Dark Matter Direct Detection: Results and Outlook

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Invisible18 Workshop,
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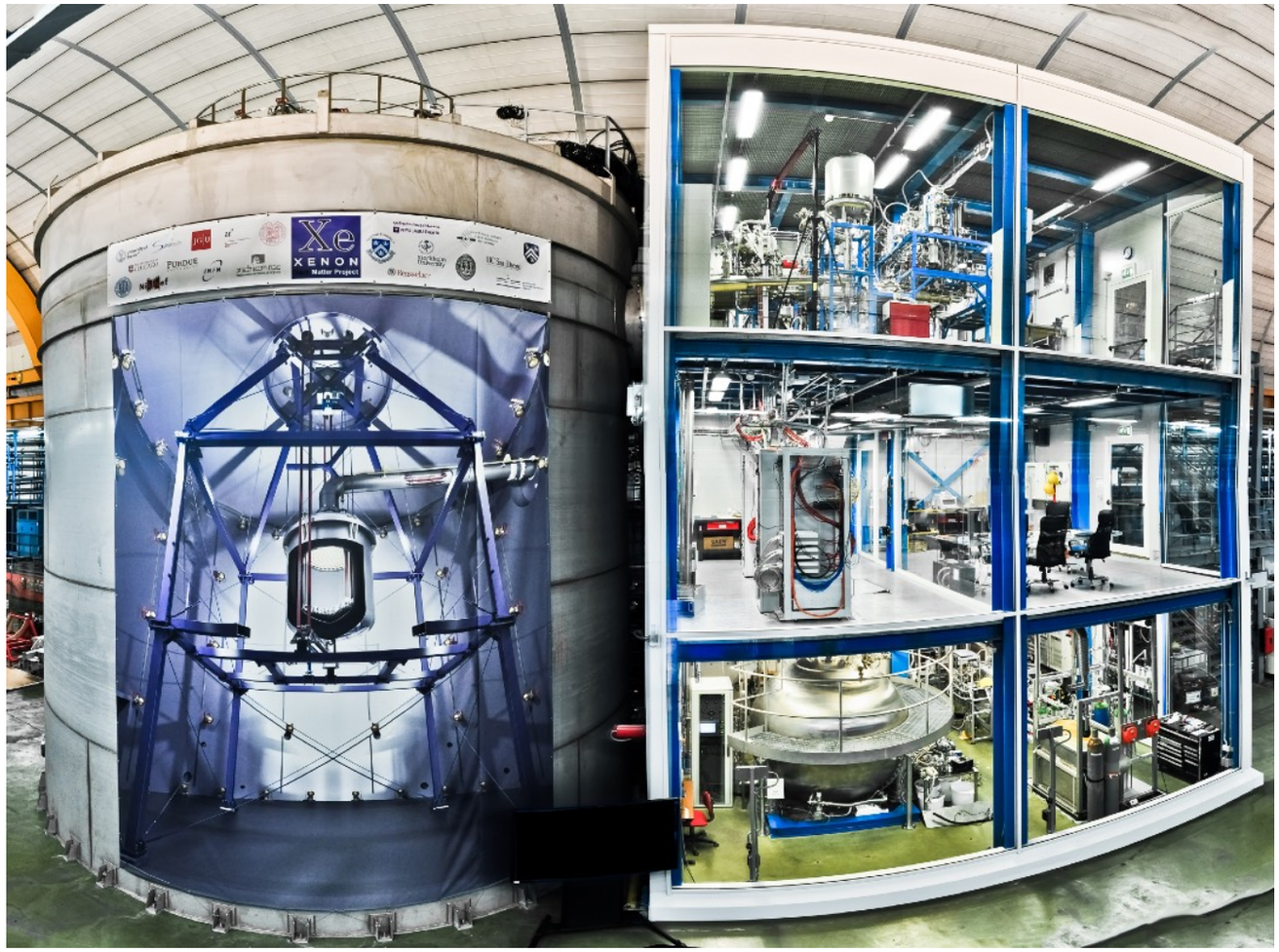
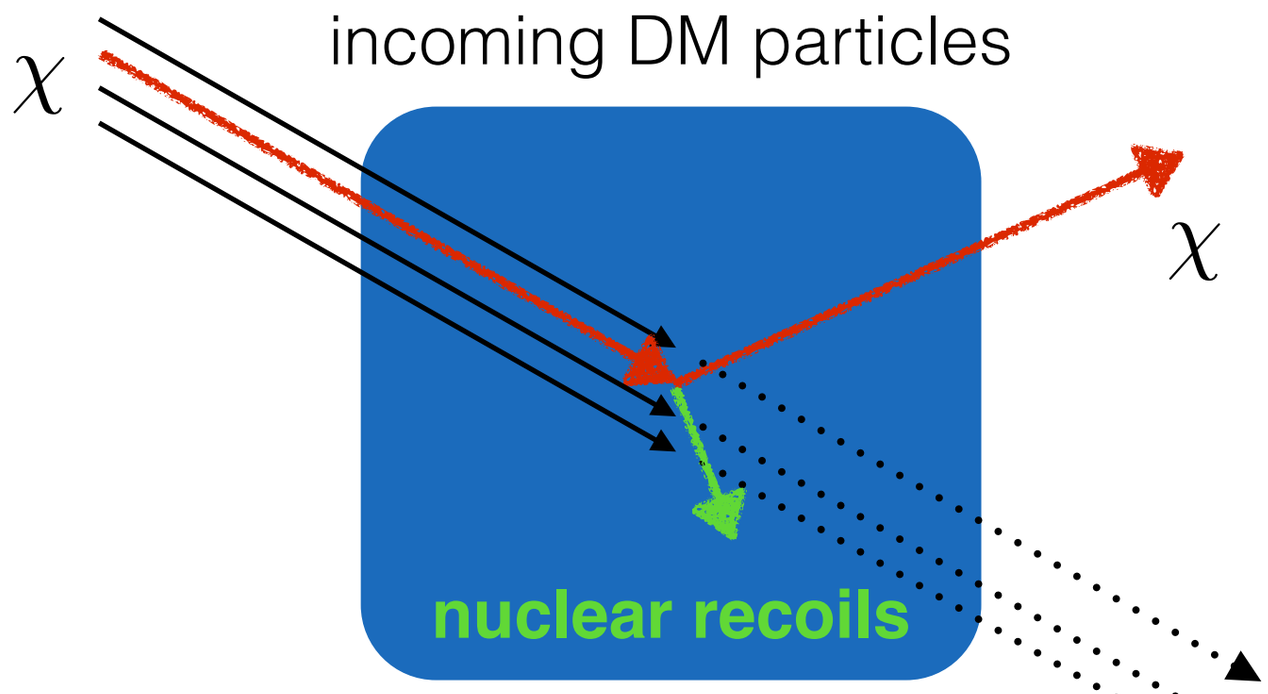
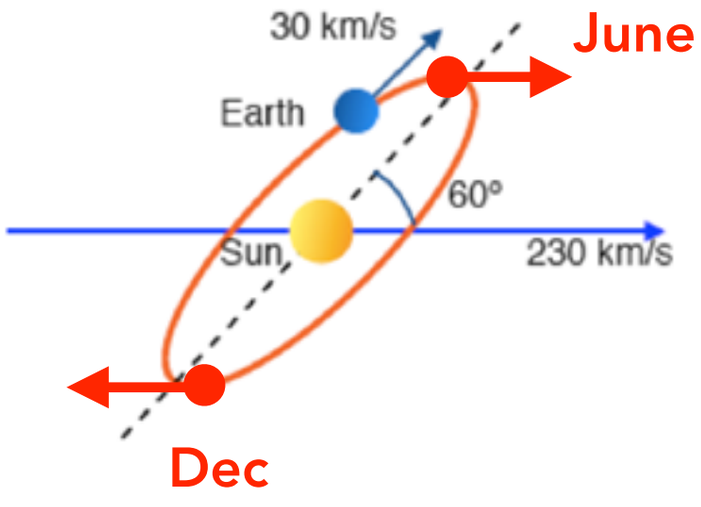


Standard Assumptions for Dark Matter Direct Detection

- **DM mass range: GeV~TeV**
- **local WIMP density: 0.3 GeV/cm^3**
- **Isothermal velocity distribution: v_0~220 km/s**
- **WIMP escape velocity ~544 km/s**



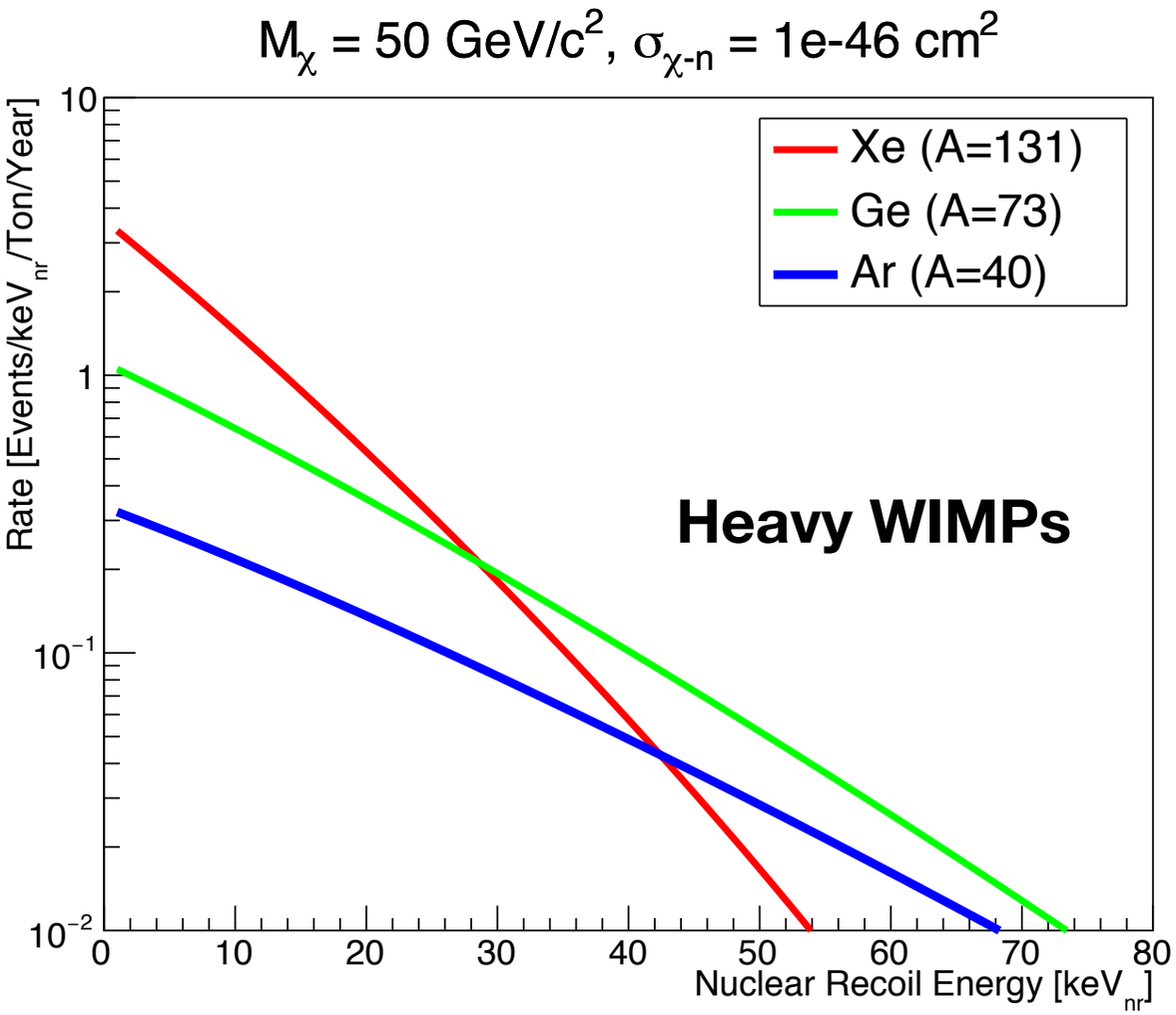
- **Standard channels: SI and SD**

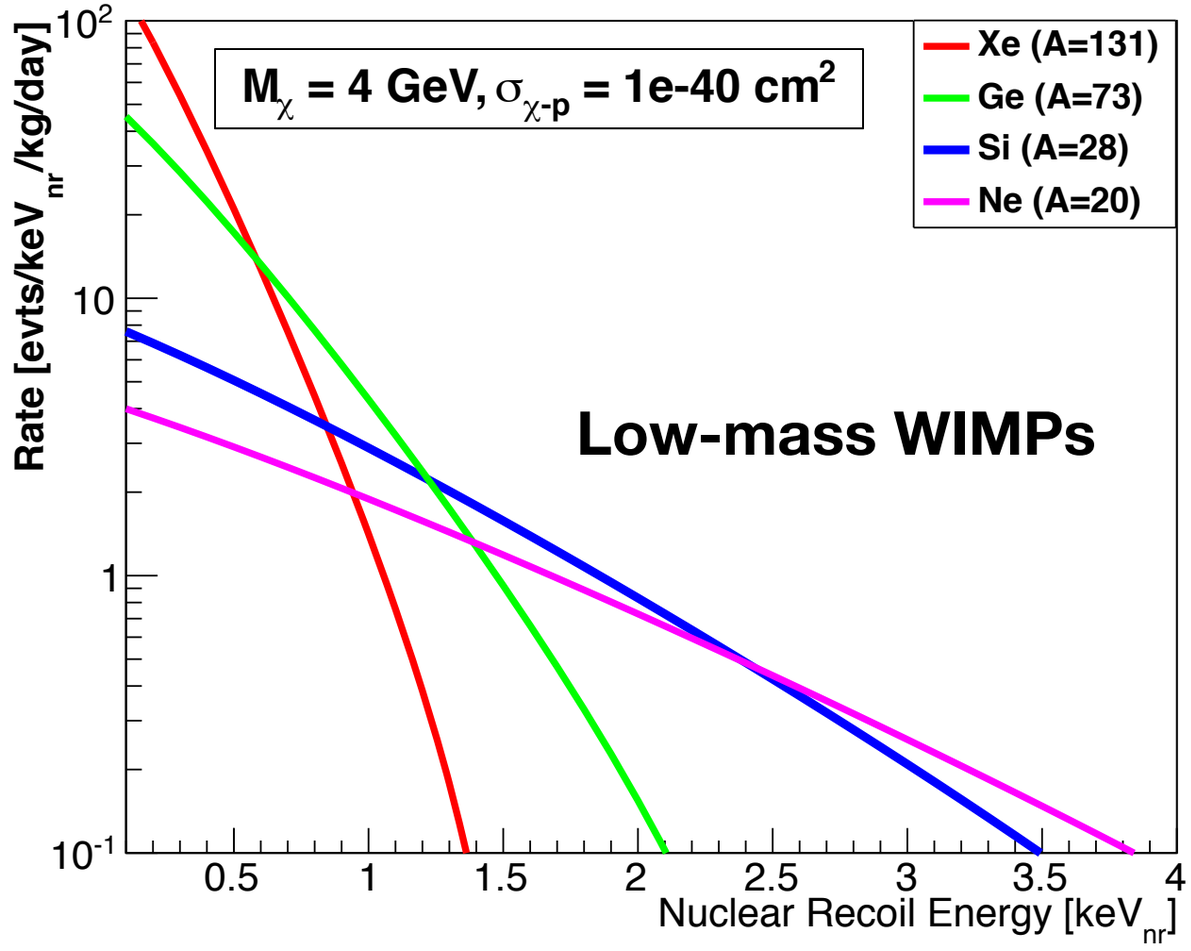


$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} \frac{d\sigma_{\chi N}}{dE_R}(v, E_R) v f(v) dv$$

$$\frac{d\sigma_{\chi N}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2}(\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R))$$

Experimental signature: Falling Nuclear Recoil Energy Spectrum





Requirements for WIMPs detectors

Low energy threshold -> Low-mass WIMPs

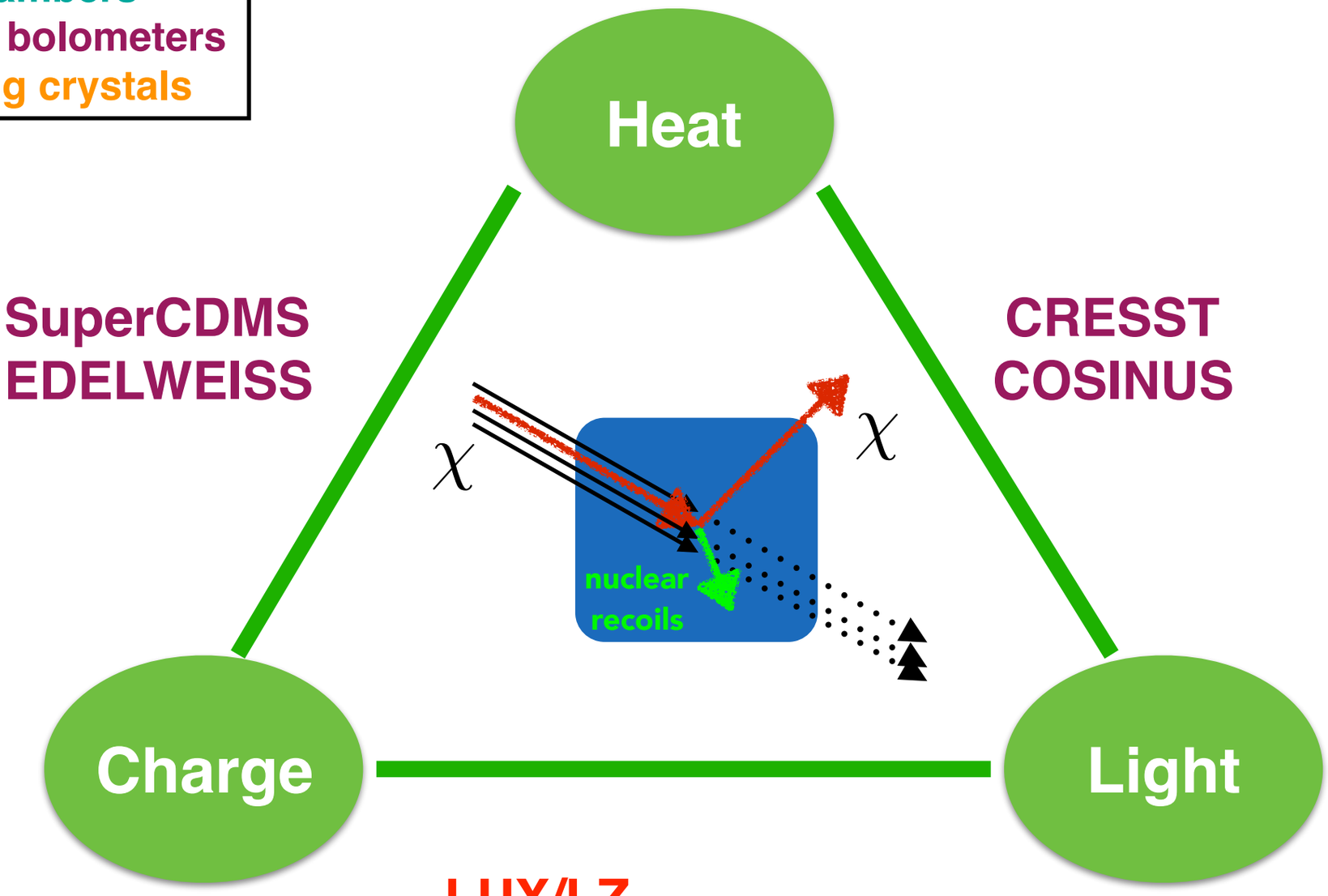
Large target mass

Ultra-low background

Direct Detection Techniques

- Liquid argon
- Liquid xenon
- Directional detectors
- Low-threshold
- Bubble chambers
- Cryogenic bolometers
- Scintillating crystals

