The Next Generation of “Revolutionary” Liquid Xenon Detectors for Dark Matter

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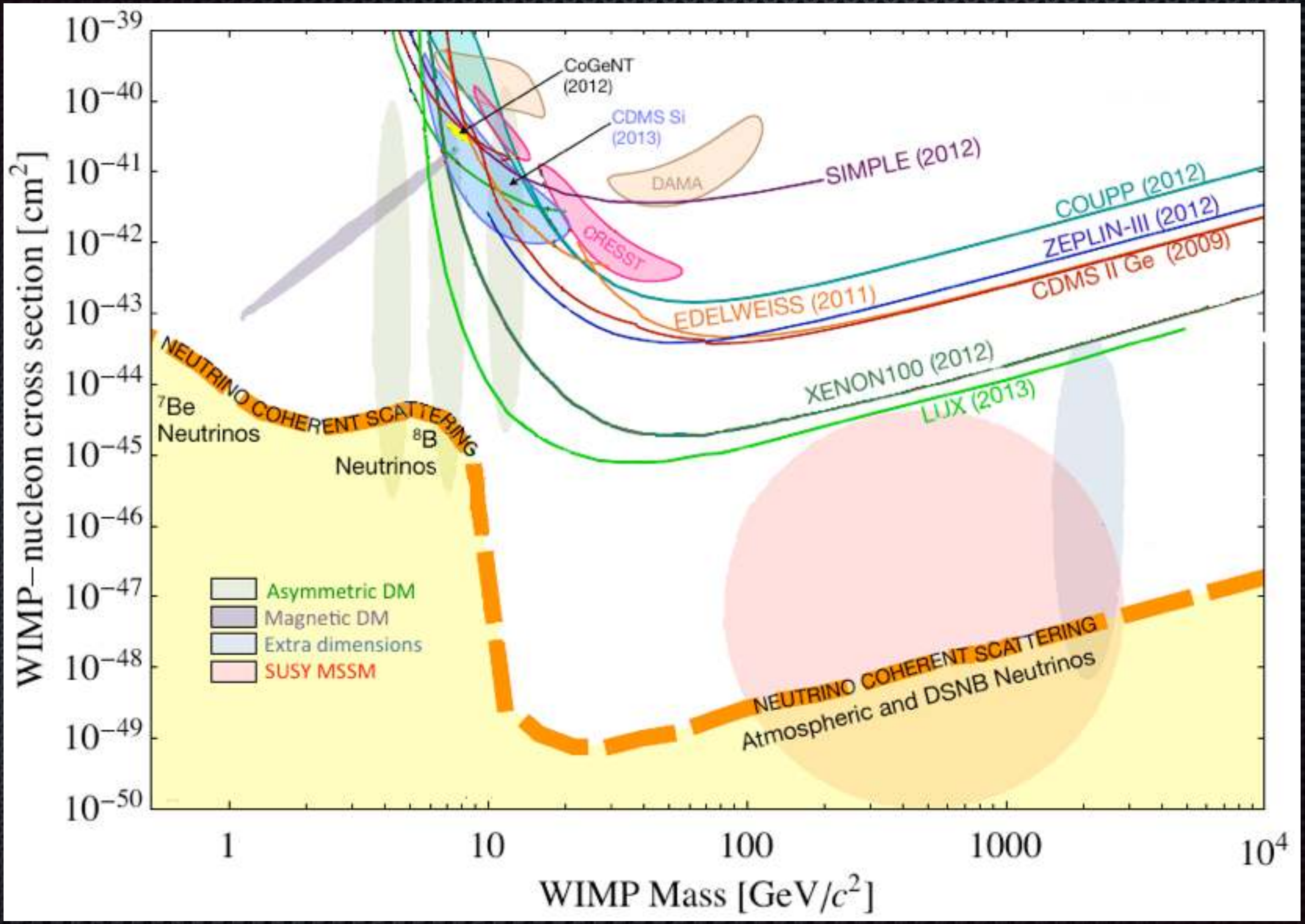
Columbia University
IN THE CITY OF NEW YORK

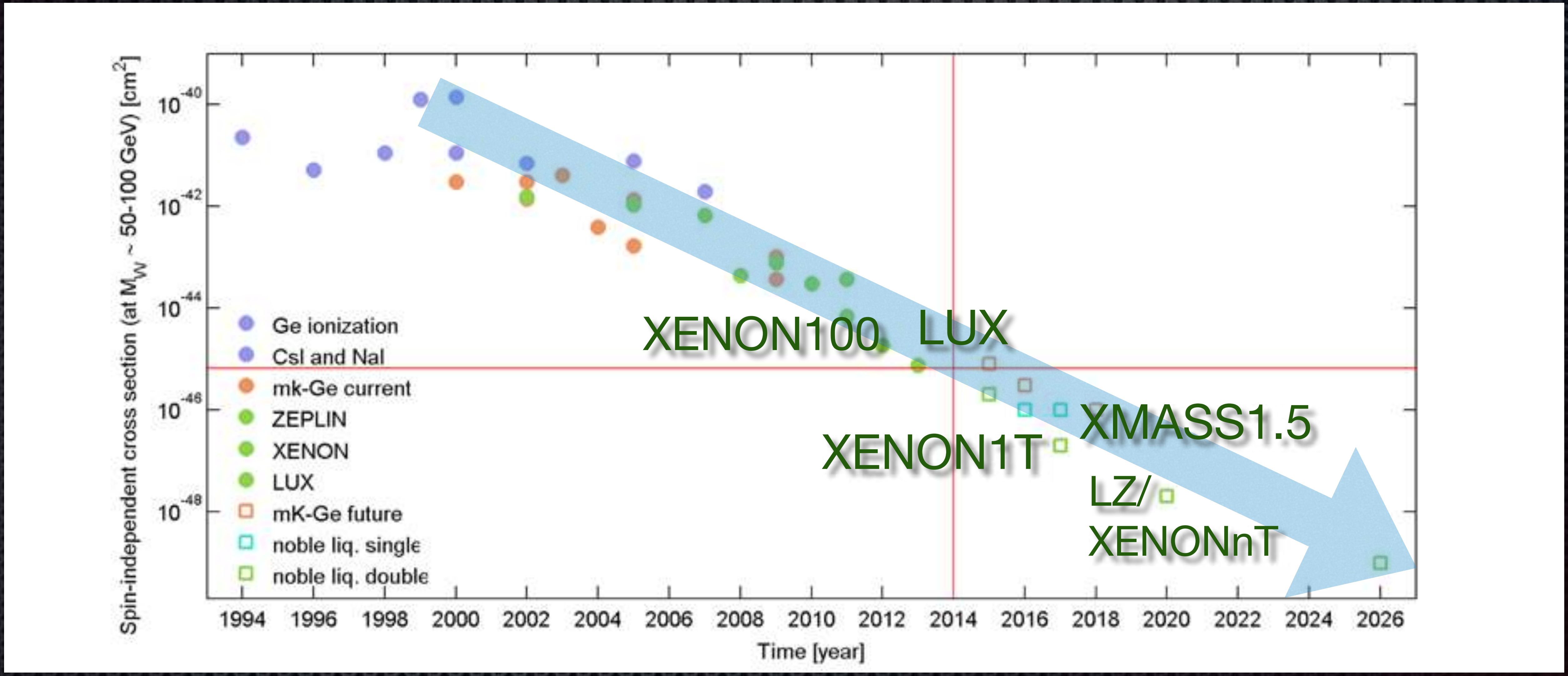
The Spacetime Odyssey Continues, Stockholm, June 5, 2015

Worldwide WIMP Searches

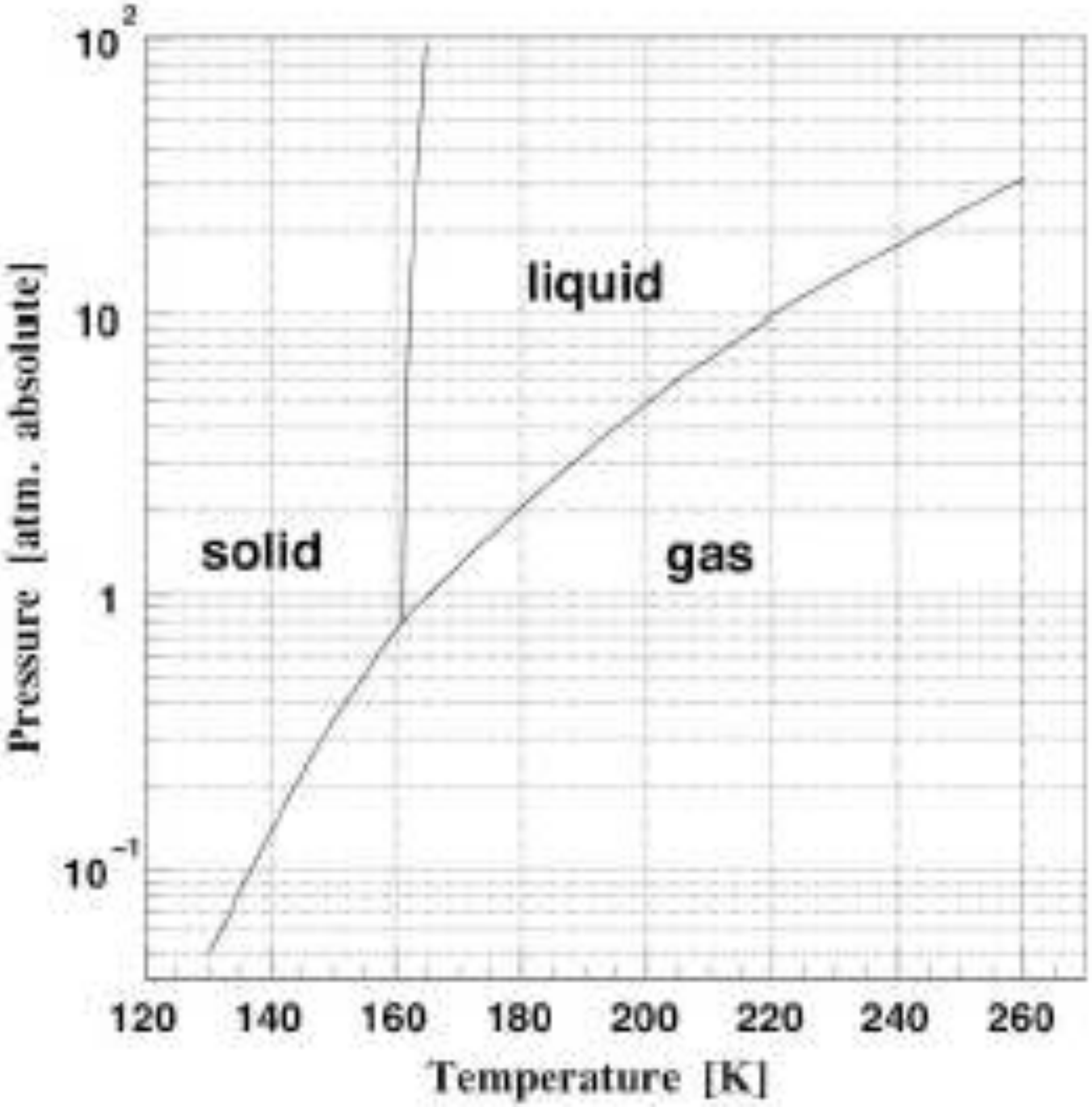
WIMP Direct Detection Situation Today



LXe detectors have enabled a factor *10 increase in sensitivity every 2 years. The trend is likely to continue with multi-ton scale next generation detectors*



A look at Liquid Xenon



Property	Value
Atomic number Z	54
Isotopes	^{124}Xe(0.09%), ^{126}Xe(0.09%), ^{128}Xe(1.92%), ^{129}Xe(26.44%) ^{130}Xe(4.08%), ^{131}Xe(21.18%) ^{132}Xe(26.89%), ^{134}Xe(10.44%) ^{136}Xe(8.87%)
Mean atomic weight A	131.30
Density	3 g·cm^{-3}
Boiling point	$T_b = 165.05$ K, $P_b = 1$ atm $\rho_b = 3.057$ g·cm^{-3}
Critical point	$T_c = 289.72$ K, $P_c = 58.4$ bar $\rho_c = 1.11$ g·cm^{-3}
Triple point	$T_t = 161.3$ K, $P_t = 0.805$ bar $\rho_t = 2.96$ g·cm^{-3}
Volume ratio (ρ_{liquid}/ρ_{gas})	519
Thermal properties	
Heat capacity	10.65 cal·g·mol^{-1}·K^{-1} for 163 – 166 K
Thermal conductivity	16.8×10^{-3} cal·s^{-1}·cm^{-1}·K^{-1}
Latent heat of a) evaporation at triple point	3048 cal·g·mol^{-1}
b) fusion at triple point	548.5 cal·g·mol^{-1}
Electronic properties	
Dieletric constant	$\epsilon_r = 1.95$

Material	Ar	Kr	Xe
Gas			
Ionization potential I (eV)	15.75	14.00	12.13
W-values (eV)	26.4[a]	24.2[a]	22.0[a]
Liquid			
Gap energy (eV)	14.3	11.7	9.28
W-value (eV)	23.6±0.3[b]	18.4±0.3[c]	15.6±0.3[d]

Ionization & Scintillation in Liquid Xenon

- Energy deposited by radiation in LXe will create a track of excited atoms or free excitons,Xe*, and e-ion pairs,
- Scintillation signal is produced after the creation of the excitons and the e-ion pairs
- Excitons can form excited molecular states, Xe*2 (excimers) by colliding with near Xe atoms.
- Ionized atoms can also form excimers through the process

$$Xe^+ + Xe \rightarrow Xe_2^+,$$

$$Xe_2^+ + e^- \rightarrow Xe^{**} + Xe,$$

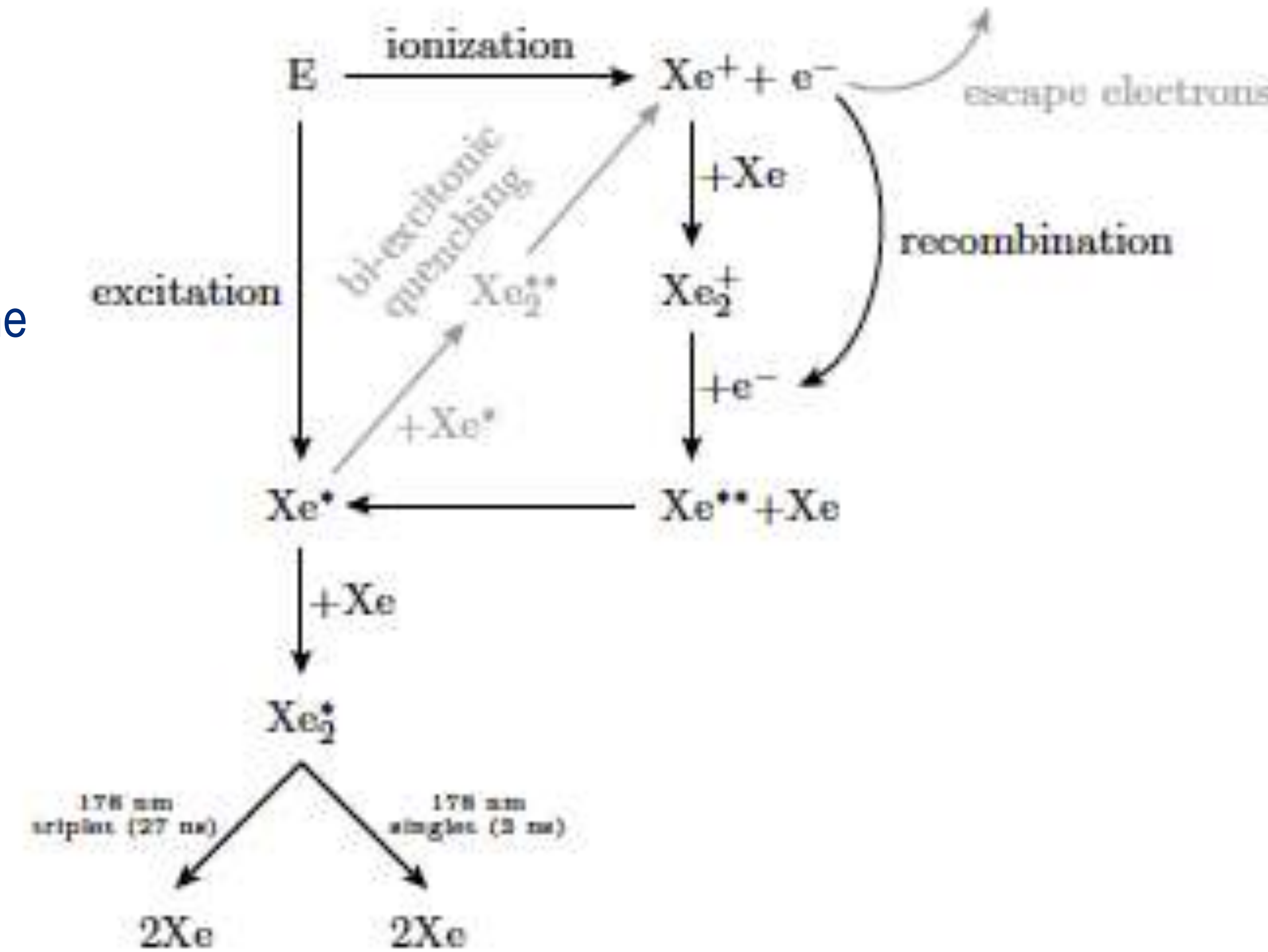
$$Xe^{**} \rightarrow Xe^* + \text{heat},$$

