Direct Detection of Dark Matter

The Fermilab experimental program in a local, national and worldwide context

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FCPA Retreat

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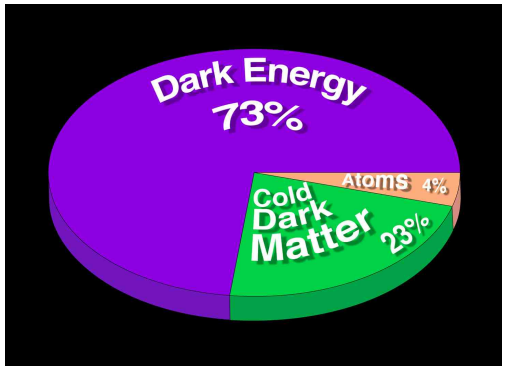
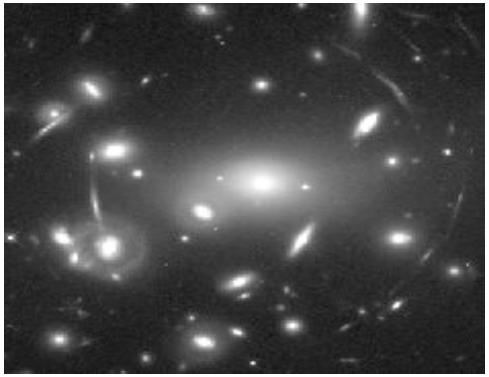
What is Dark Matter?

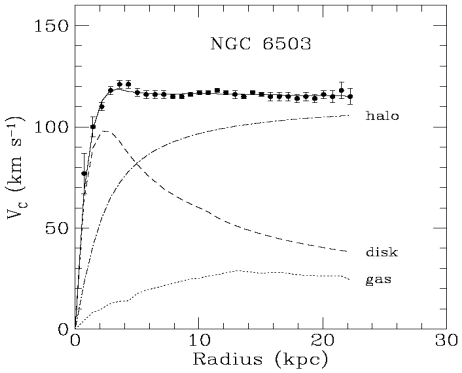
Galaxy Clusters

We know the Dark Matter is
stable / non-baryonic / non-relativistic / interacts gravitationally



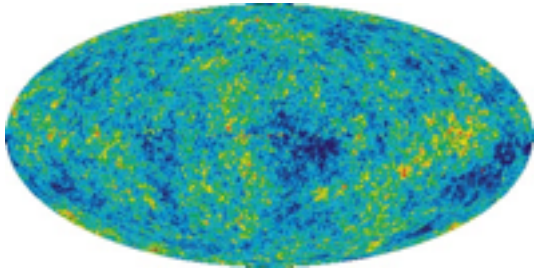


Strong Lensing



Galaxy Rotation Curves

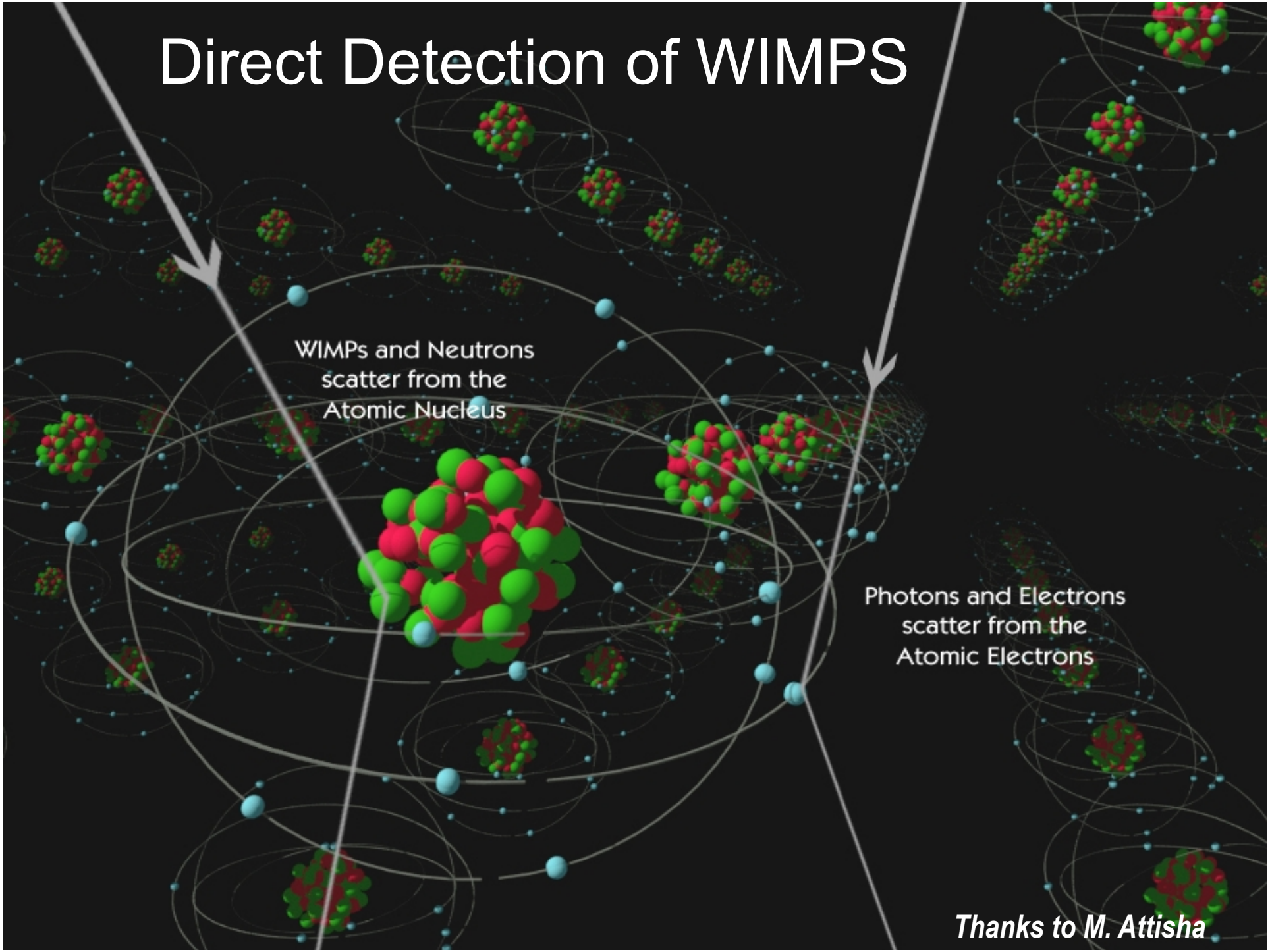
We don't know its
mass / coupling / spin / composition / distribution in our galaxy…



Cosmic Microwave Background

Best candidate for Dark Matter: Weakly Interacting Massive Particles (WIMPs)

Direct Detection of WIMPS



Thanks to M. Attisha

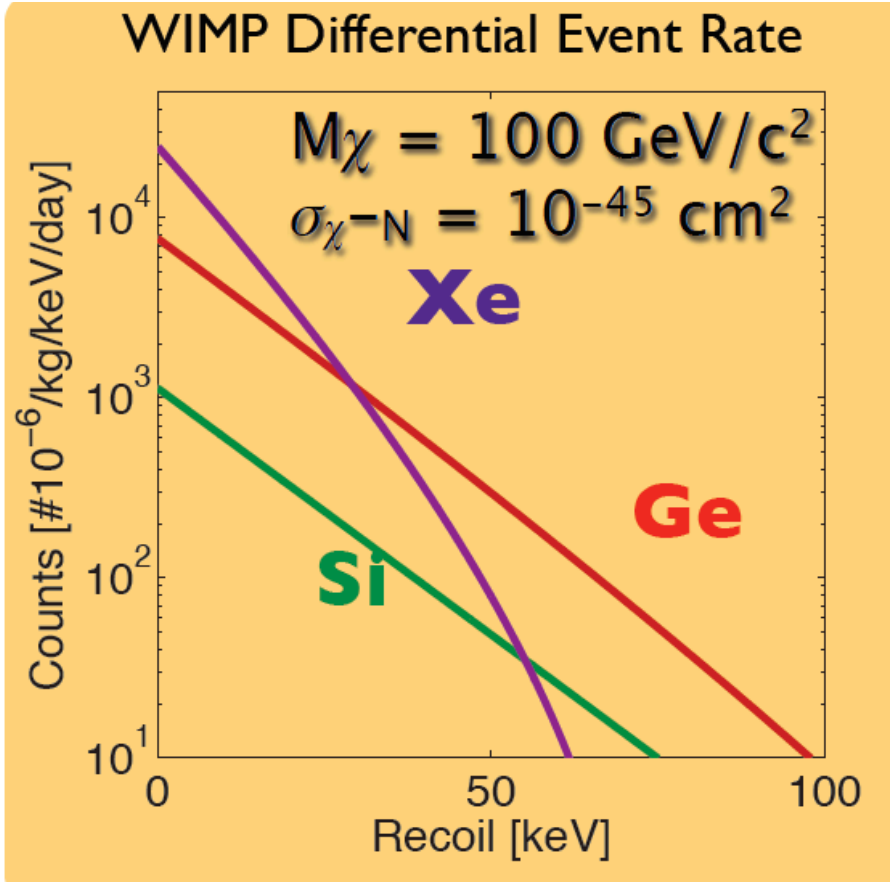
The Experimental Challenge

Expected WIMP signal:

- Exponential recoil spectrum: ~1-100 keV
- Rates <0.1 events /kg/day
- Nuclear form factors important

Experimental Requirements:

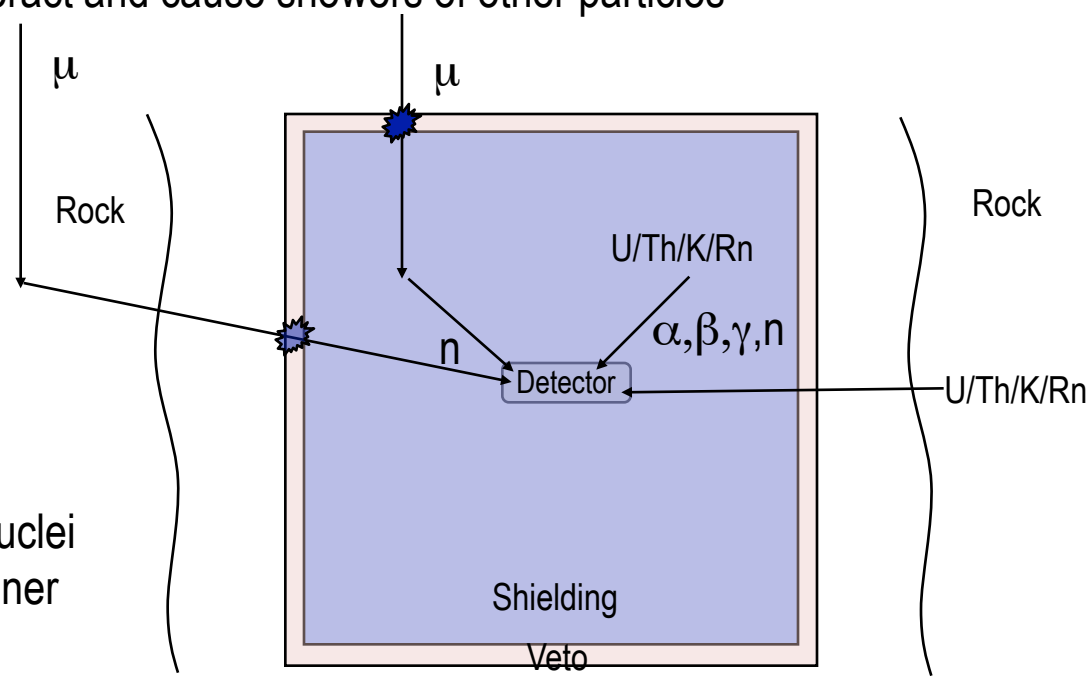
- Low energy thresholds (~1 keV)
- Mitigation of natural radioactive background
- Discrimination of nuclear from electron recoils
- Go deep underground to avoid cosmics
- Long exposures (target mass x livetime)



What are the backgrounds?

