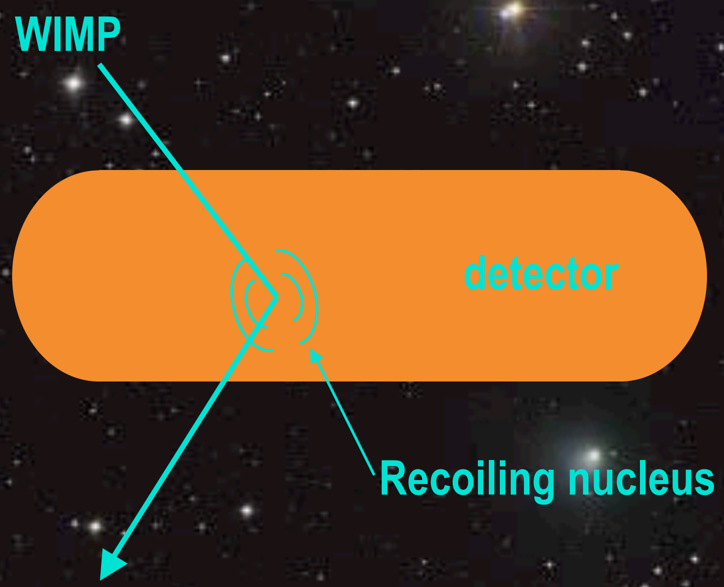
Direct Detection of Dark Matter



WIMP

detector

Recoiling nucleus

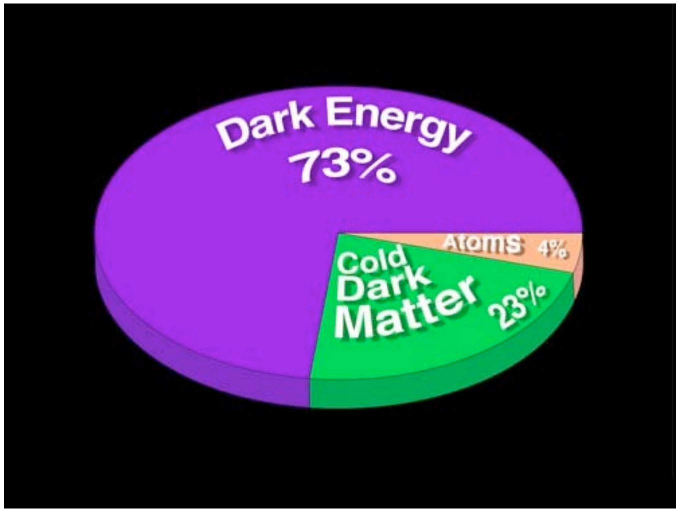
Dan Bauer

Fermilab

TeV Particle Astrophysics Workshop

July 14, 2005

Dark Matter Candidates



Baryonic Dark Matter

- Dust, Gas, Stars, MACHOs (< 20% of halo)
- BBN, light element ratio observations
  - $\Omega_B = 0.05 \pm 0.005$
- Baryonic dark matter exists but does not constitute much of the total dark matter

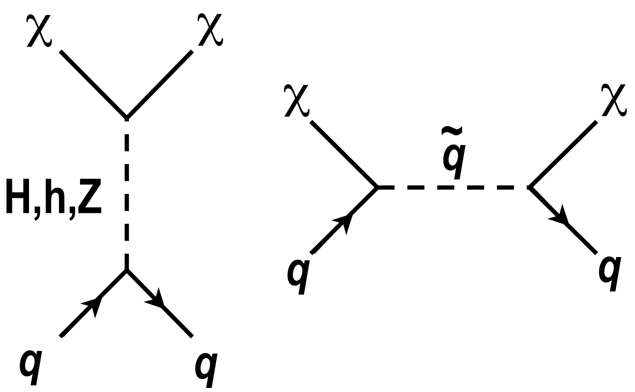
Hot Dark Matter

- Upper limit from CMB, tritium decay and neutrino oscillations $\Omega_\nu < 0.0155$
- Massive neutrinos exist, but not enough mass to explain dark matter
  - Hot dark matter cannot produce observed large scale structure of universe

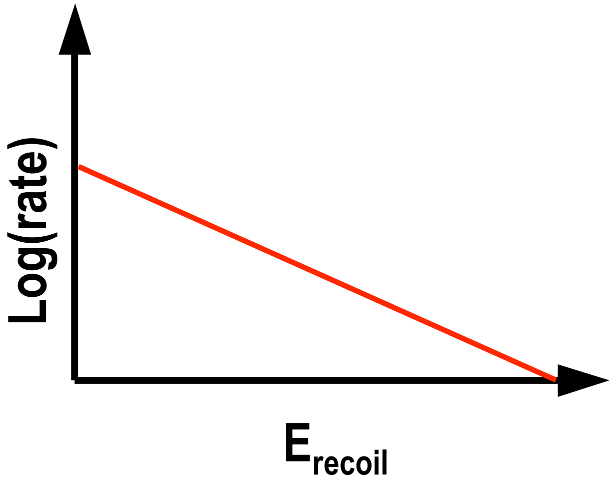
Cold Dark Matter

- Two well-motivated candidates from particle theory
  - WIMPs (Weakly Interacting Massive Particles), Axions
- Remainder of this talk concerns WIMP searches
  - Axion searches covered in a talk by L. Duffy in this session

Direct Detection of WIMPs



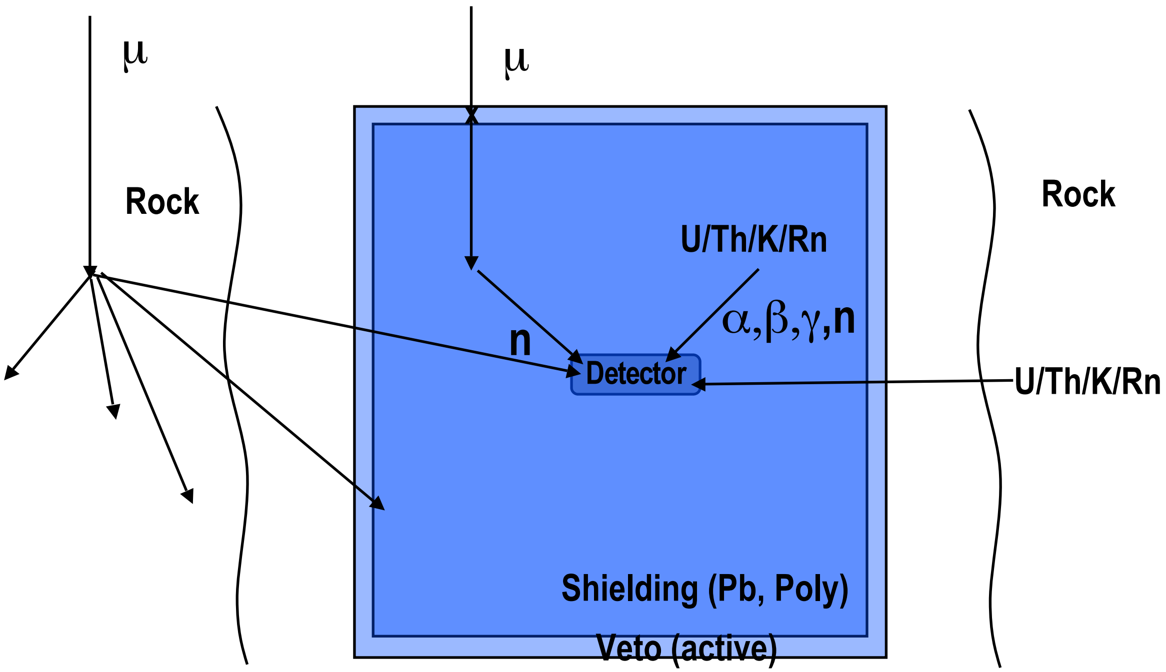
- WIMPs elastically scatter off nuclei in targets, producing nuclear recoils, with $\sigma_{n\chi}$ related roughly by crossing to σ_A(~10^{-38} cm^2)
  - Slow velocities ➔ large de Broglie λ ➔ coherent interaction with all nucleons
    - Spin-independent interaction $\propto A^2$
    - Spin-dependent needs target with net spin
  - Most sensitive to WIMP mass ~ mass of target nucleus
- Energy spectrum & rate depend on WIMP distribution in galactic halo:
  - Standard assumptions: isothermal and spherical, Maxwell-Boltzmann velocity distribution
  - V_0= 230 km/s, v_{esc}= 650 km/s,
  - ρ = 0.3 GeV / cm^3



Energy spectrum of recoils is featureless exponential with $\langle E \rangle$ ~ 50 keV

Rate (based on $\sigma_{n\chi}$ and ρ) is smaller than 0.1 event per kg material per day

Backgrounds for Direct Detection Experiments



Pb shielding to reduce EM backgrounds from radioactivity

Polyethylene contains hydrogen needed to moderate neutrons from radioactivity

Depth is necessary to reduce flux of fast neutrons from cosmic ray interactions

(although active veto may partially substitute for depth)

Experimental Requirements for Direct Detection of WIMPs

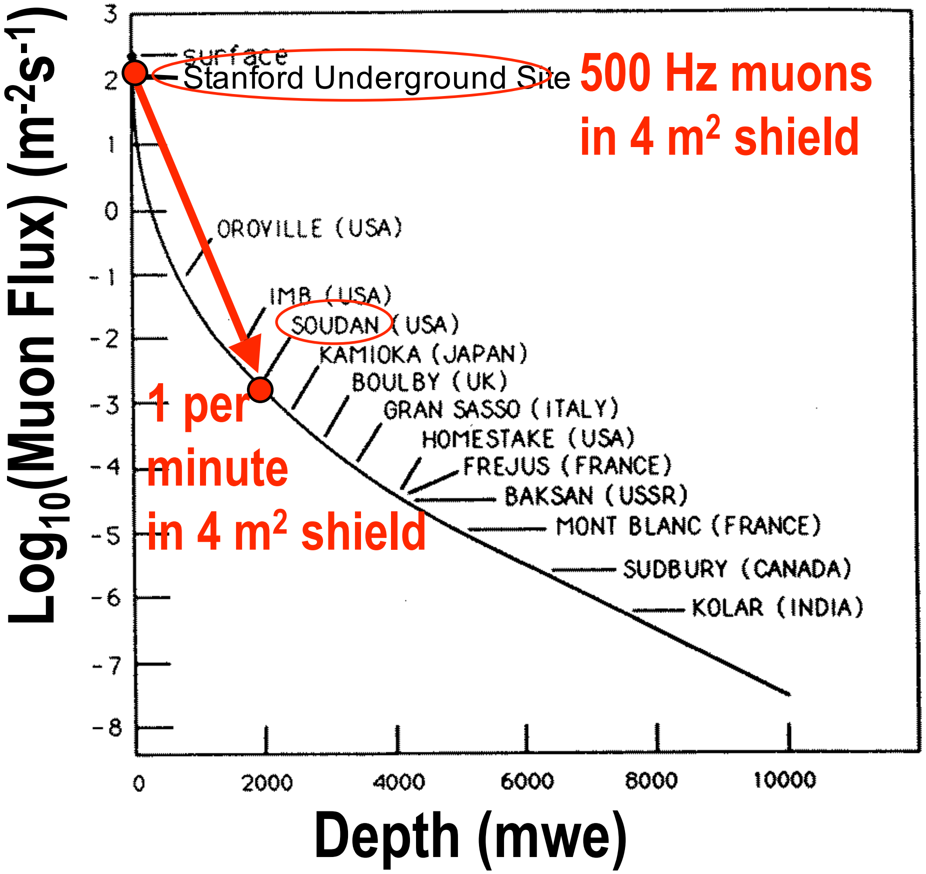
- Detect tiny energy deposits
  - Nuclear recoils deposit only 10's of keV
- Background suppression
  - Deep sites (reduced cosmic ray flux)
    - Cosmic rays produce neutrons, which interact like WIMPs
  - Passive/active shielding
    - Needed to reduce overwhelming background from radioactivity
  - Careful choice and preparation of materials
    - Radioactive impurities $\propto$ surface area
- Residual background rejection
  - Recognize and reject electron recoils
- Large Target Mass
  - WIMP interaction rate very low, so need lots of detectors
- Some signal unique to WIMPs
  - This is where there are interesting differences among experiments

