DMSAG Draft Report

Steve Elliott

HEPAP Meeting

February 23, 2007

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

Closed meeting: September 19 & 20;
Three video conferences: November 20, December 18, January 12.
DRAFT submitted to AAAC & HEPAP: January 23, 2007
AAAC suggested more detail on recommendation 8
Report Due: February 21, 2007
Review: Reviewers being chosen now
Final Report: soon after reviews returned (2 weeks?)

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 one of the strongest pieces 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 the field in dark matter (WIMP/Axion) sensitivity
- Rapid advances in detector technology have reached interesting areas and can go further.
- Broad spectrum of technologies.

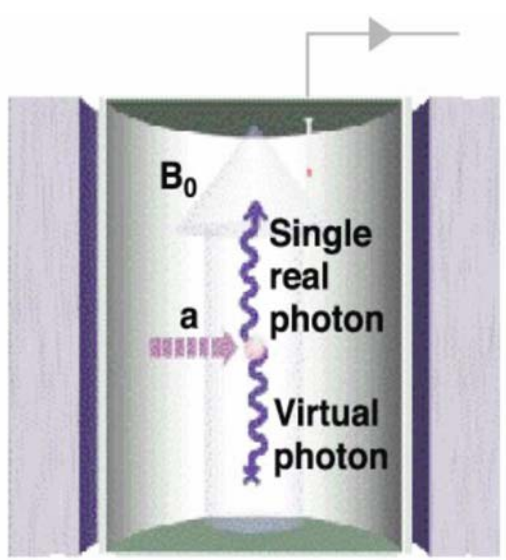
Axions

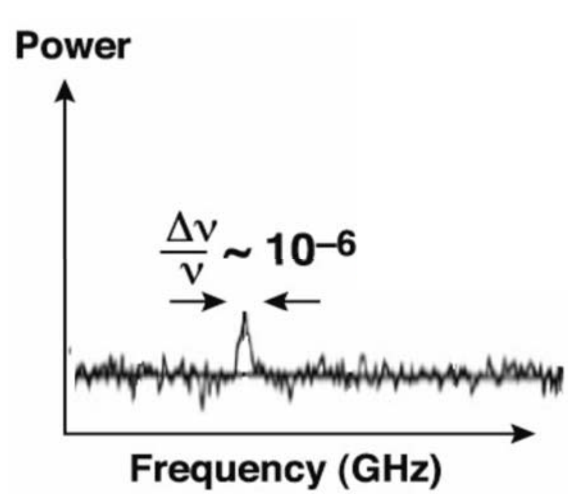
- **The theory of the strong interactions naturally predicts large CP violating effects that have not been observed. Axions resolve this problem by elegantly suppressing CP violation to experimentally allowed levels.**

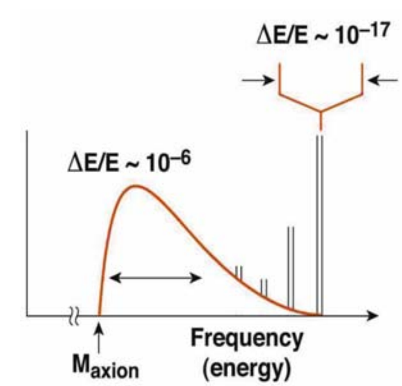
- **Cosmology and astrophysics set the allowed axion mass range from 1 μeV to 1 meV, where the lower limit follows from the requirement that axions not provide too much dark matter, and the upper limit is set by other astrophysical constraints.**

Axions - ADMX

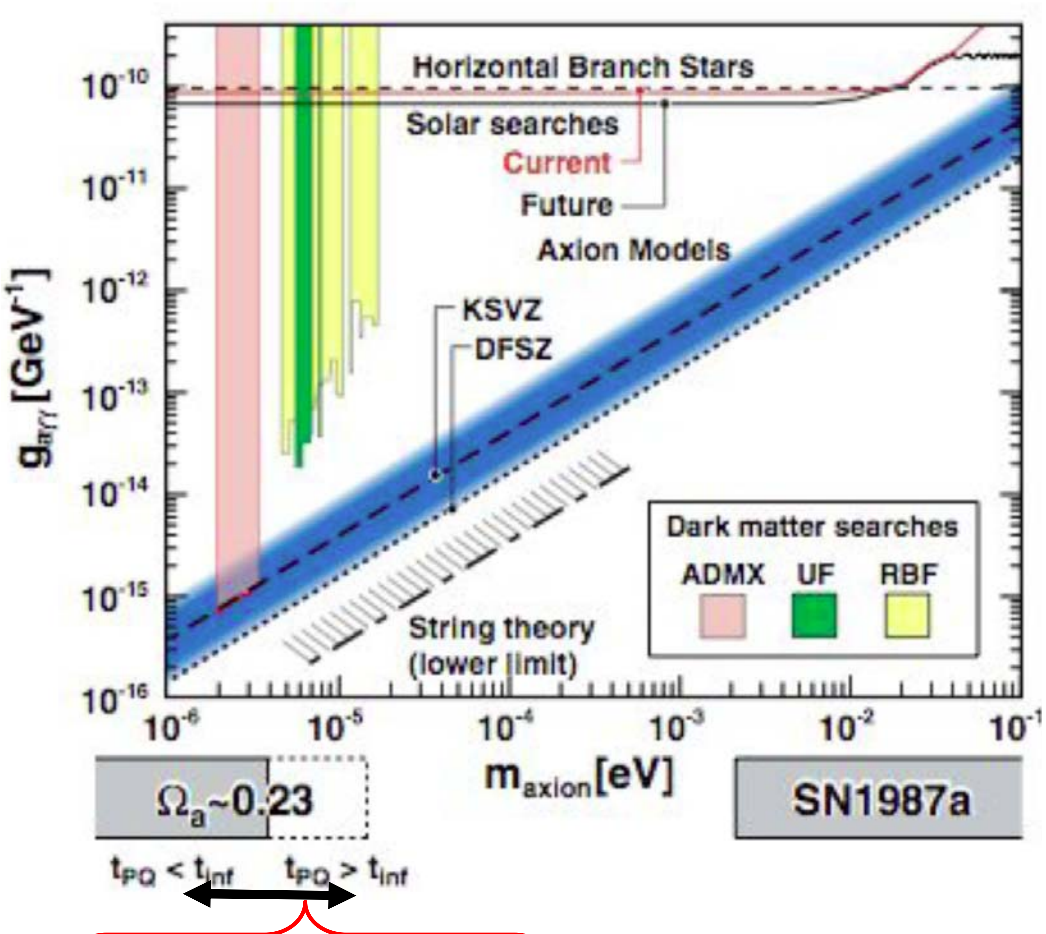
In a static magnetic field, there is a small probability for halo axions to be converted by virtual photons to a real microwave photon by the Primakoff effect. This would produce a faint monochromatic signal with a line width of $\Delta E/E$ of 10^{-6}. The experiment consists of a high-Q (Q=200,000)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







ADMX



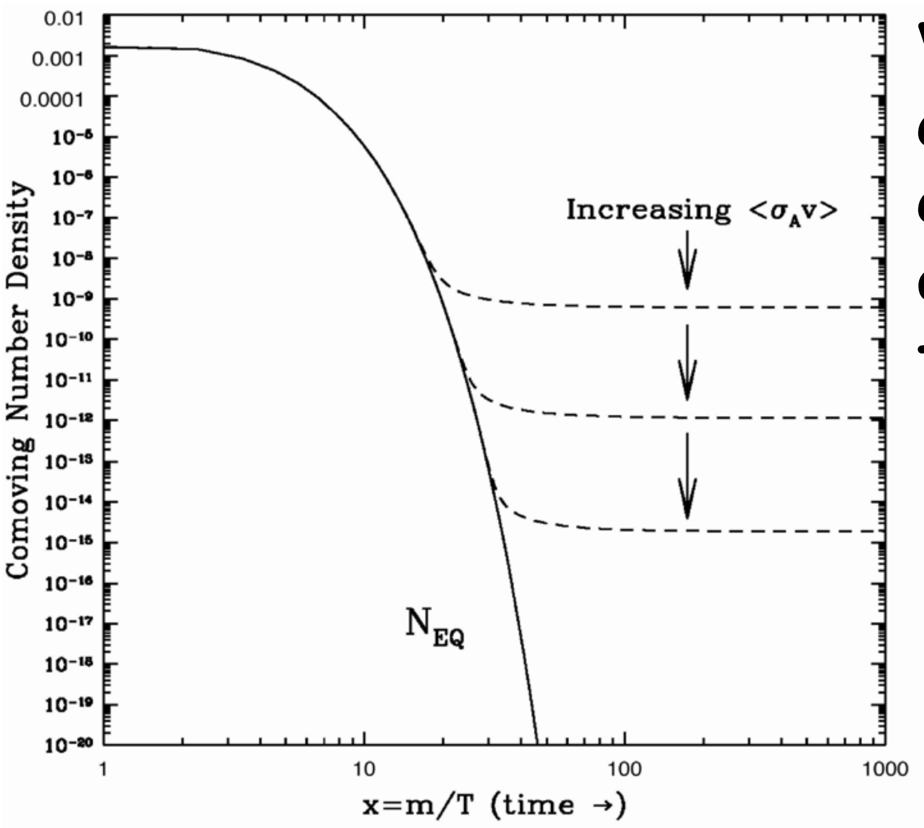
Region of mass where axions are a significant component of dark matter

