清華大學
Tsinghua University

10th Symposium on Large TPCs for low-energy rare event detection, Dec 15-17, 2021, Paris

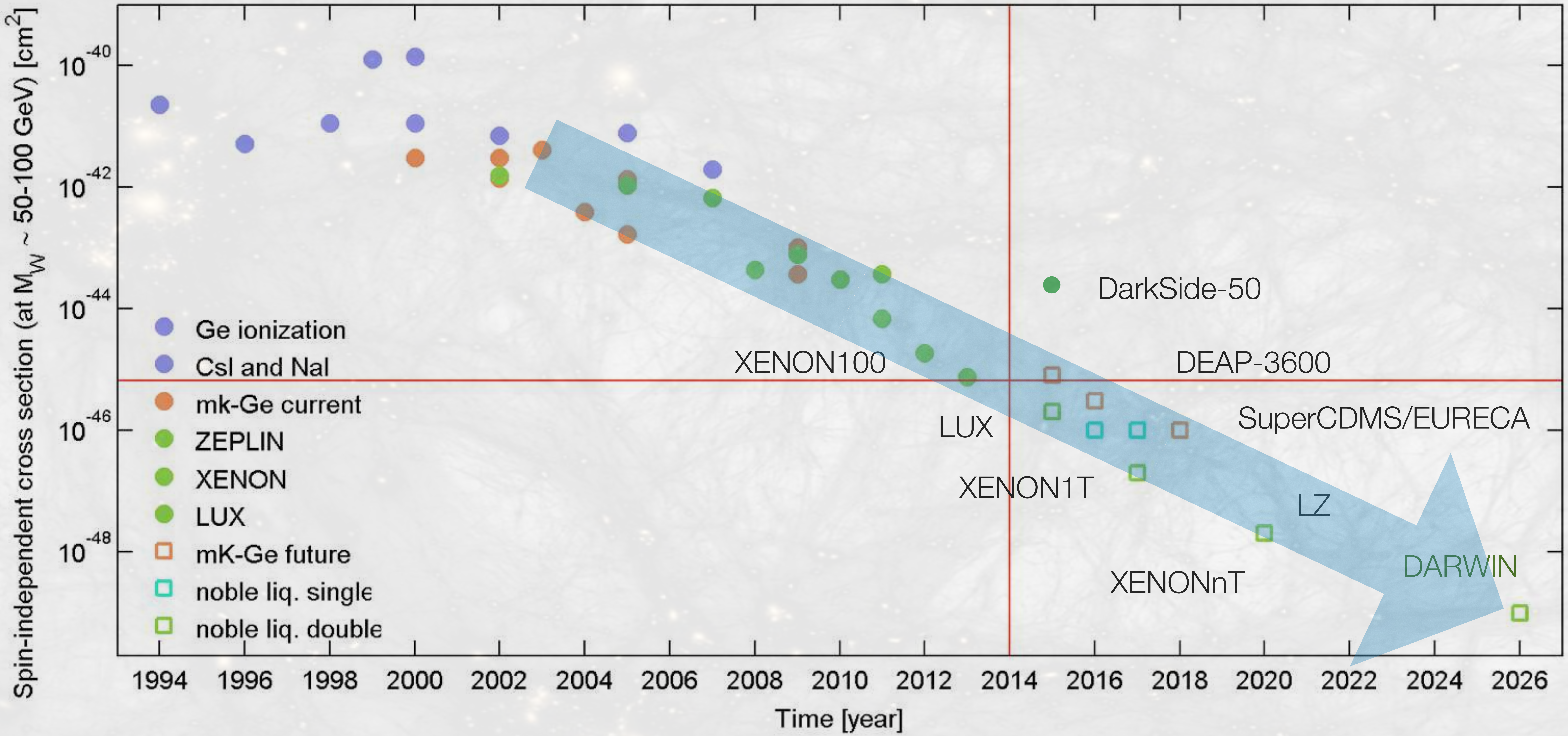
Noble Liquid TPCs for Dark Matter Search

Fei Gao
Tsinghua University

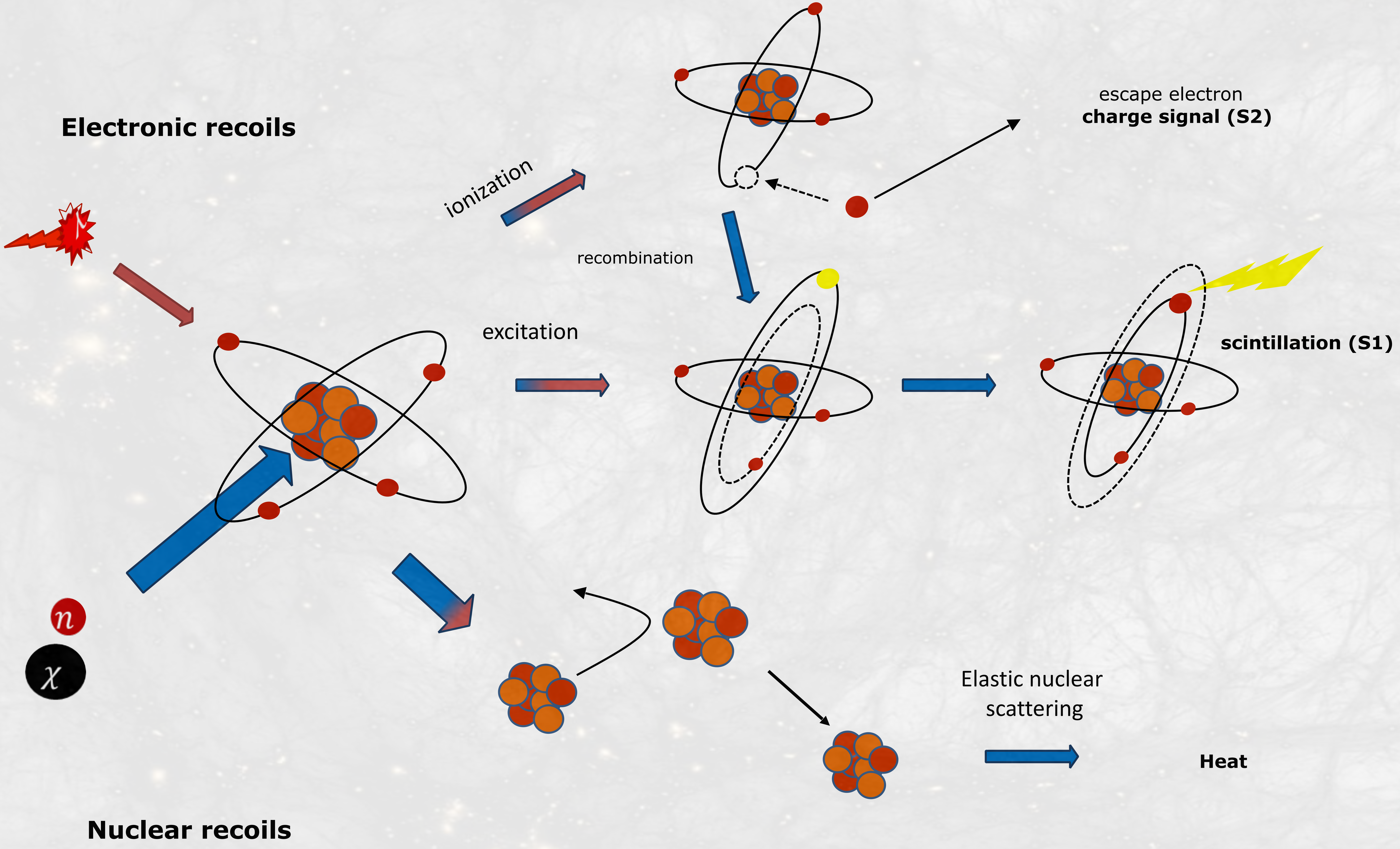
DARKSIDE LZ XENON

WIMP search sensitivity vs time

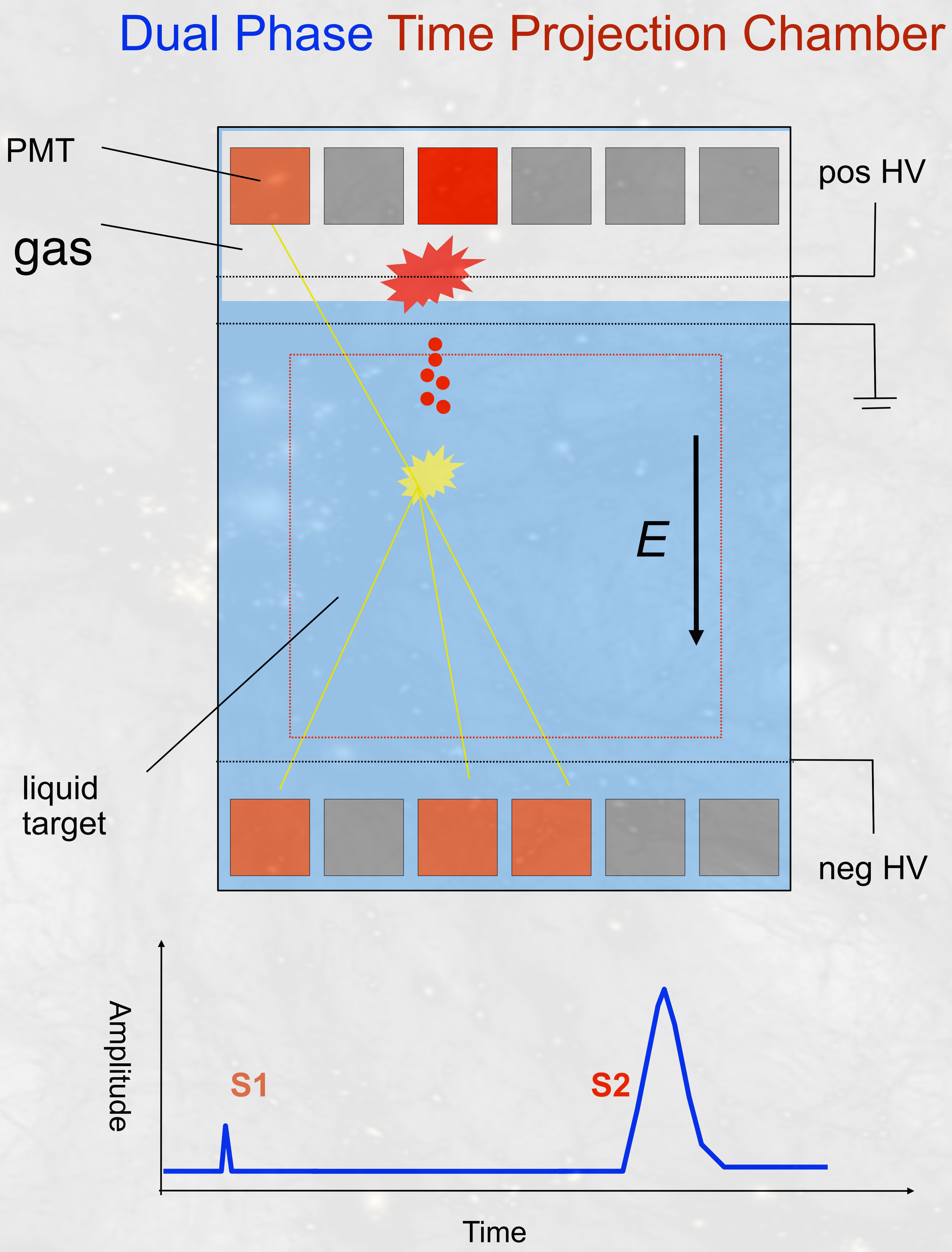
- About a factor of 10 increase every ~ 2 years
- Progress led by searches using **noble liquids**



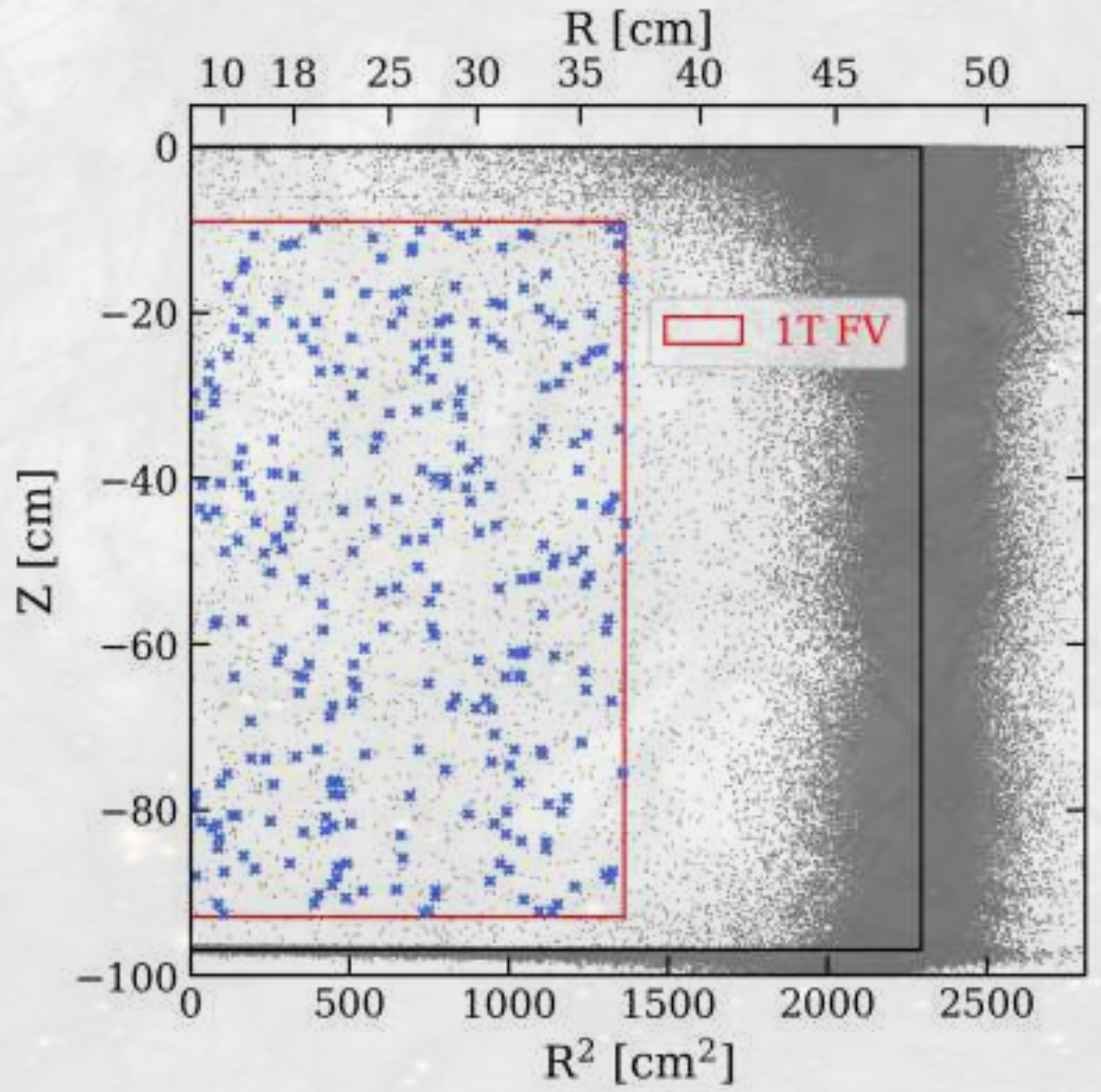
Signals in noble liquids

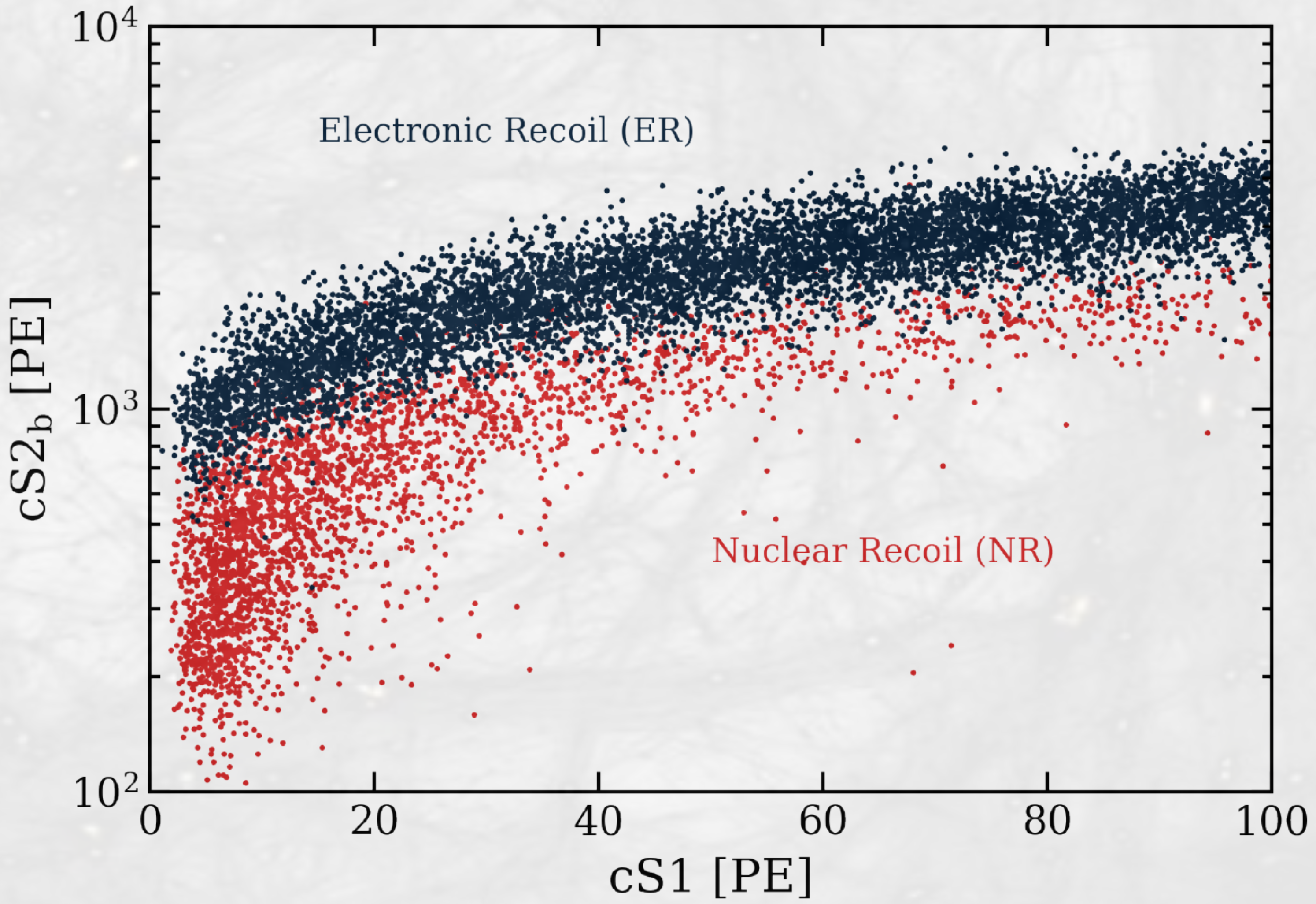


Dual-phase Noble Liquid Time Projection Chambers



- two signals for each event:
  - 3D event imaging: x-y (S2) and z (drift time)
  - self-shielding, surface event rejection, single vs multiple scatter events
- Recoil type discrimination from ratio of charge (S2) to light (S1)

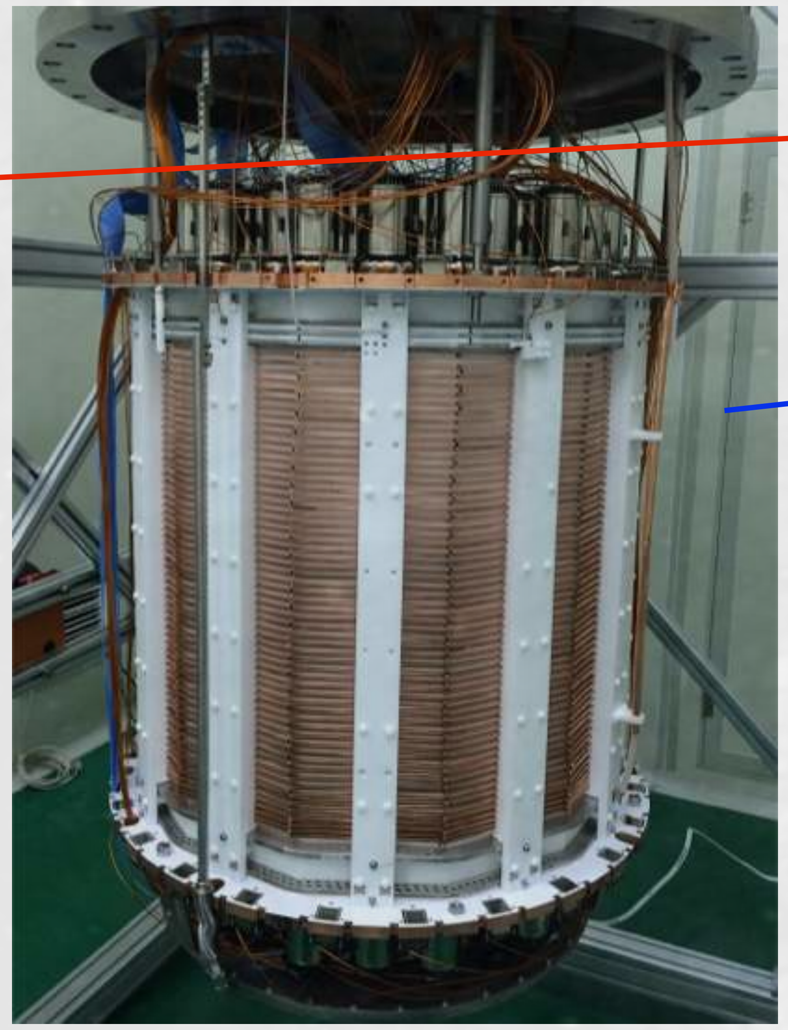




Liquid Xenon TPCs

48 cm

LUX at SURF
Active Target: ~250 kg
completed

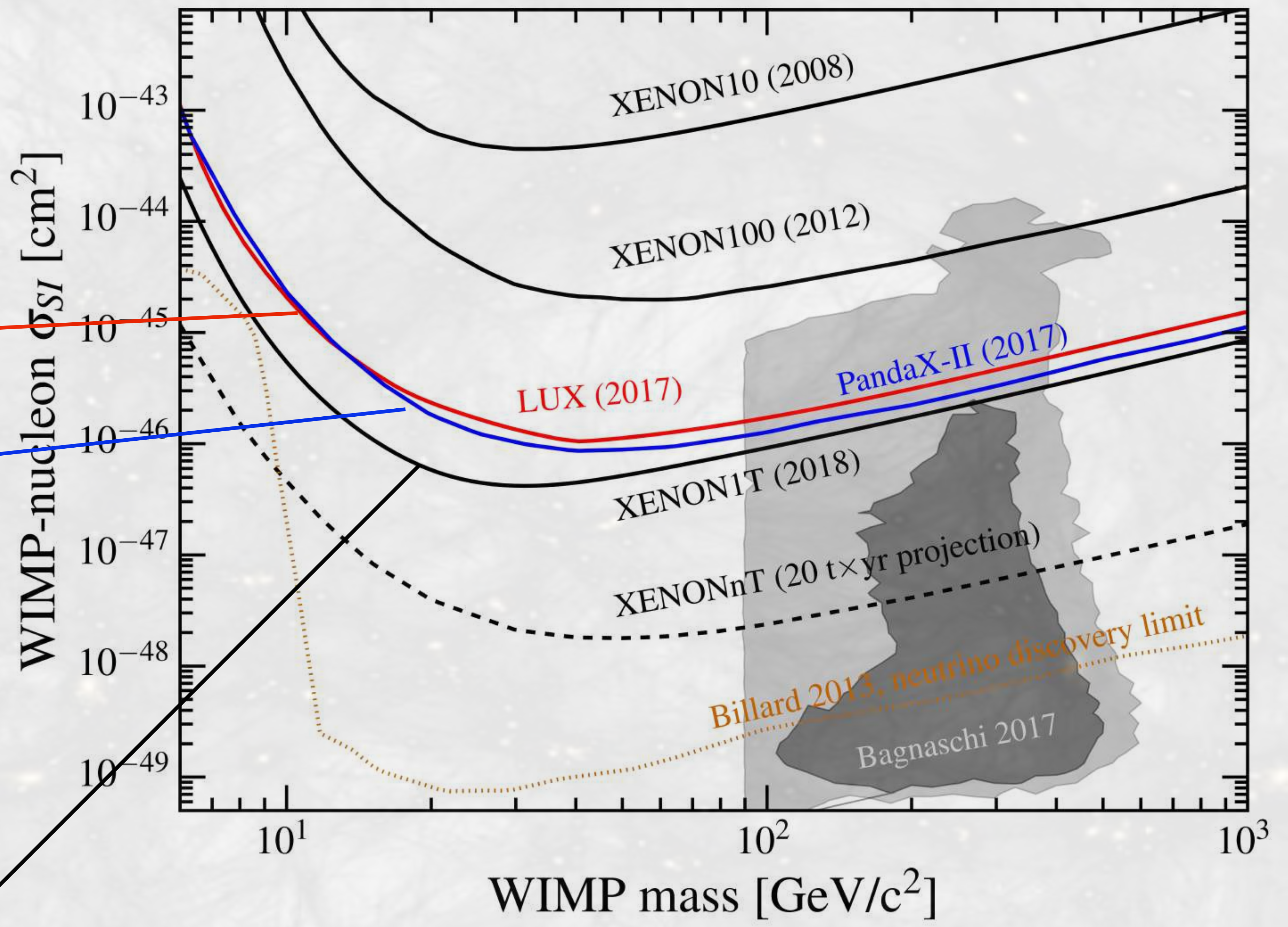


60 cm

PandaX-II at CJPL-I
Active Target: ~580 kg

XENON1T at LNGS
Active Target: 2000 kg

100 cm



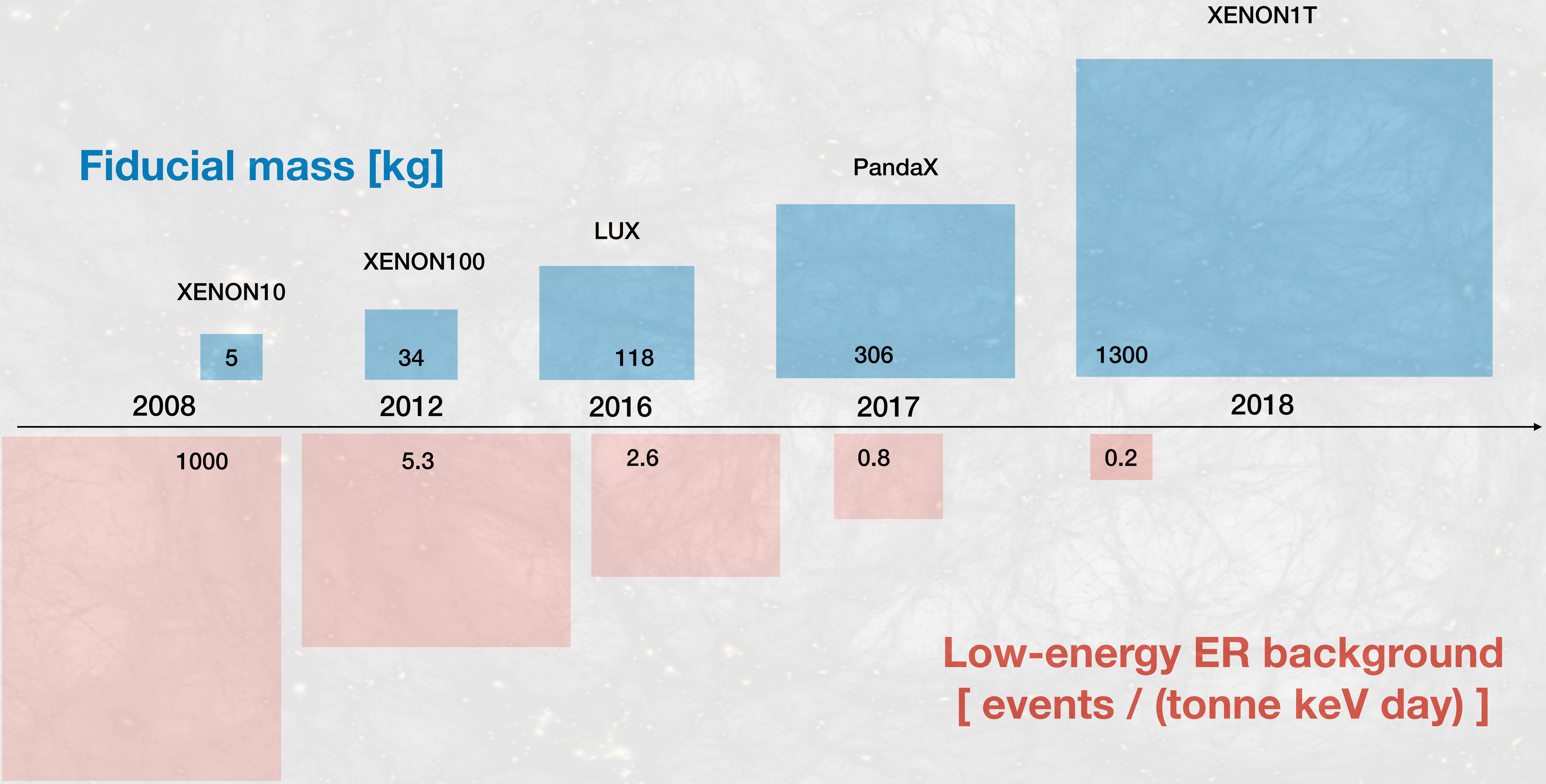
REVIEWS OF MODERN PHYSICS

REVIEWS OF MODERN PHYSICS, VOLUME 82, JULY–SEPTEMBER 2010

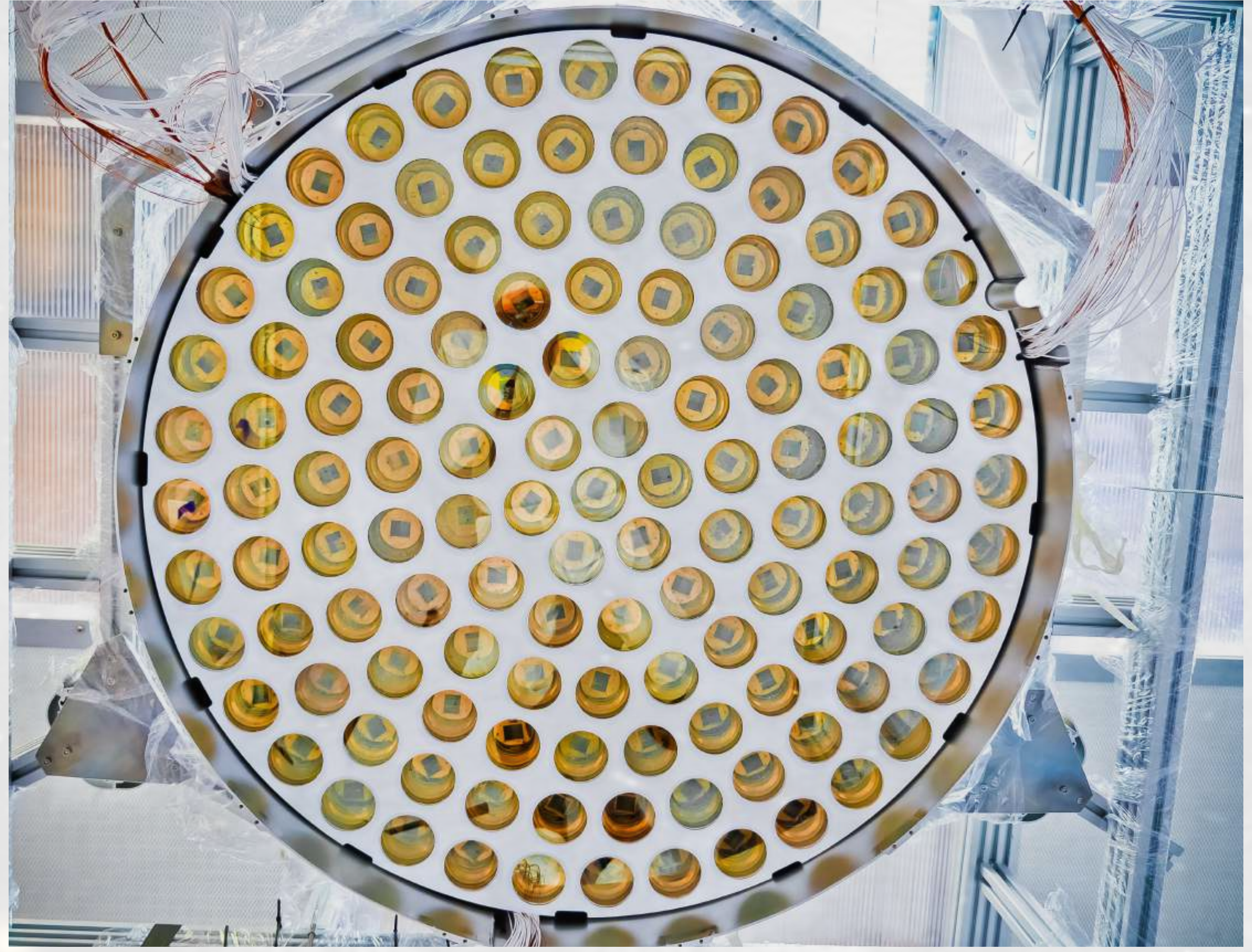
Liquid xenon detectors for particle physics and astrophysics

