The Fermilab Program for Direct Detection of Dark Matter

Do you believe in (WIMP) miracles?

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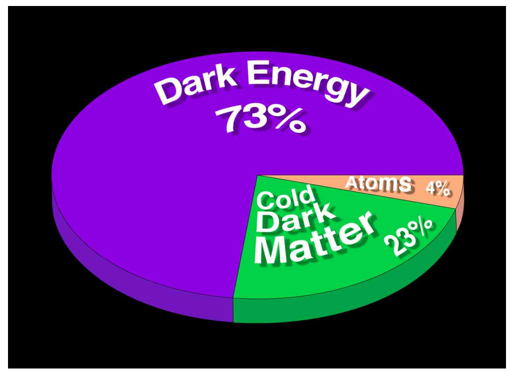
Fermilab PAC Meeting

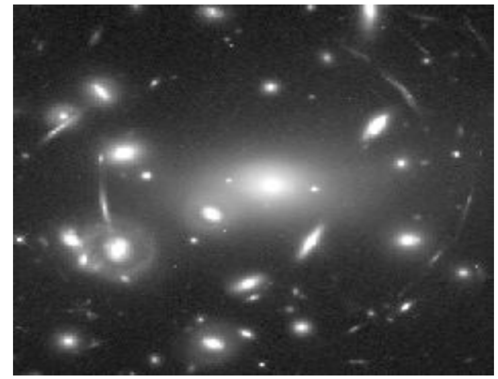
June 7, 2013

Dark Matter Exists!

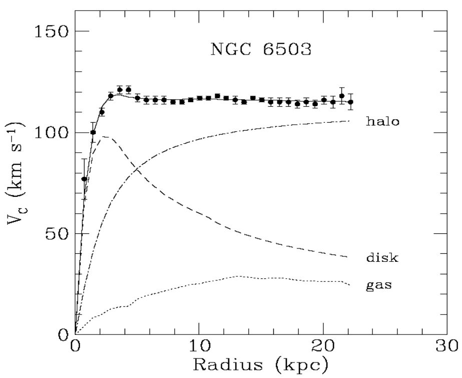
Galaxy Clusters

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



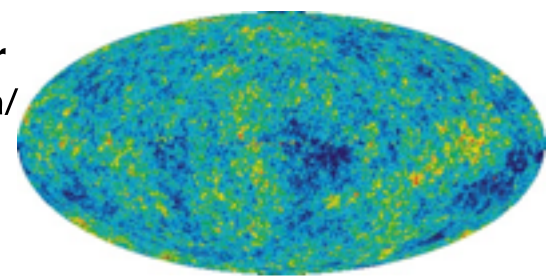


Strong Lensing



Galaxy Rotation Curves

We don't know the Dark Matter
mass / coupling / spin / composition/ distribution in our galaxy

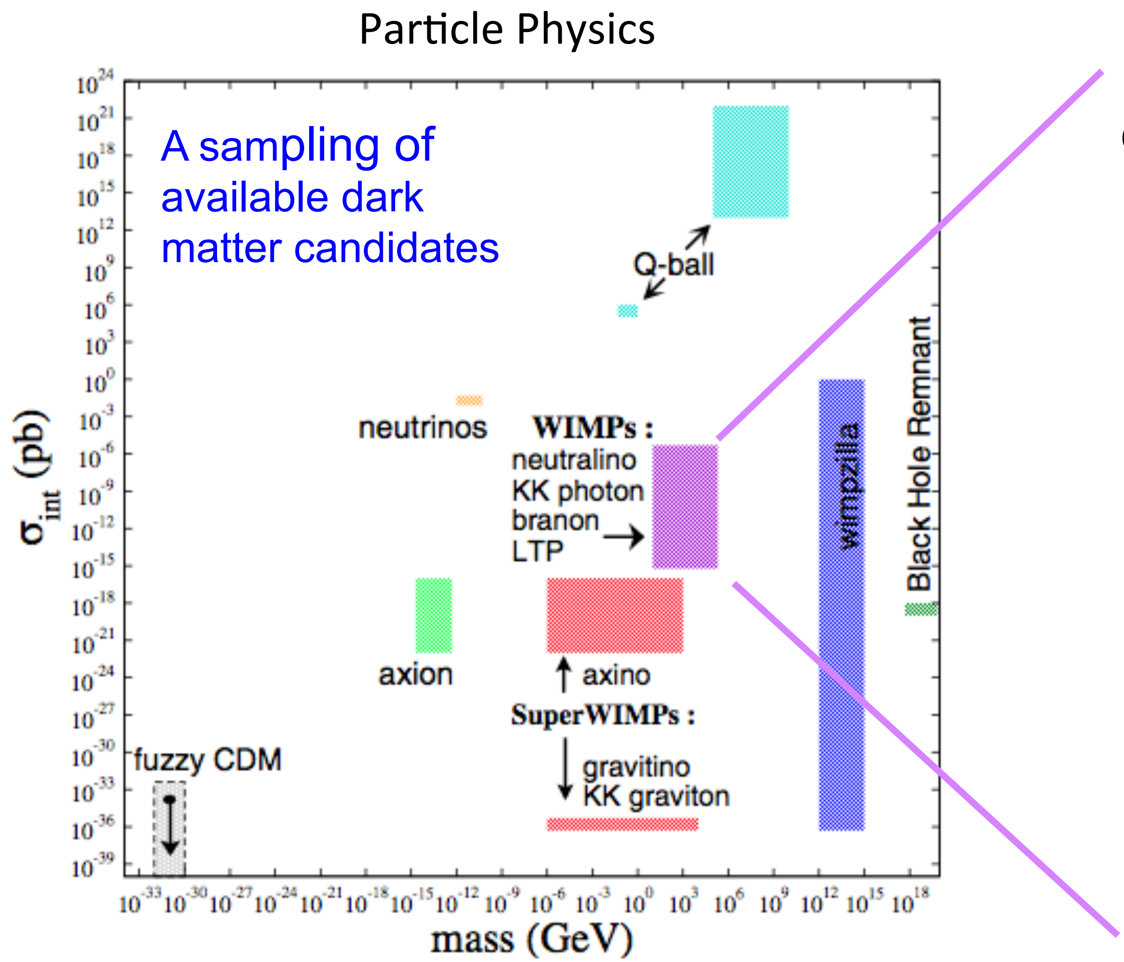


Cosmic Microwave Background

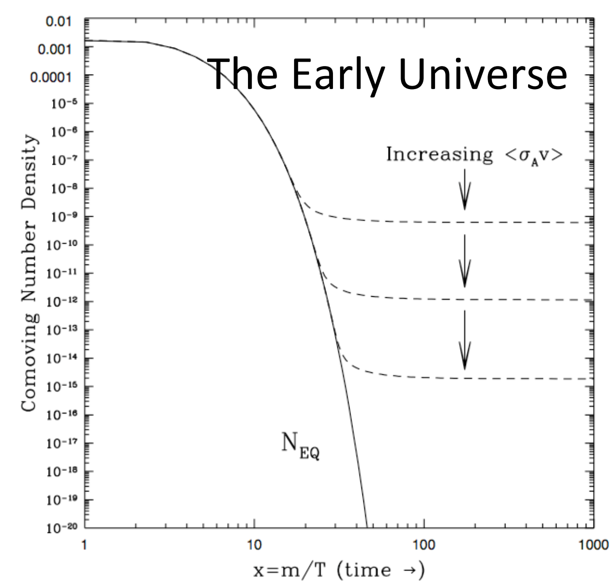
What does dark matter have to do with particle physics?

The WIMP "Miracle"

(WIMP = **W**eakly **I**nteracting **M**assive **P**article)



Particles with mass and couplings at the weak scale yield cross sections that correspond to ~correct relic density of cold dark matter

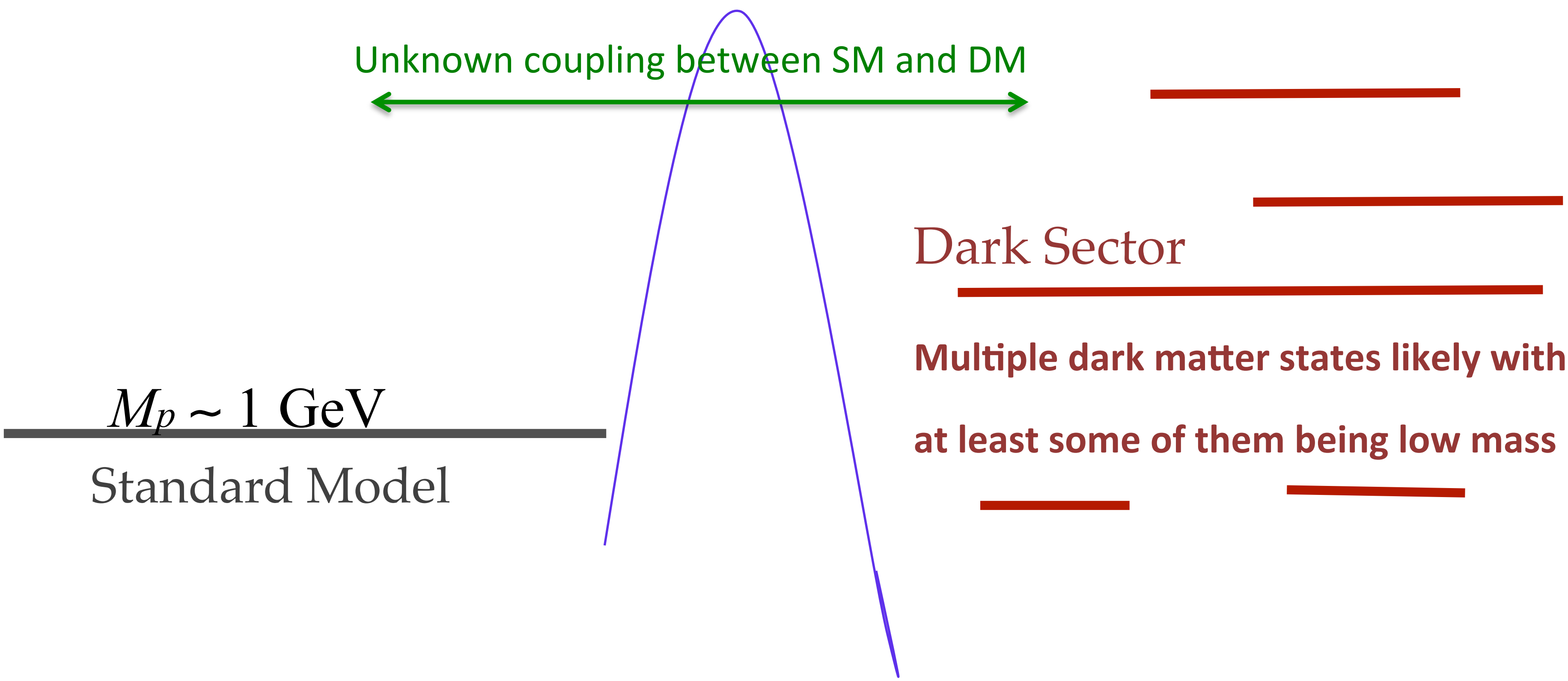


WIMPS are not necessarily from SUSY

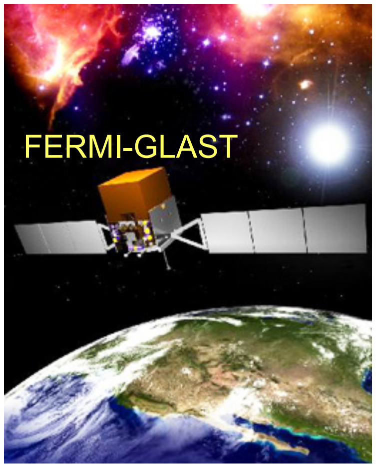
There is no reason why dark matter shouldn't be as complicated as normal matter

Searches shouldn't be limited by expectations from SUSY models

Explore as far as we can in both WIMP mass and WIMP-nucleon cross section

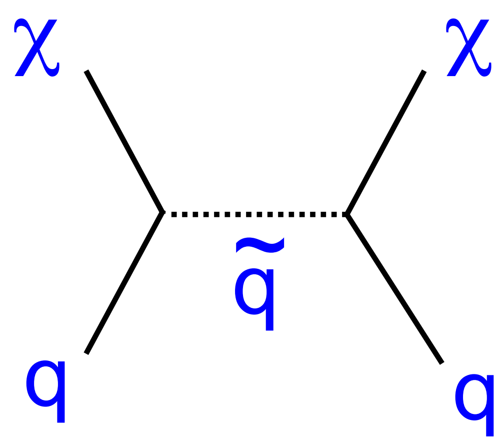


How to detect WIMPs



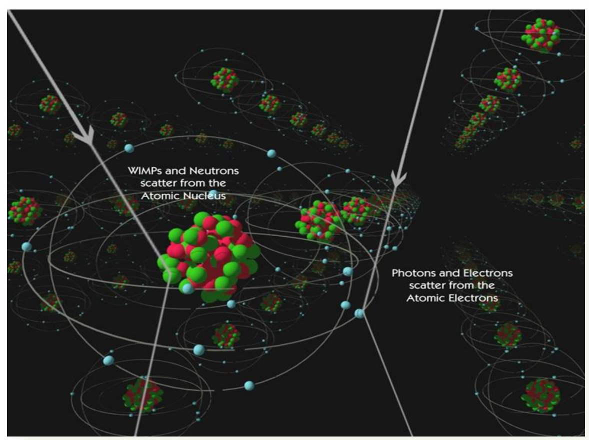
Relic annihilation in the cosmos

INDIRECT DETECTION



man-made COLLIDER production

M. Attisha

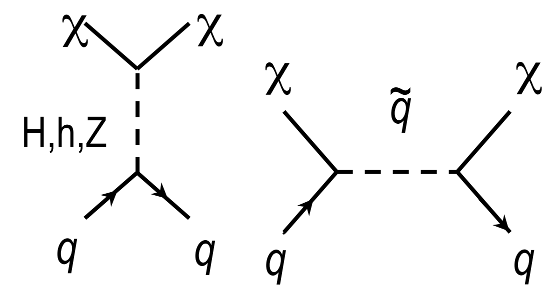


Relic WIMP-nucleon elastic scattering

DIRECT DETECTION

WIMP Direct Detection Basics

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



Particle Physics: $N \frac{\sigma_{\chi N}}{m_\chi} \rho_\chi$

WIMPs elastically scatter off nuclei in targets, producing nuclear recoils

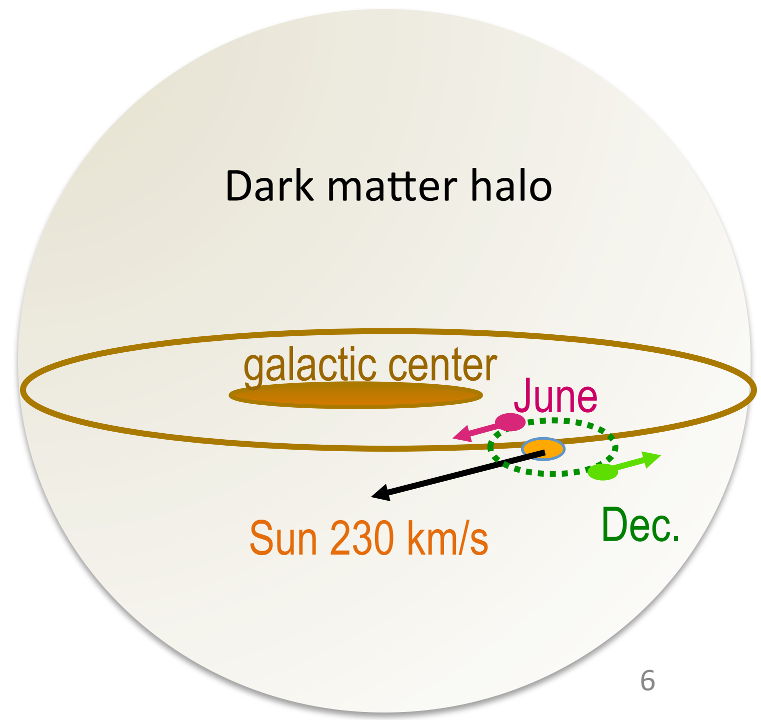
(a) Spin-independent interaction ~A^2
(large λ_{dB} ➔ coherent interaction)

(b) Spin-dependent needs target with net spin

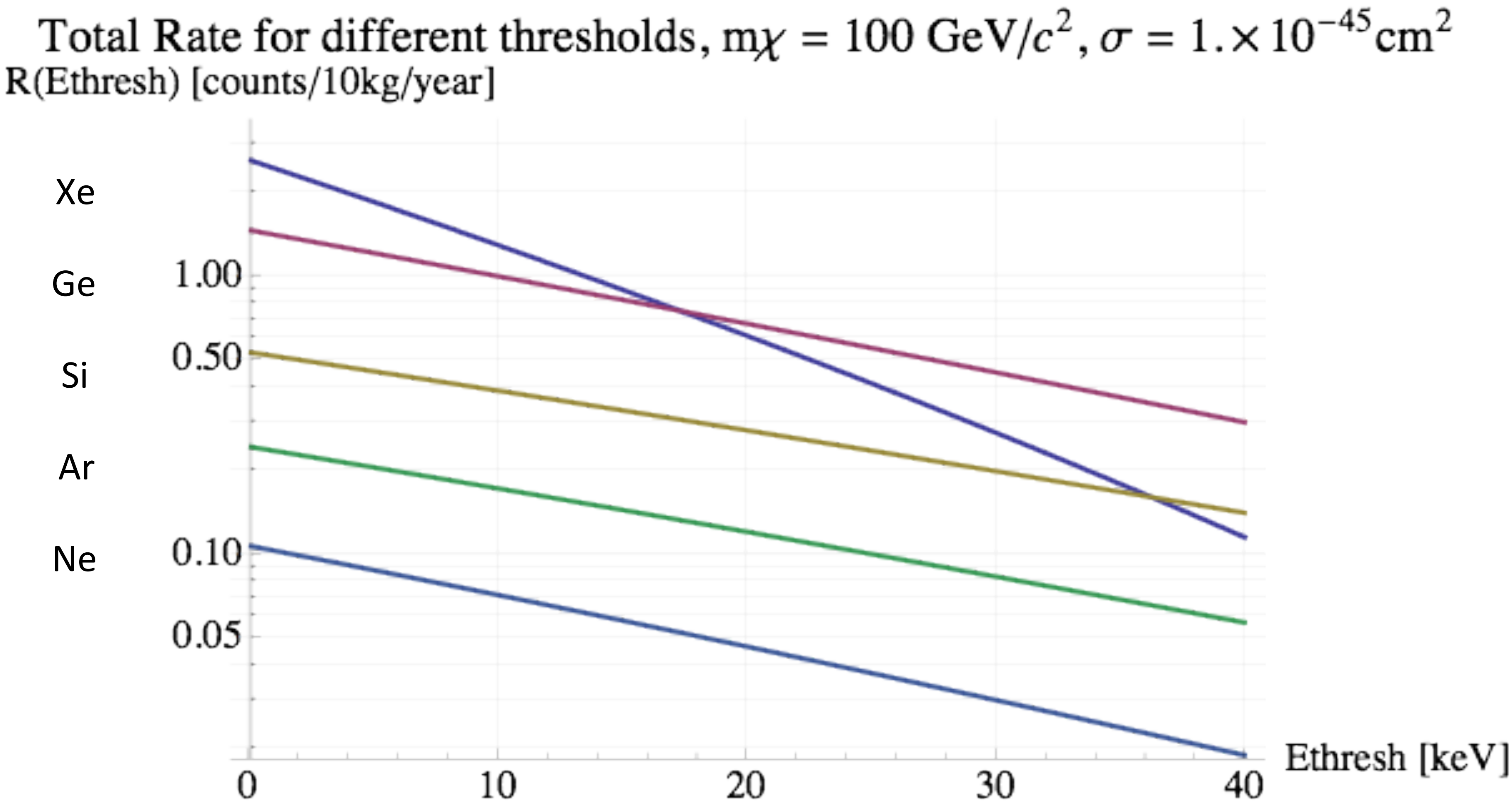
Astrophysics: $f(v)dv = \frac{4v^2}{v_0^3\sqrt{\pi}} e^{-v^2/v_0^2} d^3v$

