Review of liquid noble gas detectors for Dark Matter search and latest results of Xenon1T

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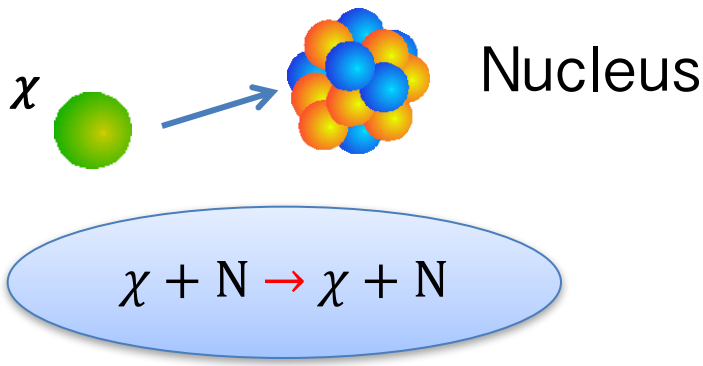
13th Rencontres du Vietnam July 23-29

ICISE

Exploring the Dark Universe 2017

Direct dark matter detection principle

Nuclear Recoil (NR)



Direct dark matter detection principle

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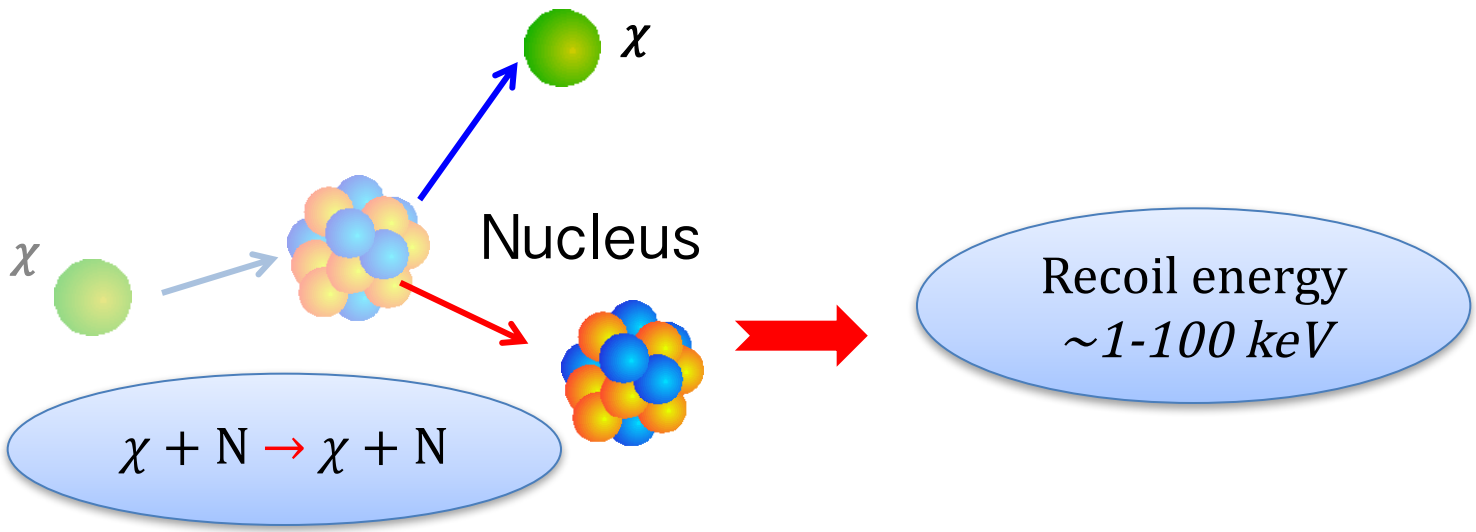
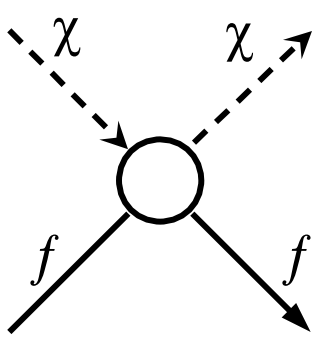


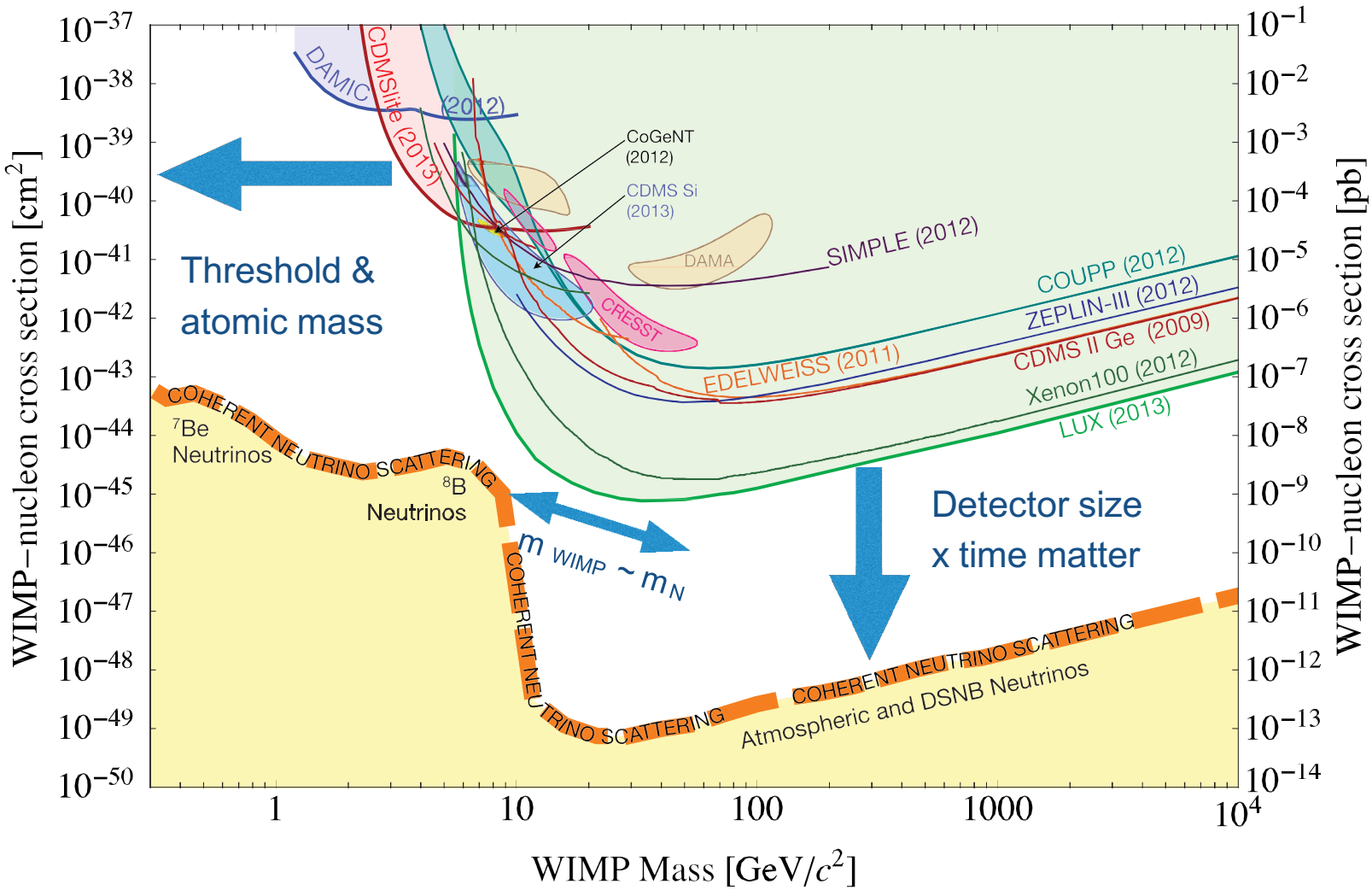


Electronic Recoil (ER)

γ and β particles
interact with the atomic electrons
→ background

How is evolving the field of Direct Detection ?

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



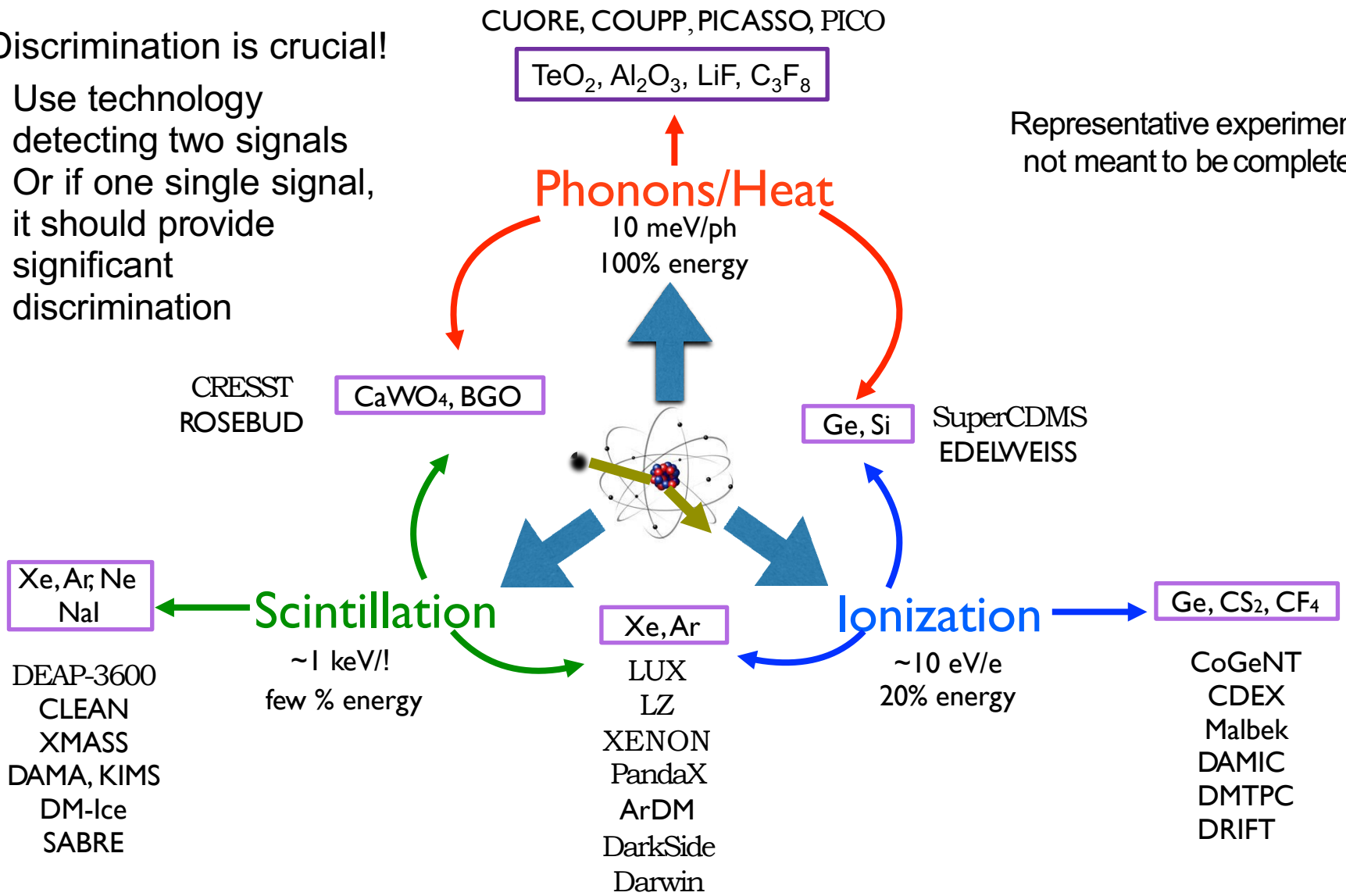
Direct Detection Techniques

from Carmen Carmona

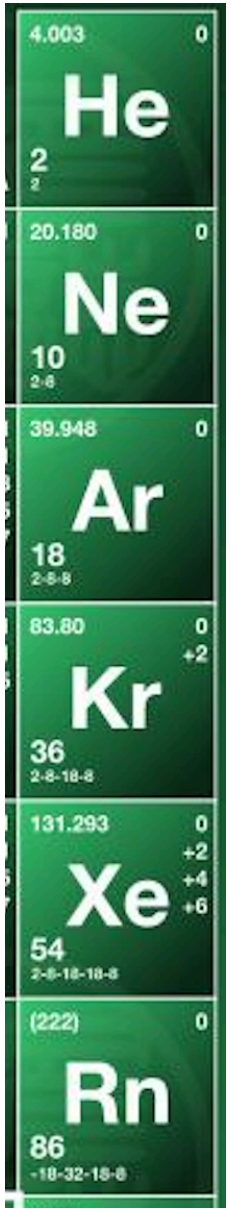
Discrimination is crucial!

- Use technology detecting two signals
- Or if one single signal, it should provide significant discrimination

Representative experiments, not meant to be completed



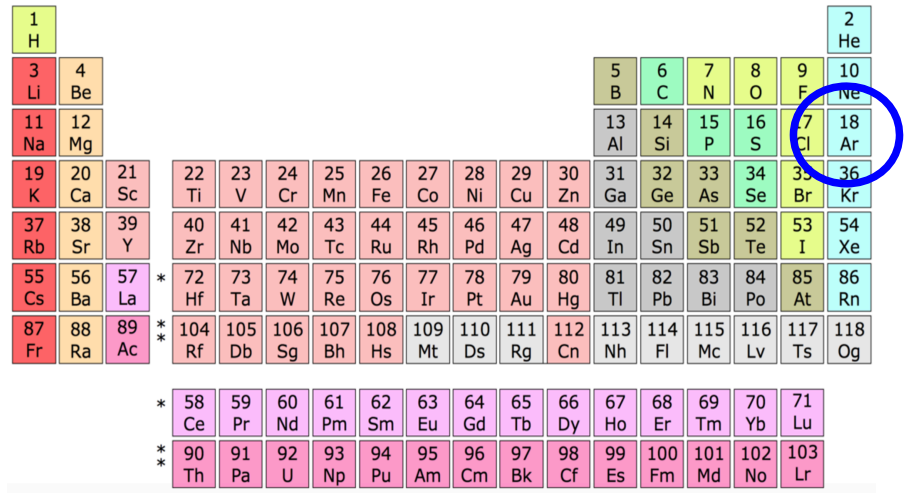
Noble gases

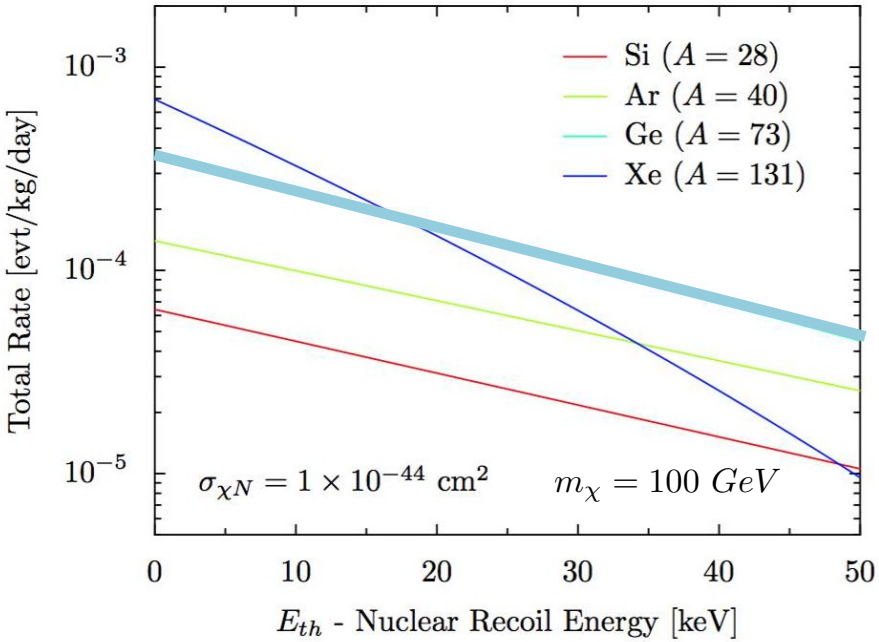


	Neon	Argon	Krypton	Xenon
Atomic Number	10	18	36	54
Density	1.2	1.4	2.4	3
Scintillation (γ/keV)	30	40	25	42
Wavelength (nm)	85	128	150	178
Decay Time (ns)	15400	6.3, 1500	2, 91	2.2, 27, 45
Ionization (e-/keV)	46	42	49	64
Boiling Point (K)	27.1	87.3	119.8	165.0
Radioactivity	No	^{39}Ar 1Bq/kg (1mBq/kg)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

