Status of direct detection experiments and their approaches to statistical inference

PHYSTAT-DM, 31st July 2019, Stockholm

Jim Dobson, STFC Ernest Rutherford Fellow @ UCL

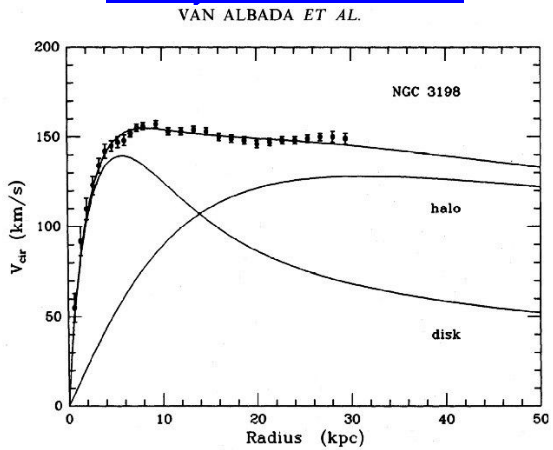
Science & Technology Facilities Council

UCL

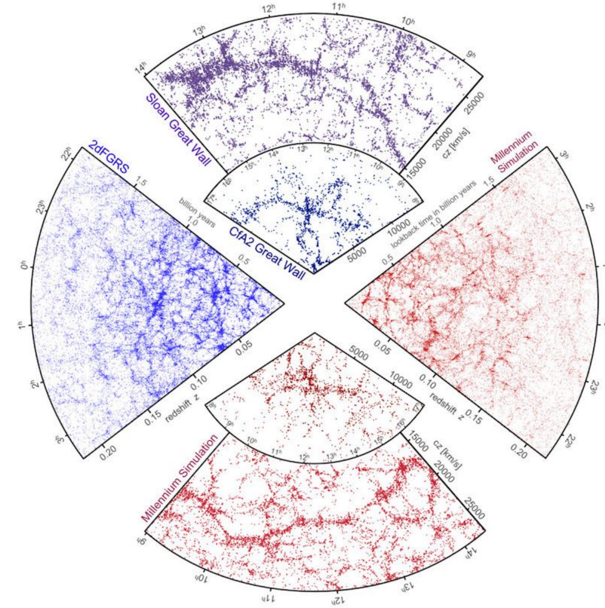
Dark Matter ← evidence from gravitational effects @ many scales

Galaxy clusters

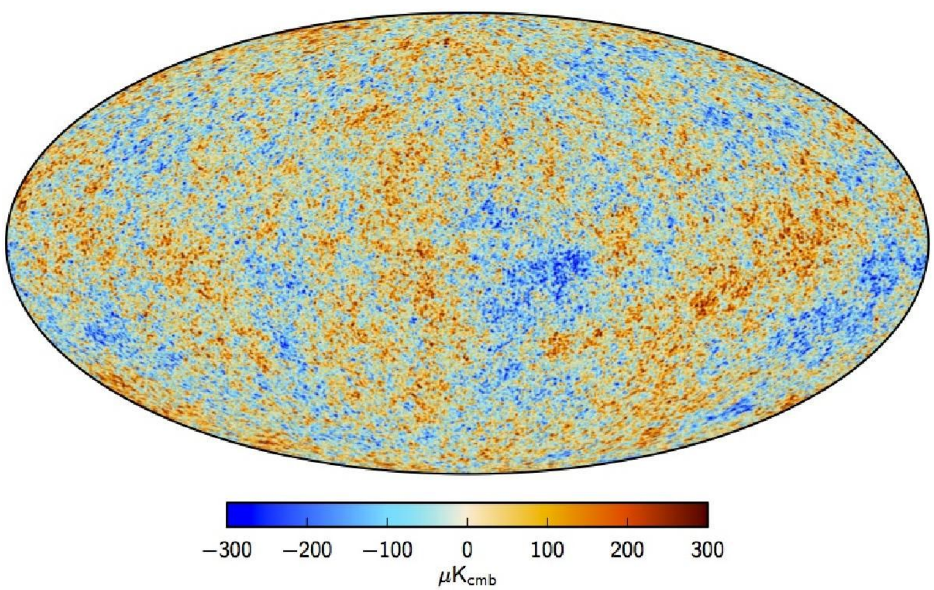
Galaxy rotation curves



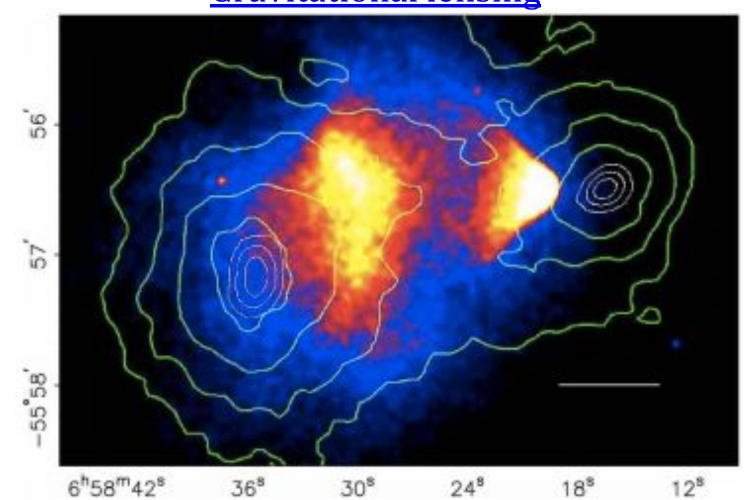
Large scale structure



Cosmic Microwave Background



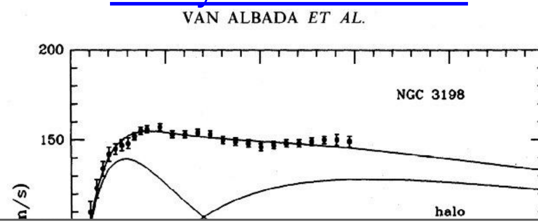
Gravitational lensing



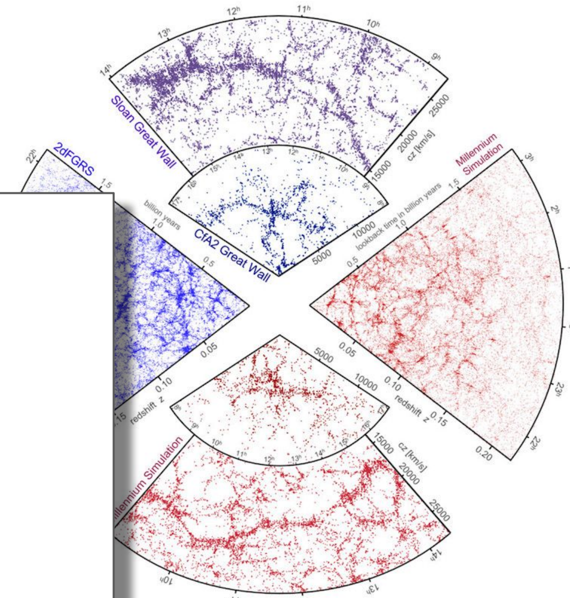
Dark Matter ← evidence from gravitational effects @ many scales

