Imperial College London

MINING FOR WIMPS

THE SEARCH FOR GALACTIC DARK MATTER UNDERGROUND

Henrique Araújo

Imperial College London

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SUSY2014:
The 22nd International Conference on Supersymmetry and Unification of Fundamental Interactions

OUTLINE

- Dark matter candidates
- How to catch a WIMP
- Technologies
- The front line
- The (near) future

Motivation →

DARK MATTER CANDIDATES

G. Bertone

- **WIMPs**

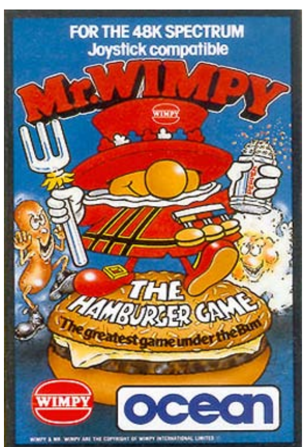
  Solve DM problem

  Electroweak stabilisation

- **Axions**

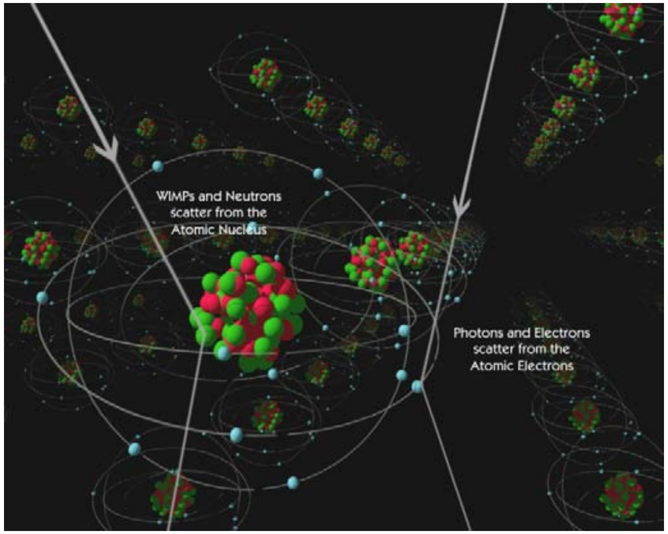
  Solve DM problem

  Strong CP problem



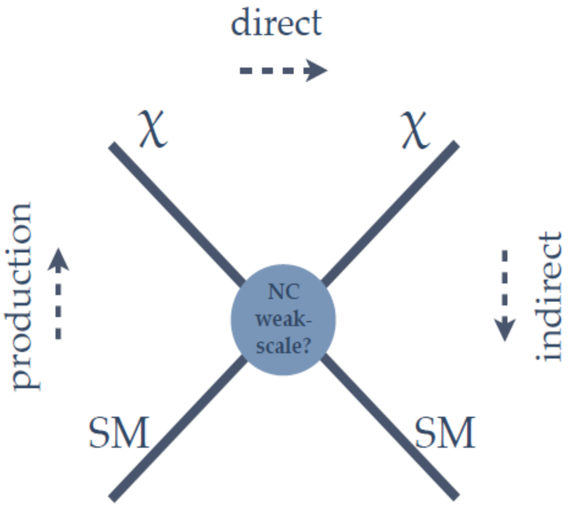
- Focus on WIMPs: stable, neutral, cold, heavy particles, interacting via gravity – and hopefully the weak force
- Can solve the DM problem in all its glory: astrophysical, cosmological and particle physics
- Λ-CDM was made for WIMPs; but there are puzzles too: e.g. why is their present density similar to that of baryons?

HOW TO CATCH A WIMP



1. Direct detection (scattering XS)

- **Nuclear (atomic) recoils from elastic scattering**
- A- & J-dependence, annual modulation, directionality
- Galactic DM at the Sun's position – our DM!
- Mass measurement (if not too heavy)



2. Indirect detection (decay, annihilation XS)

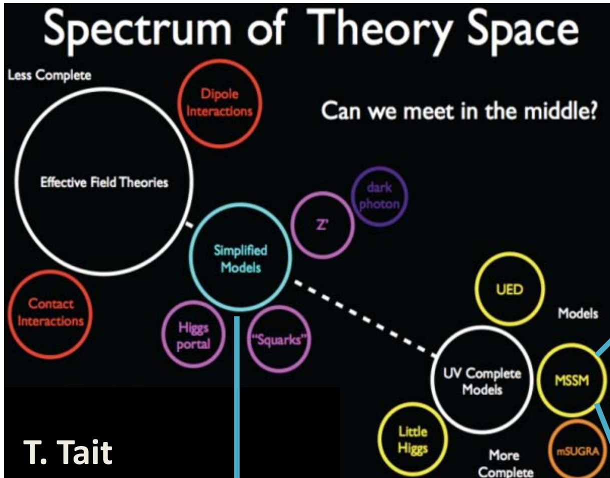
- High-energy cosmic-rays, γ-rays, neutrinos, etc.
- Over-dense regions, annihilation signal $\propto n^2$
- Very challenging backgrounds

3. Accelerator searches (production XS)

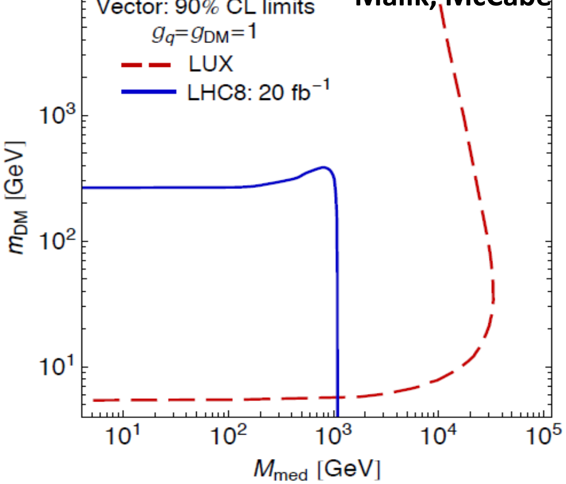
- MET, mono-X, dark photons, etc.
- Mass measurement may be poor at least initially
- Can it establish that new particle is the DM?

