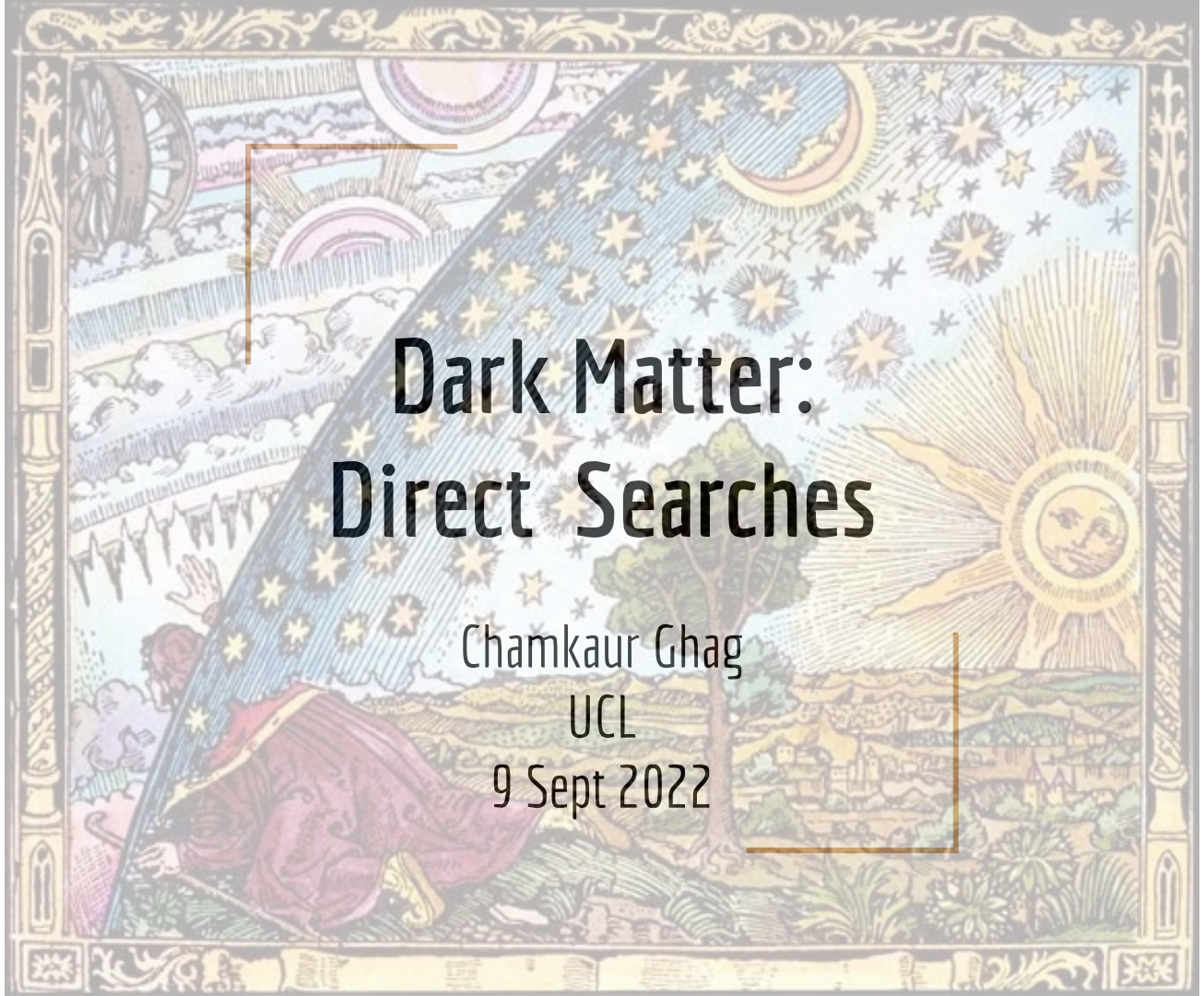
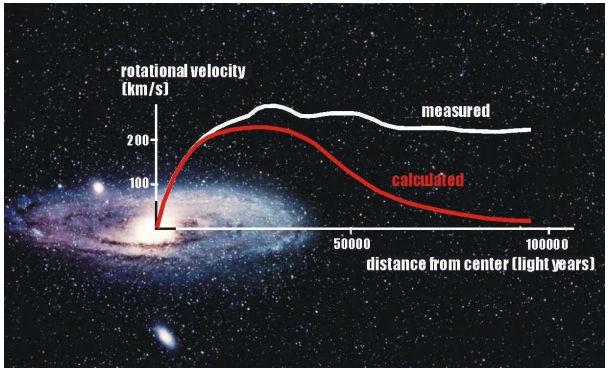
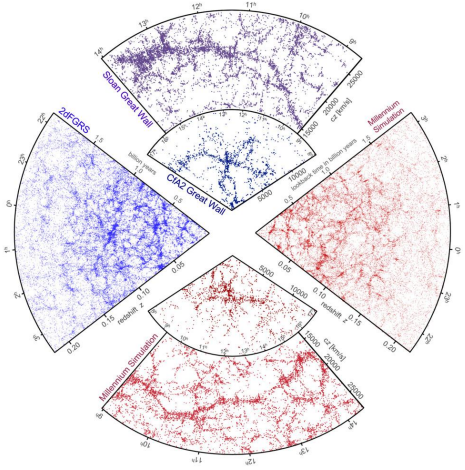


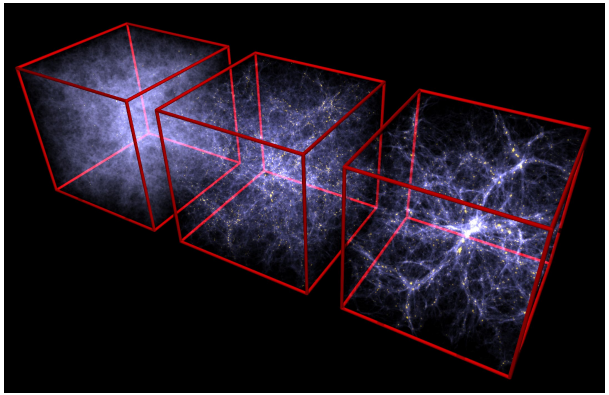
Dark Matter: Direct Searches

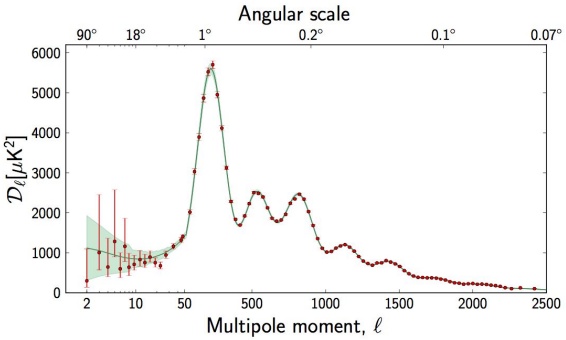
Chamkaur Ghag
UCL
9 Sept 2022

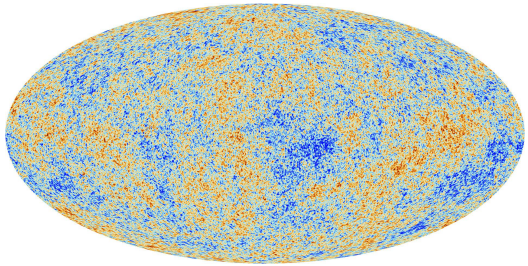
Dark Matter

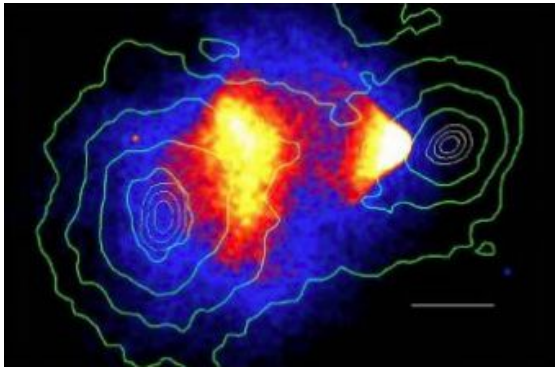

rotational velocity
(km/s)
200
100
measured
calculated
50000
100000
distance from center (light years)


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

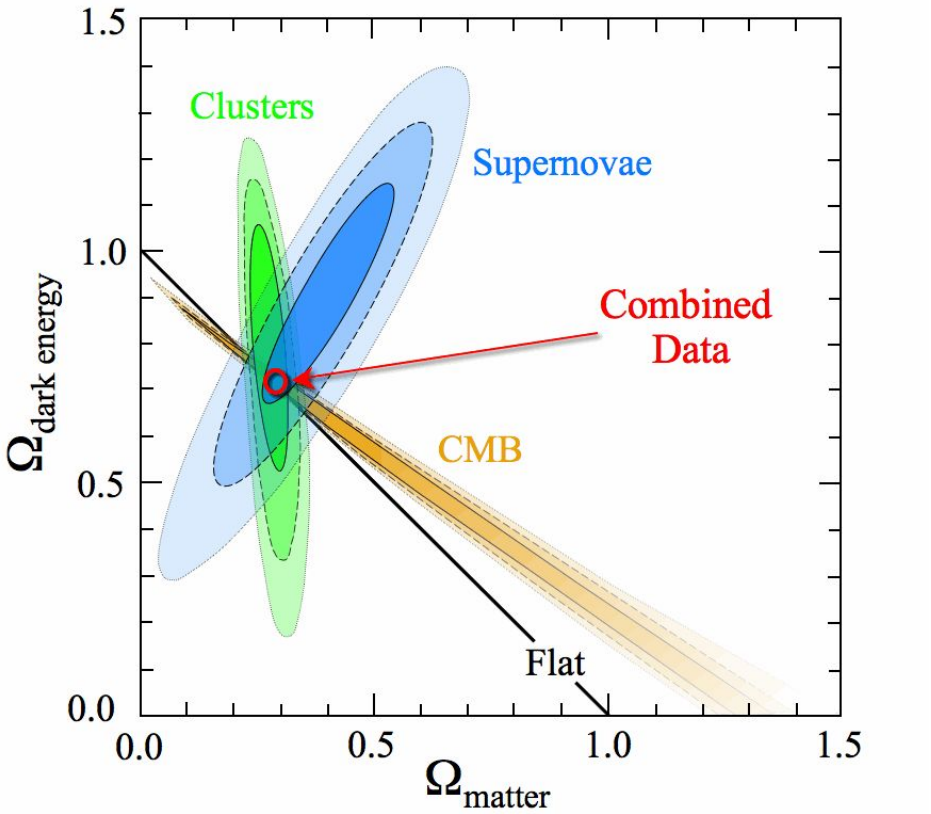


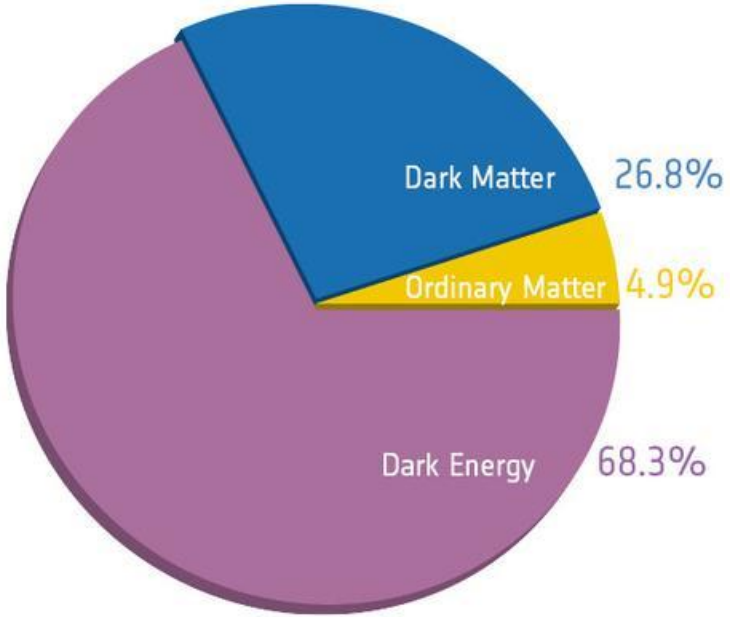

Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
$\mathcal{D}_\ell [\mu K^2]$
6000
5000
4000
3000
2000
1000
0
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ