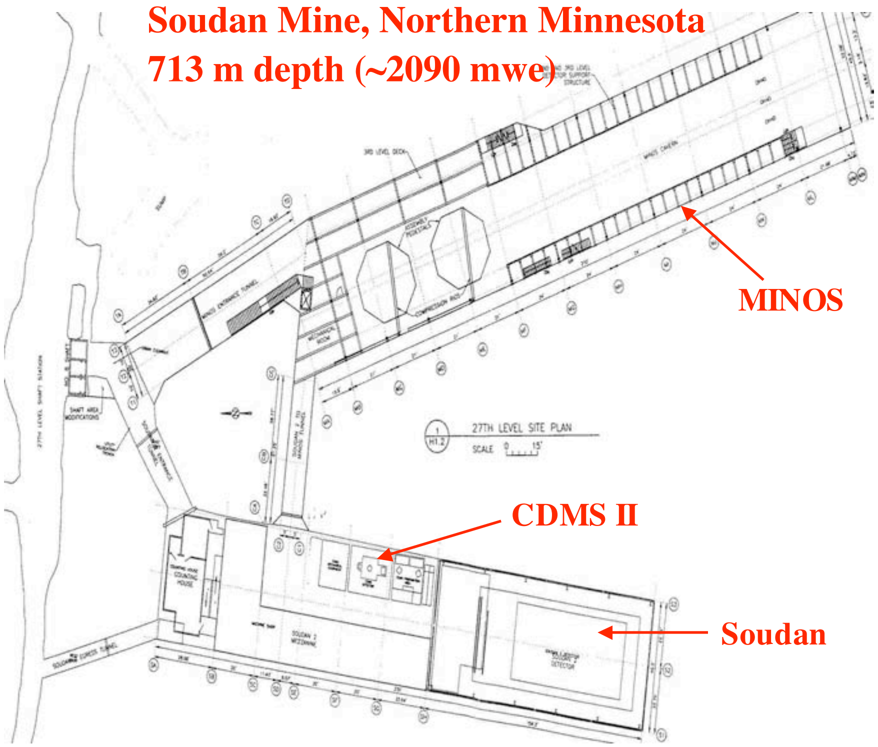
This looks like a nice place to look for cold dark matter

Why are direct detection experiments underground?

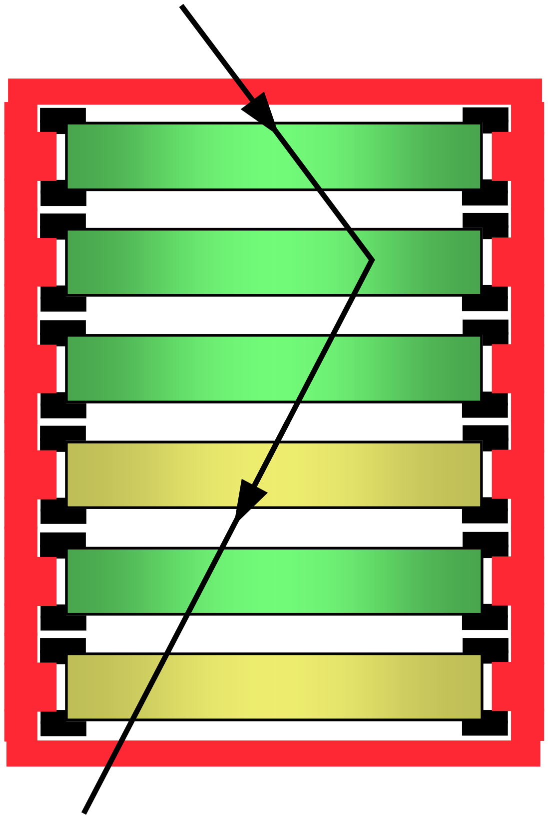
Most difficult background is neutrons from cosmic ray interactions

- Soudan depth reduces neutron background to ~1 / kg / year (< 5 neutrons/year)
- WIMP sensitivity goal is 0.01 events / kg / kev / day (~ 20 WIMPS/year)

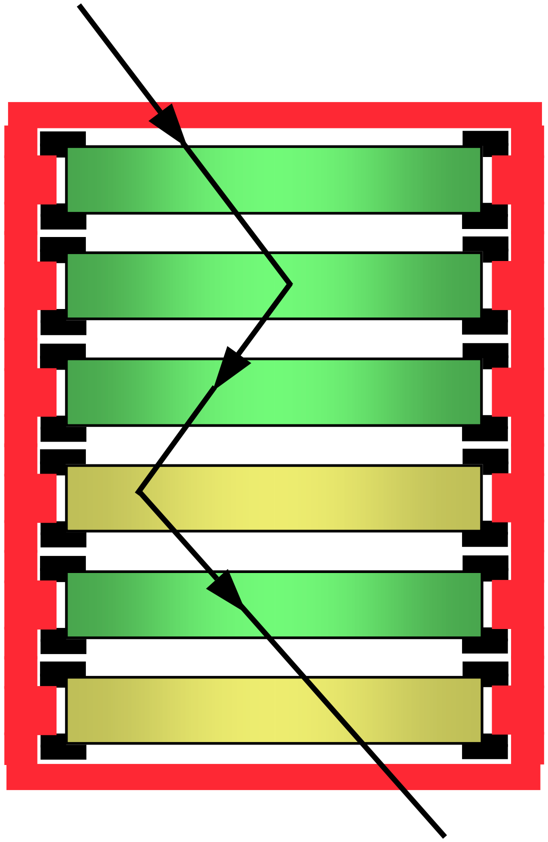




Neutrons: Single Scatters vs Multiple Scatters



Single-scatter nuclear-recoils are produced by WIMPs or neutrons.



Multiple-scatter nuclear-recoils are only produced by neutrons.

The advantage of multiple targets

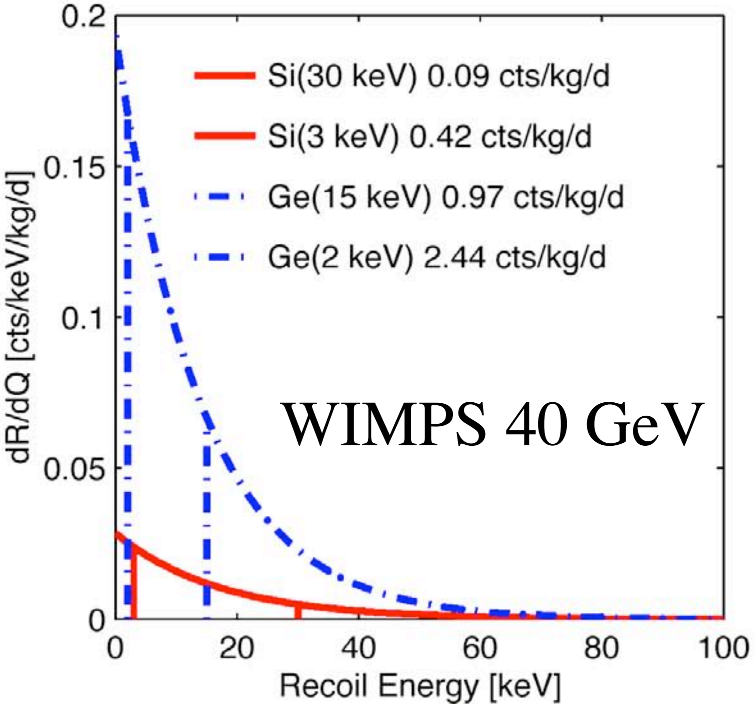
For neutrons 50 keV - 10 MeV

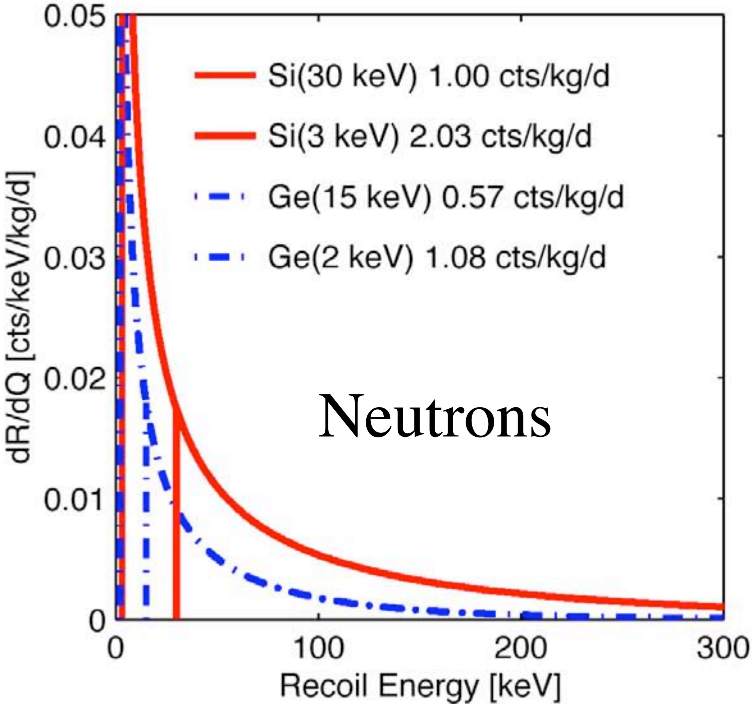
Si has ~2x higher interaction rate per kg than Ge

For WIMPs

Si has ~6x lower interaction rate per kg than Ge

If nuclear recoils appear in Ge, and not in Si, they are WIMPs!





An example of a direct detection experiment
Cryogenic Dark Matter Search - CDMS

Dark Matter Search

- Goal is direct detection of as few as 20 WIMPS/year

Cryogenic

- Cool very pure Ge and Si crystals to < 50 mK, to detect heat from individual particle interactions

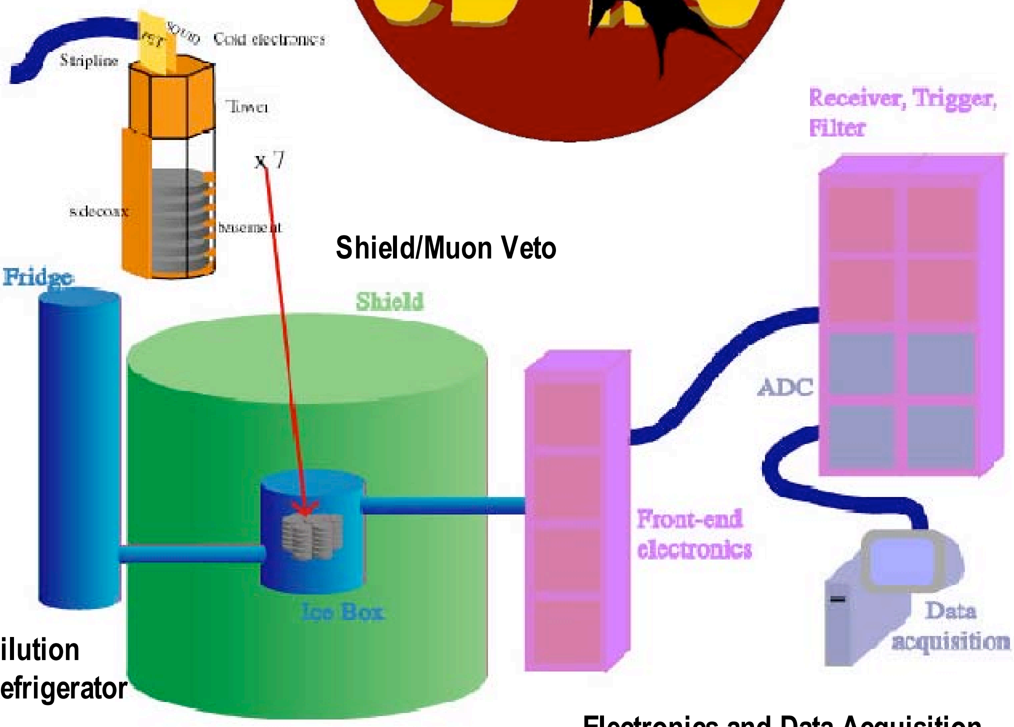
Active Background Rejection

- Detect both heat and charge
  - Nuclear recoils produce less charge for the same heat as electron recoils

Shielding

- Prevent radioactive decay products from reaching detectors and moderate neutrons to low energies

Detector Tower



Shield/Muon Veto

Dilution Refrigerator

Electronics and Data Acquisition

CDMS Active Background Rejection

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

Much better than expected in CDMS II proposal!

