The Direct Detection of Dark Matter

Prospects and Techniques

An Update to the July 2007 DMSAG Report

Hank Sobel

March 6, 2008

Charge Letter to HEPAP and AAAC from DOE and NSF

- We are requesting that the High Energy Physics Advisory Panel (HEPAP) and the Astronomy and Astrophysics Advisory Committee (AAAC) form a joint subpanel to provide advice on priorities and strategies for the direct detection and study of the dark matter that dominates the mass of the universe.

In particular,

- What are the most promising experimental approaches … using particle detectors in underground laboratories?
- Optimum strategy to operate at the sensitivity frontier while making the investments required to reach the ultimate sensitivity

Panel

Hank Sobel, Chair (UCI)
Howard Baer (FSU)
Frank Calaprice (Princeton)
Gabriel Chardin (SACLAY)
Steve Elliott (LANL)
Jonathan Feng (UCI)
Bonnie Fleming (Yale)
Katie Freese (U. of Michigan)
Robert Lanou (Brown)
Charles Prescott (SLAC)
Hamish Robertson (UW)
Andre Rubbia (ETH-Zurich)
Kate Scholberg (Duke)
Yoichiro Suzuki (U. of Tokyo)
Michael Witherell (UCSB)
Jonathan Bagger, Ex-Officio (Johns Hopkins University)
Garth Illingworth, Ex-Officio (UCSC)

The material for this talk comes from the DMSAG panel plus updates from the experimental groups.

Background

- In the past decade, breakthroughs in cosmology have transformed our understanding of the Universe.
- A wide variety of observations now support a unified picture in which the known particles make up only one-fifth of the matter in the Universe, with the remaining four-fifths composed of dark matter.
- The evidence for dark matter is now overwhelming, and the required amount of dark matter is becoming precisely known.

Despite this progress, the identity of dark matter remains a mystery

- Constraints on dark matter properties ⇒ the bulk of dark matter cannot be any of the known particles.
  - One of the strongest pieces of evidence that the current theory of fundamental particles and forces, is incomplete.
- Because dark matter is the dominant form of matter in the Universe, an understanding of its properties is essential to attempts to determine how galaxies formed and how the Universe evolved.
  - Dark matter therefore plays a central role in both particle physics and cosmology, and the discovery of the identity of dark matter is among the most important goals in basic science today.

Dark Matter

What We Know

- How much:

  $\Omega_{DM} = 0.23 \pm 0.04$
- What it's not:

  Not short-lived: $\tau > 10^{10}$ years

  Not baryonic: $\Omega_B = 0.04 \pm 0.004$

  Not hot: "slow" DM is required to form structure

What We Don't know

- Mass?
- Spin?
- Other quantum numbers and interactions?
- Absolutely stable?
- One particle species or many?
- How produced?
- When produced?
- Why does Ω_{DM} have the observed value?
- Role in structure formation?
- How distributed now?

The Properties of a Good Dark Matter Candidate

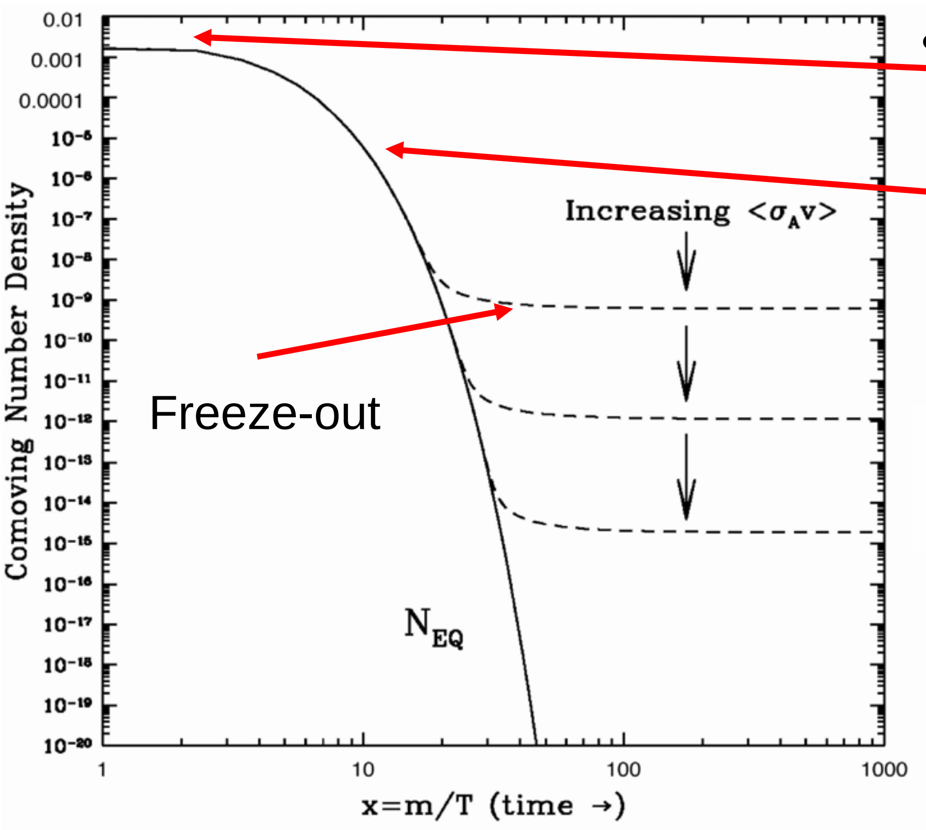
- stable (protected by a conserved quantum number)
- no charge, no color (weakly interacting)
- cold, non dissipative
- relic abundance compatible to observation
- motivated by theory (vs. “ad hoc”)

Dark Matter Candidates

- The theoretical study of dark matter is very well-developed, and has led to many concrete and attractive possibilities.
- Two leading candidates for dark matter are Axions and weakly-interacting massive particles (WIMPs). These are well-motivated, not only because they resolve the dark matter puzzle, but also because they simultaneously solve longstanding problems associated with the standard model of particle physics.

Independently of this, if we try to understand the weak scale in particle physics, new particles appear. If we add these to the universe:

Add New Particle to the Universe



- Particle initially in thermal equilibrium. As universe cools:

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{eff} v \rangle \left(n^2 - n_{eq}^2 \right)$$

Decrease due to expansion of universe

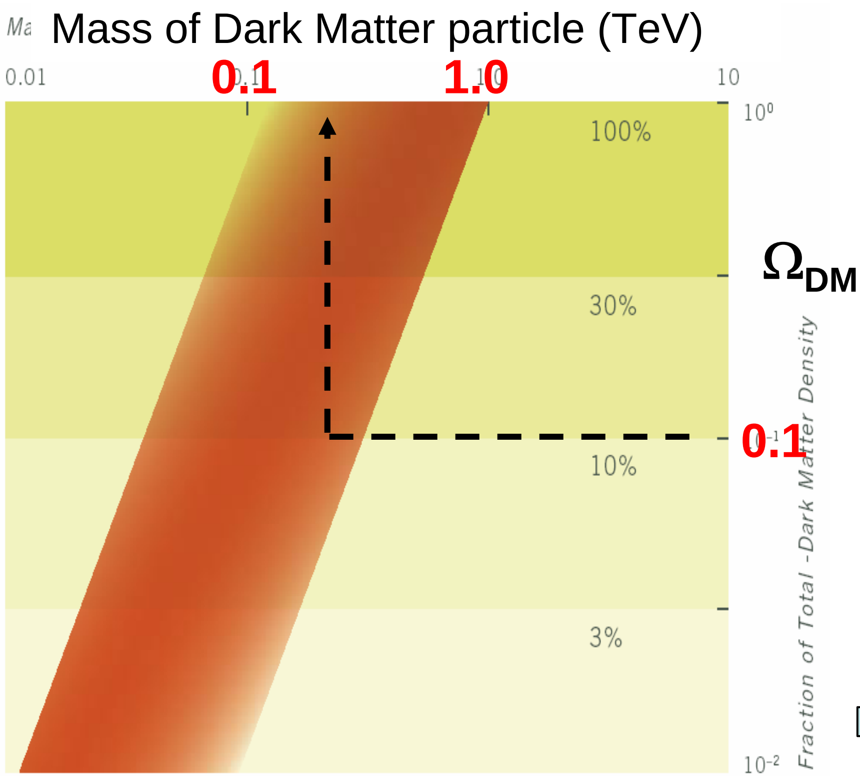
Change due to annihilation and creation

Number density now by integrating from freeze-out to present:

$$\Omega_{DM} \sim \langle \sigma_A v \rangle^{-1}$$

The "WIMP Miracle"

(Weakly Interacting Massive Particle)



HEPAP LHC/ILC Subpanel (2006)

The amount of dark matter left over is inversely proportional to the annihilation cross section:

$\Omega_{DM} \sim \langle\sigma_A v\rangle^{-1}$

If we take : $\sigma_A = k\alpha^2/m^2$,

then $\Omega_{DM} \sim m^2$

and

For $\Omega_{DM} \sim 0.1$

M ~ 100 GeV – 1 TeV.

"WIMP"

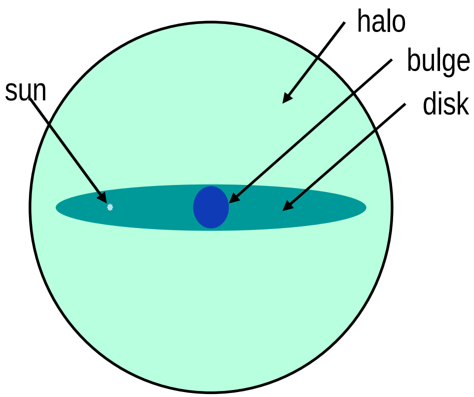
Cosmology alone tells us we should explore the weak scale.

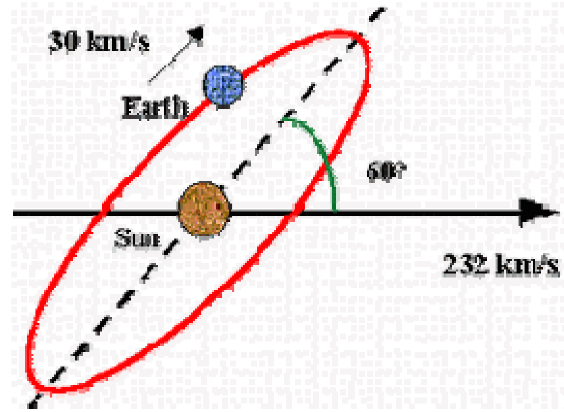
WIMPs

- In many supersymmetric models, the lightest supersymmetric particle is, stable, neutral, weakly-interacting, mass ~ 100 GeV. All the right properties for WIMP dark matter!
- In addition:

Ω_{DM} = 23% ± 4% stringently constrains models

Direct Detection of WIMPs





Dark matter responsible for galaxy formation (including ours).
We are moving through a dark matter halo.

Usually assume spherical distribution with Maxwell-Boltzmann velocity distribution.
V=230 km/s, ρ=0.3 GeV/cm^3

WIMP nucleus scattering rate calculated from theory.
Elastic nuclear scattering: interactions are either spin-dependent or spin-independent.
Low velocity →coherent interaction

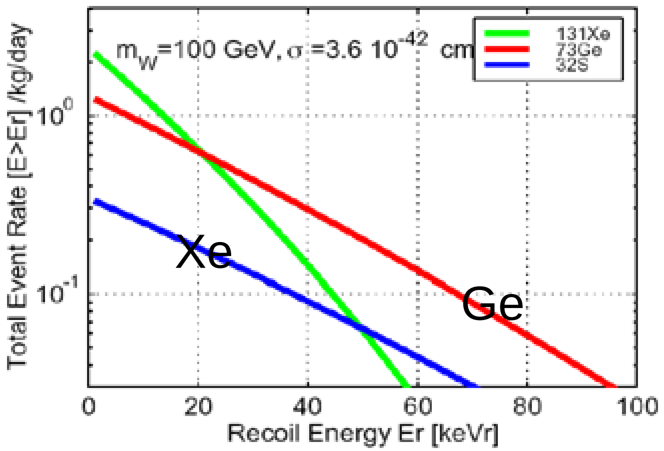
Experimental Challenges

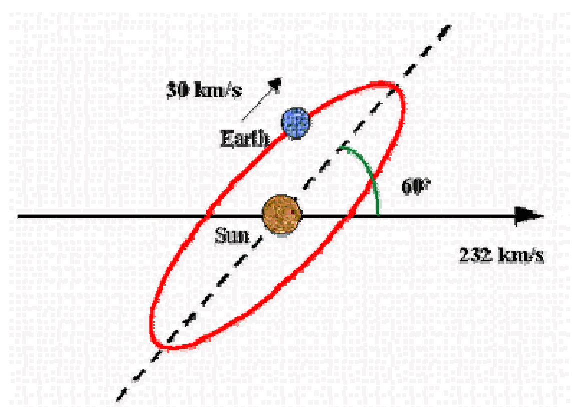
The WIMP "signal" is a low energy (10-100 keV) nuclear recoil.

