Status of the XENON Dark Matter Project

Recent Results from XENON100 and Prospects for Detection with XENON1T

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on behalf of the XENON Collaboration

DBD 2014 - Waikoloa, Hawaii - October 5-7, 2014

XENON Program

XENON10

2005-2007

25 kg

Achieved (2007)
$\sigma_{\mathrm{SI}} = 8.8 \times 10^{-44}\,\mathrm{cm}^2$

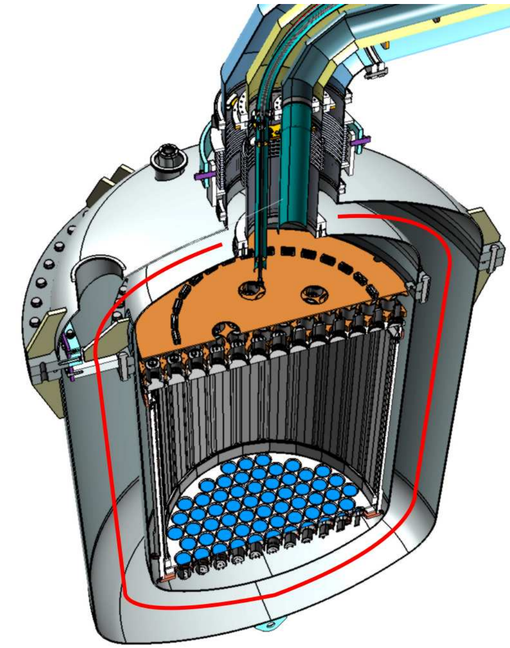
XENON100

2008-2015

161 kg

Achieved (2011)
$\sigma_{\mathrm{SI}} = 7.0 \times 10^{-45}\,\mathrm{cm}^2$
Achieved (2012)
$\sigma_{\mathrm{SI}} = 2.0 \times 10^{-45}\,\mathrm{cm}^2$

XENON1T/XENONnT

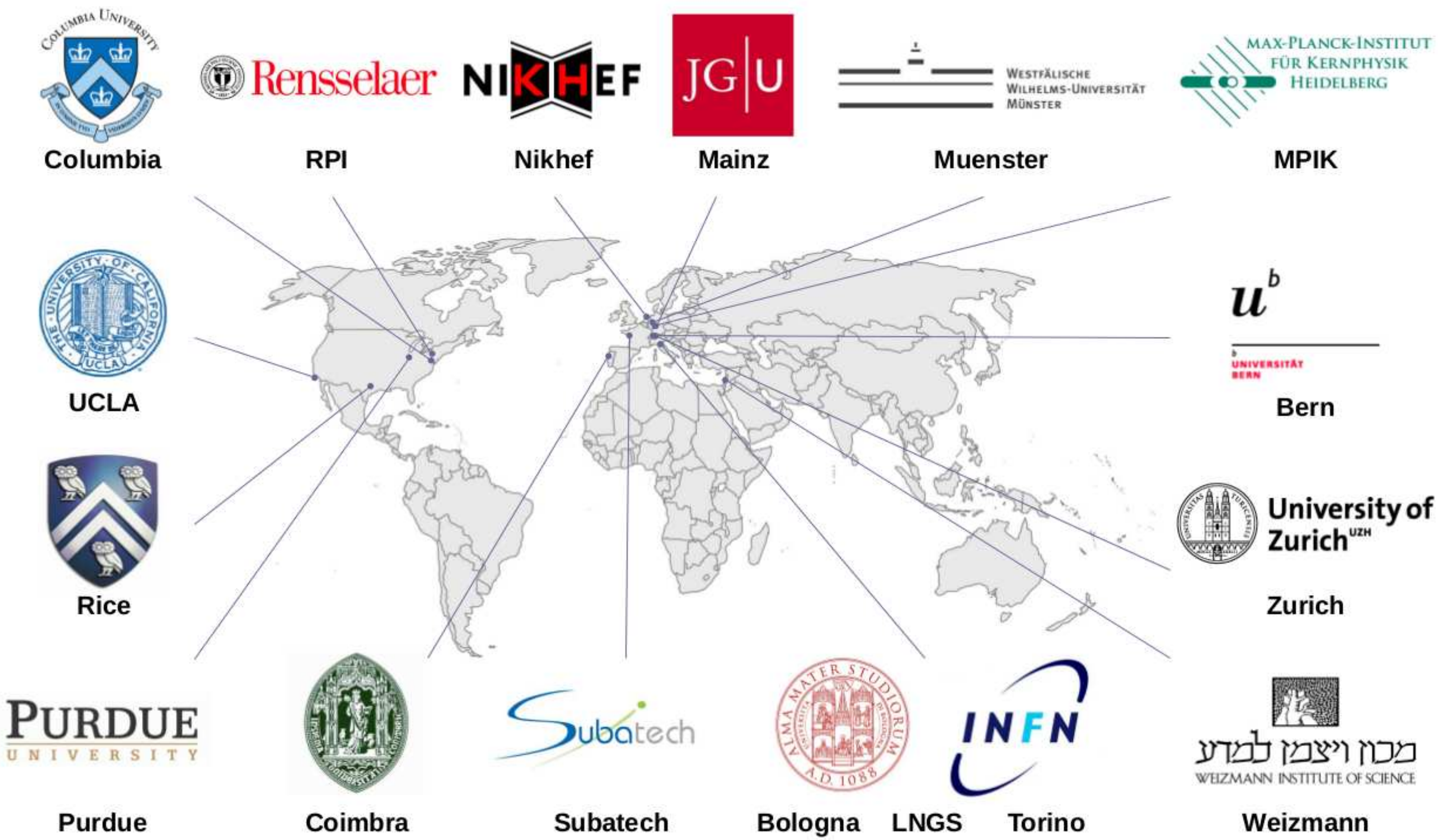


2012-2017 / ~2017-2022

3300 kg / 7000 kg

Projected (2017) / Projected (2022)
$\sigma_{\mathrm{SI}} \sim 2 \times 10^{-47}\,\mathrm{cm}^2$ / $\sigma_{\mathrm{SI}} \sim 3 \times 10^{-48}\,\mathrm{cm}^2$

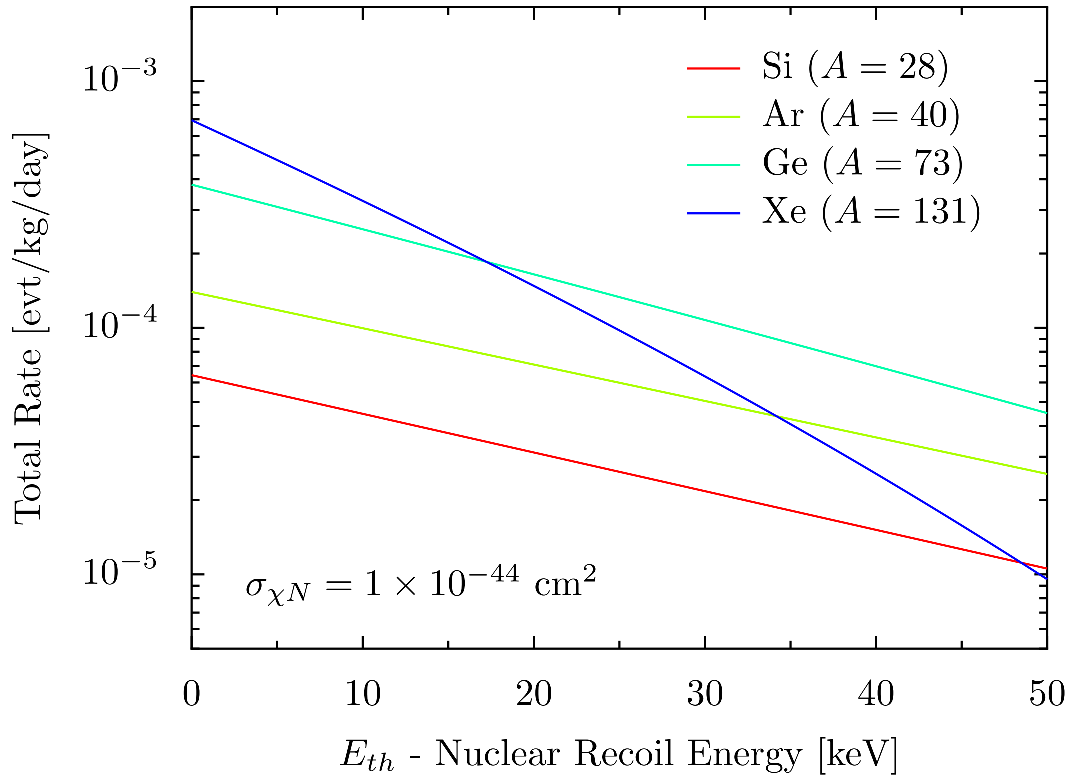
XENON Collaboration



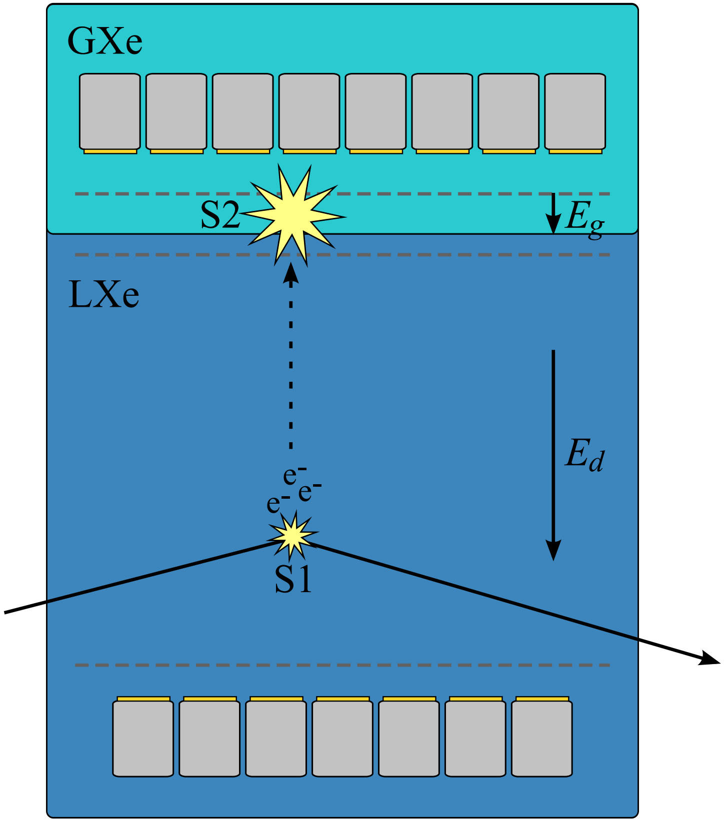
XENON Collaboration

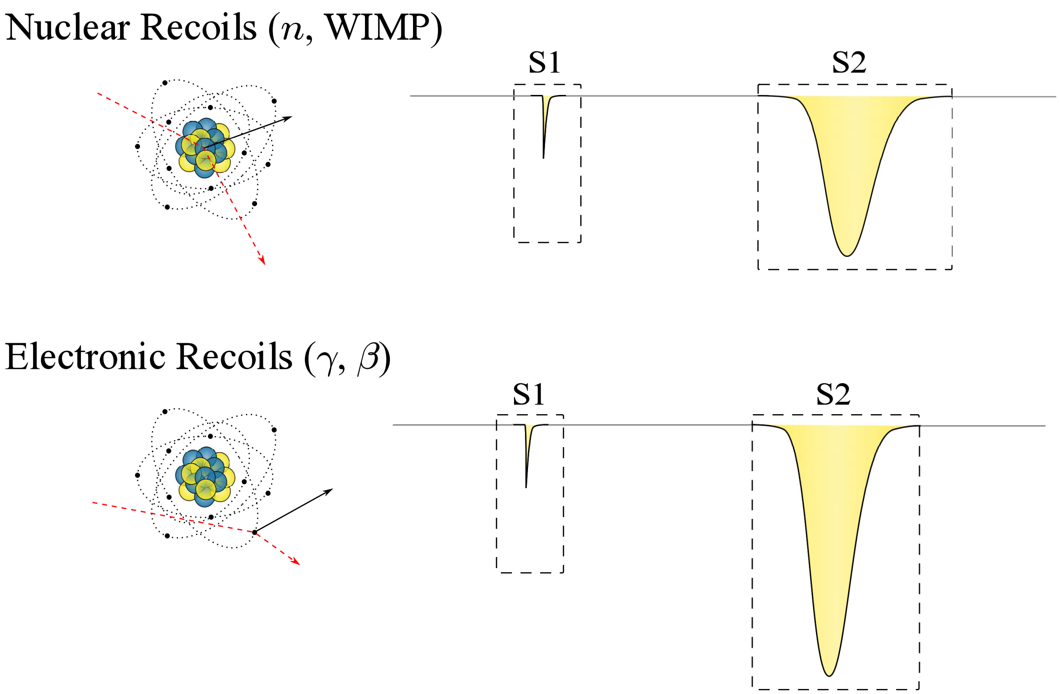
Why Xenon?