- 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. When expansion outpaces annihilation, WIMPS freeze out:

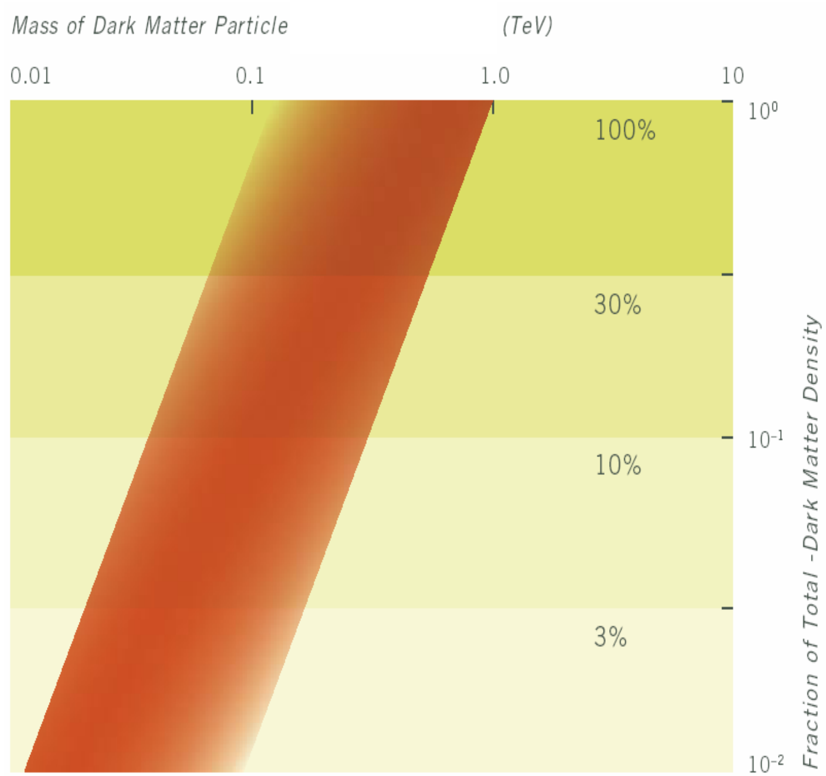
$$\frac{dn}{dt} = -3Hn - \langle \sigma_{eff} v \rangle \left(n^2 - n_{eq}^2 \right)$$

Decrease due to expansion of universe

Change due to annihilation and creation

Present Number density determined 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 $\Omega_{DM} \sim m^2$ 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 →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 (CDMS), mSUGRA models go to ~ 10^{-46}cm^2).

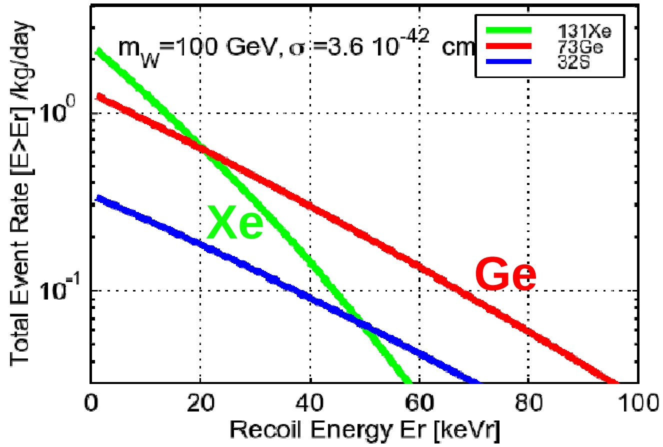
Experimental Challenges

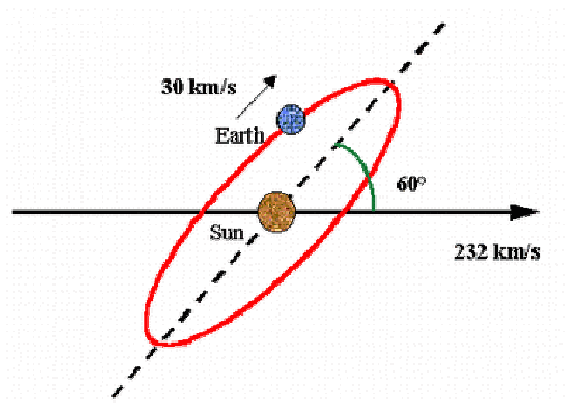
The WIMP "signal" is a low energy (10-100 keV) nuclear recoil.

- **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

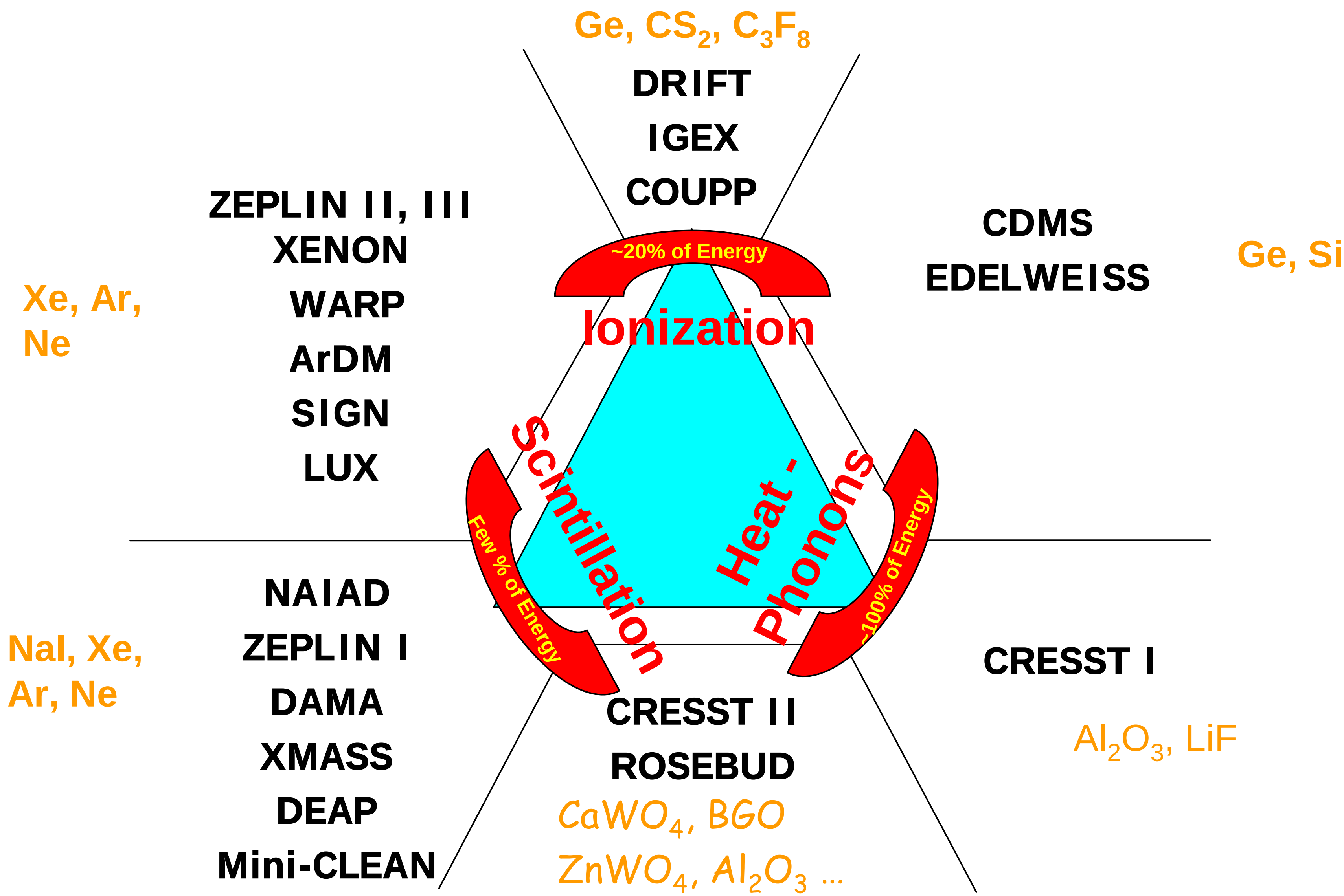
Possible WIMP Signatures

- **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 5σ detection)
- **Diurnal direction modulation**
  - (nice signature, but very short tracks requires low pressure gaseous target)





