First Results from the XENON1T Dark Matter Experiment @LNGS

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(on behalf of the XENON collaboration)

Seminar @ LNGS
May 30th, 2017

XENON World

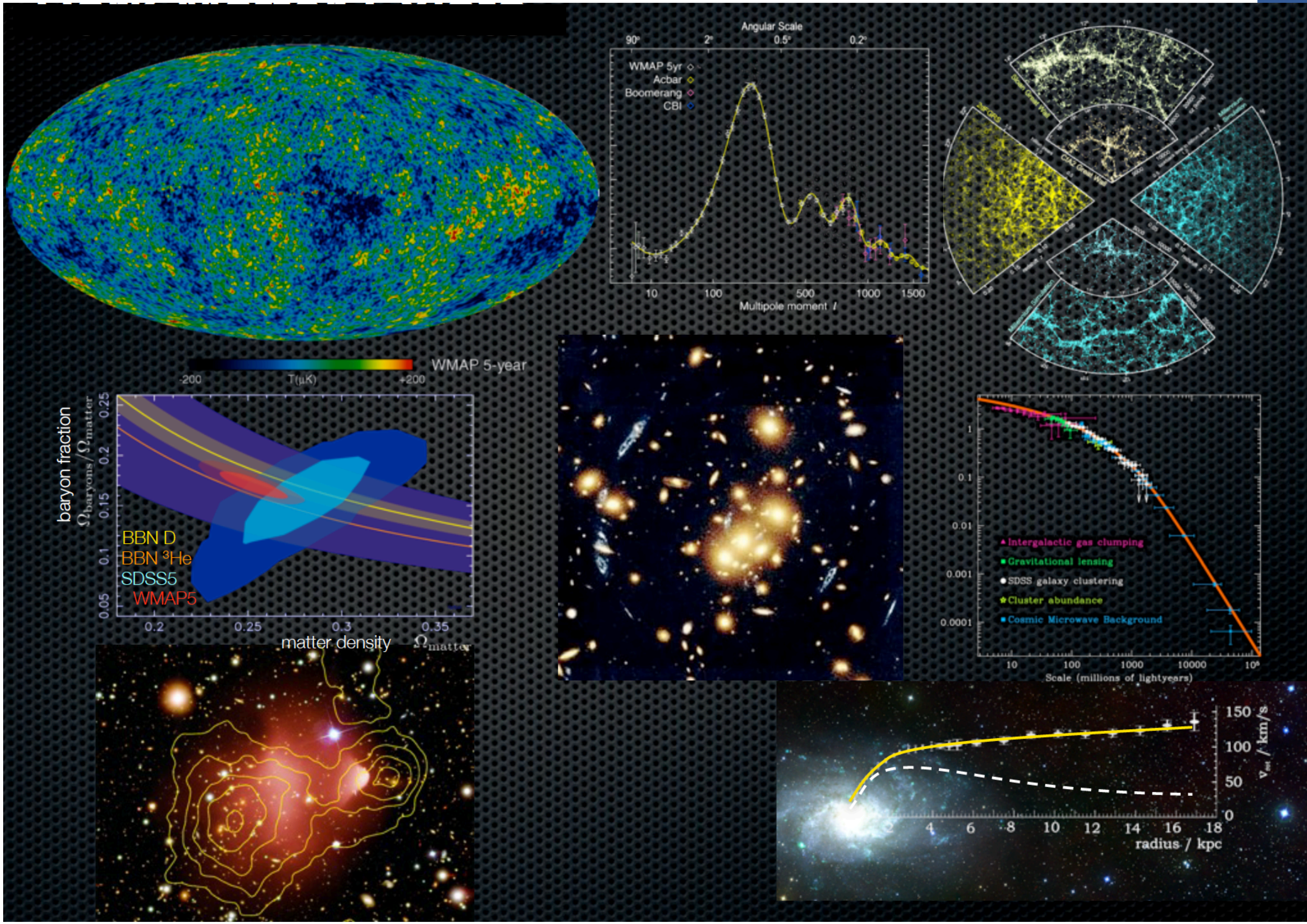
Columbia | RPI | Nikhef | Stockholm | Muenster | Mainz

Chicago | UCLA | UCSD | Rice

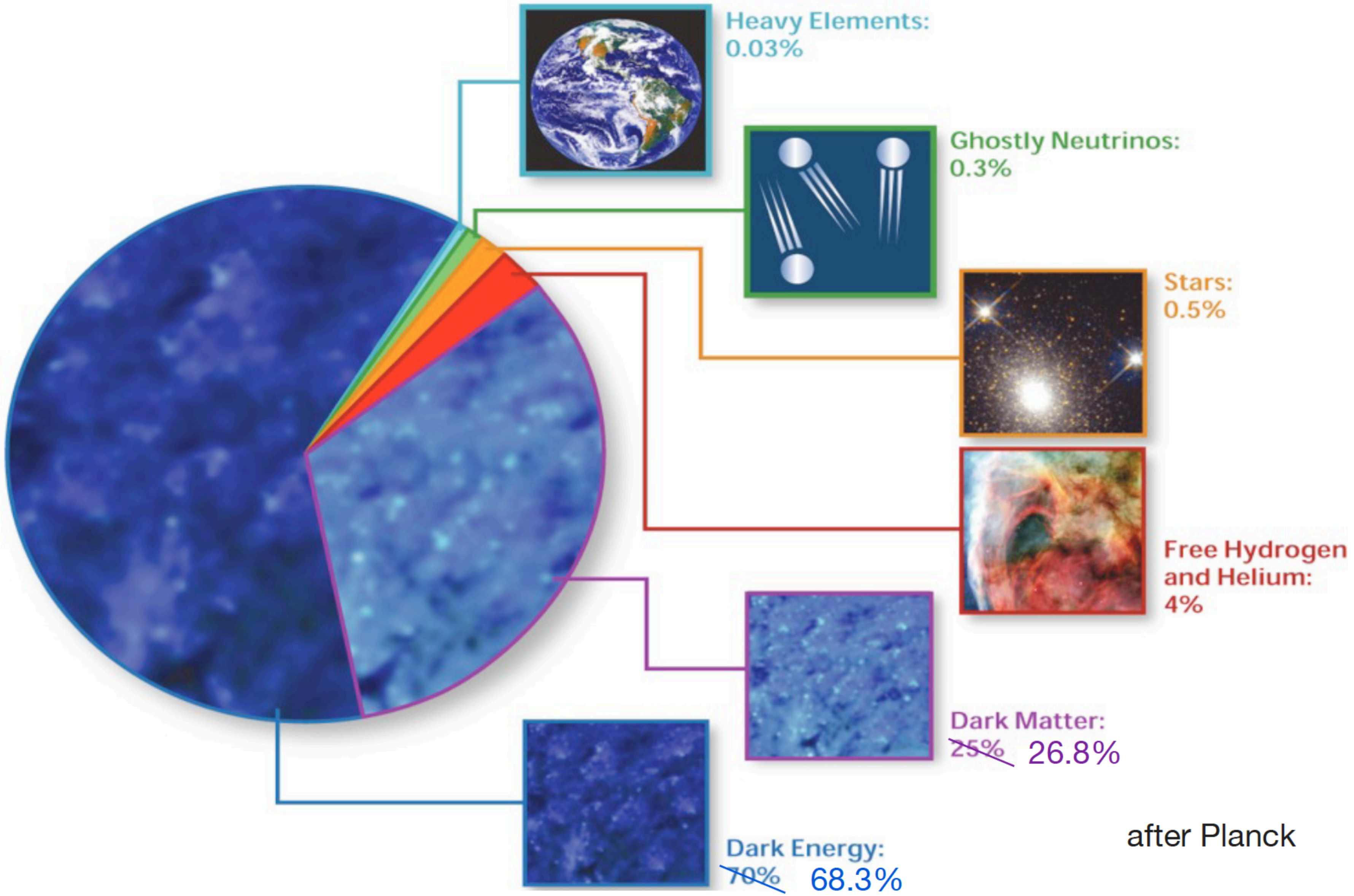
MPIK | Freiburg | Zurich | NYUAD

Purdue | Coimbra | Subatech | LPNHE | Bologna | LNGS | Torino | Weizmann

Dark Matter exists



… and it dominates the Universe Matter budget

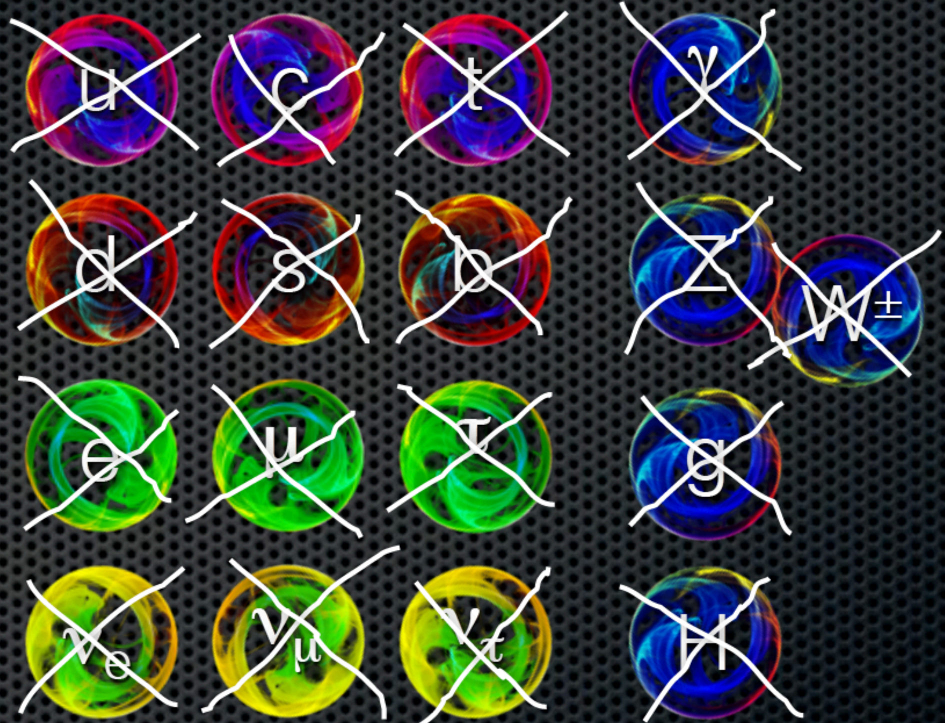


after Planck

… but what is it made of ?

We know Dark Matter has to be

- neutral
- cold
- stable
- no EM interaction
- non-baryonic
- correct density



-> No Standard Model Candidate

The WIMP hypothesis

Weakly Interacting Massive particle

- if a **neutral, massive, weakly interacting particle** (WIMP) existed in the early Universe

$$\chi + \bar{\chi} \leftrightarrow X + \bar{X}$$

- it was in equilibrium as long as the **reaction rate** was larger than the **expansion rate**

$$\Gamma \gg H$$

- after **Γ drops below H** ⇒ "freeze-out", we are left with a **relic density**

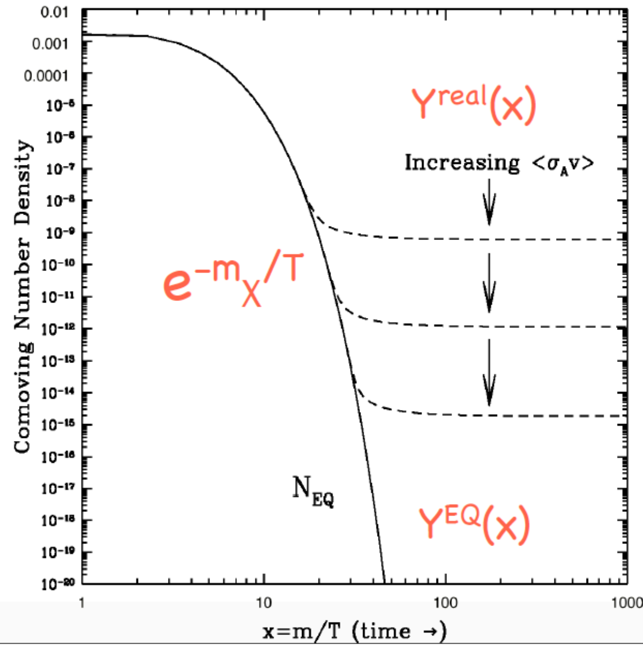
$$\frac{dn}{dt} = -3Hn - \langle \sigma_{eff} v \rangle \left(n^2 - n_{eq}^2 \right)$$

decrease due to expansion of the Universe

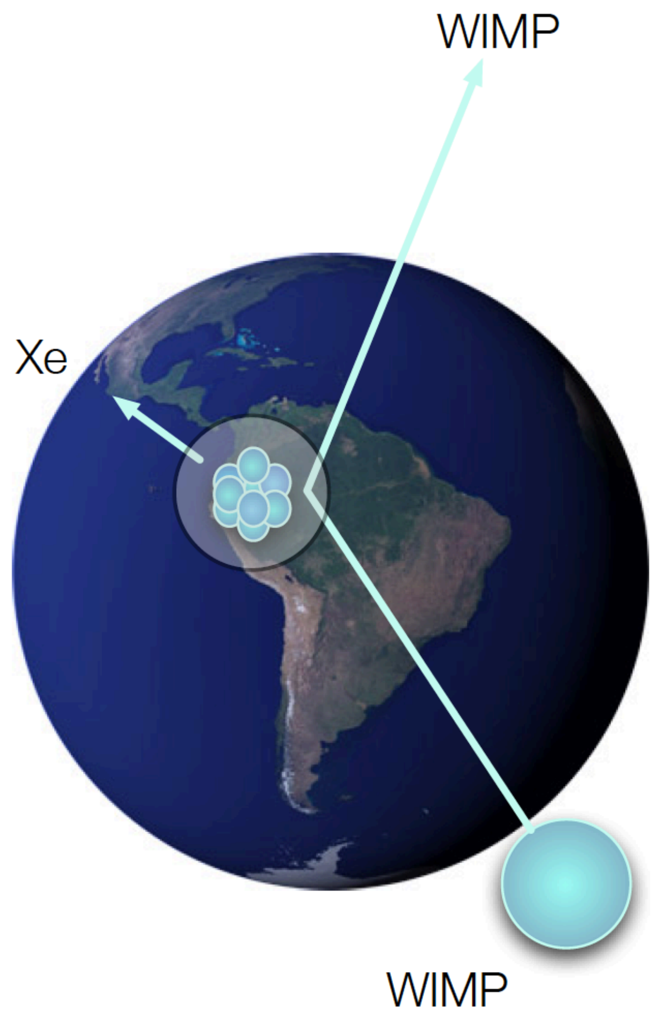
change due to annihilation and creation

Number density now: **integrate from freeze-out to present**

$$\Omega_\chi \propto \langle \sigma_A v \rangle^{-1}$$



WIMP direct detection



- Elastic collisions with nuclei
- The recoil energy is:

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \le 50\ keV$$

- and the expected rate:

$$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi N} \rangle \qquad \mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

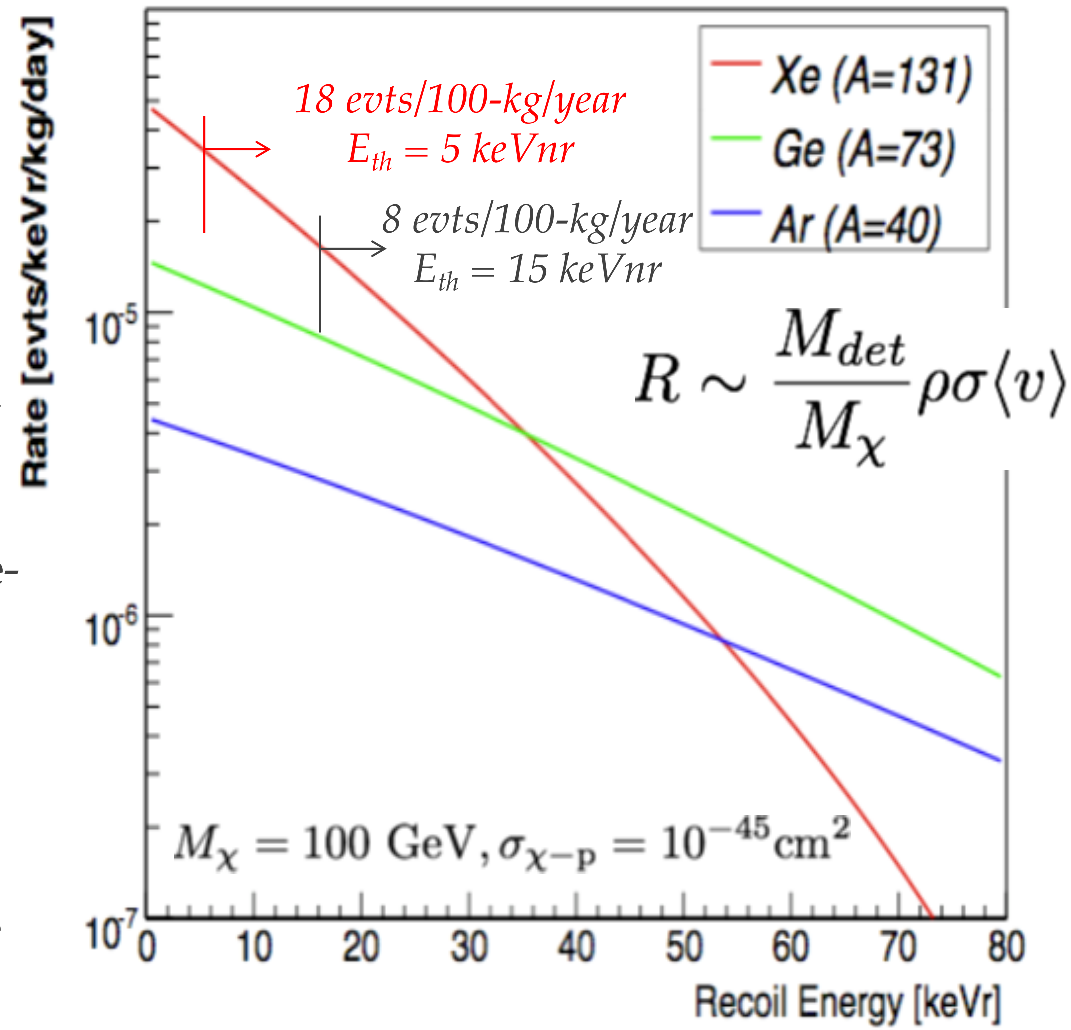
N = number of target nuclei in detector
ρ_χ = local WIMP density, m_χ = WIMP mass
$\langle\sigma_{\chi N}\rangle$ = scattering cross section

Which target ?

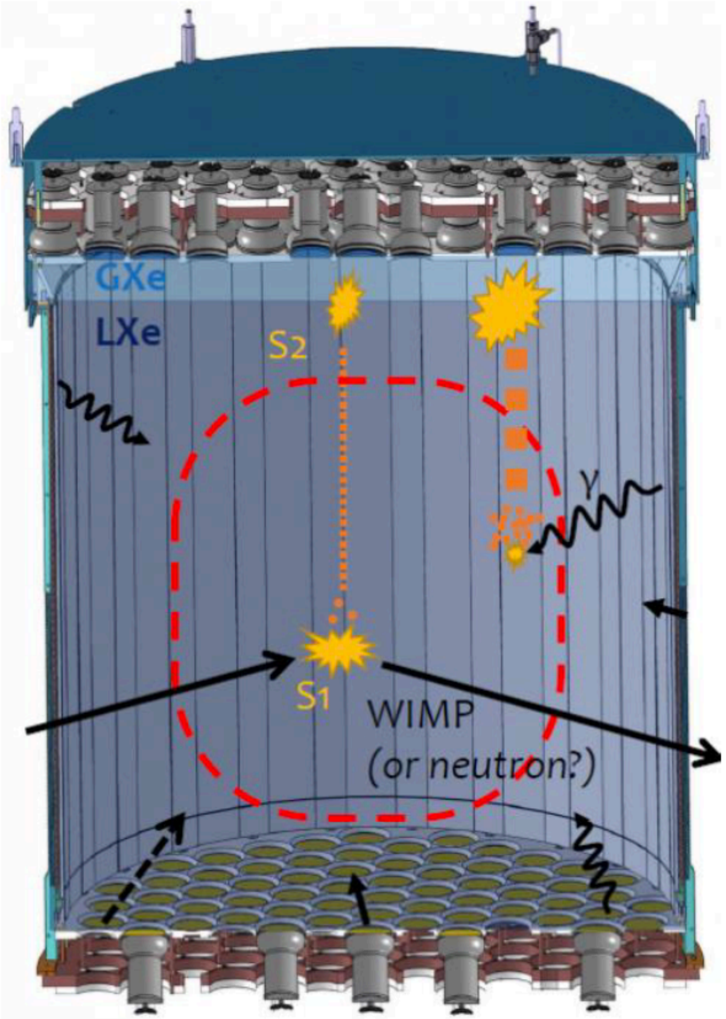
… choose Xenon !!

