Status of Searches for Dark Matter (Direct Detection)

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Princeton University

Starting Point and Focus of Talk

- Non-baryonic dark matter exists.
- Weakly Interacting Massive Particles (WIMPS) are a good candidate for dark matter.
- Focus on recent developments and status of direct detection of WIMP-nuclear collisions.

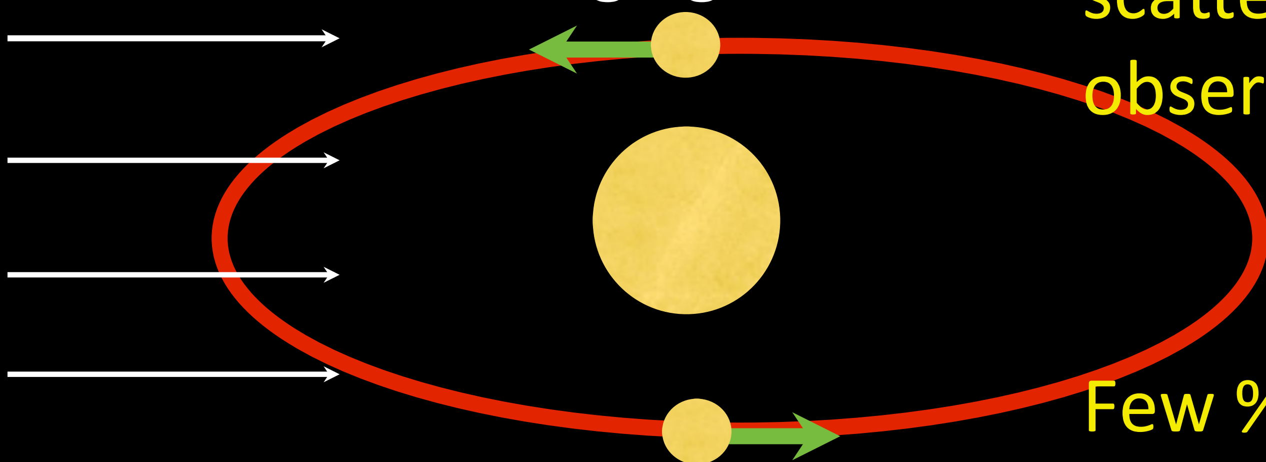
Topics Not Covered

- Evidence for non-baryonic dark matter
  - CMB acoustic oscillations, etc.
- Indirect detection experiments.
  - Search dense regions of galaxy for mono-energetic WIMP annihilation radiation.
- Axion search (ADMIX)
- Null evidence for new particles at LHC
  - Lack of evidence for non-standard particles raises questions about 100 GeV WIMP.

Dark Matter Wind Signatures

in the summer,
moving against wind

DM "wind"

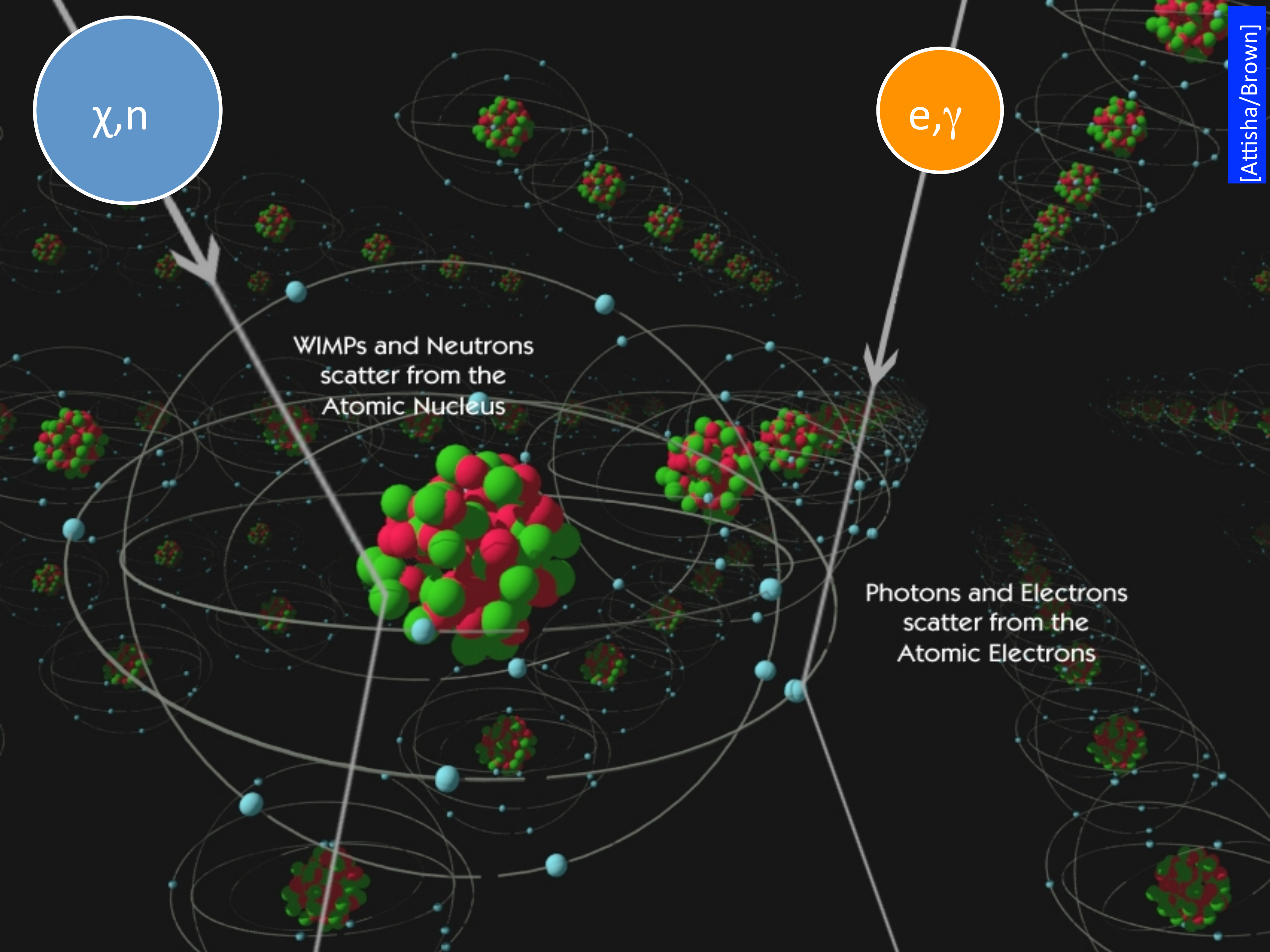


in the winter,
moving away from wind

~100% asymmetry in backward-forward scattering if tail/head is observed.

Few % annual modulation in DM spectrum

[Drukier, Freese, and Spergel PRD **33**, 3495 (1986)]


χ,n
e,γ
[Attisha/Brown]
WIMPs and Neutrons
scatter from the
Atomic Nucleus
Photons and Electrons
scatter from the
Atomic Electrons

Signal and Background

- WIMP rates could be 1 event/ton/yr or lower
  - WIMP mass range: 1 GeV – 10 Tev
  - Nuclear recoil energy range: 1 keV- 100 keV

- Achieving backgrounds low enough to detect such rates is a very difficult challenge.

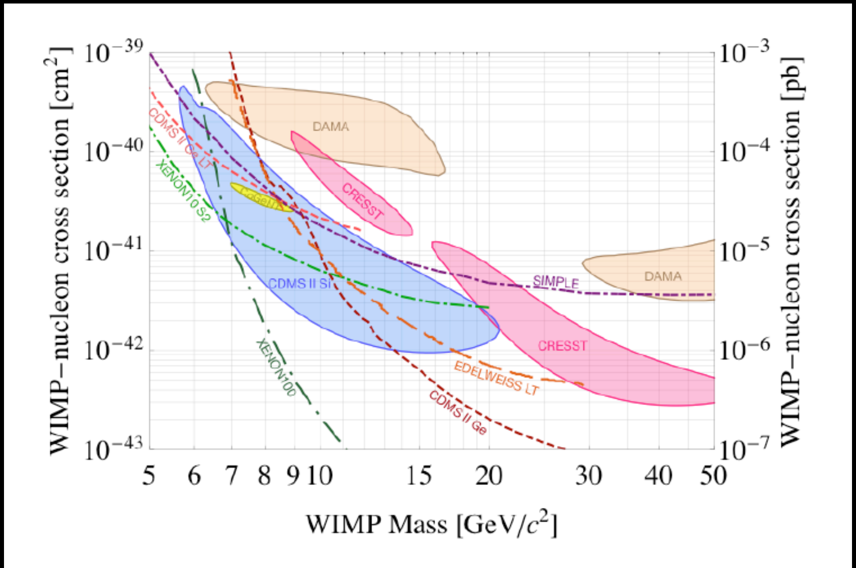
- Much progress in detecting low energy nuclear recoils and reducing backgrounds.
  - Background reduced with
    - Underground labs, ultrahigh purity materials, active shielding, etc.
    - Multiple readout signals that provide discrimination.

Nuclear and electron recoils separated by charge/energy ratio

- DM signal is a low energy nuclear recoil: 1-100 keV
  - Nuclear recoil has short track with high ionization density.
  - Electron-ion recombination is very likely.
  - Small fraction of electrons swept away with E ~1 kV/cm
- Electron recoil of same energy has longer track.
  - Dilute ionization density makes electron-ion recombination less likely.
  - Drift electric fields can sweep away large fraction of electrons.
- Discriminate nuclear and electron recoils by ionization charge collected with electric field for an energy.

Direct Detection Experiments with Possible DM Signals

- DAMA/LIBRA
- CoGeNT
- CRESST
- CDMS- silicon



Growing evidence for light WIMPs is motivating new experiments.

Start our discussion with look at these 4 experiments.

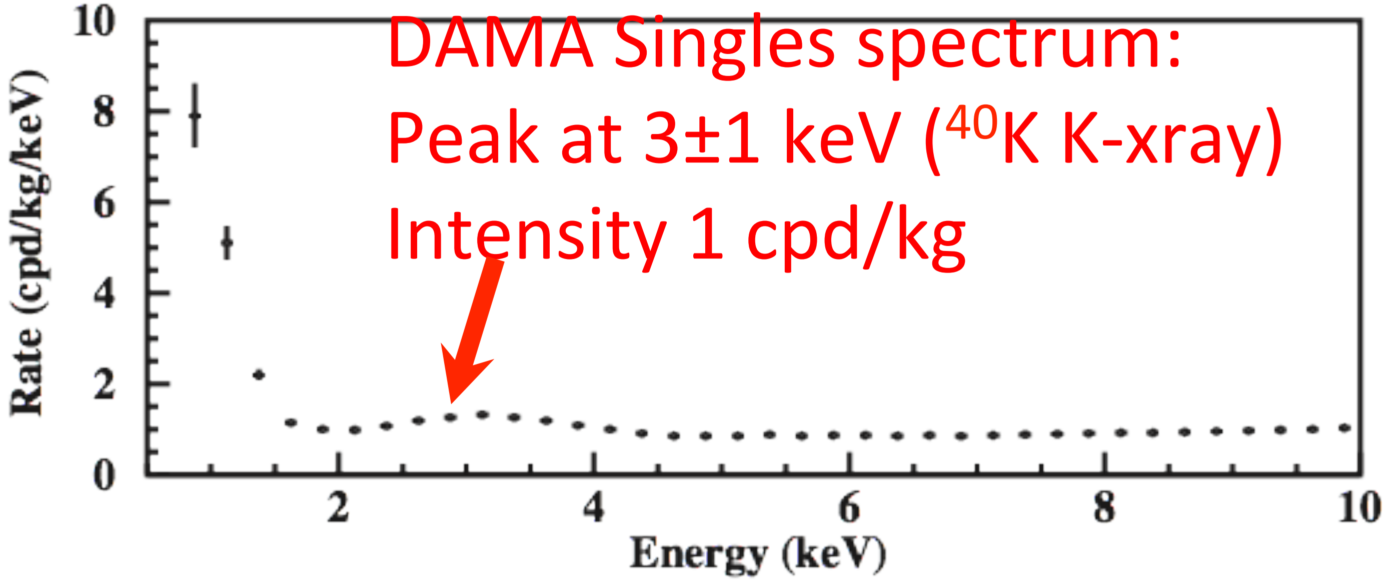
DAMA/LIBRA

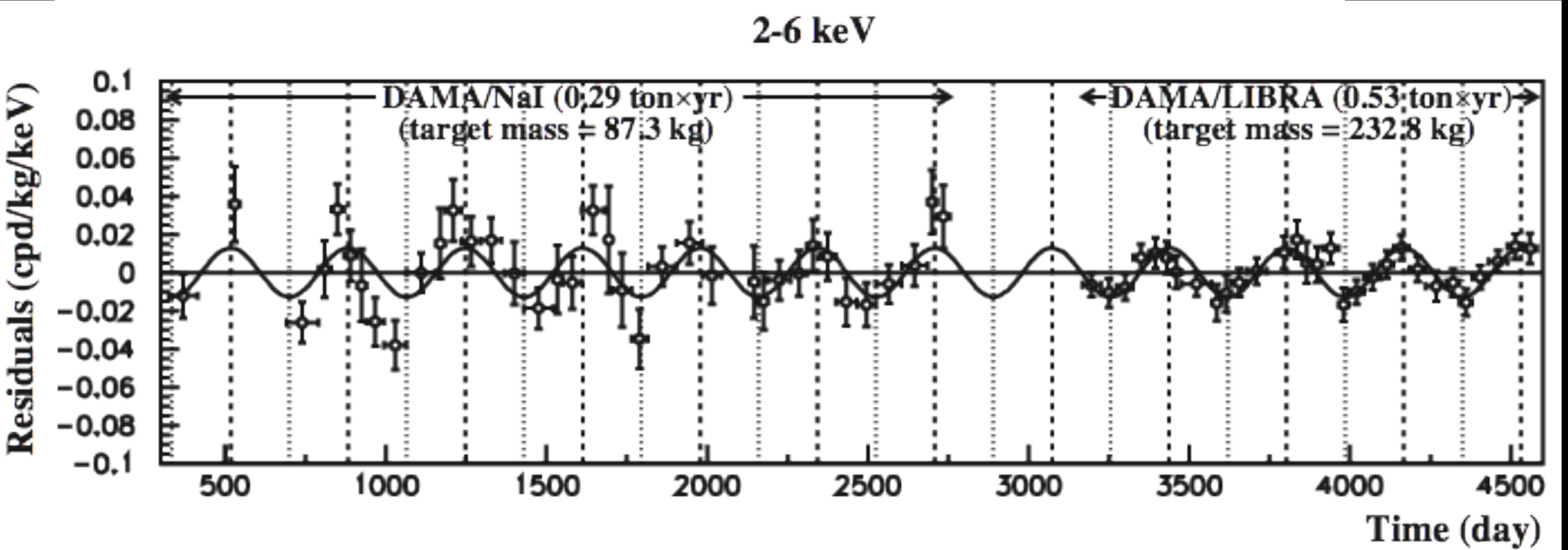
DARK MATTER

Large sodium Iodide Bulk for RAre processes

DAMA/LIBRA

- Simple strategy: Look for annual modulation expected for WIMPS with 250 kg of special radio-pure NaI(Tl) scintillators.
- Simple passive copper and lead shielding to reduce background.
- NaI crystal radio-purity is unique and, until recently, not possible for other groups to obtain.





