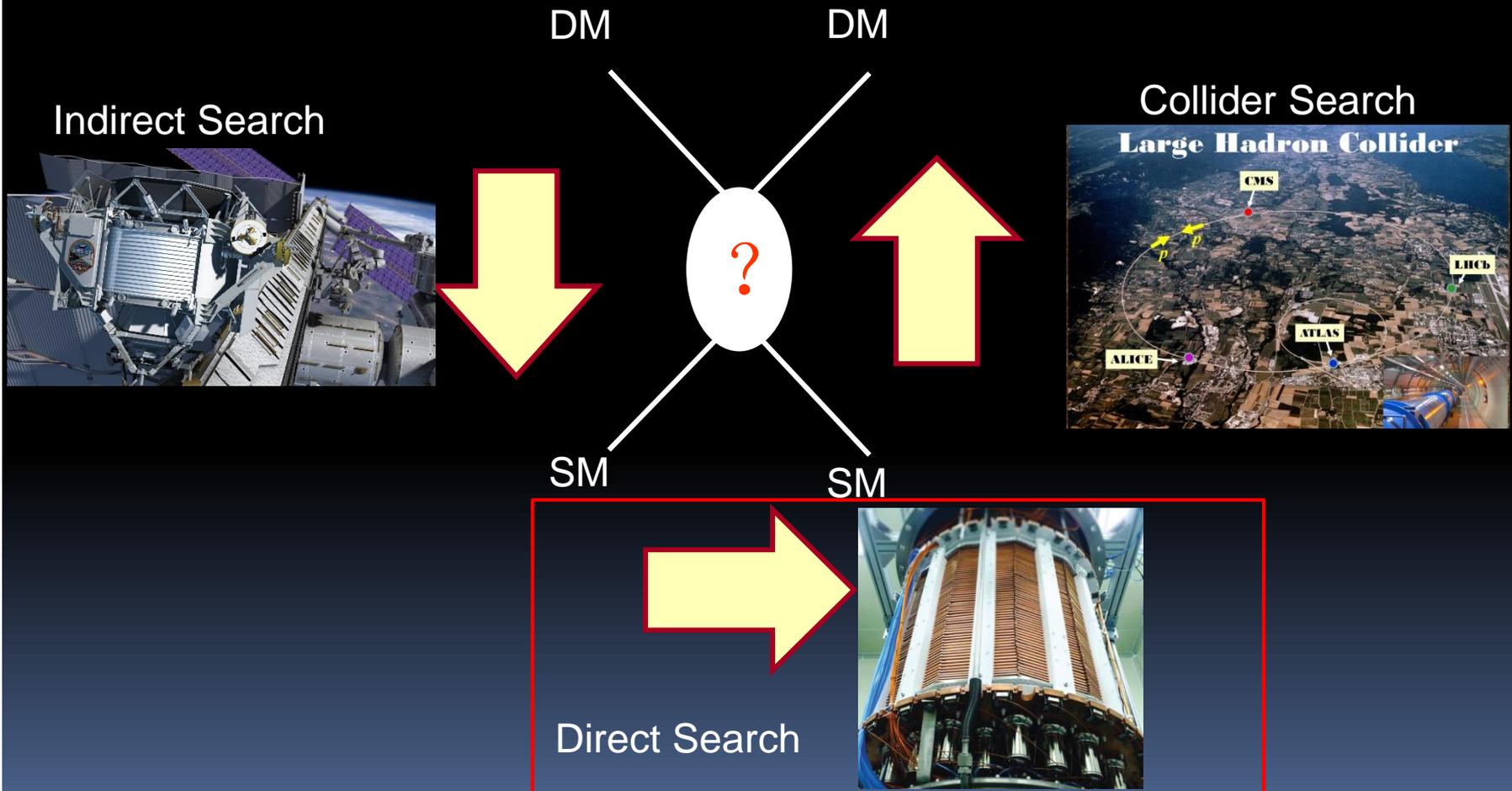




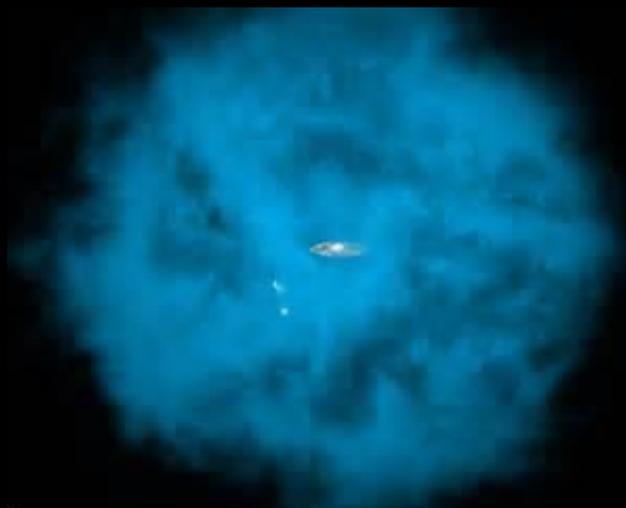
Dark Matter Direct Detection: Status and Prospects

Jianglai Liu
Shanghai Jiao Tong University

If DM particles have non-gravitational interaction with normal matter, can be detected in “laboratories”.



Galactic halo

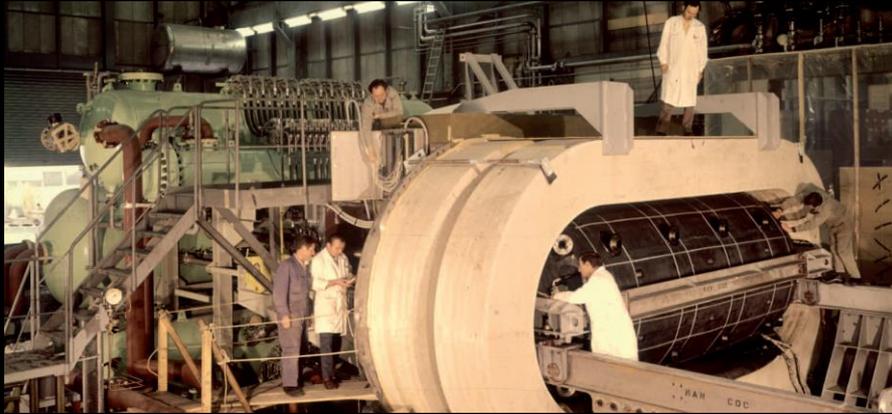


- The solar system is cycling the center of galaxy with on average 220 km/s speed (annual modulation in earth movement)
- DM local density around us: $0.3(0.1) \text{ GeV/cm}^3$ *Astrophys.* 756:89
 - Inclusion of new LAMOST survey data: $0.32(0.02)$, arXiv:1604.01216



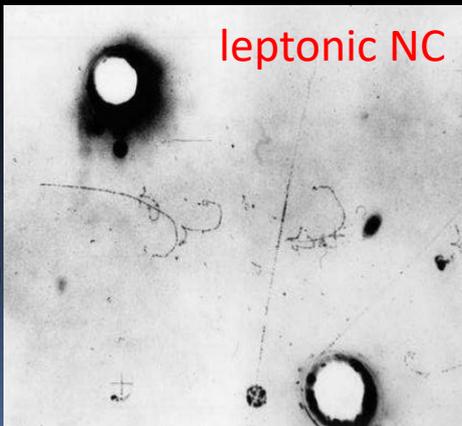
1973: discovery of neutral current

Gargamelle detector in CERN neutrino beam



Dieter Haidt, CERN Courier Oct 2004: *“The searches for neutral currents in previous neutrino experiments resulted in discouragingly low limits (@1968), and it was somehow commonly concluded that no weak neutral currents existed.”*

$\bar{\nu}_\mu$ beam



Direct detection

PHYSICAL REVIEW D

VOLUME 31, NUMBER 12

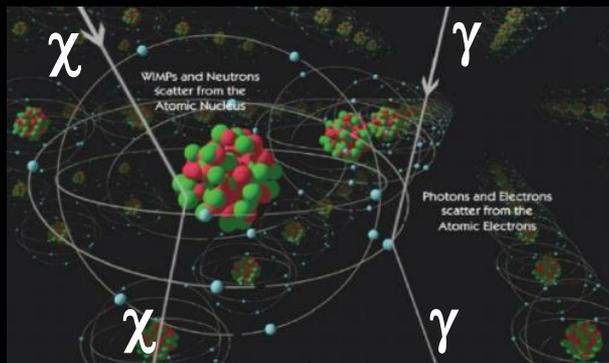
15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten

Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

(Received 7 January 1985)



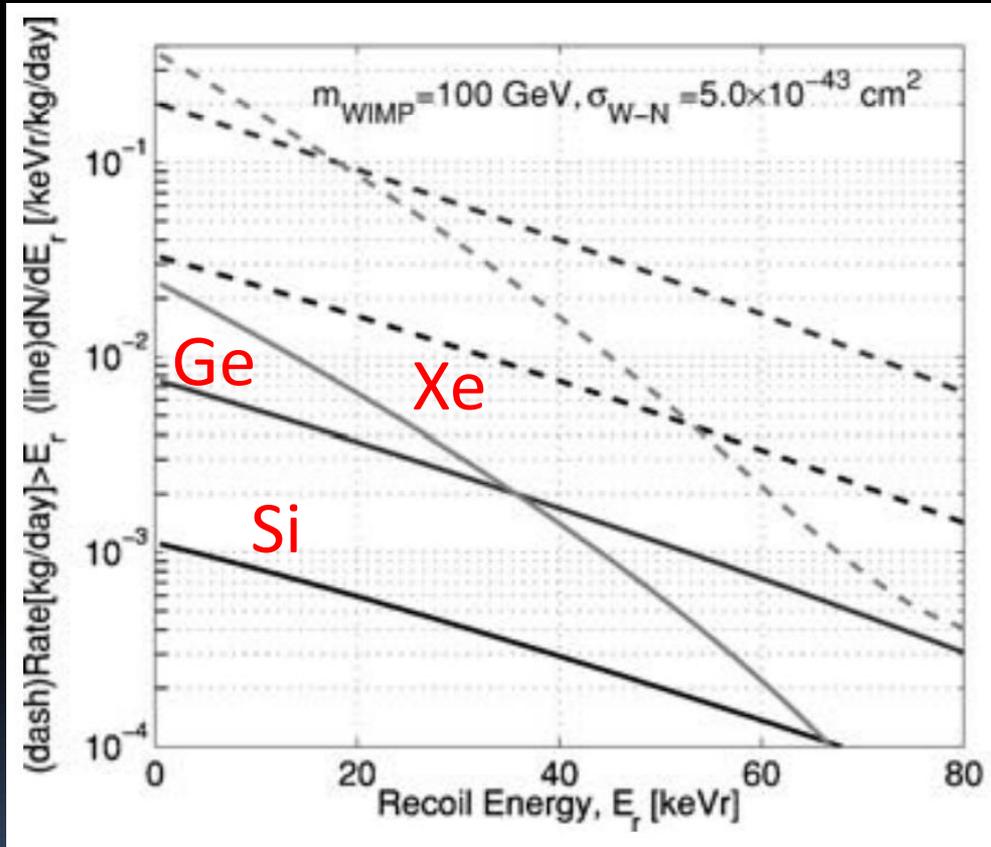
$$E_1 = \frac{E_0}{(1+A)^2} (\cos\theta \pm \sqrt{A^2 - \sin^2\theta})^2$$

$$T = E_2 = \frac{4A}{(1+A)^2} E_0 \cos^2\phi$$

$$A = m_2/m_1$$

- DM: velocity $\sim 1/1500 c$, mass ~ 100 GeV, KE ~ 20 keV
- Nuclear recoil (NR, “hadronic”): recoiling energy ~ 10 keV
- Electron recoil (ER, “leptonic”): 10^{-4} suppression in energy, very difficult to detect
 - New ideas exist, e.g. Hochberg, Zhao, and Zurek, PRL 116, 011301

Elastic recoil spectrum



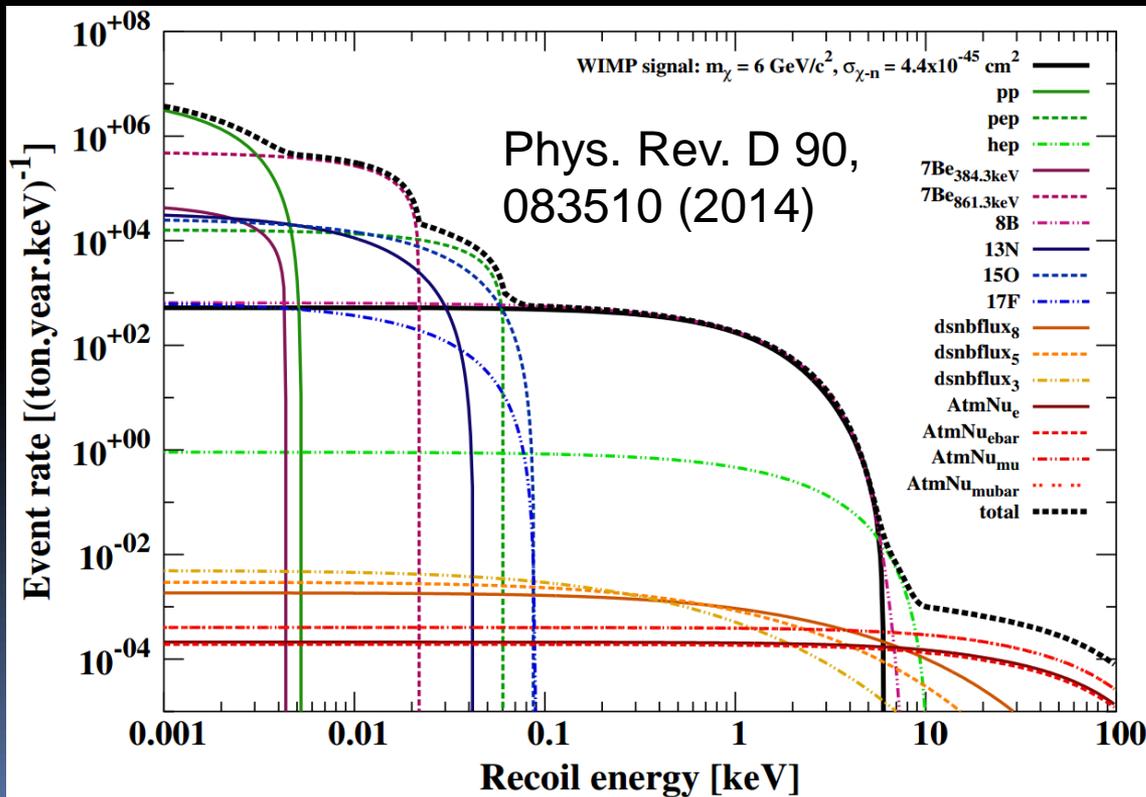
Gaitskell, Annu. Rev. Nucl. Part. Sci. 2004

- Energy threshold \downarrow
 \Rightarrow mass DM \downarrow
- SI: coherent scattering on all nucleons (A^2 enhancement)
- Note, spin-dependent effect can be viewed as scattering with outer unpaired nucleon. No luxury of A^2 enhancement

Neutrino “floor”