E. Aprile
Department of Physics, Columbia University, New York, New York 10027, USA
T. Doke
Advanced Research Institute for Science and Engineering, Waseda University, Tokyo 169-8555, Japan

Evolution of LXeTPCs as WIMP detectors

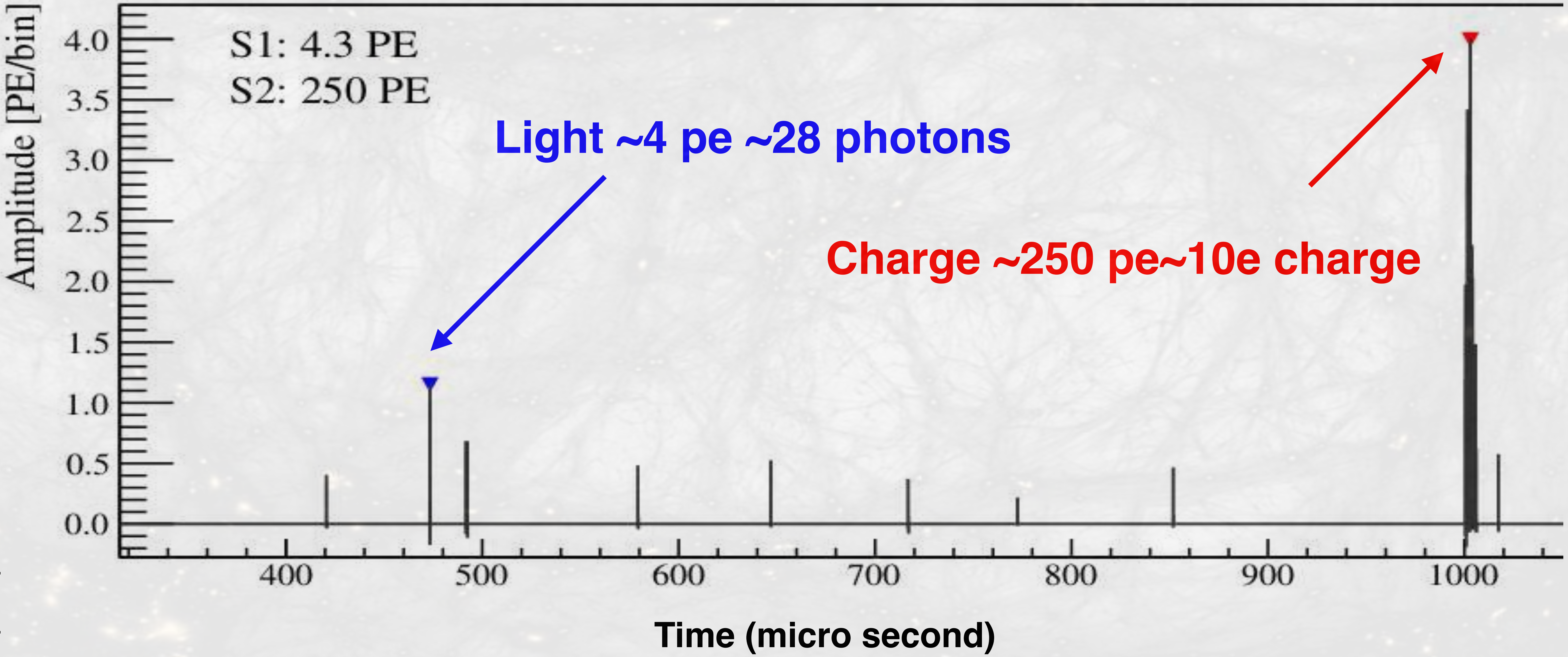


The XENON1T Time Projection Chamber

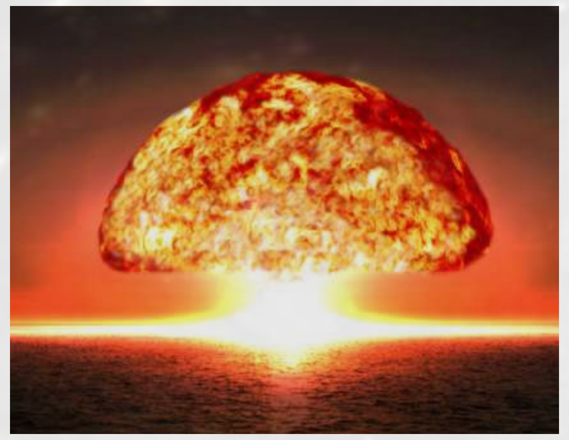


127 PMTs in the top array

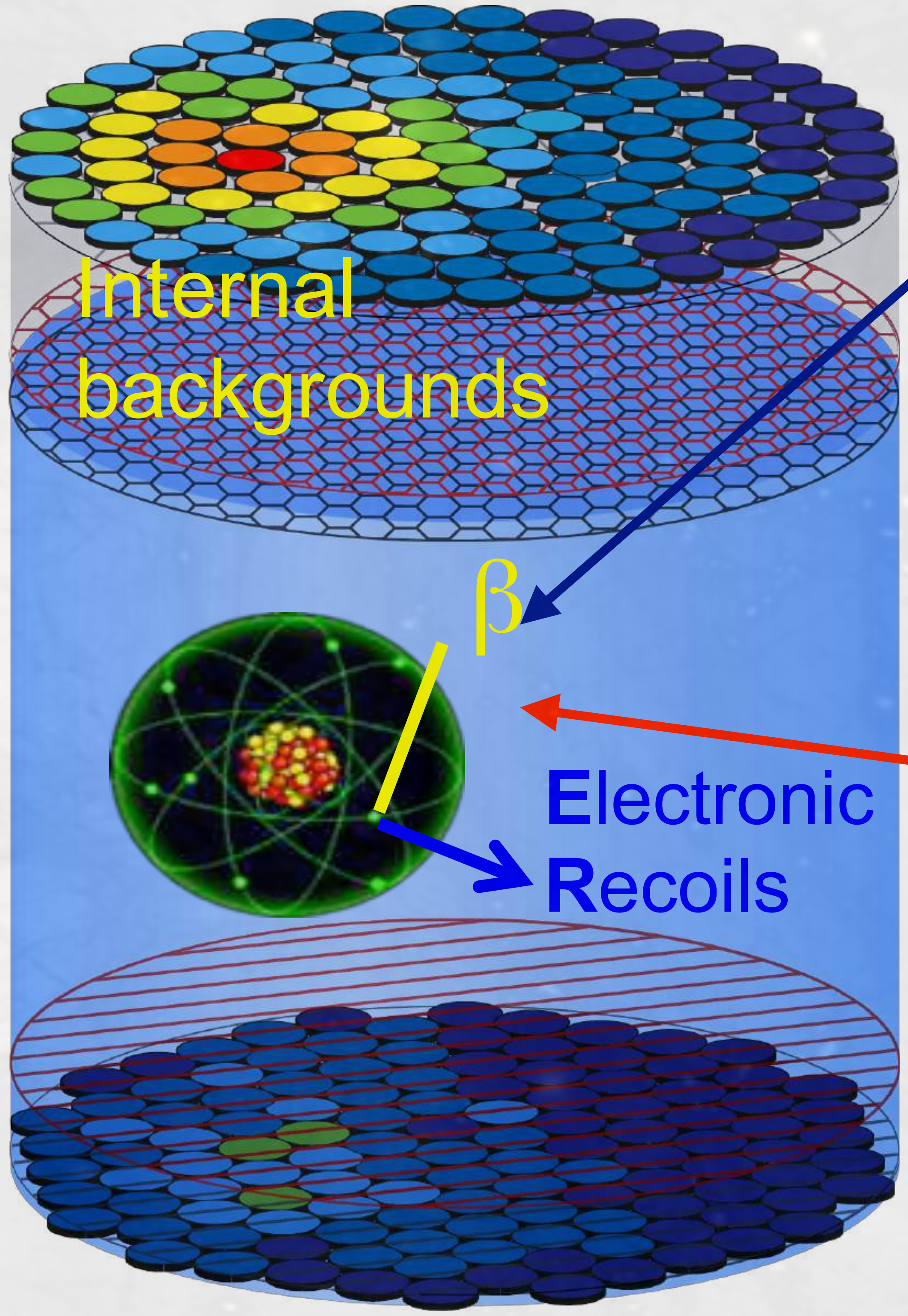
121 PMTs in the bottom array

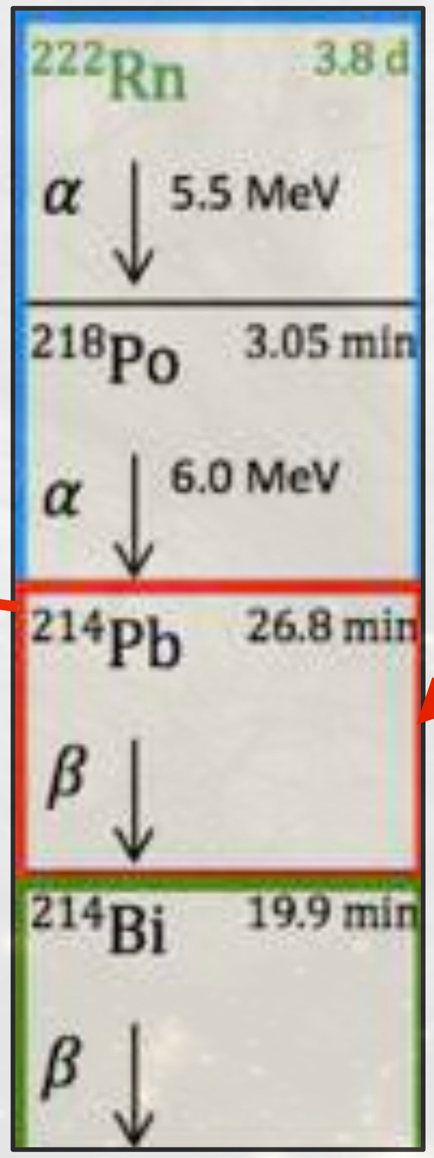


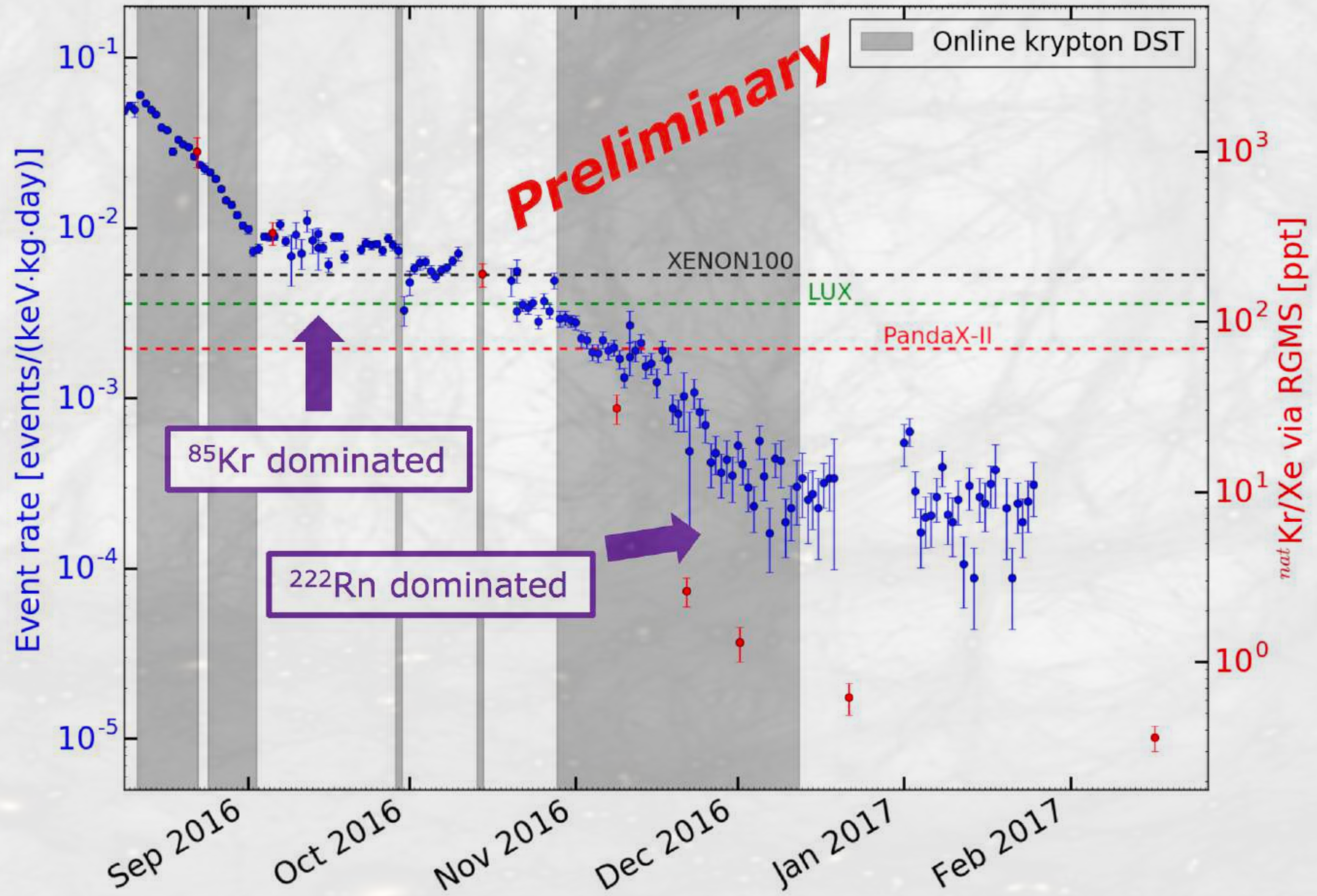
Background Challenge: Kr and Rn



85Kr → Air → Xenon







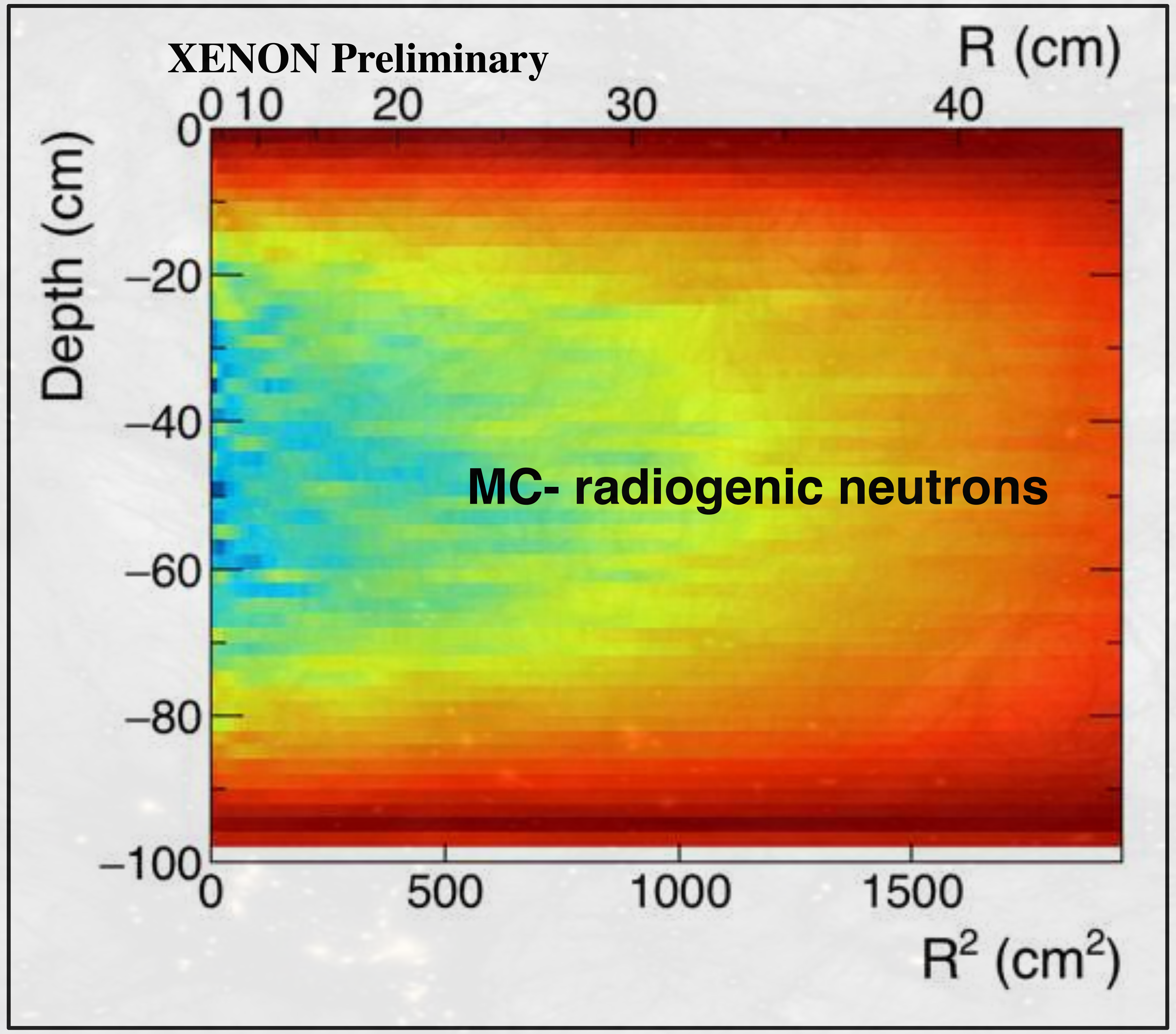
Background Challenge: Neutrons

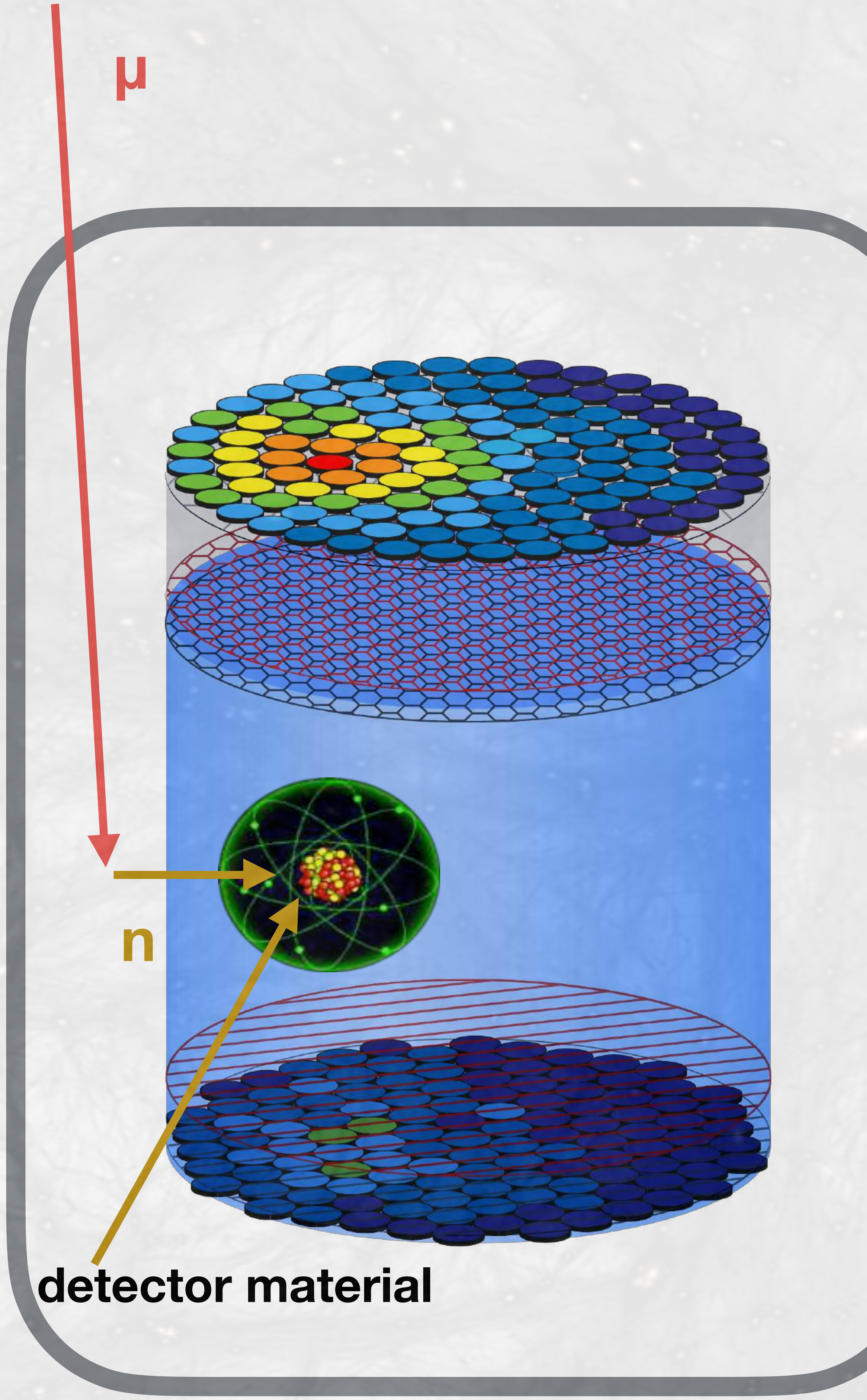
- Cosmogenic μ-induced neutrons
  - significantly reduced by muon veto detector
- Radiogenic neutrons from (α, n) reactions and fission from ^{238}U and ^{232}Th chains
  - reduced via careful material selection

Source	Rate [t^{-1} y^{-1}]
Radiogenic n	0.6 ± 0.1
Cosmogenic n	< 0.01

(Expectations in 4-50 keV search window, 1t FV, single scatters)