COMPLEMENTARITY – PART I

DIRECT/ACCELERATOR

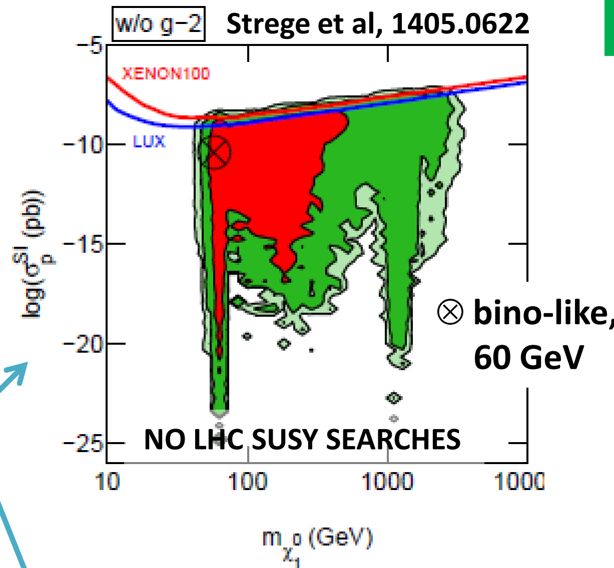


Buchmueller, Dolan, Malik, McCabe

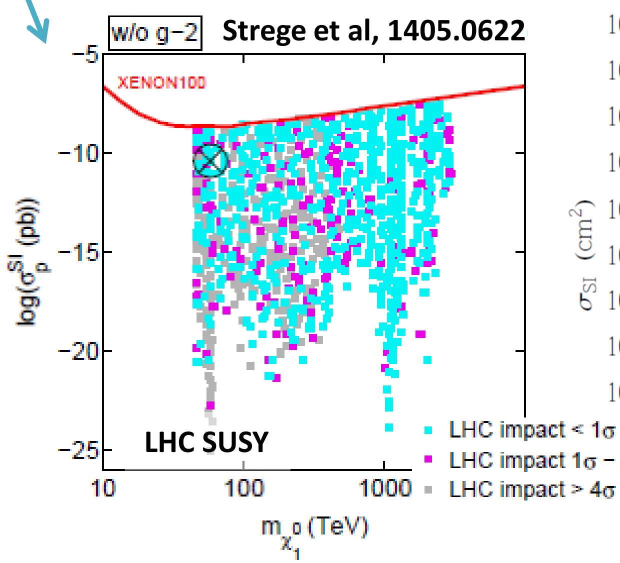


MSSM-15

Strege et al, 1405.0622

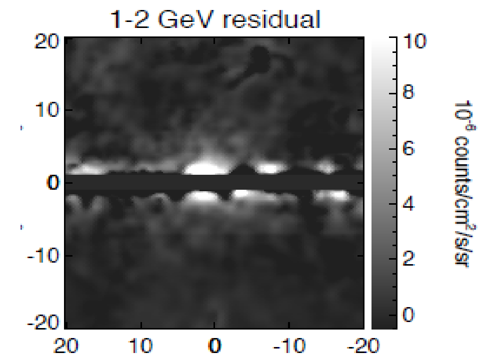


Strege et al, 1405.0622



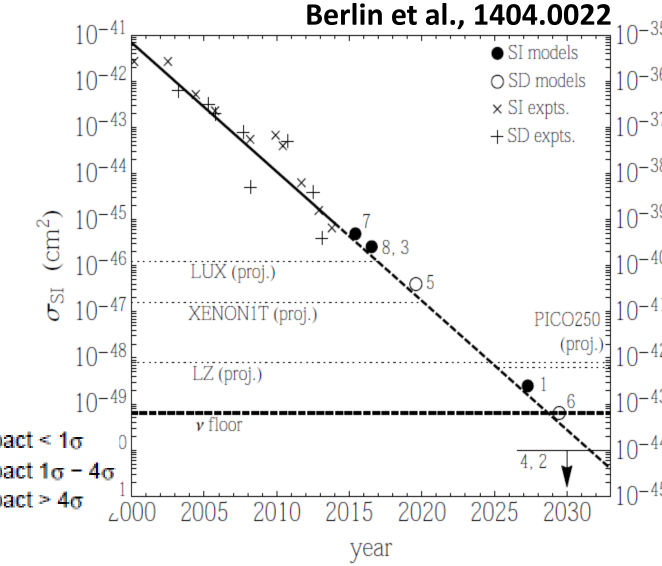
DIRECT/INDIRECT

Daylan et al 1402.6703



m_{DM}~30 GeV, $\langle\sigma v\rangle$~10^{-26} cm^3/s

Berlin et al., 1404.0022



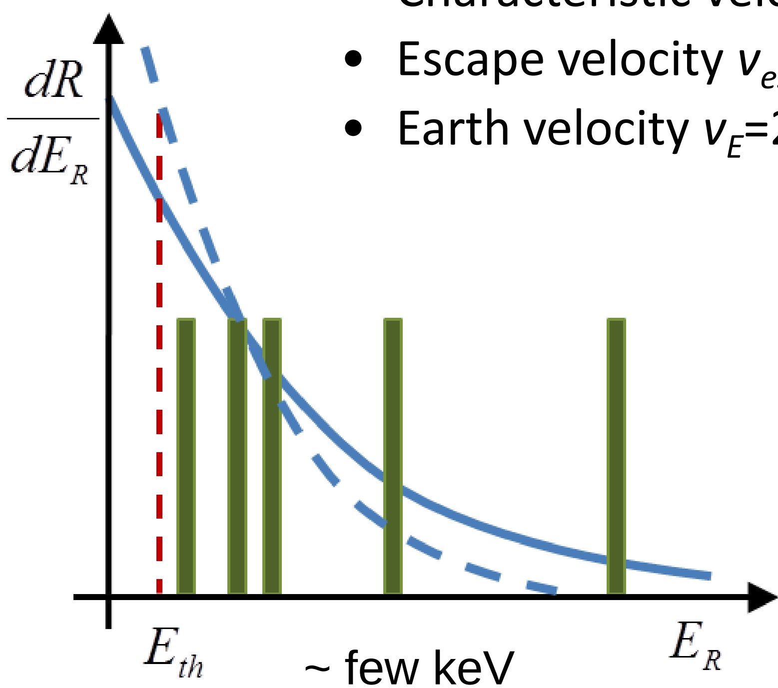
WIMP-NUCLEUS ELASTIC SCATTERING RATES

The ‘spherical cow’ galactic model

- DM halo is 3-dimensional, stationary, with no lumps
- Isothermal sphere with density profile $\rho \propto r^{-2}$
- Local density ρ_0 ~ 0.3 GeV/cm^3 (~1/pint for 100 GeV WIMPs)

Maxwellian (truncated) velocity distribution, f(v)

- Characteristic velocity v_0=220 km/s
- Escape velocity v_{esc}=544 km/s
- Earth velocity v_E=230 km/s



Nuclear recoil energy spectrum [events/kg/day/keV]

$$\frac{dR}{dE_R} = \frac{\rho_0 \sigma_A}{2 m_\chi \mu_A^2} F^2(q) \int_{v_{\min}}^{v_{\max}} \frac{f(\vec{v})}{v} d^3 v$$

$$\frac{dR}{dE_R} \approx \frac{R_0}{E_0 r} e^{-E_R / E_0 r}, \quad r = \frac{4 m_W m_T}{(m_W + m_T)^2} \leq 1$$

WIMP-NUCLEON ELASTIC SCATTERING XS

- **Coupling to p and n more useful than coupling to nucleus**
  - Compare different targets materials, accelerator & indirect searches
- **Spin-independent (scalar) interaction**

$$\sigma_A^{SI}(q \to 0) = \frac{4\mu_A^2}{\pi}[Zf_p + (A-Z)f_n]^2 \approx \frac{\mu_A^2}{\mu_p^2}\sigma_p A^2$$

  – Note A^2 enhancement factor (coherence) – c/pMSSM within reach

- **Spin-dependent (axial-vector) interaction**

$$\sigma_A^{SD}(q \to 0) = \frac{\mu_A^2}{\mu_p^2}\sigma_{p,n}^{SD}\left[\frac{4}{3}\frac{J+1}{J}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2\right]$$

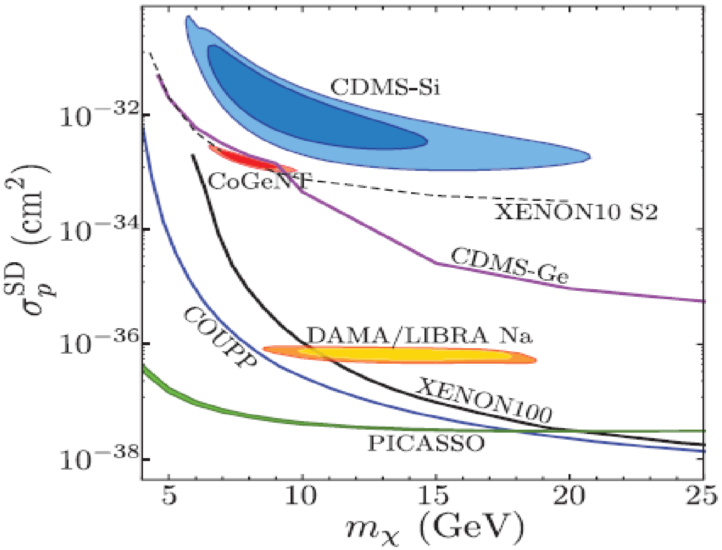
  – Note J (nuclear spin) replaces A^2 enhancement – less sensitive than SI

  – Some targets more sensitive to proton, others to neutron scattering

– **Effective Theory: WIMP-nucleon XS has 6 components, not just these two**
(cf. Fitzpatrick, Haxton, Anand, et al: 1203.3542, 1405.6690)

COMPLEMENTARITY – PART II

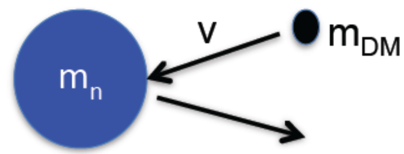
TARGETS : SPIN SENSITIVITY



Isotope	Abundance	J	$\langle S_p \rangle$	$\langle S_n \rangle$
^{19}F [28]	100%	$\frac{1}{2}$	0.441	-0.109
^{23}Na [26]	100%	$\frac{3}{2}$	0.248	0.020
^{29}Si [28]	4.7%	$\frac{1}{2}$	-0.002	0.130
^{73}Ge [28]	7.8%	$\frac{9}{2}$	0.030	0.378
^{127}I [26]	100%	$\frac{5}{2}$	0.309	0.075
^{129}Xe [27]	26.4%	$\frac{1}{2}$	0.010	0.329
^{131}Xe [27]	21.2%	$\frac{3}{2}$	-0.009	-0.272

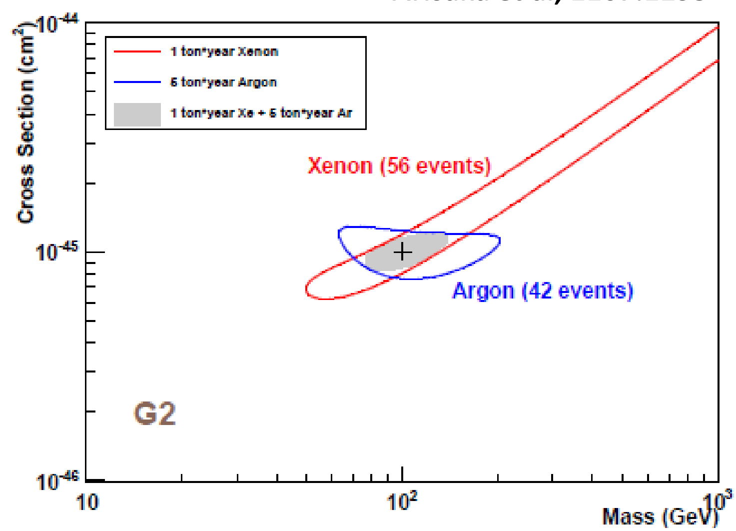
Buckley & Lippincott, 1306.2349

TARGETS : NUCLEAR MASS



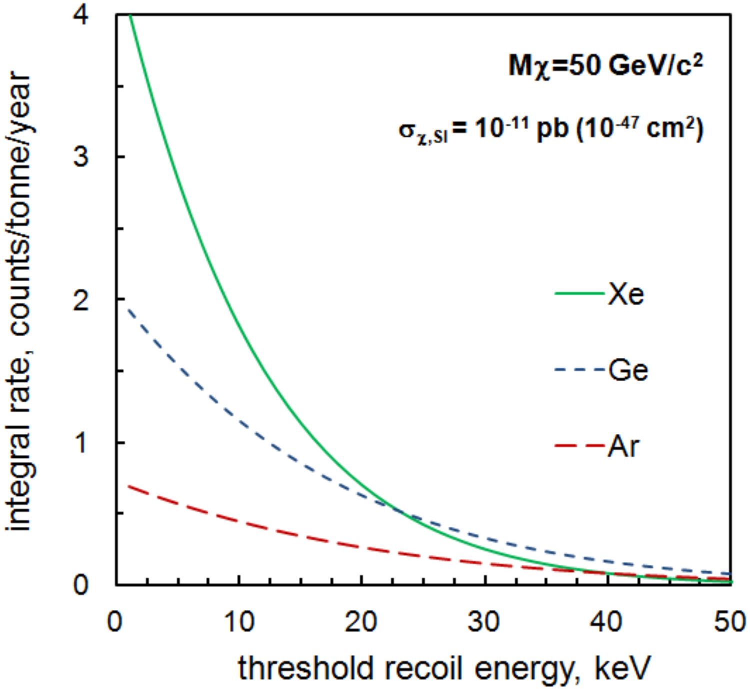
$$E_R \sim \frac{1}{m_n}$$

Arisaka et al, 1107.1295



- Kinematics is a fact of life
- Form Factor is a factor

THE EXPERIMENTAL CHALLENGE



Key requirements

- Large mass x time
  - Low E_R threshold
    - Low background
      - ER/NR discrimination