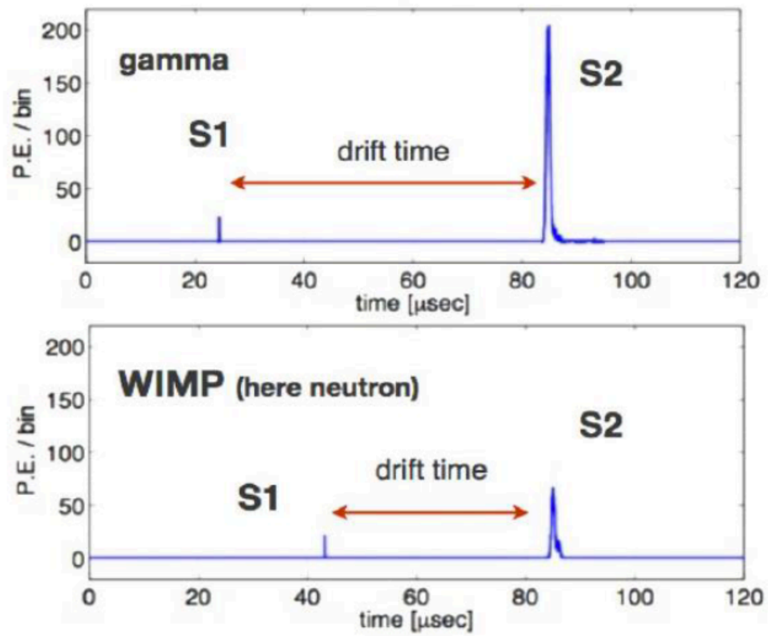
Xenon properties

- High A: large number of SI interactions
- Self shielding: high Z=54 and and high density ϱ=2.83 kg/l
- Scalability: possibility to build compact detectors, scalable to larger dimensions
- Odd-nucleon isotopes: high A=131 with ~50% of odd isotopes. Good for SD.
- Wavelength 178 nm: no need for a wave-length shifter
- Intrinsically pure: ^{136}Xe has very small decay rate; Kr can be removed to <ppt
- Charge & light: highest yield among the noble liquids
- "Easy" cryogenics: -100 °C



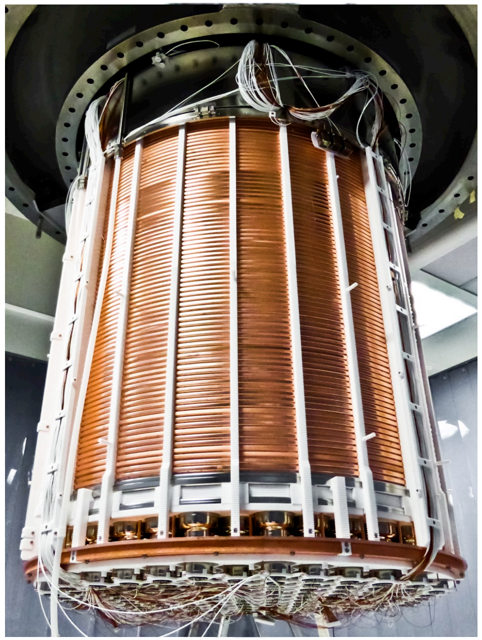
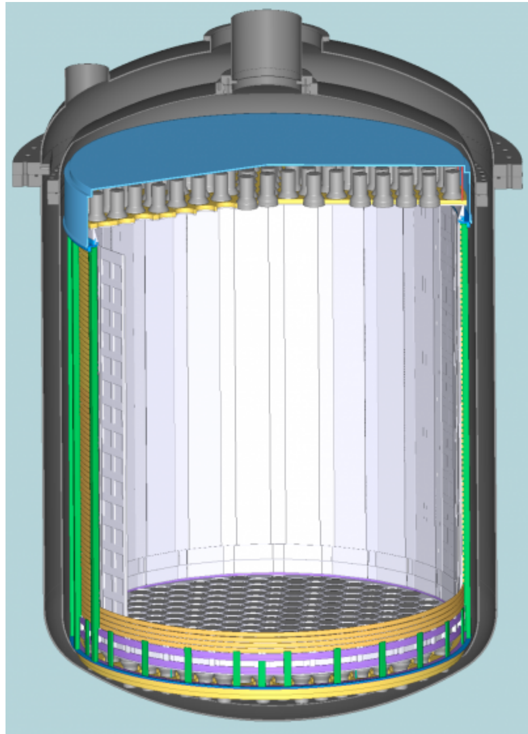
Double phase LXe/GXe TPC





- 3-D position reconstruction using drift time and top array hit pattern
- NR/ER discrimination from S2/S1 ratio

Phases of the XENON program

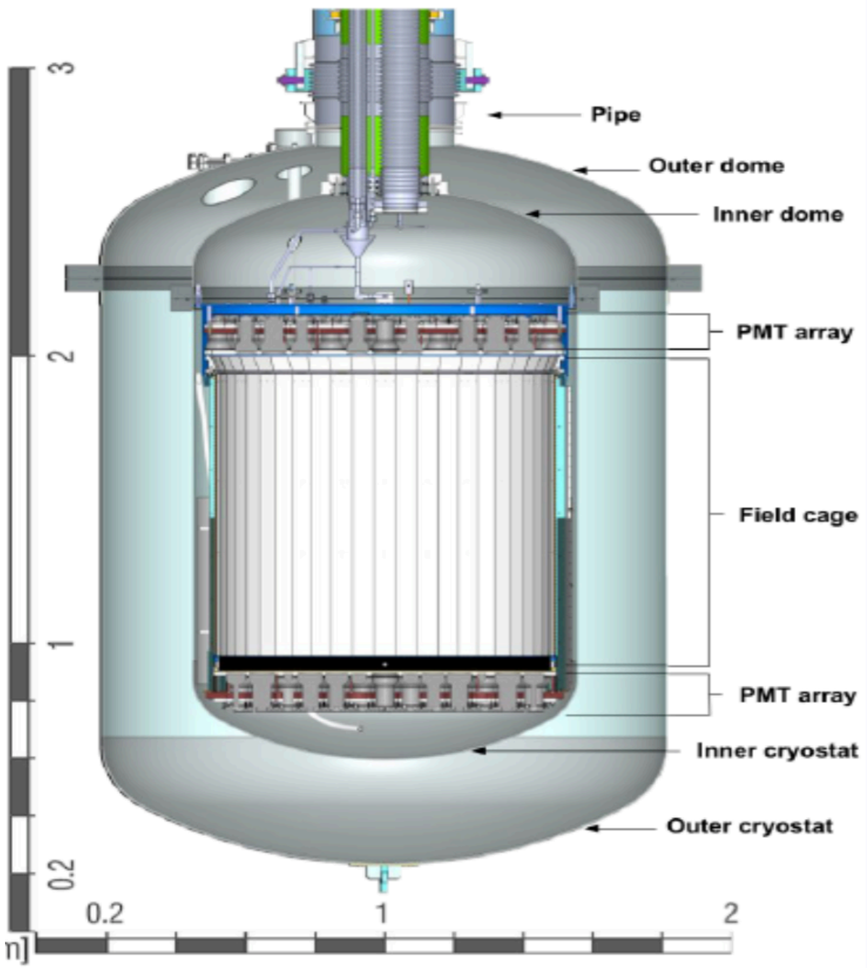
XENON10	XENON100	XENON1T / XENONnT
		 
2005-2007 15 cm drift TPC – 25 kg	2008-2016 30 cm drift TPC – 161 kg	2013-2018 / 2019-2023 100 cm / 144 cm drift TPC - 3200 kg / ~8000 kg
Achieved (2007) $\sigma_{SI} = 8.8 \times 10^{-44}$ cm^2	Achieved (2016) $\sigma_{SI} = 1.1 \times 10^{-45}$ cm^2	Projected (2018) / Projected (2023) $\sigma_{SI} = 1.6 \times 10^{-47}$ cm^2 / $\sigma_{SI} = 1.6 \times 10^{-48}$ cm^2

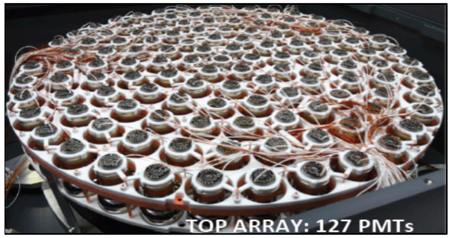
The XENON1T Experiment

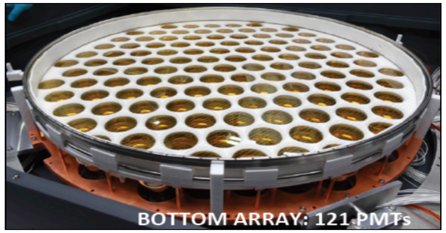

July 2013

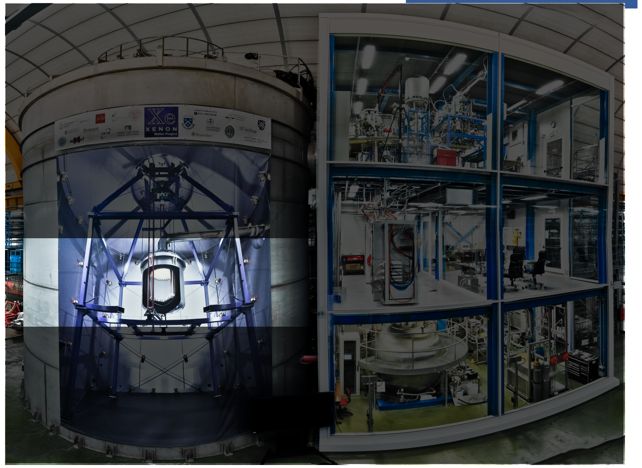

XENON
Aug. 2014

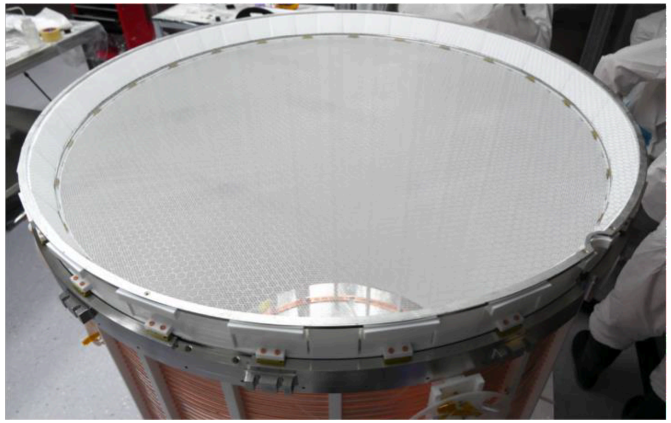
Time Projection Chamber











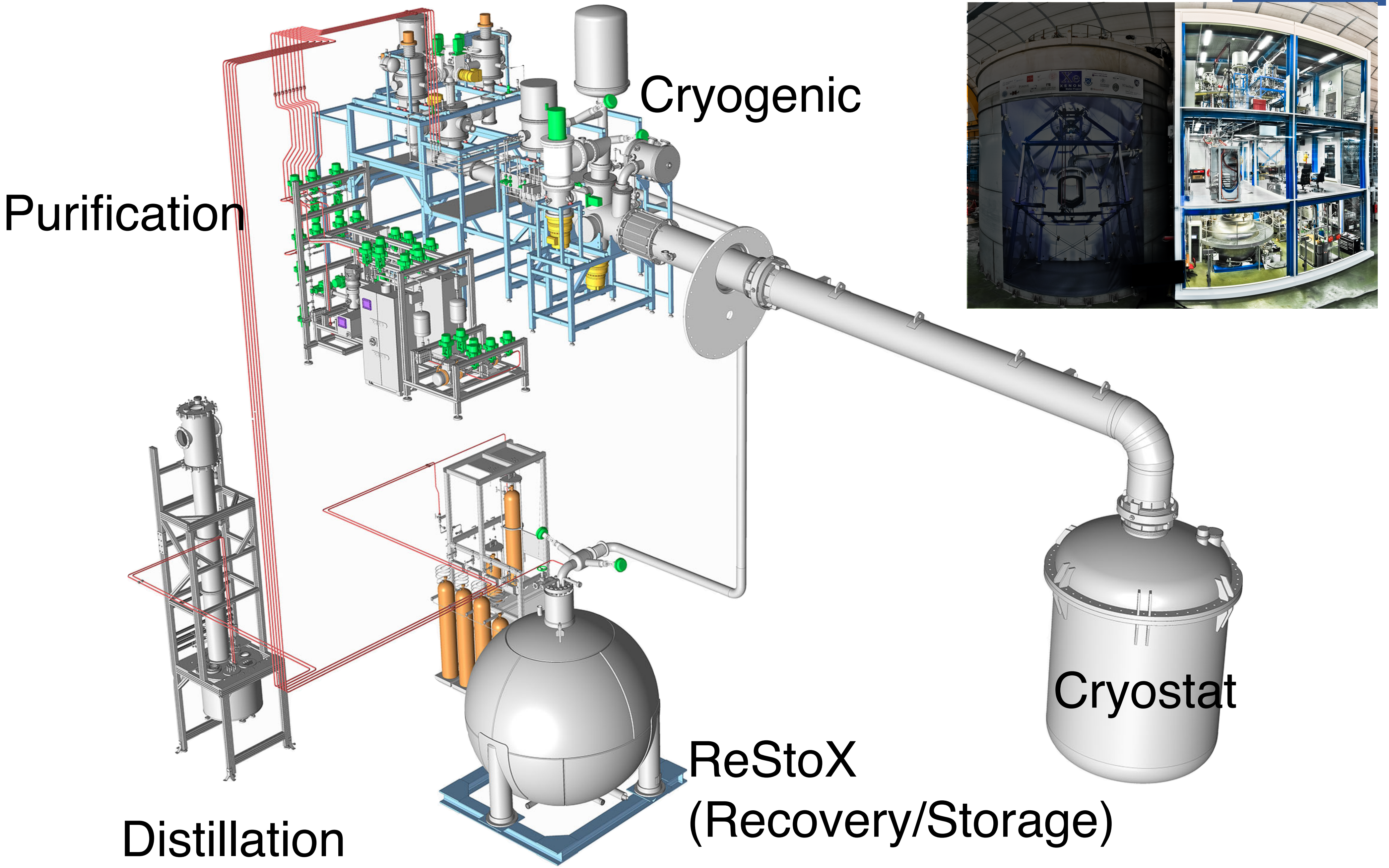
TPC: 1m x 1m. LXe mass: 3.2 t (total), 2 t (active).
Internal part fully covered with high reflectivity PTFE.
Electric field: 120 V/cm.

PMTs: Hamamatsu R11410-21 (127 top, 121 bottom).
Average QE= 34% @178 nm, Gain = 5 10^6 @ 1.5 kV
Low radioactivity components. Eur. Phys. J. C75, 11, 546 (2015)

Nov 2015: XENON1T inauguration

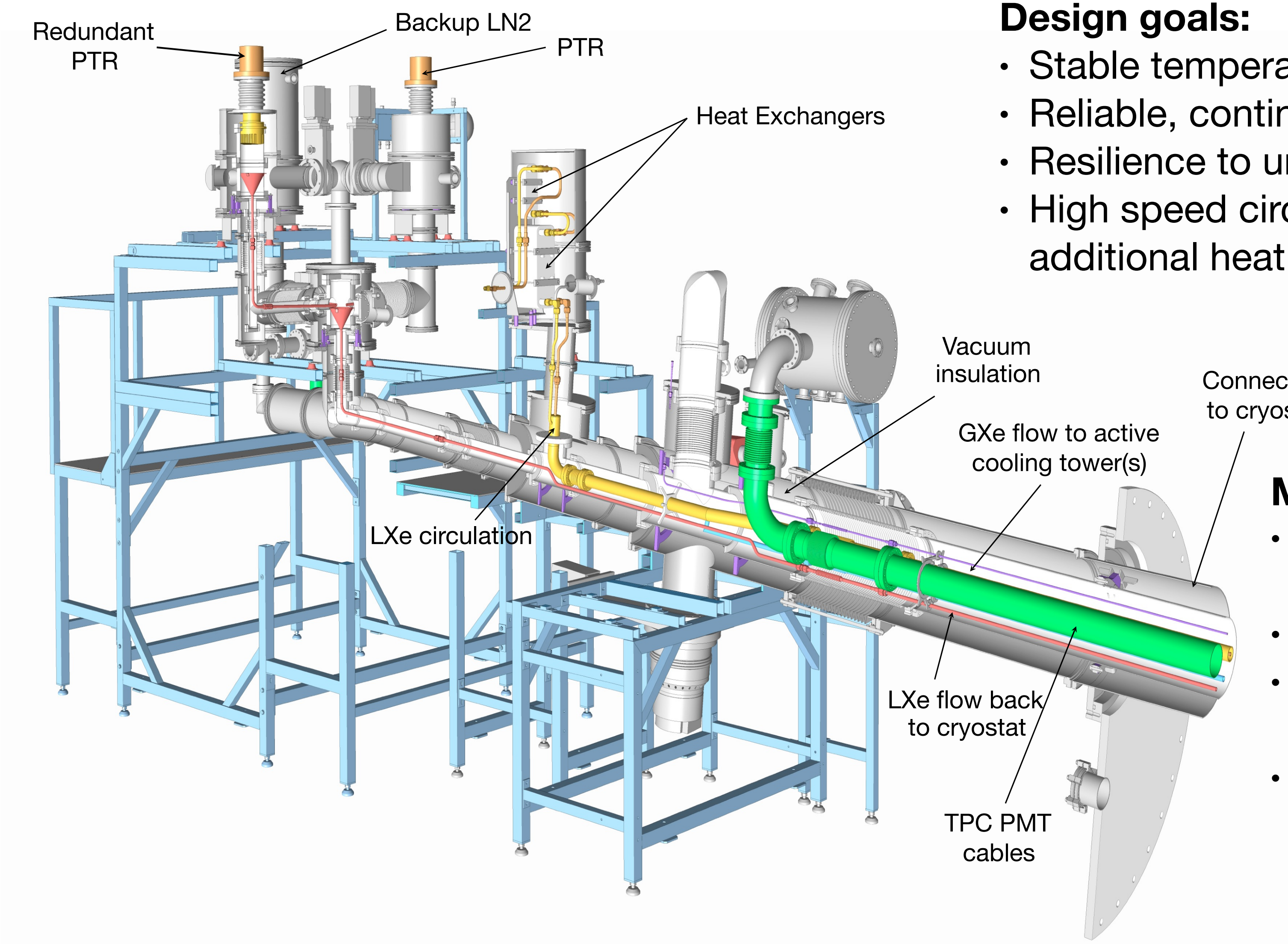
XENON1T: All Systems

Xenon Plants



Xe Cooling System

Goal: liquefy 3200 kg of Xe and maintain the xenon in the cryostat in liquid form, at a constant temperature and pressure, and so for years without interruption.



