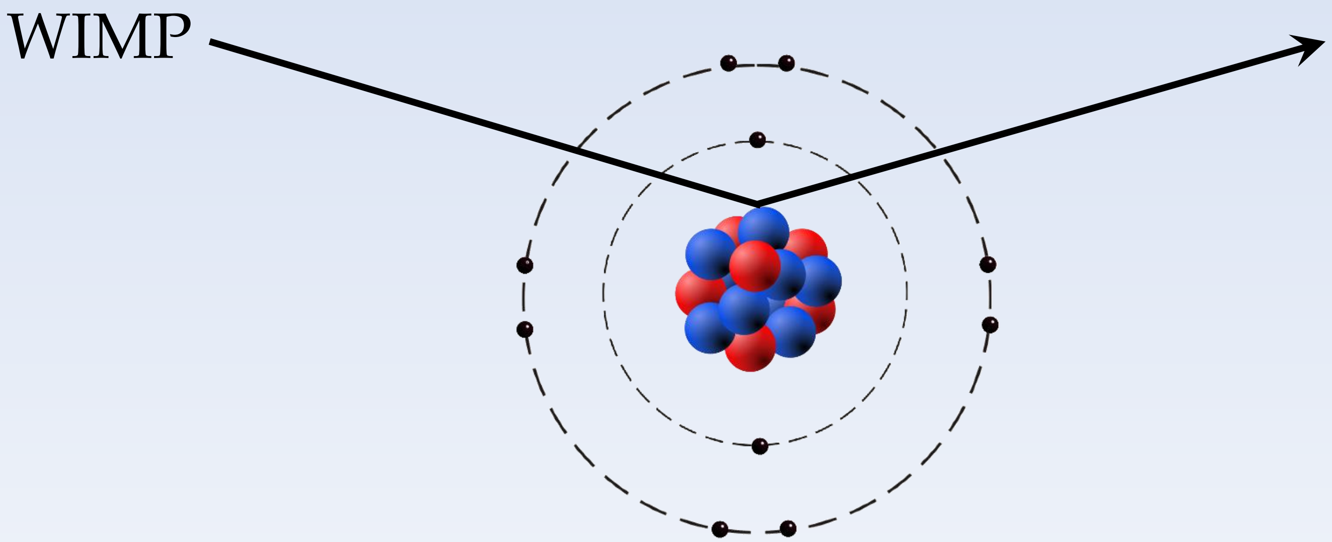
The direct detection of dark matter

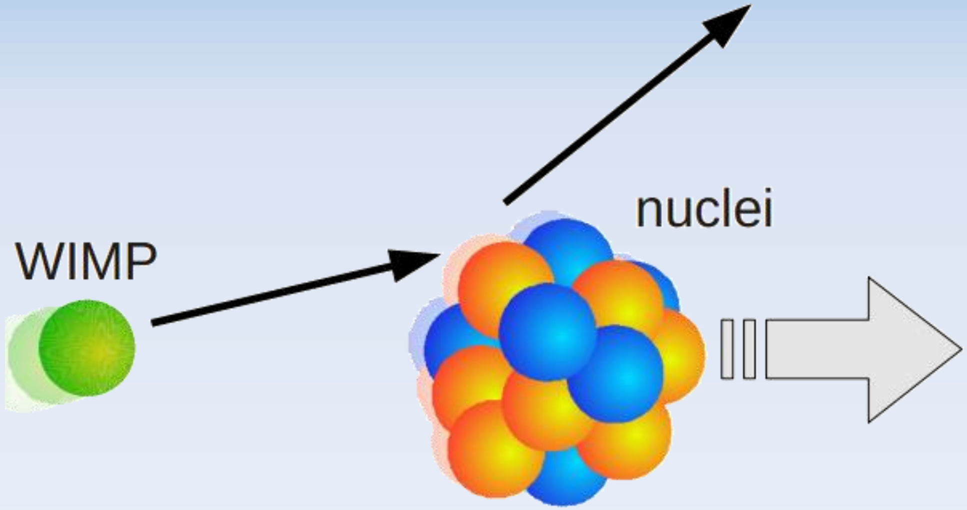


current status and future prospects

Andrew Brown, Nikhef, Netherlands
abrown@nikhef.nl

Revealing the history of the universe with underground particle and nuclear research
11th - 13th of May, 2016

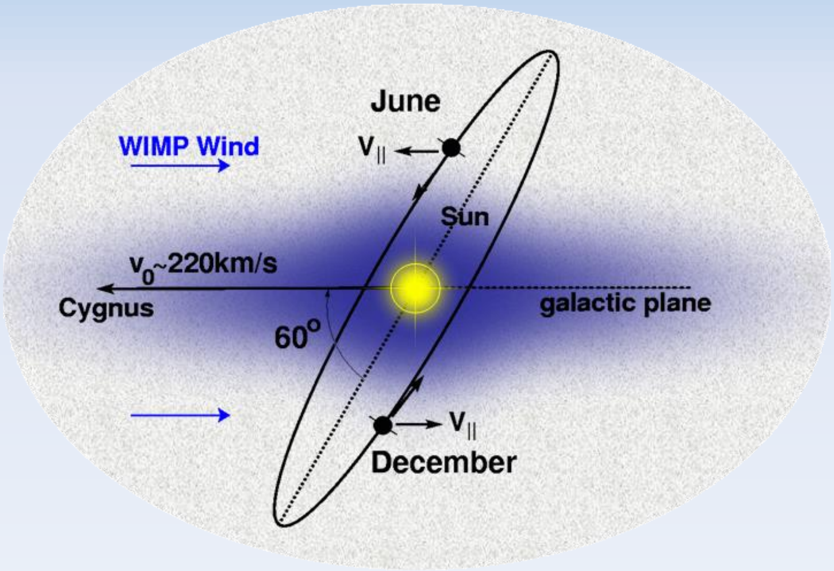
Elastic WIMP interactions

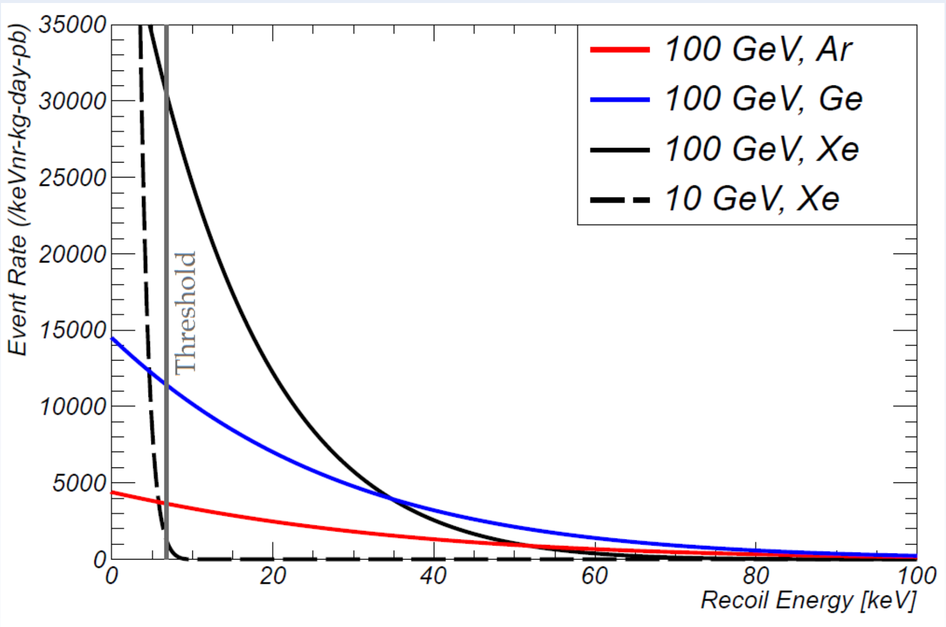


- Dark matter WIMPs could scatter of terrestrial atomic nuclei
  - Speeds of O(200 km/s), approximate rotation speed of sun in galaxy
  - Masses ~$(10 - 10^4)$ GeV/c^2 - recoil energies ~< 10 keVnr
- Interactions rare
  - Density ~ 0.3 GeV / cm^3 , about half a kg in the earth at any one time
  - cross-section very low < 0.6 × 10^{-45} cm^2 @ ~30 GeV/c^2
  - Very low rates, less than 10s of events per tonne and year

Direct detection signatures

- Small nuclear recoils (~<10 keV)
  - Electronic recoil models also exist
- SI or SD interactions

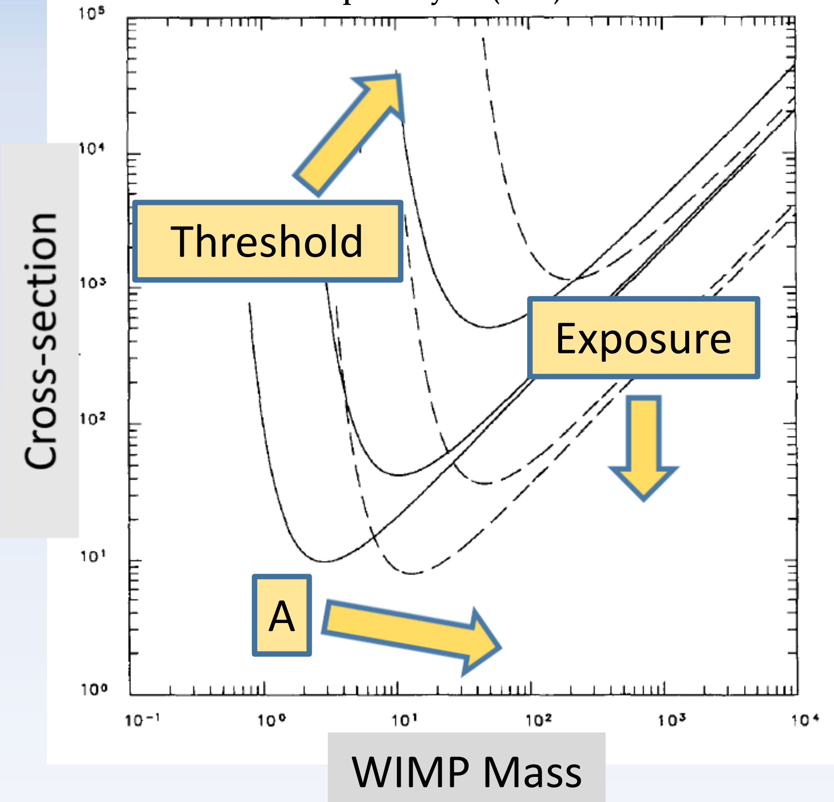




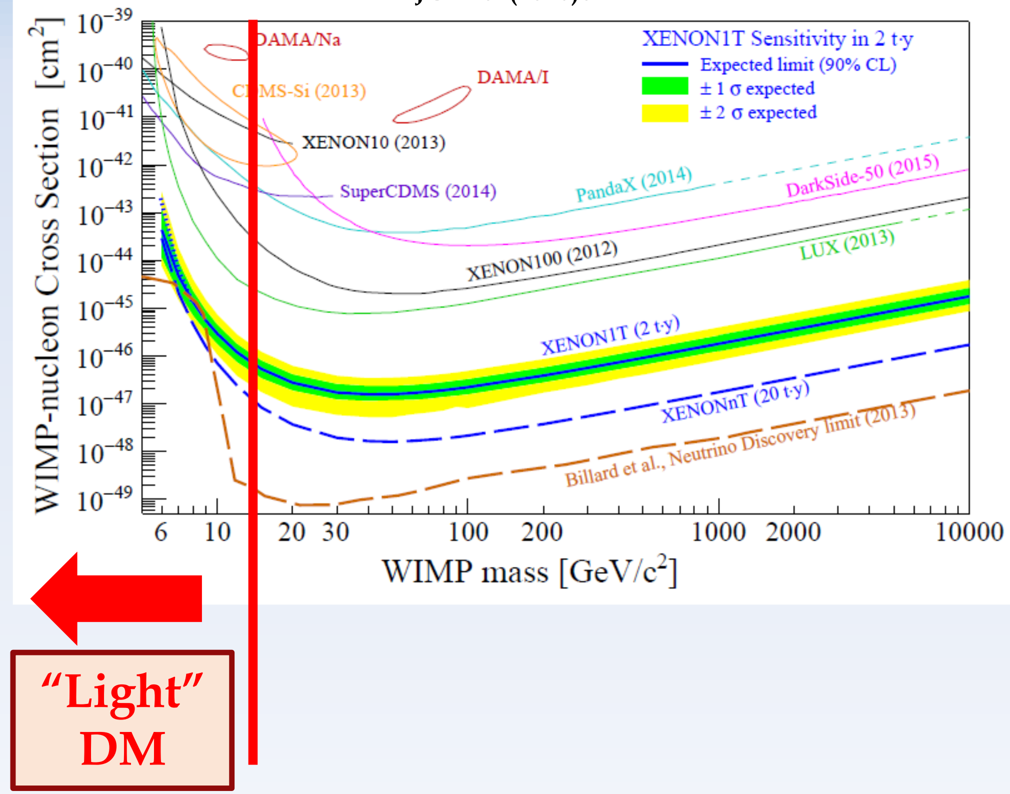
- Exponential shape
- Modulates across year
- Directionality of signal
  - See N. Spooner talk!
  - See NEWAGE talk!