Direct Detection Techniques

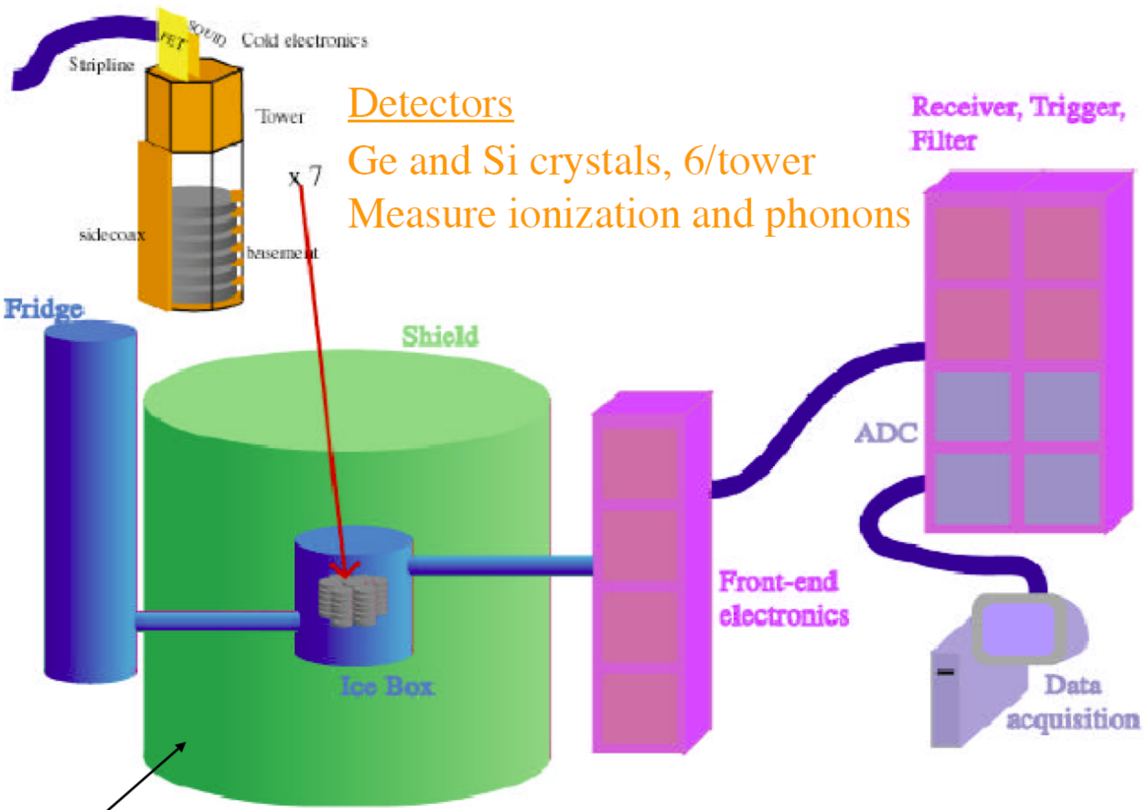


CDMS

- 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

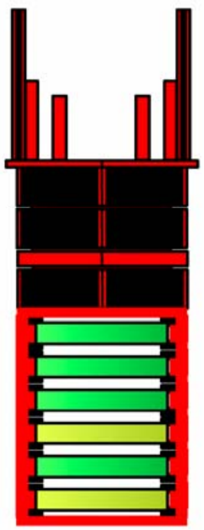
4 Ge

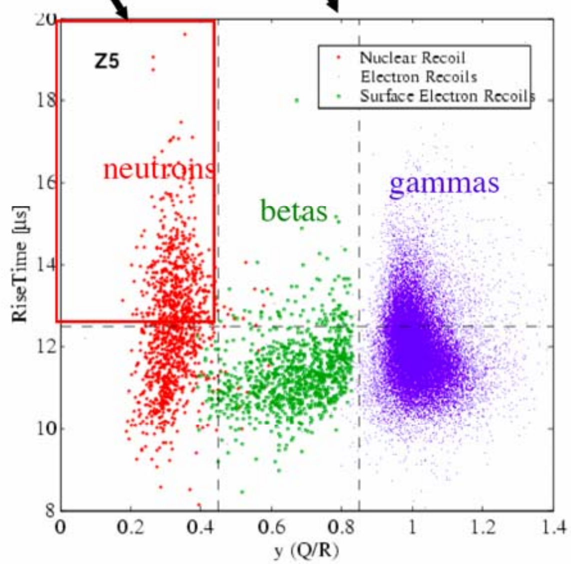
2 Si

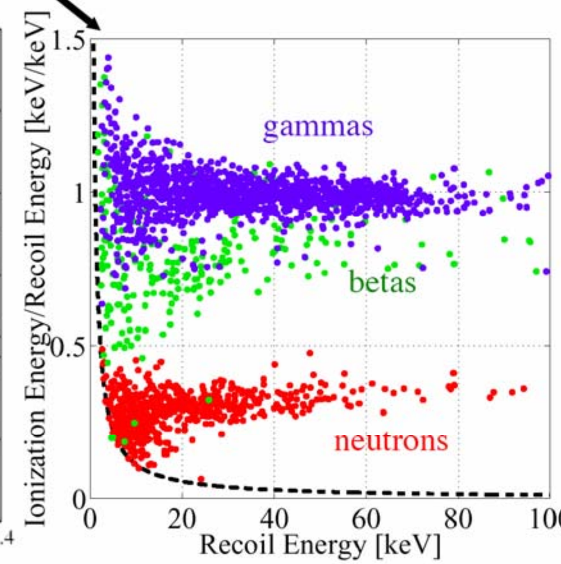
Tower 2

2 Ge

4 Si



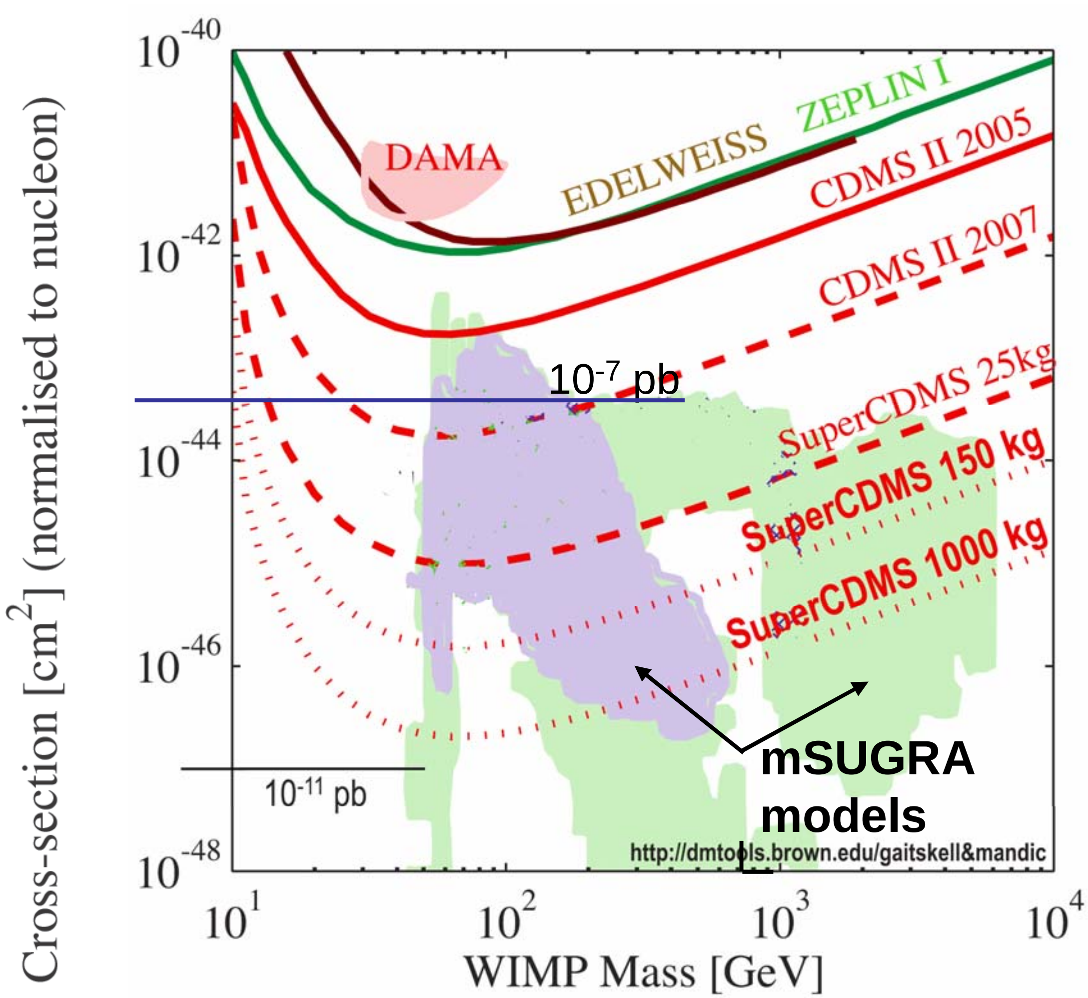




Possible comparison of Si to Ge

Charge/Heat much smaller for nuclear recoils

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)	1.6×10^{-43} cm^2
CDMS II 5-T (2007)	2.1×10^{-44} cm^2
SuperCDMS Detectors 2-ST at Soudan (2009)	7.2×10^{-45} cm^2
SuperCDMS 25 kg 7-ST at SNOLAB (2012)	1.3×10^{-45} cm^2

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

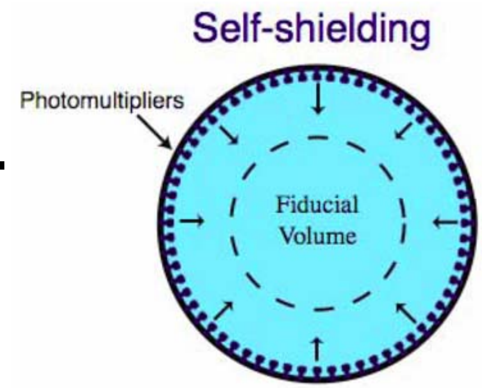
- Relatively inexpensive, easy to obtain, dense target material.
- Easily purified as contaminants freeze out at cryogenic temperatures.
- Very small electron attachment probability.
- Large electron mobility.
- High scintillation efficiency.
- Possibility for large, homogenous detectors.