SIMPLE
PICASSO
COUPP
PICO



CoGeNT
CDEX
DAMIC
SENSEI
NEWS-G
DRIFT
MIMAC
DMTPC

LUX/LZ
PandaX
XENON

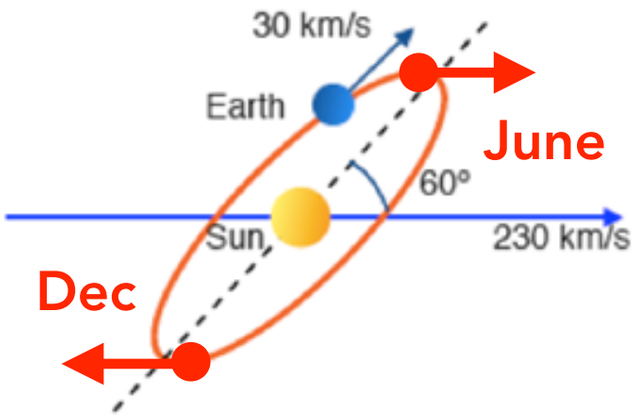
ArDM
DarkSide

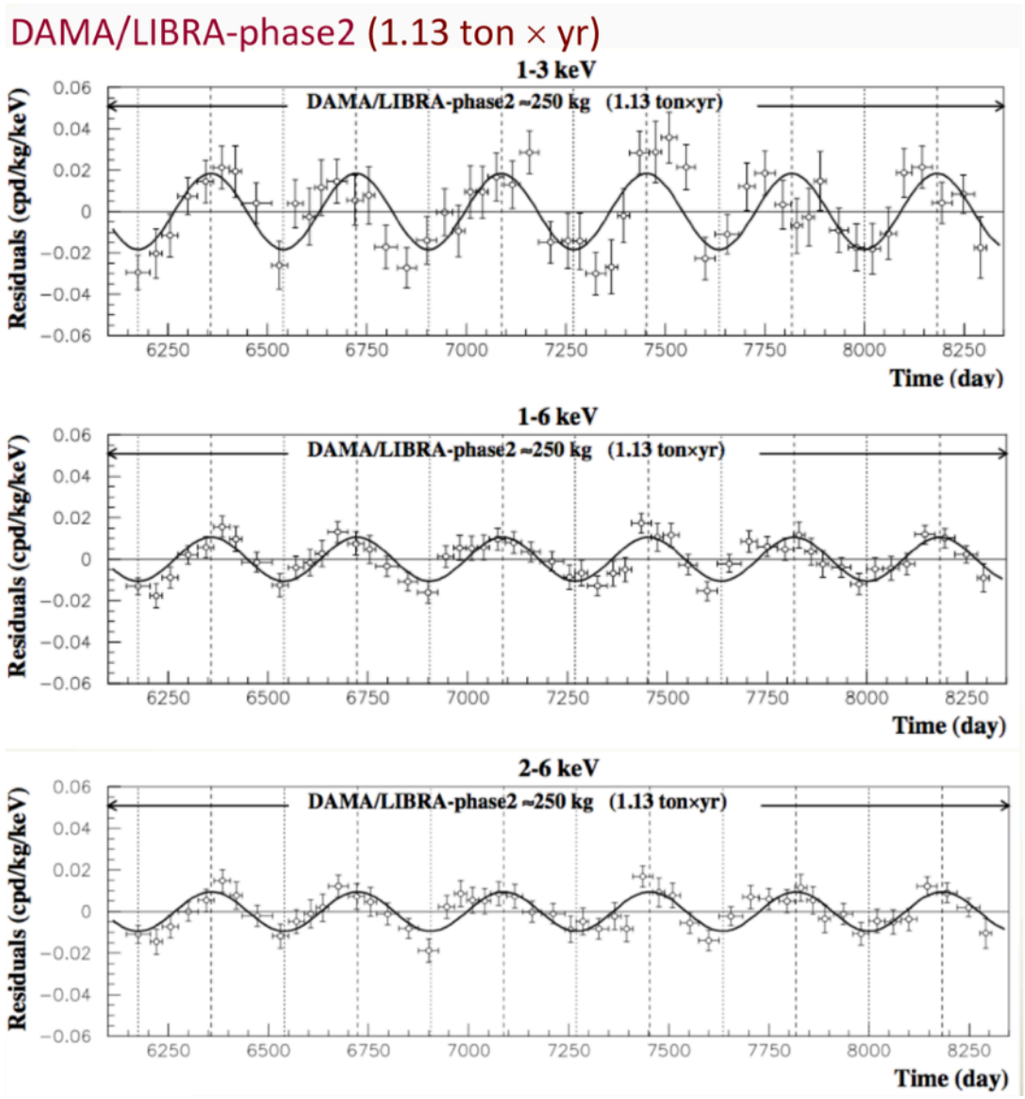
DAMA
DM-Ice
COSINE
SABRE
ANAIS
PICO-LON
DEAP
XMASS

Various Type of WIMPs Searches

- Annual Modulation Searches
- Spin-dependent Searches -> **not** covered
- Ultra-light (<1 GeV) WIMPs searches (covered by **Kathryn Zurek's** opening talk on Monday)
- Low Mass (<10 GeV) WIMPs searches
- Heavy (>10 GeV) WIMPs searches

DAMA: so far the Only Experiment detected "Dark Matter" with >>5 sigma C.L.



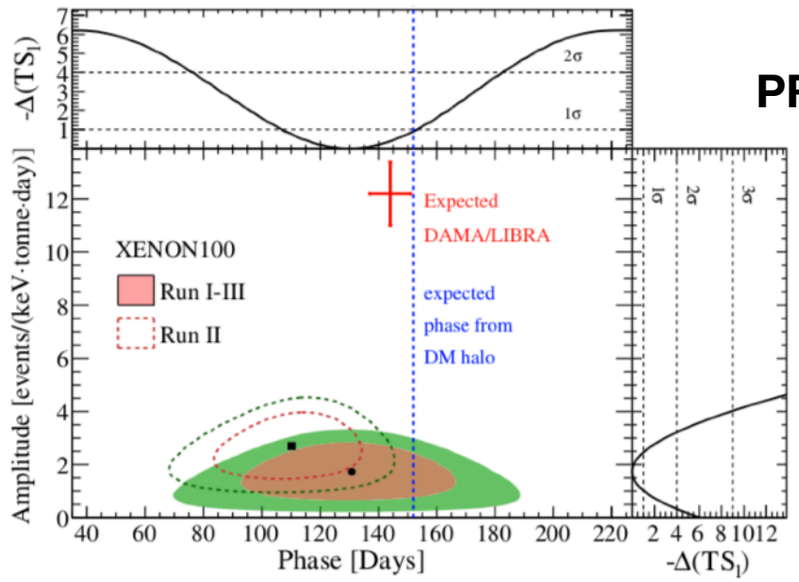


from R. Bernabei talk, Mar. 26, 2018, LNGS

arXiv:1805.10486

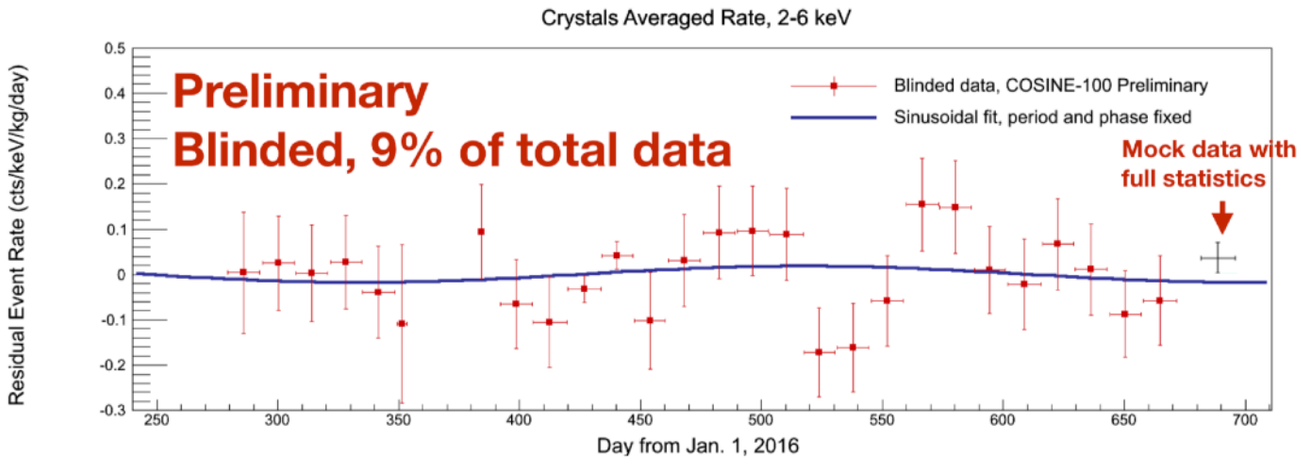
- Not compatible with experiments with other targets

XENON100 4-year ER modulation study, PRL 118, 101101 (2017)

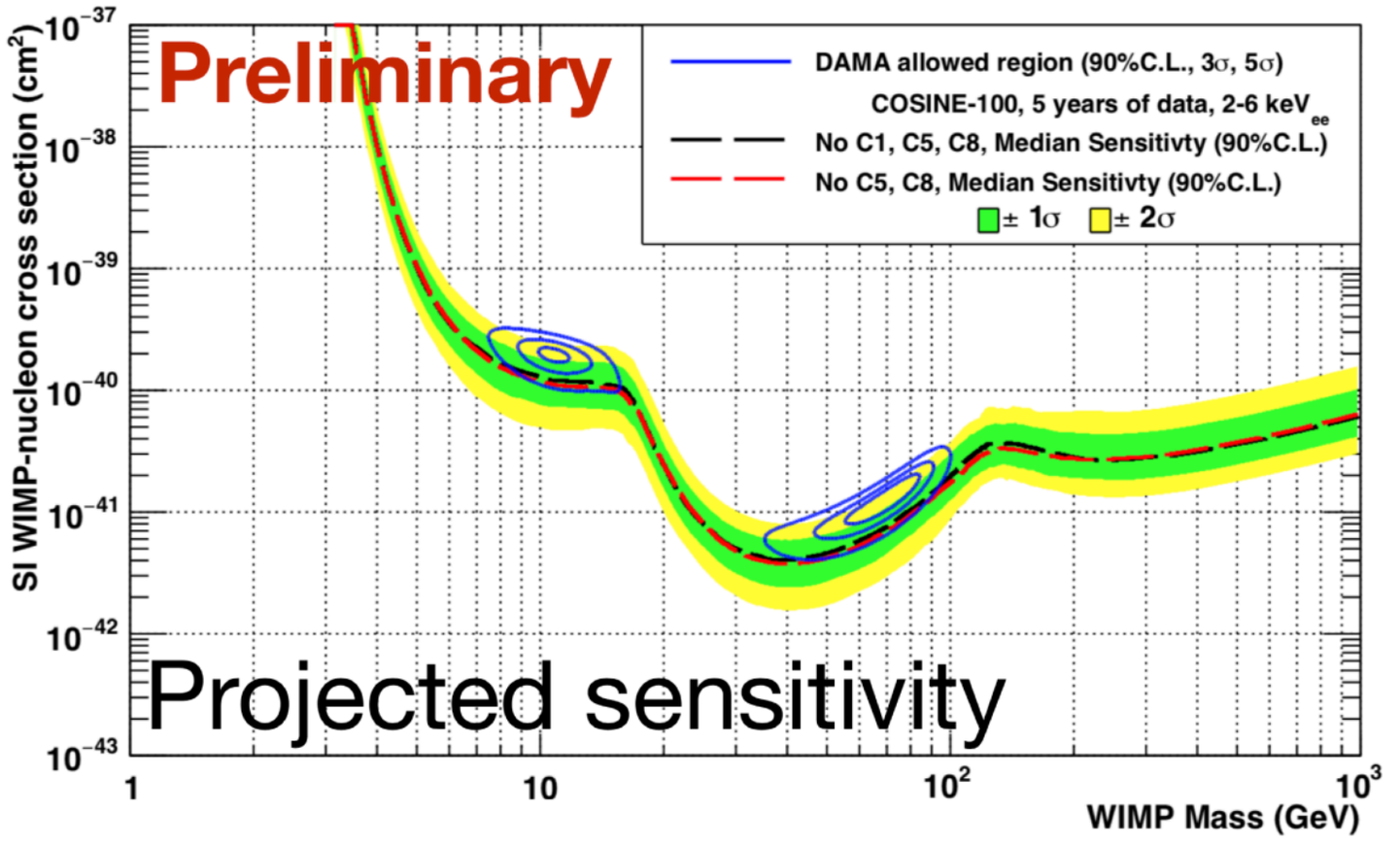


- Similar exclusion from LUX analysis (arXiv:1807.07113)
- need other NaI experiments:
  - COSINE/ANAIS/SABRE/PICO-LON
  - COSINUS

COSINE-100 Experiment to test DAMA/LIBRA Modulation

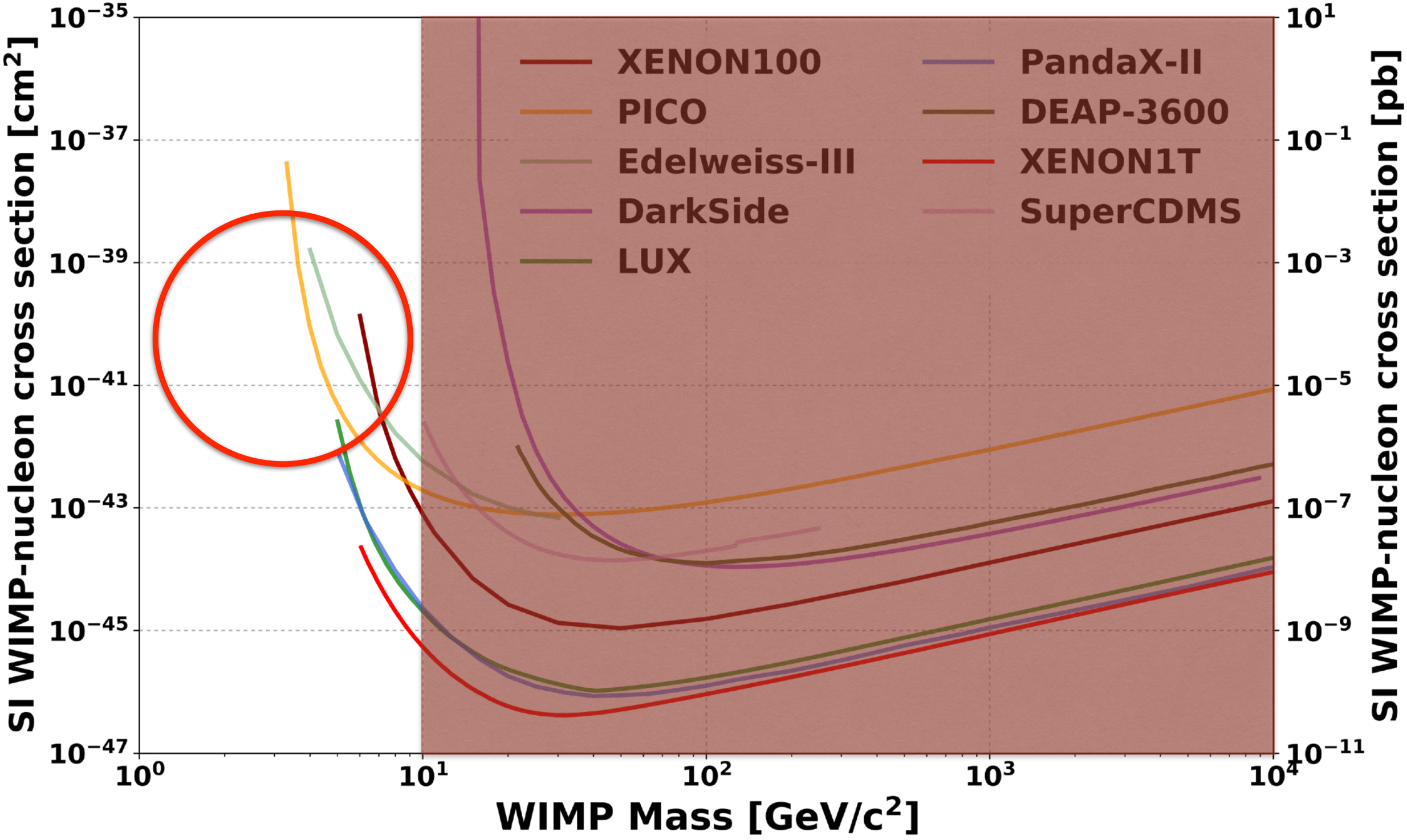


- KIMS+DM-Ice collaborations using NaI crystal, running at Yangyang in Korea
- Data taking since Sep 2016
- Spectrum analysis to validate whether DAMA/Libra is consistent with WIMPs/ SHM
- Modulation search ongoing with a blind analysis

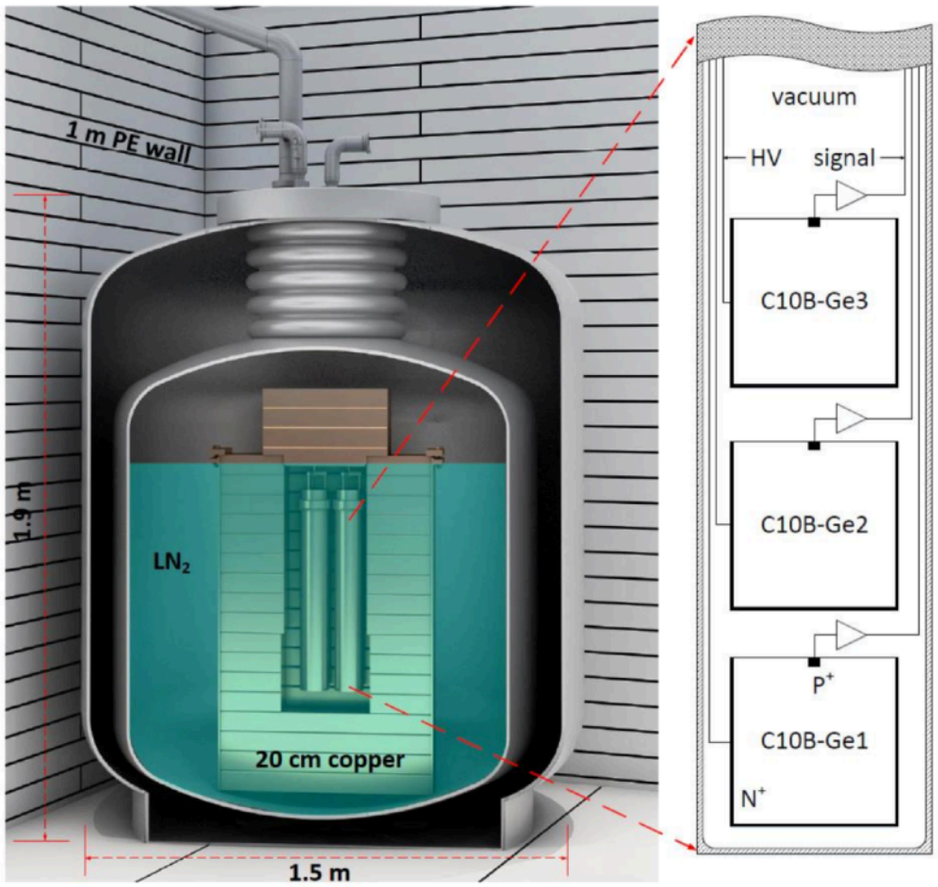


from IDM2018

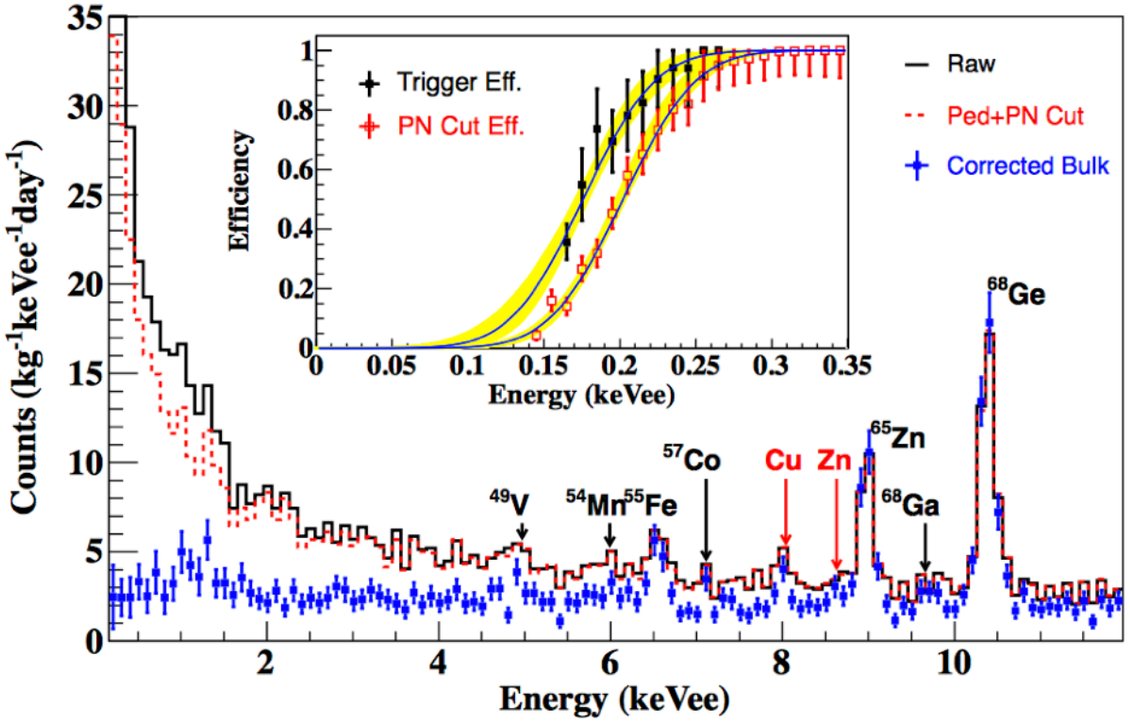
Low Mass WIMPs Searches

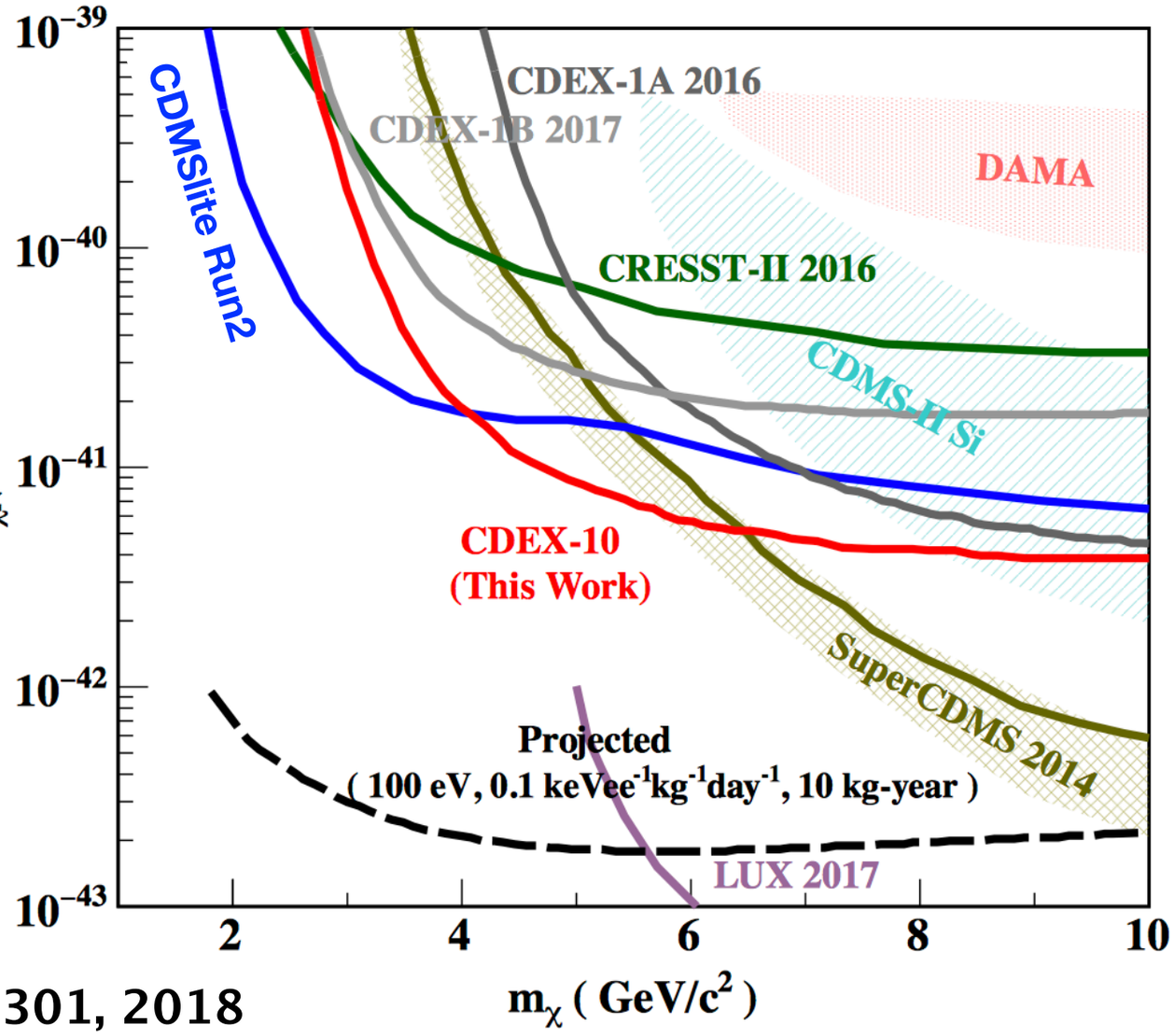


CDEX at CJPL



- 10kg Ge detector in liquid nitrogen
- 102.8 kg-days exposure
- analysis threshold: 160 eVee
- residual bkg rate: ~2.5 evt/keVee/kg/day
- improved limits at 5 GeV/c²

