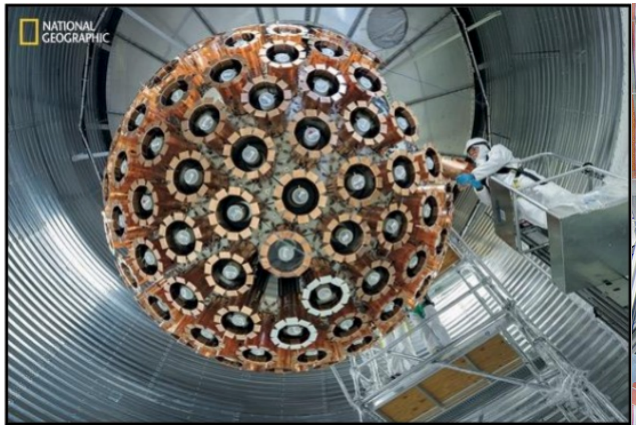
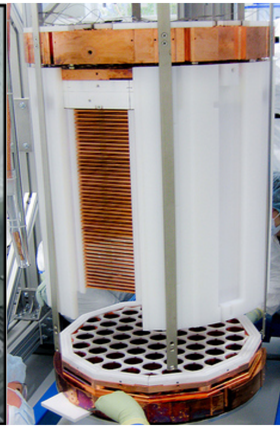
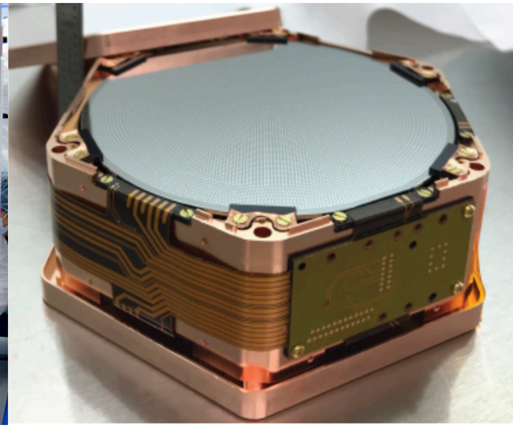
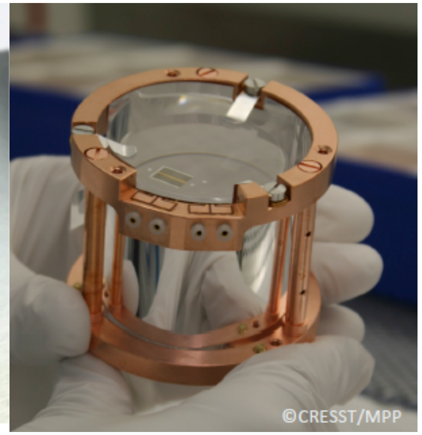
Results from Dark Matter Direct Detection Experiments



Isabel Lopes

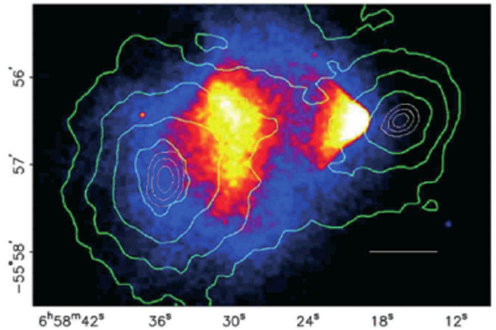
Department of Physics and LIP and University of Coimbra, Portugal

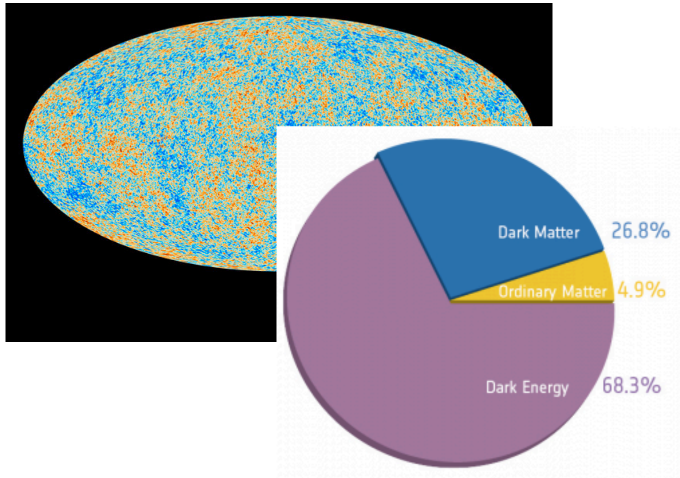
25th Rencontres du Vietnam,
Quay Nhon, Vietnam, August 5-11, 2018

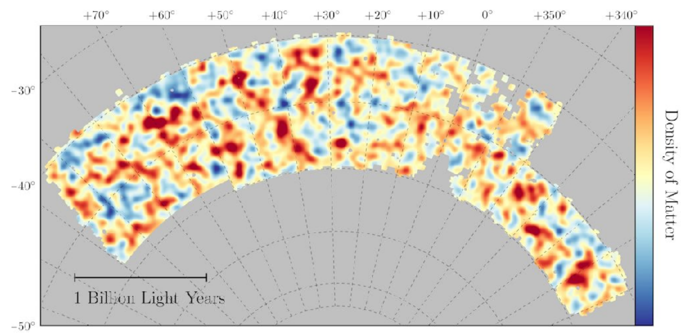
U C

The case for dark matter

- **Galactic rotation curves** exhibit behavior consistent with significant missing mass
- **Gravitational** lensing indicate existence of large amounts of dark matter
- **Cosmic Microwave Background Radiation** favors model with ~25% of the Universe mass-energy budget composed of dark matter
- **Big Bang Nucleosynthesis** implies the same
- **Large-scale structure simulations** indicate this *dark matter* is rarely interacting and non-relativistic, implying that it is heavy





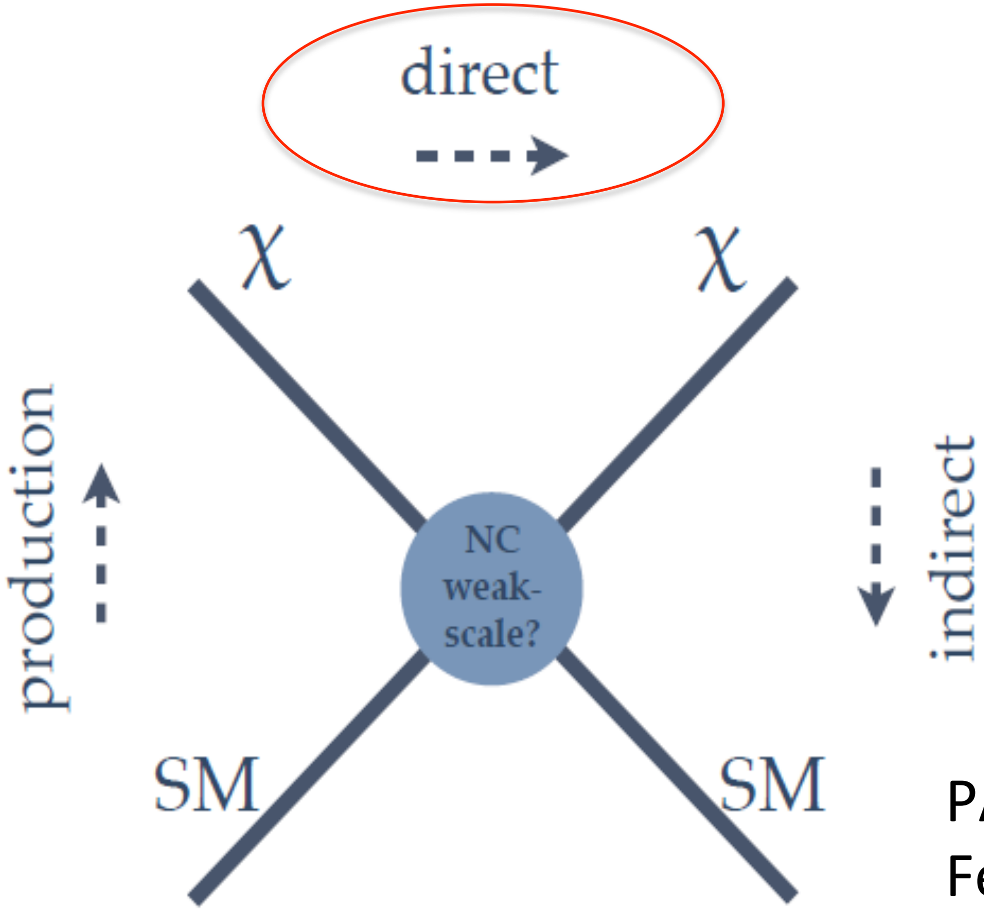


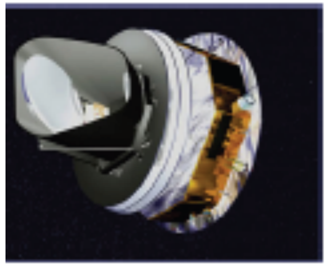
WIMP Searches

Weakly Interacting Massive Particles (WIMPs) represent a generic class of non-relativistic dark matter particles. Examples of WIMP candidates: the lightest super-symmetric or Kaluze-Klein particles.

Accelerator searches (DM production)

LHC

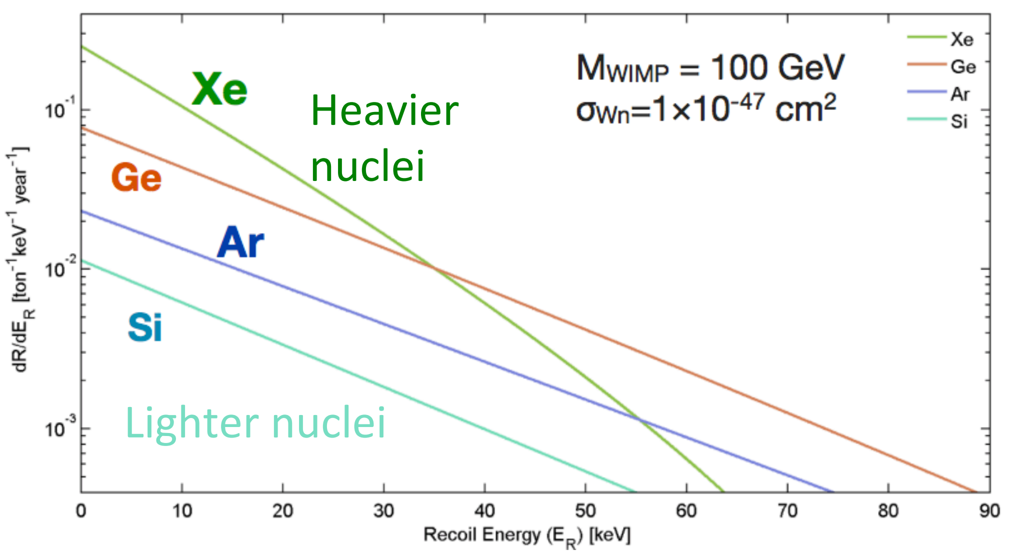


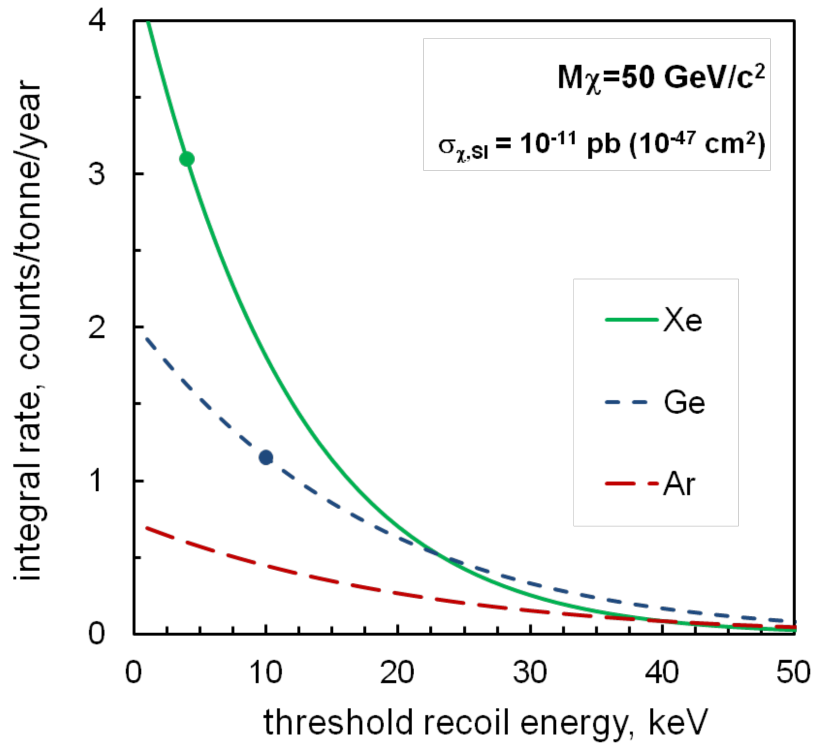


- Indirect detection (DM annihilation)

PAMELA, ANTARES, Fermi, IceCube, AMS MAGIC, CTA, HESS

WIMP direct detection challenges





- Nearly exponential, featureless spectrum
- The detector energy threshold must be as low as possible
- **E_R typically < a few tens keV**

At the present lowest Xe detector threshold and the higher limit cross section WIMP-nucleon, the total expected interaction rate for M_{WIMP}=50 GeV/c^2 is around
3 events/tonne/year

Backgrounds

Ideally below the expected signal

(< 1event/exposure;

exposure=acquisition time x fiducial mass)

Main sources:

- Cosmic rays & cosmic activation of detector materials: μ, n, γ, α
- Natural (^{238}U, ^{232}Th, ^{40}K) & anthropogenic (^{85}Kr, ^{42}Ar, ^{137}Cs) radioactivity from detector materials: γ, e^-, n, α
- Radon (^{222}Rn) daughters from environment and emanation
- Ultimately: neutrino-nucleus scattering