Single-Phase Techniques

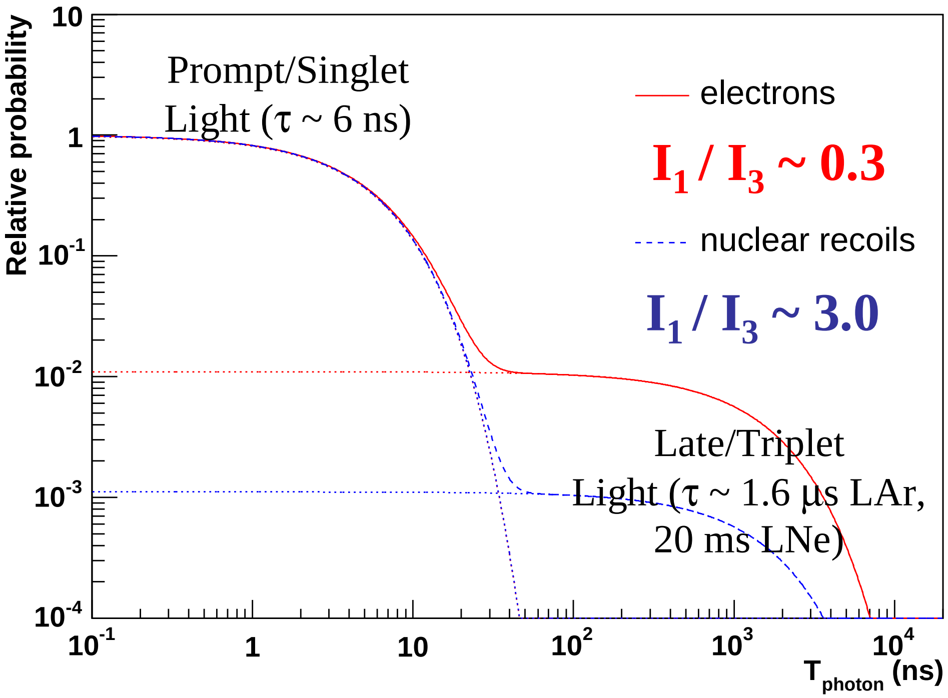
DEAP, Mini-CLEAN, XMASS

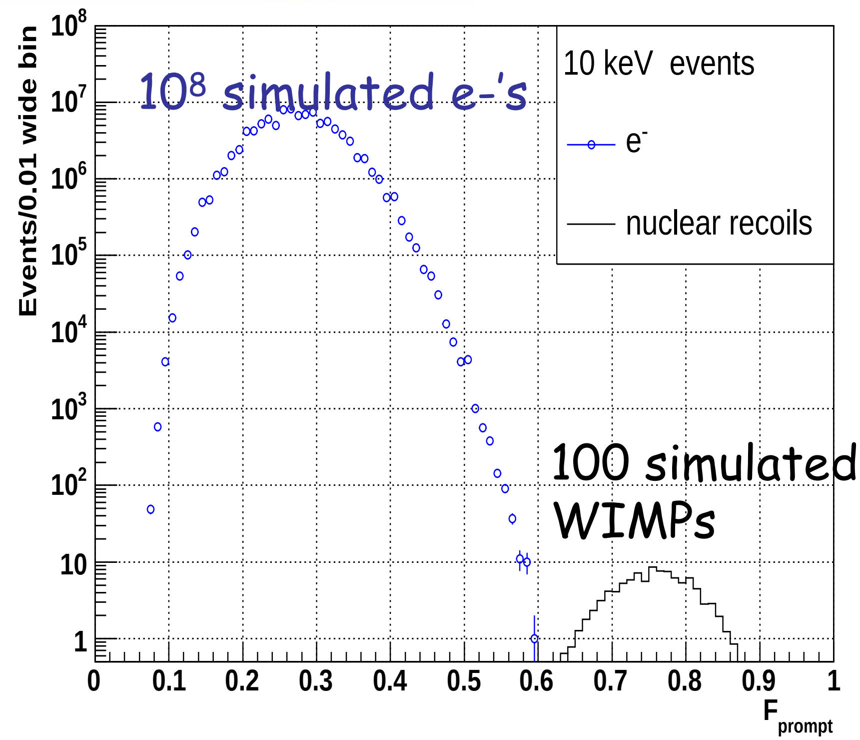
Pulse shape discrimination to discriminate electrons from nuclear recoils.

+



Gets better as size increases.





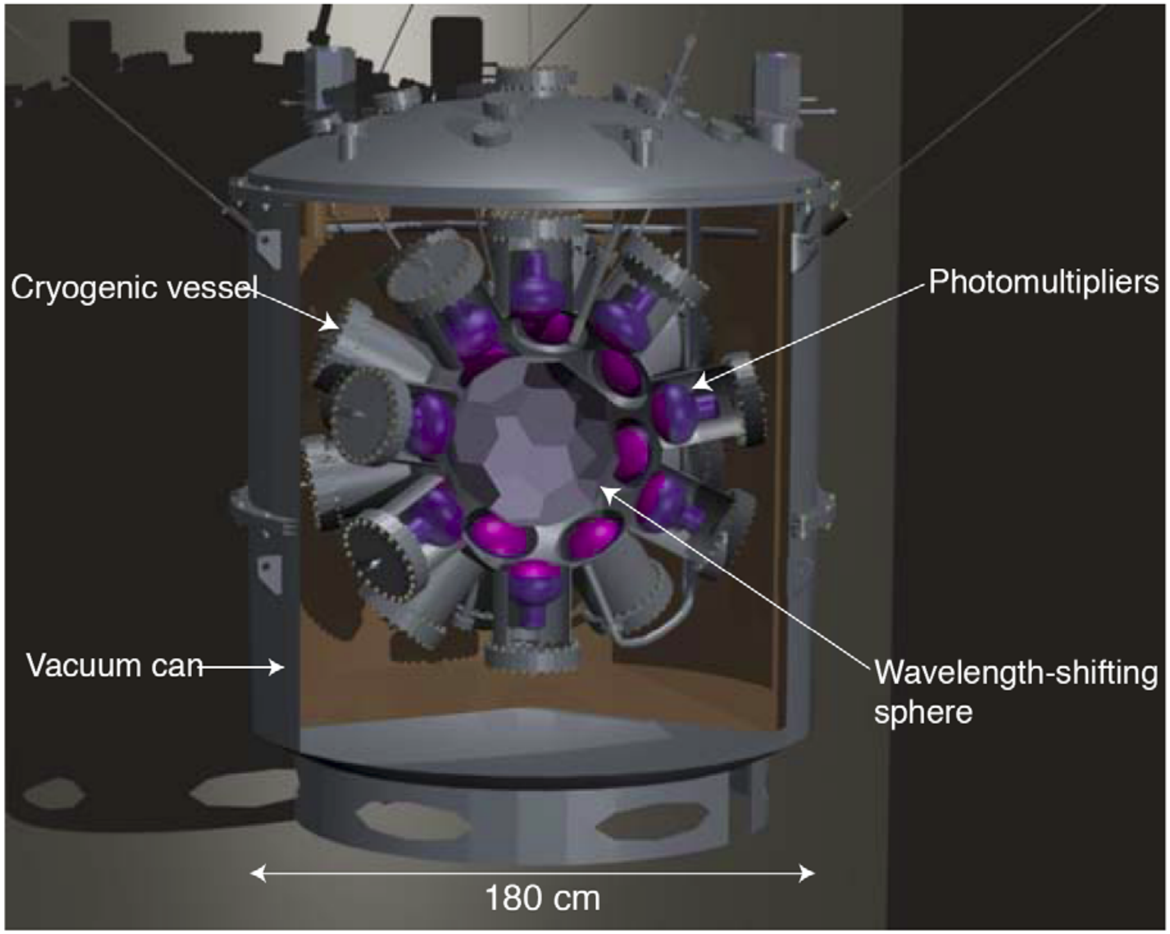
M.G.Boulay and A.Hime, Astroparticle Physics 25, 179 (2006)