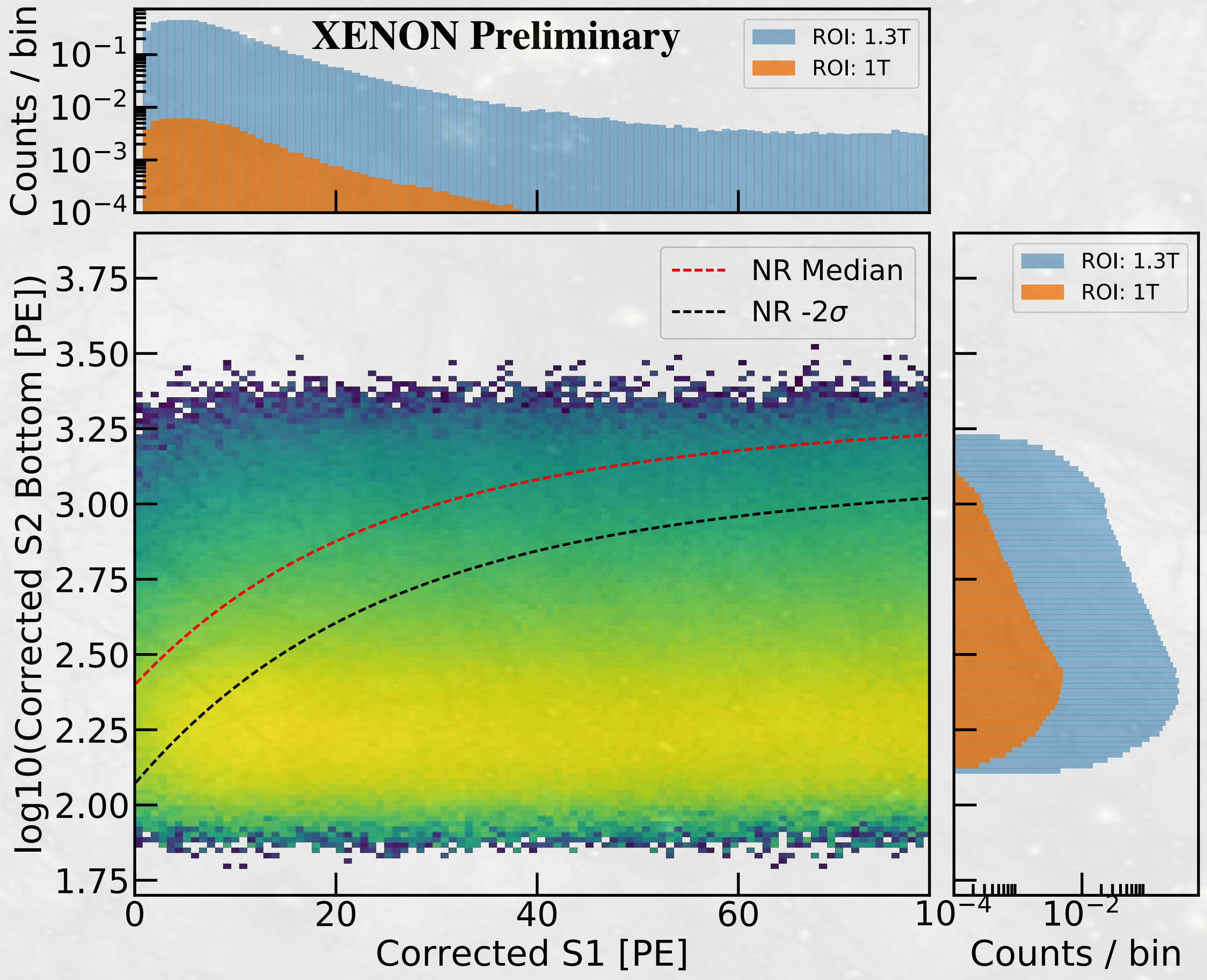
JCAP04 (2016) 027

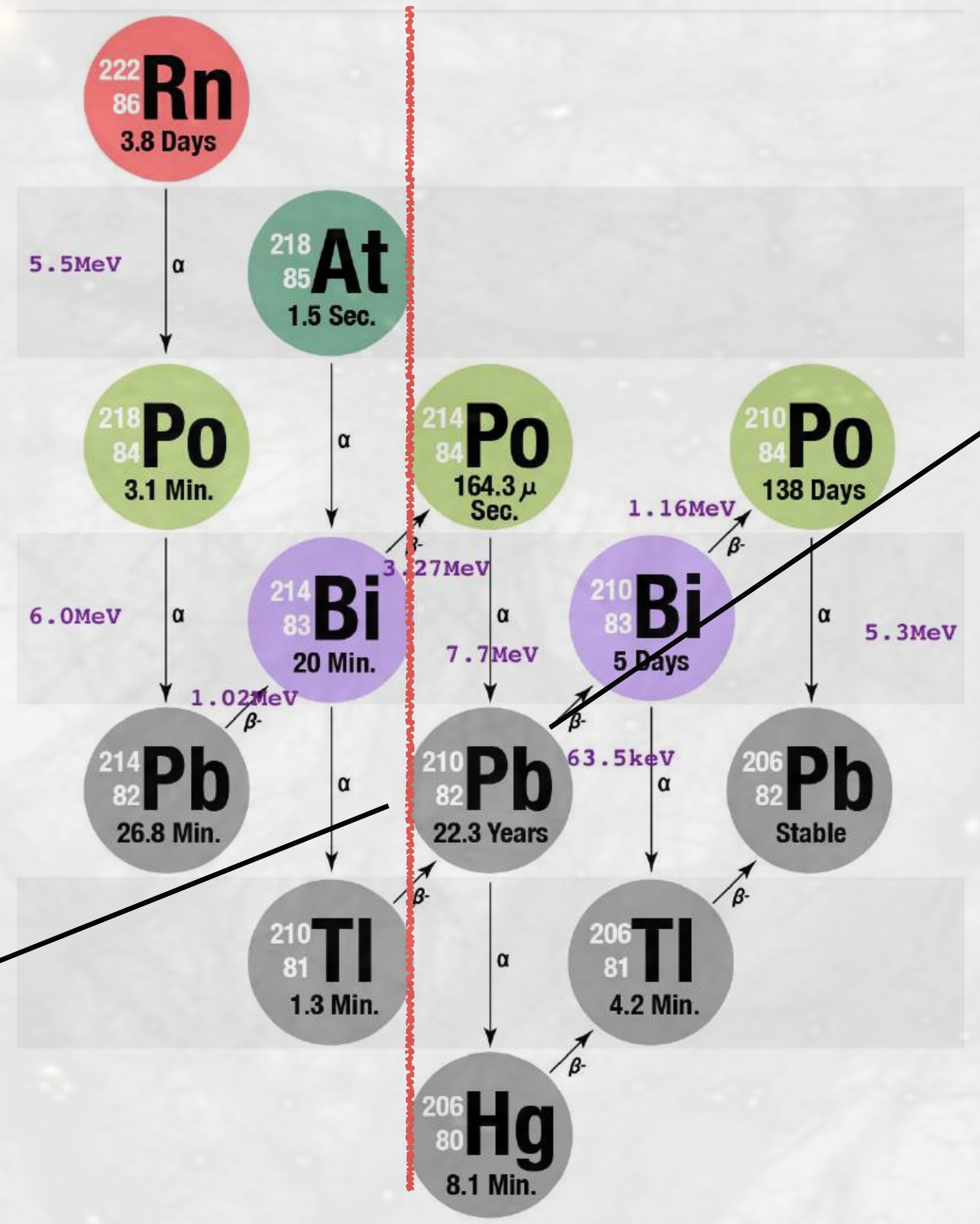


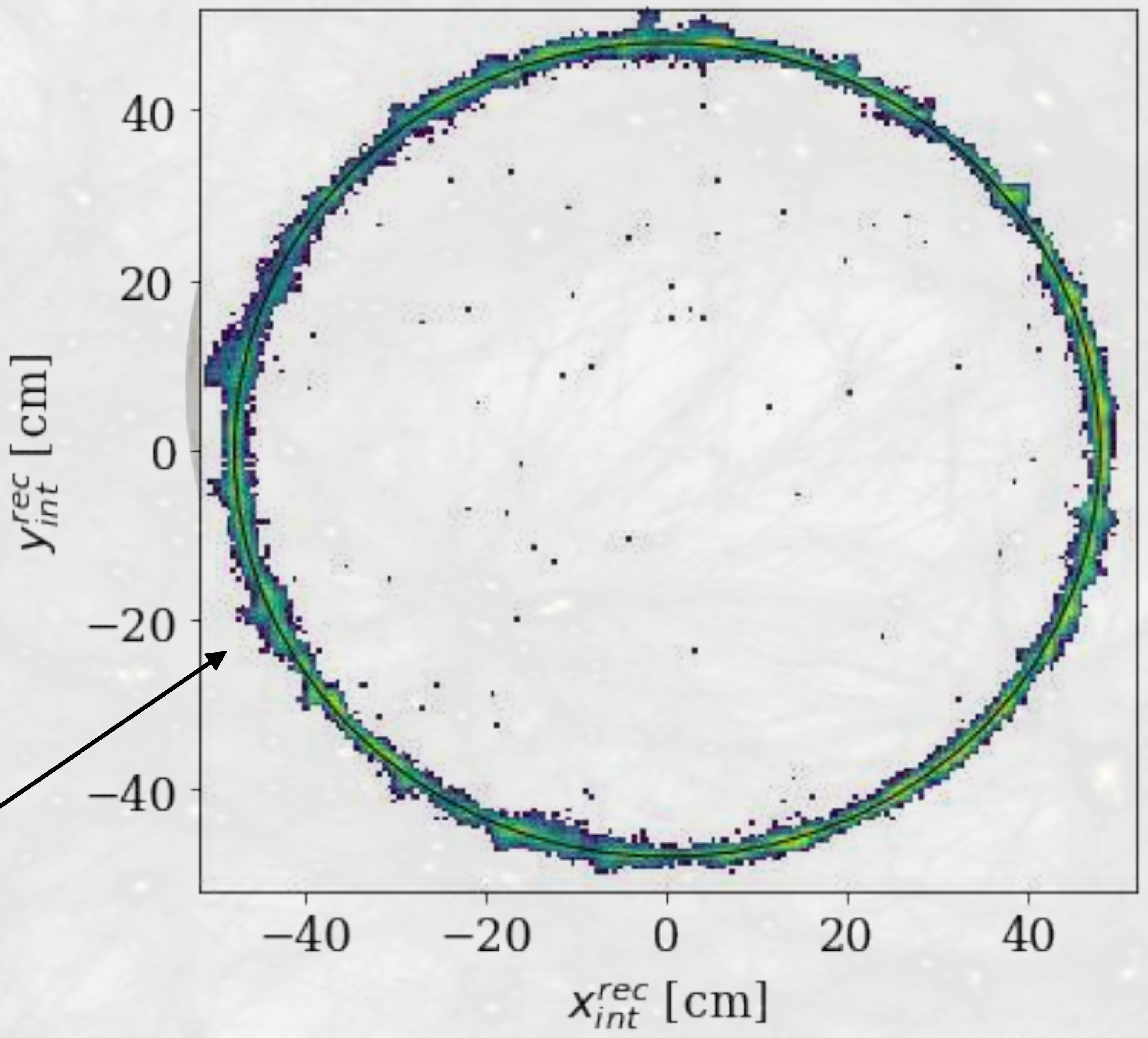


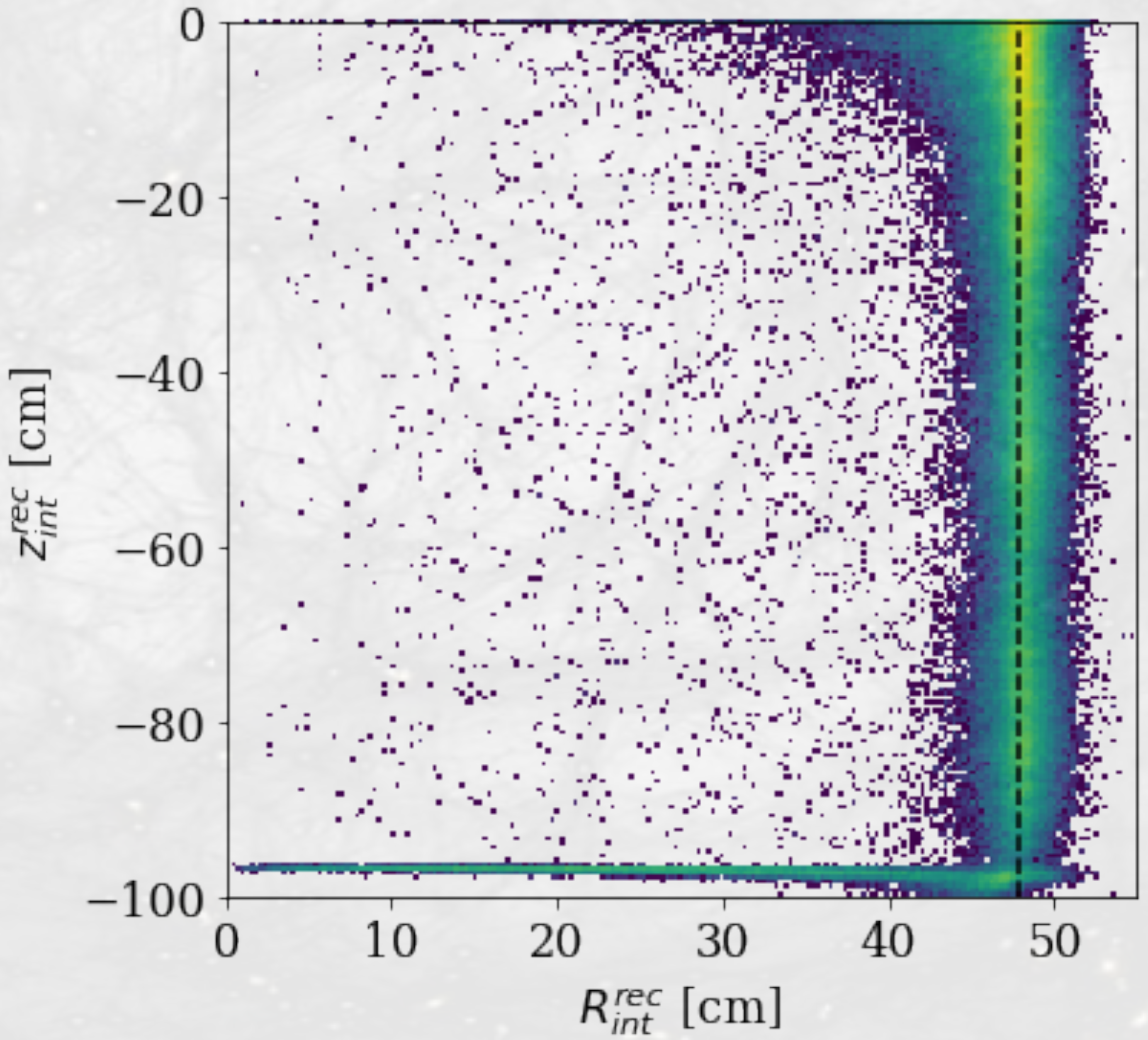
Background Challenge: Surface Radioactivity

- ^{210}Pb and ^{210}Po plate-out on PTFE surface lose S2 charge
- Suppressed by fiducialization
- Data-driven modeling



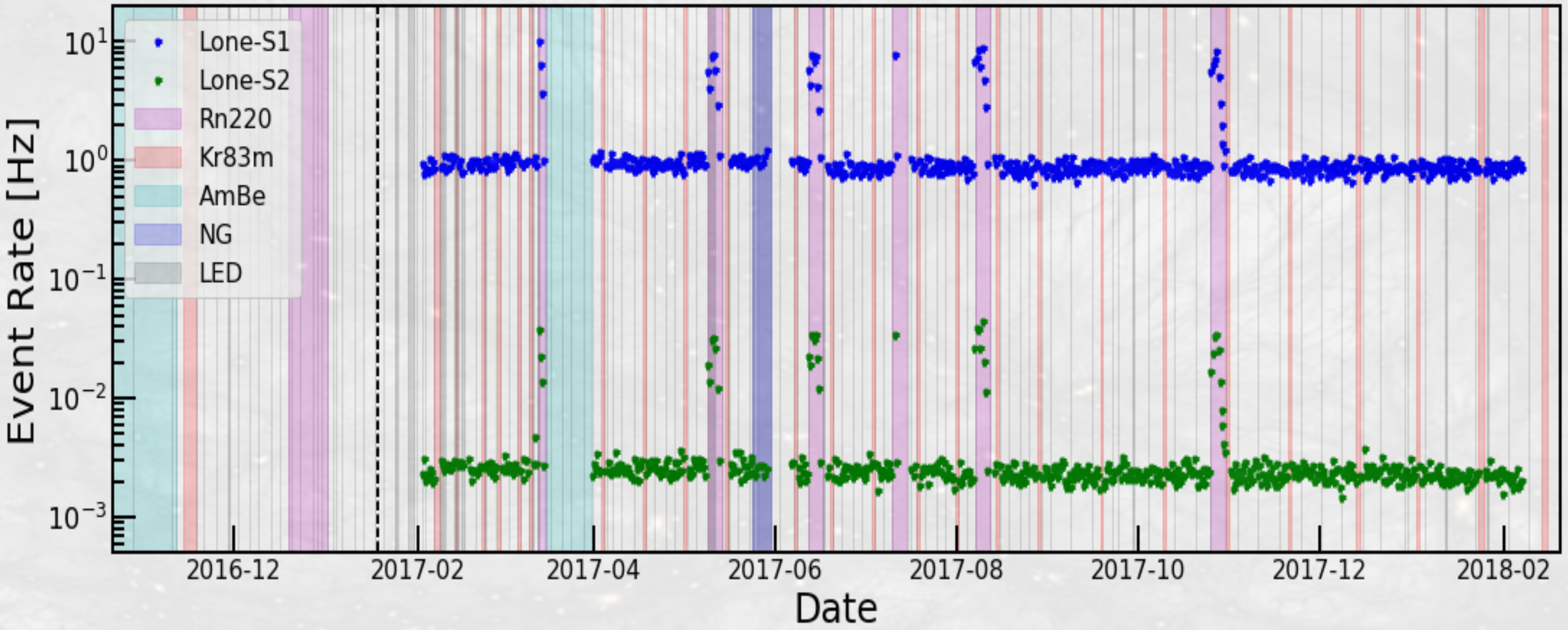


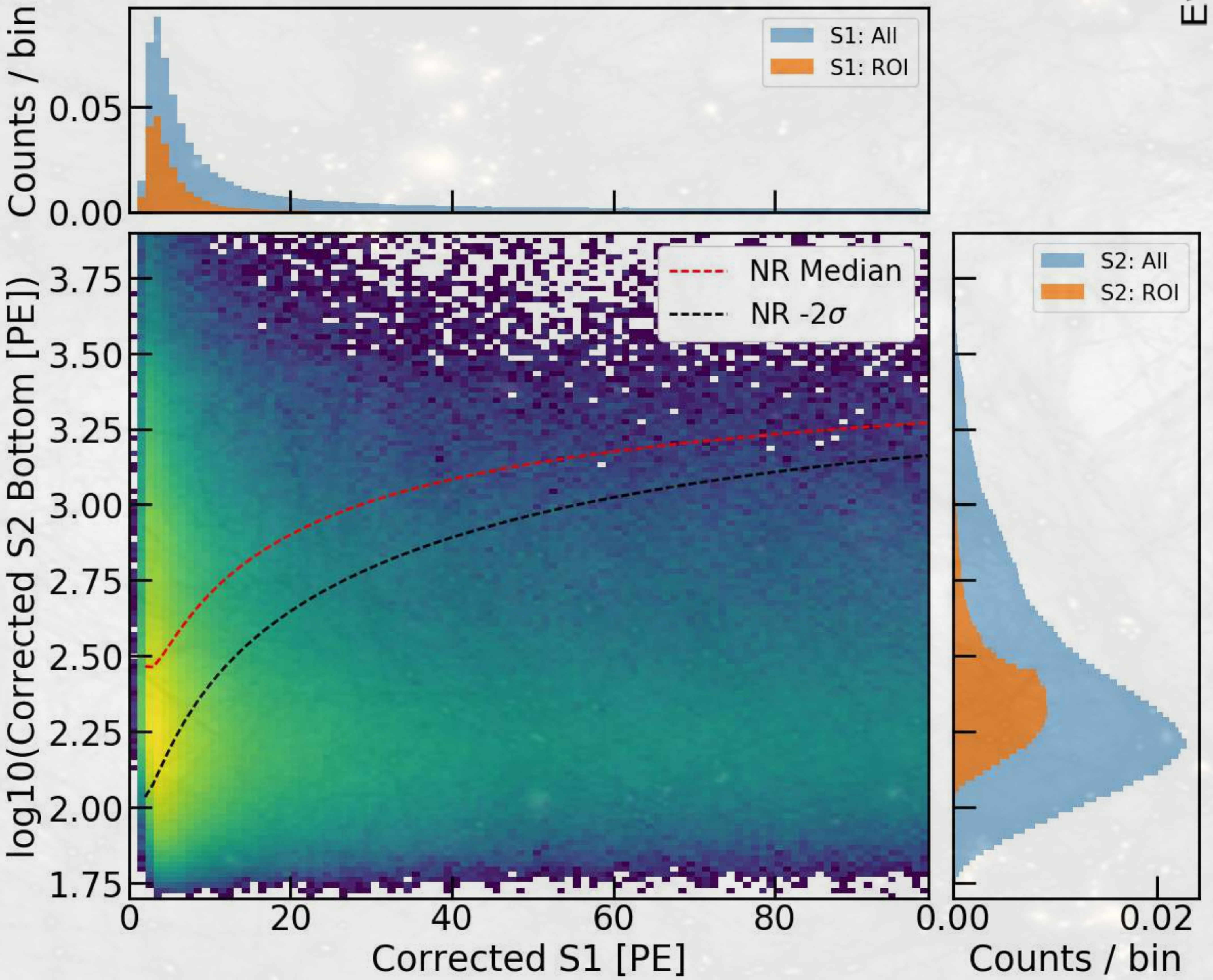




Background Challenge: Accidental Coincidence

- Pileup of Isolated S1 and S2s
  - S1 from PMT dark count pileups
  - S2s from betas on grids



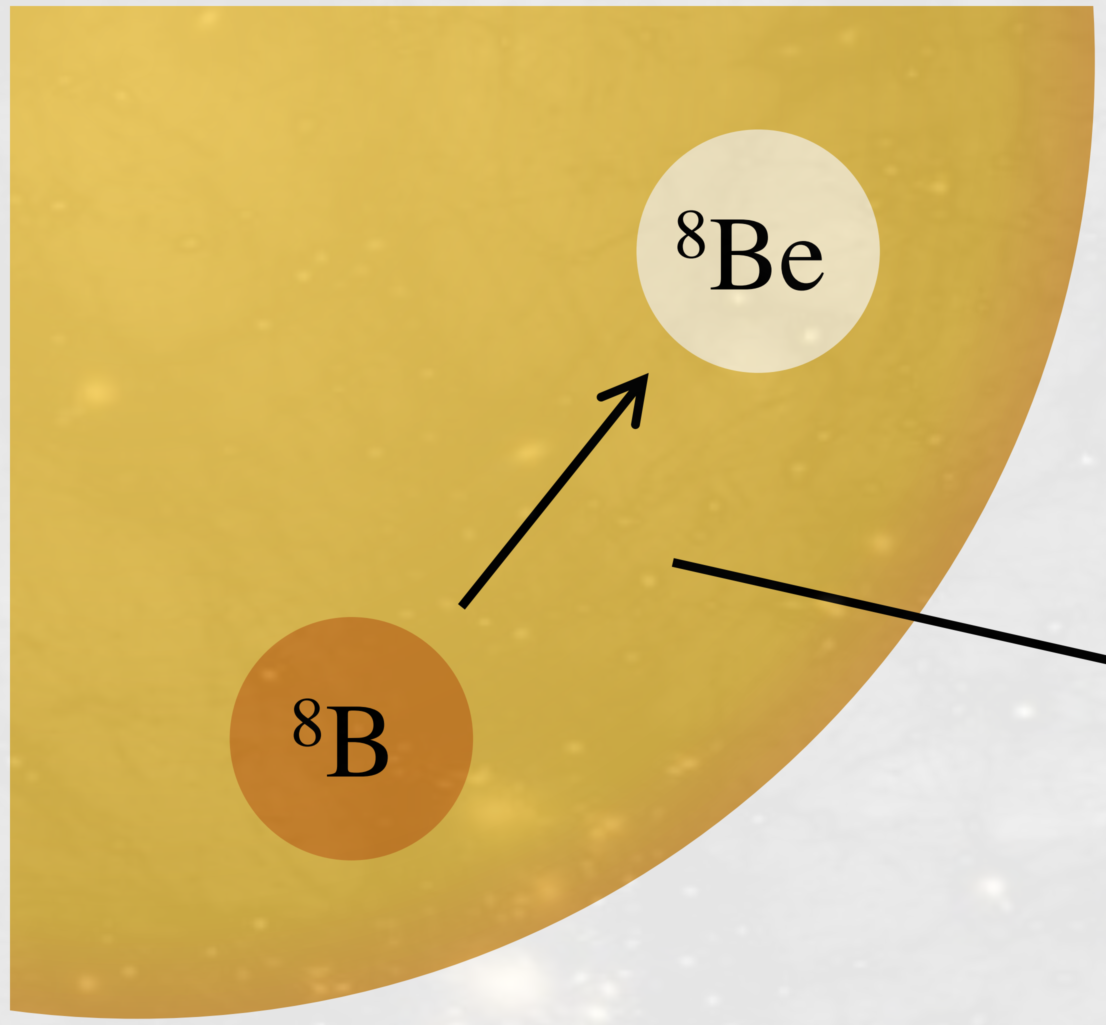


- Data-driven modeling
- Bottleneck for the energy threshold
- Challenge for future large TPCs

Background Challenge: Irreducible Neutrinos

PRL 126, 091301 (2021)

$$R = \phi(\nu) \times \sigma_\nu \times N_{Xe} \times \text{exposure}$$
$$\simeq 600\,\text{events}/(\text{tonne} \times \text{year})$$



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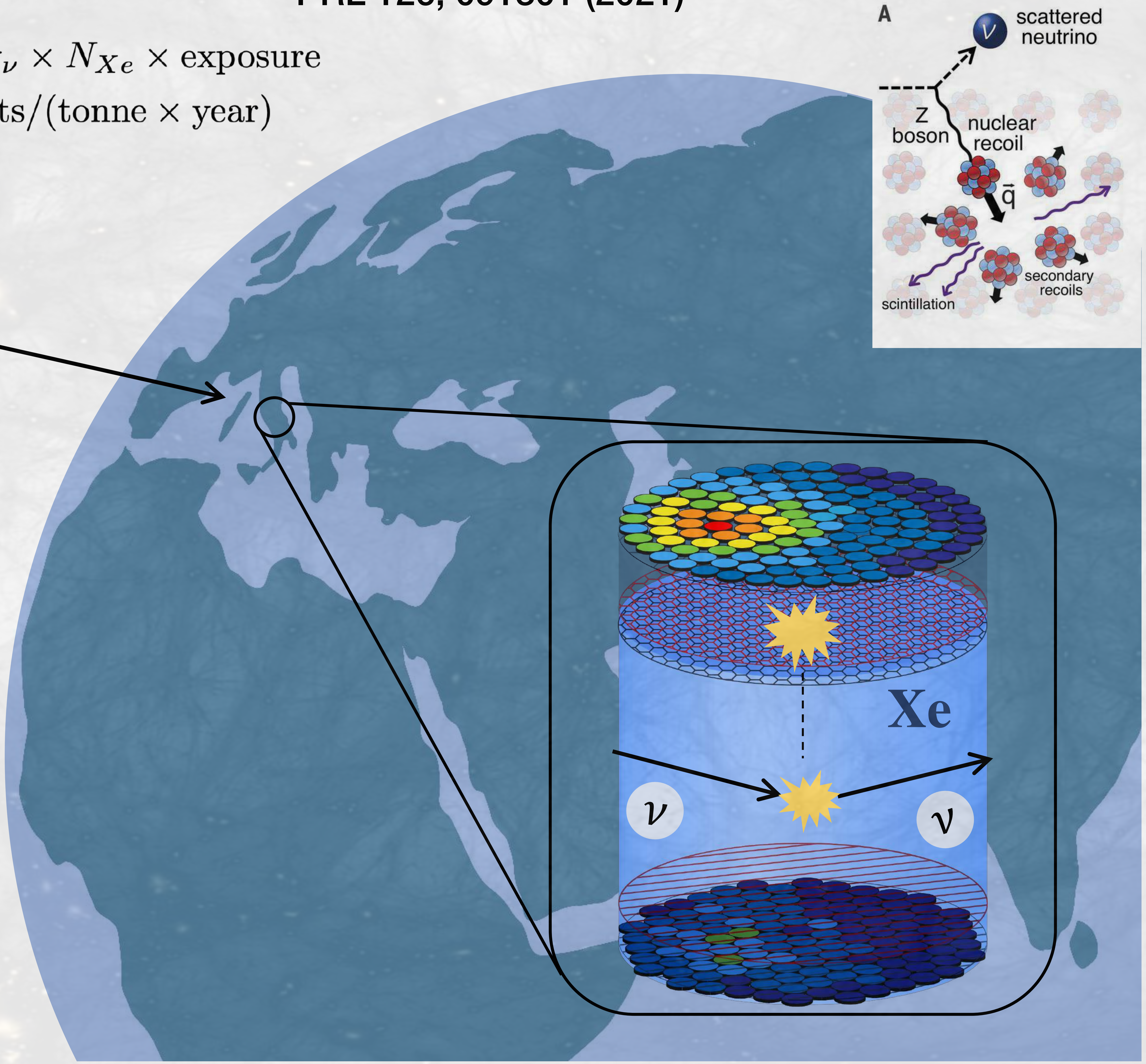
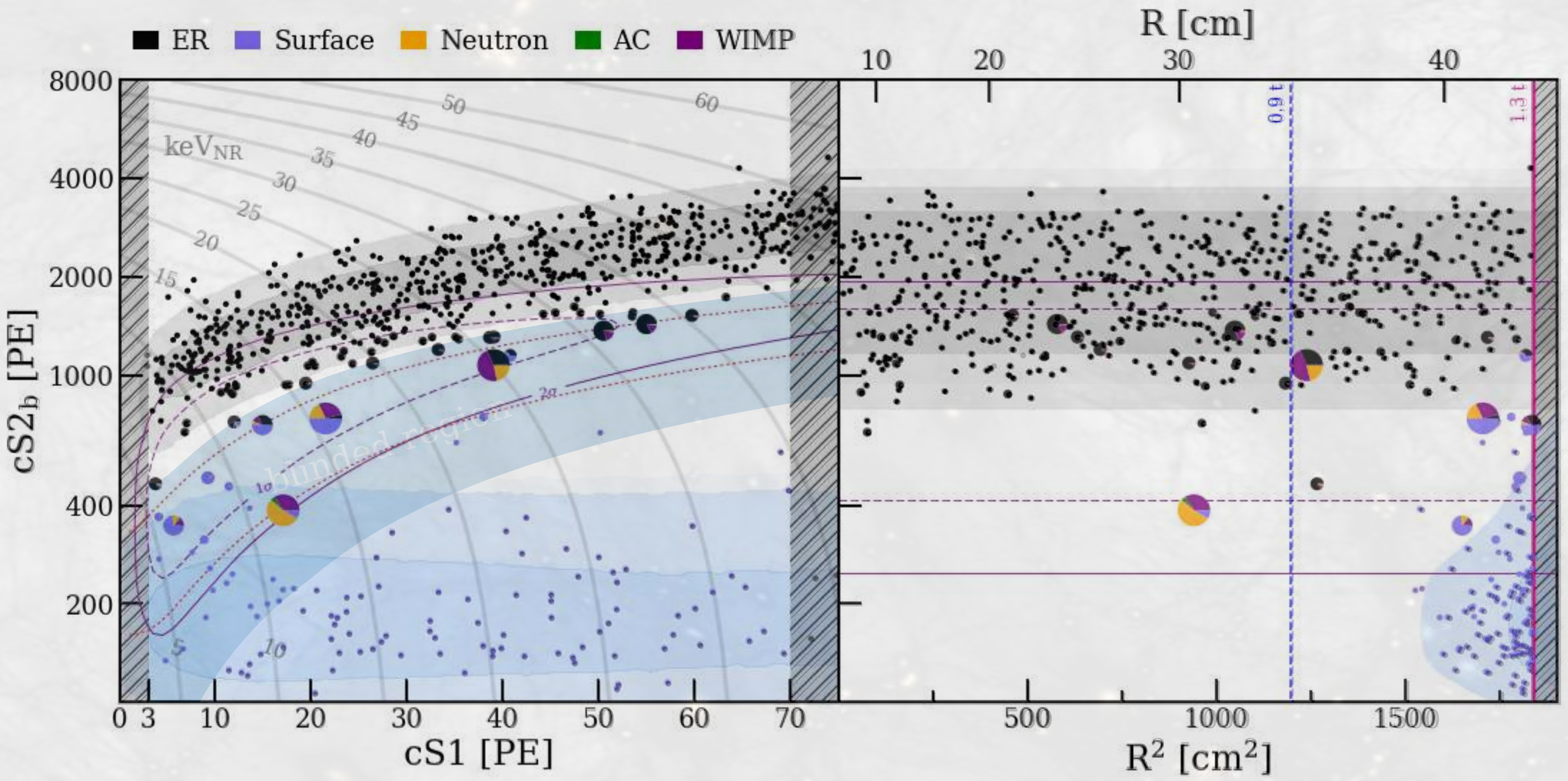


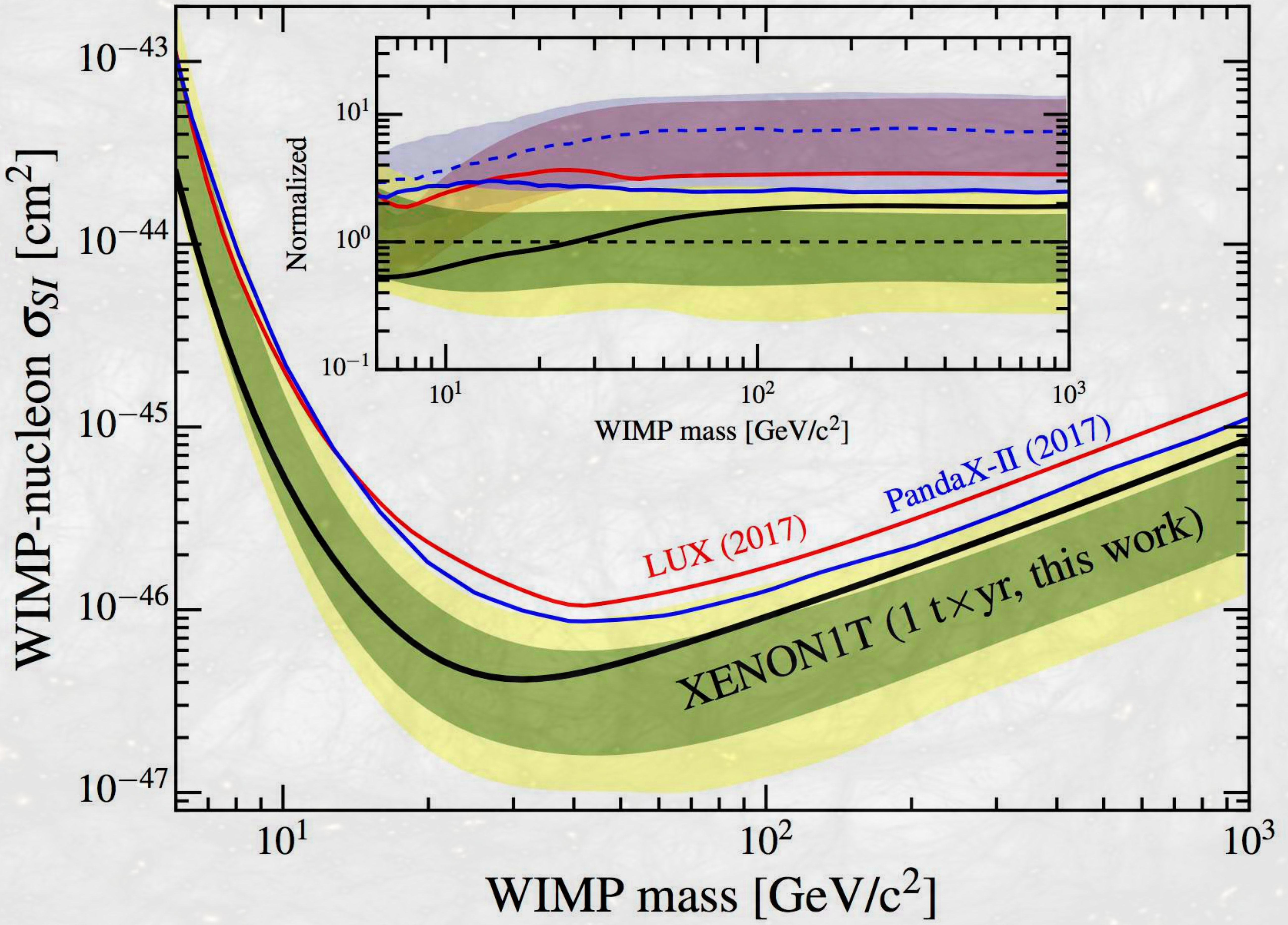
XENON1T Dark Matter Search Results

Source	1.3 t	1.3 t, NR Ref.	0.9 t, NR Ref.
ER	627 ± 18	1.6 ± 0.3	1.1 ± 0.2
Radiogenic	1.4 ± 0.7	0.8 ± 0.4	0.4 ± 0.2
CEνNS	0.05 ± 0.01	0.03 ± 0.01	0.02
Accidental	$0.5\ ^{+0.3}_{-0.0}$	$0.10\ ^{+0.06}_{-0.00}$	$0.06\ ^{+0.03}_{-0.00}$
Surface	106 ± 8	4.8 ± 0.4	0.02
Total	735 ± 20	7.4 ± 0.6	1.6 ± 0.3
200 GeV WIMP	3.6	1.7	1.2
Data	**739**	**14**	**2**

- A blind analysis
- S1, S2 and position dependent likelihood
- No Significant WIMPs signal yet!