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%

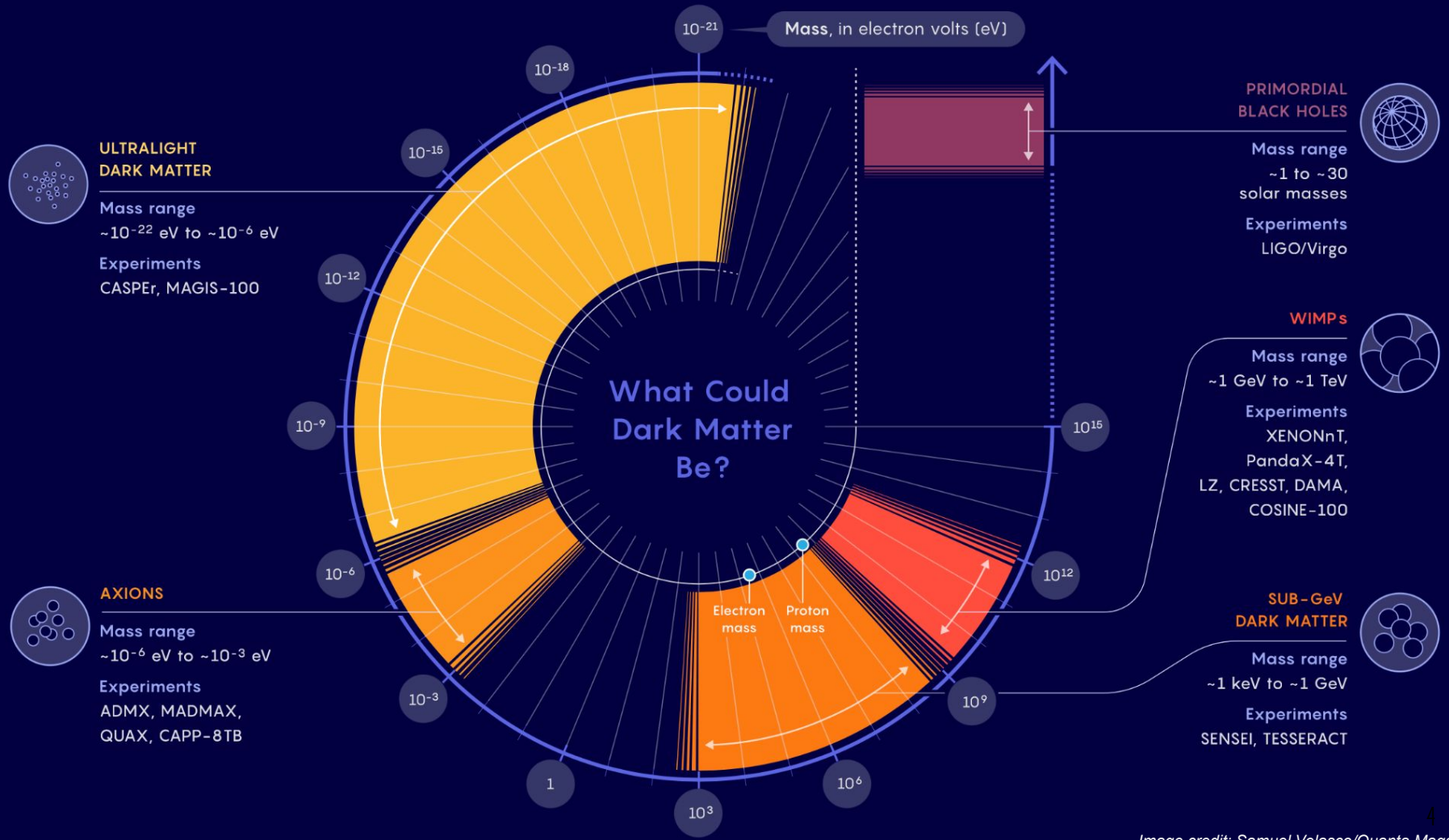
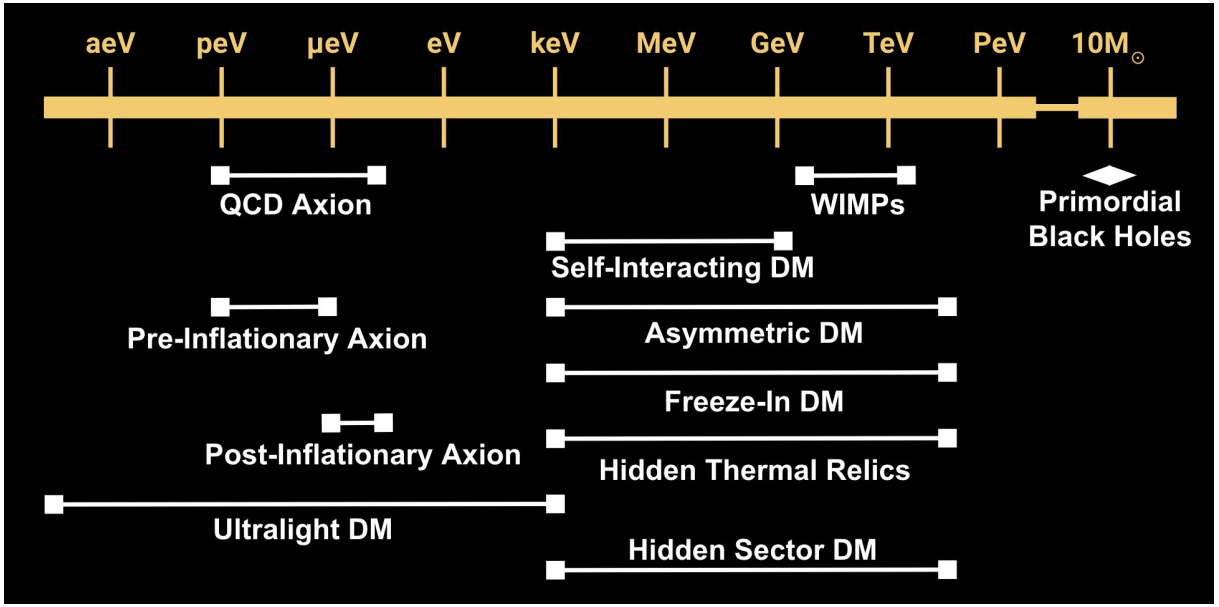
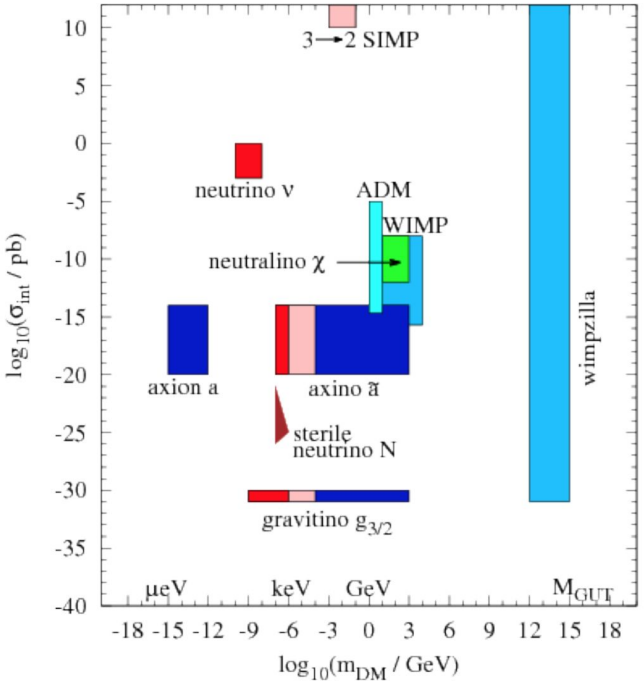
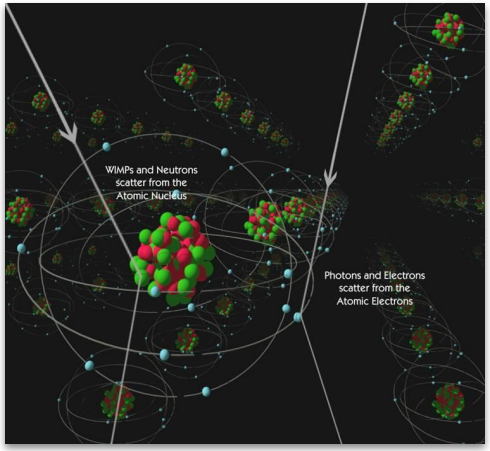
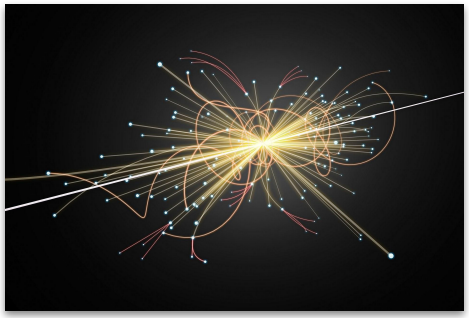


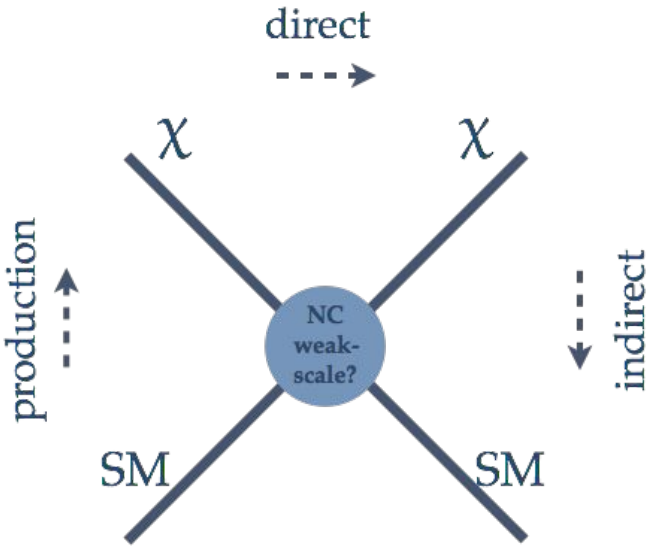
Image credit: Samuel Velasco/Quanta Magazine

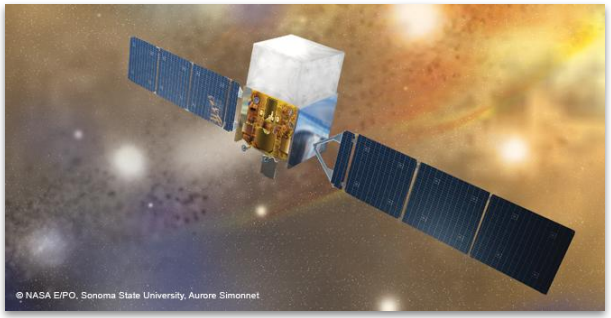

aeV
peV
μeV
eV
keV
MeV
GeV
TeV
PeV
10M⊙
QCD Axion
WIMPs
Primordial Black Holes
Self-Interacting DM
Pre-Inflationary Axion
Asymmetric DM
Freeze-In DM
Post-Inflationary Axion
Hidden Thermal Relics
Ultralight DM
Hidden Sector DM


3→2 SIMP
neutrino ν
ADM
WIMP
neutralino χ
axion a
axino ã
sterile neutrino N
gravitino g3/2
wimpzilla
μeV
keV
GeV
MGUT
log10(σint / pb)
log10(mDM / GeV)

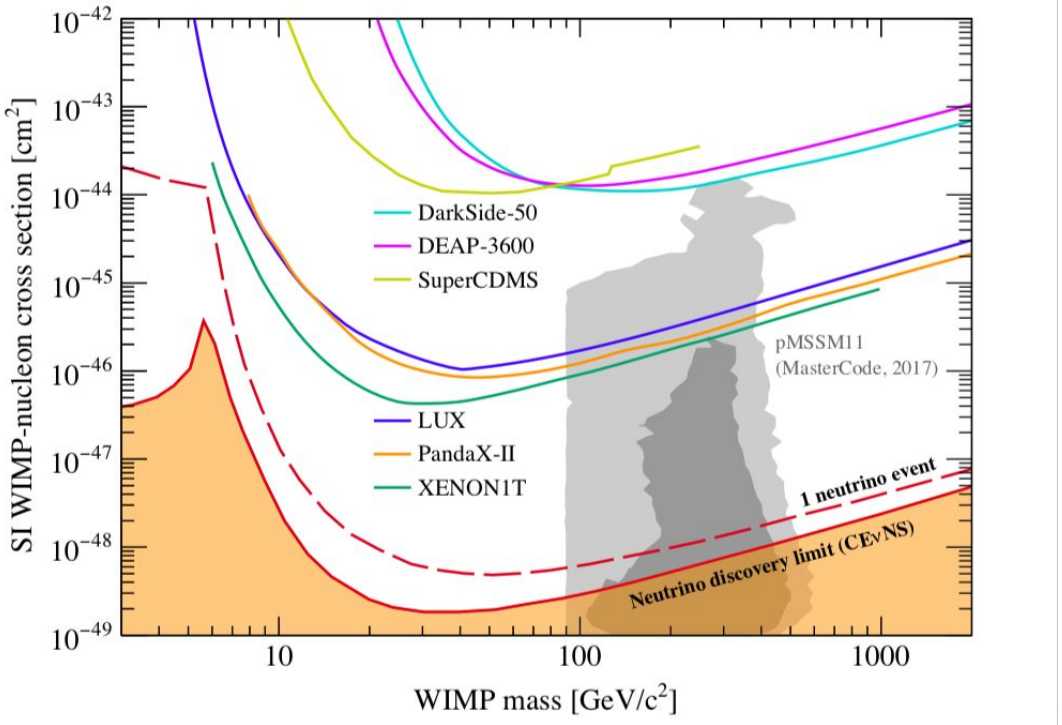

WIMPs and Neutrons
scatter from the
Atomic Nucleus
Photons and Electrons
scatter from the
Atomic Electrons