Direct DM, showing the results

Astropart.Phys. 6 (1996) 87-112

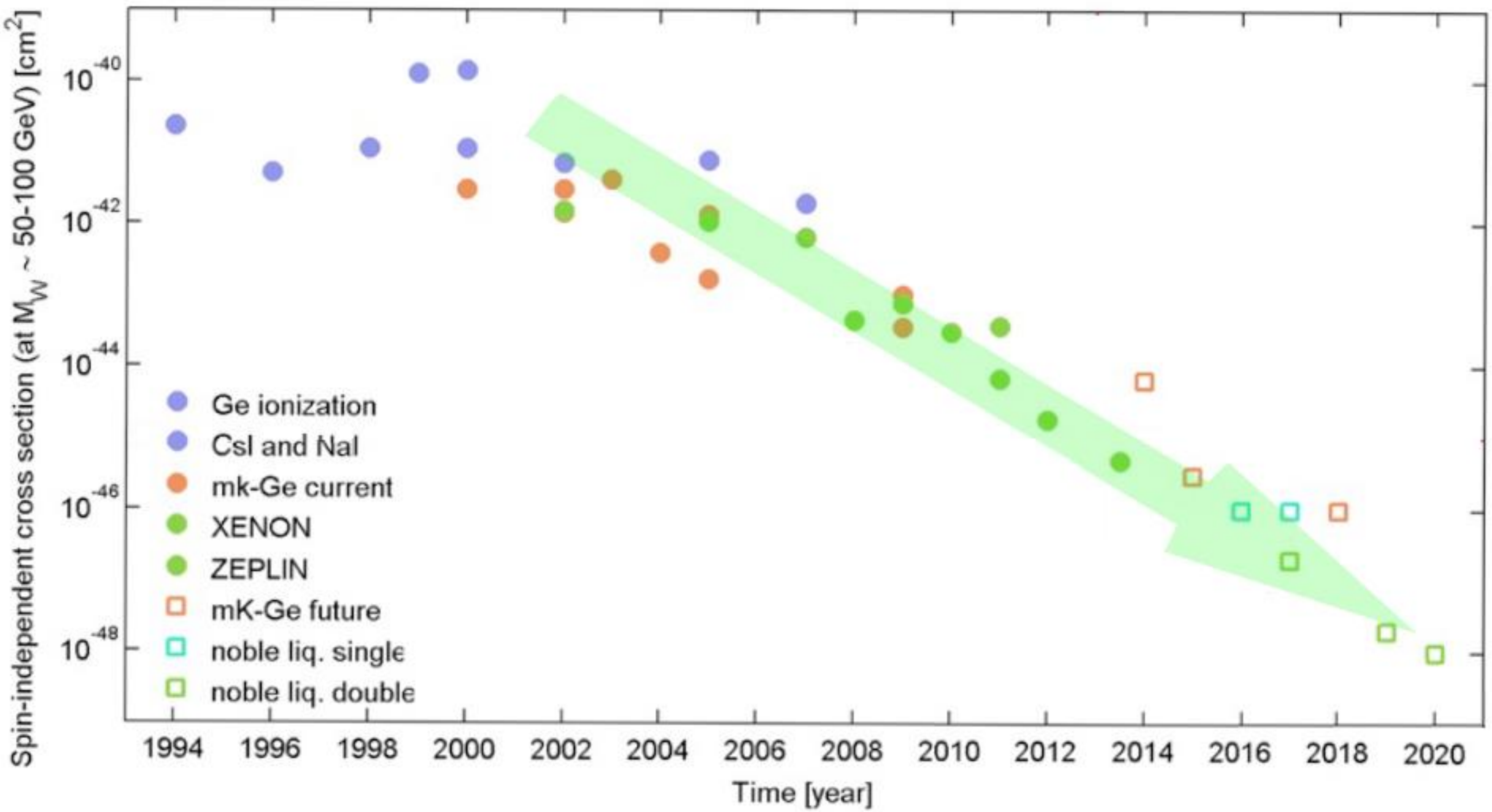


JCAP04(2016)027



- Cross-section translated to expected rate
  - (non) observation sets limit
- Mass vs. cross section limits on interaction strength
  - Strongly affected by target nuclear mass, threshold and exposure

History of detection limits



- Factor 10 improvement every 2-3 years this century

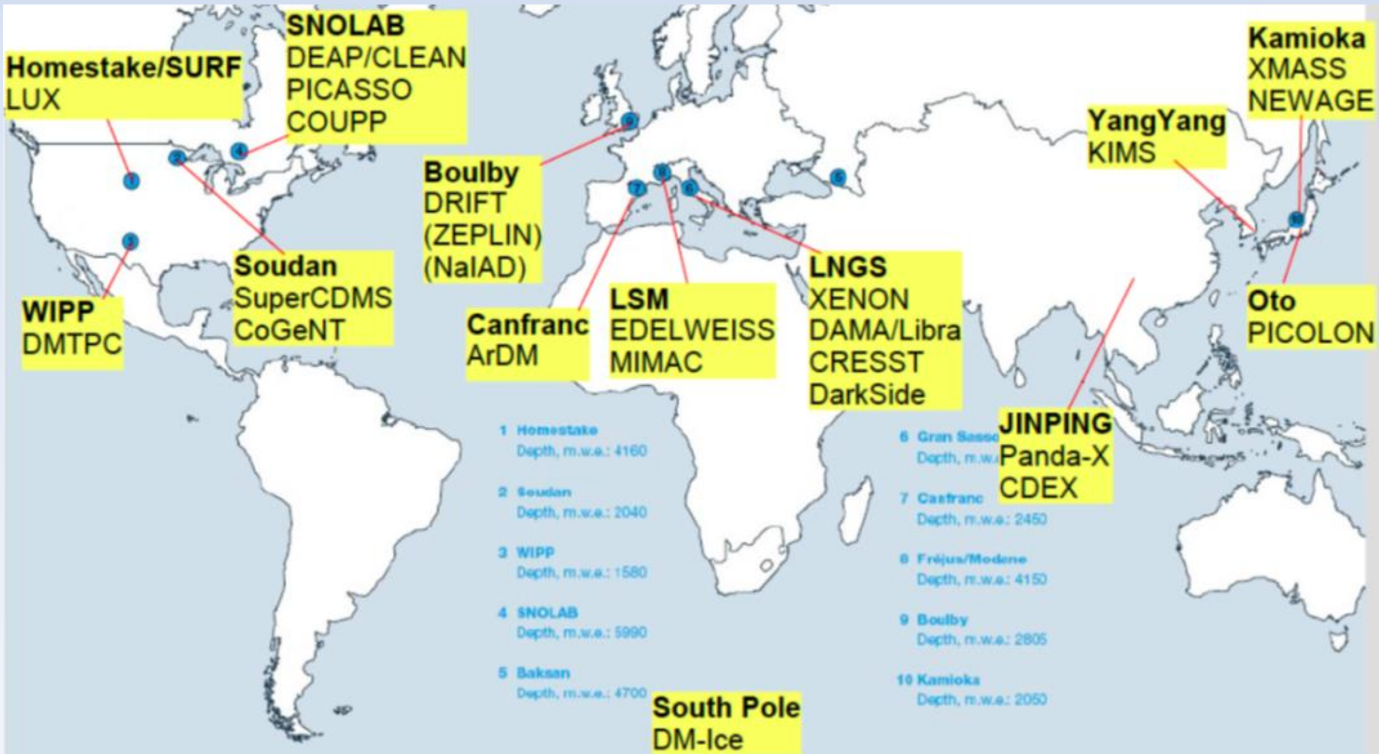
Detector backgrounds

- Natural radioactive contaminants
  - Uranium and Thorium decay chains, potassium-40, Krypton-85…
  - Give gamma and beta decays, leading to electronic recoils
  - Can also cause (α,n) neutron production leading to nuclear recoils

- Cosmic rays
  - Muons can produce neutrons by interactions with detector surroundings

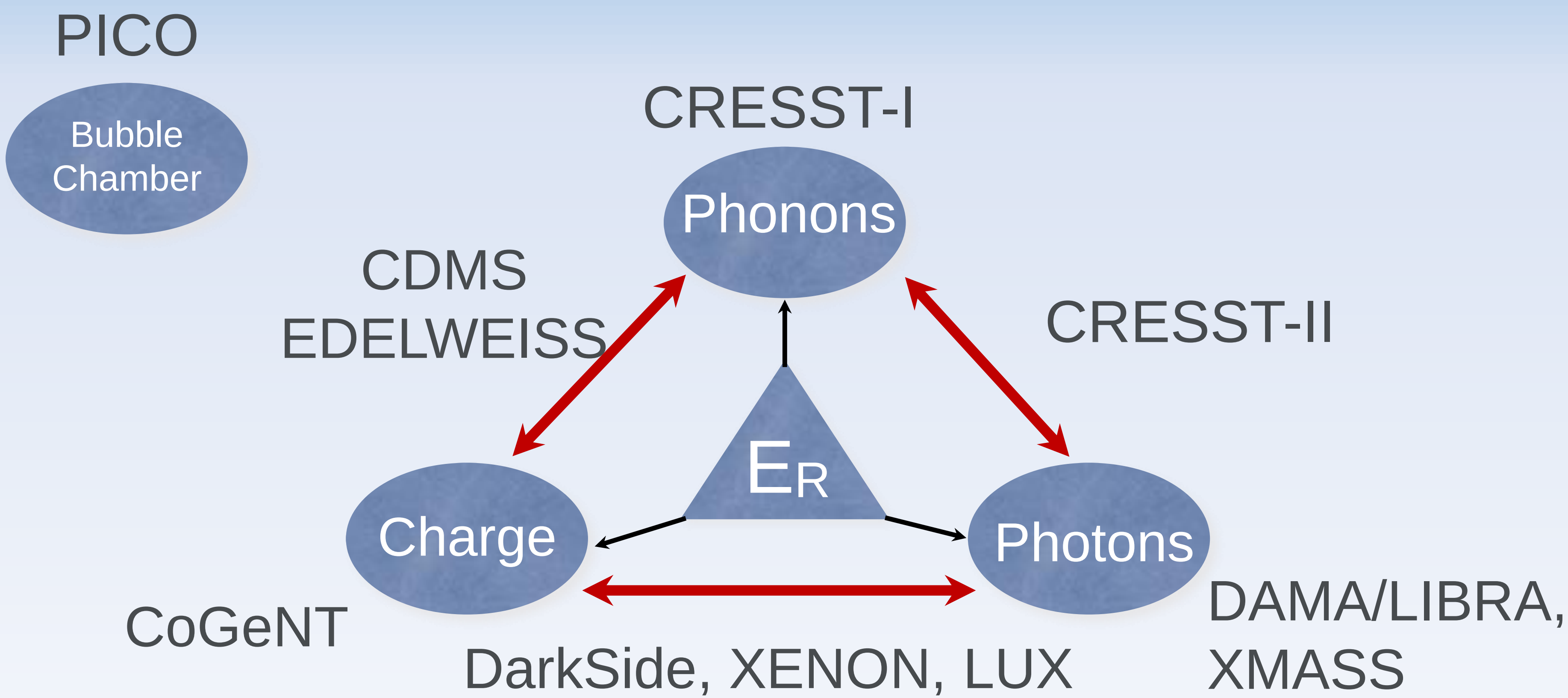
- All experiments attempt to reduce these backgrounds
  - Careful selection of detector materials for low-radioactivity
  - Online purification
  - Locating experiments deep underground

Detector locations



- All direct DM experiments located underground
  - Reduces cosmic ray muon flux
  - Usually > 2km water equivalent

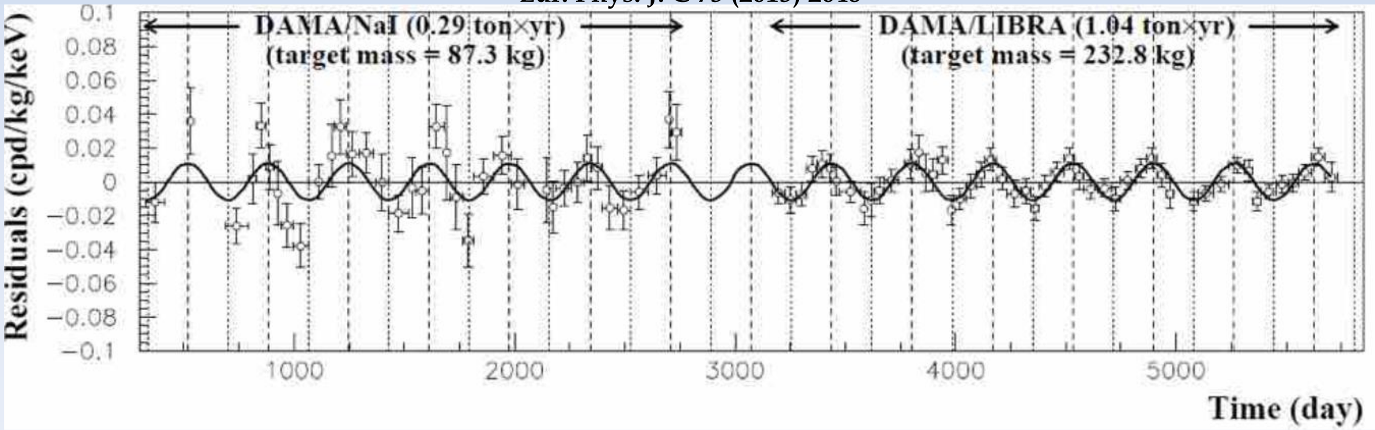
Detector types



- Three commonly used detection channels
  - Many detectors use a combination of two of these channels
- Bubble chambers offer a separate method