Design goals:

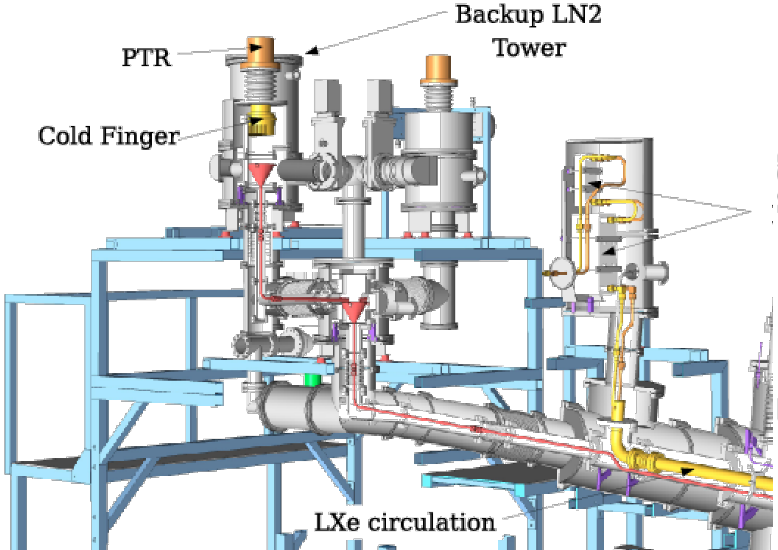
- Stable temperature and pressure control
- Reliable, continuous, long term operation
- Resilience to unexpected failures
- High speed circulation with low additional heat load

Main features:

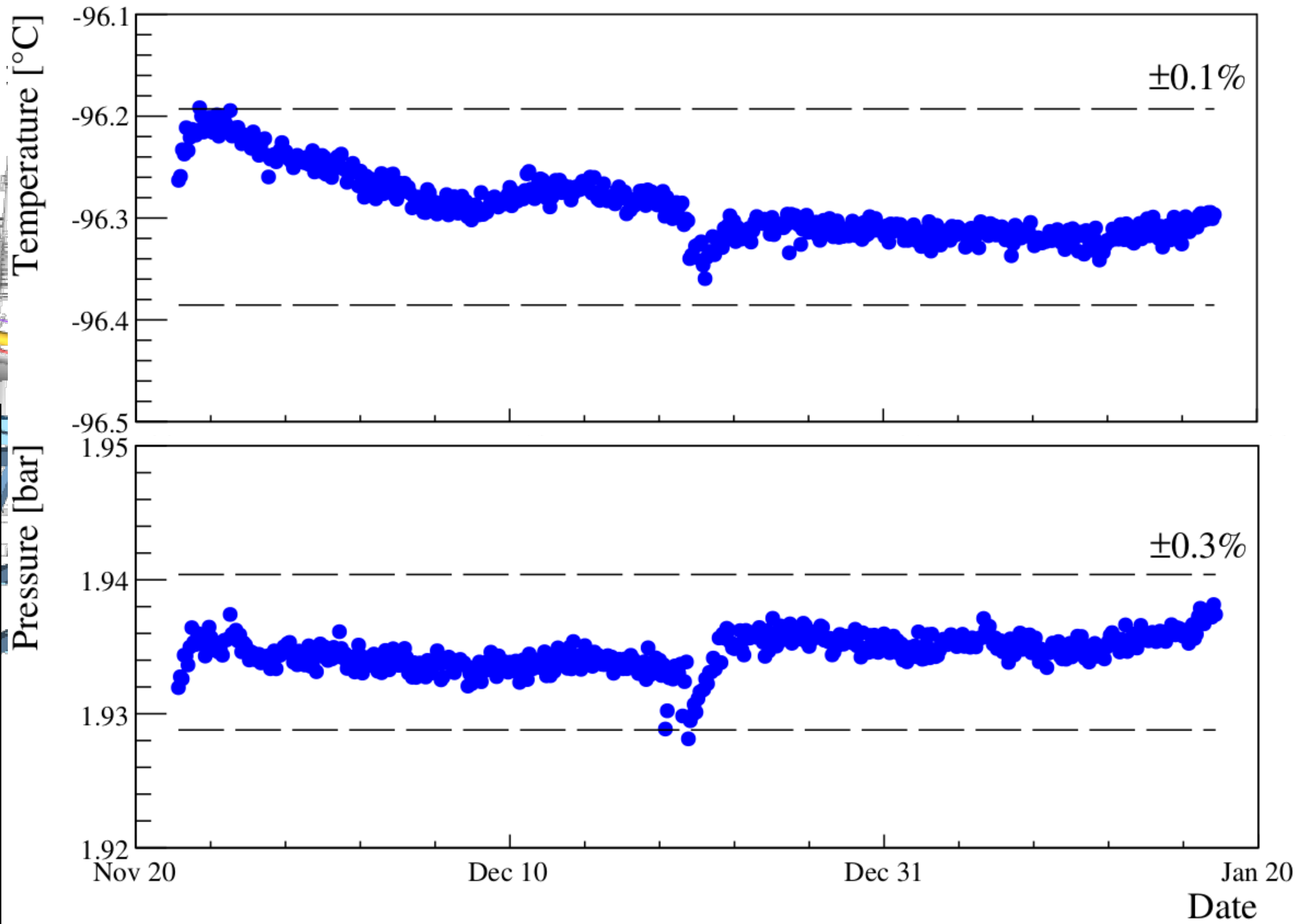
- Redundant PTR cooling systems
- Backup LN2 cooling tower
- Efficient two-phase heat exchangers
- One PTR can be serviced while the other is in operation

Detector Stability

- LXe temperature stable at -96.07 °C, RMS 0.04 °C
- GXe pressure stable at 1.934 bar, RMS 0.001 bar



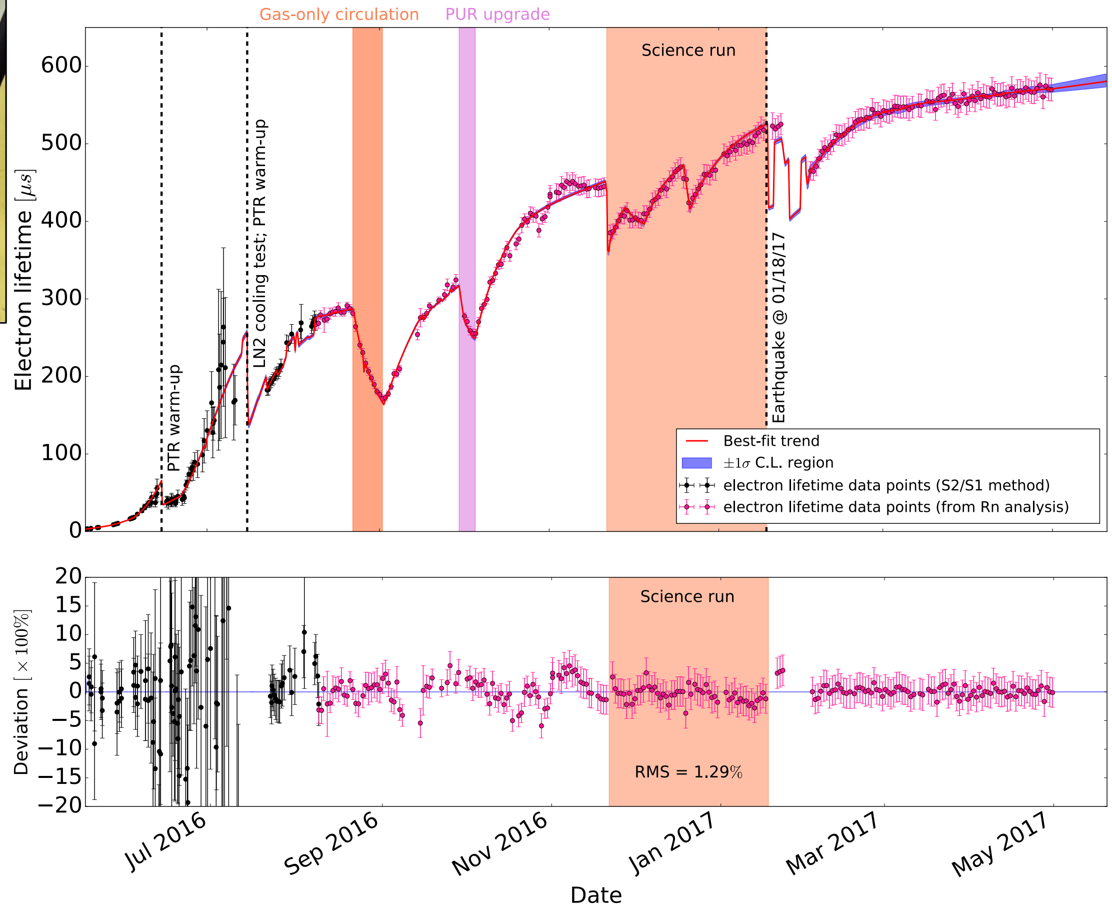
Slow control/Historian monitoring



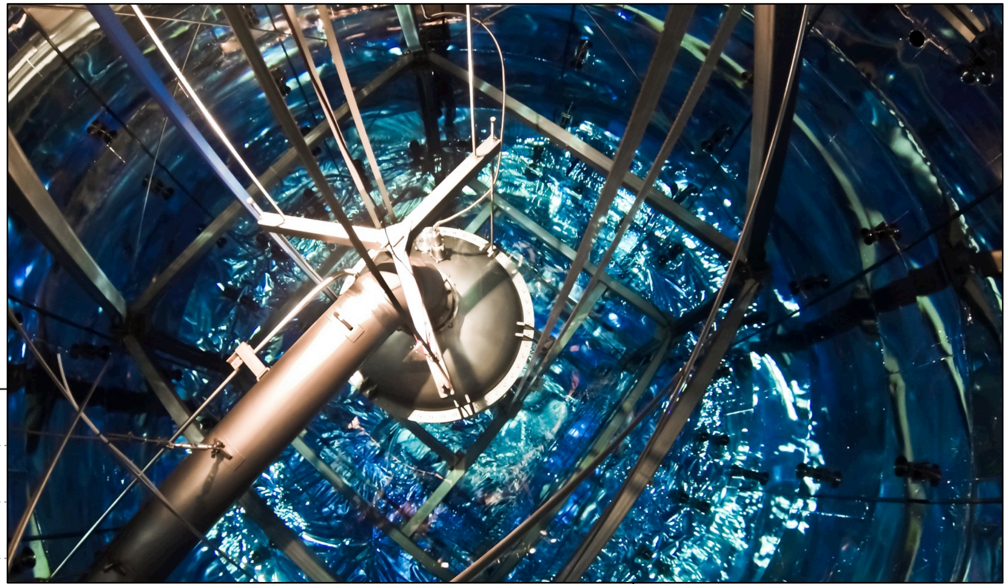
Xe Purification

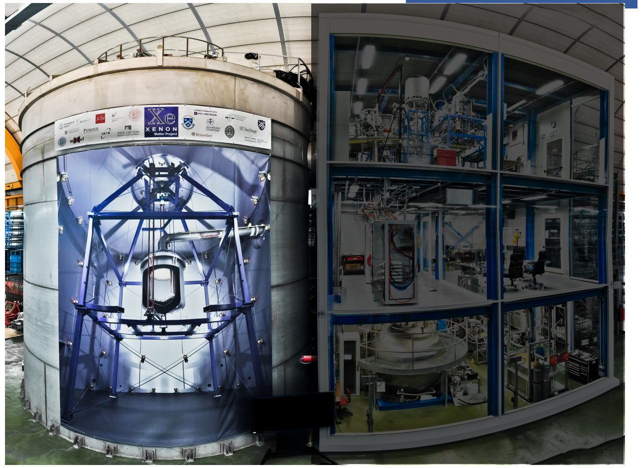
Goal: remove electronegative impurities below 1 ppb (O_2 equivalent) in the Xe gas fill and from outgassing of detector's components with continuous circulation of Xe gas at high speed through hot getters

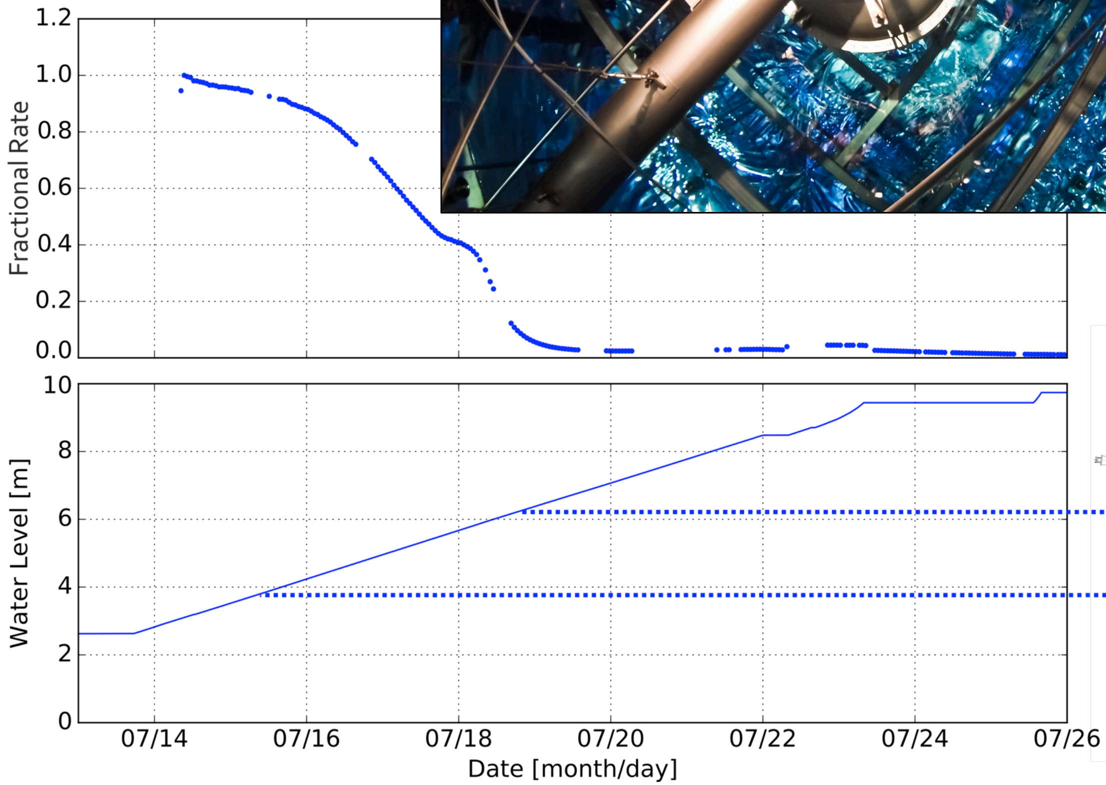
Performance: evolution of e-lifetime, monitored regularly with ERs calibration sources, well described by physical model. Current value approaching the max drift time of the LXeTPC.