direct
χ
χ
production
indirect
NC
weak-
scale?
SM
SM


© NASA E/PO, Sonoma State University, Aurore Simonnet

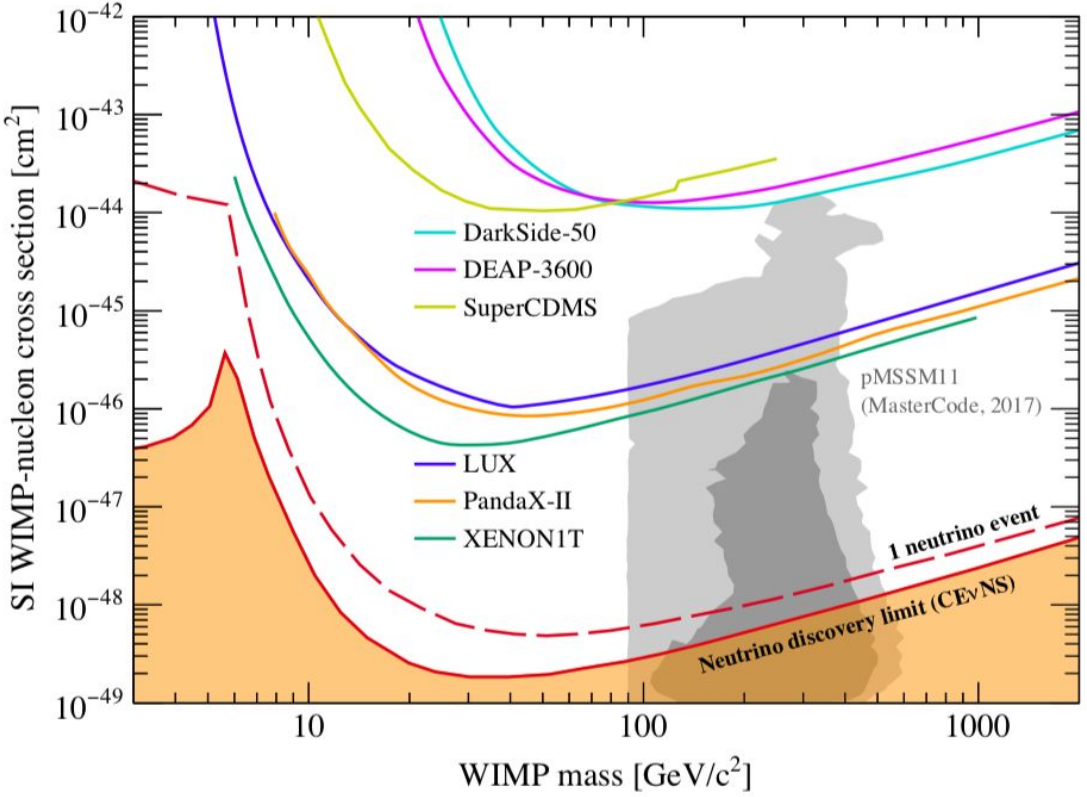
Direct Searches



- **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, …*

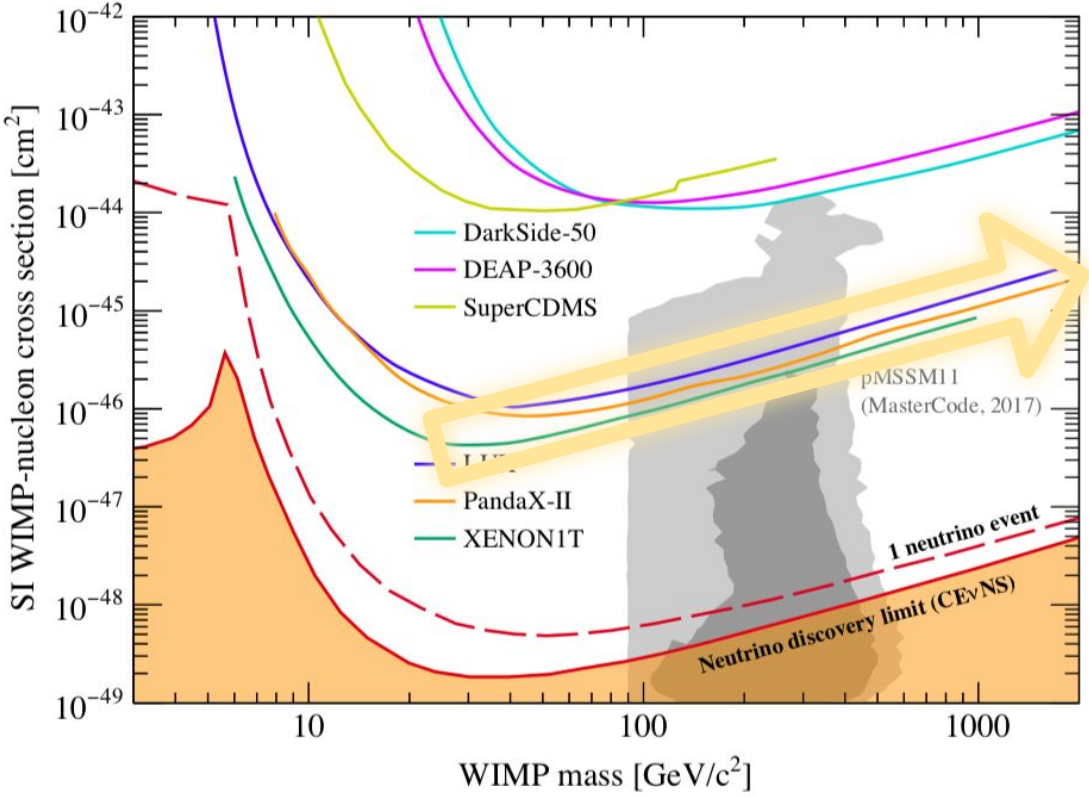
Direct Searches

THRESHOLD & ATOMIC MASS MATTERS
CRYOGENIC DETECTORS



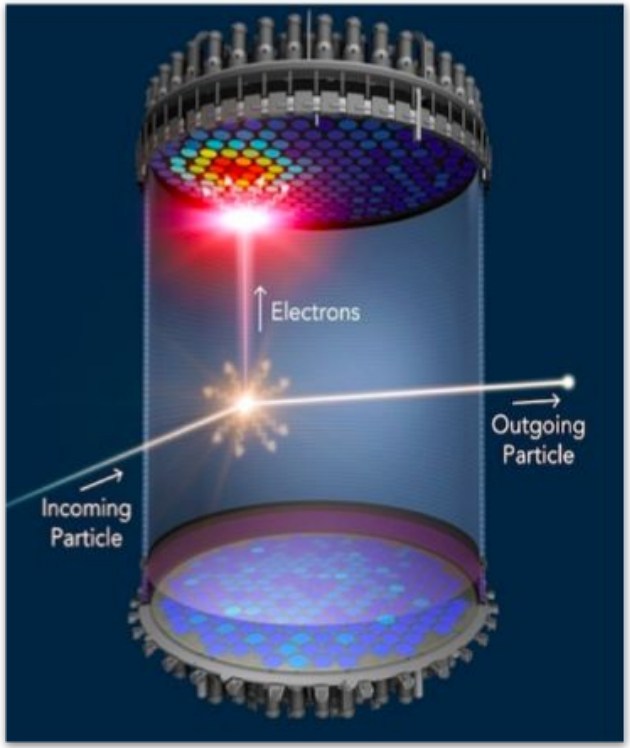
SIZE (x TIME) MATTERS
NOBLE LIQUIDS

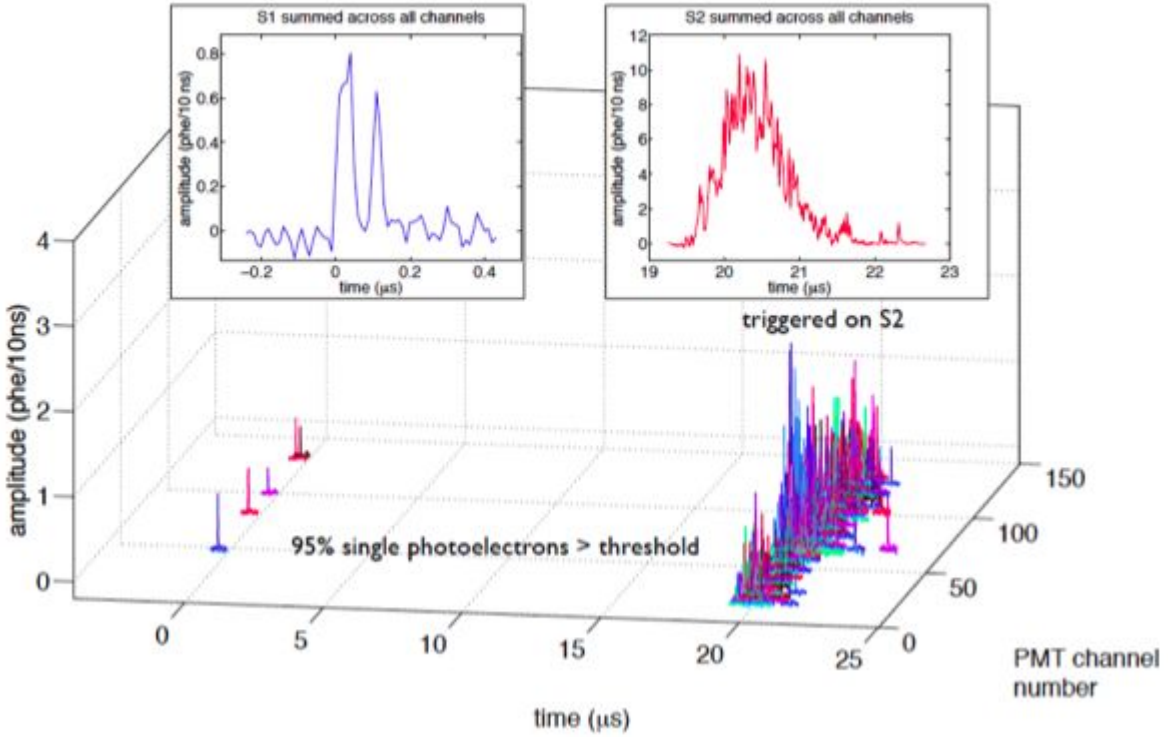
Direct Searches

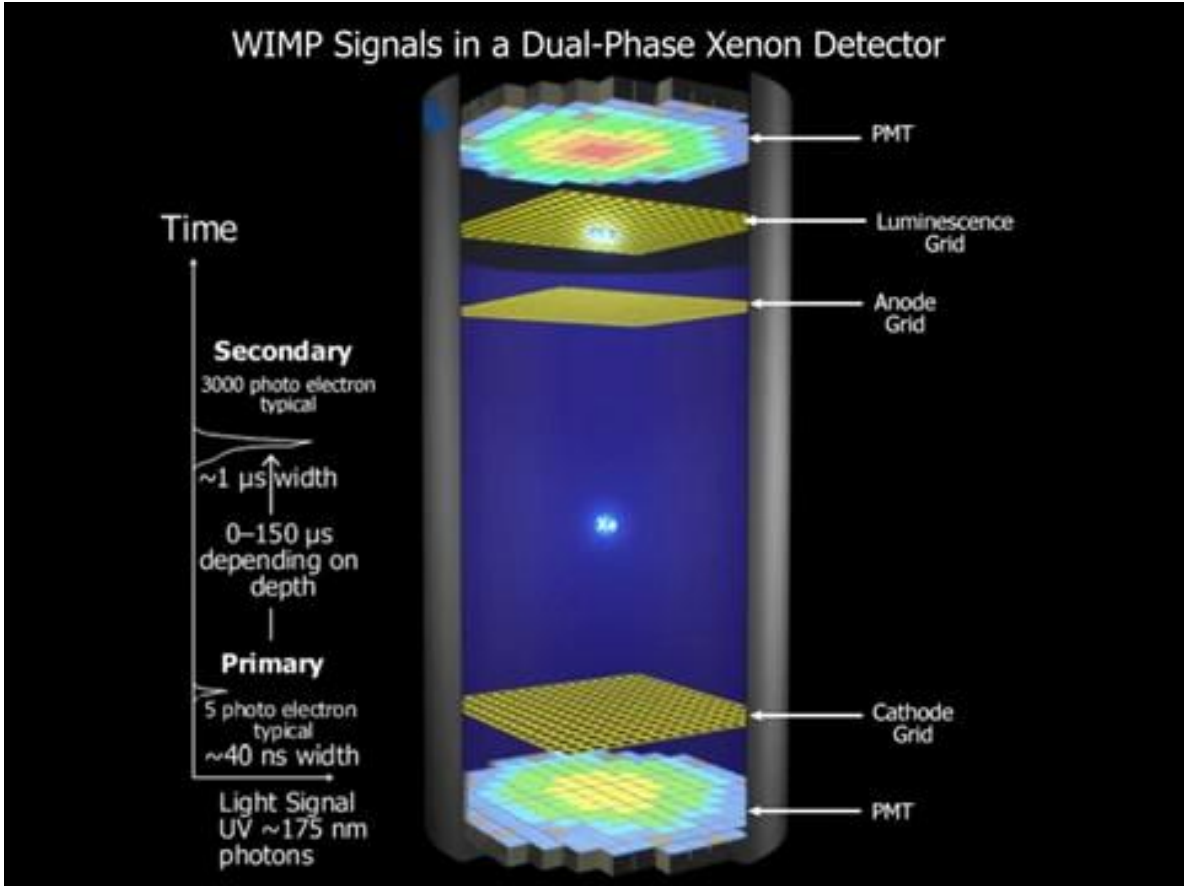


Liquid Xenon
(Time Projection Chambers)

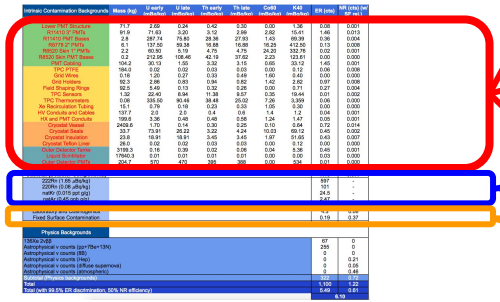
Liquid Xenon TPCs



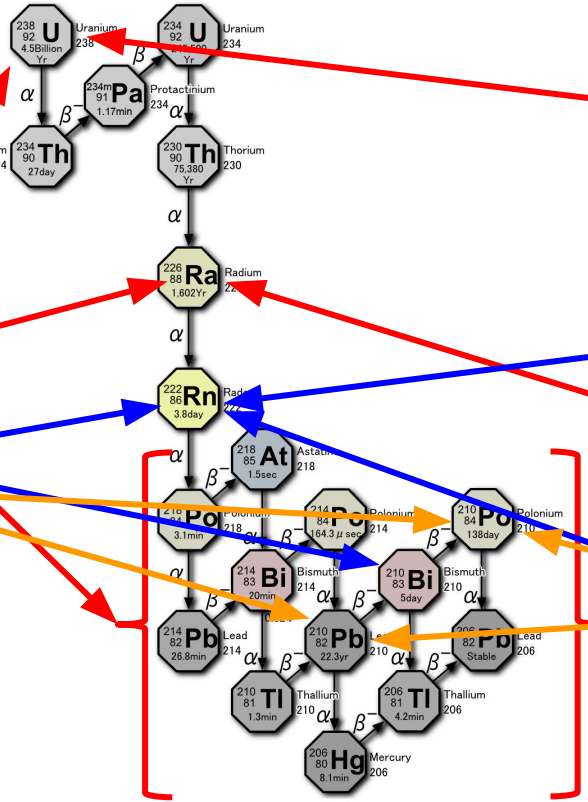


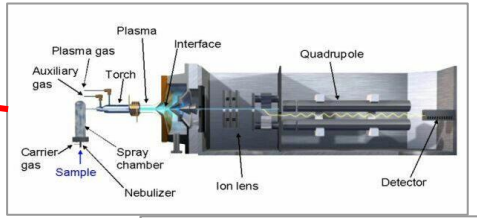

WIMP Signals in a Dual-Phase Xenon Detector
Time
Secondary
3000 photo electron typical
~1 μs width
0–150 μs depending on depth
Primary
5 photo electron typical
~40 ns width
Light Signal
UV ~175 nm photons
PMT
Luminescence Grid
Anode Grid
Xe
Cathode Grid
PMT

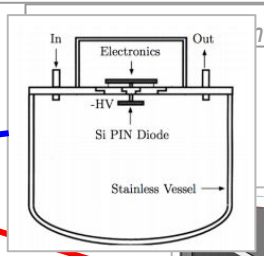
Extremely low-background construction

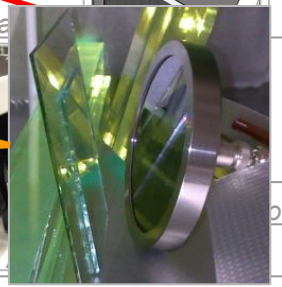


Intrinsic Contamination Backgrounds	Mass (kg)	U early In-Rock/cm²	U late In-Rock/cm²	Th early In-Rock/cm²	Th late In-Rock/cm²	Co60 In-Rock/cm²	K40 In-Rock/cm²	ER (cts)	NR (cts) for 97 keV
Lower FMT Structure	71.7	2.69	0.24	0.42	0.30	0.00	1.36	0.00	0.001
R11410 3" PMTs	91.9	71.63	3.20	5.12	2.99	2.82	15.41	1.46	0.013
R11410 PMT Bases	2.8	287.74	75.80	28.36	27.93	1.43	69.39	0.36	0.004
R8778 2" PMTs	6.1	137.50	59.38	16.88	16.89	16.28	412.50	0.13	0.008
R8520 Skin 1" PMTs	2.2	60.80	5.19	4.75	4.75	24.20	332.76	0.02	0.001
R8520 Skin PMT Bases	0.2	212.95	126.46	42.19	37.62	2.23	123.81	0.00	0.000
PMT Cabling	104.2	30.13	1.93	3.32	3.15	0.65	33.12	1.45	0.001
Cryo Vessel	92.5	5.49	0.13	0.32	0.26	0.00	0.71	0.27	0.004
GXe Wires	0.16	1.20	0.27	0.03	0.48	1.60	0.40	0.00	0.000
Grid Holders	92.3	2.86	0.83	0.94	0.82	1.42	2.82	0.97	0.006
Field Shaping Rings	92.5	5.49	0.13	0.32	0.26	0.00	0.71	0.27	0.004
TPC Sensors	1.32	22.40	8.94	11.38	9.57	0.35	19.44	0.01	0.002
TPC Thermometers	0.08	339.60	90.48	38.48	25.02	7.26	3.359	0.06	0.000
Xe Recirculation Tubing	15.1	0.79	0.18	0.23	0.33	1.05	0.30	0.00	0.000
HV Conduits and Cables	137.7	2.0	2.0	0.4	0.8	1.4	1.2	0.04	0.001
HX and PMT Conduits	169.6	5.36	0.48	0.48	0.58	1.24	1.47	0.05	0.001
Cryostat Vessel	2340.0	0.01	0.01	0.01	0.01	0.00	0.00	0.03	0.000
Cryostat Seals	33.7	73.91	26.22	3.22	4.24	10.33	69.12	0.45	0.002
Cryostat Insulation	23.8	18.91	18.91	3.45	3.45	1.97	51.65	0.43	0.007
Cryostat Teflon Liner	26.0	0.02	0.02	0.03	0.03	0.00	0.12	0.00	0.000
Outer Detector Tanks	3199.3	0.16	0.39	0.02	0.06	0.04	5.36	0.45	0.001
Liquid Scintillator	17640.3	0.01	0.01	0.01	0.01	0.00	0.00	0.03	0.000
Outer Detector PMTs	204.7	870	870	396	396	0.00	634	0.01	0.000
222Rn (1.66 uBq/kg)								597	-
222Rn (0.66 uBq/kg)								161	-
neNi (0.015 ppt gg)								24.5	-
neNi (0.45 ppb gg)								2.47	-
Fixed Surface Contamination								0.19	0.37
Physics Backgrounds									
136Xe 2νββ								67	0
Astrophysical ν counts (pp+7Be+13N)								255	0
Astrophysical ν counts (8B)								0	0
Astrophysical ν counts (Hep)								0	0.21
Astrophysical ν counts (diffuse supernova)								0	0.48
Astrophysical ν counts (atmospheric)								0	0.48
All Physics backgrounds								322	1.17
Total								1,100	1.22
Total (with 99.5% ER discrimination, 50% NR efficiency)								0.49	0.61
									0.10





