Direct Detection of Dark Matter

The Fermilab experimental program in a worldwide context

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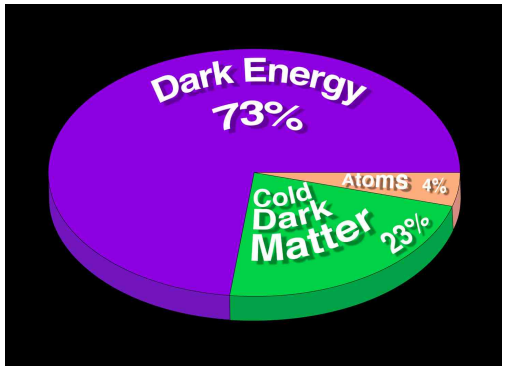
FNAL PAC Meeting
Snowmass, Colorado
June 22, 2011

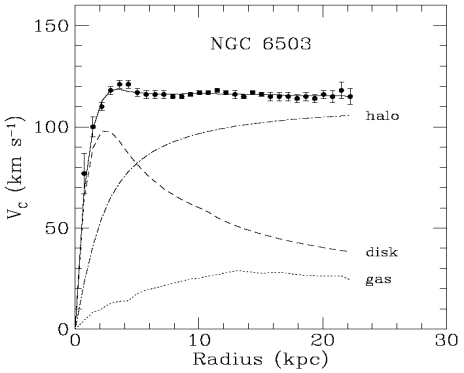
What is Dark Matter?

Galaxy Clusters

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

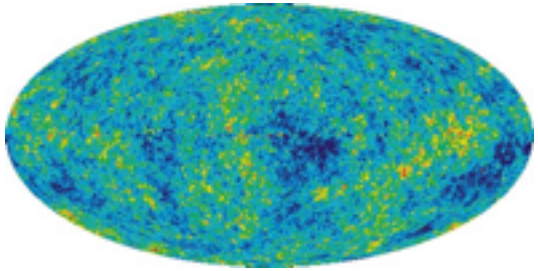


Strong Lensing



Galaxy Rotation Curves

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

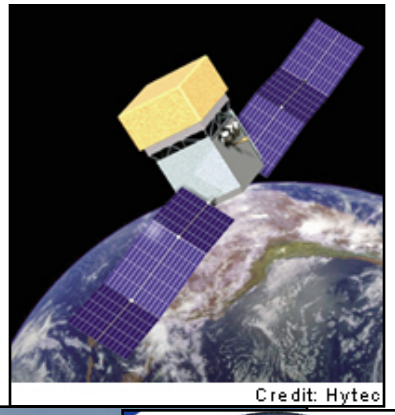


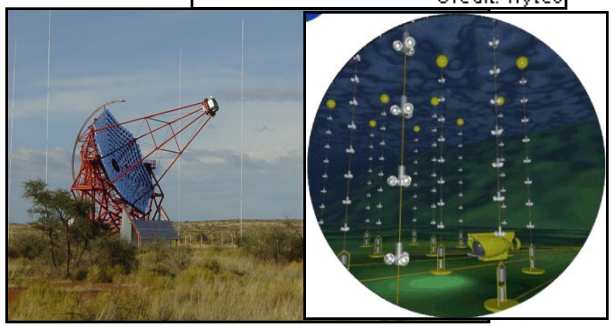
Cosmic Microwave Background

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

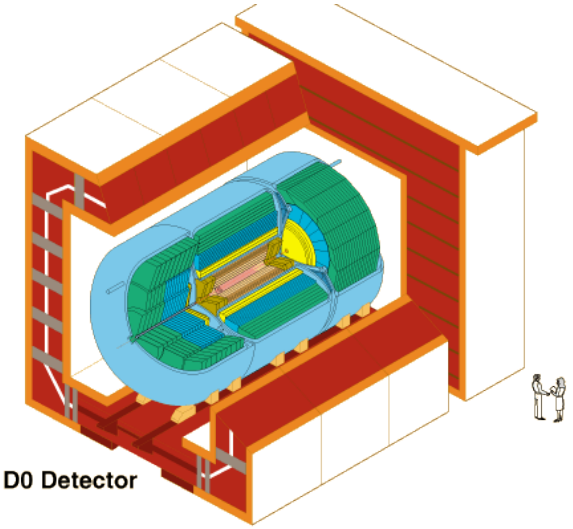
Many different ways to search for WIMPs

Direct Detection
Try to find WIMPS from the galactic halo passing through earthly laboratories.



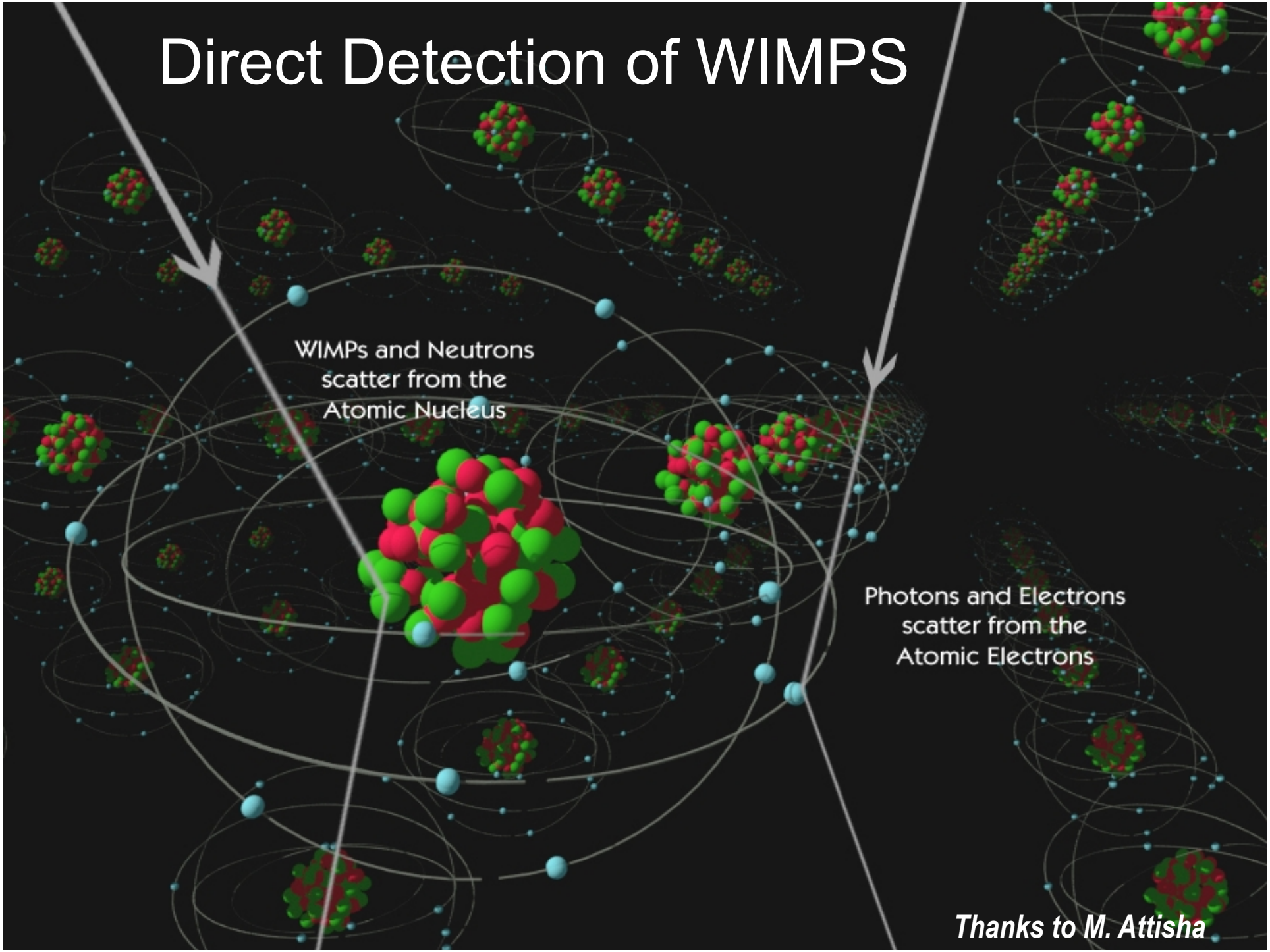


Indirect Detection
Look for evidence of WIMP annihilations to gammas, neutrinos, antiparticles occurring in our galaxy



Colliders
Try to produce WIMPS with accelerators and detect missing energy

Direct Detection of WIMPS



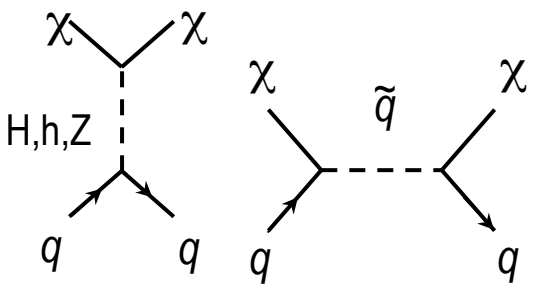
Thanks to M. Attisha

Direct Detection of WIMPs

1. Particle Physics: Interaction cross section with target material

WIMPs elastically scatter off nuclei in targets, producing nuclear recoils.

$$R \propto N \frac{\sigma_{\chi N}}{m_\chi} \rho_\chi \int_{v_{\min}}^{v_{esc}} \frac{f(v)dv}{v}$$



(a) Spin-independent interaction ~A^2
(large λ_{dB} ➔ coherent interaction)

(b) Spin-dependent interaction needs target with net spin

2. Astrophysics: WIMP distribution in our galaxy

Isothermal, spherical halo and M-B velocity dist:

$$f(v)dv = \frac{4v^2}{v_0^3\sqrt{\pi}} e^{-v^2/v_0^2} d^3v$$

v_0 ~ 230 km/s v_{esc} ~ 550 km/s ρ_χ = 0.3 GeV / cm^3

This is just a model that allows comparison between experiments.

The actual distribution is probably more complicated.

The Experimental Challenge

Expected WIMP signal:

exponential recoil spectrum ~ few 10's of keV

nuclear form factors important

rates <0.1 events /kg/day

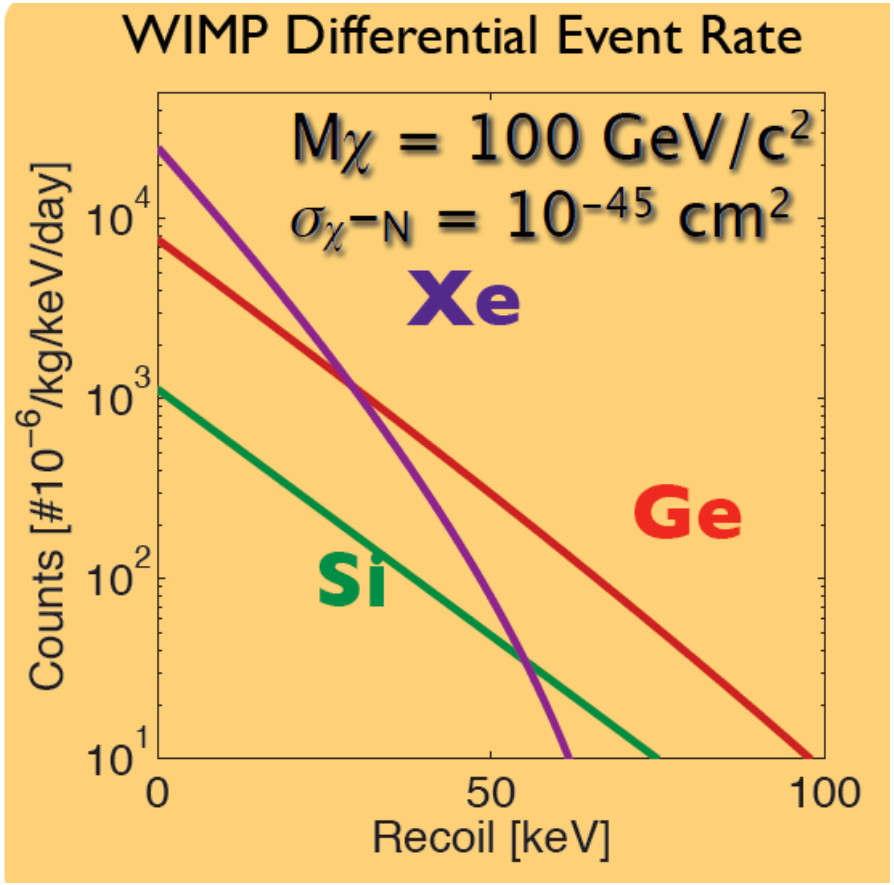
Experimental Requirements:

low energy thresholds (~1 keV)

mitigation of natural radioactive background

operation deep underground to avoid cosmics

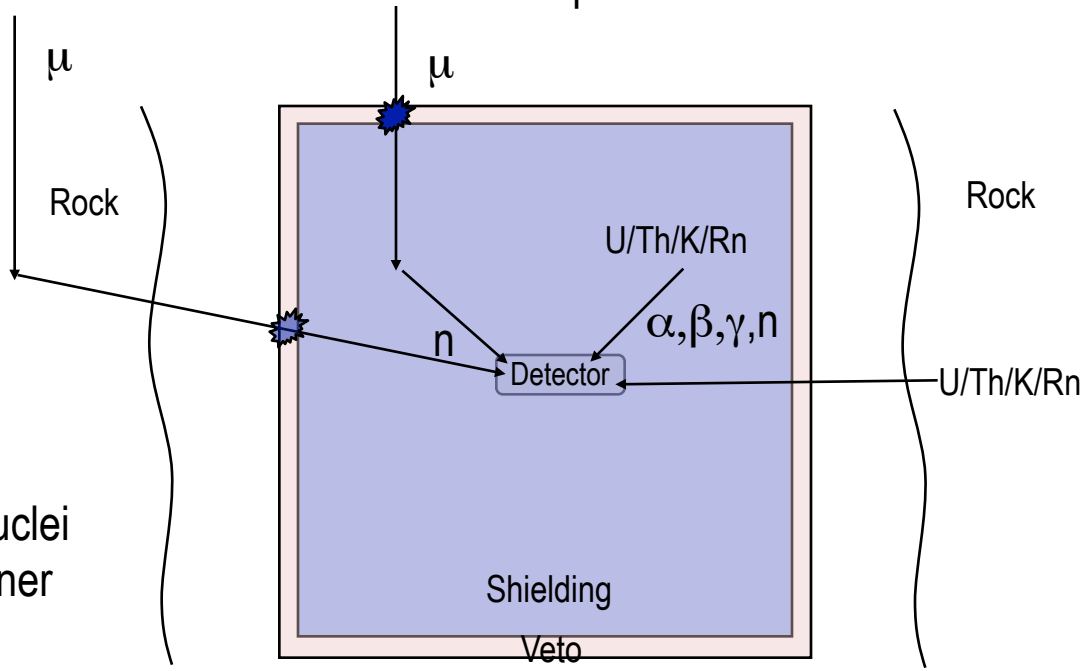
long exposures (target mass x livetime)



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?

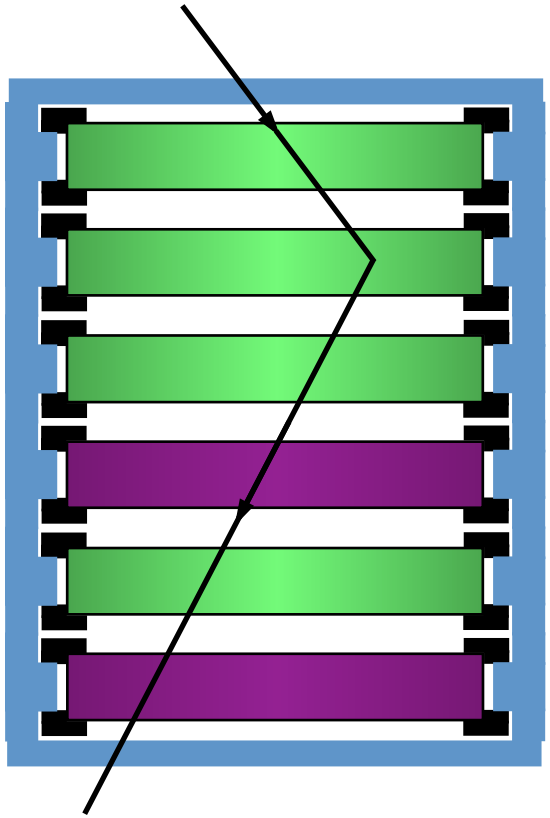
Layered shielding to reduce rate of normal particles hitting detectors

Lead, copper effective against alpha, beta, gamma rays

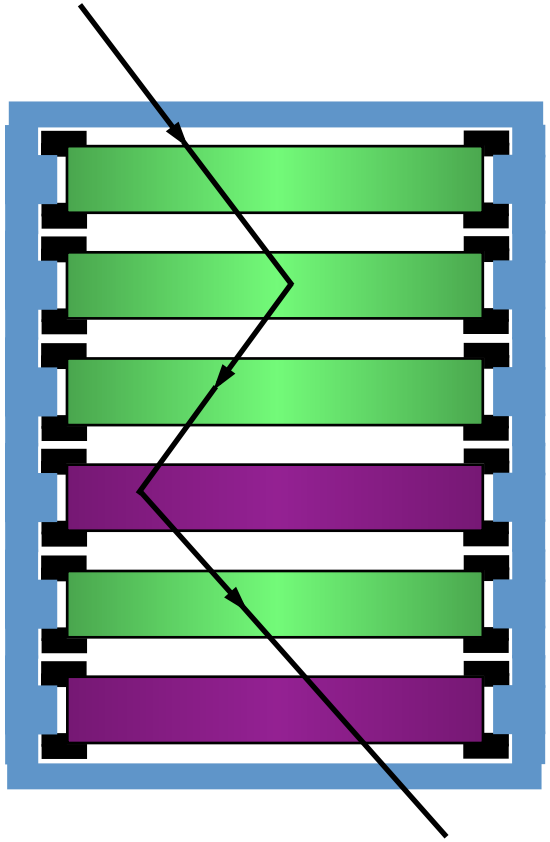
Plastic and Water moderate neutrons from radioactivity

Active veto and deep underground laboratories to reduce cosmic rays

Multiple Scattering
A tool against residual neutrons



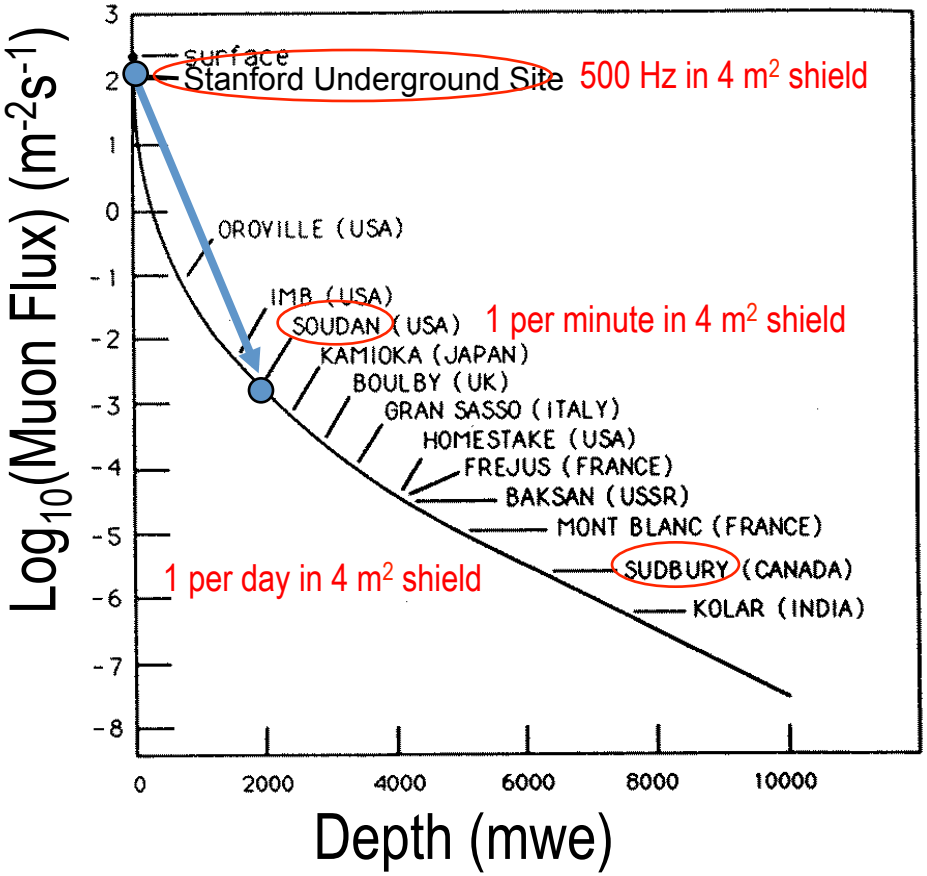
Single-scatter nuclear-recoils are produced by WIMPs or neutrons.



