# DMSAG Interim Report

Hank Sobel
For the DMSAG Panel
Oct. 13, 2006

# Charge Letter
# to HEPAP and AAAC

- 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.

# Points to Cover

- What are the most promising experimental approaches … using particle detectors in underground laboratories?

- Relative advantages and disadvantages
  - stage of development
  - realistic time to implementation
  - ultimate sensitivity
  - realistic limit of scalability
  - overburden requirements.

- Optimum strategy to operate at the sensitivity frontier while making the investments required to reach the ultimate sensitivity

- Present state of the worldwide dark matter program
- What guidance and constraints for this program can be gained from other approaches to understanding dark matter?
  - What implications for this program are likely to come from astronomical observations or theoretical astrophysics and particle physics?
  - How would direct detection by the proposed approaches complement the observation of new elementary particles at TeV-scale colliders?
  - What new understanding would be possible from the combination of these approaches compared to any one of them alone?

# 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)

# Meetings & Schedule

**June 29 & 30, 2006**

- Theory Review
- Direct Detection Review
- Indirect Detection Review
- CDMS
- XENON
- ZEPLIN
- Mini-Clean

**August 14 & 15, 2006**

- ADMX
- DEAP
- WARP
- Noble Liquid Consortium
- DRIFT
- Large Direction Sensitive Detector
- COUPP
- e-bubble
- SIGN
- HPGS

**Panel Discussions:** **September 19 & 20; November 20**
**Final Report Due:** **December 15, 2006**

# 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

- Current constraints on dark matter properties show that the bulk of dark matter cannot be any of the known particles.
- The existence of dark matter is at present the strongest 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 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.

# Current State of Experiments

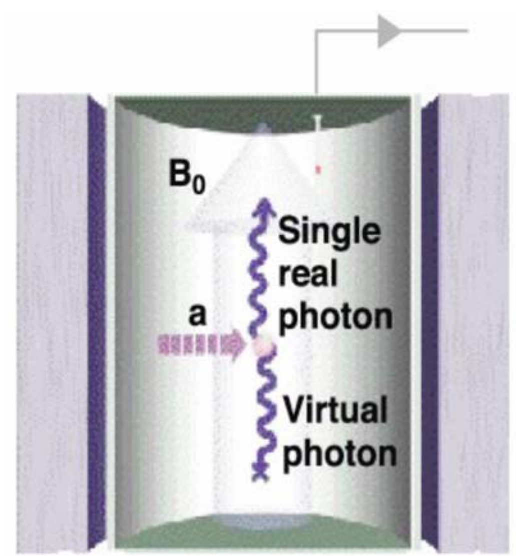
- U.S. projects CDMS and ADMX are leading field in dark matter (WIMP/Axion) sensitivity
- Rapid advances in detector technology have reached interesting areas and can go further.
- Broad spectrum of technologies.

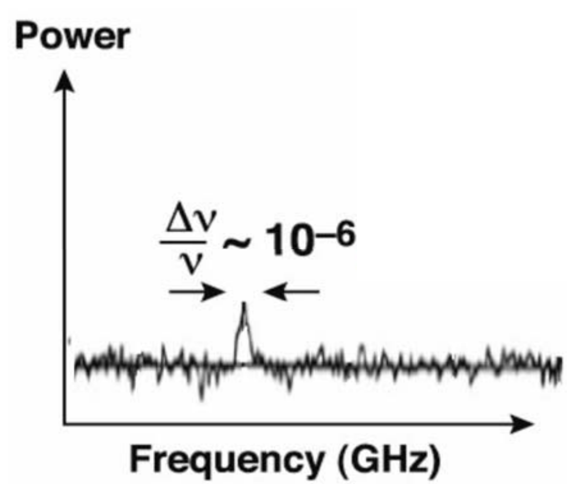
# Axions

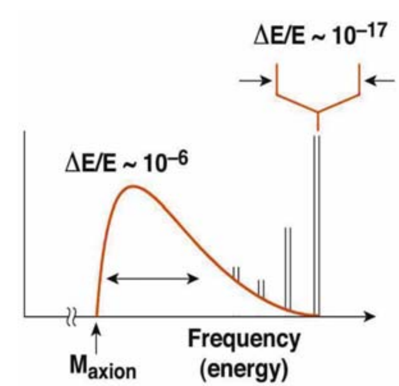
- The theory of the strong interactions naturally predicts large CP violating effects that have not been observed. Axions resolve this problem by elegantly suppressing CP violation to experimentally allowed levels.
- Cosmology and astrophysics sets the allowed axion mass range from 1 $\mu$eV to 1 meV, 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.

# Axions - ADMX

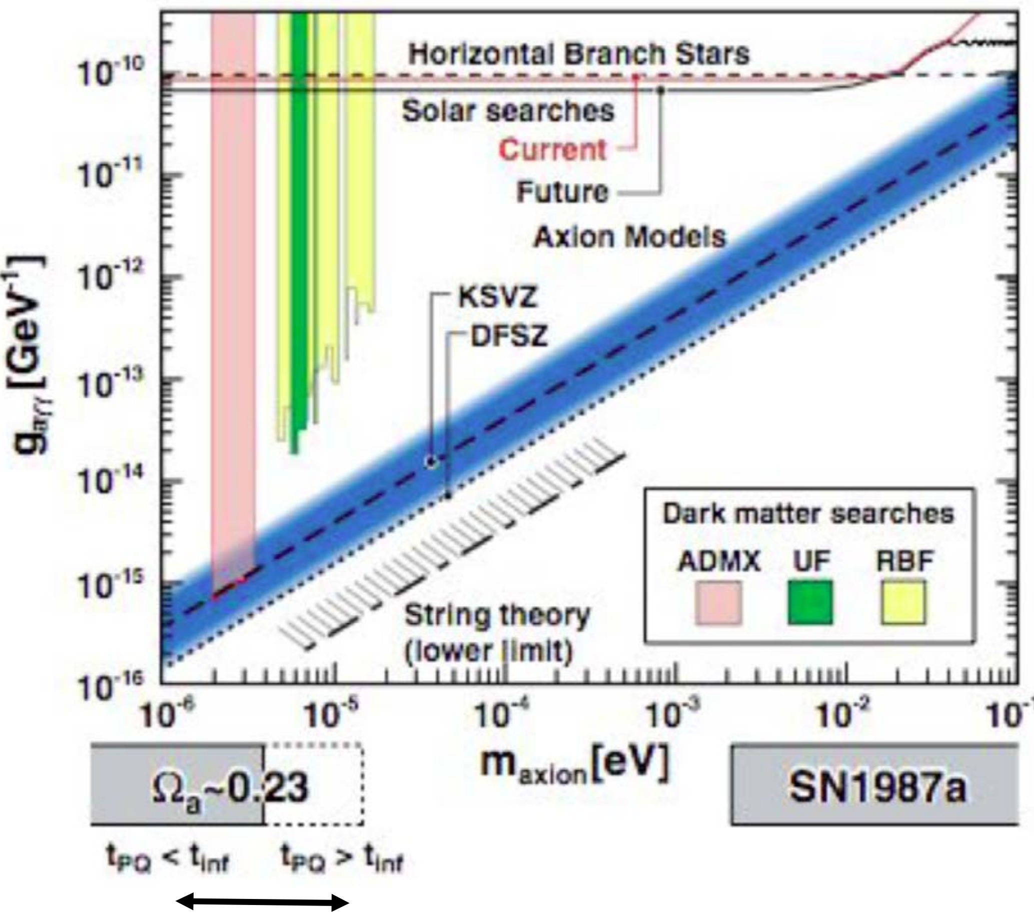
- In a static magnetic field, there is a small probability for halo axions to be converted by virtual photons to a real microwave photon by the Primakoff effect. This would produce a faint monochromatic signal with a line width of ΔE/E of $10^{-6}$. The experiment consists of a high-Q (Q=200,000) microwave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