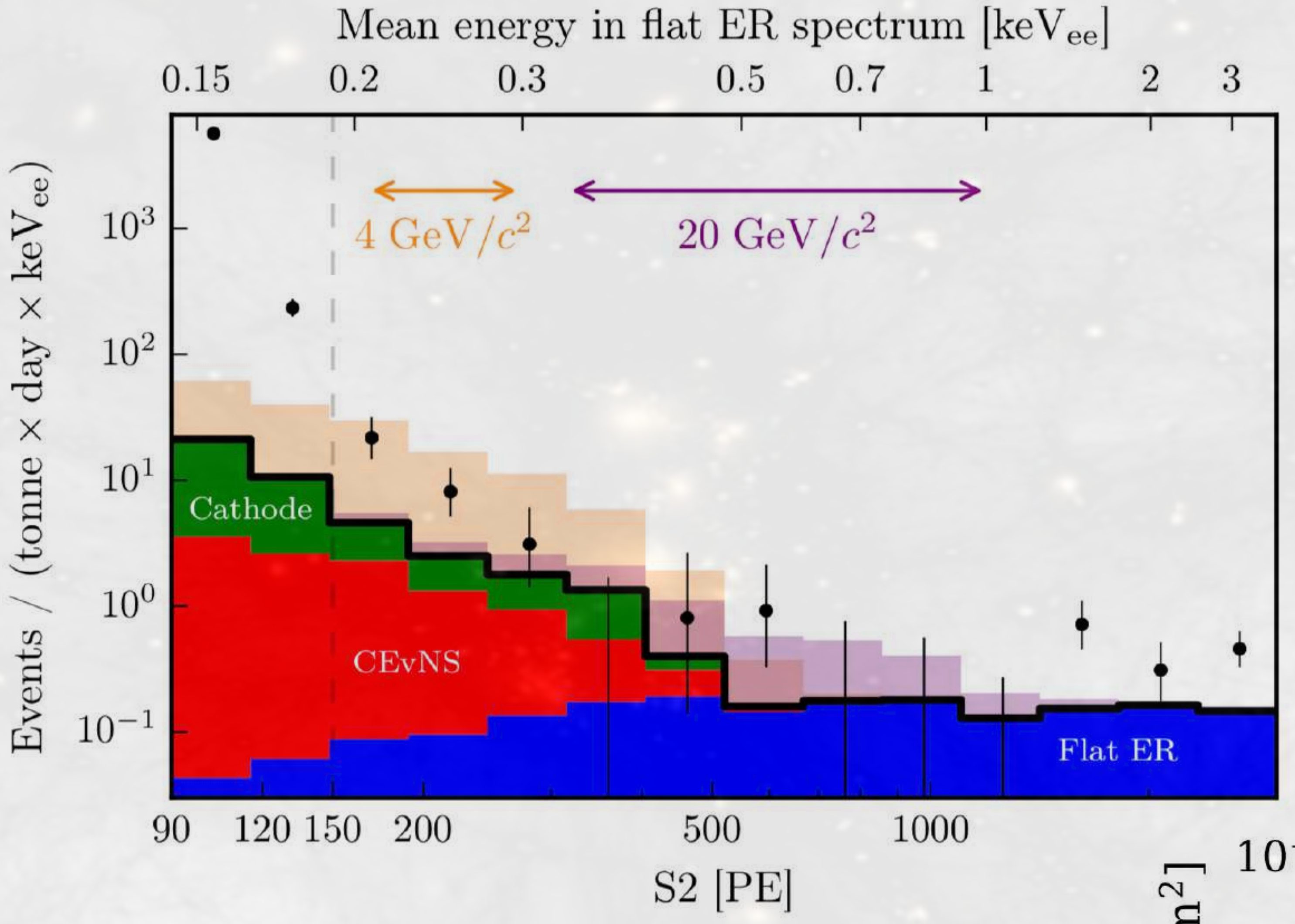
Phys. Rev. Lett. 121, 111302 (2018)



XENON1T Results towards the B8 “Neutrino Fog”

#1: “S2-only” approach

A limit setting analysis (expect 2.0±0.3 CEvNS)



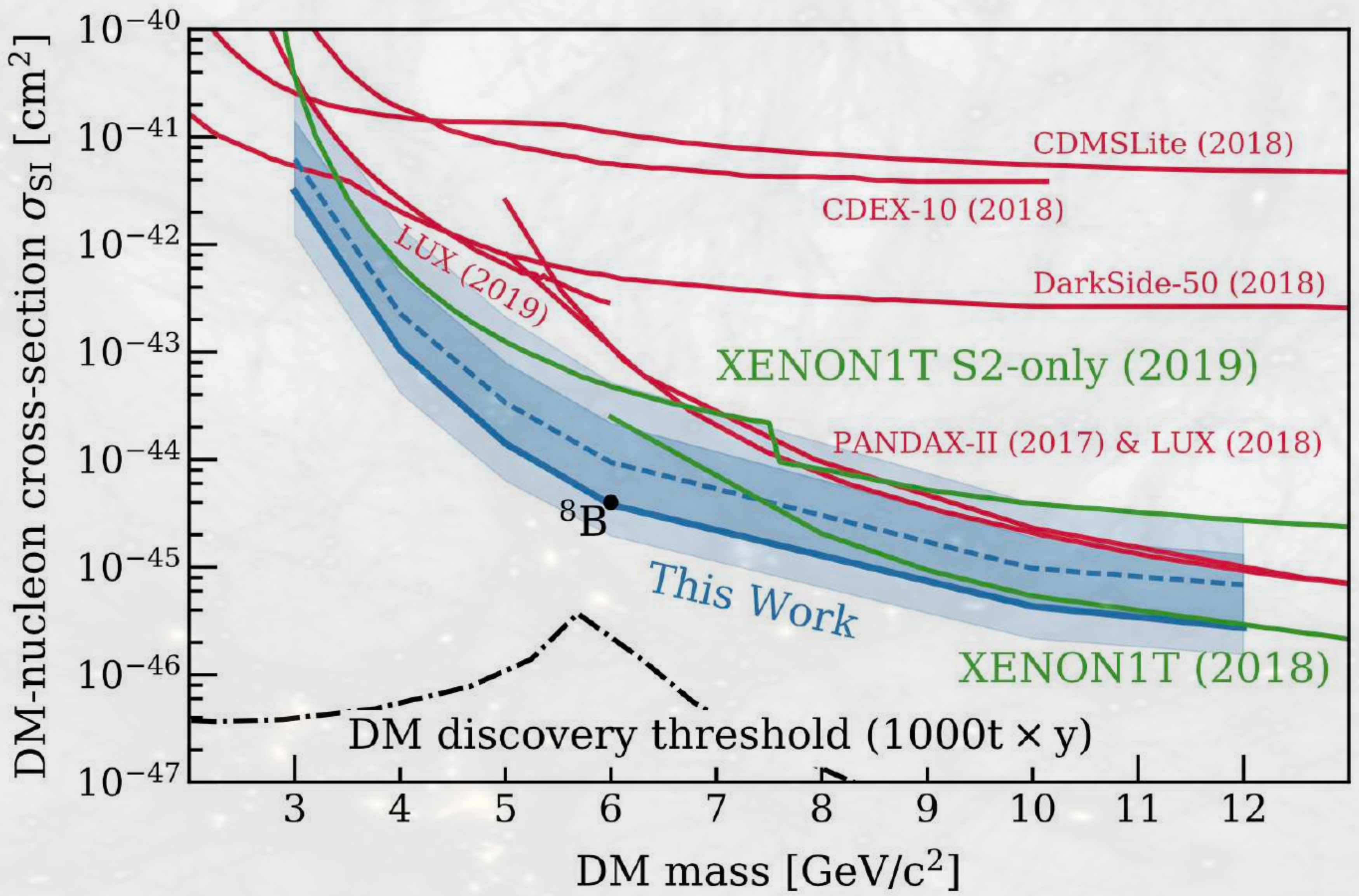
PRL 123 251801 (2019)

#2: lowering S1 & S2 together

- S1: 2 or 3 photons
- S2: ~4 - 18 electrons

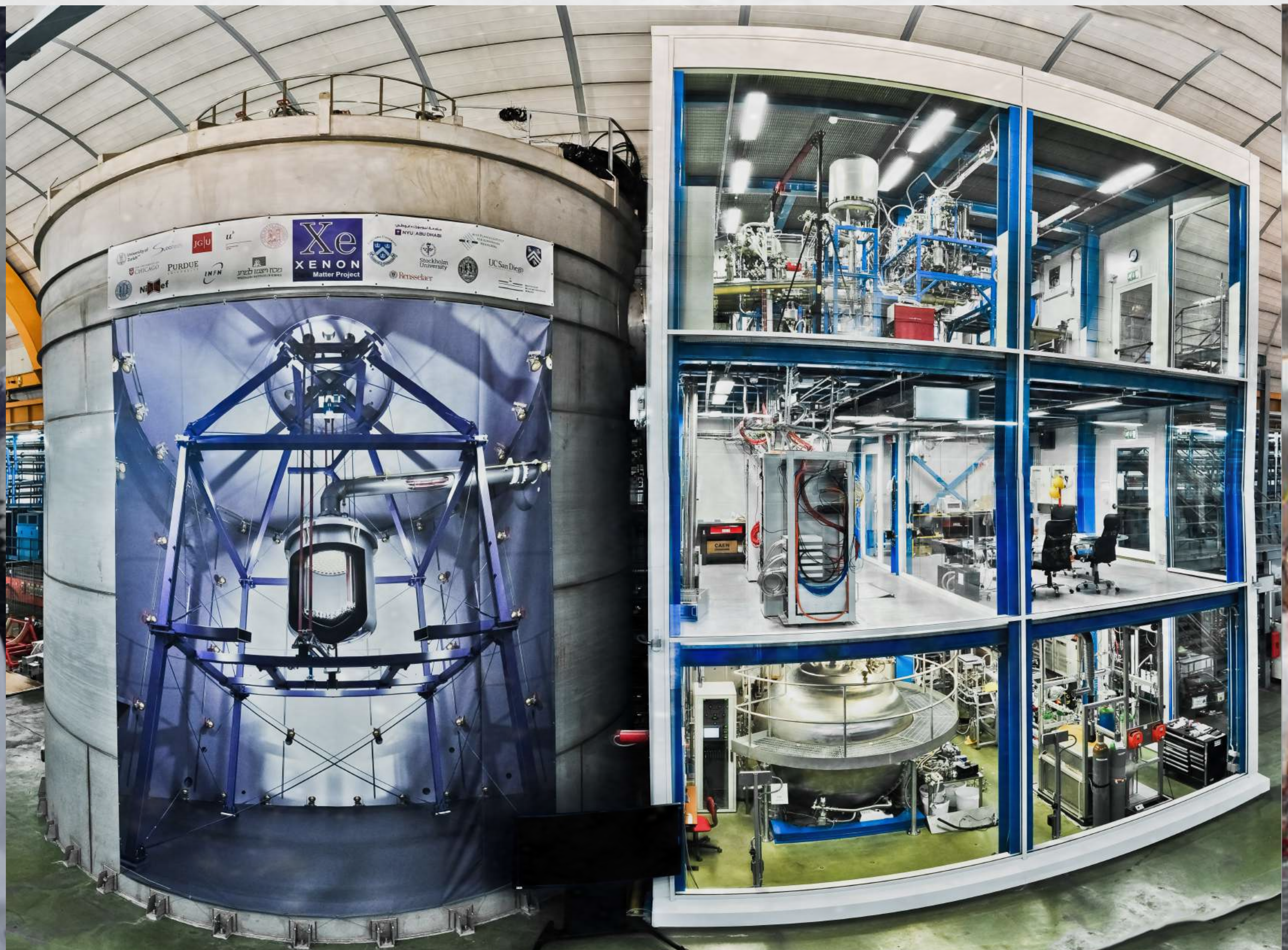
PRL 126, 091301 (2021)

Source	Expectation
CEvNS	**2.25**
Accidental	5.14
ER	0.21
Radiogenic	0.03
Total	7.65

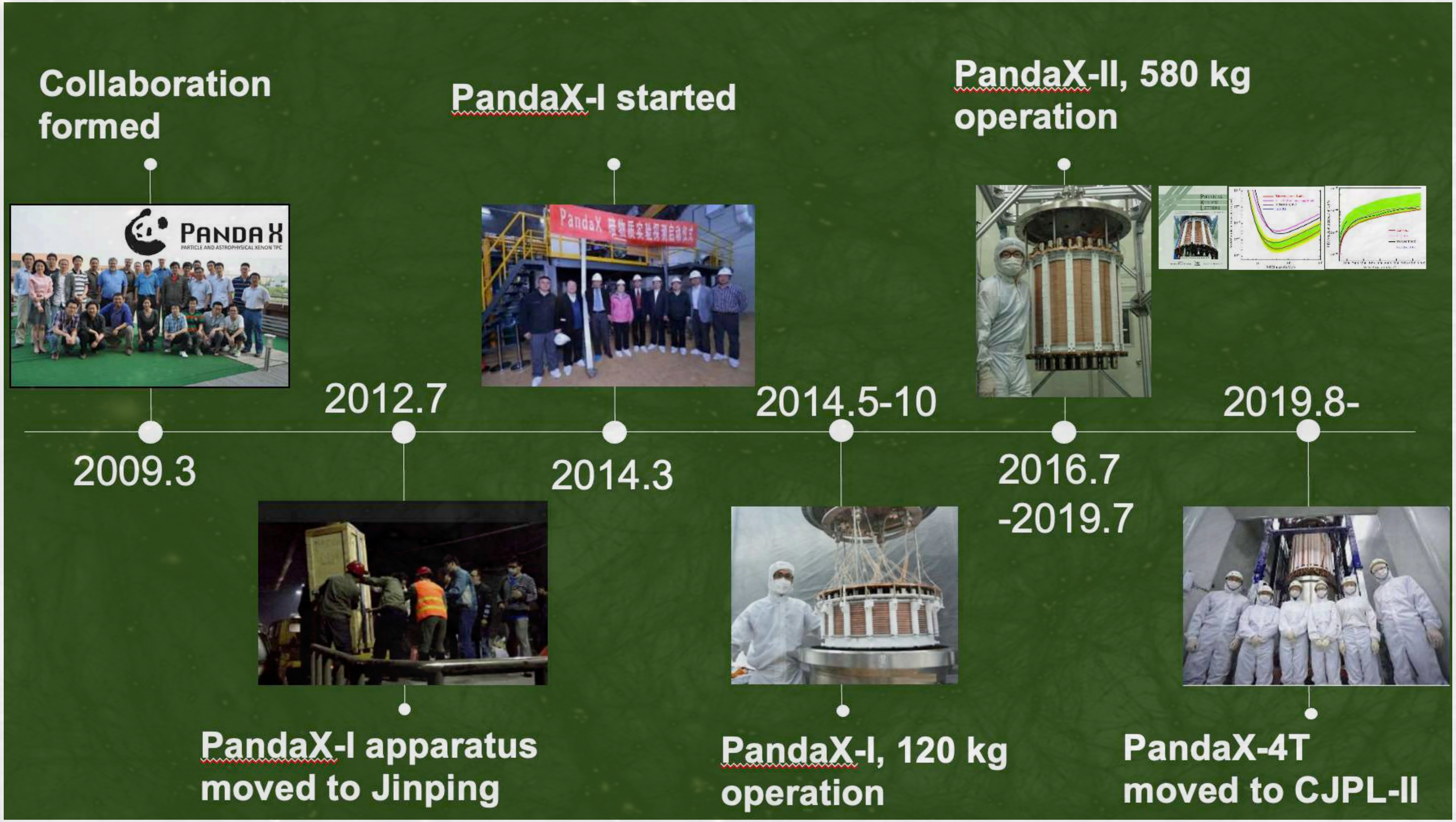


“G2” LXeTPCs for Dark Matter Search

Experiments	Location	Sensitive Mass [t]	Fiducial mass [t]	Radon reduction	Neutron veto	Data taking	First Results
PandaX-4T	CJPL (China)	4.0	2.8	Y	N	2021	2021
XENONnT	LNGS (Italy)	5.9	4.0	Y	Y	2021	2022
LZ	SURF (US)	7.0	5.6	Y	Y	2022	2022

