Direct Searches of Dark Matter

Neutrino Telescope

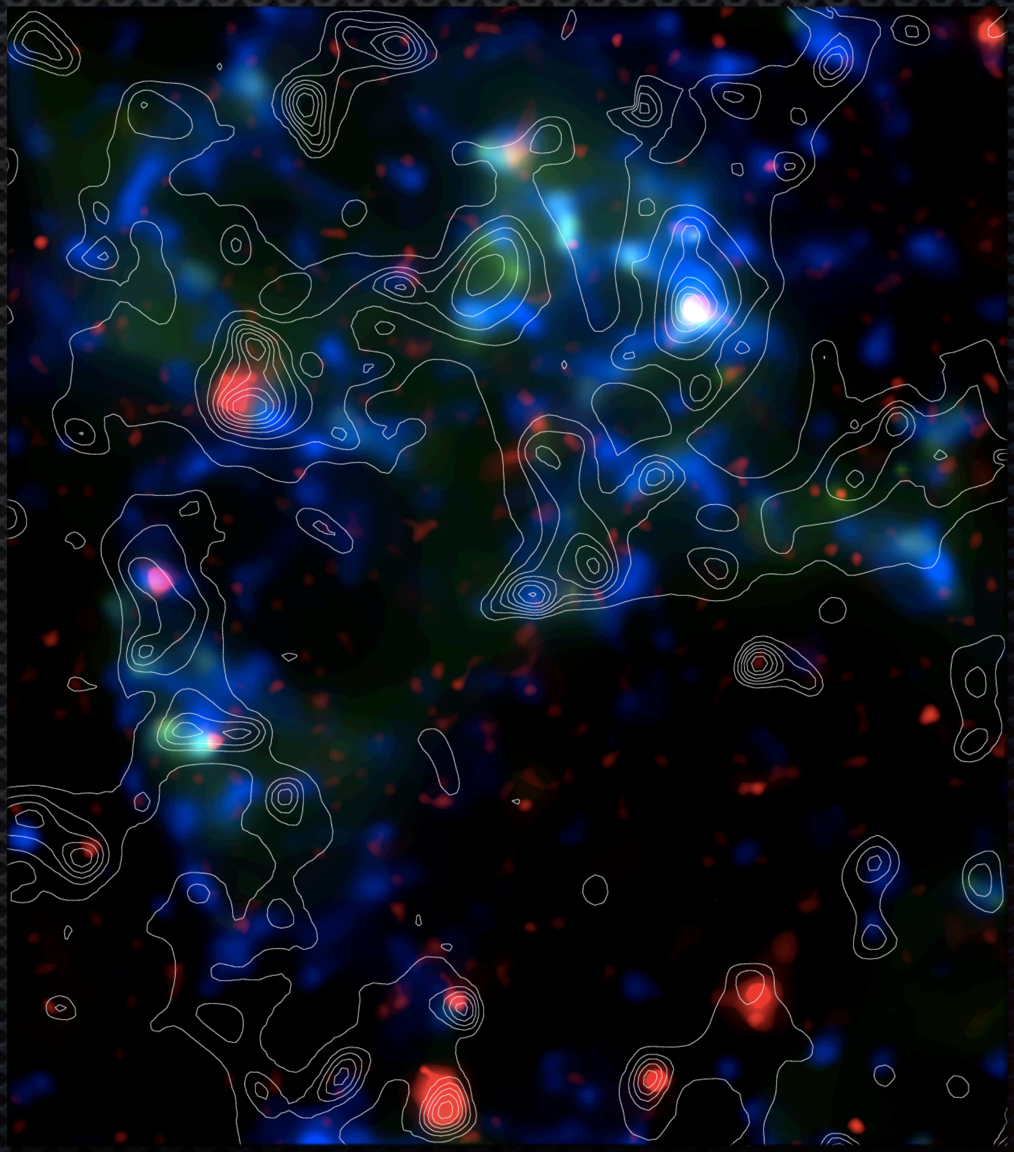
Venice, March 2, 2015

Elena Aprile

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

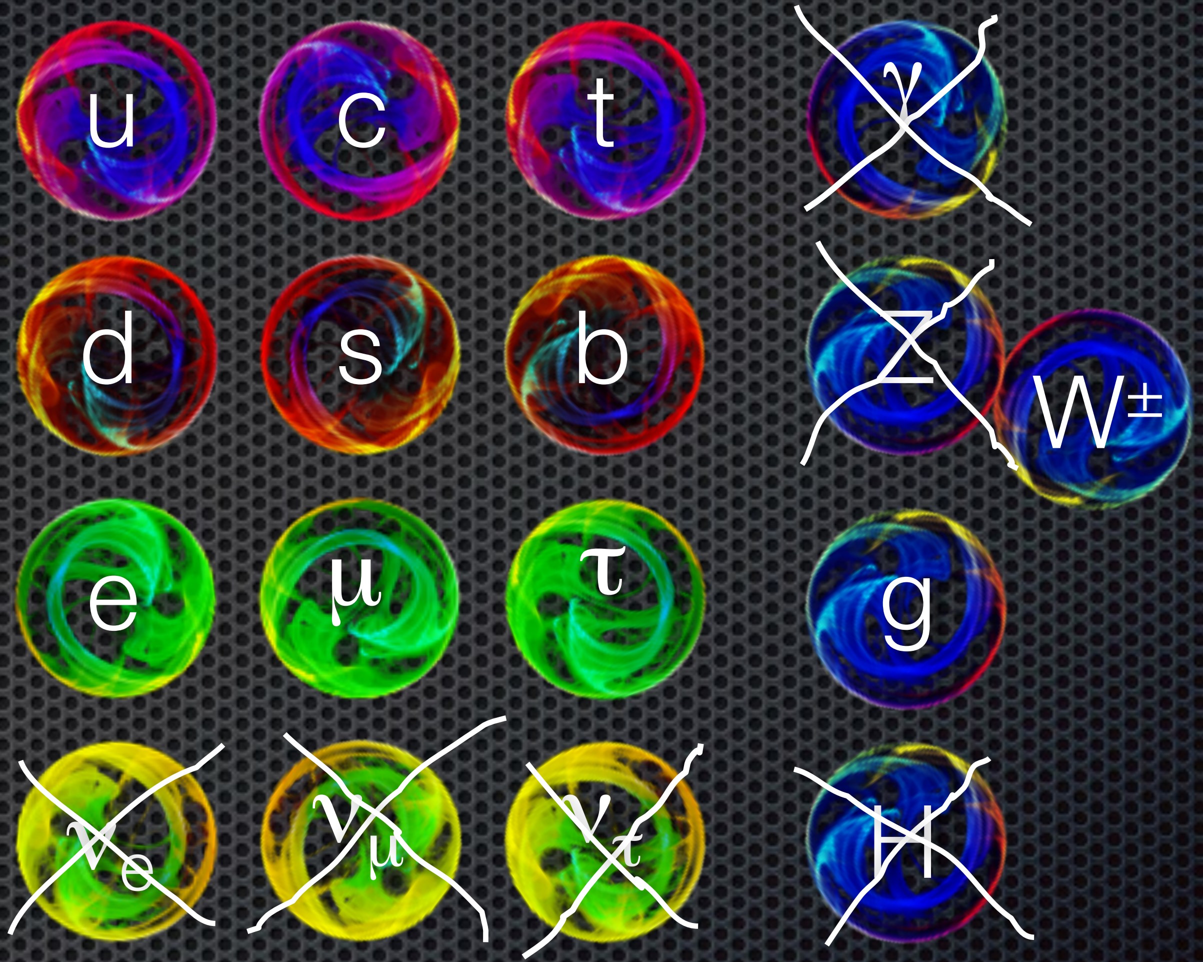
The dark matter question

- Direct detection is one of the probes we are using to answer the DM question.
- Dark Matter makes 85% of the matter in the Universe. Its presence leads to the formation of galaxies and structures which we observe.
- The "standard model" of CDM is remarkably successful at explaining CMB and large scale structure observations, but has potential problems at small scale.
- Finding the nature of dark matter remains one of the most fundamental problems in modern physics and cosmology.



What do we know about dark matter?

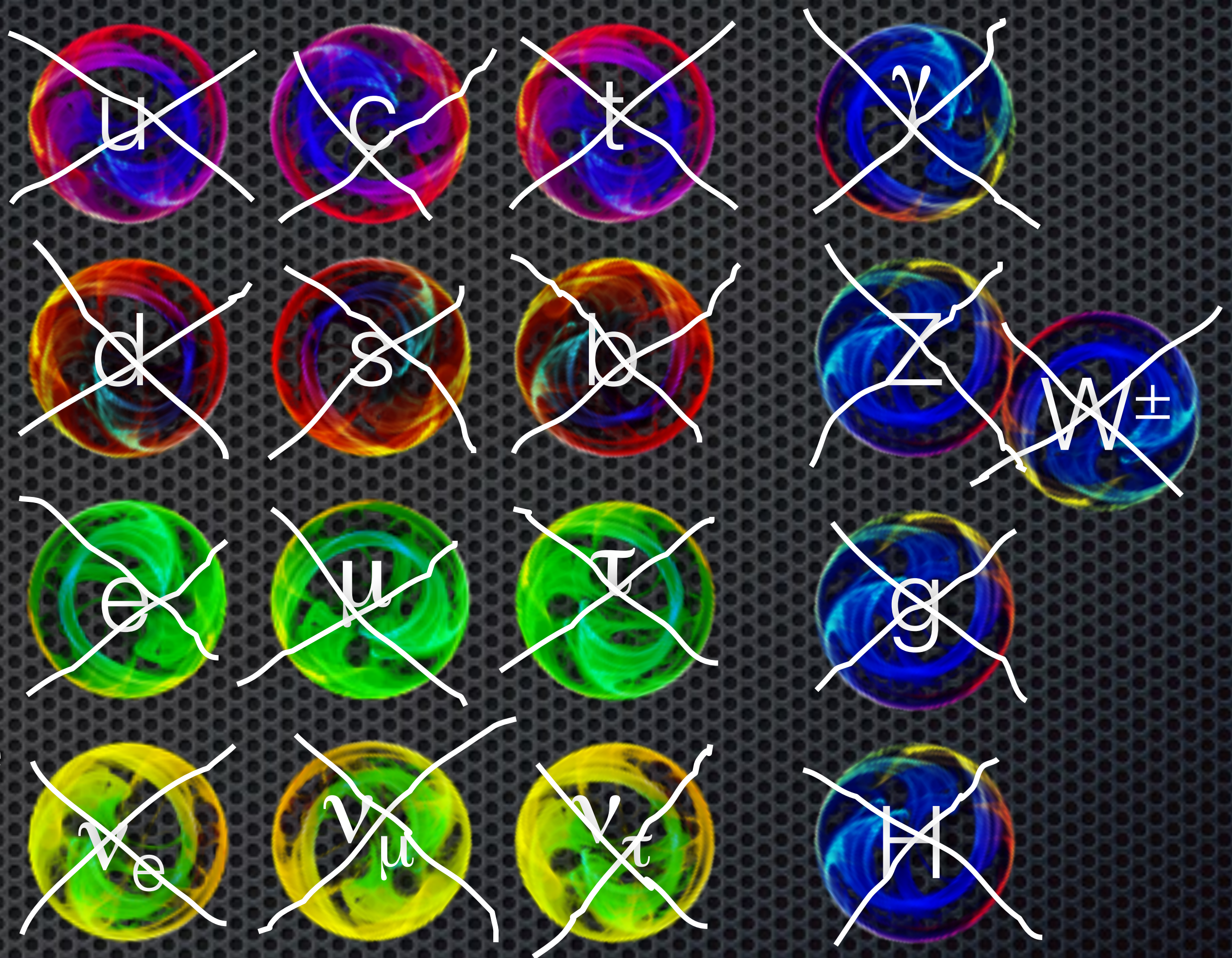
- neutral
- mostly cold
- stable
- no strong sel-interaction
- non-baryonic
- not a Standard Model particle



-> Search for new physics beyond Standard Model

What do we know about dark matter?

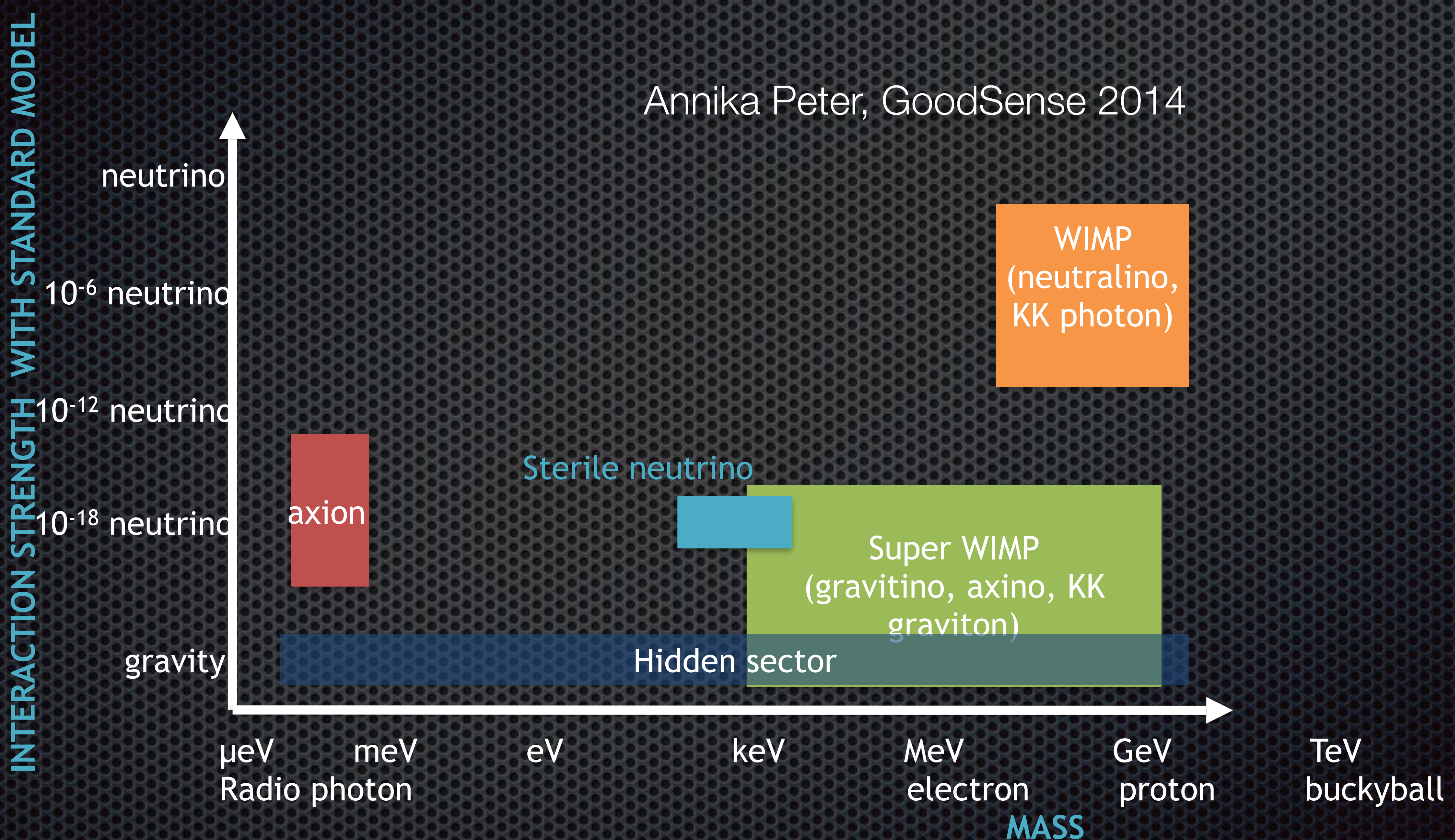
- neutral
- mostly cold
- stable
- no strong sel-interaction
- non-baryonic
- not a Standard Model particle



-> Search for new physics beyond Standard Model

Many models and a zoo of candidates

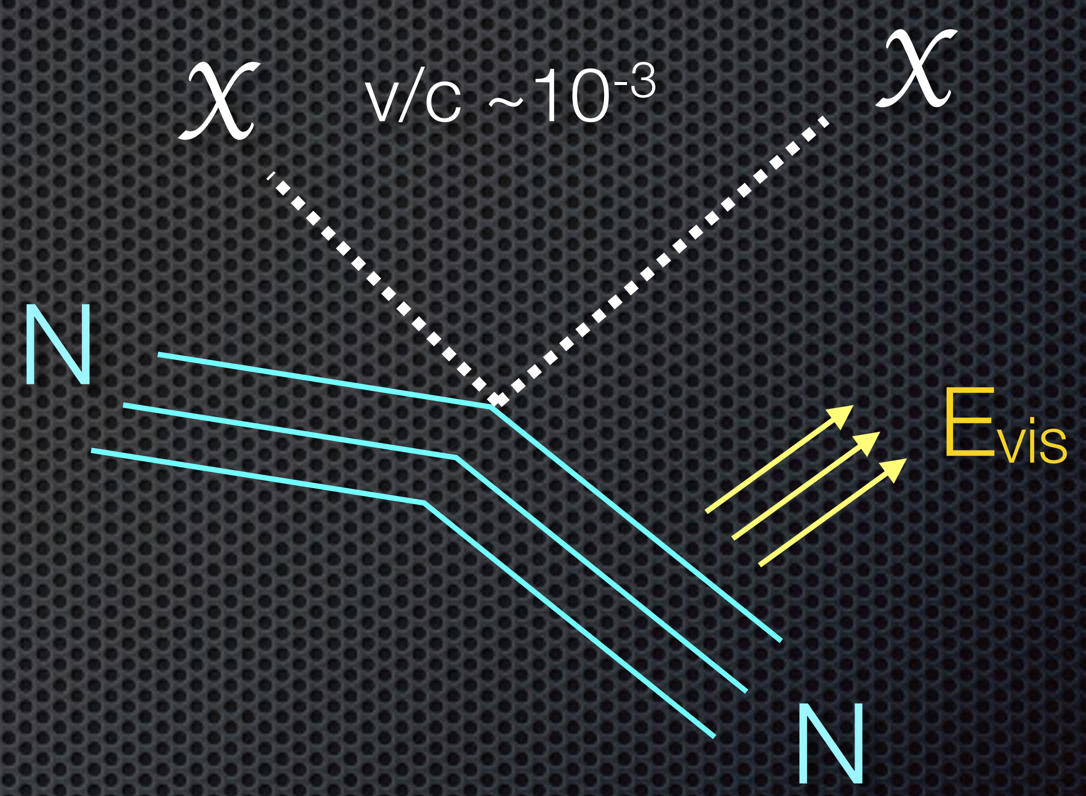
- The mass range spans merely 90 orders of magnitude



In this talk I will focus on the **weak scale,** and on direct detection

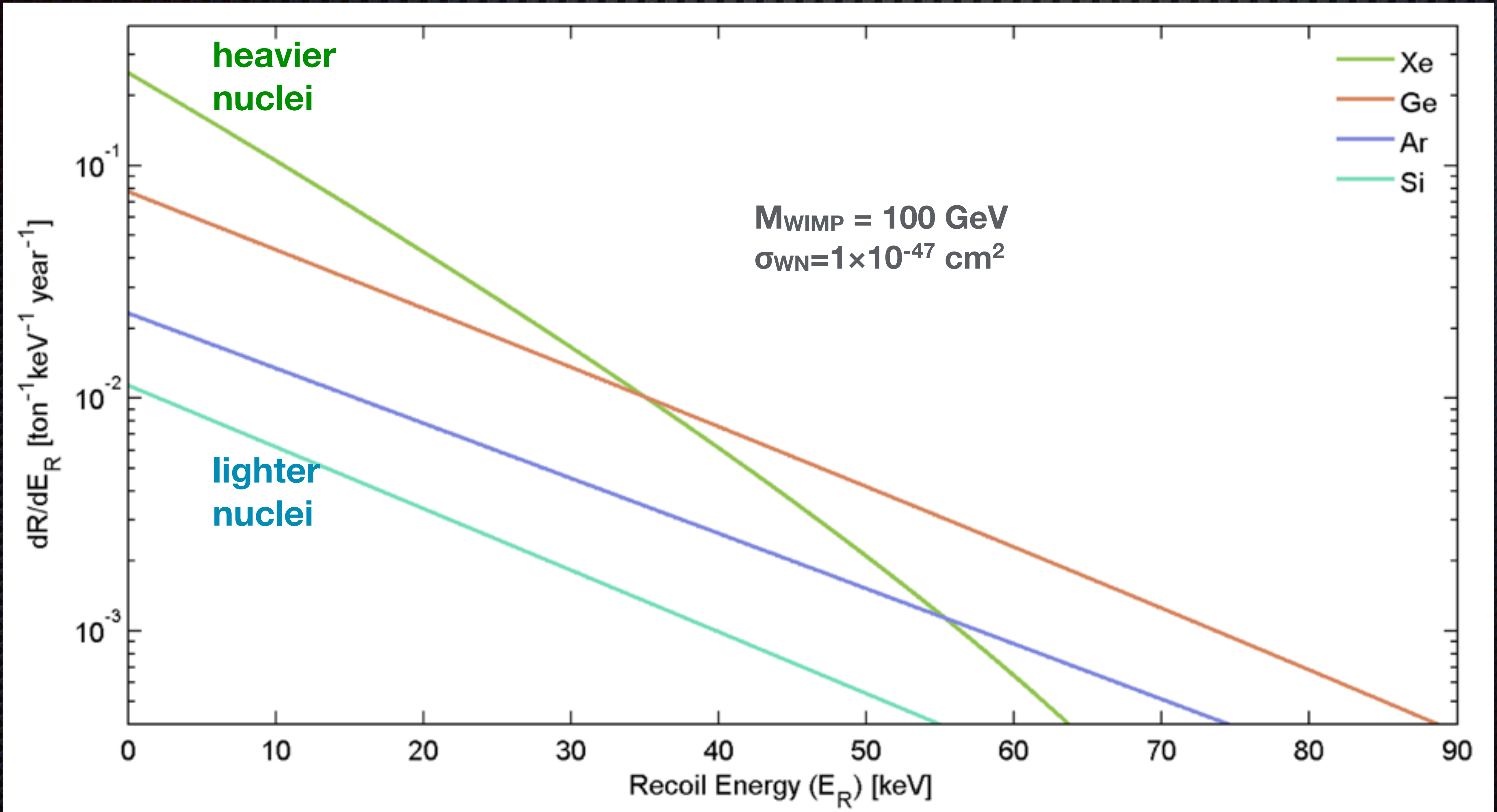
Dark Matter Direct Detection

- 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 scale easily to enable large mass to probe lowest event rate*