# ADMX



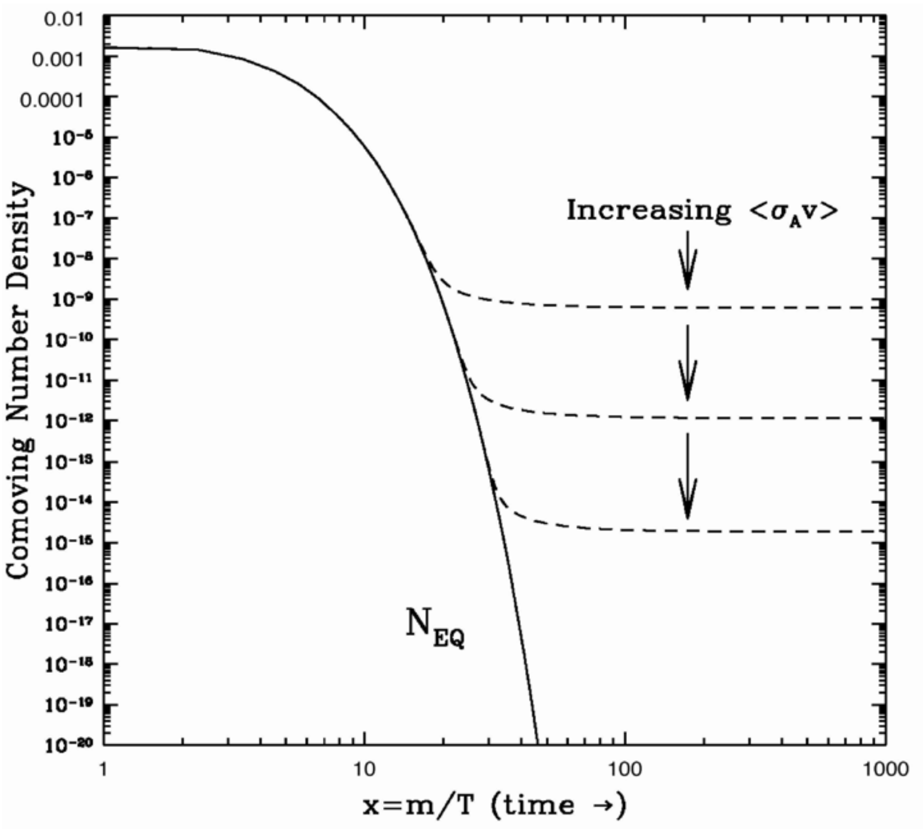

Region of mass where axions are a significant component of dark matter

- Completing phase I construction.
  - 1-2 years to cover $10^{-6}$ - $10^{-5}$ eV down to KSVZ
- Phase II to cover same range down to DFSZ
  - Requires dilution refrigerator to go from 1.7 to 0.2 K
- Beyond Phase II, they hope to develop cavities and SQUIDs making it possible to operate in the 10-100 GHz range, extending the mass range of the search.

# WIMPs

- WIMPs are particles that interact through the weak interactions of the standard model and have mass near the weak scale MW ~ 100 GeV – 1 TeV. Such particles have strong motivations.
- WIMPs appear in supersymmetric theories and many other model frameworks independently motivated by attempts to understand electroweak symmetry breaking.
- These new particles are naturally produced by the Big Bang with the cosmological densities required for dark matter. This last property is a remarkable quantitative fact. From a completely model-independent viewpoint, it implies that the weak scale is an especially promising mass scale for dark matter candidates, and experiments that probe the weak scale are required to determine if this possibility is realized in nature.

# Relic Density of a Thermal WIMP




- WIMP initially in thermal equilibrium. As universe cools:

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

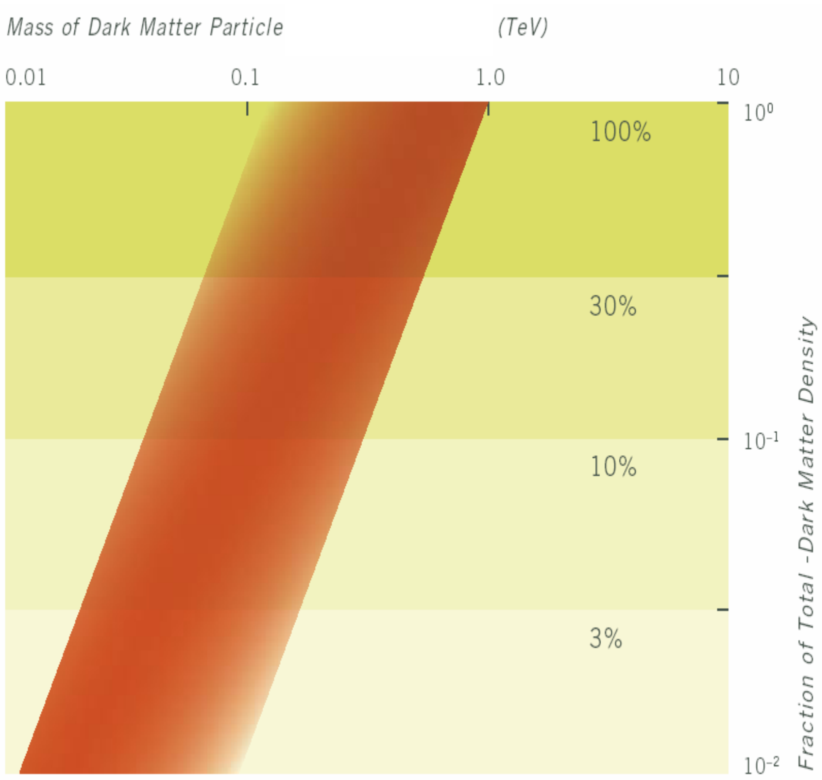
Decrease due to expansion of universe

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"




HEPAP LHC/ILC Subpanel (2006)

[band width from k = 0.5 – 2, S and P wave]

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

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

and

**For $\Omega_{DM} \sim 0.1$**

**M ~ 100 GeV – 1 TeV.**

**Cosmology alone tells us we should explore the weak scale.**

# Direct Detection of WIMPS

- Energy spectrum and density depend on distribution in DM halo.
  - Usually assume spherical distribution with Maxwell-Boltzmann velocity distribution.
  - V=230 km/s, $\rho$=0.3 GeV/cm$^3$
- Elastic nuclear scattering
  - WIMP nucleus collision rate calculated from theory
  - Low velocity $\rightarrow$coherent interaction
  - Spin-independent ~$A^2$, but very large A targets have loss of coherence.
  - Spin-dependent – need high-spin nuclear targets such as $^{73}$Ge
  - For most targets in use, scalar interaction gives more sensitivity.
- 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$^2$).

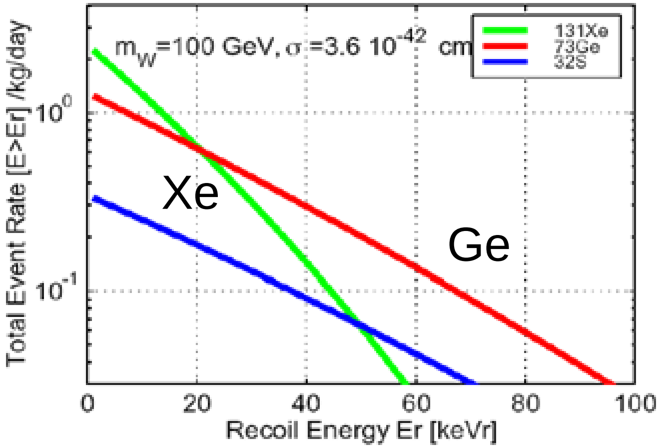
# Experimental Challenges

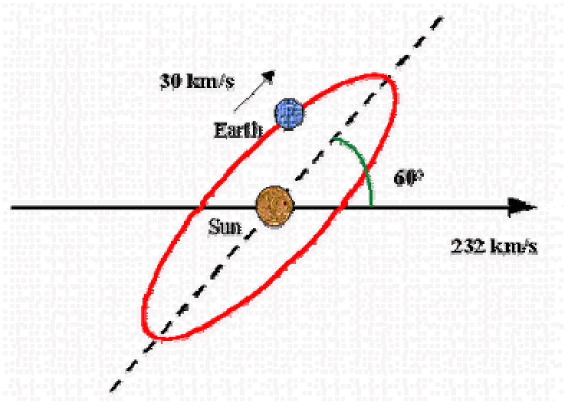
**The WIMP "signal" is a low energy (10-100 keV) nuclear recoil.**

- 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 – **DUSEL especially important for Dark Matter experiments**