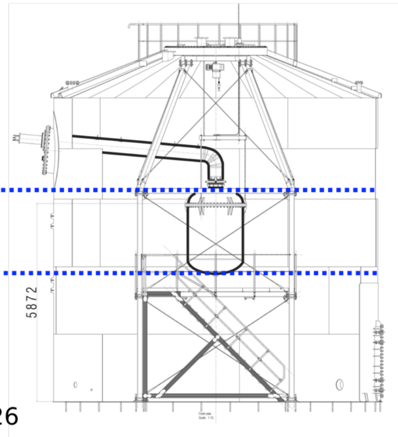


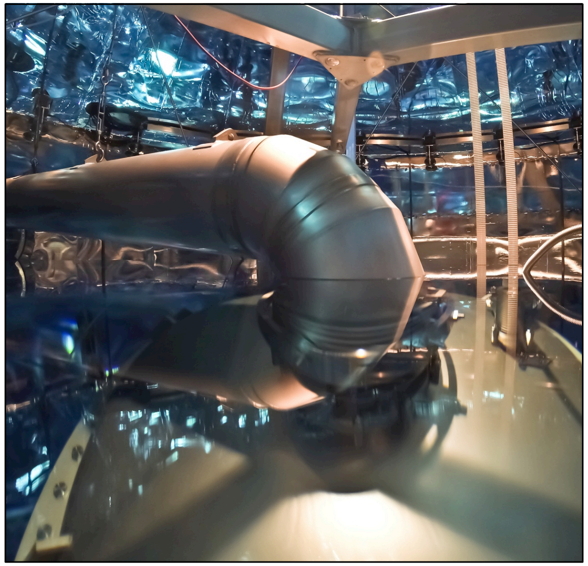
Cryostat in the Water Tank



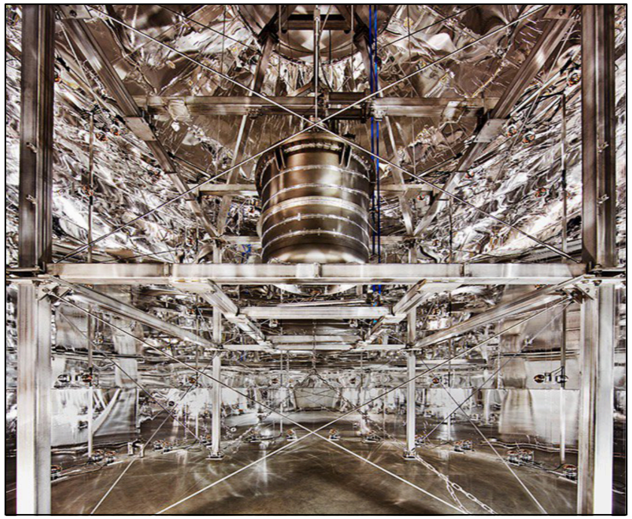


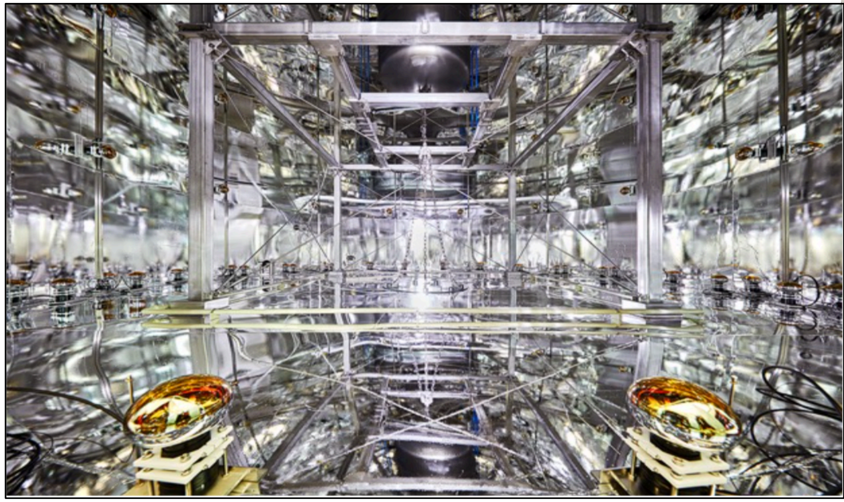


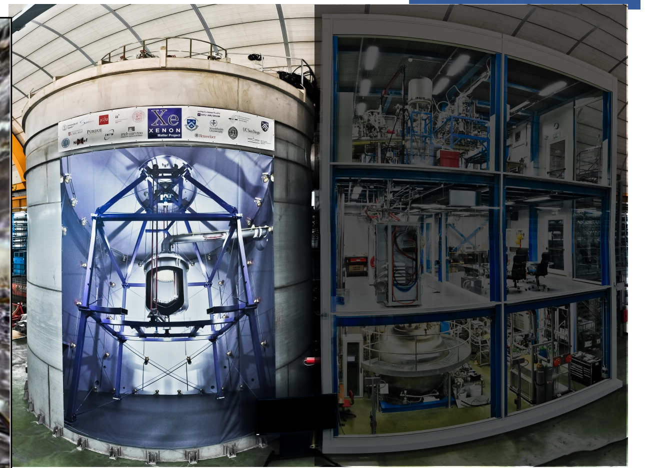




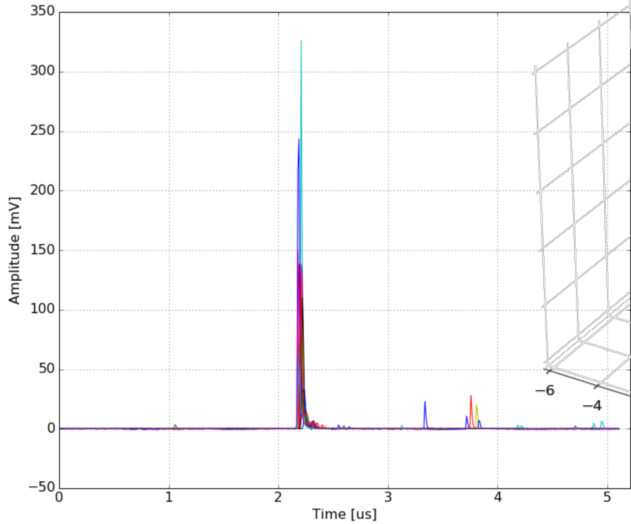
Cherenkov Muon Veto

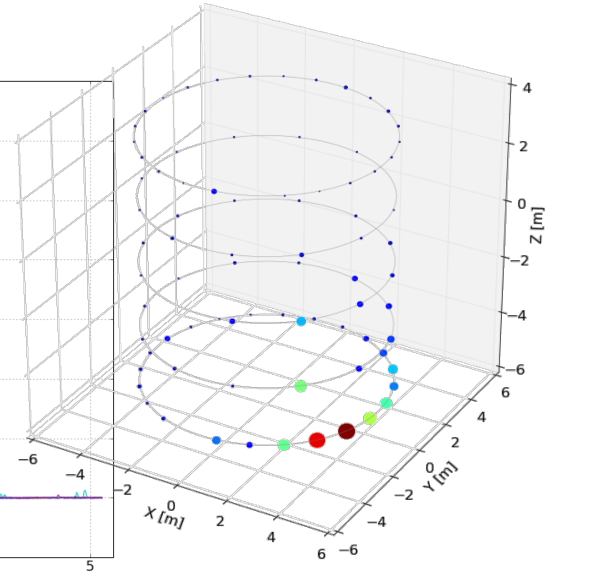


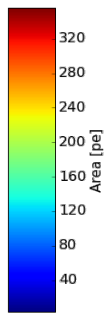




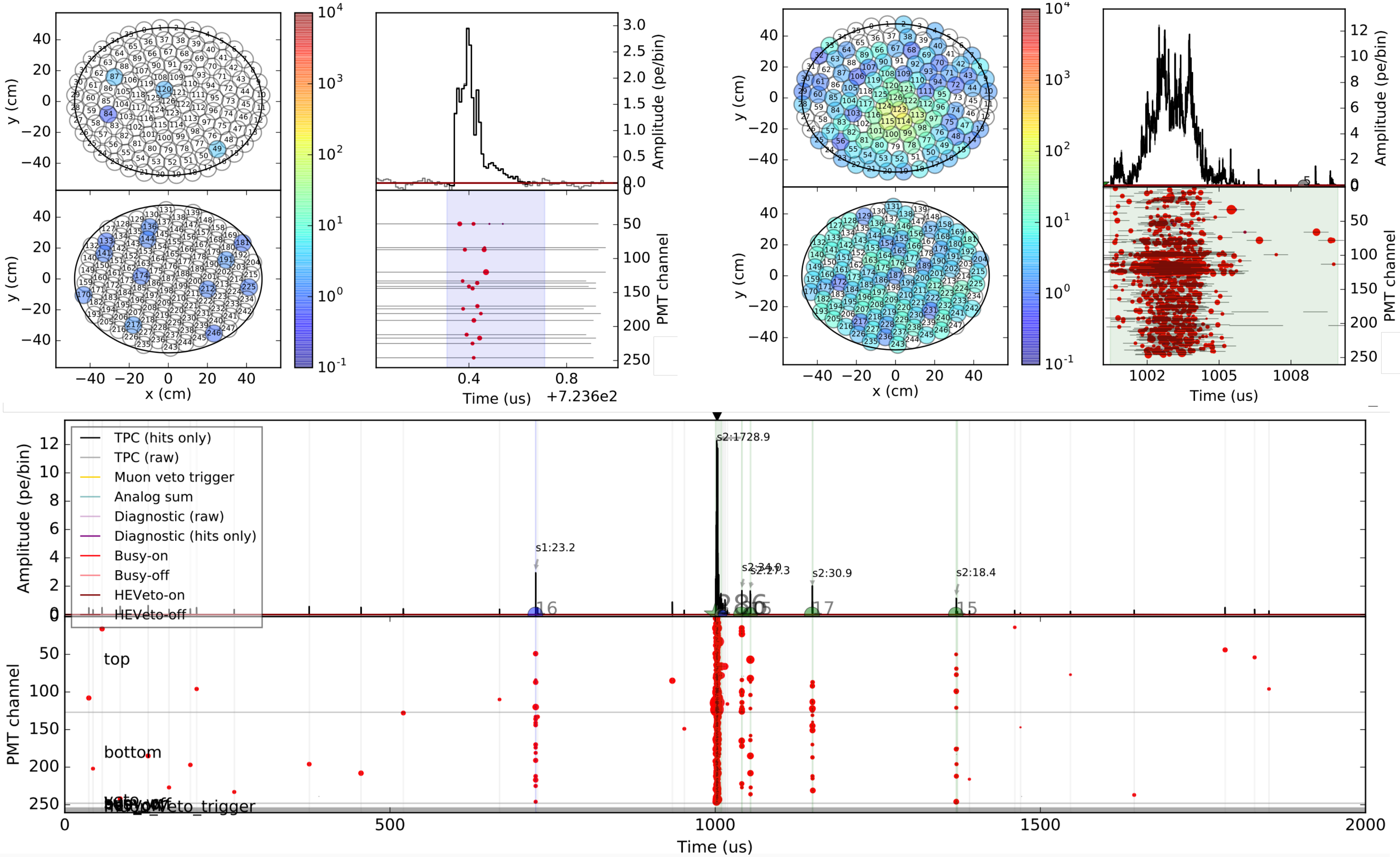
- Active shield against muons
- 84 high-QE 8" Hamamatsu R5912 PMTs
- Trigger efficiency > 99.5% for neutrons with muons in water tank
- Can suppress cosmogenic background to < 0.01 events/ton/year
- No coincidences with events in the TPC found in this science run



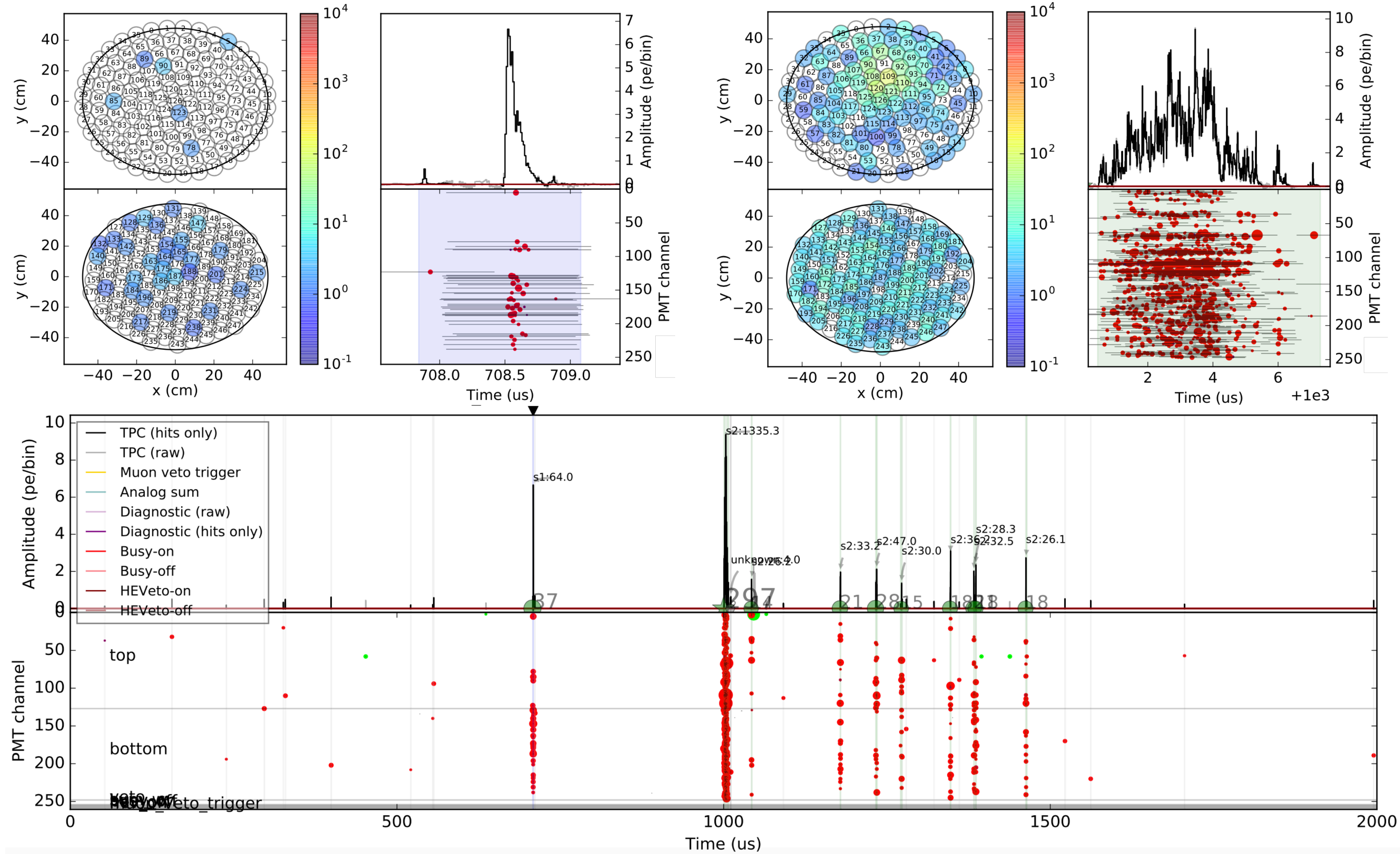




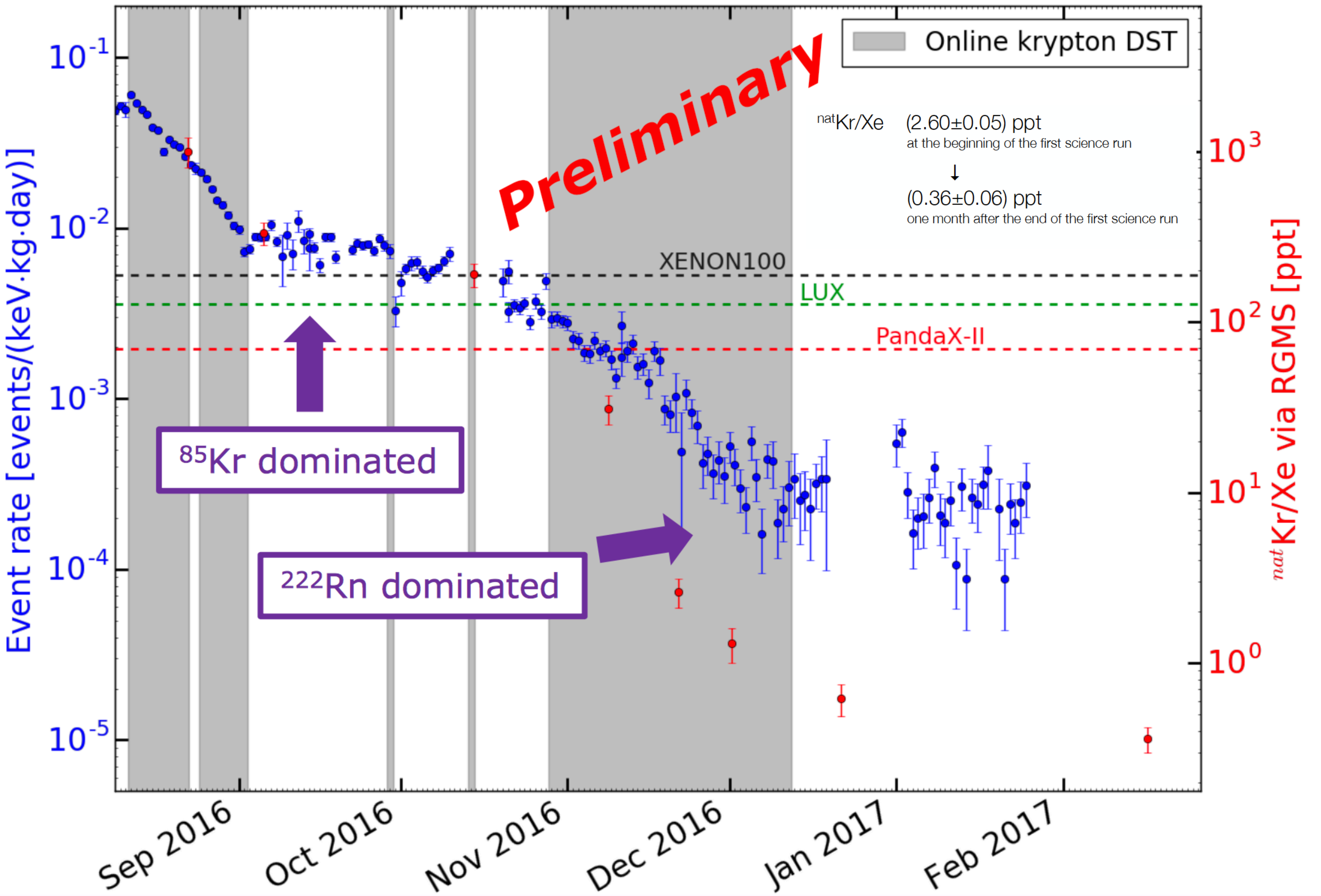
Real Waveform Example 1



Real Waveform Example 2



Kr Reduction

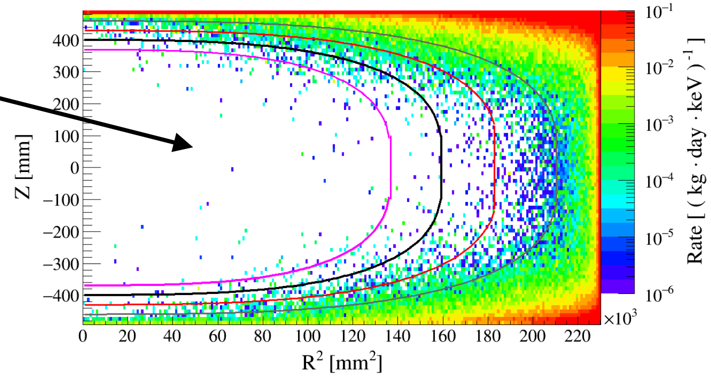


Eur. Phys. J. C77 (2017) no.5, 275 & arXiv:1702.06942

Worst enemy: Rn !

ER Backgrounds

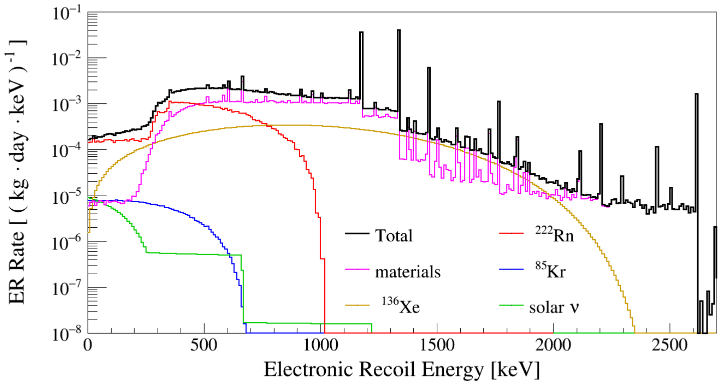
Predictions from MC simulations: ER background from materials is negligible in the 1t FV.

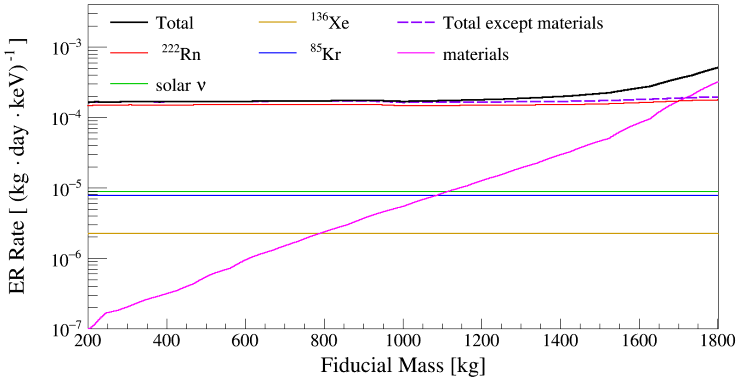


MC assumptions on the intrinsic backgrounds:

- 0.2 ppt of ^{nat}Kr (achieved in XENON1T distillation column tests),
- 10 μBq/kg of ^{222}Rn (estimation based on Rn emanation measurements).

"Physics reach of the XENON1T dark matter experiment", JCAP 1604 (2016) 027, arXiv:1512.07501,





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

Measured: (1.93 +/- 0.25) 10^{-4} events / (kg day keV)

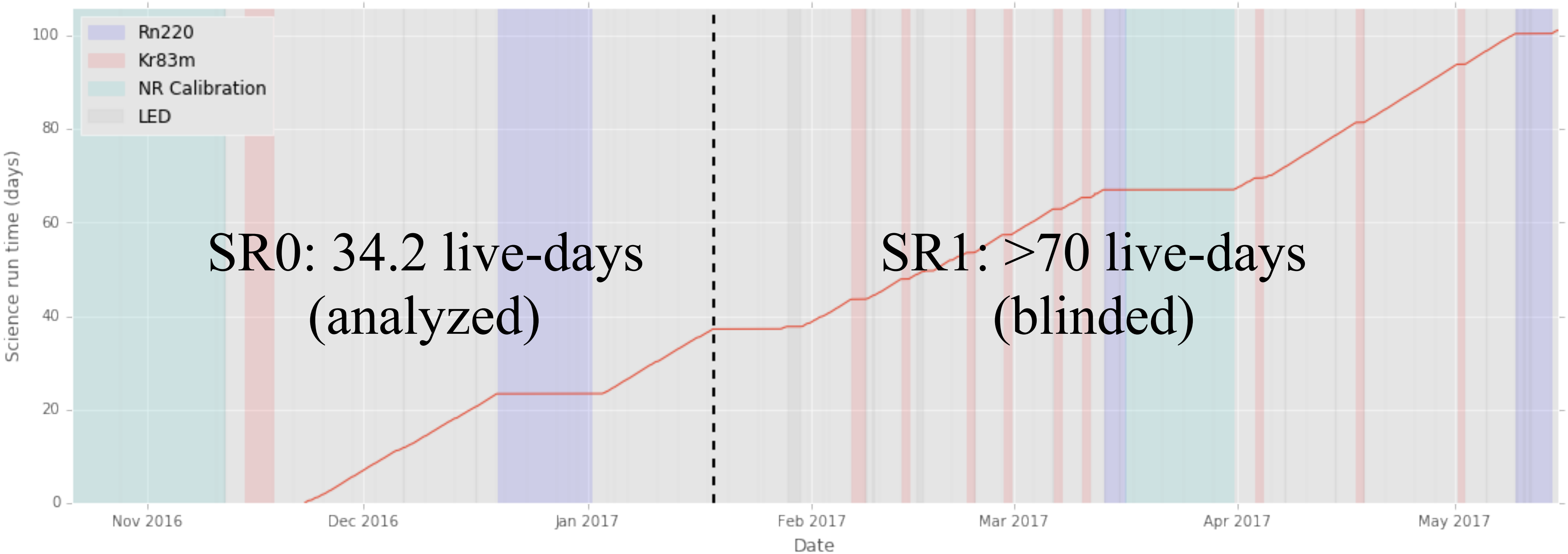
Predicted (considering the average 1.5 ppt of Kr in first run): (2.3 +/- 0.2) 10^{-4} events / (kg day keV)

Lowest ER background ever achieved in a DM detector !