- Low-energy detection is easy ;)
  - Several technologies allow sub-keV NR detection
- Rare event searches are also easy ;)
  - Not a problem at >100 MeV, think neutrinos
- But doing both is hard!
  - Large is better for shielding against external backgrounds
  - But harder to collect signal 'carriers' from deep inside detector volume

- Also: there is no trigger…

WIMP SEARCH TECHNOLOGY ZOO

Ionisation Detectors

Targets: Ge, Si, CS_2, CdTe

CoGeNT, CDEX, **DAMIC**, DRIFT,
DM-TPC, GENIUS, IGEX, NEWAGE

Light & Ionisation Detectors

Targets: Xe, Ar

ArDM, **LUX**, WARP, DarkSide
Panda-X, **XENON**, ZEPLIN, **LZ**

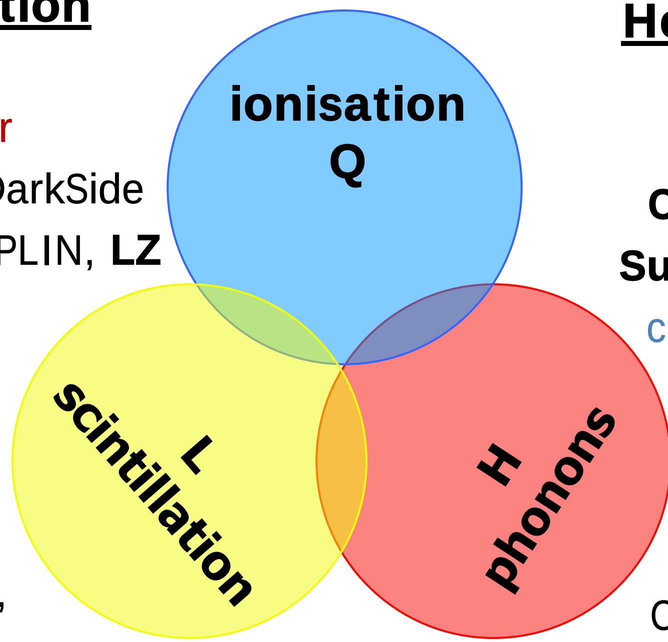
cold (LN_2)

Heat & Ionisation Bolometers

Targets: Ge,Si

CDMS, EDELWEISS
SuperCDMS, EURECA

cryogenic (<50 mK)



Scintillators

Targets: NaI, Xe, Ar

ANAIS, CLEAN, DAMA,
DEAP3600, KIMS, LIBRA,
NAIAD, 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