Isothermal, spherical halo and M-B velocity dist:

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



Integrated Rate as a function of low-energy threshold of experiment



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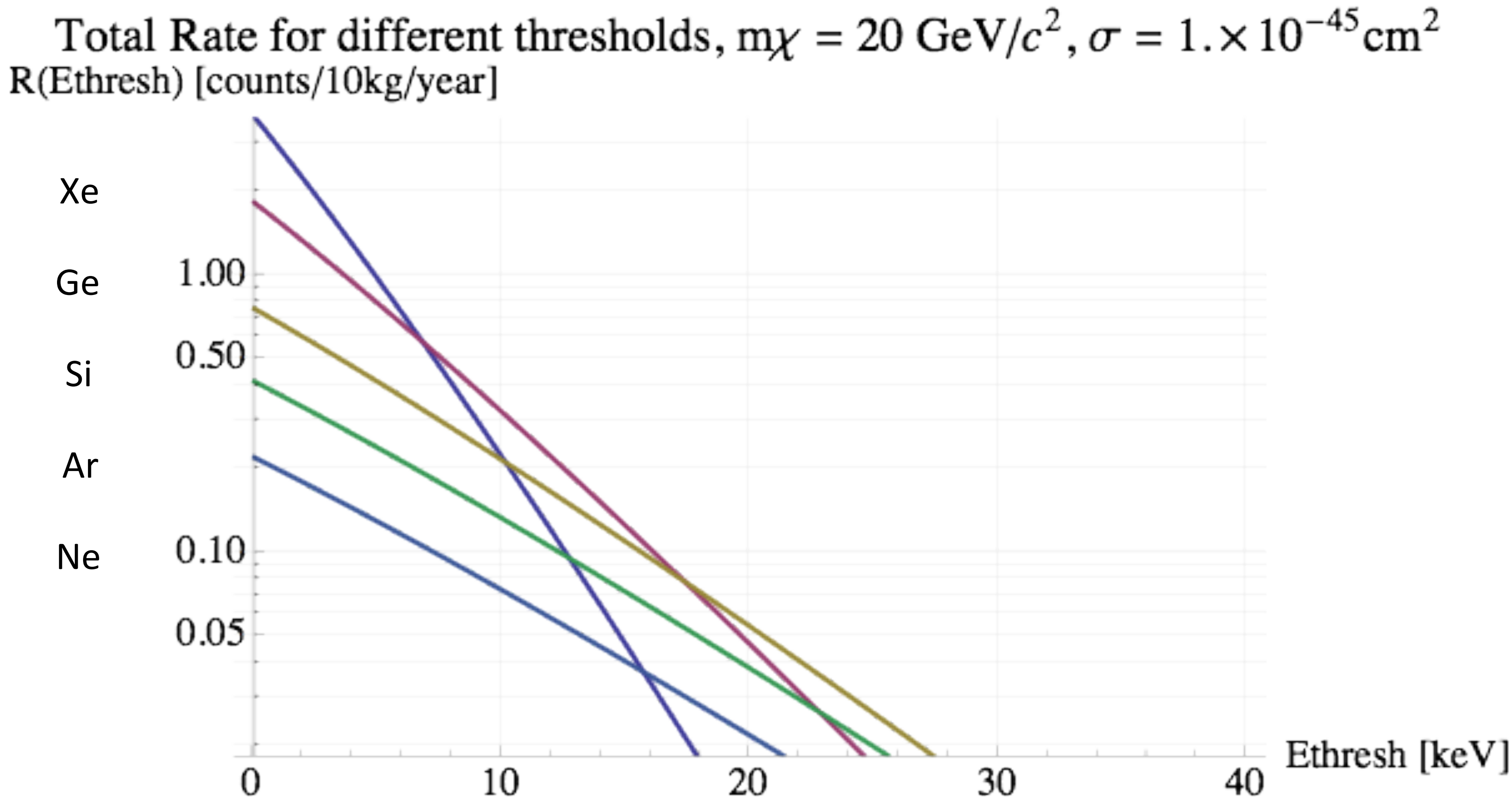

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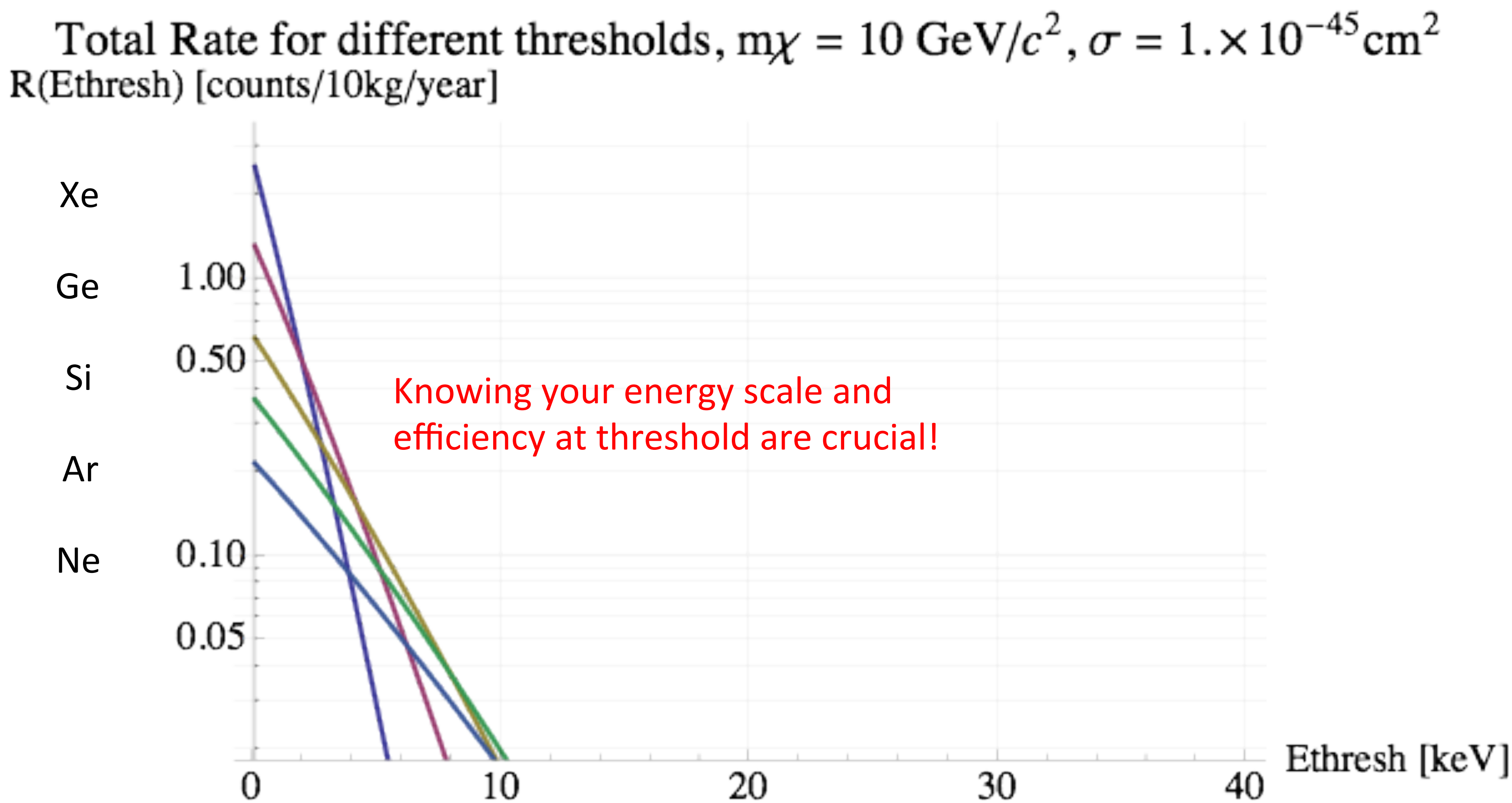
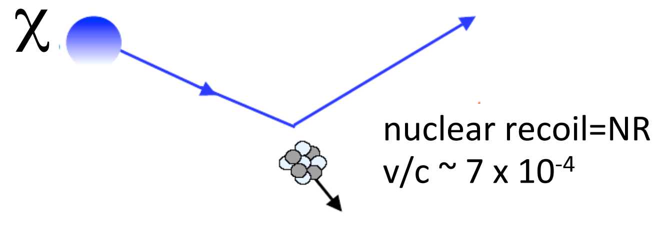


Detecting a WIMP signal

Counting

Eliminate conventional sources of nuclear recoils; count any that remain as WIMPs

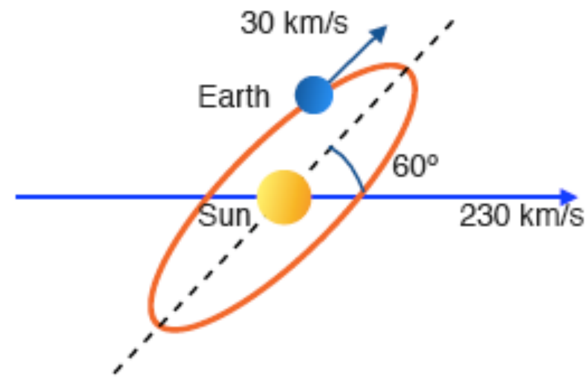
Already down to < 1/keV/100kg/year!



Annual Modulation

Rate varies slightly due to earth velocity relative to solar system through halo

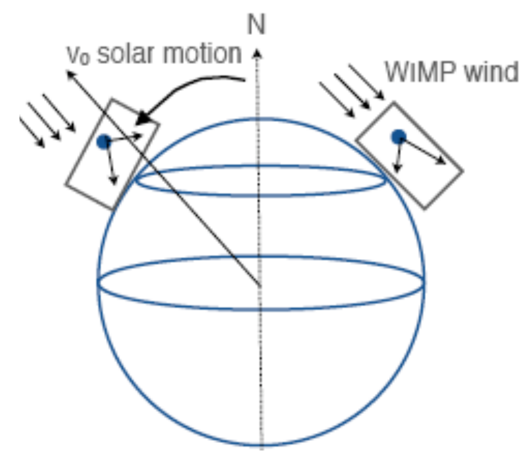
Requires precise control of experimental variations over years of operation



Diurnal Modulation

Rate varies daily with earth's rotation

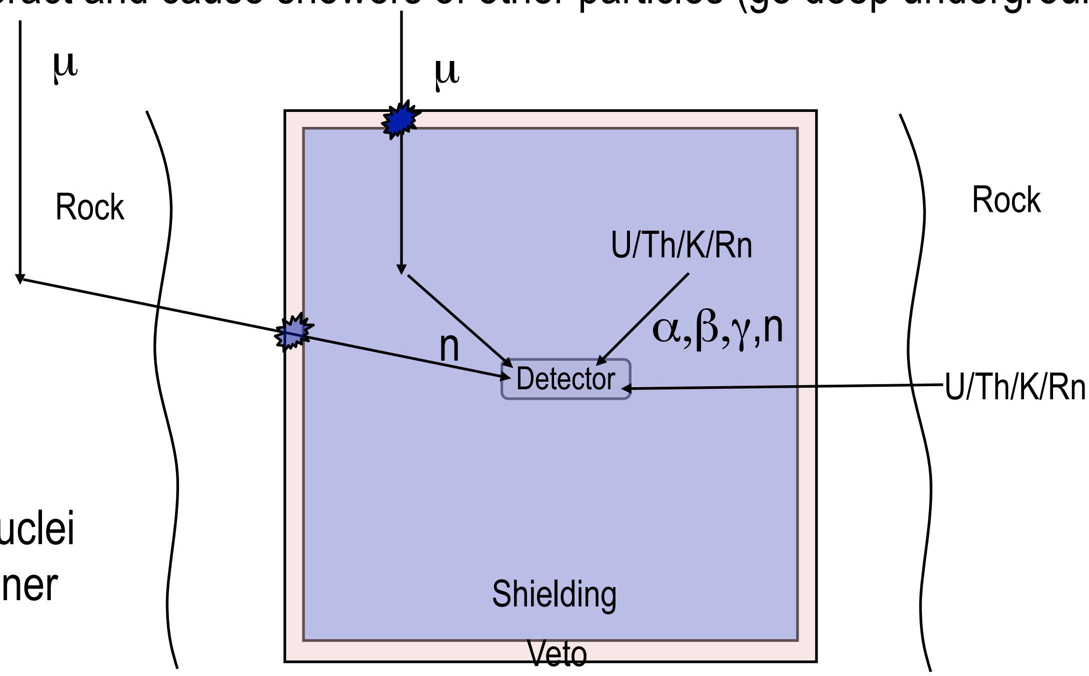
Need directional detectors to interpret as dark matter



Those nasty backgrounds

Cosmic rays

High energy particles from space hit the atmosphere and produce muons which can interact and cause showers of other particles (go deep underground to avoid)



Neutrons

These interact elastically with nuclei in the same manner as WIMPS

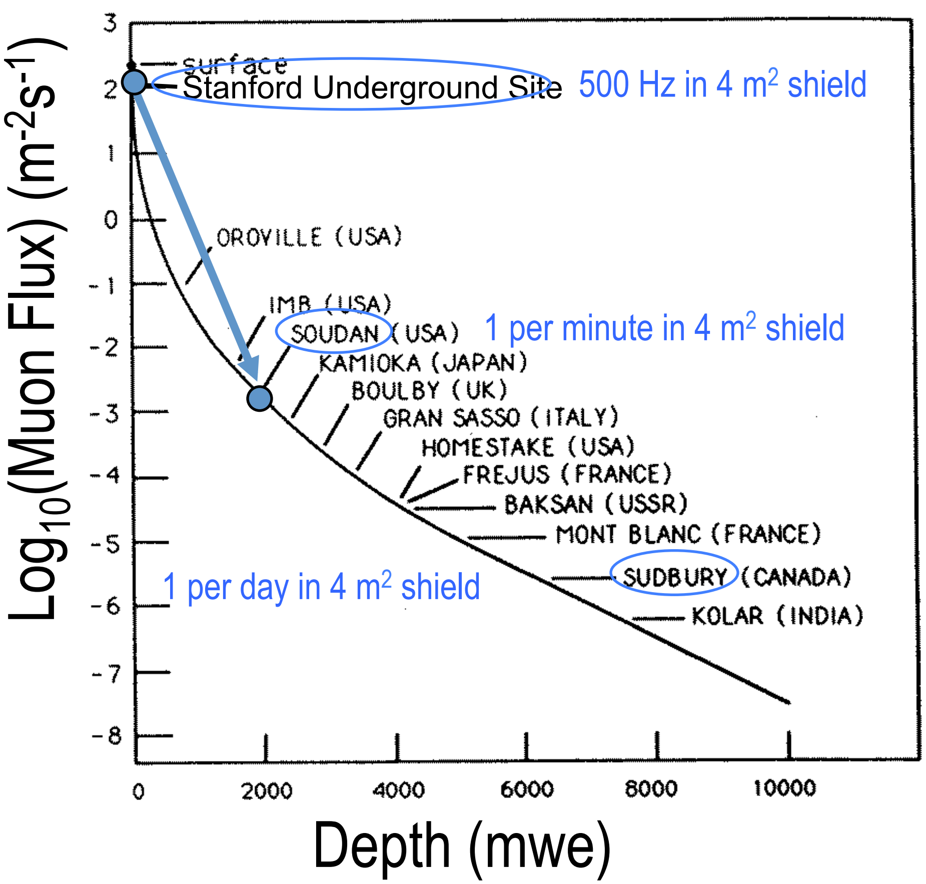
Radioactivity

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

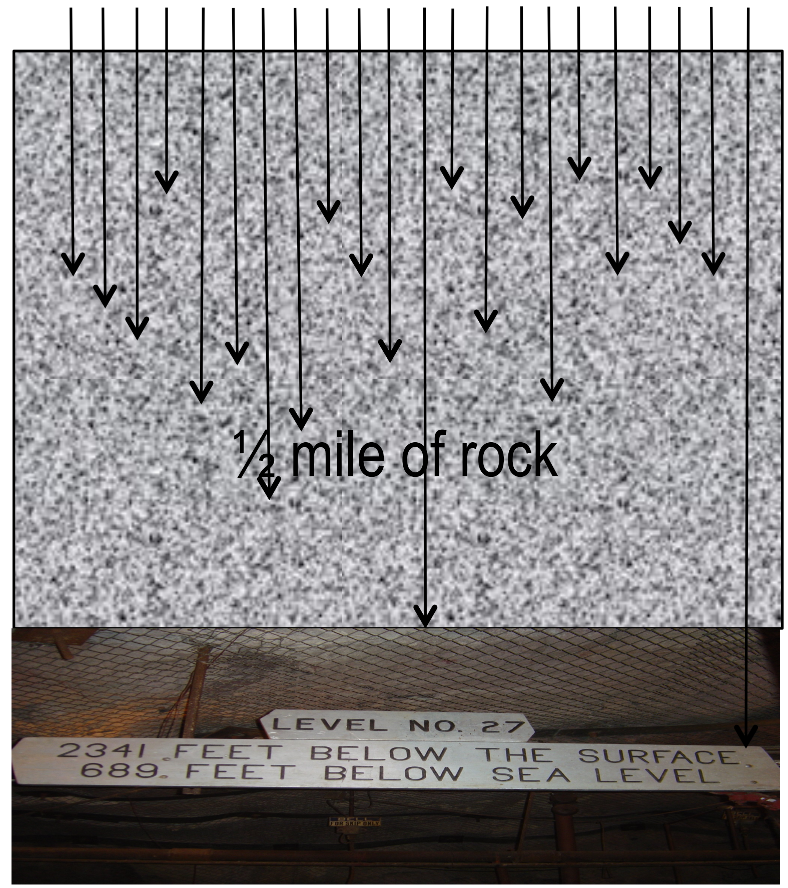
We are entering the sensitivity range where neutrons from radioactivity will become the limiting background and these are very hard to estimate ahead of time from screening and material selection!