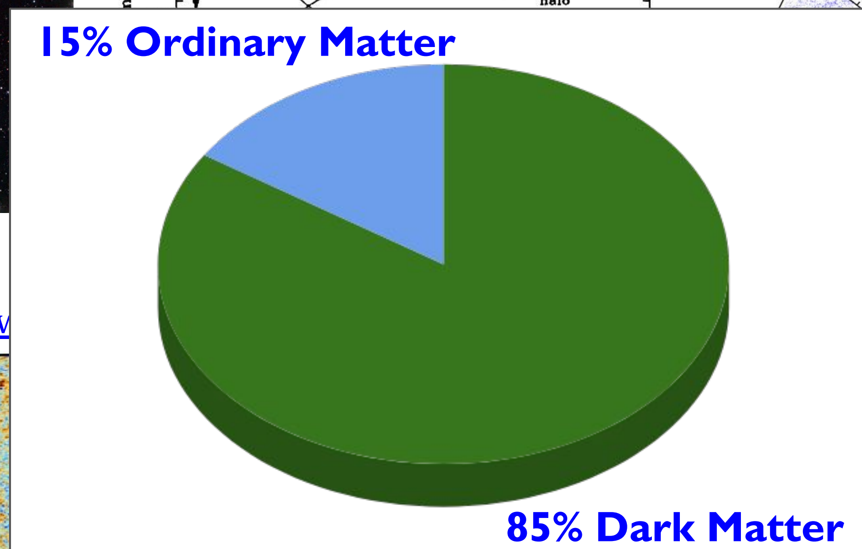
Galaxy clusters

Galaxy rotation curves

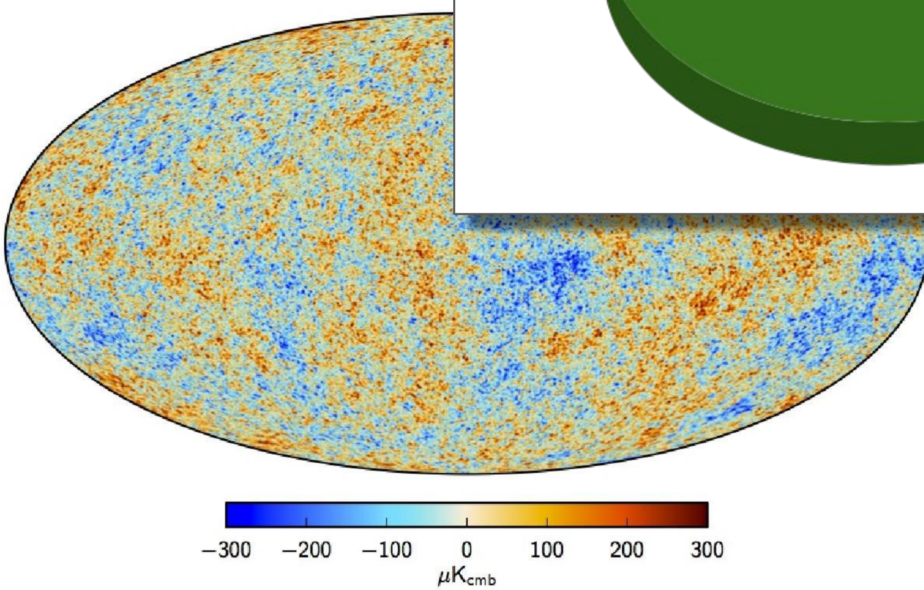


Large scale structure

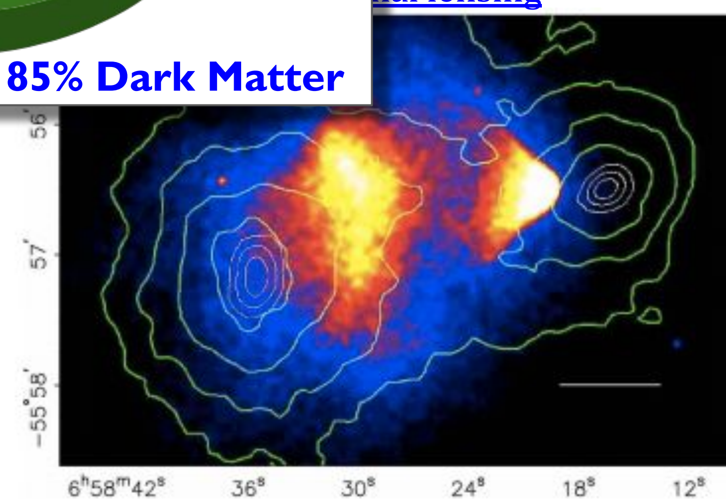




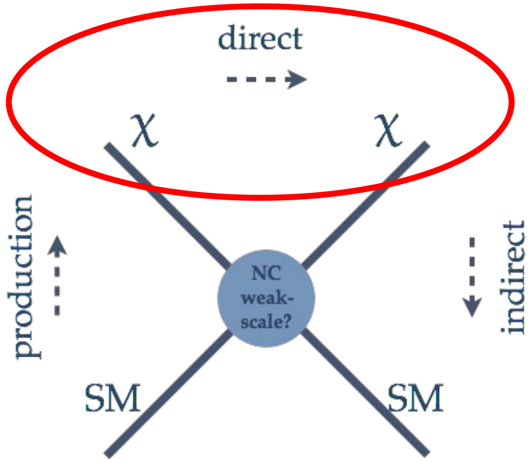
Cosmic Microv

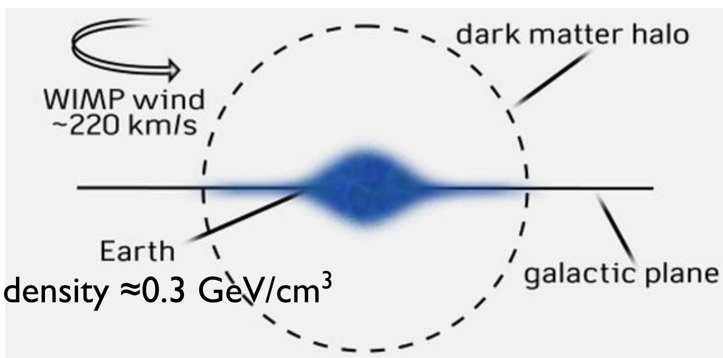


nal lensing

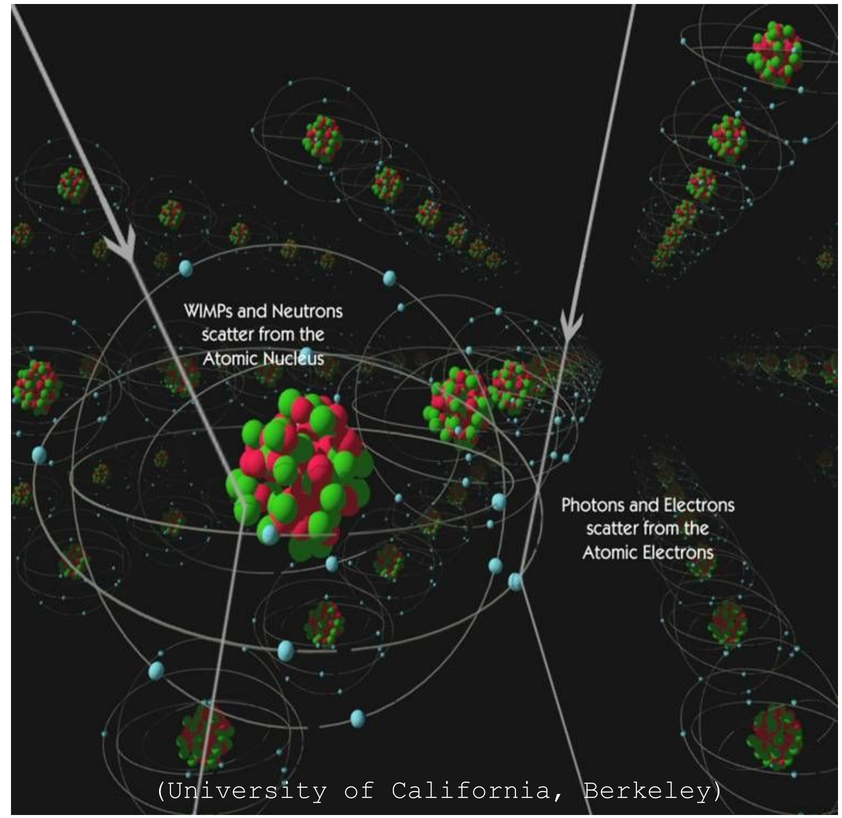


Direct Detection



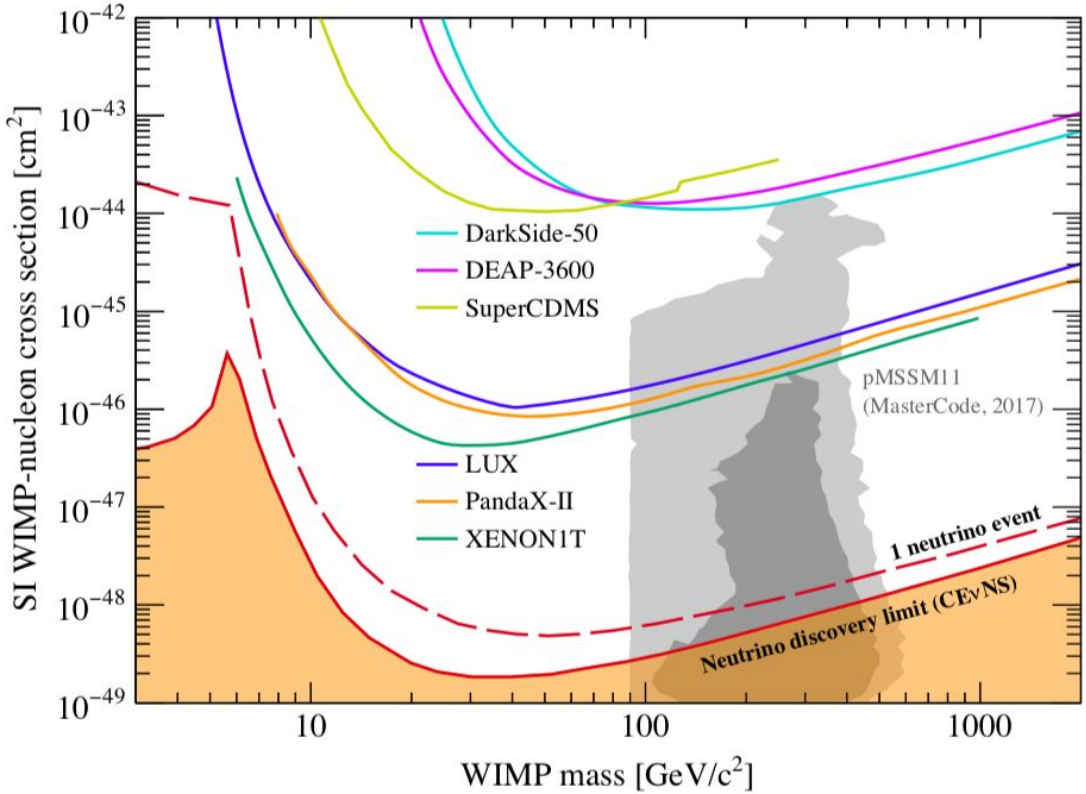


local density ≈0.3 GeV/cm^3



Direct searches for **rare** (<0.0001 /kg/day), **low-energy** (~keV) scattering of **thermal relics** (e.g. galactic WIMPs)

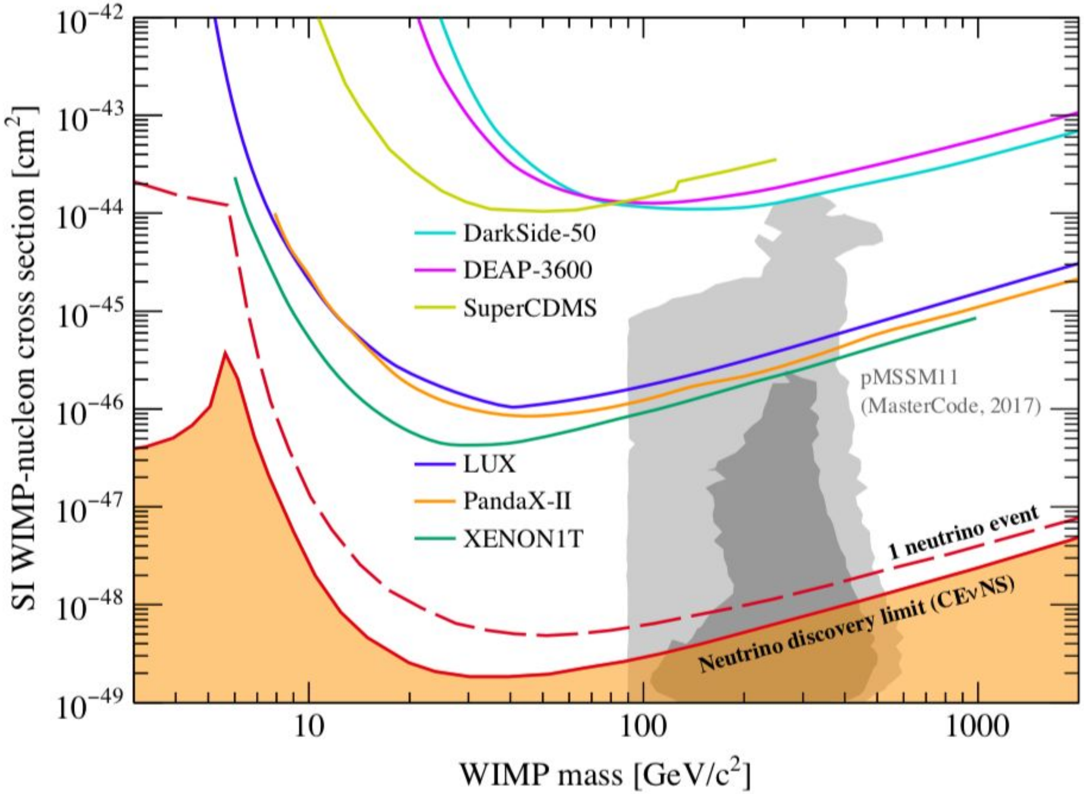
Direct Detection: sensitivity drivers



Direct detection requires detector with: **large target + low threshold + <u>low background</u>**

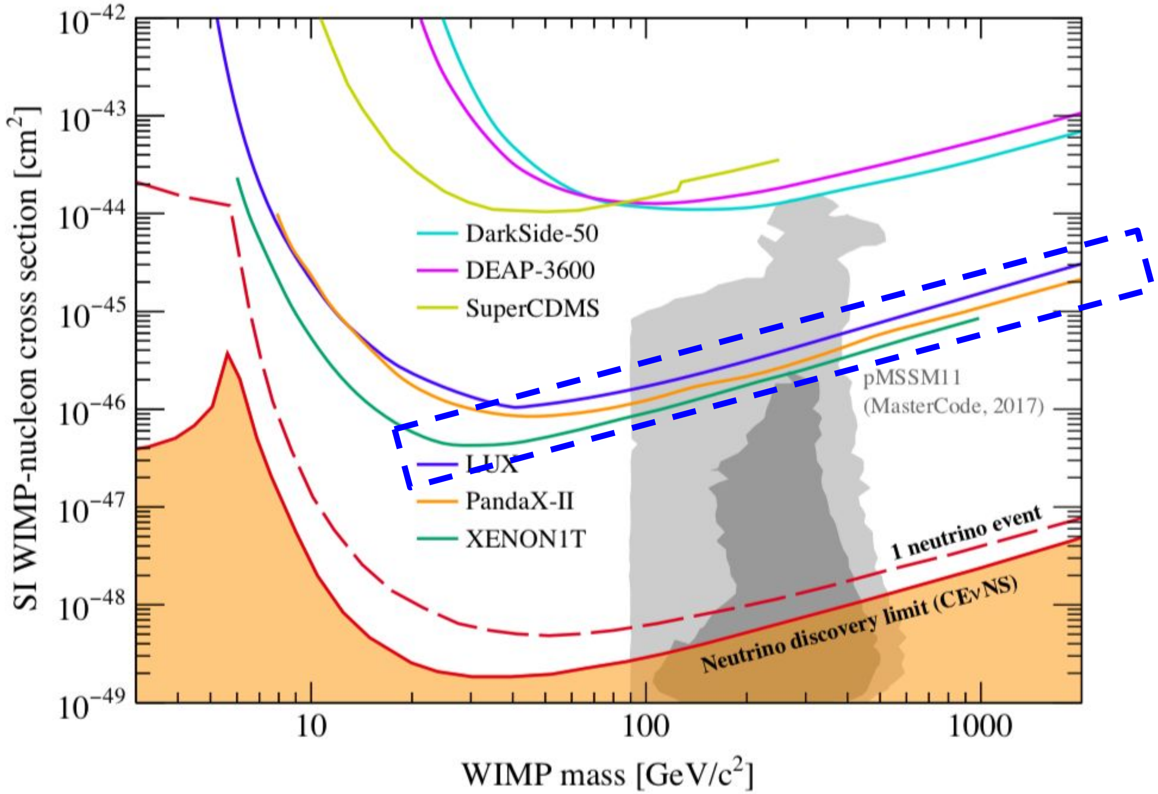
Direct Detection: sensitivity drivers

THRESHOLD & ATOMIC MASS MATTERS
CRYOGENIC DETECTORS



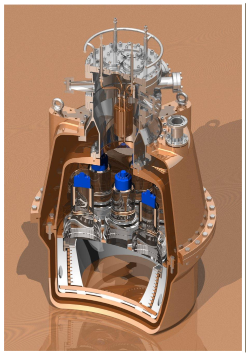
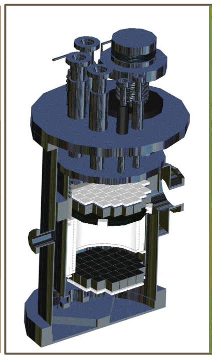
SIZE (x TIME) MATTERS
NOBLE LIQUIDS

