Direct Dark Matter Searches

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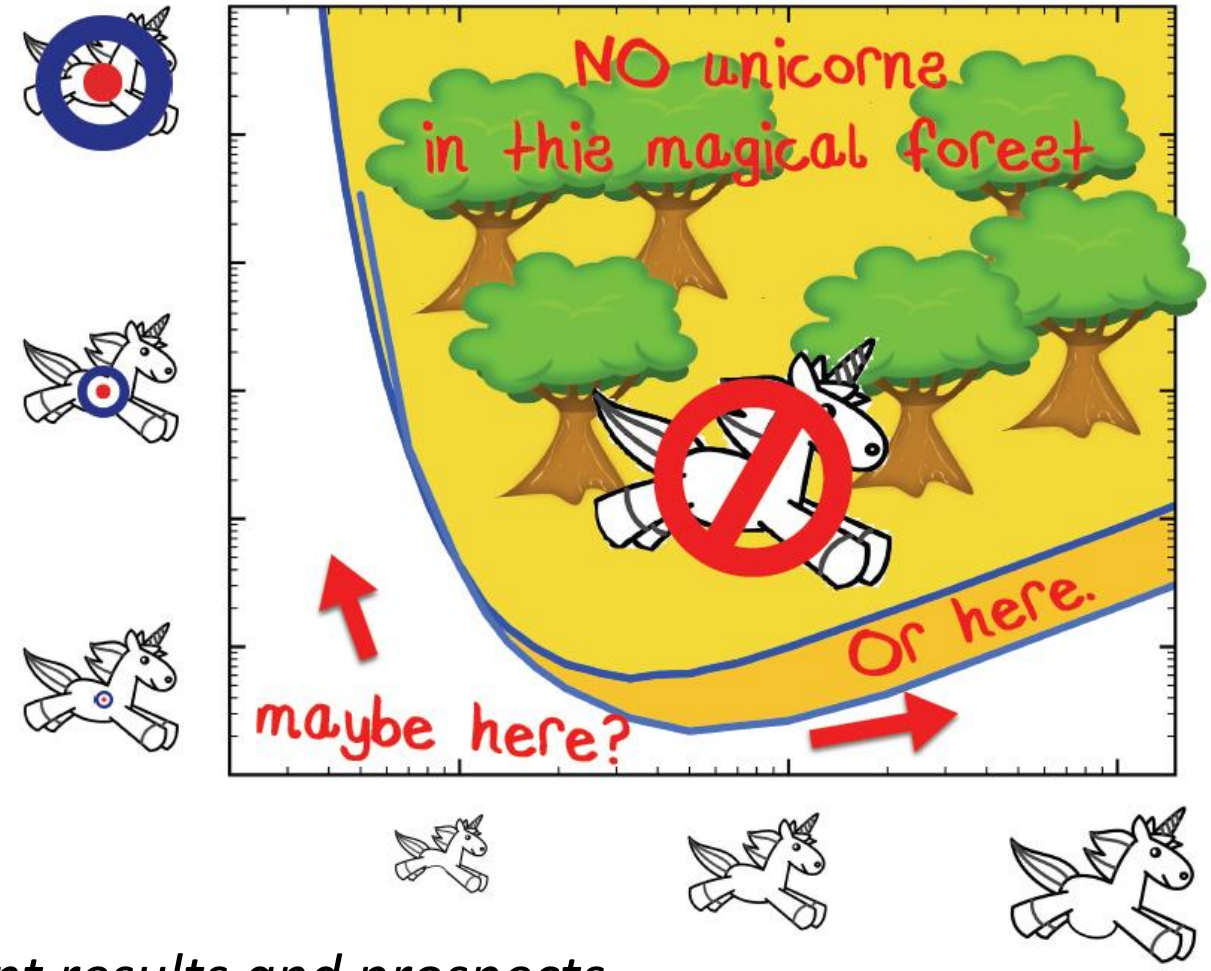
Imperial College London

PPAP Community Meeting 2016, 26-27 July, University of Birmingham

OUTLINE

- Direct dark matter detection
- Complementarity
- State of the art
- Prospects
- UK community board

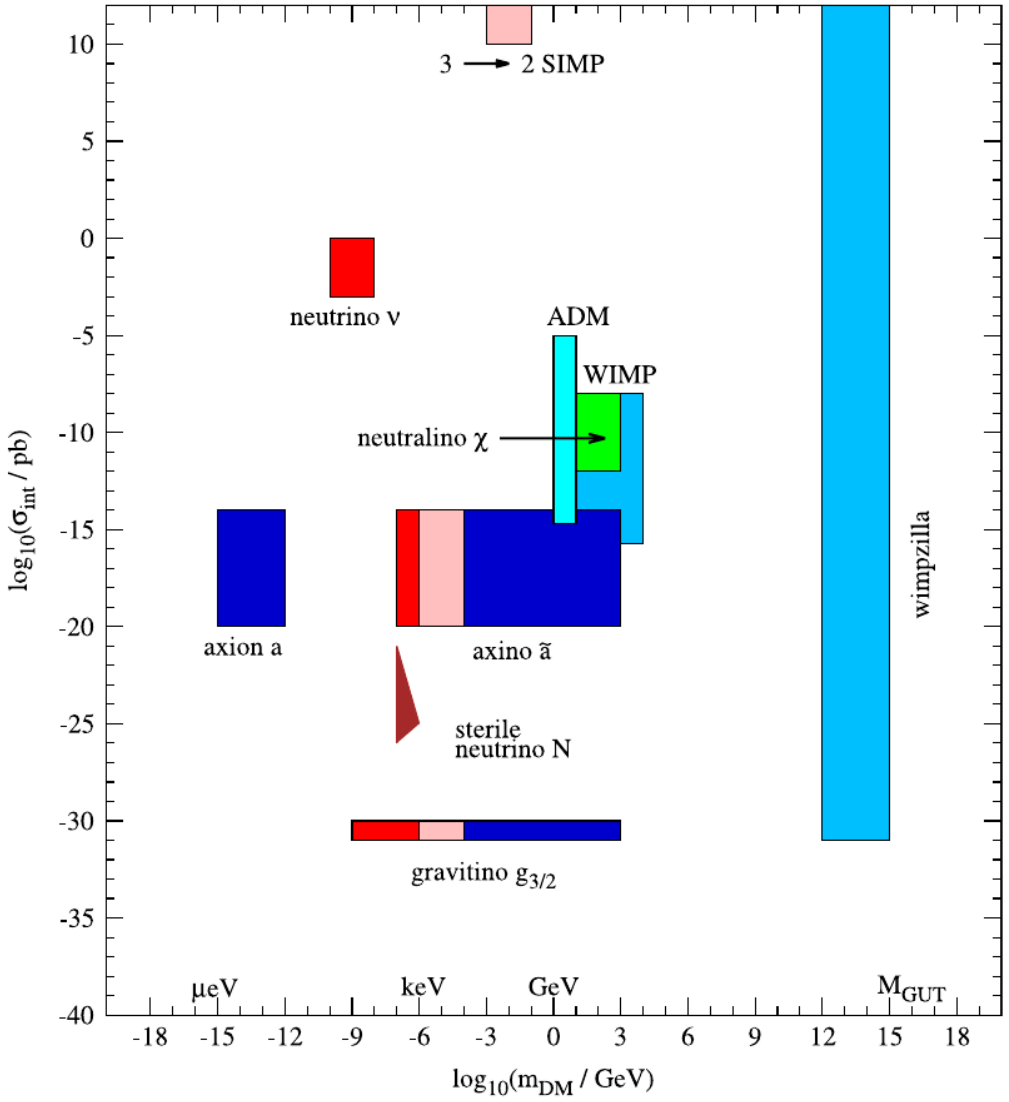
M. Horn, SURF



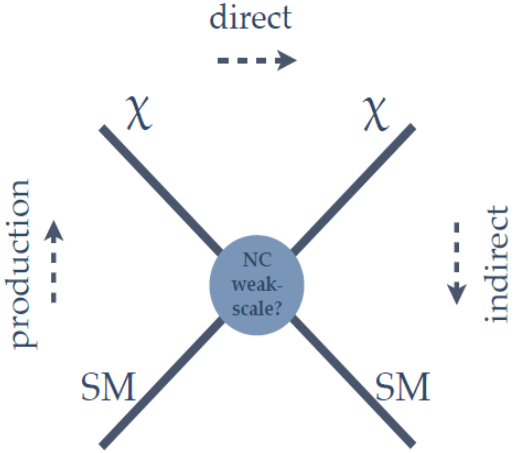
Note: I will focus only on the most significant results and prospects.
This is somewhat UK-centric and yet that matters little – we are in the thick of it!

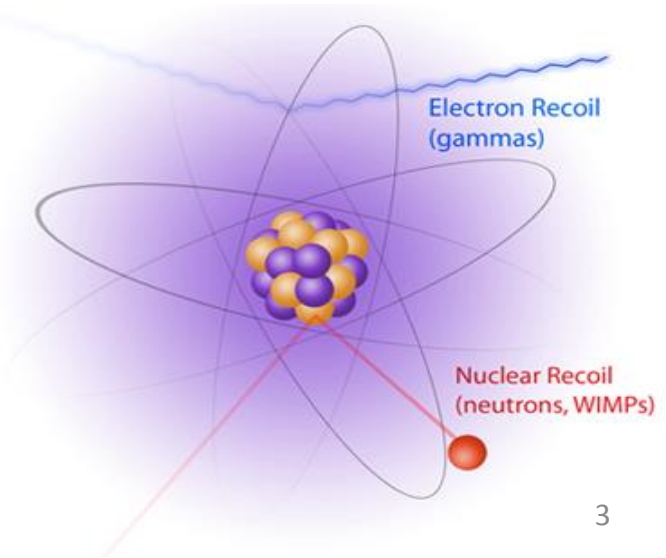
A more extensive review of the field can be found in the backup slides, for your perusal…

MINING FOR WIMPS & ALPS



- Most experimental effort in searching for the **rare** (<0.0001 /kg/day) and **low-energy** (~few keV) scattering of **galactic WIMPs** from ordinary atoms, using very sensitive detectors operating underground
- **Elastic scattering off nuclei**, spin-independent, spin-dependent, EFT operators, inelastic scattering, electron scattering, annual modulation, signal directionality, …
- Galactic Axion-Like Particles (ALPs) also interesting





WIMP SEARCH TECHNOLOGY ZOO

Not even complete;
It is a vibrant field!

Ionisation Detectors

Targets: Ge, Si, CS_2, CdTe

CoGeNT, CDEX, D3, DAMIC, **DRIFT**, **DM-TPC**, GENIUS, IGEX, MIMAC, NEWAGE, NEWS, TREX

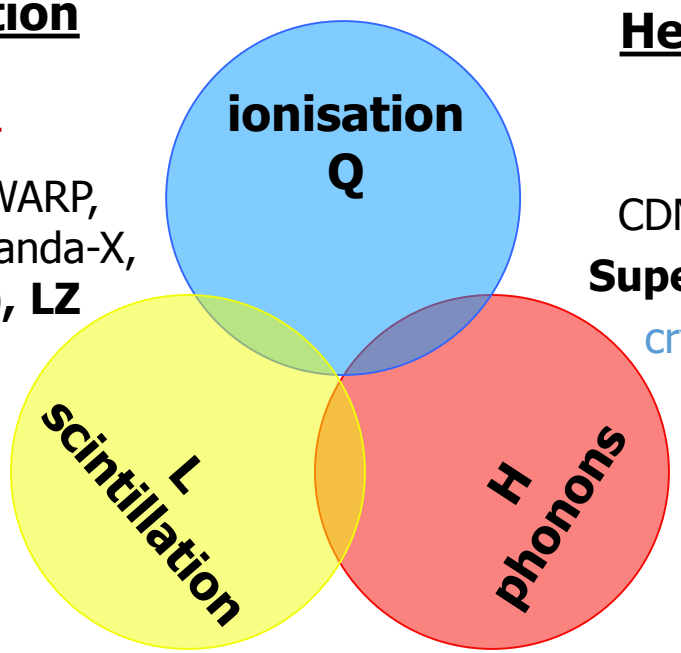
UK involvement in **bold** (past involvement in brackets)

Light & Ionisation Detectors

Targets: Xe, Ar

ArDM, Argo, **LUX**, WARP, DarkSide, DARWIN, Panda-X, XENON, **(ZEPLIN), LZ**

cold (LN_2)



Heat & Ionisation Bolometers

Targets: Ge,Si

CDMS, **(EDELWEISS)** **SuperCDMS**, **(EURECA)**

cryogenic (<50 mK)

Scintillators

Targets: NaI, Xe, Ar

ANAIS, MiniCLEAN, DAMA, **DEAP-3600**, **DM-ICE**, KIMS, LIBRA, **(NAIAD)**, **SABRE**, XMASS, **(ZEPLIN-I)**

Bolometers

Targets: Ge, Si, Al_2O_3, TeO_2

CRESST-I, CUORE, CUORICINO

Light & Heat Bolometers

Targets: $CaWO_4$, BGO, Al_2O_3

(CRESST), ROSEBUD

cryogenic (<50 mK)

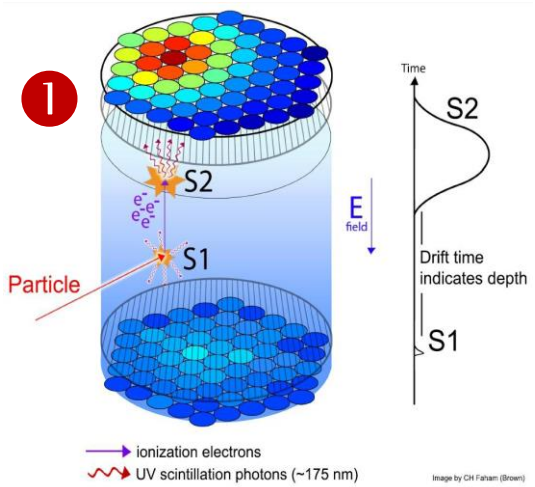
Bubbles & Droplets

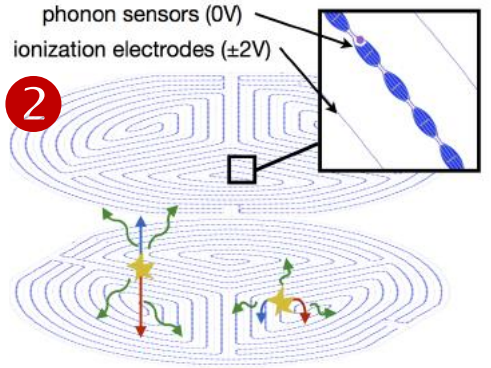
CF_3Br, CF_3I, C_3F_8, C_4F_{10}

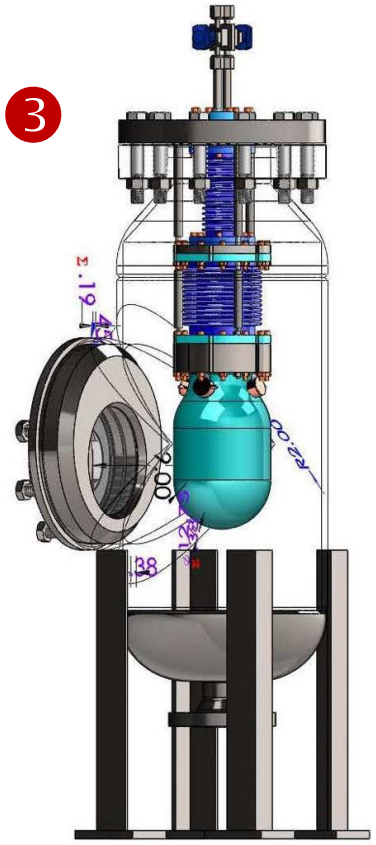
COUPP, PICASSO, PICO, SIMPLE

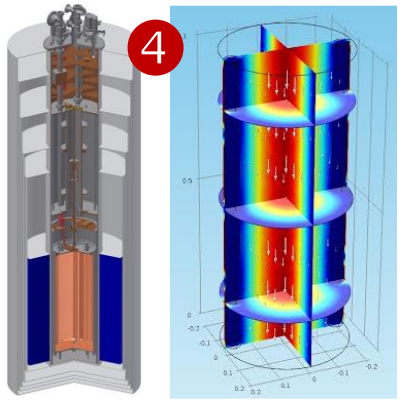
MINING FOR WIMPS & ALPS

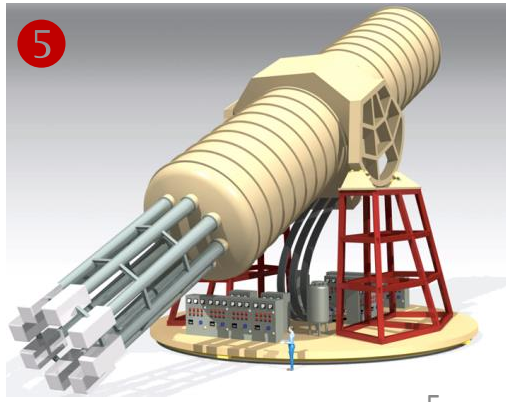
- **WIMP search technologies**
  - **Dual-phase xenon (LXe TPC)** ❶
    Leading SI and SD WIMP-neutron for mid/high WIMP masses for several years
  - **Cryogenic detectors (Ge, Si, $CaWO_4$)** ❷
    Leading SI for light WIMPs (<few GeV)
  - **Bubble chambers (C_3F_8, CF_3I)** ❸
    Leading SD WIMP-proton searches
- **Axion & ALP search technologies**
  - Axion searches (holoscopes, helioscopes,…) ❹ ❺
  - ALP searches through (~keV) axioelectric effect using the above WIMP technologies





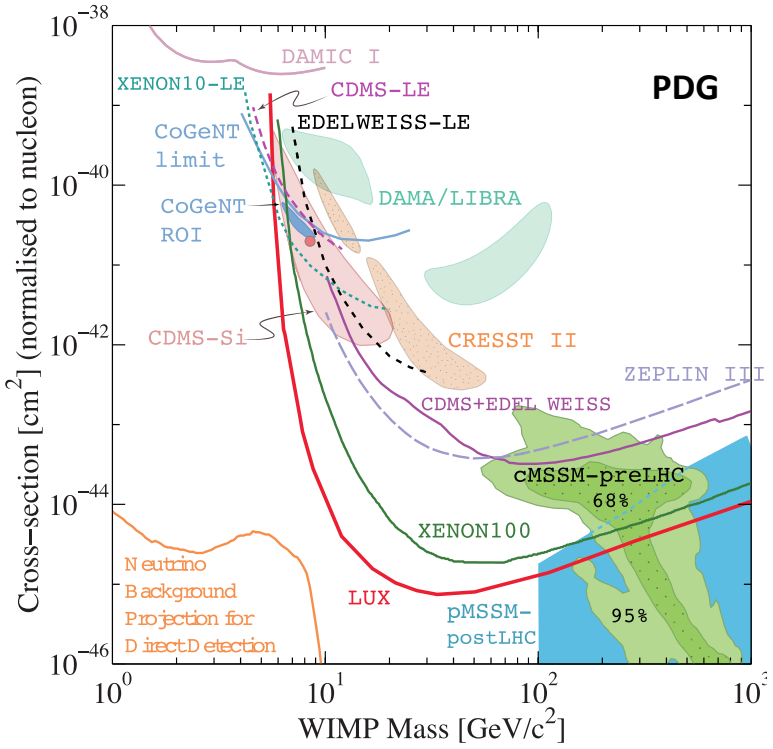


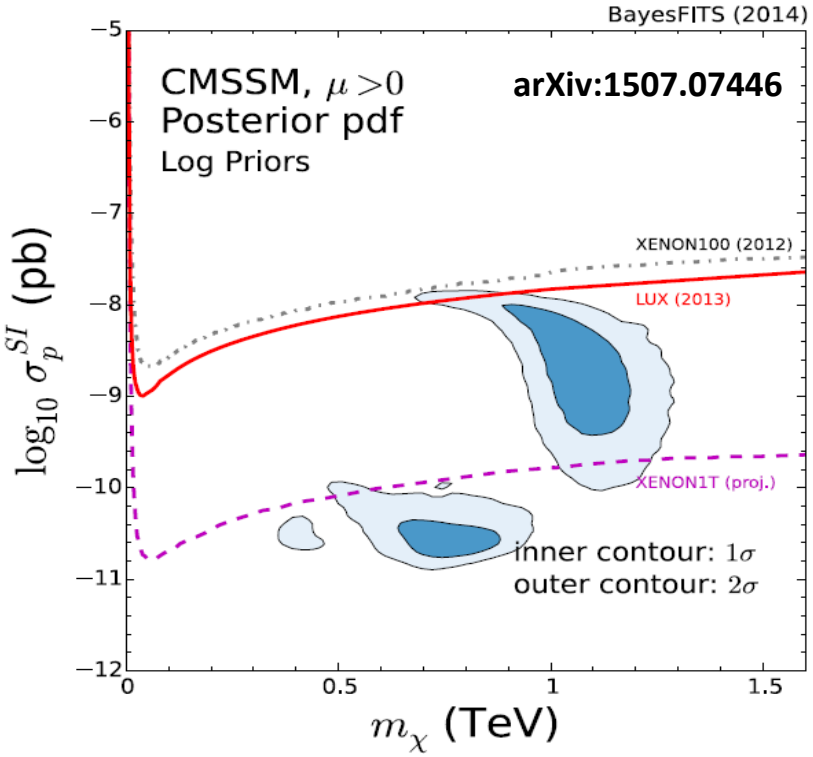


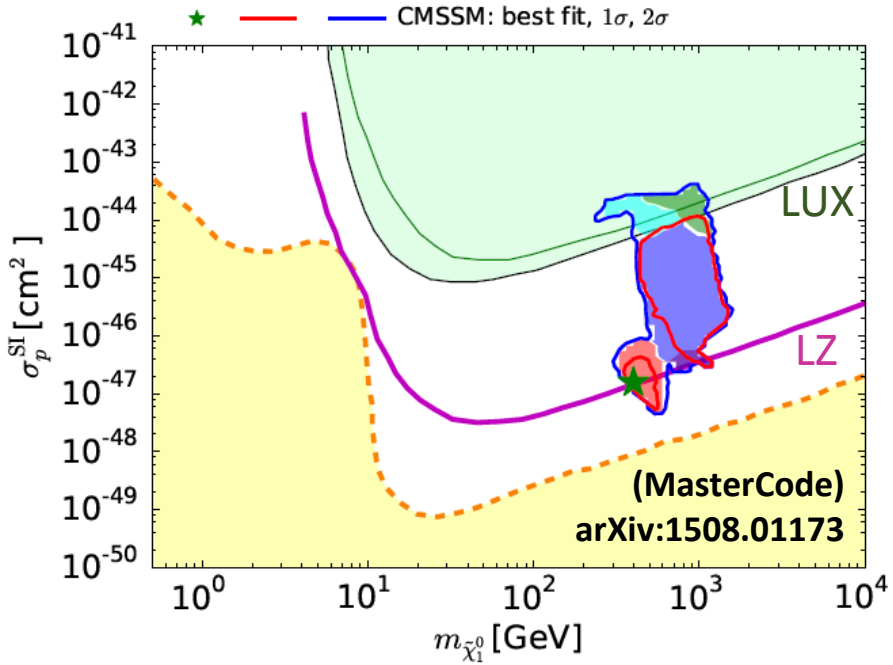


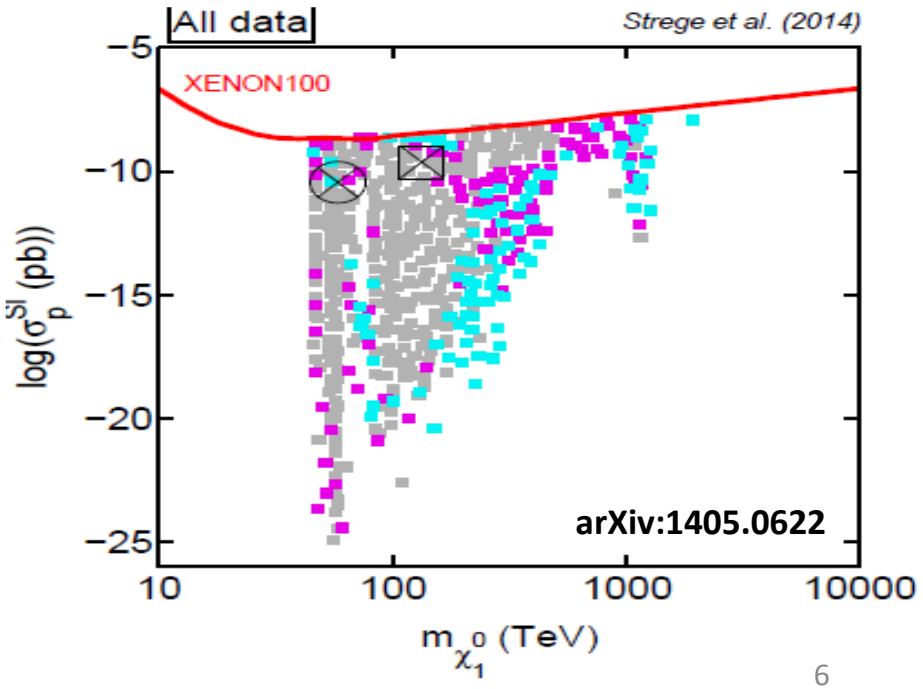
COMPLEMENTARITY: DD + LHC

- Clear complementarity and opportunity
- SUSY global fits and mono-X searches
- ~1 TeV Higgsinos interesting in various MSSM flavours