- Large mass number A (~131), expect high rate for SI interactions ($\sigma \sim A^2$) if energy threshold for nuclear recoils is low
- ~50% odd isotopes ($^{129}\mathrm{Xe}$, $^{131}\mathrm{Xe}$) for SD interactions
- No long-lived radioisotopes (with the exception of $^{136}\mathrm{Xe}$, $T_{1/2} = 2.1 \times 10^{21}$ yr), Kr can be reduced to ppt levels
- High stopping power ($Z = 54$, $\rho = 3\,\mathrm{g\,cm^{-3}}$), active volume is self shielding
- Efficient scintillator (~80% light yield of NaI), fast response
- Scalable to large target masses
- Nuclear recoil discrimination with simultaneous measurement of scintillation and ionization



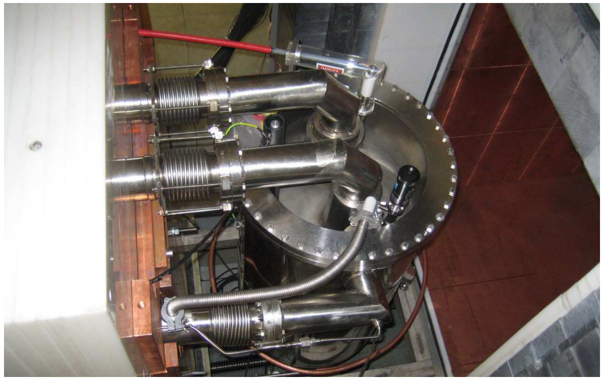
Dual Phase TPC Principle



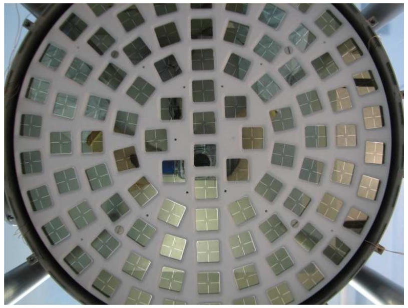


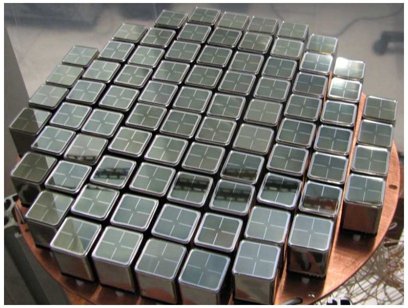
- Bottom PMT array below cathode, fully immersed in LXe to efficiently detect scintillation signal (S1).
- Top PMTs in GXe to detect the proportional signal (S2).
- Distribution of the S2 signal on top PMTs gives xy coordinates while drift time measurement provides z coordinate of the event (XENON100: $\Delta r < 3\,\mathrm{mm}$, $\Delta z < 300\,\mu\mathrm{m}$)
- Ratio of ionization and scintillation (S2/S1) allows discrimination between electron and nuclear recoils.

XENON100: Detector

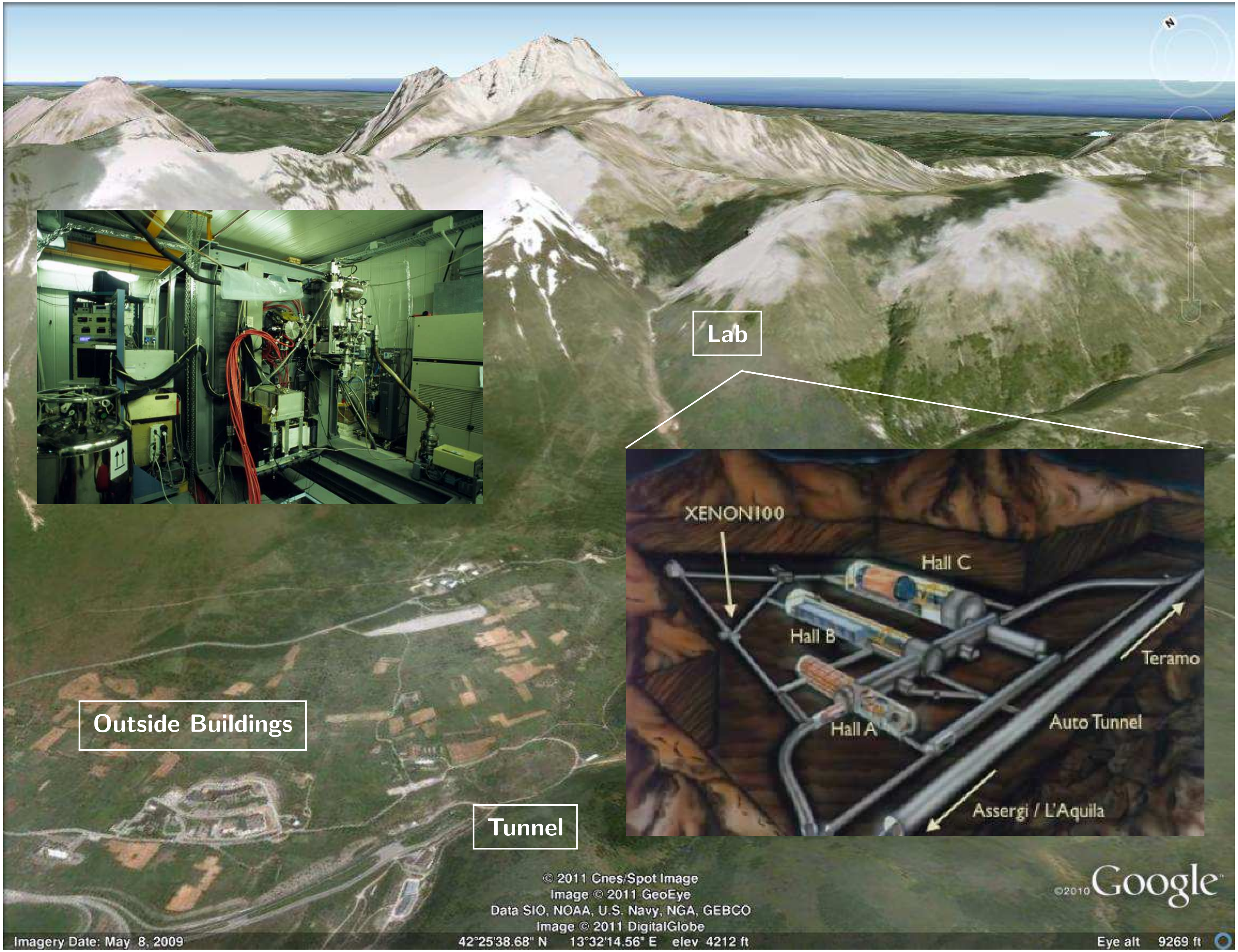


- Goal was to build a detector with a $\times 10$ increase in fiducial mass and a $\times 100$ reduction in background compared to XENON10
- All detector materials and components were screened in a dedicated low-background counting facility
- 161 kg LXe: 62 kg target surrounded by a 99 kg active veto
- 15 cm radius, 30 cm drift length active volume
- 242 low-activity Hamamatsu R8520-06-Al 1" square PMTs
- 98 tubes on top, 80 on bottom, 64 in the active veto
- Cathode at -16 kV, drift field of 0.533 kV/cm. Anode at 4.4 kV, proportional scintillation region with field ~12 kV/cm
- Installed in a 20 cm H_2O, 20 cm Pb, 20 cm polyethylene, 5 cm Cu passive shield to suppress external backgrounds
- Aprile *et al.*, Astropart. Phys. **35**, 573, 2012