Cosmic rays

High energy particles from space hit the atmosphere and produce muons which can interact and cause showers of other particles



Neutrons

These interact elastically with nuclei in the same manner as WIMPS

Radioactivity

Long-lived isotopes of natural uranium, thorium, potassium produce α, β, γ, n

How do we guard against these backgrounds?

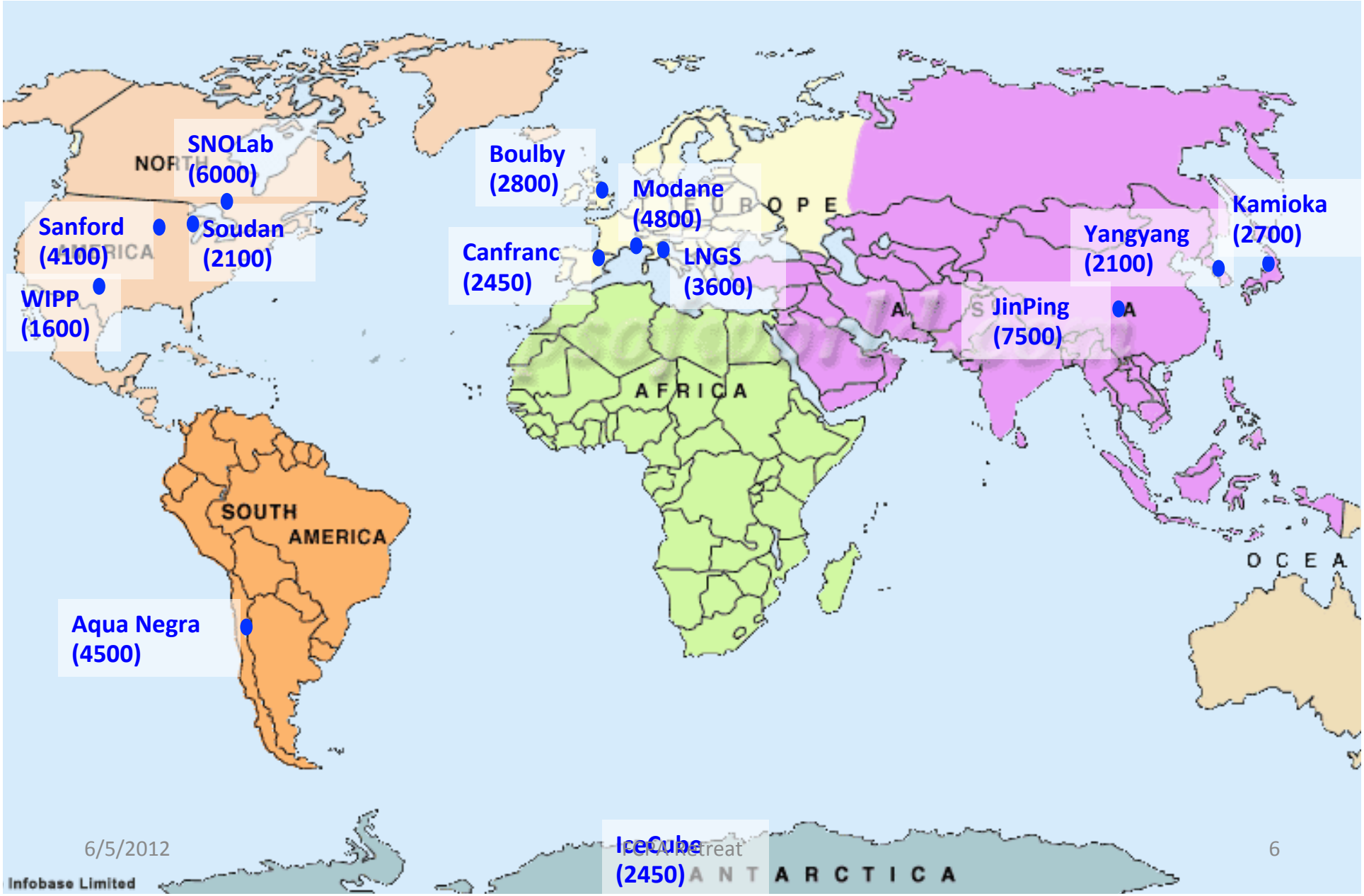
Layered shielding to reduce rate of normal particles hitting detectors

Lead, copper effective against alpha, beta, gamma rays

Plastic and Water moderate neutrons from radioactivity

Active veto and deep underground laboratories to reduce cosmic rays

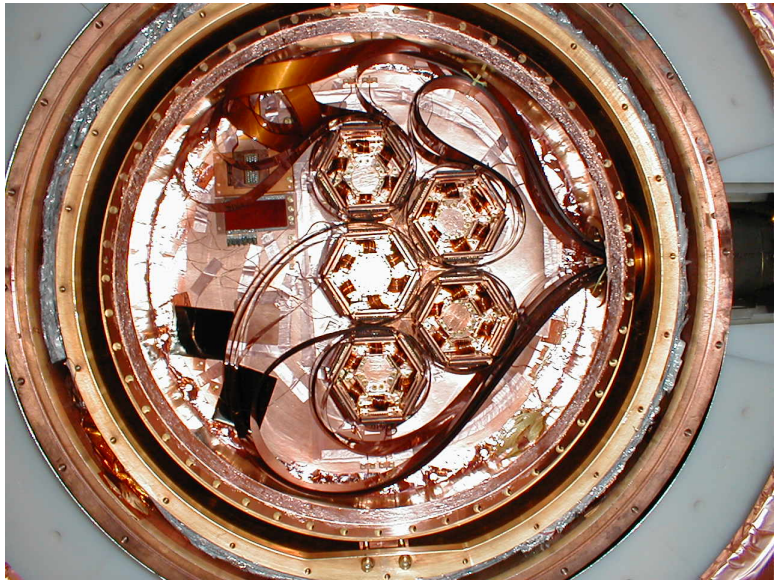
Underground Laboratories



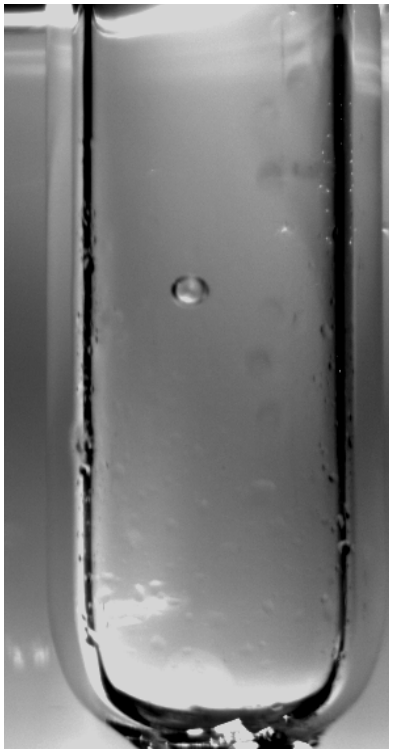
The Fermilab Direct Detection Suite

Many different technologies to reject backgrounds

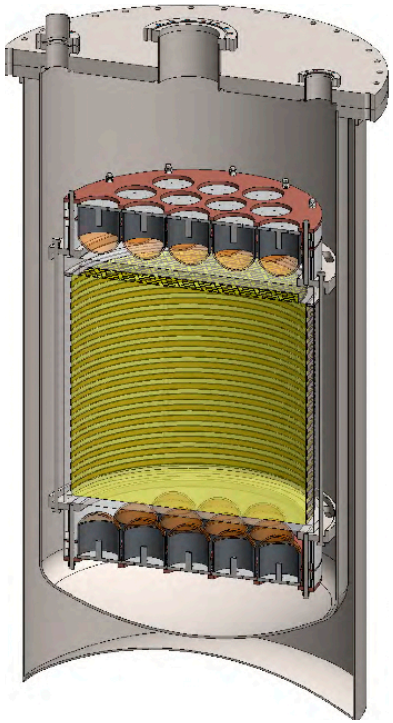
CDMS (cryogenic Ge)



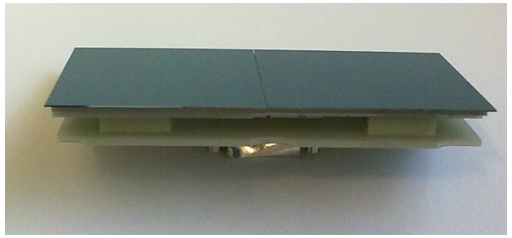
COUPP (Bubble Chamber)



DarkSide (LAr TPC)

