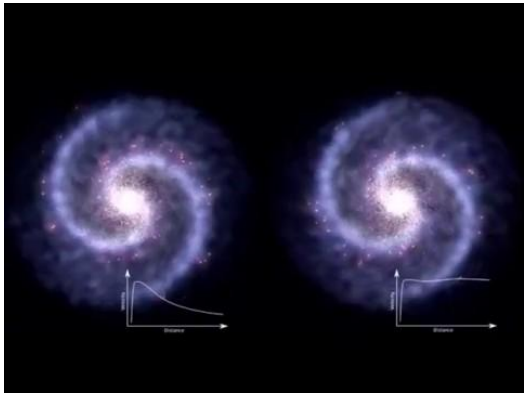
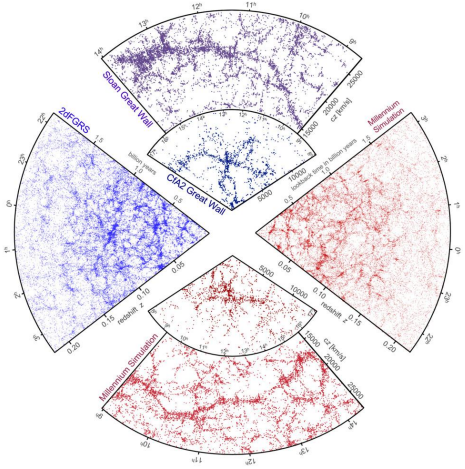
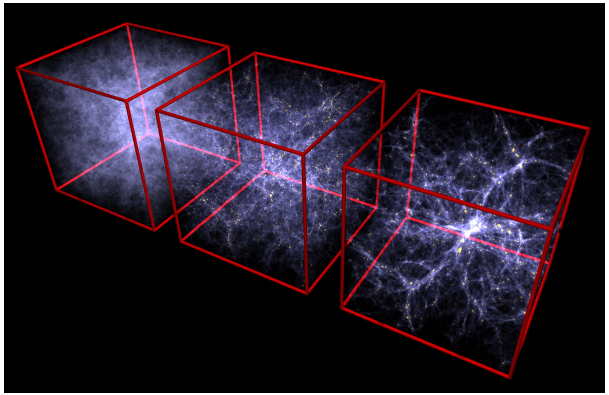
Dark Matter: The next decade

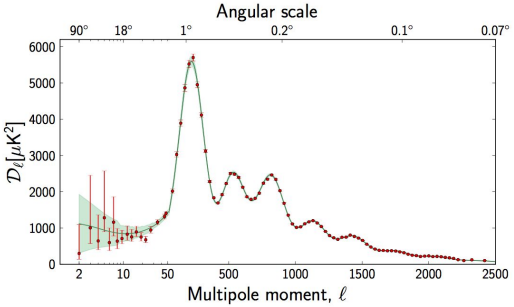
Chamkaur Ghag
UCL
24 September 2019

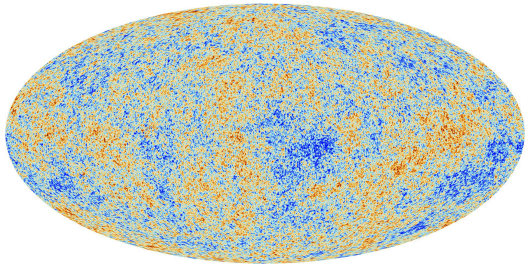
Dark Matter

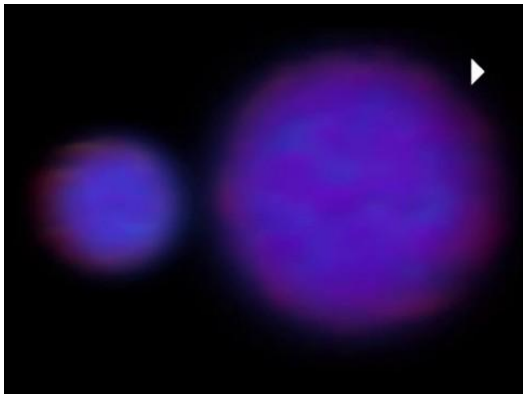



Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
Millennium Simulation

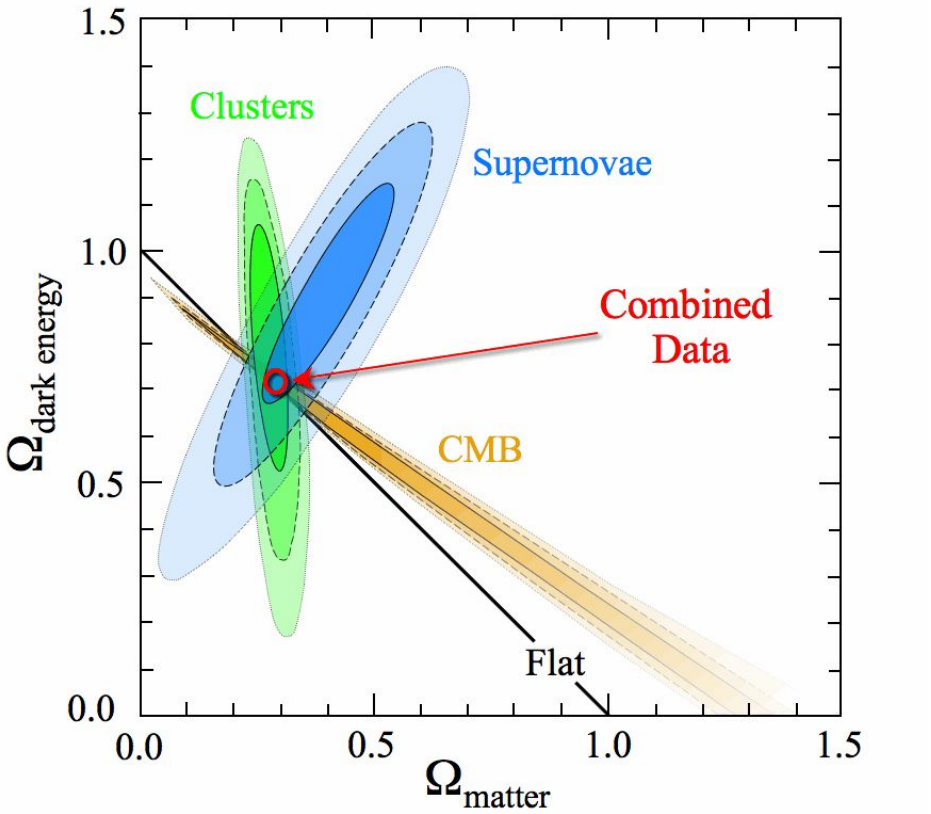


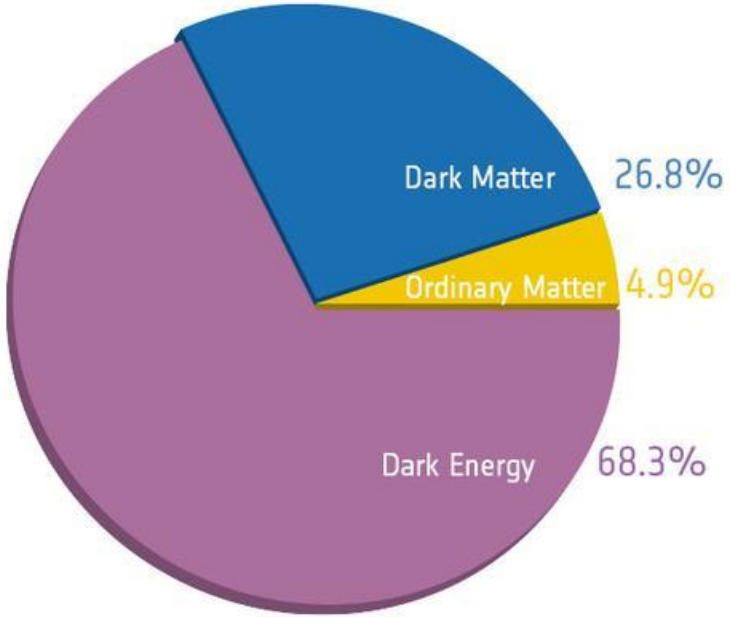

Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
$\mathcal{D}_\ell[\mu K^2]$
Multipole moment, ℓ

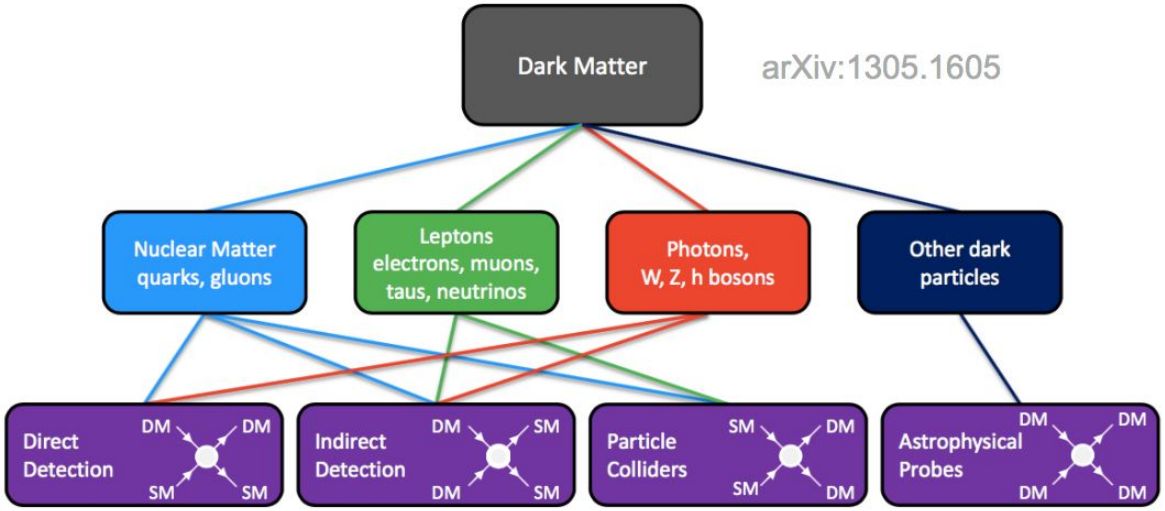


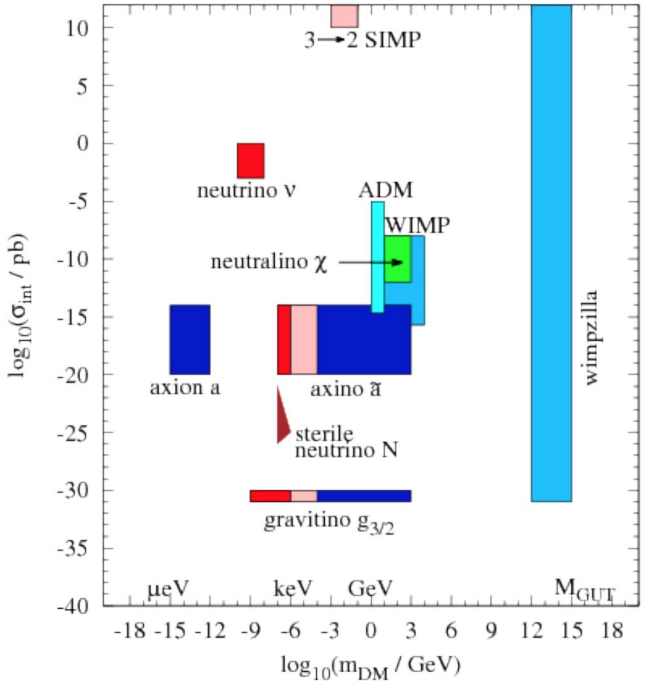


Dark Matter


Clusters
Supernovae
Combined Data
CMB
Flat
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
$\Omega_{dark\ energy}$
Ω_{matter}

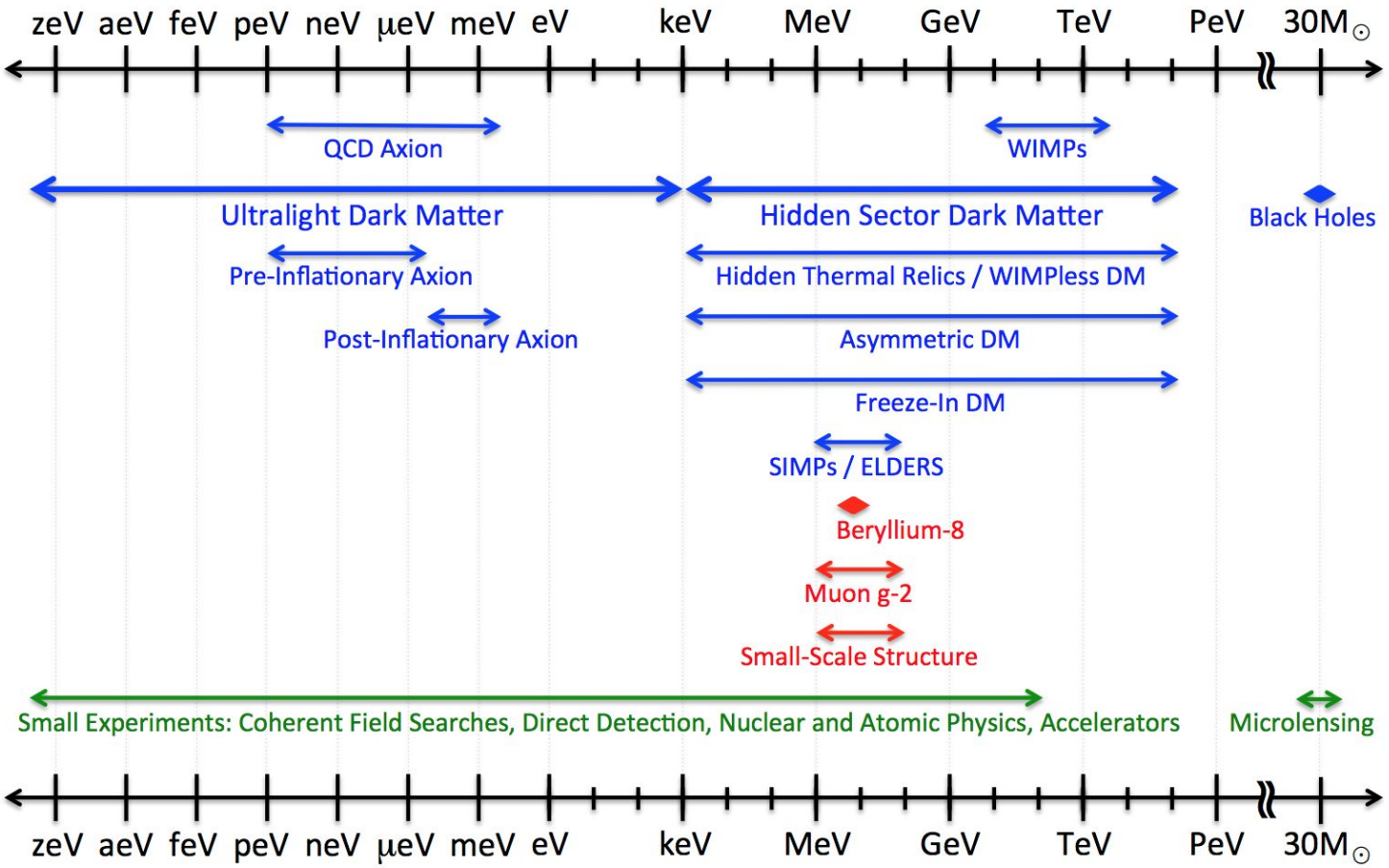

Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%



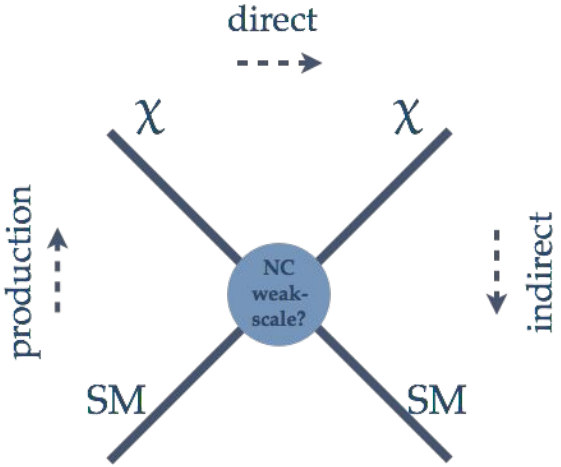


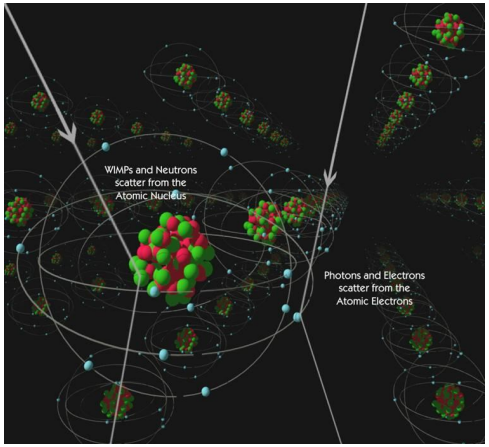
- Indirect, accelerator and beam dump experiments
  - *Satellite: e.g., Fermi-LAT, PAMELA, AMS-02, …*
  - *Terrestrial: e.g, CTA, IceCube-Gen2, …*
  - *LHC, MiniBooNe, …*
- Astrophysics
  - *New datasets and implications (e.g., GAIA; Sagittarius, S1 stream, …)*
  - *Advances in simulations and modelling (e.g., baryon feedback)*
  - *Constraints from astrophysics (e.g., self-interactions)*

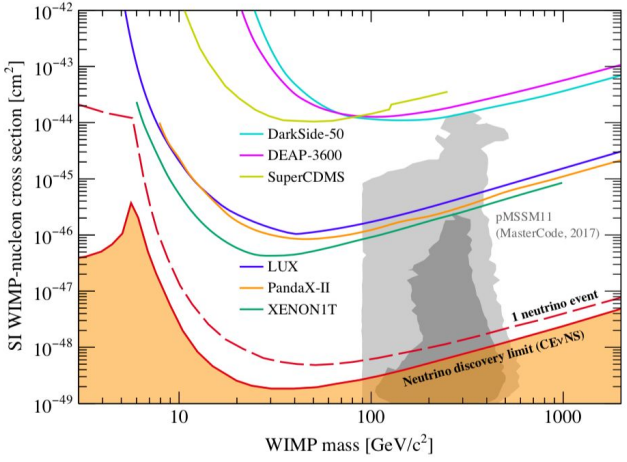
Dark Sector Candidates, Anomalies, and Search Techniques