$$Xe^* + Xe \rightarrow Xe_2^*.$$

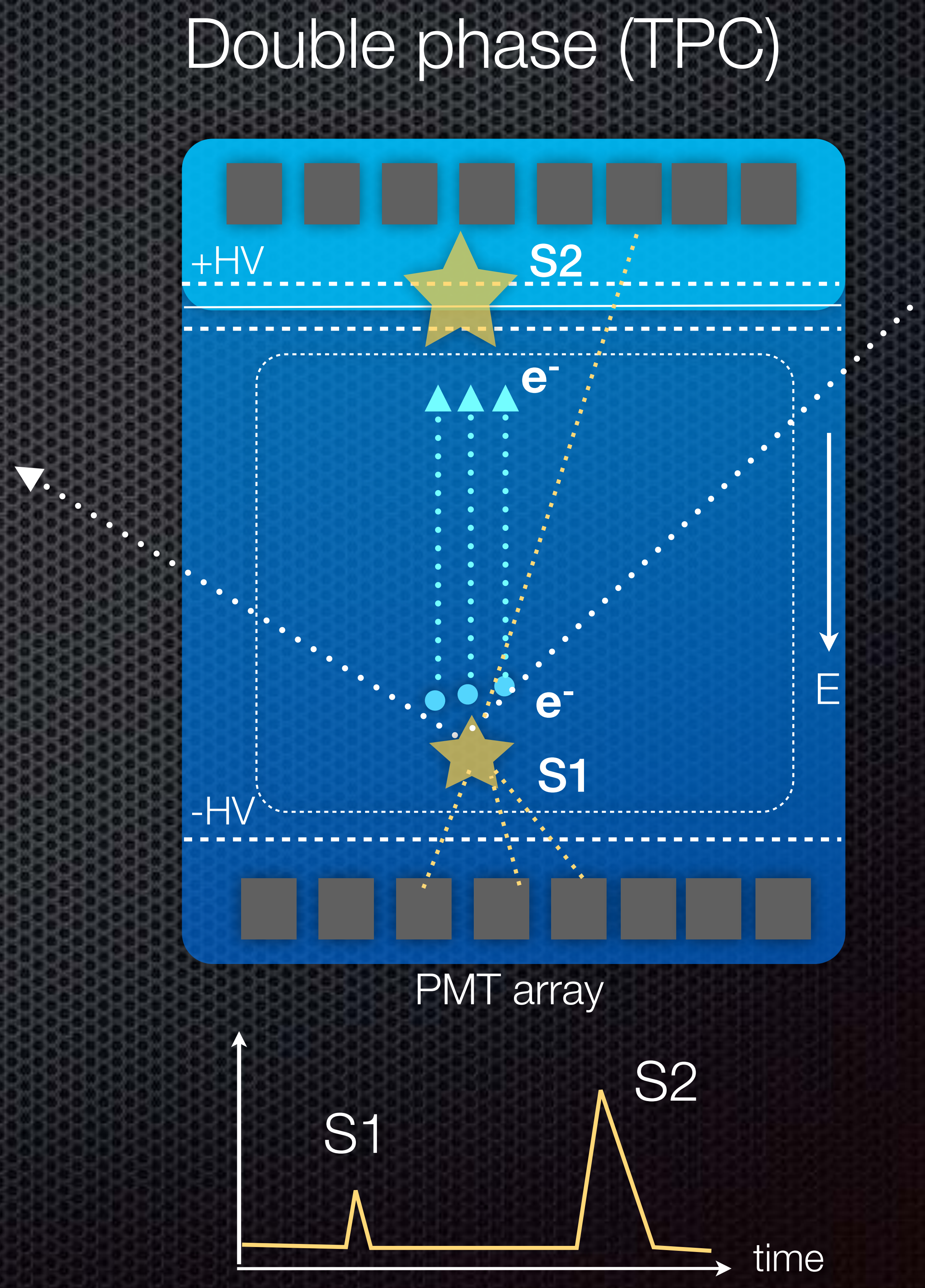
- The excimers decay to the dissociative ground sate by emission of one scintillation photon

$$Xe_2^* \rightarrow 2Xe + h\nu.$$

- Scintillation with two components due to de-excitation of singlet and triplet state of excimers



Two Liquid Xenon Detector Concepts



XMASS @ Kamioka (single-phase LXe)

850 kg (100 kg fiducial) liquid xenon in copper vessel, immersed in water tank

62% of inner surface covered by 632 high QE, HEX PMTs : 13 PE/keV

Low background: light WIMP/solar axion/bosonic super-WIMP searches published

> 1yr data accumulated since detector refurbishment to reduce surface backgrounds

Annual modulation of Low Mass region under study. Expect results by Summer 2015

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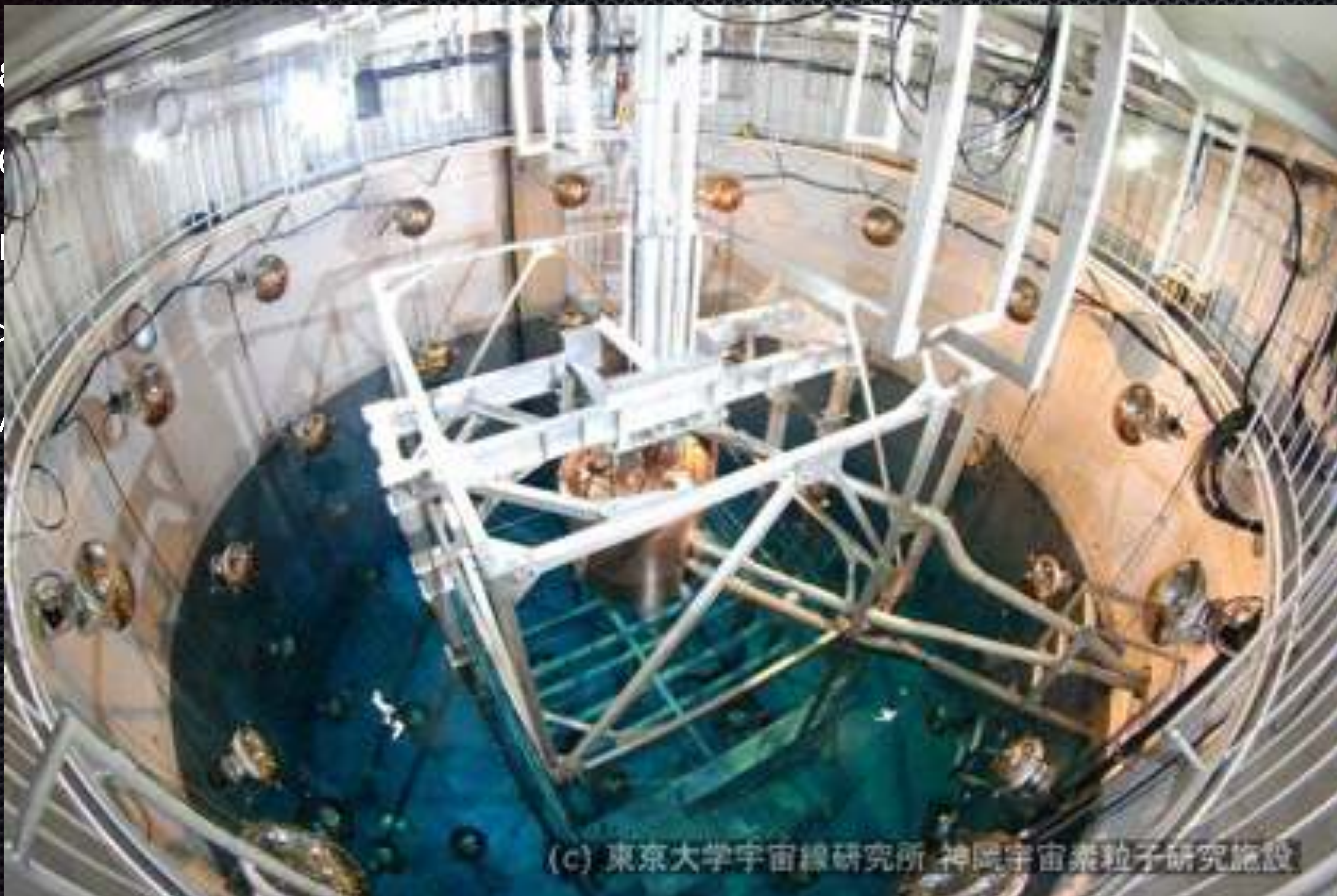

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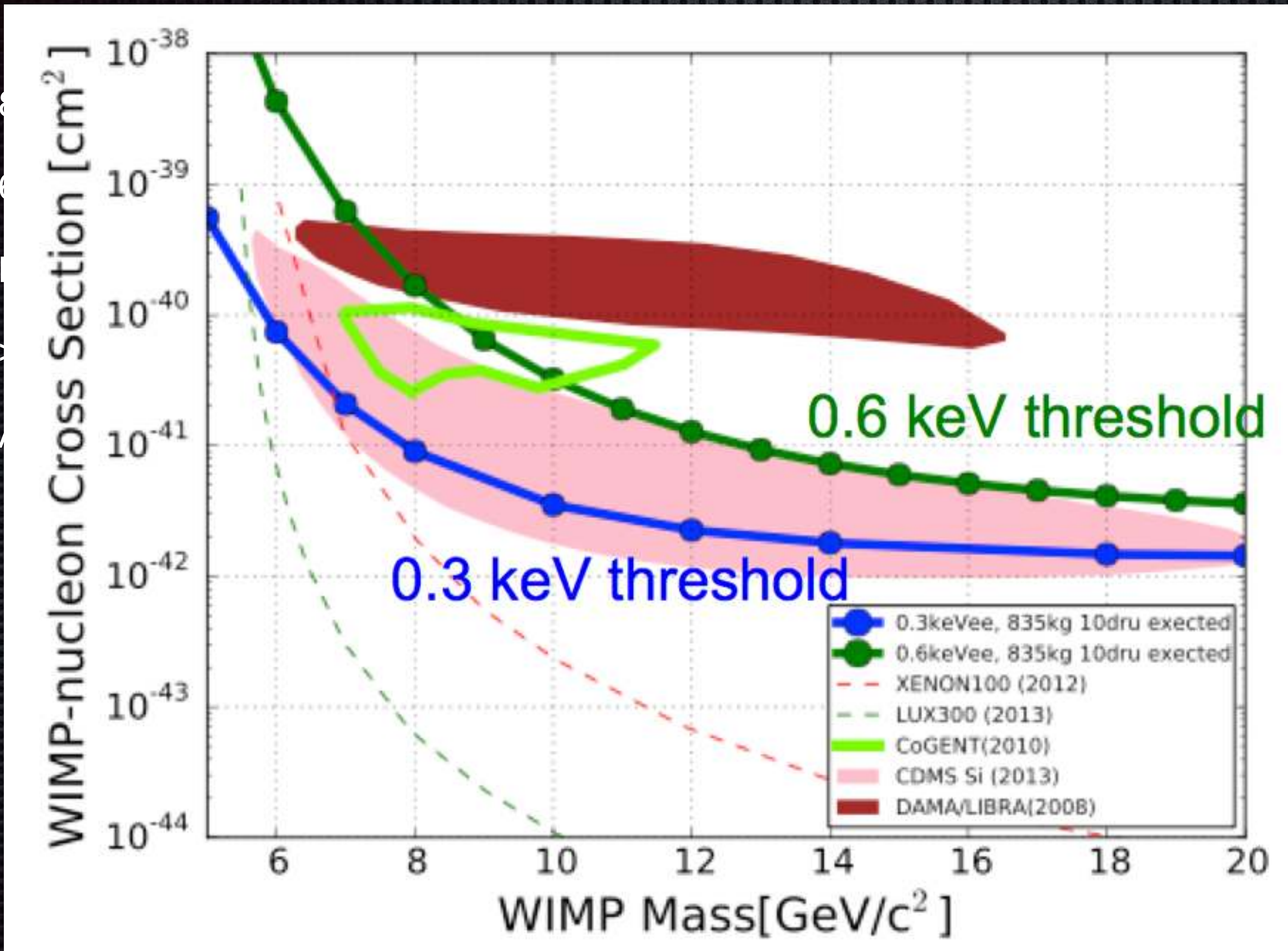
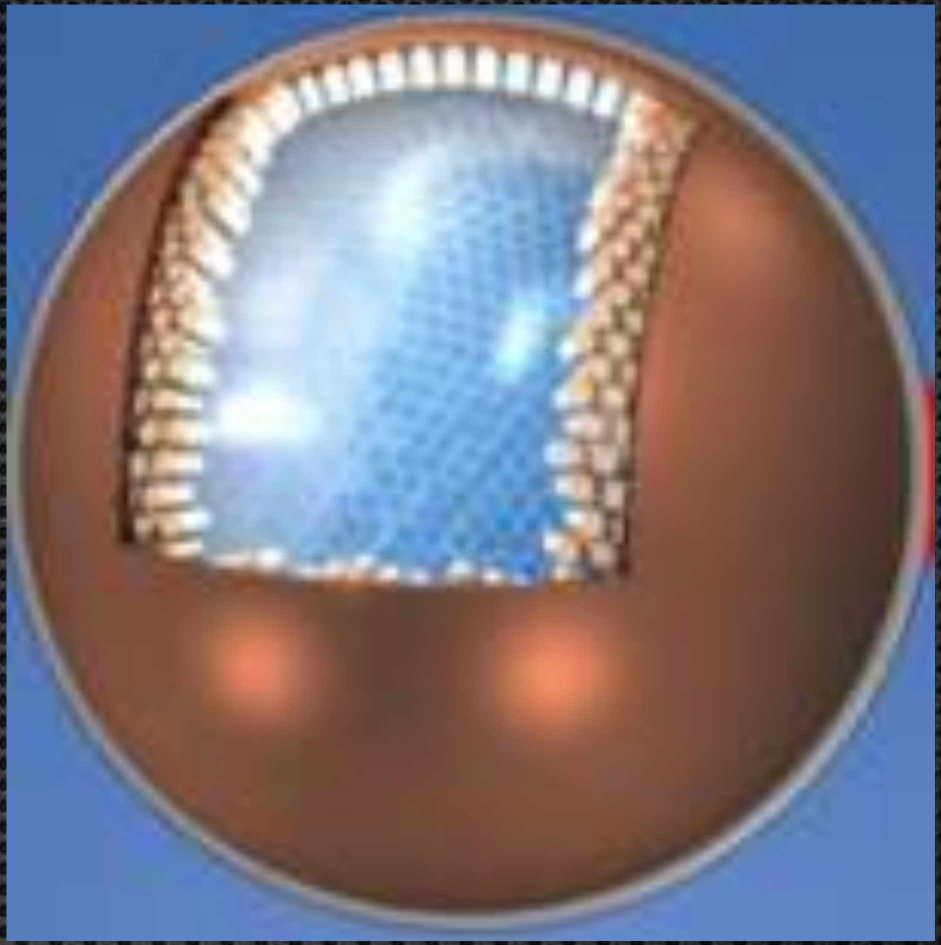


XMASS: Next Steps



- XMASS1.5 ➔ 5 ton total mass (3 ton fiducial)
- New PMTs to achieve 10^{-5} ev/keV/kg/day
- Projected Sensitivity: $\sigma_{SI} = 10^{-47}$ cm^2 @50 GeV and for the fiducial volume @ 2 keVee thresh
- Status: start in ~2017 ?
- XMASSII ➔ 24 ton total mass (10 ton fiducial)

Two-phase Xe TPCs (current generation)

XENON100 at LNGS:

161 kg LXe
(~50 kg fiducial)

242 1-inch PMTs

still in operation
new DM data still blinded
Modulation study completed

LUX at SURF:

370 kg LXe
(100 kg fiducial)

122 2-inch PMTs
physics run and first results in 2013
new run started end 2014

PandaX-1 at CJPL:

125 kg LXe
(37 kg fiducial)

143 1-inch PMTs
37 3-inch PMTs
first results in Aug 2014
80 days DM data still blinded

