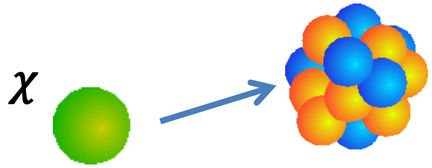
First Results from the XENON1T Experiment

J. Masbou,
on behalf of the XENON Collaboration

Direct dark matter detection principle

Nuclear
Recoil
(NR)



$$\chi + \mathrm{N} \rightarrow \chi + \mathrm{N}$$

Direct dark matter detection principle

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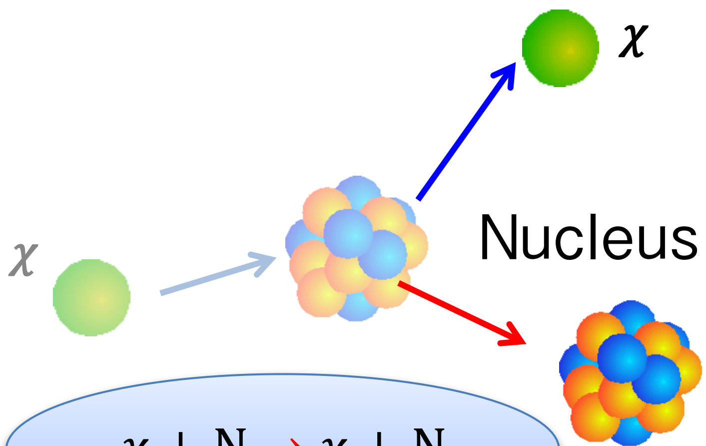
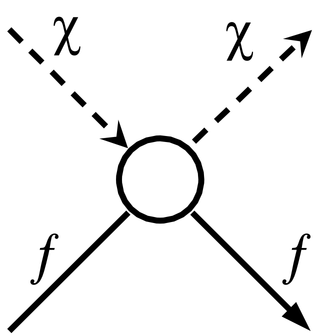


$\chi + N \rightarrow \chi + N$

Recoil energy
~1-100 keV



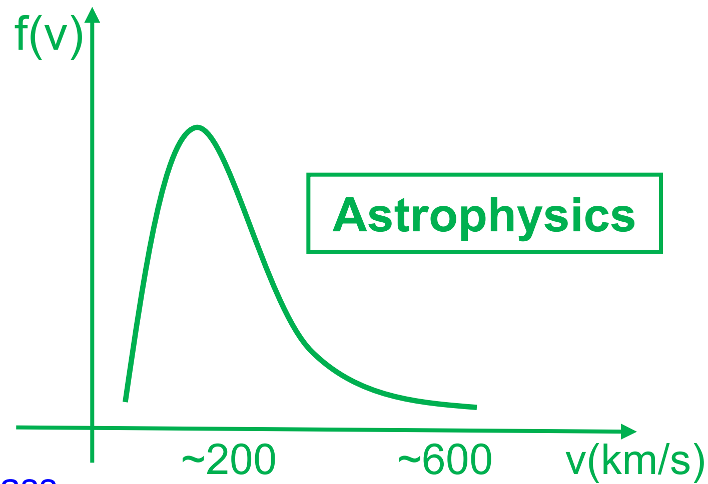
Electronic Recoil (ER)

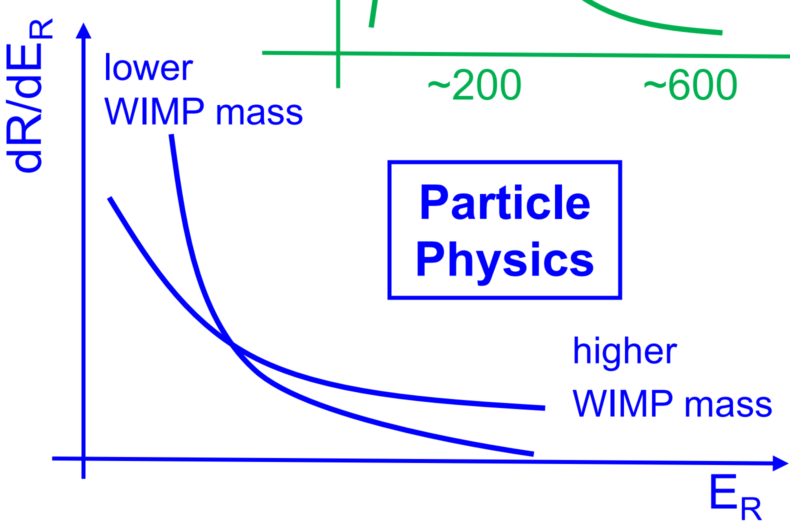
γ and β particles interact with the atomic electrons → background

Expected rate for terrestrial detector

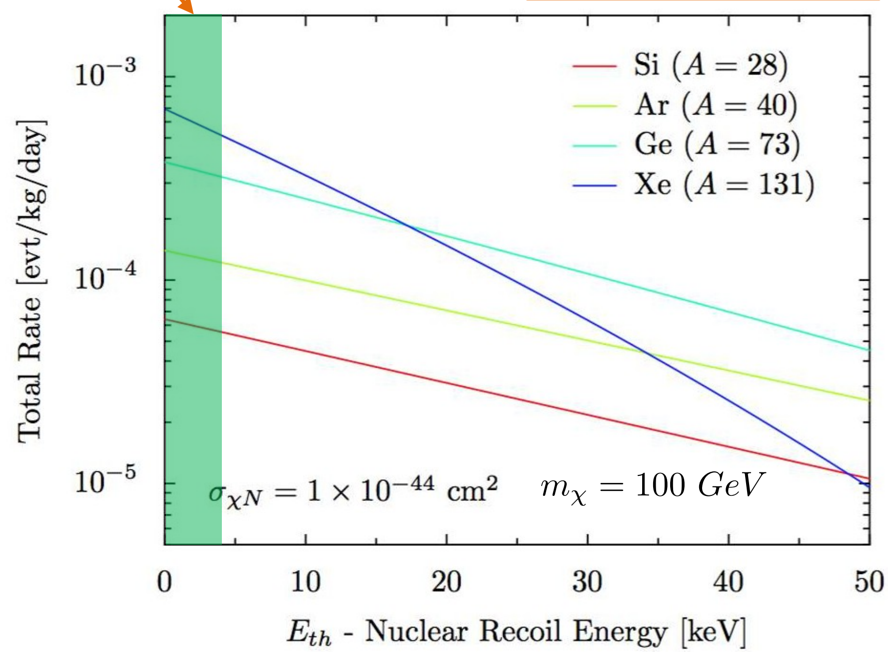
$$\frac{dR}{dE_R} = N_N \frac{\rho_\odot}{m_\chi} \int_{v_{min}}^{v_{max}} f(v) v \frac{d\sigma}{dE_R} dv$$

$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu}}$$



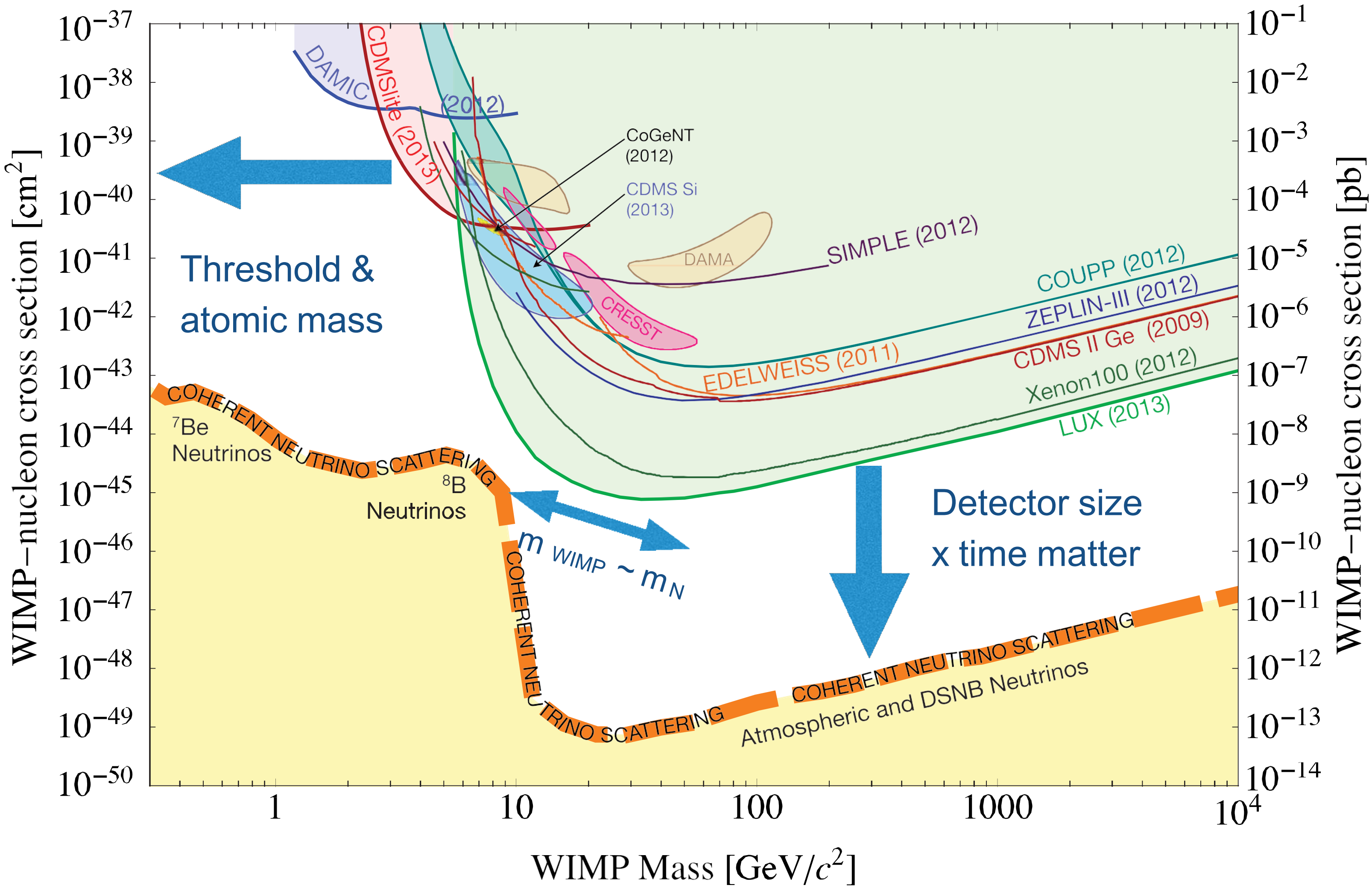


Detector

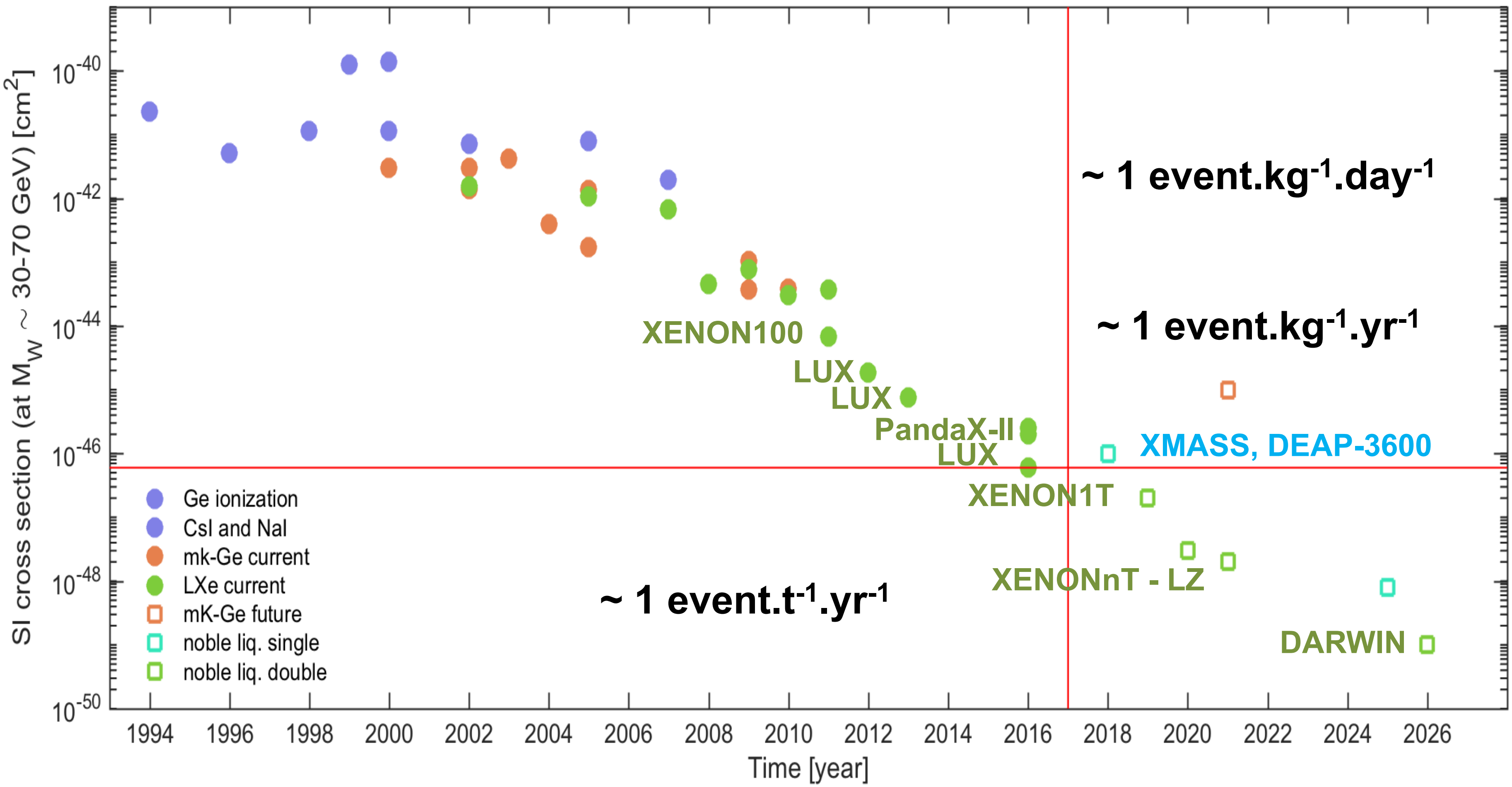


How is evolving the field of Direct Detection ?

$$R \sim 0.13 \frac{\text{events}}{\text{kg . year}} \left[\frac{A}{100} \times \frac{\sigma_{\chi N}}{10^{-38}\ \text{cm}^2} \times \frac{\langle v \rangle}{220\ \text{km.s}^{-1}} \times \frac{\rho_\odot}{0.3\ \text{GeV.cm}^{-3}} \right]$$



Direct detection : progress over time



The fight against the background

- **Avoid background**

- **External γ's** from natural radioactivity

- Material screening
- Self shielding (fiducialization)

- **External neutrons**
  muon-induced (α,n) and fission reaction

- Material screening (low U and Th)
- Underground experiments
- Shield & active veto

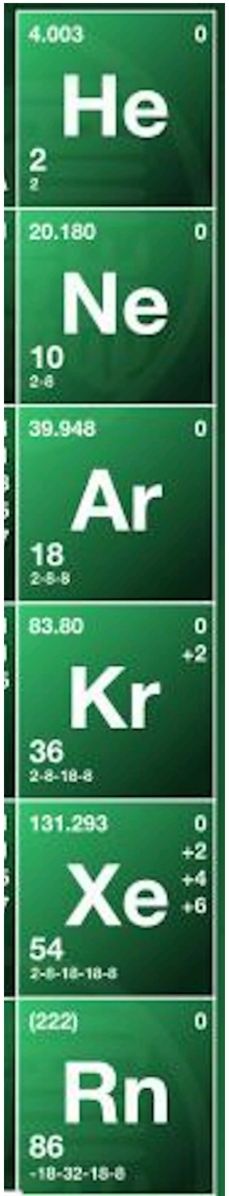
- **Internal contamination**

- ^{85}Kr : removed by cryogenic distillation
- ^{222}Rn : removed by cryogenic distillation
- ^{136}Xe : $\beta\beta$ decay, long lifetime ($T_{1/2}$ = 2.2x10^{21} years)

- **Use WIMP properties**

- No double scatter
- Homogeneously distributed
  → *Position reconstruction*
- Nuclear recoils
  → *ER/NR Discrimination*

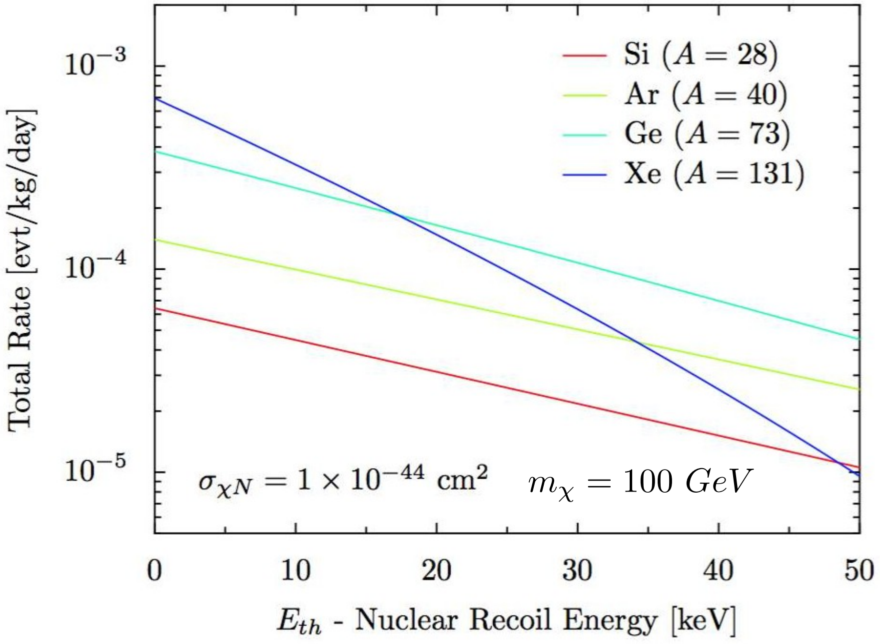
Noble gases



	Neon	Argon	Krypton	Xenon
Atomic Number	10	18	36	54
Density	1.2	1.4	2.4	3
Scintillation (γ/keV)	30	40	25	42
Wavelength (nm)	85	128	150	178
Decay Time (ns)	15400	6.3, 1500	2, 91	2.2, 27, 45
Ionization (e-/keV)	46	42	49	64
Boiling Point (K)	27.1	87.3	119.8	165.0
Radioactivity	No	^{39}Ar 1Bq/kg (1mBq/kg)	Yes	^{136}Xe / Kr can be removed to ppt level
Price	$$	$ ($$$)	$$$	$$$$

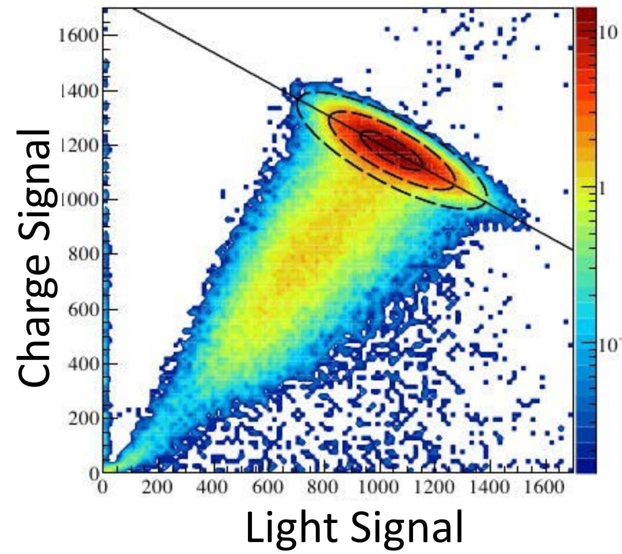
Why Xenon ?