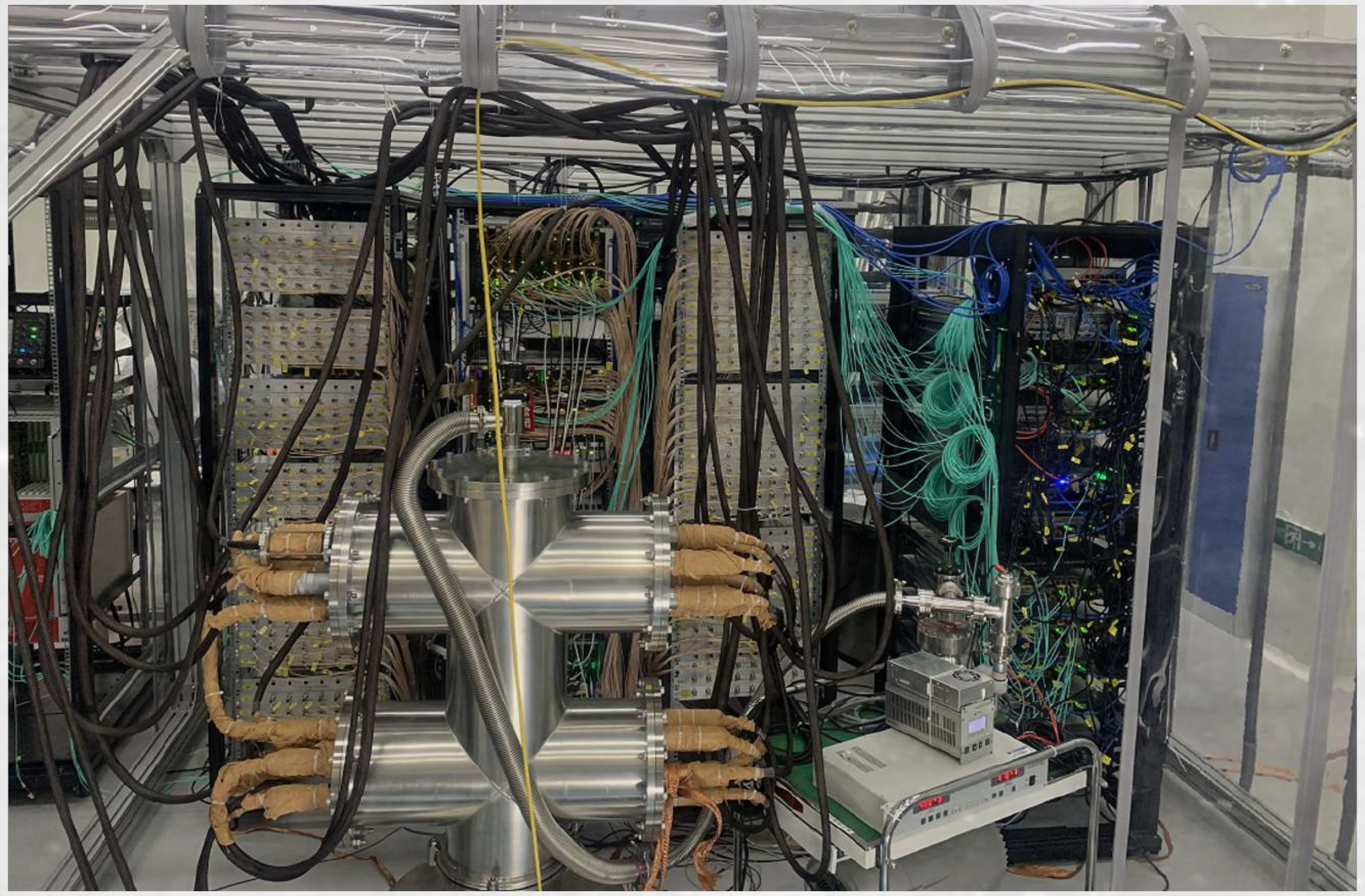



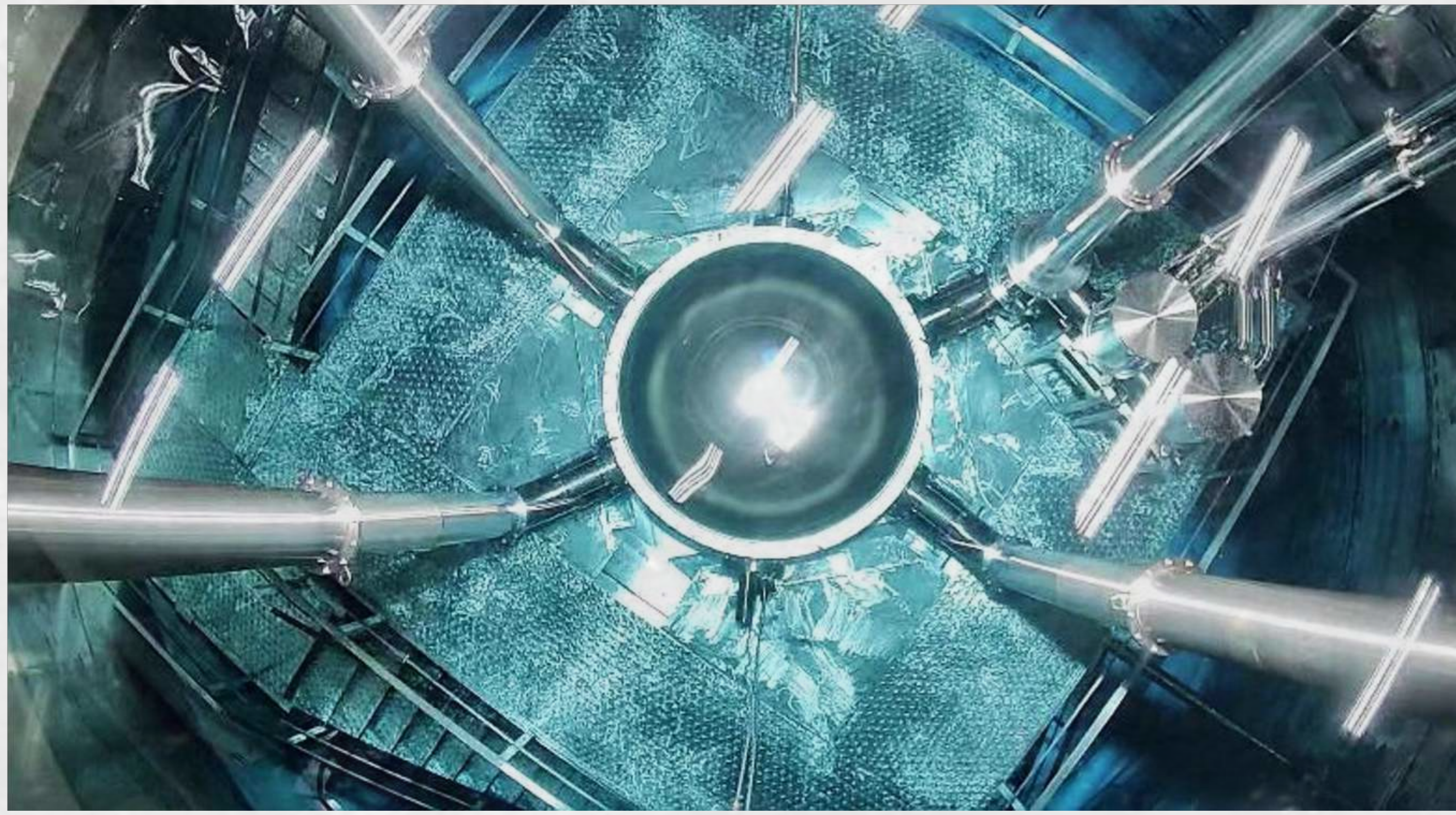
PandaX Roadmap

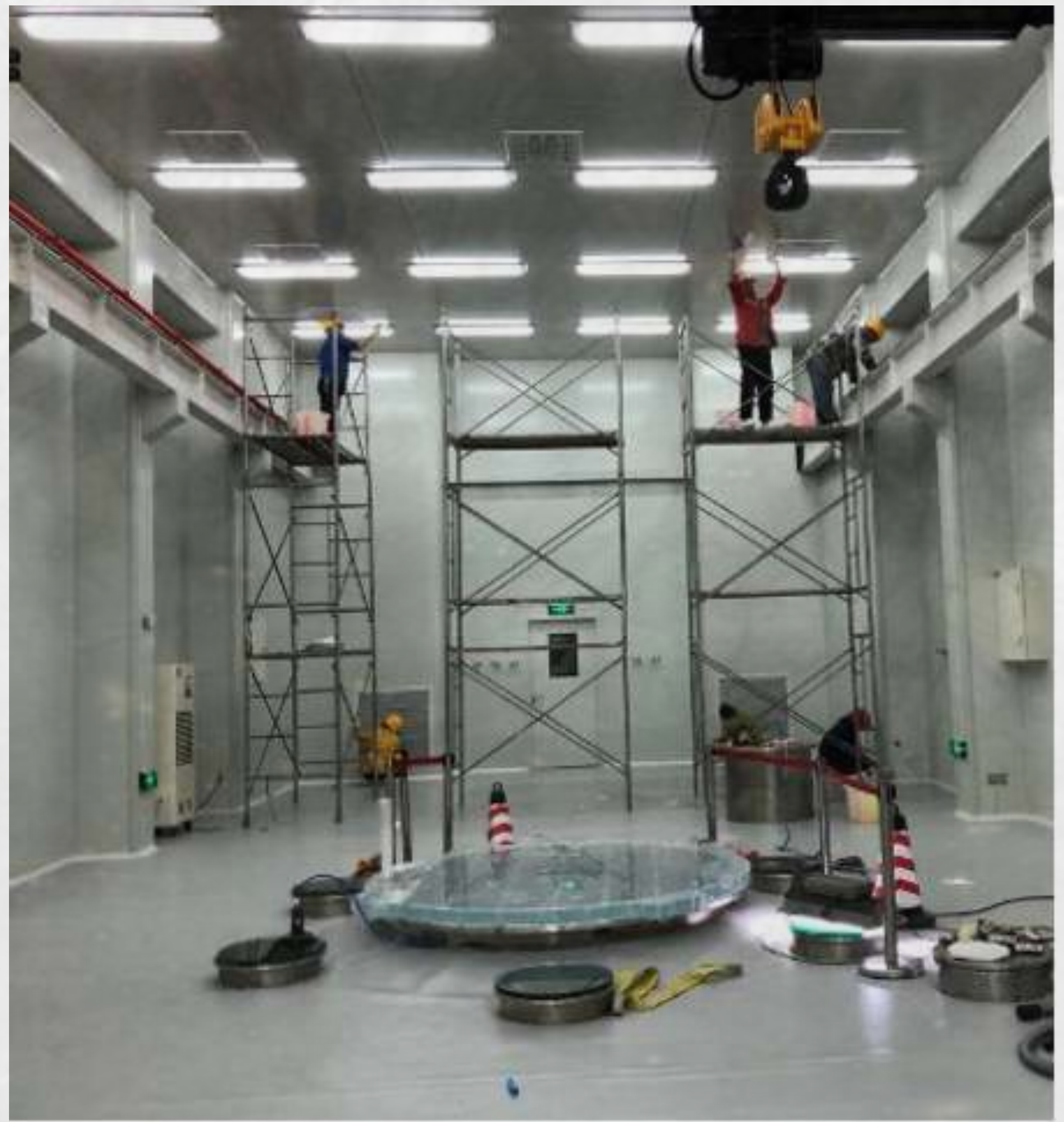


from Q. Lin

PandaX-4T Highlights: Detector Construction

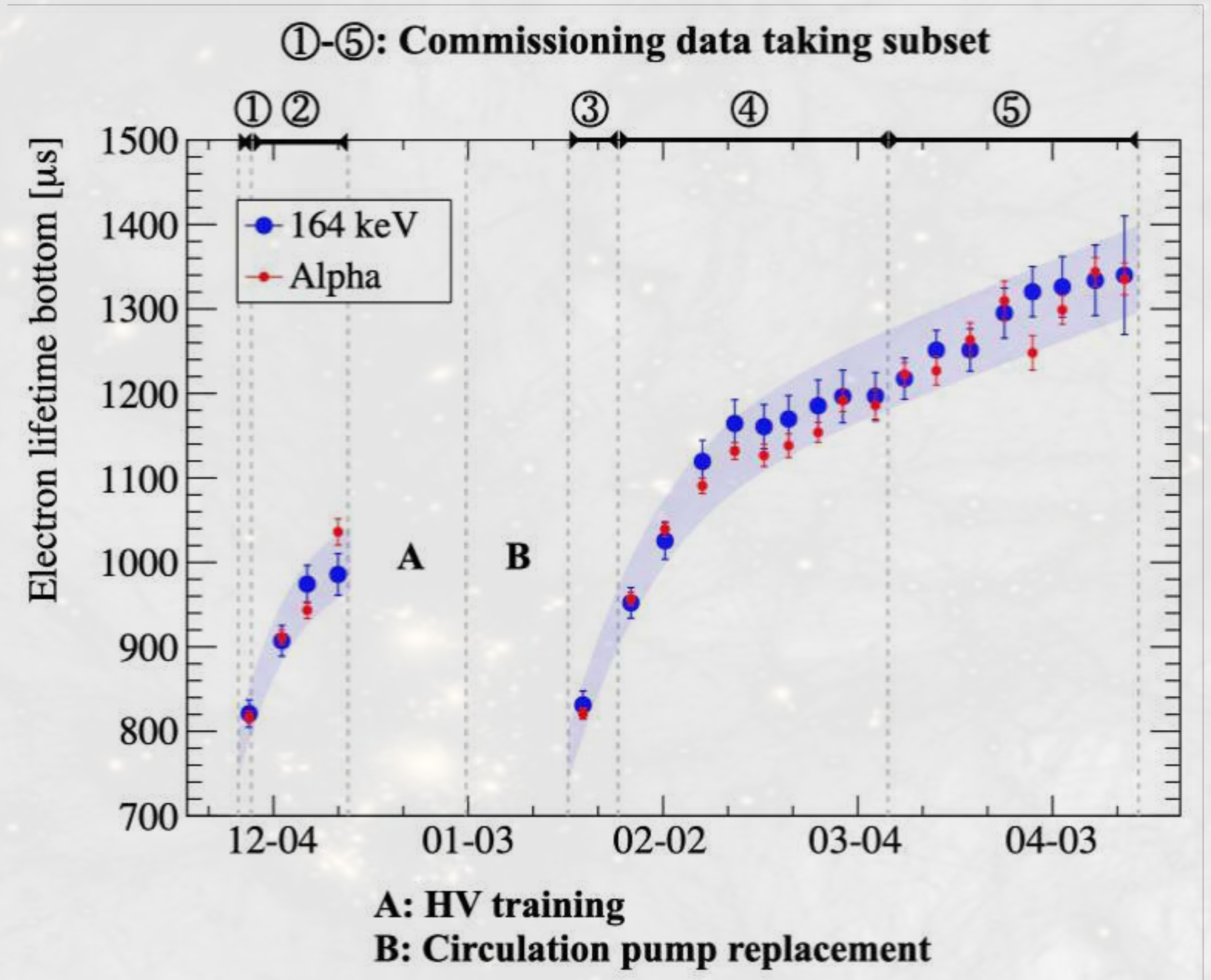


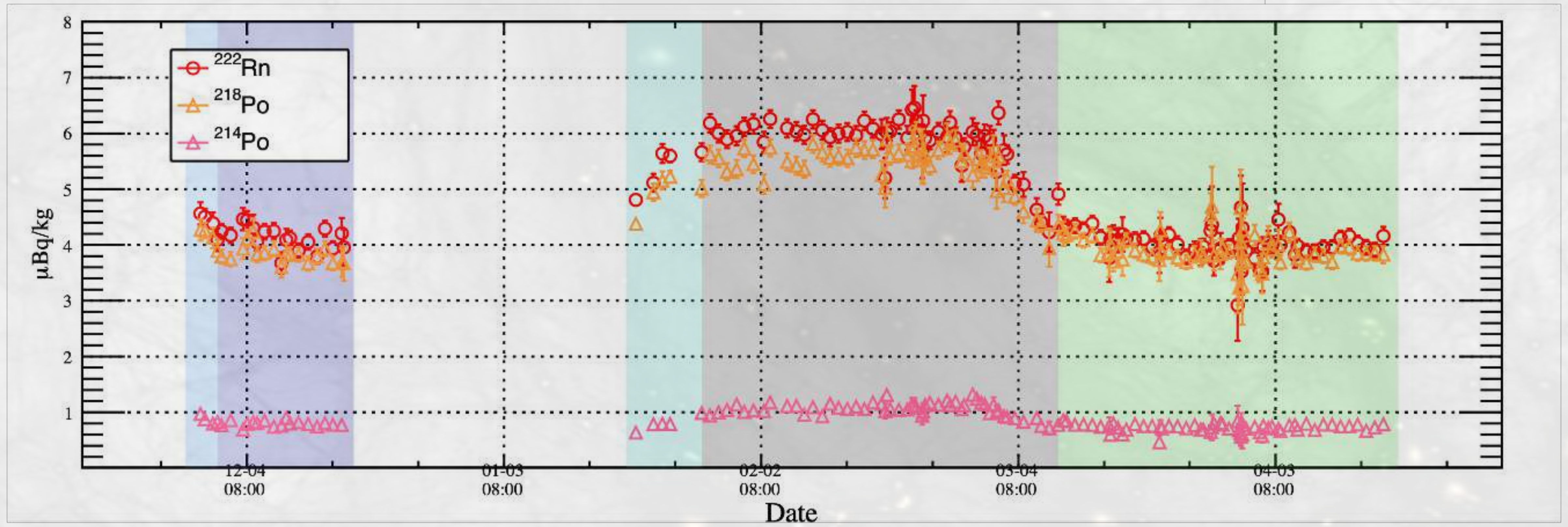




from Q. Lin

PandaX-4T Highlights: Data and Backgrounds

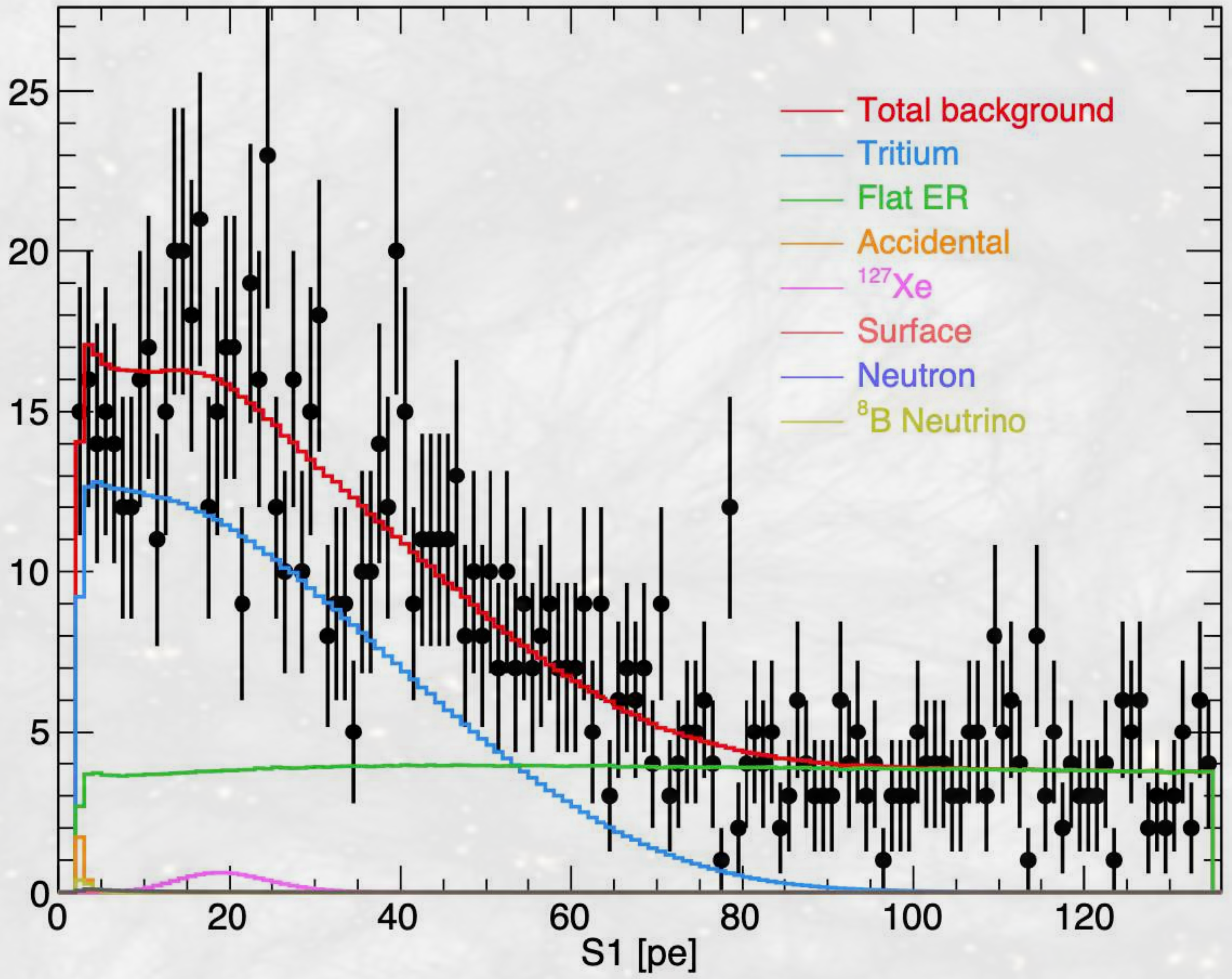




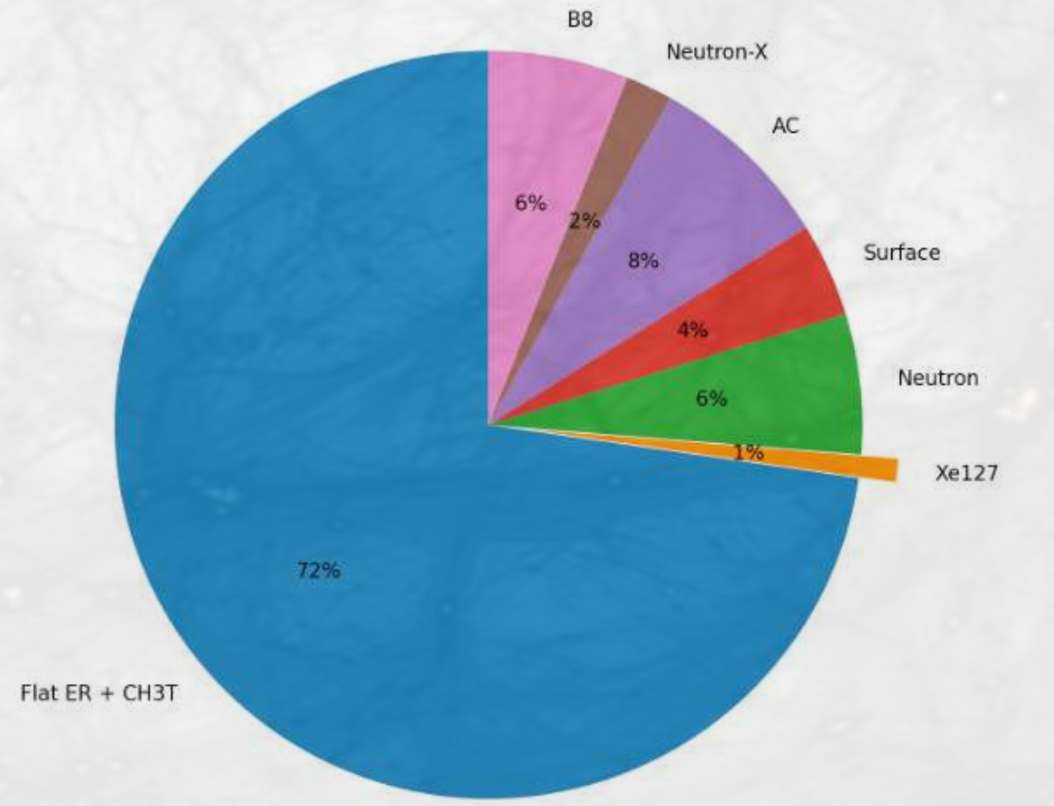
A factor of 6 reduction compared to PandaX-II

A factor of 3 reduction compared to XENON1T ton-year data

Component	Nominal (evts)
^{3}T (from fit to data)	527 (50)
Flat ER* (18-30keV side band)	492 (31)
Rn	347 (190)
Kr	53 (34)
Material	33 (4)
Xe127	8 (1)
Neutron	0.9 (0.5)
Neutron-X	0.2 (0.1)
Surface	0.5 (0.1)
Accidental	2.4 (0.5)
B8	0.6 (0.3)
Sum	1032 (59)

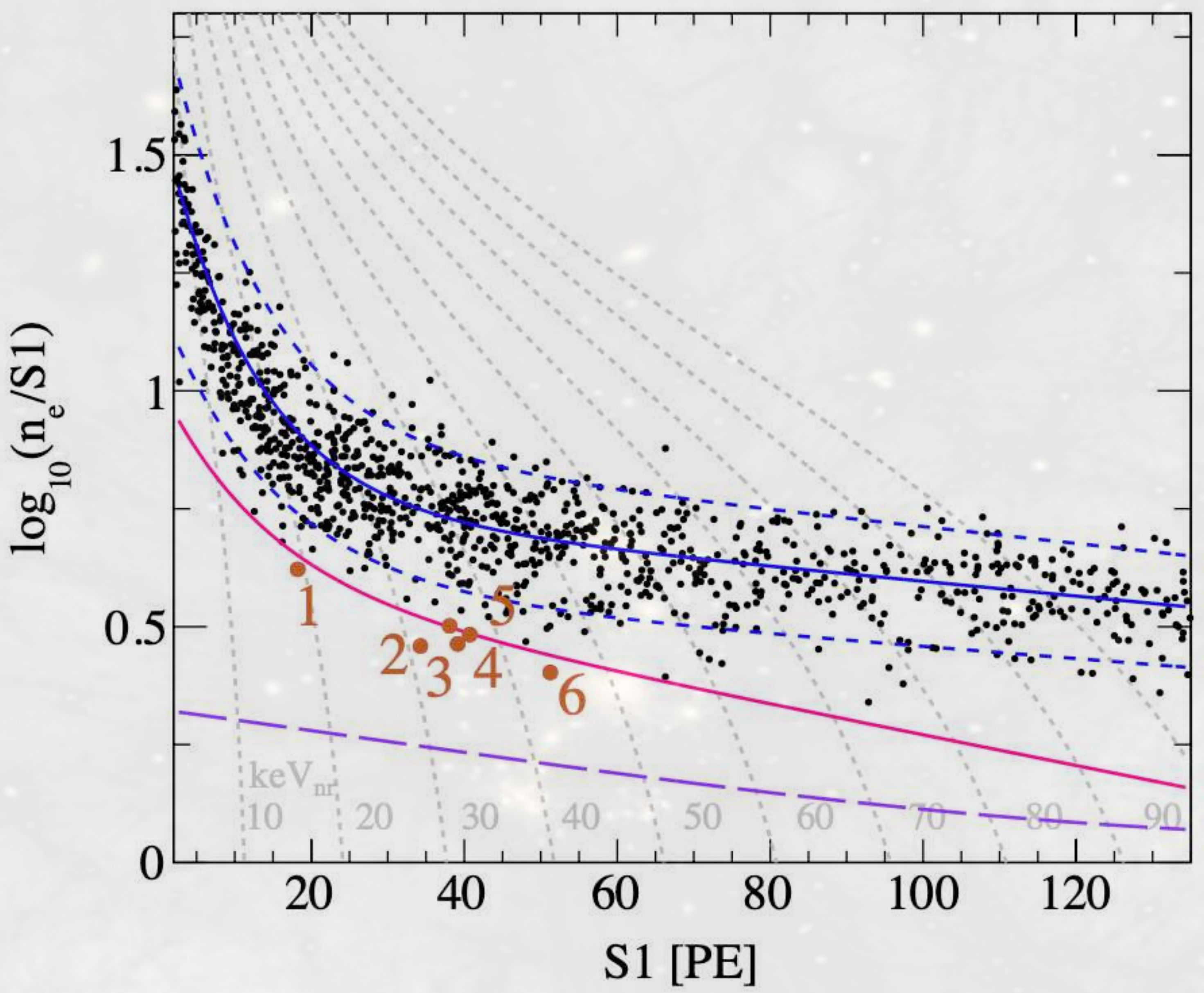


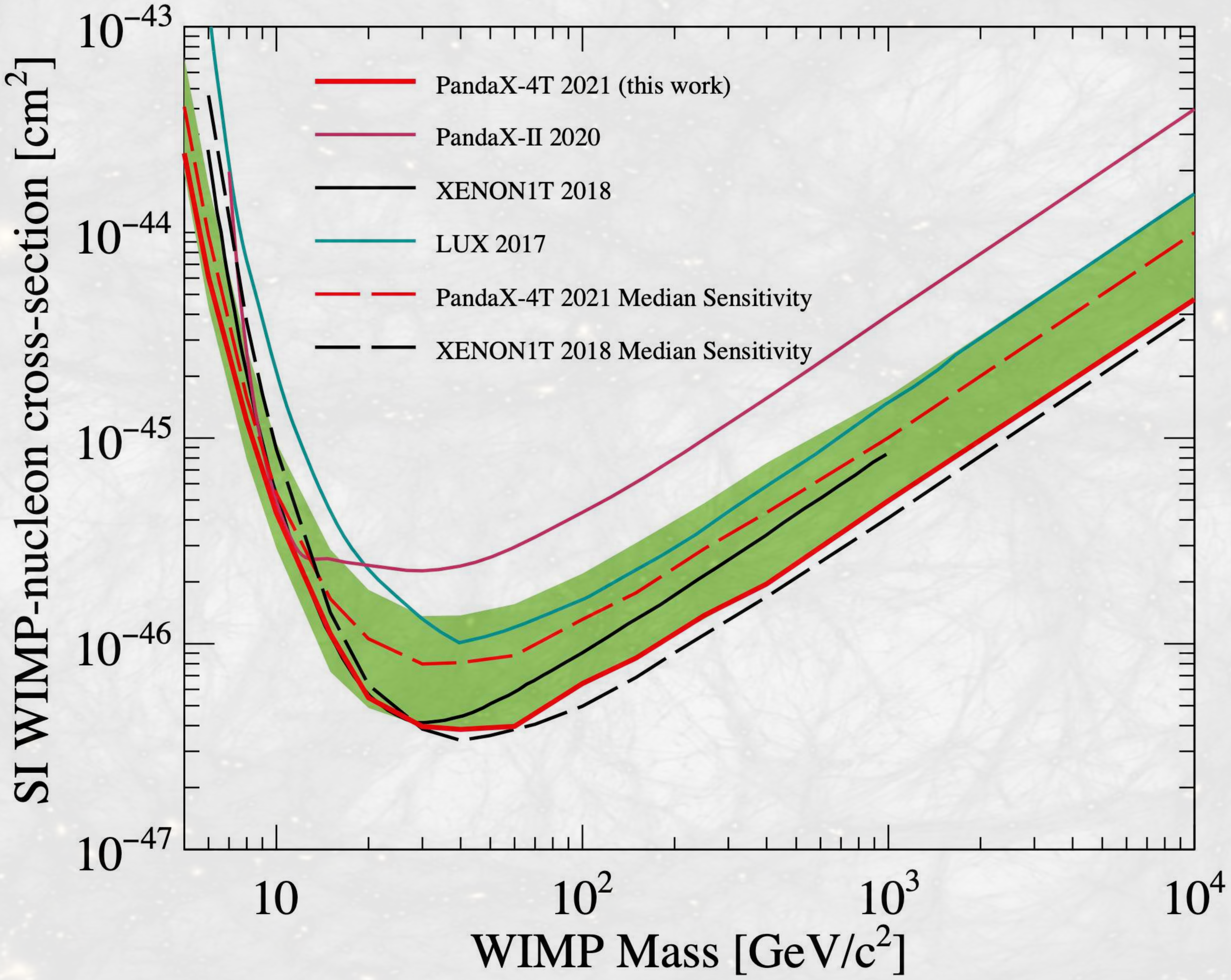
Significant amount of tritium seen in lowest energies



from Q. Lin

PandaX-4T Highlights: WIMPs Search





A factor of 2 weaker WIMPs sensitivity than XENON1T due to tritium contamination.

Background downward fluctuation -> New world leading limit!

