The Direct Detection of Dark Matter

Prospects and Techniques

Neutrino Helicity at 50

A Celebration of the Goldhaber-Grodzins-Sunyar Experiment

Hank Sobel

Brookhaven, May 2, 2008

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

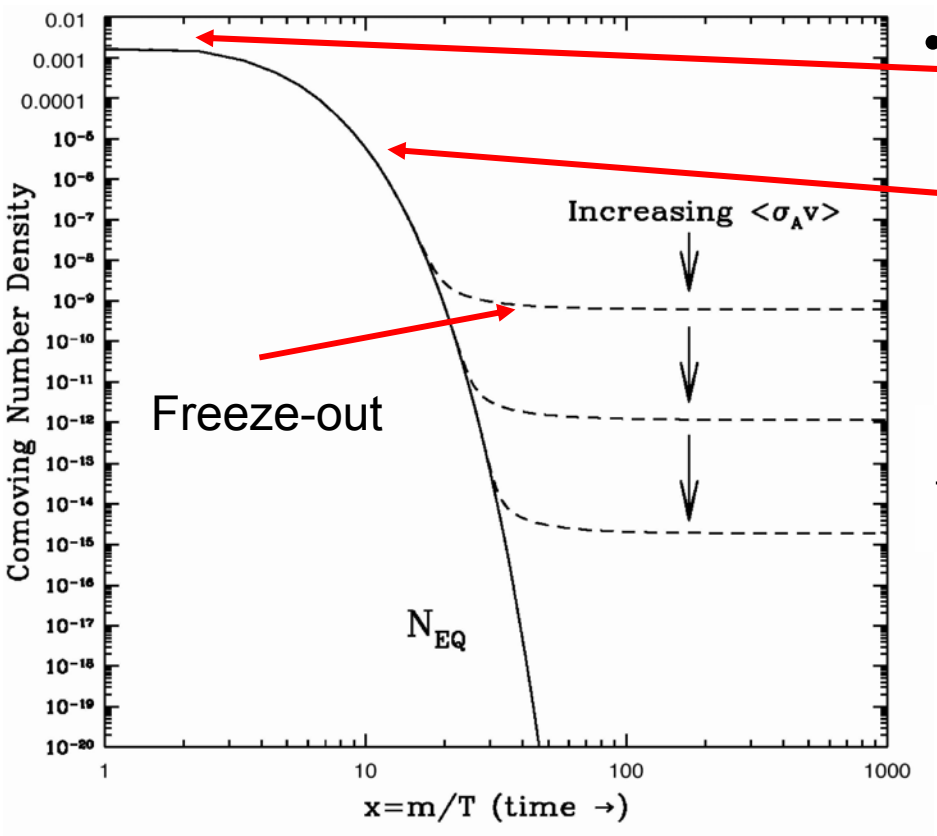
- stable (protected by a conserved quantum number)
- no charge, no color (weakly interacting)
- cold, non-dissipative
- relic abundance compatible to observation
- motivated by theory (vs. “ad hoc”)

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

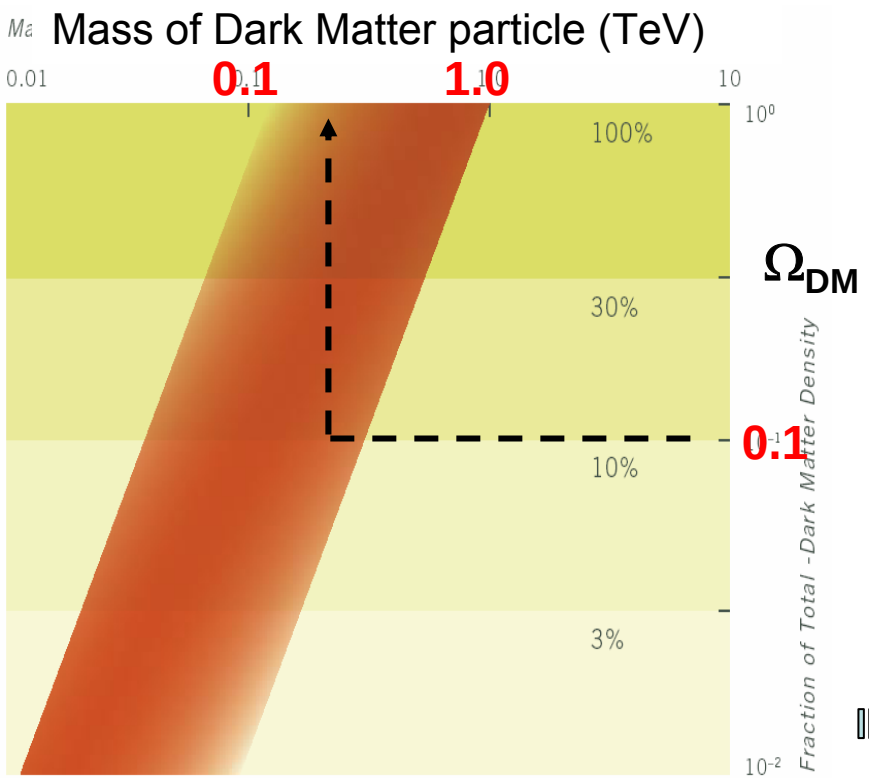
Change due to annihilation and creation

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"

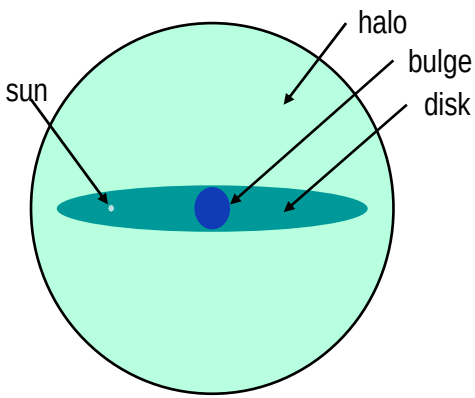
Cosmology alone tells us we should explore the weak scale.

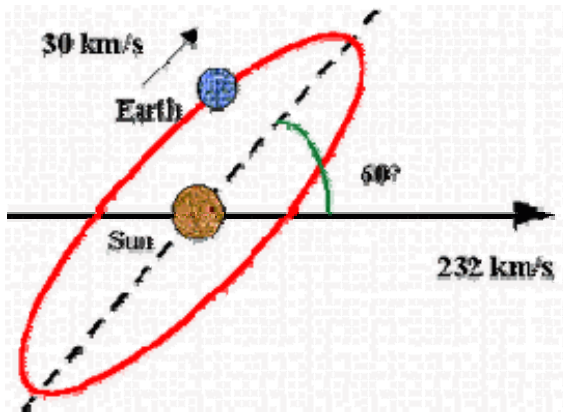
WIMPs

- 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. Large uncertainty
Elastic nuclear scattering: interactions are either spin-dependent or spin-independent.
For SI, Low velocity →coherent interaction ~ A^2

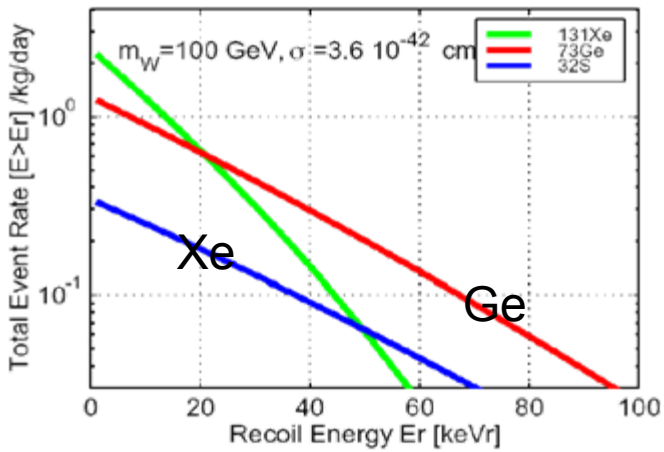
Experimental Challenges

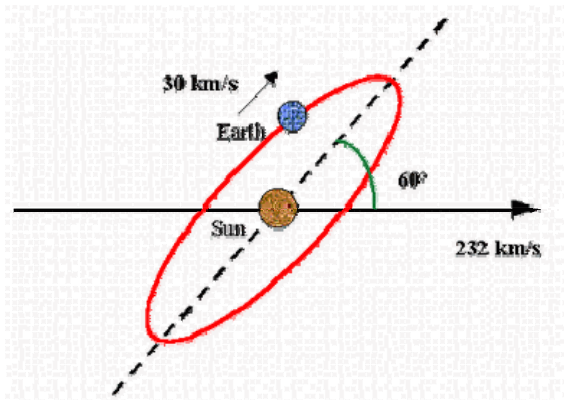
The WIMP "signal" is a low energy (~10-100 keV) nuclear recoil.