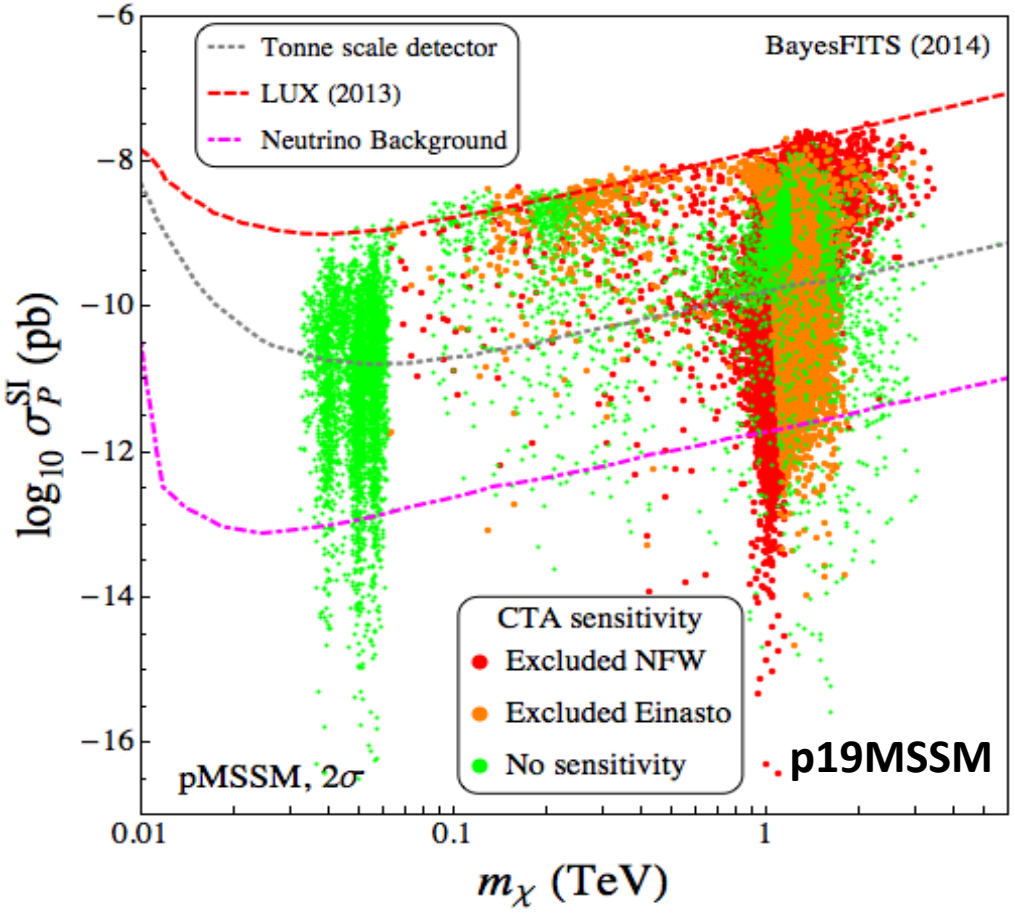


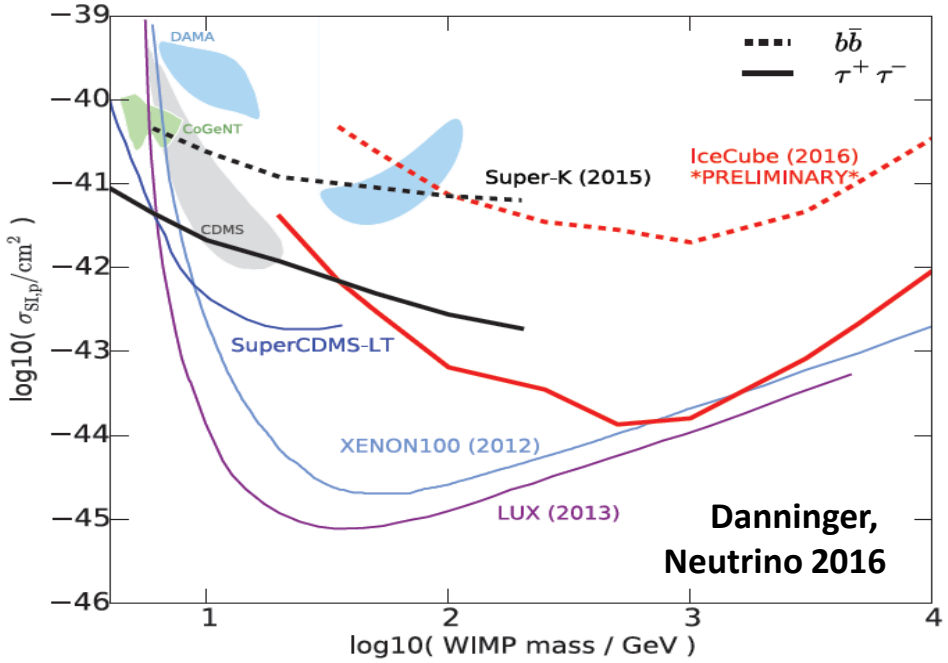


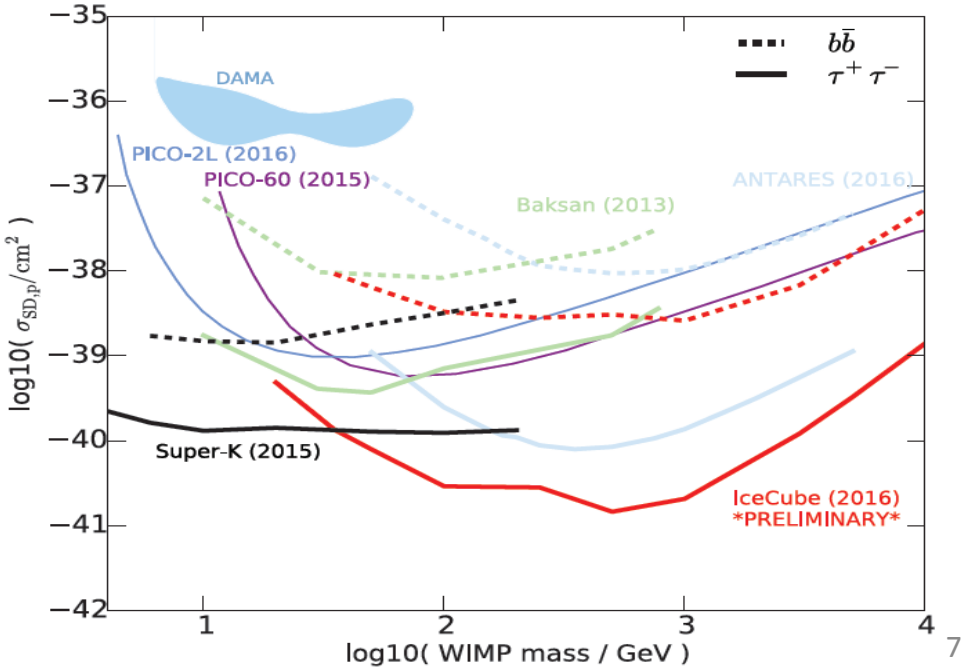


COMPLEMENTARITY: DD + ID

arXiv:1411.5214





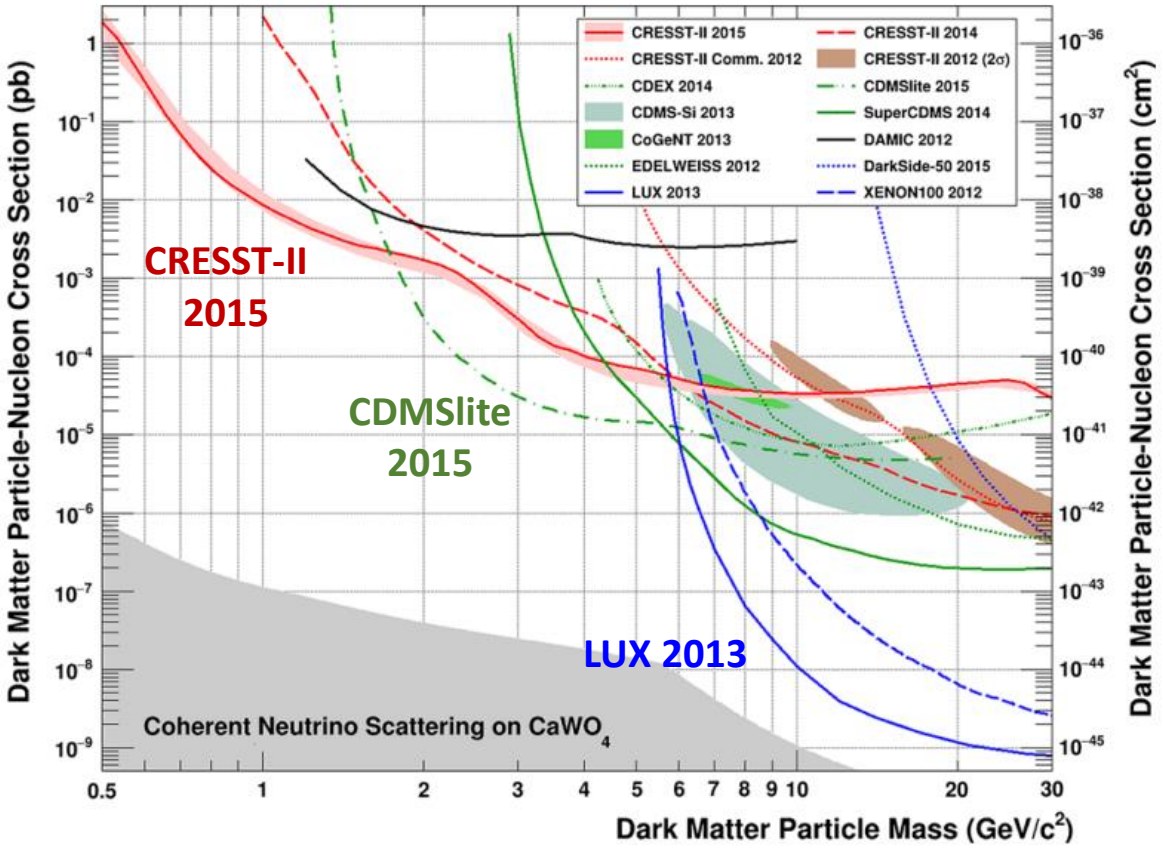


SPIN-INDEPENDENT XS – STATE OF THE ART

AS OF ONE WEEK AGO

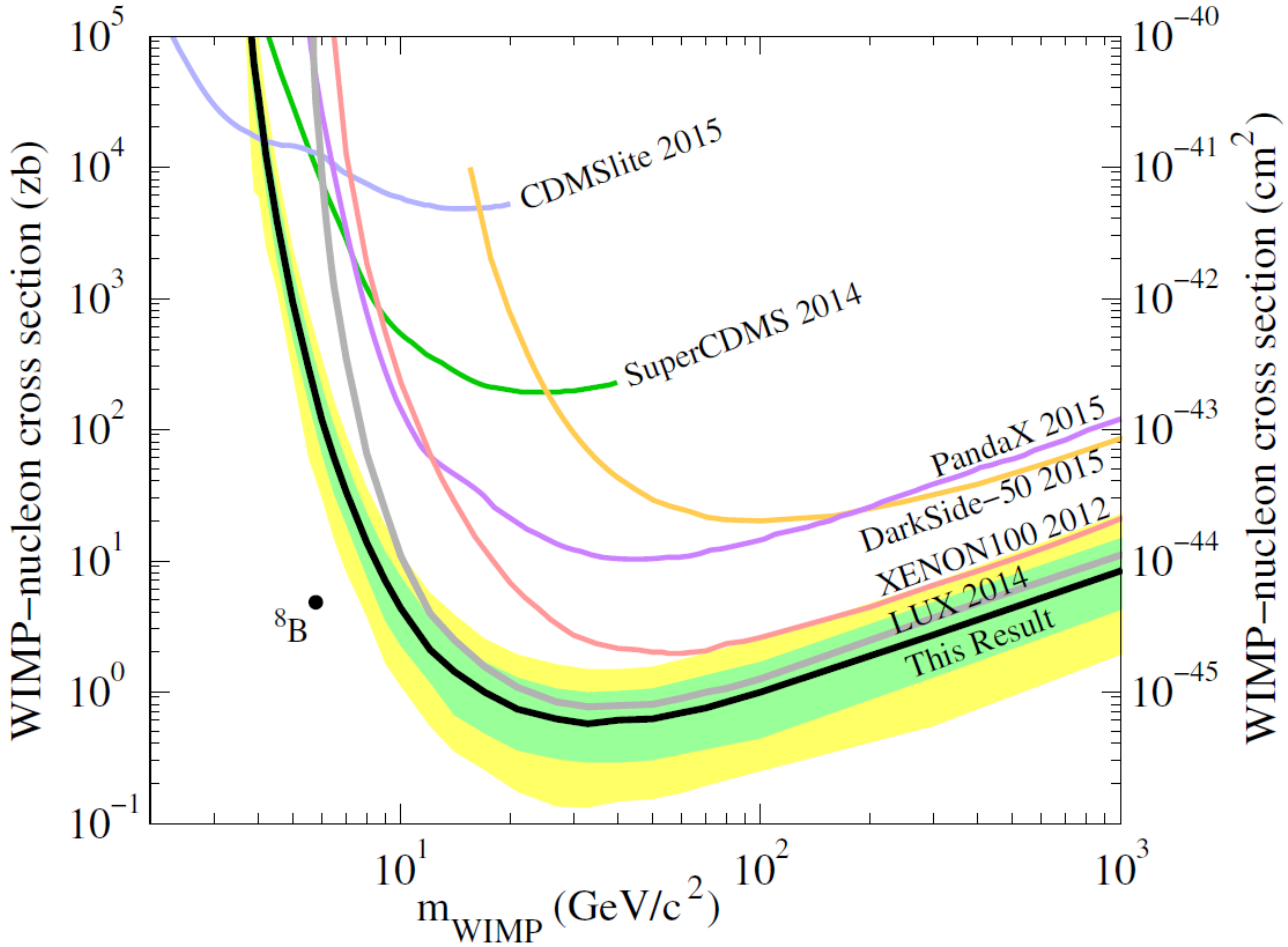
LOW MASS (FEW GeV)

(CRESST) Eur. Phys. J. C (2016) 76:25



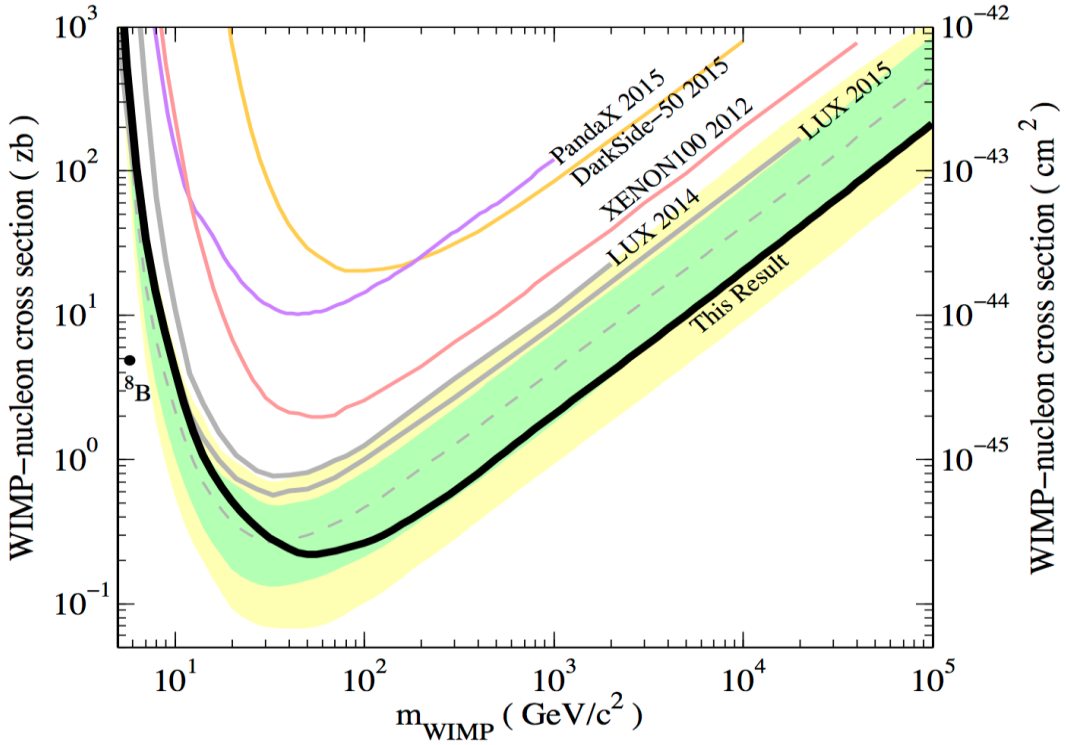
MID/HIGH MASS

(LUX) Phys. Rev. Lett. 116, 161301

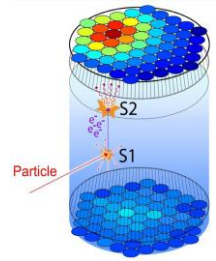


NEW RESULT FROM 332 LIVE DAYS

- 250 kg (active) two-phase xenon detector at SURF (South Dakota, US)
- First results in 2013 ruled out “light WIMP” claims
- Reanalysis following novel calibrations of LXe to ~1 keV published in 2015
- New SI result announced last week: **4x improvement at high masses**

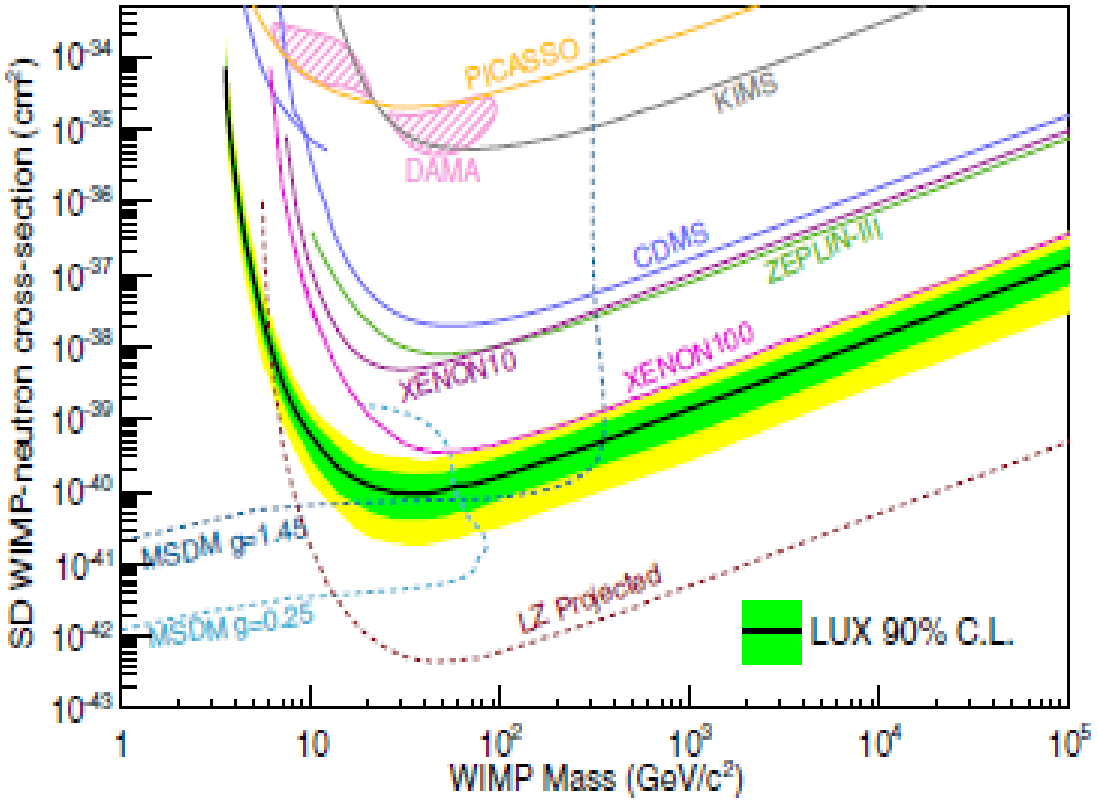


Imperial, Edinburgh, UCL (mostly non STFC)