- Overall expected rate is very small ($\sigma=10^{-42}cm^2$ gives about 1 event/kg/day , limit now $\sigma < 10^{-43}cm^2$, mSUGRA models go to ~ $10^{-46}cm^2$).
- Need a large low-threshold detector which can discriminate against various backgrounds.
  - Photons scatter off electrons.
  - WIMPs and neutrons scatter off nuclei.
- Need to minimize internal radioactive contamination.
- Need to minimize external incoming radiation.
  - Deep underground location

Possible WIMP Signatures

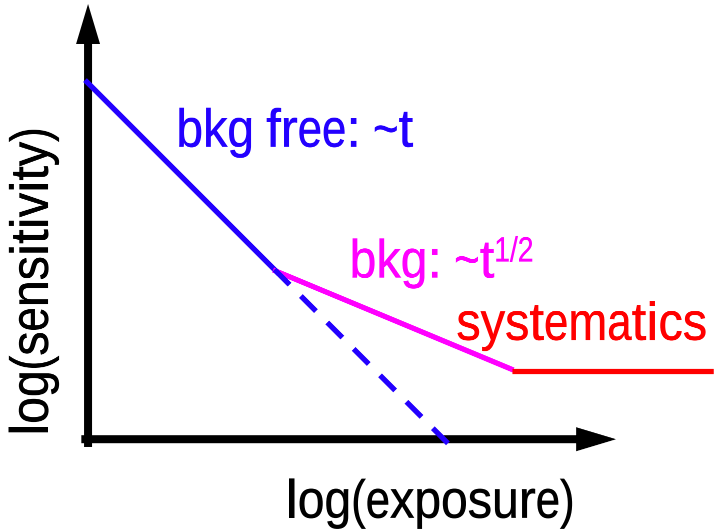
- Nuclear vs electronic recoil
  - **(discrimination required)**
- No multiple interactions
- Recoil energy spectrum shape
  - **(exponential, rather similar to background…)**
- Consistency between targets of different nuclei
  - **(essential once first signal is clearly identified)**
- Annual flux modulation
  - **(Most events close to threshold, small effect ~2%)**
- Diurnal direction modulation
  - **(nice signature, but very short tracks requires low pressure gaseous target,**





Minimizing backgrounds

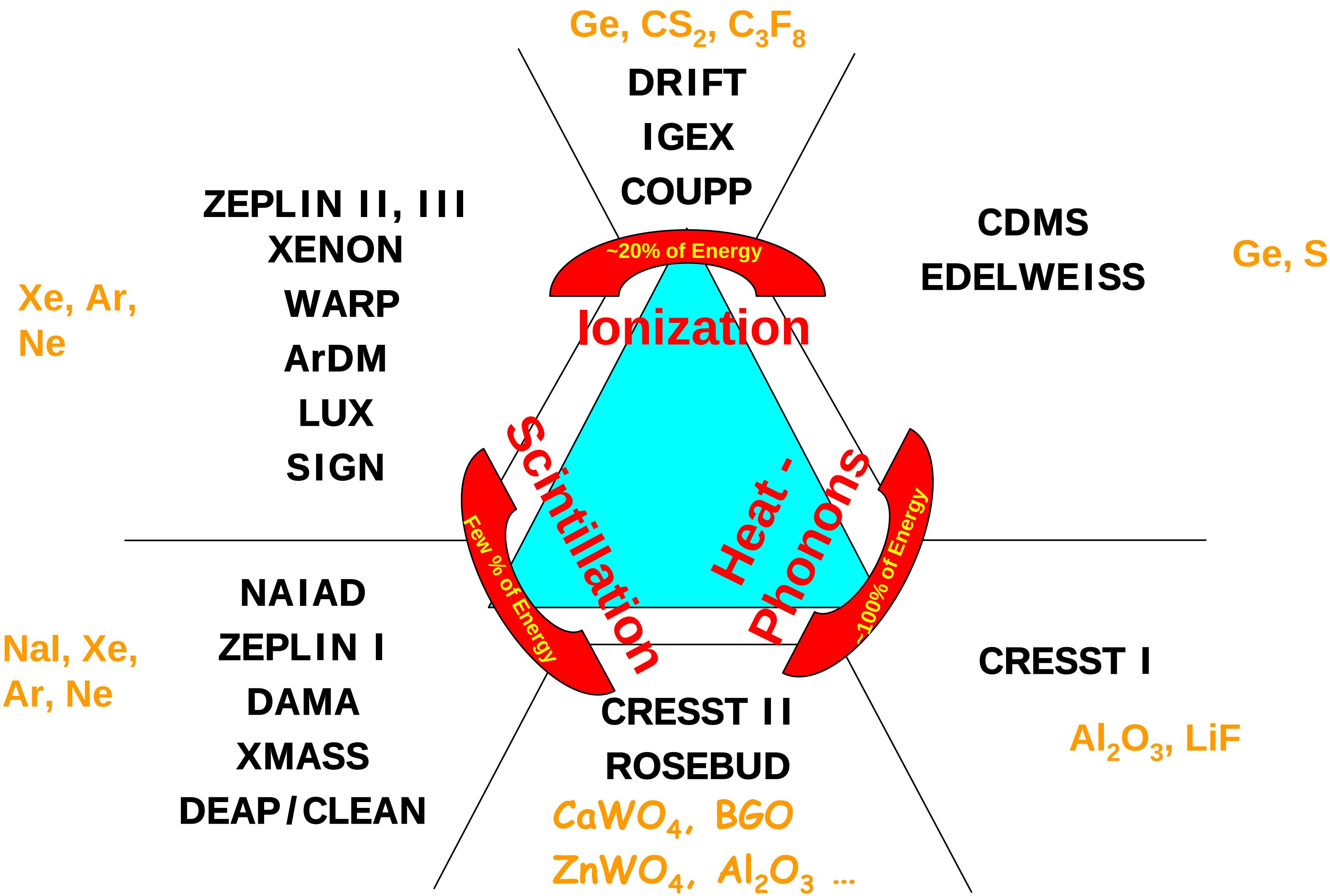
- **Critical aspect of any rare event search**
- Purity of materials
  - Copper, germanium, xenon, neon among the cleanest with no naturally occurring long-lived isotopes
  - Ancient Lead, if free of Pb-210 ($T_{1/2}$ = 22 years)
- Shielding
  - External U/Th/K backgrounds
- Radon mitigation
- Material handling and assaying
  - surface preparation
  - cosmogenic activation
- Underground siting and active veto
  - Avoid cosmic-induced neutrons
- Detector-based discrimination



Current State of Experiments

- Rapid advances in detector technology have reached interesting sensitivity limits and should be able to go further.
- Broad spectrum of technologies.
- New ideas, and new collaborations are appearing…
- Relatively small amount of funding going into this area to date.
- The rest of this talk will describe progress in the experiments since the DMSAG report (July 2007).

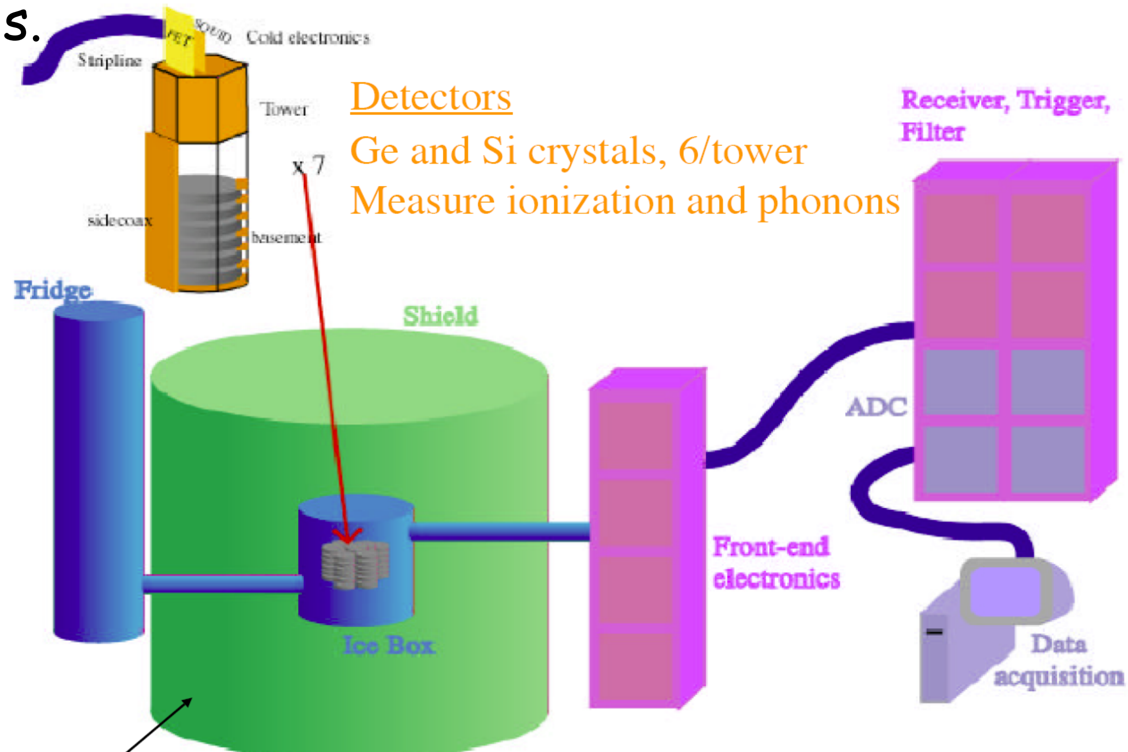
Direct Detection Techniques



CDMS

(Brown, Caltech, CWRU, FNAL, LBNL, MIT, Queens, Santa Clara, Stanford, Syracuse, UCB, UCSB, Colorado, Florida, UM, Zurich)

- The Cryogenic Dark Matter Search (CDMS) Collaboration, currently operating in the Soudan mine in Minnesota has pioneered the use of low temperature phonon-mediated Ge or Si crystals.



Detectors
Ge and Si crystals, 6/tower
Measure ionization and phonons

Cryogenics
Maintain detectors at 50 mK

Electronics /DAQ
Record signals from detectors and veto; form trigger

Shielding
Layered shielding (Cu, Pb, polyethylene) reduces radioactive backgrounds and active scintillator veto is >99.9% efficient against cosmic rays.

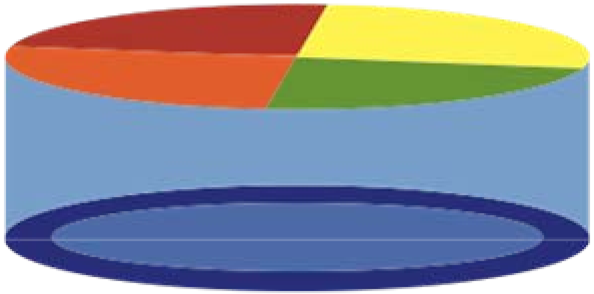
Discrimination and Shielding to maintain a Nearly Background Free Experiment

Shielding
- Passive (Mine Depth, Pb, Poly)
- Active (muon veto shield)

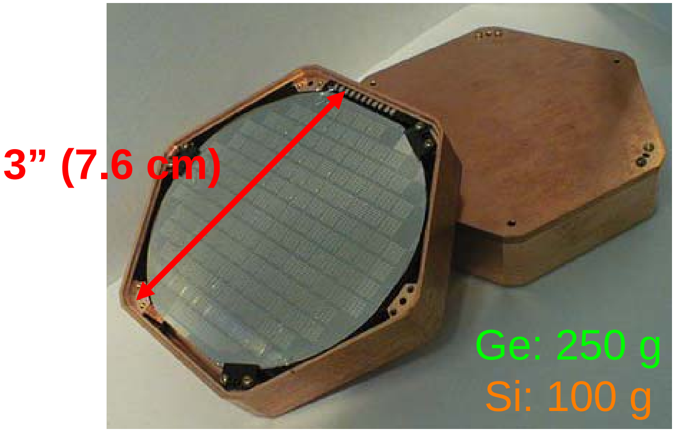
•Energy Measurement
- •Phonon (True recoil energy)
- •Charge (Reduced for Nuclear)

Position measurement X-Y-Z
- •From phonon pulse timing

Phonon side: 4 quadrants of athermal phonon sensors
Energy & Position (Timing)

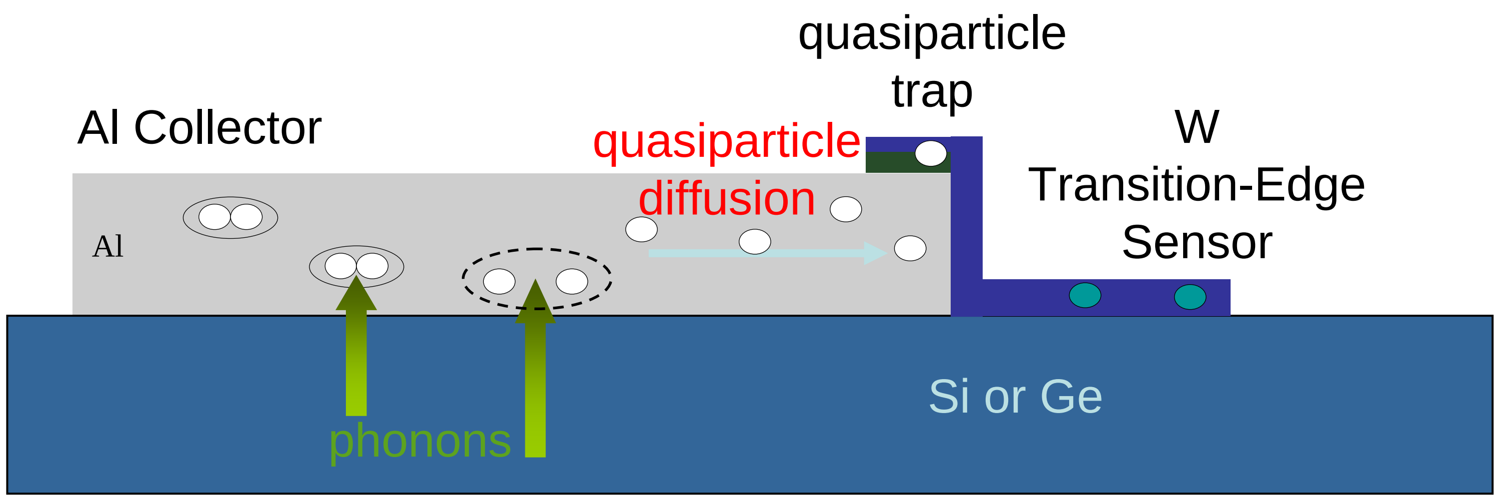


Charge side: 2 concentric electrodes (Inner & Outer)
Energy (& Veto)



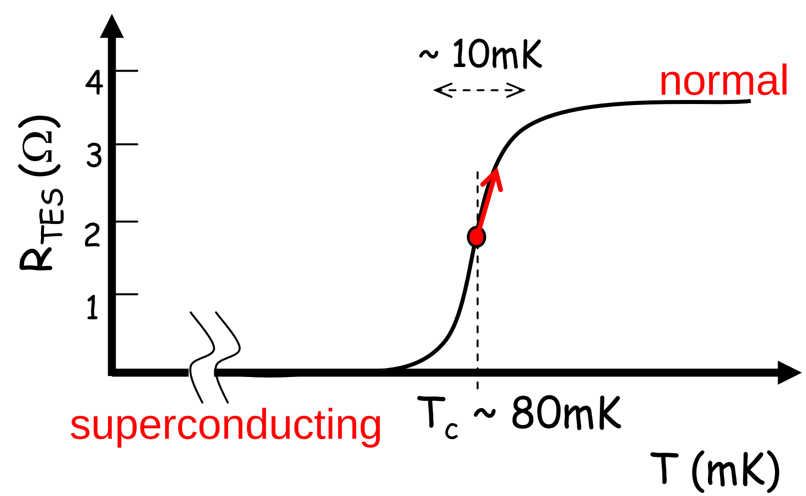
Transition Edge Sensors (TES) Operated at ~40 mK for good phonon signal-to-noise

ZIP Detector Phonon Sensor Technology

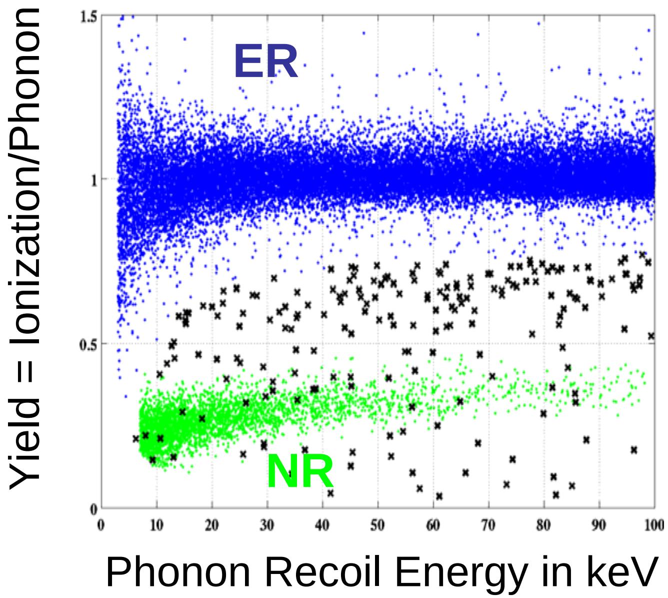


- Nucleus is hit, it recoils, causing the whole germanium crystal to vibrate.
- Vibrations (phonons) propagate to surface of crystal. They excite quasi-particle states, which propagate to the tungsten and heat it up.
- Temperature of the tungsten rises, and therefore so does the resistance of the circuit.
- Bias current decreases since the voltage across the tungsten held constant.

