DARK MATTER EXPERIMENTS

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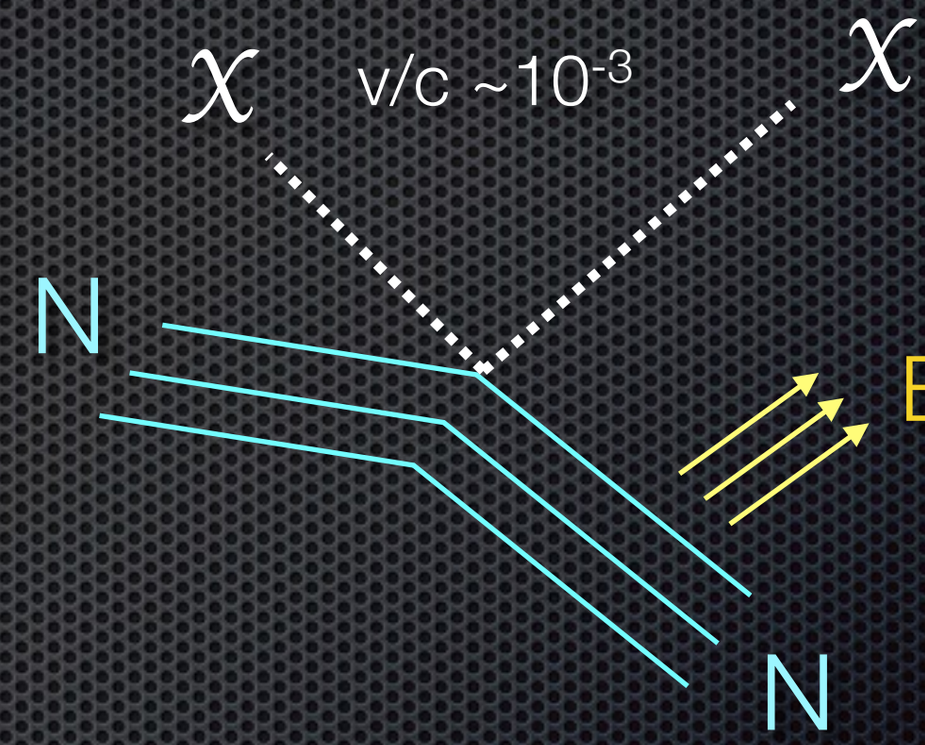
Invisibles, Madrid, June 25, 2015

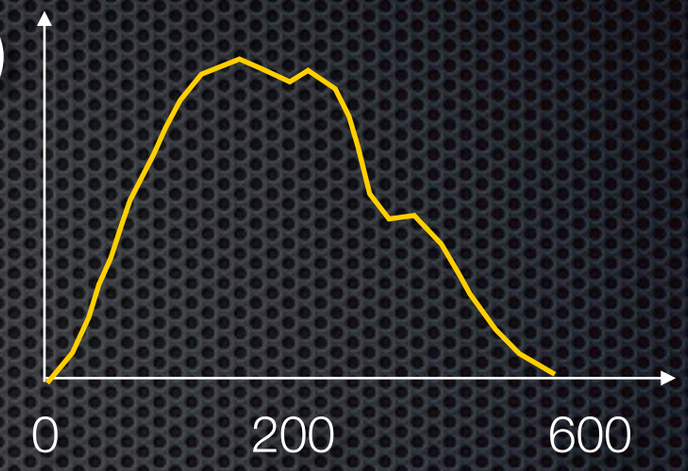
Dark Matter Direct Detection

- Search for collisions of WIMPs with atomic nuclei in a detector on Earth => E_{vis} (q ~ tens of MeV)
- Need *very low energy threshold*
- Need *ultra-low backgrounds*, good background understanding and signal/noise discrimination
- Need detector *technologies and target materials which enable to probe a very low event rate*



$$E_R = \frac{q^2}{2m_N} < 100\,\mathrm{keV}$$

What do we expect in a detector?



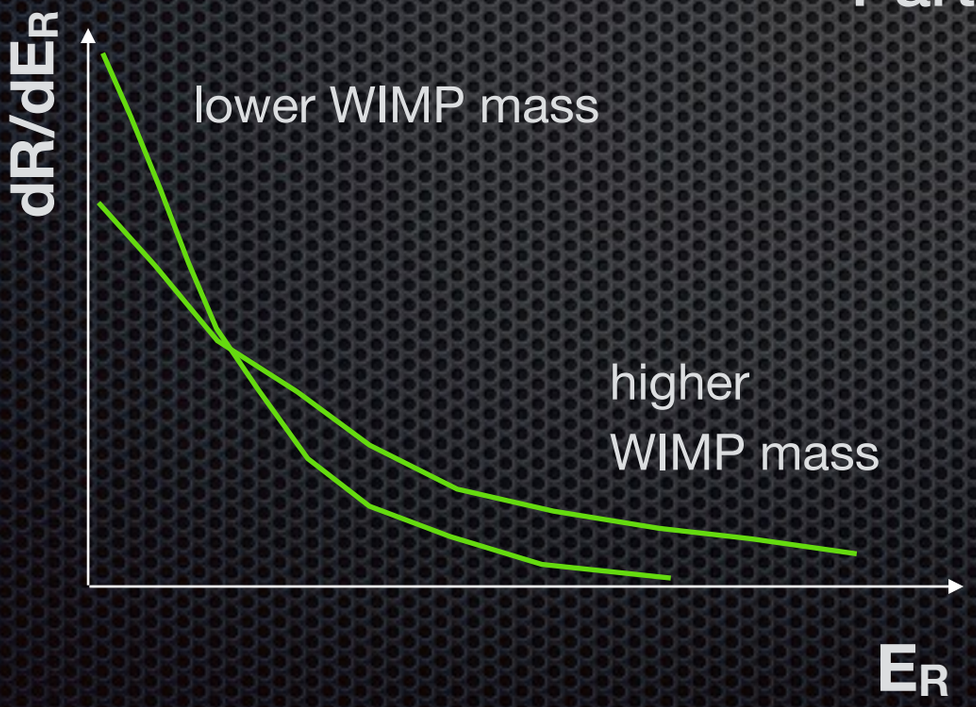
Astrophysics

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{\min}}^{v_{\max}} d\mathbf{v}\, f(\mathbf{v})\, v\, \frac{d\sigma}{dE_R}$$

Detector physics

Particle/nuclear physics

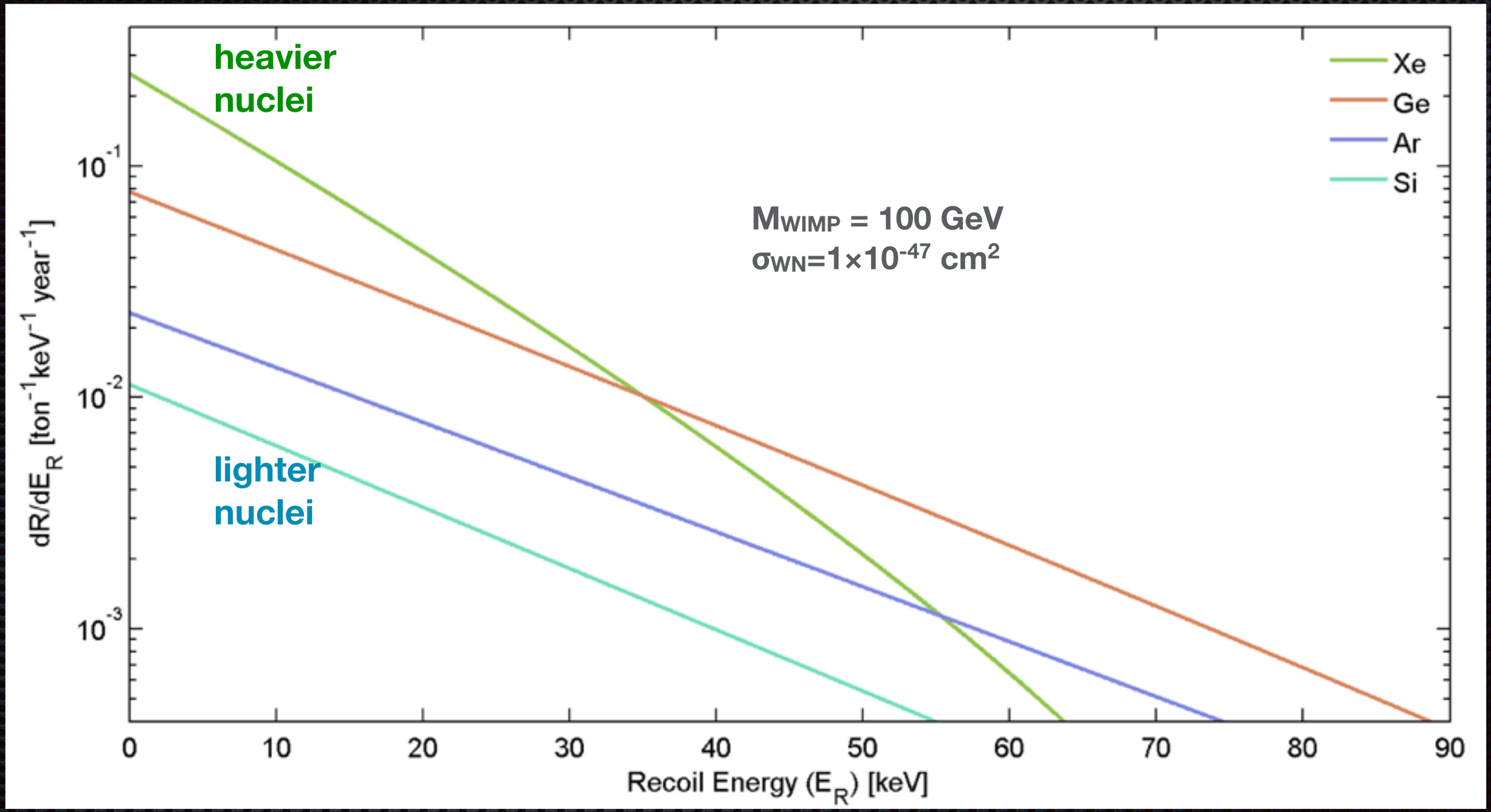
$$v_{\min} = \sqrt{\frac{m_N E_{th}}{2m_r^2}}$$



$$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV}\cdot\mathrm{cm}^{-3}$$

Justin Read, arXiv:1404.1938

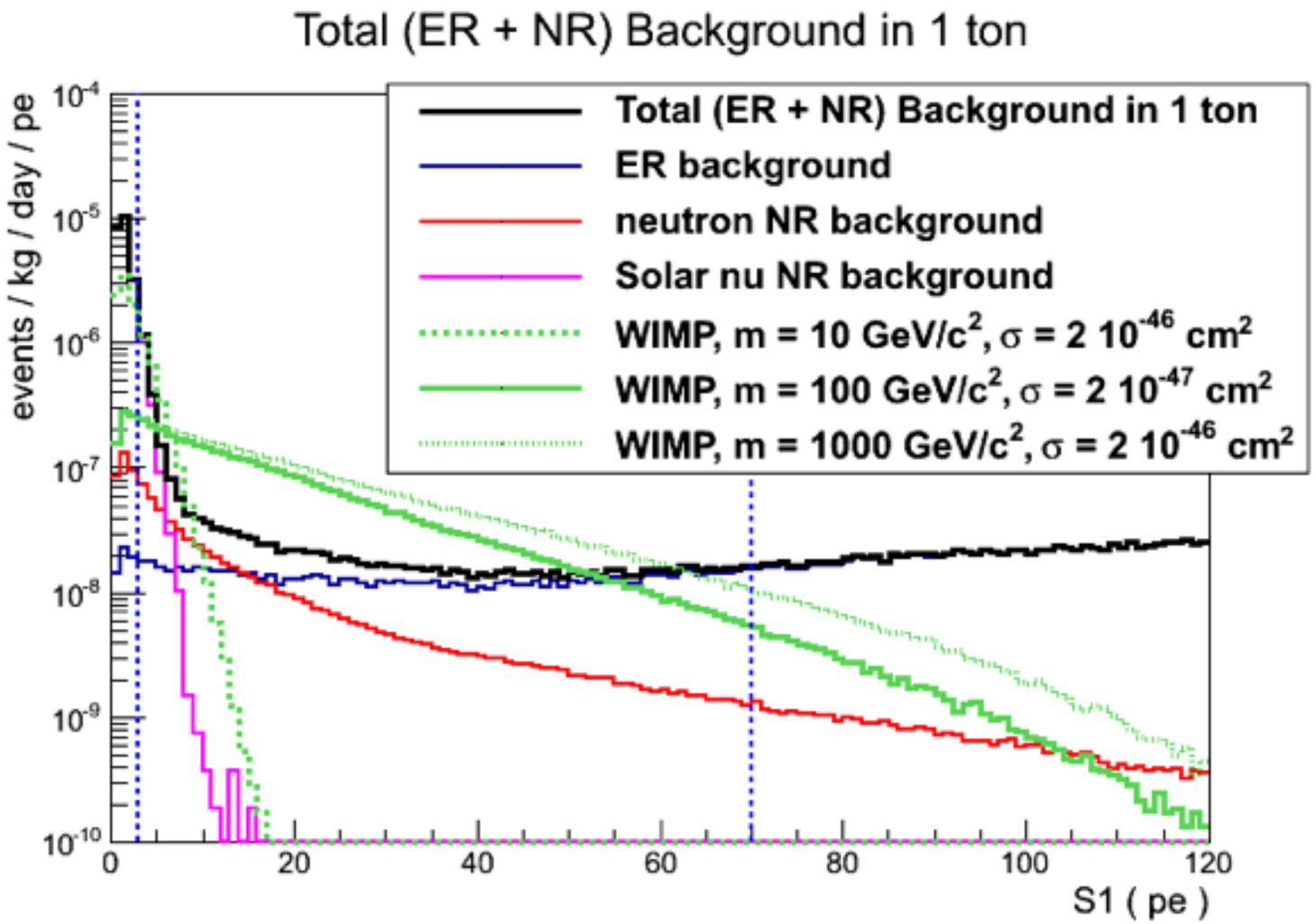
Expected rate with some favored targets



WIMP Detection Backgrounds

- **Electromagnetic radiation**
  - natural radioactivity in detector and shield materials
  - airborne radon (^{222}Rn)
  - cosmic activation of materials during storage/transport at the Earth's surface
- **Neutrons**
  - radiogenic from (α,n) and fission reactions
  - cosmogenic from spallation of nuclei in materials by cosmic muons
- **Alpha particles**
  - ^{210}Pb decays at the detector surfaces
  - nuclear recoils from the Rn daughters
- **Neutrinos (solar,atm,SN)**
  - neutrino-electron scattering and neutrino-nucleus coherent scattering

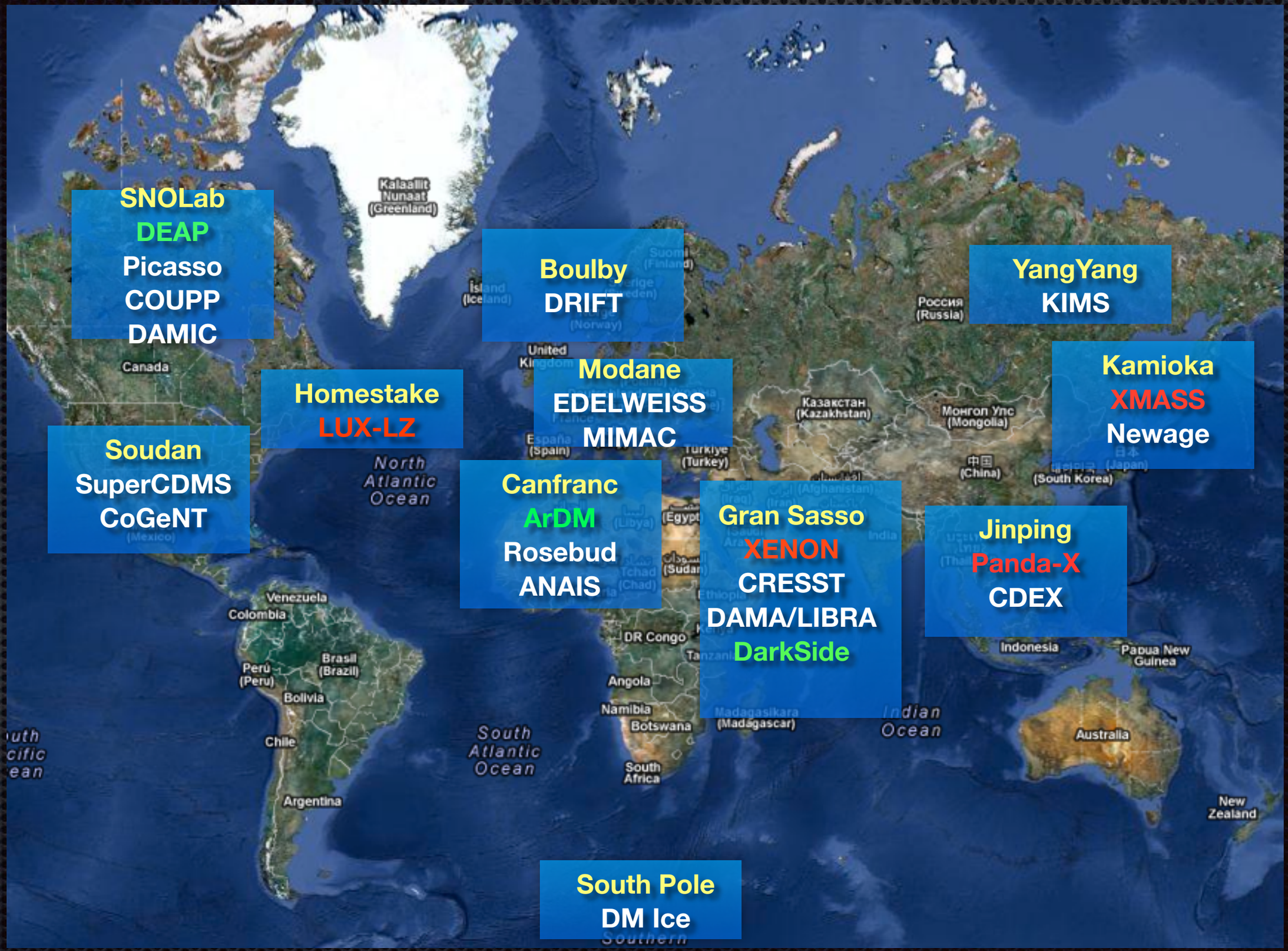
Example: XENON1T Backgrounds



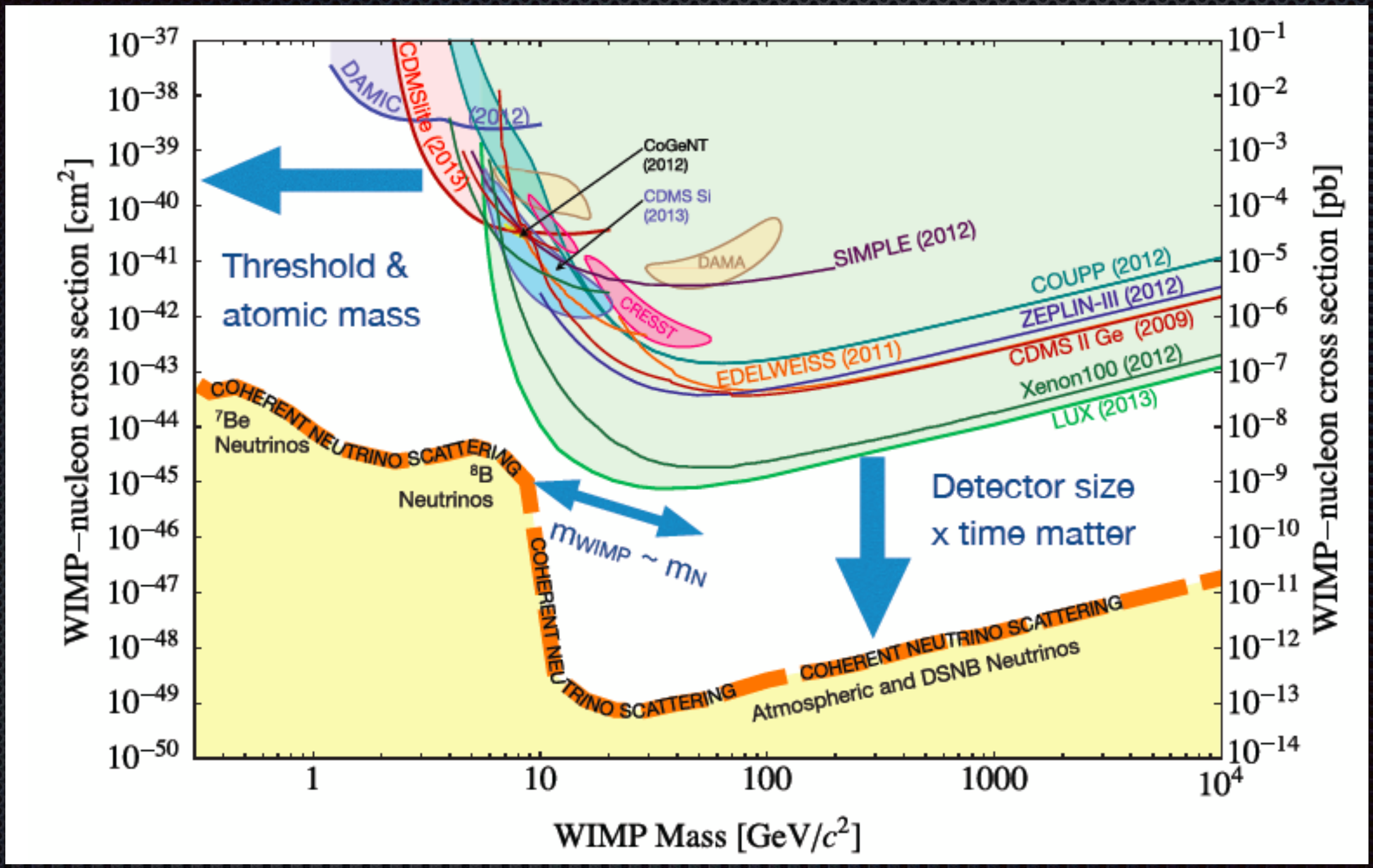
1 ton fiducial volume,
S1 in [3, 70] pe,
ER discrimination 99.75%,
NR acceptance 40%.