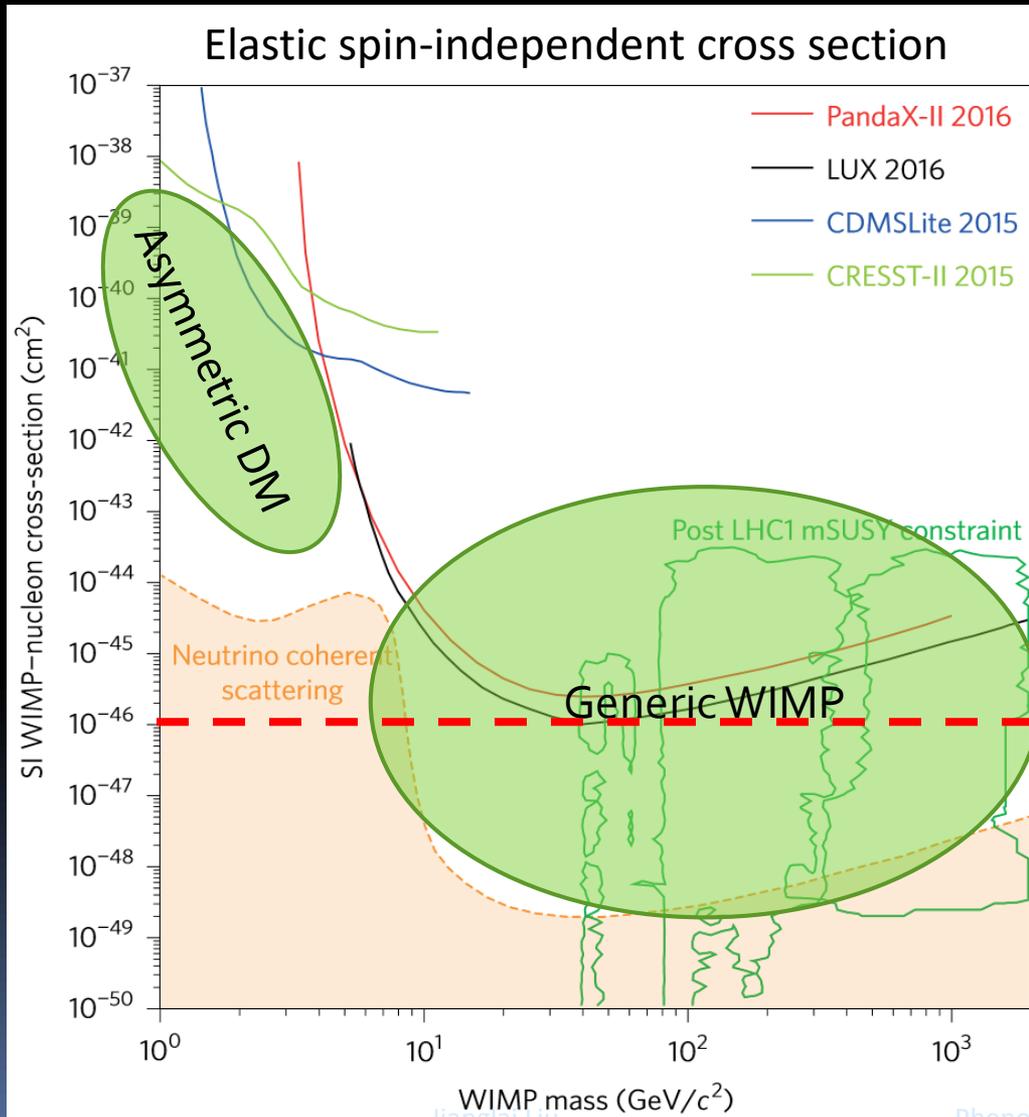
Goodman & Witten

Recently, Drukier and Stodolsky proposed⁵ a new way of detecting solar and reactor neutrinos. The idea is to exploit elastic neutral-current scattering of nuclei by neutrinos (a mechanism that is also believed to play an important role in supernovas).⁶ The detector will consist of su-



Ideas do exist how to go beyond this “floor” (directional, annual modulation, etc), but the pragmatic issue is still how to get there

Available hiding space for DM

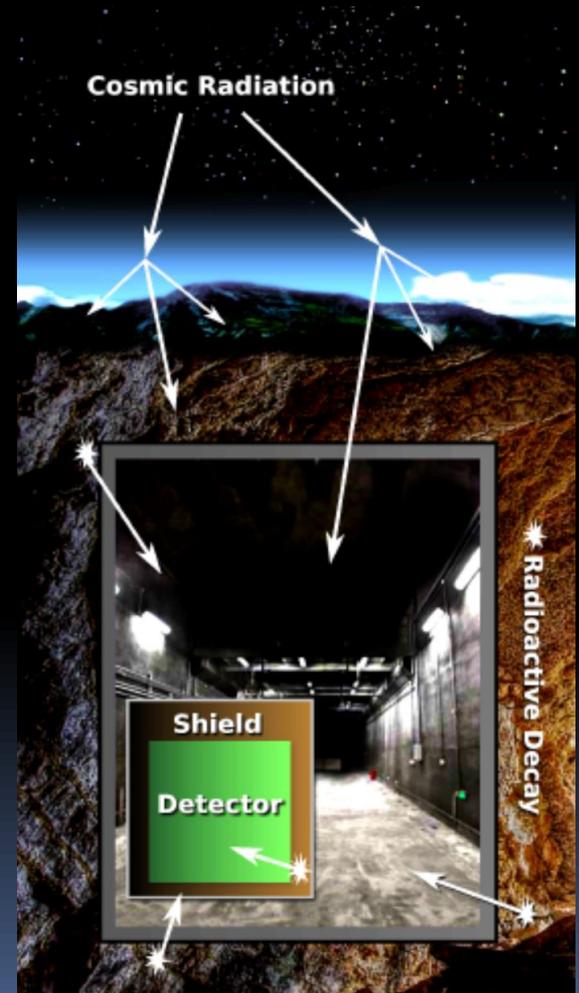


a few
events/100kg/year

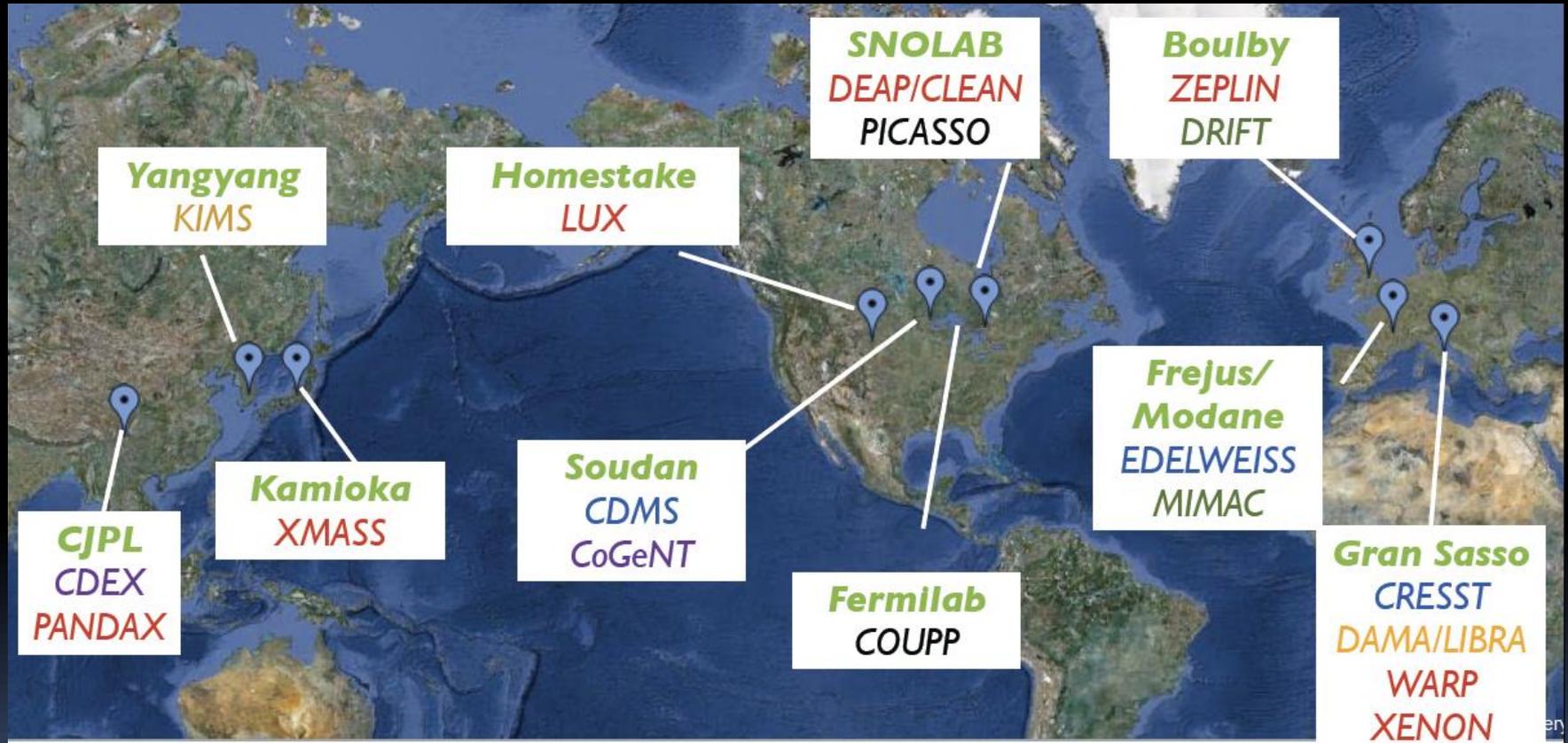
Nature Physics 13, 212–
216 (2017)

Name of the game: background

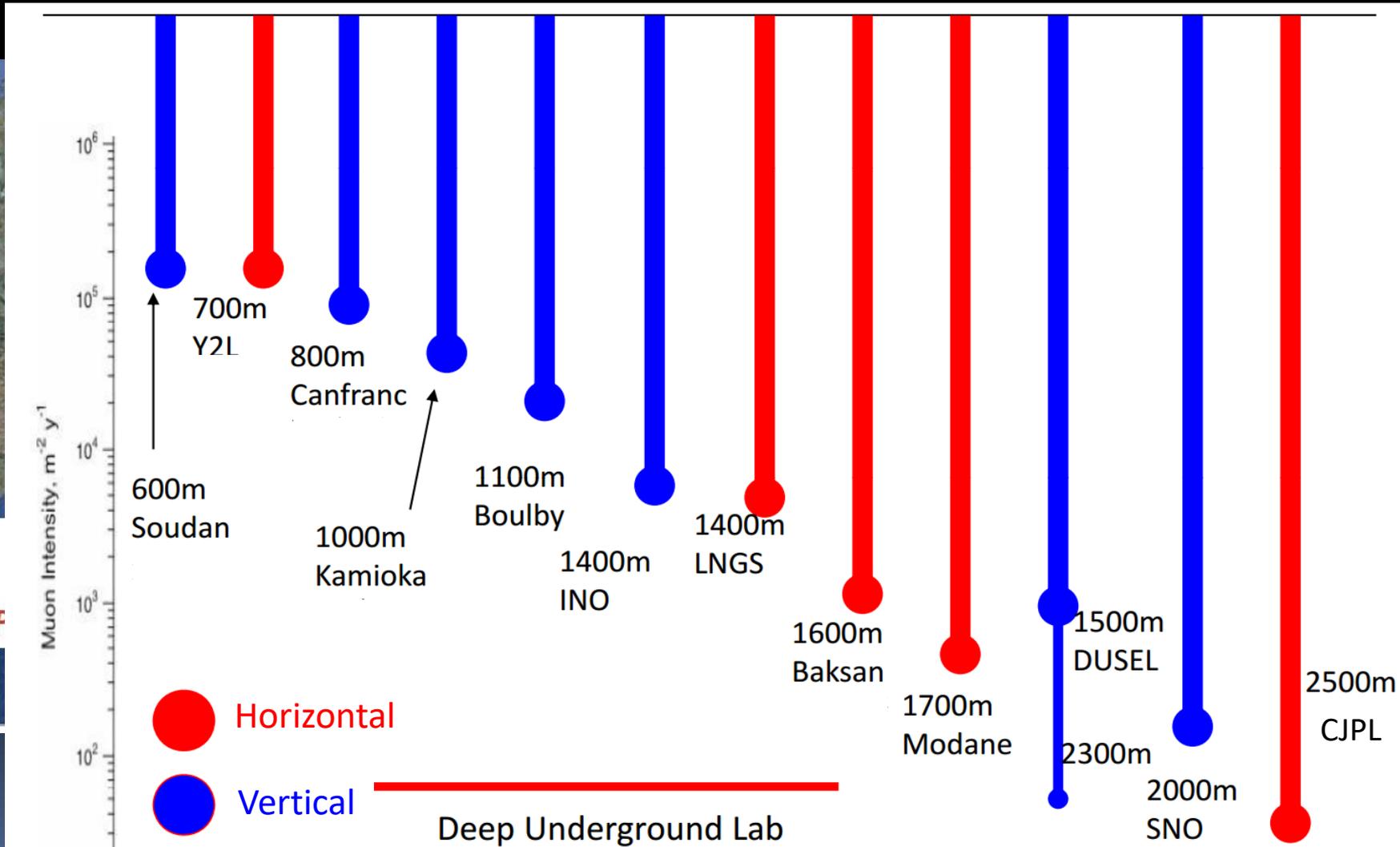
- Assume: 1 nucleus in our body is hit per year!
- But our body is hit 10^8 /day by environmental background radiation!
- Hide detector in deep underground lab, and put massive shield



A “dark matter rush”

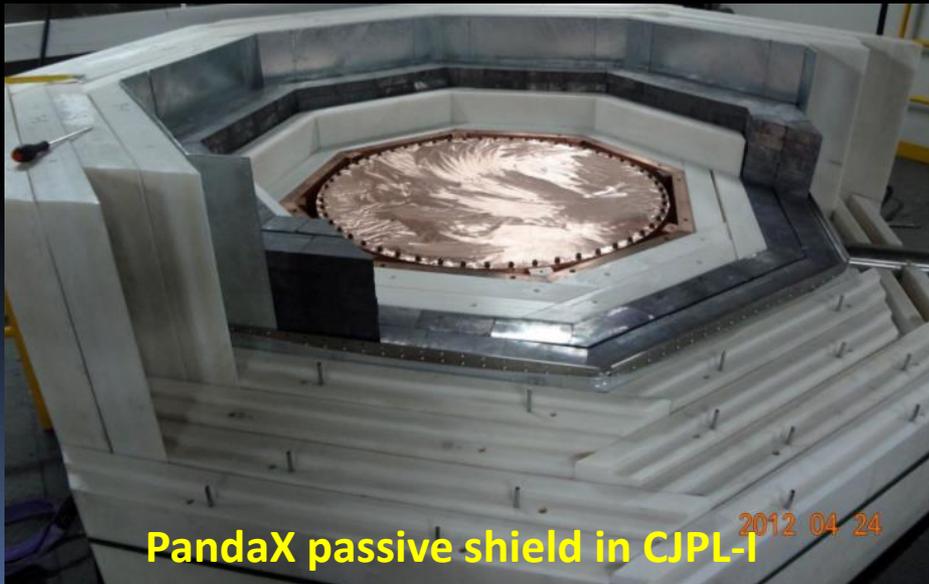


A “dark matter rush”

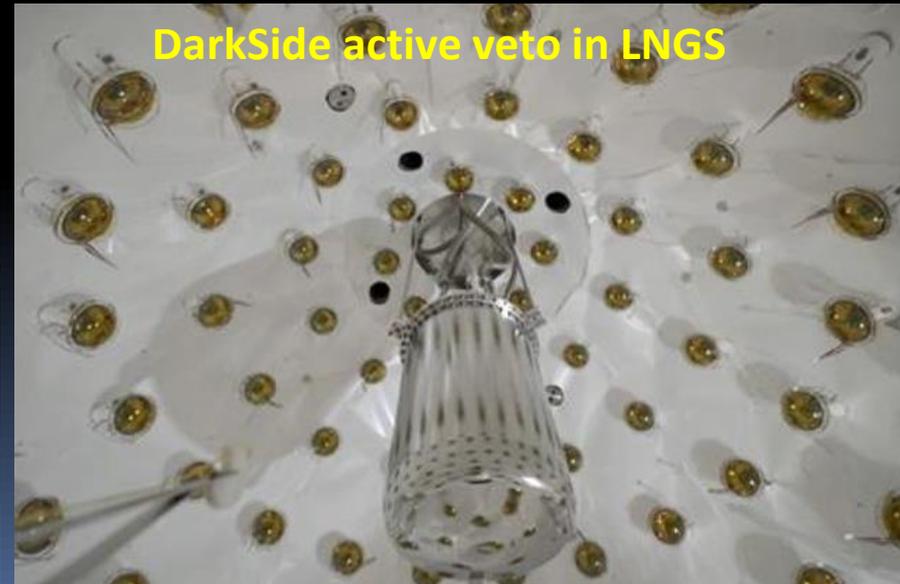


Background: external

- Cosmogenic background hugely suppressed in underground labs
- External background (gamma ray and neutrons) can be shielded or vetoed