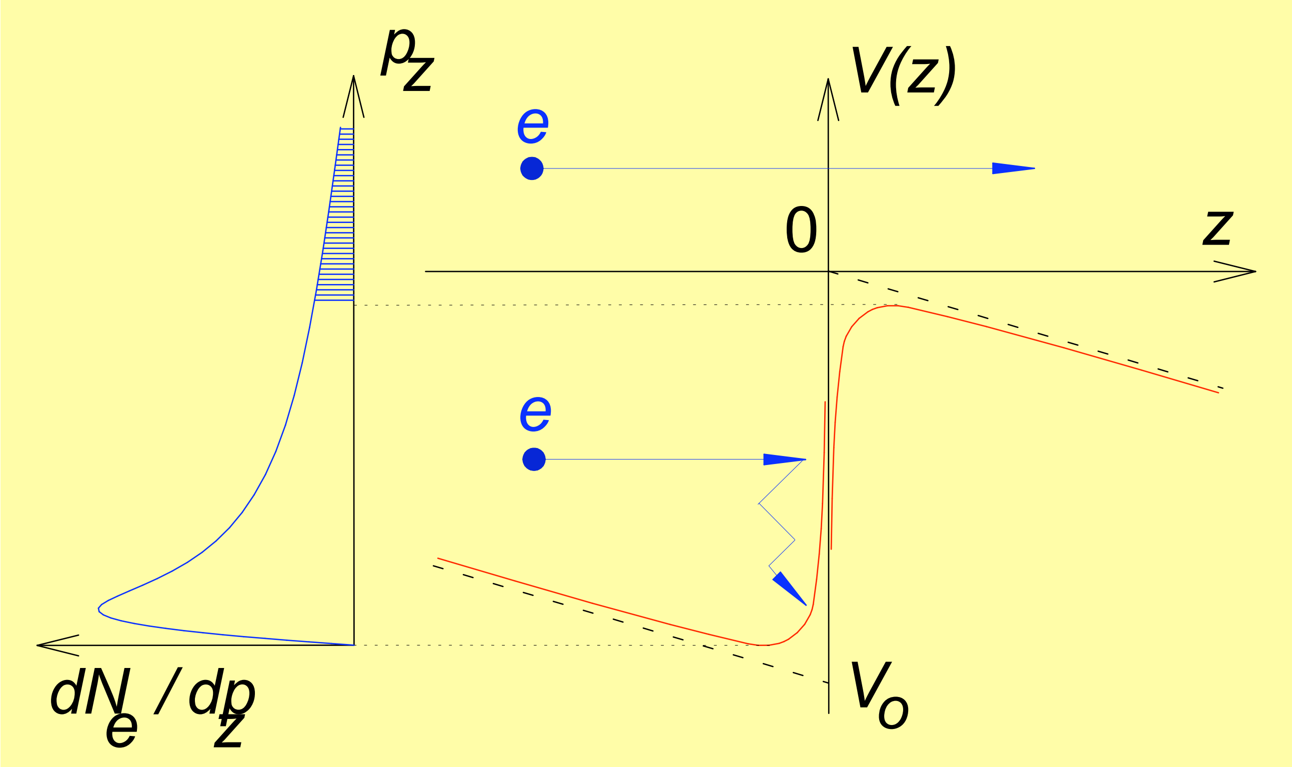
Electron Emission and Proportional Scintillation from Liquid Xenon

• Electrons drifting in the gas, under a high electric field (>1kV/(cm bar) in Xe) generate electroluminescence or proportional scintillation. One electron in gas Xe can produce more than 1000 UV photons/cm of drift path.

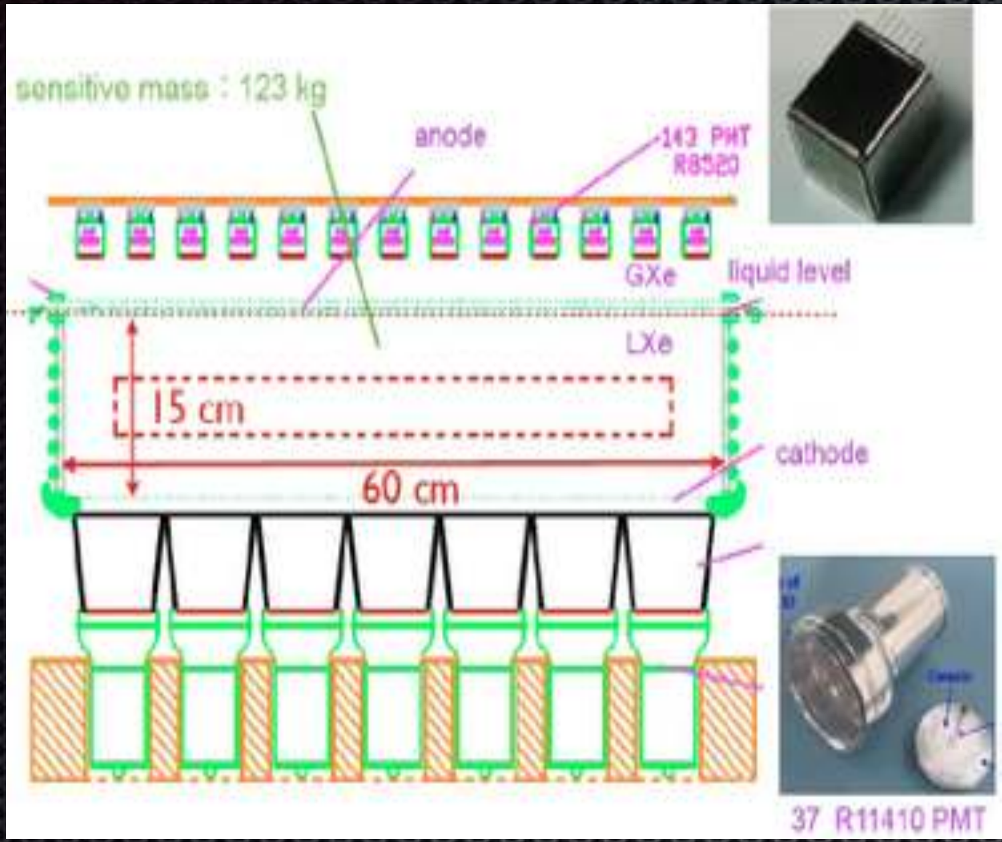
• A built-in amplifier based on emission of electrons liberated by ionizing radiation. The potential energy distribution near the interface of two-phase dielectrics favors emission of excess electrons from the quasi-free state.

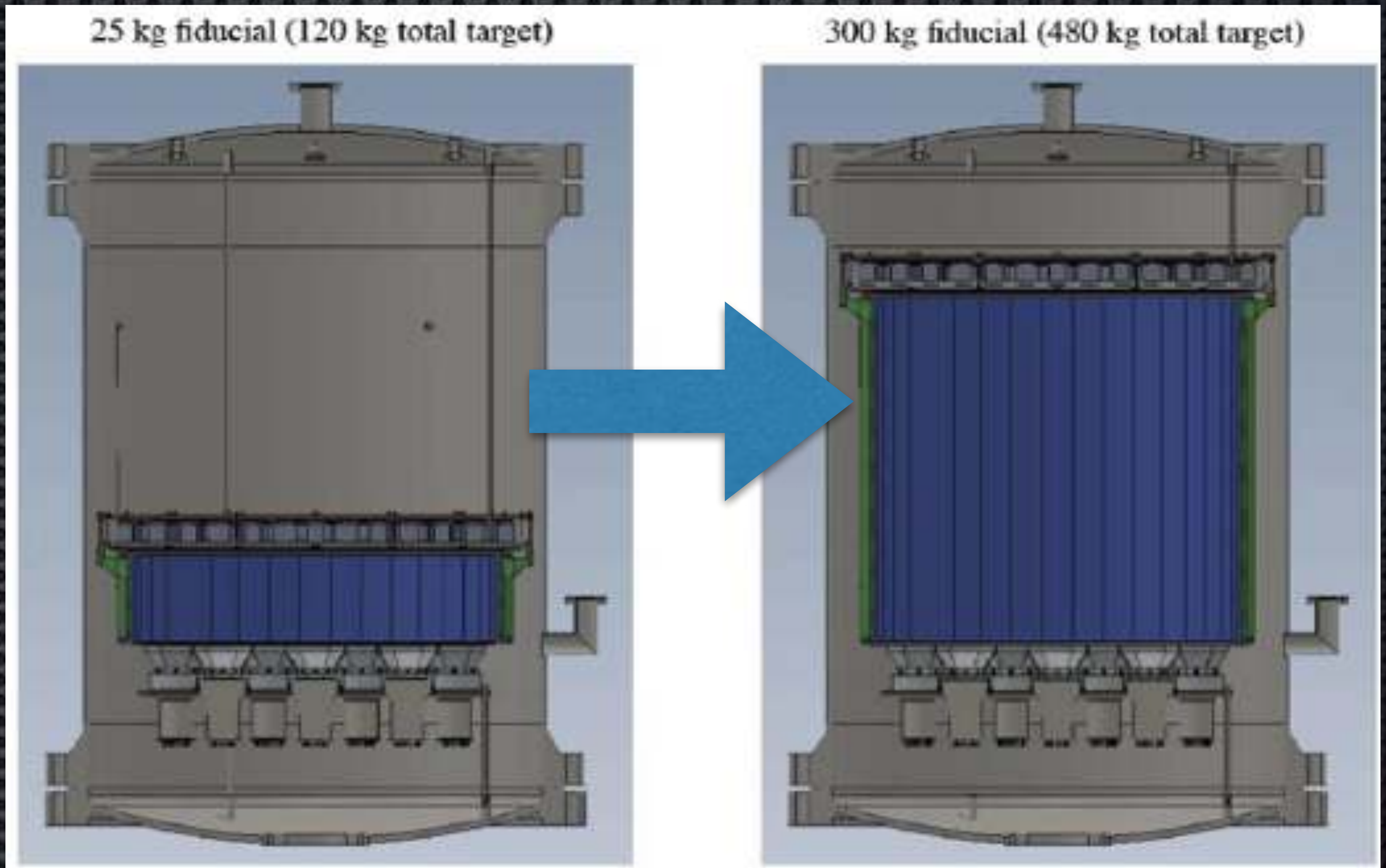
• In LXe the potential barrier $|V_0| \gg kT$ and spontaneous emission is not easily achieved. However, with a high electric field, electrons are heated and when $p_z > p_0$ they escape from the liquid.

B. Dolgoshein et al. JETP Lett. 11 (1970) 513



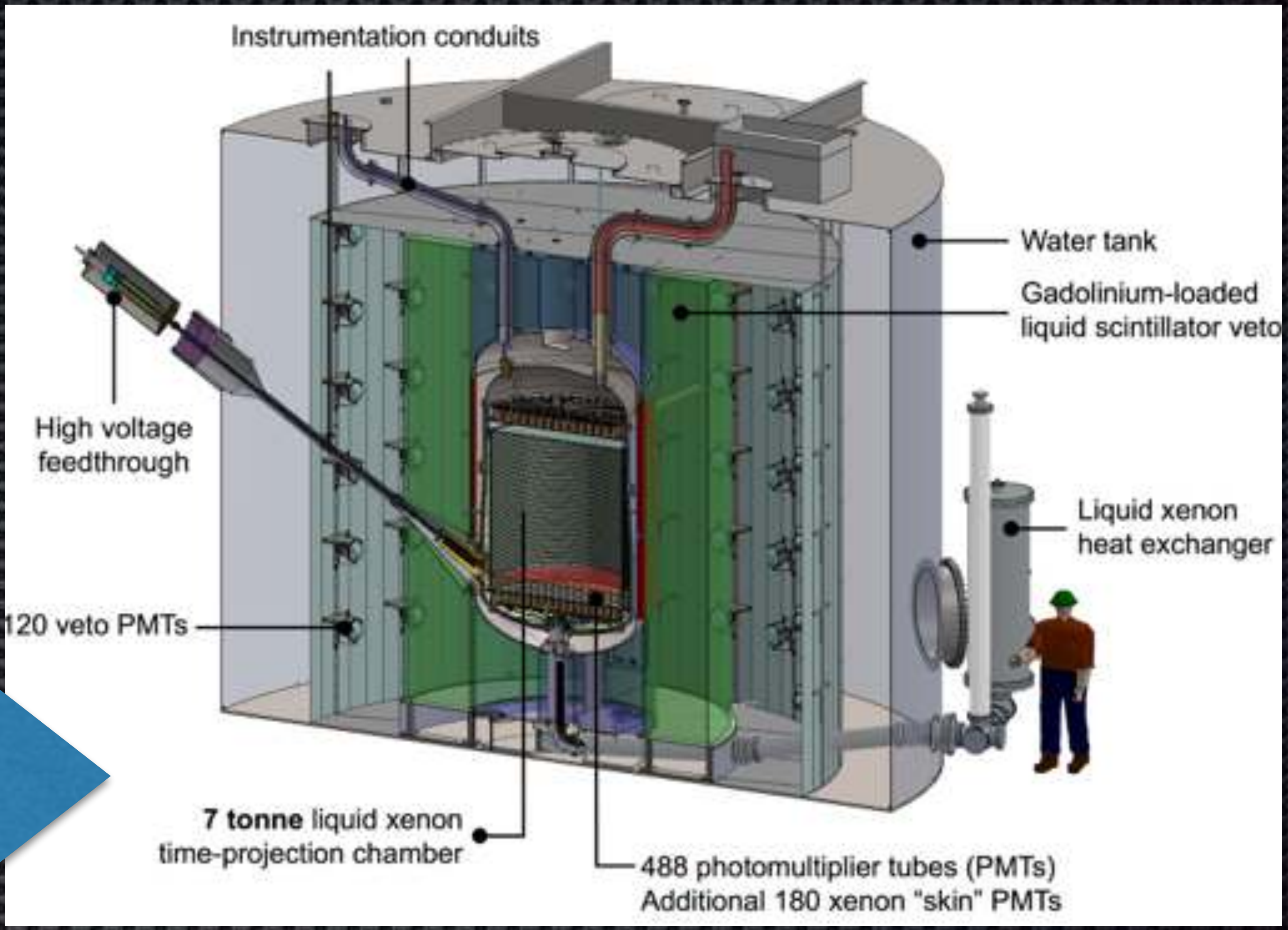
PandaX: Next Steps





- PandaX-1 → PandaX-2 (500 kg fiducial mass)
- Same PMTs arrays as in PandaX-1
- Status: under commissioning at CJPL-I. Currently the largest mass XeTPC for DM.
- Future: multi-ton detector in CJPL-II

LUX: Next Steps



- LUX + ZEPLIN (LZ) → 7 ton new detector surrounded by a Gd-loaded liquid scintillator in same water shield as LUX
- About 500 new 3 " PMTs similar to those of XENON1T
- Projected Sensitivity: $\sigma_{SI} = 10^{-48}$ cm^2 @50 GeV and after 1000 live days
- Status: approved as DOE-only supported G2 project. Conceptual design accepted and initial funding secured. Projected to start in 2019 ?

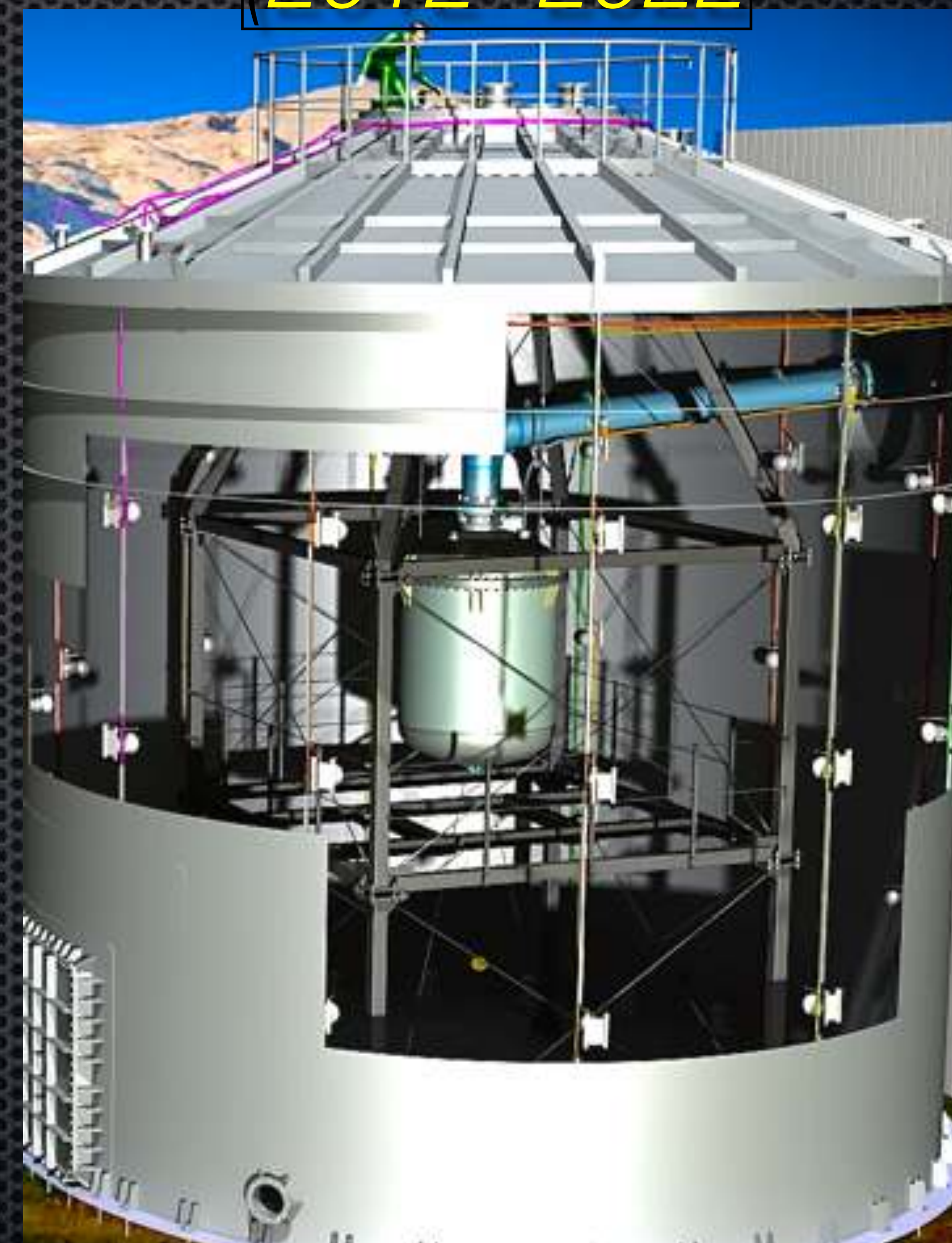
XENON: Next Steps

2007-2015

XENON100

30 cm drift TPC - 161 kg

2012- 2022



XENON1T/XENONnT

100 cm drift TPC - 3300 kg/7000 kg

XENON1T /nT: in a nutshell

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- **Location/Cost:** LNGS - Hall B. TDR submitted to LNGS in Fall 2010. US groups proposal submitted to the NSF in Fall 2011. Approved by NSF in FY12. Capital cost ~20M$ (50% from non-US groups)
- **Detector:** 1m- drift dual-phase TPC with 3.3 t LXe viewed by 250 3-inch PMTs . Cryostat/Cryogenics built with the idea to upgrade detector by 2018: replace TPC with one of larger sensitive mass (7 tons of Xe) using larger diameter PMT arrays (~400 PMTs) but same drift length.
- **Shield**: 10 m diameter water tank instrumented as efficient Cherenkov muon veto.
- **Back goal:** *100 x lower than XENON100, ~5 x 10^{-2} events/(t-d-keV)*
- **Status:** commissioning of all cryogenic plants under way. Detector installation by end of Summer. Start first science run within 2015.
- **Projected Sensitivity:** 10^{-47} cm^2 for 50 GeV WIMP with 2 ton x yr data (${10^{-48}}$ cm^2 for XENONnT)