[DAMA Coll. EPJC **56**, 333 (2008)]

Comments

- Because of background, the ~1% modulation is larger than expected for simple halo of WIMPs.
- Cosmic muon flux has ~1% seasonal variation, but it peaks about a month after the peak of DAMA-LIBRA (Borexino data).
  - The delayed peak rate of muons makes it difficult to explain the DAMA effect by seasonal cosmic ray background.
- Radio-pure NaI powder exceeding purity used for DAMA-LIBRA has been developed commercially in collaboration with Princeton group.
  - New NaI experiment with lower crystal radioactivity and active shielding is being developed.

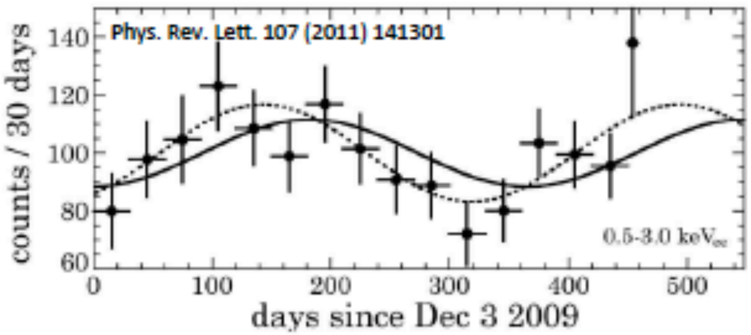
CoGeNT

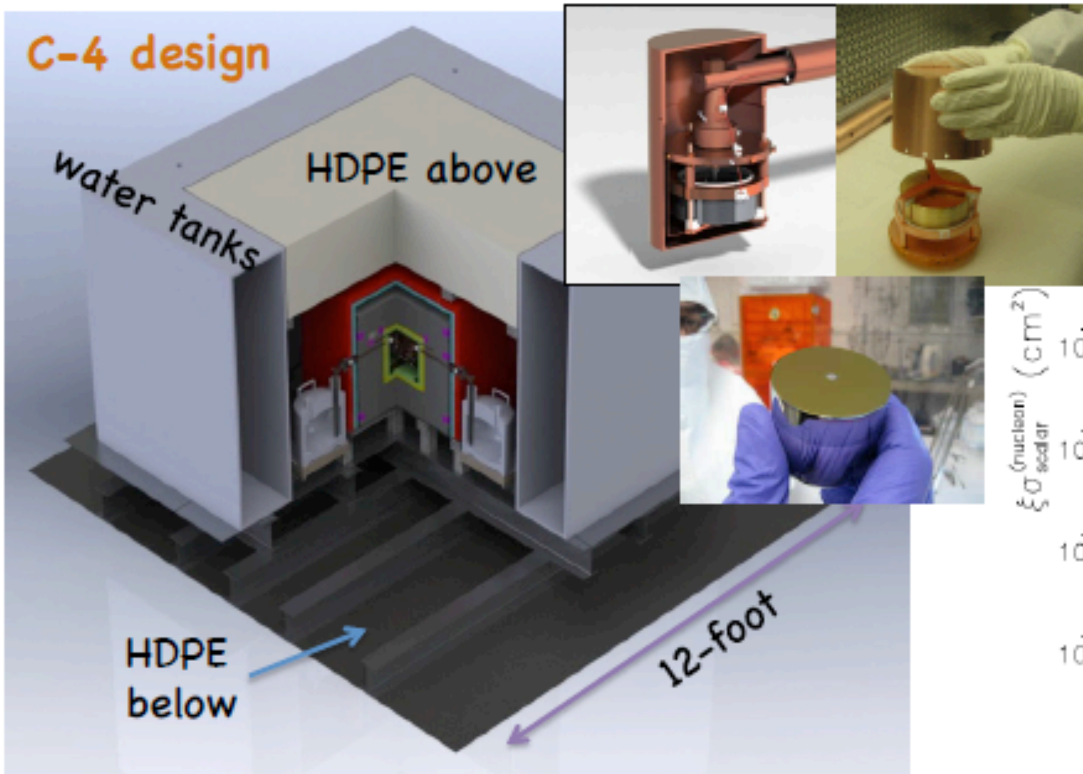
Coherent Germanium Neutrino Technology

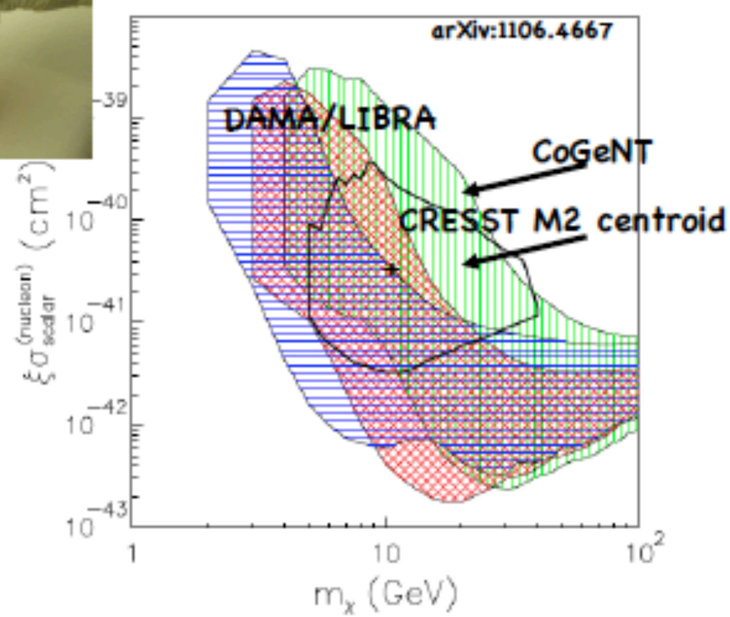
(and then Dark Matter)

CoGeNT: dedicated search for light-mass WIMPs

- Annual modulation of unknown origin, measured with 0.4 kg PPC germanium crystal at Soudan, in possible agreement with DAMA/LIBRA, CRESST & CDMS-Si anomalies. Compatible with a light WIMP interpretation.
- C-4 expansion to start 2013 in Soudan (x12 present target mass, significant reduction in bckg and threshold expected). First C-4 detector has x3 the mass, 1/3 the electronic noise of CoGeNT detector at Soudan.
- 3.4 years of continuous data-taking from detector at Soudan to be released very soon. Test of non-Maxwellian halo interpretations for DAMA/LIBRA.







P-type point contact Ge detectors

A Breakthrough for Light WIMP Detection

- The small capacitance of the point-like electrode reduces noise, allowing for very energy threshold energy (few hundred eV).
- The low energy threshold gives these detectors unique sensitivity to light WIMPS.
- Gamma backgrounds: The time profile of ionization arriving at a point contact can reveal Compton scatter multi-hits, allowing gamma background rejection.
- These detectors will be used in the Majorana neutrino-less $\beta\beta$ experiment to be operational in near future in SURF (Homestake).

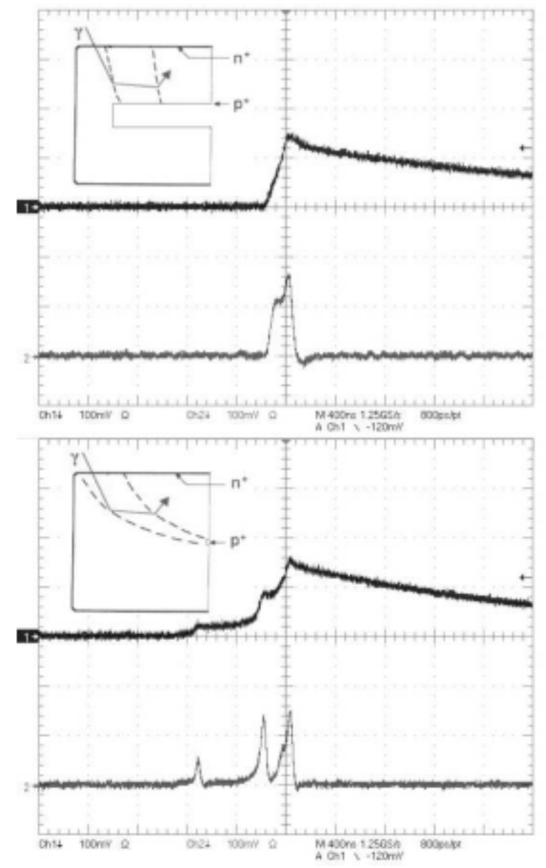


FIG. 10: Effect of electrode geometry on pulse formation for a multiple-site gamma interaction (see text).

Luke et al. IEEE Trans. Nuc. Sci.36, 926,(1989)
P.S. Barbeau, J.I. Collar. and O. Tench
J. Cosm. Astro. Phys. 0709 (2008)

Recent Developments

- New CoGeNT data to be released in a few weeks at TAUP 2013 in Asilomar.
  - Total of 3.5 years will more than double statistics.

CRESST

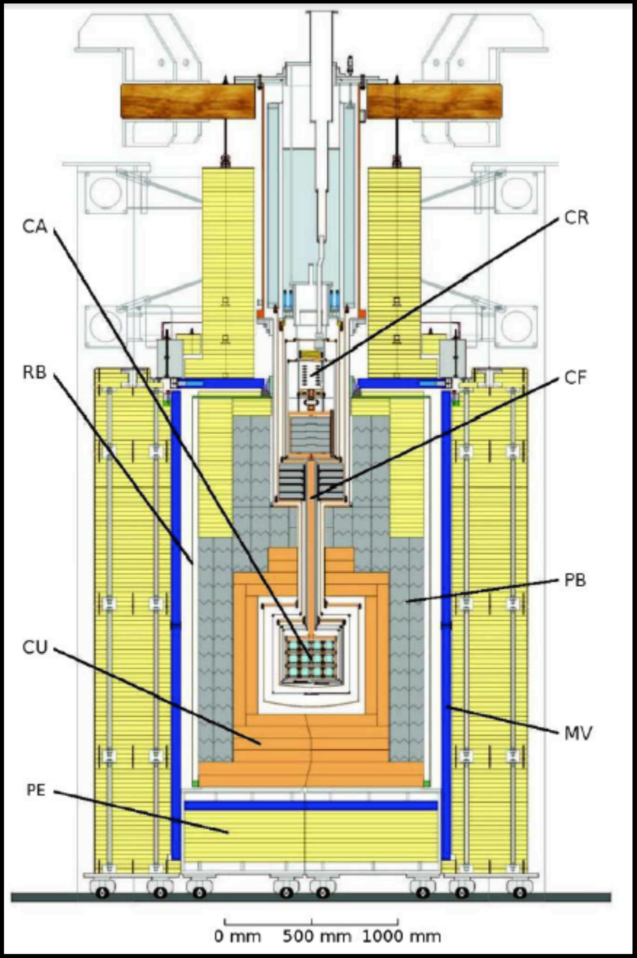
Cryogenic Rare Event

Search with Superconducting

Thermometers

CRESST Detector Assembly

- Scintillating $CaWO_4$ Crystals
- Exposure: 730 kg-d
- Signals: Phonons and scintillation photons
- Passive shielding of Cu, Pb, PE.



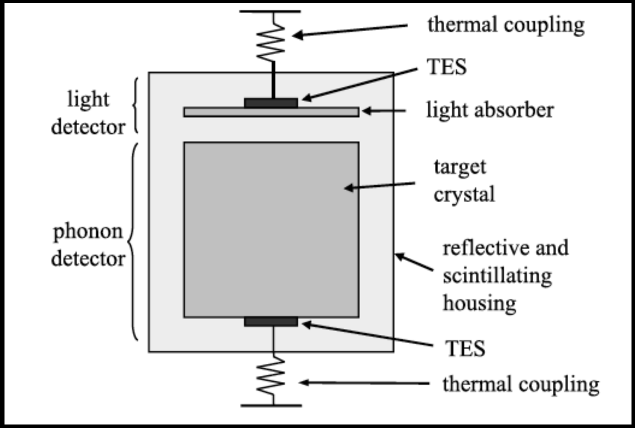
CRESST Crystals and Background

Phonons: Cryogenic bolometer @ 10 mK (TEC)

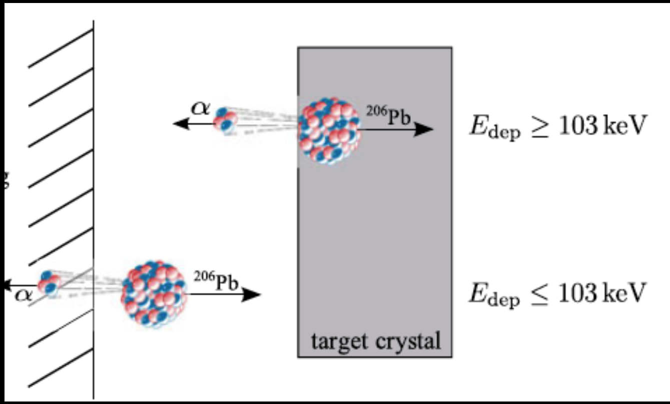
Photons: Bolometric light absorber.