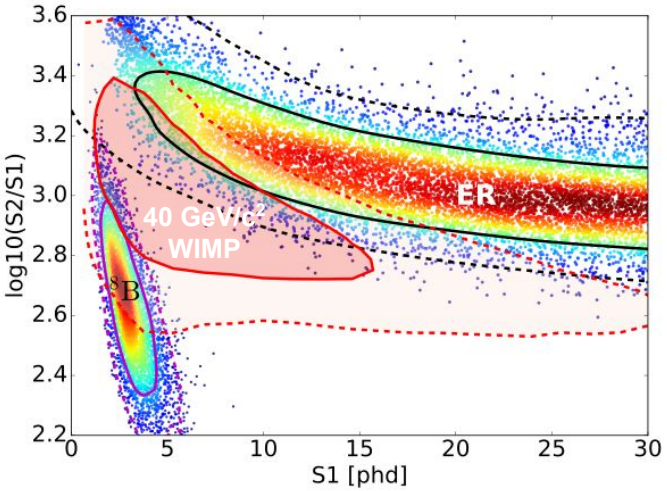


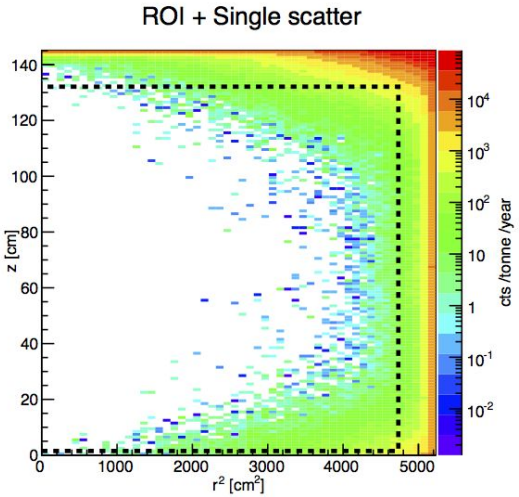


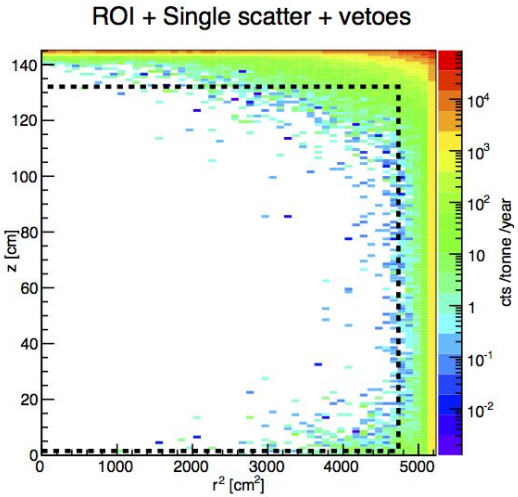
Optical Microscopy

Alpha detectors

Liquid Xenon TPCs





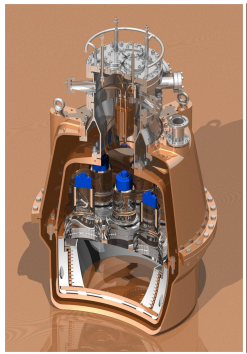
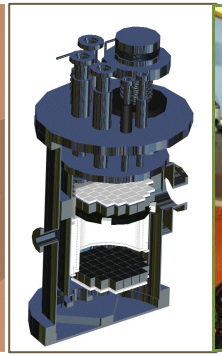
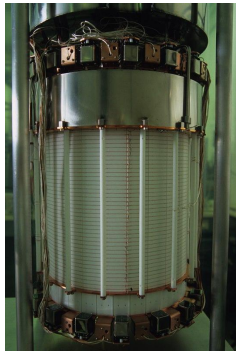
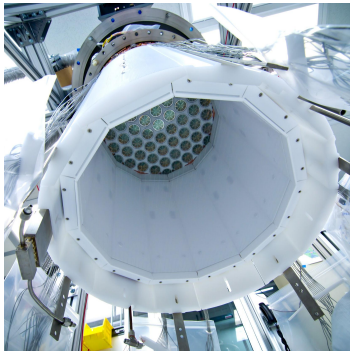


PARTICLE DISCRIMINATION

3D EVENT VERTEX RECONSTRUCTION

ANTI-COINCIDENCE VETOES

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

Liquid Xenon TPCs

PANDAX-II

580 kg
(362 kg)

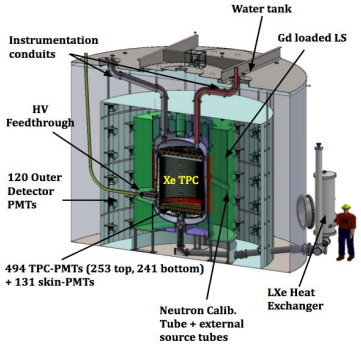
XENON1T

2000 kg
(1,042 kg)

PANDAX-4T

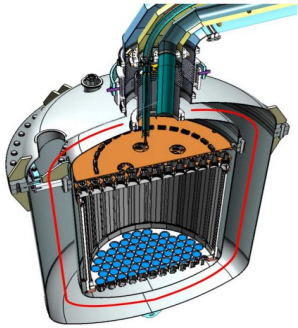
3,700 kg
(2,670 kg)

LZ



7,000 kg
(5,600 kg)

XENONnT

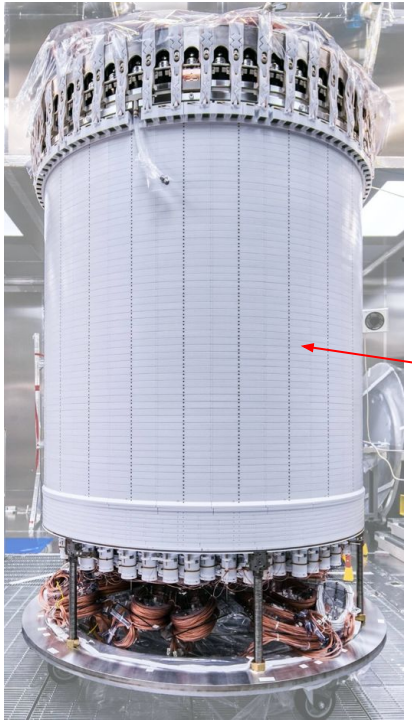


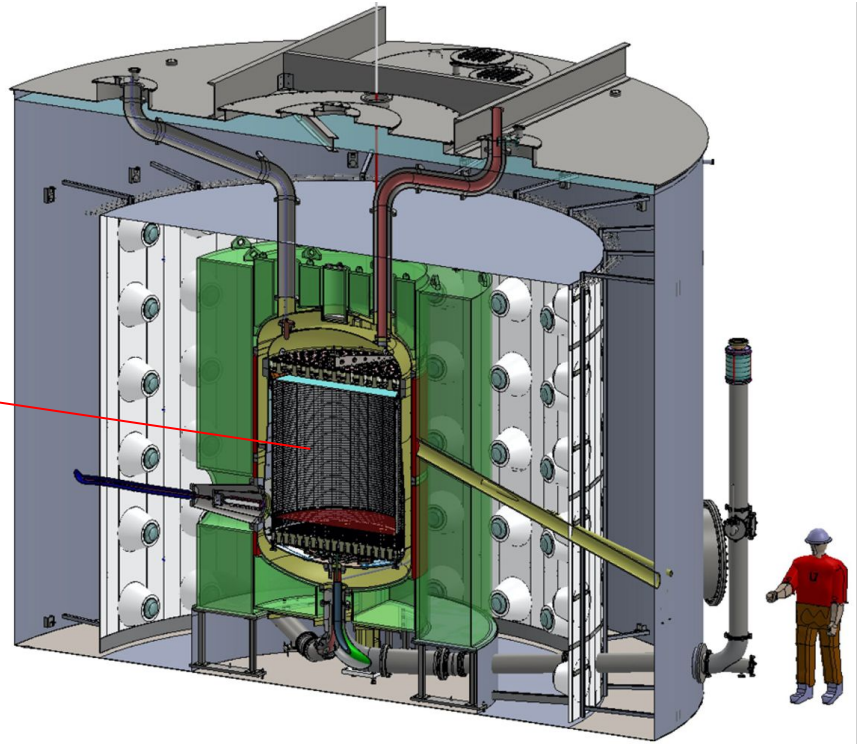
5,900 kg
(4,000 kg)

2016 — 2017 — 2021 — 2022 + 3 live years — 2022 + 5 live years

2.5×10^{-46} cm^2 — 7.7×10^{-47} cm^2 — 3.8×10^{-47} cm^2 — 1.6×10^{-48} cm^2 — 1.6×10^{-48} cm^2

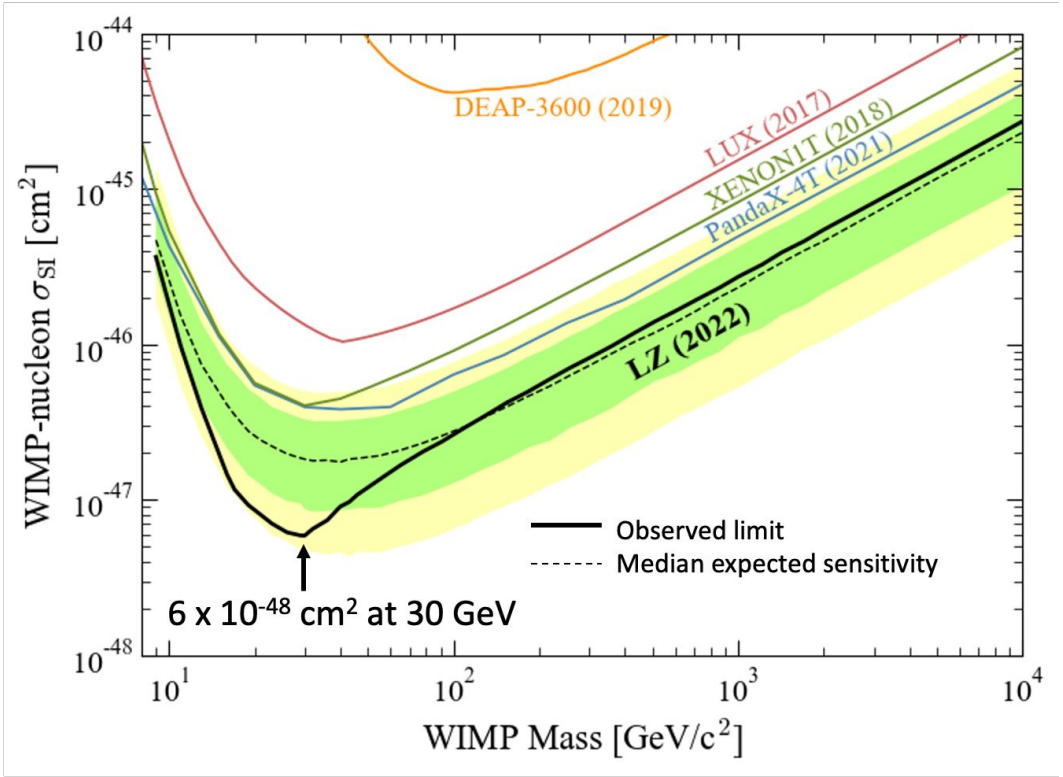
LUX-ZEPLIN (LZ)





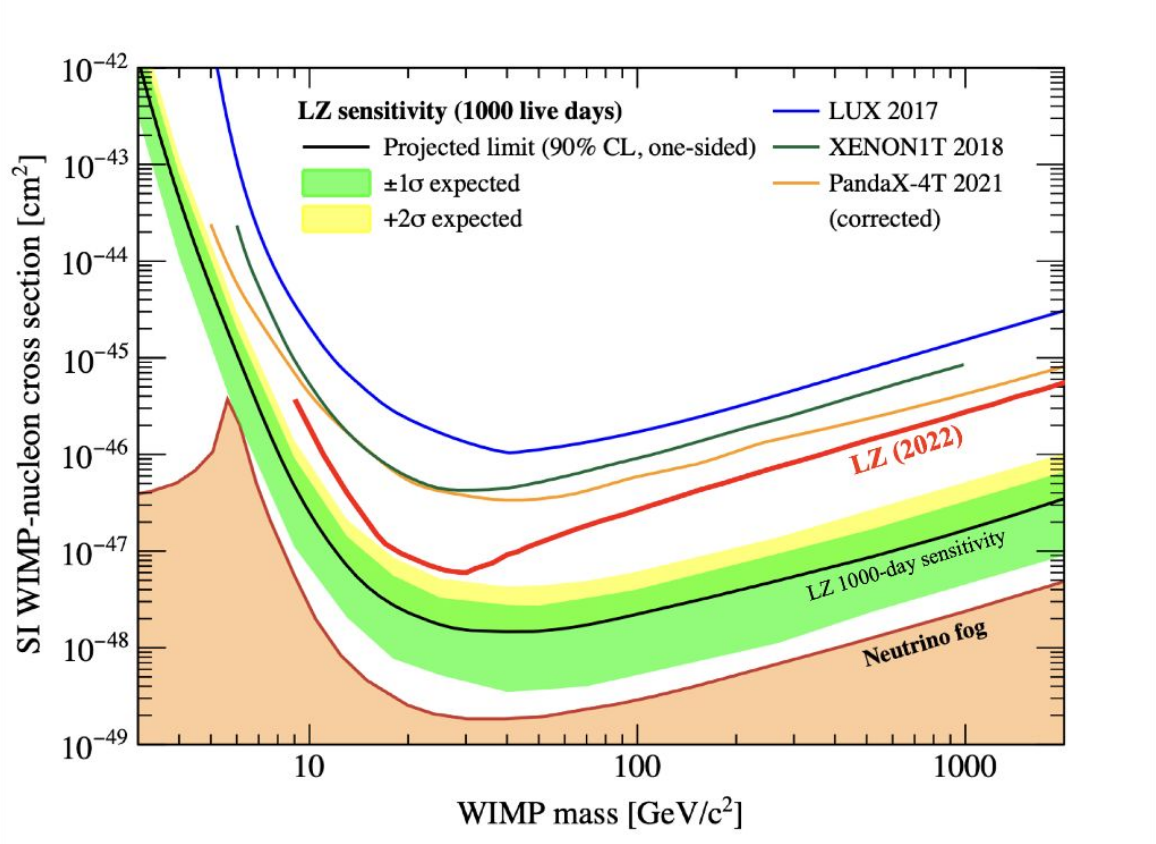
[NIM A953 (2020)163047]