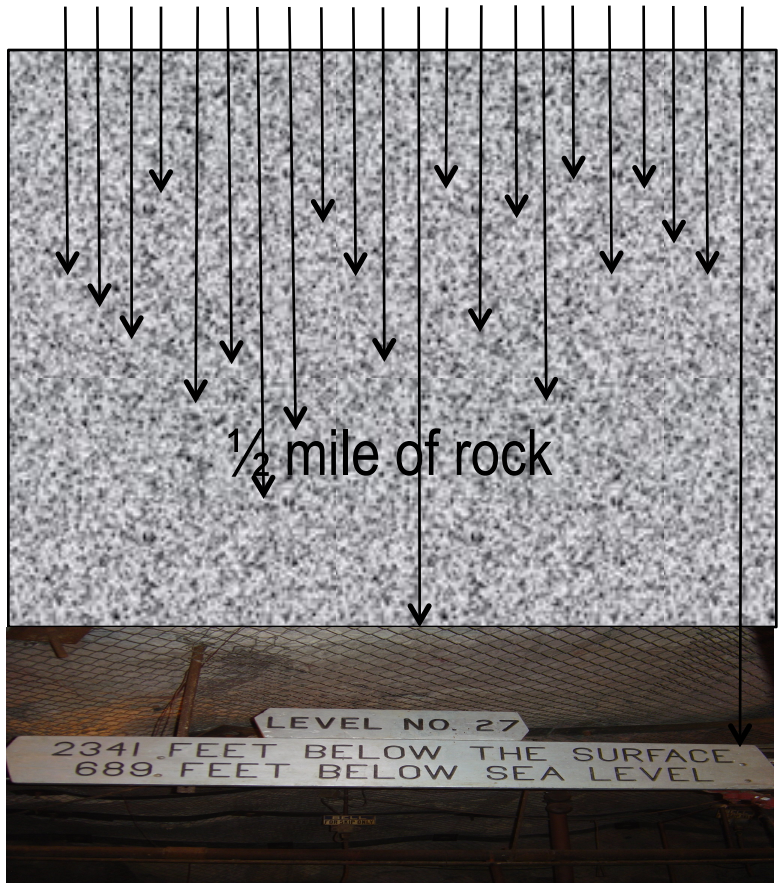
Multiple-scatter nuclear-recoils are only produced by neutrons.

How to escape cosmic ray backgrounds Go Deep

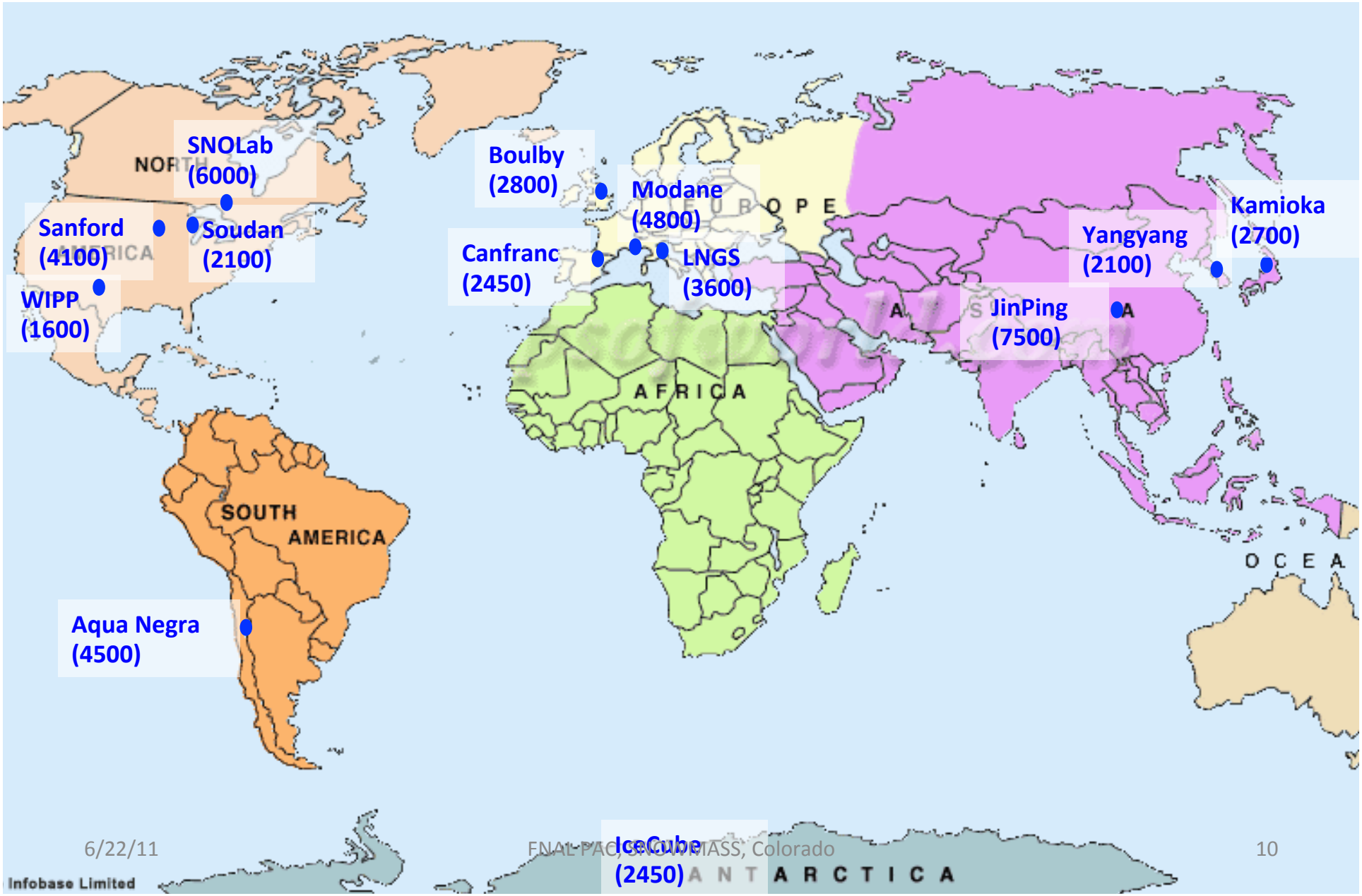
Cosmic ray muons in underground labs



Cosmic Rays from Space



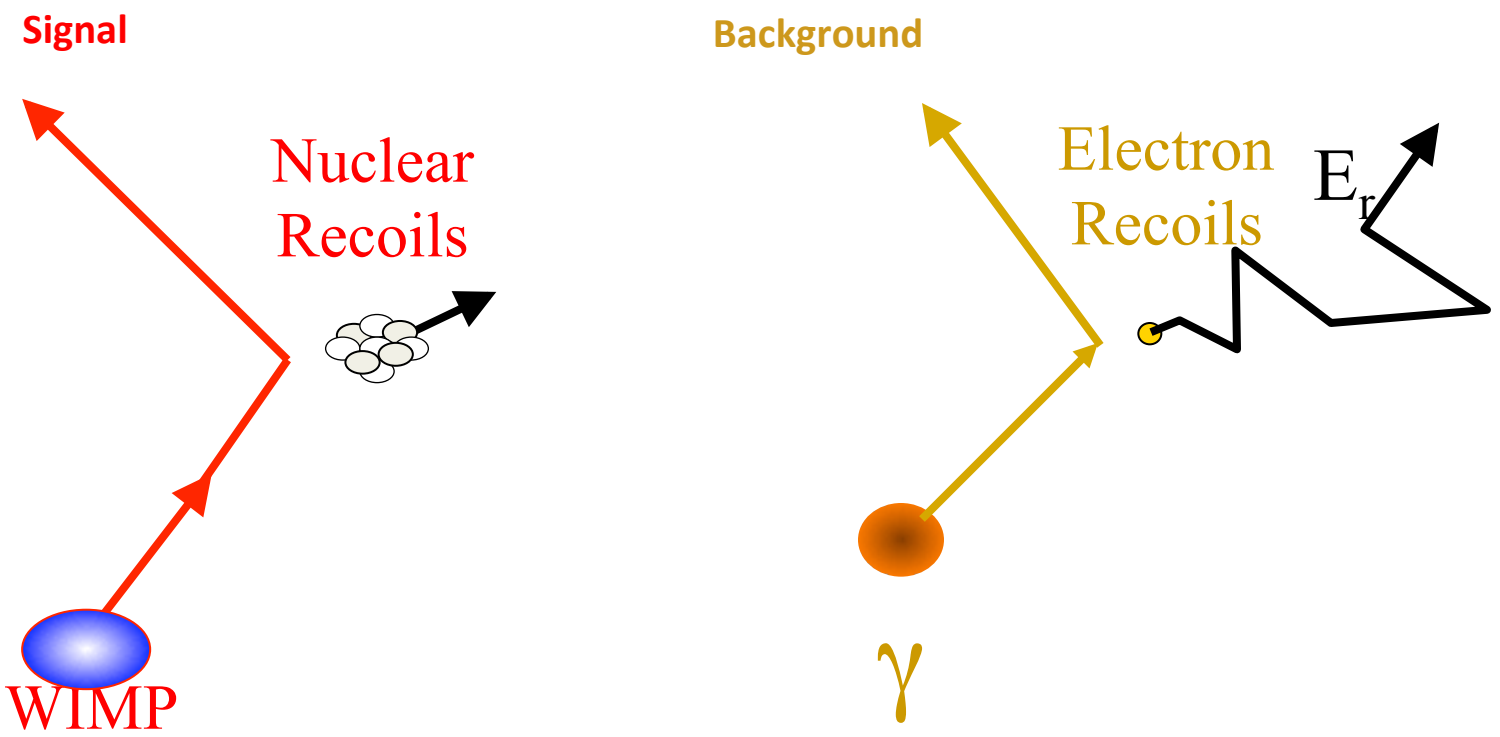
Underground Laboratories



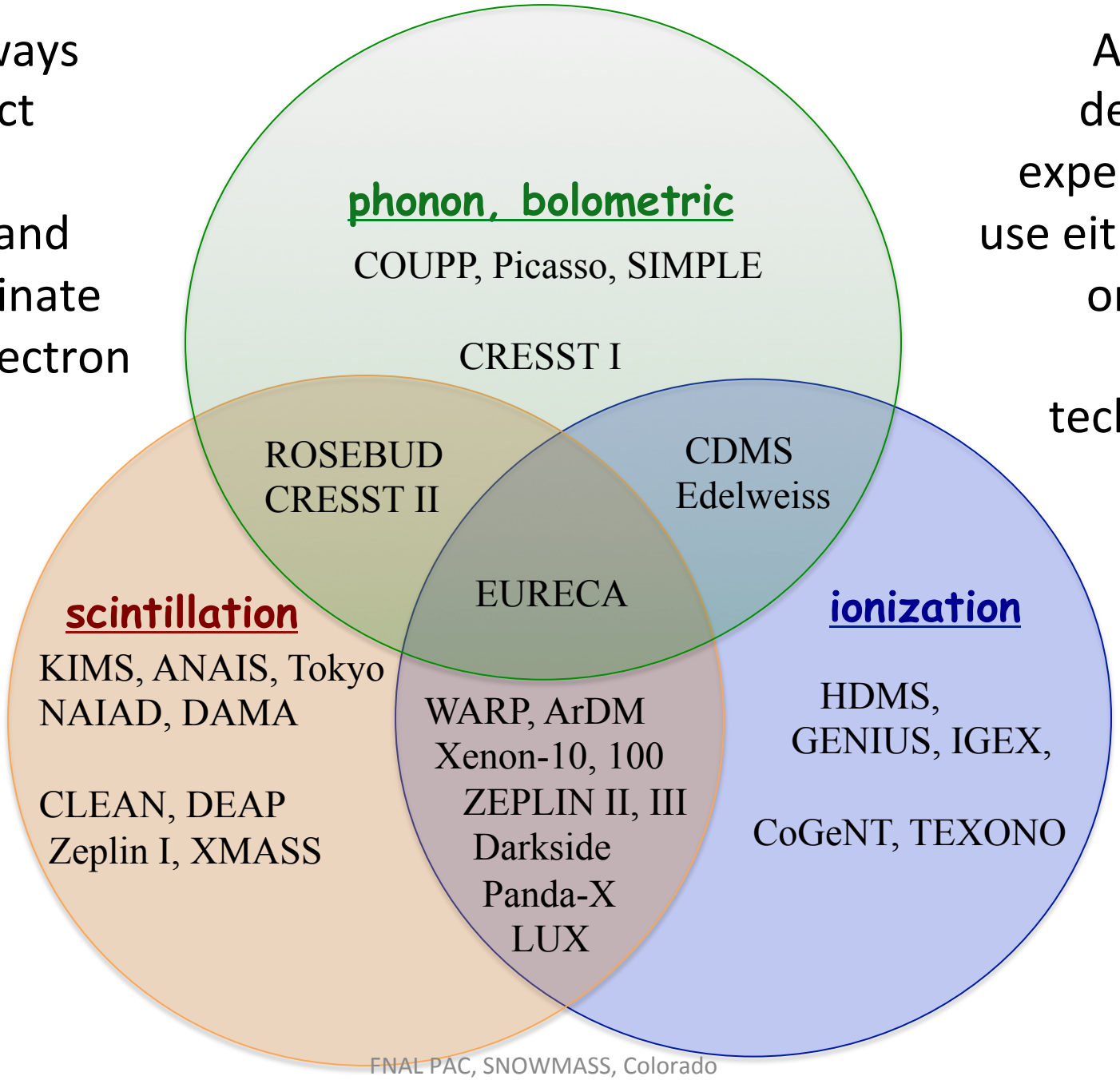
Active Background Discrimination

The variety in direct detection experiments comes primarily from how detectors distinguish background interactions from WIMP interactions

Most experiments detect particle interactions in two ways and compare (e.g. charge/phonon, charge/scintillation light, …)



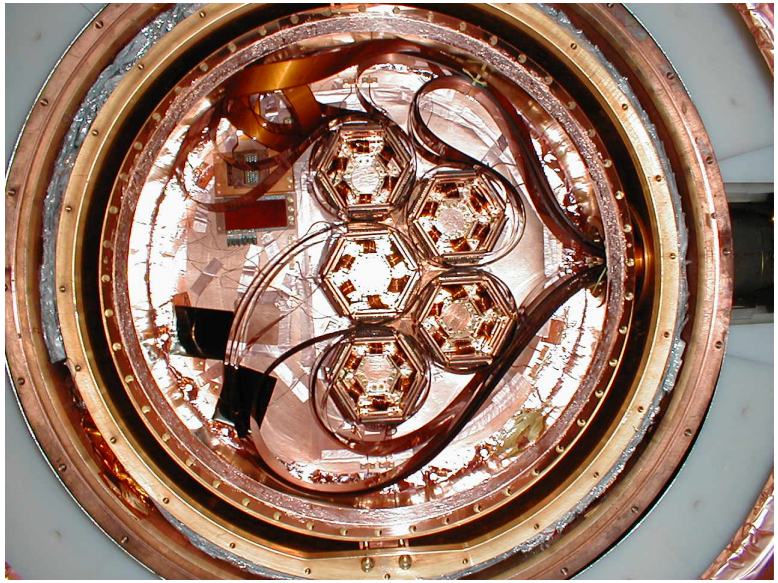
Many ways to detect nuclear recoils and discriminate from electron recoils



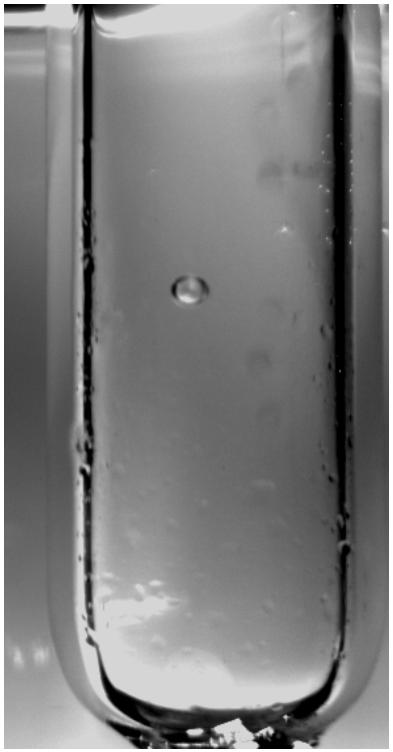
All direct detection experiments use either one or two of these techniques