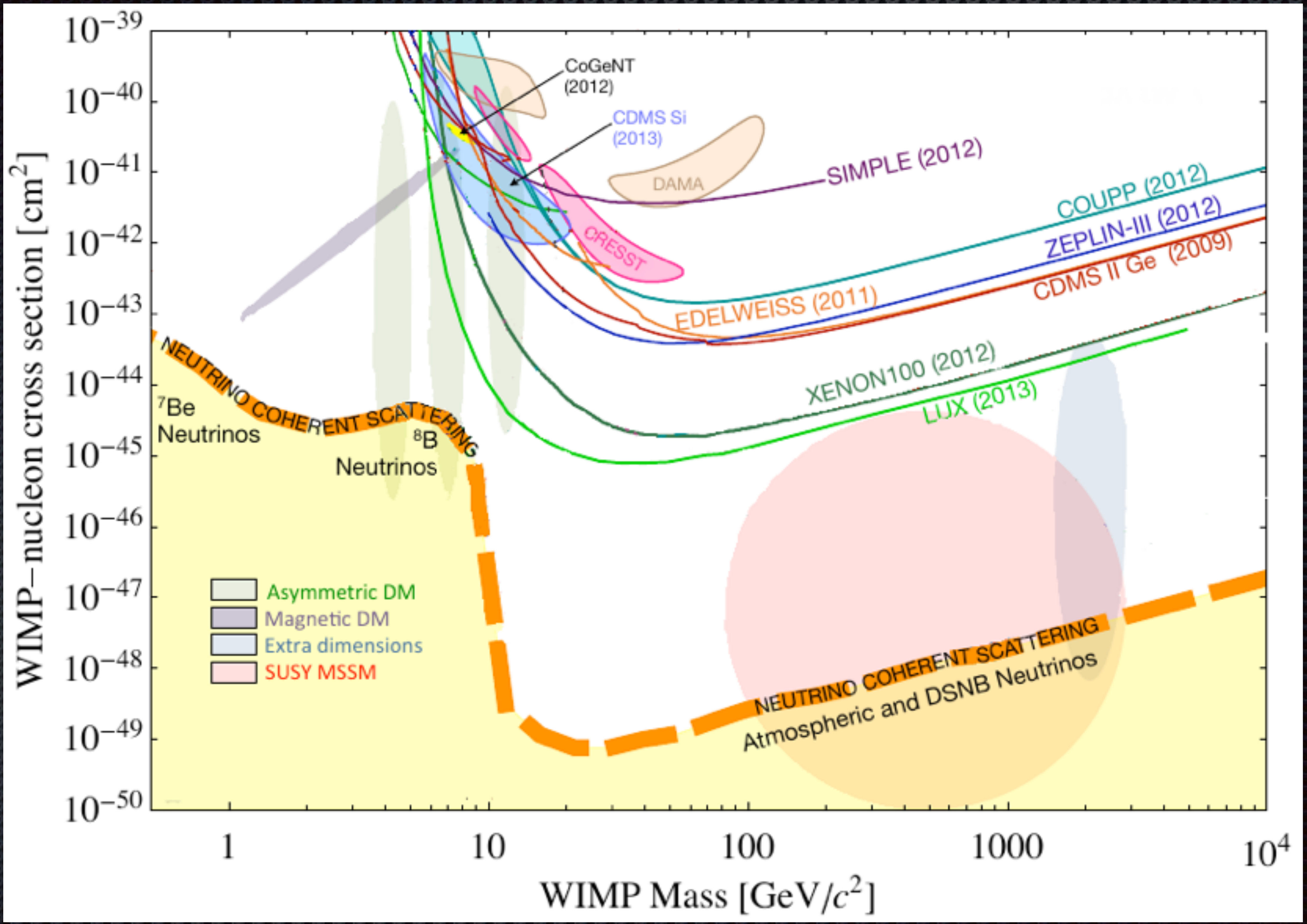
$$E_R = \frac{q^2}{2m_N} < 100\,\mathrm{keV}$$

Expected rate with some favored targets



Worldwide WIMP Searches

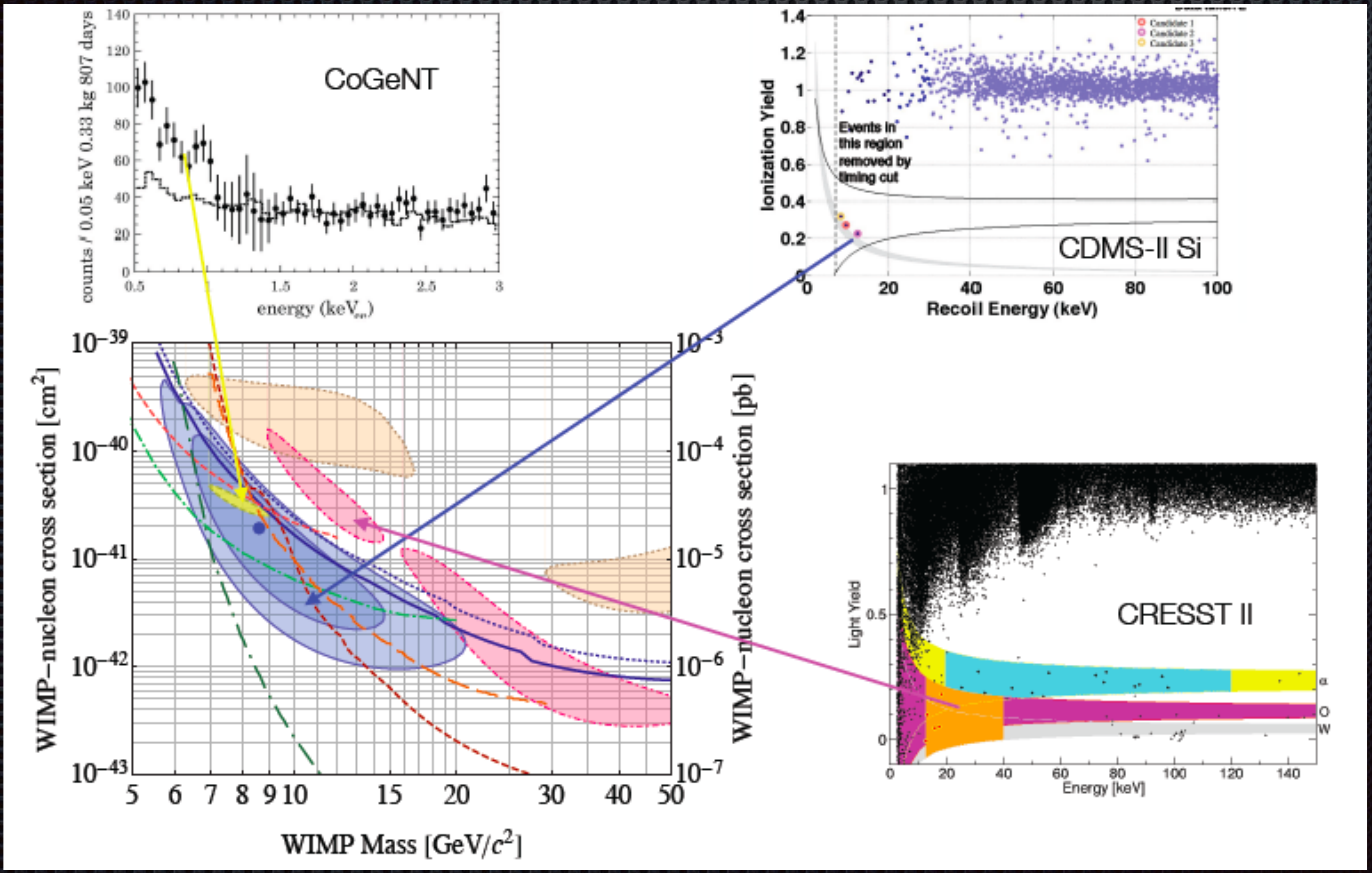
WIMP Direct Detection Situation Today



Low Mass WIMPs

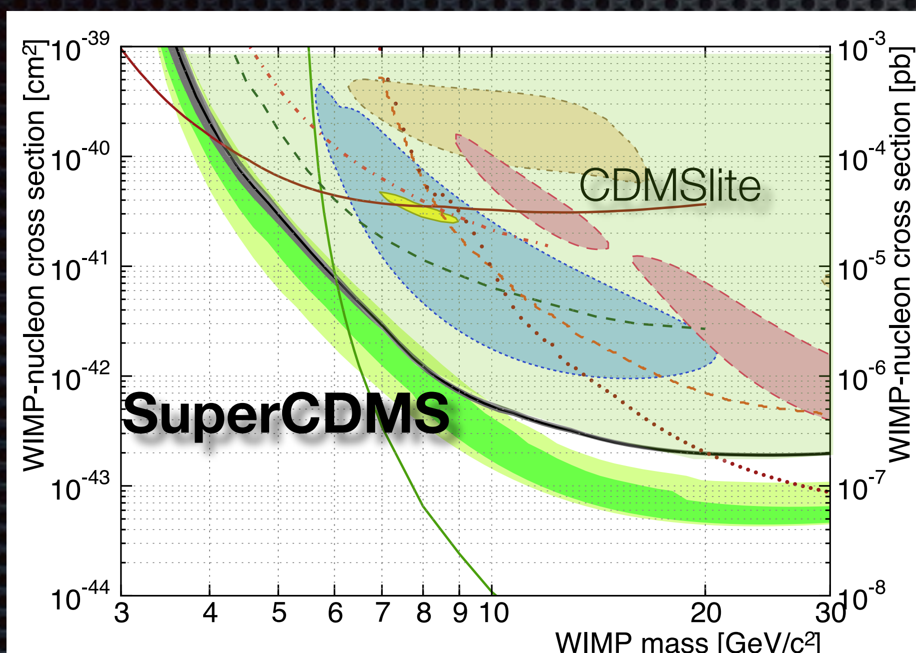
Challenges and Opportunities

In addition to DAMA/LIBRA, interest in low-mass WIMPs has been triggered by signals from CoGeNT, CRESST, CDMS-Si: excess of events above the *known* backgrounds

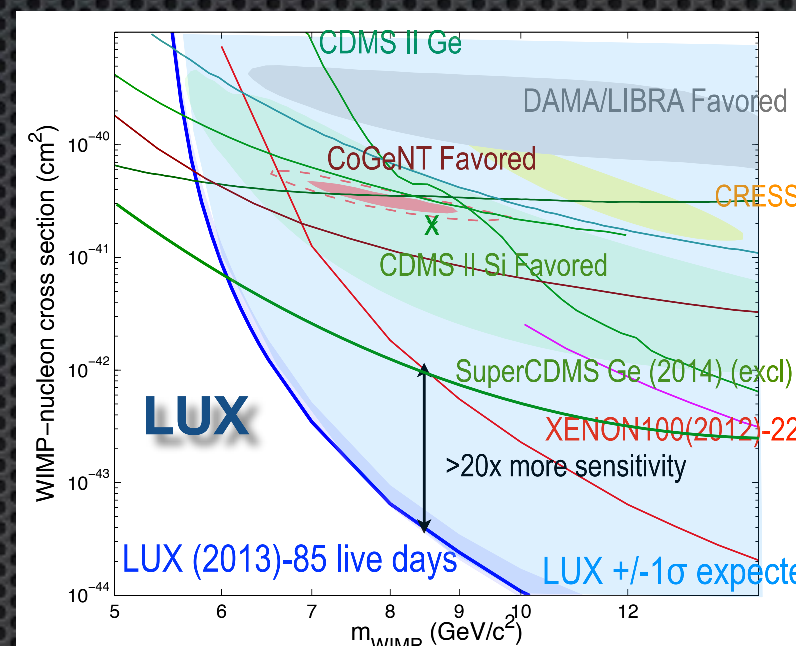


Interpretation of these signals as light DM disfavored by results from CDMS-Ge, XENON100, LUX, EDELWEISS, CRESST & CoGeNT (updated), CDEX and PandaX

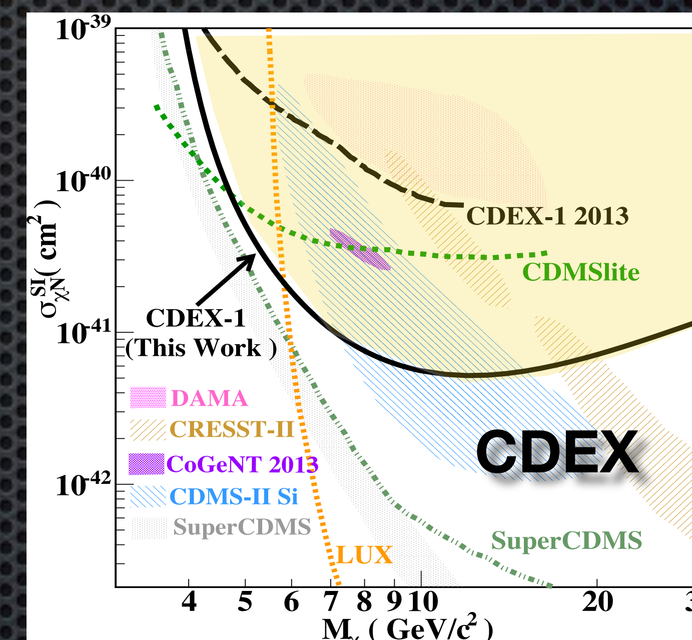
CDMS, PRL 112, 2014

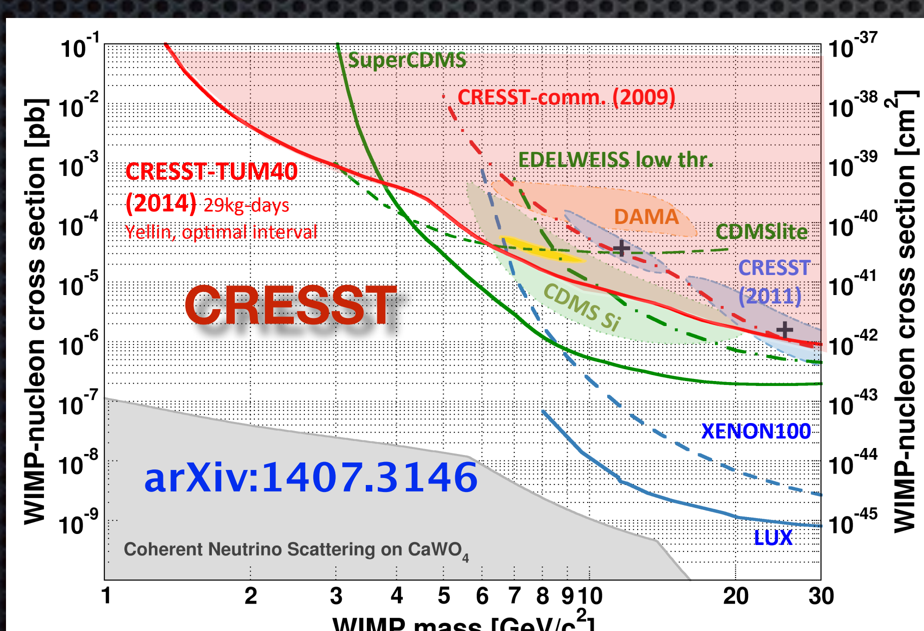


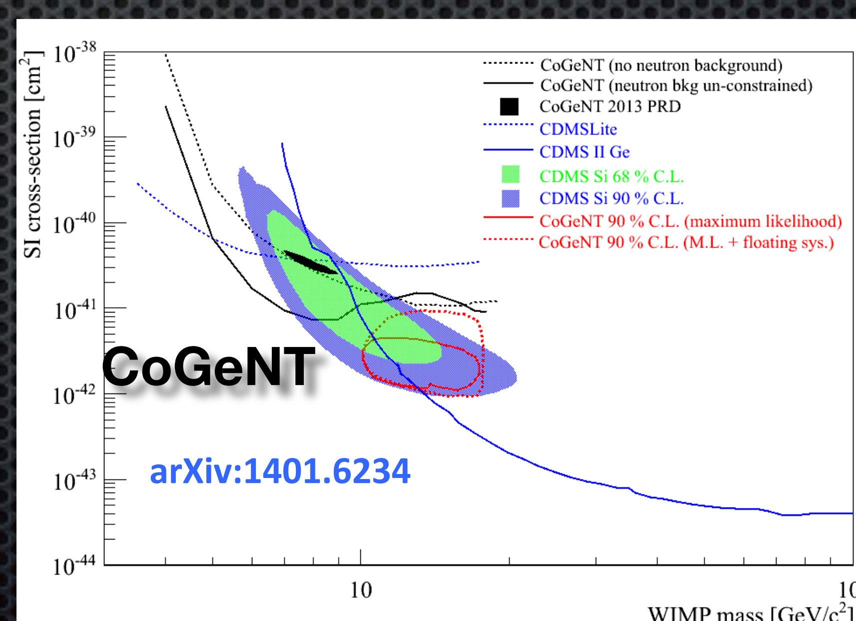
LUX, PRL, arXix: 1310.8214

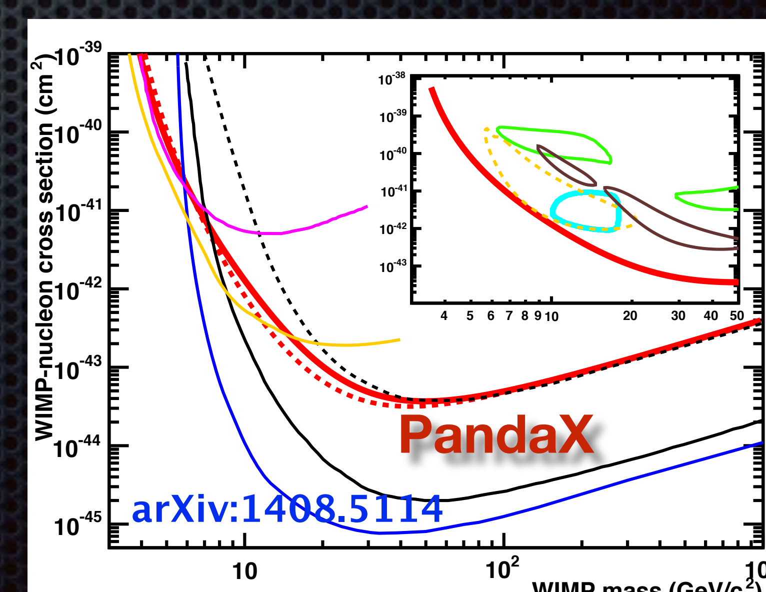


CDEX, arXiv:1404.4946





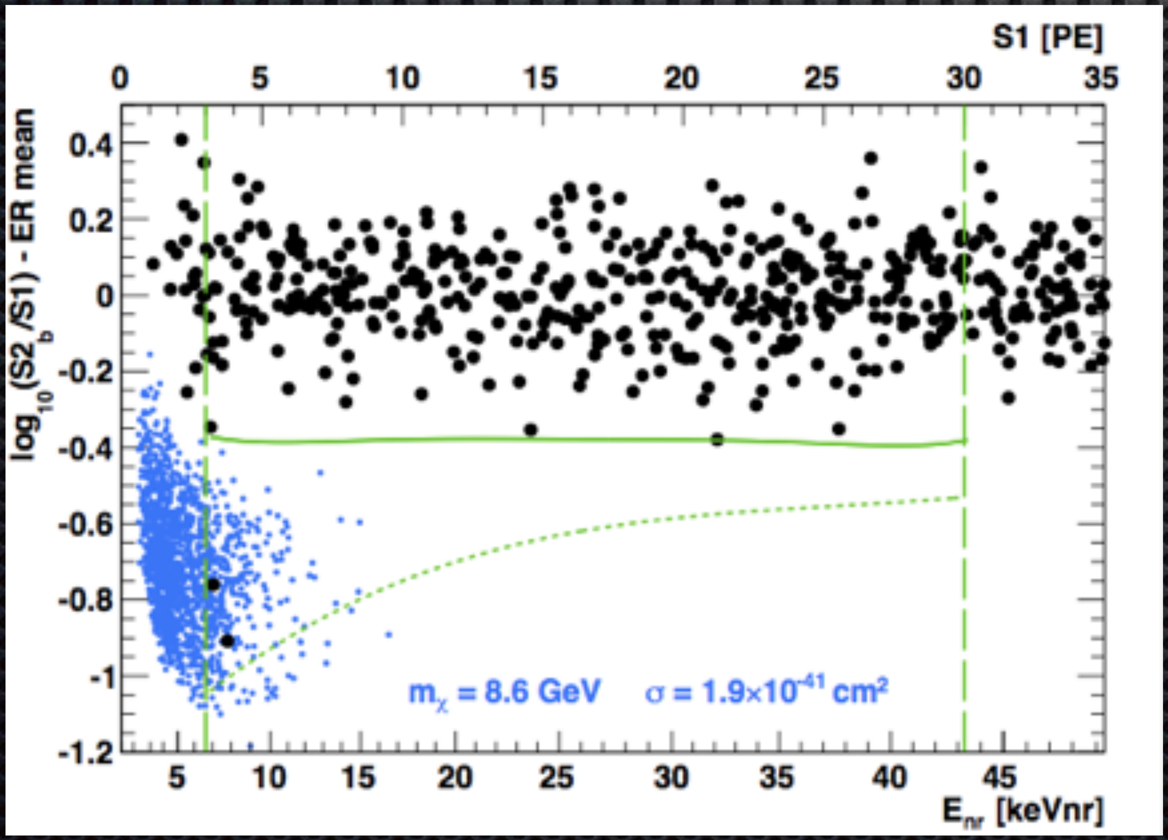




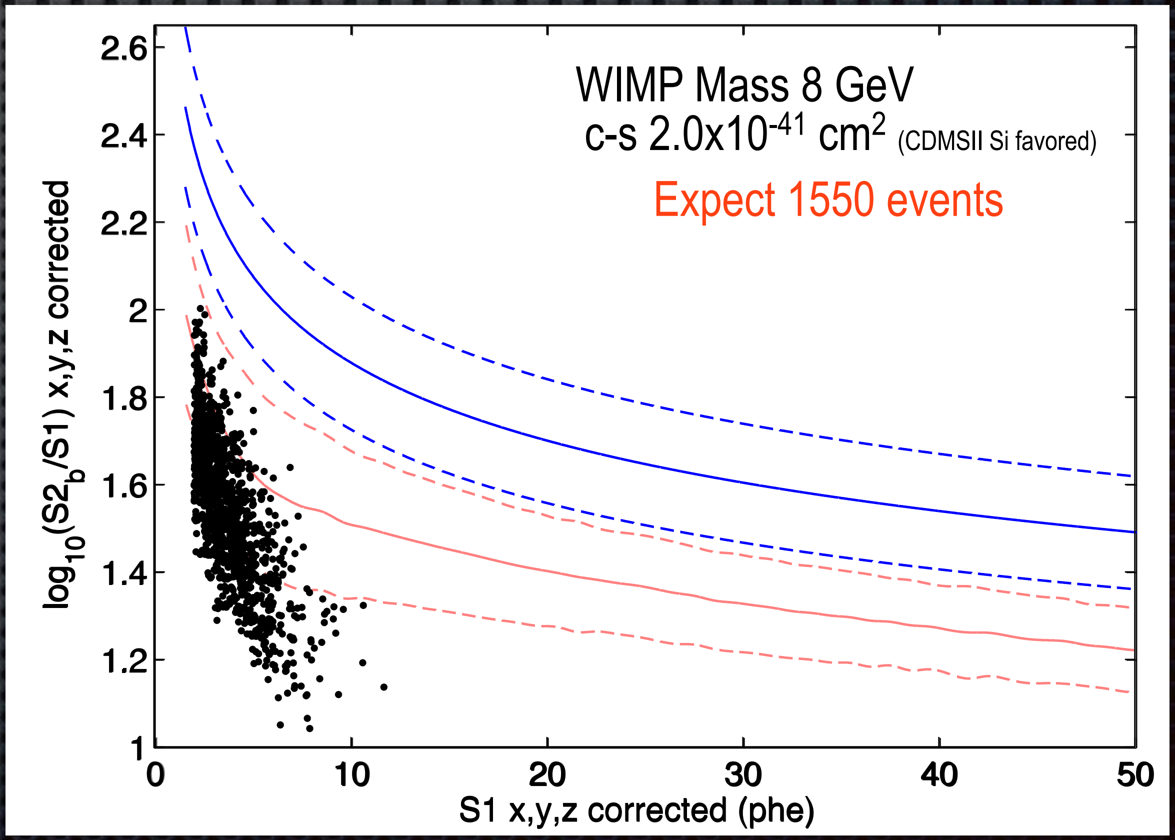
How would a CDMS-Si like signal look like in XENON100 and LUX?