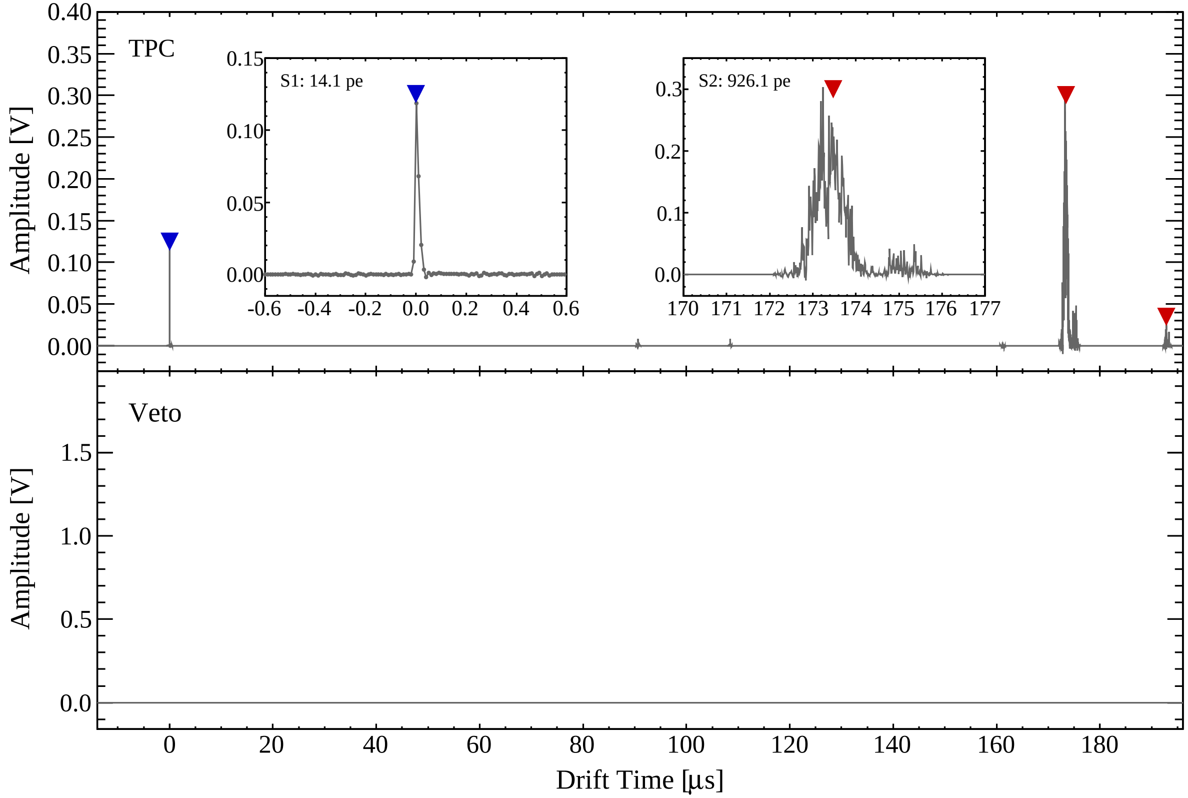


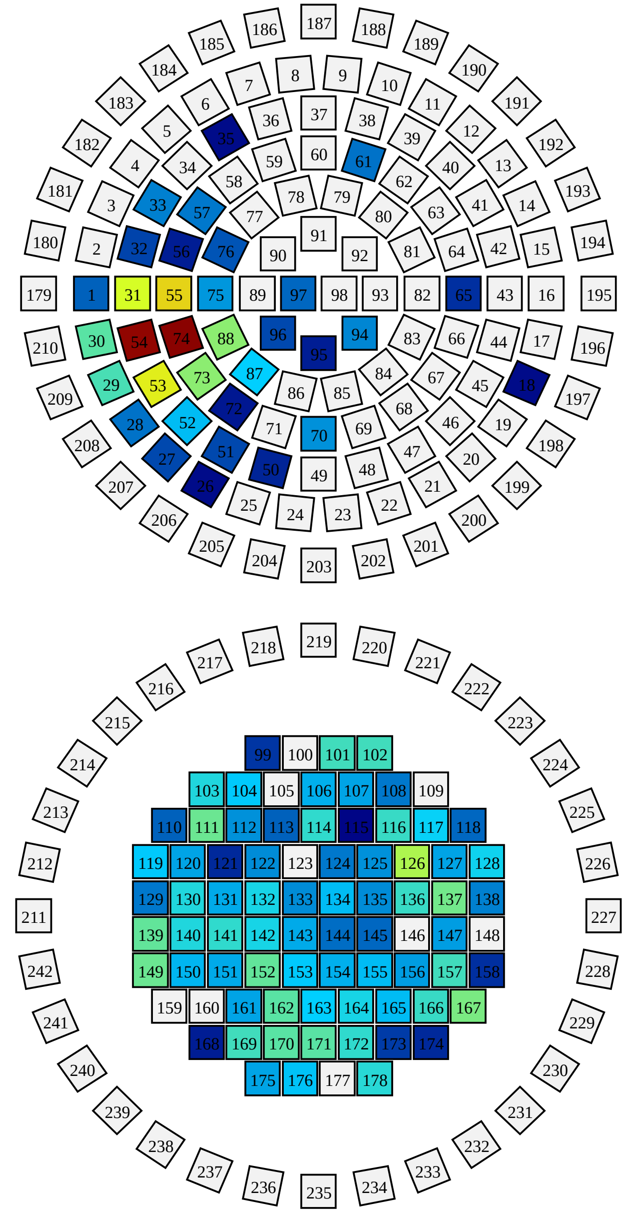


XENON100: LNGS

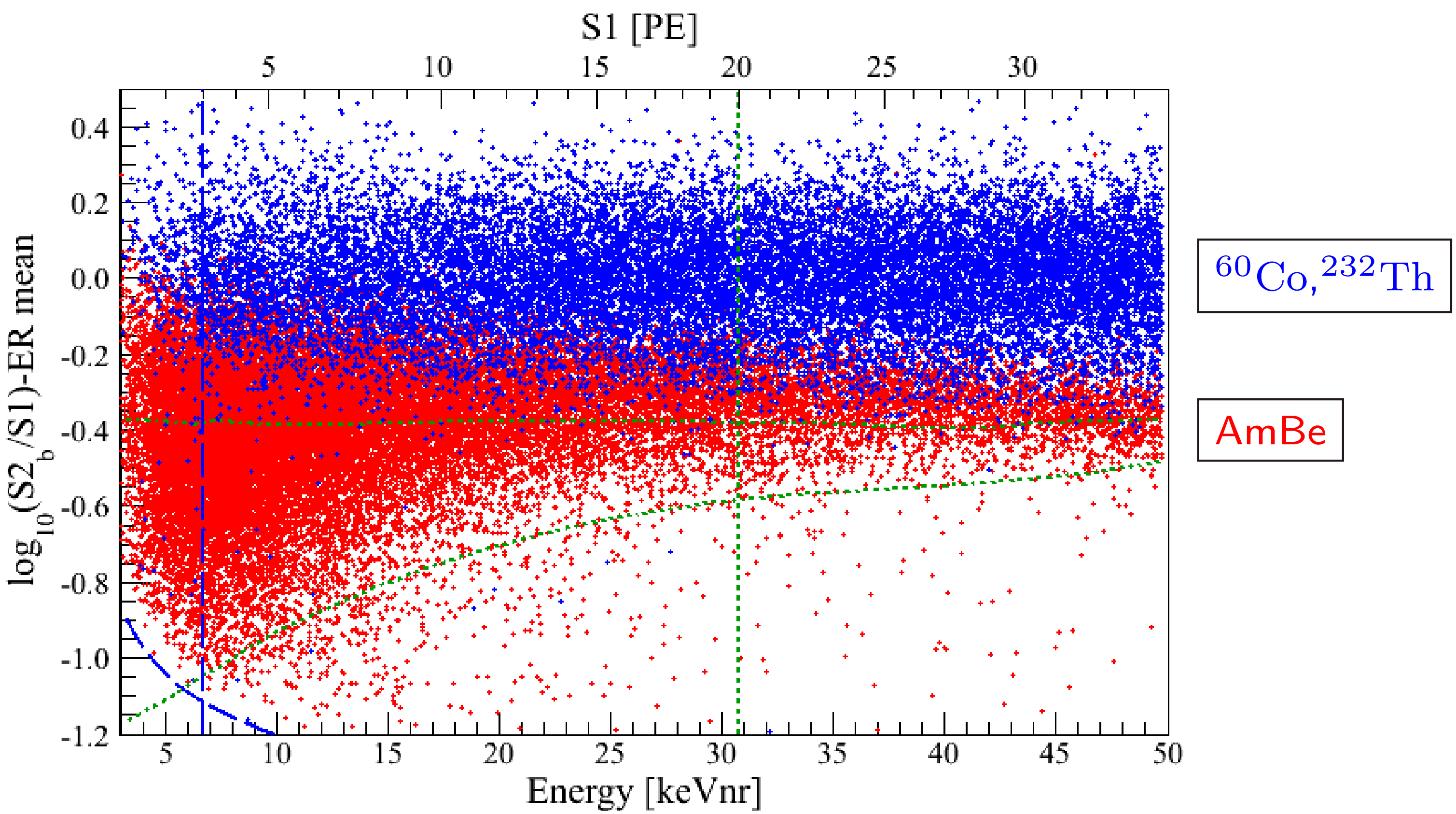


XENON100: Typical Low Energy Event





XENON100: ER/NR Discrimination



- Background in the energy region of interest is due to low energy Compton scatters from high energy gamma rays or β decays.
- Electronic recoil band calibration performed with high energy gammas from ^{60}Co and ^{232}Th. Nuclear recoil band calibration performed with AmBe neutron source.
- Since WIMPs are expected to elastically scatter off of nuclei understanding the behavior of single elastic nuclear recoils in Xe is essential.

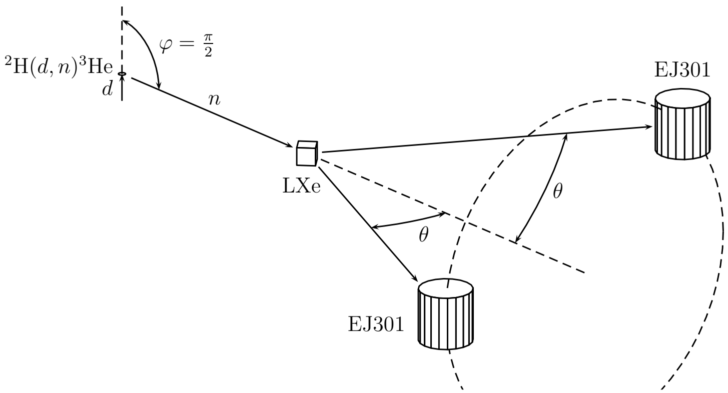
XENON100: Nuclear Recoil Energy Scale

- Nuclear recoil equivalent energy $E_{\rm nr}$ is obtained from the S1 signal

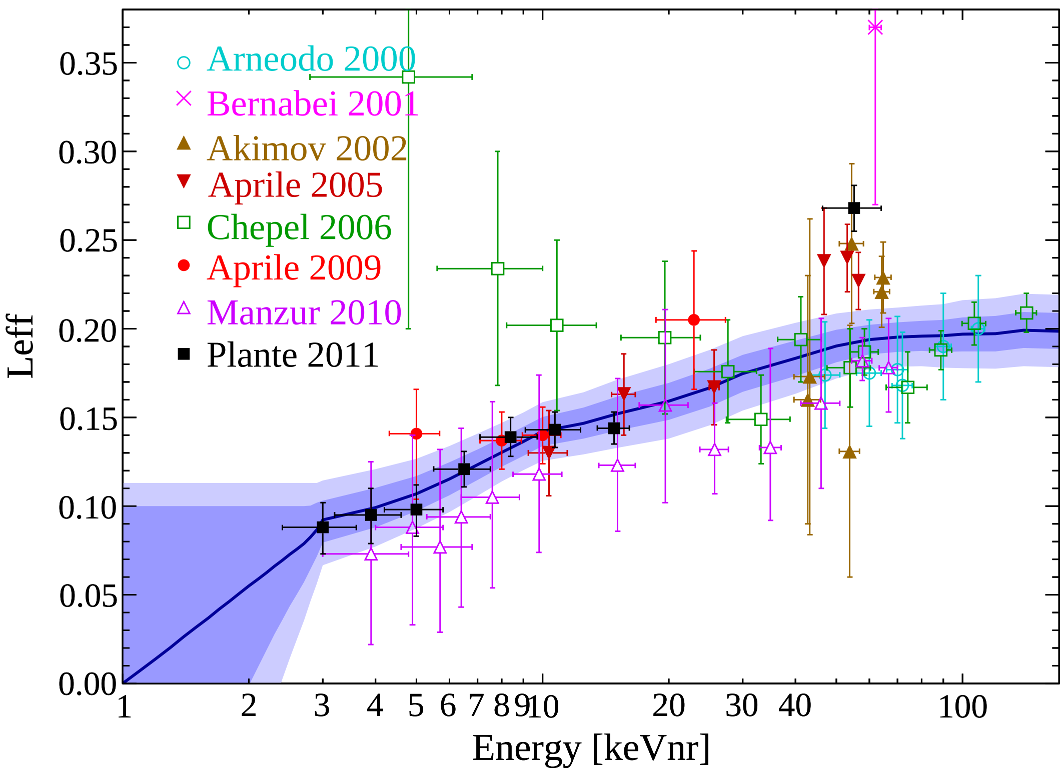
$$E_{\rm nr} = \frac{S1}{L_{y,\rm er}} \frac{1}{\mathcal{L}_{\rm eff}(E_{\rm nr})} \frac{S_{\rm er}}{S_{\rm nr}}$$

- $L_{y,\rm er} = 2.28 \pm 0.04\,\rm pe/keVee$, light yield of ER from 122 keV γ rays
- $S_{\rm er} = 0.58$, $S_{\rm nr} = 0.95$, scintillation light quenching due to drift field
- Relative scintillation efficiency $\mathcal{L}_{\rm eff}$

$$\mathcal{L}_{\rm eff}\left(E_{\rm nr}\right) = \frac{L_{y,\rm nr}\left(E_{\rm nr}\right)}{L_{y,\rm er}\left(E_{\rm ee} = 122\,\rm keV\right)}$$

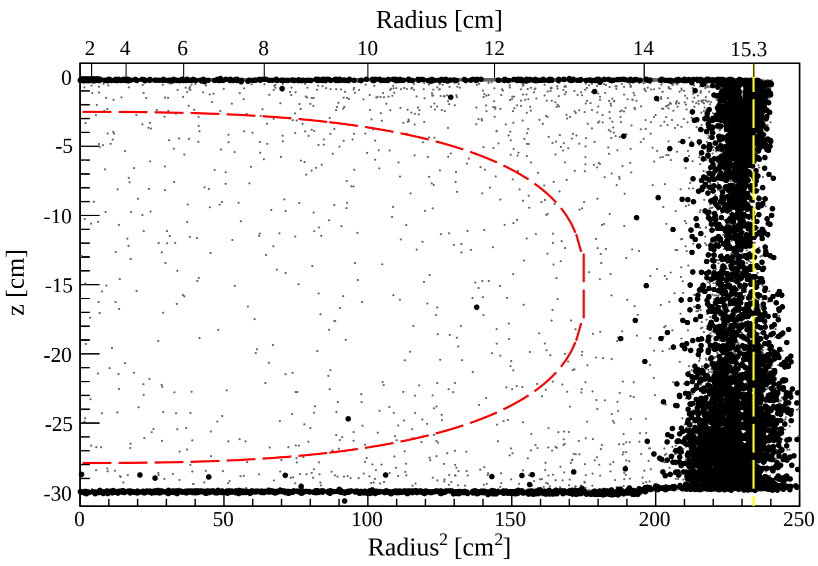


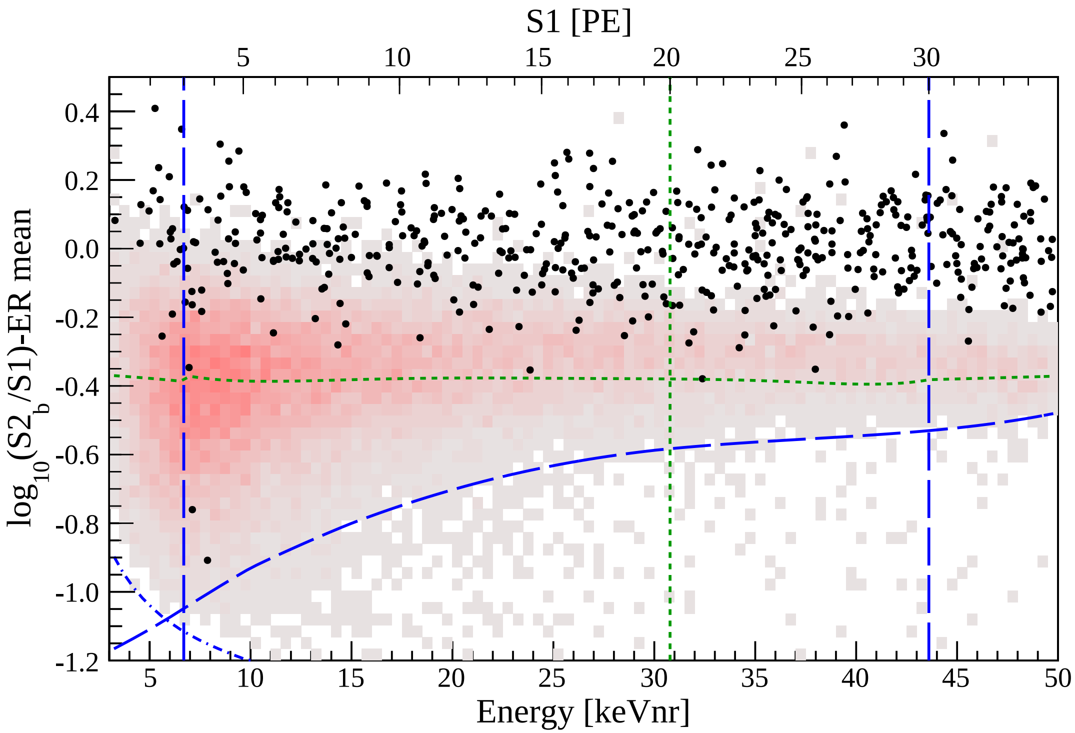
$$E_r \approx 2E_n \frac{m_n M_{\rm Xe}}{(m_n + M_{\rm Xe})^2}\,(1 - \cos\theta)$$