W Transition-Edge Sensor:
a really good thermometer

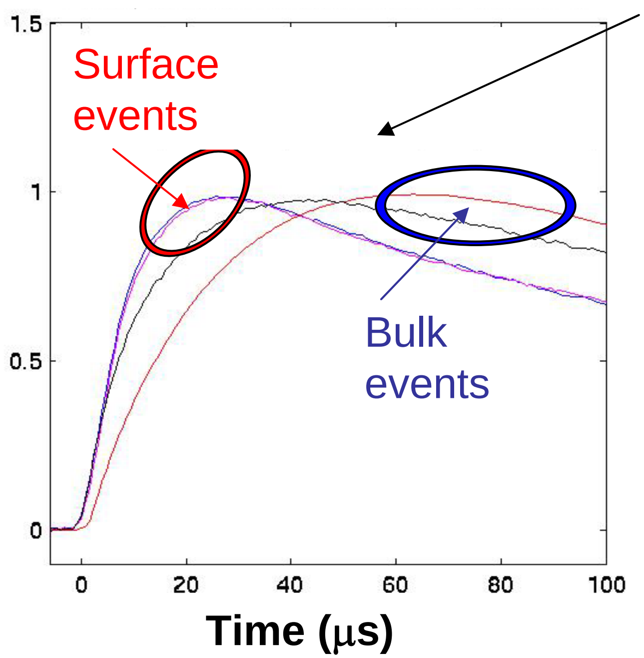


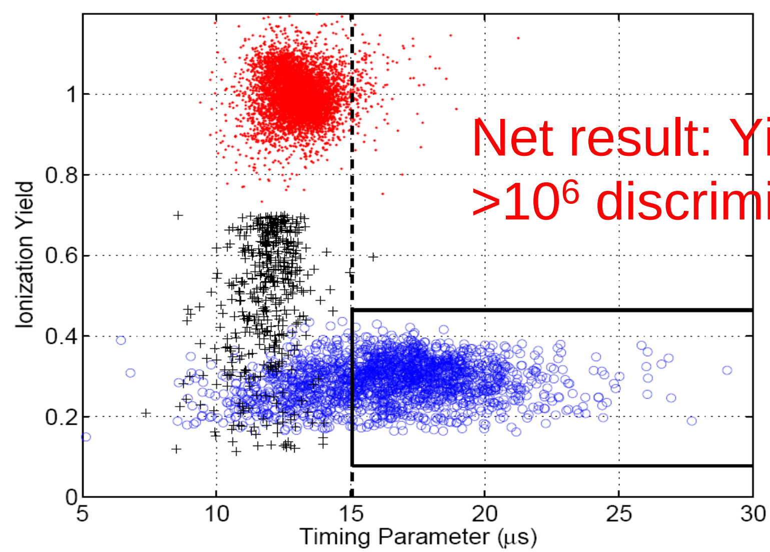
CDMS II Active Background Rejection



- 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

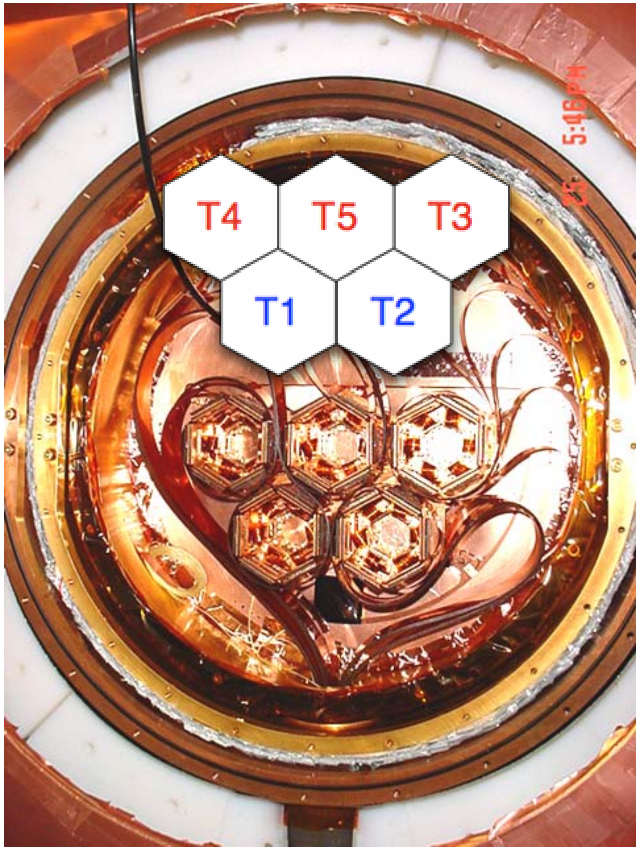
Faster down conversion of athermal phonons at surface provides faster phonon signal for β's





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

Update from DMSAG - Five Tower Runs (2006-8)



30 ZIPs (5 Towers) 4.75 kg Ge, 1.1 kg Si
Newer towers have 2-3 lower β background from Radon.

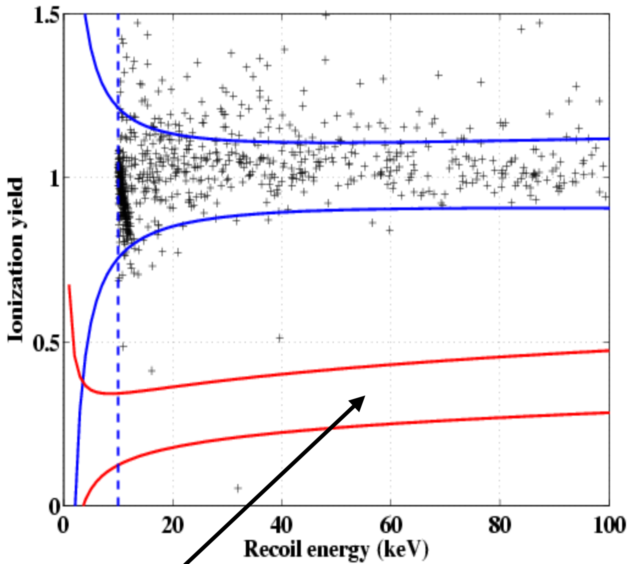
Data Cuts:

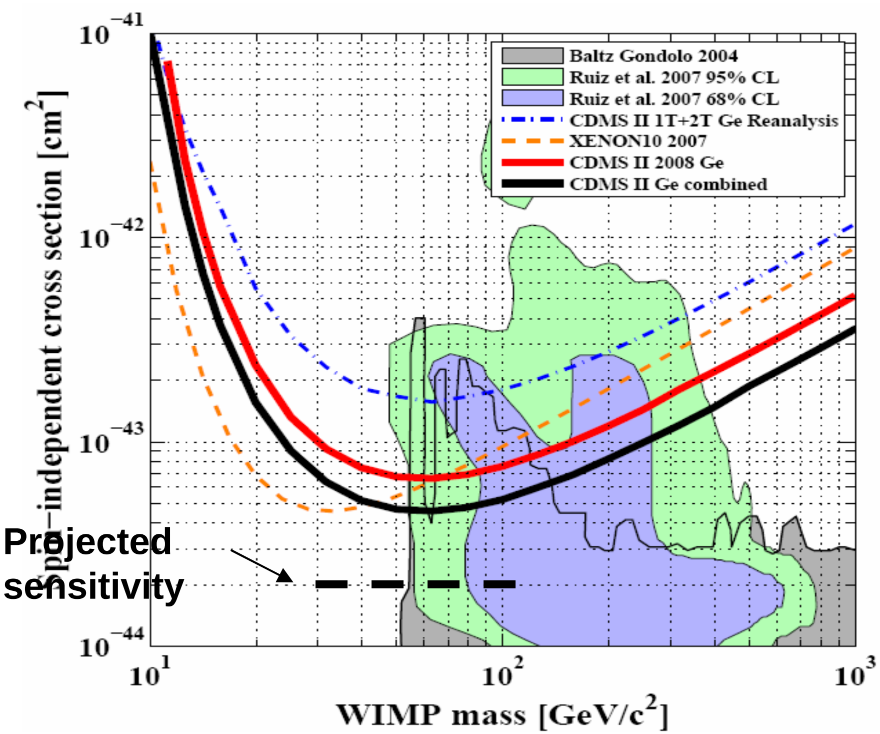
- Fiducial Volume
- Nuclear recoil band
- Not surface event
- Not multiple scatterer

Expected background:

- β leakage ~0.6 +/- 0.5 events
- Un-vetoed cosmogenic neutron background <0.1 events
- Fission neutrons <0.1 events
- α,n <0.03 events

Results and Plans





Zero background maintained

Equal to best spin-independent limits above WIMP mass of ~40 GeV/c^2.

About factor of two more data already collected; double again by end 2008.

Pre-DUSEL plans for SuperCDMS 25 kg in SNOLAB (ZIP's 3"diax1" thick)
FY07 NSF/DOE approval for 2 or 7 SuperTowers in SNOLAB
FY08 CD1-4 in preparation for 7 SuperTowers at SNOLAB
FY09 earliest start for new cryosystem & complete 7 SuperTowers
SuperCDMS One-Ton for DUSEL

New Technologies

- The field has been energized by the emergence of noble liquids (argon, xenon, neon) in various detector configurations, as well as new ideas for use of warm liquids and various gases under high or low pressure.
- These offer several things, some are:
  - An increased reach in sensitivity by at least three orders of magnitude for WIMP's .
  - The possibility of recoil particle direction measurement.
  - Detector sizes well beyond the ton scale.
- The complementarity of detector capabilities provides:
  - A range of target types suitable for establishing WIMP signature
  - Diverse background control methods (e.g., single phase vs. two-phase in noble liquids; various combinations of multiple signatures).

Noble Liquids

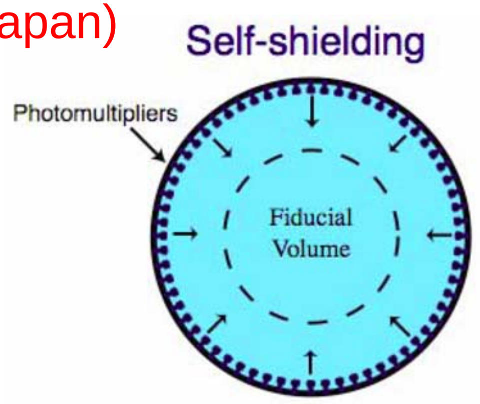
- Relatively inexpensive, easy to obtain, dense target material.
- Easily purified as contaminants freeze out at cryogenic temperatures.
- Very small electron attachment probability.
- Large electron mobility (Large drift velocity for small E-field).
- High scintillation efficiency
- Possibility for large, homogenous detectors.
- Problem - ^{39}Ar, ^{85}Kr

Single-Phase Techniques

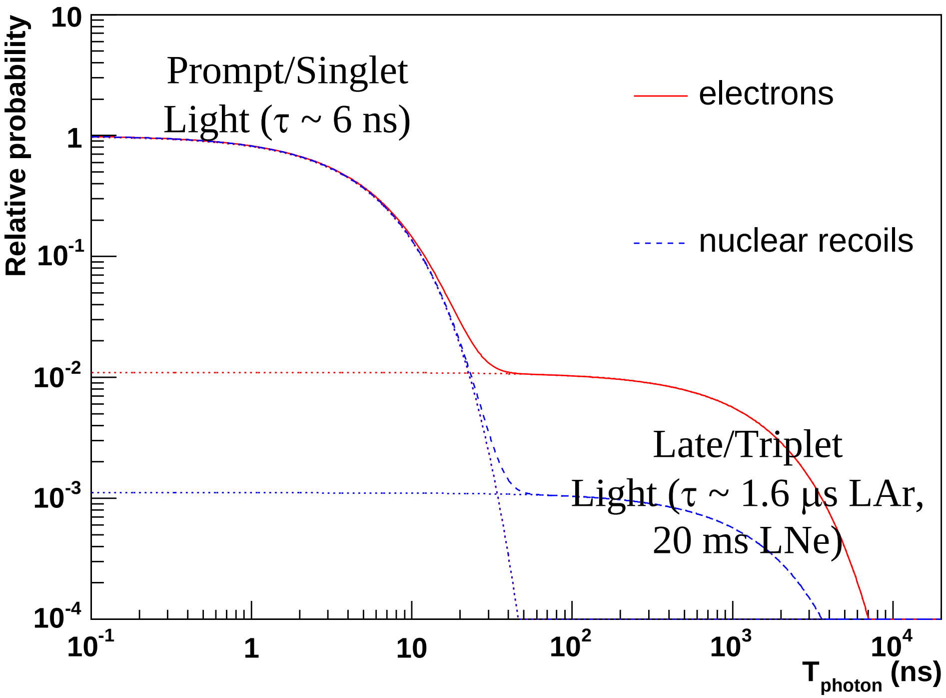
DEAP/CLEAN (Canada, US), XMASS (Japan)

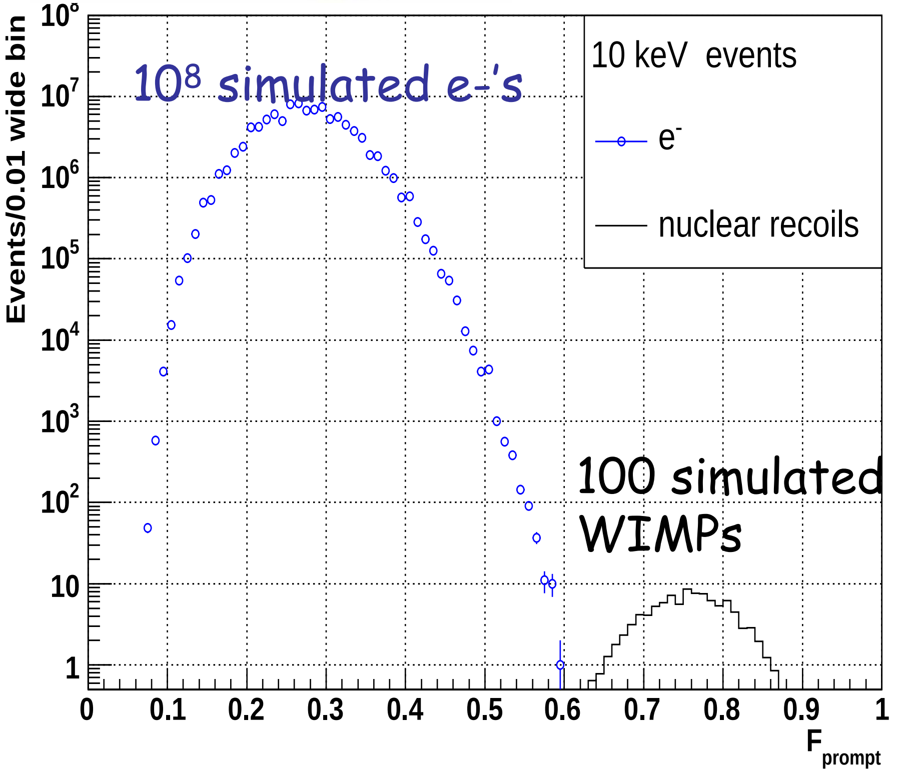
- Pulse shape discrimination to discriminate electrons from nuclear recoils.
  - <u>Argon and Neon especially good</u>

\+



Gets better as size increases.