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

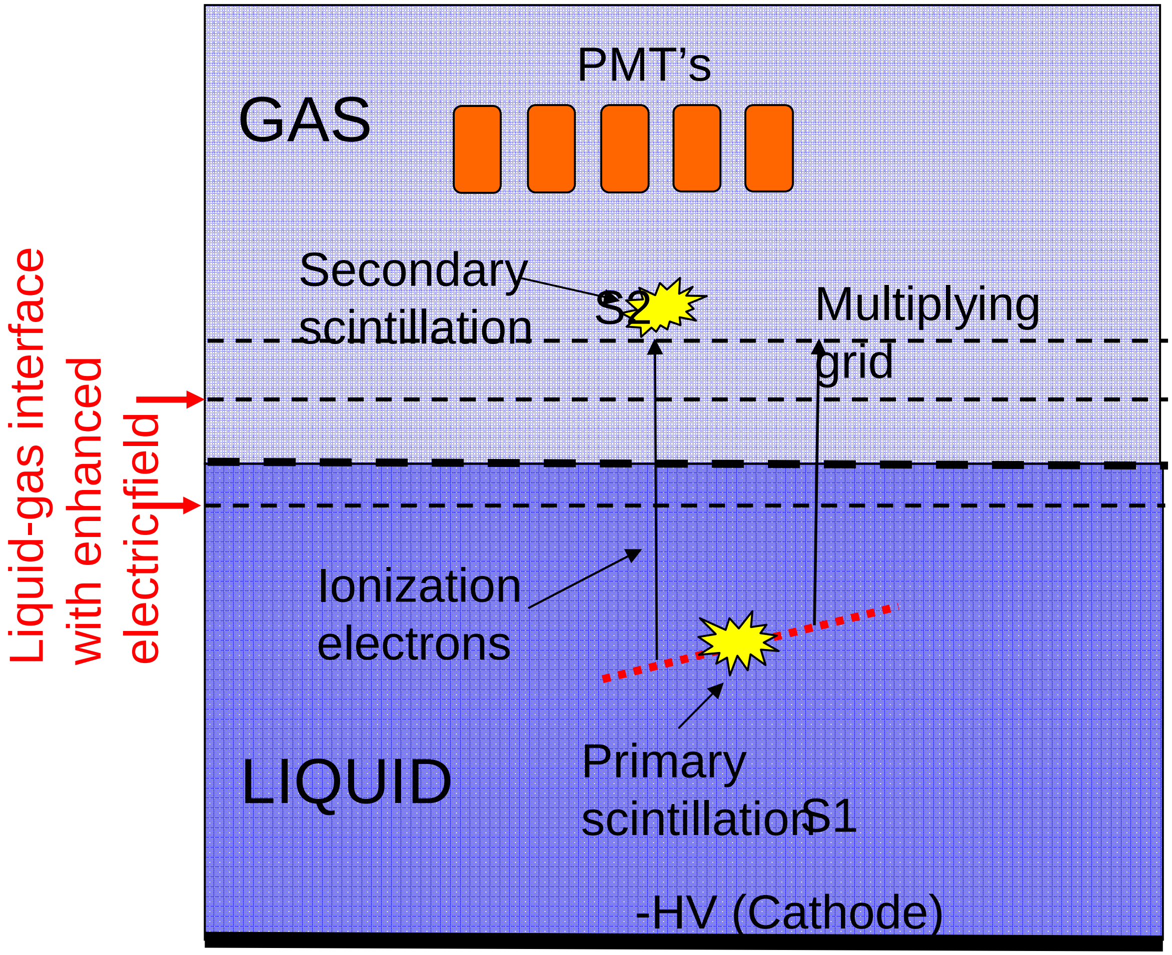


- Micro-CLEAN (4 kg currently operating, R&D on scintillation, test discrimination down to 40 KeV.
- Mini-CLEAN (100 kg detector) 2007-2009
- If low-background achieved, could reach 10^{-45} cm^2 for 100 GeV WIMP.

Schedule under re-evaluation due to recent LANL funding

2-Phase Noble Liquids

WARP, ArDM, XENON, ZEPLIN (Argon, Xenon)



<u>Experimental handles</u>

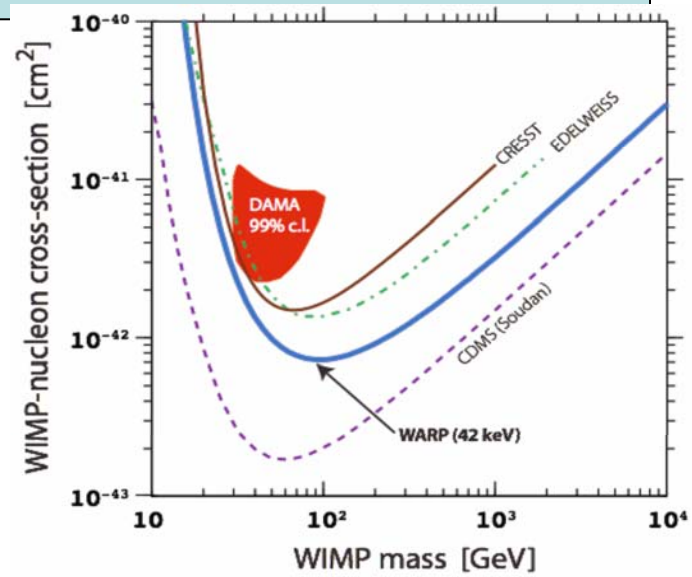
- Primary scintillation intensity
- Primary scintillation pulse shape
- Secondary scintillation intensity
- S2/S1
- Multiple recoils
- Fiducial volume

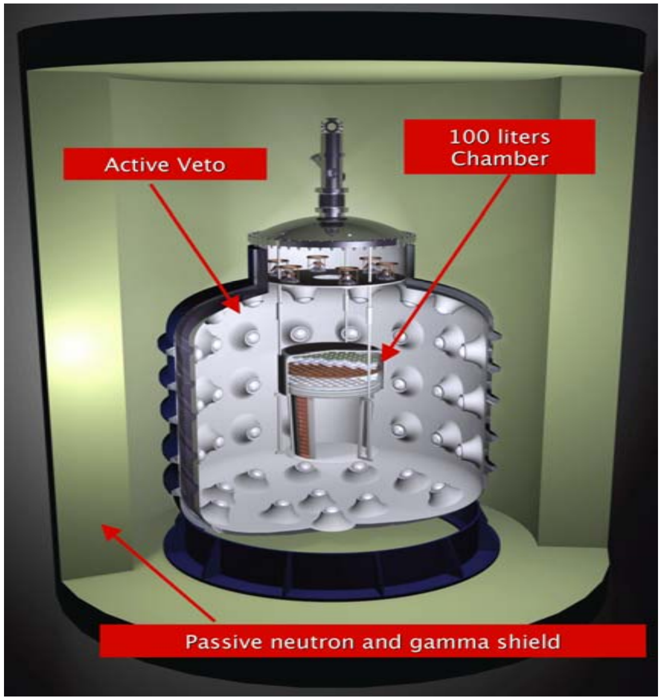
Some handles best in Argon, some best in Xenon

WARP Results and Future

(Italy, U.S., Poland)

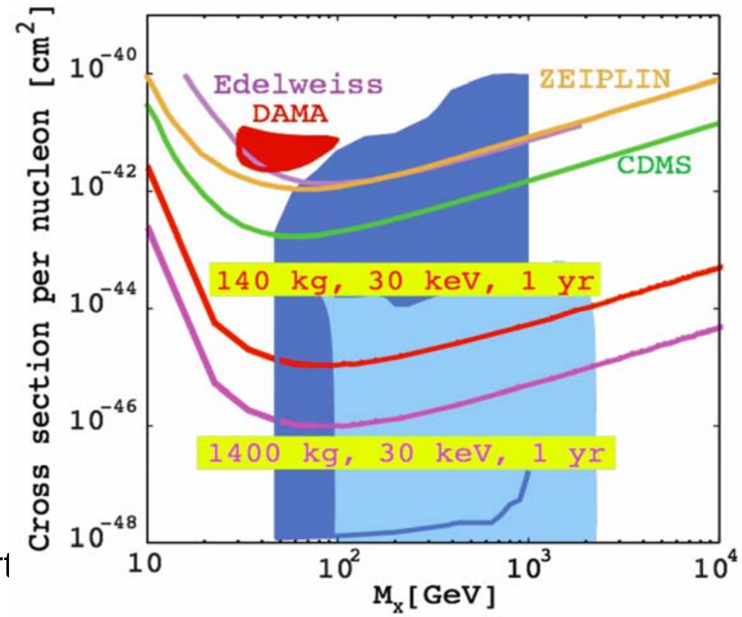
WARP 3.2 kg prototype had 95.4 kg day exposure.