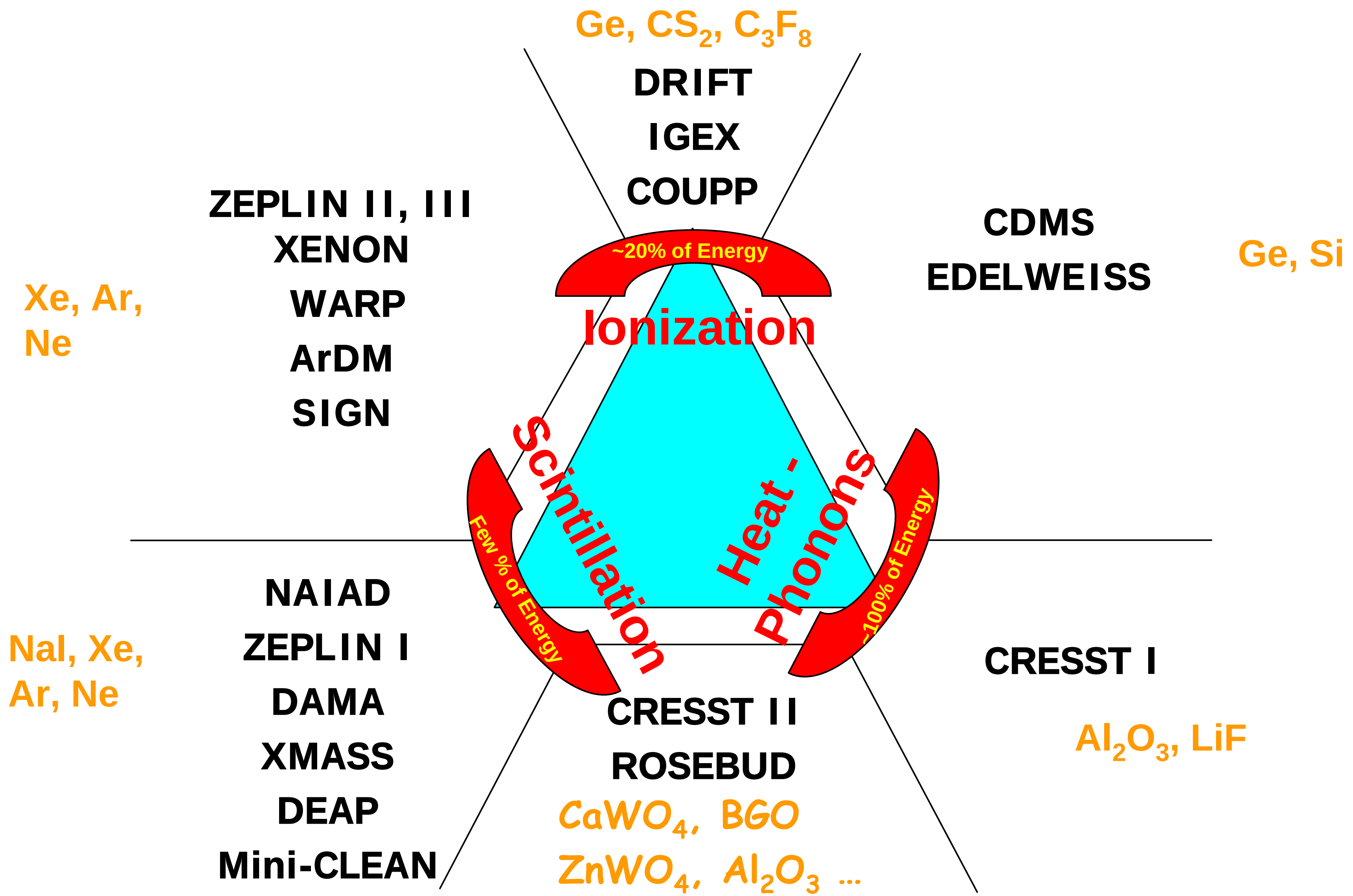
# Possible WIMP Signatures

- 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%, Requires > 500 kg target for > 5 years and 5$\sigma$ detection)**
- Diurnal direction modulation
  - **(nice signature, but very short tracks requires low pressure gaseous target,**



# Direct Detection Techniques

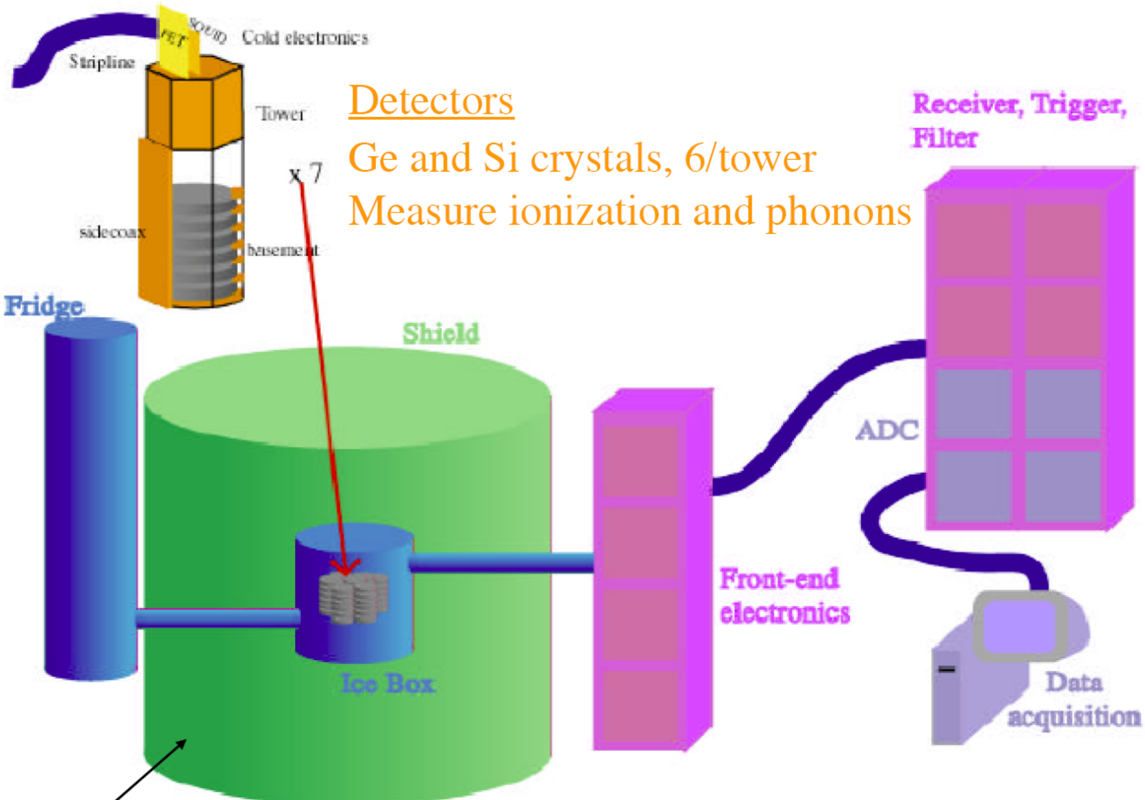


# CDMS

- The Cryogenic Dark Matter Search (CDMS) Collaboration has pioneered the use of low temperature phonon-mediated Ge or Si crystals to detect the rare scattering of WIMPs on nuclei and distinguish them from backgrounds. With this powerful technology, operating deep underground in the Soudan mine in Minnesota, the CMDS group has produced the most sensitive WIMP search in the world, and their reach is projected to grow by factor of eight by the end of 2007.

# CDMS Detector Schematic


Dan Bauer
DMSAG
June 29, 2006


Detectors

Ge and Si crystals, 6/tower

Measure ionization and phonons

Electronics /DAQ

Record signals from detectors and veto; form trigger

Cryogenics

Maintain detectors at 50 mK

Shielding

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

# CDMS II Active Background Rejection

Dan Bauer
DMSAG
June 29, 2006

## Detectors with excellent event-by-event background rejection

Measured background rejection:

99.995% for EM backgrounds using charge/heat

99.4% for β's using pulse risetime as well

Clean nuclear recoil selection

Tower of 6 ZIPs

Tower 1

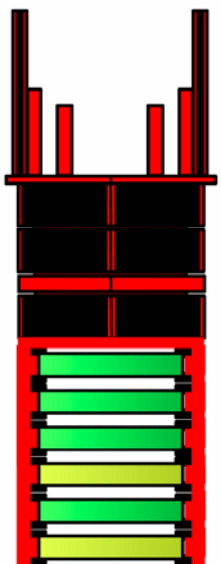
4 Ge

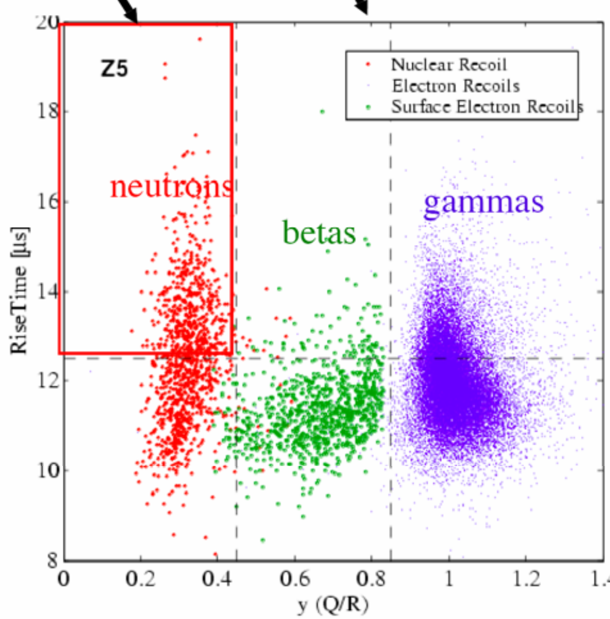
2 Si

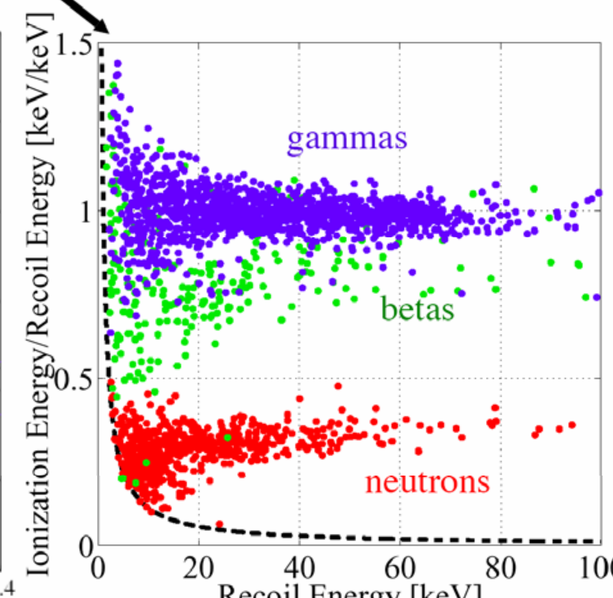
Tower 2

2 Ge

4 Si





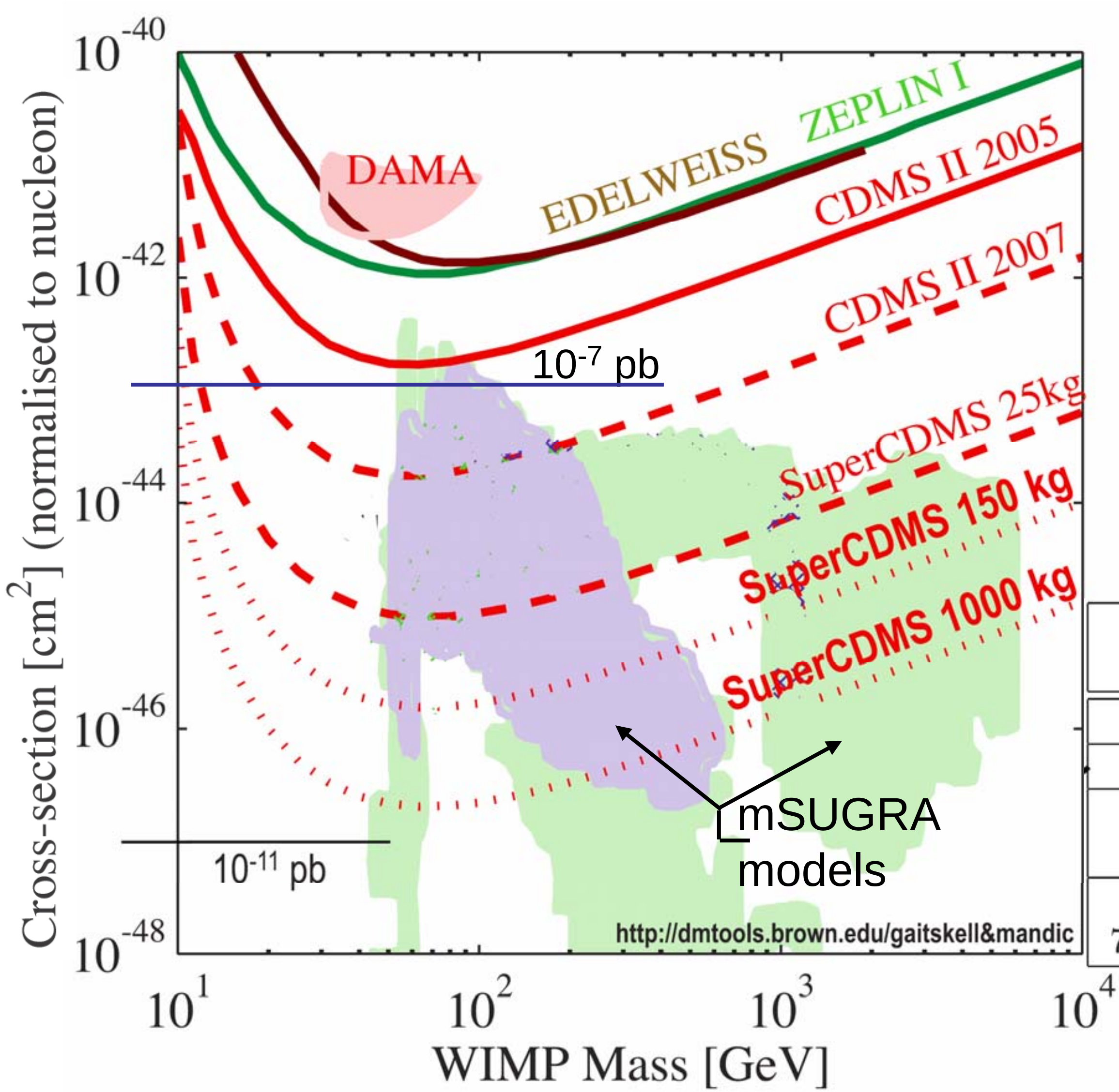




Charge/Heat much smaller for nuclear recoils

# CDMS Highlights

- Detectors with excellent event-by event background rejection.
- Experimentally measured gamma (99.995%) and beta (99.4%) suppression.
- Clean nuclear recoil selection.
- No other technology has been yet demonstrated at the CDMS level of sensitivity.
- Possible comparison of Si to Ge to confirm origin of signal.
- Sensitivity to Spin-Dependent cross-section, although Spin-Independent is much larger.

# World’s Best Limit, Future Plans




- Run in Soudan through 2007 with existing setup 5-T
- Run in Soudan with two new supertowers through 2009
    - Zip’s 1.0 → 2.5 cm thick
    - Study improved rejection
    - Prepare for SNOlab with new Cryo-vacuum setup
- Run 7-ST at SNOlab

| Experiment | Cross-section sensitivity |
|---|---|
| CDMS II 2-T (2005) | $1.6\times10^{-43}$ cm$^2$ |
| CDMS II 5-T (2007) | $2.1\times10^{-44}$ cm$^2$ |
| SuperCDMS Detectors 2-ST at Soudan (2009) | $7.2\times10^{-45}$ cm$^2$ |
| SuperCDMS 25 kg 7-ST at SNOLAB (2012) | $1.3\times10^{-45}$ cm$^2$ |

# CDMS Challenges

- Detectors must be maintained at 50mK
  - development of a new cryogenic system for SNOlab
- Complex technology.
- No fiducial volume free of surfaces can be defined.
  - background beta events from detector surface events
- Neutrons from internal activity need to be understood
- Relatively large cost to sensitive mass ratio
  - Scalability a challenge
  - Much larger versions will require new ideas for background control and major reduction in the cost and turn-around time for construction.

# New Technologies

- The field has been energized by the emergence of noble liquid gasses (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:
  - An increased reach in sensitivity by at least three orders of magnitude for WIMP's .
  - The possibility of recoil particle direction measurement.
  - Increased sensitivity to spin-dependent interactions.
  - 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.
- High scintillation efficiency
- Possibility for large, homogenous detectors.

# Single-Phase Techniques

DEAP, Mini-CLEAN, XMASS

- Pulse shape discrimination to discriminate electrons from nuclear recoils.