Source	Background (ev. / ton /y)
ER (materials + intrinsic + solar ν)	***0.32***
NR from radiogenic neutrons	***0.22***
NR from neutrino coherent scattering	***0.55***
Total	***1.1***

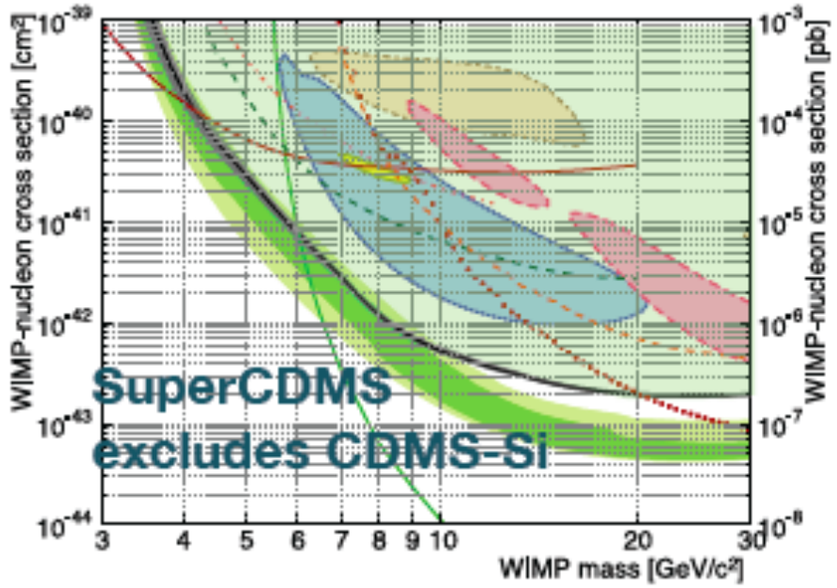
Worldwide WIMP Searches

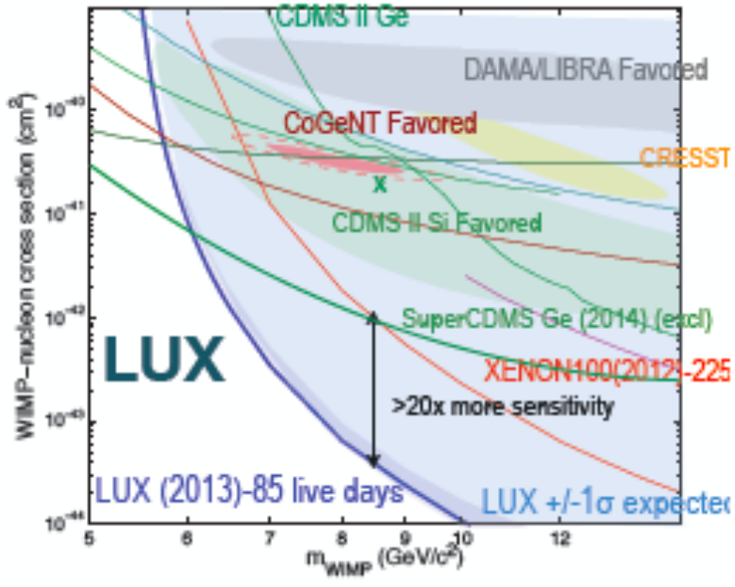


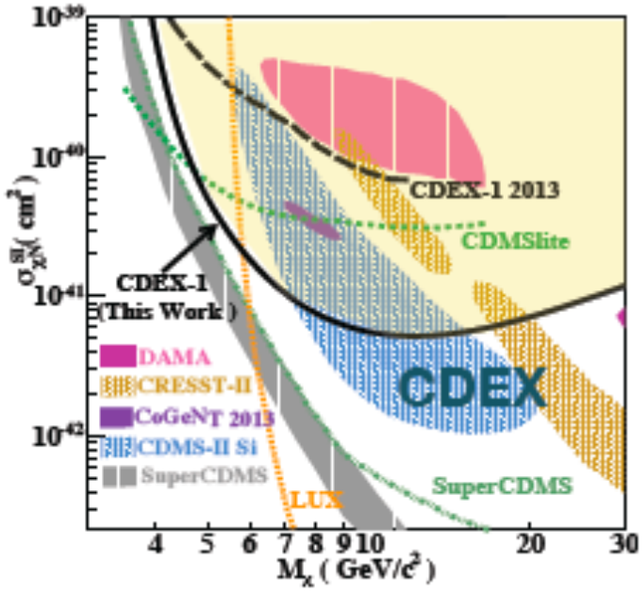
WIMP Direct Detection Situation Today

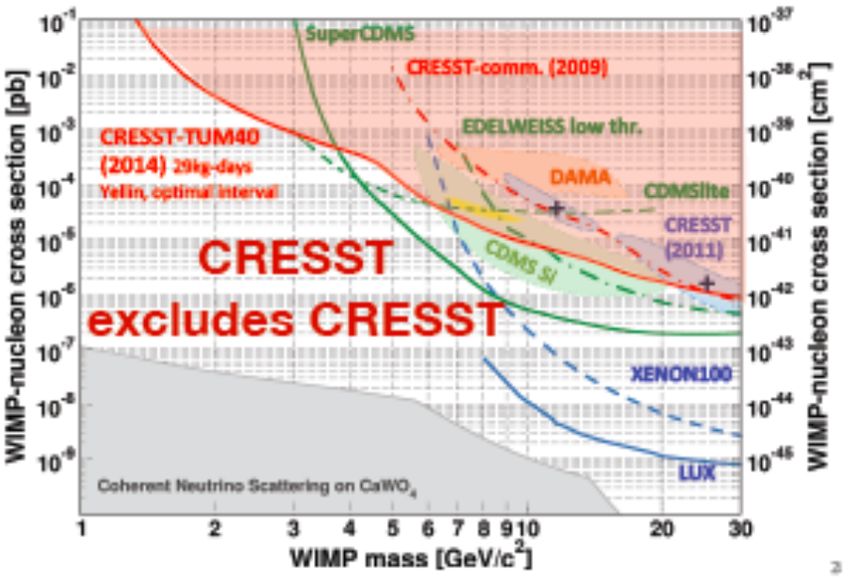


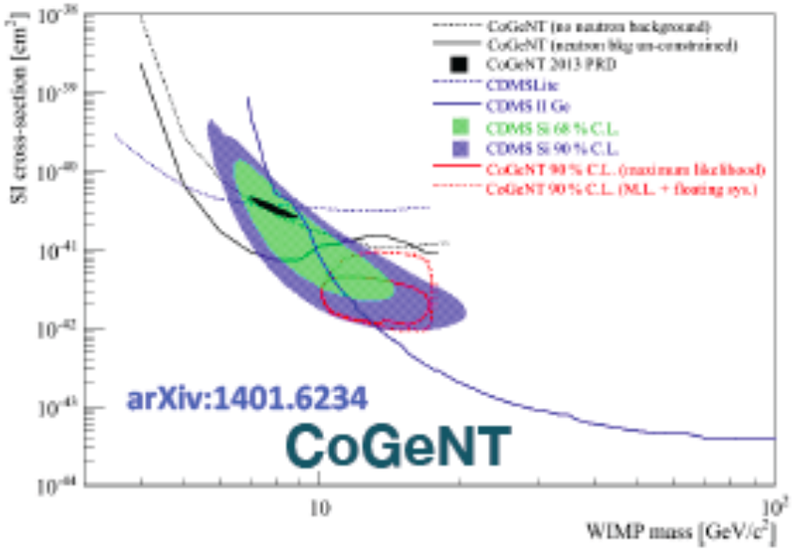
Low mass region: confused situation cleared by several experiments

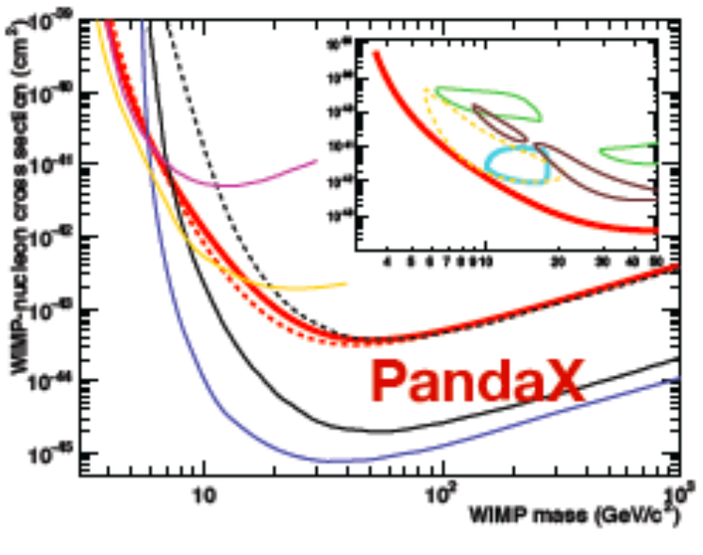






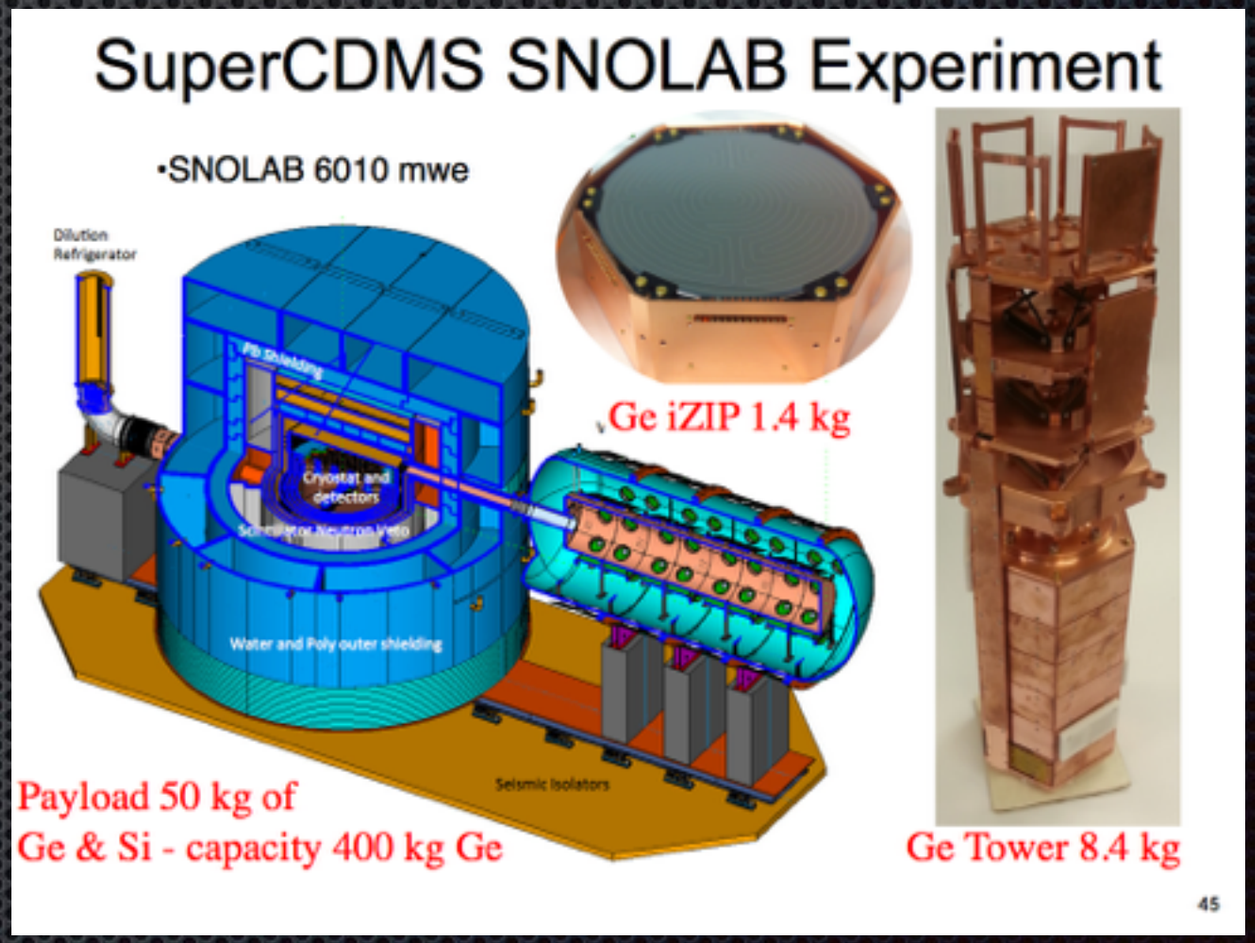






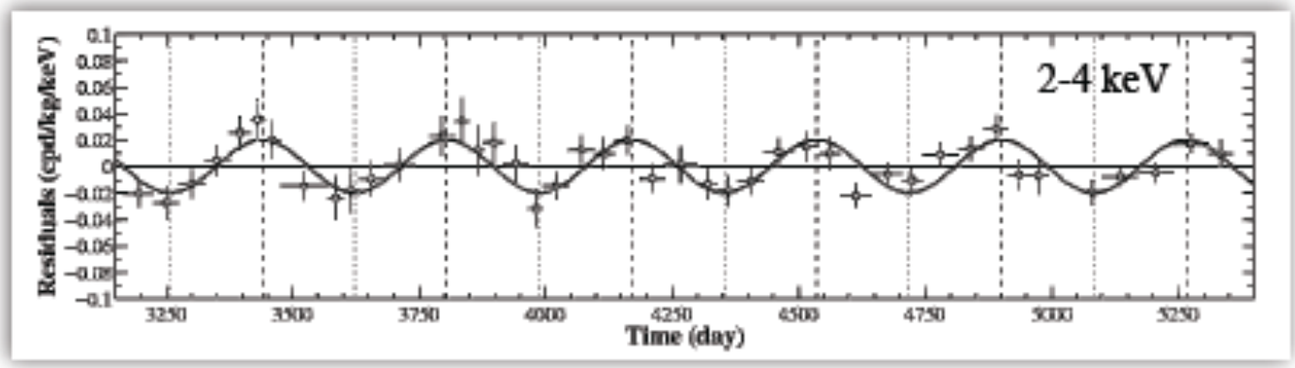
Future: increase sensitivity with next generation cryogenic detectors at T~ mK

- SuperCDMS at SNOLab. Low-temperature Ge/Si detectors. Focus on low mass 0.3-10GeV/c^2
  - Above 5 GeV/c^2 6 towers ≈50kg Ge full nuclear recoils recognition through ionization + athermal phonon
  - 0.3-5 GeV/c^2, 1 tower of e.g., 3 Ge, 3 Si, CDMS HV (Luke Neganov amplification of ionization). No discrimination. Background limited after 1 year
- Upgrade path to 400 kg: discussions with EURECA for multi-target approach ($CaWO_3$, Ge) and increased target mass.

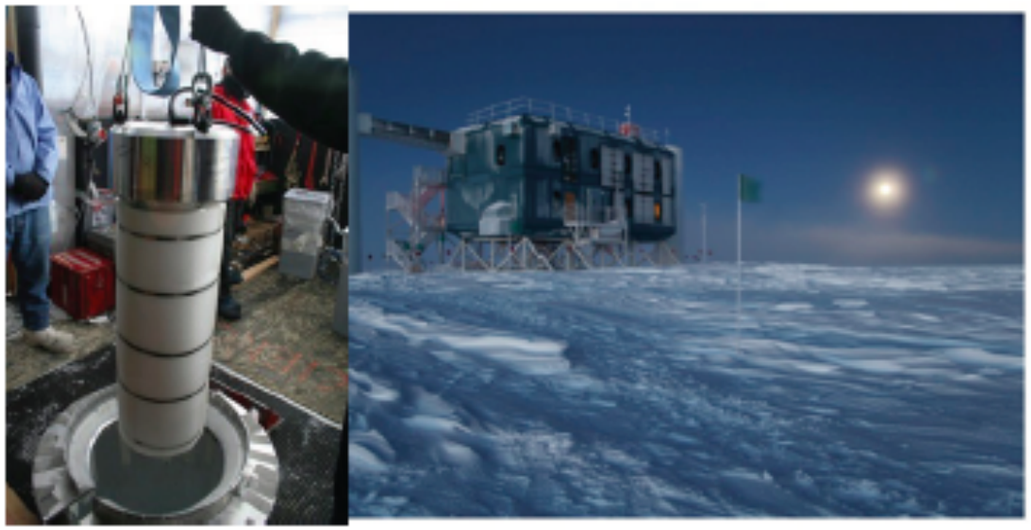


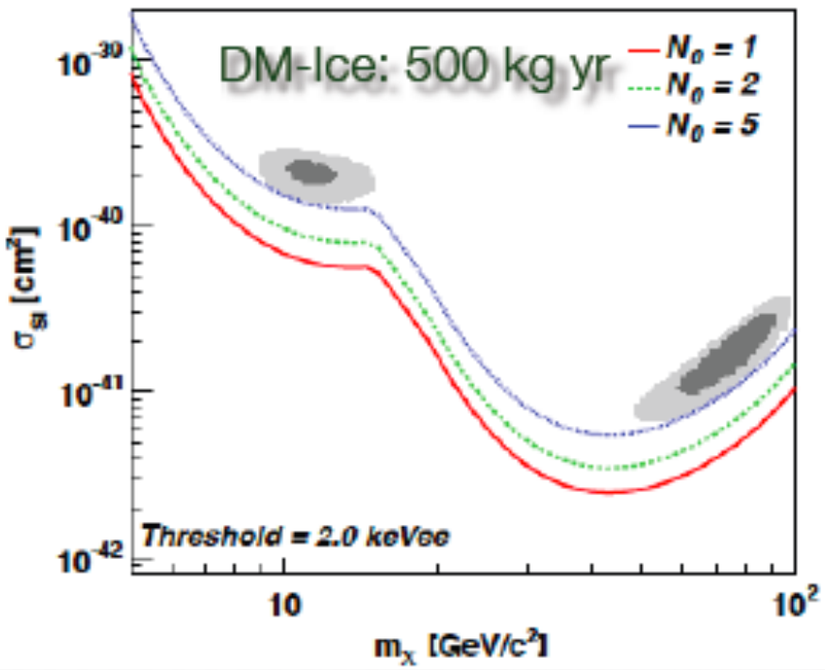
DAMA/LIBRA annual modulation signal

- Period = 1 year, phase = June 2 ± 7 days
- Several experiments to directly probe the modulation signal with similar detectors (NaI, CsI): SABRE, ANAIS, DM-Ice, KIMS



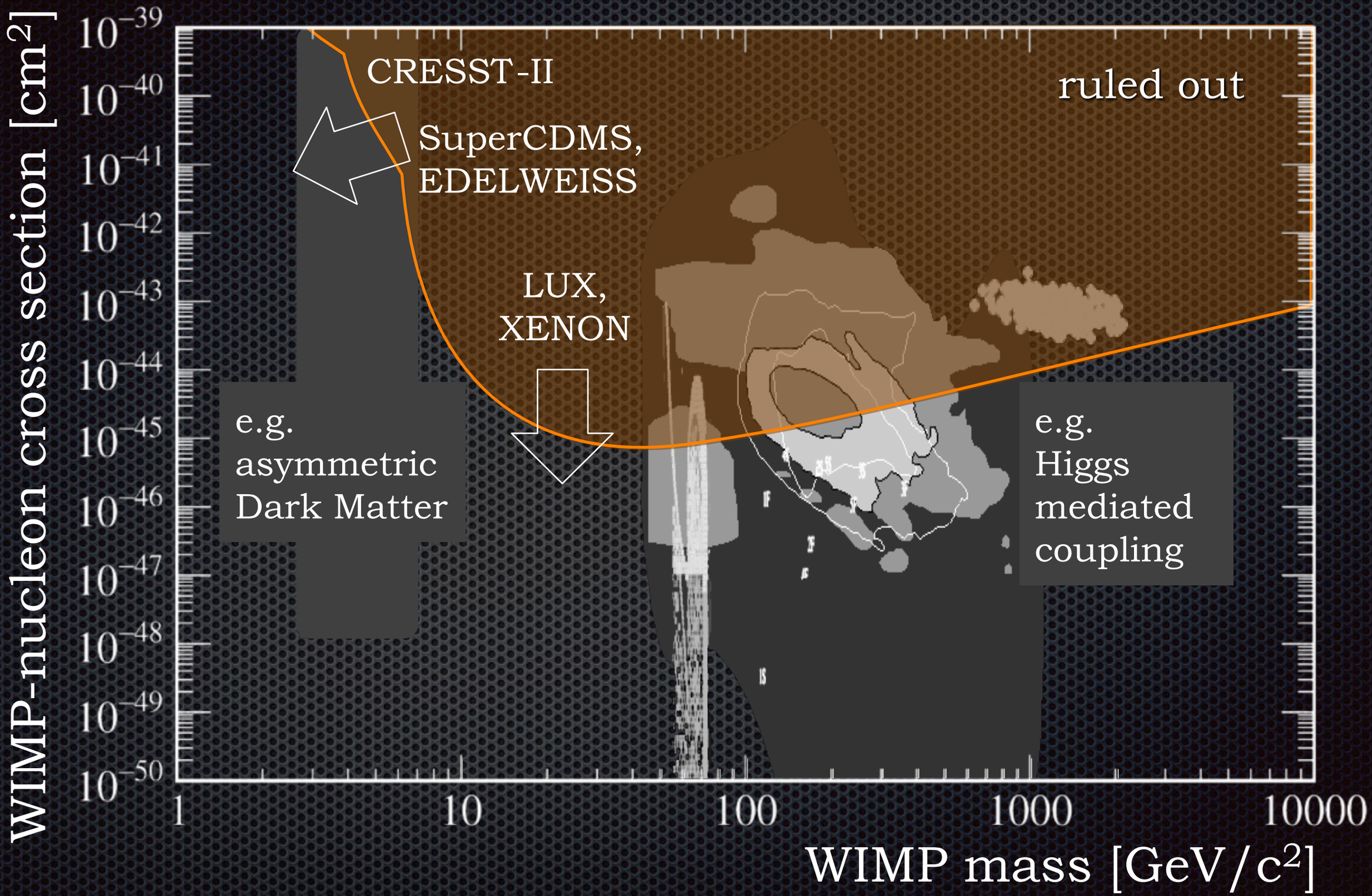
R. Bernabei et al, EPJ-C67 (2010)



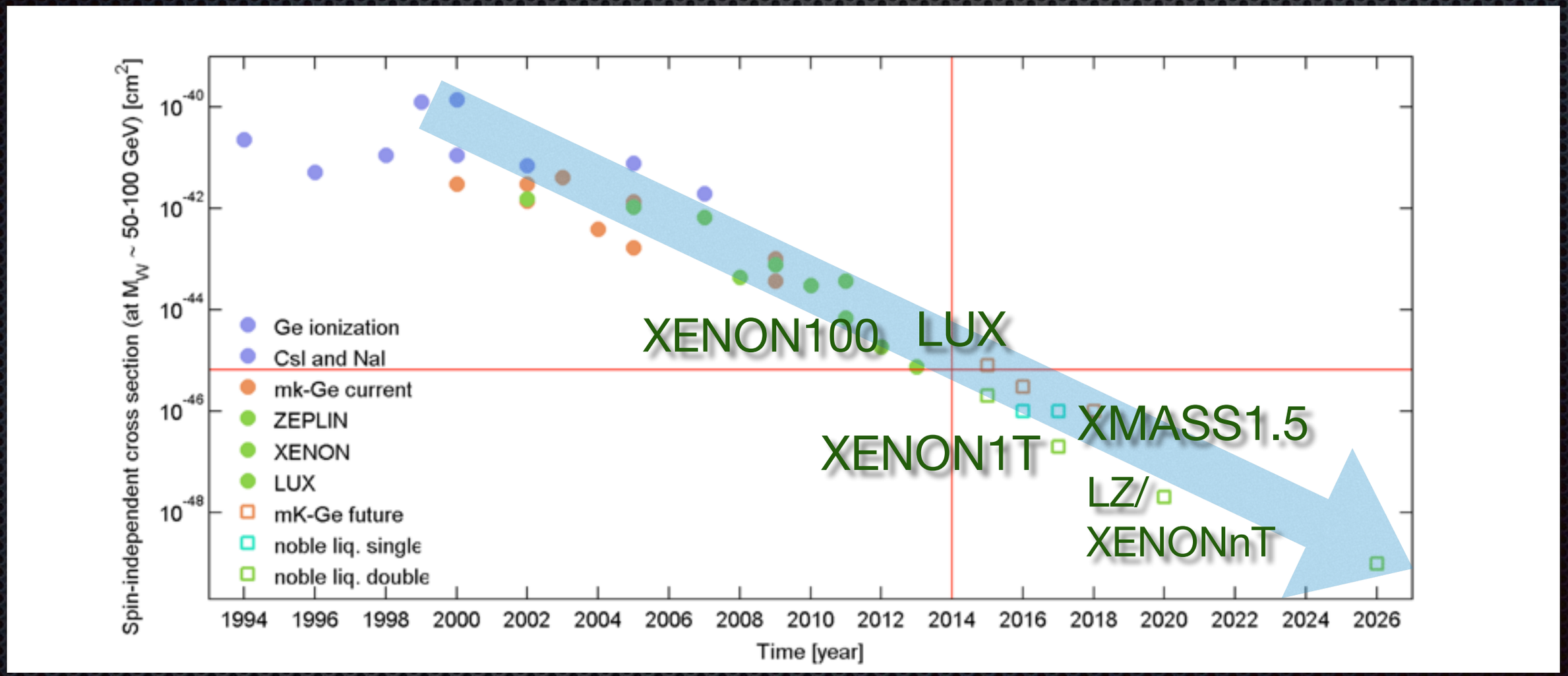


Definitive (5σ) detection or exclusion with 500 kg-yr NaI(Tl) (DAMA x 2 yrs) and same or lower threshold (< 2 keV_{ee})