Observation: 67 events in nuclear recoil region

Significant background due to ^{210}Po on surface



	M1	M2
e/γ-events	8.00 ± 0.05	8.00 ± 0.05
α-events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
Neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
Signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$

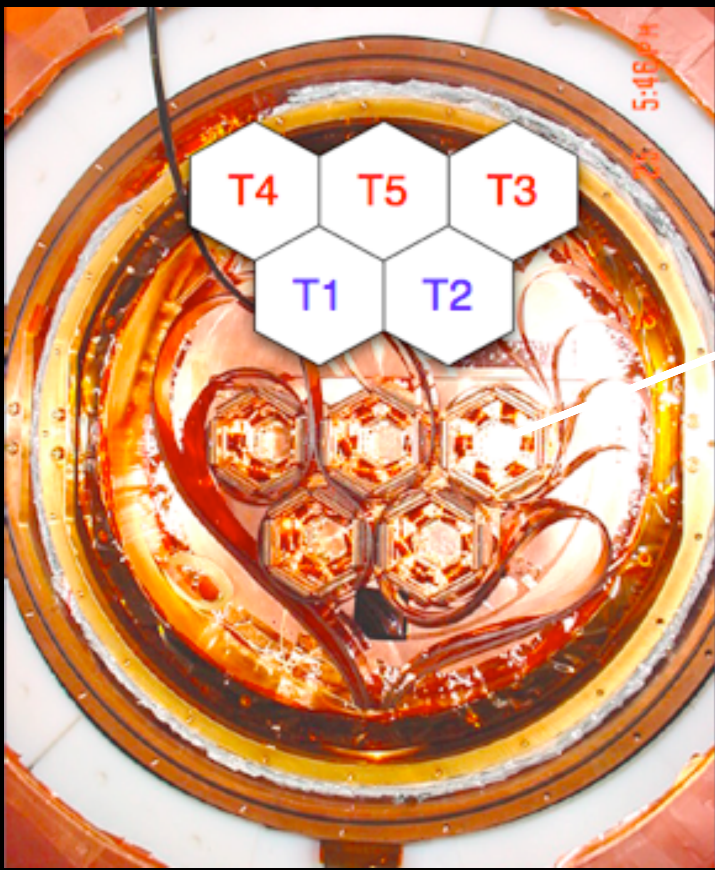


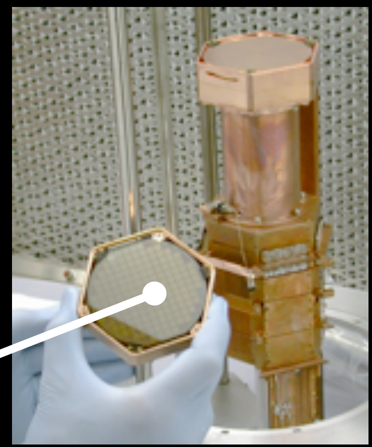
CDMS - Silicon

Cryogenic Dark Matter Search

CDMS II Search with Silicon

- Reporting results from blind analysis of 140 kg-days of Si data (8 detectors), gathered from July 2007- September 2008
- Lighter Si target nucleus is advantageous for low mass WIMP searches !

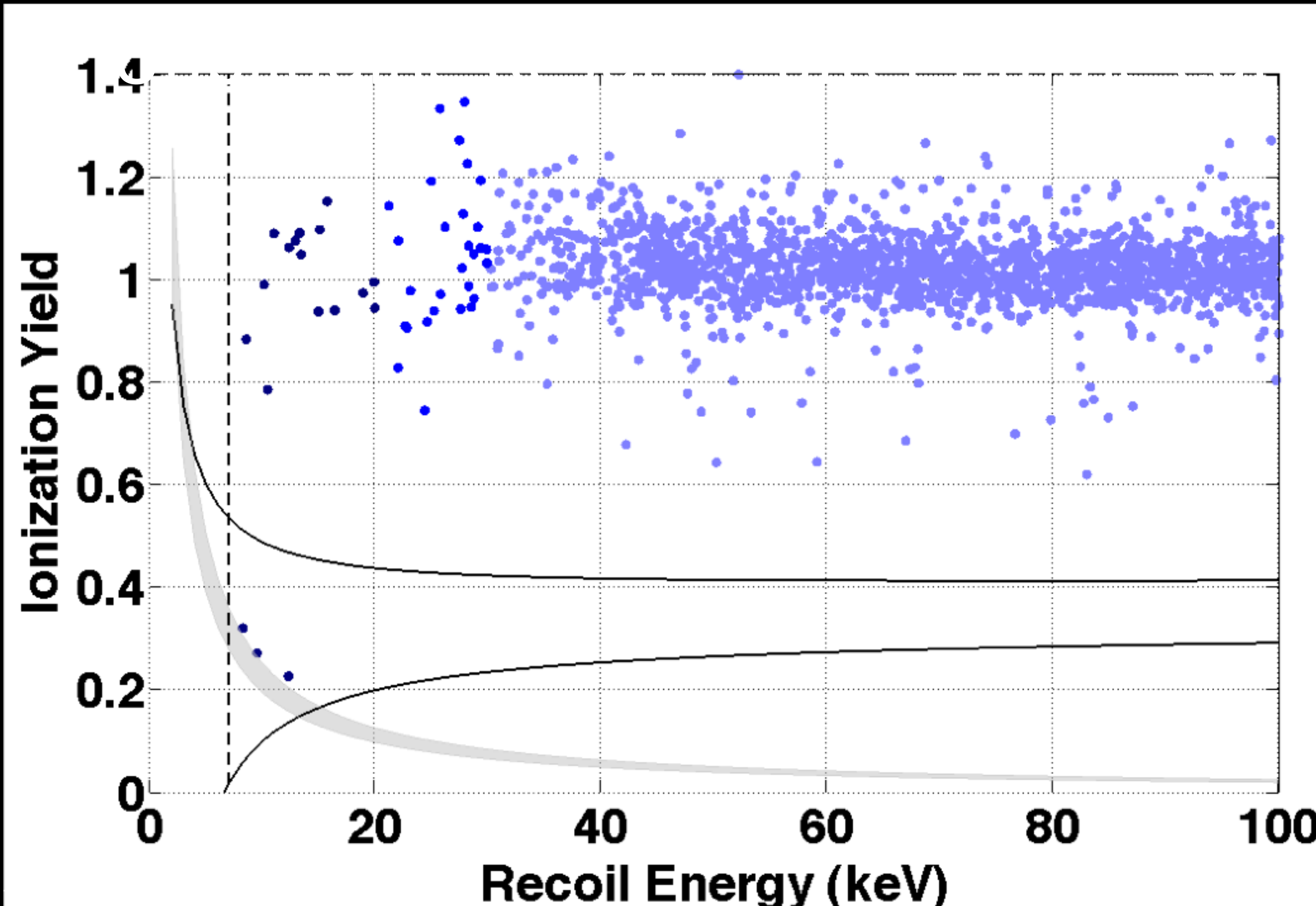




Five Towers (30 ZIPS)
Operated 2006-2009 4.6 kg Ge (A=73)
1.2 kg Si (A=28)

	T1	T2	T3	T4	T5
Z1	G6	S14	S17	S12	G7
Z2	G11	S28	G25	G37	G36
Z3	G8	G13	S30	S10	S29
Z4	S3	S25	G33	G35	G26
Z5	G9	G31	G32	G34	G39
Z6	S1	S26	G29	G38	G24

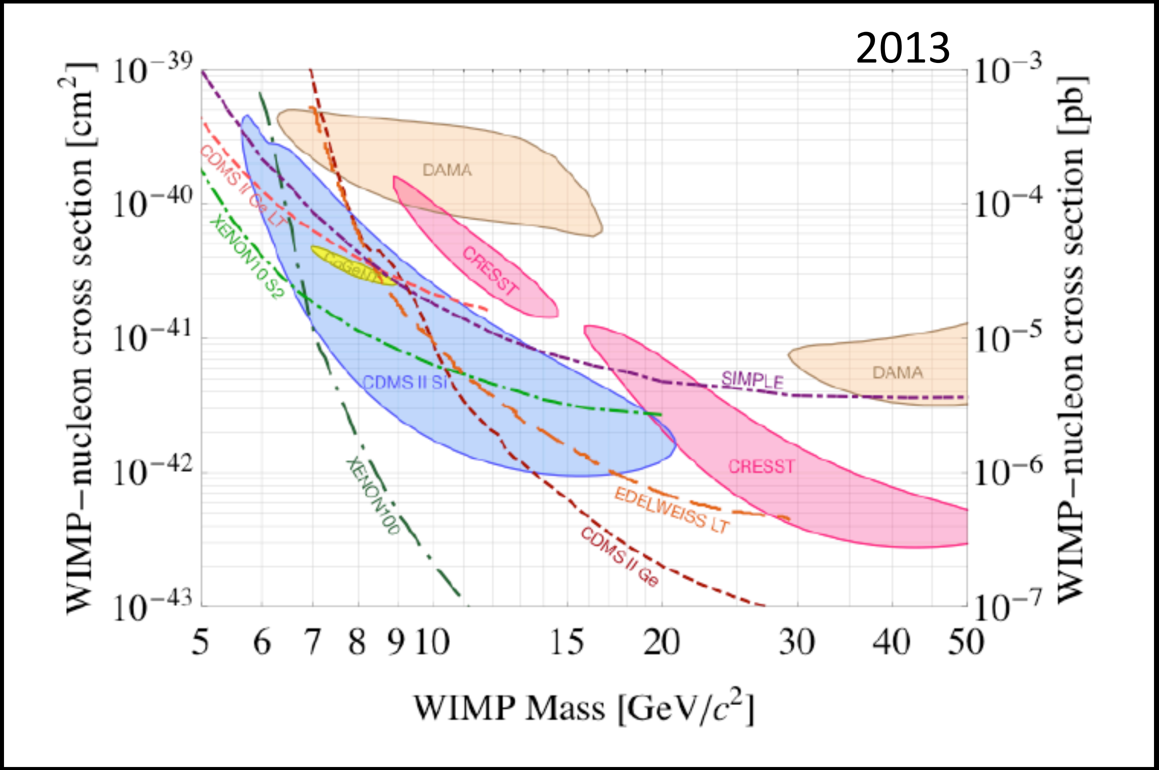
Side View



Ionization Yield
Recoil Energy (keV)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100

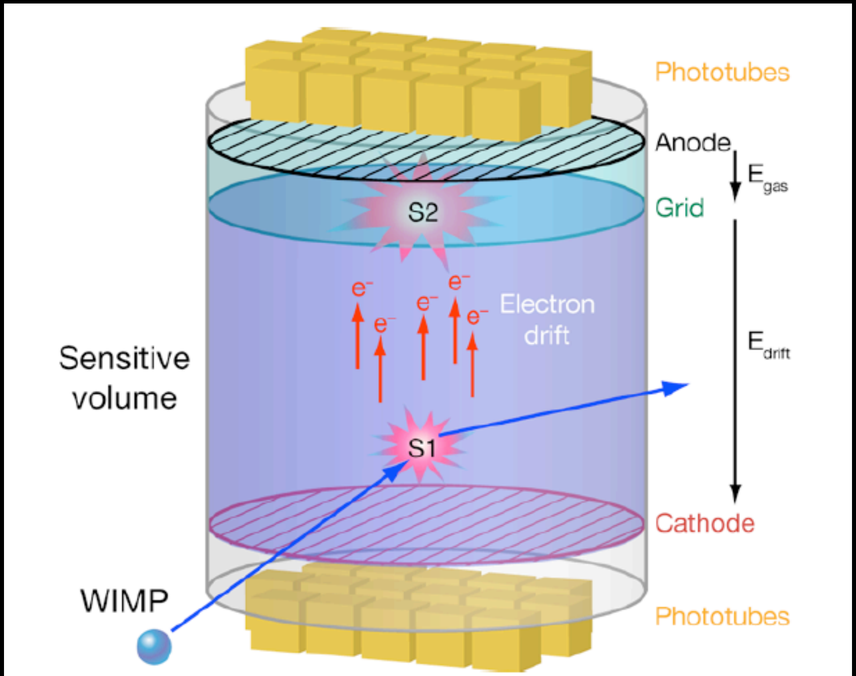
Profile Likelihood Analysis

- A profile likelihood analysis favors a WIMP+background hypothesis over the known background estimate as the source of our signal at the 99.81% confidence level (~3σ, p-value: 0.19%).
- The maximum likelihood occurs at a WIMP mass of 8.6 GeV/c^2 and WIMP-nucleon cross section of 1.9×10^{-41} cm^2.
  - Probability of a statistical fluctuation producing ≥ 3 events anywhere in signal region 5.4%
  - We do not believe this result rises to the level of a discovery, but does call for further investigation.



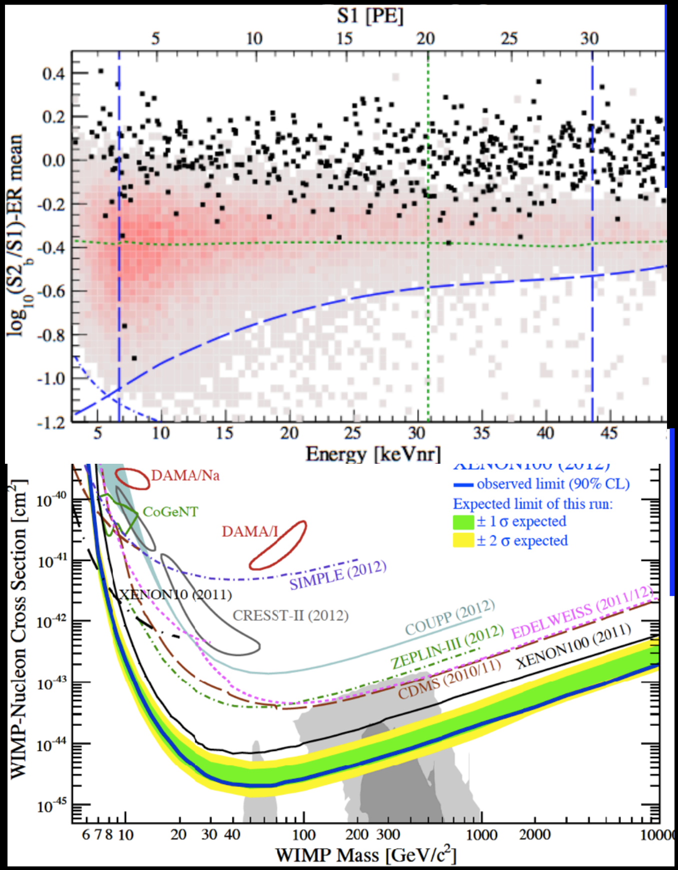
LXe Two-Phase TPC Dectector

- WIMP scattering produces ionization in liquid xenon.
- Partial recombination produces scintillation photons S1. (Energy ~ S1)
- Remaining electrons drift to gas phase and excite scintillation S2 (Q ~S2)
- S1 and S2 detected with array of PMTs.
- S2/S1 separates electron recoils from nuclear recoils
  - (S2/S1)er > (S2/S1)nr



XENON100 Results

- Exposure: 34 kg x 224.6 d
- Energy thresh: 6.6 keV_{nr}
- 2 events seen with 26.4% likelihood to be consisitent with background estimate of 1.0 +/- 0.2 events
- Large mass of Xe is not ideal for light WIMPs.
  - 8 GeV WIMPS produce low energy Xe nuclear recoils.
  - Energy calibration for nuclear recoils at threshold is crucial to exclude light WIMPS.