How to escape cosmic ray backgrounds Go Deep

Cosmic ray muons in underground labs



Cosmic Rays absorbed by rock



Anatomy of a Direct Detection Experiment

<u>Active Detection Material</u>
Radiopure, produces detectable response to nuclear recoils, active rejection of electron recoils, high A or nuclear spin (or both)

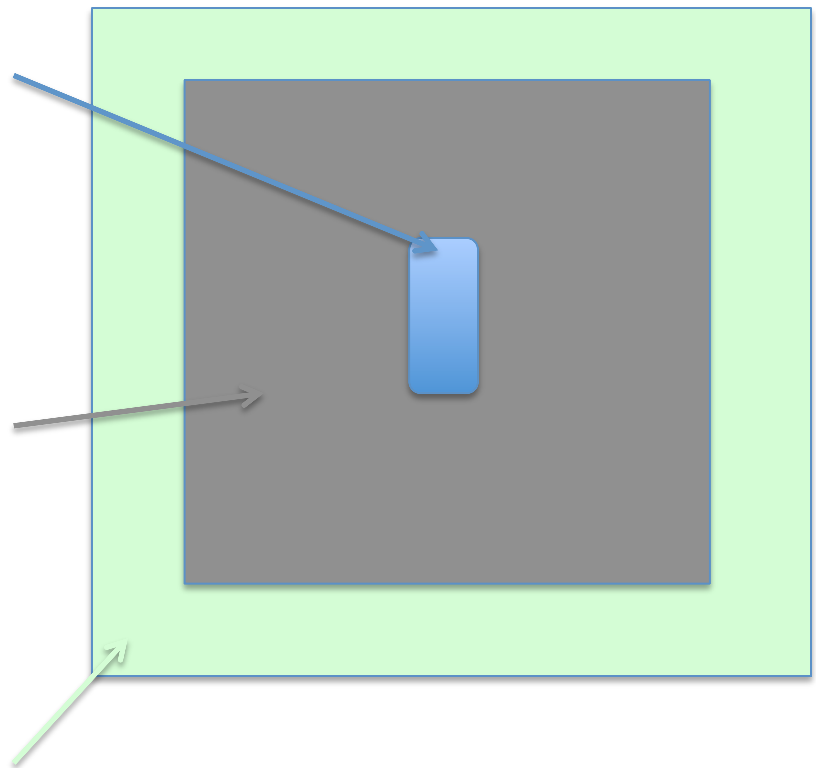
Typical materials: Ge, Si, Xe, Ar, F, I

<u>Passive Shielding</u>
Radiopure, efficiently block external gammas and moderates neutrons

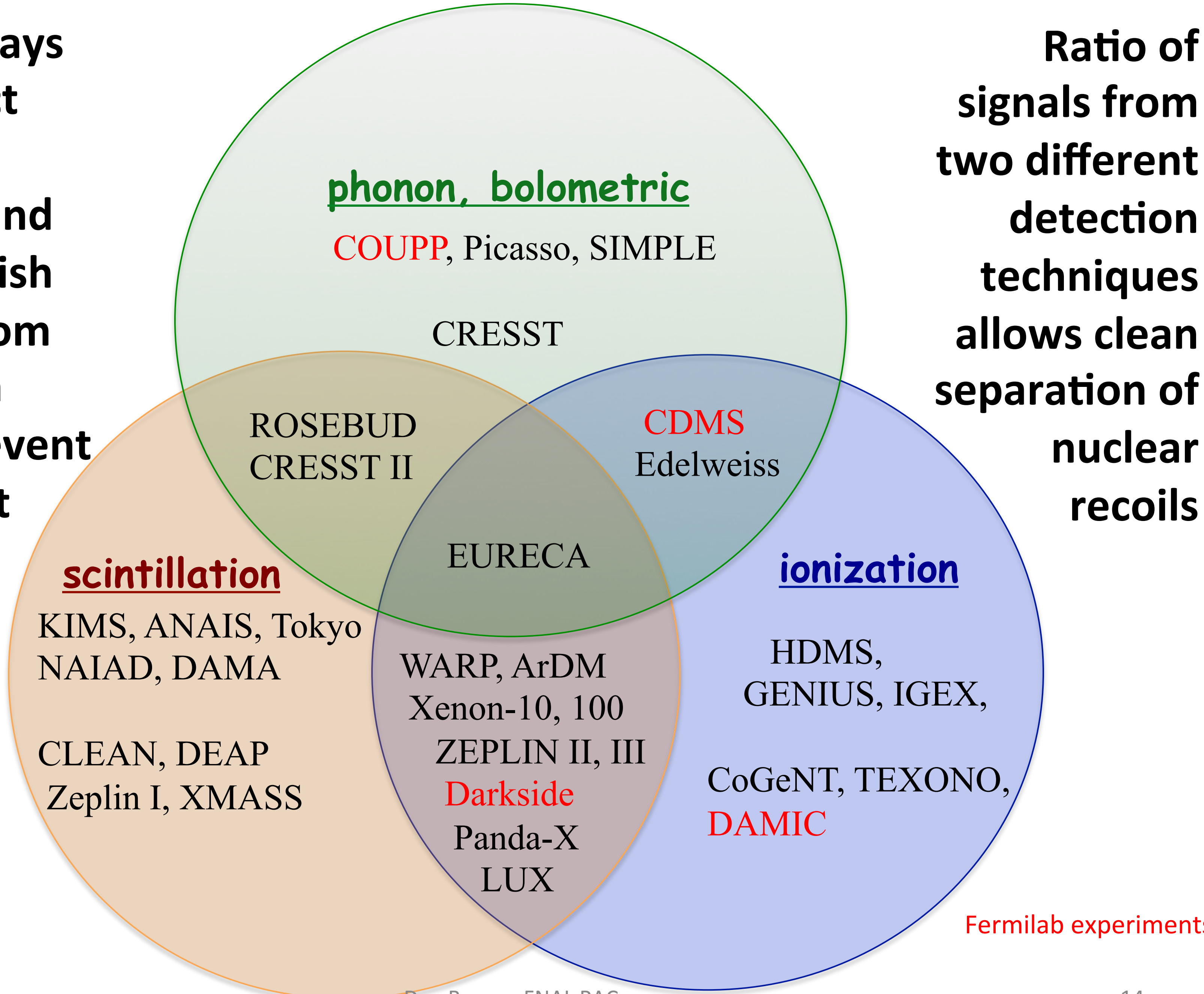
Typical materials: Cu, Pb, Polyethylene, Water

<u>Active Shielding</u>
Efficiently veto external neutrons and cosmic ray muons

Typical detectors: Water Cherenkov, Scintillator



Many ways to detect nuclear recoils and distinguish them from electron recoils event by event

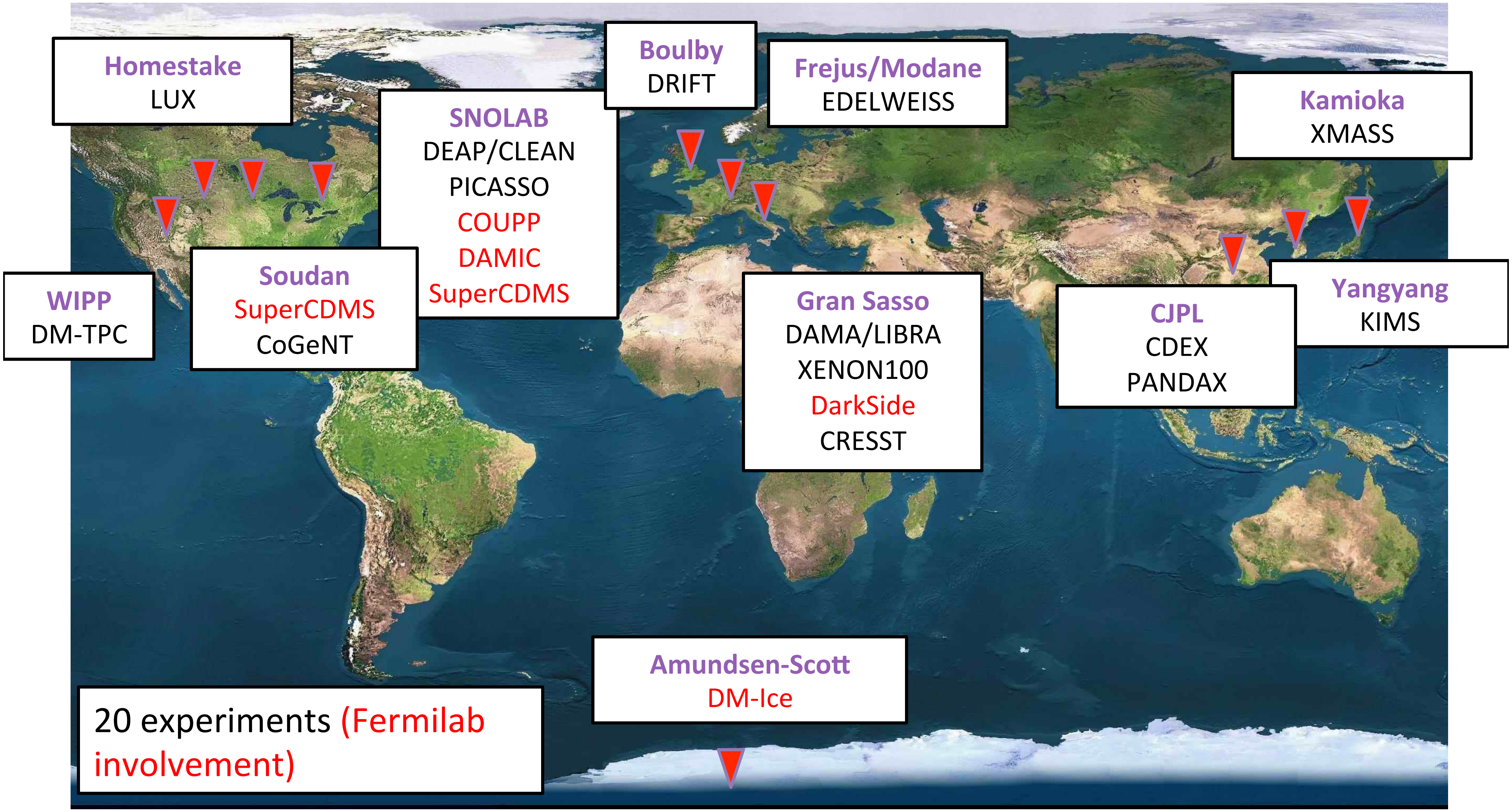


Ratio of signals from two different detection techniques allows clean separation of nuclear recoils

Residual Backgrounds

- Experiments strive to be "background free"
  - Really means <0.5 event in the expected exposure with optimized nuclear recoil acceptance
- But they usually fall short of that goal
  - Conservative option is to count all remaining events as WIMPs and set limit based on that
  - IF one understands the background very well, can subtract it
    - But systematics then dominate limit and improvement goes like √(time) or worse.
- Convincing the community that WIMPs have been seen likely requires a "background free" detection.

World-wide search



Cryogenic Solid State Detectors

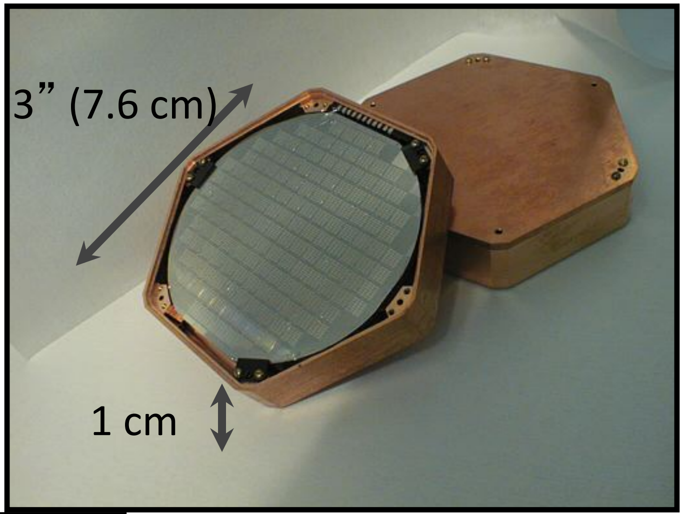
- Technique
  - Detect phonons (heat) and either ionization or light from solid state detectors held at cryogenic (~50 mK) temperatures
- Strengths
  - Proven excellent background discrimination
  - Superb energy resolution and low energy thresholds
  - Radiopurity of detector material
- Weaknesses
  - Difficult to deploy large target masses
  - Surface events that can mimic nuclear recoils
- Operating Experiments
  - SuperCDMS Soudan, Edelweiss II/III, CRESST II/III
- Future Experiments
  - SuperCDMS SNOLAB, Eureca (merger of these efforts under discussion)
- New Developments
  - New ways to reject surface events and reach lower WIMP masses

Fermilab experiments

CDMS at Soudan

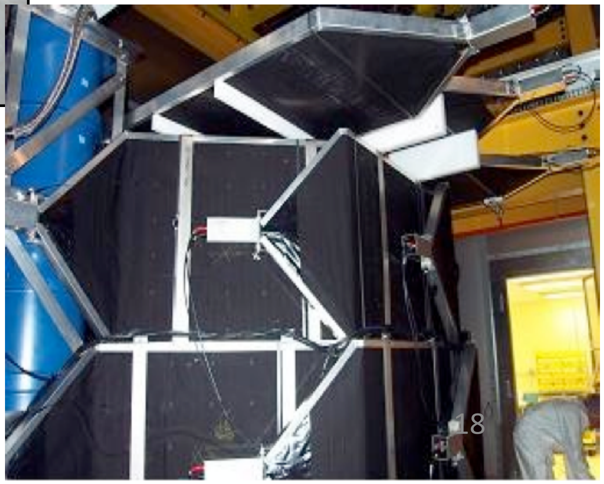
ZIP Detectors

- **Z**-sensitive **I**onization and **P**honon mediated
- 230 g Ge or 106 g Si crystals
  (1 cm thick, 7.5 cm diameter)
- Photolithographically patterned to collect athermal phonons and ionization signals
- Operated at 50 mK
- Direct xy-position imaging
- Surface (z) event rejection from pulse shapes and timing
- 30 detectors stacked into
  5 towers of 6 detectors



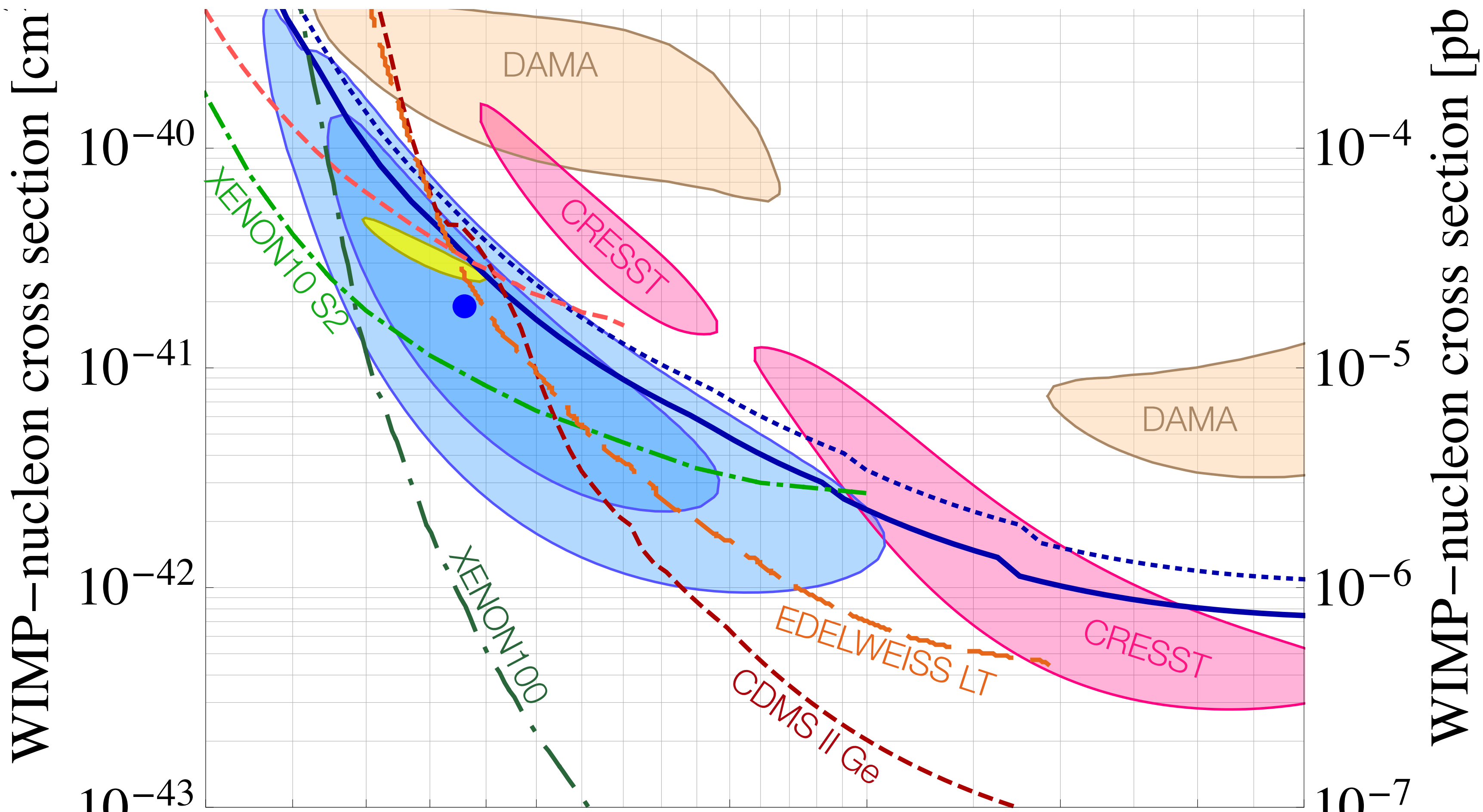
CDMS Infrastructure at Soudan

- Cleanroom around entire experiment (class-10000)
- Layered, radiopure shielding (Poly, Pb, Copper)
- Active scintillator muon veto around shielding
- Dilution refrigerator and special copper cryostat
- Cryocoolers and Helium recovery system
- Full backup power (UPS and diesel generator)



CDMS II Silicon Recent Results

Hint for light WIMPS, but could also be background
Shows value of having multiple targets in one experiment