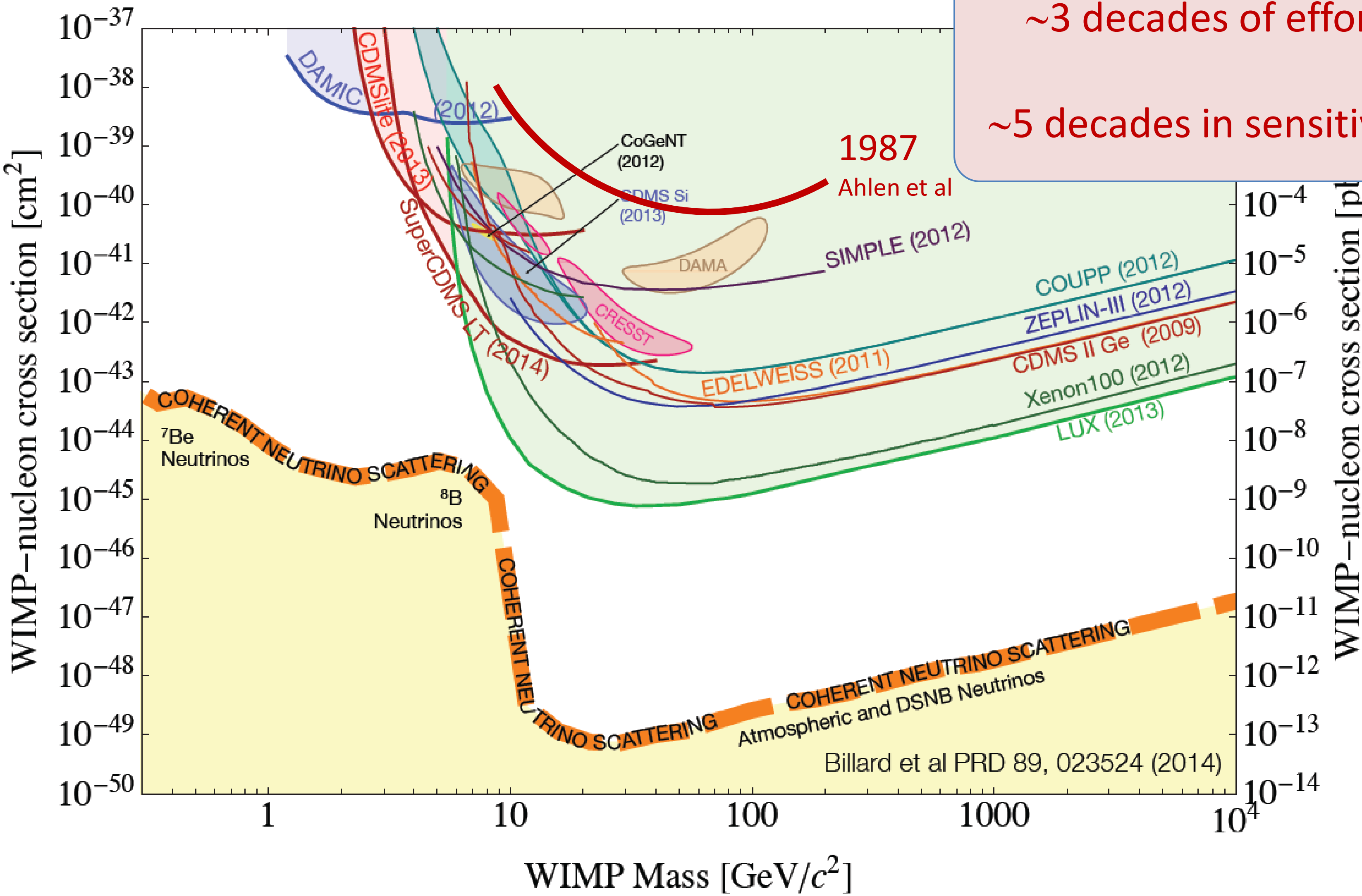
CF_3Br, CF_3I, C_3F_8, C_4F_{10}

COUPP, PICASSO, PICO, SIMPLE

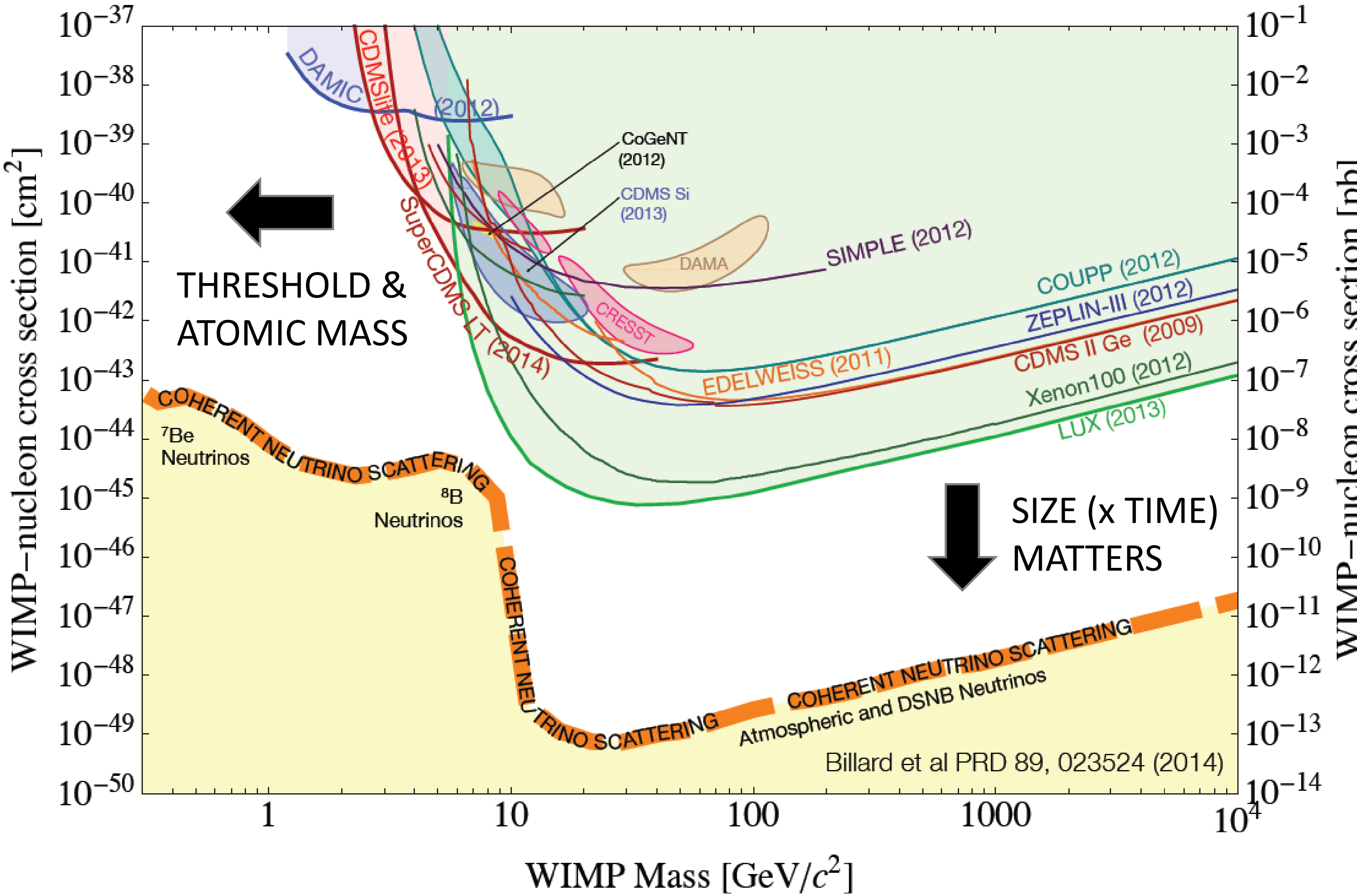
PRESENT STATUS

~3 decades of effort

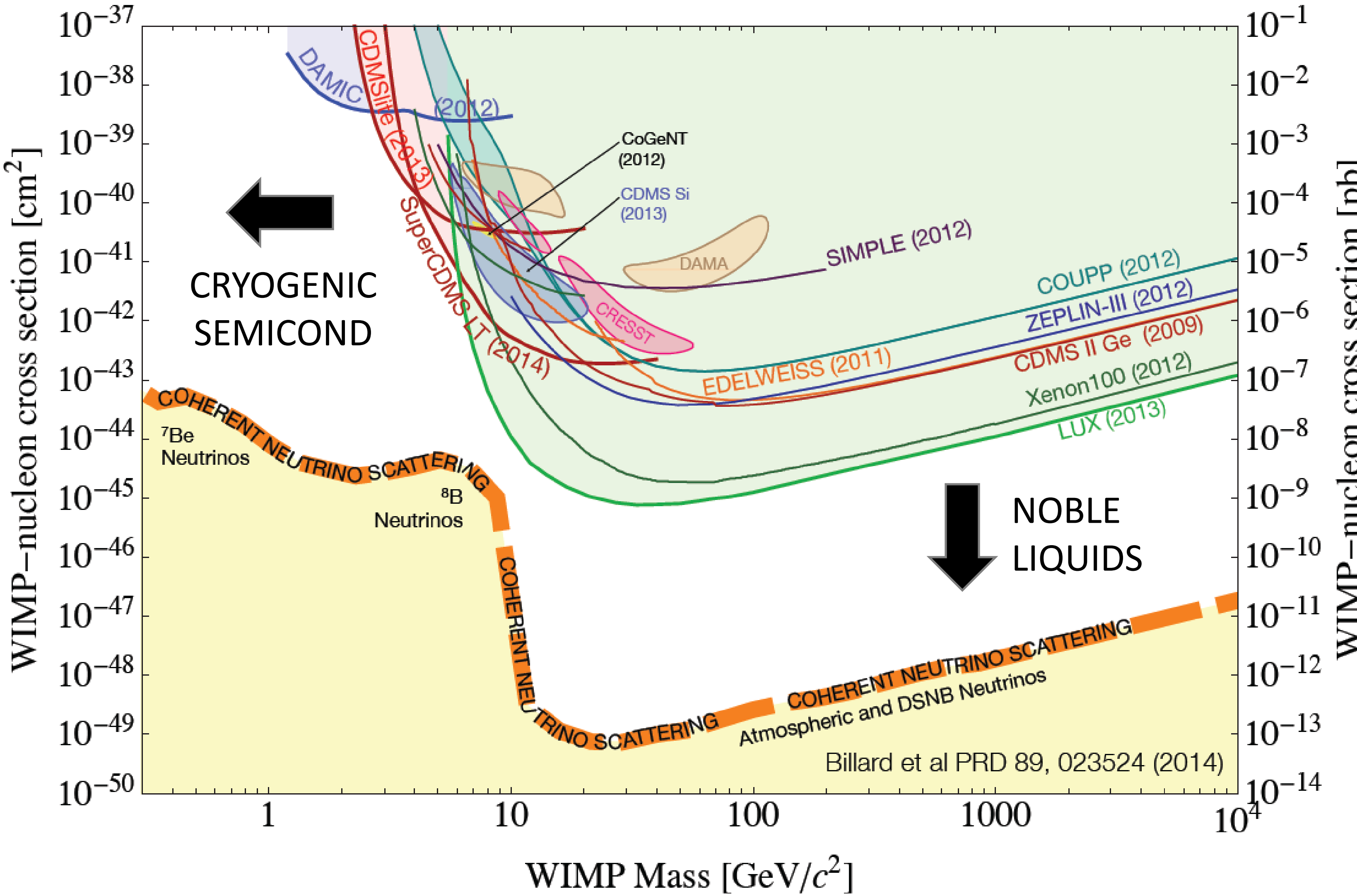
~5 decades in sensitivity



PRESENT STATUS



PRESENT STATUS



DISCLAIMER

- Hereafter I list only the leading experiments or those that may be able to tell us something new about WIMP dark matter in the next decade or sooner.

- My starting assumption is that we have not found it yet.

DECLARATION OF INTERESTS

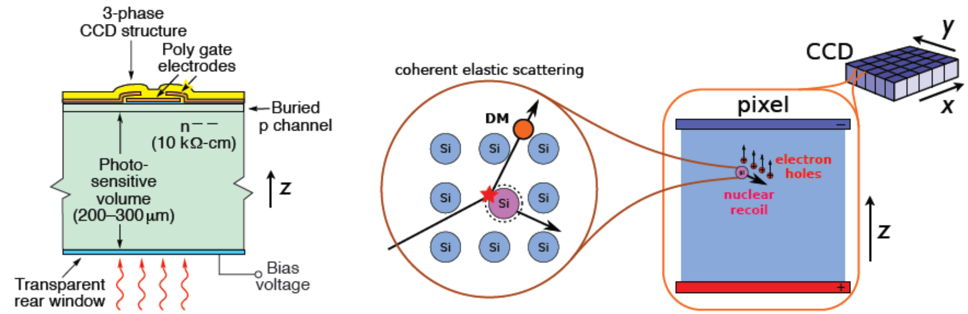
- I work on LUX and LZ

DAMIC: CCD DETECTORS

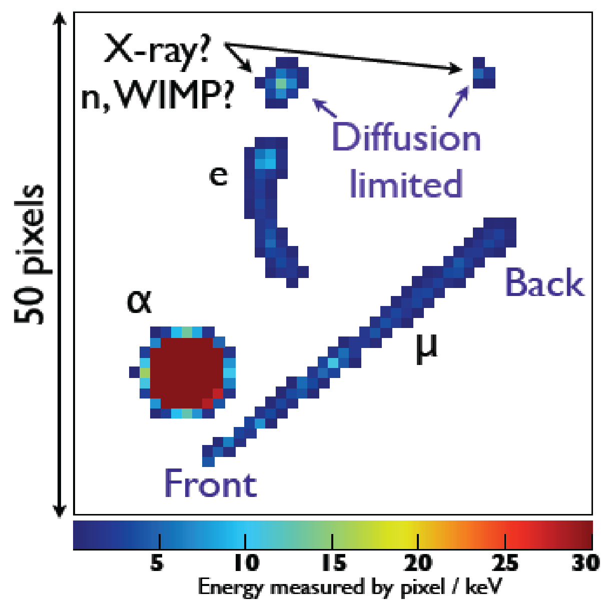
1105.5191
1407.0347

250 μm fully-depleted CCDs (Si)

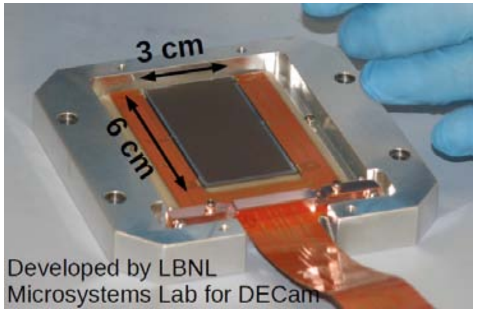
- 8 Mpixels, ~1 g/detector
- 2.5 e *rms* pixel noise
- Integration ~hours
- Operation at 150 K
- Particle ID, surface rejection
- **Key performance parameters**
  - ER threshold:
    0.05 keVee, ~0.5 keVnr
  - Background:
    100 evts/kg/day/keVee
- **Sensitivity**
  - Run 1: 4x10^{-39} cm^2 at 2-4 GeV
  - Run 2: ongoing at SNOLab
- Onwards: DAMIC100 (100 g) expected 2015

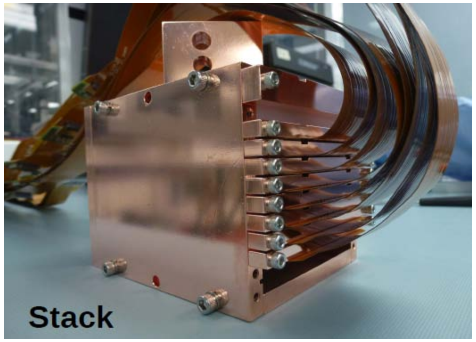


(a) A CCD pixel (b) WIMP detection principle



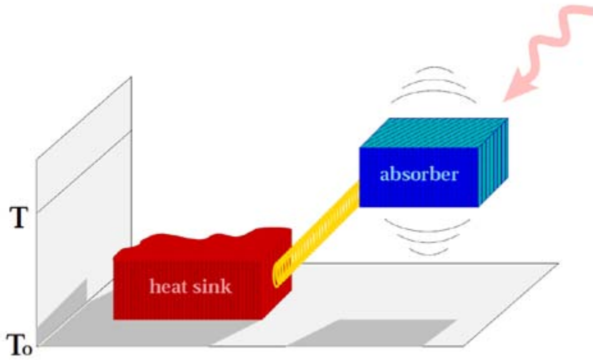
(b) Segment of a DAMIC image





Izraelevitch/TIPP'14

CRYOGENIC DETECTORS



T_0~10-50 mK

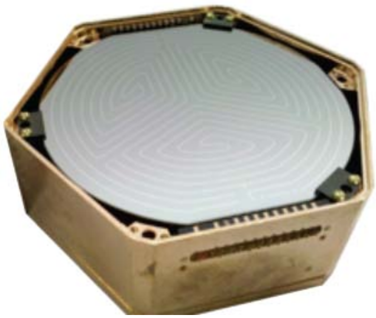
$$\Delta T_{\max} = \frac{E}{C}$$

Thermal signal lost with increasing mass: ideally, collect phonons *before* they thermalise