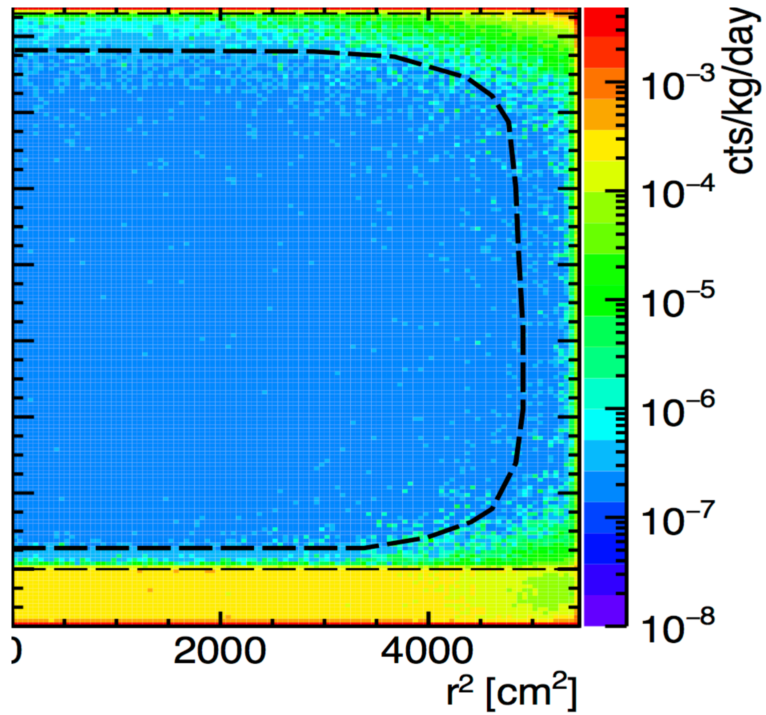
Coping with background

Passive suppression

- Operation deep underground
- Select ultra low radioactive materials

Identification

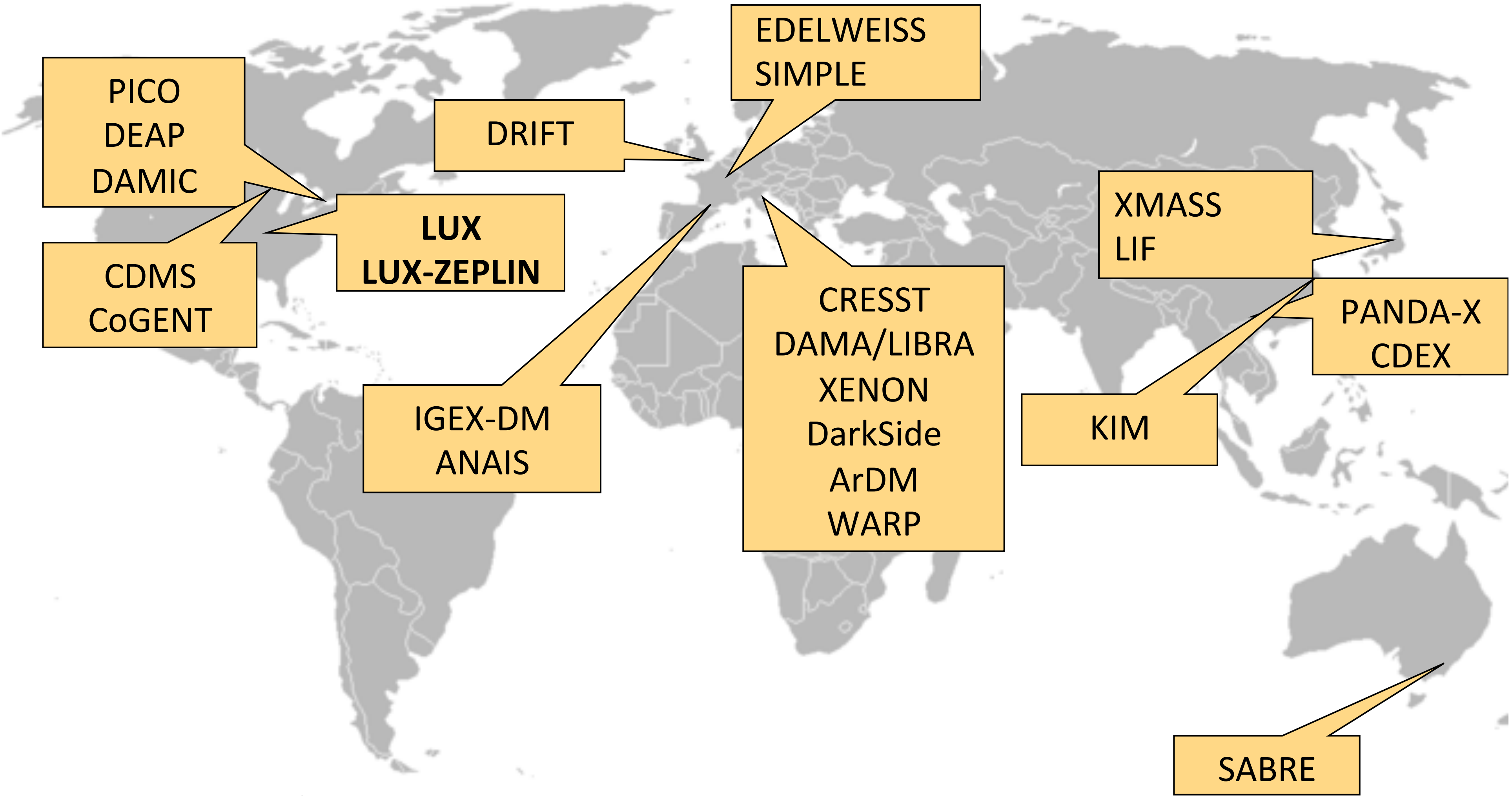
- Detector ability to discriminate ER (background) from NR (signal)
- 3D reconstruction of interactions
  → **Fiducialization** (use only the central part of the detector)
  → rejection of multiscatters



Active shielding

- Neutron veto (e.g. liquid scintillator)
- Muon veto (e.g. water Cherenkov detector)
- Instrumented "skin" surrounding the detector active area

Direct Detection Dark Matter Experiments



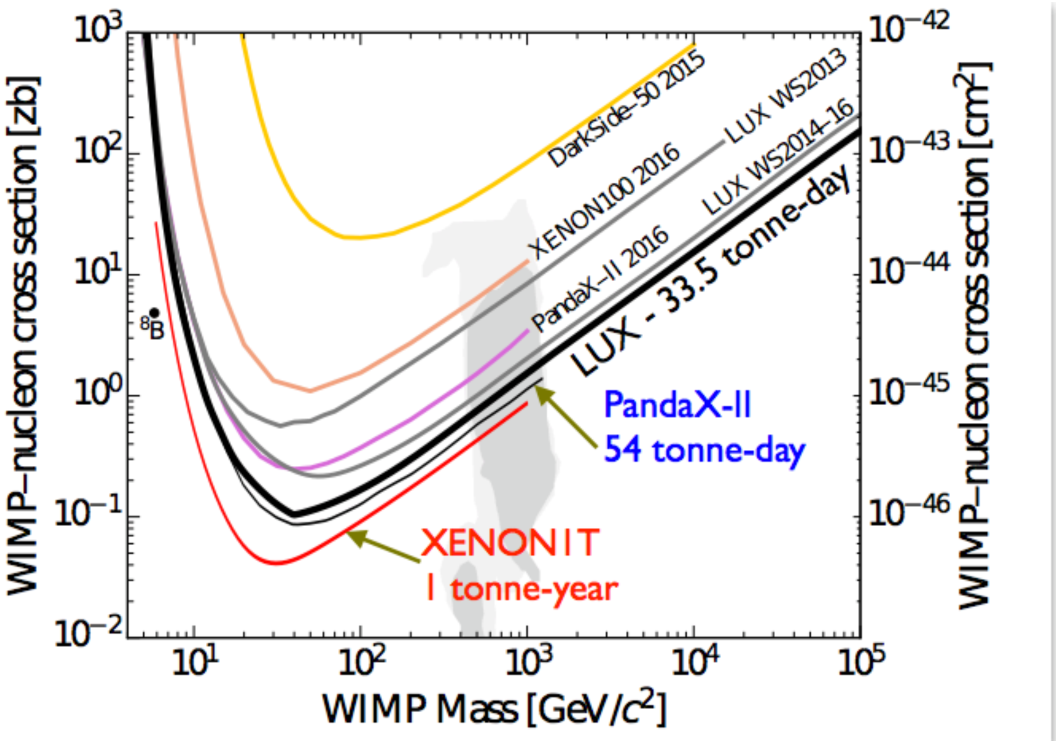
WIMP Direct detection: present status

At High Mass >10 GeV/c²

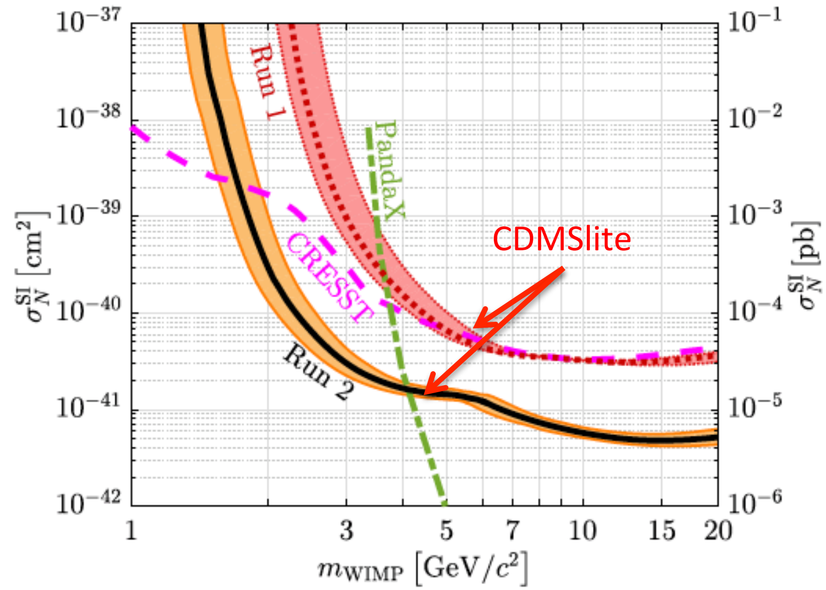
- Nothing so far
- Broadly consistent with the absence of Super Sym. observation at LHC

At Intermediate Mass <10GeV/c²

- Nothing so far …but much less explored

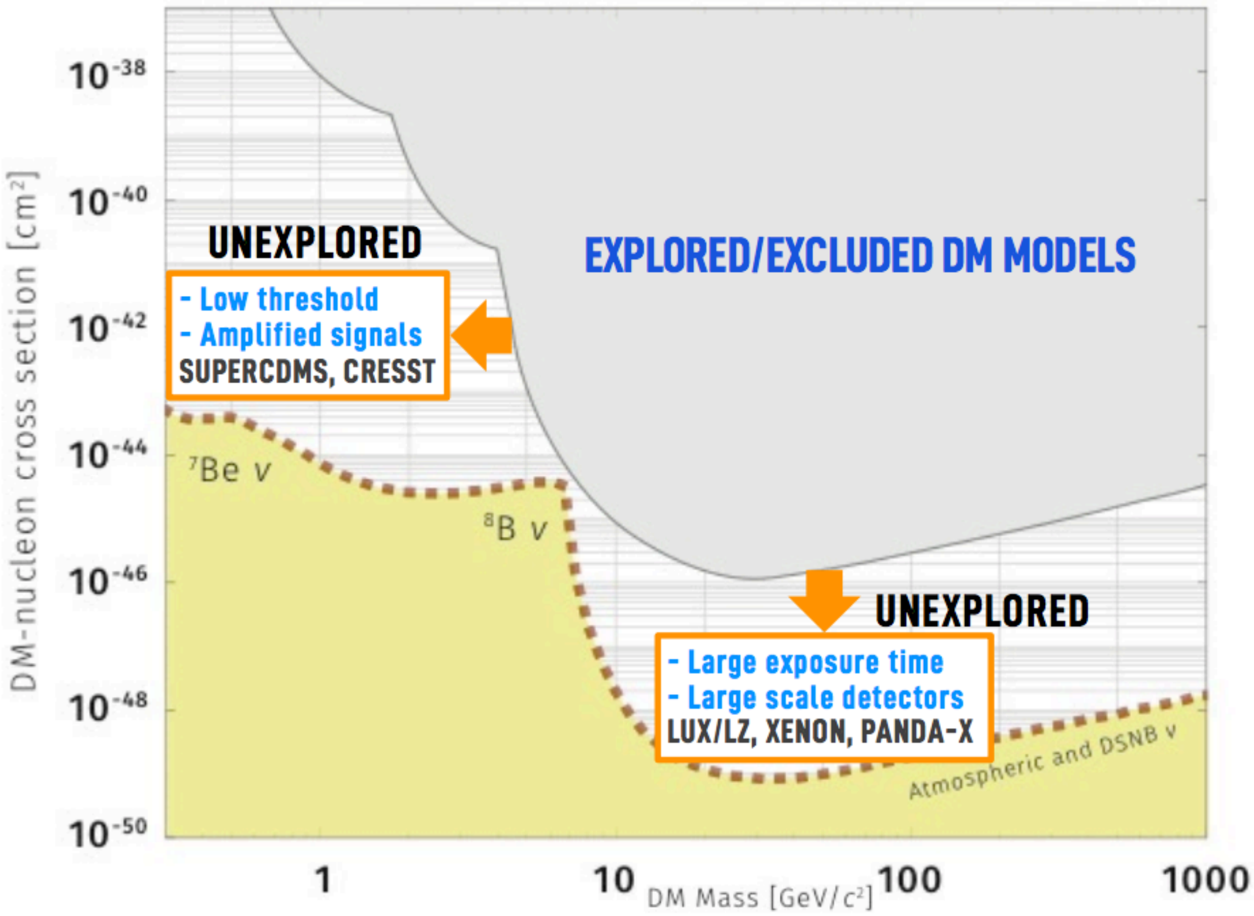


Noble liquid detectors are the winners for WIMP masses < 10 GeV/c²



For intermediate masses, the cryogenic detectors (@tens mK) are the most sensitive

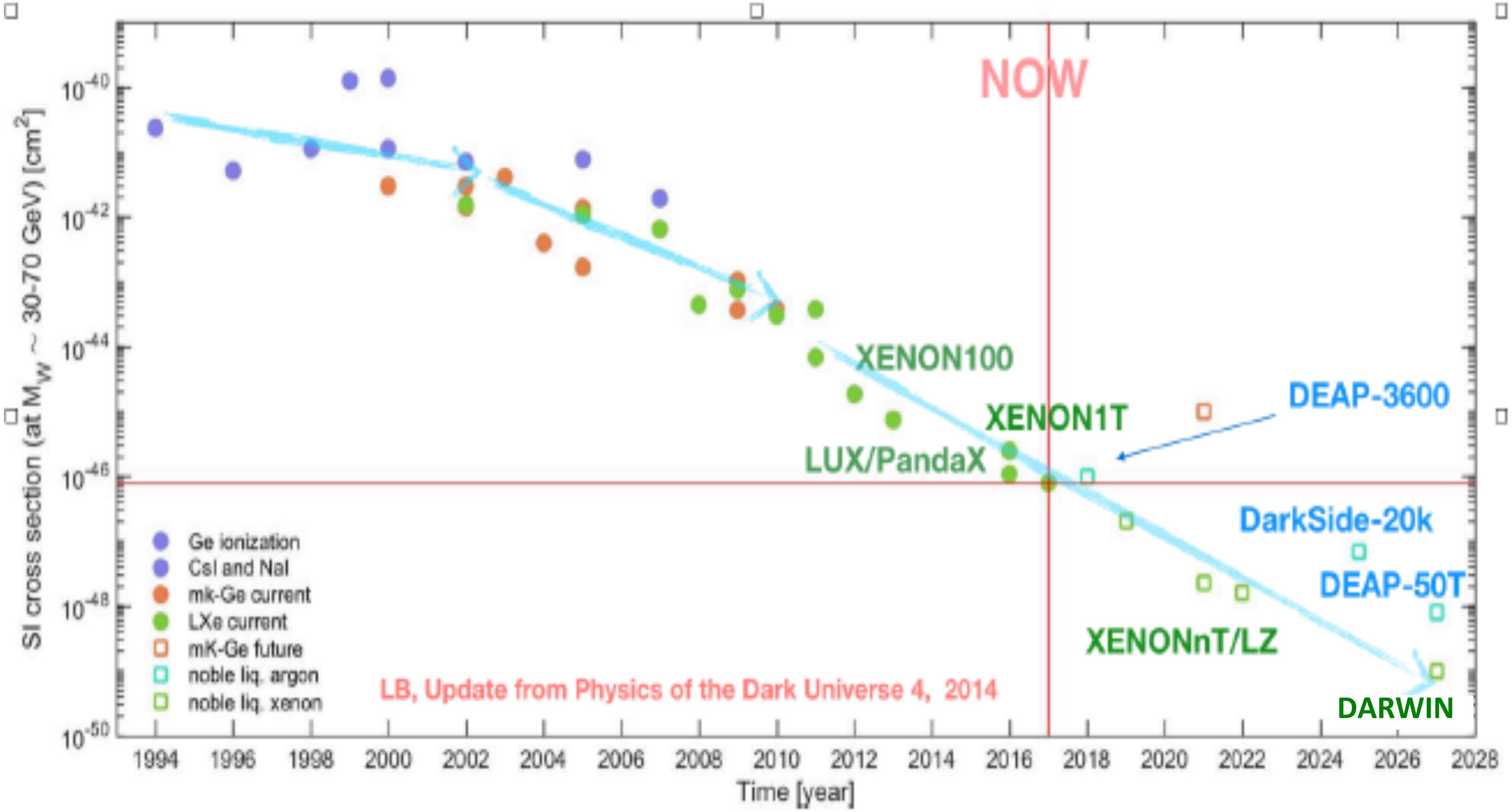
WIMP Direct detection: the present and the near future