Science Run: Timeline

- Average DAQ lifetime = 92%

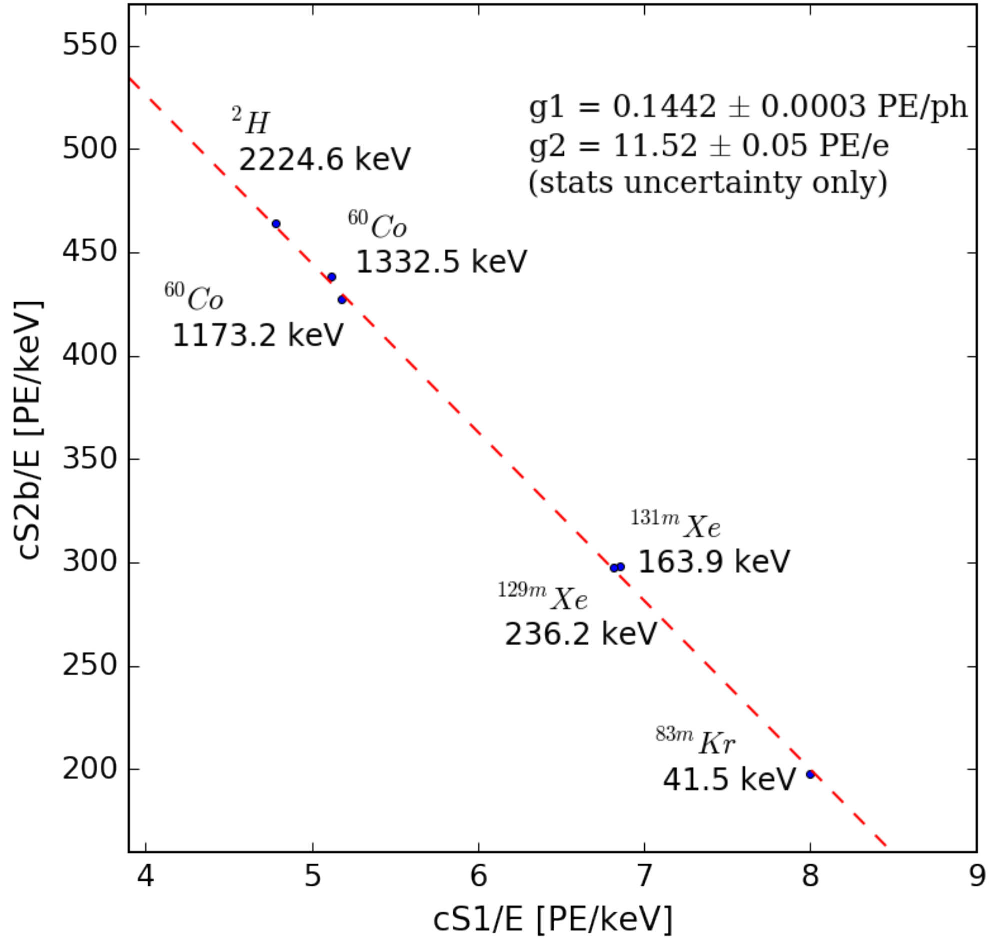
Science Run: Exposure



- This talk highlights the analysis of the first science run (SR0)
- We continue to take data after the earthquake and analyzing SR1 now

Energy response

$$E = (n_{ph} + n_e) \cdot W = (\frac{S1}{g1} + \frac{S2}{g2}) \cdot W$$

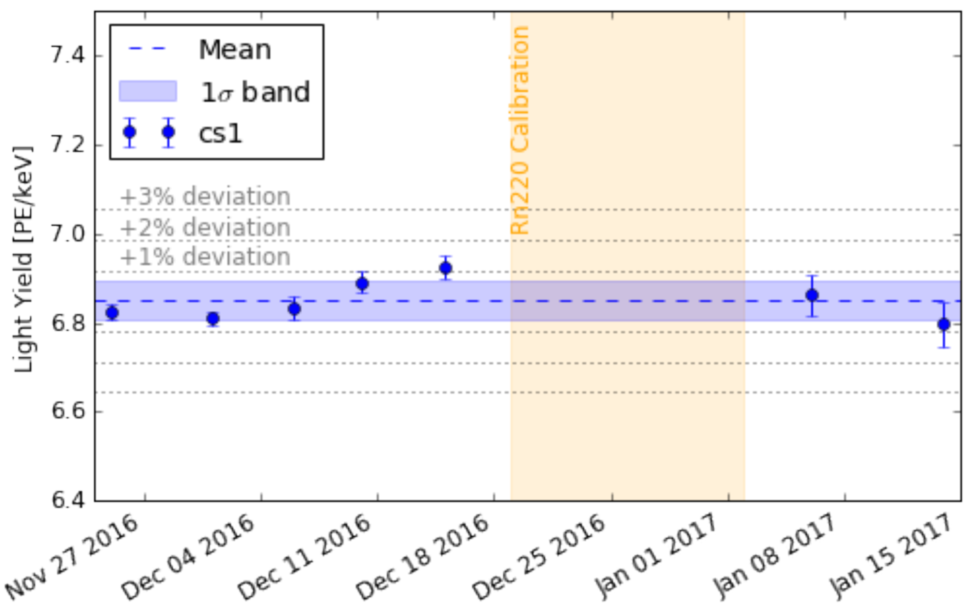


- Excellent linearity with electronic recoil energy from 40 keV to 2.2 MeV
- g1 = 0.1442 ± 0.0068 (sys) PE/photon corresponds to a light detection efficiency of 12.5 ± 0.6%
  - Assumptions of past MC sensitivity projected 12.1%.
- The amplification in gas (g2) corresponds to ~100% extraction of charges from the liquid.

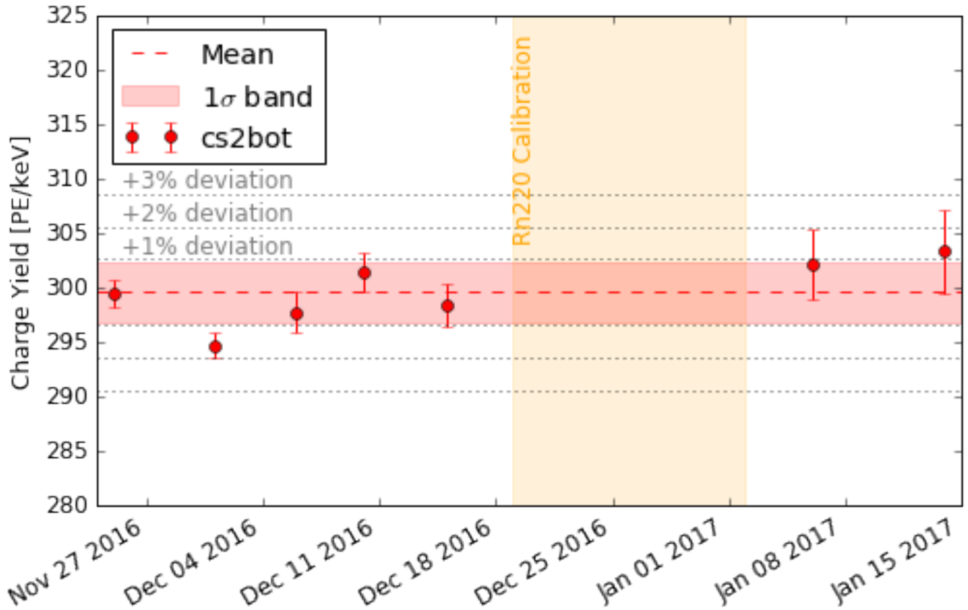
Light/Charge Yield Stability

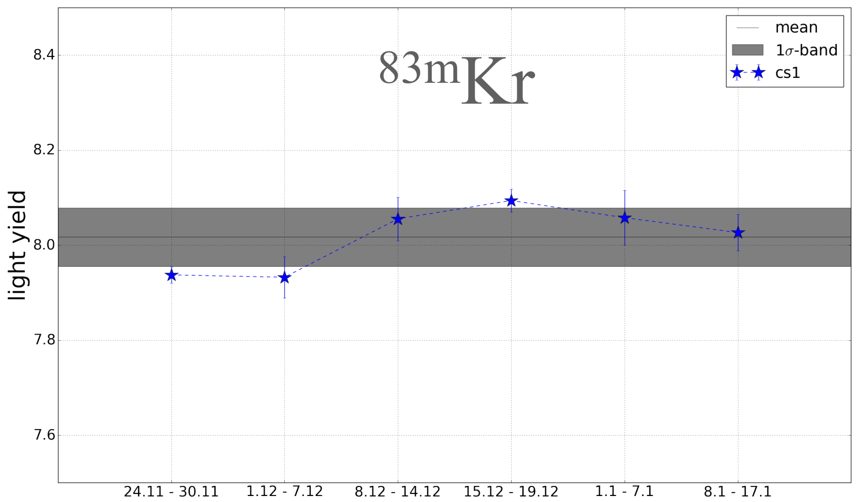
From ^{83m}Kr and activated ^{131m}Xe, variation in LY and CY is at ~1% level.

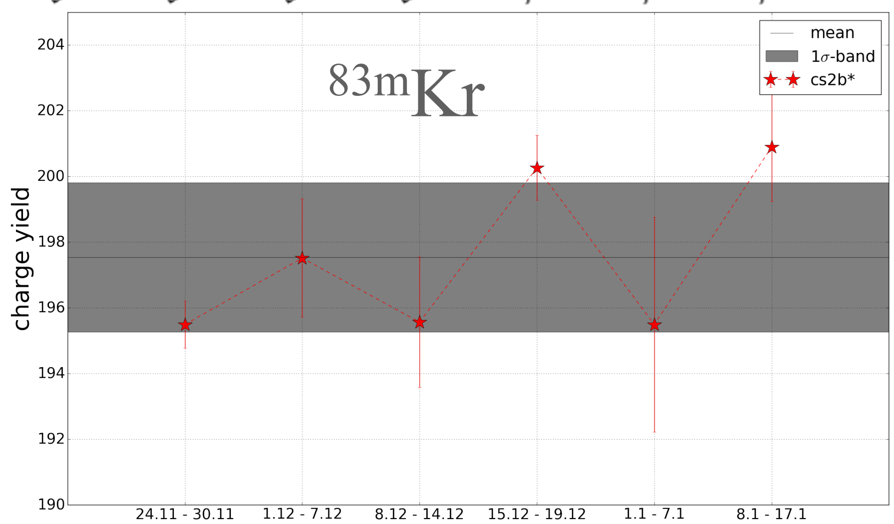
Light yield (164 keV) over SR0



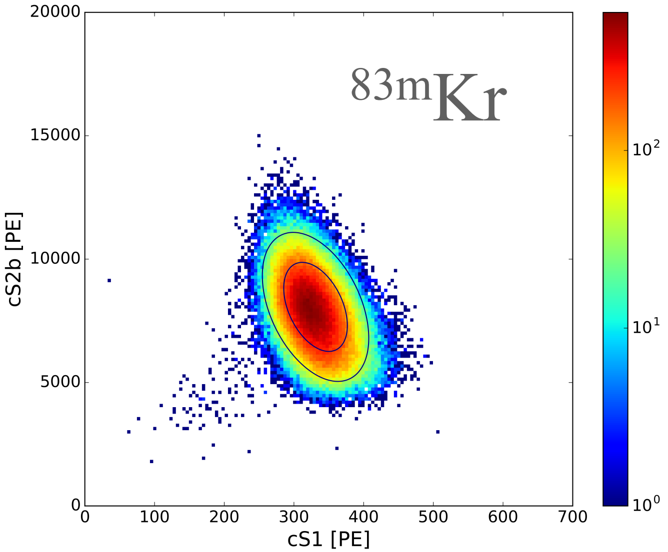
Charge yield (164 keV) over SR0

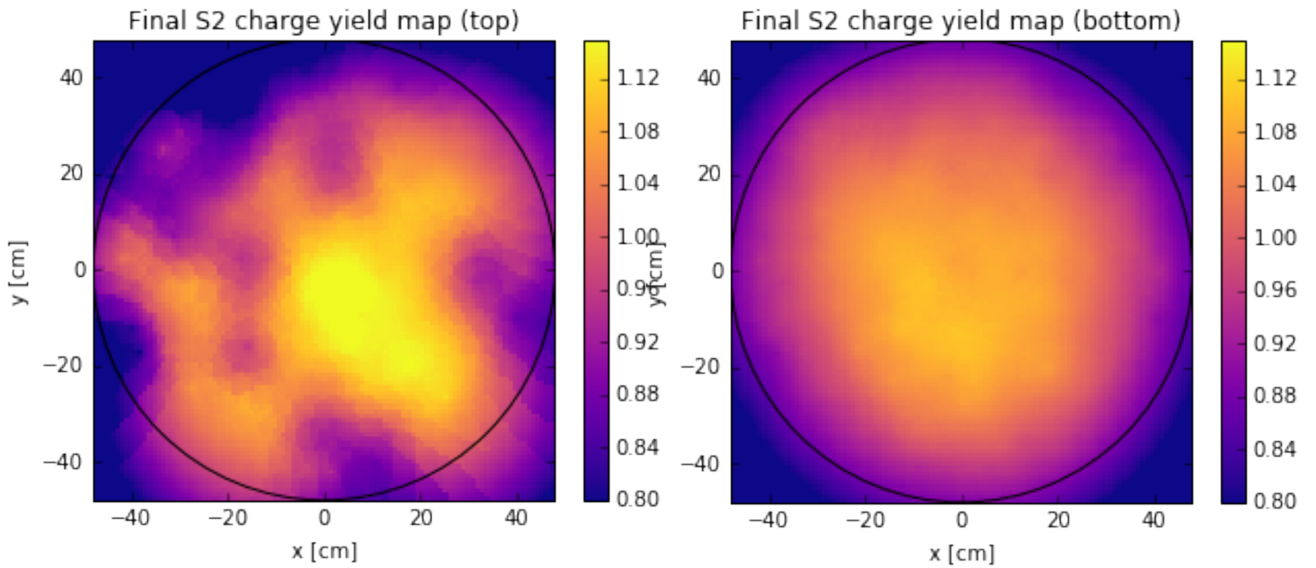




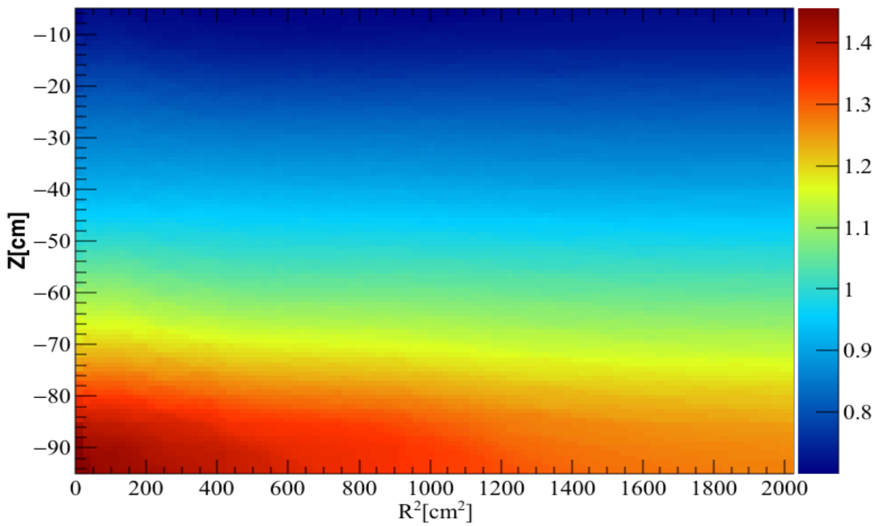


Signal Corrections

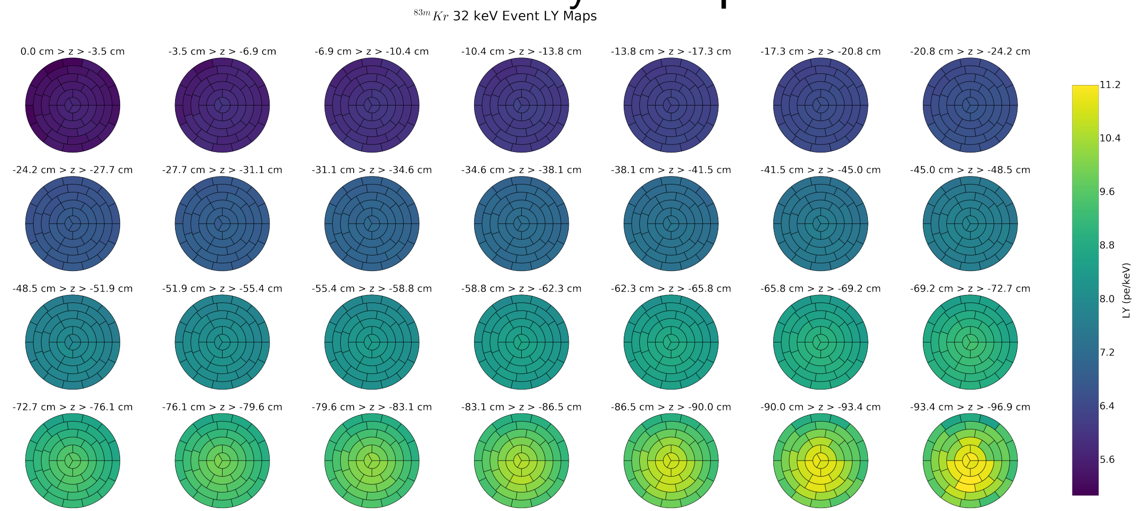




S1 Relative LCE

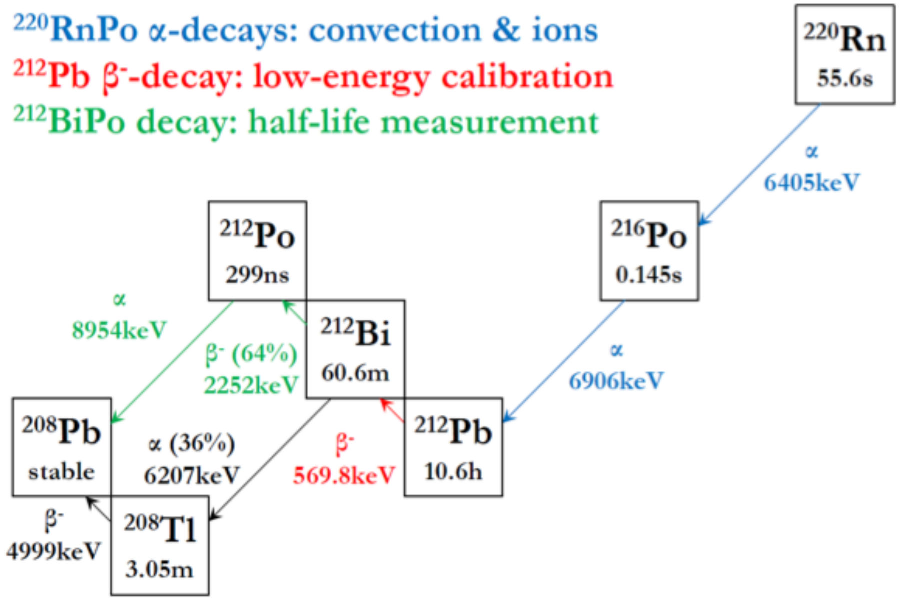


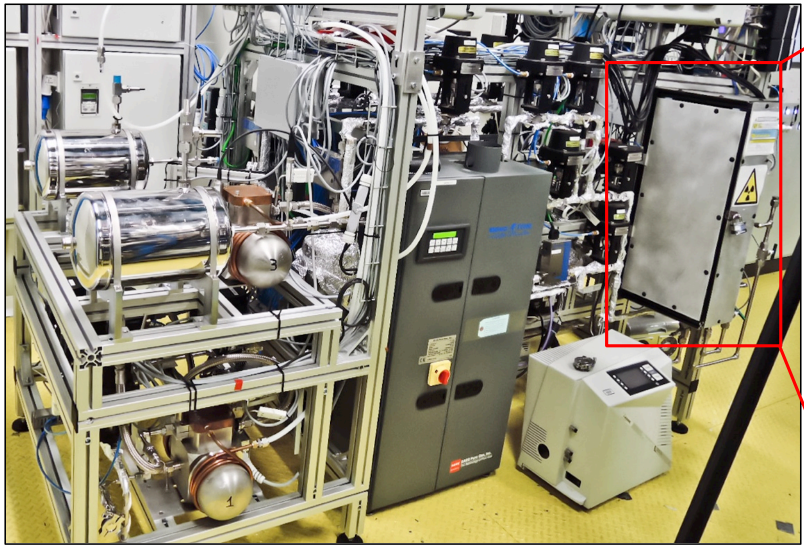
Detailed L_y Maps



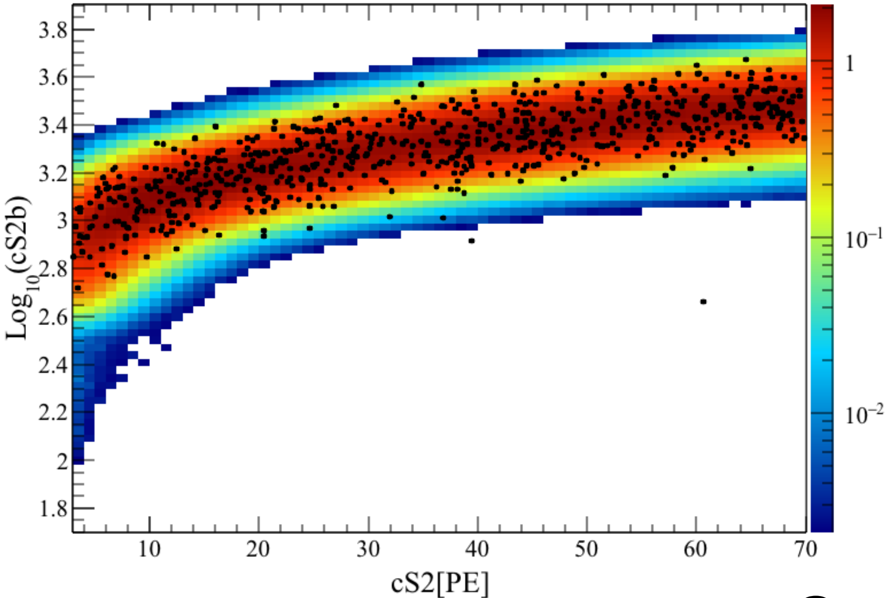
^{220}Rn Calibration

- Energies of commonly used γ-rays, not sufficient to reach fiducial volume
- Inject ^{220}Rn (decay product of ^{228}Th source)
- Low energy section of β-decay of ^{212}Pb used to calibrate ER-band
- Decay of activity dominated by ^{212}Pb half-life (10.6 hours).
  - No long lived isotopes
  - No purification requirement on LXe