Argon main characteristics

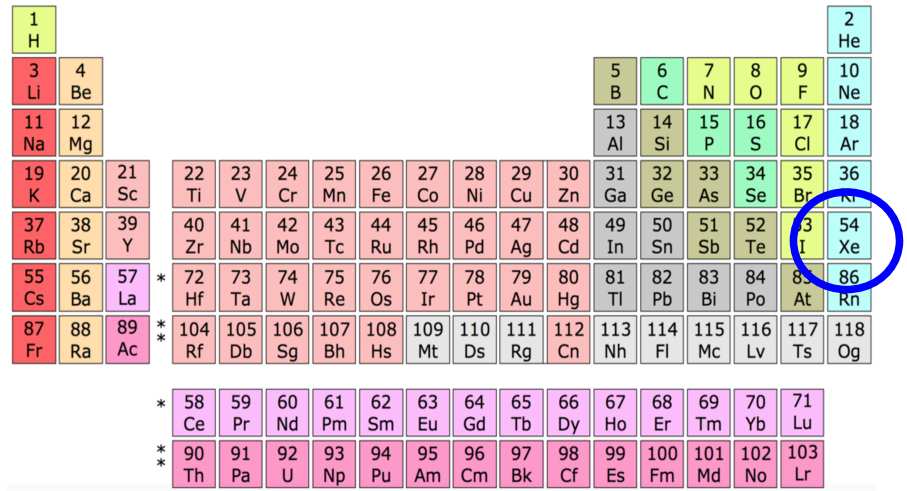
- Large abundance
  - Modest price
  - Giant detector are possible
- Relatively compact detectors
  - Self shielding
- Cryogenic feasible: 90K > 77K (LN_2)
- Scalable to large target masses
- Excellent Electronic recoil discrimination event with only light detection
- Need “Shift” Light (128 nm)
- Reduce threshold for detection
- Intrinsic radioactivity (1 - 0.001 Bq/kg)

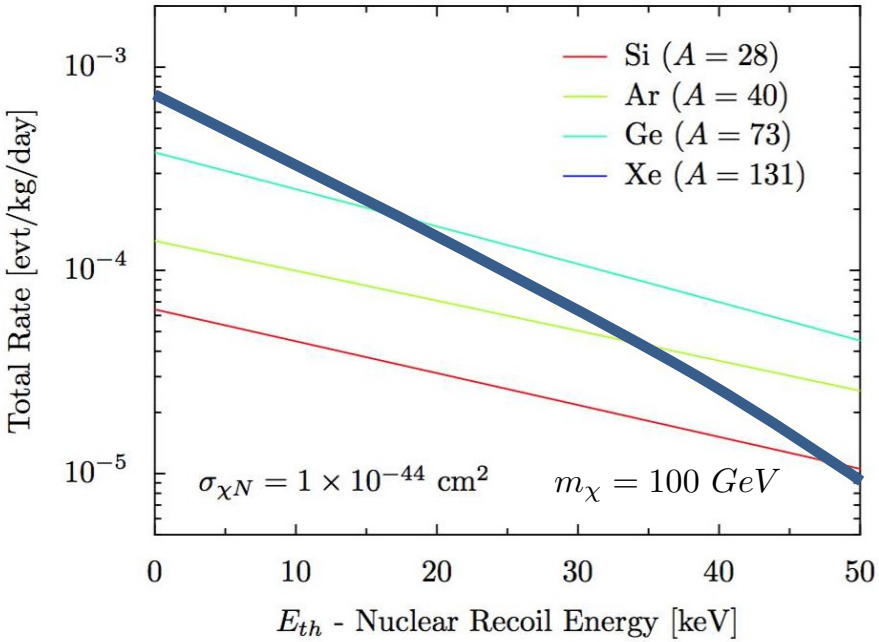




Xenon main characteristics

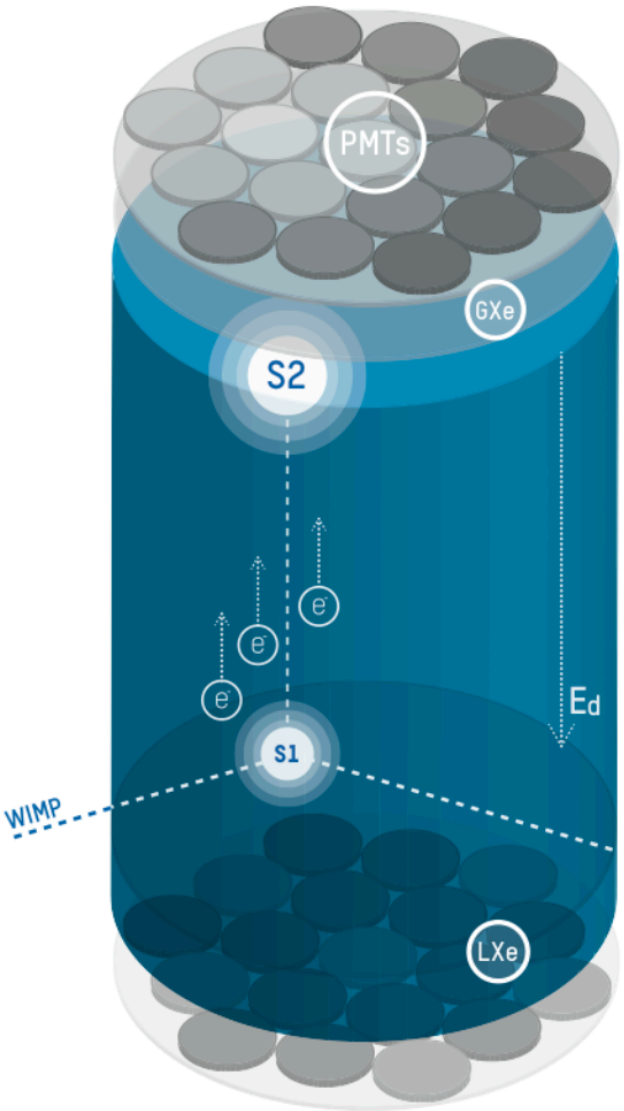
- Large mass number A (131)
  - Interaction cross section $\propto A^2$
- 50% odd isotopes (^{129}Xe, ^{131}Xe)
  - for Spin-Dependent interactions
- Kr can be reduced to ppt levels
- High stopping power
  - active volume is self-shielding
- Efficient scintillator (178 nm)
- Scalable to large target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





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

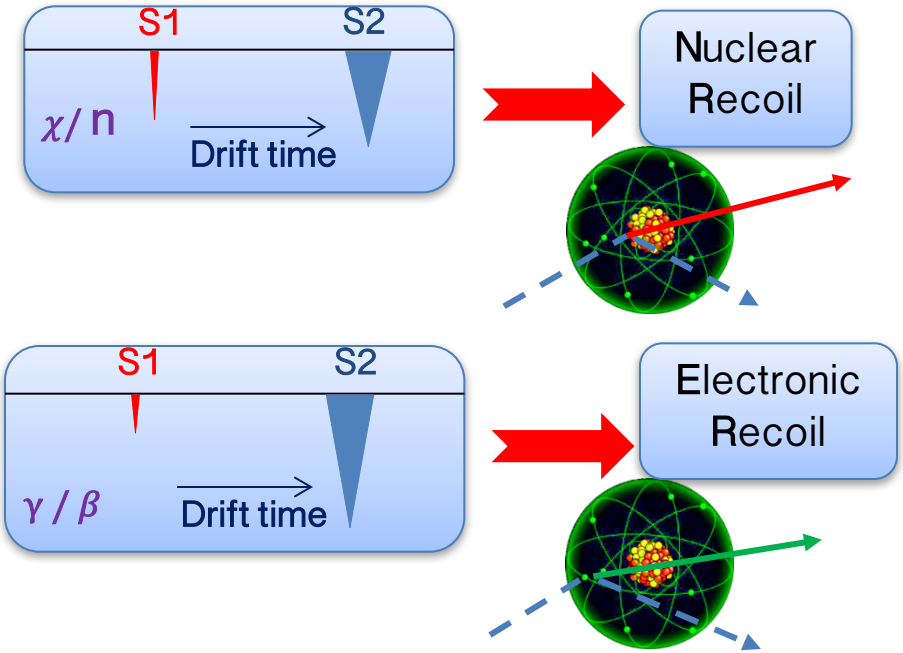
→ Extraction in gaseous phase

→ Proportional scintillation light

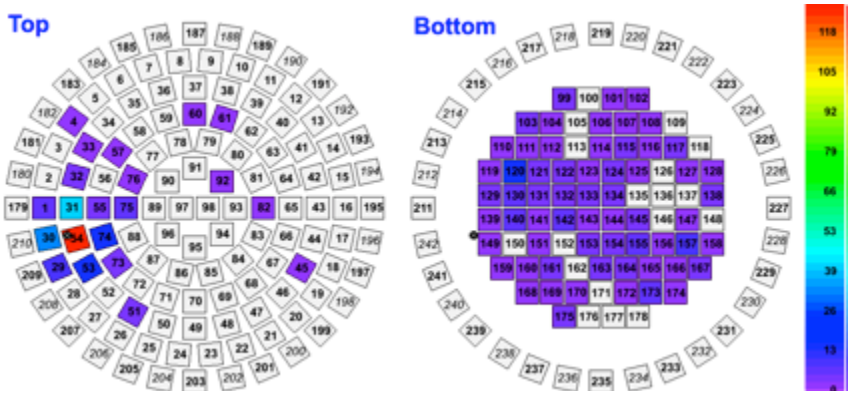
3D reconstruction :

→ X,Y from top array

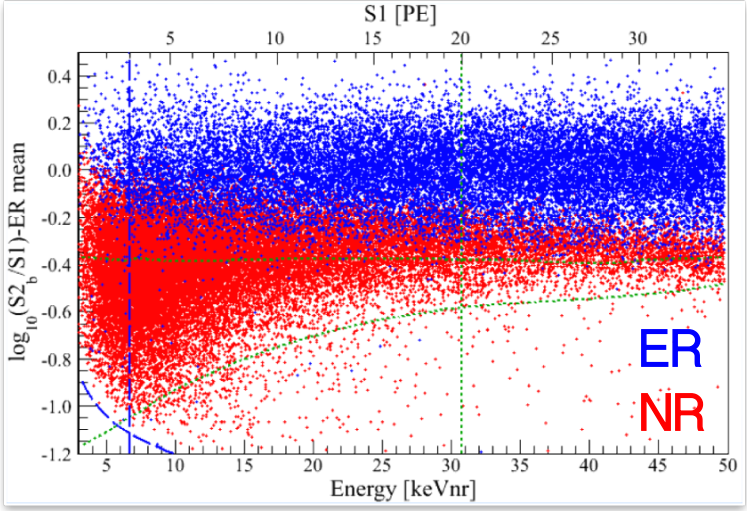
→ Z from Drift time

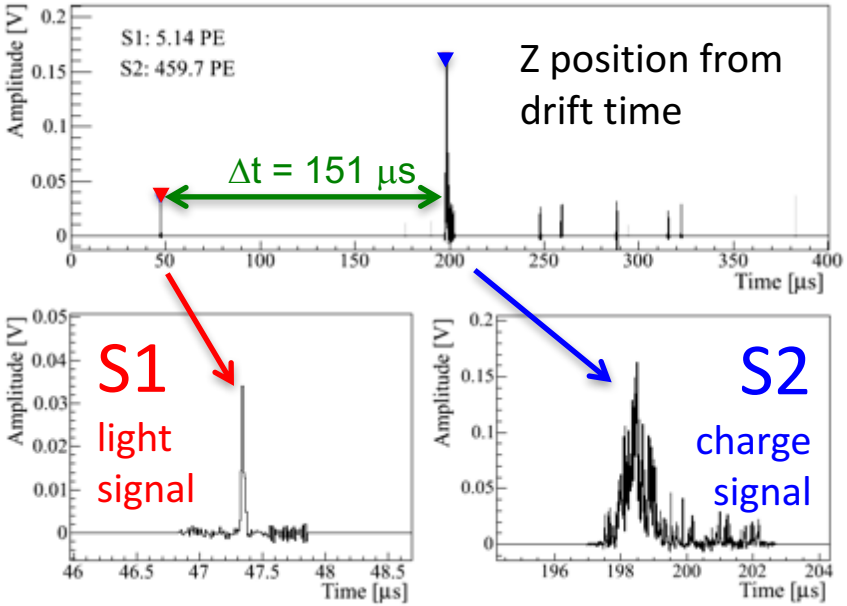


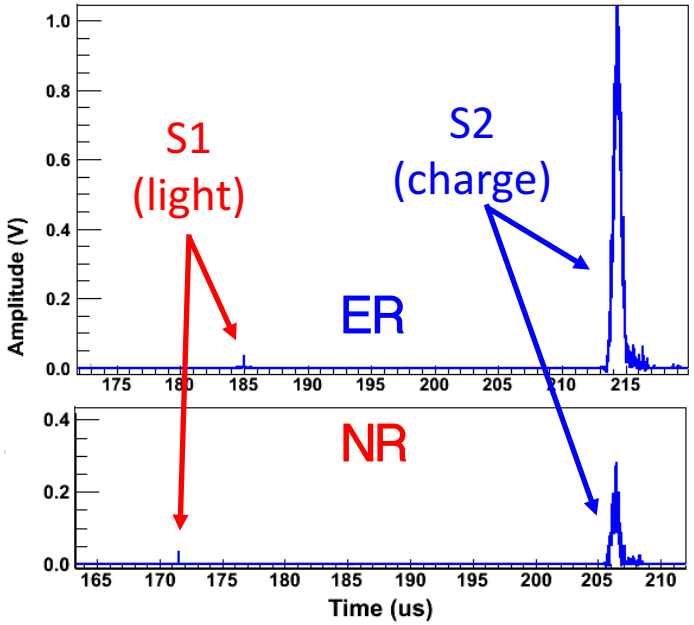
Dual phase TPC: real life



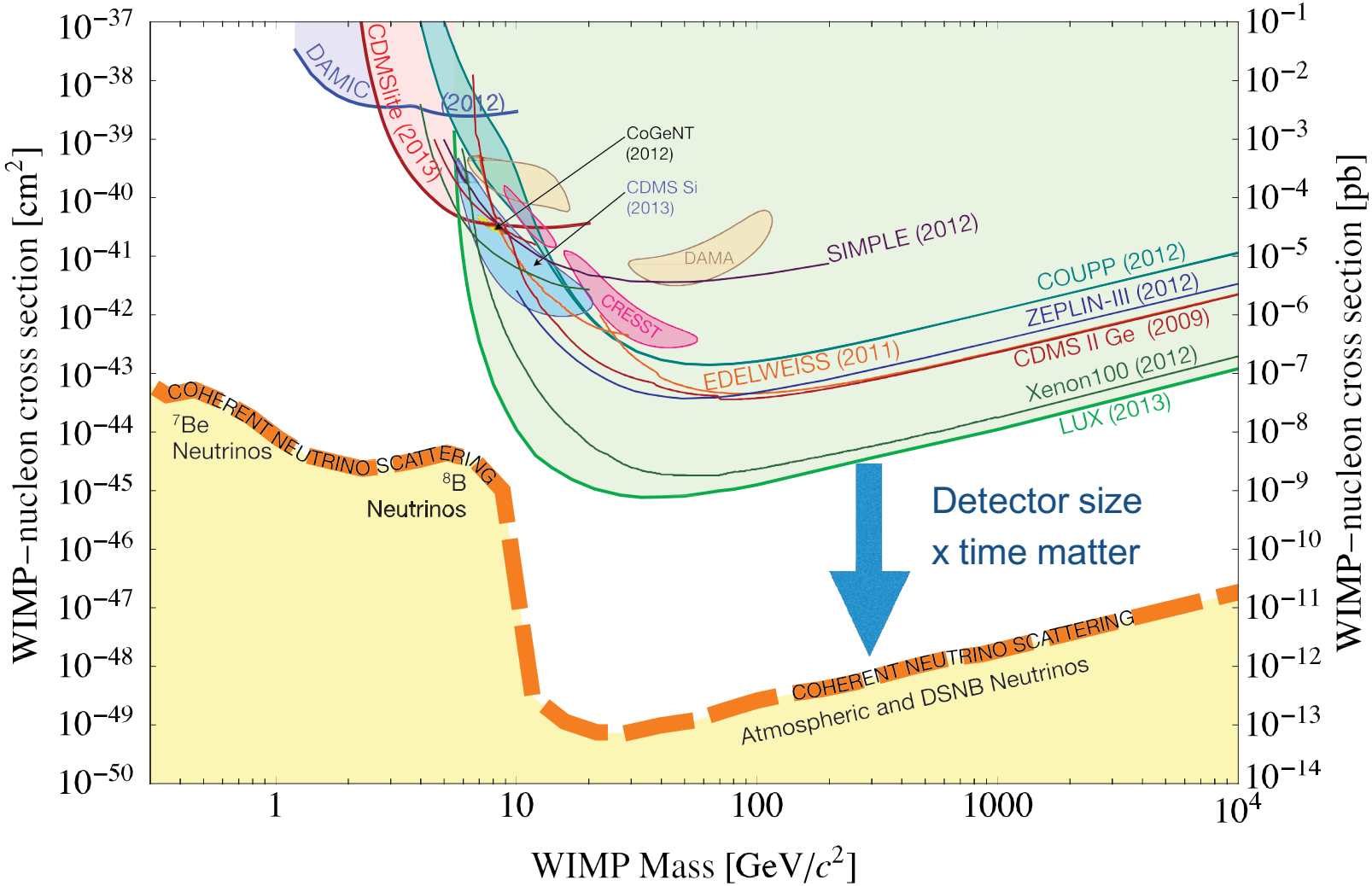
X and Y position from S2 hit pattern on the top PMTs