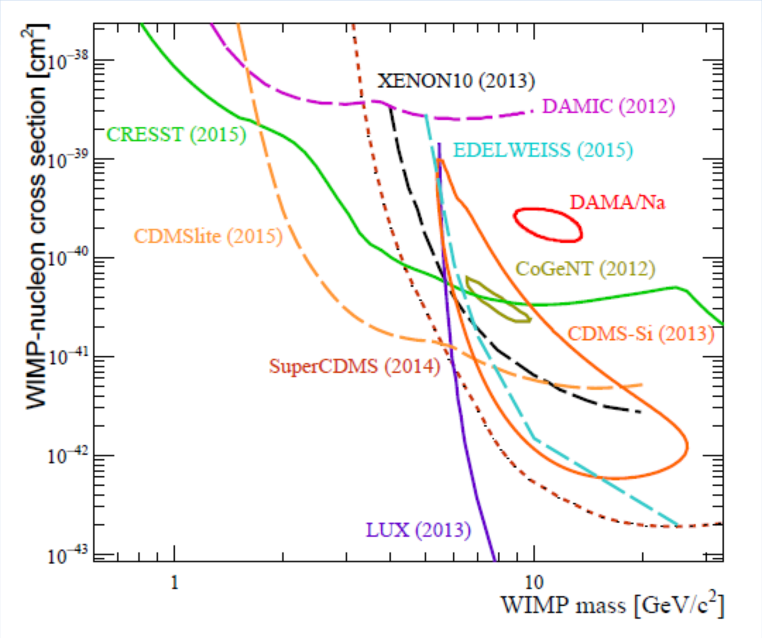
DAMA

Eur. Phys. J. C 73 (2013) 2648



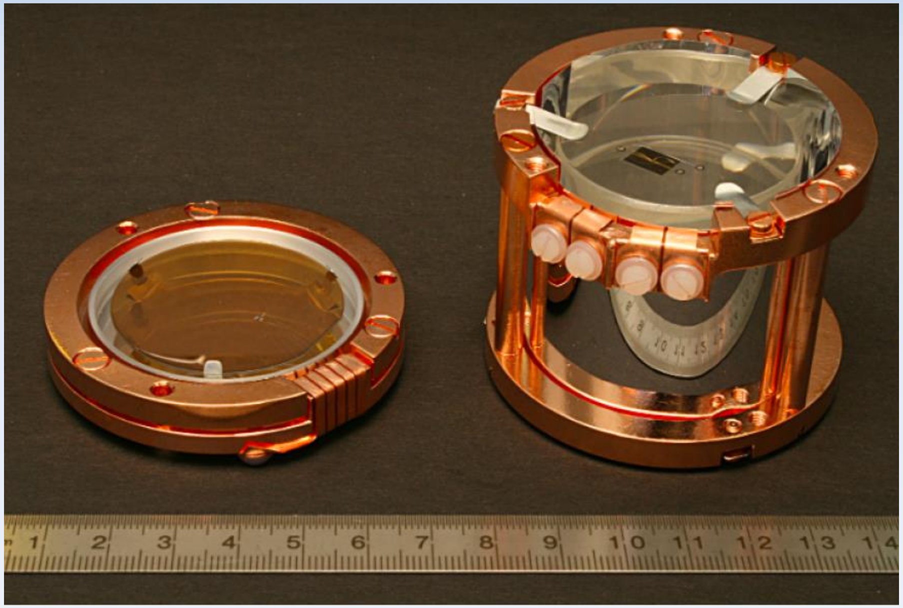
- NaI scintillation detectors
- Annual modulation observed
  - 9.3σ significance in 2 – 6 keV range
  - Collected over 14 years

DAMA

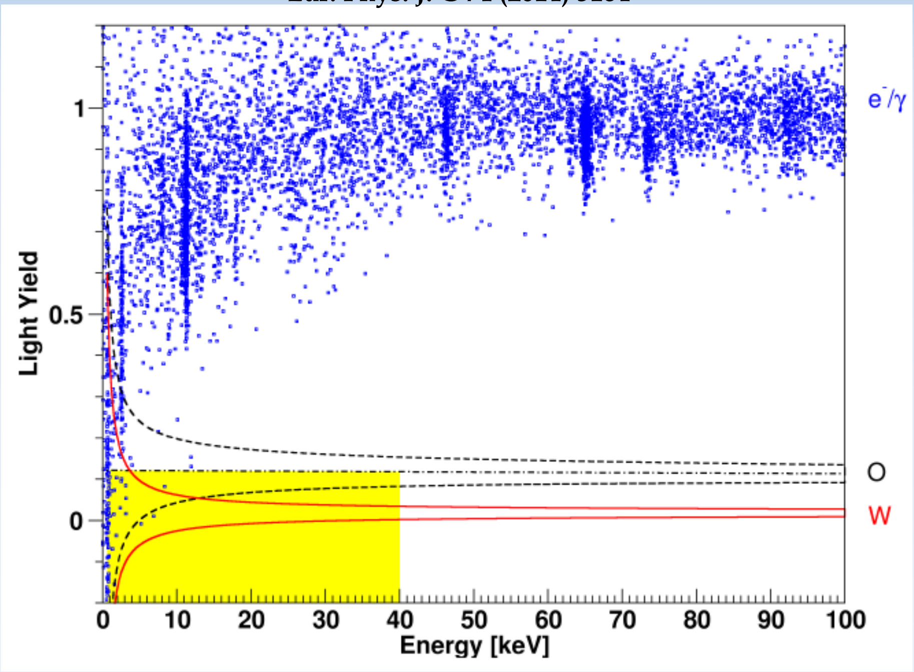


- Elastic SI DM ruled out by half a dozen experiments
- Many explanations offered, also ruled out
  - Leptophillic DM excluded by XENON100
- CsI expt (KIMS) has partially excluded DAMA
  - Further NaI expts (e.g. DM-ICE, KamLAND-Pico) to probe same region

CRESST-II



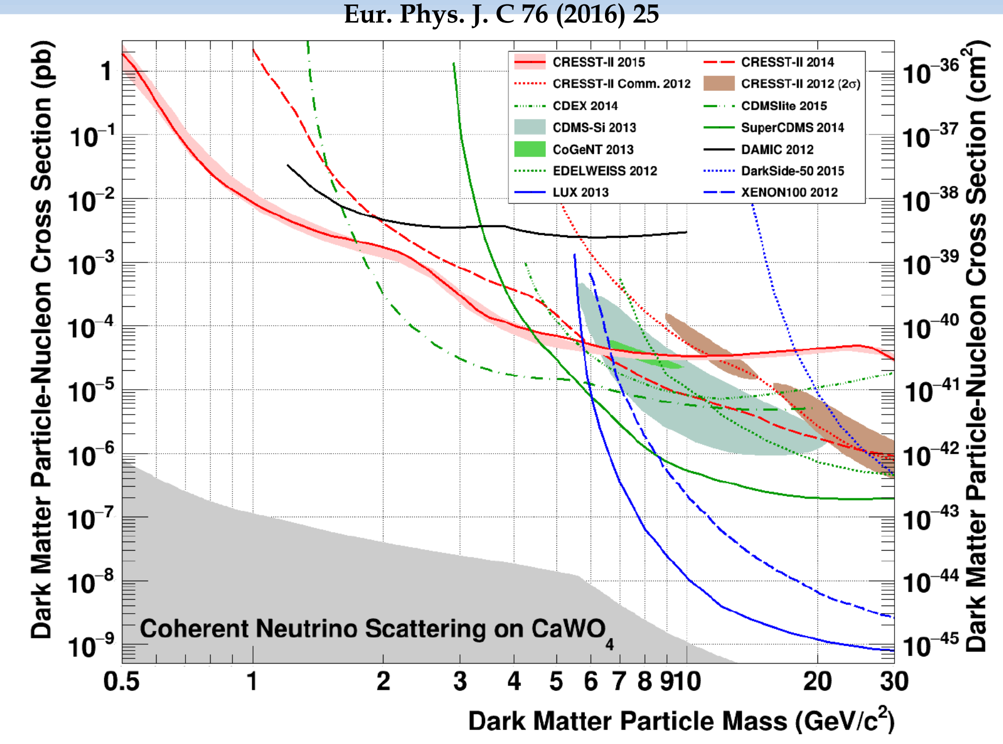
Eur. Phys. J. C 74 (2014) 3184



- Cryogenic scintillating $CaWO_4$ crystals
  - Measure light and phonon signals
  - Electronic and nuclear recoils cause different light/phonon ratios
    - Allows discrimination
  - Several 300g detectors held at mK temperatures
- Located in LNGS, Italy, first science data since 2007

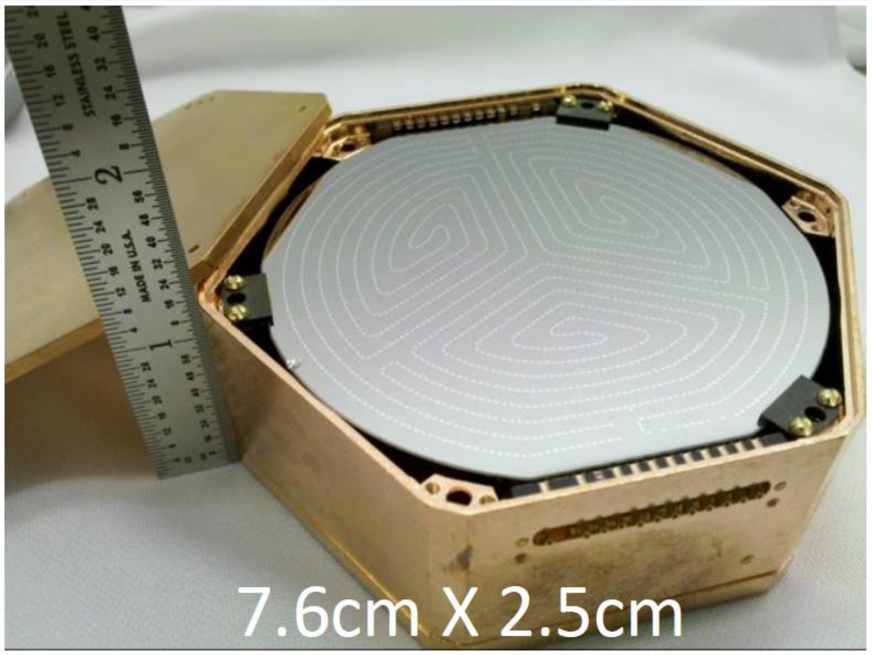
CRESST-II

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

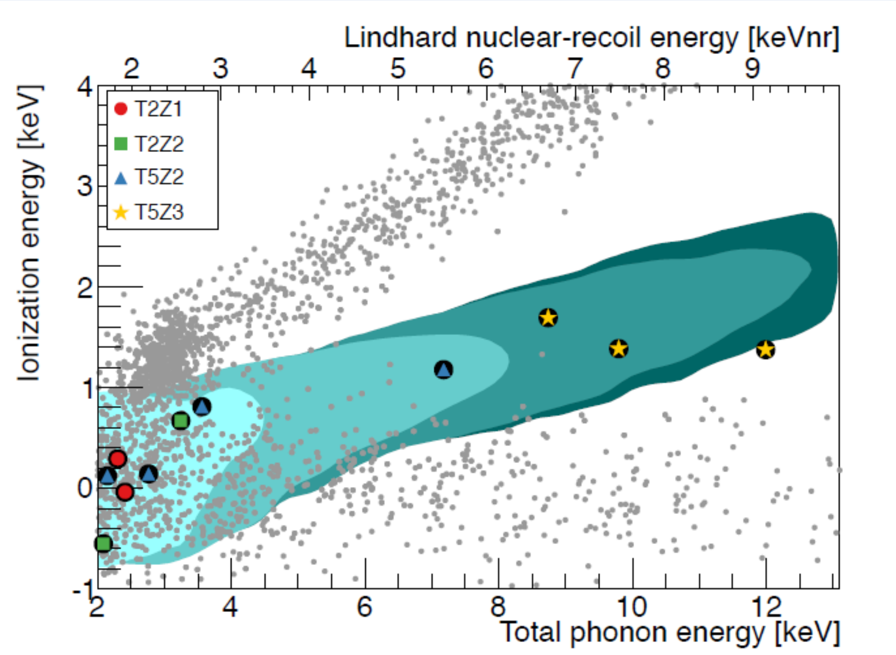


- In 2012 CRESST-II saw hints of a positive signal (brown region)
  - In mild conflict with earlier run (pink)
- Later results (red dashed and red solid) have ruled out signal
- Capable of reaching an extremely low threshold (307eV)
  - Allows world's strongest SI elastic limits below 2 GeV/c^2