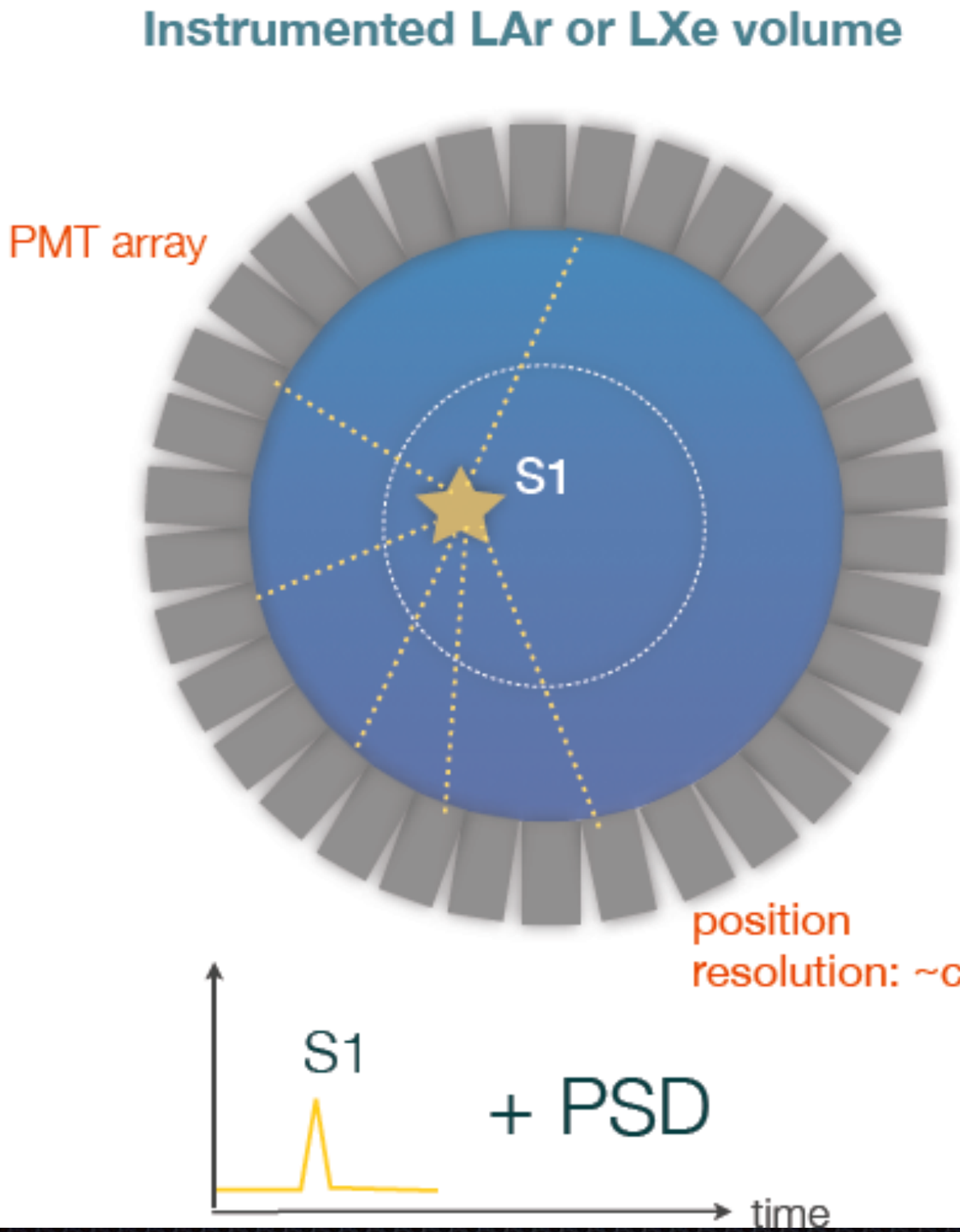
High mass region: led by LXe experiments



Outstanding performance: a factor *10 increase in sensitivity every 2 years. Trend is likely to continue with multi-ton scale next generation detectors*



Single-phase noble liquid detectors



LXe: XMASS at Kamioka
New dark matter run with "refurbished" detector

LAr: DEAP-3600 at SNOLAB
In commissioning
First results in late 2015

DEAP 3600 @ SNOLAB

3.6 tonnes liquid argon in ultraclean acrylic vessel, 255 8-inch HQE PMTs

1 tonne fiducial mass designed for < 0.2 background events/year

Steel containment sphere immersed in 8 m water tank

10^{-46} cm^2 sensitivity for ~100-GeV WIMP with 3-year exposure

Ar-test, commissioning in Fall 2014. Physics start this Summer

XMASS @ Kamioka

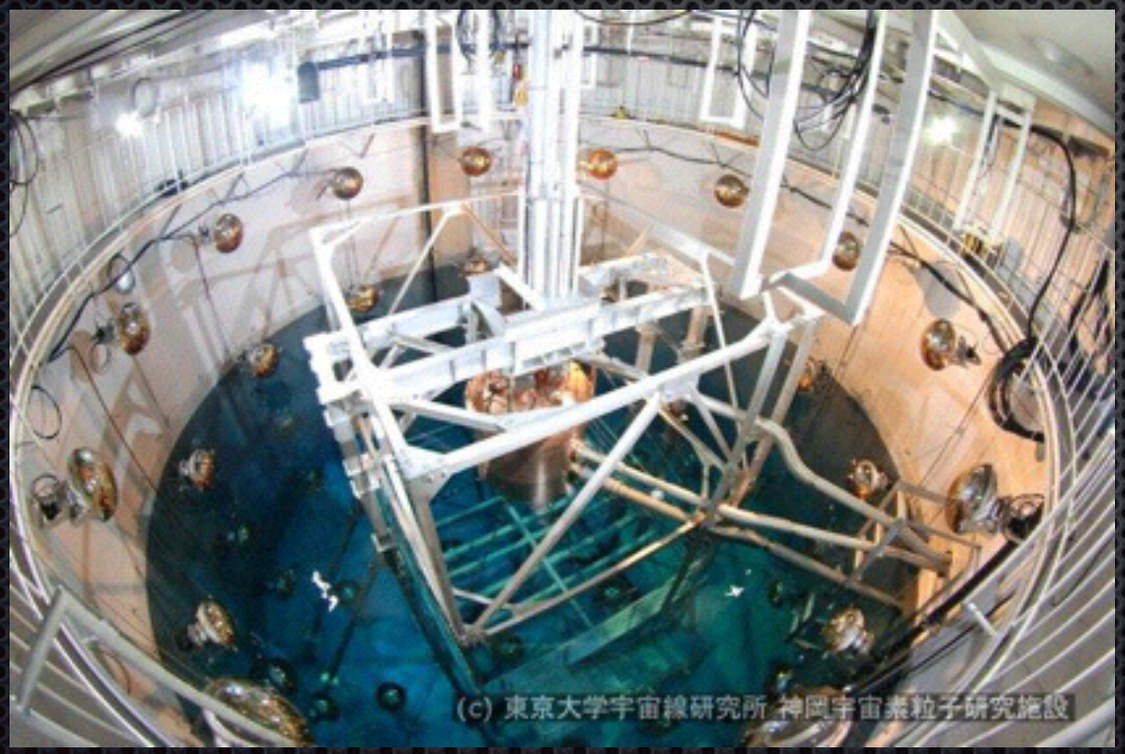
850 kg (100 kg fiducial) liquid xenon in copper vessel, immersed in water tank

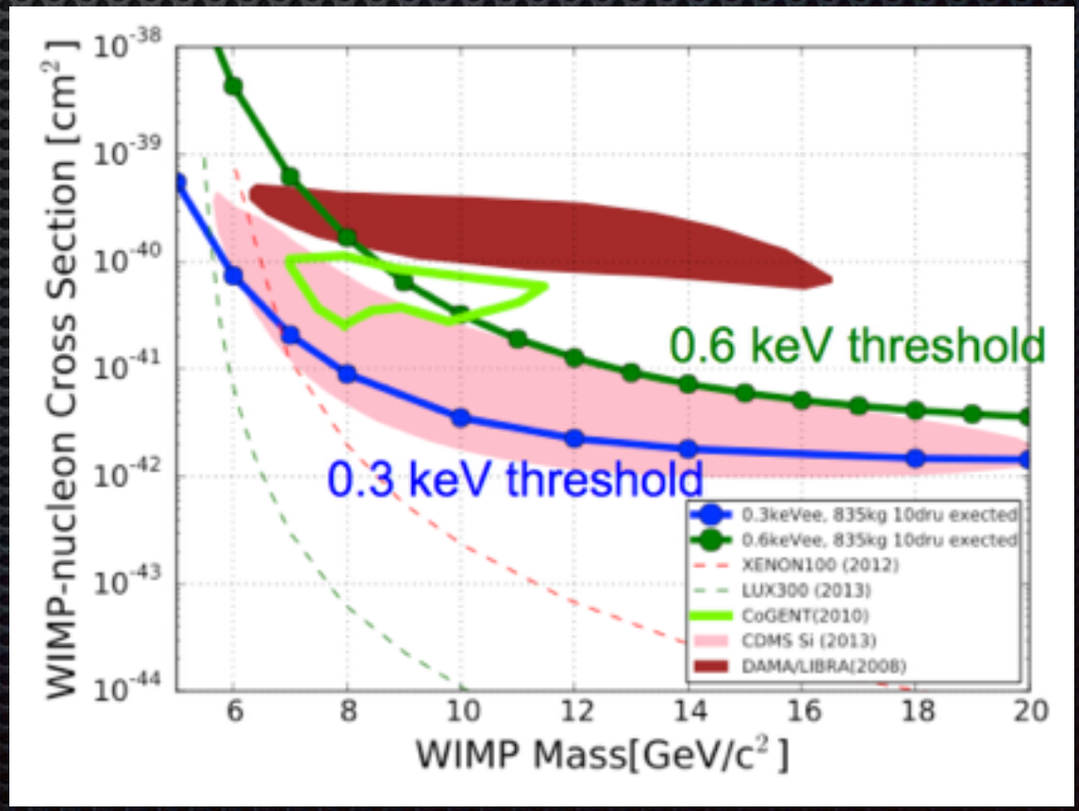
62% of inner surface covered by 632 high QE, HEX PMTs : 13 PE/keV

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

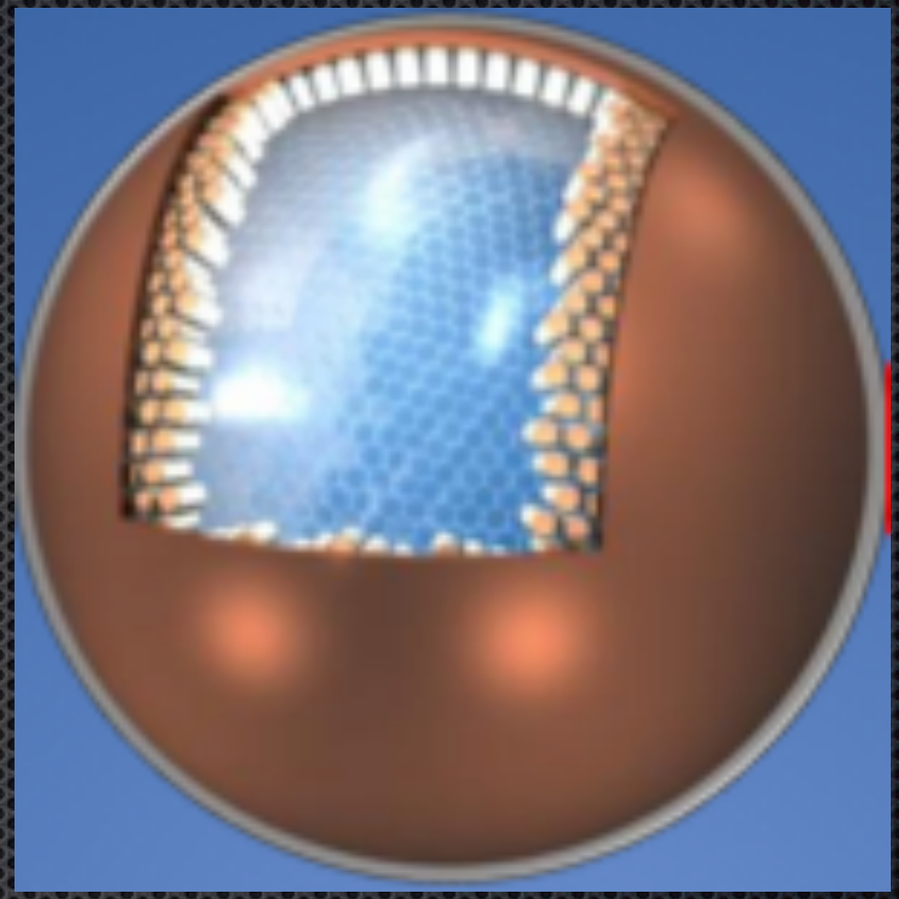
> 1yr data accumulated since detector refurbishment to reduce surface backgrounds

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



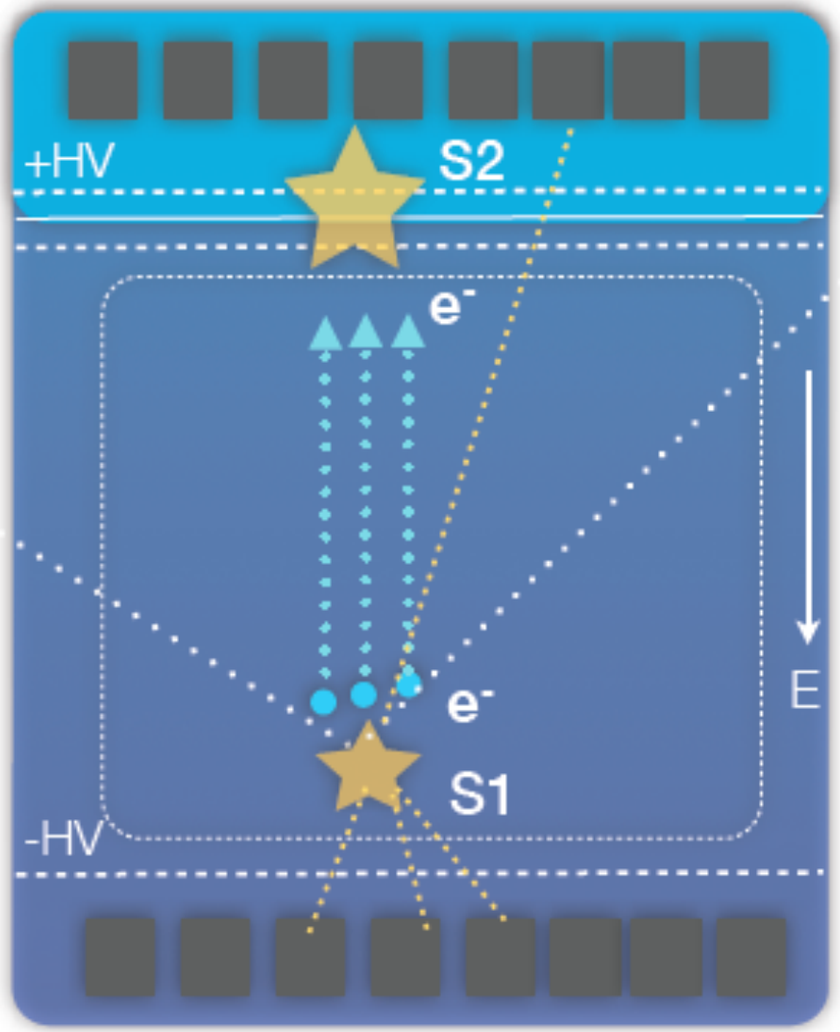


XMASS: Next Steps

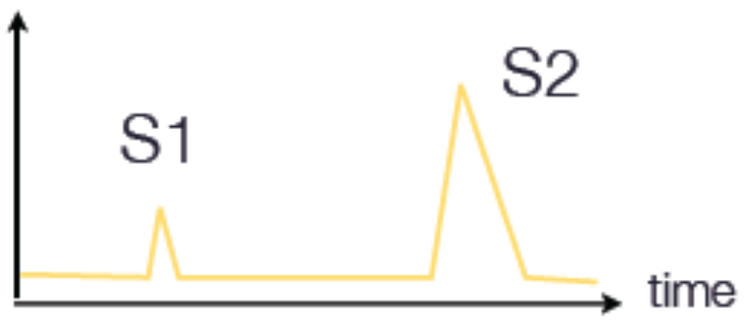


- XMASS1.5 → 5 ton total mass (3 ton fiducial)
- New PMTs to achieve 10^{-5} ev/keV/kg/day
- Projected Sensitivity: $\sigma_{SI} = 10^{-47}$ cm^2 @50 GeV and for the fiducial volume @ 2 keVee thresh
- Status: start in ~2017 ?
- XMASSII → 24 ton total mass (10 ton fiducial)

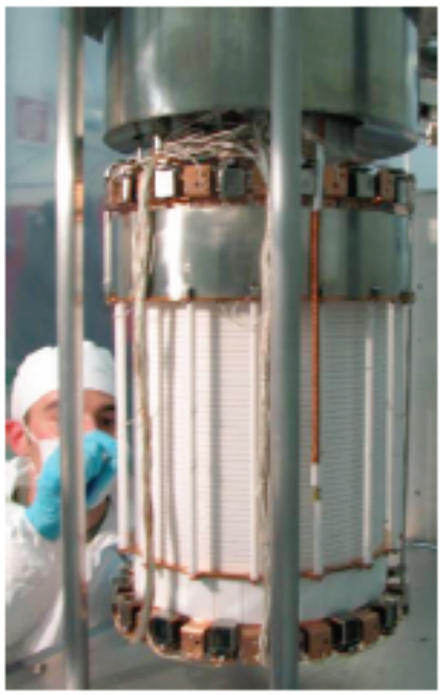
Dual-phase noble liquid detectors



PMT array



LXe: XENON100



LXe: LUX

LAr: DarkSide

XENON100 (LXe) and DarkSide (LAr) at LNGS

LUX (LXe) at SURF, PandaX (LXe) at CJPL

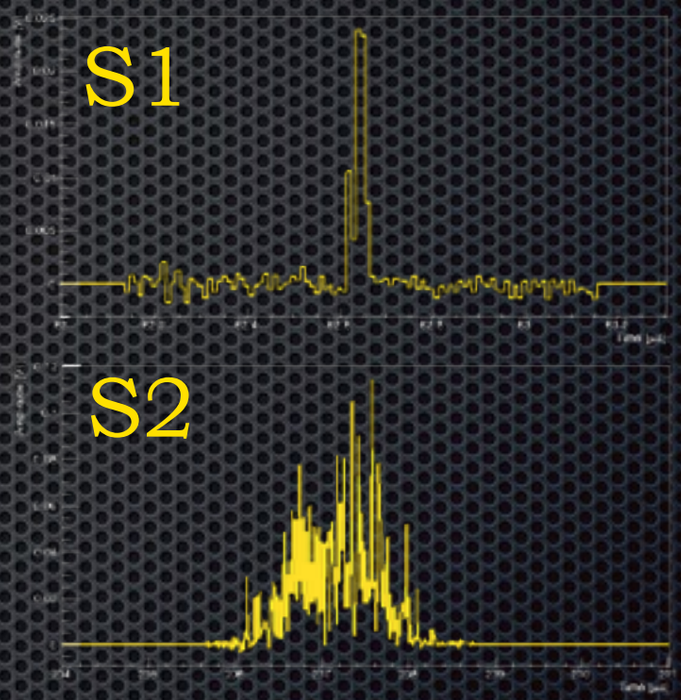
ArDM (LAr) at Canfranc

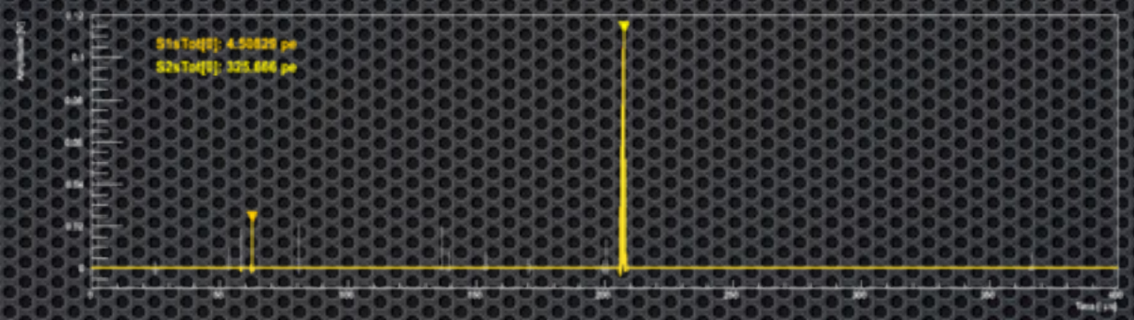
Target masses between ~ 50 kg - 1 ton

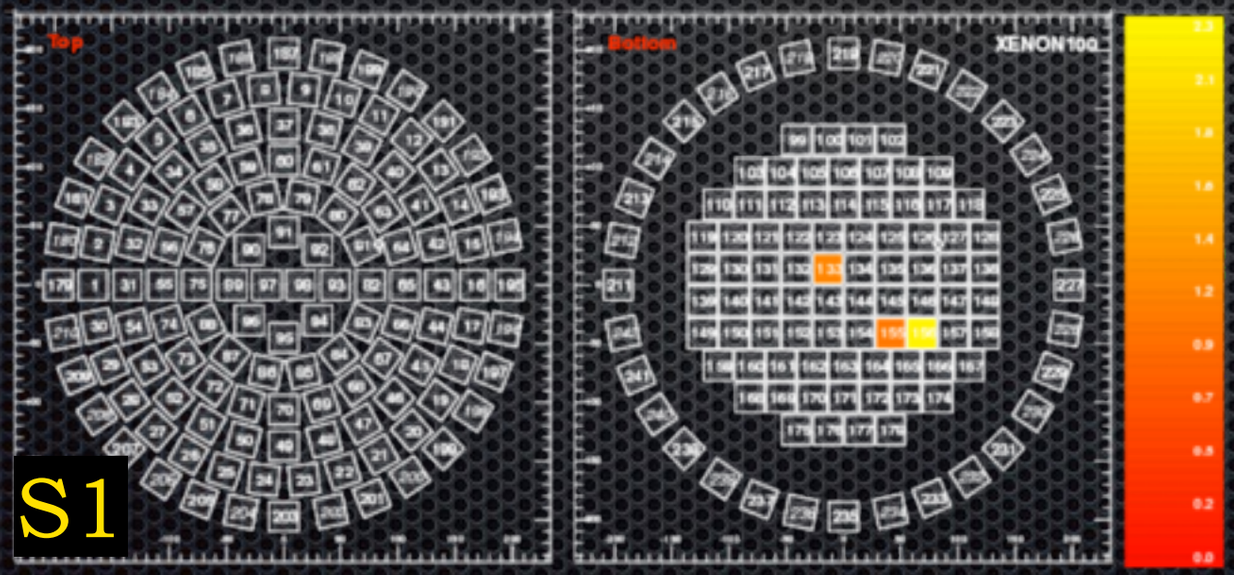
XENON100 Candidate, E~3keV$_{nr}$

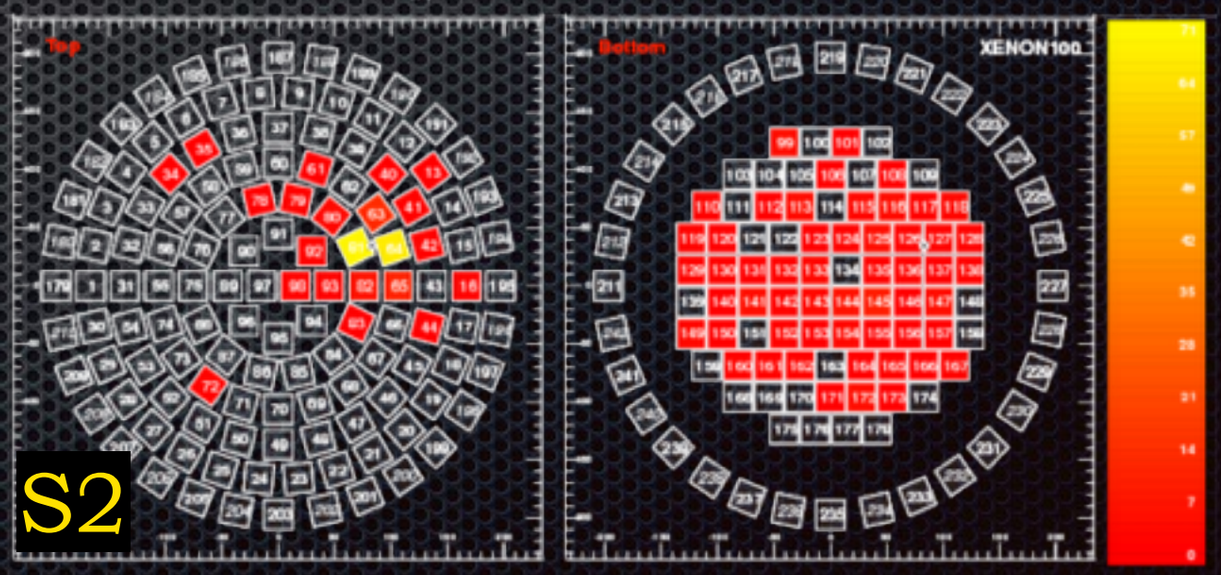
Ample information even at lowest energies:

- Scintillation S1 size and PMT pattern
- Ionization S2 size and PMT pattern
- Single/Multiple Scatter
- Electronic/Nuclear Recoil
- Vertex position
- S2 width
- Time