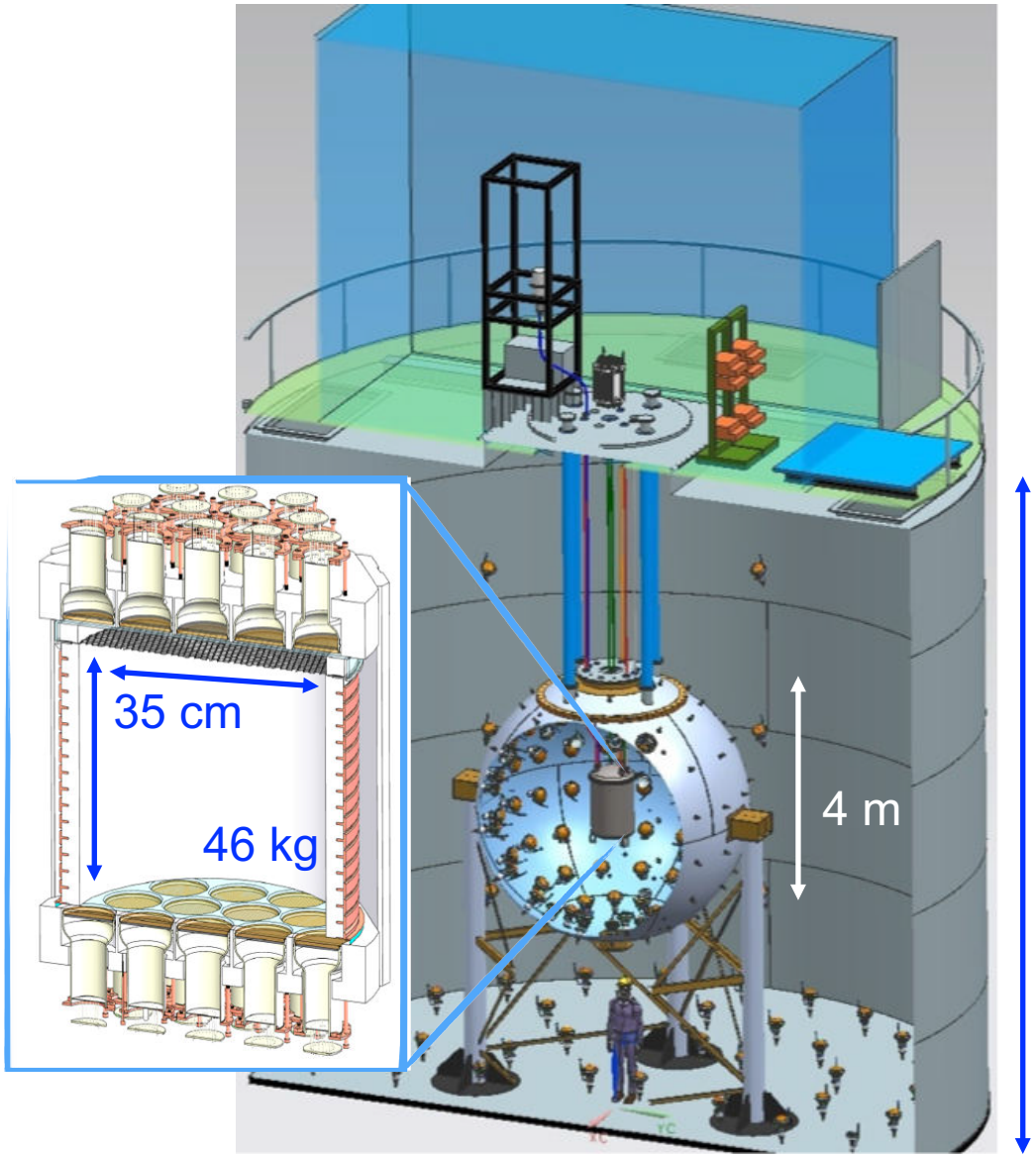




How is evolving the field of Direct Detection ?



DarkSide-50



Darside-50 (LAr)
@ LNGS (Italy)

- 35 cm x 35 cm, ~ 37 kg fiducial
- 47.1 d ARr / 70.9 d UAr
- 1.4 x 10^3 kg.day / 2.6 x 10^3 kg.day
- No excess
- Data taking continue

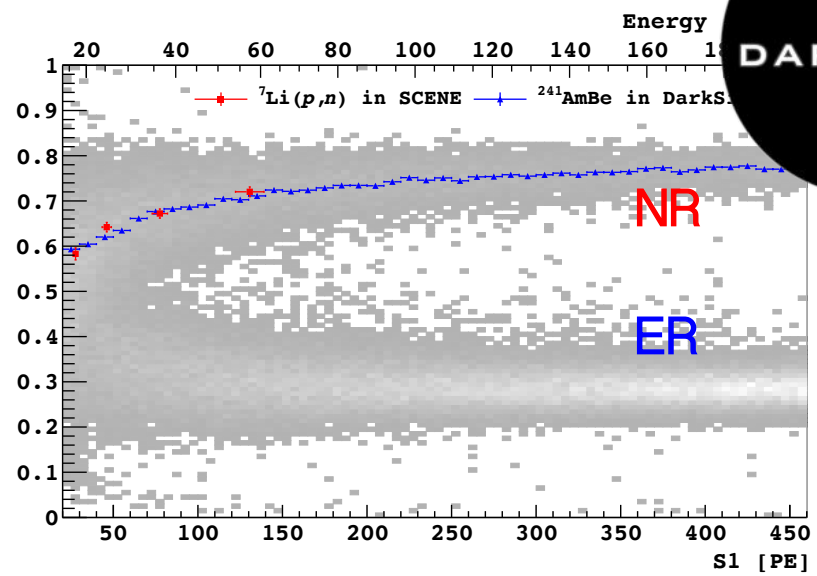
More info about future of DarkSide on Friday (C. Savarese)

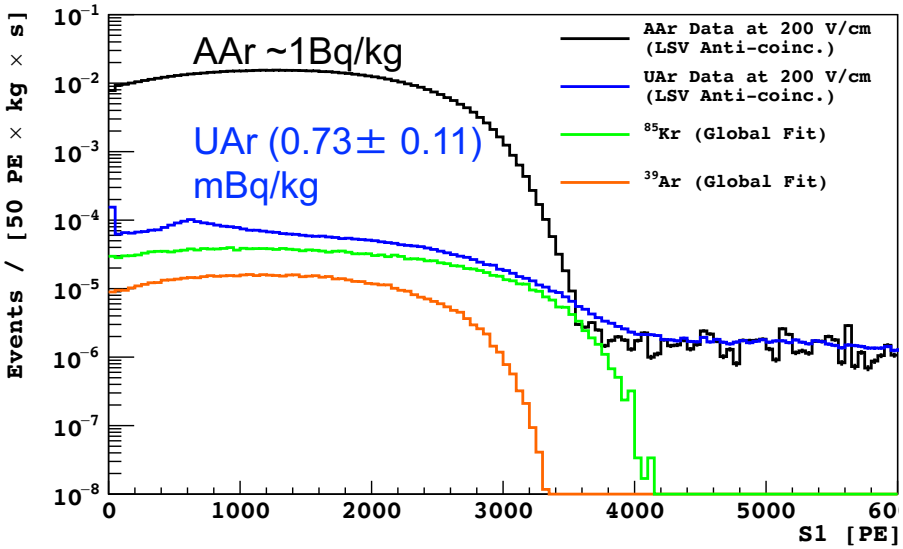
Darkside analysis

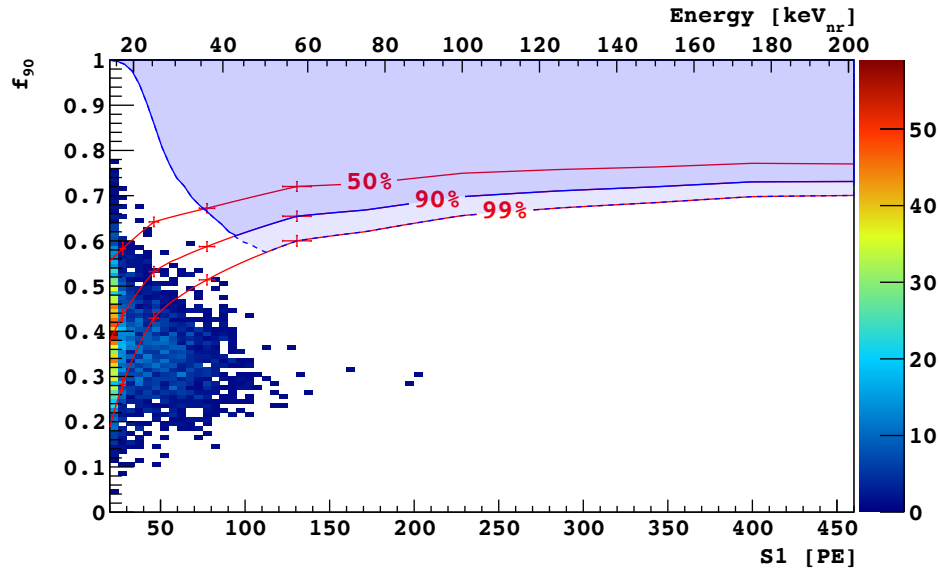
50 days with Atmospheric Ar (AAr)
07->09/2014
Physics Letters B, 743 (2015): 456-466

70 days with Underground Ar (UAr)
04->07/2015
Physical Review D, 93 (2016): 081101(R)

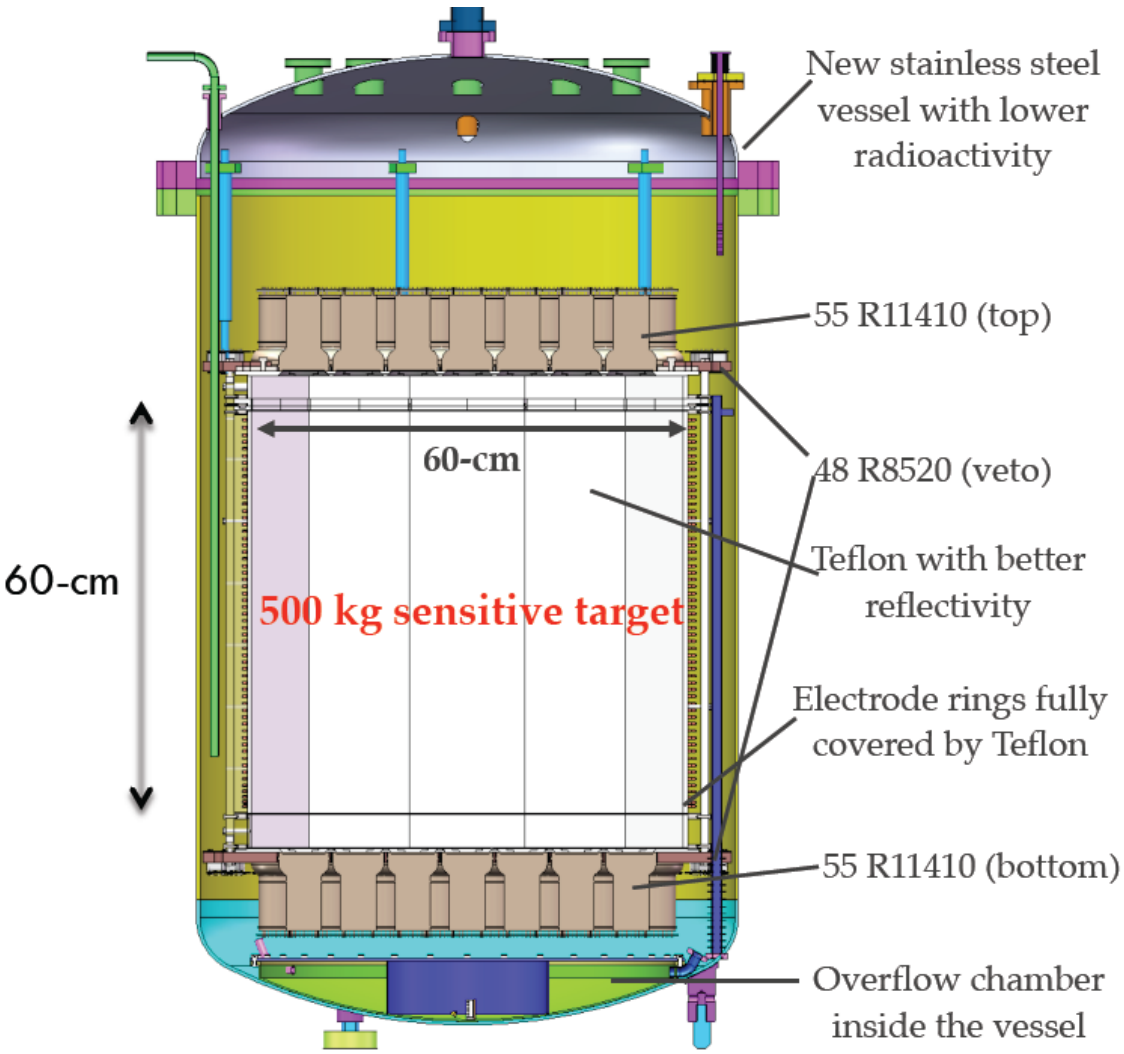
Today, in taking data
> 1 yr lifetime (still blinded)







PandaX II



Particle and Astrophysical Xenon Experiments

PandaX-II (LXe)
@ CJPL (China)

- 60 cm x 60 cm, ~400 kg fiducial
- 2nd largest operating LXe TPC
- 3.3 x 10^4 kg.day = 0.1 t.year
- No excess
- Data taking for the 2 next years

More info about future of CJPL on Friday (H. Wong)

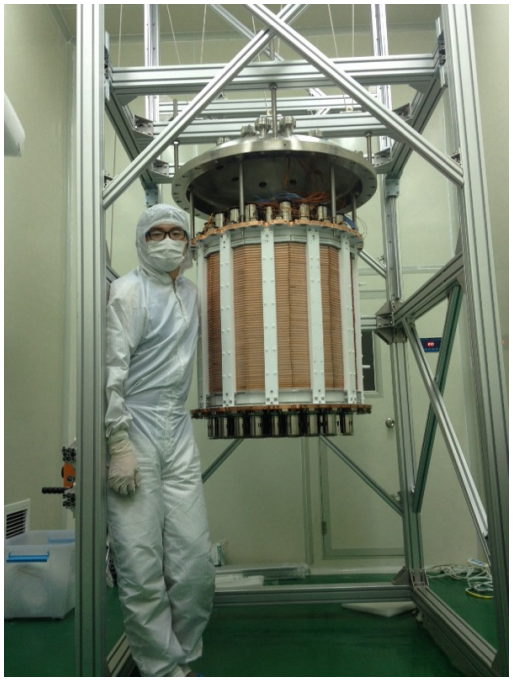
PandaX II new results SI limits

PANDA X

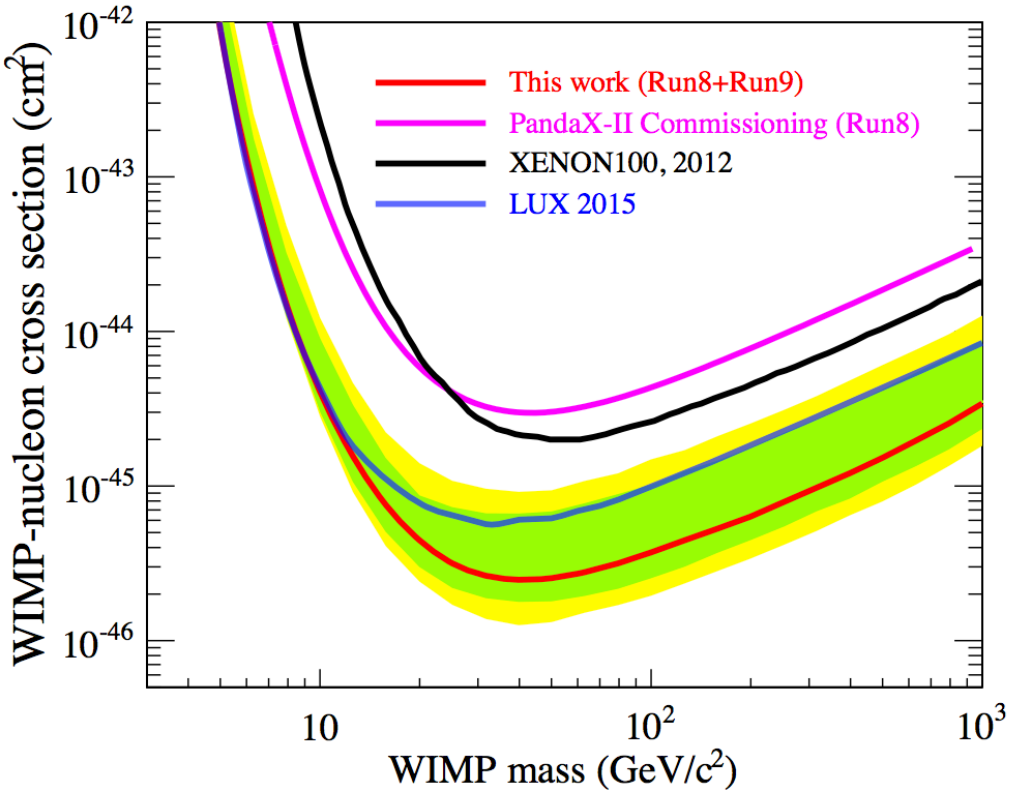
Particle and Astrophysical Xenon Experiments