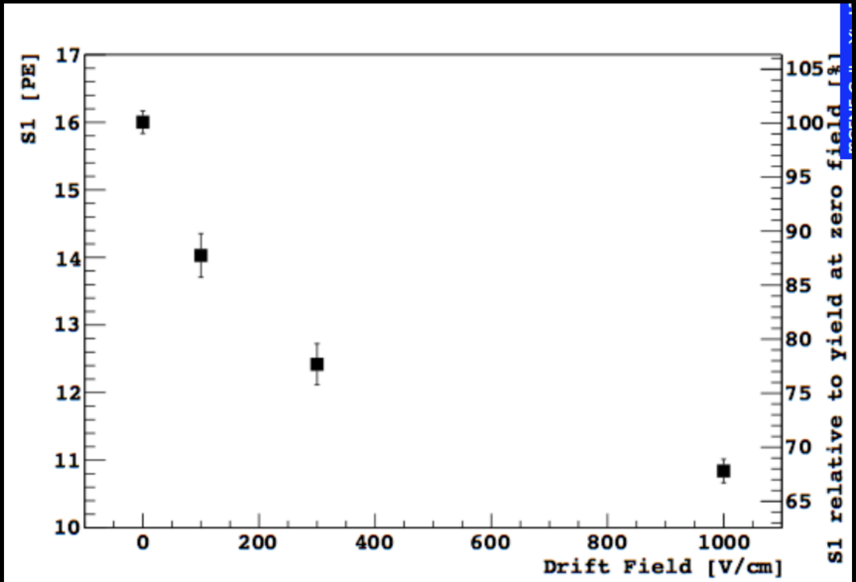


Low Energy Nuclear Recoil Calibration

- The rapidly rising wall at low energies is the effect of the 6.6 keVnr energy threshold, and the small energy light WIMPs impart to Xe.
- Energy calibration on nuclear recoils is crucial.
  - It based on measured scintillation light using electron recoils ^{52}Cr gamma rays, cross-calibrated with neutron source to produce nuclear recoils.
  - Nuclear recoils produce less scintillation than electrons.
  - Electric field reduces the scintillation light of electron recoils by 0.58, but less for nuclear recoils, 0.95.
  - Based on other XENON group studies, the electric field reduction of light from recoils is 0.95, even for nuclear recoils at the 6.6 keV threshold.
    - This study should be re-examined because new results in liquid argon.

Electric Field on LAr Scintillation

- A drift field of ~1 kV/cm is used to drift ionization electrons in LAr.
- The E-field reduces the scintillation light yield because electron-ion recombination is reduced.
- Scintillation reduction:
  - Electron recoils: ~50%
  - Nuclear recoils (nr): ~5%
- SCENE data show large effect on LAr scintillation for low energy nr.
  - 35% for 11 keV nuclear recoils.
- Xenon100 has data that a 5% effect for energies of 6.6 keV and lower is correct.
- Because, raising the threshold energy could change the tension with other experiments, further studies of the effect of electric field are advisable.



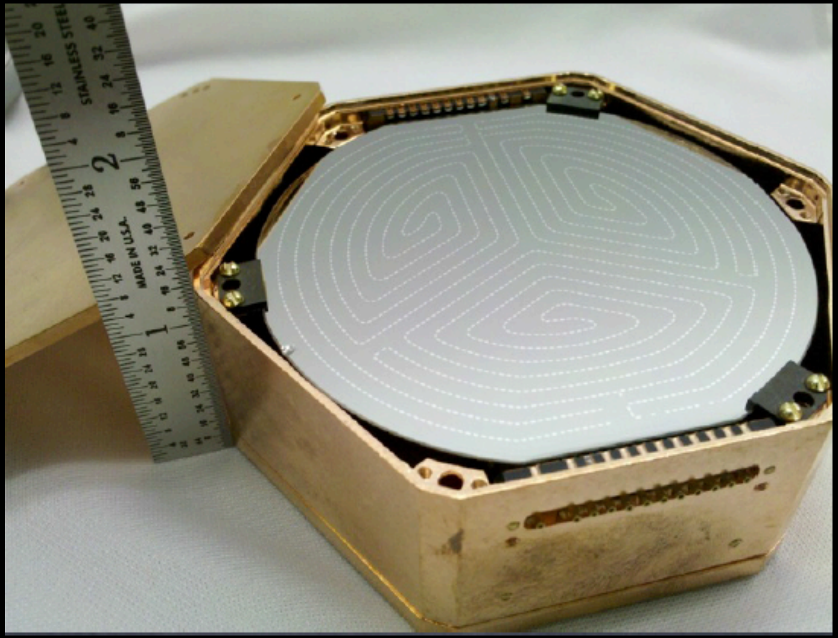
Variation of Scintillation Light Yield with electric field for 11 keV Ar recoils.
Mono-energetic pulsed neutron beam
SCENE Collab. arXiv: 1306.5675

Next Generation Experiments

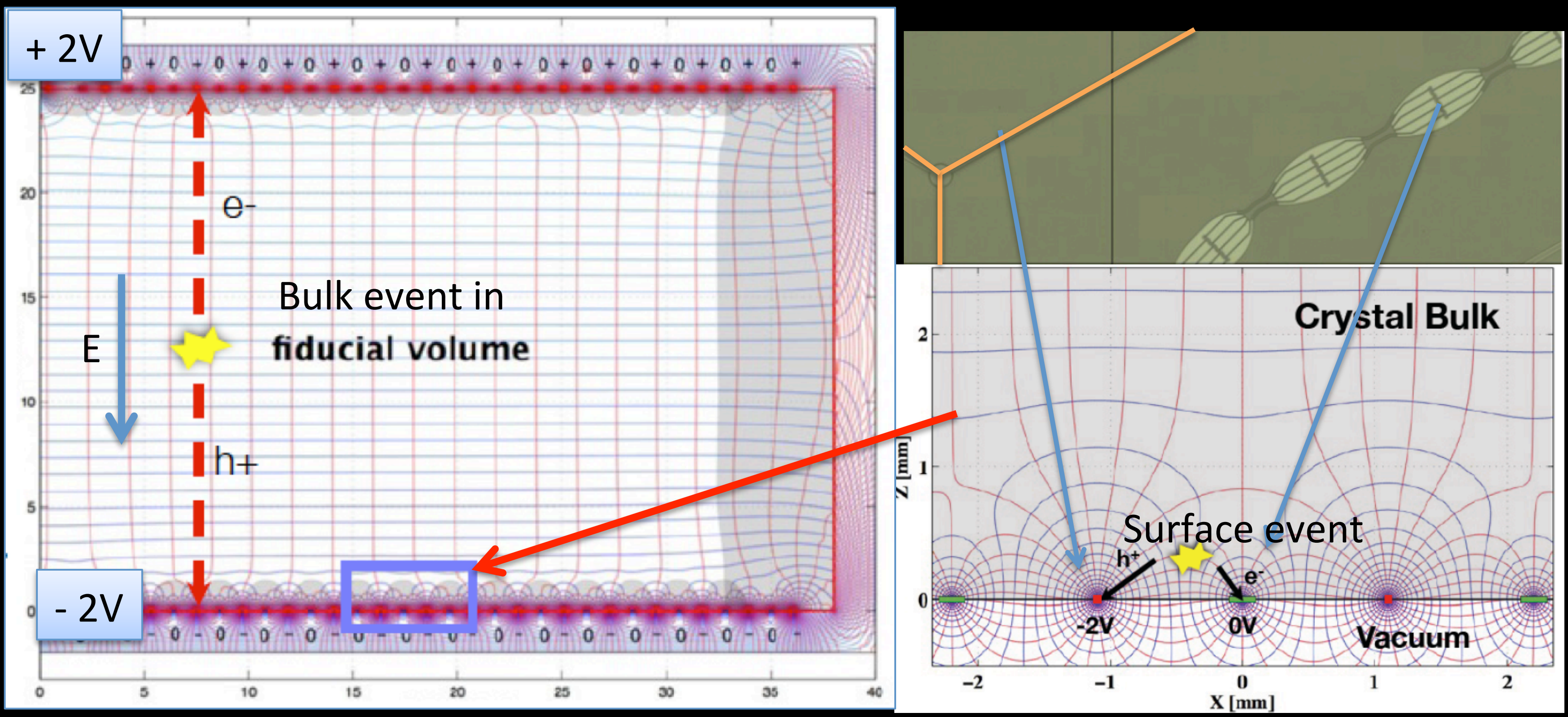
- Cryogenic solid state
- Liquid Xenon
- Liquid Argon
- Superheated liquids
- Scintillating crystals
- Directional detectors
- New Ideas

Super-CDMS IZIP Detector

- Phonon and charge read-out on both sides.
- Electric field at surface prevents ionization charge from drifting to opposite side.
- Surface background leakage ~ 10^{-5}.
  - Major breakthrough!
- Some iZIP detectors already runnning in Super CDMS-Soudan



iZIP detector up close



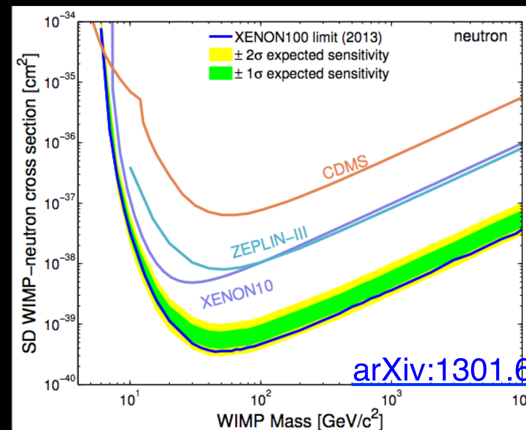
Liquid Xenon

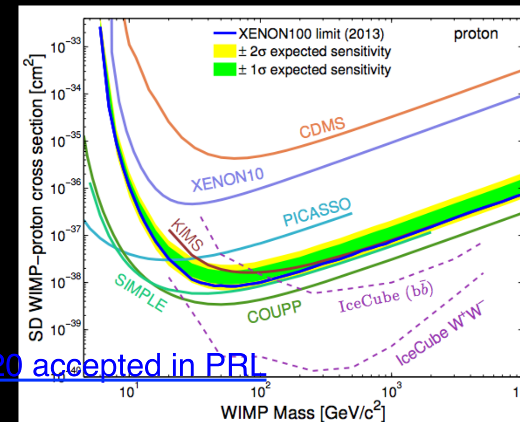
- XENON 1-ton
- LUX/LZ
- XMASS

The XENON Dark Matter Search @ LNGS

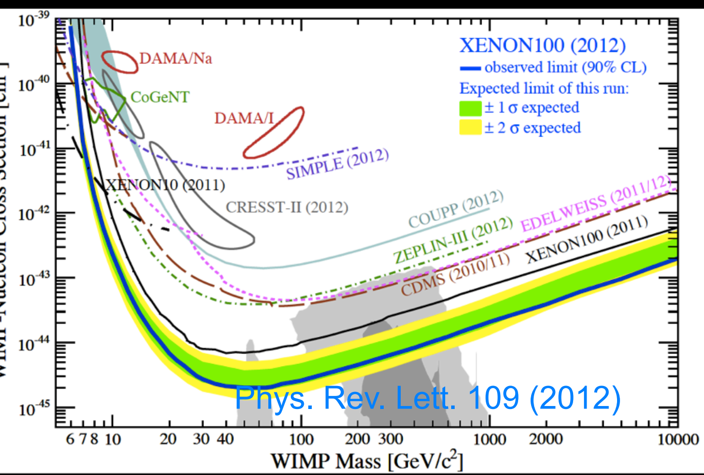
[XENON Coll.]

- XENON10: 15 kg active mass
- XENON100: 62 kg active mass
  - Currently running
- XENON1T: ~2.2 T active mass
  - construction just started!