T. Arakami, IDM2018

Progress in WIMP search

Exclusion limit for WIMP-nucleus SI interaction (M_W ~50 GeV/c^2)

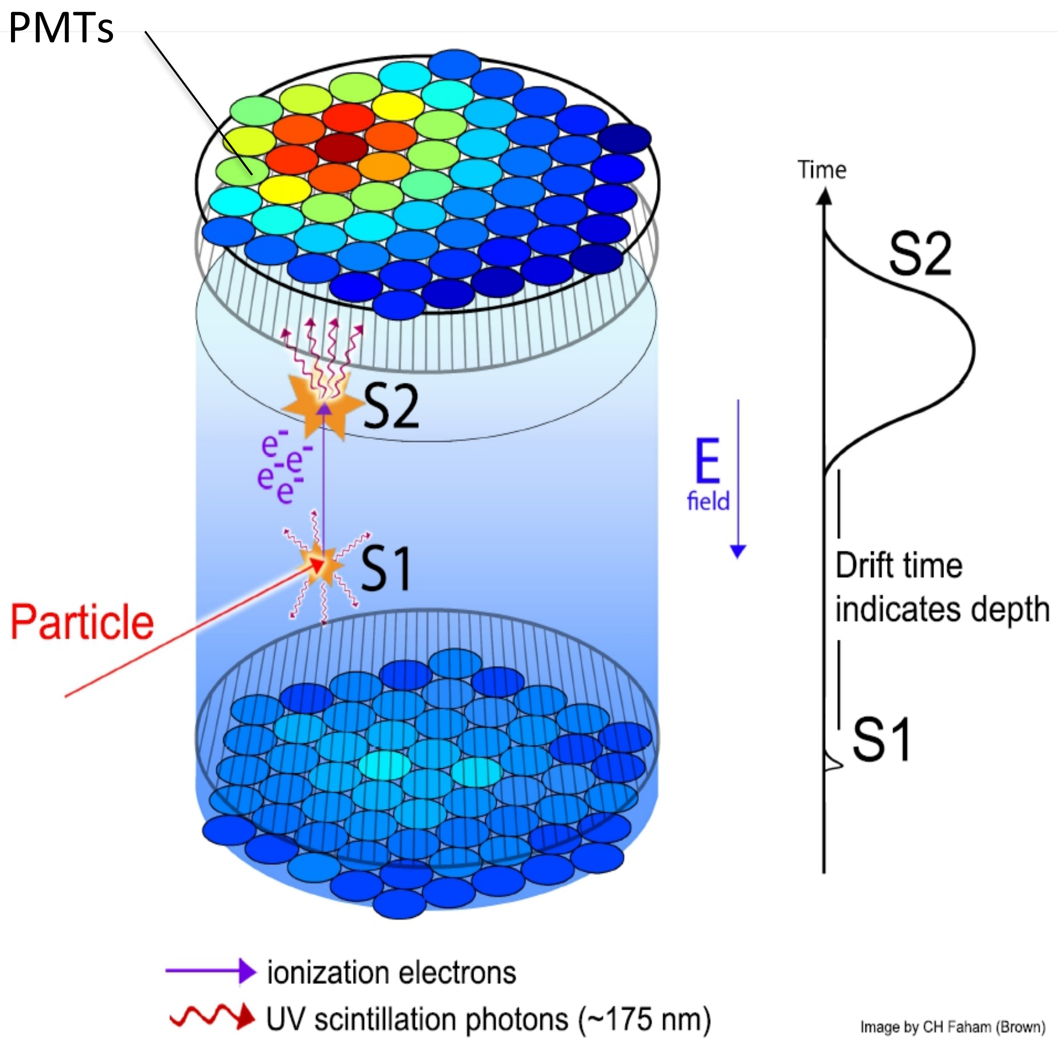


Direct detection sensitivities improving by a factor of 25 every 5 years

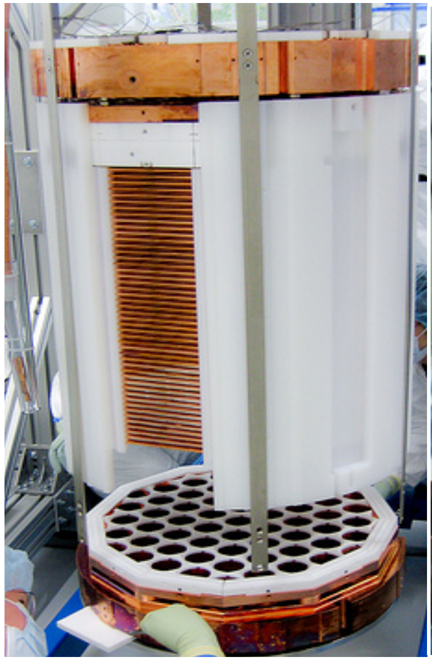
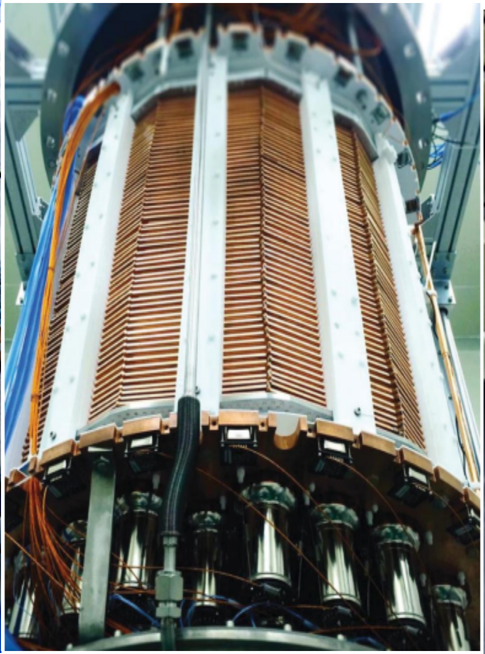
Present most stringent limit: 4.1×10^{-47} cm^2 at 30 GeV/c^2 and 90% CL.

Two Phase Noble Liquid TPCs

- Primary scintillation (S1)
- Secondary scintillation (S2) in the gas
- 3D imaging
  - Z from S1 – S2 timing
  - X-Y from light pattern in PMT array(s)



Two-phase noble liquid TPCs

LUX	PANDAX	XENON1T	DarkSide-50
			
M_T= 350 kg M_{fid}=118 kg	M_T= 1200 kg $\mathbf{M_{fid}}$=306 kg	M_T= 3200 kg M_{fid}=1300 kg	M_T= 50 kg M_{fid}=39 kg

Xenon TPCs (LUX, PANDAX, XENON1T)

Argon TPC (DarkSide-50)

LUX experiment

- First two-phase Xe TPC with Xe mass of several hundred kg to be built
- Pioneered cryogenic, HV solutions and calibration methods
- Paved the way to ton and multi-ton two-phase xenon TPC

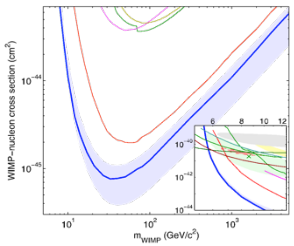
2006: LUX collaboration formed

2008: LUX funded (DOE + NSF)

July 2012: LUX moves UG

April 2013: First science run starts

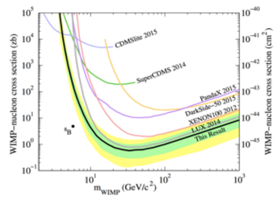
Nov 2013: First WS results reported (85.3 live-days)



PRL, 112, 091303 (2014)

Sept 2014: 332-day run start

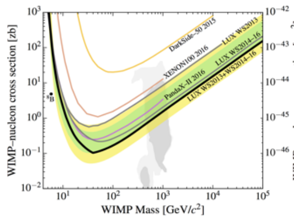
Dec 2015: Re-analysis of WS2013 published



PRL, 116, 161301 (2016)
PRL, 116, 161302 (2016)

May 2016: WS2014-16 finished

July 2016: 332-day WS result announced



PRL, 118, 021303 (2017)

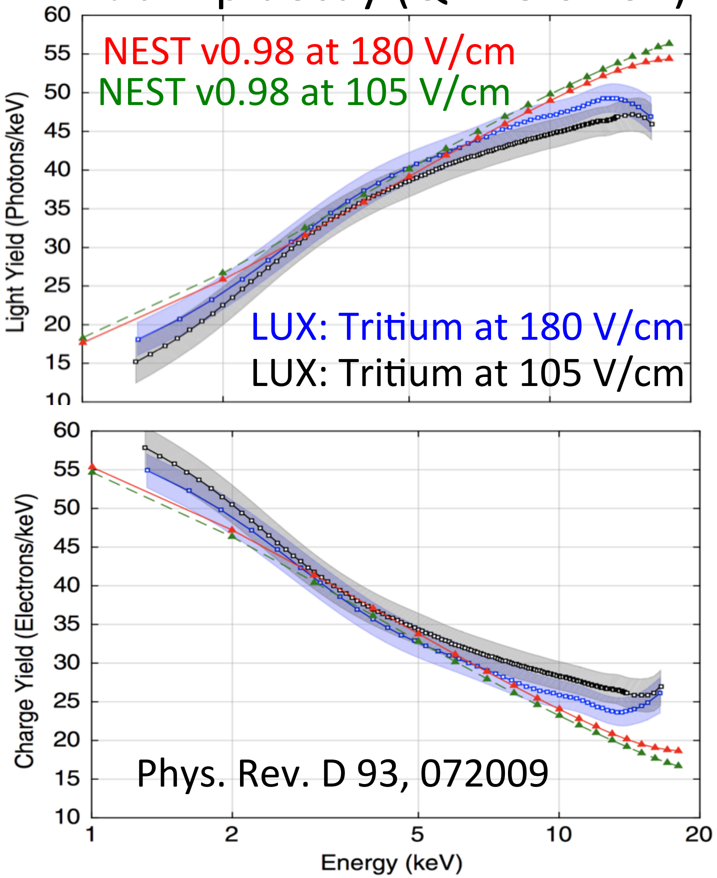
Sept 2016: decommissioning start

June 2017: LUX installed in a museum

Analysis still ongoing

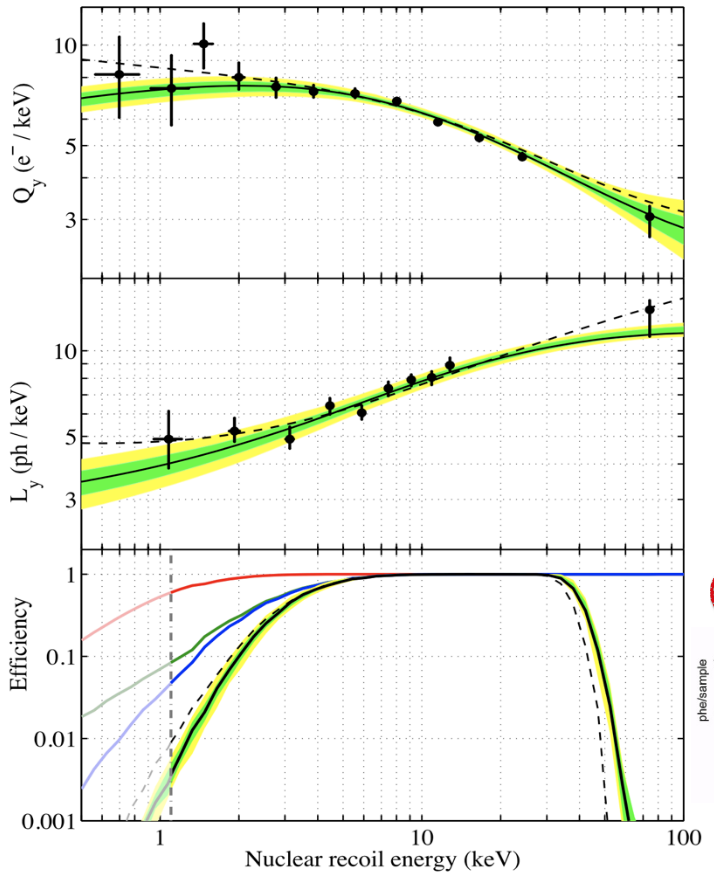
Innovative Calibration Techniques

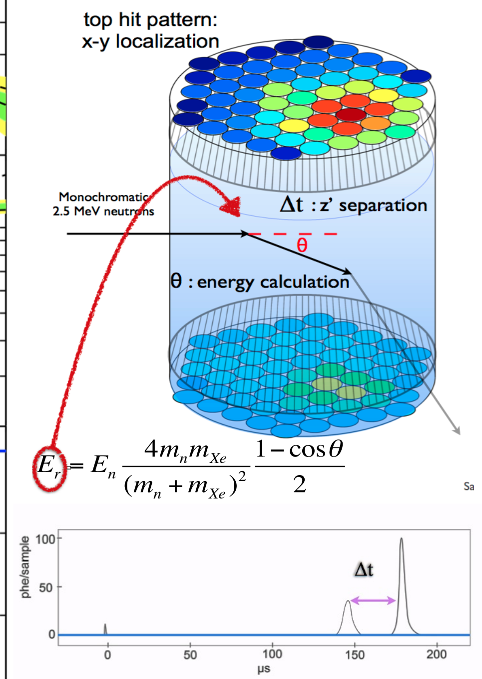
Tritium β decay (Q= 18.6 keV)



- Absolute calibration of Q_Y and L_Y for ER down to ~1 keVee
- Detection efficiency vs energy