Mar. 9-Jun 30 2016, in total 98.7 live-day of under slightly different conditions

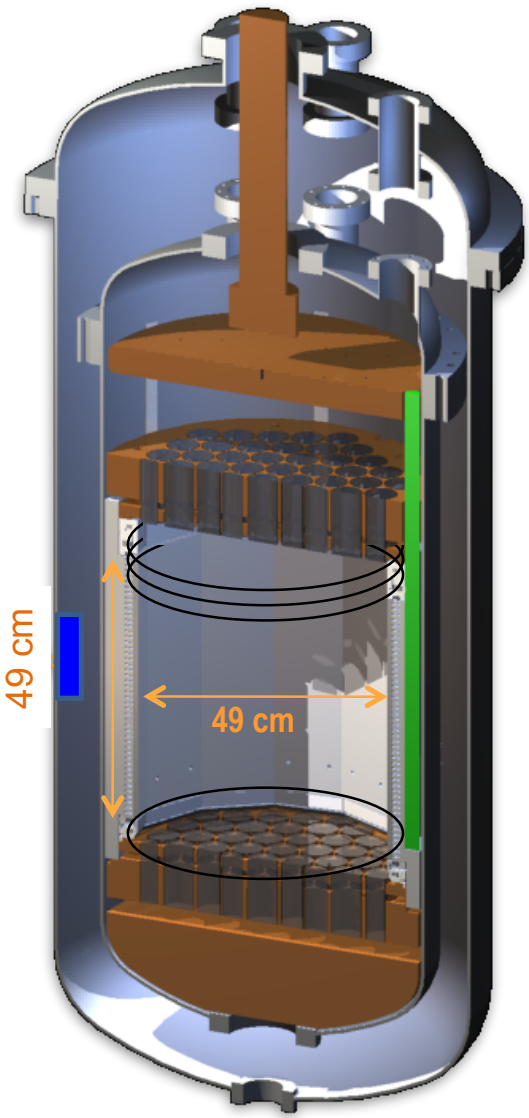
Condition	live time (day)	E_{drift} (V/cm)	E_{extract} (kV/cm)
1	7.76	397.3	4.56
2	6.82	394.3	4.86
3	1.17	391.9	5.01
4	63.85	399.3	4.56



Phys. Rev. Lett. 117, 121303 (2016)
arXiv:1607.07400



LUX

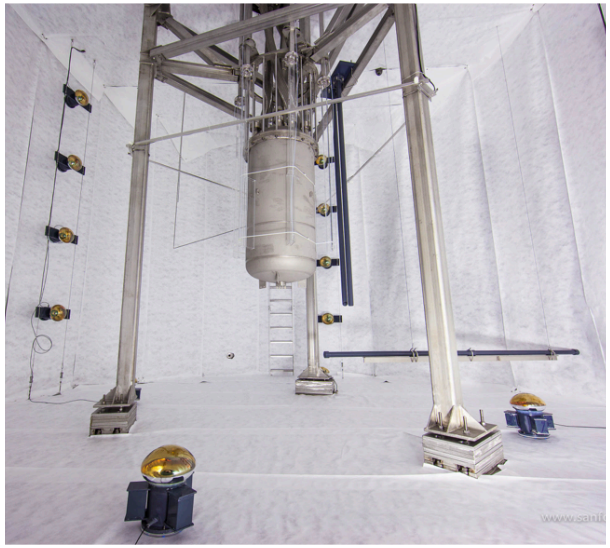


370 kg

LUX (LXe)
@ SURF (USA)

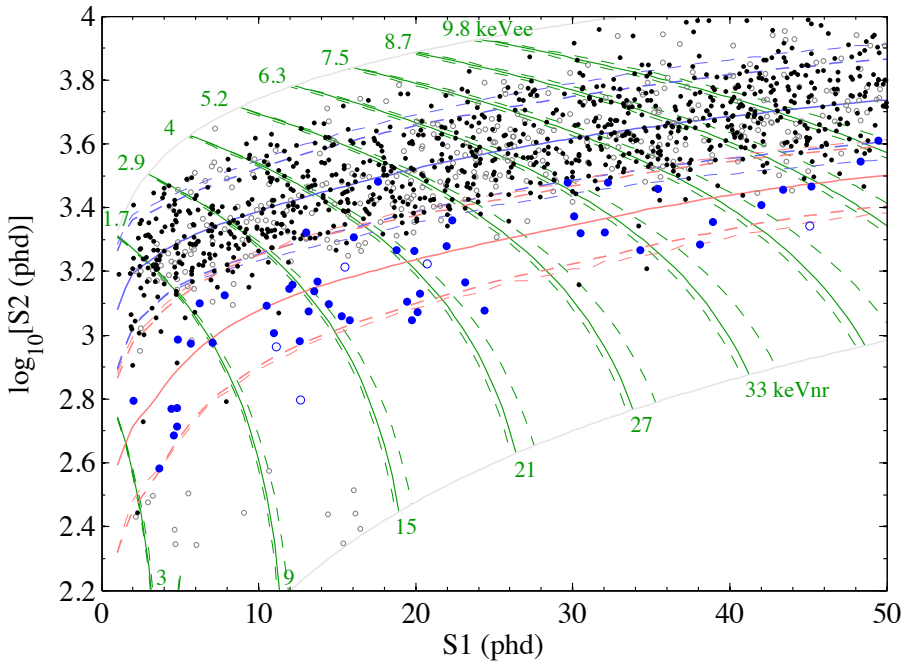
Large Underground Xenon experiment

- 49 cm x 49 cm, ~100kg fiducial
- 332 live-days
- 3.4 x 10^4 kg.day = 0.1 t.year
- No excess
- Stopped



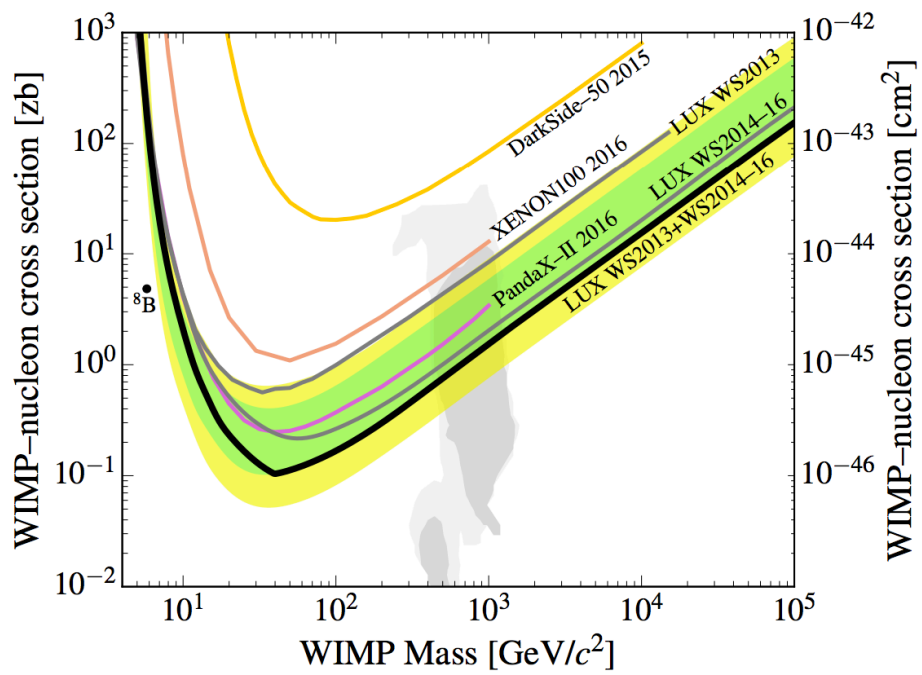
More info about future (LZ) in 1 hour (H. Lippincott)

LUX new results SI limits



Large Underground Xenon experiment

Phys. Rev. Lett. 118, 021303 (2017)
arXiv: 1608.07648



Instead of traditional blinding, we employ a technique where fake signal events ("salt") are injected into data stream. NOT SIMULATION!!

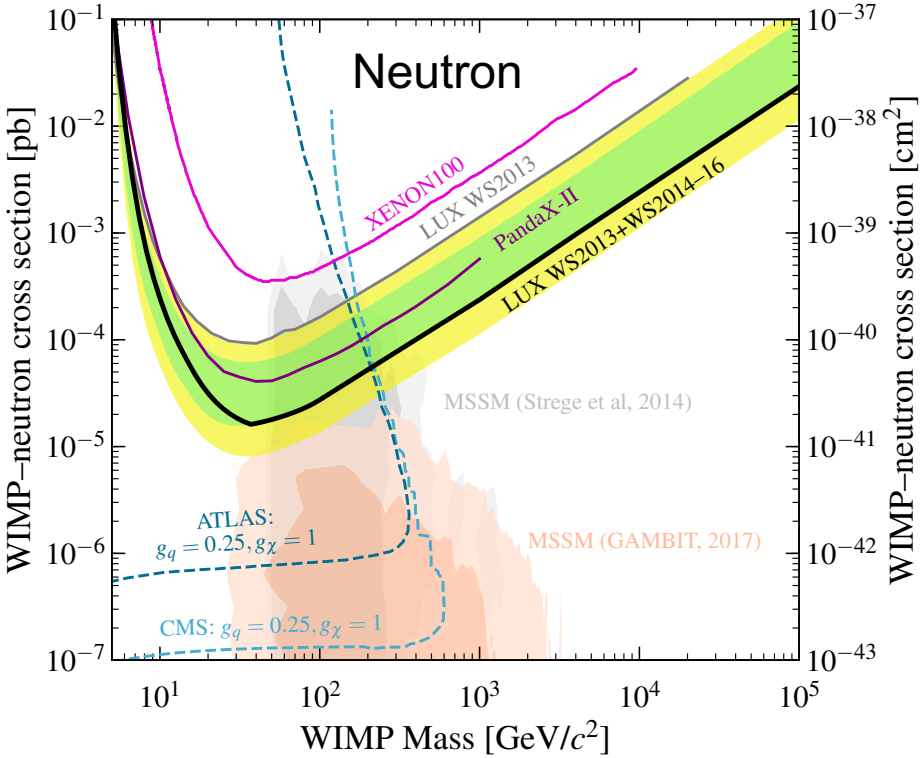
LUX recent results on SD limits

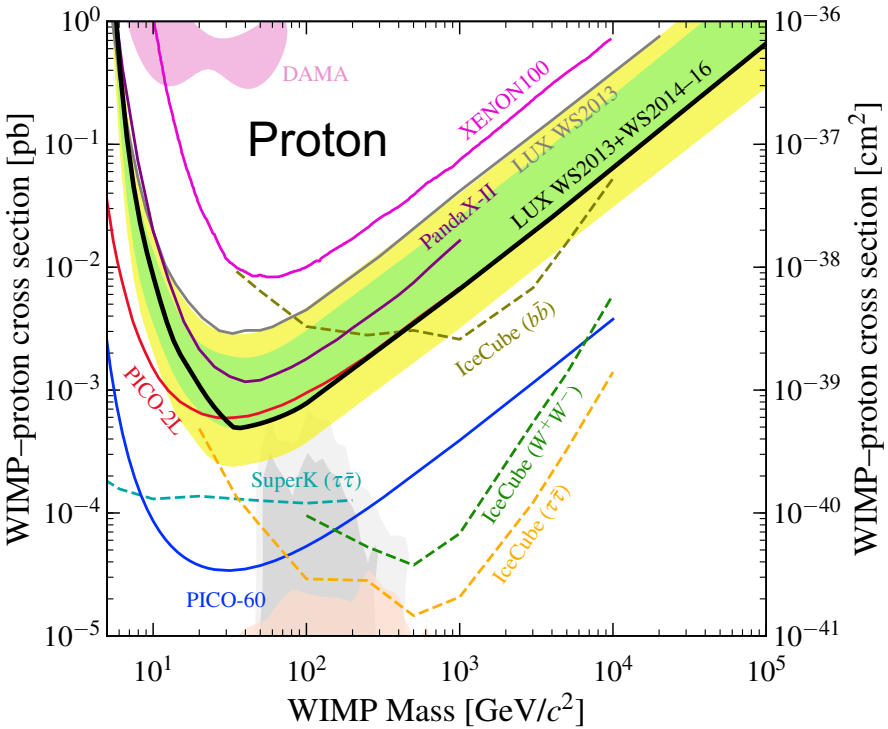
- 49 cm x 49 cm, ~100kg fiducial
- 332 live-days
- 3.4 x 10^4 kg.day = 0.1 t.year
- No excess

Large Underground Xenon experiment

Improvement of a factor of six compared with the results from the first science run – 95 days (PRL, 116, 161302 (2016))

arXiv:1705.03380





XENON World

23 Institutions
10 Countries
135 Scientists

Columbia, RPI, Nikhef, Stockholm, Muenster, Mainz, MPIK, Chicago, Freiburg, UCLA, Zurich, UCSD, NYUAD, Rice, Weizmann, Purdue, Coimbra, Subatech, LPNHE, LAL, Bologna, LNGS, Torino

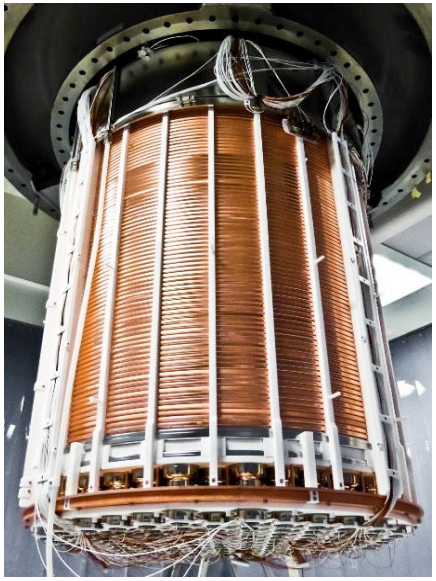
Phases of the XENON Program

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

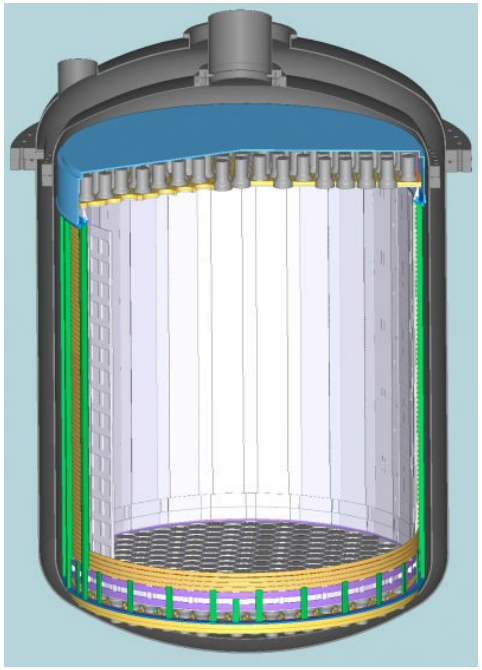
XENON100
2008 – 2016
30 cm drift TPC
Total: 161 kg
Target: **62** kg
Fiducial: 34/48 kg

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

First Results (2017)
$\sigma_{SI} = 7.7 \cdot 10^{-47}$ cm^2
@ 35 GeV/c^2
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