- Overall expected rate is very small
  - (limit now $\sigma < 10^{-43} cm^2$ gives about 0.1 event/kg/day , 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

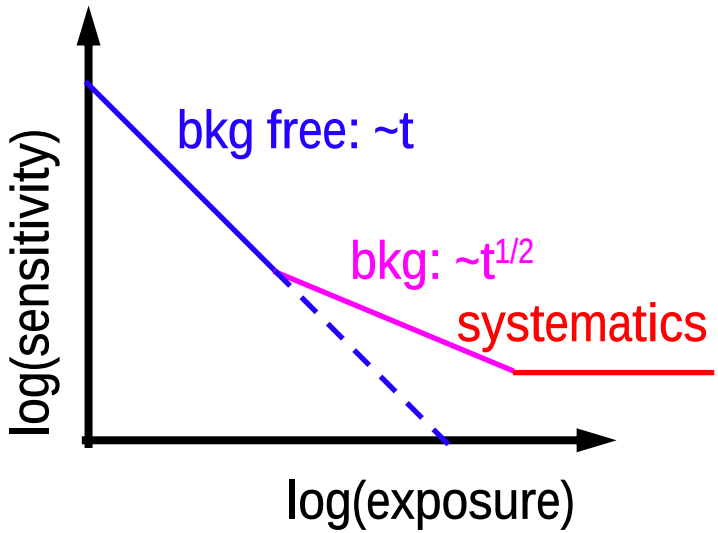
- Nuclear vs electronic recoil
  - **(discrimination required)**
- No multiple interactions
- Recoil energy spectrum shape
  - **(exponential, rather similar to background…)**
- Consistency between targets of different nuclei
  - **(essential once first signal is clearly identified)**
- Annual flux modulation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





Minimizing backgrounds

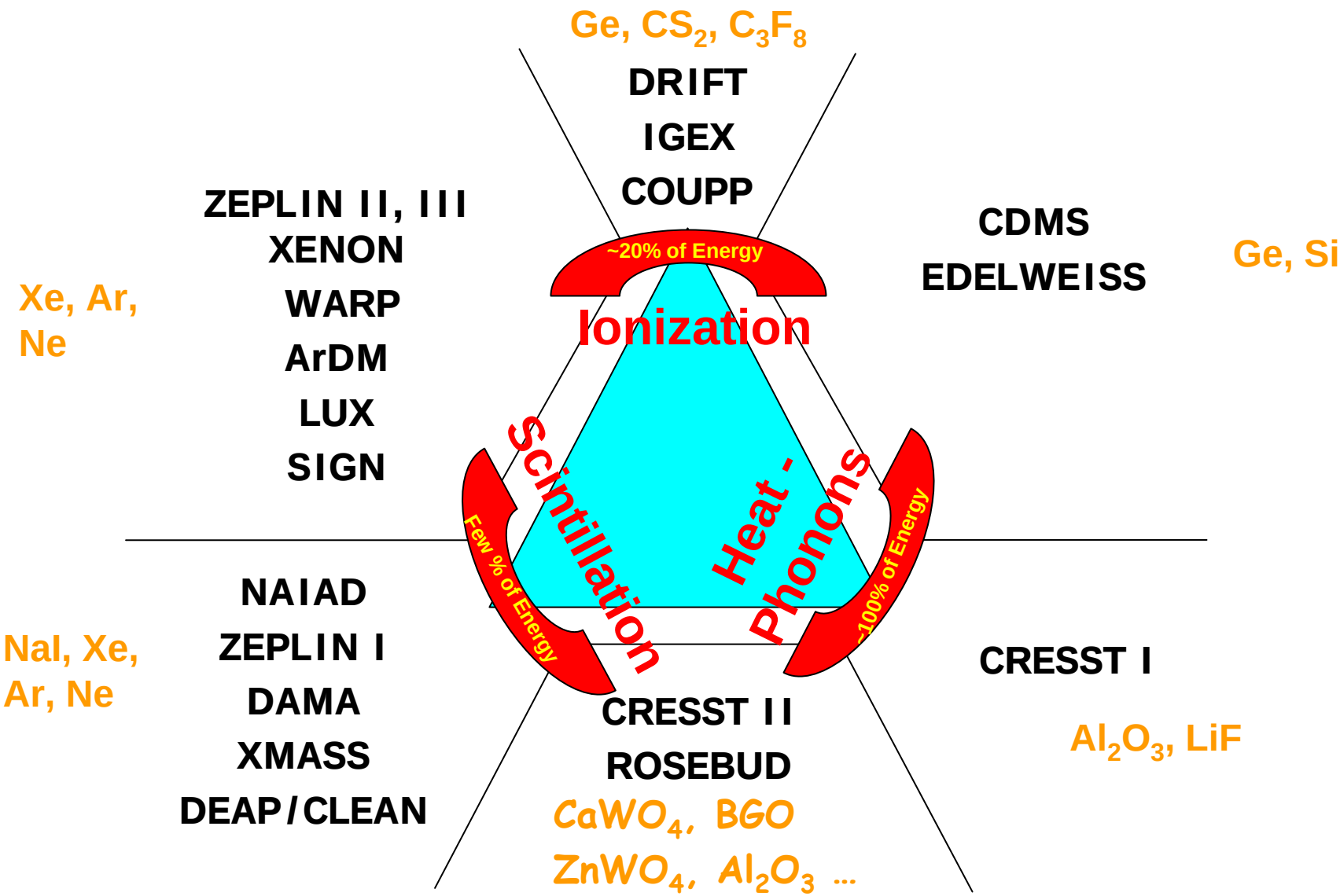
- **Critical aspect of any rare event search**
- Purity of materials
  - Copper, germanium, xenon, neon among the cleanest with no naturally occurring long-lived isotopes
  - Ancient Lead, if free of Pb-210 ($T_{1/2}$ = 22 years)
- Shielding
  - External U/Th/K backgrounds
- Radon mitigation
- Material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



Current State of Experiments

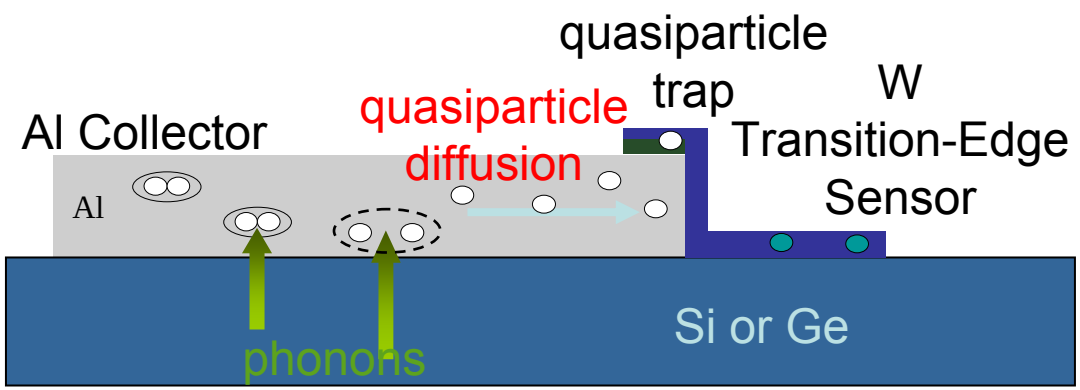
- Rapid advances in detector technology have reached interesting sensitivity limits and should be able to go further.
- Broad spectrum of technologies.
- New ideas, and new collaborations are appearing…

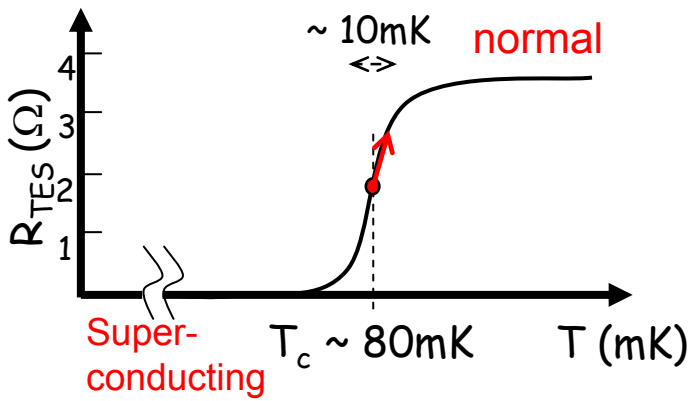
Direct Detection Techniques



CDMS

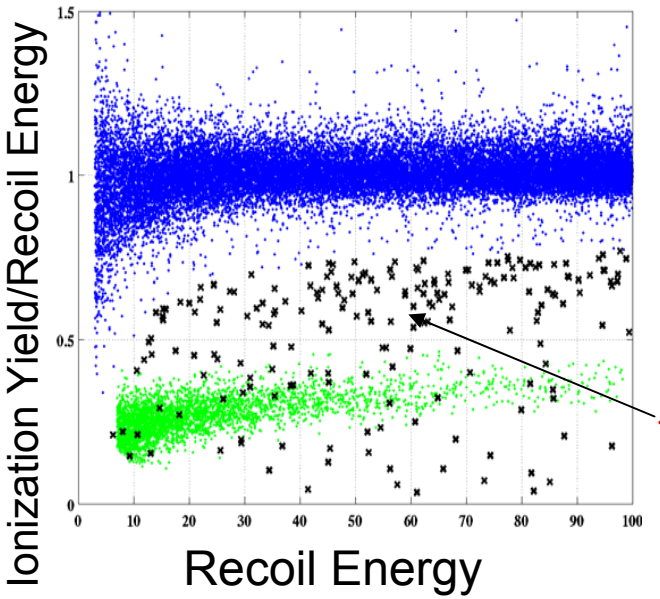
- The Cryogenic Dark Matter Search (CDMS) Collaboration, currently operating in the Soudan mine in Minnesota has pioneered the use of low temperature phonon-mediated Ge or Si crystals.



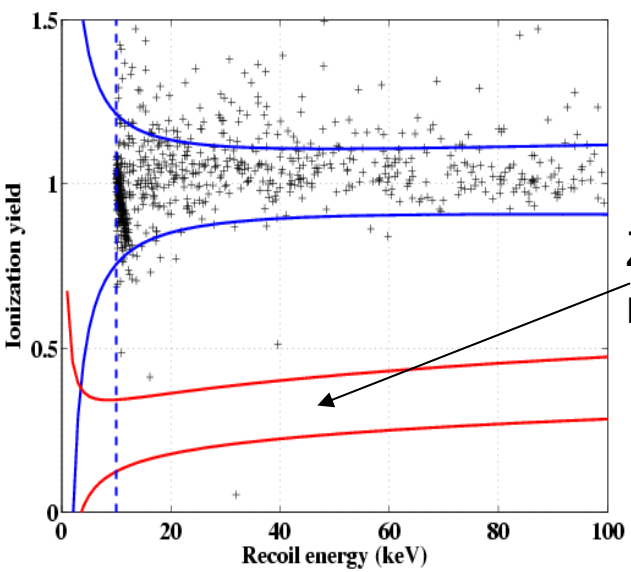


- Nucleus is hit, it recoils, causing the whole germanium crystal to vibrate.
- Vibrations (phonons) propagate to surface of crystal. They excite quasi-particle states, which propagate to the tungsten and heat it up.
- Temperature of the tungsten rises, and therefore so does the resistance of the circuit.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