The Fermilab Direct Detection Suite

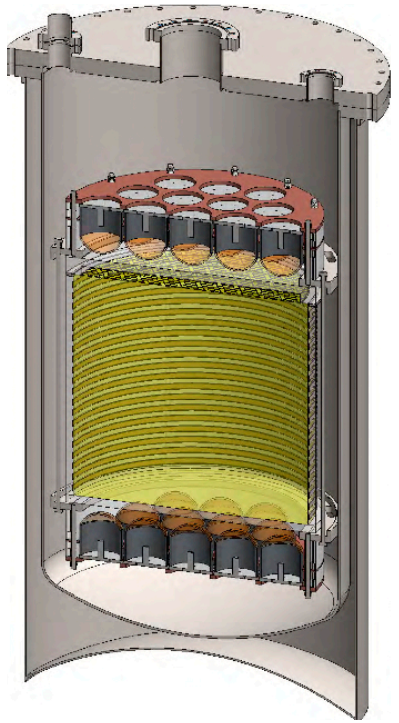
CDMS (cryogenic Ge)



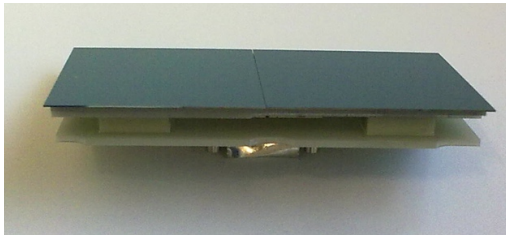
COUPP (Bubble Chamber)



DarkSide (LAr TPC)



DAMIC (CCDs)



Cryogenic Dark Matter Search (CDMS)
Cryogenic Germanium Detectors

FNAL responsibilities include everything except the detectors
Involved since 1998. Currently 3 FTE scientist

Detectors

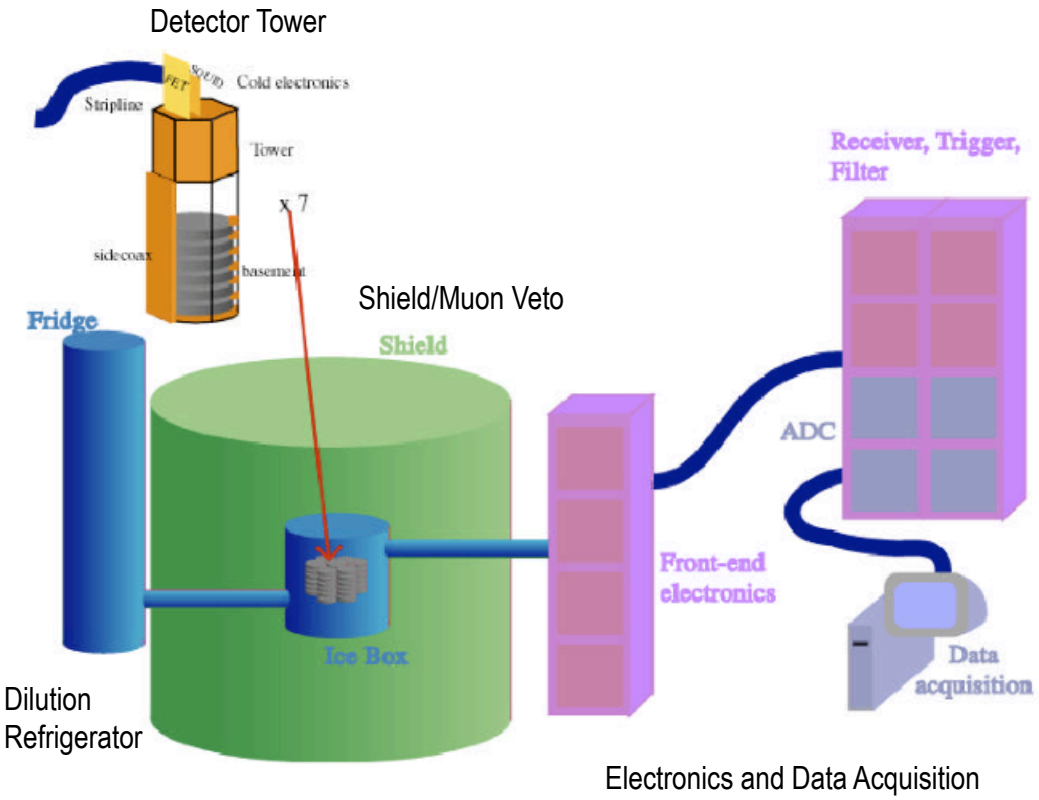
Pure Ge and Si crystals
Detect charge and phonon signals to provide excellent background rejection

Cryogenics

Cool to near absolute zero in order to see single particles

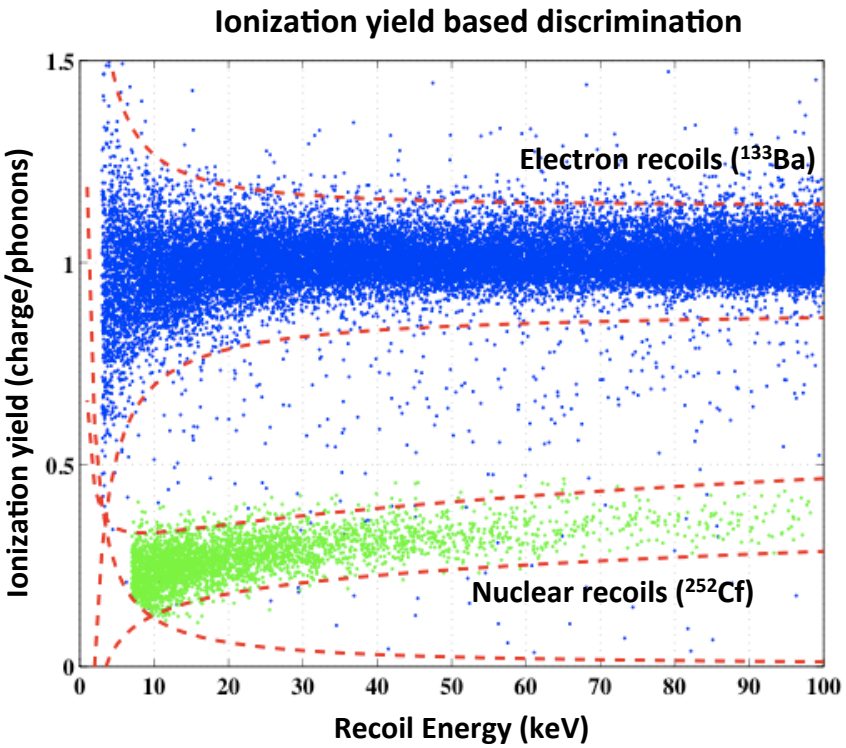
Shielding and Veto

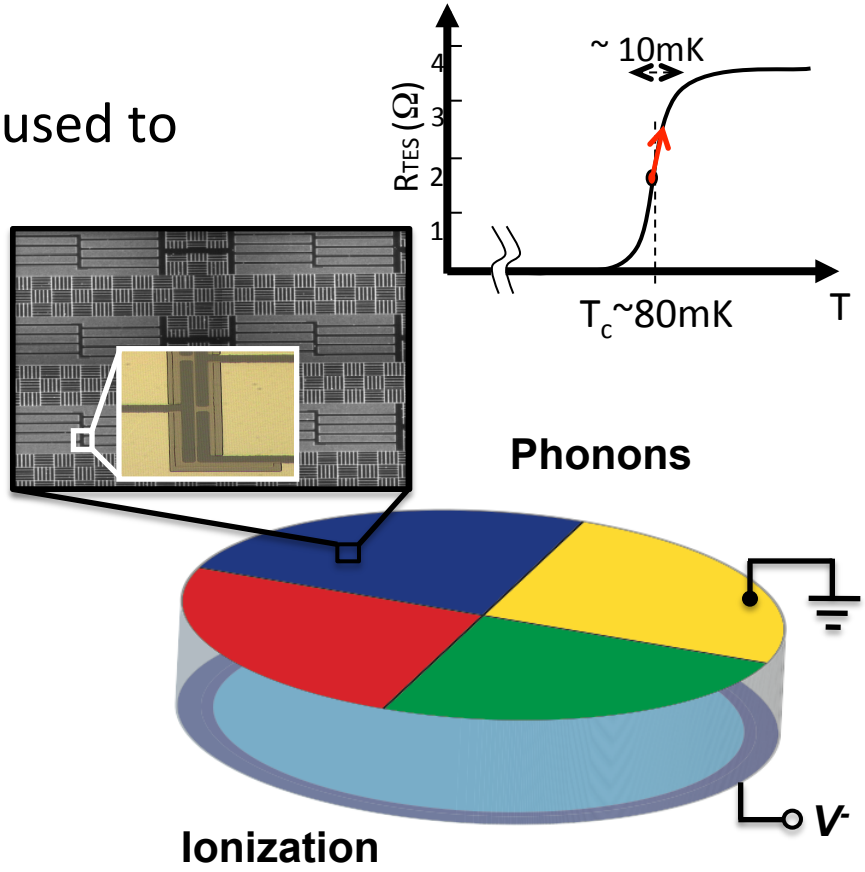
Reduce flux of radioactive decay particles near the detectors
Actively tag any interactions associated with cosmic rays



CDMS Detectors

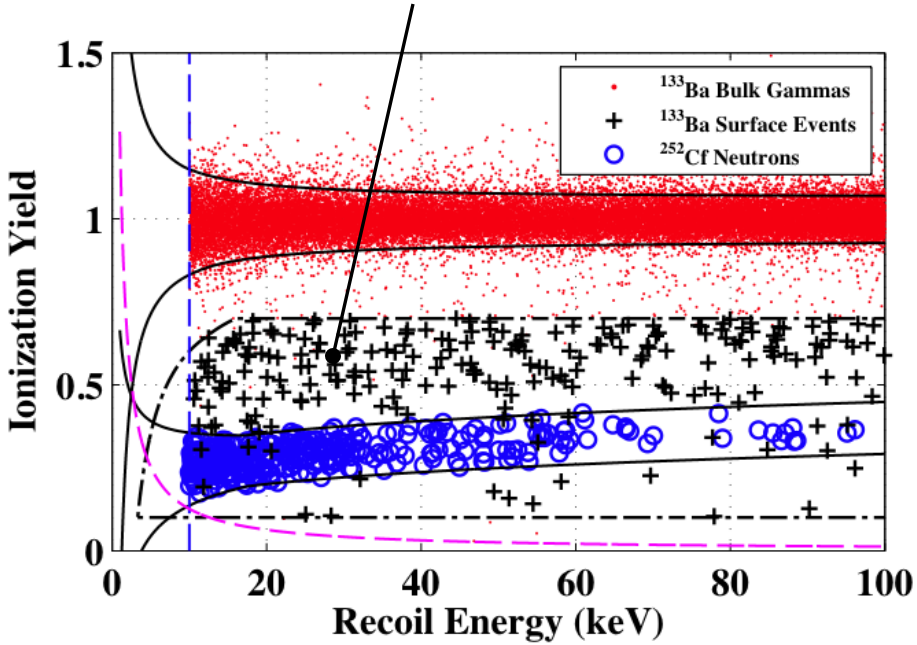
- Measure both phonons and ionization for each particle interaction
- Ratio of ionization to recoil energy used to identify nuclear recoils





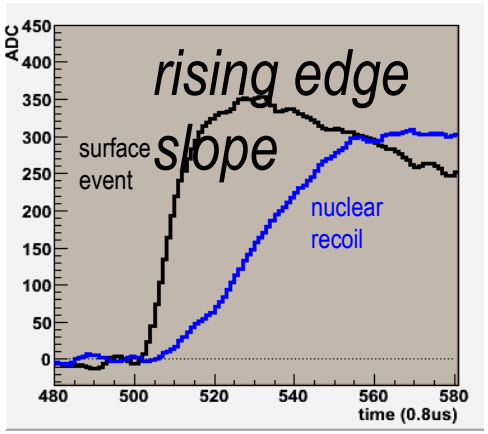
Rejection of Surface Events

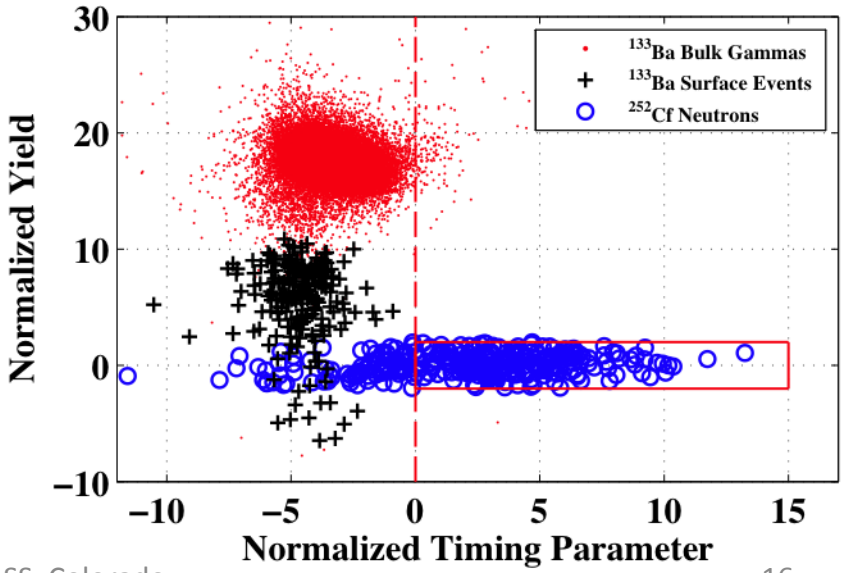
10 μm "dead layer" results in reduced ionization collection



These events are primarily due to electrons and soft x-rays originating from Radon daughters on faces of the detectors and nearby materials

Phonon pulse shape (timing) distinguishes surface events





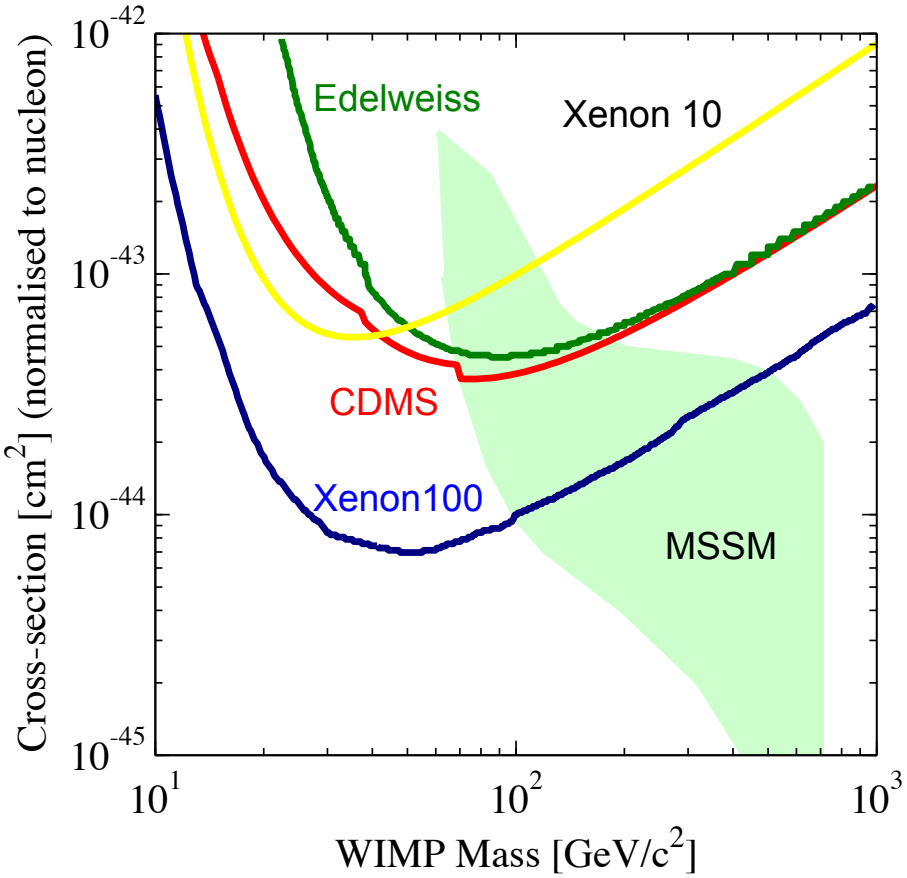
Limits on Spin-Independent WIMP Interactions

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**

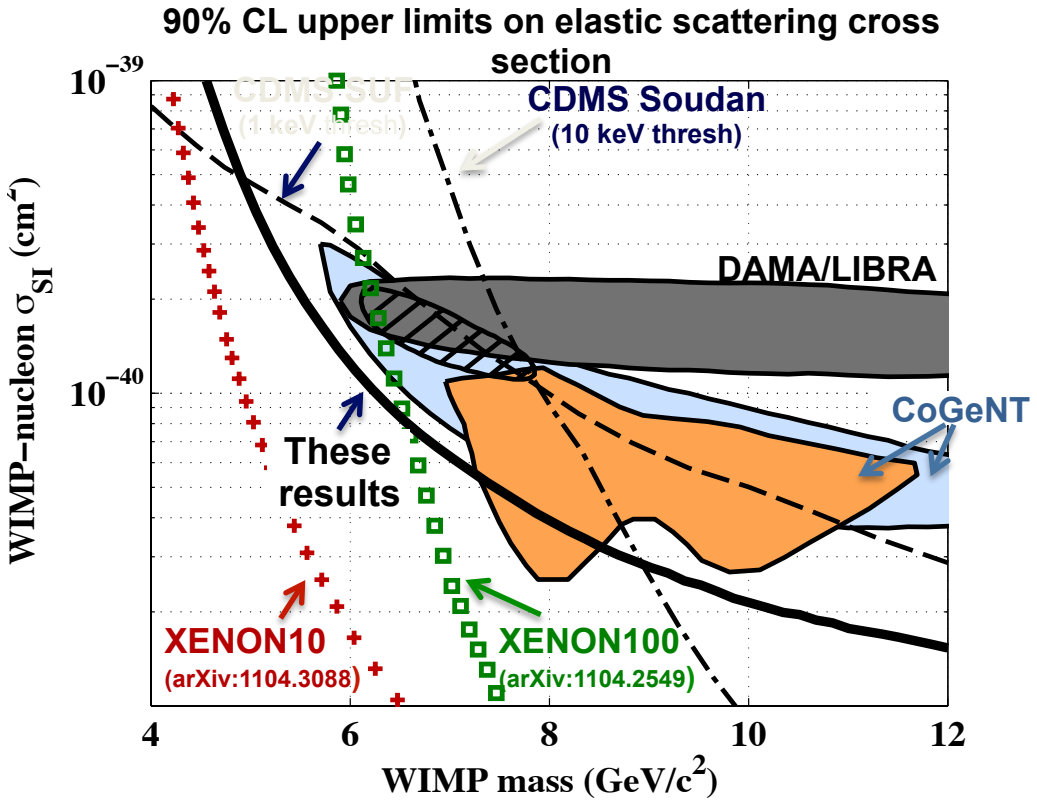
Surpassed by March 2011 limits from Xenon100 at **7×10^{-45} cm^2.**

Still no sign of WIMPS, so the race continues!