SuperCDMS – A Detector Breakthrough

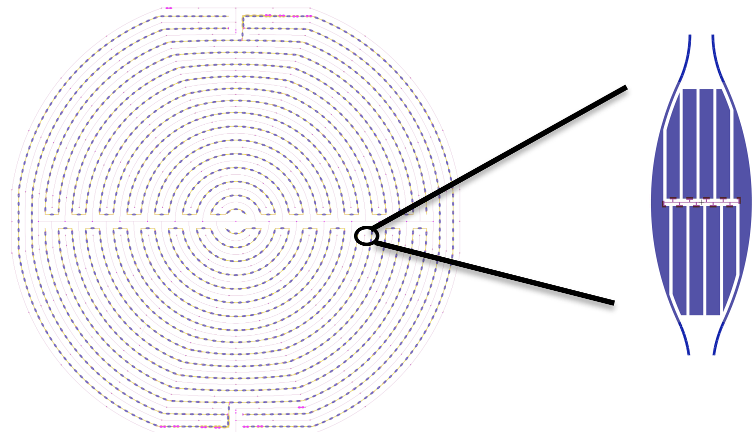
<u>iZIP = in</u>terleavened charge and phonon channels

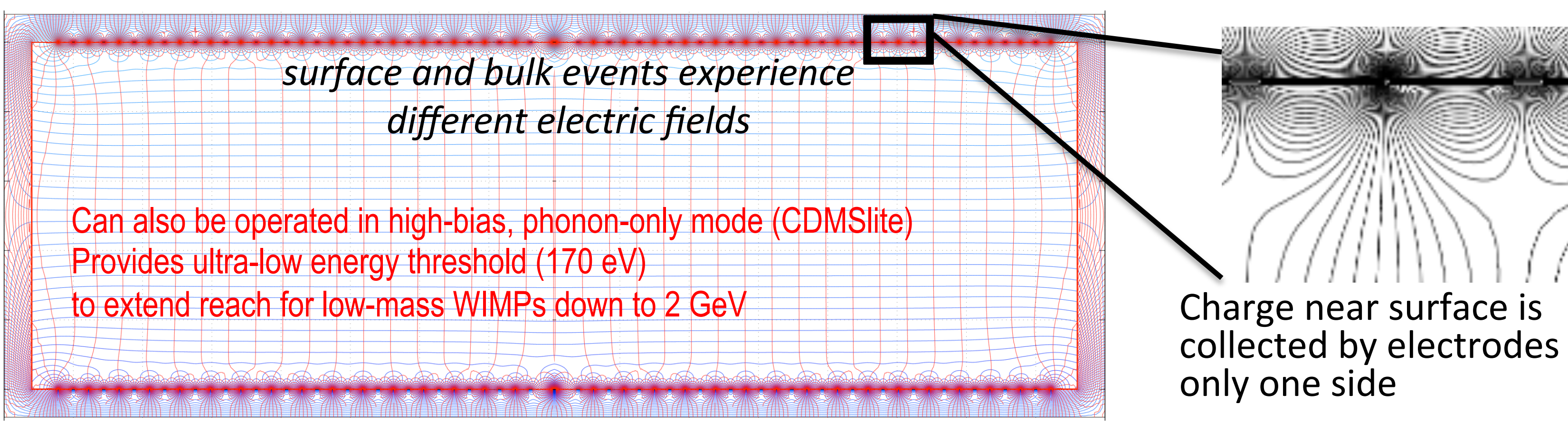
Excellent rejection of surface events that limited CDMS II

Fiducial volume is 75% of the crystal

9kg currently operating as SuperCDMS Soudan

200 kg planned for SuperCDMS SNOLAB

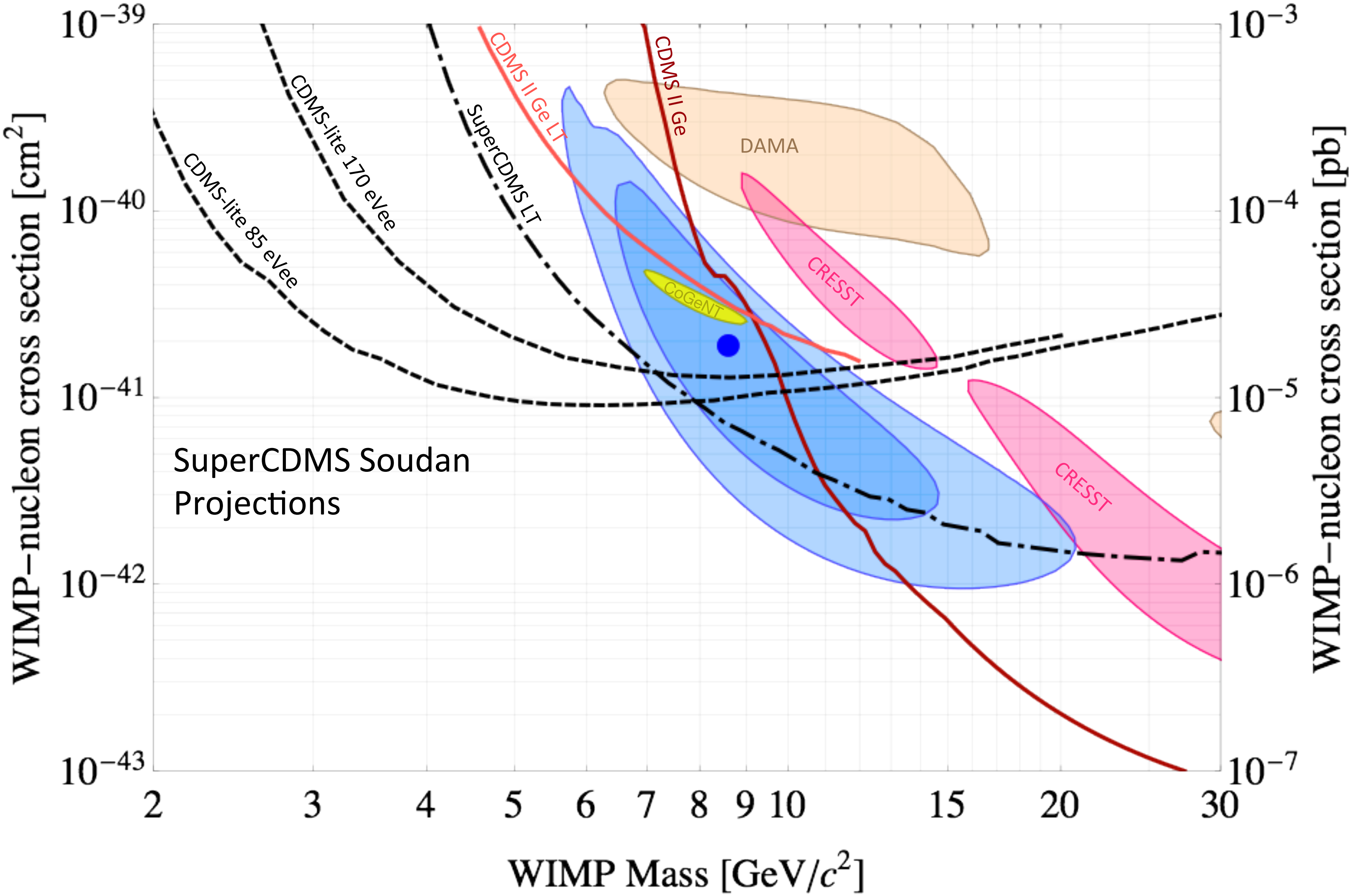




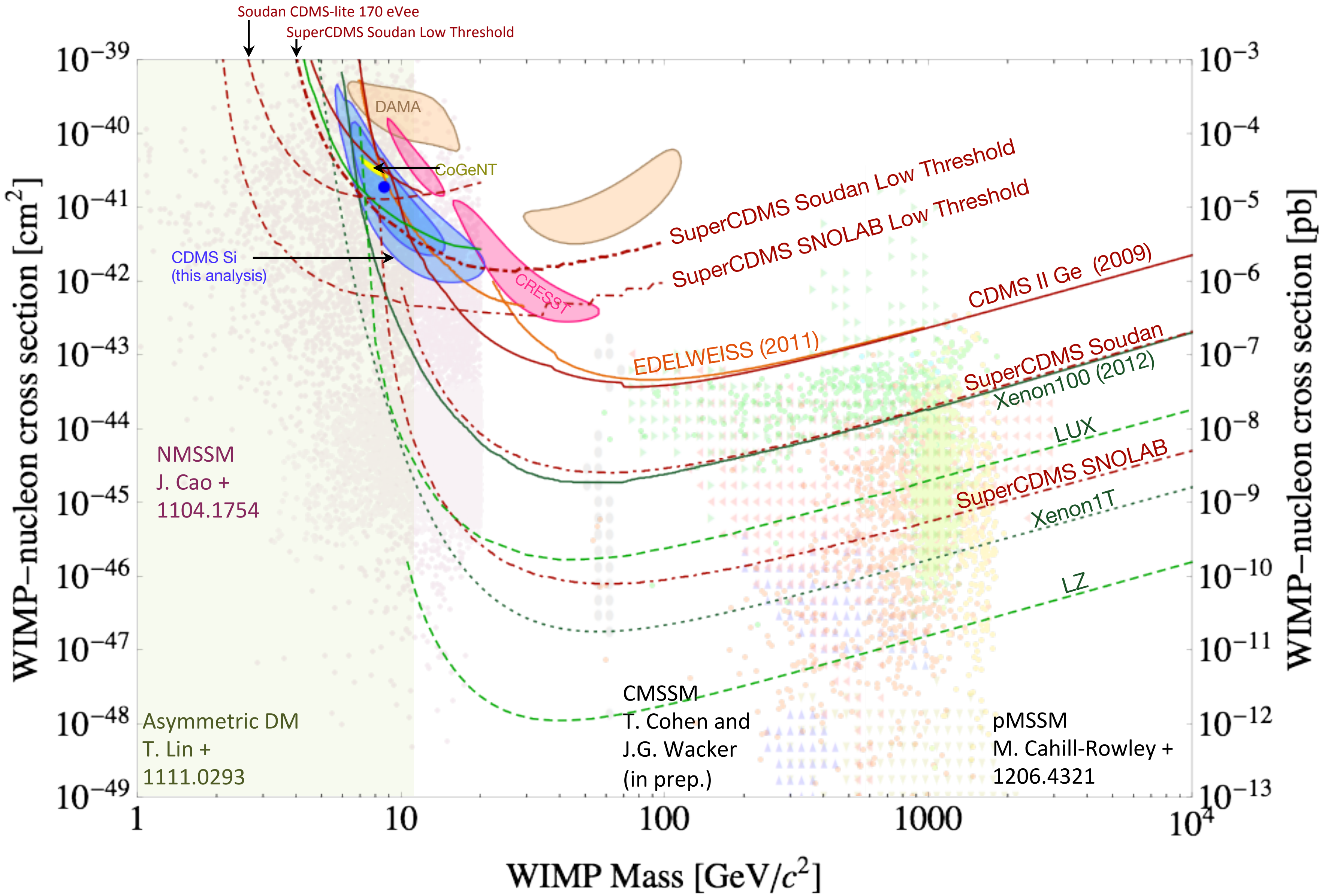
Can also be operated in high-bias, phonon-only mode (CDMSlite)
Provides ultra-low energy threshold (170 eV)
to extend reach for low-mass WIMPs down to 2 GeV

Charge near surface is collected by electrodes on only one side

SuperCDMS Soudan projections



SuperCDMS SNOLAB projections



Fermilab Roles in SuperCDMS SNOLAB

- Project Management
  - Need more help here for a CD-scale project
- Cryogenics and Mechanical Design
  - Conceptual design well along, but may need to reduce base temperature further
  - Lead engineer in place, but need more technical help
- Neutron Veto
  - Exploring a B or Gd loaded scintillator veto to make sure we can identify possible radiogenic neutron backgrounds
- Warm Electronics
  - Already have a working prototype
- Software, data management and analysis

Solid State Ionization Detectors

- Technique
  - Detect ionization from particle interactions in ultra-pure crystals
- Strengths
  - Excellent energy resolution and low thresholds; specialize in low-mass WIMP searches
  - Radiopurity of detector material
- Weaknesses
  - No discrimination against electron recoils
  - Difficult to deploy large target masses
- Two flavors
  - HpGE (CoGeNT, DAMIC, MALBEK, TEXONO)
  - Double beta decay crystals (AMORE, COURE)
- New developments
  - Expect new results soon on very low-mass WIMPs

Fermilab experiments

Dark Matter in CCDs (DAMIC)

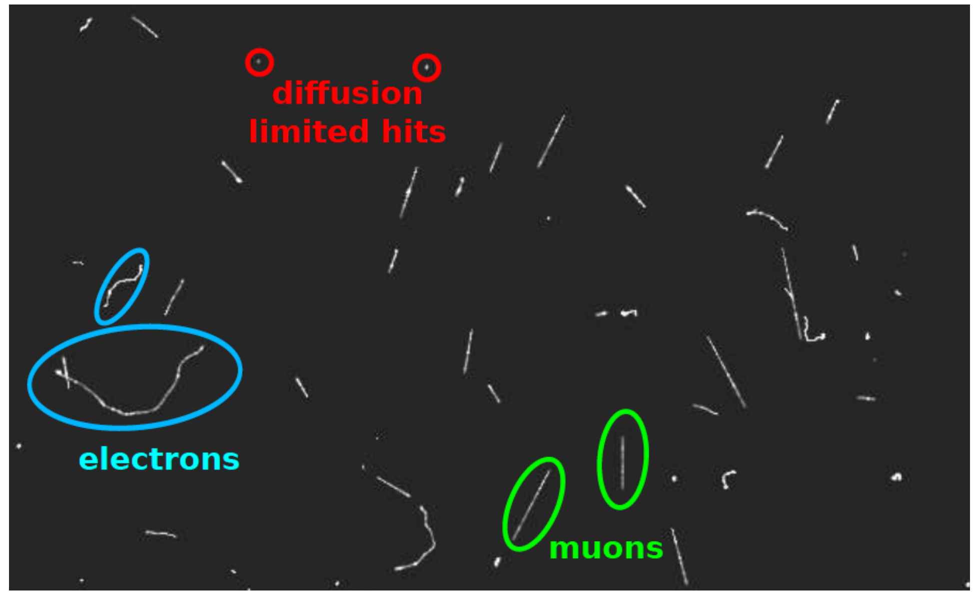
Target consists of nuclei in silicon pixel detectors of thick (250 µm, 0.5 g) CCDs cooled to -150 C to reduce noise

40 eVee energy threshold!

Unique reach for lowest mass WIMPS (<3 GeV)

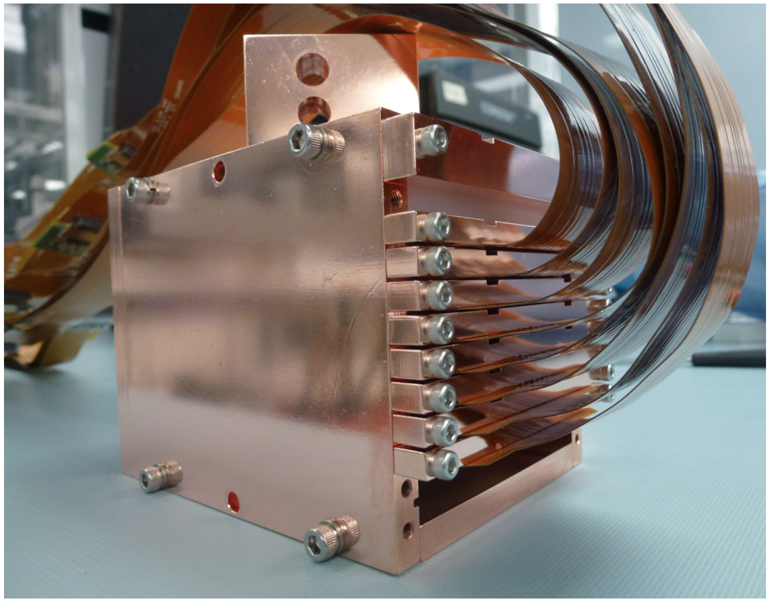
10 g prototype just deployed at SNOLAB to study backgrounds

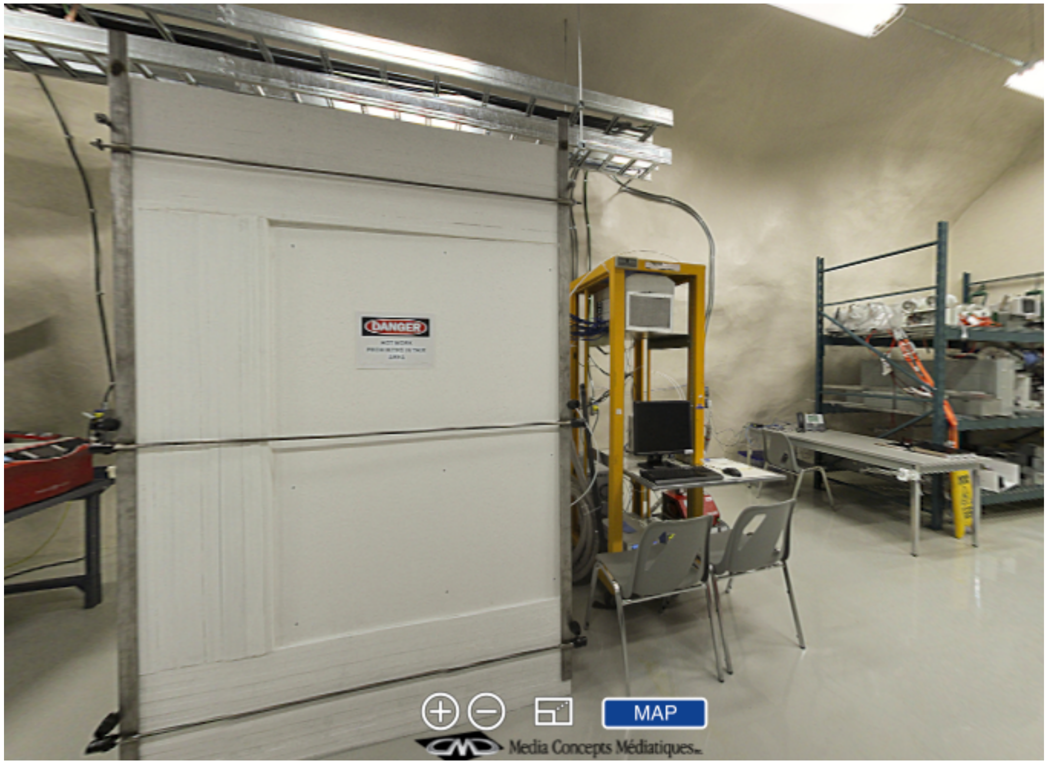
Goal is to deploy 100 g at SNOLAB and in southern hemisphere



Nuclear recoils produce diffusion limited hits
Electron recoils produce tracks or larger blobs