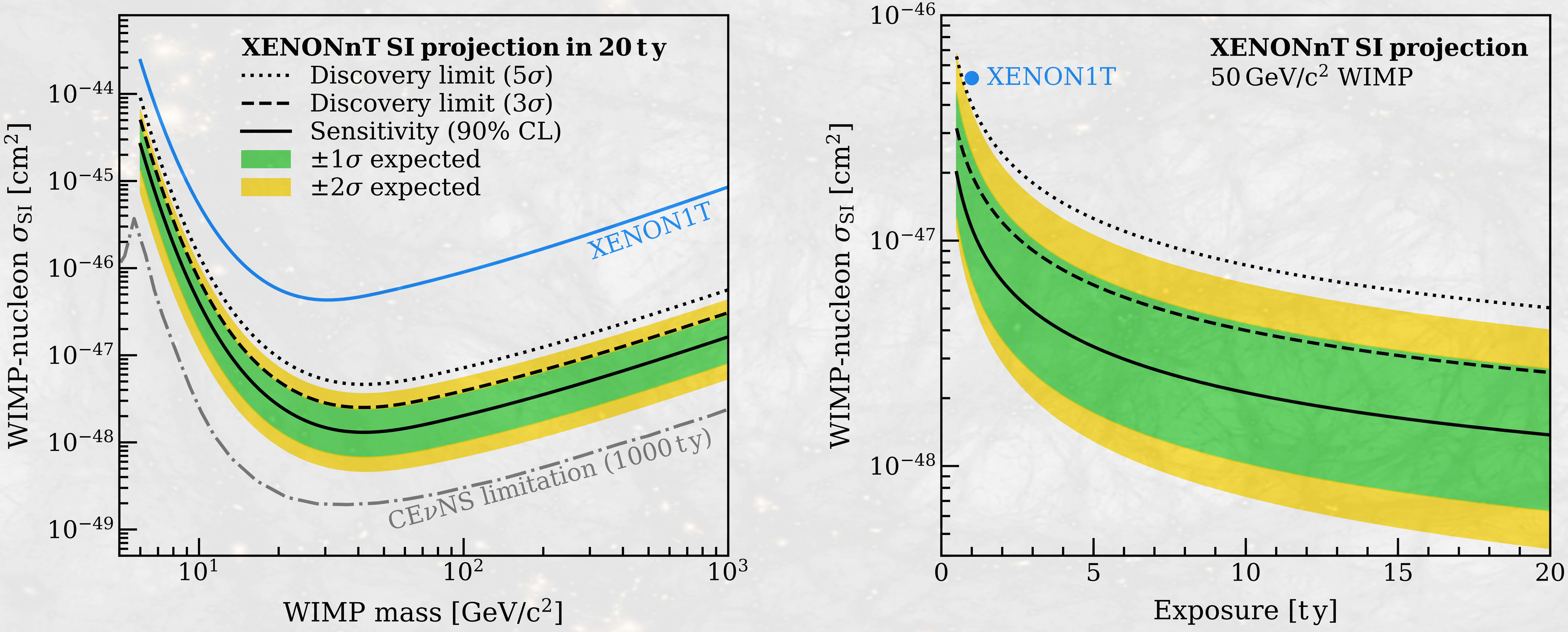
from Q. Lin

XENONnT: Currently running at Gran Sasso

Goal: ~4.0 ton fiducial volume

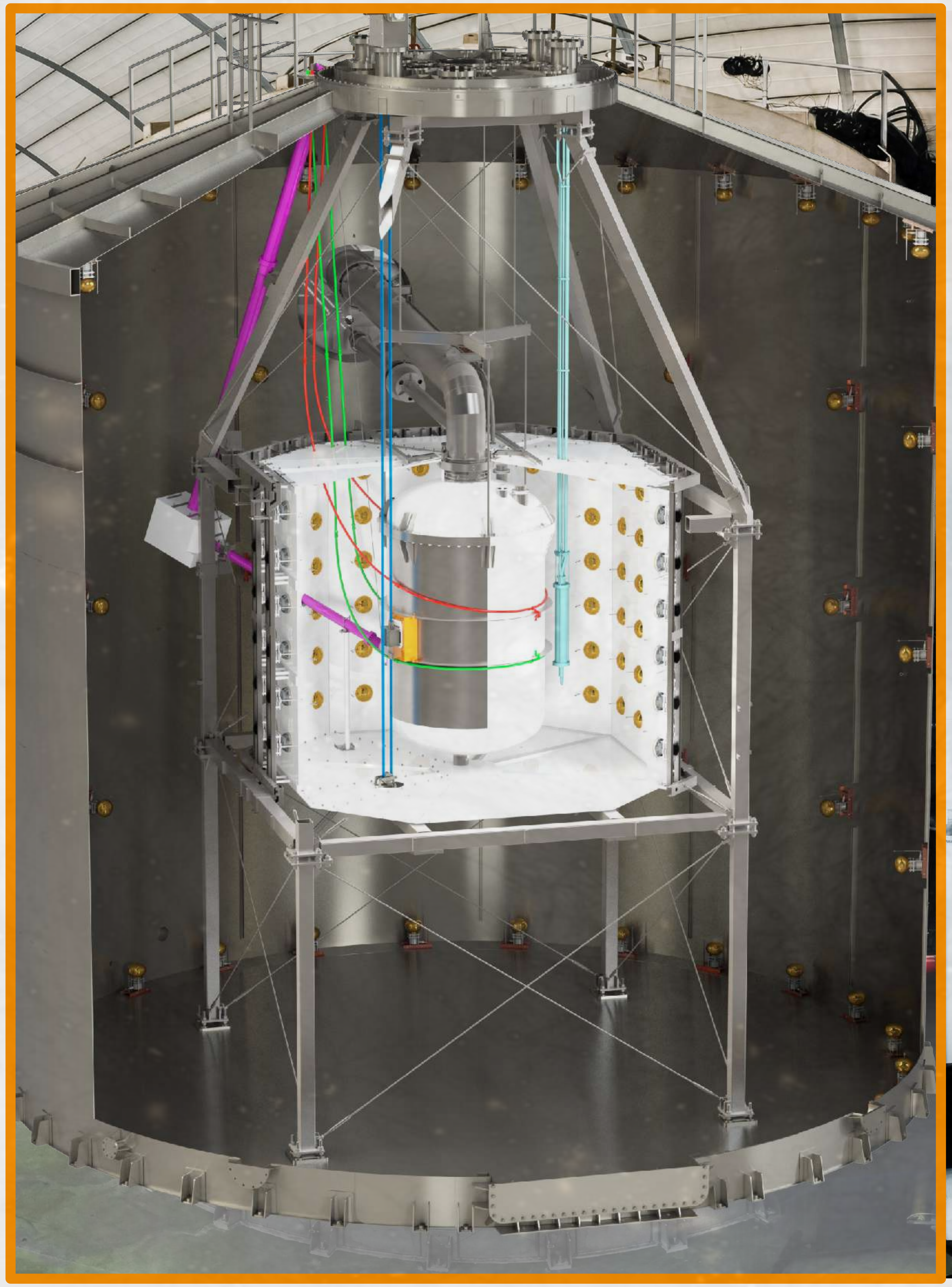
~1/6 XENON1T ER background level

~1 neutron induced background in 20 ton-year exposure



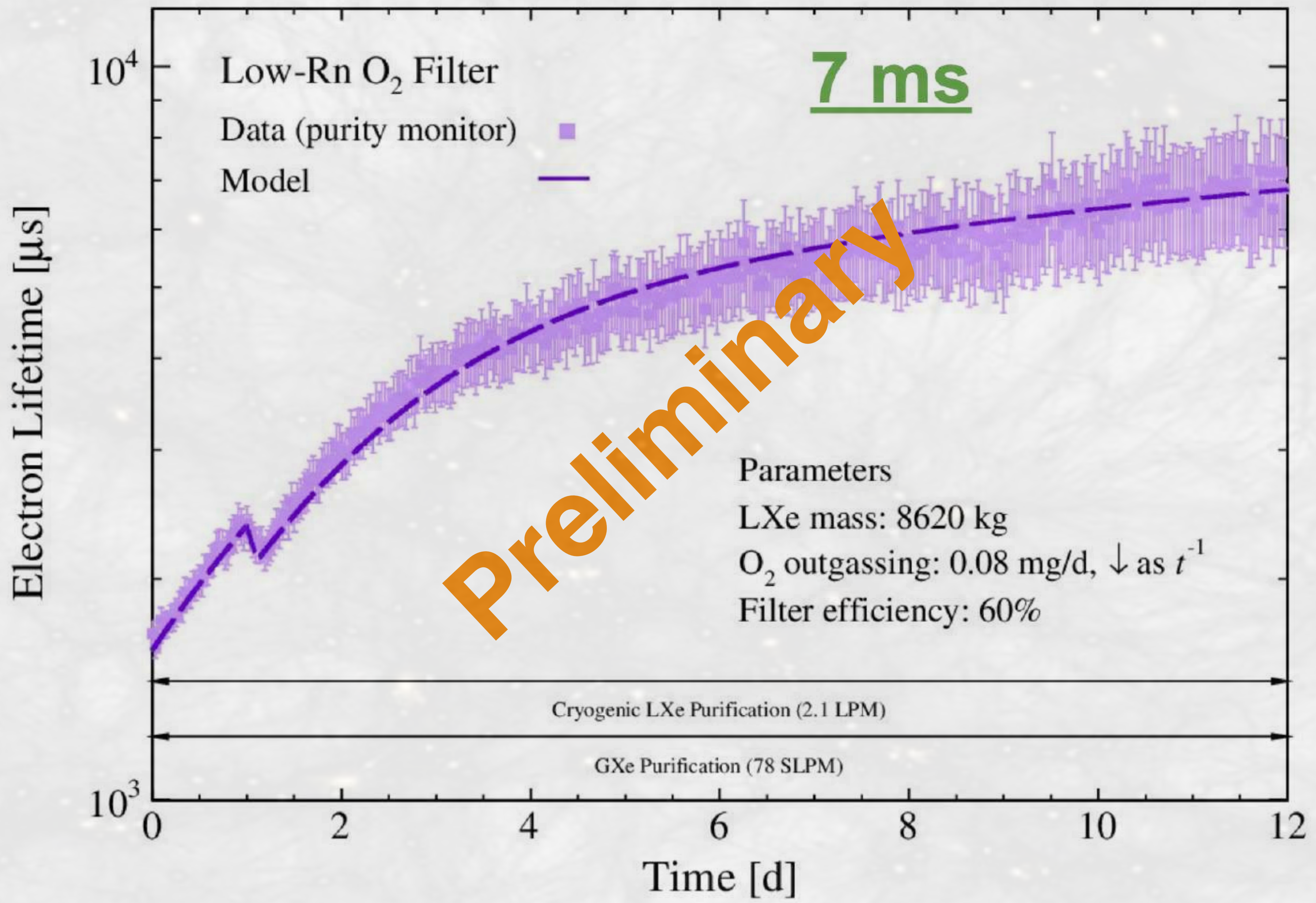
JCAP 11 (2020) 031

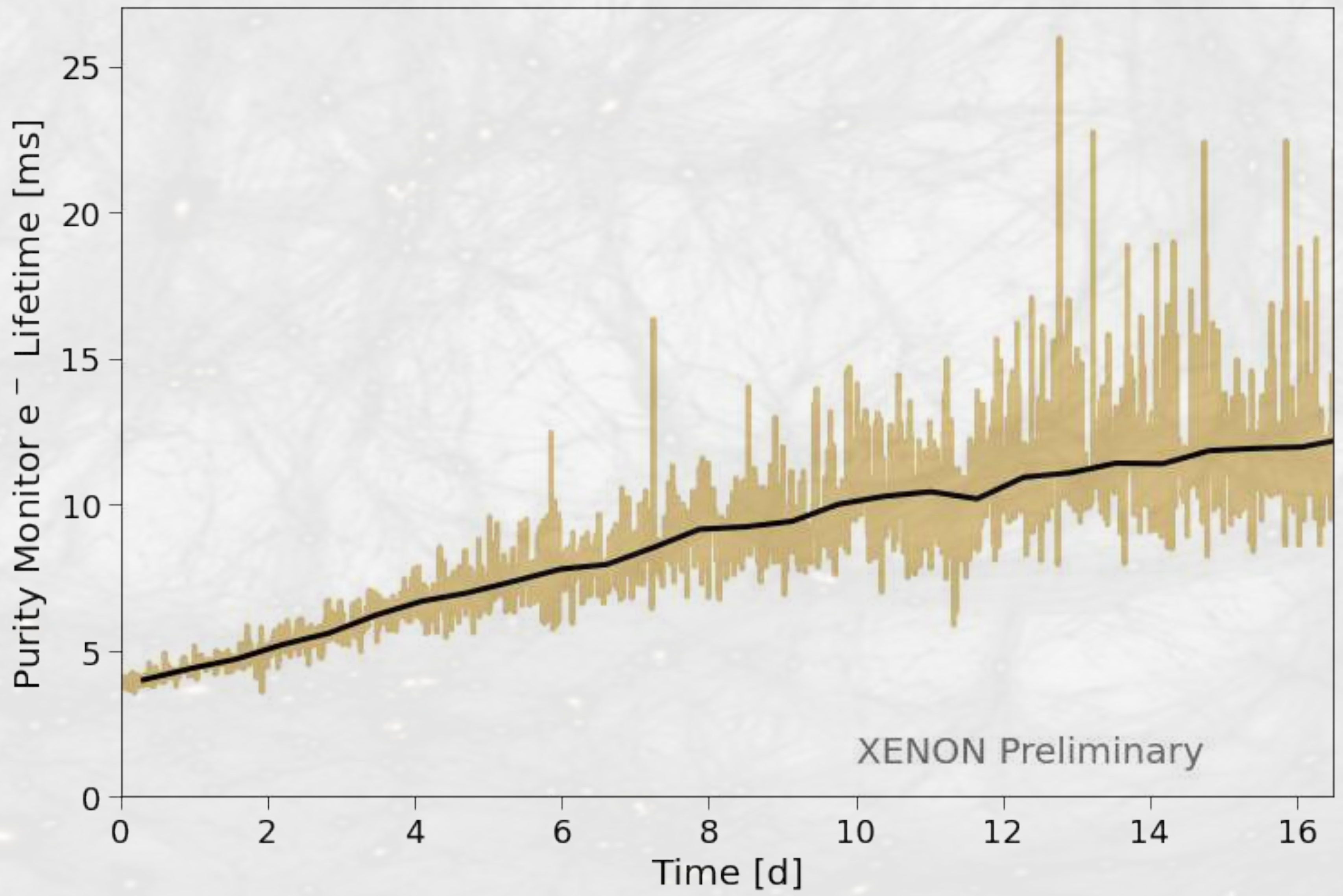
Upgrading XENON1T to XENONnT



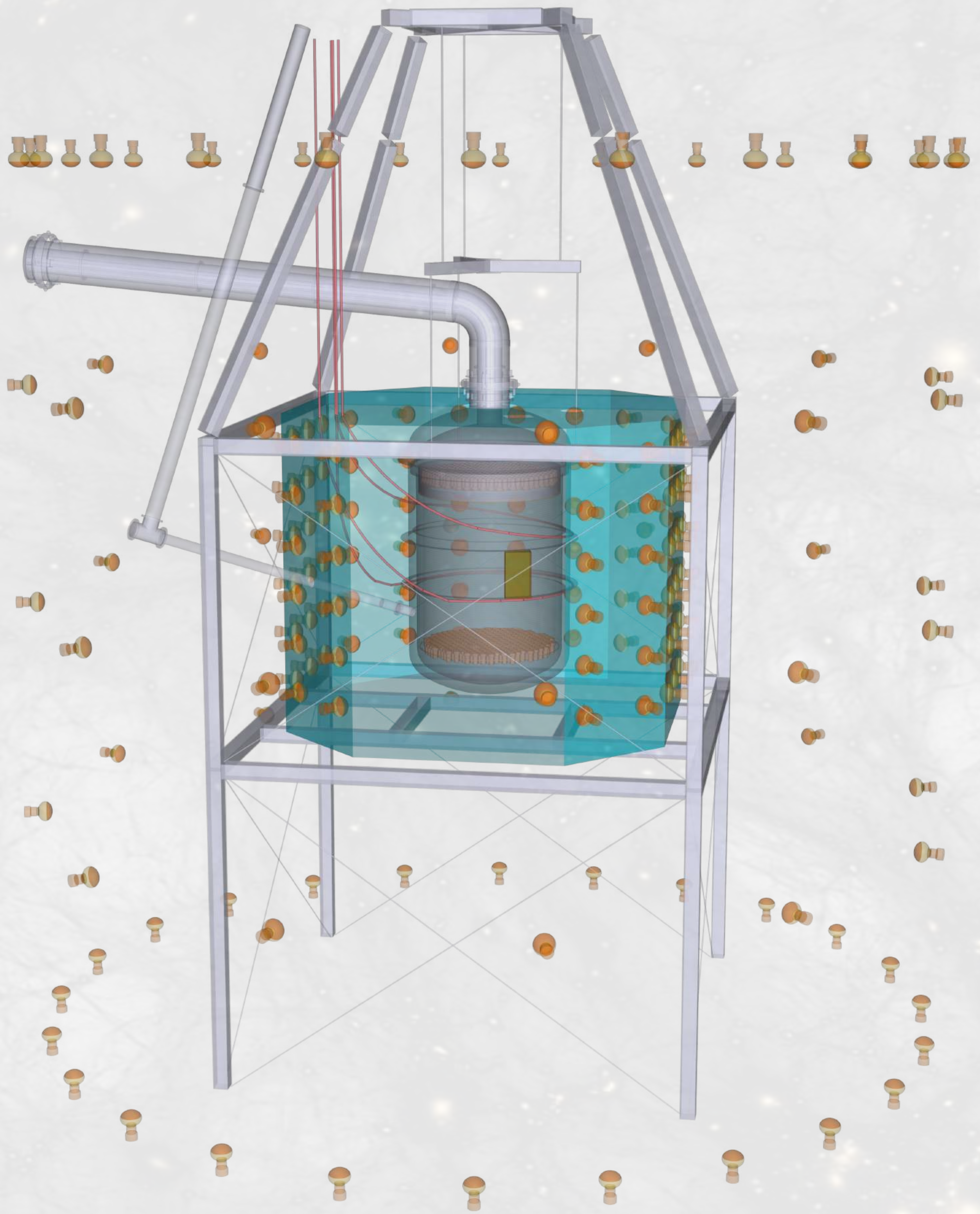
XENONnT: Cryogenic Purification

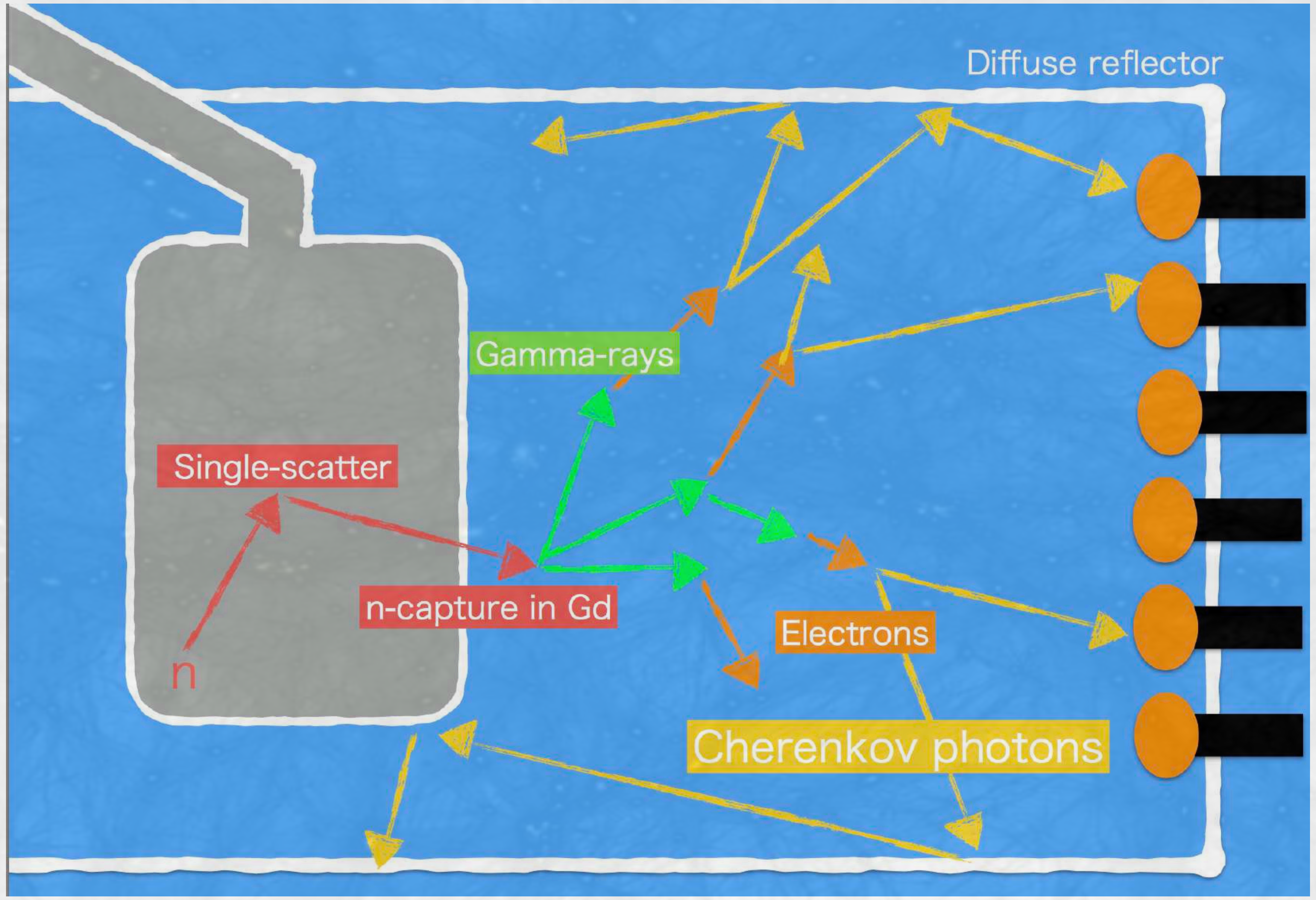
Exp	Xenon mass [t]	Max Drift [ms]	Electron lifetime [ms]	Cathode electron survival	Purification speed
XENON1T	3.2	0.73	0.65	30%	0.65ms in ~ 3 months
XENONnT	8.5	2.2	~10	>90%	5ms in ~5 days





XENONnT: Neutron Veto



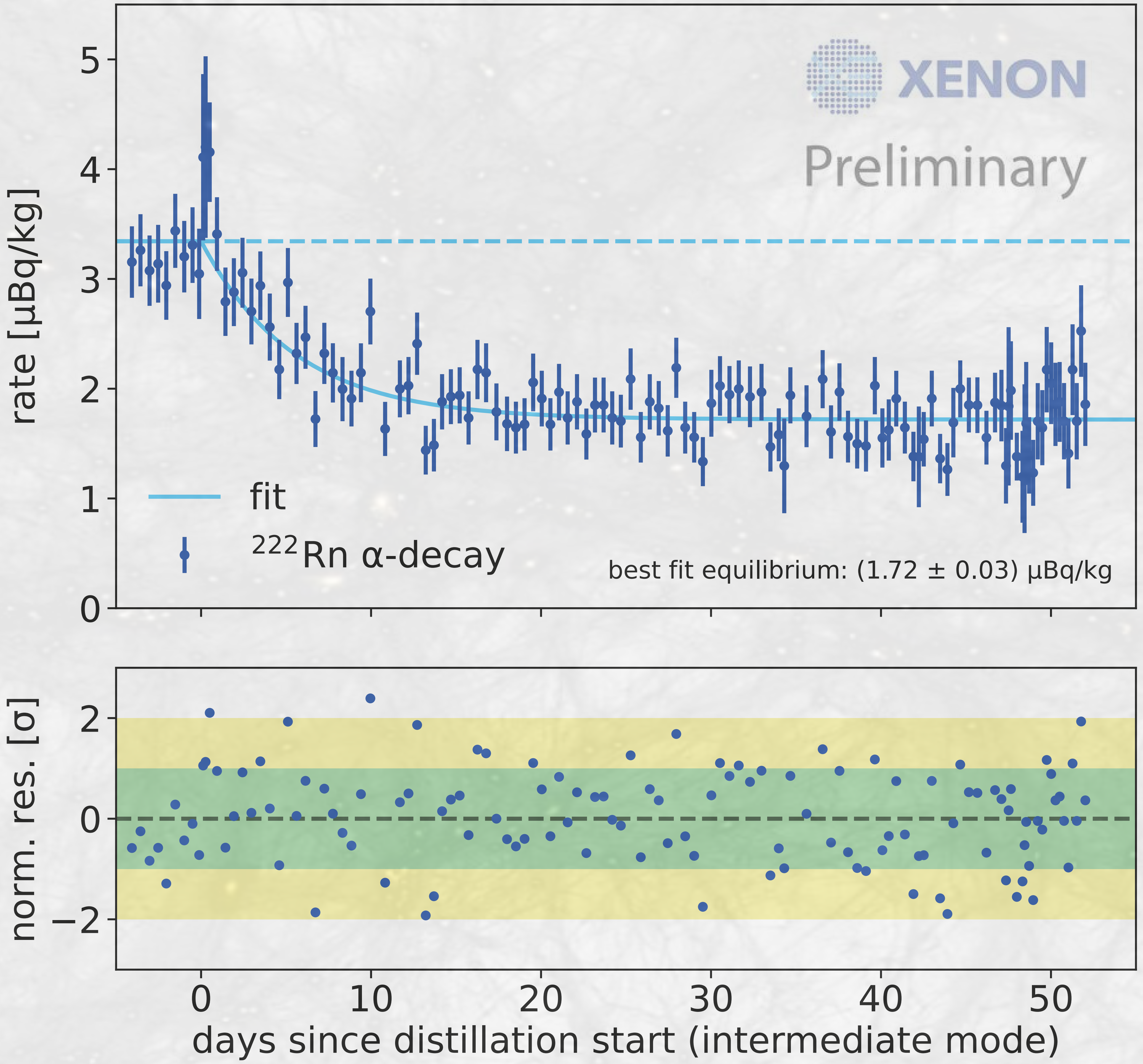


- Gd-Water Cherenkov veto detection (designed efficiency >85%)
- Neutron background reduced to < 1 events / (20 tonne year)

XENONnT Radon Distillation Column

Xenon

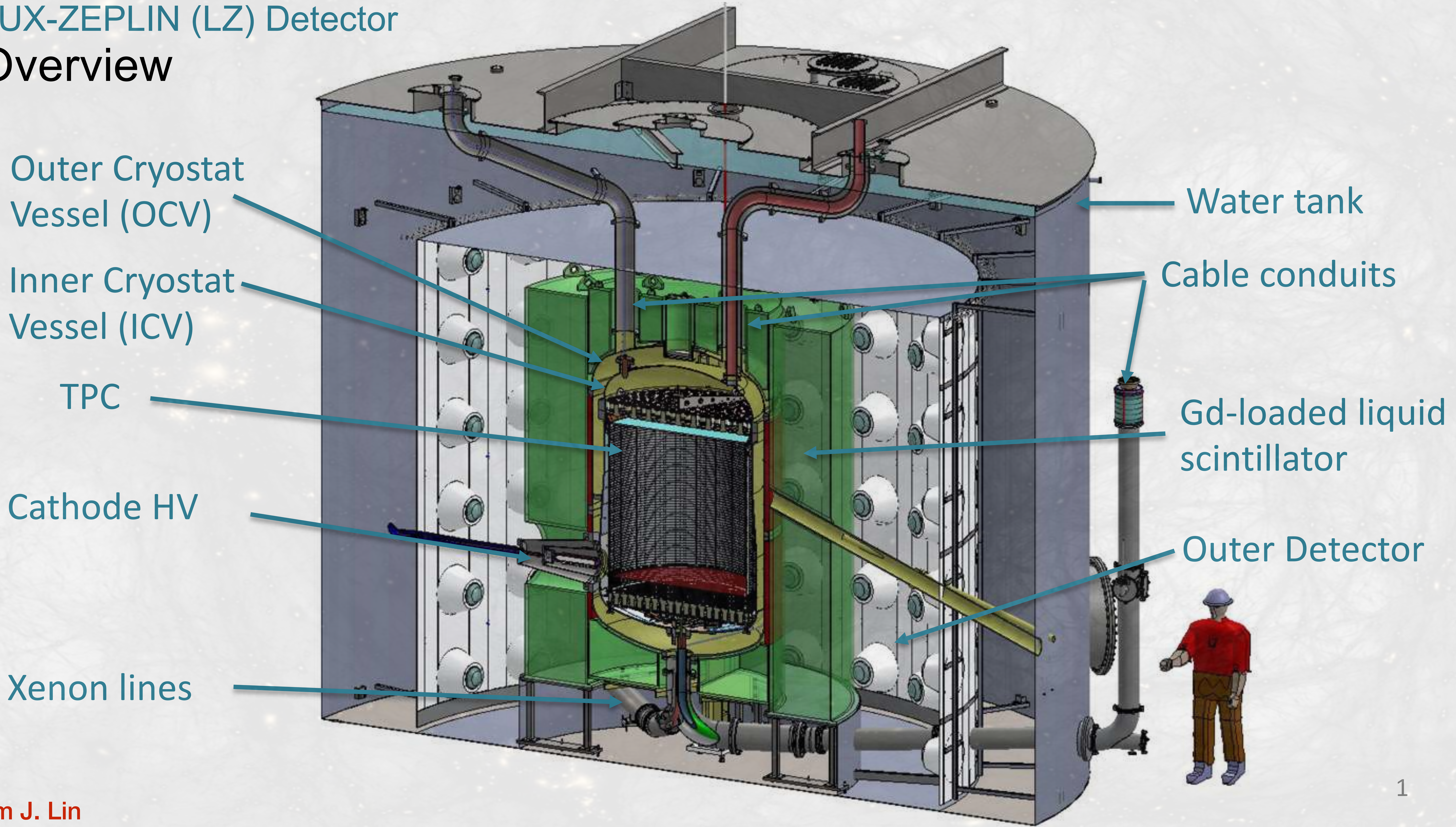
Radon



- Initial gas phase only distillation reduced the radon level to 1.7 µBq/kg
- Lowest radon level ever achieved in a LXeTPC