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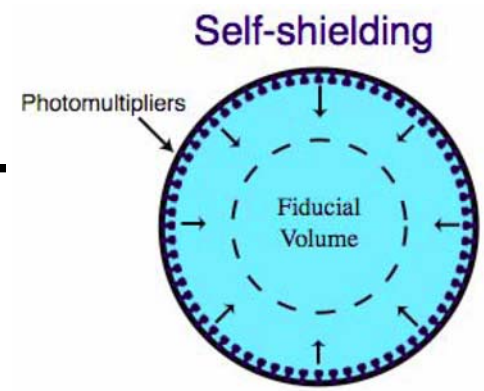
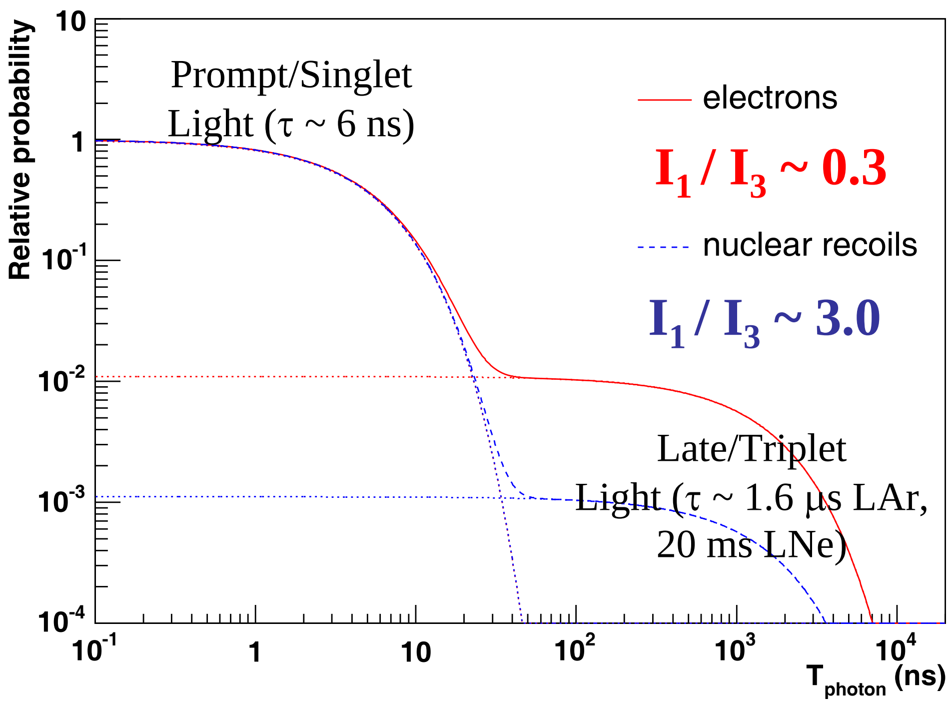
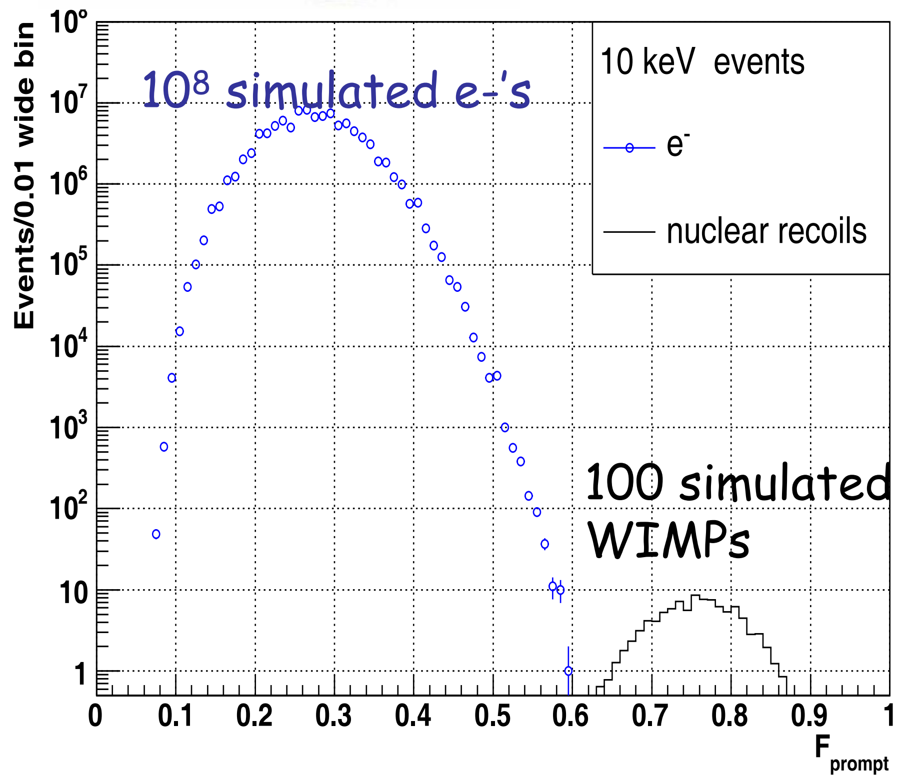



Gets better as size increases.



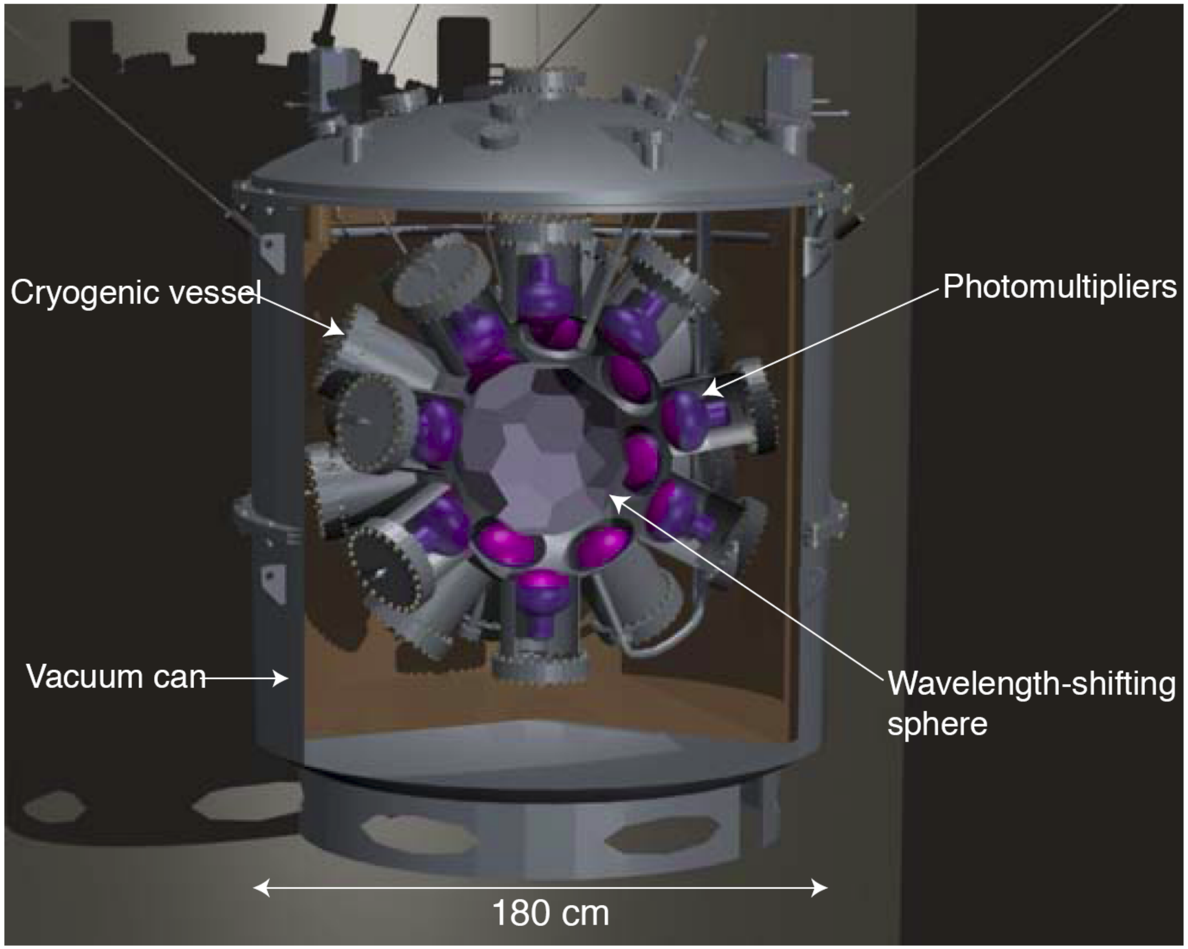

M.G.Boulay and A.Hime, Astroparticle Physics 25, 179 (2006)

# DEAP/Mini-CLEAN

(Canada, U.S.) (U.S.)