Tower of 6 ZIPs

Tower 1

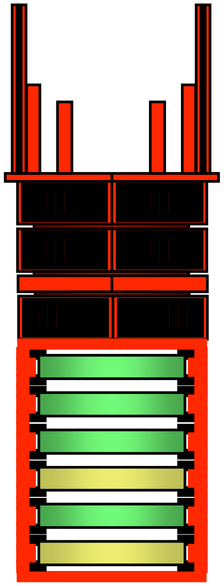
4 Ge

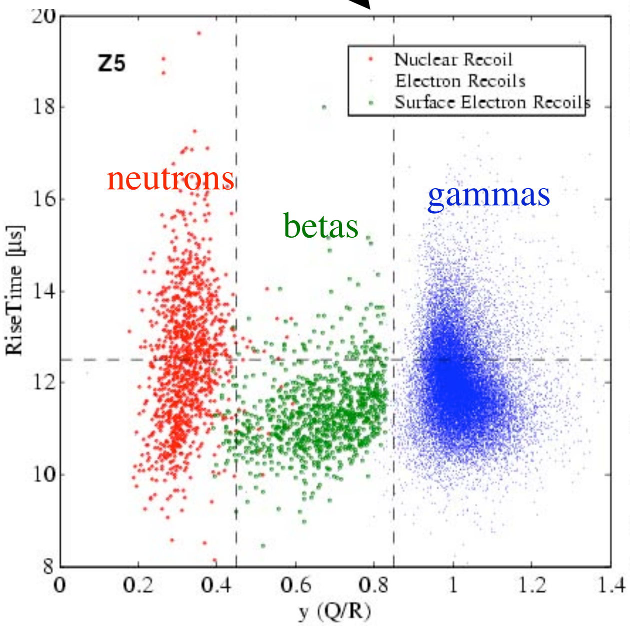
2 Si

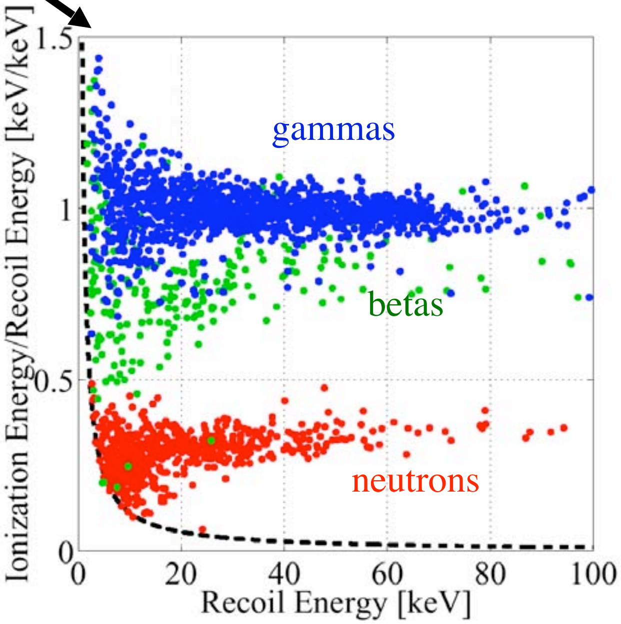
Tower 2

2 Ge

4 Si

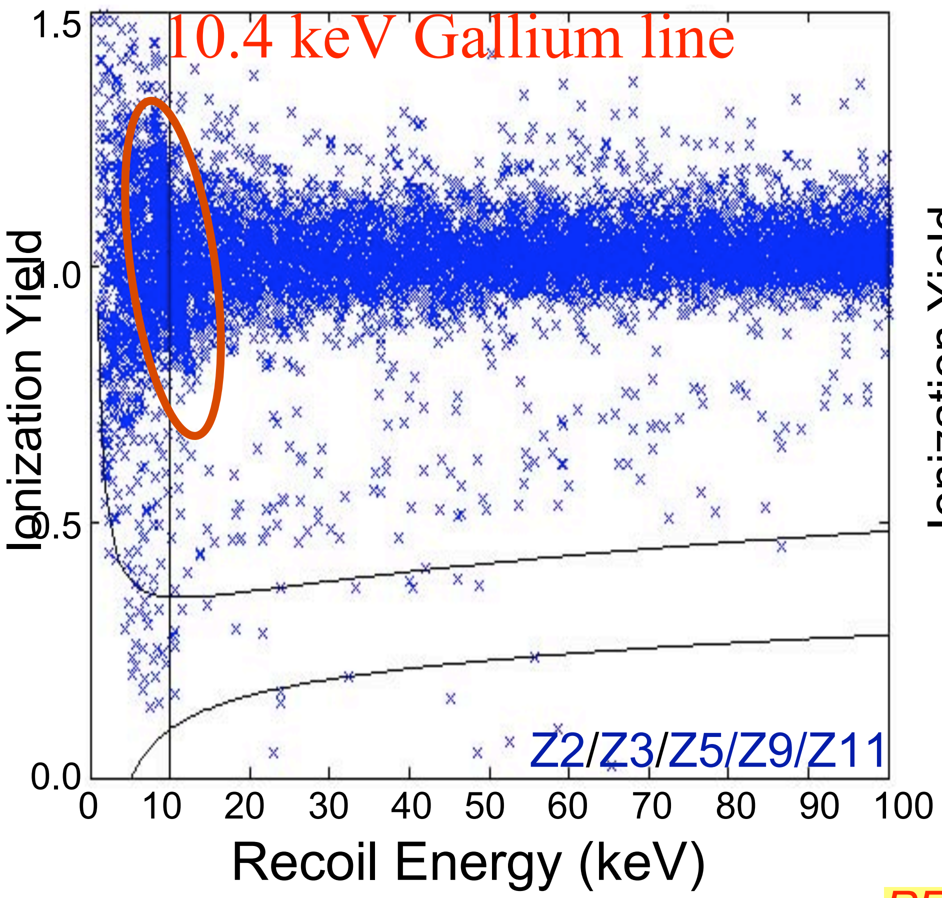




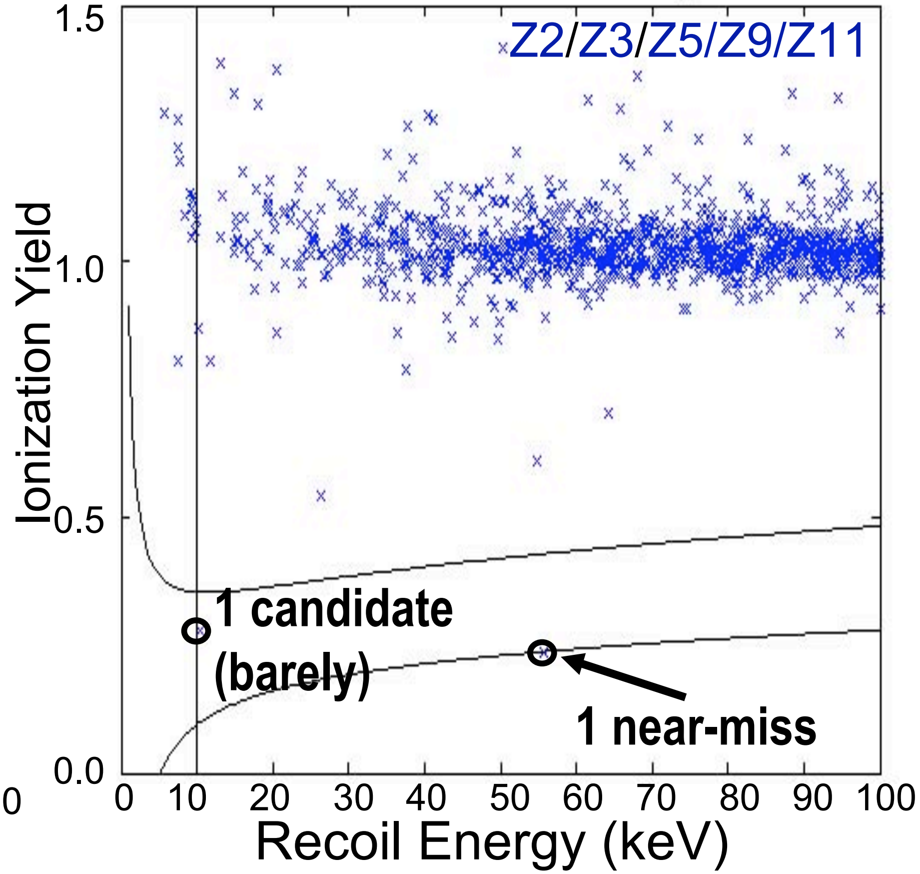


New CDMS Results from Two Towers

Prior to timing cuts

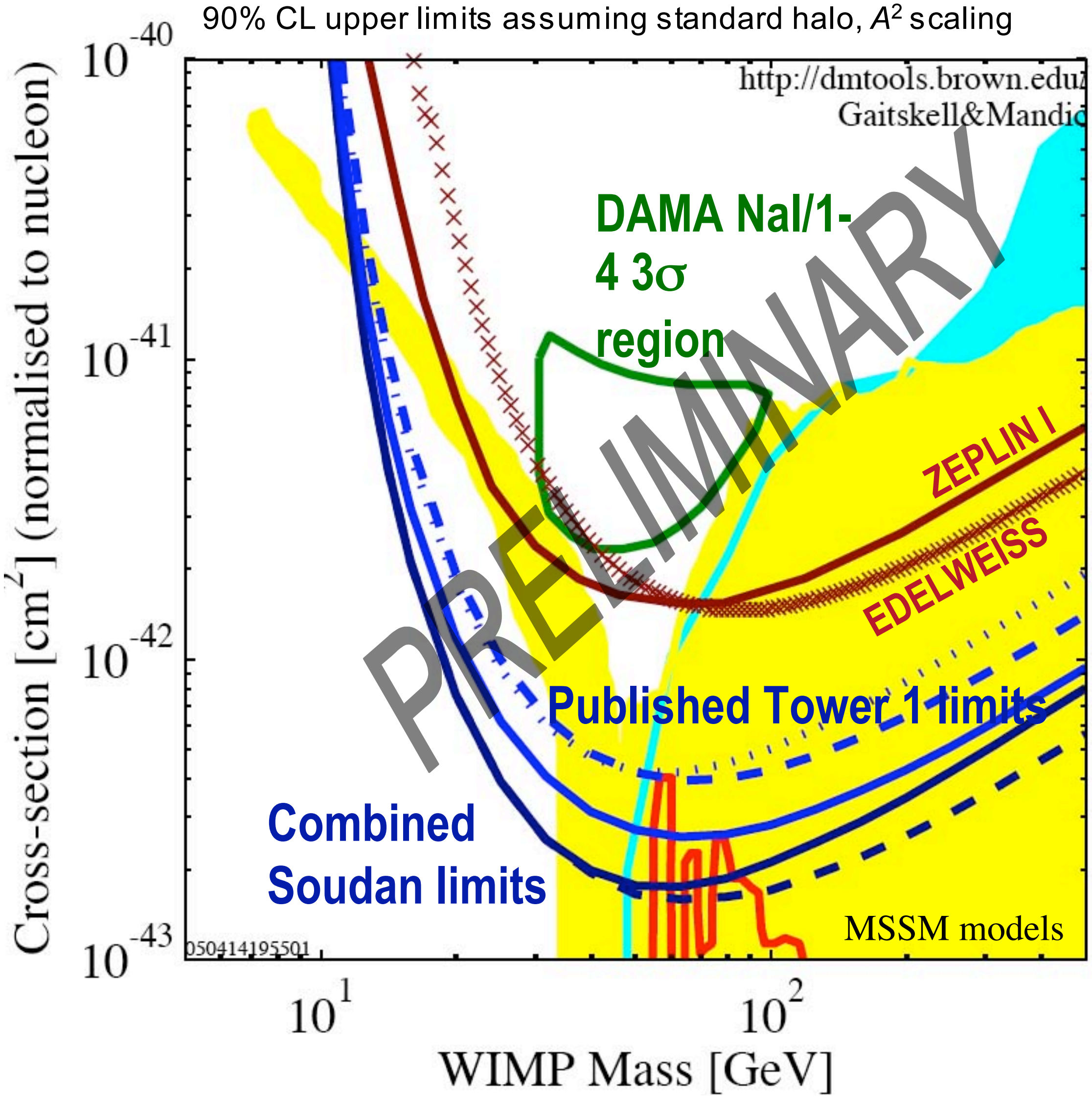


After timing cuts, which reject most electron recoils



PRELIMINARY ESTIMATE: 0.37 ± 0.20 (sys.) ± 0.15 (stat.) electron recoils, 0.05 recoils from neutrons expected