XENON1T /nT: in a nutshell

The XENON Collaboration

currently 125 scientists from 20 institutions

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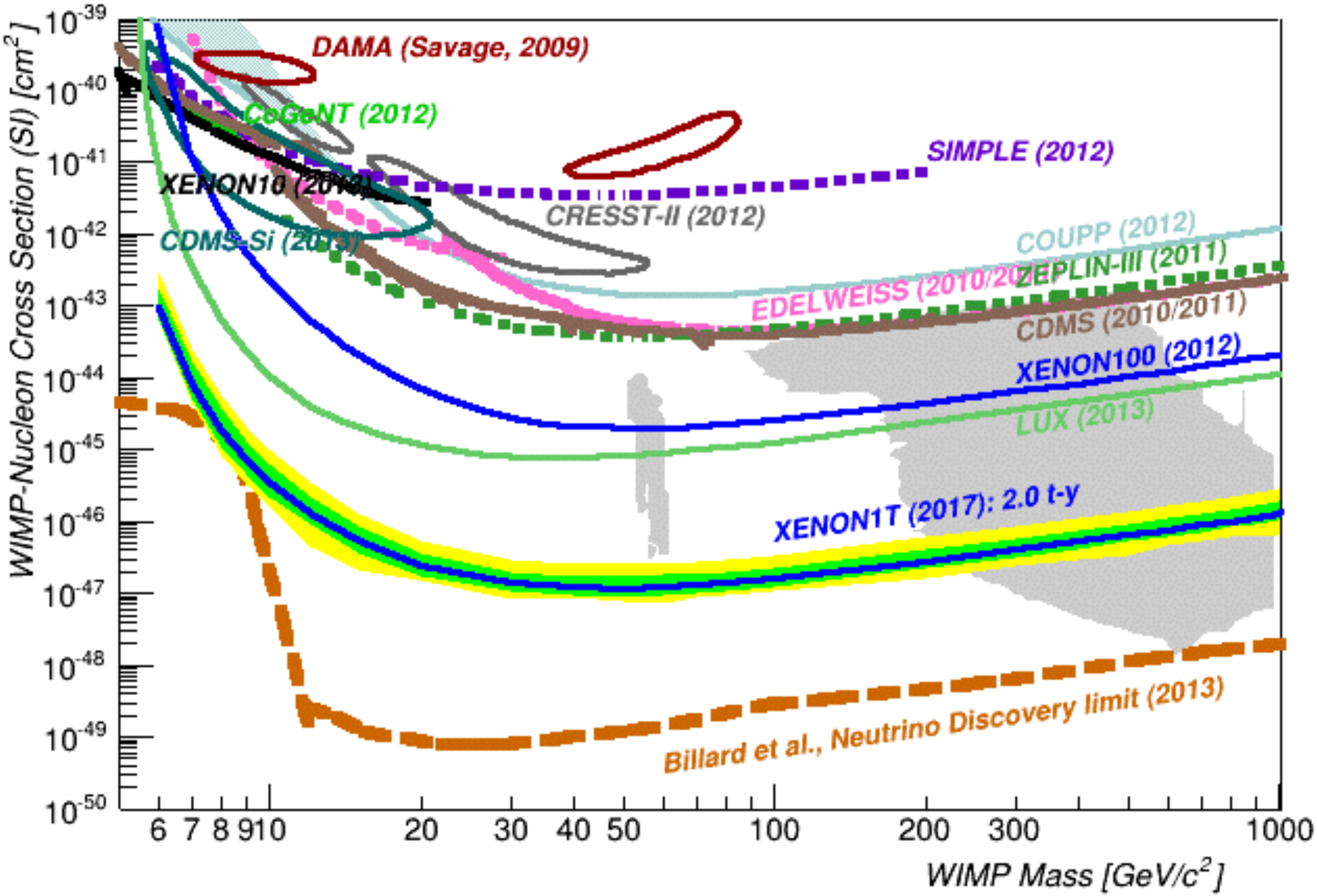
Columbia, RPI, Nikhef, Mainz, Stockholm, Muenster

Chicago, UCLA, Rice

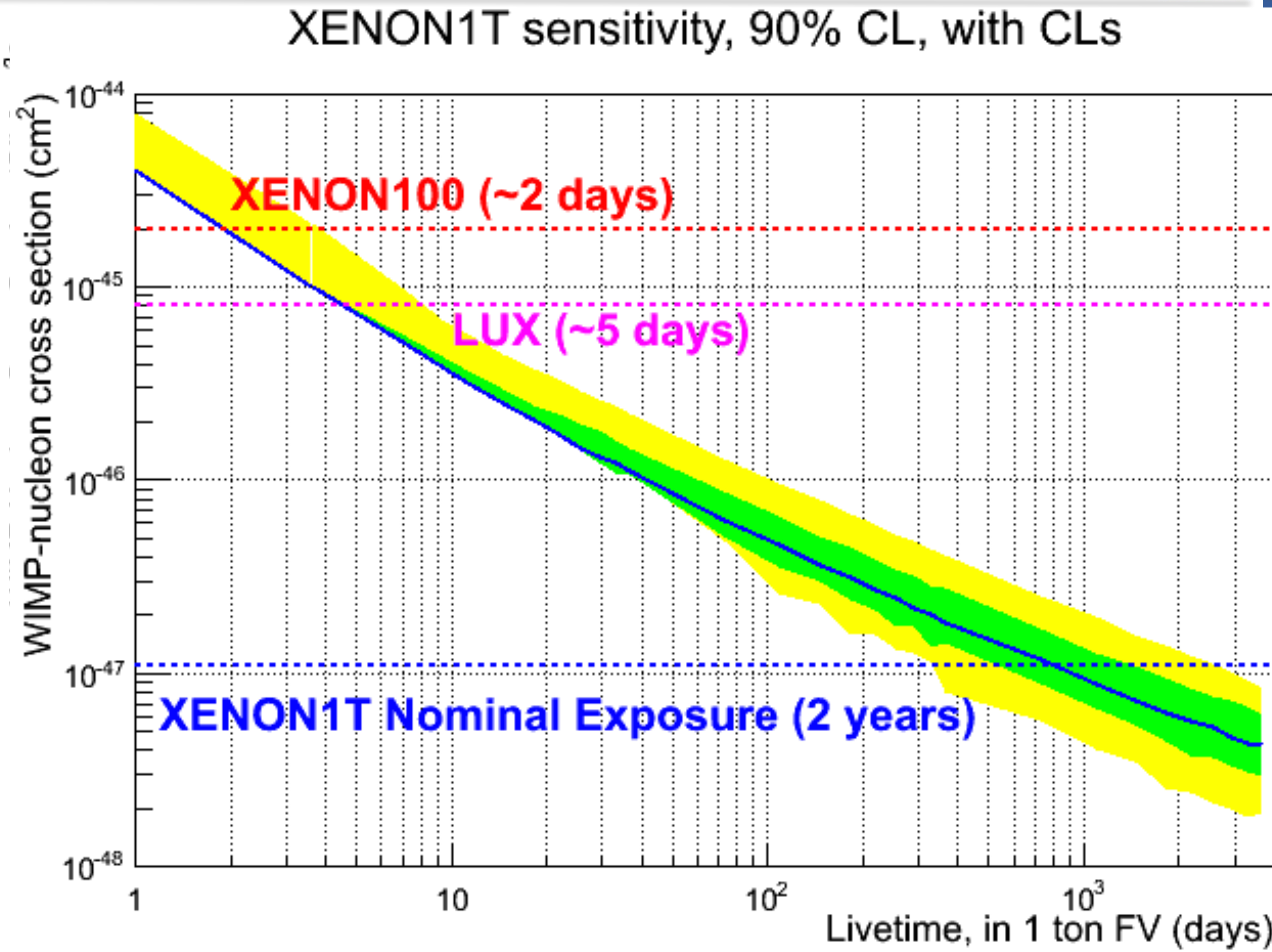
MPIK, Bern, Zurich

Purdue, Coimbra, Subatech, Bologna, LNGS, Torino, Weizmann, NYUAD

XENON1T sensitivity

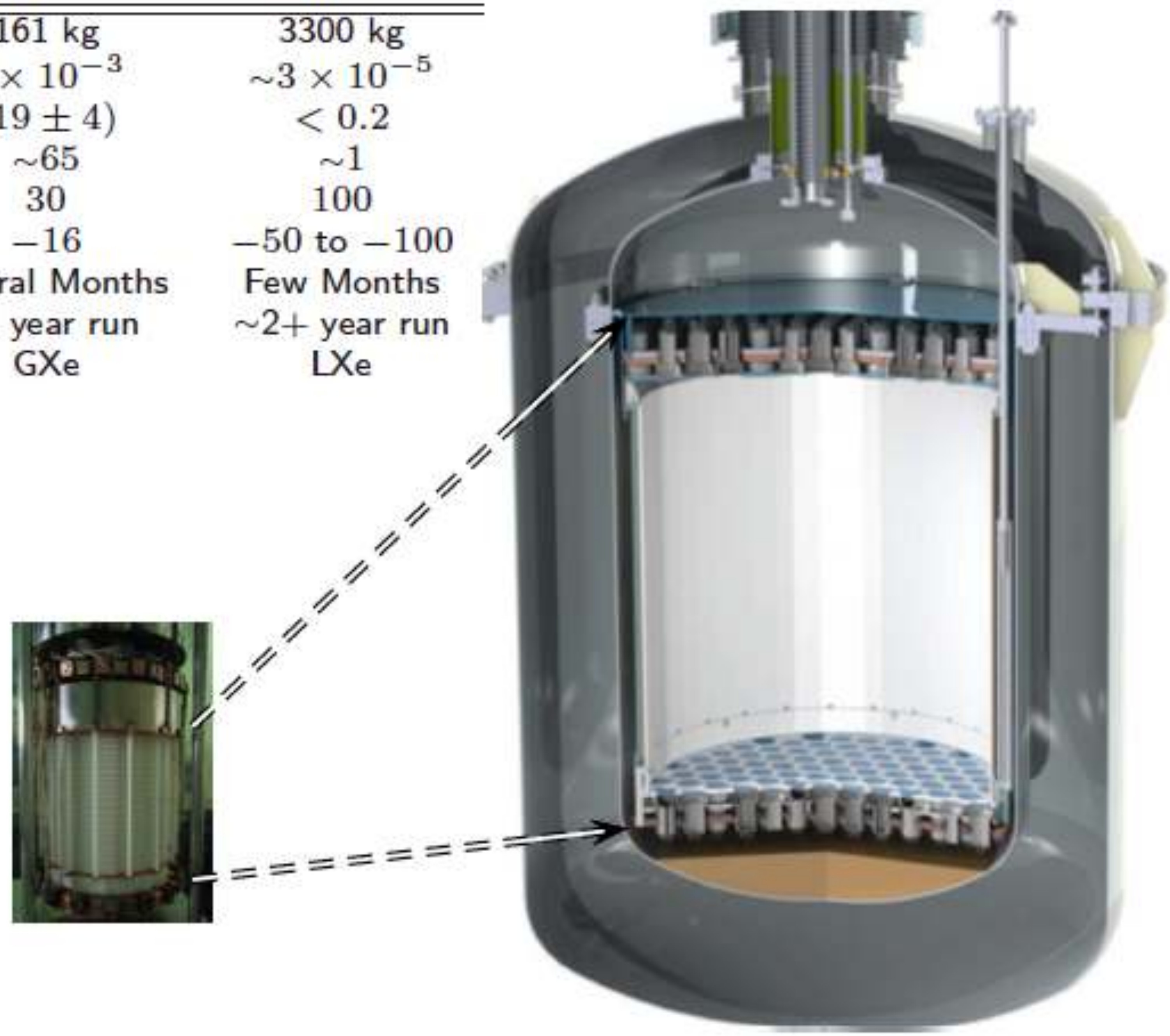


XENON1T sensitivity



From XENON100 to XENON1T: some of the challenges

	XENON100	XENON1T
LXe Mass (kg)	161 kg	3300 kg
ER Bkgnd (evts/keV/kg/d)	5×10^{-3}	$\sim 3 \times 10^{-5}$
Kr Concentration (ppt)	(19 ± 4)	< 0.2
Rn Concentration (μBq/kg)	~65	~1
Charge drift (cm)	30	100
Cathode HV (kV)	−16	−50 to −100
LXe Purification	Several Months	Few Months
Cryogenics	~1 year run	~2+ year run
Storage/Recovery	GXe	LXe