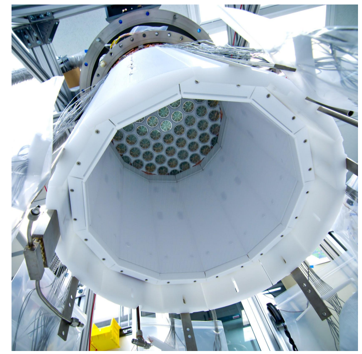
Direct Detection status: LXe



Liquid Xenon time projection chambers

Direct Detection status: LXe

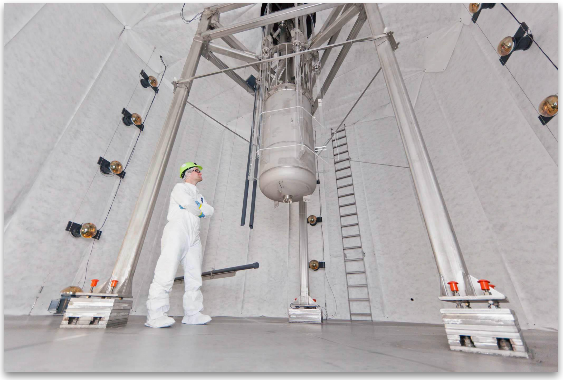



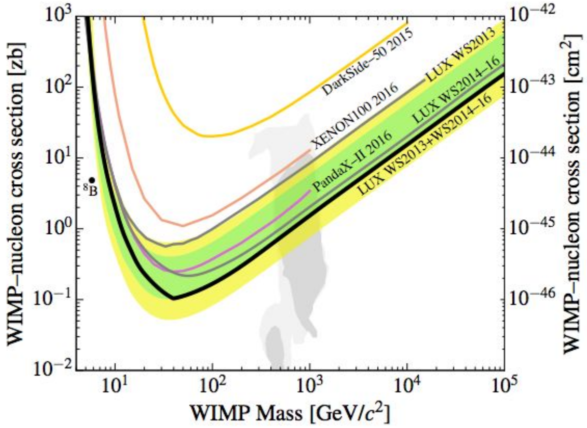
ZEPLIN-II	XENON10	ZEPLIN-III	XENON100	LUX	PANDAX-II	XENON1T
31 kg (7.2 kg)	15 kg (5 kg)	12 kg (7 kg)	62 kg (34 kg)	250 kg (100 kg)	580 kg (362 kg)	2,000 kg (1,042 kg)
2007	2007	2008	2010	2013	2016	2017
6.6×10^{-43} cm^2	8.8×10^{-44} cm^2	8.1×10^{-44} cm^2	3.4×10^{-44} cm^2	3.4×10^{-46} cm^2	2.5×10^{-46} cm^2	7.7×10^{-47} cm^2

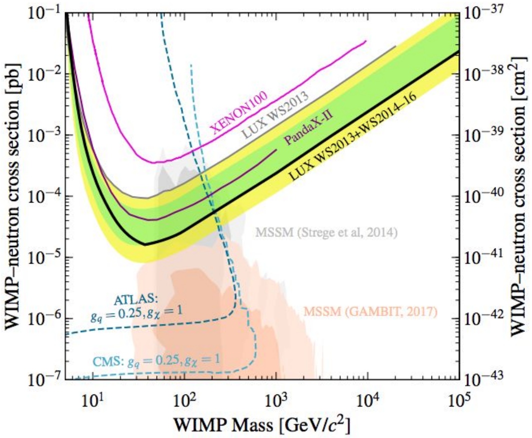
*disclaimer: will only show latest/leading results in more detail

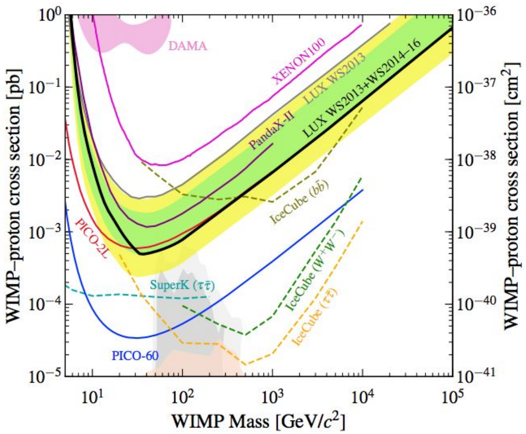
LUX @ SURF (USA)

- First results in 2013, decommissioning in 2018
  - S.I. WIMP-nucleon constraints (Phys. Rev. Lett. 118, 021303 (2017)
  - S.D. WIMP-neutron constraints (Phys. Rev. Lett. 118, 251302 (2017)
- Axions/ALPs results (Phys. Rev. Lett. 118, 261301 (2017)
- Multiple analyses completed / ongoing (non-WIMP DM, modulations, multiple-scatter, EFT, ...)
- Novel techniques to extend to low mass: DPE, Migdel
- Calibrations and light/charge yields: strong legacy



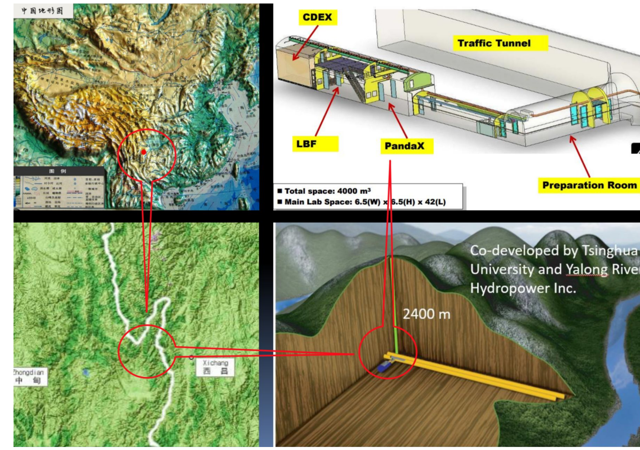


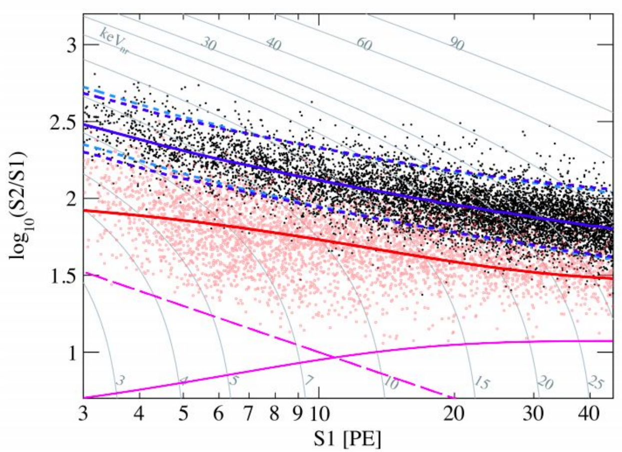


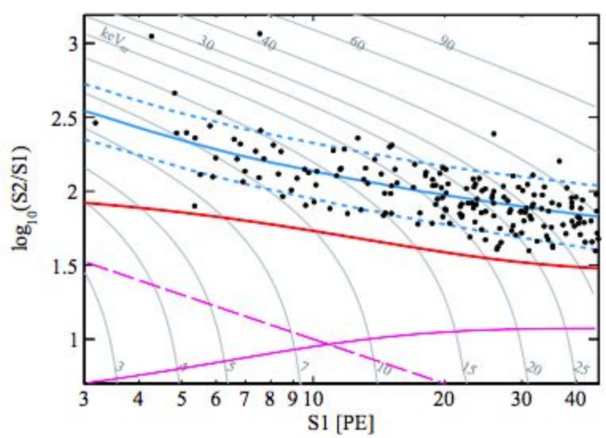


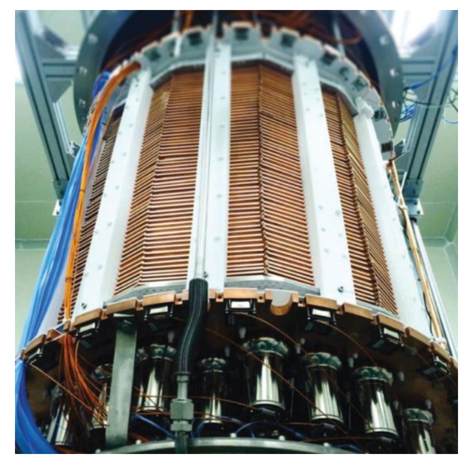
PandaX @ Jin Ping (China)

- 580 kg LXe TPC
- Very first results were competitive with LUX
- Rapid construction and deployment
- S.I. constraints:
  - Phys. Rev. Lett. 119, 181302 (2017)
- Science runs to be completed in 2019



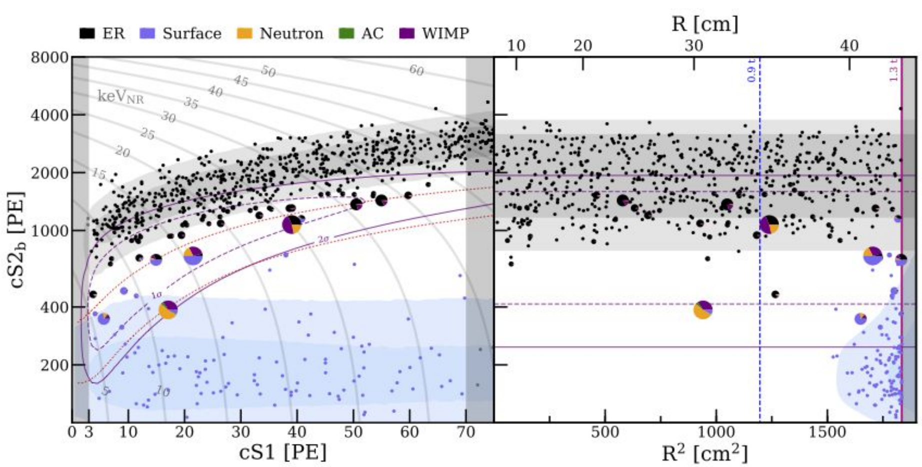


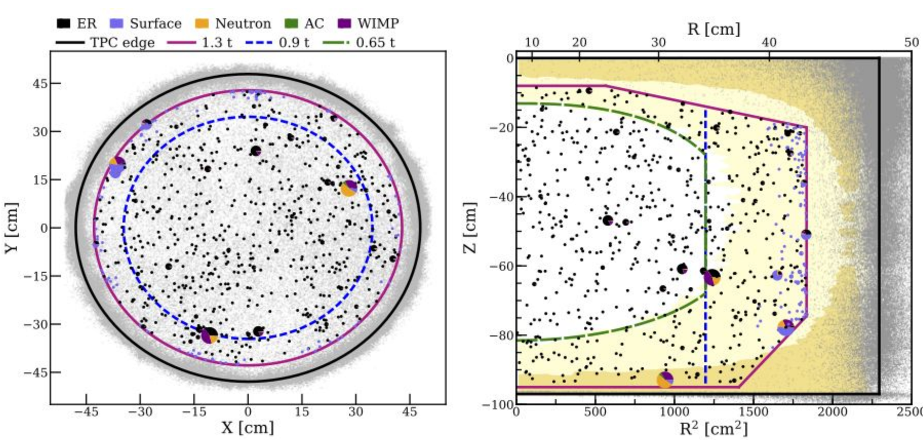




XENON1T @ Gran Sasso (Italy)