EDELWEISS DETECTORS

CRESST DETECTORS

S-CDMS DETECTORS

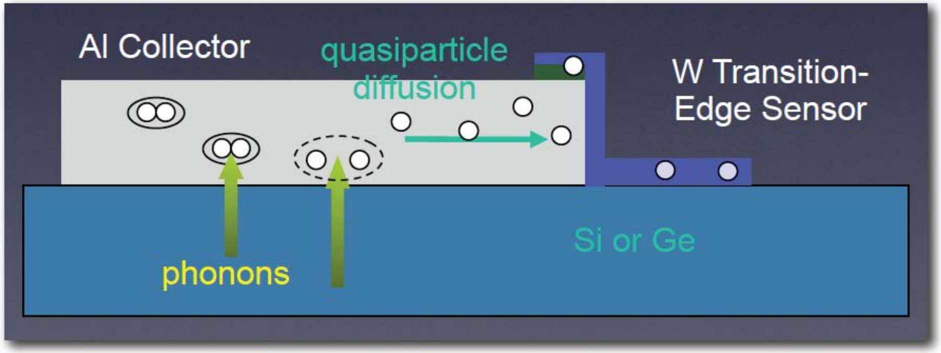


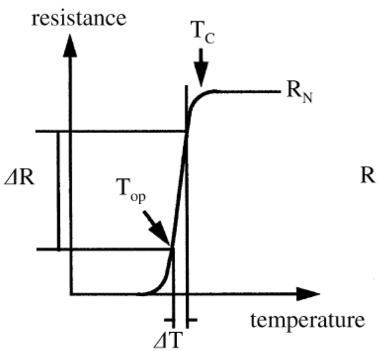
Phonon channel: ~keV threshold, no quenching

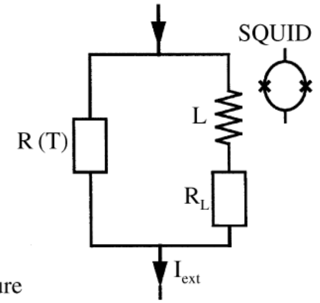
Can collect a second signature for discrimination:

- Phonons + ionisation (e.g. CDMS, EDELWEISS)
- Phonons + scintillation (e.g. CRESST)

Superconducting Transition-Edge Sensor (CDMS)





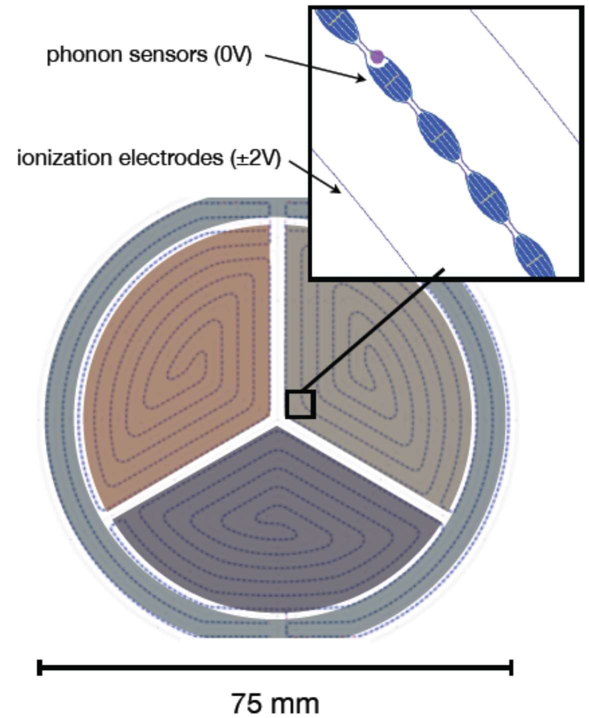


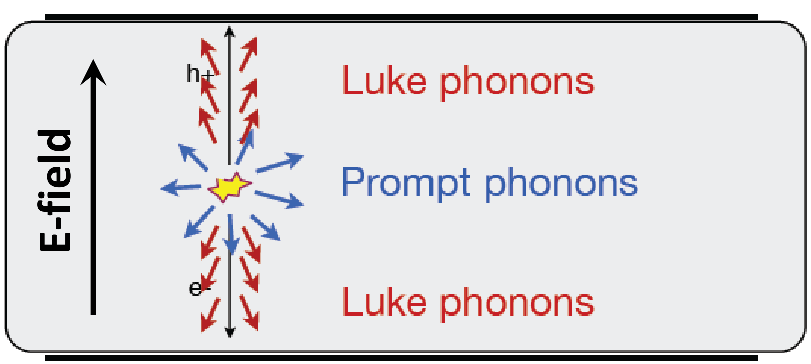
CDMSLite/SuperCDMS SOUDAN

1309.3259
1402.7137

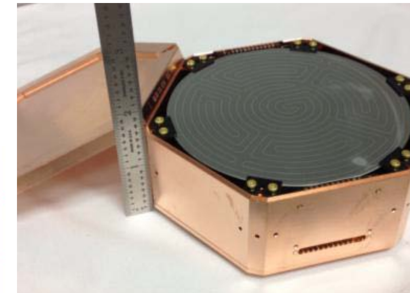
iZIPs, interleaved ionisation & phonon readout

- Improved fiducialisation wrt CDMS-II
- Same location & infrastructure
- **CDMSLite:** low ionisation threshold
  via Luke-Neganov phonon amplification
  1 iZIP, 6 kg*days Ge
- **SuperCDMS**: LE analysis on selected detectors
  7 iZIPs (15 installed), 577 kg*days Ge
- **Key parameters**
  - CDMSLite: 0.8 keVr (no discrimination)
  - S-CDMS LE: 1.6-10 keVr (some discriminatior
- **Sensitivity**
  - 3.4×10^{-41} cm^2 at 8 GeV (Lite)
  - 1.2×10^{-42} cm2 at 8 GeV
- Onwards: SuperCDMS at SNOLab (~100 kg)