Direct Searches

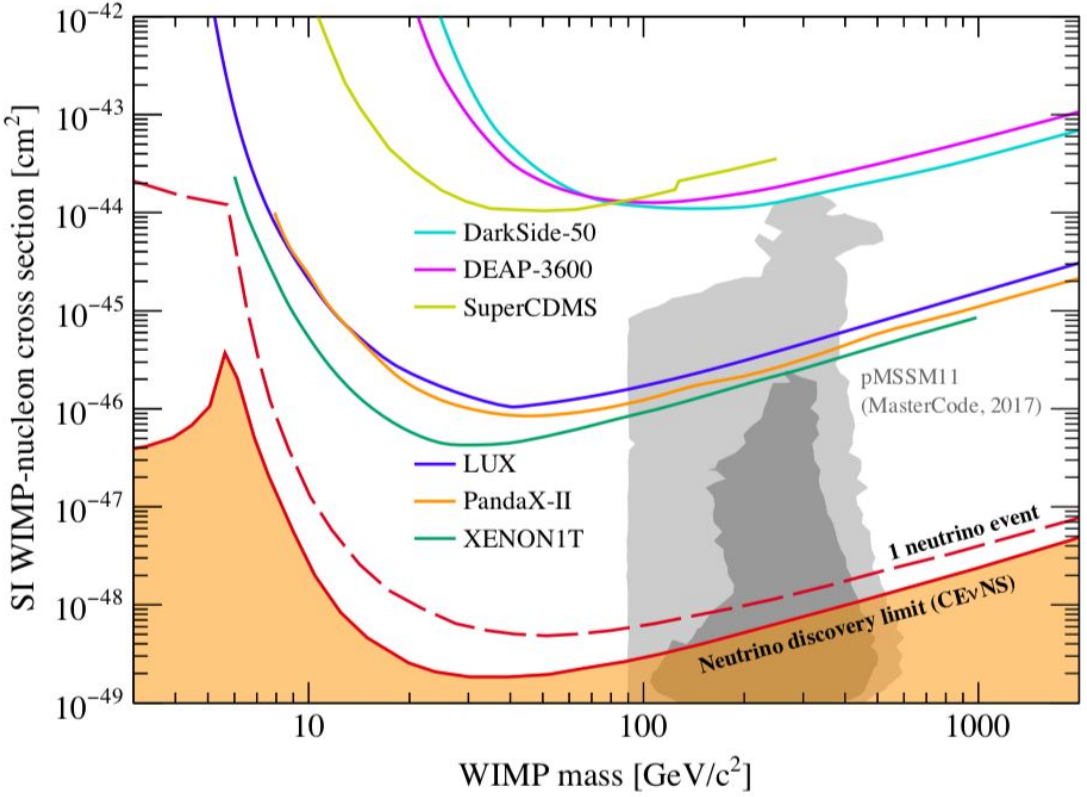






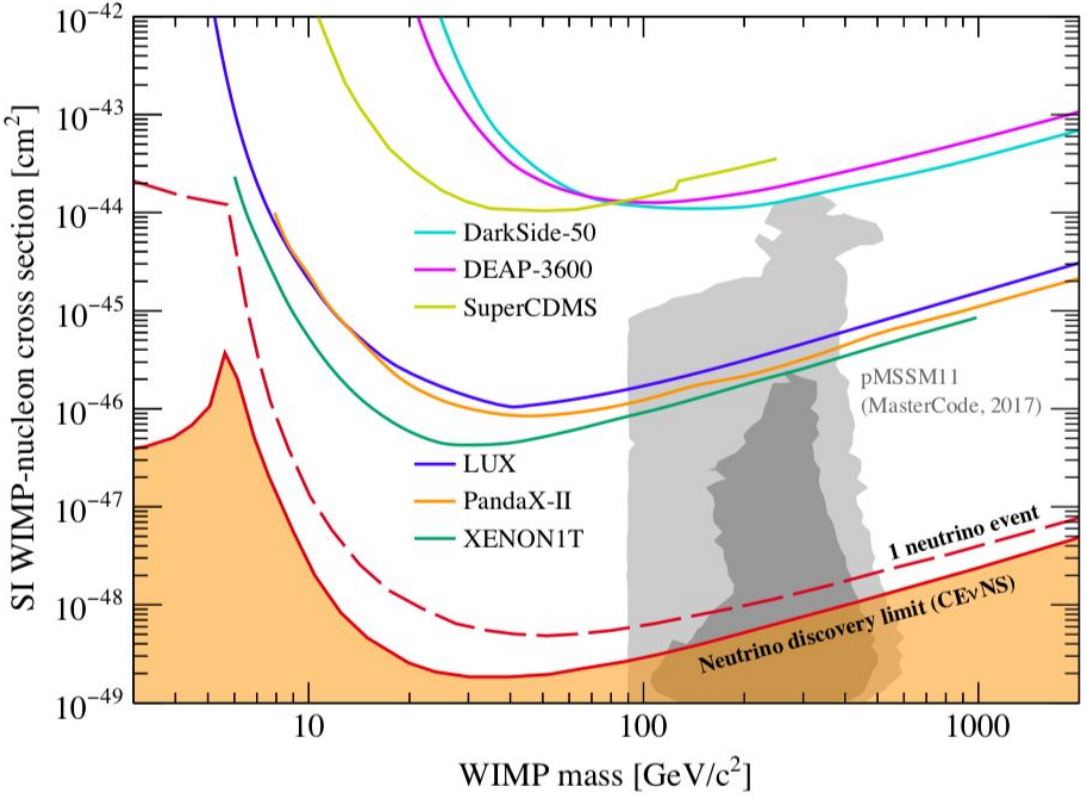
- Direct searches for **rare** (<0.0001 /kg/day), **low-energy** (~keV) scattering of **thermal relics** (e.g. galactic WIMPs)
  - *Very sensitive detectors operating underground*
  - ***Elastic scattering off nuclei**, spin-independent, spin-dependent, EFT operators, inelastic scattering, electron scattering, annual modulation, signal directionality, …*

Direct Searches



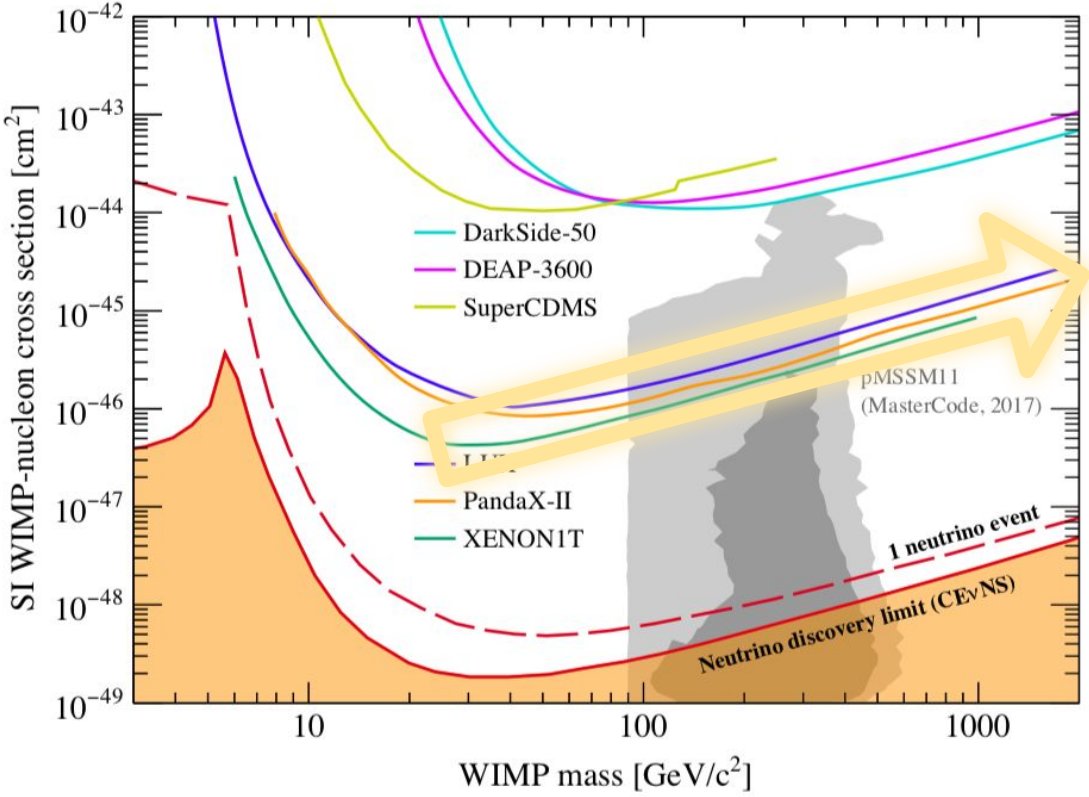
Direct Searches

THRESHOLD & ATOMIC MASS MATTERS
CRYOGENIC DETECTORS



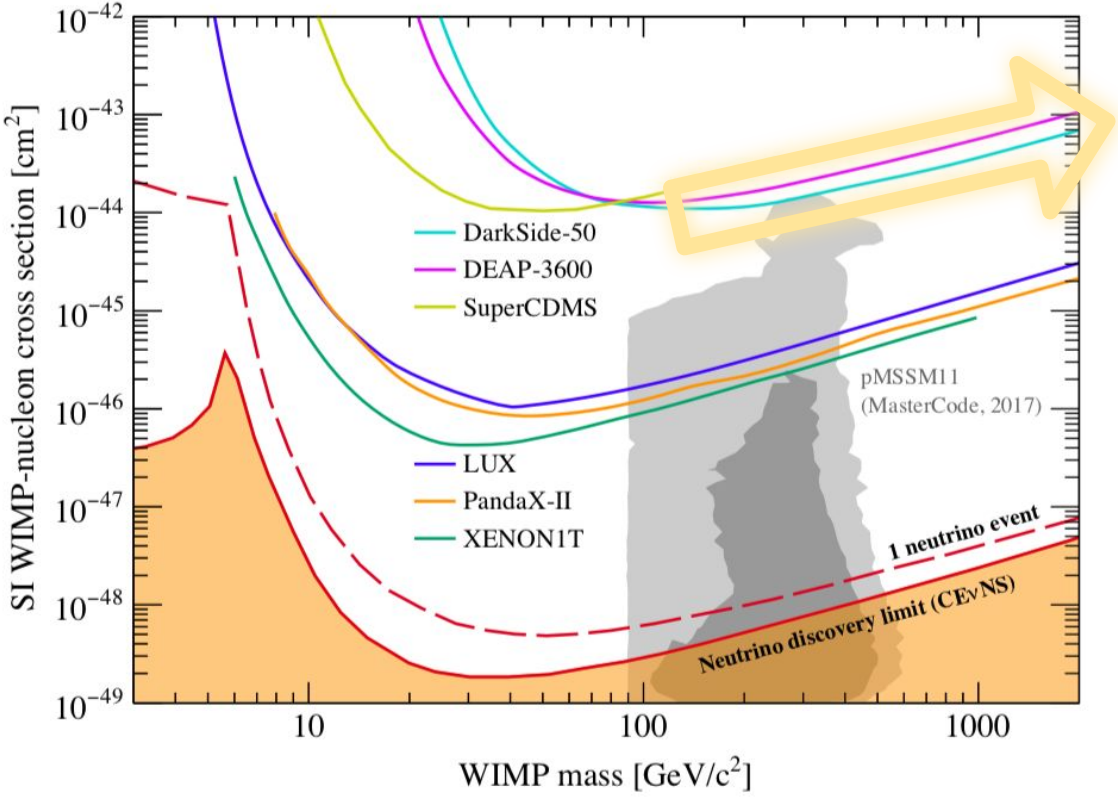
SIZE (x TIME) MATTERS
NOBLE LIQUIDS

Direct Searches



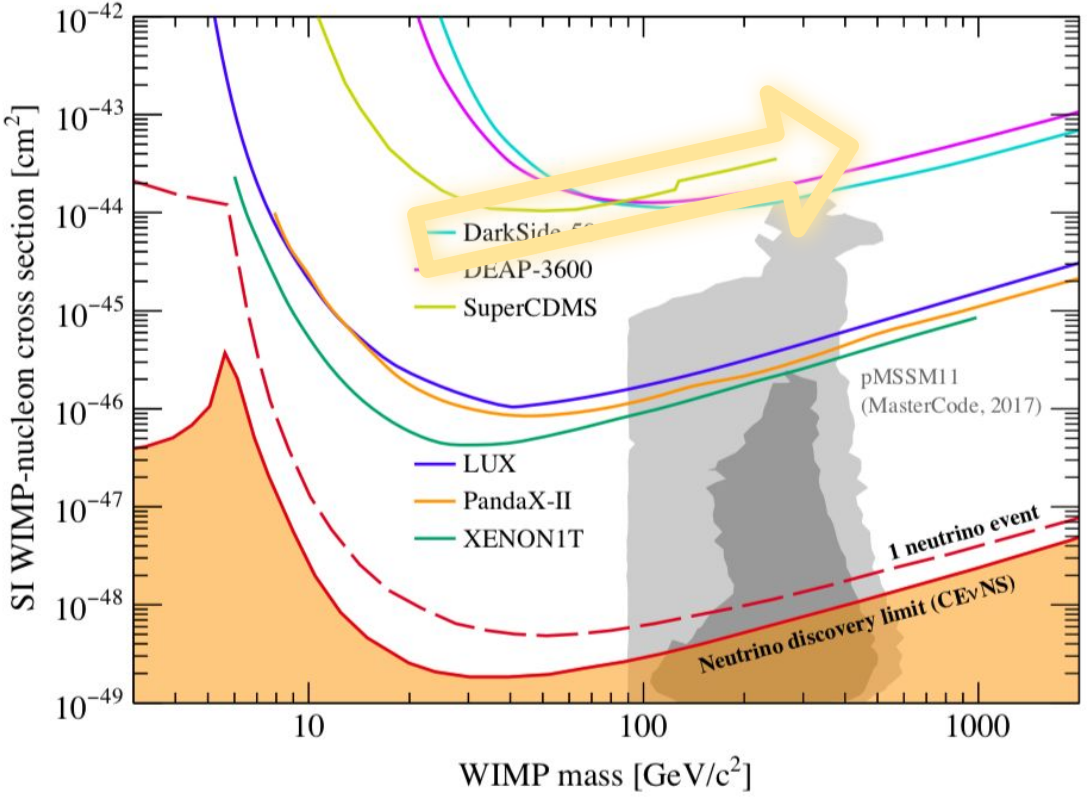
Liquid Xenon
(Time Projection Chambers)