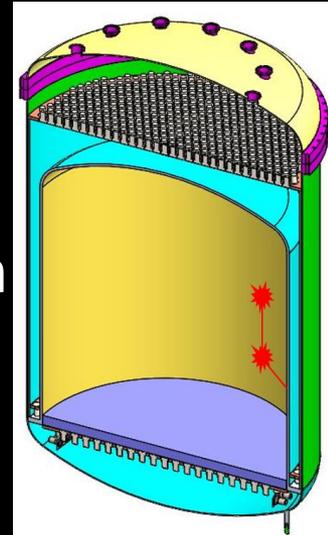
Jianglai Liu



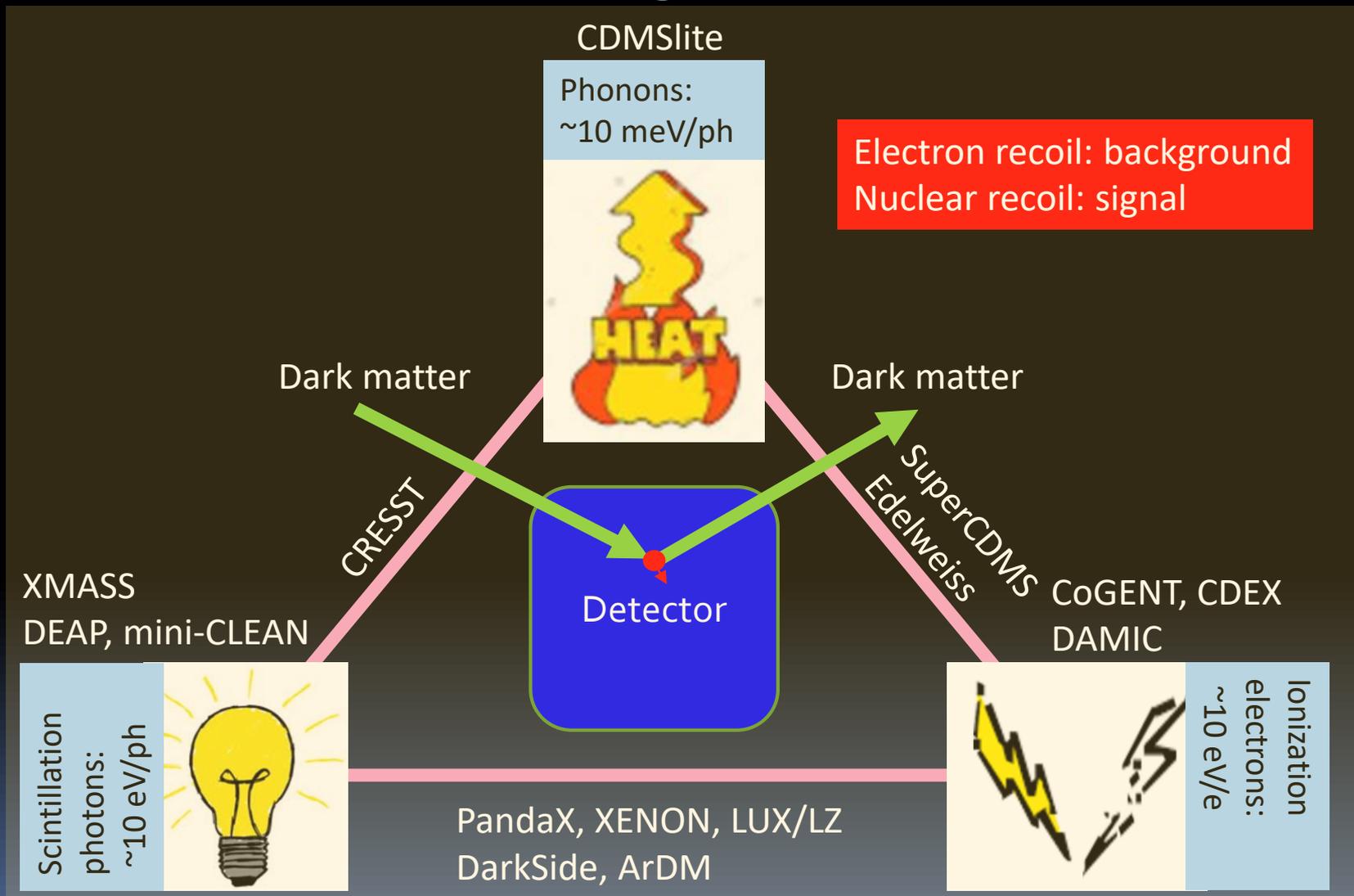
Pheno 2017

Background: internal

- Detector components (gammas/neutrons)
 - Cluster @ boundary
 - Multi-site
 - Low energy scatter deep in target without high E scattering in outskirts further suppressed!
 - ⇒ “self-shielding” if reconstruct vertex
 - ⇒ power of monolithic large detector
- (Uniform) background in target, e.g. Rn, Kr
- Crucial: further ways to suppress ER background (light/charge ratio, pulse shape, etc ...)



Detection technologies*



* with representative experiments, not meant to be complete

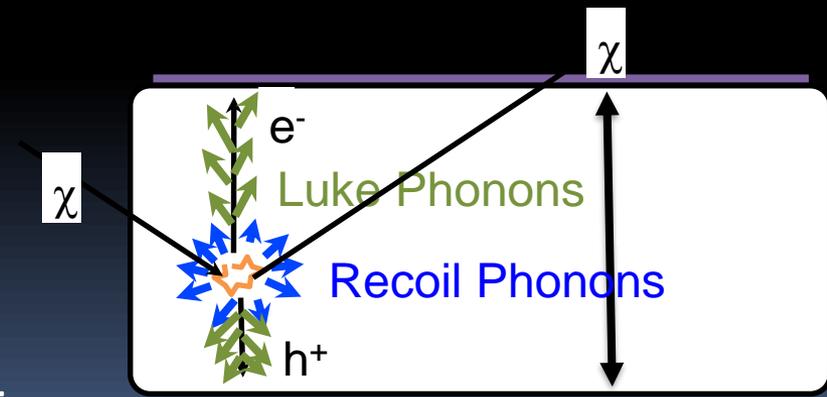
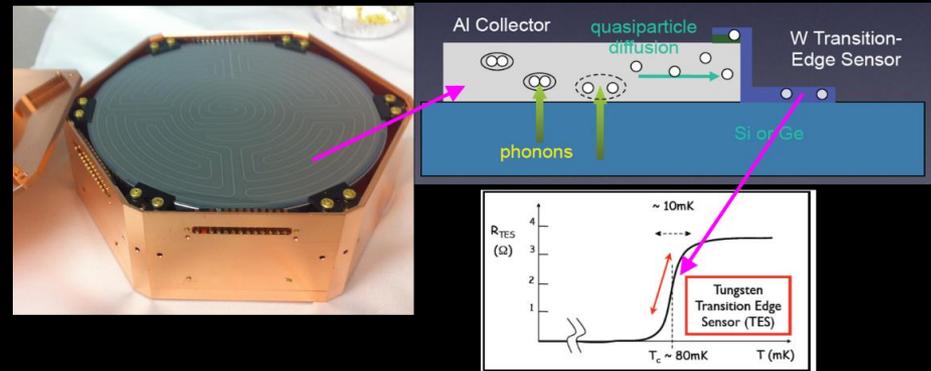
Cryogenic **low threshold** detector

Cost per kg	Very high*
Difficulty in target scaling	Moderate: build arrays
Radioactive isotope	Ge/Si can be very pure
Position reconstruction ability	iZIP: yes via interdigitated electrodes Surface/volume available via PSD
Self shielding	Moderate: not monolithic, surface background important
ER background suppression	Excellent if phonon and ionization detection 10^{-6}
RoI	Low mass WIMPs

* difficult to give \$/kg due to significant cost on processing/fabrication.

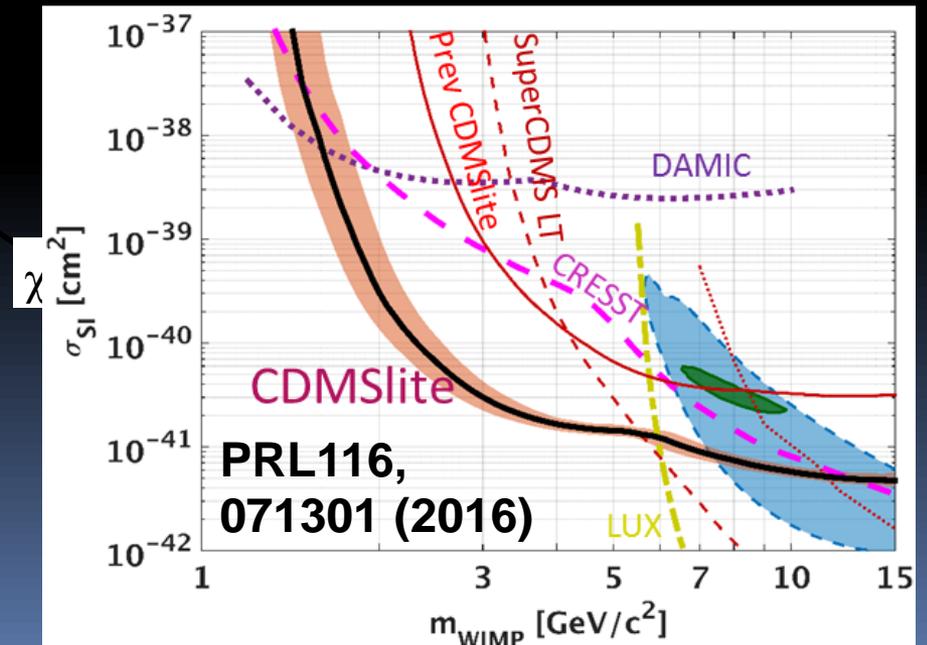
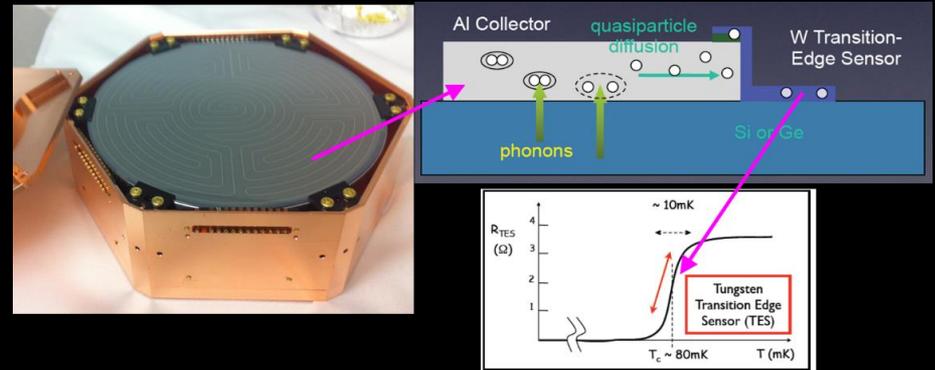
SuperCDMS @ Soudan

- Solid-state Ge and Si detectors at < 50 mK. detect ionization and phonon signals from dark matter nuclear recoil scattering
- CDMSlite: larger bias boosts phonon signals from drifting charges \Rightarrow low energy thresholds, excellent resolution, but no discrimination

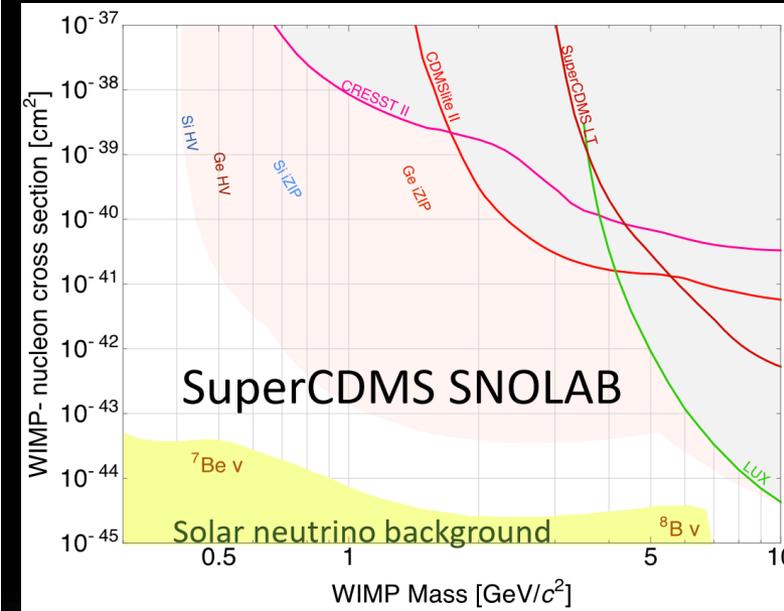
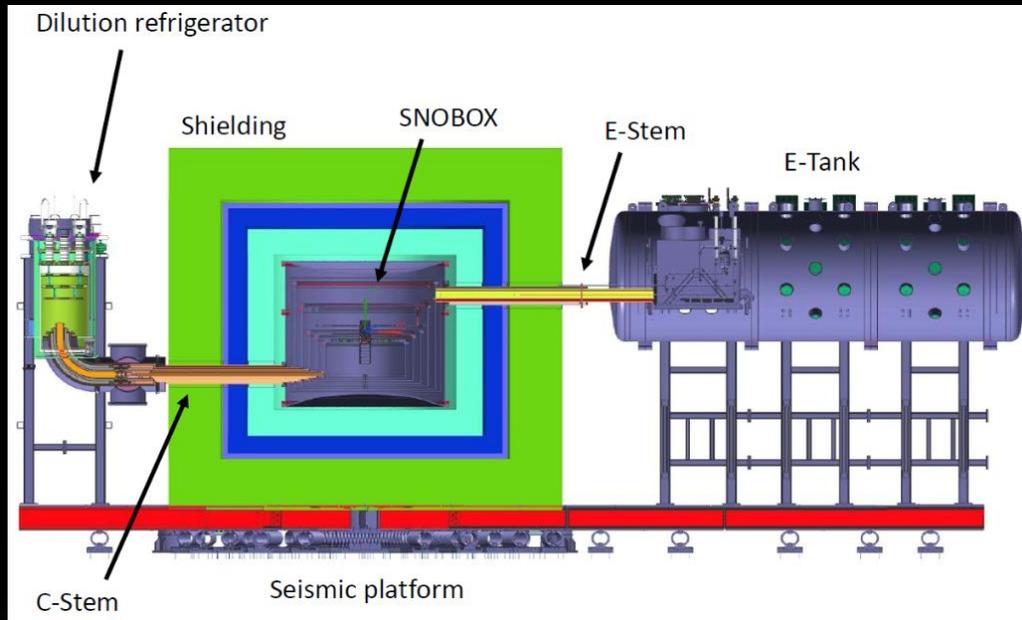


SuperCDMS @ Soudan

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SuperCDMS: Soudan to SNOLAB

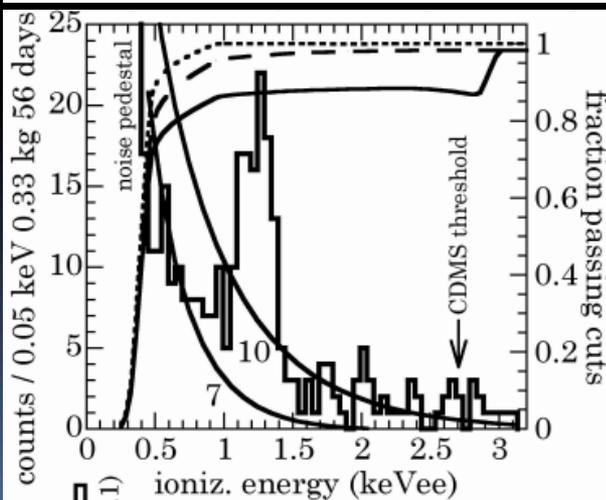


Designing new SuperCDMS (G2, ~ 100 kg) experiment for the deeper and cleaner SNOLAB underground laboratory in Canada (operation @ 2020)

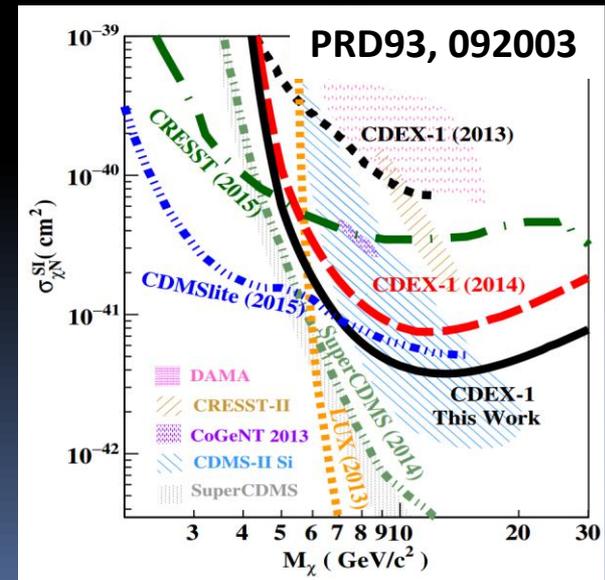
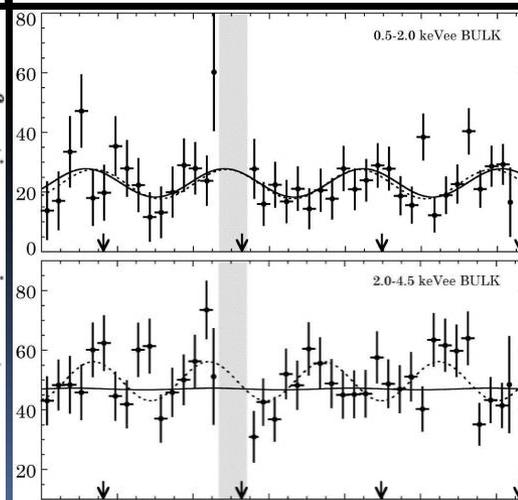
Point-contact Ge

- LN2 temperature, pure ionization channel
- Point-contact detector (small cap \sim pF: **low electric noise**)
- CoGENT (Soudan, positive, with annual modulation) and CDEX (CJPL, negative). CDEX long exposure measurement of annual modulation ongoing.