M.G.Boulay and A.Hime, Astroparticle Physics <u>25</u>, 179 (2006)

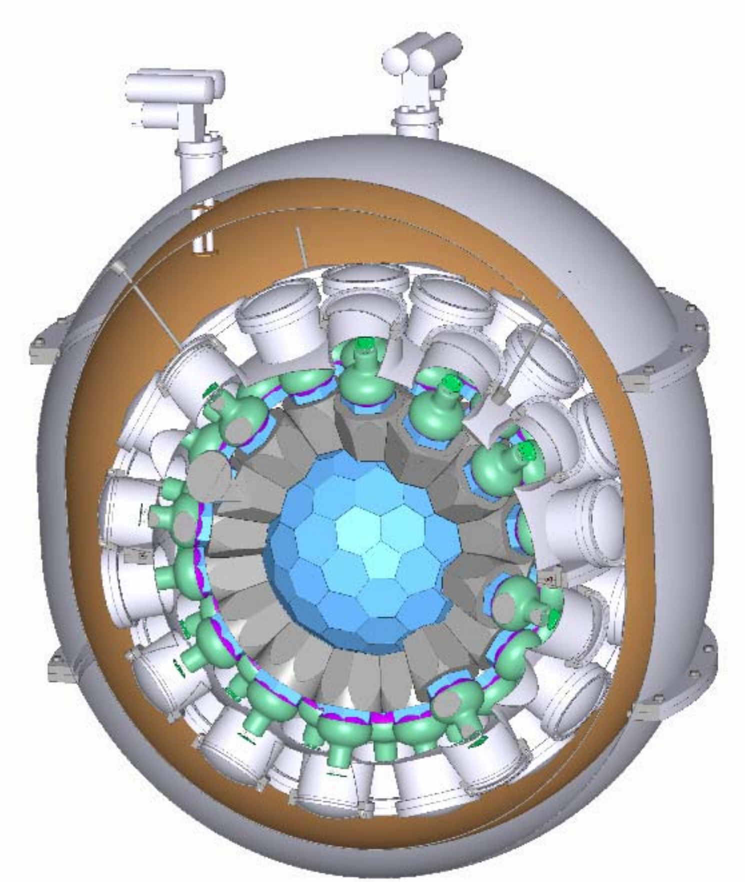
DEAP/CLEAN (Canada, U.S.)

Progress-Plans Since DMSAG

(Alberta, BU, Carleton, LANL, MIT, NIST, New Mexico, North Carolina, Queens, South Dakota, SNOLAB, UT, Yale)

- International collaboration formed - staged approach.
- R&D with micro-CLEAN and DEAP-1 measuring salient properties of LAr & LNe
    - DEAP-1 operating underground at SNOLAB
    - Demonstration of PSD in LAr relevant to ton-scale
- Full engineering design and construction plan for Mini-CLEAN (360 kg) under completion
- Full engineering design underway for DEAP/CLEAN (3600 kg)
- Preparing to submit proposal to S4 solicitation for 50 ton CLEAN as part of an initial suite of experiments at DUSEL

360 kg Mini-CLEAN



Spherical vessel filled with purified LNe or LAr at a temperature of 27 K or 87 K respectively. Wavelength shifting film is coated on the inside surface of acrylic plates, which fit together to form a 92-sided expanded dodecahedron pattern. Acrylic light guides transport the light to the photomultipliers.

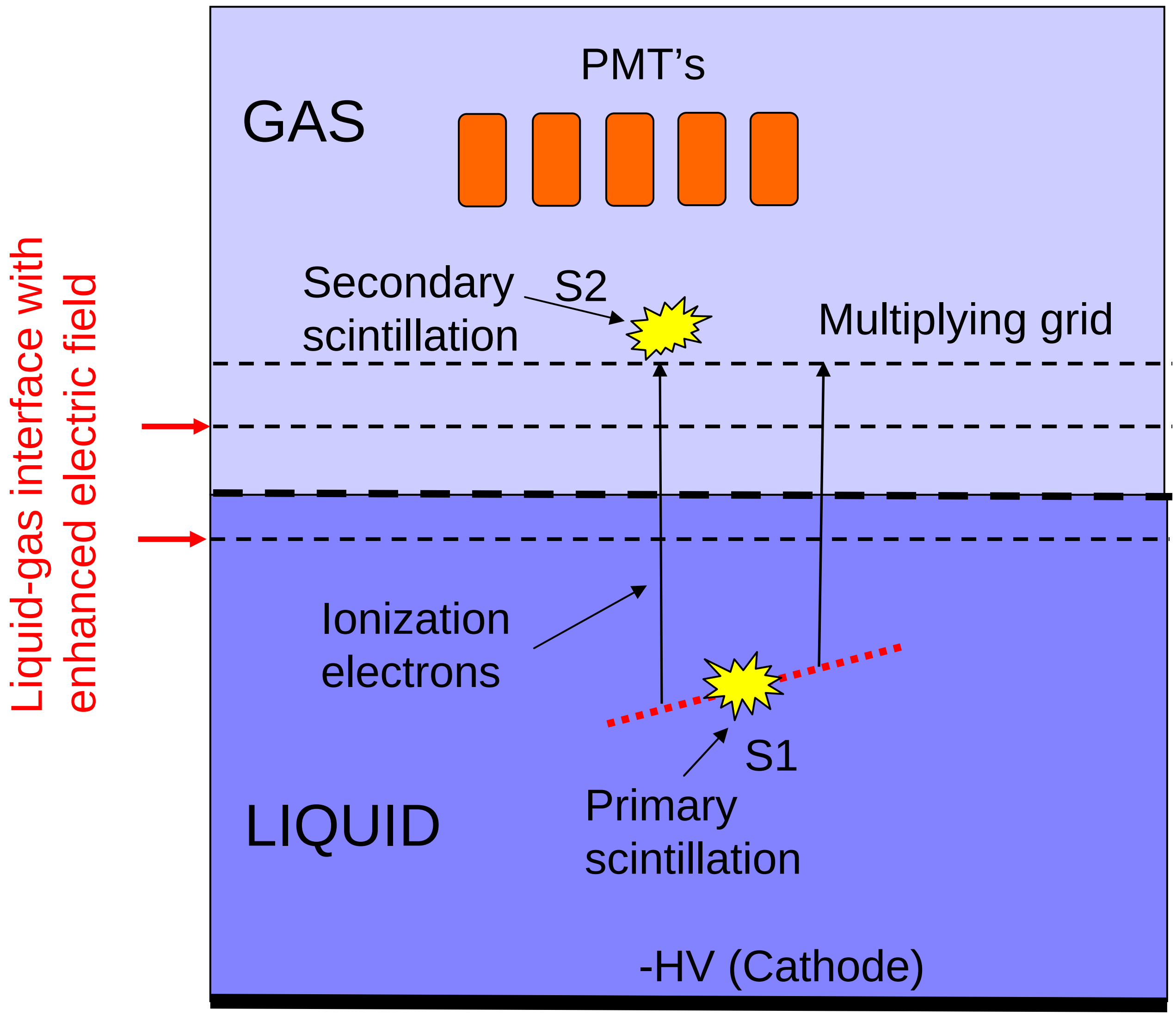
If low-background achieved, could reach 10^{-45} cm^2 for 100 GeV WIMP.

- **Technical review underway with SNOLAB**
- **Joint proposal under review at NSF/DOE**
- **Procurement of major sub-systems and underground infrastructure starts this FY**

2-Phase Noble Liquids

WARP, ArDM, XENON, ZEPLIN, LUX

(Argon, Xenon)



__Experimental handles__

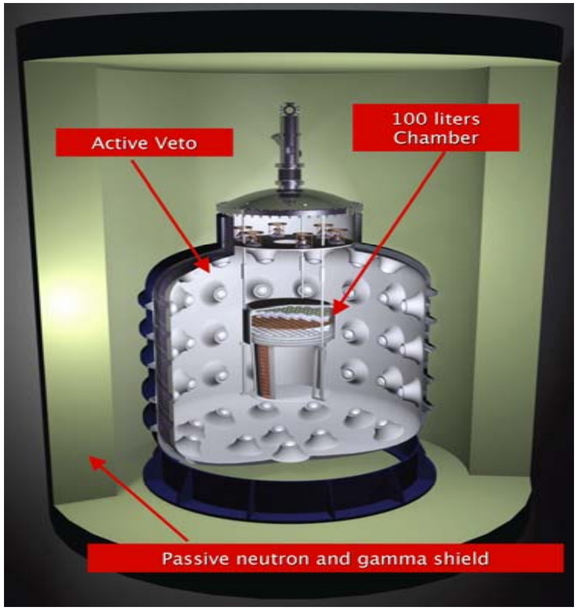
- Primary scintillation intensity
- Primary scintillation pulse shape
- Secondary scintillation intensity
- S2/S1
- Multiple recoils
- Fiducial volume

Some best in Argon, some best in Xenon

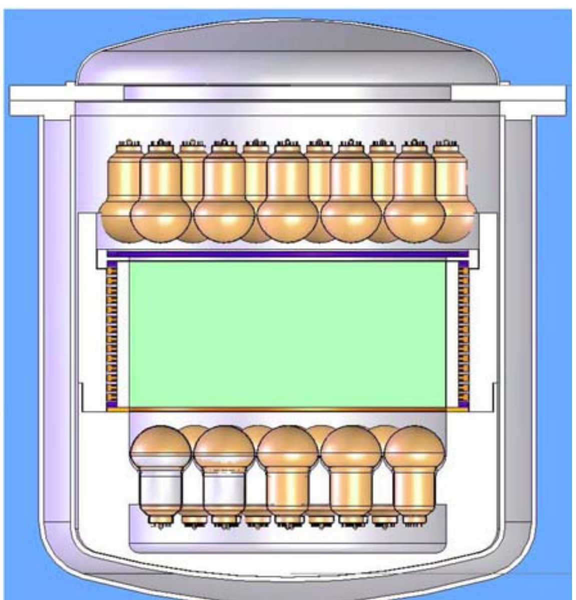
Current Detectors Under Construction

~100 kg Fiducial Size

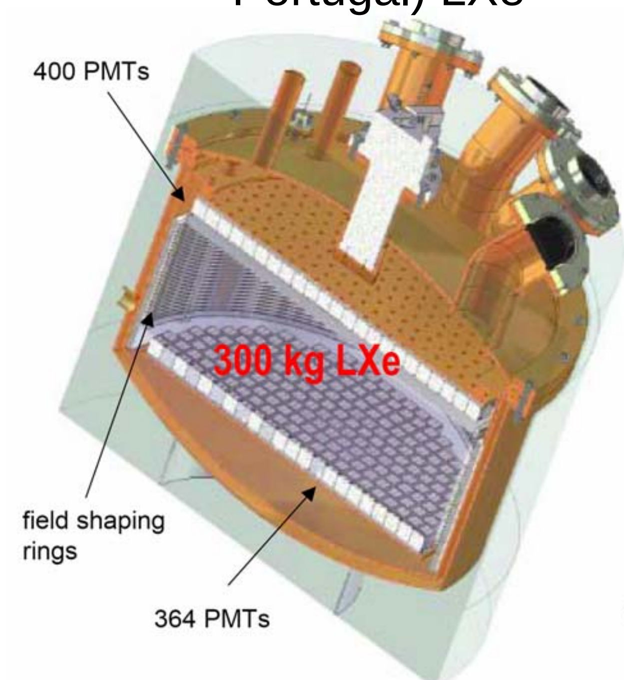
WARP (Italy, U.S., Poland) LAr



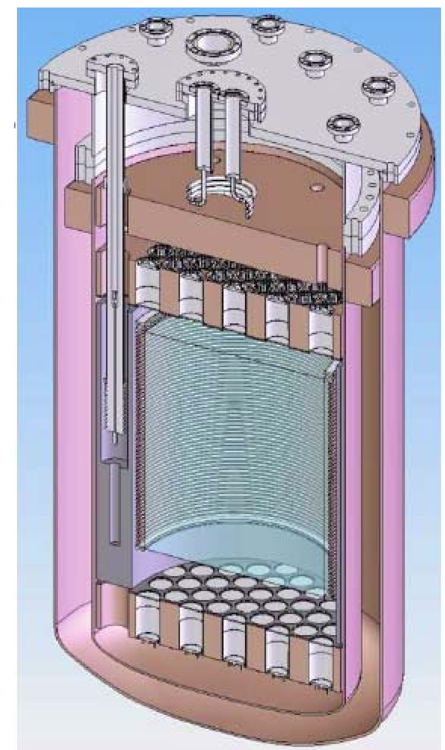
ZEPLIN (UK, U.S.) LXe



XENON-100 (U.S., Germany, Italy, Portugal) LXe



LUX (U.S.) LXe

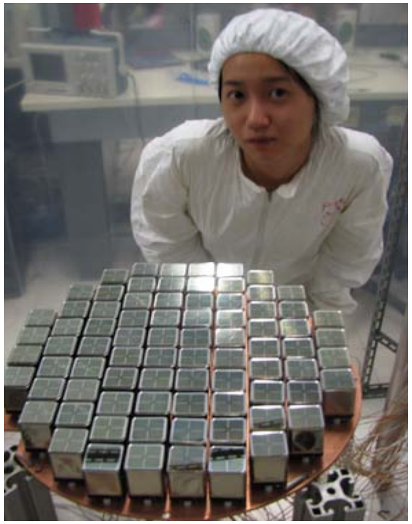


The XENON Phased Program

- XENON10 Reached $\sigma_I \sim 10^{-43}$ cm^2 sensitivity in 2007 for 100 GeV WIMP
- XENON100 currently under commissioning at LNGS. Physics run starts Summer 2008.
  - Sensitivity reach : **$\sigma_I \sim 2x10^{-45}$ cm^2** for 100 GeV WIMP after 3 months operation. Supported by NSF and foreign contributions
- XENON1T
  - Under study by larger collaboration in US & Europe. Proposal Fall 08 to NSF (CU/Rice/UCLA) & DOE (UCLA), plus Swiss National Foundation (UZurich), INFN (Bologna/Torino/LNGS), FCT (Portugal)etc. Funding request: FY09-12. Sensitivity reach (pre-DUSEL): **$\sigma_I \sim 10^{-47}$ cm^2** for 100 GeV WIMP
- 10 ton LXe experiment for DM WIMP physics at DUSEL