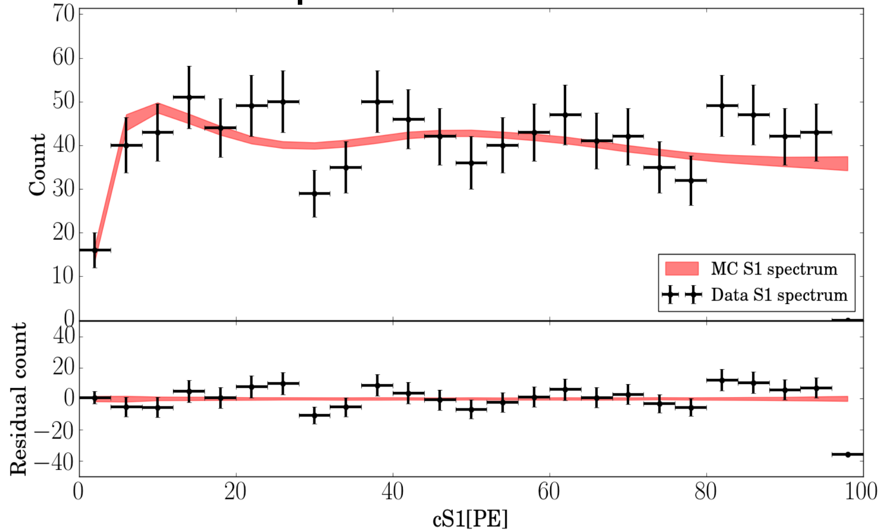




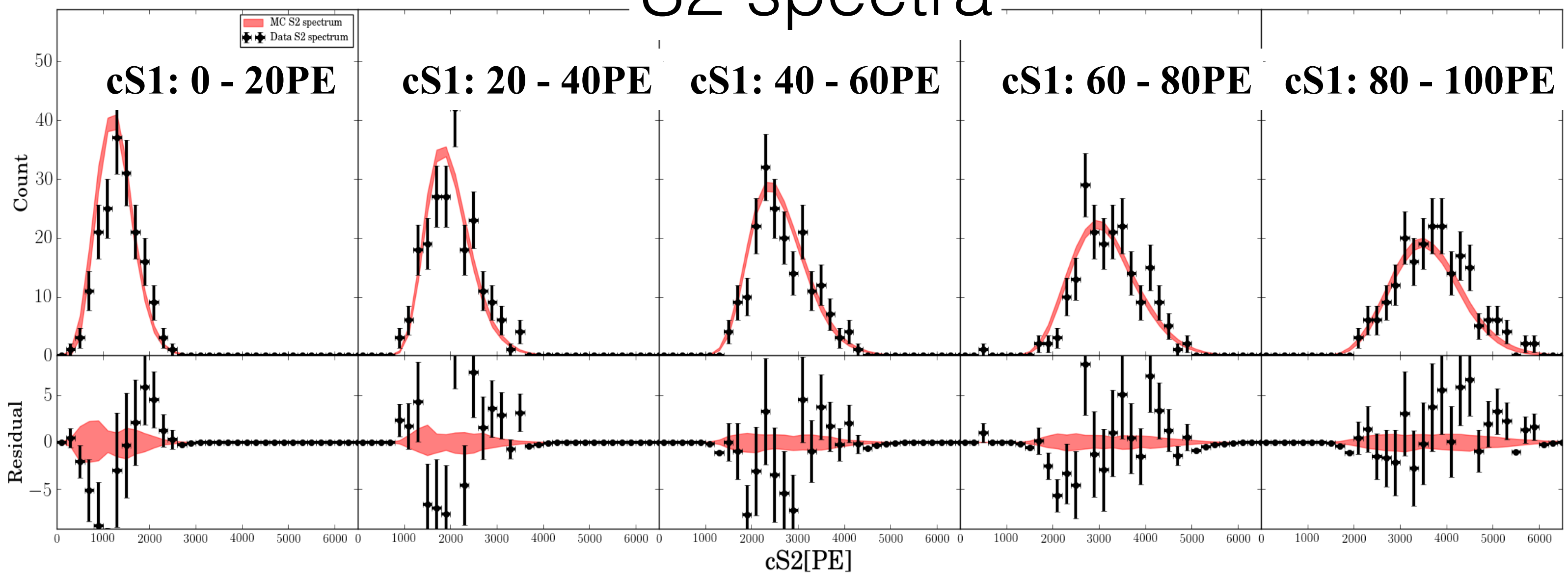
^{220}Rn Calibration



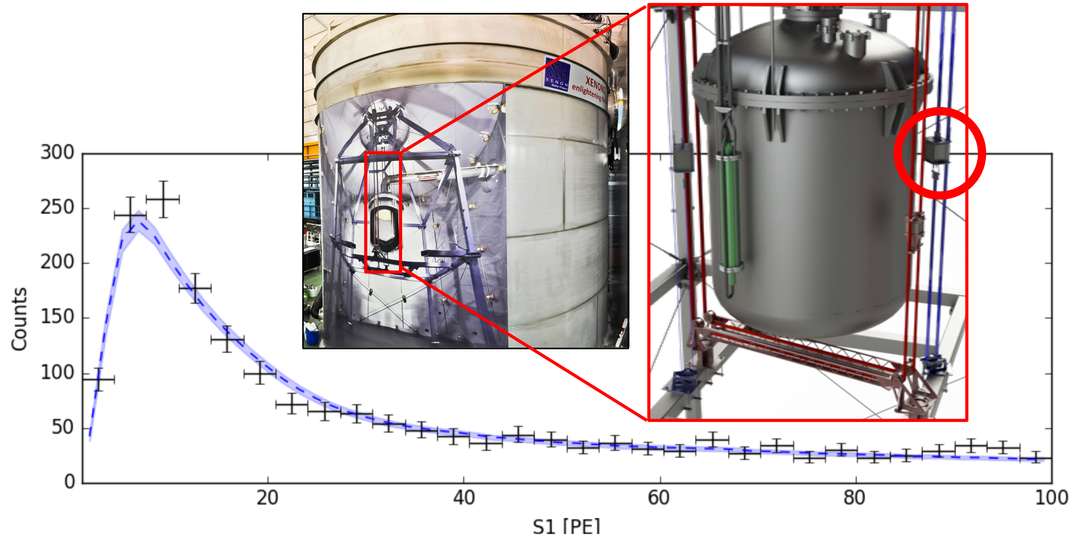
S1 spectrum

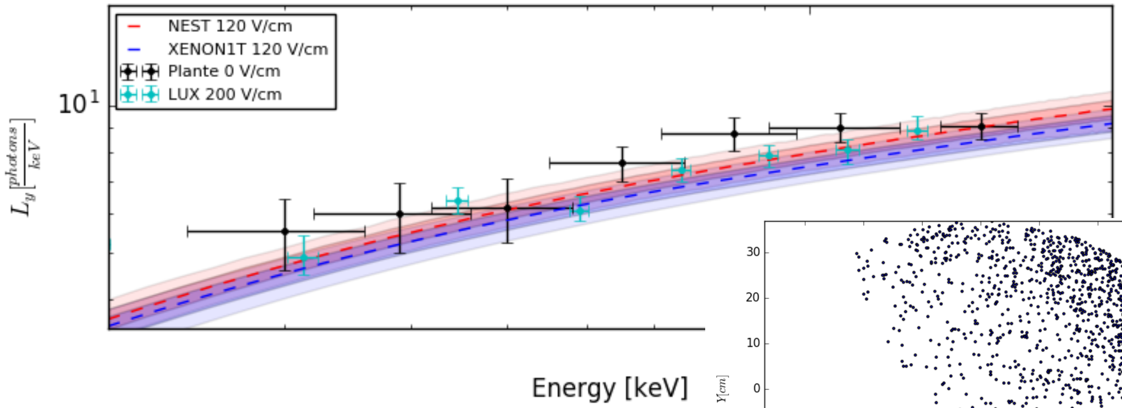


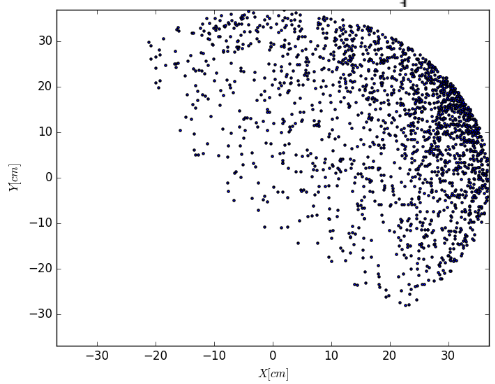
S2 spectra

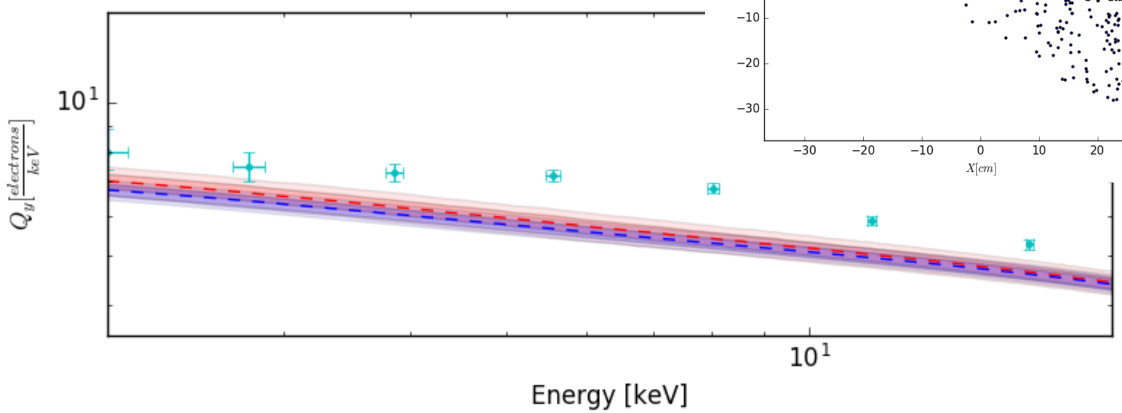


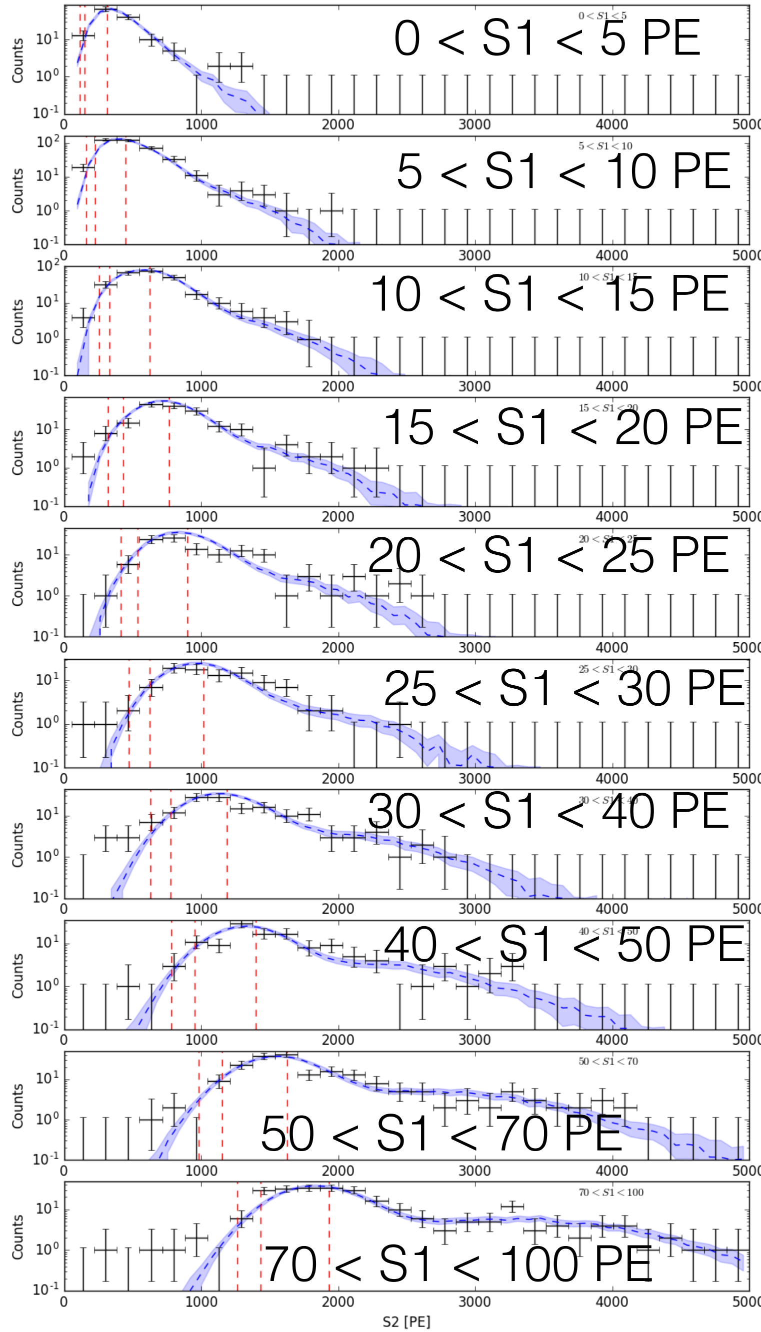
AmBe Calibration



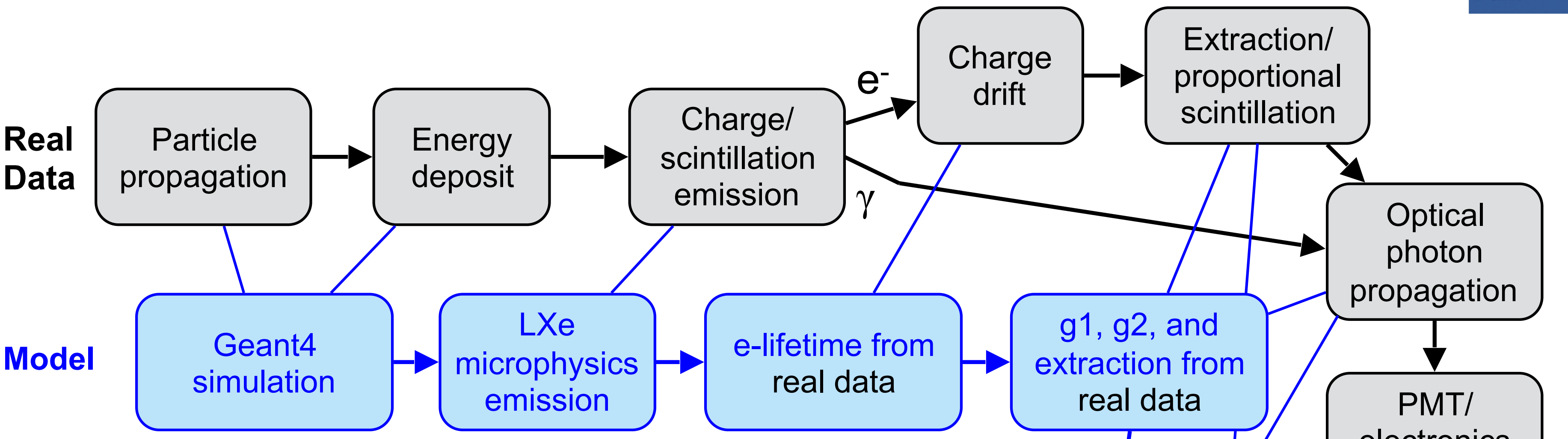


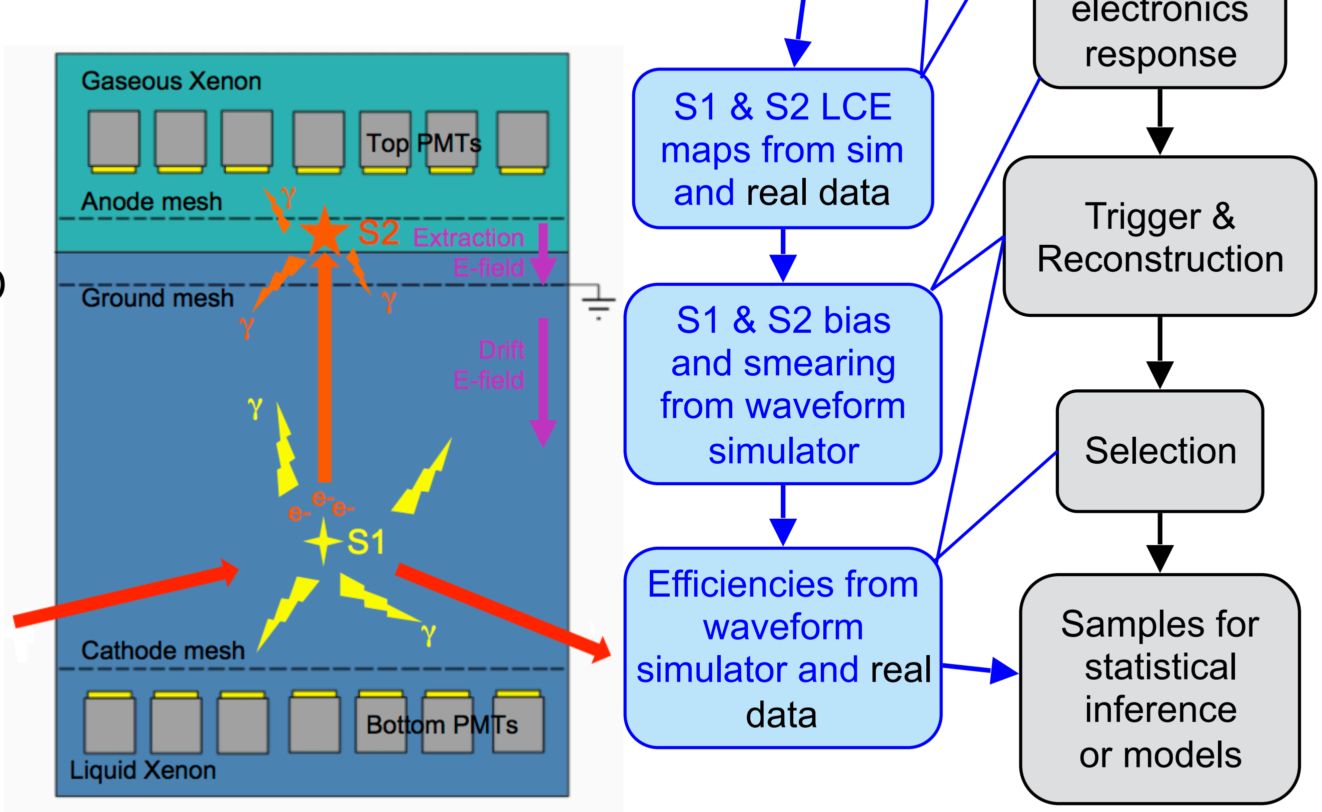






The ER and NR Models

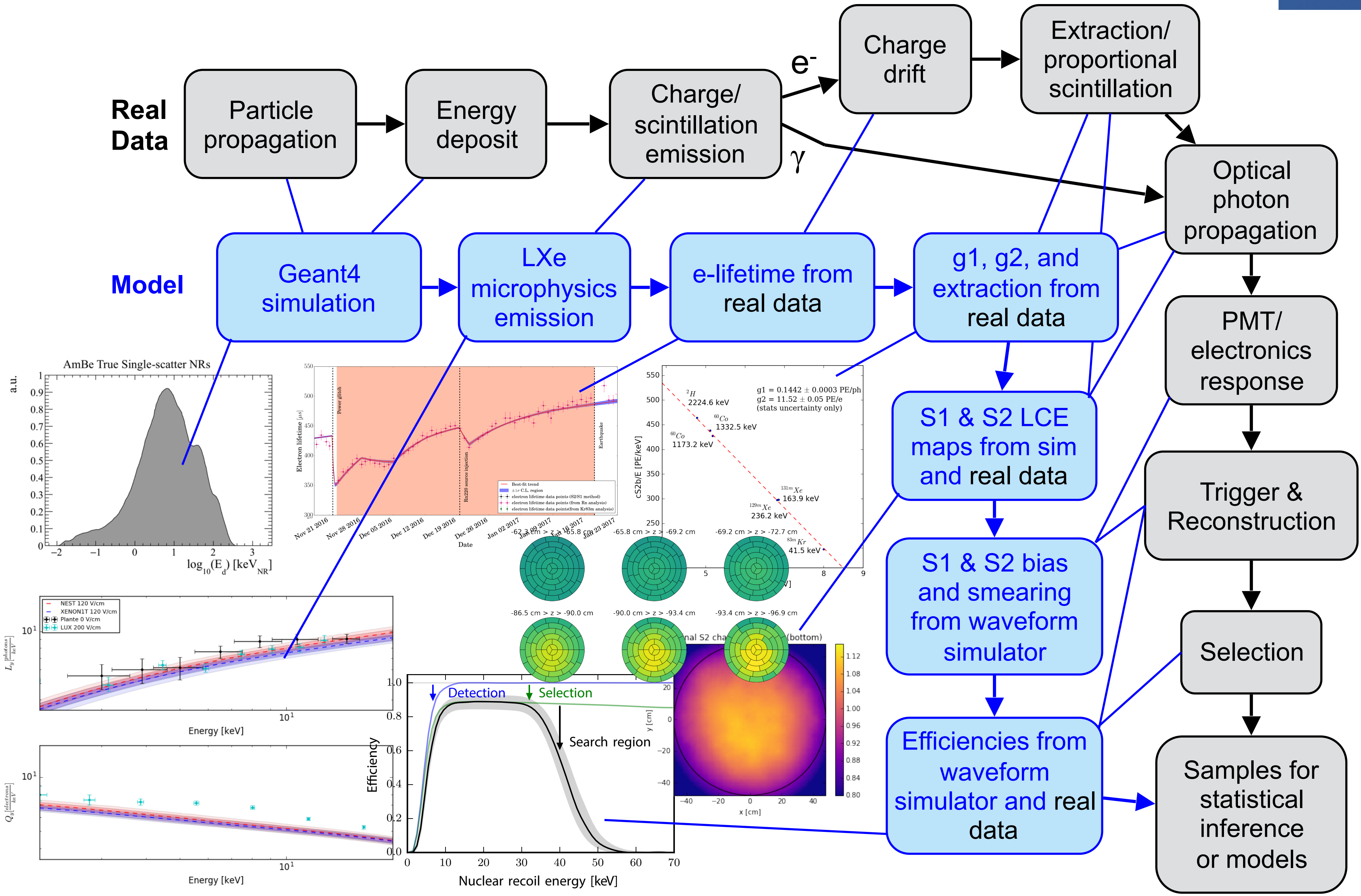




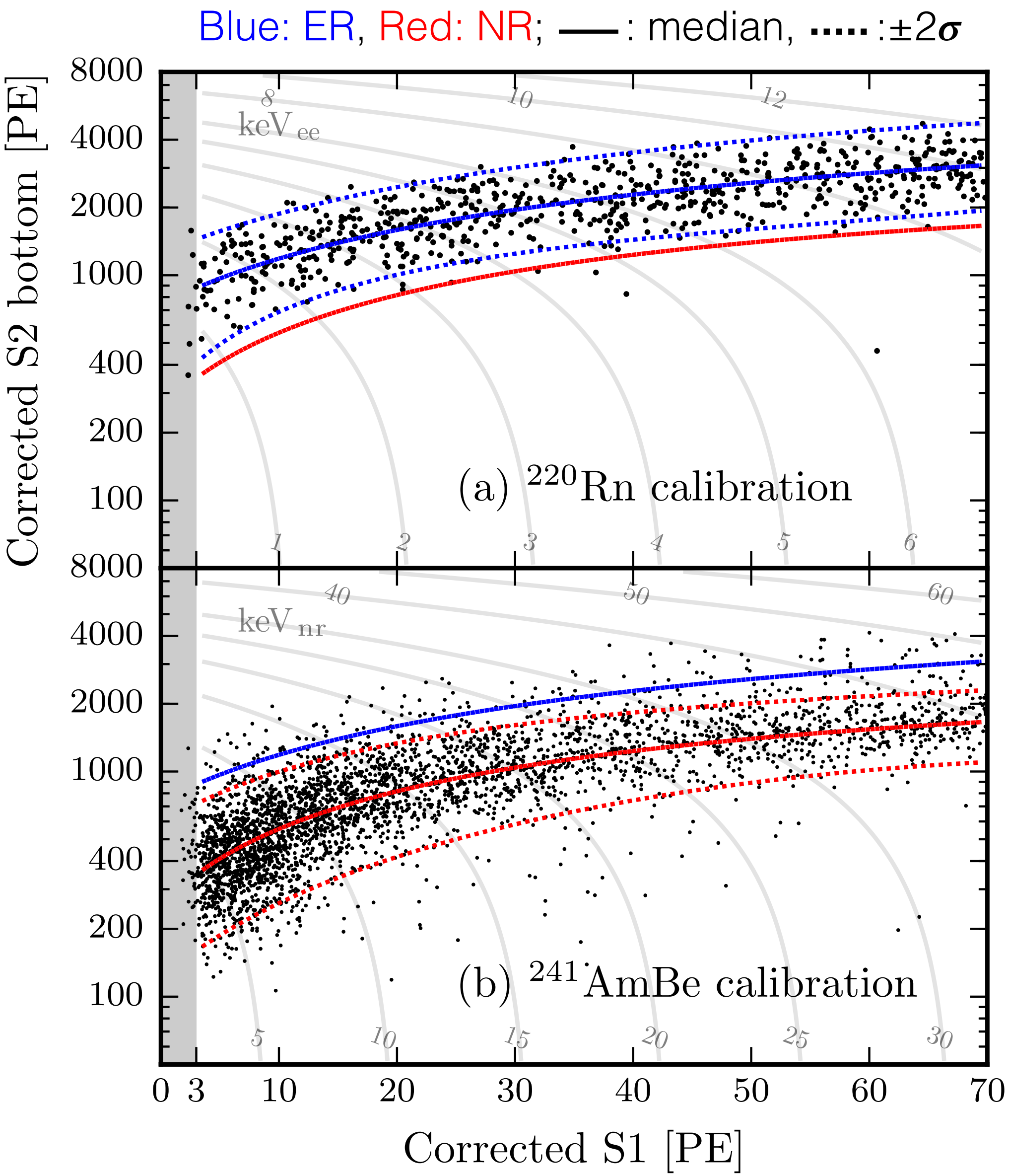
- Simulate LXe microphysics & detector response to fit Rn220 and AmBe calibration data

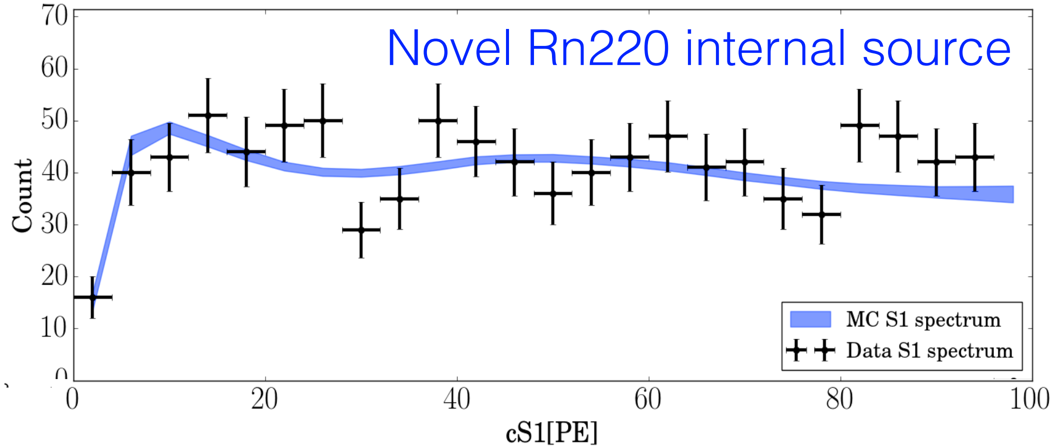
- Background and signal predictions from tuned models

The ER and NR Models

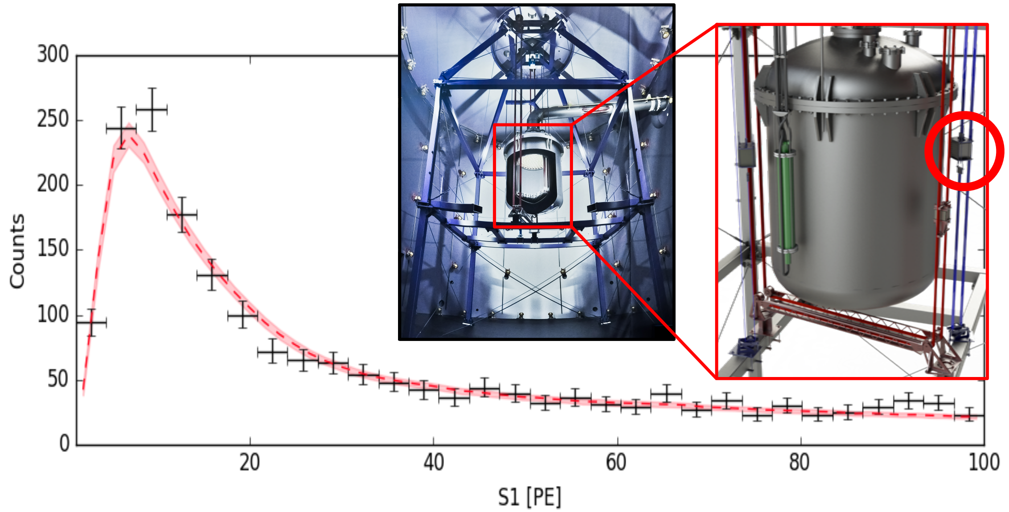


Fitting Models to Calibration



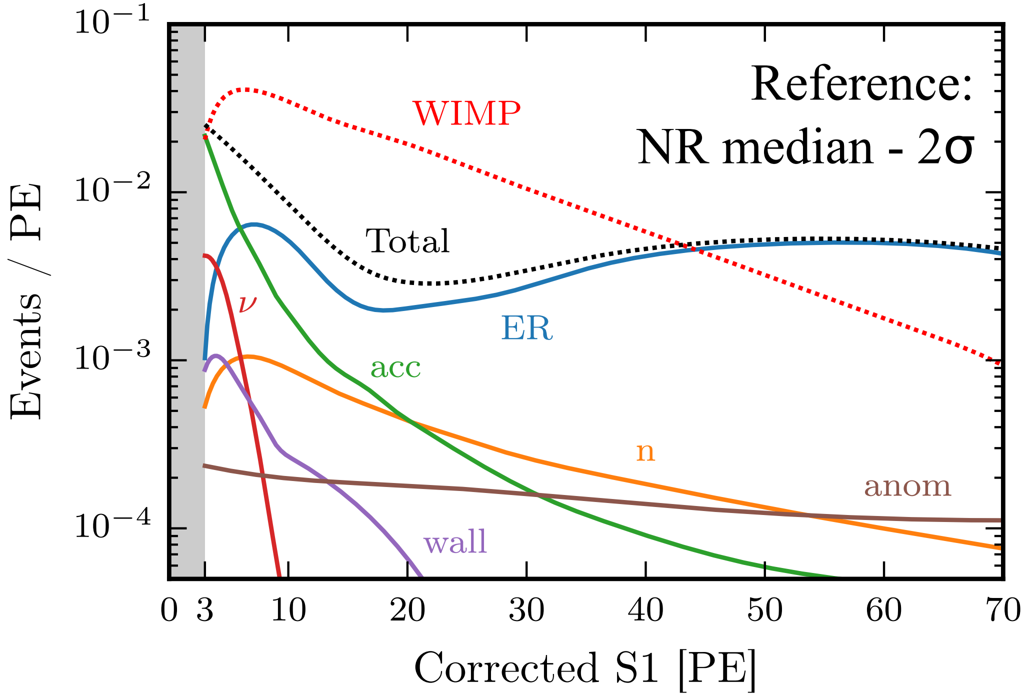


- Full modeling of LXe and detector response in $cS2_b$ vs cS1 space
- All parameters fitted with no significant deviation from priors