LUX-ZEPLIN (LZ) Detector

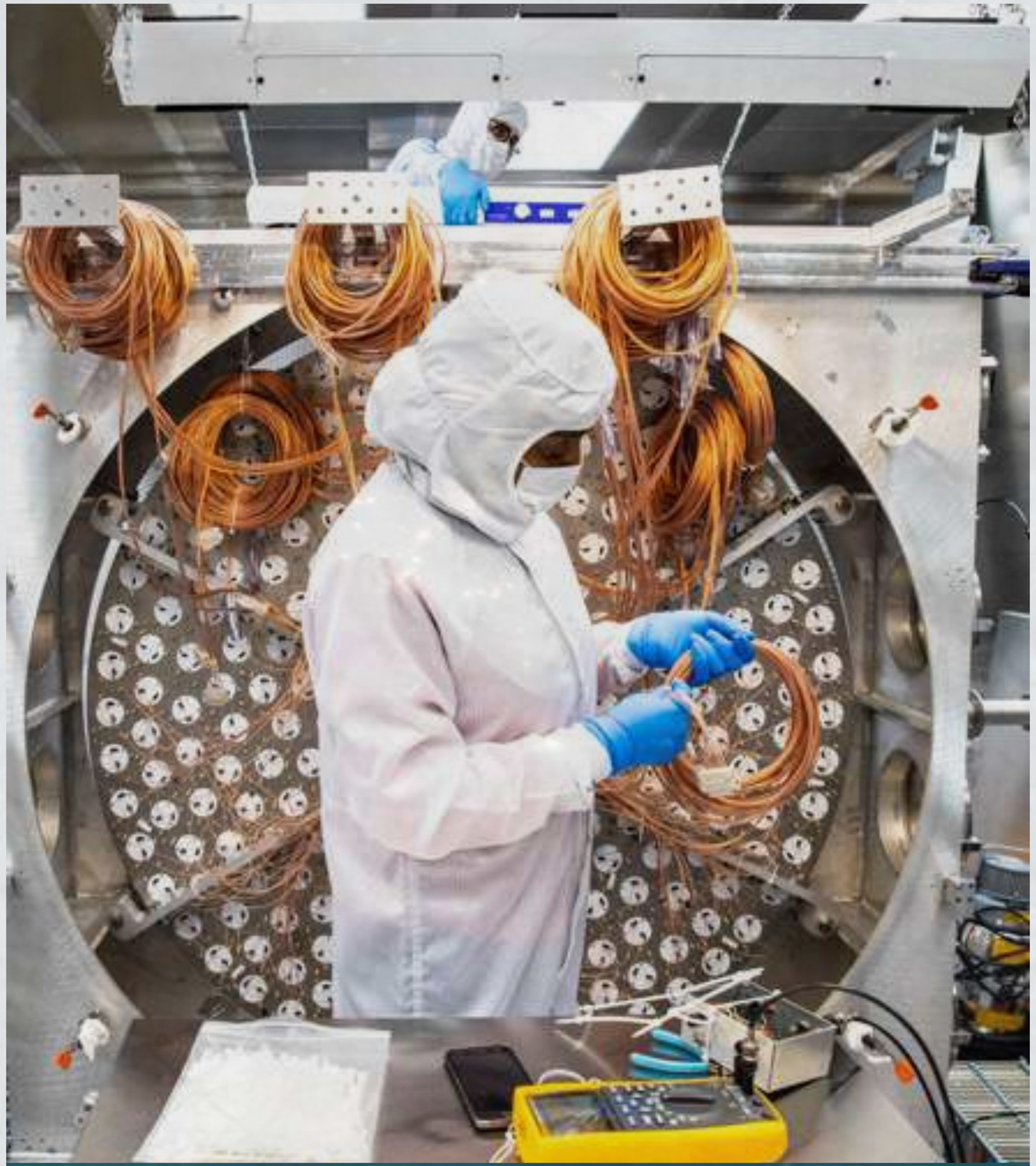
Overview



from J. Lin

LZ Detector construction

TPC



PMT array cabling at SURF

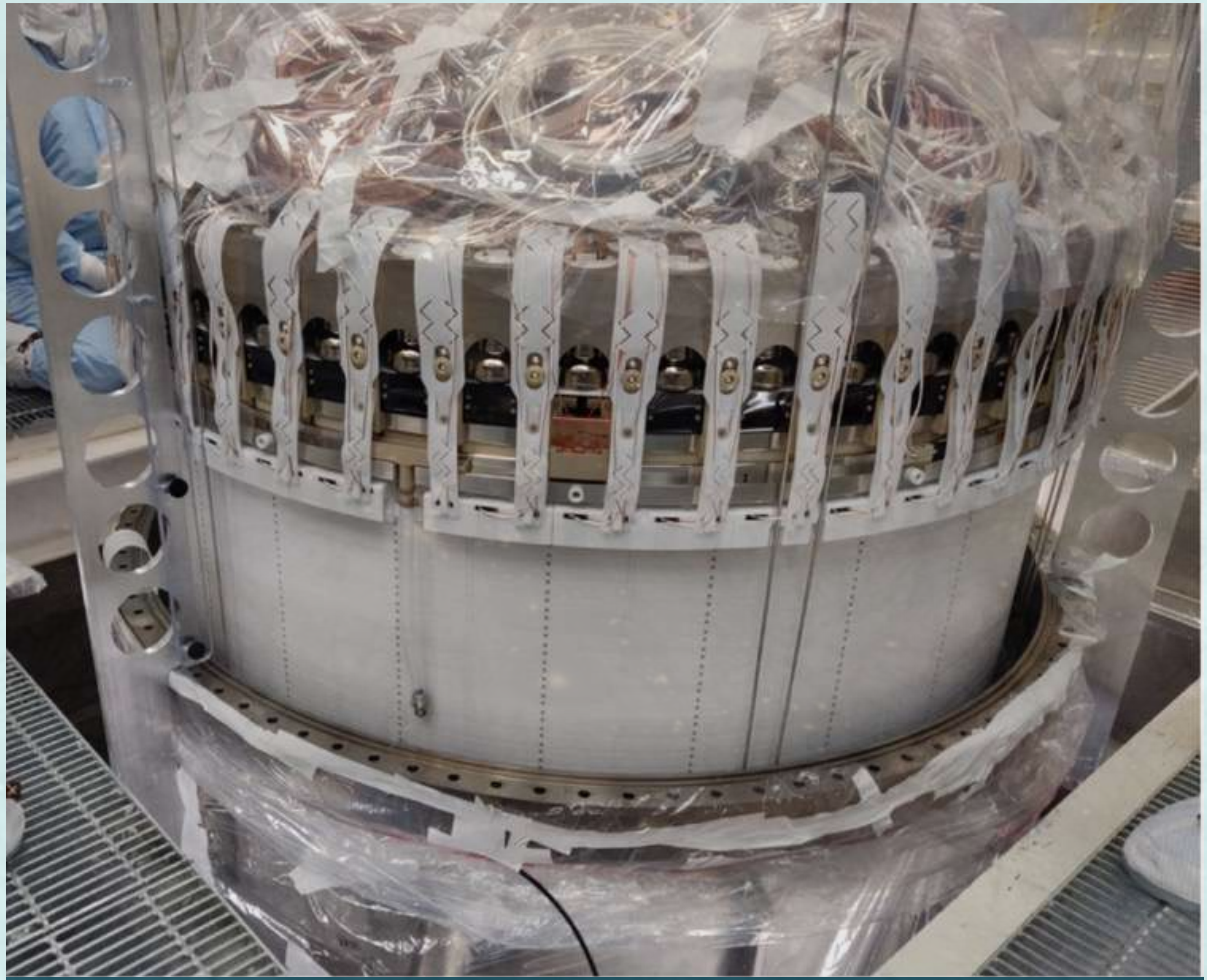
Grid weaving at SLAC

Bottom array with grids and field cage

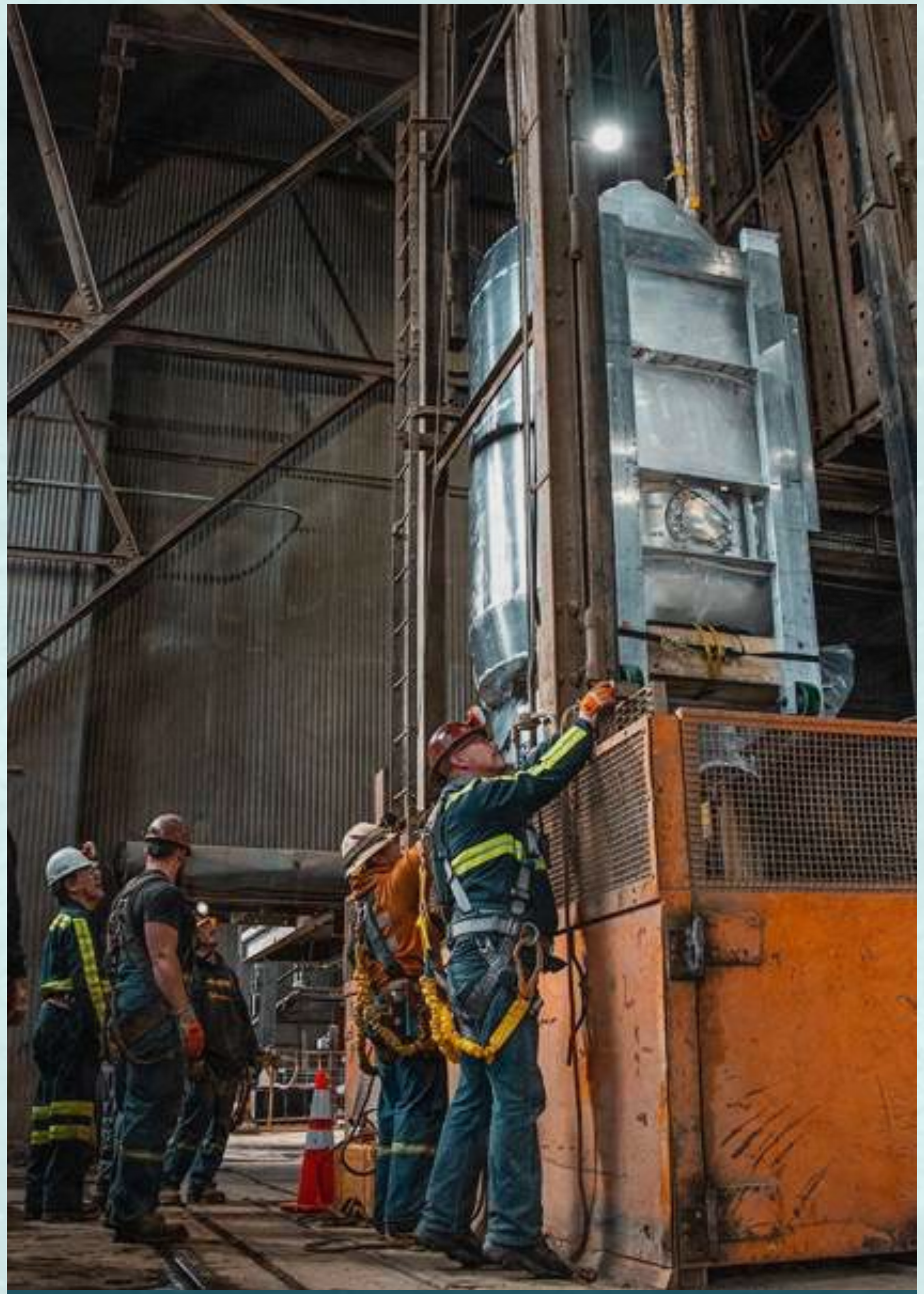
Assembled TPC

from J. Lin

ICV transport & installation



TPC insertion into cryostat



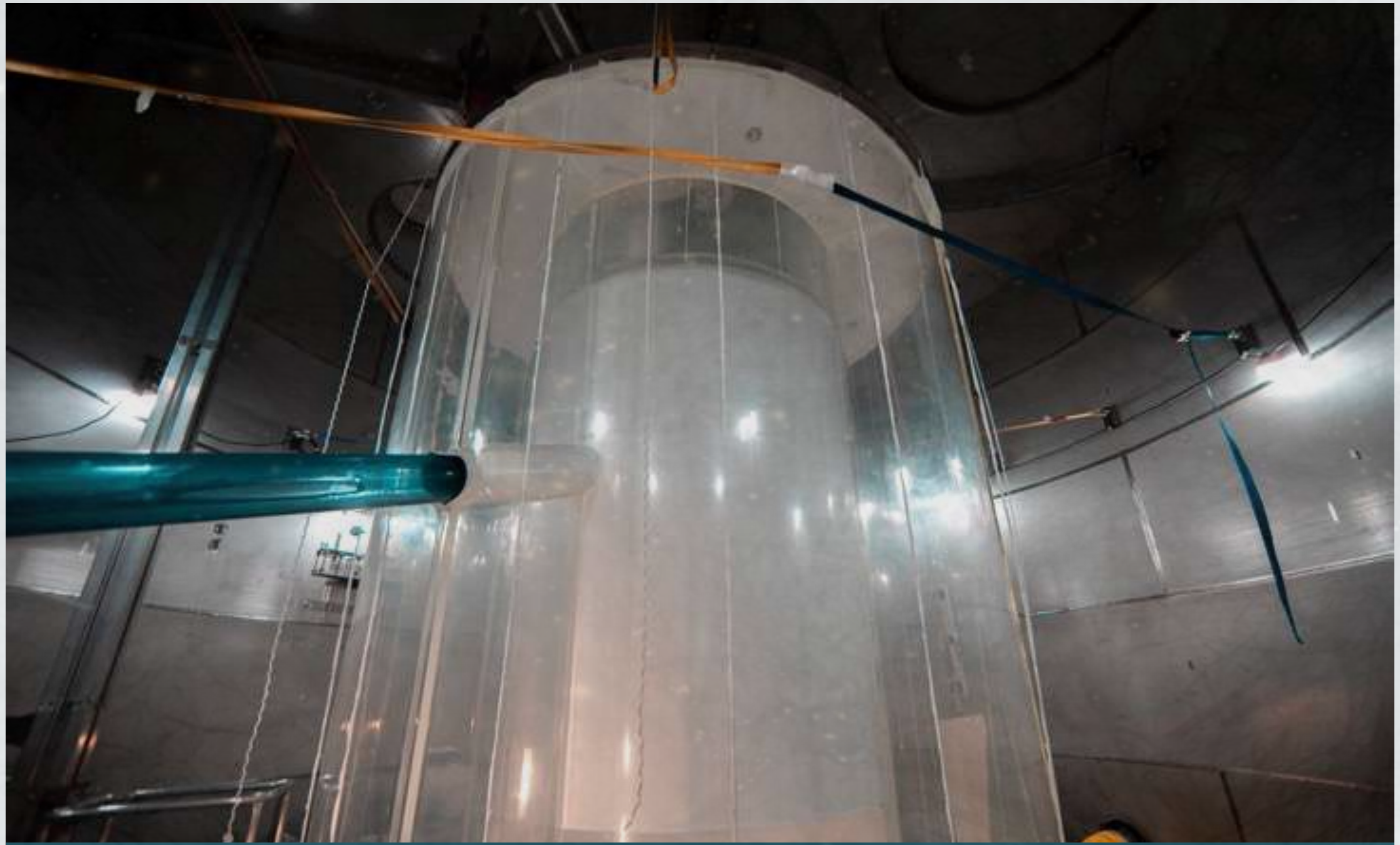
ICV transport underground

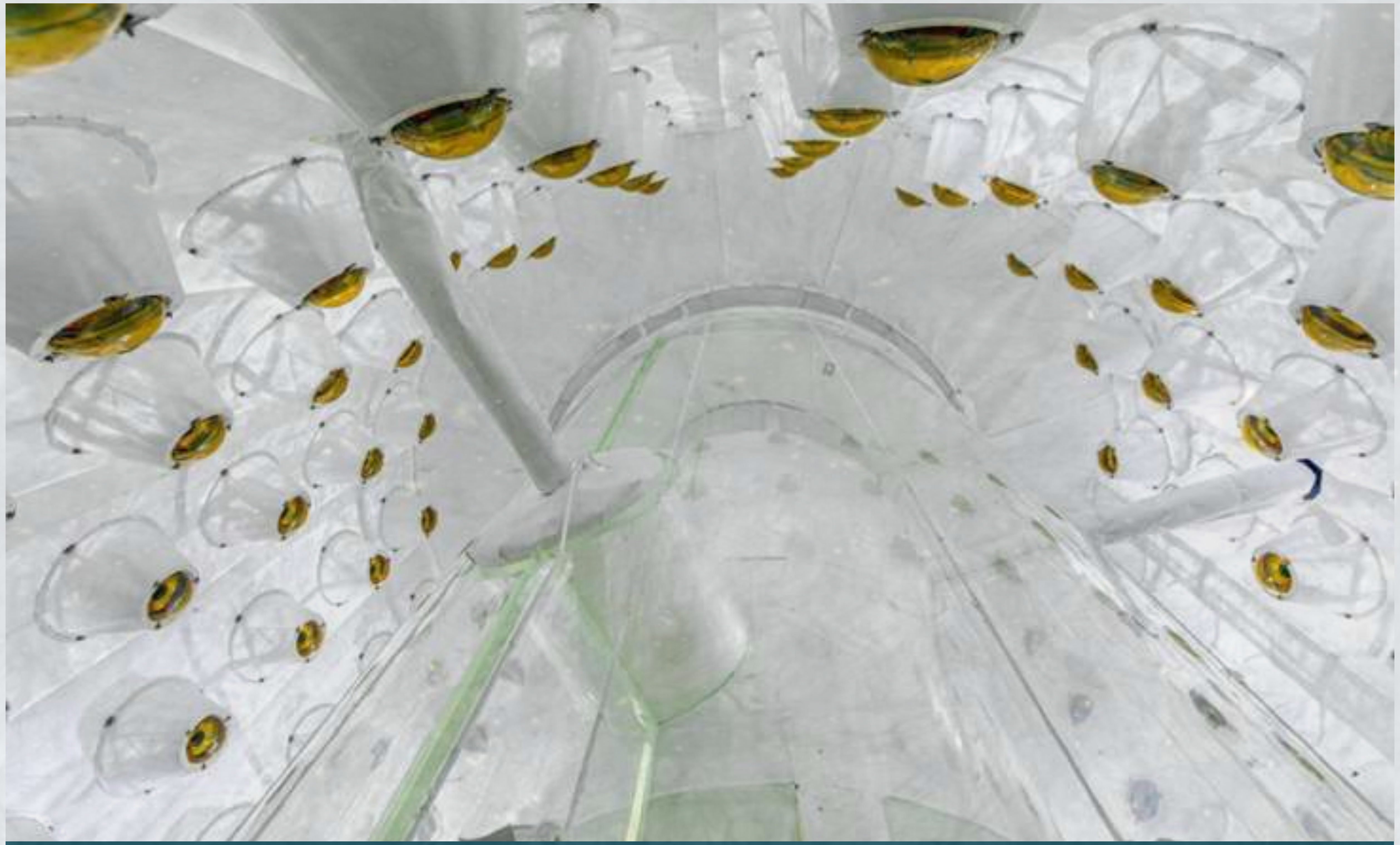
ICV installation in OCV

from J. Lin

Integration underground

Outer Detector

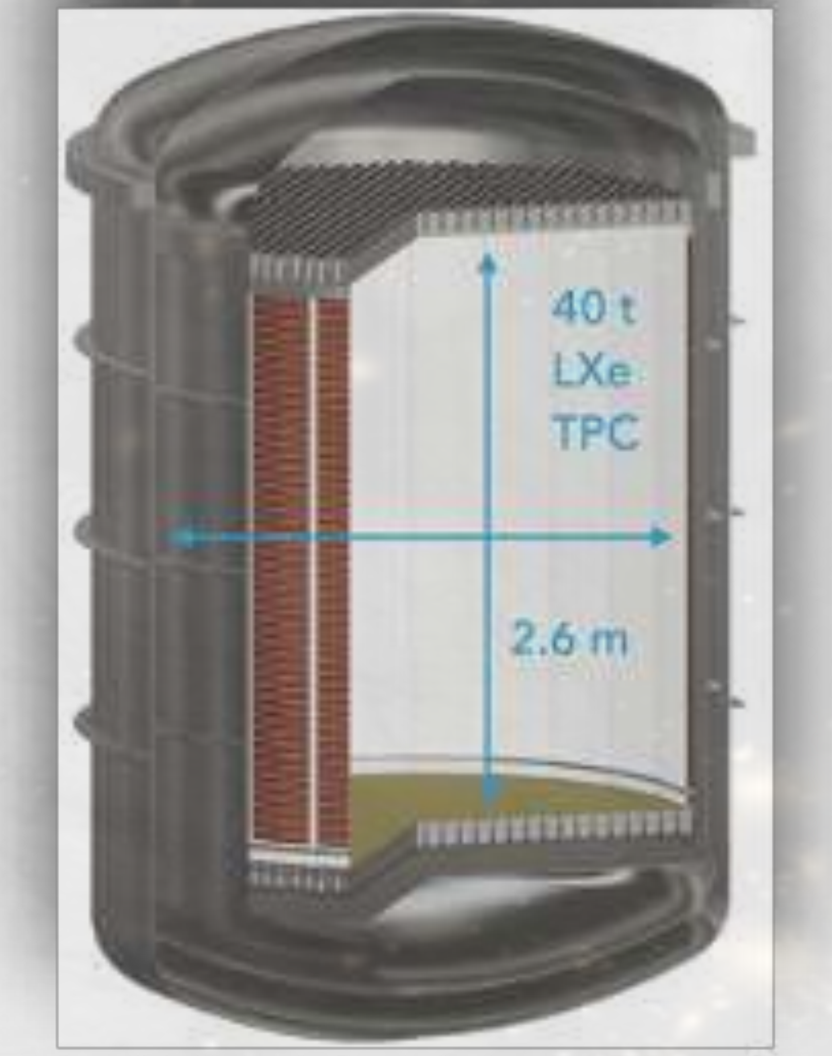

Installation of OD tanks around Outer Cryostat Vessel

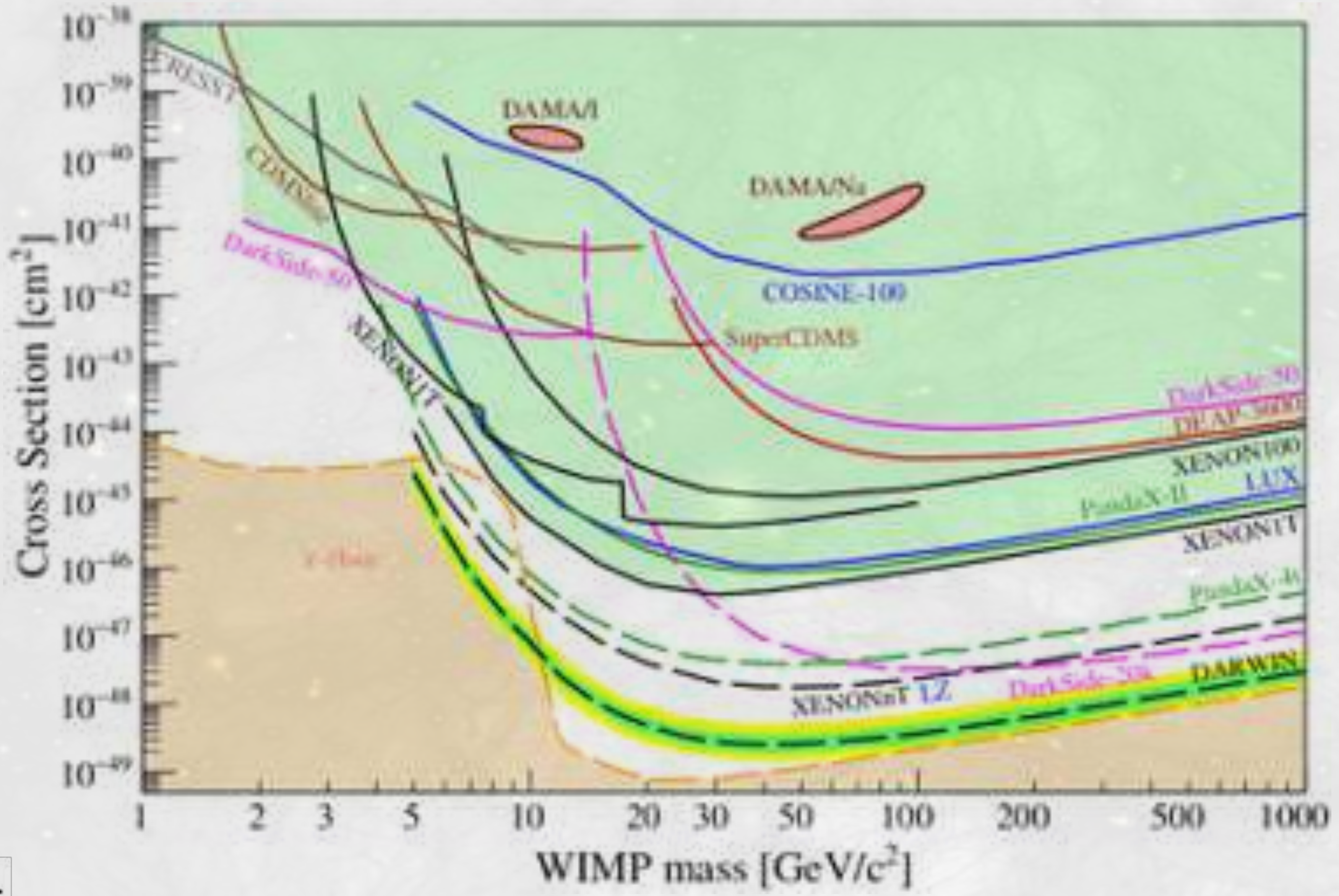

Completed Outer Detector

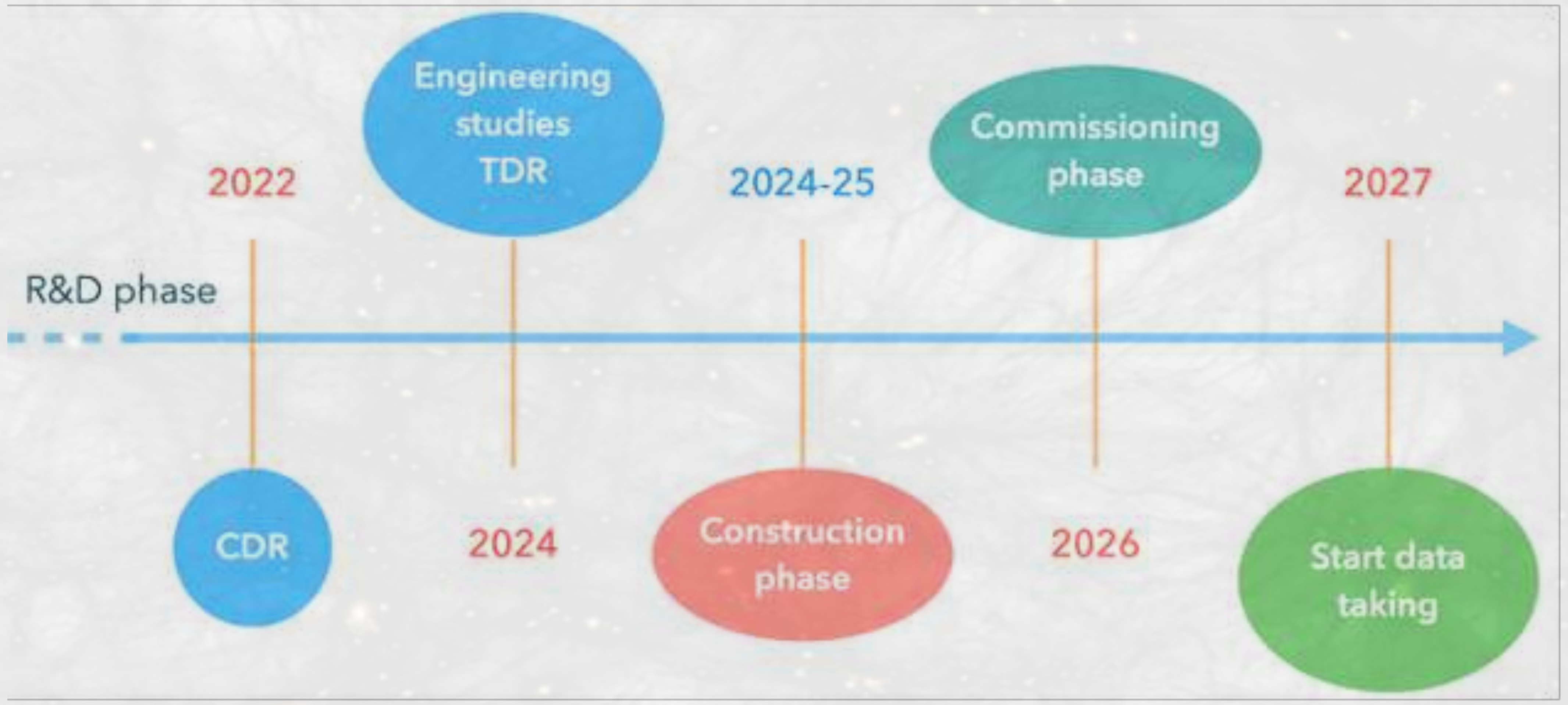
LZ Status:
- LZ construction and underground circulation test complete
- Commissioning is underway!
  - The detector has been cooled down and all PMTs have been tested with LEDs
- 2022 will be an exciting year for LZ

from J. Lin

Efforts towards “G3” LXeTPCs







[20.07.2021] DARWIN and LZ join forces to build next-generation Dark Matter Detector

The XENON/DARWIN and LUX-ZEPLIN (LZ) collaborations have now joined forces to work together on the de
tonne scale xenon observatory to explore dark matter. The detector will be highly sensitive to a wide range c
with visible matter. Over the last 20+ years, experiments using liquified xenon targets have delivered world
detection. This next-generation detector aims to continue the pursuit.

Dark matter makes up 85% of the matter in the Universe, but its nature remains a mystery. The direct ider
highest priorities in science and also one of the most challenging. The primary science goal of the new joint
matter in our galaxy by at least a factor of 10 beyond that of the current generation of detectors.

Laura Baudis from the University of Zurich and spokesperson of DARWIN says: "Xenon-based detectors are
the upcoming years if nature decided to put it in reach of any direct detection instrument."

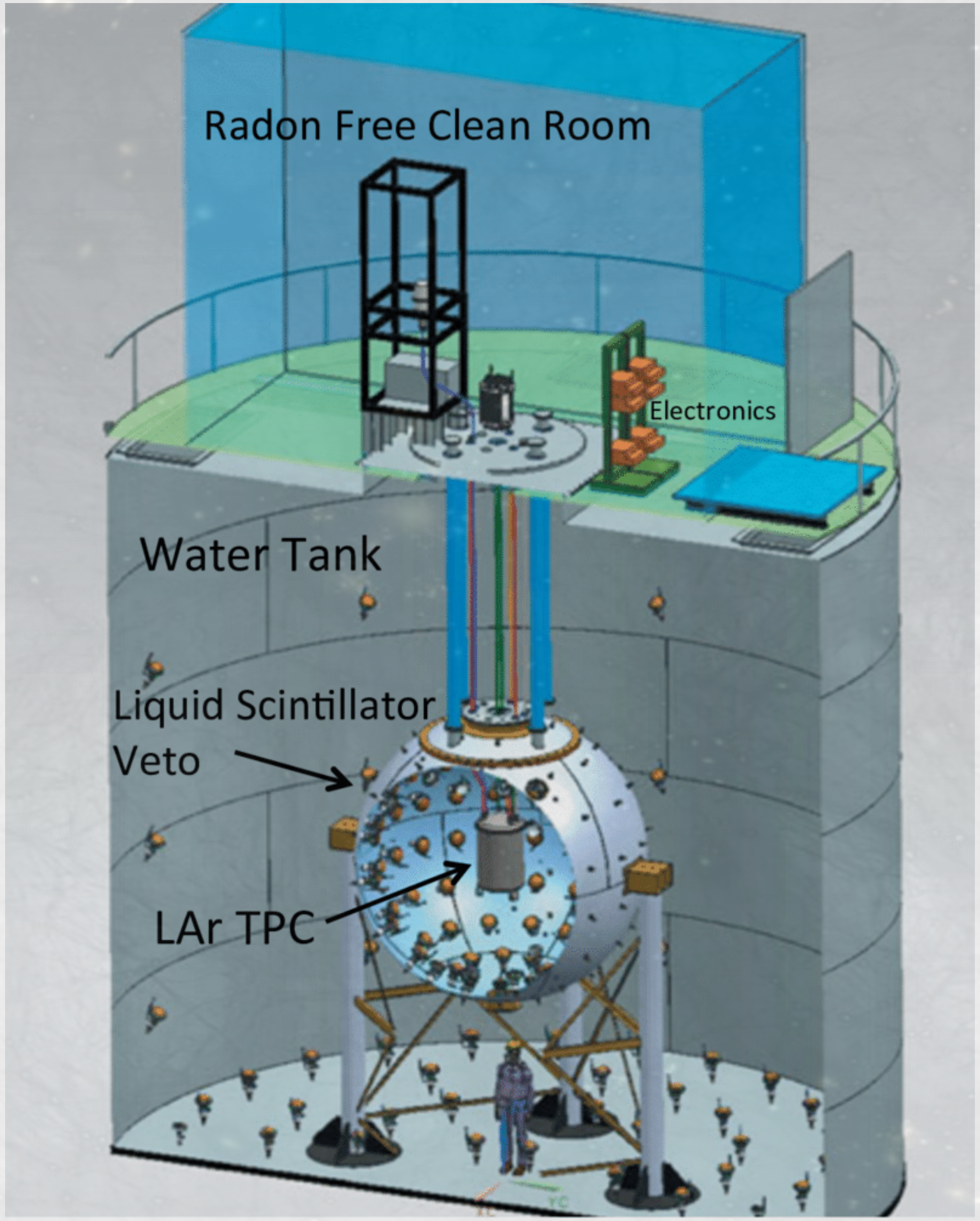
The current xenon-based experiments **XENONnT** and **LUX-ZEPLIN** will start their first science runs in 2021
and interactions. These experiments employ 5.9 and 7.0 tonnes of liquid xenon for the search, respectively.