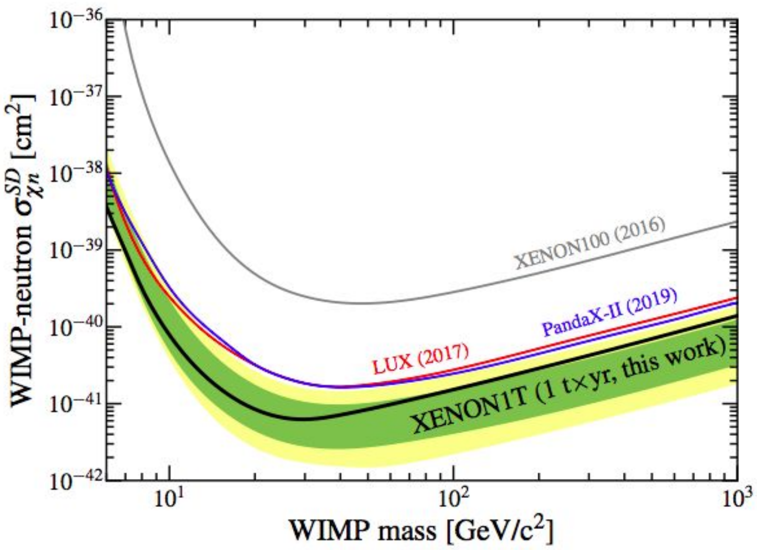
- 2 tonne LXe TPC (1.3 tonne FV)
- Lowest BG rate to date
- World-leading limits on WIMP interactions
  - S.I. WIMP-nucleon constraints: Phys. Rev. Lett. 121, 111302 (2018)
  - S.D. WIMP-neutron constraints: Phys. Rev. Lett. 122, 141301 (2019)
- + 4.4σ observation of 2ν DEC ^{124}Xe [Nature 568 (2019)]

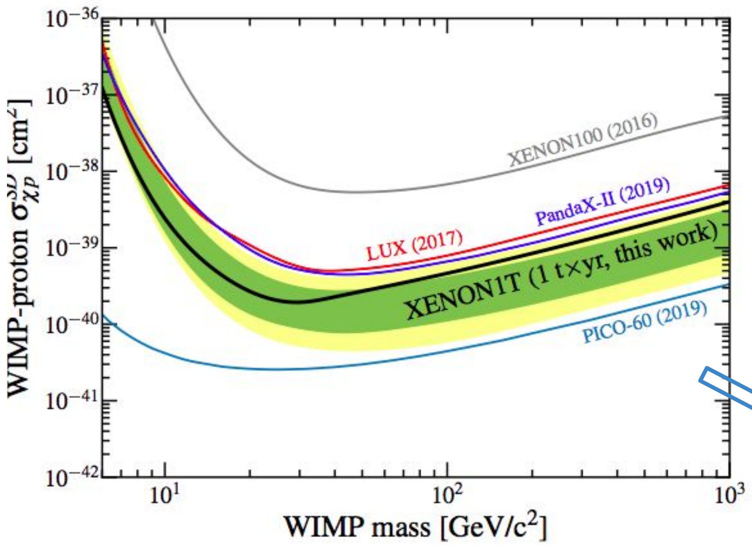




arXiv:1805.12562

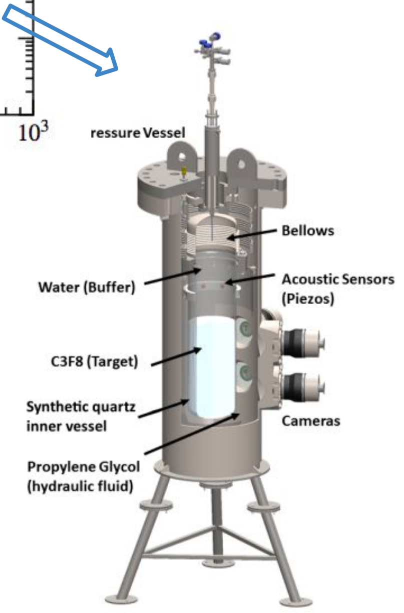
Spin-dependent: XENON1T/PICO-60



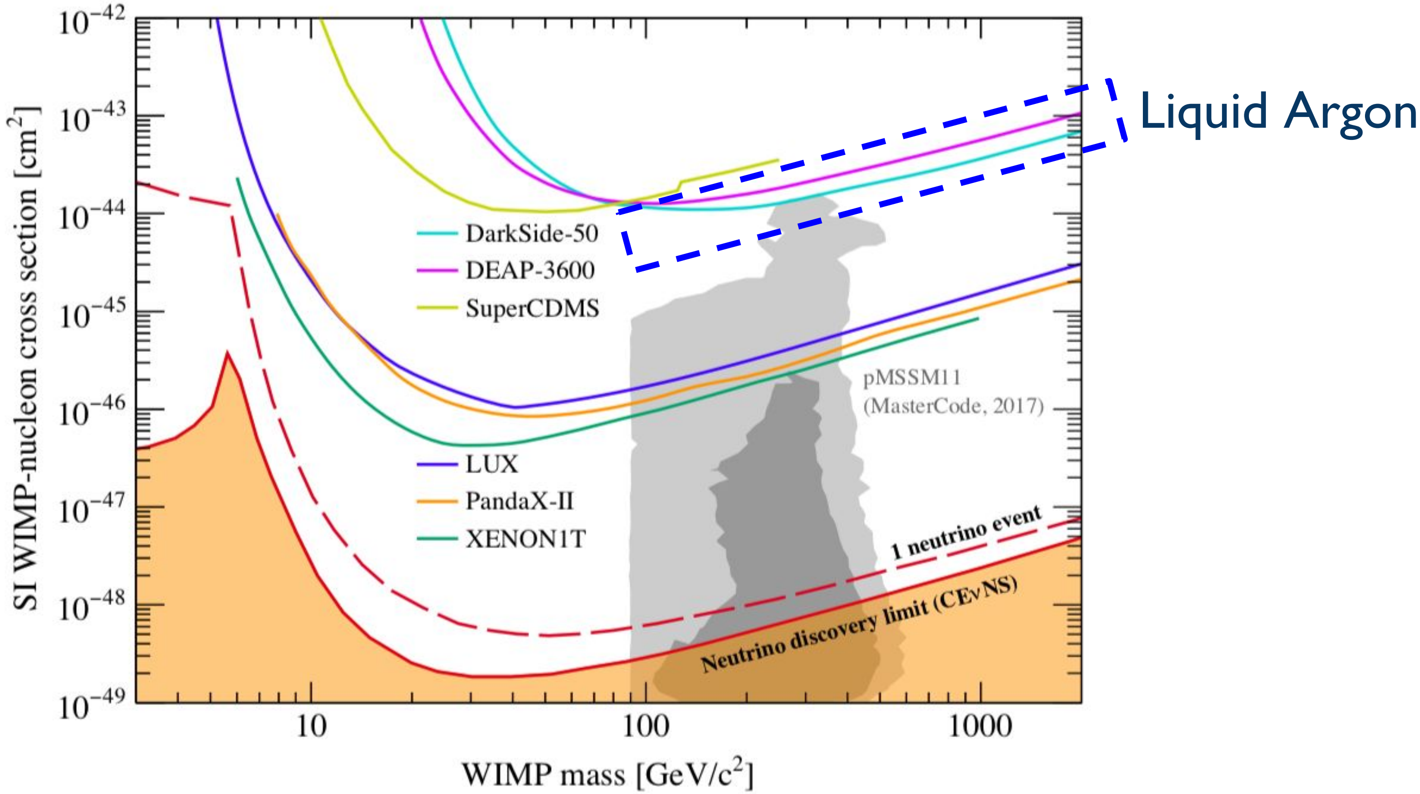


XENON1T leading
SD-neutron
arXiv:1805.12562

PICO-60 bubble chamber with
52 kg of C3F8 leads SD-p
[arxiv.org/1902.04031]

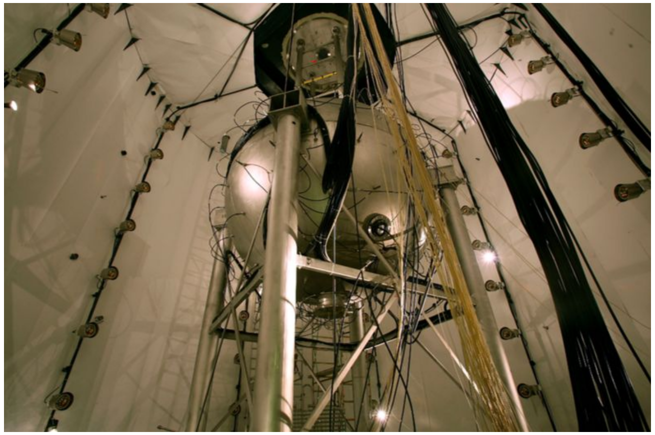


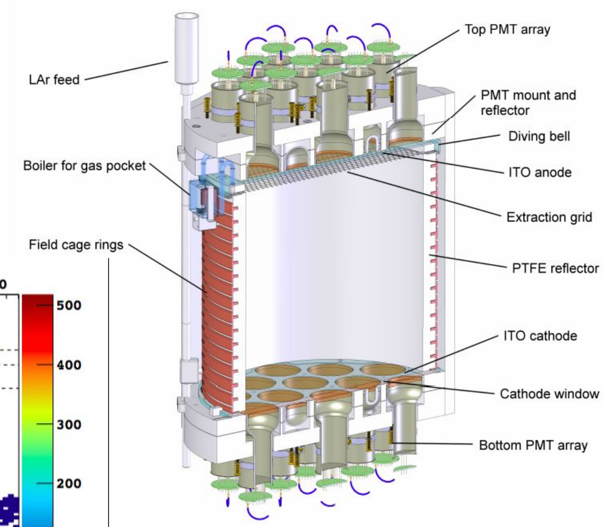
Direct Detection status: LAr

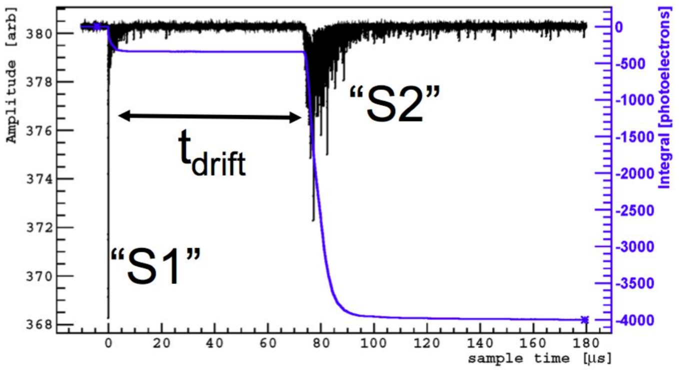


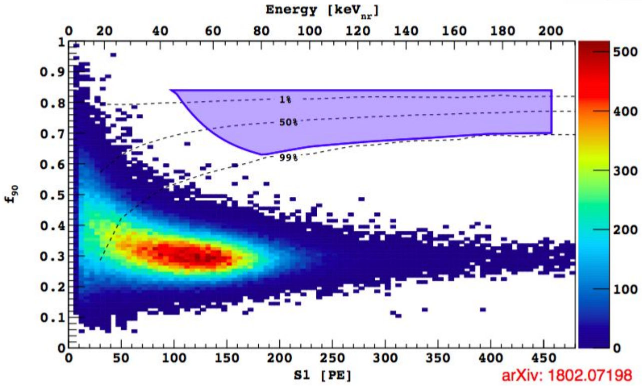
DarkSide-50 @ Gran Sasso (Italy)