Assumption:
m_W = 8.6 GeV and WIMP-nucleon cross section of 1.9 x 10^{-41} cm^2

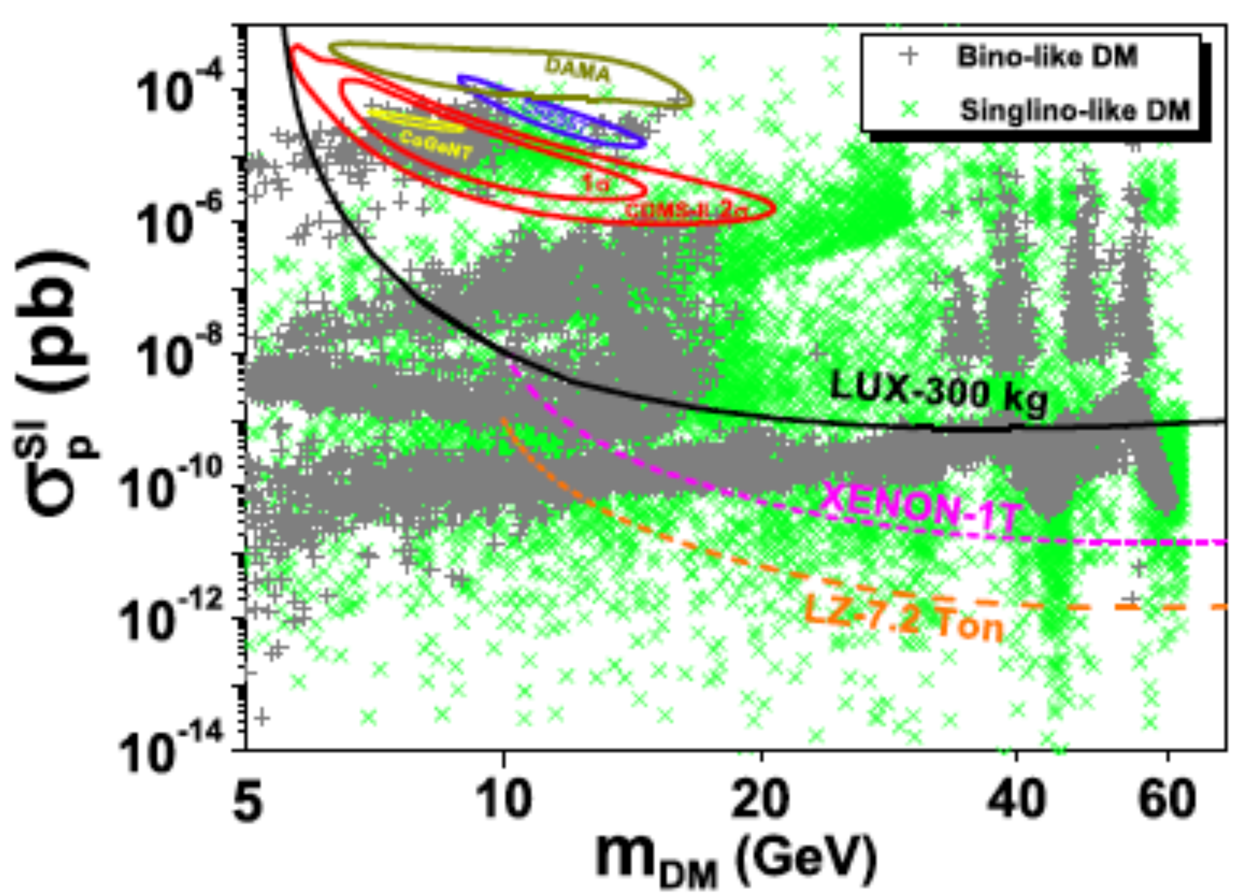
XENON100 Run10
expect: ~ 220 events



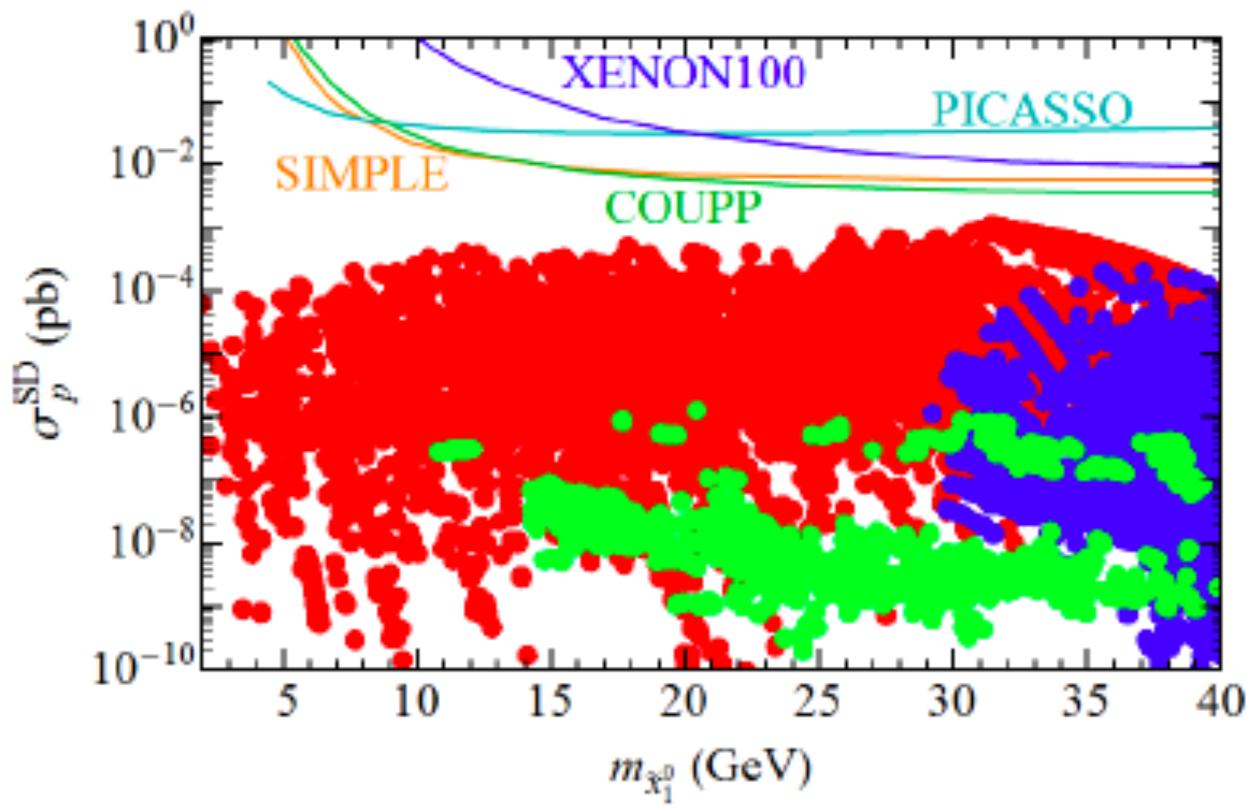
LUX first run
expect: ~ 1550 events



Nevertheless, light SUSY dark matter is still a viable candidate after Direct Detection and Collider constraints



Allowed light DM parameters in NMSSM after colliders and relic density constraints. [Cao et al., 1311.0678]



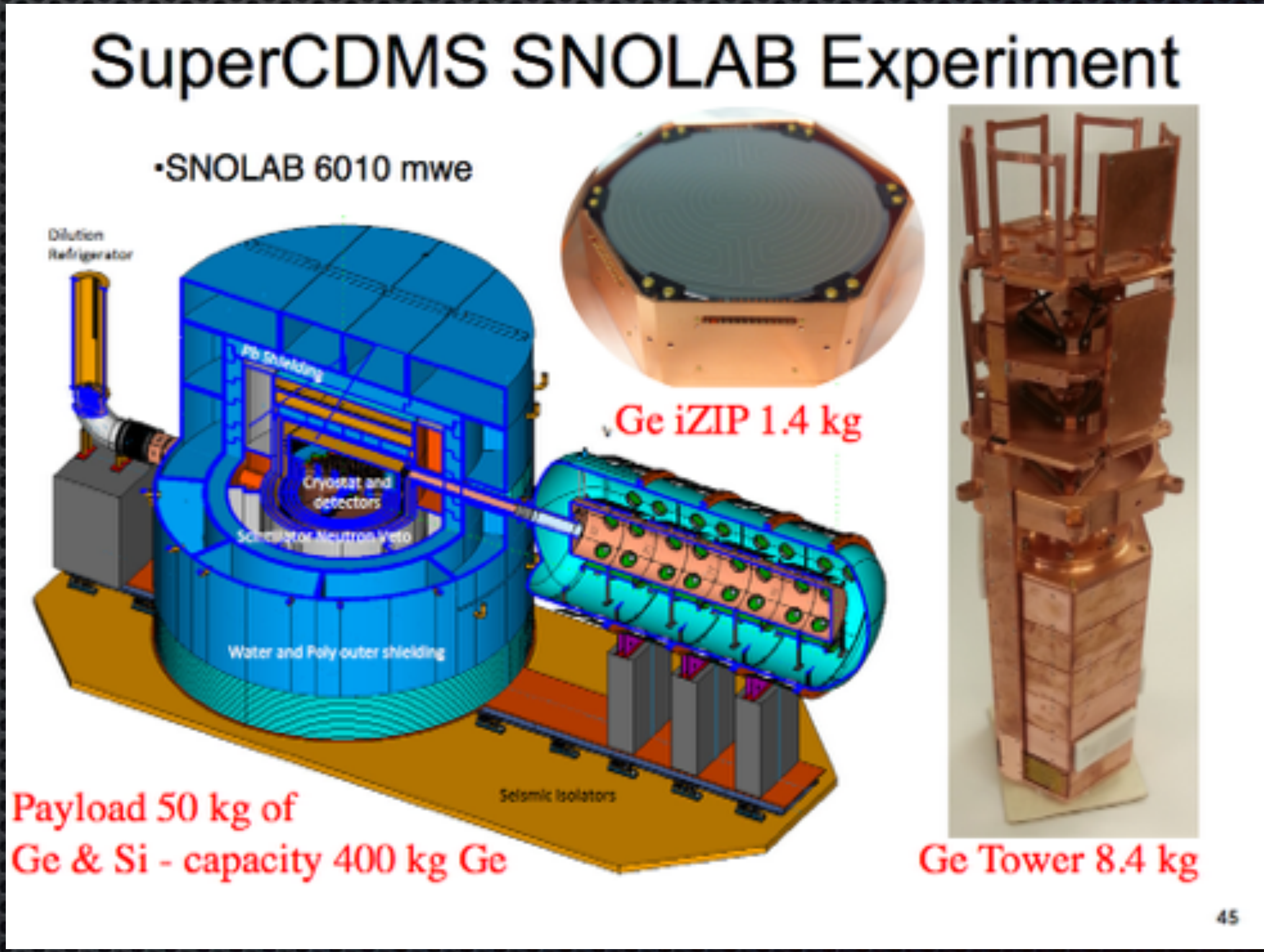
Light DM constraints and allowed parameters in NMSSM for SD interactions [Han, Liu, Su, 1406.1181]

increase sensitivity to light WIMPs with next generation Cryogenic Experiments at T~ mK

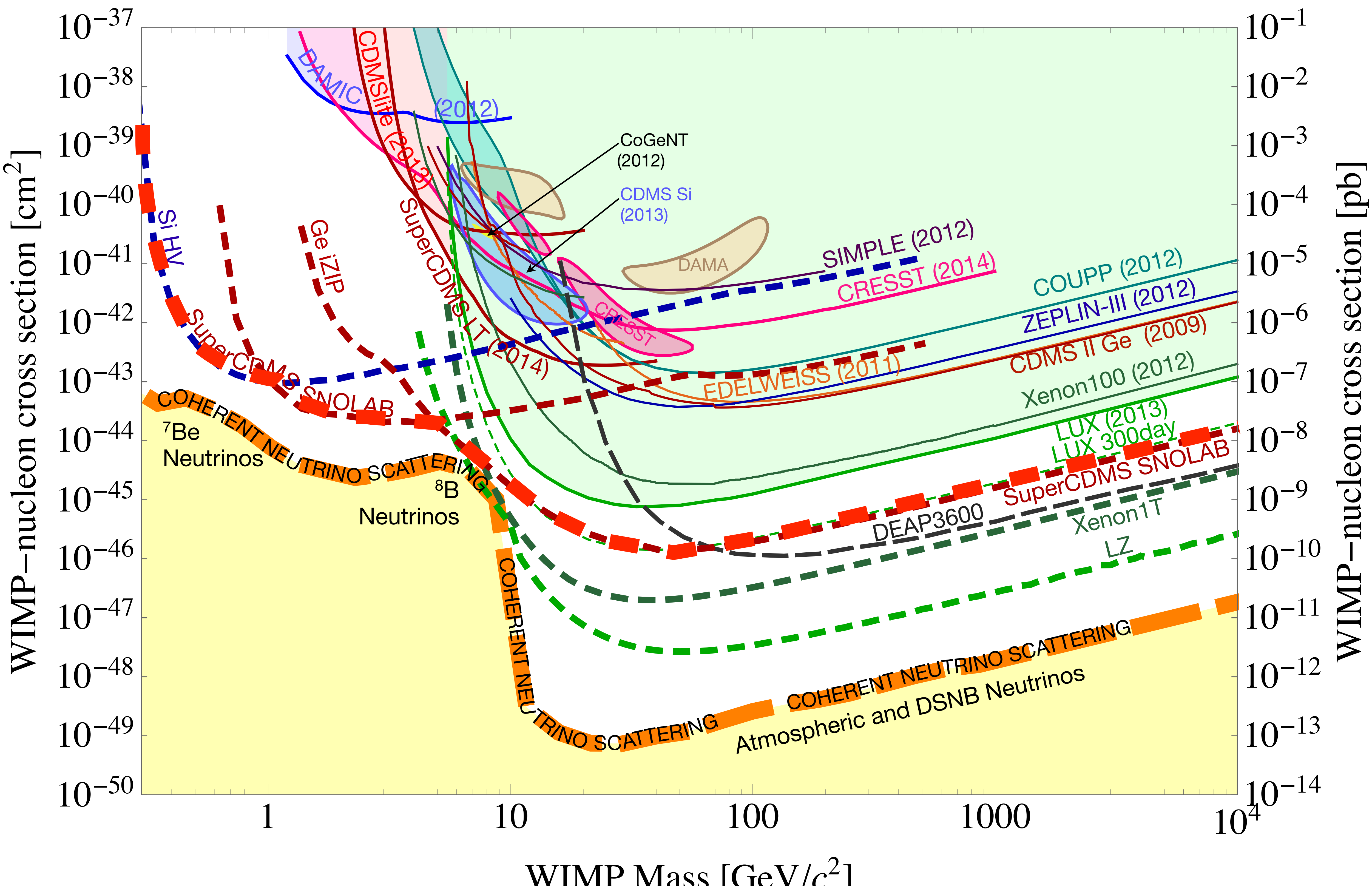
- SuperCDMS at SNOLab. Low-temperature Ge/Si detectors. Focus on low mass 0.3-10GeV/c^2
  - Above 5 GeV/c^2 6 towers ≈50kg Ge full nuclear recoils recognition through ionization + athermal phonon
  - 0.3-5 GeV/c^2, 1 tower of e.g., 3 Ge, 3 Si, CDMS HV (Luke Neganov amplification of ionization). No discrimination. Background limited after 1 year
- Start data taking in 2018. Ultimate goal (SI) : 8×10^{-47} cm^2
- Collaboration with EURECA for multi-target approach ($CaWO_3$, Ge) and increased target mass. Potentially increase Ge mass to ~200 kg

increase sensitivity to light WIMPs with next generation Cryogenic Experiments 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
- Start data taking in 2018. Ultimate goal (SI) : 8×10^{-47} cm^2
- Collaboration with EURECA for multi-target approach ($CaWO_3$, Ge) and increased target mass. Potentially increase Ge mass to ~200 kg

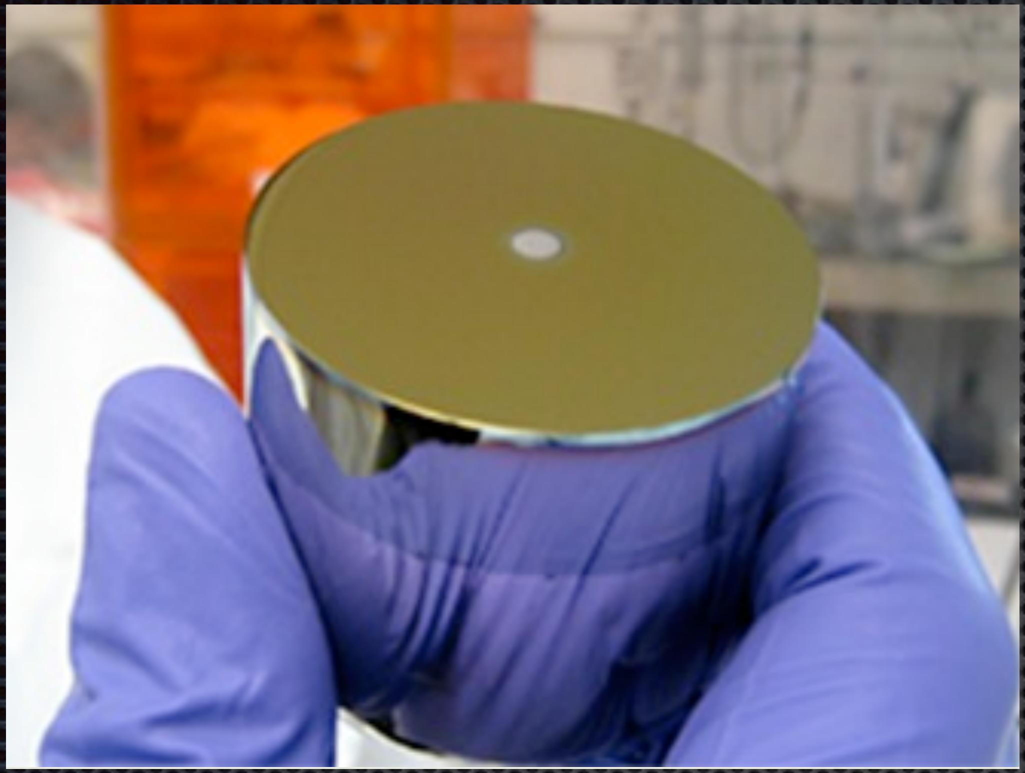


SCDMS 50kg on Snowmass über Plot



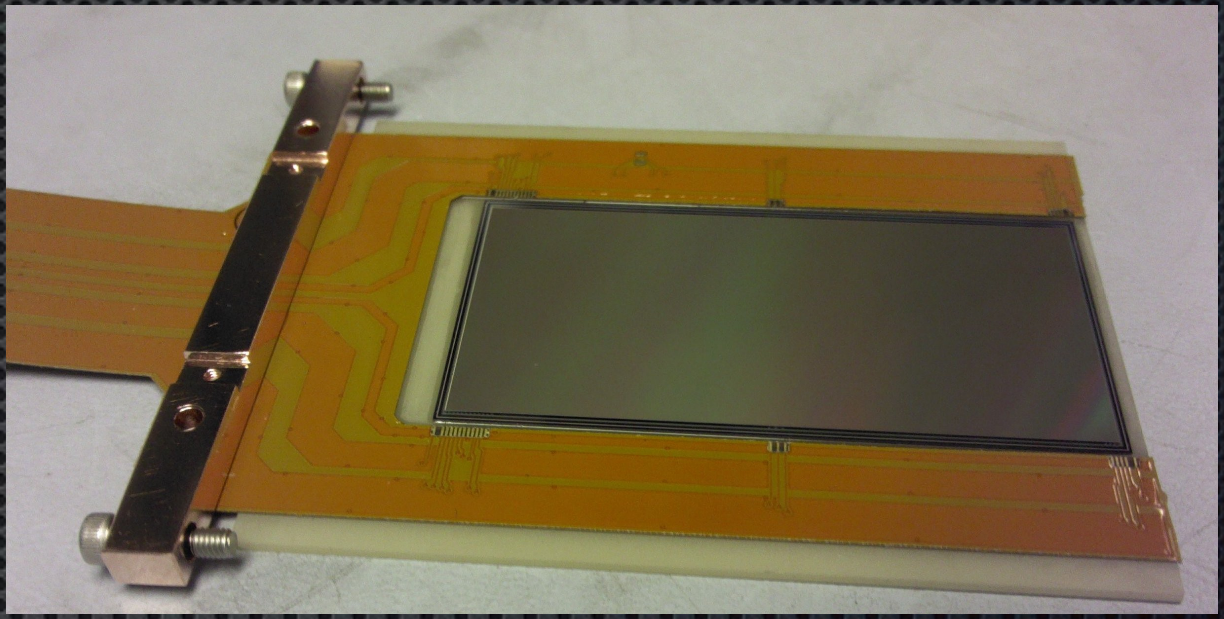
but small detectors with solid targets (Ge, Si) are equally promising