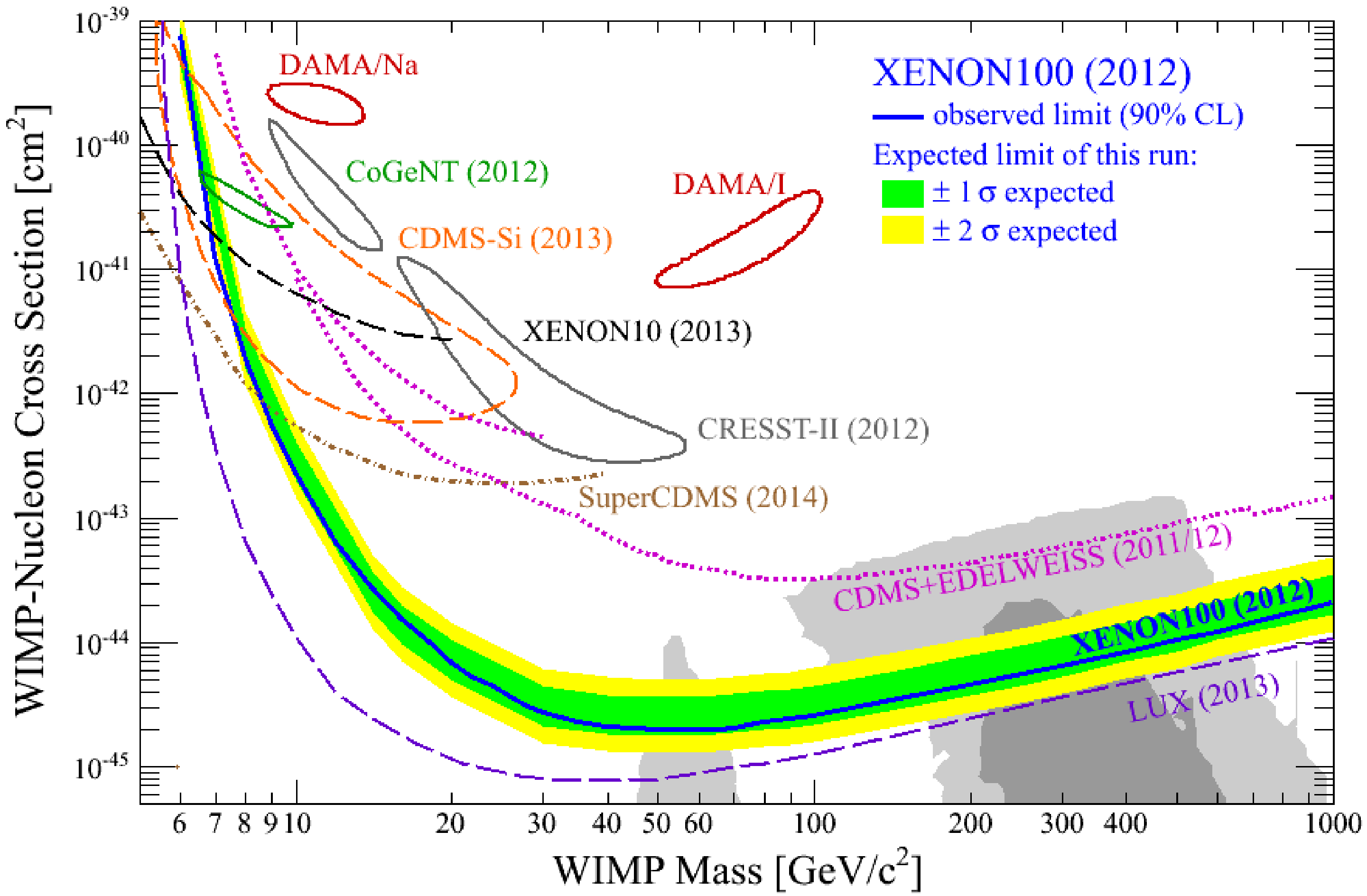
- Record fixed-angle elastic scatters of monoenergetic neutrons tagged by organic liquid scintillators with n/γ discrimination
- Measurement performed at Columbia University, lowest energy measured 3 keV
- Plante *et al.*, Phys. Rev. C **84**, 045805 (2011)

XENON100: Latest WIMP Search Data Released: 225 Days





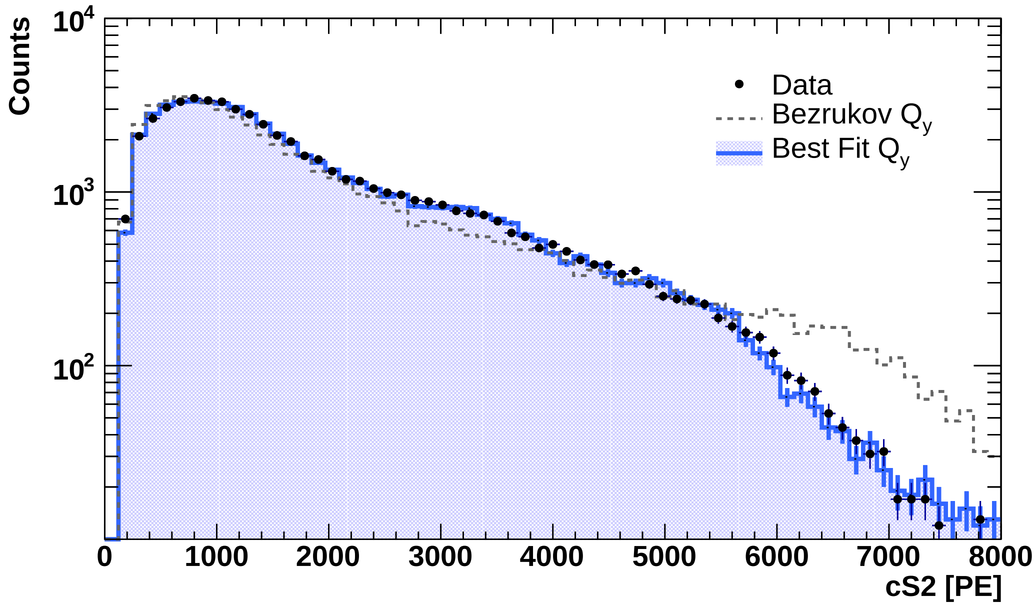
- 2 candidate events observed within 34 kg fiducial volume
- Probability that the background fluctuates to 2 events when expecting 1.0 ± 0.2 is 26.4%
- Profile Likelihood analysis cannot reject background-only hypothesis
- No evidence for a dark matter signal

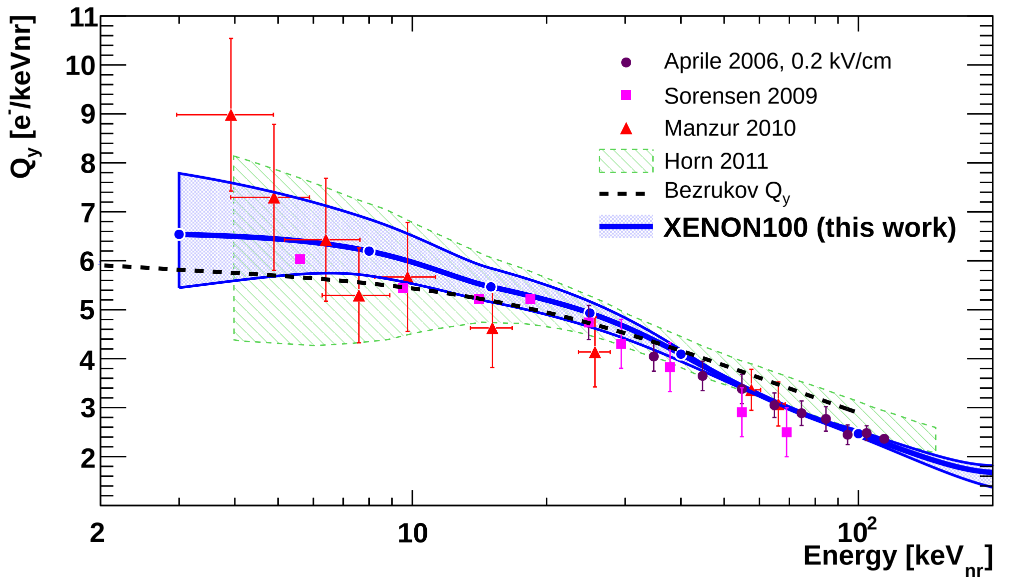


- Exclusion limits derived with profile likelihood method, $\sigma_{\mathrm{SI}} < 2.0 \times 10^{-45}\,\mathrm{cm}^2$ @ $50\,\mathrm{GeV}/c^2$
- Up until the latest LUX results (10/2013), was the strongest limit over a large WIMP mass range
- Aprile *et al.*, Phys. Rev. Lett. **109**, 181301 (2012)

XENON100: Response to Nuclear Recoils

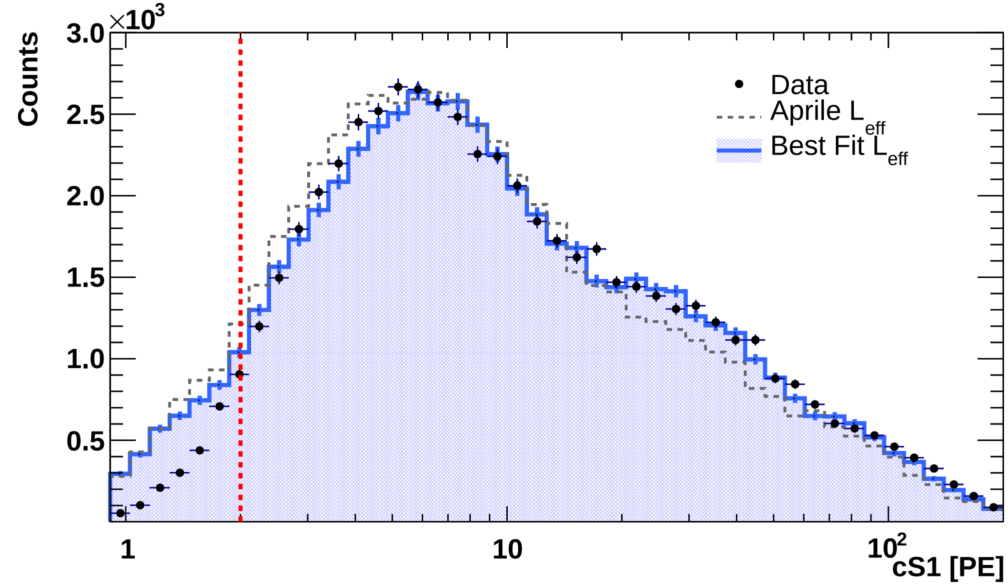
- Calculate the NR response
  - Start with $^{241}\mathrm{AmBe}$ neutron emission spectrum
  - Source strength measured (PTB) as $160 \pm 4\,\mathrm{n/s}$
  - Propagate neutrons through a detailed Geant4 detector geometry
  - Convert energy deposits into observable S1 and S2 signals using $\mathcal{L}_{\mathrm{eff}}$ and $\mathcal{Q}_y$, including thresholds, resolutions, and acceptances from data
- First step: use the measured $\mathcal{L}_{\mathrm{eff}}$ from scattering experiments and derive the optimum $\mathcal{Q}_y$ by reproducing the measured S2 spectrum
- Excellent agreement between MC and measured S2 spectrum
- E. Aprile *et al.*, Phys. Rev. D **88**, 012006 (2013)

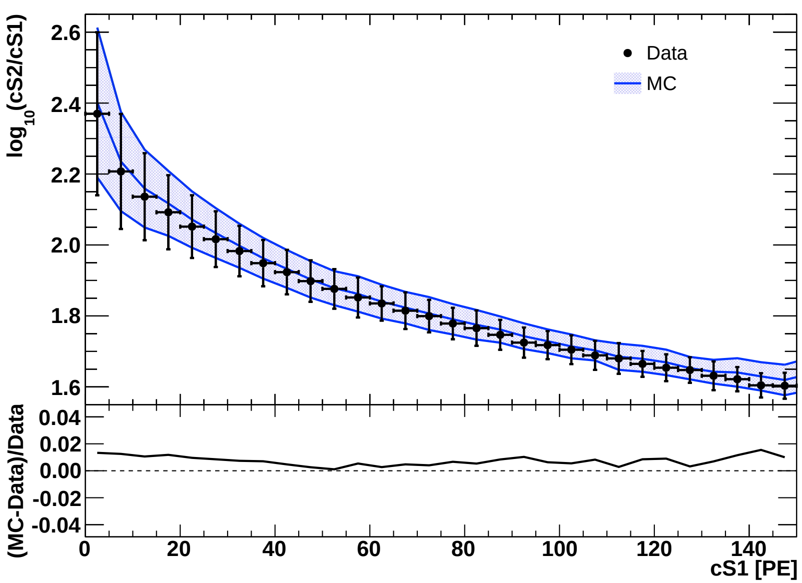


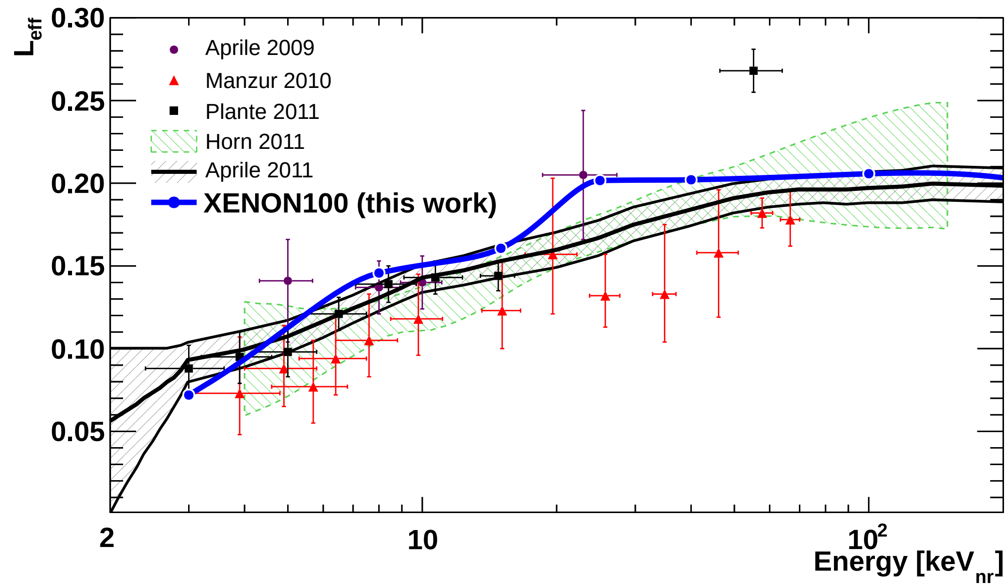


XENON100: Response to Nuclear Recoils

- Second step: use the optimum $\mathcal{Q}_y$ obtained to calculate the MC S1 spectrum and derive a new $\mathcal{L}_{\mathrm{eff}}$
- Excellent agreement between measured S1 spectrum and MC down to 2 pe
- Indirect $\mathcal{L}_{\mathrm{eff}}$ obtained consistent with direct measurements
- Confirms robustness of the XENON100 $\mathcal{L}_{\mathrm{eff}}$ parametrization down to 3 keVr