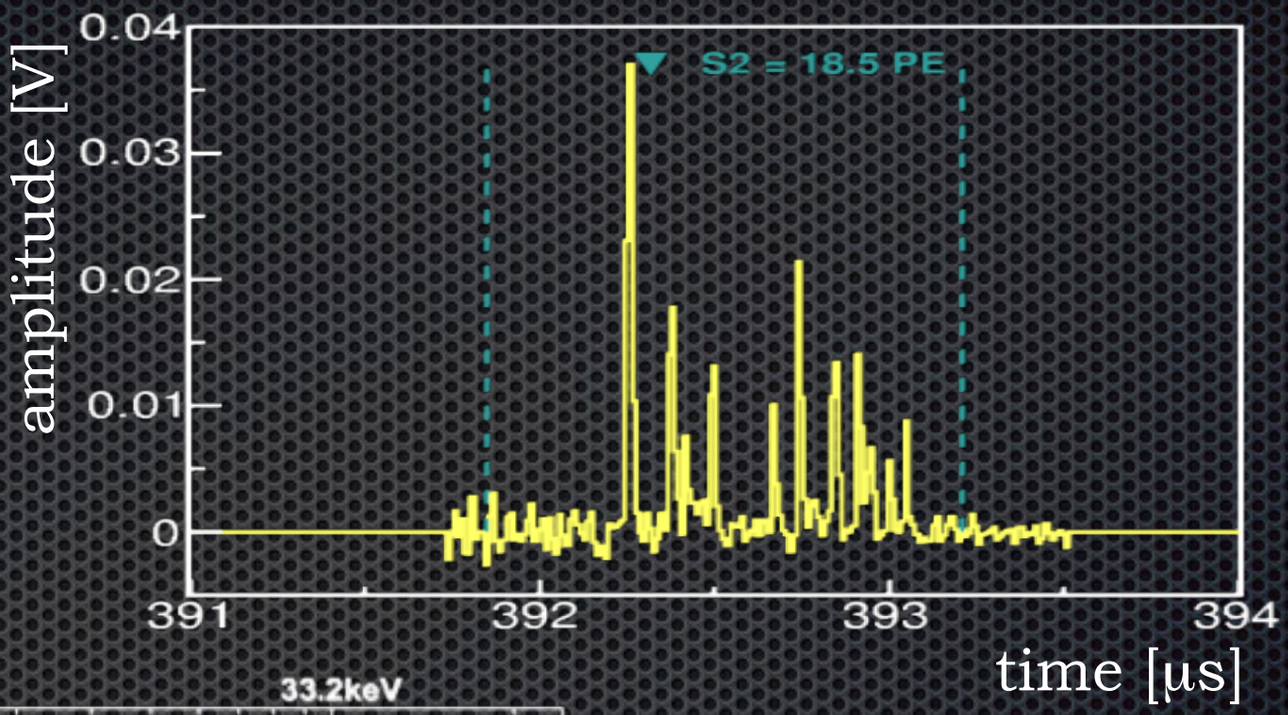




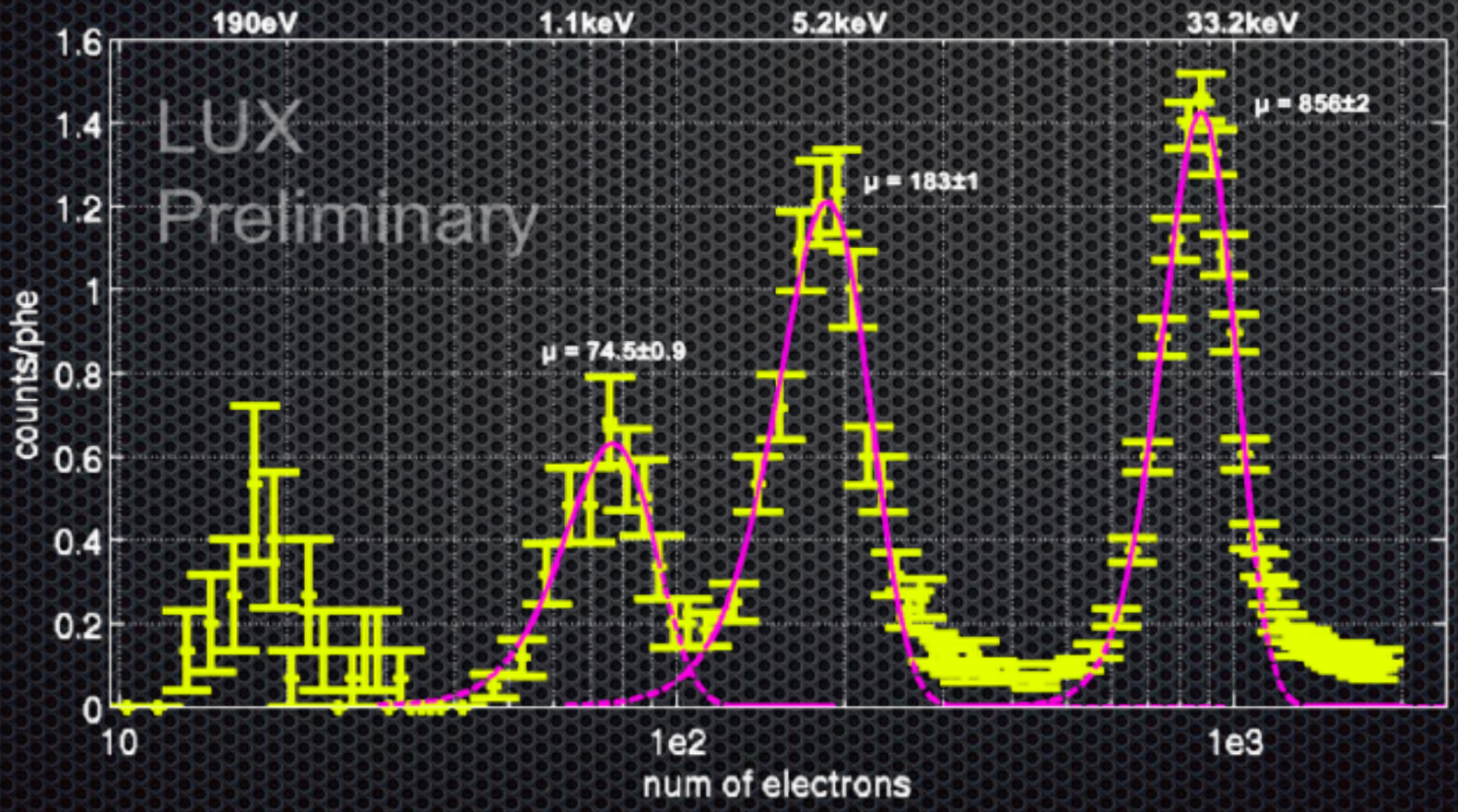


Extreme Low-Energy Sensitivity

Detect even individual electrons liberated in an interaction:



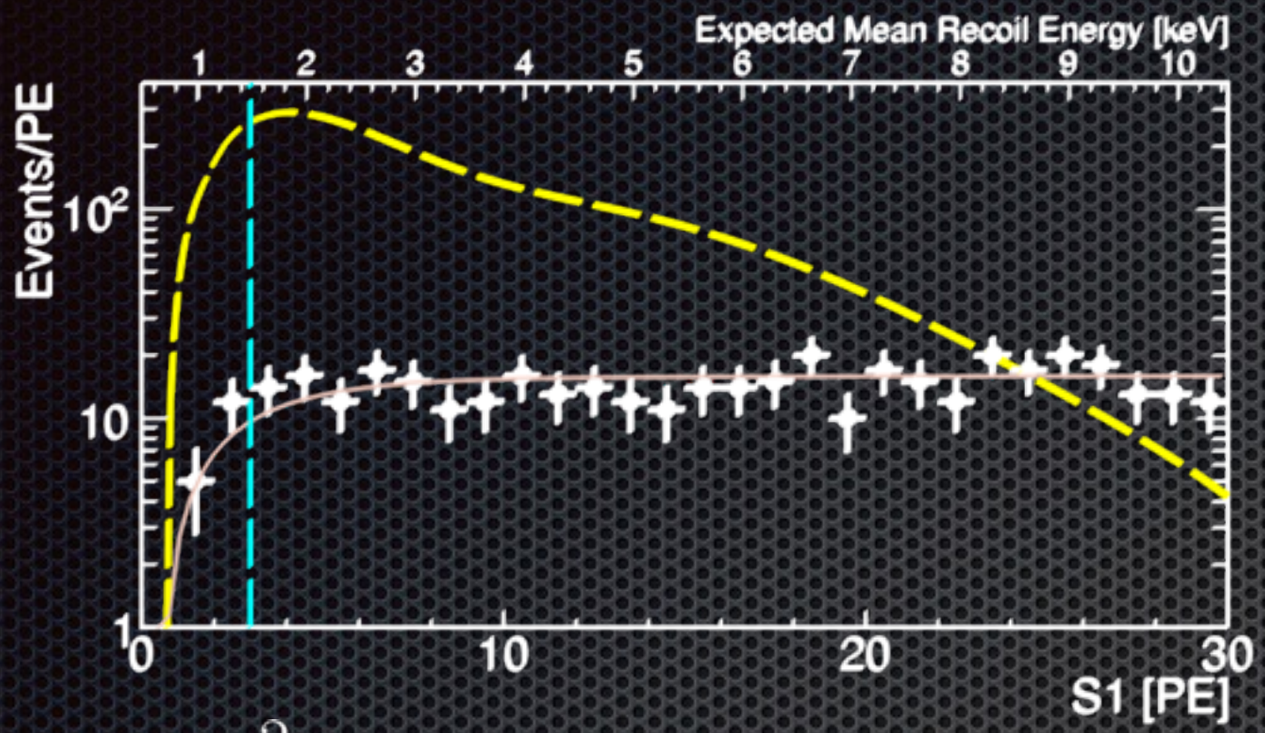
XENON100 1311.1088



LUX D.Huang APS2015

^{127}Xe EC calibration as low as 190 eV

Ultra-low Background: XENON100 Solar Axion Search



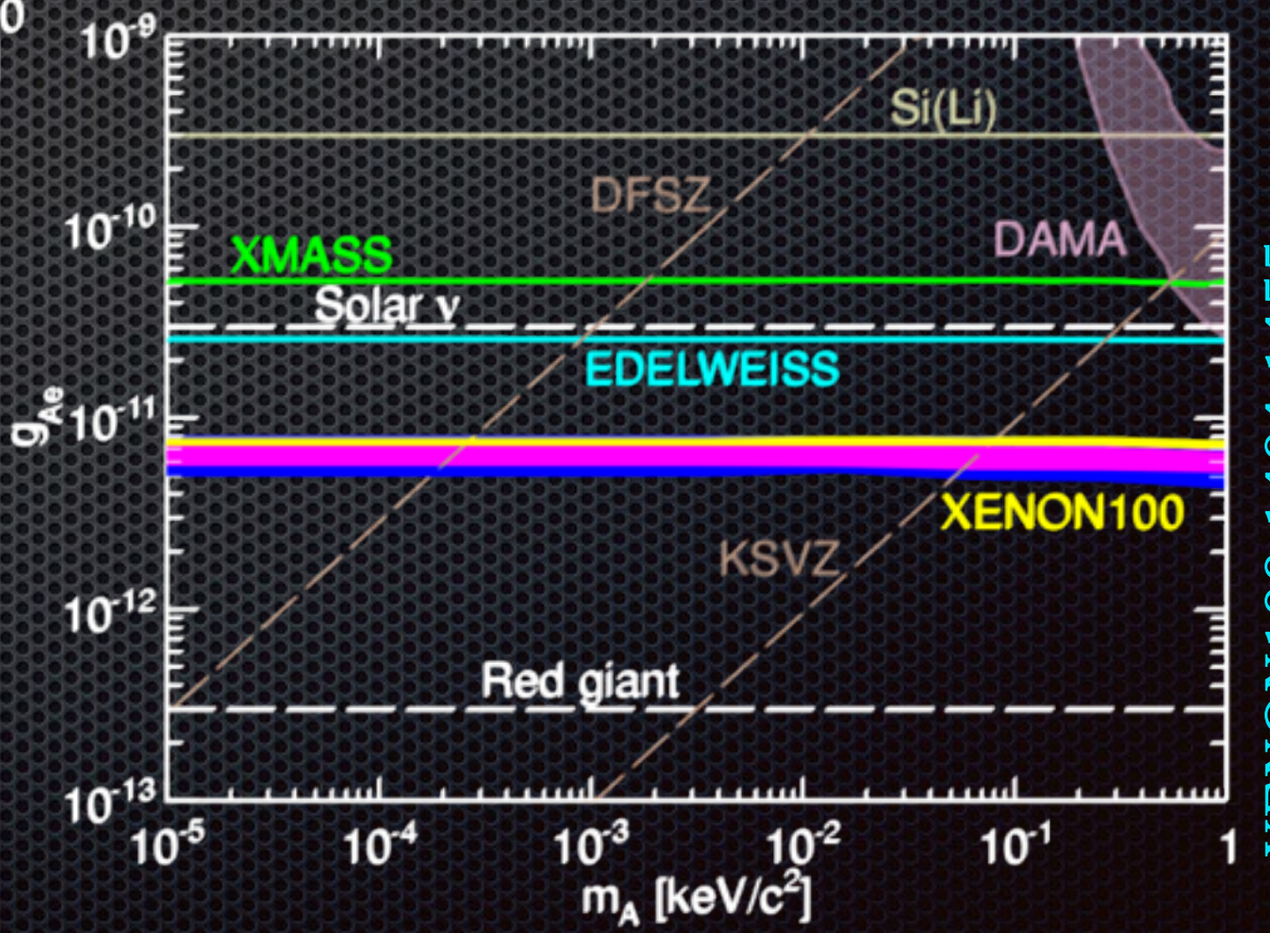
$$\sigma \propto g_{Ae}^2$$

$$\phi_A \propto g_{Ae}^2$$

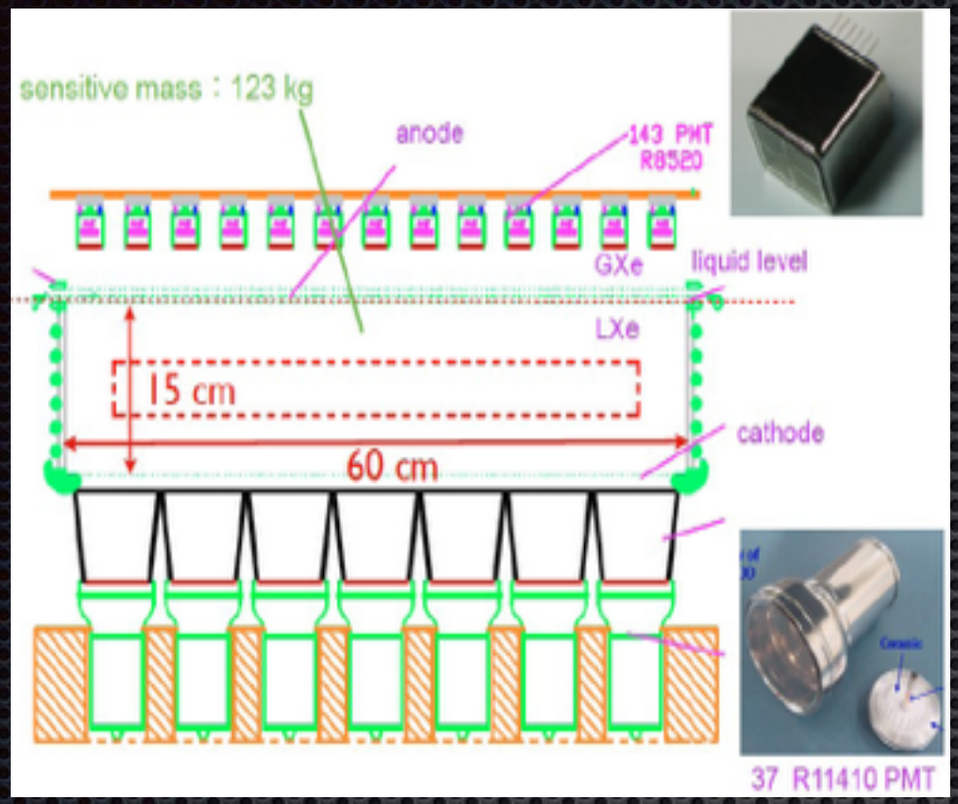
$$\Rightarrow \text{rate} \propto g_{Ae}^4$$

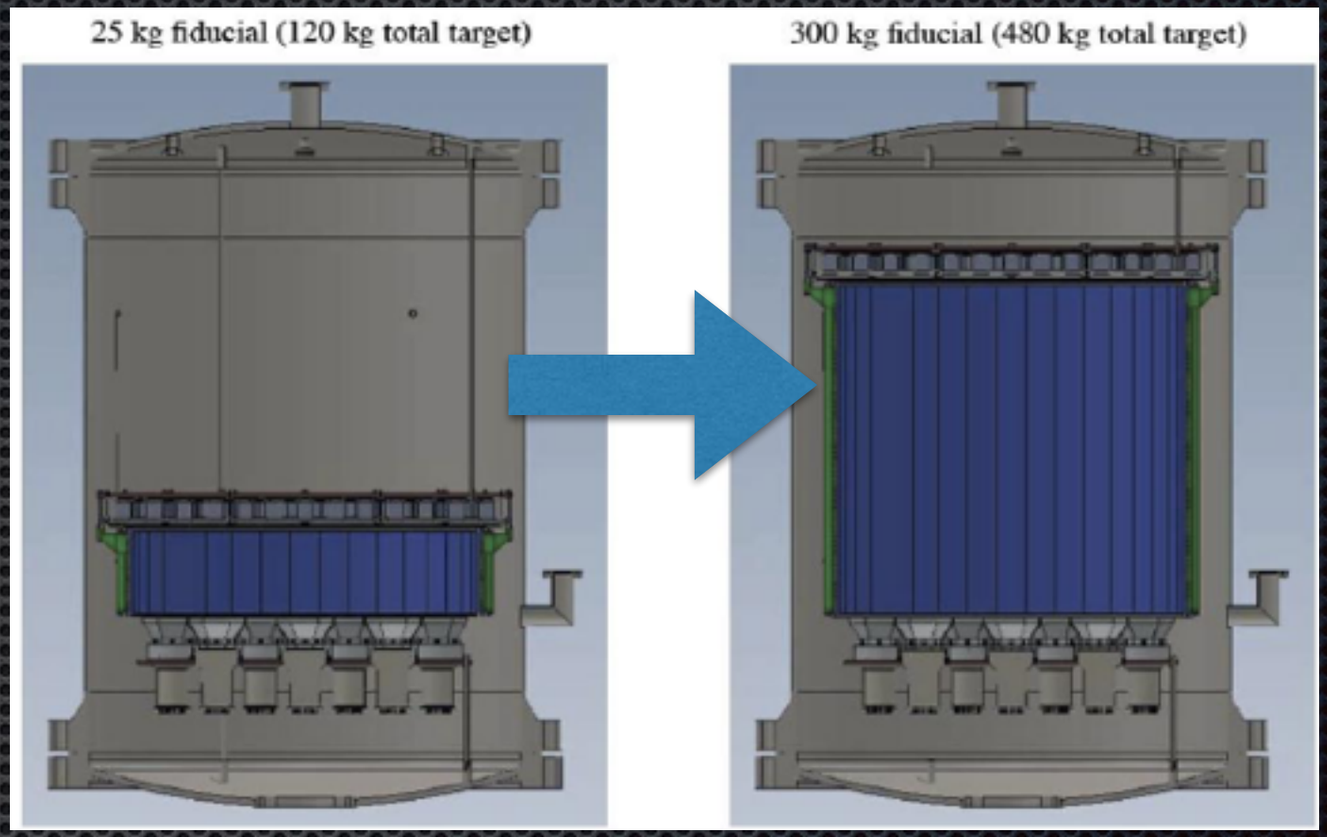
exclude QCD axions
> 0.3 eV (DFSZ)
> 80 eV (KSVZ)
also derived limit on ALPs

use ER background
to search for axions
coupling to electrons via
axio-electric effect g_{Ae}



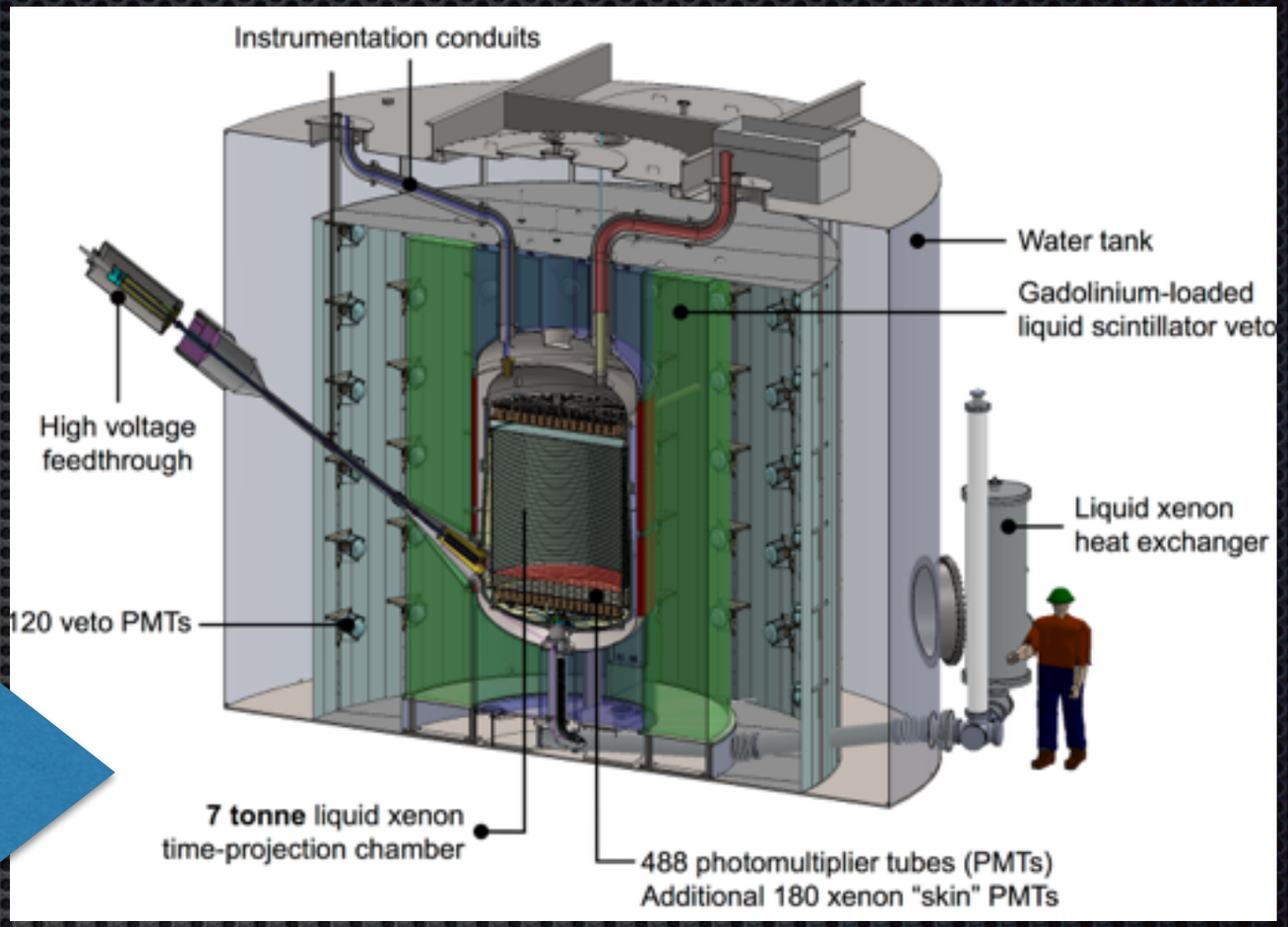
PandaX: Next Steps





- 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 ?

