Direct Detection of WIMP Dark Matter

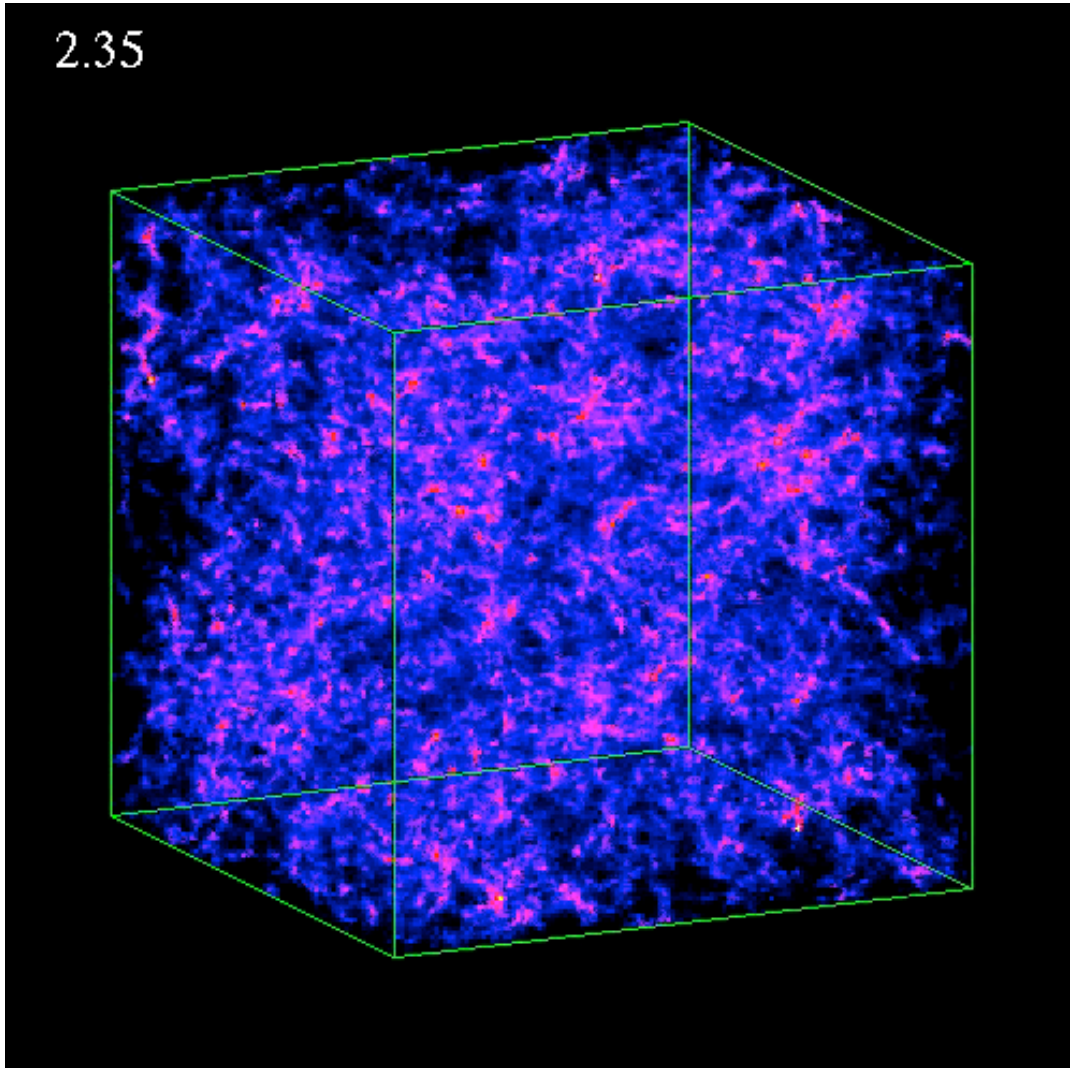
SLAC Summer Institute
July 29, 2011

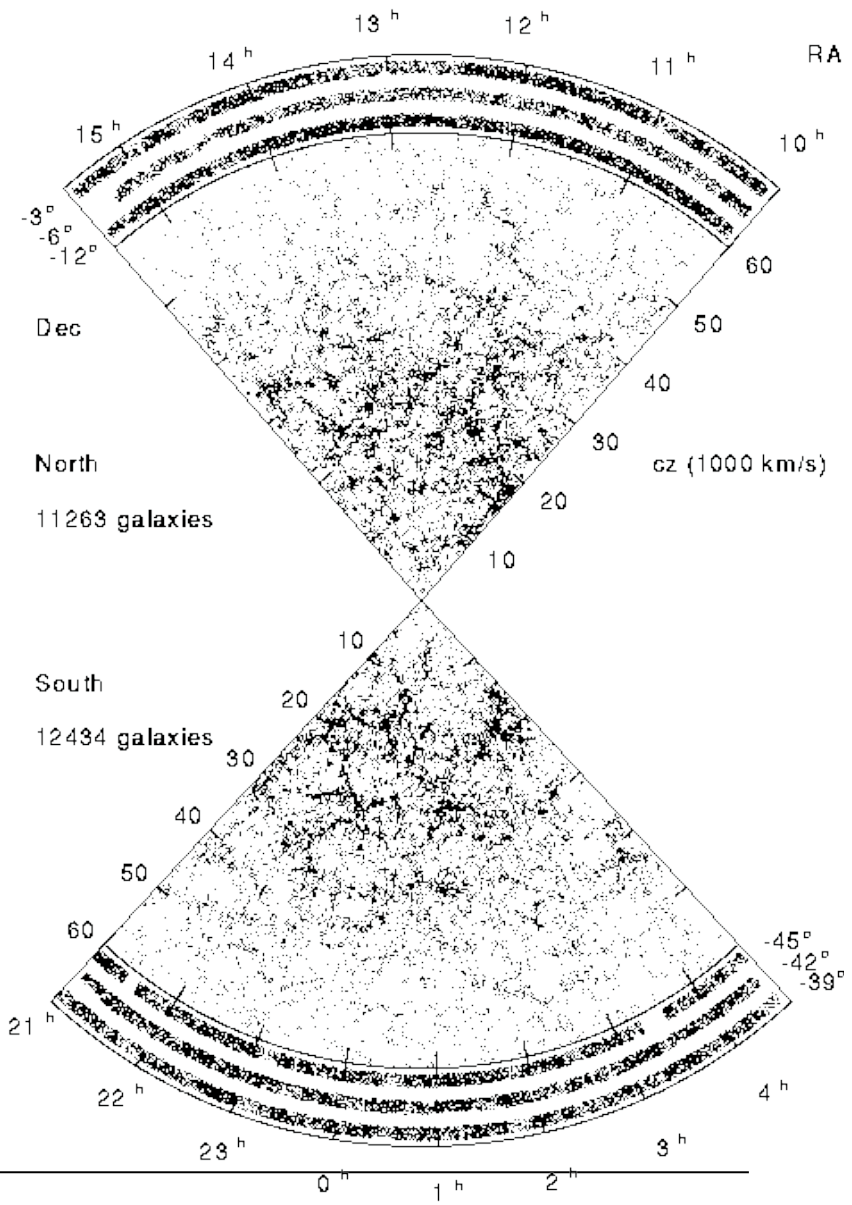
Blas Cabrera
Spokesperson for SuperCDMS
Physics Department
and
KIPAC (Kavli Institute for Particle Astrophysics and Cosmology)
Stanford University
and
SLAC National Accelerator Center member of SuperCDMS

Outline

- After many years the field of direct detection has entered most interesting sensitivity region.
- CDMS has lead field for most of past decade and is continuing with SuperCDMS Soudan and SNOLAB
- Exciting new technologies based on noble liquids making significant advances with XENON100 now leading the field.
- DAMA/LIBRA continued to claim annual modulation signal with NaI detectors, and now CoGeNT and CRESST claim consistency for low mass WIMPs
- Recent analysis of phonon only signals from CDMS-II rule out the nuclear recoil interpretation for CoGeNT.

Expanding universe - simulations and data



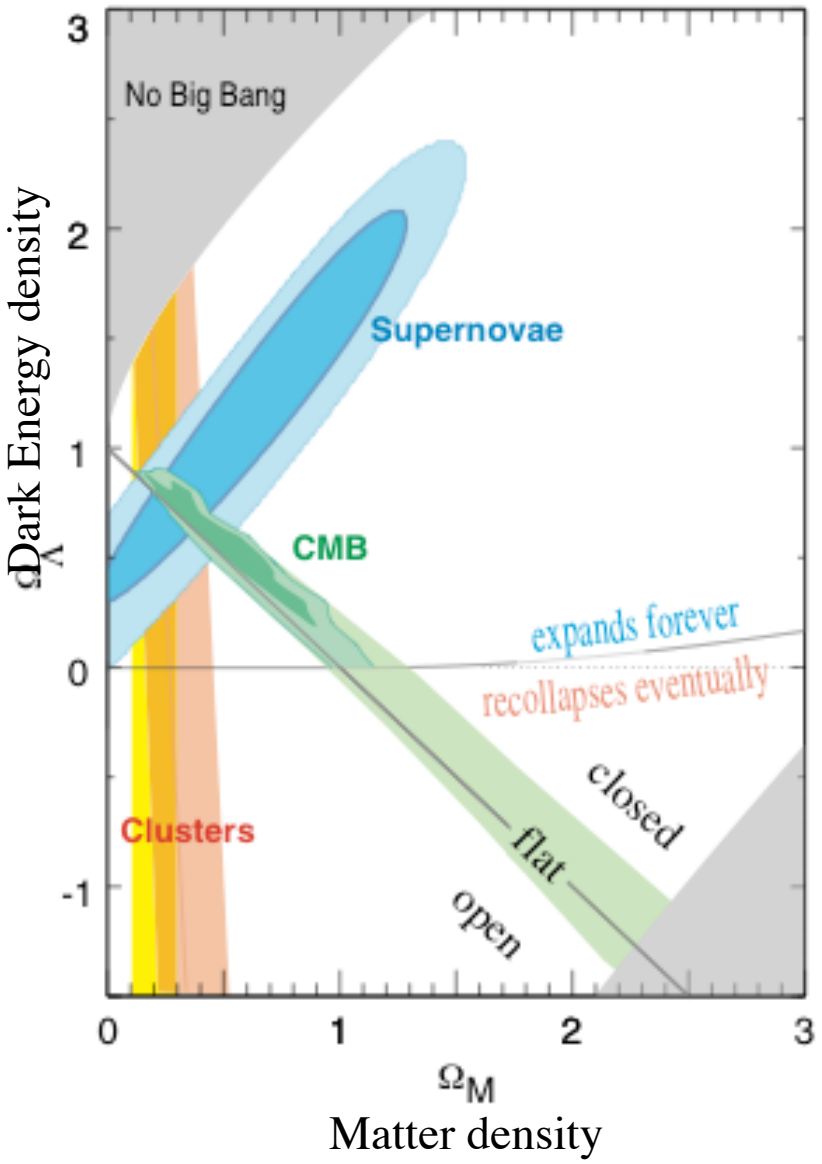


Concordance Model of Cosmology

- Supernovae + Cosmic Microwave Background + Large Scale Structure

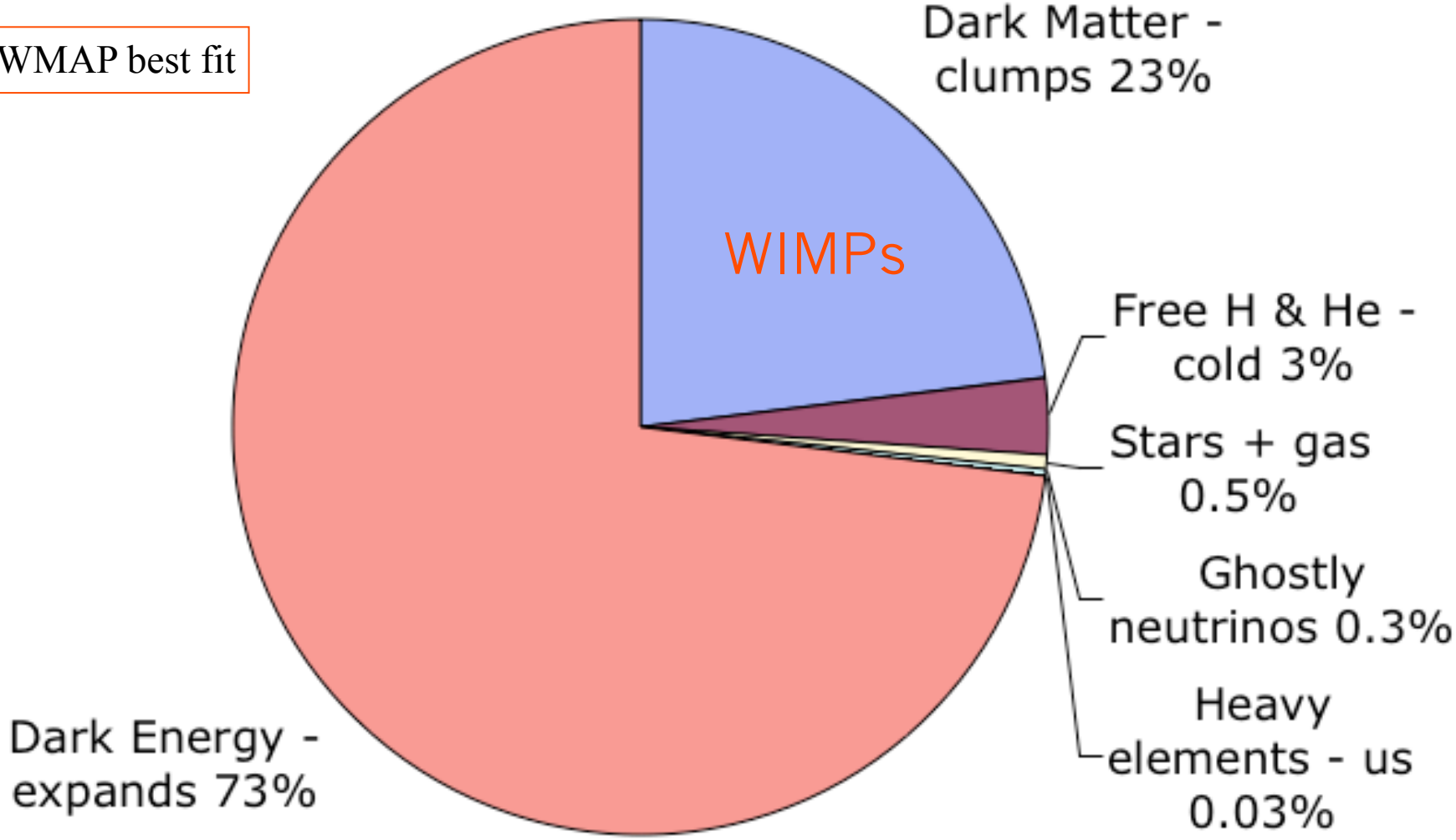
$$\text{WMAP} + \text{flat}: \quad \Omega_m = 0.27 \pm 0.04, \quad \Omega_\Lambda = 0.73 \pm 0.04$$

- Great overall success!
- However raises even more questions about origin of dark energy



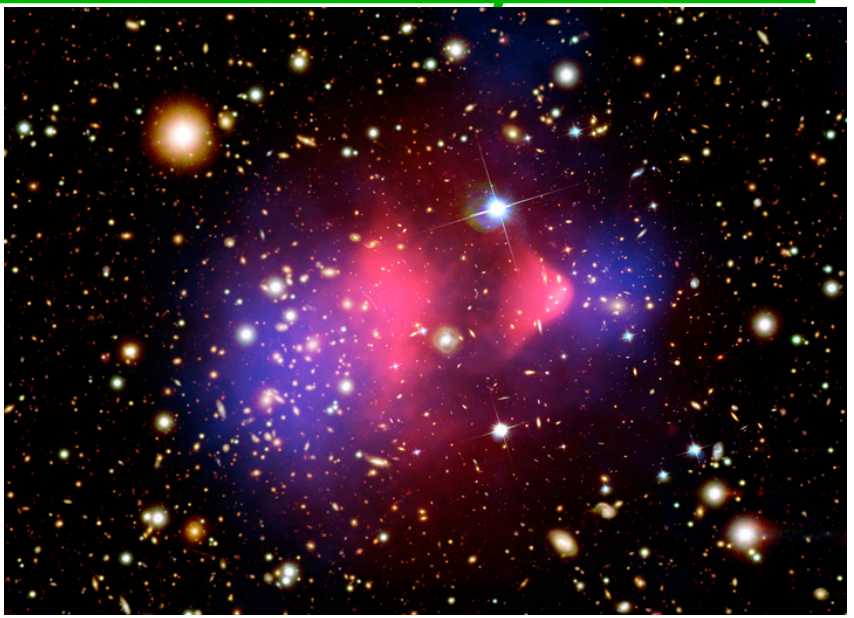
Composition of the Cosmos

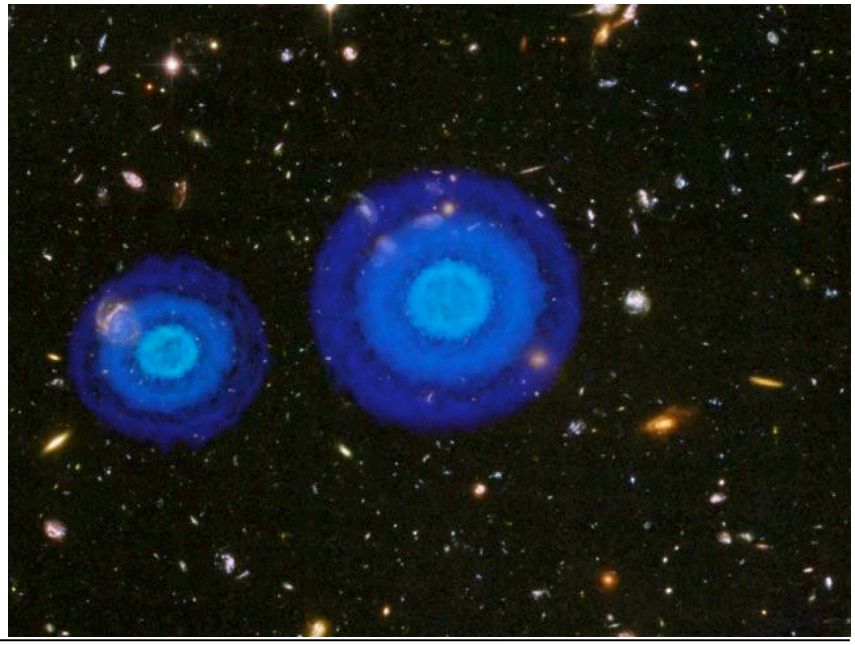
WMAP best fit



Bullet Cluster demonstrates reality of DM

- Stars 4% of cluster mass - optical image from Hubble and Magellan telescopes (D. Clowe, et al)
- Gas 16% of cluster mass - x-ray image in red from Chandra satellite (M. Markevitch, et al)
- Dark matter 80% of cluster mass - weak lensing of background galaxies (M. Bradac, et al)

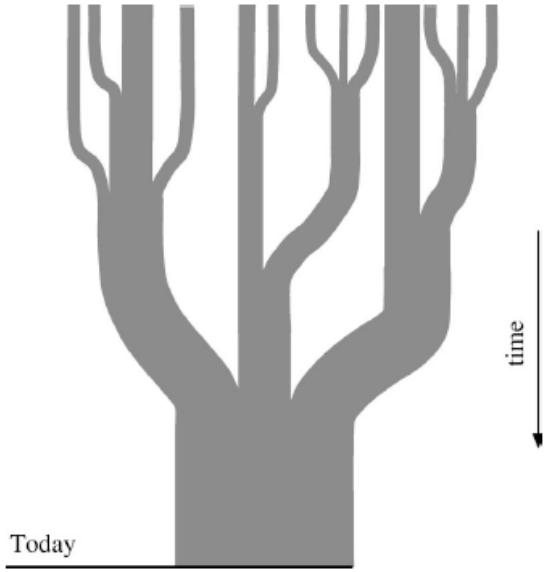


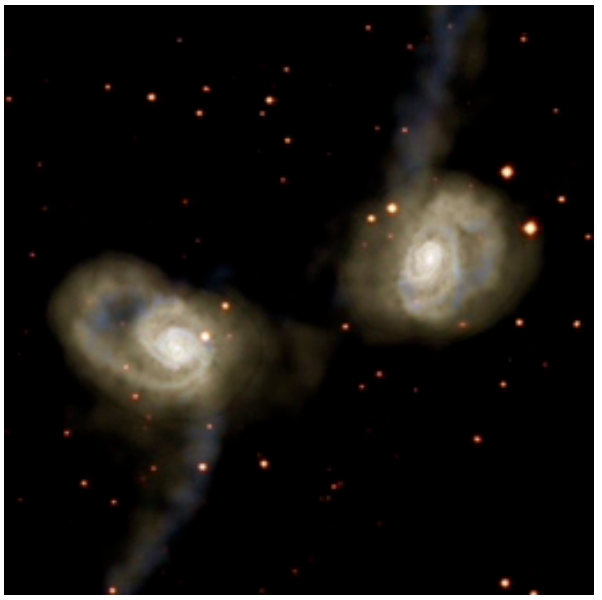


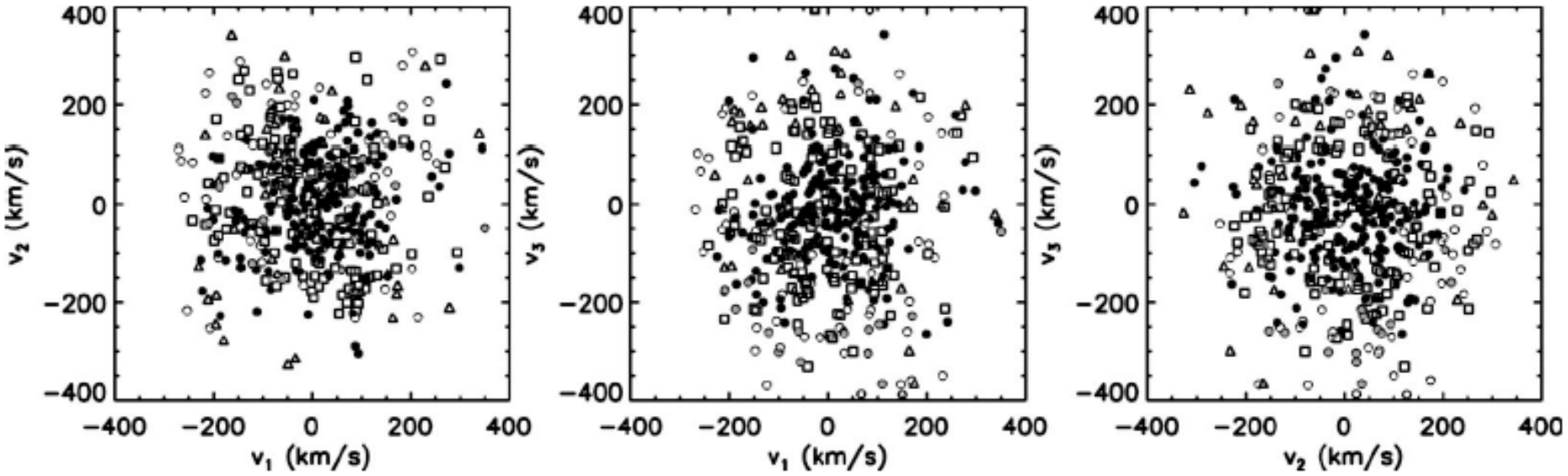
Credit: John Wise & Tom Abel (KIPAC)

Numerical simulations

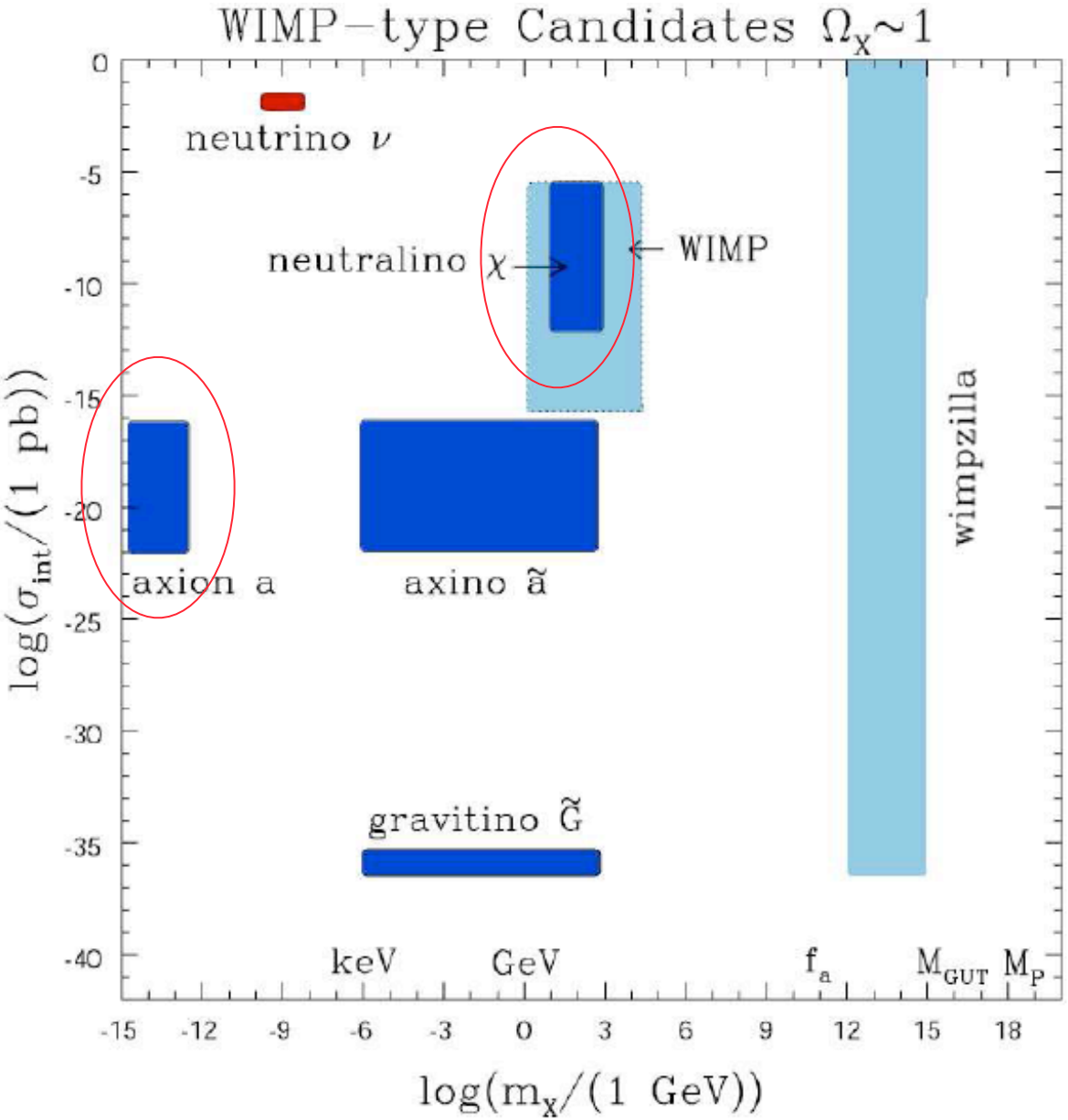
- The phase-space structure of a dark-matter halo: Implications for dark-matter direct detection experiments, A. Helmi, S. White, and V. Springel
  PRD 66, 063502 (2002)
- Solar system moves with respect to zero mean velocity halo at 220 km/s







What is the dark matter?