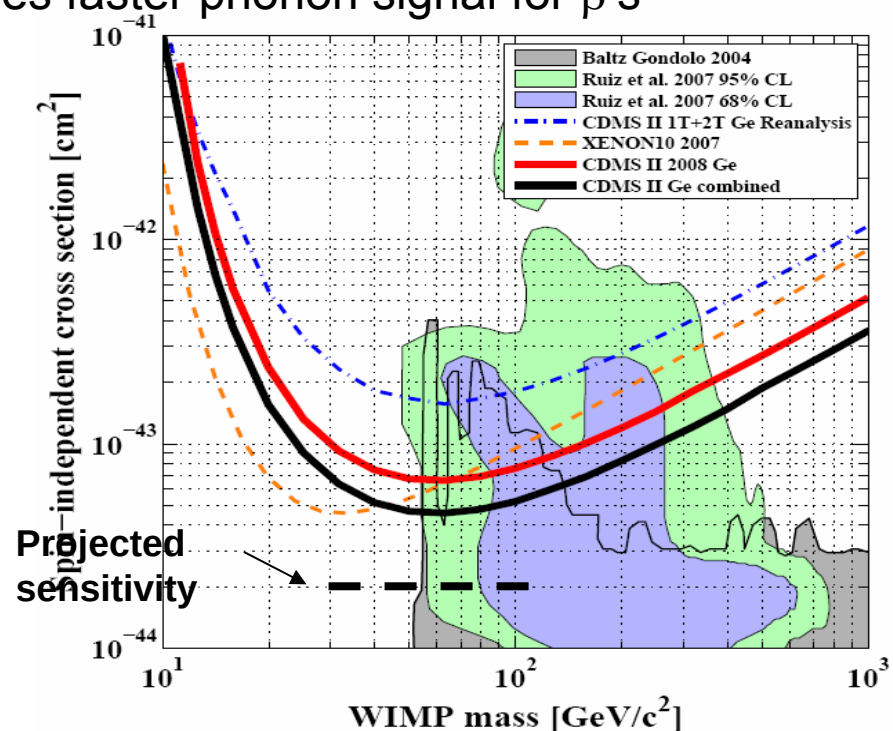
CDMS II Active Background Rejection



- Radioactive source data defines the signal (NR – neutrons from ^{252}Cf) and background (ER – gammas from ^{133}Ba) regions.
- Ionization Yield (Charge/Heat)>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



Zero background maintained



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

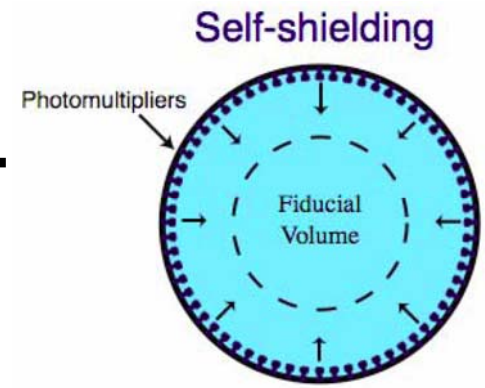
- Relatively inexpensive, easy to obtain, dense target material.
- Easily purified as contaminants freeze out at cryogenic temperatures.
- Very small electron attachment probability.
- Large electron mobility (Large drift velocity for small E-field).
- High scintillation efficiency
- Possibility for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

Single-Phase Techniques

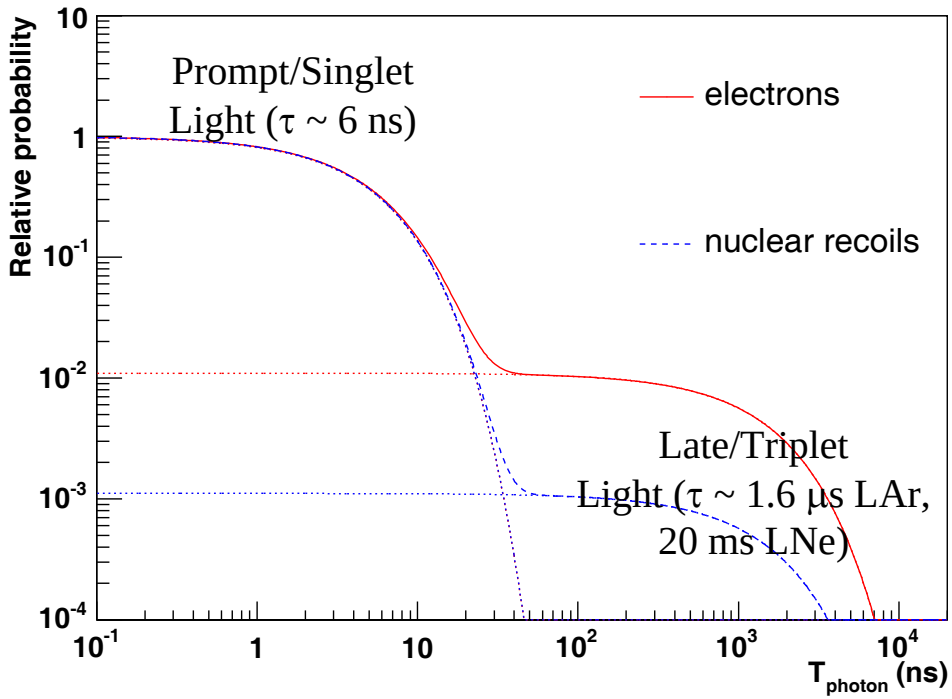
CLEAN, XMASS

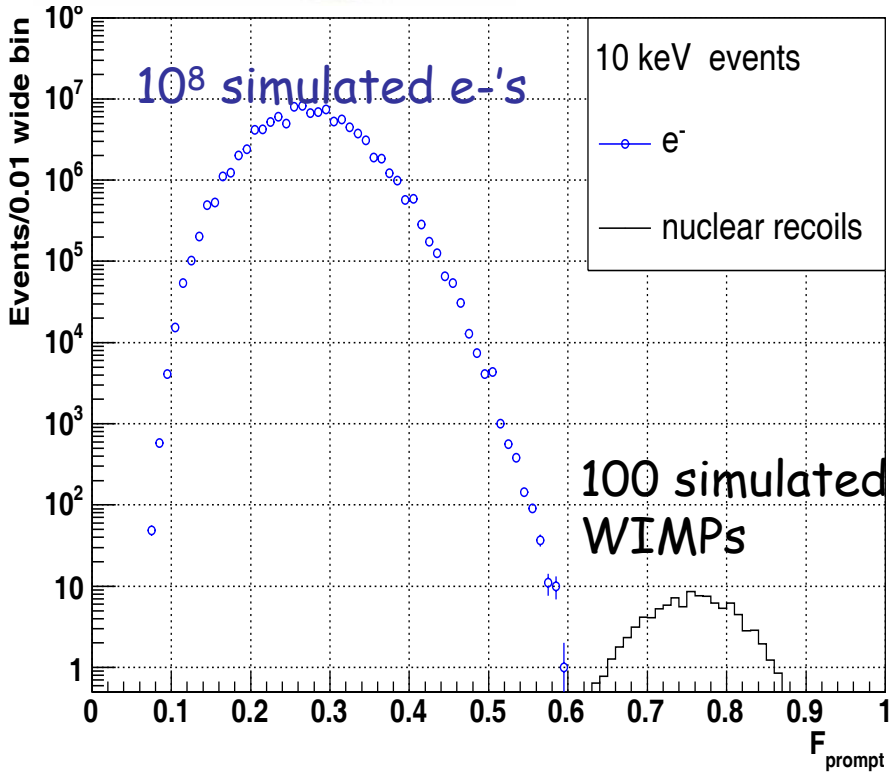
- Pulse shape discrimination to discriminate electrons from nuclear recoils.
  - <u>Argon and Neon especially good</u>

+



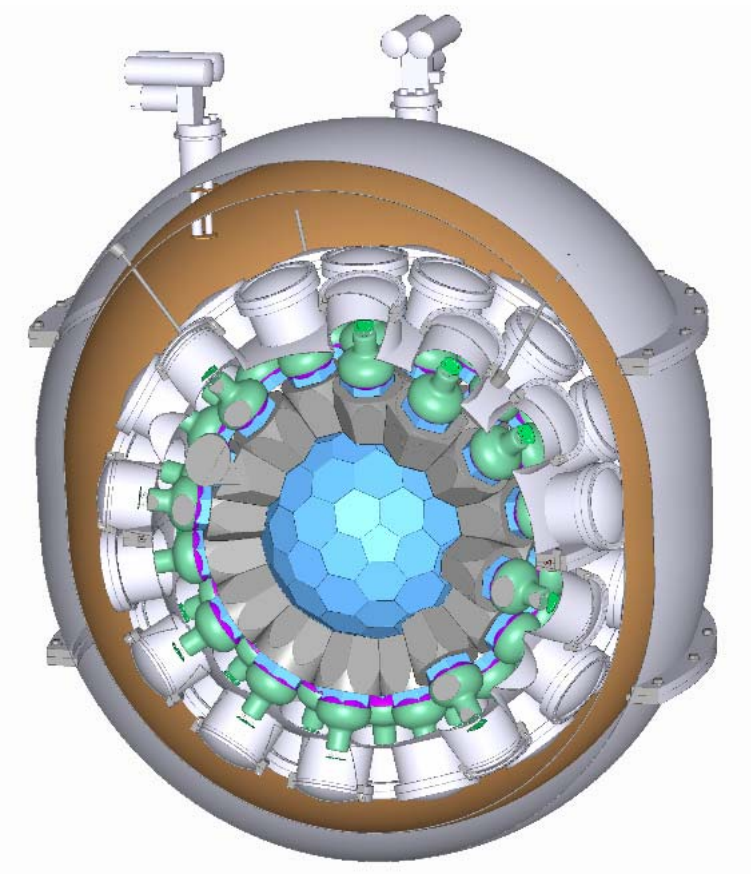
Gets better as size increases.