- 50 kg LAr TPC
  - Installed 2012
  - 37 kg fiducial volume
  - PSD with S1, S2 signals for position
  - TPB wavelength shifter; ITO on quartz as electrodes
- ^{39}Ar β-decay, 1 Bq/kg, Q-value ~550 keV
  - First use of UAr (^{39}Ar depleted)
- Results in 2018: Spin-independent WIMP-nucleon limit above 1.1×10^{-44} cm^2









DEAP-3600 @ SNOLab (Canada)

- Single phase LAr, 3.6 Ton (1 Ton fiducial)
- 'Re-surfaced' acrylic vessel; 255 8" PMTs
- Pulse shape discrimination (PSD) for particle ID
- x250 difference in scintillation time constants between ER and NR
- E_{th} ~ 39 keV determined by PSD
    - (^{39}Ar β-decay, 1 Bq/kg, Q-value ~550 keV)
- 231 day exposure, S.I. limit above 3.9 x 10^{-45} cm^2 (2019)

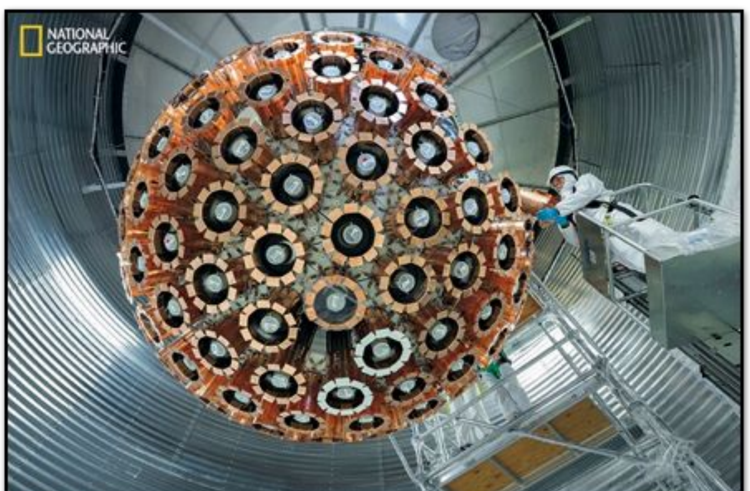
Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB

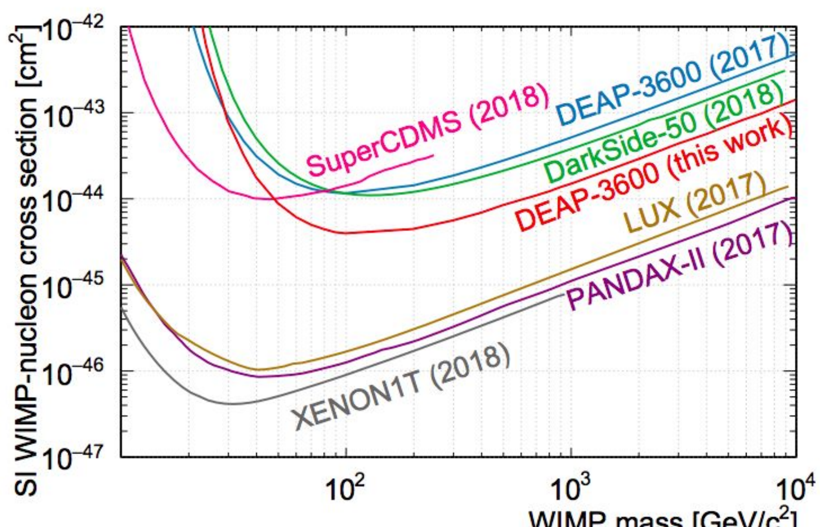
R. Ajaj,[3] P.-A. Amaudruz,[17] G.R. Araujo,[7] M. Baldwin,[14] M. Batygov,[5] B. Beltran,[1] C.E. Bina,[1] J. Bonatt,[12] M.G. Boulay,[3,12] B. Broerman,[12] J.F. Bueno,[1] P.M. Burghardt,[7] A. Butcher,[13] B. Cai,[12] S. Cavuoti,[9,8] M. Chen,[12] Y. Chen,[1] B.T. Cleveland,[15,5] D. Cranshaw,[12] K. Dering,[12] J. DiGioseffo,[3] L. Doria,[11] F.A. Duncan,[15,†] M. Dunford,[3] A. Erlandson,[3,2] N. Fatemighomi,[15,13] G. Fiorillo,[9,8] S. Florian,[12] A. Flower,[3,12] R.J. Ford,[15,5] R. Gagnon,[12] D. Gallacher,[3] E.A. Garcés,[6] S. Garg,[3] P. Giampa,[17,12] D. Goeldi,[3] V.V. Golovko,[2] P. Gorel,[15,5,1] K. Graham,[3] D.R. Grant,[1] A.L. Hallin,[1] M. Hamstra,[3,12] P.J. Harvey,[12] C. Hearns,[12] A. Joy,[1] C.J. Jillings,[15,5] O. Kamaev,[2] G. Kaur,[3] A. Kemp,[13] I. Kochanek,[4] M. Kuźniak,[3,12] S. Langrock,[5] F. La Zia,[13] B. Lehnert,[3] X. Li,[10] J. Lidgard,[12] T. Lindner,[17] O. Litvinov,[17] J. Lock,[3] G. Longo,[9,8] P. Majewski,[14] A.B. McDonald,[12] T. McElroy,[1] T. McGinn,[3,12,†] J.B. McLaughlin,[13,12] R. Mehdiyev,[3] C. Mielnichuk,[1] J. Monroe,[13] P. Nadeau,[3] C. Nantais,[12] C. Ng,[1] A.J. Noble,[12] E. O'Dwyer,[12] C. Ouellet,[3] P. Pasuthip,[12] S.J.M. Peeters,[16] M.-C. Piro,[1] T.R. Pollmann,[7] E.T. Rand,[2] C. Rethmeier,[12] F. Retière,[17] N. Seeburn,[13] K. Singhrao,[1] P. Skensved,[12] B. Smith,[17] N.J.T. Smith,[15,5] T. Sonley,[3,15] J. Soukup,[1] R. Stainforth,[3,*] C. Stone,[12] V. Strickland,[17,3] B. Sur,[2] J. Tang,[1] E. Vázquez-Jáuregui,[6] L. Veloce,[12] S. Viel,[3] J. Walding,[13] M. Waqar,[3] M. Ward,[12] S. Westerdale,[3,‖] J. Willis,[1] and A. Zuñiga-Reyes[6]
(DEAP Collaboration)

[1] *Department of Physics, University of Alberta, Edmonton, Alberta, T6G 2R3, Canada*
[2] *Canadian Nuclear Laboratories Ltd, Chalk River, Ontario, K0J 1J0, Canada*
[3] *Department of Physics, Carleton University, Ottawa, Ontario, K1S 5B6, Canada*
[4] *INFN Laboratori Nazionali del Gran Sasso, Assergi (AQ) 67100, Italy*
[5] *Department of Physics and Astronomy, Laurentian University, Sudbury, Ontario, P3E 2C6, Canada*
[6] *Instituto de Física, Universidad Nacional Autónoma de México, A. P. 20-364, México D. F. 01000, Mexico*
[7] *Department of Physics, Technische Universität München, 80333 Munich, Germany*
[8] *INFN Napoli, Napoli 80126, Italy*
[9] *Physics Department, Università degli Studi "Federico II" di Napoli, Napoli 80126, Italy*
[10] *Physics Department, Princeton University, Princeton, NJ 08544, USA*
[11] *PRISMA Cluster of Excellence and Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany*
[12] *Department of Physics, Engineering Physics, and Astronomy, Queen's University, Kingston, Ontario, K7L 3N6, Canada*
[13] *Royal Holloway University London, Egham Hill, Egham, Surrey TW20 0EX, United Kingdom*
[14] *Rutherford Appleton Laboratory, Harwell Oxford, Didcot OX11 0QX, United Kingdom*
[15] *SNOLAB, Lively, Ontario, P3Y 1M3, Canada*
[16] *University of Sussex, Sussex House, Brighton, East Sussex BN1 9RH, United Kingdom*
[17] *TRIUMF, Vancouver, British Columbia, V6T 2A3, Canada*

(Dated: February 12, 2019)

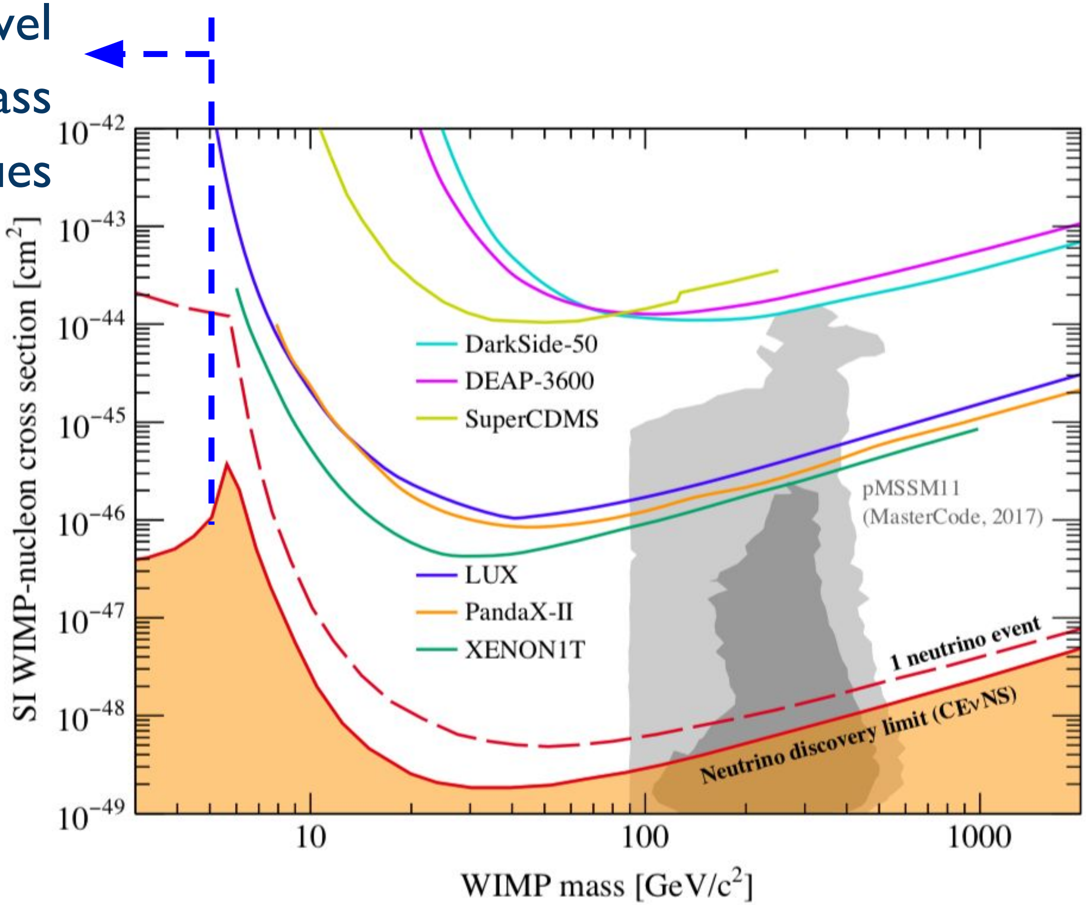
DEAP-3600 is a single-phase liquid argon (LAr) direct-detection dark matter experiment, operating 2 km underground at SNOLAB (Sudbury, Canada). The detector consists of 3279 kg of LAr contained in a spherical acrylic vessel. This paper reports on the analysis of a 758 tonne-day exposure taken over a period of 231 live-days during the first year of operation. No candidate signal events are observed in the WIMP-search region of interest, which results in the leading limit on the WIMP-nucleon spin-independent cross section on a LAr target of 3.9×10^{-45} cm^2 (1.5×10^{-44} cm^2) for a 100 GeV/c^2 (1 TeV/c^2) WIMP mass at 90% C. L. In addition to a detailed background model, this analysis demonstrates the best pulse-shape discrimination in LAr at threshold, employs a Bayesian photoelectron-counting technique to improve the energy resolution and discrimination efficiency, and utilizes two position reconstruction algorithms based on PMT charge and photon arrival times.