- Goal is "simple and scalable" approach.
- Based solely on the use of scintillation and therefore is free from the complications of high voltages and minimizes optical effects at phase boundaries.
- Both argon and neon have strong scintillation and singlet/triplet excimer lifetimes suitable to make PSD attractive and practical.
- Swapping Ne for Ar in the same detector gives a direct check of the total background level.
  - The expected spin-independent WIMP event rates in Ne are factor 5 lower than in Ar but the backgrounds in the 100kg version are expected to be similar in both.

# Proposed 100kg Mini-CLEAN

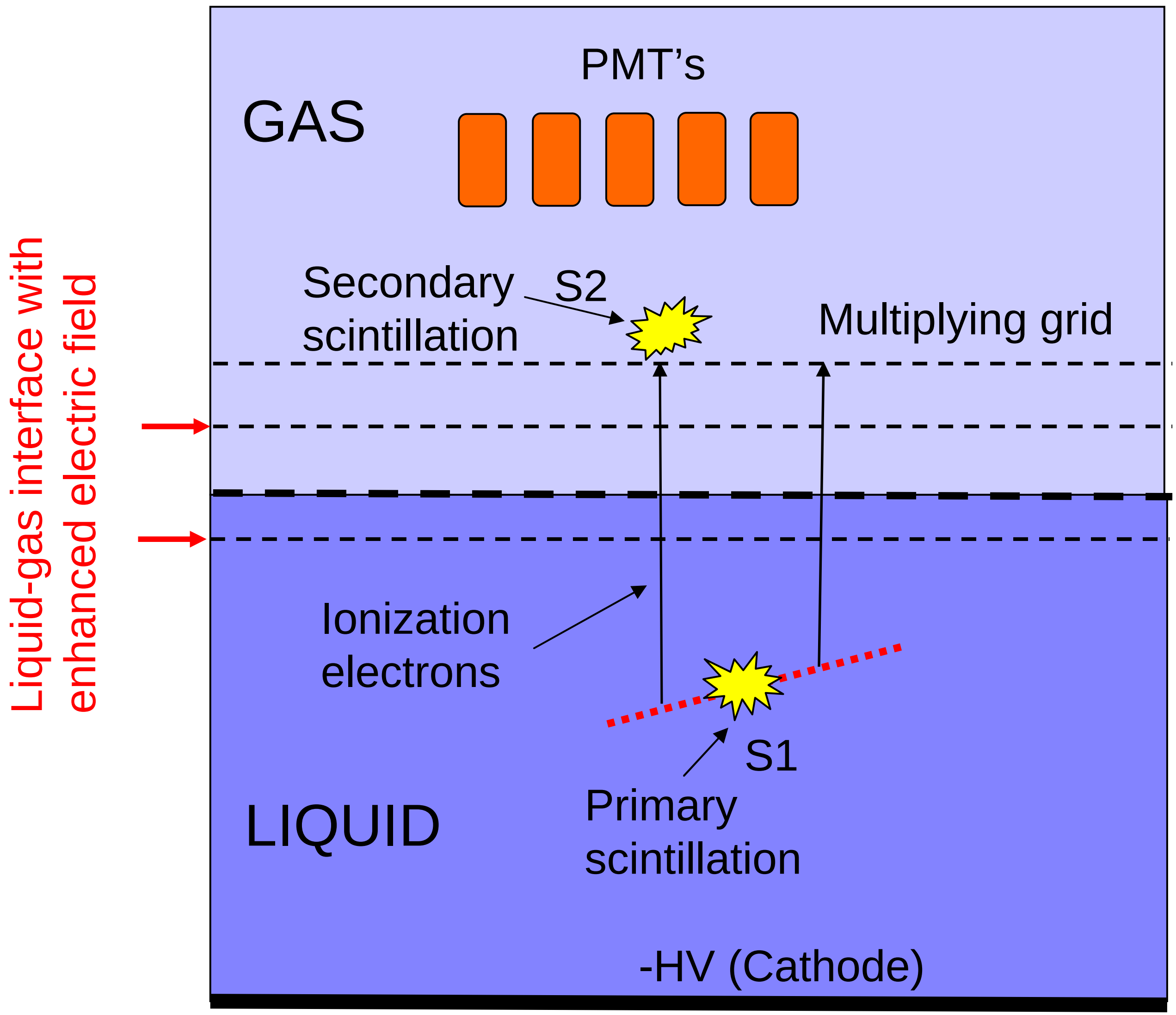



- Micro-CLEAN (4 kg currently operating, R&D on scintillation, test discrimination down to 40 KeV.
- Mini-CLEAN (100 kg detector) 2007-2009
- If low-background achieved, could reach $10^{-45}$ $cm^2$ for 100 GeV WIMP.

# 2-Phase Noble Liquids

WARP, ArDM, XENON, ZEPLIN

(Argon, Xenon)




<u>Experimental handles</u>

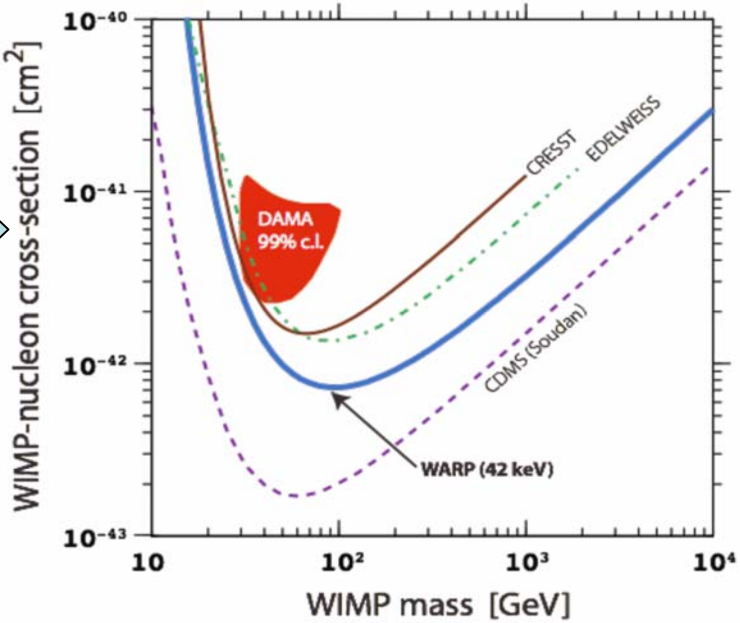
- Primary scintillation intensity
- Primary scintillation pulse shape
- Secondary scintillation intensity
- S2/S1
- Multiple recoils
- Fiducial volume