1st Year CDMS Soudan Limits



Upper limit on the WIMP-nucleon spin-independent cross section is 1.7×10^{-43} cm^2 for a WIMP with mass of 60 GeV/c^2

Factor 10 lower than any other experiment

Excludes large regions of SUSY parameter space under some frameworks (not yet much of MSUGRA)

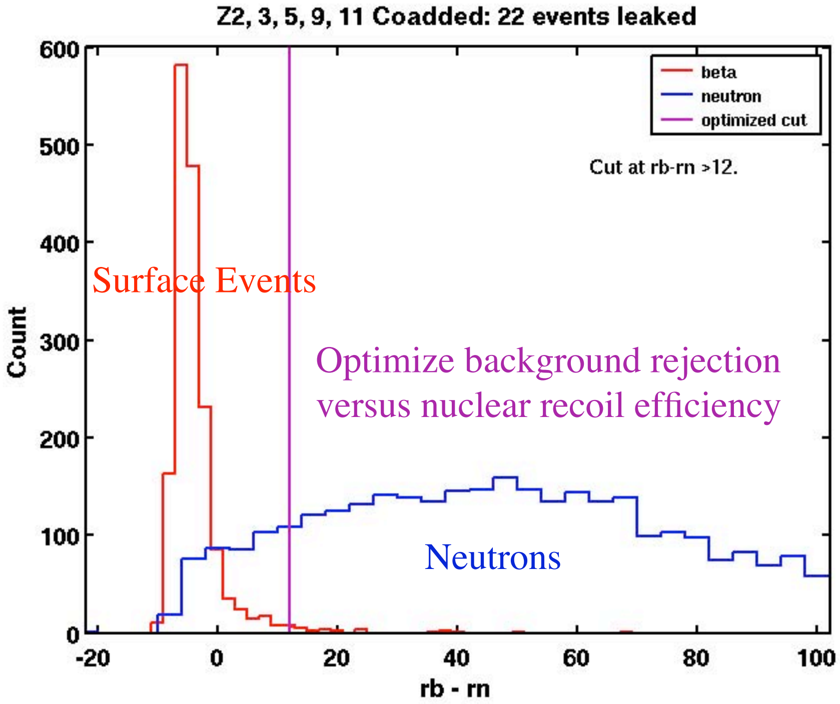
Improvements in Surface Event Rejection

Significant improvements in our analysis of phonon timing information

- Surface event rejection improved by x3; kept pace with exposure increase!
- Cuts are set from calibration data (blind analysis)

We still have more discrimination power available as needed

- Can continue to keep backgrounds < 1 event as more data accumulates
- This is the real strength of CDMS detectors!

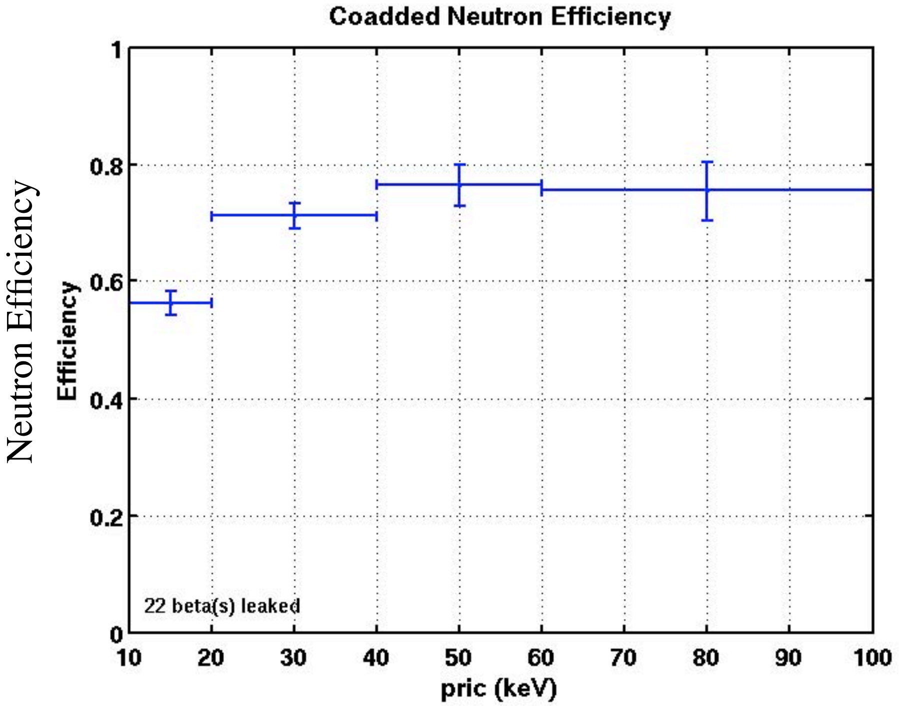


Surface Events

Optimize background rejection versus nuclear recoil efficiency

Neutrons

Chi-square (background pulse shape) - Chi-squared (neutron pulse shape)

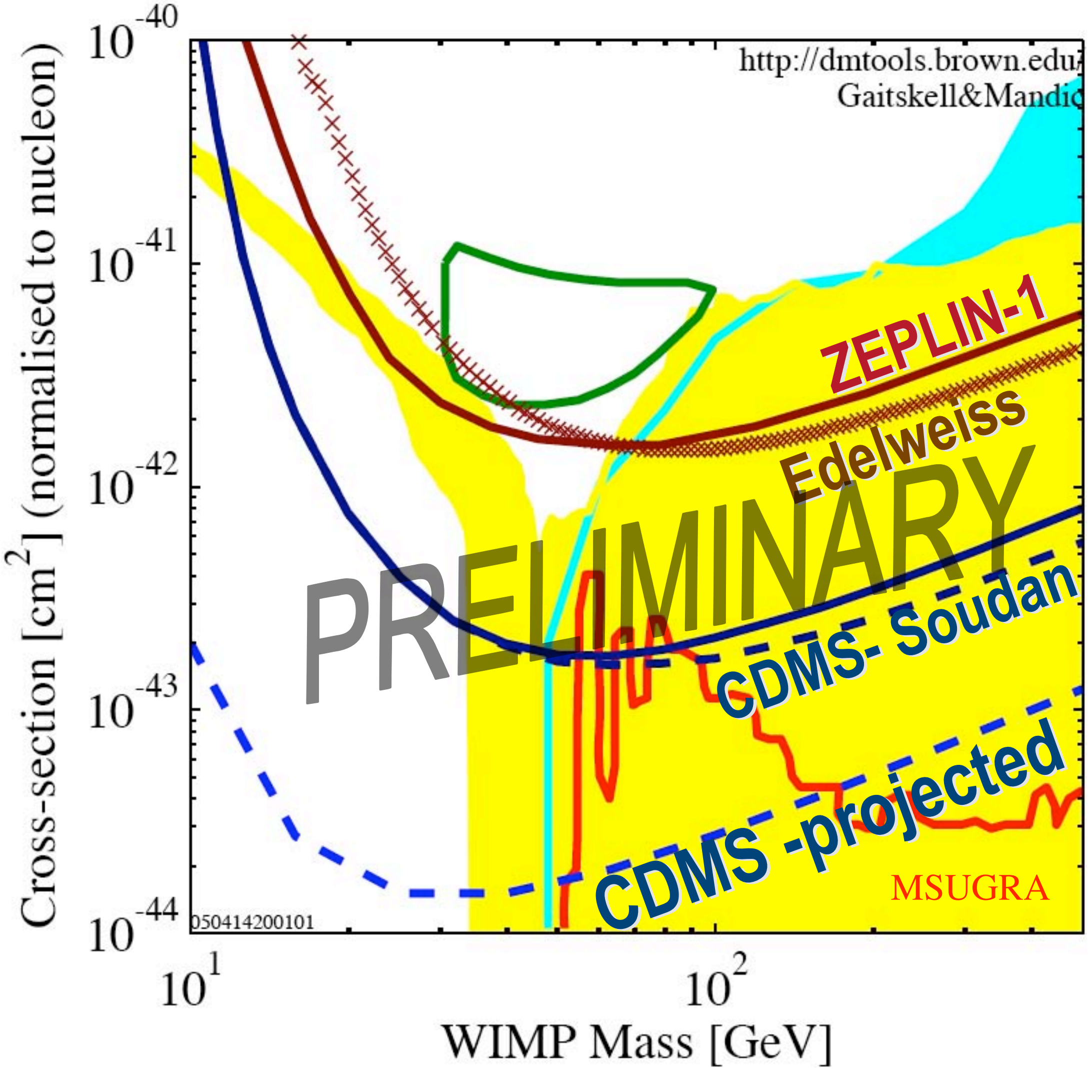


Neutron Efficiency

Recoil Energy (keV)

Projected CDMS Sensitivity at Soudan

Have now installed 3 additional towers

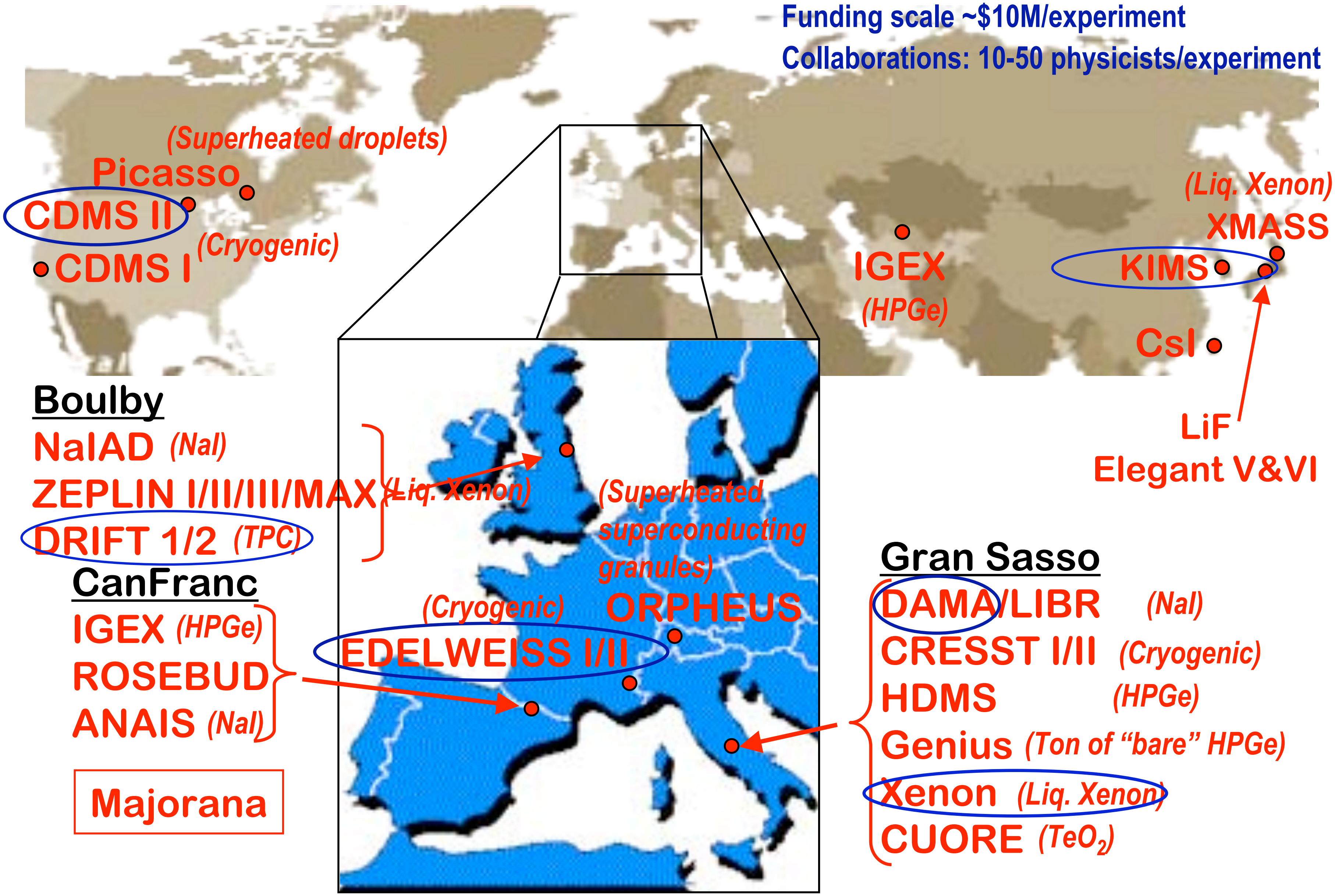


30 detectors in 5 towers of 6

4.75 kg of Ge, 1.1 kg of Si

Improve sensitivity by another x10 over next two years

WIMP-detection Experiments Worldwide



Funding scale ~$10M/experiment

Collaborations: 10-50 physicists/experiment

(Superheated droplets)
Picasso

CDMS II *(Cryogenic)*

CDMS I

IGEX *(HPGe)*

(Liq. Xenon)
XMASS

KIMS

CsI

LiF

Elegant V&VI

Boulby

- **NaIAD** *(NaI)*
- **ZEPLIN I/II/III/MAX** *(Liq. Xenon)*
- **DRIFT 1/2** *(TPC)*