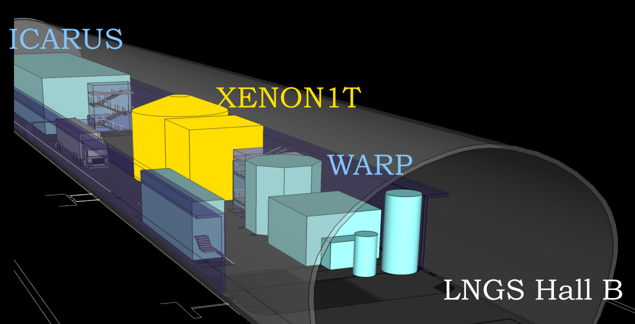


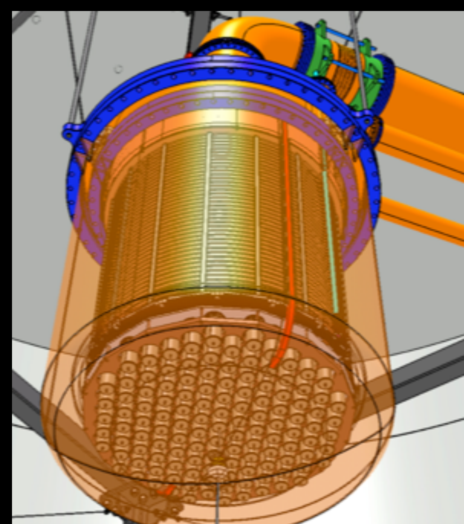


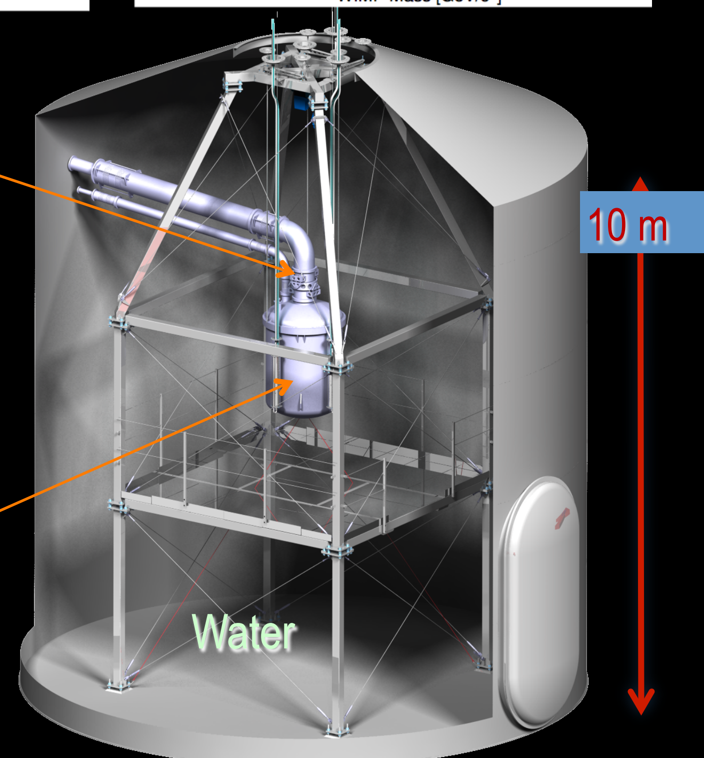
arXiv:1301.6620 accepted in PRL



Phys. Rev. Lett. 109 (2012)



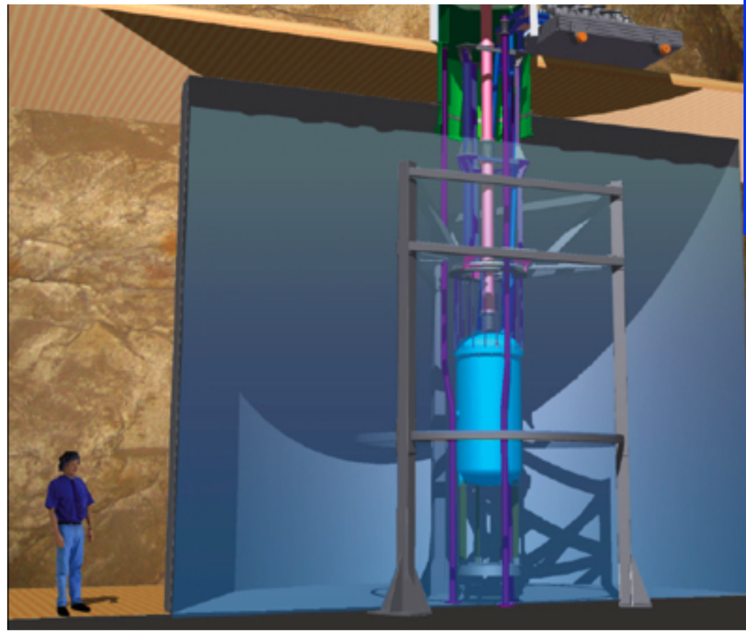




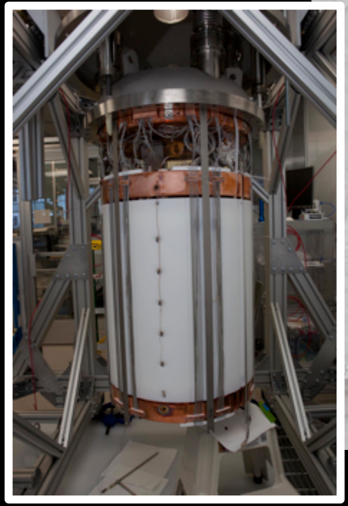
LUX @ Sanford Lab 2013

Large Underground Xenon Experiment

- LXe TPC - 300 kg active / 100 kg fid.
  - Installed in water shield at Sanford Lab Davis Campus 4850' level Aug 2012
  - Xenon condensed Feb 2013
- Detector
  - Circulating > 20 SLPM with 2-phase heat exchanger @ >90% eff.
  - Good purity after < 2 months (Electron drift attenuation >100 cm)
  - Excellent light yield - 8 phe/keVee, zero field, 122 keVee
  - ^{85}Kr @ 4ppt (less than PMT bkg.)
- WIMP Searches
  - Plan short (~ 60 day) WIMP search run - result by end 2013 - non-blind analysis
  - Full year-long WIMP search run to begin in 2014/5 - blind analysis



[LUX/LZ Coll.]



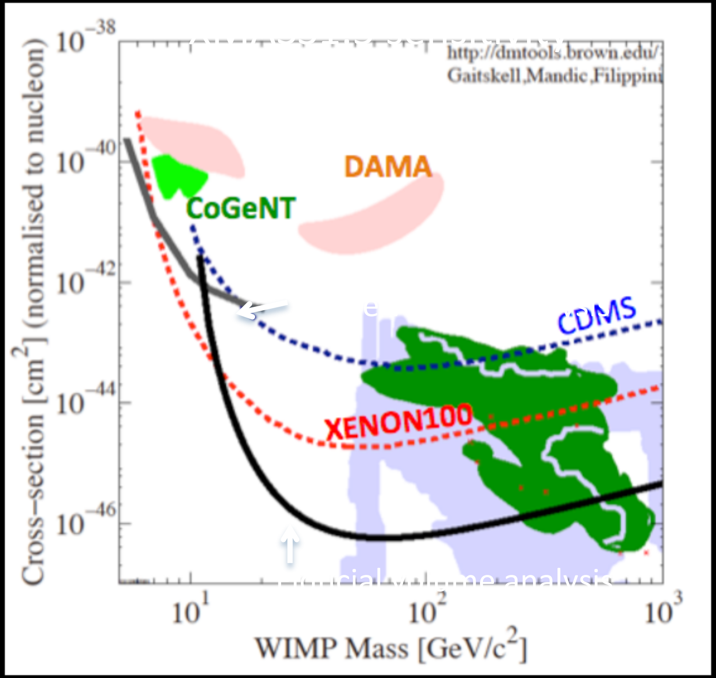
122 Hamamatsu R8778 Low bkg. PMTs

XMASS experiment:
A single phase liquid xenon detector with a large photo-cathode coverage

- The next step, XMASS1.5 (1 ton fiducial and 5 ton total mass) will be expected to start in 2015. The sensitivity is shown in right figure, reaching to σ_{SI} $<10^{-46}cm^2$

- XMASS-I (100 kg fid. and 835 kg total) has operated very limited time periods and stopped in May 2012 for refurbishment, but achieved high light yields of 14.7 pe/keVee and lowest energy threshold of 0.3 keVee for the whole volume analysis.
  - By using 6.8 days of data using whole volume, we have conducted
    - Low mass WIMP search (PLB719(2013)78)
    - Solar axion search (arXiv:1212.6153, accepted for publication in PLB): world best results on g_{aee} among other terrestrial experiments

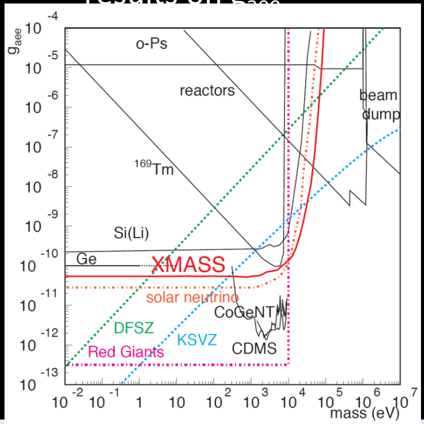
- Quick refurbishment of XMASS-1 is in progress to reduce backgrounds by 1 to 2 orders of magnitude and we expected to complete the refurbishment in autumn of 2013.



[XMASS Coll.]

XMASS-I detector

XMASS-I
arXiv:1212.6153
Solar axion search results on g_{aee}



- Our final Goal, XMASS-II is 10 ton fiducial mass (25 ton total mass) and scheduled to operate in 10 years.

Liquid Argon

- Darkside-50
- DEAP 3600
- MiniCLEAN

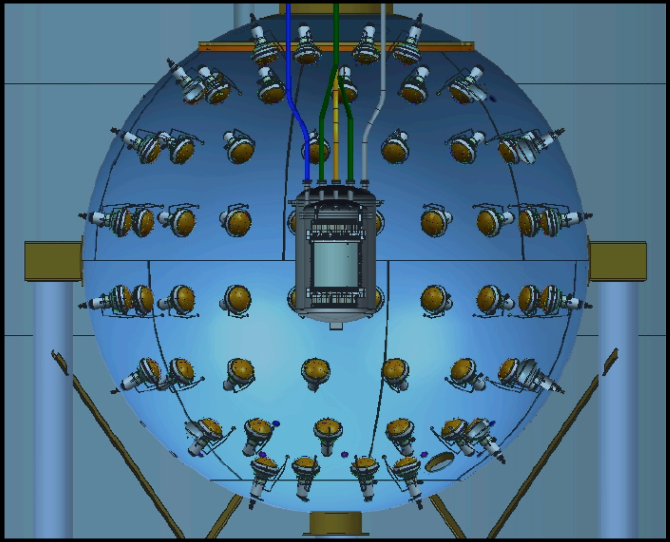
DarkSide@LNGS

[DarkSide Coll.]

2-phase argon TPC
Underground argon depleted from ^{39}Ar
Three-fold discrimination
(S1 pulse shape, S2/S1, sub-mm reconstruction)
Installed in LNGS Hall C, CTF of BX
30 tons liquid scintillator neutron veto1,000
tons water Cerenkov muon veto

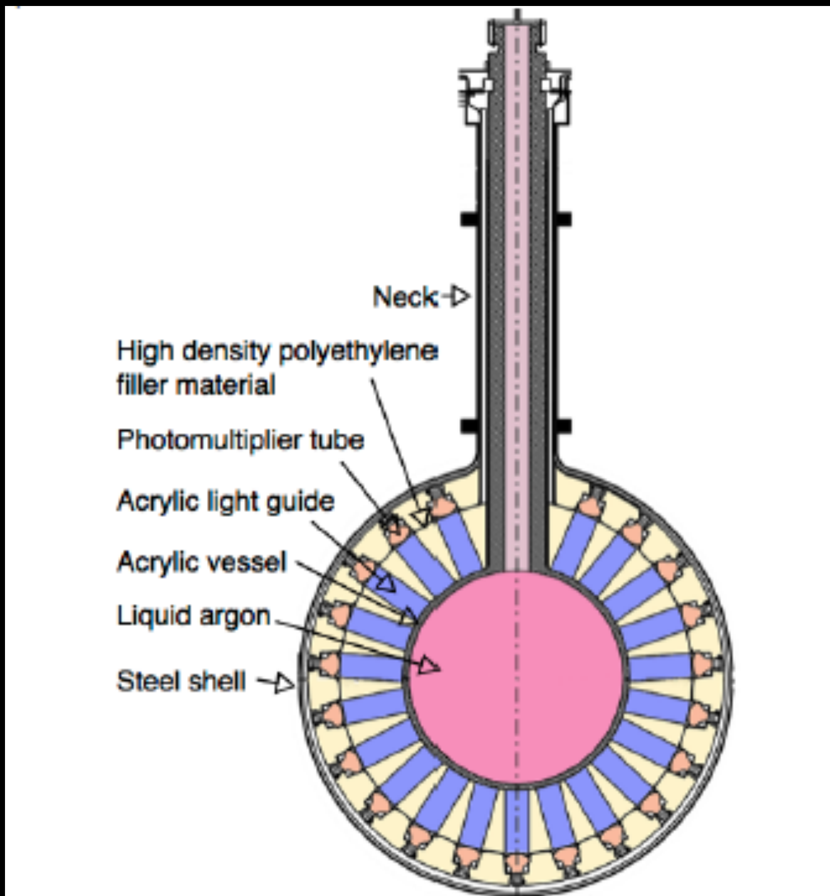
2013-: DarkSide-50 (2×10^{-45} cm^2)

2015-: DarkSide-G2 (2×10^{-47} cm^2)

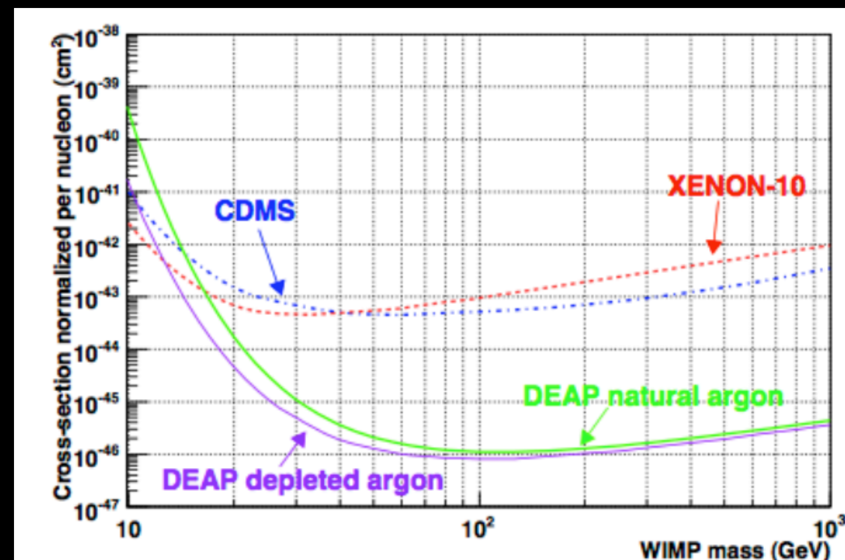


DEAP 3600

- Single phase 3.6 ton LAr. (1 ton fiducial)
- Employ pulse shape and fiducial volume cuts to reduce all background.
- Room temp. PMTs with acrylic light guides
- Construction well underway in SNOLab