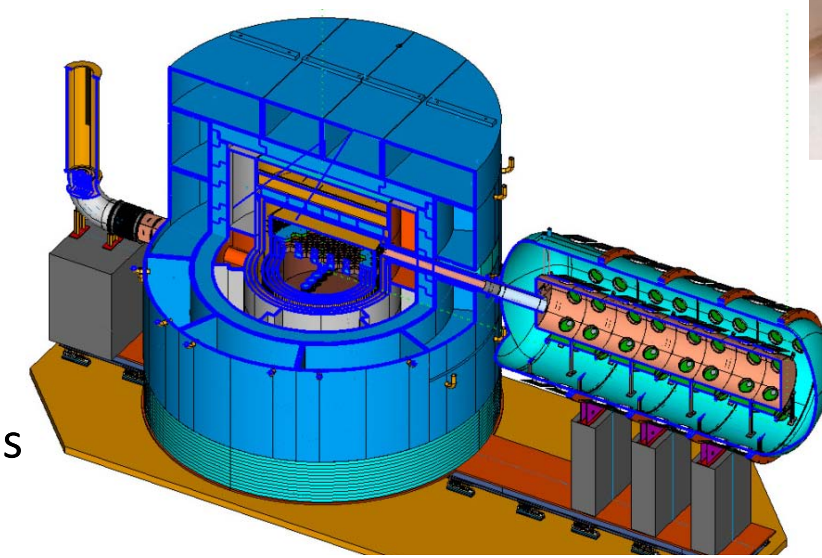


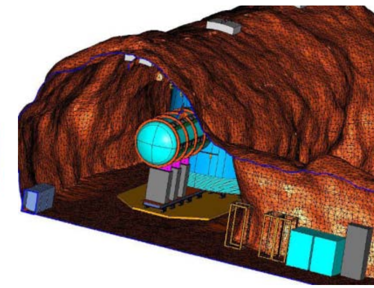


SuperCDMS AT SNOLab



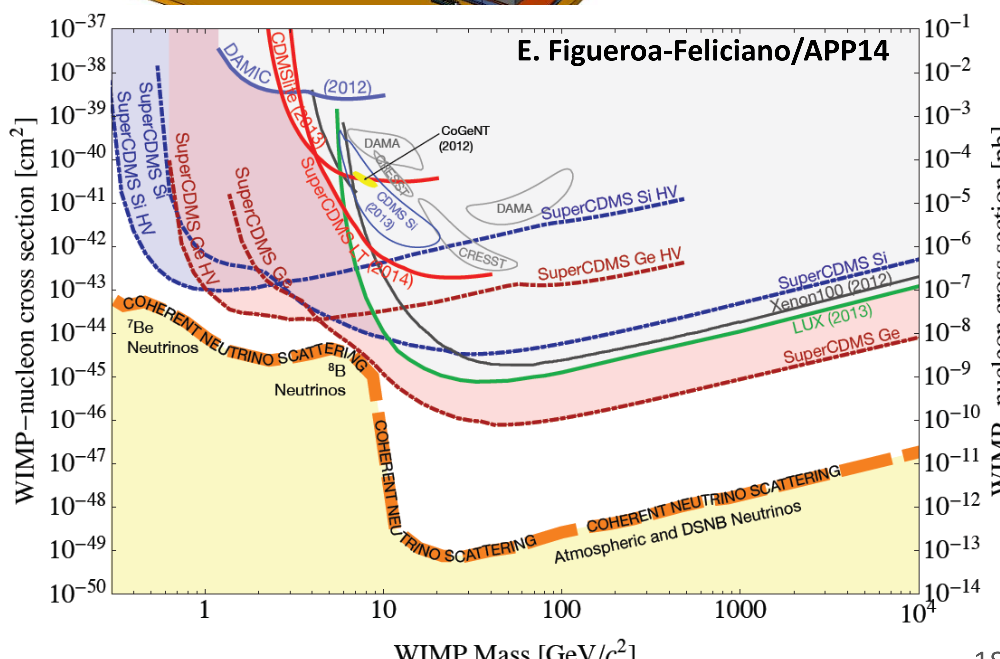
B. Loer, DM2014



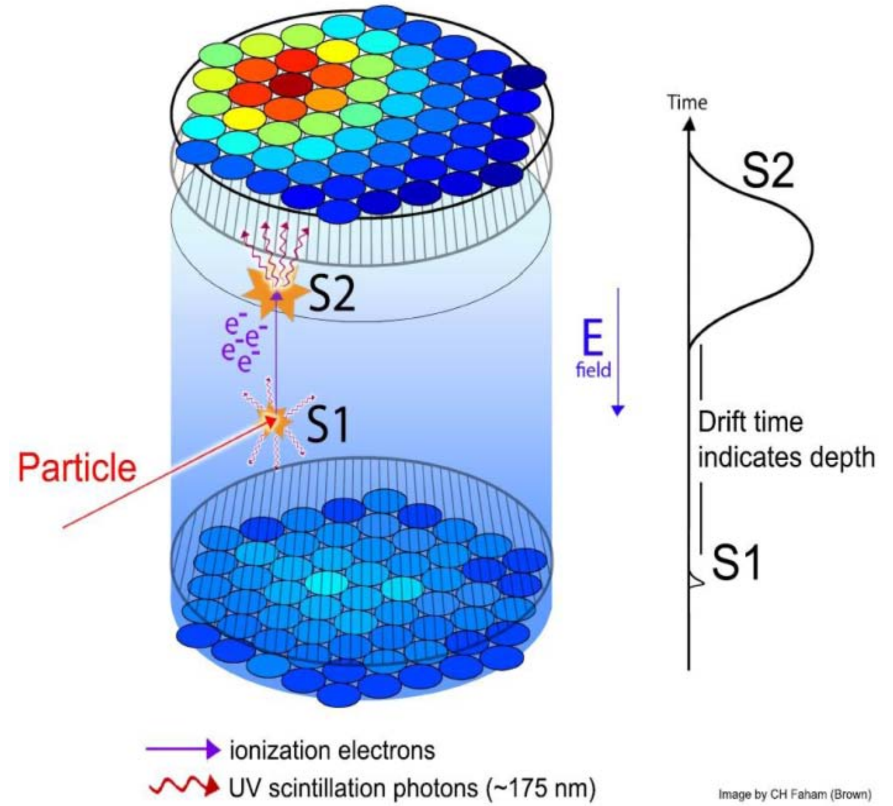


iZIP detectors

- 98 kg Ge (70 x 1.4 kg)
- 12 kg Si (20 x 0.6 kg)
- 10 cm diam, 3.3 cm thick
- 12 phonon, 4 charge chans
- Adding LAB active veto
- Det fabrication from late 2014
- Commissioning 2016
- *Common phase w/ EURECA?*
- **Key parameters**
  - NR threshold: 0.8 keV, 8 keV
  - Background: <0.2 evts (5 yrs)
- **Sensitivity**
  - ~1x10^{-46} cm^2 at 40 GeV by 2021



TWO-PHASE XENON TPC



S1: prompt scintillation signal

- Light yield: ~60 ph/keV (ER, 0 field)
- Scintillation light: 178 nm (VUV)
- **Nuclear recoil threshold ~5 keV**

S2: delayed ionisation signal

- Electroluminescence in vapour phase
- Sensitive to single ionisation electrons
- **Nuclear recoil threshold <1 keV**

S1+S2 event by event

- ER/NR discrimination (>99.5% rejection)
- mm vertex resolution + high density: *self-shielding* of radioactivity backgrounds

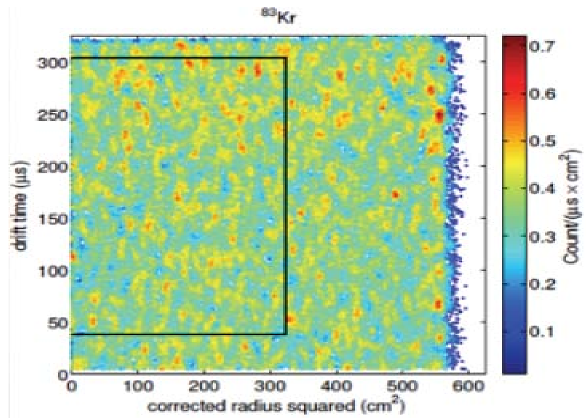
LXe is the leading WIMP target:

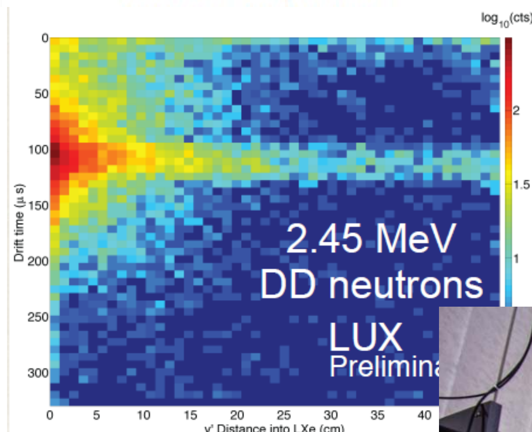
- Scalar WIMP-nucleon scattering rate dR/dE~A^2, broad mass coverage >5 GeV
- Odd-neutron isotopes (^{129}Xe, ^{131}Xe) enable SD sensitivity; target exchange
- No damaging intrinsic nasties (^{127}Xe short-lived, ^{85}Kr removable, ^{136}Xe $2\nu\beta\beta$ ok)

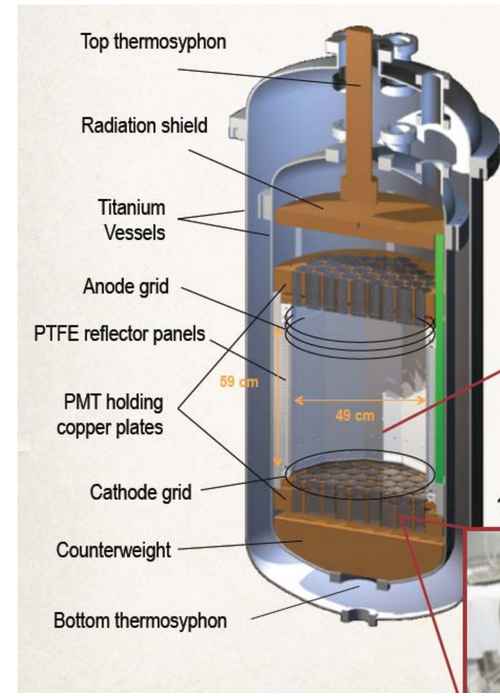
LUX: TWO-PHASE XENON

Liquid xenon TPC

- 250 kg LXe (118 kg fiducial)
- PTFE field cage, 122 PMTs
- 3D imaging (<1 cm)
- Calibration: ^{83m}Kr and ^{3}H (ER)
- D-D neutron generator (NR)
- **Key parameters**
  - Light yield: >8 phe/keVee
  - Drift field: 0.2 kV/cm
  - NR threshold: 4.3 keV
  - ER discrimination: 99.6%
  - Background: 2 ER/day (ROI total!)
- **Sensitivity**
  - 7.6x10^{-46} cm^2 at 33 GeV (Run 3)
- Onwards: LUX-ZEPLIN (7-tonne TPC)

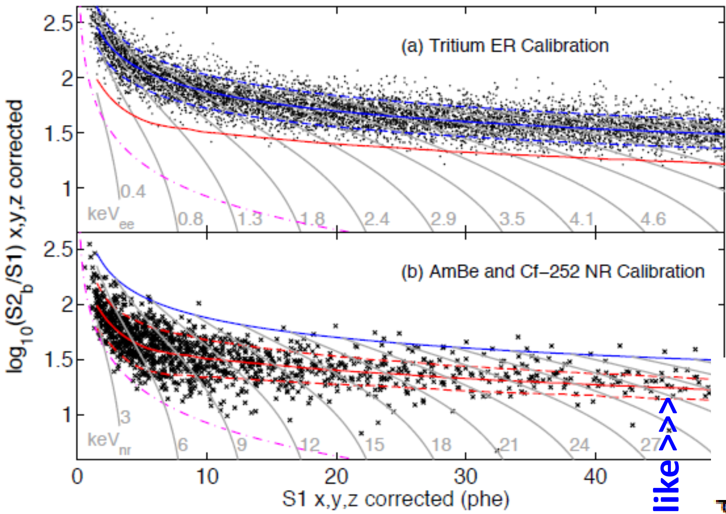


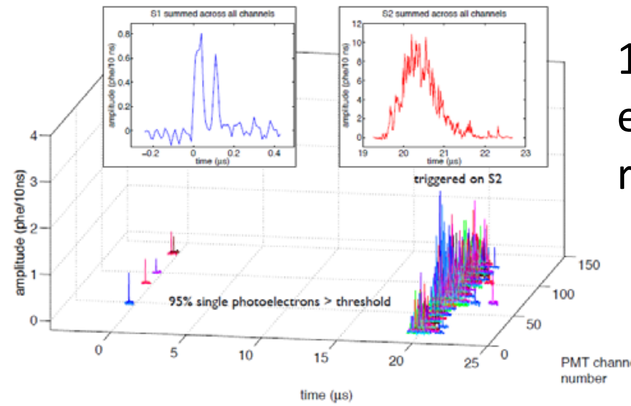




See talk by A. Manalaysay on Friday (F14)