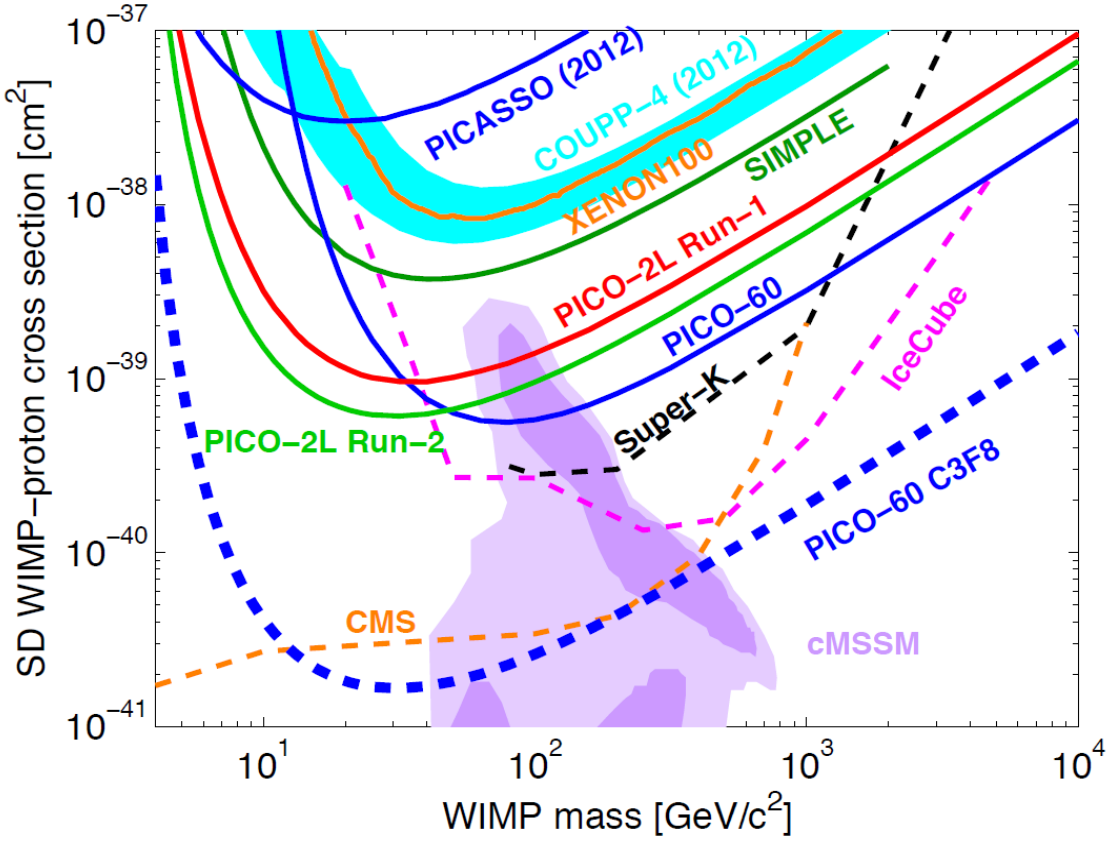


SPIN-DEPENDENT XS – STATE OF THE ART

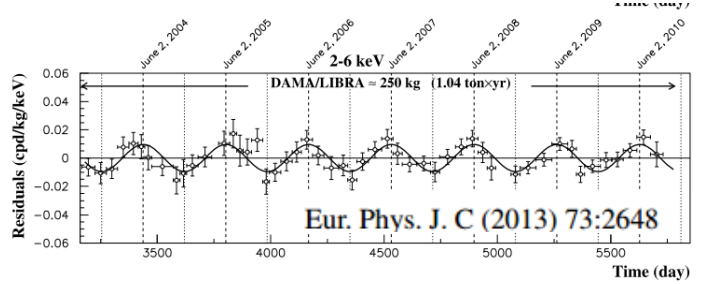
WIMP-NEUTRON
Phys. Rev. Lett. 116, 161302



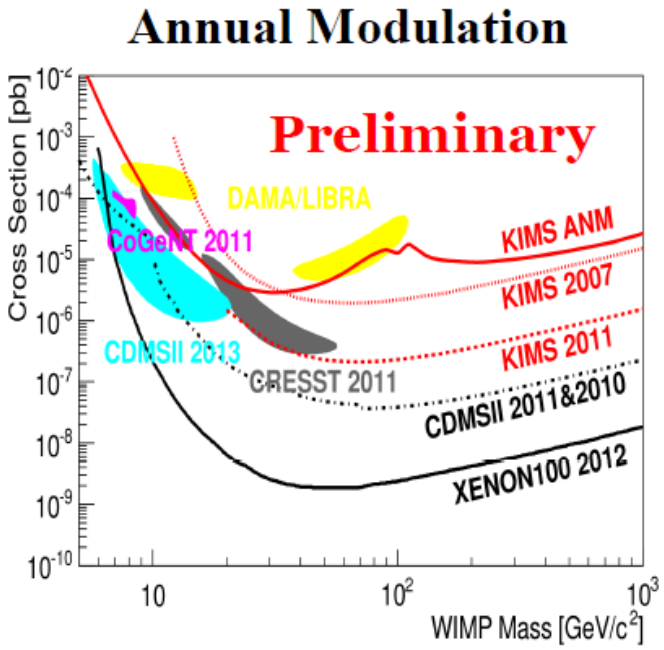
WIMP-PROTON
Phys. Rev. D. 83, 061101 (R) (2016)



ANNUAL MODULATION

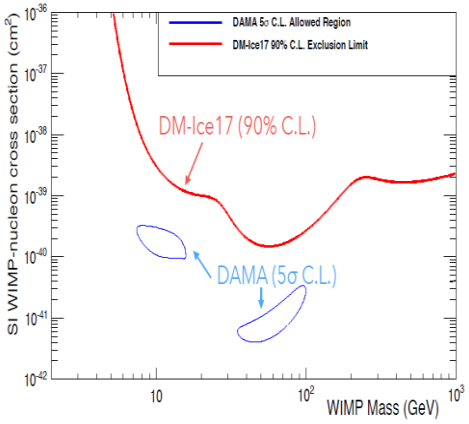


- 9.2σ evidence for annual modulation of something by DAMA (NaI) – 14 cycles published
- Annual modulation limits from LXe experiments already incompatible with DAMA
- Several NaI experiments to confirm/disprove, becoming competitive (CsI there already!)

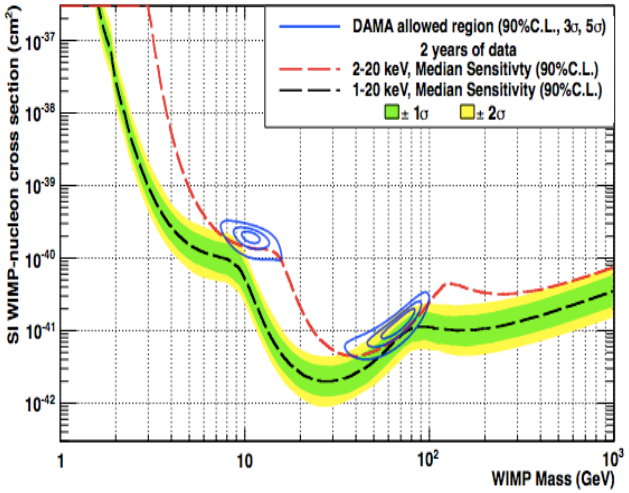


DM-ICE

Jay Hyun Jo, IDM2016



Model-independent rejection of DAMA signals interpreted as WIMP-Iodine interaction



COSINE 100 ready for physics

SABRE

Sensitivity

- 3 years stable detector operations
- No other seasonal effect in ROI (2-6 keV_{ee})
- 50 kg NaI(Tl) array
- 0.15 cpd/kg/keV total background in ROI

  ⇒ 6σ to refute modulation

  ⇒ 4σ to verify modulation

Sheffield, Boulby (mostly non STFC)

Imperial (H2020)

ANNUAL MODULATION – XENON TARGETS

XENON100 ANNUAL MOD, PRL 115, 091302 (2015)

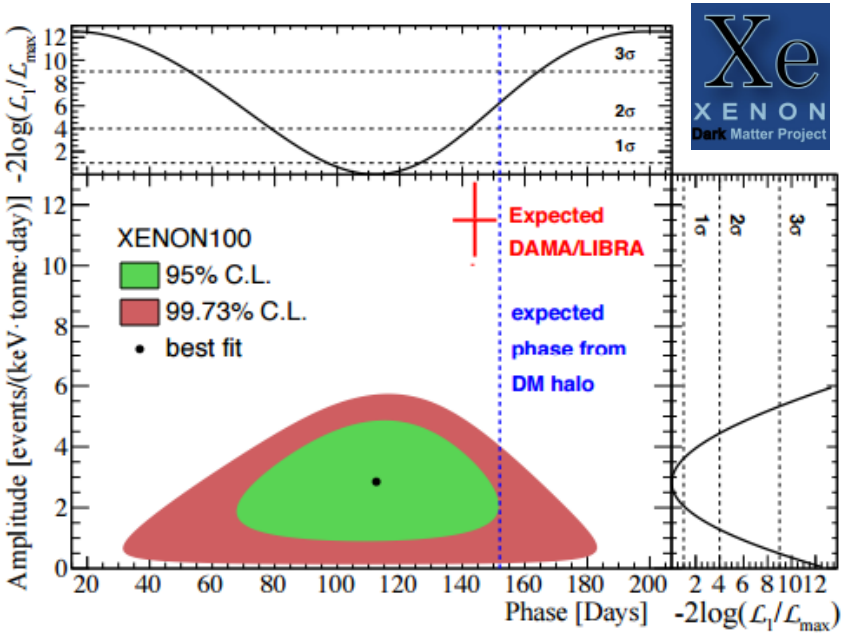


FIG. 4: The XENON100 best-fit, 95% and 99.73% confidence level contours as a function of amplitude and phase relative to January 1, 2011 for period $P = 1$ year. The expected DAMA/LIBRA signal with statistical uncertainties only and the phase expected from a standard dark matter (DM) halo are overlaid for comparison. Top and side panels show $-2\log(\mathcal{L}_1/\mathcal{L}_{max})$ as a function of phase and amplitude, respectively, along with two-sided significance levels.

Excludes DAMA/LIBRA signal at 4.8 sigma

XMASS ANNUAL MOD, PLB 759, 272-276 (2016)

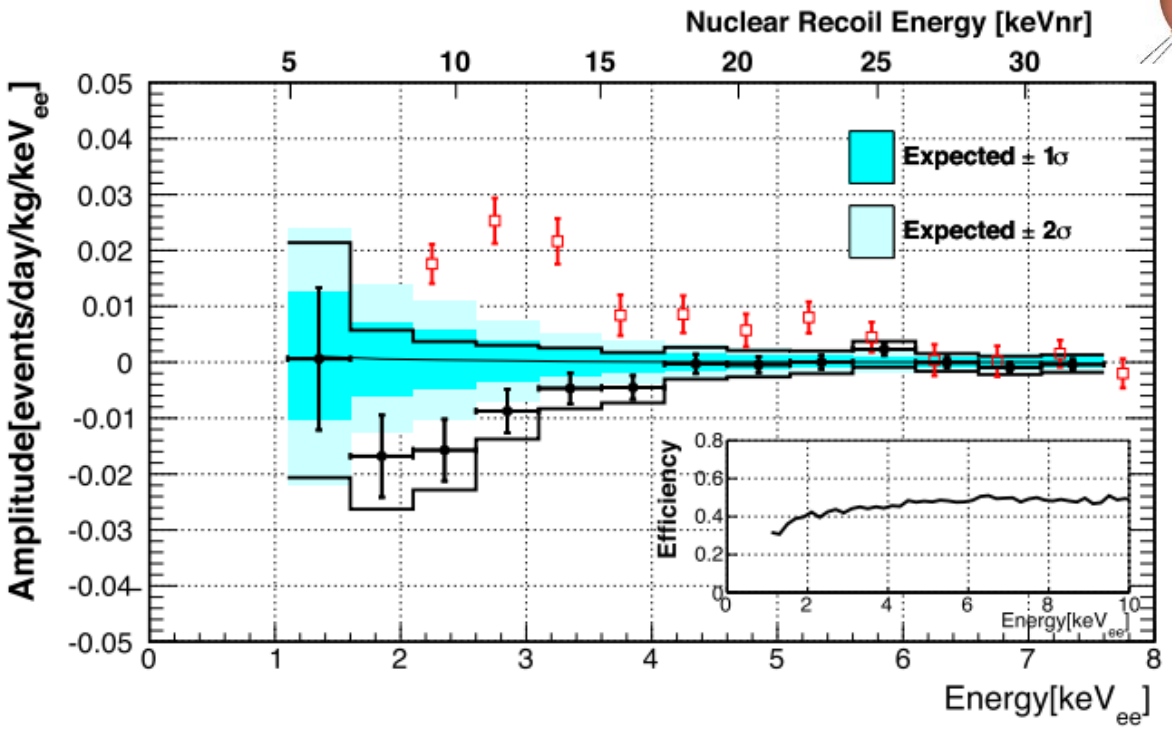
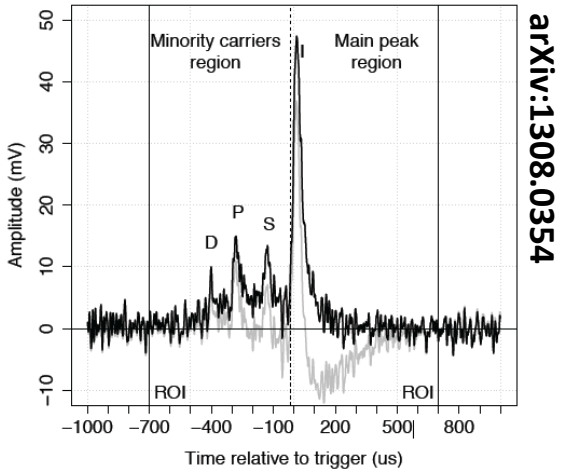


Fig. 4. (Color online.) Modulation amplitude as a function of energy for the model independent analyses using the 'pull term' method (solid circle). Solid lines represent 90% positive (negative) upper limits on the amplitude. The $\pm 1\sigma$ and $\pm 2\sigma$ bands represent the expected amplitude region (see detail in the text). DAMA/LIBRA result (square) is also shown [11].

DIRECTIONAL DETECTION

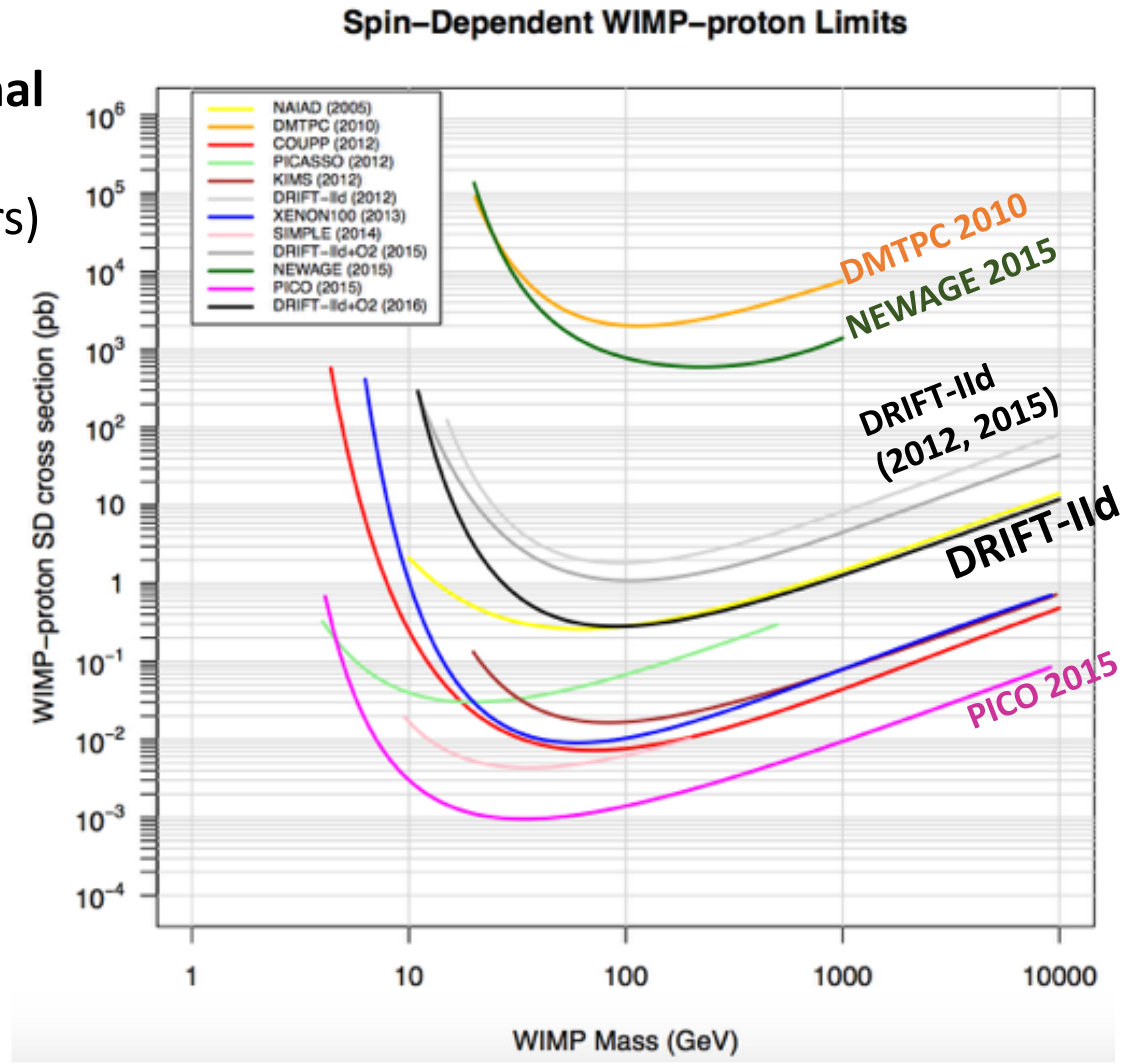
WIMP 'wind' should point towards Cygnus constellation
Low-pressure gas TPCs sensitive to directional recoil signal

- DRIFT-IId running background free, owing to thin-film cathode and z-fiducialisation (minority carriers)
- Additional 3x improvement from lowered threshold
- Now moved to new Boulby lab



arXiv:1308.0354

Sheffield, Edinburgh (mostly NSF)



PROSPECTS

(SI, mid/high mass)

Post-LUX, imminent

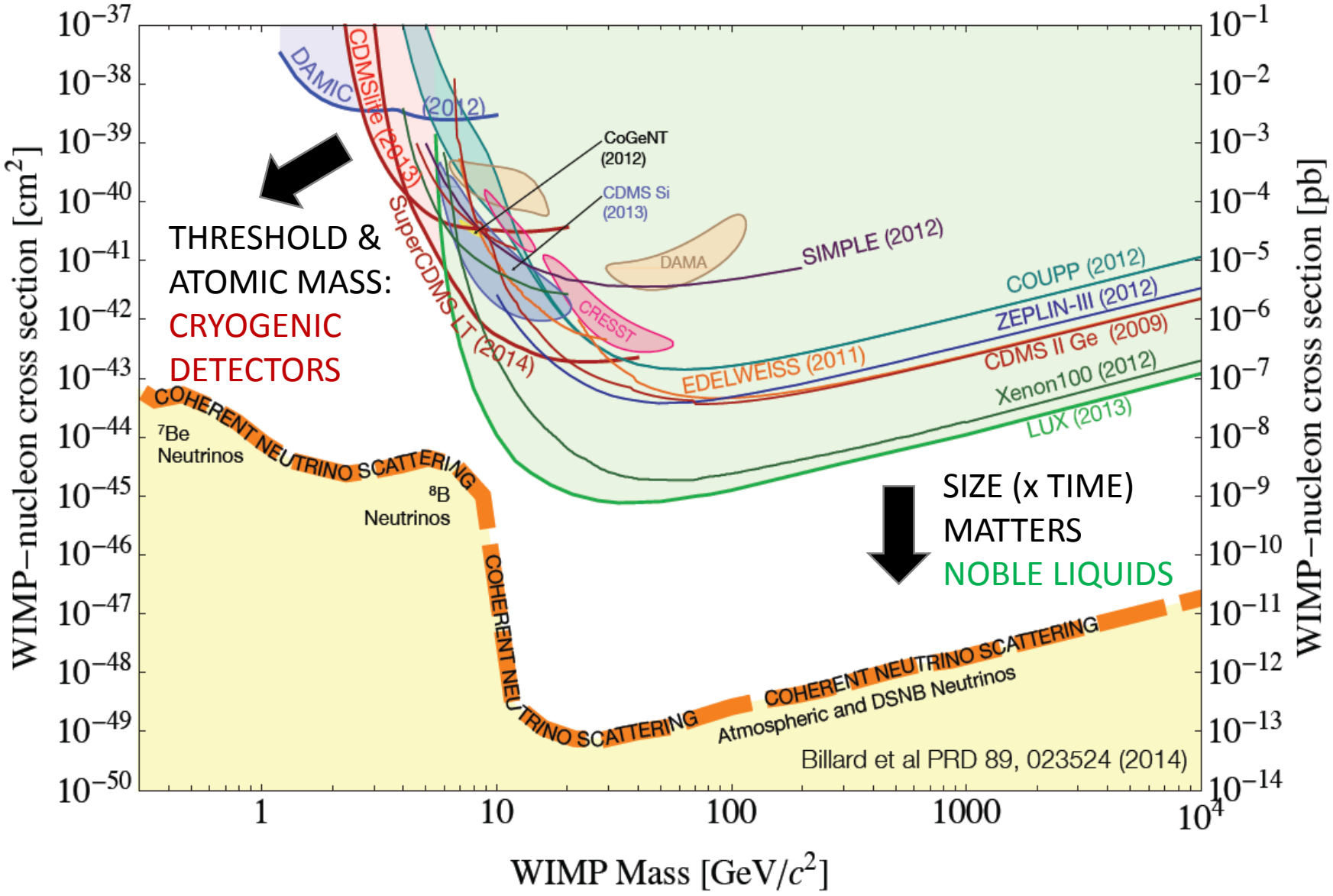
- PandaX-II (LXe)
- DEAP-3600 (LAr)
- XENON1T (LXe)

G2 construction

- XENONnT (LXe) >2018
- LZ (LXe) >2020

G3 plans

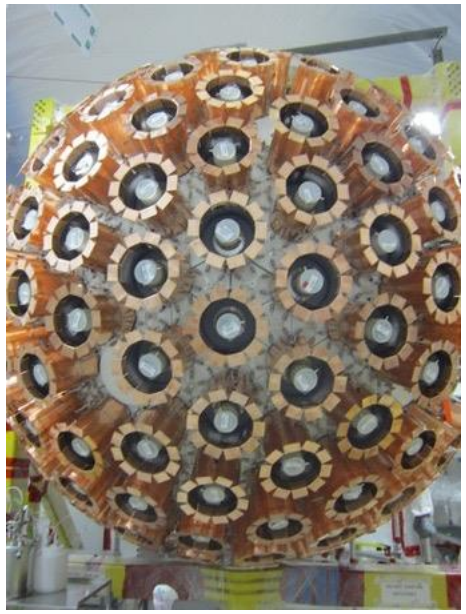
- DS-20k (LAr) >2020
- DARWIN (LXe) >2025
- There will be more….