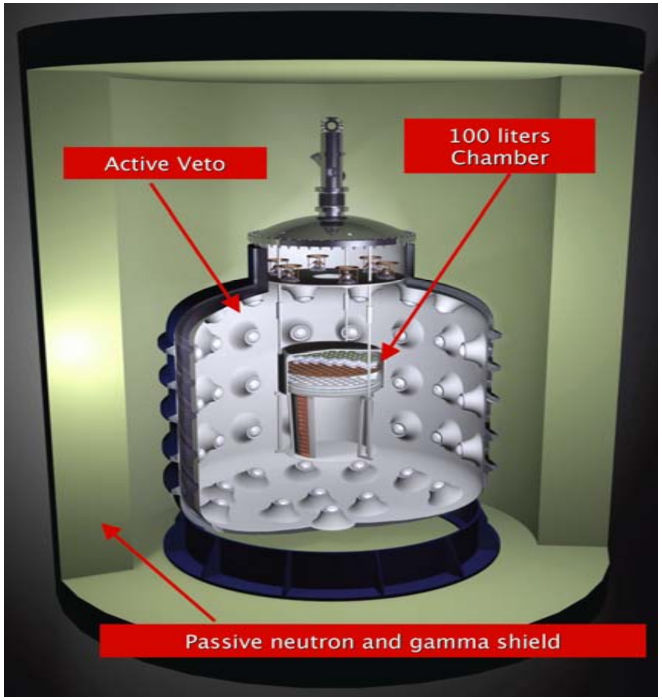
Some best in Argon, some best in Xenon

# WARP Results and Future

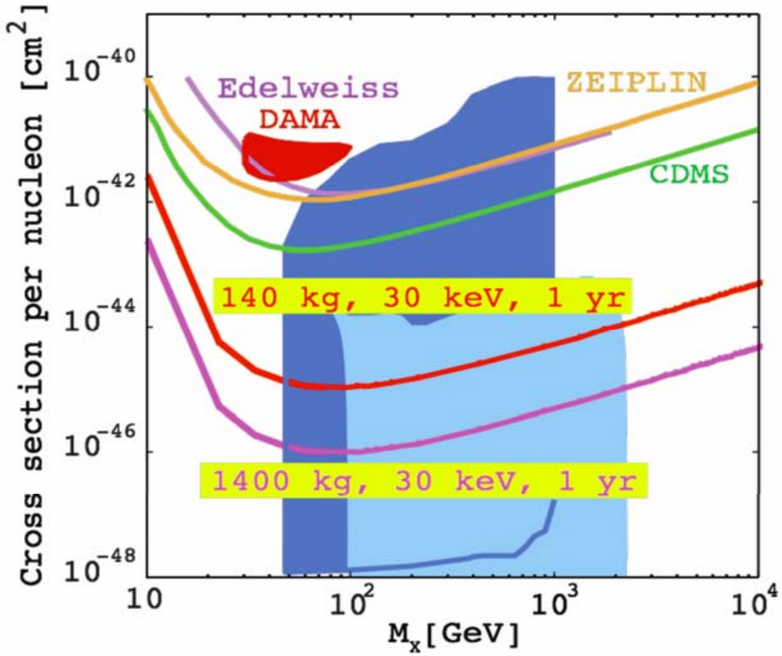
(Italy, U.S., Poland)

WARP 3.2 kg prototype had 95.4 kg day exposure.




Projected sensitivity



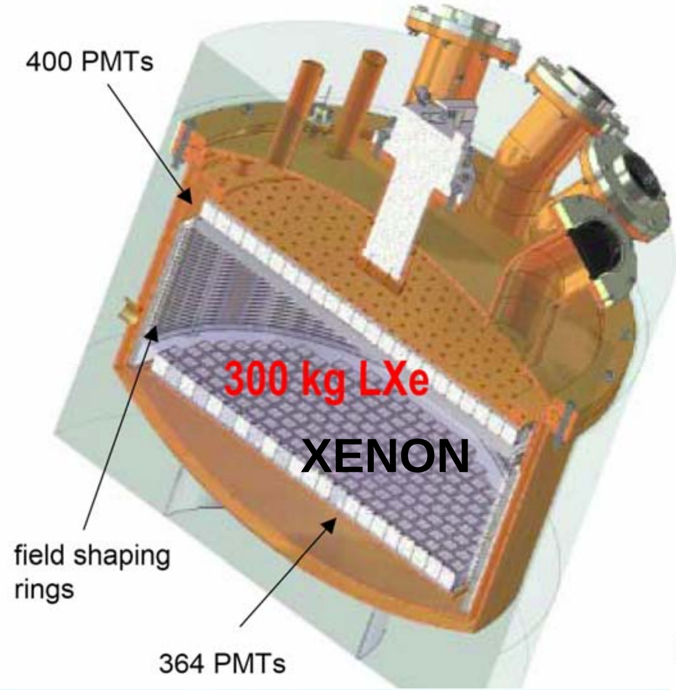

140 kg detector currently being constructed

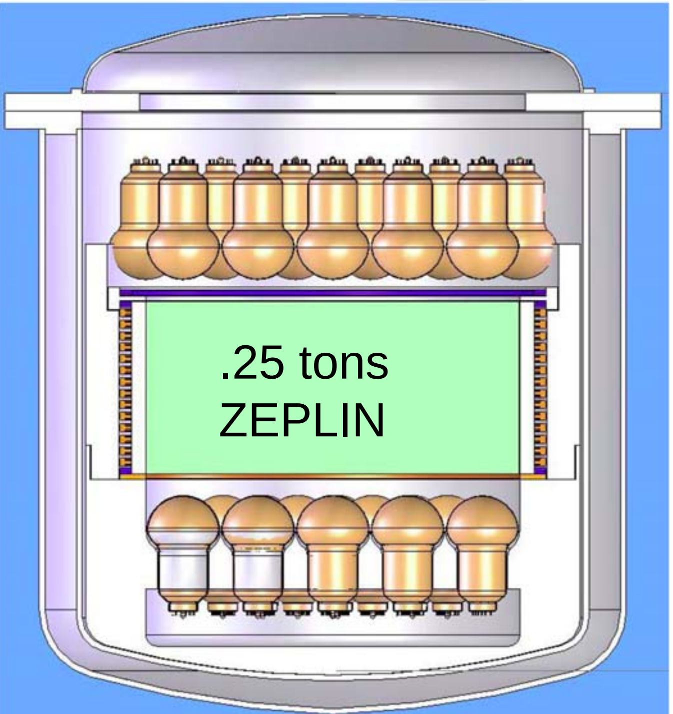
# XENON, ZEPLIN Results and Future

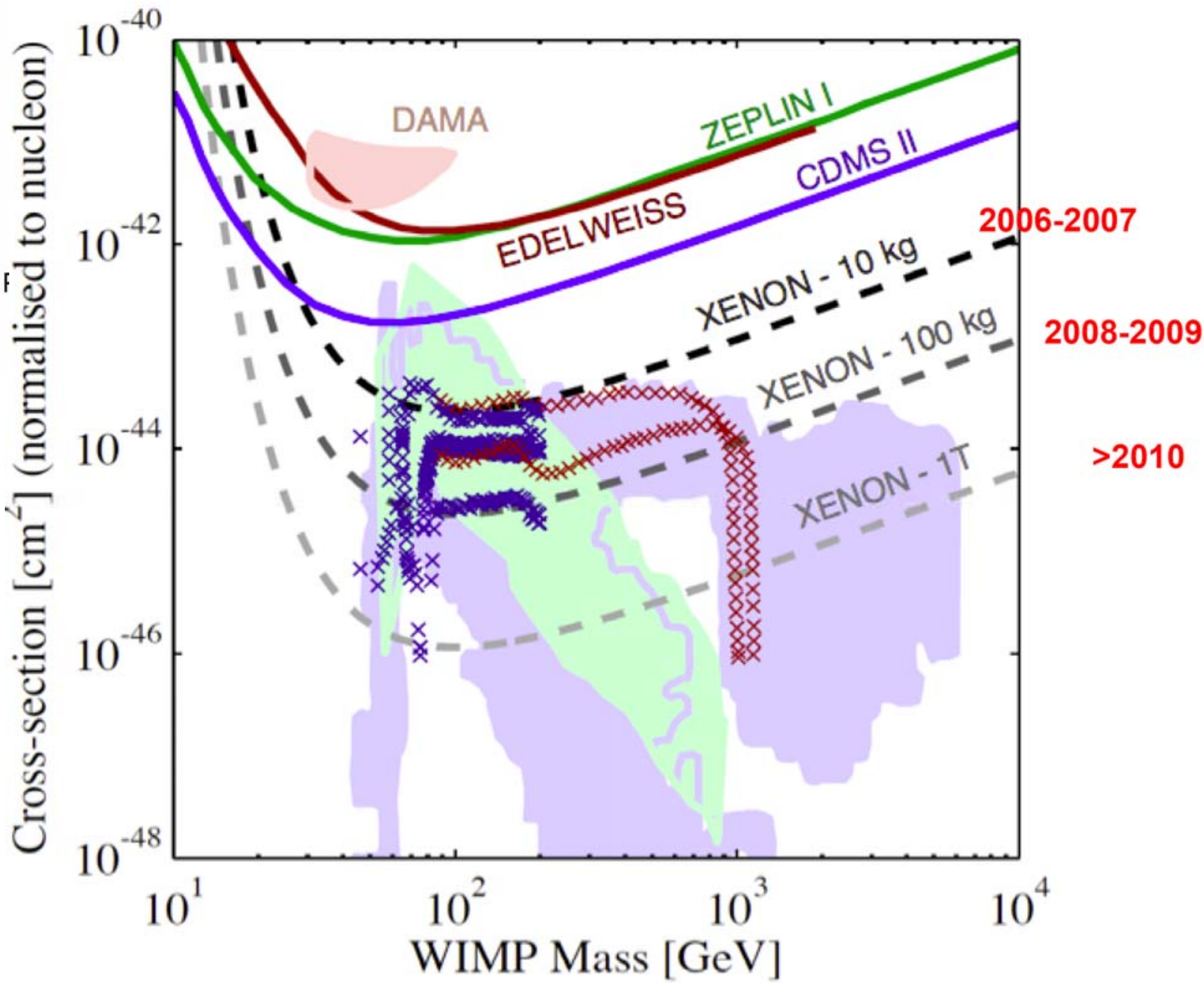
(U.S., Germany, Italy, Portugal) (U.S., G.B.)