Background model

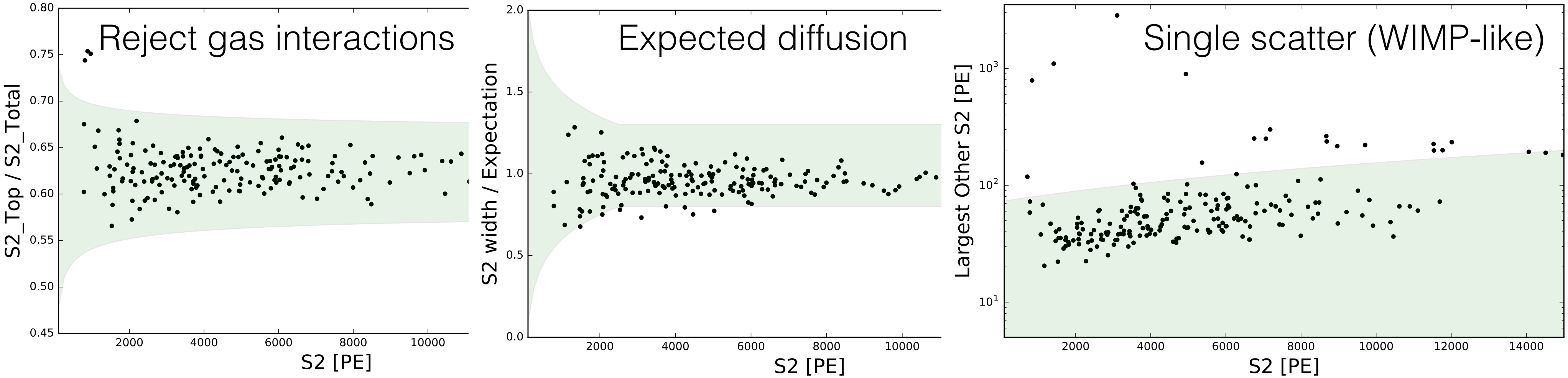
- ER and NR spectral shapes derived from models fitted to calibration data
- Other background expectations are data-driven, derived from control samples

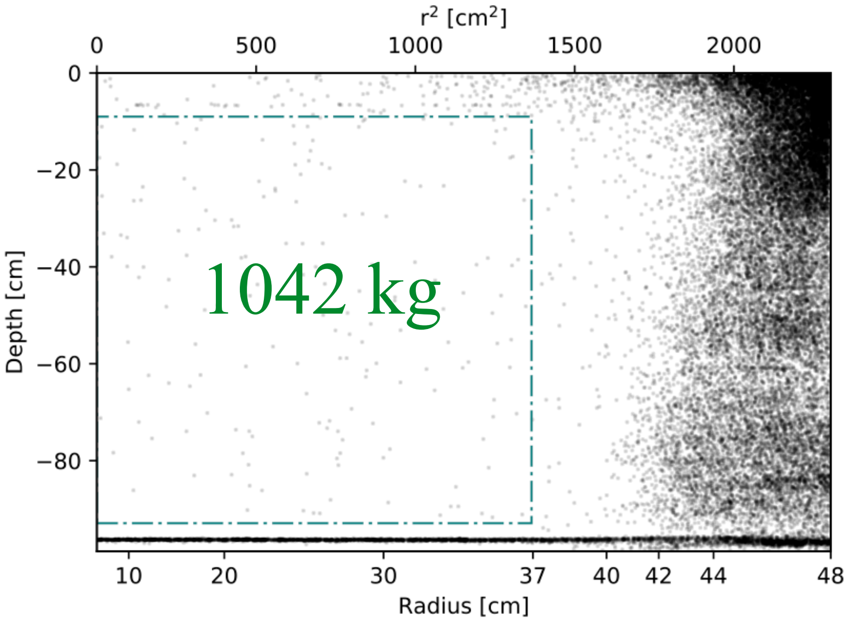


Background & Signal Rates	Total	Reference
Electronic recoils *(ER)*	62 ± 8	0.26 (+0.11)(-0.07)
Radiogenic neutrons *(n)*	0.05 ± 0.01	0,02
CNNS (ν)	0,02	0,01
Accidental coincidences (*acc*)	0.22 ± 0.01	0,06
Wall leakage (*wall*)	0.52 ± 0.32	0,01
Anomalous (*anom*)	0.09 (+0.12)(-0.06)	0.01 ± 0.01
Total background	**63 ± 8**	**0.36 (+0.11)(-0.07)**
50 GeV/c^2, 10^{-46} cm^2 WIMP *(NR)*	1.66 ± 0.01	0.82 ± 0.06

Event Selection

- Data quality and selection cuts tuned to calibration data

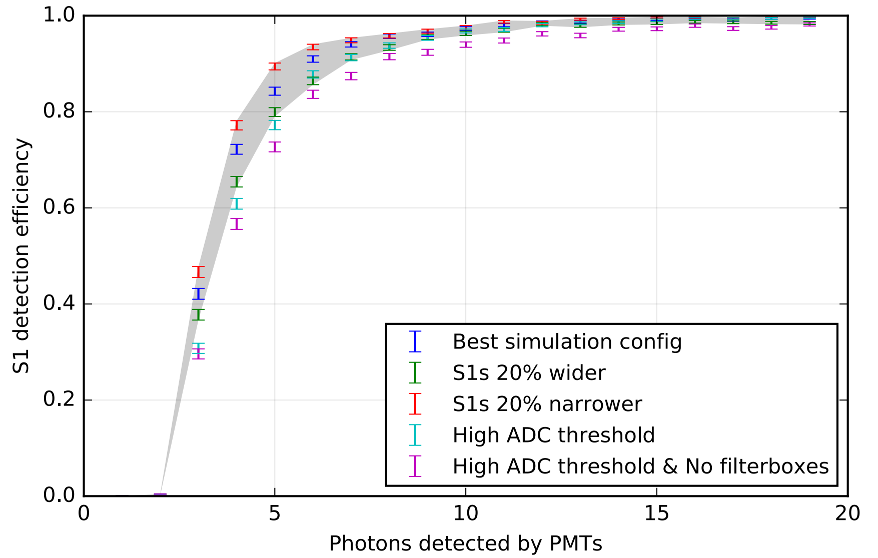


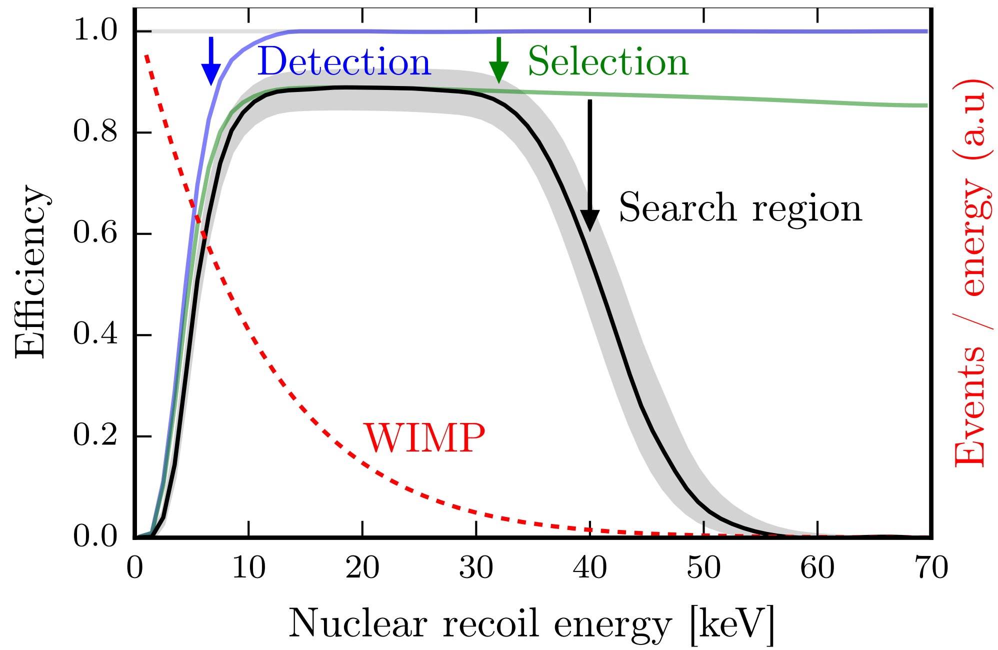


Cut	Events remaining
All Events (cS1 < 200 PE)	128144
Data Quality and Selection	48955
Fiducial Volume	180
S1 Range (3 < cS1 < 70 PE)	63