LZ: First Results!



https://arxiv.org/abs/2207.03764

LUX-ZEPLIN (LZ): Sensitivity projection (1000 day)

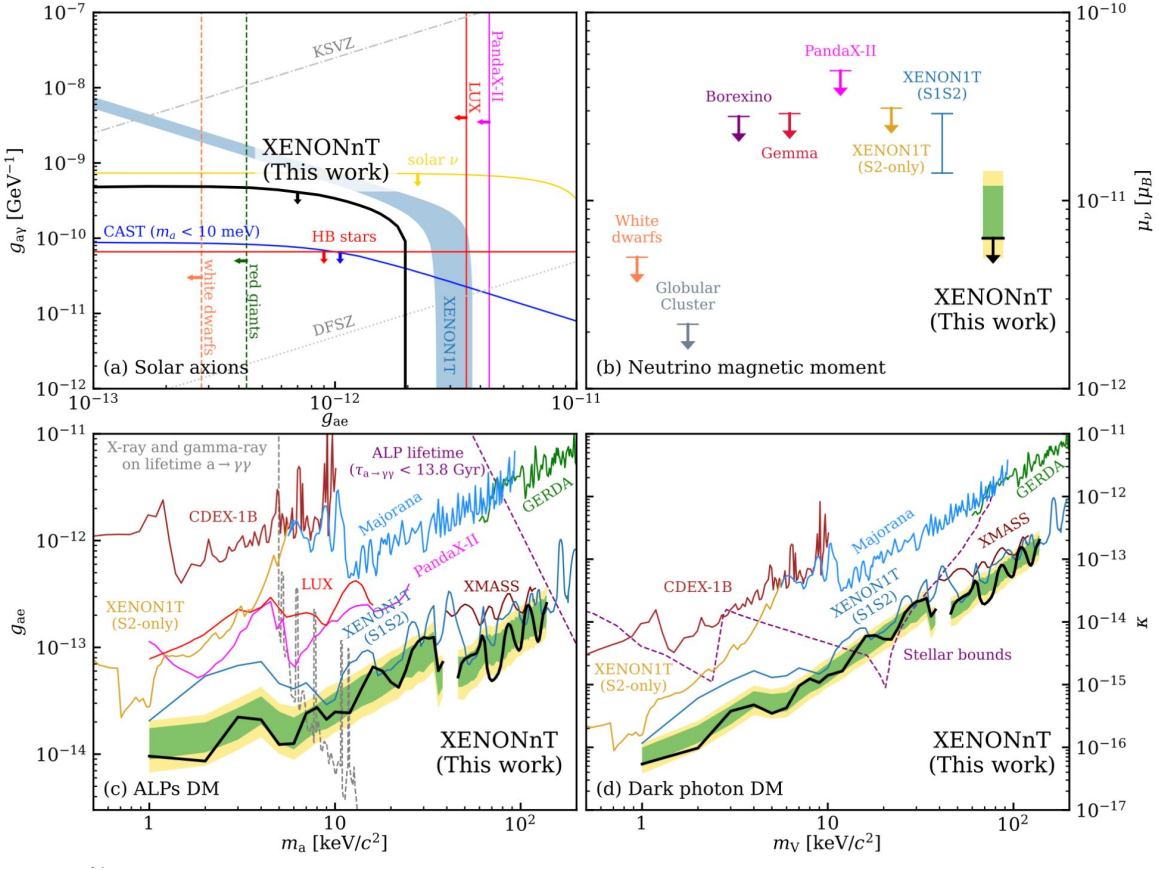


XENONnT

Background rate: 16.1 +/- 1.3 events/(tonne.year.keV)

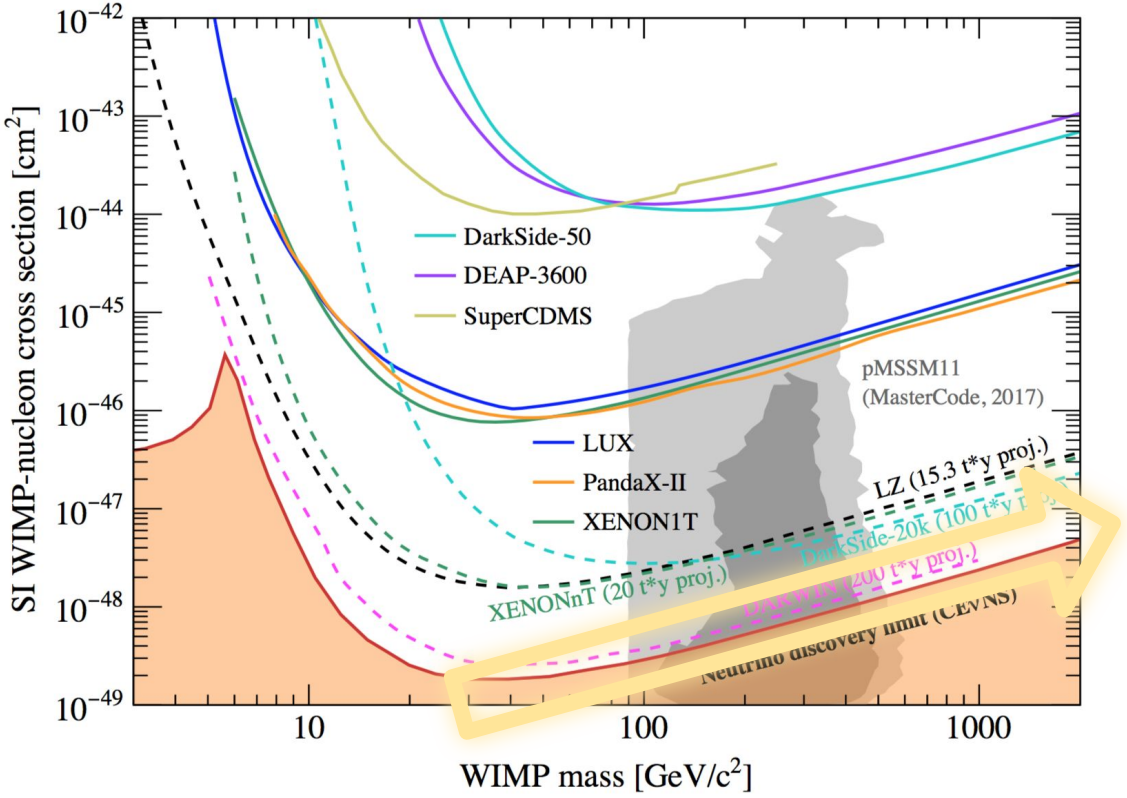
arXiv:2207.11330

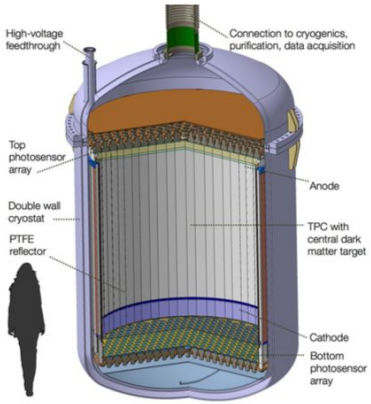
XENONnT: First Results (Electron Recoils)



arXiv:2207.11330

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

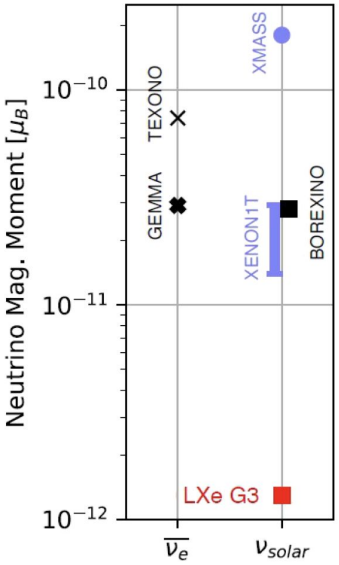


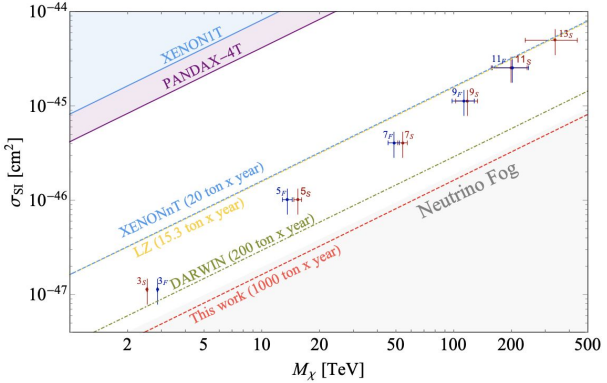


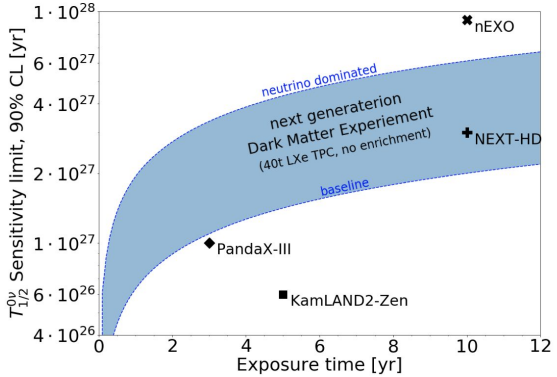
Generation-3

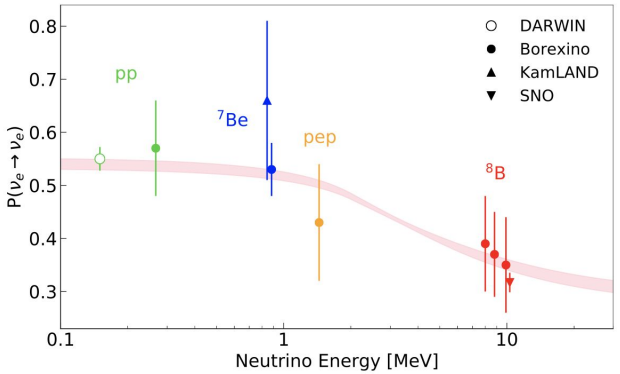
‘Generation-3’ (G3)

- High stats confirmation/measurement ***or*** explore remaining ‘accessible’ WIMPs
- Size + low-background + NR + ER = Much science beyond standard WIMPs
  - *Neutrinoless double beta decay; low-energy solar neutrino flux; solar axions; galactic axion like particles: supernovae; sterile neutrinos; …*







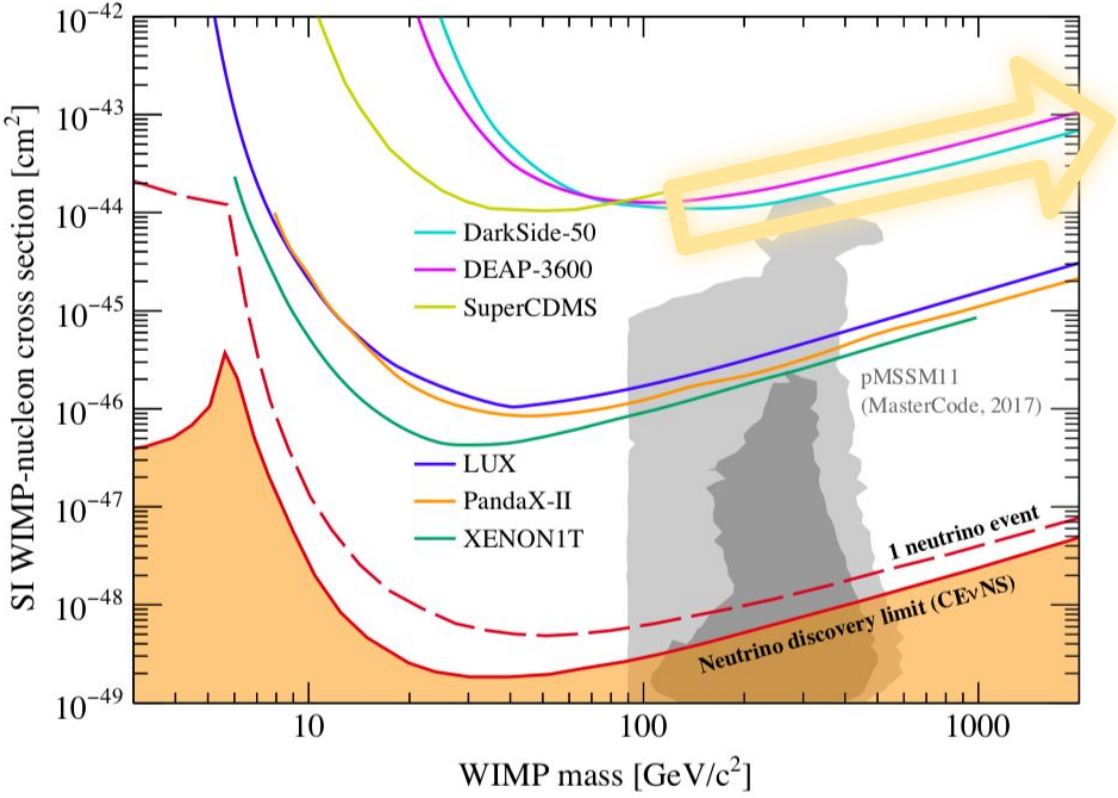


G3 white paper: arXiv:2203.02309

The **XLZD** Consortium

- MOU between LZ, XENON, DARWIN to construct G3 (~600 scientists)
- G3 white paper: *arxiv:2203.02309* (~700 authors)
- See xlzd.org for more