DEAP-3600: STARTING NOW

- **3.6-T Single Phase LAr with 4π PMT coverage**
- Background rejection via Pulse Shape Discrimination
- Collaboration: 11 institutions in Canada, UK, Mexico

RAL, RHUL, SUSSEX
PRD 2012-15, CG 2015-19

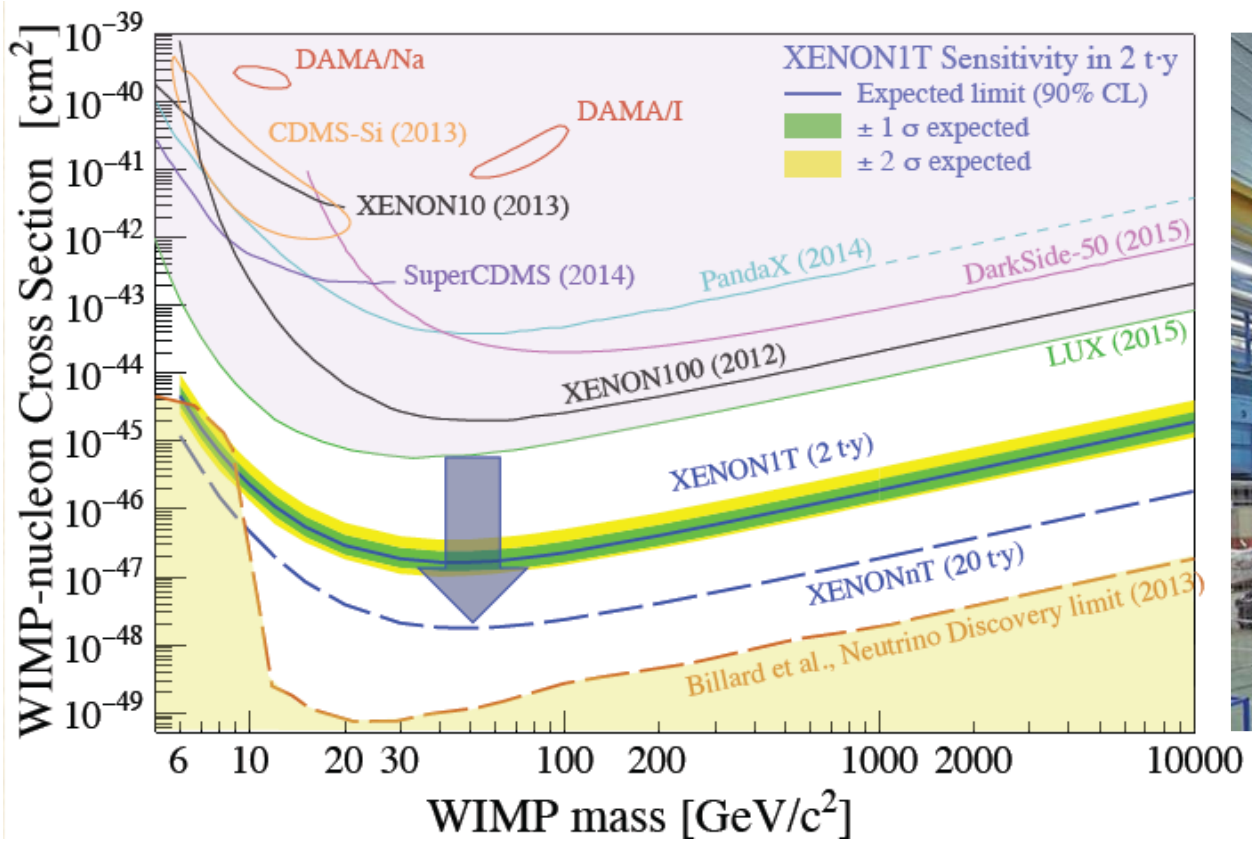


DEAP-3600 AT SNOLAB

- Construction completed; calibration 2015-16; **3-year physics run from August 2016**
- Measured light yield and surface alpha backgrounds in line with sensitivity projections:
  - SI sensitivity target $1x10^{-46}$ cm^2 @ 100 GeV with 3,000 kg-yr exposure
- UK delivered calibration systems, instrumental to understand detector performance (optical: laser and fibre systems, source: Na-22, AmBe, Ar-39)
- Plans: global coordination towards 20-T LAr detector at Gran Sasso; MoU on depleted Ar in place, joint funding from Canada, US, Italy, Spain, new groups in Mexico (UNAM) and Germany (TUM)

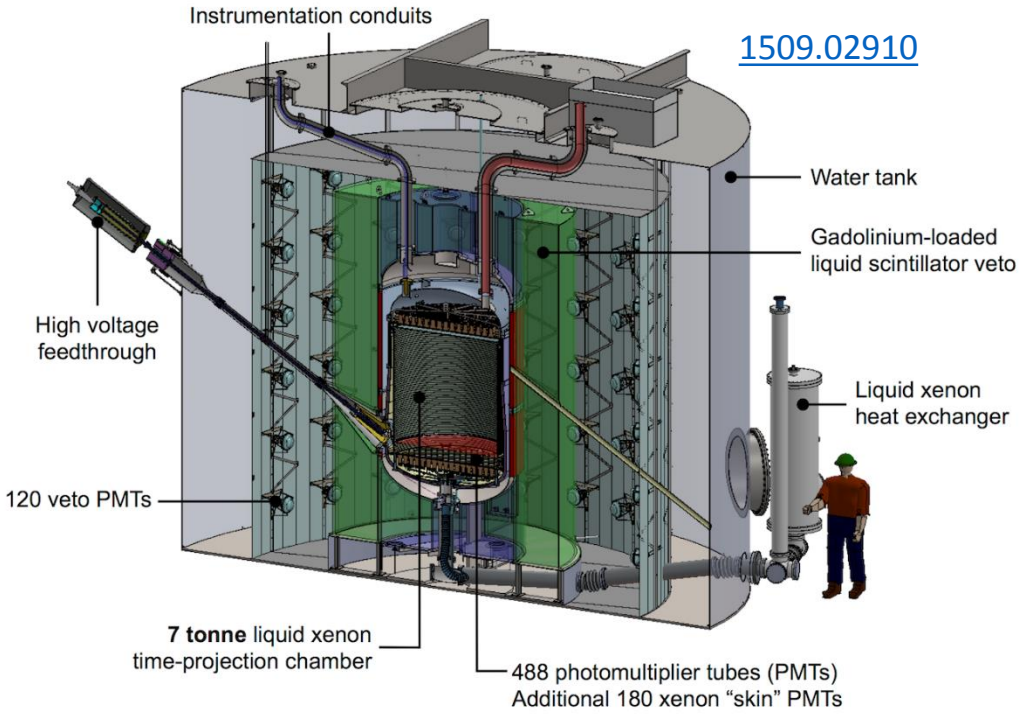
XENON1T: STARTING NOW

- **3.2-T LXe TPC, 2-T fiducial mass**
- Commissioning now; xenon purification under way
- **Physics data soon**



LUX-ZEPLIN (LZ): UNDER CONSTRUCTION

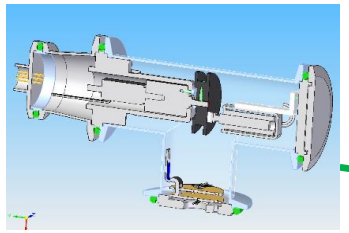
- Next-generation two-phase xenon experiment to follows LUX at SURF
- 10-T (active) LXe target + 2-T LXe Skin Veto + 20-T Gd-loaded LS Outer Detector
- 200+ researchers in 31 institutes in the US, UK, Portugal, Russia and South Korea



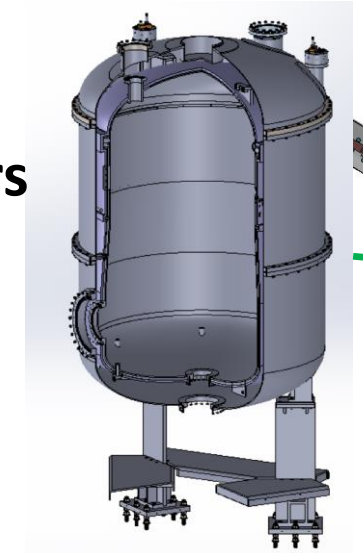
Date	Activity
March 2012	LZ collaboration formed
July 2014	Project selected in the US and UK
April 2015	DOE CD-1/3a approval, UK project kick-off *Conceptual Design Report* arXiv:1509.02910
April 2016	DOE CD-2/3b review *Technical Design Report* – to be published soon
January 2018	Begin preparations for surface assembly @ SURF
October 2019	Begin underground installation
July 2020	Commissioning

UK SCOPE

- **7 UK institutes, ~50 physicists & engineers**
- **Construction phase is main STFC investment**
- Contributions across whole experiment
- Building on the success of ZEPLIN and LUX



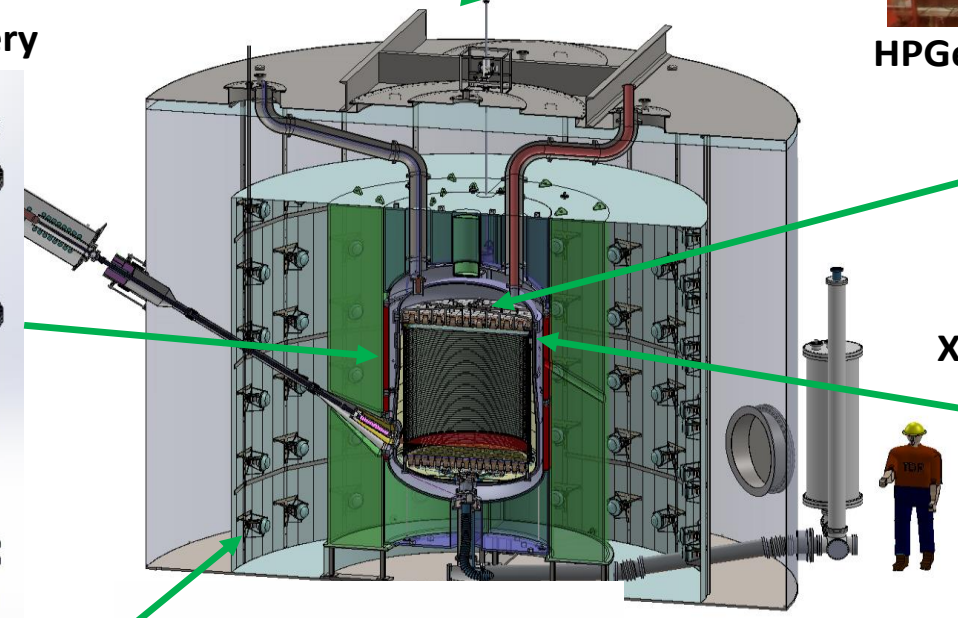
Calibration delivery



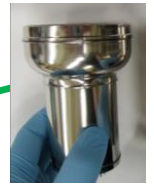
Titanium cryostat

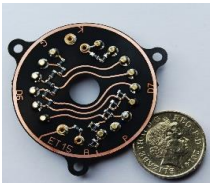
OD optical calibration

UK Data Centre



HPGe/ICP-MS/Rn screening

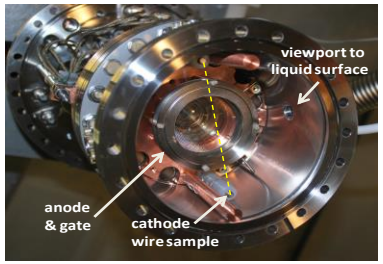


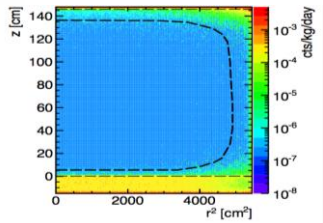


1/3 TPC PMTs
Xenon-space PMT bases

Monitoring sensors

System Testing

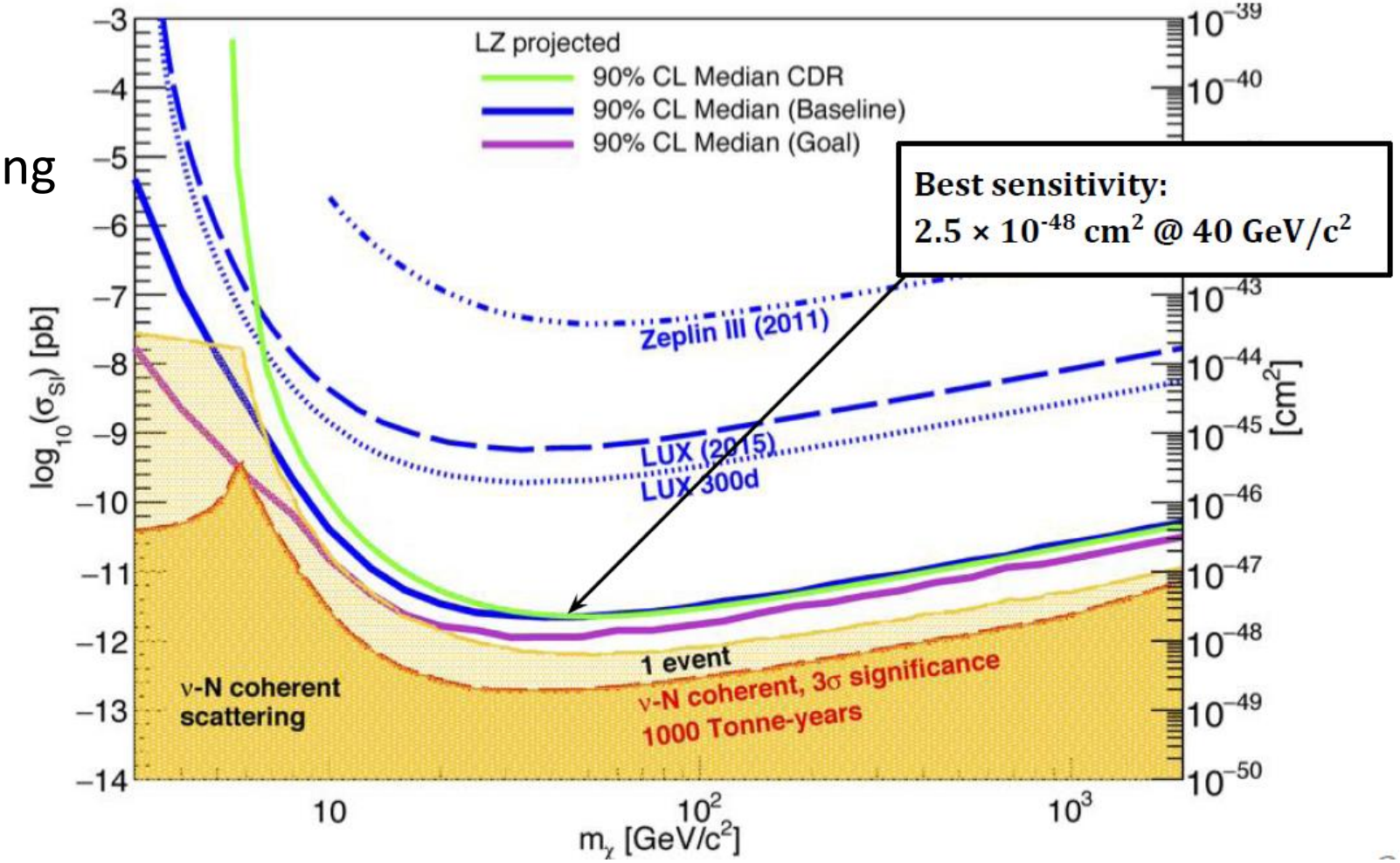




Simulations

LUX-ZEPLIN (LZ) – SCIENCE OPPORTUNITIES

- WIMP SI sensitivity approaching neutrino floor (ν-A CNS)
  - Requirement 3×10^{-48} cm^2
  - Goal 1×10^{-48} cm^2 at 40 GeV
- Leading SD sensitivity
- Coherent ν-A Scattering
  - Detection of B-8 ν
  - O(1) event from Atm/DSNB
  - Sensitive to supernova ν
- Solar pp neutrino flux (ν-e)
- 0NBB decay search in Xe-136



COMMUNITY BOARD

Dark Matter, PAAP & PPAP

- PAAP advises on construction / R&D projects
- PPAP advises mostly on exploitation

PAAP ROADMAP

- Community consultation in 2015, Roadmap update expected September 2016
- R&D areas
  - Engineering design studies: in case a G3 experiment becomes well motivated
  - Materials screening: throughput and sensitivity; cleanliness controls
  - Dispersible (i.e. non-fiducialisable) backgrounds (e.g. radon): data, assay, removal
  - Noble liquid technology (e.g. optical and electrical properties of critical materials)
  - Low background optical sensors (PMT, Si) for LXe and LAr: quantum efficiency and cost /cm2
  - Directional detector technology

COMMUNITY BOARD

- **PPAP ROADMAP (2015)**

*The UK has a leading role in the **LUX-ZEPLIN (LZ)** consortium, which aims to develop a multi-tonne detector at the SURF facility in South Dakota, based on the two-phase xenon technology pioneered by the UK-led ZEPLIN collaboration. Some institutes also participate in the LUX experiment, which has the current world-leading sensitivity. In addition, the **DRIFT** and **DMTPC** gas TPC technologies have directional capability and may be able to determine whether the Dark Matter flux is correlated with the Earth's galactic motion. Funding for LZ has recently been approved through the experiments grants line and is being sought through Consolidated Grants for exploitation. DMTPC is supported in the UK through Consolidated Grants.*

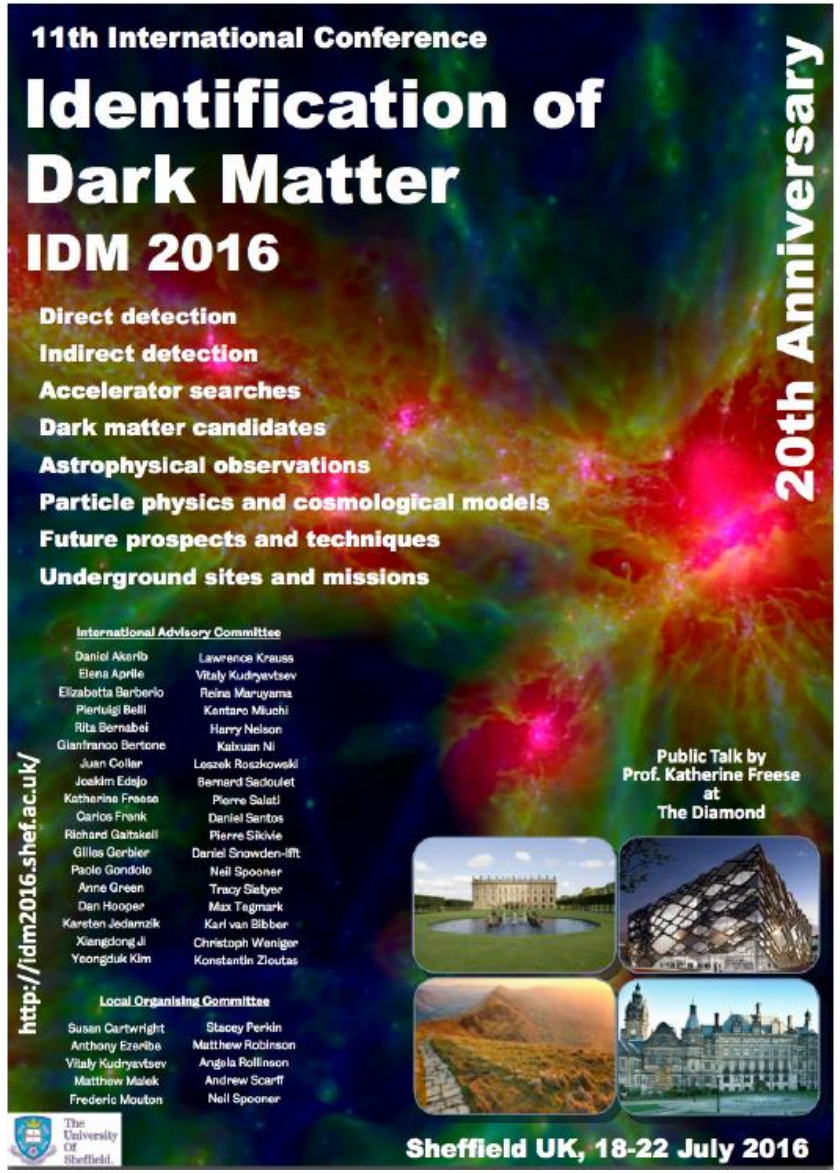
- ***Recommendation 22: The UK should provide capital-phase support for construction of the tonne-scale LUX-ZEPLIN Dark Matter experiment and continue R&D towards directional sensitivity.***