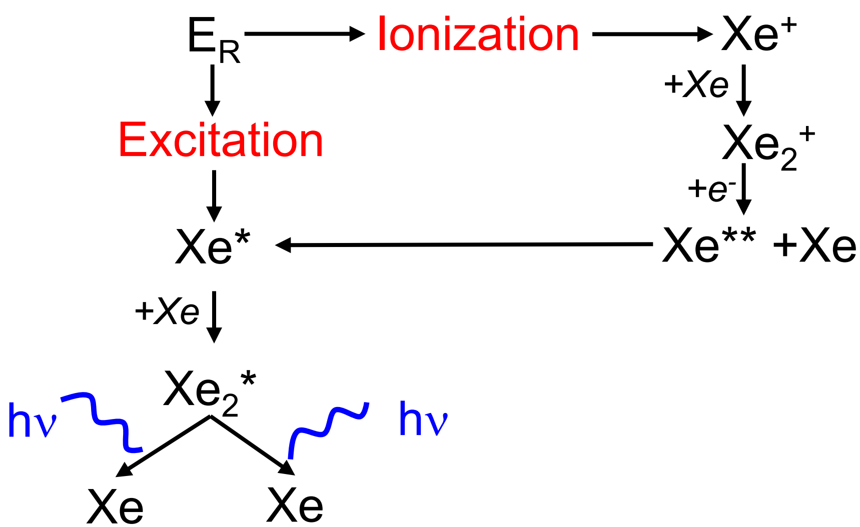
- Large mass number A (131) (Interaction cross section $\propto A^2$)
- 50% odd isotopes (^{129}Xe, ^{131}Xe) for Spin-Dependent interactions
- Kr can be reduced to ppt levels
- High stopping power, i.e. active volume is self-shielding
- Efficient scintillator (178 nm)
- Scalable to large target masses
- Electronic recoil discrimination with simultaneous measurement of scintillation and ionization

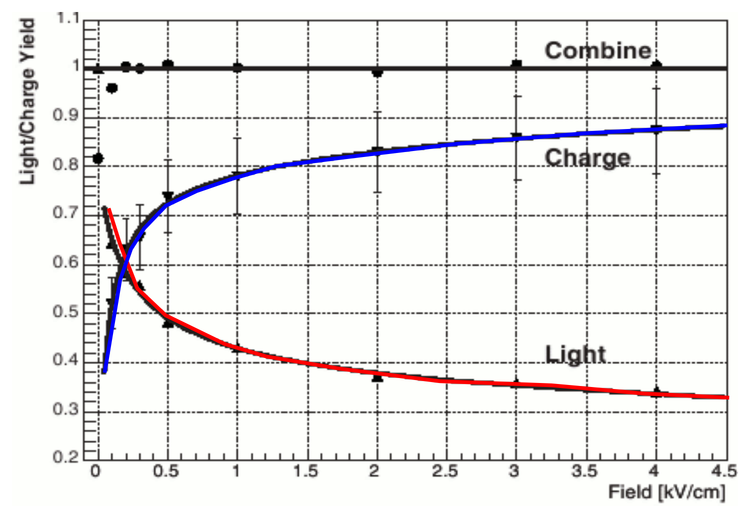


Scintillation and ionization in noble liquids

- Energy deposit produce both:
  - Electron-ion pair
  - Excited atom states
- Anti-correlation between charge and light
  → Improve energy resolution
- Excitation depends on dE/dx
  → Discrimination capabilities

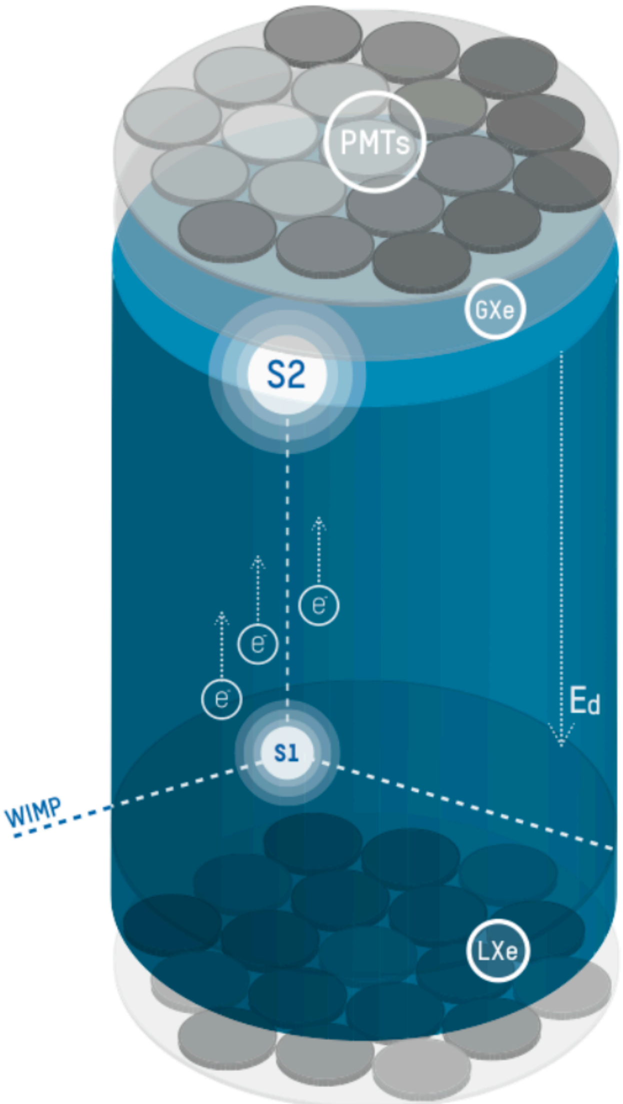






Dual phase TPC: principle

TPC = Time Projection Chamber



S1:

→ Photon (λ = 178 nm) from Scintillation process → Dectected by PMTs (mainly botton array)

S2:

→ Electrons drift

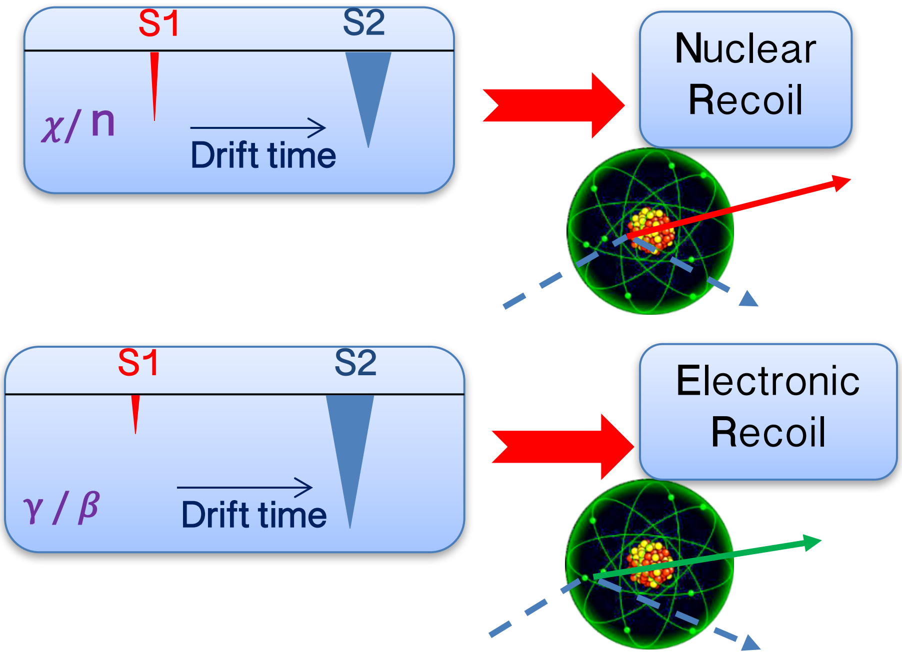
→ Extraction in gaseous phase

→ Proportional scintillation light

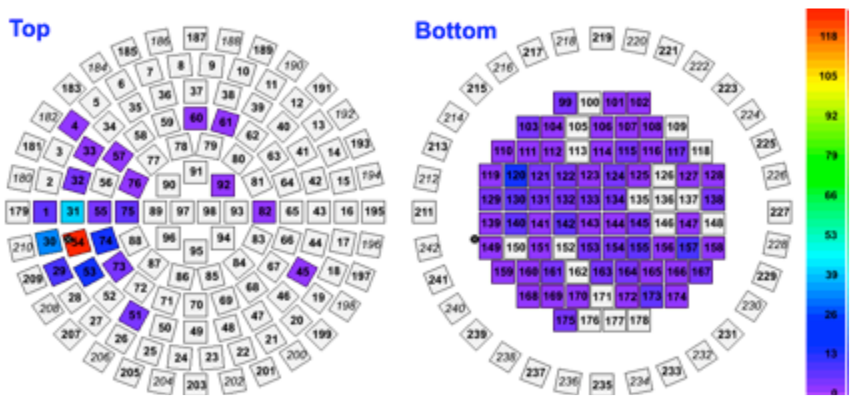
3D reconstruction :

→ X,Y from top array

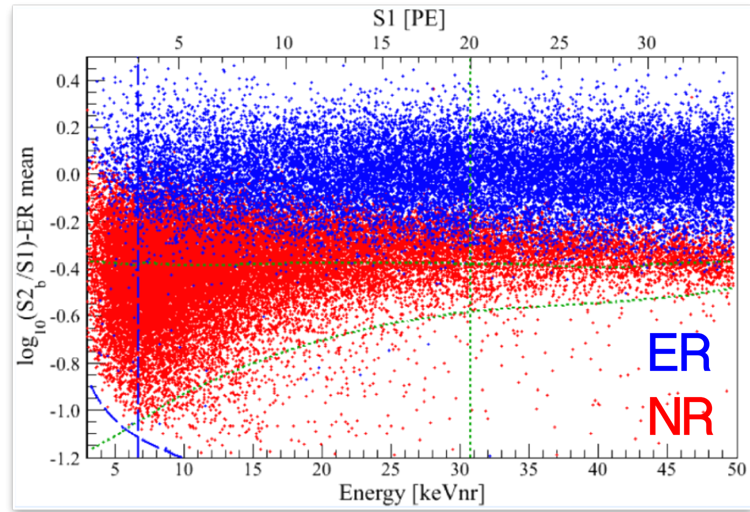
→ Z from Drift time

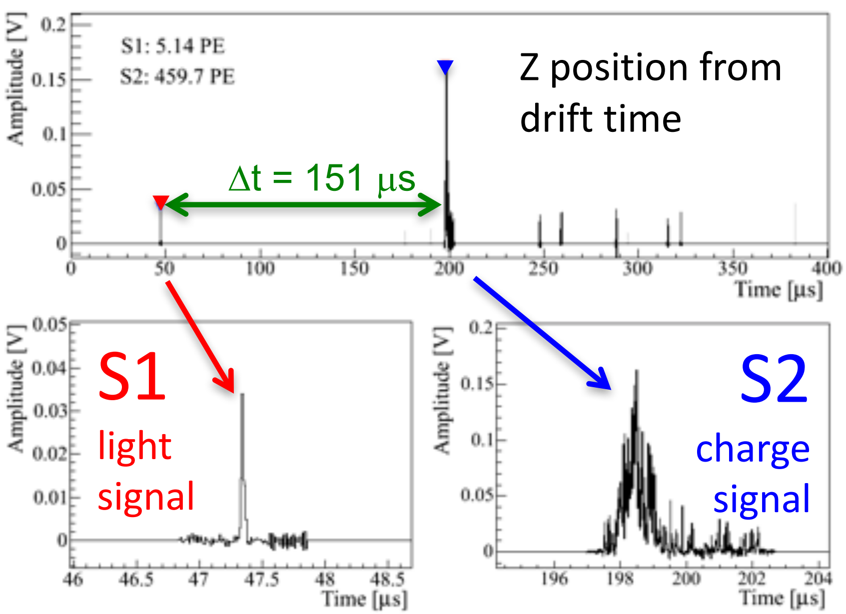


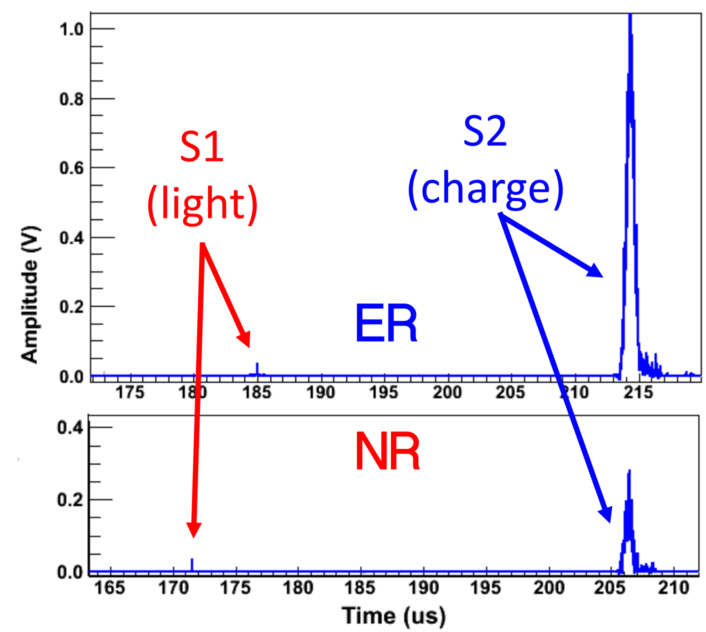
Dual phase TPC: real life



X and Y position from S2 hit pattern on the top PMTs







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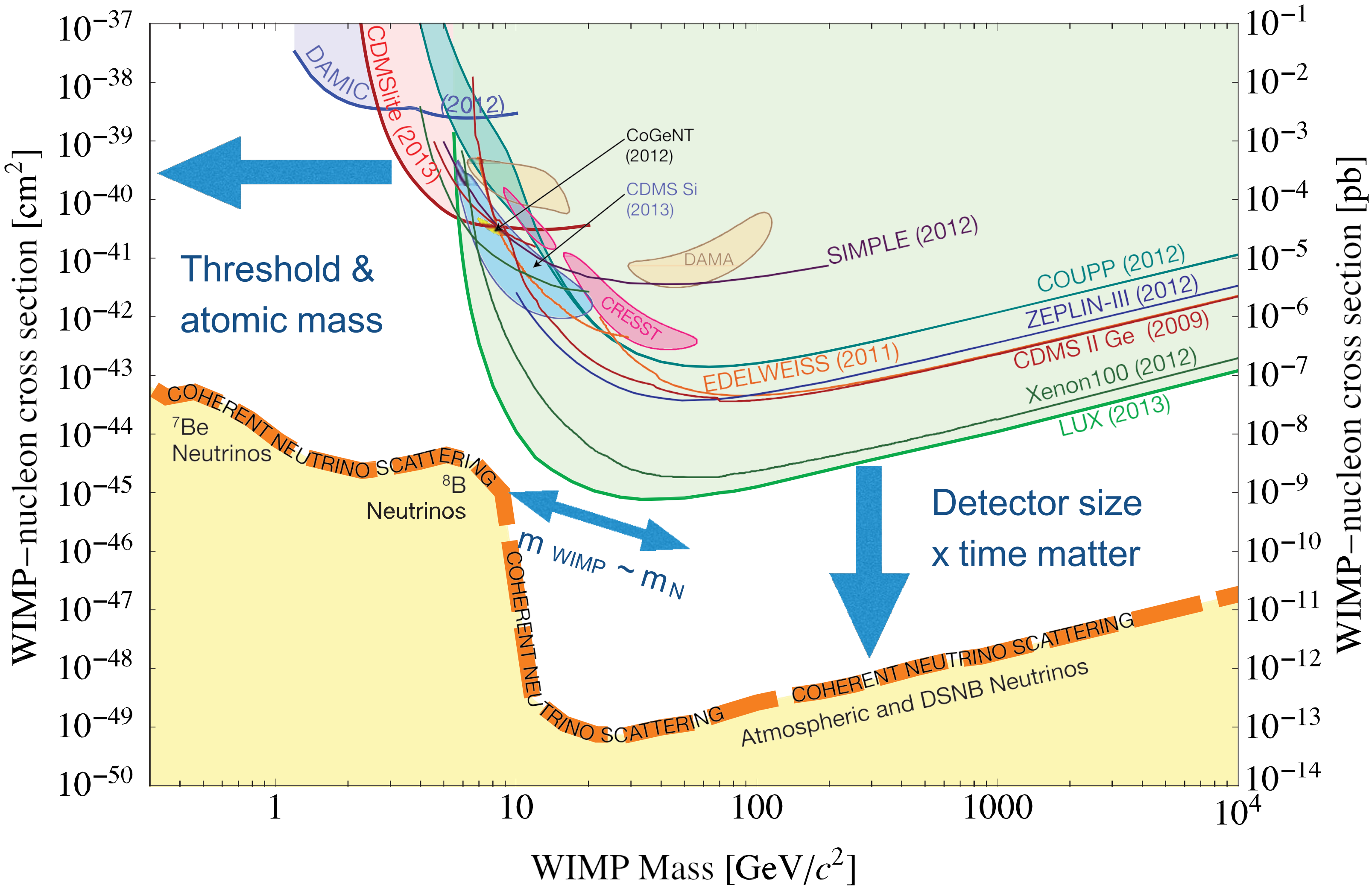