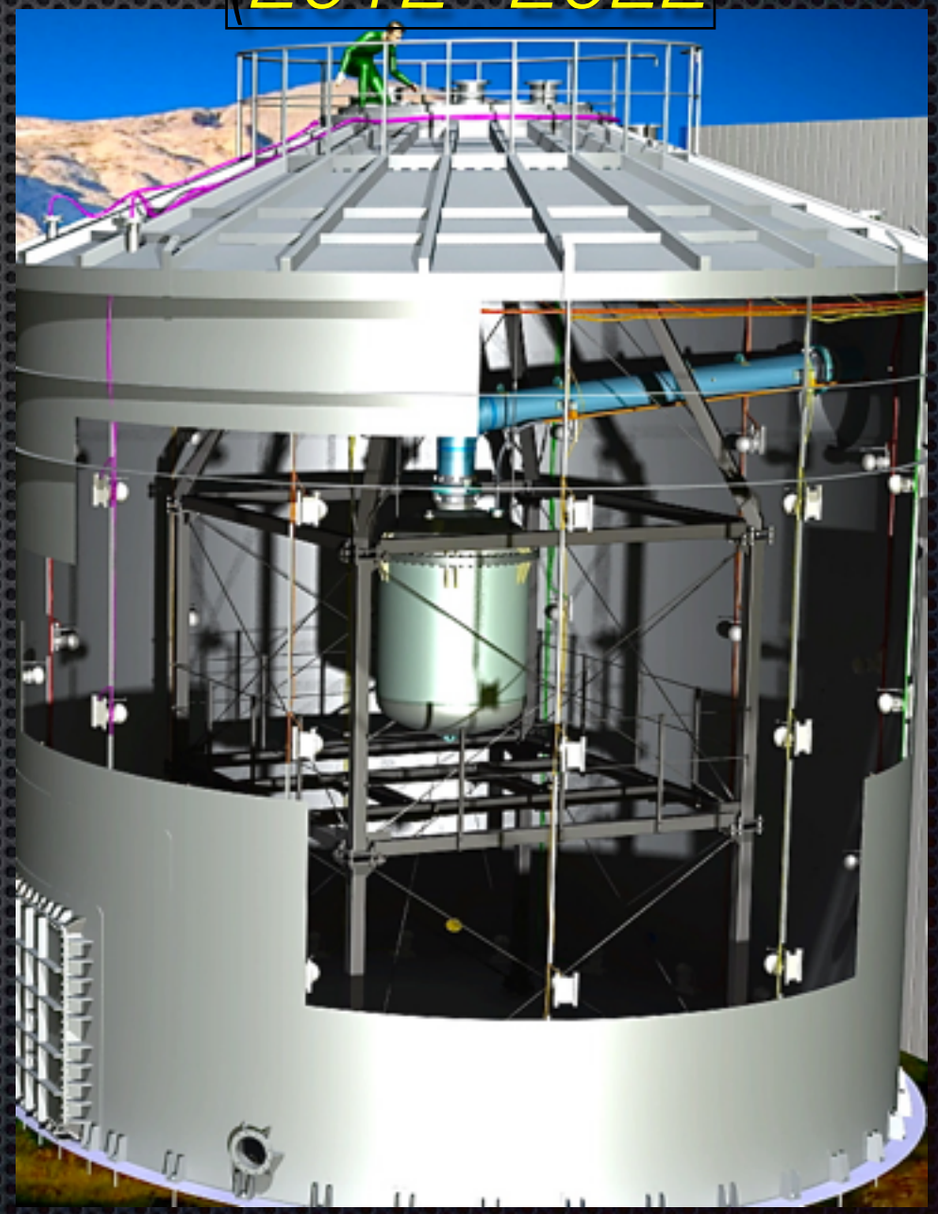
XENON @ LNGS: Next Steps

2007-2015

XENON100

30 cm drift TPC - 161 kg

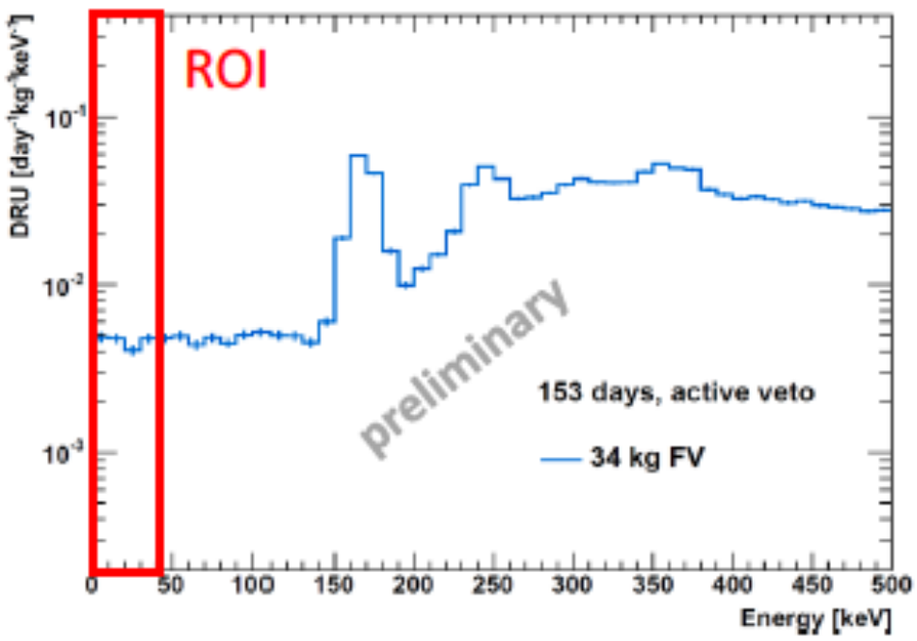
2012- 2022

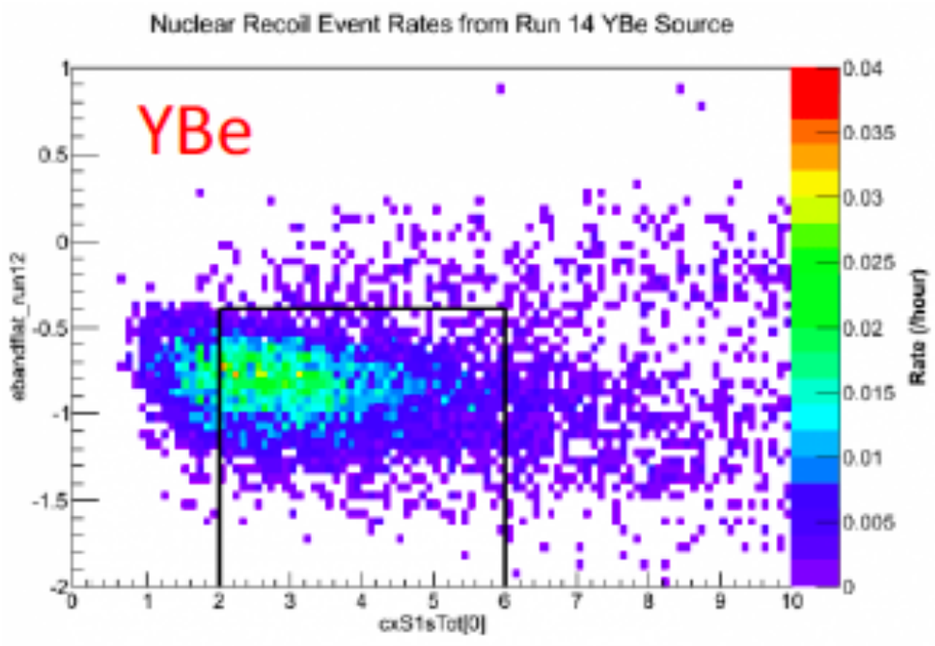


XENON1T/XENONnT

100 cm drift TPC - 3300 kg/7000 kg

XENON100: upcoming results this year





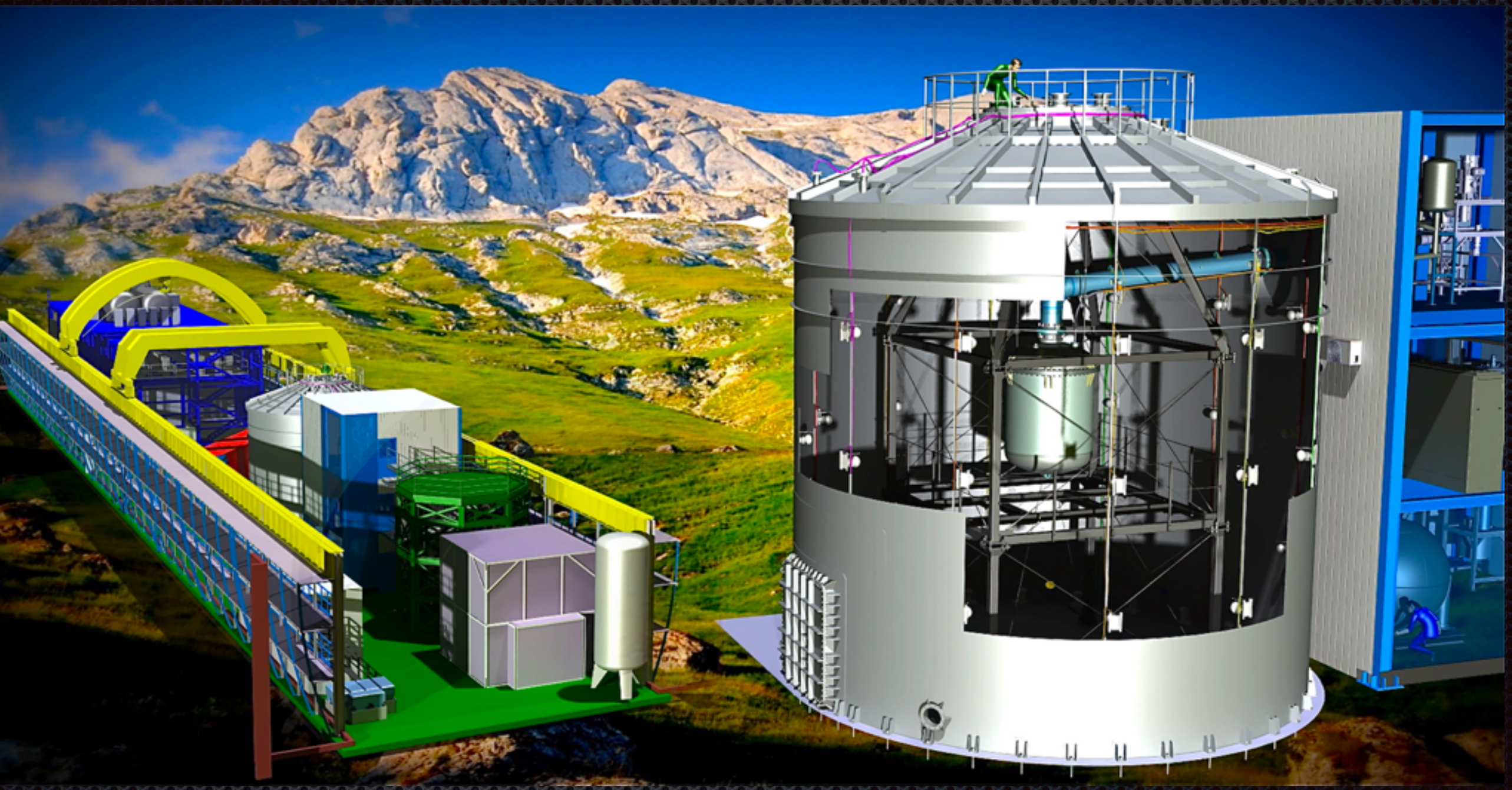
- Search for annual modulation (2 papers submitted)
- Analysis of 153 live days of blinded dark matter search data close to unblinding; search for inelastic scattering on ^{129}Xe, search for low-mass WIMPs
- Calibration measurements:
  - probe lowest nuclear recoil energies (max at 4.5 keVnr) with YBe source placed inside the shield; more than 80 live days collected and clear signal due to neutron scatters observed
  - currently ^{83m}Kr calibration run & analysis
- XENON100 is also used as a test facility for XENON1T/nT: novel online radon purification technique, by cryogenic distillation (Rn has 10 x lower vapour pressure than xenon) verified

XENON1T /nT: in a nutshell

XENON1T /nT: in a nutshell

- **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 Cherenkov muon veto.
- **Background 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