- neutrino ν – hot DM
- neutralino χ
- "generic" WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\tilde{G}$
- wimpzilla,. . .

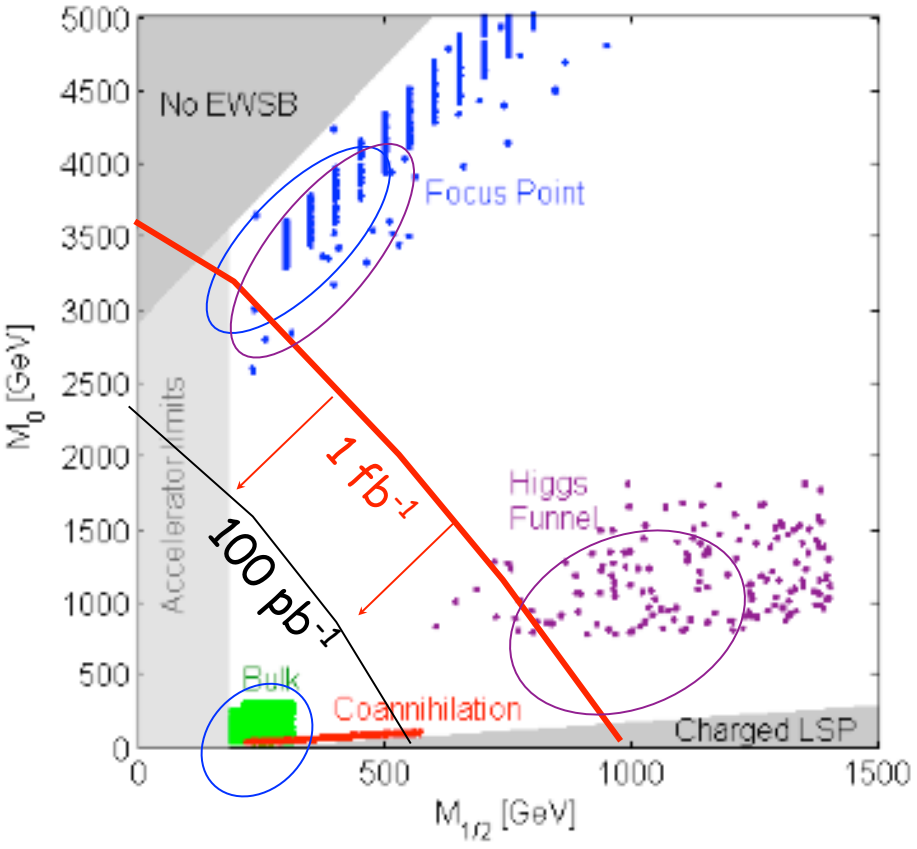
L. Roszkowski

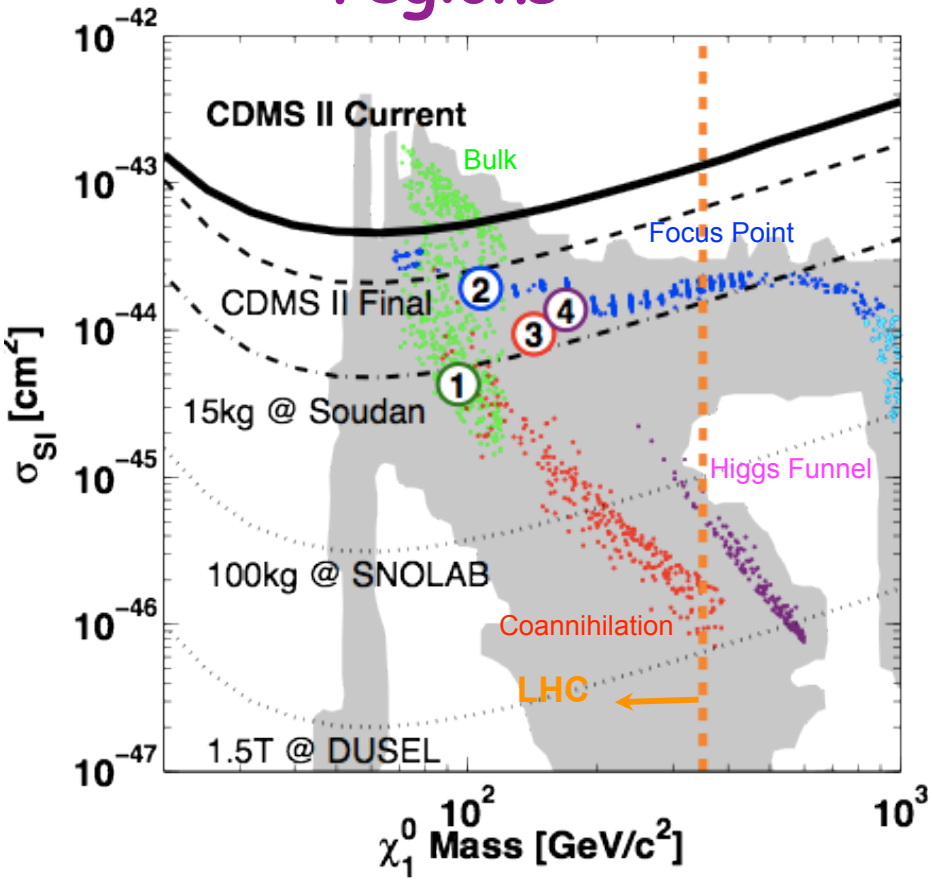
Complementarity mSugra/CMSSM

Direct Detection: sensitive to Bulk and Focus point regions

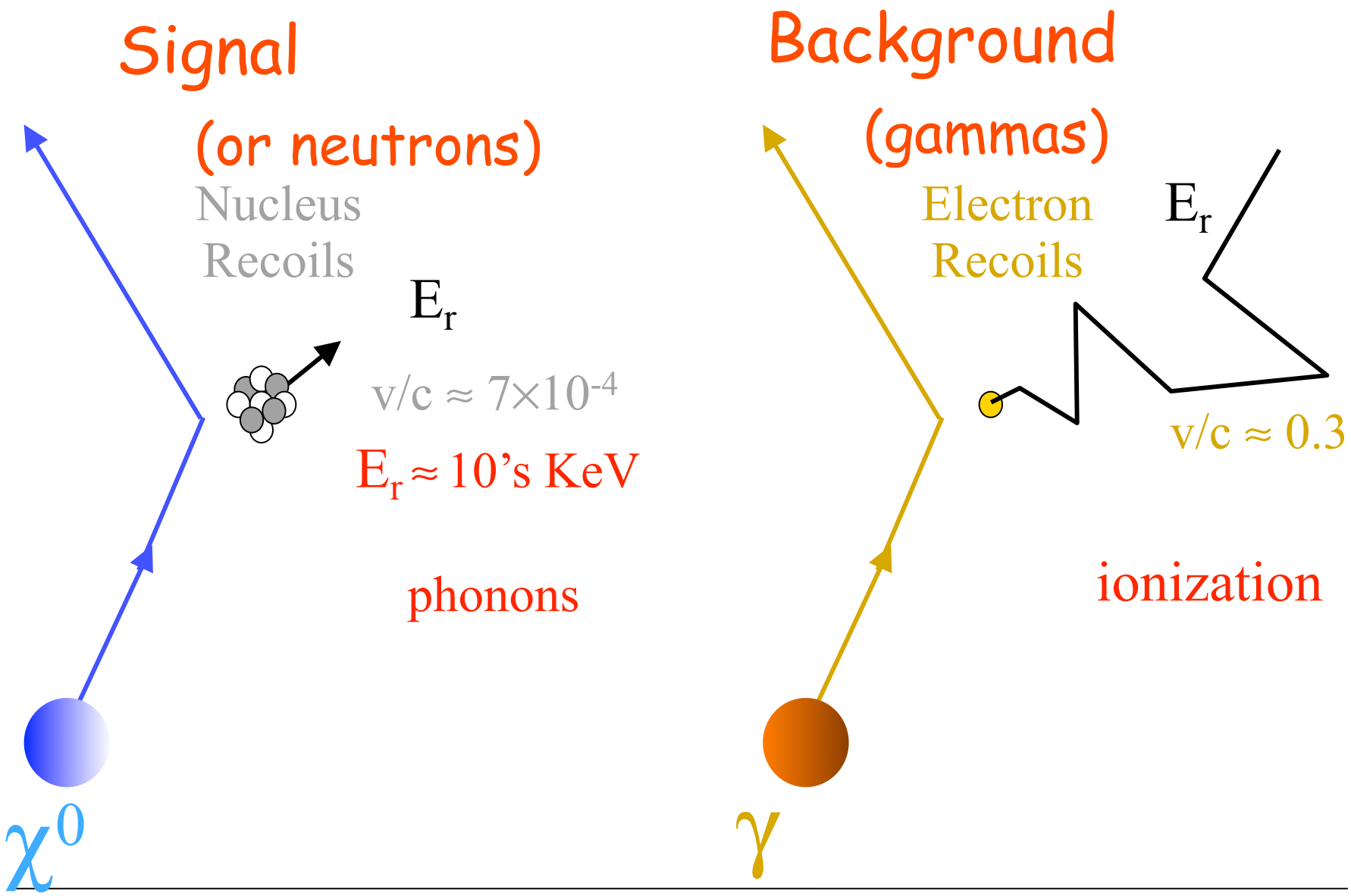
LHC sensitive to low energy or low mass region

Indirect Detection e.g. Fermi/GLAST sensitive to Focus and Higgs funnel regions

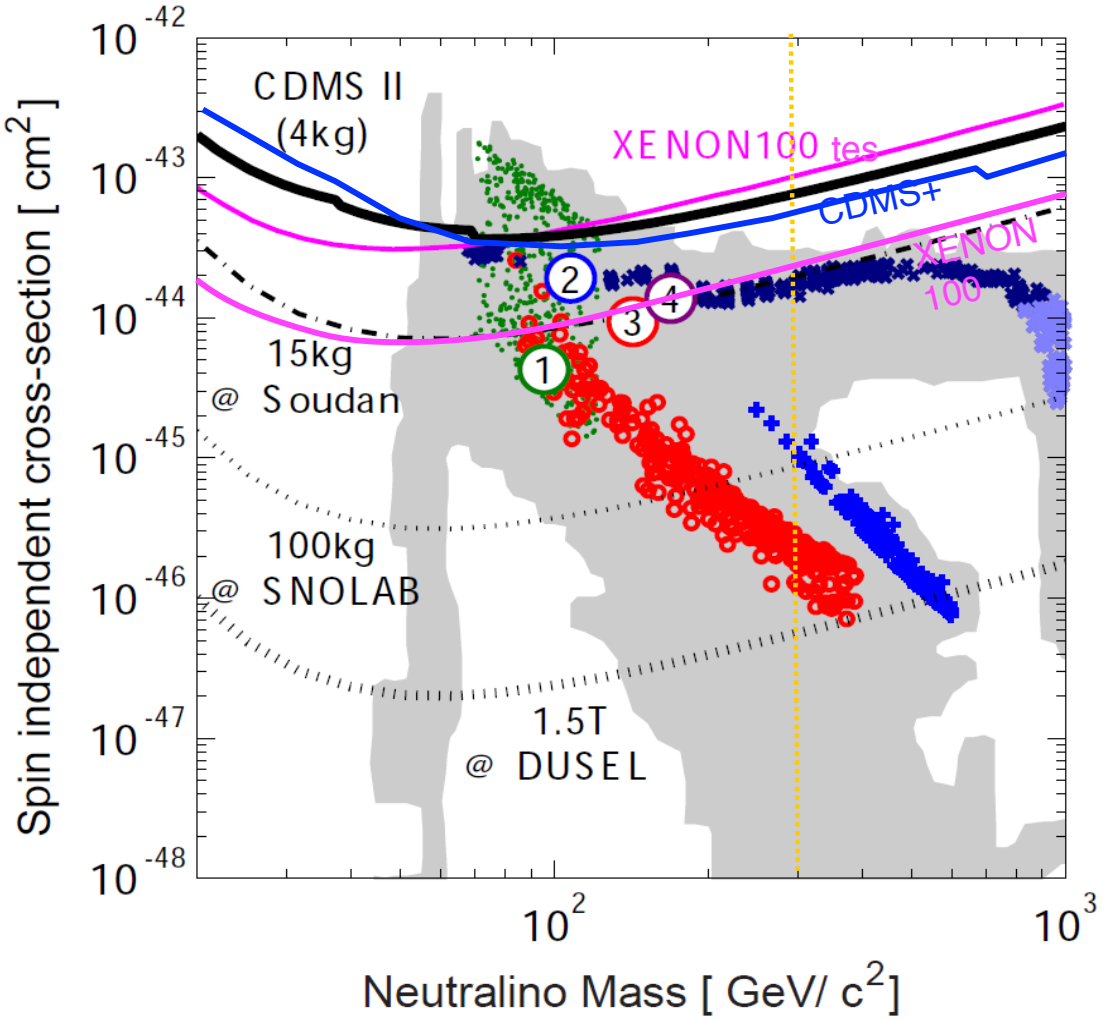




The Signal and Main Background



Status of Direction Detection Search



~1 evt/kg/month

~1 evt/kg/year

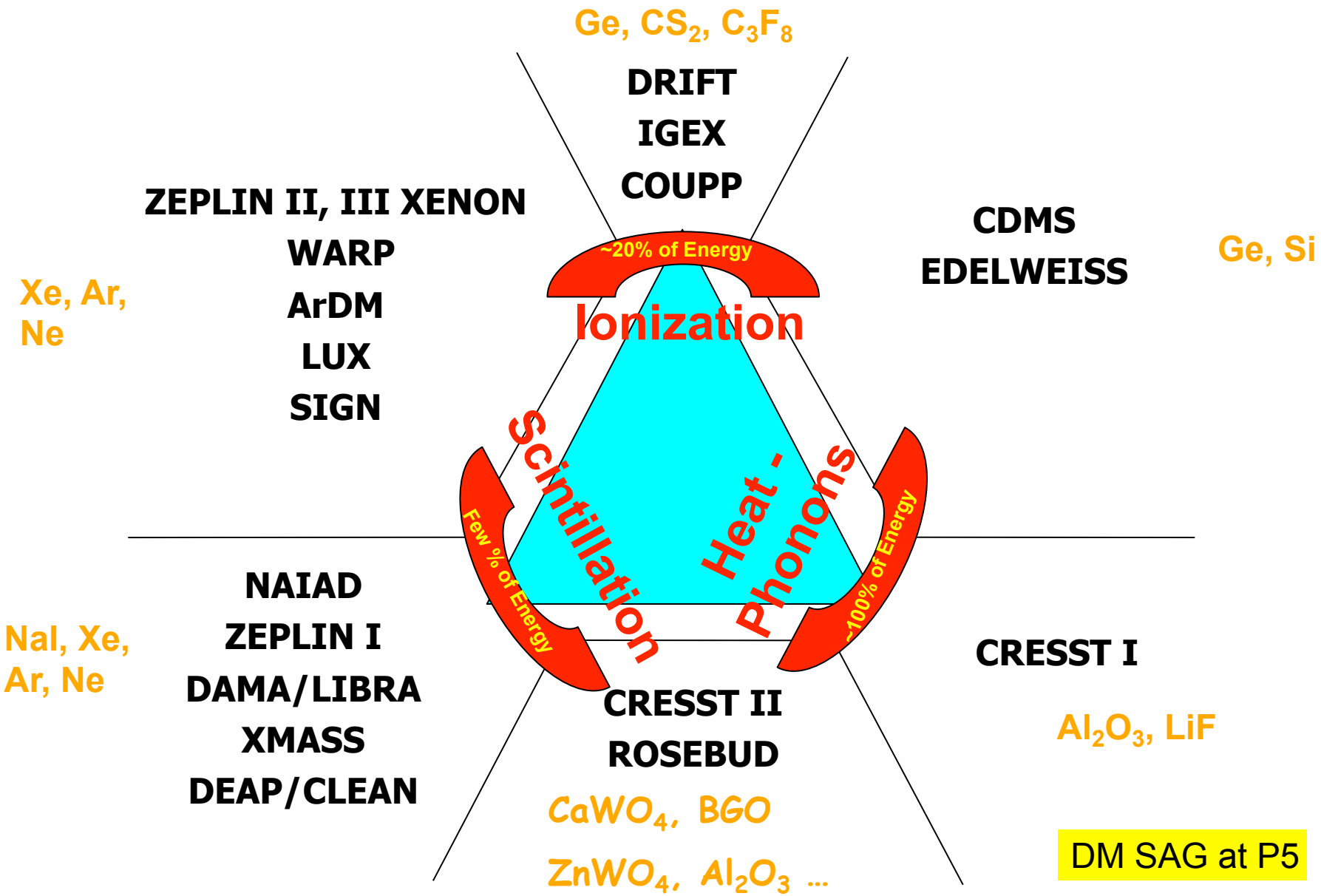
~1 evt/10kg/year

~1 evt/100kg/year

~1 evt/ton/year

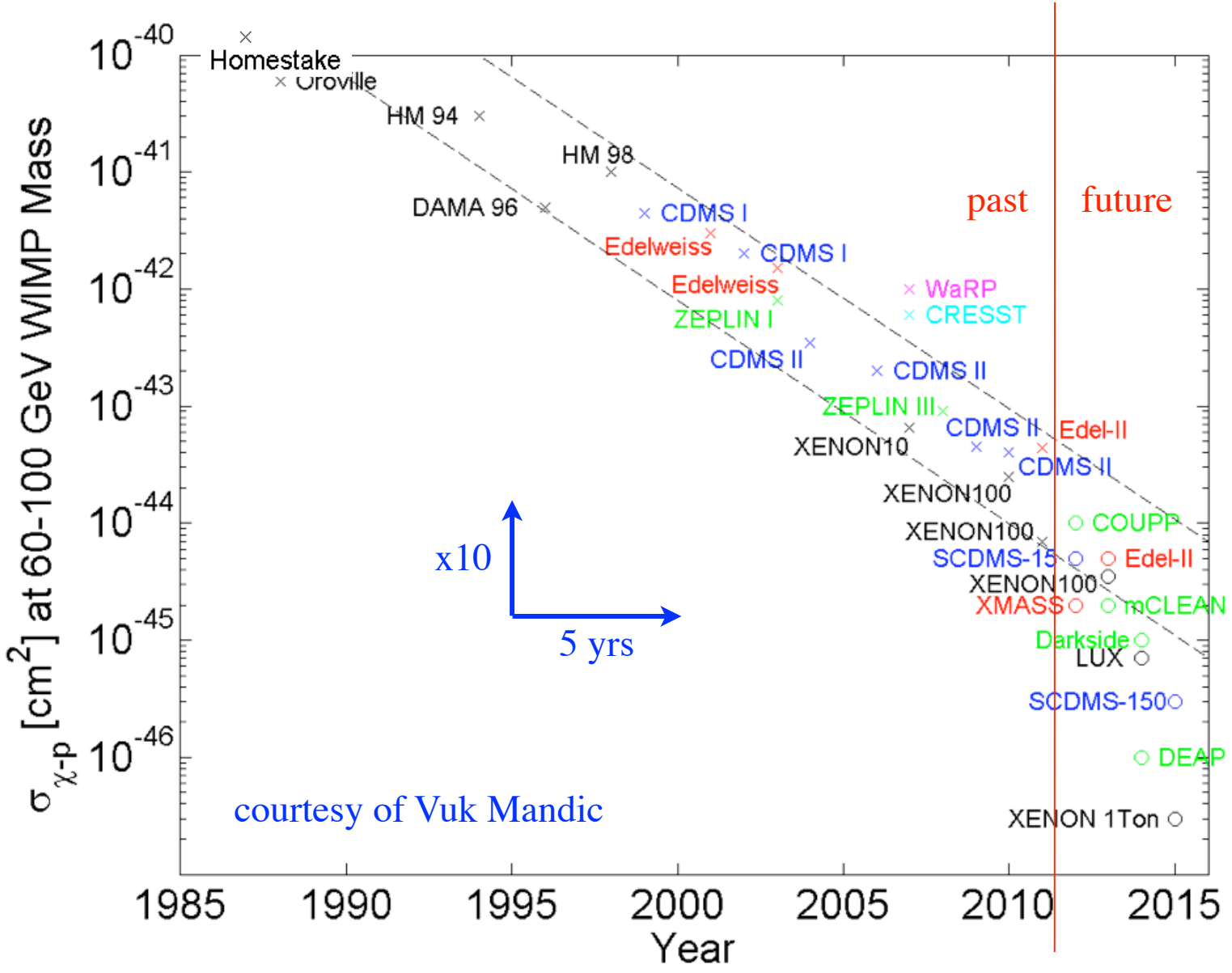
- Variety of techniques search for WIMP dark matter - interesting sensitivity
- Several have the potential to reach 10^{-44} cm^2 soon and 10^{-46} cm^2 in future