XENON World

23 Institutions
10 Countries
135 Scientists

Columbia · RPI · Nikhef · Stockholm · Muenster · Mainz · MPIK

Chicago · UCLA · UCSD · Rice

Freiburg · Zurich · NYUAD · Weizmann

Purdue · Coimbra · Subatech · LPNHE · LAL · Bologna · LNGS · Torino

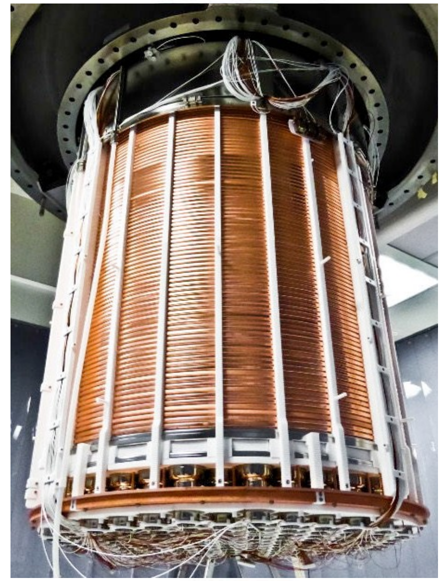
Phases of the XENON Program

XENON10
2005 – 2007
15 cm drift TPC
Total: 25 kg
Target: **14** kg
Fiducial: 5.4 kg

Achieved (2007)
$\sigma_{SI} = 8.8 \cdot 10^{-44}$ cm^2
@ 100 GeV/c^2

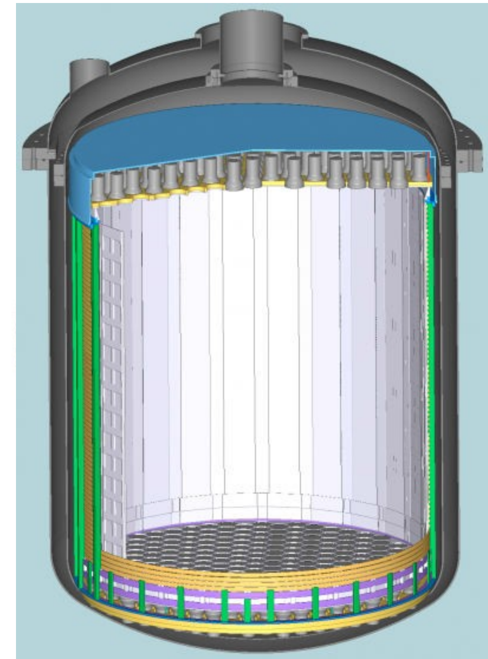
XENON100
2008 – 2016
30 cm drift TPC
Total: 161 kg
Target: **62** kg
Fiducial: 34/48 kg

Achieved (2016)
$\sigma_{SI} = 1.1 \cdot 10^{-45}$ cm^2
@ 55 GeV/c^2



XENON1T
2012 – 2019
100 cm drift TPC
Total: 3 200 kg
Target: **2 000** kg
Fiducial: 1 000 kg

Projected (2018)
$\sigma_{SI} = 1.6 \cdot 10^{-47}$ cm^2
@ 50 GeV/c^2



XENONnT
2017 (R&D) – 2023
144 cm drift TPC
Total: 8 000 kg
Target: **6 000** kg
Fiducial: 4 500 kg

Projected (2022)
$\sigma_{SI} = 1.6 \times 10^{-48}$ cm^2
@ 50 GeV/c^2

XENON1T facility

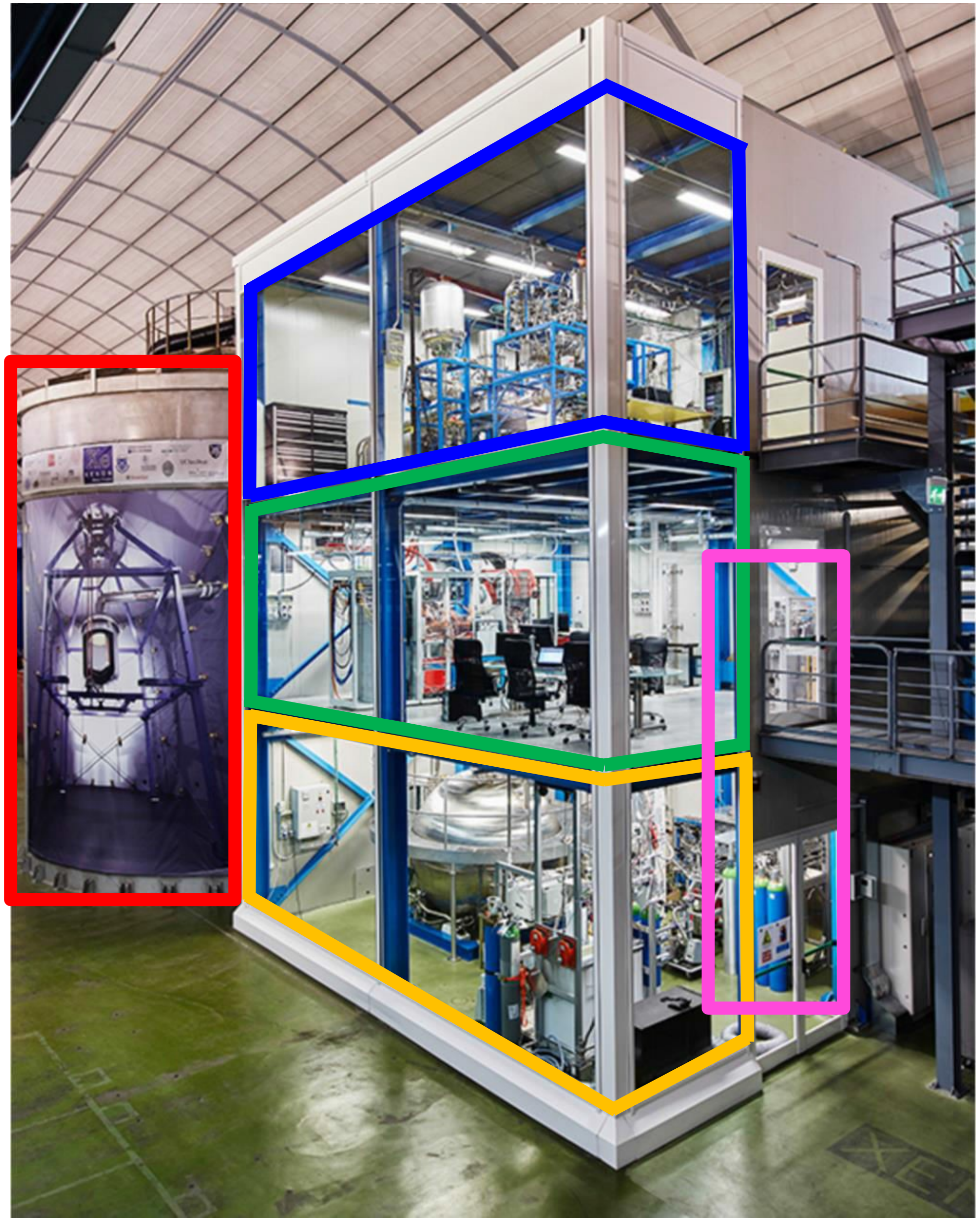
Water shield: deionized water as passive radiation shield
Muon veto: Active muon veto against muon induced neutrons (84 PMTs)

Cryogenics: Stable conditions(3.2t LXe)
Purification: LXe flow through getters, remove impurities

DAQ: Each channel has its own threshold, Flexible software algorithms
Readout: Up to 300MB/s for high rate calibrations

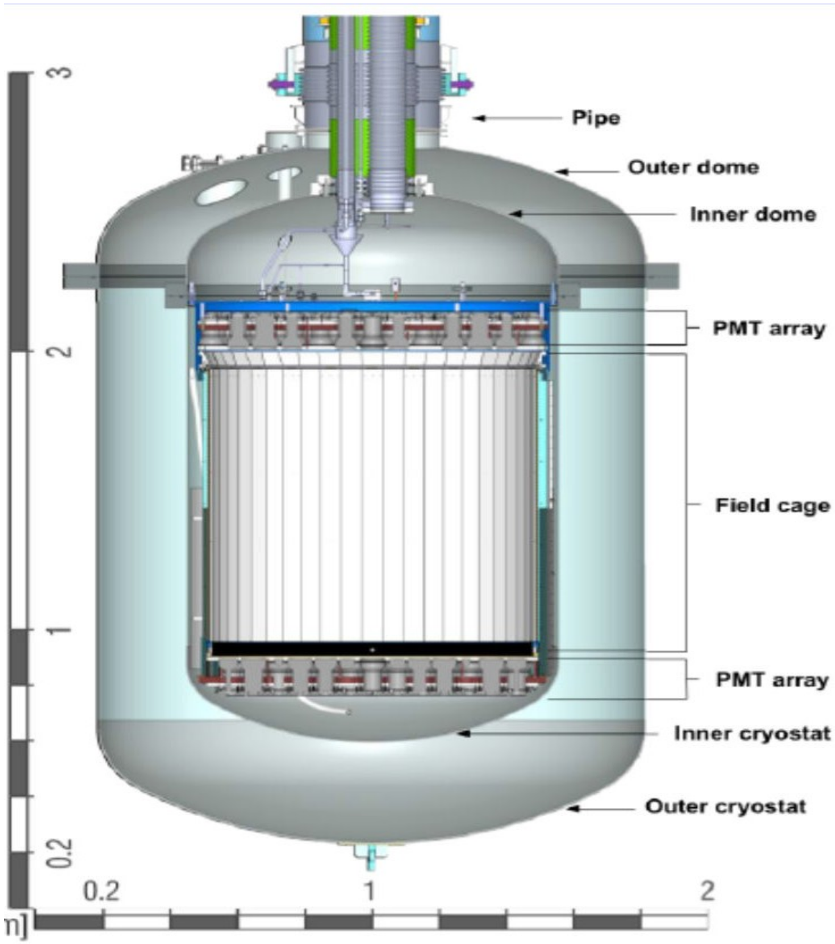
ReStoX: Emergency recovery up to 7.6 tons of LXe
Passive: No active cooling required to keep Xe contained

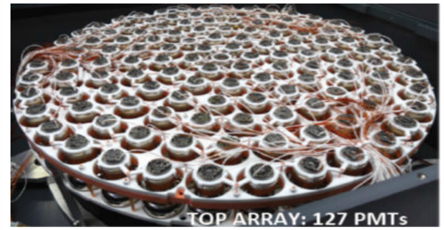
Kr Distillation: Remove Kr from system during fill or online
Rn Distillation: Initial tests show promising reduction for Rn



TPC

The largest Xe double-phase TPC ever built !

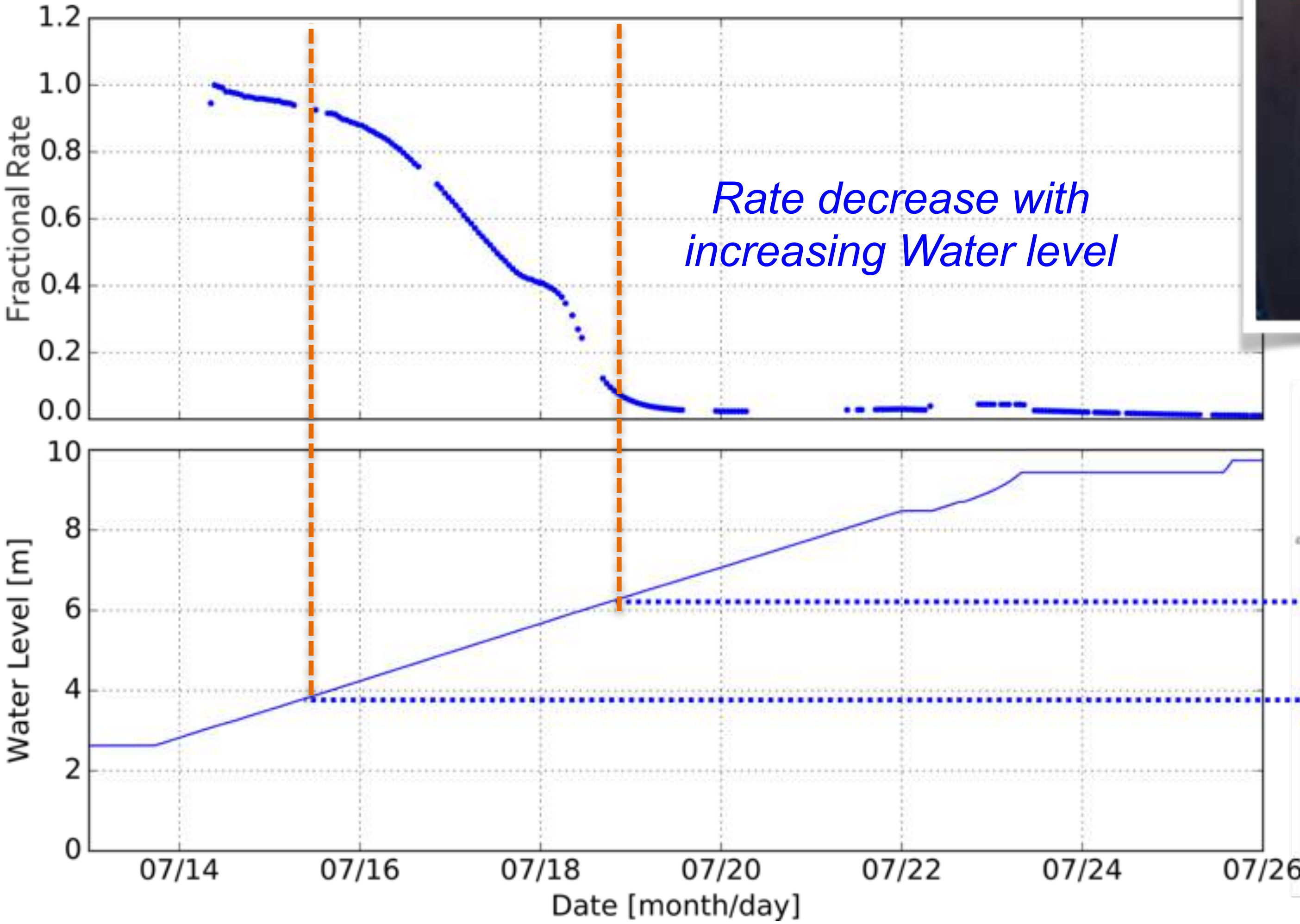


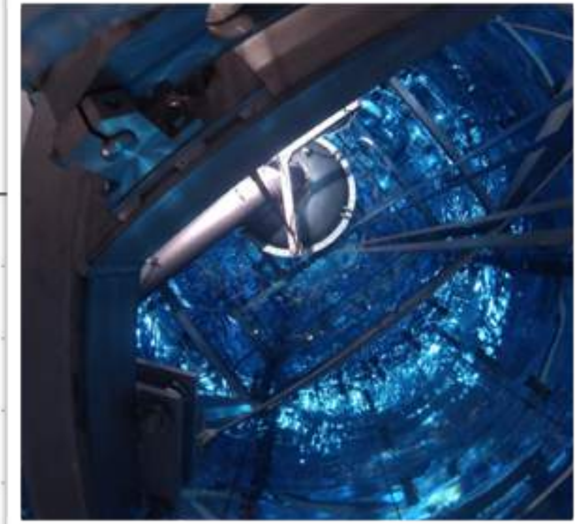


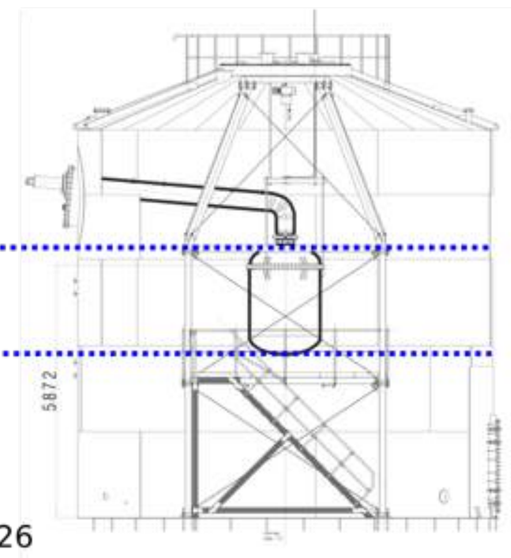
- Active Xe mass: 2 tons.
- Light sensors: 127+121 3” PMTs average QE = 35%
- Fully covered with high reflectivity PTFE to maximize light collection.
- Drift region: 1m height, 1m diameter.