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

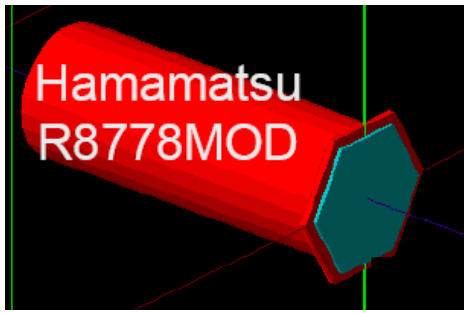
360 kg Mini-CLEAN Liquid Argon/Neon



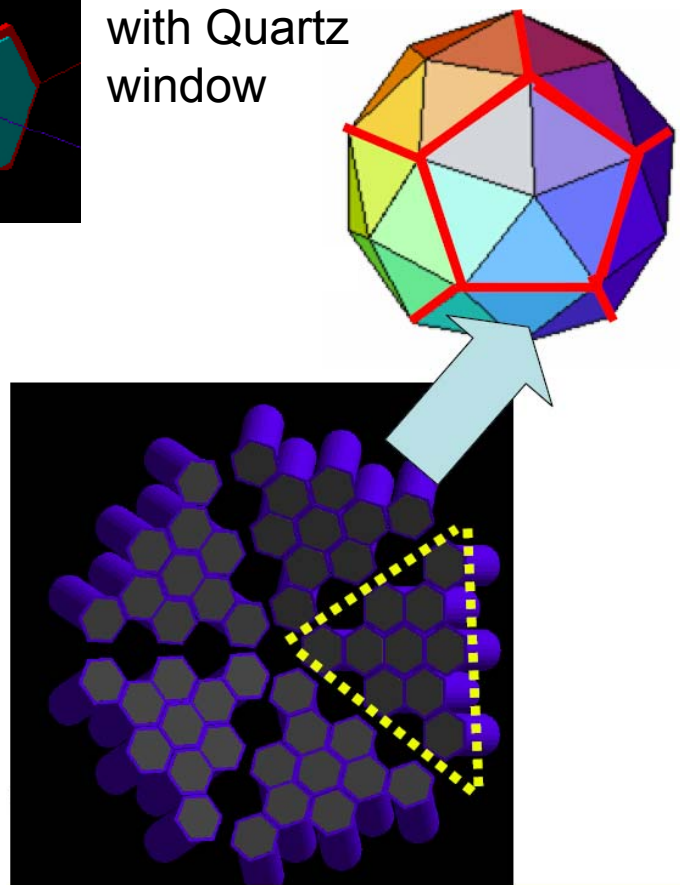
- Spherical vessel filled with purified LNe or LAr.
- R&D with micro-CLEAN and DEAP-1 measuring salient properties of LAr & LNe
- Engineering design and construction plan for Mini-CLEAN (360 kg) under completion.
- Engineering design underway for DEAP/CLEAN (3600 kg)

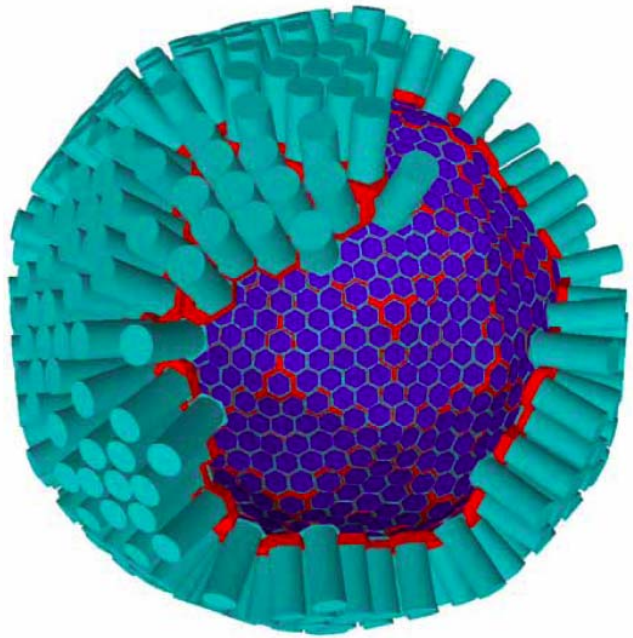
Installation planned in SNOLAB

800 kg XMASS Liquid Xenon



Hexagonal tube with Quartz window



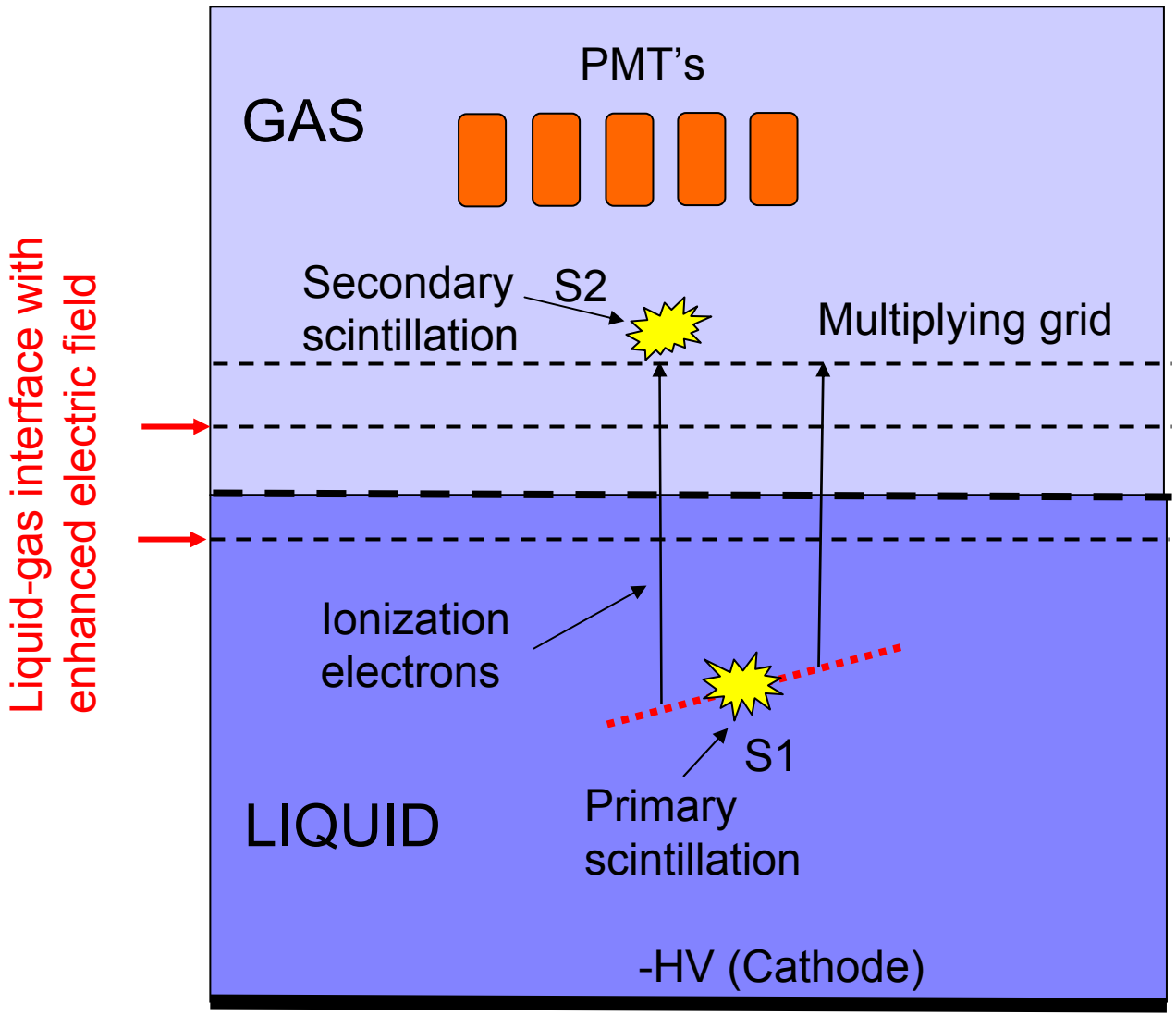


- R&D with 100kg detector successful
- Very low background PMT's inside LXe
- Purification of Xe, => ^{85}Kr reduced
- Installation in Kamioka this Spring

2-Phase Noble Liquids

WARP, ArDM, XENON, ZEPLIN, LUX

(Argon, Xenon)



<u>Experimental handles</u>

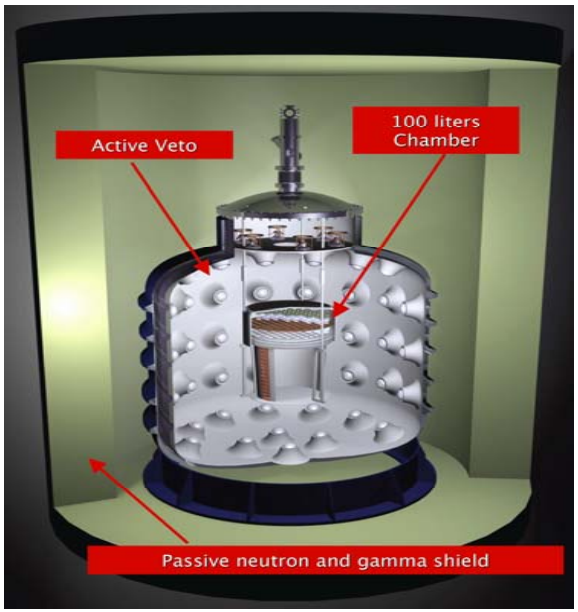
- Primary scintillation intensity
- Primary scintillation pulse shape
- Secondary scintillation intensity
- S2/S1
- Multiple recoils
- Fiducial volume