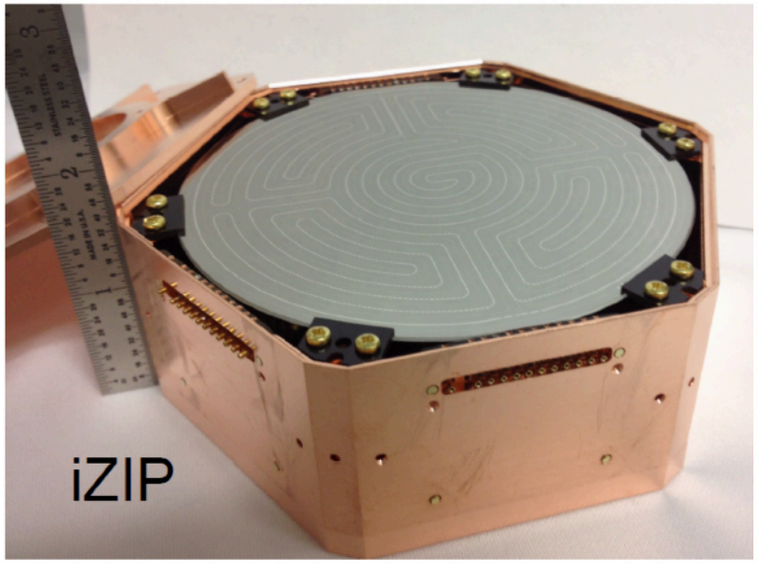


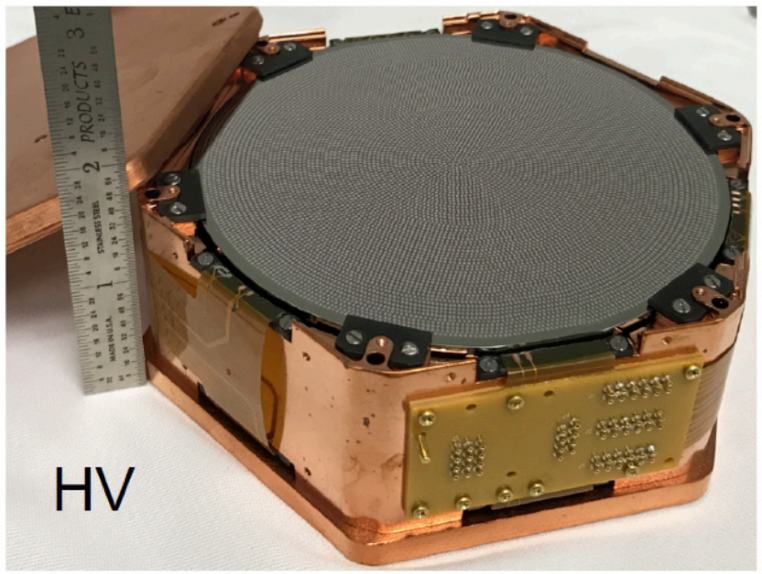


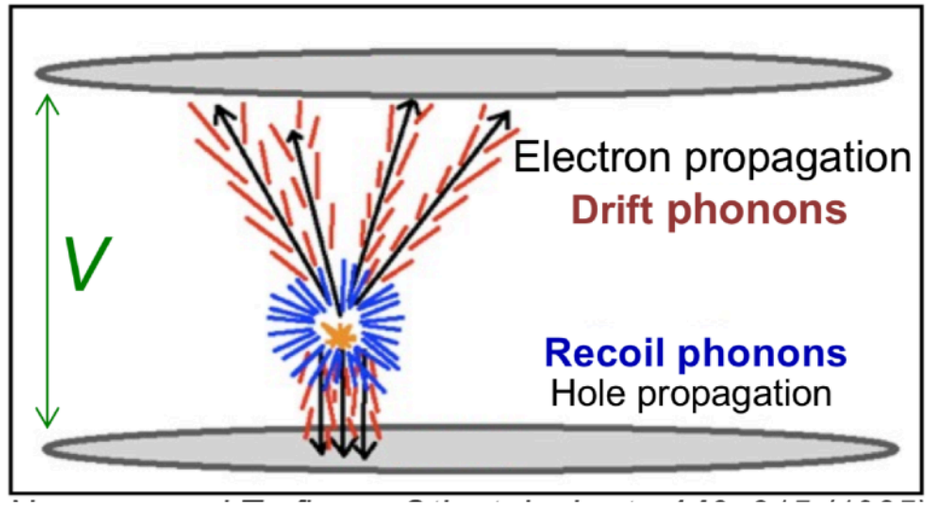
PRL 120, 241301, 2018

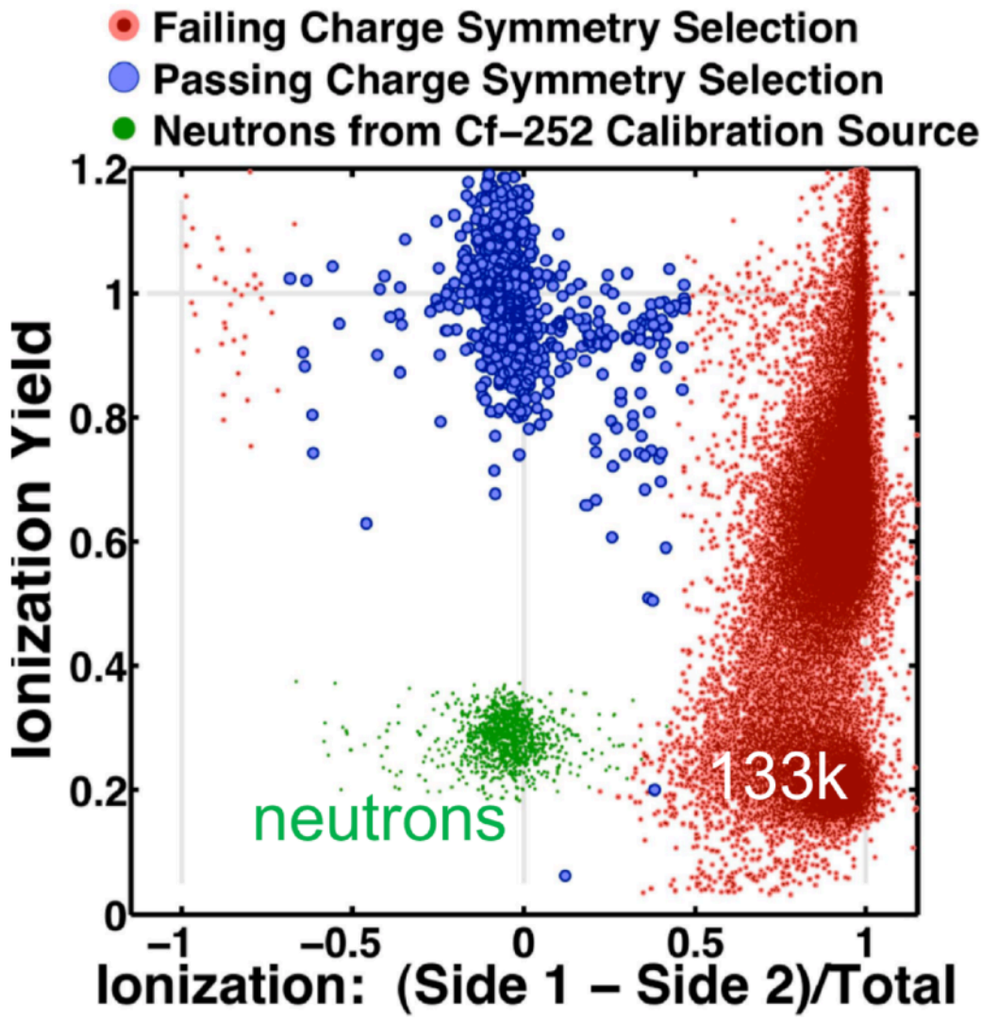
from IDM2018

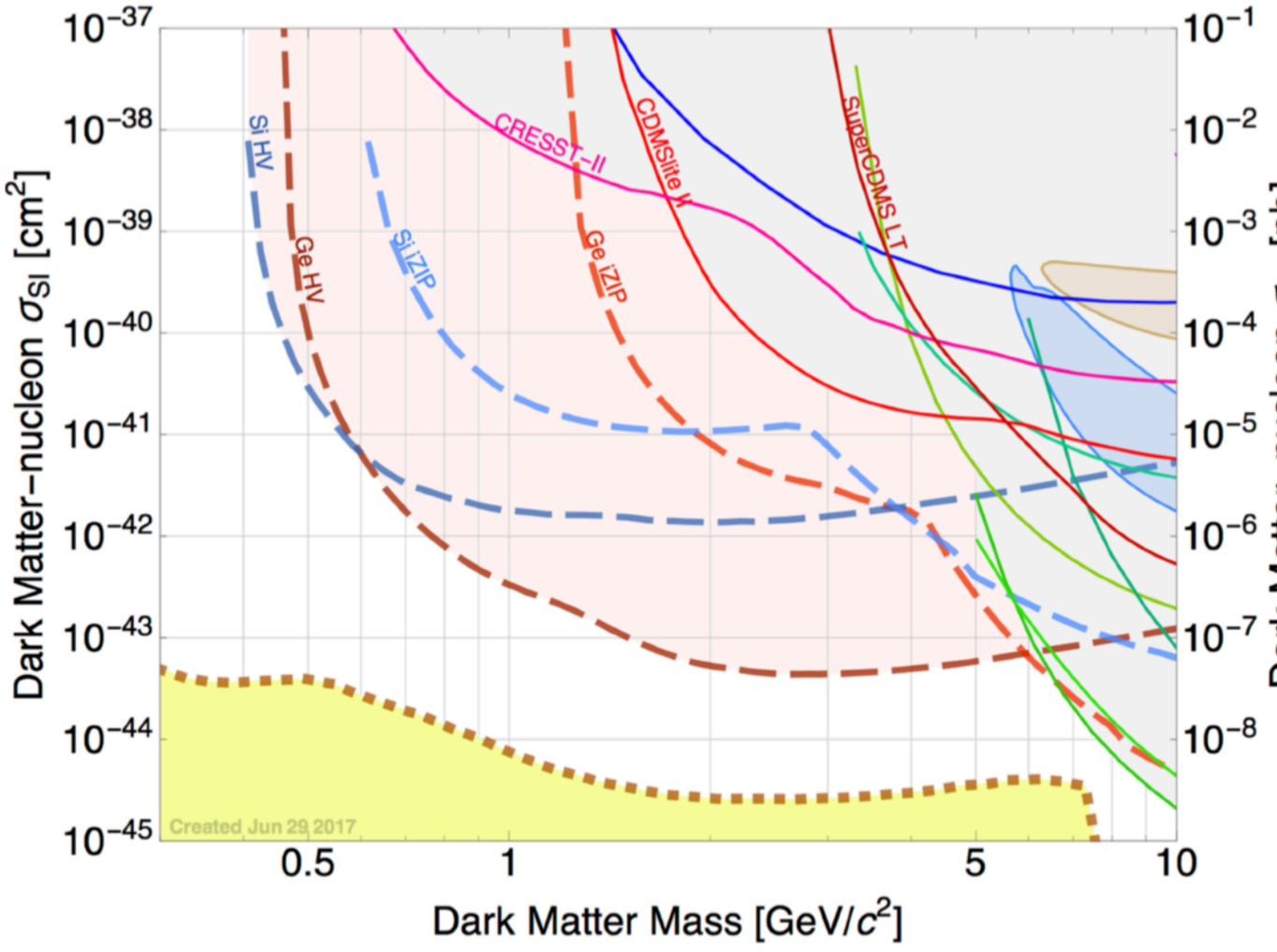
SuperCDMS at Soudan/SNOLAB





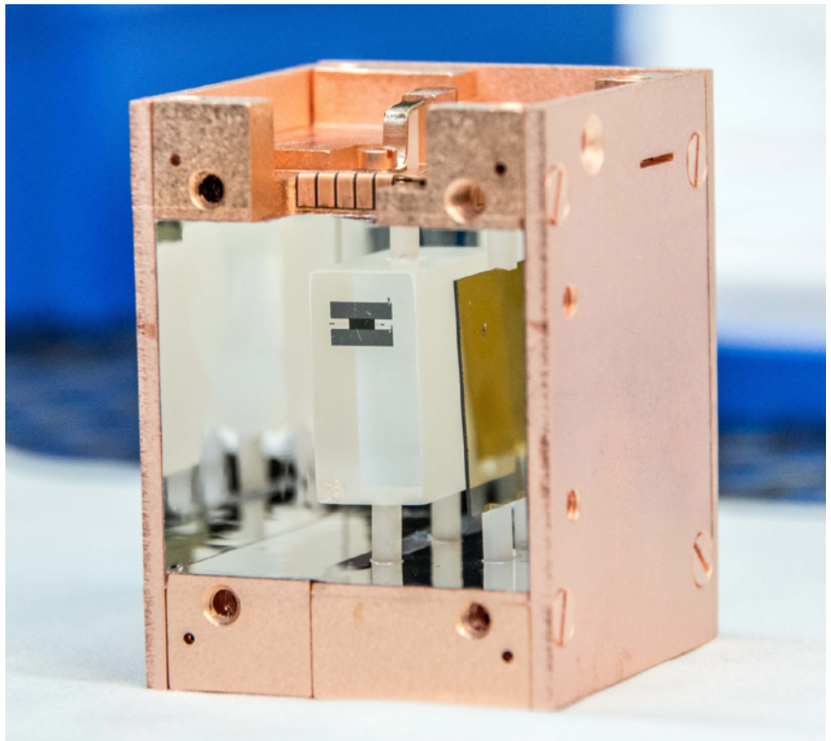




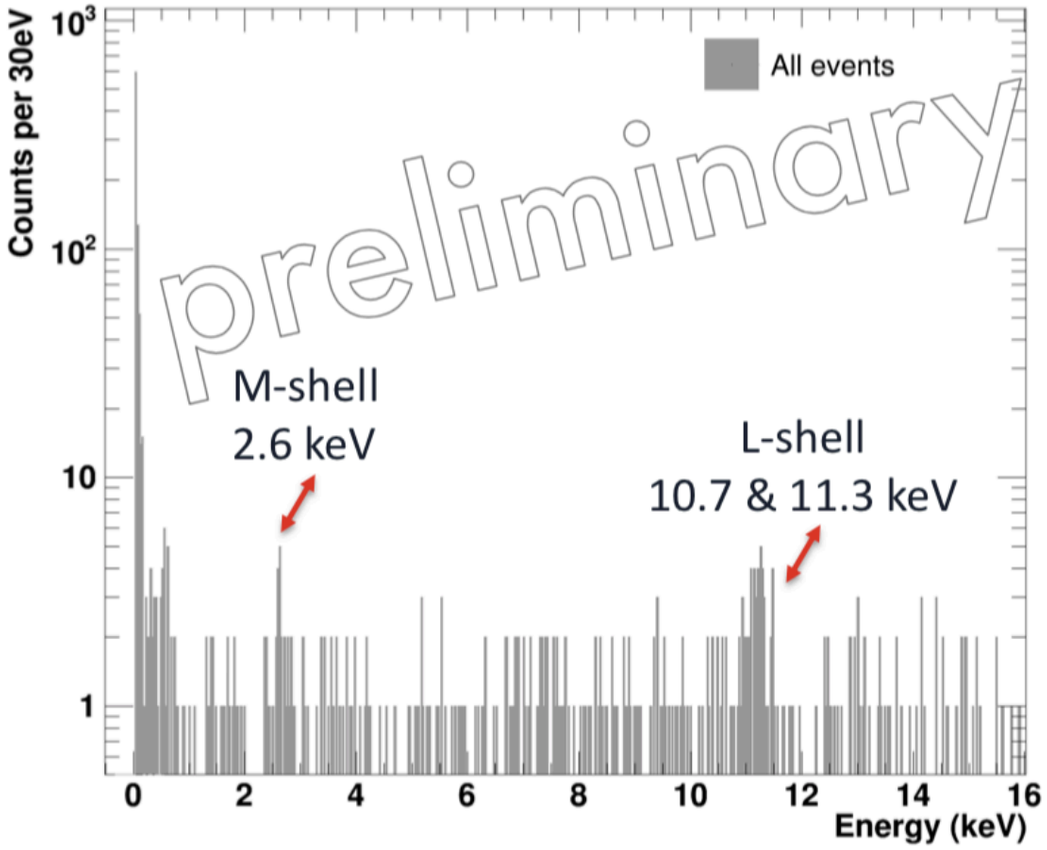


from IDM2018

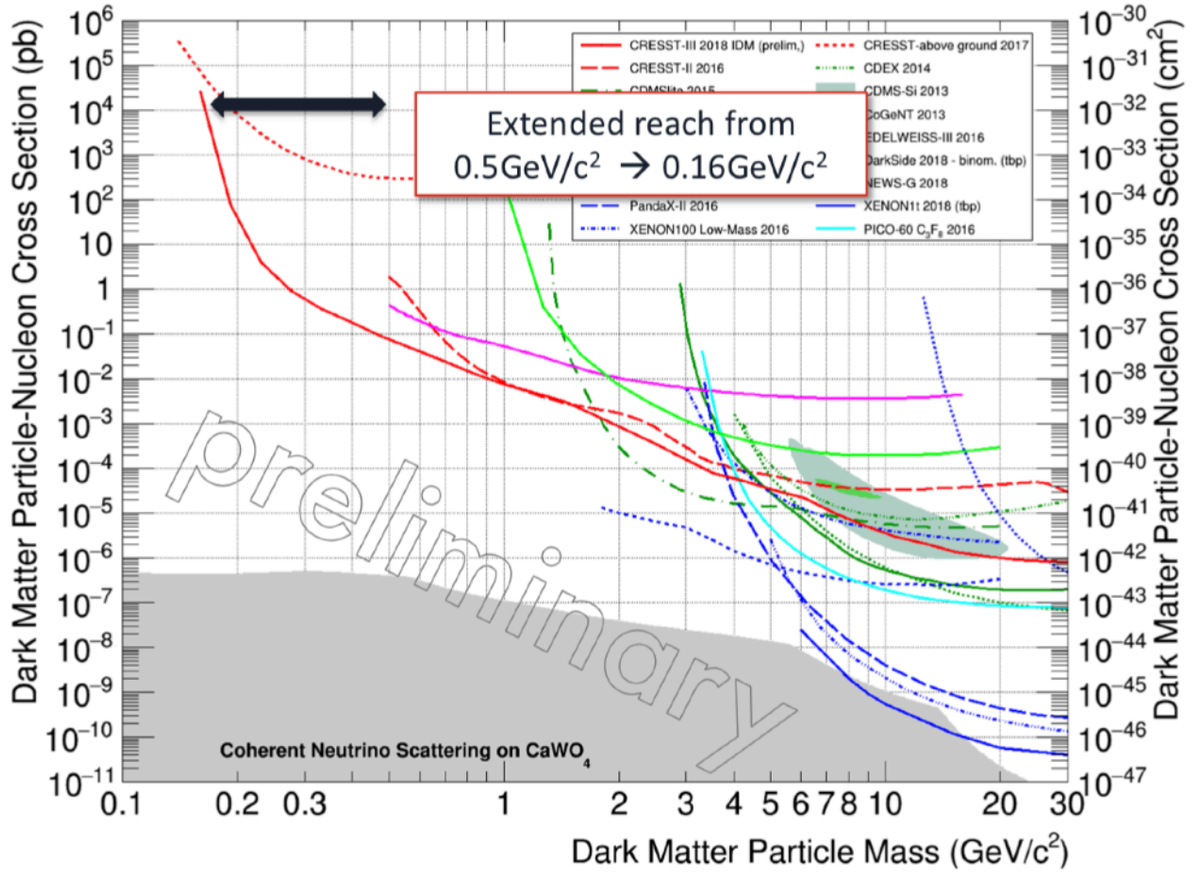
CRESST-III at Gran Sasso



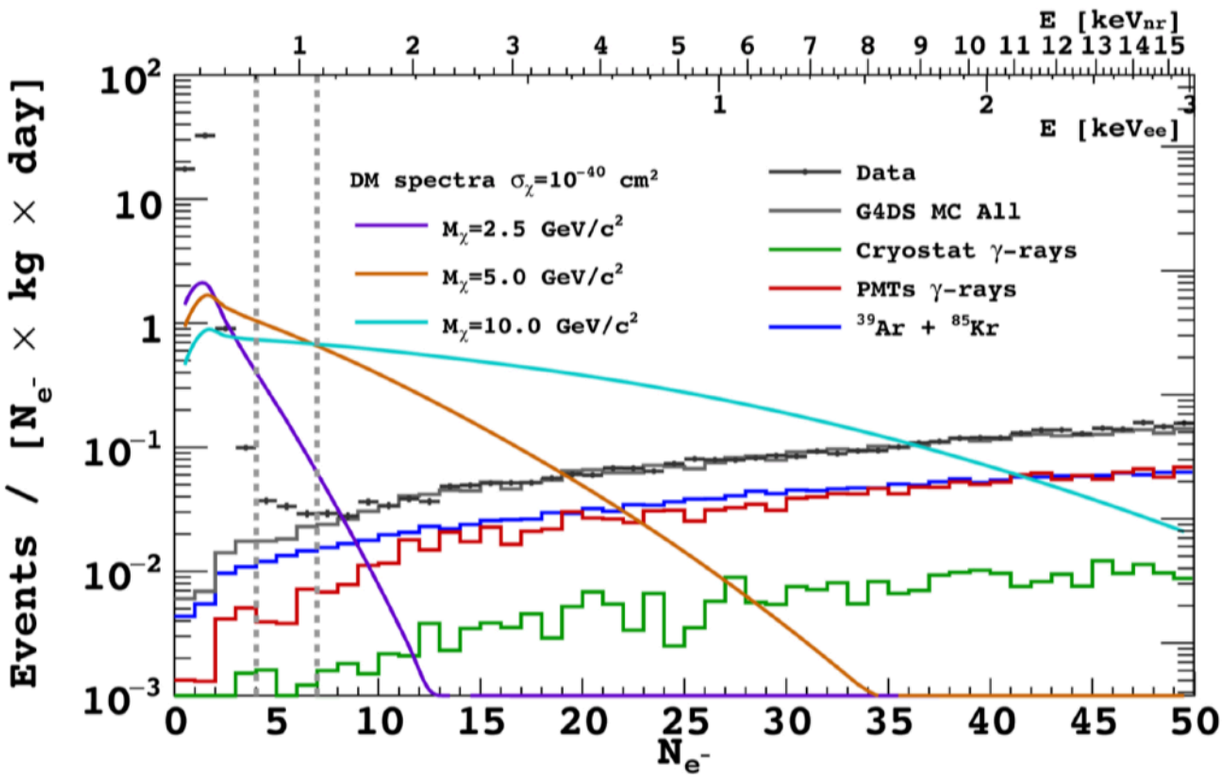
- 23.6g of CaWO4 detector
- First Run 07/2016 - 02/2018, resulting in an exposure of 5.7 kg-days