PRL106 (2011) 131301



arXiv:1401.3295



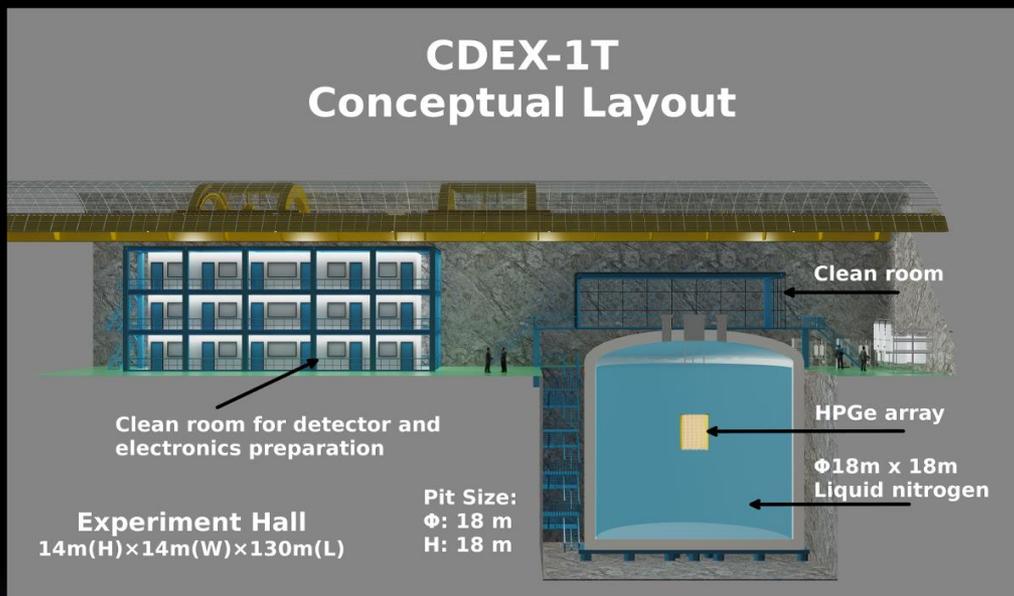
CDEX-10 to CDEX-1T

10-kg CDEX ongoing

longer term plan of a ton-scale Ge experiment CJPL-II

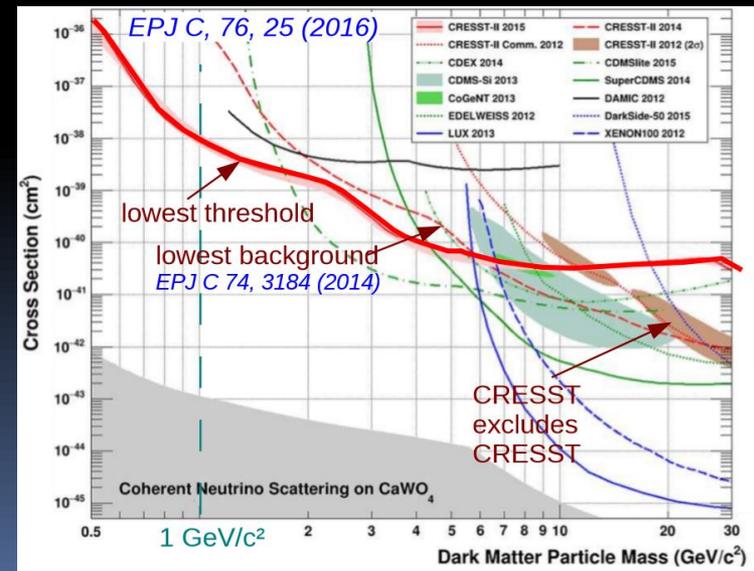
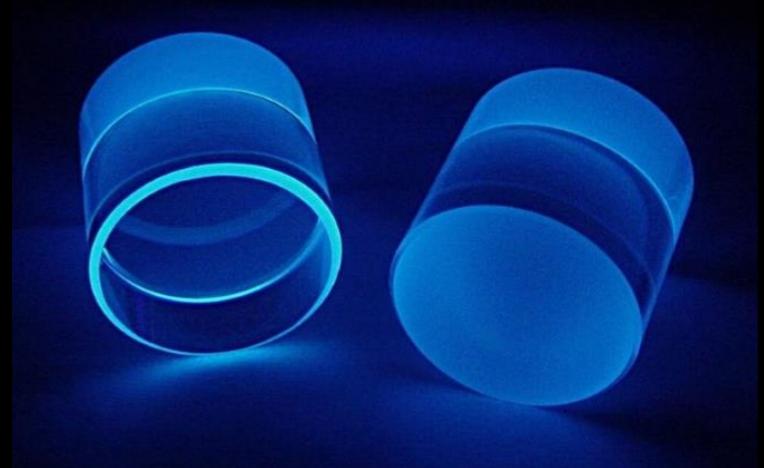


Jianglai Liu



CRESST @ LNGS: low mass record

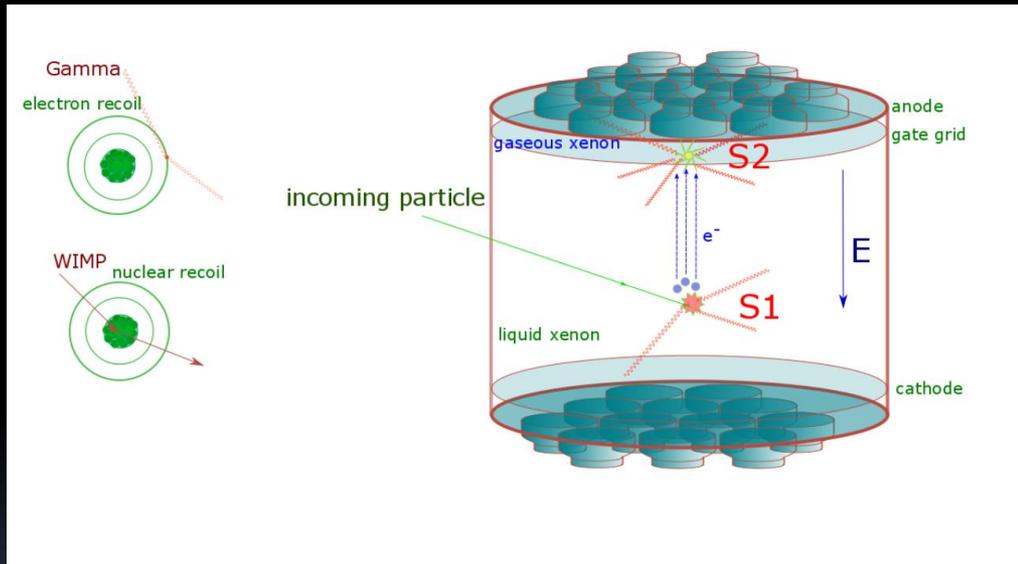
- CaWO₄ crystals (10 mK)
➔ phonon & photons
- 300 eV_{nr} achieved in CRESST-II
- CRESST-III with lower mass (24 g) started commissioning 2016, threshold ~50 eV_{nr} achieved



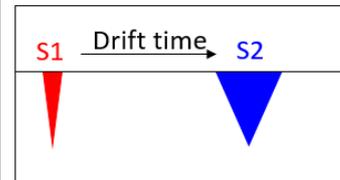
Xe detector

Cost per kg	High: ~\$1500/kg (material only)
Difficulty in scaling	Easy: monolithic
Radioactive isotope	Very pure except ^{136}Xe , other than short lived cosmogenic isotopes
Position reconstruction ability	TPC: excellent (few mm) Single phase: ~cm
Self shielding	Excellent
ER background suppression	TPC: good with charge/light ratio 0.5% Single phase: moderate with PSD
RoI	Medium to high mass WIMPs

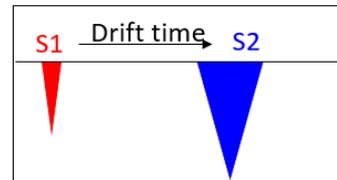
Dual phase xenon experiments



Dark matter: nuclear recoil (NR)

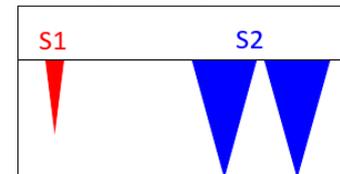


γ background: electron recoil (ER)



$$(S2/S1)_{NR} \ll (S2/S1)_{ER}$$

Multi-site scattering background (ER or NR)



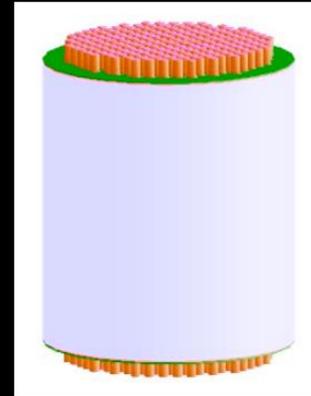
PandaX @ CJPL



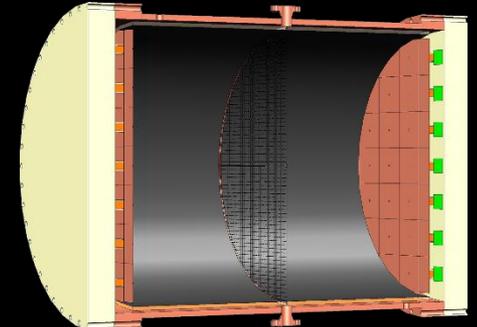
PandaX-I: 120 kg
DM experiment
2009-2014



PandaX-II: 500 kg
DM experiment
2014-2018



PandaX-xT:
multi-ton (~4-T)
DM experiment
Future



PandaX-III: 200 kg to
1 ton HP gas ^{136}Xe
OvDBD experiment
Future

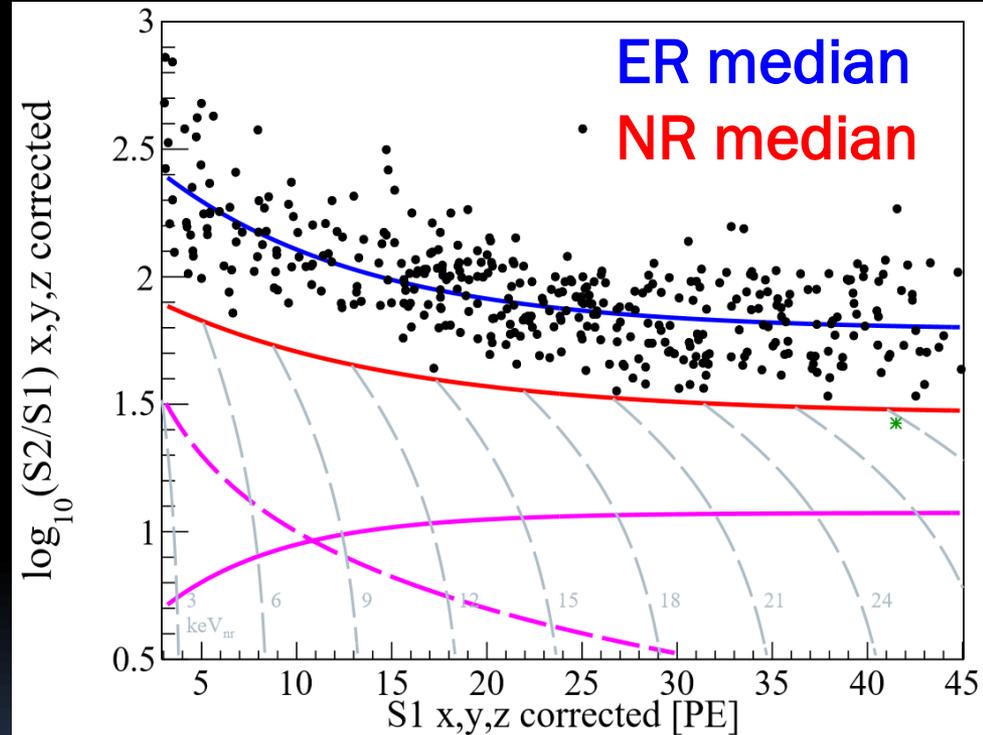
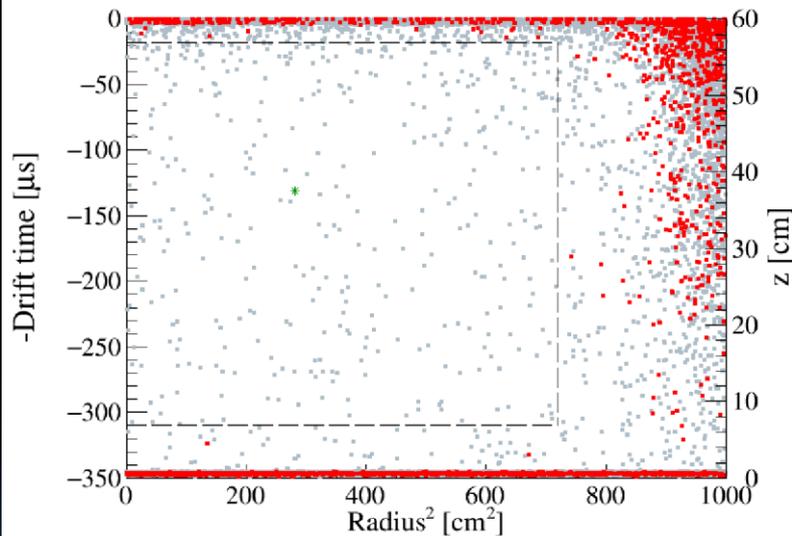
CJPL-I

CJPL-II

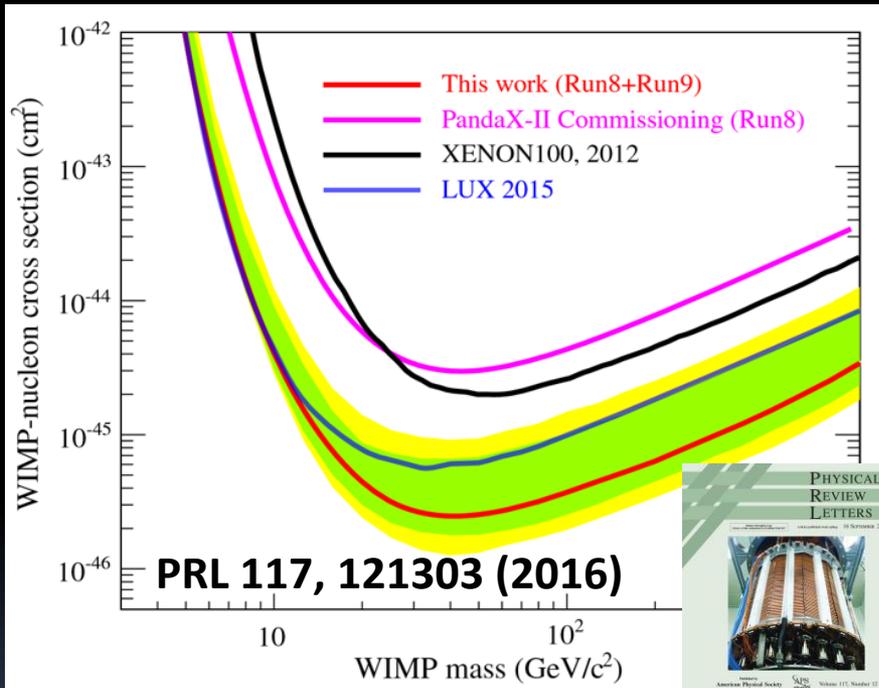
 **PANDA X** = Particle and Astrophysical Xenon Experiments