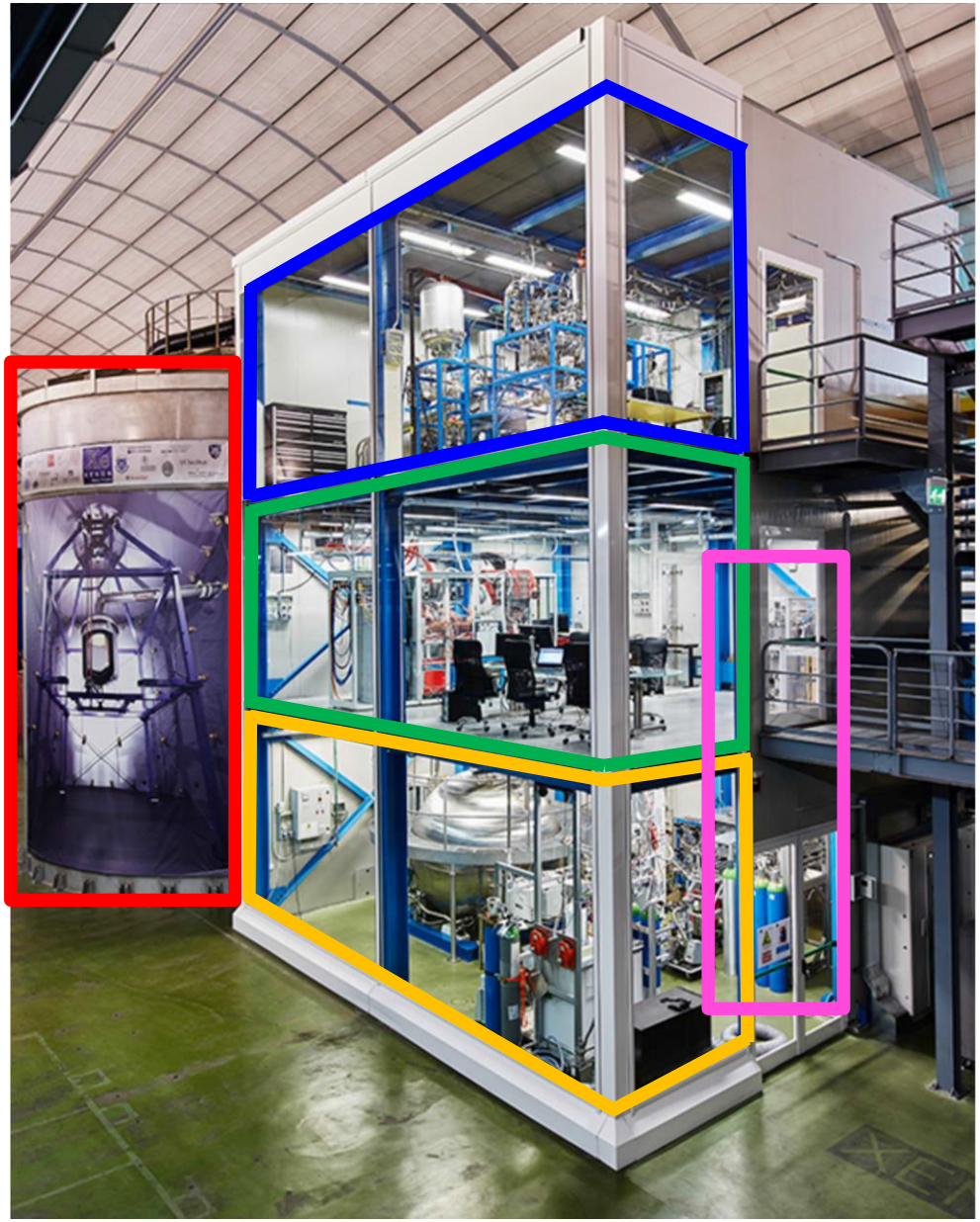
Water shield: deionized water as passive radiation shield
Muon veto: Active muon veto against muon induced neutrons (84 PMTs)

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

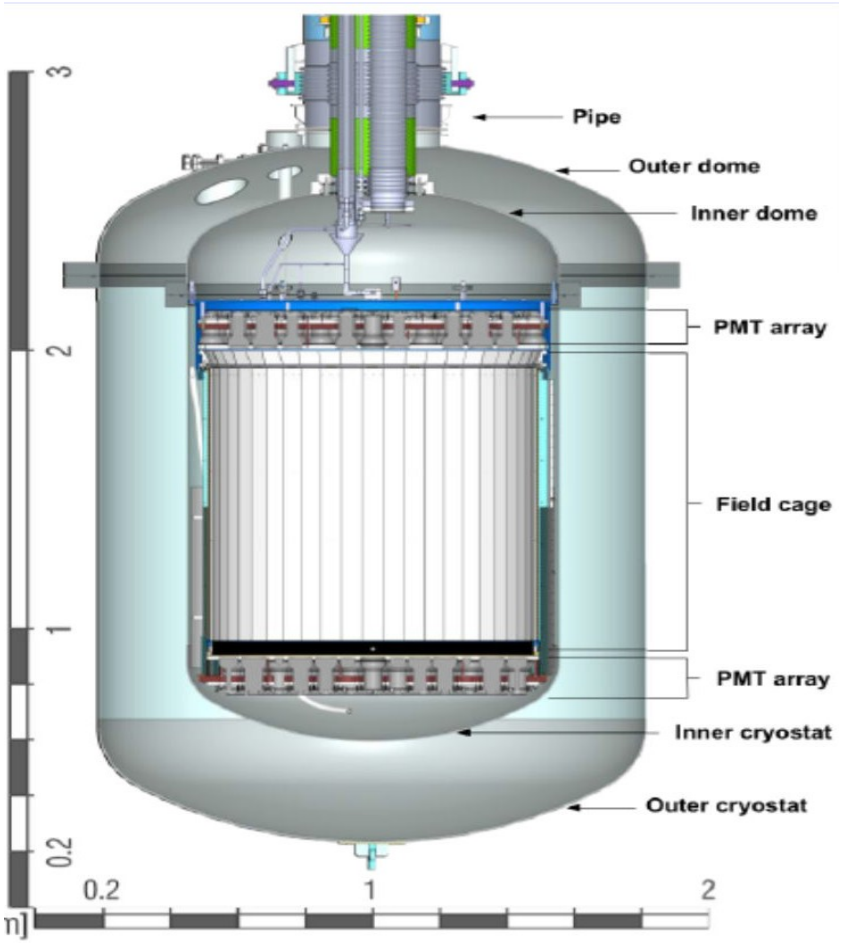
ReStoX: Emergency recovery up to 7.6 tons of LXe
Passive: No active cooling required to keep Xe contained

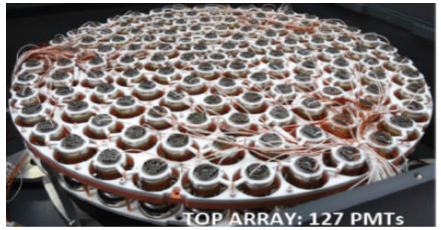
Kr Distillation: Remove Kr from system during fill or online
Rn Distillation: Initial tests show promising reduction for Rn

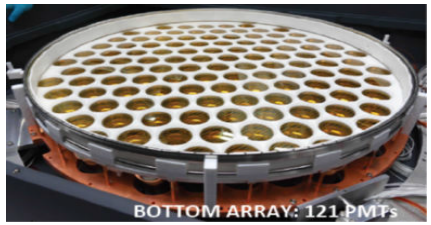


TPC

The largest Xe double-phase TPC ever built !



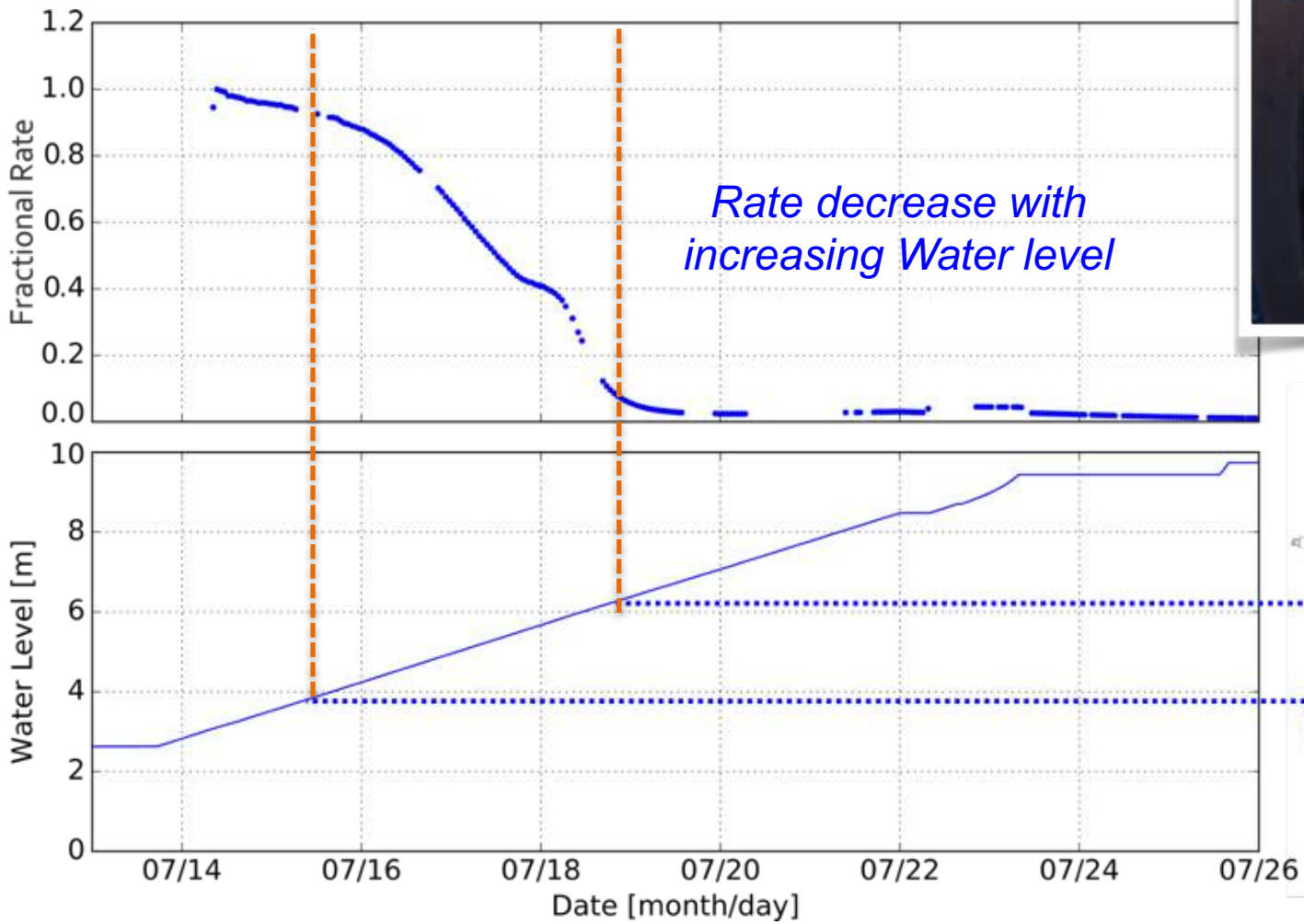


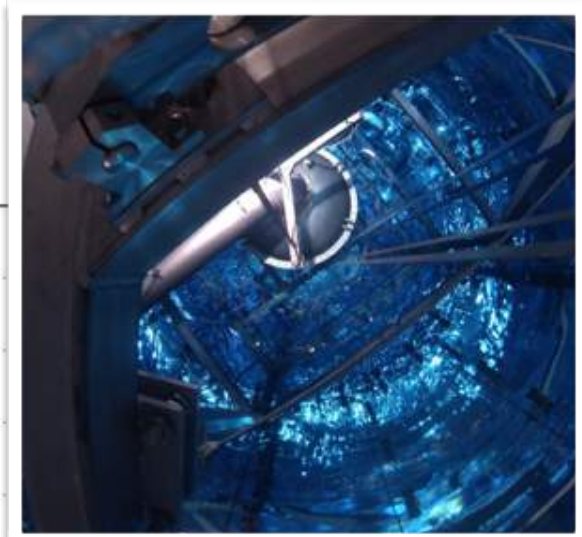


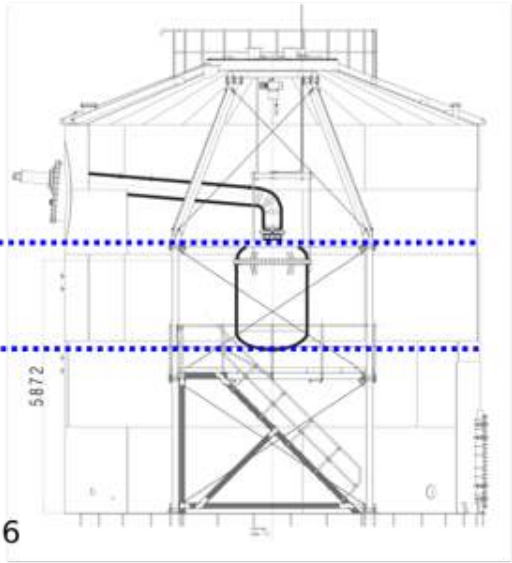
- Active Xe mass: 2 tons.
- Light sensors: 127+121 3” PMTs average QE = 35%
- Fully covered with high reflectivity PTFE to maximize light collection.
- Drift region: 1m height, 1m diameter.

Water Shield filling

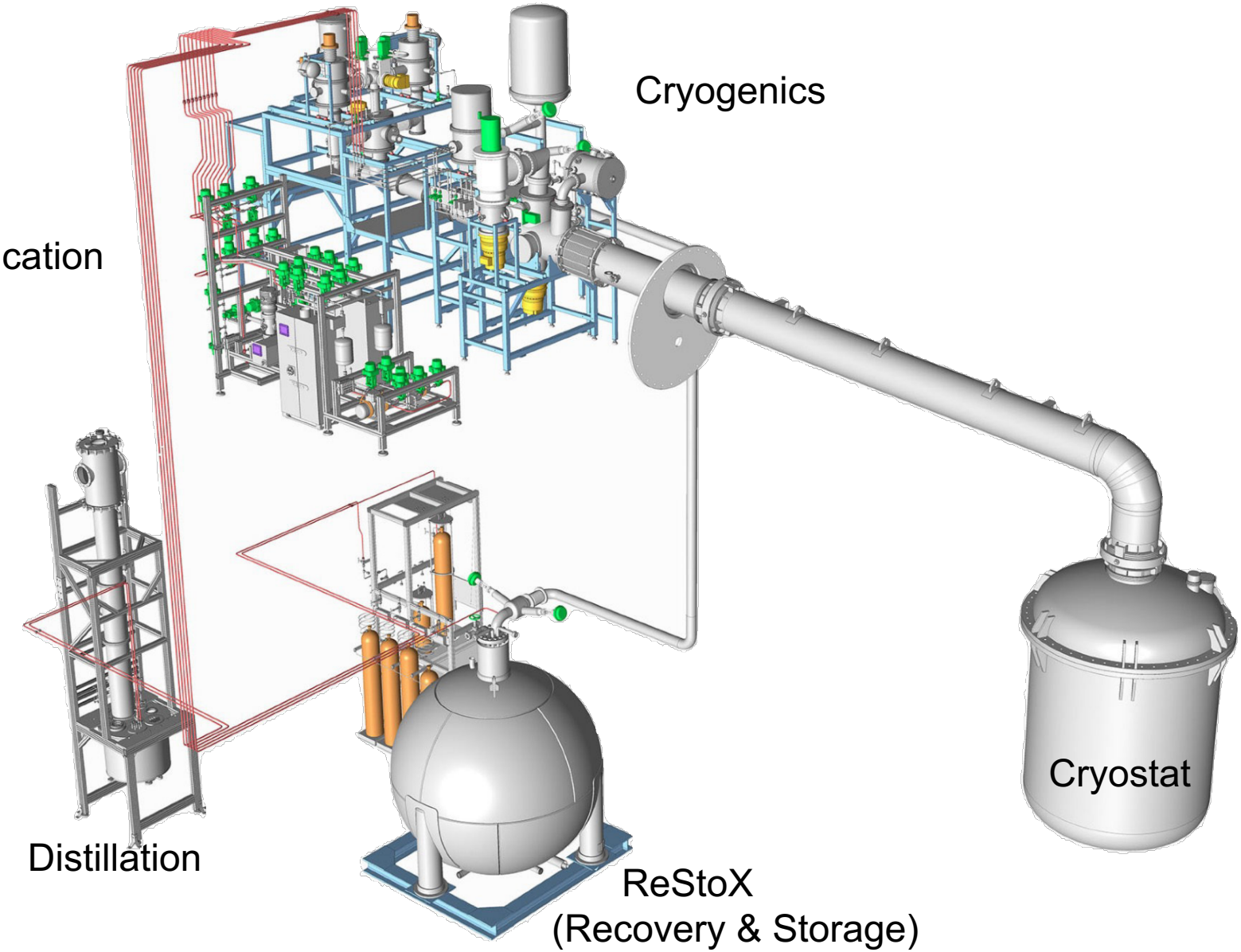
- TPC fully immersed in water since July 2016
- Background studies and calibration runs started