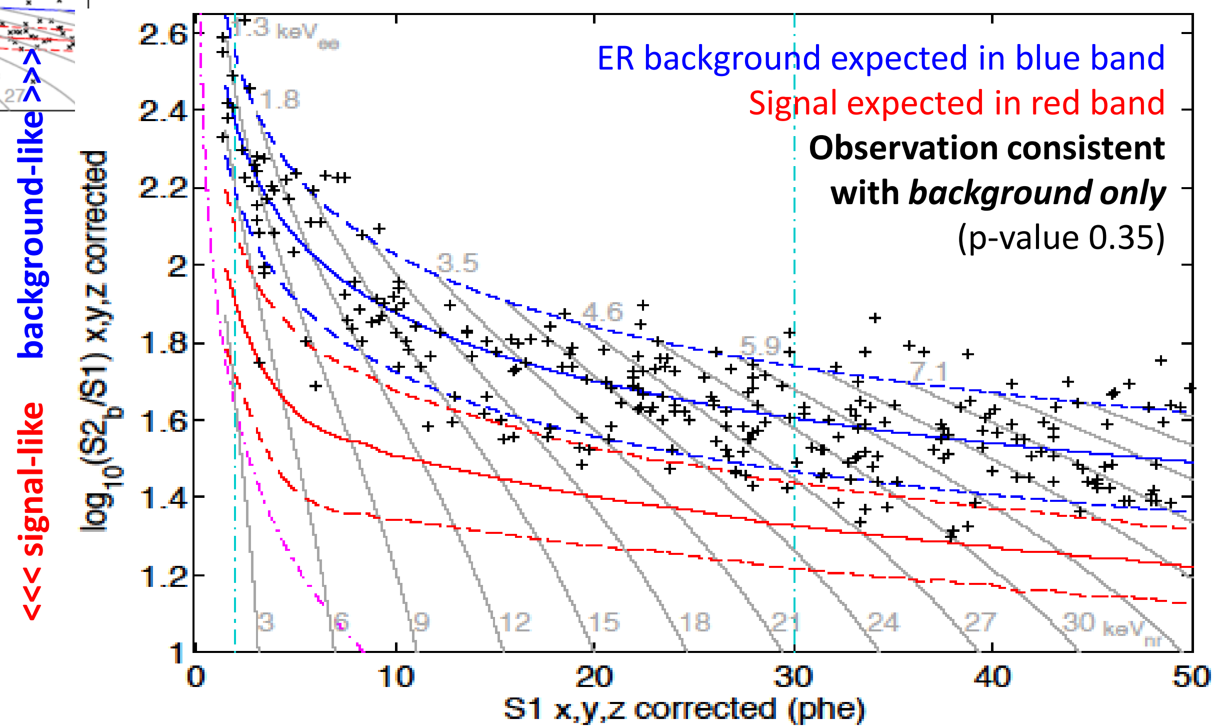
LUX: RESULTS





1.5 keV electron recoil

Events recorded in 85.3 live days of exposure



recoil energy (loosely) >>>

The Economist

“Absence of evidence, or evidence of absence?”

New York Times

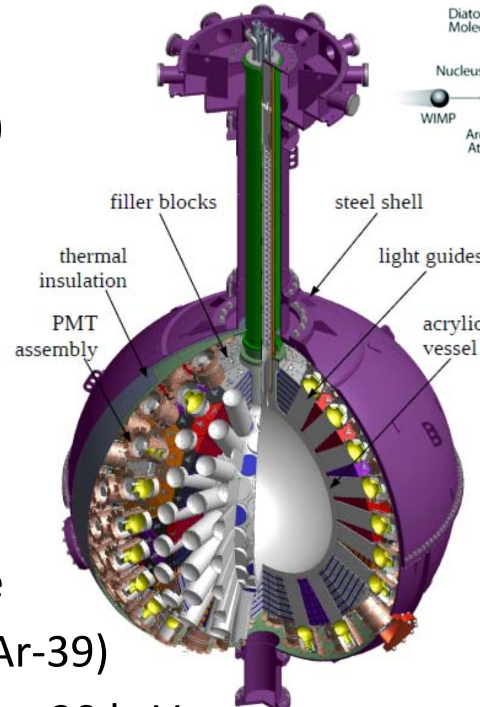
“Dark Matter Experiment Has Detected Nothing, Researchers Say Proudly”

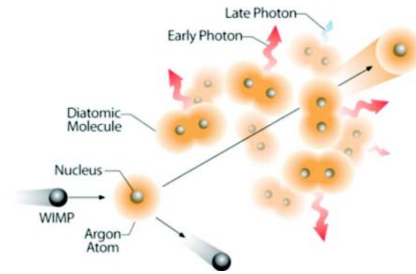
0904.2930

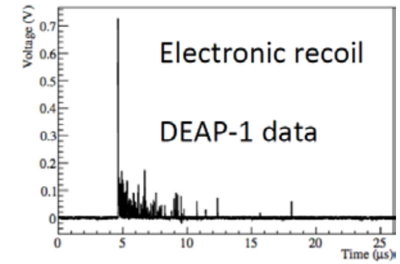
DEAP-3600: SINGLE PHASE LAr

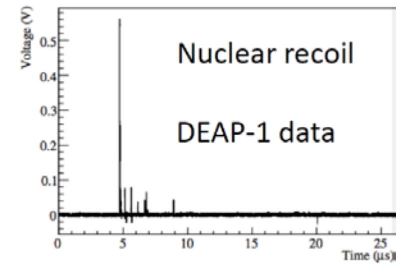
PSD in single phase LAr

- 3.6 t LAr (1 t kg fiducial)
- 255 PMTs (75% coverage) light-guide coupled
- Inside 8 m water shield
- Vessel resurfaced *in situ* prior to WLS evaporation

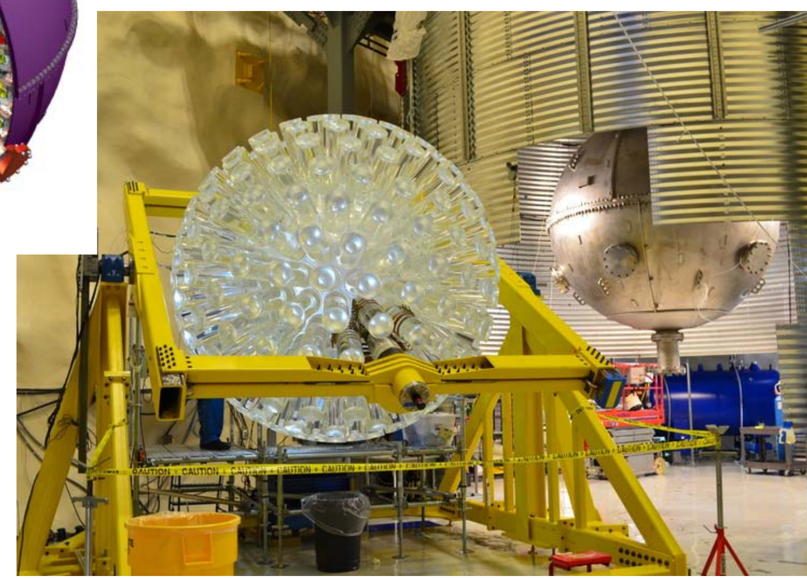






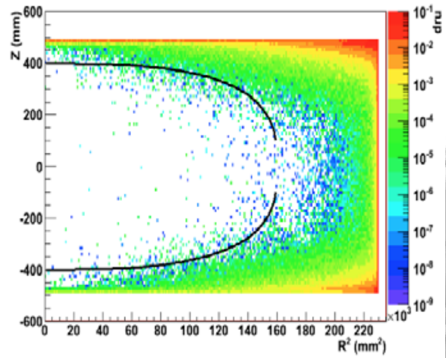


S. Peeters/APP14

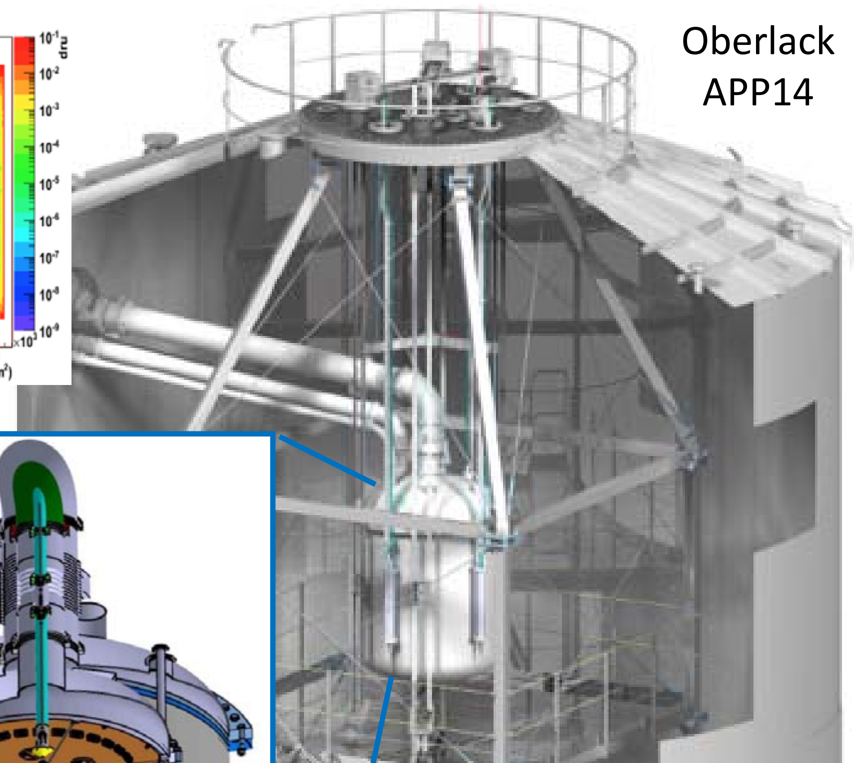


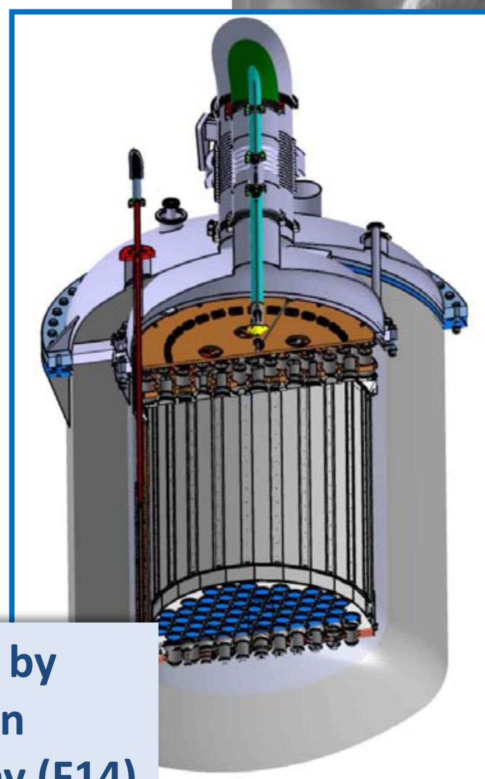
- **Key parameters**
  - Light yield: 8 phe/keVee
  - NR threshold: 60 keVr (Ar-39)
  - ER discrimination: 10^{-10} at 20 keVee
  - Background: <0.3 events (3 t·yr)
- **Sensitivity goal**
  - $1\text{x}10^{-46}$ cm^2 at 100 GeV by 2017
- Onwards: CLEAN (50-tonne fiducial)