Example: background suppression

Gray: all
Red: below NR median
Green: below NR median and in FV



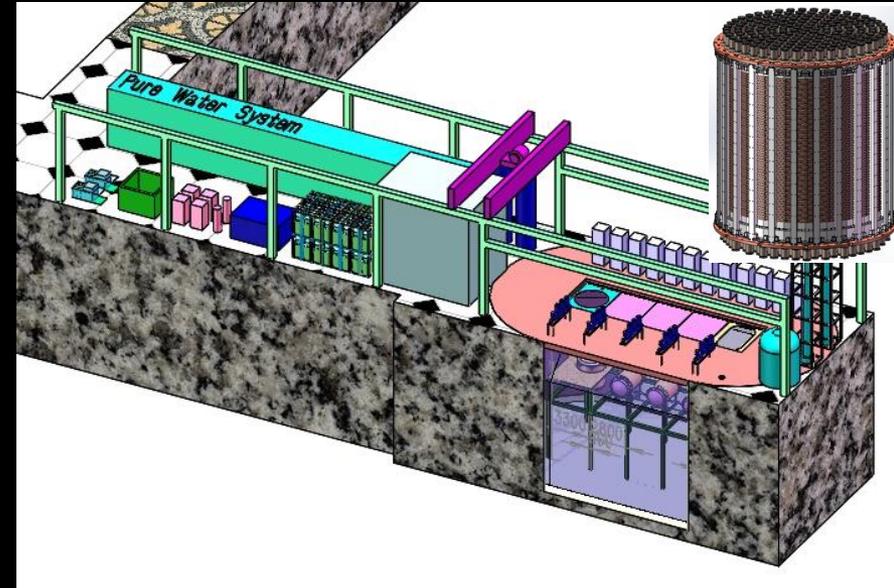
PandaX-II Dark Matter Run



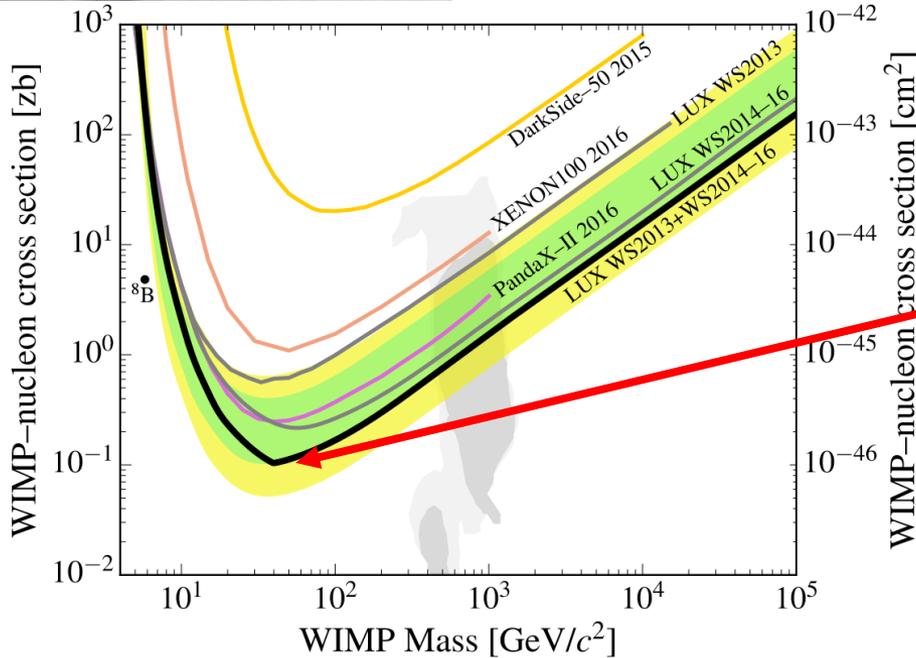
- First low background run concluded June 2016 with 33,000 kg-day exposure. Minimum elastic SI exclusion: $2.5 \times 10^{-46} \text{ cm}^2 @ 40 \text{ GeV}/c^2$
- After the first low background run, experienced some difficulties in background control, which cost an extended down time
- Now taking dark matter data under an excellent running condition.

PandaX-xT Experiment

- Preparing new experiments in CJPL-II, hall #B2 (civil completed late 2016)
- Intermediate stage:
 - PandaX-4T (4-ton target) with SI sensitivity $\sim 10^{-47} \text{ cm}^2$
 - On-site assembly and commissioning: 2019-2020
- Eventual goal: G3 xenon dark matter detector ($\sim 30\text{T}$) in CJPL to “neutrino floor” sensitivity



LUX @ Sanford

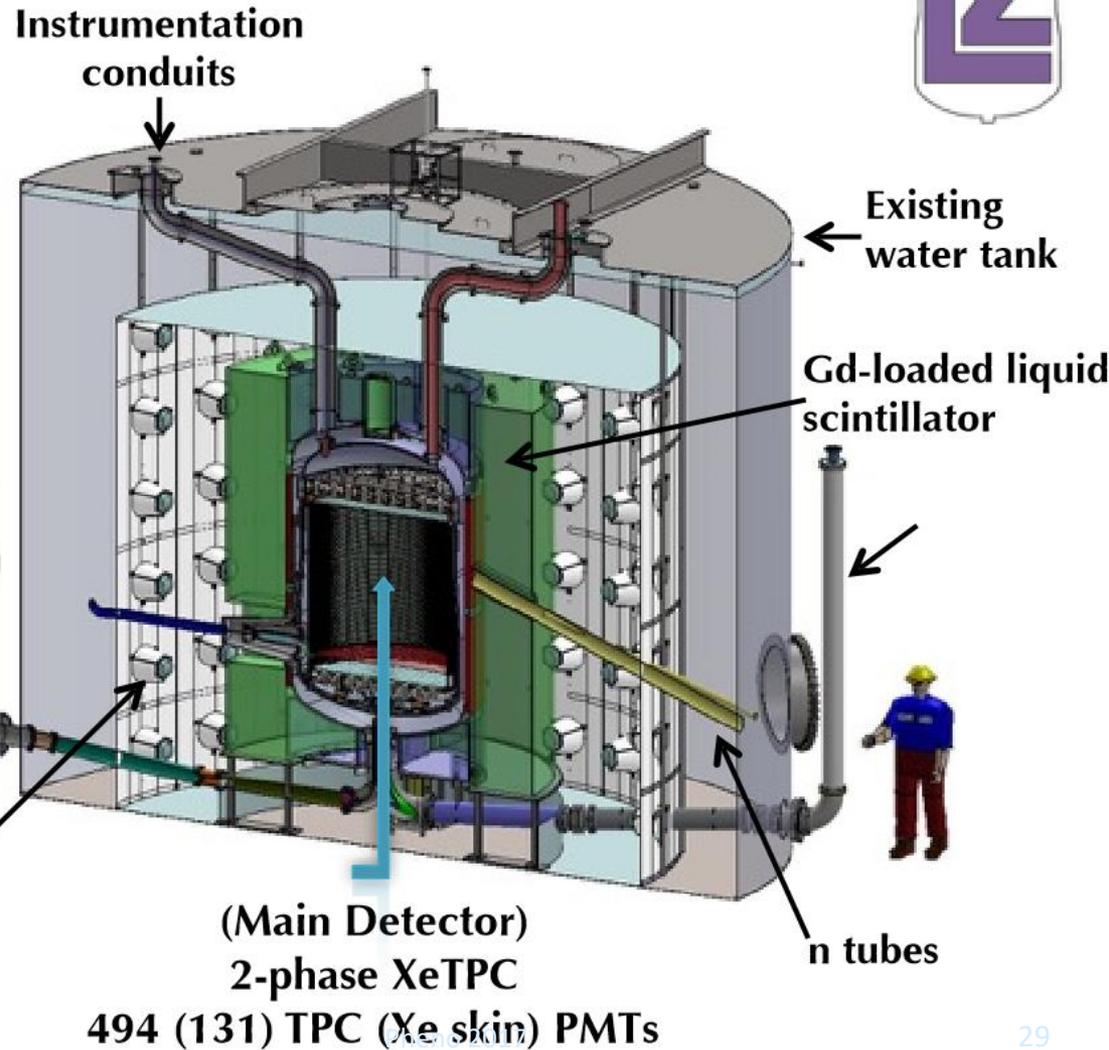


- Combination of both science runs (95+332 live-days)
- World leading SI cross section limit, $1.1 \times 10^{-46} \text{ cm}^2 @ 50 \text{ GeV}/c^2$, **PRL 118, 021303**
- Excludes significant portions of the 1-sigma regions for WIMPs favored by certain SUSY models.

The LUX-ZEPLIN Experiment



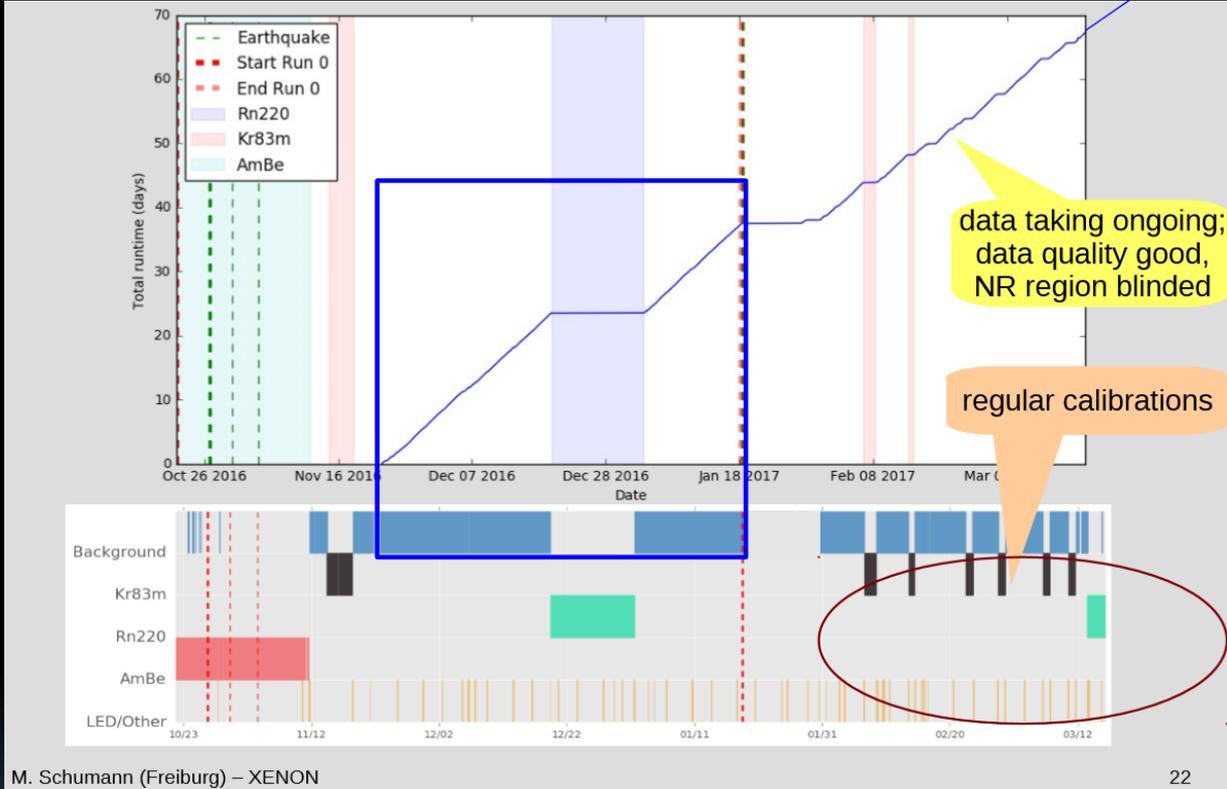
- Turning on by 2020 with 1,000 initial live-days plan
- In the same location of LUX
- 10 tons total, 7 tons active, ~5.6 ton fiducial
- Unique triple veto system



XENON1T @ LNGS



largest LXe TPC ever built
 cylinder: 96 × 97 cm
 active LXe target: 2.0t (3.2t total)
 248 PMTs (Hamamatsu R11410-21)



- First science run data taking completed with ~35 live-days!
- Data release expected very soon!

XENON1T → XENONnT

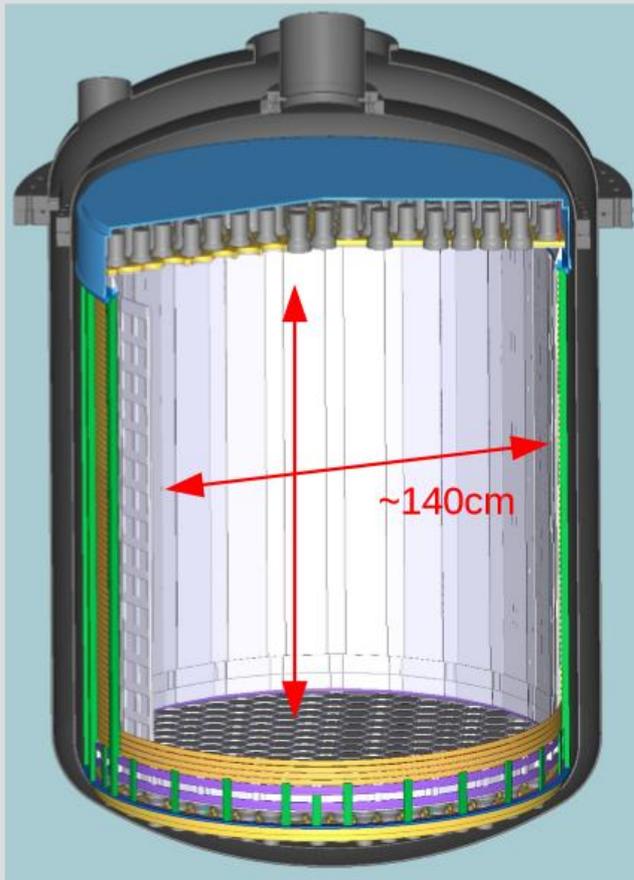
JCAP 04, 027 (2016)

XENON1T

- 2t active LXe target
- operating in DM mode
- first results soon

XENONnT

- 6t active target
- projected to start science in 2019



Already existing/operational:

- Muon Veto
- Cryostat Support
- Outer Cryostat
- in-LXe Cabling
- LXe storage system
- Cryogenic system
- Purification system
- Kr removal
- DAQ
- 95% of Electronics
- Calibration System
- 260 PMTs
- >8t of LXe
(was 4.5t one year ago!)
- Screening facilities
- dedicated nT funding

Already started:

- 230 new PMTs ordered
- TPC/Cryostat design
- first material orders
- Screening campaign
- Neutron veto studies
- 2nd storage vessel ordered
- Rn reduction system design
- purification improvements
- etc.