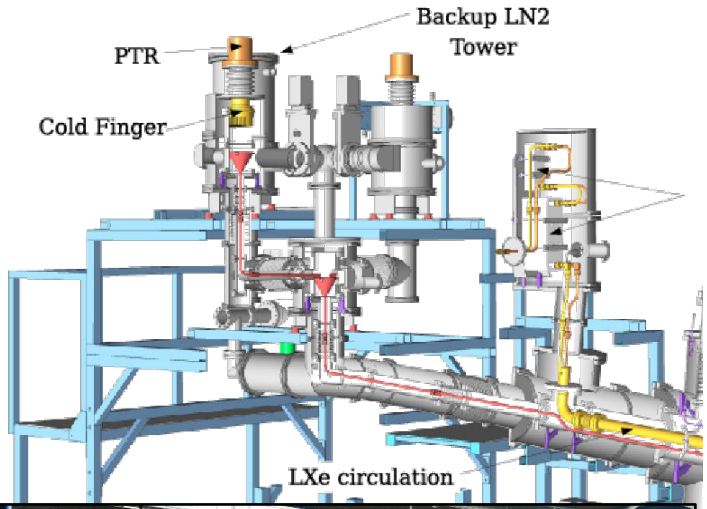


XENON Plants

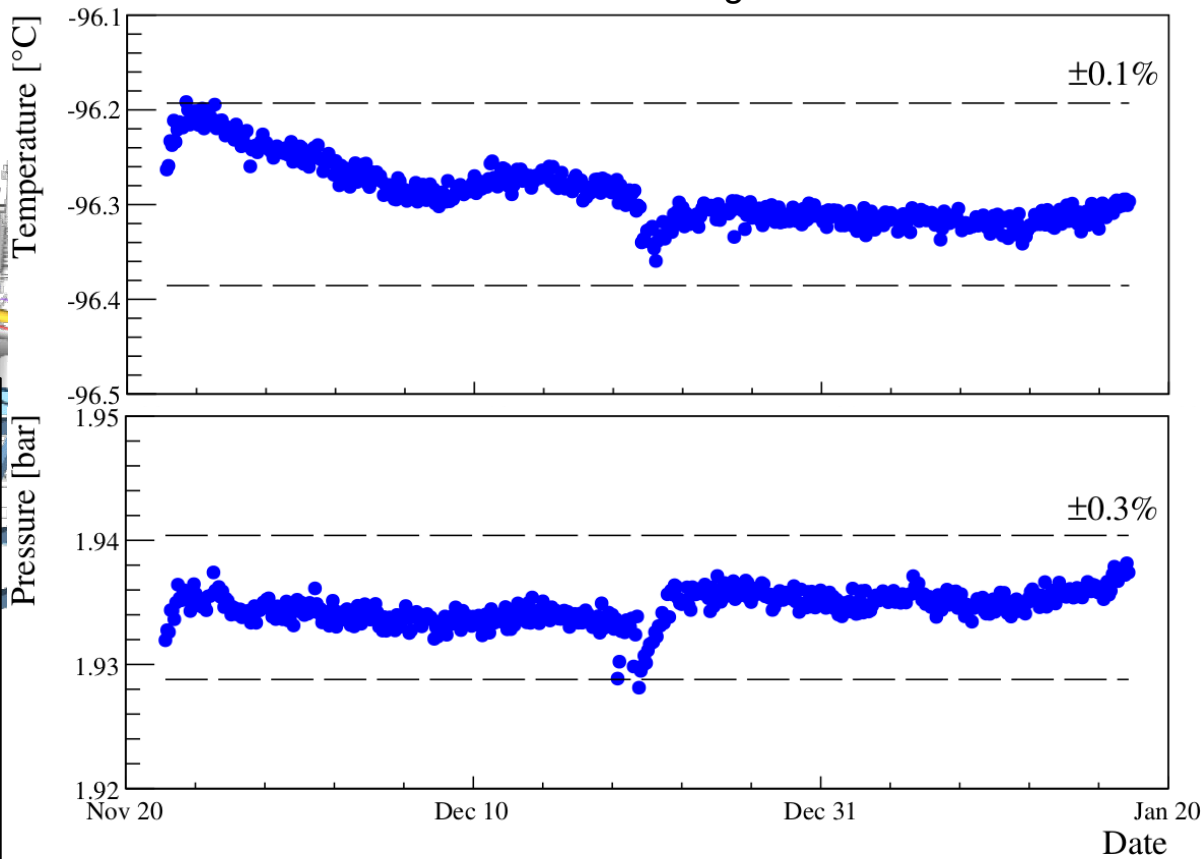


Detector Stability

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

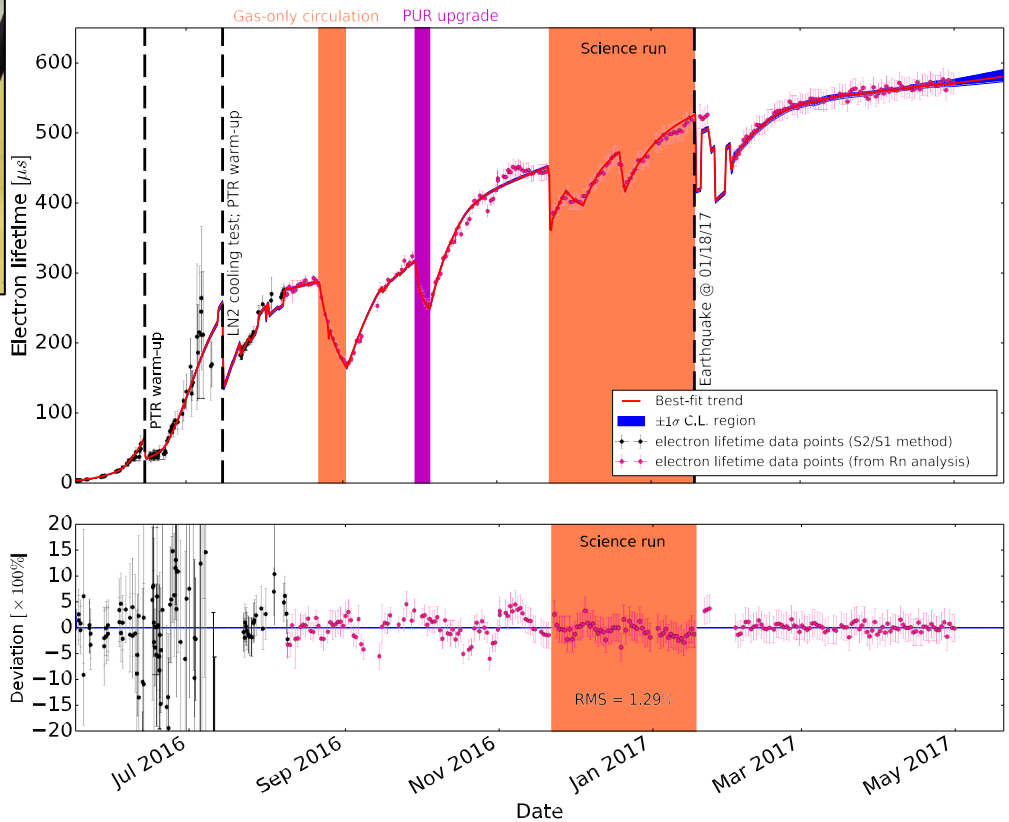


Slow control/Historian monitoring



Xenon purification

Goal: remove electronegative impurities below 1 ppb (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



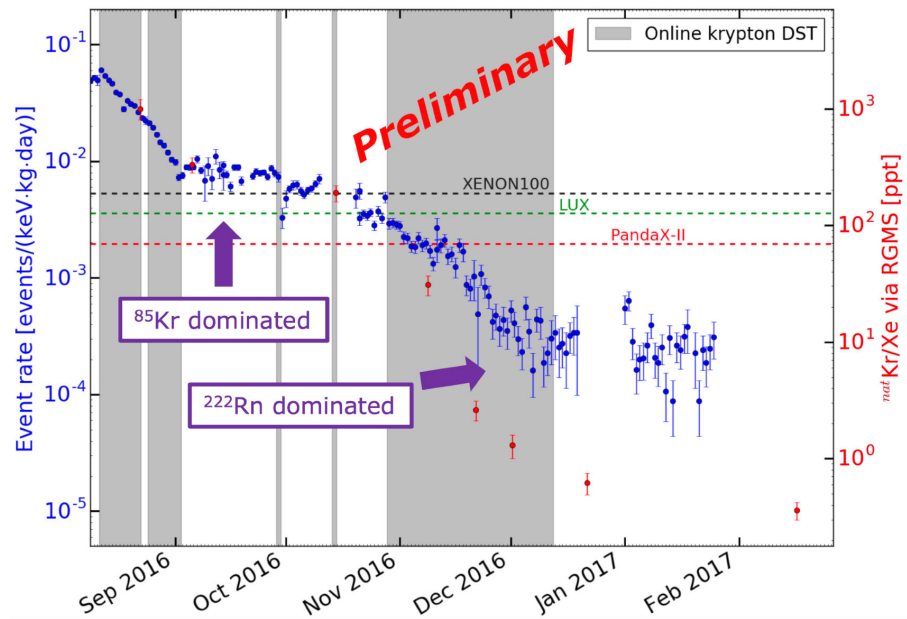
Performance: evolution of e-lifetime, monitored regularly with ERs calibration sources, well described by physical model. Current value approaching the max drift time of the LXe TPC.

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)
- $>6.4 \times 10^5$ 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

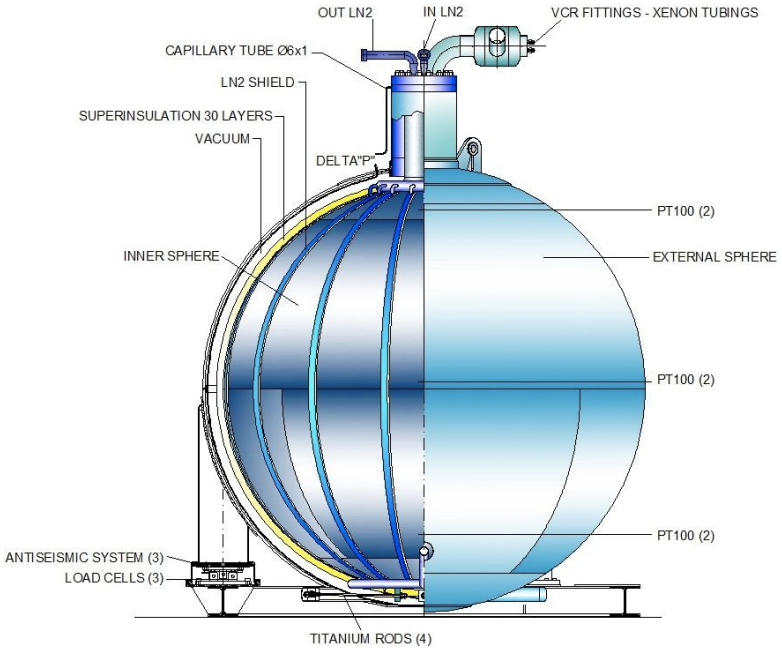


arXiv:1702.06942
Eur. Phys. J. C77 (2017) no.5, 275

Recovery and Storage System: ReStoX

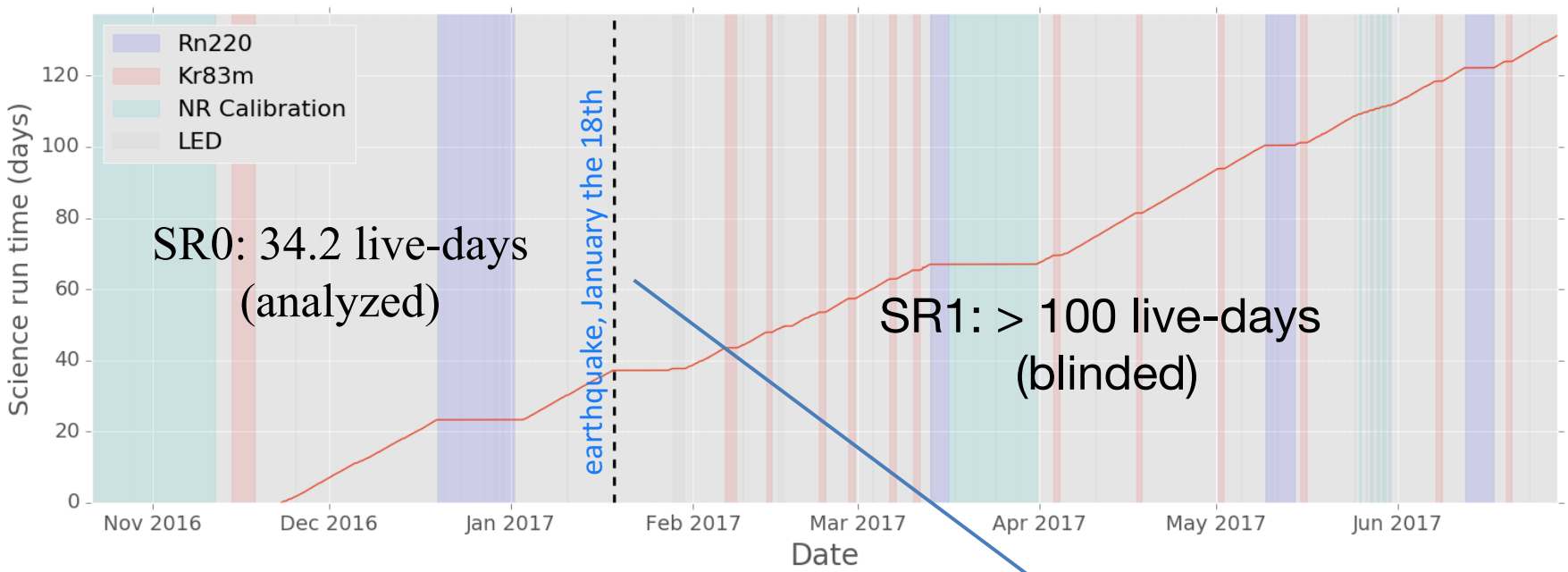
Goals:

- 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

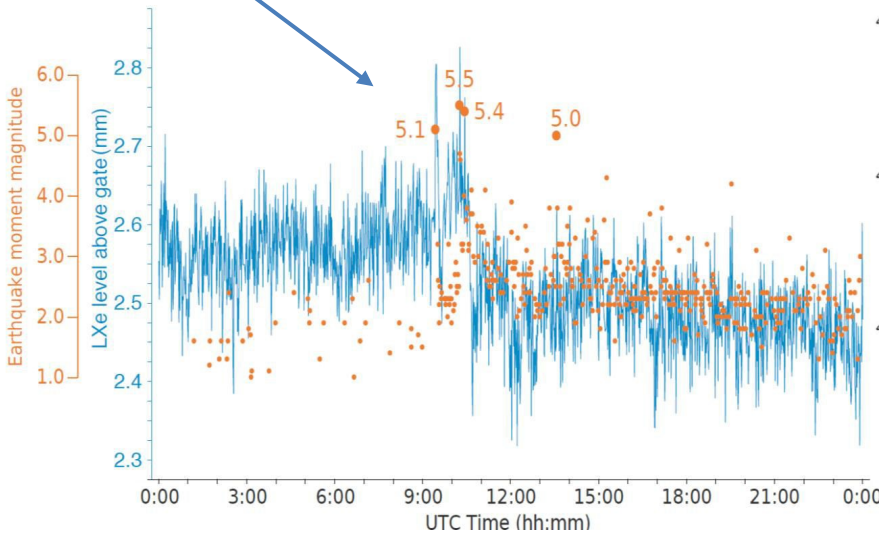


Double walled, high pressure (72 bar) vacuum insulated sphere of 2.1 meter diameter, cooled by LN2 and by an internal LN-based condenser.

Science Run: Exposure



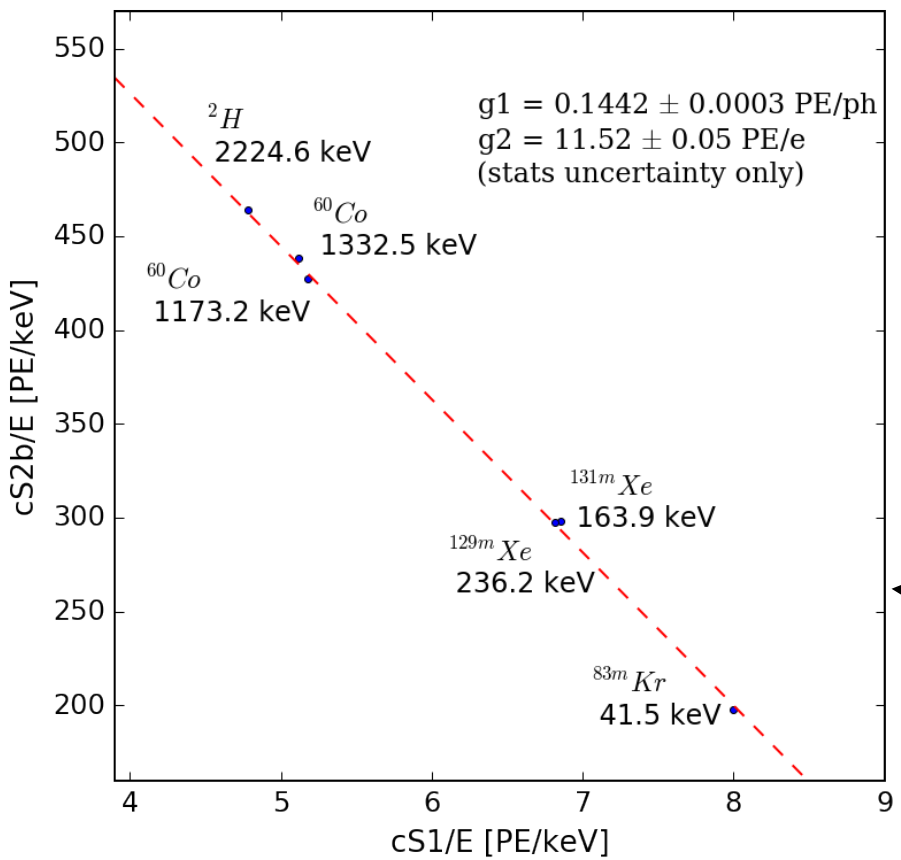
- Dark matter exposure: 34.2 Live days
- Calibration Data:
  - ^{83m}Kr ➔ Spacial Response
  - ^{220}Rn ➔ ER-Bands
  - ^{241}AmBe ➔ NR-Bands
- Interrupted by a 5.5 magnitude earthquake