A CoGeNT PCGe detector



- ultra-low threshold: sub keV_{ee}
- mass: kg scale
- background: O(1) evt/kg/keV/day
- similar exps: CDEX, MALBEK

A DAMIC CCD detector



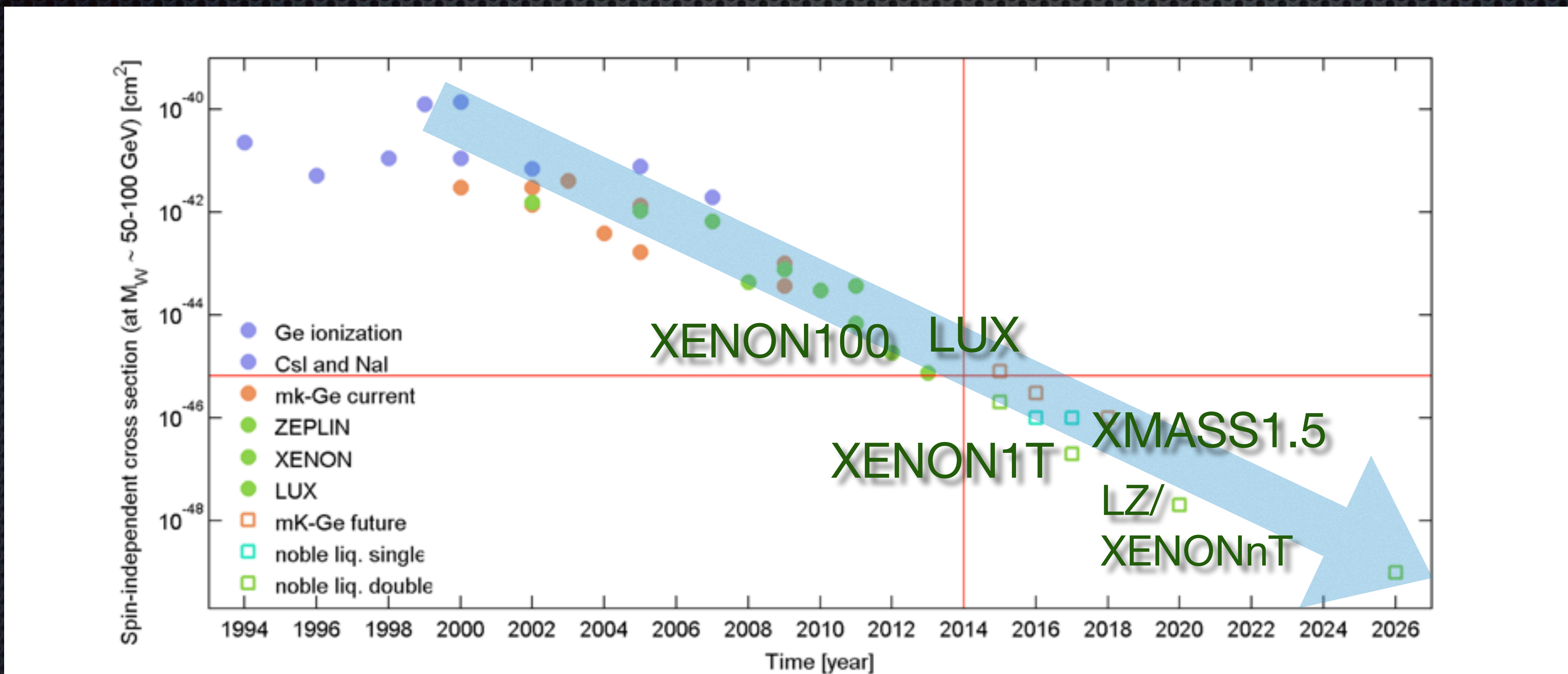
- ultra-low threshold: <50 eV_{ee}
- mass: 100 g (DAMIC100)
- background goal: O(1) evt/kg/keV/day
- most sensitive DM mass: 1~10 GeV

The key is to further lower the threshold and to understand and reduce the background. Not necessary to have a large target mass.

High Mass WIMPs

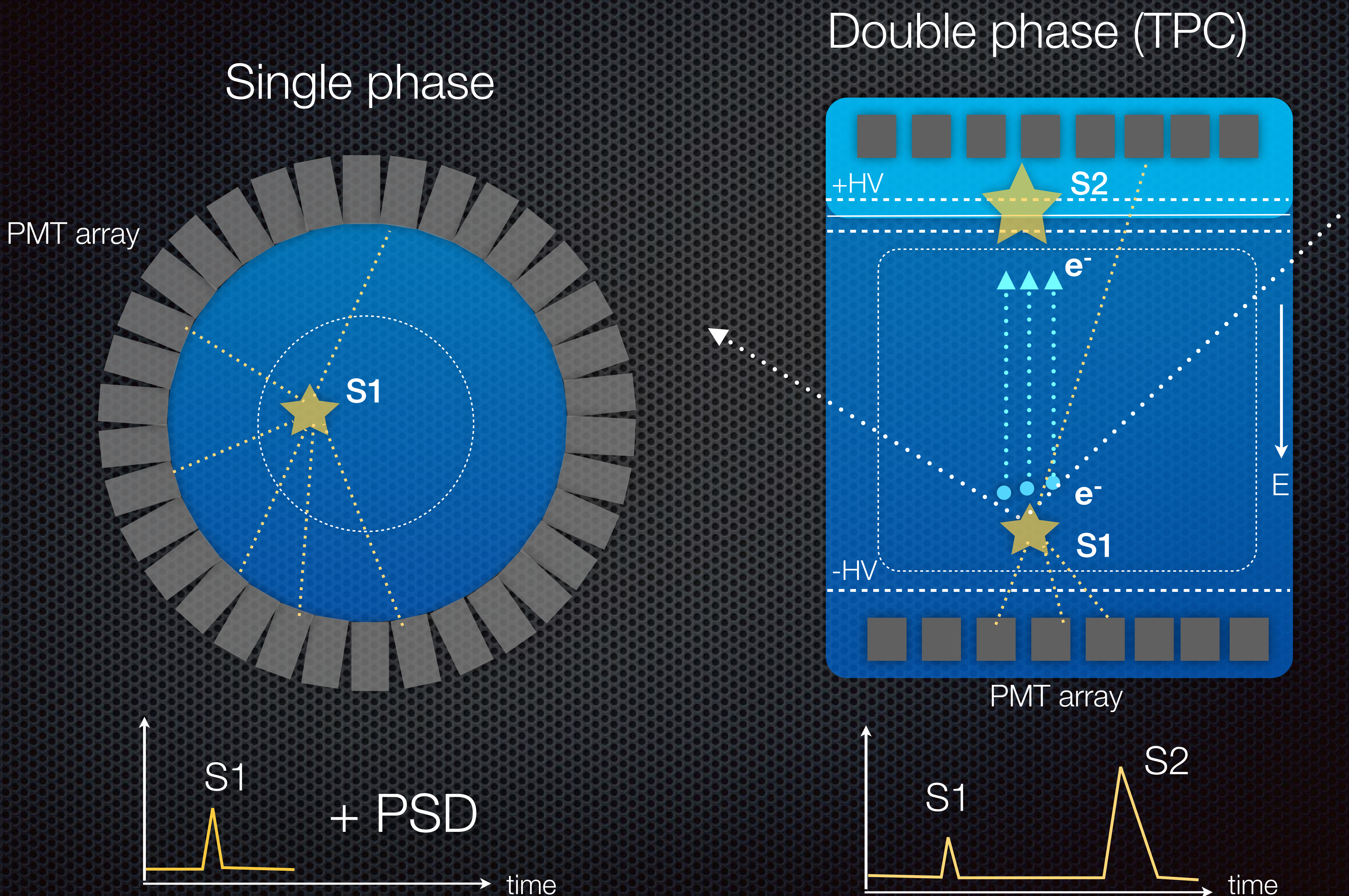
Challenges and Opportunities

keep increasing sensitivity to heavy WIMPs with multi-ton scale noble liquid experiments



About a factor of *10 increase in sensitivity every 2 years*

Noble liquid detector concepts



XMASS @ Kamioka (single-phase LXe)

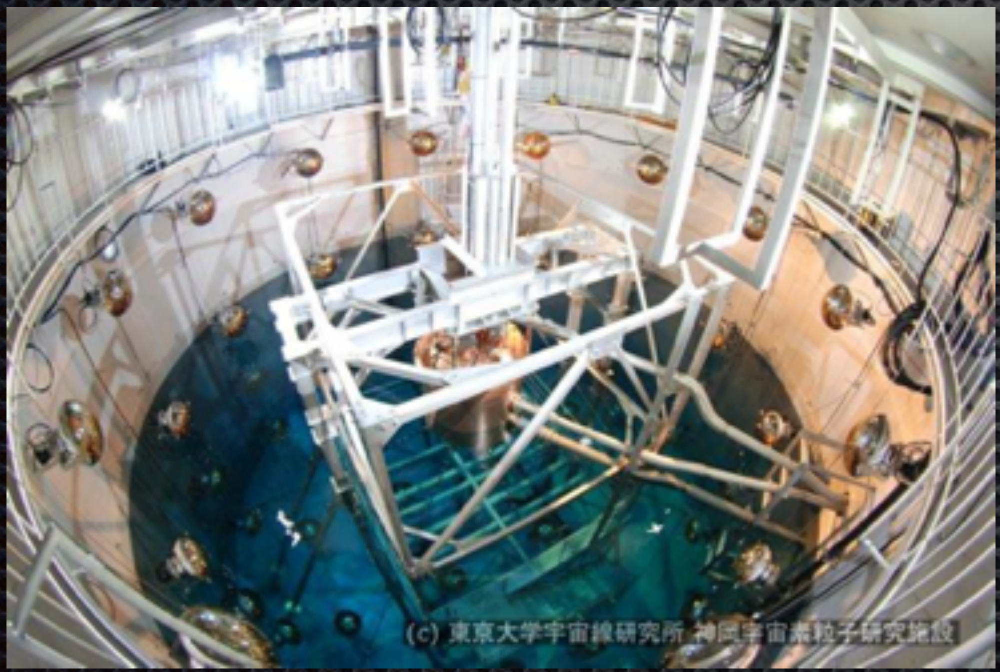
850 kg (100 kg fiducial) liquid xenon in copper vessel, immersed in water tank

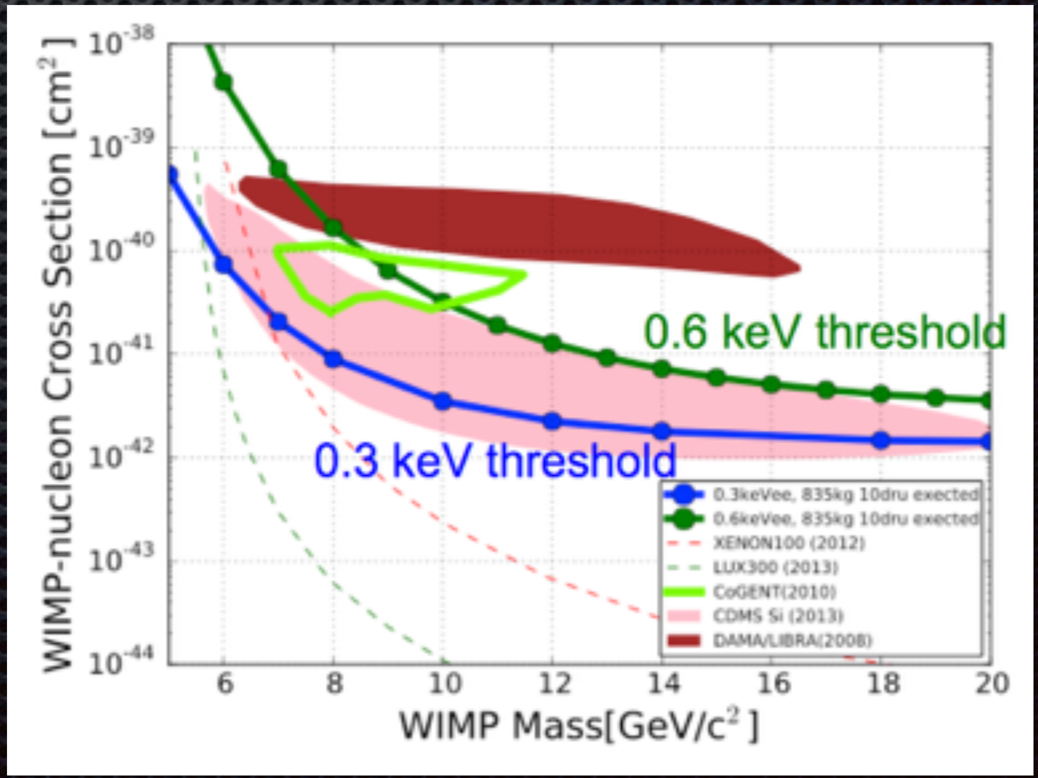
62% of inner surface covered by 632 high QE, HEX PMTs : 13 PE/keV

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





DEAP 3600 @ SNOLAB (single-phase LAr)

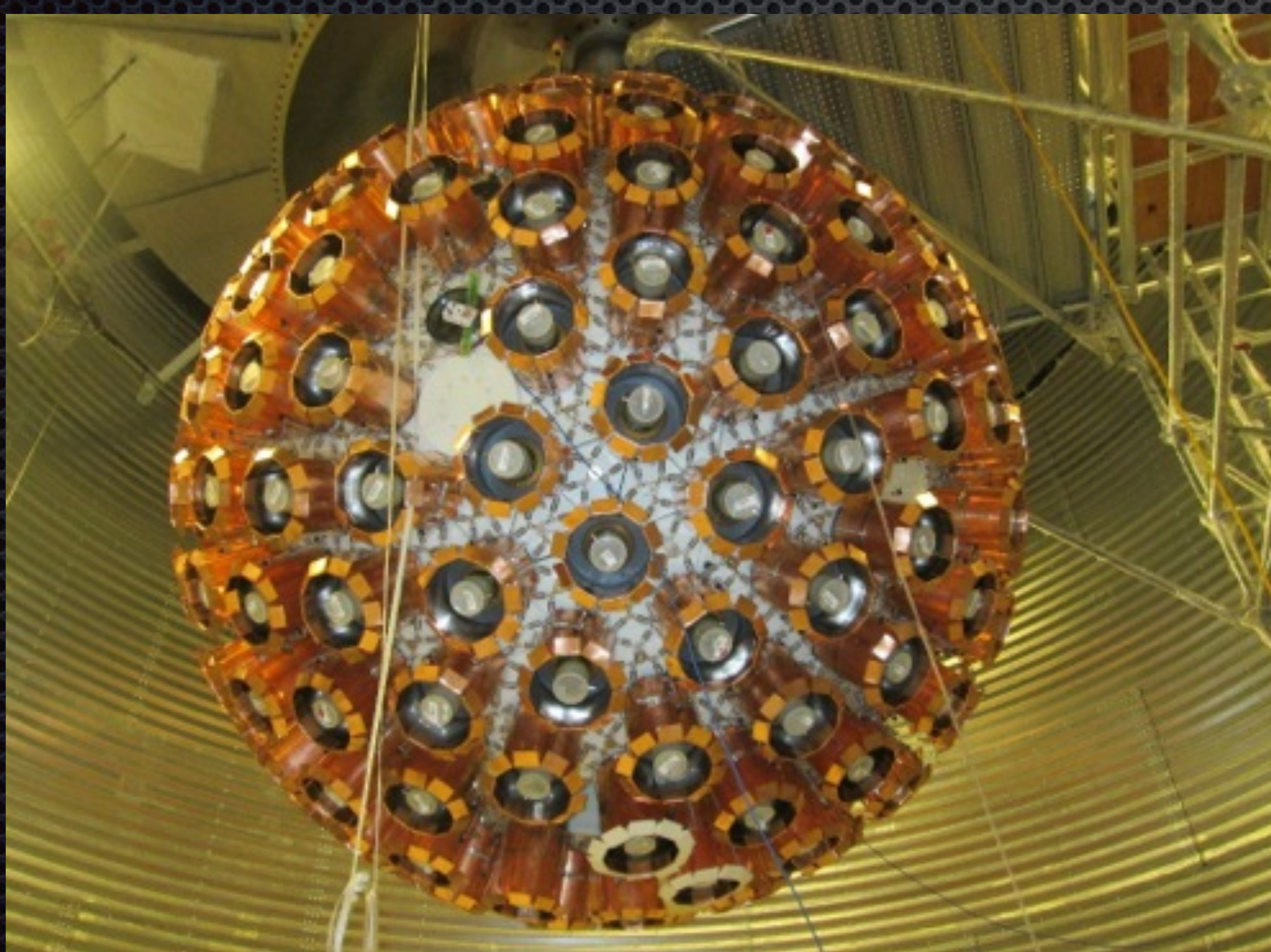
3.6 tonnes liquid argon in ultraclean acrylic vessel, 255 8-inch HQE PMTs

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

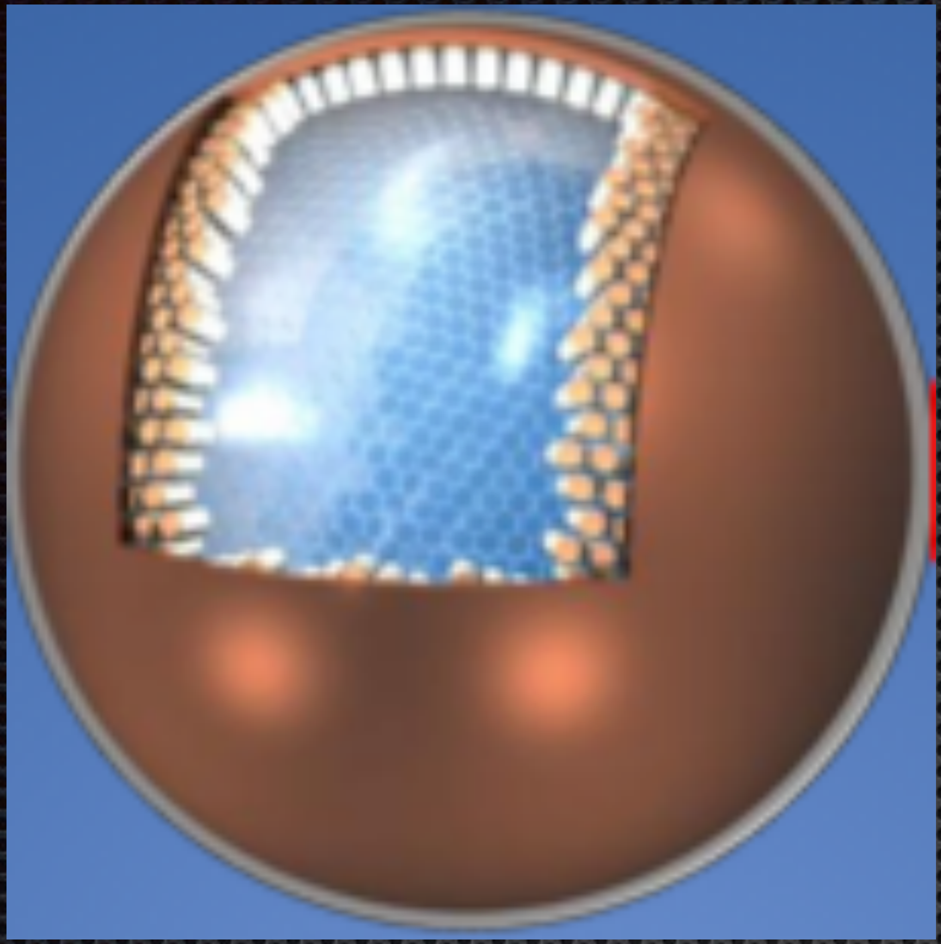
Steel containment sphere immersed in 8 m water tank