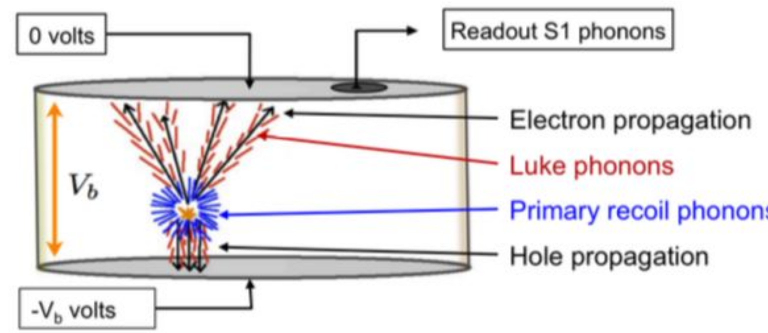
Direct Detection status: low-mass

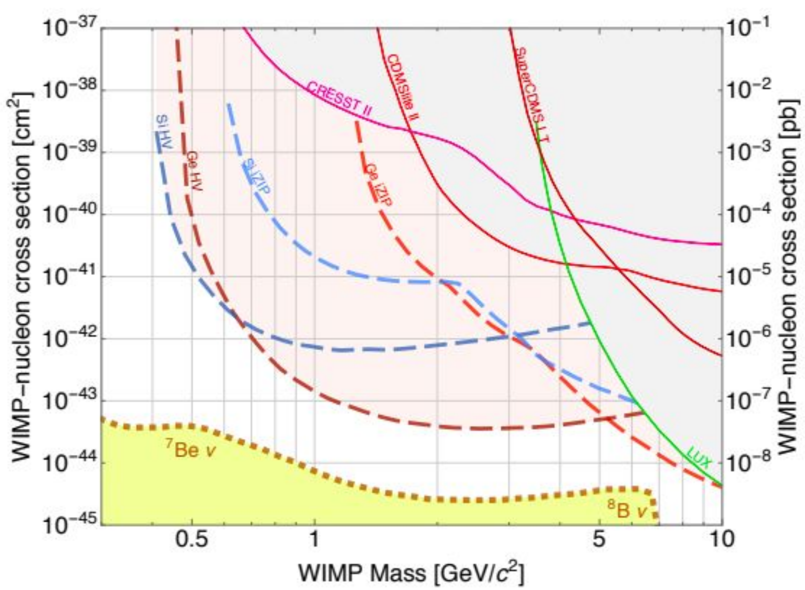
Cryogenic/novel low-mass techniques



Super-CDMS @ SNOLab (Canada)

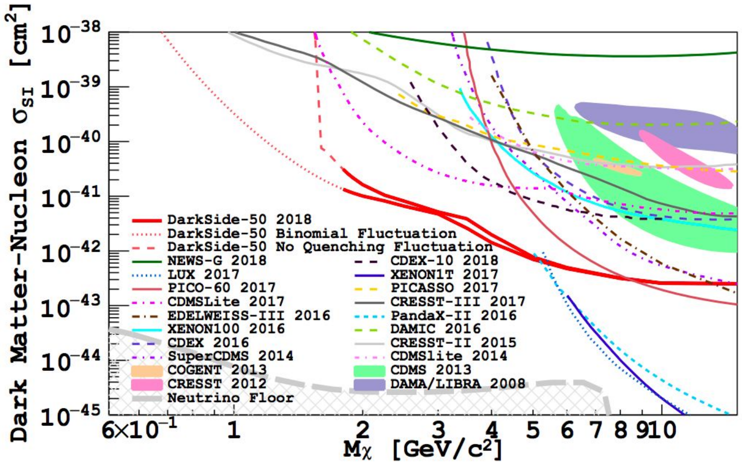
- 1.4 kg Ge and 0.6 kg Si crystals
- Phonons + charge
- Targeting <10 GeV/c^2 mass range
  - Sensitivity to sub-GeV dark matter
- Band gap in Ge is 0.7 eV, Si is 1.1 eV
  - Energy thresholds in tens of eV range
- Operation at SNOLab from 2020/21



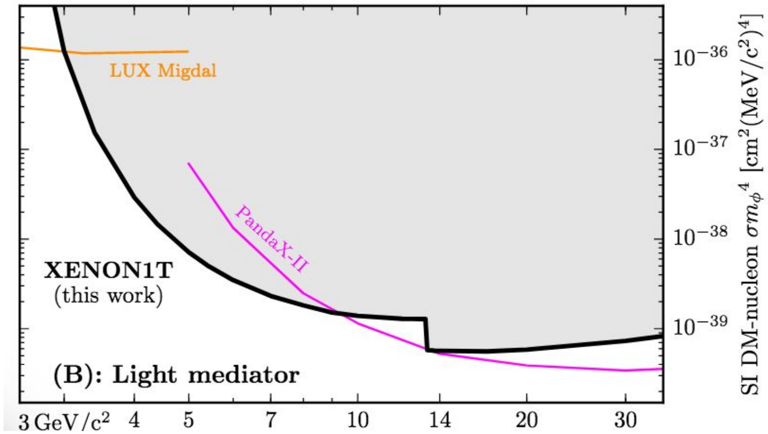


Novel techniques for low-mass searches

DS-50 S2-only [arxiv.org/1802.06994]

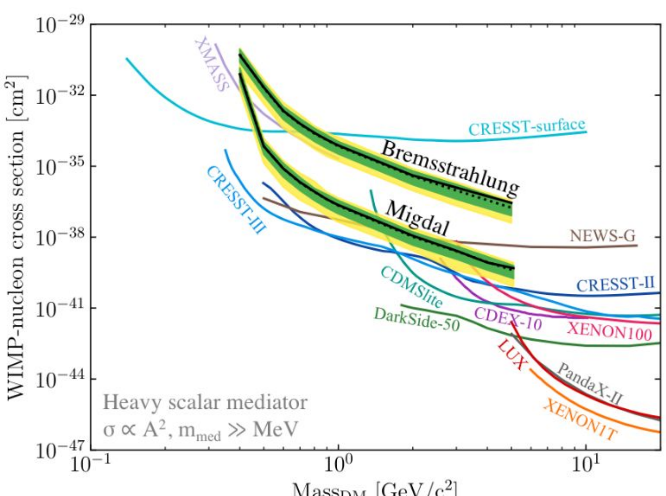


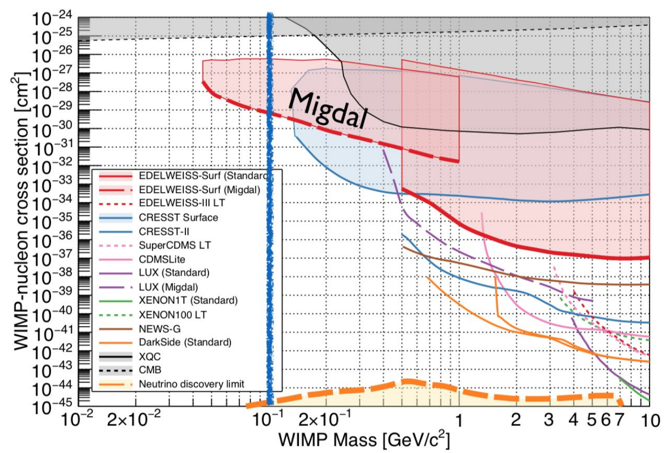
Recent XENON1T S2-only [arxiv.org/1907.11485]



Using Migdal effect (see Dolan, McCabe, Kahlhoefer arxiv.org/1711.09906)

LUX [arxiv.org/1811.11241] and EDELWEISS+Kavanagh [arXiv:1901.03588]





Novel techniques for low-mass searches

LUX low-mass using double photoelectron effect (DPE)

[arxiv.org/1907.06272]

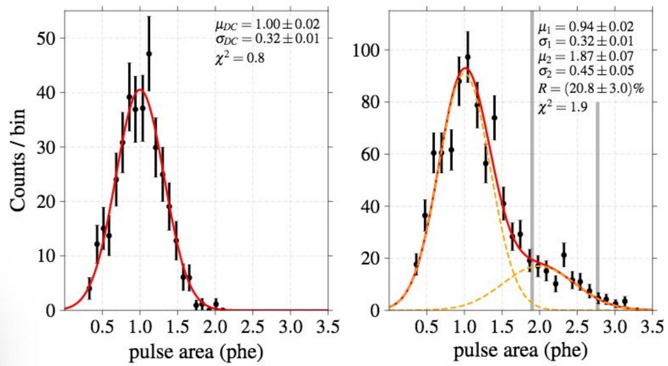
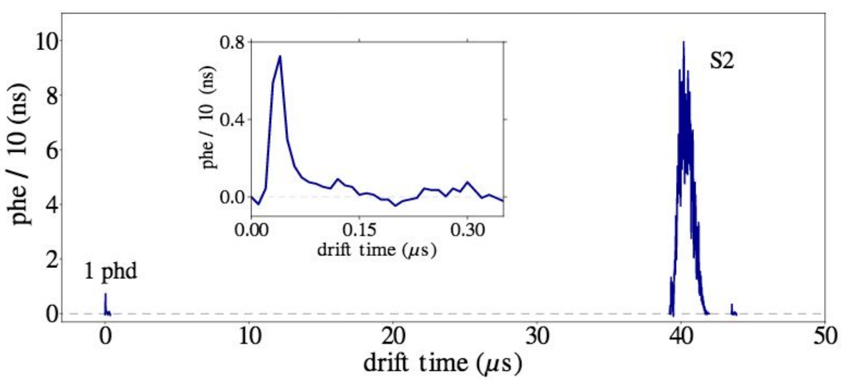
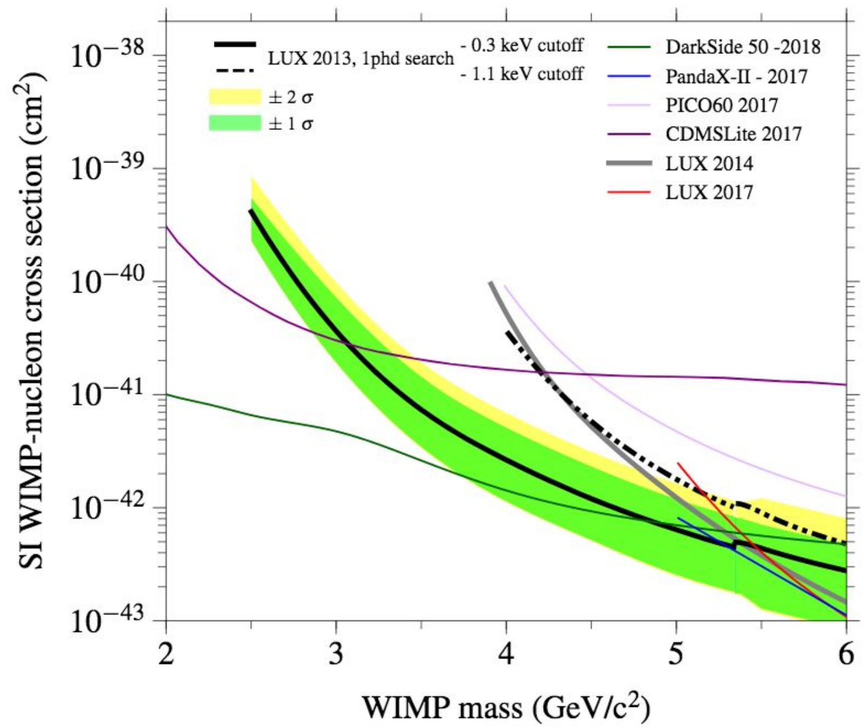