Since then:

- *LZ*
  - *Funding profile approved by the DOE through to commissioning*
  - *CG funding approved for period Mar 2018 – Sep 2019*
  - *R&D for potential G3 from 2017/2018*

COMMUNITY BOARD

- Much of the information presented here comes from presentations at **IDM 2016**, Sheffield, 18-22 July 2016; One of the oldest DM conferences, started in the UK
- Although this summary explores the experimental effort, there is a very significant and vibrant community of **theorists and phenomenologists** which I would like to acknowledge
- There has been significant infrastructure investment at the **Boulby Underground Laboratory** and this benefits the dark matter community; it is essential that STFC invest also in support/physics staff
- The **DMUK Consortium** continues to bring together the UK community; its initial focus was experimental consolidation, now focusing on bringing experimental/theoretical communities together and on screening resource coordination (Boulby); New DMUK chair C. Ghag (UCL) replacing H. Kraus (Oxford)

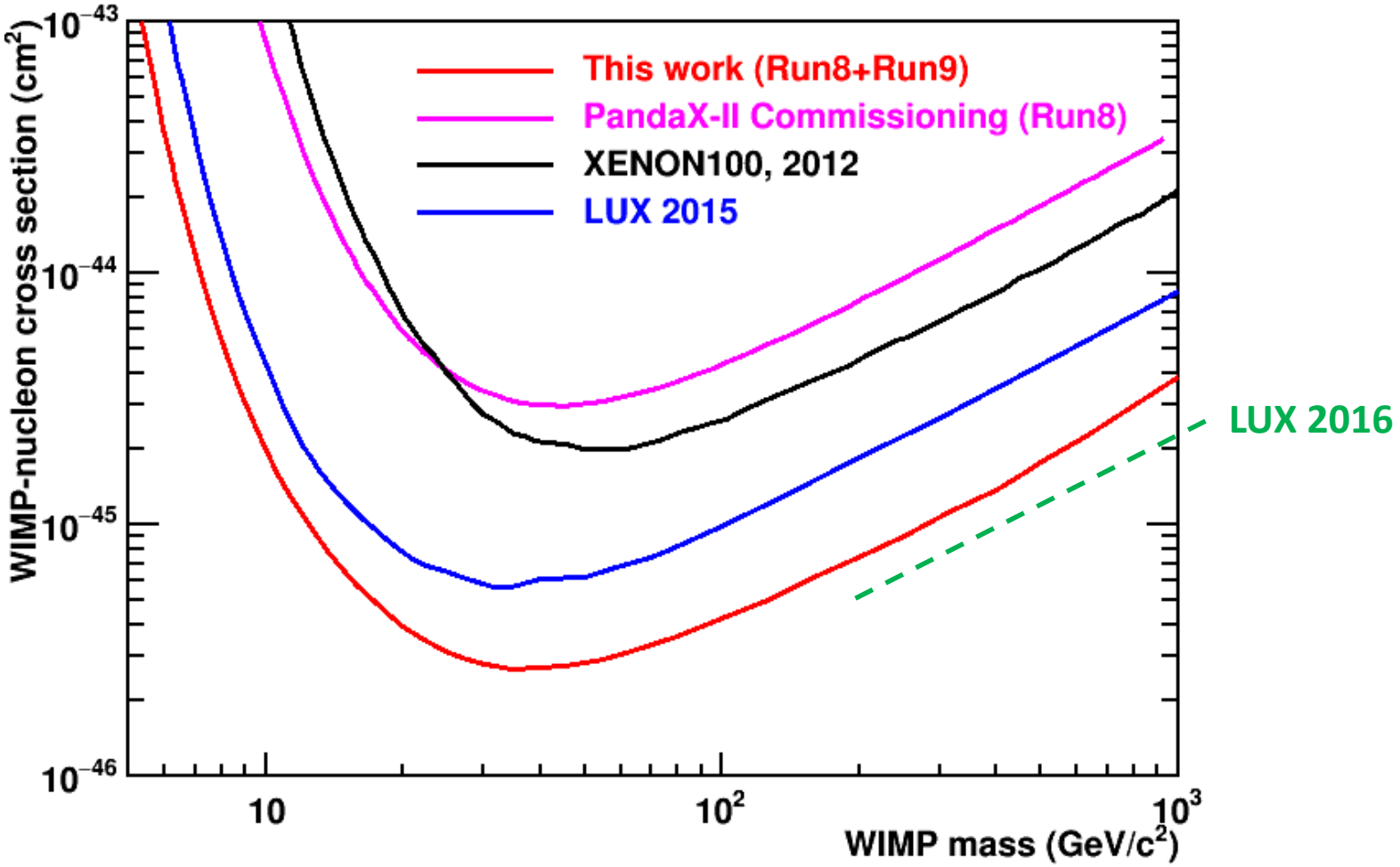


THANK YOU

ADDITIONAL SLIDES HEREAFTER

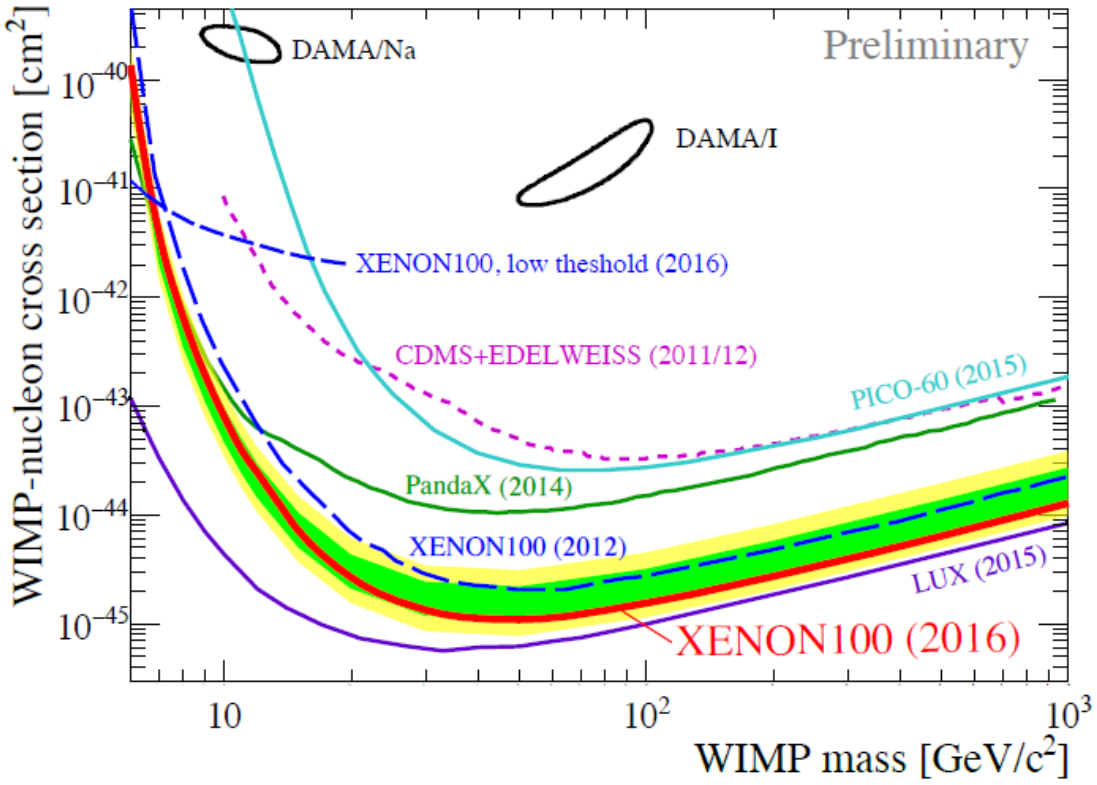
STANDARD WIMPS – OTHER RECENT RESULTS

Preliminary Result
PandaX-II, IDM2016

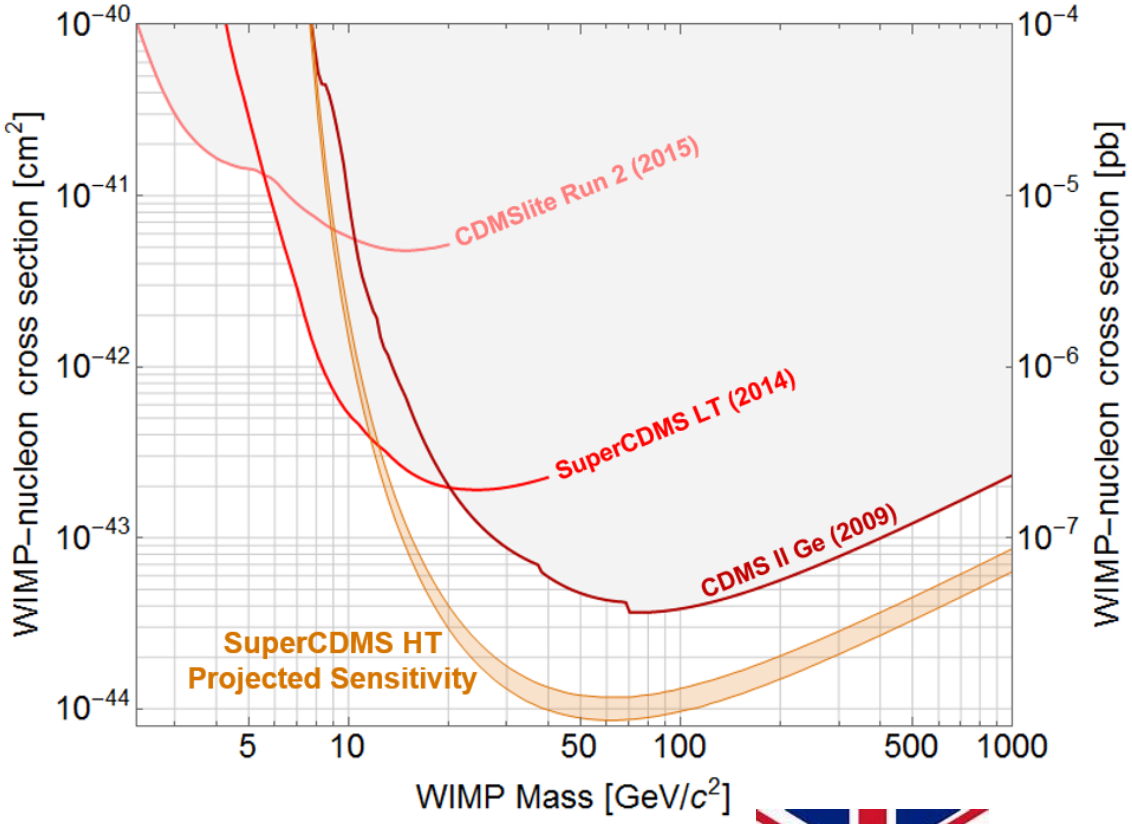


STANDARD WIMPS – OTHER RECENT RESULTS

XENON100 COMBINATION RESULTS, IDM2016

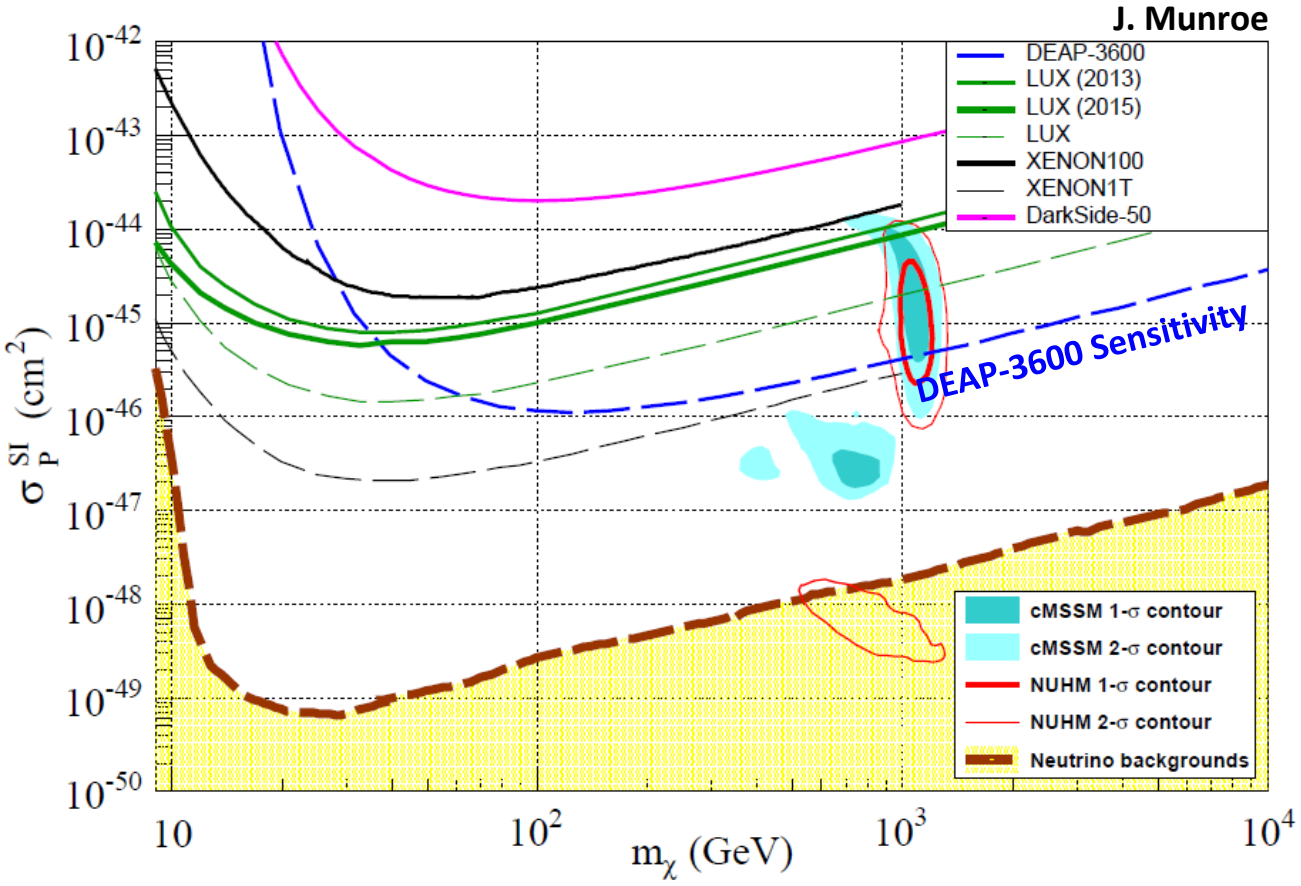


SuperCDMS, IDM2016

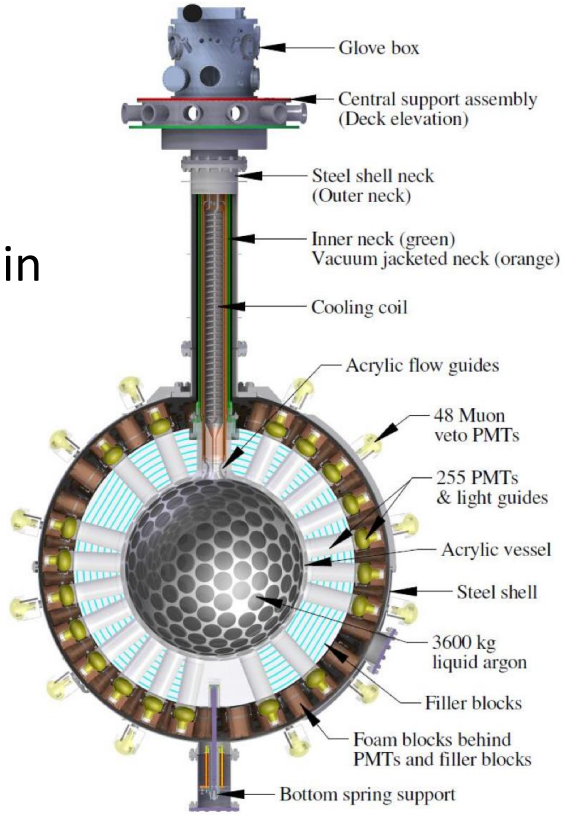


DURHAM (non STFC)

STANDARD WIMPS – DEAP-3600



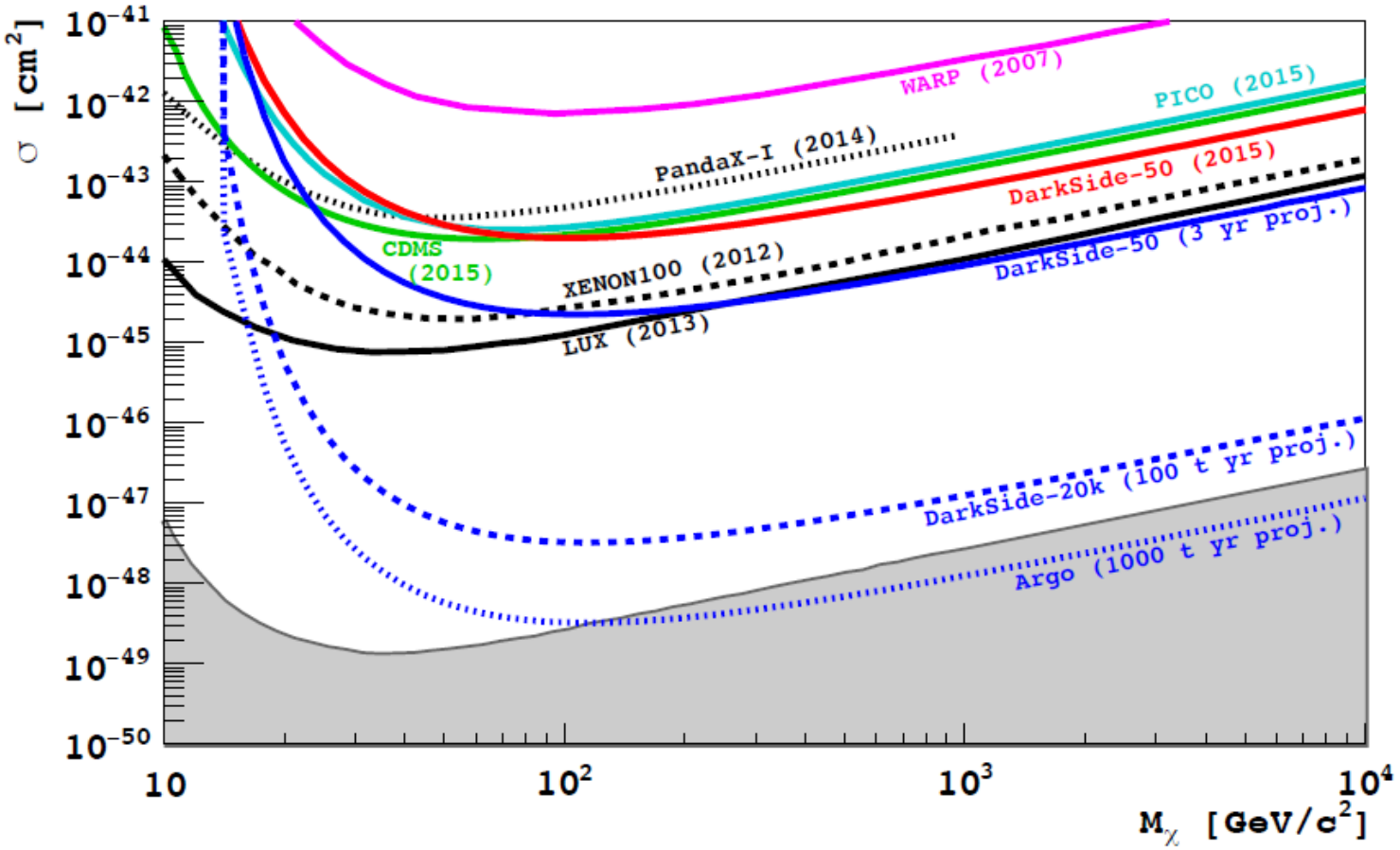
Recent developments in depleted Ar (1,600x depleted relative to atmospheric Ar) mitigate triggering requirements for large-scale LAr detectors, moving the scale at which pile-up limits PSD power to O(500-T)



20-T LAr detector capital proposal to Italy, US, engineering proposal to Canada, LoI to CERN SPSC, European bid preparation underway

STANDARD WIMPS – TWO-PHASE ARGON

Fiorillo (DarkSide), IDM2016



HA notes

Actual result (2015)

Sensitivity prediction

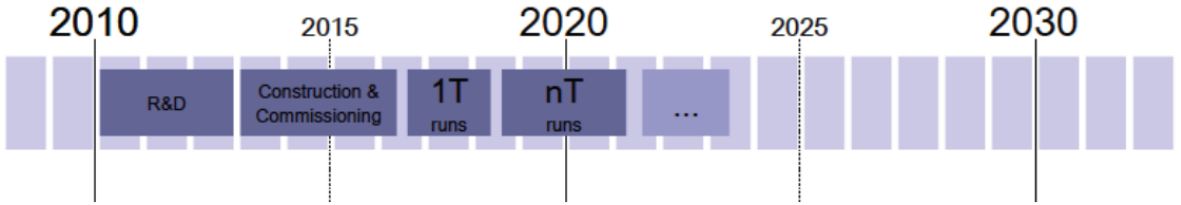
G2 (3.6-T) abandoned

DS-20k starting in 2020 (?)