Direct Searches



Liquid Argon

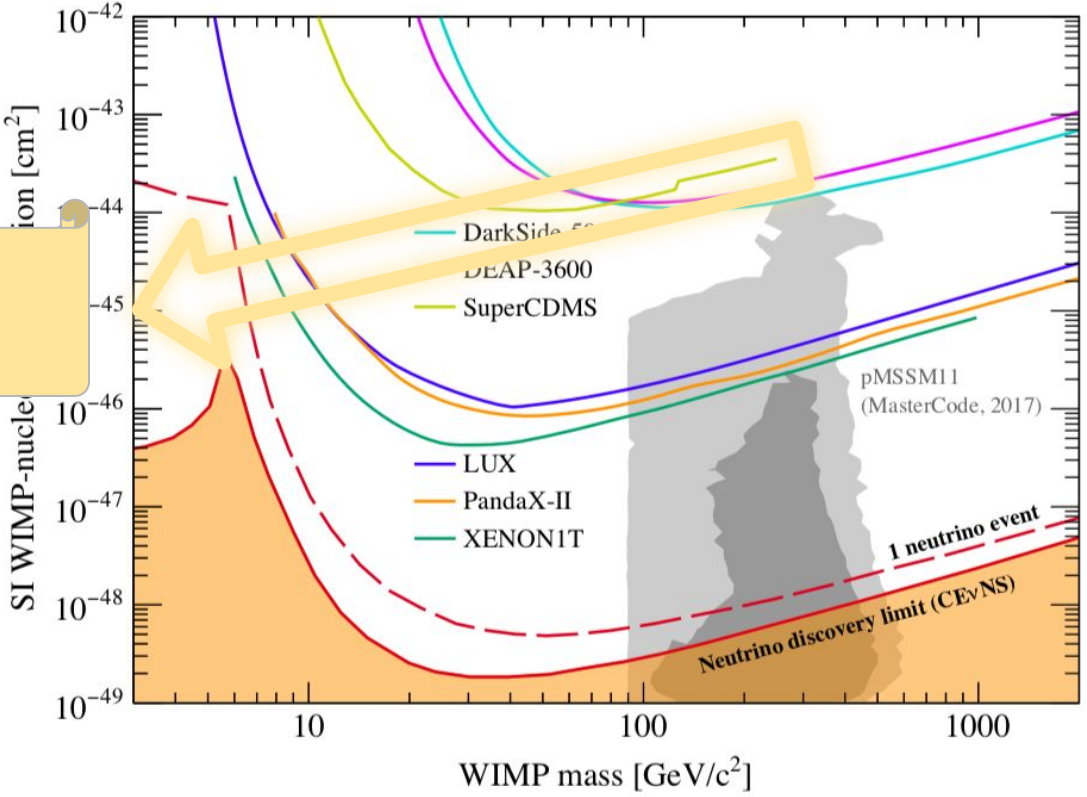
Direct Searches



Crystals

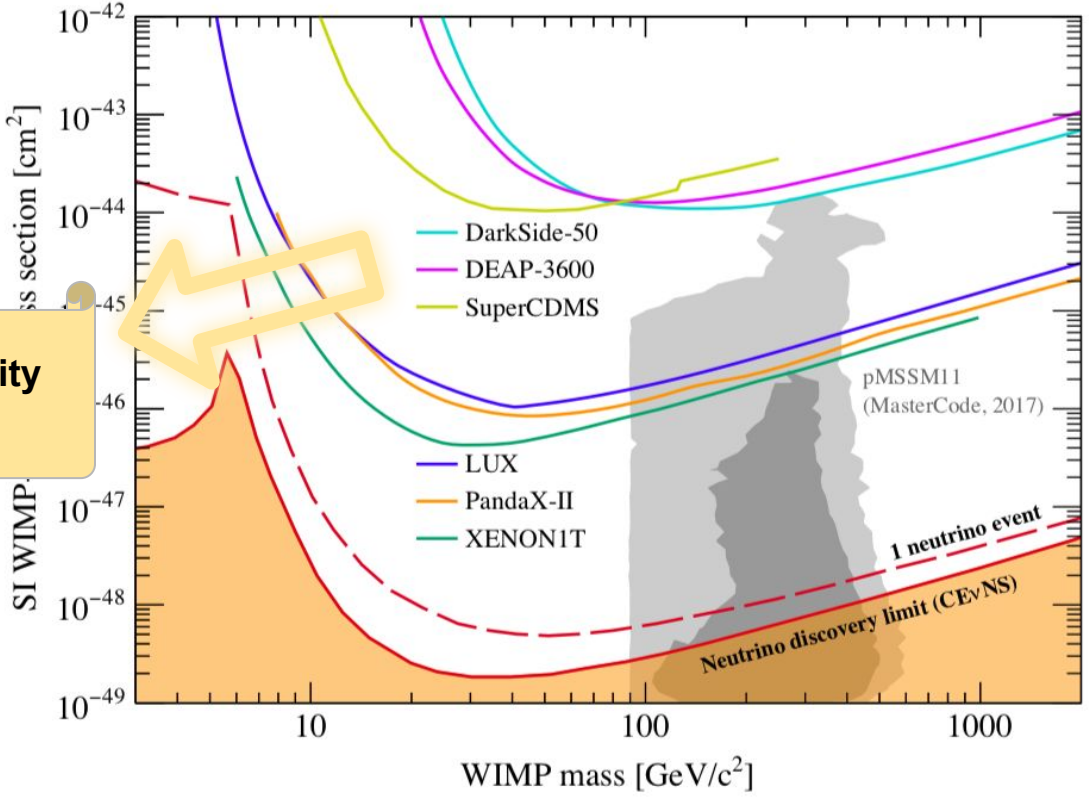
Direct Searches

Crystals

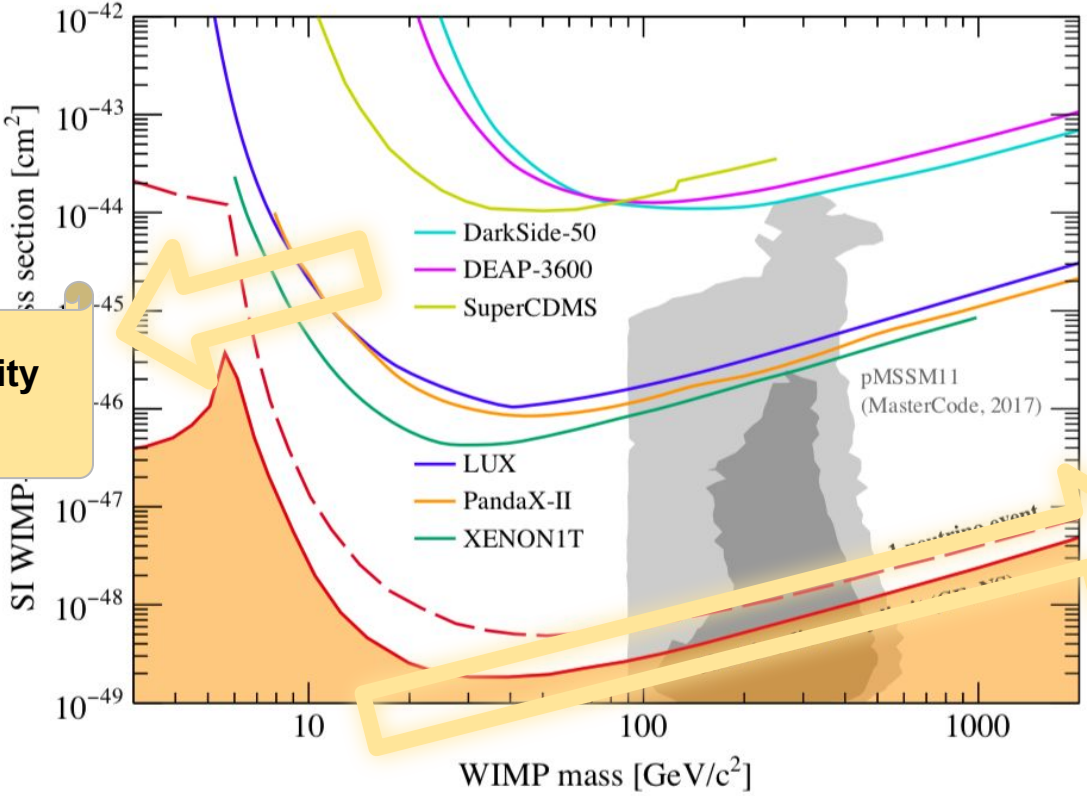


Direct Searches

Directionality R&D



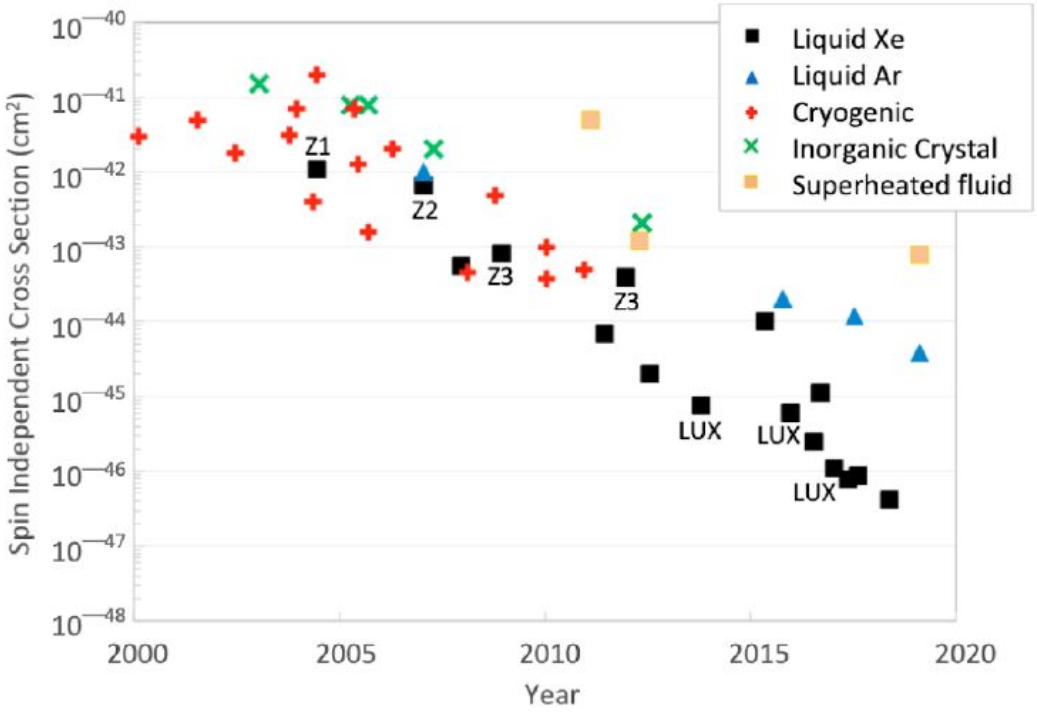
Direct Searches



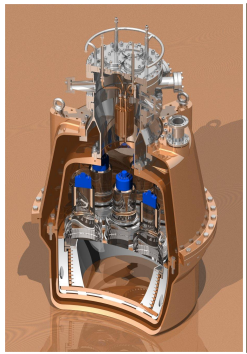
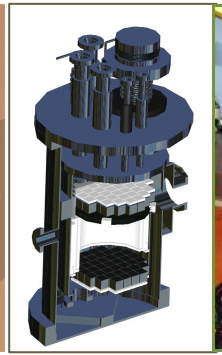
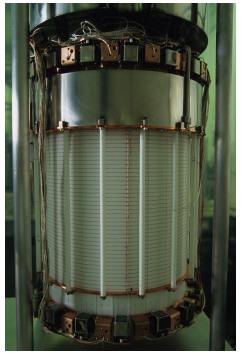
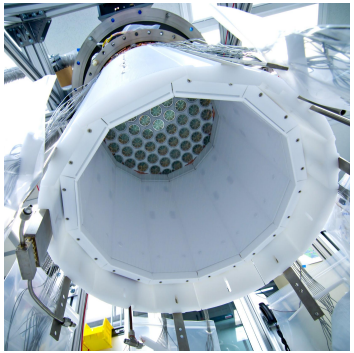
Directionality R&D

Directionality useful here too!

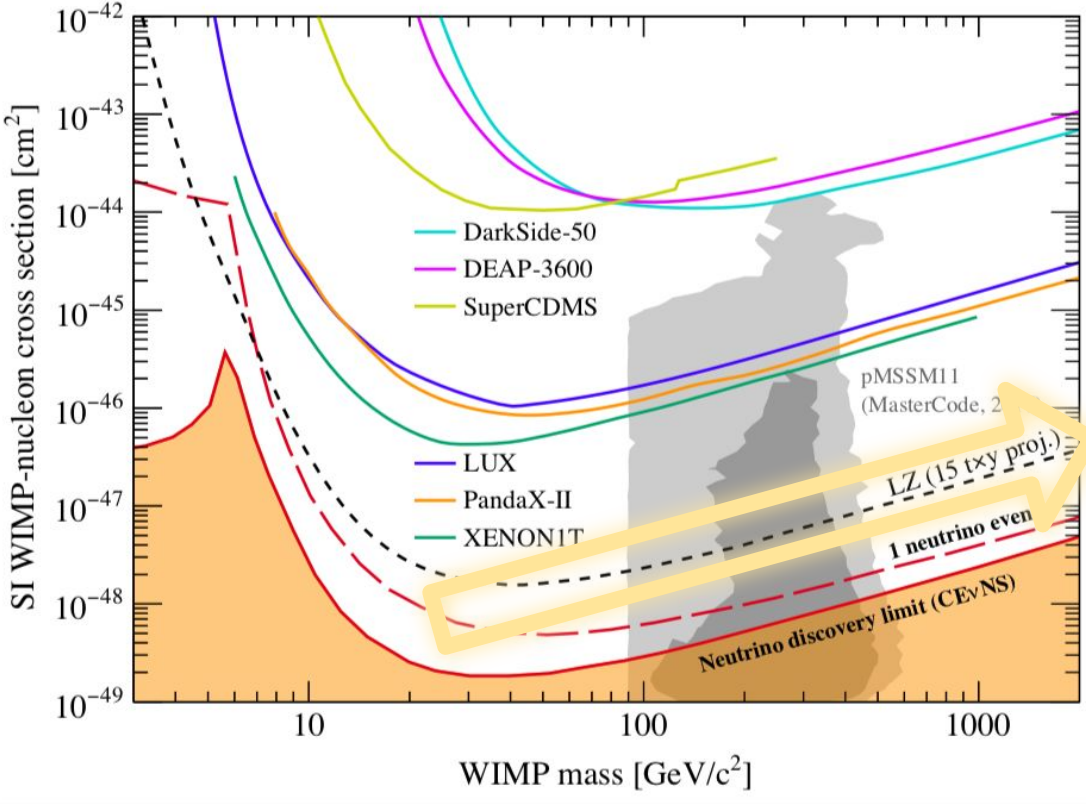
Technologies



Liquid Xenon TPCs

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

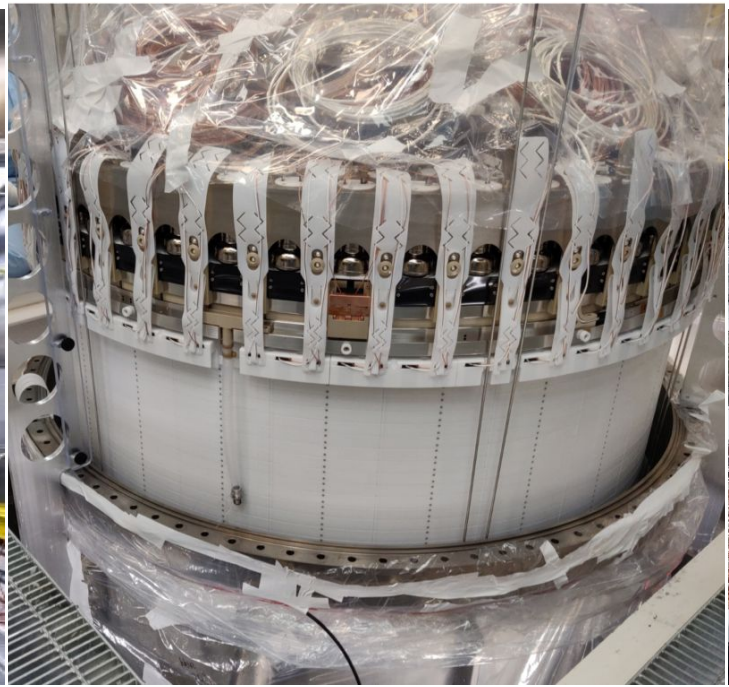
Direct Searches: The next generation



LZ (Liquid Xenon TPC)

LZ @ SURF (USA)

- Underground installation: **NOW!**
- Data taking: **mid-2020**
- Sensitivity projection: **3 years, 5.6t fiducial target**



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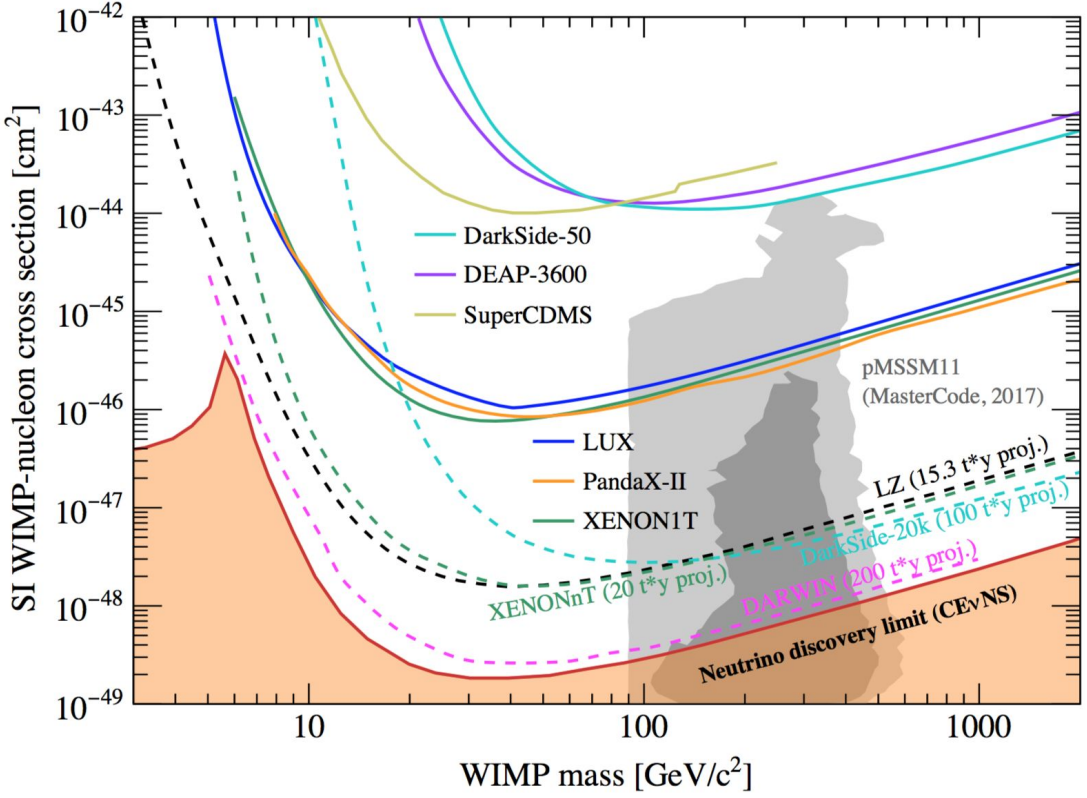
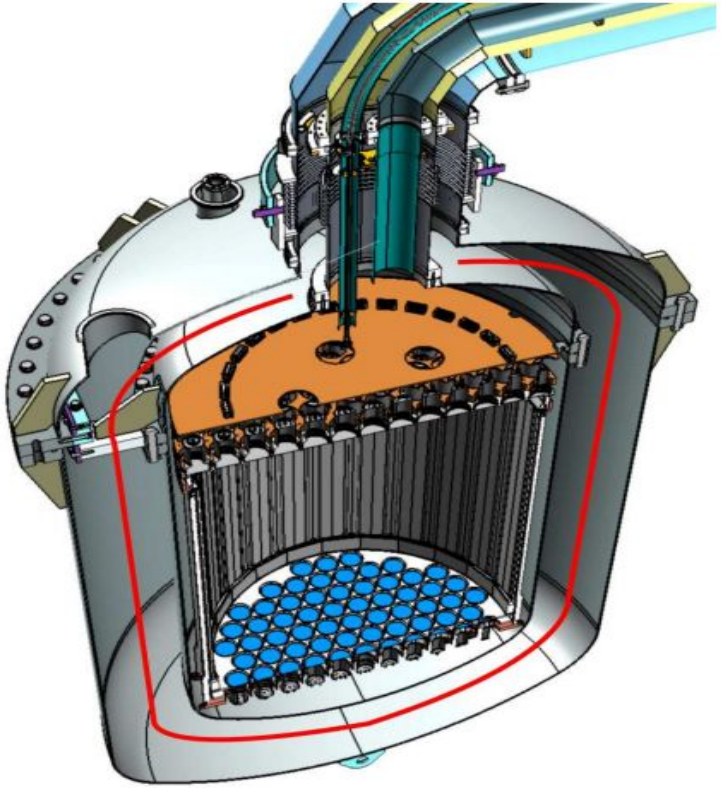
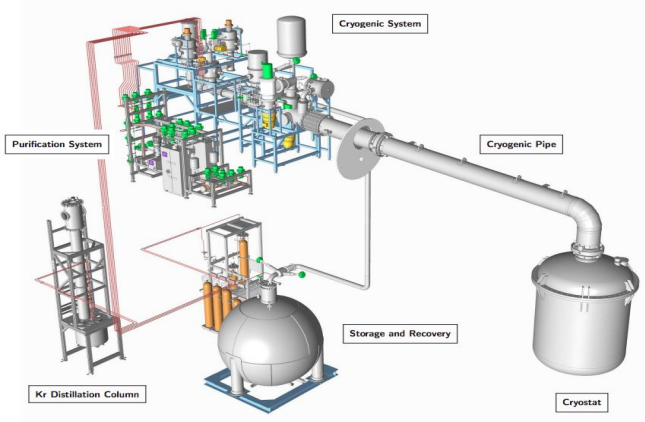


XENONnT @ Gran Sasso (Italy)





Liquid Xenon TPCs

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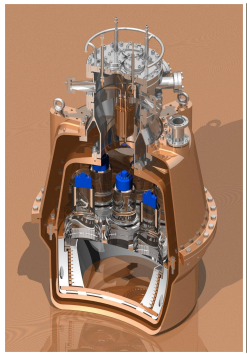	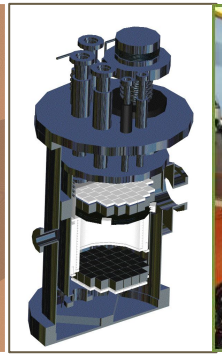		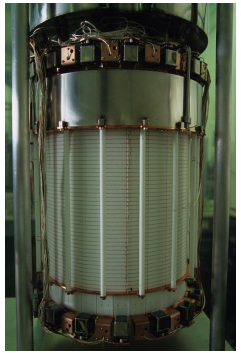	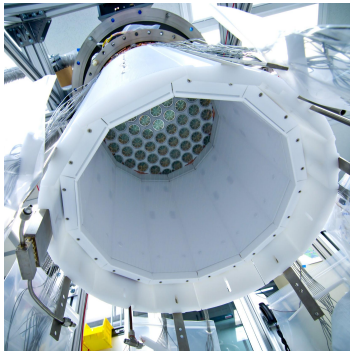		
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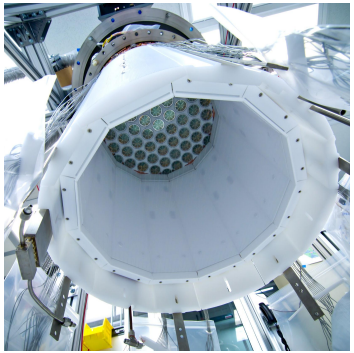
Liquid Xenon TPCs

LUX



250 kg
(100 kg)

PANDAX-II

580 kg
(362 kg)

XENON1T

2,000 kg
(1,042 kg)