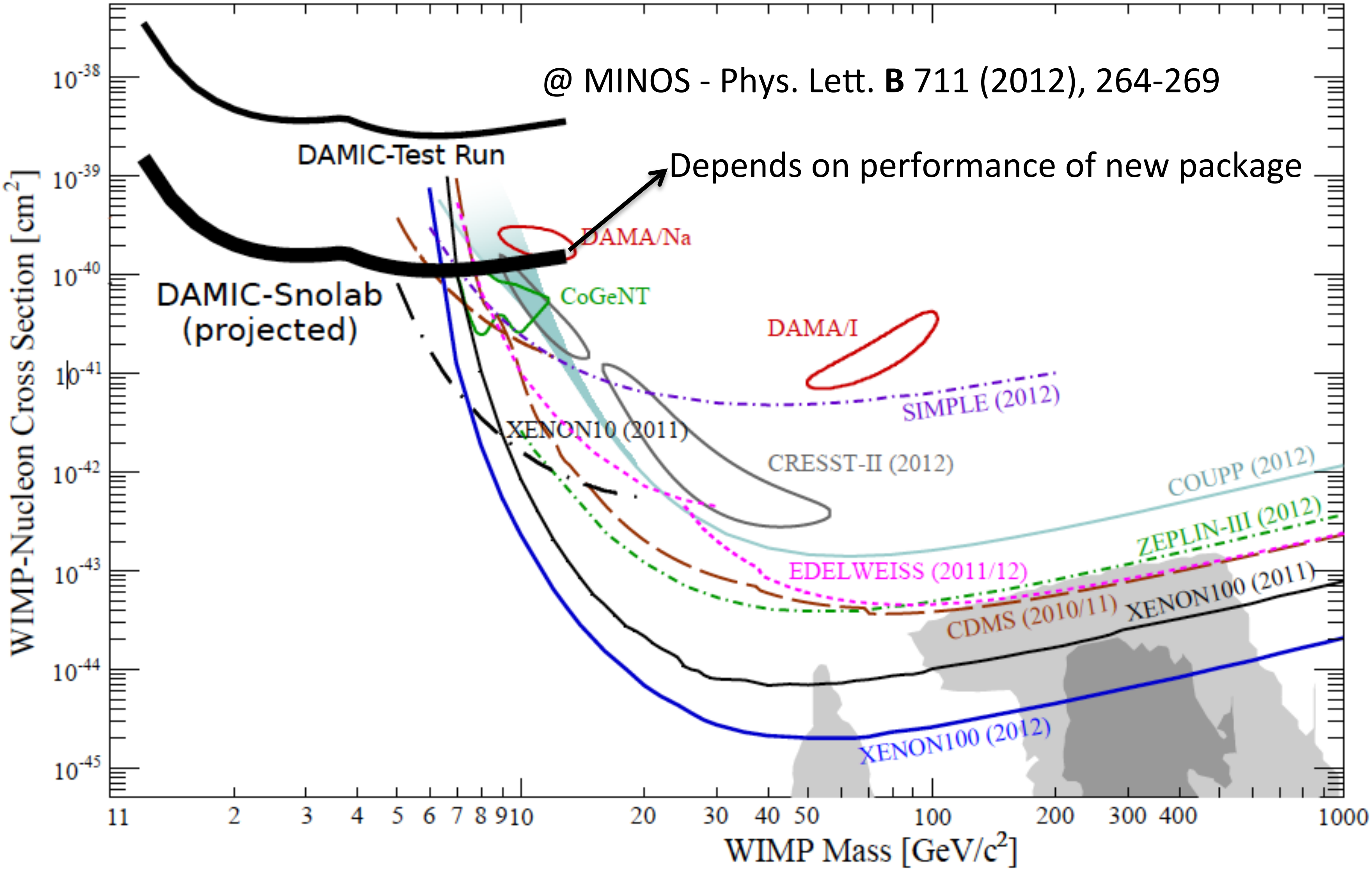
DAMIC at SNOLAB





~10g array installed at SNOLAB in December 2012.
Operating with threshold of 40eV.

Projected reach for DAMIC-SNOLAB (10g)



J.Tiffenberg (FNAL)

SuperHeated Liquid Detectors

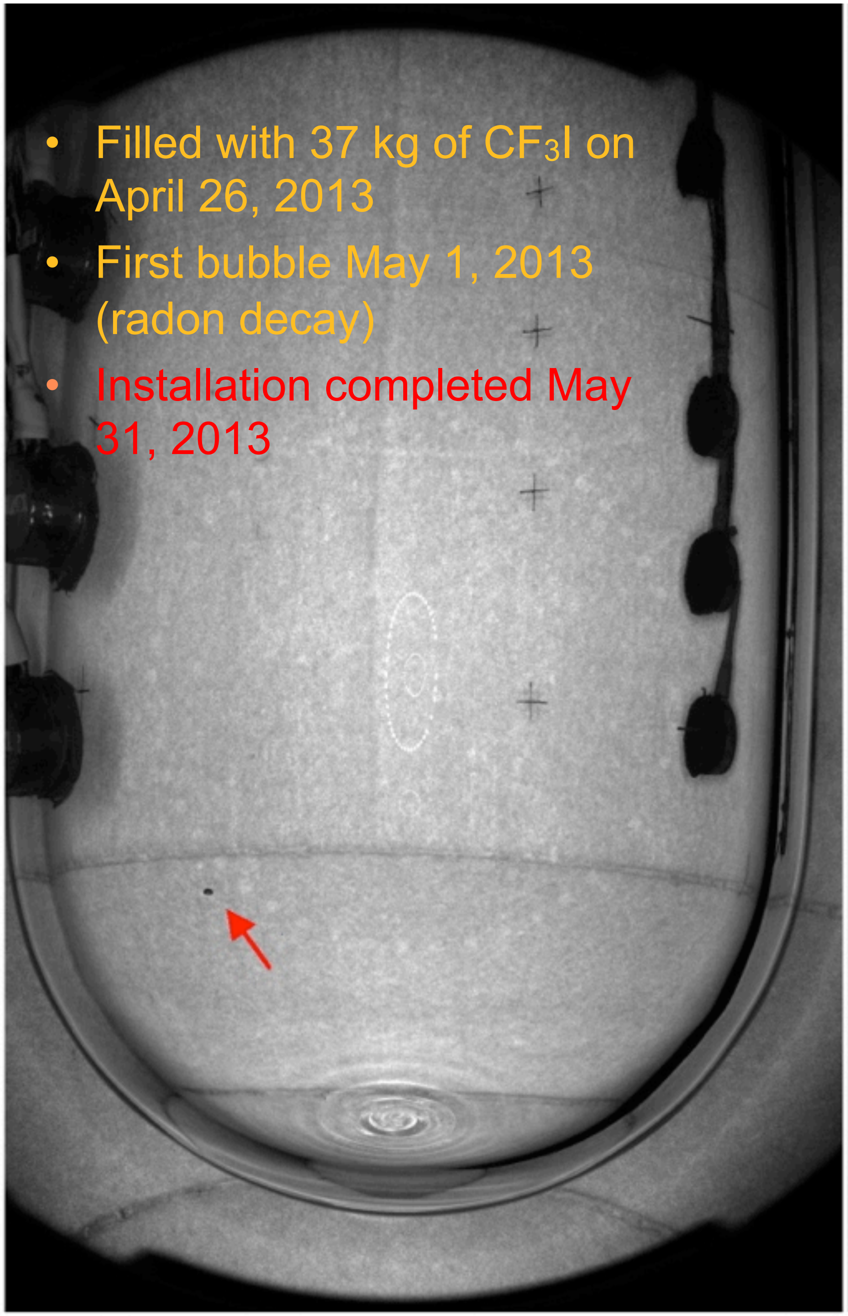
- Technique
  - Hold liquids in superheated state and detect bubbles formed by localized energy depositions from nuclear recoils
- Strengths
  - Nearly insensitive to electromagnetic backgrounds
  - Target material can be changed
  - Especially sensitive to spin-dependent interactions
- Weaknesses
  - Threshold detectors; no energy information
  - Sensitive to alpha particle backgrounds
- Two flavors
  - Bubble Chambers (COUPP)
  - Droplet Detectors (PICASSO, SIMPLE)
  - COUPP and PICASSO are merging (Picouppso??)
- New Developments
  - Acoustic rejection of alpha backgrounds demonstrated

Fermilab experiments

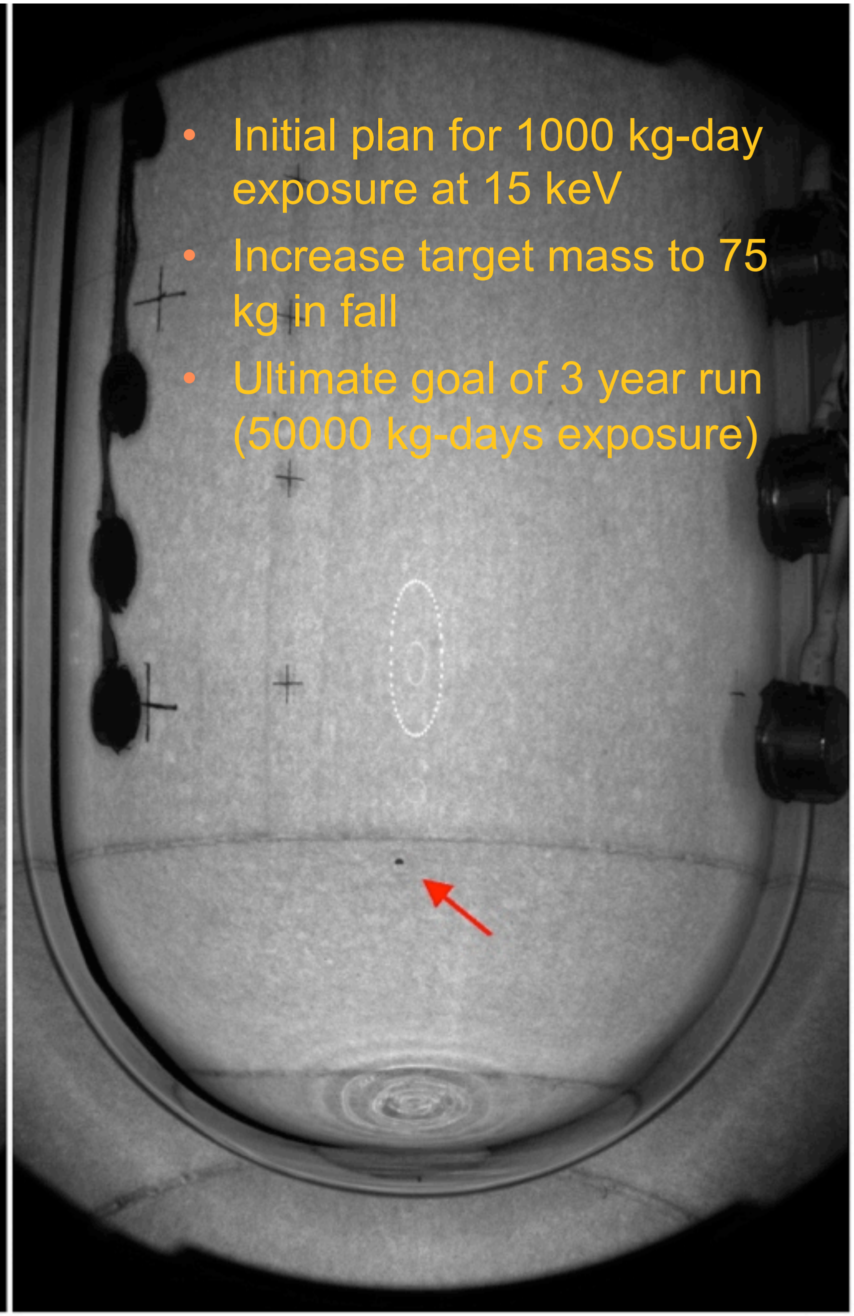
COUPP

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

COUPP-60



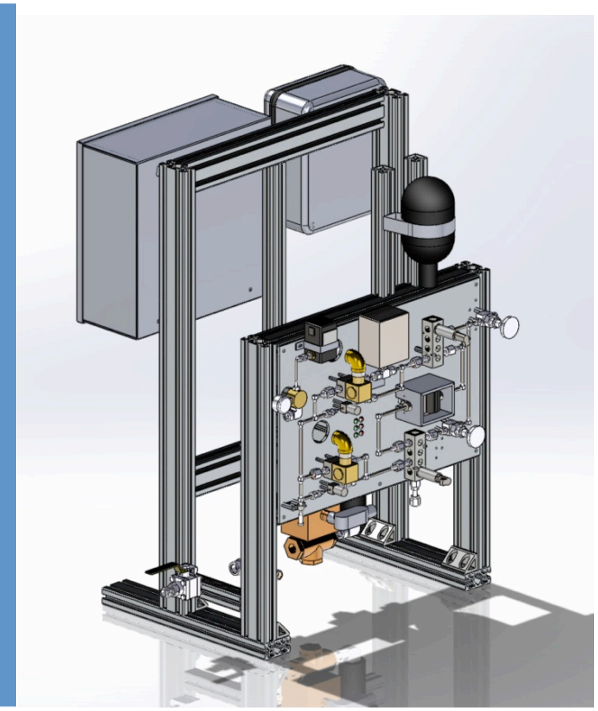
- Filled with 37 kg of CF_3I on April 26, 2013
- First bubble May 1, 2013 (radon decay)
- Installation completed May 31, 2013

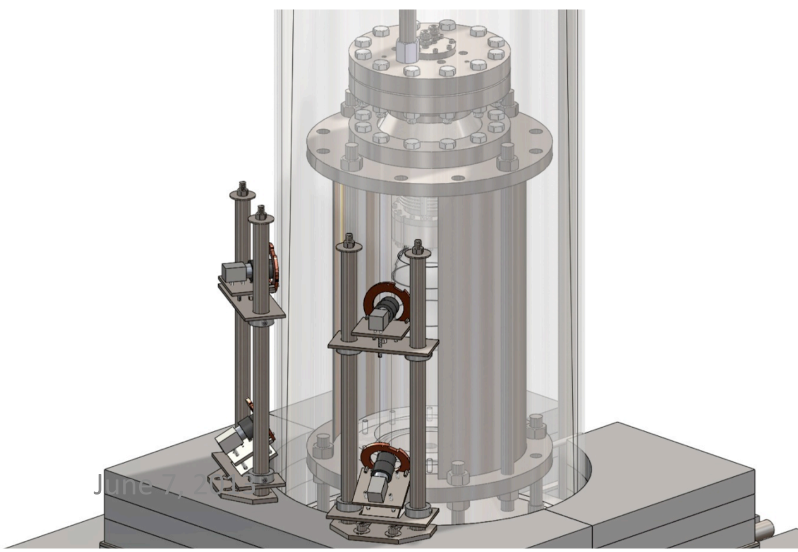


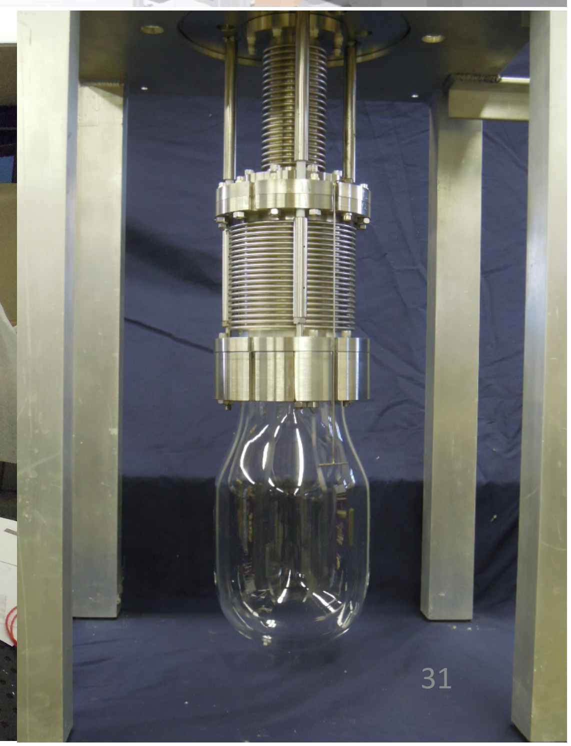
- Initial plan for 1000 kg-day exposure at 15 keV
- Increase target mass to 75 kg in fall
- Ultimate goal of 3 year run (50000 kg-days exposure)

COUPP-4lite

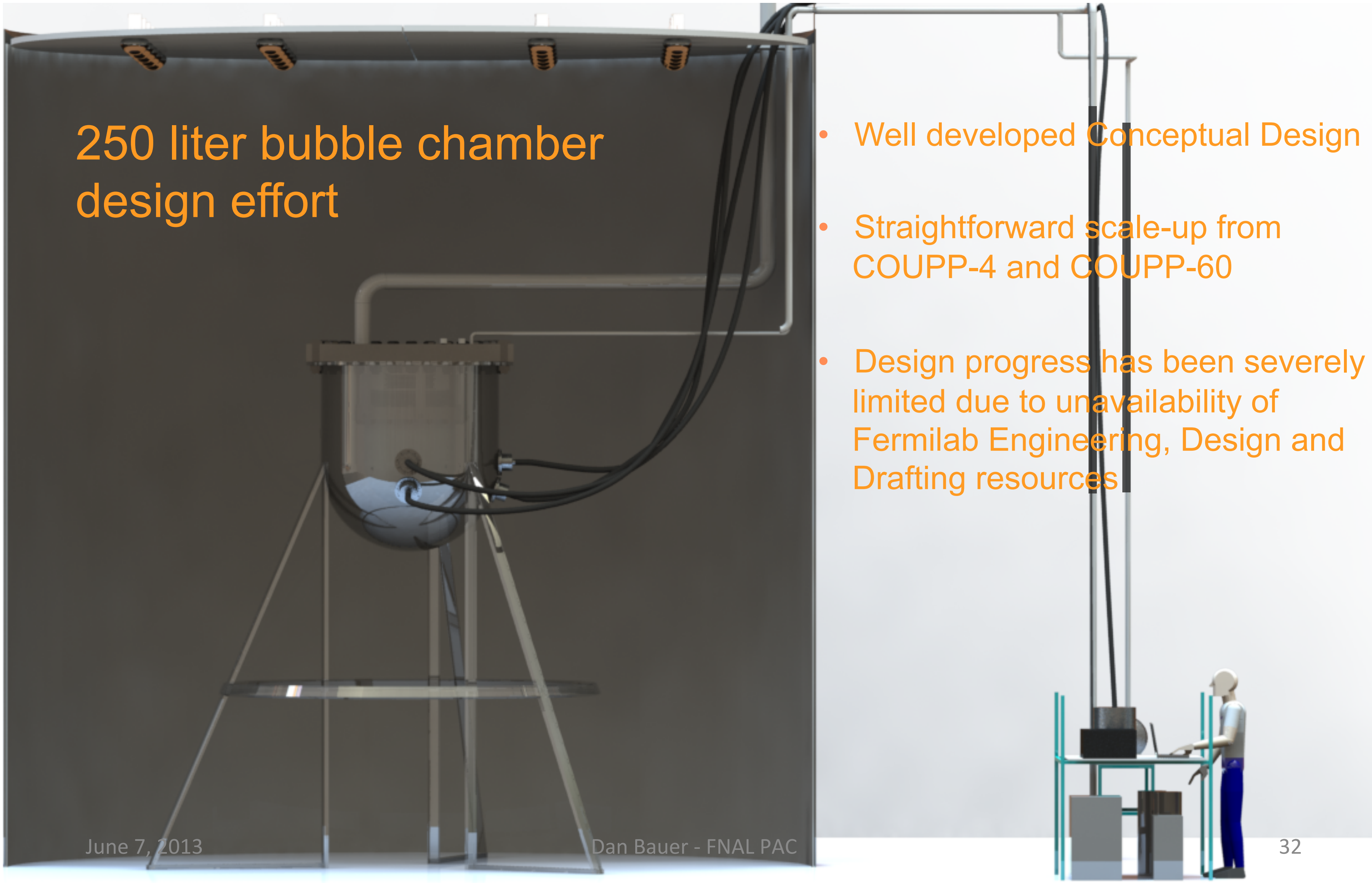
- C_3F_8 chamber in existing COUPP-4 infrastructure at SNOLAB
- 3 keV threshold
- Excellent low-mass WIMP and SD coupling sensitivity
- CDMS-Si result gives 1 event/day in COUPP-4lite
- First joint effort with PICASSO
- Deploy summer 2013