July 2013

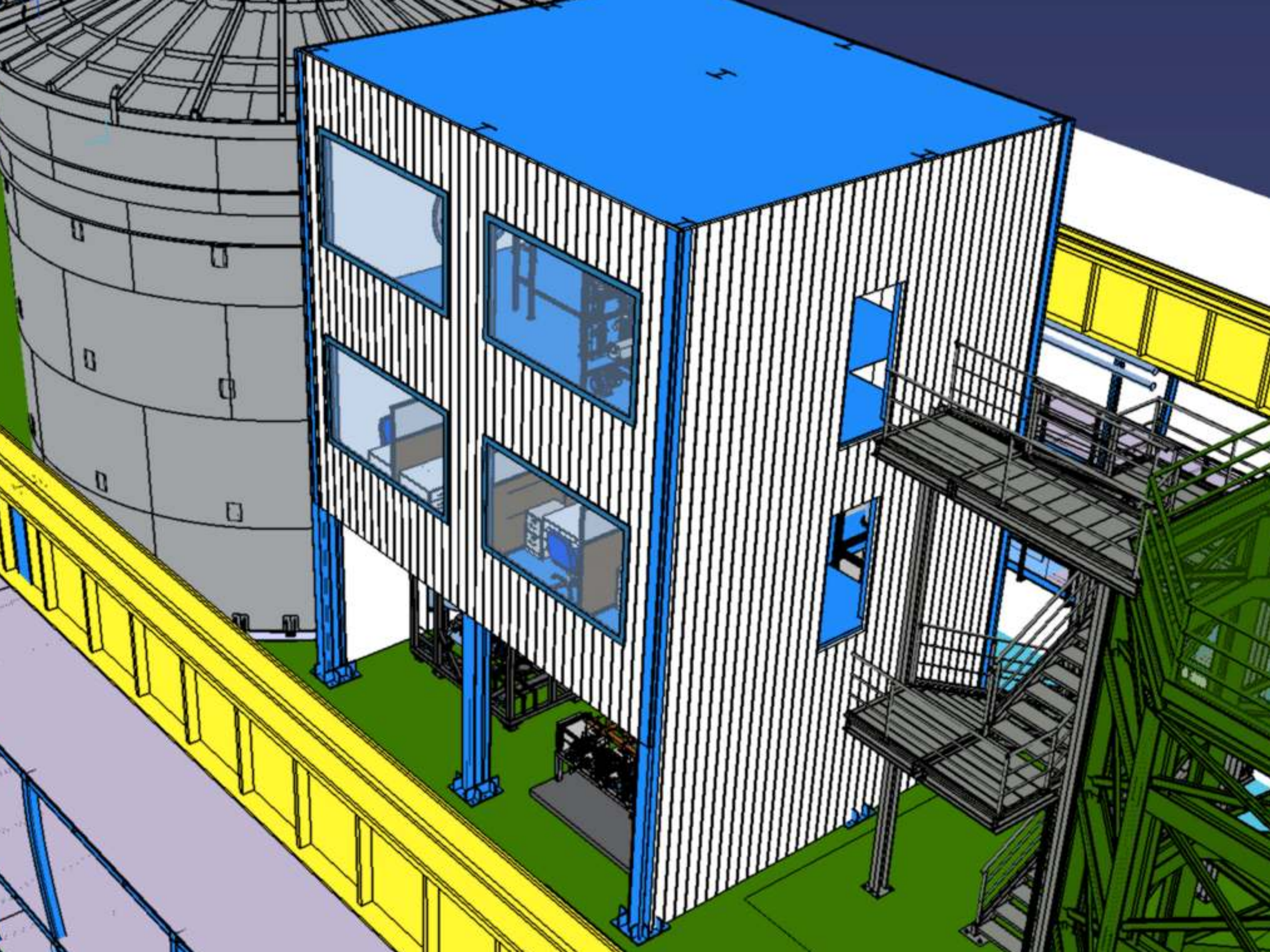

XEN
enlighten

June 2015


Oct. 2013

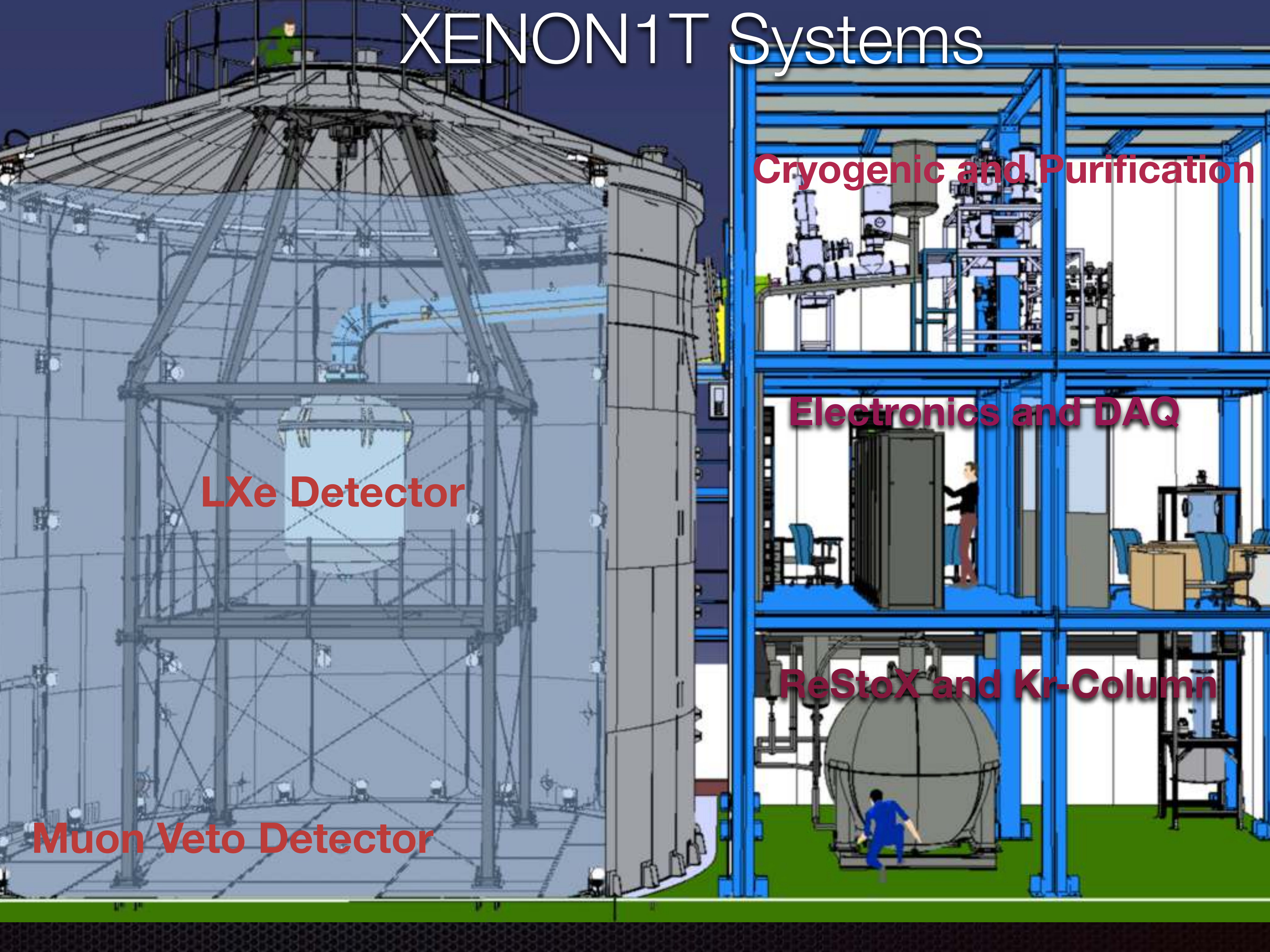

photo by R. Corrieri


Jan 2014
photo by R. Corrieri



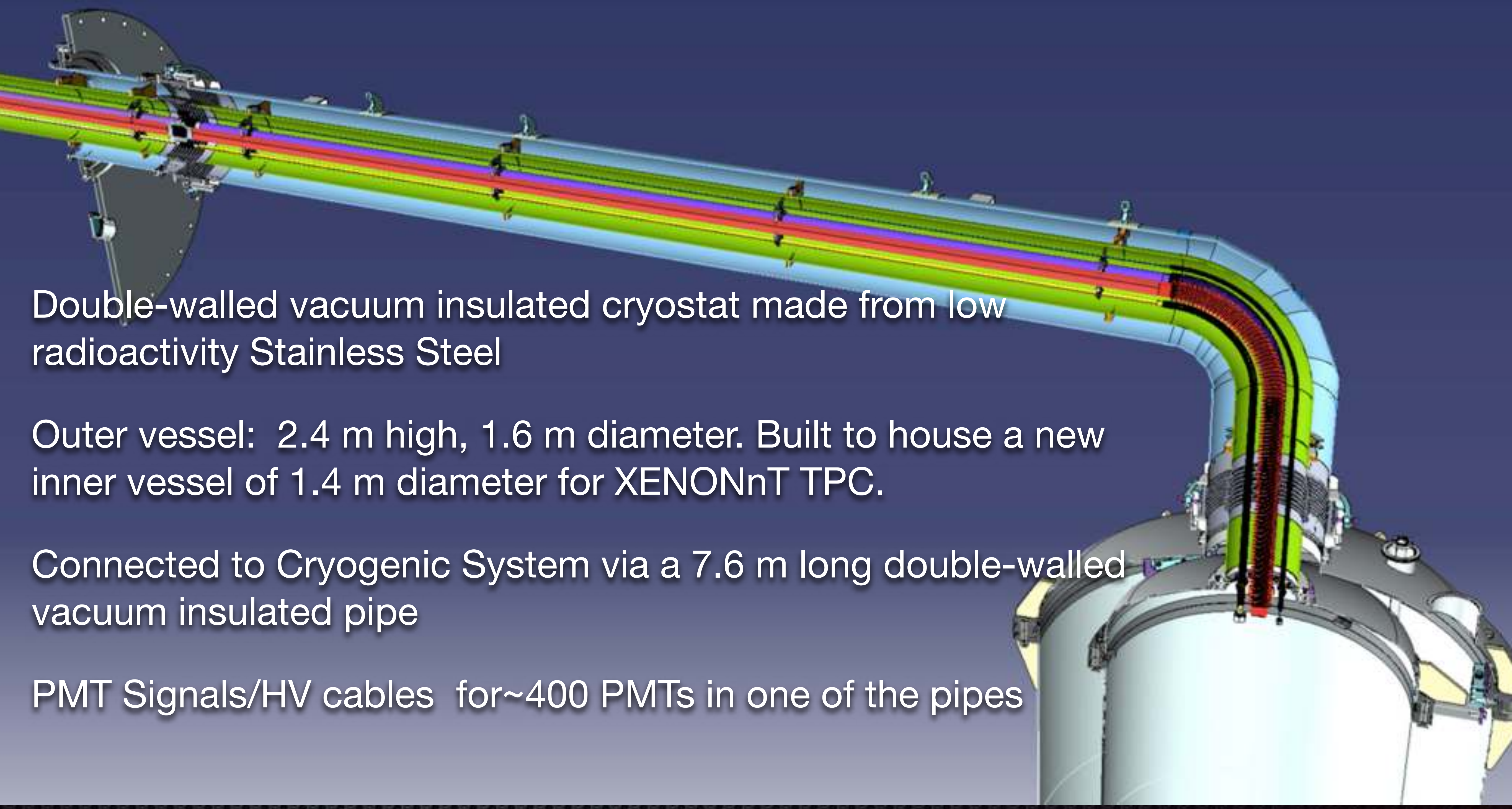

Aug 2014

XENON1T Systems



XENON1T Systems

Cryostat



Double-walled vacuum insulated cryostat made from low radioactivity Stainless Steel

Outer vessel: 2.4 m high, 1.6 m diameter. Built to house a new inner vessel of 1.4 m diameter for XENONnT TPC.

Connected to Cryogenic System via a 7.6 m long double-walled vacuum insulated pipe