140 kg detector under construction

Projected sensitivity

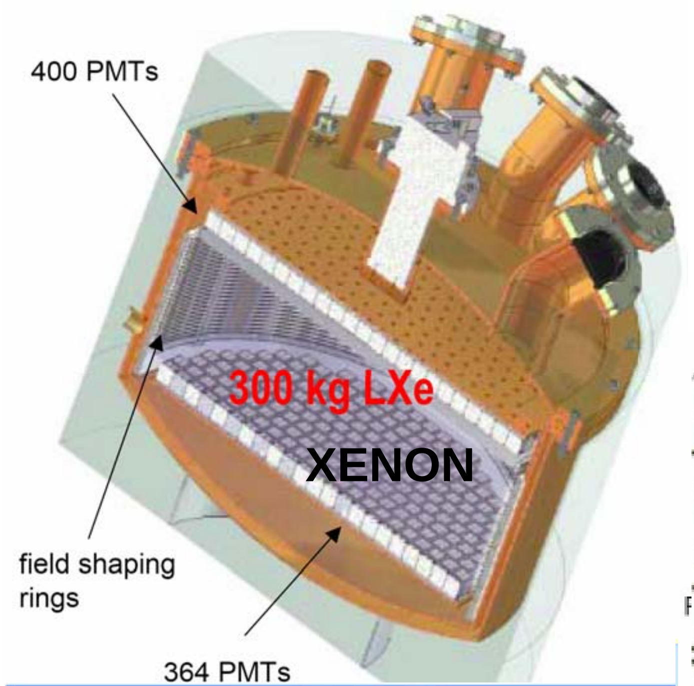


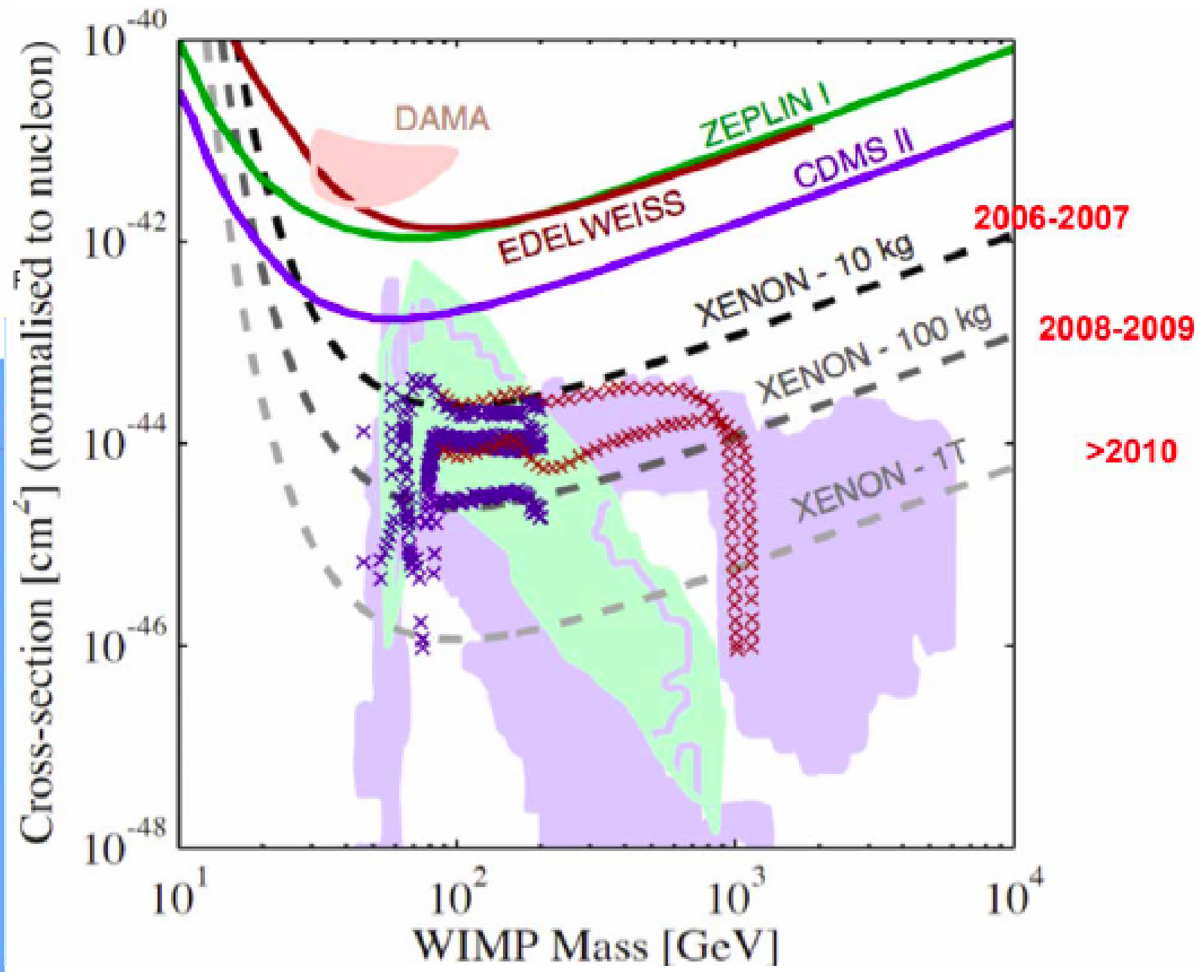
XENON, ZEPLIN Results and Future

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

- Zeplin II
  - Operating with 32 kg total mass of Xe
  - Already collected >1200 kg-days.
  - 6.6×10^{-43} cm^2 (225 kg-days)astro-ph/0701858v2
- XENON10
  - Operating with 15 kg of Xe (10 kg fiducial)
  - Began at Gran Sasso ~March 2006.
  - Similar recent results (Not public)
- Both Zeplin II and XENON10 anticipate they will reach a dark matter constraint ~10^{-44} cm^2.
- Recent proposals for XENON-100, LUX (300kg)

Projected Sensitivity
Preliminary designs of Next generation detectors

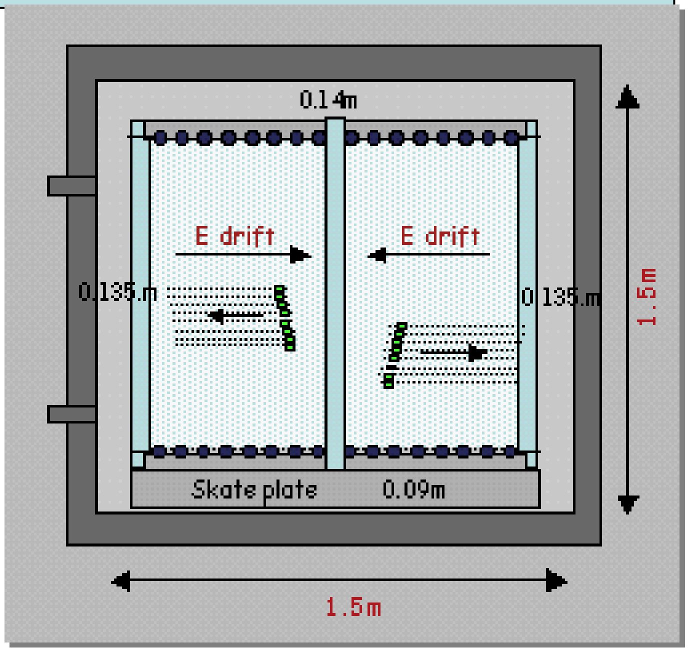




Gaseous Detectors

- **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.)

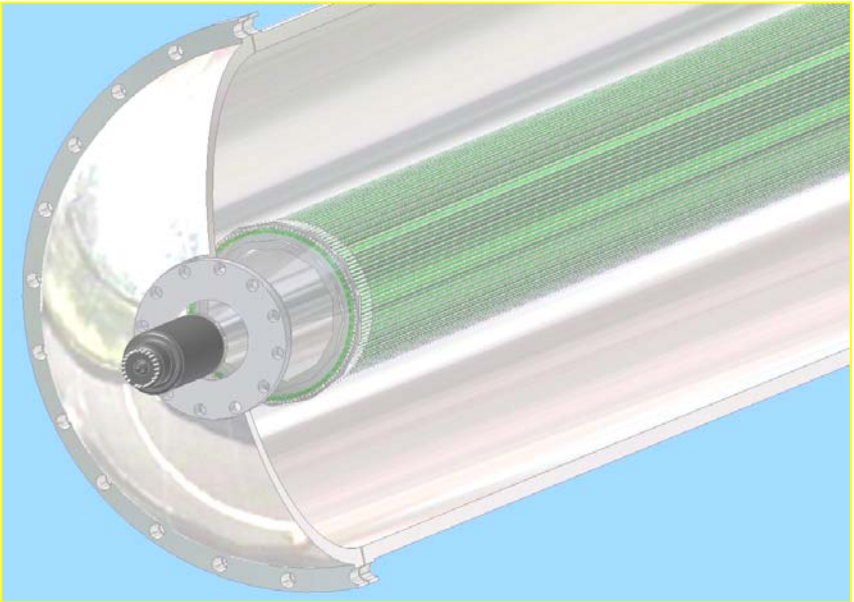


- TPC filled with low-pressure electro-negative gas (CS_2) (electrons captured)
- Recoil tracks are ~few mm long, Ion drift limits diffusion in all 3 dimensions
- End planes allow determination of range, orientation & energy
- Excellent discrimination based on range and ionization-density
- Important R&D efforts by DRIFT groups and others, include improvements in readout sufficient for achieving 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.