SuperCDMS/CDMSLite



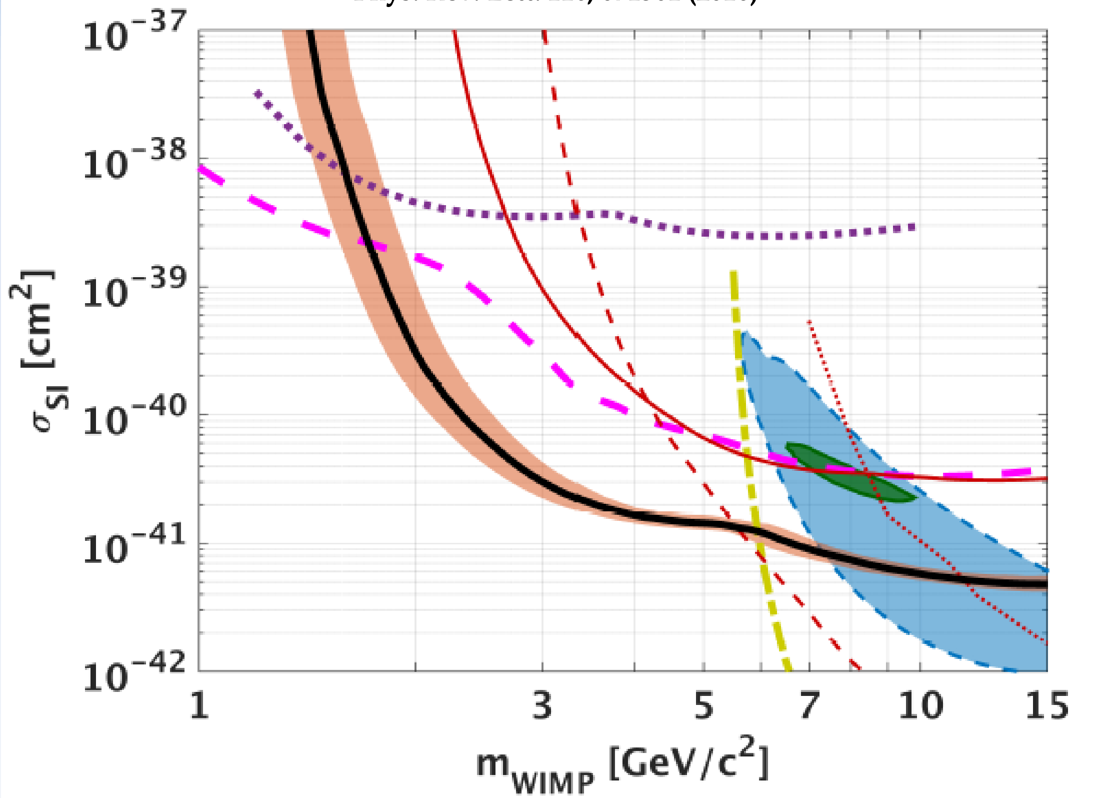
Phys. Rev. Lett. 112, 241302 (2014)



- Cryogenic germanium detectors
  - iZIP detector configuration, looking at phonon and ionization signals
- Capable of extremely low thresholds
  - CDMSLite 2015 - 56 eVee

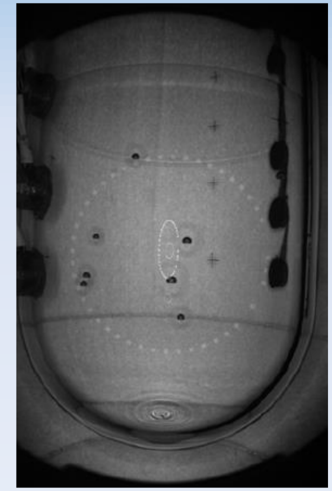
SuperCDMS/CDMSLite

Phys. Rev. Lett. 116, 071301 (2016)

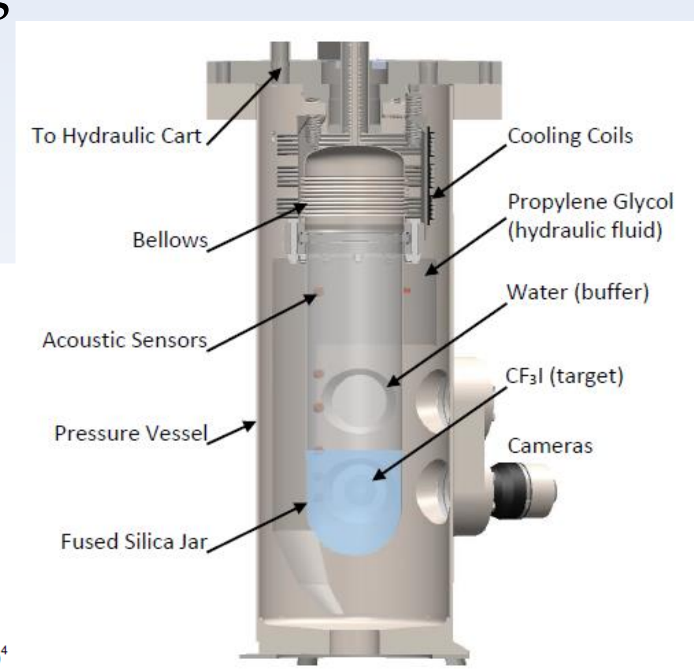


- Produced strongest limits in ~ 2 - ~6 GeV/c^2 range
- SuperCDMS SNOLAB – future expansion up to 400kg target
  - Focus on light WIMP searches < 10 GeV/c^2

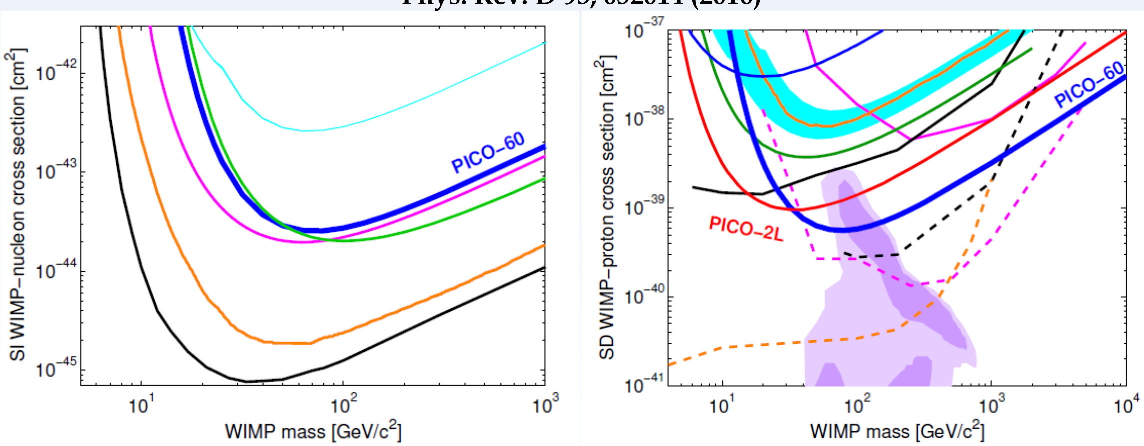
PICO-2L / PICO-60



- Bubble chamber experiment
  - Listens to "sounds" of bubbles
- Threshold experiment
- Gamma/beta do not produce bubbles
- Produce very strong SD-Proton limits
  - New clean run of PICO-60 in near term



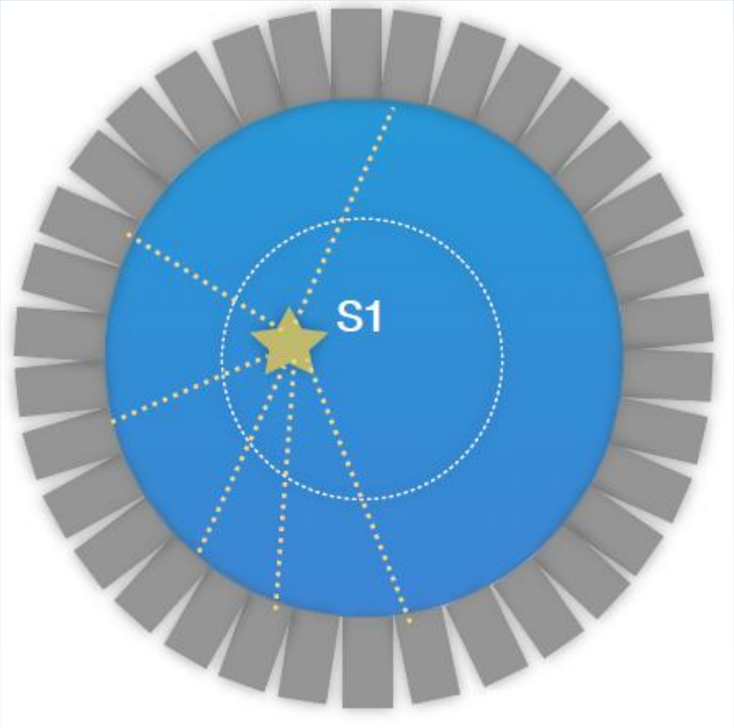
Phys. Rev. D 93, 052014 (2016)



Liquid noble gas detectors

- Currently the most promising technology at high mass
  - Frequently use liquid xenon or argon as a target
  - Many different experiments, dual phase and single phase
  - Large, scalable target masses

Single phase

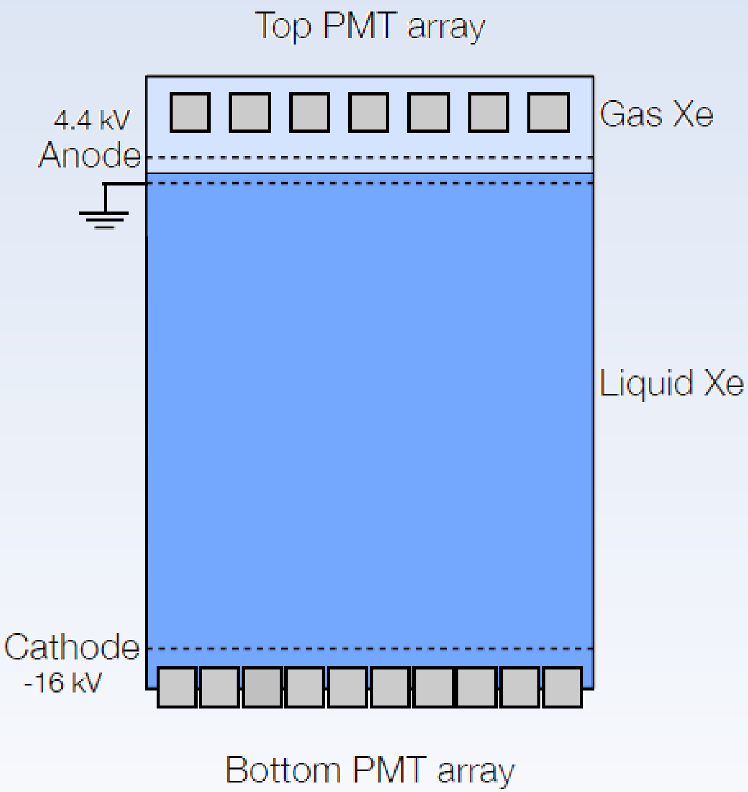


- Detect prompt scintillation signal (S1) with very high efficiency
  - Position reconstruction on S1 allows surface event removal
  - Pulse shape discrimination possible for LAr
- Pursued in both LXe (e.g. XMASS) and LAr (e.g. DEAP 3600)

Dual phase

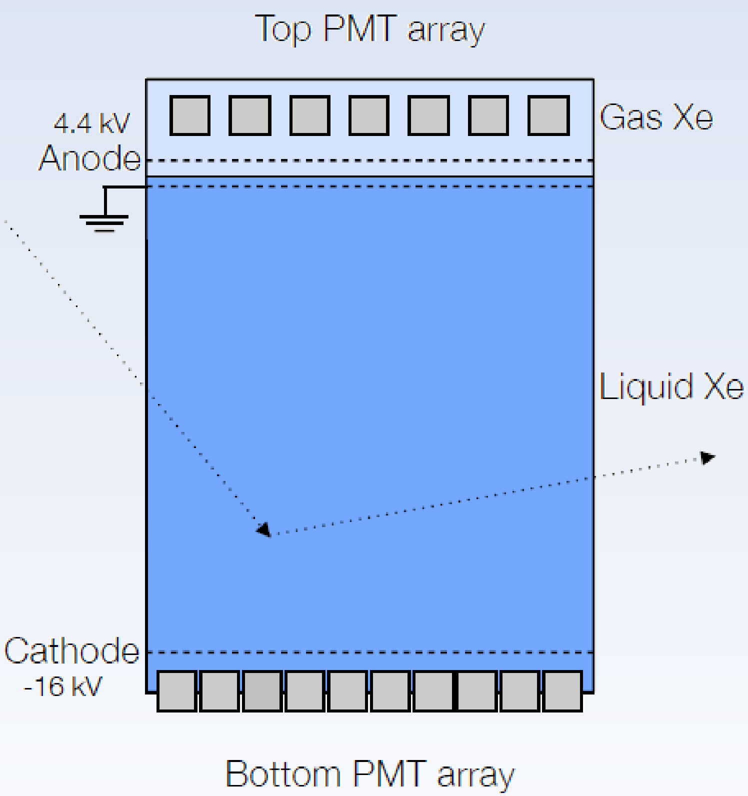
- Many DM detectors follow the "dual phase" noble gas TPC design
  - Liquid as a target with gas used to generate secondary signal
- Most detectors aiming at masses (>50GeV/c^2) are of this design
  - DarkSide, LUX/LZ, XENON
- LUX most sensitive of all detectors
  - Subject of next talk!