Calibration with 2.45 MeV neutrons from DD generator

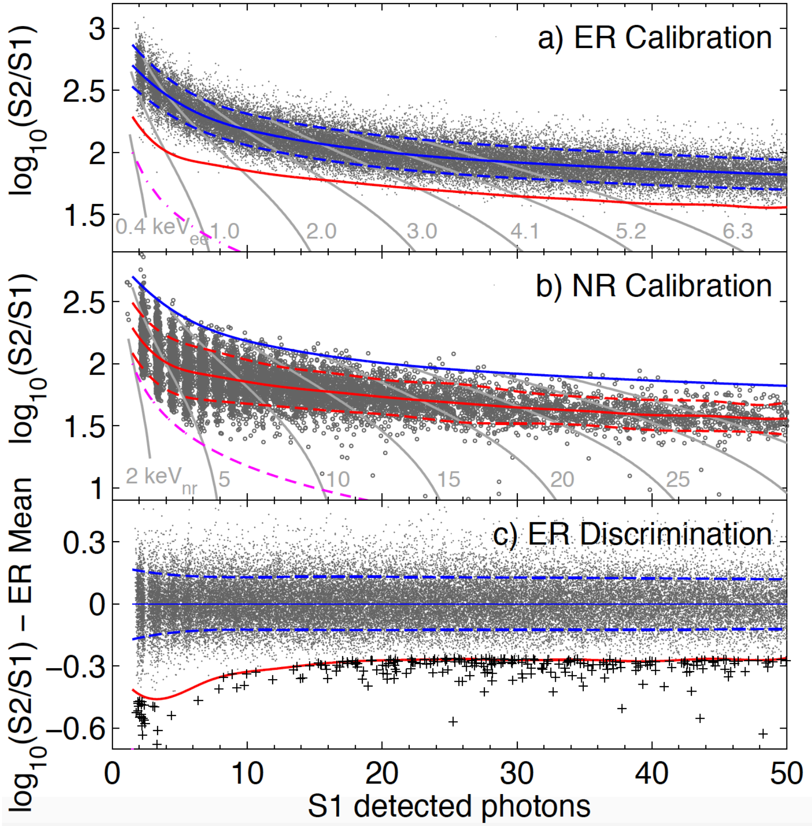


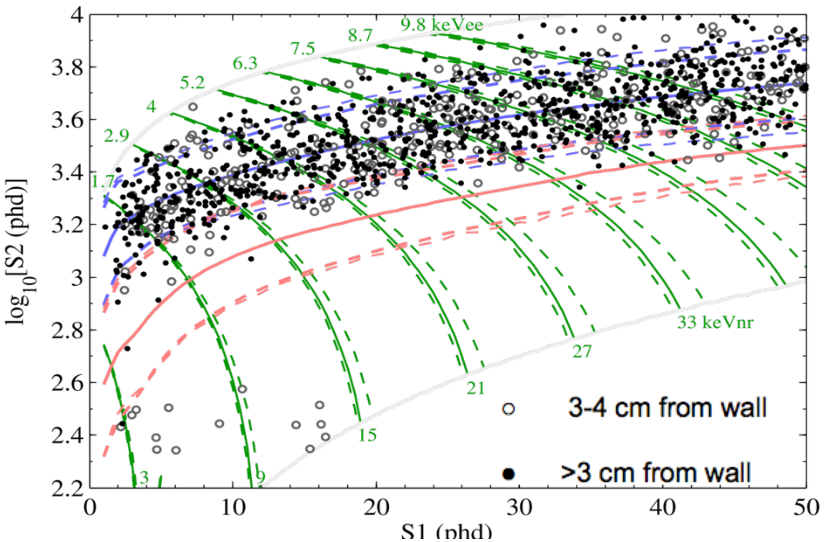


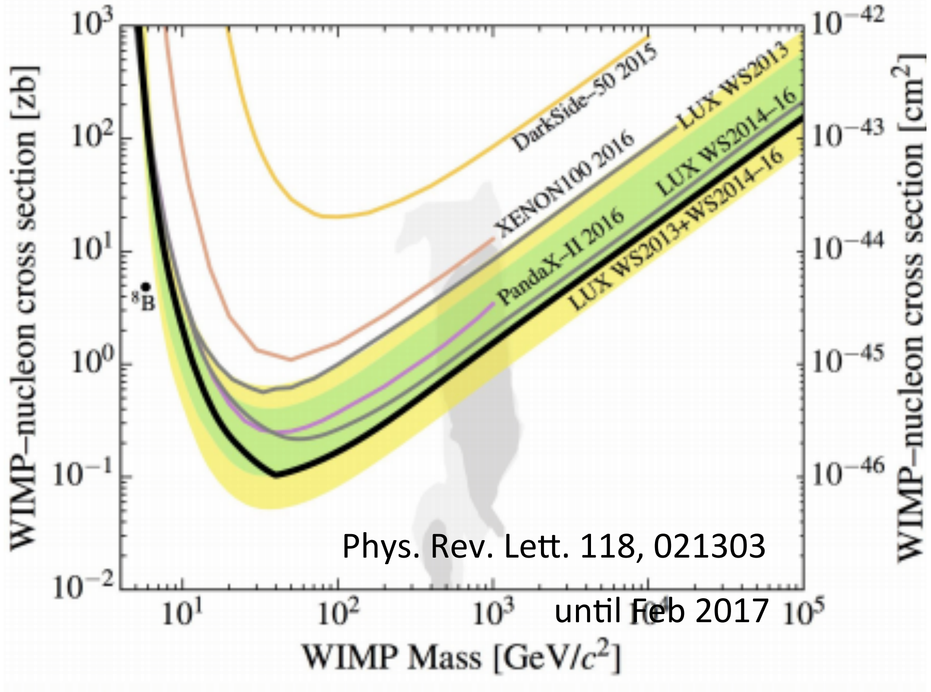
arXiv:1608.05381v2

- Absolute calibration of Q_Y and L_Y for NR down to ~0.7 keVee (Q_y) / 1.1 keVee (L_y)
- Efficiency NR detection

LUX results

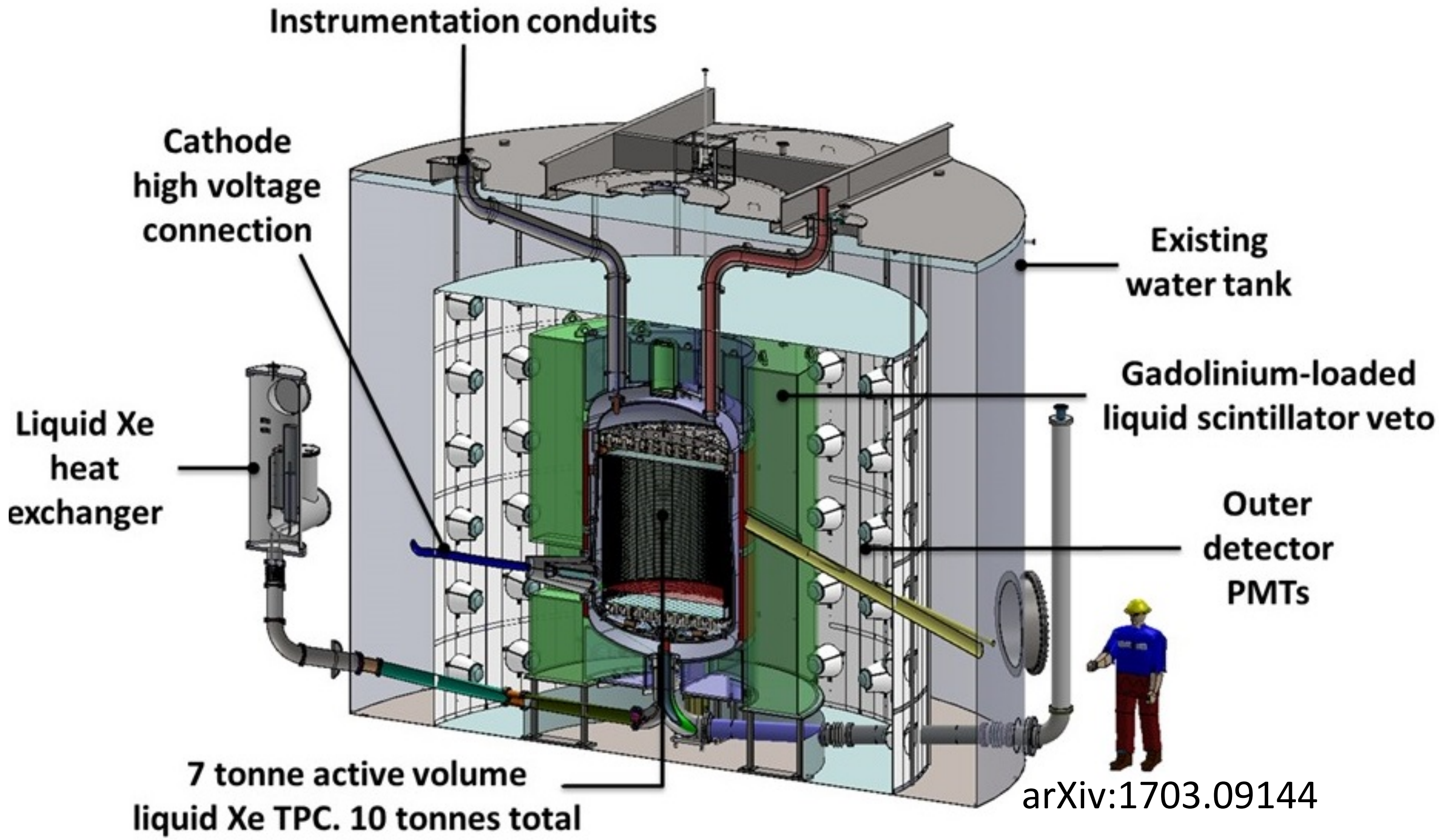






- LUX 332+85 live-day WIMP search run
- Total exposure 33.5 ton.days
- Limit: $1.1{\times}10^{-46}$ cm^2 at 50 GeV/c^2
- World leader of WIMP searches from 2013 –Feb 2017

LZ Detector Overview



arXiv:1703.09144

- To be installed in the same laboratory used for **LUX** and inside the **same water tank**;
- Additional **liquid scintillator active veto**
- **Instrumented skin** region around the TPC field cage as additional veto
- Unprecedented levels of Kr (<15 ppq)

LZ Backgrounds

Background source	RE cts	NR cts
Detector components	6.2	0.07
Dispersed radionuclides (Rn, Kr, Ar)	911	–
Laboratory and cosmogenic	4.3	0.06
Fixed surface contamination	0.19	0.37
^{136}Xe 2υββ	67.0	–
Neutrinos (ν-e, ν-A)*	255	0.72
Total	**1240**	**1.22**
Total (99.5% ER desc., 50% NR eff.)	**6.22**	**0.61**
Total ER+NR background events	**6.82**	

arXiv:1802.06039

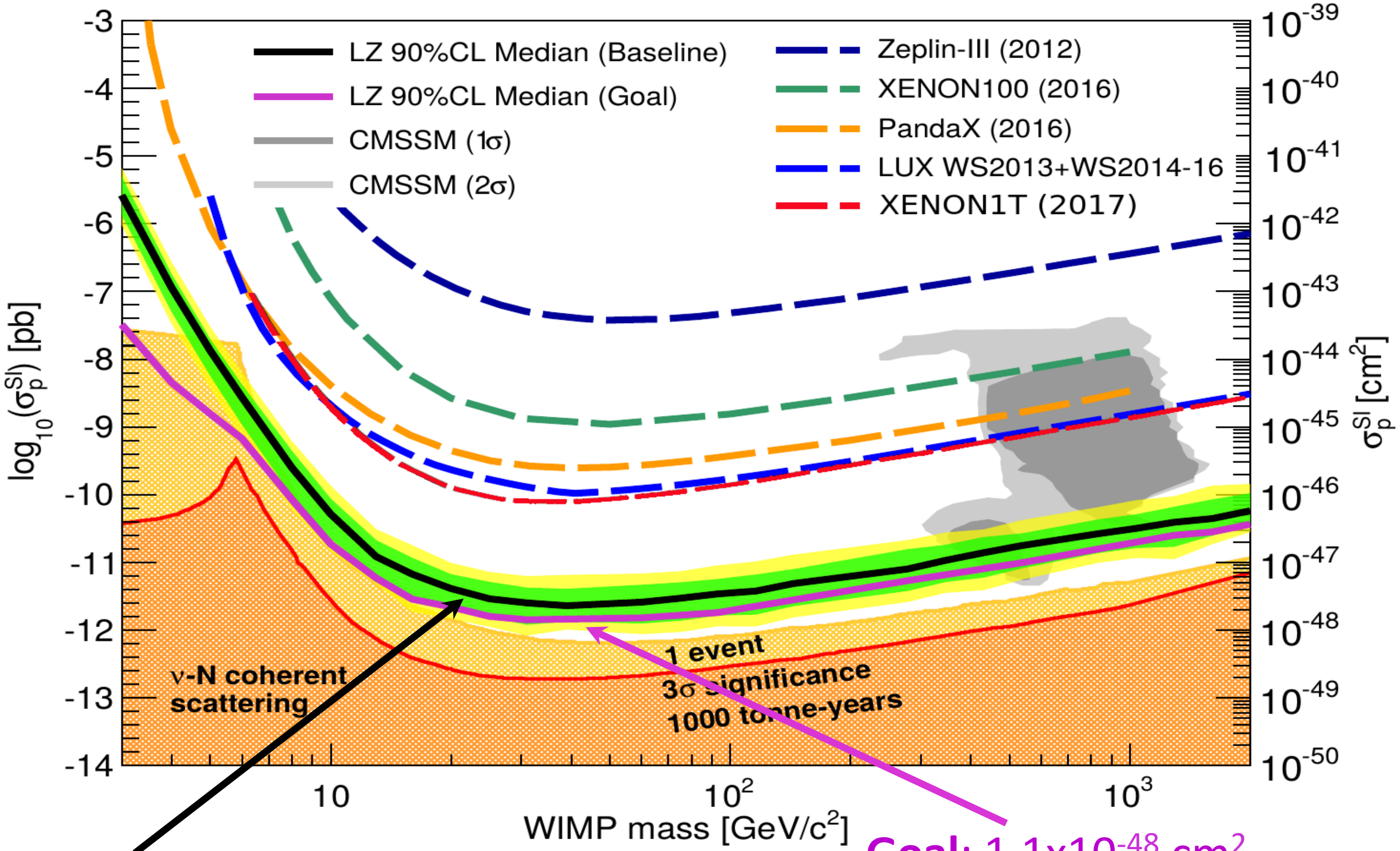
* neutrinos events from ^{8}B not included

- Signal-like background events in 1000 live-days with 5.6-tonne fiducial mass: single scatters in ~1.5 - 6.5 keV (6- 30 keVnr),
- Largest contribution comes from **Rn**, followed by **ν-e** solar neutrino scattering and atmospheric **ν-A** scattering;