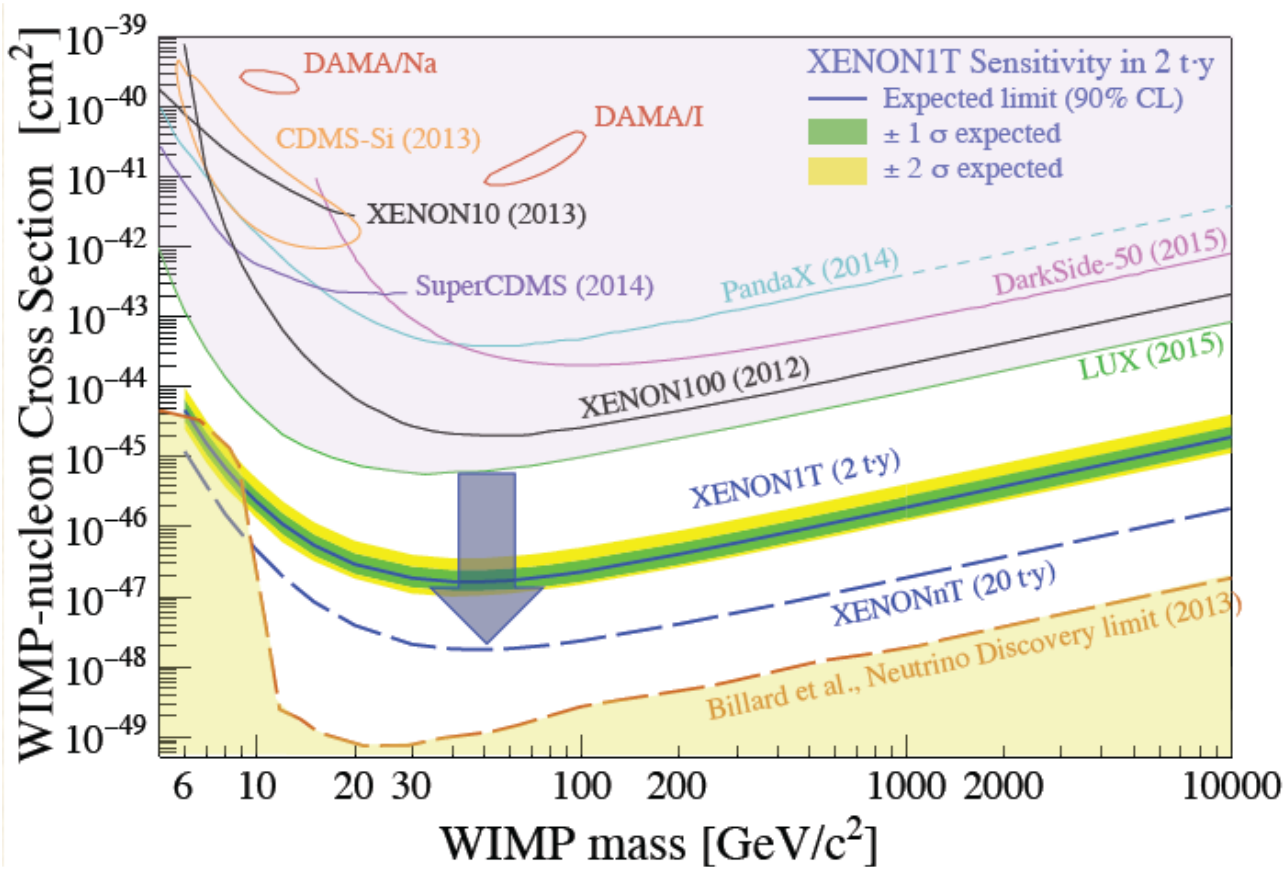
STANDARD WIMPS – XENONnT

XENONnT
M. Galloway , IDM2016

XENON1T/
nT



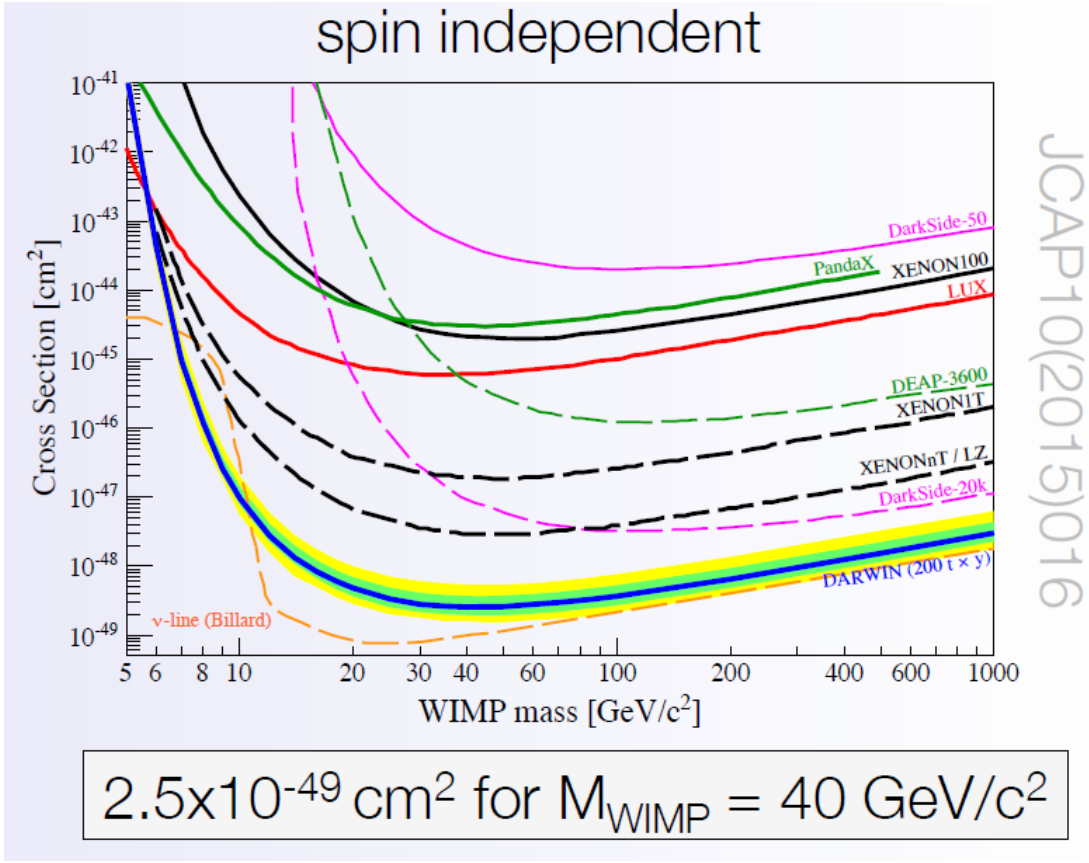
- 7 tonne LXe TPC, 5.6 tonne fiducial
- Reusing X1T infrastructure for rapid upgrade
- Construction phase 2017-18



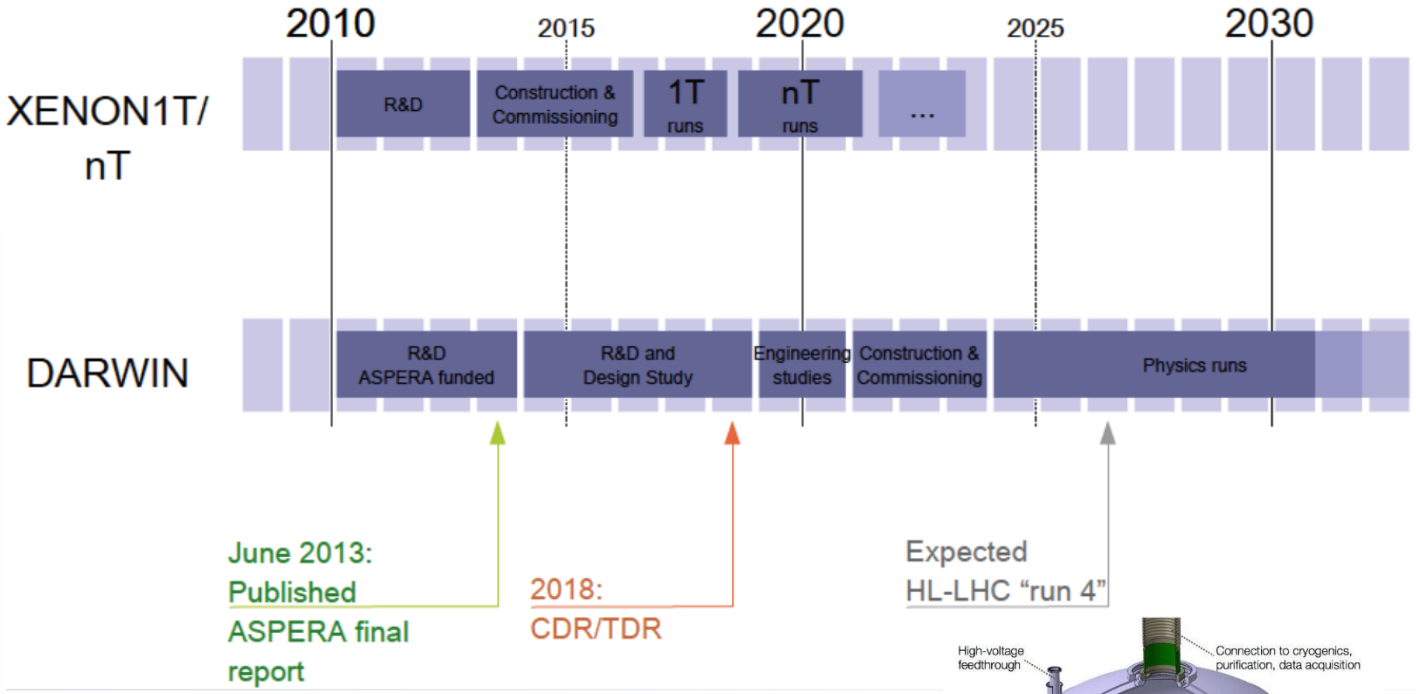
STANDARD WIMPS – DARWIN

DARWIN

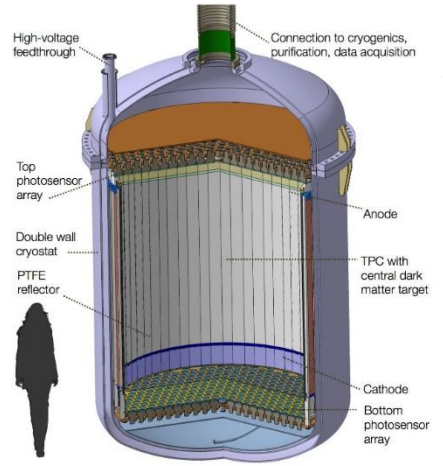
A. Colijn, IDM2016



2.5×10^{-49} cm² for $M_{WIMP} = 40$ GeV/c²

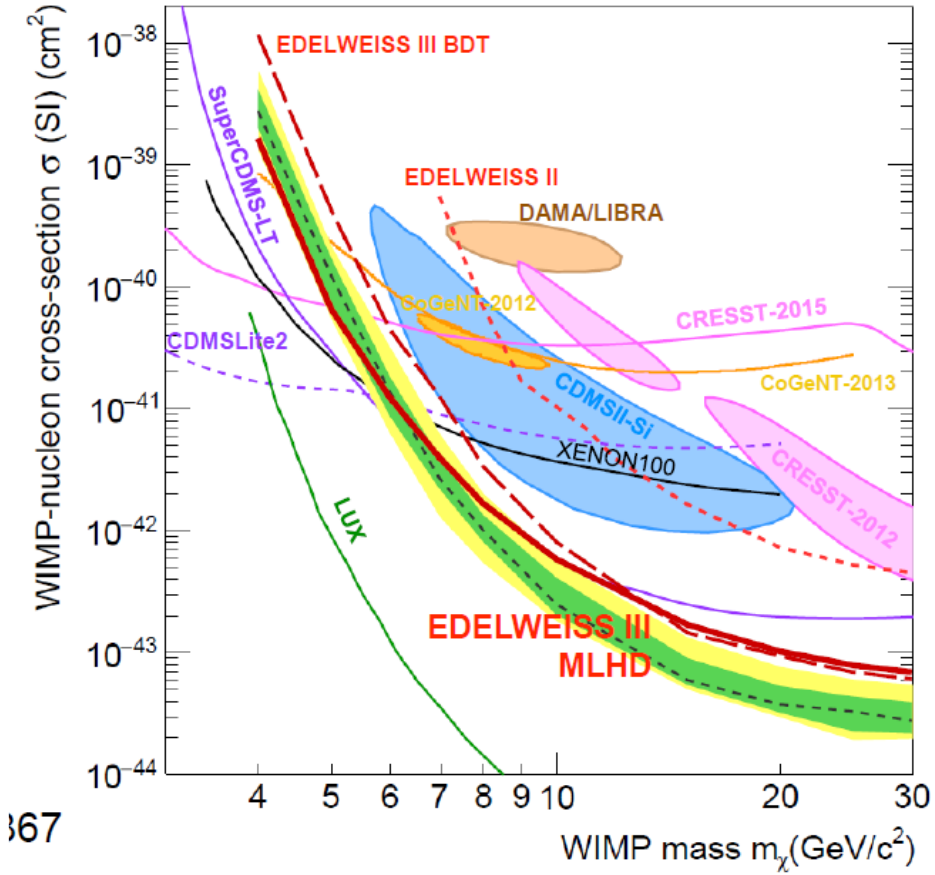


- 40 tonne LXe TPC, 50 tonne LXe total
- (no longer LXe/LAr)
- Pushing down to neutrino floor

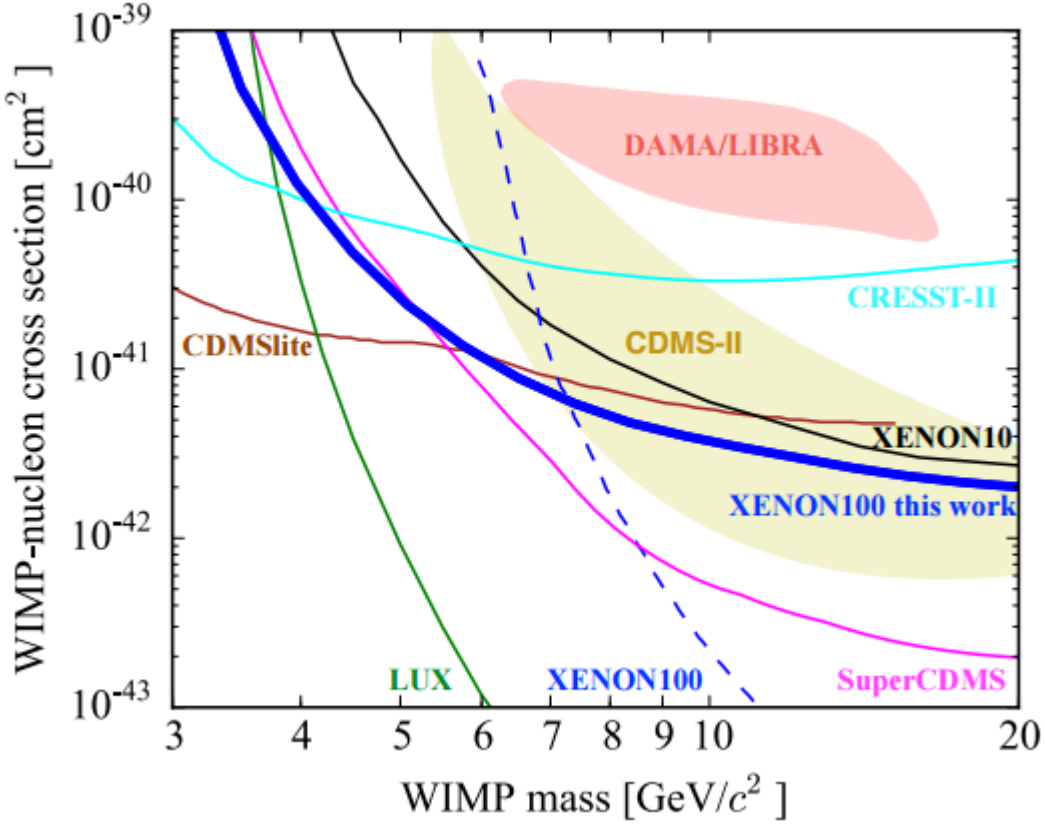


LOW MASS WIMPS – OTHER RECENT RESULTS

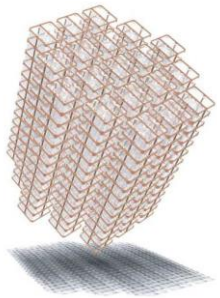
EDELWEISS
arXiv:1607.03367



XENON100 "S2-ONLY"
arXiv:1605.06262



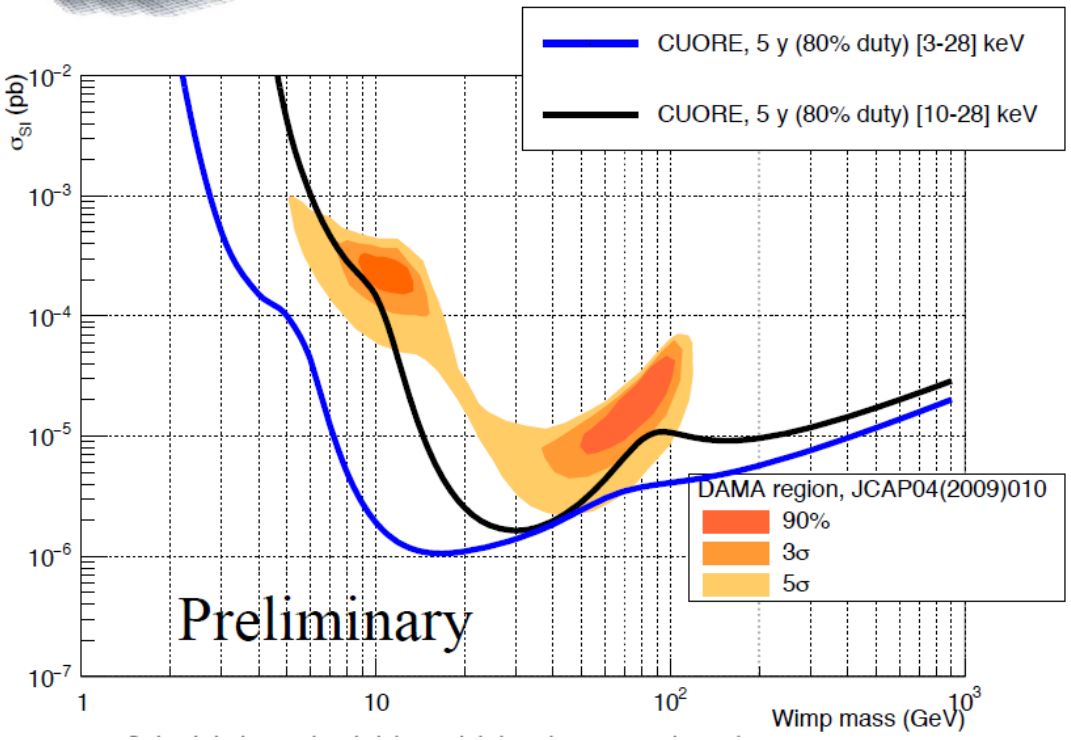
ANNUAL MODULATION – OTHERS



CUORE (TeO_2 BOLOMETERS)

G. Piperno, IDM2016

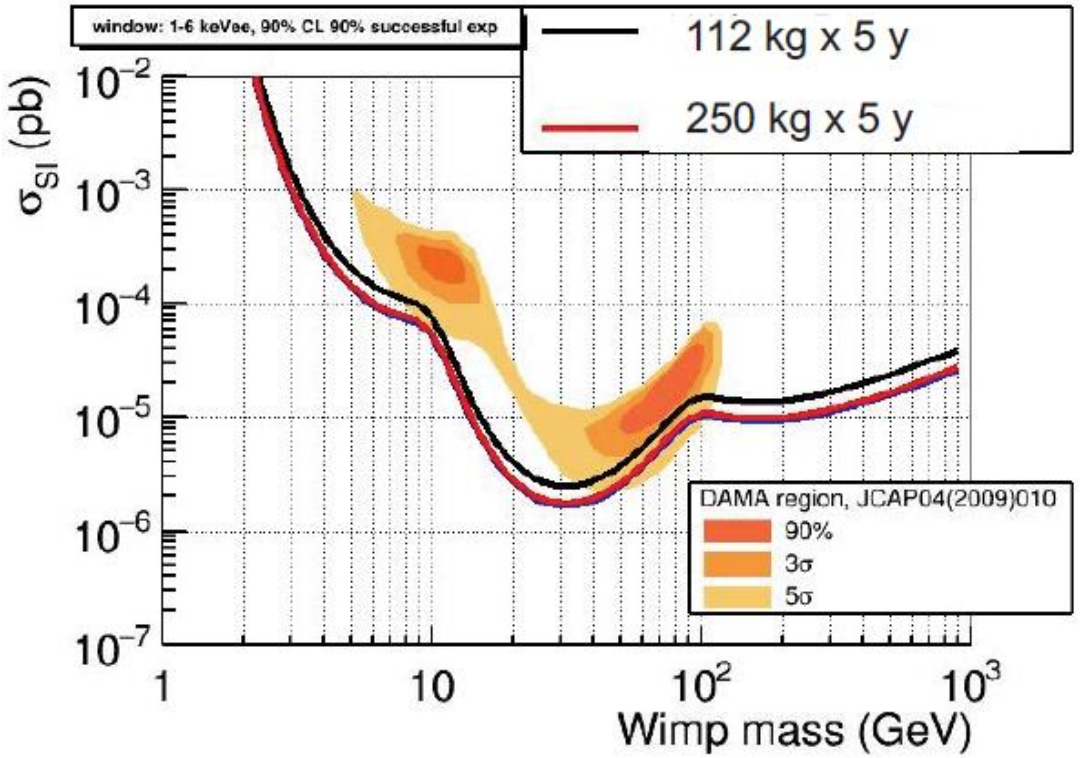
(predicted sensitivity)



ANAIS (NaI CRYSTALS)