MPIK

UCLA

Bern

Rice

University of Zurich

Zurich

Purdue

Coimbra

Subatech

Bologna

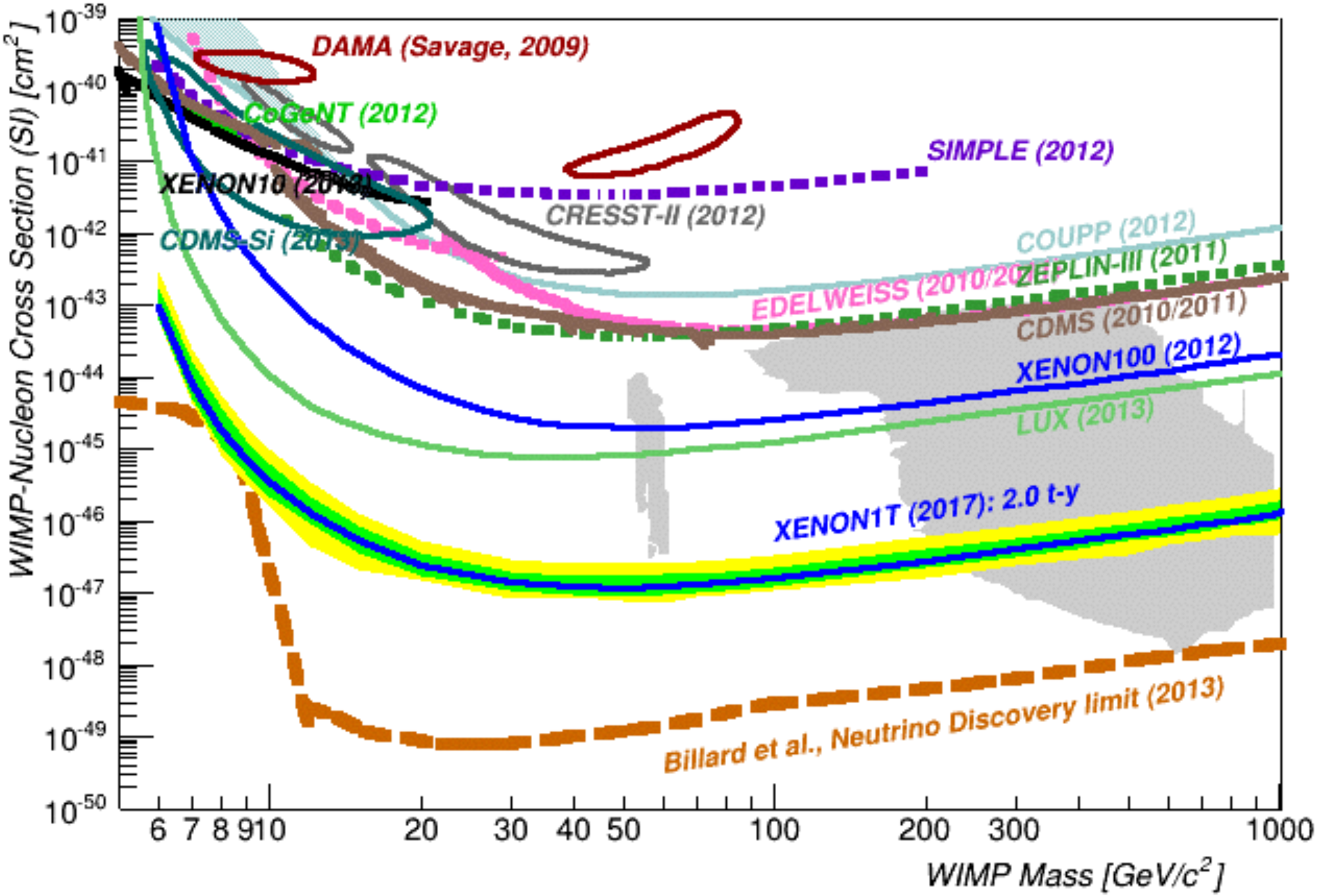
LNGS

Torino

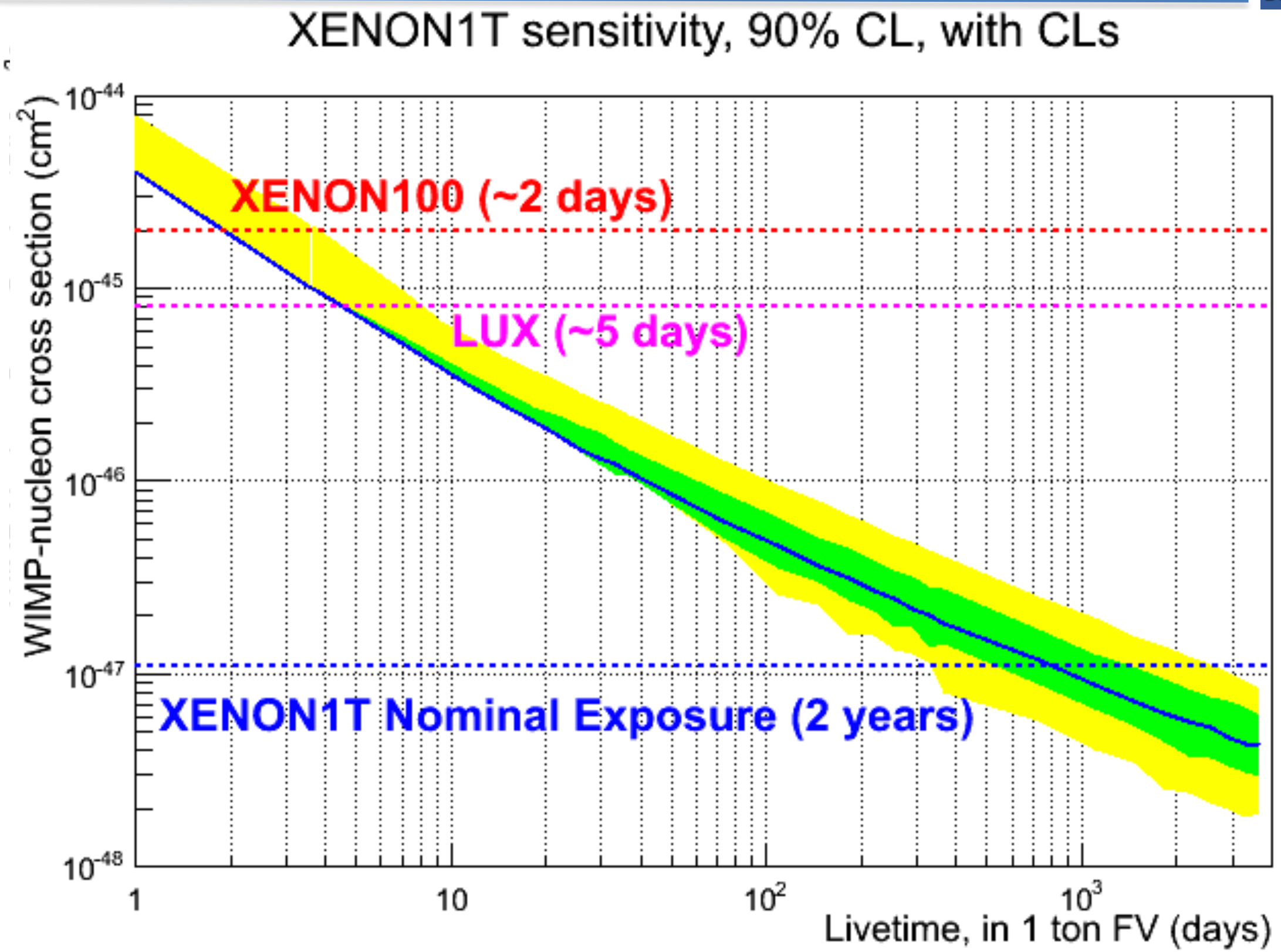
Weizmann

NYUAD

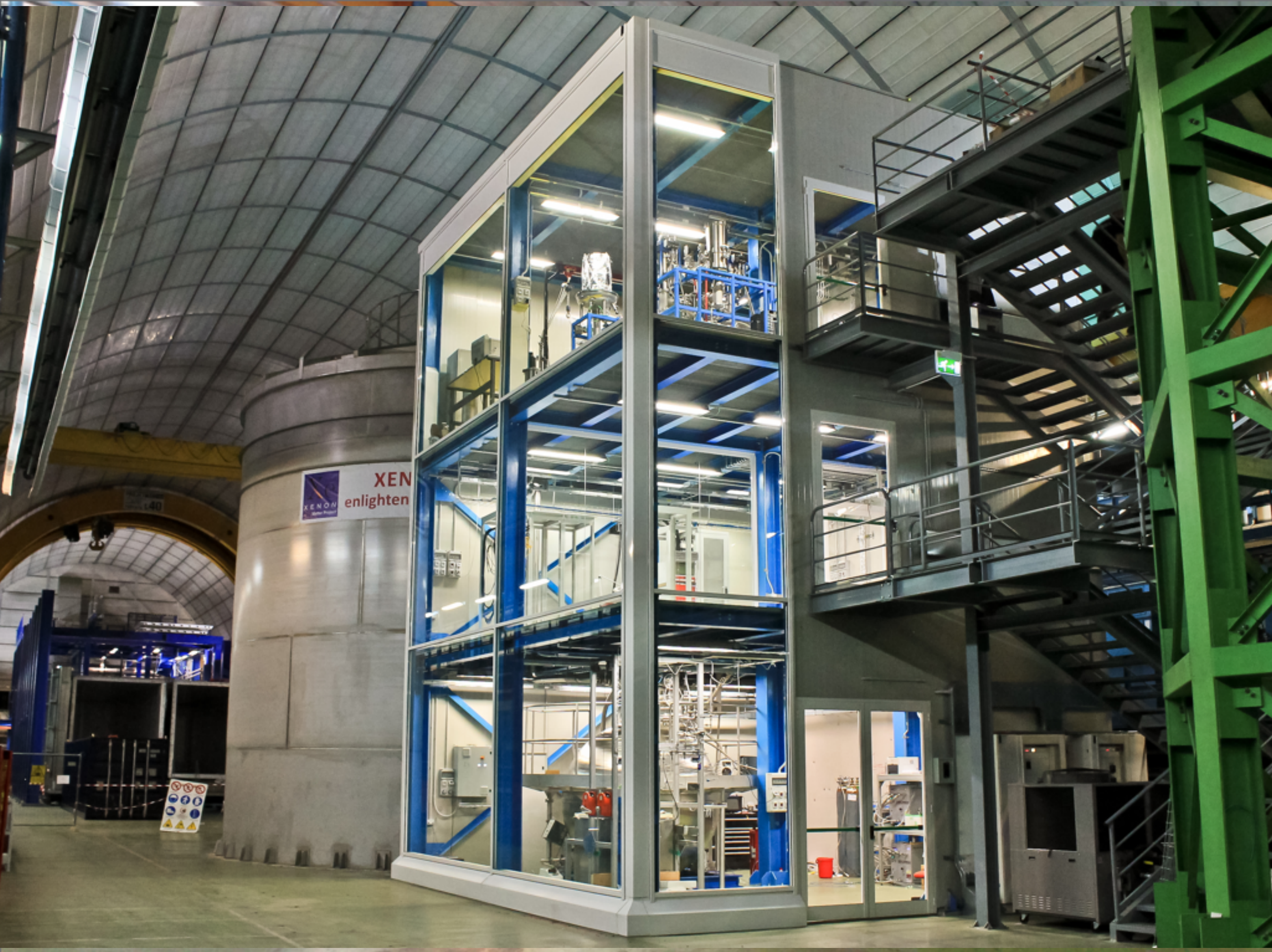
XENON1T sensitivity



XENON1T sensitivity

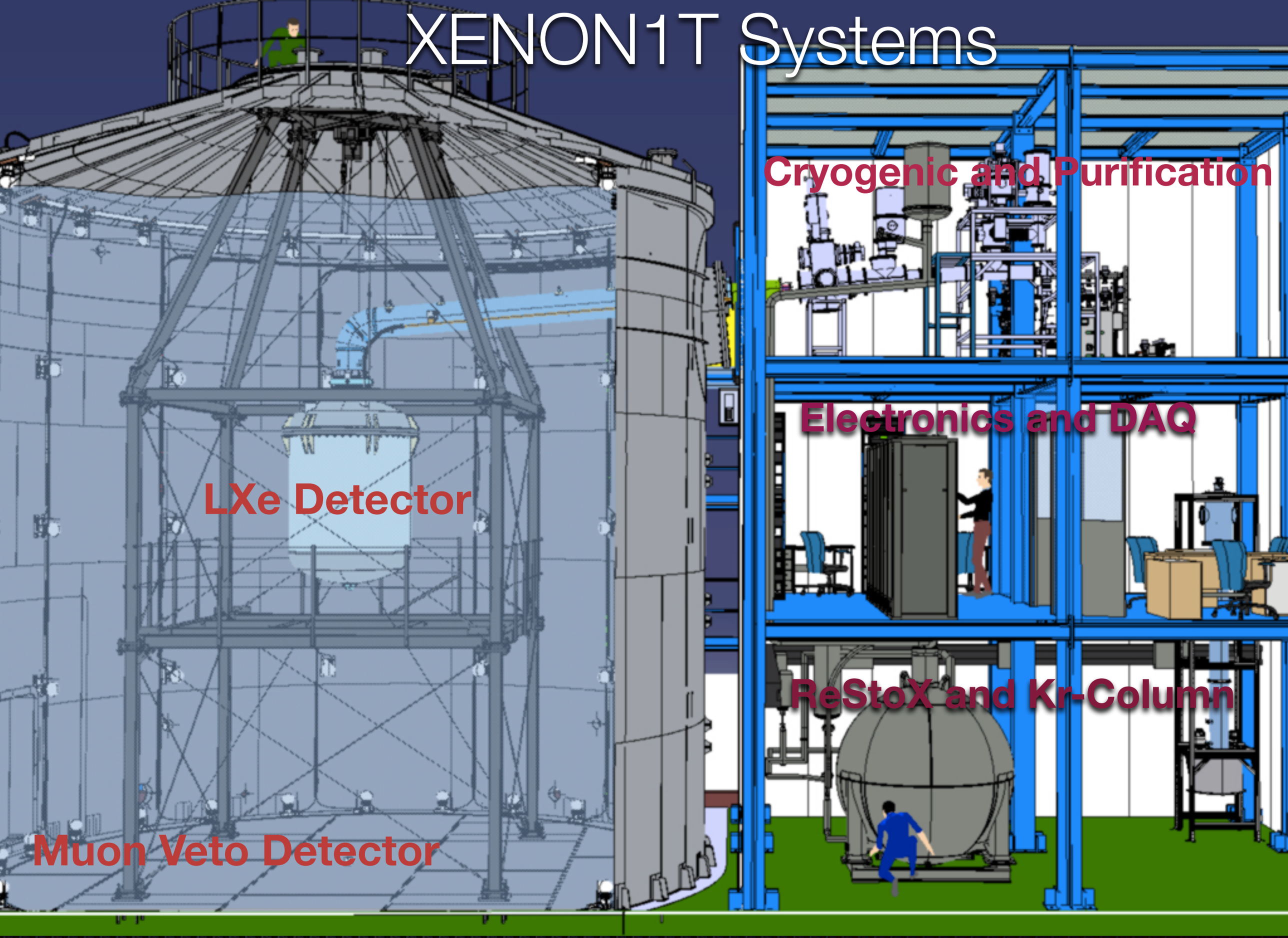


July 2013

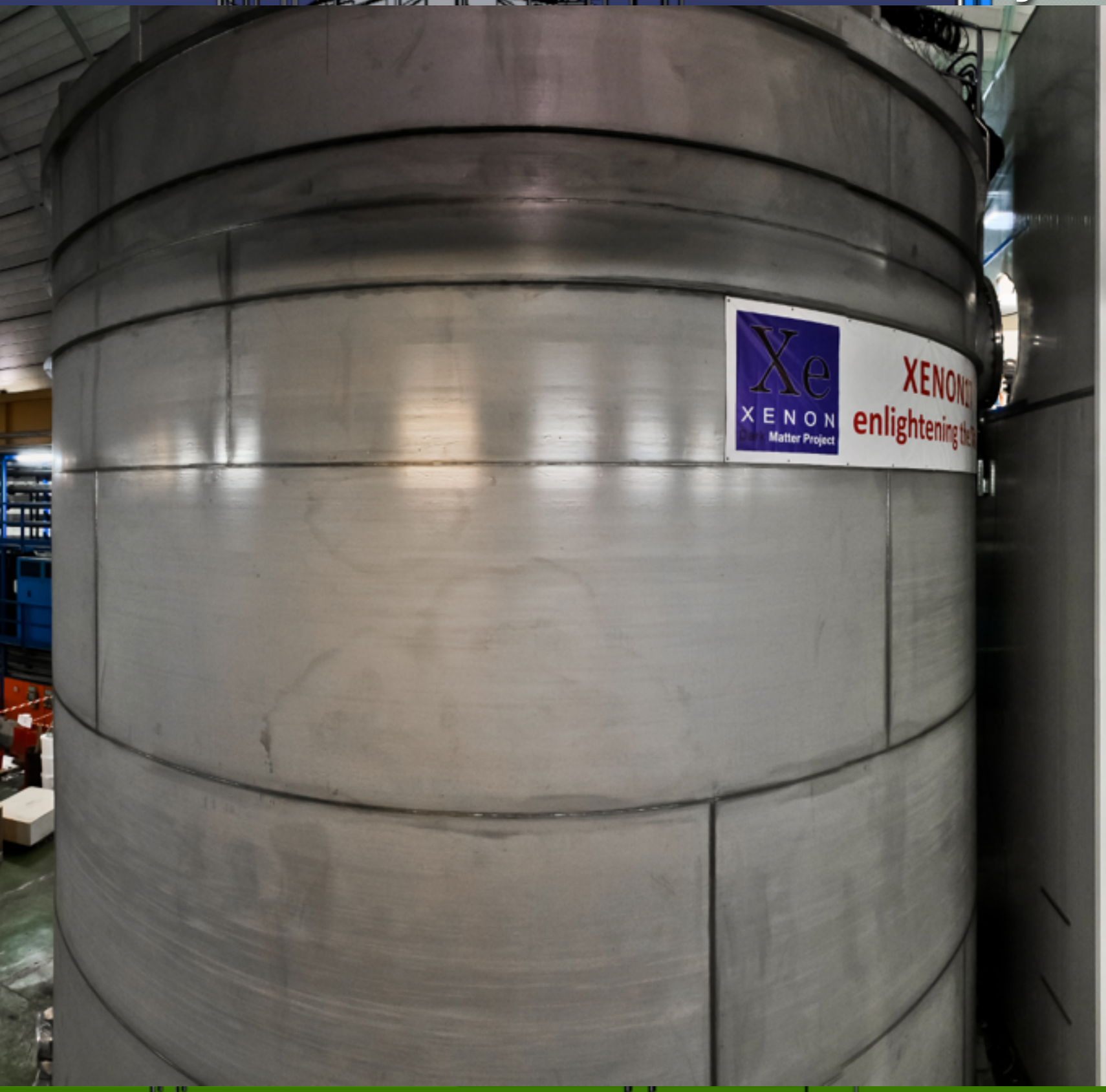

XEN
enlighten

June 2015

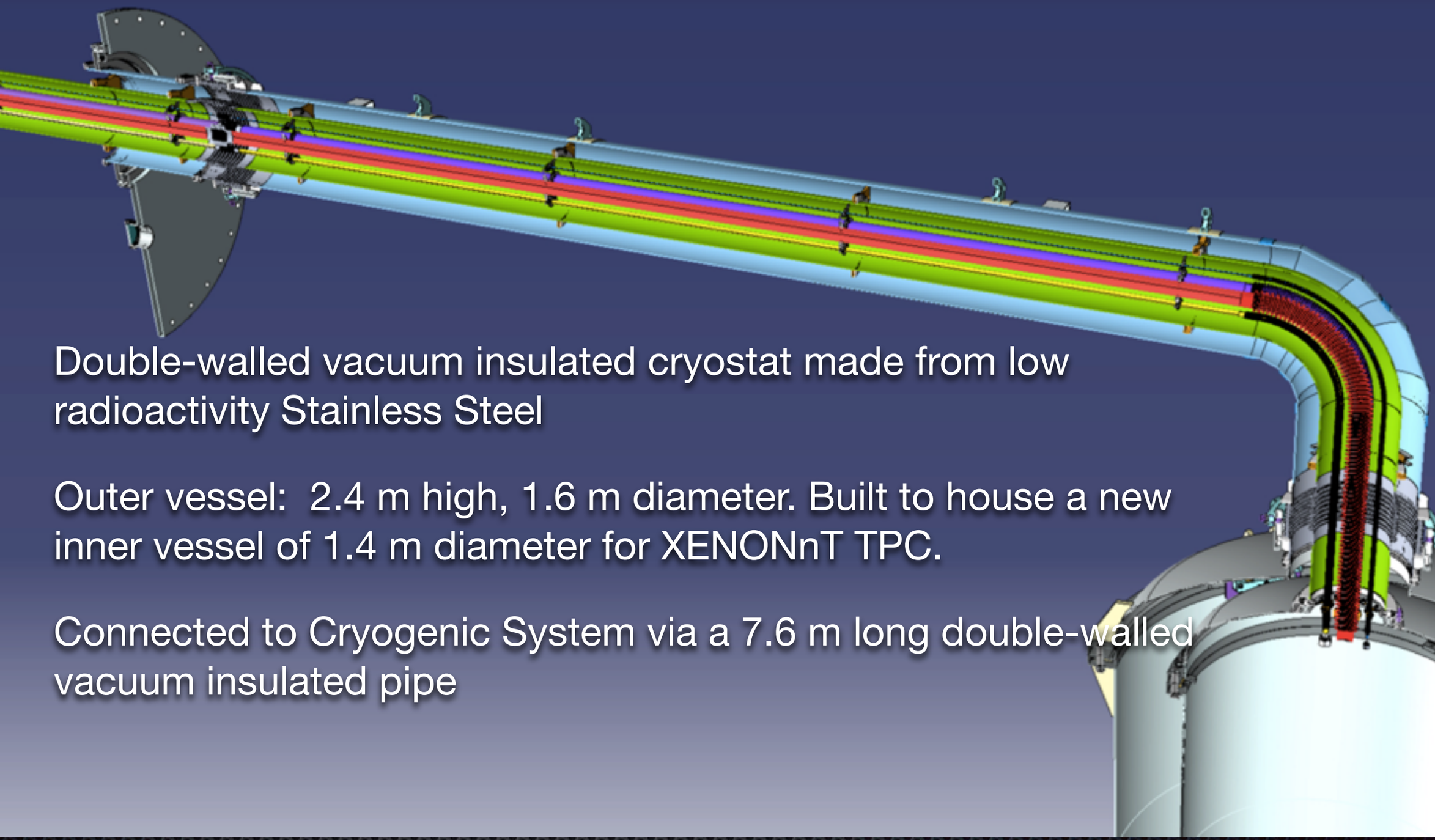
XENON1T Systems



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

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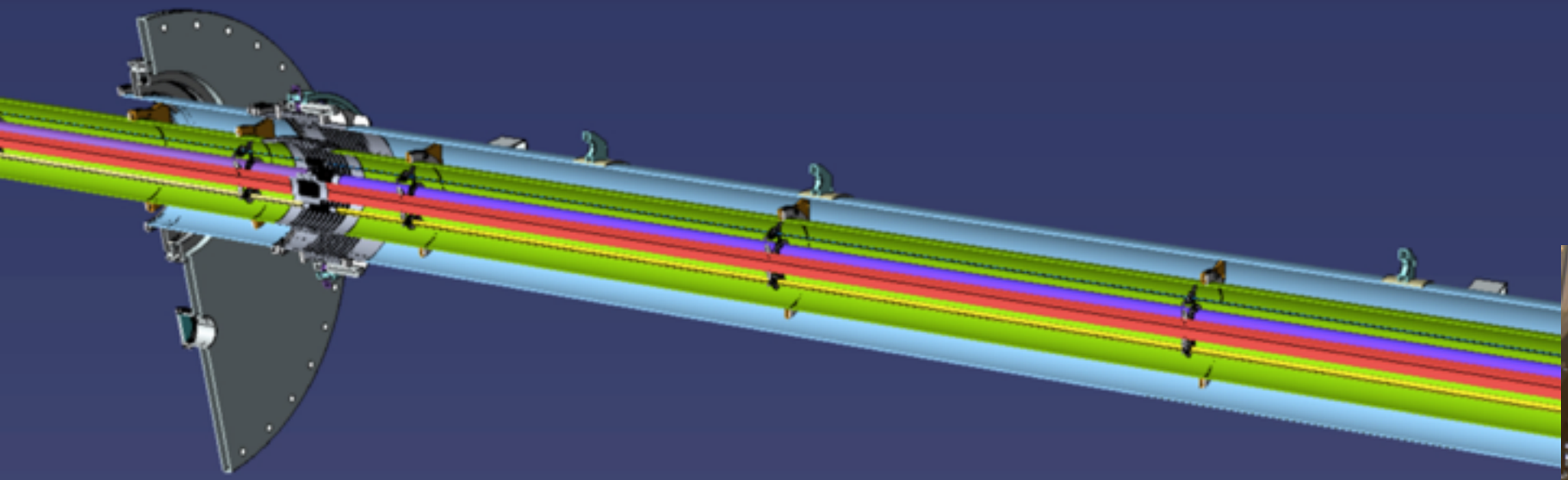

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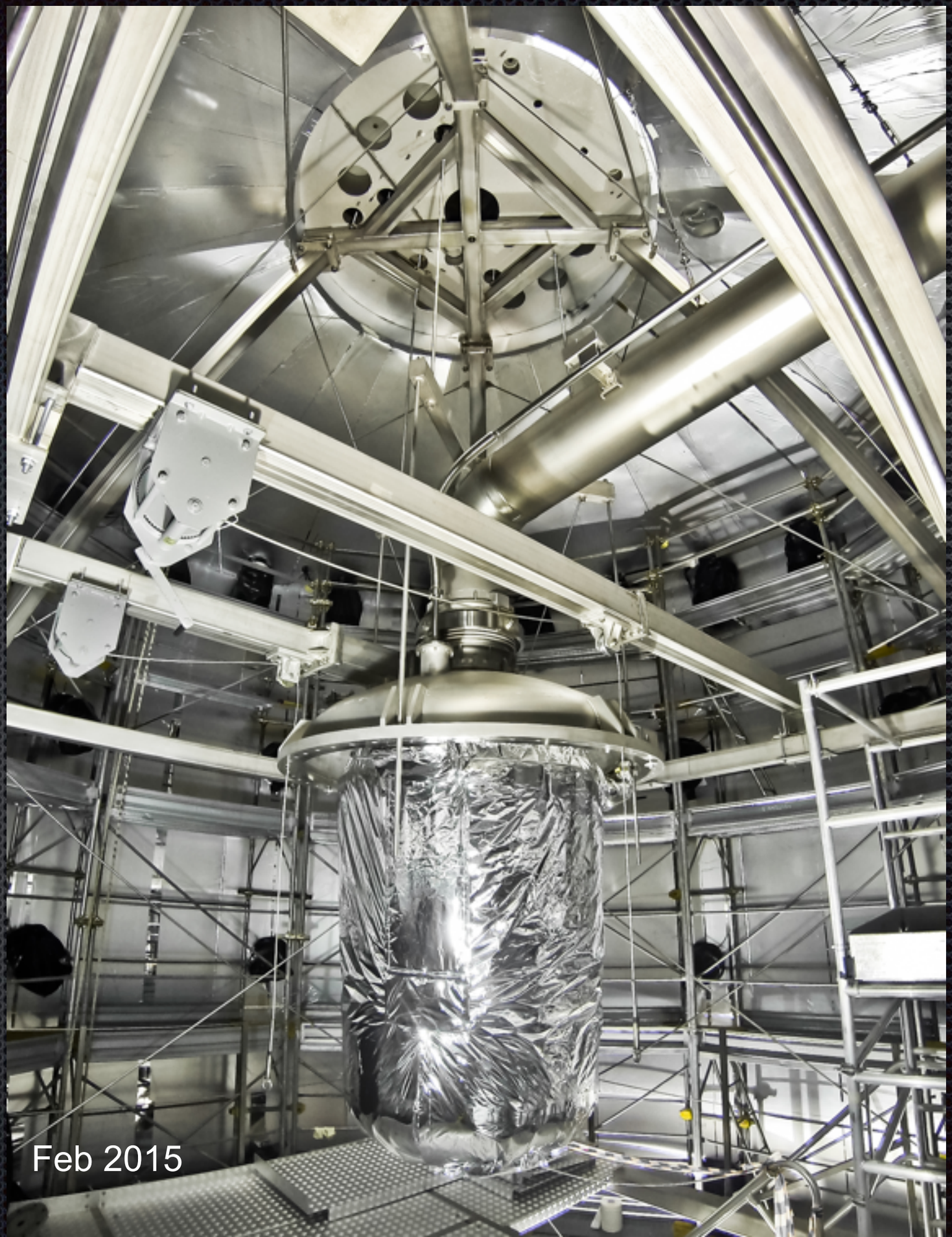
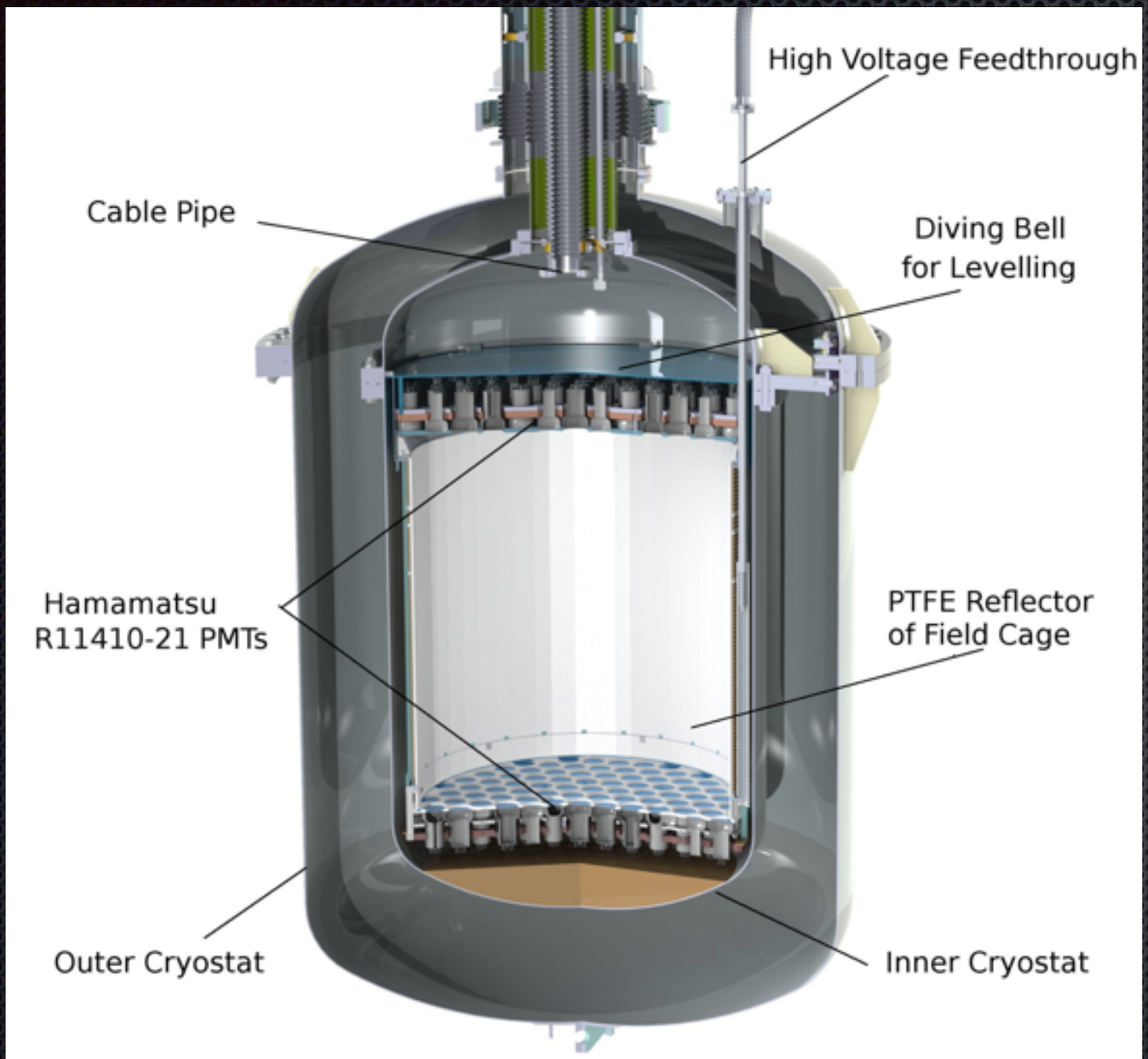

Feb 2015

XENON1T TPC



a larger and improved version of the XENON100 detector

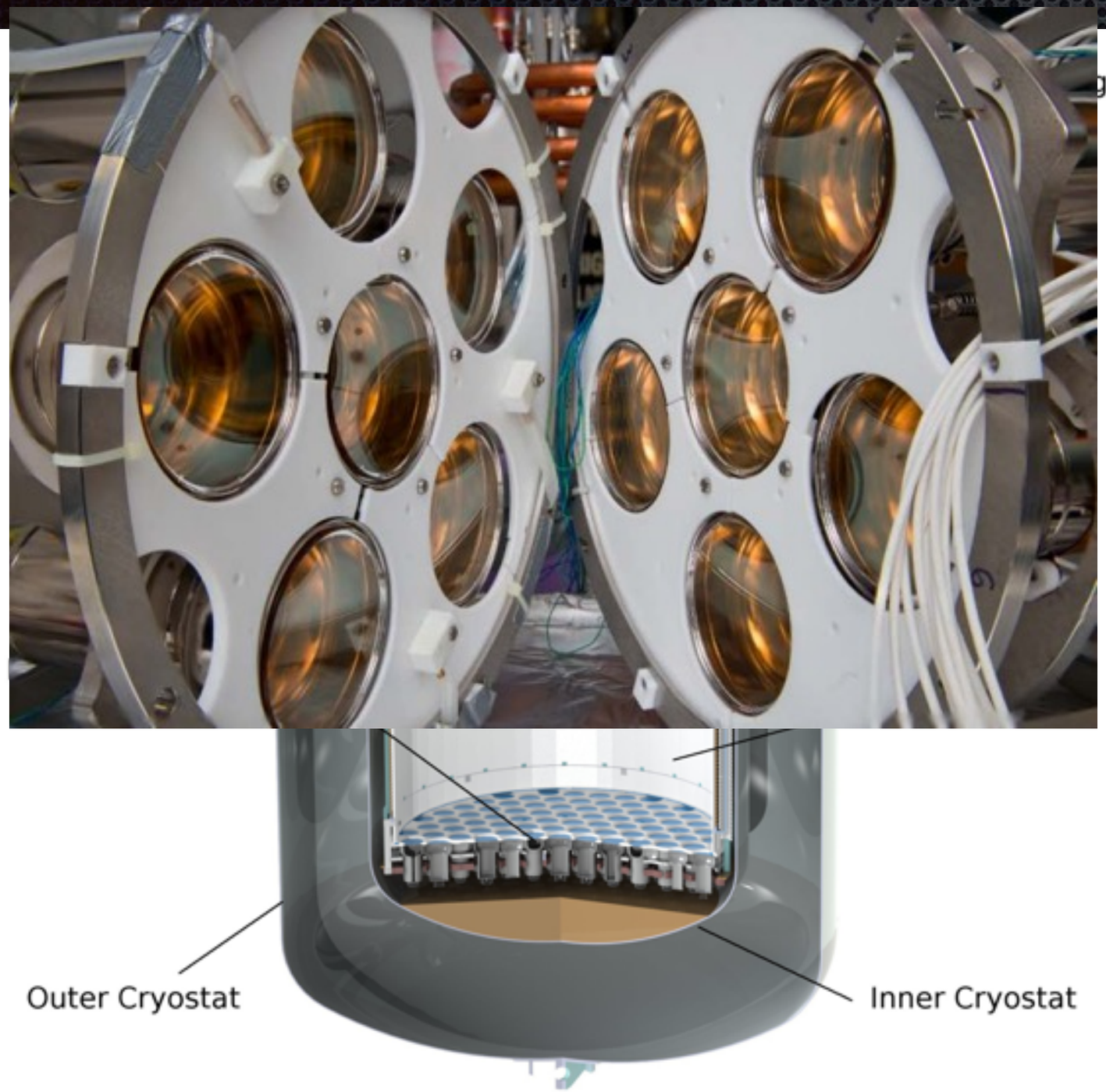
More extensive materials selection to control background, particularly from Rn