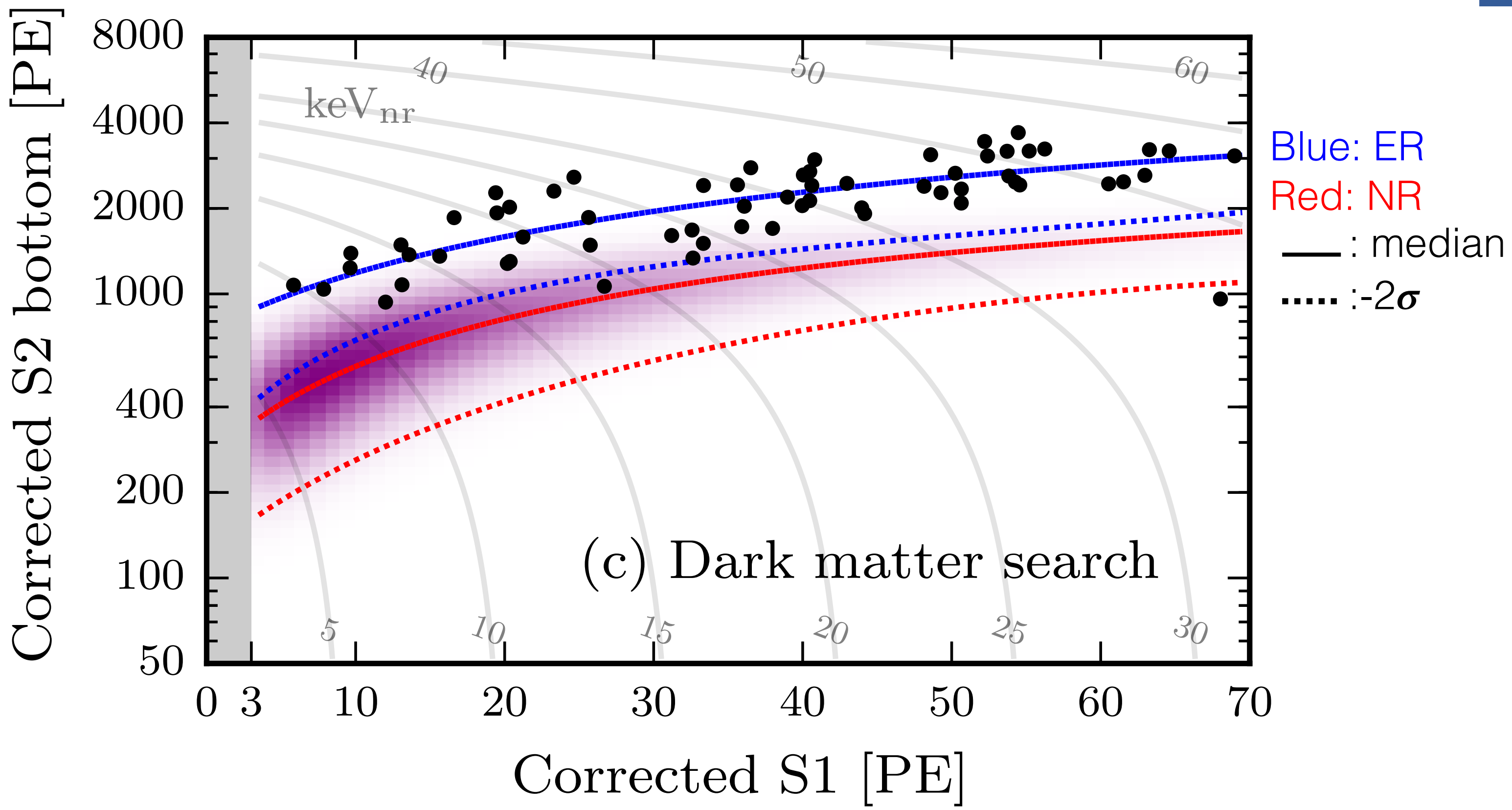
Efficiencies

- Detection efficiency dominated by 3-fold coincidence requirement
  - Estimated via novel waveform simulation including systematic uncertainties
- Selection efficiencies estimated from control samples or simulation
- Search region defined within 3-70 PE in cS1



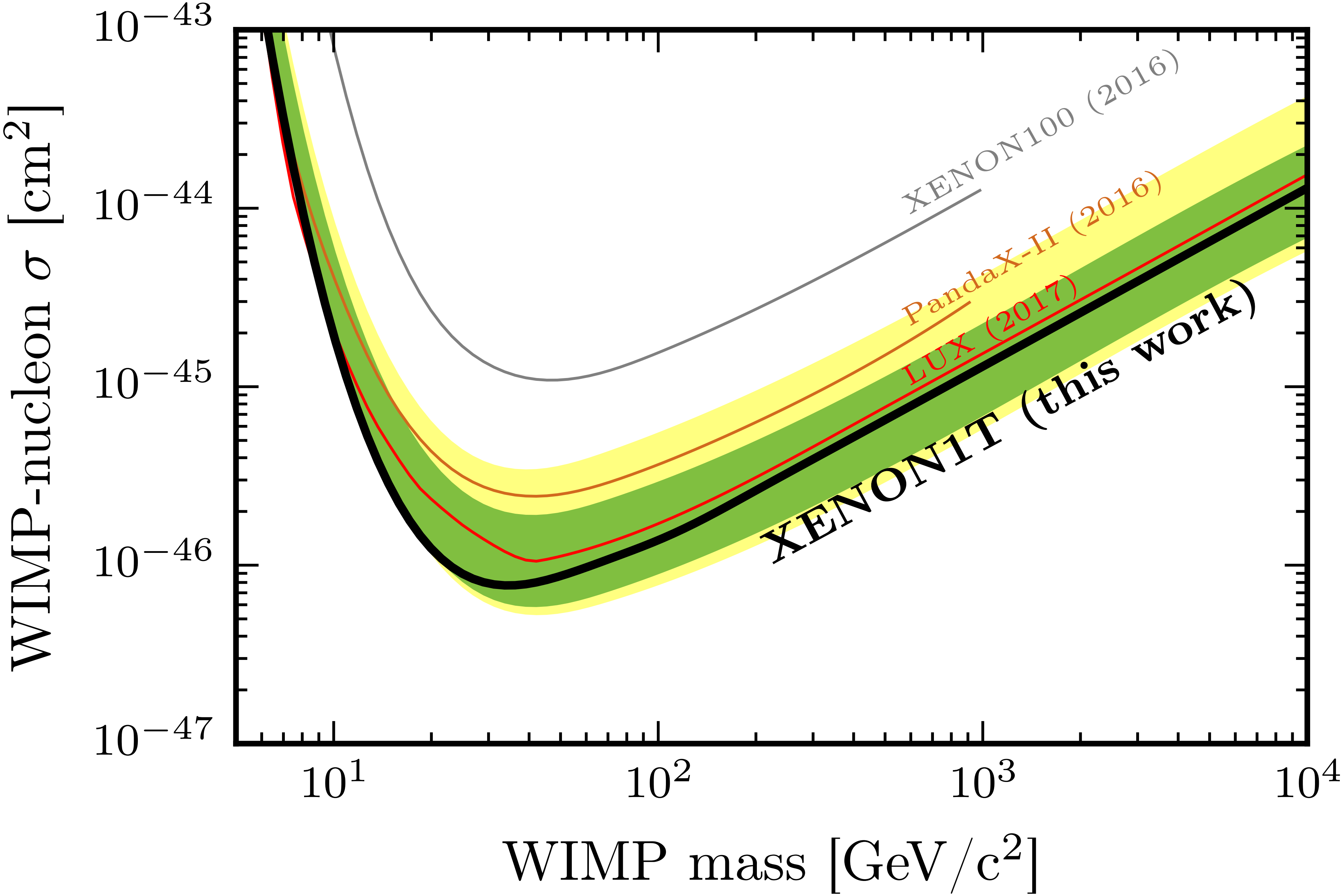


Dark Matter Search



- Extended unbinned profile likelihood analysis
- Most significant ER & NR shape parameters included from cal. fits
- Normalization uncertainties for all components
- Safeguard to protect against spurious mis-modeling of background

XENON1T Results



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- Lowest background ever achieved in a DM experiment
- First result paper submitted to PRL. arXiv:1705.06655
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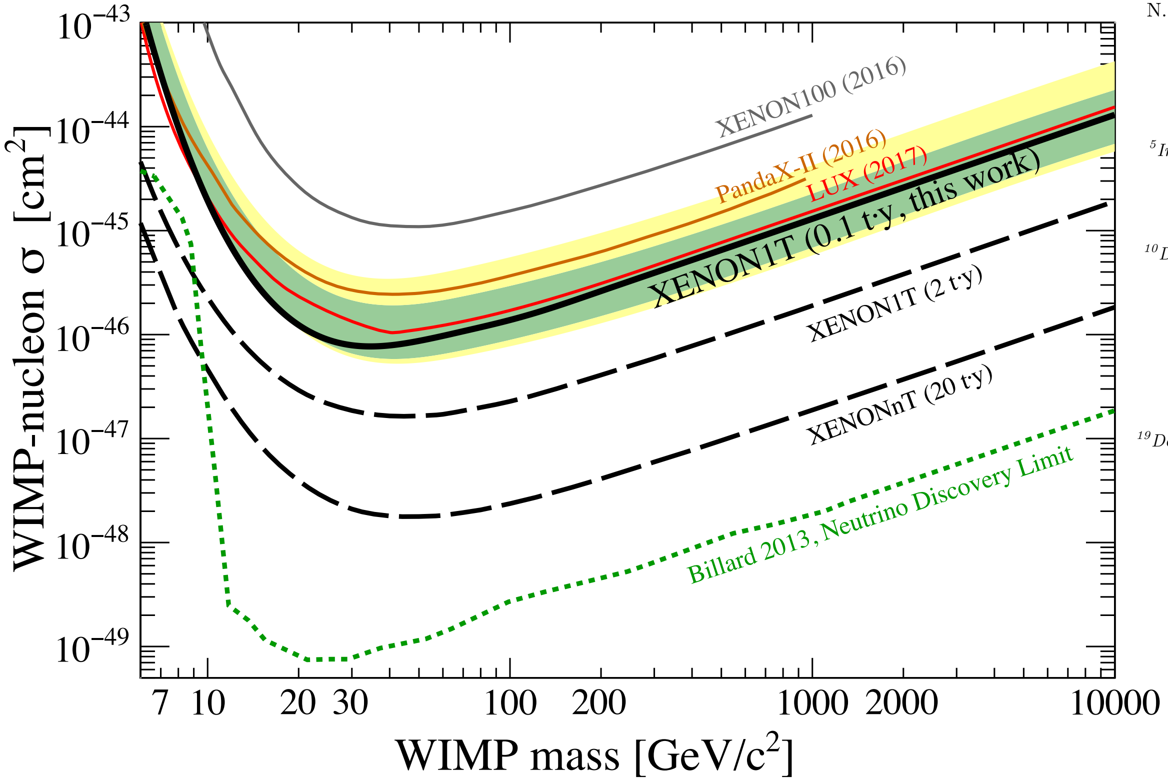

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[22]*Physics & Astronomy Department, University of California, Los Angeles, CA 90095, USA*

(Dated: May 17, 2017)

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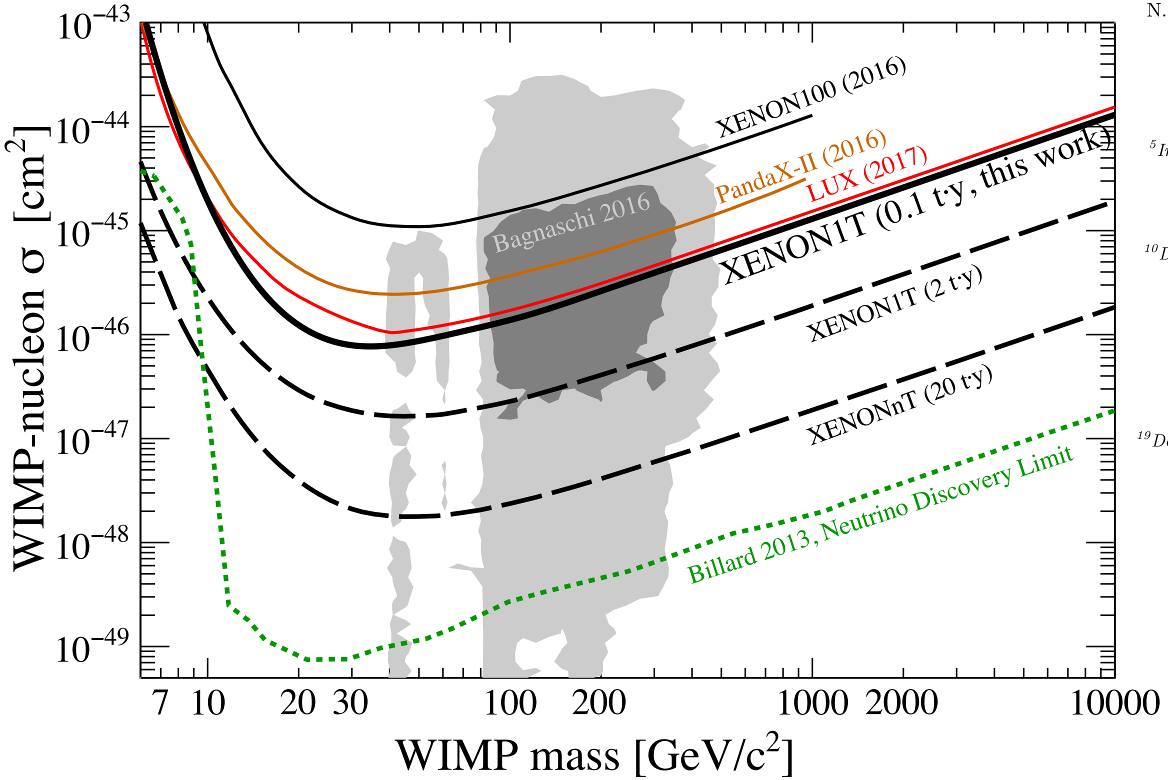

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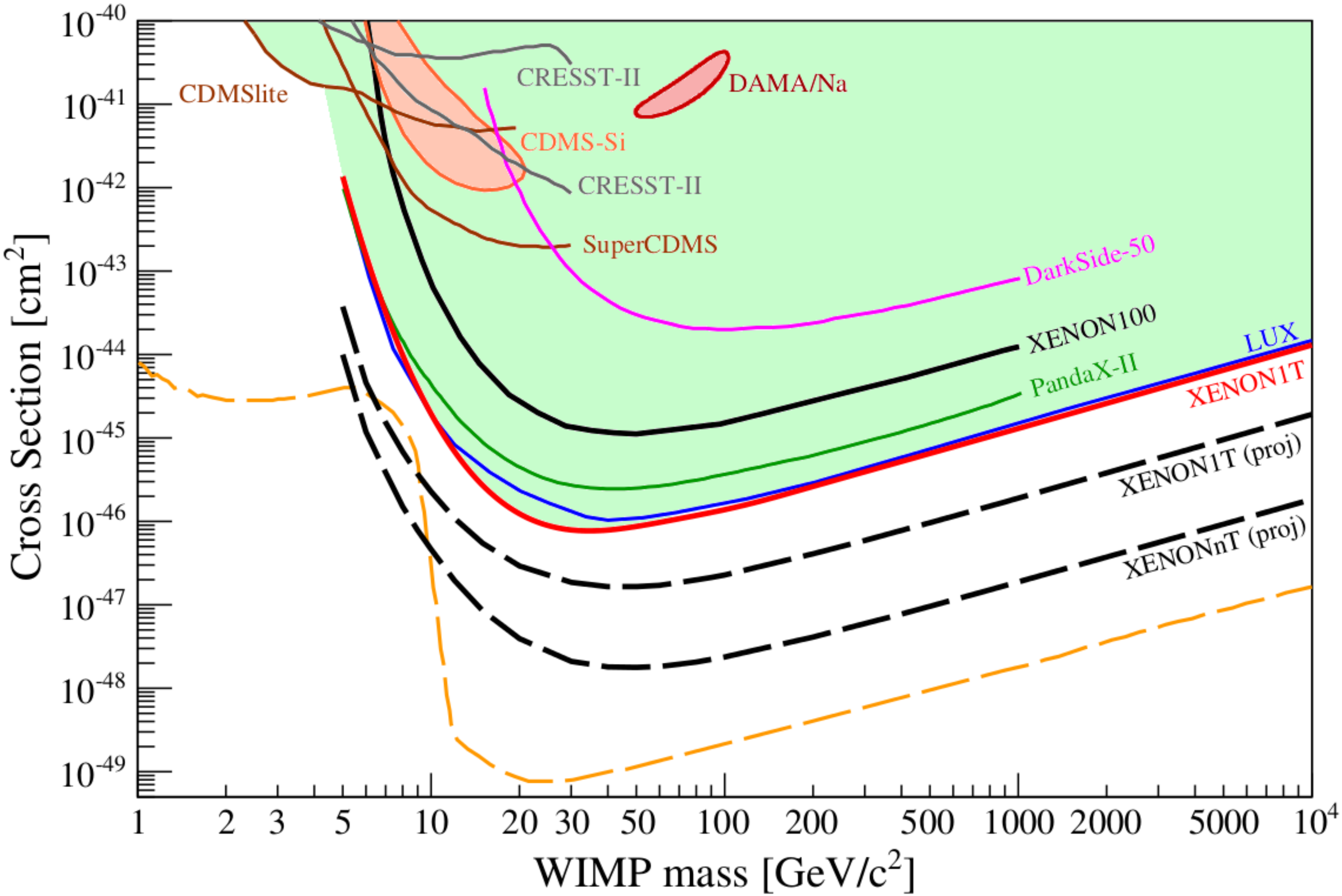
From XENON1T to XENONnT

XENONnT is a rapid upgrade of the XENON1T detector:

- New inner cryostat vessel inside the same outer vessel
- Total LXe mass will be ~8 t with 6 t active- x3 more than XENON1T
- New TPC structure with increased diameter and height (x1.4), additional PMTs (and electronics): 248 -> 476
- All other systems can handle a larger detector with a target mass of up to 10t: Cryogenics, Purification, Recovery, Support structure, DAQ, Slow Control, Muon veto. Their established performance will enable the operation of XENONnT on a fast timescale.
- Under study the need of a modular nVeto around the detector.

- Current schedule: start XENONnT in early 2019

From XENON1T to XENONnT



Conclusions

- **XENON1T** first results demonstrate that the detector is performing very well.
- The measured ER background is the lowest ever achieved in a DM detector: (1.93 +/- 0.25) 10^{-4} events / (kg day keV)
- With only 34.2 days of exposure, we have already obtained the best exclusion limit in the world: 7.7 10^{-47} cm^2 @ 35 GeV/c^2 WIMP. **XENON1T** (**and LNGS**) are again in the frontline of the DM search race.
- Additional >70 days of data have been acquired, and are currently under analysis.
- The foreseen sensitivity of **XENON1T**, in 2 t x y, is 1.6 10^{-47} cm^2.
- Planning a fast upgrade to **XENONnT**, for another order of magnitude in sensitivity.

Thanks !

XENON
Dark Matter Project
PURDUE
CHICAGO
INFN
Stockholm University
UC San Diego
Rensselaer
NYU ABU DHABI
CAEN