Projected Sensitivity - Spin Independent

5.6 Tons, 1000 live days

PLR used to estimate the sensitivity

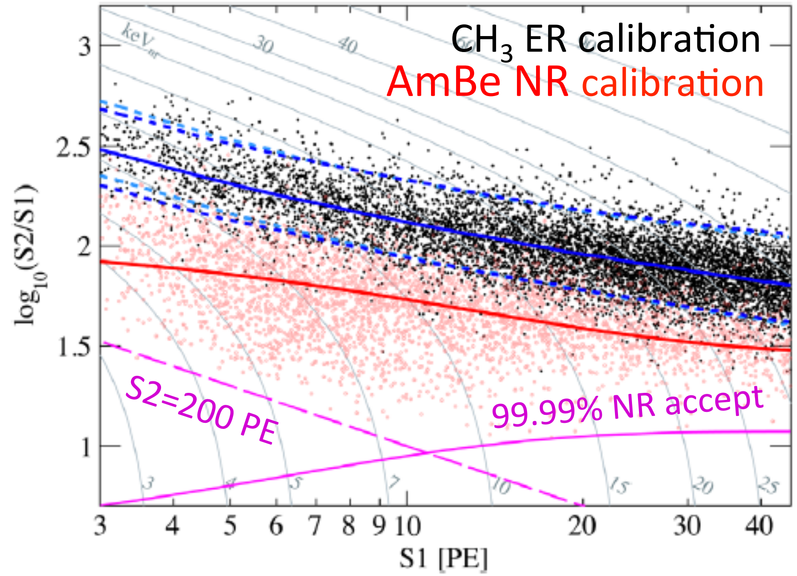


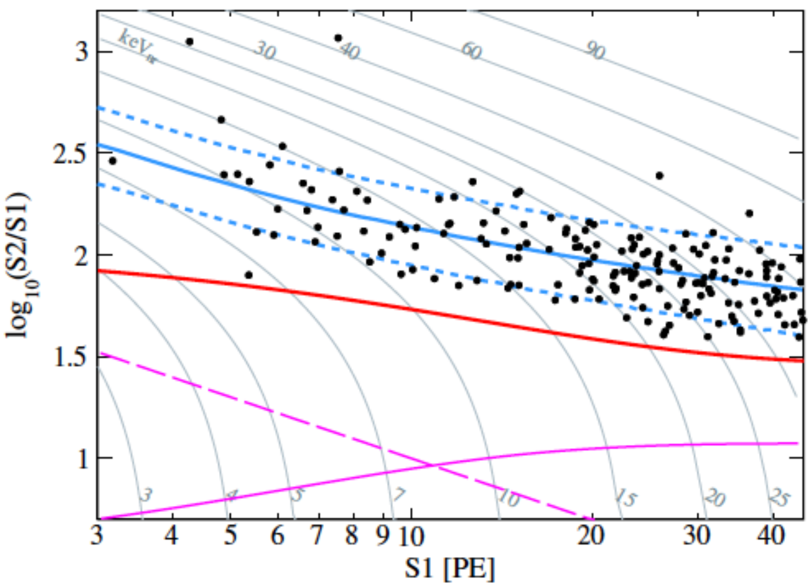
Baseline: 2.3×10^{-48} cm^2 @40 GeV WIMP

Goal: 1.1×10^{-48} cm^2 @ 40 GeV WIMP

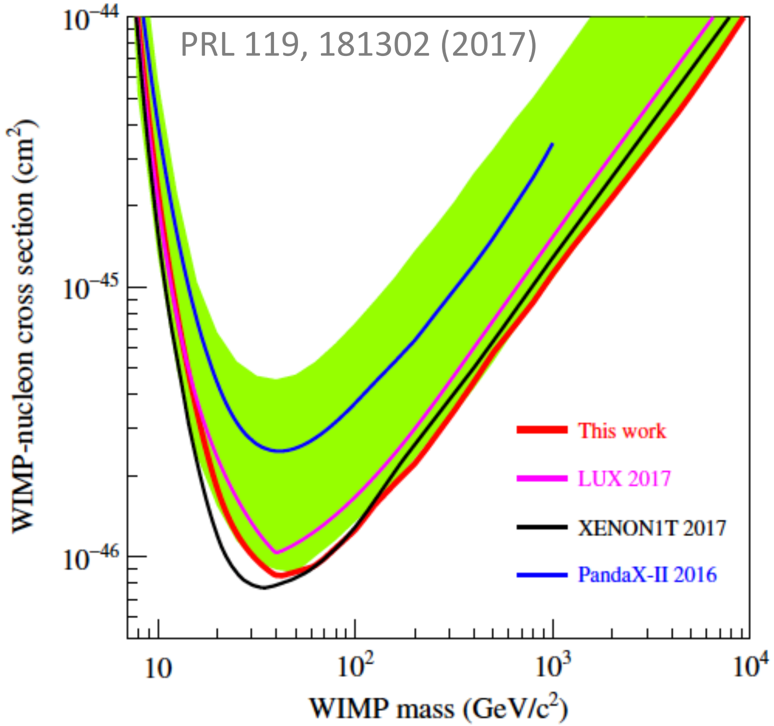
arXiv:1802.06039

PANDAX-II: latest results





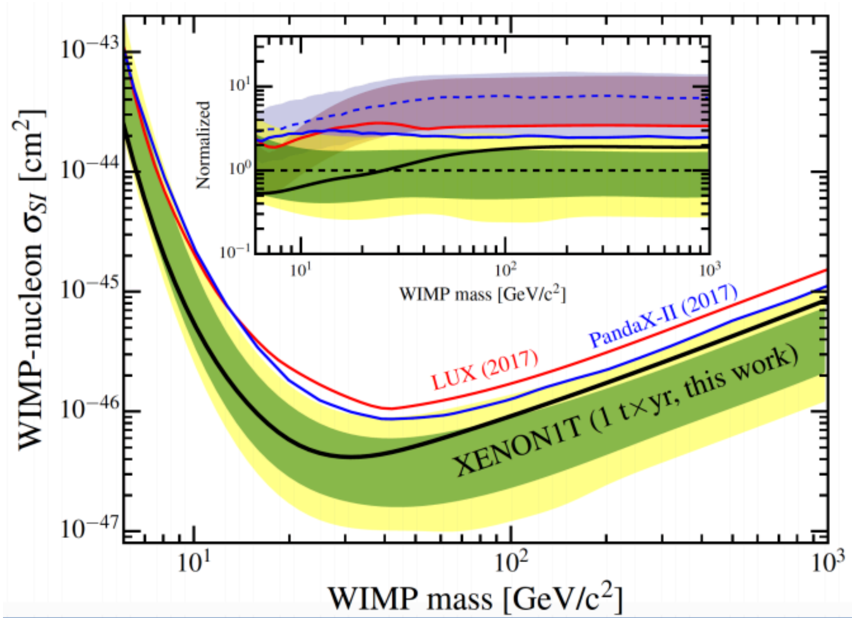
- 500 kg
- 54 ton.days exposure
- Very low background (10^{-3} evt/kg/day/keV)
- ^{222}Rn level: 8.6 μBq/kg



Future: PandaX-4T with projected sensitivity ~10^{-47} cm^2. Commissioning: 2019-2020

XENON1T & XENONnT

- 1.3 tonne liquid xenon fiducial volume
- 279 live-days → exposure= 363 ton*days
- online cryogenic distillation for further ^{85}Kr and ^{222}Rn reduction
- ROI: **[1.4, 10.6] keV** ([4.9, 40.9] keVnr)
- **Ultra low background dominated by ^{222}Rn**
- Present most stringent upper limit on WIMP-nucleon cross section above 6 GeV

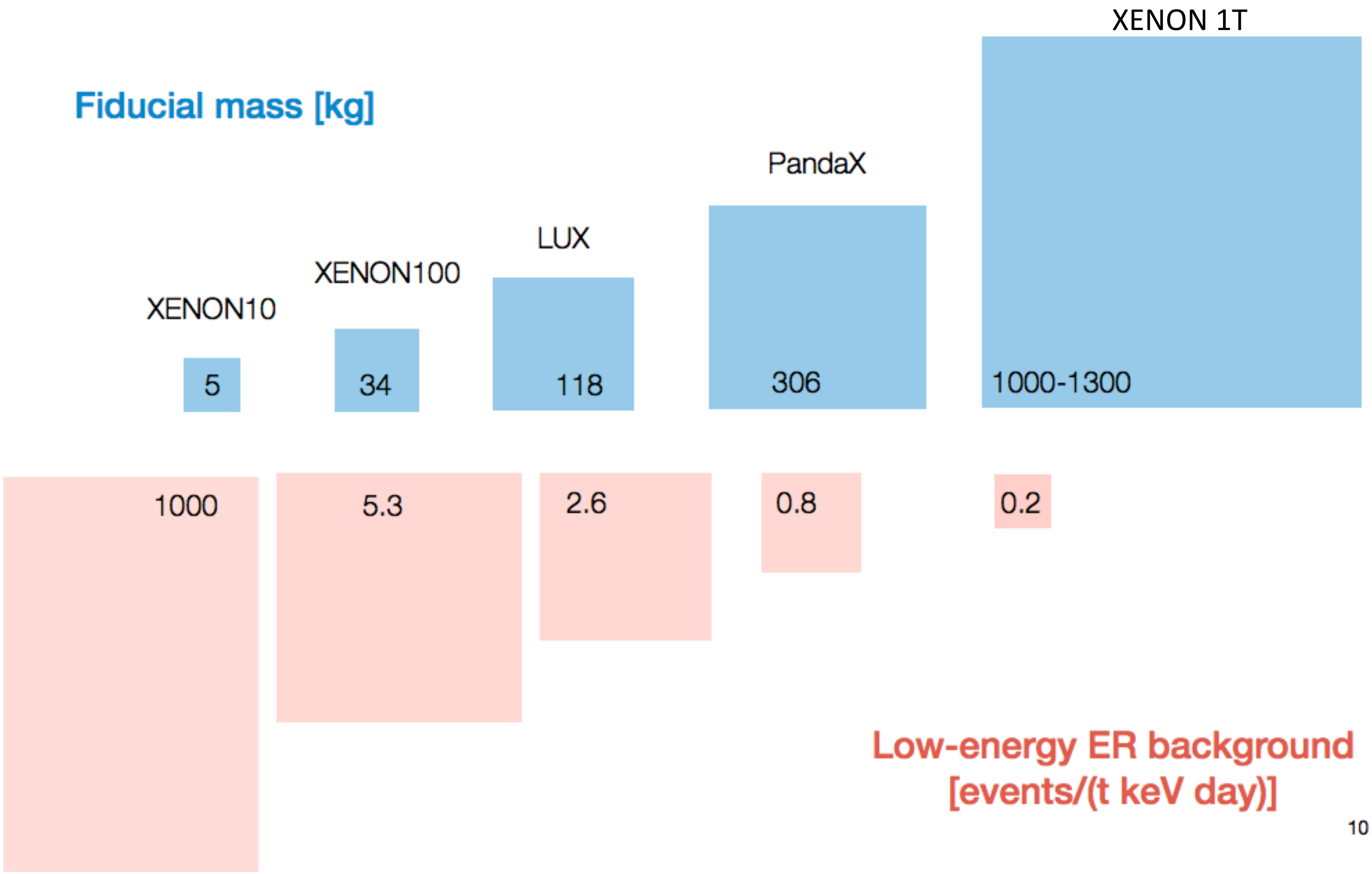


Future: XENONnT

total Xe mass = 8 t
target mass = 5.9 t
fiducial mass = ~4 t

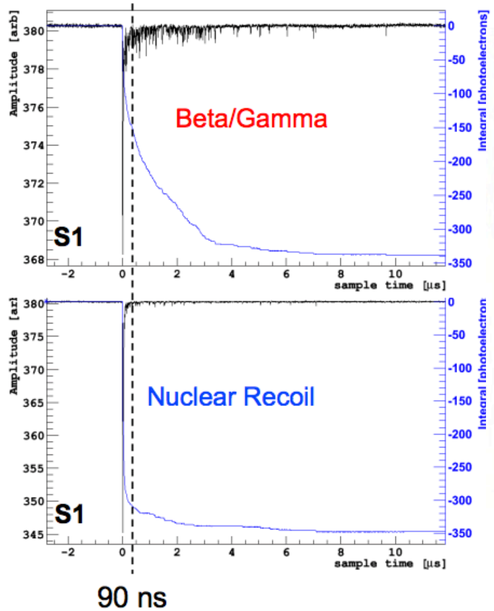
- Use XENON1T subsystems already tested
- Liquid Scintillator Neutron Veto to be added
- Main challenge: reduce ^{222}Rn by x 10

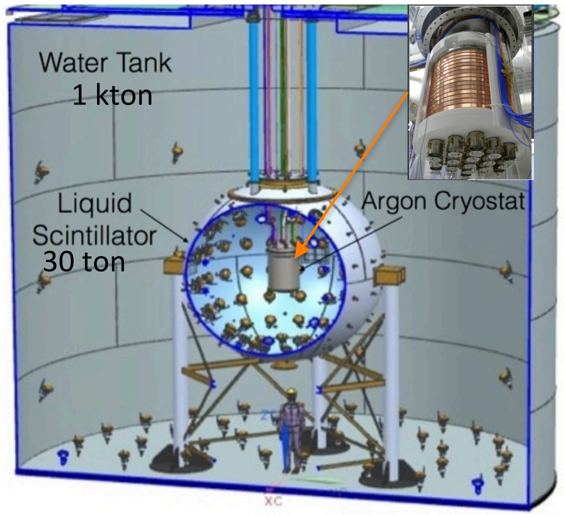
Two-phase xenon TPC evolution

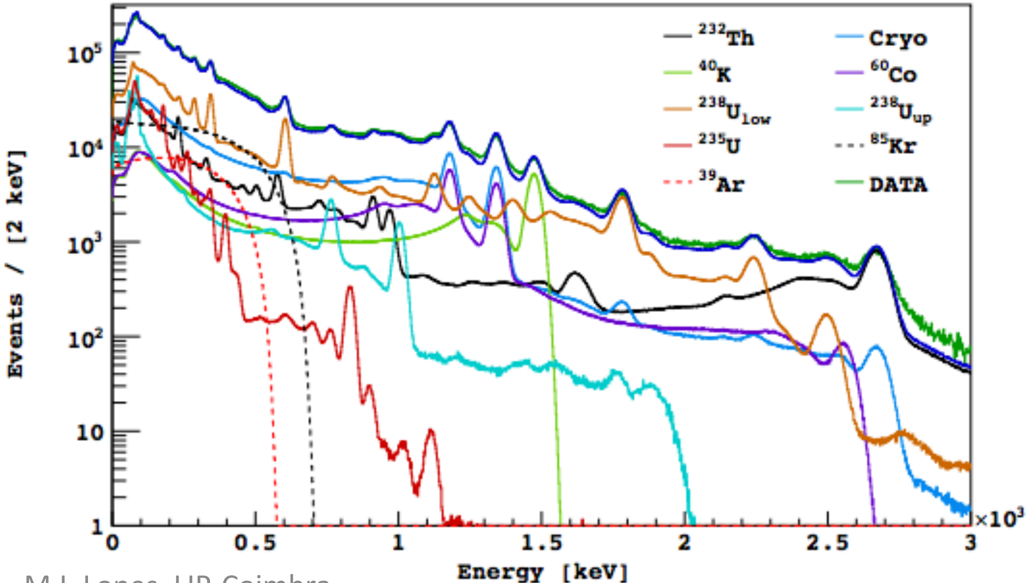


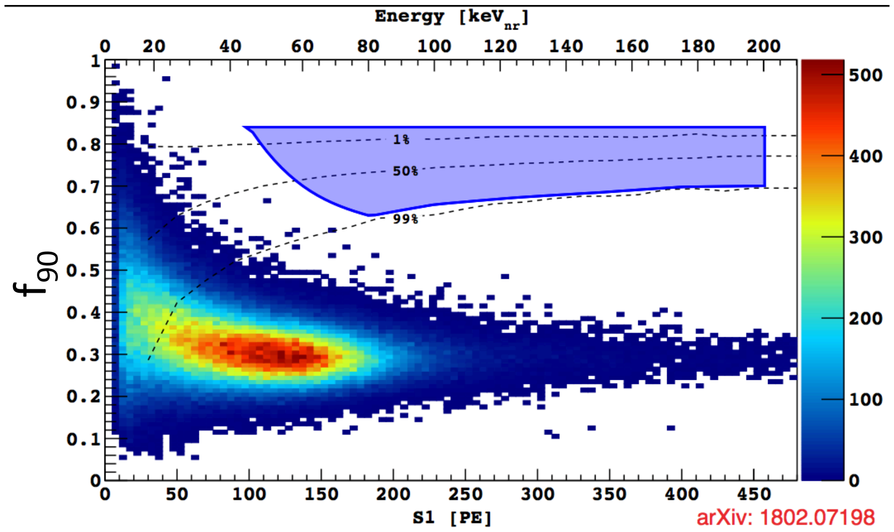
Dark Side -50

- Pulse shape discrimination (via f_{90}= S1 fraction in first 90 ns):
  - $f_{90} \approx 0.3$ for electron recoils (ER)
  - $f_{90} \approx 0.75$ for nuclear recoils (NR)
  - ER/NR rejection ~ 10^8
- Use **underground Argon with 0.73 ± 0.11 mBq/kg of ^{39}Ar activity**
- Dominant background: γs from PMTs