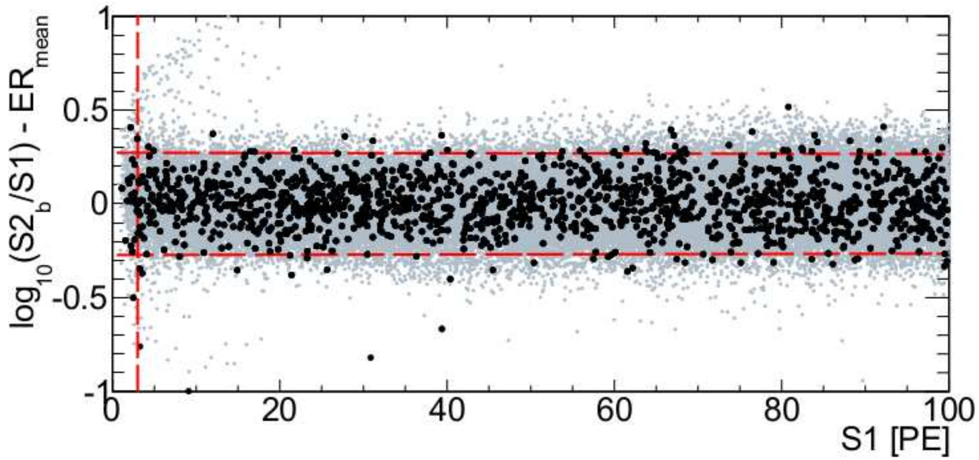
XENON100: Axion Searches

Xe XENON Dark Matter Project

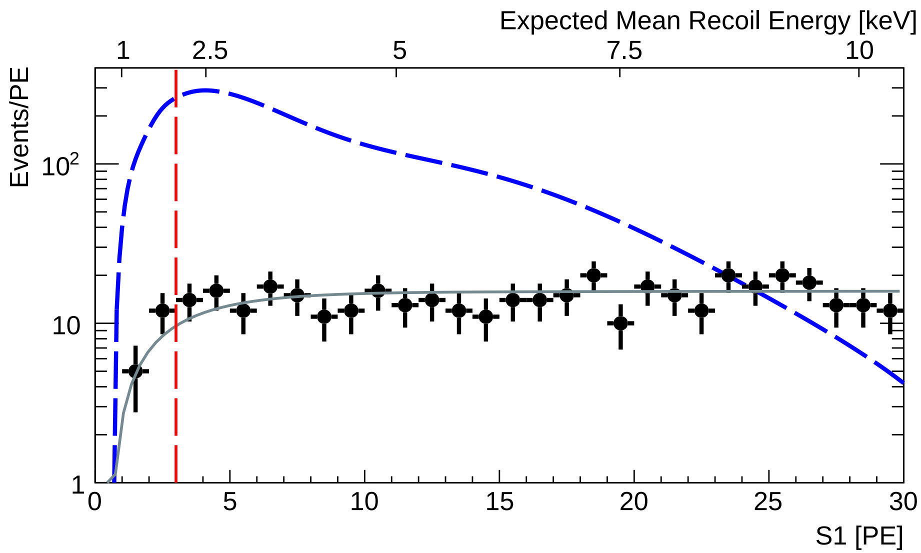
- Axions and axion-like particles can couple to electrons via the axio-electric effect

$$\sigma_{Ae} = \sigma_{pe}(E)\frac{{g_{Ae}}^2}{\beta}\frac{3E^2}{16\pi\alpha {m_e}^2}\left(1-\frac{\beta^{2/3}}{3}\right)$$

- Analogous to the photoelectric effect with an absorbed axion instead of a photon
- Expect electronic recoils from axio-electric interactions

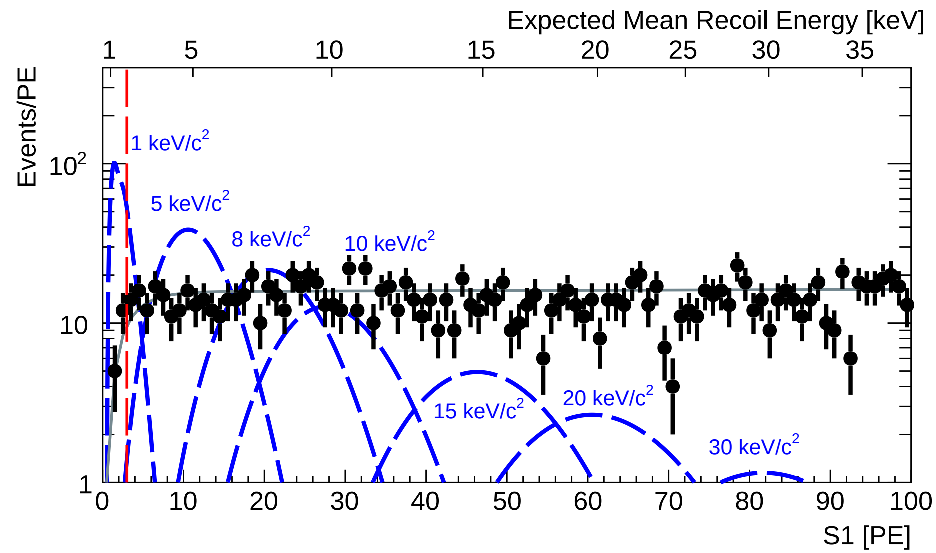


Solar axions



Expected signal for $m_A < 1\,\mathrm{keV}/c^2$ and $g_{Ae} = 2\times10^{-11}$

Galactic axion-like particles



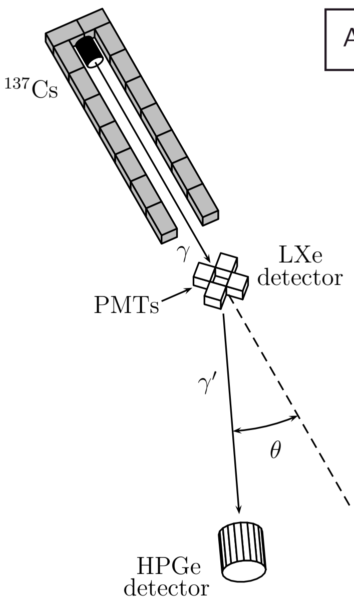
Expected signal assuming ALP constitute all of galactic DM and $g_{Ae} = 4\times10^{-12}$

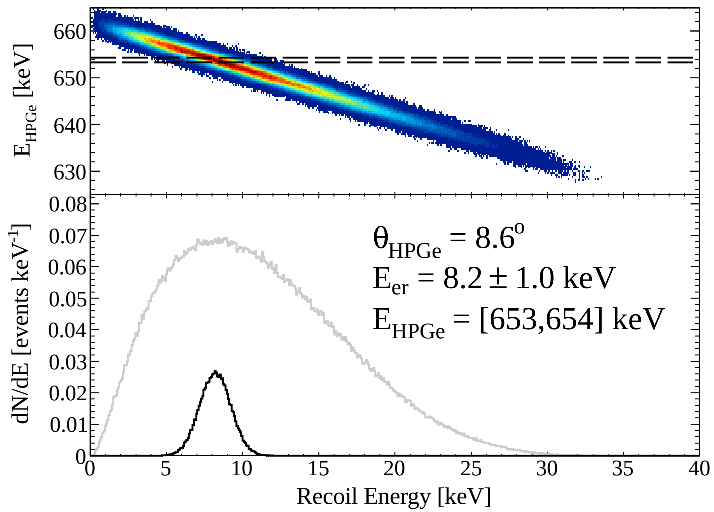
XENON100: Electronic Recoil Energy Scale

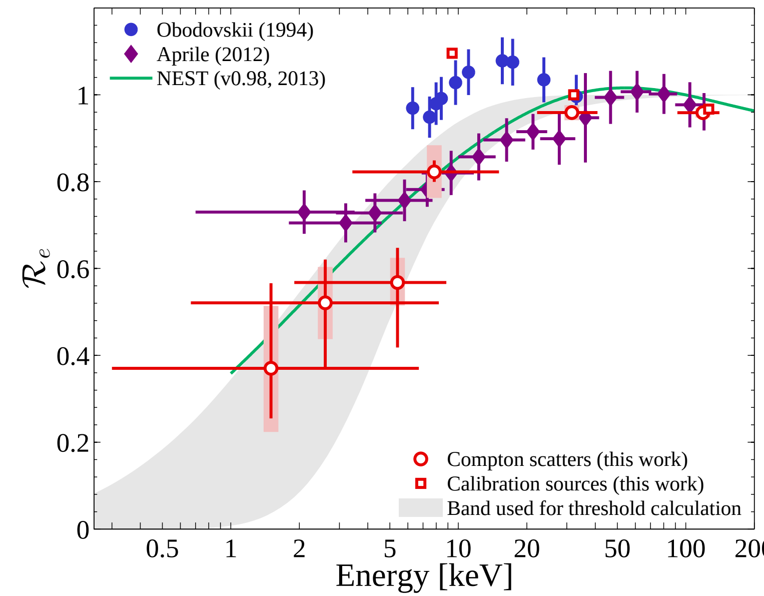
- Need to know the response of LXe to low energy ER
- Two recent measurements of the scintillation yield of ER using the "Compton coincidence technique"

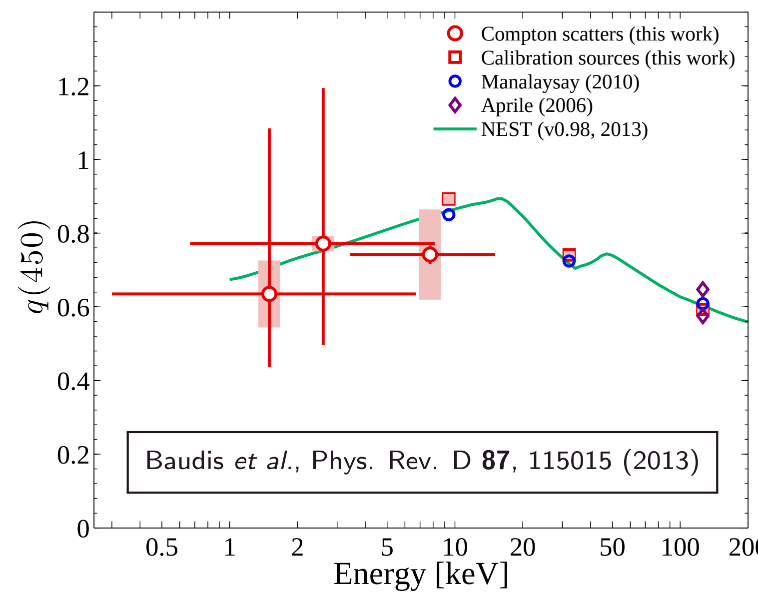
$$E_r = E_\gamma - \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e}(1 - \cos\theta)}$$

Aprile *et al.*, Phys. Rev. D **86**, 112004 (2012)





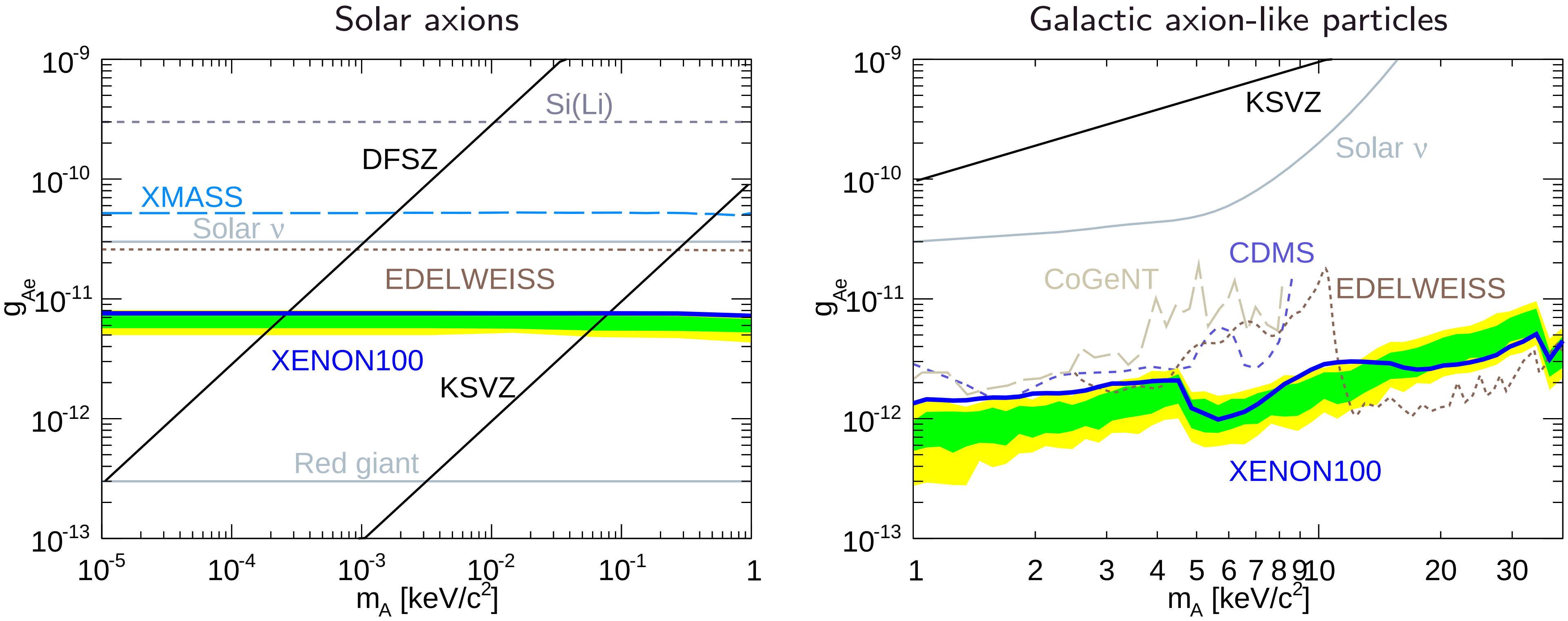




- At zero field, scintillation yield decreases below $60\,\mathrm{keV}$
- Field quenching ~ 0.75 at low energies
- XENON100 energy threshold $2.04 \pm 0.21\,\mathrm{keV}$