Liquid noble gas TPC principles

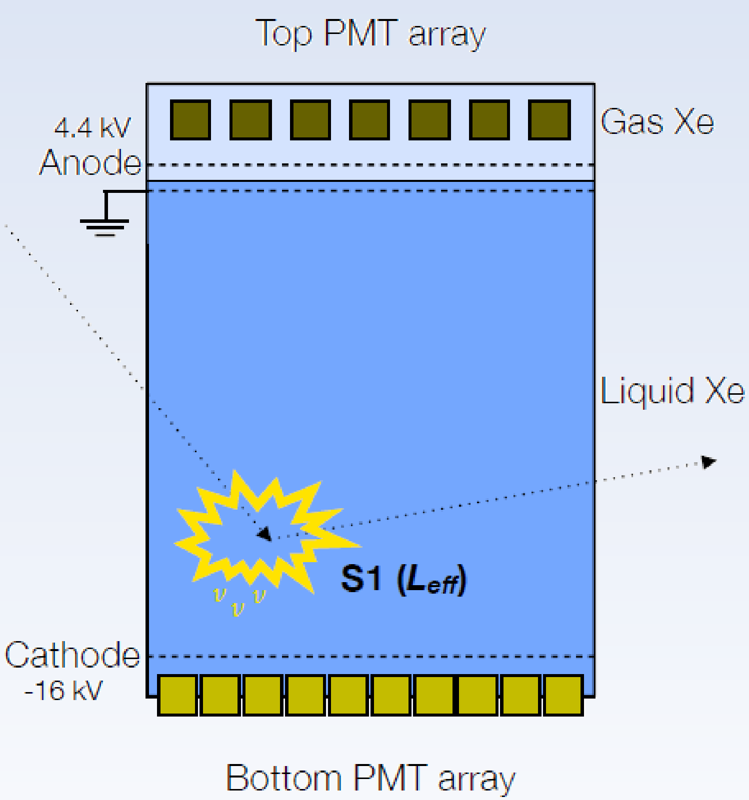


Liquid noble gas TPC principles

- Interactions in TPC give two signals

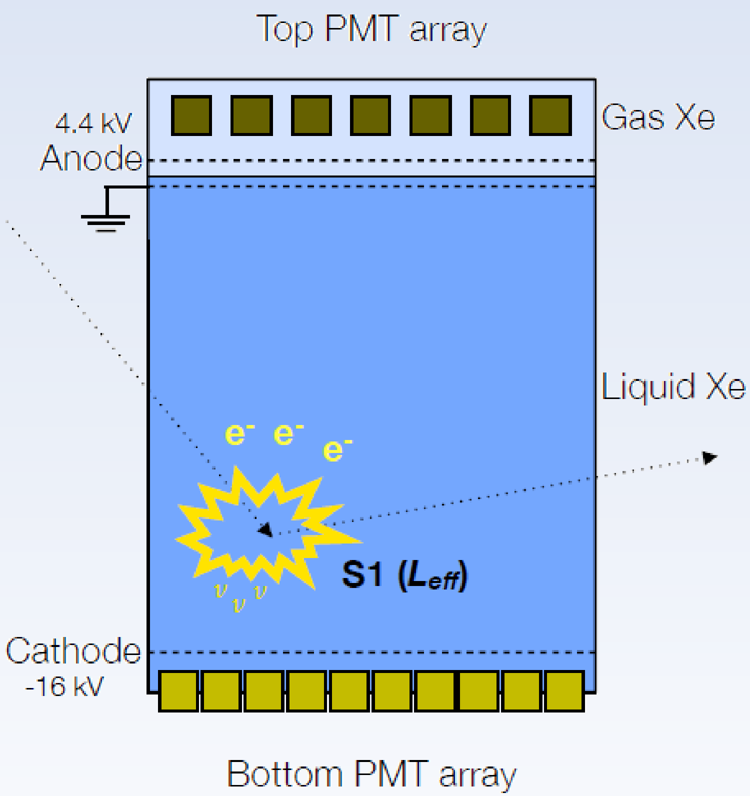


Liquid noble gas TPC principles



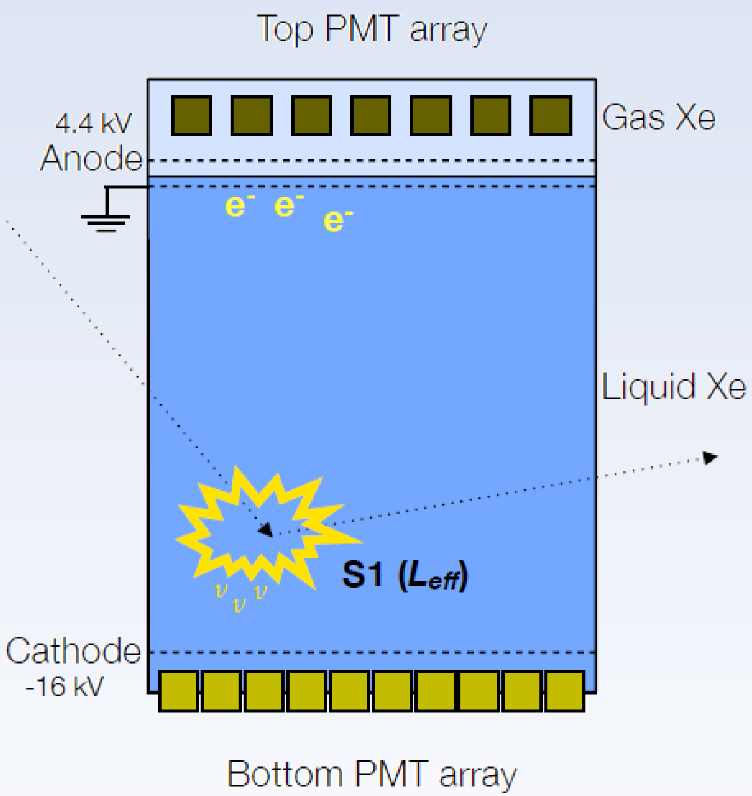
- Interactions in TPC give two signals
  - Prompt (S1)

Liquid noble gas TPC principles



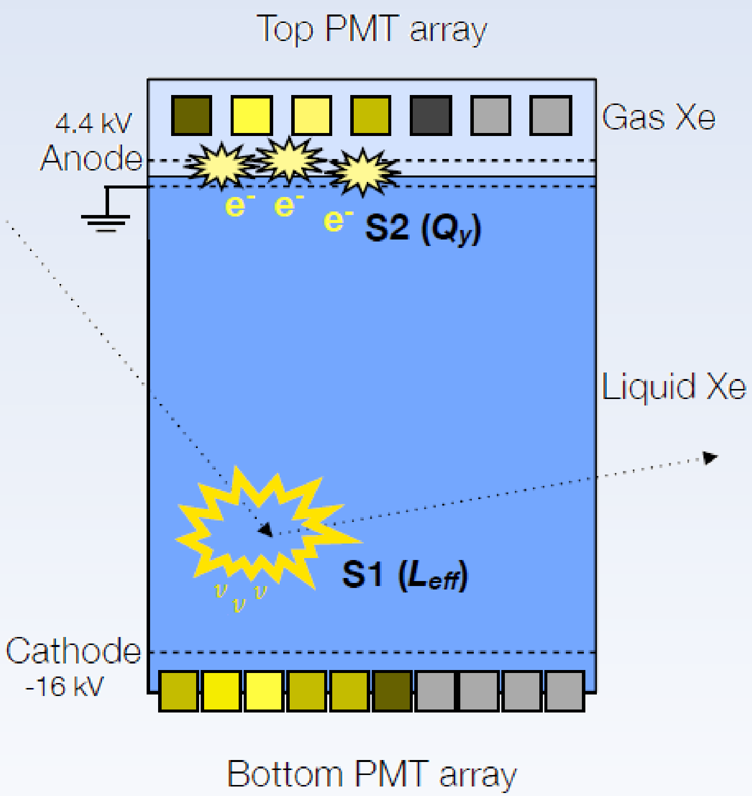
- Interactions in TPC give two signals
  - Prompt (S1) and Proportional (S2)

Liquid noble gas TPC principles

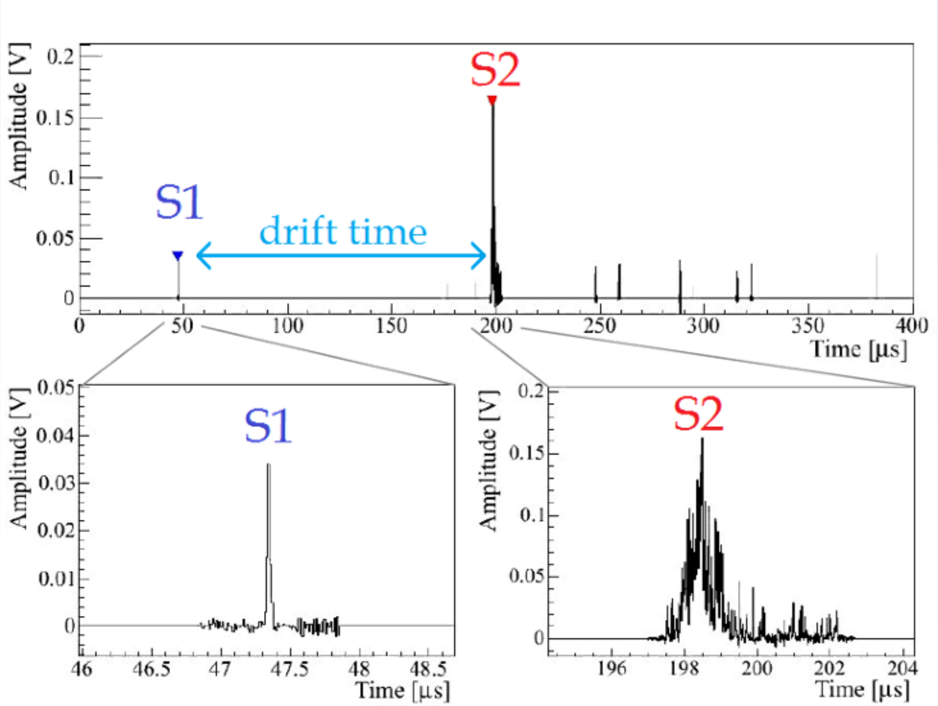


- Interactions in TPC give two signals
  - Prompt (S1) and Proportional (S2)

Liquid noble gas TPC principles



- Interactions in TPC give two signals
  - Prompt (S1) and Proportional (S2)
- Allows position reconstruction
  - S1-S2 time difference gives z depth
  - S2 hit pattern gives x-y position



XENON Project

2005-2007

Astropart.Phys.34:679-698, (2011)

XENON10

2008-2016

Astropart.Phys.35:573-590, (2012)

XENON100

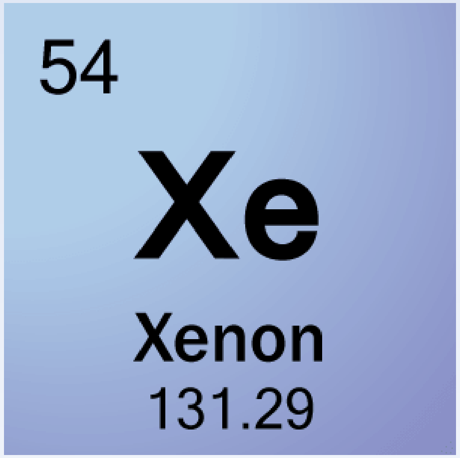
2015-2022

arXiv:1512.07501

XENON1T / XENONnT

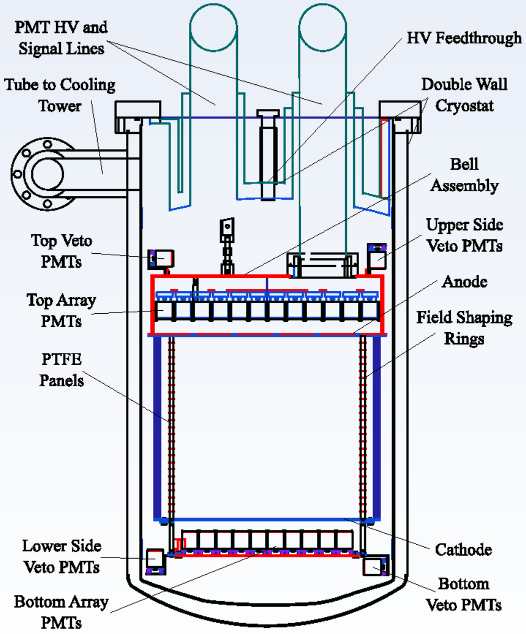
Xenon as a dark matter target

- Virtually no long-lived radio-isotopes in pure Xe
- SI and SD (from ^{129}Xe and ^{131}Xe)
- Low threshold (few keVnr)
- Two-phase operation allows:
  - 3D position reconstruction, fiducialisation
  - Background discrimination
- Relatively high density (~3g/cm^3)
  - High A (~131), with SI WIMP-nucleon $\sigma \propto A^2$
  - Good self-shielding