SARSA, IDM2016

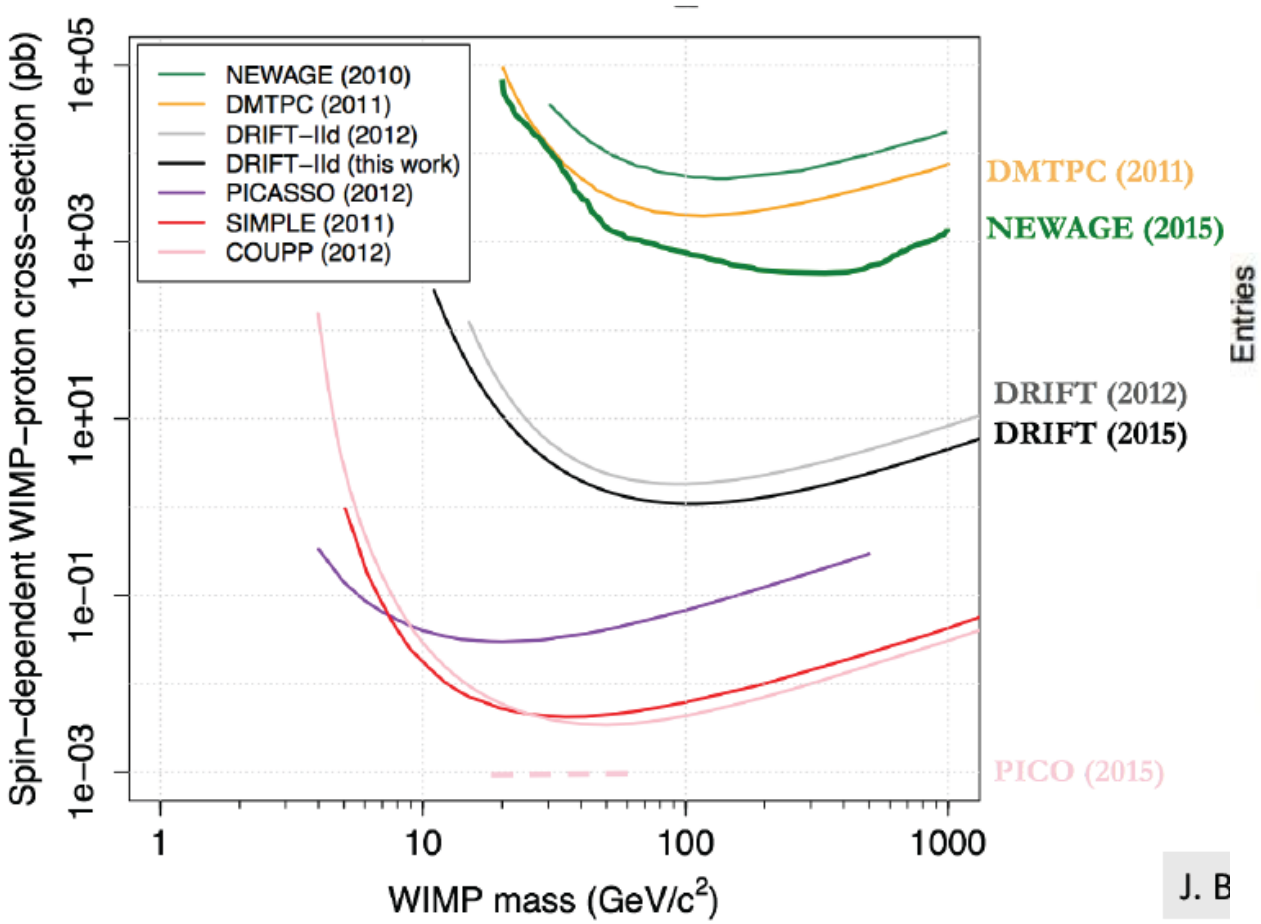
(predicted sensitivity)



DIRECTIONAL SEARCHES – OTHERS

DRIFT

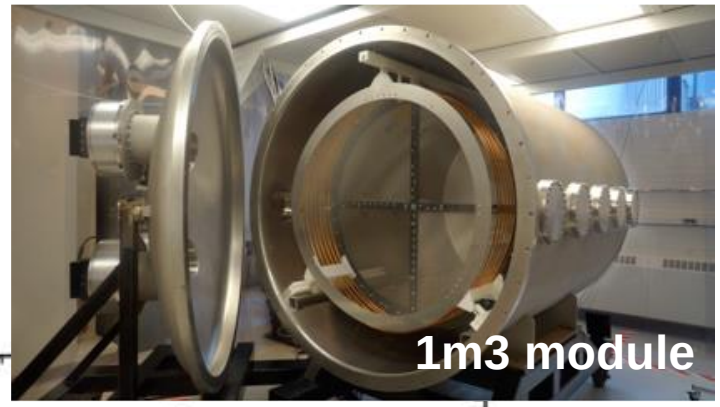
arXiv:1410.7821

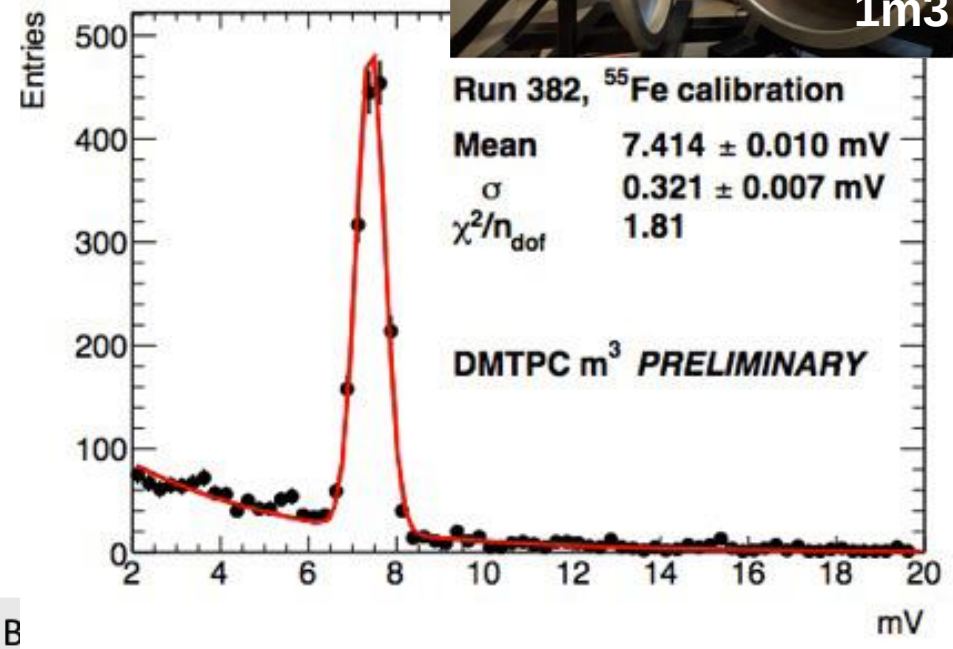


DMTPC

G. DRUITT, IDM2016

RHUL





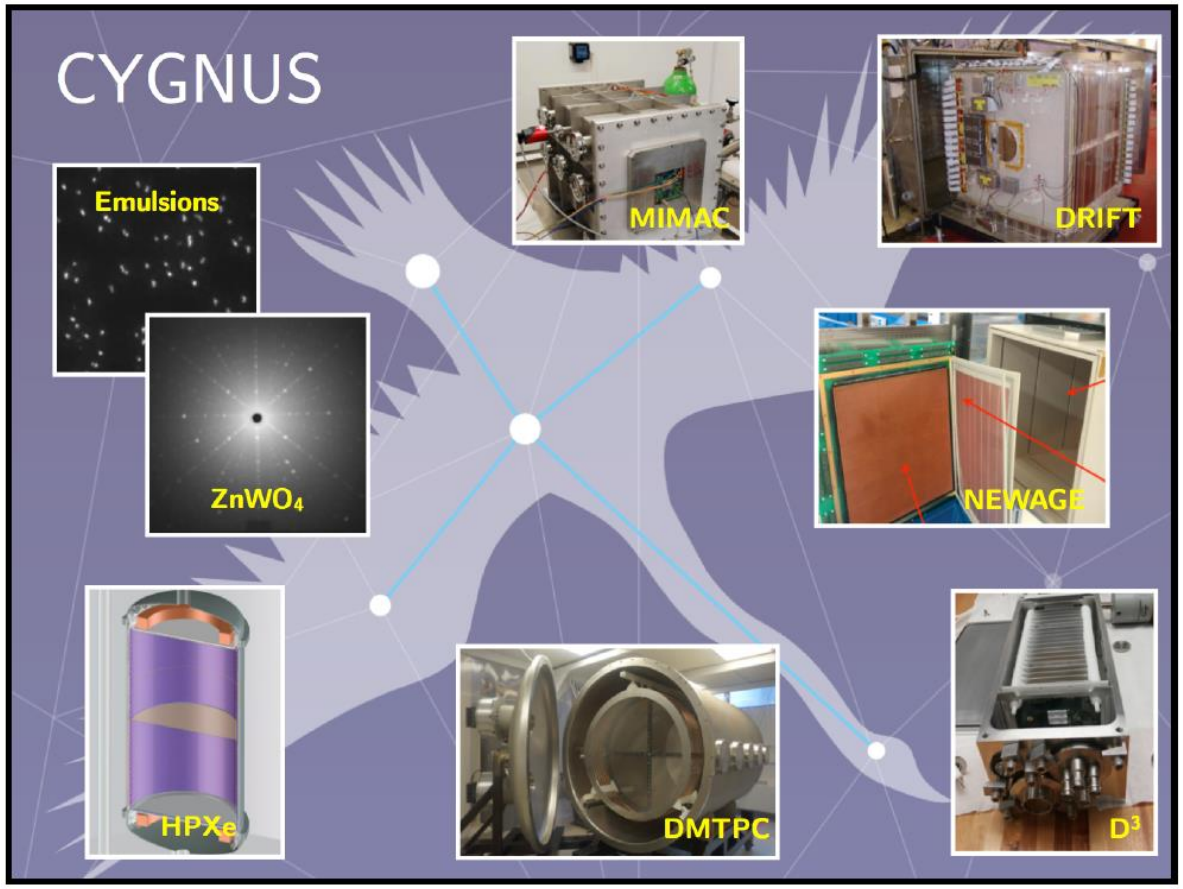
DIRECTIONAL SEARCHES – PROSPECTS

CYGNUS Collaboration

N. Spooner

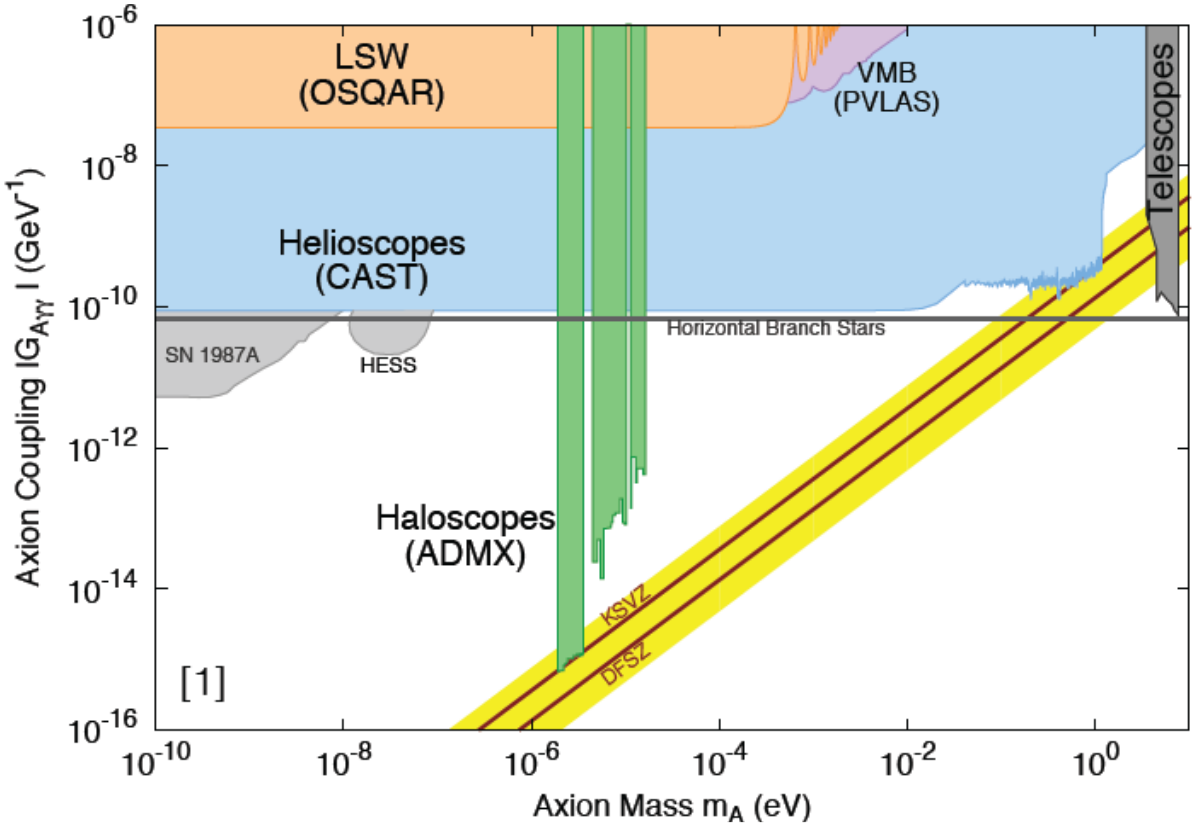
Two existing LOIs cover:

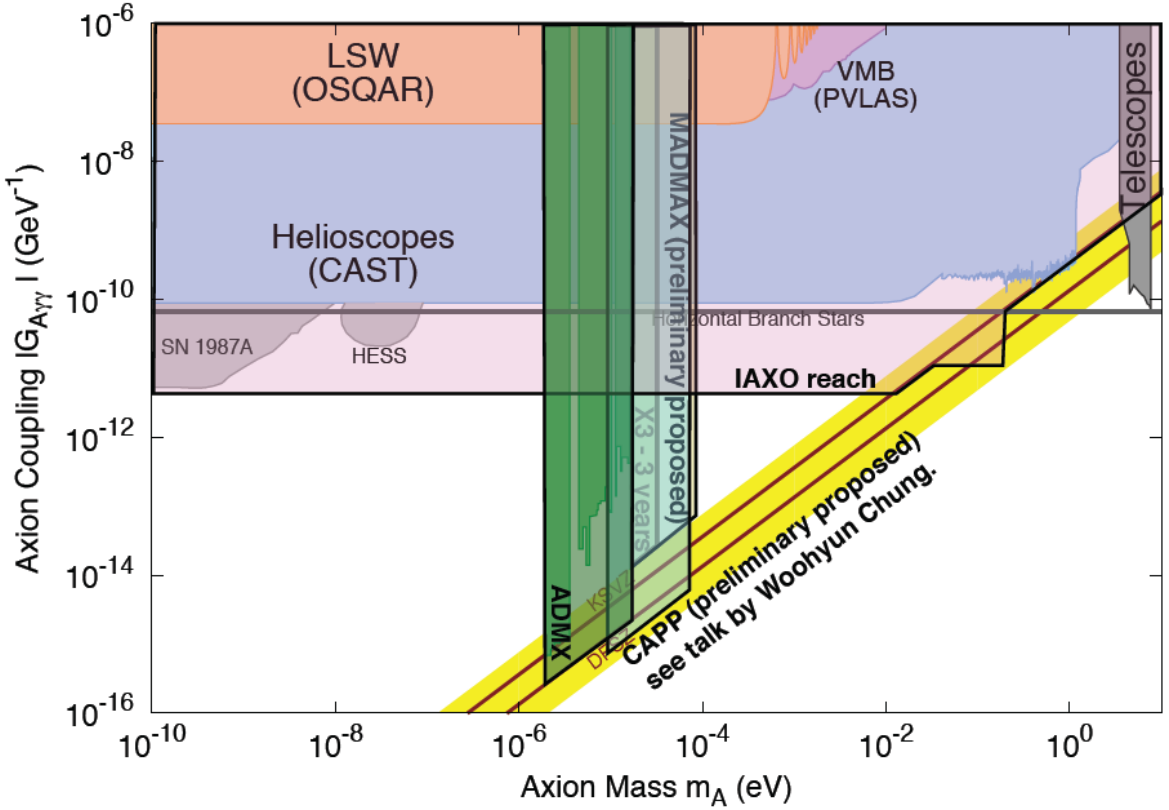
- Experimental efforts on directional detection including NEWS (emulsions at LNGS) and other **non-gas efforts**
- **CYGNUS-TPC**
  (all the TPC groups, France, Italy, Japan, US, UK, Australia)
- The first stage planned is two ~8 m^3 detectors,
  in the North (Boulby, UK) and in the South (Stawell, AUS)
  Various funds secured and vessels designed



Sheffield, RHUL, Edinburgh
(mostly non STFC)

AXIONS



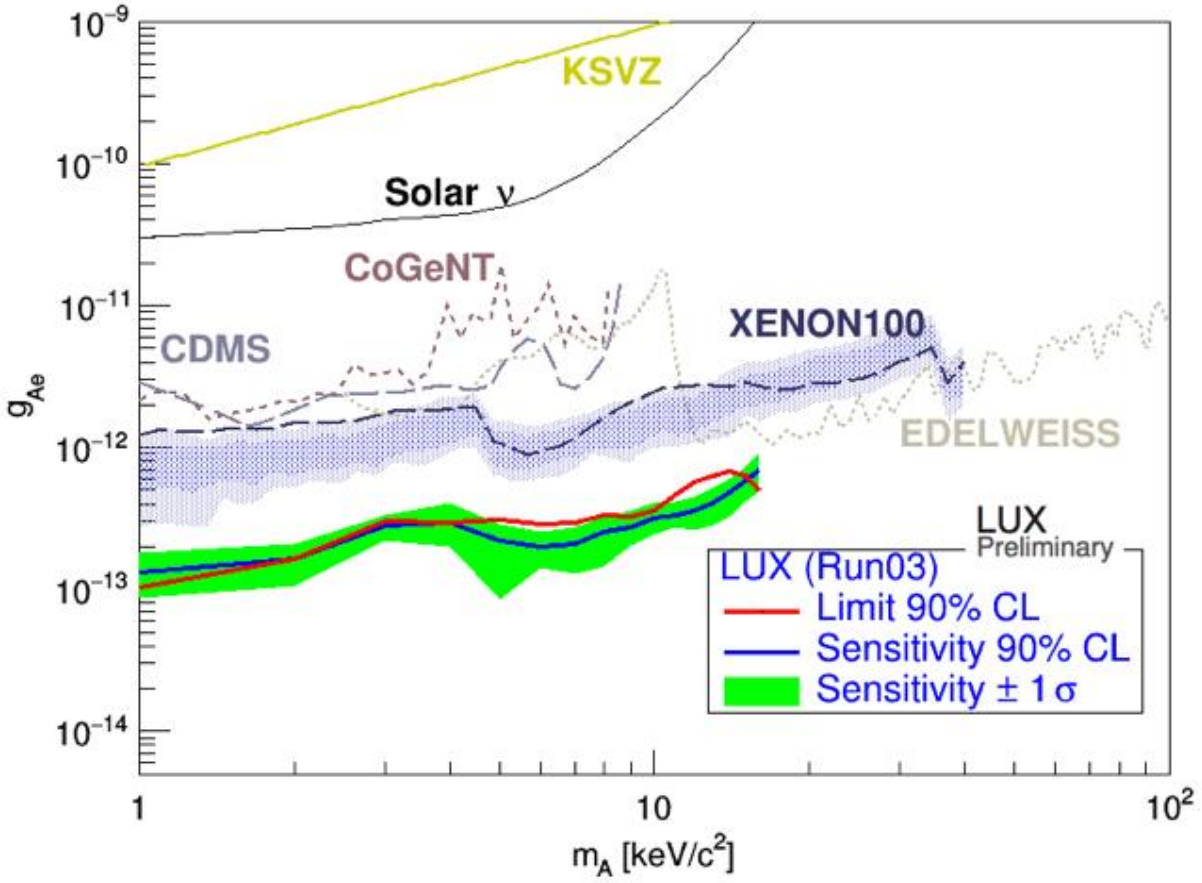


Review by E. Daw at IDM2016
Review by A. Ringwald at IDM2016

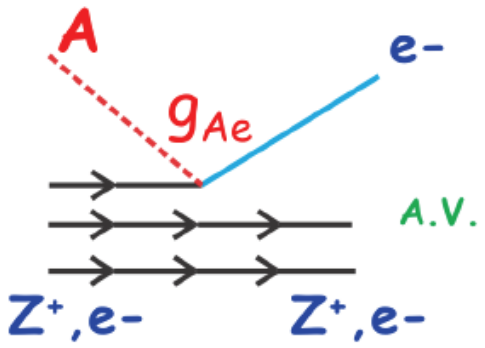
(GALACTIC) AXION-LIKE PARTICLES (ALPS)

