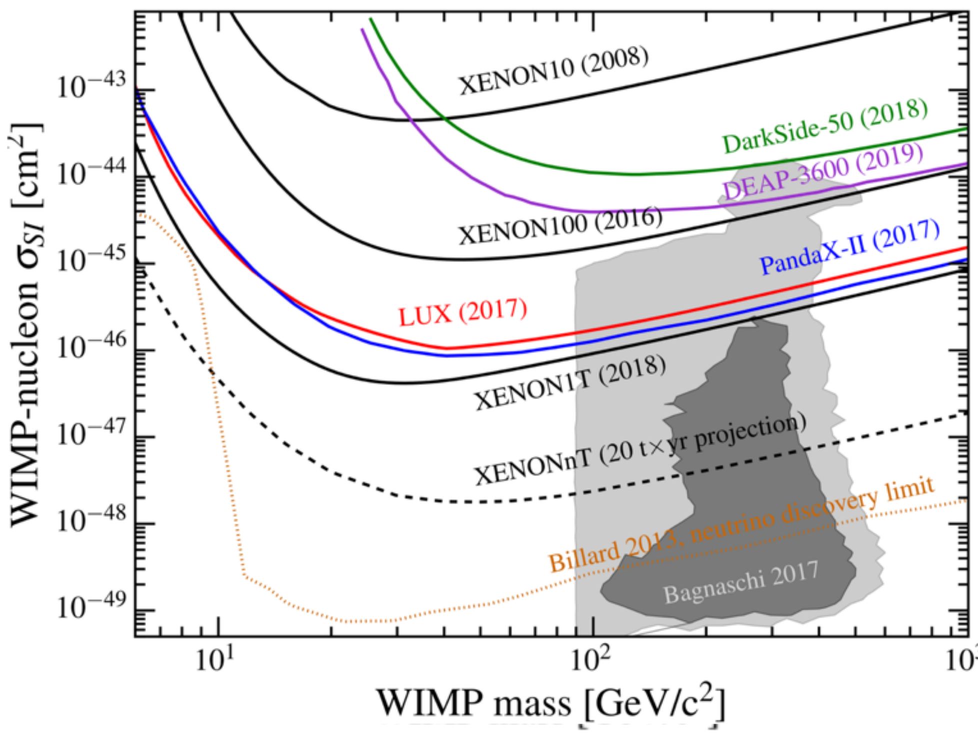
XENONnT

Use most of XENON1T subsystem

To increase sensitivity by one order of magnitude:

$\sigma_{SI} \sim 10^{-48}\ cm^2$

Construction in 2019



Increase fiducial mass by factor 4

Reduce background by factor 10

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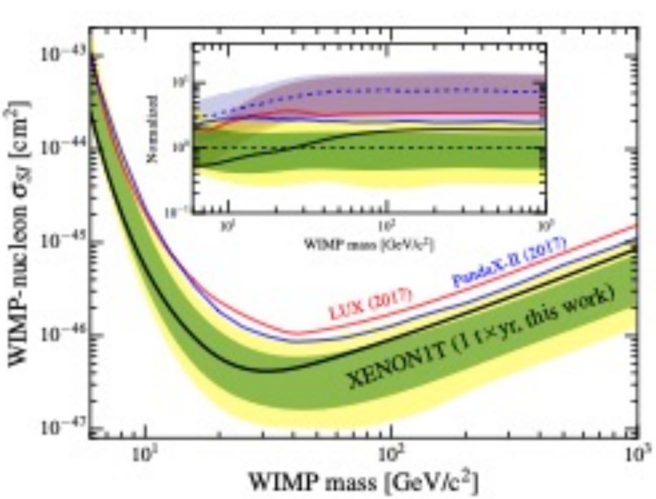
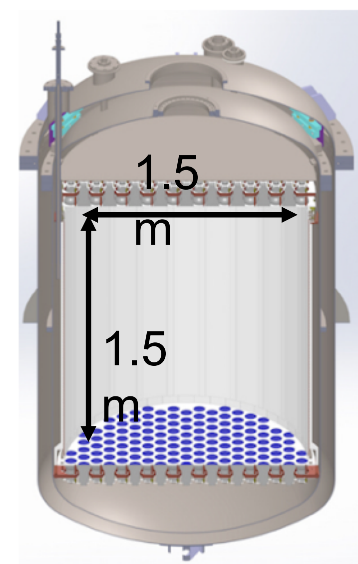
Three parts of talk summary:

XENON1T is leading the xenon detector race to DM



Longest directly measured half life!

Fast upgrade underway



DANCE 2019

Dark-matter **A**nd **N**eutrino **C**omputation **E**xplored

Analysis Software, Machine Learning,

Data Acquisition & Distributed Computing

October 28th and 29th, 2019

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