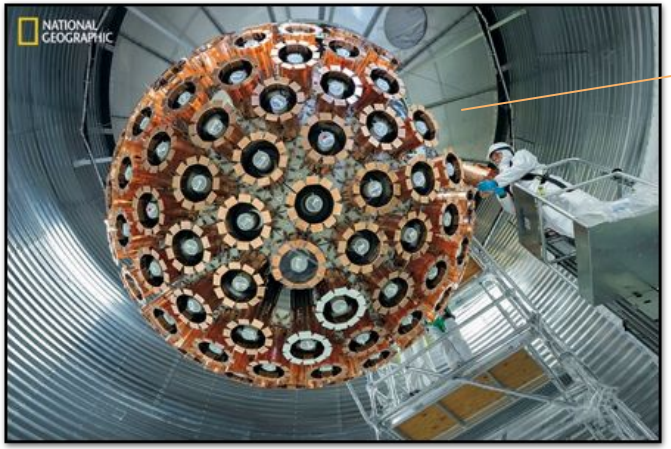
Direct Searches

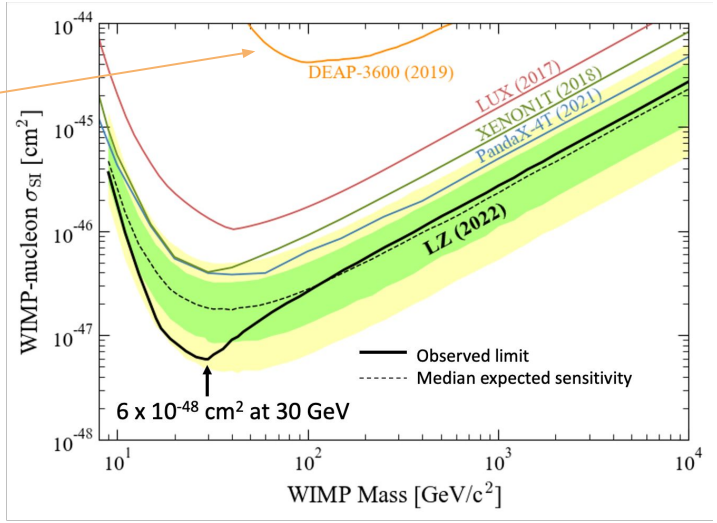


Liquid Argon

DEAP-3600 @ SNOLab (Canada)

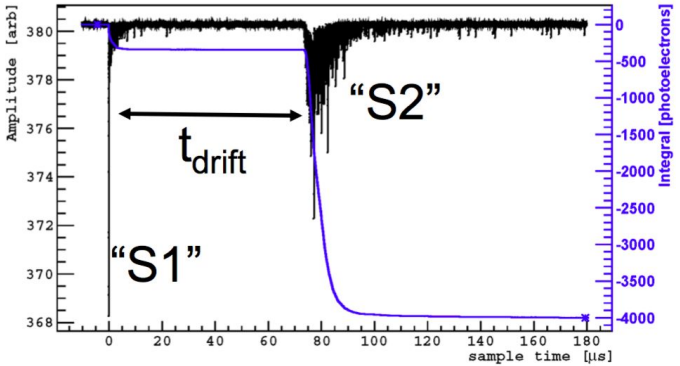
- Single phase LAr, 3.6 Ton (1 Ton fiducial); 255 8” PMTs
- Pulse shape discrimination (PSD) for particle ID
- *E_{th} ~ 39 keV determined by PSD (^{39}Ar β-decay, 1 Bq/kg, Q-value ~550 keV)*
- Promising initial (4.4 day) run but latest result suffers from ‘neck backgrounds’
  - 231 day exposure, S.I. limit above *3.9 x 10^{-45} cm^2* (2019)
  - Expect some improvement from PLR analysis (ongoing)

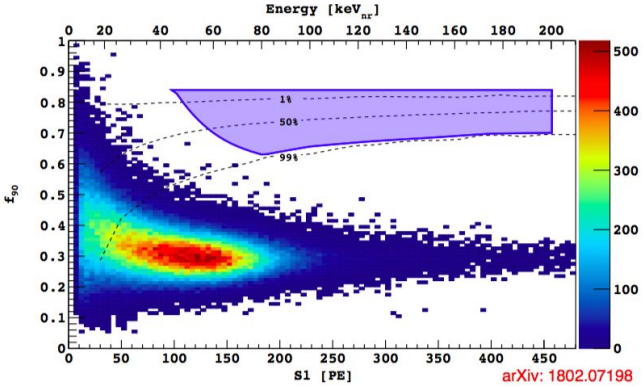


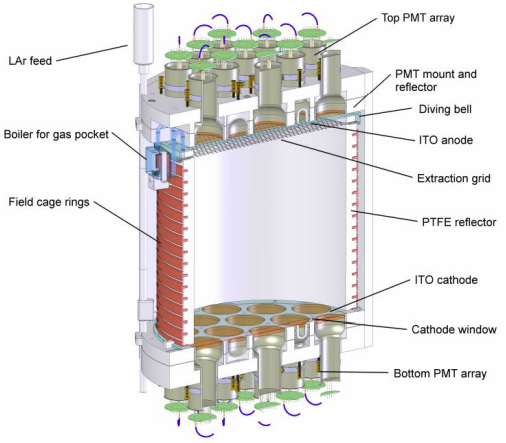


DarkSide-50 @ Gran Sasso (Italy)

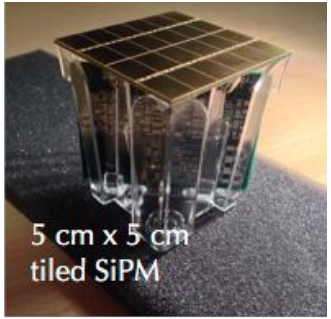
- 50 kg LAr TPC
  - *Installed 2012*
  - *37 kg fiducial volume*
  - *PSD with S1, S2 signals for position*
  - *TPB wavelength shifter; ITO on quartz as electrodes*
  - *First use of UAr (^{39}Ar depleted)*



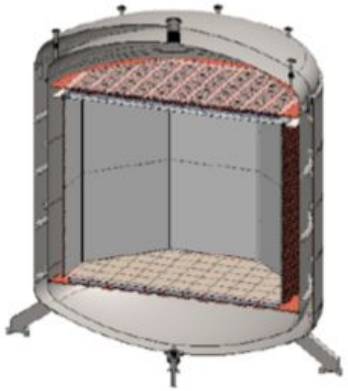


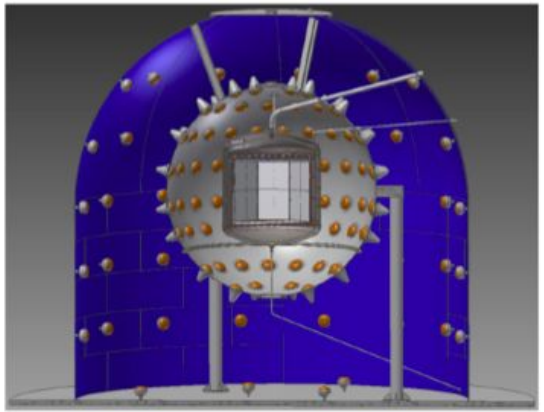


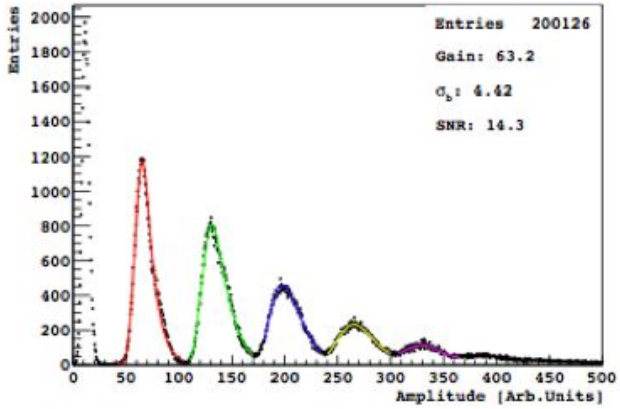
DARKSIDE-20k @ Gran Sasso (Italy)



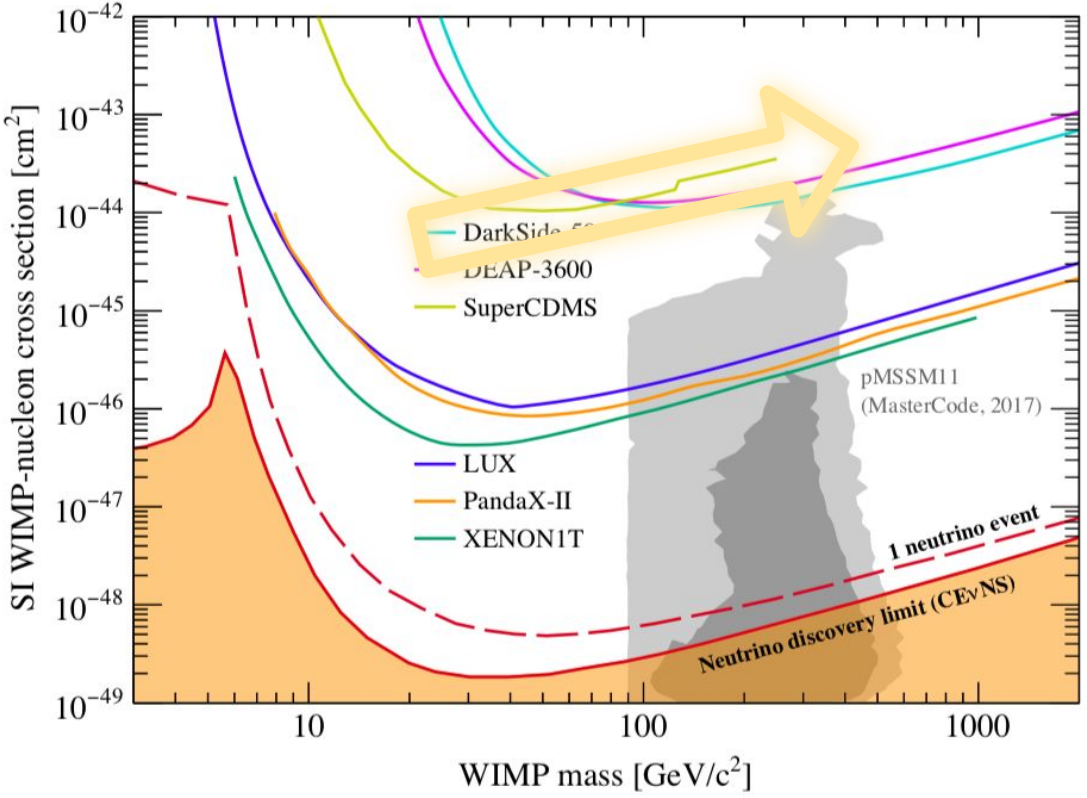
- **DarkSide-20k**
  - *>400x scale-up from DarkSide-50 for 23 ton LAr 2-phase TPC*
  - *Design employs large-area cryogenic SiPMs for light readout*
  - *Ops. planned from ~2025; 5+ year exposure*
  - *Alternative target useful for (high-mass) WIMP confirmation*
    - *Sensitivity comparable to LZ/XENONnT at high masses*







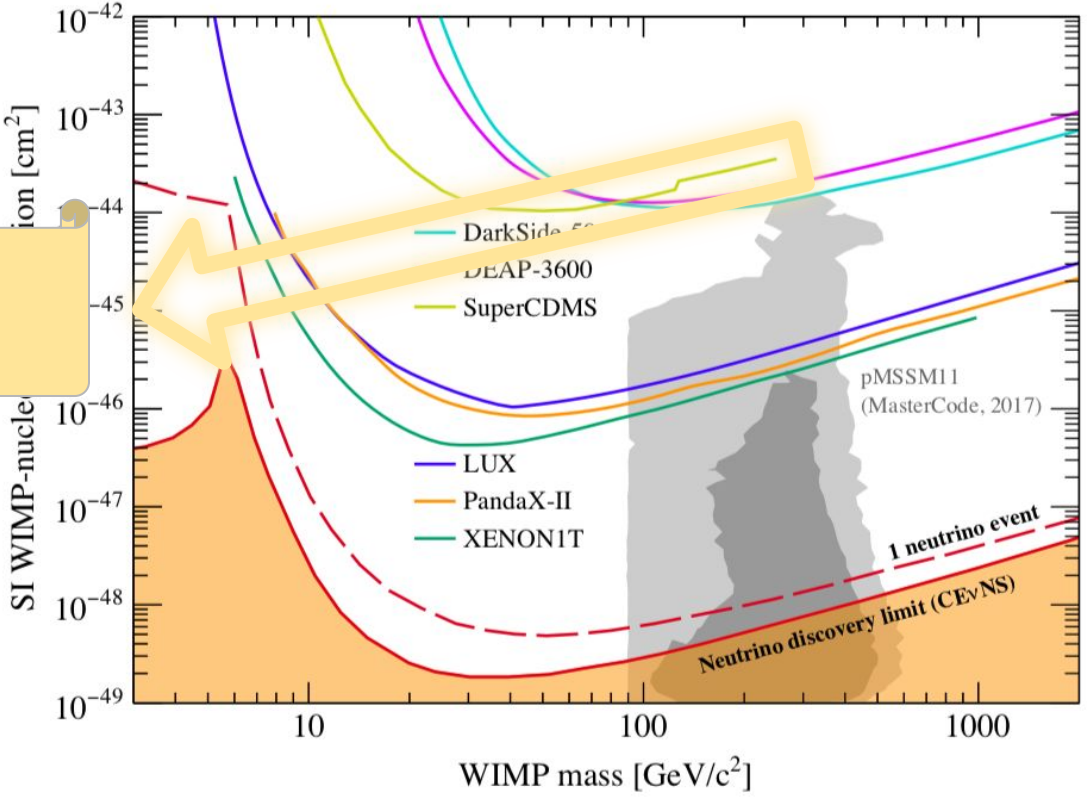
Direct Searches



Crystals

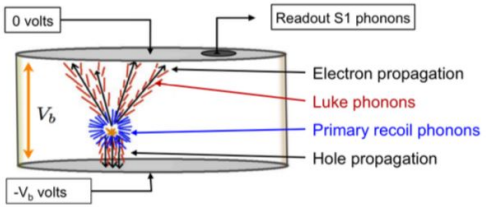
Direct Searches

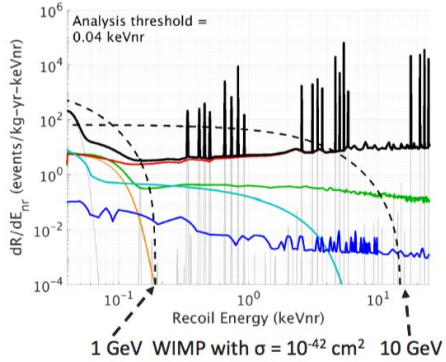
Crystals

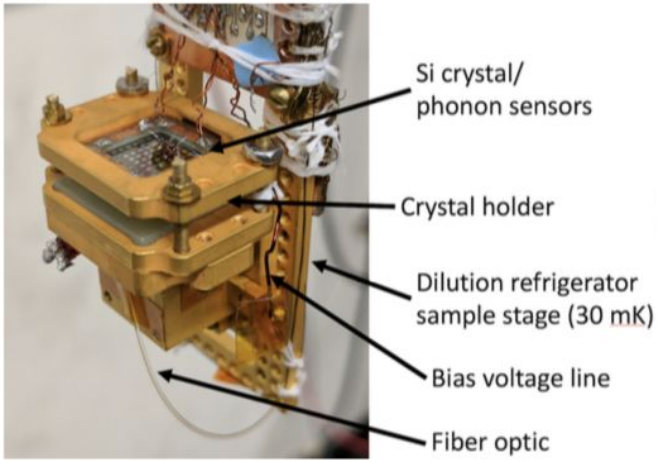


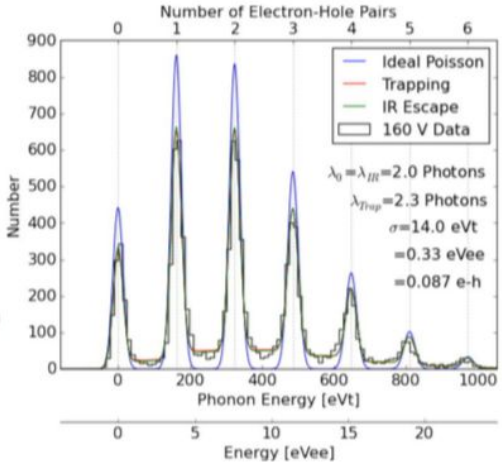
SuperCDMS @ SNOLab (Canada)