CanFranc

- **IGEX** *(HPGe)*
- **ROSEBUD**
- **ANAIS** *(NaI)*

Majorana

(Cryogenic) **EDELWEISS I/II**

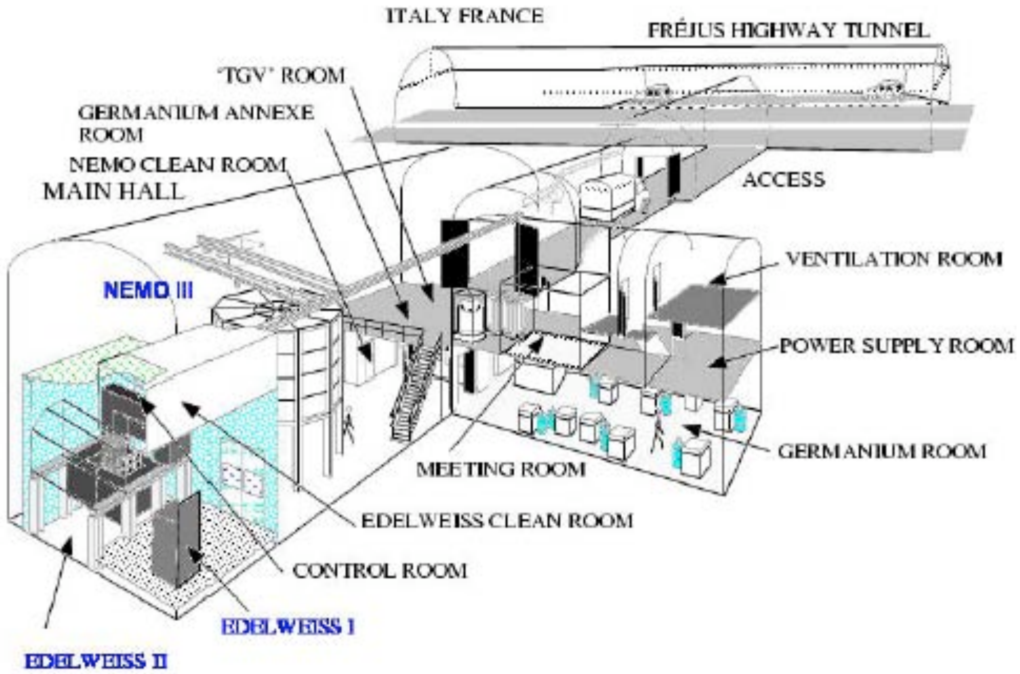
(Superheated superconducting granules) **ORPHEUS**

Gran Sasso

- **DAMA/LIBR** *(NaI)*
- **CRESST I/II** *(Cryogenic)*
- **HDMS** *(HPGe)*
- **Genius** *(Ton of “bare” HPGe)*
- **Xenon** *(Liq. Xenon)*
- **CUORE** *(TeO_2)*

EDELWEISS – Similar techniques to CDMS

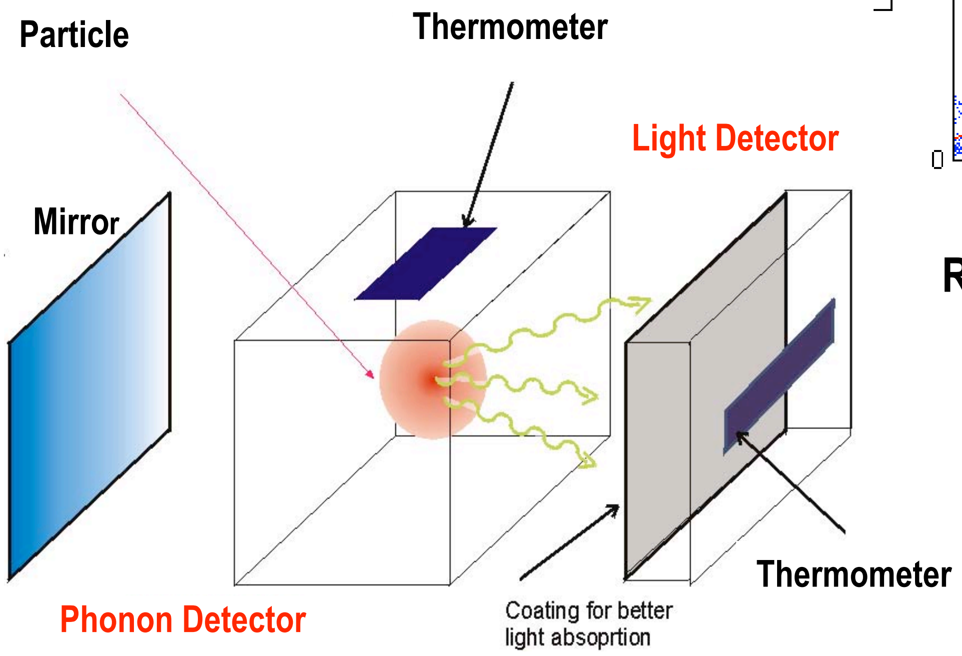
Edelweiss II @ Modane (4800 m w.e.)

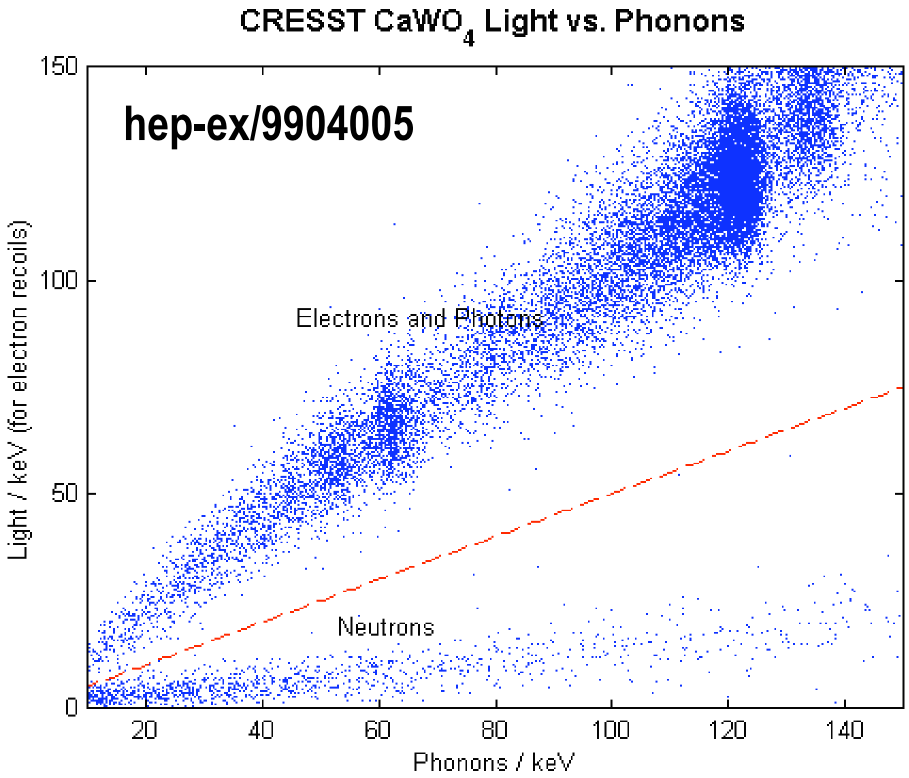


- Aim for sensitivity improvement × 100 (competitive with CDMS II)
- Installation started 04/04 – expected to finish summer 05
- 1st phase: 21 NTD detectors (~7 kg total), 7 NbSi detectors (~3 kg total)
  - Only NbSi competitive in background rejection with CDMS II

CRESST: Phonons and Scintillation

- Nuclear recoils have much smaller light yield than electron recoils
- Photon and electron interactions can be distinguished from nuclear recoils (WIMPs, neutrons, ...)




CRESST $CaWO_4$ Light vs. Phonons

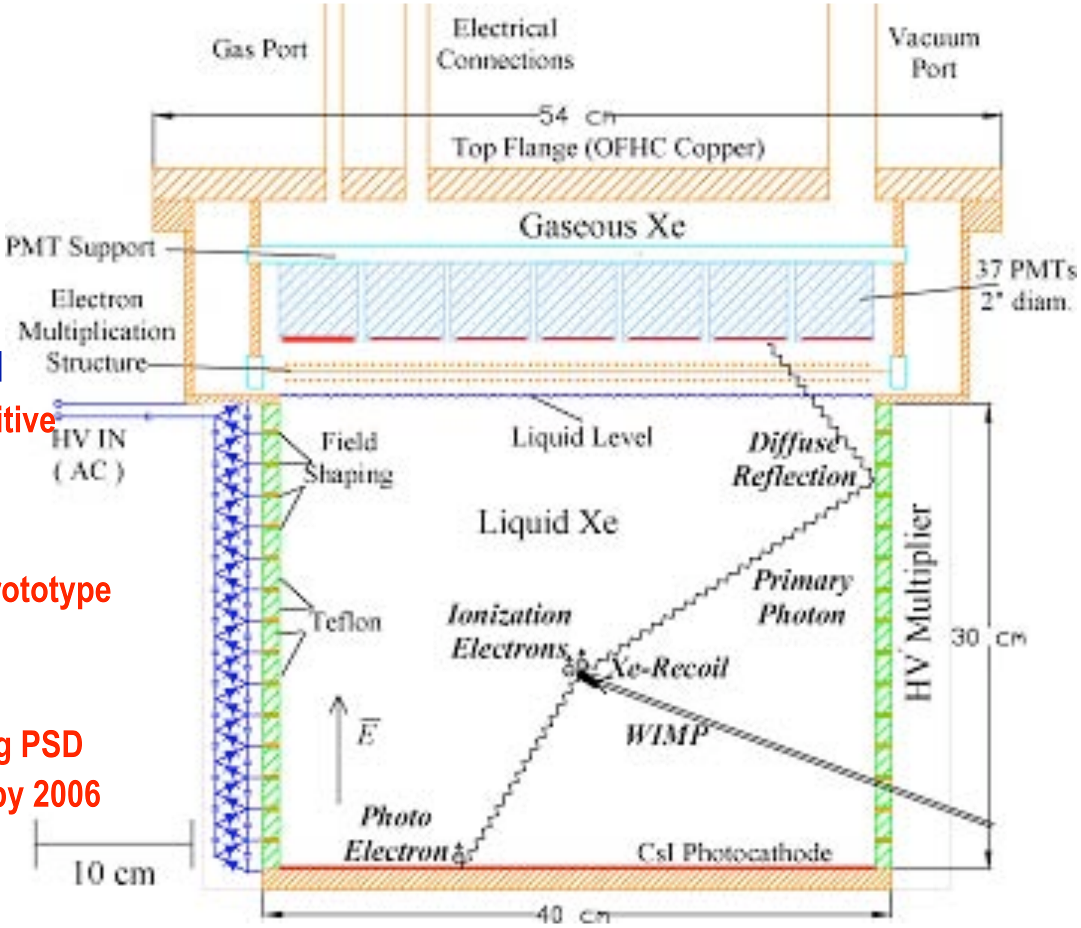
Results from a 6g $CaWO_4$ prototype

- No problem from surface electrons
- Very small scintillation signal
  - Scintillation threshold will determine minimum recoil energy
- Scaling up to 300g detectors
- May begin running in Gran Sasso in 2005

Liquid Xenon Detectors:

Compromise between large mass and background rejection

- Potential to challenge cryogenic detectors
  - Background rejection
    - Pulse shape discrimination now
    - R&D towards scintillation + ionization
  - May scale more readily to high mass
- Challenges
  - Implementing “dual-phase” to improve scintillation signal near threshold
  - Ionization signal/noise poor near threshold
    - Must show 16 keV threshold to be competitive
- Several programs
  - XMASS (Japan)
    - Results from 3 kg fiducial, single-phase prototype
    - Aim for 100 kg within few years
  - Zeplin (UK/UCLA et al)
    - Preliminary results from 3 kg fiducial using PSD
    - Aiming for 6-30 kg deployment at Boulby by 2006
  - XENON expt (Columbia et al)
    - R&D on dual-phase experiment
    - Hope to deploy 10 kg at Gran Sasso in 2006



Columbia Univ.