2013

3.4×10^{-46} cm^2

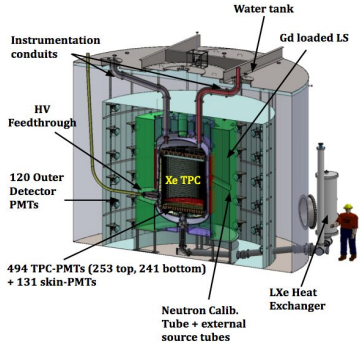
2016

2.5×10^{-46} cm^2

2017

7.7×10^{-47} cm^2

LZ

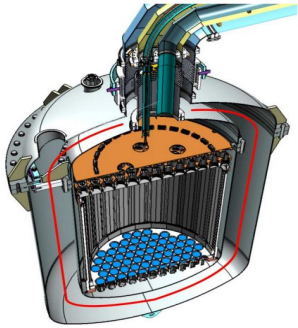


7,000 kg
(5,600 kg)

2020 + 3 live years

1.6×10^{-48} cm^2

XENONnT

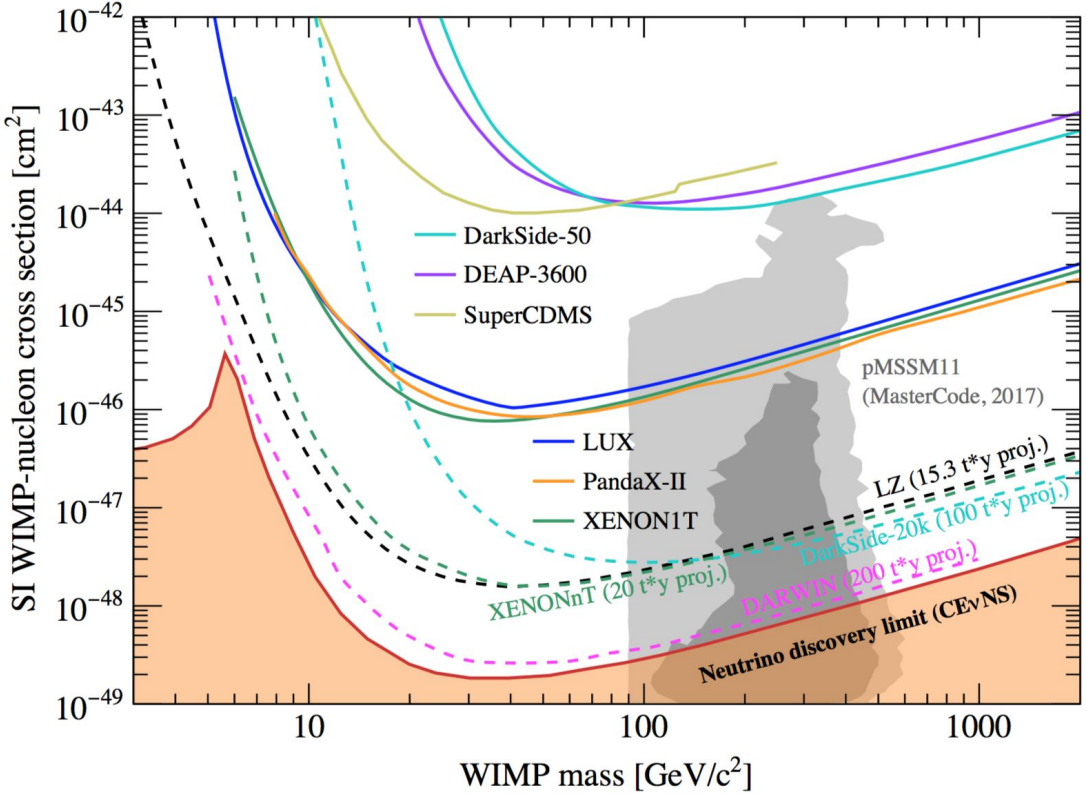


5,900 kg
(4,000 kg)

2020 + 5 live years

1.6×10^{-48} cm^2

Direct Searches: The next generation



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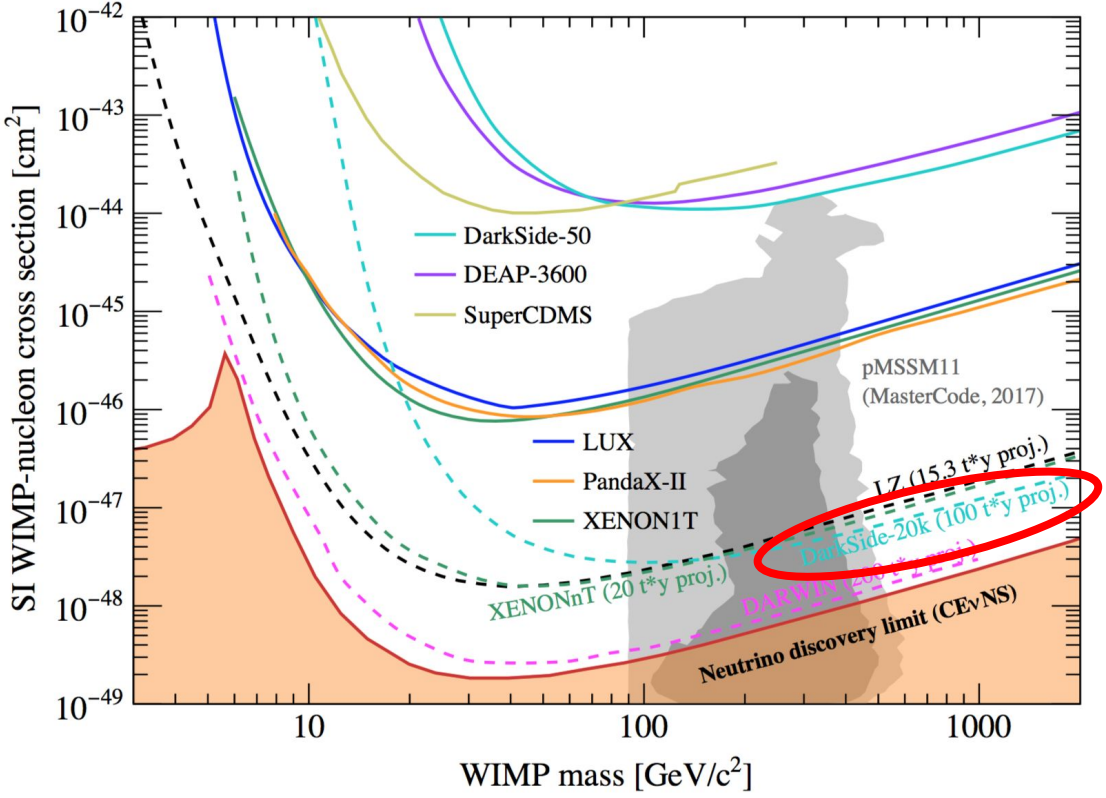
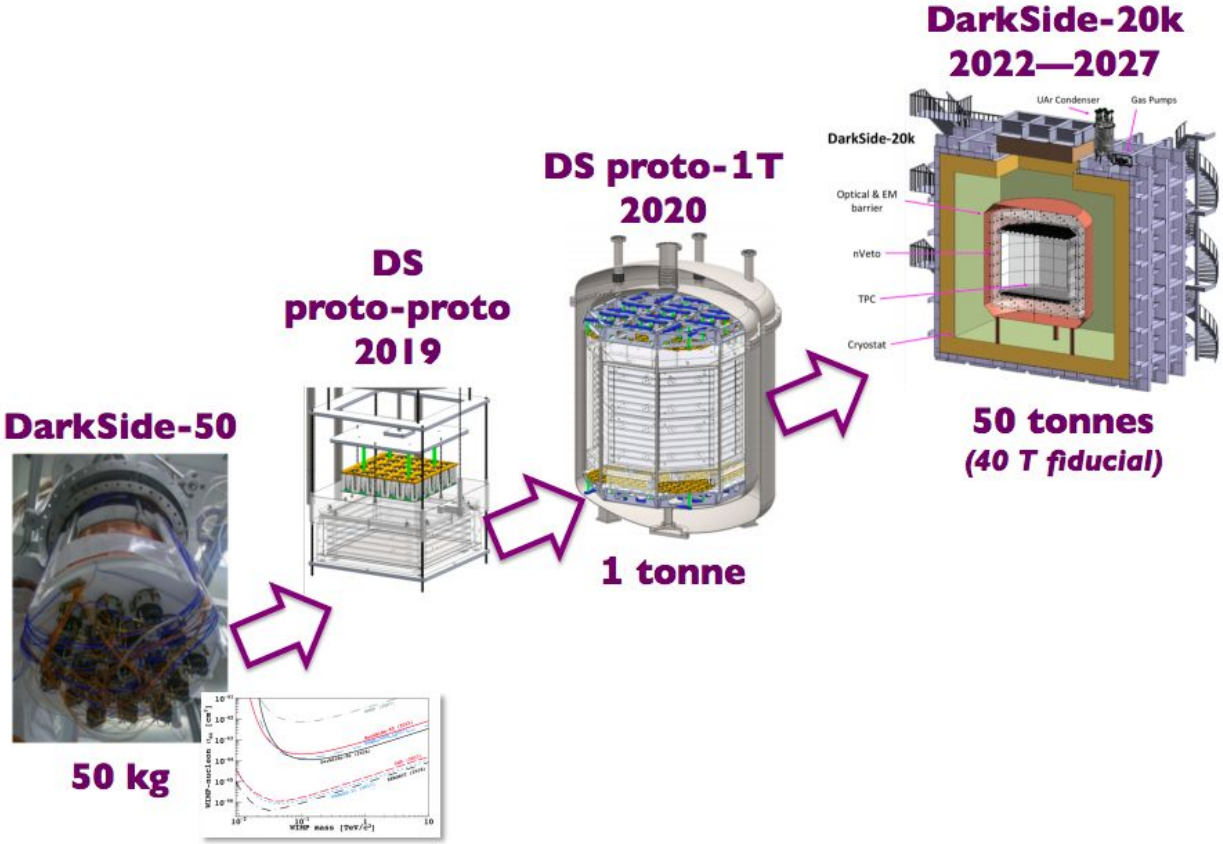


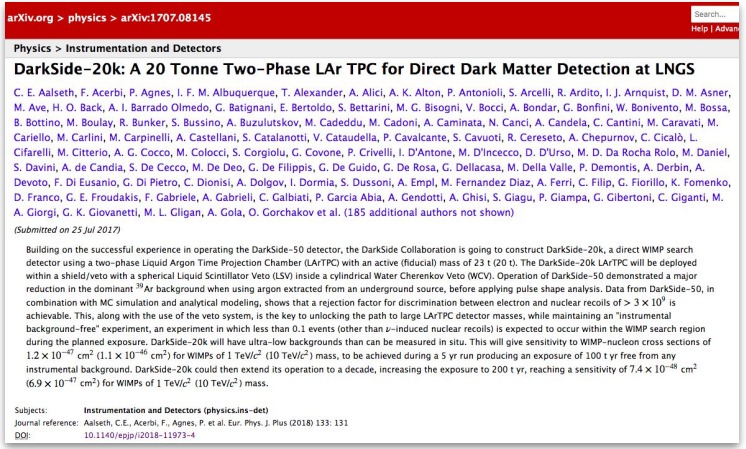
DARKSIDE-20k @ Gran Sasso (Italy)



D. Price, DMUK Meeting, Apr 2019

DARKSIDE-20k @ Gran Sasso (Italy)

- Preliminary design report (20t): 1707.08145
  - *Technical design report in prep.*
- Design evolved from 20t -> 50t
  - *to remain competitive with Xe*
  - *scale-up is >1,000x over DarkSide-50*
- Large scale deployment of SiPMs
- High efficiency veto strategy



arXiv.org > physics > arXiv:1707.08145

Search... Help | Advan

Physics > Instrumentation and Detectors

DarkSide-20k: A 20 Tonne Two-Phase LAr TPC for Direct Dark Matter Detection at LNGS

C. E. Aalseth, F. Acerbi, P. Agnes, I. F. M. Albuquerque, T. Alexander, A. Alici, A. K. Alton, P. Antonioli, S. Arcelli, R. Ardito, I. J. Arnquist, D. M. Asner, M. Ave, H. O. Back, A. I. Barrado Olmedo, G. Batignani, E. Bertoldo, S. Bettarini, M. G. Bisogni, V. Bocci, A. Bondar, G. Bonfini, W. Bonivento, M. Bossa, B. Bottino, M. Boulay, R. Bunker, S. Bussino, A. Buzulutskov, M. Cadeddu, M. Cadoni, A. Caminata, N. Canci, A. Candela, C. Cantini, M. Caravati, M. Cariello, M. Carlini, M. Carpinelli, A. Castellani, S. Catalanotti, V. Cataudella, P. Cavalcante, S. Cavuoti, R. Cereseto, A. Chepurnov, C. Cicalò, L. Cifarelli, M. Citterio, A. G. Cocco, M. Colocci, S. Corgiolu, G. Covone, P. Crivelli, I. D'Antone, M. D'Incecco, D. D'Urso, M. D. Da Rocha Rolo, M. Daniel, S. Davini, A. de Candia, S. De Cecco, M. De Deo, G. De Filippis, G. De Guido, G. De Rosa, G. Dellacasa, M. Della Valle, P. Demontis, A. Derbin, A. Devoto, F. Di Eusanio, G. Di Pietro, C. Dionisi, A. Dolgov, I. Dormia, S. Dussoni, A. Empl, M. Fernandez Diaz, A. Ferri, C. Filip, G. Fiorillo, K. Fomenko, D. Franco, G. E. Froudakis, F. Gabriele, A. Gabrieli, C. Galbiati, P. Garcia Abia, A. Gendotti, A. Ghisi, S. Giagu, P. Giampa, G. Gibertoni, C. Giganti, M. A. Giorgi, G. K. Giovanetti, M. L. Gligan, A. Gola, O. Gorchakov et al. (185 additional authors not shown)

(Submitted on 25 Jul 2017)

Building on the successful experience in operating the DarkSide-50 detector, the DarkSide Collaboration is going to construct DarkSide-20k, a direct WIMP search detector using a two-phase Liquid Argon Time Projection Chamber (LArTPC) with an active (fiducial) mass of 23 t (20 t). The DarkSide-20k LArTPC will be deployed within a shield/veto with a spherical Liquid Scintillator Veto (LSV) inside a cylindrical Water Cherenkov Veto (WCV). Operation of DarkSide-50 demonstrated a major reduction in the dominant ^{39}Ar background when using argon extracted from an underground source, before applying pulse shape analysis. Data from DarkSide-50, in combination with MC simulation and analytical modeling, shows that a rejection factor for discrimination between electron and nuclear recoils of $> 3 \times 10^9$ is achievable. This, along with the use of the veto system, is the key to unlocking the path to large LArTPC detector masses, while maintaining an "instrumental background-free" experiment, an experiment in which less than 0.1 events (other than ν-induced nuclear recoils) is expected to occur within the WIMP search region during the planned exposure. DarkSide-20k will have ultra-low backgrounds than can be measured in situ. This will give sensitivity to WIMP-nucleon cross sections of 1.2×10^{-47} cm^2 (1.1×10^{-46} cm^2) for WIMPs of 1 TeV/c^2 (10 TeV/c^2) mass, to be achieved during a 5 yr run producing an exposure of 100 t yr free from any instrumental background. DarkSide-20k could then extend its operation to a decade, increasing the exposure to 200 t yr, reaching a sensitivity of 7.4×10^{-48} cm^2 (6.9×10^{-47} cm^2) for WIMPs of 1 TeV/c^2 (10 TeV/c^2) mass.

Subjects: **Instrumentation and Detectors (physics.ins-det)**
Journal reference: Aalseth, C.E., Acerbi, F., Agnes, P. et al. Eur. Phys. J. Plus (2018) 133: 131
DOI: 10.1140/epjp/i2018-11973-4

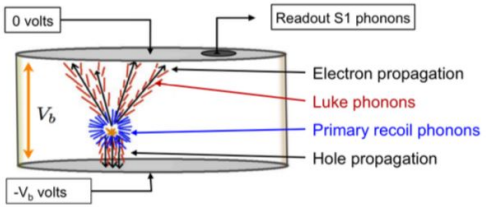
Data taking projected from **start 2023**

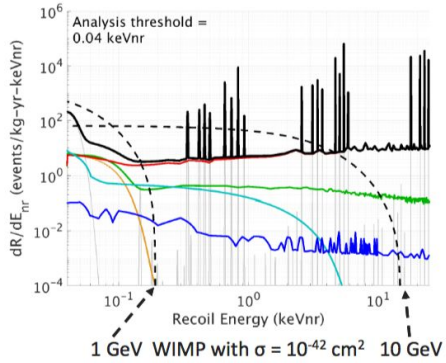
- *Global Ar community*
- *Follows end of projected DEAP-3600 science run*
- *Aggressive timescale to be competitive with liquid Xe*

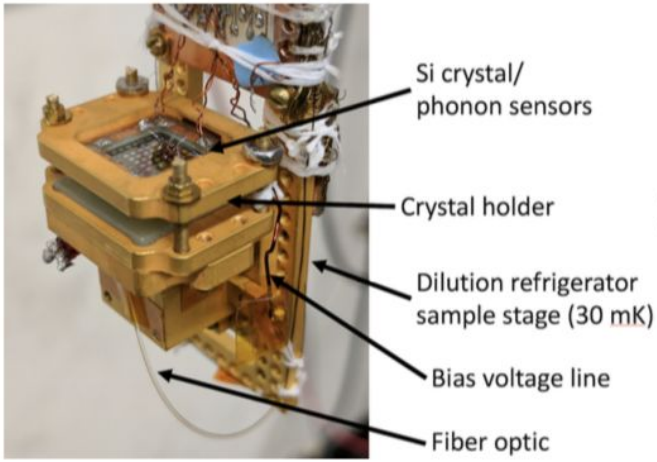
Multiple targets useful for confirmation of WIMP-hypothesis

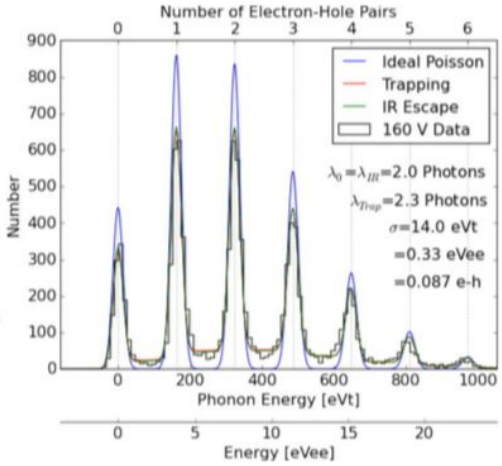
SuperCDMS @ SNOLab (Canada)

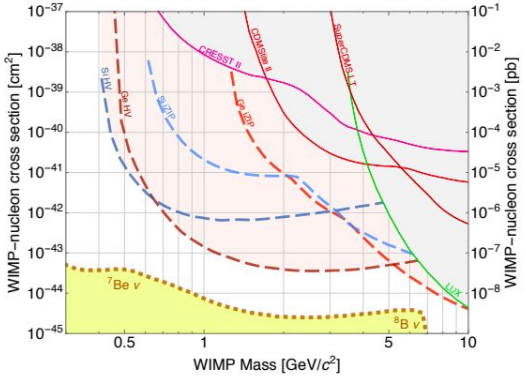
- 1.4 kg Ge and 0.6 kg Si crystals
- Targeting <10 GeV/c^2 mass range
  - *Sensitivity to sub-GeV dark matter*
- Band gap in Ge is 0.7 eV, Si is 1.1 eV
  - *Energy thresholds in tens of eV range*
- Operation at SNOLab from **2020/21**