Low-threshold searches for 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
- Considerable controversy about Xenon low-mass limits



Ahmed et al., PRL **106**, 131302 (2011), *arXiv:1011.2482*
Akerib et al., PRD **82**, 122004 (2010), *arXiv:1010.4290*

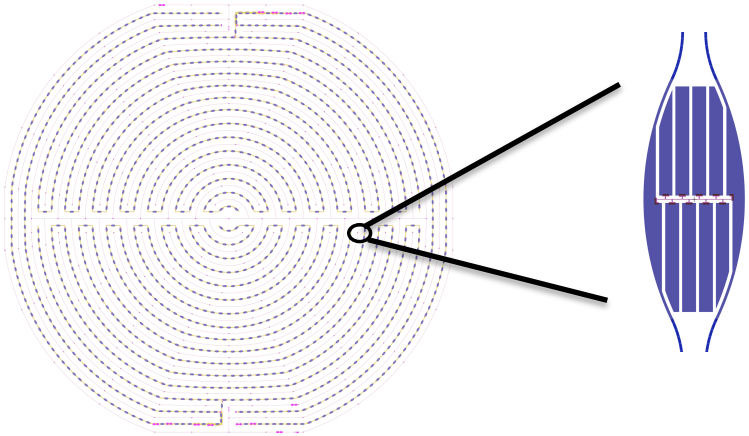
SuperCDMS – A Detector Breakthrough

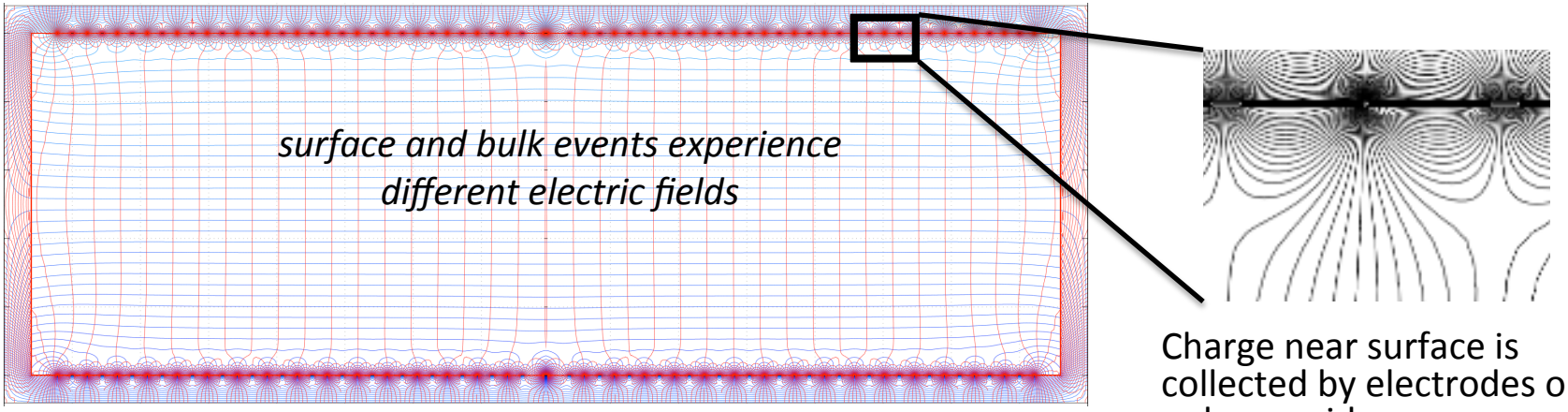
iZIP = interleavened charge and phonon channels

Rejection of surface events > x30 better than single-sided detectors

Fiducial volume x2 better than CDMS II (~80% of the crystal)

At least 3 iZIP towers will be included in SuperCDMS Soudan





Charge near surface is collected by electrodes on only one side

The Future – SuperCDMS

- Run new iZIPs at Soudan
  - Prove background performance
  - Provide better WIMP limits than Xenon100 for low and high mass
- 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
- Compete in the ‘generic’ dark matter DOE CD process
  - FNAL will manage the SNOLAB project, and do cryogenics, shielding, DAQ
  - SLAC joins to lead production of the Ge towers
  - Significant Canadian involvement (Queens, SNOLAB)
  - DOE and NSF supported University group contributions vital

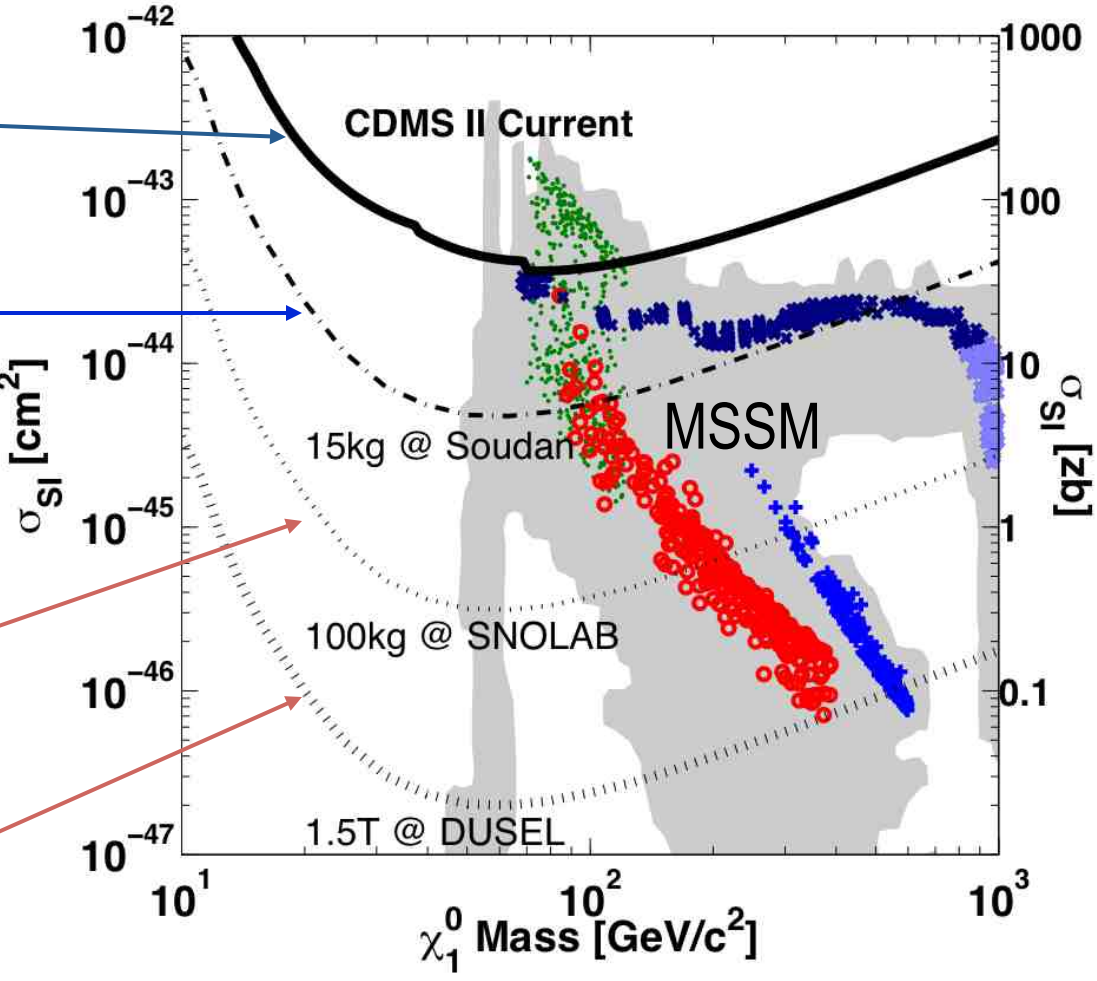
CDMS Future Projections

CDMS II
4 kg Ge
~ 2 yrs operation
Background limited

SuperCDMS @ Soudan
15 kg Ge
~ 2 yrs operation
Probably background limited

SuperCDMS @ Snolab
100 kg Ge
~ 2 yrs operation
Should be background free

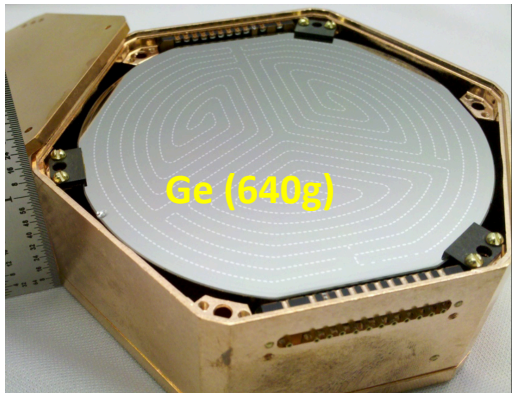
GEODM
1.5T
iZIPs should ensure background free

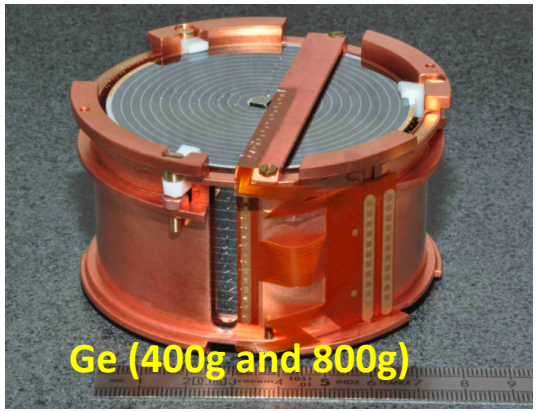


Current Cryogenic Experiment Status

SuperCDMS (Soudan) | **EDELWEISS II** (Modane) | **CRESST II** (Gran Sasso)

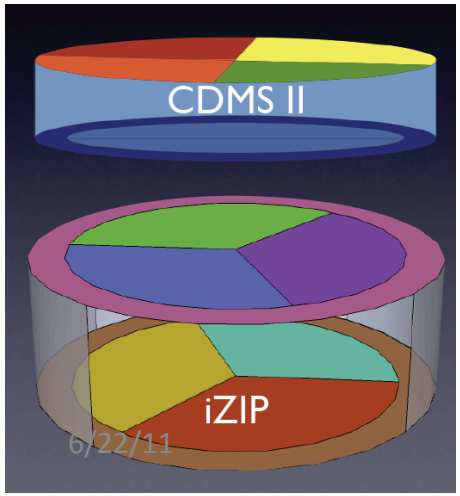
Improved Surface Event rejections via Larger Detectors
New interleaved electrodes ➔ surface event rejection

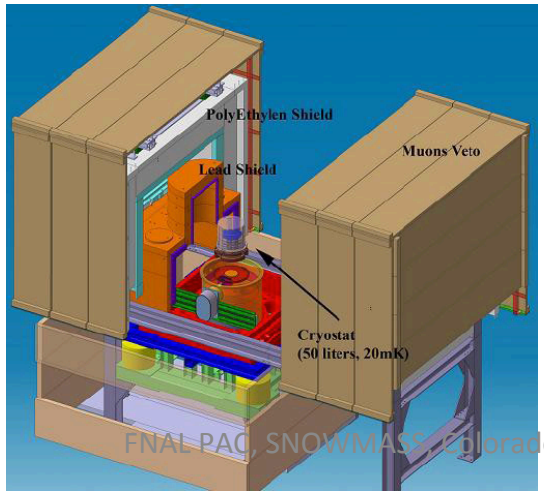




Deploying 10 kg iZIPs

2 NTD, 6 electrodes
new cryostat – up to 40 kg





More mass & multiple targets
Composite detector design
(simplified TES)
Improve clamps to reduce bkgd
mechanical (dark evts)
scint veto (^{210}Pb α,NR)

Chicagoland Observatory for Underground Particle Physics (COUPP)
Bubble Chambers

Fermilab Responsibilities includes everything except acoustic sensors
Involved since 2004. Currently 4 FTE scientist effort

Large target masses

Multi ton chambers were built in the 50's- 80's.

Choice of target nuclei

"Heavy Liquids": Xe, Ne, CF_3I are good targets for both spin-dependent and spin-independent scattering

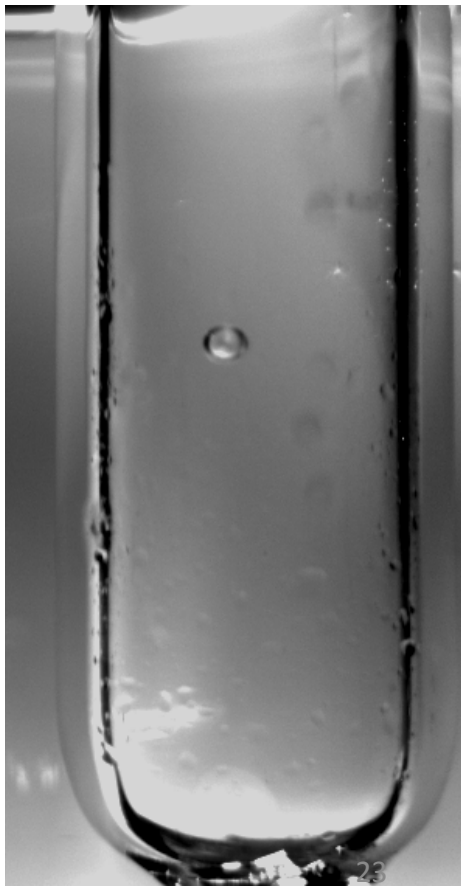
Possible to "swap" liquids to check suspicious signals