Direct Detection Techniques



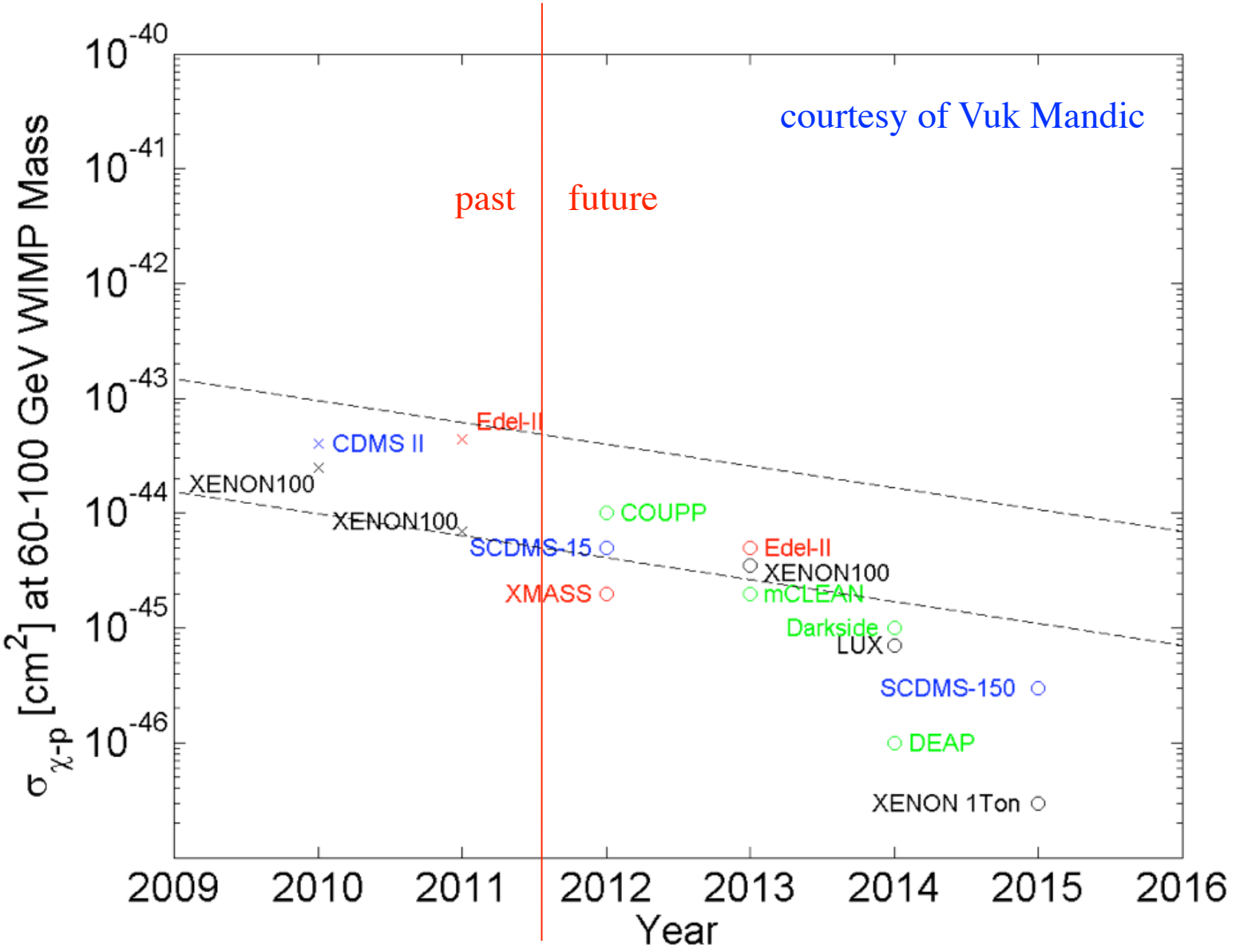
WIMP Search Sensitivity

from Mandic



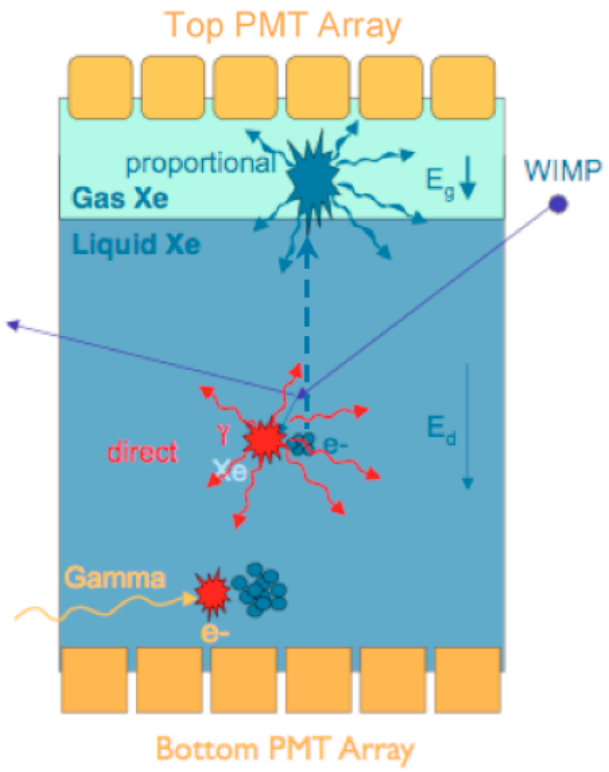
Recent WIMP Search Limits

from Mandic



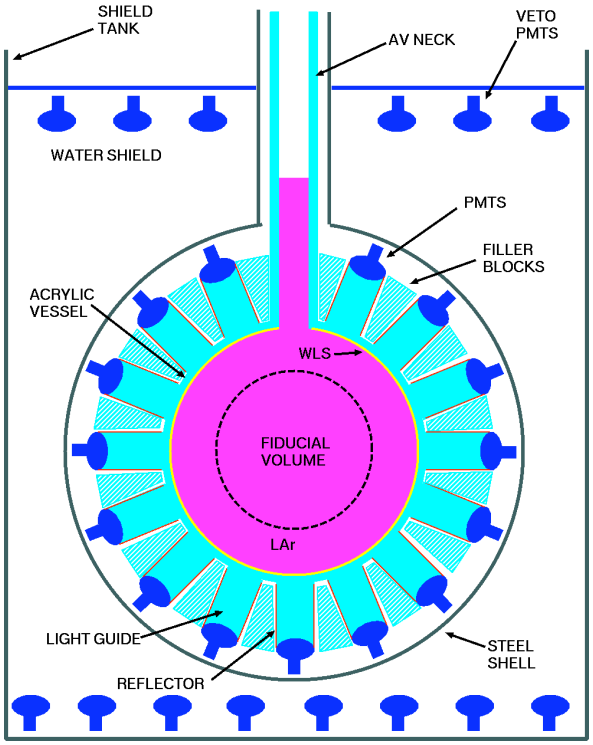
Single-Phase versus Dual-Phase

Dual-Phase



Courtesy E. Aprile

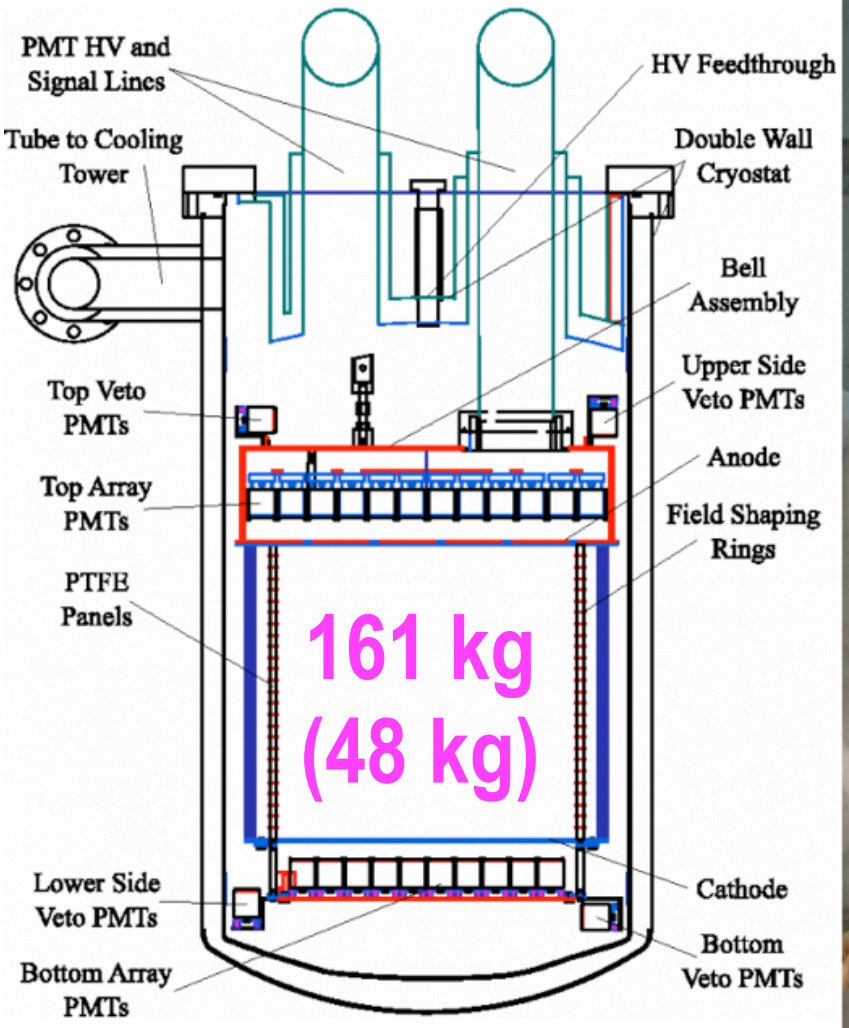
Single-Phase



D. N. McKinsey and J. M. Doyle, J. Low Temp. Phys. 118, 153 (2000).
D. N. McKinsey and K. J. Coakley, Astropart. Phys. 22, 355 (2005).
M. Boulay, J. Lidgard, and A. Hime, nucl-ex/0410025.
M. Boulay and A. Hime, Astropart. Phys. 25, 179 (2006).

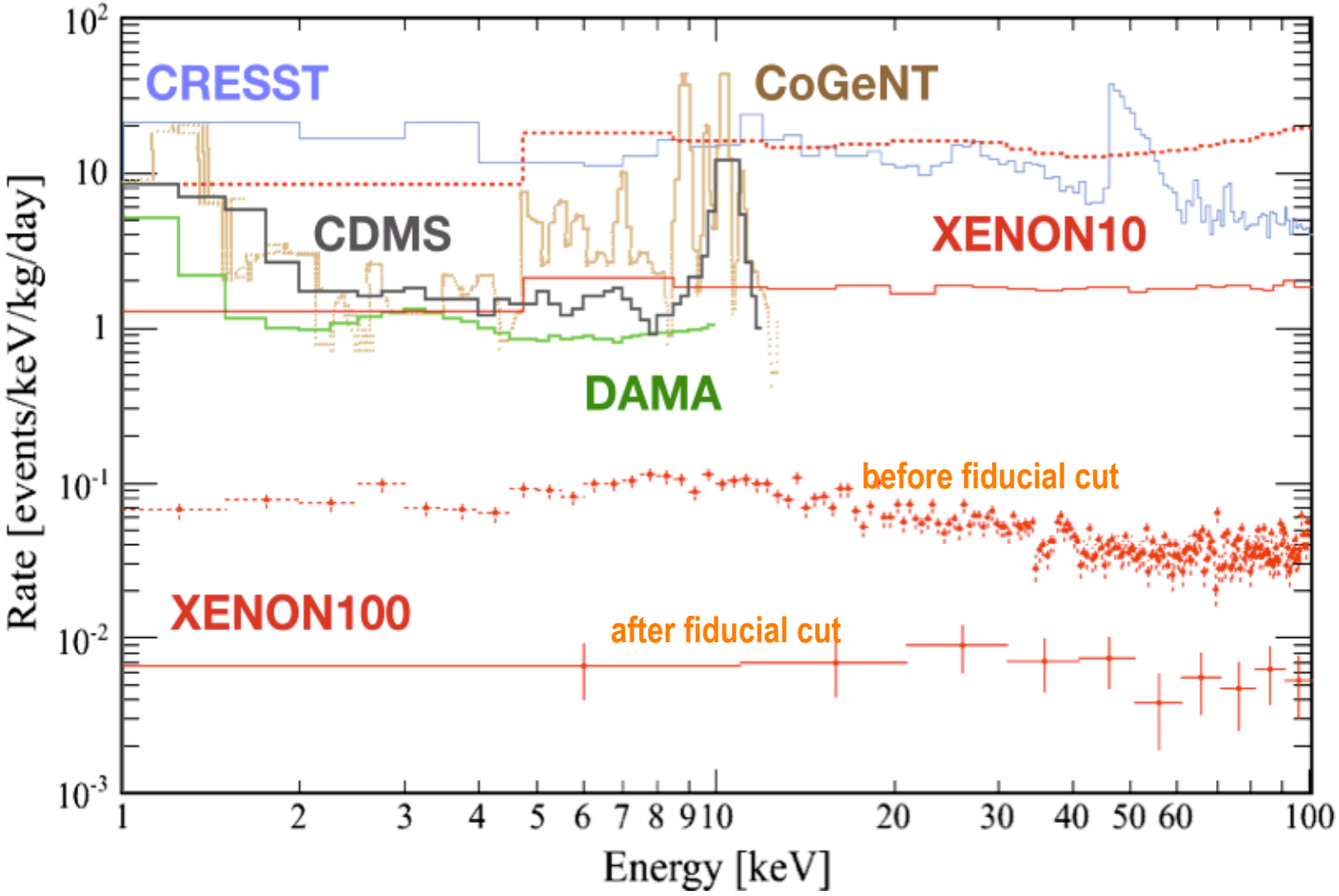
XENON100 Leads Field in Sensitivity

XENON100 (Double phase Xenon)



Best Background Rate

Level of Backgrounds (before S2/S1 cut)

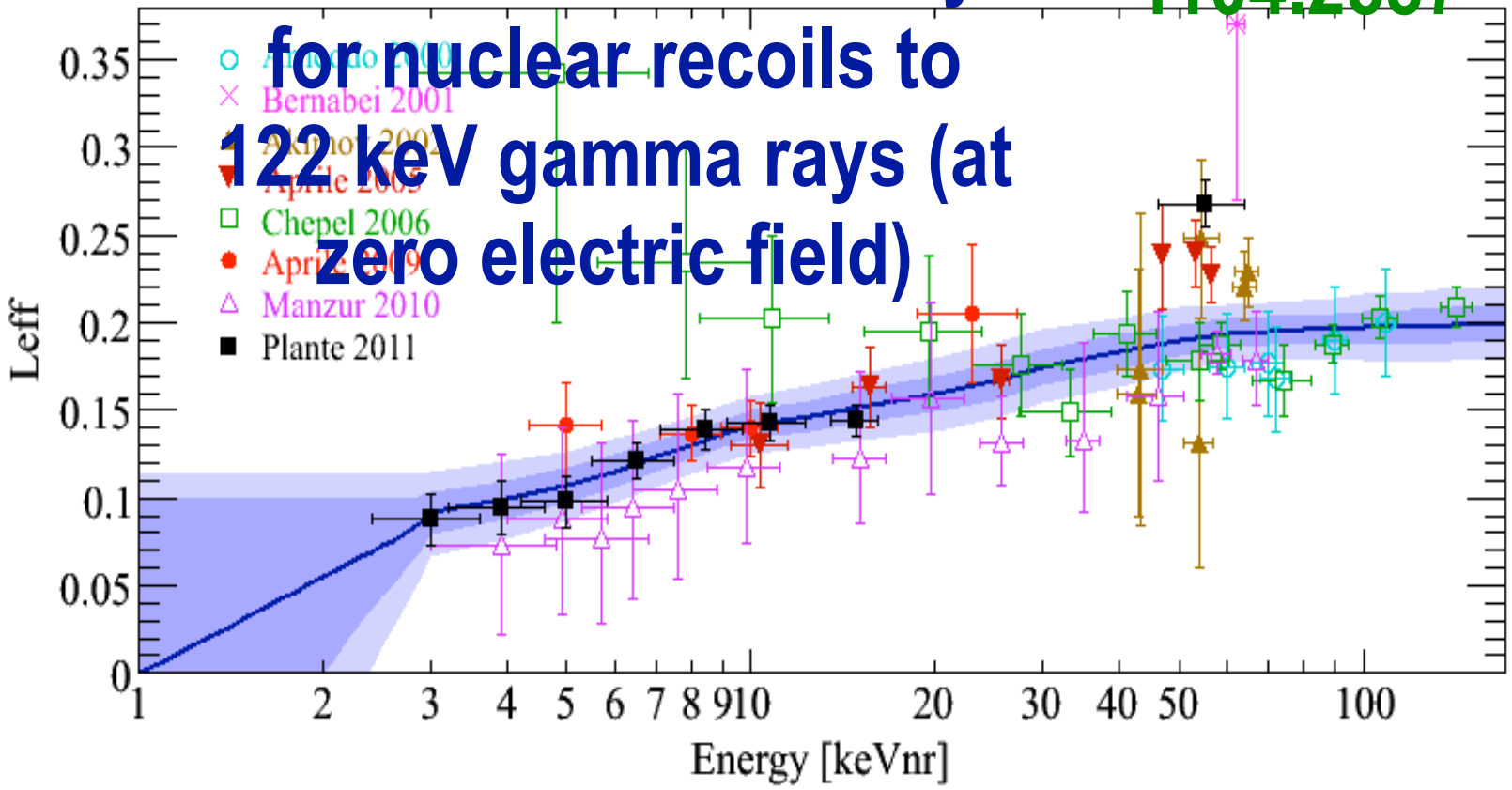


Quenching Factor Measurements

New L_{eff} vs. Energy

Leff : Relative scintillation efficiency for nuclear recoils to 122 keV gamma rays (at zero electric field)