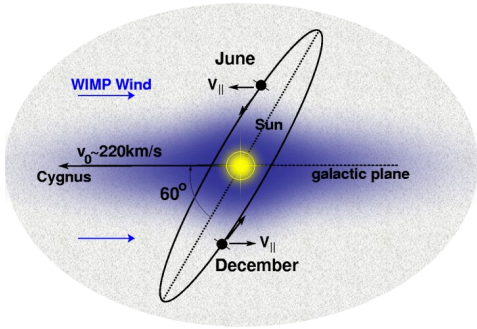




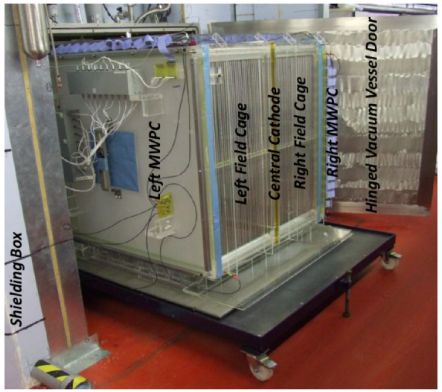


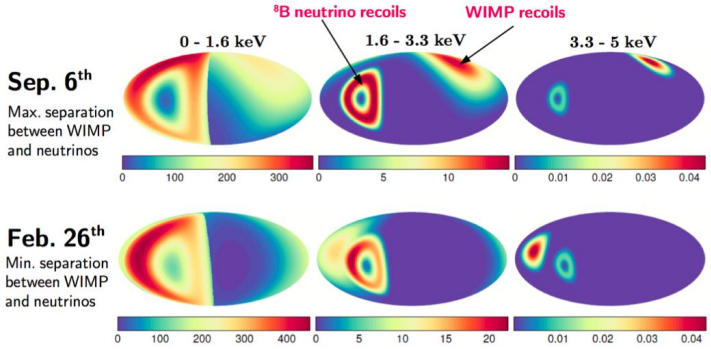


CYGNUS (Directional R&D)

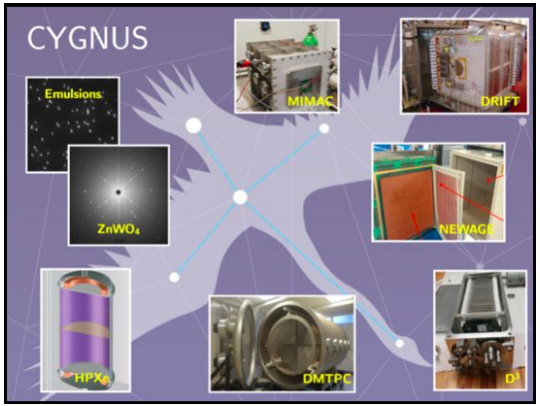


- **DRIFT**: Directionality pioneer based at Boulby
  - *DRIFT-IIe testing large area thick GEM readouts*
- **CYGNUS**: International collaboration of directionality experiments
  - *25 institutes (Australia, China, Italy, Japan, UK, US); UK spokesperson*
  - *Negative ion SF_6+He target with high demonstrated (UK)*
  - *Targeting low-mass WIMP region (~10 keV) with directionality and recoil discrimination*
  - *Distributed network of 10 m^3 (CYGNUS-10) experiments at different latitudes*
  - *New sites at Stawell (Australia), Boulby (UK), Gran Sasso (Italy) for CYGNUS-UNDER 1m^3 test*

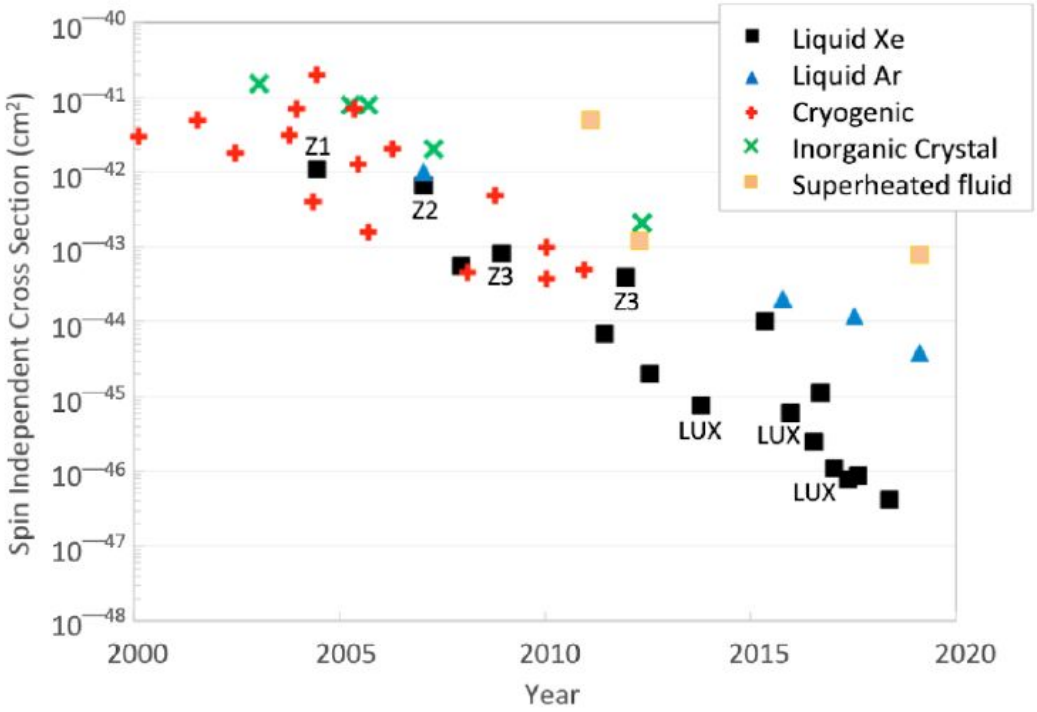




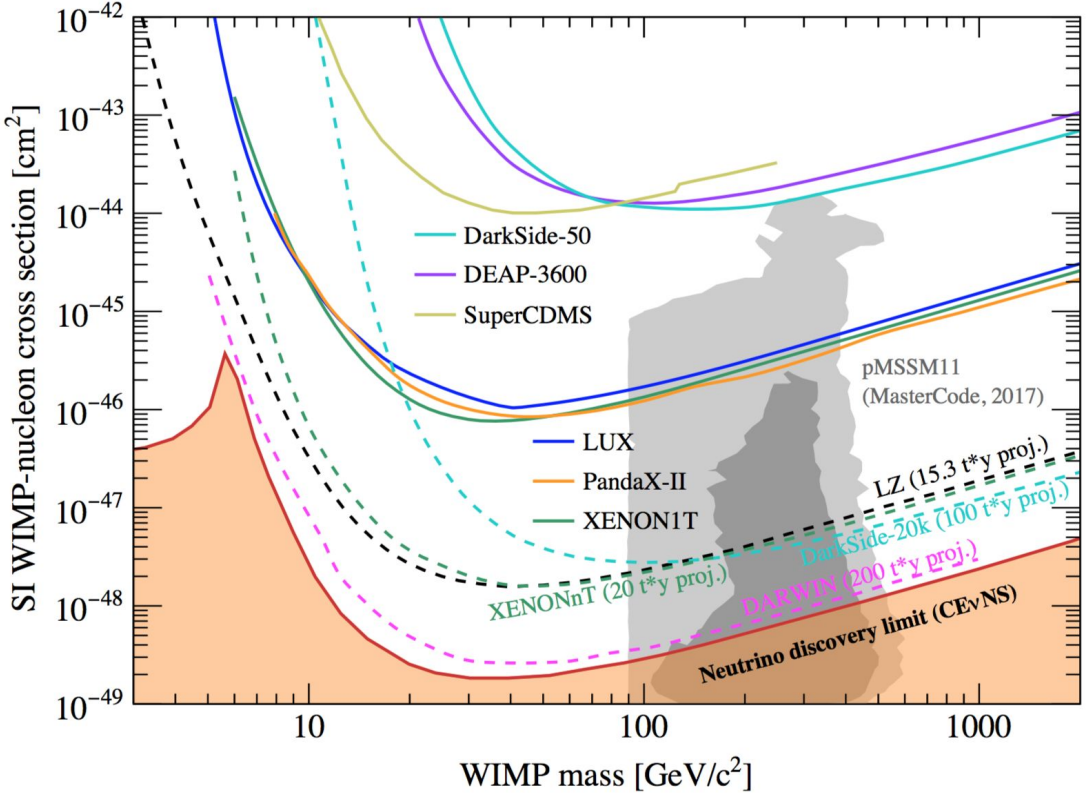
CAJ O'Hare et. al. Phys. Rev. D 92, 063518 (2015)



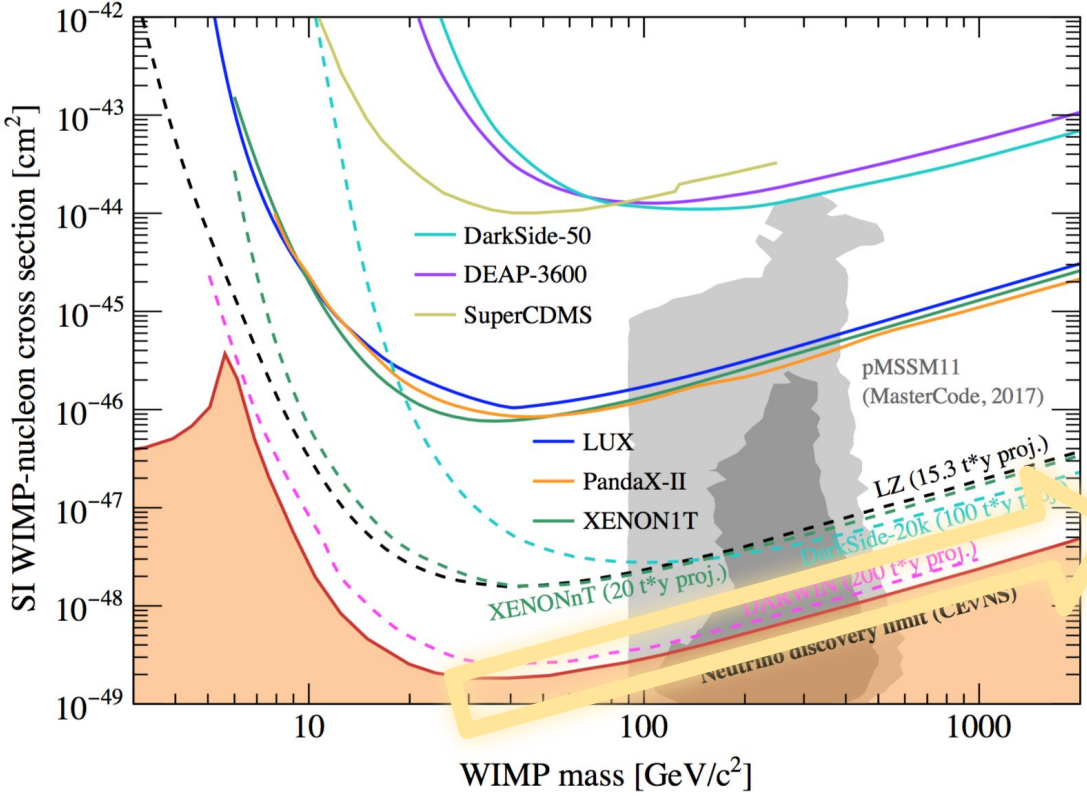
Technologies

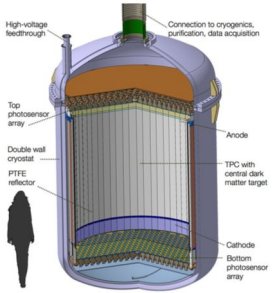


Direct Searches: The 3rd generation ('G3')



Direct Searches: The 3rd generation ('G3')



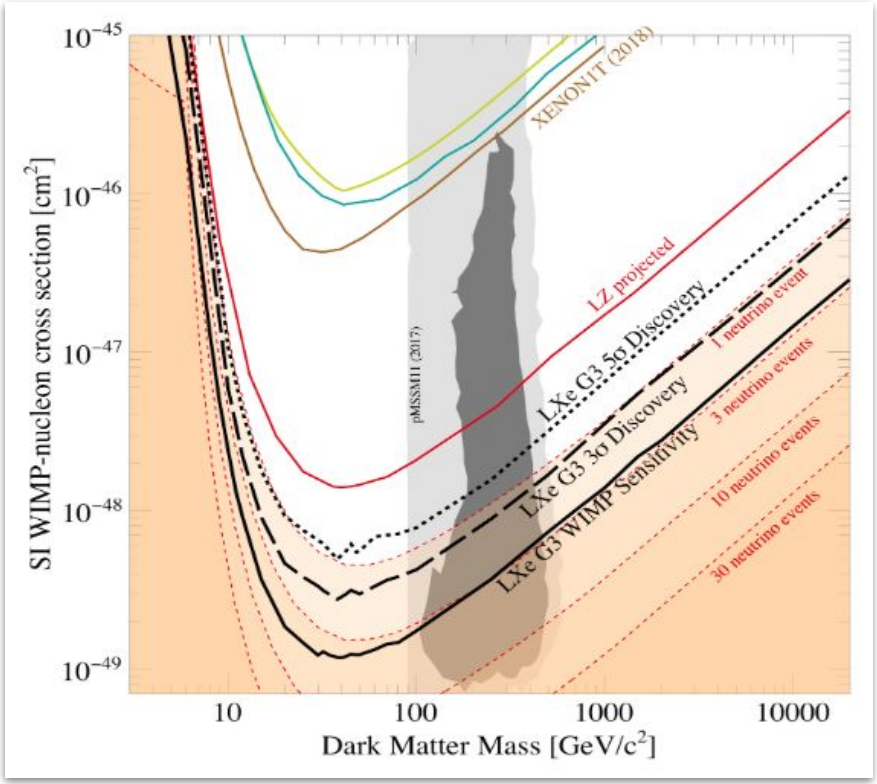


Generation-3

‘Generation-3’ (G3) Projected Timescales

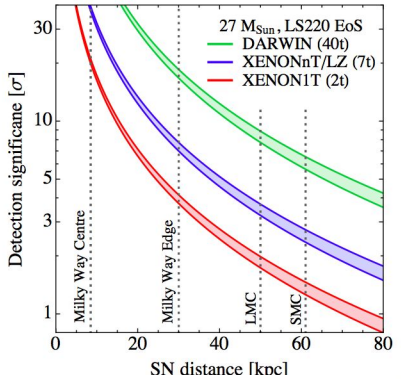
- 2019 - 2023 : LXe G3 R&D
- 2023 - 2025 : Pre-construction phase for technical design
- 2025 - 2029 : Construction phase
- 2029 - 2034+ : Exploitation

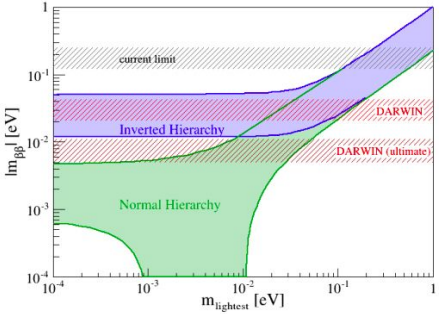
‘Generation-3’ (G3) : WIMPs

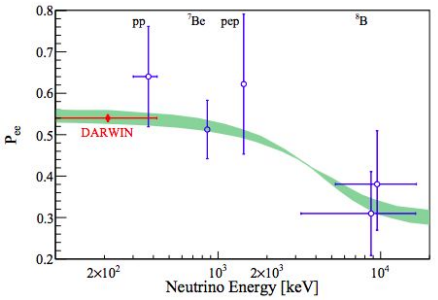


‘Generation-3’ (G3): An observatory

- High stats confirmation/measurement ***or*** explore remaining ‘accessible’ WIMPs
- **Size** + **low-background** + **NR** + **ER** = Science **beyond standard WIMPs** in Xe G3
  - *Neutrinoless double beta decay; low-energy solar neutrino flux; solar axions; galactic axion like particles: supernovae; sterile neutrinos; …*
- R&D effort started/starting around the world:
  - *WIMPs and Neutrinoless double beta decay*
    - *engineering issues related to up-scaling*
    - *Identification and mitigation of non-fiducialisable backgrounds*
  - *Single electrons backgrounds (ionisation-only searches)*
    - *Optical and electrical properties of materials*
    - *Grids and HV delivery*
  - *Asymmetric dark matter / FIMPs (low threshold)*
    - *Light yield, ionisation yield*
    - *Migdal effect*
    - *Doping*
  - *Inelastic / magnetic dark matter (electron + nuclear recoils)*
    - *Position reconstruction*
- *Xe-based G3 R&D begun already in Europe, starting in the UK*
- *Co-ordinated U.S. proposals (XENON + LZ groups)*