FIG. 3. Pulse area distributions (in phe) for the single photoelectron response (left) and the single VUV photon response (right) of an example PMT, along with the fit pa-





Next generation (G2) → starting this/next year

LUX

250 kg
(100 kg)

2013

3.4×10^{-46} cm^2

PANDAX-II

580 kg
(362 kg)

2016

2.5×10^{-46} cm^2

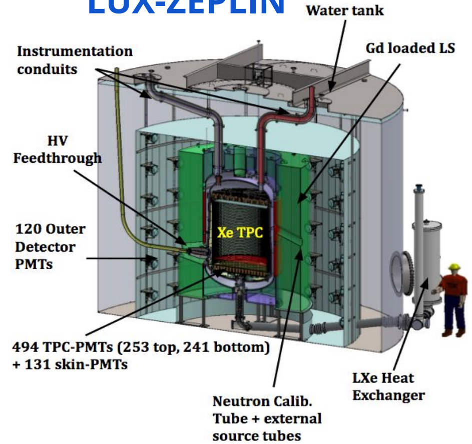
XENON1T

2,000 kg
(1,042 kg)

2017

7.7×10^{-47} cm^2

LUX-ZEPLIN

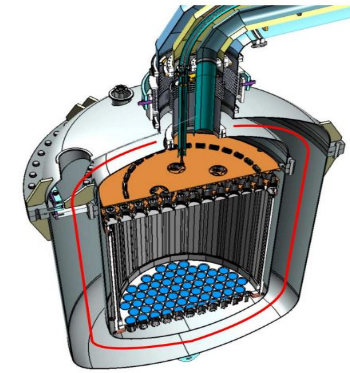


7,000 kg
(5,600 kg)

2020 + 3 live years

1.6×10^{-48} cm^2

XENONnT

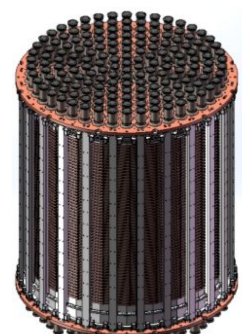


5,900 kg
(4,000 kg)

2019/20 + 5 live years

1.6×10^{-48} cm^2

PandaX-4T

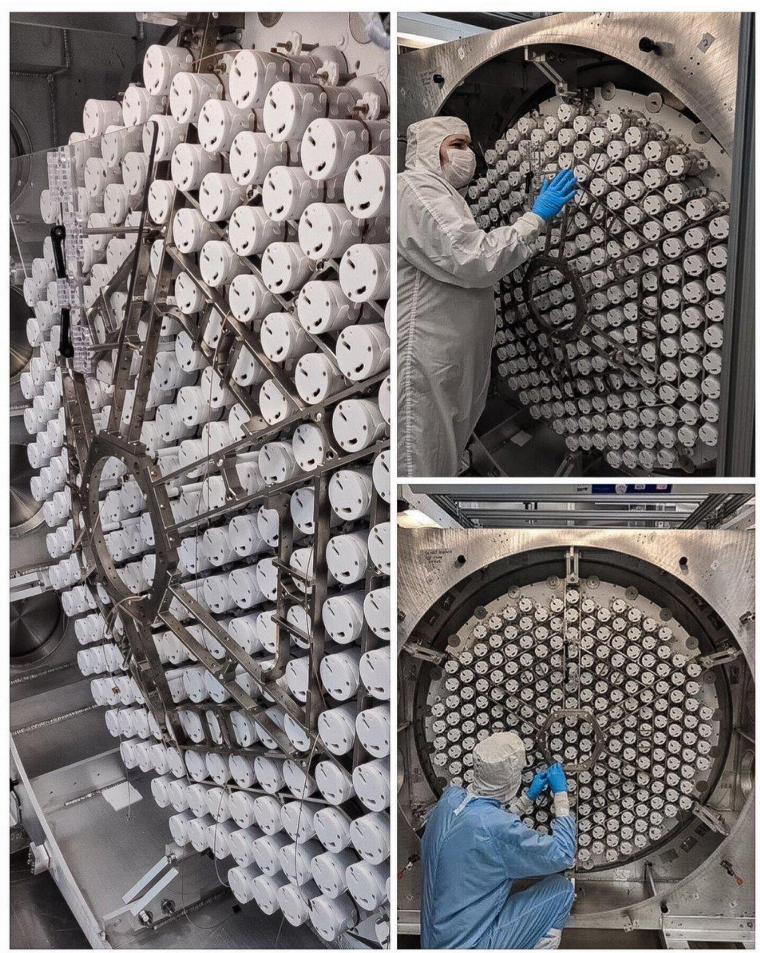


4000 kg (2800 kg)

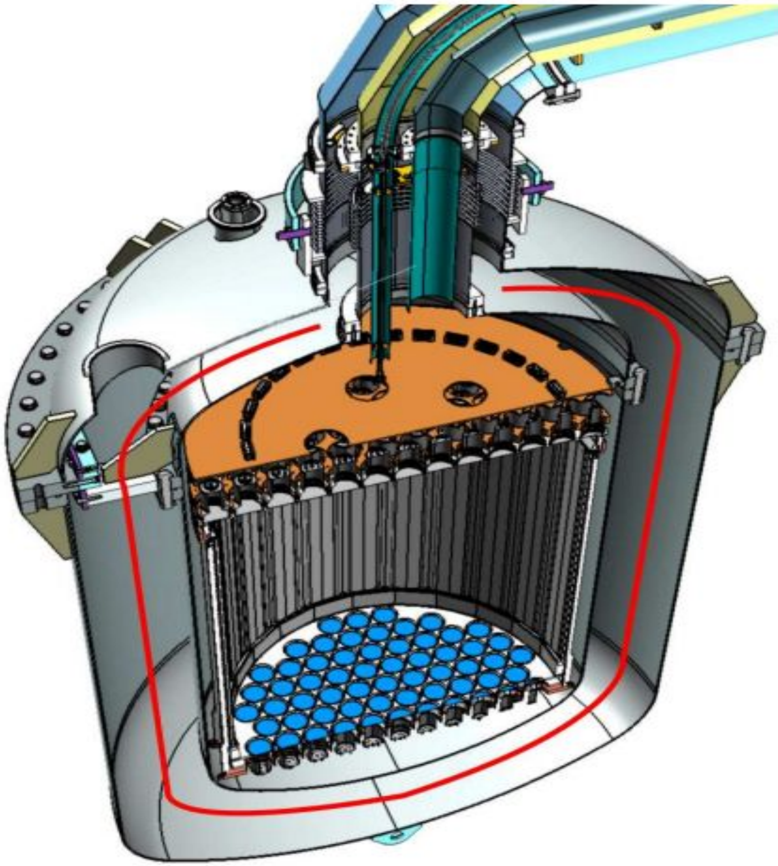
2021(?) + 2 live years

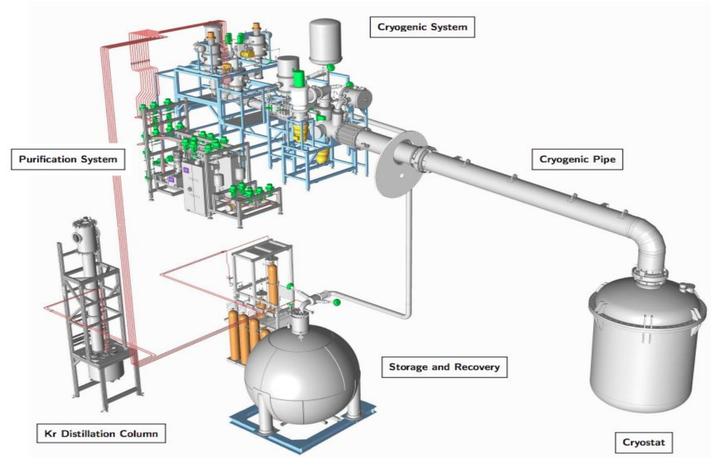
6×10^{-48} cm^2

LZ @ SURF (USA)

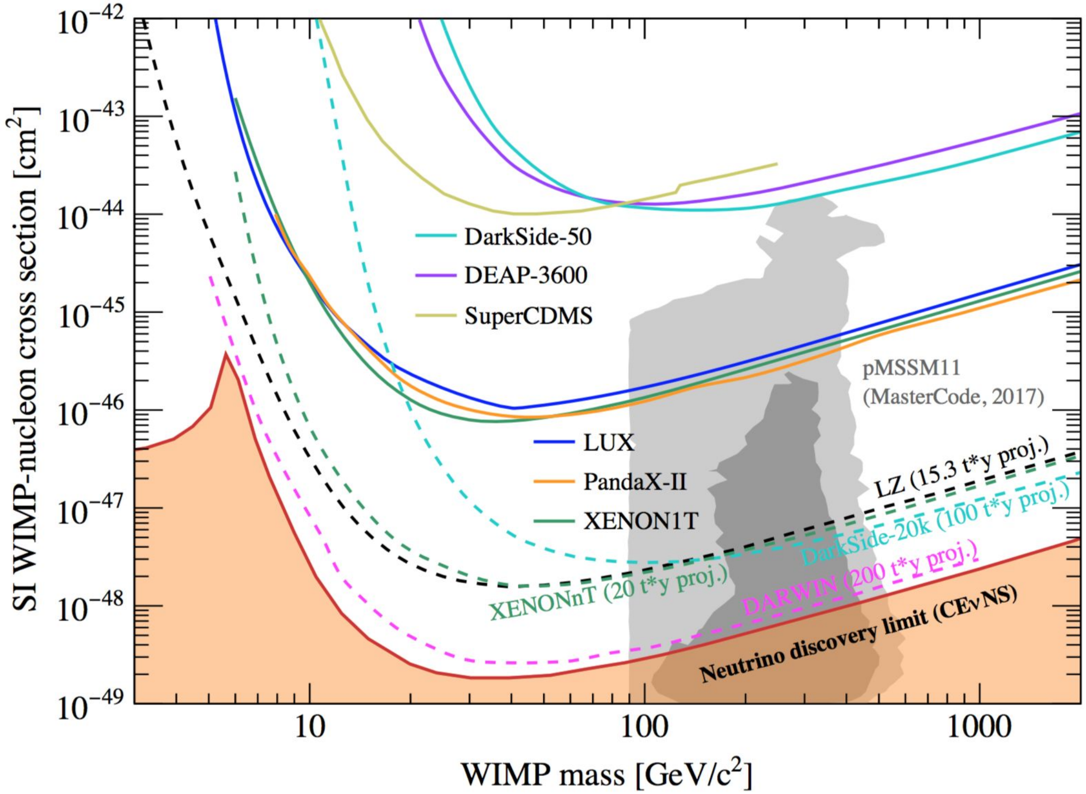


XENONnT @ Gran Sasso (Italy)