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

Ar-test, commissioning in Fall 2014. Physics start in 2015

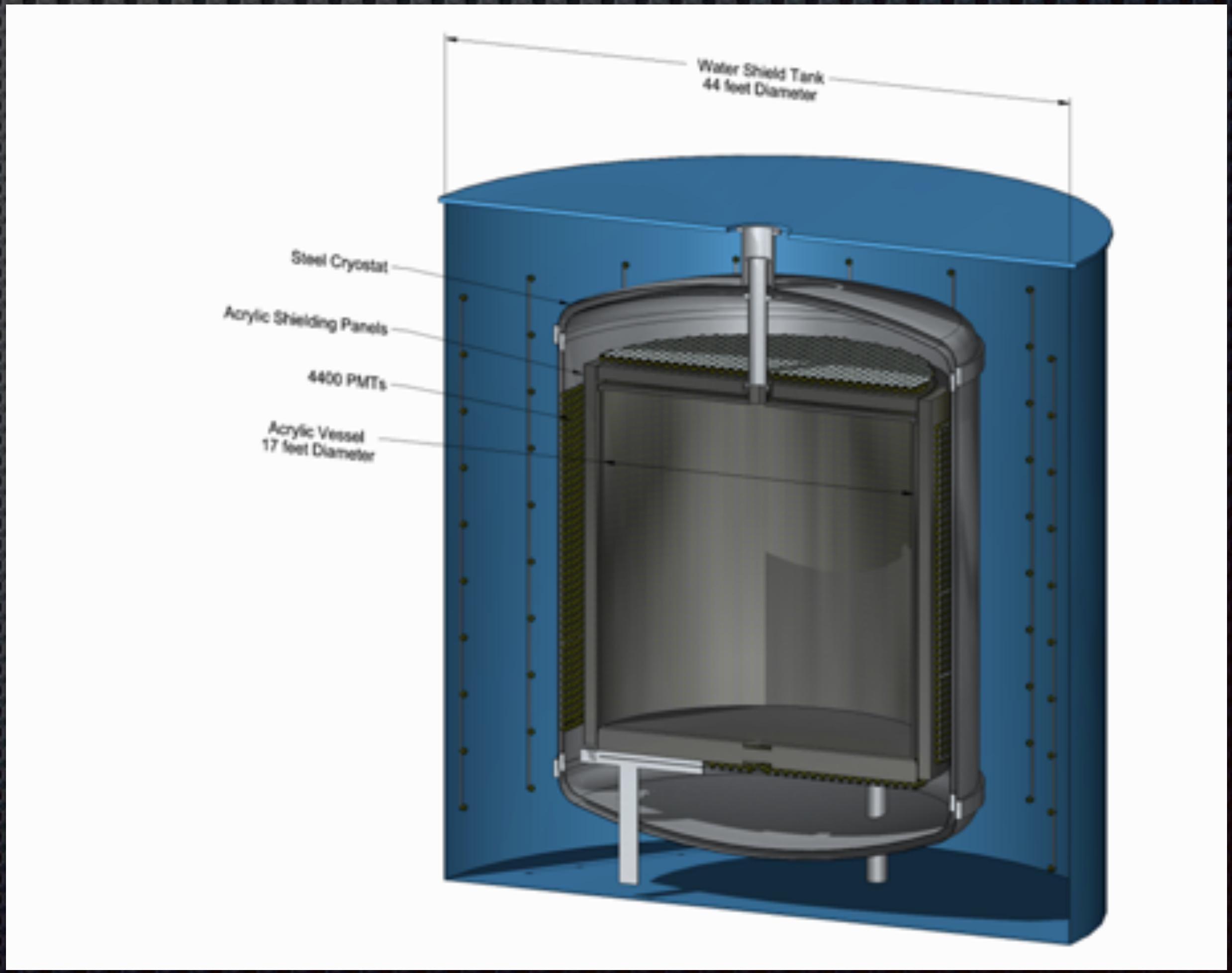


Outlook for XMASS and DEAP

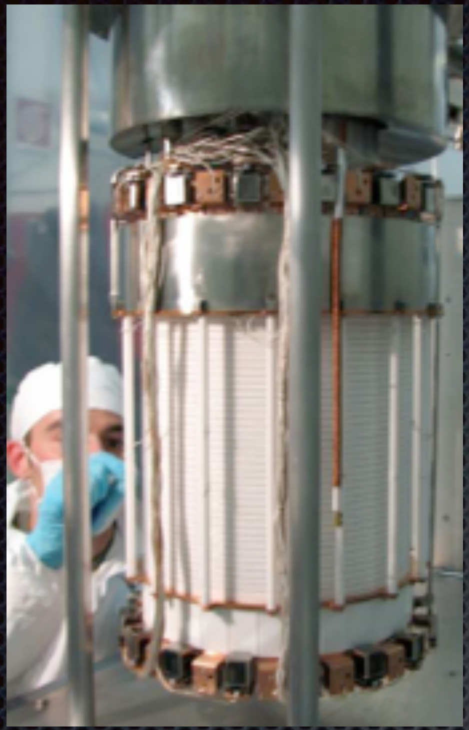


- XMASS1.5 ➔ 5 ton total mass (3 ton fiducial)
- New PMTs to achieve 10^{-5} ev/keV/kg/day
- Projected Sensitivity: $\sigma_{SI} = 10^{-47}$ cm^2 @50 GeV and for the fiducial volume @ 2 keVee thresh
- Status: start in ~2017 ?
- XMASSII ➔ 24 ton total mass (10 ton fiducial)

- DEAP - 50T ➔ 150 tonnes (50T fiducial) Depleted Ar in acrylic vessel
- New 4400 PMTs to achieve low background (development)
- Projected Sensitivity $\sigma_{SI} = 10^{-48}$ cm^2
- Development Proposal only



Two-phase Xe and Ar TPCs (current generation)



XENON100 at LNGS:

161 kg LXe
(~50 kg fiducial)

242 1-inch PMTs

still in operation
new DM still blinded
Modulation study completed

LUX at SURF:

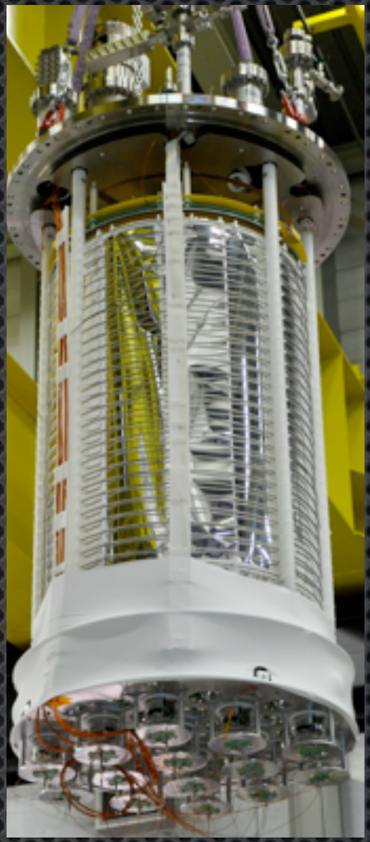
370 kg LXe
(100 kg fiducial)

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
Preparing 500kg PandaX-II



ArDM at Canfranc:

850 kg LAr
(~500 kg fiducial)?

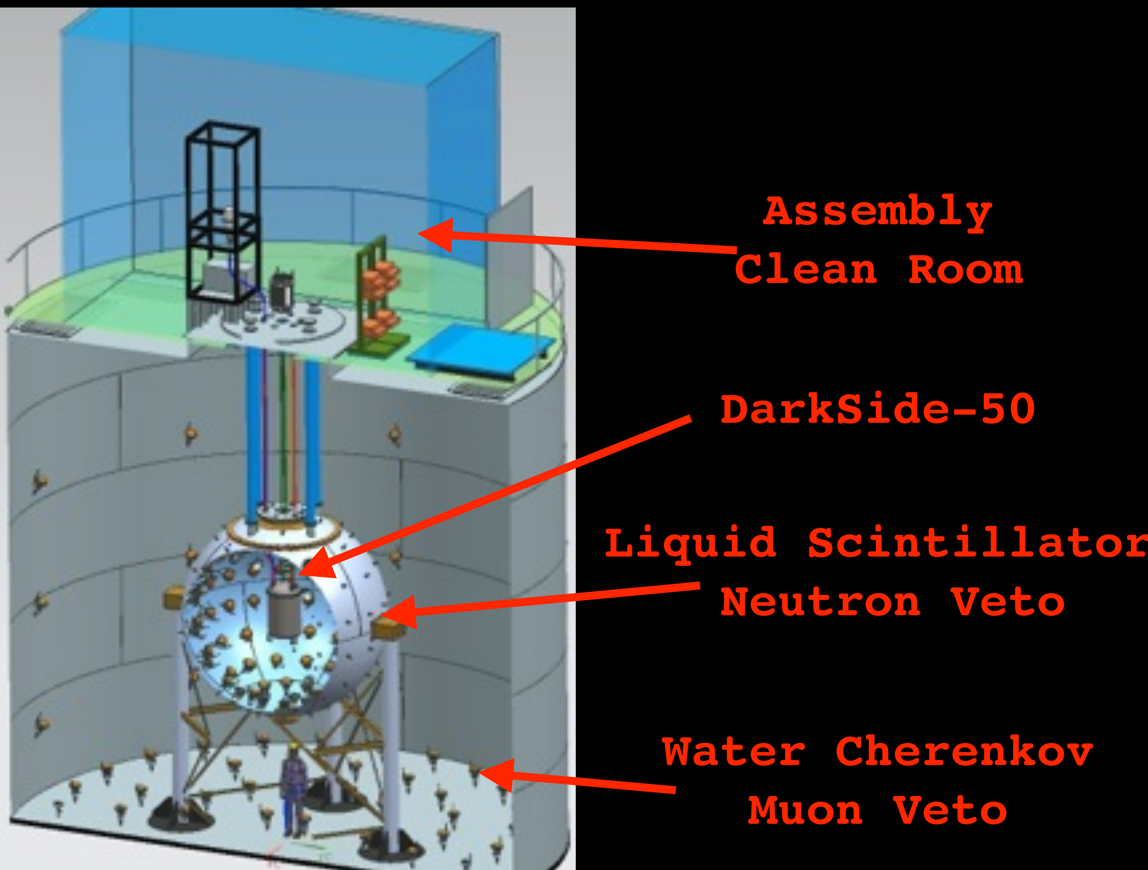
28 3-inch PMTs
Filled in Feb 15. but no field. First science run in 2015?

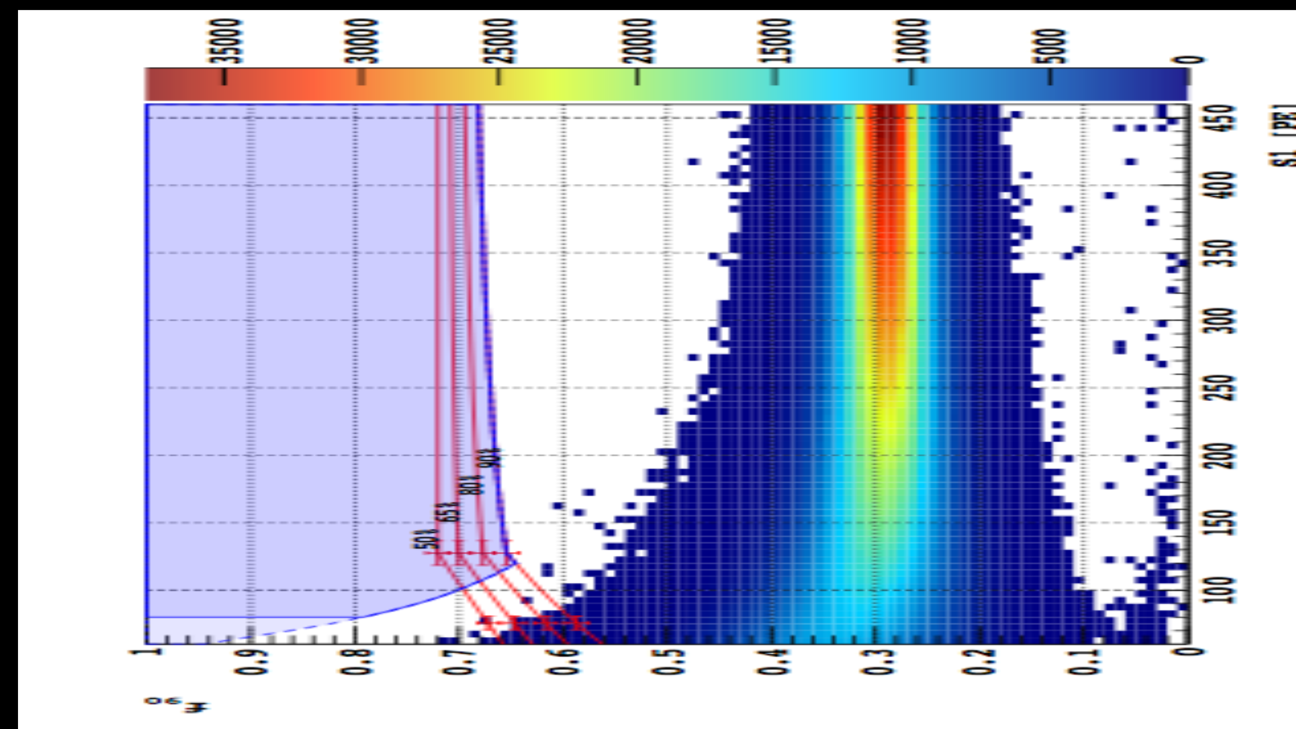
DarkSide at LNGS:

50 kg LAr (dep in ^{39}Ar)
(33 kg fiducial)

38 3-inch PMTs
first result in late 2014. First run with DA in 2015

Outlook for DarkSide

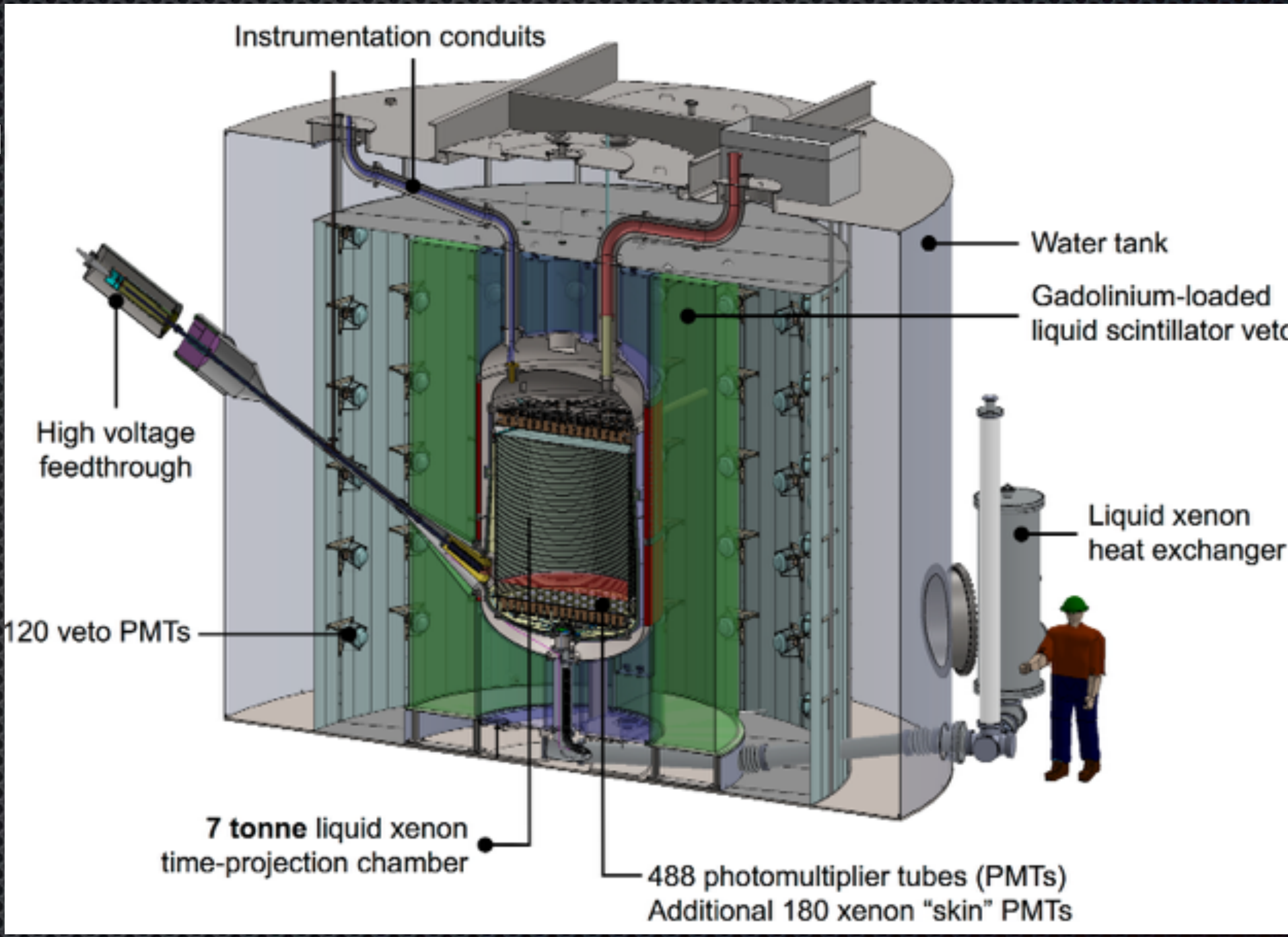




- Published in October 2014 results of DarkSide-50: 1,422 kg×day exposure with no signal and no background. Third best in sensitivity for direct dark matter searches
- March 2015 (now): replacement of atmospheric argon with with underground argon with reduced ^{39}Ar
- Results with atmospheric argon in DarkSide-50 indicate zero background strategy can work also for next generation of detectors, which require operation with underground or otherwise depleted argon
- Next step: O(5 tons) detector at LNGS (within existing DarkSide-50 veto)
- 2020: O(100 tons) detector at LNGS to tackle ultimate dark matter search at “neutrino floor”, which requires 400 tons×yr exposure with no background

Outlook for LUX: LUX + ZEPLIN (LZ)

- **Location/Cost:** SURF. Approved in mid-2014 as DOE-only supported project. Total cost ~55M$ (of which 21M$ assumed from non-US groups and private funds)
- **Detector:** dual-phase TPC with 7t LXe viewed by 488 3-inch PMTs
- **Shield**: Gd-loaded liquid scintillator and LUX water shield
- **Status:** CD-1 review completed? Desired start in 2018 but depends on available budget
- **Projected Sensitivity:** 10^{-48} cm^2 for 50 GeV WIMP with 1000 live days

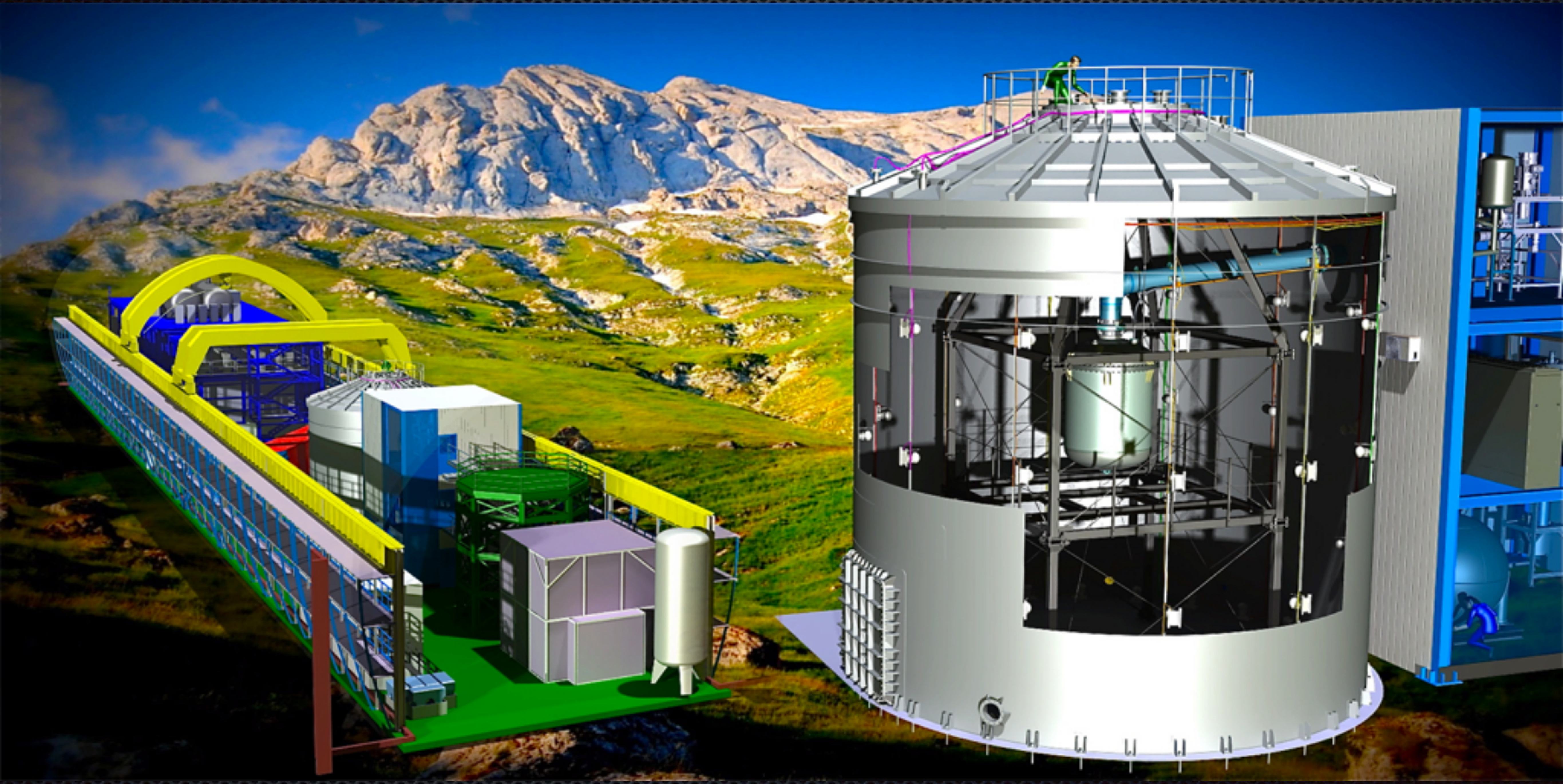


Outlook for XENON: XENON1T /nT

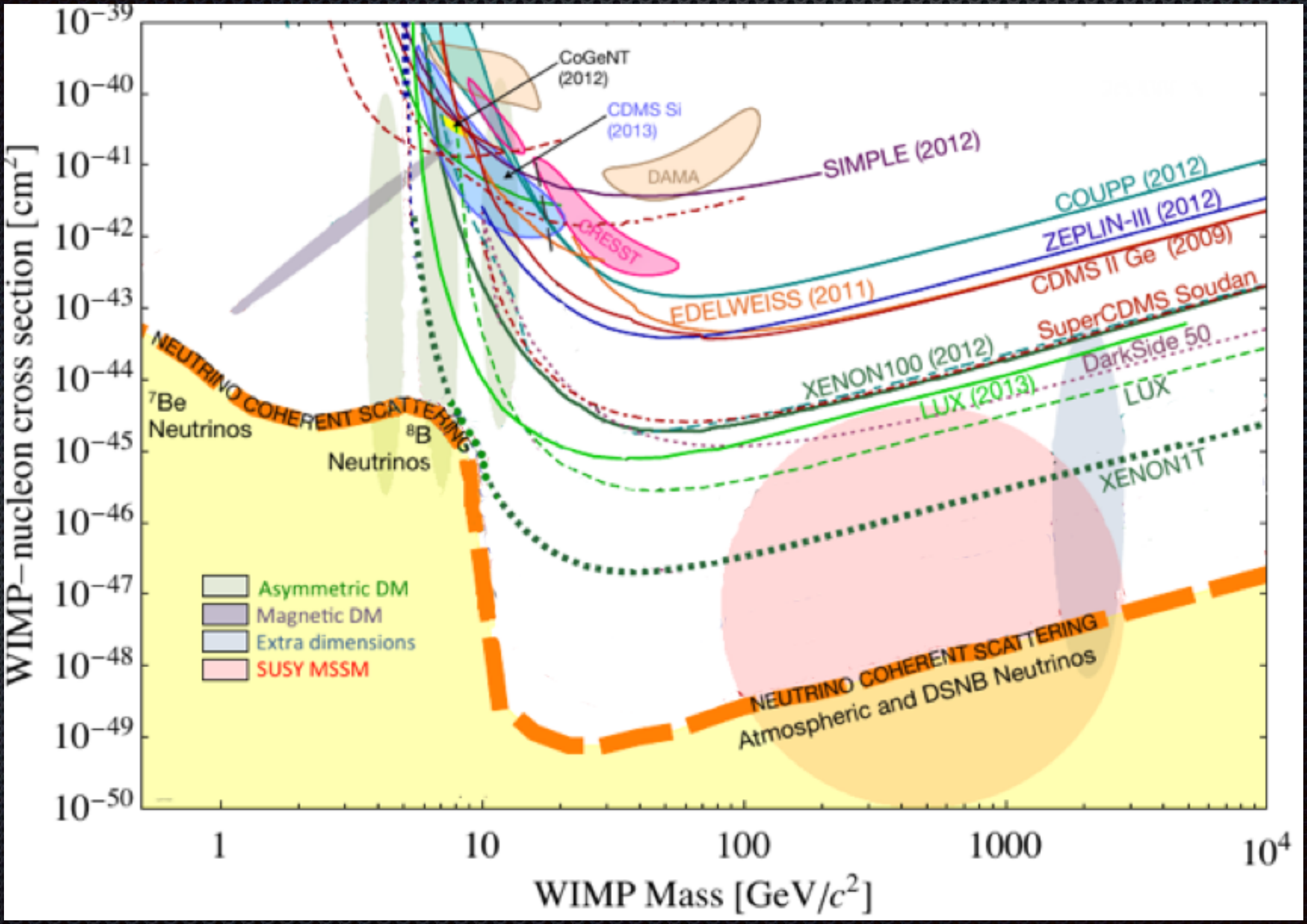
Outlook for XENON: XENON1T /nT

- **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 (7 t & 400 PMTs for upgraded detector (XENONnT) planned for 2018.
- **Shield**: water Cherenkov muon veto. **Back goal:***100 x lower than XENON100, ~5 x 10^{-2} events/(t-d-keV)*
- **Status:** In commissioning. Detector installation by Summer 15. Science data start by late 2015.
- **Projected Sensitivity:** 10^{-47} cm^2 for 50 GeV WIMP with 2 ton x yr data (${10^{-48}}$ cm^2 for XENONnT)