Low energy thresholds

<10 keV threshold achievable

Background Suppressions

Immune to electromagnetic backgrounds



The Technique

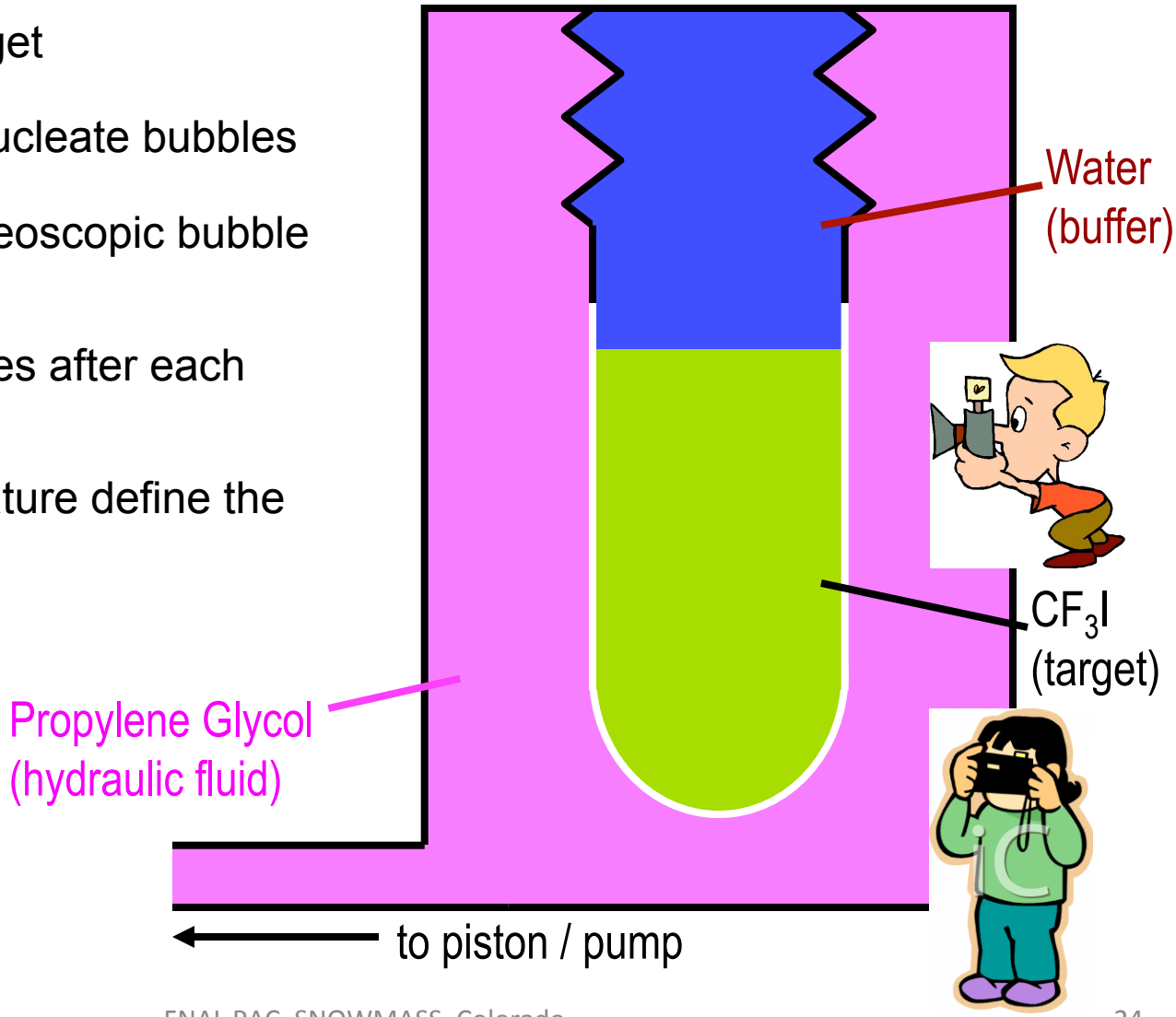
Superheated CF_3I target

Particle interactions nucleate bubbles

Cameras capture stereoscopic bubble images

Chamber recompresses after each event

Pressure and temperature define the operating point



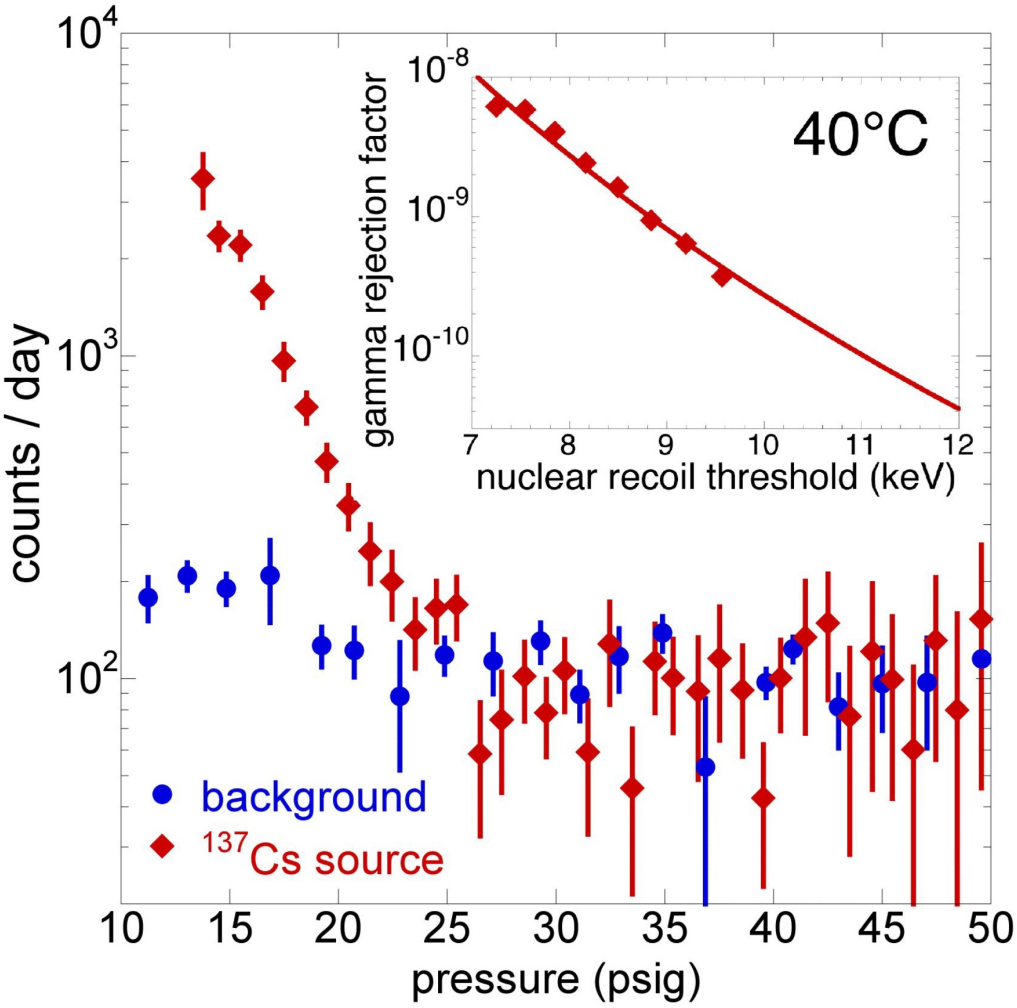
Thresholds for Bubble Nucleation

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 ☹



Progress in Bubble Chamber R&D

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

Important test bed in the NUMI underground hall

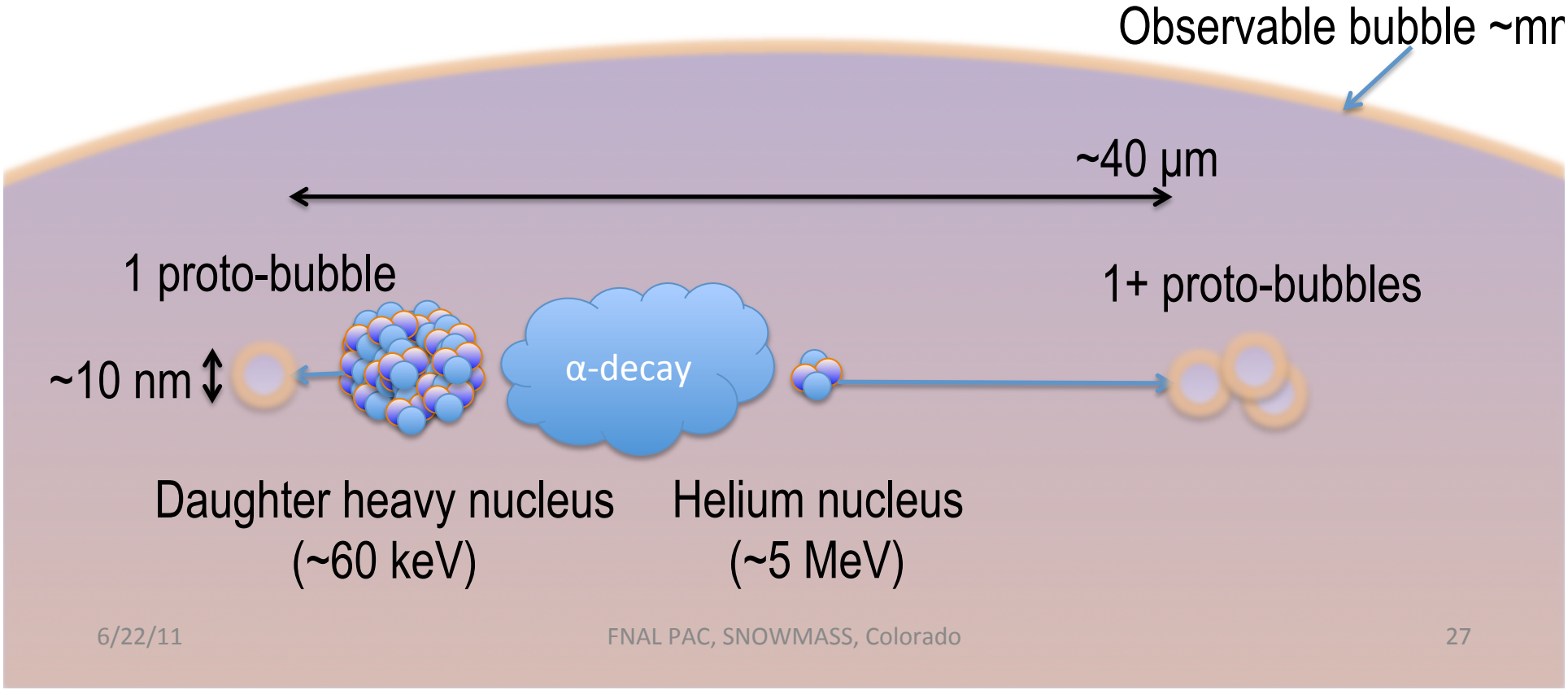
Ultimate goal is ton-scale bubble chamber

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	

Acoustic Discrimination Against Alphas

High frequency acoustic information probes smaller scales

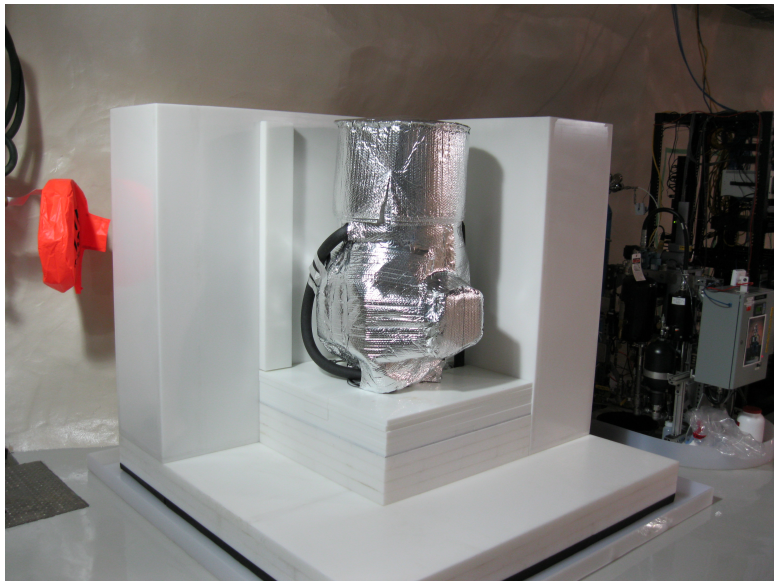
Alpha decays produce many bubbles, louder at high frequencies

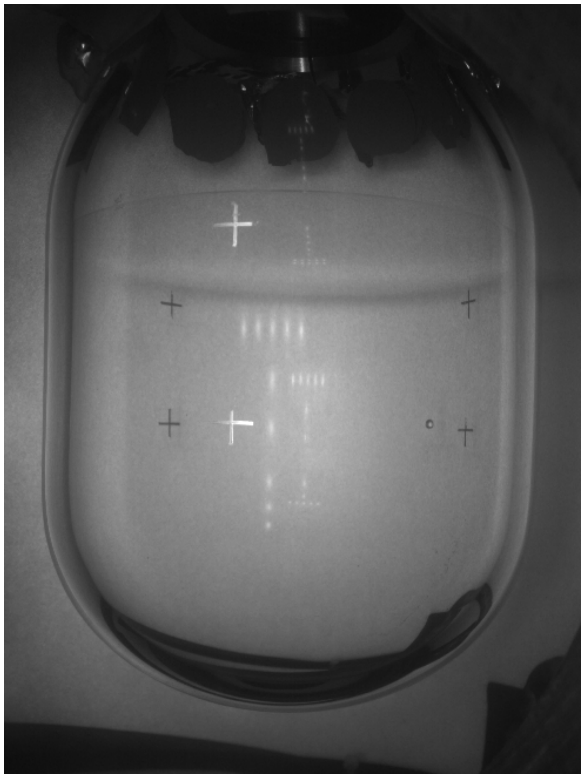


COUPP 4 kg – Installed at SNOLAB

The 4 kg chamber has recently been relocated to the deep underground SNOLAB facility

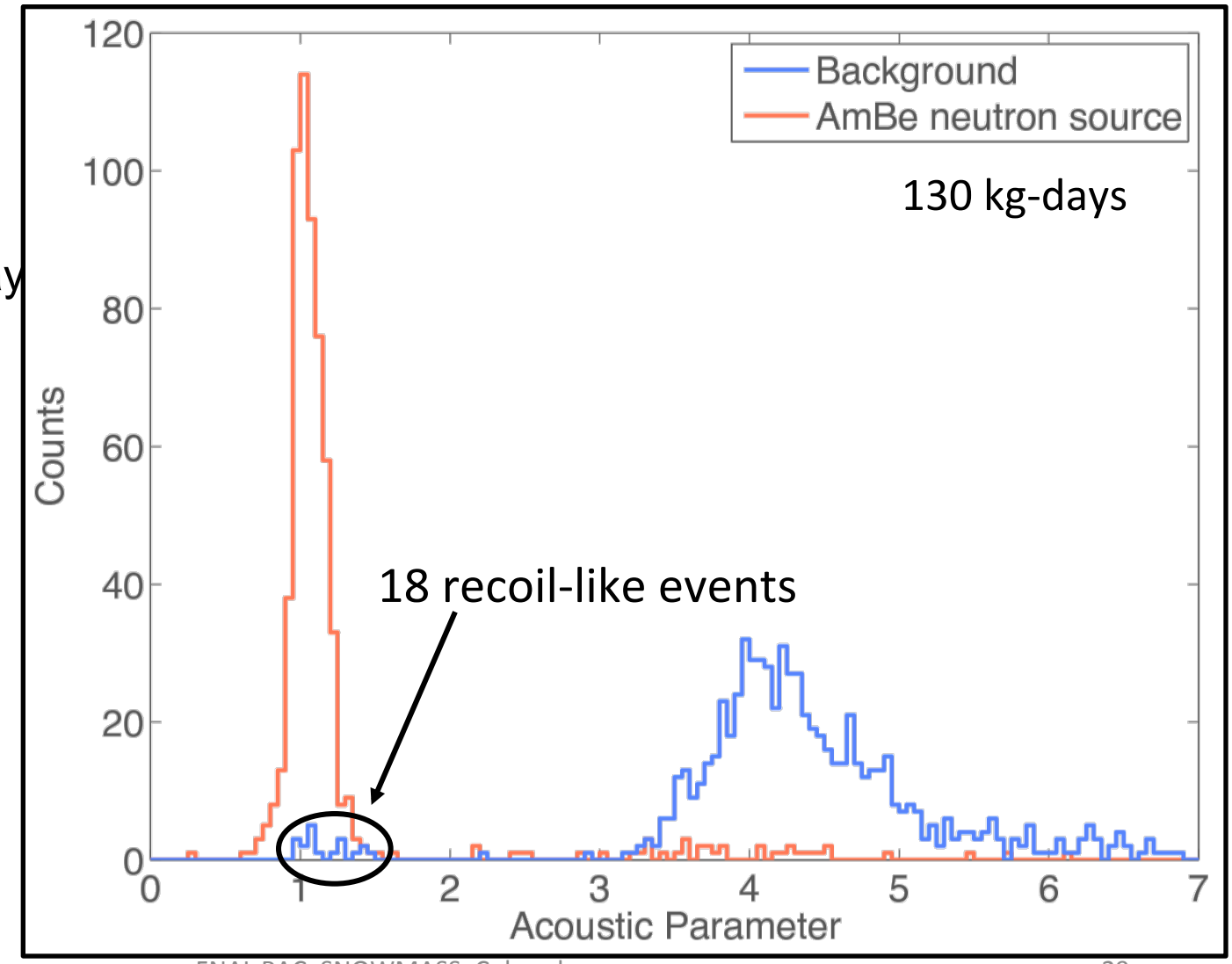
Main goal is to measure acoustic alpha discrimination



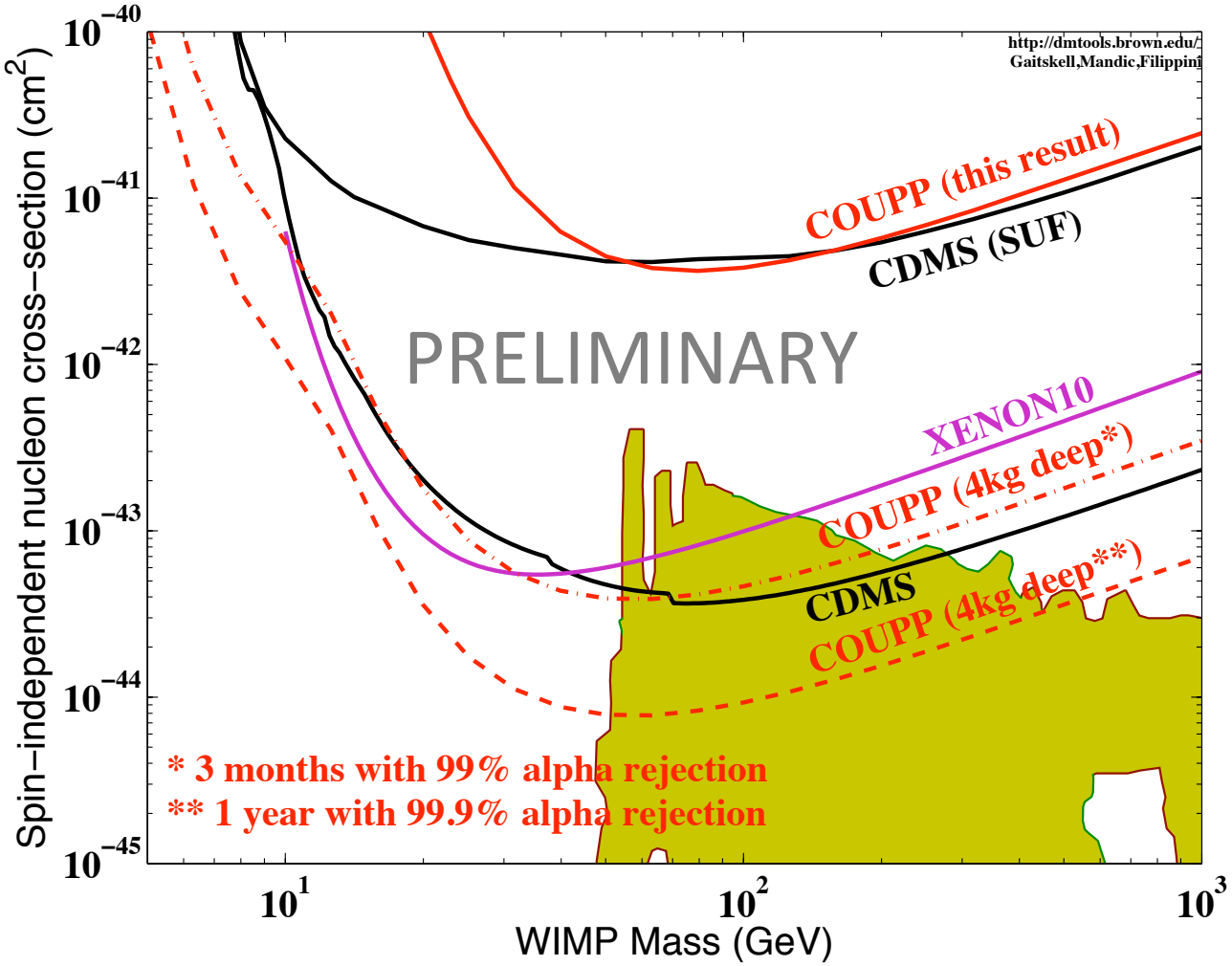


COUPP 4kg @ SNOLAB; early results

- Alpha rejection at least 98%
- Single-bubble background of ~0.05 events/kg-day from neutrons (***big*** statistical error bar)
- *O*(1) event/year expected from cosmogenic and environmental neutrons



Projected Sensitivity for 4kg at SNOLAB



COUPP 60 kg - R&D for a larger experiment

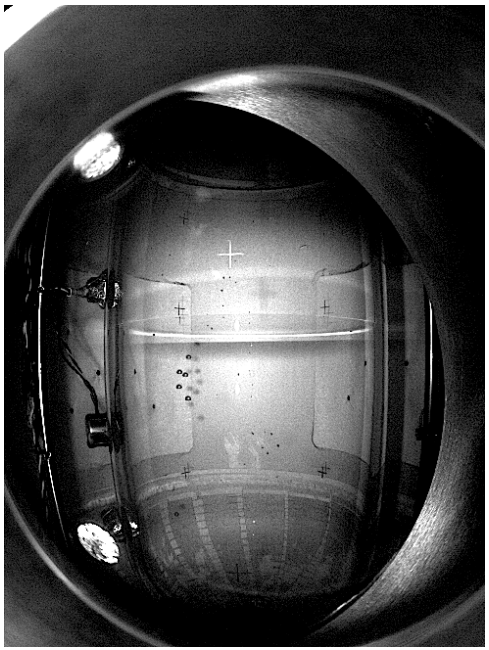
Data

Several live days of operation during July and August

Milestones

Successful commissioning of chamber and DAQ system

Demonstration of acoustic discrimination in large chamber



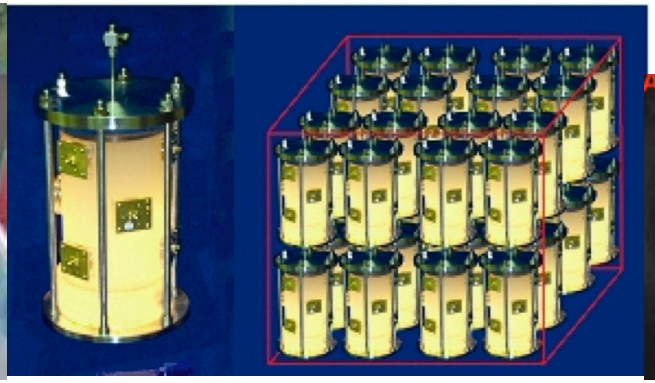
COUPP 60 Technical Issues

- Chemistry
  - CF_3I reacting with impurities or illumination
  - High bubble nucleation rate at CF_3I-H_2O interface
- Optics, Imaging
  - Higher resolution and frame-rate desired
  - More uniform illumination, lower intensity light source
- Neutron Backgrounds
  - Acoustic sensor replacement needed
  - Screening of other elements ongoing…