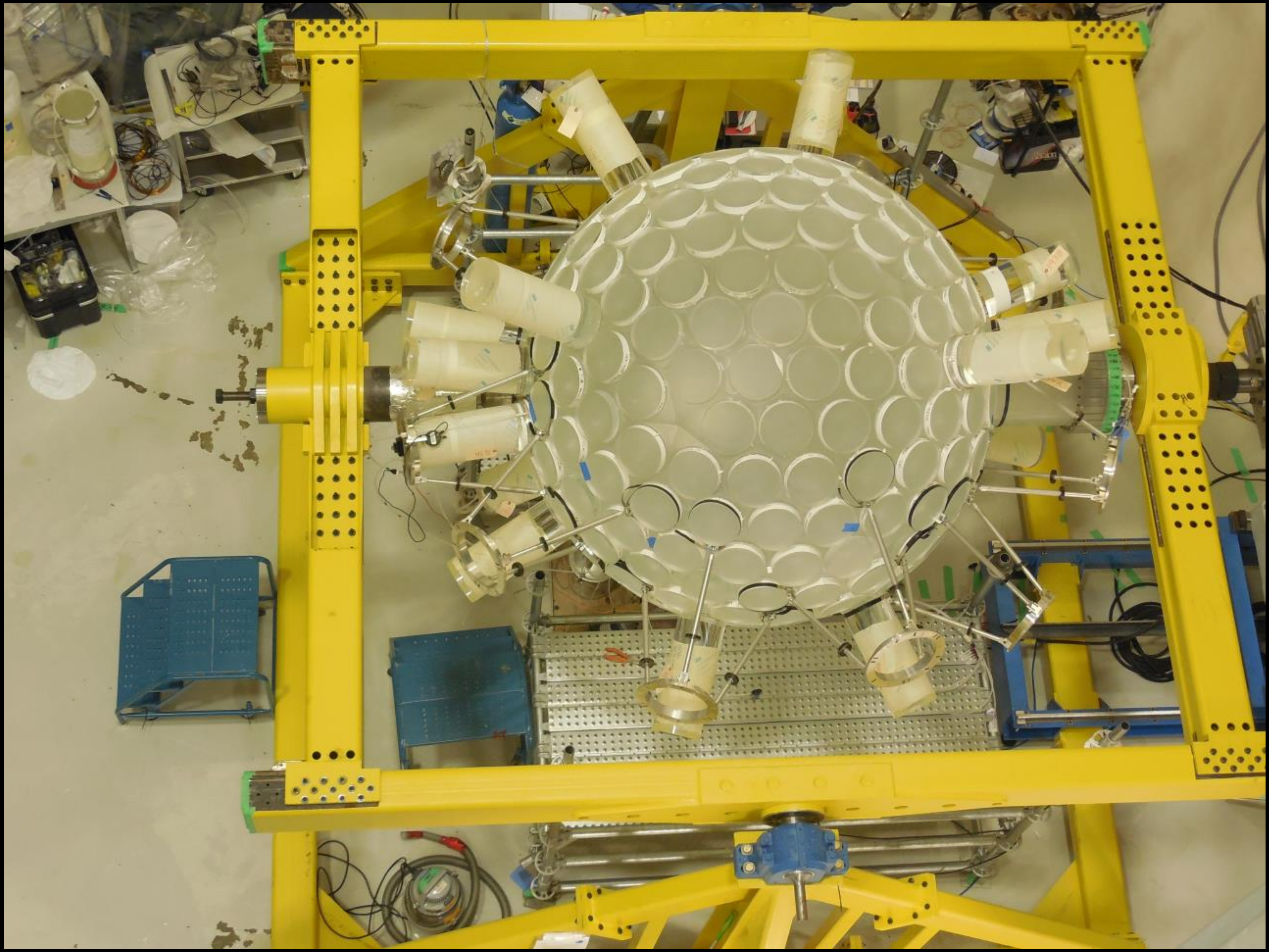


Cross section of the DEAP-3600 detector.



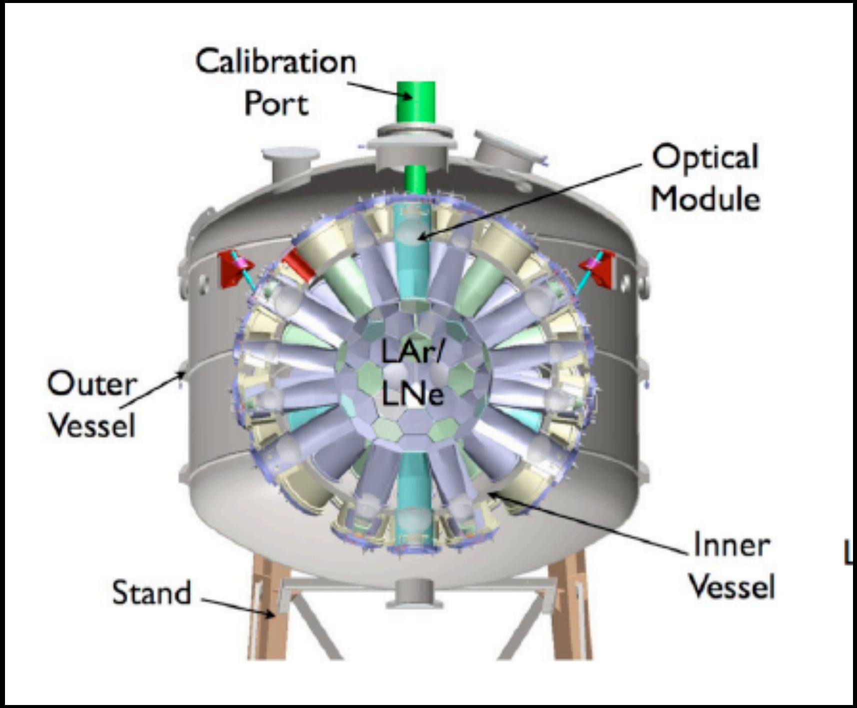
Projected sensitivity of the DEAP-3600 detector.

Light Guide Bonding onto Acrylic Vessel



MiniCLEAN

- Single phase 500 kg LAr
  - Fiducial mass 150 kg
- Optimize for high light yield to exploit unique LAr pulse shape discrimination.
- Option for LNe.
- Under construction in SNOLab.



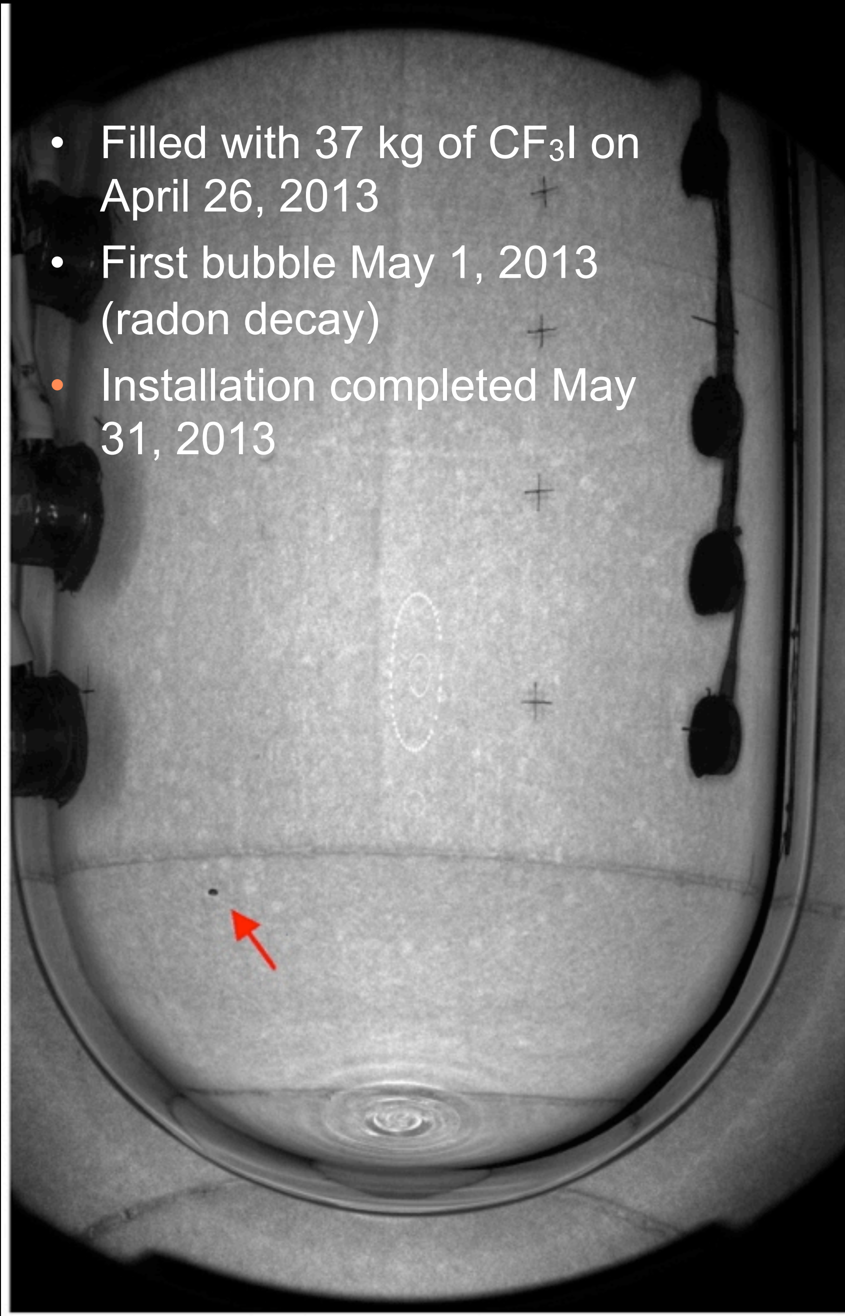
Superheated Liquids

- COUPP
- Picasso
- COUPP+PICASSO = PICO
  - "Pico-light" aimed at addressing the light WIMPS

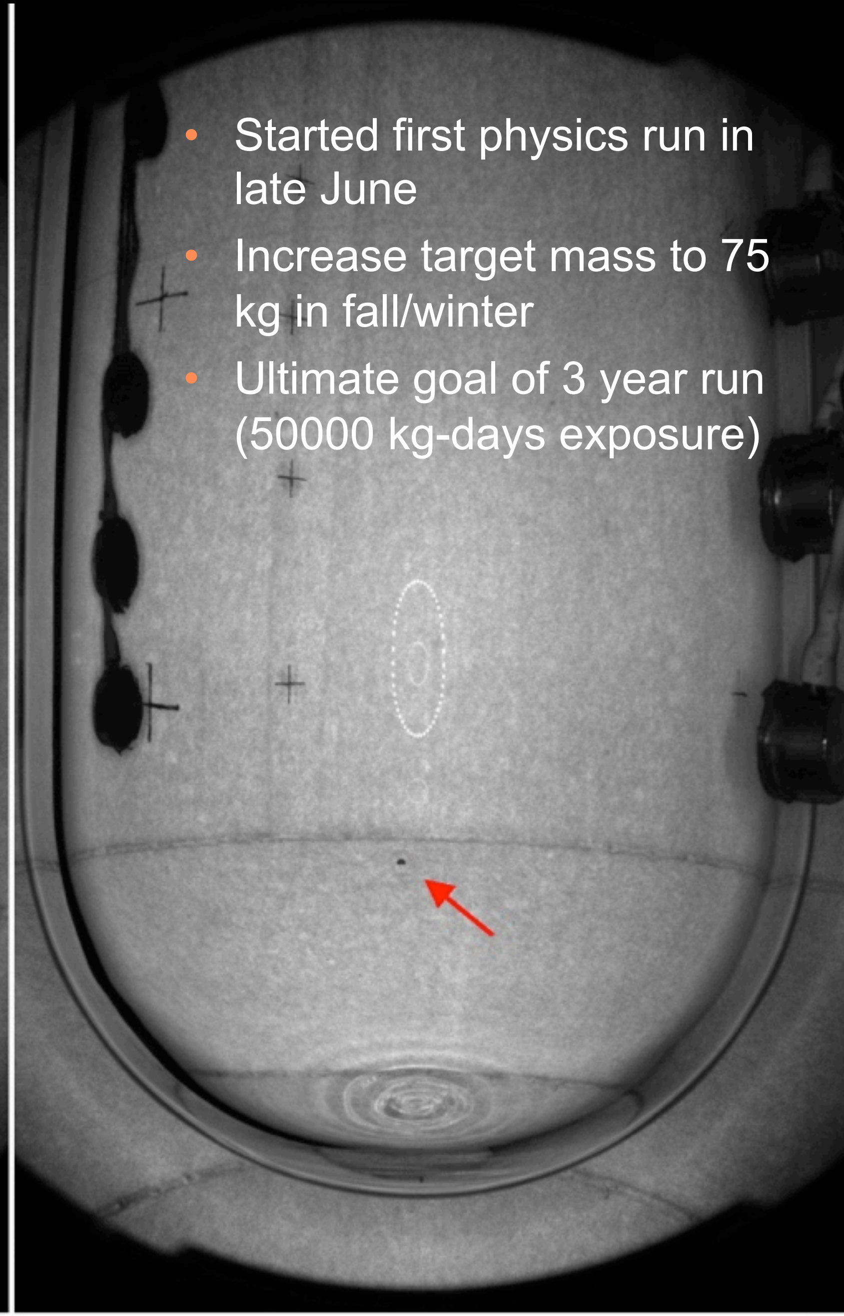
COUPP

- $>10^{10}$ γ/β insensitivity
- >99.3% acoustic
  α-discrimination
- Multi-target Capability
  SD- and SI-coupling
  High- and low-mass WIMPs
- Easily scalable,
  Inexpensive to replicate
- Growing Collaboration
  Newly merged with PICASSO

COUPP-60



- Filled with 37 kg of CF_3I on April 26, 2013
- First bubble May 1, 2013 (radon decay)
- Installation completed May 31, 2013



- Started first physics run in late June
- Increase target mass to 75 kg in fall/winter
- Ultimate goal of 3 year run (50000 kg-days exposure)

Scintillating Crystals: NaI(Tl)

Long awaited tests of DAMA/LIBRA are coming with new commercially available radio-pure NaI.