arXiv: 1104.2587

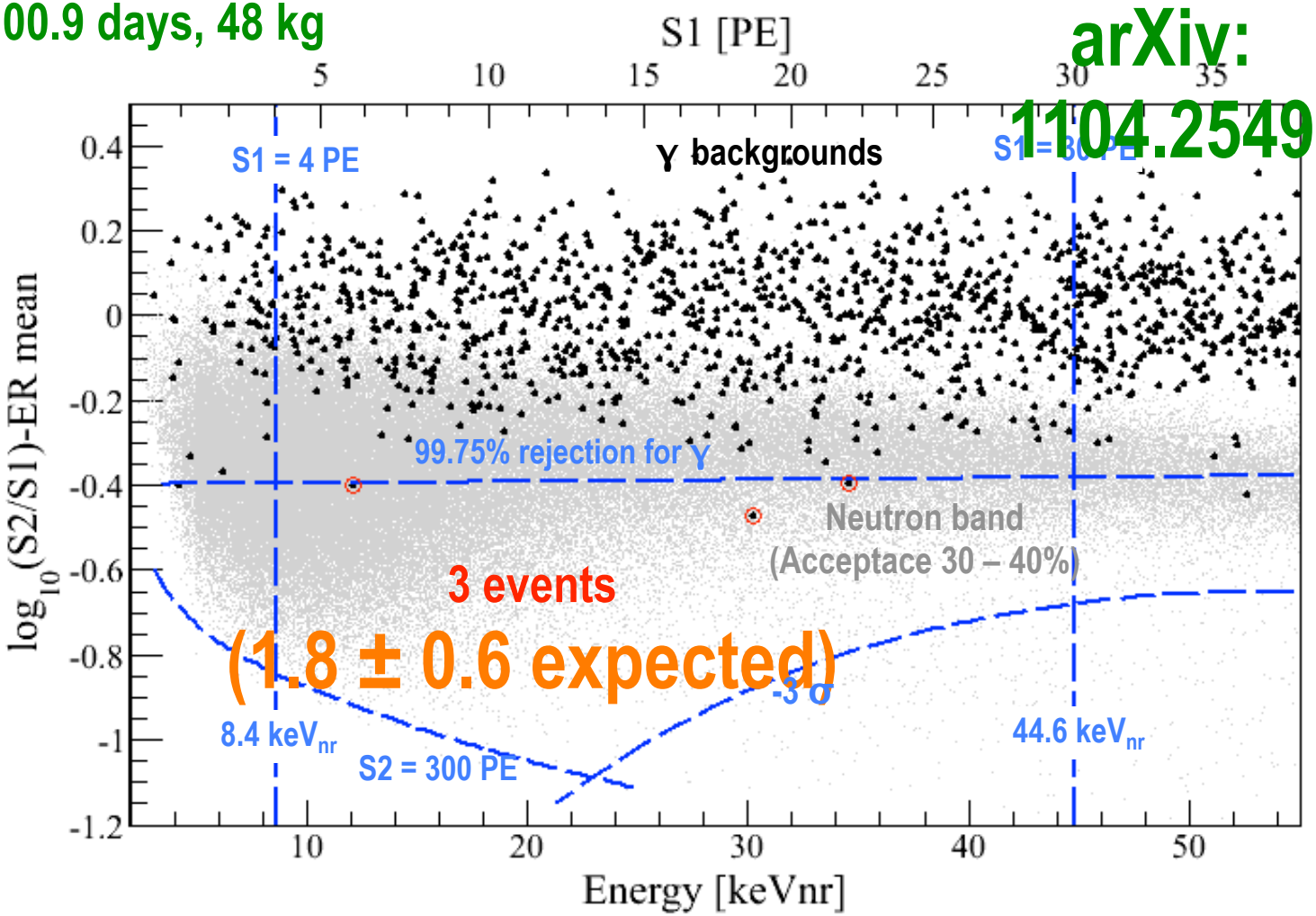


XENON100 Results

Log(S2/S1) vs. Energy

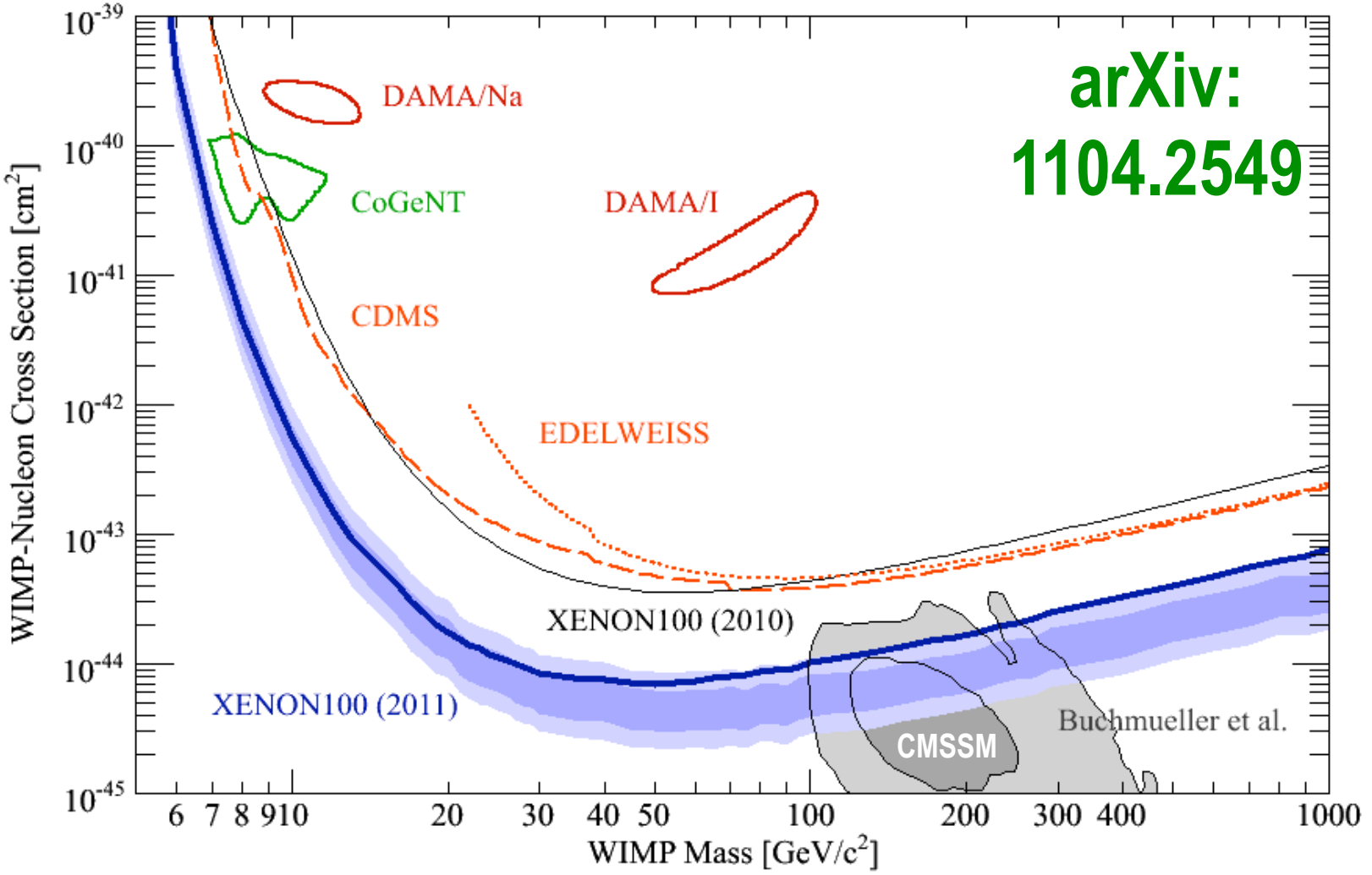
100.9 days, 48 kg

arXiv: 1104.2549



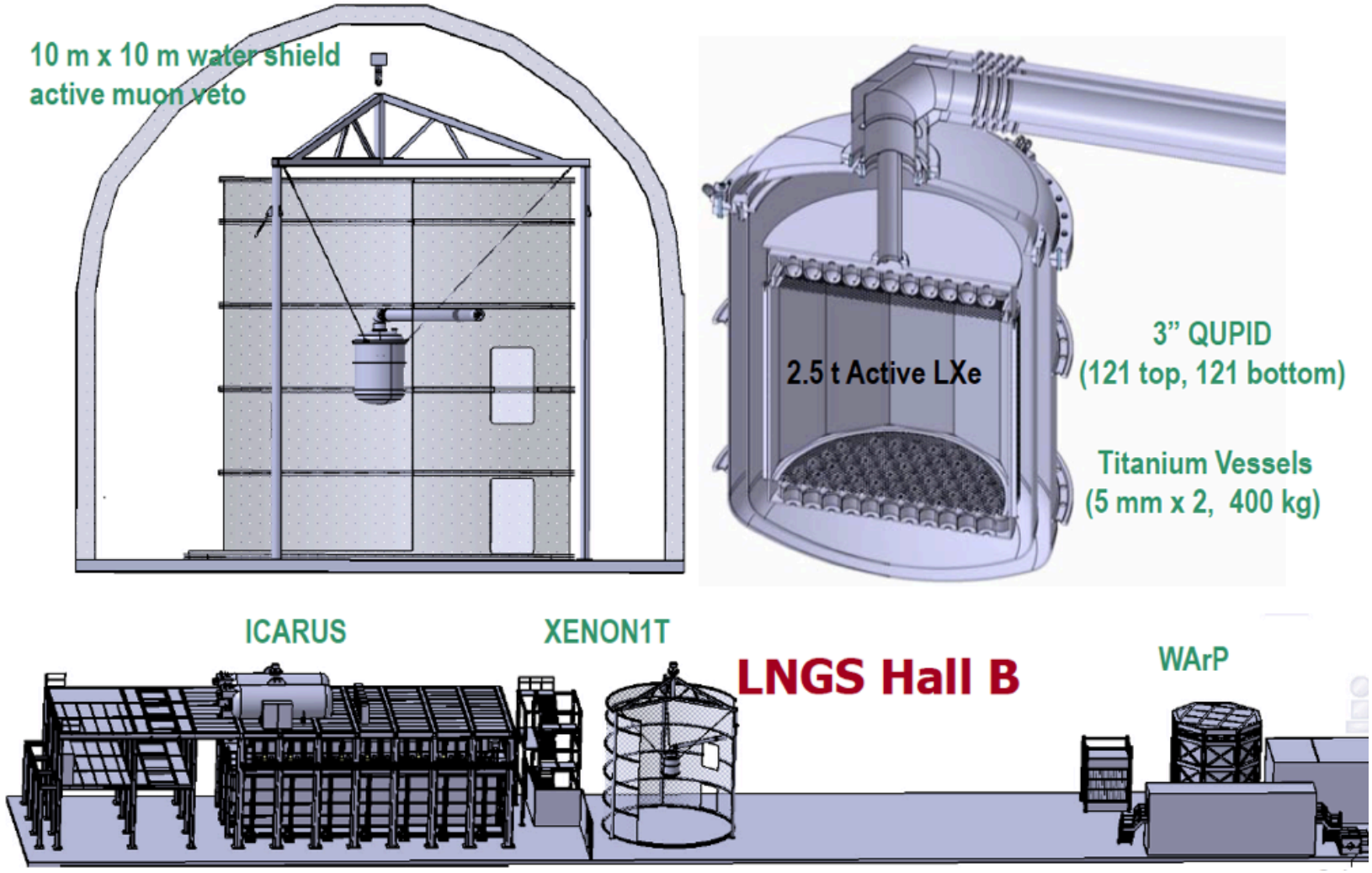
XENON100 Sensitivity and Limits

90% CL Limits of SI Cross Section (April, 2011)



Future XENON 1T

XENON1T (G2)



LUX - Status Summary

- LUX 350 kg
  - LUX detector has started series of cryogenic runs in Surface Lab -testing the full deployment configuration in water tank.
  - May 2011: $8m contract for outfitting work on new Davis Complex at 4850 level of Sanford Lab has been signed, and work is underway. (Excavation was completed in earlier in 2011.)
  - LUX will continue surface operation to verify all systems are fully functioning, and then move detector underground for physics run when outfitting is completed in Spring 2012
  - Self shielding of 350 kg LXe mass will deliver very low raw background rates for electron recoils (even before ER discrimination)
    - See next slide
  - Important for clear discovery of WIMP nuclear recoil signal

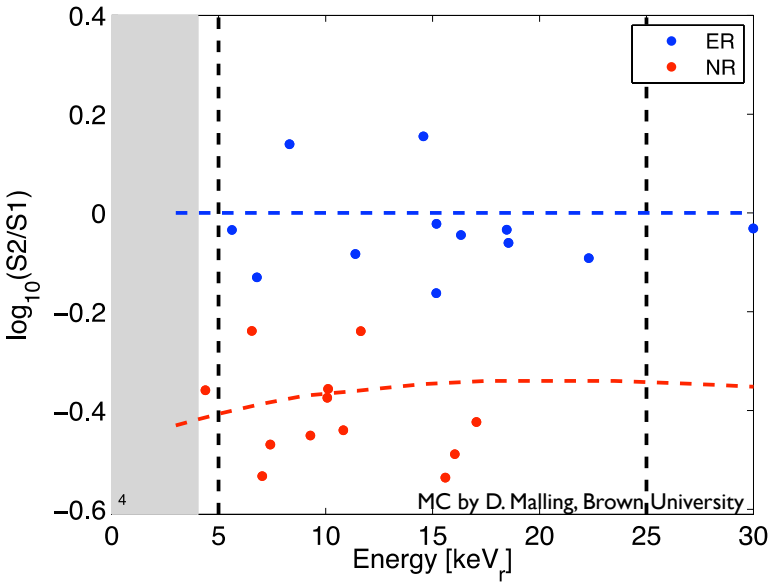
from Galbiati

LUX Detector in Water Tank
Prior to May 2011 Cooldown
Sanford Surface Facility

LUX Predicts lower background

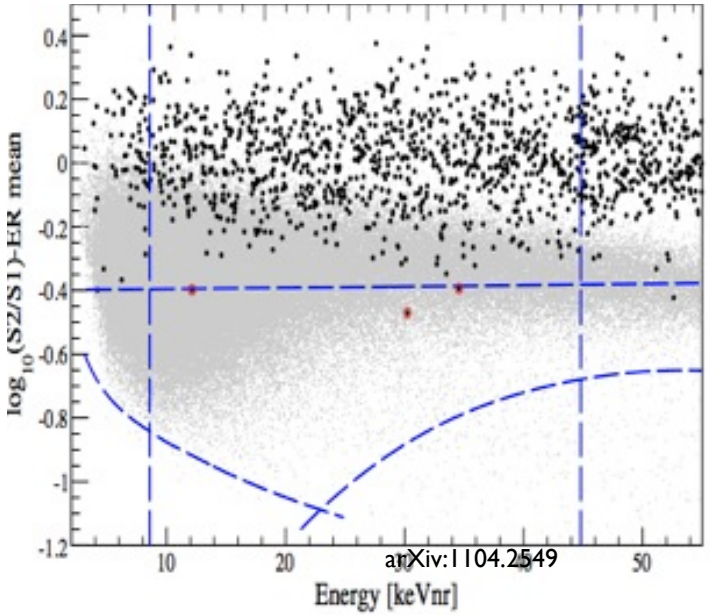
LUX: The First 40 Days

LUX (Monte Carlo)



LUX signal and background expectation for 4,000 kg-days net exposure. WIMP events assume m = 100 GeV, $\sigma = 1 \times 10^{-44}$ cm^2.

XENON100



XENON100 4,000 kg-days result for comparison.
Note higher ER rate - ~800 events in 100 days x 40 kg fiducial
~60% due to 85Kr with remaining 40% due to Compton scattering of external gamma background

- **Red Points:** WIMP events after only 40 days (equivalent exposure to all of XENON100 run) assuming a WIMP model for mass 100 GeV at current best 90% CL Exclusion Limit
- **Blue Points:** Total # of single scatter electron recoil events in LUX (before any other cuts) after 40 days of running. Expect only 11 events in 100 kg fiducial x 40 days for a net 4,000 kg exposure.
- **LUX - Strong Emphasis on WIMP Discovery / Plan to run LUX for 300 days**

from Galbiati

from Galbiati

WARP 140-kg Detector

The WARP 140-kg detector, currently under commissioning at LNGS

140 kg active target, to reach into 5×10^{-45} cm^2 and cover critical part of SUSY parameter space

Complete neutron shield!

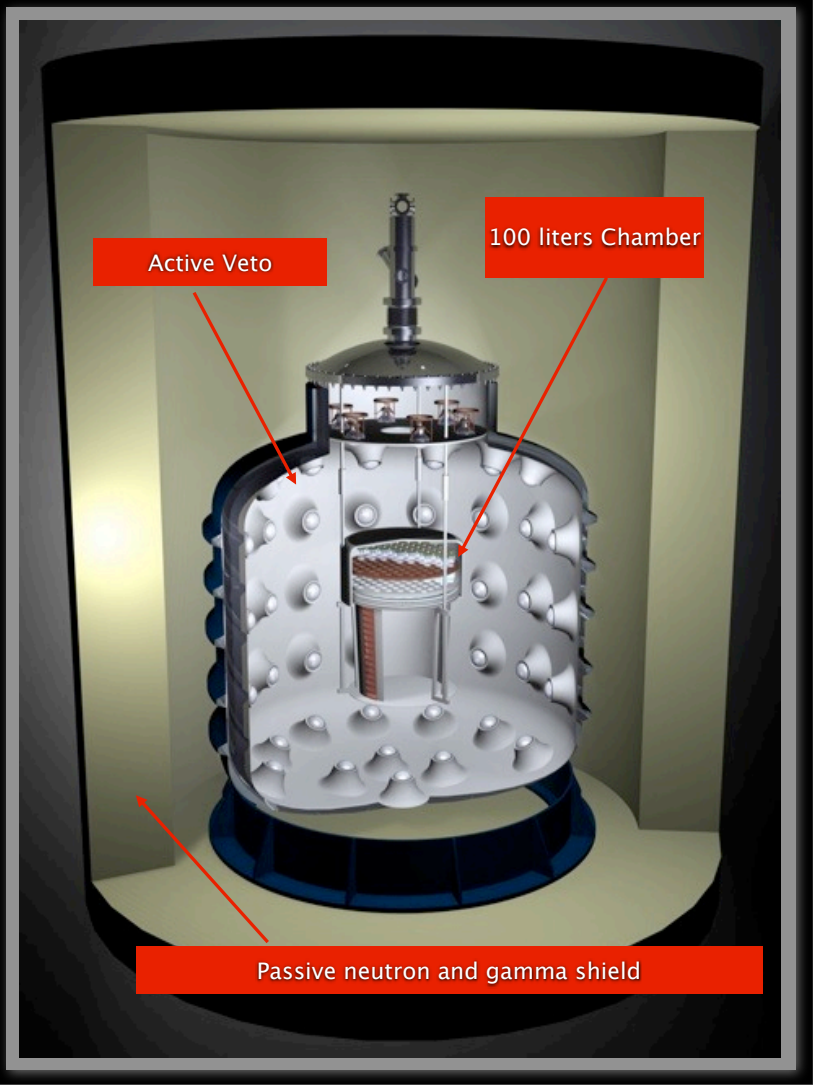
4π active neutron veto (9 tons Liquid Argon, 300 PMTs)

Active control on nuclide-recoil background, owing to unique feature (LAr active veto)

3D Event localization and definition of fiducial volume for surface background rejection

Detector designed for positive confirmation of a possible WIMP discovery

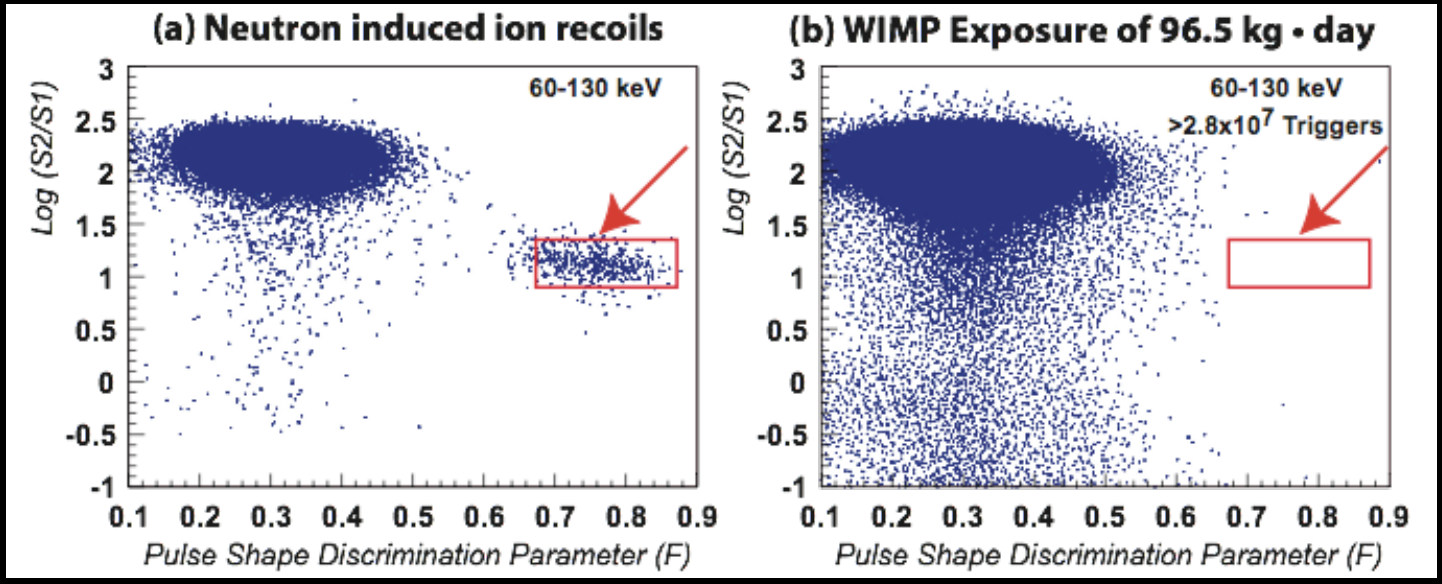
Cryostat designed to allocate a possible 1400 kg detector



First Results for High Threshold

from Galbiati

First Dark Matter Results



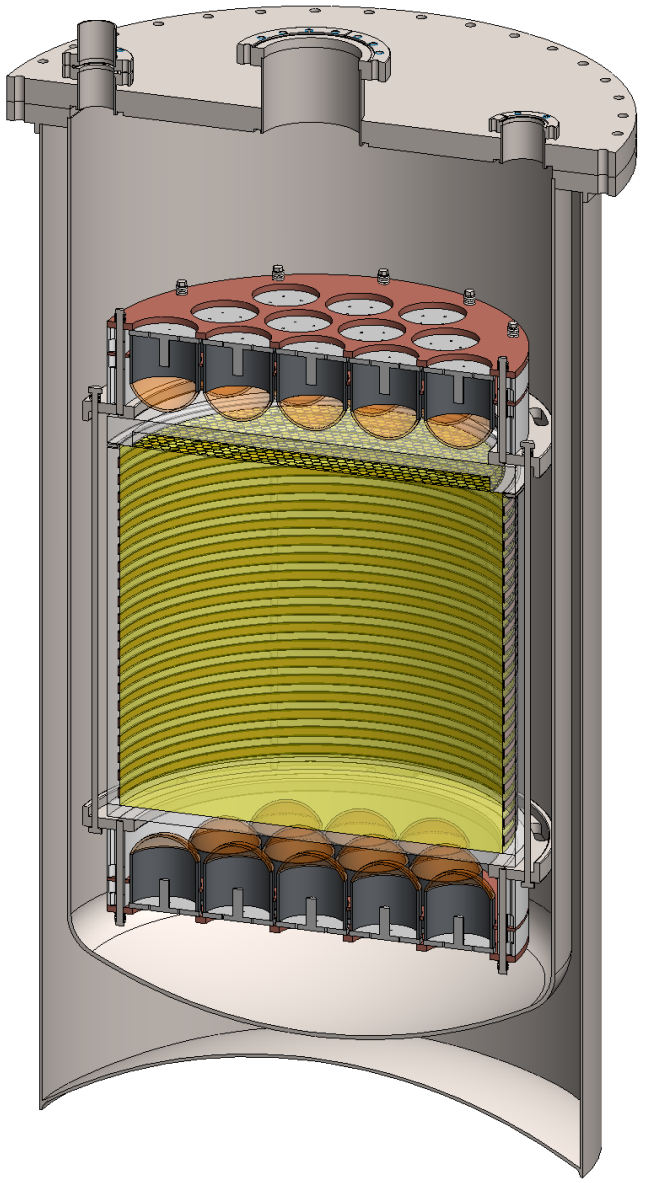
Selected events in the n-induced single recoils window during the WIMP search run: None

Astropart. Phys. **28**, 495 (2008)

DarkSide-50

from Galbiati

- First implementation of new technologies
- Depleted argon, QUPIDs, organic-scintillator-based neutron veto
- Dual-phase TPC as WARP 50 kg DAr active mass
- Sensitivity 10-45 cm2 in 3-yrs background-free operation
- Demonstrate potential of the technology for multi-ton year background-free sensitivity

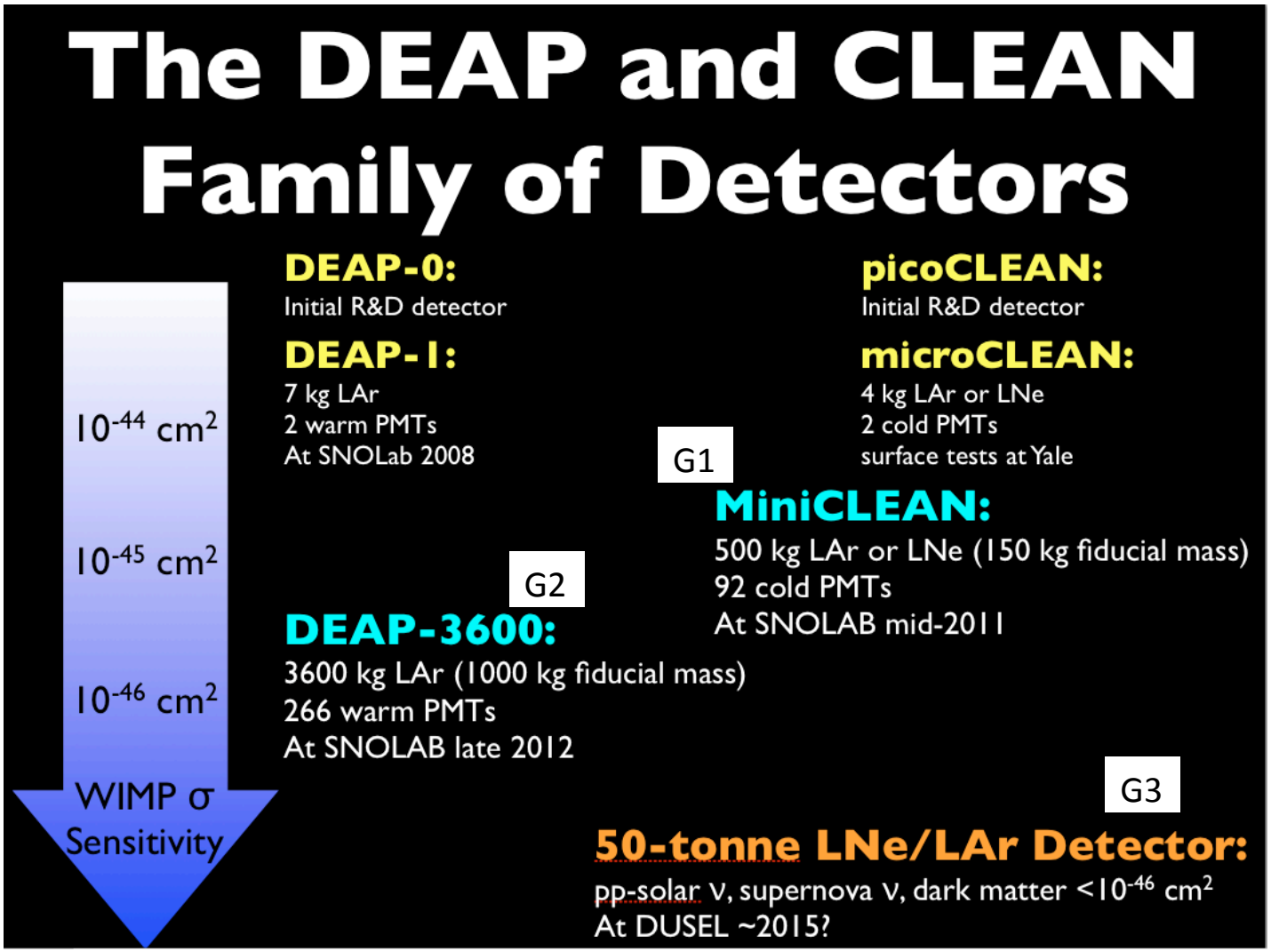


Successful Underground Ar Source

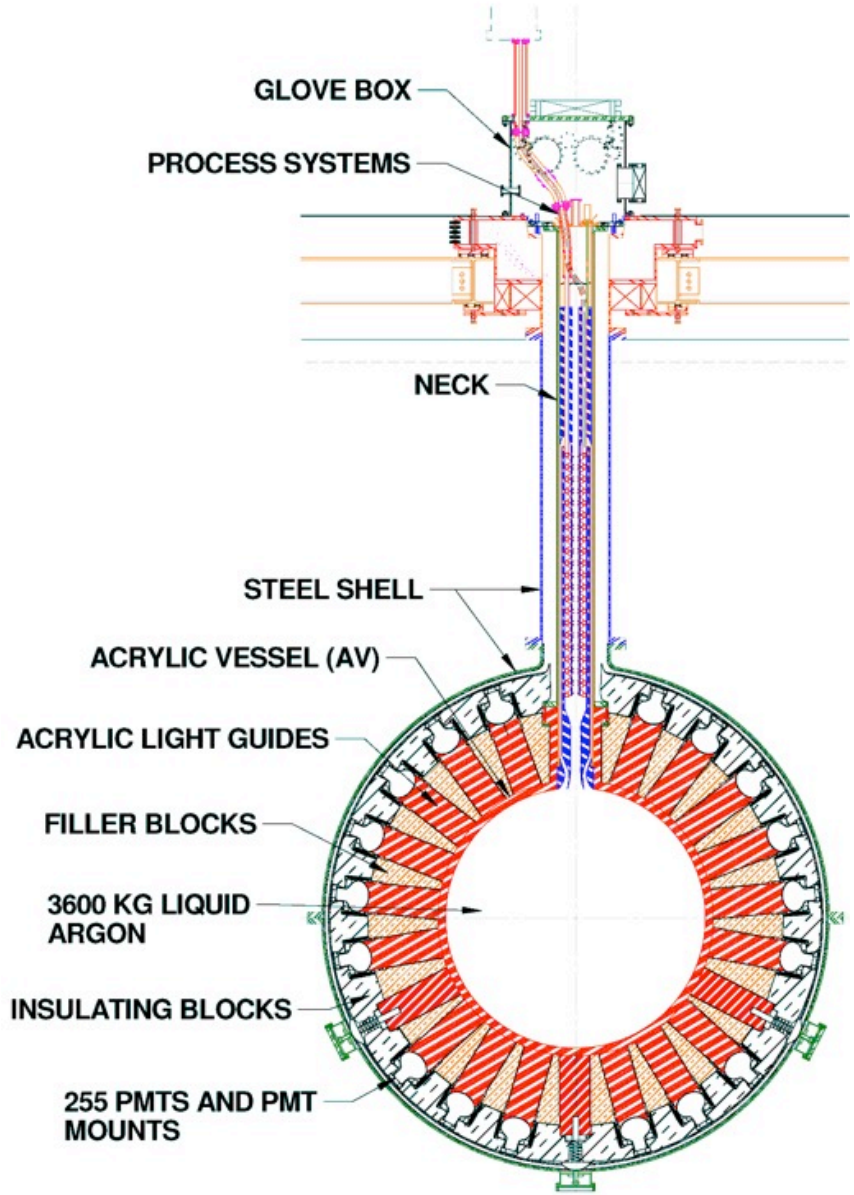
from Galbiati

Princeton Extraction Plant
Achieved 1.0 kg/day, Collected ~40 kg

DEAP & CLEAN


The DEAP and CLEAN Family of Detectors
DEAP-0:
Initial R&D detector
DEAP-1:
7 kg LAr
2 warm PMTs
At SNOLab 2008
picoCLEAN:
Initial R&D detector
microCLEAN:
4 kg LAr or LNe
2 cold PMTs
surface tests at Yale
G1
MiniCLEAN:
500 kg LAr or LNe (150 kg fiducial mass)
92 cold PMTs
At SNOLAB mid-2011
G2
DEAP-3600:
3600 kg LAr (1000 kg fiducial mass)
266 warm PMTs
At SNOLAB late 2012
G3
50-tonne LNe/LAr Detector:
pp-solar ν, supernova ν, dark matter <10-46 cm2
At DUSEL ~2015?
10-44 cm2
10-45 cm2
10-46 cm2
WIMP σ Sensitivity