Goal is to fix problems at FNAL in 2011 and deploy to SNOLAB in 2012

Current Status of Threshold Detectors

Neutron dosimeter technology



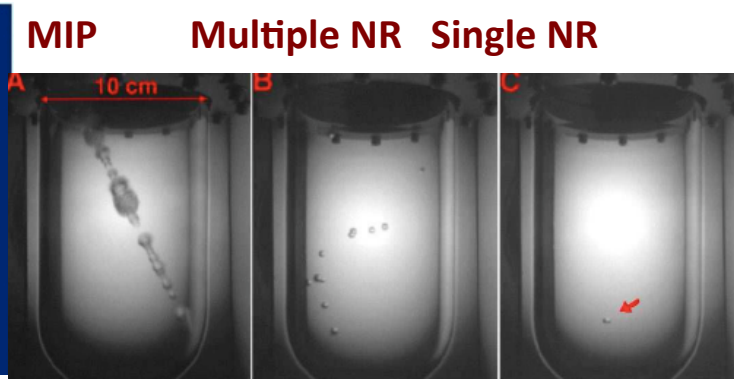
SIMPLE (Bas Bruit)

1-4 % suspension of superheated C_2ClF_5 droplets in gel.
shielded pool, shallow

PICASSO (SNOLab)

0.5% C_4F_{10} droplets in water-based gel
piezoelectric transducers

Bubble Chamber

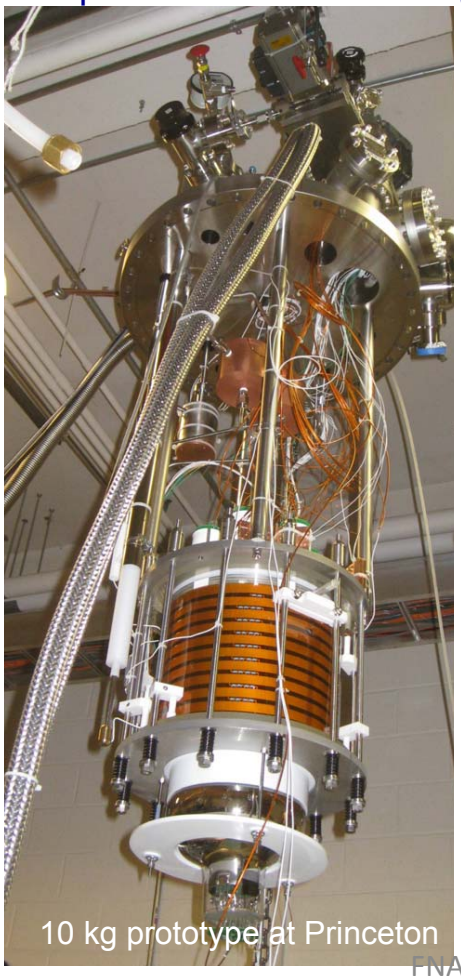


COUPP (SNOLab)

Superheated bubble chamber
CF_3I, multiple targets
CCD camera (+ acoustic)

DarkSide: *Liquid Argon TPC*

Fermilab responsibilities include liquid argon distillation, DAQ, electronics
Involvement began in 2008; currently 0.3 FTE scientist
Stephen Pordes now acting as project manager



10 kg prototype at Princeton

LAr distillation column at Fermilab

Why a Liquid Argon TPC?

- Pulse shape of primary scintillation provides very powerful discrimination between nuclear and electron recoils
  - Rejection factor expected to be $>10^8$ for > 60 photoelectrons
- Ionization to scintillation ratio is another semi-independent discrimination mechanism to extend pulse shape discrimination
  - Measured rejection factor ~10^2
- Spatial resolution of a few mm allows rejection of multiple interactions and "wall events”
- Main problem is large 39Ar radioactive contamination in atmospheric Argon gas

New technology introduced in DarkSide

Depleted Argon from underground sources

< 0.04 ^{39}Ar of atmospheric argon

Borated liquid scintillator neutron veto

Estimate >99.8% rejection efficiency for radiogenic neutrons

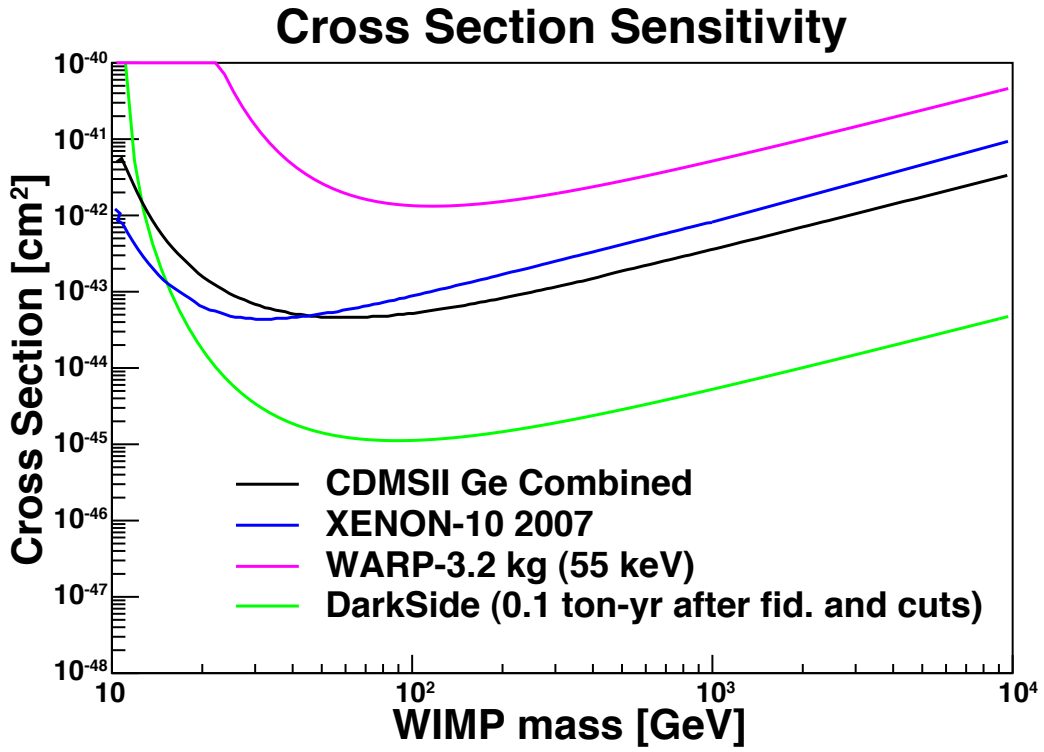
QUPID photosensors

no radioactive background detected in best HpGe screener
new photocathode with 35% QE at liquid argon temperature

DarkSide Goals

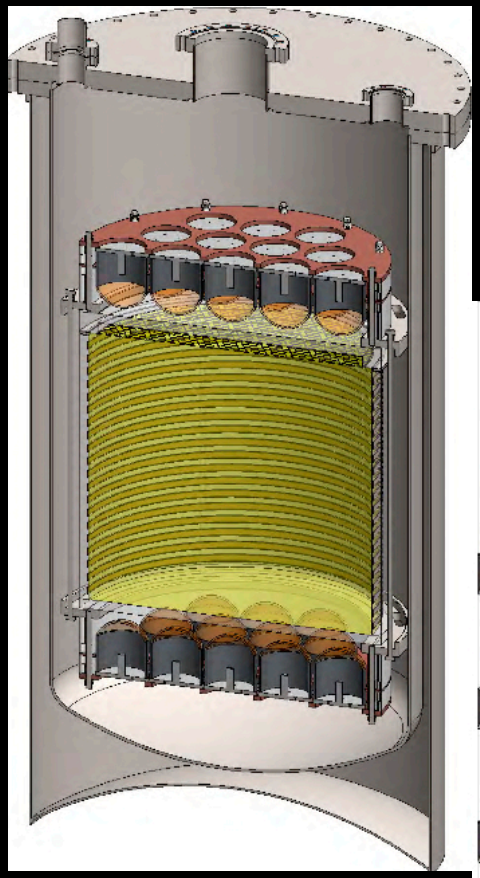
DarkSide 50 kg recently received DOE/NSF R&D funding

Plan to install at Gran Sasso in 2012

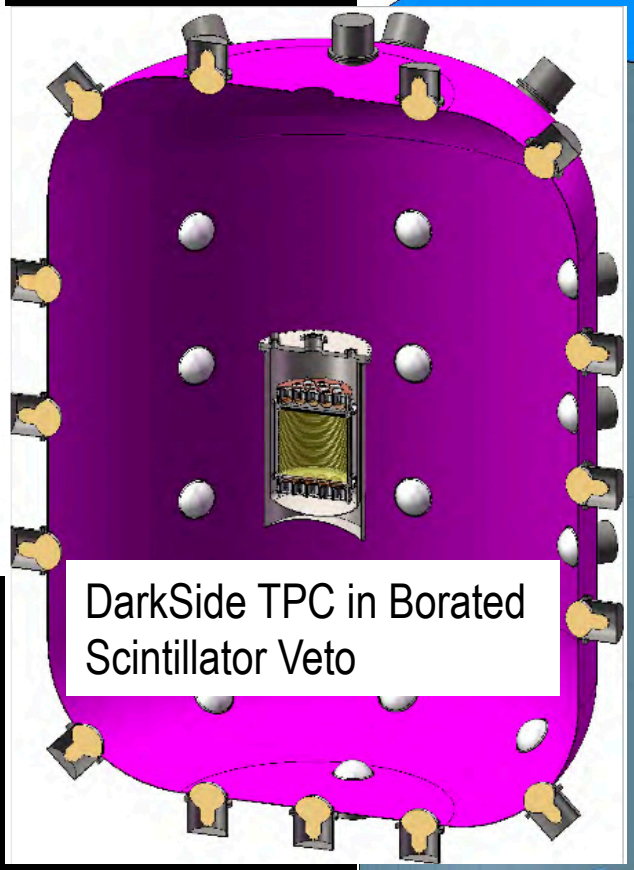


Projected Sensitivity assuming 3 years x 33 kg (fiducial) and < 0.1 event background

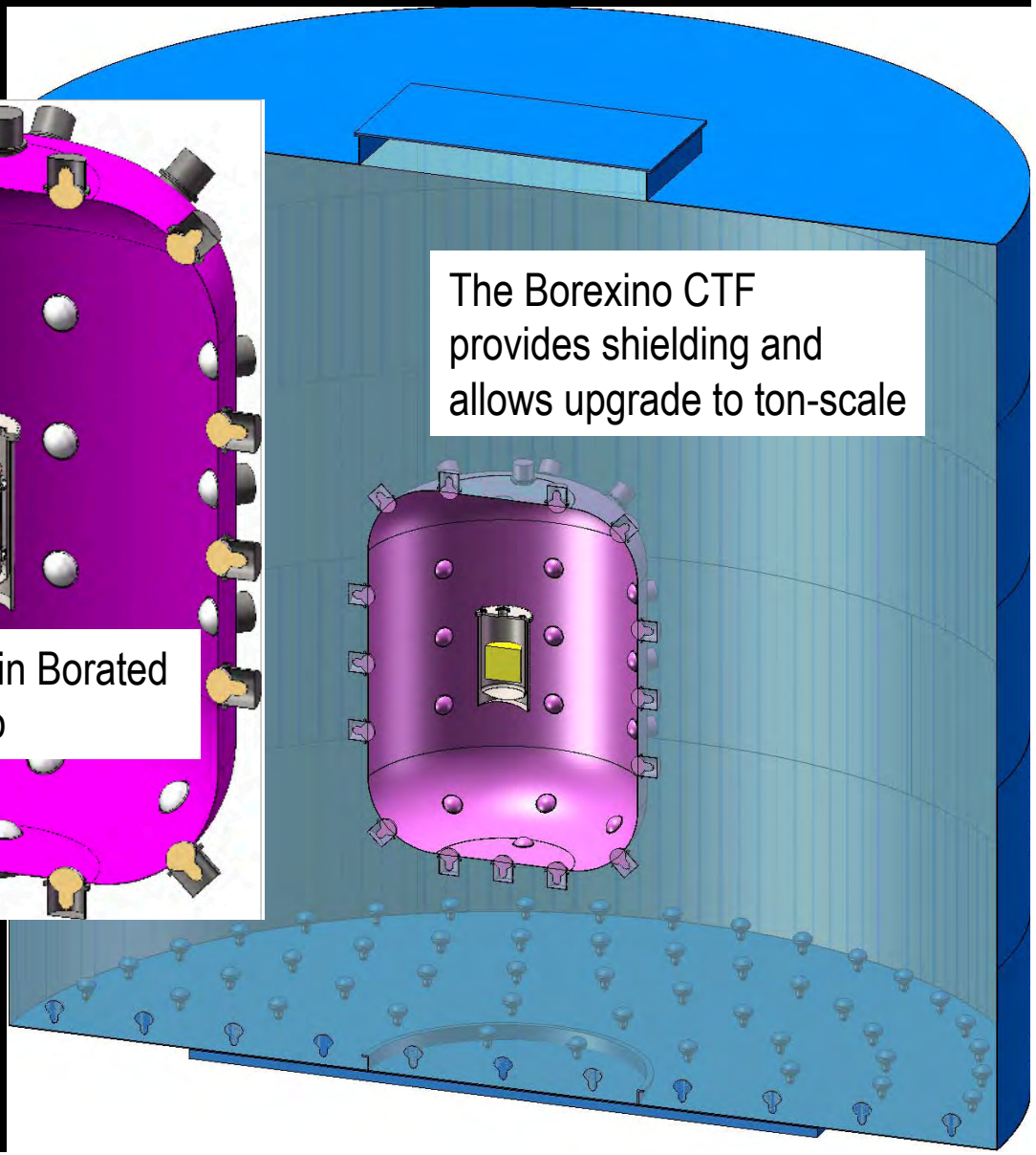
DARKSIDE installation in Borexino `Counting Test Facility' at Gran Sasso



50 kg LAr TPC



DarkSide TPC in Borated Scintillator Veto



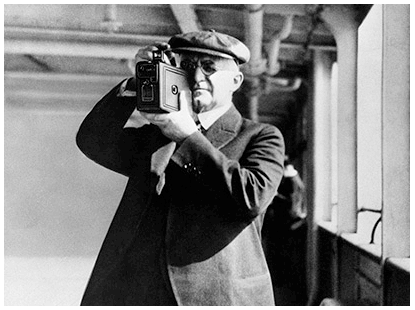
The Borexino CTF provides shielding and allows upgrade to ton-scale

Many Dual-Phase Noble Liquid Efforts

Liq Xenon	Location	Tot (Fid) kg	
Xenon10	LNGS	15 (5.4)	finished
Xenon100	LNGS	170 (35)	running
Zeplin II	Boulby	31 (7.2)	finished
Zeplin III	Boulby	12 (6.5)	running
LUX	Sanford	300 (100)	testing
Panda-X	JinPing	120 (25)	testing

Xenon 100 currently has the best limits on WIMPS

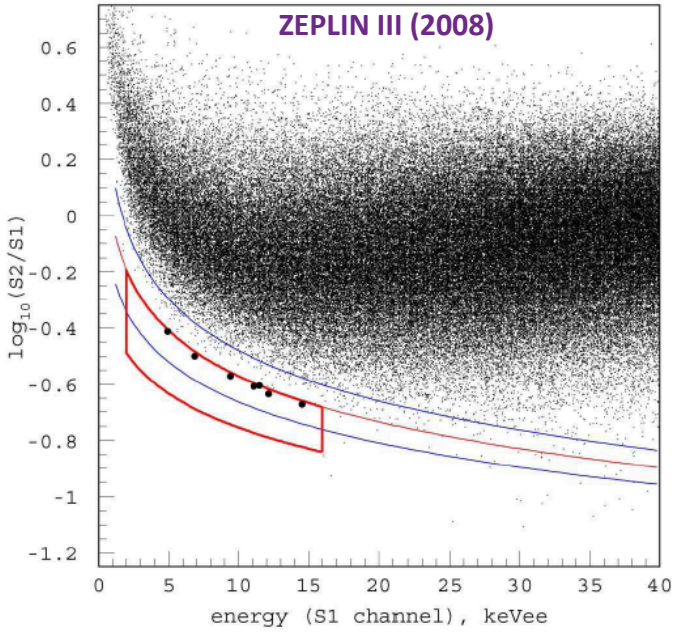
Liq. Argon	Location	Tot (Fid) kg	
WArP	LNGS	3.2	finished
WArP	LNGS	8T (140)	running
ArDM	CERN/Canfranc	850 kg	testing
Darkside	LNGS	50 kg prototype	testing



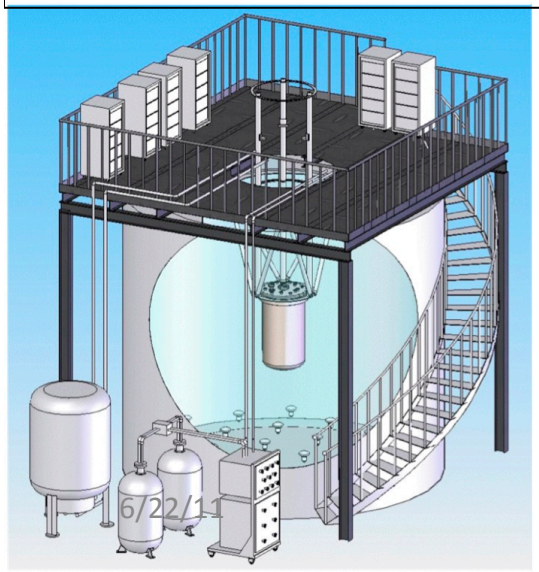
Other results expected soon

WArP-140 is currently running

ZEPLIN III final run will end this spring
- ~1500 kg-d with neutron veto
- new PMTs (18x bkgd reduction)