XENON-1T: TWO-PHASE XENON



Oberlack APP14





Liquid xenon TPC

- 3.3 t LXe (1 t fiducial)
- 1 m long TPC, 248 PMTs
- 10 m water Cherenkov
- Construction now
- Operation from 2015
- (Oversized OV for nT phase)

- **Key parameters**
  - Drift field: 1 kV/cm
  - Background: ~1.5 evt (2.7 t·yr)

- **Sensitivity**
  - 2×10^{-47} cm^2 by 2017

- Onwards: XENON-nT, and DARWIN

See talk by A. Brown on Friday (F14)

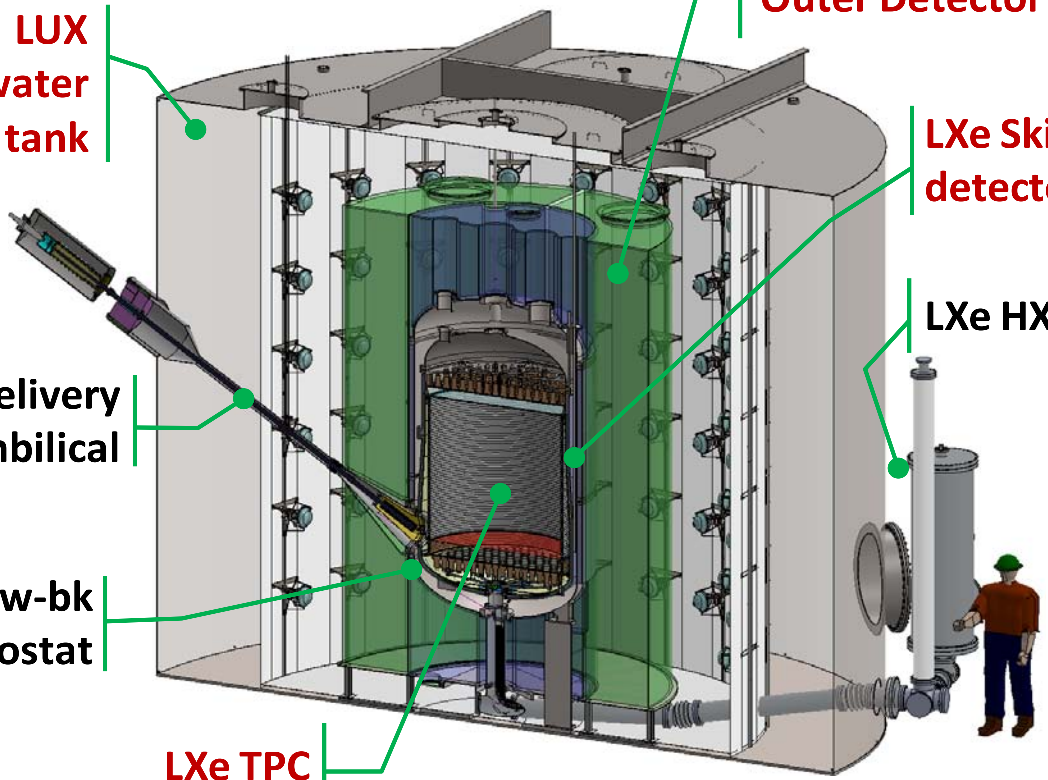
LZ: TWO-PHASE XENON

Liquid xenon TPC

- 7.0 t LXe active (5-6 t fiducial)
- LXe Skin detector (~2 t)
- Gd-loaded Scintillator Veto
- 8-m water tank (post-LUX)
- Construction from 2014

- **Key parameters**
  - Light yield: >6 phe/keVee
  - NR threshold: 6 keV
  - ER discrimination: >99.5%
  - Background: ~1.8 evt (8 t·yr)
- **Sensitivity**
  - 2.5×10^{-48} cm^2 circa 2020
- Onwards: G3 experiment ?

LZ DETECTOR(S)



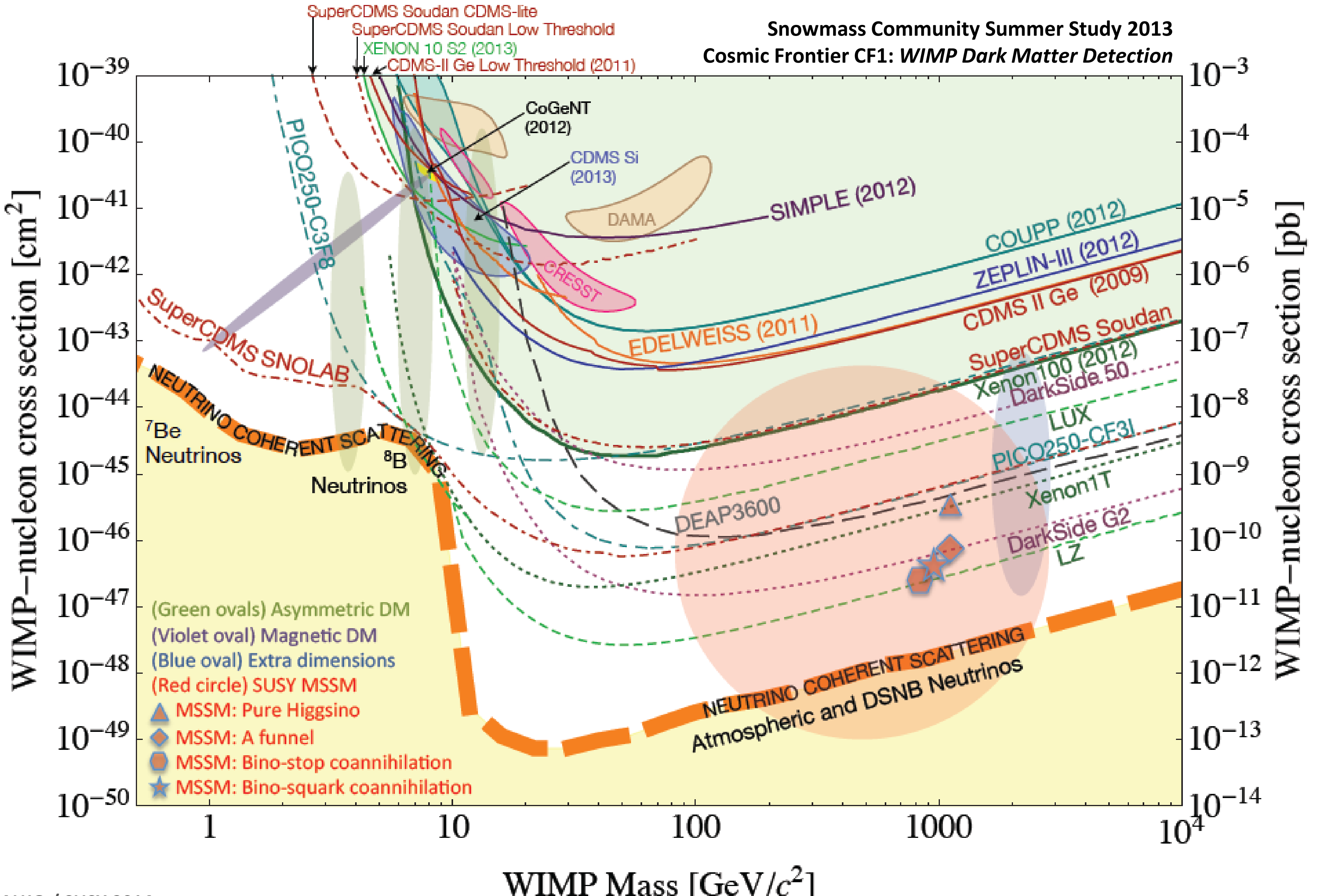
US DM GEN-2 'DOWN-SELECTION'

- DOE/NSF announcement (11 July 2014)

  "The DOE Office of High Energy Physics and the NSF Physics Division have jointly selected a portfolio of projects for the "second generation" of direct detection dark matter experiments. We are pleased to announce that the joint DOE/NSF second-generation program will include the LZ and SuperCDMS-SNOLAB experiments with their collective sensitivity to both low and high mass WIMPS, and ADMX-Gen2 to search for axions. It will also include a program of R&D to test and develop technologies for future experiments, consistent with the recent P5 recommendations. The agencies will work with the proponents to develop project plans that can achieve their compelling science goals as expeditiously as possible."

- LZ also proposed to UK's STFC

MINING DOWN TO THE NEUTRINO FLOOR



CONCLUSIONS

- We have the tools to explore most of the favoured WIMP parameter space, probing down to the neutrino floor

- Although the field is as vibrant as ever,
  there is now a better understanding of the scope of the task
  and which technologies are best placed to address it

- There is great complementarity between direct,
  indirect and accelerator searches;
  there is also target complementarity

- We must keep digging!

Motivation →