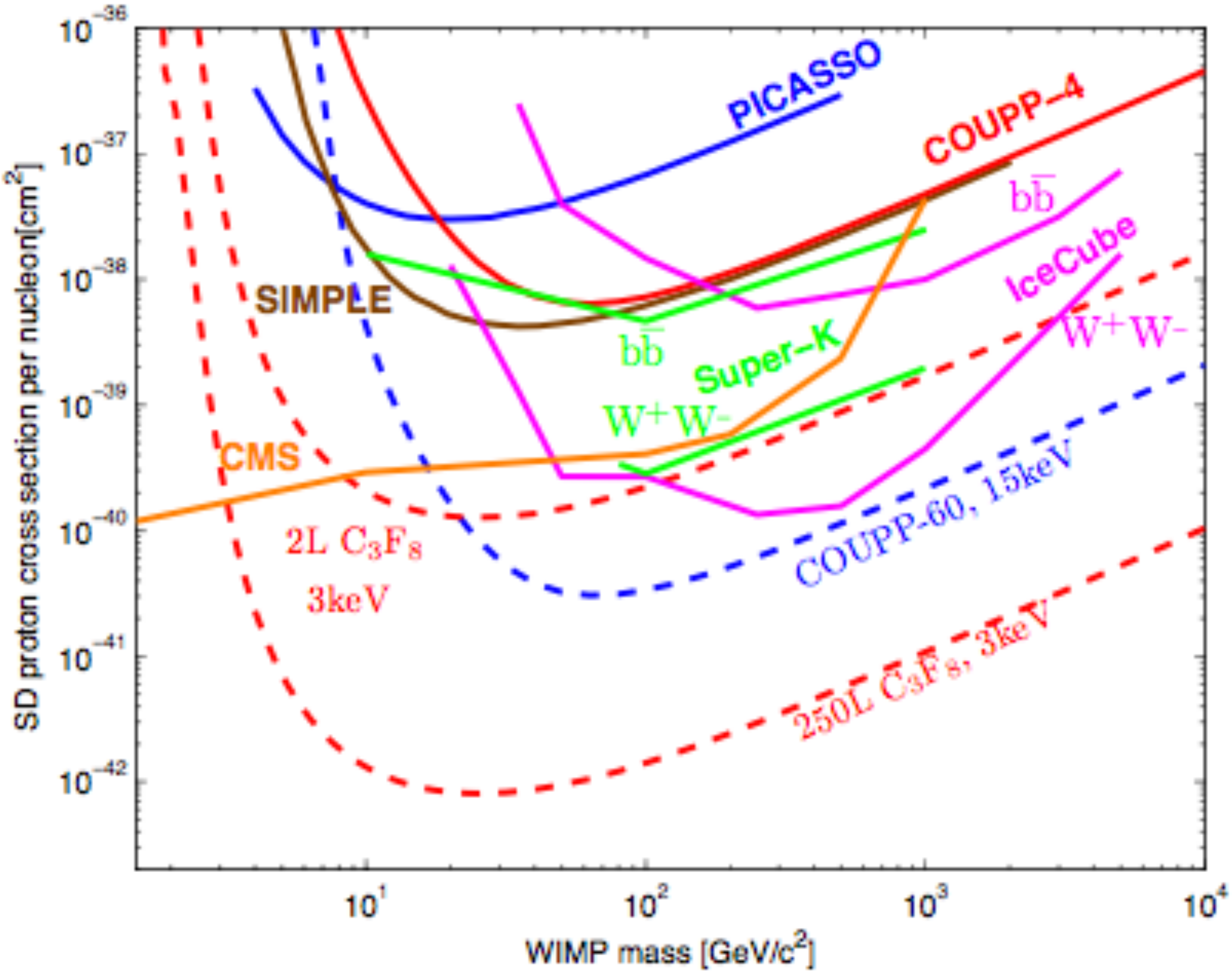
COUPP-500



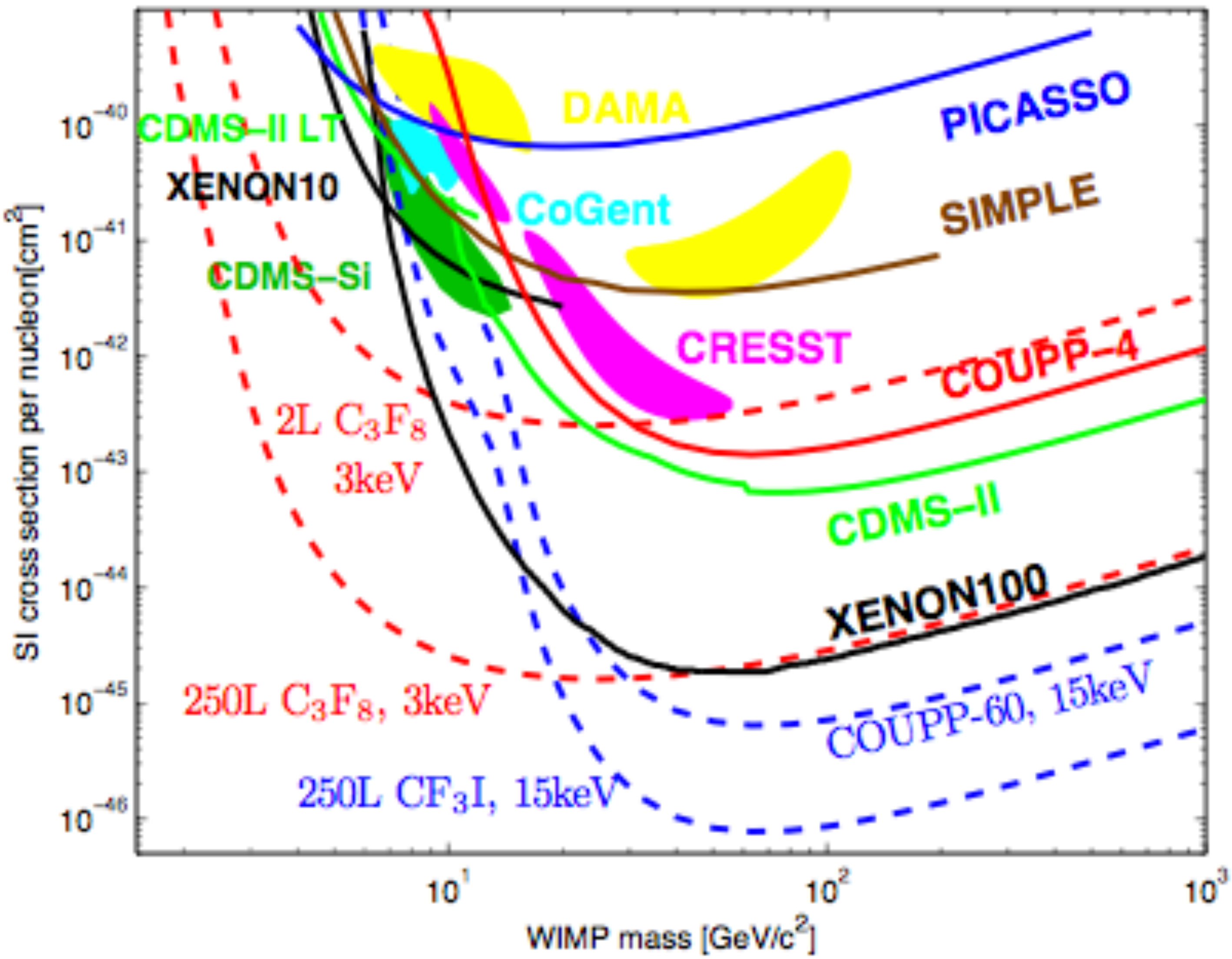
250 liter bubble chamber design effort

- Well developed Conceptual Design
- Straightforward scale-up from COUPP-4 and COUPP-60
- Design progress has been severely limited due to unavailability of Fermilab Engineering, Design and Drafting resources

COUPP – Spin Dependent WIMP projections



COUPP – Spin Independent WIMP projections



Noble Element Experiments

- Technique
  - Liquefy noble elements and detect scintillation light (and charge in some cases) from particle interactions
- Many different flavors
  - Xenon
    - Liquid only (XMASS)
    - Dual-phase TPCs (Zeplin III, Xenon100/1T, LUX/LZ, Panda-X)
  - Argon
    - Liquid only (DEAP, miniCLEAN)
    - Dual-phase TPCs (Darkside, ArDM)
  - Neon (CLEAN: solar neutrinos, low mass WIMPs)
  - Superfluid Helium (low mass WIMPS)

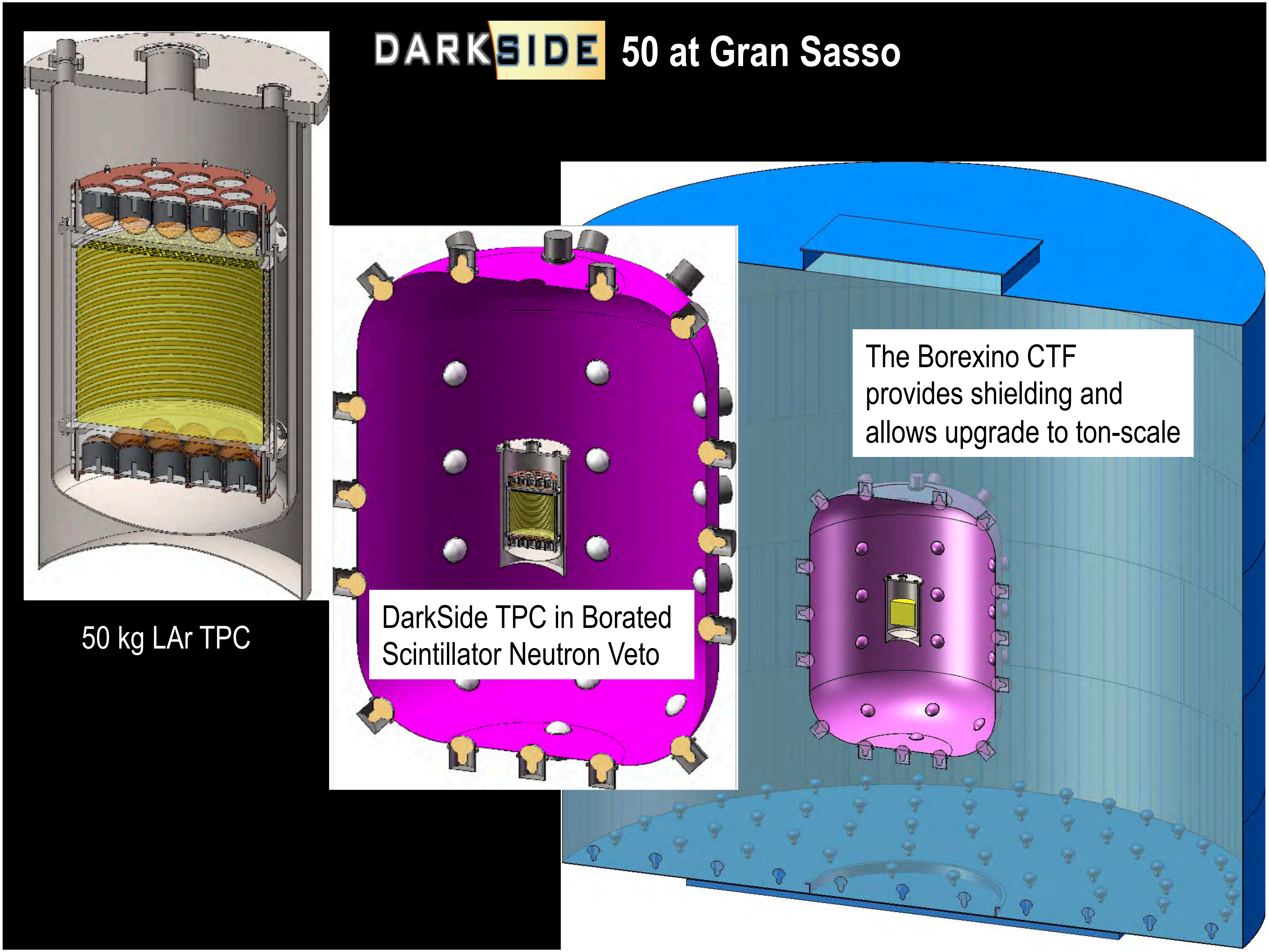
Fermilab experiments

Liquid Xenon

- Strengths
  - Large A, low energy threshold => good sensitivity
  - Liquid purity and self shielding
  - Large target masses possible (but Xe is expensive)
  - Both SI and SD interactions can be probed
- Weaknesses
  - Relatively poor intrinsic detector discrimination
  - Maintaining extreme purity for the LXe
- New Developments
  - Self shielding of inner volume demonstrated

Liquid Argon

- Strengths
  - Excellent EM discrimination using pulse shape
  - Very large target masses possible at reasonable cost
- Weaknesses
  - Low A => low spin-independent rate
    - no nuclear spin isotopes, so insensitive to SD interactions
  - High energy threshold
    - 40 keV demonstrated, 20 keV possible
    - Not a good target for low-mass WIMPS, but excellent for > 1 TeV
  - 39Ar is an intrinsic background
- New Developments
  - Underground argon source with low 39Ar


DARKSIDE 50 at Gran Sasso
50 kg LAr TPC
DarkSide TPC in Borated Scintillator Neutron Veto
The Borexino CTF provides shielding and allows upgrade to ton-scale

DarkSide
Aim at zero-background technology

- Pulse Shape Discrimination (PSD) of Primary Scintillation, S1, (rejects e/gamma) (unique to Argon - atomic physics of Argon dimer)
- Ionization:Scintillation Ratio, S2/S1 (rejects e/gamma - not unique to Argon)
- Sub-cm Spatial Resolution (identify surface bkgs) (advantage of two-phase)
- Underground argon (avoid event pile-up from ^{39}Ar)
- Neutron Veto (identify neutrons with high efficiency in finite volume)
- Water shield (identify muons and avoid cosmogenic neutrons)
- Screen and select all detector materials for minimum radioactivity

Fermilab Participation in DS-50

- Underground Argon Purification (PPD *with Princeton)*
- Argon handling system (PPD *with Princeton & UCLA*)
- TPC Data Acquisition System (SCD *with LNGS*)
- Trigger (PPD)
- PMT Bases (PPD)
- Data Storage & Analysis system (SCD & CCD)
- Project management & DOE funds co-ordination