See talk by K. Ni in this session

CUOPP (Heavy Liquid Bubble Chamber)

Ultimate in background rejection?

- Superheated heavy liquid (e.g. CF_3I)
  - Get more target mass from heavy liquid bubble chamber
  - Only high-ionization energy density tracks from nuclear recoils sufficient to cause nucleation
    - Insensitive to gammas, betas, & minimum ionizing particles
  - Demonstrated bubble rates consistent with neutrons from cosmic rays at shallow site with 1 liter prototype
    - Setting up now at 300 mwe site at Fermilab
    - Eventually will go to Soudan
- Challenges
  - How to get energy spectrum
    - Multiple exposures at different pressures
  - Possible alpha backgrounds
  - Operational stability
    - Will a bubble chamber really stay in superheated state for months?

See talk by Andrew Sonnenschein in this session

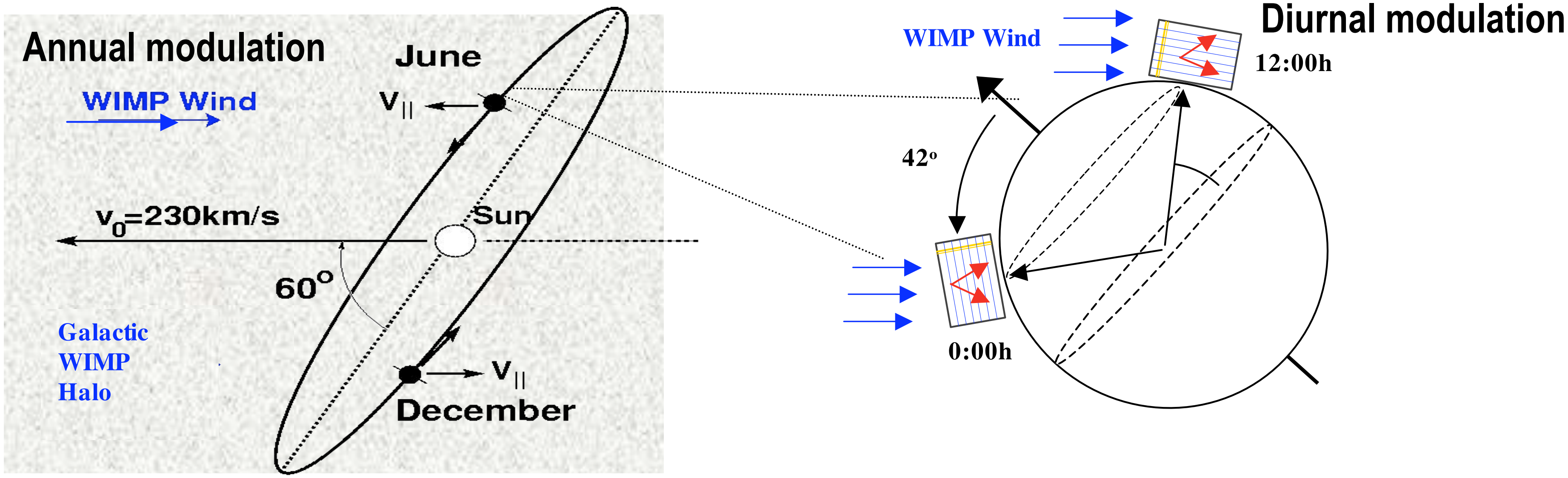
Directionality: Can we detect a WIMP wind?

Look for variation in WIMP flux with time of year (annual)

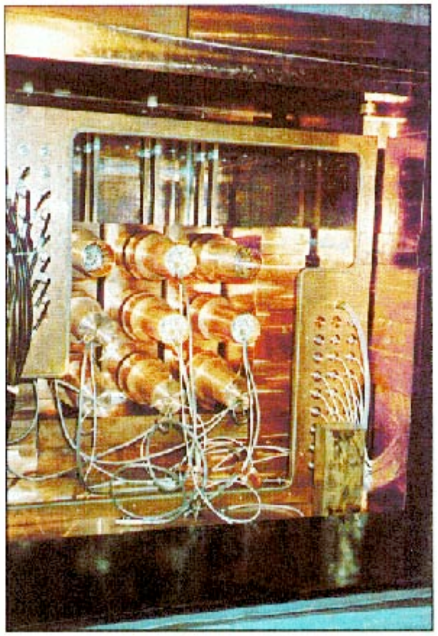
Requires long exposure and large mass to measure small effect (~5%)

Look for directionality of WIMP nuclear recoils on a daily basis (diurnal)

Requires detectors which can reconstruct direction of recoil with reasonable precision



DAMA: Search for annual modulation



100 kg of NaI crystals read out by phototubes

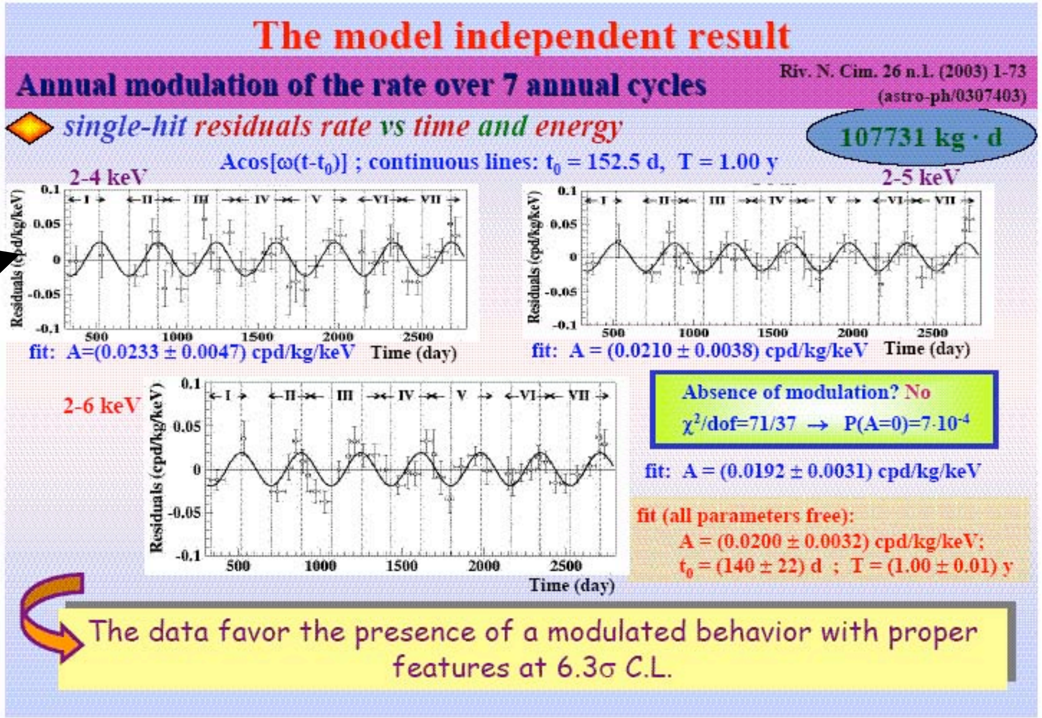
Deep underground (Gran Sasso, Italy)

Huge target mass, no background rejection

Claim a WIMP signal

6σ annual modulation is observed in the rate.

BUT, the modulation is only a 5% effect and is all in the lowest energy bin.



The model independent result

Annual modulation of the rate over 7 annual cycles

Riv. N. Cim. 26 n.1. (2003) 1-73 (astro-ph/0307403)

single-hit residuals rate vs time and energy

107731 kg · d

$A\cos[\omega(t-t_0)]$; continuous lines: $t_0 = 152.5$ d, $T = 1.00$ y

2-4 keV

fit: $A=(0.0233 \pm 0.0047)$ cpd/kg/keV

2-5 keV

fit: $A = (0.0210 \pm 0.0038)$ cpd/kg/keV

2-6 keV

Absence of modulation? No

$\chi^2/\text{dof}=71/37 \rightarrow P(A=0)=7\cdot 10^{-4}$

fit: $A = (0.0192 \pm 0.0031)$ cpd/kg/keV

fit (all parameters free):
$A = (0.0200 \pm 0.0032)$ cpd/kg/keV;
$t_0 = (140 \pm 22)$ d ; $T = (1.00 \pm 0.01)$ y

The data favor the presence of a modulated behavior with proper features at 6.3σ C.L.

Is this due to dark matter interactions or some other annual effect?
Not seen in CDMS or Edelweiss experiments, which have higher sensitivity!

KIMS - Similar to DAMA but with CsI

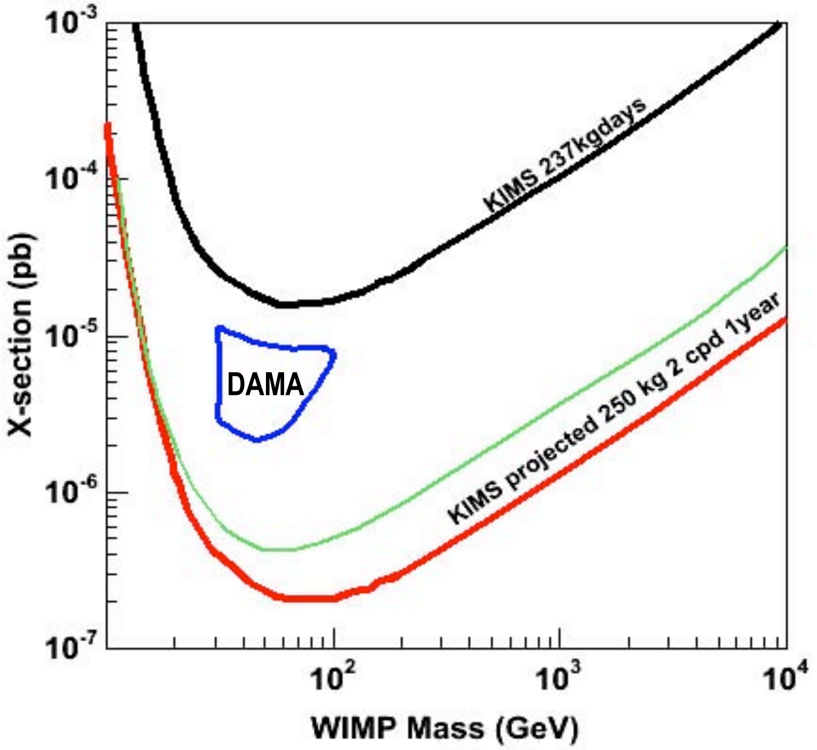
Challenge: Construct large CsI crystals without ^{137}Cs contamination

250 kg(25 crystals) may start in 2005 with < 2 cpd background level.

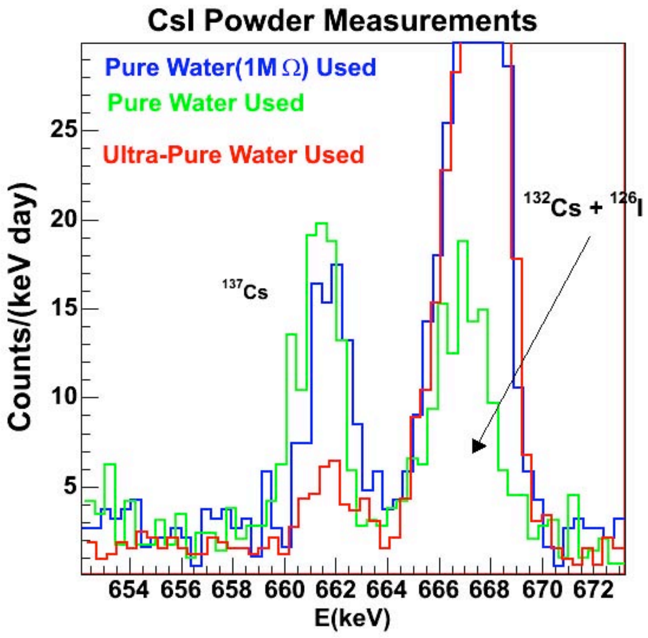
Located at 700 mwe underground in Korea

Test DAMA data with similar crystal detector containing Iodine.