- ANAIS
- SABRE
- DM Ice
- KIMS
- Kamland-Pico

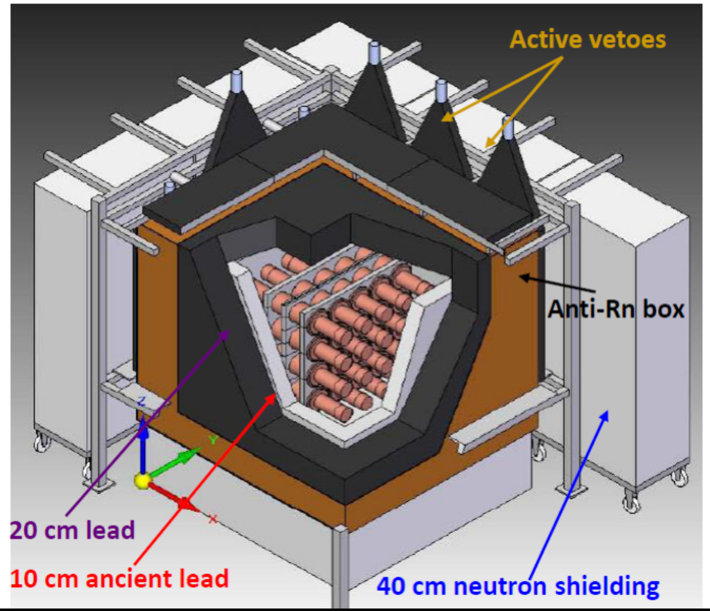
ANAIS Experiment

(Annual modulation with NAI Scintillators)

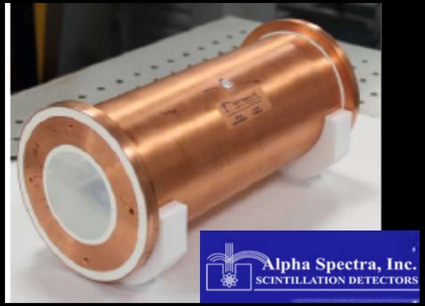
[ANAIS Coll.]

250 kg of NaI(Tl) detectors to study the annual modulation effect at the Canfranc Underground Laboratory, LSC (Spain)

Same target and technique used by DAMA/LIBRA

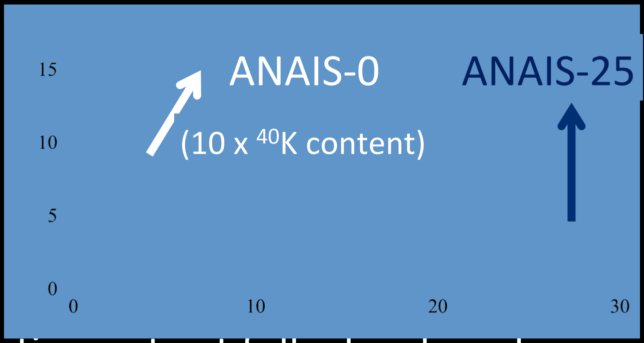


2 prototypes taking data at LSC – 25 kg (ANAIS-25)



Ham PMT – R12669 SEL coupled at LSC clean room

Overall background asessment ongoing



ANAIS-25 PRELIMINARY RESULTS

Excellent light collection efficiency: 12-16 phe/keV

^{40}K bulk NaI content = 41.7 ± 3.7 ppb

Cosmogenic activation still decaying & low energy events selection not yet fully developed

SABRE

Sodium iodide with Active Background Rejection

- Radio-pure NaI crystals.
- K in NaI powder <10 ppb
  - DAMA X-tals : 15-20 ppb
  - NaI(Tl) crystals should be < 10 ppb. Demonstration underway
- Active LS veto and water shielding planned in Darkside facility.
  - LS Veto reduces the ^{40}K 3 keV X-ray, coincident with 1.46 MeV gamma
  - Decreases ^{40}K background x 10
- Crystals being grown for test in Fall.
- SNOLab being considered as second phase deeper site with maller LS veto.

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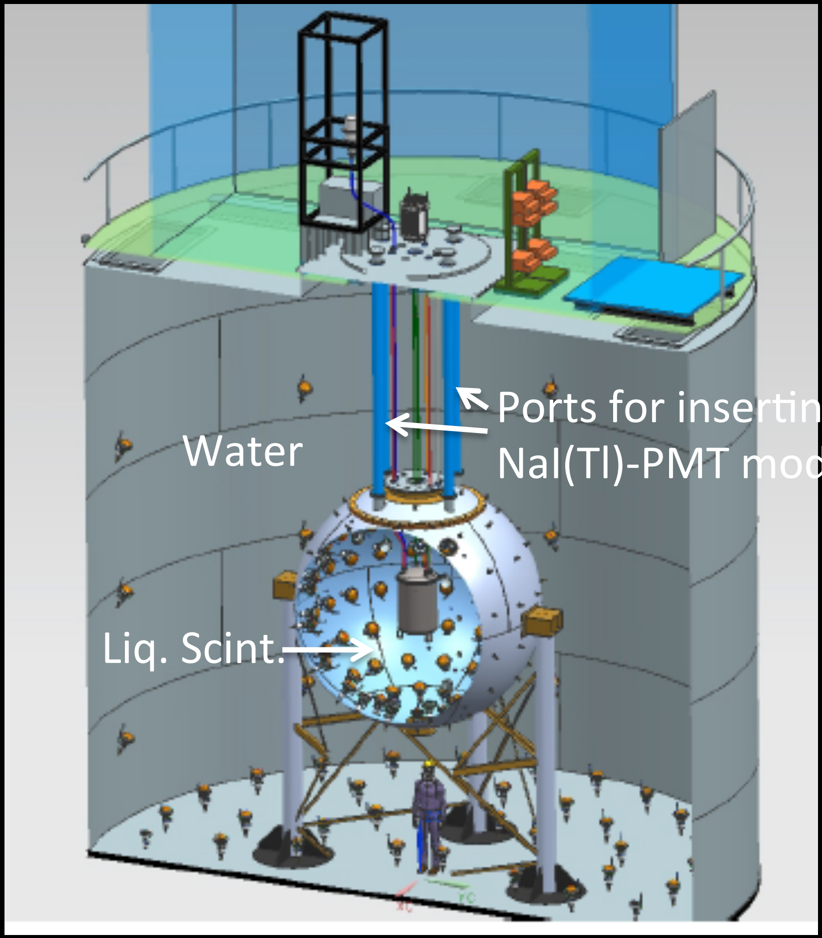
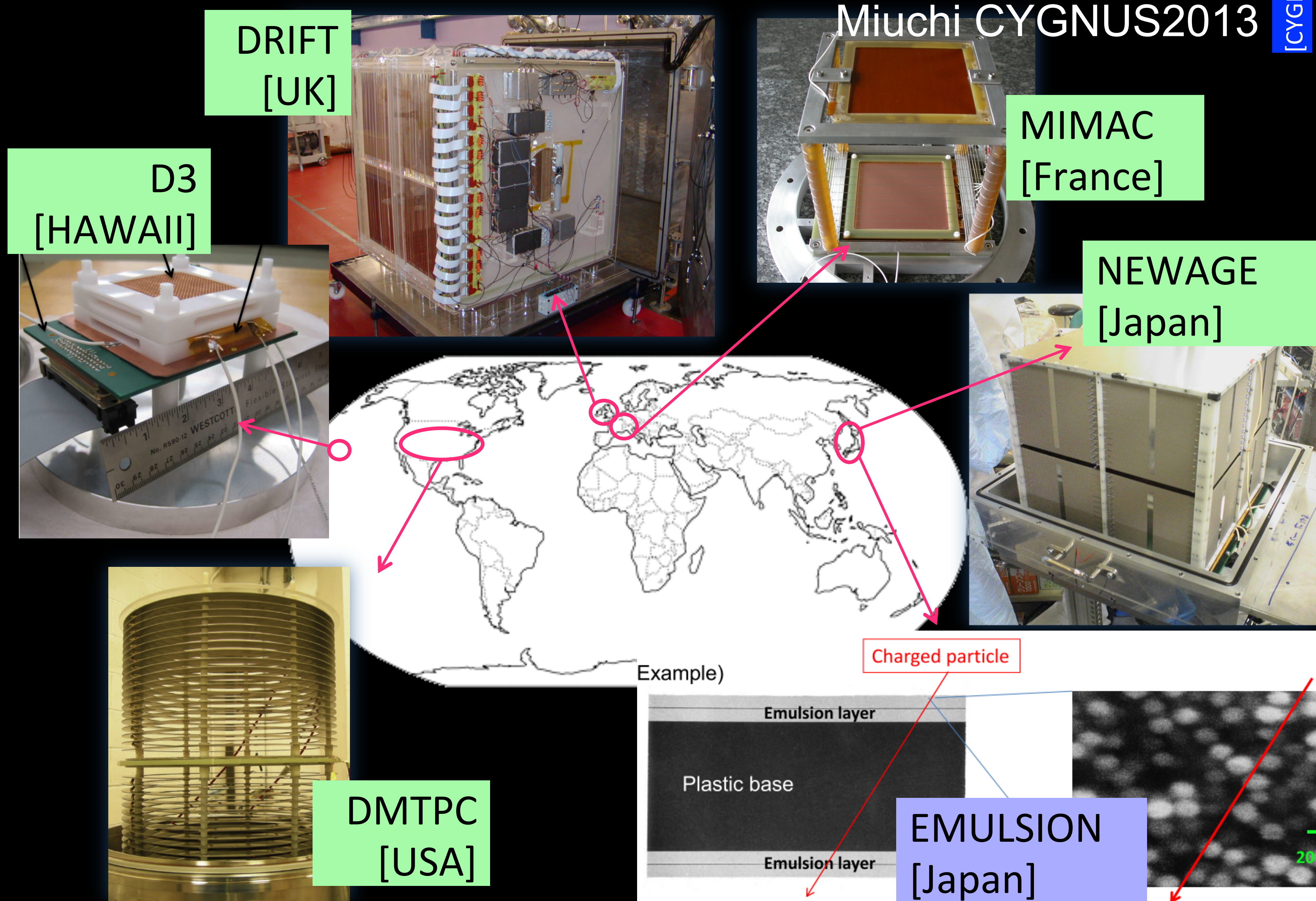
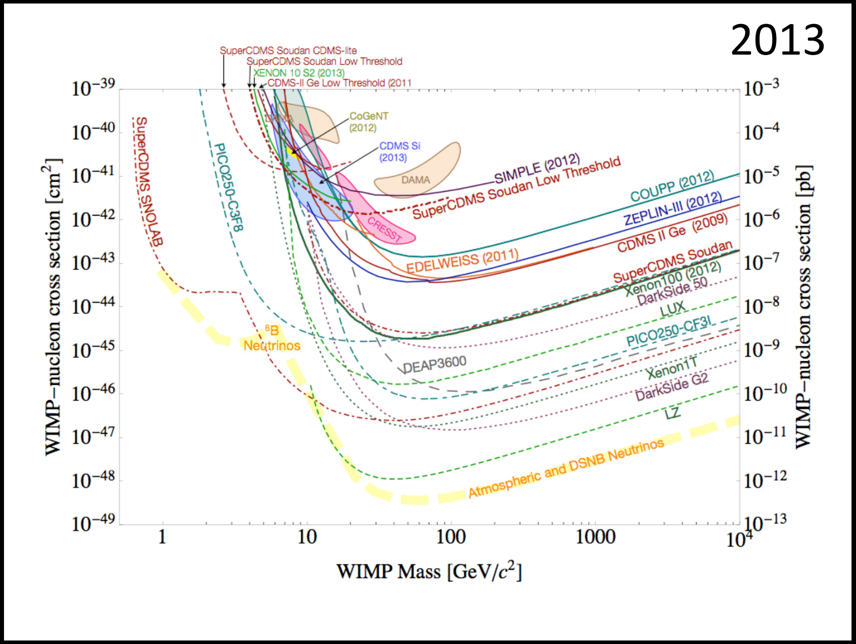


Directional Detectors



The Roadmap

- Discovery
  - Search for WIMPS within mass 1-1000 GeV until discovered, or ν background is reached.
  - Improve by x10/Generation
- Confirmation
  - Use complementary technologies with same target, if possible.
- Study
  - Employ multiple technologies to extract maximal information about WIMP mass.
- R & D
  - Maintain robust detector development for discovery, confirmation, and study.



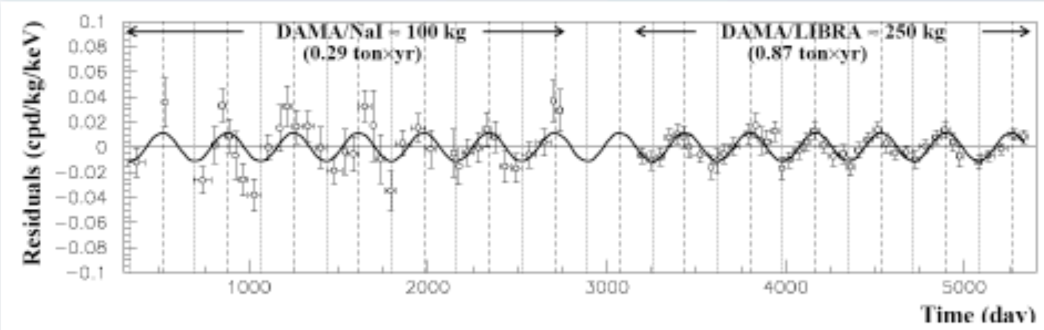
The End

DAMA Model Independent Annual Modulation Result

DAMA/NaI (7 years) + **DAMA/LIBRA** (6 years)   Total exposure: 425428 kg×day = **1.17 ton×yr**

Single-hit residuals rate vs time in 2-6 keV

EPJC 56(2008)333, EPJC 67(2010)39



continuous line: t_0 = 152.5 d, T = 1.0 y

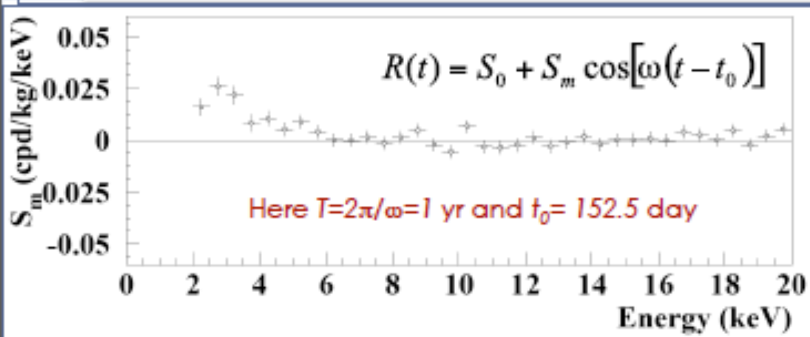
A=(0.0114±0.0013) cpd/kg/keV

χ^2/dof = 64.7/79   8.8 σ C.L.