Some best in Argon, some best in Xenon

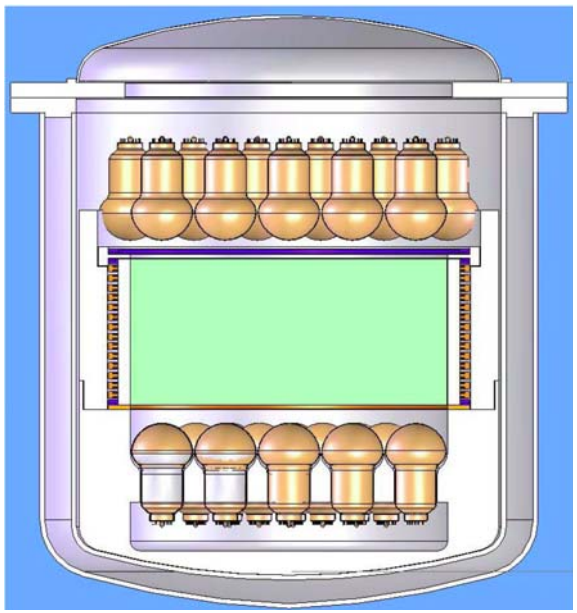
Current Detectors Under Construction

~100 kg Fiducial Size

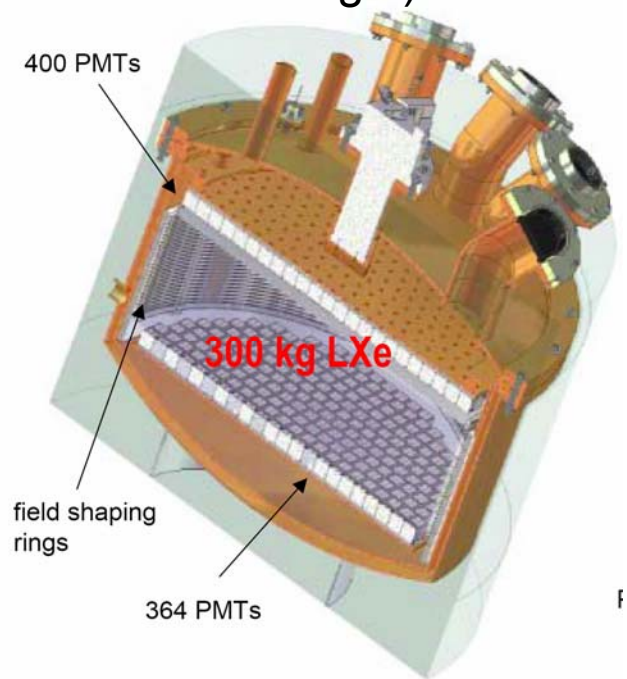
WARP (Italy, U.S., Poland) LAr



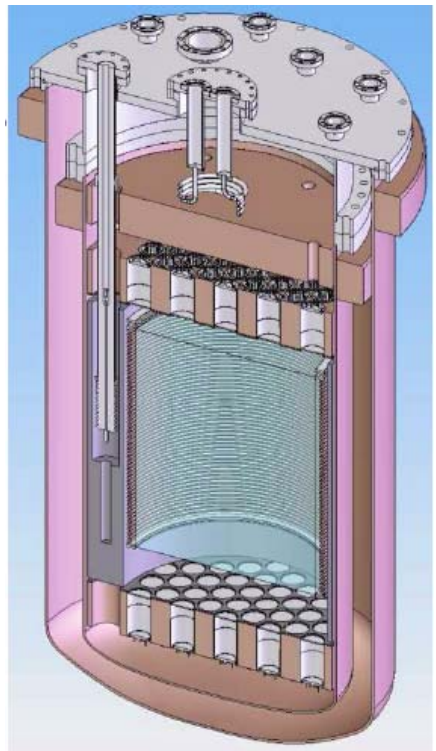
ZEPLIN (UK, U.S.) LXe



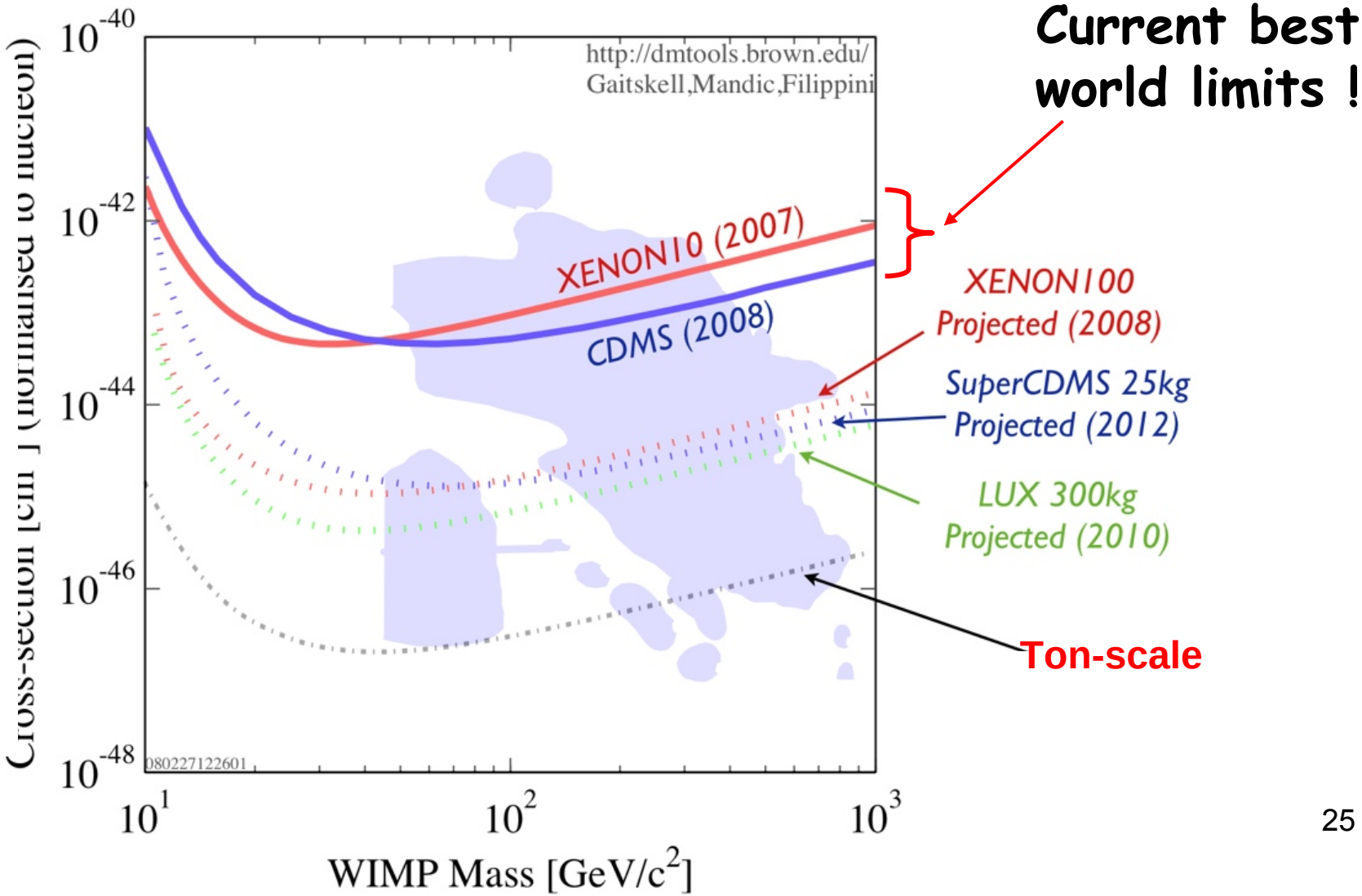
XENON-100 (U.S., Germany, Italy, Portugal) LXe



LUX (U.S.) LXe



Dark Matter Sensitivity Reach: 2008-12

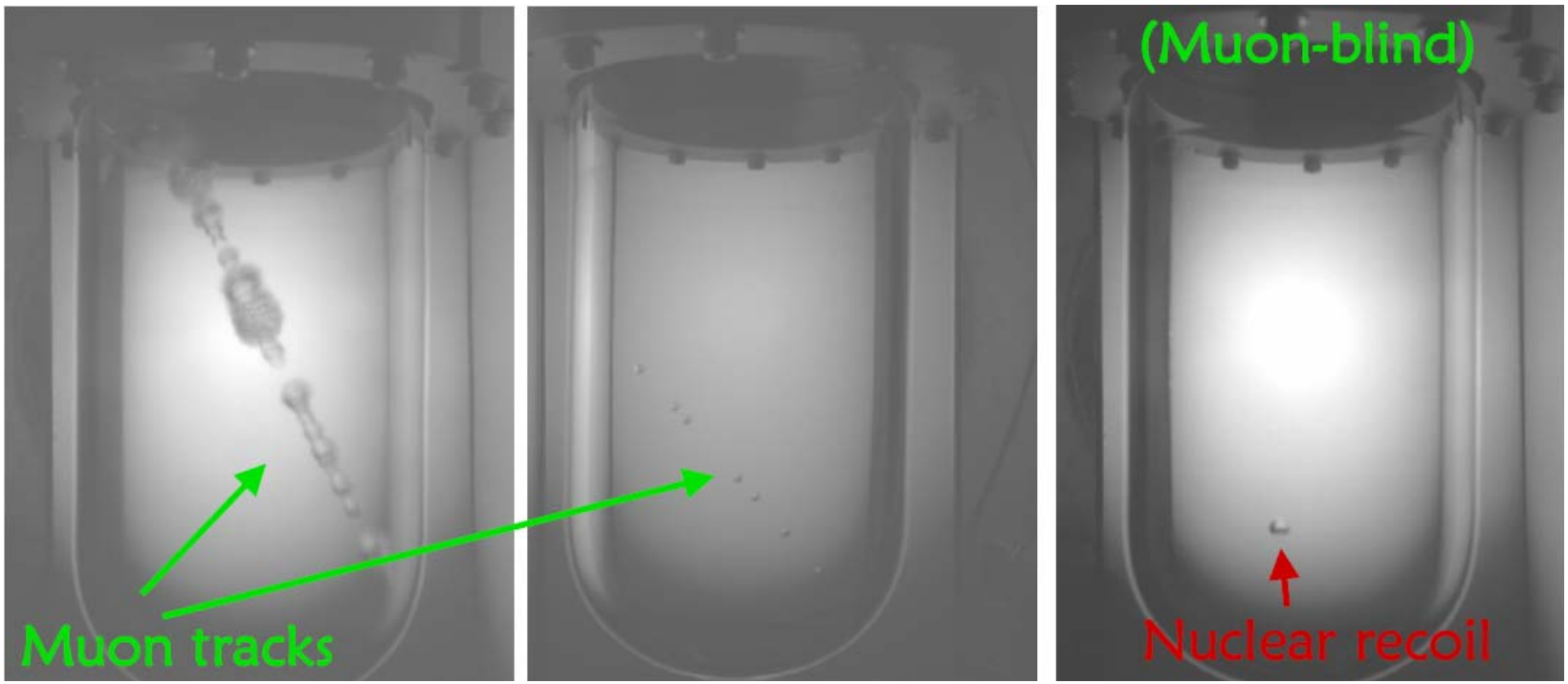


Warm Liquids - COUPP

- 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.