Water Shield filling

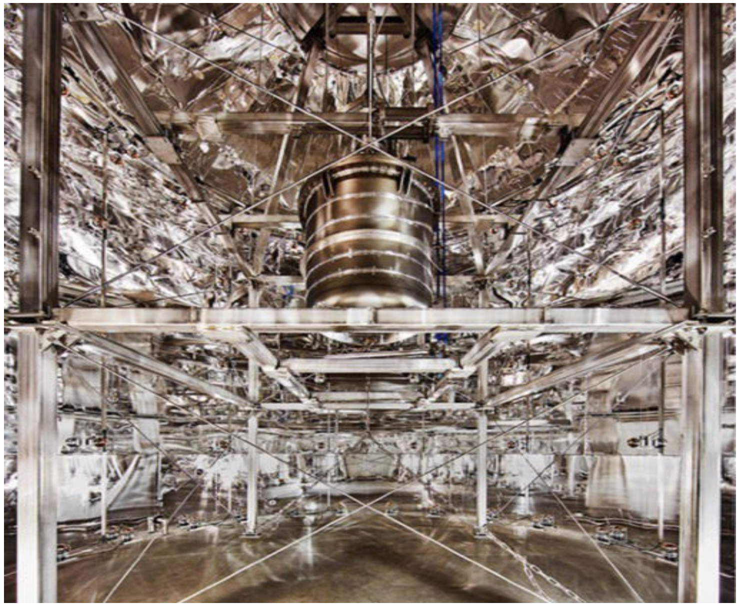
- TPC fully immersed in water since July 2016
- Background studies and calibration runs started



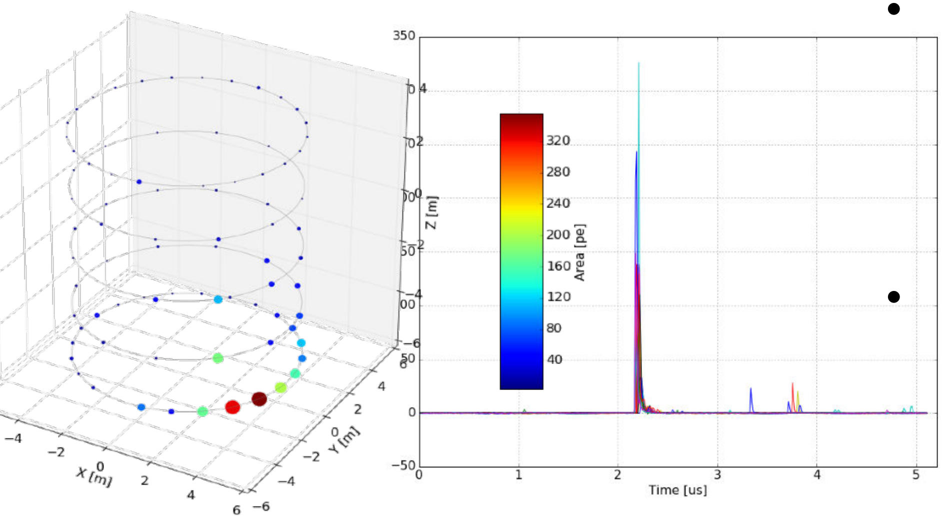




Muon Veto Cherenkov Detector

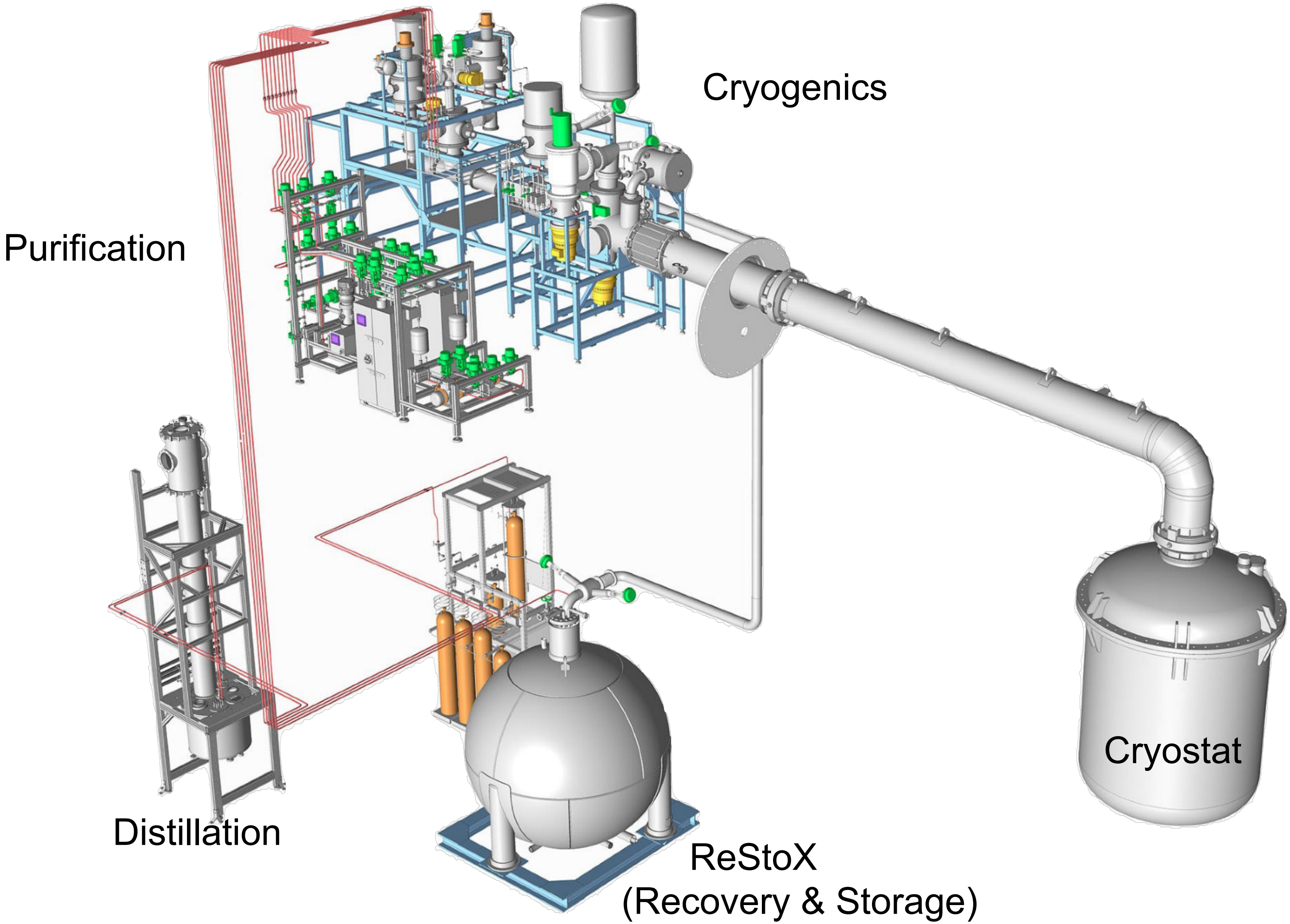


- The cryostat is immersed in a water shield filled with 700 tons of water
- Deionized water is used as passive shield from environmental radiation
- Water is constantly purified
- Equipped with 84 high-QE, 8" PMTs
- All walls are covered with reflective foil Detects Cherenkov light to tag muons.
- Expected muon flux underground is 1.2 $/m^2h^{-1}$ → muon-induced neutron background is reduced to less than 0.01 ev/y thanks to muon tagging
- No coincidences with TPC found in this science run



JINST 9 P11006 (2014)

XENON Plants

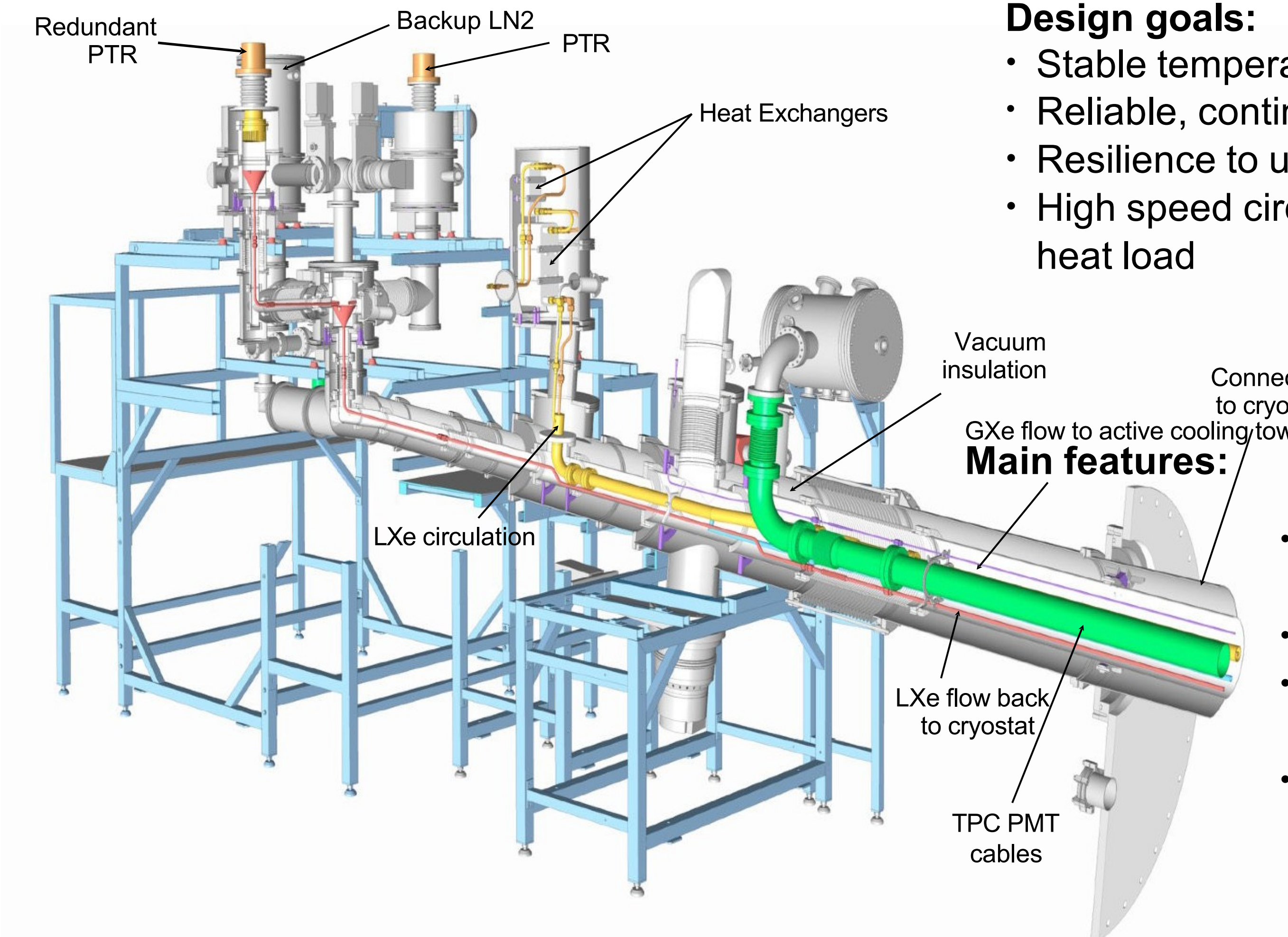


Xenon Cooling System

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

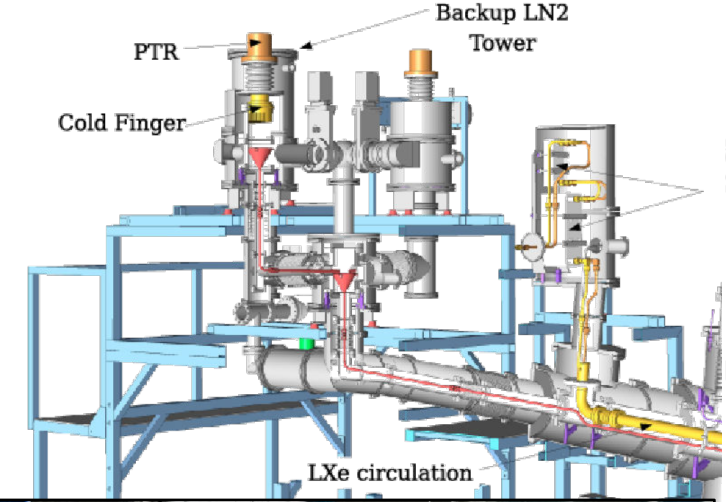


Main features:

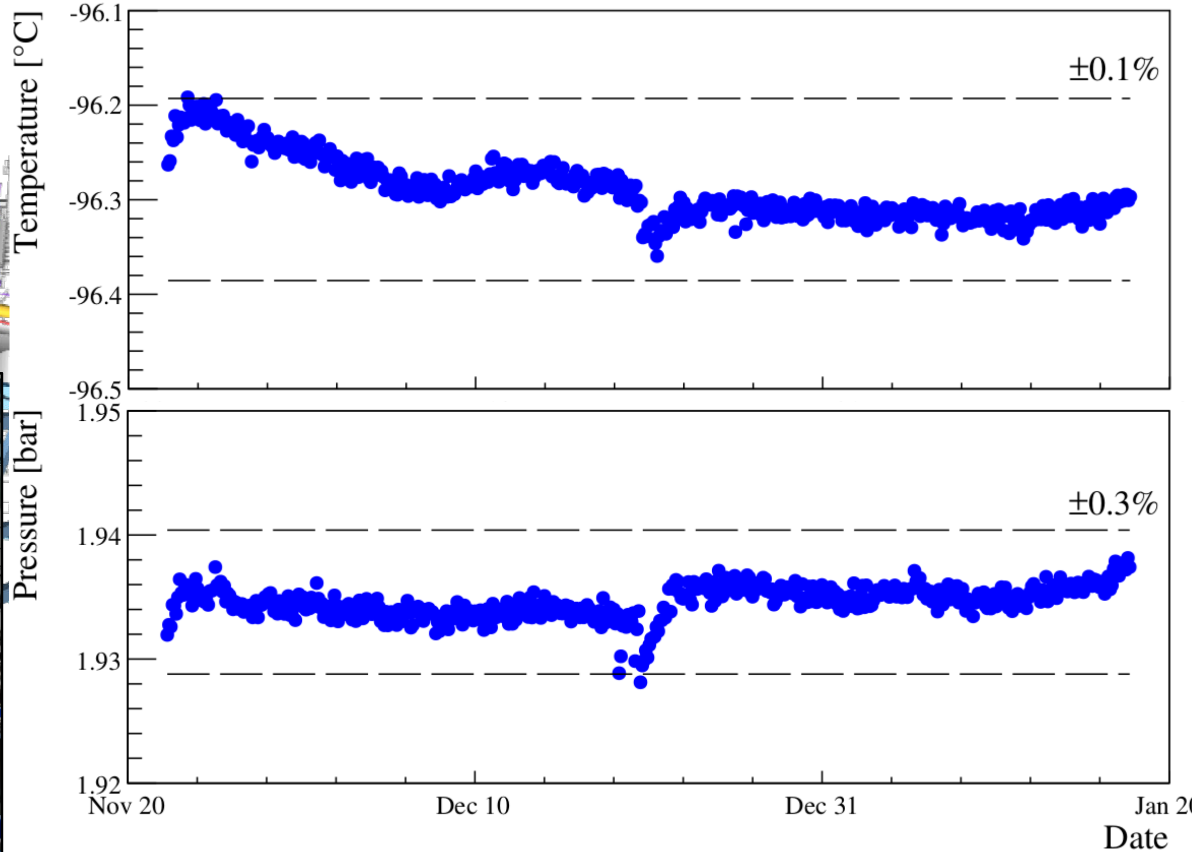
- Redundant PTR cooling systems
- Backup LN2 cooling tower
- Efficient two-phase heat exchangers
- One PTR can be serviced while the other is in operation