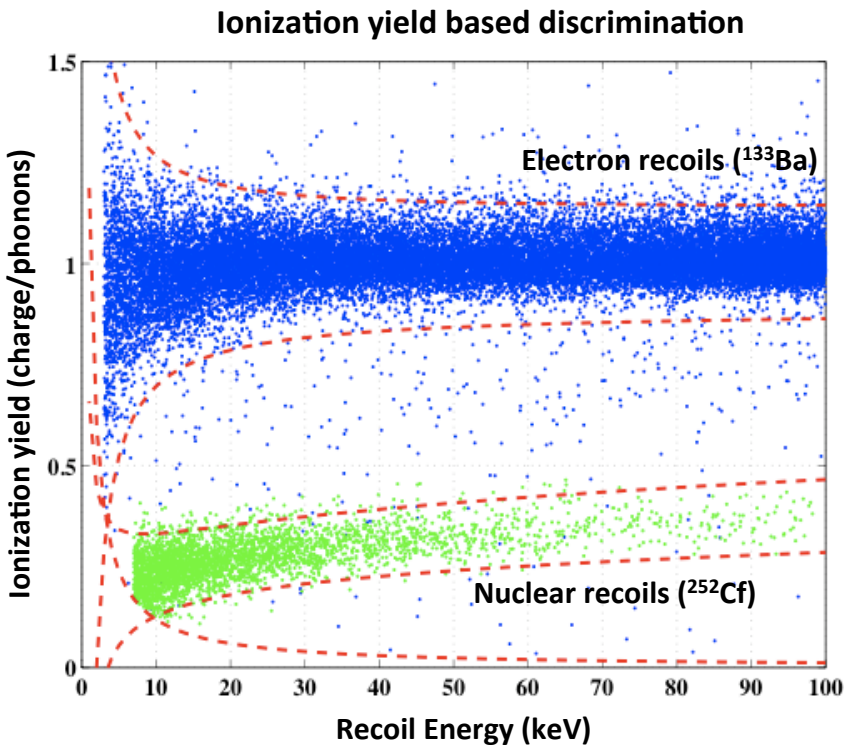


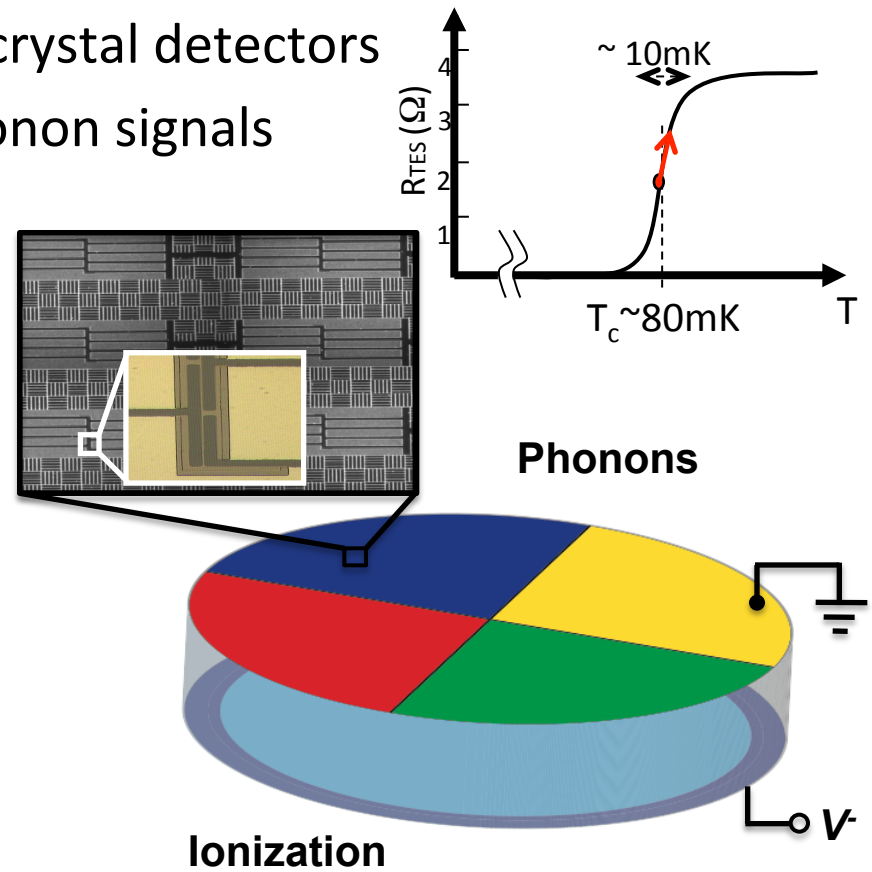
DAMIC (CCDs)



CDMS Technology

- Measure both phonons and ionization for each particle interaction in cryogenic Ge crystal detectors
- Ratio and timing of ionization to phonon signals used to identify nuclear recoils





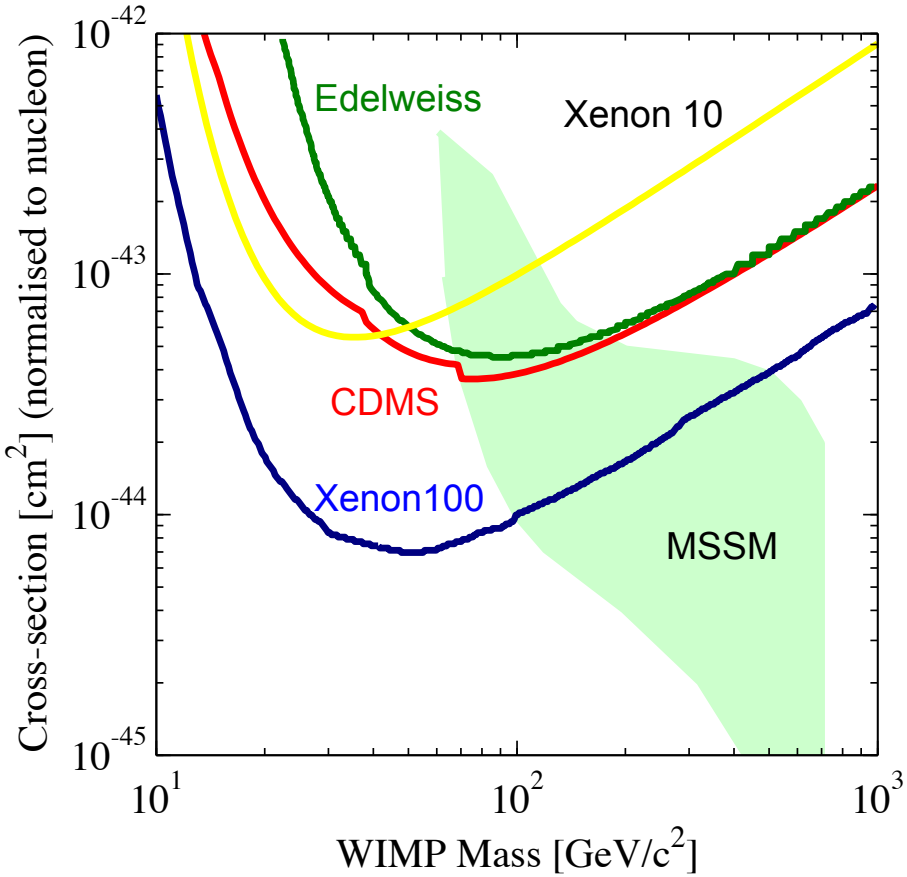
CDMS II – The Past

CDMS II background limited by two surface events in Dec 2010.

Still better than Xenon 10 for masses > 40 GeV. Upper limit at the 90% C.L. on the SI WIMP-nucleon cross-section is **3.8×10^{-44} cm^2**

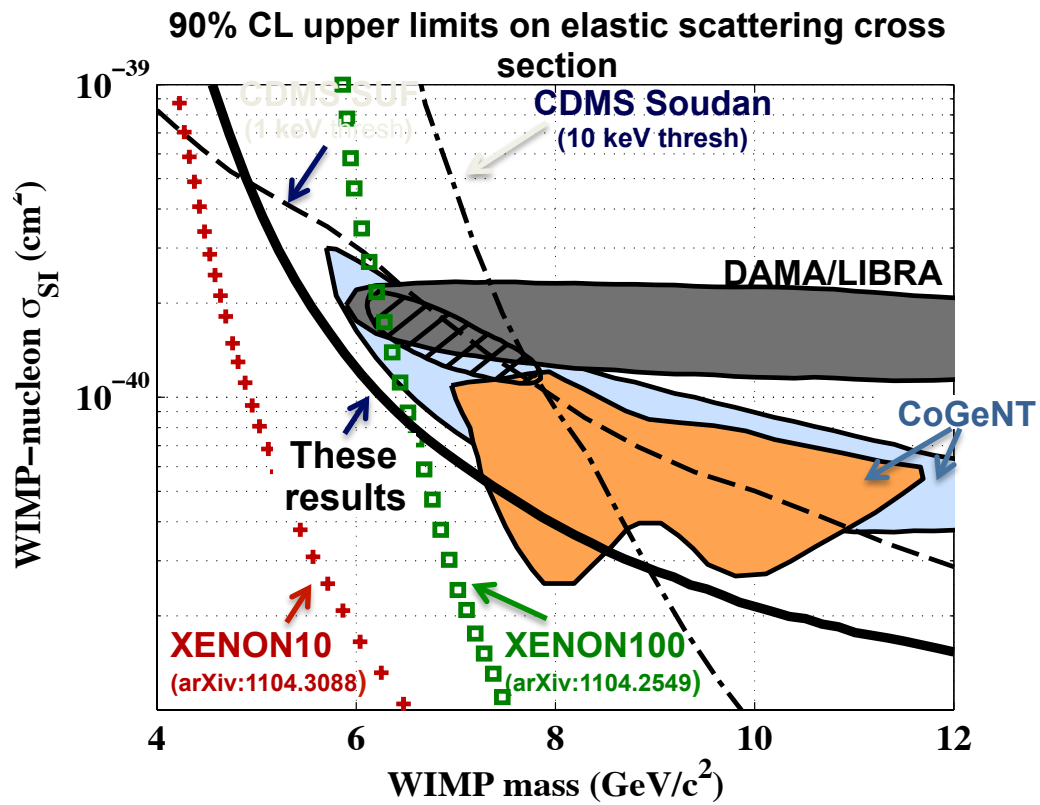
Surpassed by March 2011 limits from Xenon100 at **7×10^{-45} cm^2.**

Still no sign of WIMPS, so the race continues!



CDMS II: Low-Mass WIMPs

- CDMS energy threshold ~ 2 keV
  - EM background rejection not as good
  - Treat all candidates as if WIMPS even though background well understood
- For spin-independent, elastic scattering, 90% CL limits incompatible with DAMA/LIBRA and entire CoGeNT excess
- Some parameter space for CoGeNT remains if majority of excess events not due to WIMPs



- No annual modulation signal seen *Ahmed et al.*, PRL **106**, 131302 (2011), *arXiv:1011.2482*
  Akerib et al., PRD **82**, 122004 (2010), *arXiv:1010.4290*

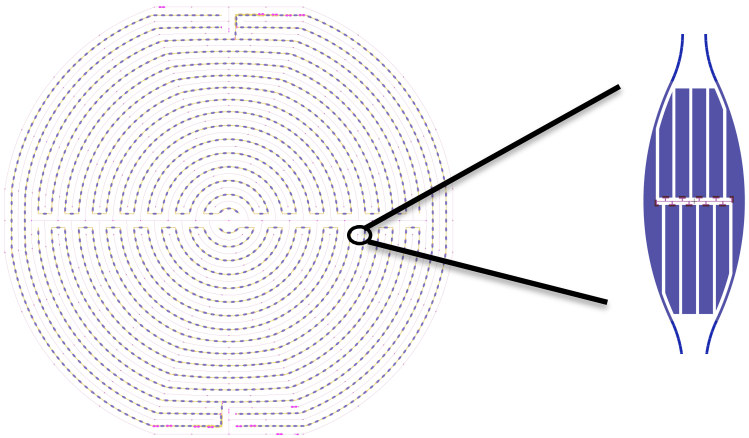
SuperCDMS – The Present

iZIP = interleavened charge and phonon channels

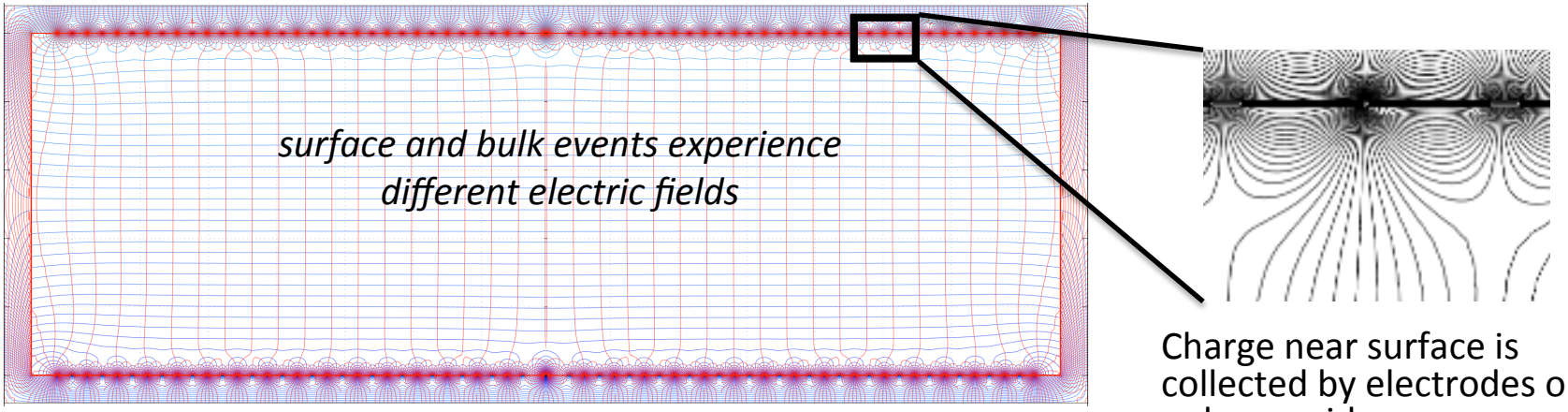
Rejection of surface events > x50 better than single-sided detectors