Status of XENON100: Installed @ LNGS

(Columbia, Zurich, Rice, Coimbra, LNGS)

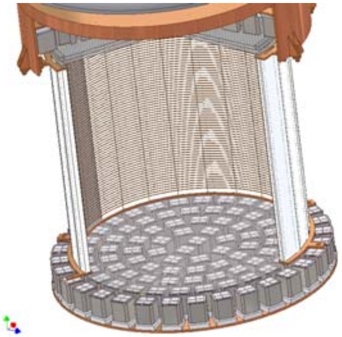


PMT's 98 on top - 80 on bottom - 64 in active LXe shield

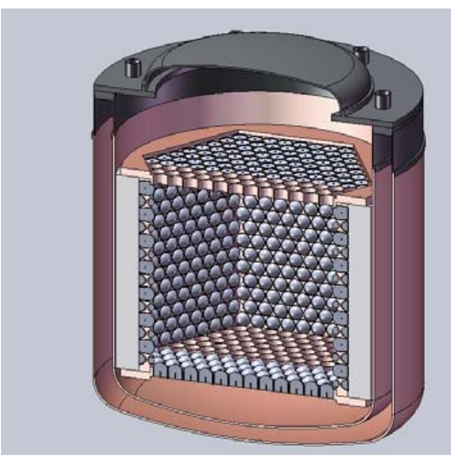
TPC Assembly

- XENON 10 Shield modification/improvement completed Jan 08
- Detector moved underground in its shield Feb 08
- Cryocooler/Feedthroughs/Cables outside shield
- LXe purification w/circulation ongoing March 08

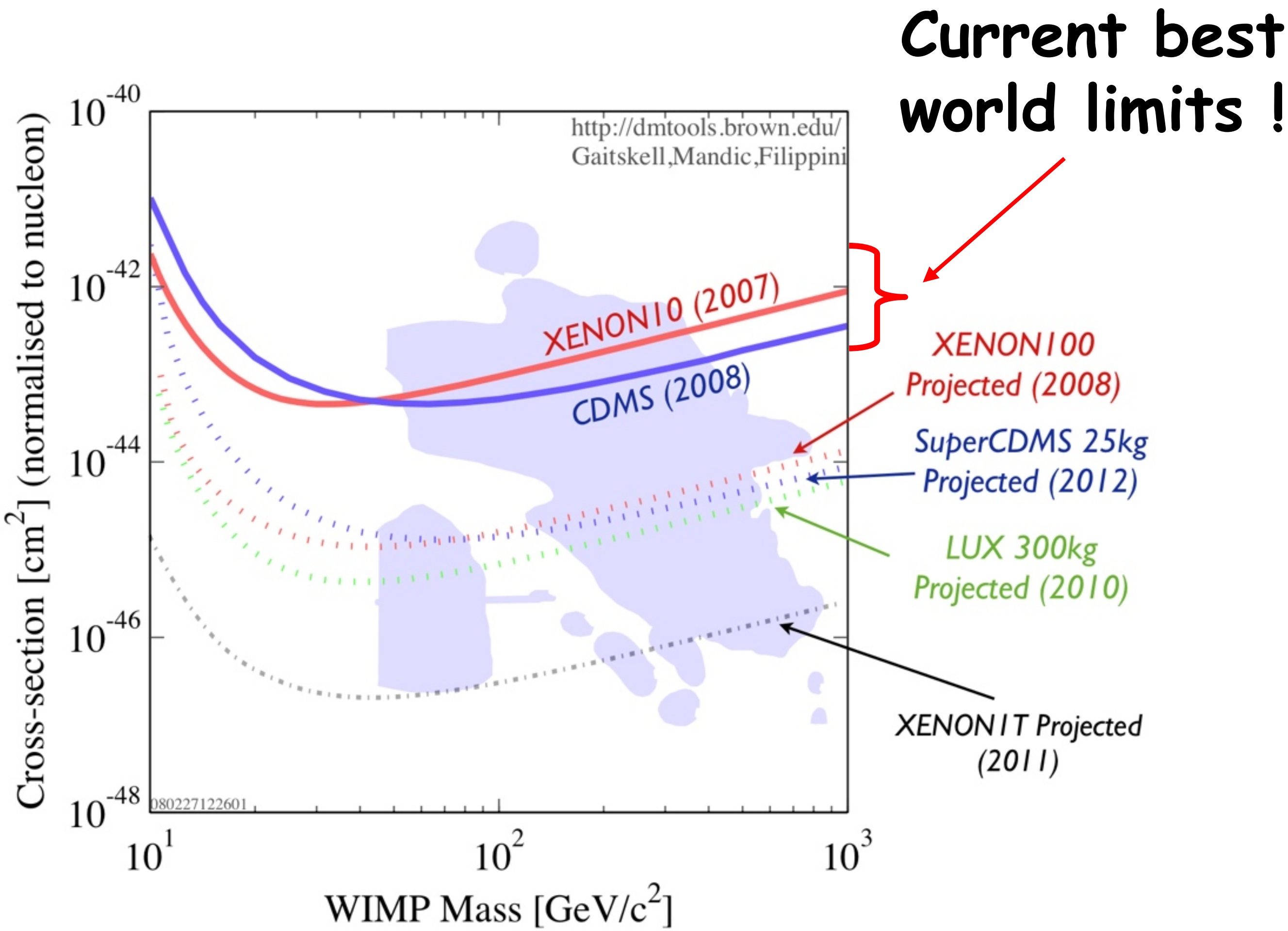
XENON Dark Matter Sensitivity Reach: 2008-12



XENON100



XENON1T

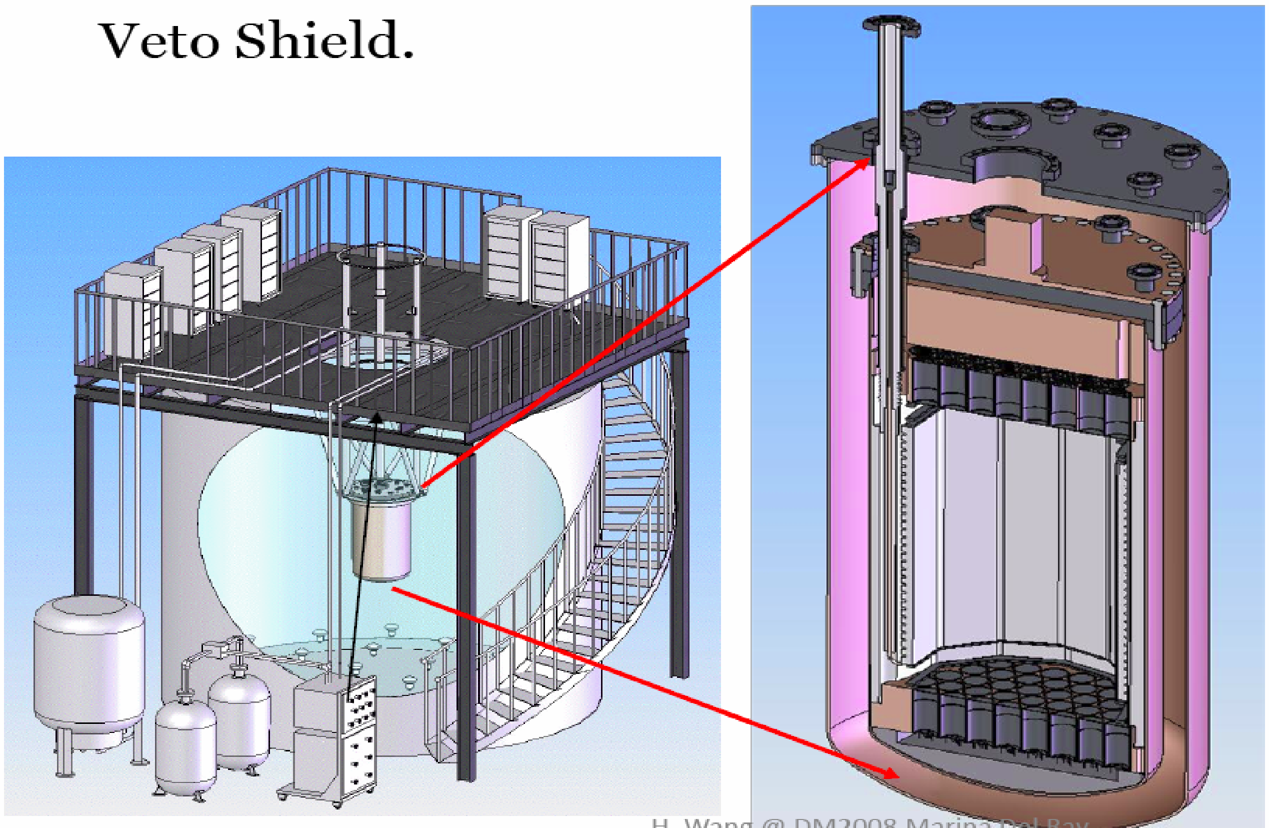


LUX

Brown, CWRU, LNNL, LLL, Maryland, U.C. Davis, UCLA, Rochester, TAMU, Yale

~ 2.5m Water Cerenkov Veto Shield.

To be installed in SUSEL



Dual Phase Xe

350kg, 100kg FV

2x60 PMTs

3-D TPC

1kV/cm drift

60cm total drift

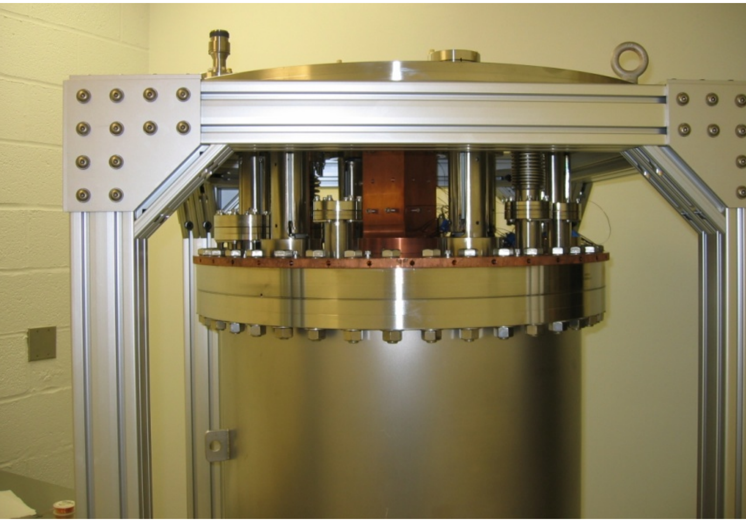
5kV/cm extraction

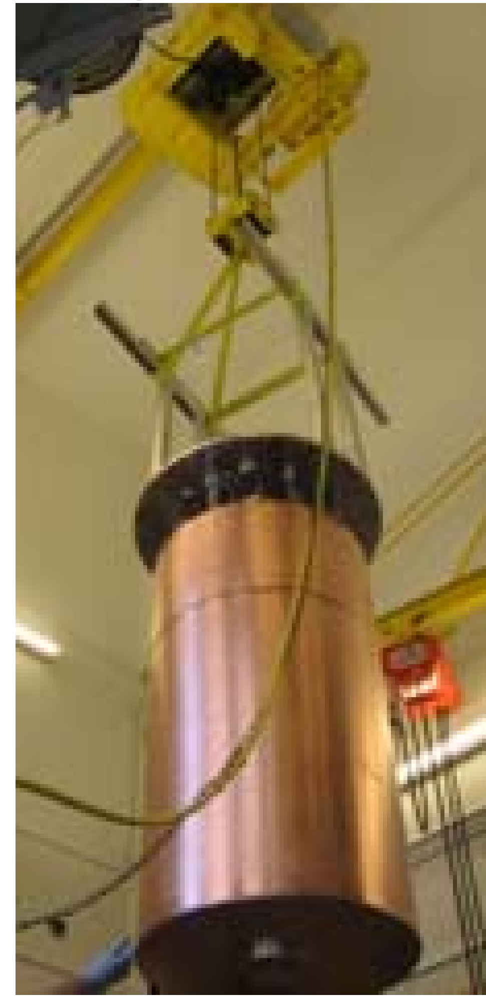
10kV/cm gas gain

LUX Progress- Plans

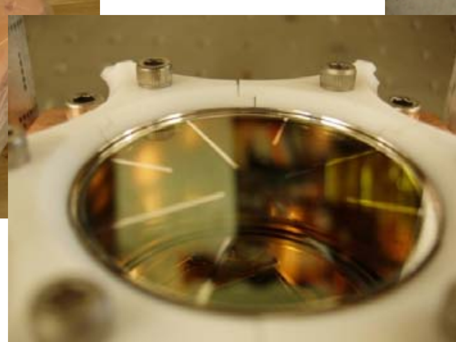
- Constructing 360kg detector
  - Xenon and PMTs already on hand.
  - Cryostat, prototype components, sub-systems being assembled.
  - Project is in final stage of approval with DOE/NSF (50:50) for project funds starting immediately (FY08 $)
  - Homestake projecting initial occupancy late 2008, deployment can begin at that point.
  - Physics data can start as early as end of 2008.
- Experimental Goals (350 kg phase)
  - DM search with sensitivity which is >50x better than best current experiments (~0.4 evts/100kg/mth in 100kg fiducial
  - demonstrate technologies necessary for larger multi-tonne LXe dark matter detectors
- Next step - future proposal FY10
  - 3 tonne detector - constructed and operated in the Davis Cavern water shield
- DUSEL ISE Construction FY12
  - ~20 tonne Xe TPC detector Sensitivity >100x better than LUX 350 kg.