Detector Stability

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

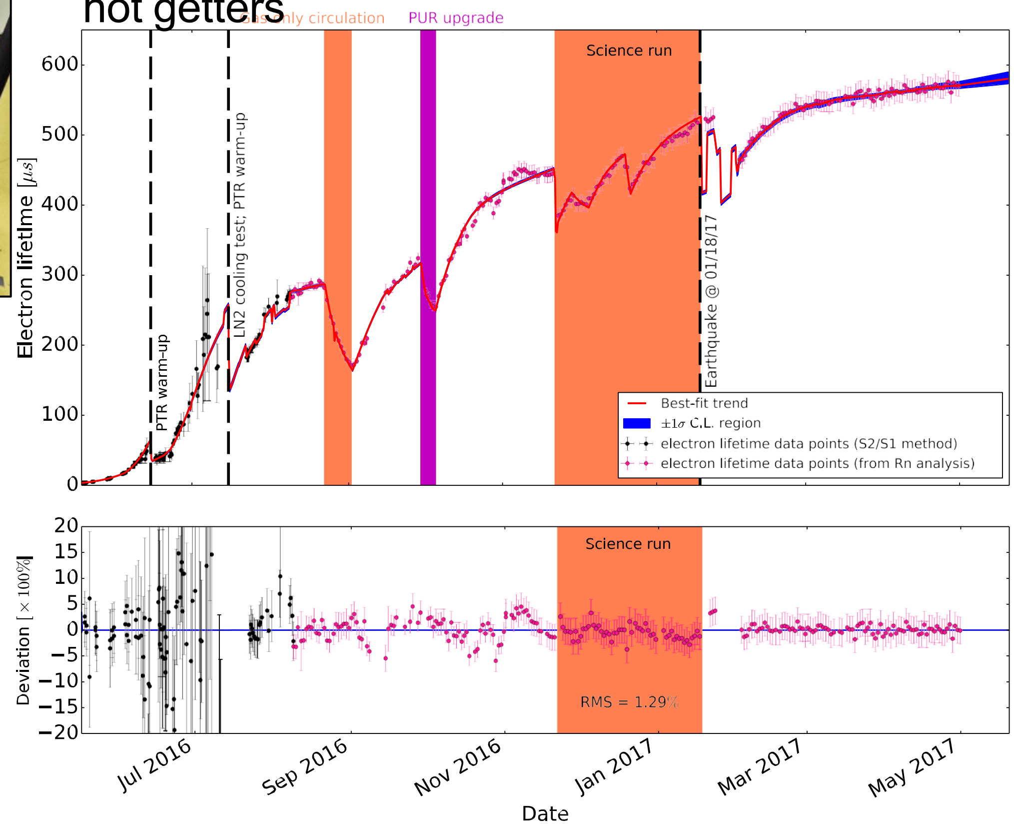


Slow control/Historian monitoring



Xenon purification

Goal: remove electronegative impurities below 1 ppb (O2 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



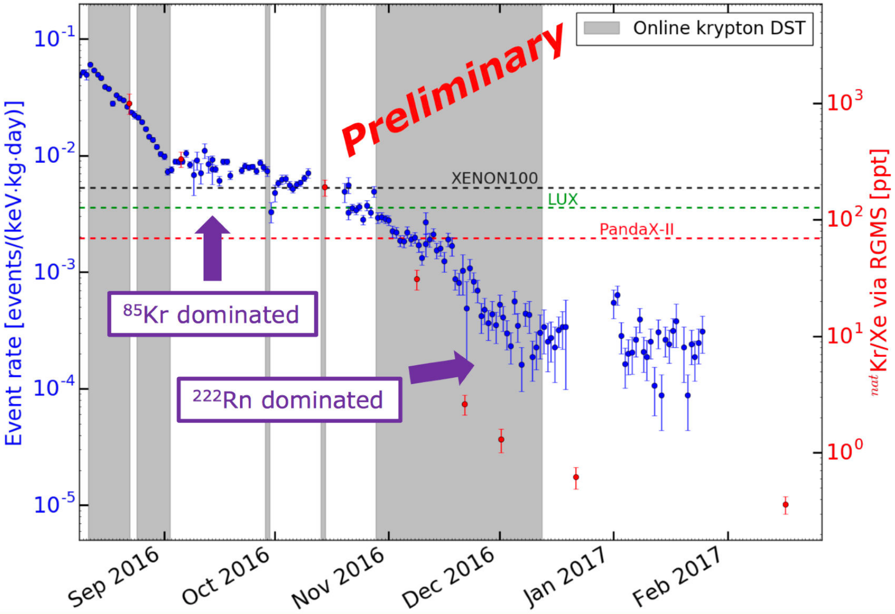
Performance: evolution of e-lifetime, monitored regularly with ERs calibration sources, well described by physical model. Current value approaching the max drift time of the LXeTPC.

Background Reduction: ^{85}Kr

- Commercial Xe contains ~ ppb of Kr
- Column principle : remove Kr from Xe by means of cryogenic distillation (gases have different boiling points)
- >6.4 × 10^5 separation, output concentration < 0.048 ppt
- 5.5 m column, 6.5 kg/hr,

- New approach: Online Distillation
- Successfully reduced Kr to (0.62 +- 0.13) ppt measured by RGMS

- Background is now radon dominated

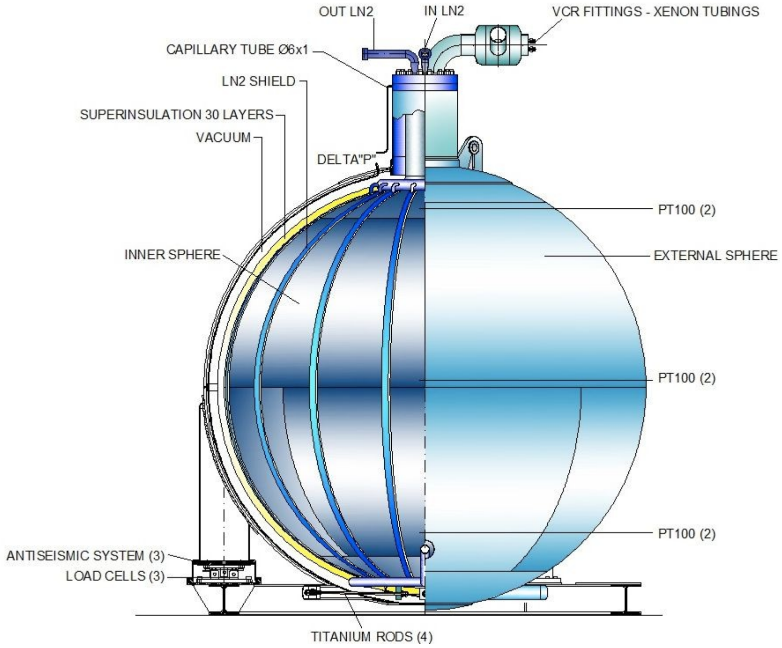


arXiv:1702.06942
Eur. Phys. J. C77 (2017) no.5, 275

Recovery and Storage System: ReStoX

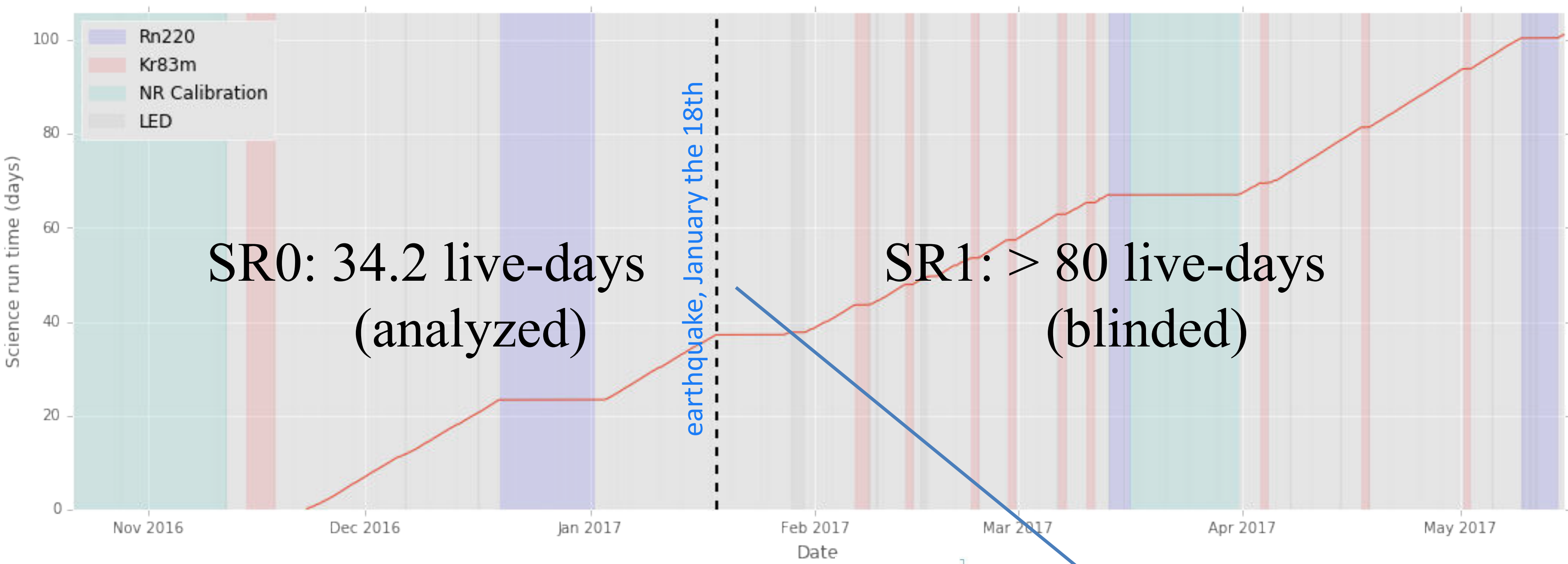
Goals:

- Store up to 7600 kg of Xe in gaseous or liquid/solid phase under high purity conditions
- Fill Xe in ultra-high-purity conditions into detector vessel
- Recover all the Xe from the detector. In case of emergency all Xe can be safely recovered in a few hours

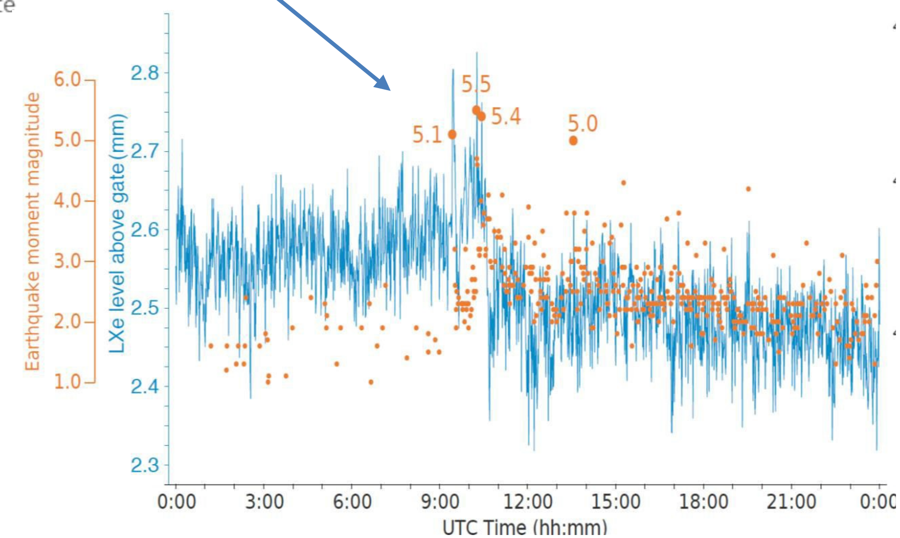


Double walled, high pressure (72 bar) vacuum insulated sphere of 2.1 meter diameter, cooled by LN2 and by an internal LN-based condenser.

Science Run: Exposure

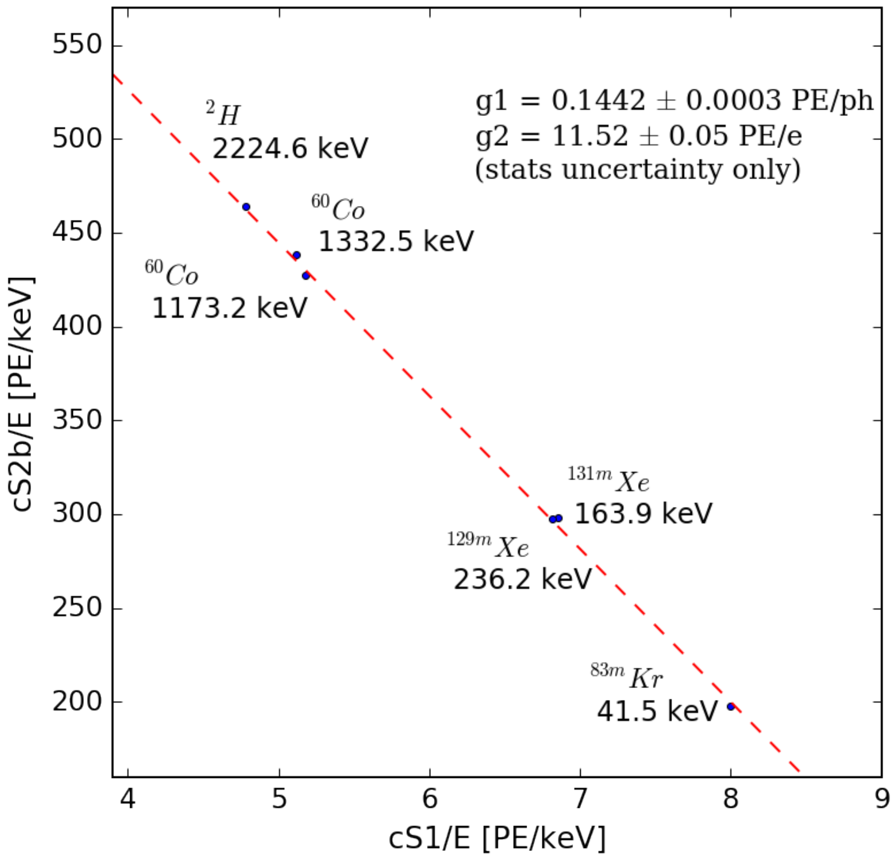


- Dark matter exposure: 34.2 Live days
- Calibration Data:
  - 83mKr ➔ Spacial Response
  - 220Rn ➔ ER-Bands
  - 241AmBe ➔ NR-Bands
- Interrupted by a 5.5 magnitude earthquake



Energy Response

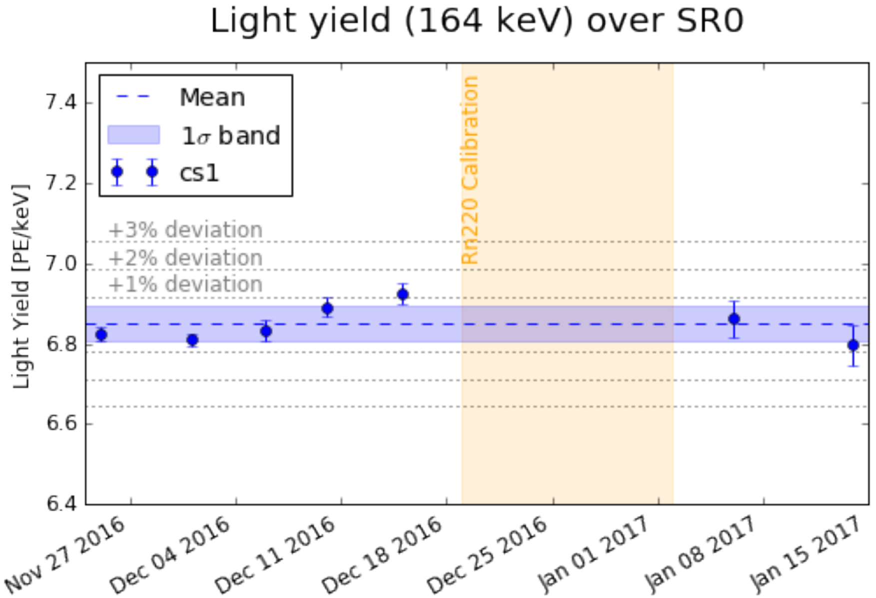
$$E = (n_{ph} + n_e) \cdot W = \left(\frac{S1}{g1} + \frac{S2}{g2}\right) \cdot W$$

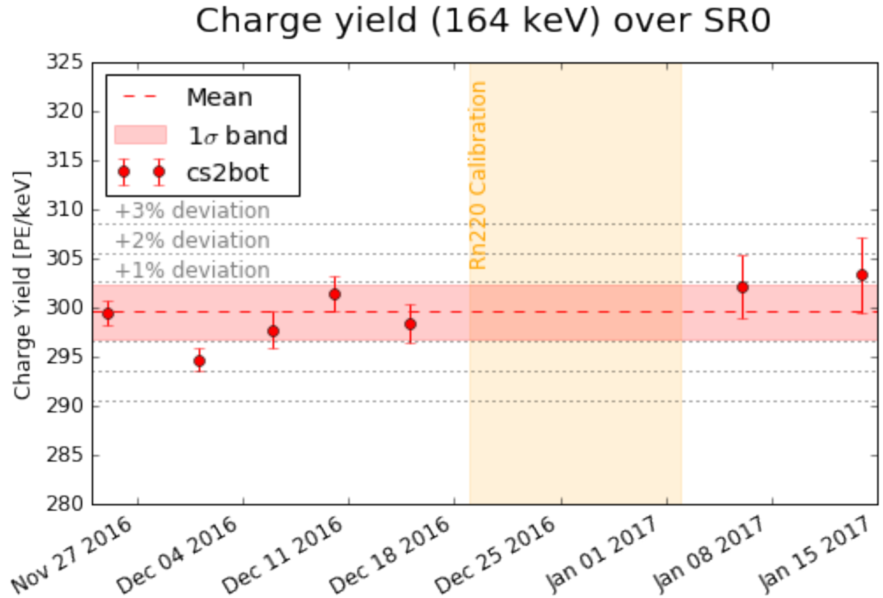


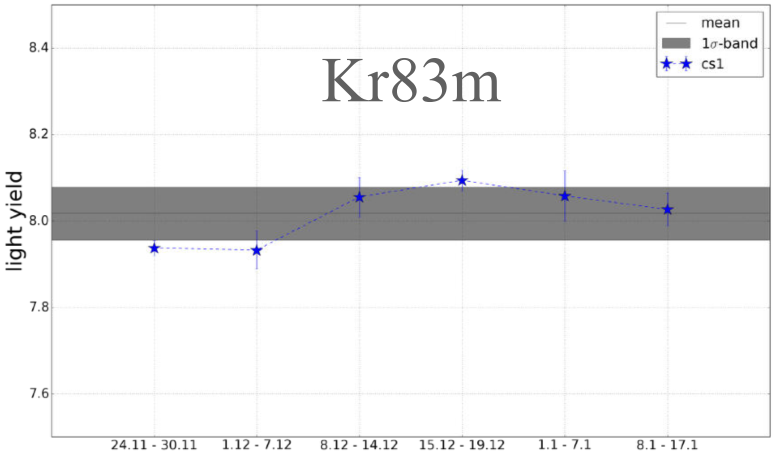
- Excellent linearity with electronic recoil energy from 40 keV to 2.2 MeV
- g1 = 0.1442 ± 0.0068 (sys) PE/photon corresponds to a photon detection efficiency of 12.5 ± 0.6% (taking into account double PE emission) Assumptions of past MC sensitivity projected 12.1%.
- g2: the amplification of charge signal corresponds to near full extraction of charges from the liquid.