Fiducial volume nearly x2 better than CDMS II (~65% of the crystal)

5 iZIP towers (10 kg) running at Soudan



Closeup of phonon sensor



Charge near surface is collected by electrodes on only one side

SuperCDMS SNOLAB – The Future

New experimental apparatus at SNOLAB

- x3 deeper than Soudan => no cosmogenic neutron background
- Reduced radioactive backgrounds due to material selection
- Larger iZIP detectors 4” diameter x 1.3” thick, 1.5 kg each
- Need ~75 detectors for 100 kg experiment
- Challenge is to keep costs down and build detectors quickly

Currently in R&D, through FY2013

- Streamlining detector fabrication and testing
- Improved tower mechanical, thermal and electrical design
- Larger cryostat and shield; active neutron veto

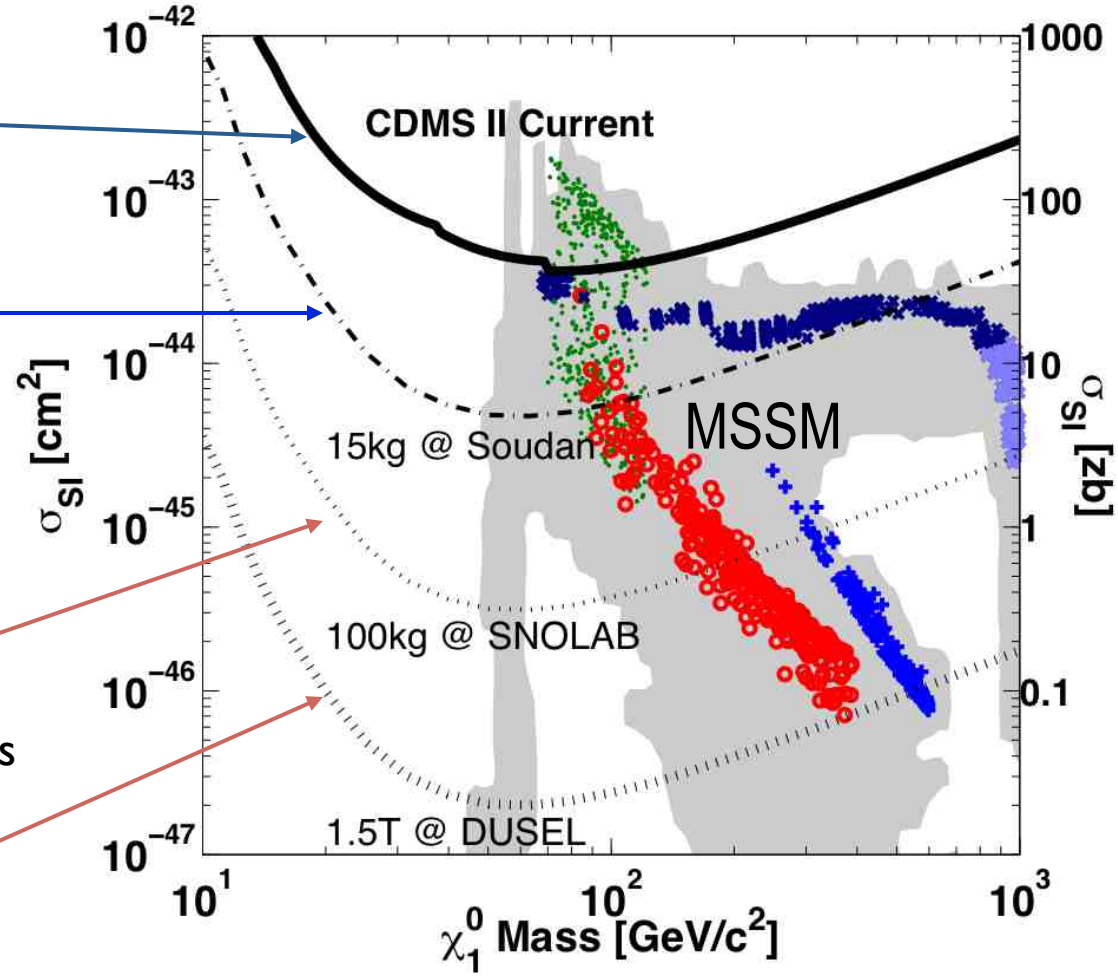
CDMS Future Projections

<u>CDMS II</u>
4 kg Ge
~ 2 yrs operation
Background limited

<u>SuperCDMS @ Soudan</u>
15 kg Ge
~ 2 yrs operation
Probably background limited

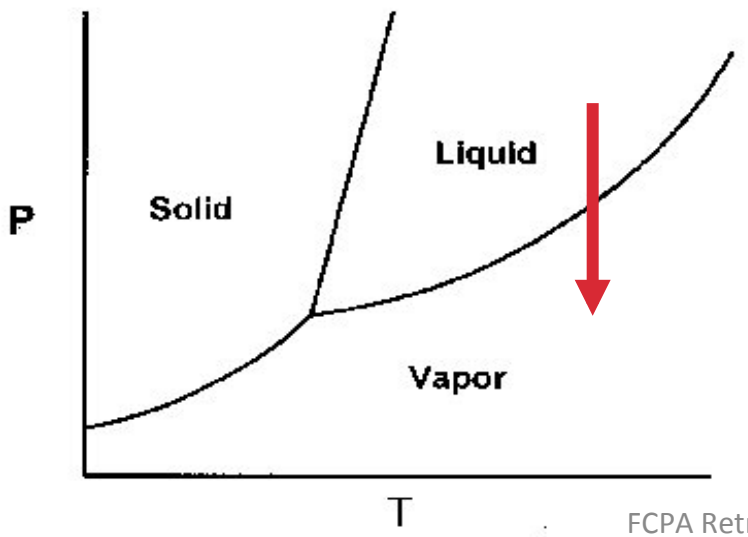
<u>SuperCDMS @ Snolab</u>
100 kg Ge
~ 2 yrs operation
Should be background free for 5 years

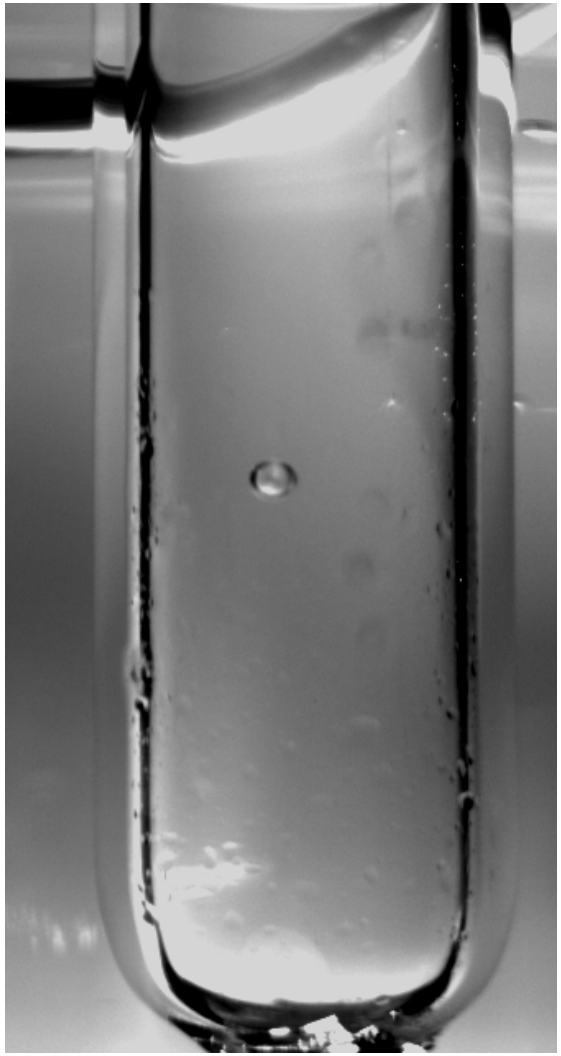
<u>GEODM</u>
1.5T
Probably will stay at SNOLAB



COUPP Technology

1. Prepare volume of target liquid in a very clean, smooth glass container. Eliminate surface bubble nucleation sites!
2. Reduce the pressure of the liquid until it becomes superheated.
3. Record video images and sound while waiting for a bubble to appear.
4. When a bubble does appear, immediately pressurize the liquid to stop the bubble from growing.
5. Repeat cycle.