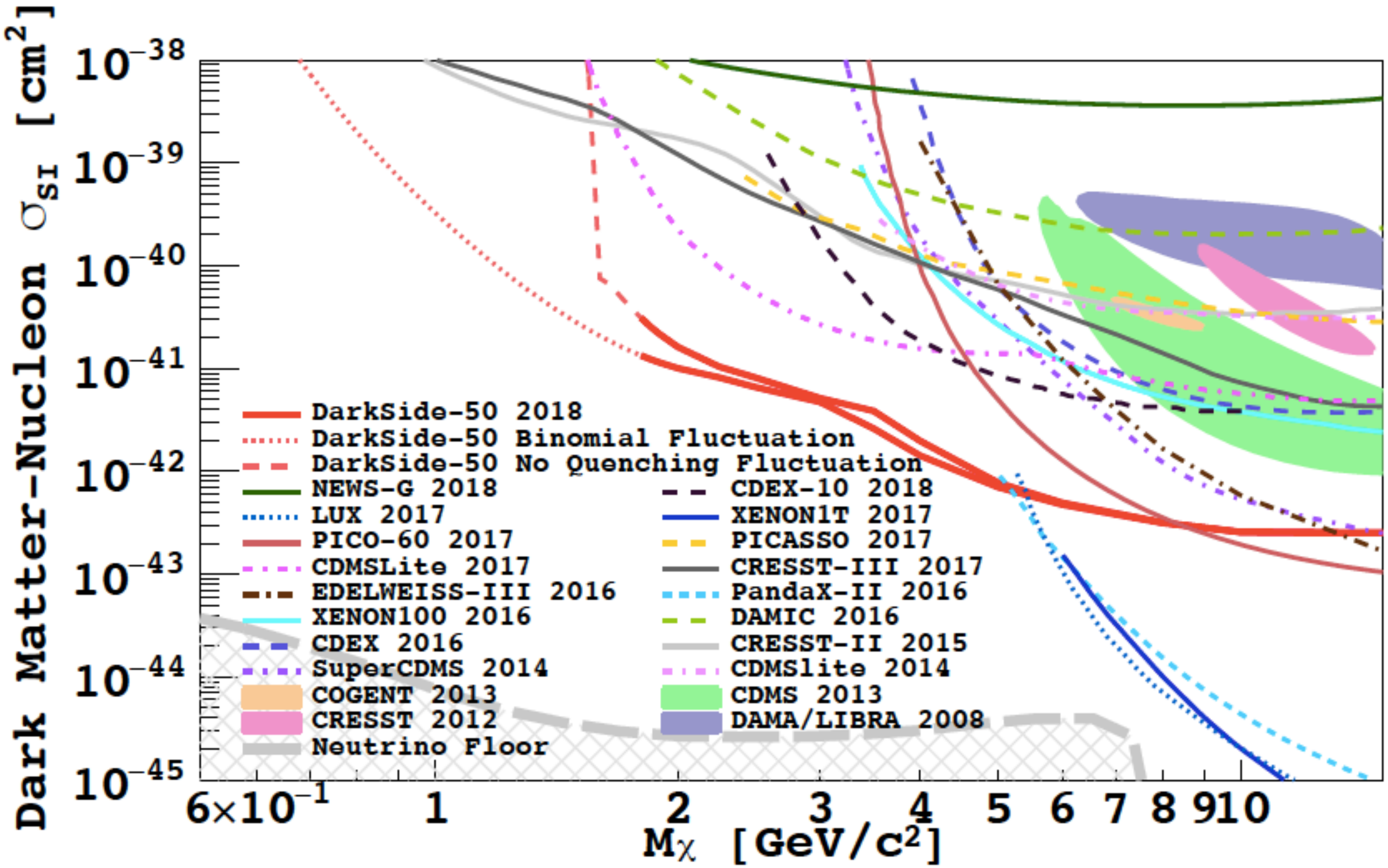






Data from 19.6 ton.day exposure

Dark-Side (S2-only analysis)



arXiv:1802.06994v2

Dark Side: present and future

arXiv: 1802.07198

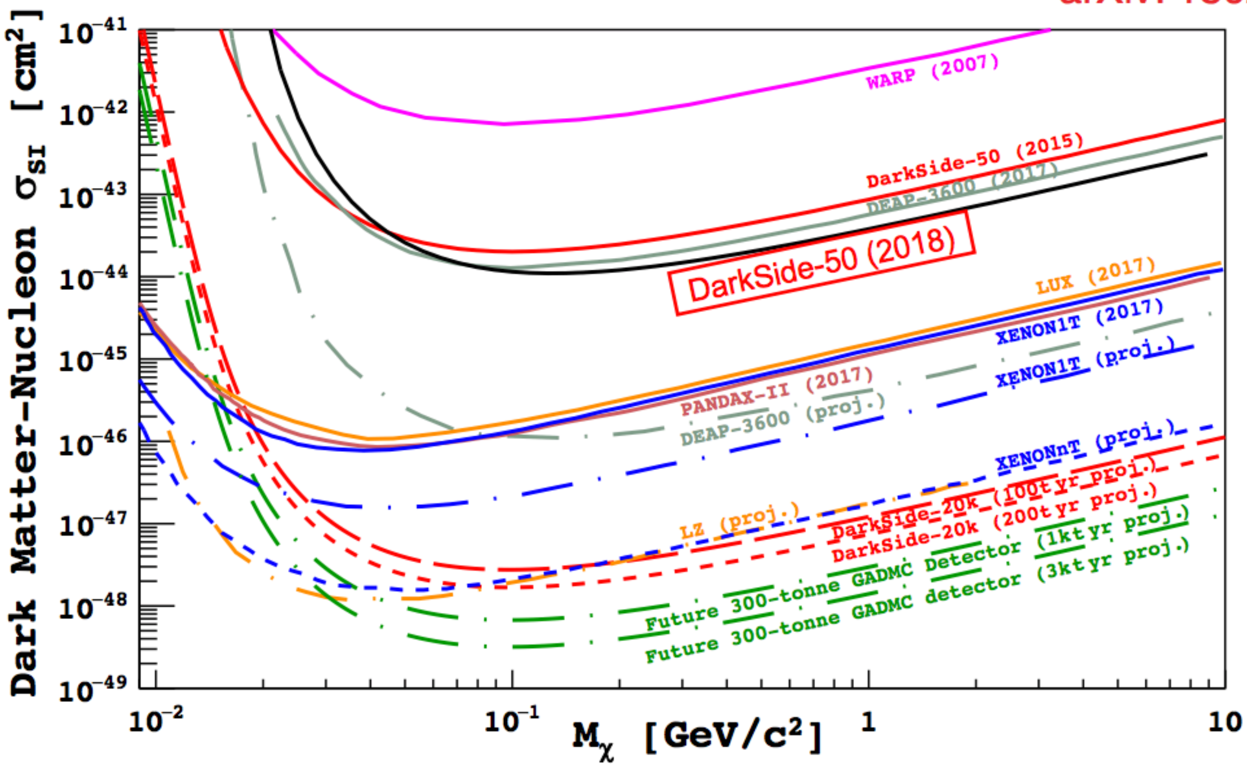
DarkSide-20k

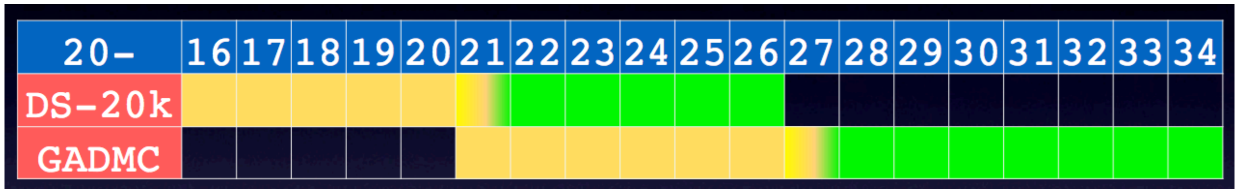
a **20-tonnes** fiducial LAr two-phase TPC → 100 tonne×year background-free

GADMC detector

a **300-tonnes** depleted argon detector

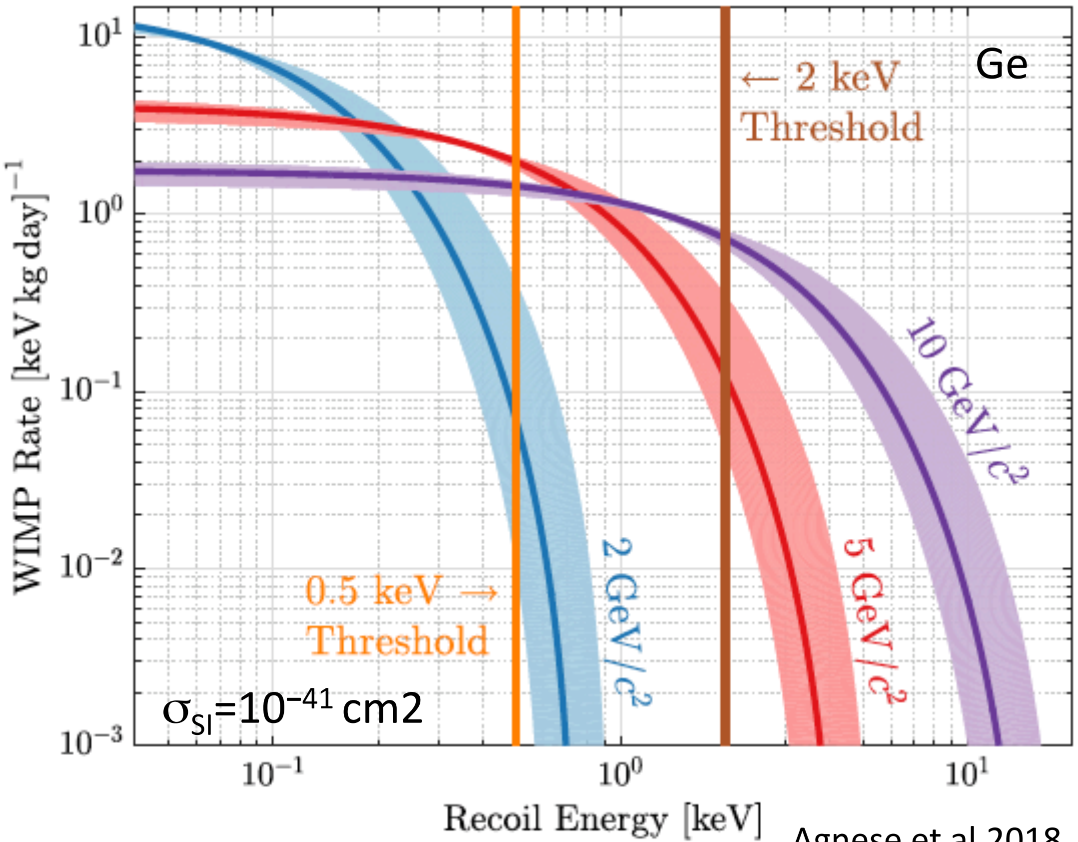
1,000 tonne×year background-free





- Upgrade of production of depleted argon to many tons
- PMTs replaced by SiPM arrays with area of 15 m2 (NOA)

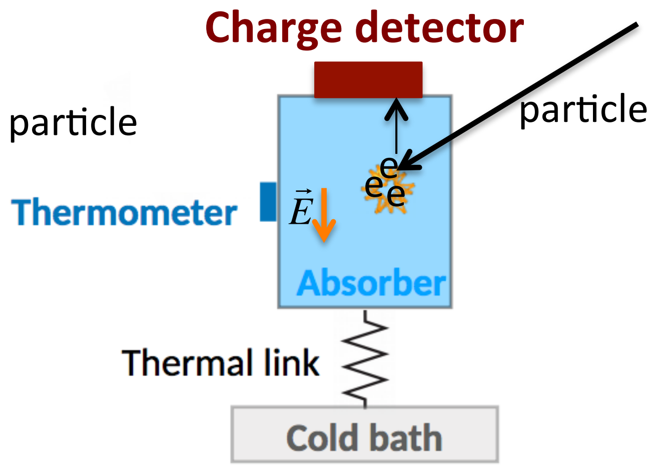
Searching for low-mass Dark Matter (a few GeV-scale)



Agnese et al.2018

It is mandatory to have energy threshold < 0.5 keV

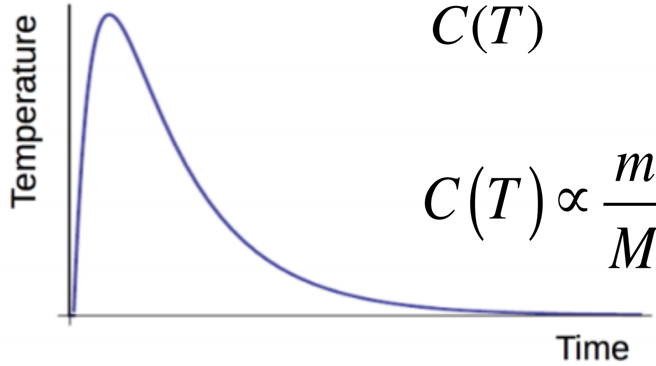
Cryogenic Detectors



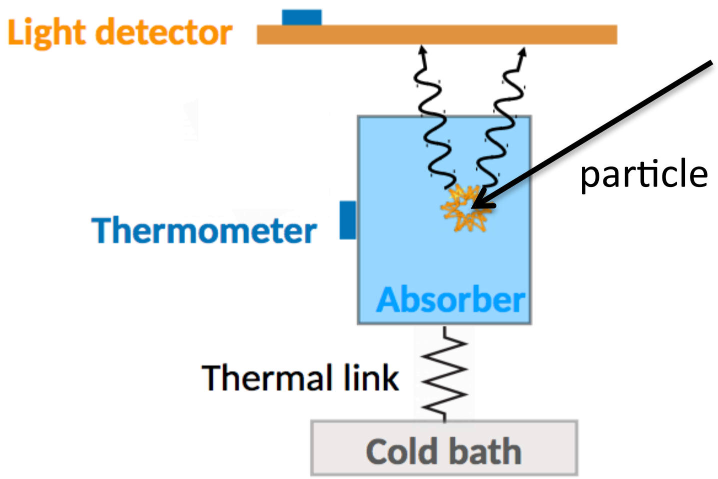
CDMS, Edelweiss – absorber: **Si, Ge**

Absorber at cryogenic temperatures (10-50 mK)

$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}} \quad \text{with} \quad \tau = \frac{C(T)}{G(T)}$$



$$C(T) \propto \frac{m}{M}\left(\frac{T}{\Theta_D}\right)^3$$



CRESST – absorber: **$CaWO_4$**

Order of magnitude of ΔT:

At 10 mK, for **E=1 keV** in a 100 mg detector,

$$\Delta T \approx 1 \mu K$$

Challenging but possible to measure.