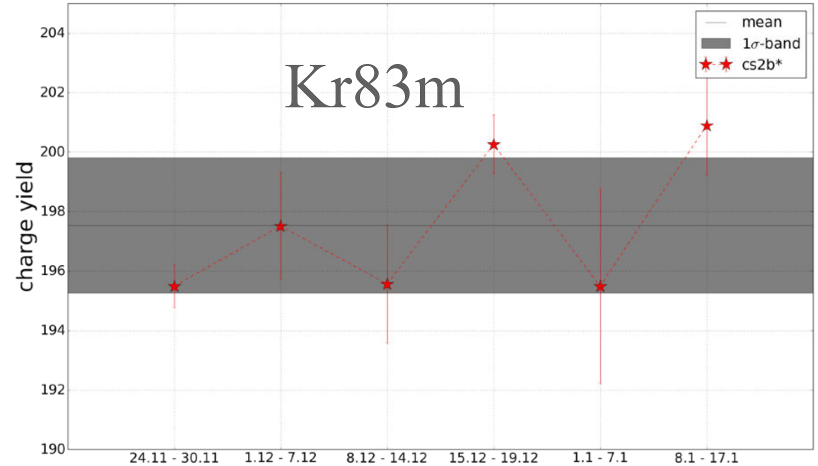
Light/Charge Yield Stability

From Kr83m and activated Xe131m, variation in LY and CY is at ~1% level.



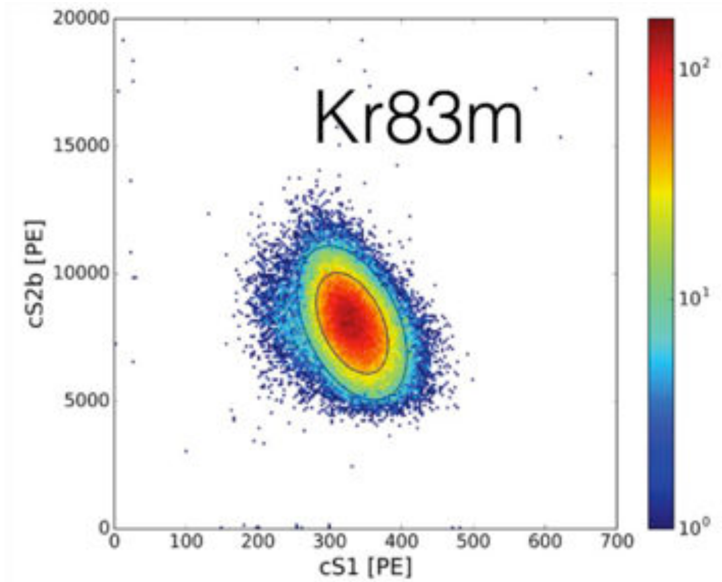




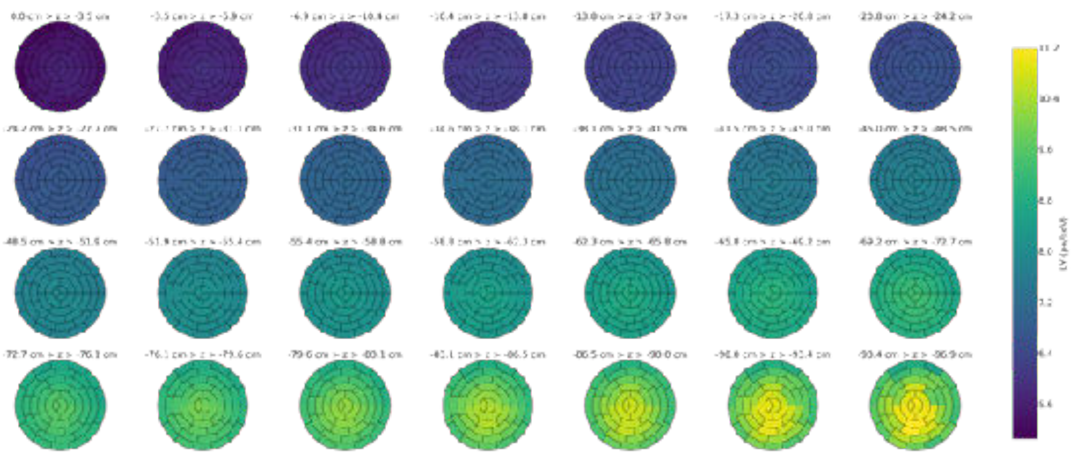


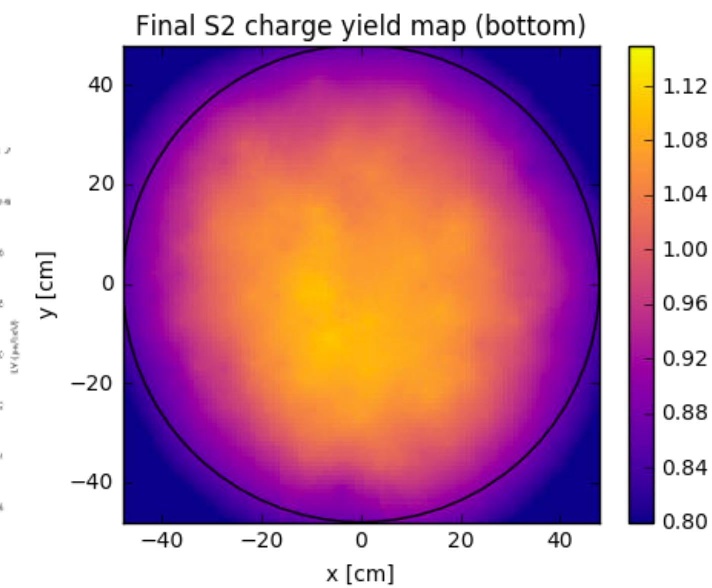
^{83m}Kr Calibration

- Signal corrections:
  - Position dependent light collection efficiency
  - Position dependent S2 amplification
  - Electric field non-uniformity
- Electron lifetime cross-check
- Light/Charge yield stability



Light collecIon efficiency maps

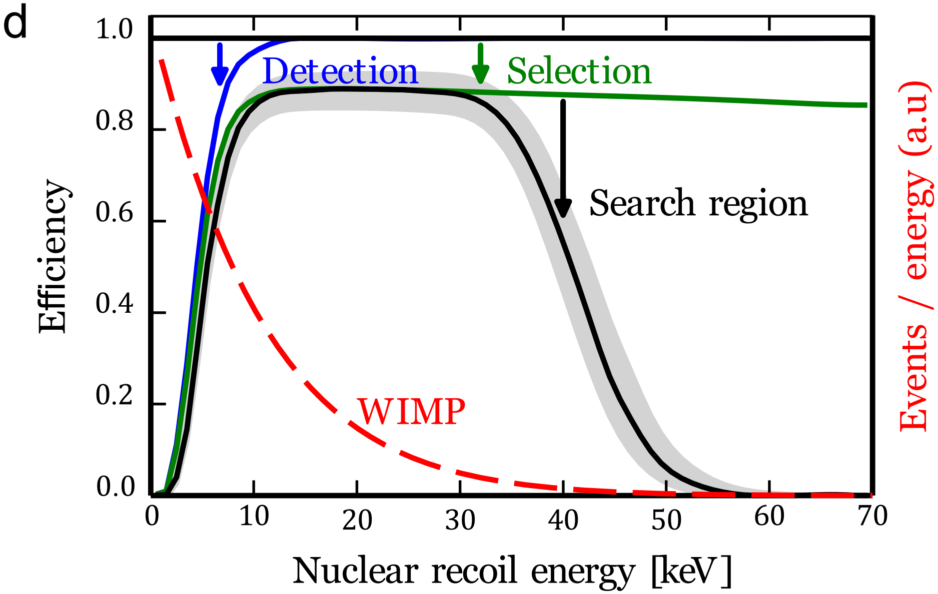


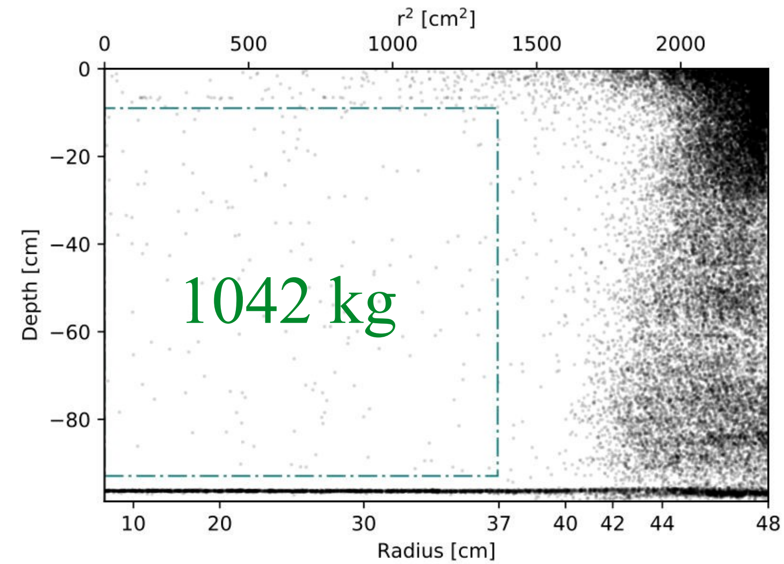


Efficiencies

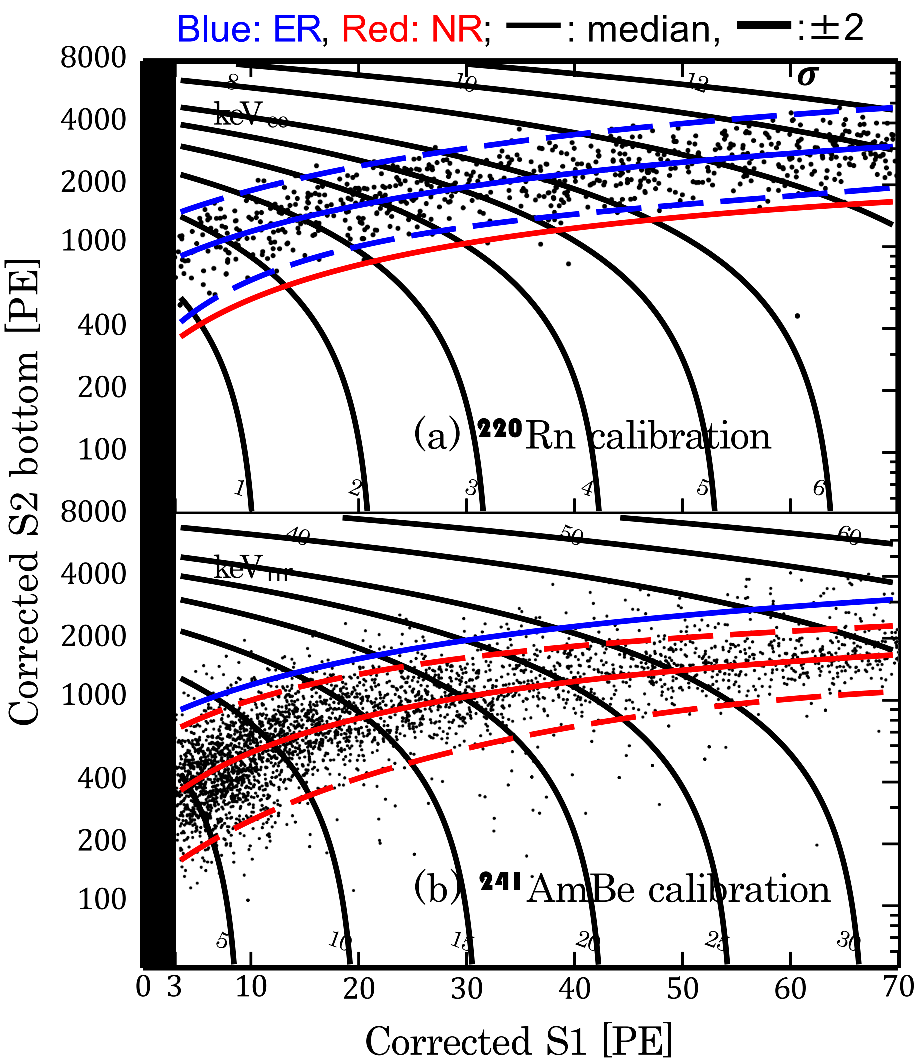
- **Detection efficiency** dominated by 3-fold coincidence requirement
  - Estimated via novel waveform simulation including systematic uncertainties
- **Selection efficiencies** estimated from control samples or simulation
  Data quality and seleclon cuts tuned to calibralon data o single scaRer (WIMP-like) events
- **Search region** defined within 3-70 PE in corrected S1

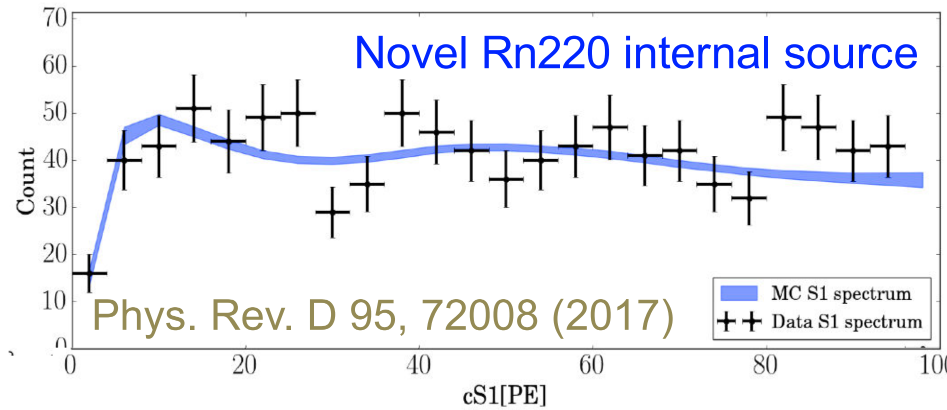
Cuts	Events remaining
All events (cS1<200 PE)	128144
Data Quality & Selection	48955
Fiducial Volume	180
3 PE < cS1 < 70 PE	**63**



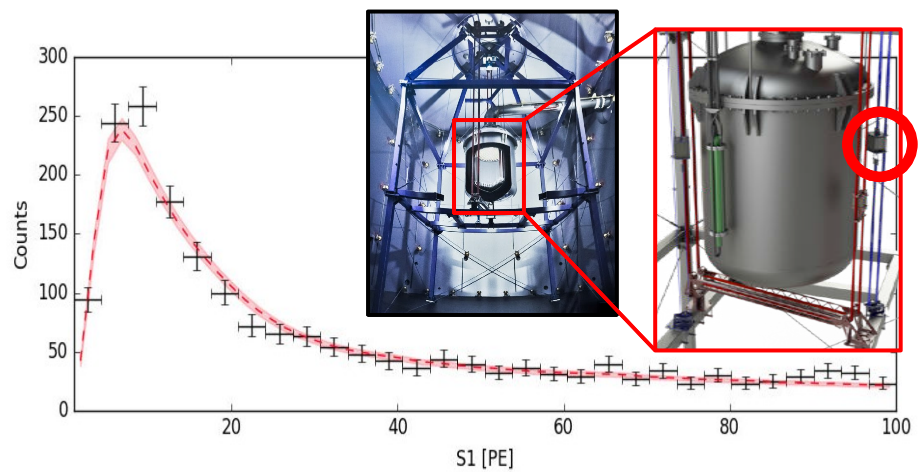


Fitting Models to Calibration



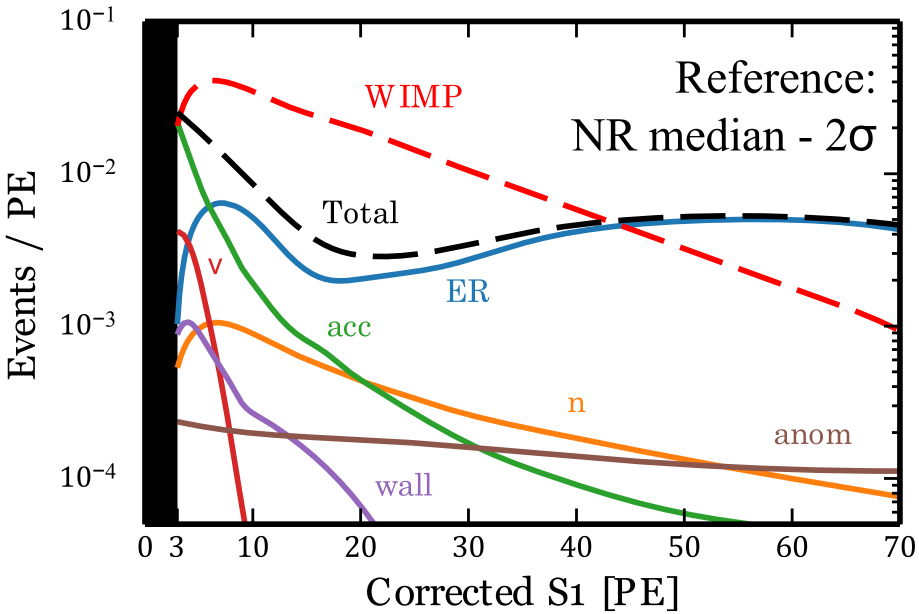


- Full modeling of LXe and detector response in $cS2_b$ vs cS1 space
- All parameters fitted with no significant deviation from priors