LUX Cryostat Assembly + Cold Testing





PMT Hardware Testing



Depleted Argon TPC at DUSEL

Princeton, Notre Dame, Temple

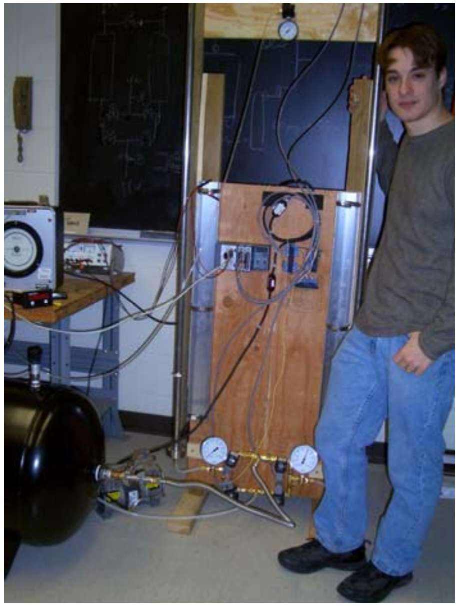
- 2-phase TPC pioneered by WARP using argon
  - 3-fold discrimination: pulse shape, S2/S1, position reconstruction. Very effective strategy for null background experiment
- Size of argon TPC detector limited at ~500 kg when operated with atmospheric argon, due to ^{39}Ar pile-up
- Argon depleted in ^{39}Ar by factor 20 required for development of ~10 ton detector (sensitivity 10^{-46} cm^2)
- Depleted argon produced by centrifugation extremely expensive ($40k per kg) and would require extremely long production campaign

Depleted Argon TPC at DUSEL

- NSF funded in May 2007 Princeton & Notre Dame Program for exploration of underground gas wells in central US states.
  - Goals: Survey of $^{39}Ar/Ar$ ratio Studies on the origin of terrestrial atmosphere by measurement of isotopic ratio of noble gasses
- Identified one source capable of producing ~15 ton per year of argon, depleted by factor >20
  - Plans for development of source for full-scale production (50 kg/day) of depleted argon in cooperation with industry are already in advanced state.
  - Funding sought (DUSEL R&D, proposal submitted Dec 2007) for technological demonstration of depleted argon production at small scale (1 kg/day) with a prototype plant.
- Program Goal: Production of 10 ton for Large Depleted Argon TPC @ DUSEL

Steps Towards 10-ton Depleted Argon TPC @ DUSEL

- S4/S5 process: 2008-09
- Depleted Argon
  - demonstration of production on small scale: 2008-09
  - full scale depleted argon procurement: 2009-2012
- 1-ton detector as intermediate step: 2010-12
- 10-ton detector as part of DUSEL ISE, construction to start in 2012



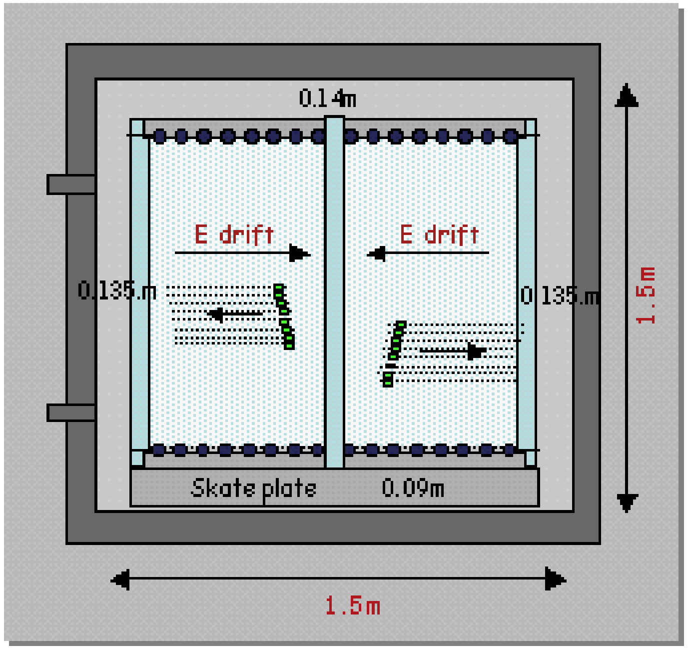
Prototype Purification Plant under Construction at Princeton

Sampling in the gas field

Gaseous Detectors

- Low Pressure gas
  - Major goal is to identify dark matter by observing diurnal periodicity.
  - Direction of the recoil nucleus must be reliably measured.
    - Achieve a full 3-D reconstruction for very short tracks (<2 mm) with ability to distinguish the leading from the trailing end of the track.
- High Pressure gas
  - Ionization & scintillation signals also available from gases at normal temperature.
  - Could provide reasonable size competitive detectors at high pressure. Efforts on Xe at 5-10 atm, and Ne at100-300 atm.
  - Room temperature requirement could simplify design and operation.

DRIFT-II (U.S.,G.B.)

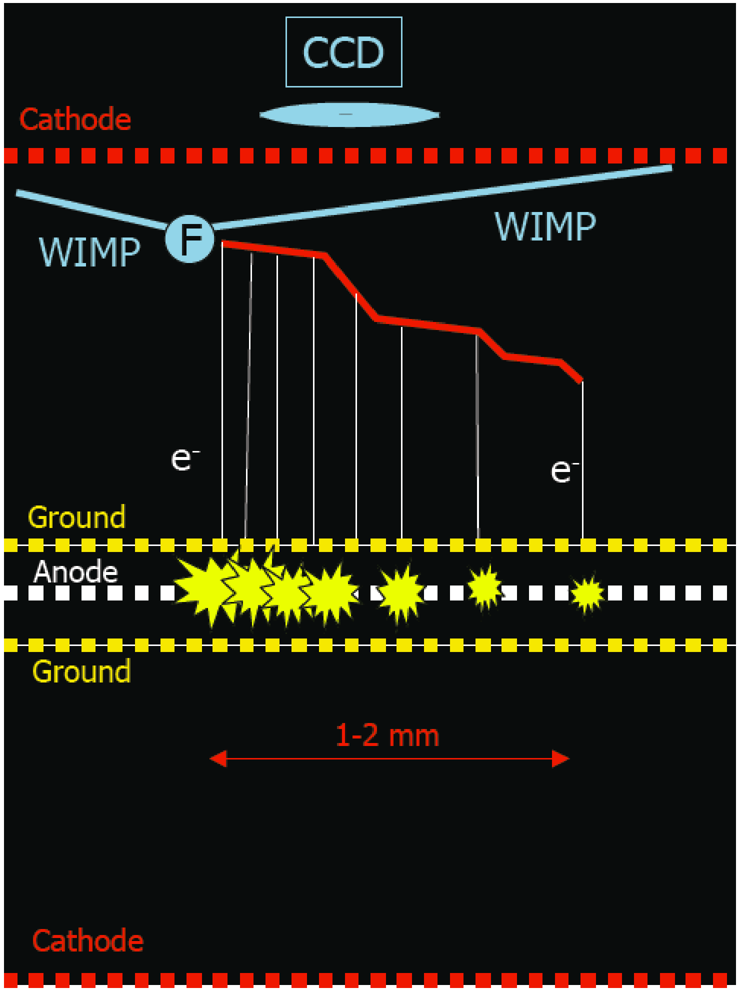


- TPC filled with low-pressure electro-negative gas (CS_2).
- Recoil tracks are ~few mm long
- Ion drift limits diffusion in all 3 dimensions
- End planes allow determination of range, orientation & energy
- Excellent discrimination based on range and ionisation-density
- Important R&D efforts by DRIFT groups and others, include improvements in readout sufficient for the achieving of full directionality…GEMs, Micromegas, combinations of wires and scintillation optics or isochronous cells and time-resolved pads.

DM-PPC

(Boston, Brandeis, MIT)

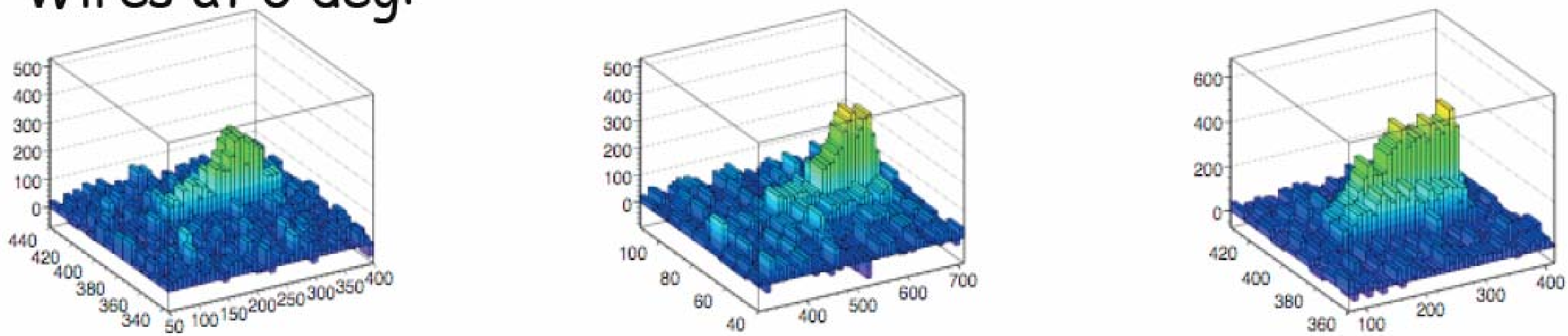
- Low-pressure CF_4 TPC
  - 50-100 torr→F recoil ~1-2mm
- CF_4 is ideal gas
  - F: spin-dependent interactions
  - Good scintillation efficiency
  - Low transverse diffusion
  - Non flammable, non toxic
- CCD readout
  - Image scintillation photons produced in avalanche
    - $\# \gamma_{\text{scintillation}} \propto \# e_{\text{ionization}}$
  - Low-cost, proven technology
- Amplification region (camera) serves 2 drift regions



NIM A584:327-333,2008

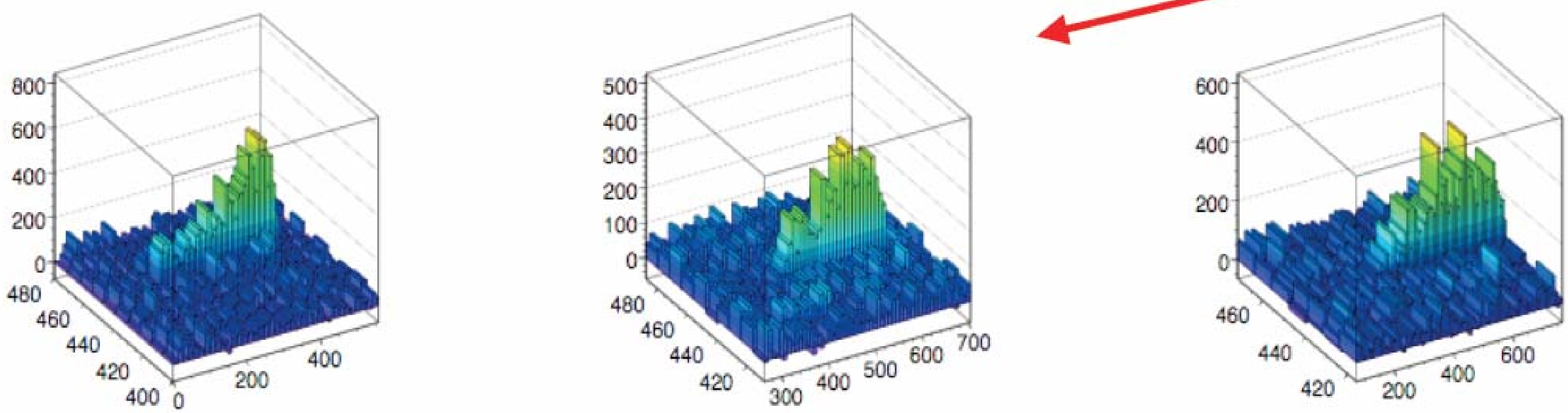
Observation of "head-tail" in F recoils

Wires at 0 deg:



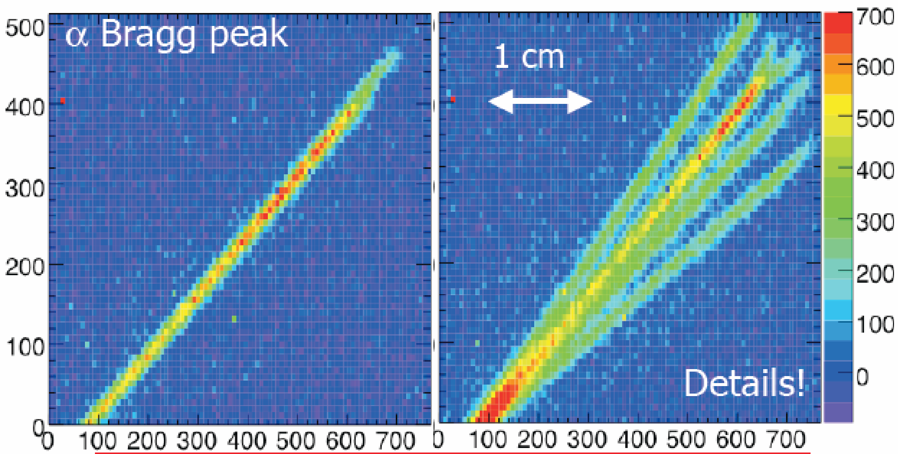
Wires at 180 deg:

Direction of neutrons

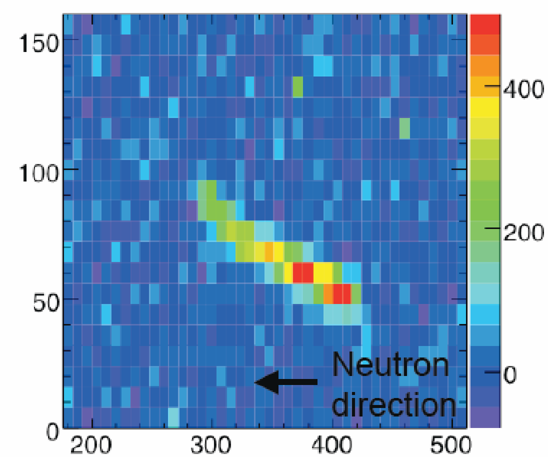


Recent progress: mesh detectors

- Moved from wire-based to mesh-based amplification region
  - 1D --> 2D at no additional cost!
  - Sensitive to a whole new level of details: "digital bubble chamber"
- Head-tail capability preserved



5.5 MeV alphas, 200 Torr
V_{anode}=2kV (E~$1.5 \cdot 10^5$ V/cm)



^{252}Cf neutrons, 100 Torr

Gabriella Sciolla DM-TPC: a new approach to directional detection of Dark Matter 17

Plans for coming year:

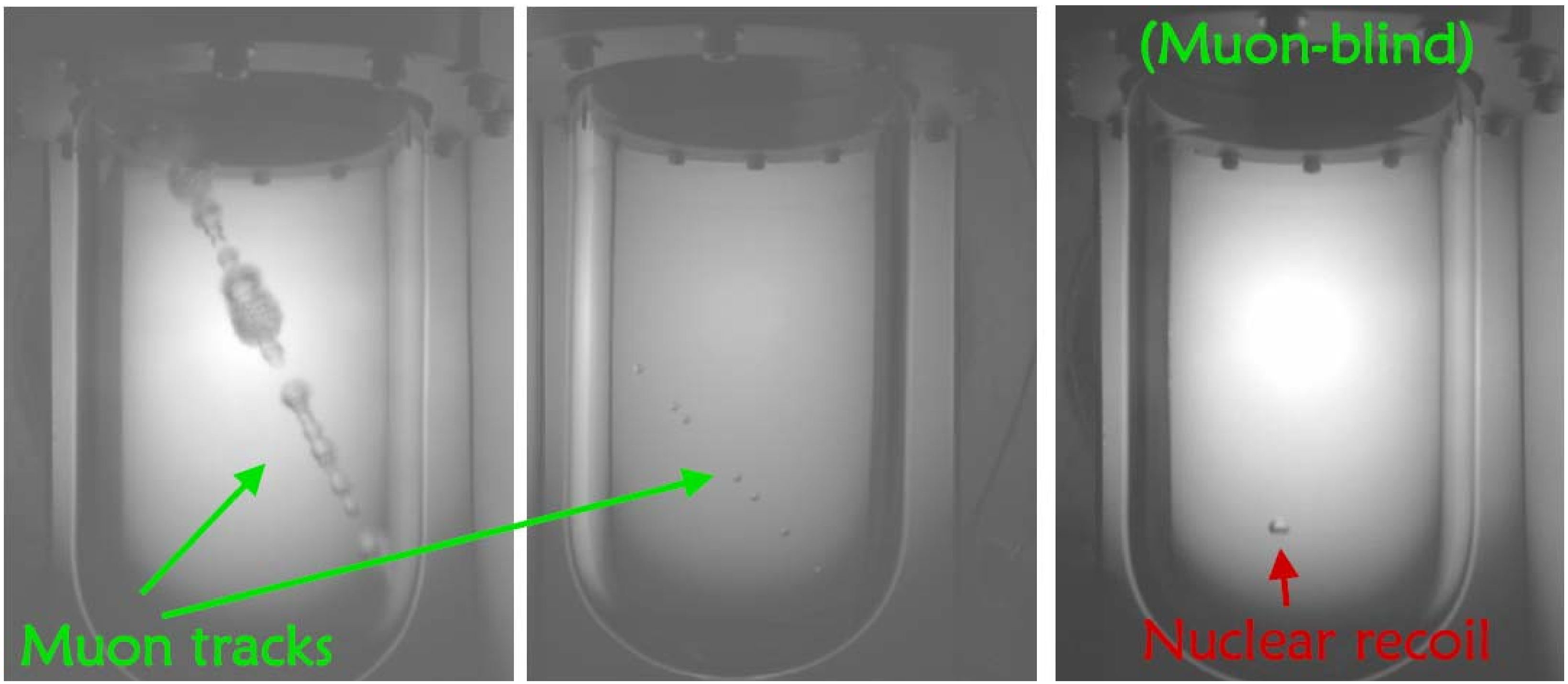
Prototypes to measure properties of cosmic ray neutrons and to gain experience in building and operating large chamber

Warm Liquids - COUPP (U.S.)

- Based on room temperature bubble chamber of CF_3I. Other targets possible
- Fundamentally new idea is to operate the chamber with a threshold in specific ionization (dE/dx) above the sensitivity needed to detect minimum ionizing particles, so that it is triggered only by nuclear recoils. (~10^{10} rejection of MIP's.)
- Already reached stable operation of a 1-liter (2kg) version at shallow depth.
- Demonstrated excellent γ rejection.

Control Nucleation Rate and Triggering

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

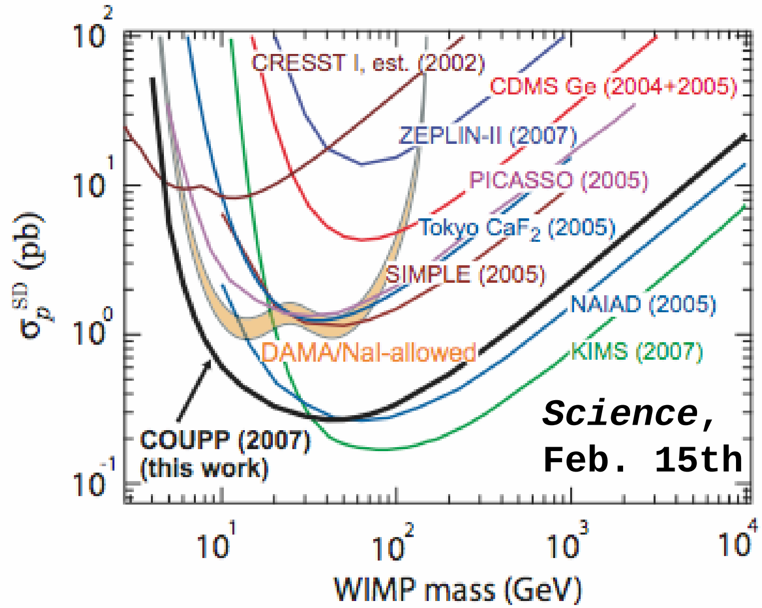


Decreasing superheat

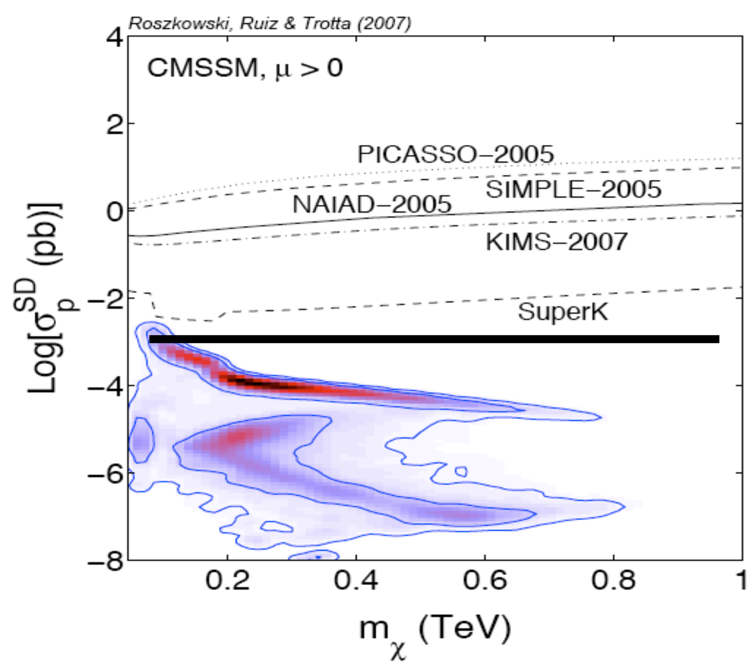
Intrinsic γ rejection >10^{10} at 10 KeV threshold

Muon tracks only visible with high superheats
Operate at low superheat → MIP blind 1 nuclear recoil = 1 bubble

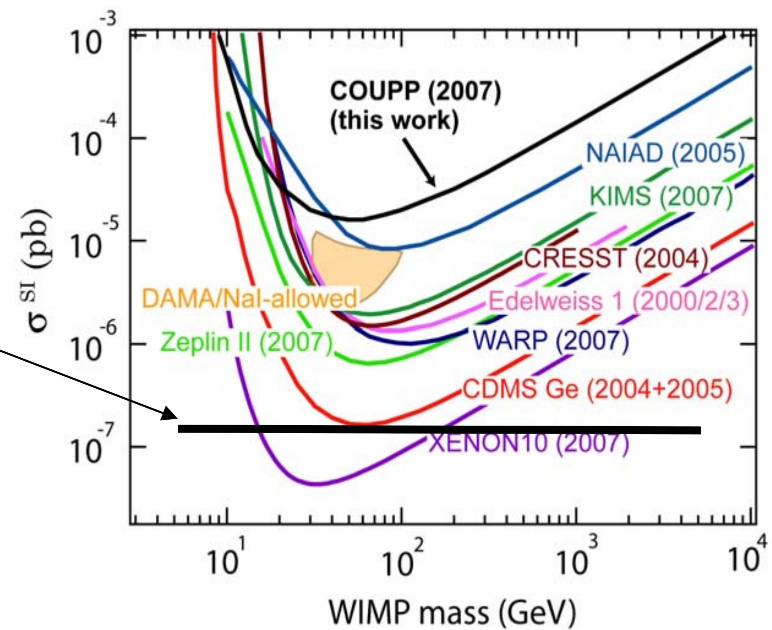
COUPP



- First results (*Science*, Feb. 15th) No attempt to control Rn during those engineering runs.
- Rn has been abated in the ongoing runs. A 98% efficient muon veto is now installed around the 2 kg chamber (300 m.w.e). Foresee a large improvement in SD sensitivity during 2008.



COUPP 300 m.w.e. target goal (2008 runs)



COUPP

- ~100 kg target mass under (advanced) construction. Tests at 300 m.w.e. spring-summer 2008. Deployment to a deeper underground site end of 2008.
- MOU signed with PICASSO. We expect an active collaboration, with special emphasis on refrigerant purification (SNO expertise).

60 kg & 20 kg (windowless) chambers

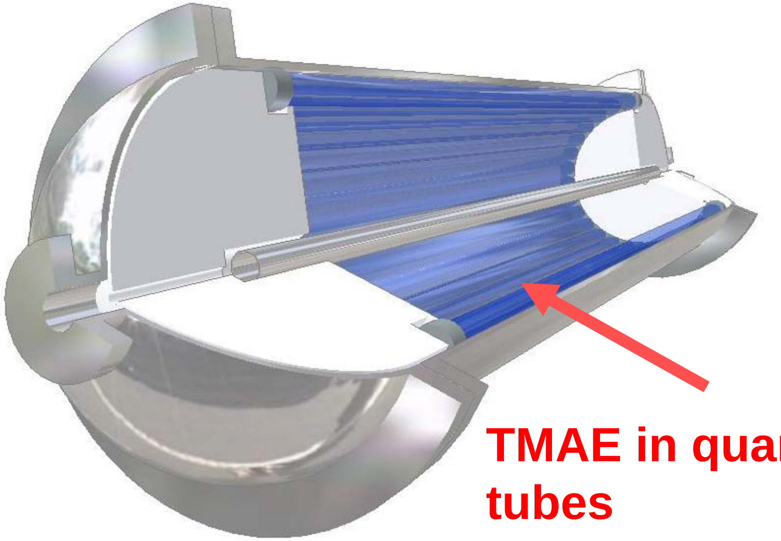
SIGN: Scintillation and Ionization in Gaseous Nobles

(TAMU, UCLA, LBL)

WIMP Detector employing S2/S1 discrimination in modular, room temperature, pressurized gas cylinders.

New:
Completed preliminary investigation of light yield, charge yield and S2/S1 discrimination for selection of gasses/mixtures including **neon, argon and xenon** at pressures up to 100 atm. Developed new Tubular VUV detectors using TMAE in quartz tubes.

- Light yields similar to those in LXe
- Nuclear recoil discrimination appears to be much better in gaseous xenon compared to liquid xenon…partially due to large fluctuations on energy sharing, ionization/scintillation in liquid.



TMAE in quartz tubes

SS vessel
Active region:
48” length
12” diameter

Plans:
Proposed 5kg 20 bar xenon proto-experiment for coming year. Plan to propose 100kg experiment for Homestake early implementation program.

AXIONS AND OTHER CANDIDATES

- The relic density argument could be an accident, or just part of the picture.
- Axions and other candidates not produced through freeze-out could be some or all of the dark matter.

Axions

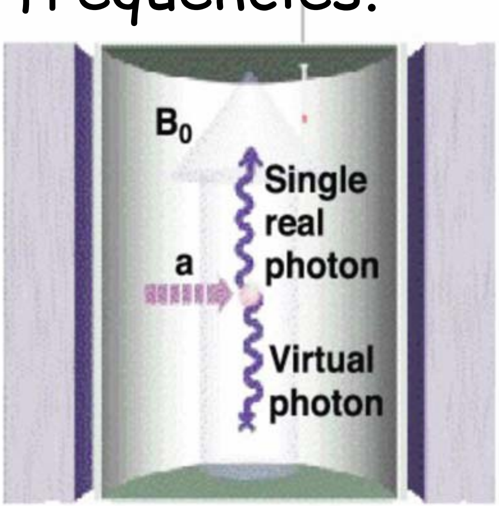
Peccei, Quinn (1977); Wilczek (1978); Weinberg (1978)

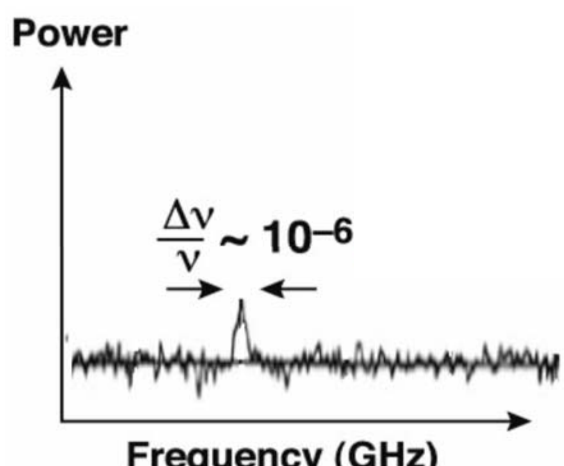
- The theory of the strong interactions naturally predicts large CP violating effects that have not been observed. Axions resolve this problem by elegantly suppressing CP violation to experimentally allowed levels.
- Cosmology and astrophysics sets the allowed axion mass range from 1 μeV to 1 meV, where the lower limit follows from the requirement that axions not provide too much dark matter, and the upper limit is set by other astrophysical constraints.