- nuclear recoil energy threshold: **30.1 eV**
- Leading sensitivity over one order of magnitude: 160 MeV -> 1.8 GeV

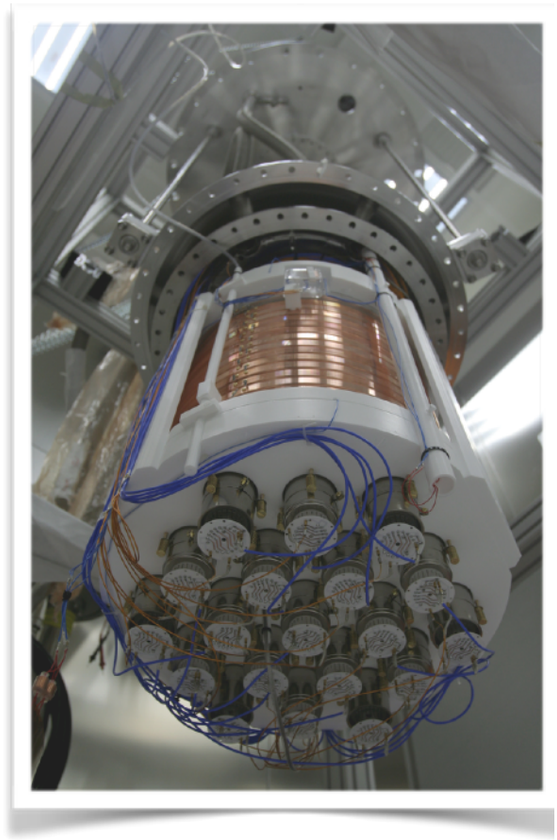


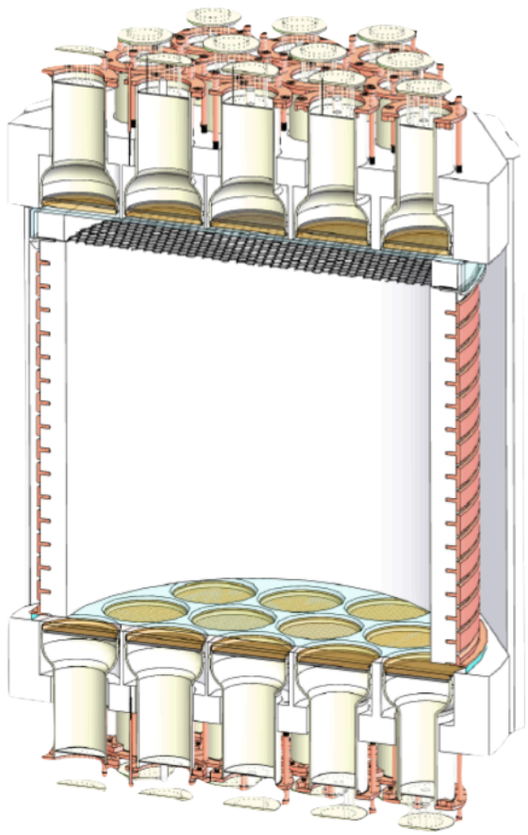
from IDM2018



Ionization Only Search with DarkSide-50

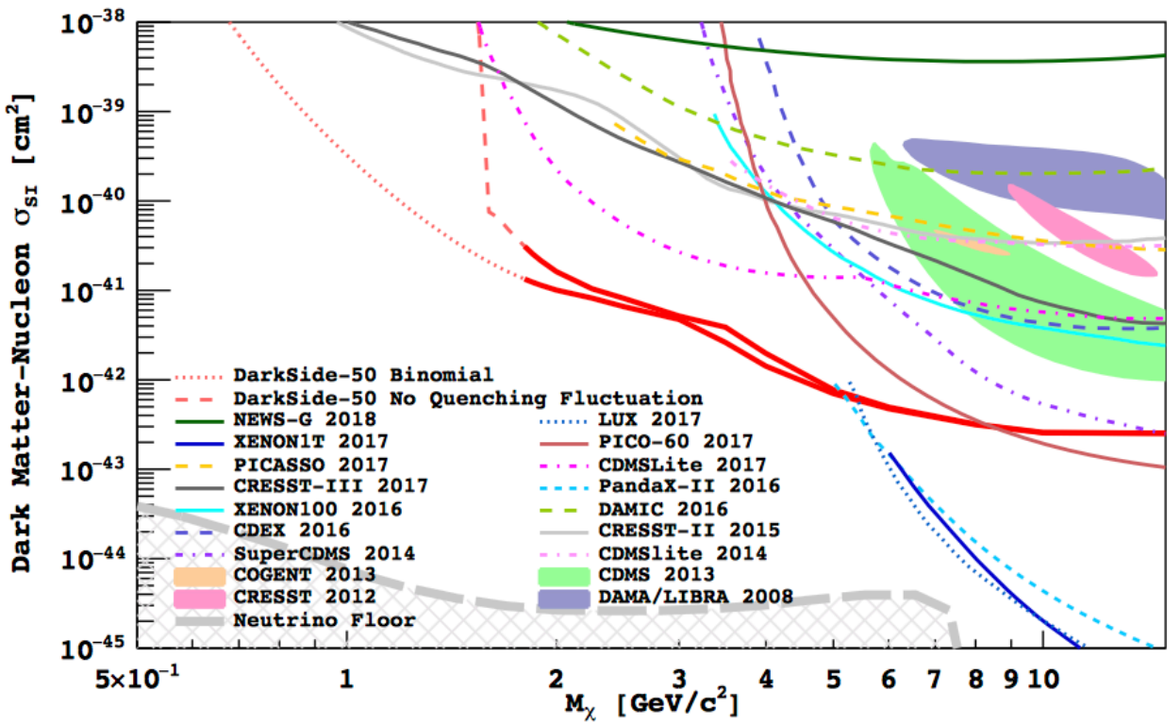






DarkSide-50 S2-only search

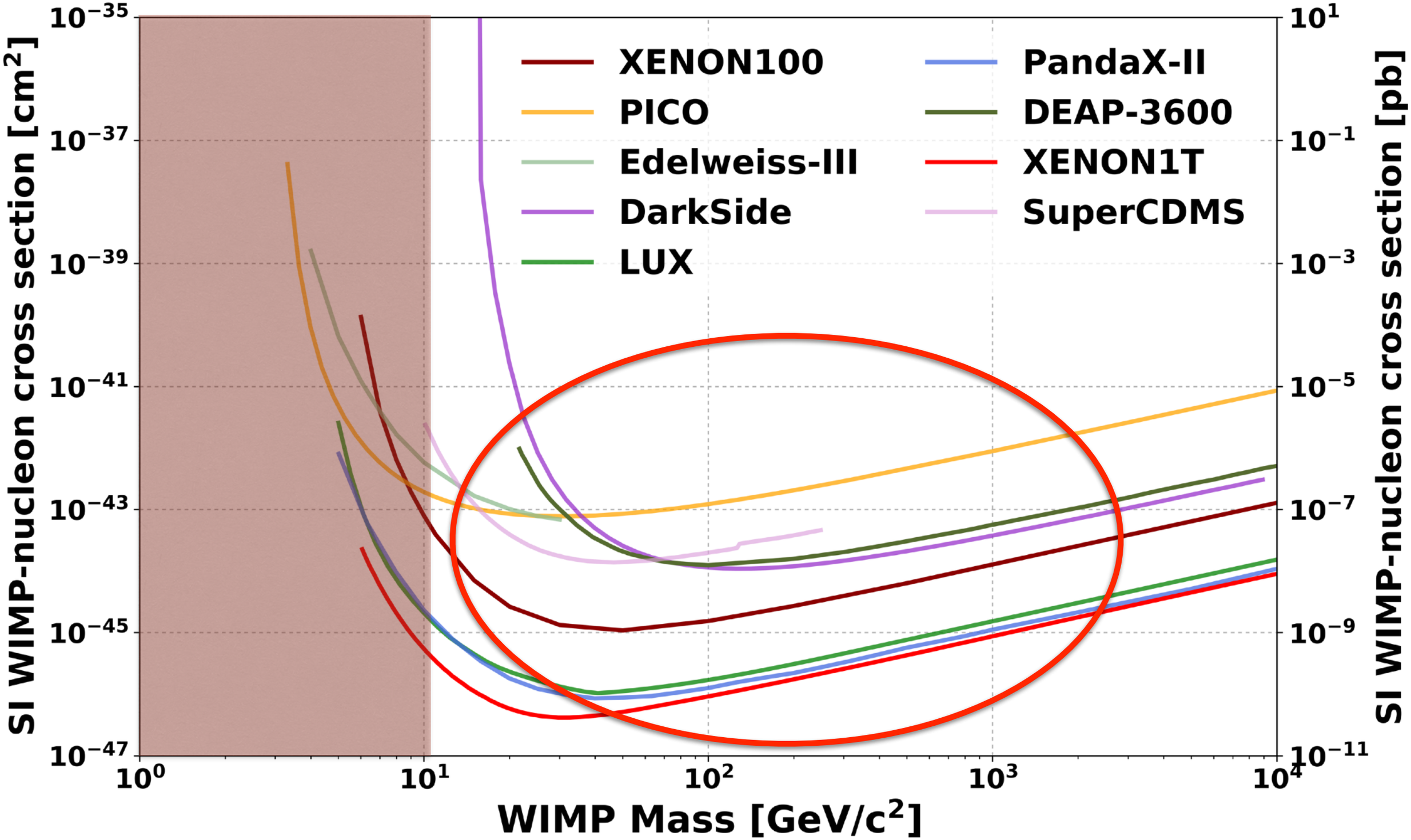
- no ER/NR discrimination
- low threshold: ~100 eVee
- bkg: ~1.5 event/keVee/kg/d at 0.5 keVee
- spectrum consistent with known background
- **Liquid argon now gives the best limits for low-mass DM between 2-5 GeV/c²**