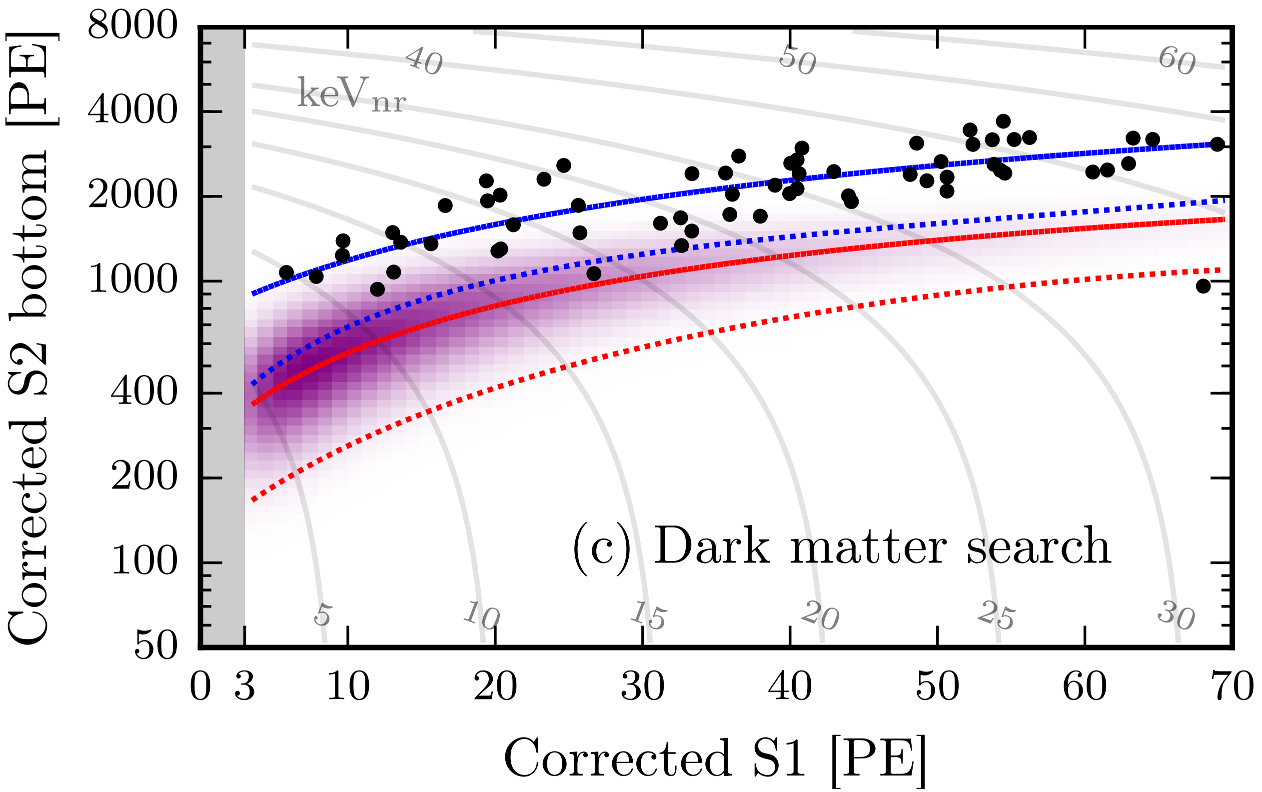
Background Model

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



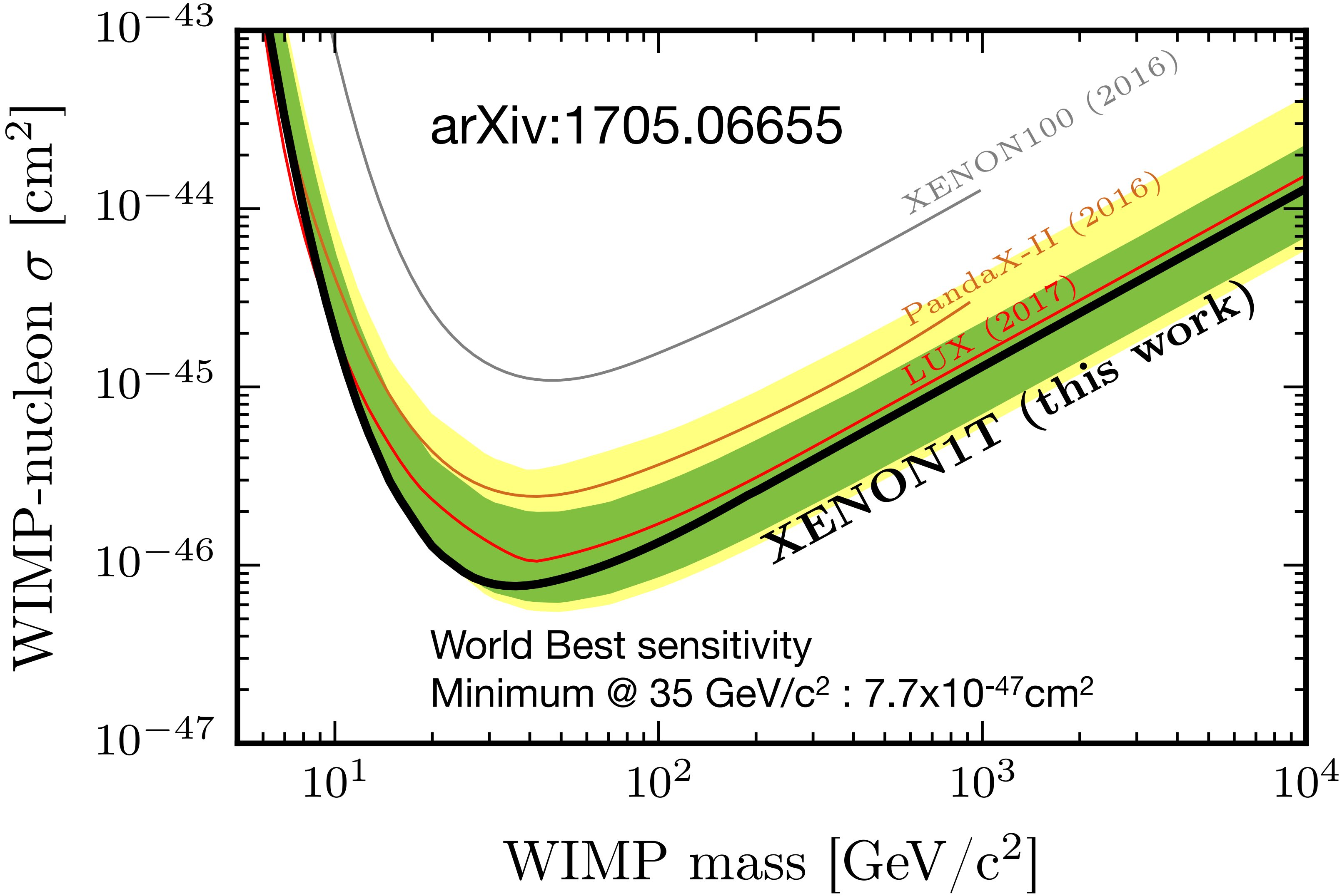
Background	Total	NR median - 2σ, 3-70pe
Electronic Recoil	(62 ± 8)	0.26 (+0.11)(-0.07)
Radiogenic neutrons (n)	(0.05 ± 0.01)	0.02
CNNS (ν)	0.02	0.01
Accidental coincidences (acc)	(0.22 ± 0.01)	0.06
Wall leakage (wall)	(0.52 ± 0.32)	0.01
Anomalous (anom)	0.09 (+0.12)(-0.06)	(0.01 ± 0.01)
Total background	**(63 ± 8)**	**(0.36 ± 0.09)**
50 GeV/c^2 , 10^{-46}cm^2 WIMP	**(1.66 ± 0.01)**	**(0.82 ± 0.06)**

Dark Matter Search

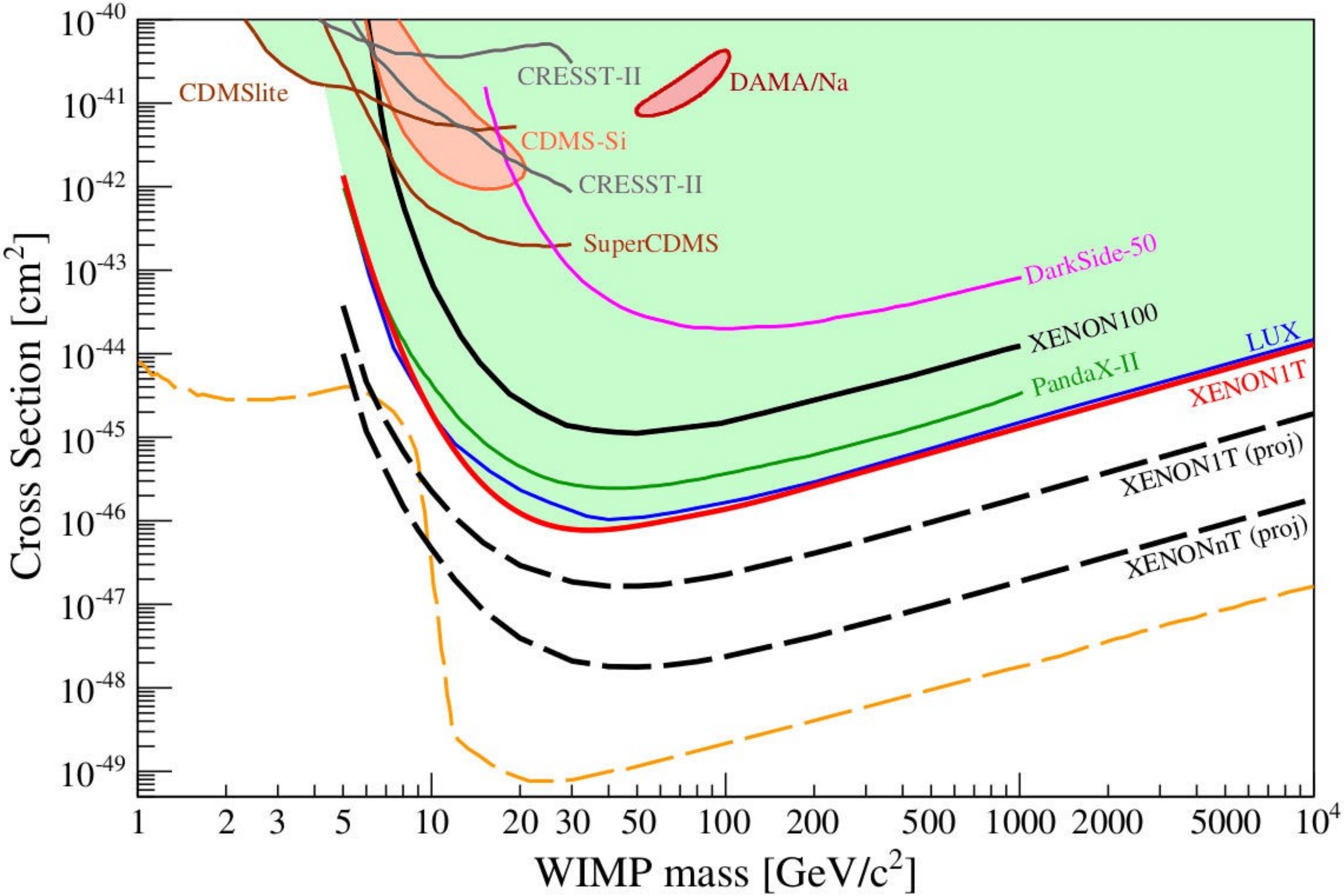


- Extended unbinned profile likelihood analysis
- Most significant ER & NR shape parameters included from cal. fits
- Normalization uncertainties for all components
- Safeguard to protect against spurious mis-modeling of background

XENON1T Results



From XENON1T to XENONnT



From XENON1T to XENONnT

All major systems remain unchanged, XENON1T infrastructure designed for the rapid deployment of an upgraded detector

- Muon veto efficiency essentially the same for XENONnT
- Cryostat support and levelling systems designed for an enlarged detector
- Cryostat outer vessel can accommodate new larger inner vessel
- Cryogenic system designed to handle additional heat load
- Modular and scalable GXe purification system
- Kr distillation column can fulfill XENONnT ^{85}Kr requirement
- Modular, parallelized DAQ system ready for XENONnT

Upgrades required for XENONnT

+ Larger cryostat inner vessel

+ New TPC

+ Additional ~200 PMTs, with lower radioactivity already ordered

+ Additional minor DAQ electronics

+ LXe (~ 8t in our hands)

+ New Storage System

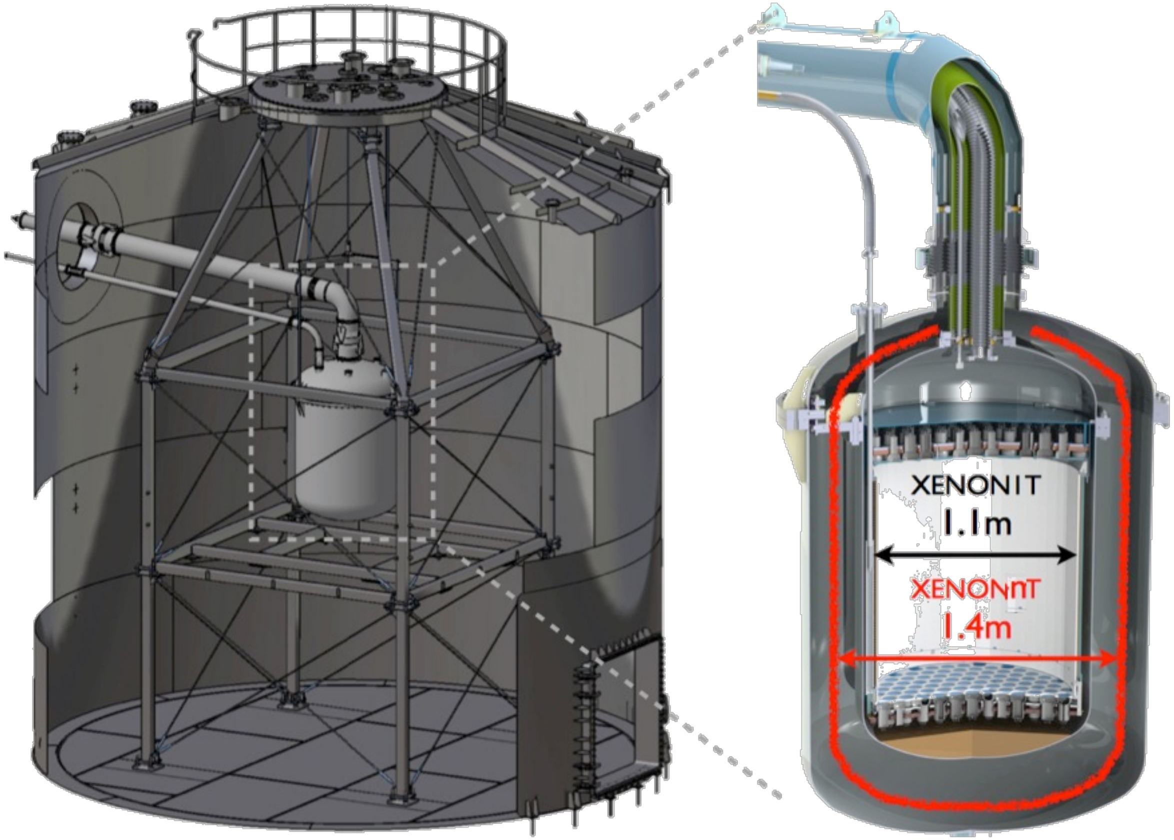
+ Rn material selection (screening, treatment) and new Rn distillation column

Target mass of 6 tons, sensitivity to spin-independent WIMP-nucleon elastic scattering cross sections of 1.6×10^{-48} cm^2

Current schedule:
start XENONnT in early 2019

Upgrade: XENONnT

- Quick upgrade of TPC and inner cryostat
- All major systems remain unchanged
- Construct TPC in parallel to XENON1T operation
- Upgrade starting 2018



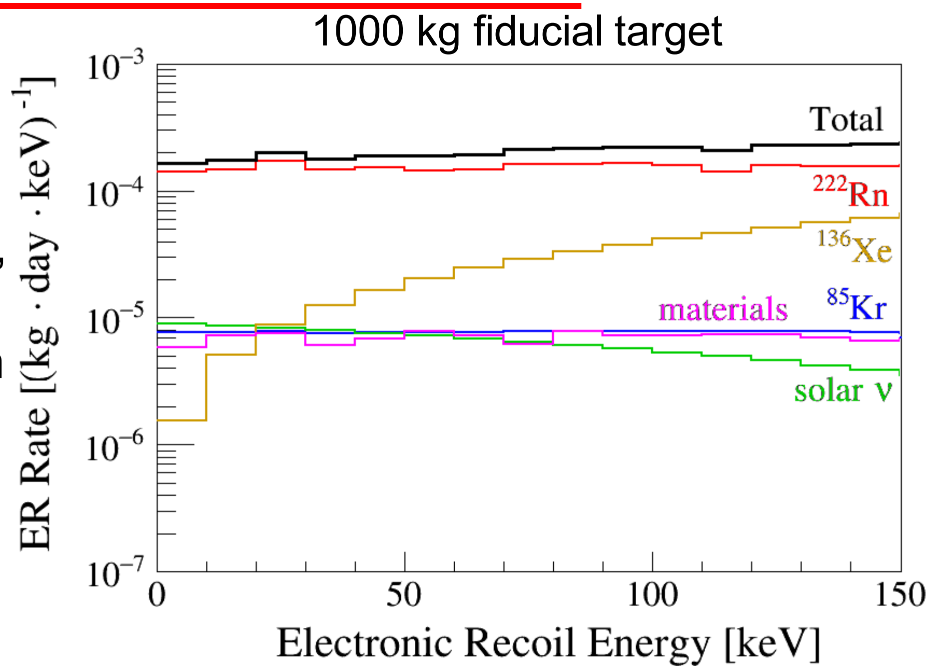
Conclusion

- **XENON1T** first results demonstrate that the detector is performing very well
- The measured 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 x 10^{--47} cm^2 @ 35 GeV/c^2
- Up to now, > 80 days addilonal days of science run have been acquired (and detector sIll running) and are currently under analysis
- The foreseen sensilvity of **XENON1T** in 2 t y is 1.6 x 10^{--47} cm^2
- Planning a fast upgrade to **XENONnT** for another order of magnitude in sensilvity