XENON100: First Axion Search Results

- Uses the same 225 days data as for spin-independent WIMP search
- Profile Likelihood analysis cannot reject background-only hypothesis
- Ultra-low background and low energy threshold enable XENON100 to set competitive limits
- Analysis made possible by recent measurements of scintillation yield and field quenching of ERs

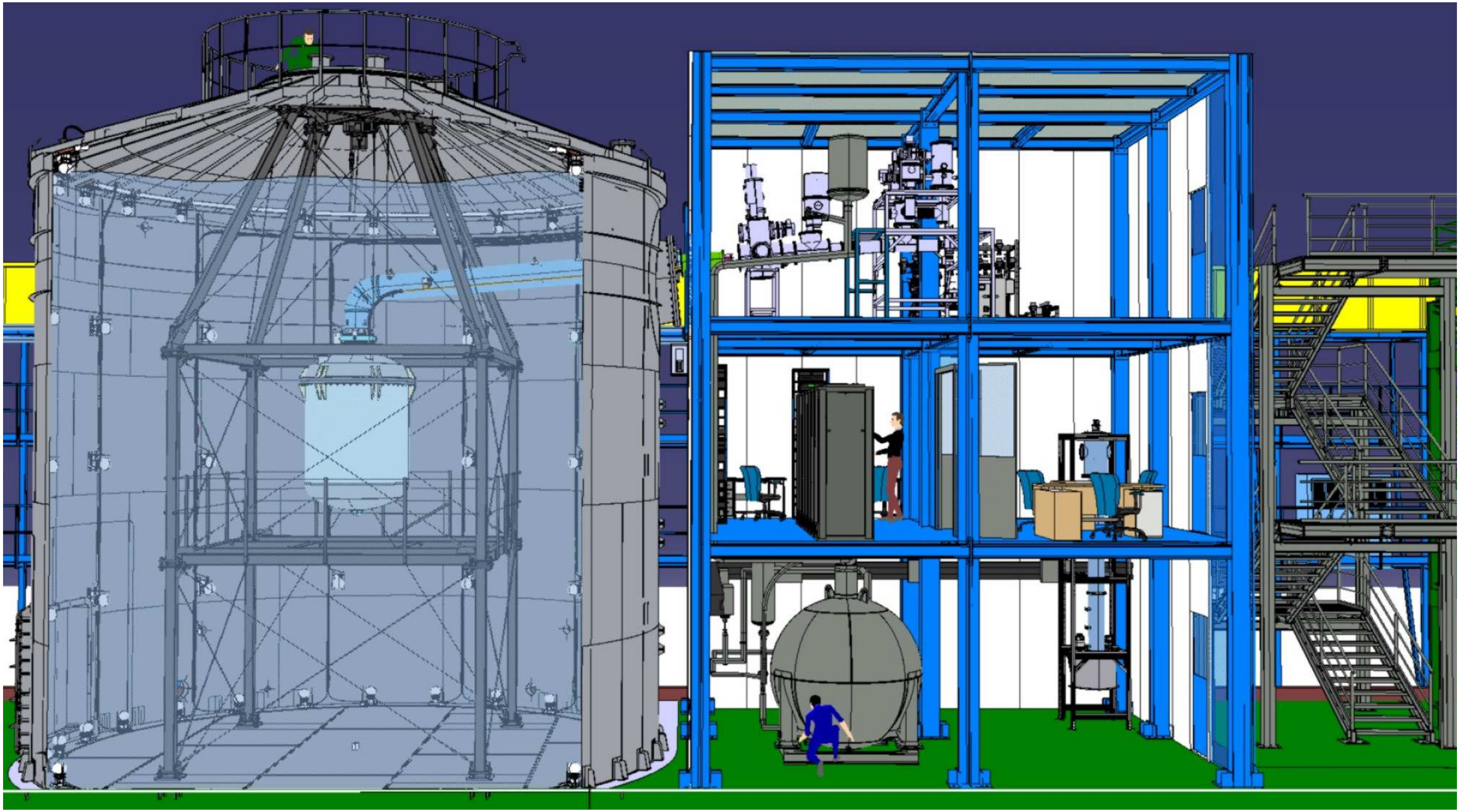


E. Aprile *et al.*, Phys. Rev. D **90**, 062009 (2014)

XENON100: Status

- Upcoming analysis results
  - Electronic recoil rate stability analysis
  - Light dark matter ("few electrons" S2-only analysis)
  - WIMP-nucleus inelastic interactions
  - 154 days of new DM data in 2013 (blinded) under analysis
- Improvements in detector characterization
  - Calibrations with AmBe at different drift fields
  - Measurement of low-energy ($<5\,\mathrm{keVr}$) NRs from YBe
- Continuing data acquisition
  - Online Rn removal tests
  - Novel calibration methods

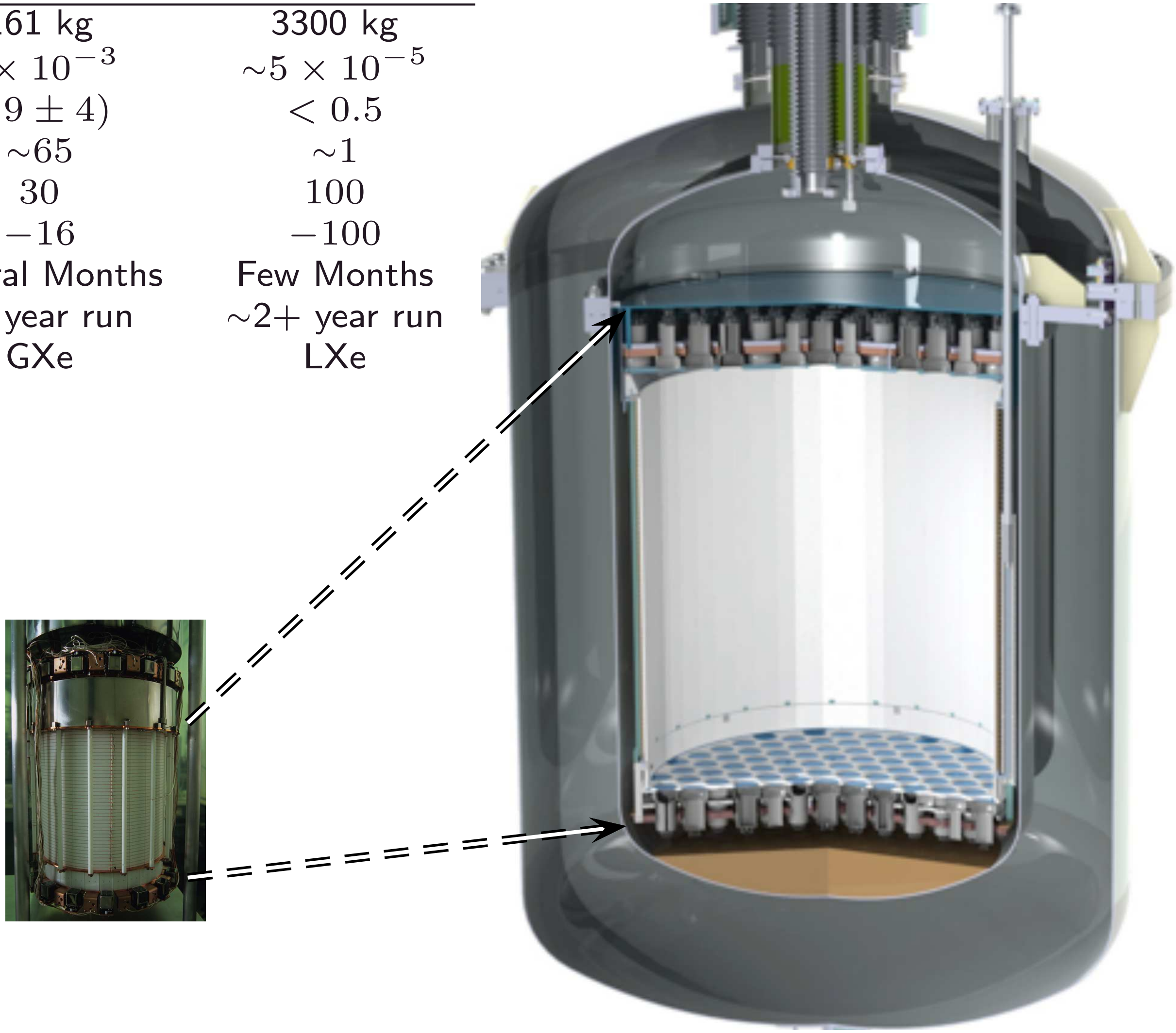
XENON1T: (Very Near) Future



XENON1T: (Very Near) Future

From XENON100 to XENON1T: A Few of the Challenges

	XENON100	XENON1T
LXe Mass (kg)	161 kg	3300 kg
ER Bkgnd (evts/keV/kg/d)	5×10^{-3}	$\sim 5 \times 10^{-5}$
Kr Concentration (ppt)	(19 ± 4)	< 0.5
Rn Concentration (μBq/kg)	~ 65	~ 1
Charge drift (cm)	30	100
Cathode HV (kV)	-16	-100
LXe Purification	Several Months	Few Months
Cryogenics	~1 year run	~2+ year run
Storage/Recovery	GXe	LXe



XENON1T: Construction Milestones

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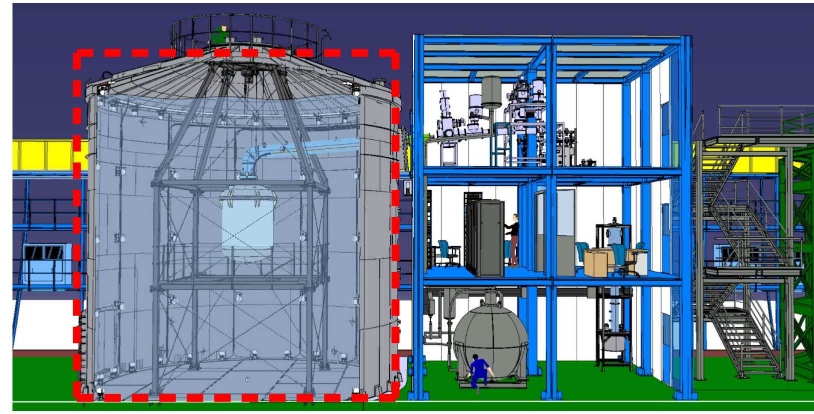
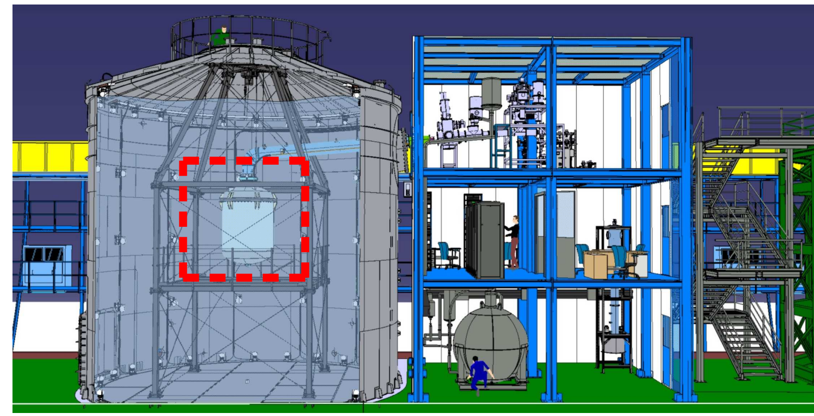
XENON1T: Water Cherenkov Muon Veto



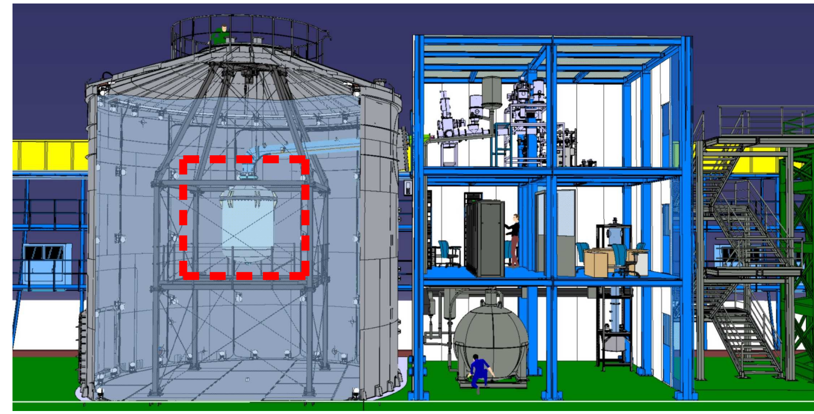
- Water tank $10\,\mathrm{m}$ high and $9.6\,\mathrm{m}$ diameter
- Interior lined with 3M specular reflector foil
- Water tank construction completed 2013/12
- 84 high QE 8" Hamamatsu R5912 PMTs
- μ-induced neutron background < 0.01 evt/yr
- Trigger efficiency $> 99.5\%$ for neutrons with μ in water tank, ~78% with μ outside