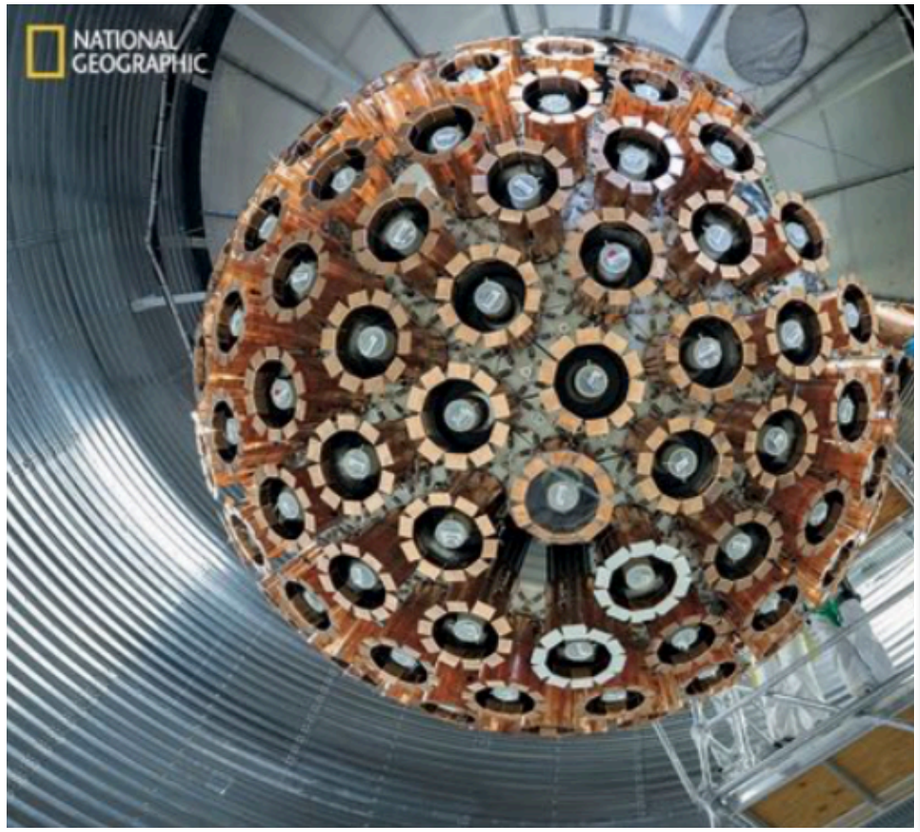
PRL 121, 081307, 2018

from IDM2018

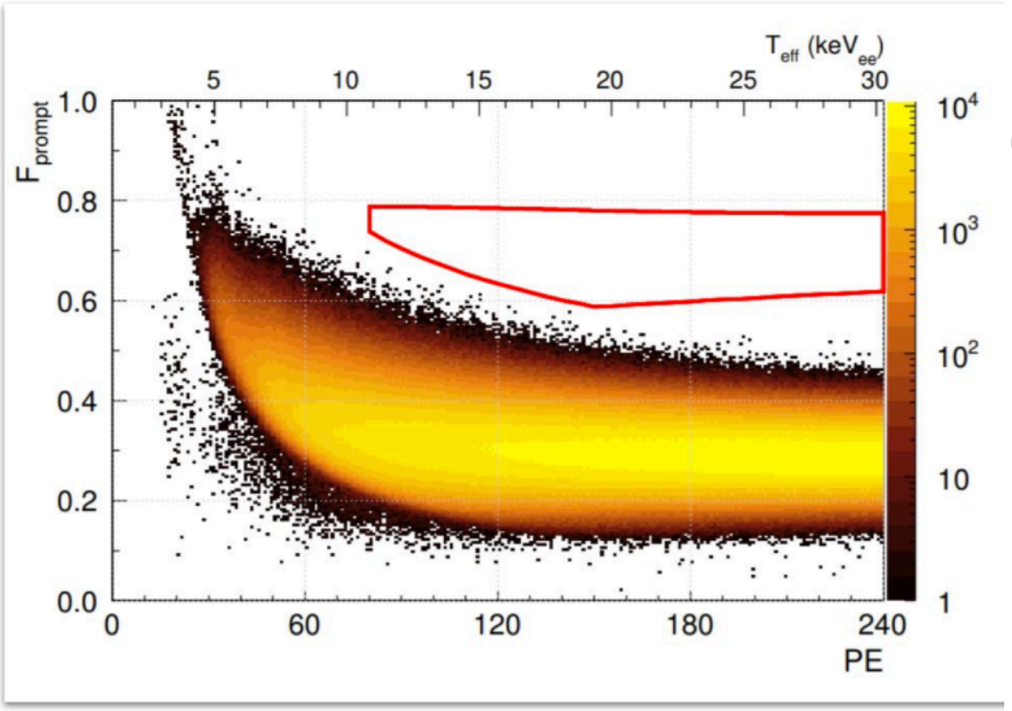
High Mass WIMPs Searches

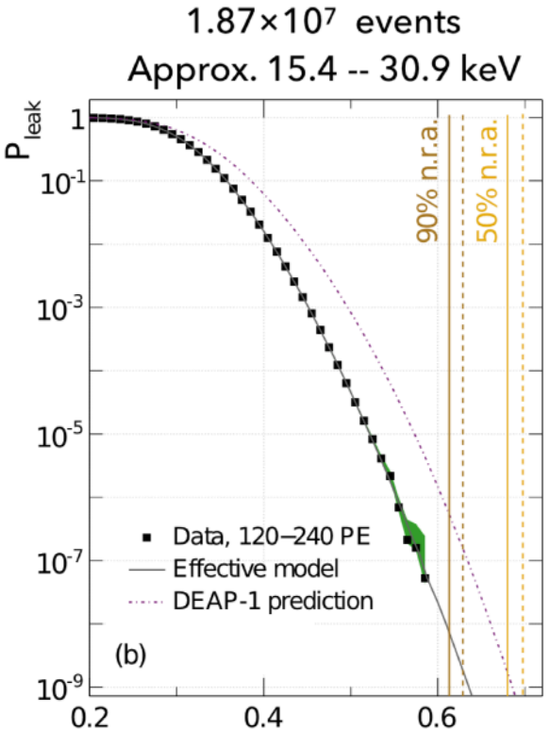


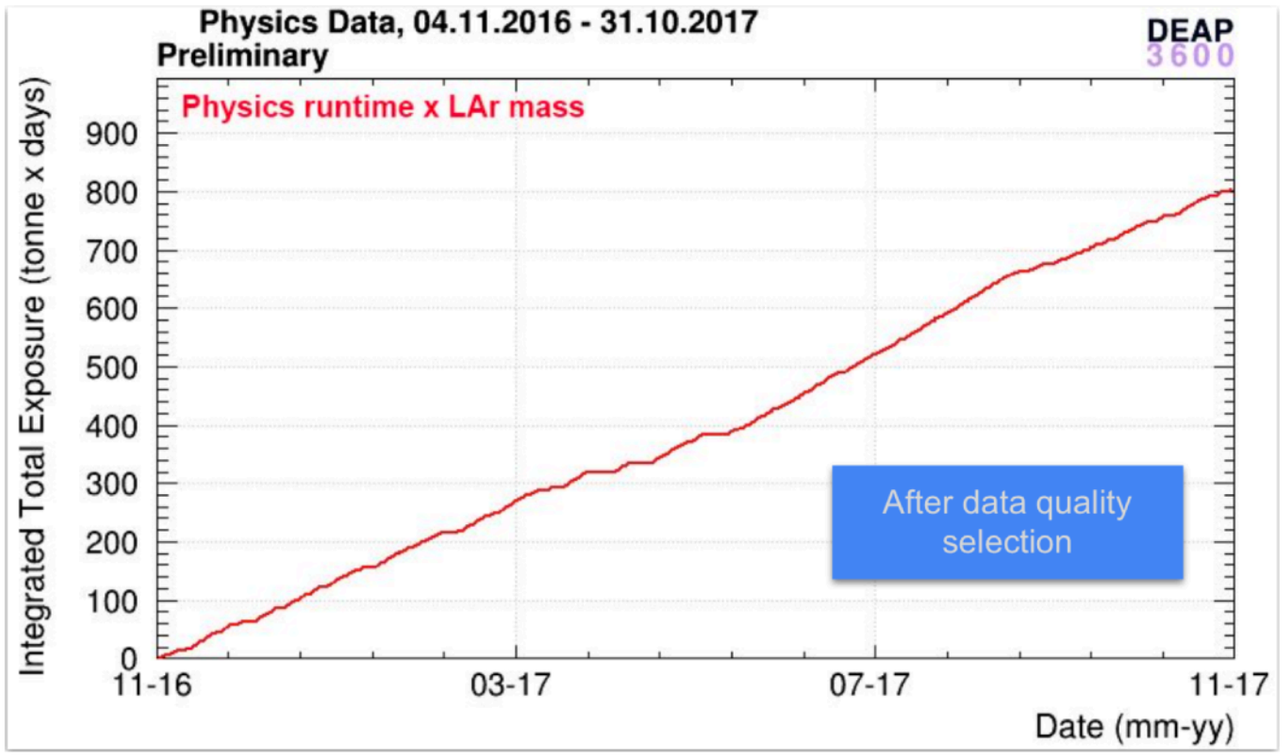
DEAP-3600 Liquid Argon Experiment

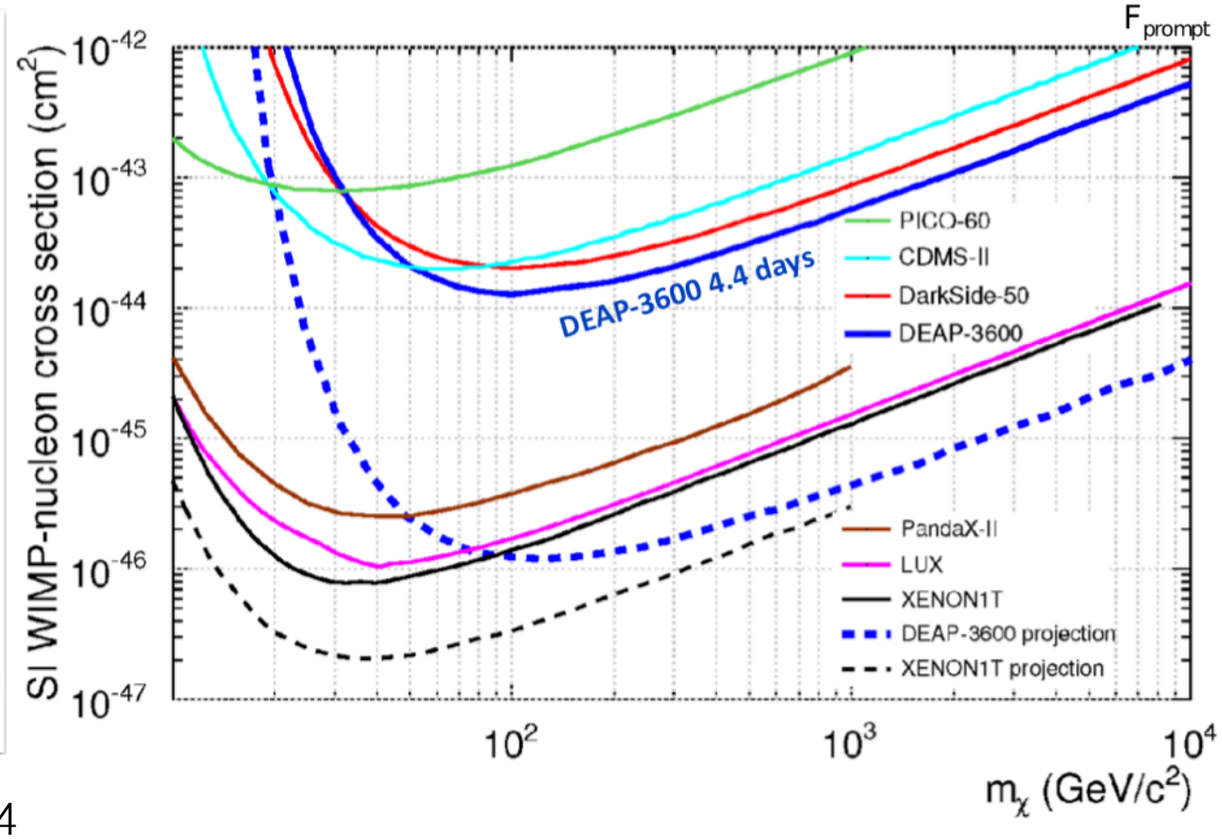


In the region of interest, after all cuts

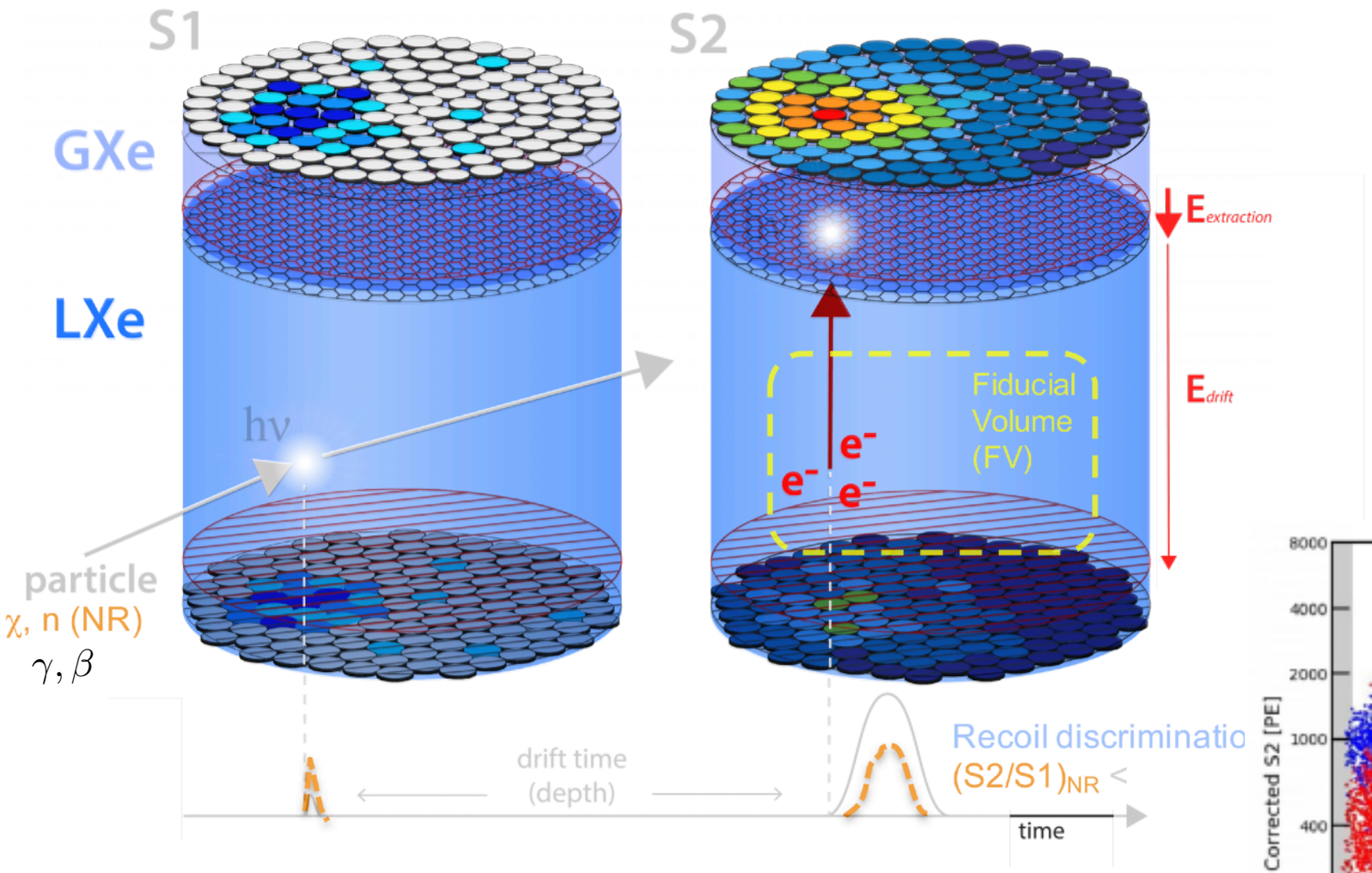




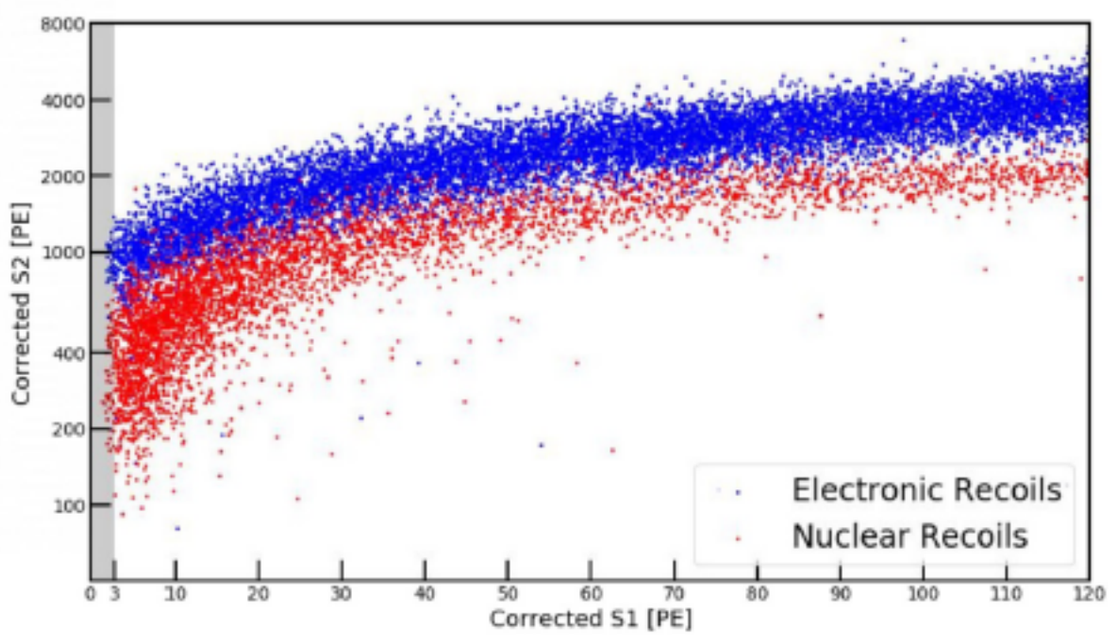




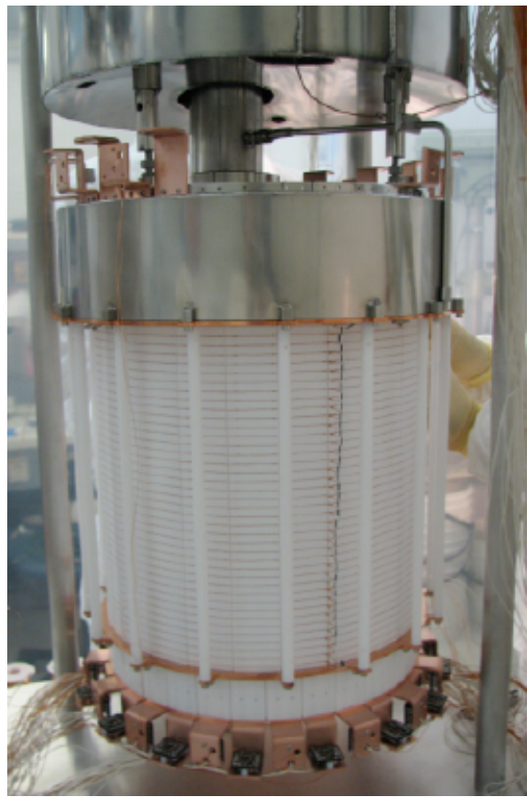
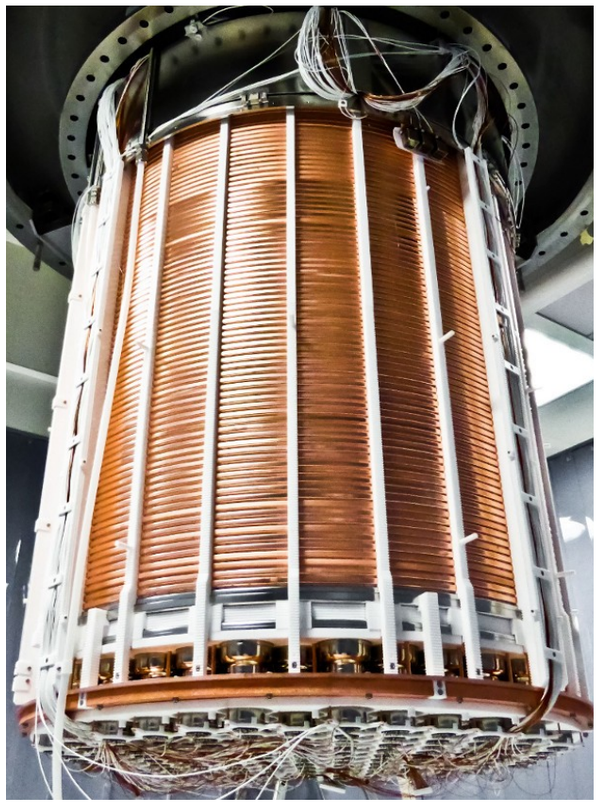
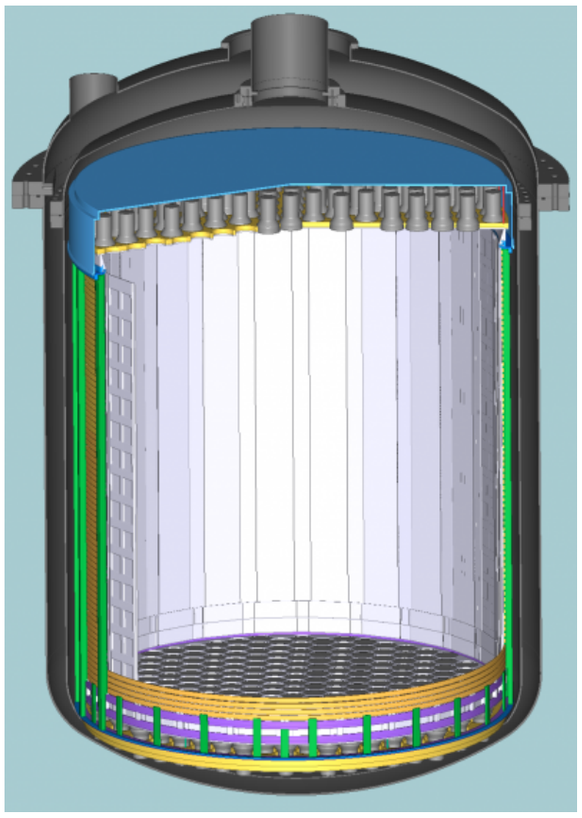
Two-phase Xe Time Projection Chamber as WIMP detector



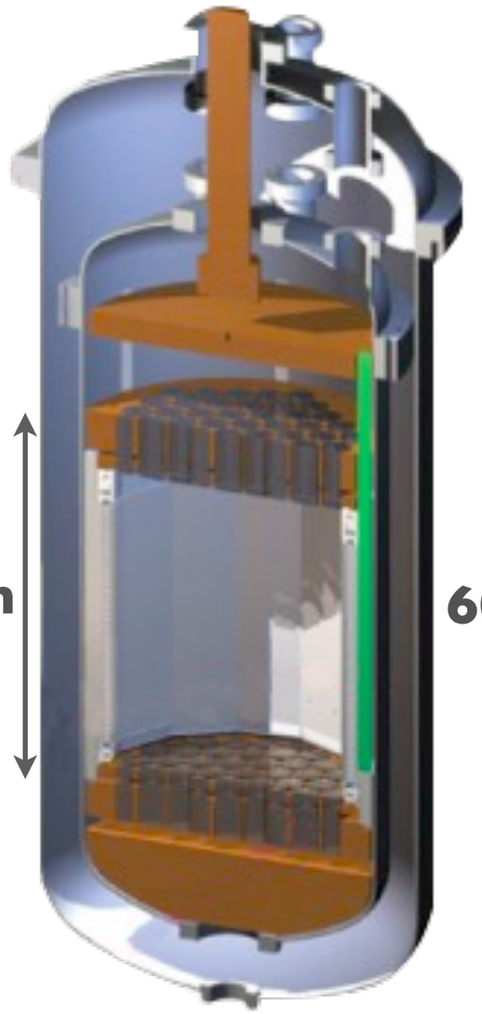
- *two signals for each event:*
  - *Energy from S1 and S2 area*
  - *3D event imaging: x-y (S2) and z (drift time)*
  - *self-shielding, surface event rejection, single vs multiple scatter events*
- *Recoil type discrimination form ratio of charge (S2) to light (S1)*



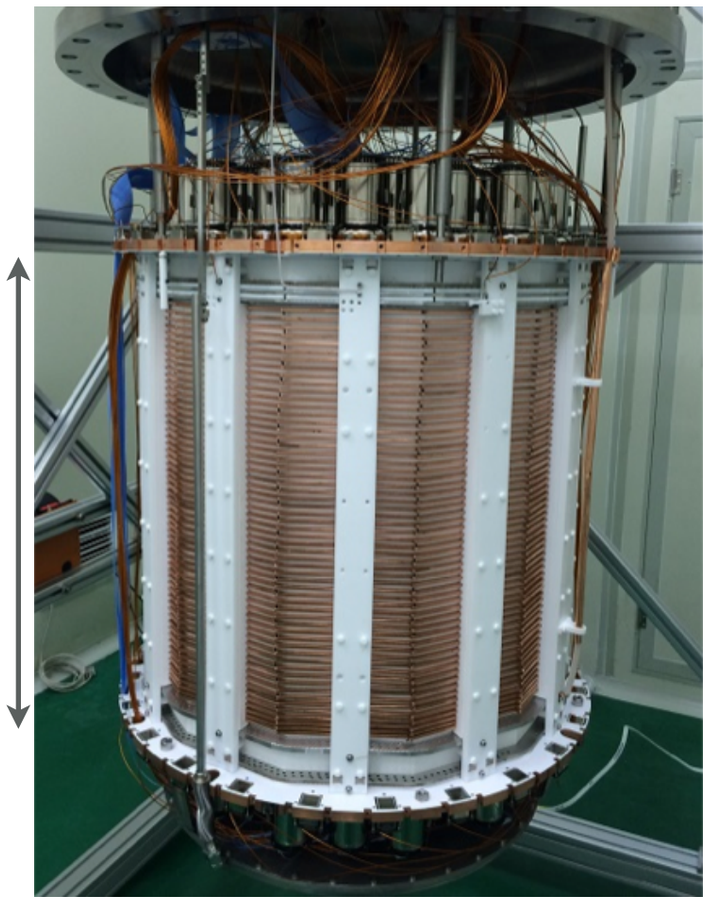
Development of XENON program

XENON10	XENON100	XENON1T	XENONnT
			
2005-2007	2008-2016	2012-2018	2019-2023
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8 ton - 1.5 m drift
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2