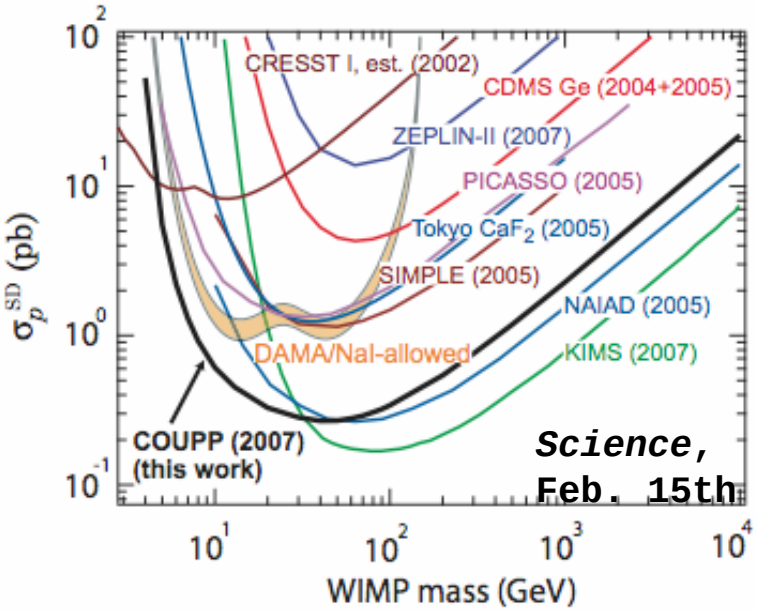


Decreasing superheat

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

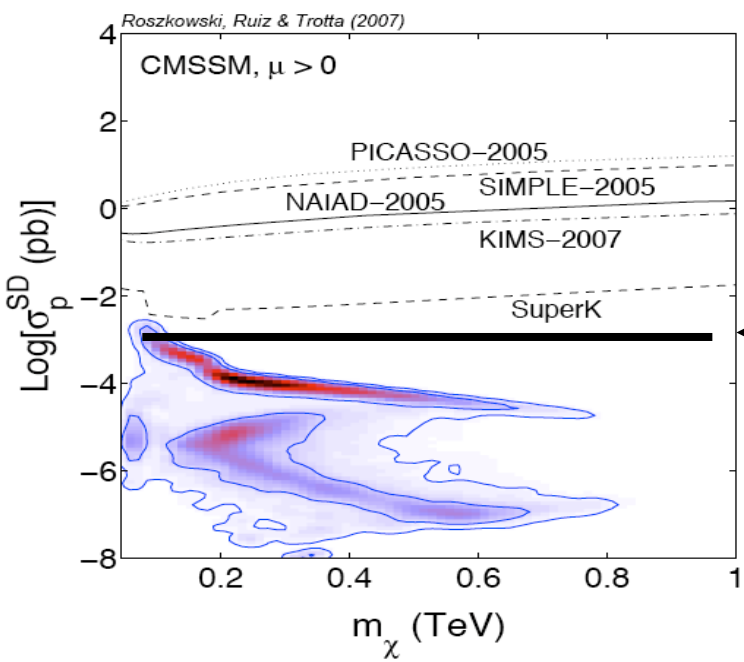
Muon tracks only visible with high superheats
Operate at low superheat → MIP blind 1 nuclear recoil = 1 bubble

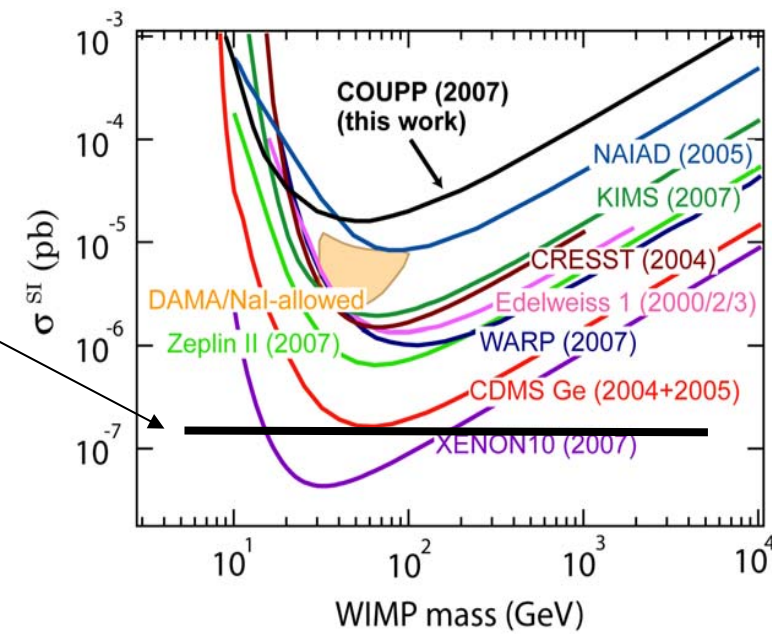
COUPP



- First results, no attempt to control Rn during these engineering runs.

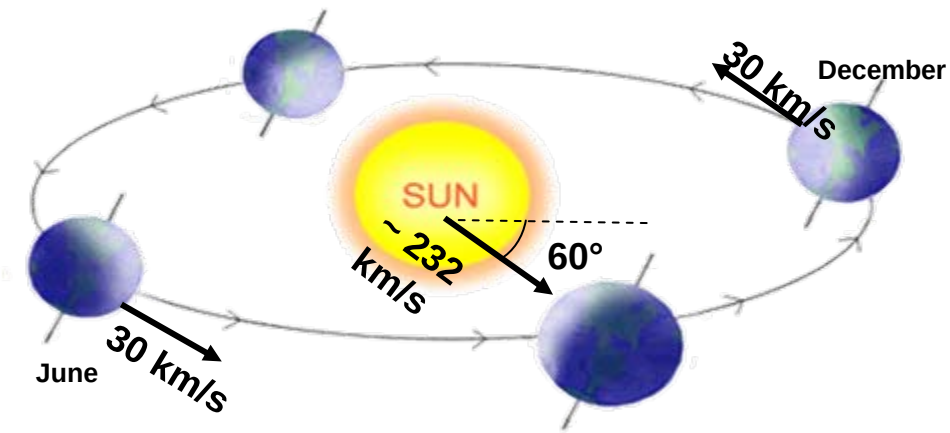
With Rn abatement and more depth (300 m.w.e.) project this.





DAMA/LIBRA – 250 kg NaI

Annual Modulation Signal



Expect:

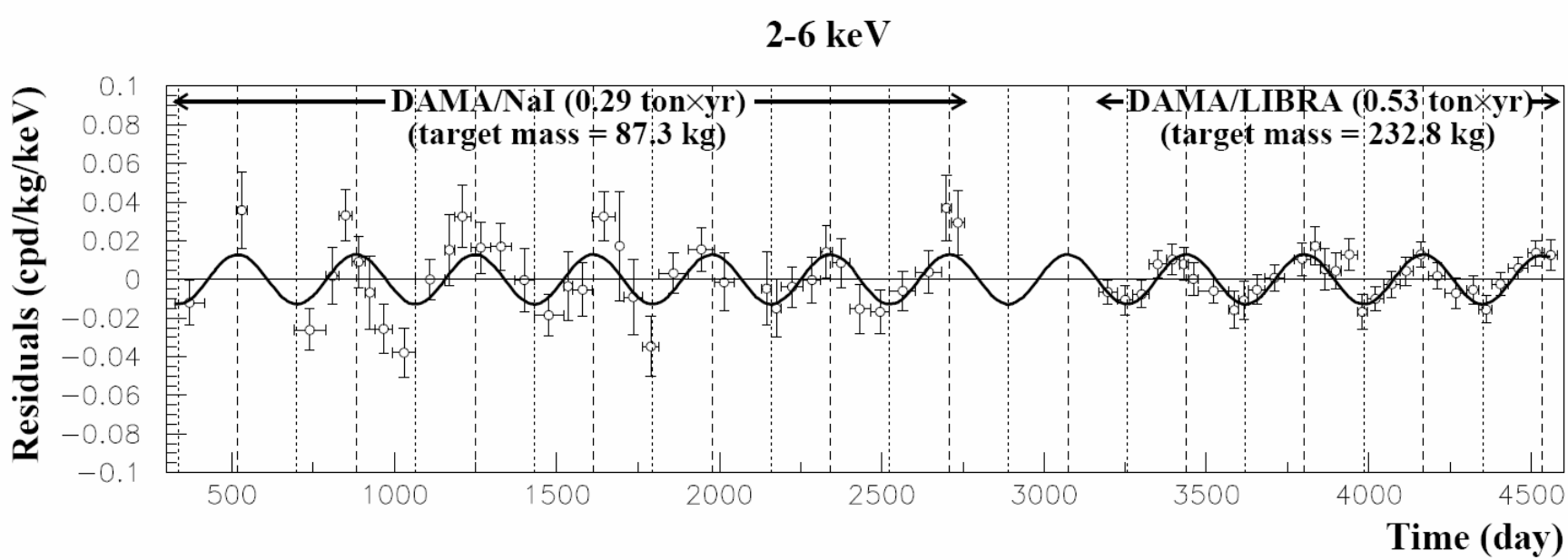
Modulated sinusoidal rate in particular energy range.

Proper period (1 year)

Proper phase ($v_{\oplus}$ is maximum ~2 June: V~245, compared to December V~215 km/s).

Modulation amplitude expected to be ~5% for usually adopted halo distributions.