LUX surface testing now
Underground Spring 2012
Large water tank



Panda-X
complete by Fall 2011
Deep! no active shield

Single Phase Noble Liquids

XMASS has extraordinary purity and low radioactivity PMTs
100 kg is running now, 800 kg expected in 2012 (Kamioka)

DEAP/CLEAN (SNOLAB)

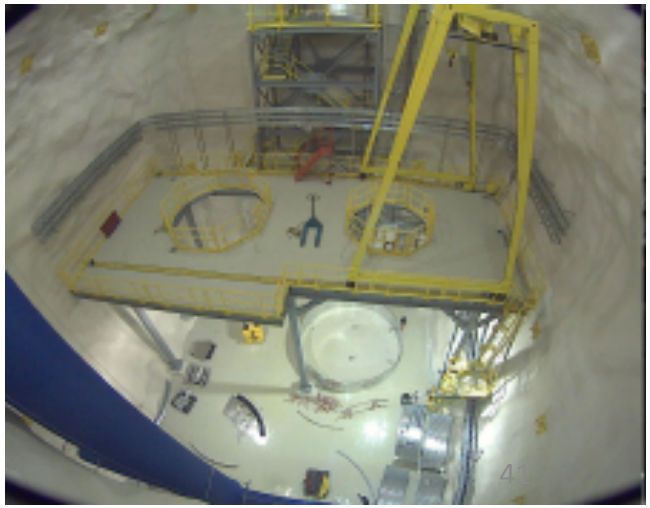
R&D **microCLEAN** (4 kg) LAr/LNe scintillation, PSD, NR quenching
DEAP-1 (7 kg) PSD rejection of 4.7×10^{-8} for 25-86 keV_{ee}

MiniCLEAN (500 kg) LAr/LNe to ~ 10^{-45} cm^2
Max light collection/sensitivity (> 6 pe/keV)

DEAP-3600 (3600 kg) LAr/DAr to ~ 10^{-46} cm^2

Both expected to start operations in 2012

Eventually **CLEAN** 10-100 Tons ~ 2×10^{-47} cm^2

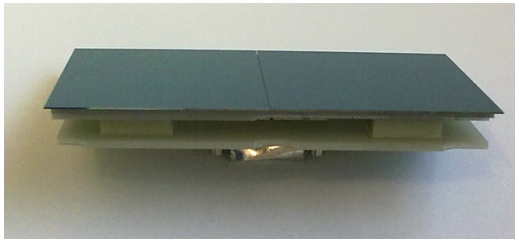


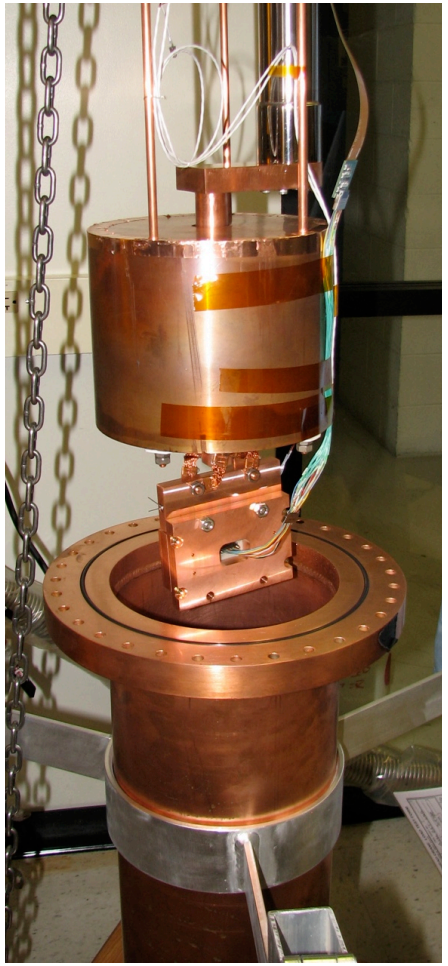
DAMIC
Very low mass WIMP search

Fermilab responsibilities in all aspects of experiment.

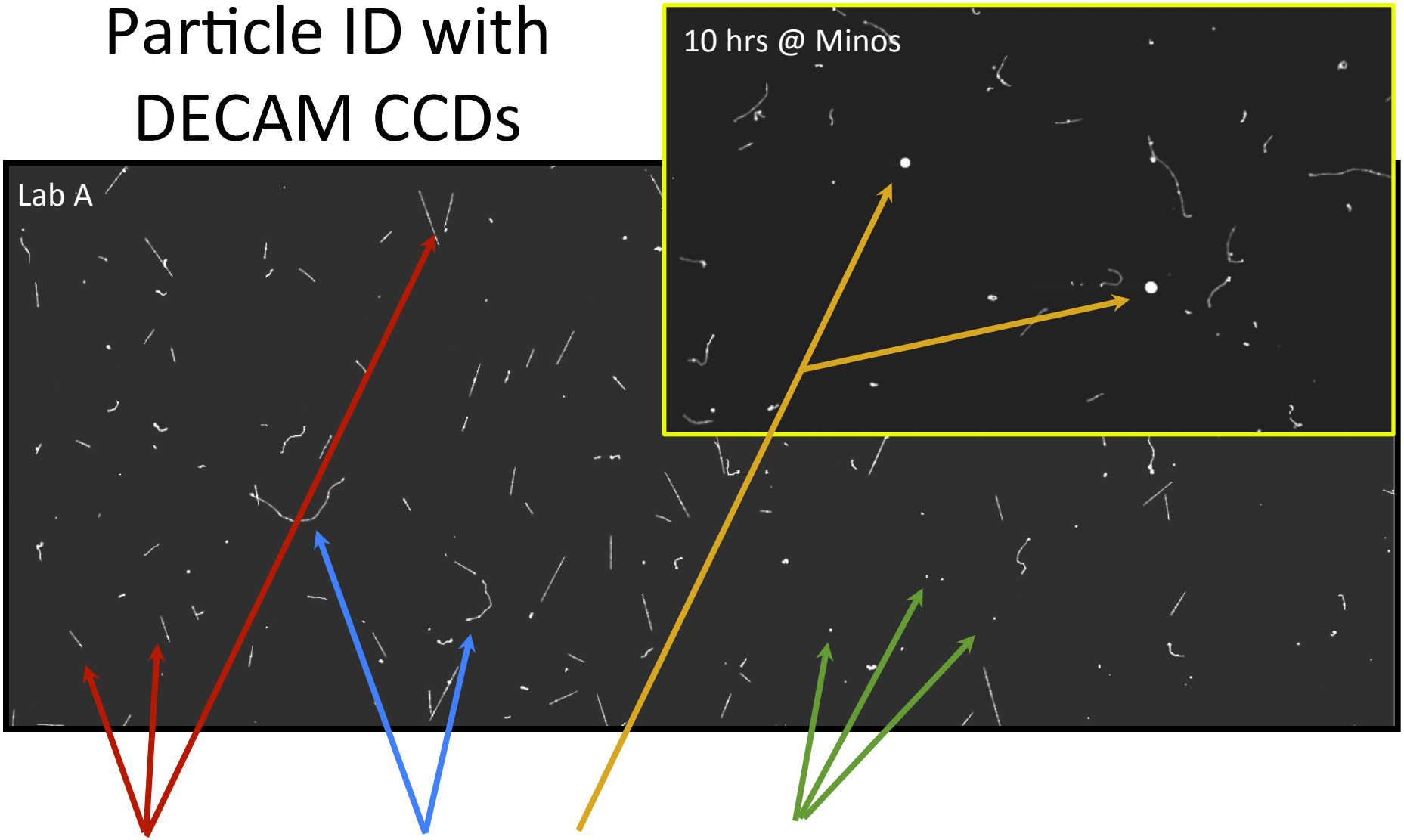
Led by Juan Estrada (PECASE award); 0.5 FTE

Goal is to explore low-mass WIMP sensitivity of thick CCD DECAM spares





Particle ID with DECAM CCDs

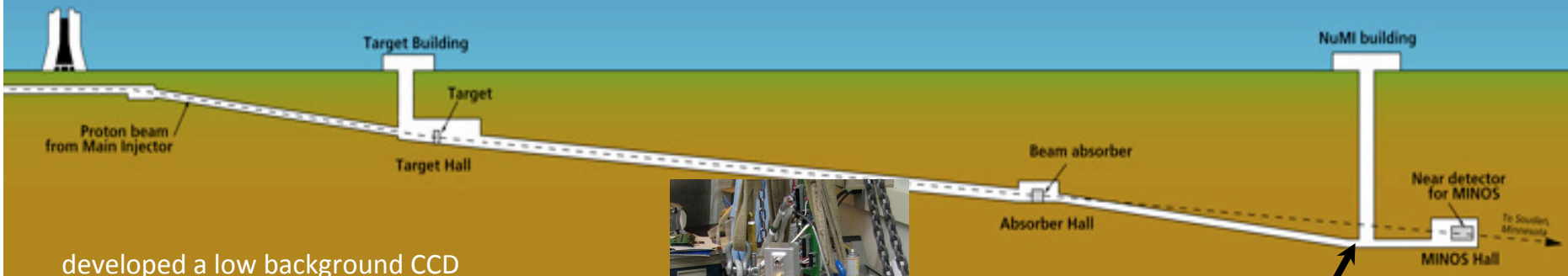


muons electrons alphas diffusion limited hits

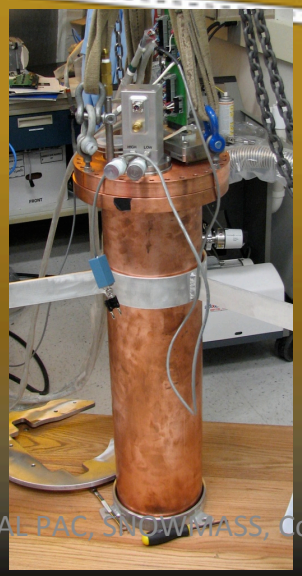
nuclear recoils will produce diffusion limited hits

DAMIC underground test at FNAL

CCD operated at 350' underground (MINOS hall)



developed a low background CCD package operated inside a Cu vessel shielded with lead.



Sensitivity to low Mass WIMPS

Direct Dark Matter Sensitivity with DAMIC CCD with a 40 eV threshold.

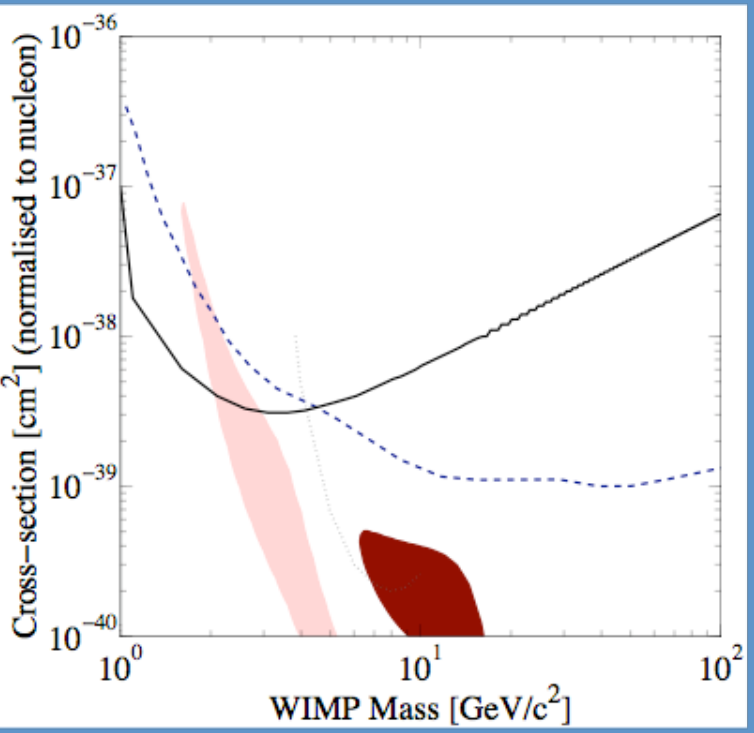
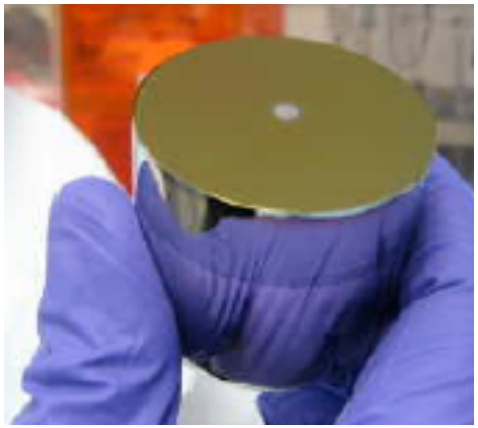


FIG. 8: Cross section upper limit with 90% C.L. for the DAMIC results (solid-black) compared to CRESST 2001 (dashed) and CoGent 2008 (dotted) results. The shaded area corresponds to the 3-sigma contour consistent with the DAMA/LIBRA annual modulation signal (dark: no ion channeling, light: ion channeling) [53].

High Purity Crystal Detectors

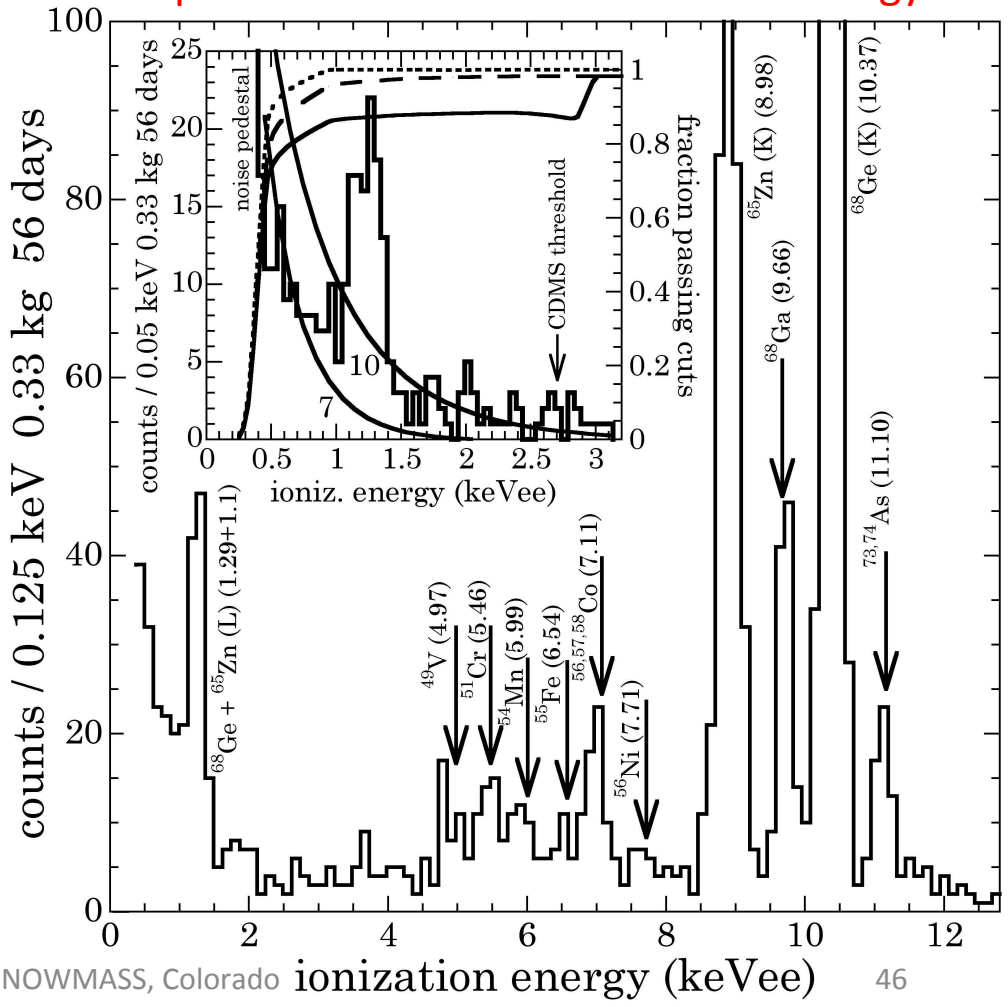


CoGeNT: P-type point contact HPGe

$\beta\beta0\nu$ (Majorana)
ν detector
DM detector

Aalseth et al., arXiv:1002.4703

Unexplained excess of events at low energy



Other players

CDEX (China Dark matter EXperiment) at new Jin-Ping Lab
Merging of collaborations and technologies

TEXONO (Taiwan EXperiment On neutrinO) at Kuo Sheng Reactor
ULB-HPGe (1 kg)
CsI(Tl) (200 kg)
ULE-ULB-HPGe (20g)

Diurnal Directional Modulation

Robust Signature – Promises WIMP astronomy!

large modulation (20-50%), compared with 3% for annual sidereal – hard to fake it with background

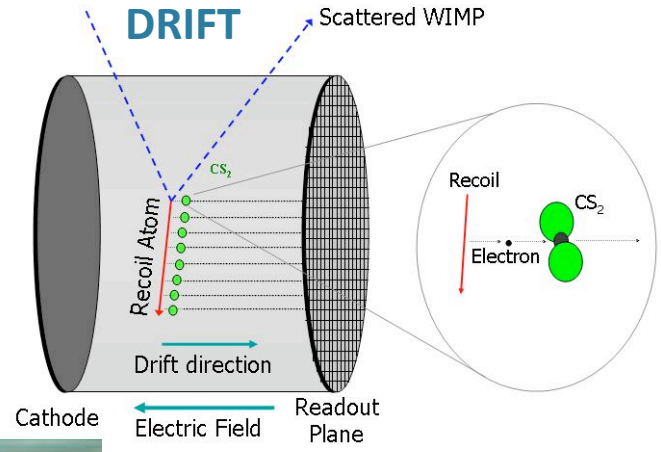
To see tracks or head-tail difference ➔ gas target
But gas targets need to be huge to have enough mass

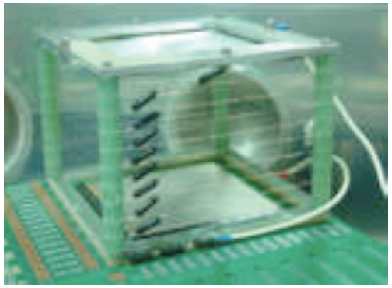
DRIFT II (running – Boulby)
Competitive SD limits
Negative ion TPC w/ MWPC readout
CS_2 molecule (less diffusion)