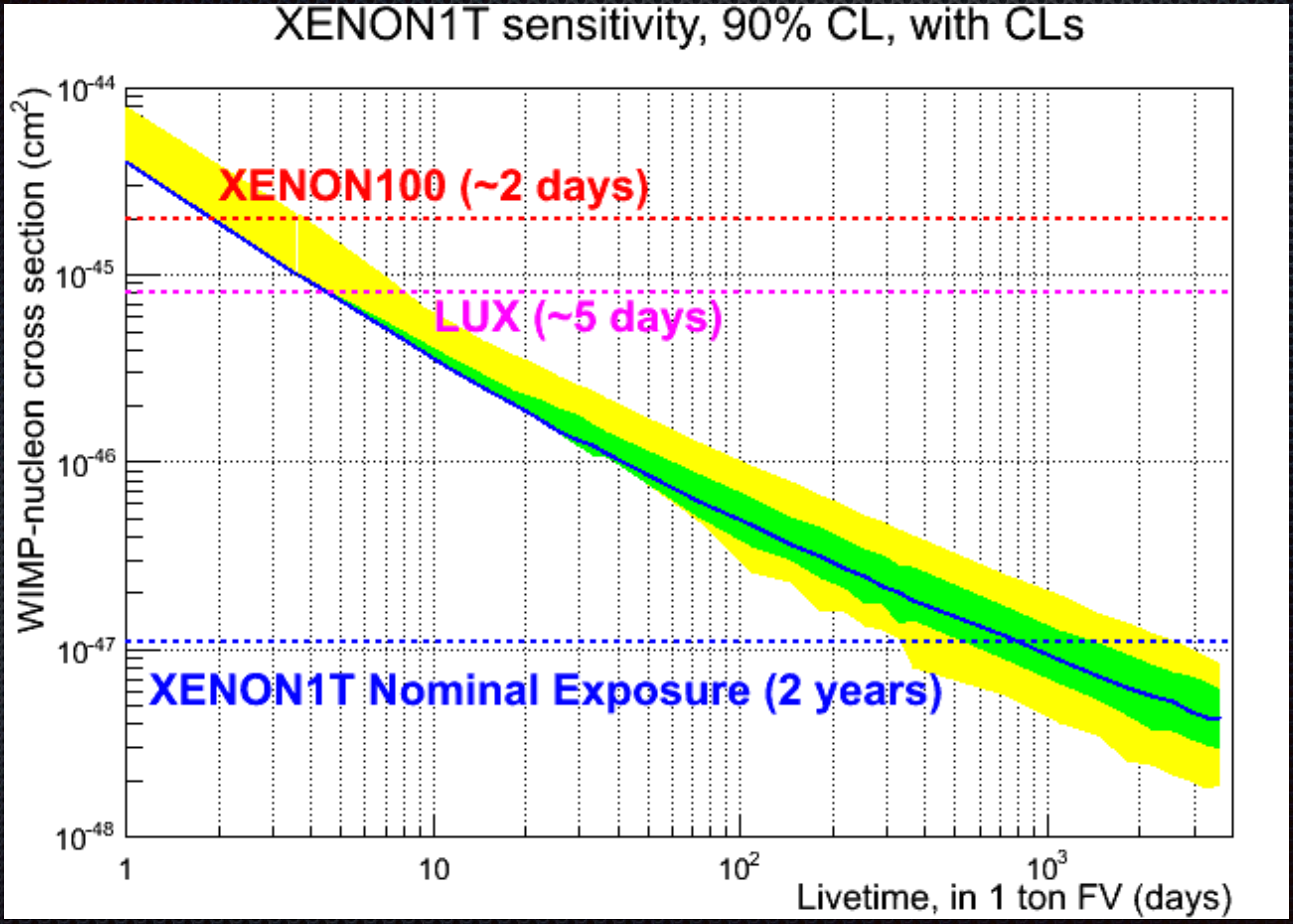
Outlook for XENON: XENON1T /nT



XENON1T Sensitivity Reach



XENON1T Sensitivity Reach



The XENON Collaboration

currently ~ 120 scientists from 17 institutions

Columbia RPI Nikhef Mainz Muenster MPIK

UCLA

Rice

Bern

Zurich

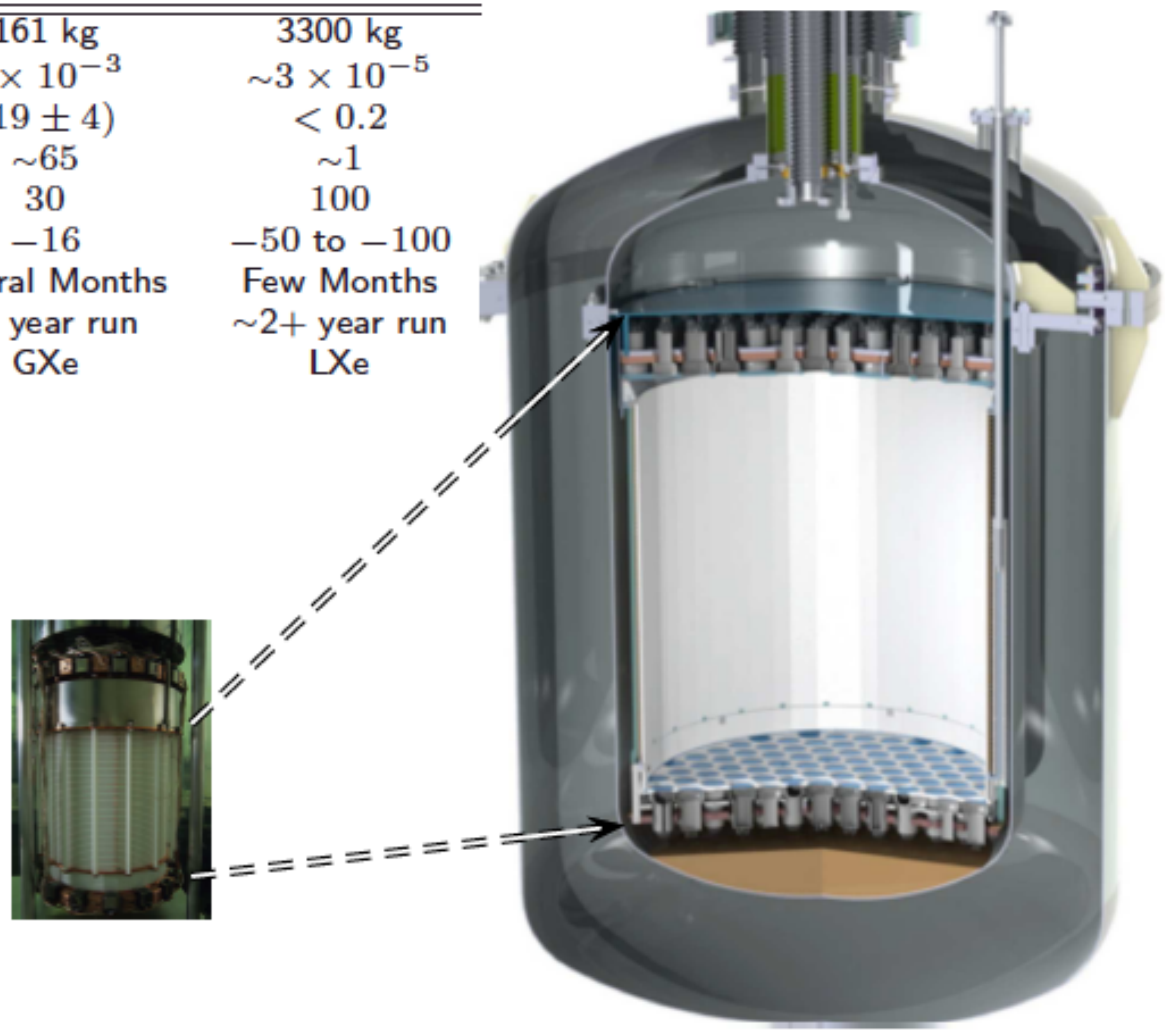
Purdue Coimbra Subatech Bologna LNGS Torino Weizmann NYUAD

The XENON Collaboration

currently ~ 120 scientists from 17 institutions

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	$\sim$1 year run	$\sim$2+ year run
Storage/Recovery	GXe	LXe



Construction Milestones


July 2013

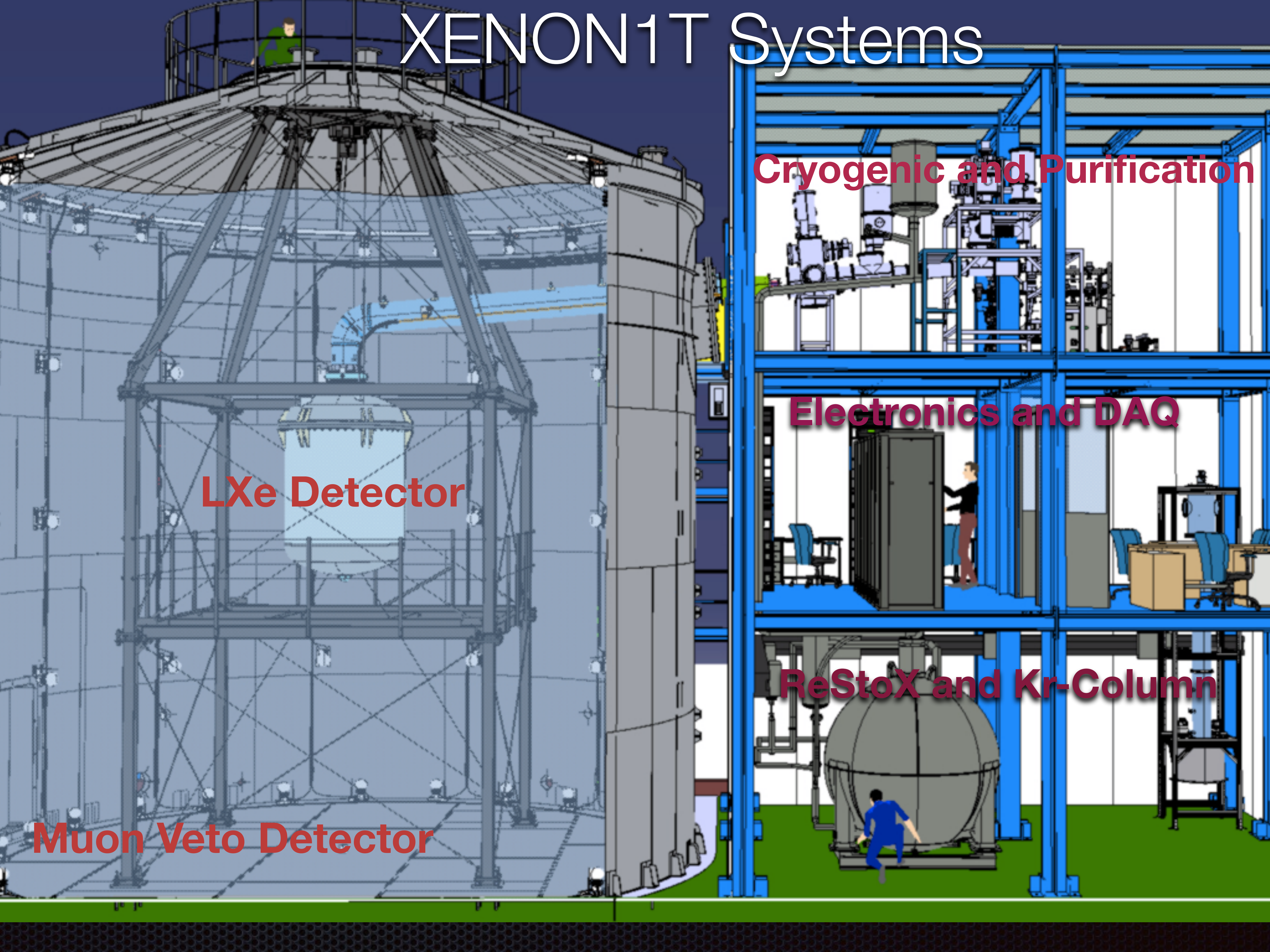

Oct. 2013


photo by R. Corrieri


Jan 2014
photo by R. Corrieri

Aug 2014

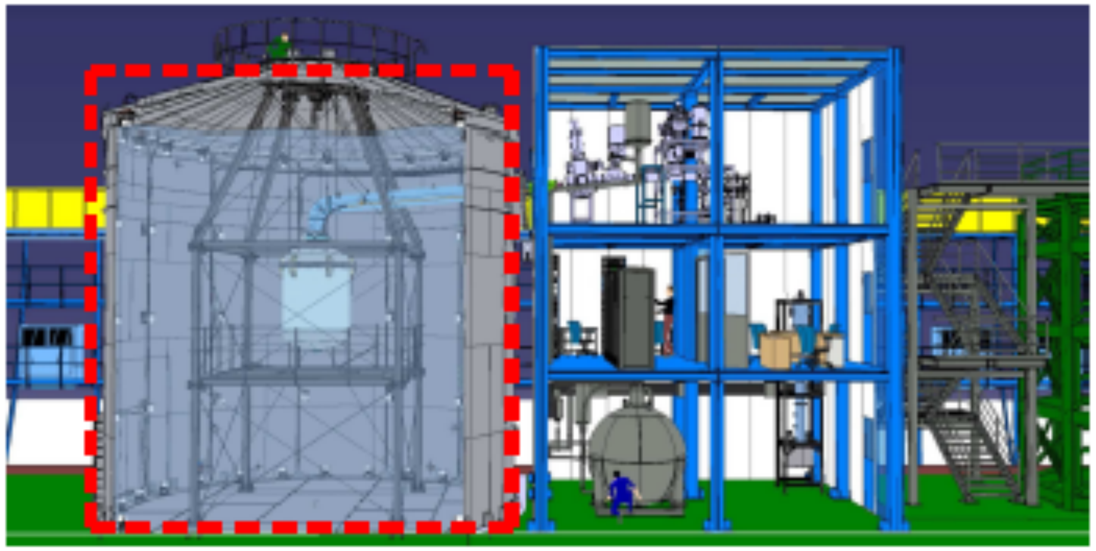
XENON1T Systems



XENON1T Systems

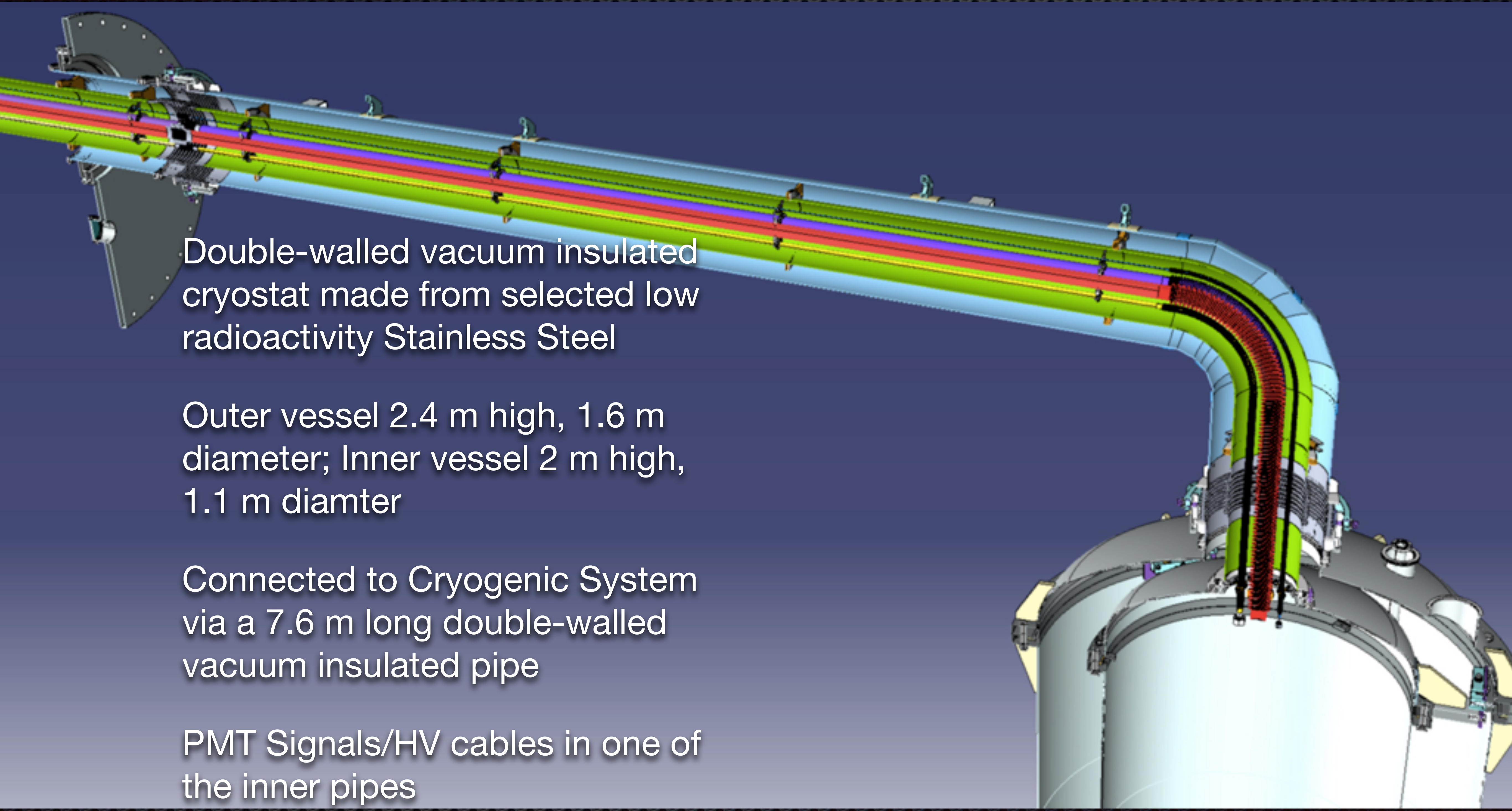
XENON1T Systems

XENON1T: Water Cerenkov Muon Veto



- Water tank $10\,\mathrm{m}$ high and $9.6\,\mathrm{m}$ diameter
- Interior lined with 3M specular reflector foil
- Water tank construction completed 2013/12
- 84 high QE 8" Hamamatsu R5912 PMTs
- μ-induced neutron background < 0.01 evt/yr
- Trigger efficiency $> 99.5\%$ for neutrons with μ in water tank, ~78% with μ outside
- Details in Aprile *et al.*, JINST **9**, P11006, 2014