Results – April 2008



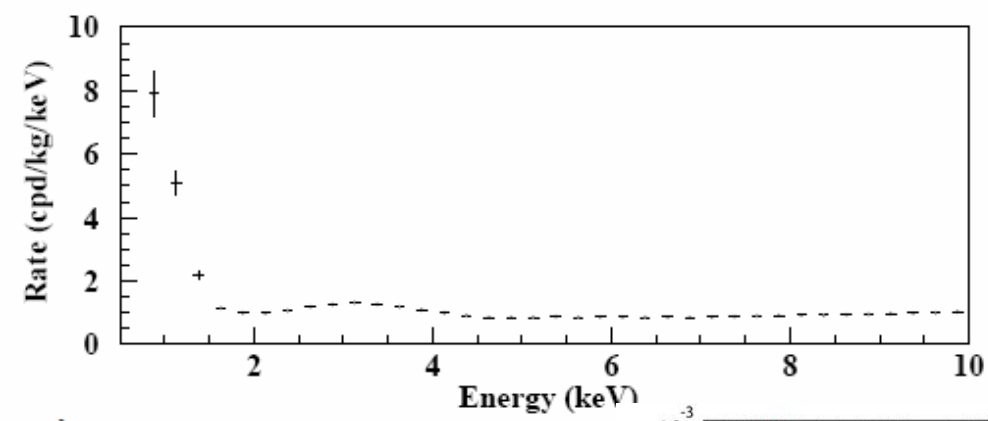
•"A clear modulation is present in all the energy intervals (2-6 keV) and the periods and phases agree with those expected in the case of a DM particle induced effect. The cumulative analysis favors the presence of a modulated cosinelike behaviour at 8.2 σ C.L."

•"The superimposed curve represents $A\cos \omega(t - t_0)$ with a period $T = 2\pi/\omega = 1$ yr, with a phase $t_0 = 152.5$ day (June 2nd)". Amplitude based on best fit to all data.

Questions…

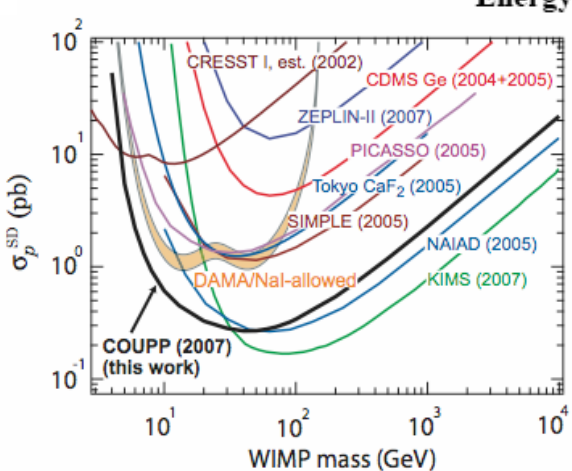
Different halo models predict different phase and amplitudes.

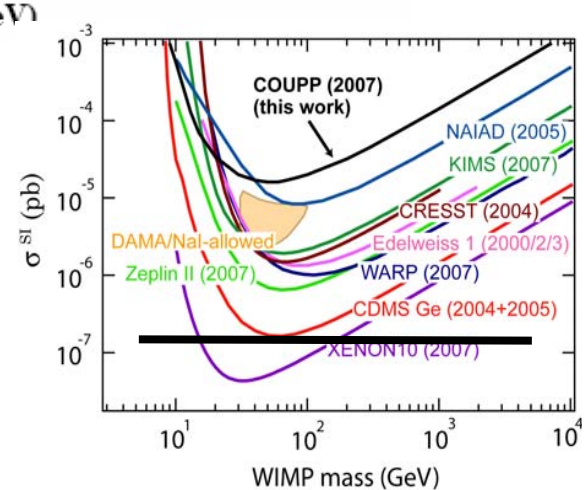
Because many processes vary with the seasons on Earth, and because the expected modulation is so slight, minor errors in the analysis could produce a false signal.



Modulation in PMT noise.

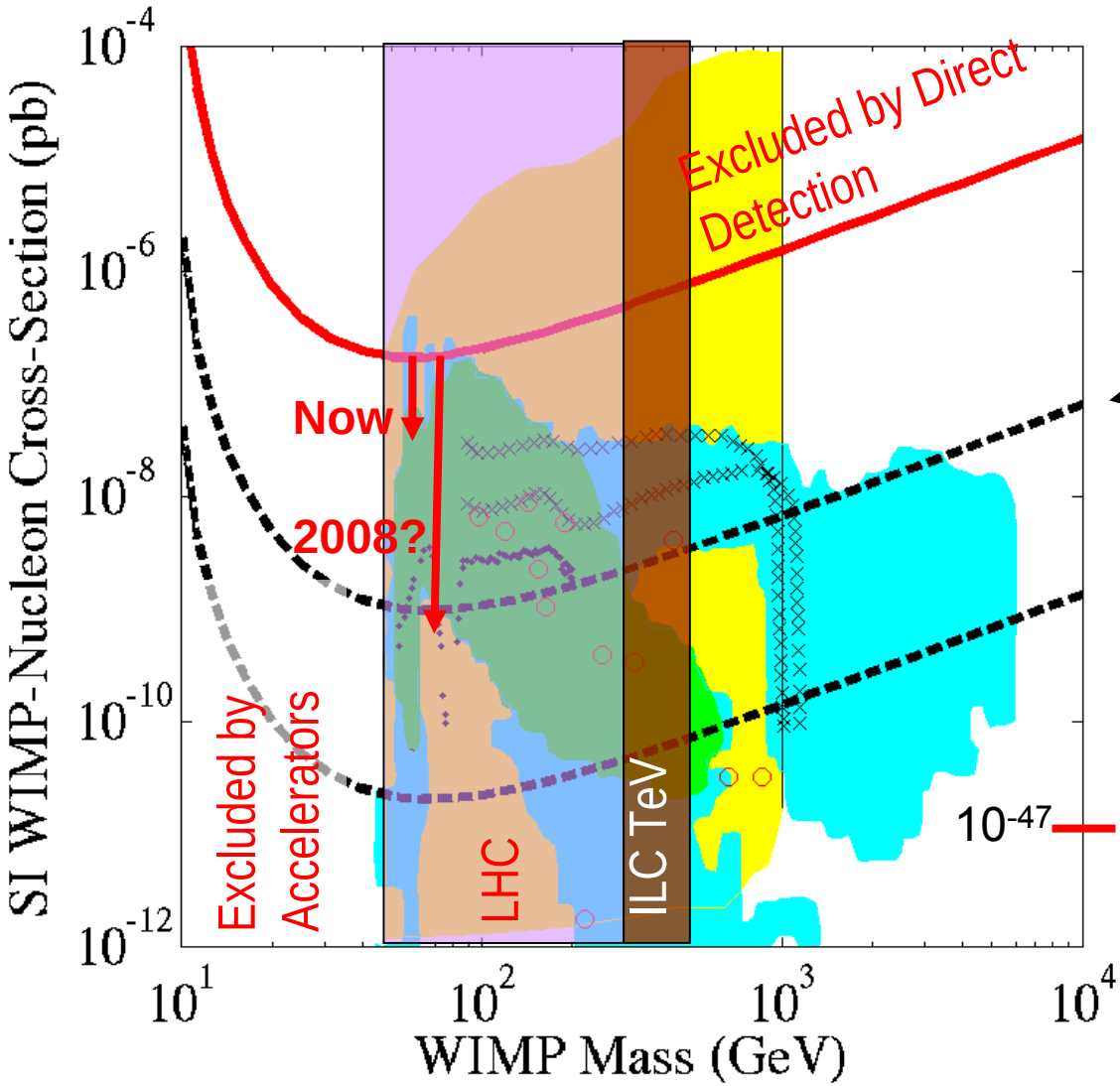
Modulation in 1-2 keV region?





Other experiments, both SI and SD rule it out…need to understand why.

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.