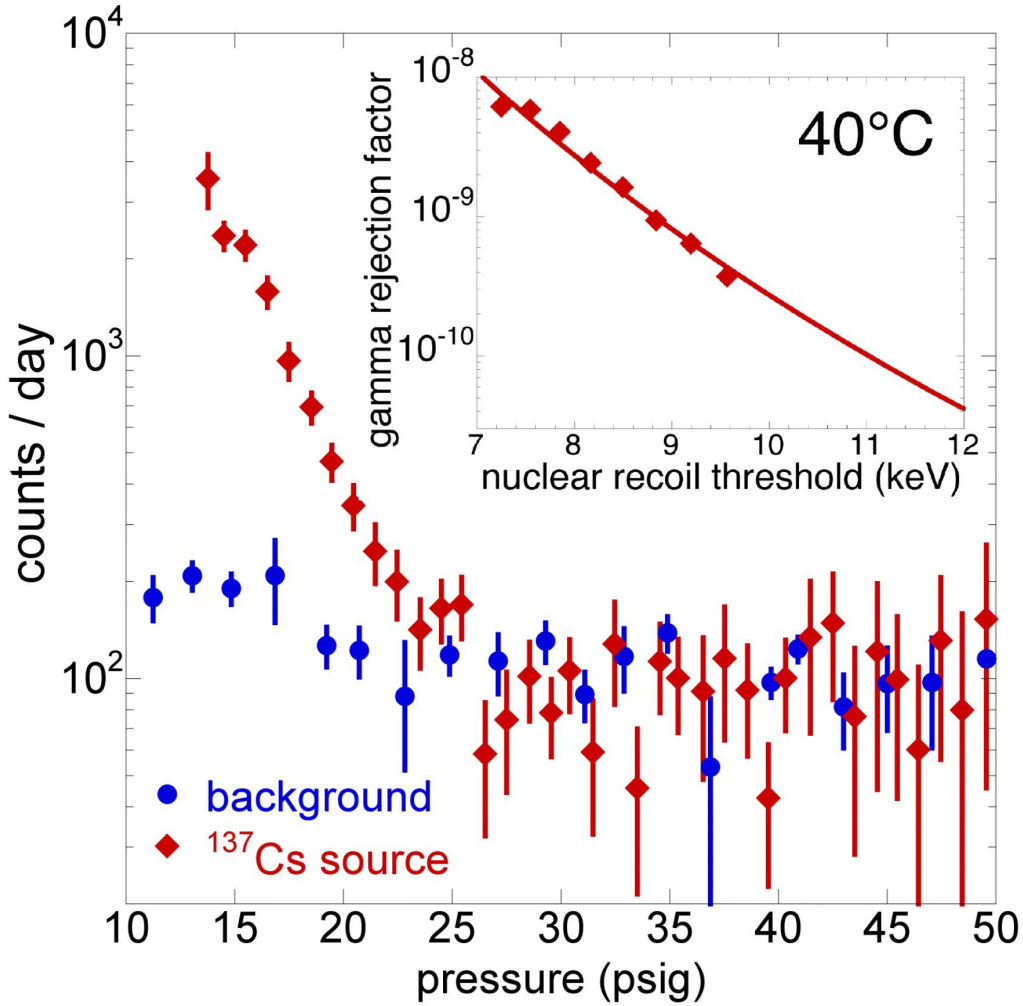
Thresholds for Bubble Nucleation

Only proto-bubbles with sufficient energy and dE/dx grow to macroscopic sizes

γ's or β's do not ☺

Nuclear recoils do ☺

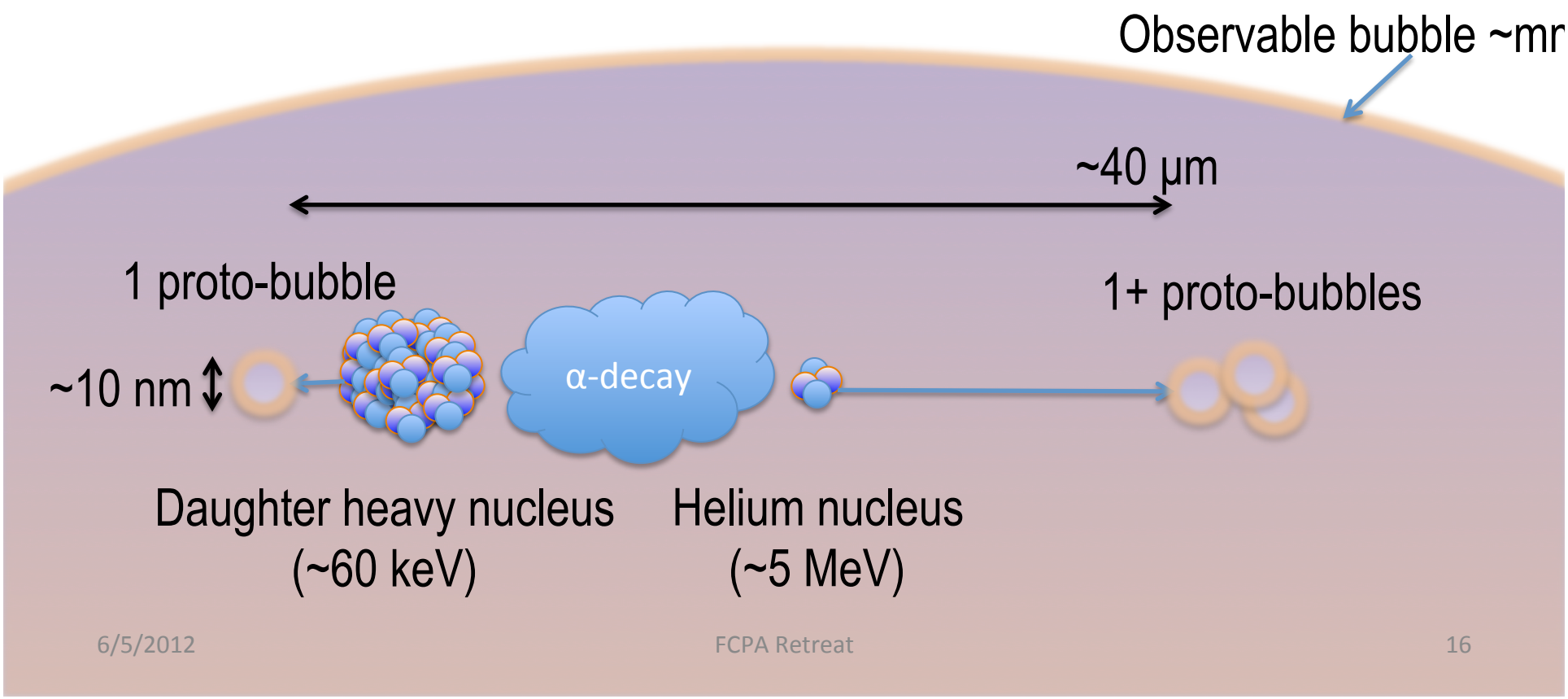
α's also do ☹



Acoustic Discrimination Against Alphas

High frequency acoustic information probes smaller scales

Alpha decays produce many bubbles, louder at high frequencies



COUPP – The Past

Continuing R&D on larger, cleaner bubble chambers; science along the way!

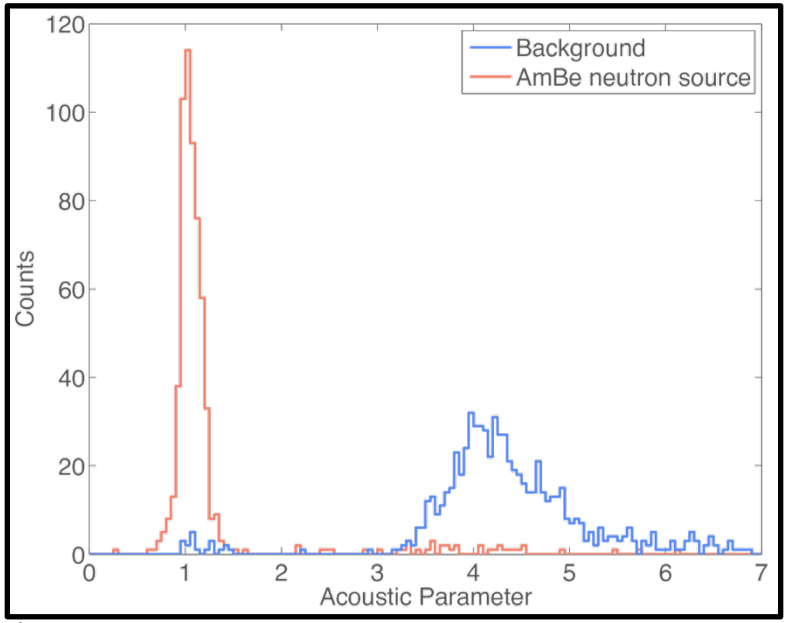
Important test bed in the NUMI underground hall

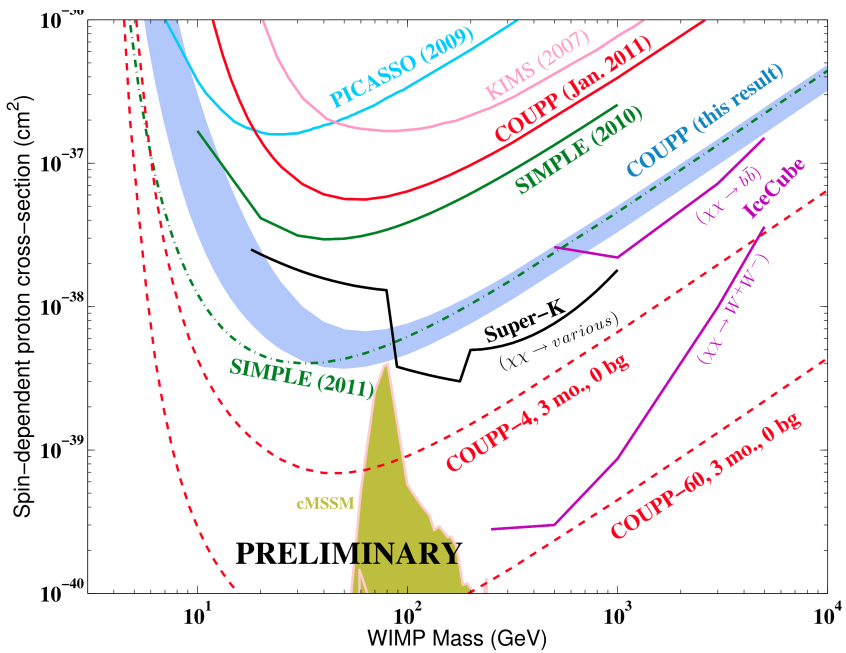
Ultimate goal is ton-scale bubble chamber

Date	2003	2005	2007	2009	2011
Mass (kg)	0.018	2		4	4, 60
Site	Chicago	NUMI	NUMI	NUMI	SNOLAB, NUMI
Depth (mwe)	10	300	300	300	6000
Backgrounds (/kg/day)	7000	77	7	0.7	0.1 or lower
Technical	Continuously sensitive bubble chamber	Pressure control	Metal seals, radon eliminated	Synthetic silica, high purity fluid handling	Acoustic discrimination
Publications		*Science* **319**:93(2008)		arXiv: 1008.3518	

COUPP 4kg @ SNOLAB – The Present

- Alpha rejection at least 98%
- Single-bubble background of ~0.05 events/kg-day from neutrons
  - *Acoustic sensors and view ports proved to be neutron sources*
  - *These are being replaced and a new run will commence soon*
- *O*(1) event/year expected from environmental neutrons