PMT Signals/HV cables for~400 PMTs in one of the pipes

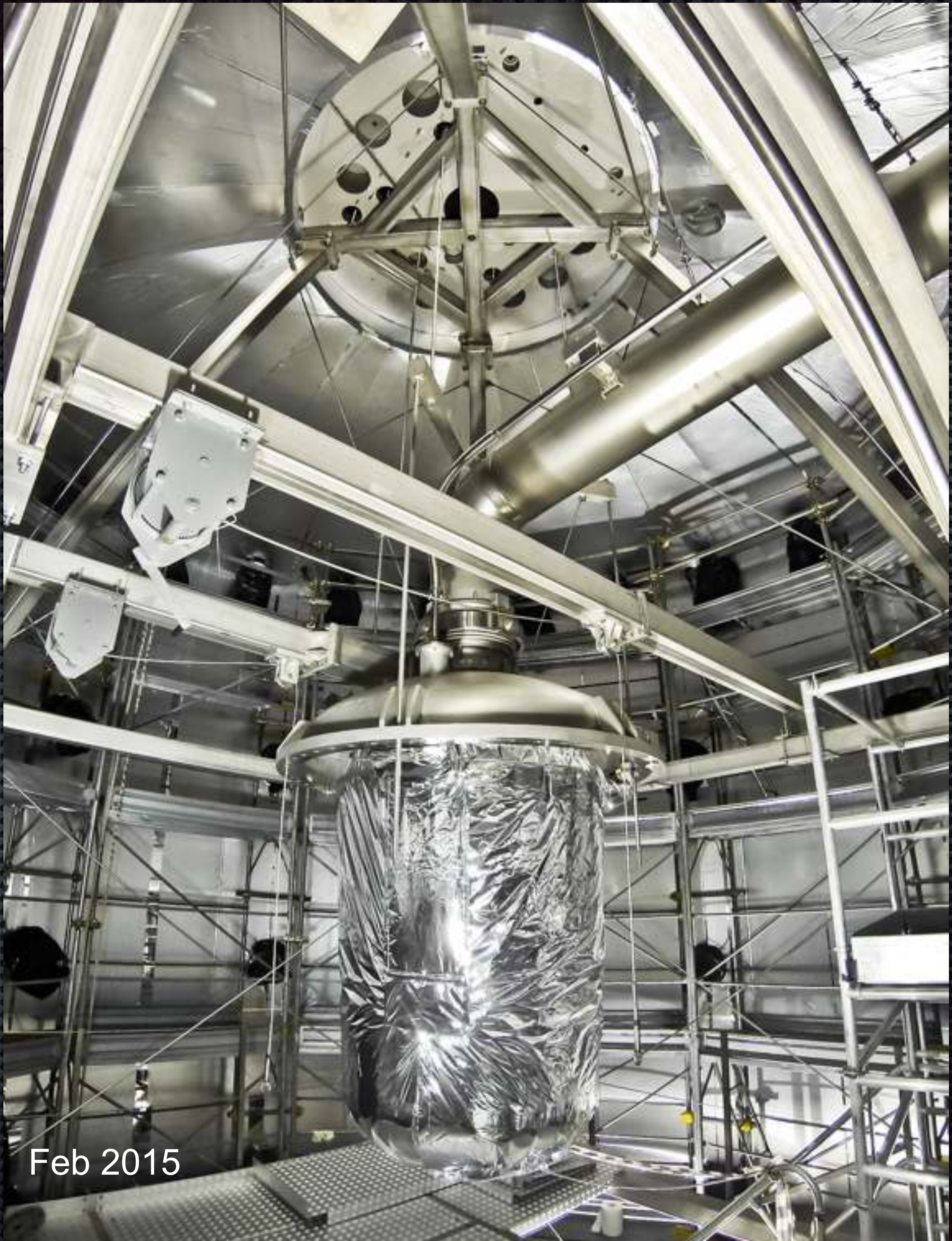
Cryostat

Cryostat

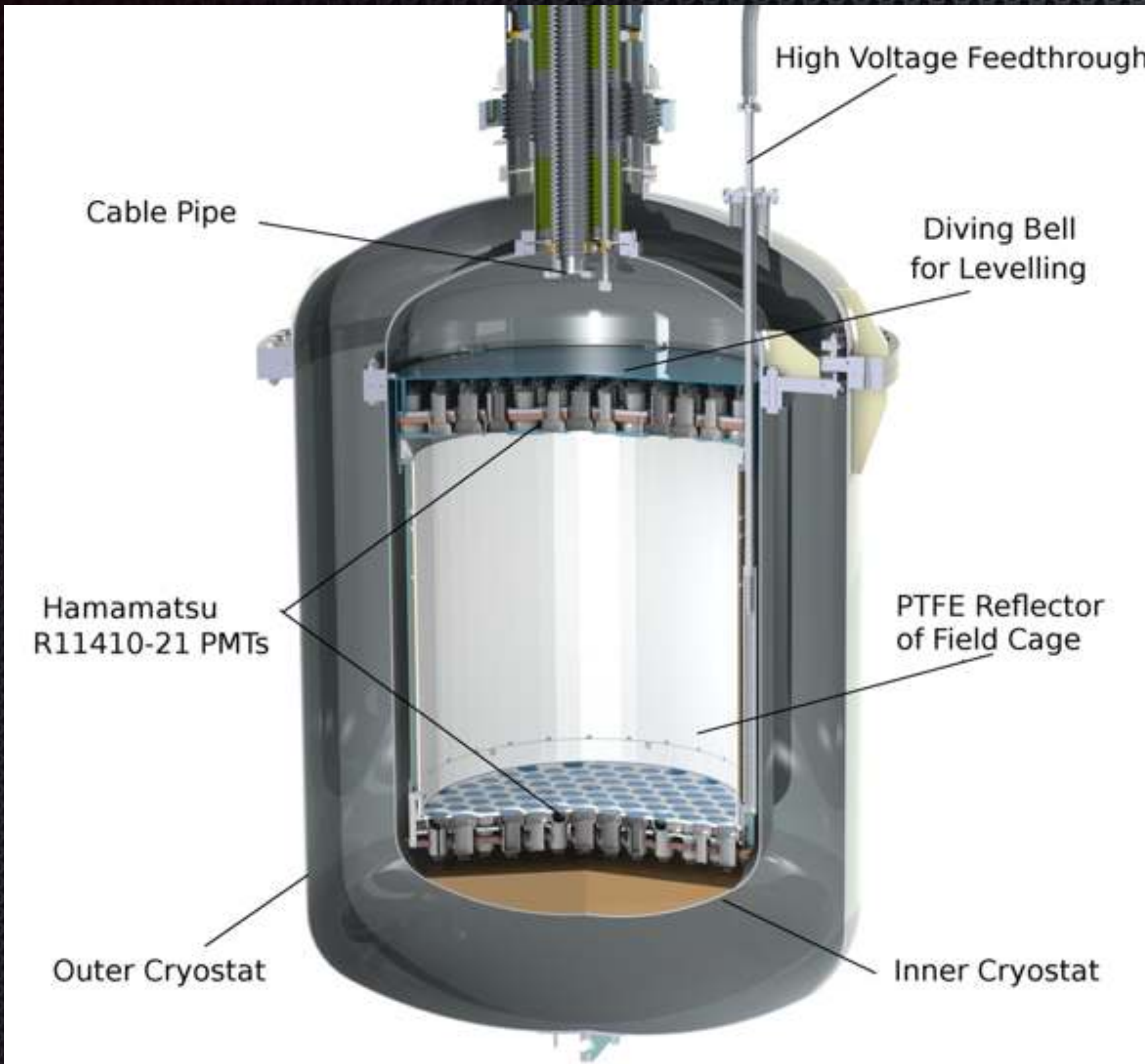
Cryostat

Cryostat

Cryostat


Feb 2015

XENON1T TPC



a larger and improved version of the XENON100 detector

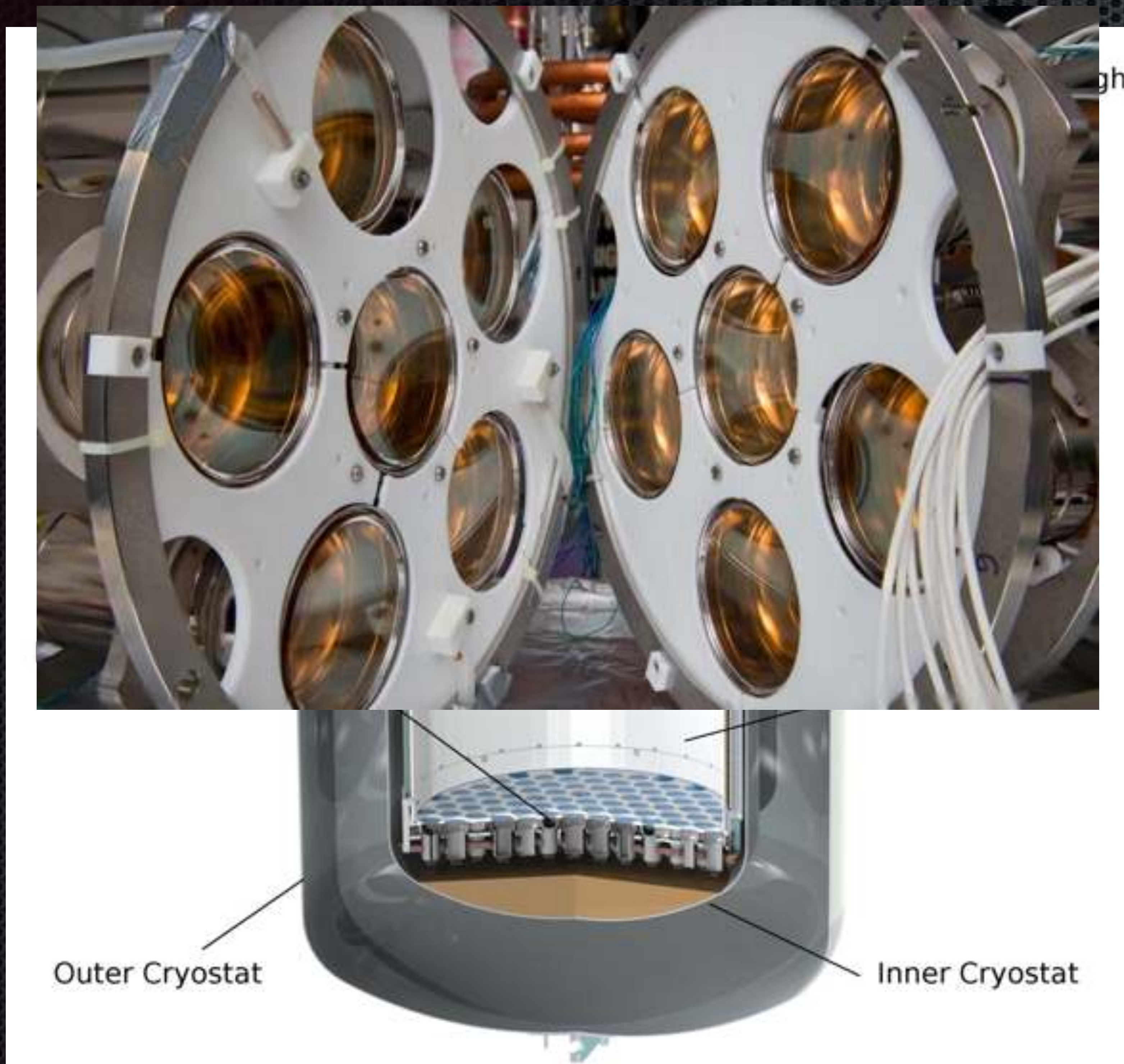
More extensive materials selection to control background, particularly from Rn

248 x R11410-21 (3 inch PMTs) with average QE (178nm) of 34%

Design completed. Assembly procedure in place. Construction of components ongoing (grids/ PMT supports/HV FT/E-shaping)

Schedule: install ~ Aug 2015

XENON1T TPC



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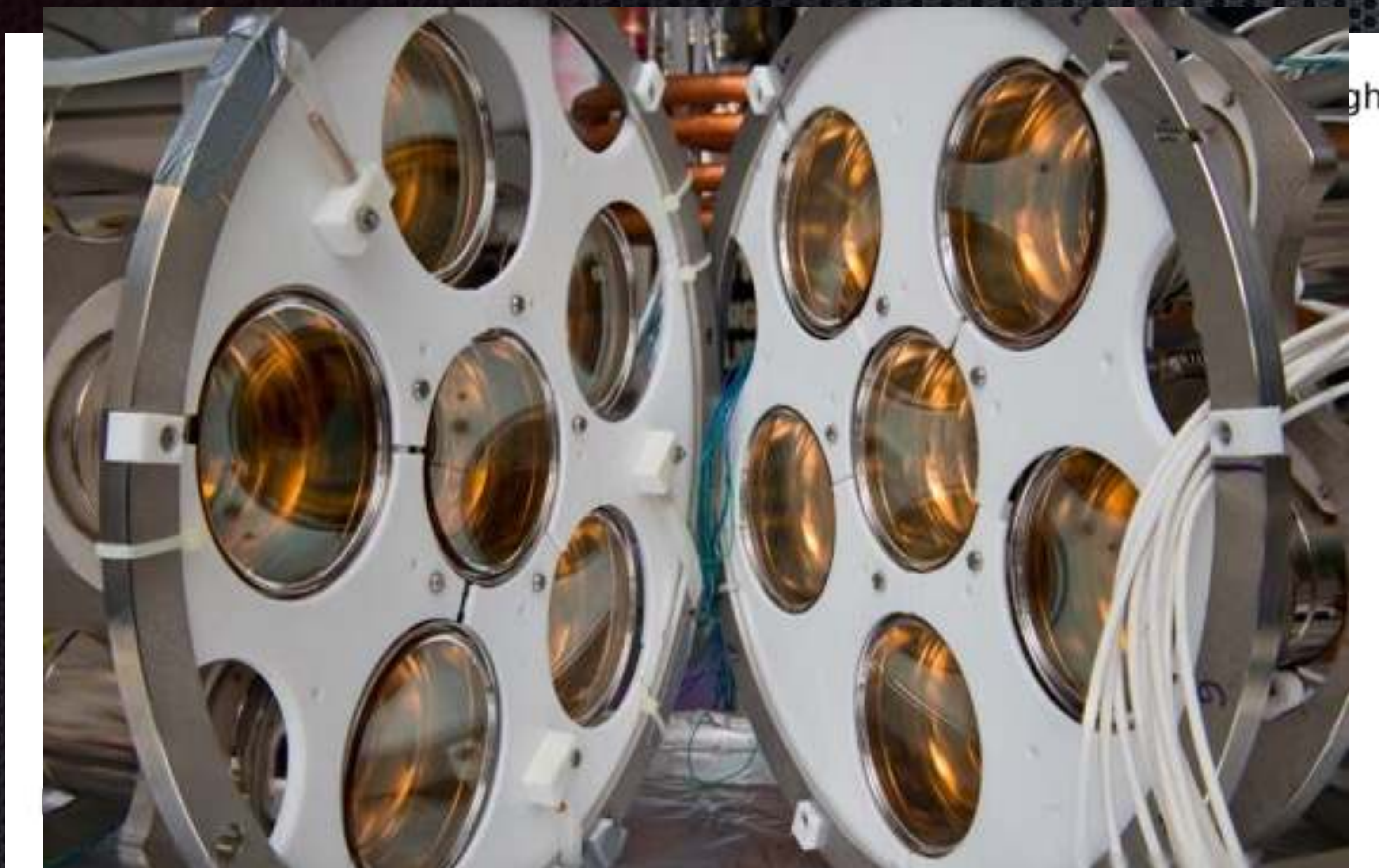

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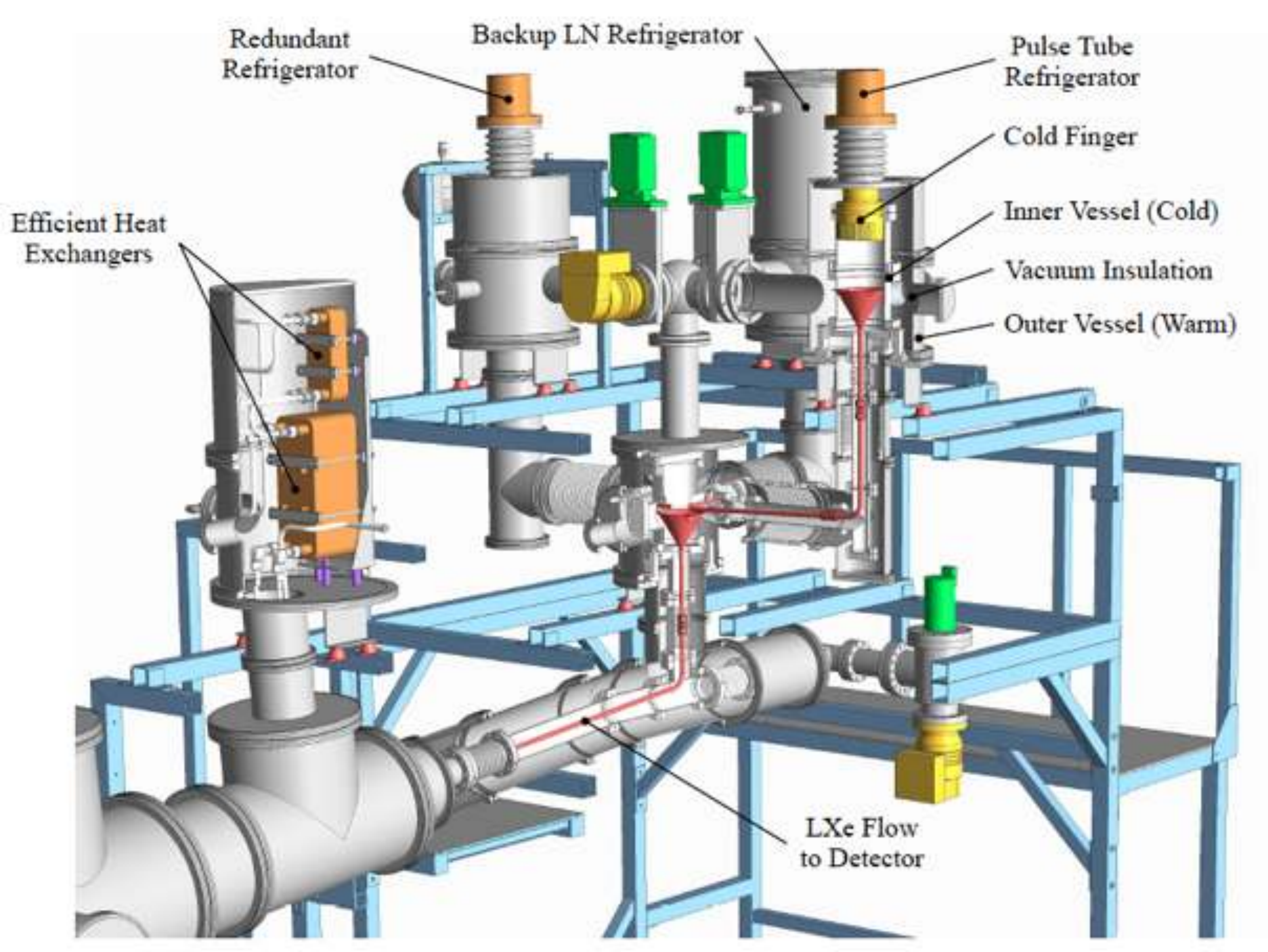
ug 2015

Cryogenic System

- Design based on experience acquired by operating XENNON10, XENON100 and XENON1T Demonstrator
- Heat load below 50W (without Xe gas circulation through purifiers)
- Redundant 200 W Pulse Tube Refrigerators
- One PTR can be serviced while other is in operation
- Back-up Liquid Nitrogen Cooling
- Stable and reliable long term continuous operation (3+ years)
- Circulation at ~100 slpm through efficient heat-exchangers



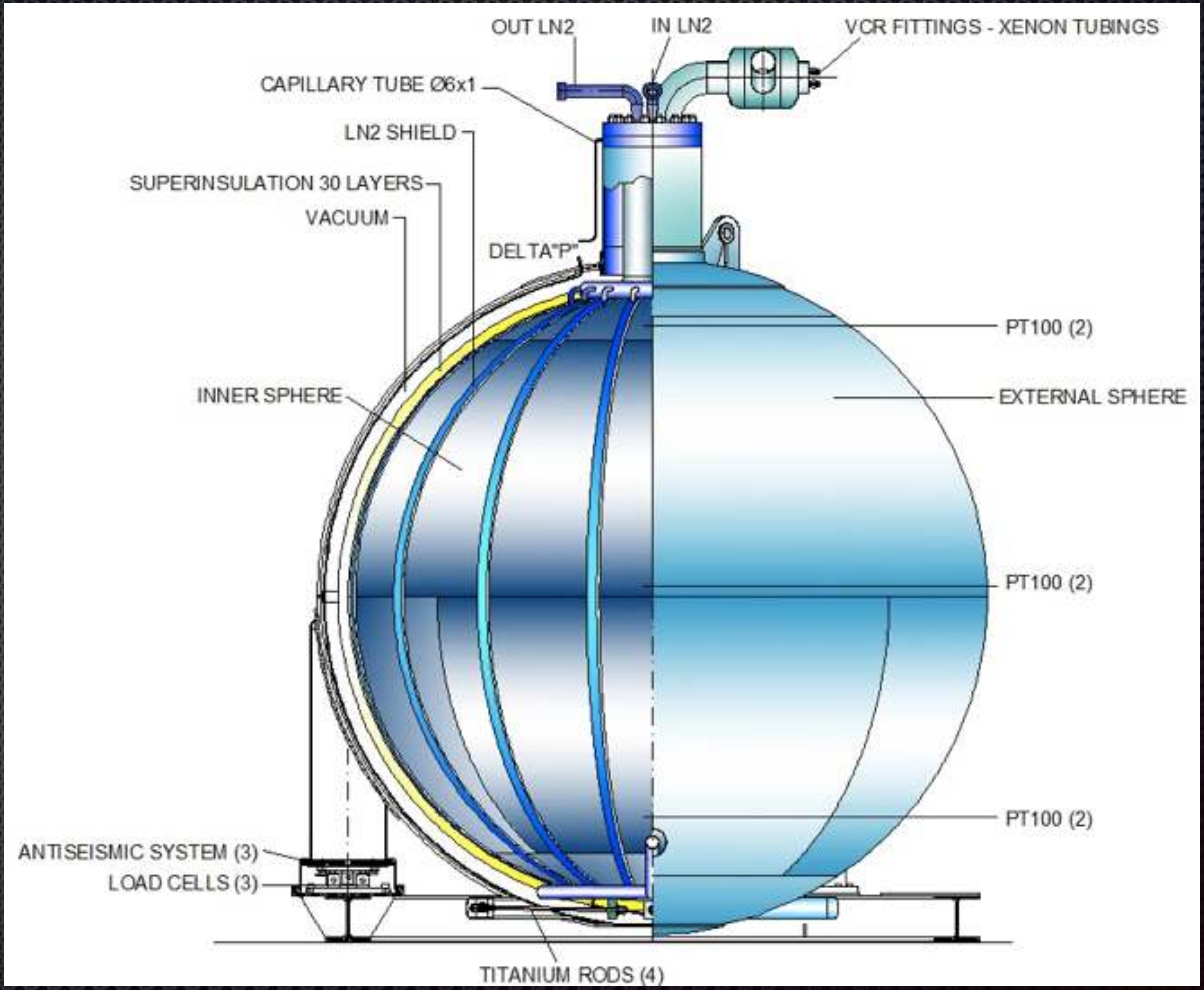
Cryogenic System

Cryogenic System

Cryogenic System

ReStoX System (Recovery & Storage of Xe)

- Double-walled, high pressure (70 atm), vacuum-insulated, LN2 cooled sphere of 2.1 diameter
- To store 7.6 tons of Xe either in gas or liquid/ solid phase under high purity conditions
- To recover in a safe and controlled way LXe from detector. In case of emergency all LXe is recovered in a few hours



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(Recovery &

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ReStoX Sy
(Recovery

- Double-walled, high pressure (70 atm), vacuum-insulated, L cooled sphere of 2.7 diameter
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- To recover in a safe controlled way LXe f detector. In case of emergency all LXe is recovered in a few h