Energy Response

$$E = (n_{ph} + n_{e^-}) = \left(\frac{S_1}{g_1} + \frac{S_2}{g_2}\right).W$$

How much energy is needed to produce a quantum (e- or γ): **13.7 eV**

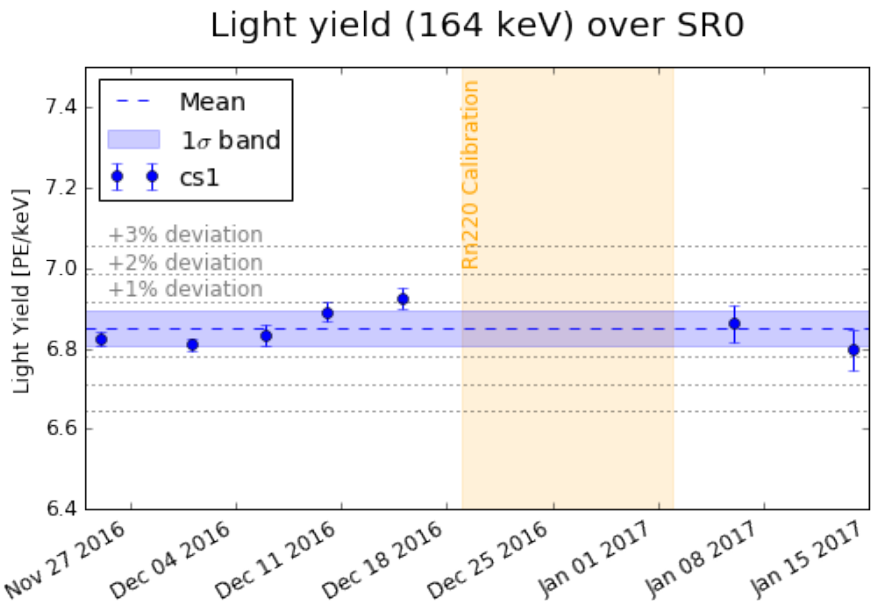


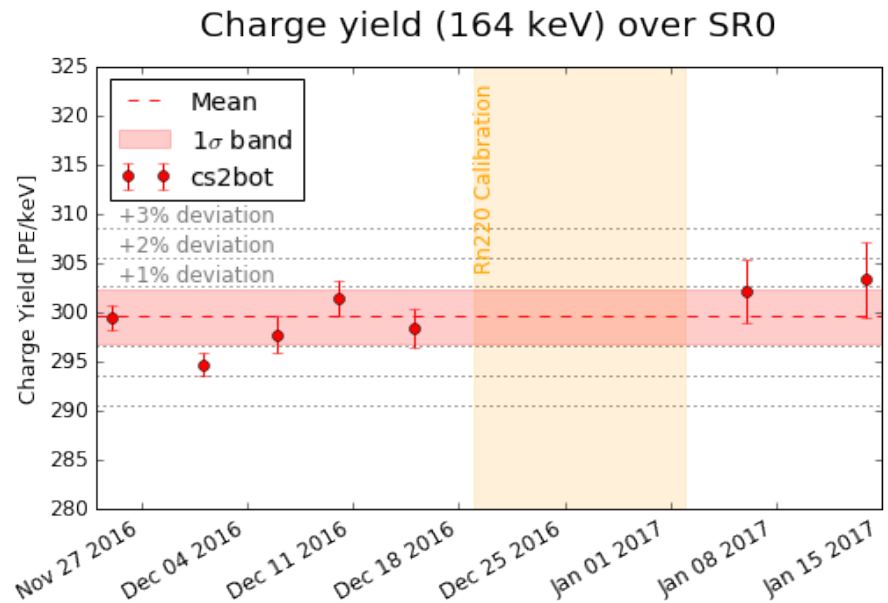
Light
+
Charge
= Total quanta

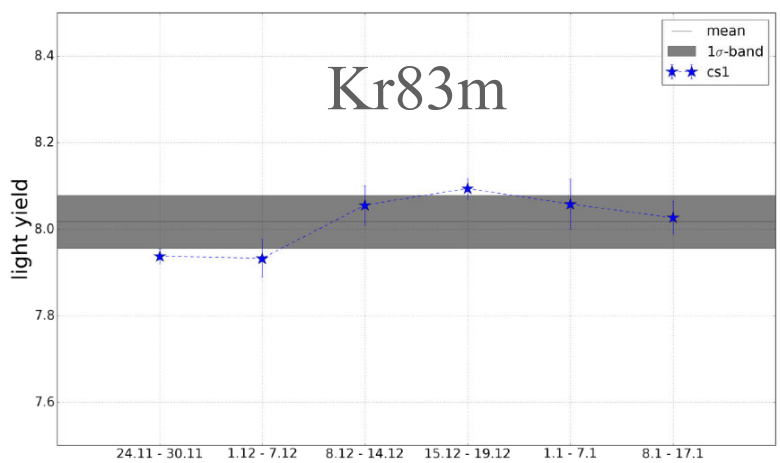
Conserved!
Excellent linearity with electronic recoil energy from 40 keV to 2.2 MeV

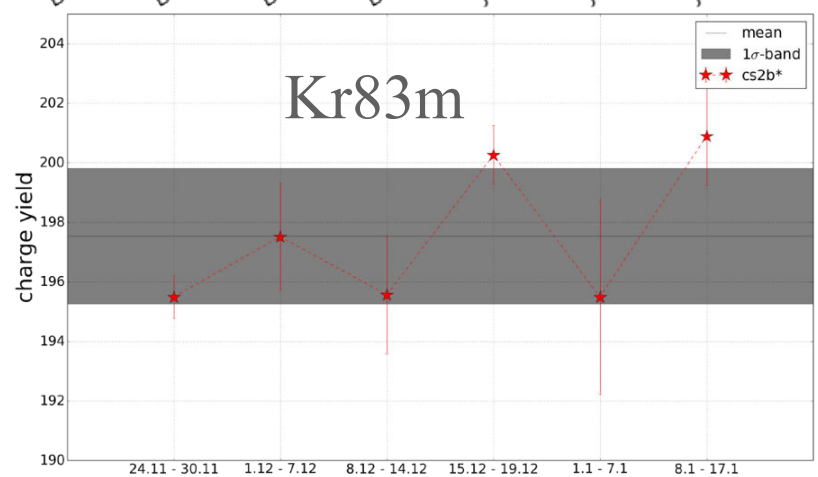
Light/Charge Yield Stability

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

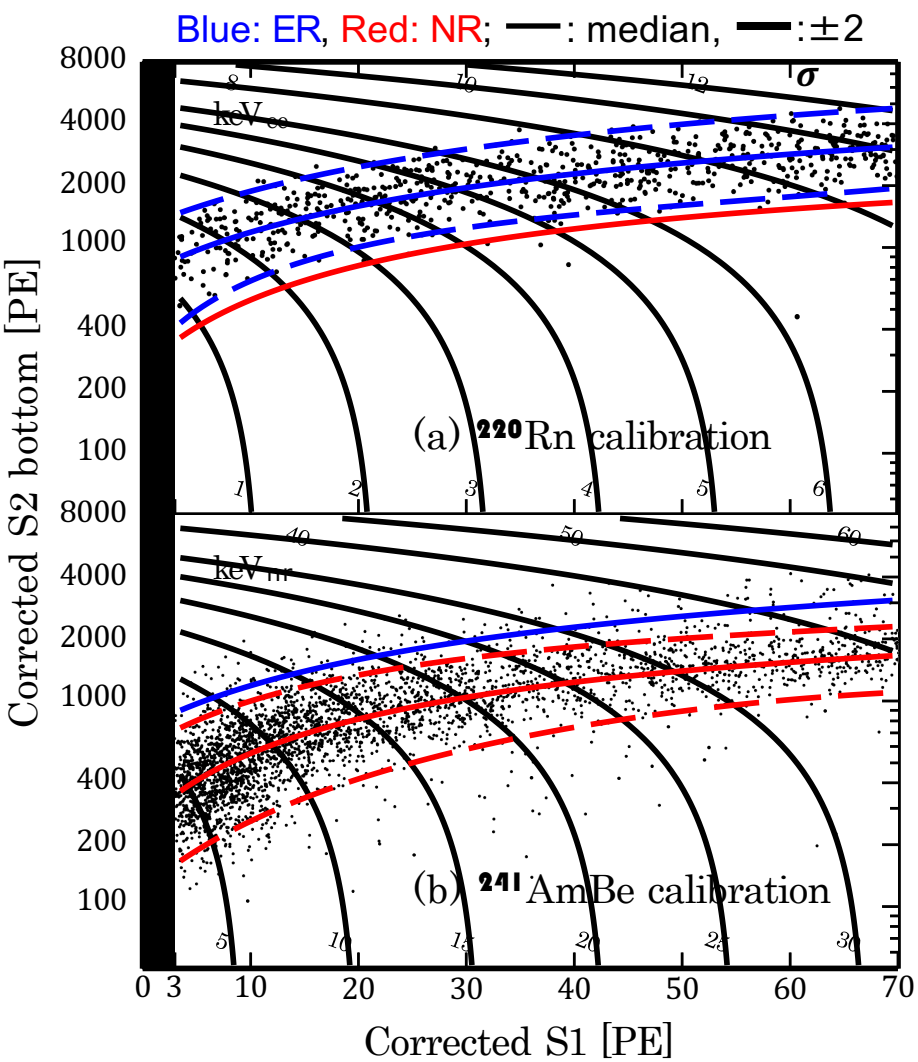


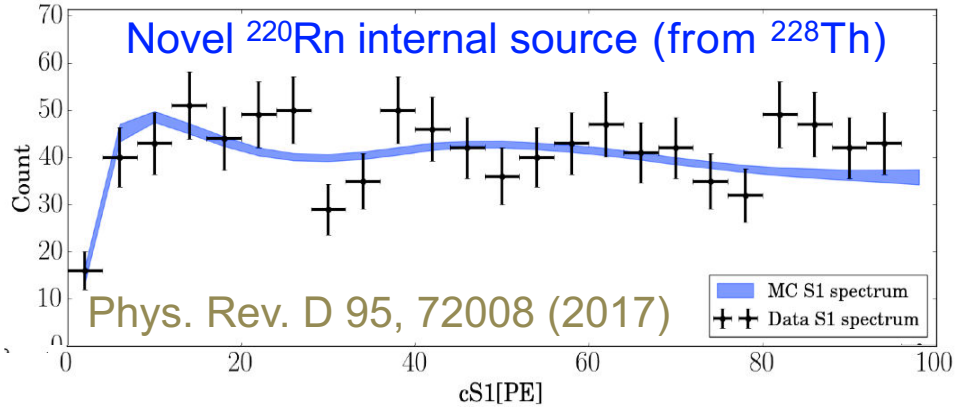




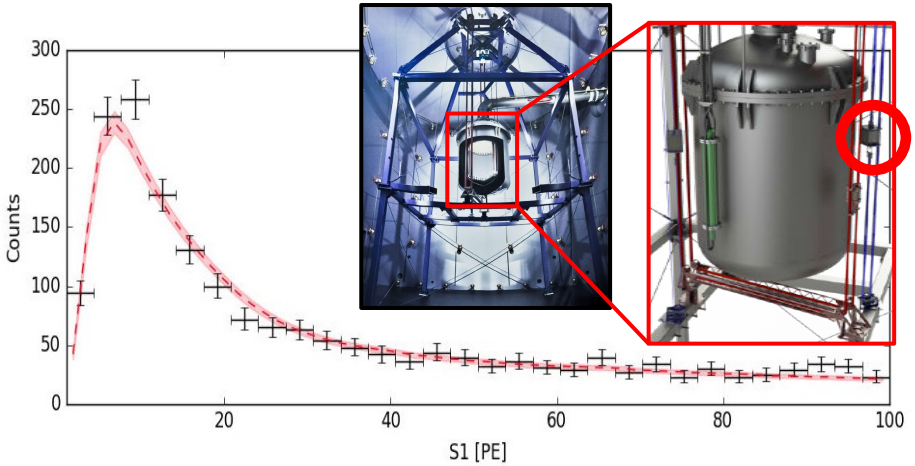


Fitting Models to Calibration





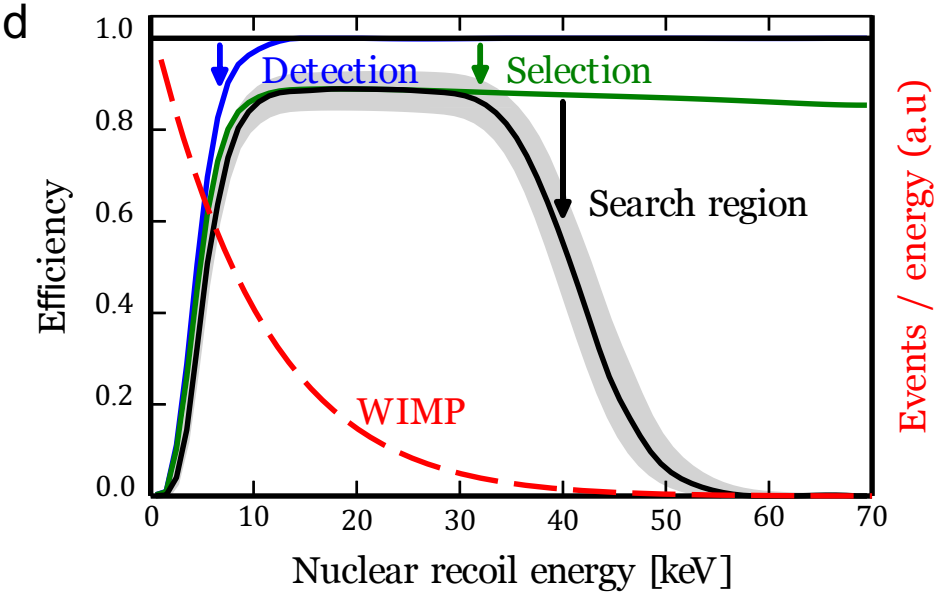
- Full modeling of LXe and detector response in $cS2_b$ vs cS1 space
- All parameters fitted with no significant deviation from priors

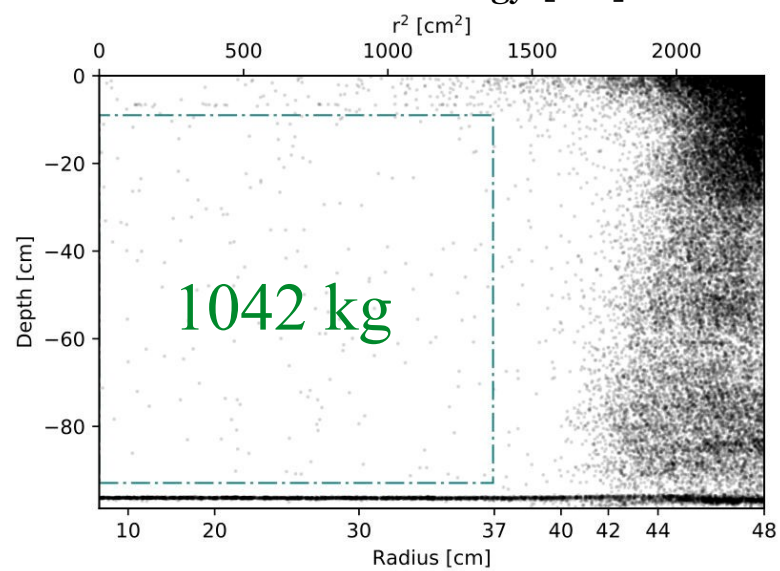


Efficiencies

- **Detection efficiency** dominated by 3-fold PMTs 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

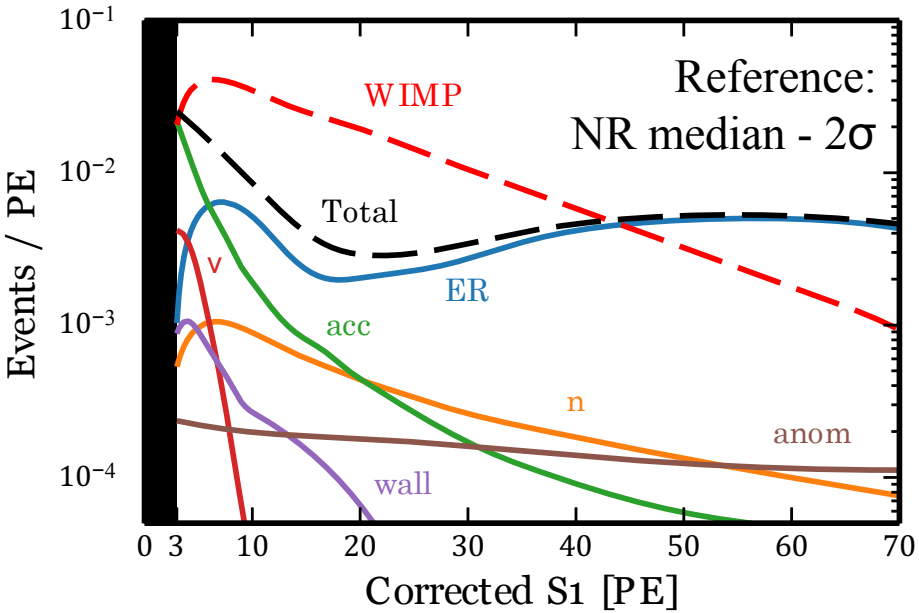
Cuts	Events remaining
All events (cS1<200 PE)	128144
Data Quality & Selection	48955
Fiducial Volume	180
3 PE < cS1 < 70 PE	**63**