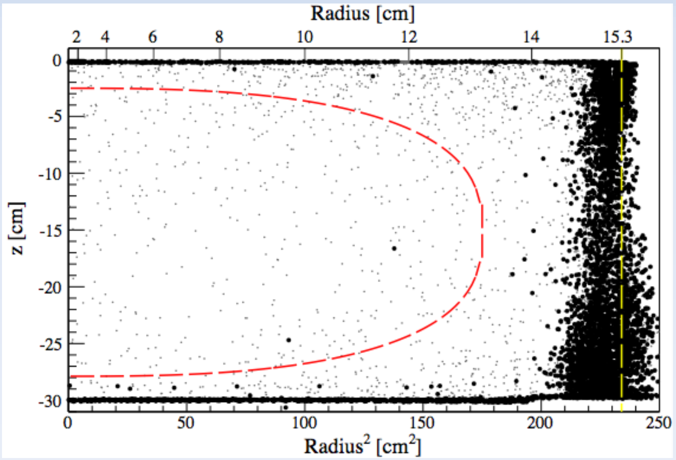
XENON100

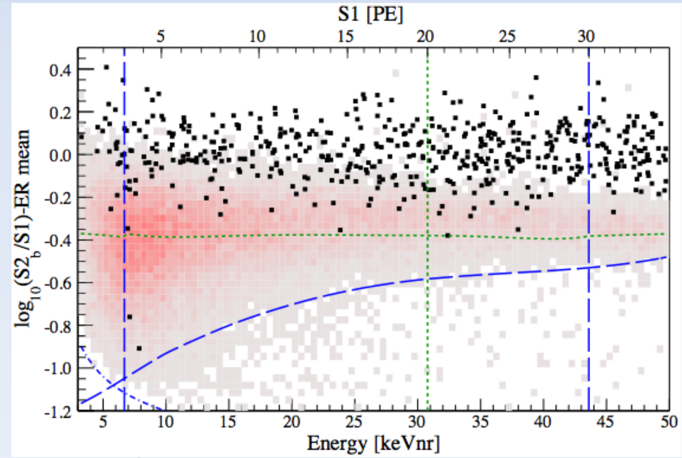
- Liquid xenon TPC
  - Fiducial mass 34kg - 48kg
- Longest DM search run completed in 2012
  - World's strongest DM limits at the time
  - Further run unblinded, combined analysis ~done
- Longest continuous running of a LXe TPC
  - Over 1 year of data taking in 2011-2012 DM run
  - Recent calibration run longer, over 1.5 years
  - Now used for research and development



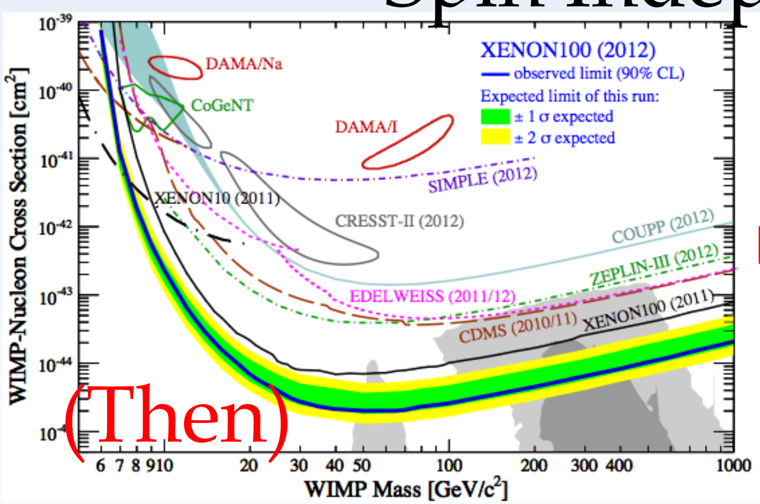
XENON100: 225 days SI results

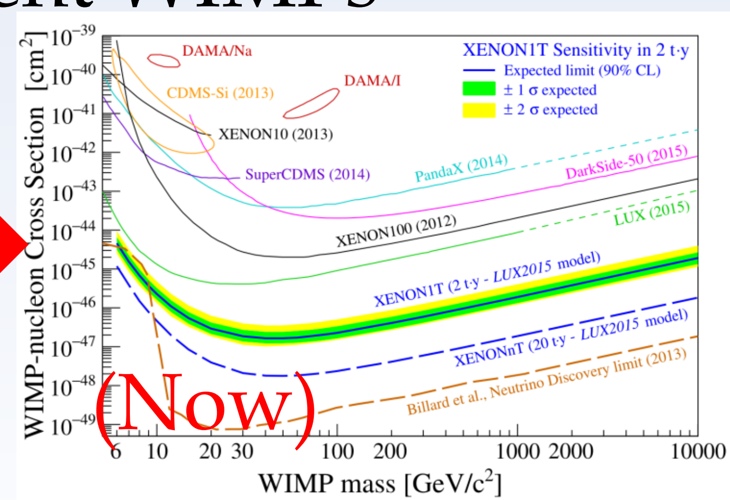
Phys. Rev. Lett. 109, 181301 (2012)



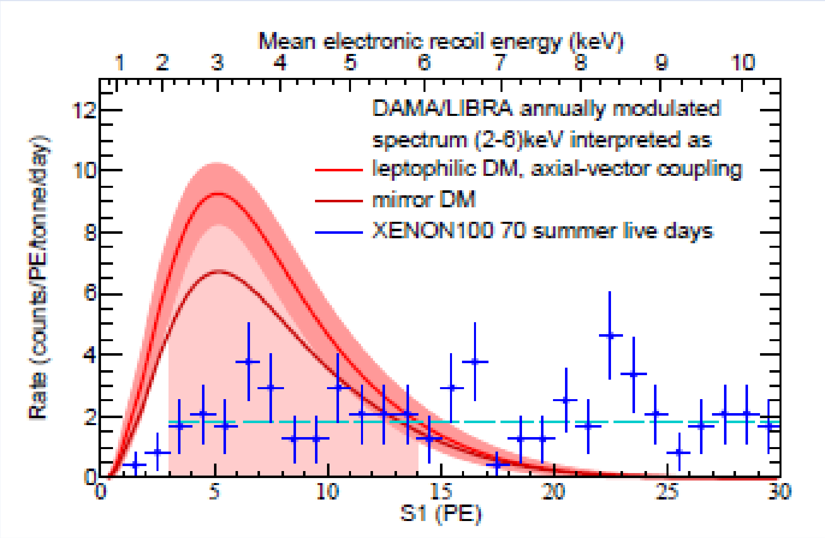


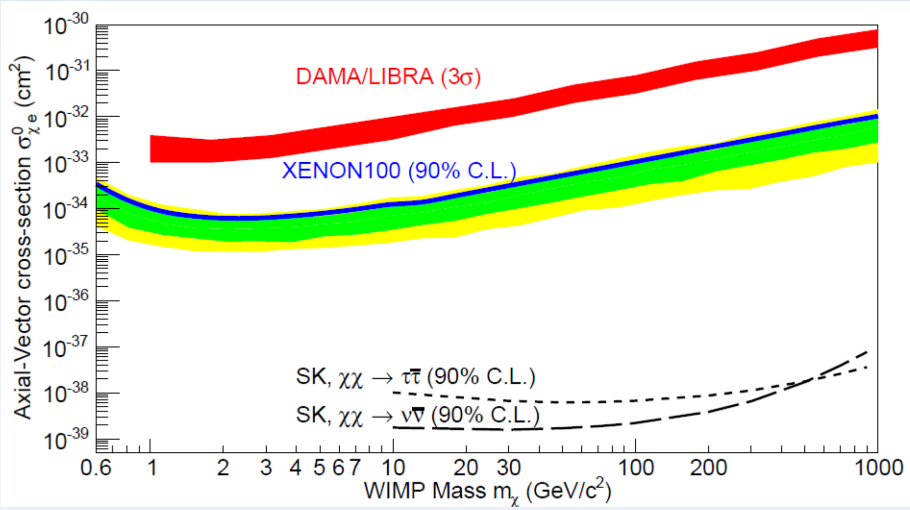
Spin Independent WIMPs





XENON100 - exclusion of leptophilic DM

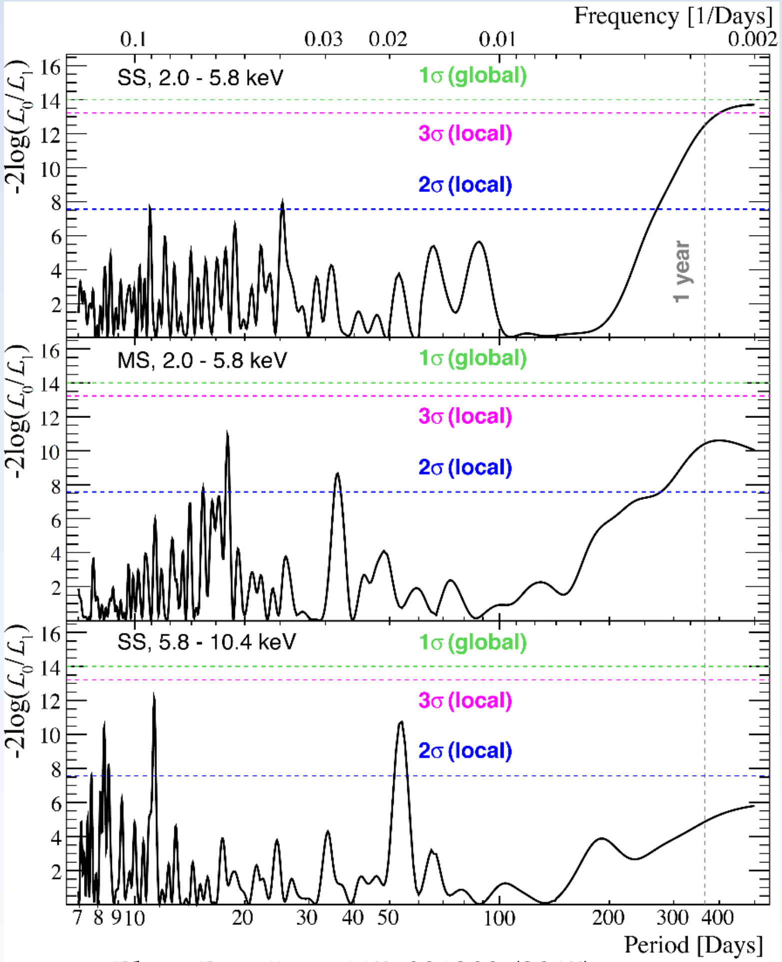




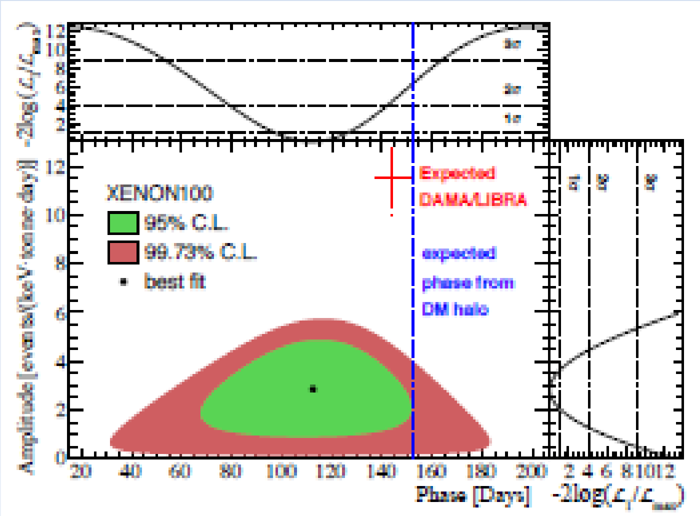
Science 2015 vol. 349 no. 6250 pp. 851-854

- Three representative models of leptophillic DM tested
  - ~halo-independent due to similar electronic structure between xenon and iodine
  - XENON100 well understood background lower than DAMA expectation
  - All exclude DAMA with significances > 3.6σ

XENON100 – Modulation search



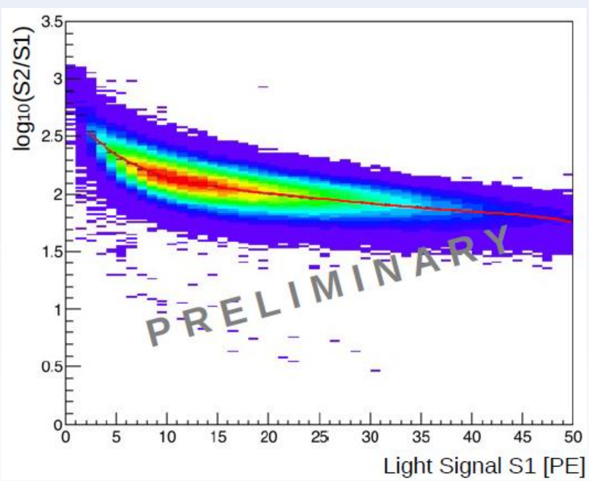
Phys. Rev. Lett. 115, 091302 (2015)