ReStoX Sy
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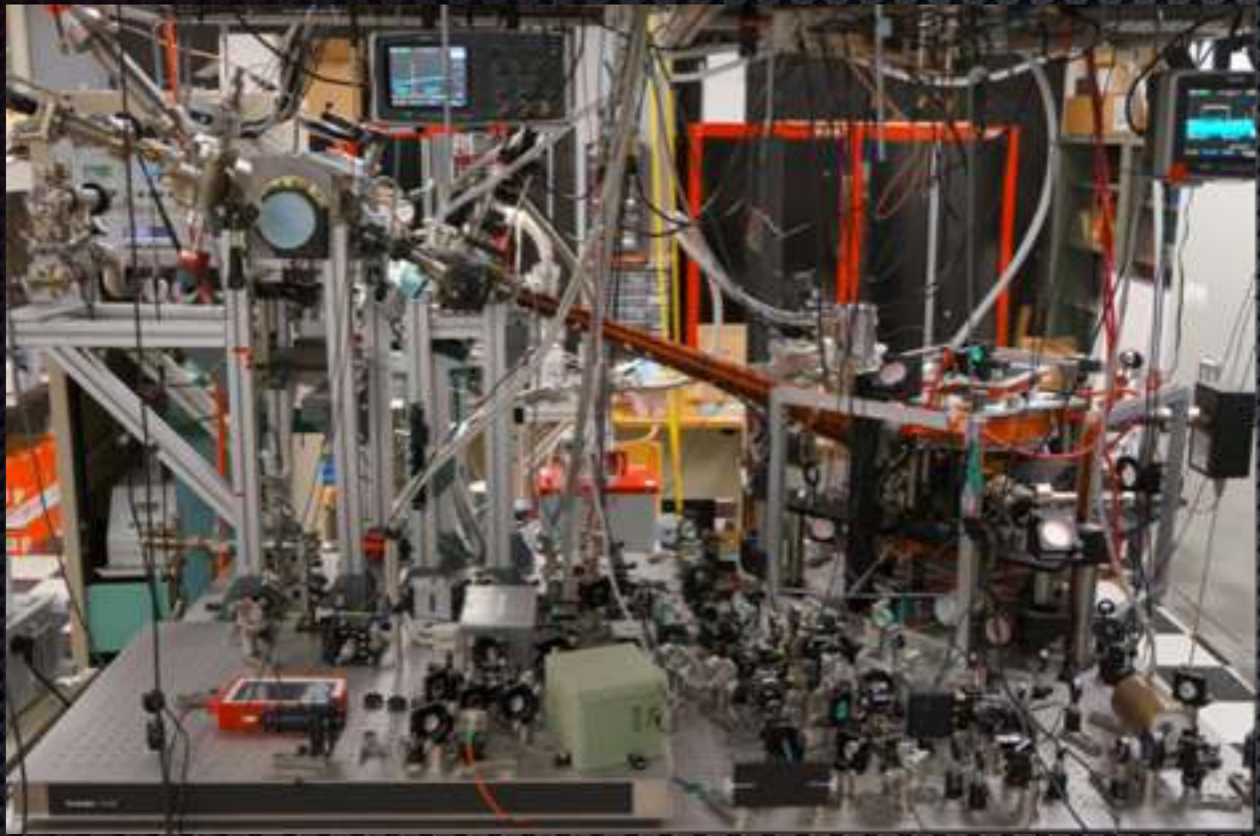
Kr Removal and Kr/Xe Analytics

- 1ppt Kr/Xe gives ~ 4 x 10^{-5} cts/keV/kg/d XENON1T sensitivity demands ~ 0.2 ppt
- Custom-designed 5m distillation column with 3kg/hr @ 10^5 separation
- 3m version successfully used to reduce Kr in Xe below 1 ppt as measured by RGMS
- 3m column also used on XENON100 to test Radon purification in LXe through cryogenic distillation
- two systems developed to measure ^{nat}Kr/^{nat}Xe and infer ^{85}Kr/nat from known ^{85}Kr/^{nat}Kr:
    - RGMS at MPIK (S. Lindemann and H. Simgen Eur. Phys. J. C (2014) 74:2746)
    - Atom Trap at Columbia (Aprile et al. : Rev. Sci. Instrum. 84 (2013)

Precise measurements of Kr in Xe

Atom Trap Trace Analysis



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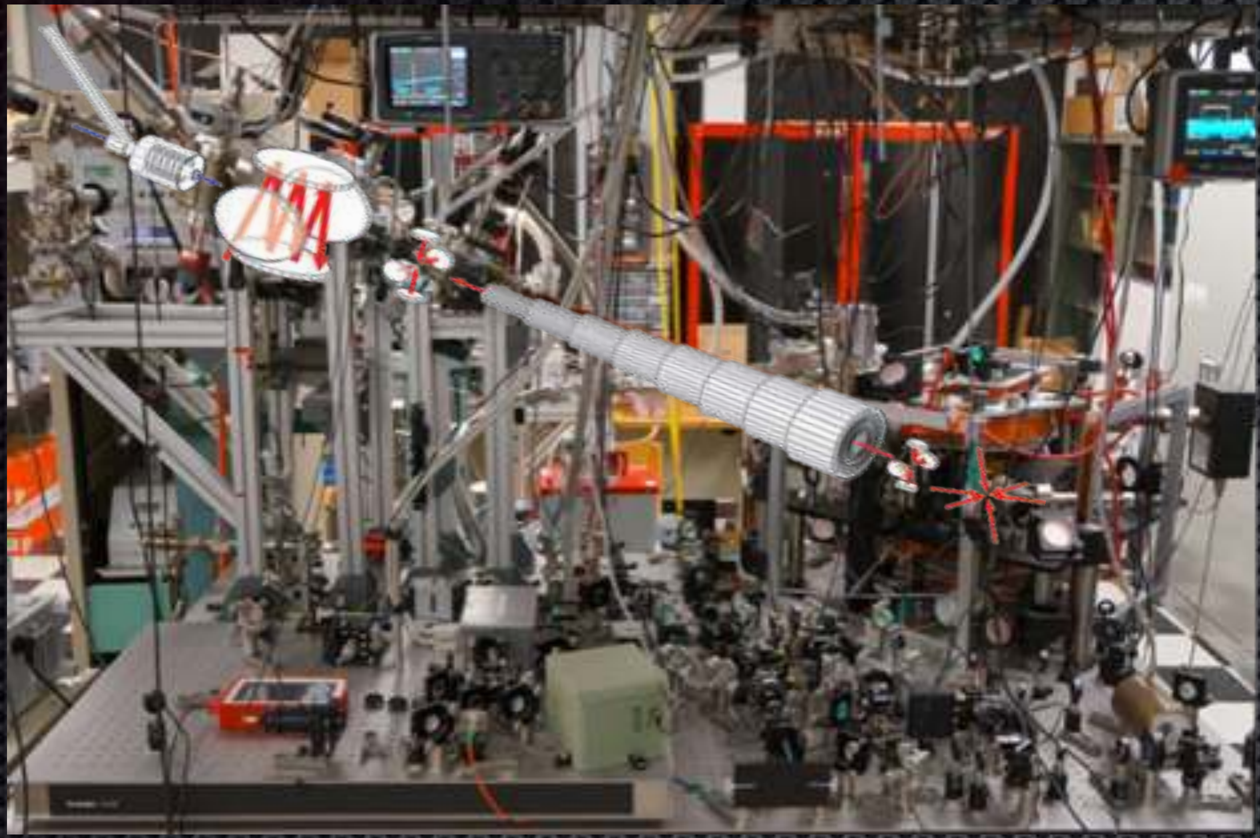

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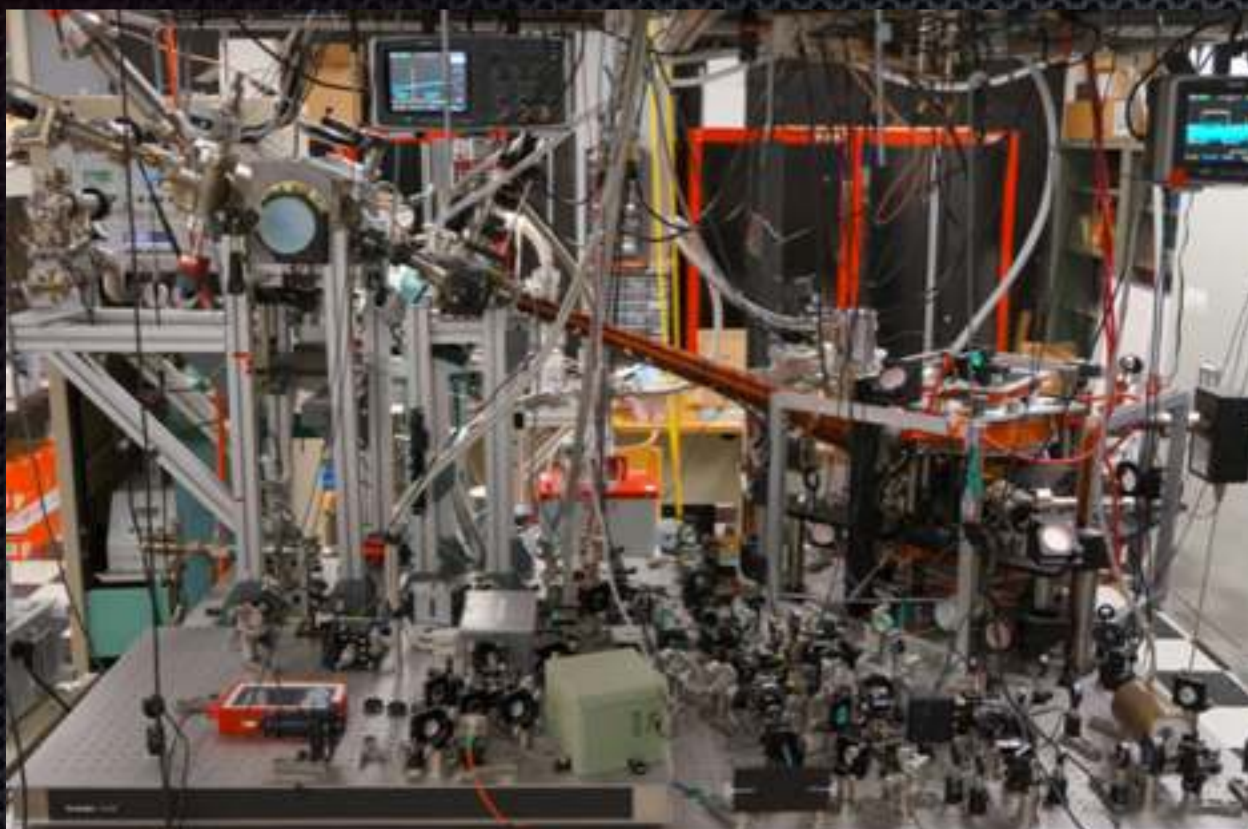

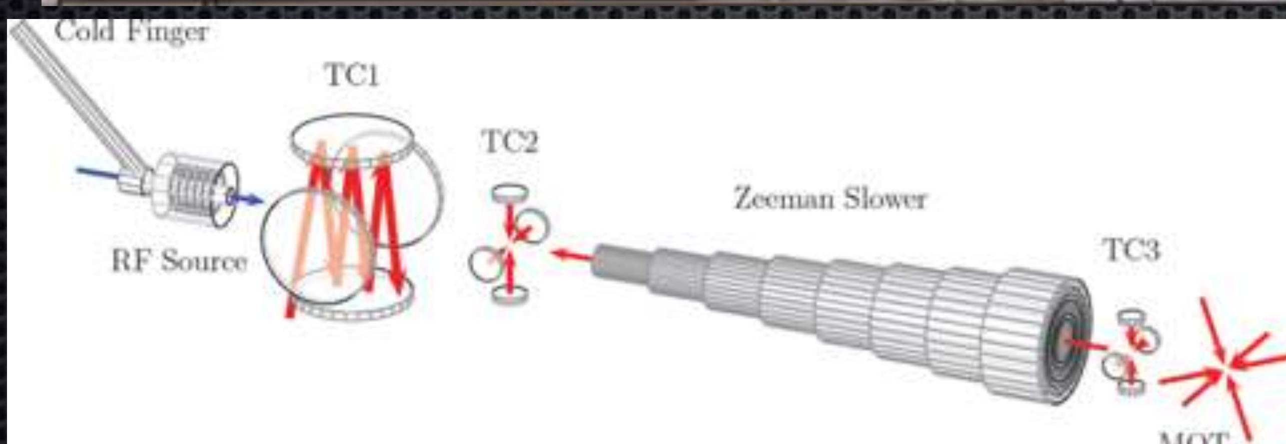

- Kr atoms excited in plasma, laser-focused and cooled in Zeeman Slower and trapped and observed in MOT
- Background free technique (sensitive to λ of atomic transition: 811 nm for kr-84)
- Detection limit depends only on measuring time. 1 ppt achieved within hours

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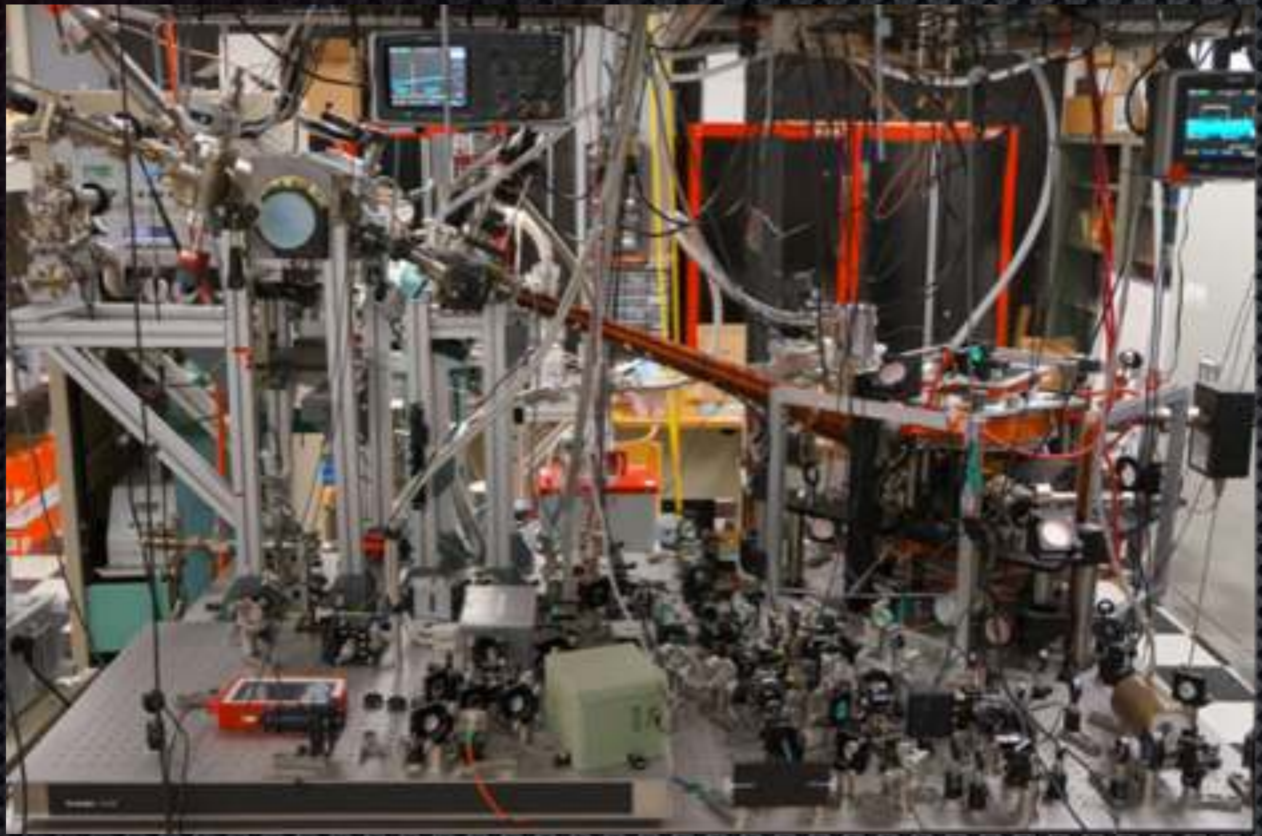