XENON1T: Cryostat, TPC



- Double-wall vacuum insulated cryostat, constructed from selected low-activity stainless steel
- Outer vessel $2.4\,\mathrm{m}$ high, $1.6\,\mathrm{m}$ diameter, inner vessel $\sim 2\,\mathrm{m}$ high, $1.1\,\mathrm{m}$ diameter
- 3.3 tons LXe, $\sim 1\,\mathrm{m}^3$ TPC, fiducial mass between 1 and 1.5 tons
- 248 3" PMTs Hamamatsu R11410-21, 36% average QE, $< 1\,\mathrm{mBq/PMT}$ in U/Th
- Background $\times 100$ lower than XENON100
- Custom low-activity high voltage feedthrough

XENON1T: Cryostat, TPC



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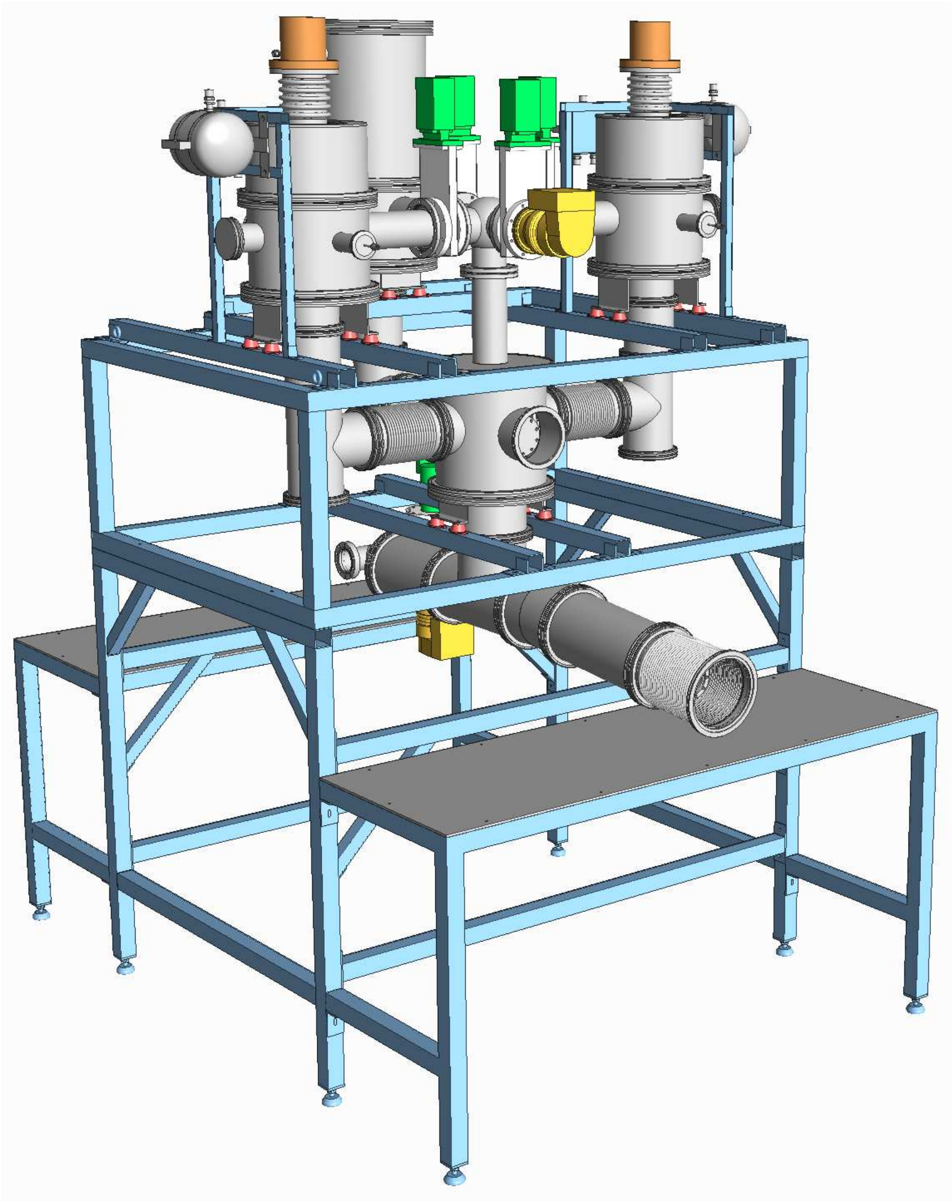
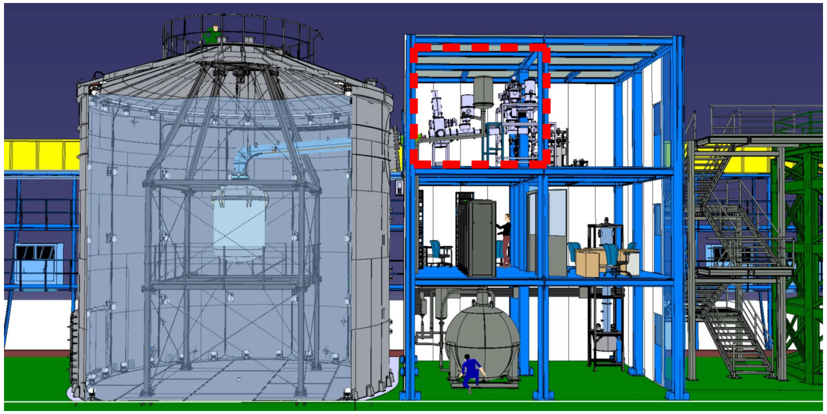
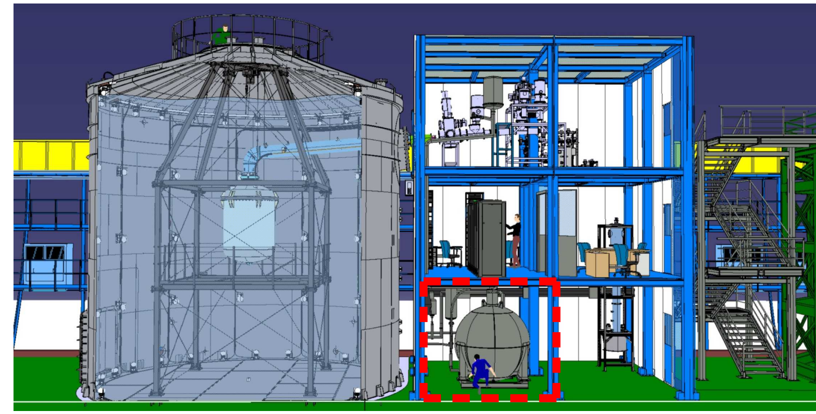
XENON1T: Cryogenics





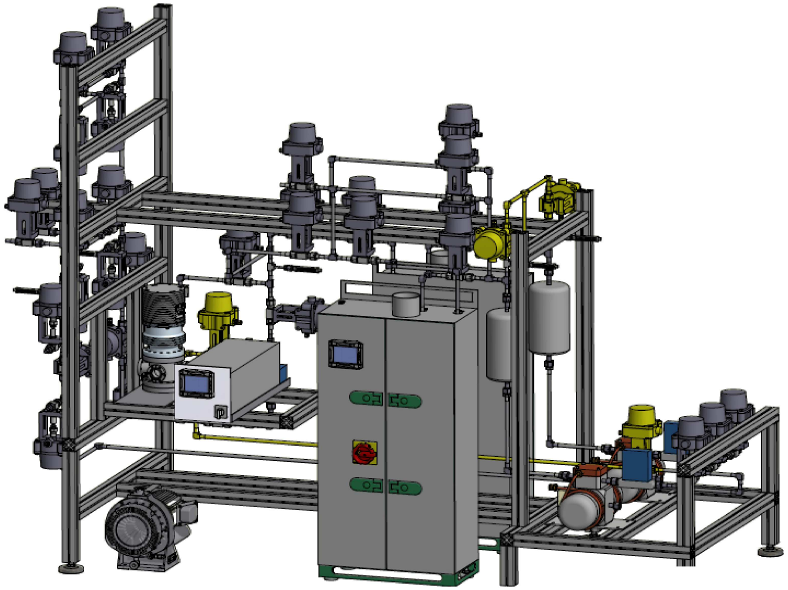
- Design based on experience acquired by operating XENON10, XENON100, and XENON1T Demonstrator
- Heat load below 50 W (without circulation)
- Redundant 200 W pulse tube refrigerators
- One PTR can be serviced while the other is in operation
- Backup liquid nitrogen cooling
- Circulation at ∼100 slpm through heat ex-changers

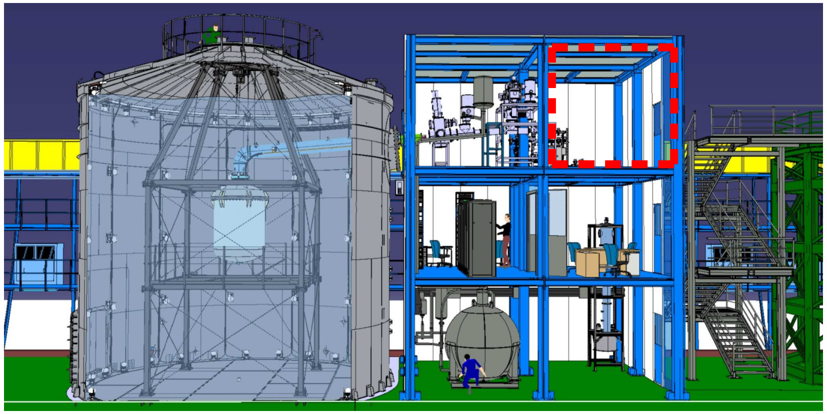
XENON1T: Xe Storage



- Double-wall, high-pressure (70 atm), vacuum insulated, LN2 cooled sphere
- Designed to store ∼7.6 tons of xenon, in liquid form at $-100°\mathrm{C}$ or in gaseous form at room temperature
- Detector can be filled with liquid xenon directly instead of condensing xenon gas
- In case of emergency, liquid xenon from the detector can be recovered in a few hours

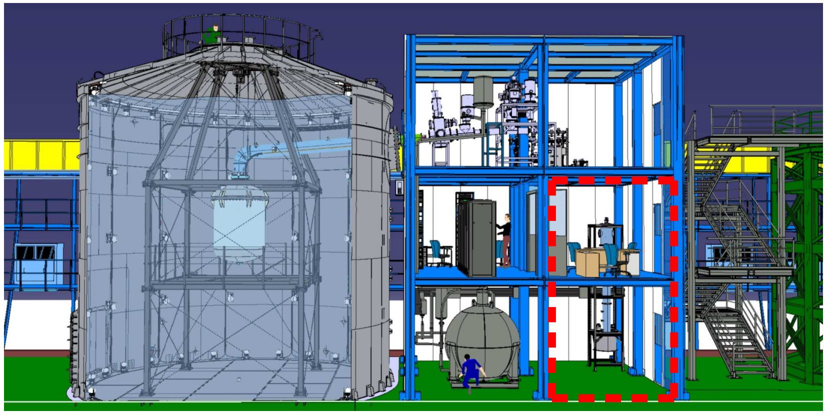
XENON1T: Purification



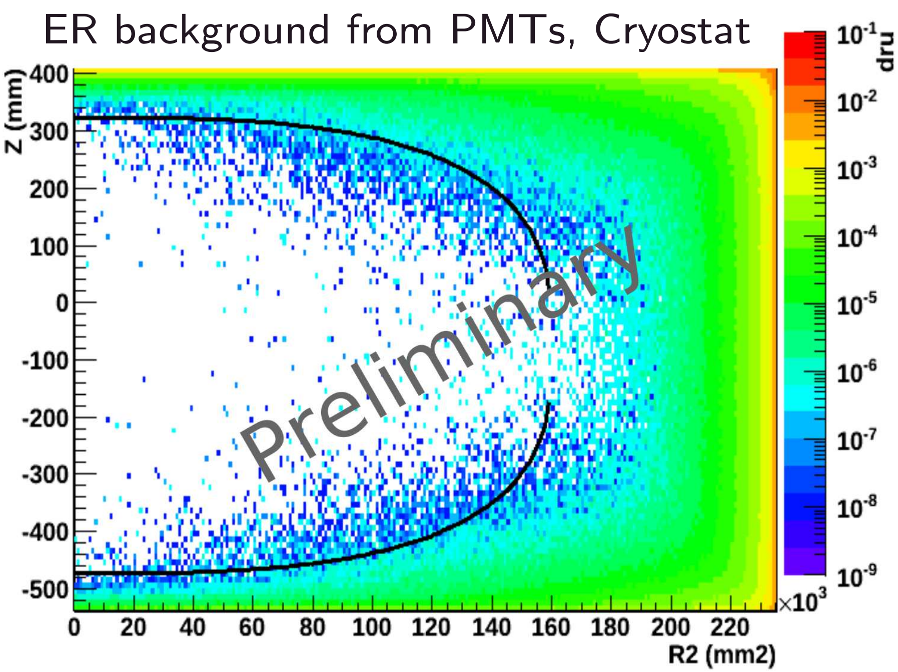


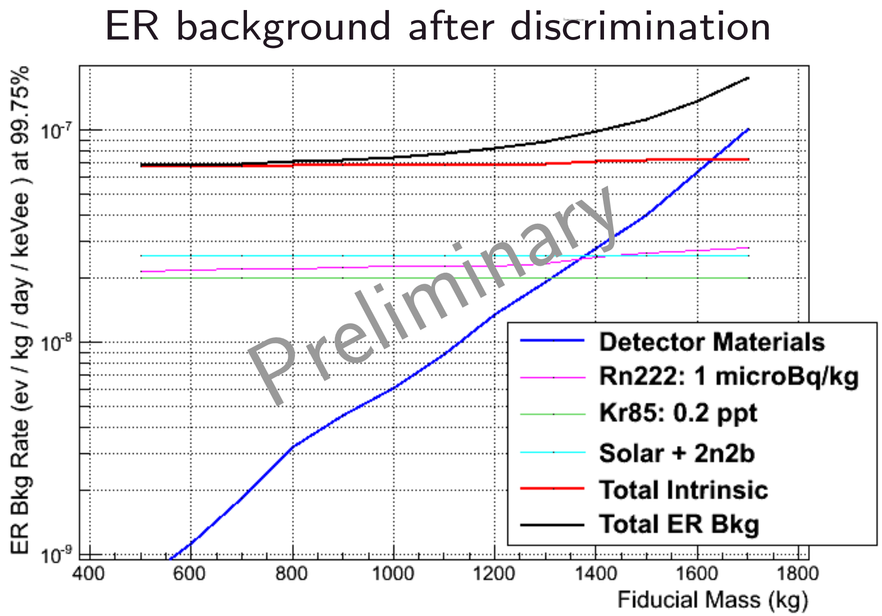
- Continuous GXe circulation at ~100 slpm
- Purification using high-flow heated getters
- Two parallel circulation pumps and purification circuits
- GXe purity in-situ analytics
- Continuous monitoring of impurity concentrations (e.g. H_2O)