The frontline detectors using the LXeTPC



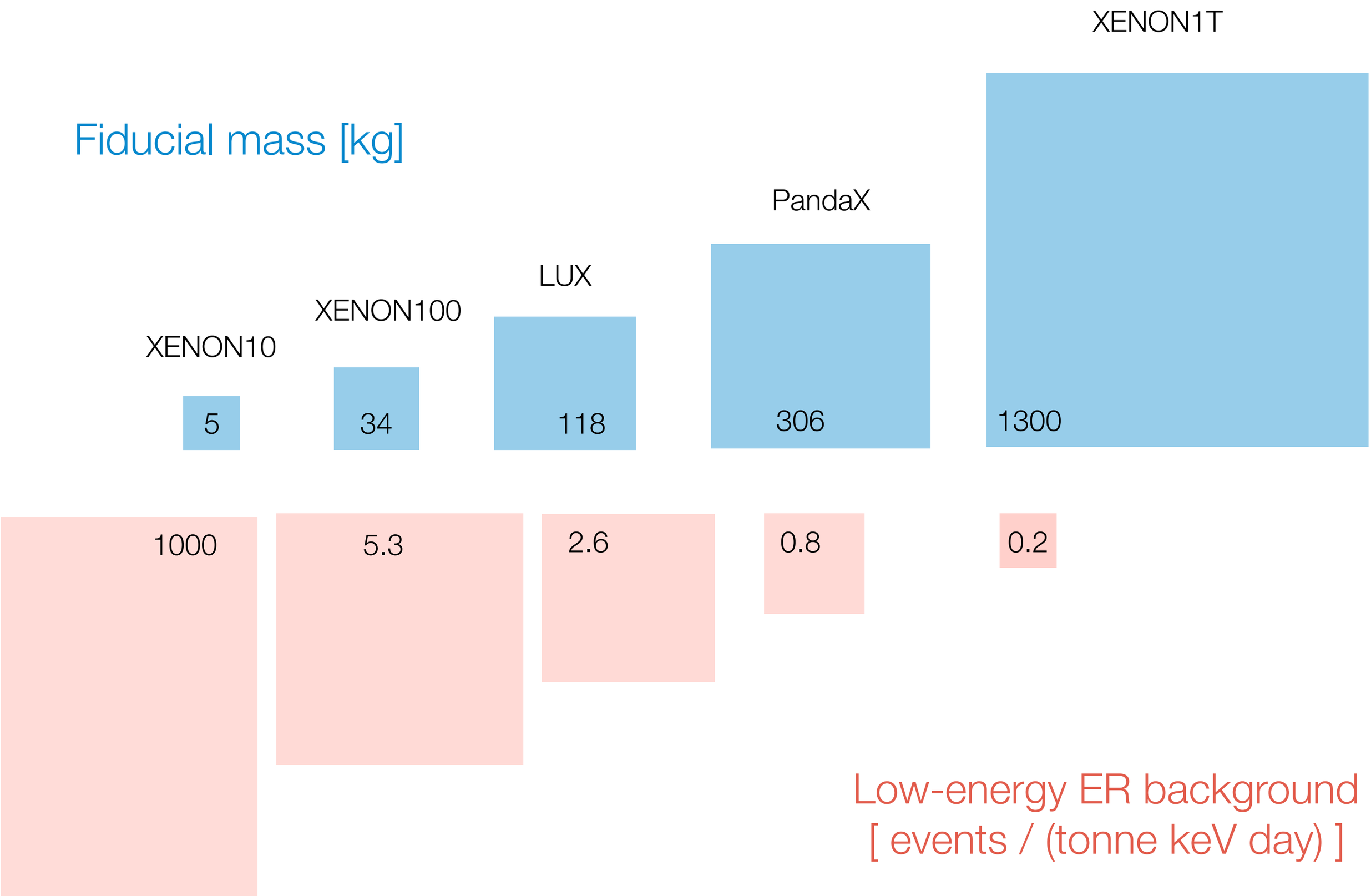
LUX
Active Target: ~250 kg
completed



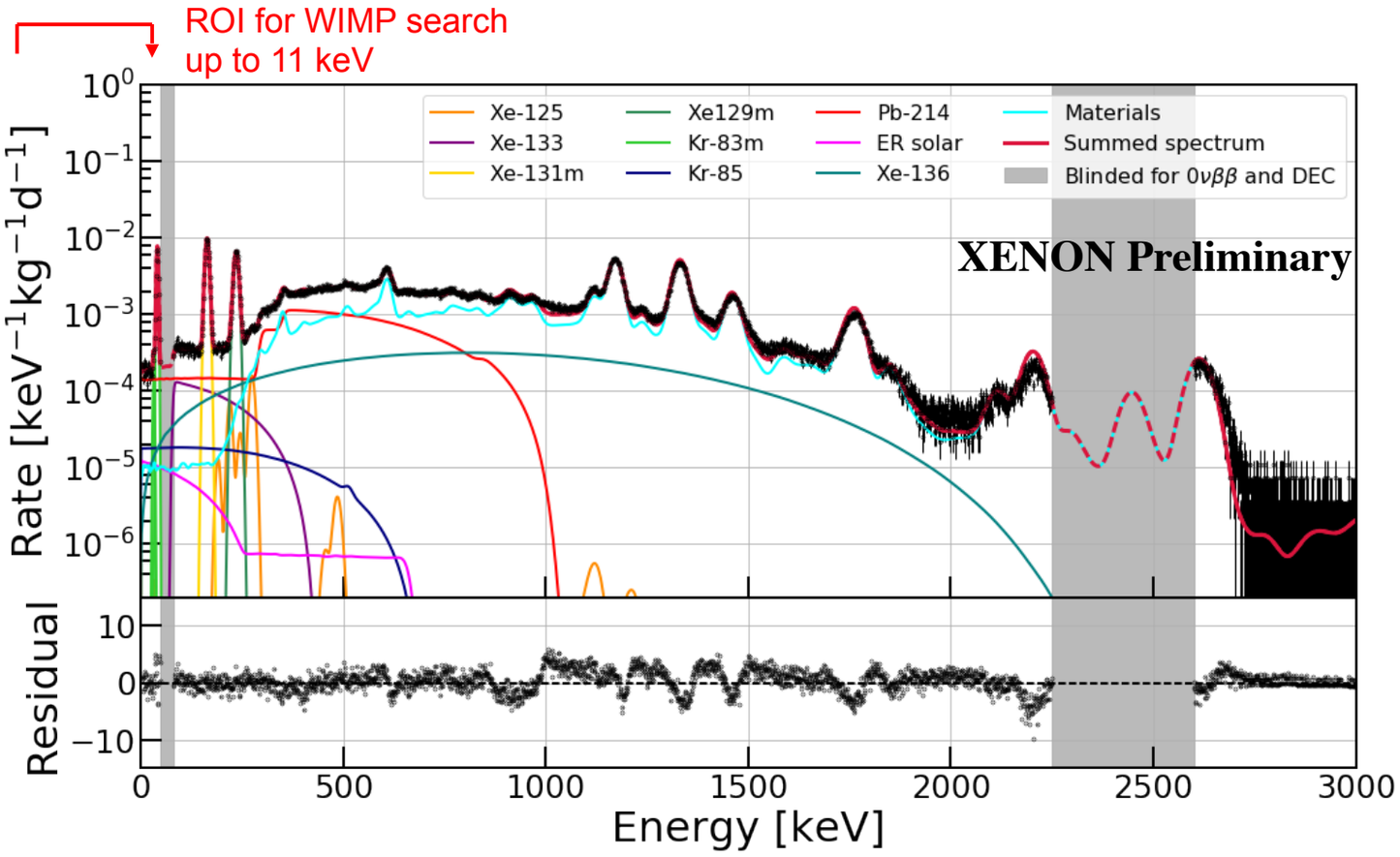
PandaX-II
Active Target: ~580 kg
Status: running

XENON1T
Active Target: 2000 kg
Status: running

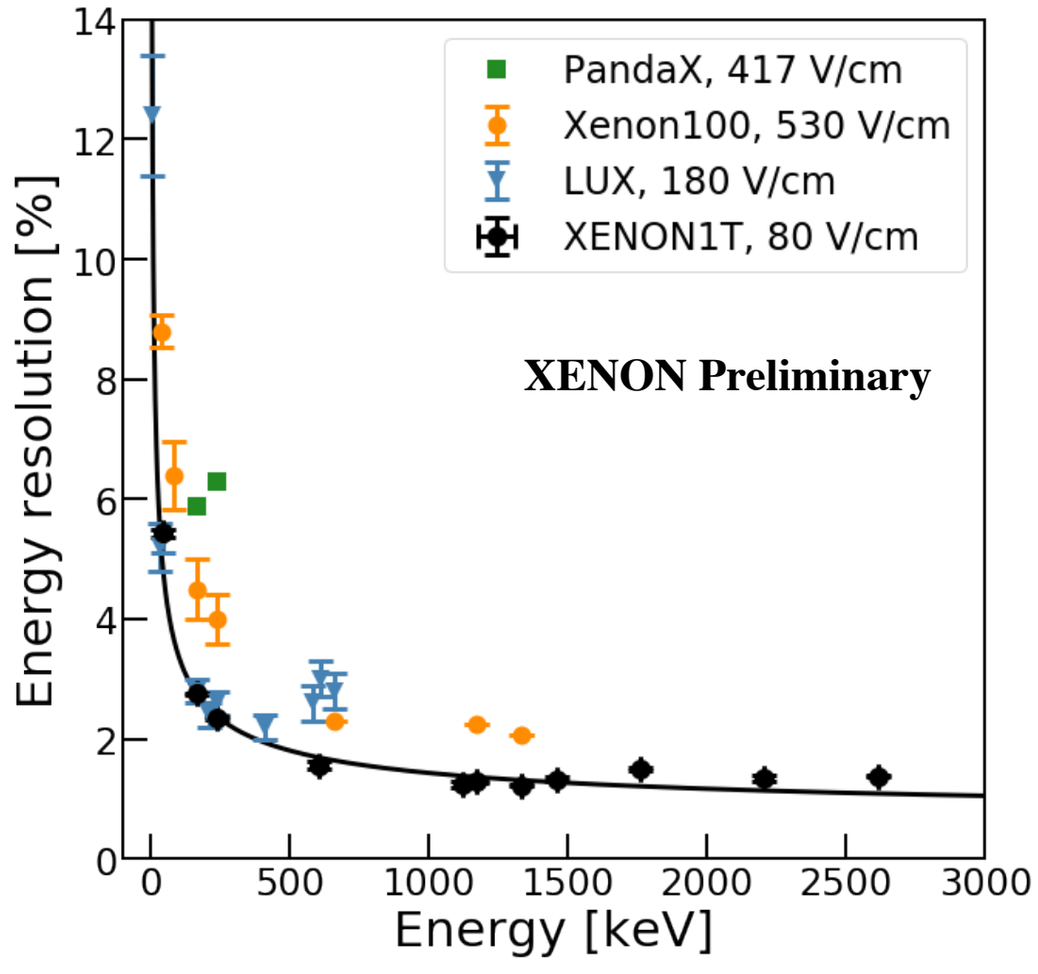
Impressive evolution of LXeTPCs as WIMP detectors



The Global Picture of ER Background

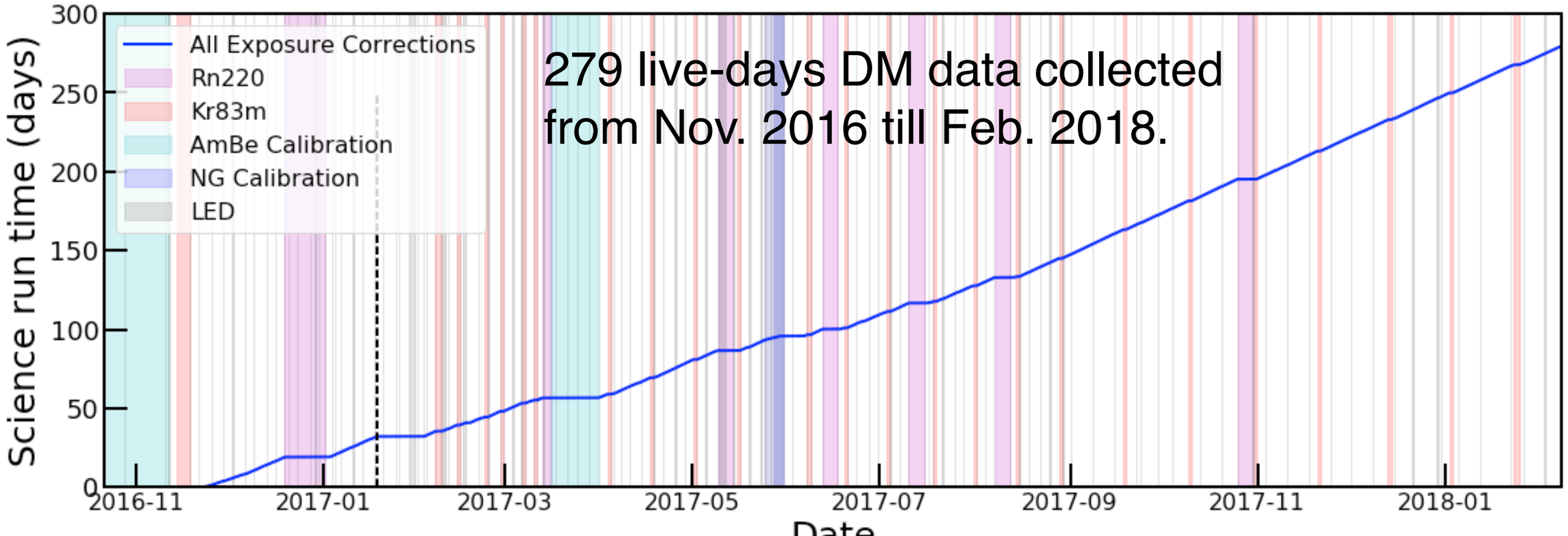


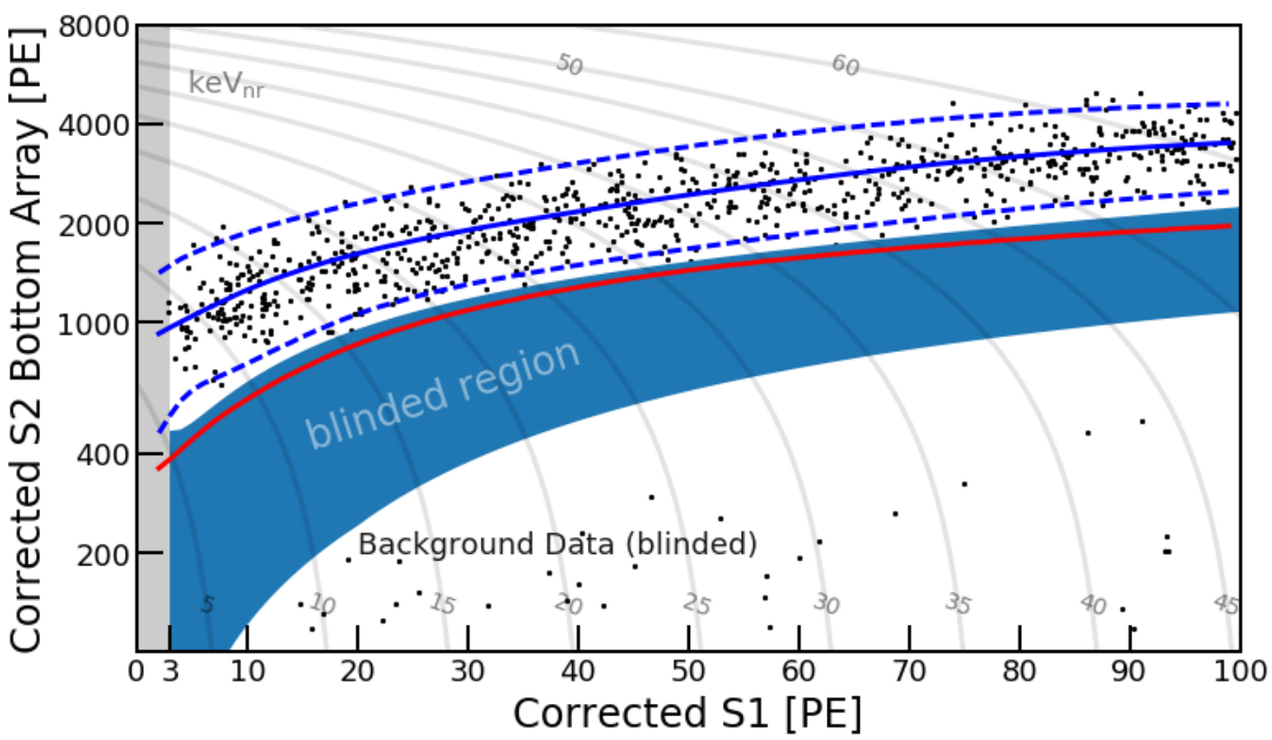
- Energy reconstructed from anti correlated S1 and S2. Excellent linearity from keV to MeV
- Best energy resolution measured with this large LXeTPC ~1.6% resolution (sigma) at 2.5 MeV



- Good agreement between predicted and measured background spectrum
- ^{nat}Kr: 0.6 ppt; ^{214}Pb: 10 uBq/kg
- Gammas based on screening measurements

1 t-year of WIMPs Search

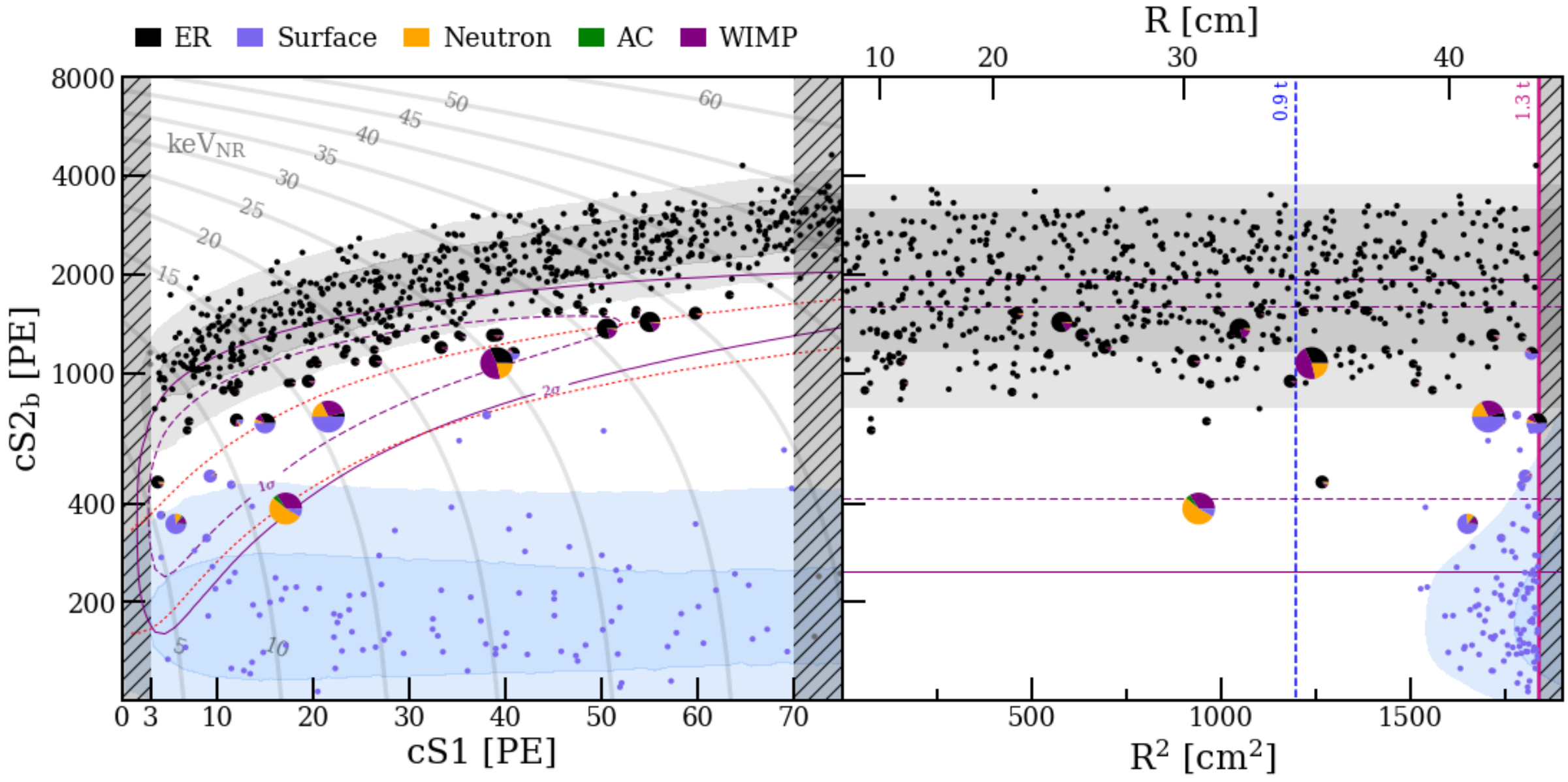




- 1.3t fiducial mass, resulting in 1 t-yr exposure for WIMPs search
- Blinding: to avoid potential bias in event selection and the signal/ background modeling
- Position dependent likelihood for the statistical inference