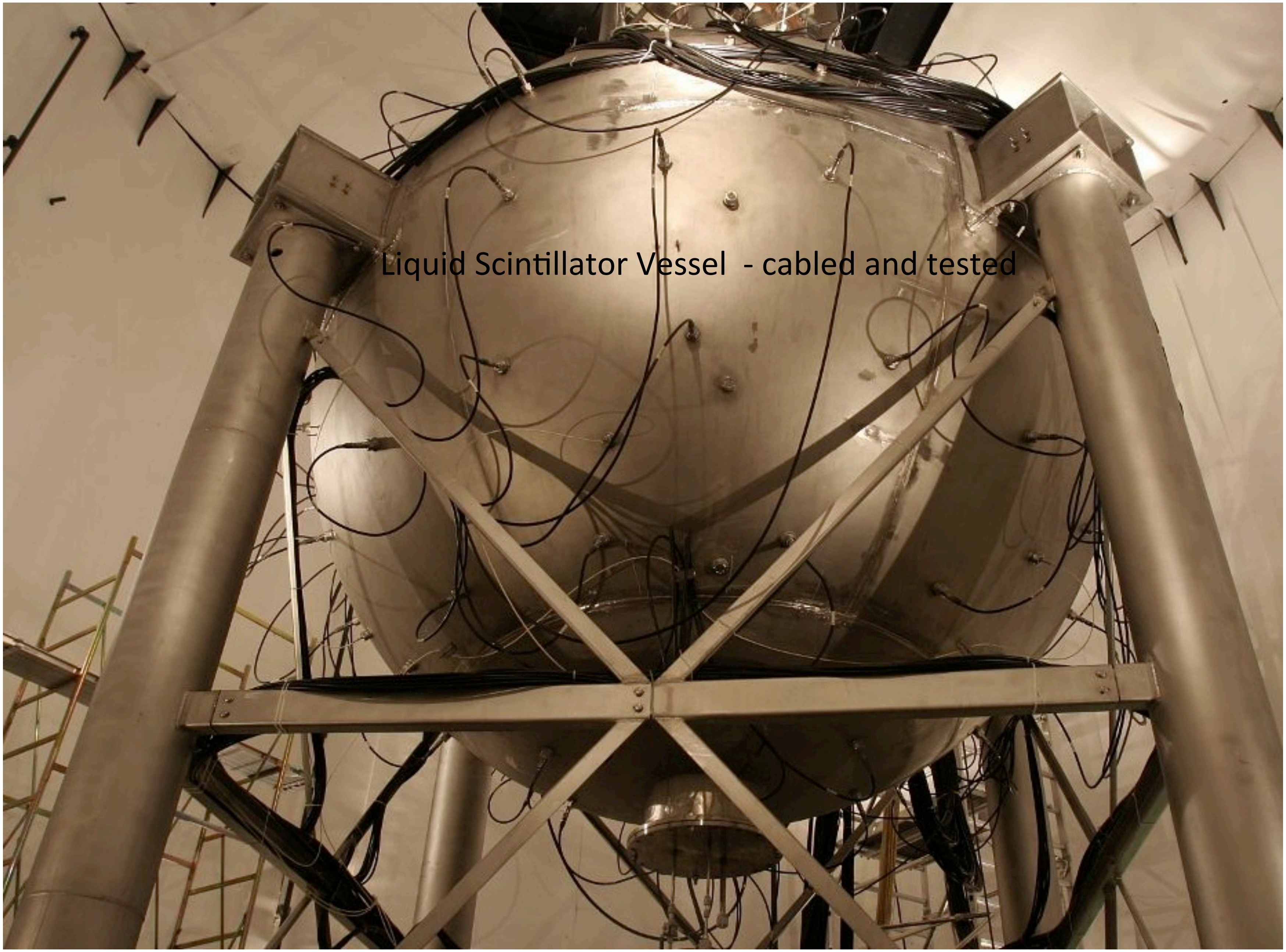
Recent Milestones

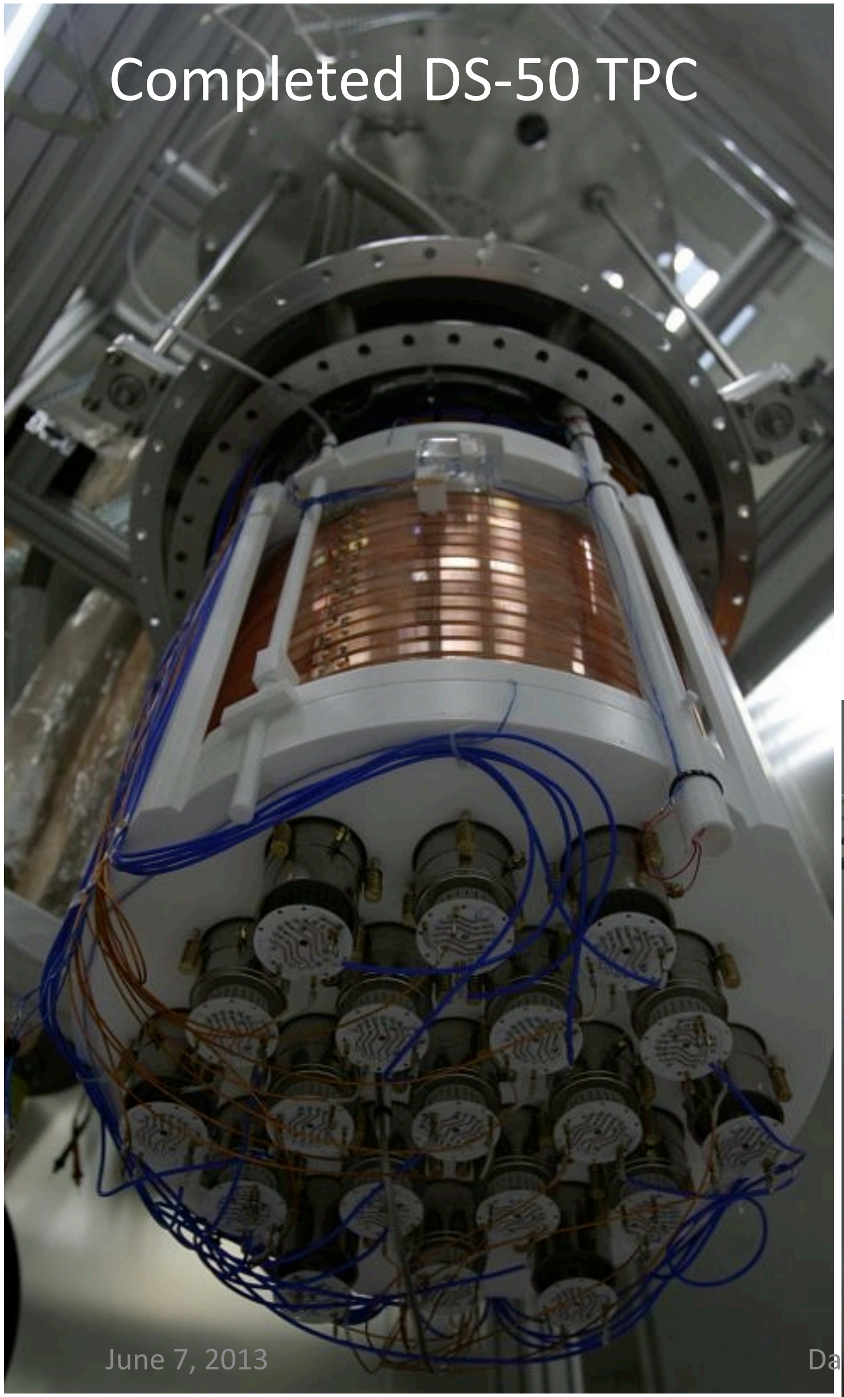
- Operated DarkSide-10 for 1 year (light yield 7 - 9 p.e./keV)
- Constructed as part of DarkSide-50:
  - 1,000 tonne water Cerenkov muon veto
  - 30 tonne organic liquid scintillator neutron veto
  - two Rn-free clean rooms for final preparation of detector
  - argon recirculation, purification, and recovery systems

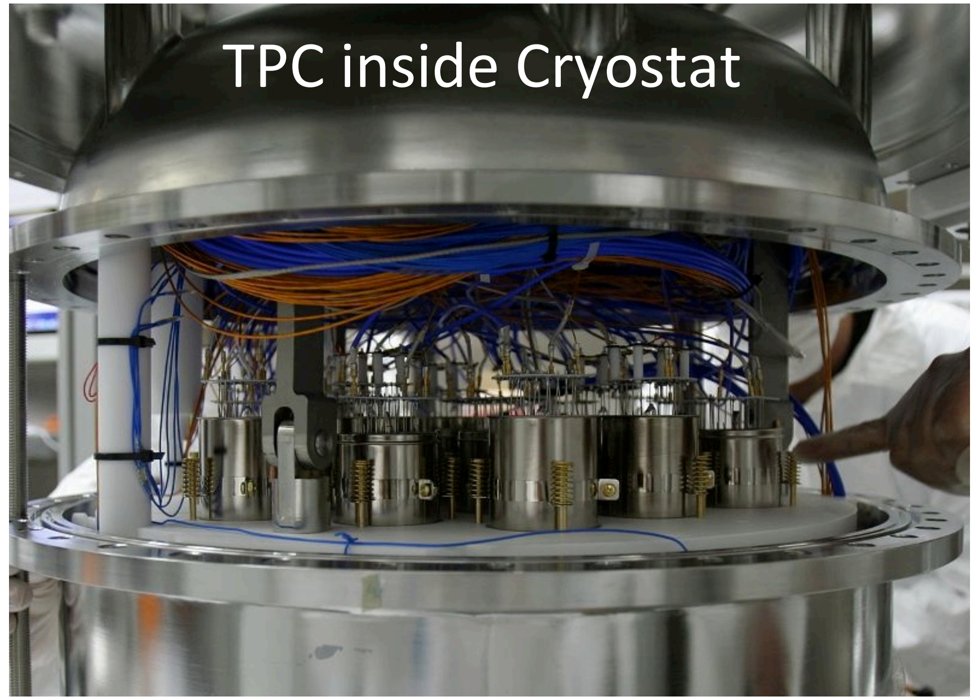
All facilities sized and built to house DarkSide-G2

- April 2013 DarkSide-50 TPC assembled at LNGS
- First DarkSide-50 TPC Commissioning Run in progress with atmospheric argon
  - 2nd TPC commissioning run starting in August
  - Fill Liquid Scintillator Vessel
  - Fill Water Tank
  - Concentrate on background rejection performance
  - Low radioactivity argon towards end of year

Radon-free Clean Room above Water Tank


Liquid Scintillator Vessel - cabled and tested


Completed DS-50 TPC

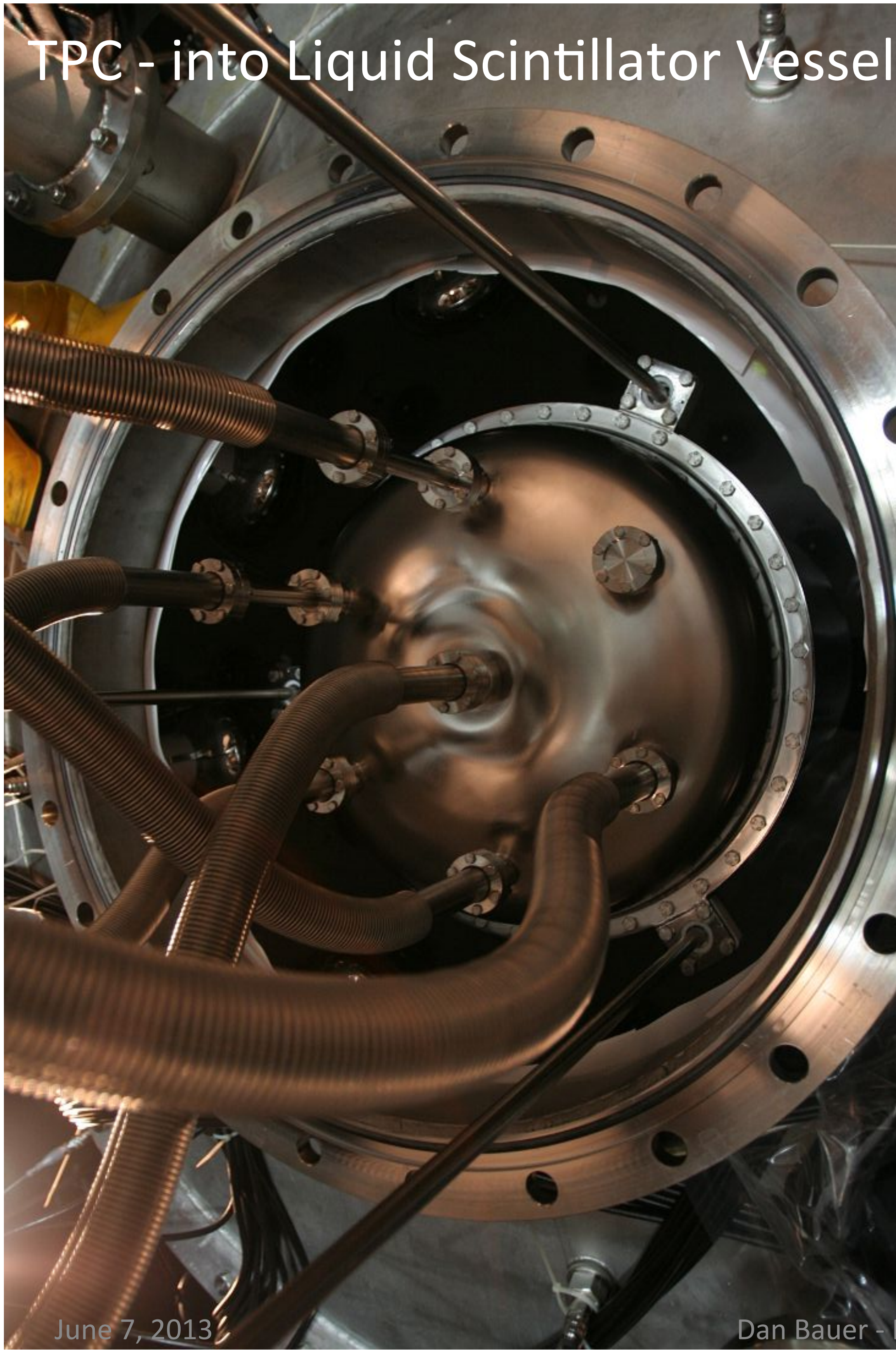

TPC inside Cryostat


Cryostat and vacuum vessel


Cryostat with umbilicals on
top flange of LSV

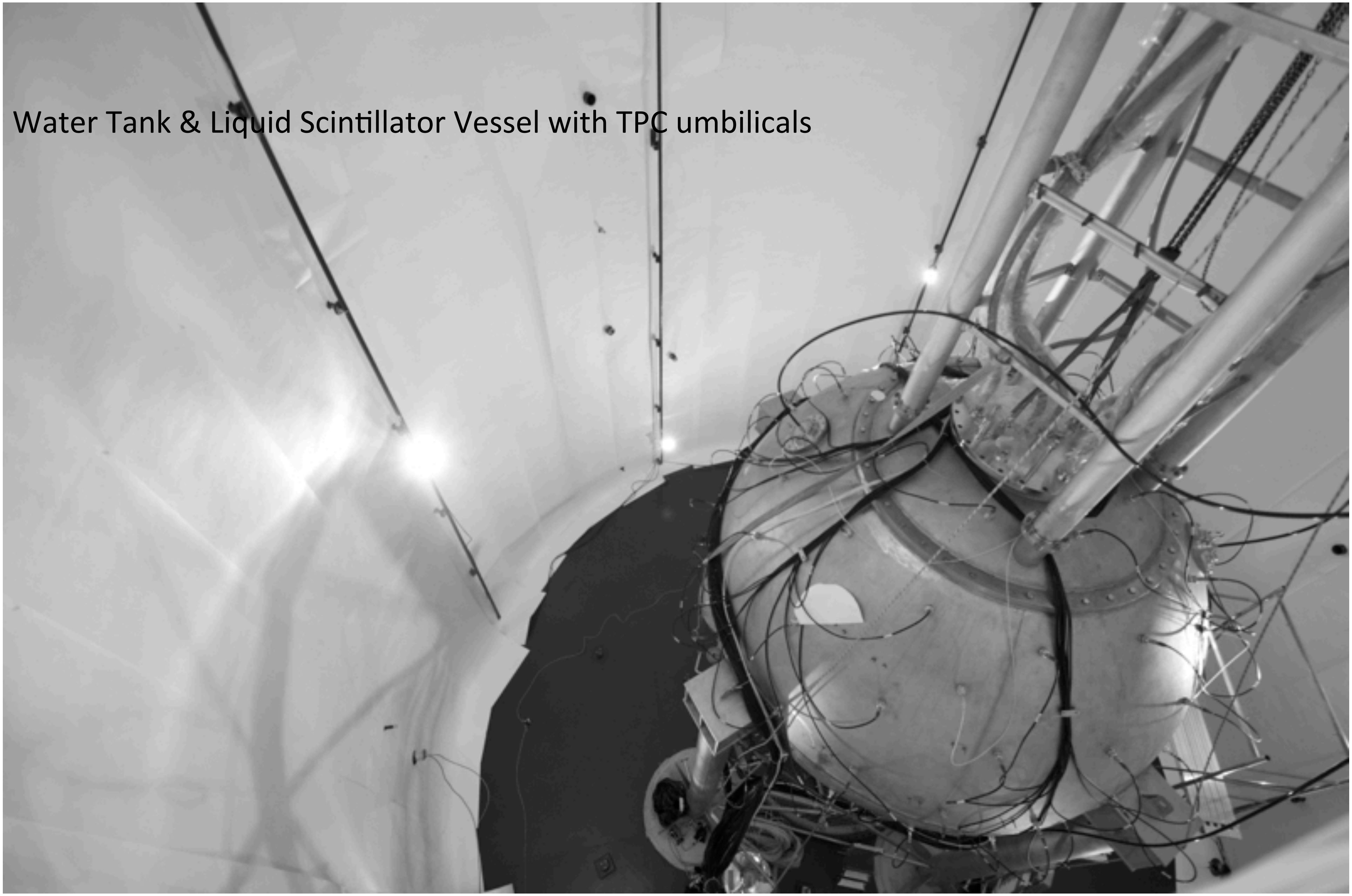

Entering Water Veto

TPC - into Liquid Scintillator Vessel

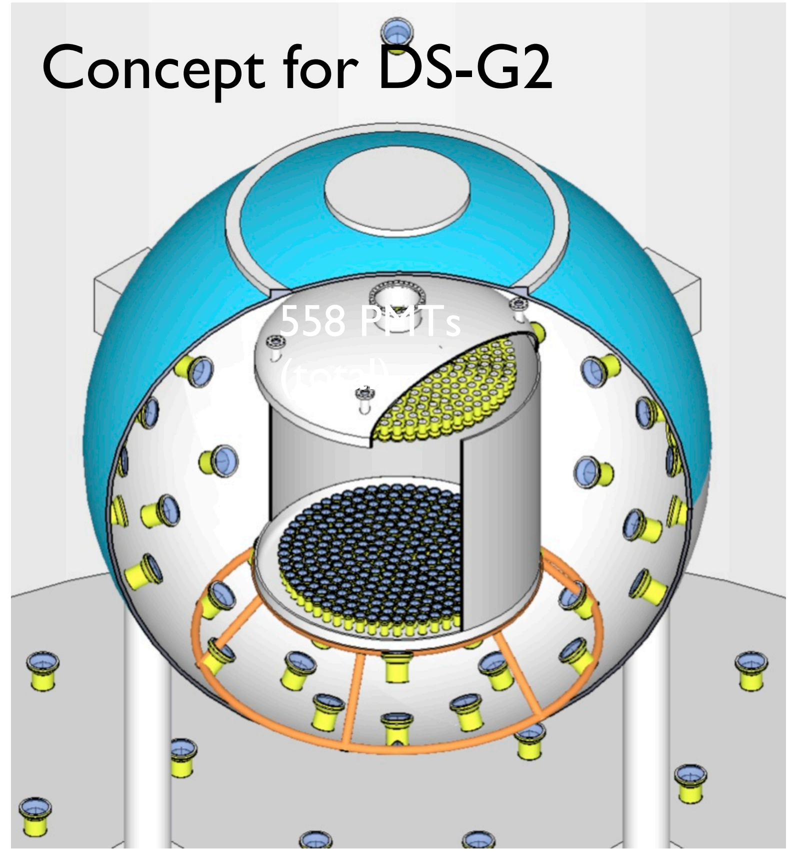


Hanging in Liquid Scintillator Vessel

Water Tank & Liquid Scintillator Vessel with TPC umbilicals



DarkSide-G2



5 tonnes argon, 2.8 tonnes fiducial, 3.3 active

Muon Veto System – built

Neutron Veto System - built

Argon Handling System – built except for recovery system

TPC - size defined by existing infrastructure

Argon – intense R & D activity to increase production & purification capability

Photosensors – program with Hamamatsu to reduce radioactivity (and to increase PMT diameter if possible)