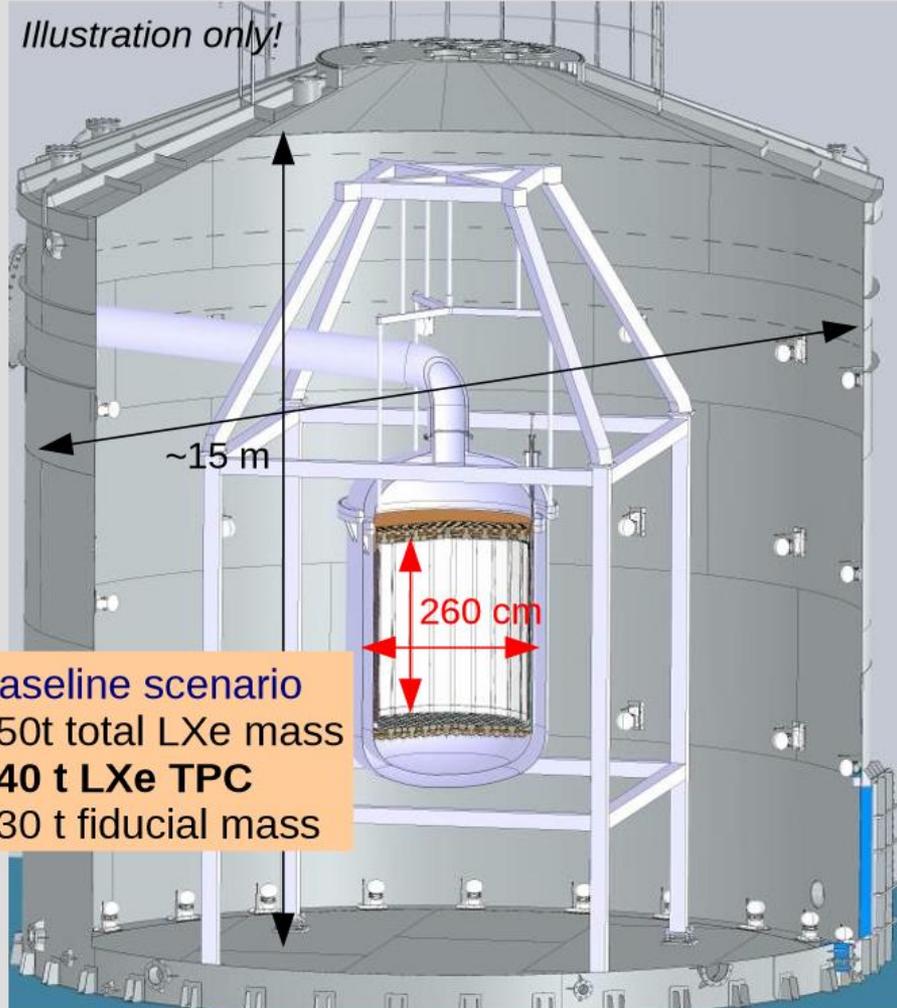
DARWIN The **ultimate** WIMP Detector

arXiv:1606.07001



LXe

Illustration only!

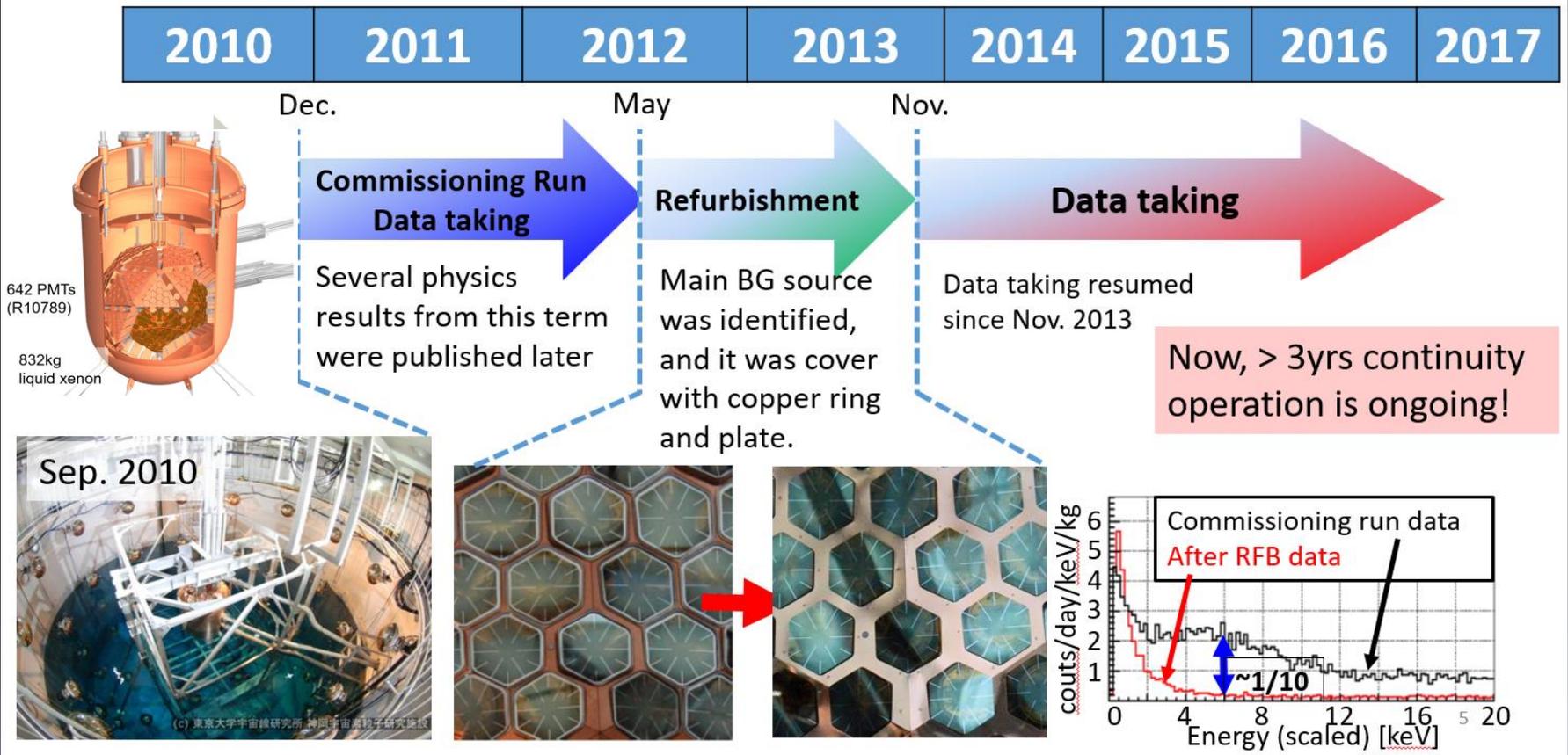


Baseline scenario
~50t total LXe mass
~40 t LXe TPC
~30 t fiducial mass

- aim at **sensitivity of a few 10^{-49} cm²**, limited by **irreducible v-backgrounds**
- international consortium, 21 groups
→ R&D ongoing
- DARWIN is sensitive to
 - spin-independent,
 - spin-dependent,
 - inelastic WIMP interactions;
 - axions, ALPs
- supernova neutrinos
- CNNS
- low- E solar neutrinos
- neutrinoless double-beta decay
- other rare nuclear processes...
- Timescale: start after XENONnT

www.darwin-observatory.org

XMASS @ Kamioka

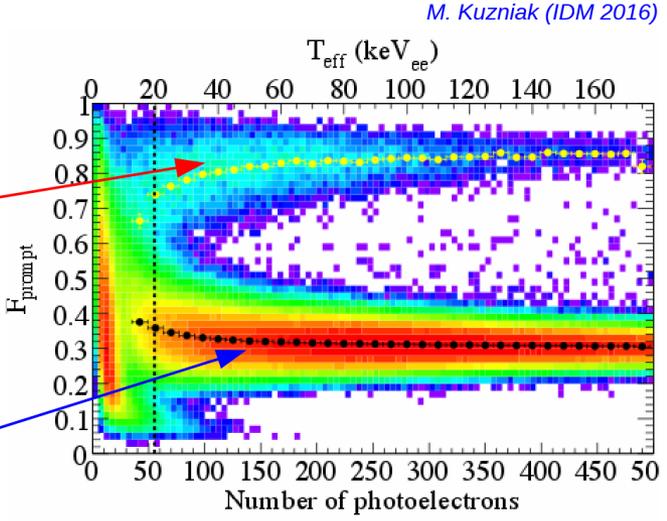
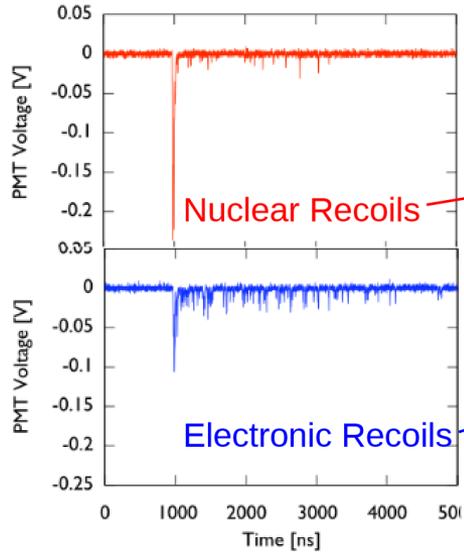
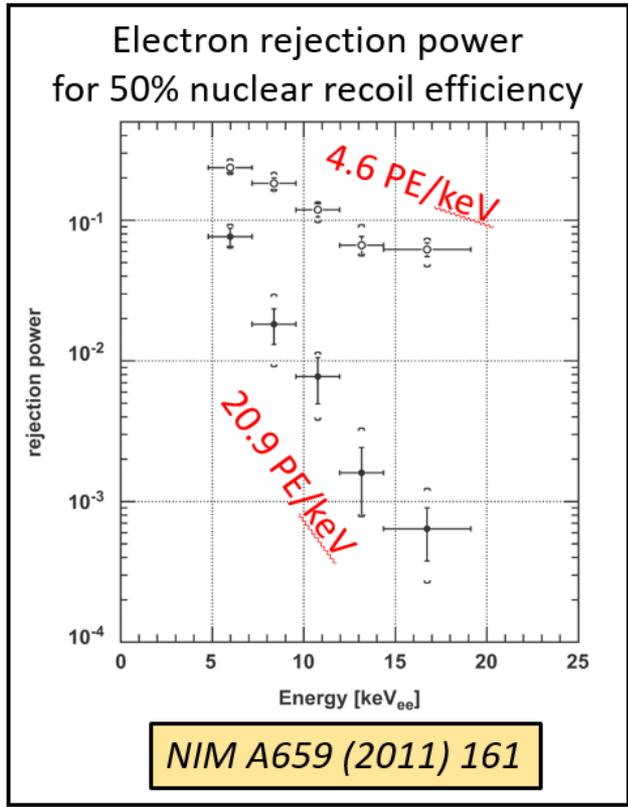


A. Takeda, XeSAT 2017

XMASS @ Kamioka

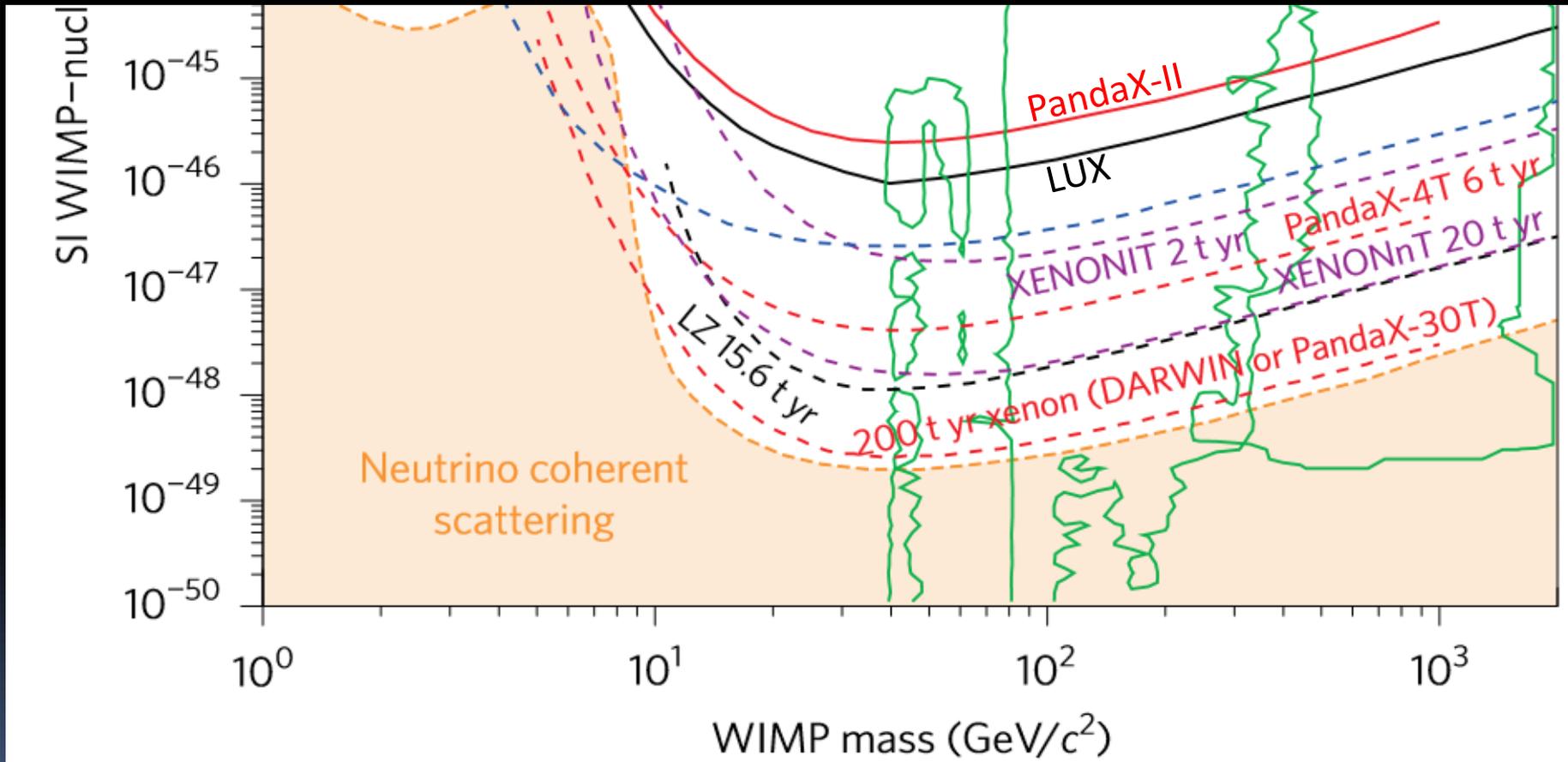


Dec. **PSD study with a small setup**



A. Takeda, XeSAT 2017

Xenon experiments: current and future

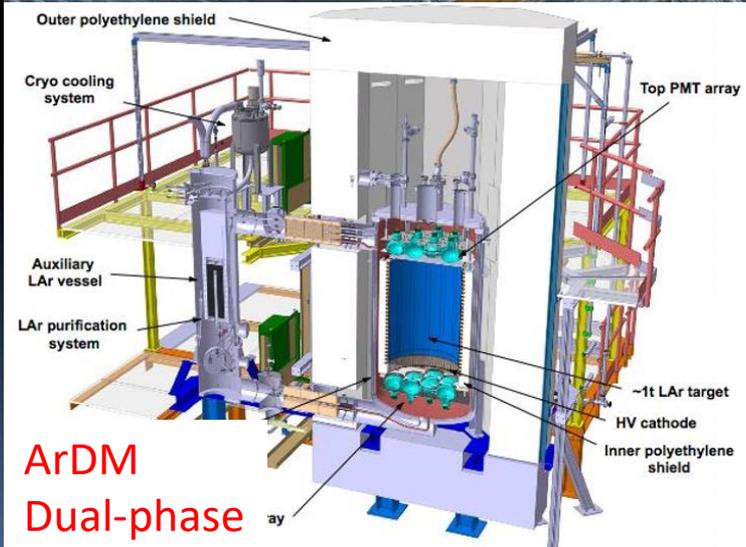


Nature Physics 13, 212–216 (2017)