XENON1T Cryostat



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

Outer vessel 2.4 m high, 1.6 m diameter; Inner vessel 2 m high, 1.1 m diamter

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

PMT Signals/HV cables in one of the inner pipes

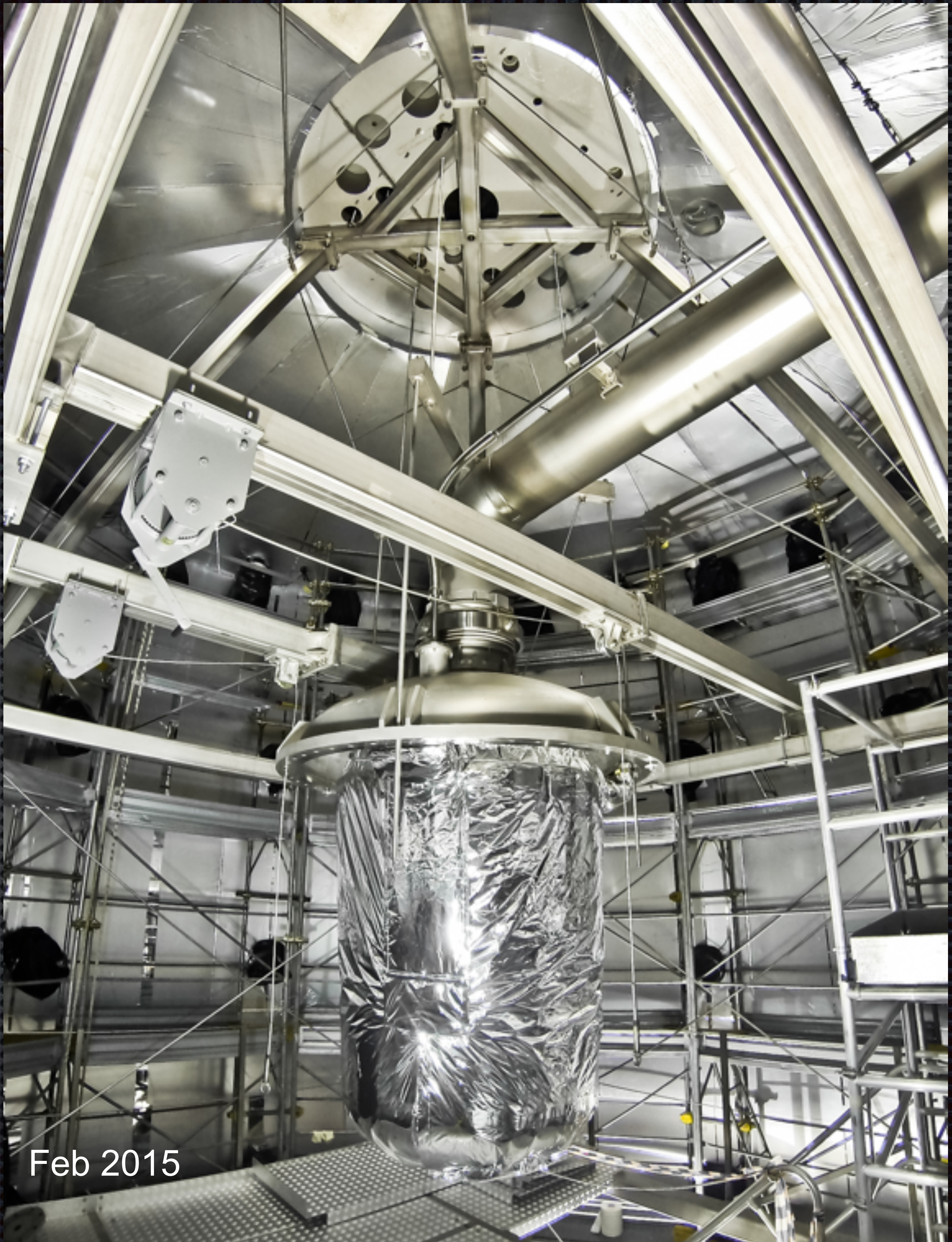
XENON1T Cryostat

XENON1T Cryostat

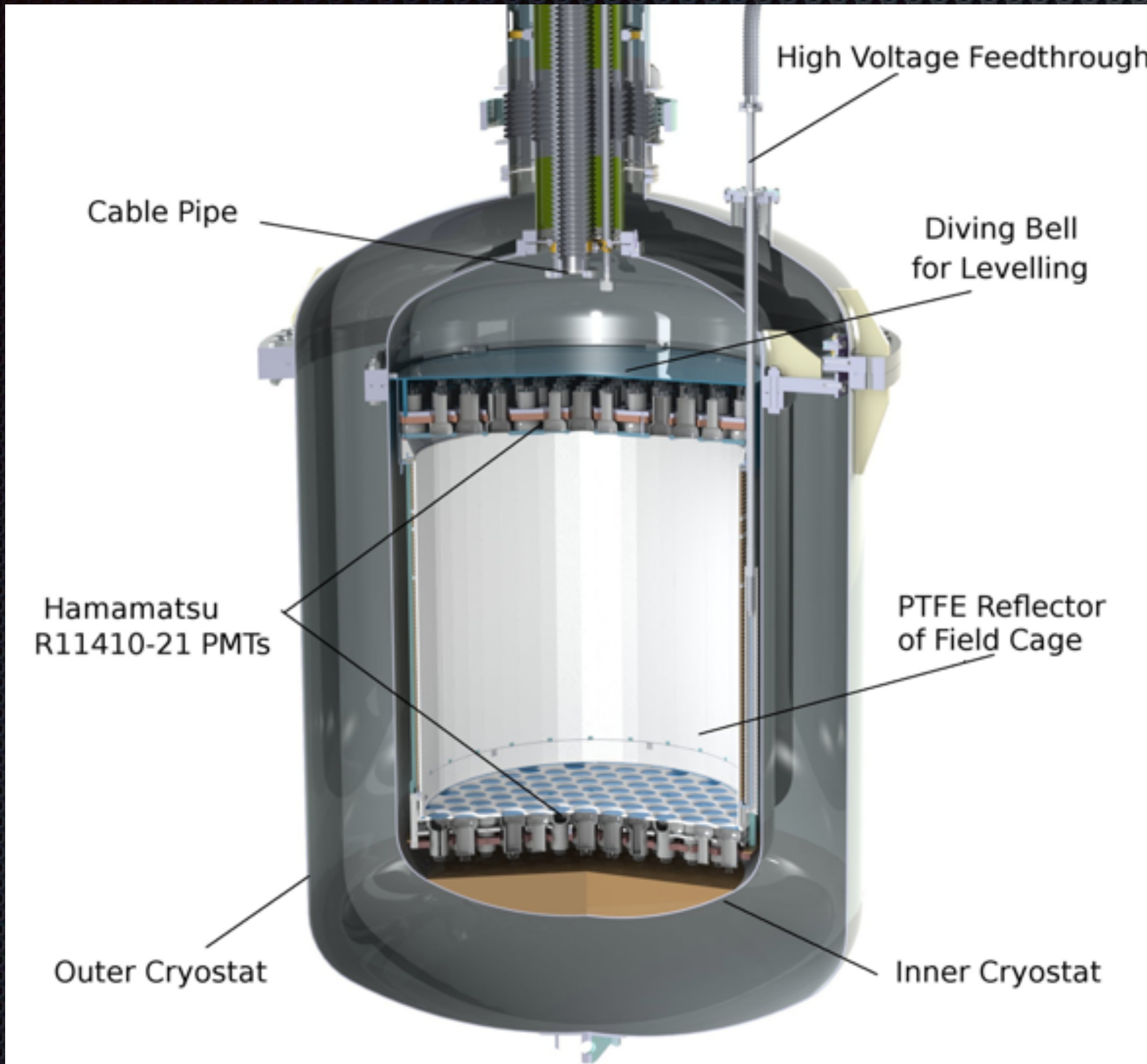
XENON1T Cryostat

XENON1T Cryostat

XENON1T Cryostat


Feb 2015

XENON1T TPC



a larger and improved version of the XENON100 detector

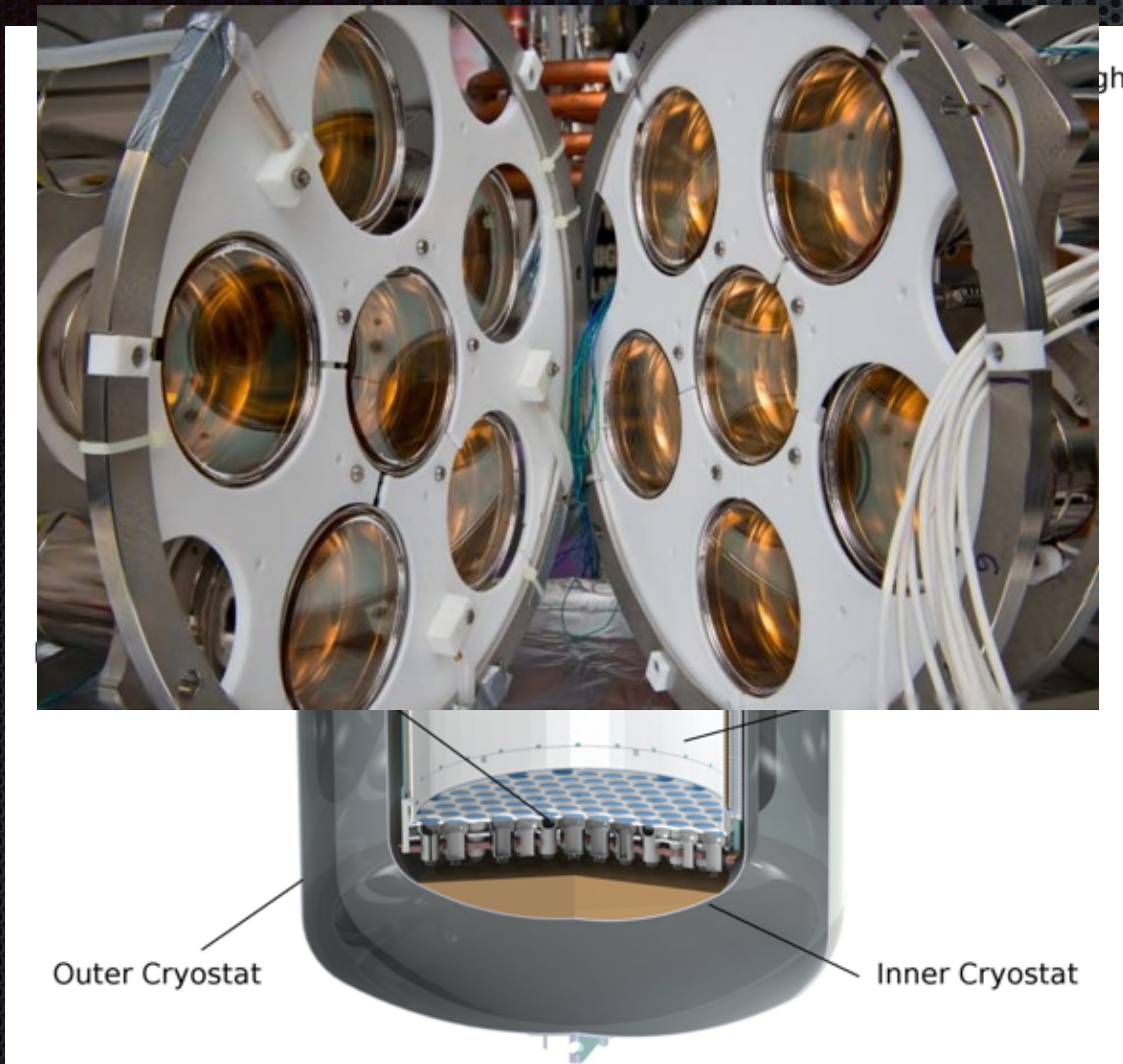
More extensive materials selection to control background, particularly from Rn

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 ~ June 2015

XENON1T TPC



a larger and improved version of the XENON100 detector

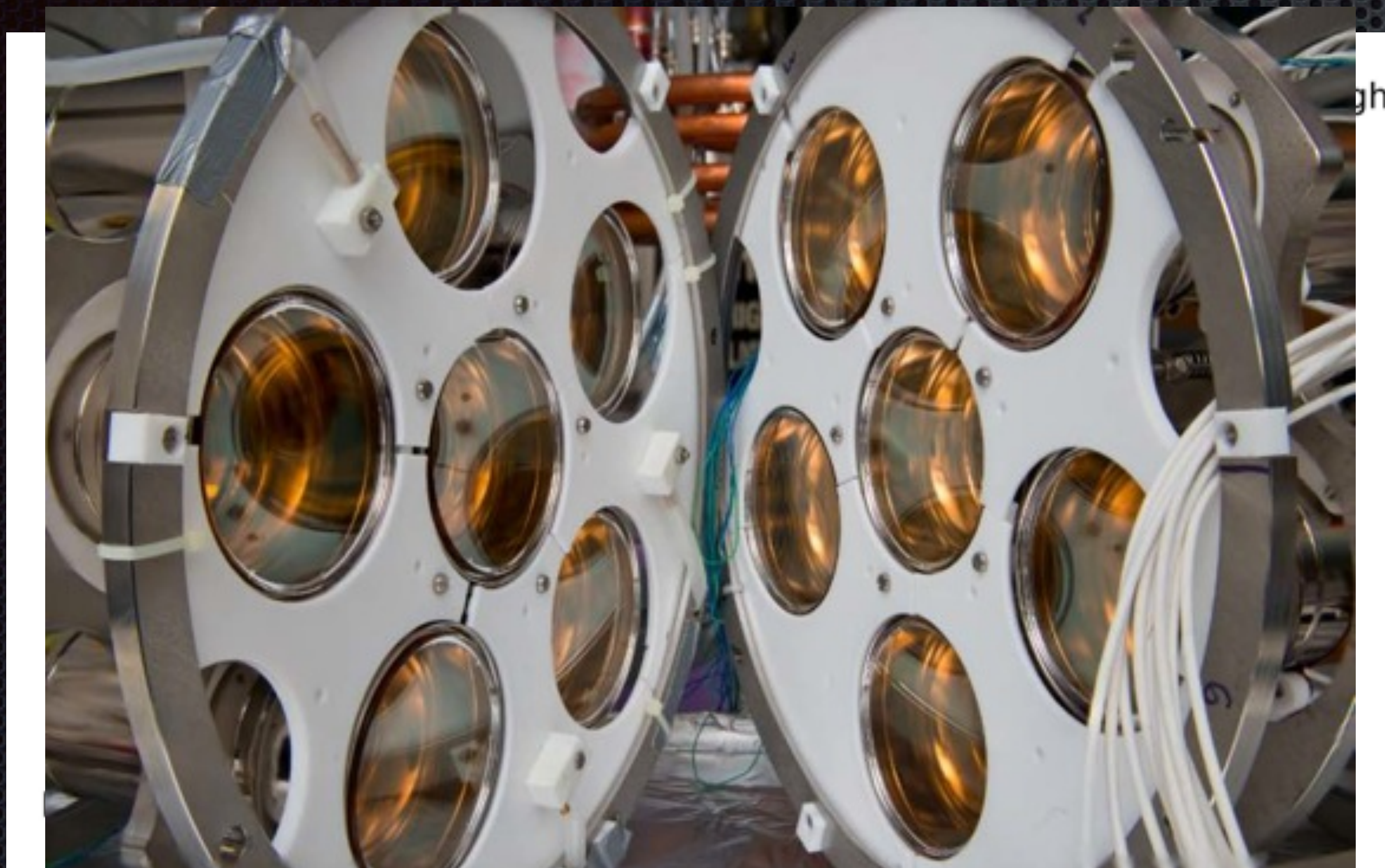
More extensive materials selection to control background, particularly from Rn

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 ~ June 2015

XENON1T TPC



a larger and improved version of the XENON100 detector

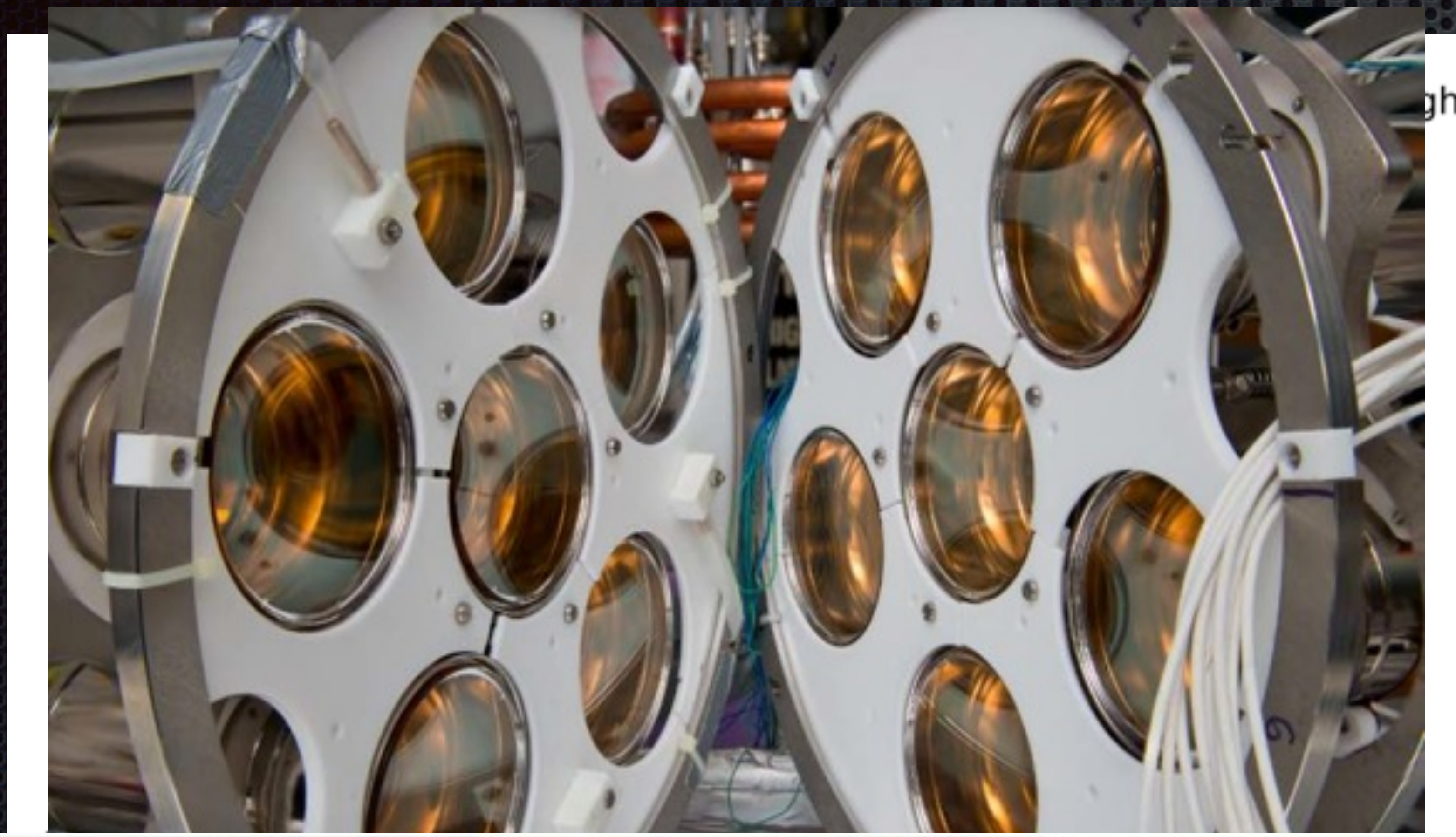
More extensive materials selection to control background, particularly from Rn

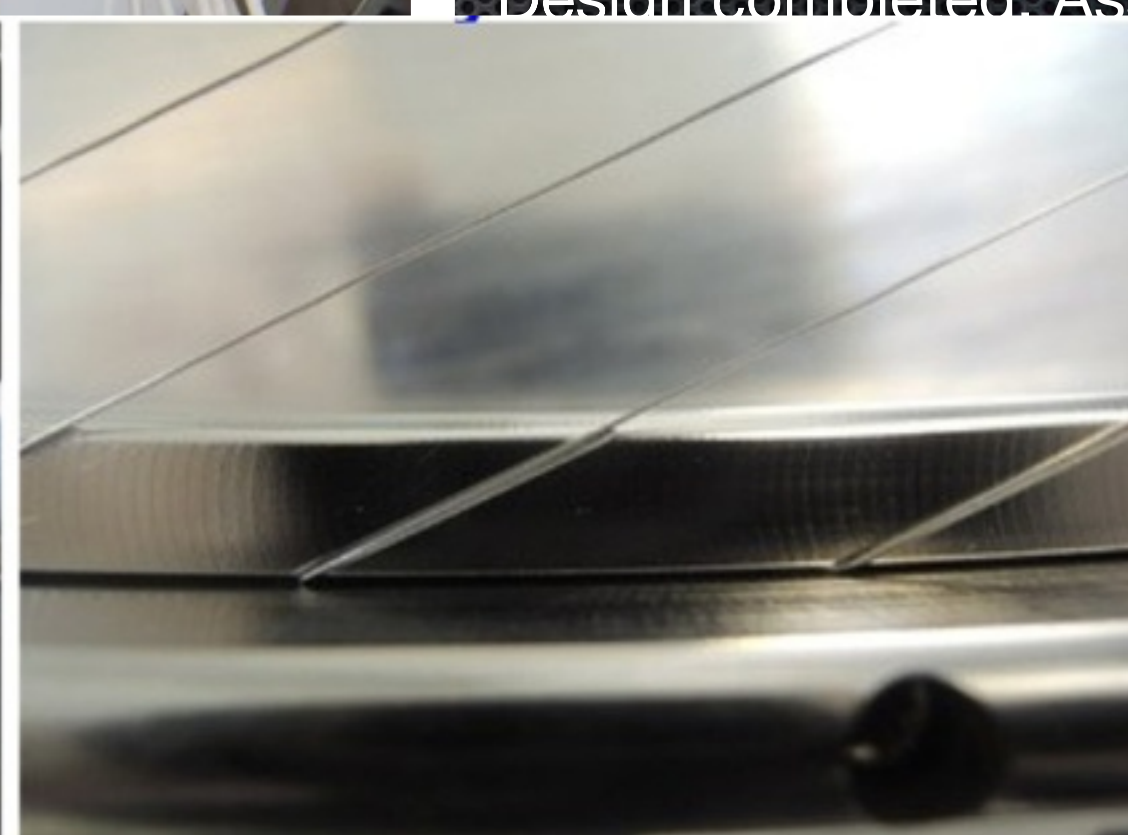
248 x R11410-21 (3 inch PMTs) with average QE (178nm) of 34%