DEAP-3600 detector



DEAP-3600 detector

85 cm radius acrylic sphere contains 3600 kg LAr (55 cm, 1000 kg fiducial)

255 8" PMTs (warm)

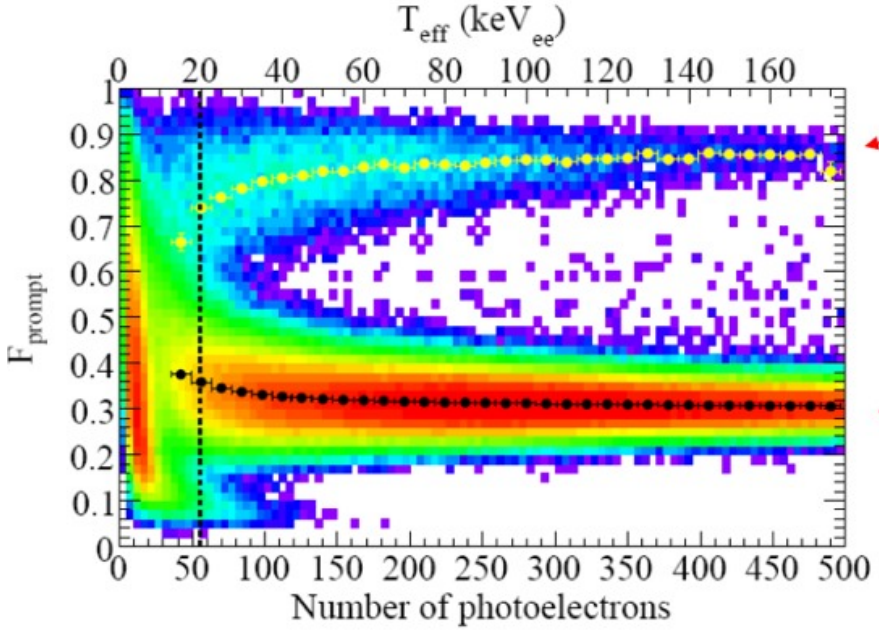
50 cm acrylic light guides and fillers for neutron shielding (from PMTs)

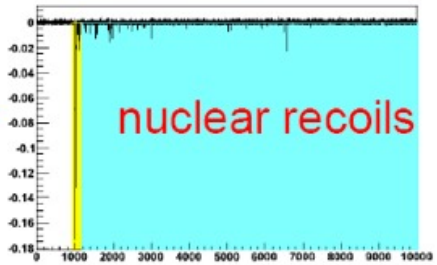
Steel shell for safety to prevent cryogen/water mixing (AV failure)

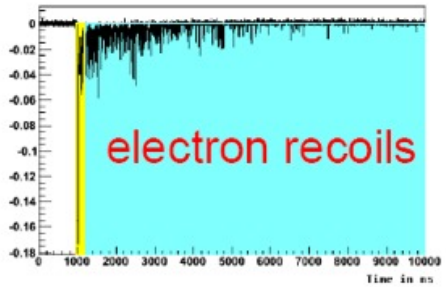
Only LAr, acrylic, and WLS (10 g) inside of neutron shield

8.5 m diameter water shielding tank

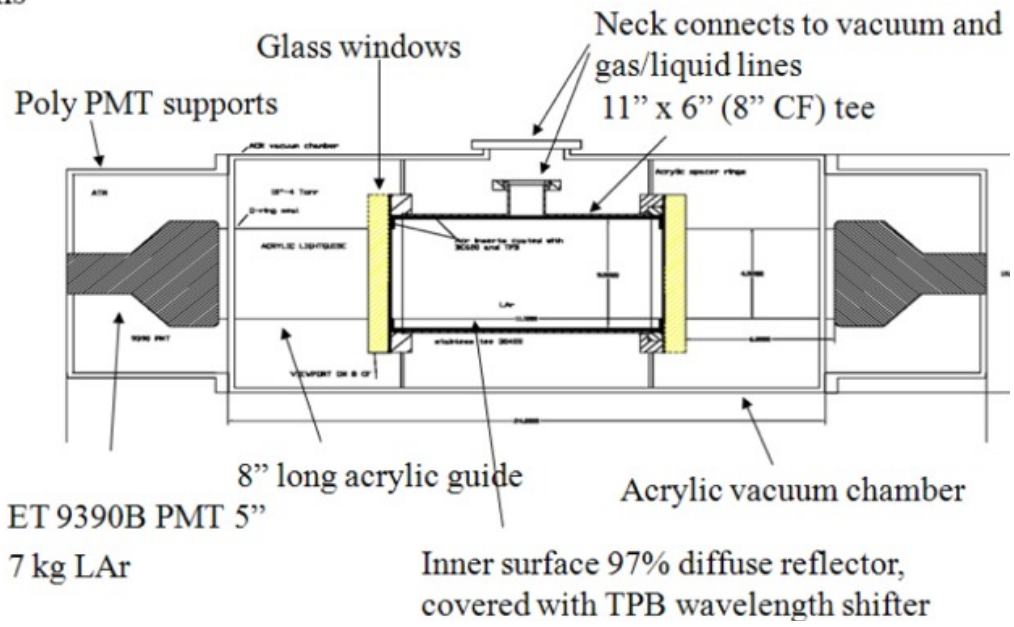
DEAP-1 demonstrations





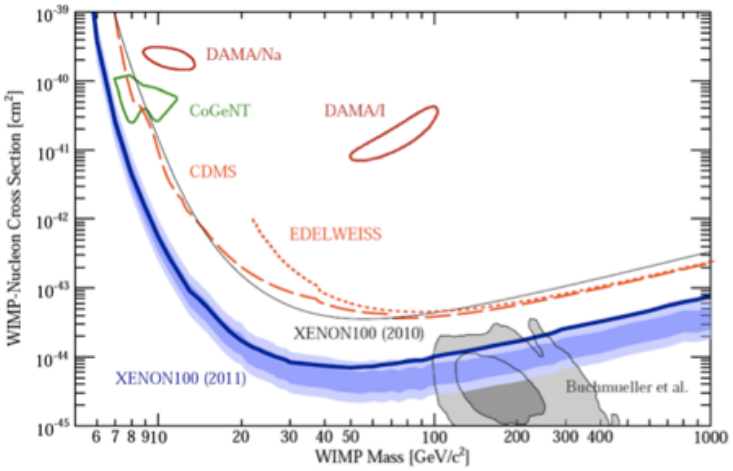


The DEAP-1 Detector

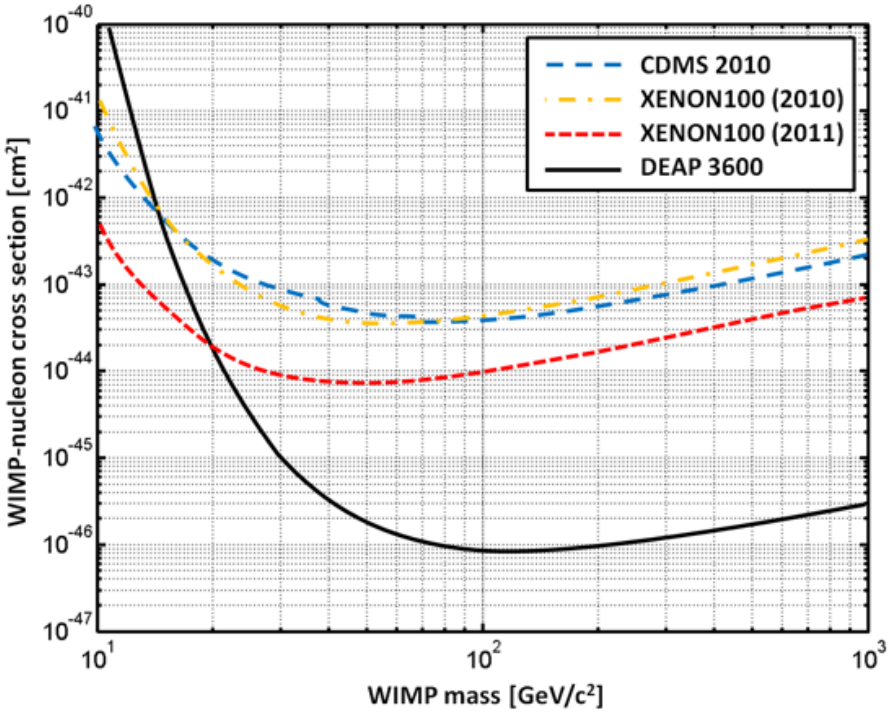


DEAP-3600 projected sensitivity

Plot courtesy of Wolfgang Rau



XENON100 arXiv:1104.2549



80 keVr threshold, without depletion of ^{39}Ar

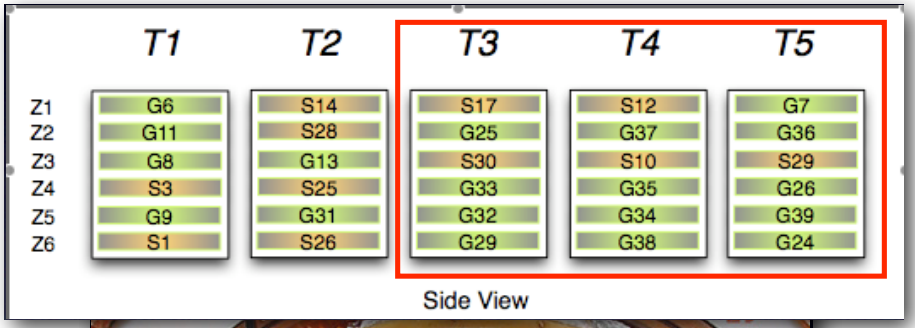
CDMS 2010:	612 kg-days (Ge)
XENON100 2011:	1471 kg-days (Xe)
DEAP-3600:	1,000,000 kg-days (LAr)
	(3 years)

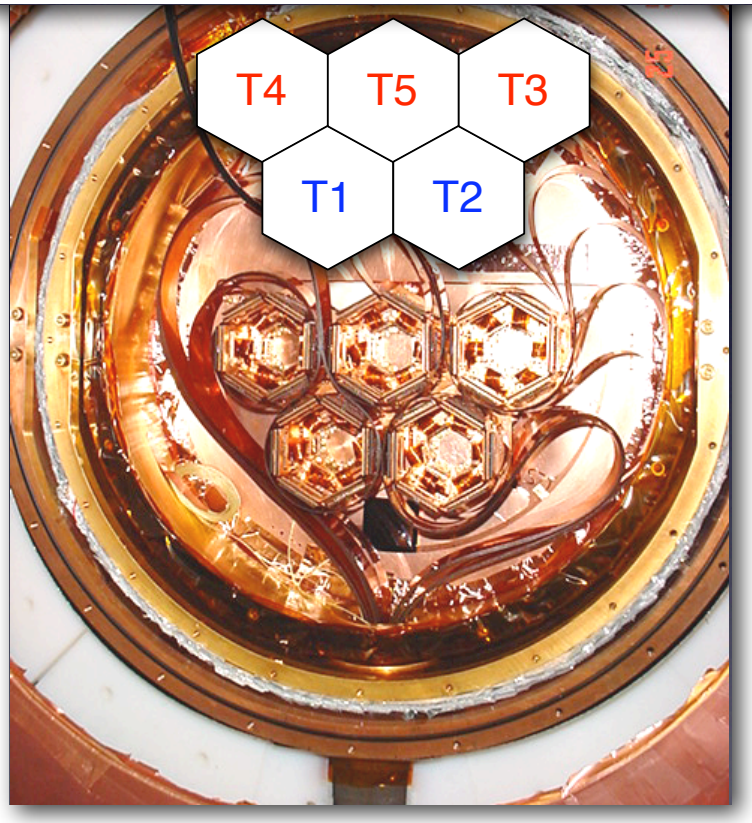
DEAP-3600 commissioning late 2012

DEAP-3600 Shield Tank (8.5 m diameter) in SNOLAB Cube Hall (June 2011)

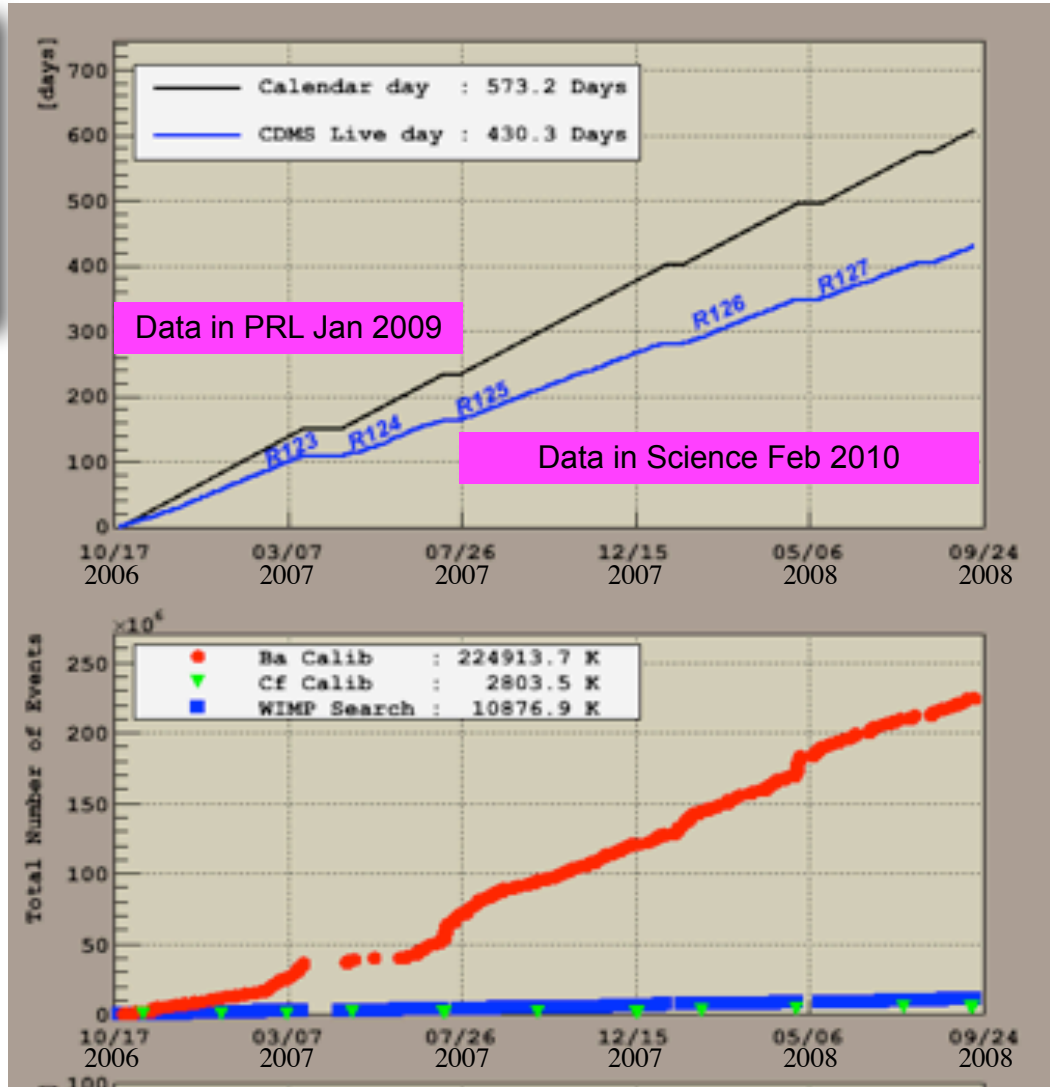
CDMS II Experiment

- 30 detectors - **4.75 kg of Ge**, **1.1 kg of Si**

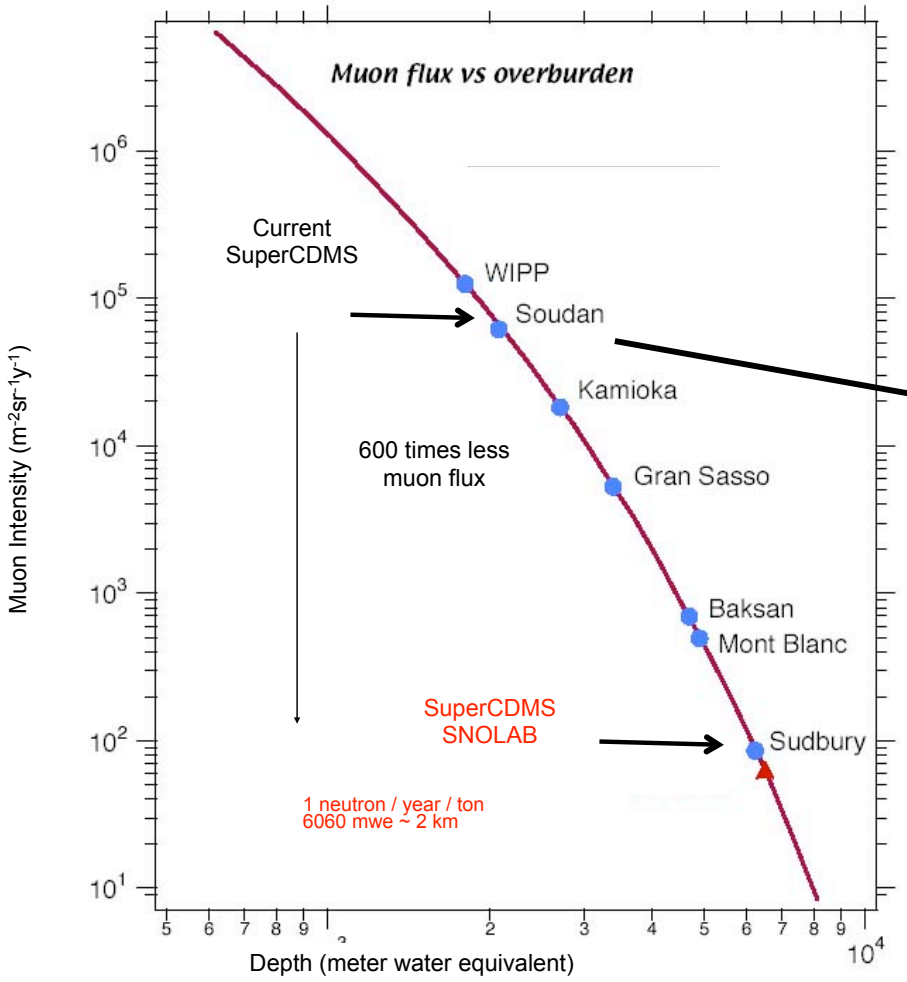




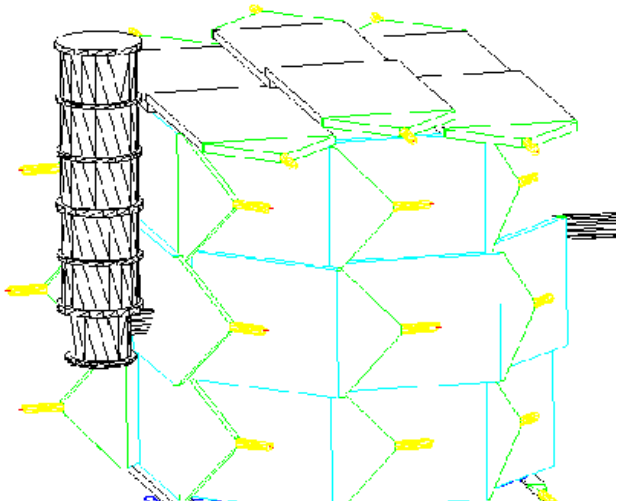
- **Data Run History:**

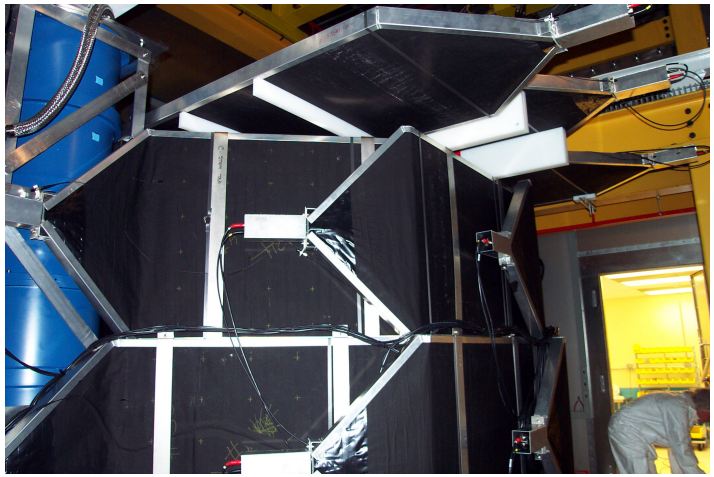


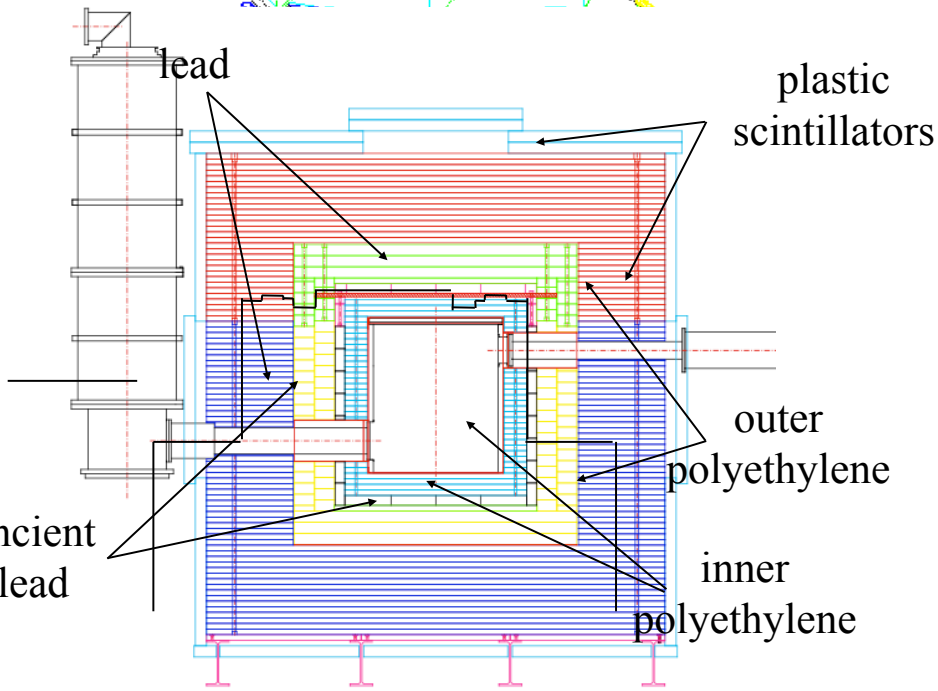
CDMS-II at Soudan (2090 mwe)