Liquid Argon as detector

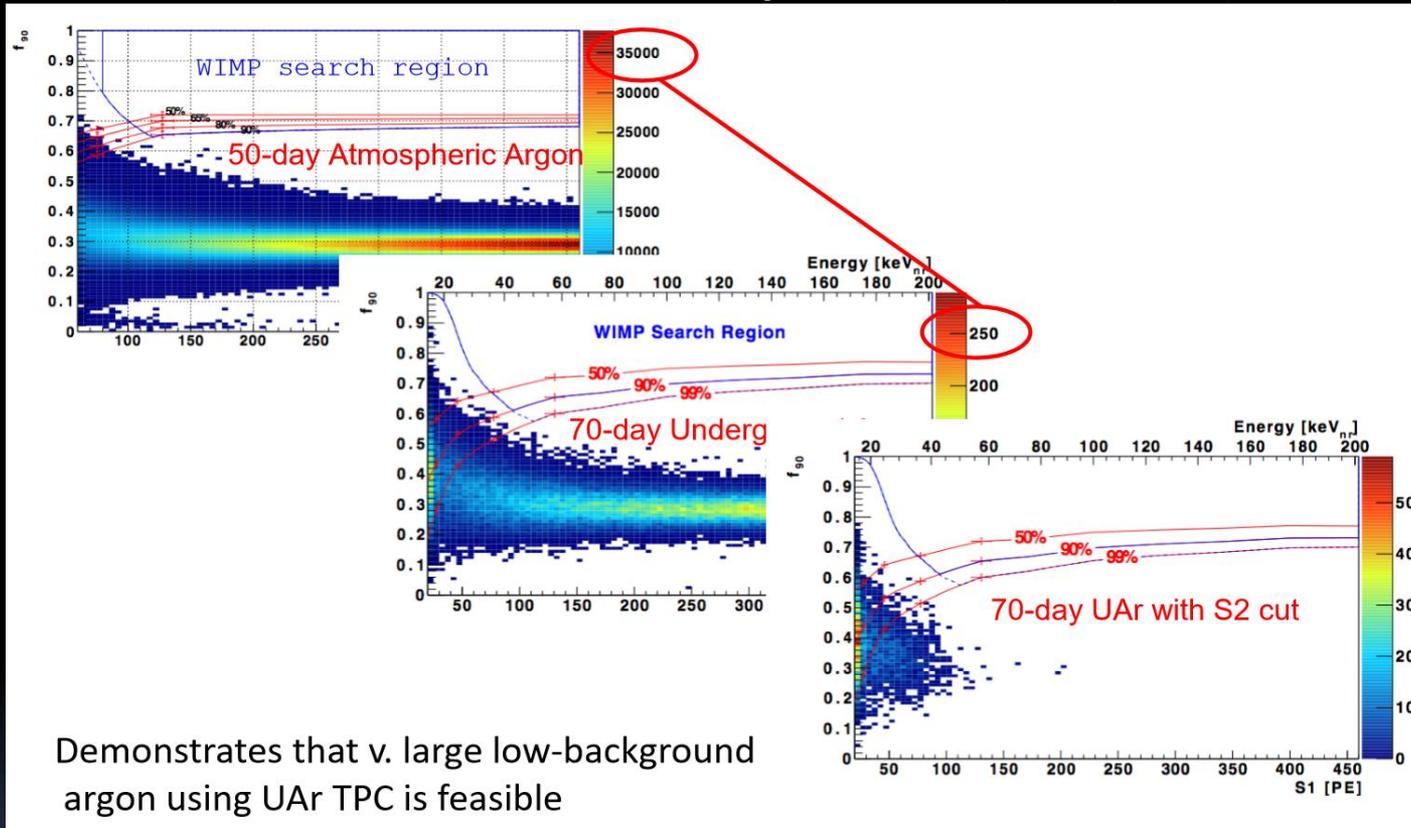
Cost per kg	cheap
Difficulty in scaling	Easy (monolithic detector)
Radioactive isotope	^{39}Ar (1Bq/kg) except using underground Ar (UAr)
Position reconstruction ability	TPC: excellent (few mm) Single-phase: yes (cm)
Self shielding	Good
ER background suppression	Excellent via PSD (10^{-8}), additional in TPC
Energy threshold	High (needed for PSD)

Argon world running program



DarkSide-50

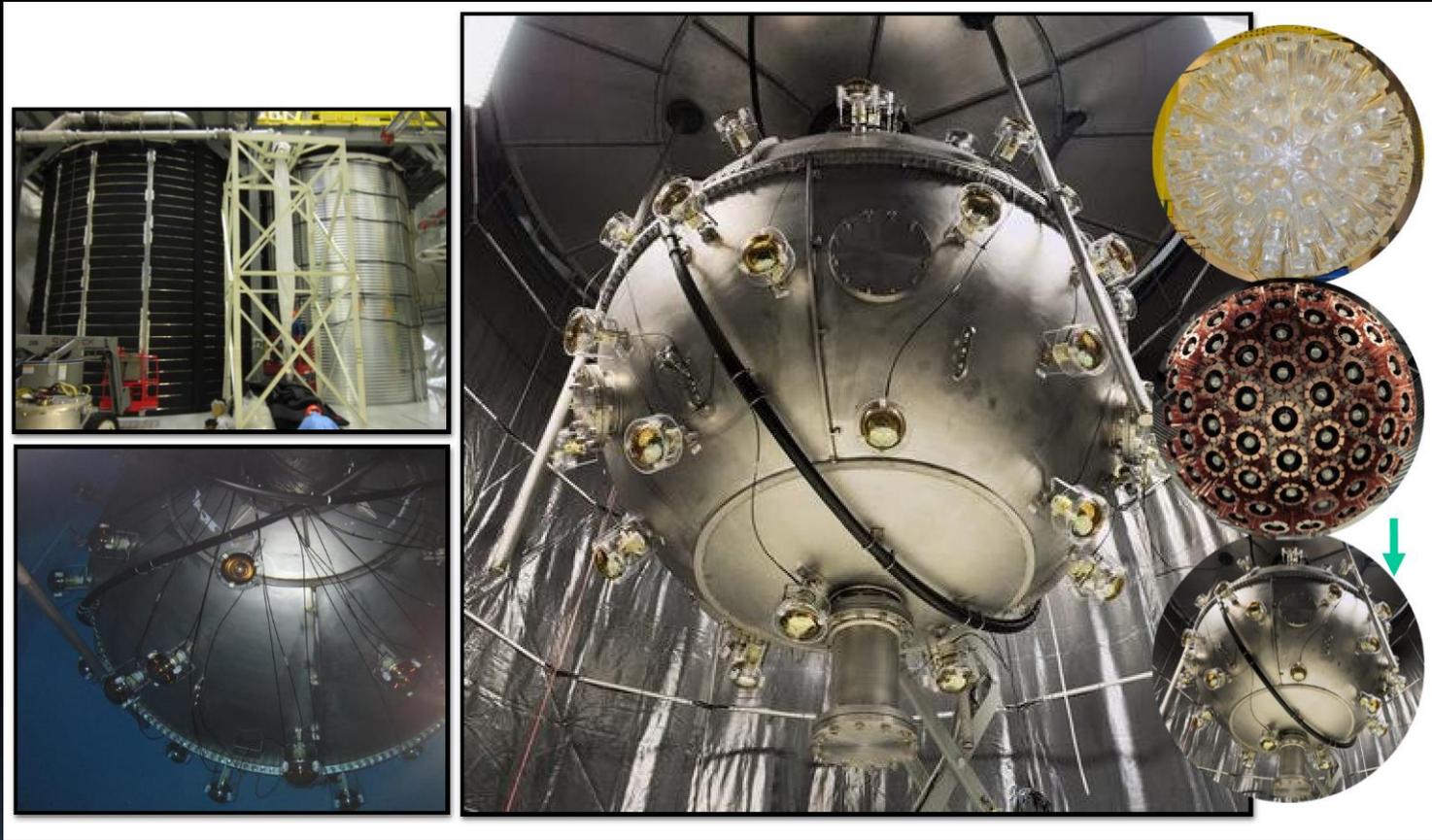
Phys.Rev. D93 (2016) no.8, 081101



Demonstrates that v. large low-background argon using UAr TPC is feasible

- Pioneered the use of underground Ar
- Demonstrated UAr can reduce ^{39}Ar by 1400 times
- S2/S1 cuts further suppresses background

DEAP-3600@ SNOLAB: 3.6-ton Ar



- Commissioning completed
- Collecting data since late 2016. Sensitivity will reach LUX limit by 2017

Next stage world Ar program

(New) Argon Collaboration

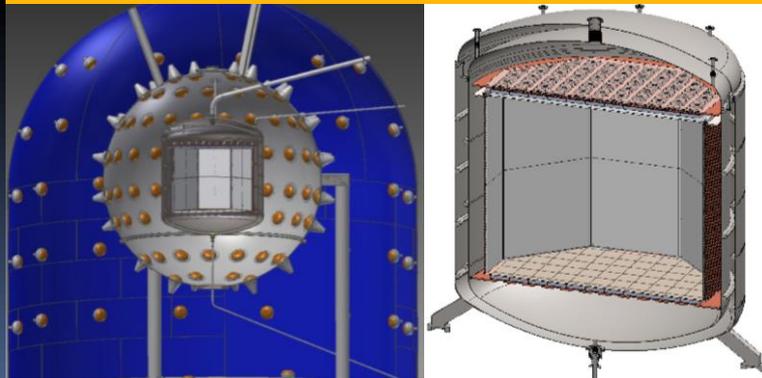
Mark Boulay, Cosmic Visions 2017

Researchers from

- DarkSide
- DEAP
- ArDM
- MiniCLEAN

DS-20K → multi-100-T

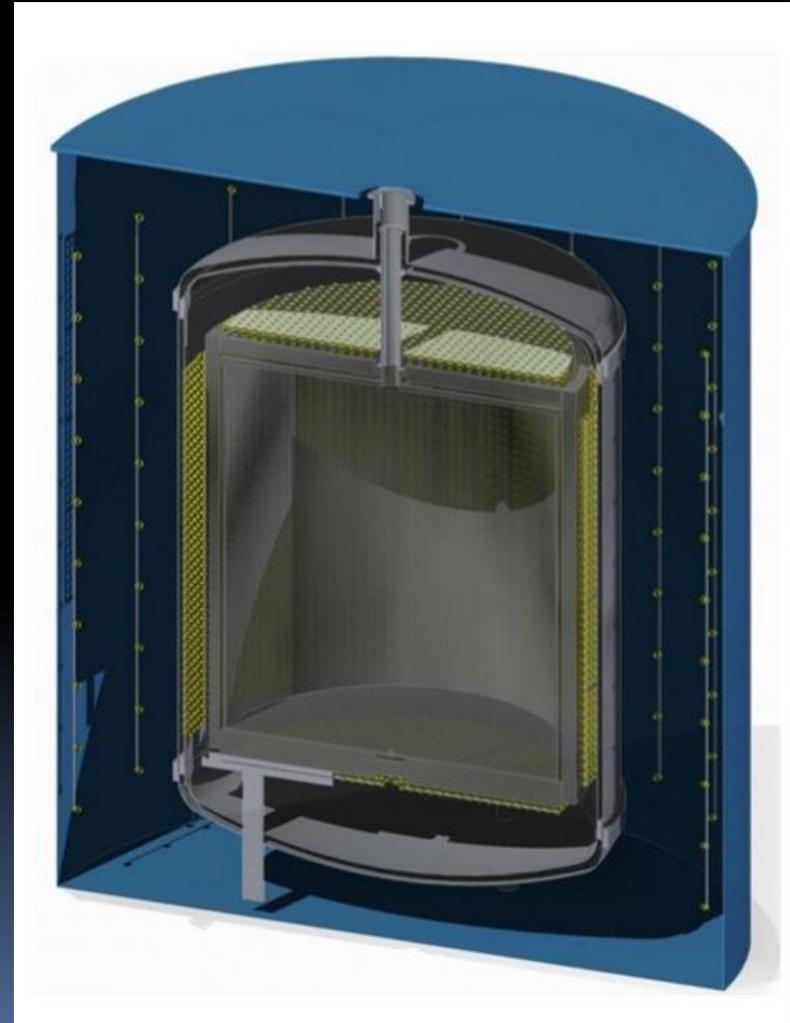
DS-20K



- 20-ton UAr two-phase TPC at LNGS
- TPC scaled from DS-50
- Crucial technologies:
 - Low rad. Ar: underground and isotopic depletion
 - SiPMs for light readout

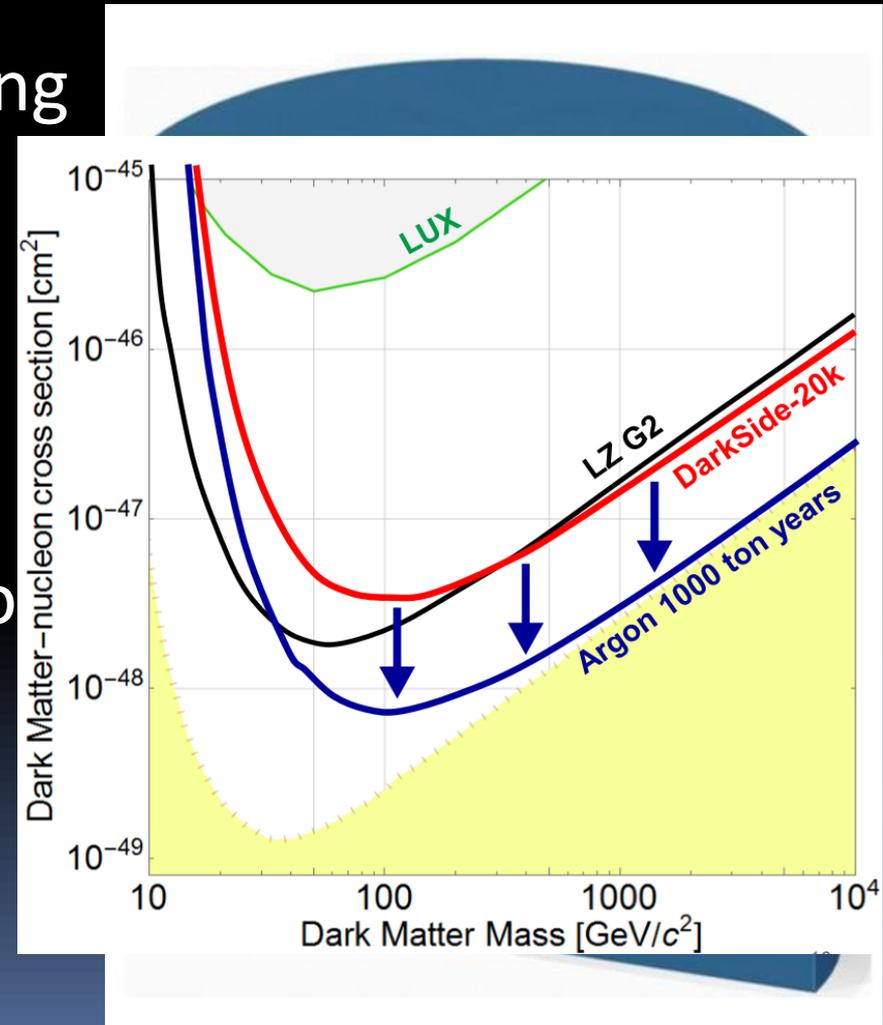
After DS-20K

- Argo/DEAP-nT targeting **1kton-year** total exposure
- Single/dual-phase considered
- Can reach neutrino floor
- Site TBD



After DS-20K

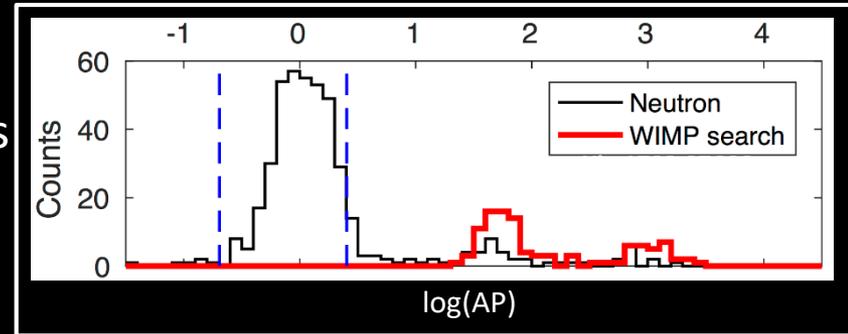
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- Can reach neutrino floor
- Site TBD