LUX

MF Marzioni IDM2016

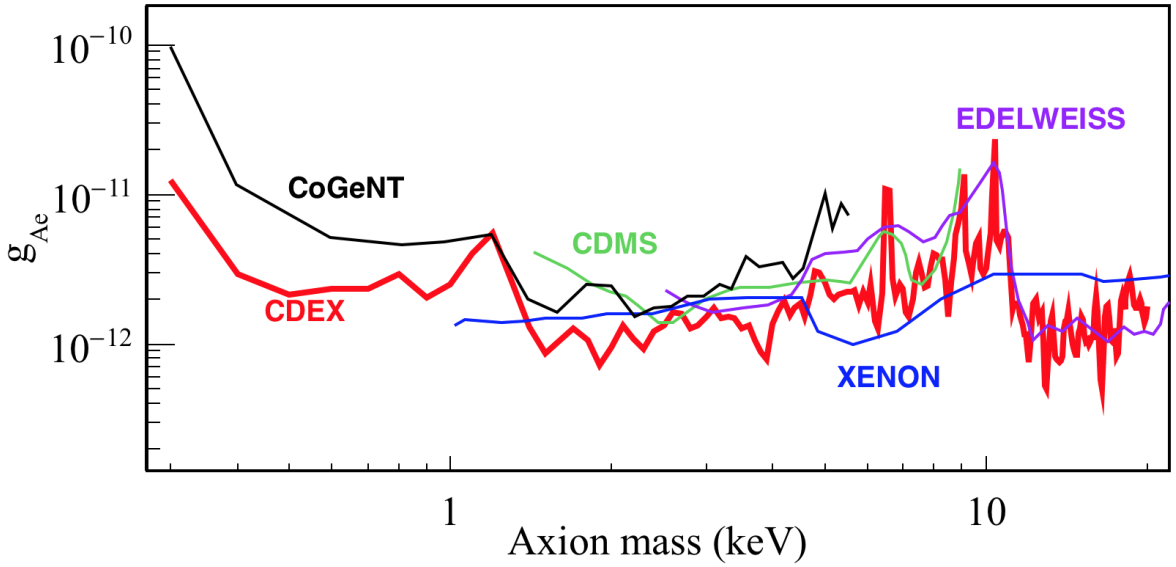


Axio-electric effect



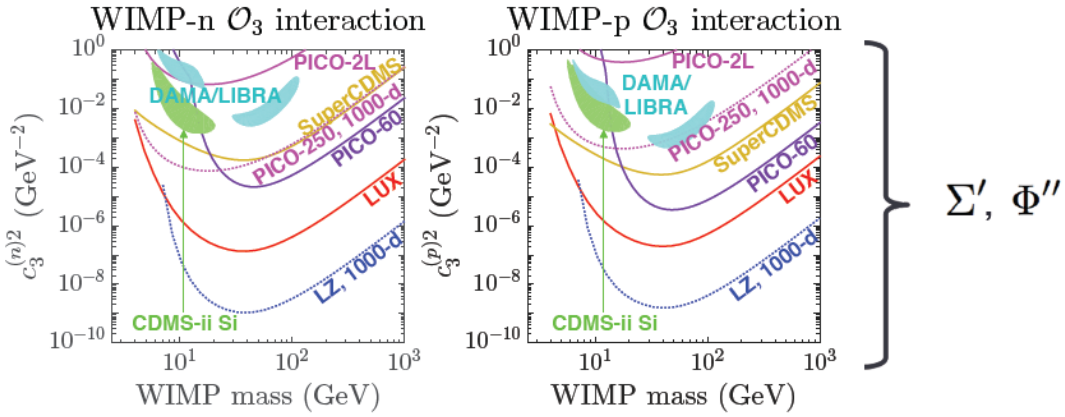
CDEX

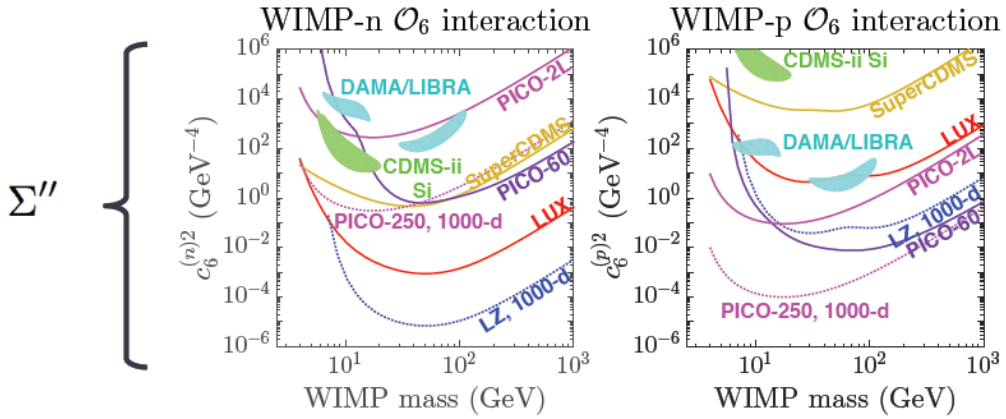
Phys. Rev. D 93, 092003



NON-RELATIVISTIC EFT LIMITS

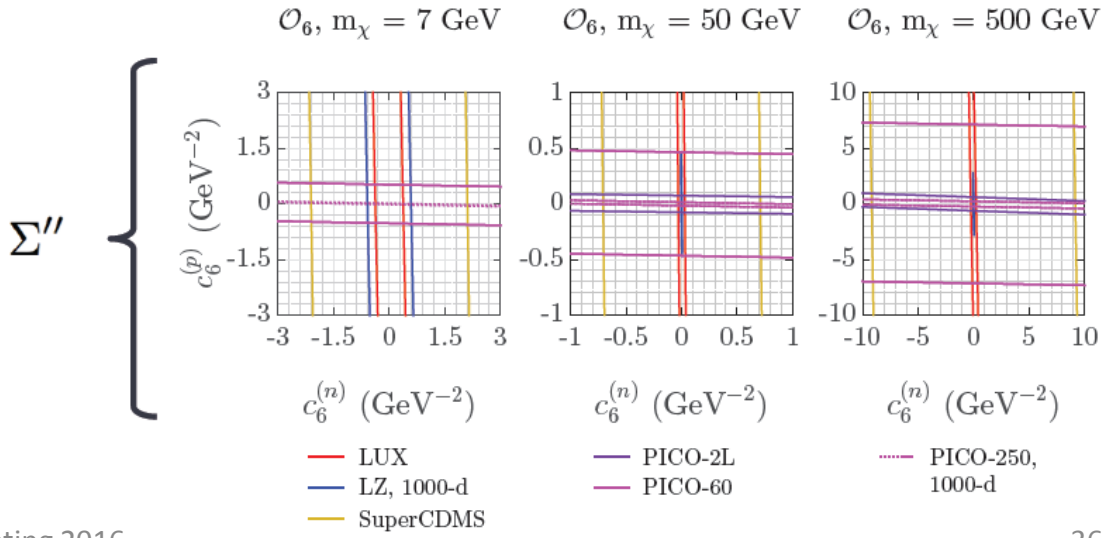
- EFT to address momentum- & velocity-dependent interactions in a complete & model-independent way:
  Fitzpatrick et al. arXiv:1203.3542, Fitzpatrick et al. arxiv:1211.2818, Anand et al. arXiv: 1308.6288, Anand et al. arXiv: 1405.6690





N. Larsen, IDM2016

Some examples, see full set here
Limits on some operators to left
Some Isospin independent limits below

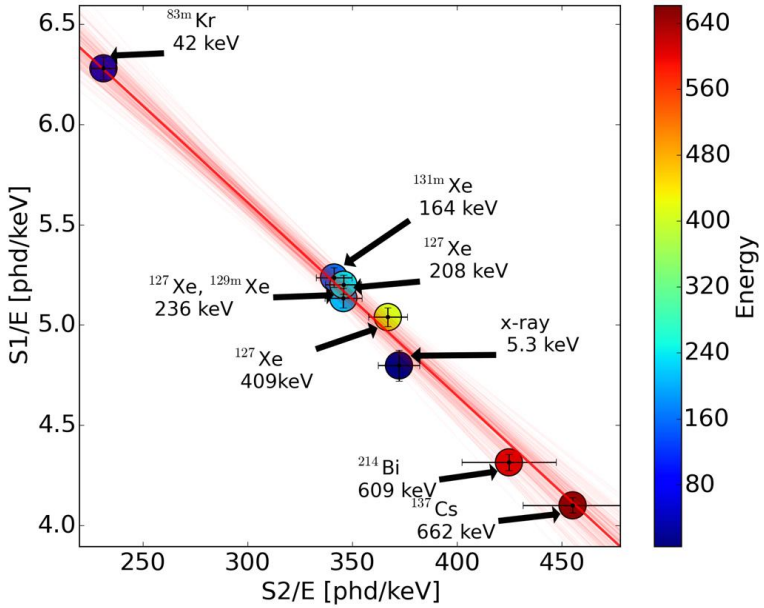


LIQUID XENON NR+ER CALIBRATION

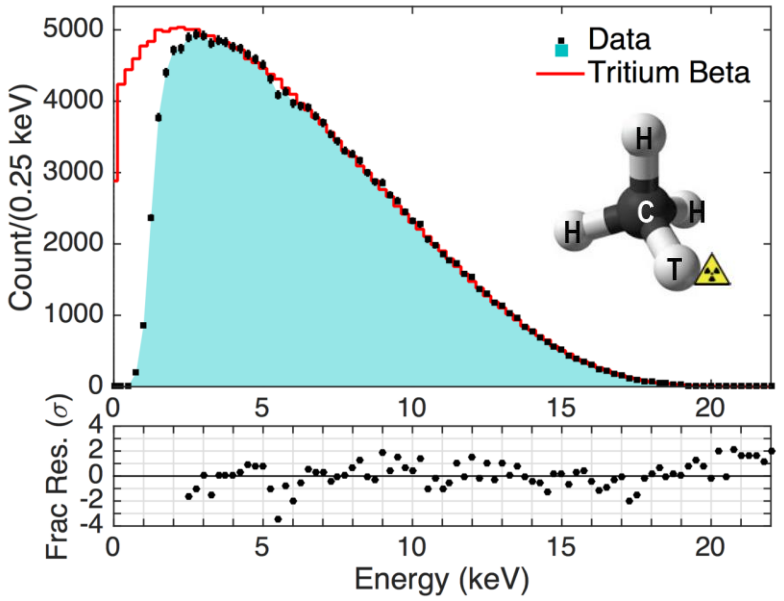
- Scintillation & ionisation yields to ~1 keV ER and ~1 keV NR
- Single W-value = 13.7 eV
- ER yields with tritiated methane
- NR yields with DD generator

$$E = (n_e + n_\gamma) \cdot W.$$

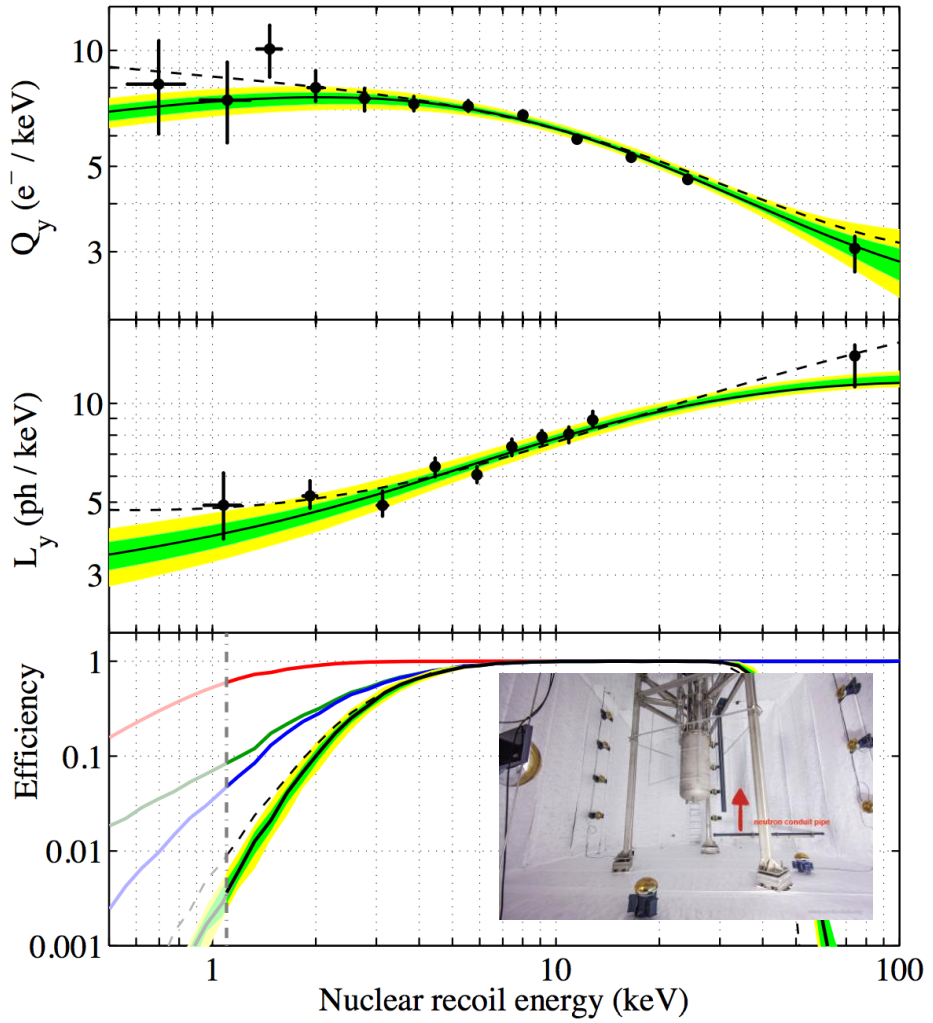
$$E_{nr} = \mathcal{L}^{-1} \cdot (n_e + n_\gamma) \cdot W.$$



PRD 93, 072009 (2016)



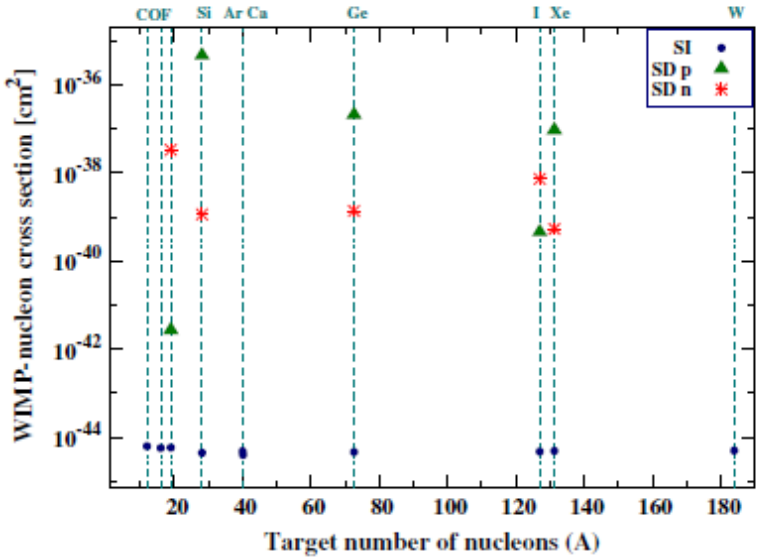
PRL 116, 161301 (2016)

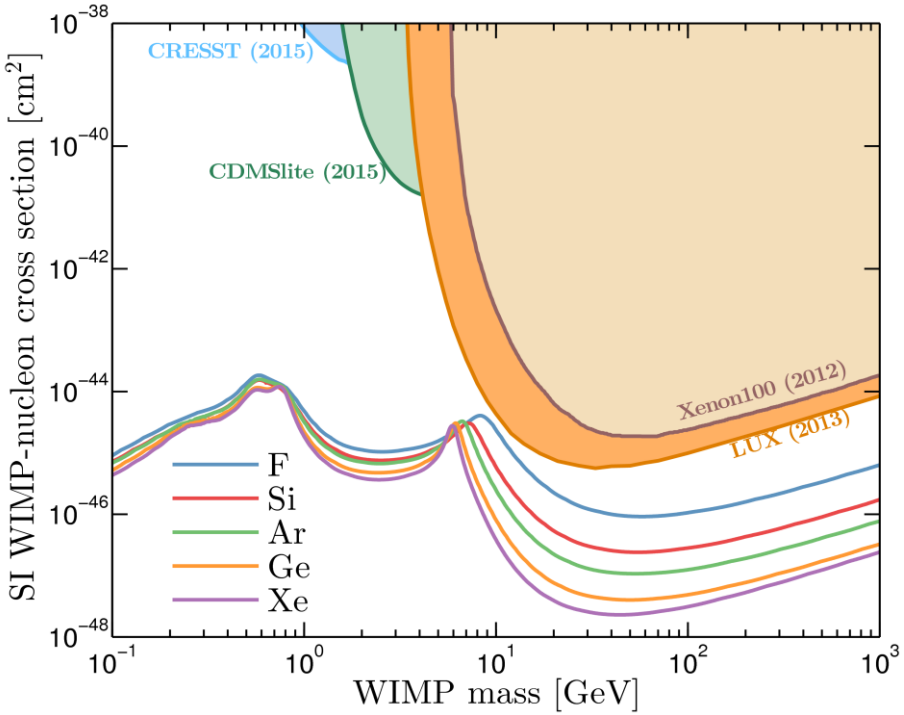


NEUTRINO FLOOR(S)

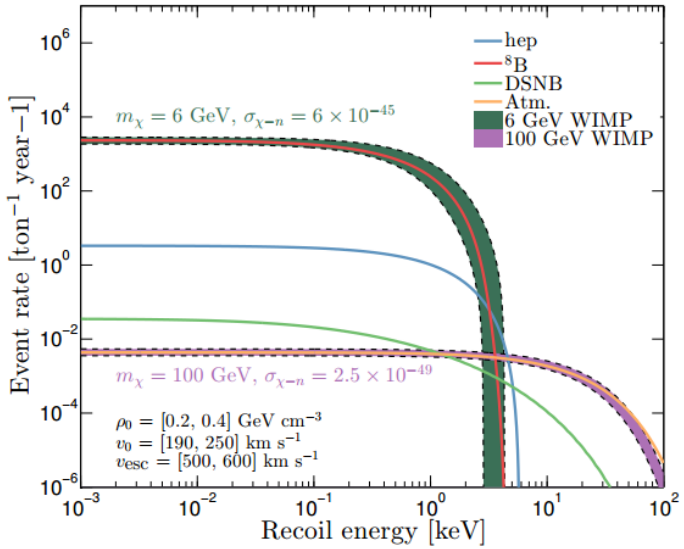
- B-8 solar neutrinos look like 6 GeV WIMPs at 6×10^{-45} cm^2
- Atm neutrinos look like 100 GeV WIMPs at 2.5×10^{-48} cm^2
- Several strategies proposed to overcome 'floor': very large detectors, better flux measurements, directionality, time, multi-target, etc.
  All easier said than done… See e.g. Fairbairn or O'Hare at IDM

Ruppin et al, PRD 90, 083510 (2014)

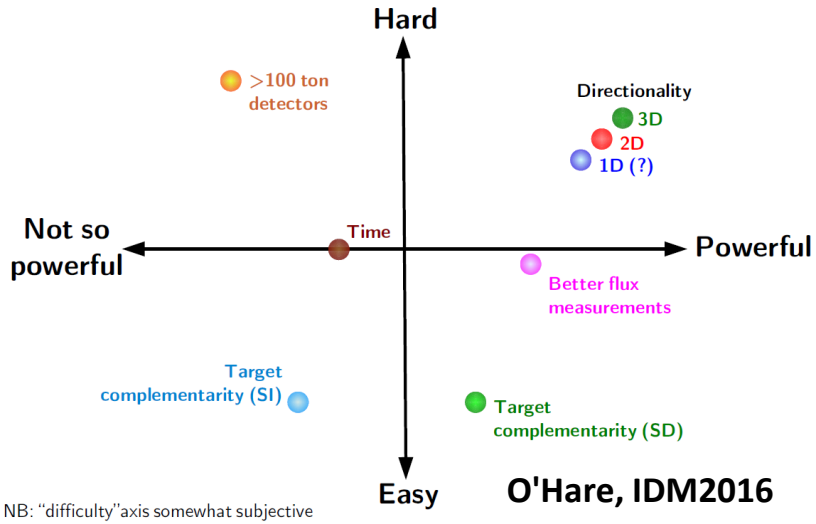




O'Hare, arXiv:1604.03858



Strategies for the neutrino floor



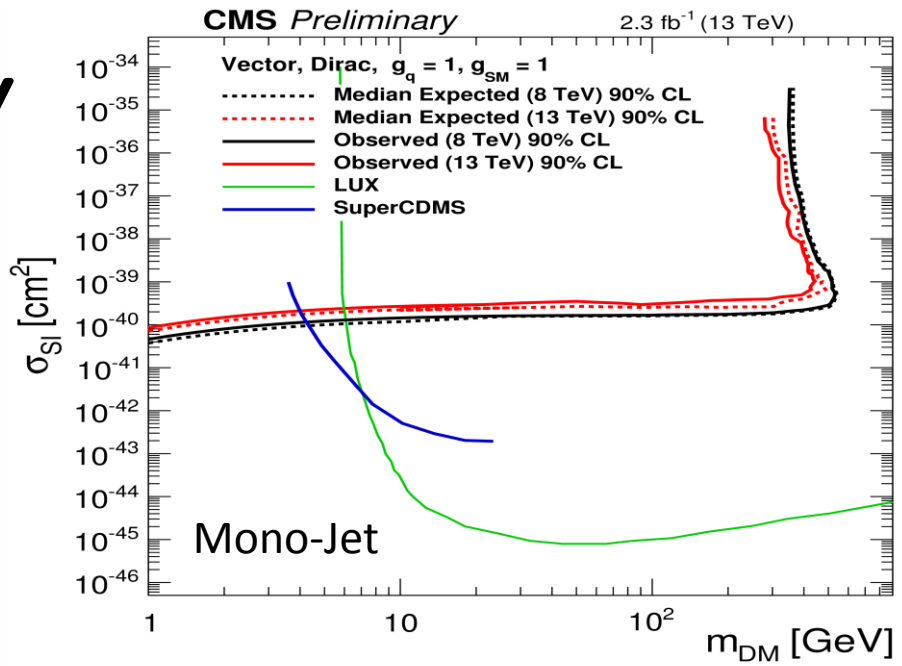
NB: "difficulty"axis somewhat subjective

O'Hare, IDM2016

DD & LHC - COMPLEMENTARITY

Mono-X results from the LHC

"X"	Expt.	Run 1 (20 fb^{-1} @ 8 TeV)	Run 2 (2-3 fb^{-1} @ 13 TeV)
>=jet	ATLAS	EPJC 75 (2015) 299 (hep-ex 1502.01518)	Submitted to PRD (hep-ex 1604.07773)
	CMS	EPJC 75 (2015) 235 (hep-ex 1408.3583)	CMS-PAS-EXO-16-013
≥2 jets	CMS	Submitted to EPJC (hep-ex 1603.08914)	
photon	ATLAS	PRD 91(2015)012008 (hep-ex 1411.1559)	JHEP06(2016)059 (hep-ex 1604.01306)
	CMS	PLB 755 (2016) 102 (hep-ex 1410.8812)	CMS-PAS-EXO-16-014
$W (\to \ell\nu)$	ATLAS	JHEP 09 (2014) 037 (hep-ex 1407.7494	
	CMS	PRD 91 (2015) 092005 (hep-ex 1408.2745)	
$Z (\to \ell\ell)$	ATLAS	PRD 90 (2014) 012004 (hep-ex 1404.0051)	
	CMS	PRD 93 052011 (2016) (hep-ex 1511.09375)	
W or $Z (q\bar{q})$	ATLAS	PRL112 (2014) 041802 (hep-ex 1309.4017)	ATLAS-CONF-2015-080
	CMS	CMS-PAS-EXO-12-055	(CMS-PAS-EXO-16-013)
$H (\to b\bar{b})$	ATLAS	PRD 93 072007 (2016) (hep-ex 1510.06218)	ATLAS-CONF-2016-019
$H (\to \gamma\gamma)$	ATLAS	PRL 115 (2015) 131801 (hep-ex 1506.01081)	
$H (\to 4l)$	ATLAS		ATLAS-CONF-2015-059
$t\bar{t}$ or t	CMS	JHEP 06 (2015) 121 (hep-ex 1504.03198)	CMS-PAS-EXO-16-017
bb	CMS		CMS-PAS-B2G-15-007
t/b jet	ATLAS	EPJC75 (2015) 92 (hep-ex 1410.4031)	



(CMS-PAS-EXO-16-013)