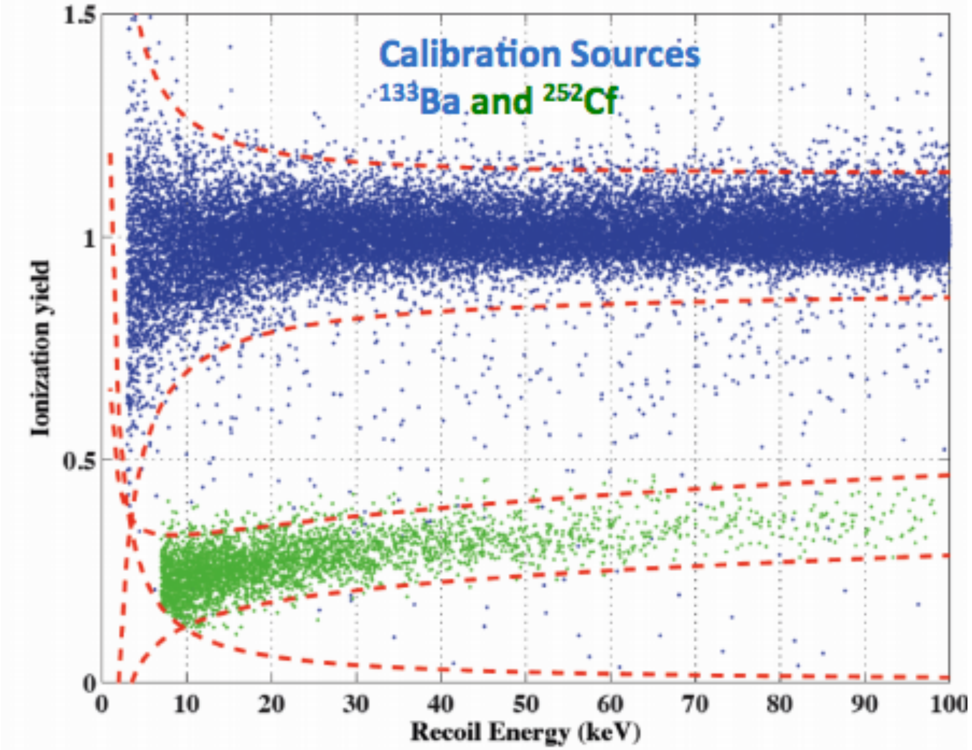
- ΔT allows to measure the total deposited energy with low threshold, (~ tens or hundreds eV)
- **Ratio light (or charge) to phonon signal amplitudes allows ER/NR discrimination**

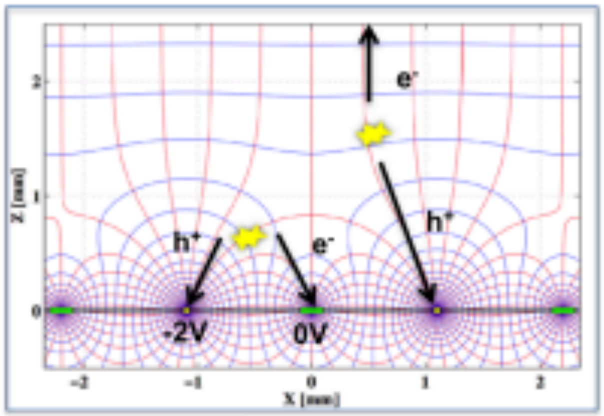
SuperCDMS

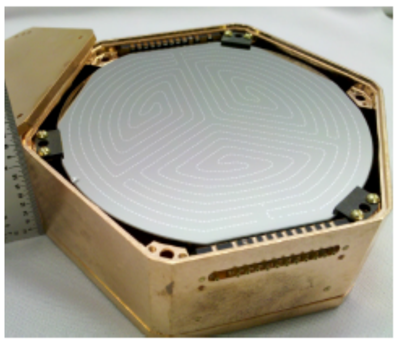
iZIPs: interleaved Z-sensitive Ionization and Phonon detectors

- Simultaneous measure charge and phonons
  → rejection main electron recoil backgrounds (>10^5)
- rejection surface events via interleaved electrodes

Low background

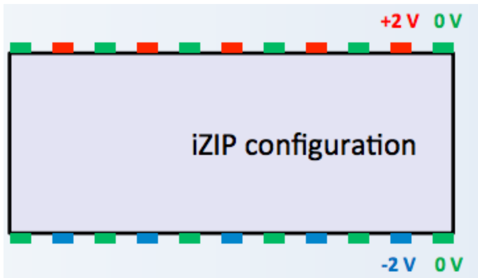






iZIP module (Ge):

2.5 cm thick and 7.7 cm ϕ ; 620 g

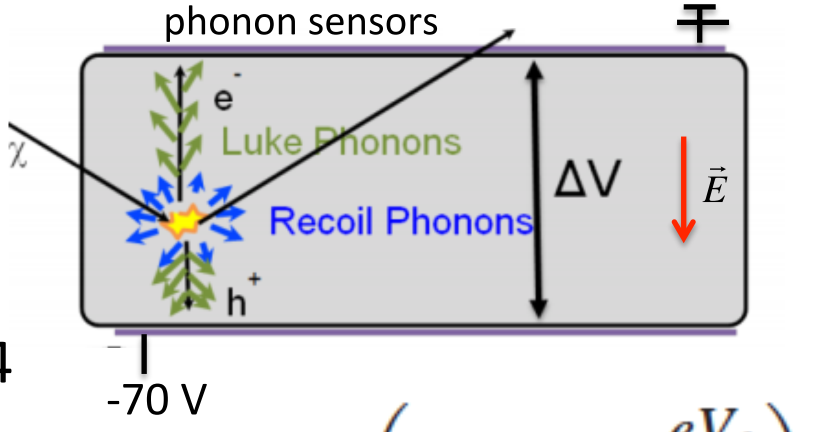


4 phonon + 2 charge channels on each detector face

SuperCDMS

CDMSlite (HV mode)

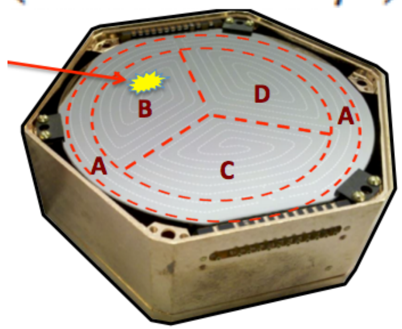
- Free e/h; energy gain from applied electric field (ΔV=70 V) → emission Luke-Neganov phonons from electron scattering on lattice (amplification =24 but only x12 for one sided readout)



$$E_t = E_r\left(1 + Y(E_r)\frac{eV_b}{\epsilon_\gamma}\right).$$

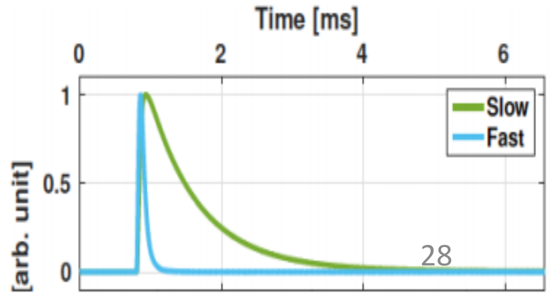
+ lower threshold (**56 eV** @ΔV=70 V) improves energy resolution (17 eV at 160 eV)

– no ER/NR discrimination through ionization yield



- Pulse shape provides position info → fiducialization (radial cut removes more than 90%)

fast component: amplitude depends on the position of the scattering event; slow component: carries the primary energy information.

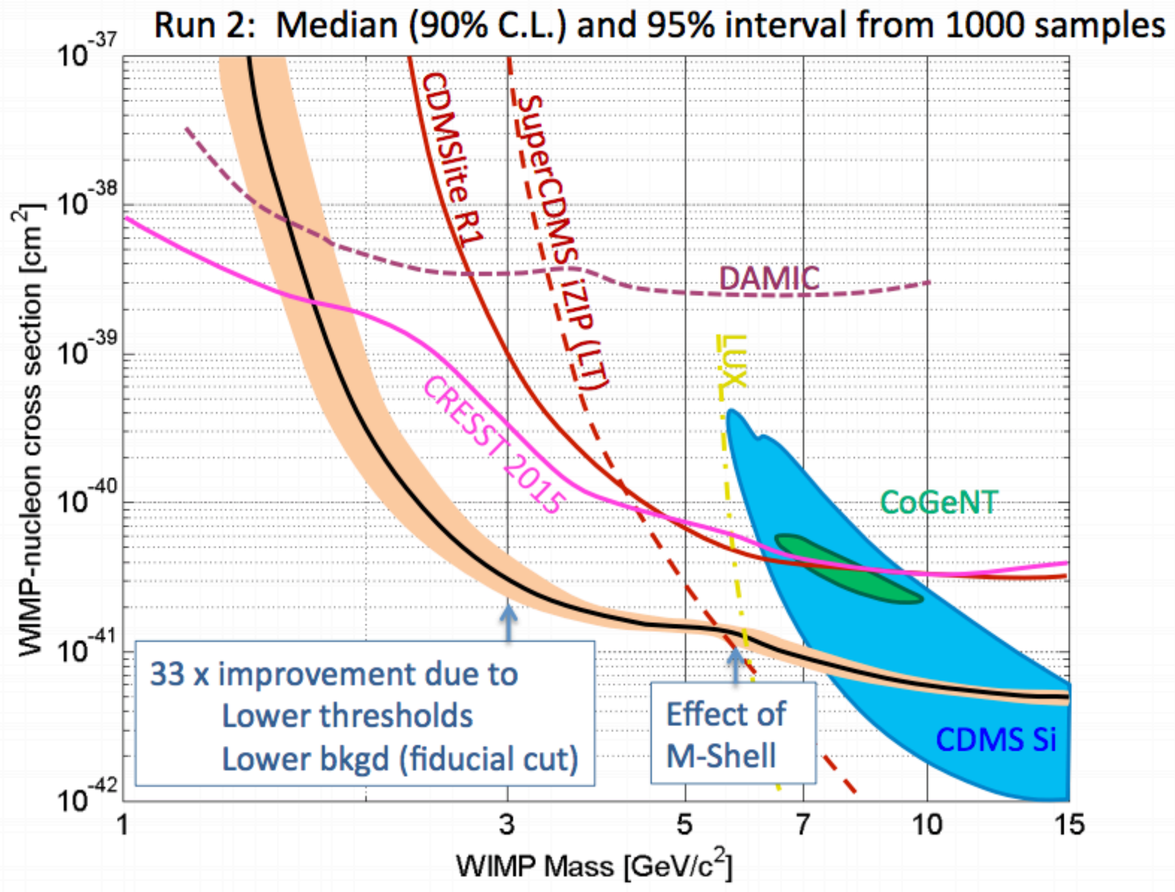


SuperCDMS – II

Detector array: 15 Ge iZIP detectors (0.6 kg each) In 5 towers of 3 detectors each
1 Ge HV detector

Data acquired from February to November 2014: 70 kg-days total exposure

Data between 56 eV and 2 keV was analysed.



R. Agnese et al. (SuperCDMS Collaboration) Phys. Rev. Lett. **116**, 071301, 2016

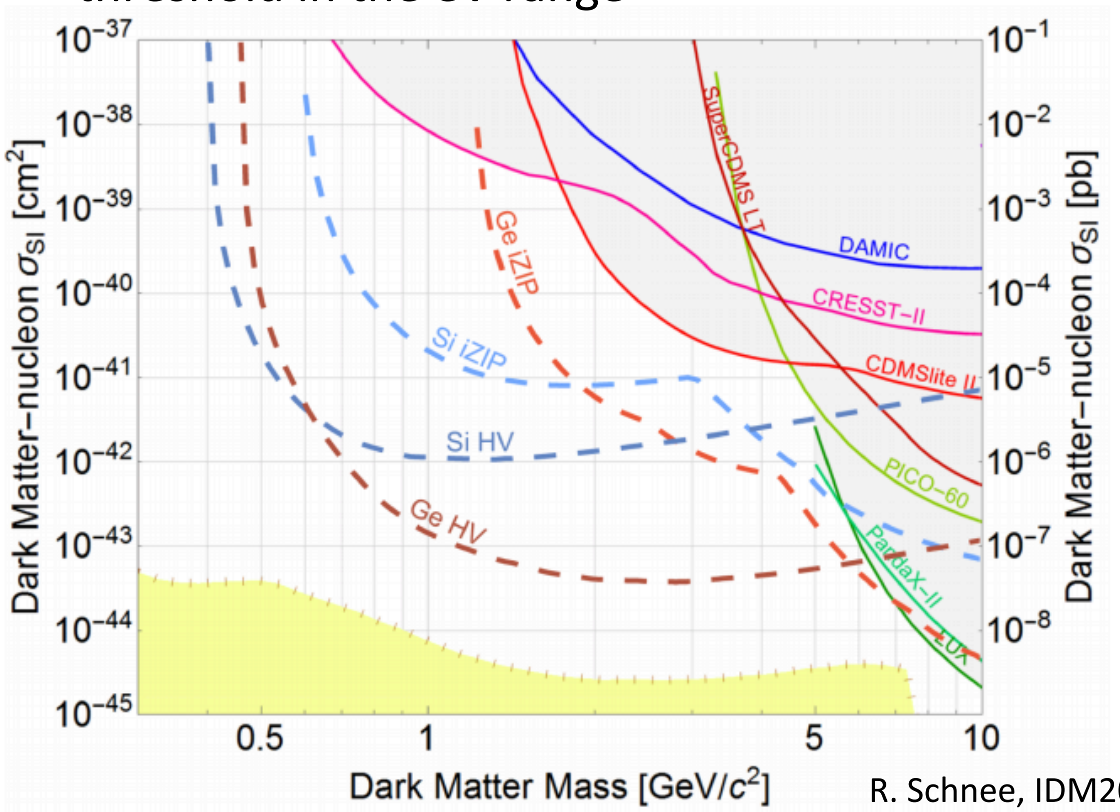
Future: CDMS @Snolab

2 HV towers (4 Ge modules, 2 Si each)

2 iZIP towers (6 Ge in 1, 4/2 Ge/Si other)

- improved phonon sensors
- double sided readout
- increased HV
- improved energy resolution
- threshold in the eV range

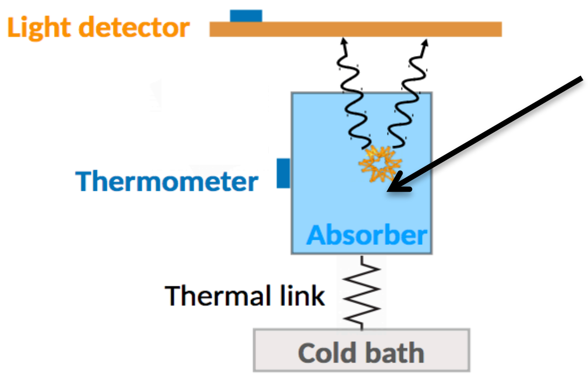
	Soudan	SNOLAB goal
Phonon resolution, eVt	~250	HV:10, iZIP:50
HV Bias Voltage, V	70	100
iZIP Charge res., eVee	~400	160
HV Threshold, eVnr	300	40