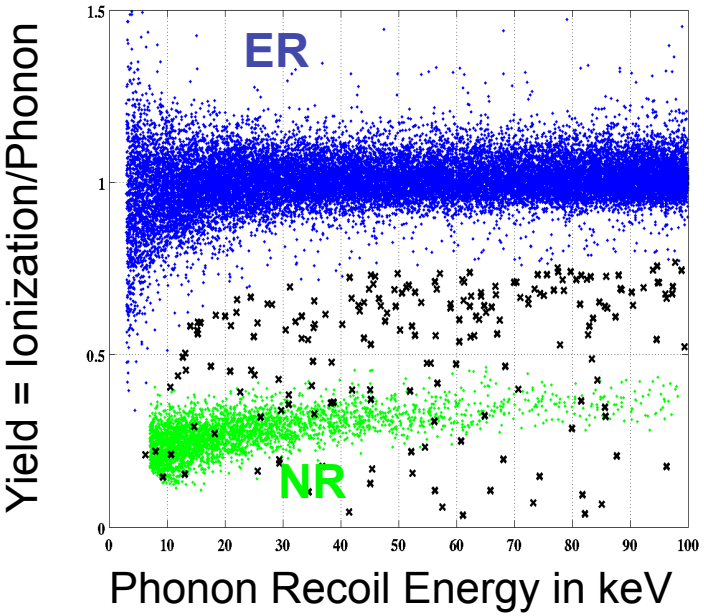
CDMS-II Soudan facility



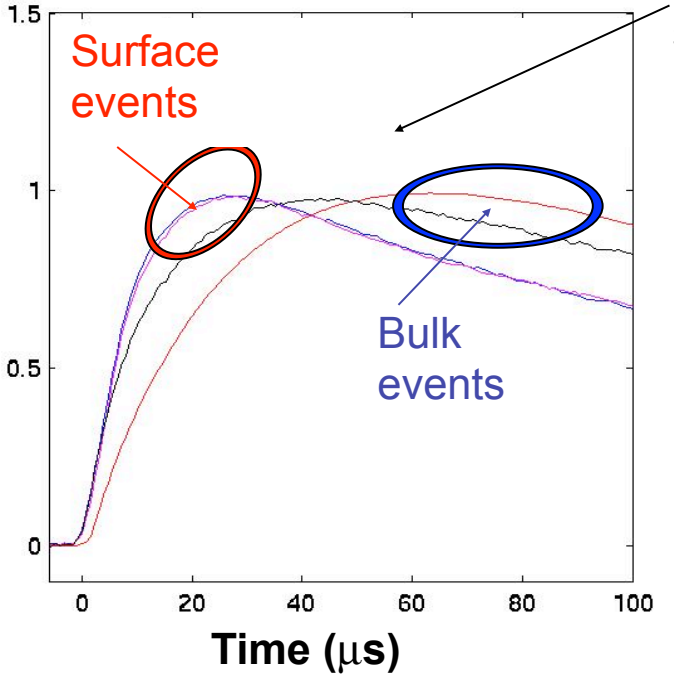




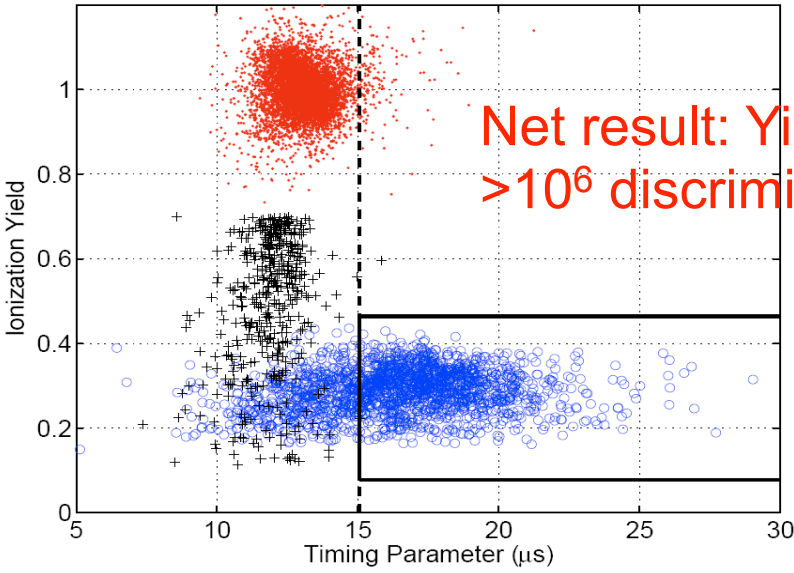
CDMS II Active Background Rejection



- Radioactive source data defines the signal (NR – neutrons from ^{252}Cf) and background (ER – gammas from ^{133}Ba) regions.
- Ionization Yield >10^4 Rejection of γ
- Ionization collection incomplete on surface. Yield can be sufficiently low to pollute the signal region



Faster down conversion of athermal phonons at surface provides faster phonon signal for β's



Net result: Yield + timing >10^6 discrimination.

DM SAG at P5

PHYSICS TODAY
February 2010

search & discovery

Underground detector yields tantalizing hint of dark matter

The dark matter that dominates the rotation and clustering of galaxies is thought to consist of heavy, weakly interacting particles not yet known but much sought after.

The cosmologists' widely accepted "concordance model" asserts that only about 15% of the mass of matter in the cosmos is baryonic—made of protons and neutrons. Most of the predominating nonbaryonic mass is presumed to consist of still unknown "dark-matter" particles without electromagnetic or strong nuclear interactions, but heavy enough to have been nonrelativistic in the early epochs of galaxy formation.

Just such weakly interacting massive particles (WIMPs) are predicted by most proposed extensions of particle theory's standard model. The leading WIMP candidate is the lightest of the many new species anticipated by the supersymmetry theories. Presumably created in the Big Bang, it could be stable and, with a mass something like 100 times that of the proton, abundant enough to account for the gravitational effects on the clustering and rotation of galaxies whose observation raised the dark-matter issue long ago.

In interactions with nucleons, WIMPs would have very small but nonvanishing elastic-scattering and production cross sections, comparable to those of the ordinary weak interactions. So particle-physics experimenters have been looking for the production of WIMP pairs in high-energy colliders. And on a more modest scale, they

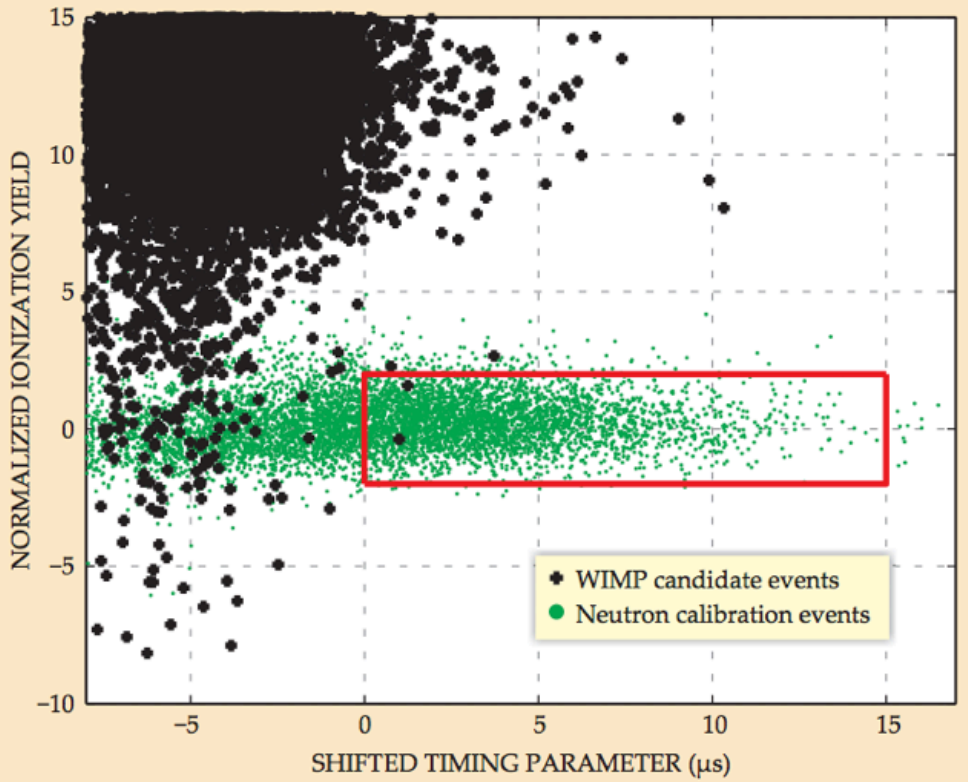


Figure 1. Ionization-yield and timing parameters for candidate WIMP-collision events that survived all prior event-selection cuts in the final year's exposure of the CDMS II dark-matter detector. The two parameters, described in the test, serve to weed out imposter events. Ionization yield is plotted in standard deviations from the mean for nuclear recoils, as measured with neutron collisions (green dots) in calibration exposures. The zero point of the timing parameter is shifted to its final cutoff value. In the signal region defined by the final cuts (red box), only two WIMP candidates survive. (Courtesy of CDMS.)

Maximum likelihood analysis points toward leakage surface electrons

CDMS II Results

Sciencexpress Report

11 February 2010 / Page 1 / 10.1126/science.1186112

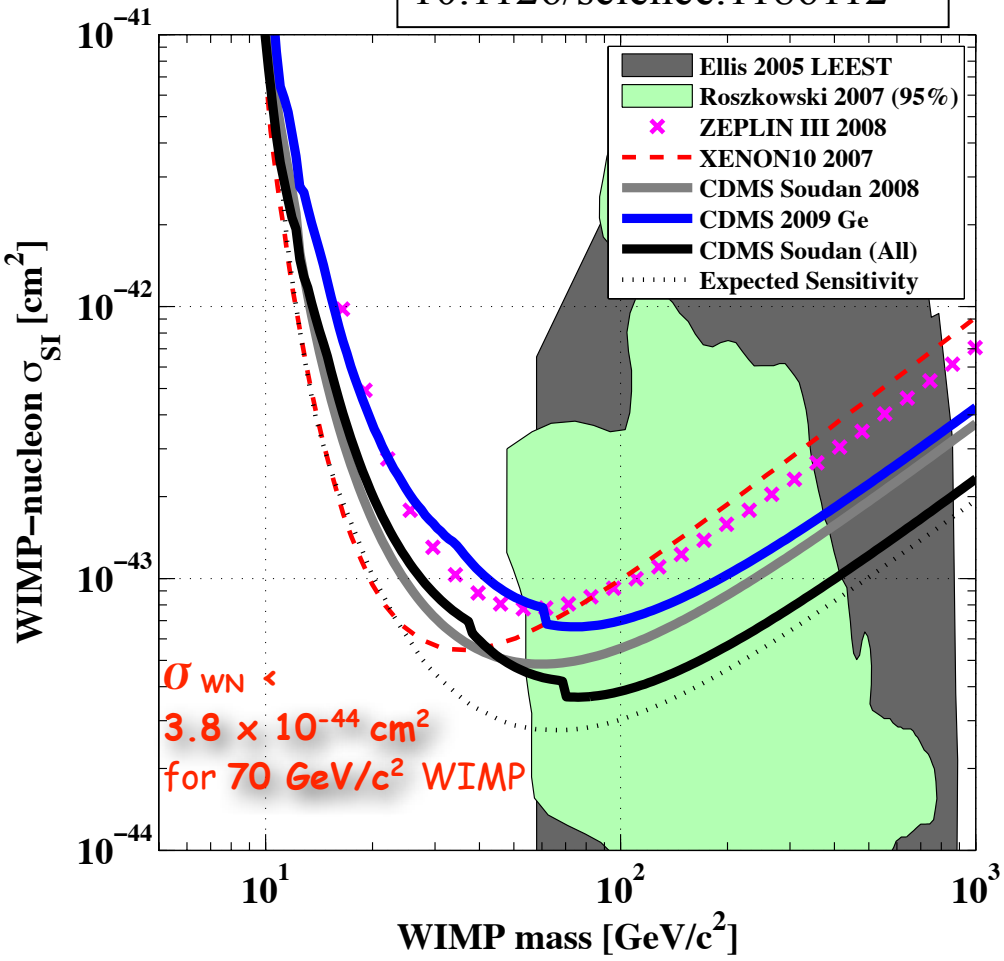
Dark Matter Search Results from the CDMS II Experiment

The CDMS II Collaboration*†

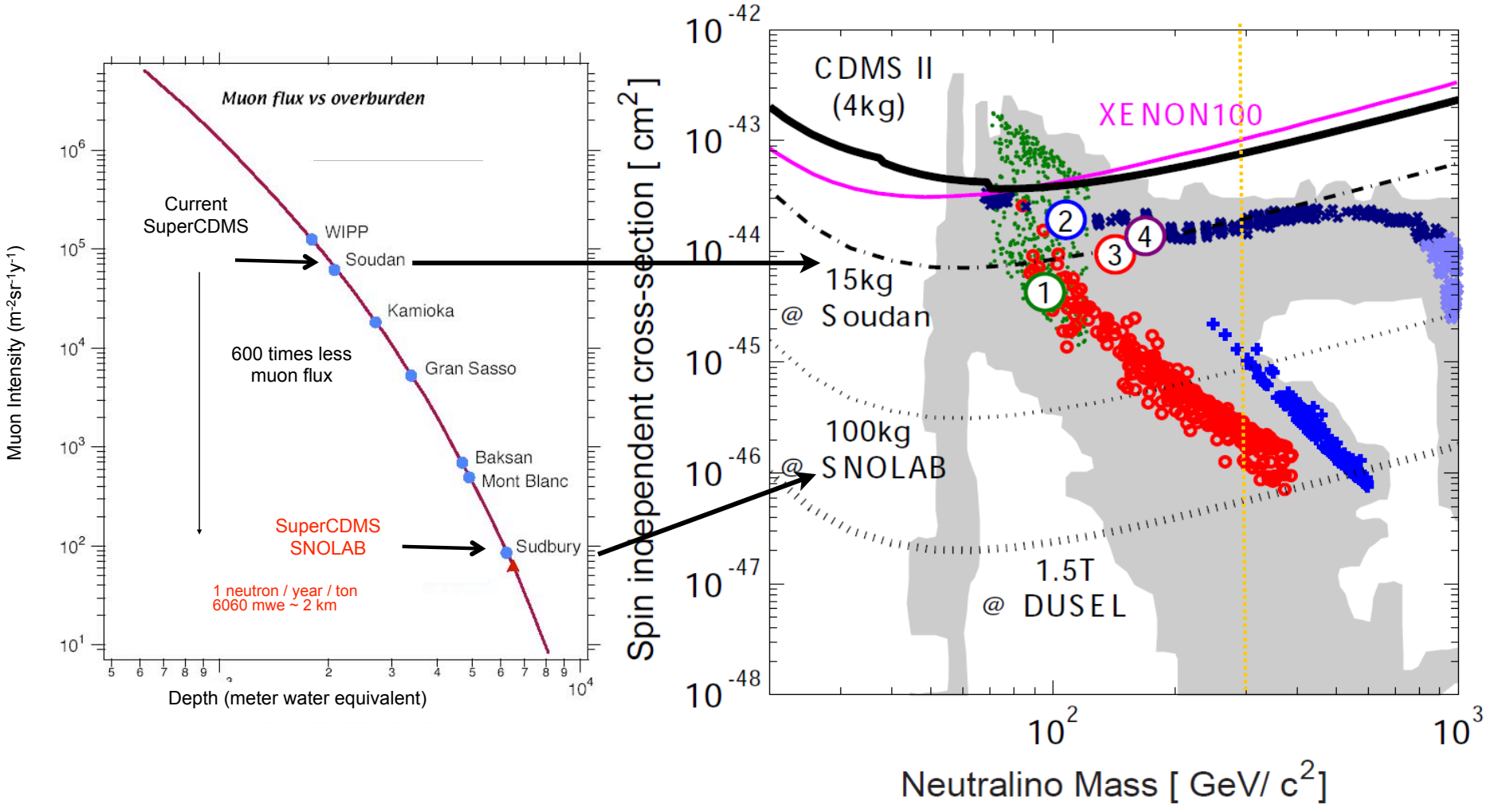
*To whom correspondence should be addressed: Jodi Cooley.

†All authors and their affiliations appear at the end of this pap

Astrophysical observations indicate that dark matter constitutes most of the mass in our universe, but its nature remains unknown. Over the past decade, the Cryogenic Dark Matter Search (CDMS II) experiment has provided world-leading sensitivity for the direct detection of Weakly Interacting Massive Particle (WIMP) dark matter. The final exposure of our low-temperature Ge particle detectors at the Soudan Underground Laboratory yielded two candidate events, with an expected background of 0.9 ± 0.2 events. This is not statistically significant evidence for a WIMP signal. The combined CDMS II data place the strongest constraints on the WIMP-nucleon spin-independent scattering cross section for a wide range of WIMP masses and exclude new parameter space in inelastic dark matter models.



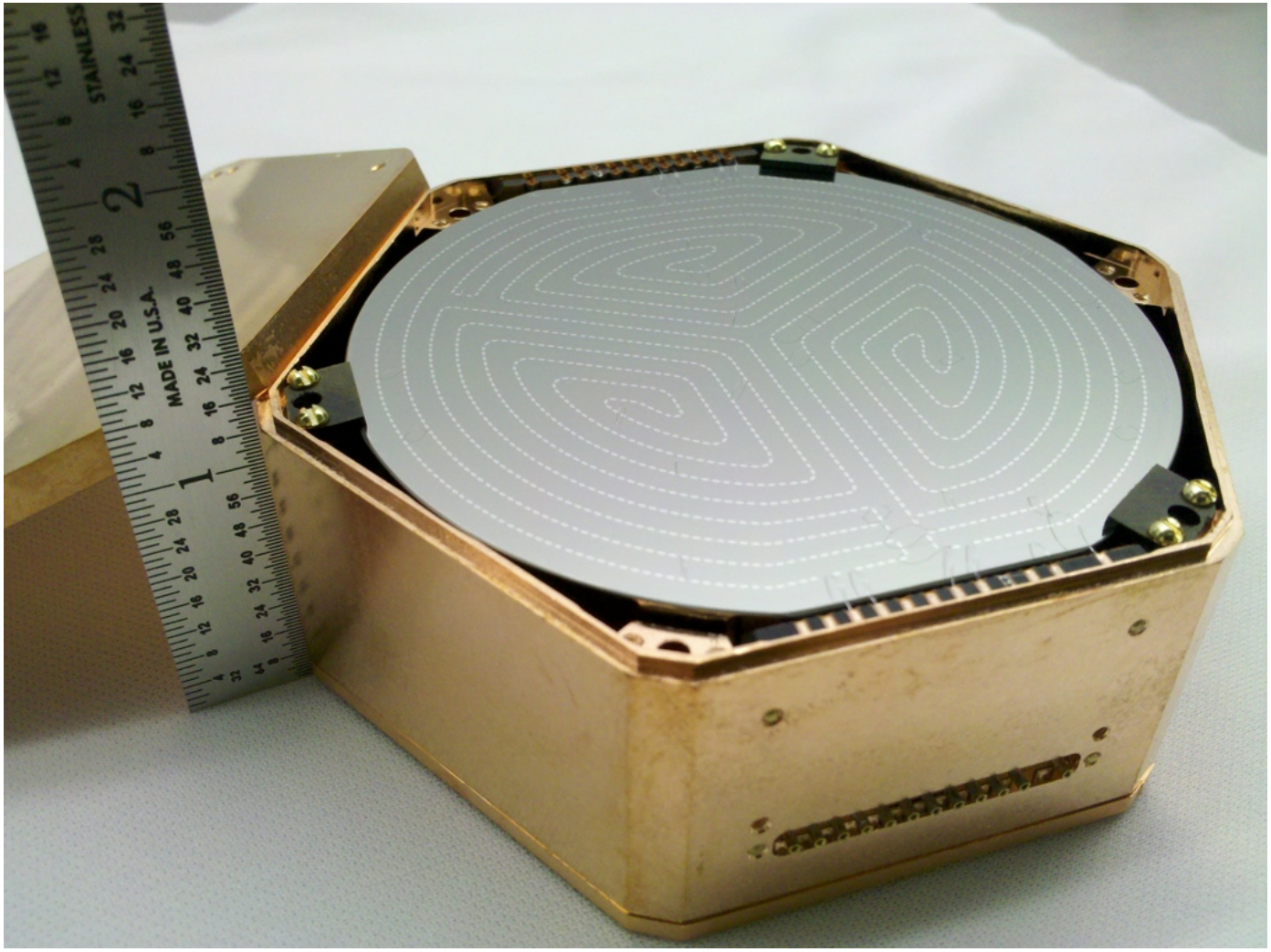
Status of Direction Detection Search



- Variety of techniques search for WIMP dark matter - interesting sensitivity
- Several have the potential to reach 10^{-44} cm^2 soon and 10^{-46} cm^2 in future