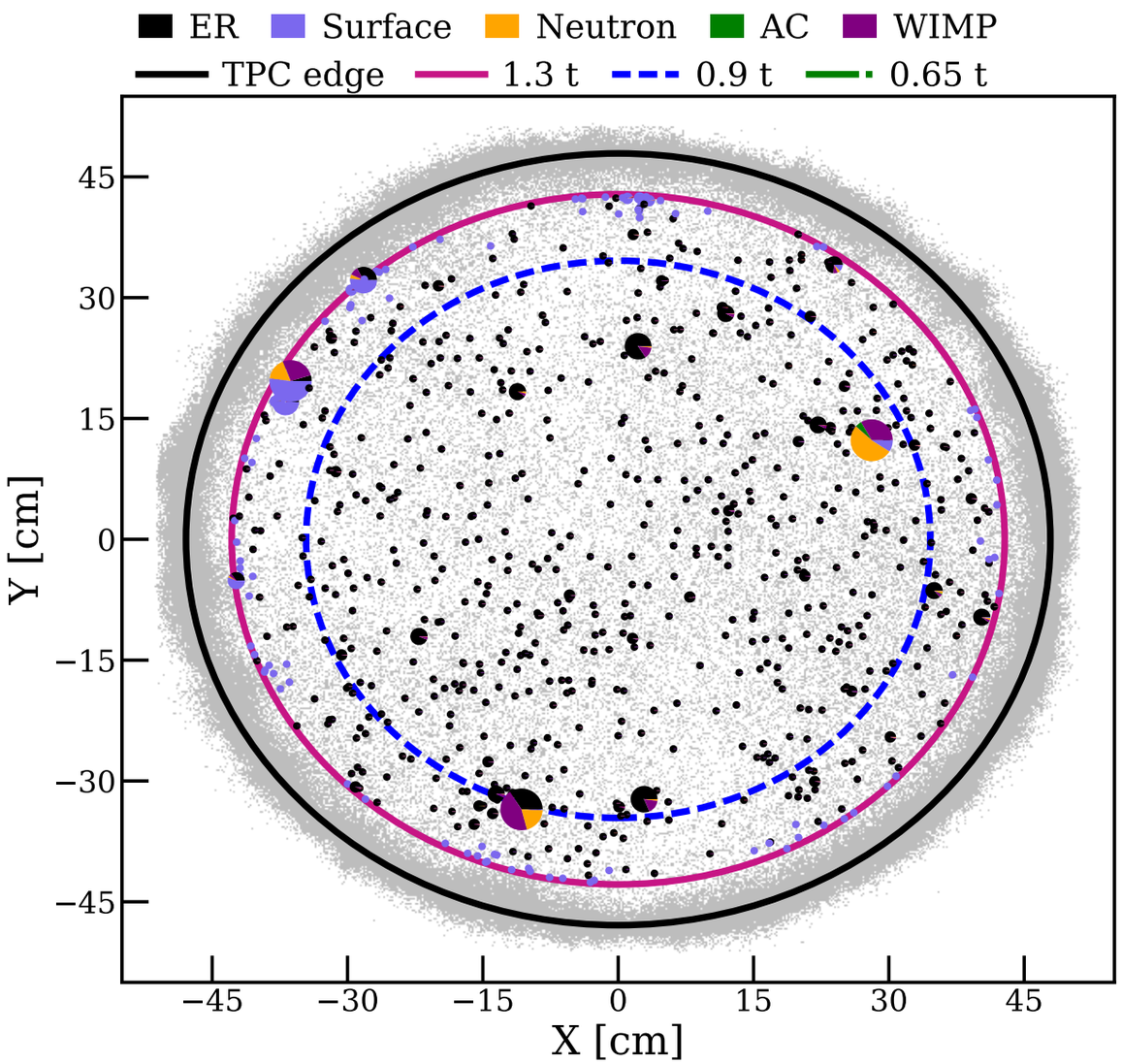
Dark Matter Search Results

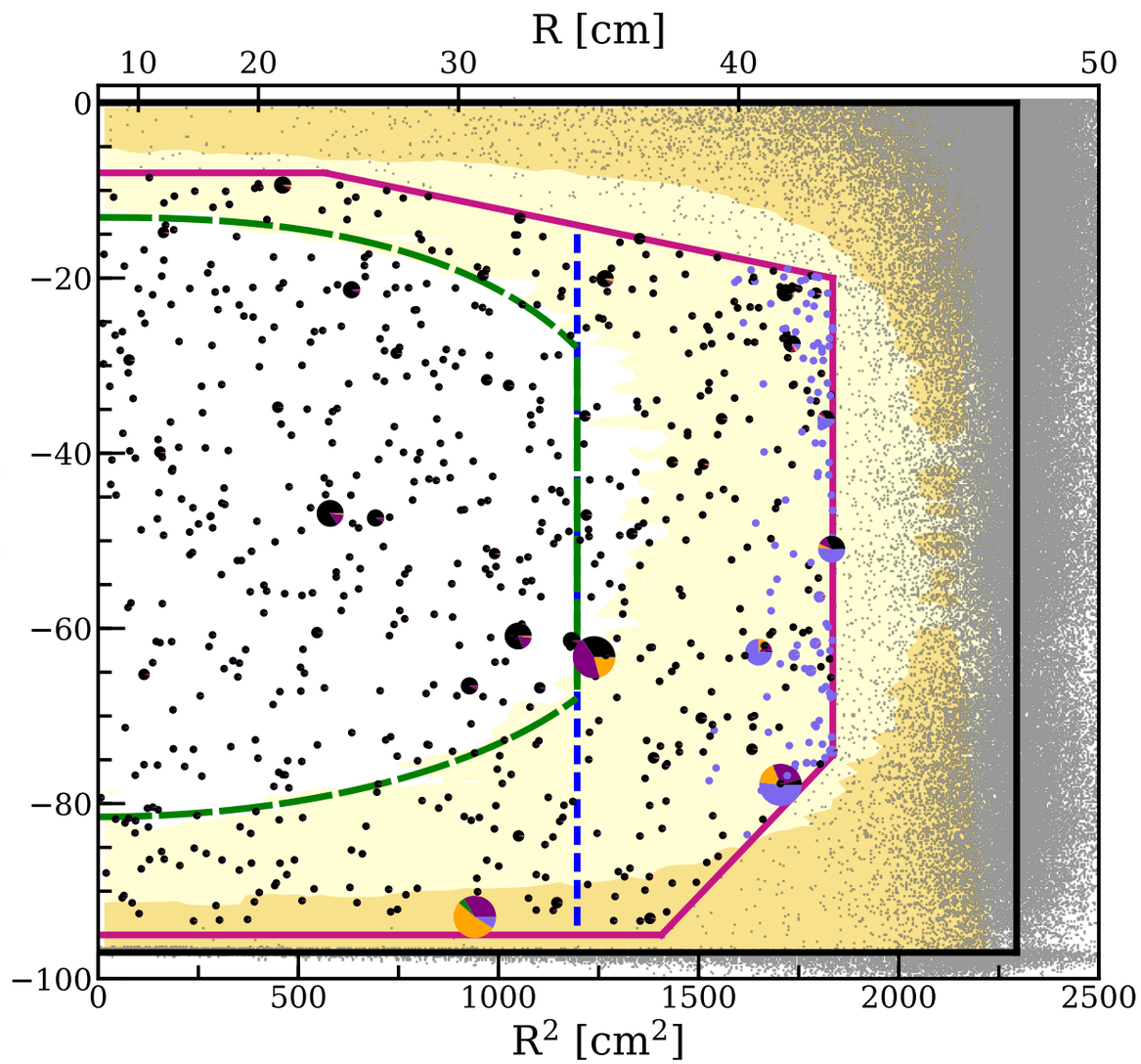
- Results interpreted with unbinned profile likelihood analysis in cs1, cs2, r space
- piechart indicate the relative PDF from the best fit of 200 GeV/c^2 WIMPs with a cross-section of 4.6×10^{-47} cm^2



Spatial Distribution of Dark Matter Search Data

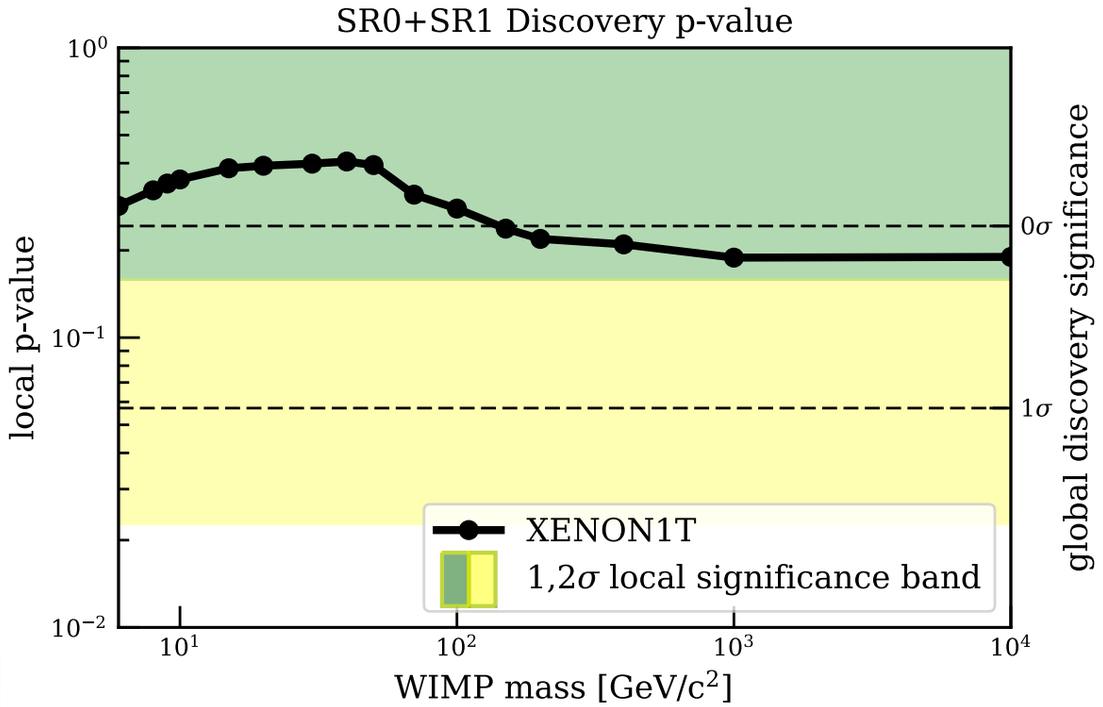
- Results interpreted with unbinned profile likelihood analysis in cS1, cS2, r space
- **Core volume** to distinguish WIMPs over neutron background

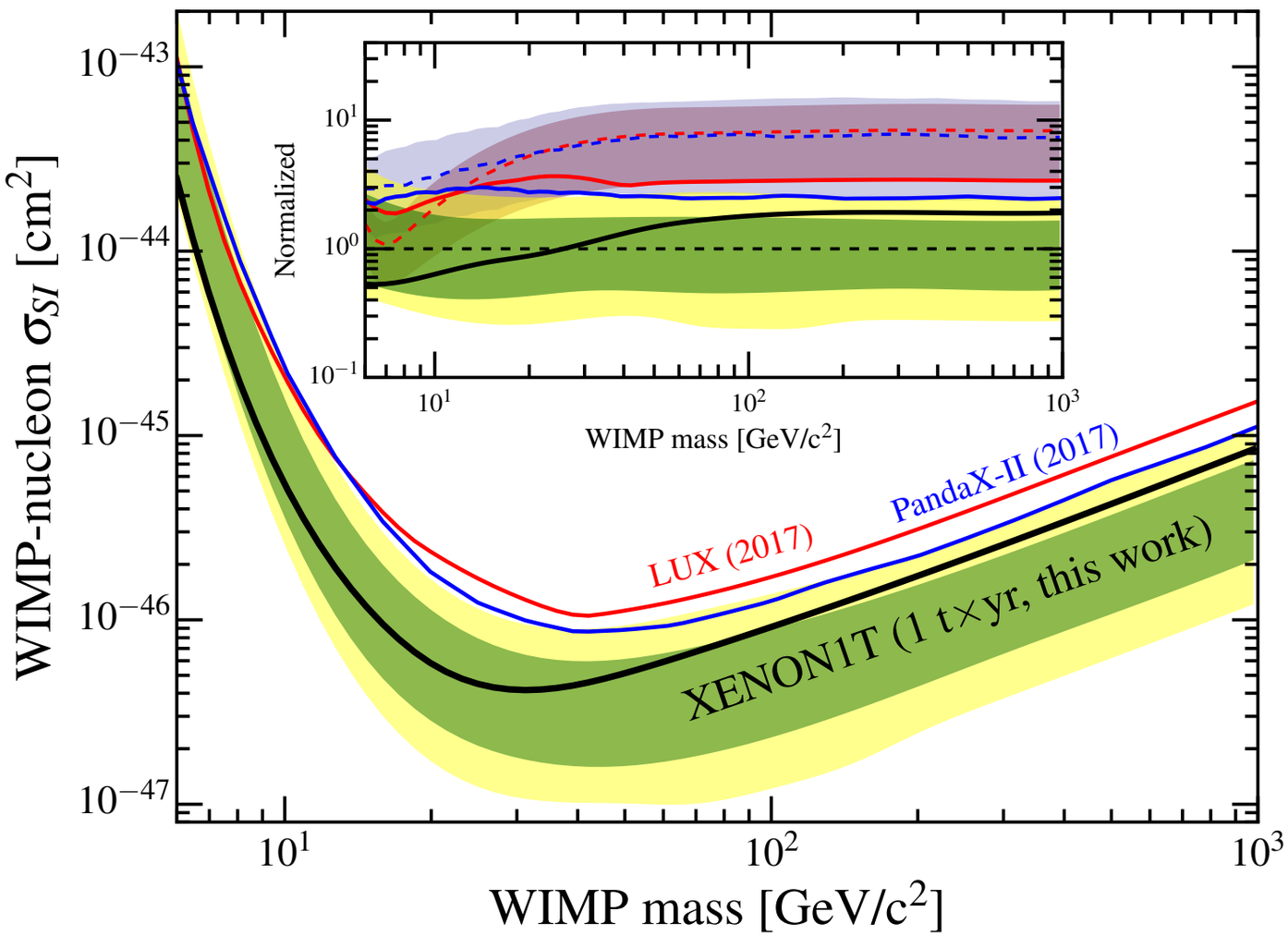




Statistical Interpretation

- Extended unbinned profile likelihood analysis
- No significant (>3 sigma) excess at any scanned WIMP mass
- Background only hypothesis is accepted with p-value of ~0.2 at high mass (200 GeV and above)

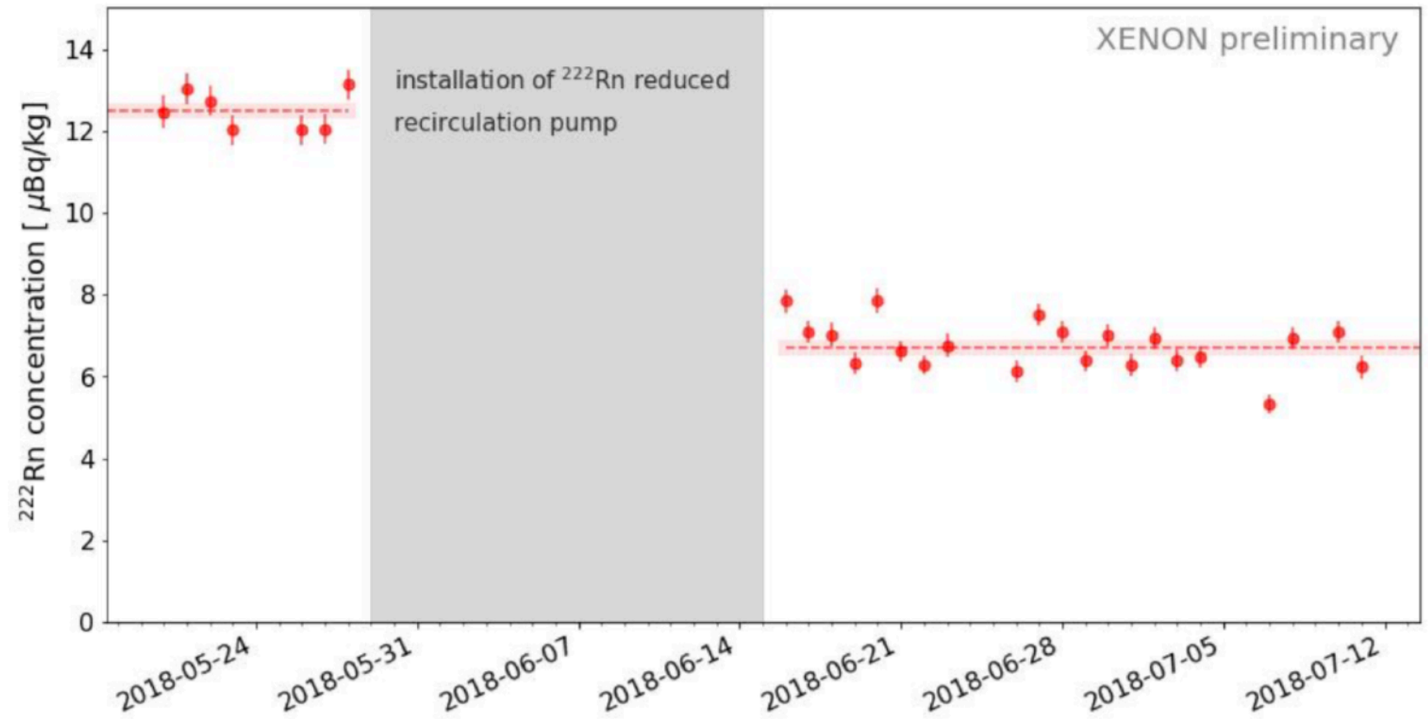




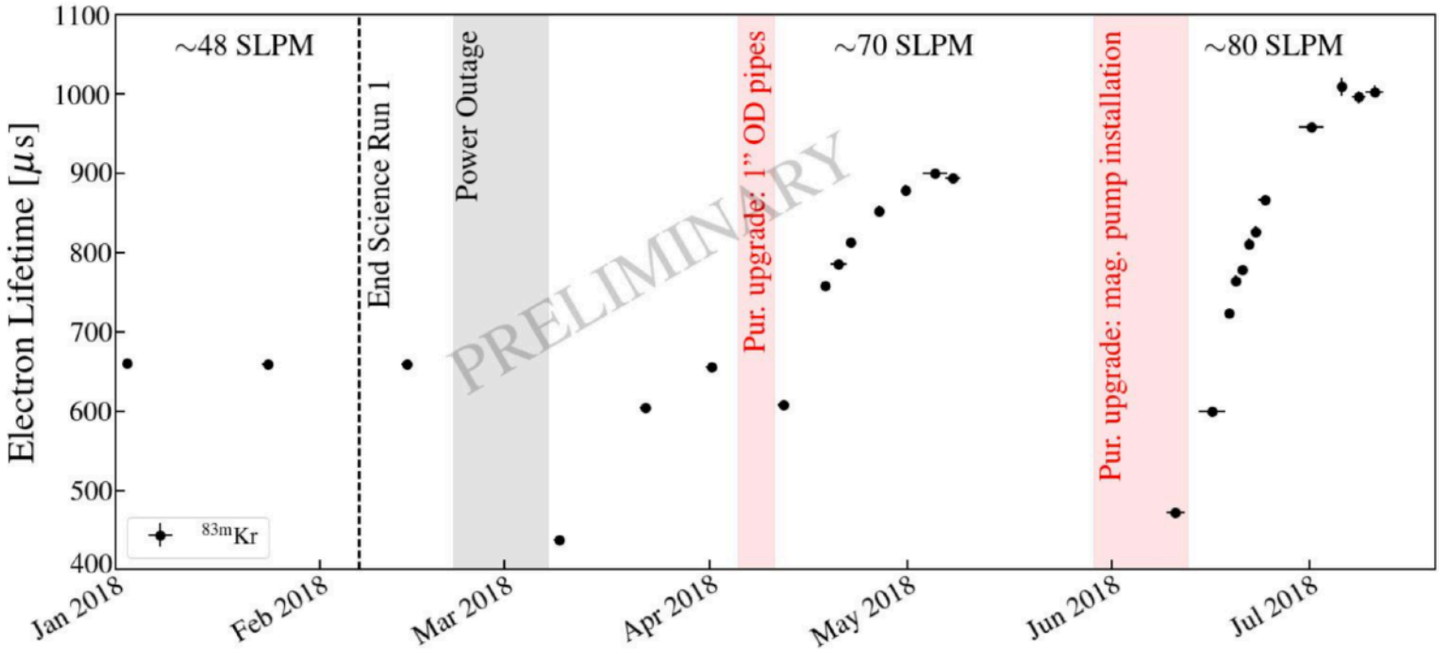
- Most stringent 90% CL upper limit on WIMP-nucleon cross section at all masses above 6 GeV
- Factor of 7 more sensitivity compared to previous experiments (LUX, PandaX-II)
- ~ 1sigma upper fluctuation at high WIMP masses, could be due to background or signal

XENON1T Upgrade in 2018

- Purpose of the Upgrades (for XENONnT):
  - Reduce Rn222 background
  - Improve the purity of LXe for better charge collection
  - Reduce neutron background



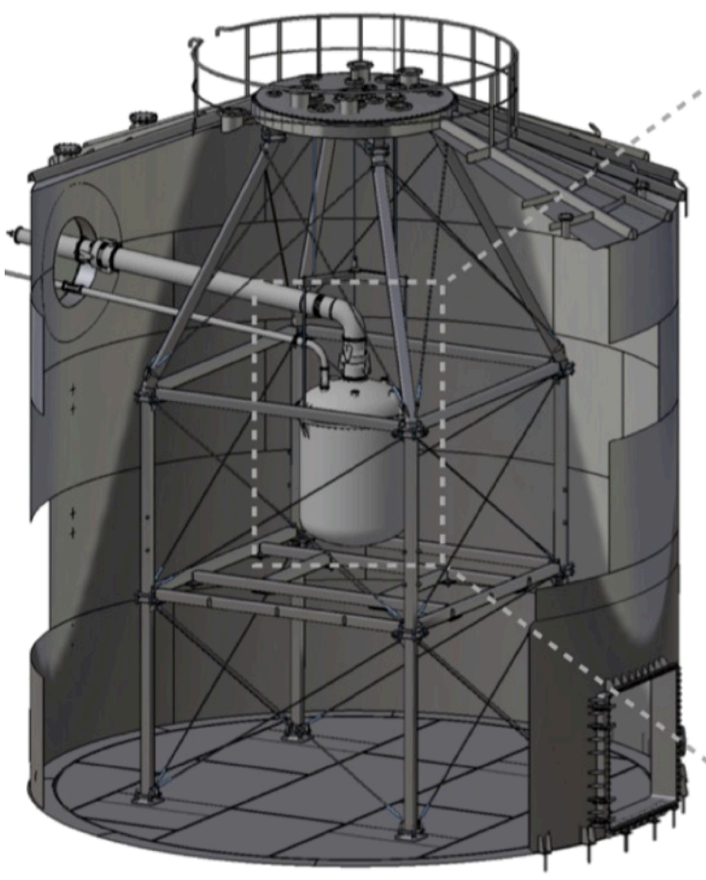
- First Solution: replacement of Q-drive pump with magnetic pump
  - Increase purification speed (80%)
  - Reduce large Rn222 emanation from (40%)