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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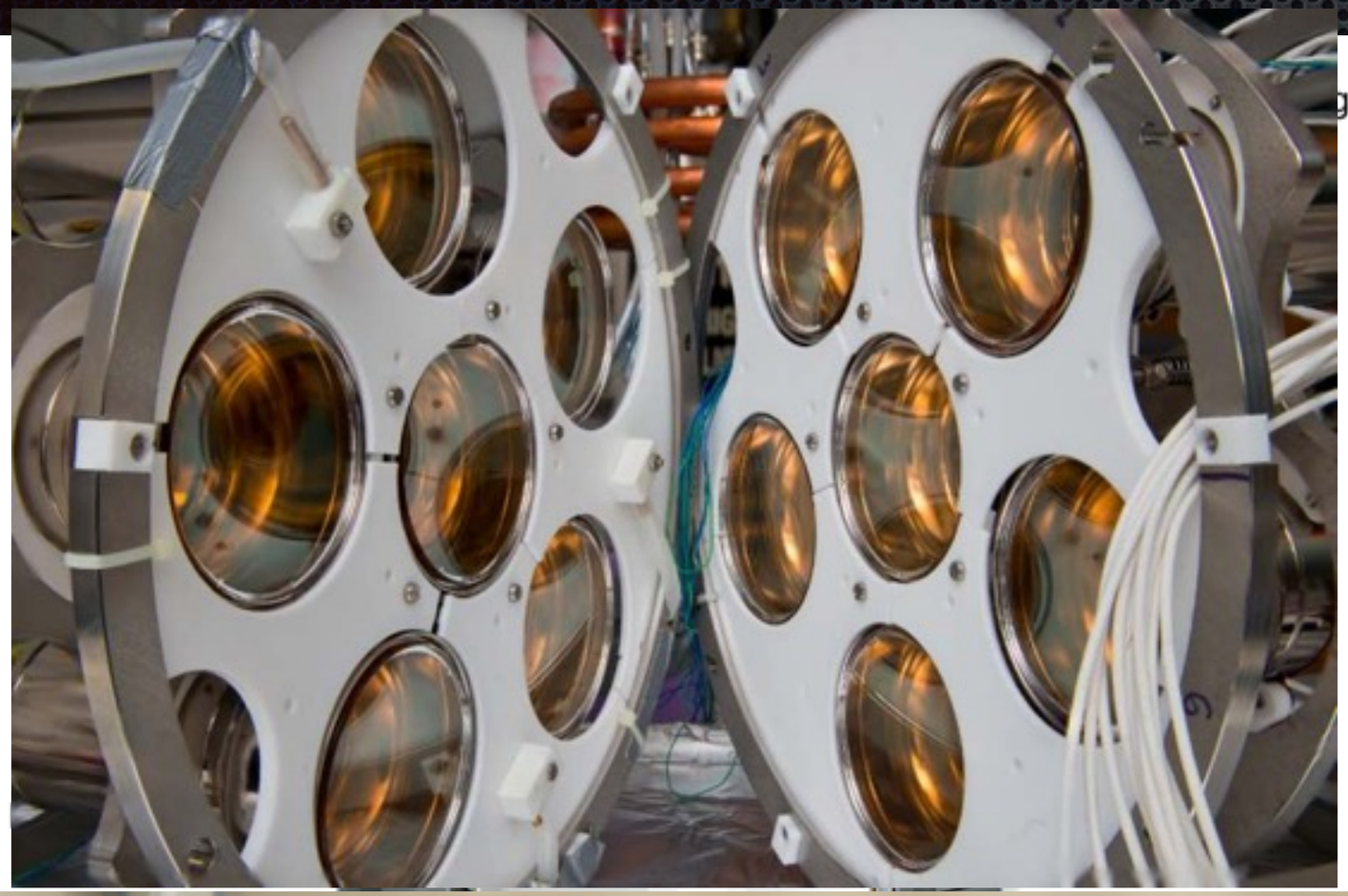

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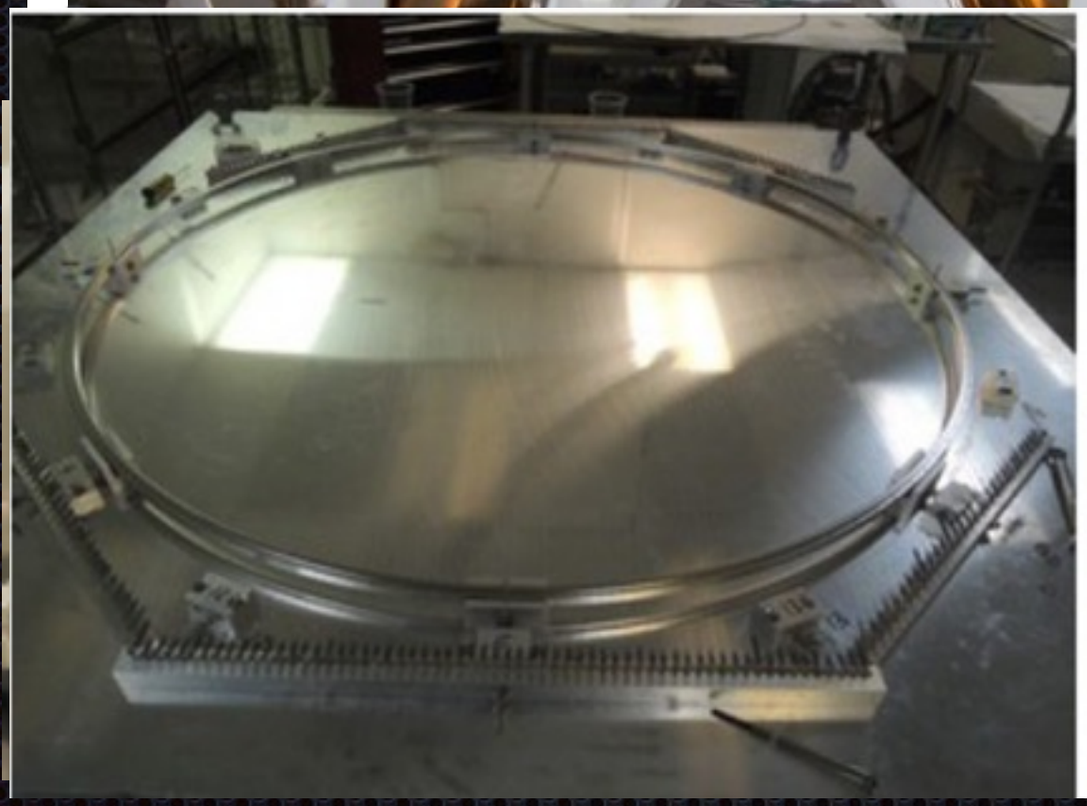

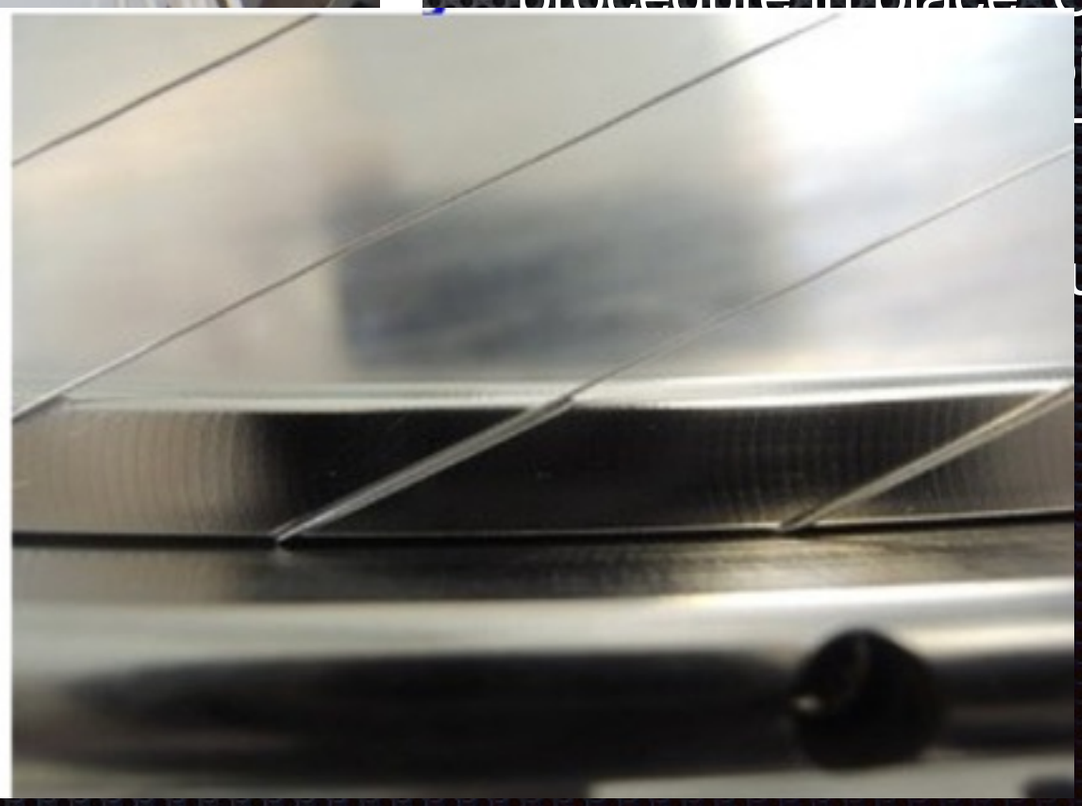

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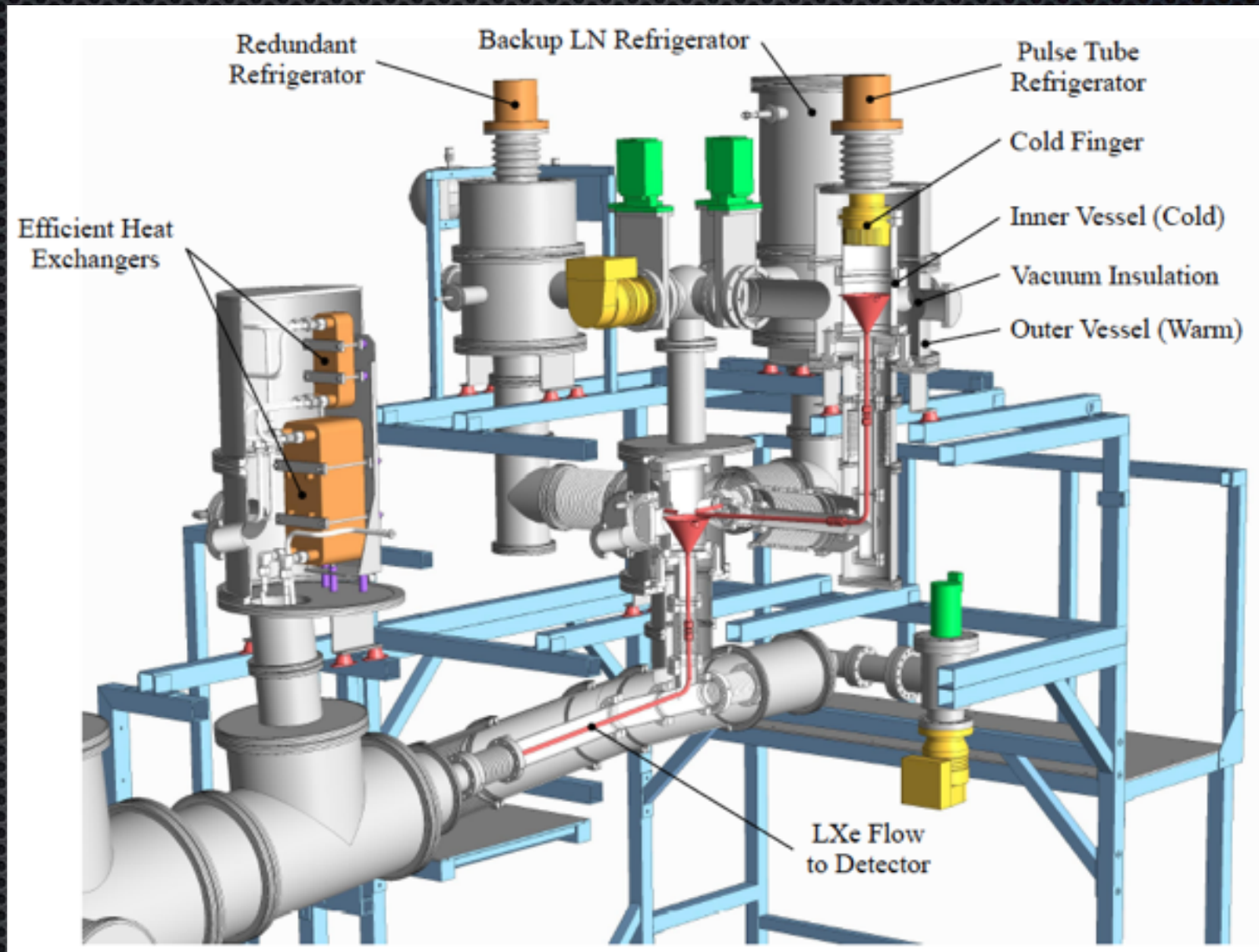
Cryogenic System

- 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

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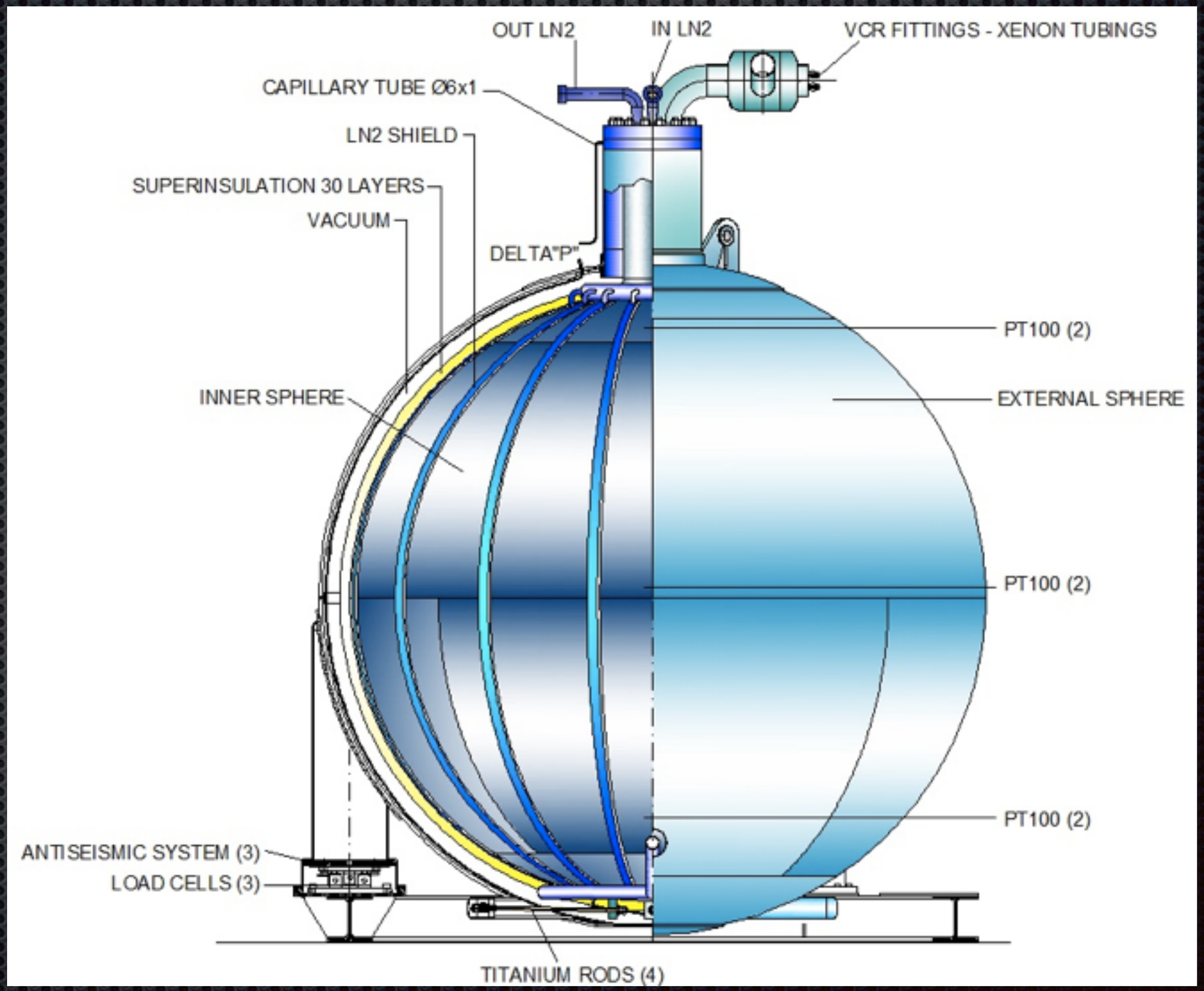
ReStoX System (Recovery & Storage of Xe)

- 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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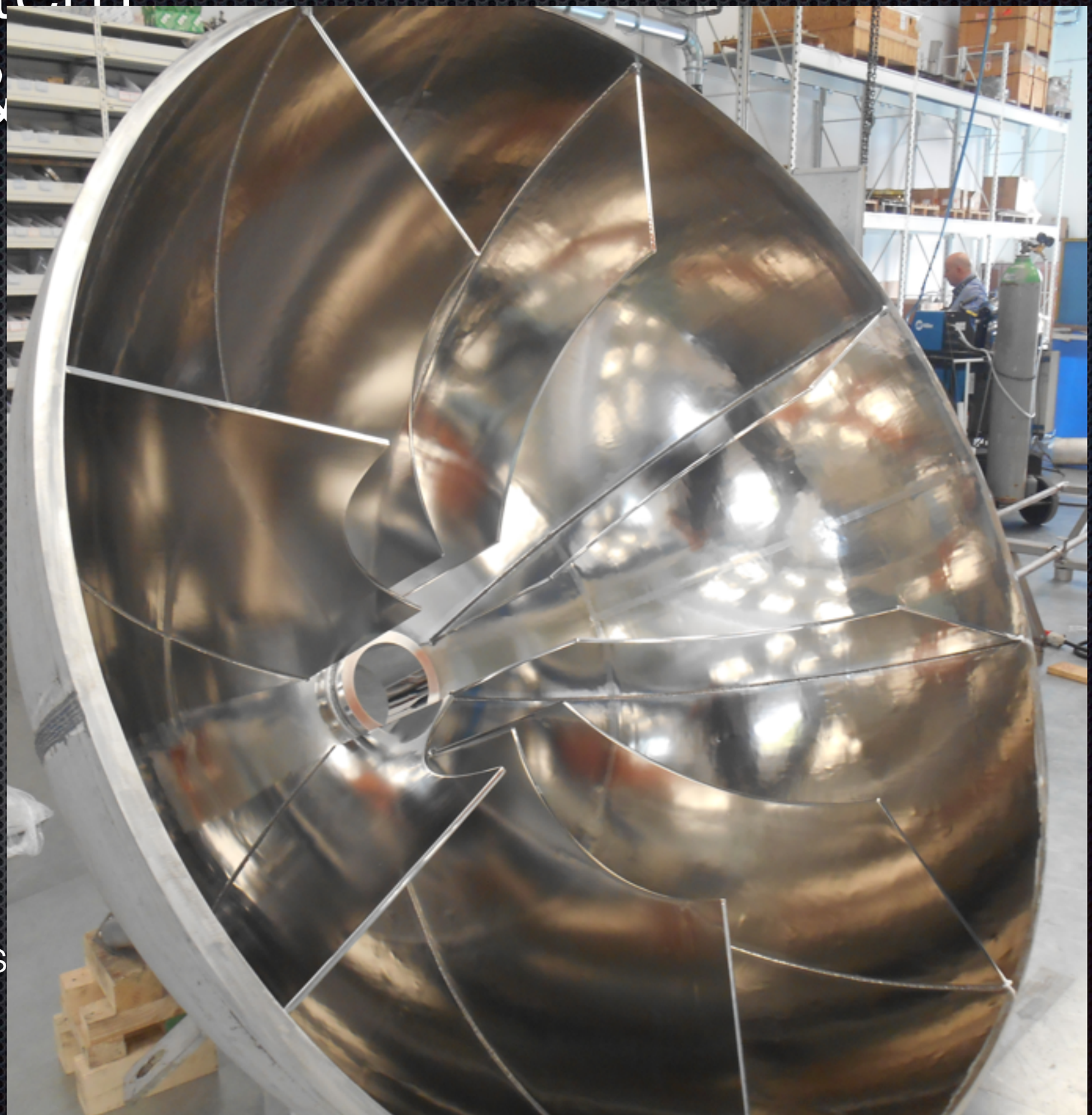
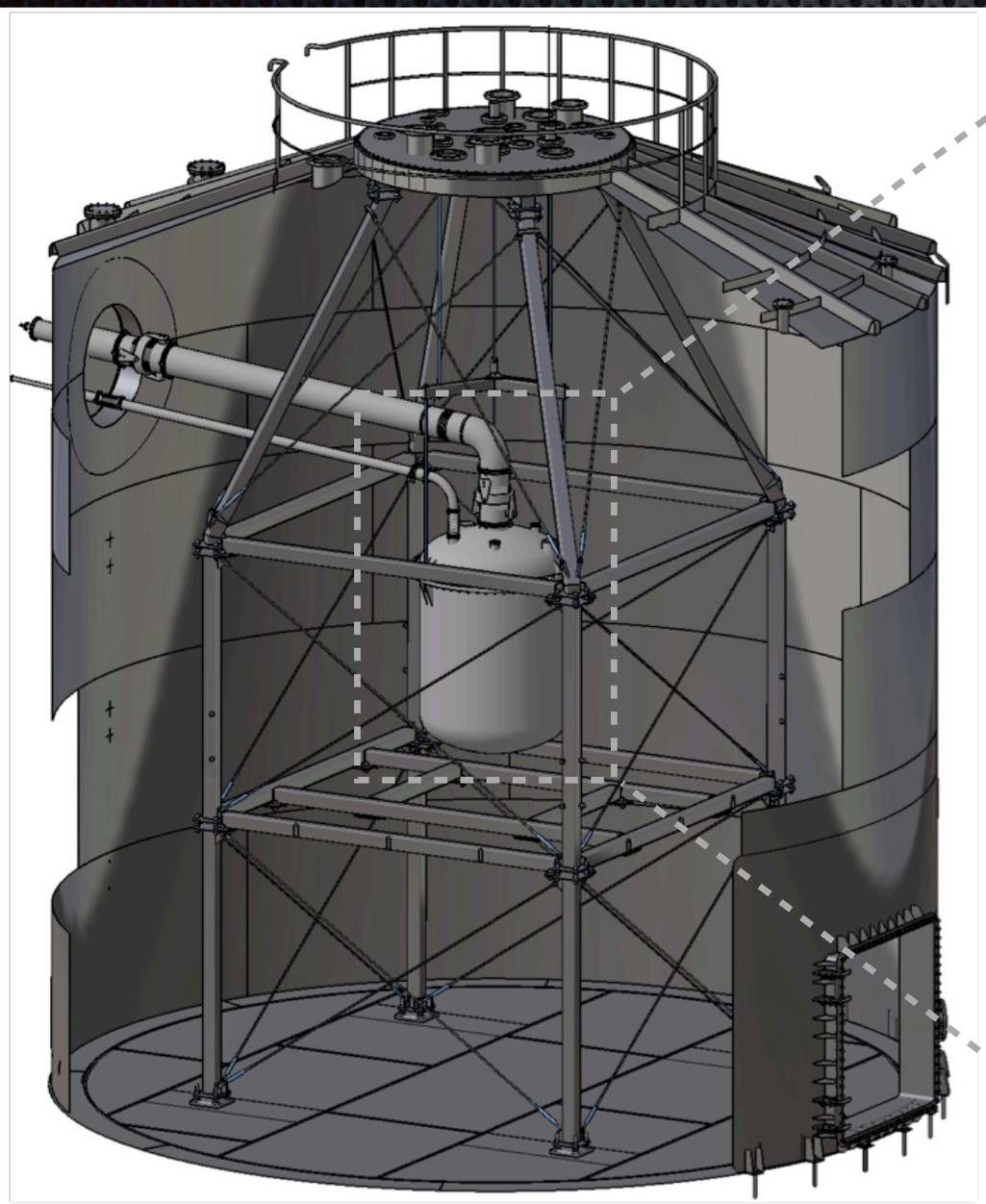
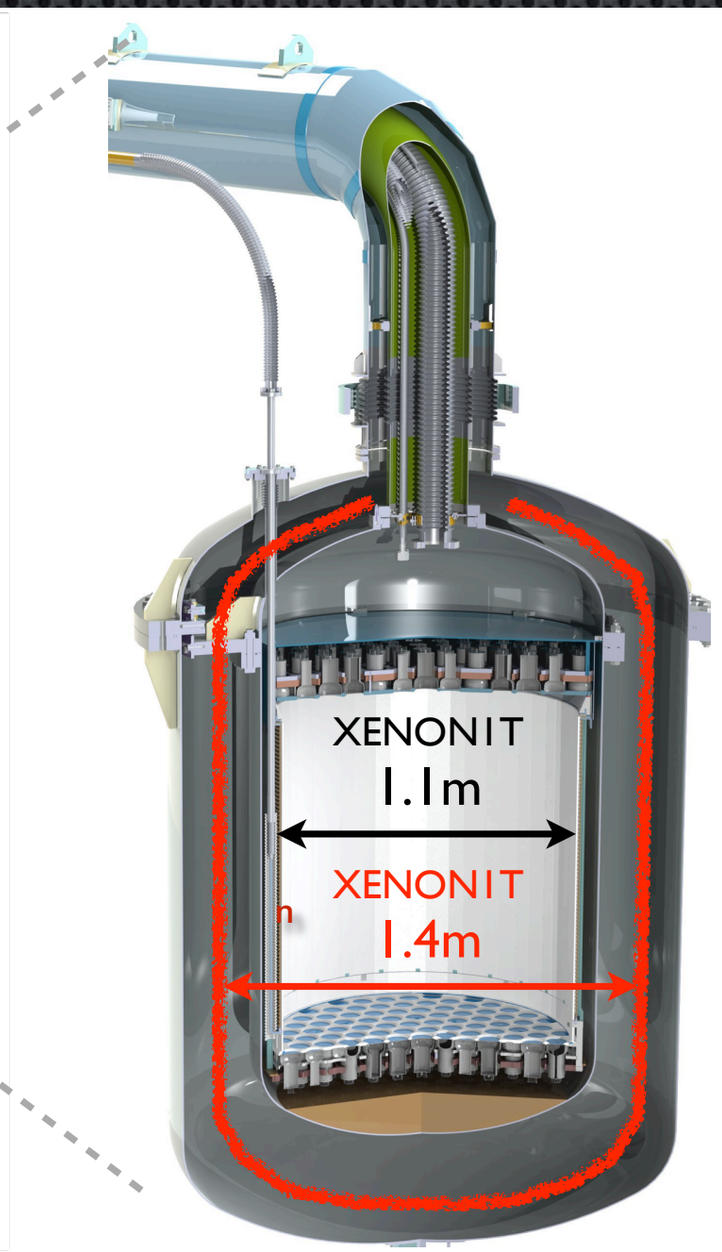