TPC mechanical design – big issue and working to secure help

DAQ – baseline concept using SLAC `RCE' module and ArtDaq

Crystal Detectors

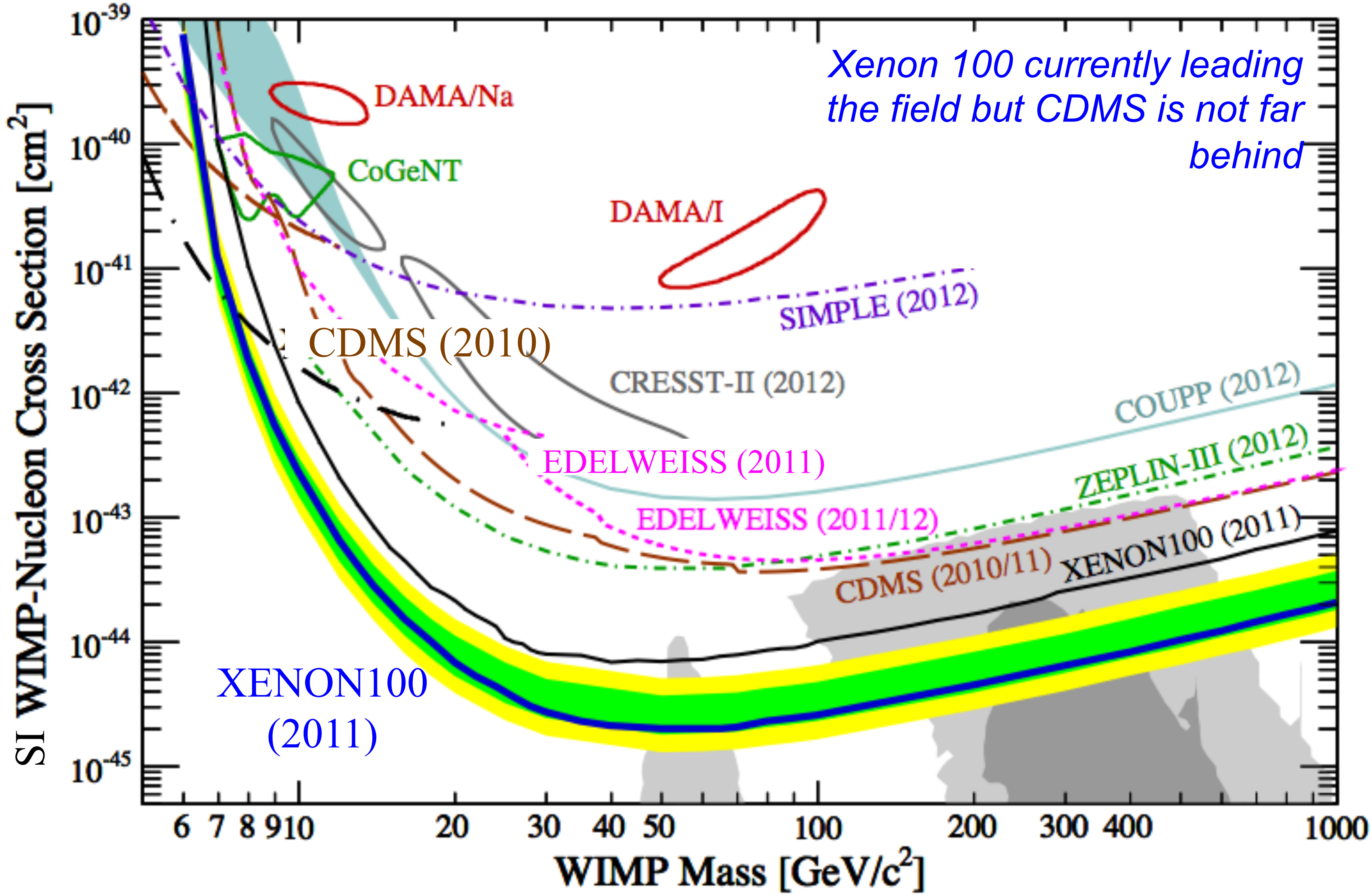
- Technique
  - Use large NaI (or CsI) crystals to detect light from nuclear recoils
- Strengths
  - Large radiopure scintillator target masses possible
- Weaknesses
  - No event by event discrimination
  - Large residual backgrounds; small annual modulation on top
  - Hard to be sure if rate and modulation signals consistent
- NaI (DAMA/LIBRA, DMIce, NAIAD, Tokyo, ANAIS, Princeton)
- CsI (KIMS)
- DAMA/LIBRA remains the only direct detection experiment that has claimed a dark matter signal!
- New Developments
  - Check whether modulation effects are really from backgrounds by using the same target in different hemisphere (DMIce)

Small Fermilab involvement

Directional Detectors

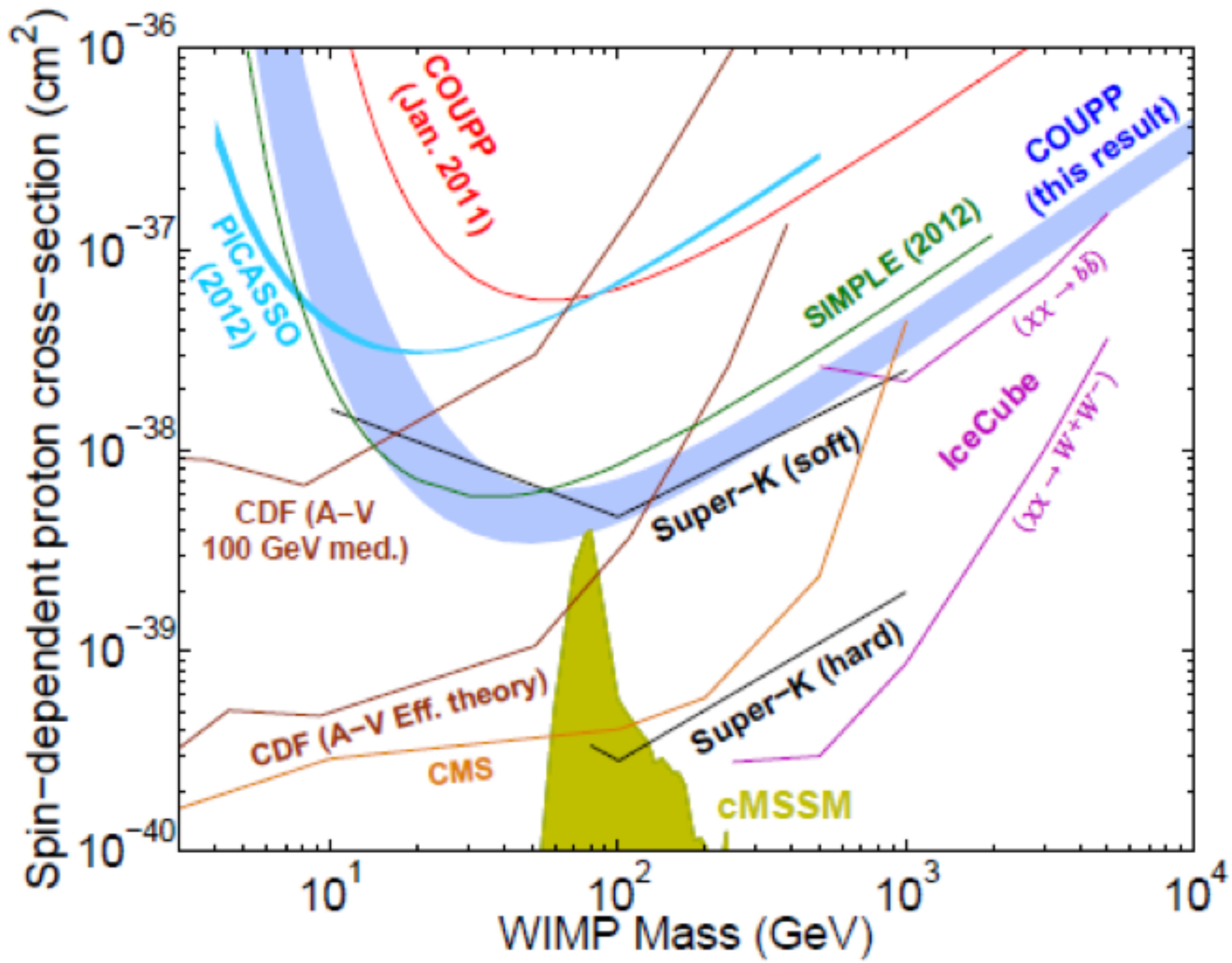
- Strengths
  - Can detect nuclear recoil (and thus WIMP) direction
- Weaknesses
  - Very difficult to get sufficient target mass
  - May only be feasible if signal found in counting exps.
- Low pressure TPCs
  - DRIFT, DMTPC, D-cubed, NEWAGE, MIMAC
- New Developments
  - High pressure gas detectors (NEXT), Nuclear emulsions, DNA
  - Possible approaches to pushing towards lower energy threshold where target mass limitation not so important
    - This may be an interesting detector R&D initiative for Fermilab (interest in both NEXT and D-cubed)

Spin-Independent Landscape

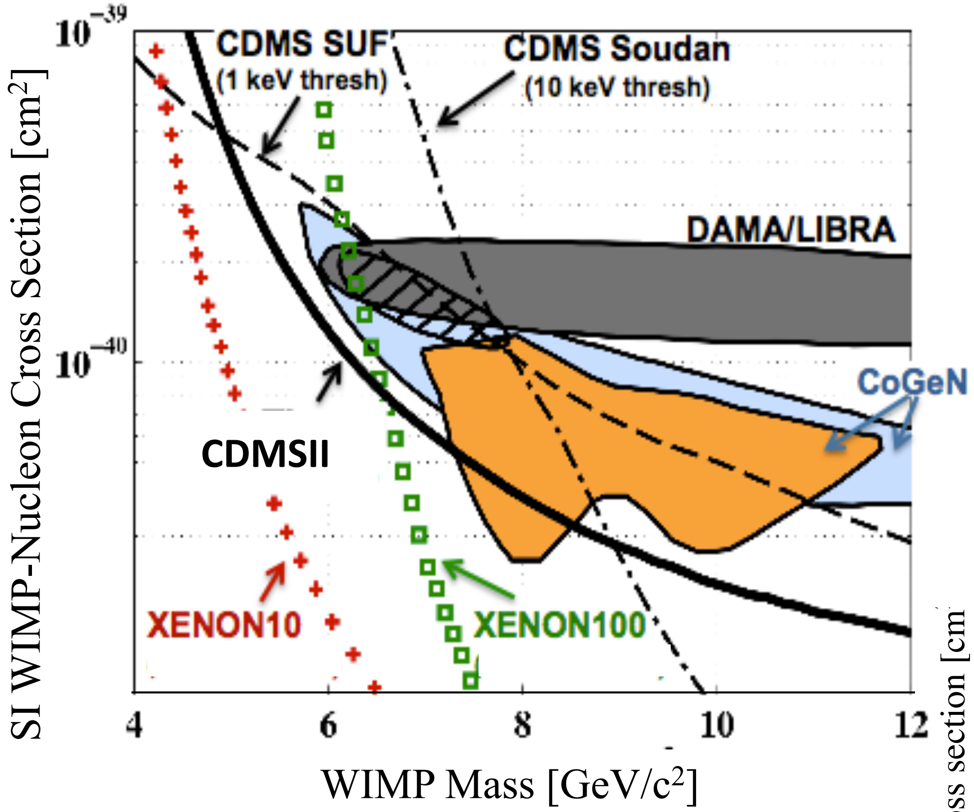


Spin-Dependent Landscape

COUPP/Picasso lead for proton coupling; neutron coupling led by XENON100



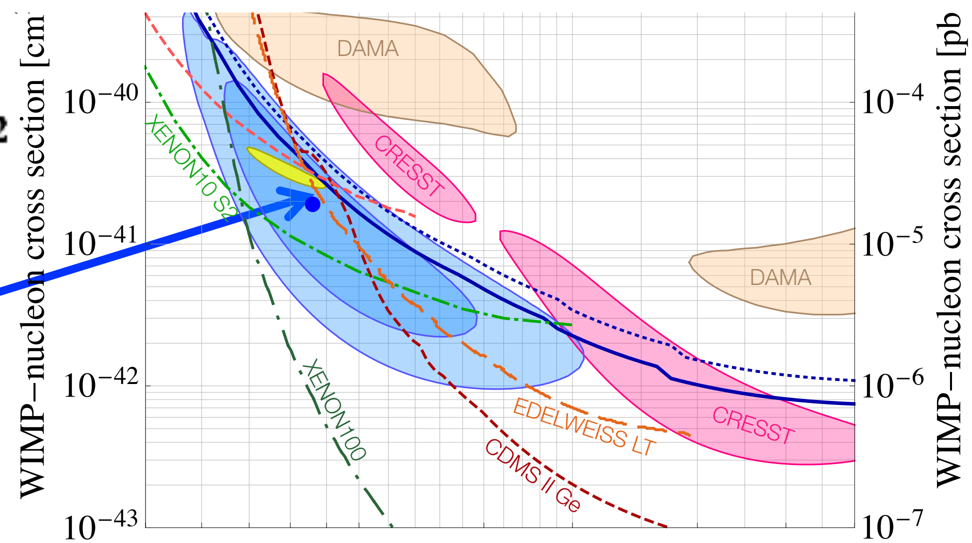
The low-mass WIMP landscape



DAMA/Libra modulation, CoGeNT low energy excess rate and CRESST excess events all can be interpreted as evidence for ~ 7 GeV WIMP

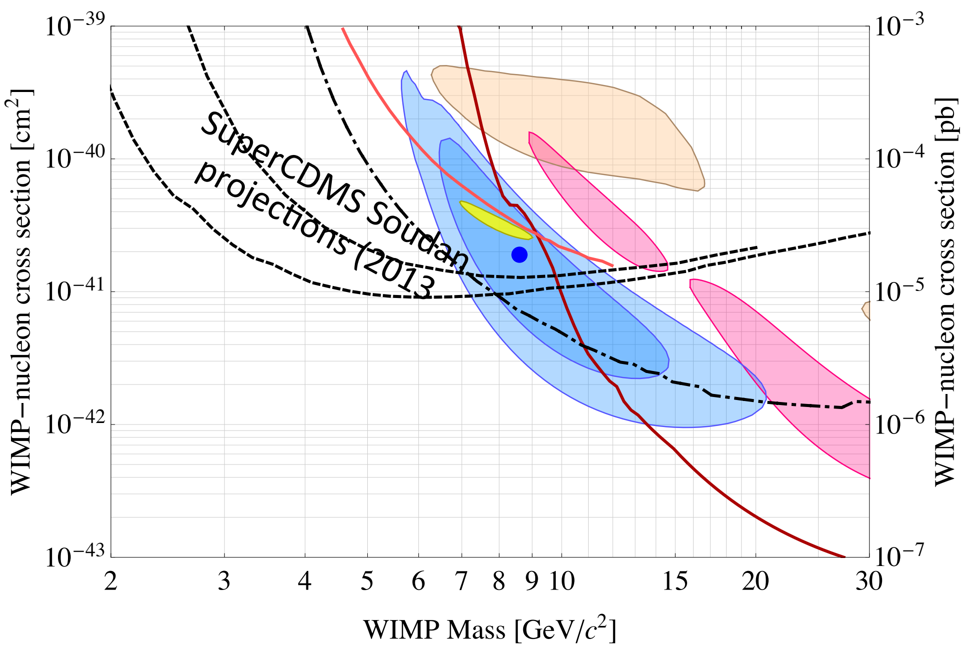
However, CDMS II Germanium and Xenon 10/100 did not see this.

CDMS II Silicon data do show something around 8.5 GeV



Shedding light on low-mass WIMPs

Avoid systematics near the energy threshold by designing an experiment where recoils of interest are well above the threshold



SuperCDMS Soudan should be able to confirm or (mostly) rule out the CDMS II Si result this year

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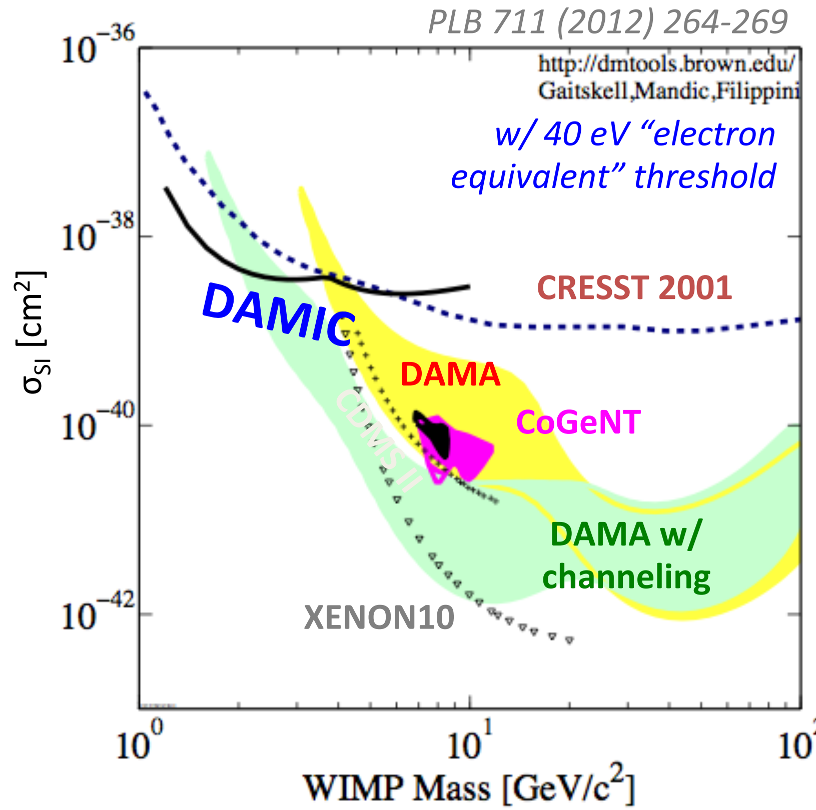

DAMIC, CoGENT and Malbek will also release new results soon

The US G2 dark matter program

- DOE process for selecting next generation dark matter experiments Already have chosen five groups for R&D funding
  - SuperCDMS SNOLAB
    - Proven low-background technology that also provides the best low-mass WIMP sensitivity
  - COUPP
    - Least expensive WIMP search with unique reach for spin-dependent interactions and possibility of low-mass WIMP sensitivity
  - Darkside
    - May be the best approach for high-mass WIMPS because very large, low-background LAr detectors seem possible. Pioneering active neutron veto.
  - LZ
    - Liquid Xenon taken to the extreme. Relies heavily on extreme radiopurity, self-shielding, which may not be completely effective against radiogenic neutron backgrounds
  - ADMX
    - Only experiment doing direct detection of axions (viable dark matter candidate)
- NSF (and Europe) are already funding a liquid Xenon G2 experiment (Xenon 1T), but DOE has little involvement in this

The US G2 dark matter program

- Further "downselect" to projects by end of 2013
  - $30M is the total for the whole DOE program
    - DOE requests are roughly: LZ (20-40M), SuperCDMS SNOLAB (16M), COUPP-500 (5M), Darkside-G2 (5M), ADMX (2M)
    - Most of these have substantial requests to NSF and foreign funding as well
  - DOE can fund 2-4 projects
    - Seem likely to continue with ADMX (unique niche)
    - Probably have to choose between LZ and SuperCDMS SNOLAB, or ask these experiments to reduce scope
    - Burden on LUX to prove that LZ is technically viable and cost effective
    - Burden on SuperCDMS to show that it can be done within cost and schedule
    - Burden on Darkside-50 to demonstrate low-background performance of LAr
    - Burden on COUPP-60 to show backgrounds under control
  - Only the winners will receive any DOE funding in 2014-2016
  - Projects are supposed to chosen on the basis of expected sensitivity and technical readiness (hopefully not on the political basis of site!)
  - DOE and NSF are "coordinating" their involvement in G2 dark matter
- Fermilab is well positioned to participate in G2
  - But lab technical resources are stretched very thin and we don't have the scientist FTEs to lead all 3 efforts
  - Will have to make decisions on support after the downselect

Summary

- Direct detection of dark matter WIMPS remains one of the best ways to spot evidence for something beyond the standard model, as well as providing an explanation for what most of the mass of the universe actually is.
- For the next generation, Fermilab's suite of direct detection experiments should push down substantially in cross section sensitivity across the whole accessible mass range.
- We shouldn't lose sight of the fact that we might actually detect WIMPS in G2 experiments, and must be well prepared to follow up on any signals with a range of different technologies!