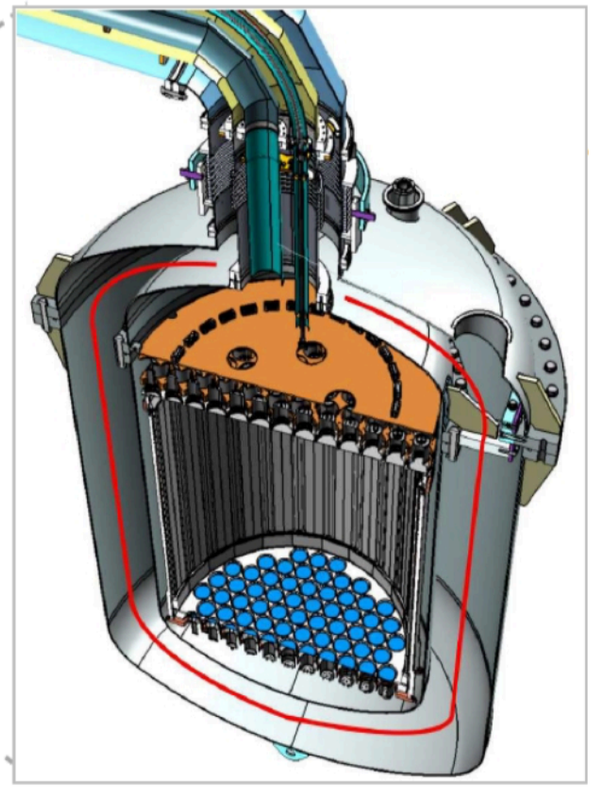


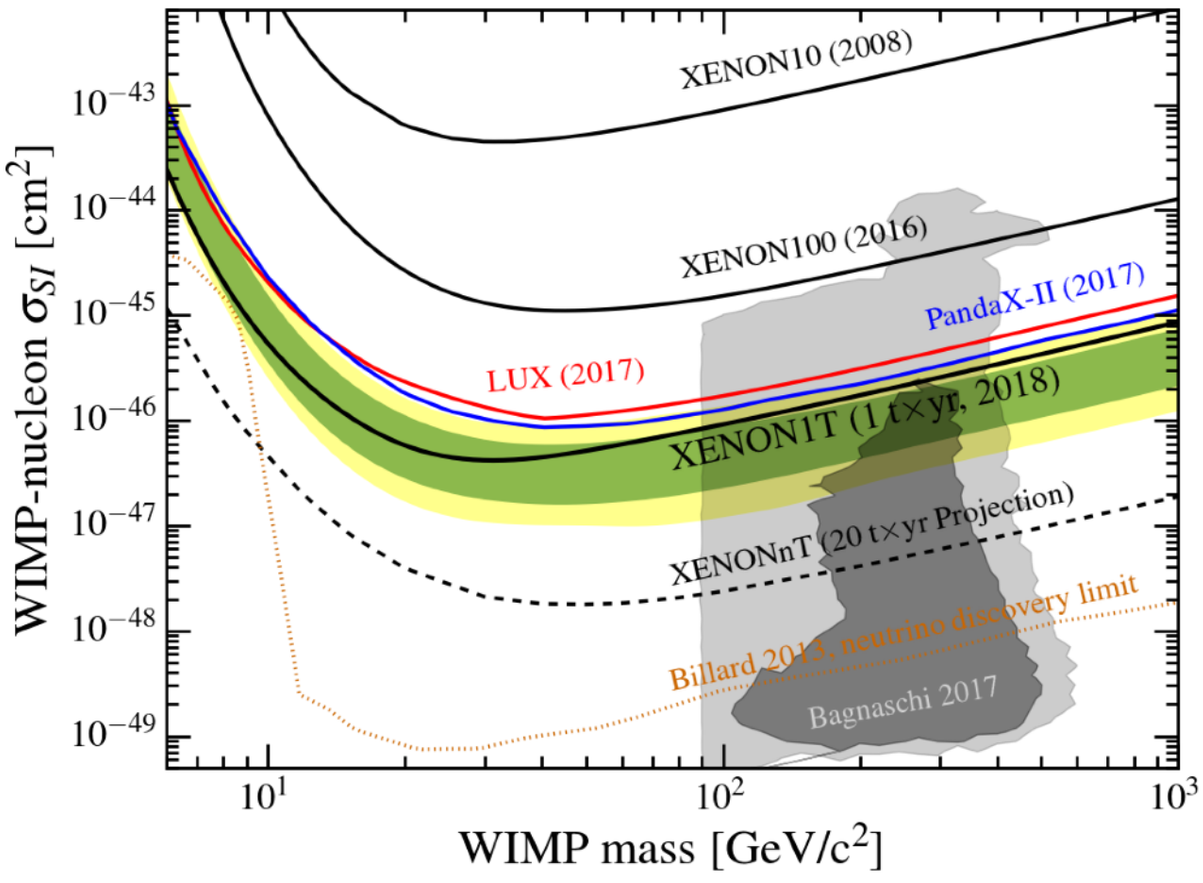
- Further Steps:
  - Online Rn222 distillation
  - Liquid purification
  - Neutron veto system

The Next Step - XENONnT

- 6t of LXe as sensitive WIMPs target, fiducial mass of >4t
- Purification upgrade to 5000 SLPM, significant improvement of electron lifetime
- Rn222 background reduction of 10
- Neutron tagging with active neutron veto system
- Start commissioning in 2019

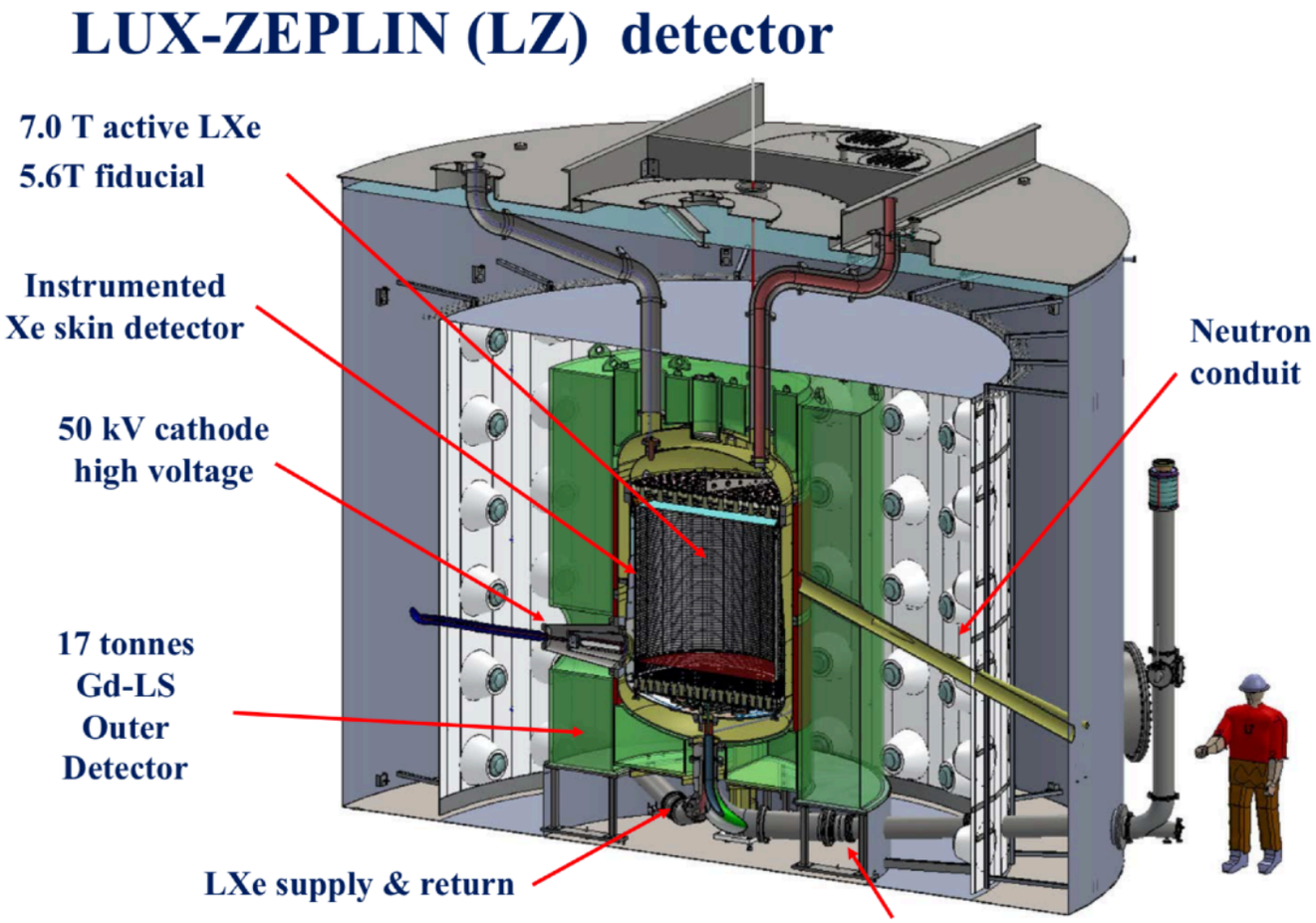


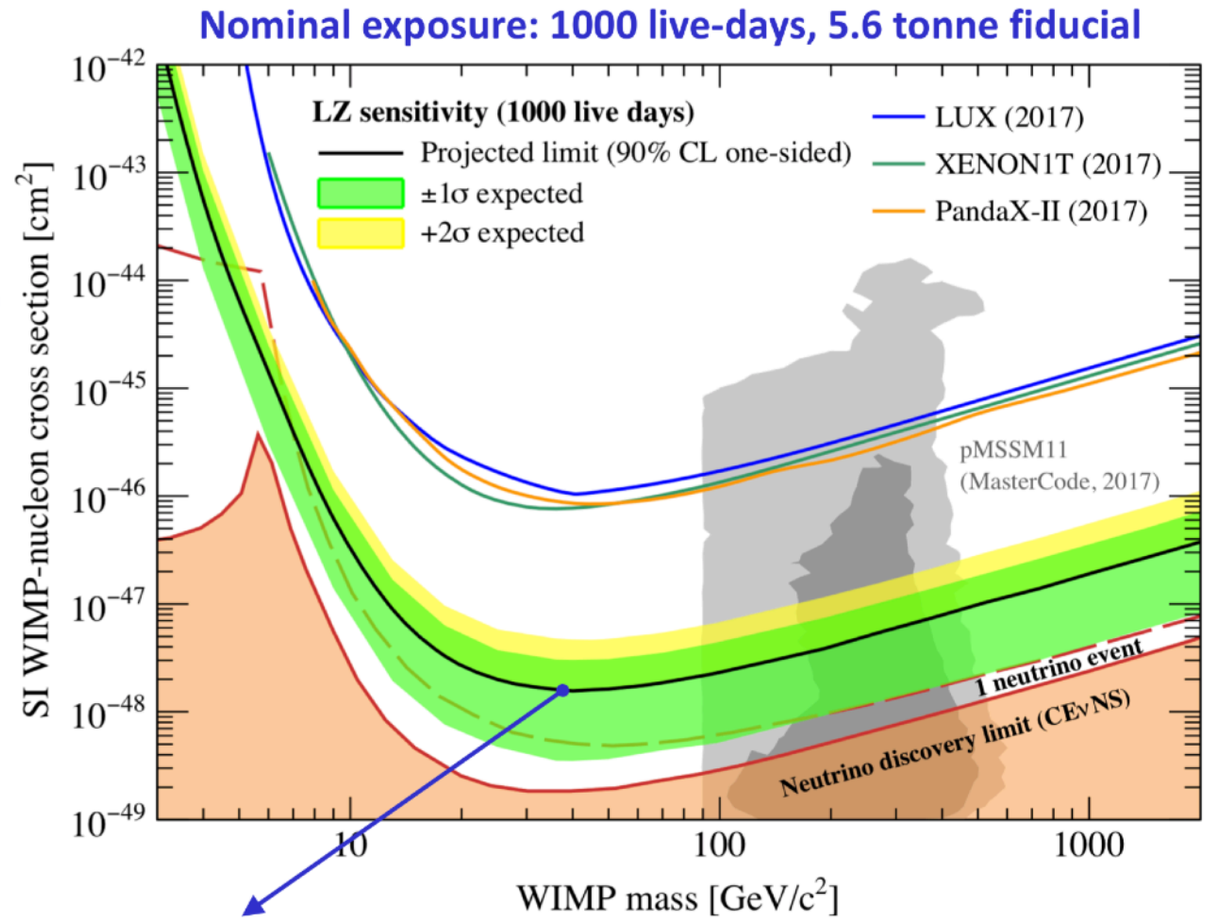




The Next Step - LZ

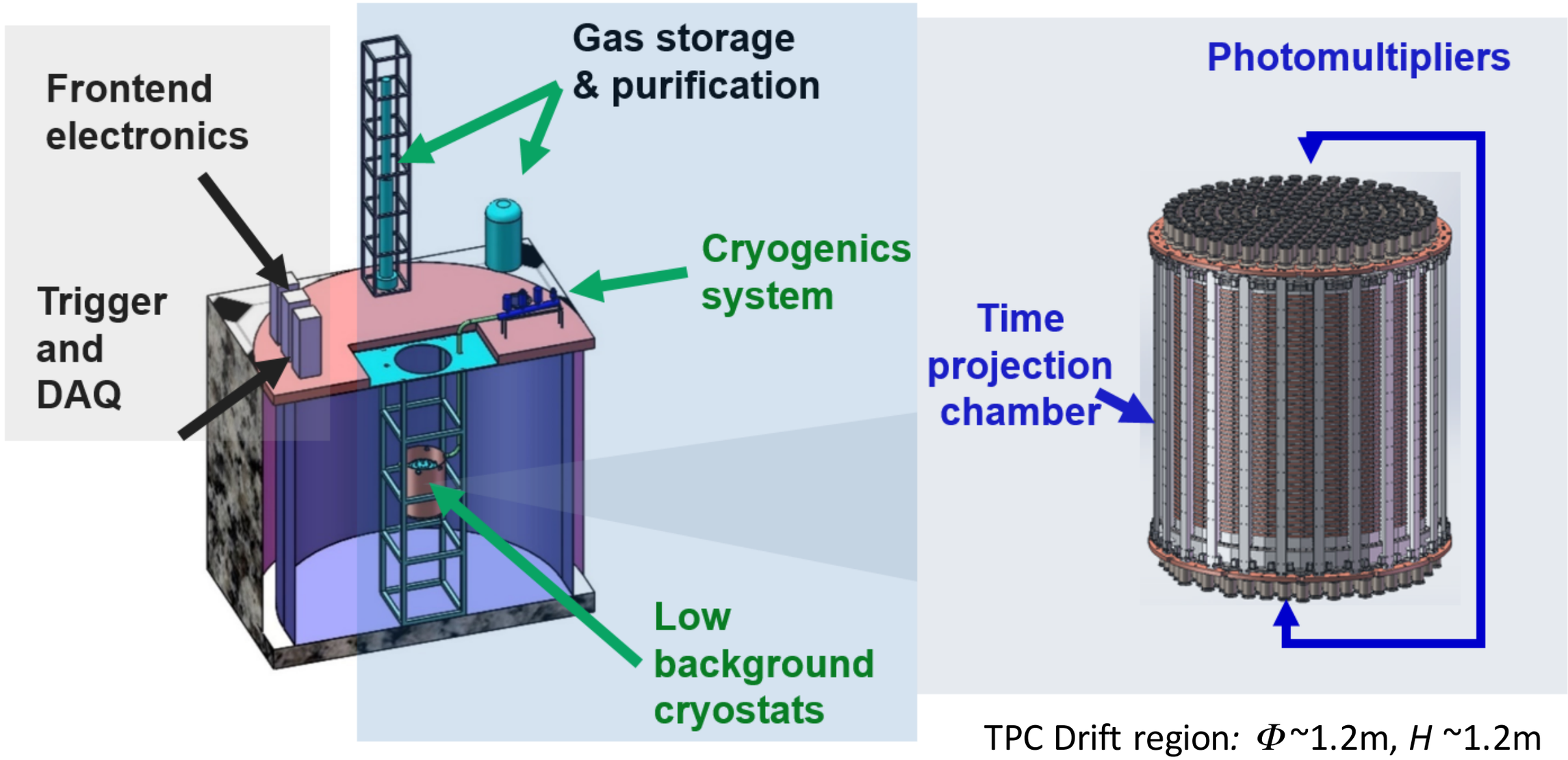
- 7t of LXe as sensitive WIMPs target, fiducial mass of 5.6t, slightly larger than XENONnT
- Background level compatible to XENONnT
- Neutron tagging with active neutron veto system
- Start commissioning and data taking in 2020, 1000 live days of data projected.





from IDM2018

The Next Step - PandaX-xT

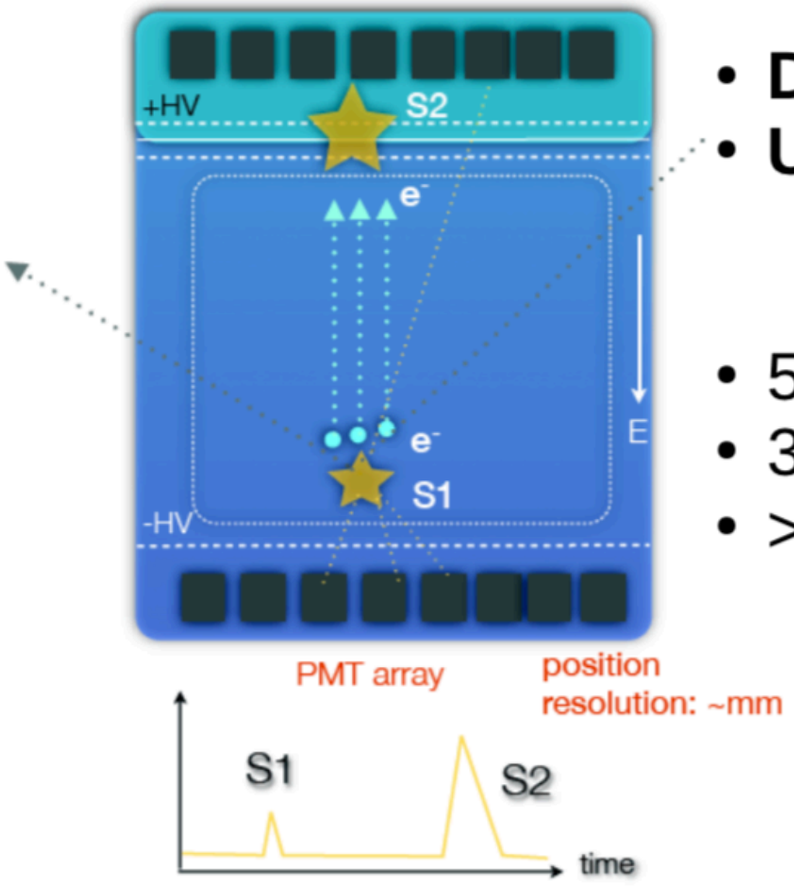


TPC Drift region: Φ~1.2m, H ~1.2m

- Intermediate stage:
  - **PandaX-4T** (4-ton in sensitive region) with SI sensitivity ~10^{-47} cm^2
  - On-site assembly and commissioning: 2019-2020

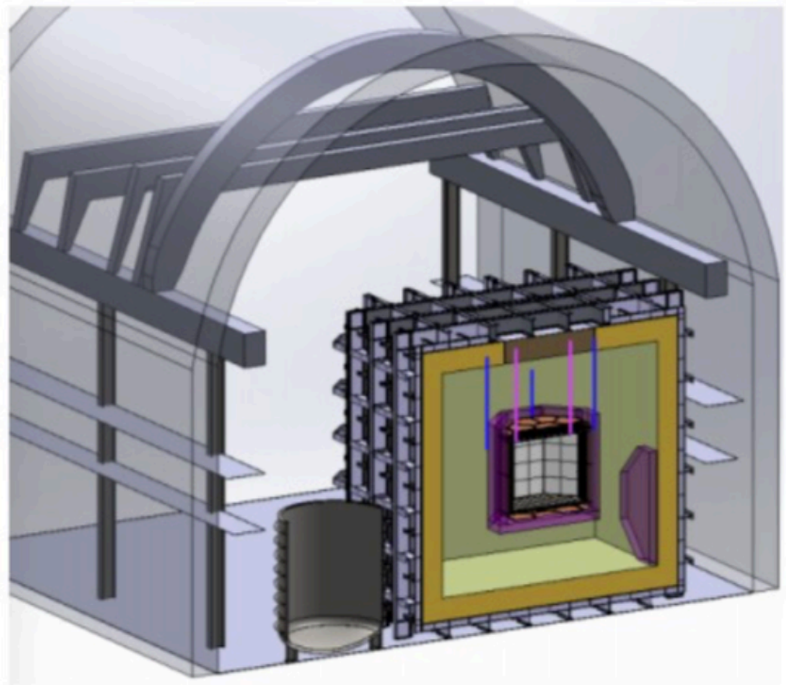
from IDM2018

The Next Step - DarkSide-20k and beyond



- **Dual-phase detector**
- **Uses low radioactivity Ar**

- 50 tonnes total mass
- 30 tonnes fiducial mass
- >20 m^2 of SiPM coverage



C. Aasleth et al. (DarkSide-20k), arXiv:1707.08145

- To be located at LNGS (Gran Sasso, Italy)
- Officially supported by underground labs: LNGS, LSC, and SNOLAB

- Planned start in 2022
- Projected LY = 10 PE/keV (highly efficient SiPMs)

- Approved by INFN and LNGS in April 2017 and by NSF in Oct 2017

Summary

- Numerous of efforts worldwide on the direct detection of dark matter!
- DAMA/Libra is so far the only experiment reporting positive signal from WIMPs, but strongly constrained by null results from experiments using other targets. A few experiments are trying to reproduce the results using NaI detectors
- Low-threshold detectors lead the search of light WIMPs. The sensitivity is 2-3 order of magnitude above neutrino floor.
- Noble liquid detectors lead the search of heavy WIMPs:
  - XENON1T reported null results from a one ton-year exposure of WIMPs search
  - XENONnT, LZ and PandaX-xT are aiming to detect dark matter by ~2025
  - Global argon network is building DarkSide-20k detector