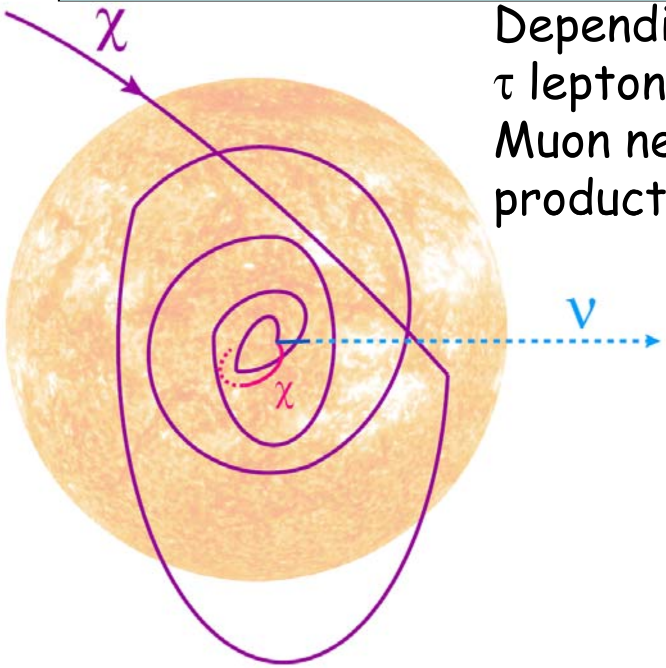
Warm Liquids - COUPP (U.S.)

- **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 γ 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.**

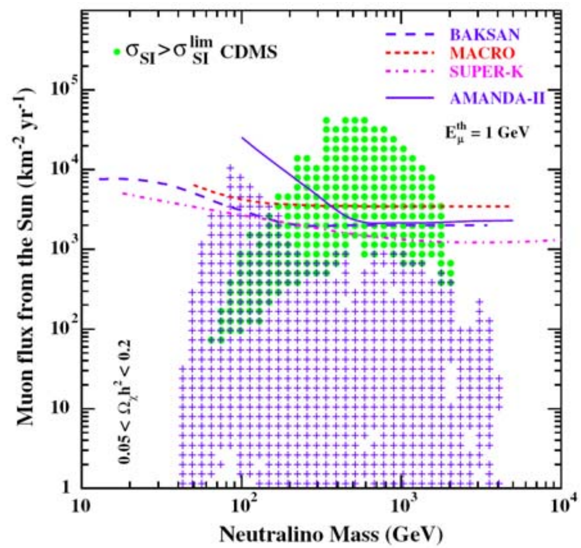
Other Approaches to Dark Matter

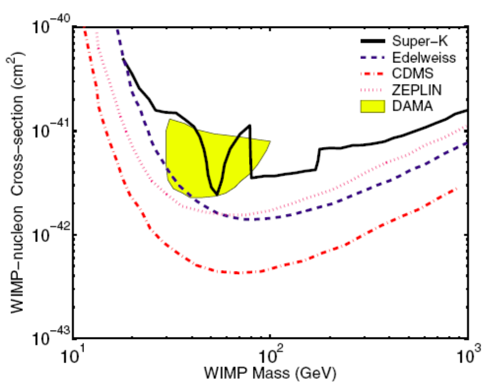
- What guidance and constraints for this program can be gained from other approaches to understanding dark matter?
  - Indirect detection of dark matter in experiments such as GLAST, ICECUBE, PAMELA, HESS, and VERITAS, offer many new dark matter detection possibilities that are complementary to direct detection.
  - If WIMPs are a significant component of dark matter, the properties that make them excellent dark matter candidates also imply that they are very likely to be produced at future colliders.

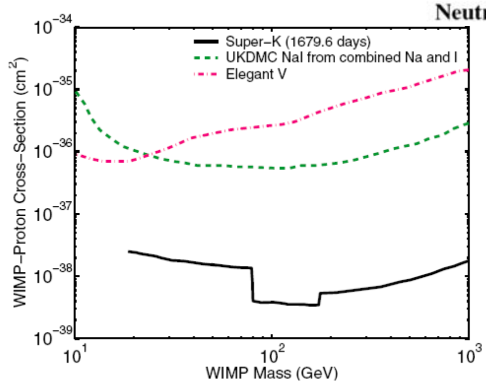
Neutrino Telescopes



Depending on mass and composition, χ annihilate in pairs to τ leptons, b, c ,t quarks, gauge bosons, Higgs.
Muon neutrinos are produced by decay of annihilation products







Limits on WIMP-proton spin dependent cross-section currently ~ 100 times more sensitive than direct detection experiments.

Phys. Rev. D 70 , 083523 (2004)

Spin-independent

Spin-dependent

WIMP Annihilation Signatures in Galaxies

- **WIMP annihilation to quarks and gluons**
  - **Hadronize to mesons and baryons, $\pi^0 \rightarrow \gamma\gamma$**
  - **Continuum signal on continuum background (different shape from C-R p-p)**
  - **Detect by γ-ray telescopes, ground based or space-based (VERITAS, GLAST).**
- **WIMP annihilation directly to $\gamma\gamma$ pairs**
  - **line signal (DM in halo very non-relativistic so $\Delta E\gamma/E\gamma$ ~10^{-3})**
  - **galactic center good place to look – high density**
  - **Uncertainty due to galactic halo modeling**
- **WIMP annihilation to particle-antiparticle pairs**
  - **e^+, anti-protons (Pamela, AMS)**
  - **Anti-deuterons (GAPs expt.)**
- **Galactic center observed to be strong source of γ-rays in 0.1-10TeV region…astrophysical sources or dark matter signal?**
  - **awaits resolution**

WIMPs at Colliders

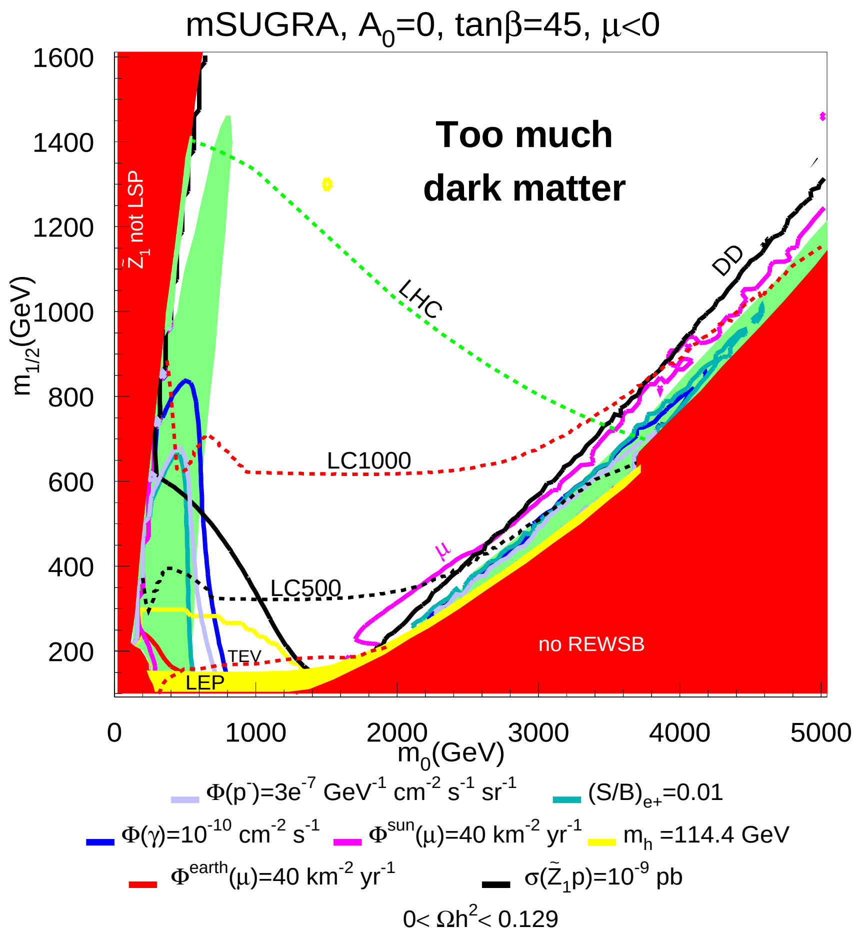
- **WIMPs couple by weak nuclear interactions to ordinary matter.**
  - **Possible to produce dark matter particles either directly or via decays of other new matter states.**
  - **Signal is events with visible particles but with missing energy-momentum – carried off by DM particles.**
  - **Studied extensively in context of SUSY.**