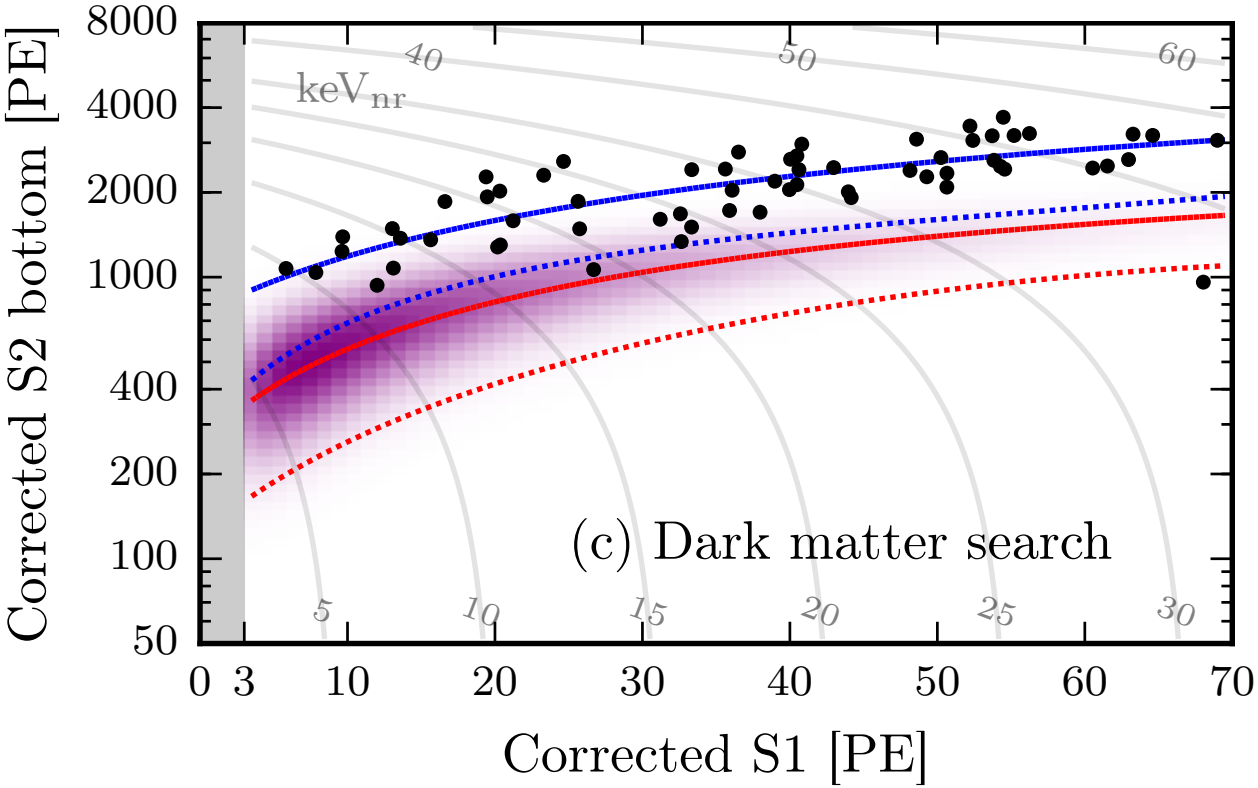
Background Model

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



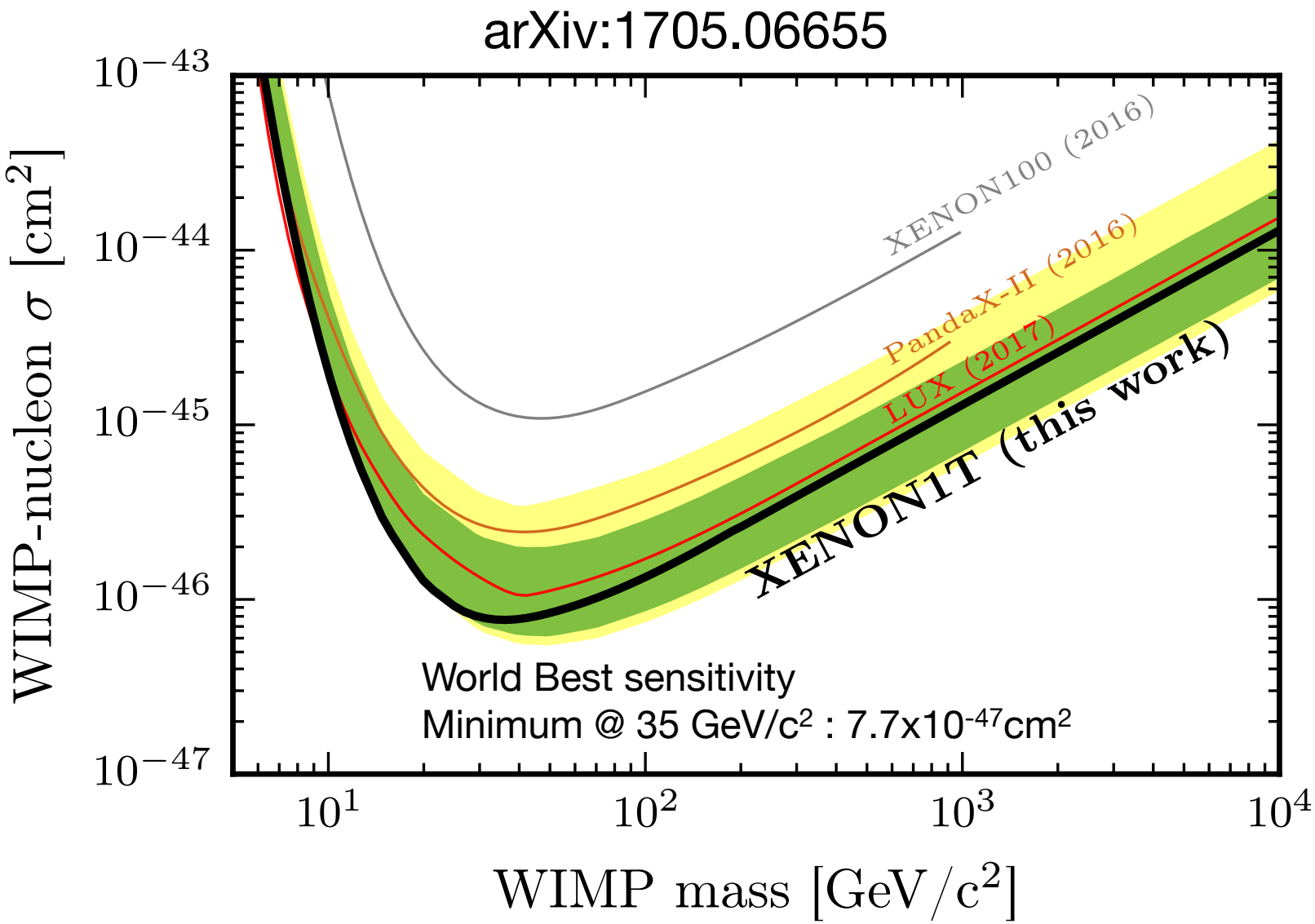
Background	Total	NR median - 2σ, 3-70pe
Electronic Recoil	(62 ± 8)	0.26 (+0.11)(-0.07)
Radiogenic neutrons (n)	(0.05 ± 0.01)	0.02
CNNS (ν)	0.02	0.01
Accidental coincidences (acc)	(0.22 ± 0.01)	0.06
Wall leakage (wall)	(0.52 ± 0.32)	0.01
Anomalous (anom)	0.09 (+0.12)(-0.06)	(0.01 ± 0.01)
Total background **50 GeV/c², 10^{-46}cm² WIMP**	**(63 ± 8)** **(1.66 ± 0.01)**	**(0.36 ± 0.09)** **(0.82 ± 0.06)**

Dark Matter Search

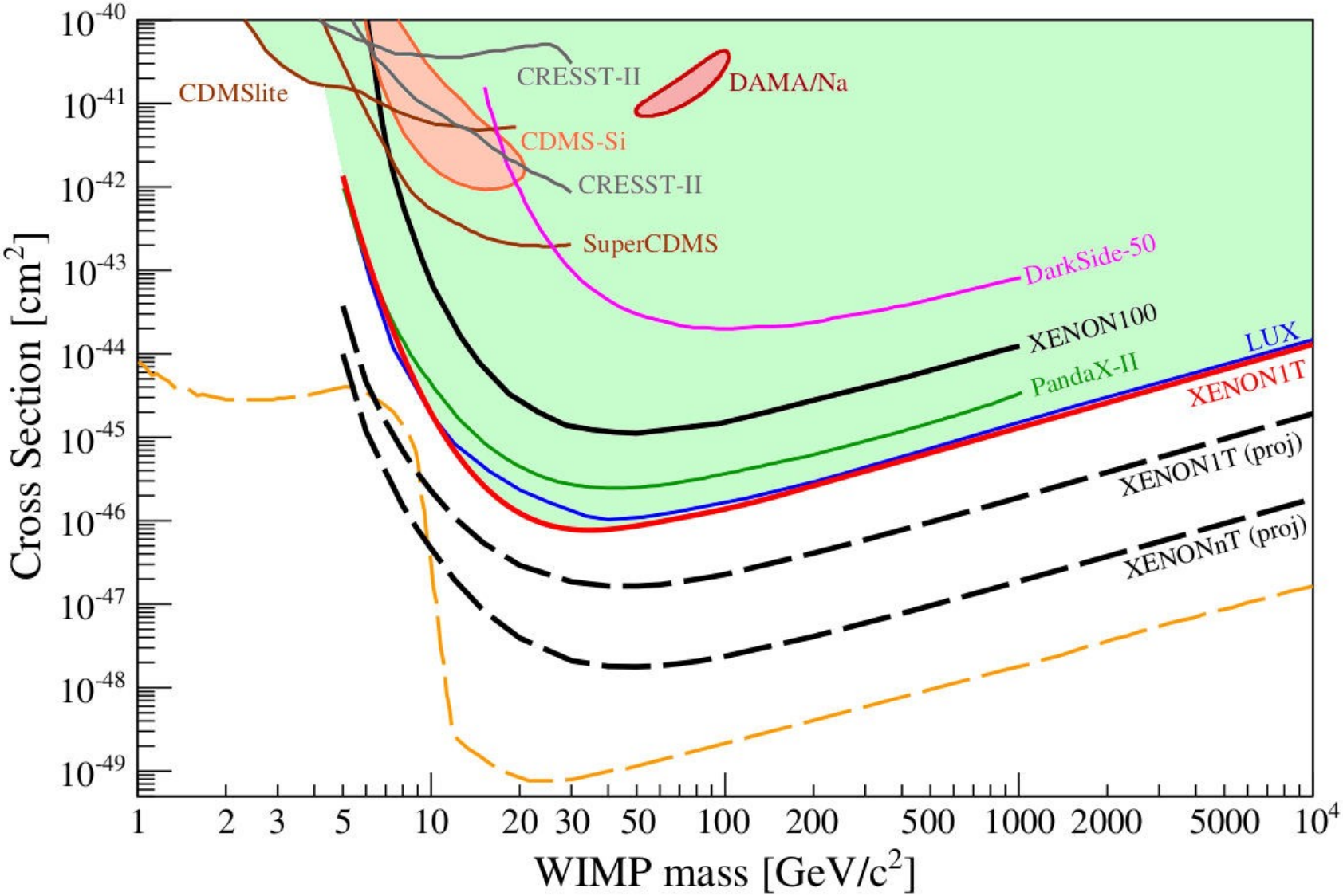


- Extended unbinned profile likelihood analysis
- Most significant ER & NR shape parameters included from calibration fits
- Normalization uncertainties for all components

XENON1T Results

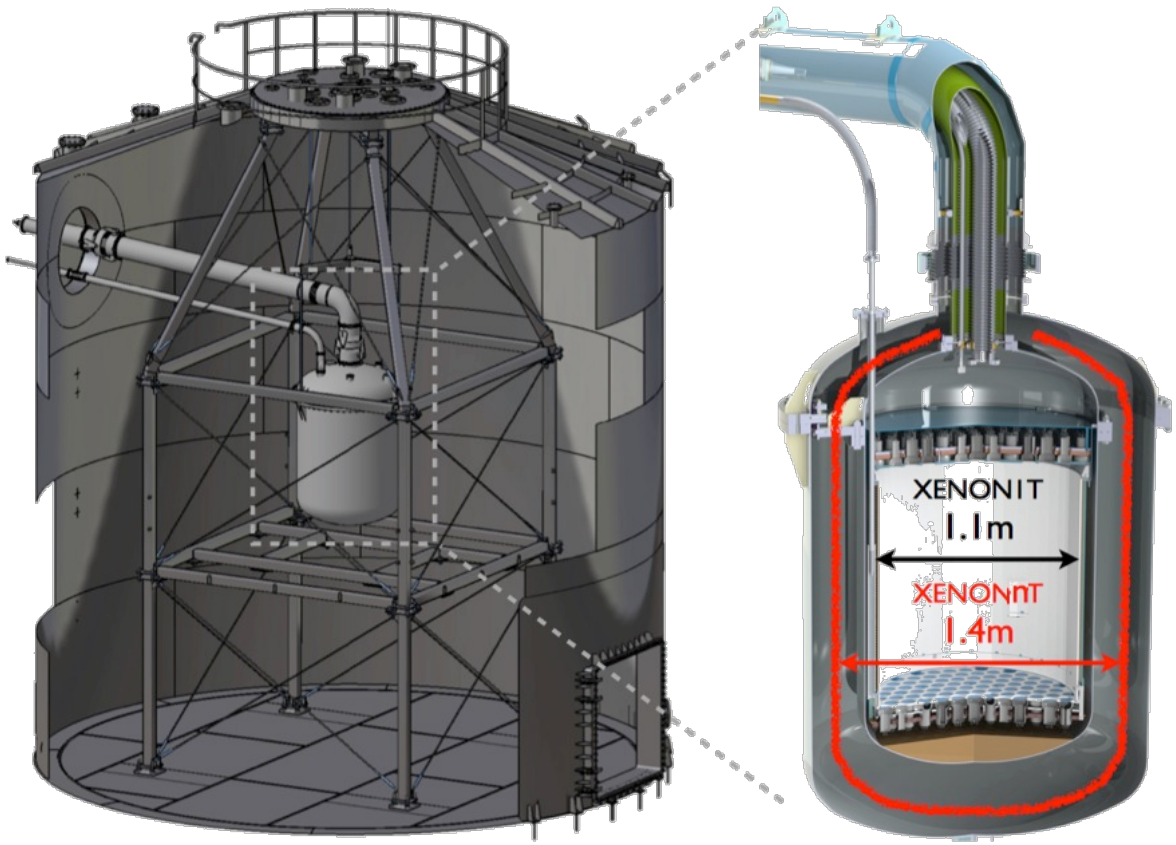


From XENON1T to XENONnT



Upgrade: XENONnT

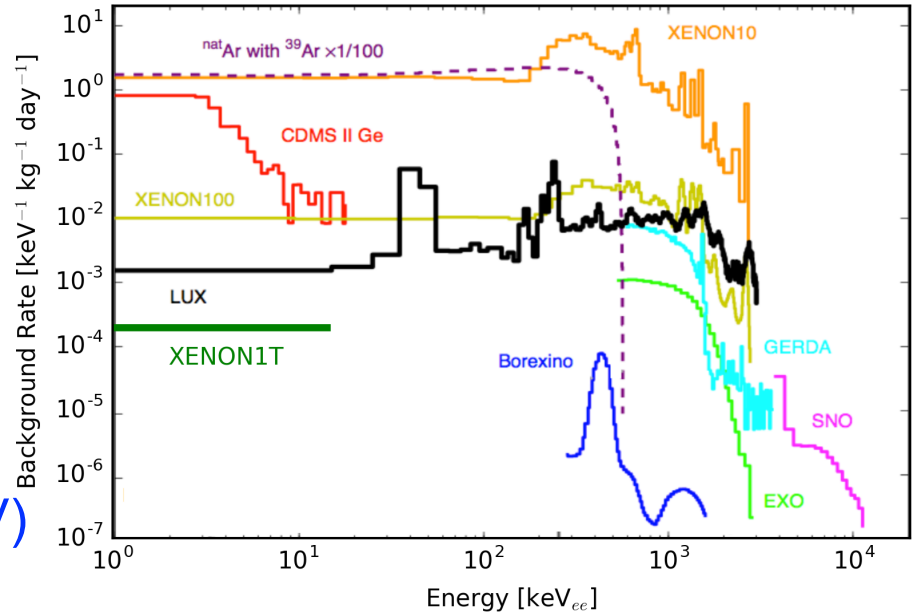
- Quick upgrade of TPC and inner cryostat
- All major systems remain unchanged
- Construct TPC in parallel to XENON1T operation
- Upgrade starting 2018



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, > 100 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

- LXe & LAr TPC are leading this field

More info about future of noble liquid on Friday