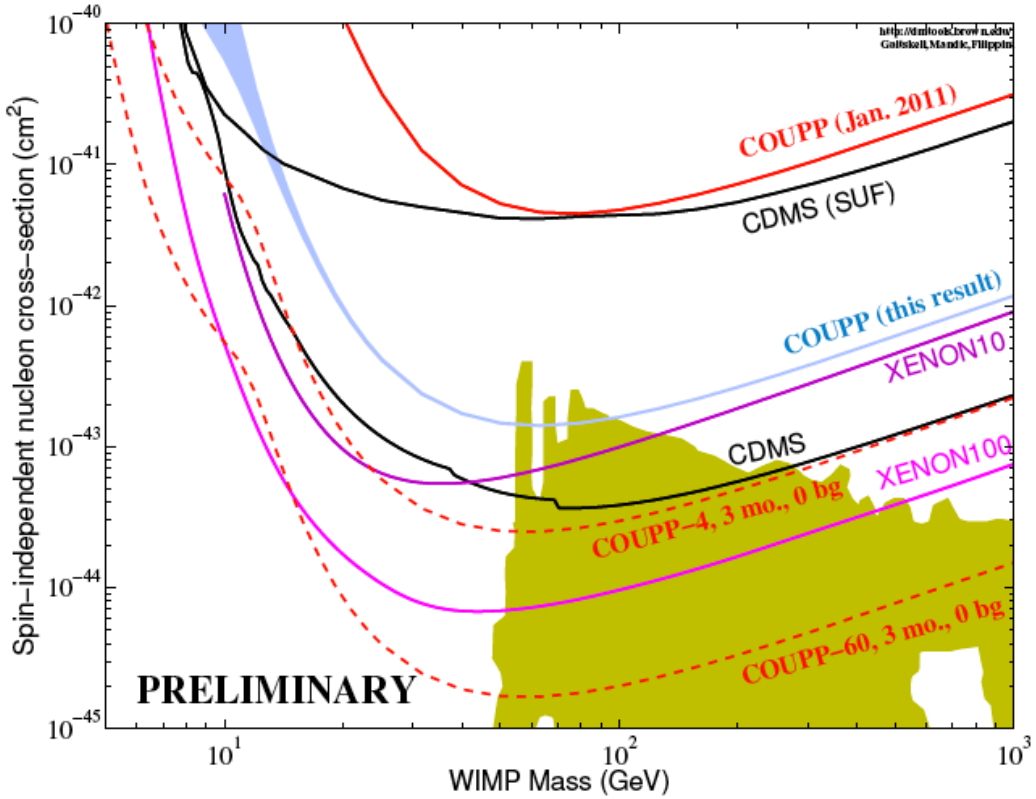
COUPP 60 kg at SNOLAB – The Future

Successful resolution of technical problems

Cf3I darkening, excess surface bubbles, poor illumination, leaks

Installation and Commissioning at SNOLAB this fall

Expect to be competitive for both SD and SI WIMP interactions

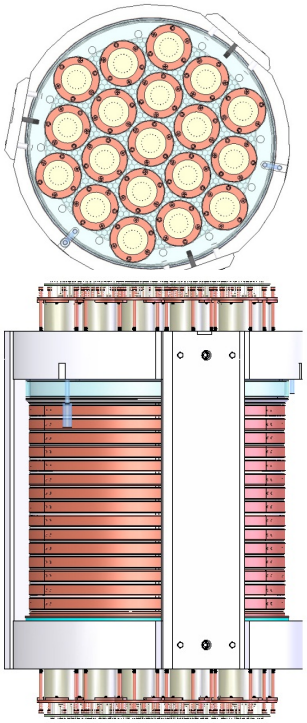


Darkside Technology

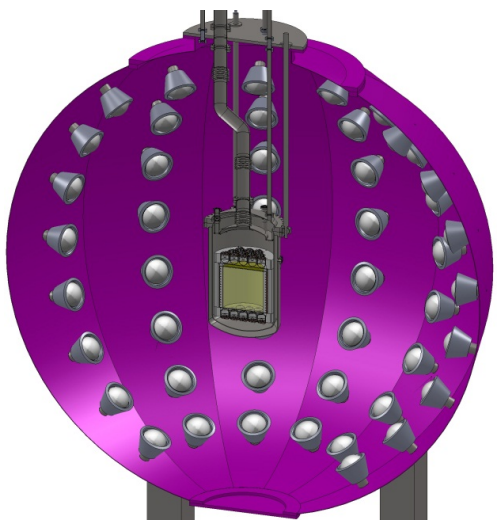
50 kg low radioactivity liquid Argon dual-phase TPC (left below) inside a 4m spherical Neutron Scintillator Veto (left center) inside an existing 10 m high and 11 m diameter cylindrical Water Tank (right center) under a mountain (right) at the Laboratori Nazionali del Gran Sasso (LNGS), Italy.

Key features:

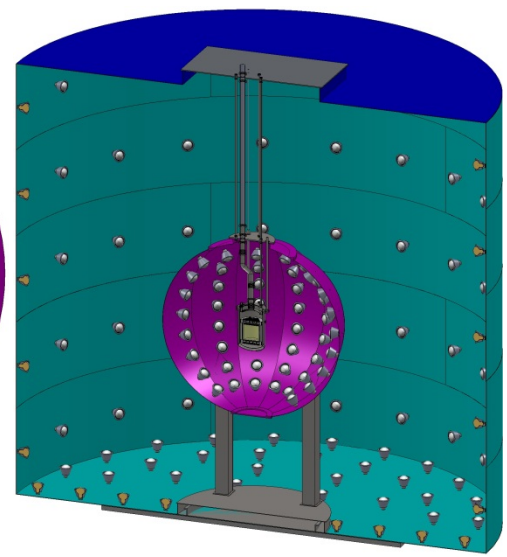
- use of low radioactivity Argon
- low radioactivity photosensors
- highly efficient Neutron veto using boron-loaded scintillator.



Dual-Phase TPC



4 m diameter Neutron Veto



10 m x 11 m Water Tank

4000 m Mountain

DarkSide-50 (FNAL E-1000)

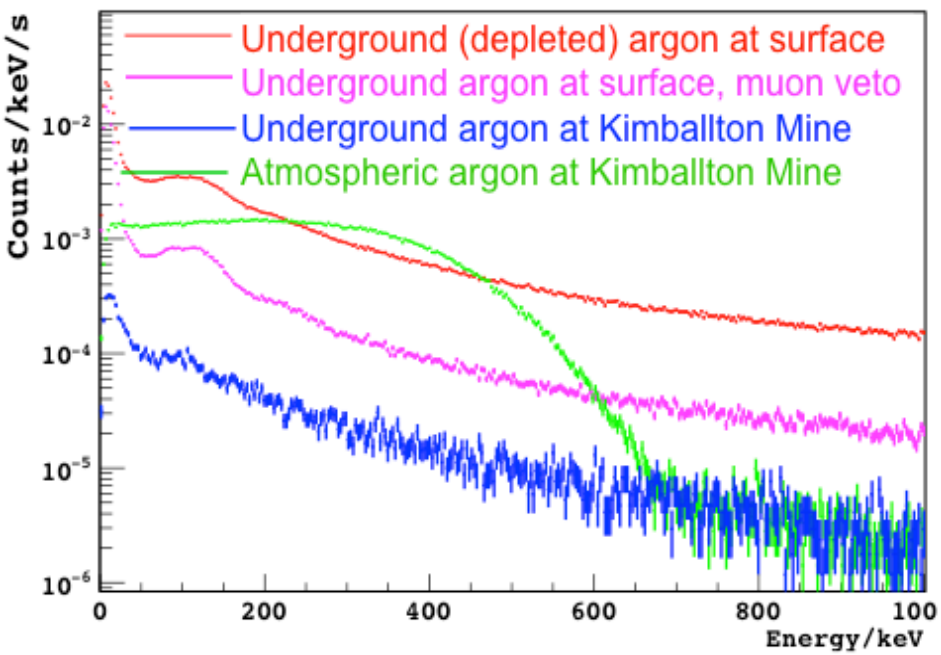
Recent noteworthy Technical Results:

Radioactivity of underground argon measured at < 1% (upper limit) of atmospheric argon (left plot)

Light yield of 9 photo-electrons/keV achieved in DarkSide-10 detector. (right plot)

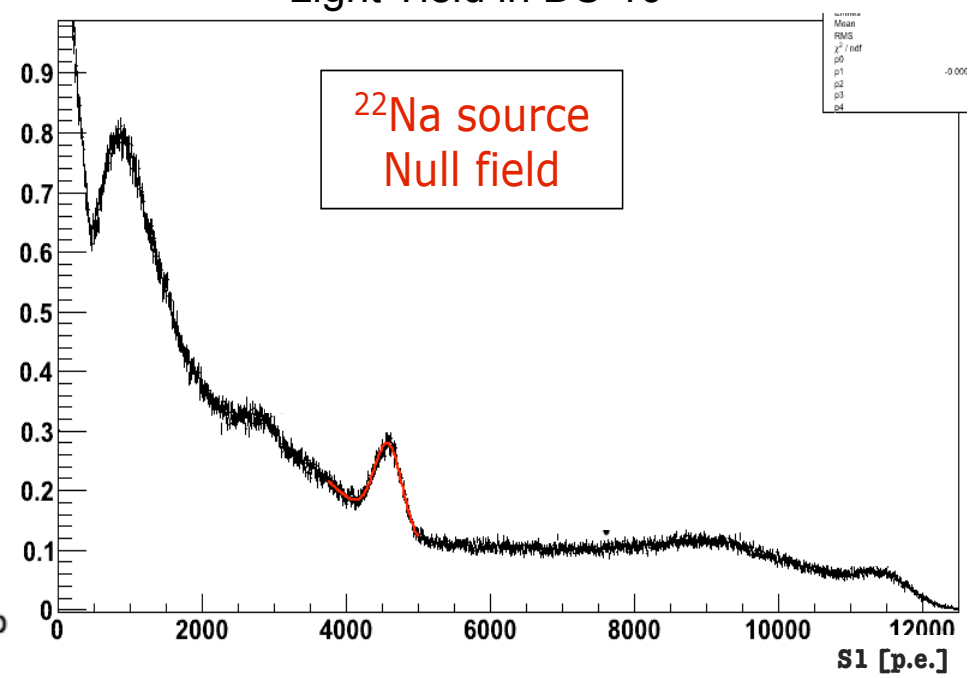
99.95% pure argon produced (by distillation) from underground Ar-N_2-He mixture.

Measurements on underground argon



There is a factor ~ 100 activity between the atmospheric argon spectrum due to Ar^{39} and the spectrum of the underground argon.

Light Yield in DS-10

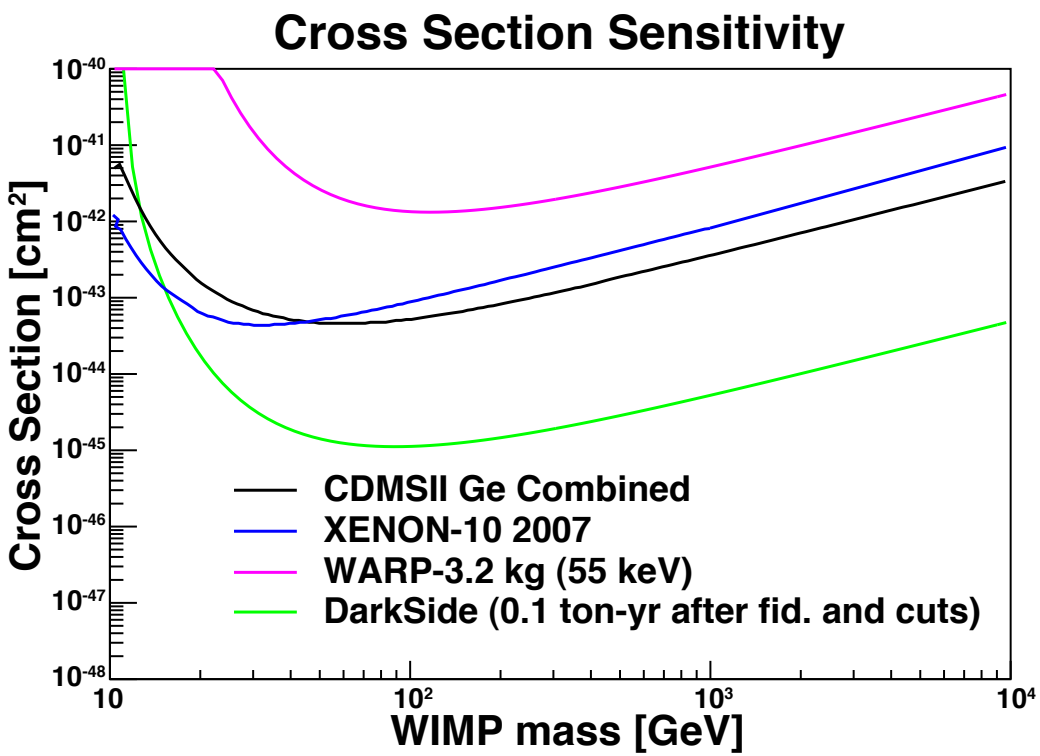


Fitting the 511 keV peak (in red) and knowing the PMT gains yields a value for photo-electrons/keV of ~9.