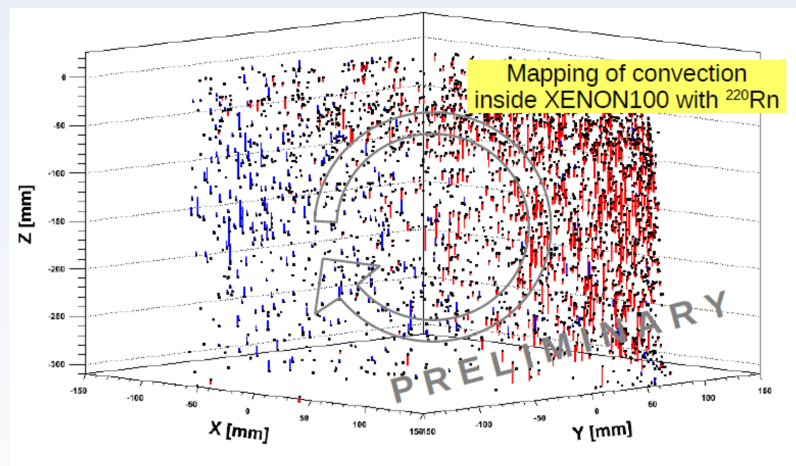


- No globally significant modulation
  - Looking at periods up to 500 days
  - Local 2.8σ significance at 1 year
  - Also seen in multiple-scatter control and high energy control, disfavouring DM interpretation
- Best-fit, exclude DM halo phase at 2.5σ
  - DAMA/LIBRA signal excluded at 4.8σ

XENON100 - ongoing analyses

- S2 only analysis soon to be published
- Since summer 2014, XENON100 has been used for Calibration / R&D
  - Now the longest stable running of a LXe TPC (>1.5 years)
- Several new calibration sources trialled
  - ^{88}Yttrium-Beryllium – low energy 152 keV neutrons
  - ^{83m}Krypton – low energy 9 keV and 32 keV gamma lines
  - ^{220}Radon – short lived isotope calibrating low energy electronic recoils (and more)
  - TCH_3 , tritiated methane – very low energy electronic recoil calibration

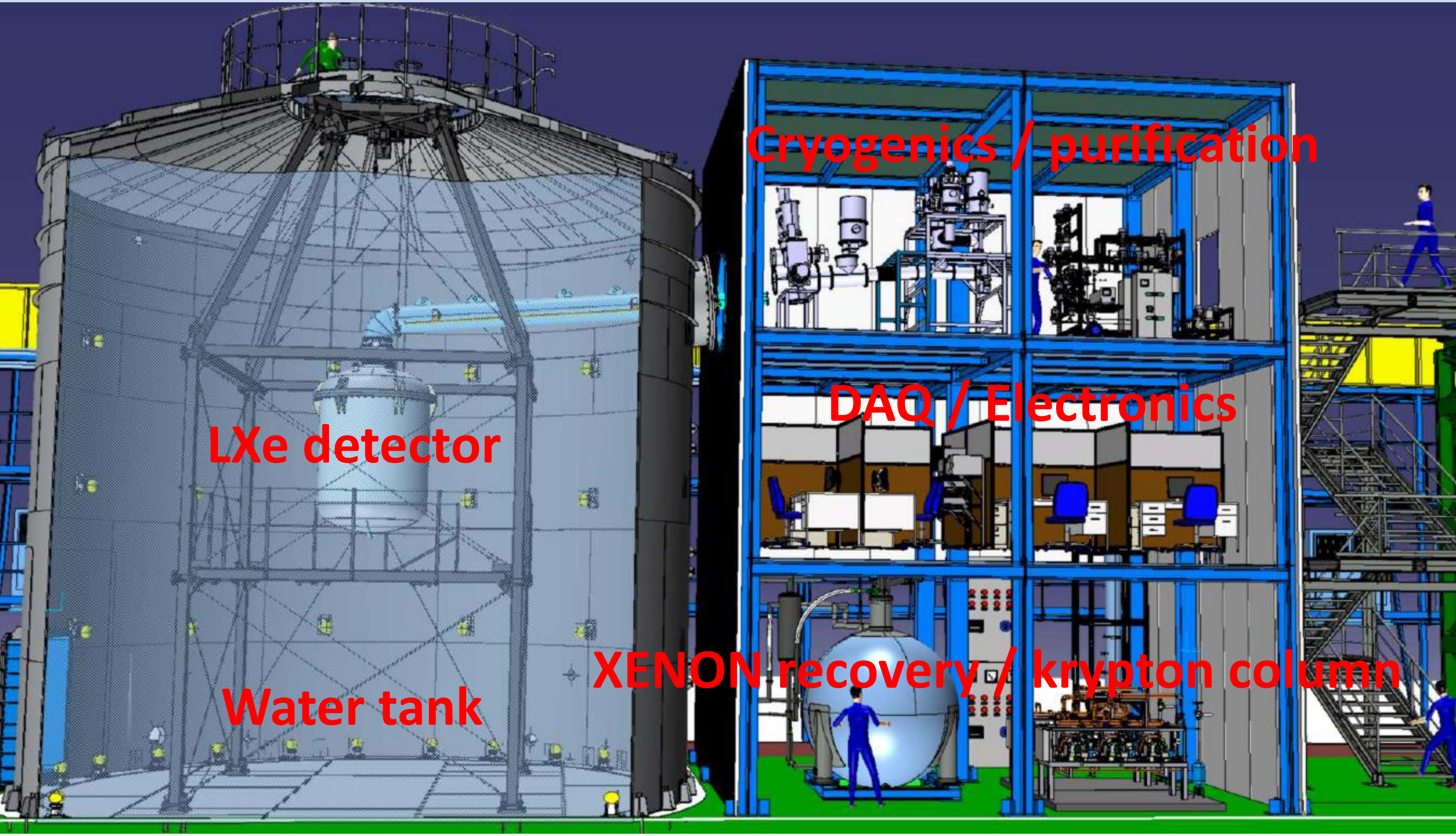




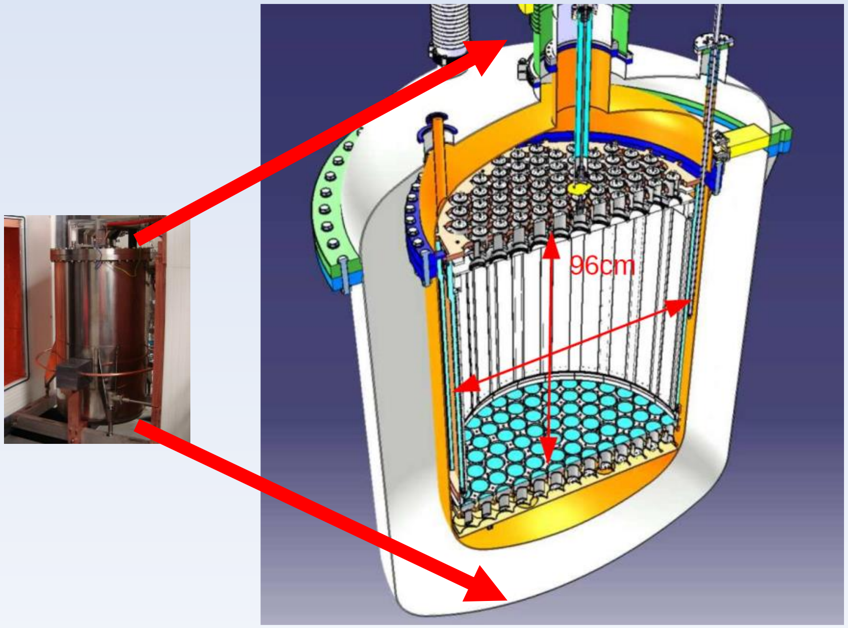
- Several 2016 papers expected on these novel calibrations!

XENON1T

XENON1T - Systems



XENON1T - Overview

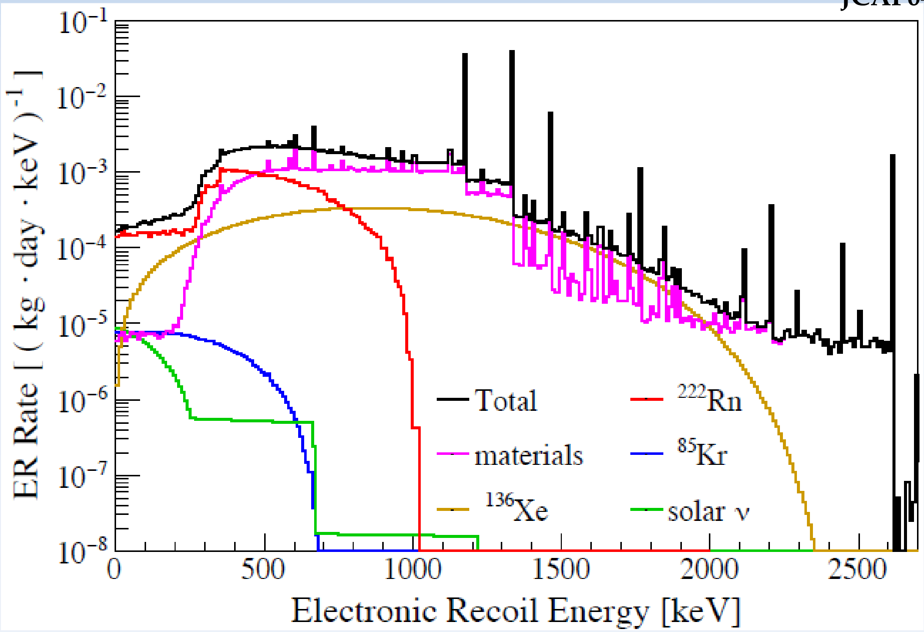


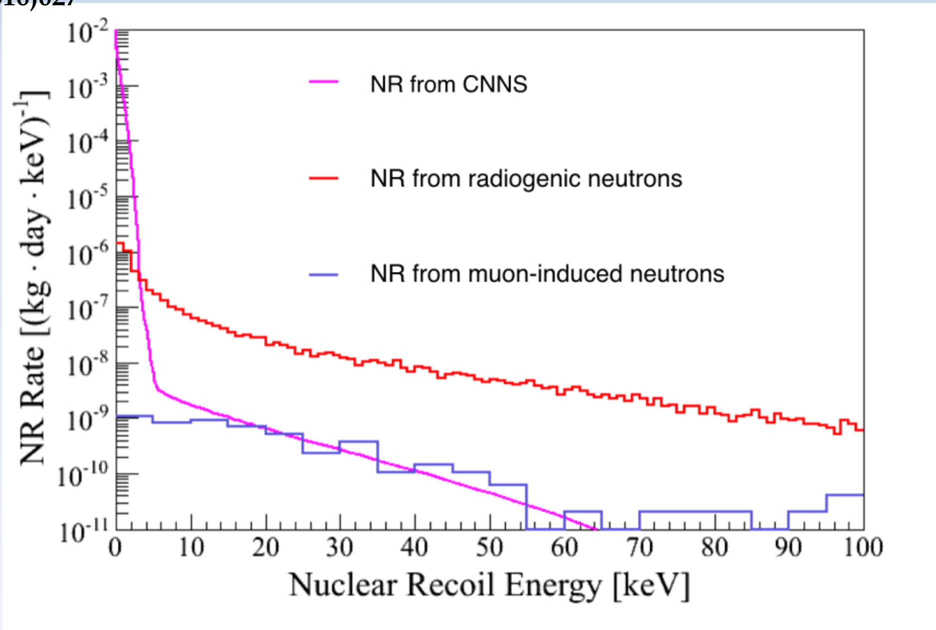
XENON100	XENON1T
161kg of Xe	3300kg of Xe
62kg active target	2000kg active target
Passive shields	Active shield (water)
30 cm drift	1m drift
5×10^{-3} events/keV/kg/day	$< 2\times10^{-4}$ events/keV/kg/day
1 ppt Kr/Xe	0.2 ppt Kr/Xe
65 µBq/kg for ^{222}Rn	<10 µBq/kg for ^{222}Rn
4.5 pe/keV @ 122 keVee	6.6 pe/keV @ 122 keVee

- Greatly increased size and purity over XENON100
  - Improved detector characteristics (e.g. light yield)