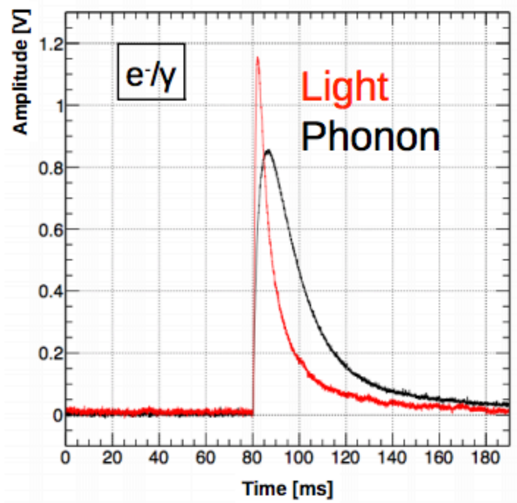


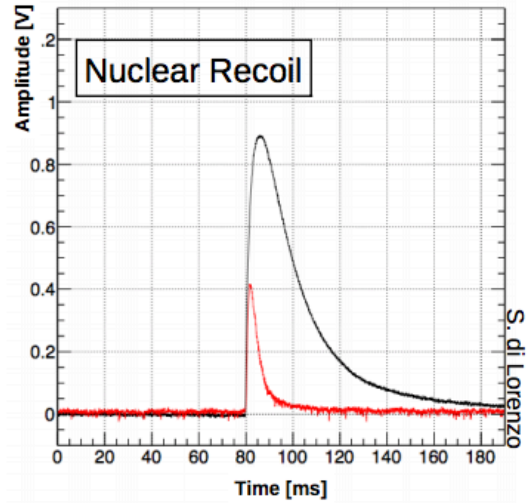
R. Schnee, IDM2018

- reduced background by a factor of 200
- start operation @Snolab in 2020

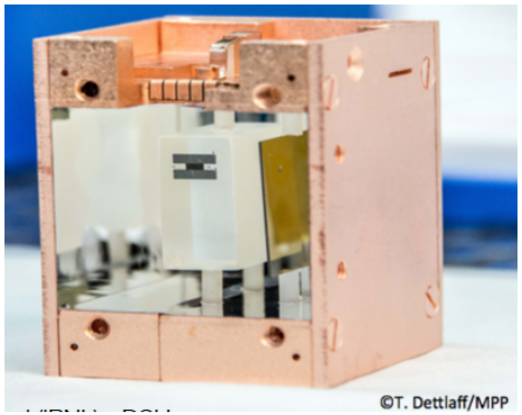
CRESST: discrimination

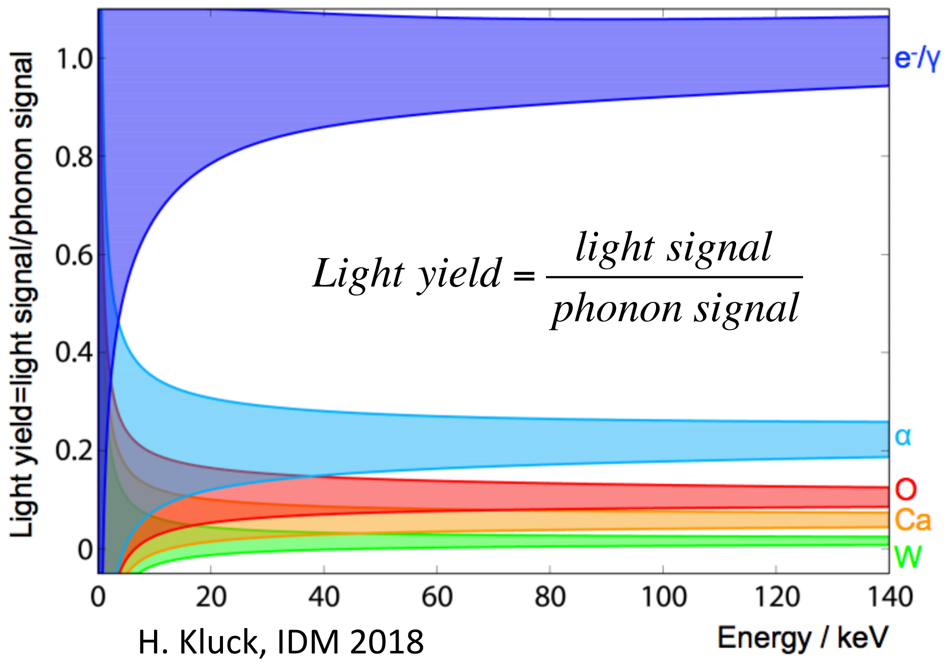






CRESST – absorber: $CaWO_4$



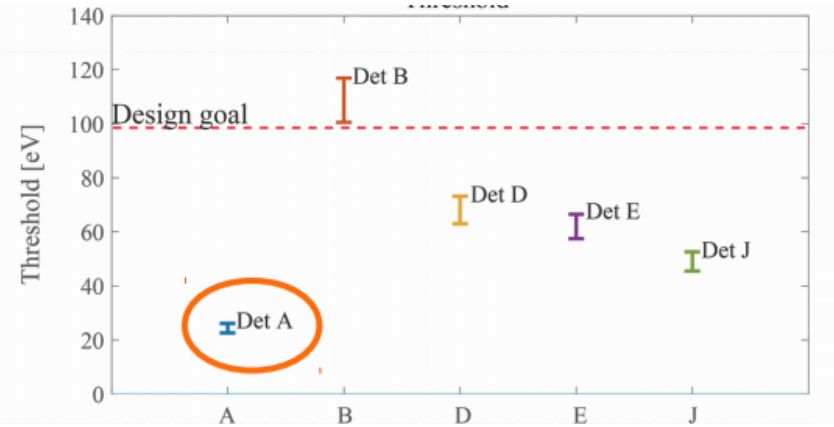


H. Kluck, IDM 2018

Cuboid CaWO4 crystals (20 x 20 x 10) mm^3 ~ 24 g

Self grown crystals ~ 3 counts/(keV kg day)

CRESST-III: last results

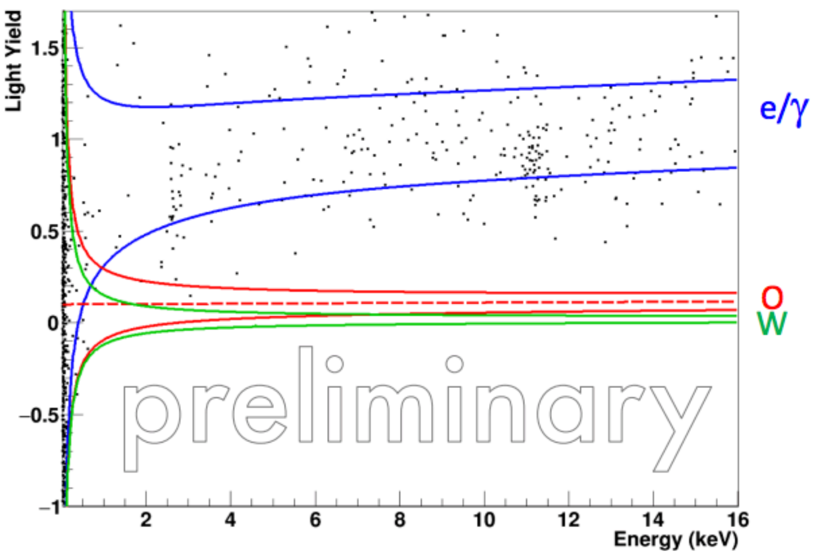


(accepted noise trigger rate above threshold: 1 count/kg/day)

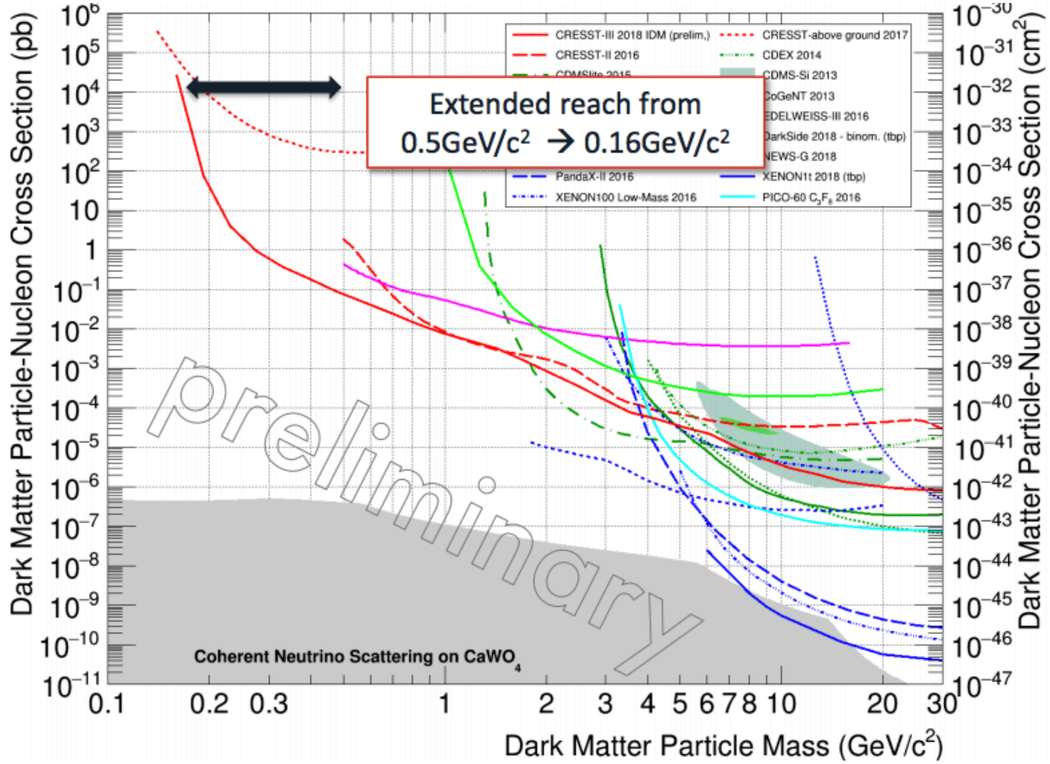
F. Reindl, IDM2018

Analysis of one detector data (Det-A)

- 5.7 kg days of raw data
- nuclear recoil threshold=30.1 eV
- Unexpected rise of background event rate < 200eV



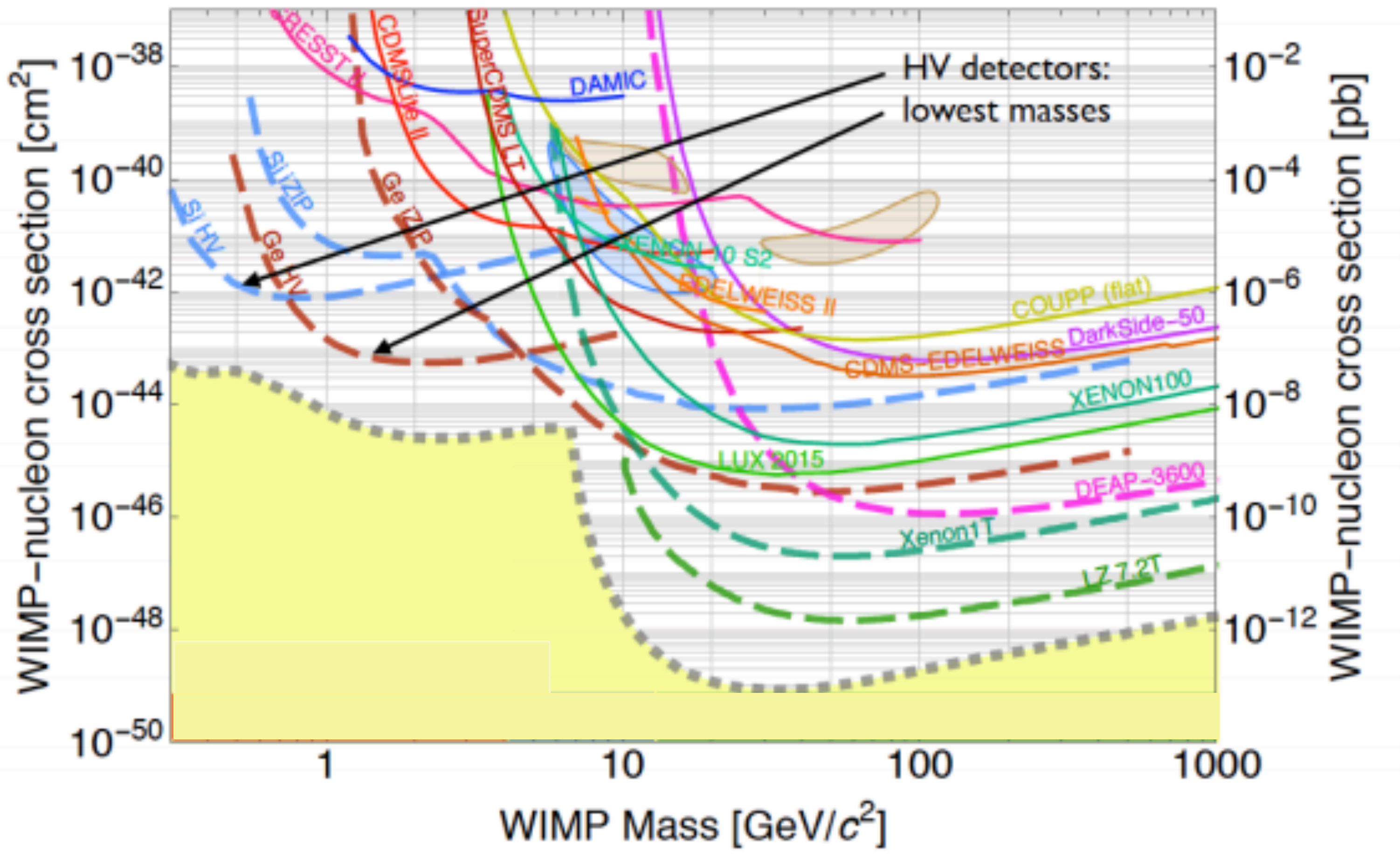
Acceptance region: [30.1 eV, 16 keV]



Experiments based on other detection techniques

- **PICO (C3F8 bubble chambers):** No energy info, but ER-blind to highest degree of any experiment; It leads the WIMP-proton spin-dependent interaction searches;
- **DAMIC (CCDs)**: aiming at extremely low threshold, O(10) eV!
- **CDEX (Ge @ 77K):** replicates CoGent
- **DAMA (NaI)**: Claims WIMP detections by observation of consistent signal annual modulation for 14 years; result not supported by many other experiments.
- **SABRE (NaI)**: reproduce DAMA / LIBRA with ultra-low-background NaI, in Australia!
- **DRIFT, CYGNOUS (gaseous TPC)**: directional information
- ….and more

WIMP search landscape



P. Cushman

Conclusions

- Many complementary approaches being employed for the WIMPs direct detection
- Very active field and tremendous progress over the past decade
- Goal: probe the experimentally reachable parameter space, down to the (possibly) irreducible neutrino background
- The sub-GeV mass region is receiving increasing attention
- R&D programs to find new detection technologies allowing to increase the sensitivity to sub-GeV dark matter particles
- Non-WIMP physics programme
  - axions/ALPs
  - double beta decay
  - solar/atm/SN neutrinos, etc