arXiv:1606.07001

Electron Recoil Physics in Xe

nature
International journal of science

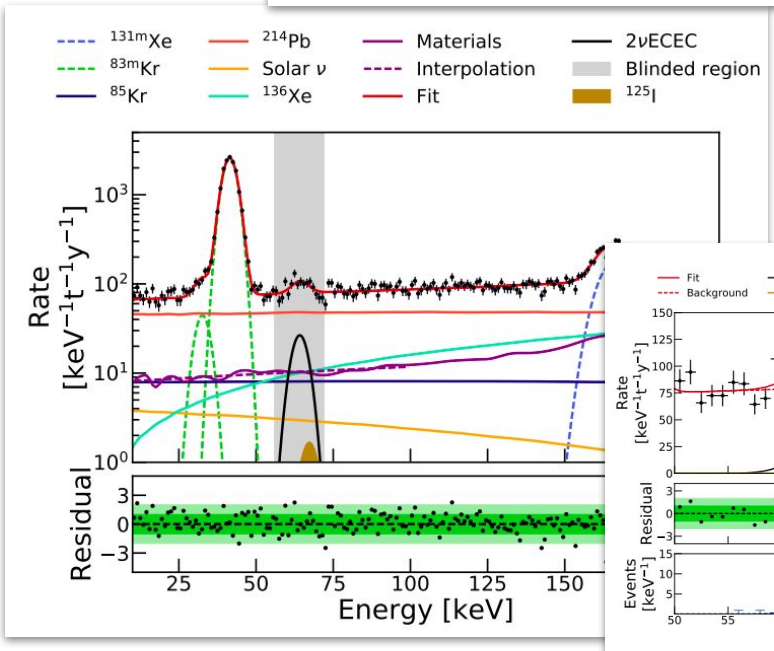
Letter | Published: 24 April 2019

Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T

XENON Collaboration*

Nature **568**, 532–535 (2019) | Download Citation

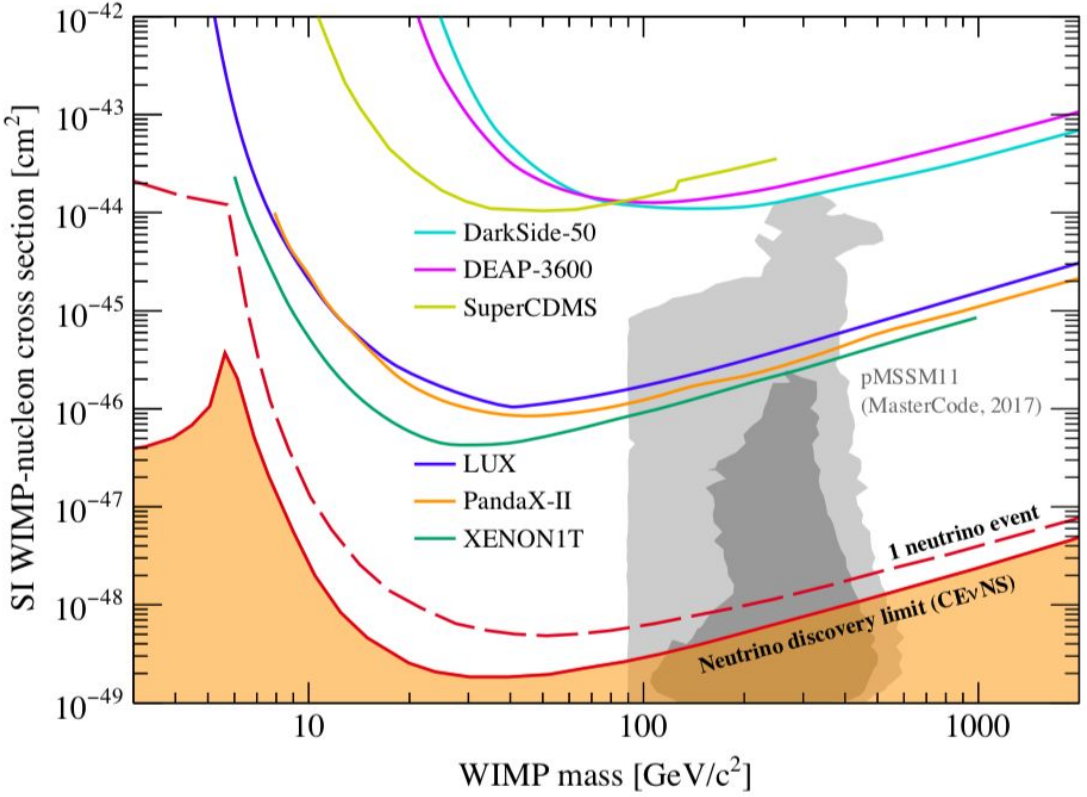
Two-neutrino double electron capture (2νECEC) is a second-order weak-interaction process with a predicted half-life that surpasses the age of the Universe by many orders of magnitude[1]. Until now, indications of 2νECEC decays have only been seen for two isotopes[2,3,4,5], ^{78}Kr and ^{130}Ba, and instruments with very low background levels are needed to detect them directly with high statistical significance[6,7]. The 2νECEC half-life is an important observable for nuclear structure models[8,9,10,11,12,13,14] and its measurement represents a meaningful step in the search for neutrinoless double electron capture—the detection of which would establish the Majorana nature of the neutrino and would give access to the absolute neutrino mass[15,16,17]. Here we report the direct observation of 2νECEC in ^{124}Xe with the XENON1T dark-matter detector. The significance of the signal is 4.4 standard deviations and the corresponding half-life of 1.8×10^{22} years (statistical uncertainty, 0.5×10^{22} years; systematic uncertainty, 0.1×10^{22} years) is the longest measured directly so far. This study demonstrates that the low background and large target mass of xenon-based dark-matter detectors make them well suited for measuring rare processes and highlights the broad physics reach of larger next-generation experiments[18,19,20].



Direct Searches

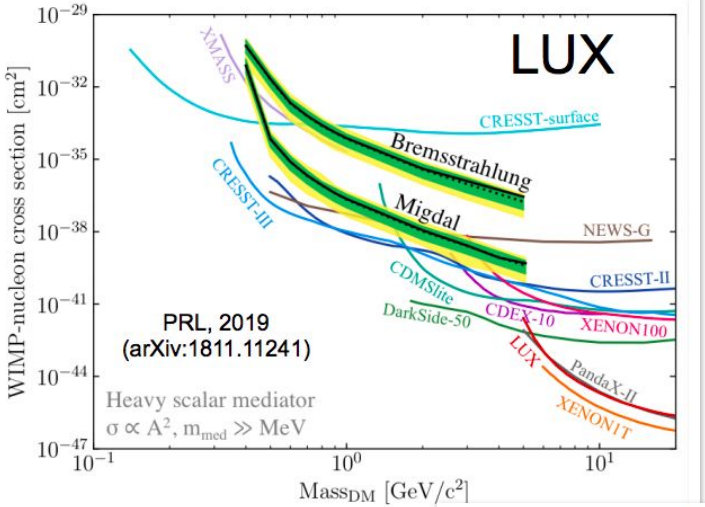
THRESHOLD & ATOMIC MASS MATTERS
CRYOGENIC DETECTORS

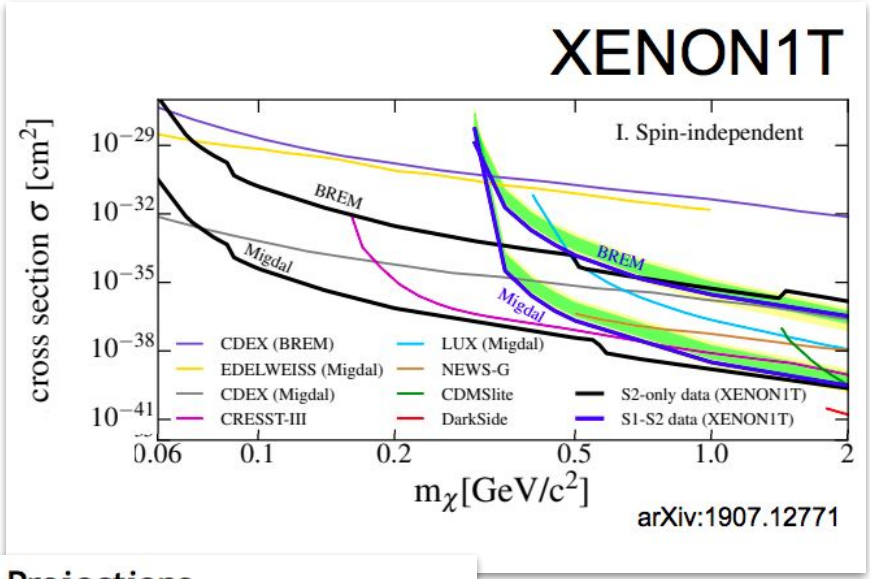
Liquid Xe
ER: 10^{-5} dru (!)
(Ionisation, Migdal, Bremm., Doping, …)

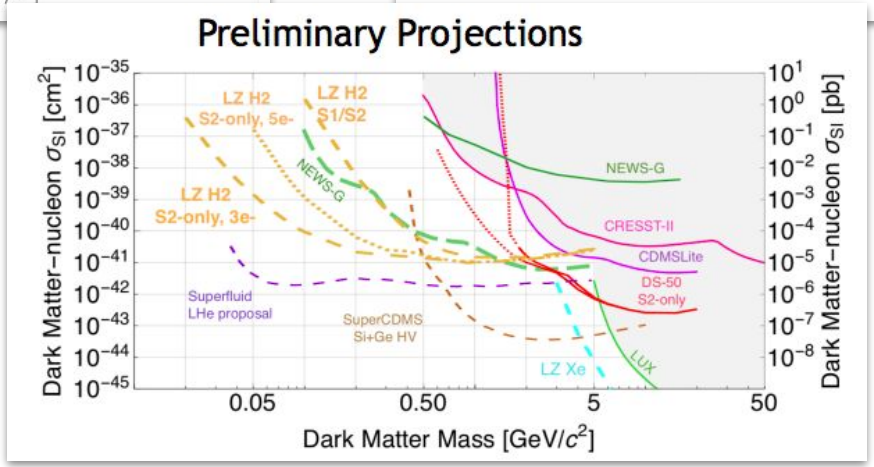


SIZE (x TIME) MATTERS
NOBLE LIQUIDS

Migdal effect:



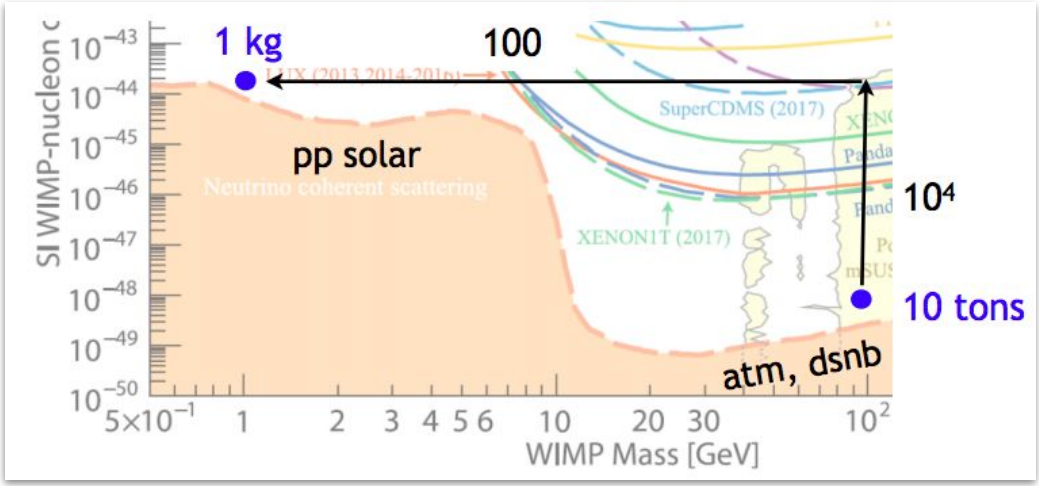




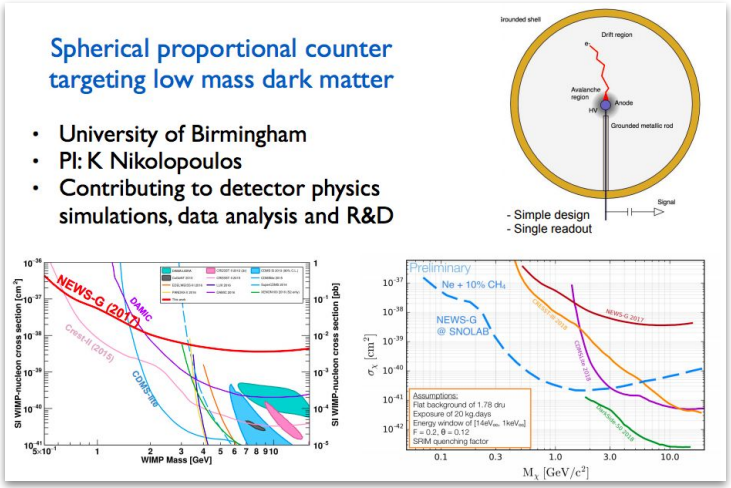
R&D required!

T. Shutt, TAUP, Sept 2019

Dedicated low-mass WIMP experiments

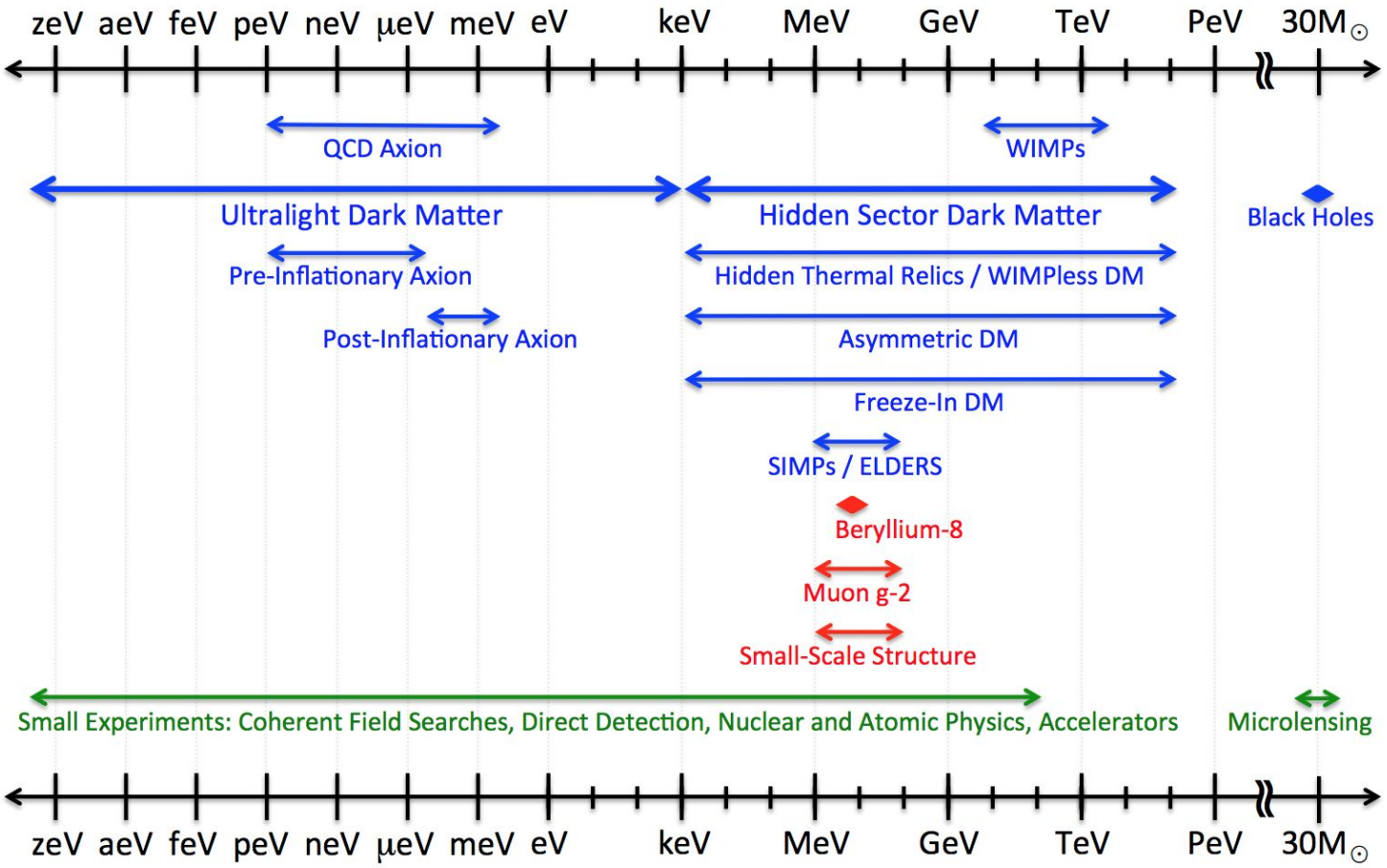


[T. Shutt, TAUP, Sept 2019]



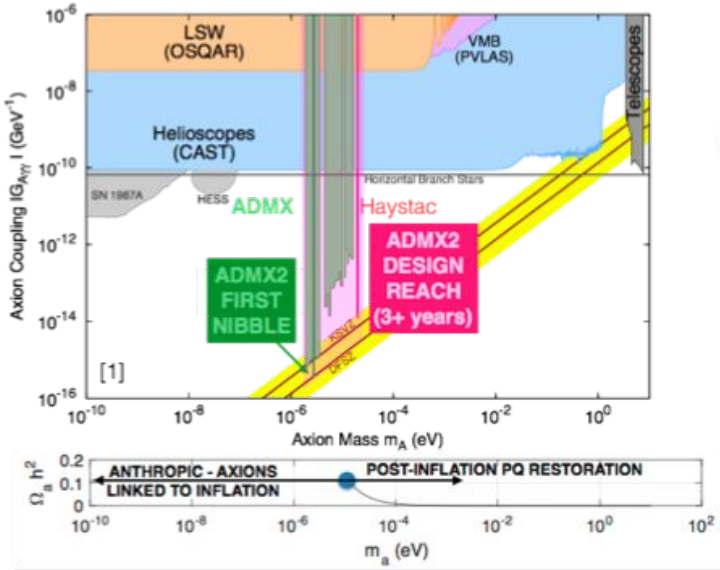
[C. McCabe, PPAP Meeting, Sept 2019]

Dark Sector Candidates, Anomalies, and Search Techniques

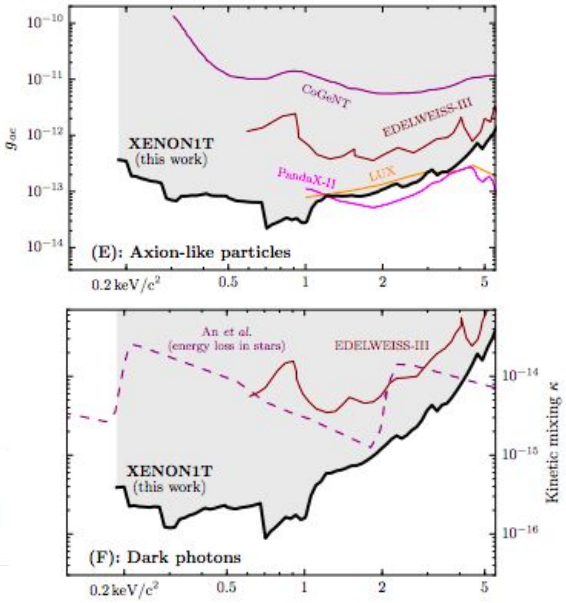


Axions/ALPs

- Axions from QCD symmetry breaking mechanism
  - *Light (order 10 μeV) pseudoscalar, stable particles*
- **ADMX-Gen2** is a Dark Matter axion search using a tuned electromagnetic resonator in a B-field
- See also **QUAX**, **IAXO**, **GNOME**, **CAST**, …
- Low-ER **direct detection** experiments, e.g., Xe/crystals, can probe via axio-electric effect



XENON1T - arXiv:1907.11485



Phys. Rev. Lett. ***120****, 151301 (2018)*

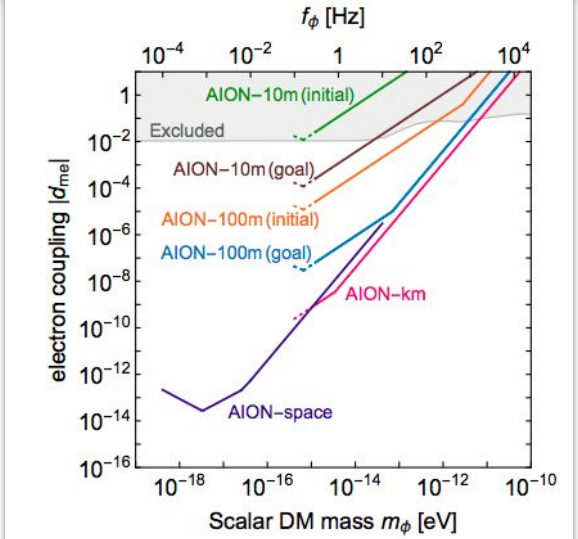
QSFP UK Institutions Partners International Institutions Workpackages QSFP Organization

http://qsfp.physics.ox.ac.uk

Quantum Sensors for Fundamental Physics

Welcome to the home page of the Quantum Sensors for Fundamental Physics consortium.