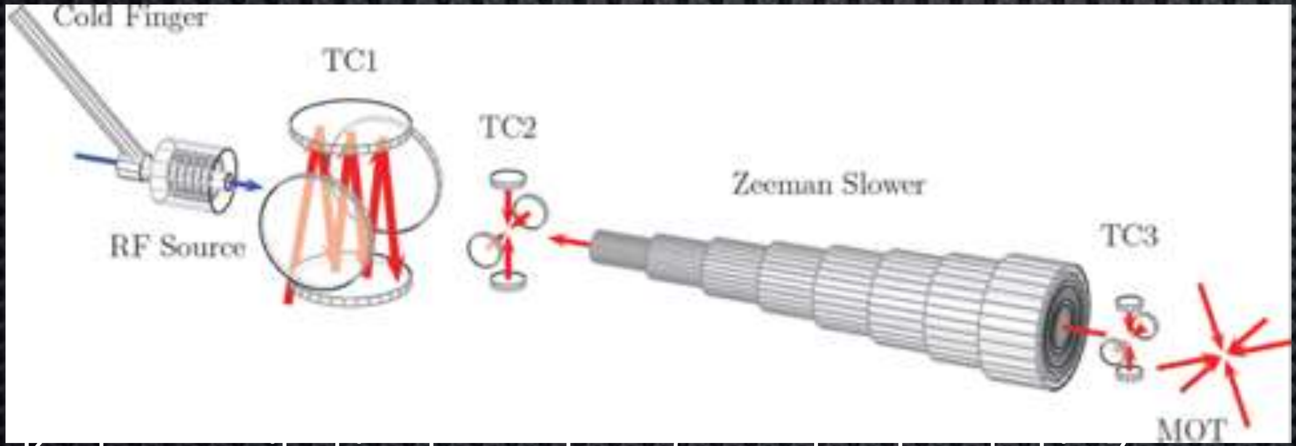

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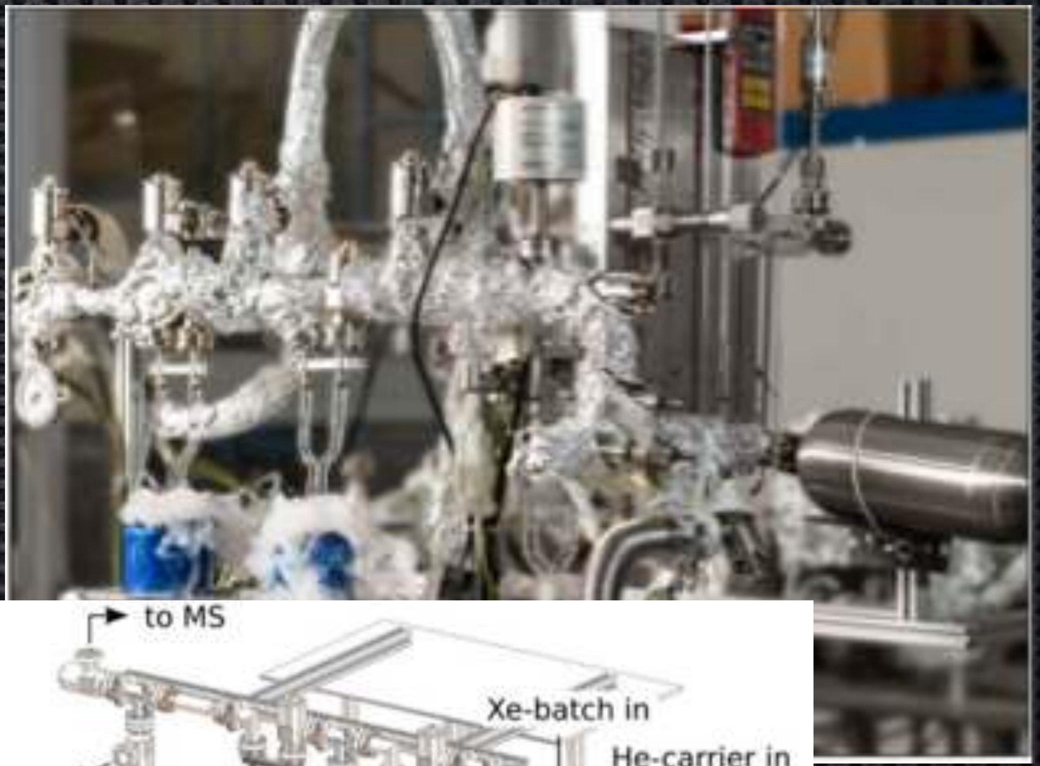
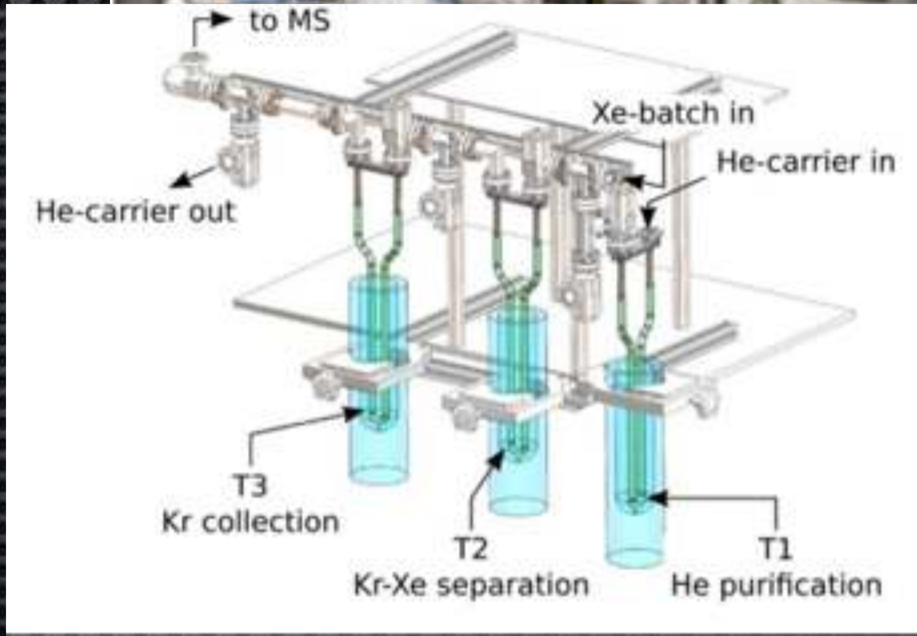
Rare Gas Mass Spectroscopy

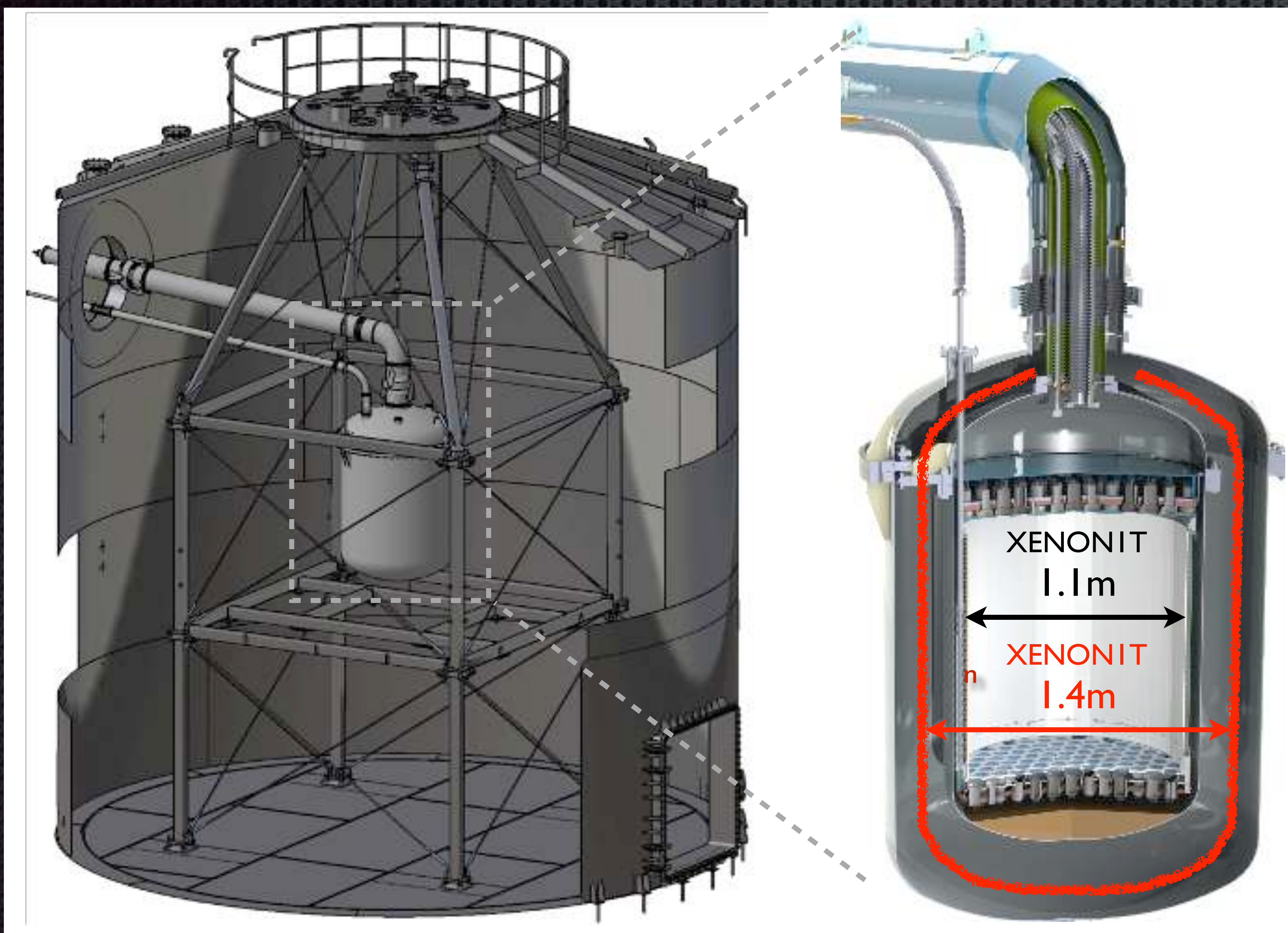




- Mass spectrometer used to analyze residual gas xenon
- Sample is passed through different cryogenic filters to capture Kr in a He carrier gas
- Kr is then filled into the mass spectrometer
- Detection limit 4 ppq

XENONnT: 2018 - 2022

- XENONnT will be serviced by the same infrastructures and sub-systems developed for XENON1T:



- Water tank + muon veto
- Outer cryostat and support structure
- Cryogenics system
- Purification system (with new circulation pumps for lower Rn)
- LXe storage /recovery system
- Kr/Rn columns

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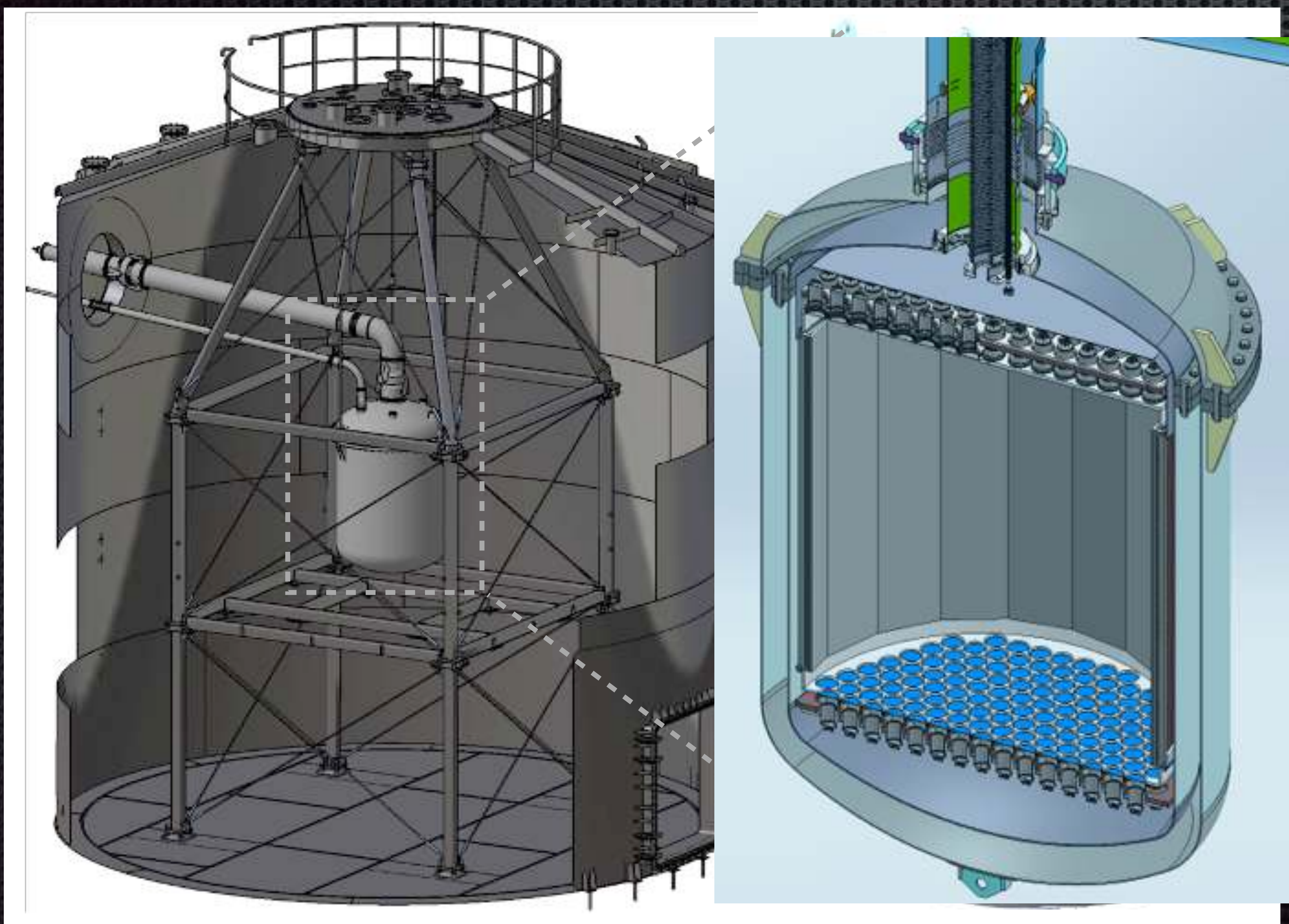

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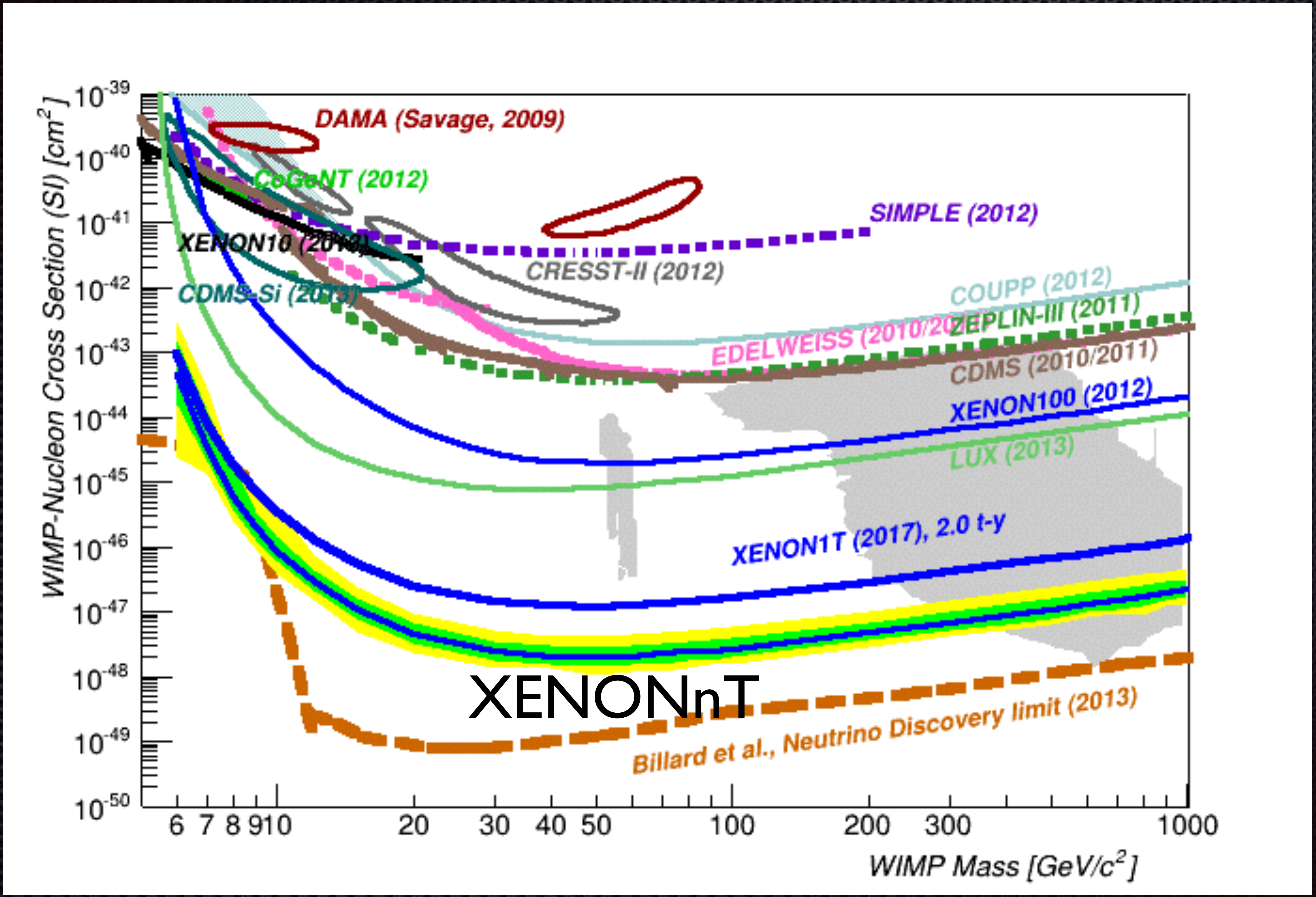
- Kr/Rn columns

XENONnT Sensitivity: 20 ton x year Exposure



Summary

- Experiments based on LXe have excluded WIMP-nucleon cross sections down to 10^{-8} pb, with about a factor 10 improvement in sensitivity every two years.
- Next generation LXe experiments aim at an additional factor 100 or better improvement to a level where a signal from neutrino interactions will become an irreducible background.
- XENON1T, under construction at LNGS, is the first such experiment. With 3300 kg of LXe and a significantly lower background than any experiment to-date, it is expected to start taking data by the end of 2015.
- A rapid upgrade path is built in the design of XENON1T, with the goal of achieving another factor of 10 in sensitivity. A larger mass (7000 kg) new detector is planned for installation in 2018, using the same cryostat, cryogenic plants and muon veto built for XENON1T.