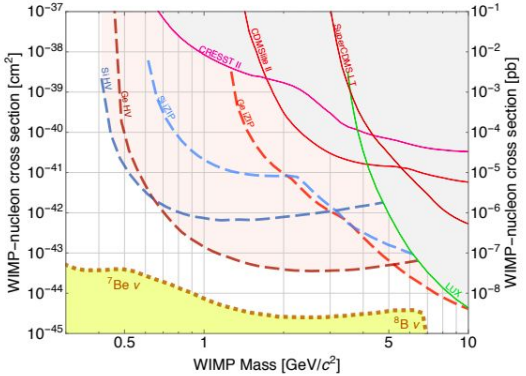
- 1.4 kg Ge and 0.6 kg Si crystals
- Targeting <10 GeV/c^2 mass range
  - *Sensitivity to sub-GeV dark matter*
- Band gap in Ge is 0.7 eV, Si is 1.1 eV
  - *Energy thresholds in tens of eV range*
- Operation at SNOLab from 2023/24



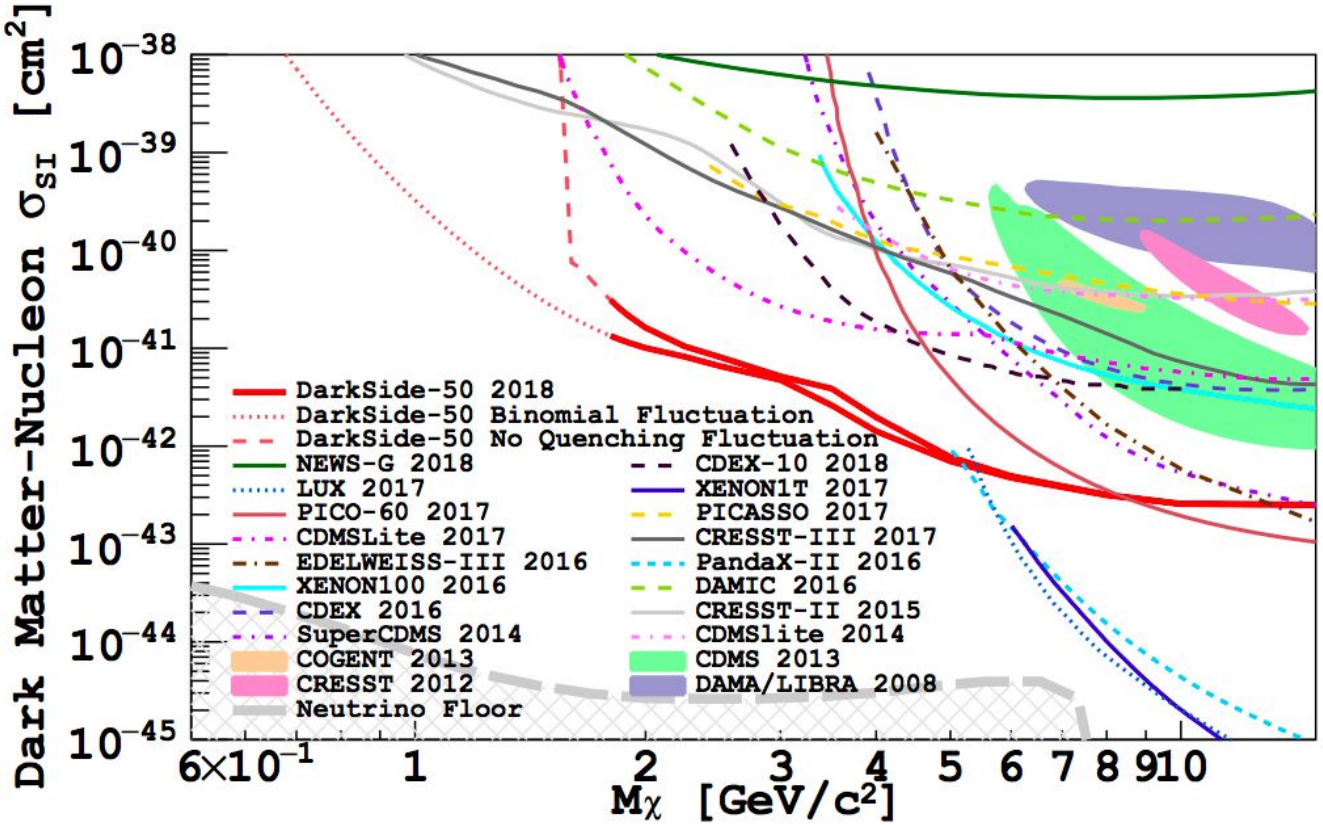






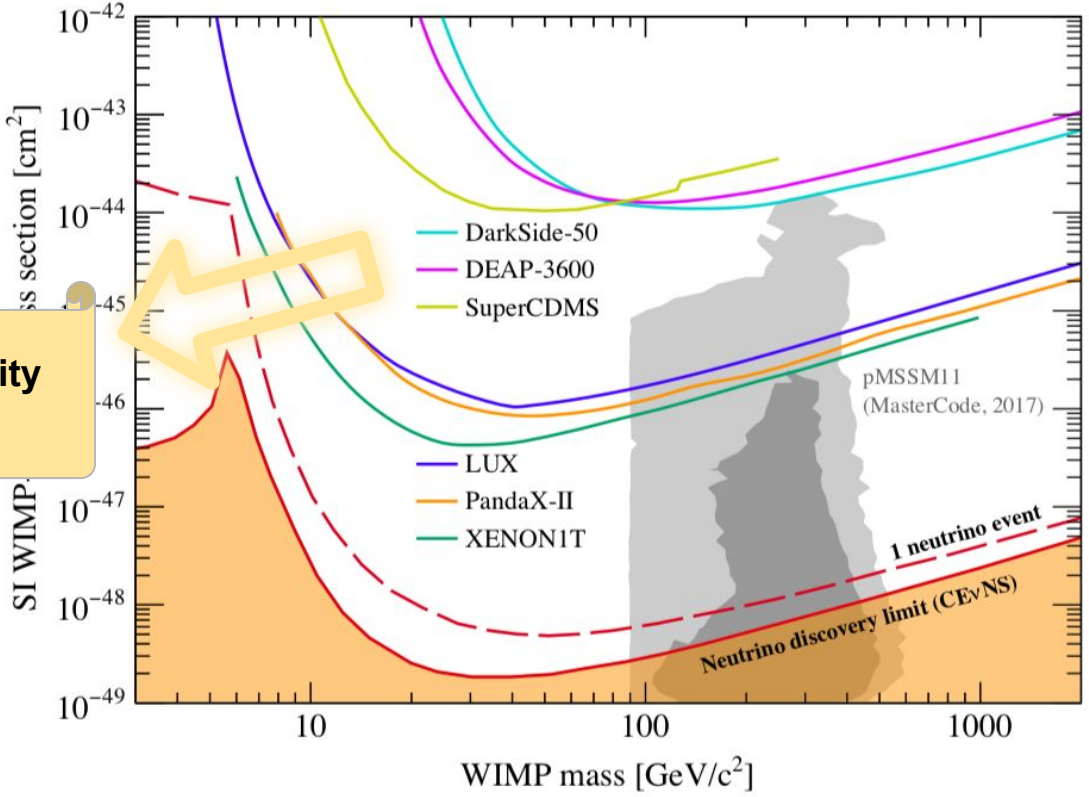


“Low Mass” WIMP searches

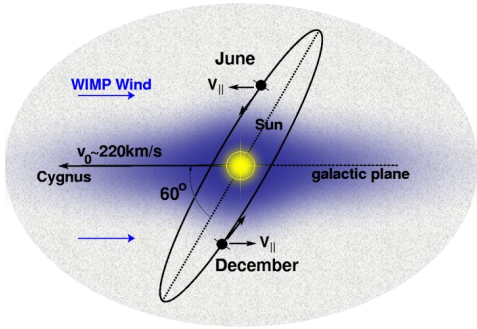


Direct Searches

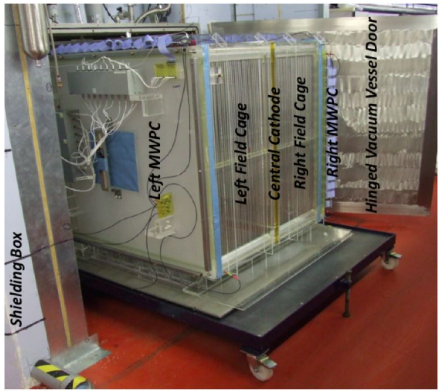
Directionality R&D

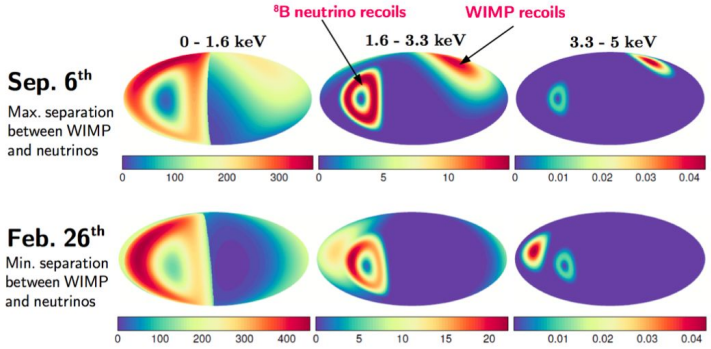


CYGNO (Directional R&D)

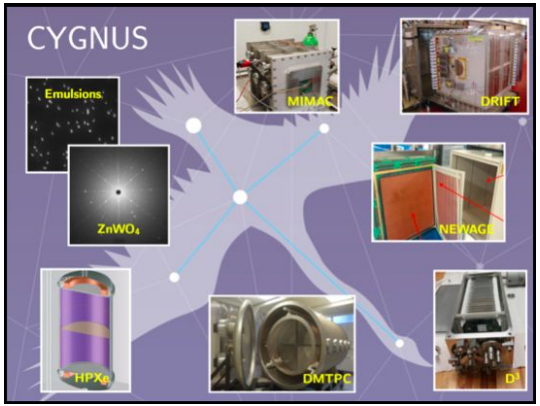


- **DRIFT**: Directionality pioneer based at Boulby
  - *DRIFT-IIe testing large area thick GEM readouts*
- **CYGNUS**: International collaboration of directionality experiments
  - *25 institutes (Australia, China, Italy, Japan, UK, US)*
  - *Negative ion SF_6+He target*
  - *Distributed network of 10 m^3 detectors at different latitudes*
  - *New sites at Stawell (Australia), Boulby (UK), Gran Sasso (Italy) for CYGNUS-UNDER 1m^3 test*

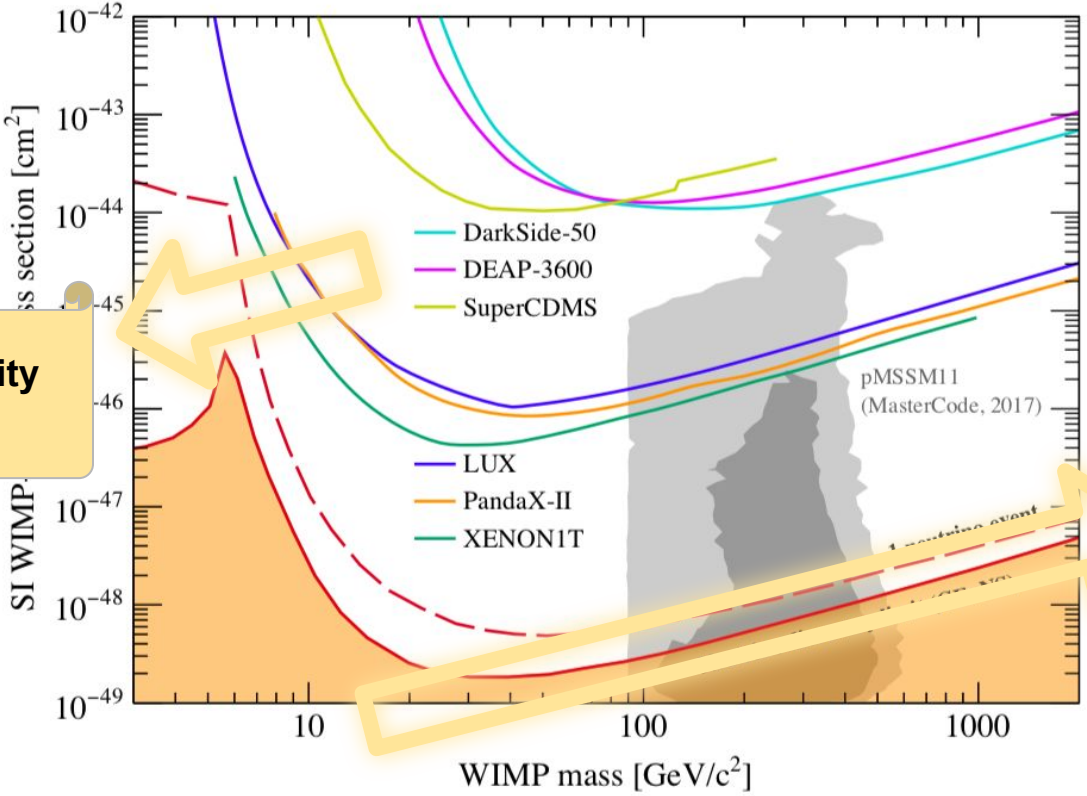




CAJ O'Hare et. al. Phys. Rev. D 92, 063518 (2015)



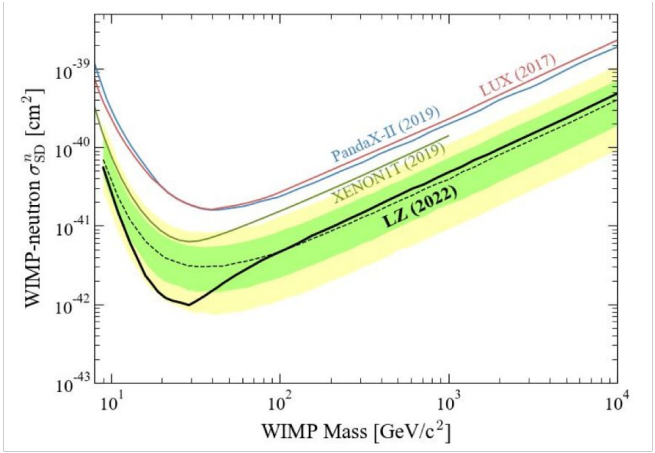
Direct Searches

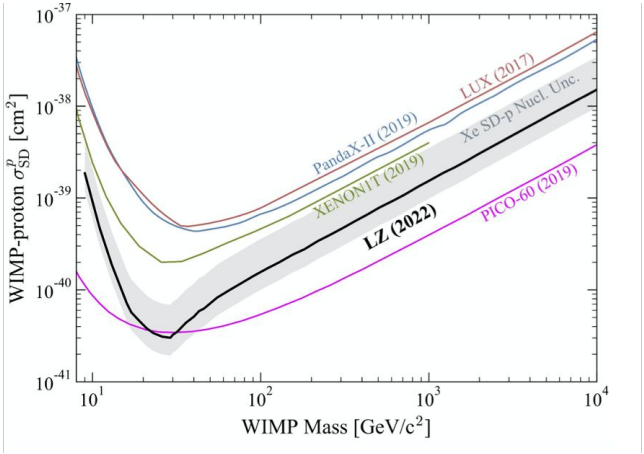


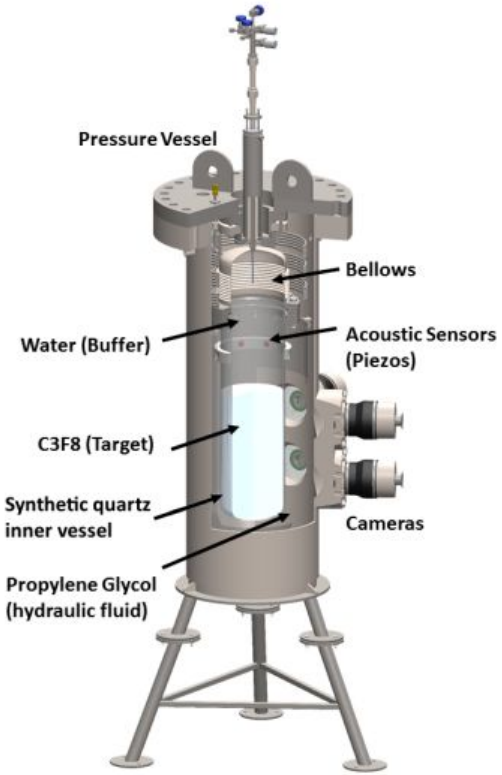
Directionality R&D

Directionality useful here too!