The consortium consists of **32 UK institutions, 7 international institutions** and **five partners.**



WP1

Using Quantum Technology to Search for Low-mass Particles in the Hidden Sector

Participants/Collaborators ›
Join this group ›

WP2

MaQS (pronounced "Max") Macroscopic quantum superpositions for physics beyond the standard model

WP2 workshop slides ›
Participants/Collaborators ›
Join this group ›

WP3

AION A UK Atom Interferometer Observatory and Network

Join this group ›

WP4

Absolute neutrino mass

Participants/Collaborators ›
Join this group ›

WP5

Quantum Simulators of Fundamental Physics

Participants/Collaborators ›
Join this group ›

WP6

QSNET Networked Quantum Sensors for Fundamental Physics

Join this group ›

WP7

Searches for a Fifth Force and Dark Matter using Precision Atomic Spectroscopy

Join this group ›

WP8

Fundamental physics from precision studies of exotic atoms

Participants/Collaborators ›
Join this group ›

WP9

LIST – Lorentz Invariance Space Test

Participants/Collaborators ›
Join this group ›

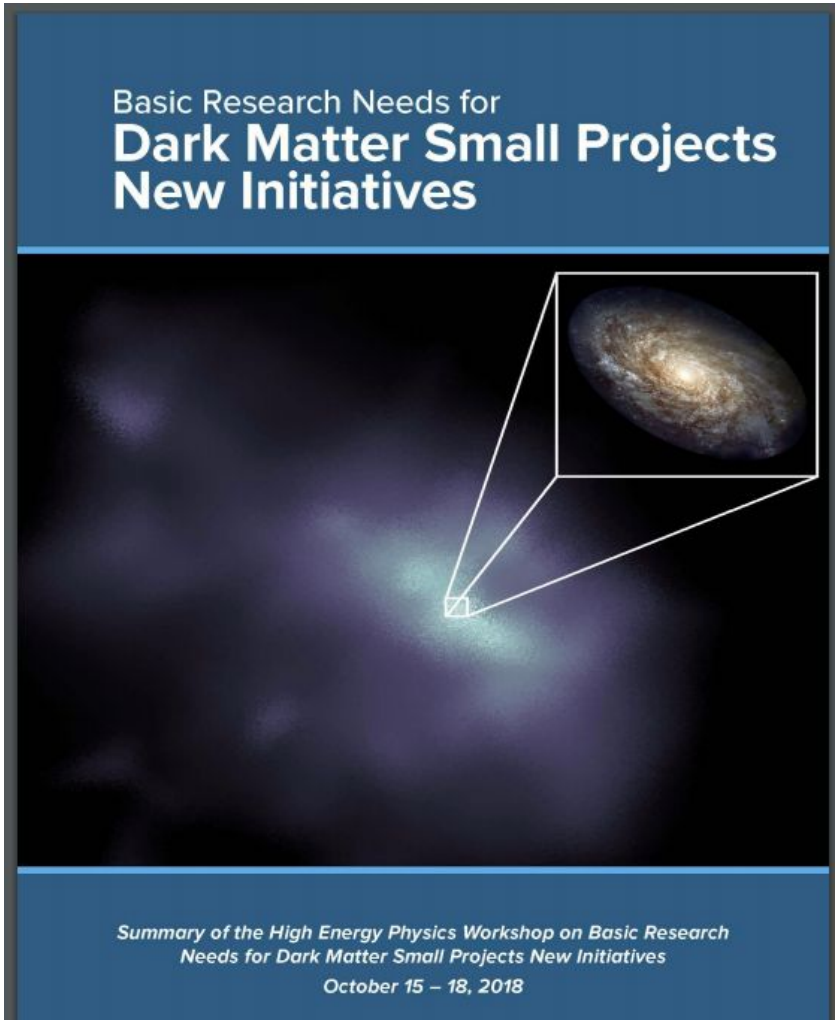
WP10

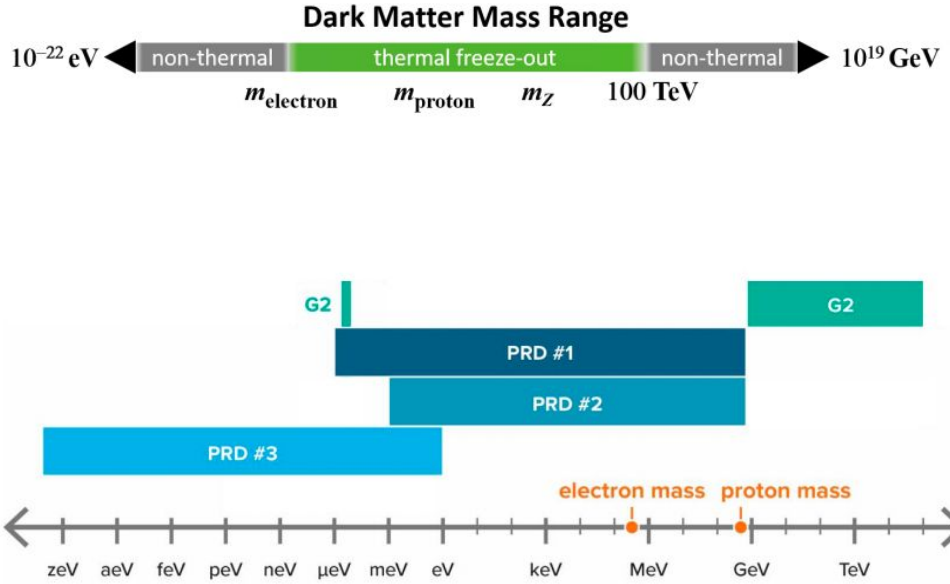
Quantum sensors for fundamental physics: Collective quantum excitations as quantum sensors

Participants/Collaborators ›
Join this group ›

WP11

QI: Quantum-enhanced Interferometry for New Physics


Basic Research Needs for
Dark Matter Small Projects
New Initiatives
Summary of the High Energy Physics Workshop on Basic Research
Needs for Dark Matter Small Projects New Initiatives
October 15 – 18, 2018

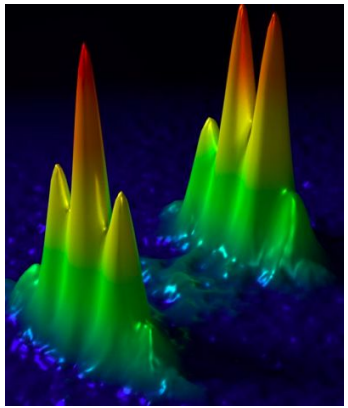

Dark Matter Mass Range
10^{-22} eV
non-thermal
thermal freeze-out
non-thermal
10^{19} GeV
$m_{electron}$
m_{proton}
m_Z
100 TeV
G2
G2
PRD #1
PRD #2
PRD #3
electron mass
proton mass
zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV

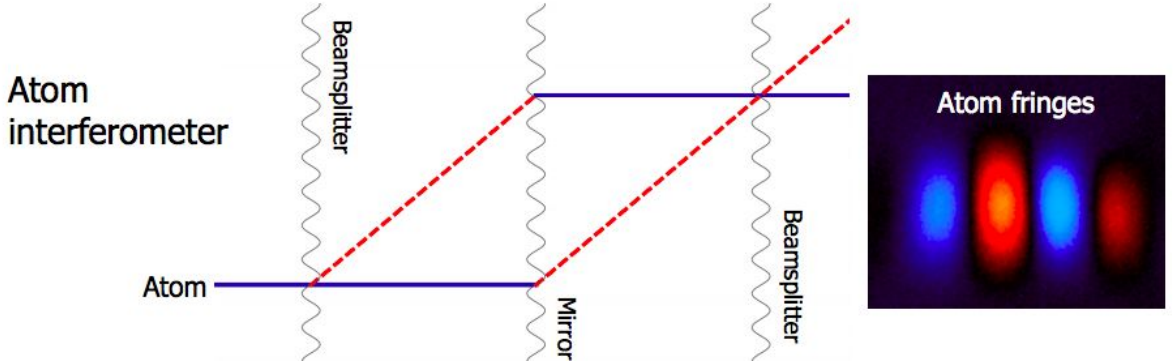
(Non-technical) Challenges/Questions

(Or, reflections upon my ignorance…)

- What does signal look like?
- How do we calibrate?
- Background subtraction?
- How do we verify potential discovery?
- How do we map to accelerator and indirect searches?

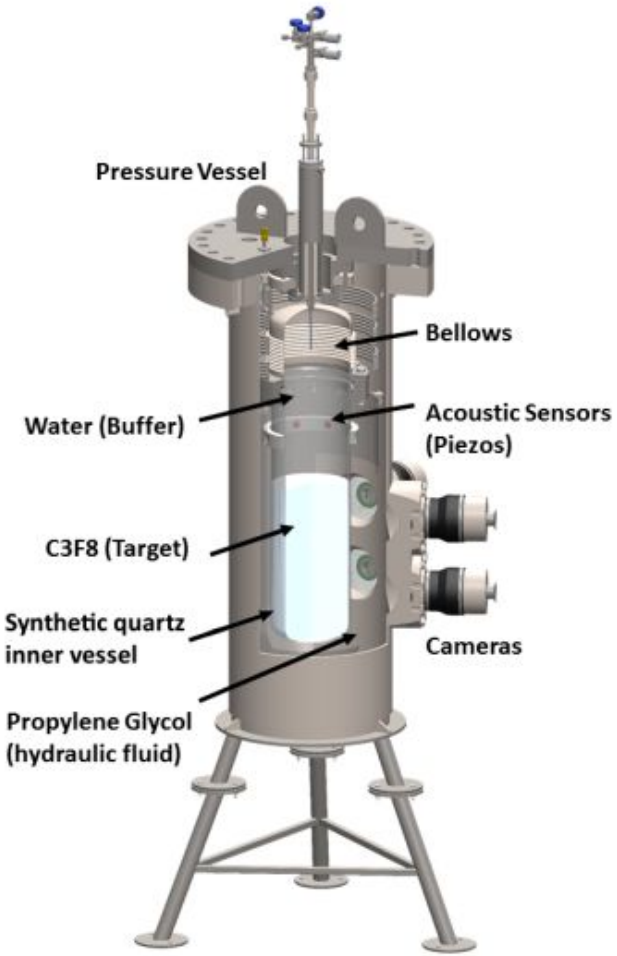
Exciting research lies ahead!





Thank you!

Extra slides...



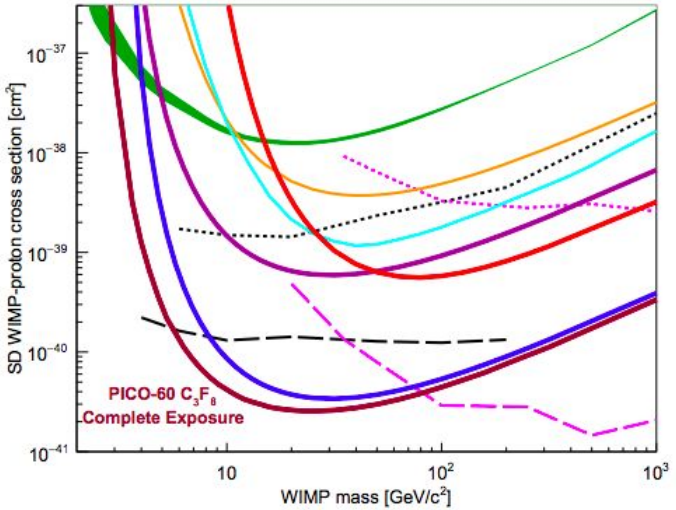
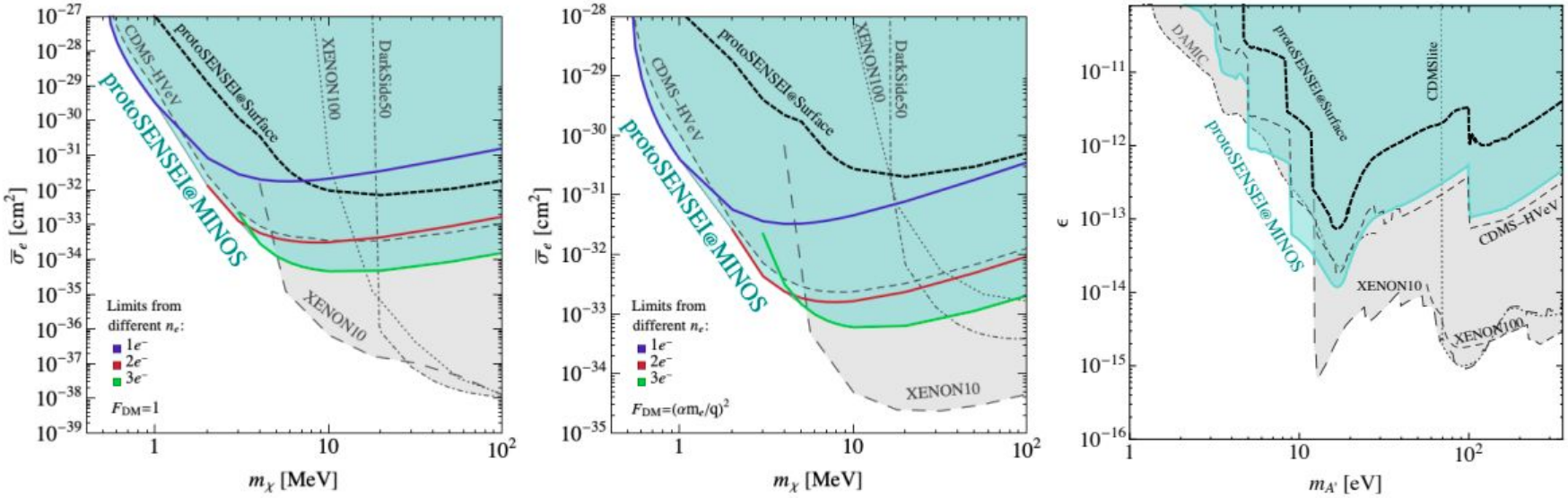


FIG. 7. The 90% C.L. limit on the SD WIMP-proton cross section from the profile likelihood analysis of the PICO-60 C_3F_8 combined blind exposure plotted in thick maroon, along with limits from the first blind exposure of PICO-60 C_3F_8 (thick blue) [14], as well as limits from PICO-60 CF_3I (thick red) [11], PICO-2L (thick purple) [10], PICASSO (green band) [20], SIMPLE (orange) [21], PandaX-II (cyan) [46], IceCube (dashed and dotted pink) [47], and SuperK (dashed and dotted black) [48, 49]. The indirect limits from IceCube and SuperK assume annihilation to τ leptons (dashed) and b quarks (dotted). Additional limits, not shown for clarity, are set by LUX [51] and XENON1T [53] (comparable to PandaX-II) and by ANTARES [54, 55] (comparable to IceCube).

SENSEI

https://arxiv.org/pdf/1901.10478.pdf



ANAIS

First results on dark matter annual modulation from ANAIS-112 experiment

J. Amaré,[1,2] S. Cebrián,[1,2] I. Coarasa,[1,2] C. Cuesta,[1,3] E. García,[1,2] M. Martínez,[1,2,4] M.A. Oliván,[1,5] Y. Ortigoza,[1,2] A. Ortiz de Solórzano,[1,2] J. Puimedón,[1,2] A. Salinas,[1,2] M.L. Sarsa*,[1,2] P. Villar,[1,2] and J.A. Villar†[1,2]

[1] *Laboratorio de Física Nuclear y Astropartículas, Universidad de Zaragoza, C/ Pedro Cerbuna 12, 50009 Zaragoza, Spain*
[2] *Laboratorio Subterráneo de Canfranc, Paseo de los Ayerbe s.n., 22880 Canfranc Estación, Huesca, Spain*
[3] *Present Address: Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, CIEMAT, 28040, Madrid, Spain*
[4] *Fundación ARAID, Av. de Ranillas 1D, 50018 Zaragoza, Spain*
[5] *Present Address: Fundación CIRCE, 50018, Zaragoza, Spain*

ANAIS is a direct detection dark matter experiment aiming at the testing of the DAMA/LIBRA annual modulation result, which standing for about two decades has neither been confirmed nor ruled out by any other experiment in a model independent way. ANAIS-112, consisting of 112.5 kg of sodium iodide crystals, is taking data at the Canfranc Underground Laboratory, Spain, since August 2017. This letter presents the annual modulation analysis of 1.5 years of data, amounting to 157.55 kg×y. We focus on the model independent analysis searching for modulation and the validation of our sensitivity prospects. ANAIS-112 data are consistent with the null hypothesis (p-values of 0.65 and 0.16 for [2-6] and [1-6] keV energy regions, respectively). The best fits for the modulation hypothesis are consistent with the absence of modulation ($S_m = -0.0044 \pm 0.0058$ cpd/kg/keV and -0.0015 ± 0.0063 cpd/kg/keV, respectively). They are in agreement with our estimated sensitivity for the accumulated exposure, supporting our projected goal of reaching a 3σ sensitivity to the DAMA/LIBRA result in 5 years of data taking.

https://arxiv.org/pdf/1903.03973.pdf

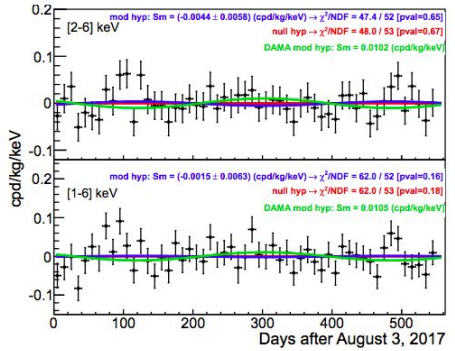


FIG. 2: ANAIS-112 data in the energy windows [1-6] keV (bottom panel) and [2-6] keV (top panel) surviving all the cuts and efficiency corrected [26]. Data is displayed after subtracting the constant and exponential functions fitted to Equation 2. Fits are also shown in the same way, both in the modulation (3 free parameters) and the null hypothesis (2 free parameters). χ^2 and p-values displayed allow the comparison of both hypothesis, and DAMA/LIBRA results on modulation amplitude in both energy windows are shown in green [8].