The scientists that have signed the Memorandum of Understanding between members of the XENON/DARWIN and LUX-ZEPLIN Collaborations towards a Next-Generation Liquid Xenon Experiment (July 6, 2021)

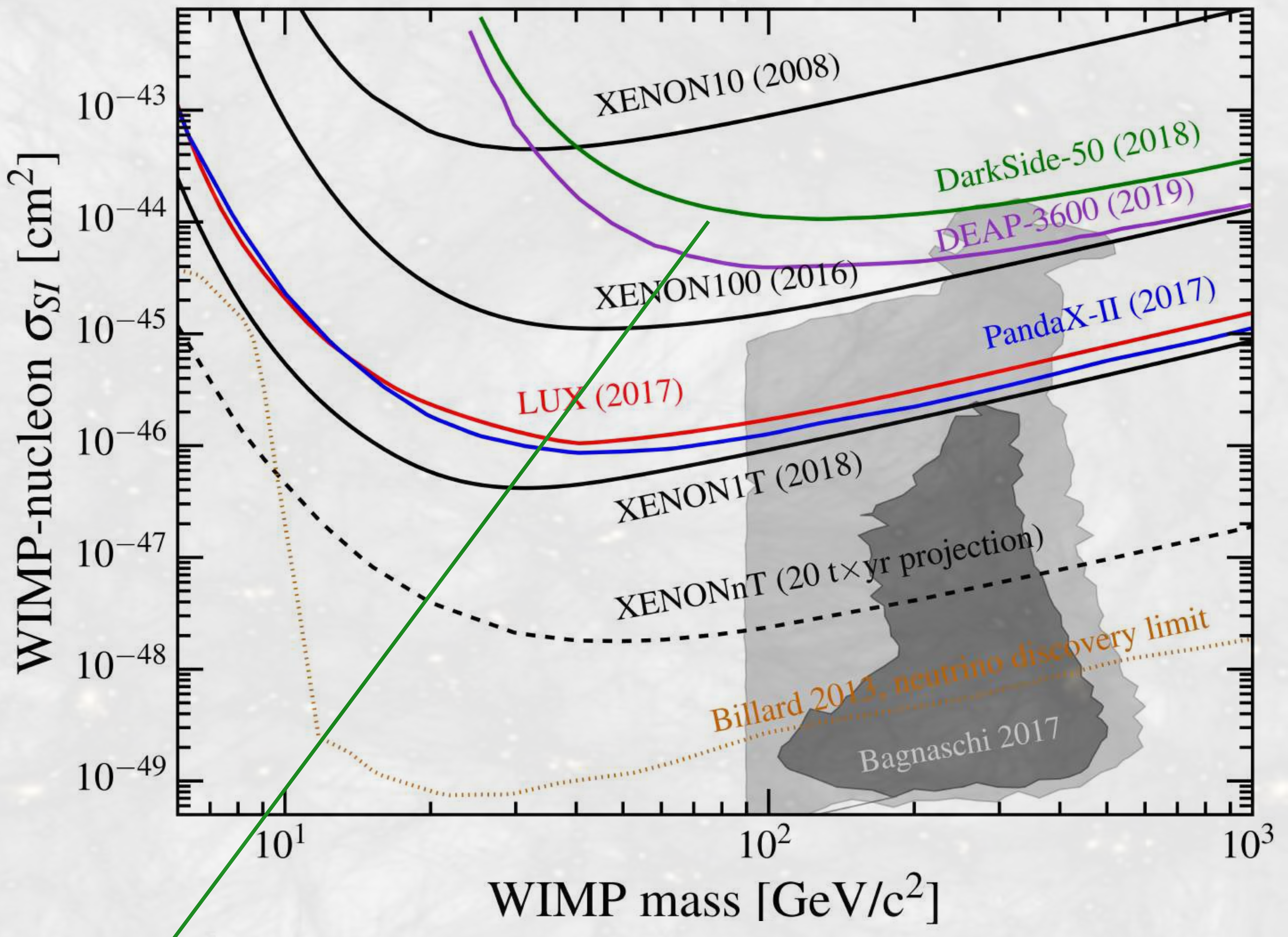
List last updated July 22, 2021:

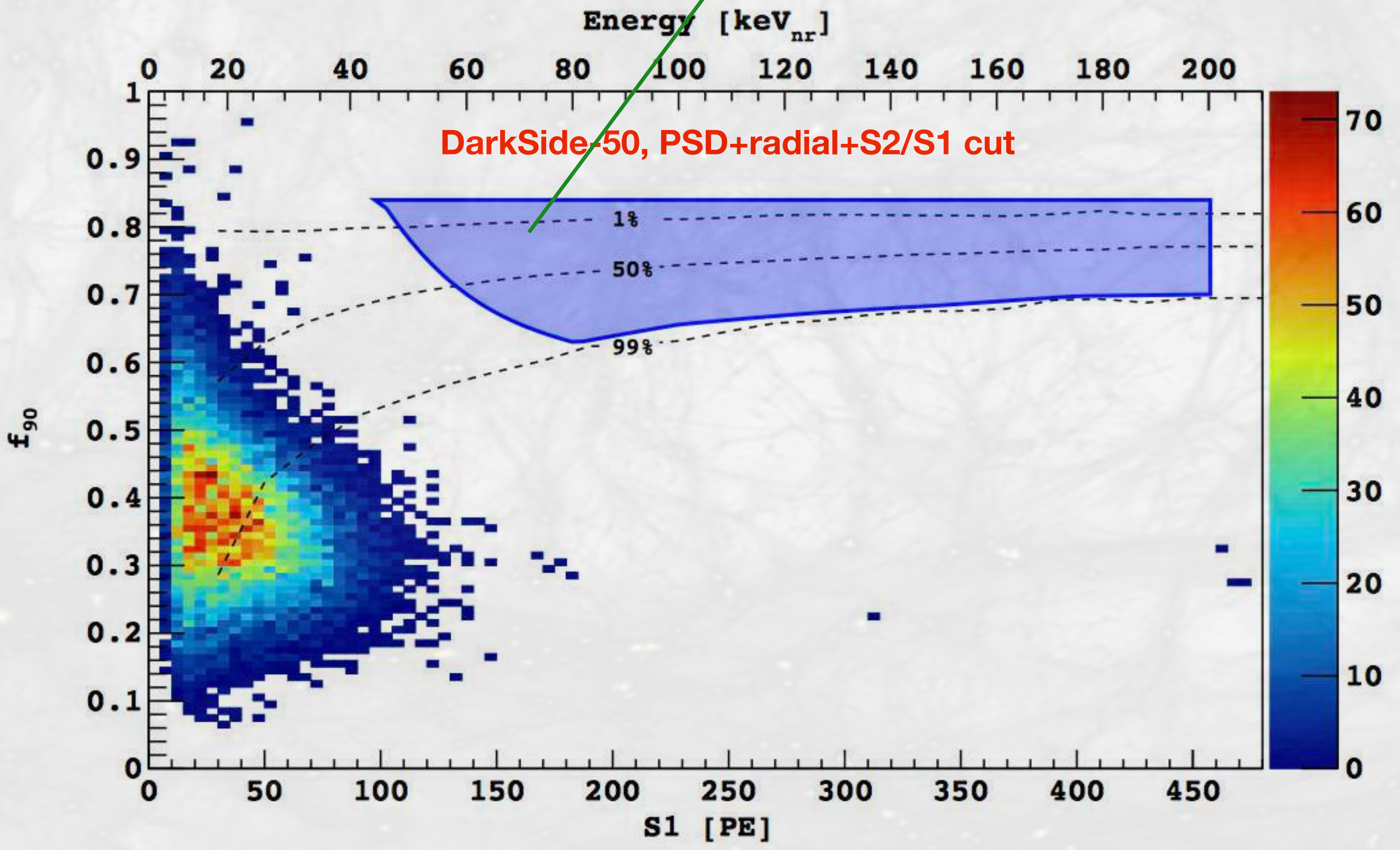
Daniel Akerib, SLAC National Accelerator Lab, United States
Elena Aprile, Columbia University, United States
Henrique Araujo, Imperial College London, United Kingdom
Francesco Arneodo, New York University Abu Dhabi, United Arab Emirates
Laura Baudis, University of Zurich, Switzerland

Liquid Argon TPCs: DarkSide-50 at Gran Sasso

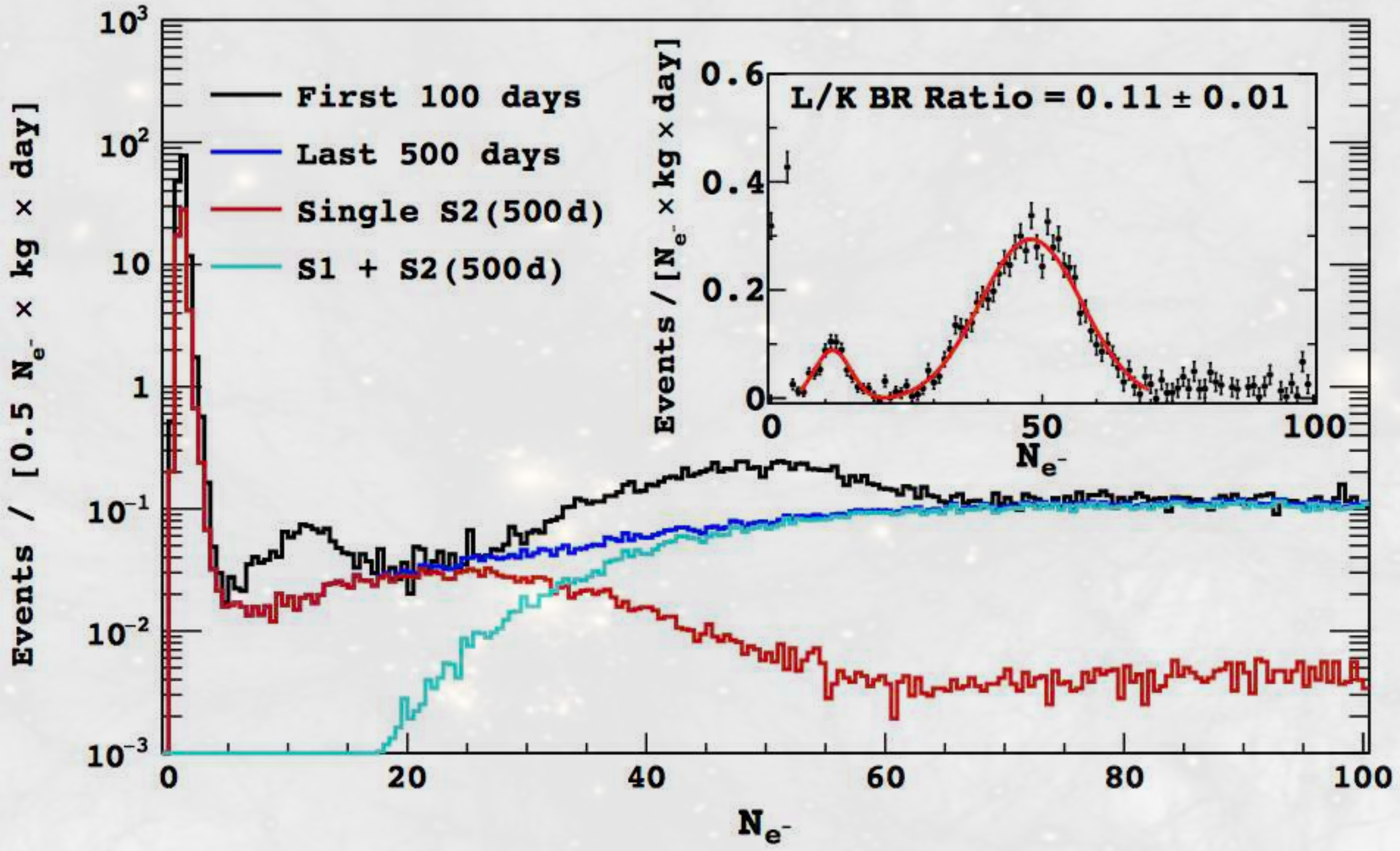


- **Target: 37 kg liquid argon (depleted in Ar39)**
- **Exposure: 532 live-days**
- **Technique: two-phase time projection chamber (TPC)**

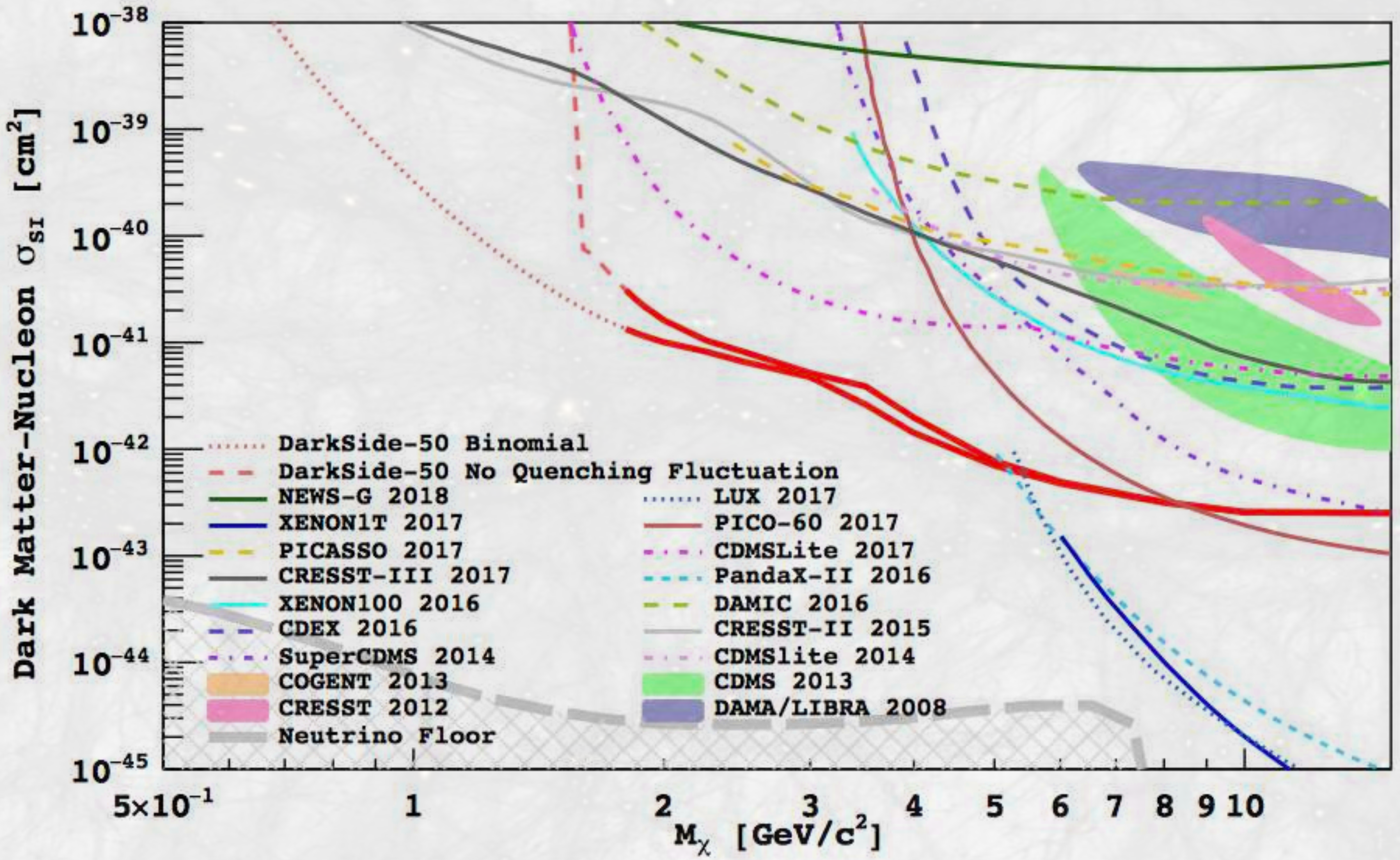




Light WIMPs Search with DarkSide 50



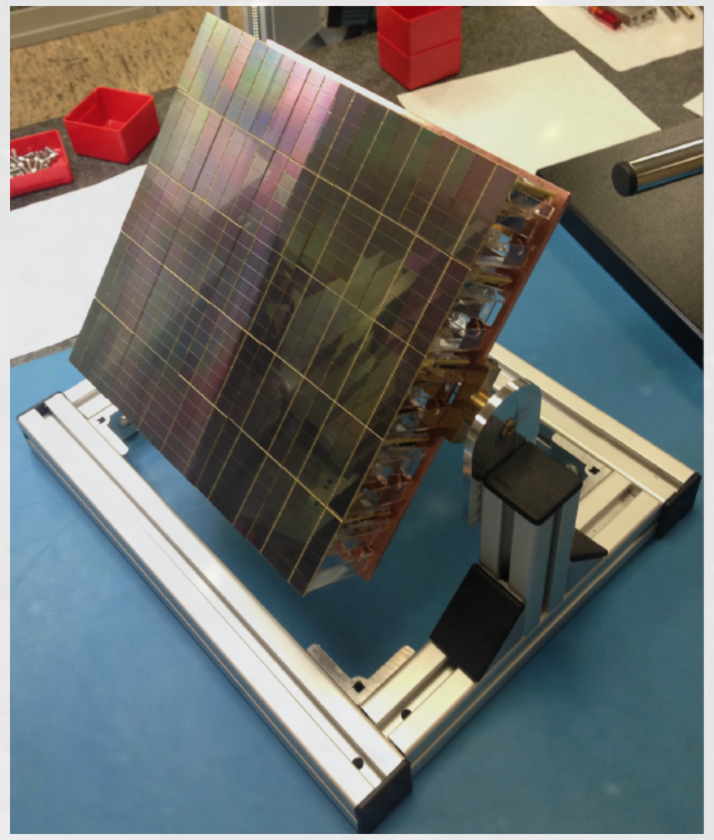
Phys. Rev. Lett. 121, 081307 (2018)

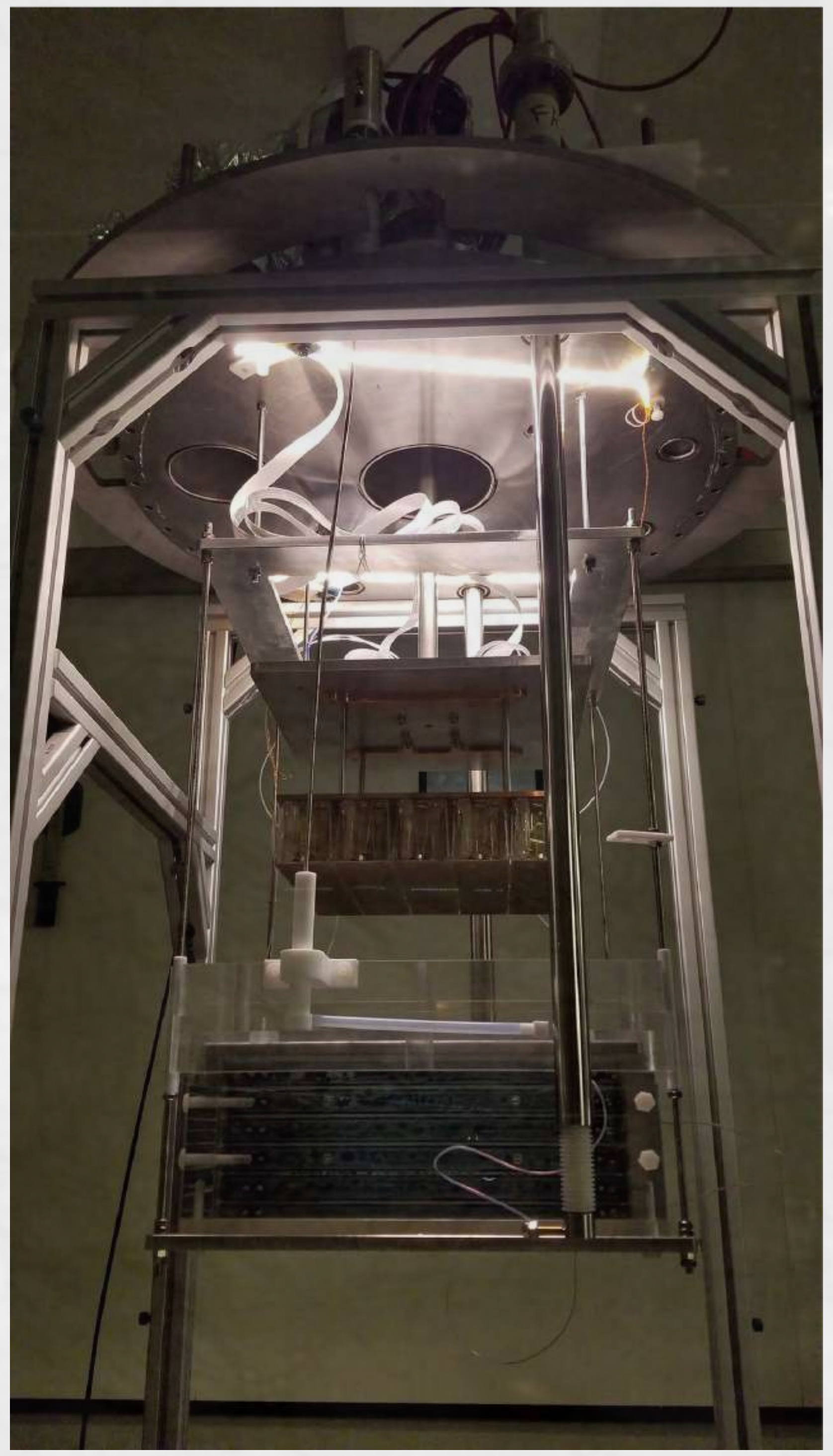


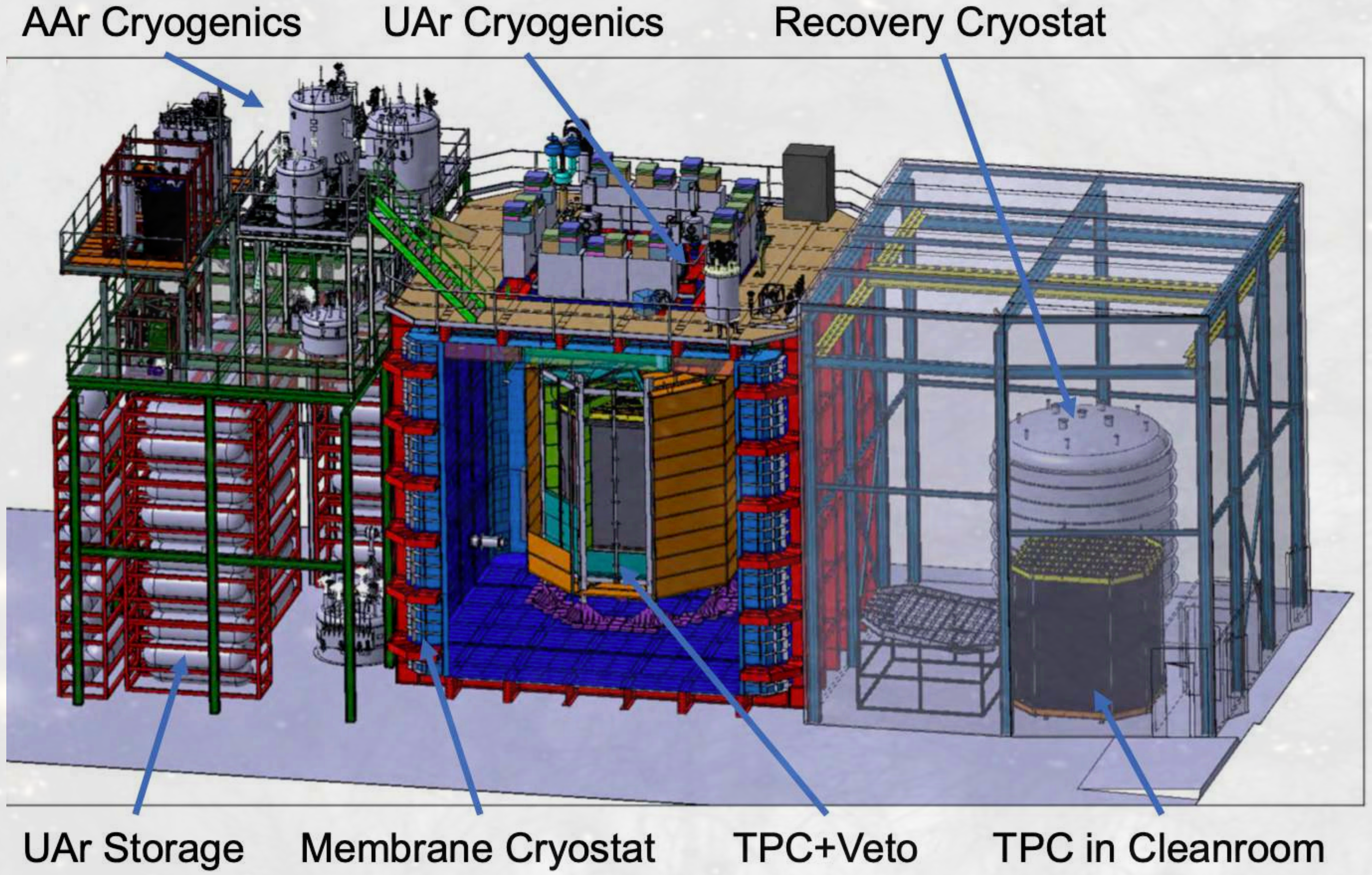
S2-only search

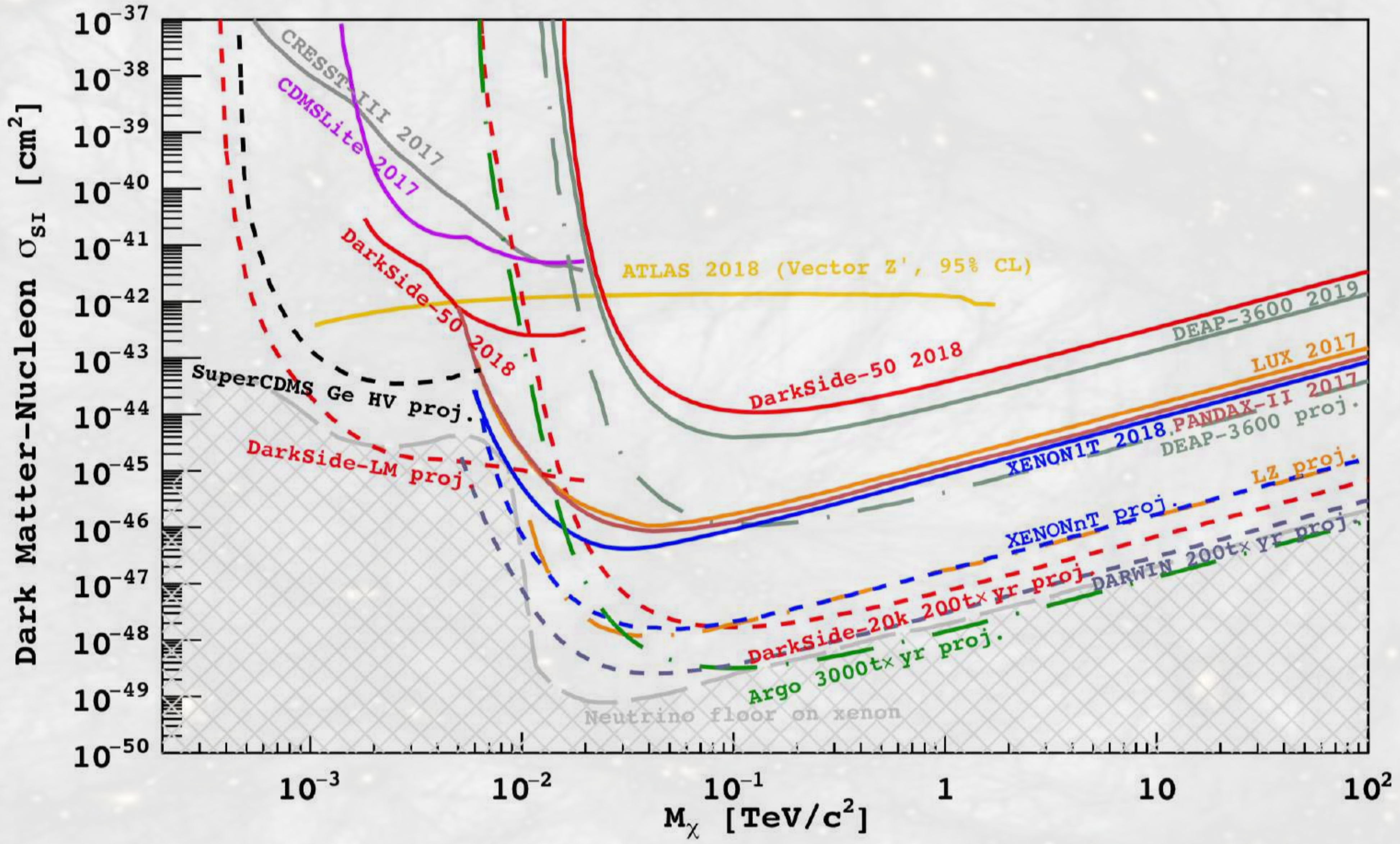
- low threshold: ~100 eV (a few electrons)
- bkg: ~1.5 event/keV/kg/d at 0.5 keVee
- spectrum consistent with known background, not limited by instrumental backgrounds yet (as in LXe TPCs)

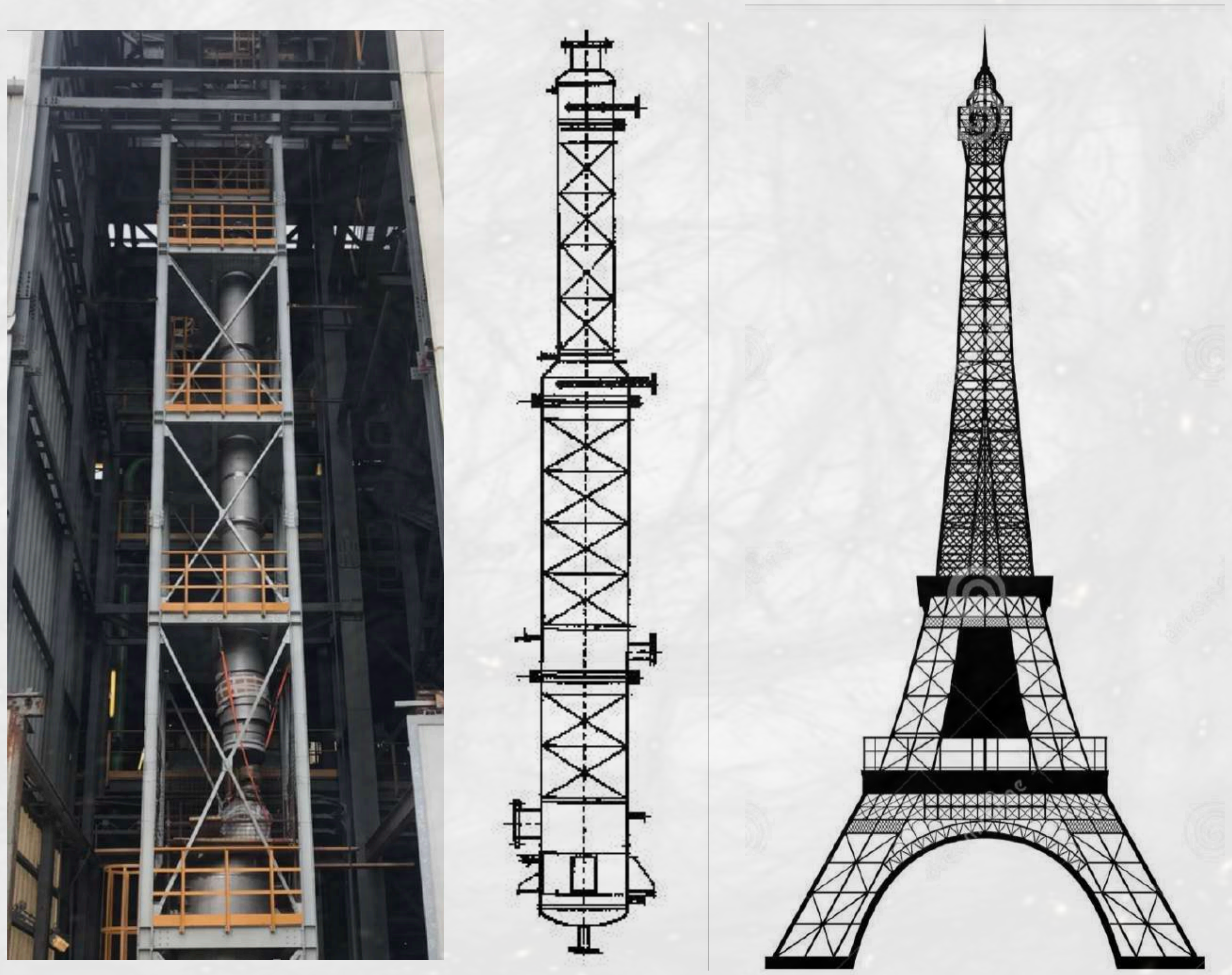
Global Argon Dark Matter Collaboration











- Officially supported by underground labs: LNGS, LSC and SNOLAB
- 50 tons total mass, 30 tons fiducial
- Underground Ar with distillation
- SiPM as photo sensors
- To start in 2025

from Y. Wang

Summary

- Huge progress in WIMPs search over past decade with noble liquid TPCs. But still no signal!
- Scalability and low-background of experiments using LXe and LAr have made them the most favorable target for heavy WIMPs.
- Over the next decade, more massive LXe (PandaX-4T / LZ / XENONnT) and LAr (DarkSide-20K) TPCs, promise another order of magnitude in sensitivity.
- A Dark Matter signal will be a major discovery! LXe and LAr TPCs cross validate each other.
- Or, we will still learn what Dark Matter is not.