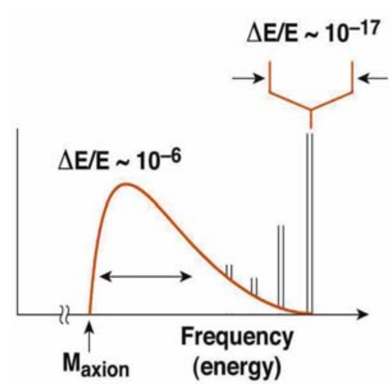
ADMX

(LLNL, U.W.)

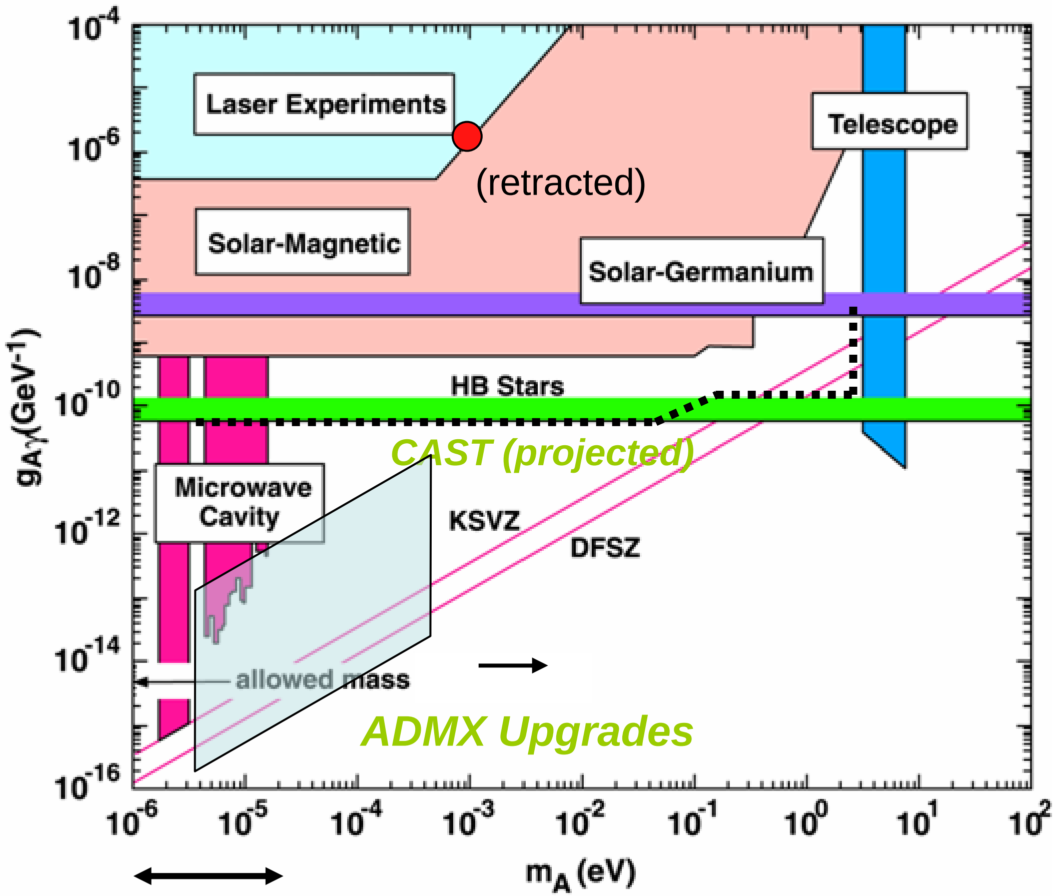
- In a static magnetic field, there is a small probability for halo axions to be converted by virtual photons to a real microwave photon by the Primakoff effect. This would produce a faint monochromatic signal with a line width of $\Delta E/E$ of 10^{-6}. The experiment consists of a high-Q (Q=200,000) microwave cavity tunable over GHz frequencies.







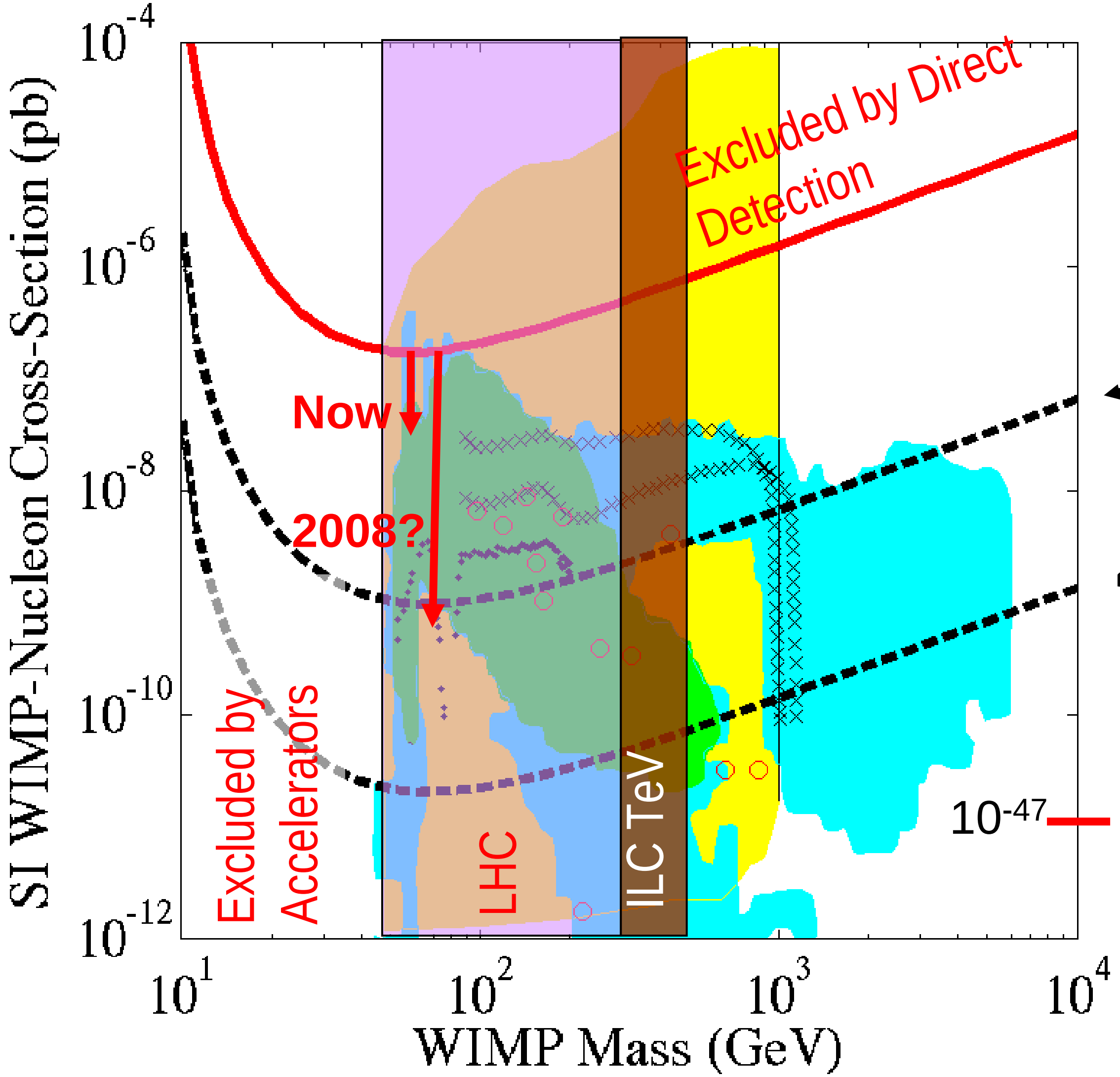
Excluded Axion Coupling $g_{A\gamma\gamma}$ vs. Axion Mass m_A



Region of mass where axions are a significant component of dark matter

- Completing phase I construction - SQUID technology.
  - 1-2 years to cover ~10^{-6} - ~10^{-4} eV down to KSVZ
- Phase II to cover same range down to DFSZ and extending the mass range of the search.
  - Requires dilution refrigerator to go from 1.7 to 0.2 K

WIMP Search Complementary to Collider Search for SUSY



CDMS II limit (2006)
(10^{-7} pb = 10^{-43} cm^2)

Assuming zero-background Sensitivity:
25 kg of Ge (Xe, I, W)
(100 kg Ar, 200 kg Ne)

1000 kg of Ge

Direct detection is cross-section limited.

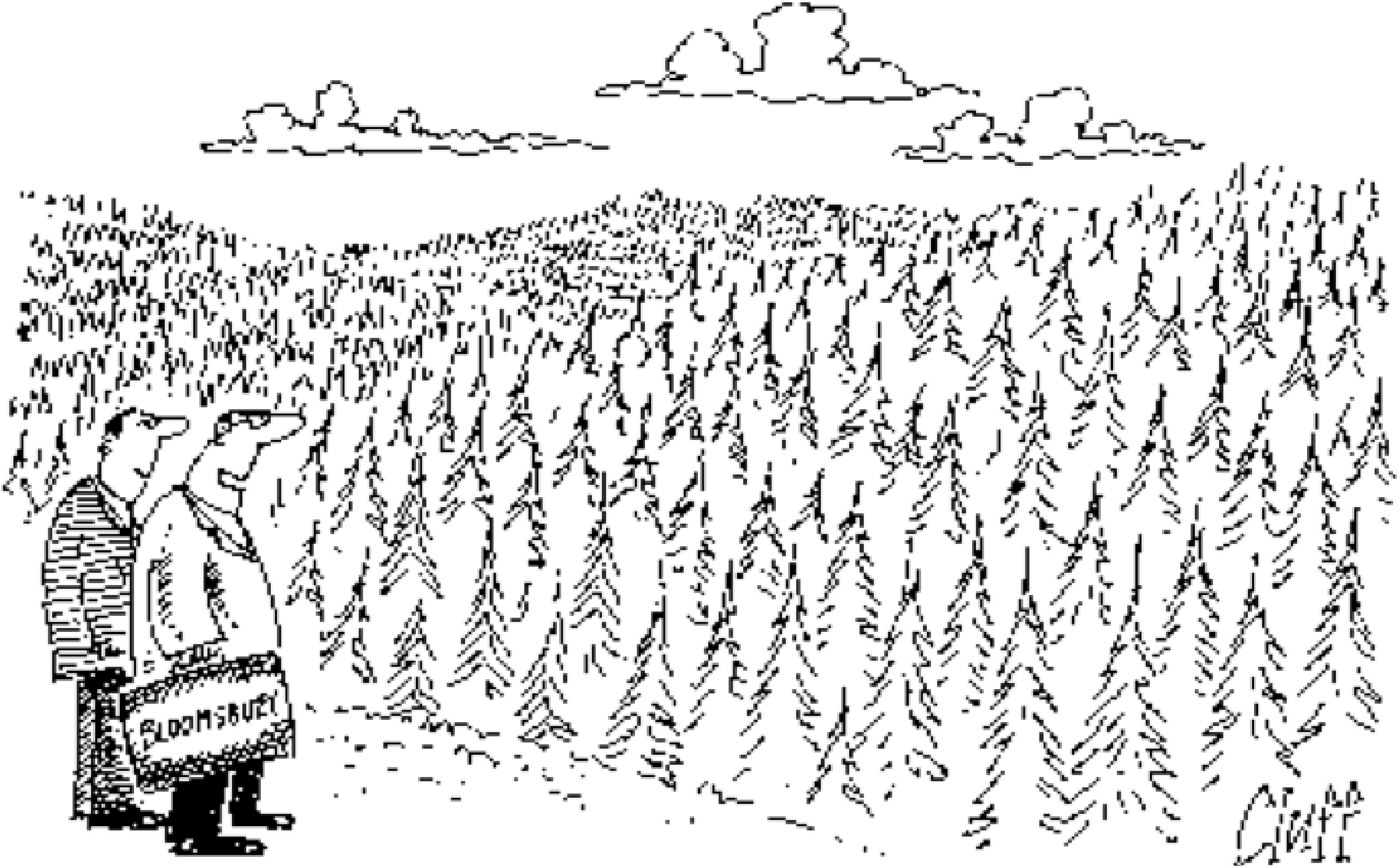
- But sensitive to >TeV mass WIMPs

Colliders are mass limited.

- And can't determine if WIMP is stable

Conclusions

- *Cosmology and particle physics independently point to the weak scale for dark matter*
- *Past investments are now paying dividends as current experiments are beginning to be sensitive to the rates predicted in well-motivated models.*
- *Recent advances in detector technology imply that these sensitivities may increase by orders of magnitude in the coming few years. Such rapid progress will revolutionize the field, and could lead to the discovery of dark matter for many of the most well-motivated WIMP candidates.*
- *Direct search experiments, in combination with colliders and indirect searches, may not only establish the identity of dark matter in the near future, but may also provide a wealth of additional cosmological information.*



“One day, all of these will be supersymmetry phenomenology papers”

Supplementary

Recommendation 8: Priorities

- Following on the above recommendations, if the comprehensive program we have
- described above is not able to be fully funded, then we recommend that the funding
- priorities during the next few years be allocated as follows. In establishing these priorities,
- we have considered both the experimental evidence of promise in a particular technique
- and our estimation of its readiness for producing significant experimental results. In
- addition, all else being equal, predominantly US efforts are given somewhat higher
- priority.
- 1. Equal priorities between (A) and (B):
  - A) Continuing the on-going CDMS and ADMX experiments and the initial construction of SuperCDMS in Soudan with two super-towers.
  - B) Funding the expansion of the noble liquids with priorities i), ii) and iii):
    - i) The expansion of the liquid Xenon experimental efforts to their next level.
    - ii) The U.S. participation in the WARP detector development.
    - iii) The next stage of the CLEAN Argon/Neon detector development.
- **(***Note on funding guidance: As we have noted elsewhere, we do not yet know which technique is the best route to the ton and larger scale. Consequently, there is a need to keep the three noble liquid techniques moving in parallel to that goal. As progress is achieved in each project, the levels of relative funding may need to change, independent of present priorities, in order to make fair evaluation of potential.)*