XENON1T: Kr Removal



- Building custom designed cryogenic distillation column for Kr removal
- XENON1T Kr/Xe concentration requirement is $< 0.5\,\mathrm{ppt}$, aim at $< 0.1\,\mathrm{ppt}$ with the column
- High throughput, $3\,\mathrm{kg/hr}$ at 10^4 separation
- 3.5 tons in ~1.8 months (single pass)
- Custom gas purity diagnostics (online, $^{83m}\mathrm{Kr}$ tracer, and offline, ATTA, RGMS, RGA + cold trap)



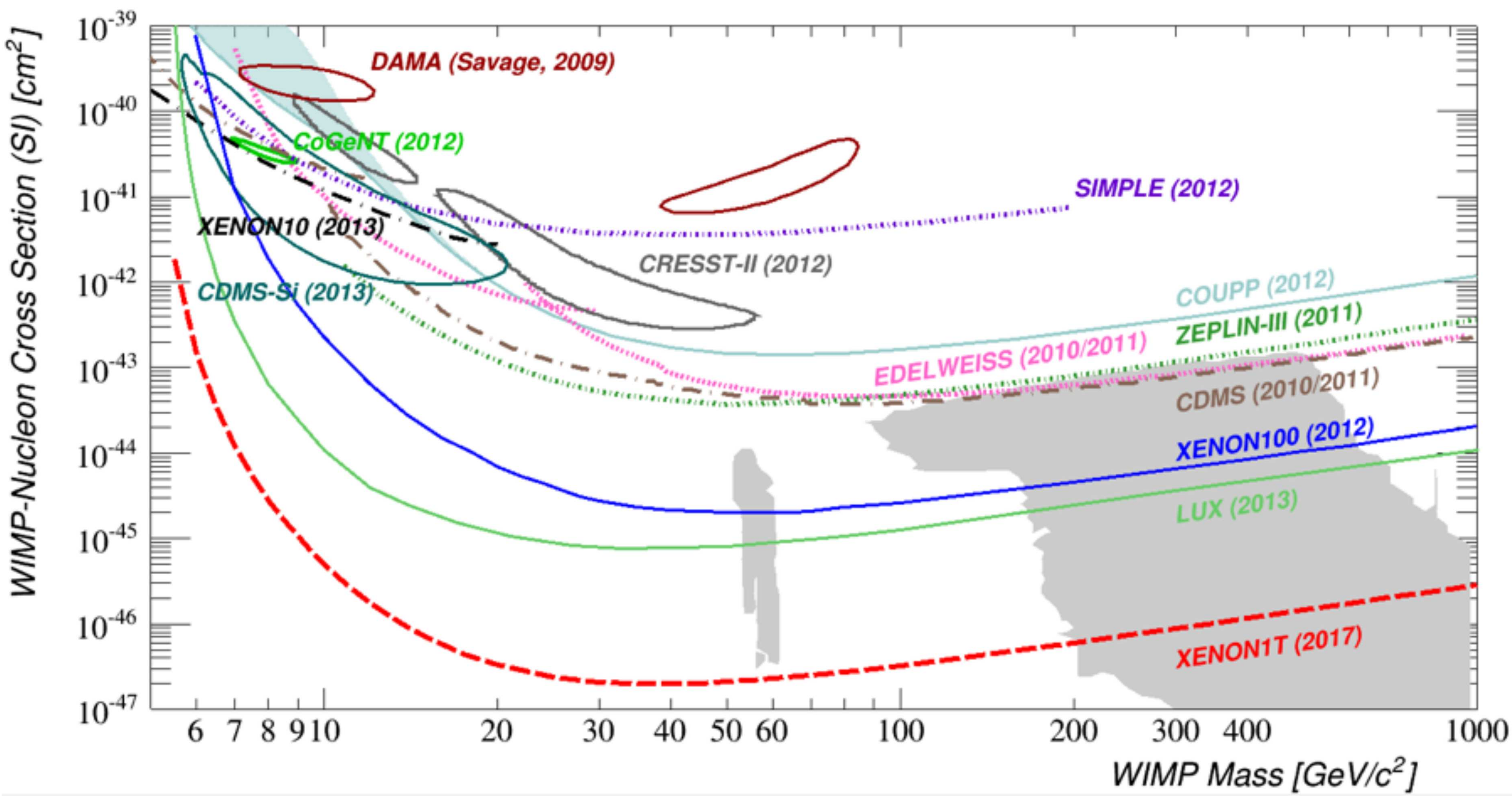


- Full MC simulation of the detector (TPC, PMTs, cryostat, water shield) with GEANT4 to predict ER background
- Neutrons from (α, n) calculated with SOURCES-4A
- Total ER background rate expected to be below $5 \times 10^{-5}\,\mathrm{evts/keV_{ee}/kg/day}$ before S2/S1 discrimination

- Single scatters, 1 ton fiducial volume, $[2, 12]$ keVee, $[5, 50]$ keVr, 99.75% S2/S1 discrimination, 40% NR acceptance

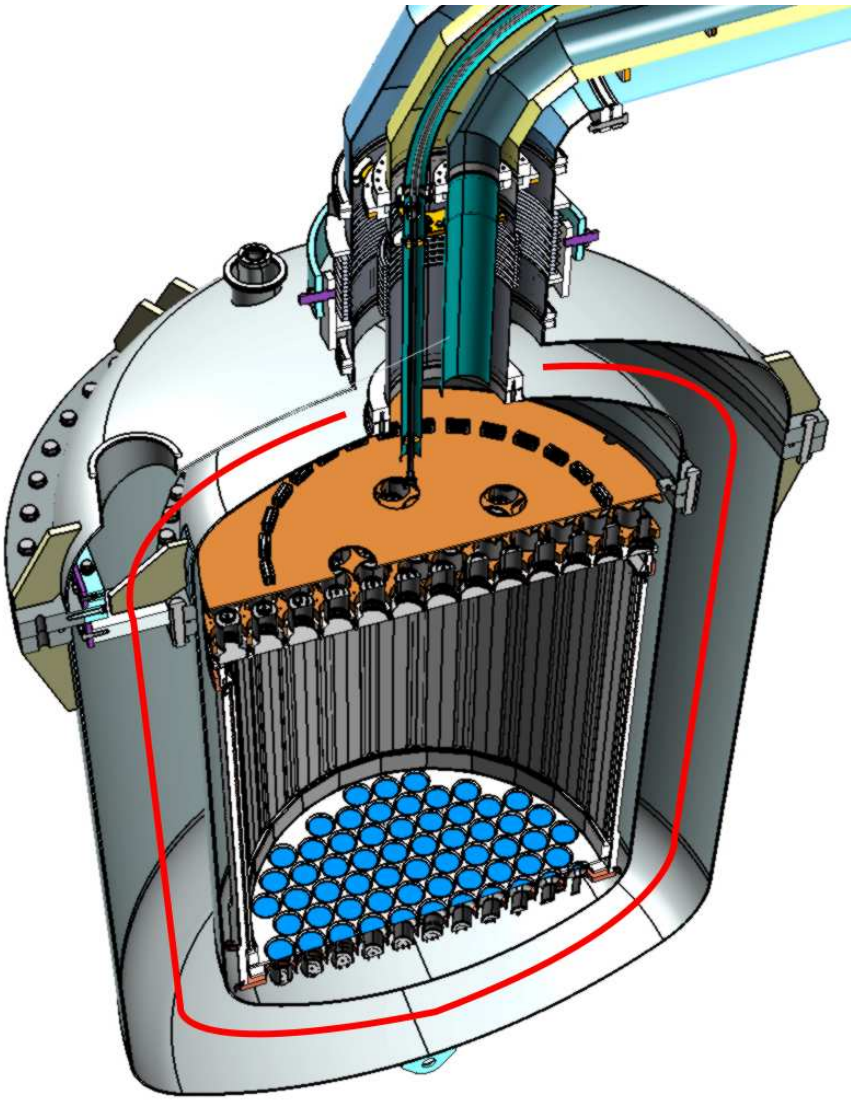
Source	Background (evts/yr)
ER from materials	0.05
$^{85}\mathrm{Kr}$ (0.2 ppt $^{\mathrm{nat}}\mathrm{Kr}$)	0.07
$^{222}\mathrm{Rn}$ (1 μBq/kg)	0.08
Solar neutrinos	0.08
$2\nu2\beta$	0.02
NR from materials	0.24
Total	0.54

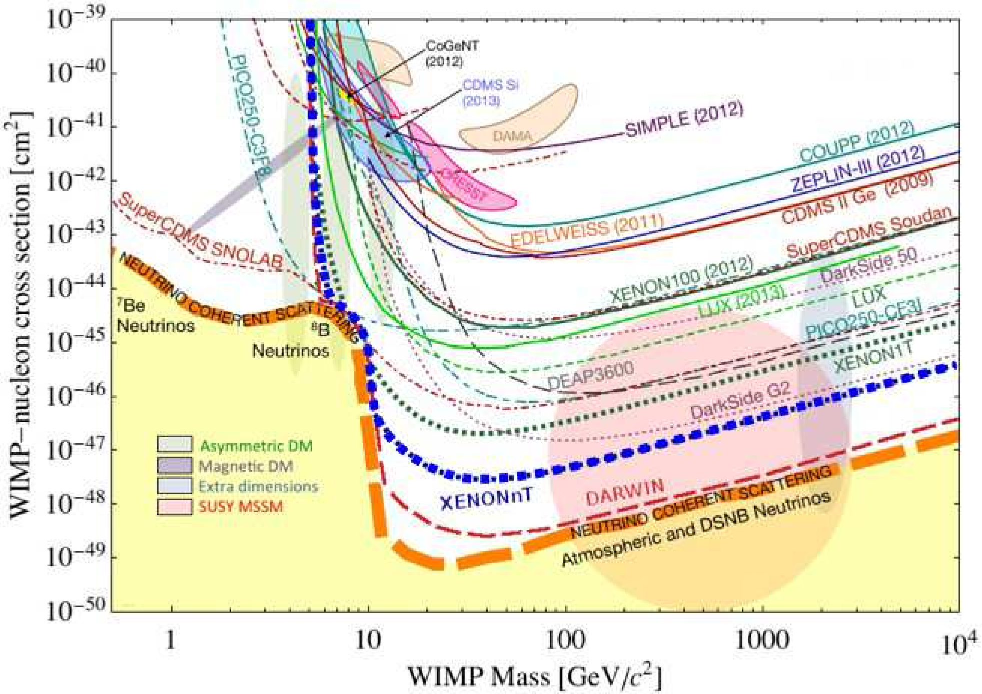
XENON1T: Sensitivity



- Spin-independent WIMP-nucleon interaction cross section sensitivity of $2 \times 10^{-47}\,\mathrm{cm}^2$ for WIMPs with a mass of $50\,\mathrm{GeV}/c^2$

XENONnT: Upgraded XENON1T Detector





- Rapid deployment possibility: no modifications to infrastructure required, only construction of a larger inner vessel and TPC
- Additional ~200 PMTs and DAQ electronics channels for the upgraded TPC
- Target mass of ~6 tons, sensitivity to spin-independent WIMP-nucleon elastic scattering cross sections of $3 \times 10^{-48}\,\mathrm{cm}^2$

Conclusion

- XENON100 recent results on axion searches, stay tuned for more results
- XENON100 is still taking data, continuing to improve detector characterization
- XENON1T is under construction at LNGS, water tank completed, service building completed
- Integration and commissionning of primary systems (cryostat, cryogenics, storage, purification) underway, detector installation by mid-2015
- Detector commissionning in 2015, first science run starts in 2015
- XENONnT, possibility of a rapid upgrade path included in the XENON1T design