SUSY at Colliders

- By picking a SUSY model plus input parameters,
  - can calculate sparticle mass spectrum, mixings, production cross-sections and decay rates.
- If these are observed at LHC, then by fitting all observables one can measure important astrophysical quantities
  - Dark matter relic density
  - Neutralino annihilation cross-section times velocity
  - Neutralino-proton spin-independent scattering rate

Complementarity

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



Excluded by LEP, LEP2

no appropriate EWSB, neutralino not LSP

WMAP allowed

Neutrino telescopes sensitivity

GLAST Gammas

Direct detection 10^{-9} pb

Note regions where:

•Indirect more sensitive than direct

•Direct more sensitive than LHC

Recommendation 1: Program and Funding

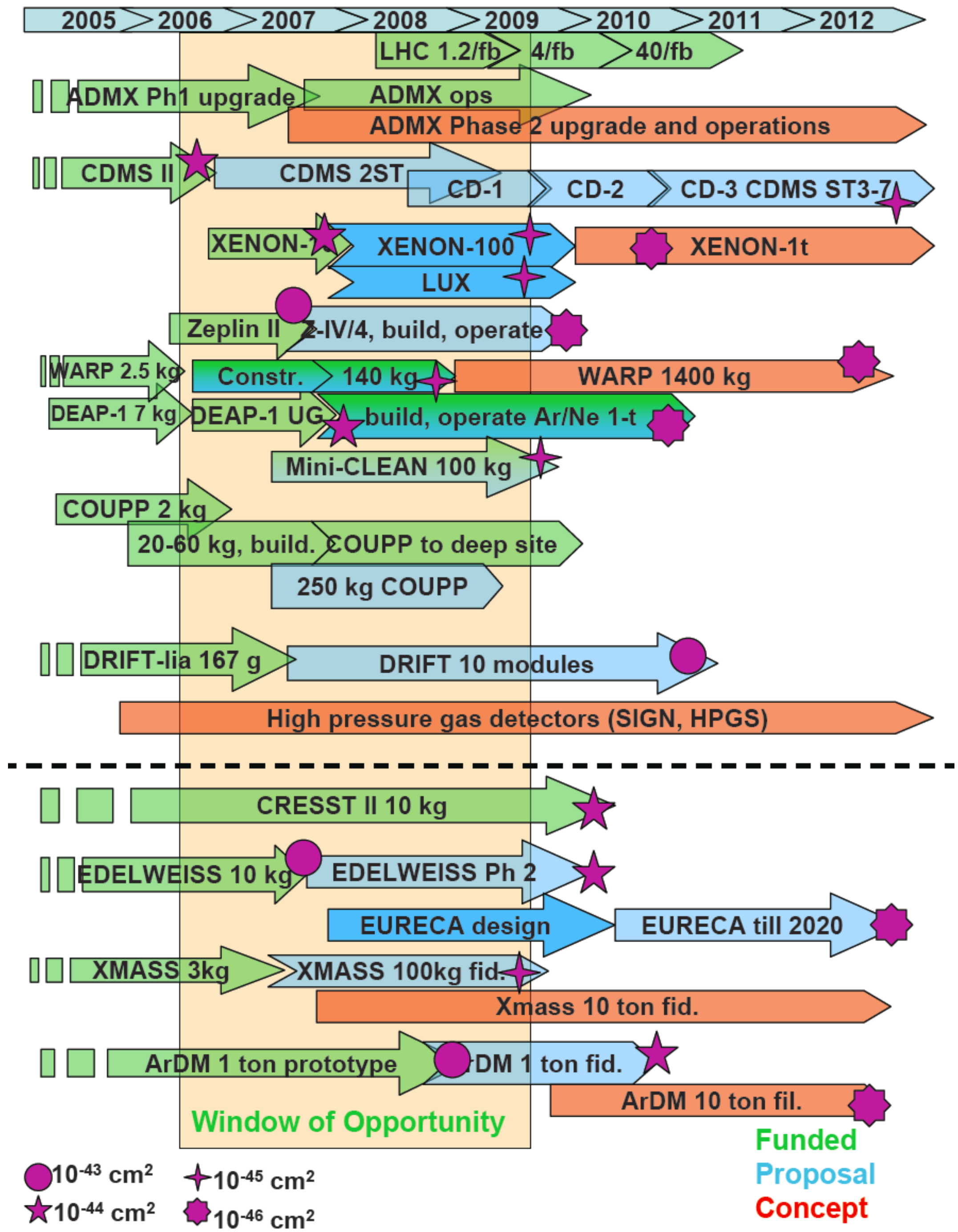
We recommend that the U.S. advance the search for dark matter using a variety of physical and technical approaches. U.S.-led experiments currently lead the world in sensitivity of the direct detection searches for both WIMPs and axions. We recommend that this leadership be preserved. This requires, in addition to supporting the running and improvement of existing detectors, that the R&D for the next stage of technology development be strongly supported with a goal of steady progress towards ton-scale and larger detectors.

To realize this program on an optimal time scale, the committee recommends that DOE and NSF increase funding for the direct detection of dark matter from the present ~$2-3M to ~$10M annually. The prospect of detecting dark matter while the LHC is operating amply justifies this increase. Such a figure is also consistent with the recommendations of P5 and EPP2010.

Estimated Timescale for Detector Development and Results

The status and timescales projected by the various experimental groups for most of the existing and proposed experimental programs. The programs above the dashed line have significant U.S. group participation, while those below the line currently have none.

The figure shows that the next few years will be a time of great opportunity as new and relatively inexpensive techniques are rapidly developed.



Recommendation: CDMS

The sub-panel recommends the completion and operation of CDMS-II and the funding of two SuperCDMS supertowers at the Soudan site. If dark matter funding is increased to the range of that suggested in Recommendation 1, we support the design and construction of the necessary refrigeration system for SuperCDMS at SNOLAB. If not, and funding is not sufficient for the rest of the program we have outlined, we recommend that the decision to go forward with SuperCDMS in SNOLAB be contingent upon a full evaluation of the field to be completed by mid-2009.

Recommendation: ADMX

The committee recommends that the ADMX collaboration be supported to operate the existing detector and, pending success of phase I, to take the necessary steps to reach greater sensitivity through lower system temperature.

Recommendation: Noble Liquid Detectors

We recommend that the R&D required for the next stage of technology development for noble liquid detectors be strongly supported. In some cases, this means that demonstration projects need to be completed, while in others it means that the next-scale detector should be constructed. For the short-term program, the emphasis should be on developing detectors using larger target masses with decreased backgrounds to reach ever-greater sensitivity.

To capitalize on recent impressive results, the sub-panel recommends that a significant fraction of the total funding resources be devoted to noble liquid target experiments, successors of the present WARP, XENON10, and ZEPLIN-II prototypes. However, given the tight funding situation and the large range of new and promising ideas, the sub-panel also believes that it cannot support duplicate development programs in the U.S. using the same target and technique. Therefore:

- **The sub-panel supports the development of one two-phase xenon-based detector at the 100 kg scale and above.**
- **The sub-panel supports the development of detectors using liquid argon and/or liquid neon technology. WARP and miniCLEAN/DEAP represent two quite different technologies in their application to liquid argon. Both of these techniques should be explored to discover which has greater potential.**

Recommendation: Superheated liquids and Directional sensitivity

In addition to the above main lines of development,

- **The sub-panel recommends the development of superheated liquid detectors. The program proposed by COUPP appears to be well balanced and has recently been approved by the Fermilab PAC.**
- **On the basis of the performance and background levels presented by the DRIFT collaboration, the sub-panel recommends the development of a single prototype detector module with the principal goal of demonstrating track reconstruction and directionality determination.**

Recommendation: DUSEL

We support the construction of a U.S. Deep Underground Science and Engineering Laboratory (DUSEL), which could host ton-size or greater direct dark matter detection experiments.

Recommendation: Scanning Facilities

We recommend additional underground scanning capability to alleviate the perceived current shortage, increase the sensitivity, and expedite the scanning of materials for the new generations of detectors. Ideally, a comprehensive facility, as described in the DUSEL S1 report, should be located in the DUSEL site.

Recommendation: Priorities (Further Discussion Planned)

Following on the above recommendations, if the comprehensive program we have described is not able to be fully funded, then we recommend that the funding priorities during the next few years be aimed equally towards:

- **continuing the on-going CDMS and ADMX experiments as indicated above and**
- **funding the expansion of the noble liquid experimental efforts to their next level.**

During the same time period, the development of superheated liquid detectors and detectors capable of determining WIMP direction should be supported with a lower priority since, although they have great promise, they still have significant R&D questions remaining to be answered.

We believe that many of the questions associated with the longer-term direction of the experimental efforts will be resolved during the next few years and that a program review in or around 2009 will be necessary.

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 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 confluence of cosmological observations, theoretical advances, and technological progress provides a timely opportunity to identify dark matter, with implications for some of the most important questions in science, such as how galaxies formed and what forces determine the behavior of fundamental particles.