XENON1T - Backgrounds

JCAP04(2016)027

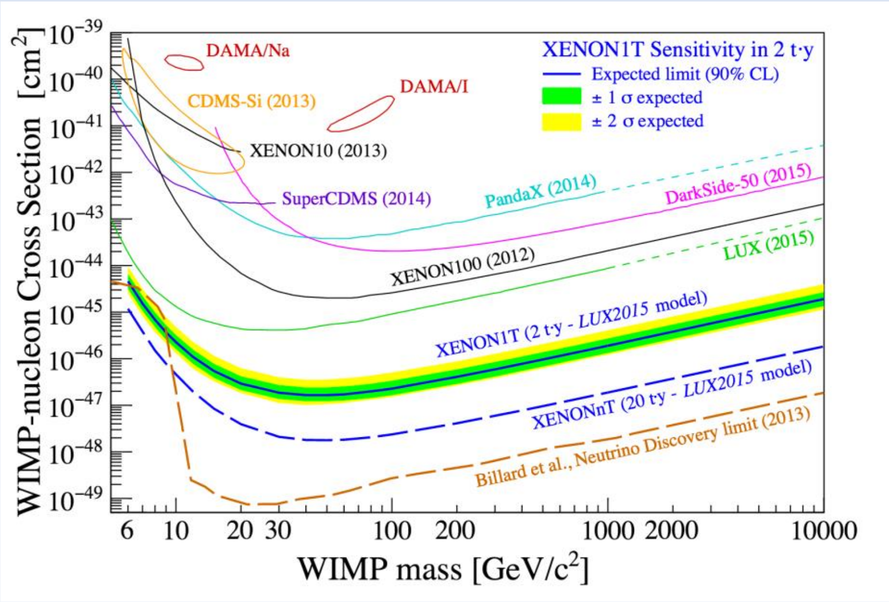


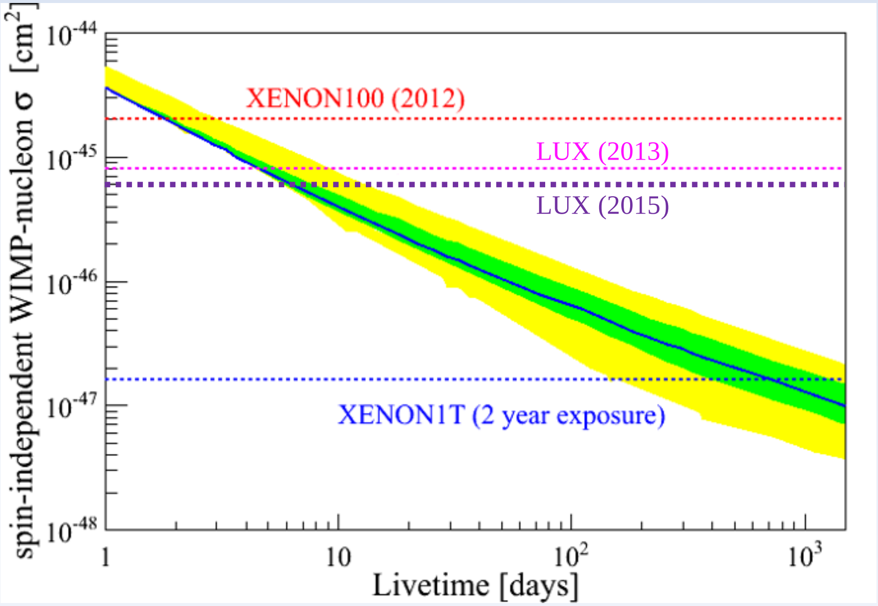


- Total ER events expected: 720 events / year in 1t FV
  - Dominant source (620 ev/yr) is 220-Rn chain, conservative 10μBq/kg
- Total NR events expected: 0.62 events / year in 1t FV
  - Mostly from radiogenic neutrons (0.6 ev/year)
  - Steep shape of CNNS at low E means S1/S2 conversion v. important!

XENON1T - Sensitivity

JCAP04(2016)027

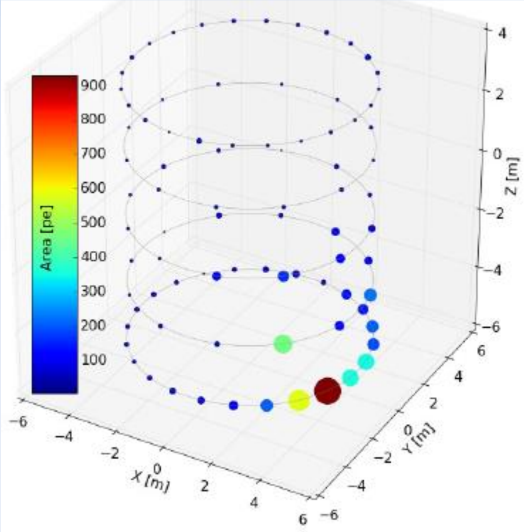


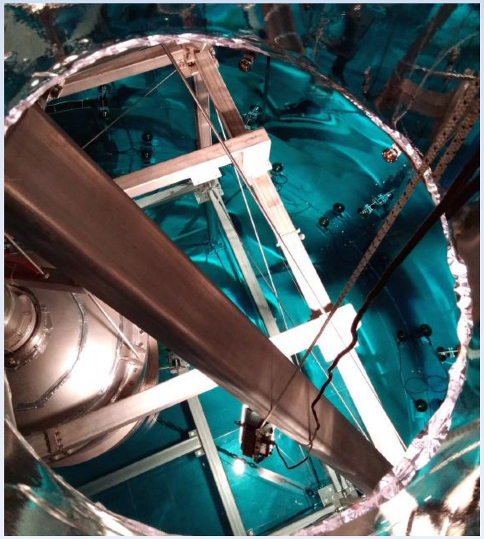


- XENON1T expected 100× improvement over XENON100
  - Greater than an order of magnitude over existing best limit (LUX)
  - Expected to reach LUX sensitivity within ~10 live-days of data taking

XENON1T – Status highlights

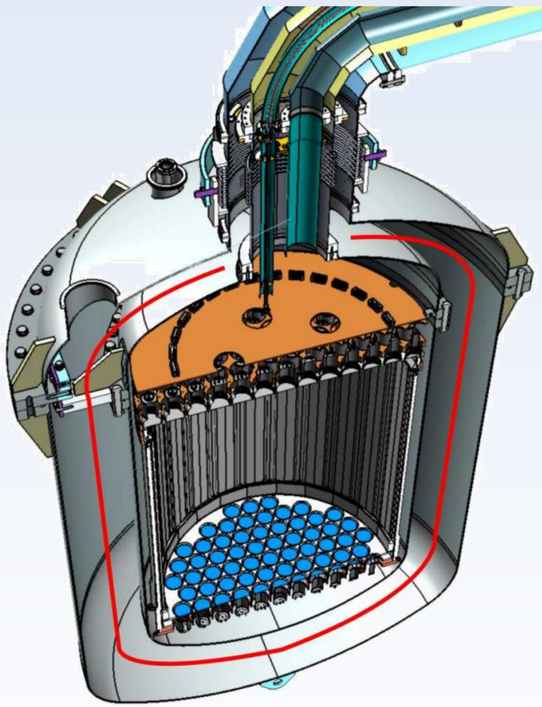
- Water tank muon veto
  - Installed ✓
  - Water filling test ✓
  - Muon veto tested ✓
- Cryostat / TPC
  - Installed ✓
  - Cooled down ✓
  - Filled with liquid xenon ✓
- High voltage / PMTs
  - Installed ✓
  - PMTs tested working (all 254) ✓
  - HV testing *(underway)*
- Current work to get first S1 / S2 signals out of TPC!

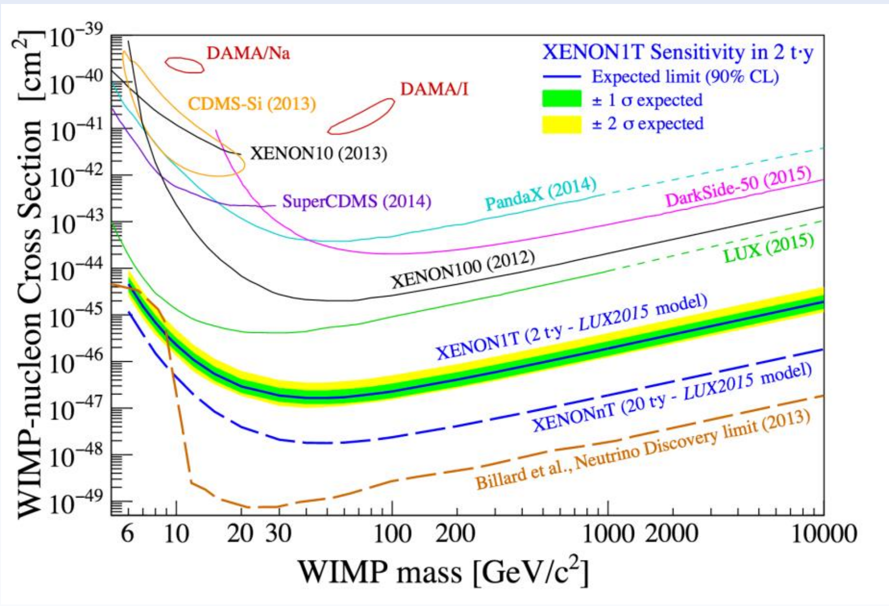




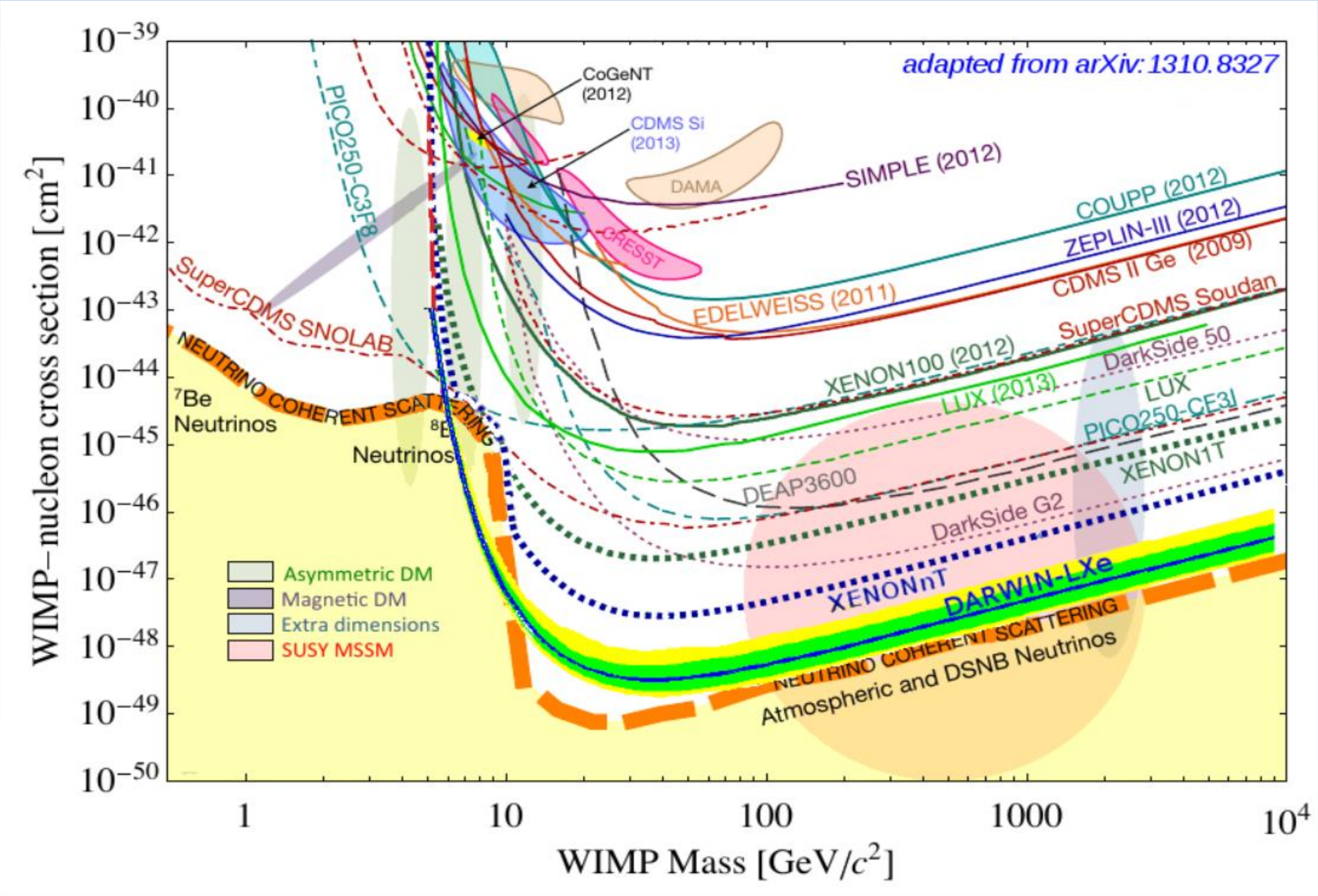
XENONnT – the XENON1T upgrade

- Increase xenon target, plan to allow 20 tonne-years of exposure
- Reuse existing outer cryostat, water tank, cooling system…
- Allows improvement by nearly order of magnitude in a few live-years





The dark matter picture



- Progress continues rapidly
- Ultimately restricted by the neutrino CNNS floor

Going forward

- Many successful experiments in the field
  - All have prospects to improve their sensitivity
- *Non-exhaustive* list
  - XENON1T - fully funded, being commissioned now
  - DarkSide-50 – continuing with extended underground argon run
  - SuperCDMS - funded by DOE in G2, design/production for SNOLAB
  - DEAP-3600 – built and cooled down, see J. Monroe talk!
  - XMASS – new run, next step XMASS 1.5 – see K. Ichimura talk!
  - LUX/LZ – new LUX run, full DOE funding for LZ, see A. Bernstein talk!
- Ultimately limited by CNNS neutrino floor
  - Irreducible neutrino background limits DM detector future
    - Estimated to be some time by mid 2020s for non-directional detectors
    - Beaten by directional detectors, see N. Spooner and K. Miuchi (NEWAGE) talks!

Summary

- The terrestrial search for dark matter interactions continues
  - A wide range of technologies has been tested over the last decade(s)
- In the next $\mathcal{O}(5)$ years
  - Different technologies will probe different mass ranges
  - Searches at masses >10 GeV/c^2 likely dominated by noble gas detectors
  - At lighter masses, variety of technologies and targets
- Several experiments are under design, building and operation
  - Still real competition in the field, expected to continue for years to come
  - Shows that funding agencies are still supportive!