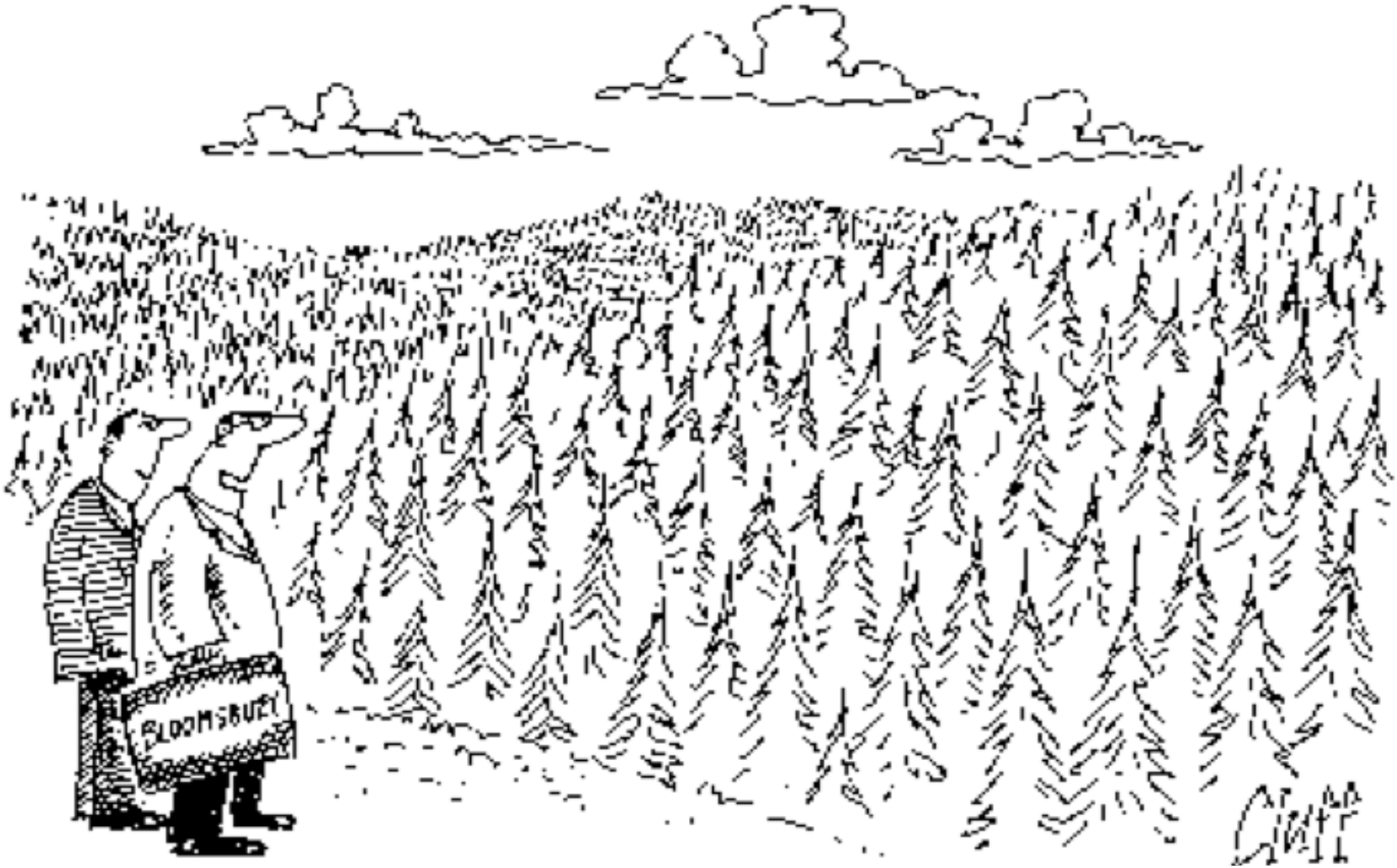
But sensitive to >TeV mass WIMPs

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.*



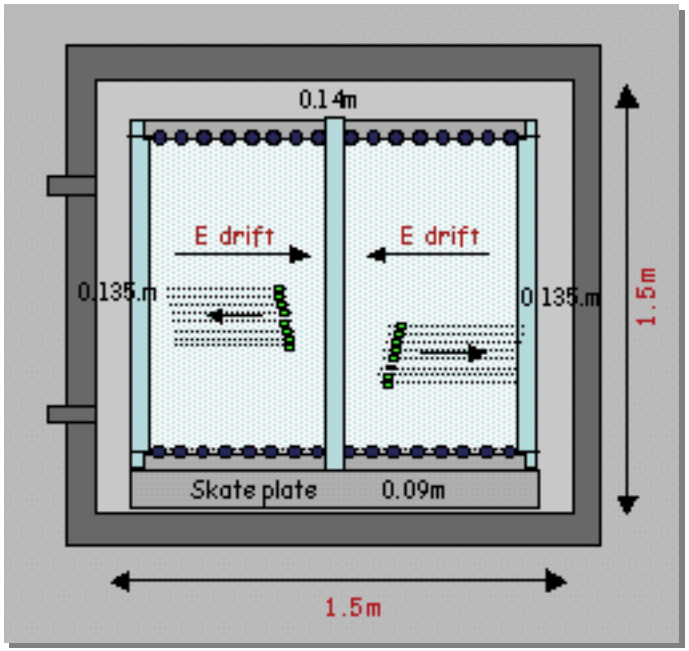
“One day, all of these will be supersymmetry phenomenology papers”

Additional Material

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.

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

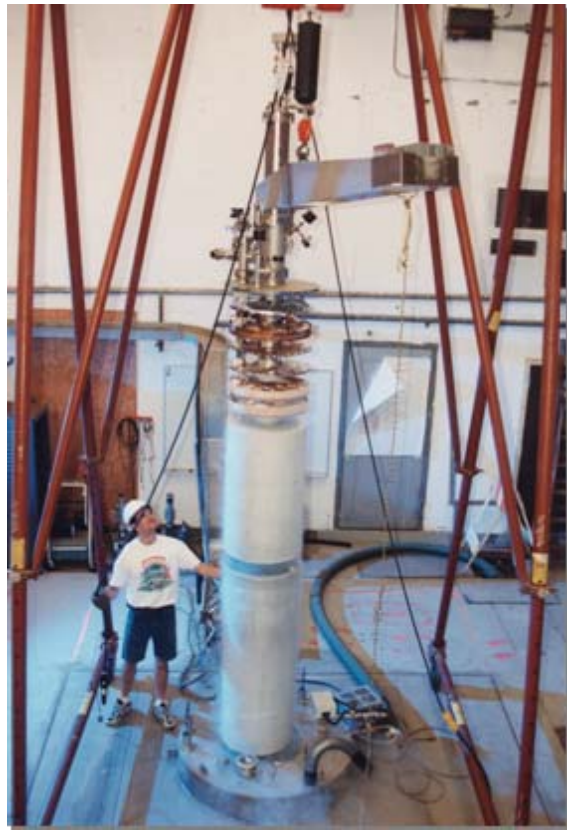
Peccei, Quinn (1977); Wilczek (1978); Weinberg (1978)

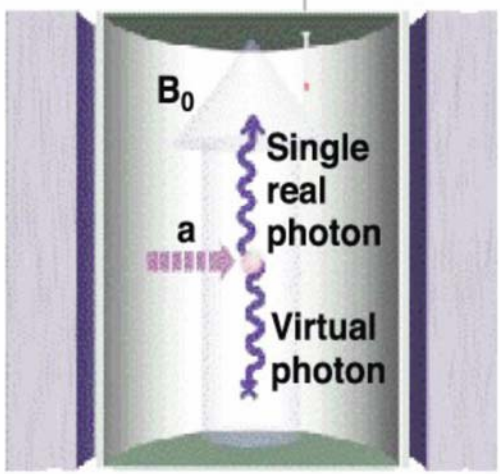
- The theory of the strong interactions naturally predicts large CP violating effects that have not been observed. Axions resolve this problem by elegantly suppressing CP violation to experimentally allowed levels.
- Cosmology and astrophysics sets the allowed axion mass range from 1 μeV to 1 meV, where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

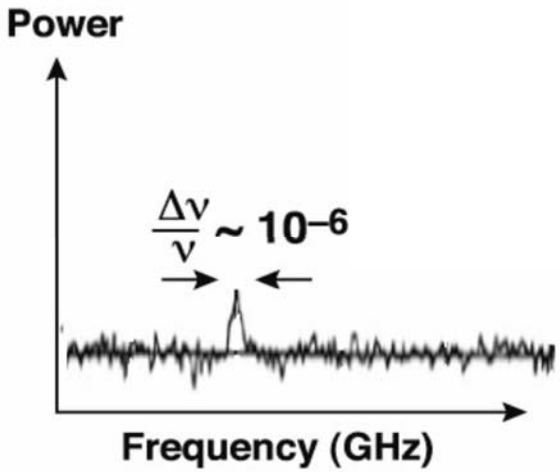
ADMX

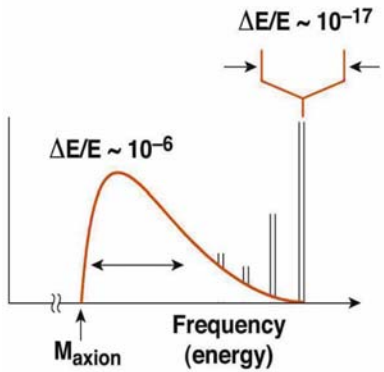
(LLNL, U.W.)

- 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.

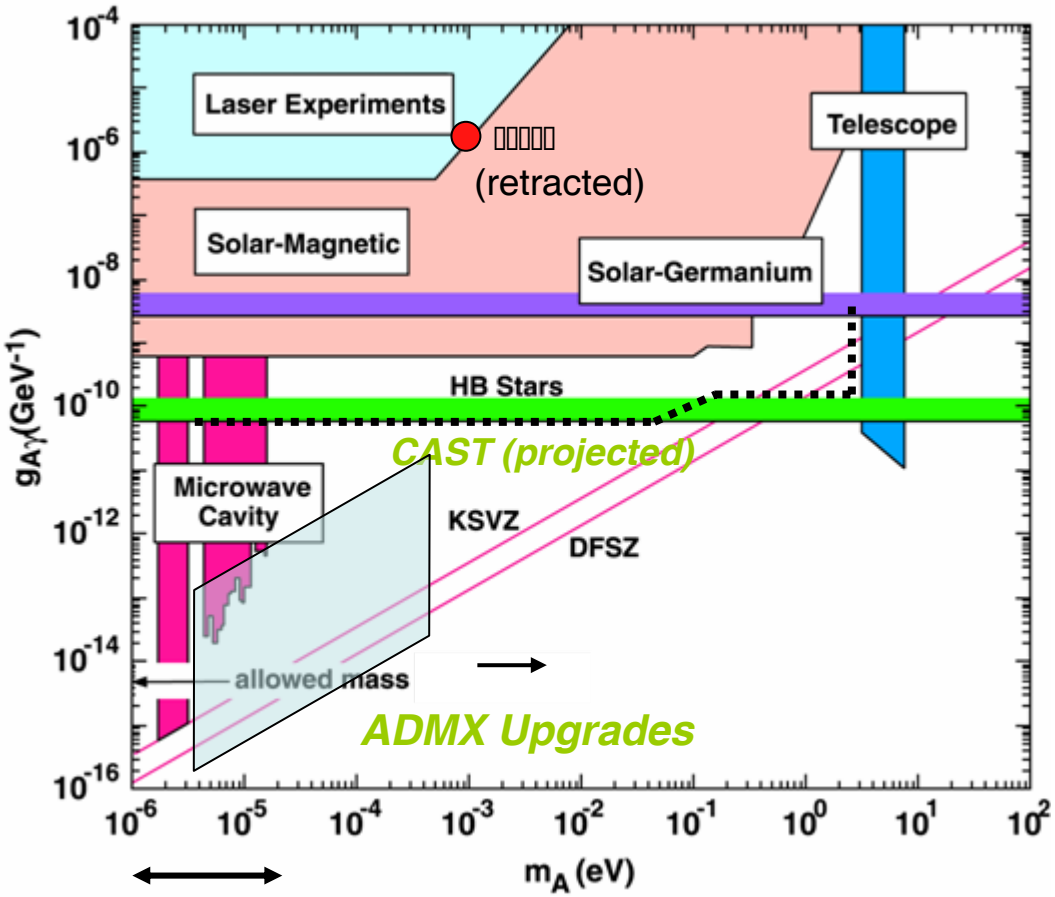








Excluded Axion Coupling $g_{A\gamma\gamma}$ vs. Axion Mass m_A



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