NEWAGE (test cell at Kamioka)
Ar + C_2H_6 micro-TPC
microdot charge readout

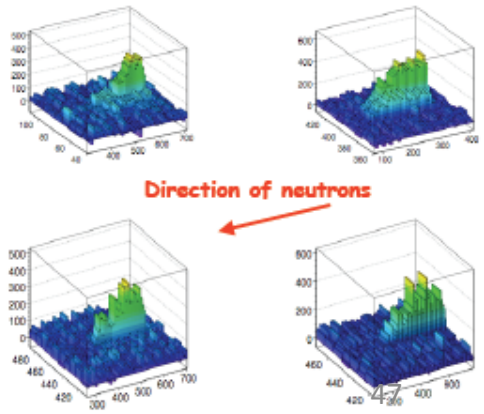
MIMAC (test chamber CEA- Saclay)
^3He or CF^4 micro-TPC

DMTPC (test chamber – MIT, WIPP)
CF_4 low pressure TPC with optical readout



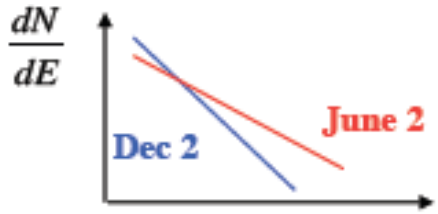


DMTPC head-tail



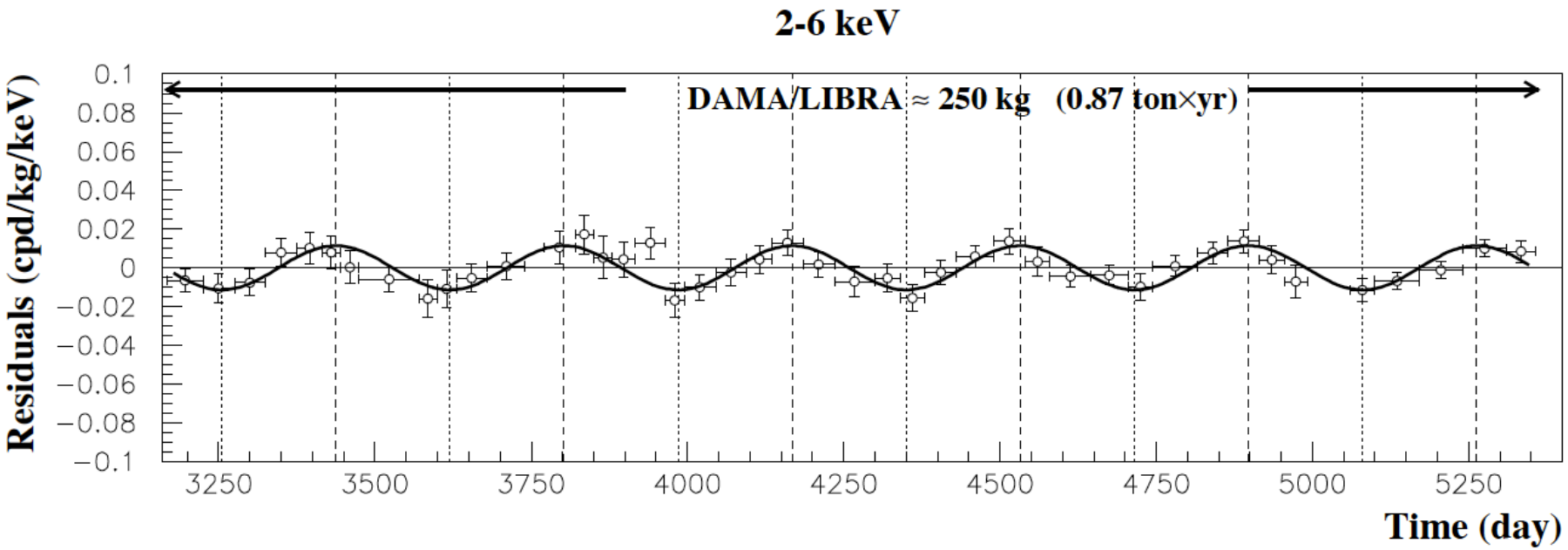
Annual Modulation

The Elephant in the Room – DAMA/LIBRA



DAMA/LIBRA exposure = 1.17 ton-years of NaI(Tl) at LNGS
25 crystals, each 9.5 kg, running for 6 y in LIBRA (13 yrs total)

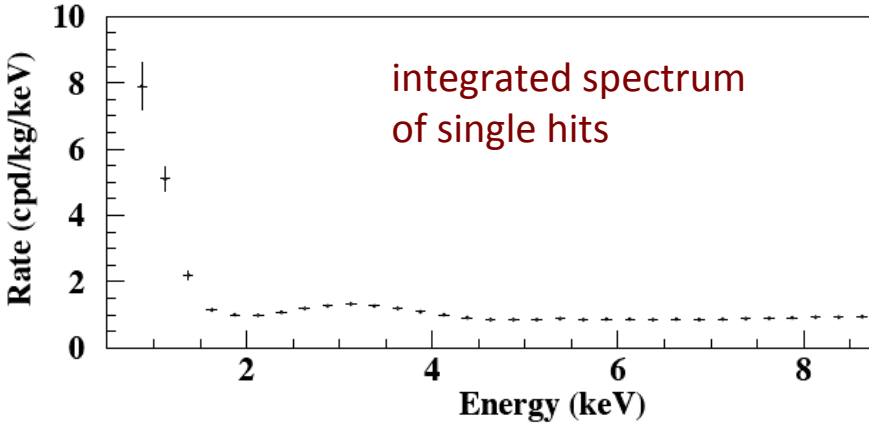
DAMA/Libra: A signal, but DM??

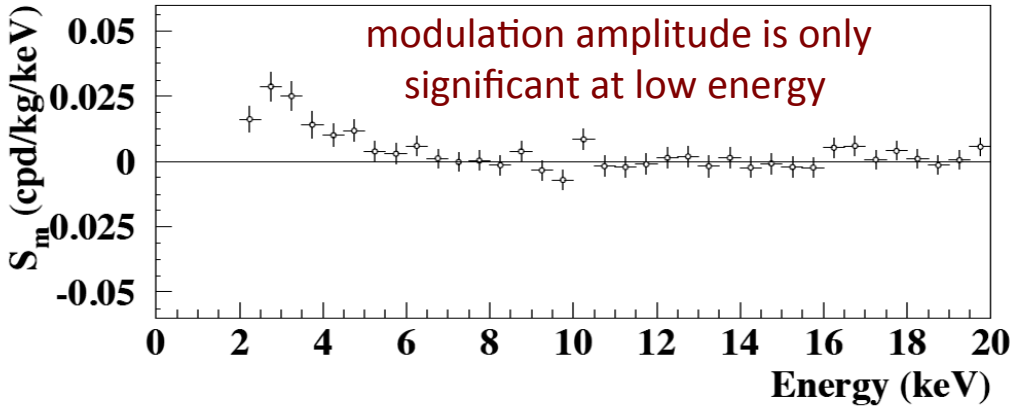


Modulation amplitude of a few percent

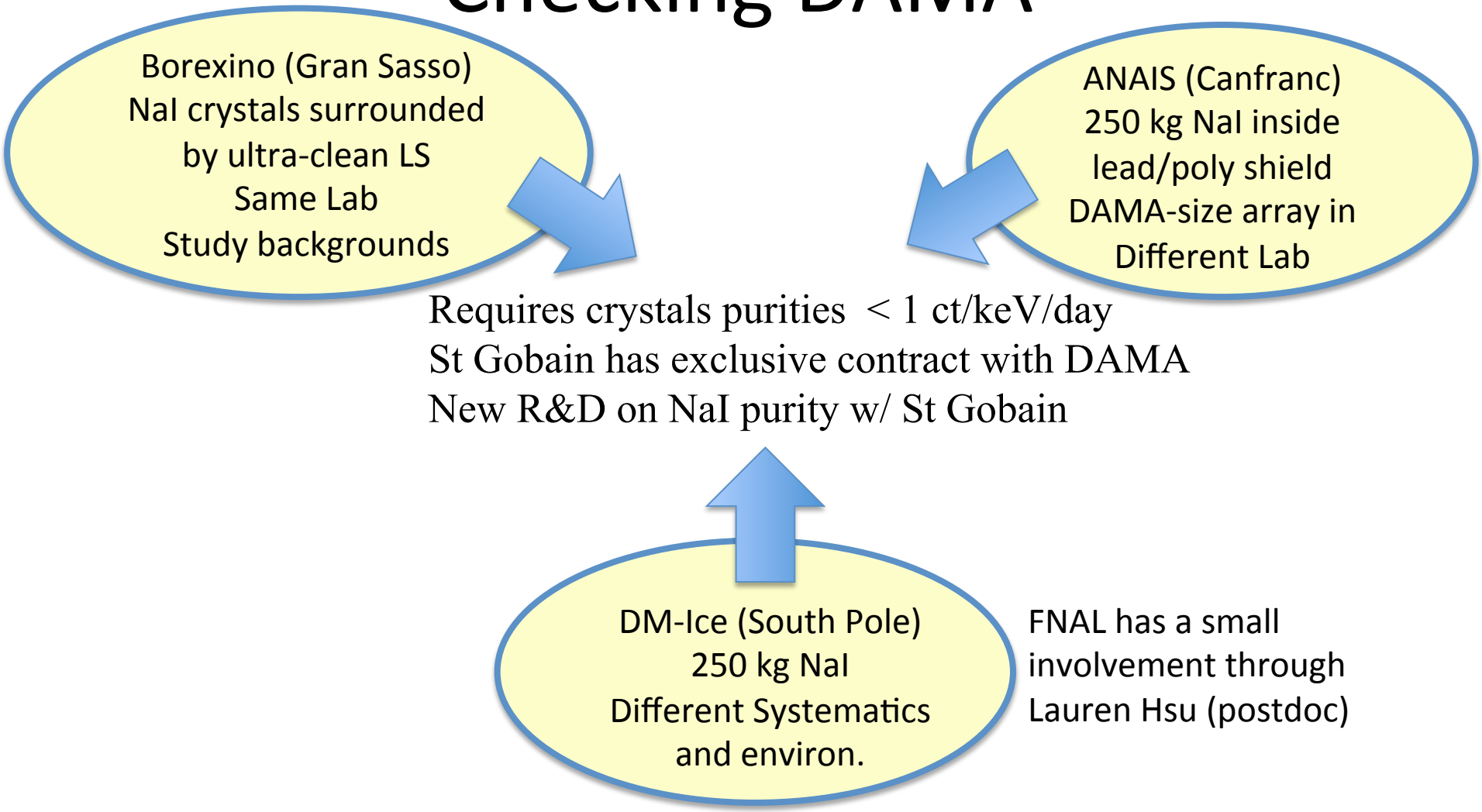
Phase Max on June 2

Significance of 8.9 σ



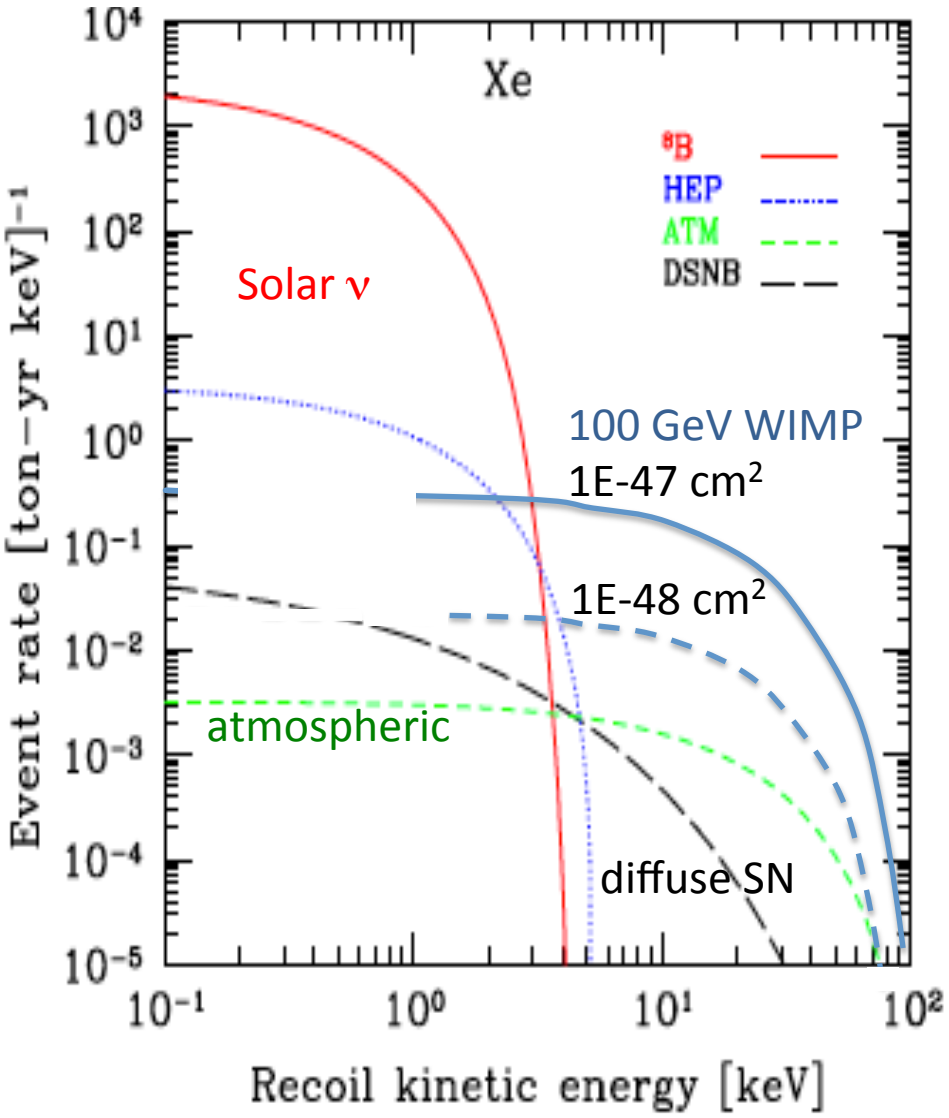


Checking DAMA



If DAMA signal is astrophysical➔ a 5-sigma measurement in 2 years with 250 kg and comparable background to DAMA.

The Ultimate Background: Neutrinos



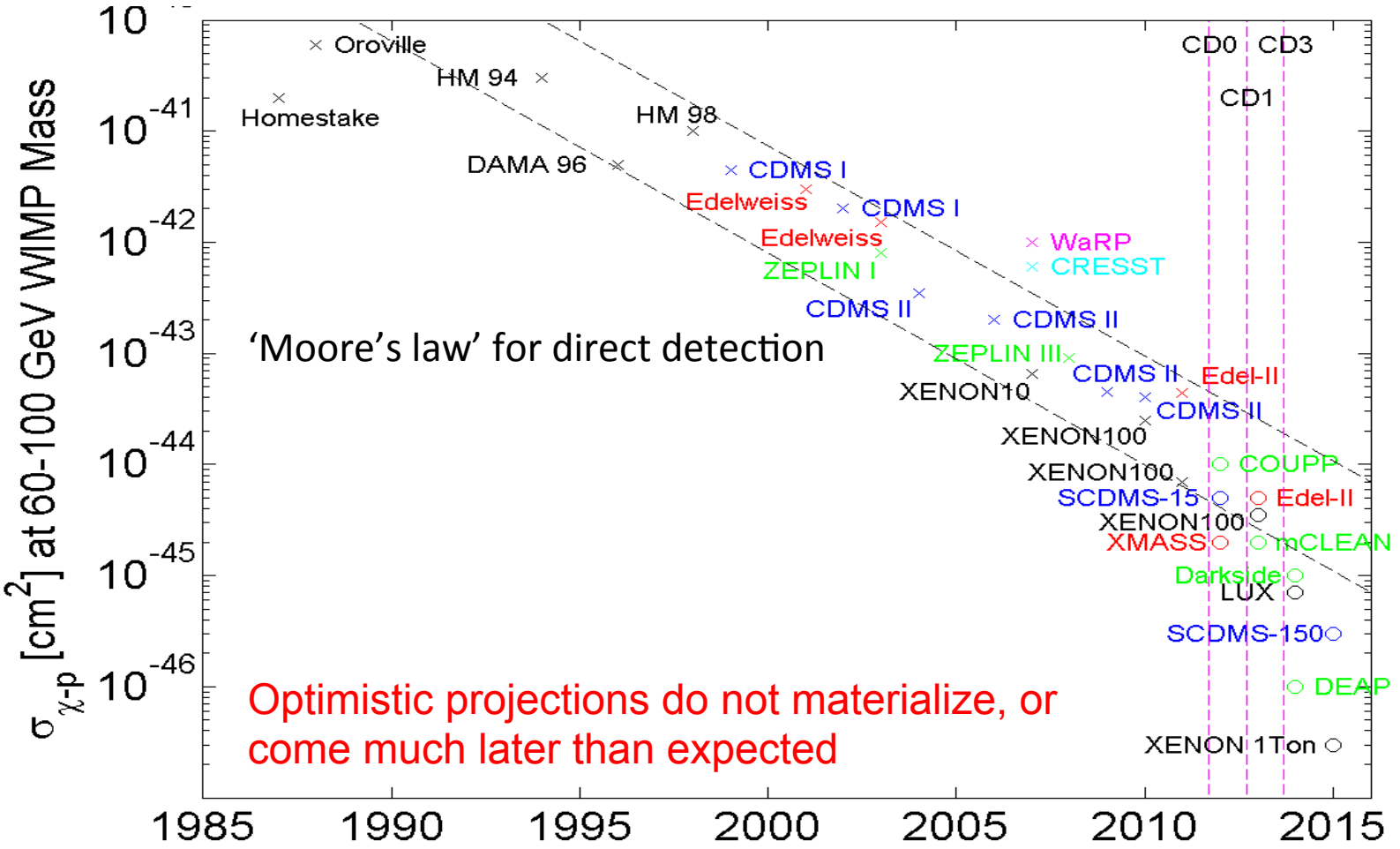
Strigari arXiv:0903.3630

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

Zero-Background Projections always wrong!



Technological Challenges

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 will likely not be a clear winner; all experiments run into backgrounds!
Multiple technologies will be needed to establish a WIMP signal

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 and hosting of symposia (Hunt for DM, Cosmic Symposium)
- Planning two additional workshops
  - Compare direct, indirect and collider probes of dark matter
  - Explore background issues for direct detection experiments

Agency Interactions

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

Summary

The field of dark matter direct detection is burgeoning, and FNAL is well prepared to continue leadership

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.