XENONnT: 2018 - 2022

- 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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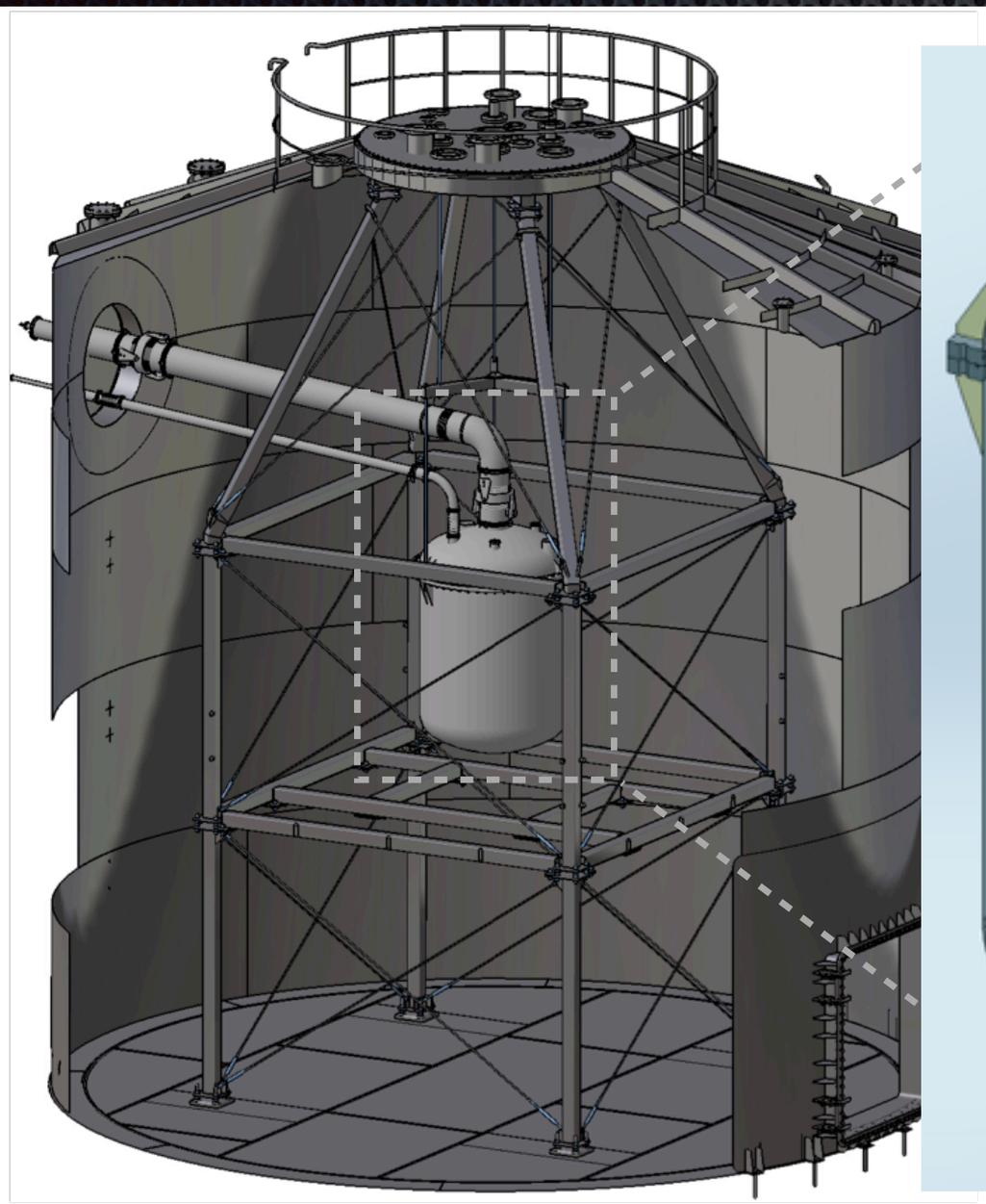

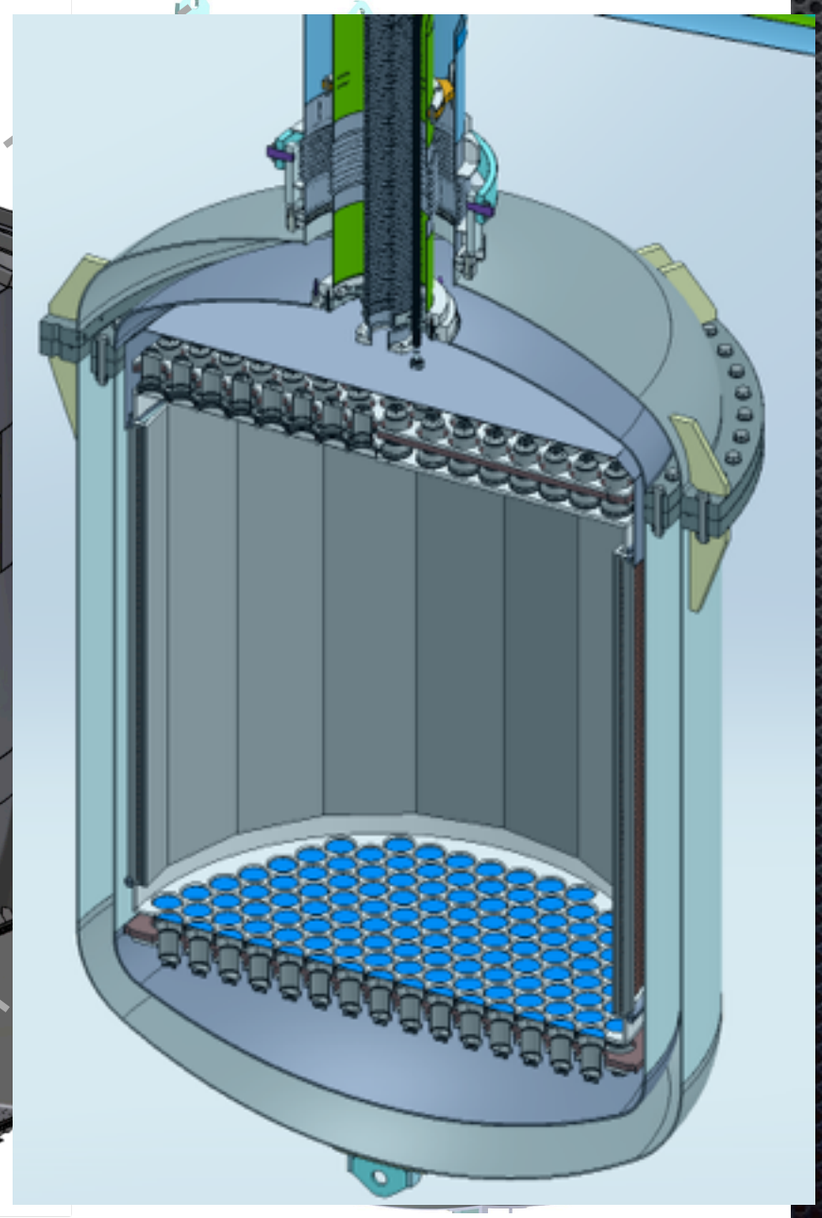

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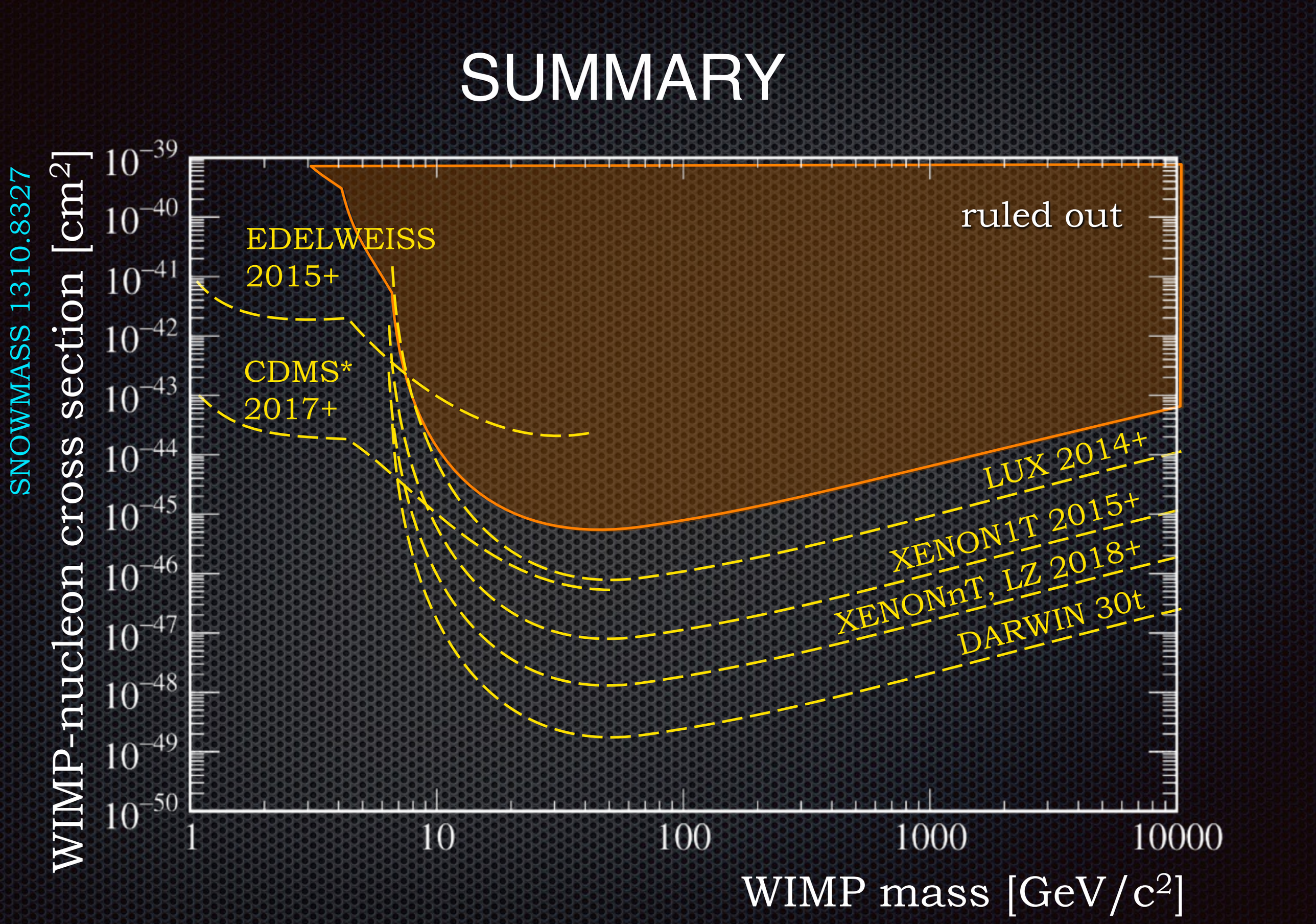
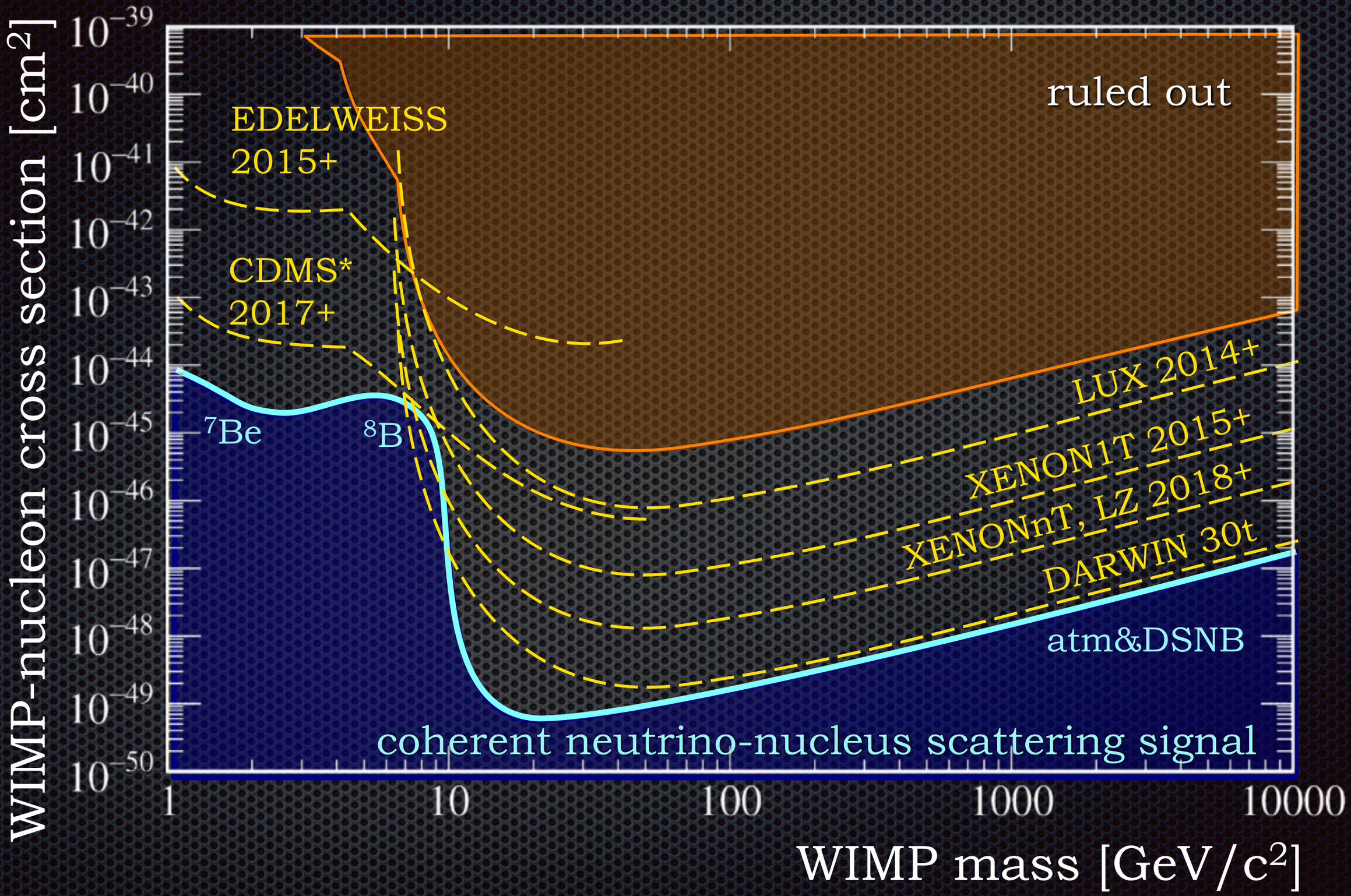

SNOWMASS 1310.8327
WIMP-nucleon cross section [cm^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
1
10
100
1000
10000
WIMP mass [GeV/c^2]
ruled out
EDELWEISS 2015+
CDMS* 2017+
LUX 2014+
XENON1T 2015+
XENONnT, LZ 2018+
DARWIN 30t

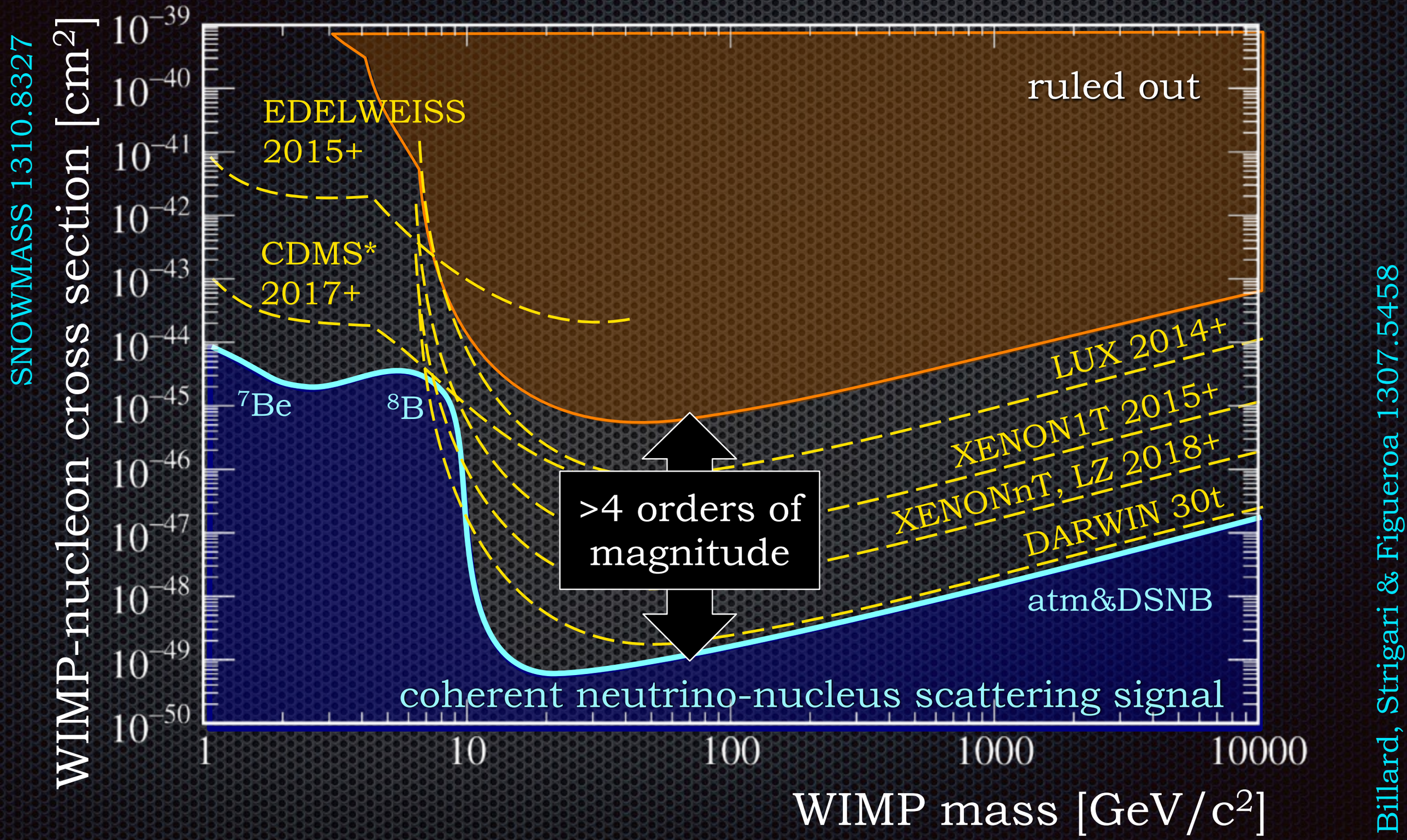
SUMMARY



SNOWMASS 1310.8327

Billard, Strigari & Figueroa 1307.5458

SUMMARY



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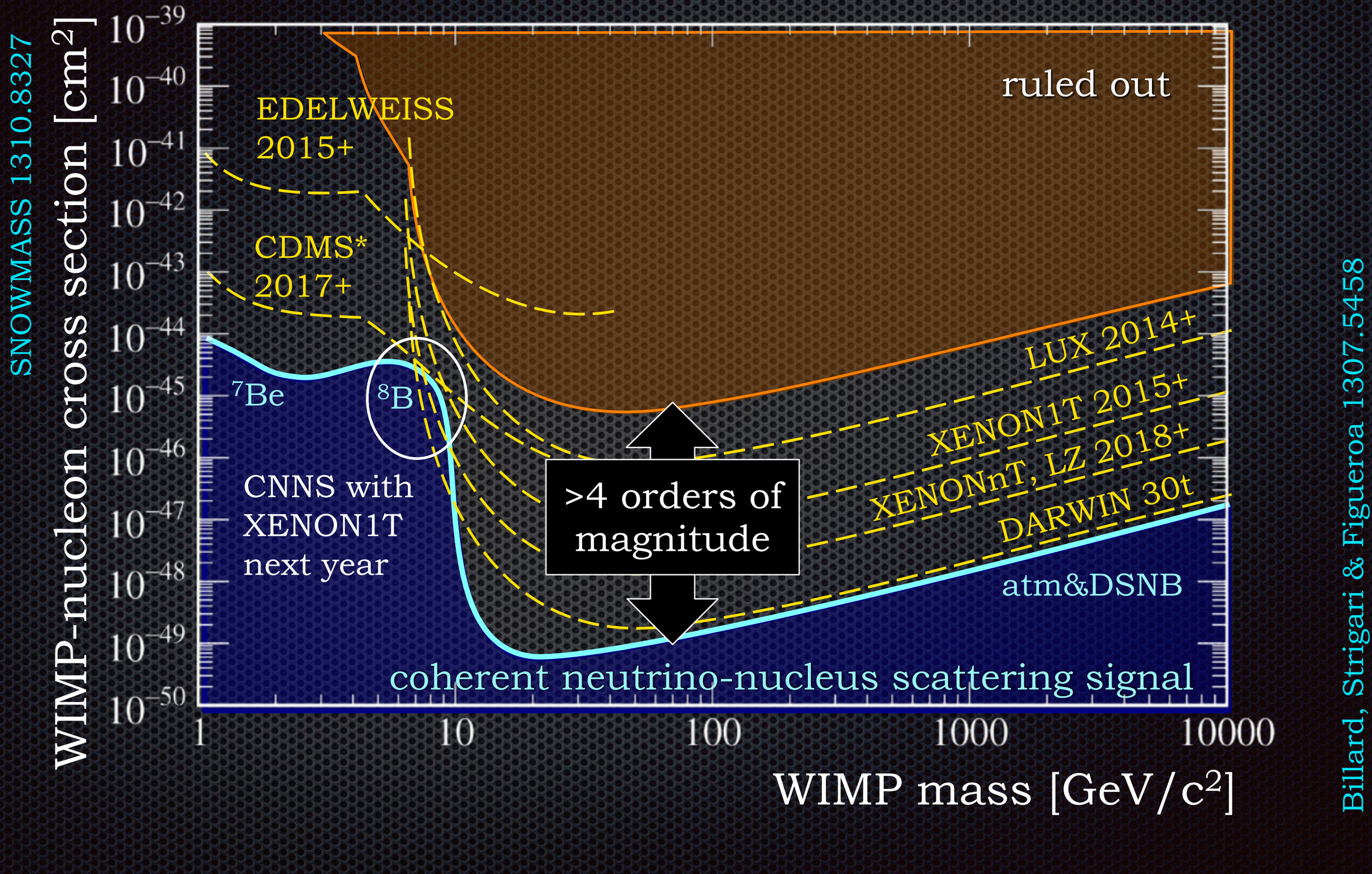

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