Background in XENON1T

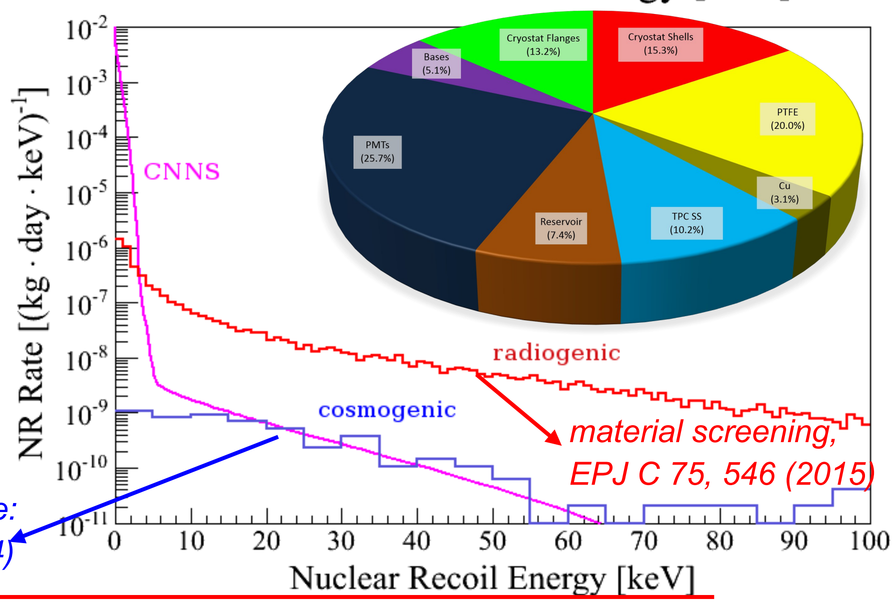
Electron recoils (ER):

- Low energy Compton scatters from the radioactive contaminants in the detector components: U and Th chains, ^{40}K, ^{60}Co, ^{137}Cs.
- Intrinsic contaminants: β decays of ^{222}Rn daughters, ^{85}Kr, ^{136}Xe.
- Elastic scattering of solar neutrinos off electrons.



Nuclear Recoils (NR):

- Radiogenic neutrons: spontaneous fission and (alpha, n) reaction from the U and Th chains in the detector components.
- Muon-induced neutrons (Cosmogenic)
- Coherent scattering of neutrinos off the Xe nuclei (CNNS).



Muon veto design and performance: XENON1T, JINST 9, P11006 (2014)

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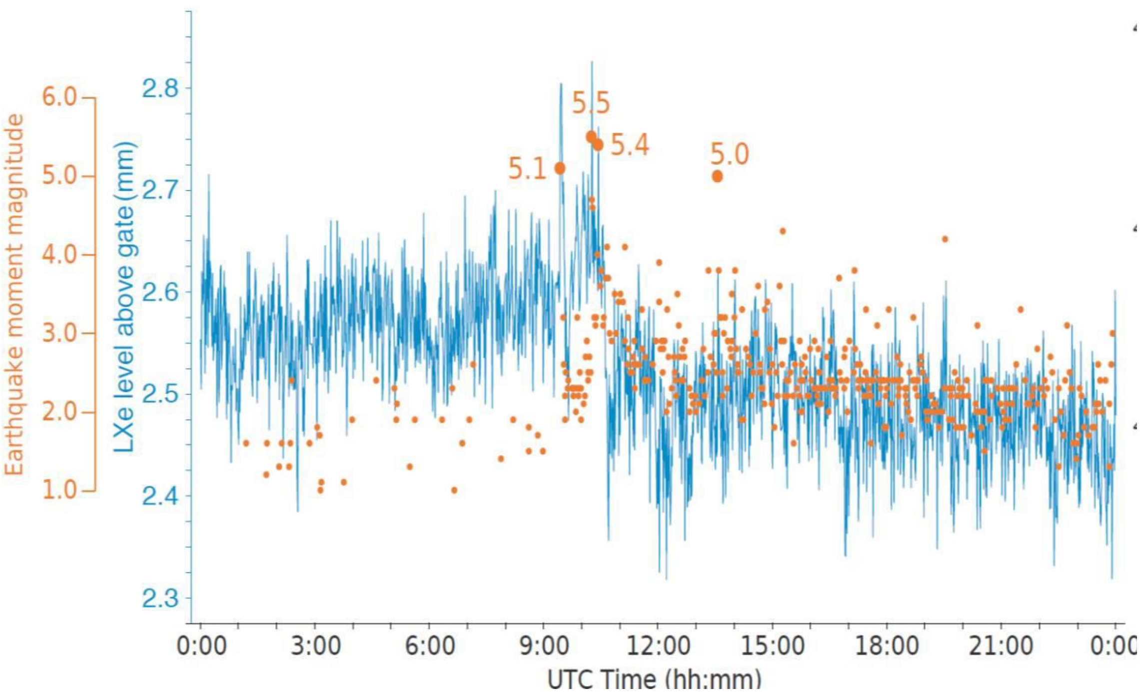
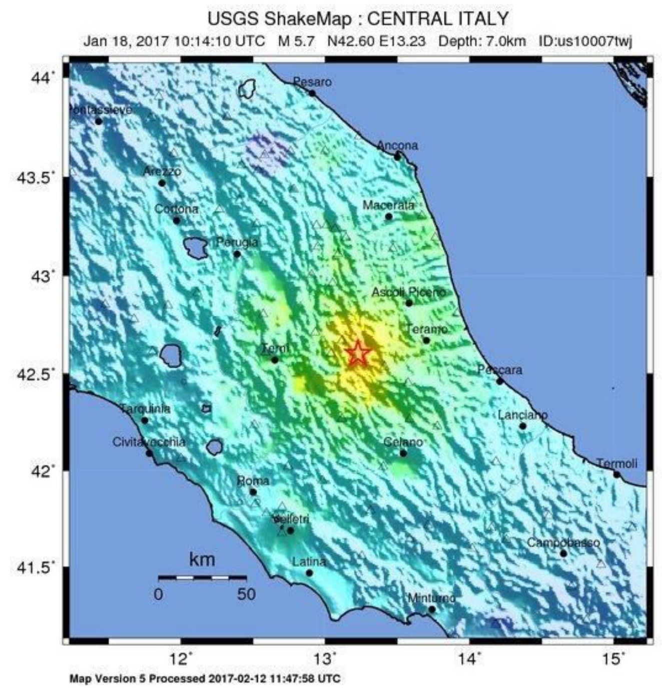
Earthquake of 18th January 2017

- Magnitude 5.5 earthquake ~20 km away detected
- Detector still operating and taking data





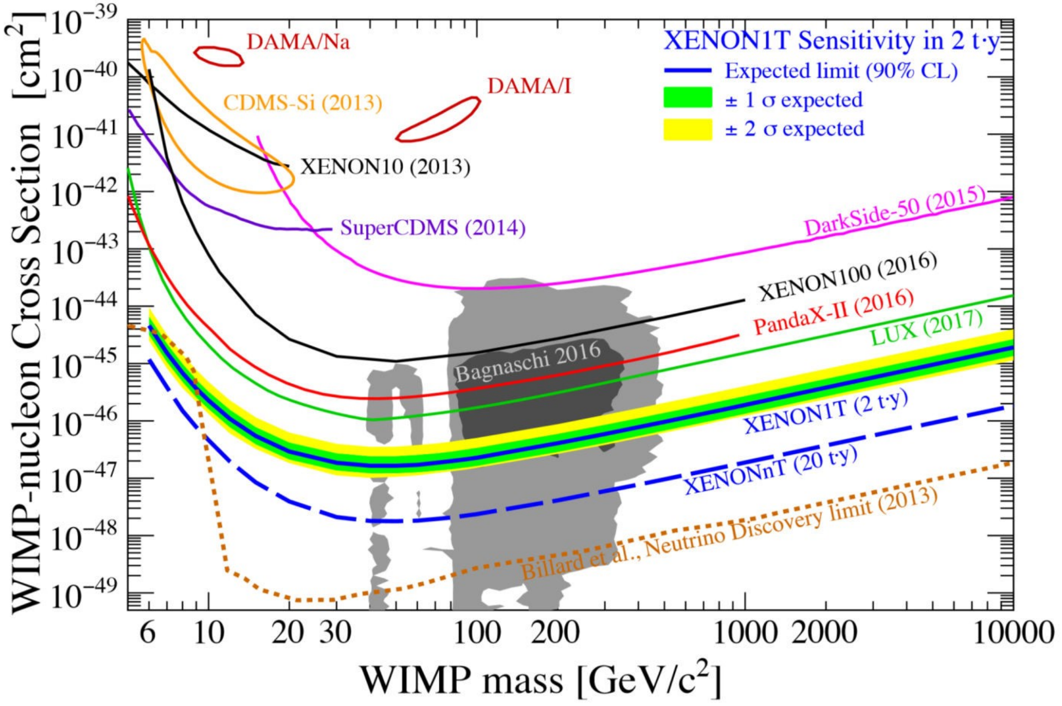
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.06	0.2	0.8	2.0	4.8	12	29	70	>171
PEAK VEL.(cm/s)	*<0.02*	*0.08*	*0.3*	*0.9*	*2.4*	*6.4*	*17*	*45*	*>120*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

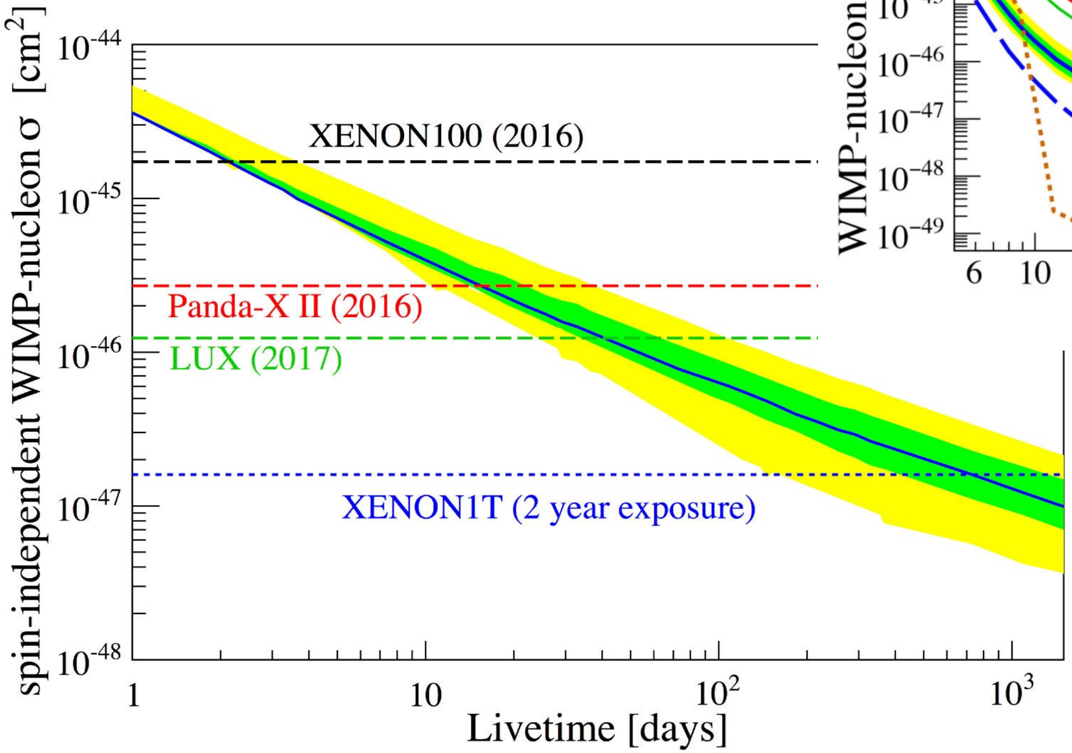
Scale based upon Faenza and Michelini, 2010, 2011

XENON1T: Expected sensitivity

JCAP04(2016)027

based on background predictions
2 t × y exposure

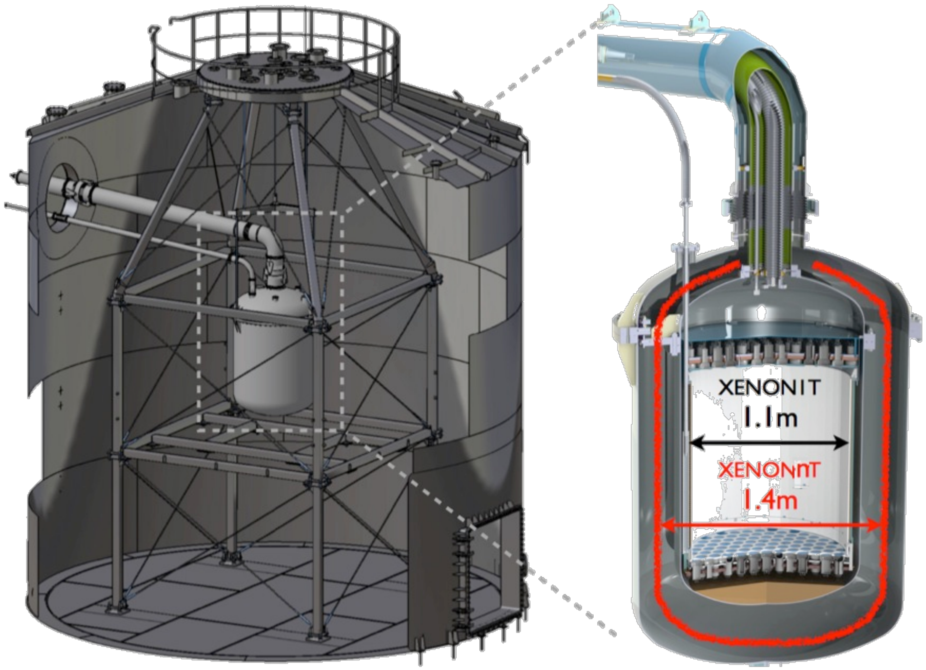




assumptions: S1 interval: 3 – 70 PE

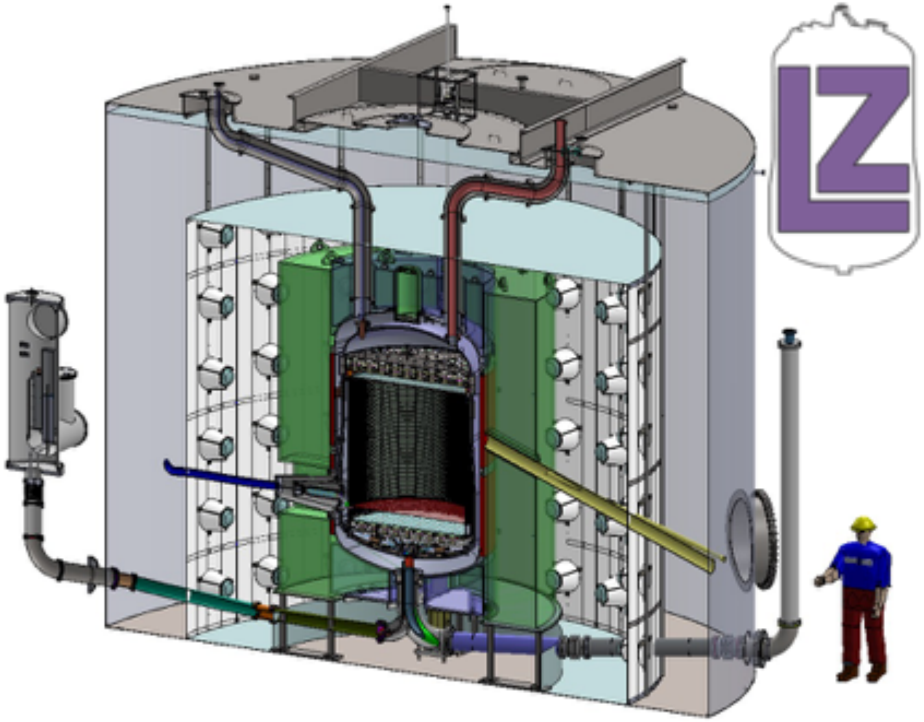
ER rejection 99.5% @ 50% NR acceptance
→ measured LY is ~2x higher than in XENON100!

Future: LZ & XENONnT



LZ = LUX + ZEPLIN

- Same location than LUX
- Turning on by 2020 with 1 000 initial live-days
- 10 tons total, 7 tons active,



XENONnT:

- Quick upgrade of TPC and inner cryostat
- All major systems remain unchanged
- Construct TPC in parallel to XENON1T operation
- Upgrade starting 2018
- 8 tons total, 6 tons active