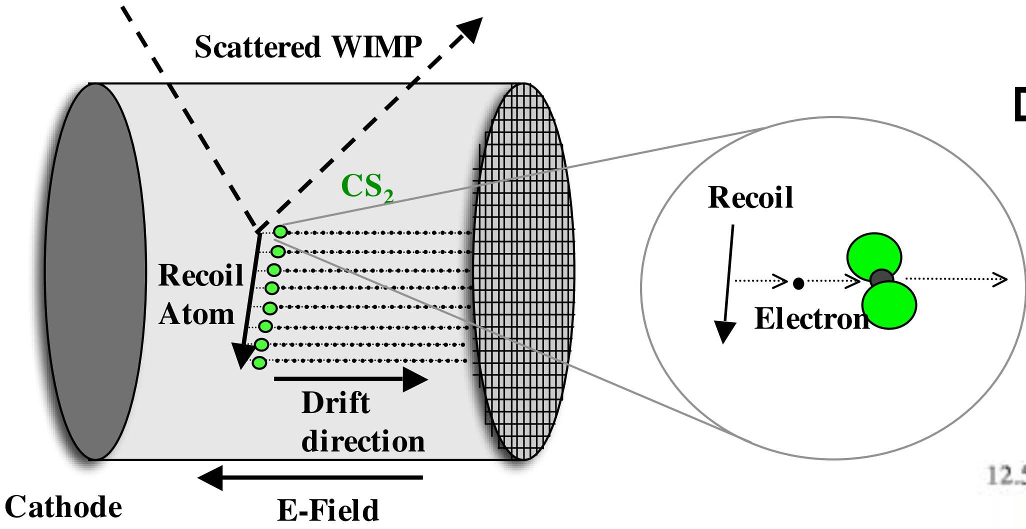
→ should be helpful to confirm or deny claimed signal



Further reduction in ^{137}Cs anticipated



DRIFT: Look for diurnal modulation

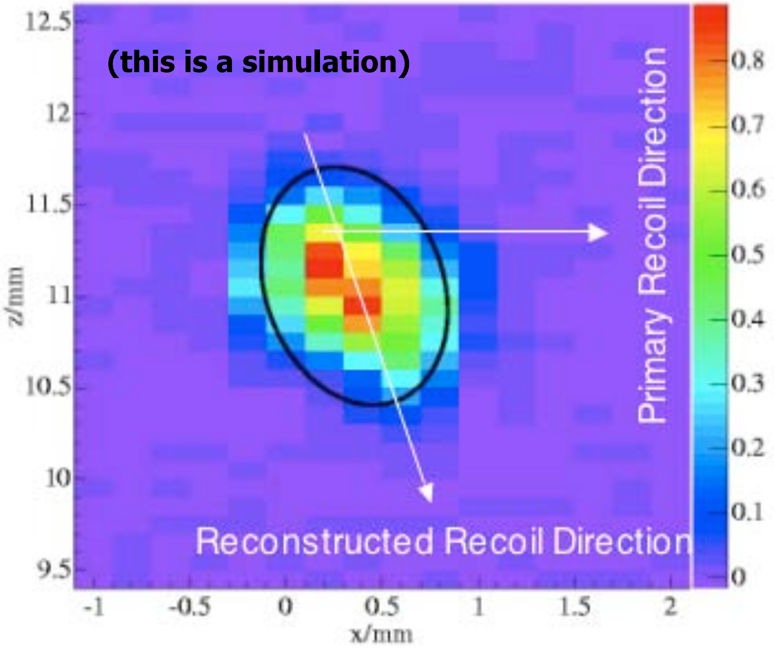


Drift negative ions in TPC

- No magnet
- Reduced diffusion

Electron recoils rejected via dE/dx, range

40 keV S recoil in 40 Torr CS_2


(this is a simulation)

Model for realistic (advanced) detectors

- 40 Torr CS_2
- 1 $kVcm^{-1}$ drift field
- 200 μm resolution
- 10 cm drift
- ***SRIM2003 - recoil scattering and diffusion***

DRIFT I

- Cubic meter in Boulby since 2001
- Engineering runs completed

DRIFT II extension to 10 kg module proposed

- But very difficult to justify expense of larger target mass until signal seen

What do we learn if we see a signal?

Current limit corresponds to
< 1 evt per 8 kg-d for Ge

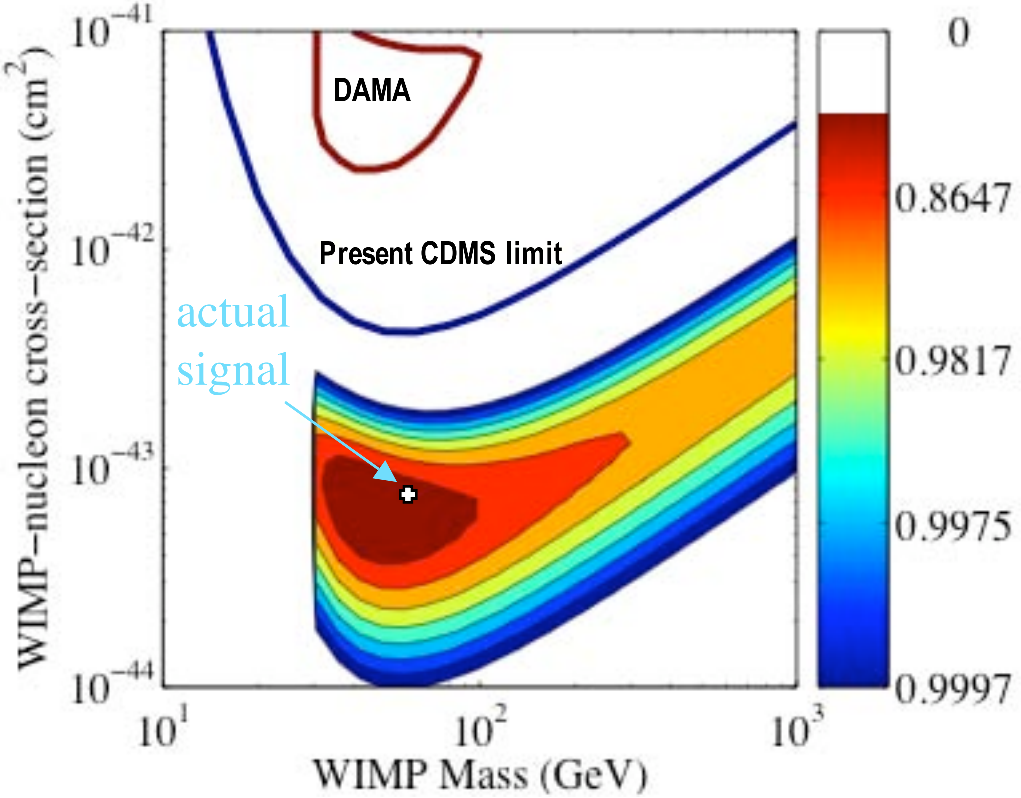
Suppose we see signal of 8 events at rate of 1 evt per 50 kg-d over next two years at Soudan

Mass and cross section determined as shown

- **(spin-dependence determined from comparing Ge and Si)**

Cannot tell if WIMPS are SUSY LSPs or not

- **But suggests where to look for neutralinos at LHC/ILC**



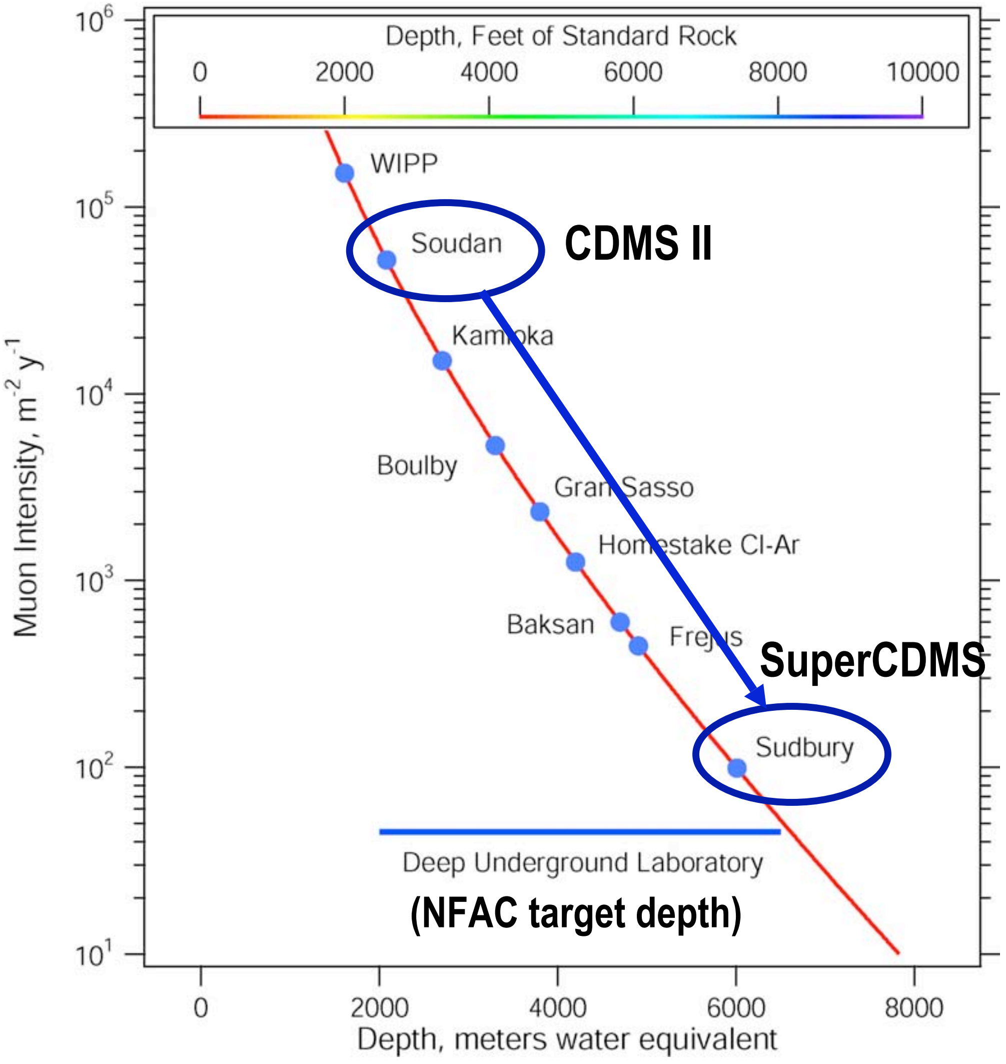
A convincing signal would motivate building DRIFT-style detector to look for directionality.