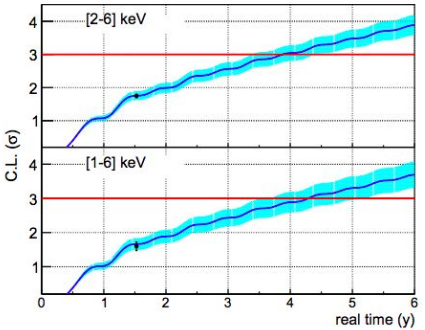
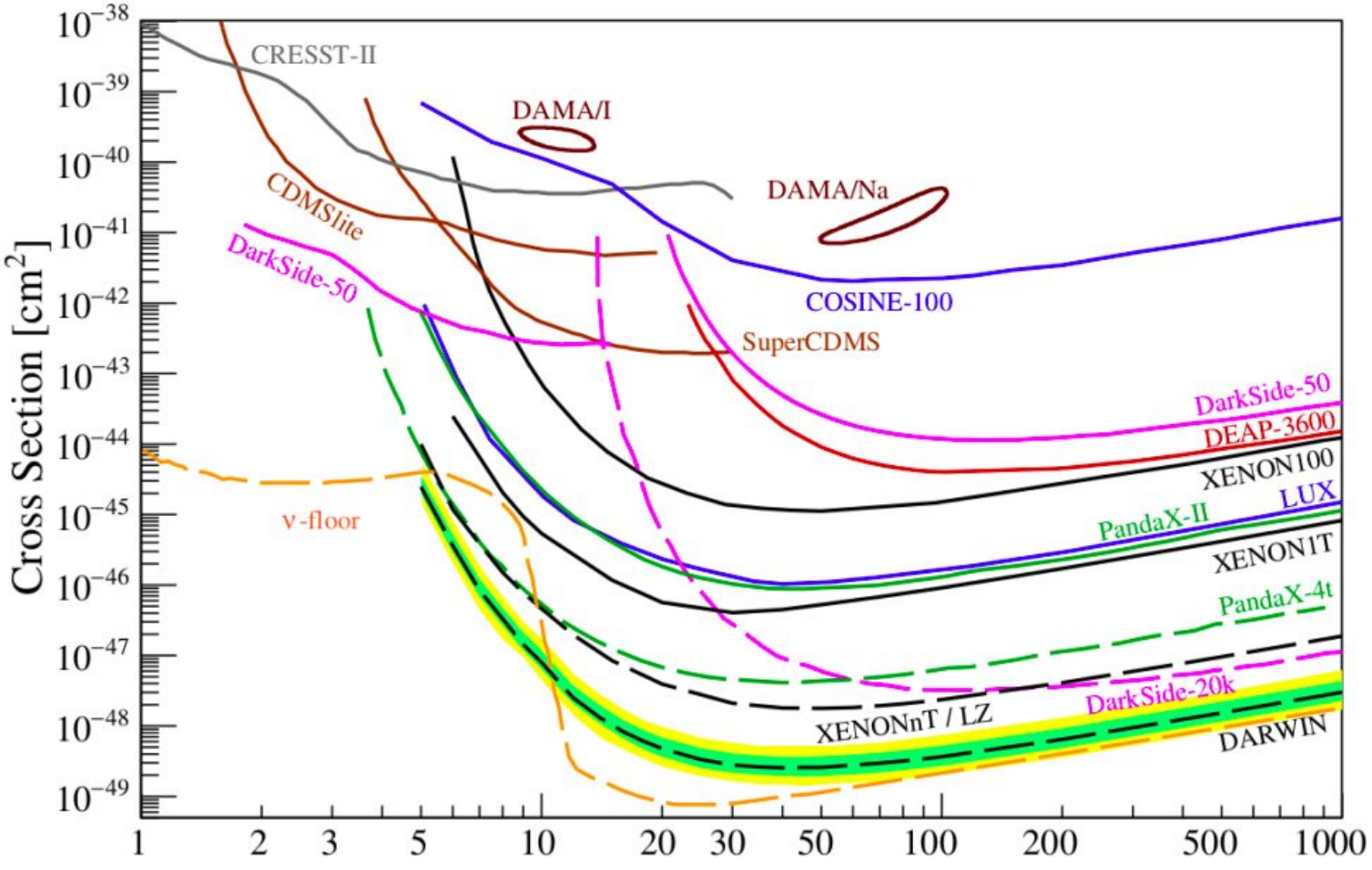
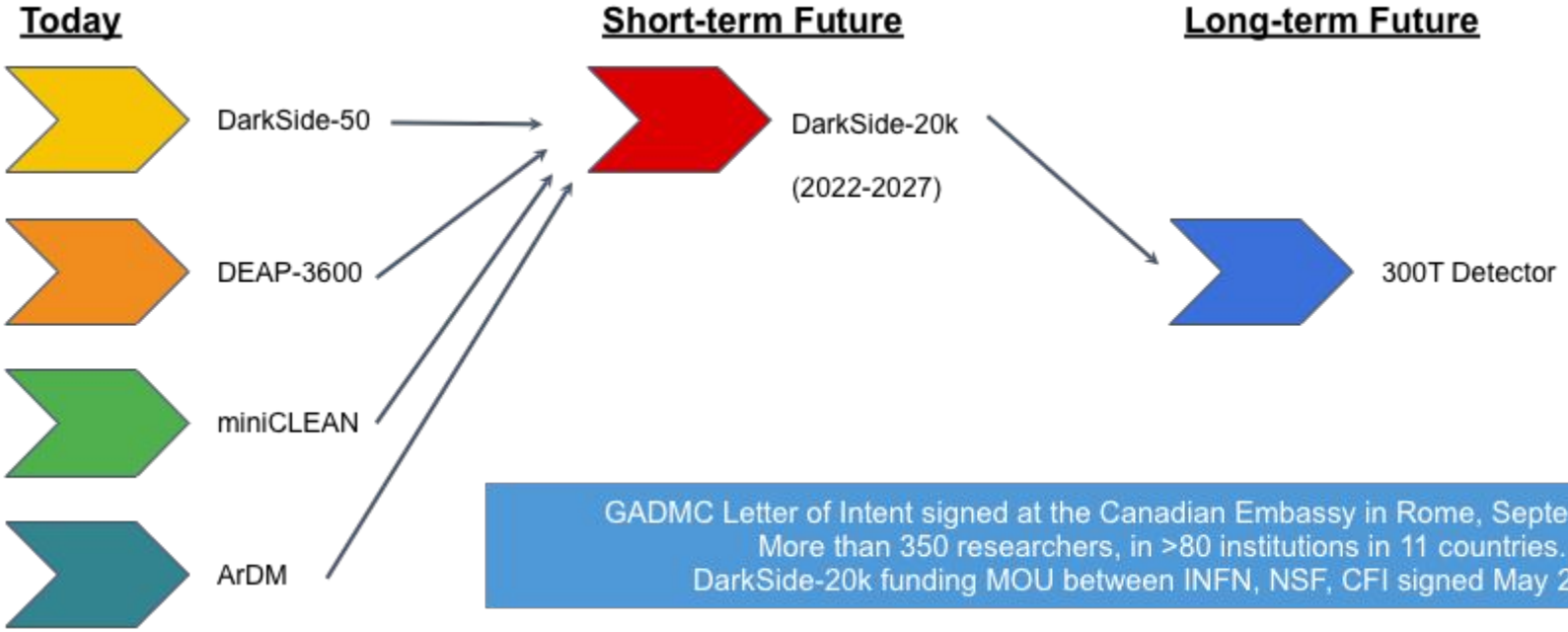


FIG. 3: ANAIS-112 sensitivity to the DAMA/LIBRA signal in σ C.L. units (see text) as a function of real time in the [2-6] keV (upper panel) and [1-6] keV (lower panel) energy regions. The black dots are the sensitivities derived in this work, $\sigma(S_m)$. The blue bands represent the 68% C.L. DAMA/LIBRA uncertainty [8].


Cross Section [cm^2]
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
1
2
3
5
10
20
30
50
100
200
500
1000
CRESST-II
DAMA/I
DAMA/Na
CDMSlite
DarkSide-50
COSINE-100
SuperCDMS
DarkSide-50
DEAP-3600
XENON100
LUX
PandaX-II
XENON1T
PandaX-4t
ν-floor
XENONnT / LZ
DarkSide-20k
DARWIN

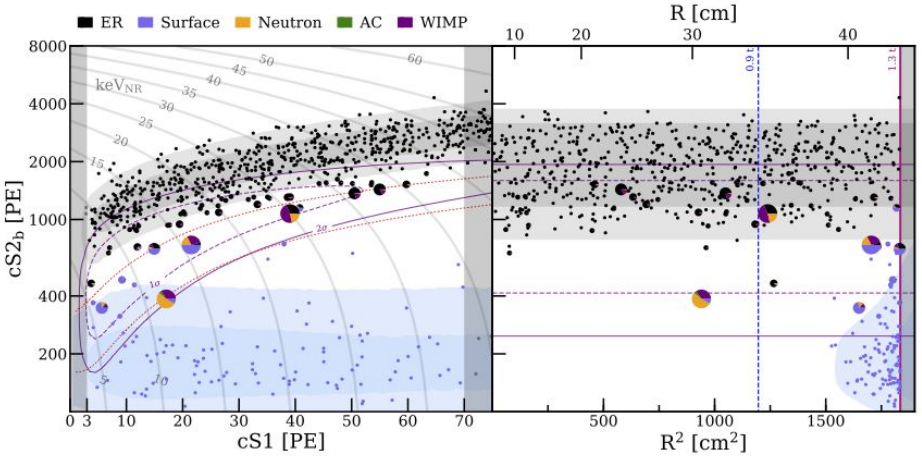
ARGO (liquid argon)

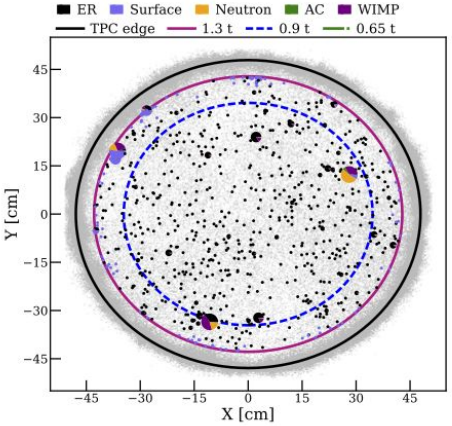


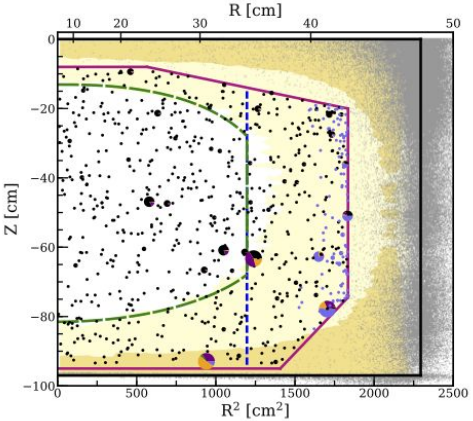
GADMC Letter of Intent signed at the Canadian Embassy in Rome, September 2017.
More than 350 researchers, in >80 institutions in 11 countries.
DarkSide-20k funding MOU between INFN, NSF, CFI signed May 2018.

XENON1T @ Gran Sasso (Italy)

- 2 ton LXe TPC
- Background: 82 events / (ton*yr*keV) in (1.4 - 10.6) keV
- 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)*



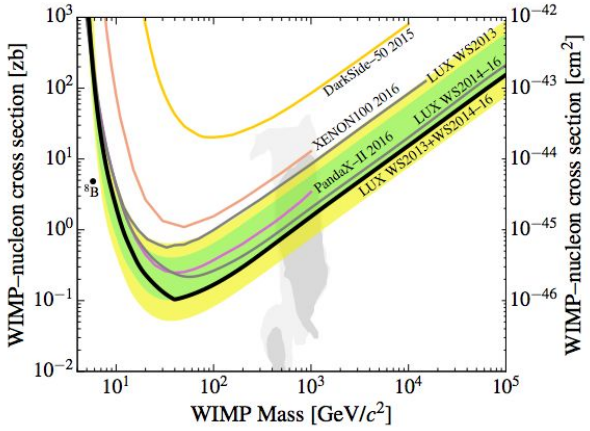


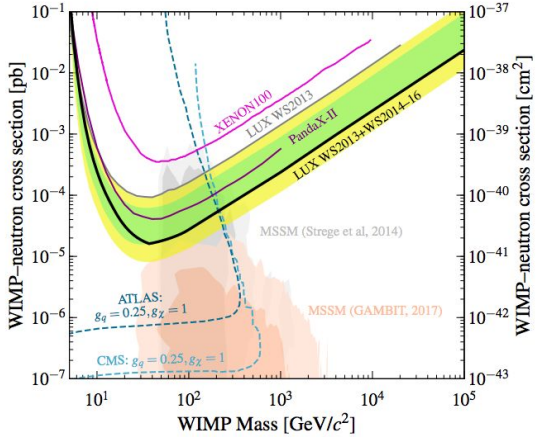


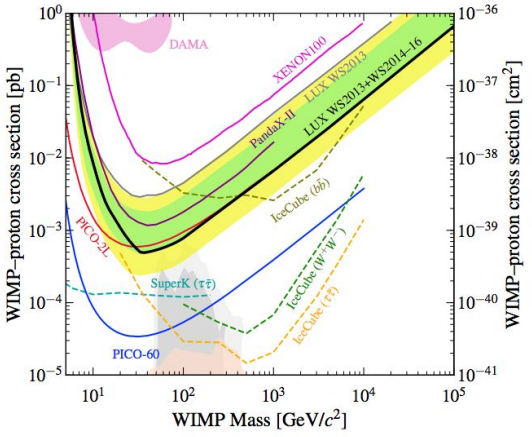
arXiv:1805.12562

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, …)
- Calibrations and light/charge yields: strong legacy

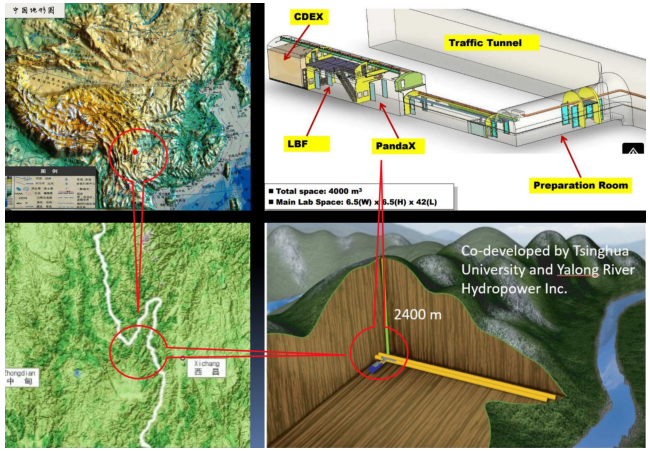


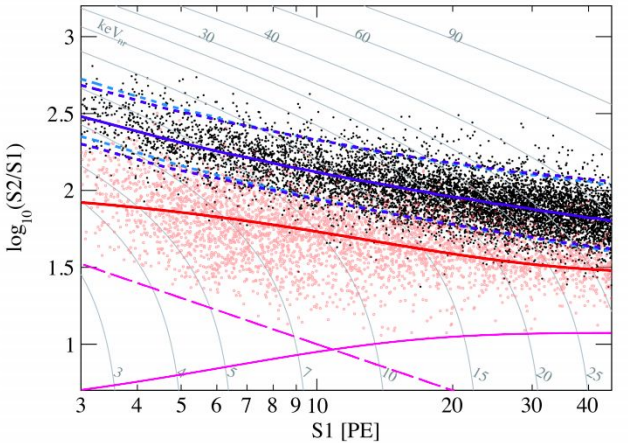


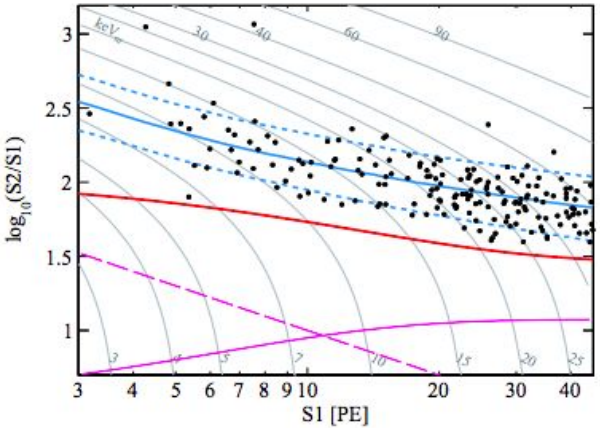


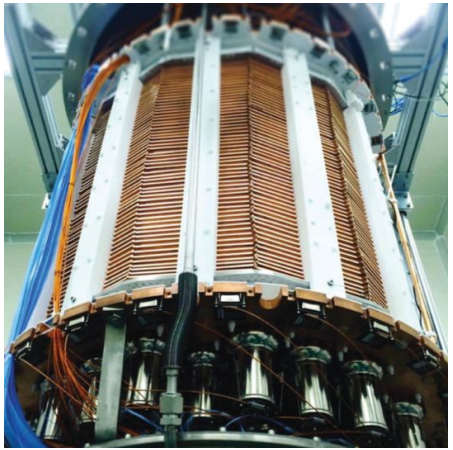
PandaX @ Jin Ping (China)

- 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

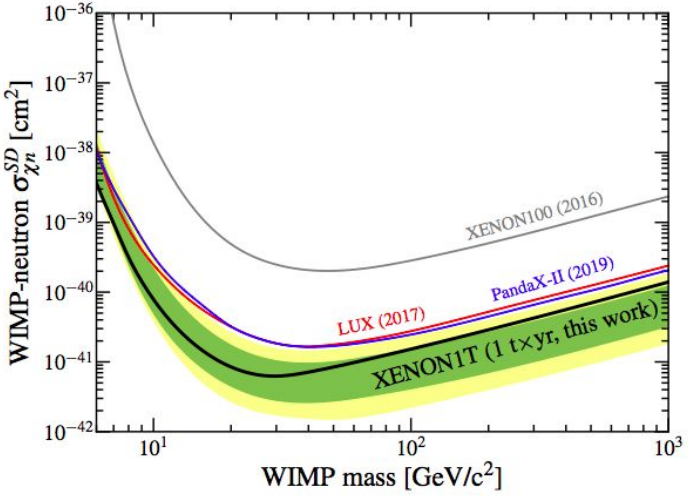


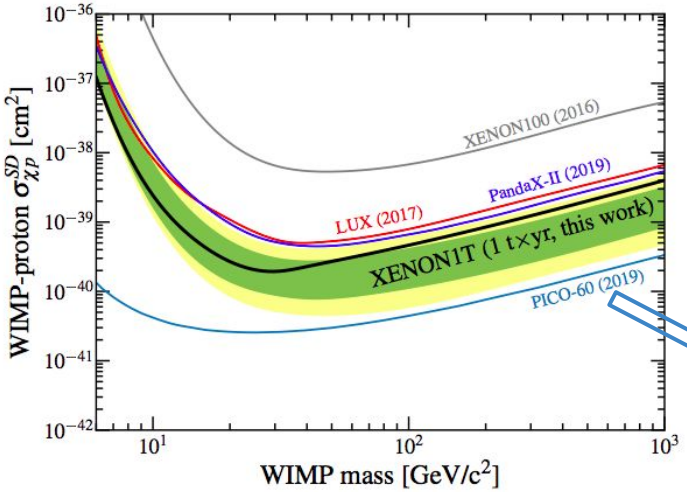


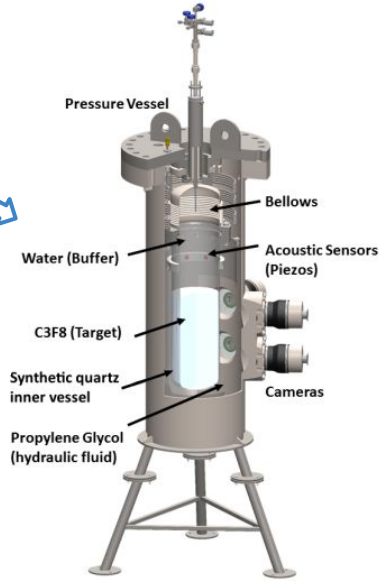




XENON1T @ Gran Sasso (Italy)







arXiv:1902.04031