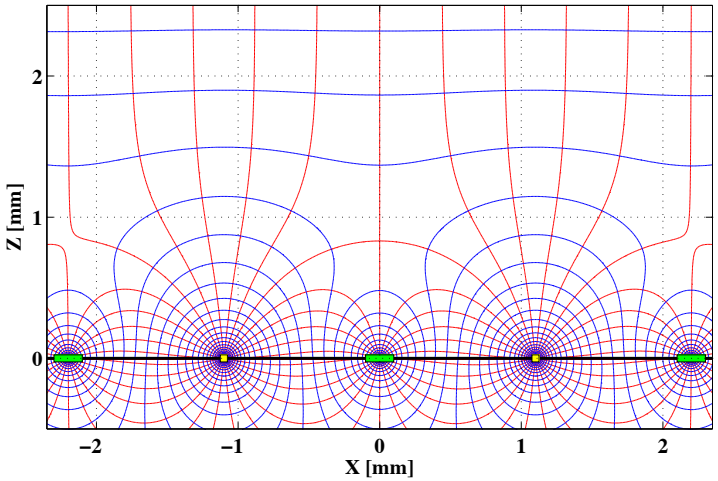
SuperCDMS Soudan iZIP Detectors

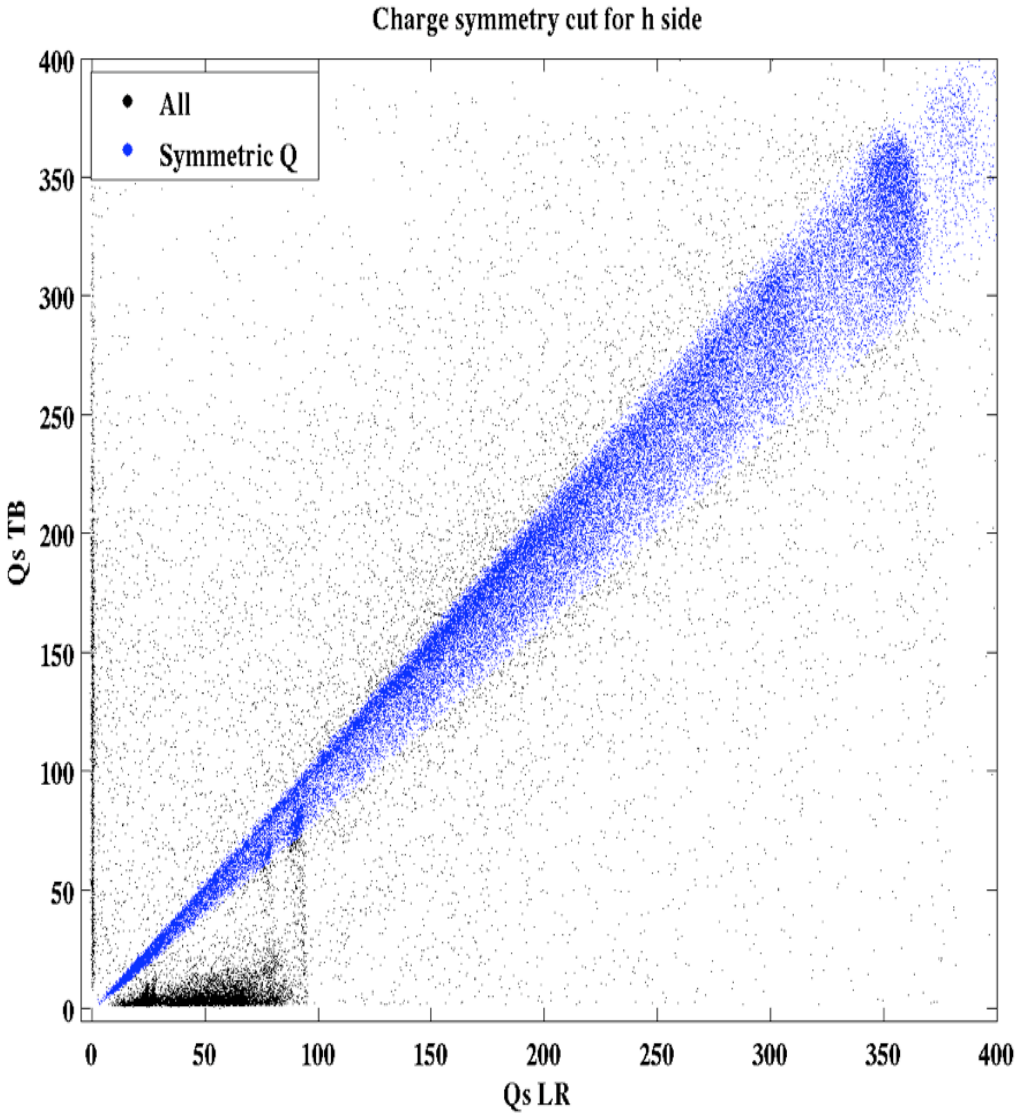
- Cool to within 0.05 degrees of absolute zero (-459.6 F)
- For each event simultaneously measure the charge produced and the heat produced.
- Allows us to tell if recoiling particle was an electron (backgrounds) or nucleus (WIMP and neutrons)
- Deep underground to avoid neutrons from cosmic ray activity



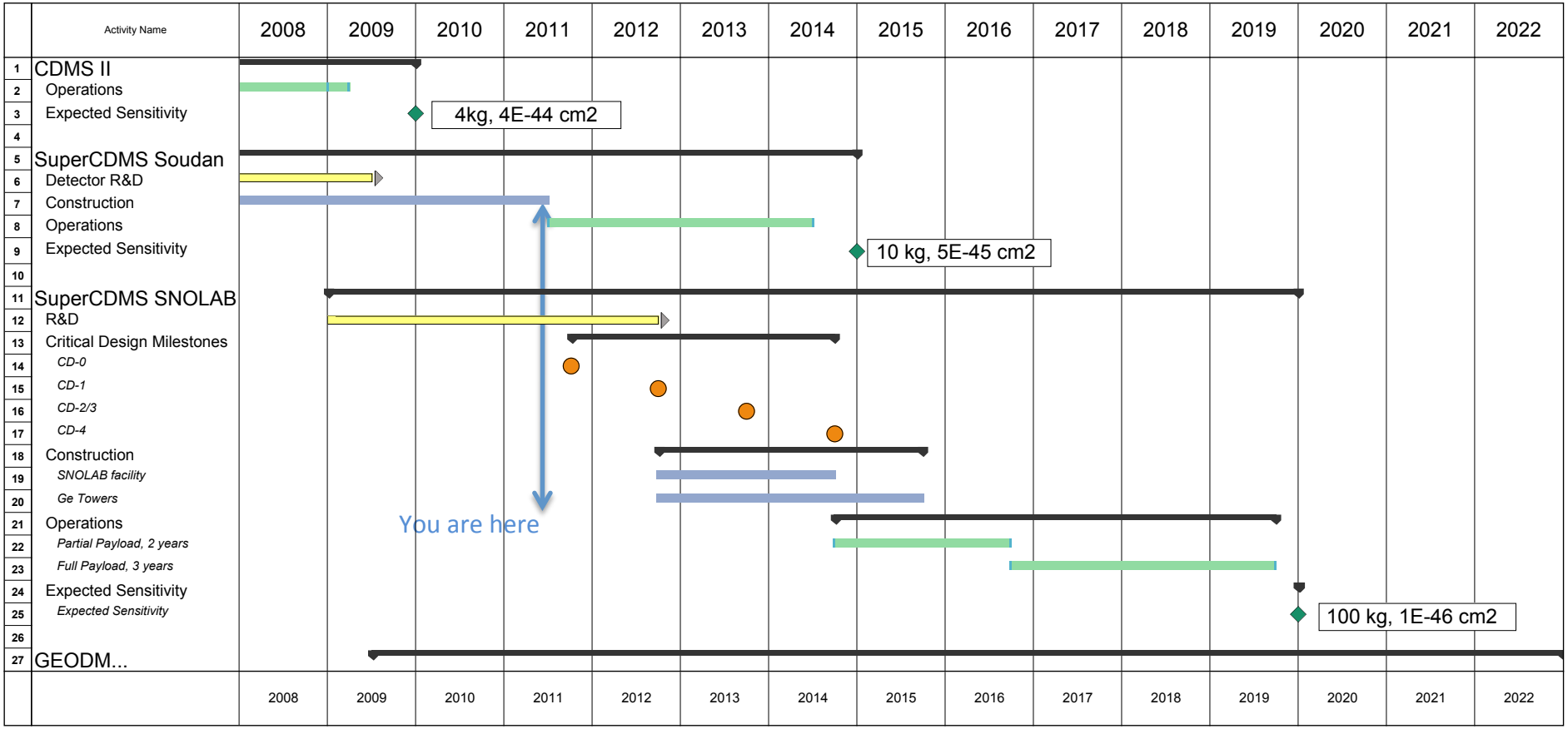
Advanced iZIP removes surface e background

- Interleaved charge and phonon lines provid extremely high rejection of surface electrons - so these no longer contribute to background only neutrons are significant

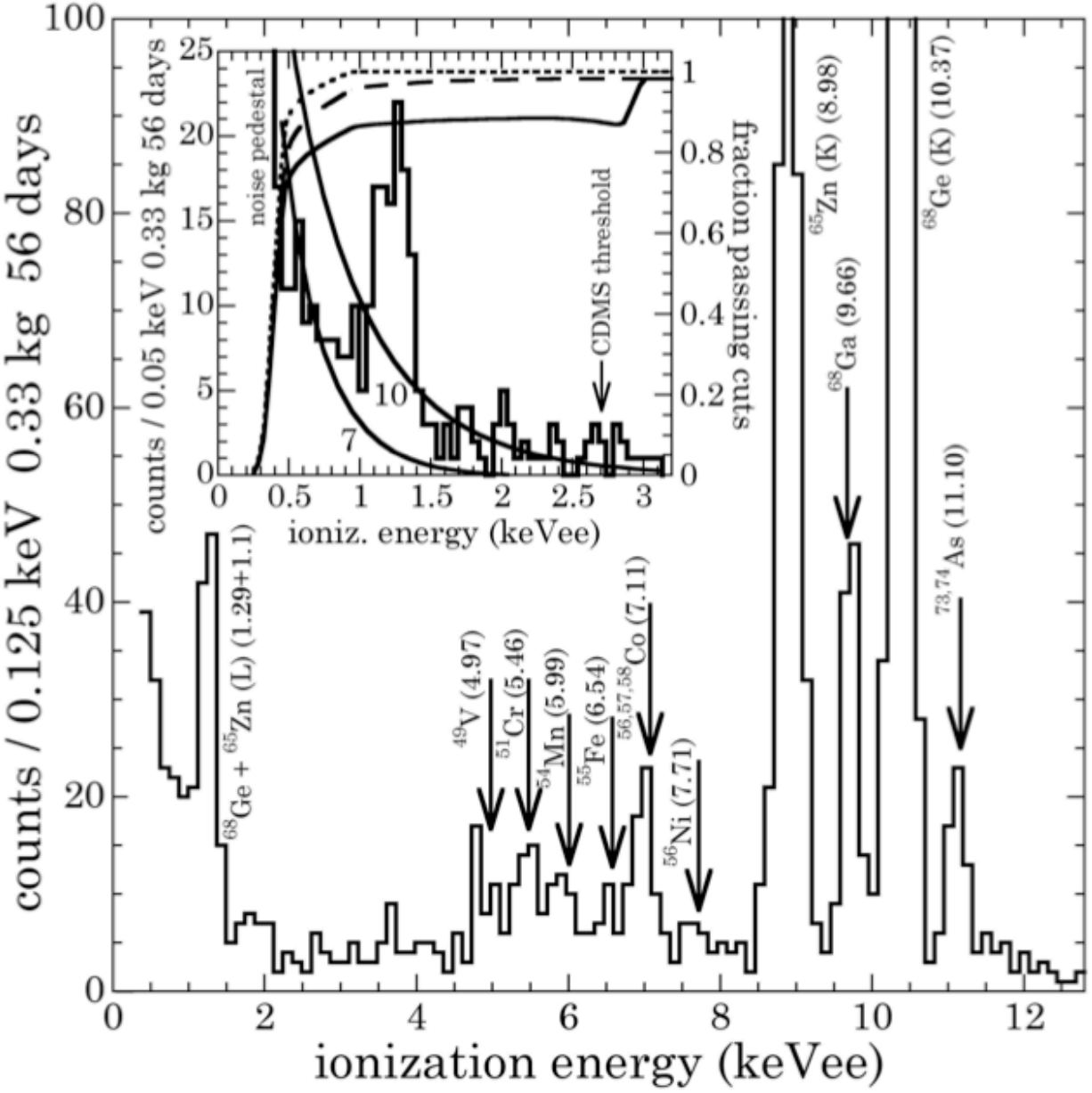




Overview of CDMS



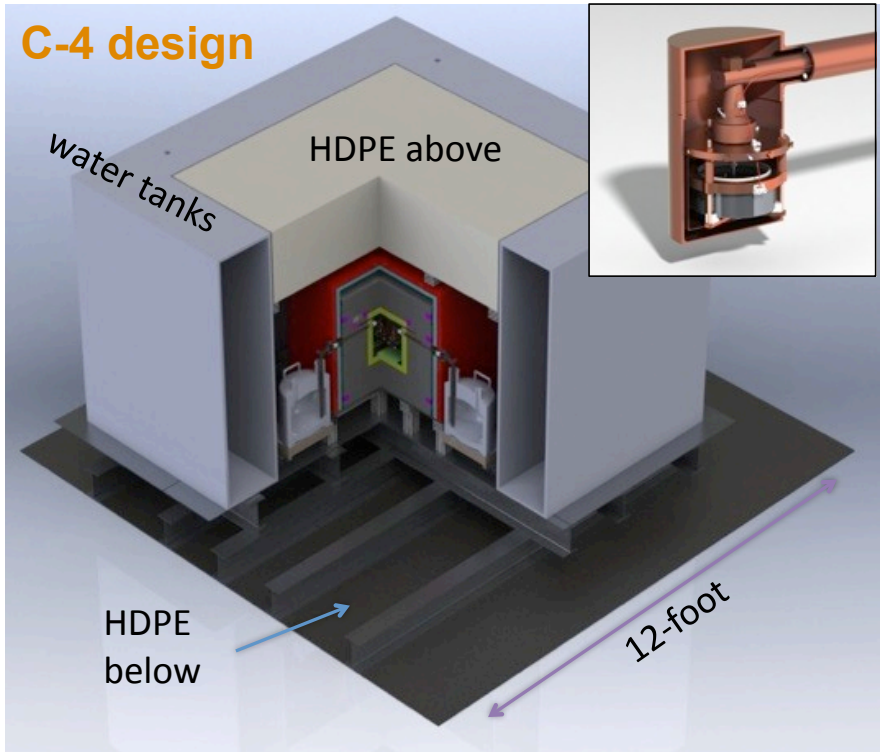
CoGeNT sees excess events at low energy

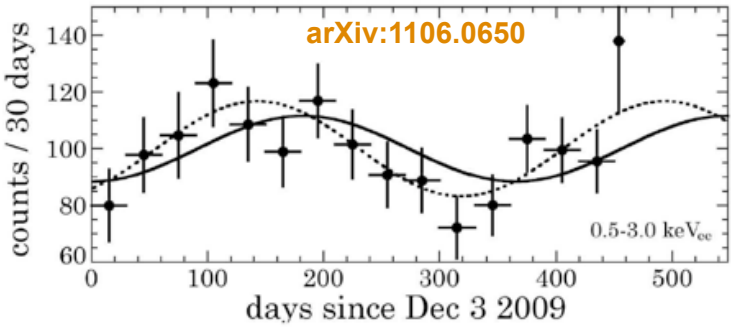


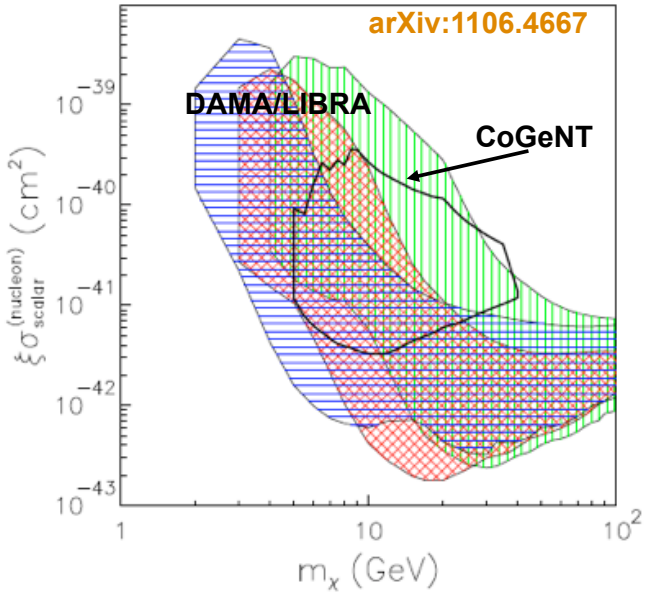
CoGeNT may see annual modulation

CoGeNT Present Status

- Annual modulation of unknown origin, measured with ~0.4 kg crystal at Soudan, in possible agreement with DAMA/LIBRA.
- C-4 to start end of 2011 in Soudan (x10 present mass, significant reduction in bckg and threshold expected).







DAMA/LIBRA

The second generation DAMA/LIBRA set-up ~250 kg ULB NaI(Tl)
(Large sodium Iodide Bulk for RAre processes)

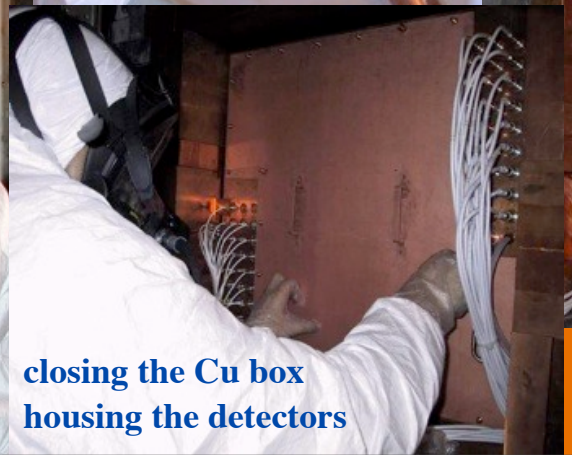
As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

installing DAMA/LIBRA detectors

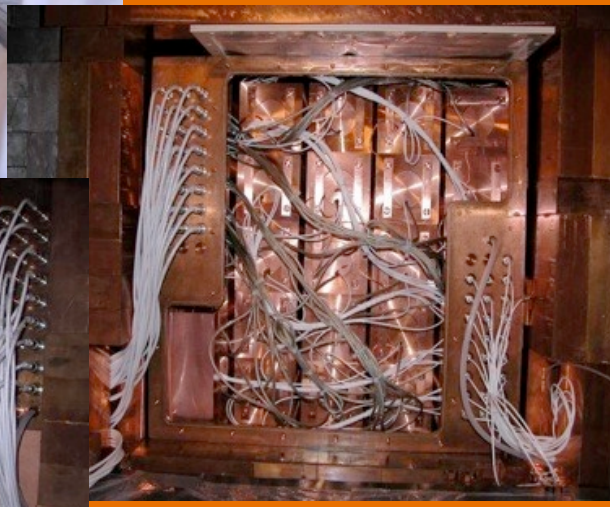
assembling a DAMA/ LIBRA detector

detectors during installation; in the central and right up detectors the new shaped Cu shield surrounding light guides (acting also as optical windows) and PMTs was not yet applied

filling the inner Cu box with further shield

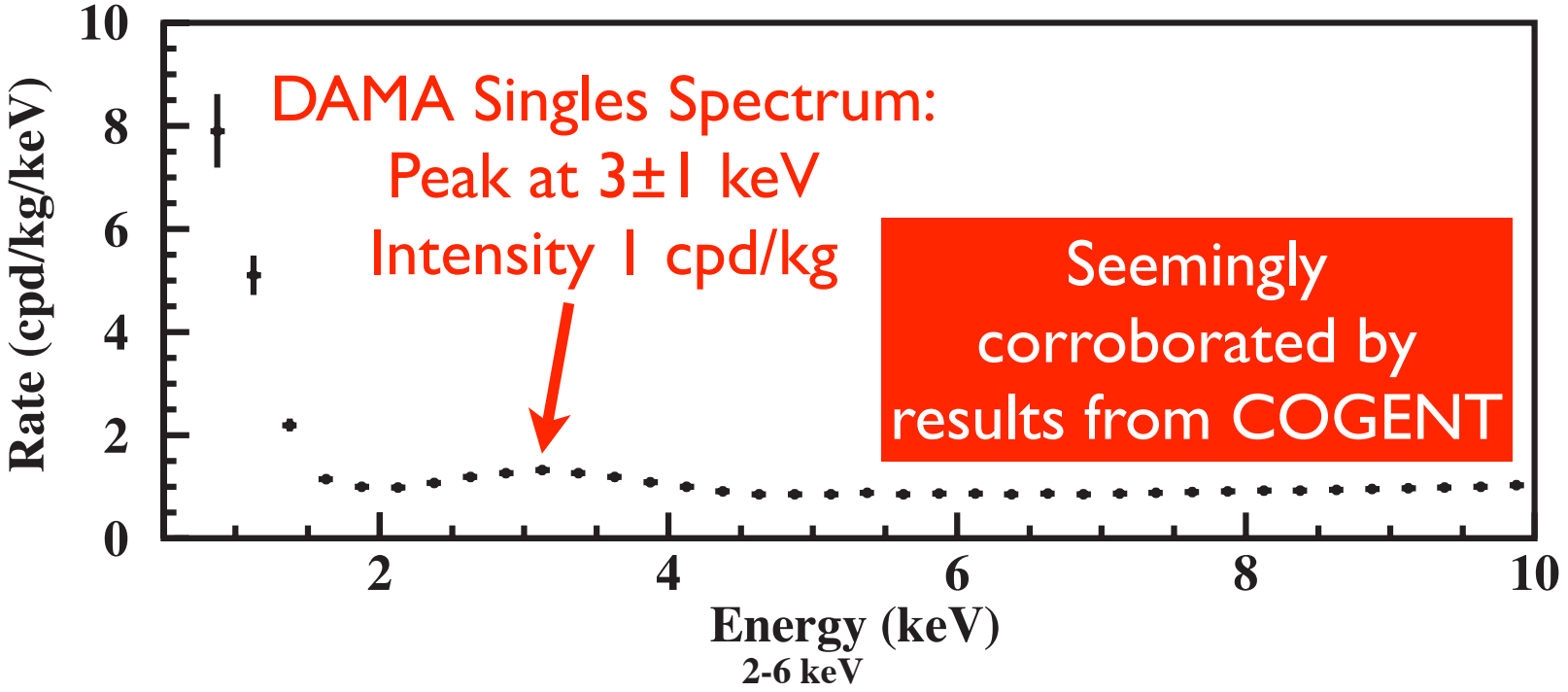


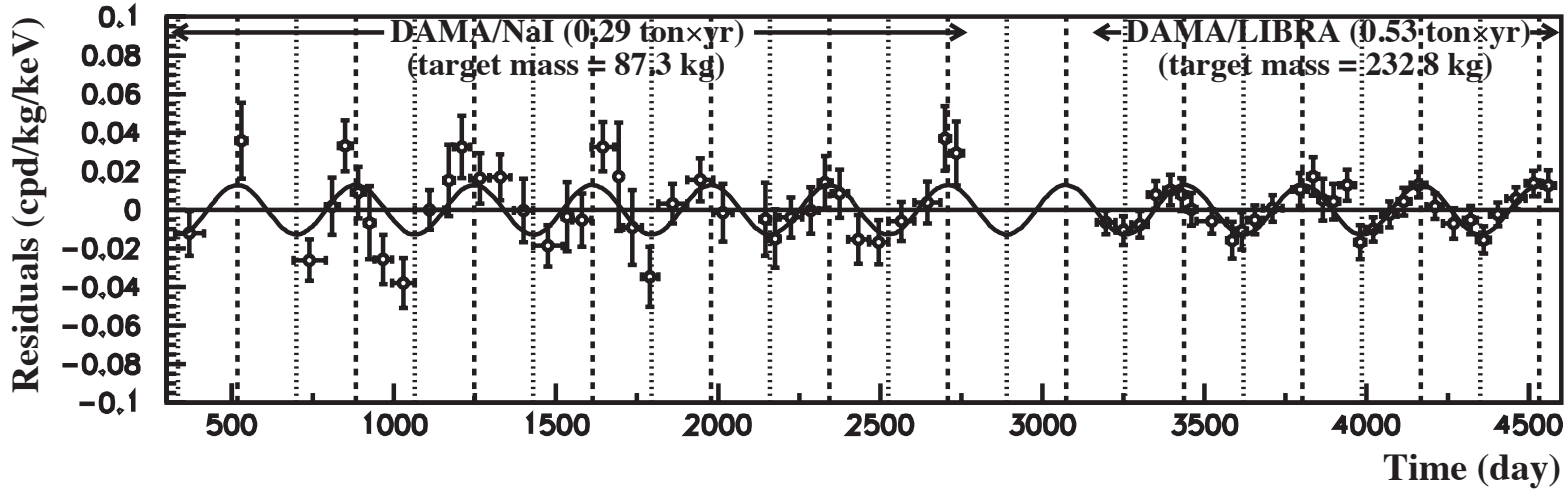
closing the Cu box housing the detectors



view at end of detectors' installation in the Cu box

DAMA annual modulation signal

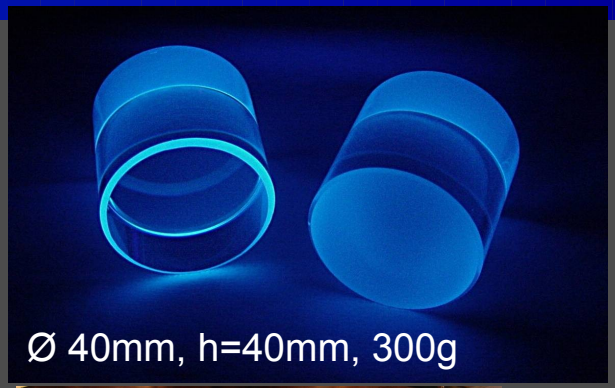




CRESST at Princeton DM Nov 2010

Recent Results from the CRESST Dark Matter Search

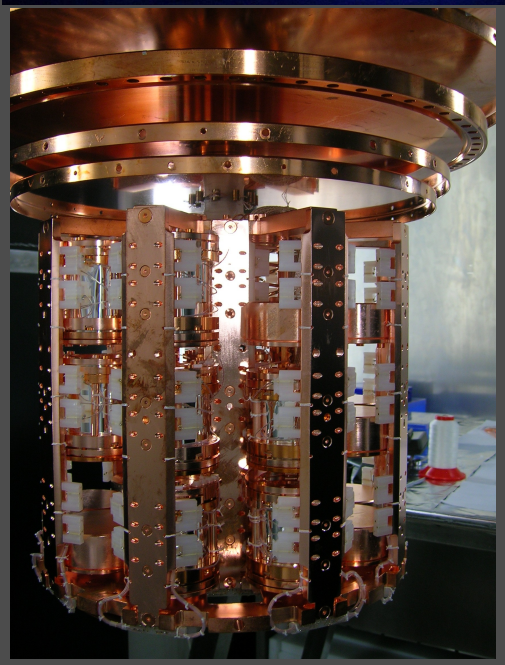
Collaboration
MPI für Physik, Oxford University, TU München, Universität Tübingen
Laboratori Nazionali del Gran Sasso