DarkSide-50 Goals

DarkSide 50 kg installation underway at Gran Sasso

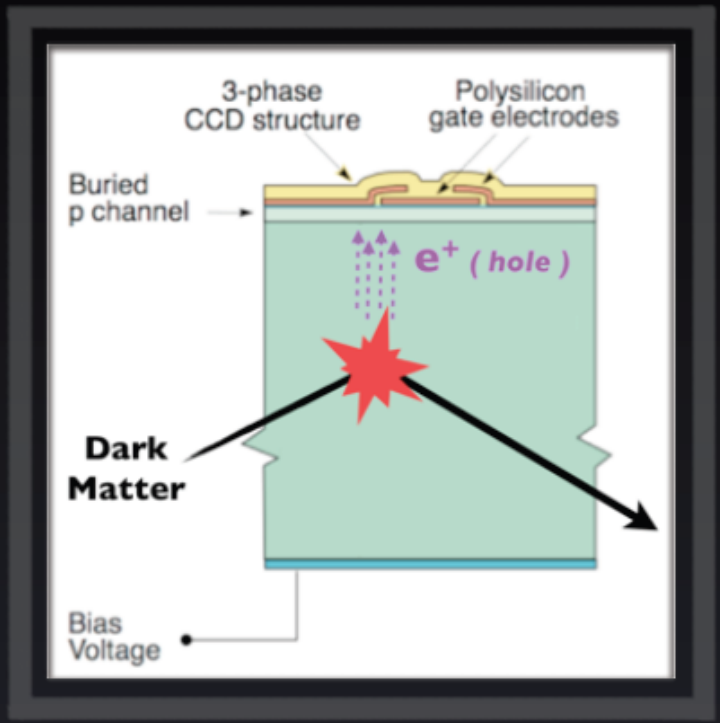
Operations expected to begin in 2013



Projected Sensitivity assuming 3 years x 33 kg (fiducial) and < 0.1 event background

DAMIC Technology

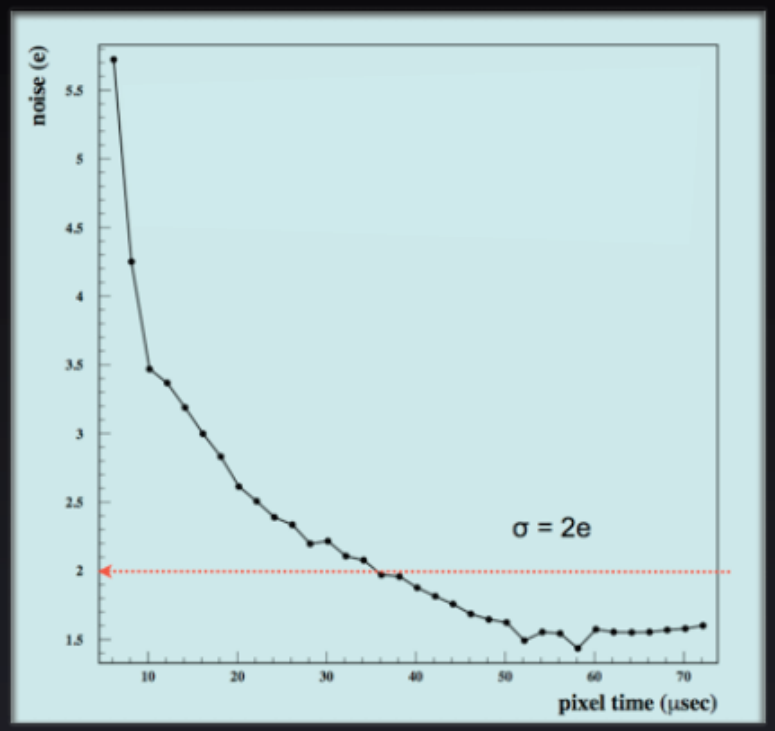
- In the DECam CCD's, the silicon itself is the volume for recoil
- DECam CCD Advantage
  - 250 μm thick (~ 1 g/ccd) → larger active mass than most CCD's
  - High resistivity silicon, so high bias voltage ~ 40 V → limits diffusion



DAMIC Technology

- **Low readout noise → RMS noise of 2 electrons (7.2 eV in ionization energy)**
- **Lowest Nuclear Recoil Energy Threshold of ANY DM Experiment → 40 eV**

Experiment	Target	Exposure (kg-d)	Threshold	Ref
CDMS-SUF	Ge	65.8	5 keV	[2]
	Si	6.58	5 keV	
CDMS-II	Ge	121.3	10 keV	[3]
	Si	12.1	7 keV	[4]
XENON10	Xe	131	4.5 keV	[5]
CRESST-I	Al_2O_3	1.51	0.6 keV	[16]



DAMIC – The Present

Direct Search for Low Mass Dark Matter Particles with CCDs

J. Barreto[1], H. Cease[2], H.T. Diehl[2], J. Estrada[2], B. Flaugher[2], N. Harrison[2] J. Jones[2], B. Kilminster[2], J. Molina[3], J. Smith [2] , T. Schwarz[4] and A. Sonnenschein[2]
[1] *Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*
[2] *Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[3] *Facultad de Ingenieria, Universidad Nacional de Asuncion (FIUNA), Asuncion, Paraguay*
[4] *University of California at Davis, USA.*

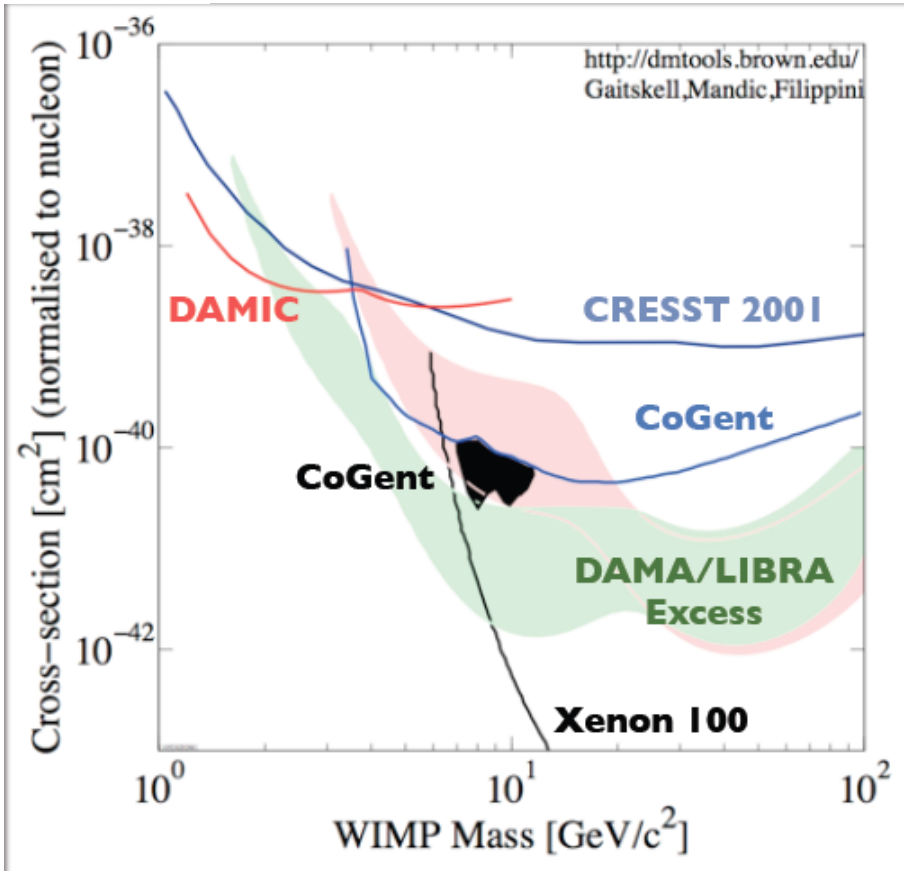
(Dated: April 3, 2012)

A direct dark matter search is performed using fully-depleted high-resistivity CCD detectors. Due to their low electronic readout noise (R.M.S. ~7 eV) these devices operate with a very low detection threshold of 40 eV, making the search for dark matter particles with low masses (~ 5 GeV) possible. The results of an engineering run performed in a shallow underground site are presented, demonstrating the potential of this technology in the low mass region.

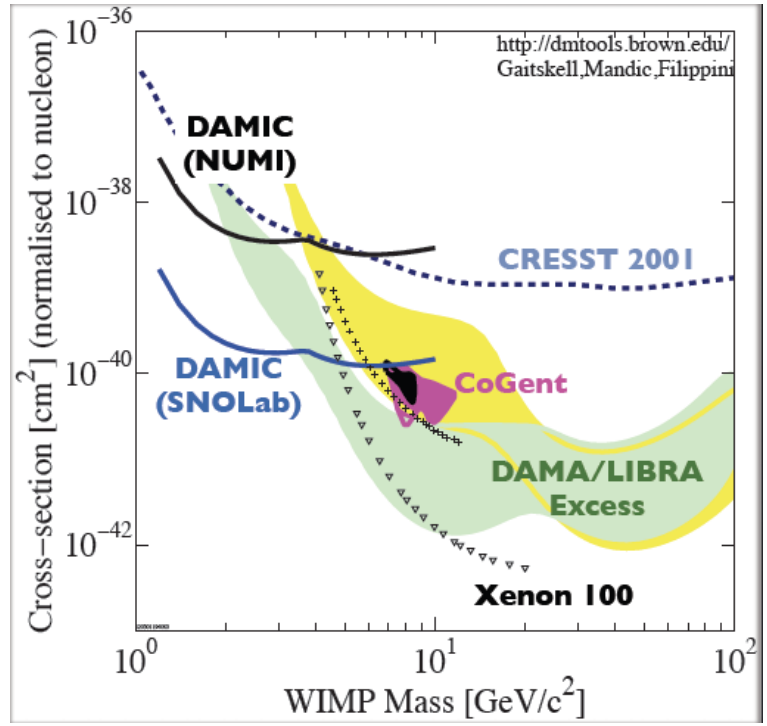
Physics Letters B, Volume 711, Issue 3, p. 264-269. (2012)

With the test at FNAL we got an interesting result, but were not able to demonstrate the final potential of the technique. No neutron shield.

Now we would like to go to SNOLAB with 10g of CCDs and a neutron shield.