Long term: Generation-3

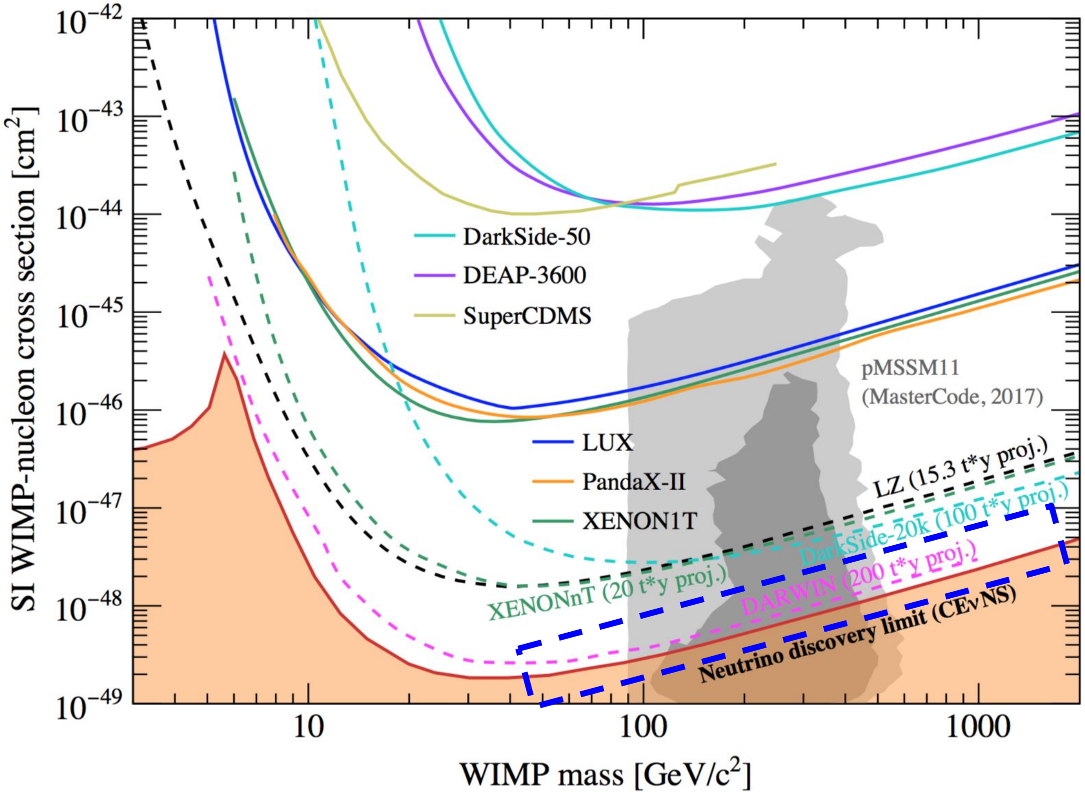


Long term: Generation-3

ARGO

300T LAr detector

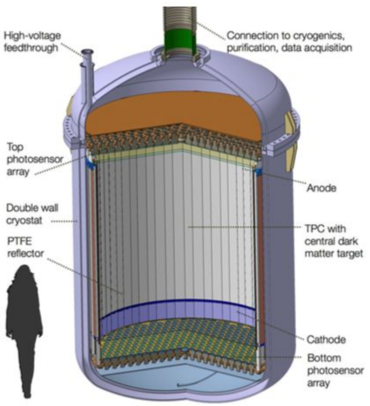
1000 tonne.year exposure



LXe-G3/DARWIN

50-100T LXe

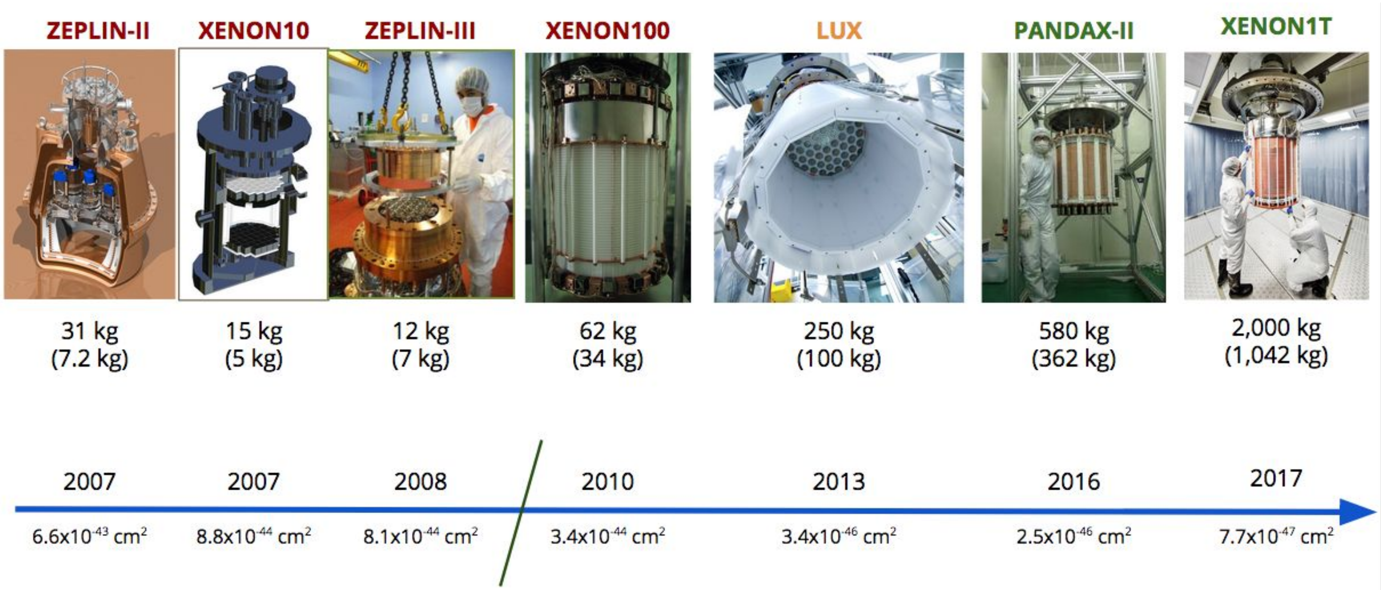
200+ tonne.year exposure



Down to the neutrino floor, 2025+

Features of Direct Detection that influence stats approach

- Exponentially falling signal dependent on threshold
- Fixed target with no opportunity to upgrade the beam...
- Ultimately background limited → follow will often require new experiment
- Tension between understanding detector/backgrounds and bias mitigation
- Any +ve signal will be re-interpreted many times
- High stakes and lots of competition

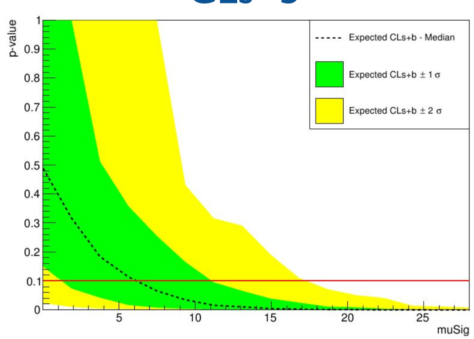


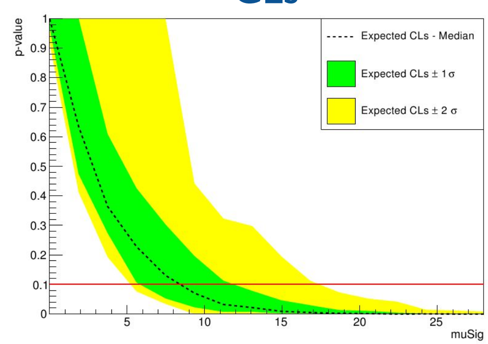
Increasing time between results as construction + run-time increase

Test statistic choice

- One-sided vs two sided
  - One-sided 90% CL upper limit is natural counterpart to discover test statistic
    - Asking complementary questions
    - How to avoid flip-flopping (Feldman & Cousins, arxiv.org/9711021)
      - If see signal, will want to characterise it!
  - Two-sided avoids flip-flopping but could conflict discovery p-value for b-only
- Forcing over-coverage:
  - CLs or power-constraining (Cowen *et al*, arxiv/1105.3166)
- Choice can shift reported limits by ~30%

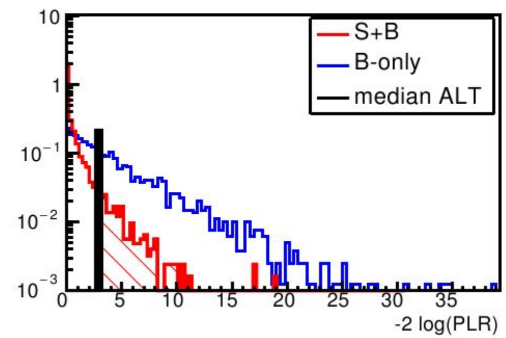
CLs+b → CLs





Courtesy of Ibles Olcina, Imperial

CLs



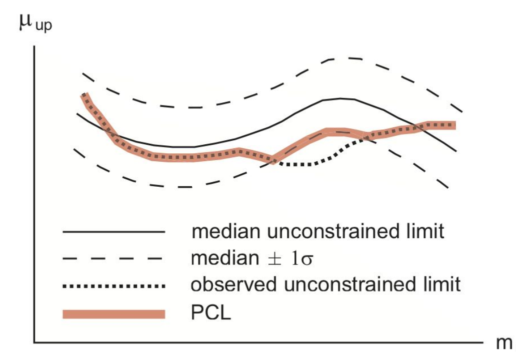
$$\mathrm{CL_s} = \frac{p_\mu}{1 - p_\mathrm{b}}$$

>> p_mu: red area to the *right* of q_obs

>> p_b: blue area to the *left* of q_obs

(reference: p32-34 from PDG_statistics)

Power constrained



arxiv/1105.3166

p-value for discovery

3-sigma, 5-sigma?...

- Is 5σ required? Depends on:
  - Level of LEE effect
  - Degree of surprise
  - Unaccounted systematics
    - Yields, backgrounds, discrimination → target/detector specific

L. Lyons, "Discovering the Significance of 5σ" arxiv.org/1310.1284

Search	Degree of surprise	Impact	LEE	Systematics	Number of σ
Higgs search	Medium	Very high	Mass	Medium	5
Single top	No	Low	No	No	3
SUSY	Yes	Very high	Very large	Yes	7
B_s oscillations	Medium/low	Medium	Δm	No	4
Neutrino oscillations	Medium	High	$sin^2(2\theta), \Delta m^2$	No	4
$B_s \to \mu\mu$	No	Low/Medium	No	Medium	3
Pentaquark	Yes	High/very high	M, decay mode	Medium	7
$(g-2)_\mu$ anomaly	Yes	High	No	Yes	4
H spin $\neq 0$	Yes	High	No	Medium	5
4^{th} generation q, l, ν	Yes	High	M, mode	No	6
$v_\nu > c$	Enormous	Enormous	No	Yes	>8
Dark matter (direct)	Medium	High	Medium	Yes	5
Dark energy	Yes	Very high	Strength	Yes	5
Grav waves	No	High	Enormous	Yes	7

- In presence of CvENS? G2 should see ^8B

What have some recent experiments done*

- **LUX:** 2017 combined WS2013+WS2014–16 limit, **PLR** with **CLs+b, two-sided** (not stated in paper), **power constrained** at -1σ level, nuisance parameters as gaussian constraints [arxiv/1608.07648]
- **PandaX-II:** 2017 54 tonne.day limit, **PLR** with **standard TS** (not clear if one/two-sided), considered power constraint but not applied as close to -1 σ, gaussian nuisance params [arxiv.org/1708.06917]
- **XENON1T:** 2019 1 tonne.year limit, + signal-like "safeguard" term, report only upper limit if < 3σ, discovery, blinding+salting [arxiv.org/1902.11297]
- **DEAP-3600:** 2019 231-day exposure limit, 90% CL upper limit using **Highland-Cousins method** [arxiv.org/1902.04048]
- **CRESST-III:** 2019 limit, used **Yellin optimum interval algorithm**, no background subtraction [arxiv.org/1904.00498]

* my understanding based on writeups

What have some recent experiments done*

- **SuperCDMS:** sensitivity projection using an optimum interval calculation [arxiv.org/1610.00006]
- **DarkSide-20k:** sensitivity projections, not clear what was used [arxiv.org/1707.08145]
- **XENONnT:** sensitivity projections, **PLR** with **one-sided TS**, **CLs**, gaussian nuisance params [arxiv.org/1512.07501]
- **LZ:** sensitivity projections, **PLR** with **one-sided TS**, **CLs+b**, power constraint at -1σ, gaussian nuisance params [arxiv.org/1802.06039]
- Plus others that I've probably missed...

* my understanding based on writeups

Summary

- Generation-2 experiments coming online soon:
  - LZ and XENONnT under construction, ops. in 2020
  - DS-20k in 2022
  - Super-CDMS from 2020/21
  - + ...
- + opening up the field to ultra-light dark matter with new technologies
- Generation-3 R&D and planning for "ultimate" rare-event search observatory started
  - LXe-G3/DARWIN, ARGO, 2025+
- Direct detection is high stakes game with unique challenges → strong motivation for common statistics approach