Cryogenic Dark Matter search

Located in LNGS

Scintillating $CaWO_4$ target crystals

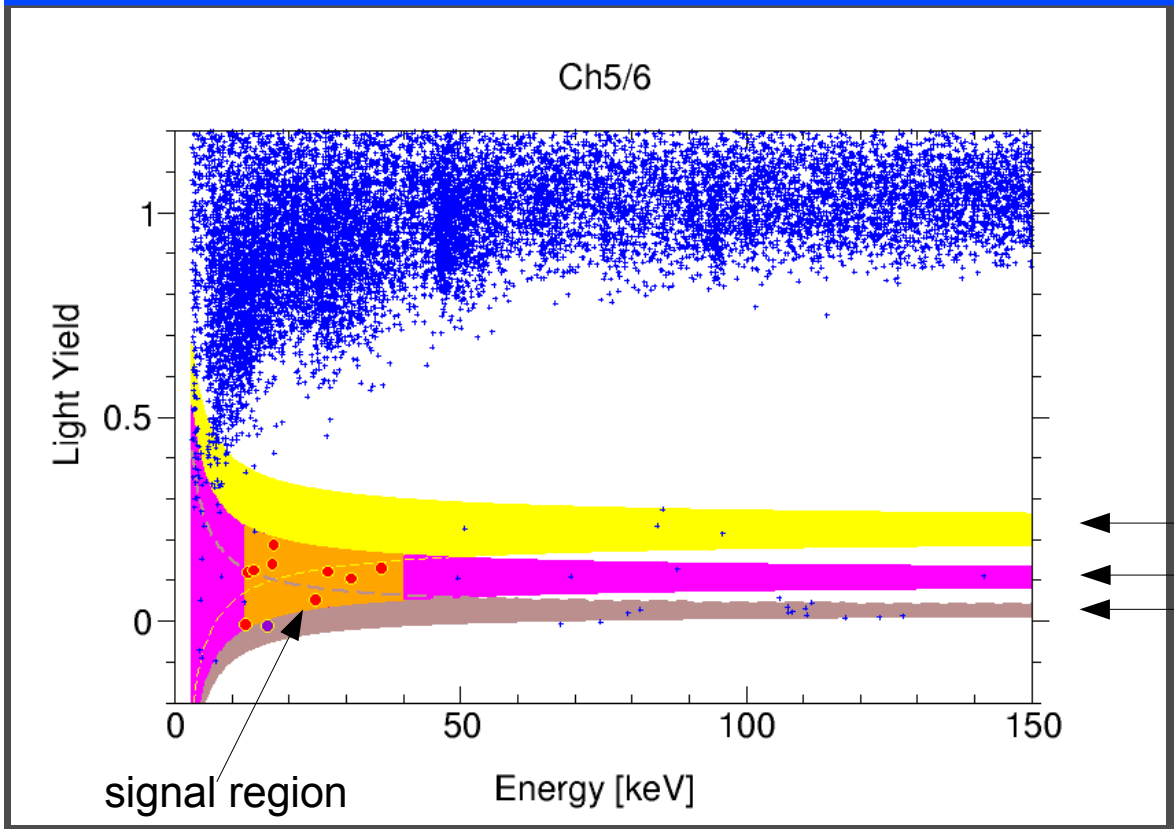


Up to 33 crystals in modular structure (10 kg target mass)

Multi target approach via different nuclei in $CaWO_4$ crystals

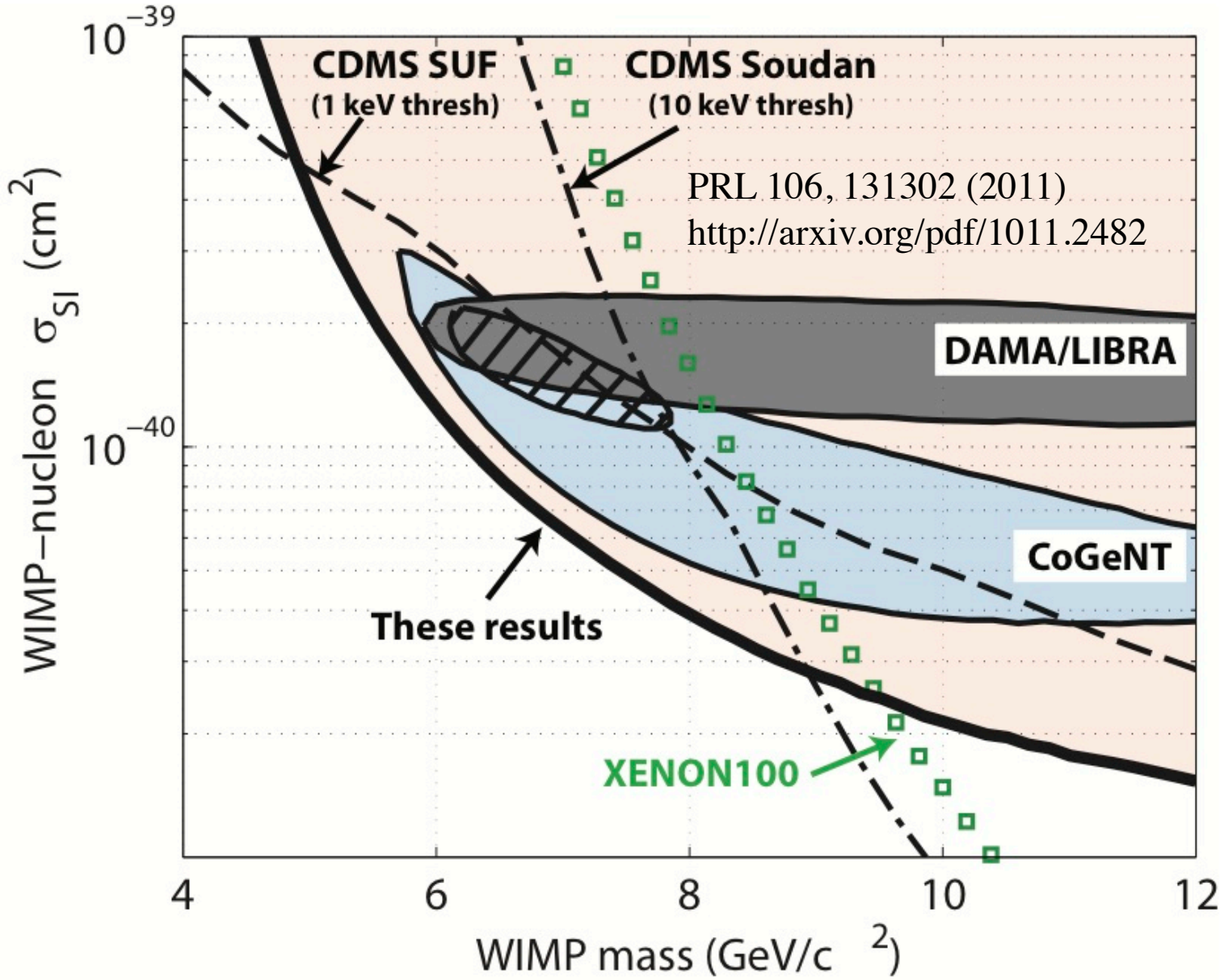
Unexplained events in Oxygen band

Data of single detector module

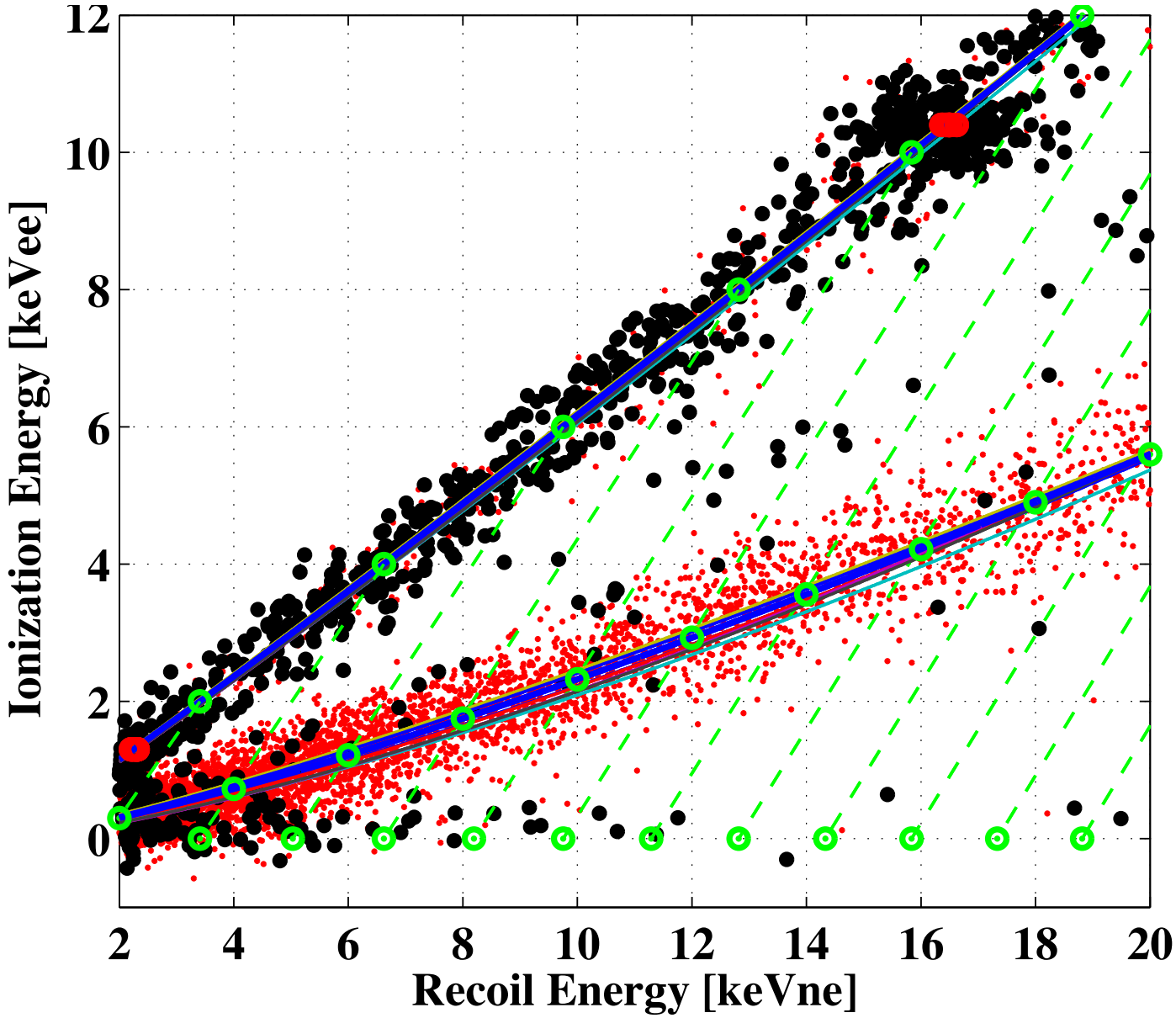


Clear signals in oxygen recoil band in signal energy range

CDMS excludes CoGeNT light WIMP signal

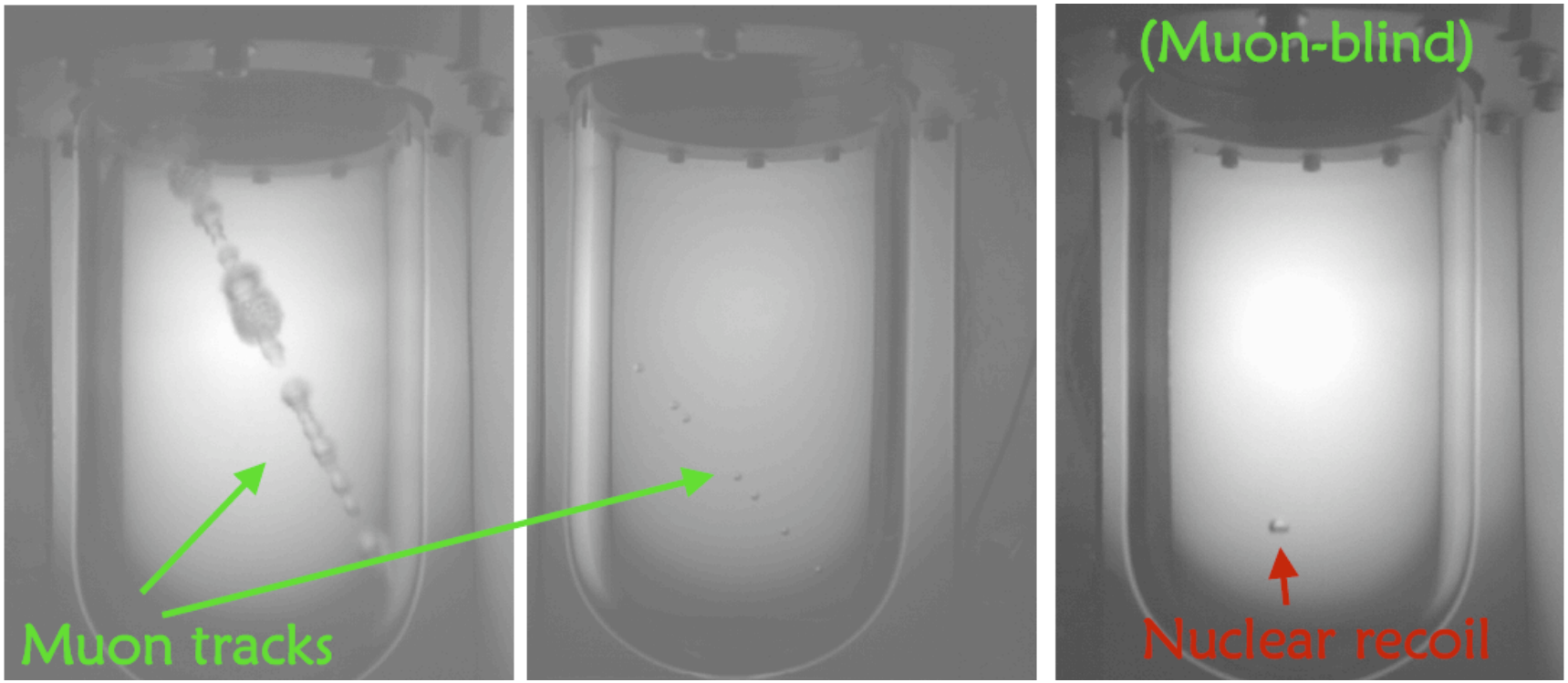


CDMS low threshold phonon only analysis



Control Nucleation Rate and Triggering

In HEP applications, bubble chambers stable for ~ 10 ms.
Surface and bulk spontaneous nucleation rates reduced.



Decreasing superheat

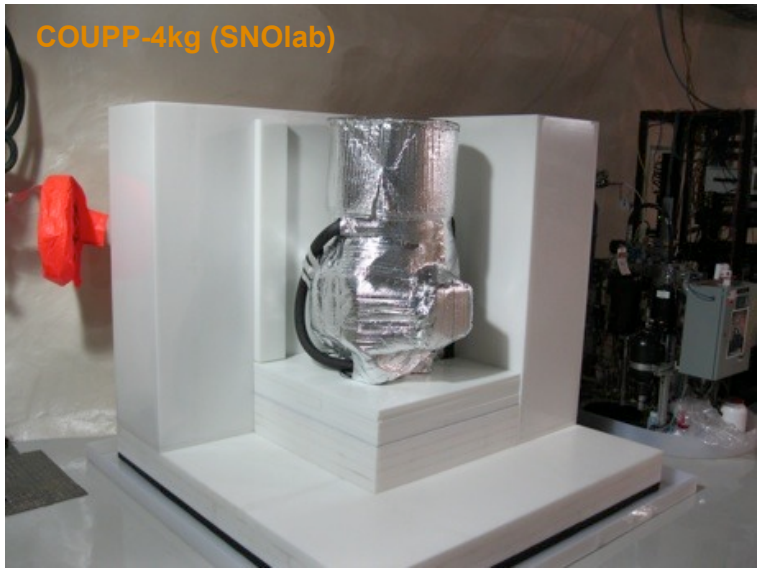
Intrinsic γ rejection >10^{10} at 10 KeV threshold

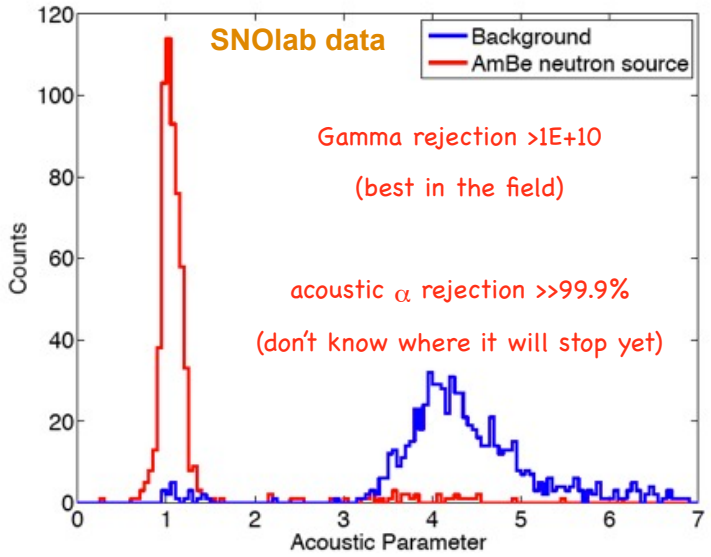
Muon tracks only visible with high superheats

Operate at low superheat → MIP blind 1 nuclear recoil = 1 bubble

COUPP Present Status

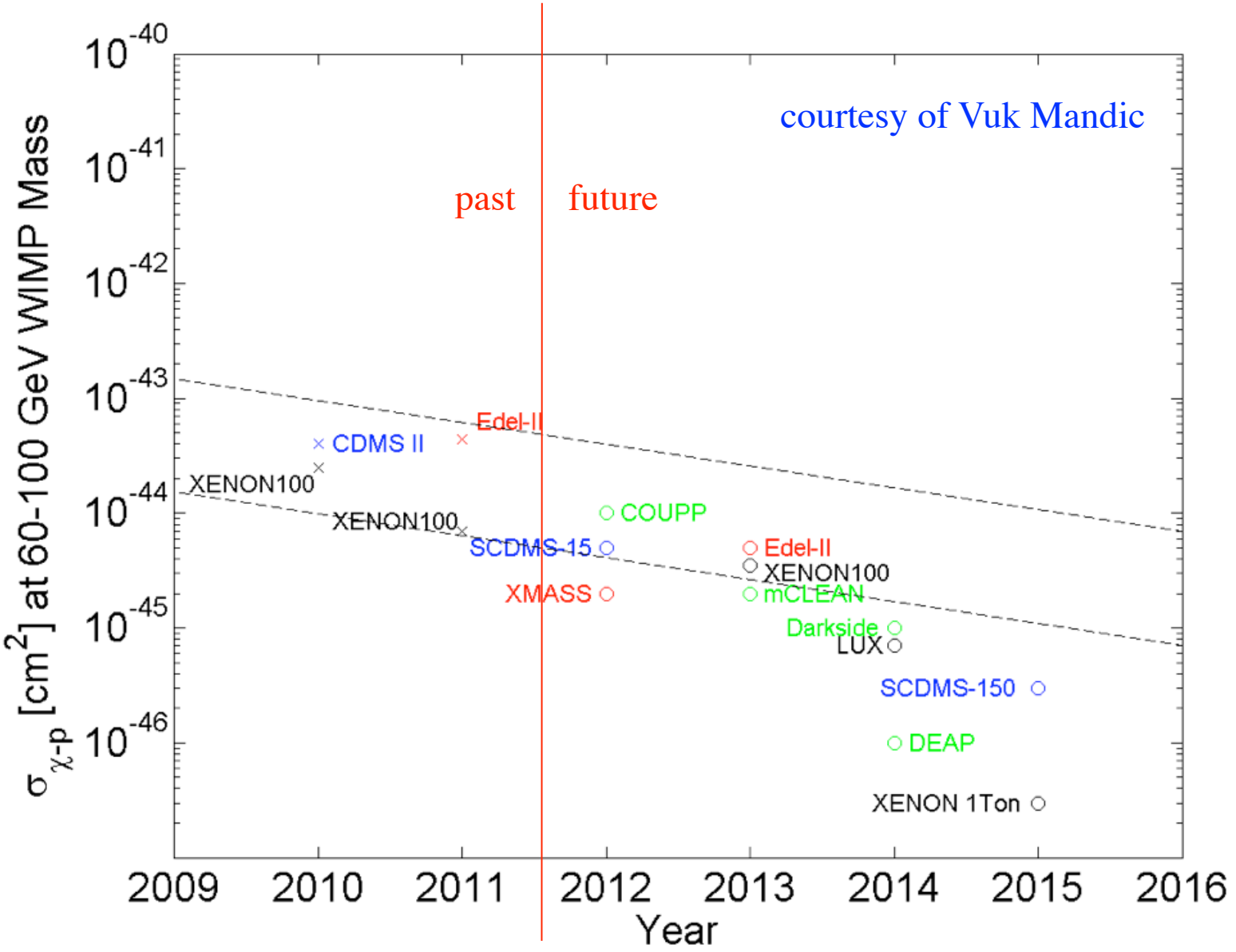
- 4 kg chamber taking data at SNOlab.
- Weak (α,n) sources identified and in the process of elimination.
- Excellent acoustic discrimination against alphas demonstrated.
- 60 kg chamber to be installed at SNOlab during 2011.





Recent WIMP Search Limits

from Mandic



Conclusion

- Experiments now in most exciting region for neutralino as dark matter in many models of supersymmetry (mSUGRA)
- XENON100 now leads field by x3 at high mass with 3 events in signal region. Plans progressing for XENON1T.
- LUX, Darkside, DEEP, CLEAN and COUP progressing as well.
- SuperCDMS Soudan will operate 10 kg of Ge starting late 2011 and run for two years improving sensitivity by x3. SuperCDMS SNOLAB with iZIP detectors totaling 100 kg is in R&D phase with plans to start operations in SNOLAB by 2015 will improve sensitivity by an additional x10.
- We have a great horse race for discovering WIMPs. Strong science case for ton scale direct detection major projects, as endorsed by Dark Matter SAG , P5 and PASAG.