DAMIC at SNOLAB



Aim for:

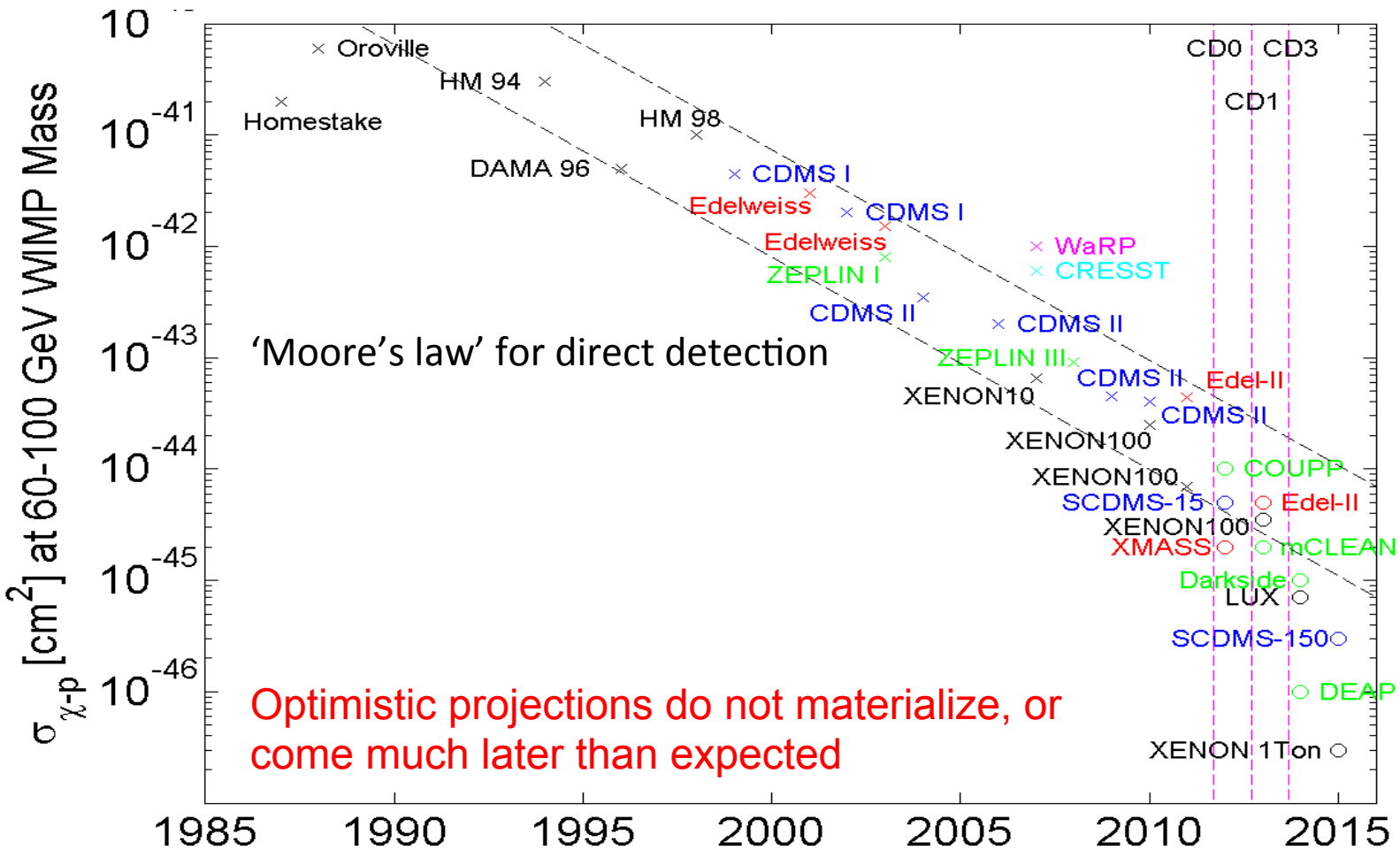
X10 background reduction
X20 increase in mass

Direct Detection Technology Summary

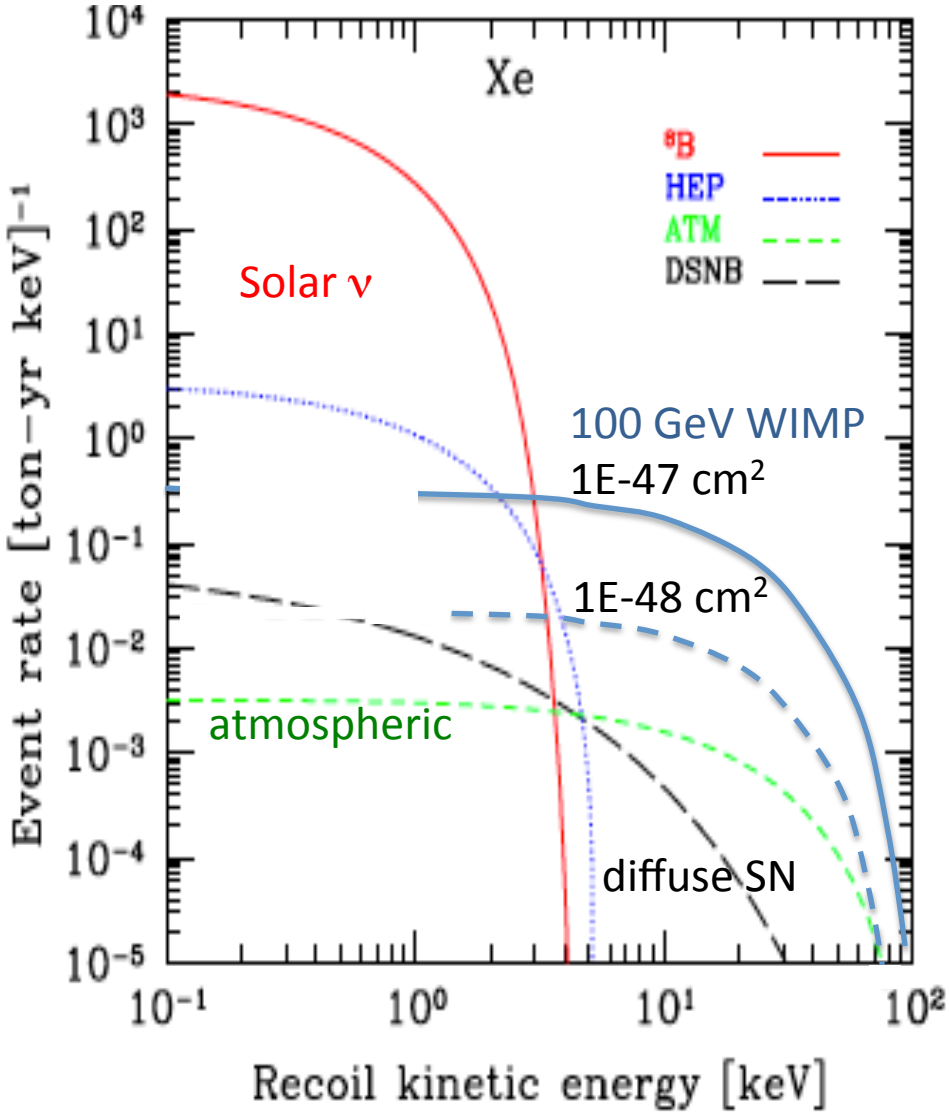
Project	Strengths	Weaknesses
Cryogenic Ge detectors (CDMS, Edelweiss, CRESST)	Proven background rejection, experience	Expensive to build/test detectors
Threshold Detectors (COUPP, SIMPLE, PICASSO)	Ultimate EM rejection, inexpensive, easy to change target material	Alpha backgrounds, no energy spectrum, scaling to large mass?
Single-phase LAr, LXe (DEAP, Clean, XMASS)	Simple and reasonably inexpensive	Not clear if rejection good enough, E thresholds high
Dual-phase LAr (Darkside, WARP)	Excellent EM rejection and relatively inexpensive compared with Xe, Ge	39Ar reduction needed, ~x10 more target mass needed than Ge or Xe, E threshold high
Dual-phase LXe (Xenon, LUX)	Suitable target for both SI and SD, low E threshold possible	Poor intrinsic EM rejection, low E performance not understood
Low pressure TPCs (DMTPC, Drift)	Directional detection of WIMPs possible	Very hard to get sufficient target mass, backgrounds unknown
Scintillating Crystals (DAMA/LIBRA, KIMS)	Annual modulation with large target mass	No background rejection. Long-term stability crucial
Ionization Detectors (CoGeNT, DAMIC,…)	Very low E threshold and good E resolution	Background rejection difficult and small target masses

There may not be one clear winner; all experiments run into backgrounds!
More than one technology will be needed to establish a WIMP signal

Zero-Background Projections always wrong!



The Ultimate Background: Neutrinos



Strigari arXiv:0903.3630

Third generation (multi-ton) experiments will be limited by this background!

Initial impact is reduced sensitivity to low mass WIMPs

Ultimately, only directionality and modulation may distinguish neutrinos from WIMPs

Direct Detection Compared with Other Dark Matter Search Techniques

- Strengths
  - Best way to be sure that a WIMP exists and is actually associated with dark matter
  - Can explore both spin-independent and spin-dependent interactions
  - Laboratory-scale experiments still relatively inexpensive
- Weaknesses
  - Very difficult to get backgrounds down to < 1 event/ton/year!
  - Wealth of different approaches with no clear winner yet
  - Ultimately limited by neutrino backgrounds ($\sigma \sim 10^{-48}$ cm^2)
- Complementarity
  - Orthogonal to colliders and indirect detection in exploration of parameter space
- Prospects
  - Generation 2 experiments are finally going to be funded by DOE/NSF, but have major technical challenges to overcome.

The role of Fermilab

Infrastructure

NUMI near-detector hall and other on-site facilities for R&D
Formal cooperation agreements with Soudan, SNOLAB and Homestake
Possible screening and background detection R&D efforts at Soudan

Experimental Leadership

Key role in four experiments (CDMS, COUPP, DarkSide LAr, DAMIC CCDs)
Continued R&D on other technologies (e.g. Solid Xenon)

Community Leadership

Organization/hosting of symposia (Hunt for DM, Cosmic Symposium, Midwest DM)

Agency Interactions

Close collaboration with DOE on the national dark matter program
Good communication with NSF as well

The Funding Landscape

- US funding agencies are finally heeding panel advice and moving forward with a dark matter program
  - DOE G2 process
    - R&D funding ($6M) in FY2013 with selection of players by start of FY2014
      - Proposals due July 6, mostly via national lab FWP
    - Separation into small (<$2M), medium ($2-5M) and large ($5-20M) projects; determines level of oversight and funding profile
    - Project funding (total of $29M) in FY2014-FY2016
  - NSF underground physics solicitation
    - Less specific than DOE, but possibly $10M available in FY2013
    - Coordination with DOE planned on major G2 projects

Building a Dark Matter Community

- We have an excellent core right here with FCPA/ANL/KICP and nearby universities
  - How can we build on our recent mini-workshop to foster that community?

- DOE may hold a workshop or convene a task force later this year
  - This would be to develop their dark matter strategy and, specifically, decide on funding levels for direct, indirect and axion searches

- DPF will be holding a Community Planning Meeting (CPM2012) October 11-13, 2012 at Fermilab
  - This will be in preparation for convening the whole particle physics community at SNOWMASS, June 2-22, 2013.
  - The dark matter community should be represented at both the planning meeting and at SNOWMASS.

Summary

The field of dark matter direct detection is burgeoning, and FCPA/KICP/ANL should play a leading role

Pursuit of multiple technologies assures that FNAL will participate in both 100 kg and ton-scale experiments.

The dark matter program at FNAL is coordinated with DOE/NSF, other national labs, and university groups. It takes advantage of the strengths of the laboratory scientists, technical staff and infrastructure.