Spin-dependent couplings







PICO-60L

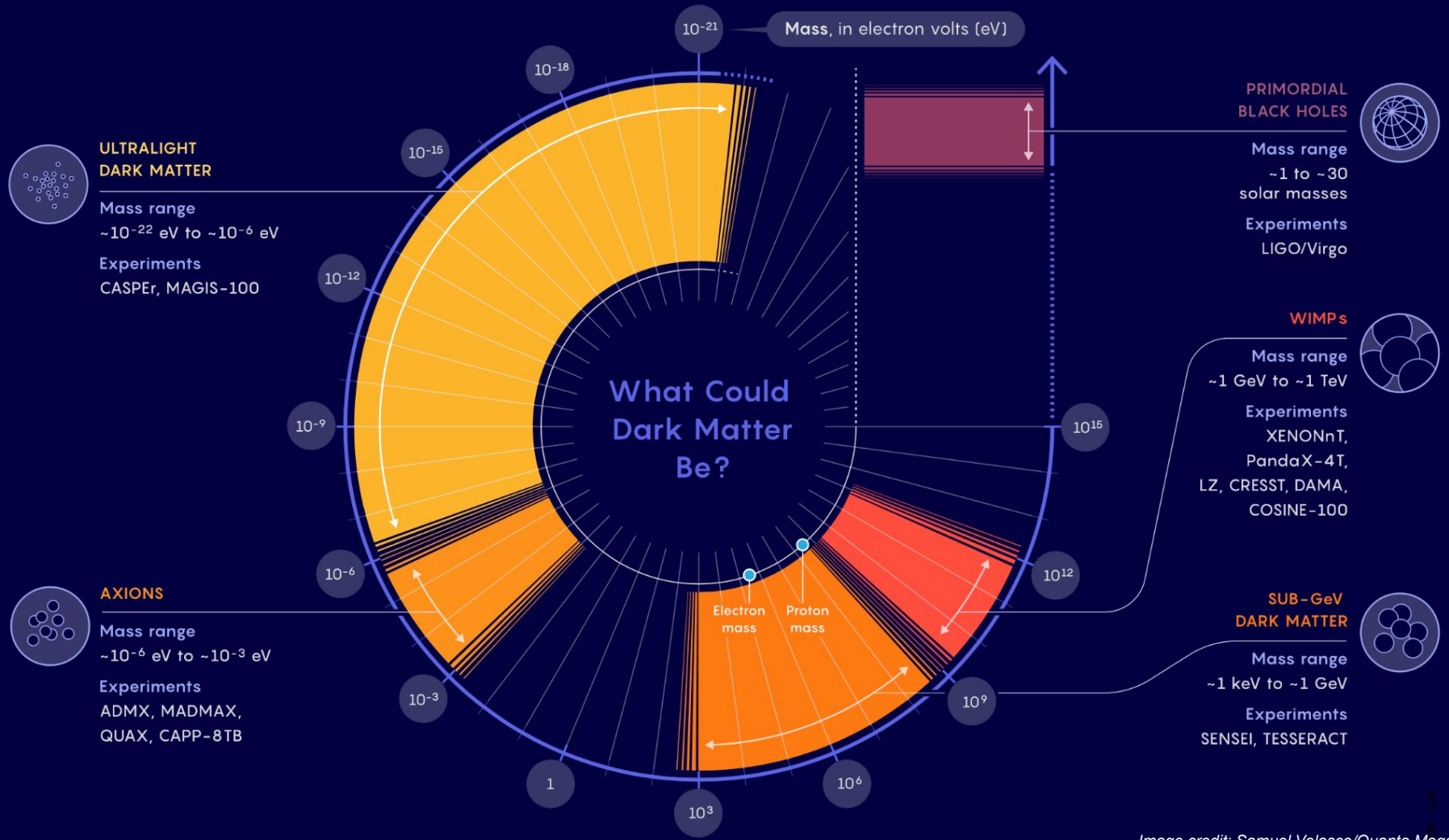
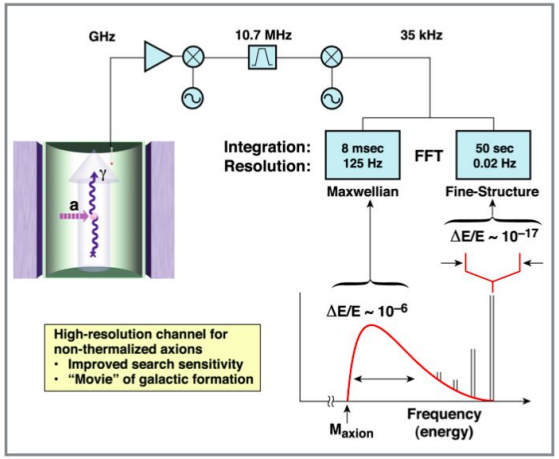
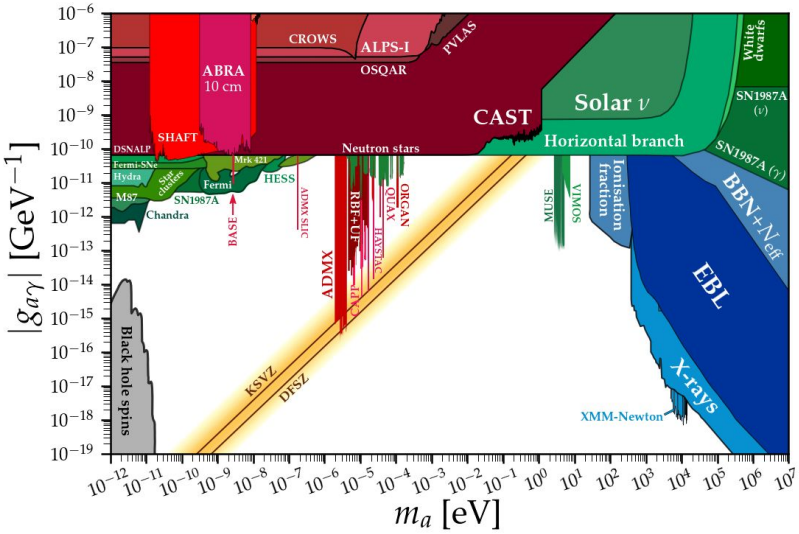


Image credit: Samuel Velasco/Quanta Magazine

ADMX-Gen2 @ Washington (USA)

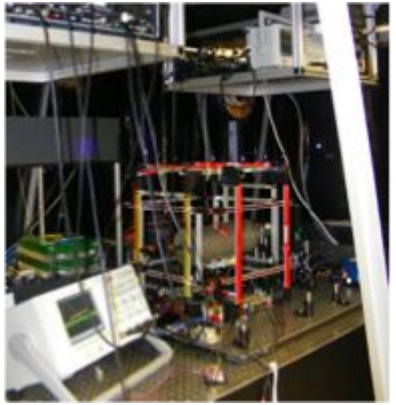
- Axions from QCD symmetry breaking mechanism
  - *Light (order 10 μeV) pseudoscalar, stable particles*
- ADMX-Gen2 is a Dark Matter axion search using a tuned electromagnetic resonator in a magnetic field
- Developing active cavity resonators to enhance rate of axion mass coverage

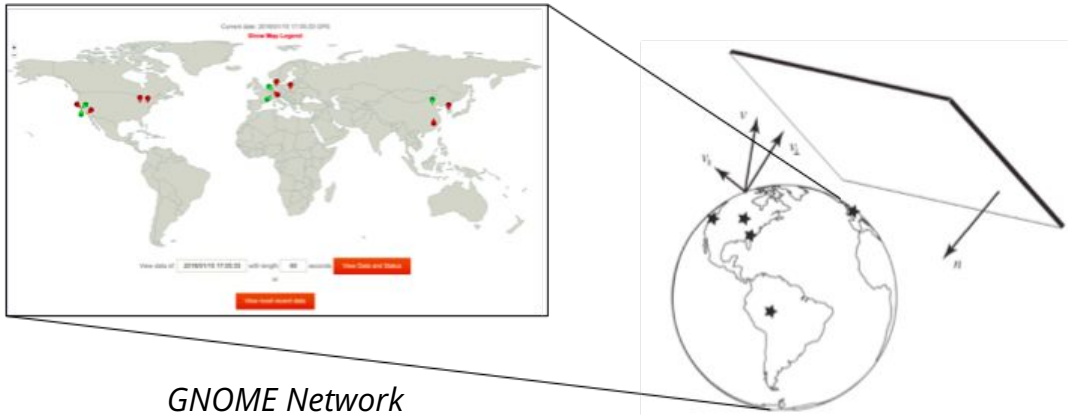




GNOME Network

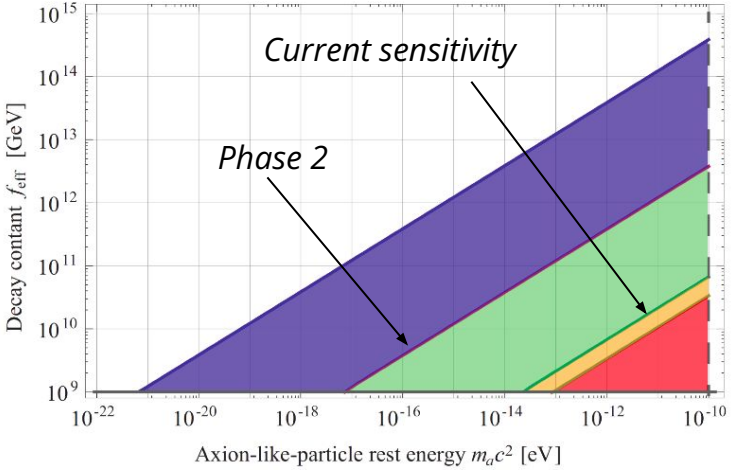
- Optically Pumped atomic Magnetometers (OPM): used to measure coupling between atomic spin and transient events of axion-like fields
  - *...like the crossing of domain walls*
- Coincident measurements between two or more instruments around the globe to reject false positives
- Impinging direction from triangulation if many instruments



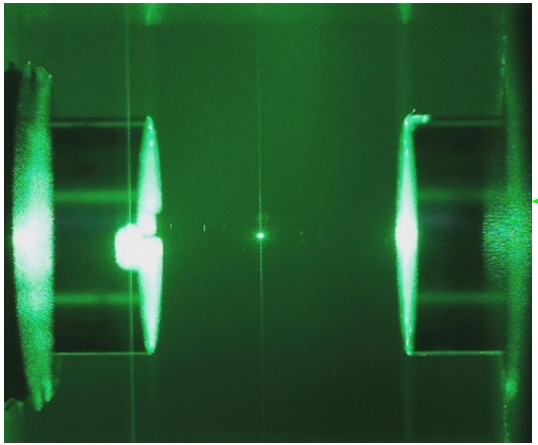


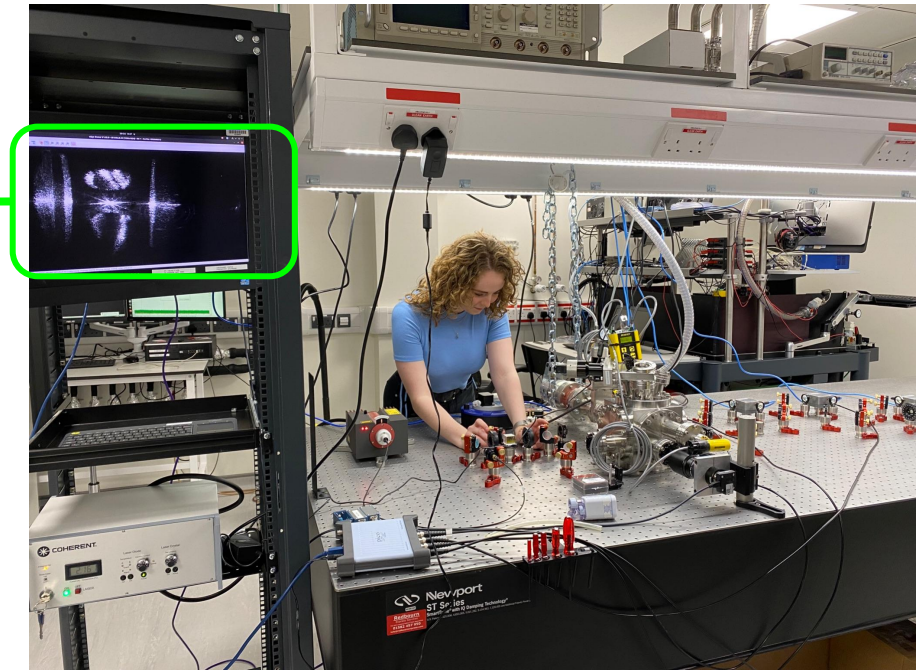
GNOME Network (USA+EU+China)

Axion domain wall detection



Quantum Sensors





Many more techniques including Atom Interferometry (e.g., AION), quantum haloscopes (e.g., Mudhi), etc.,

Prospects?

- Unexplored electroweak parameter space to neutrino fog will be searched
  - *LZ and XENONnT first results published - full exposures in 3-5 years*
  - *XLZD for G3 construction: “ultimate” LXe rare-event search observatory*
- Low-mass & ultra-light models being explored with many new technologies, incl. quantum sensors
- Clues from astro/dynamics/cosmo-particle physics most welcome!

danke!