If SUSY seen first at LHC would still want to determine if LSP is the dark matter, SO NEED TO PUSH DIRECT DETECTION EITHER WAY

The Future of Direct Detection - Bigger, Cleaner, Deeper

All experiments moving towards:

- Larger detector mass
  - Present 10 -> 100 -> 1000 kg
- Lower backgrounds
  - Deepest sites (> 4000 mwe)
  - Better U/Th/K/Rn exclusion
  - Improved detector rejection
- Longer exposures
  - Improved limits to constrain SUSY
  - Explore signals which emerge



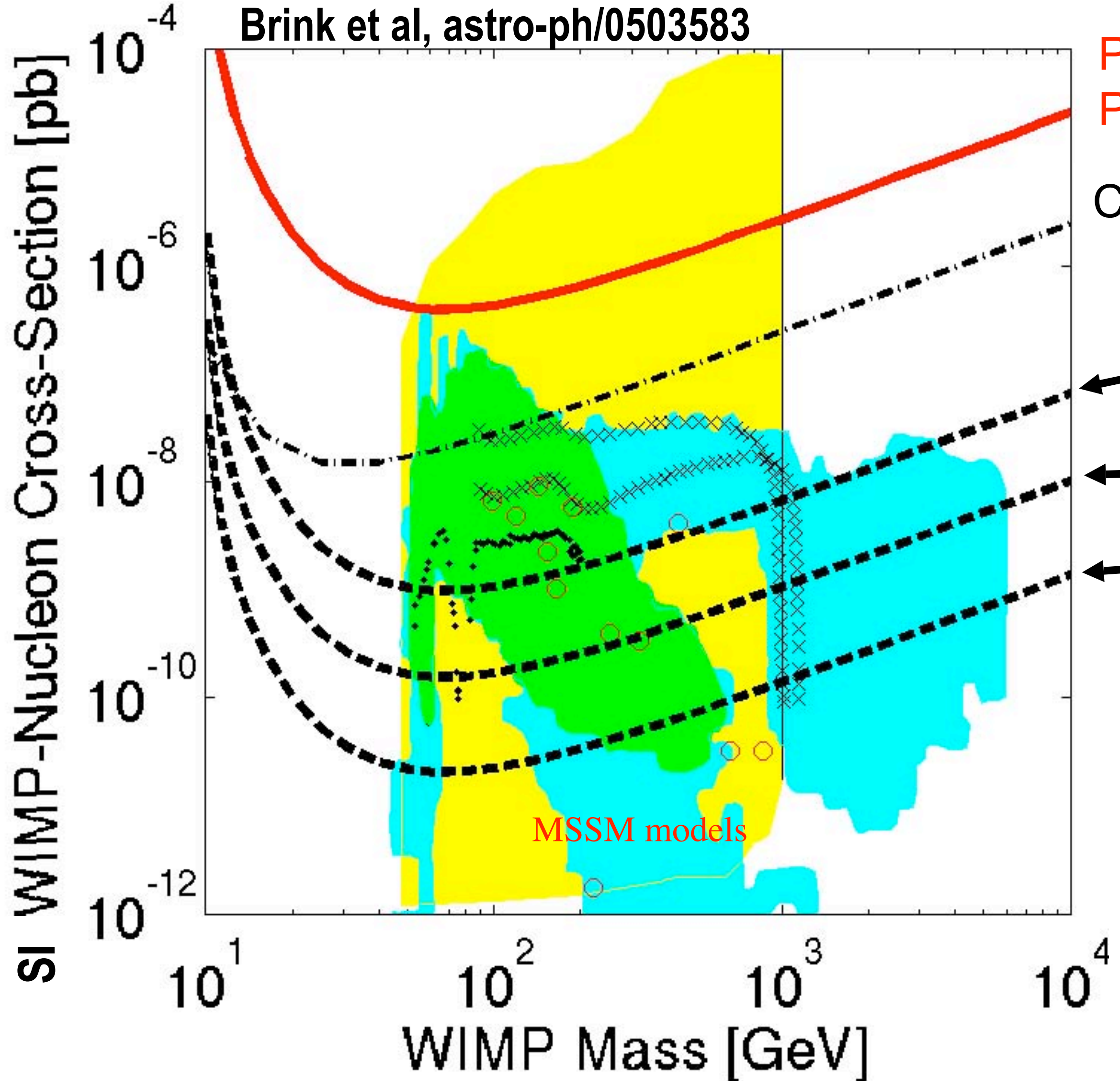
CDMS II

SuperCDMS

(NFAC target depth)

SuperCDMS Reach

Schnee et al, astro-ph/0502435
Brink et al, astro-ph/0503583



Published CDMS II limit
PRL 93, 211301 (2004)

CDMS II goal (end 2005)

SuperCDMS Phase A
25 kg of Ge 2011

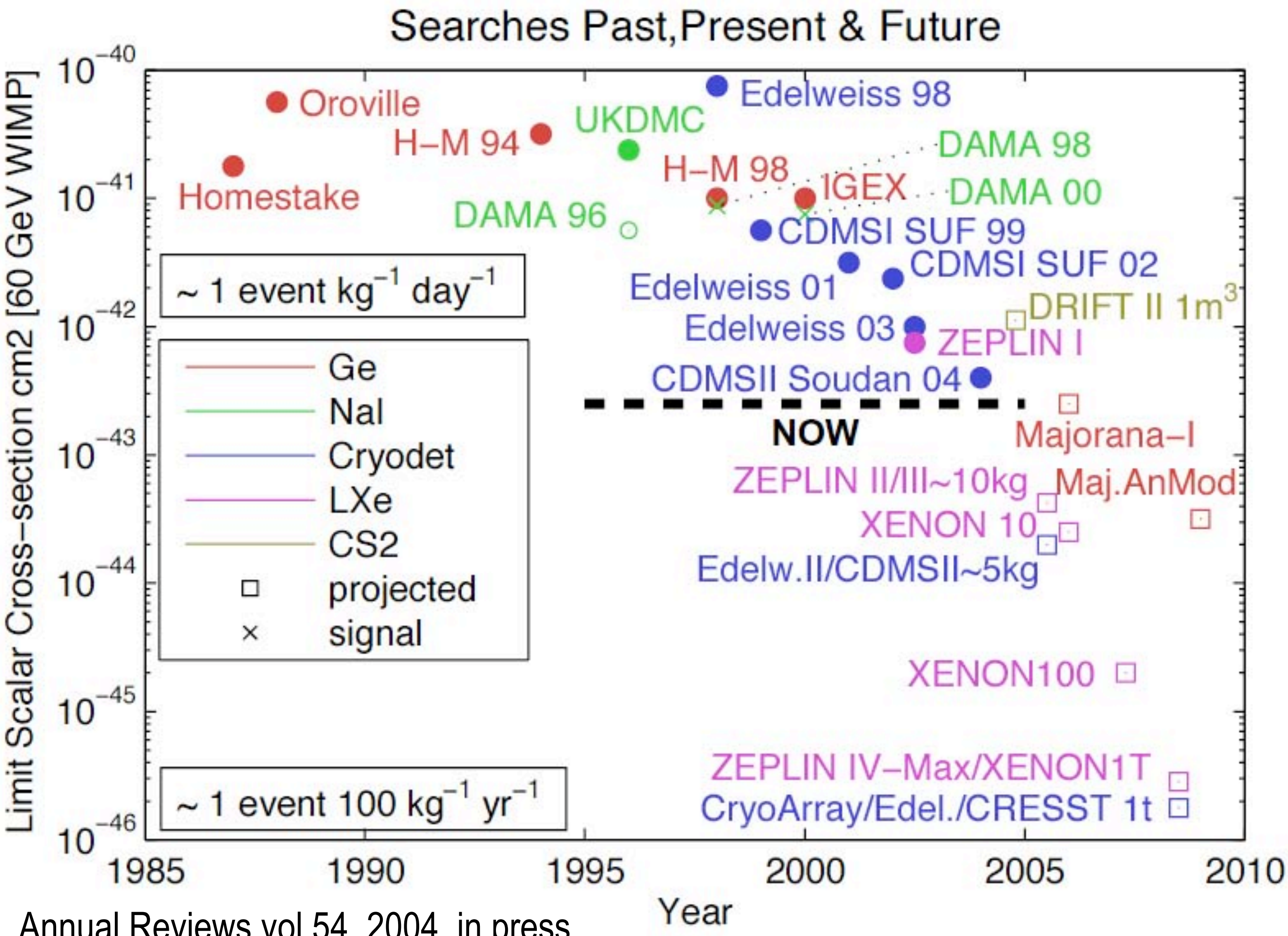
SuperCDMS Phase B
150 kg of Ge 2014

SuperCDMS Phase C
1000 kg of Ge

Maximize discovery potential by being background-free at each phase

Complementary with LHC search for neutralinos (red circles) and with similar reach!

DM Direct Search Progress Over Time

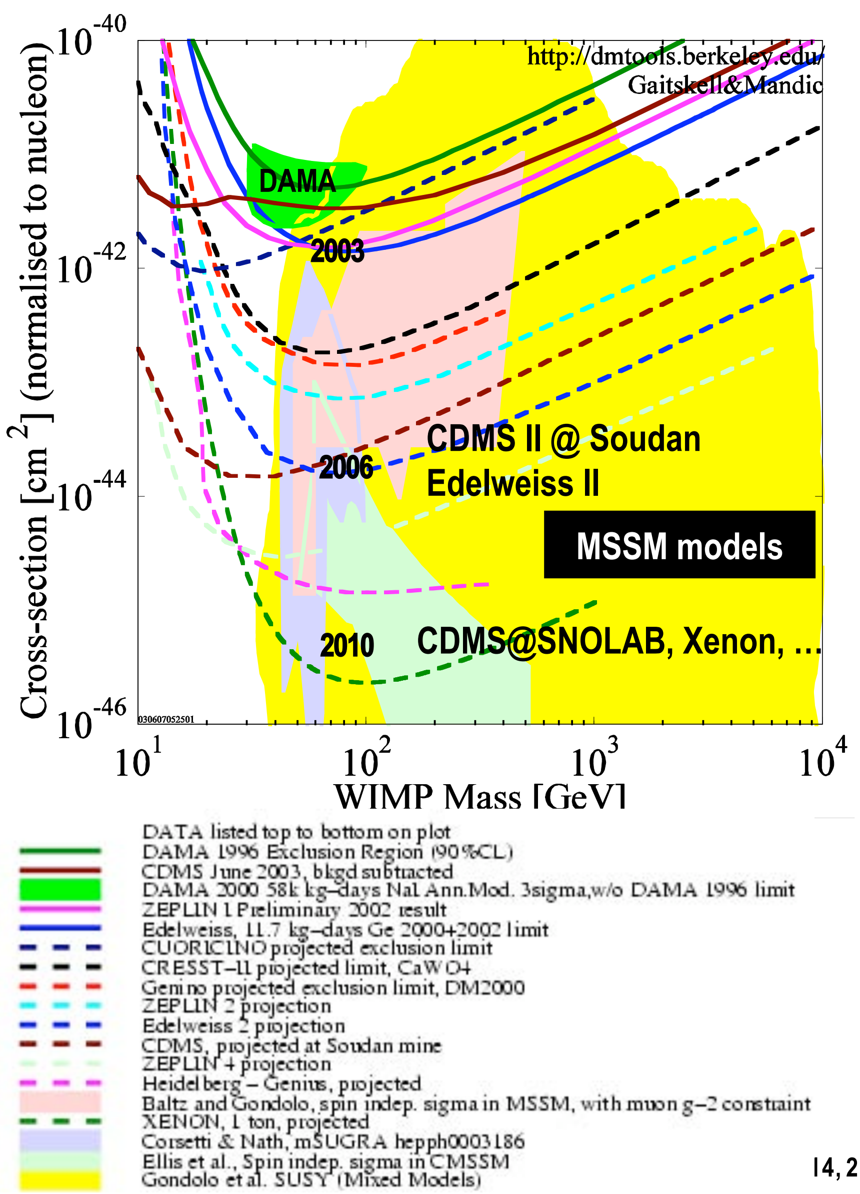


Gaitskell, Annual Reviews vol 54, 2004, in press

Summary and Projections

- **Cold Dark Matter**
  - Looking for 23% of the universe!
  - Physics outside SM (Axions, WIMPs)
- **Broad range of experimental techniques**
  - Axion searches will soon cover more of the likely parameter space
  - Intriquing hints from indirect searches for WIMPS
  - Significant improvement in direct detection limits from CDMS
- **Growing scale of experiments**
  - Excellent prospects to see signal soon!
  - Competitive reach for SUSY with LHC!
    - Direct detection sensitive to higher masses!
  - Unfortunately, costs are also growing :(
    - Field will likely contract to a few big experiments.

90% CL upper limits assuming standard halo, A^2 scaling



Advantages of CDMS approach to direct detection

We are taking data at a deep site!

- Edelweiss, CRESST are rebuilding (larger mass, better shielding)
- Xenon, bubble chamber are promising technologies, but in R&D stage

We have very low energy thresholds (< 10 keV recoil)

- Due to large phonon signal (10^6 phon/keV)
- Big advantage with respect to Xenon (~1 pe/keV)

We have a lot of information about candidate events

- Ionization yield (ratio of charge to phonon signal)
- Timing (discrimination against surface events)
- Segmented charge electrode (fiducial cut against outer regions of crystal)
- Position resolution (mostly from phonon signals)
- Multiple detectors (multiple scattered events = neutrons)
- Si vs Ge (neutrons or WIMPs)

In a discovery, we will have many checks that events are WIMPs