Absence of modulation? No

χ^2/dof=140/80 P(A=0) = 4.3×10^{-5}

fit with all the parameters free:
A = (0.0116 ± 0.0013) cpd/kg/keV
t_0 = (146±7) d - T = (0.999±0.002) y



- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

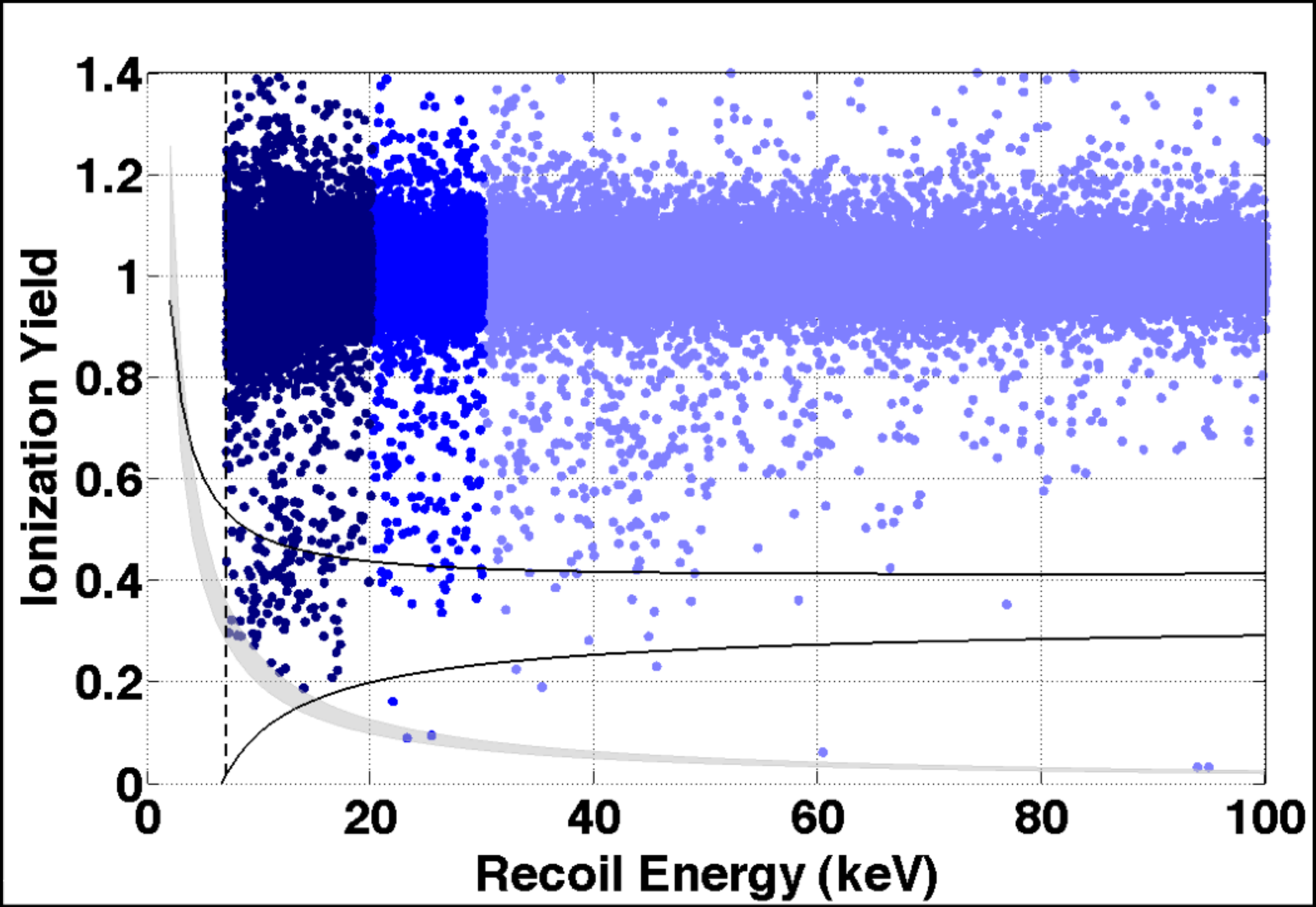
No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

✓No other experiment exists whose result can be – at least in principle – directly compared in a model-independent way with those by DAMA/NaI & DAMA/LIBRA

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9σ C.L.

✓Compatibility with many low and high mass DM candidates, interaction types and astrophysical scenarios, and in particular with recent positive model dependent hints

- DAMA/LIBRA-phase1 concluded: the data of the last 7° annual cycle will be released soon.
- DAMA/LIBRA–phase2 running: with new higher QE PMTs (lower energy threshold)

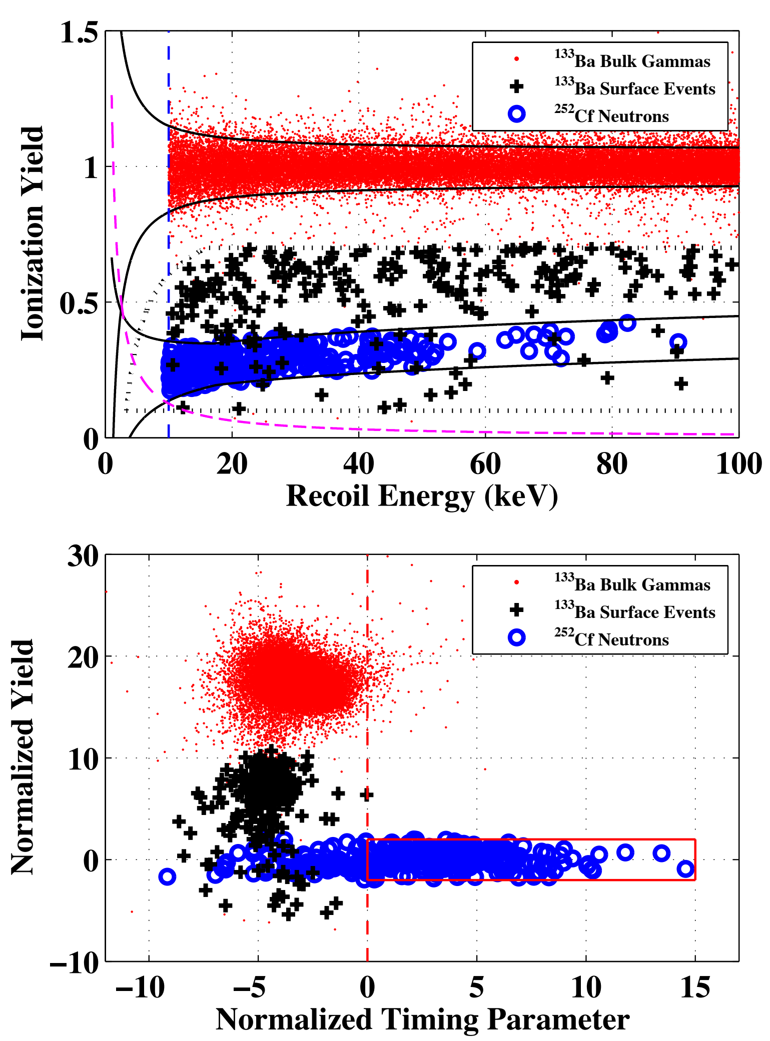


1.4
1.2
1
0.8
0.6
0.4
0.2
0
Ionization Yield
0
20
40
60
80
100
Recoil Energy (keV)

Surface Backgrounds (^{210}Pb)

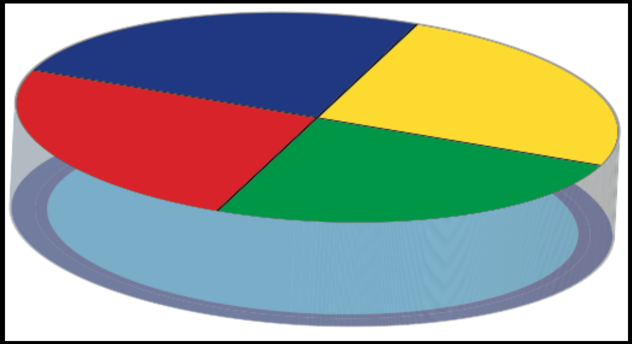
ZIP Detector Timing Cut

[CDMS Coll.]



(Science 327 1619 (2010))

Phonon channels



Charge channels

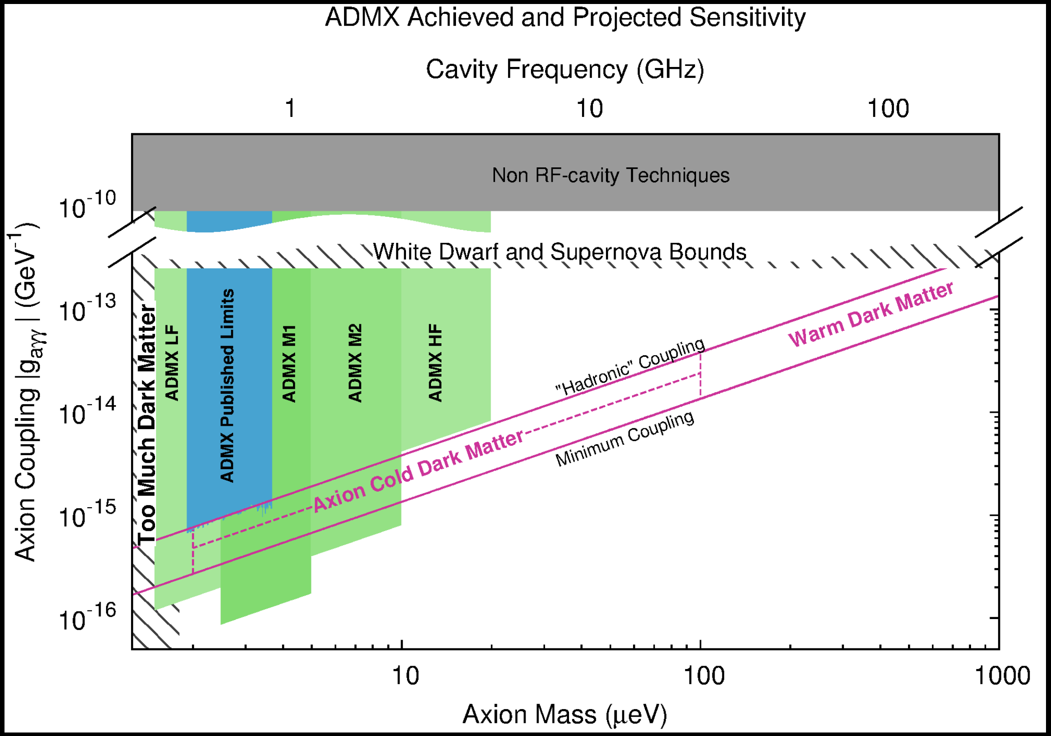
Phonon and charge channels on opposite sides.

Yield and phonon/charge timing

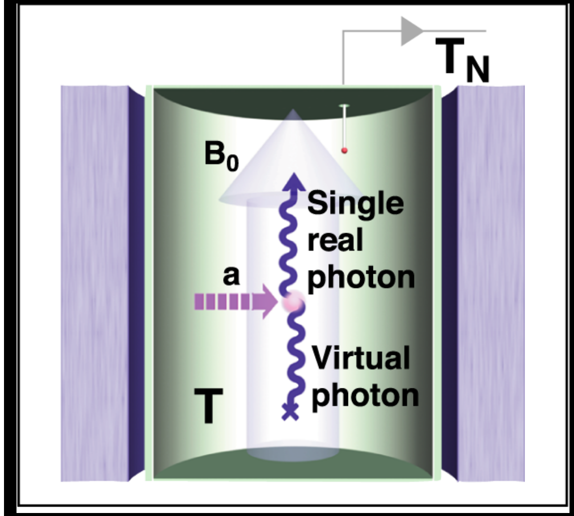
Surface events dominate background contribution → need timing cut!

Axions- ADMIX

[ADMX Coll.]



Halo axions convert into microwave photons inside a RF cavity threaded by a strong magnetic field

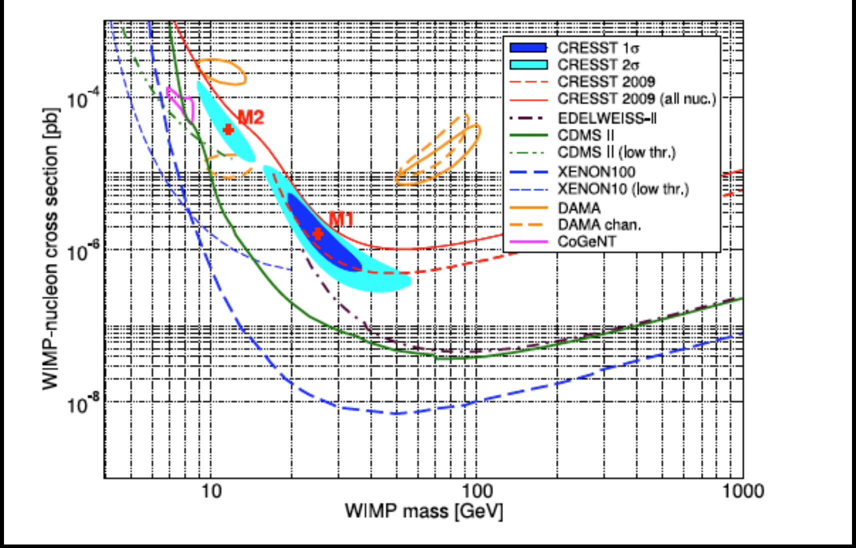


ADMX can definitely detect the dark-matter QCD axion or reject the hypothesis at high confidence

Dilution refrigerator and quantum-limited amplifiers provide ADMX's sensitivity for definitive QCD axions search

CRESST Backgrounds & extra events

	M1	M2
e/γ-events	8.00 ± 0.05	8.00 ± 0.05
α-events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
Neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
Signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$



CDMS-Silicon Summary

- The significance of these three events does not rise to the level of a discovery, but it is an interesting result which needs to be investigated.
- We are performing additional analyses on these silicon data sets from CDMS-II detectors no longer at Soudan.
- We are now operating 9 kg of germanium advanced iZIP detectors which will cover a significant portion of the suggested region for spin-independent WIMPs.
- We are doing R&D for 200 kg of germanium experiment at three times deeper site called SNOLAB in Canada.
- Given this result, we are also considering running advanced iZIP silicon detectors in the future.