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

hedule: install ~ June 2015

XENON1T TPC





a larger and improved version of the XENON100 detector

More extensive materials selection to control background, particularly from Rn

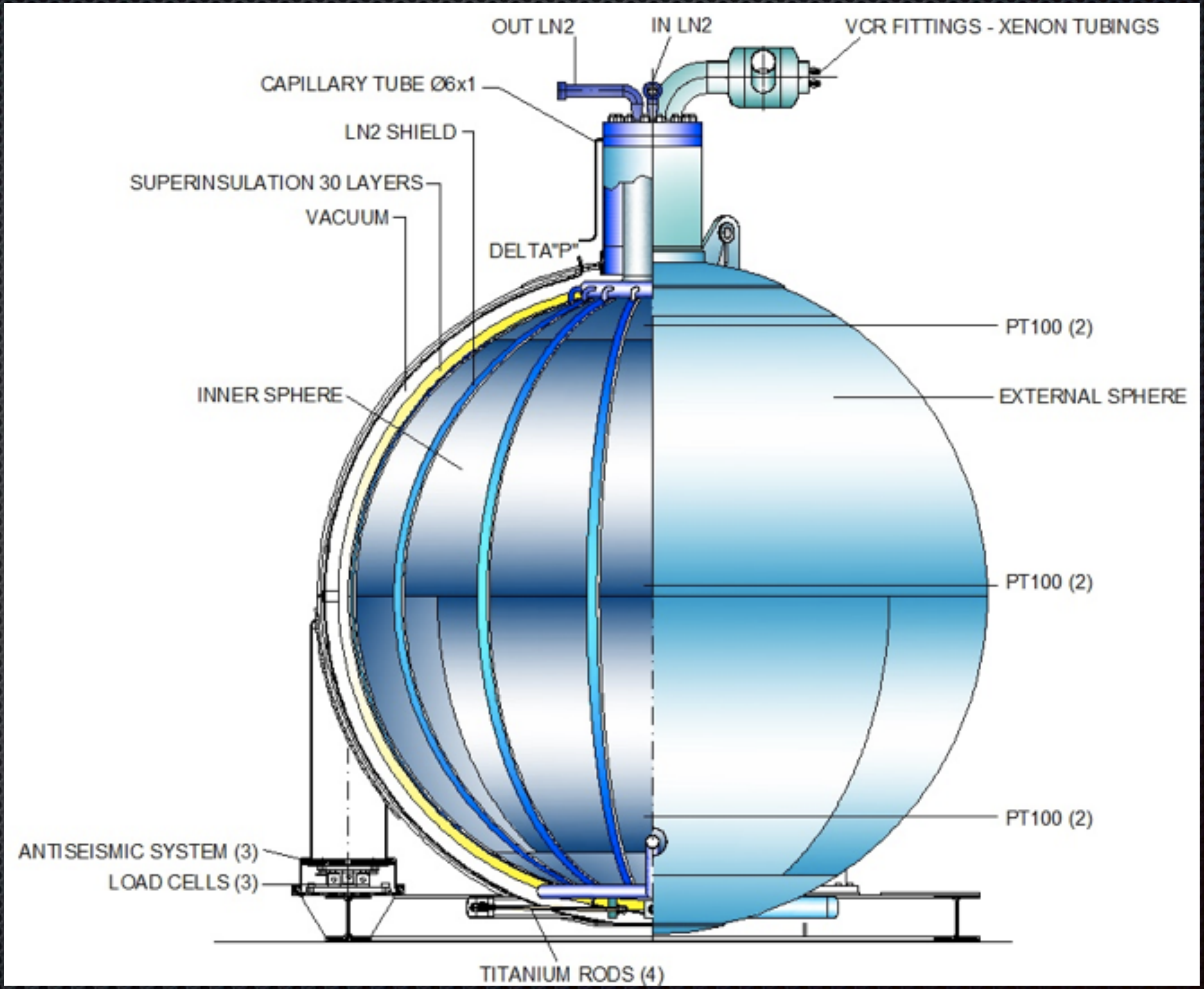
248 x R11410-21 (3 inch PMTs) with average QE (178nm) of 34%

Design completed. Assembly
nstruction
g (grids/
E-shaping)

e 2015

XENON1T 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



XENON1T ReStoX System (Recovery & Storage of Xe)

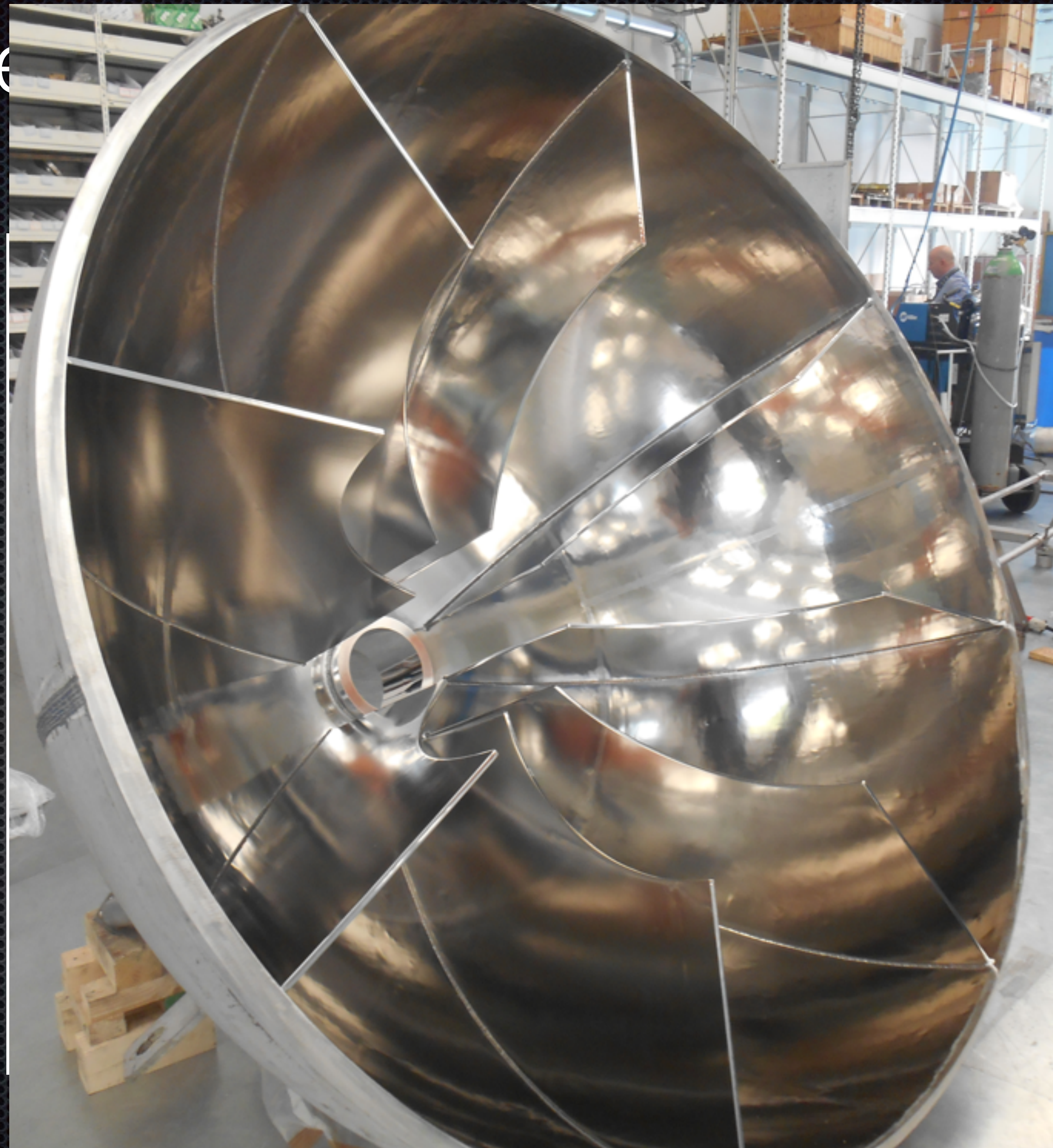
- Double-walled, high pressure (70 atm), vacuum-insulated, LN2 cooled sphere of 2.1 diameter
- To store 7.6 tons of Xe either in gas or liquid/ solid phase under high purity conditions
- To recover in a safe and controlled way LXe from detector. In case of emergency all LXe is recovered in a few hours

XENON1T 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

XENON1T Re
(Recovery &

- 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



XENON1T
(Recovery

- Double-walled, high pressure (70 atm), vacuum-insulated, L cooled sphere of 2. diameter
- To store 7.6 tons of either in gas or liquic solid phase under hi purity conditions
- To recover in a safe controlled way LXe f detector. In case of emergency all LXe is recovered in a few h

XENON1T
(Recovery

- Double-walled, high pressure (70 atm), vacuum-insulated, L cooled sphere of 2.1 diameter

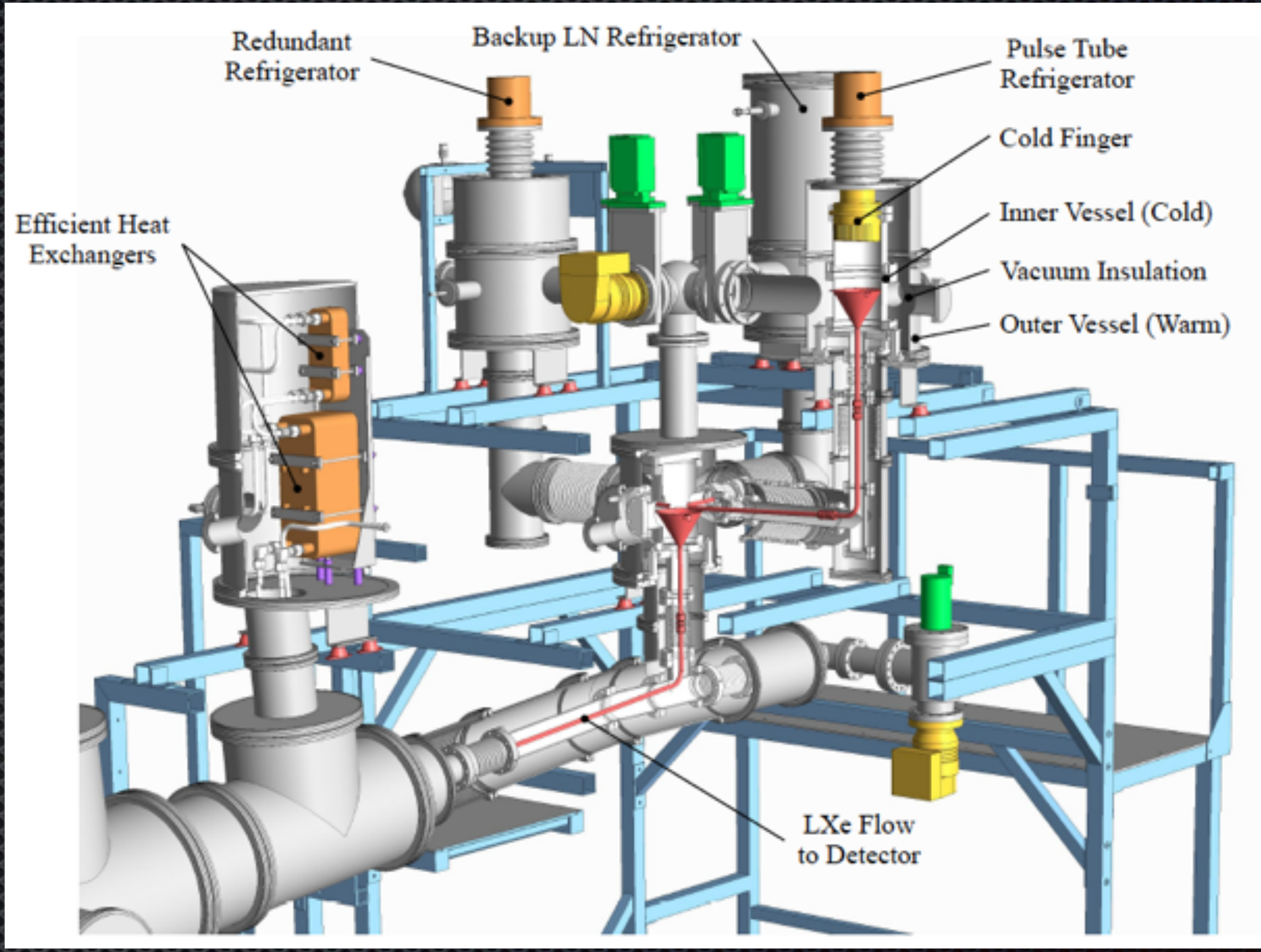
- To store 7.6 tons of either in gas or liquid solid phase under hi purity conditions

- To recover in a safe controlled way LXe f detector. In case of emergency all LXe is recovered in a few h


B3
B2
COLUMBIA
UNIVERSITY
13.08.2014 03:54

XENON1T 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



XENON1T Cryogenic System

XENON1T Cryogenic System

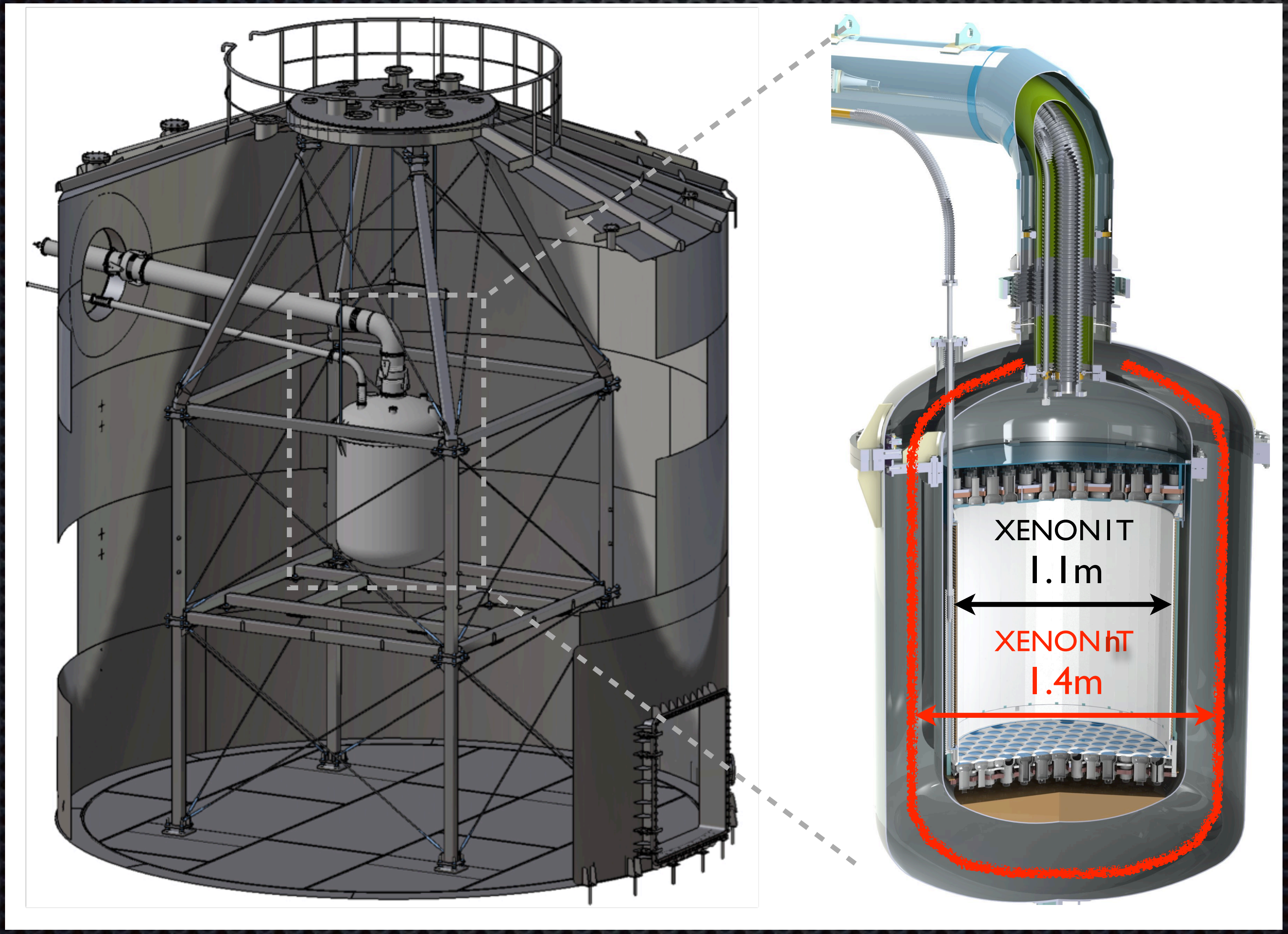
XENON1T Cryogenic System

XENON1T: Kr Removal and Kr/Xe Analytics

- 1ppt Kr/Xe contributes ~ 4 x 10^{-5} cts/keV/kg/d hence XENON1T sensitivity demands ~ 0.2 ppt
- New 5m distillation column with 3kg/hr @ 10^4 separation
- 3m version successfully used to reduce Kr in Xe below 1 ppt as measured by RGMS
- 3m column used on XENON100 to test Radon purification in LXe through cryogenic distillation - the proof of principle is quite successful
- two systems developed to measure $^{nat}Kr/^{nat}Xe$ and infer ^{85}Kr/nat from known $^{85}Kr/^{nat}Kr$: RGMS at MPIK and an Atom Trap at Columbia (Aprile et al. : Rev. Sci. Instrum. 84 (2013))

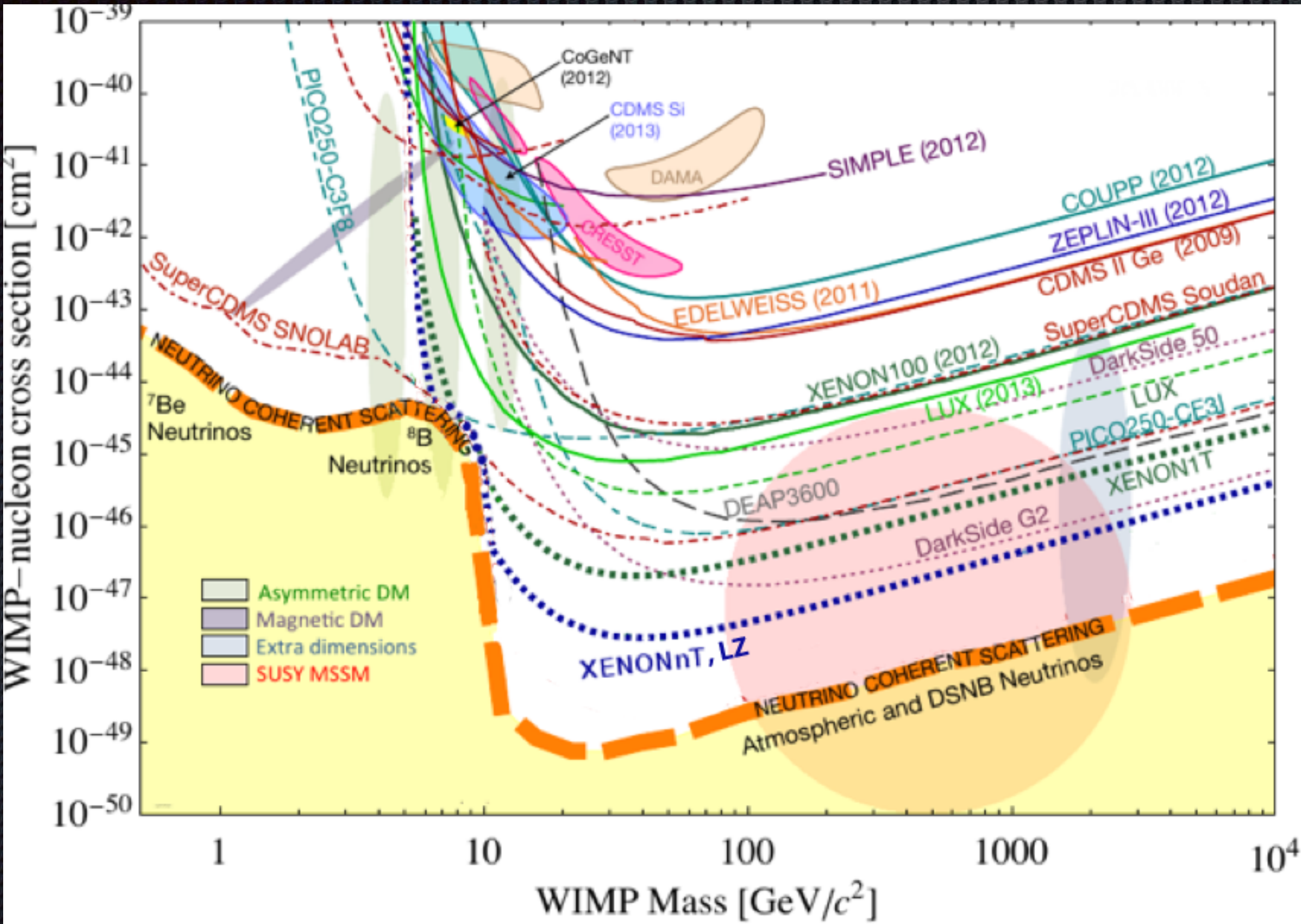
XENONnT: 2018 - 2022

- Double the amount of LXe (~7 tons), add ~200 PMTs & Readout Channels
- XENON1T is designed such that many sub-systems will be reused for the upgrade:



- Water tank + muon veto
- Outer cryostat and support structure
- Cryogenics and purification system
- LXe storage system
- Cables installed for XENONnT as well

XENONnT: 2018 - 2022



s

upgrade:

eto

upport

cation

Summary

- Direct detection experiments have excluded WIMP-nucleon cross sections down to 10^{-8} pb, with about a factor 10 improved sensitivity every two years, driven by LXe .
- The confused situation in the low-mass region has been cleared and future experiments will continue the search for light DM particles with improved sensitivity.
- Next generation LXe based experiments will explore heavy DM particle interactions with about 100 times more sensitivity than reached to-date.
- XENON1T is the first such experiment with thousands of kg of Xe, projected to start operation by 2015. It will test our ingenuity to overcome the challenges faced with the scale-up while providing new opportunities for discovery.
- XENONnT will follow XENON1T by upgrading the detector to contain ~2 x active mass while re-using all the subsystems and infrastructures built for XENON1T. Goal is another factor 10 improvement in sensitivity by 2022. Same sensitivity projected for the LZ at SURF.
- LAr based experiments continue to make progress. DEAP3600, expected to give results in the near future, is currently the only multi-ton scale LAr DM detector. Future experiments at the 50 ton - 150 ton scale under study.