- Zeplin II
  - Operating with 32 kg total mass of Xe
  - Already collected >1200 kg-days.
- XENON10
  - Operating with 15 kg of Xe (10 kg fiducial)
  - Began at Gran Sasso ~March 2006.
- Both Zeplin II and XENON10 anticipate they will reach a dark matter constraint ~$10^{-44}$ $cm^2$.
- Results not yet available, but a dark matter limit from this data set will provide a useful benchmark for the background levels and information on the electron recoil rejection capability as the devices get larger.
- Proposals expected for XENON-100, XE-500

# Projected Sensitivity



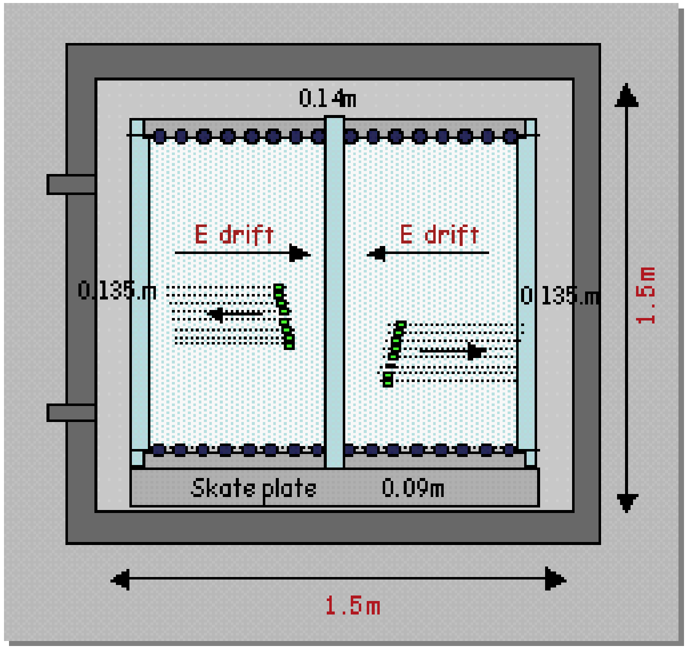
# Some of the Noble Liquid Challenges

- Elimination/or rejection of surface nuclear recoils
- Good knowledge of quenching factors
- Quality of the $\gamma$ and $\beta$ rejection at low thresholds
- Fiducialization
- Neutron tagging
- Freedom from $^{39}Ar$, $^{85}Kr$

# 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.)

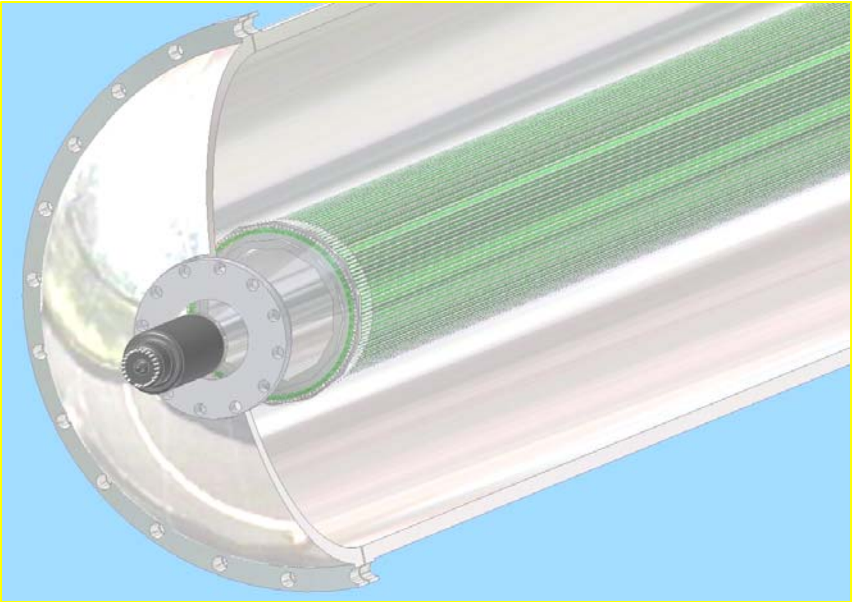



- TPC filled with low-pressure electro-negative gas ($CS_2$).
- Recoil tracks are ~few mm long
- Ion drift limits diffusion in all 3 dimensions
- End planes allow determination of range, orientation & energy
- Excellent discrimination based on range and ionisation-density
- Important R&D efforts by DRIFT 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.

# SIGN

(U.S.)

- Very high pressure (100 to 300 bar) gaseous neon contained in cylindrical modules.
- Discrimination primarily based upon prompt and delayed scintillation pulse height differences.
- Prompt scintillation producing both a PMT signal and photoelectrons produced and drifted from a CsI surface lining the cylinder into a high field region on the axis.
- Wave length shifting fibers along the axis carry light to a single PMT mounted on each end. Data suggest that some primary pulse shape discrimination might be possible in addition to the PSD.



# 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.)
- The goal is to produce a detector that has excellent sensitivity to both spin-dependent and spin-independent interactions of weakly interacting massive particles and that can be scaled up to 1-ton size at a reasonable cost.
- Already reached stable operation of a 1-liter (2kg) version at shallow depth.
- Demonstrated excellent $\gamma$ rejection.
- Principal background issue is decays of radon and its products in the vessel and in the bulk liquid; their rate determines the length of live time possible and thus must be significantly reduced.
- A well planned R&D program has been started combining several avenues to control these sources (as well as others such as U,Th) and progress on them can be expected in the next few years.

# Conclusions

- *Past investments are now paying dividends as current experiments are beginning to be sensitive to the rates predicted in well-motivated models. CDMS and ADMX are leading the way.*
- *Recent advances in detector technology imply that these sensitivities may increase by 3 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.*
- *The pace of progress is such that physics discoveries based on these new detector developments could occur as early as the next 2 to 5 years.*
- *Most of these new experimental tools are U.S. led or inspired and therefore, with appropriate investment in these technologies, the U.S. will be able to maintain its present leadership in direct detection science.*

- 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.

# Appendix

- Supplementary material

# Some current direct detection experiments

| Discrim. | Name | Location | Technique | Target | Status |
|---|---|---|---|---|---|
| None | CUORICINO | Gran Sasso | Heat | 41 kg TeO2 | running |
| | GENIUS-TF | Gran Sasso | Ionization | 42 kg Ge in liq. $N_2$ | running |
| | HDMS | Gran Sasso | Ionization | 0.2 kg Ge diode | stopped |
| | IGEX | Canfranc | Ionization | 2 kg Ge Diodes | stopped |
| Statistical | DAMA | Gran Sasso | Light | 100 kg NaI | stopped |
| | LIBRA | Gran Sasso | Light | 250 kg NaI | running |
| | NaIAD | Boulby mine | Light | 65 kg NaI | stopped |
| | **DRIFT** | Boulby mine | Low pressure TPC | $CS_2$ | running |
| | **ZEPLIN-I** | Boulby mine | Light | 4 kg Liquid Xe | stopped |
| | **XMASS** | Kamioka | Light | 100 kg Xe | running |
| Event-by-event | **CDMS-I** | Stanford | Heat + Ionization | 1 kg Ge + 0.2 kg Si | stopped |
| | **CDMS-II** | Soudan mine | Heat + Ionization | 5 kg Ge + 1 kg Si | running |
| | **CRESST-II** | Gran Sasso | Heat + Light | 10 kg CaWO4 | starting |
| | **EDELWEISS-I** | Modane | Heat + Ionization | 1 kg Ge | stopped |
| | **EDELWEISS-II** | Modane | Heat + Ionization | 10-30 kg Ge | starting |
| | **XENON-10** | Gran Sasso | Ionization + Light | 10 kg Xe | starting |
| | **WARP, ArDM** | Gran Sasso | Ionization + Light | 2-phase Ar | running |
| | **ZEPLIN-II** | Boulby mine | Ionization + Light | 2-phase Xe | starting |
| | **PICASSO** | SNO | Metastable gel | | |
| | **SIMPLE** | Rustrel | Metastable gel | | |
| | **COUPP** | Fermilab | Bubble chamber | Freon-type liquids | prototype |

# EXPERIMENT VS. THEORY