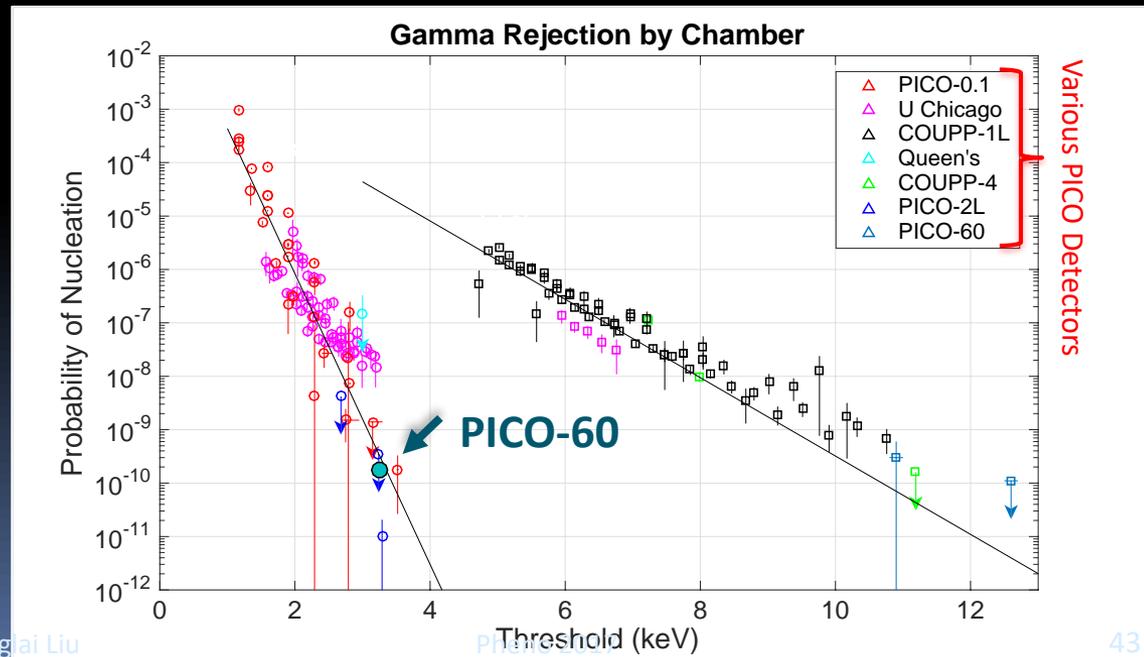
Bubble chamber detectors



- Use cameras to search for bubbles from keV scale energy deposition
- Listen to a bubble to discriminate between alpha decays and nuclear recoils using acoustic power

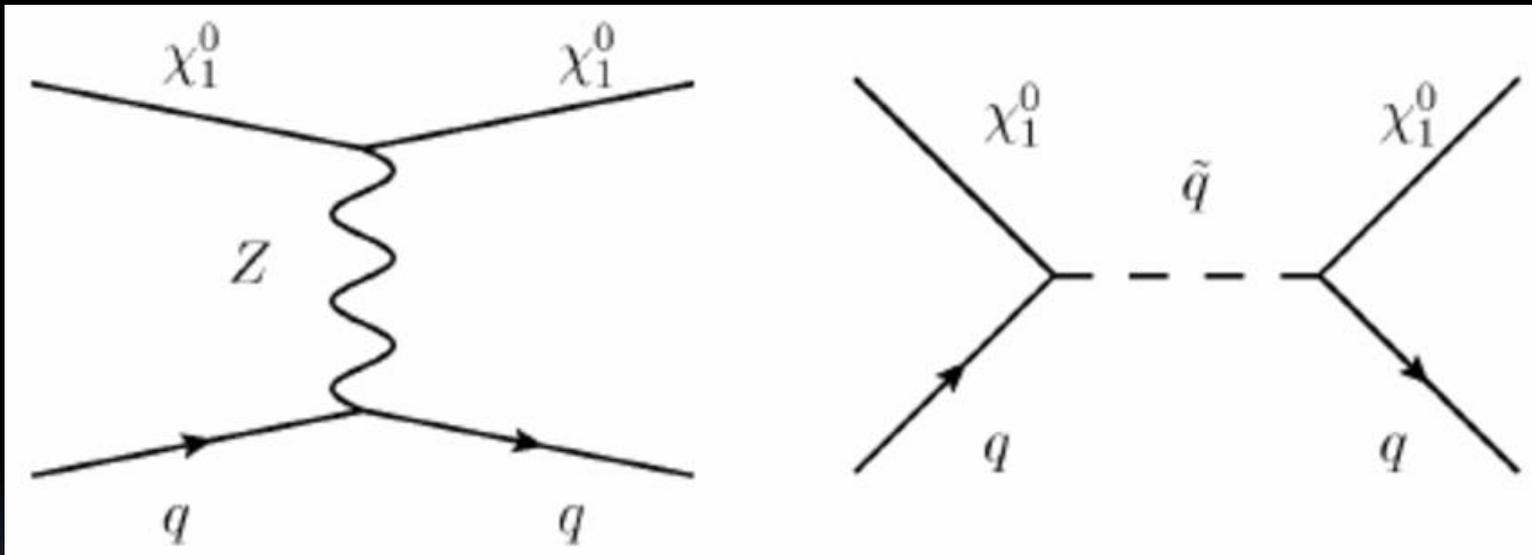


- Electron recoils deposit energy non-locally and do not nucleate bubbles
- Neutrons preferentially multiple scatter, producing multiple bubbles simultaneously



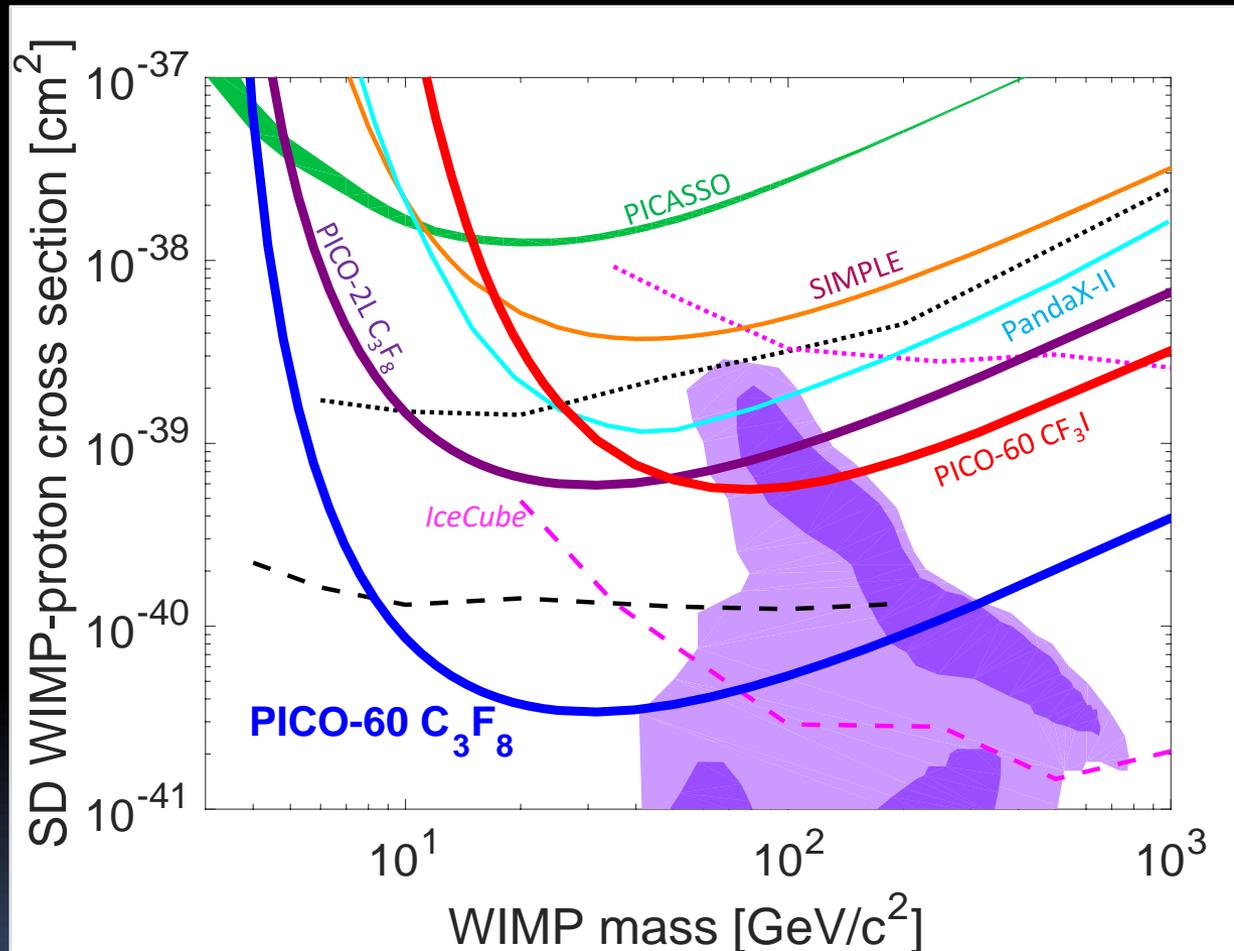
Spin-dependent interaction

- Natural to expect if WIMP has spin



PICO-60: SD χ -p coupling

arxiv: 1702.07666

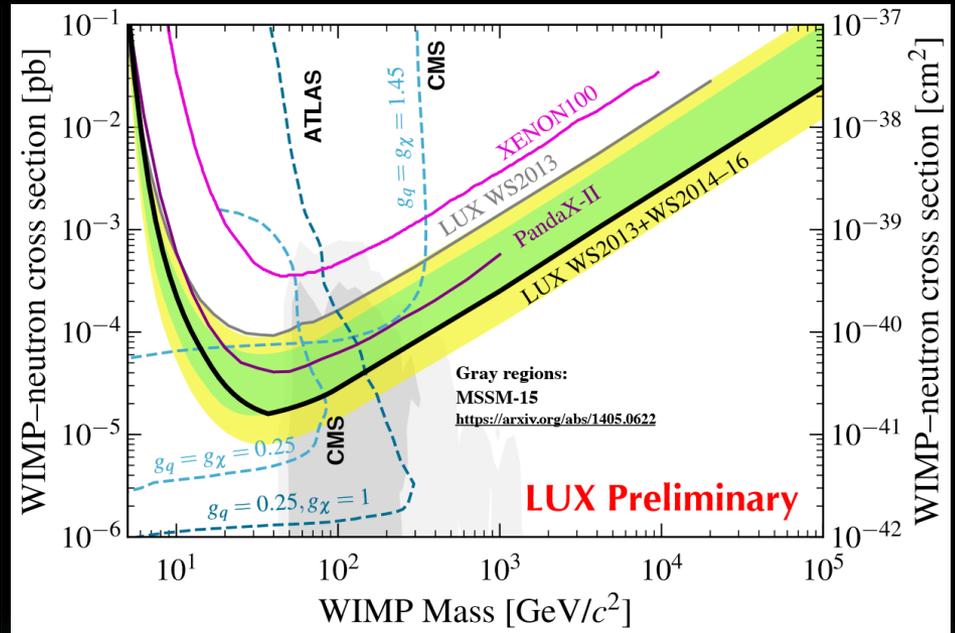
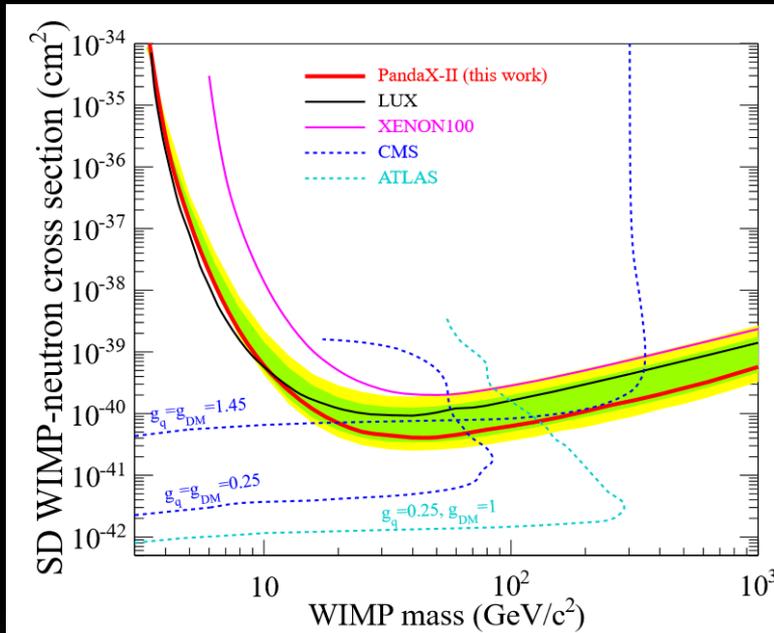


- Blind analysis, 0 events observed, x17 improvement to set world best limit on spin dependent proton coupling

^{131}Xe and ^{129}Xe : SD χ -n coupling

PandaX, PRL118, 071301

C. Silva, Rencontres de Moriond 2017

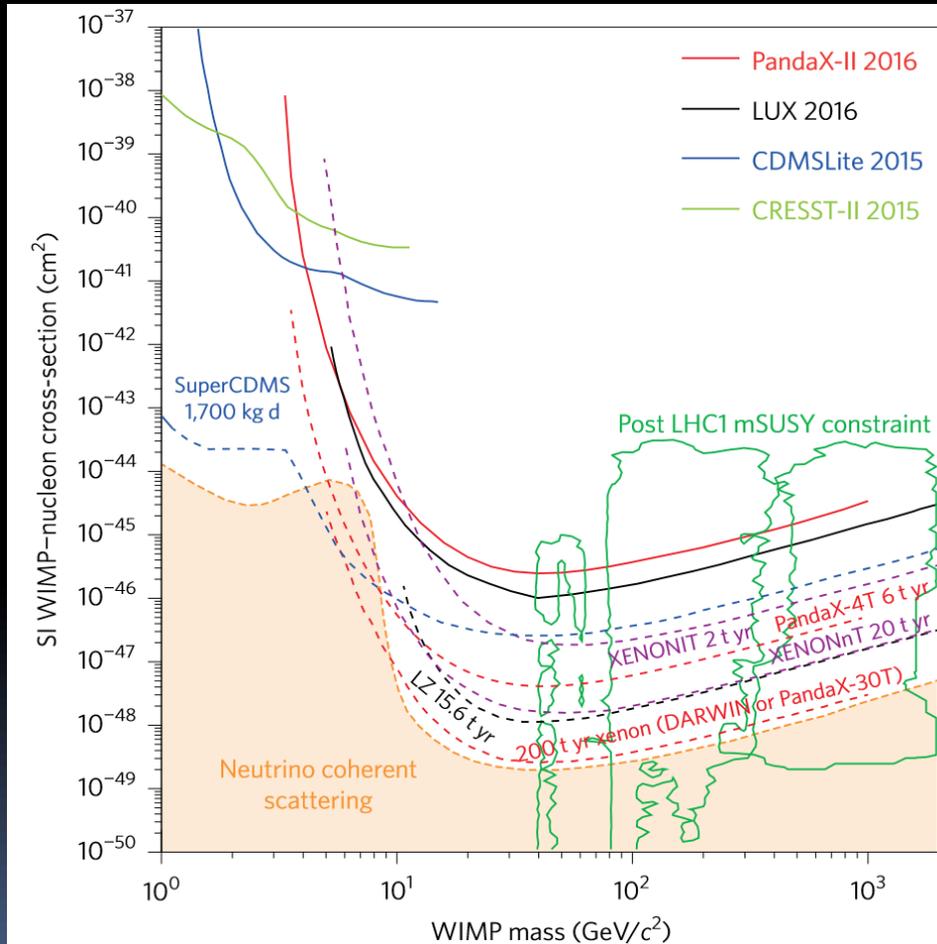


- Leading χ -n limit: PandaX, $4.1 \times 10^{-41} \text{ cm}^2$ at $40 \text{ GeV}/c^2$,
- Recently LUX presented a new limit $1.6 \times 10^{-41} \text{ cm}^2$ @ $35 \text{ GeV}/c^2$ at Moriond
- Collider search complementary for lower mass

What I have to omit

- New trend in direct detection: search signatures in electron-recoil channel
 - Axion searches
 - Dark photon and dark sector searches
- New search strategy for non-standard-WIMP particles
 - We heard a lot at this conference. For example, inelastic boosted DM search by Kim, Park and Shin, arXiv: 1612.06867
 - Many new physics opportunities

Discovery may be just around the corner



- In next 5 years, number of G2 experiments will turn on and have new results
- Stronger interplay between collider/indirect/direct experiments and the theory community

- 
- Many materials borrowed from public talks presented by individual collaborations
 - Many thanks to Dan Bauer, Qian Yue, Rick Gaitskell, Elena Aprile, Shigetaka Moriyama, Cristiano Galbiati, Juan Collar and Dan Baxter in helping me with the materials