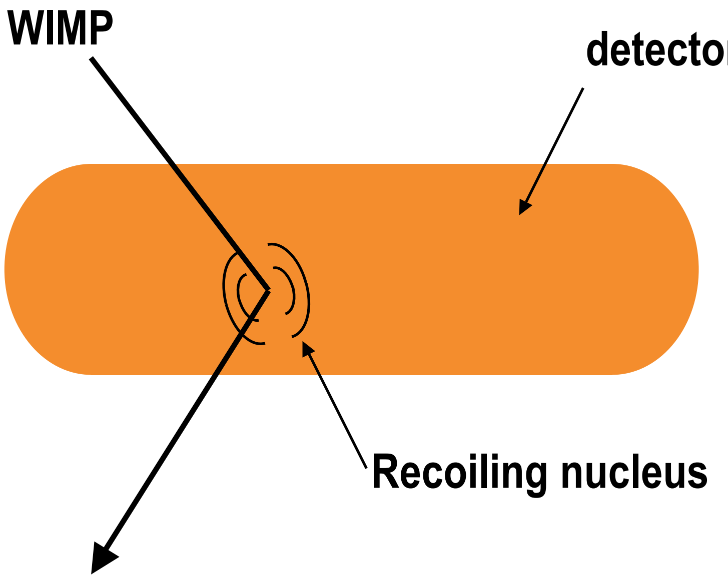
Direct Detection of Dark Matter



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Outline

Introduction
- Scientific case for dark matter in the form of WIMPs
- Take the experimental approach; let’s see what’s out there…

Direct Detection of WIMPS
- What do you have to do to spot a WIMP?

Cryogenic Dark Matter Search - A typical experiment
- What’s our angle?
- Have we seen any yet?

Other experimental approaches
- How are other people trying to find WIMPs?

The future of direct detection
- When might we expect to find WIMPs?

Conclusions

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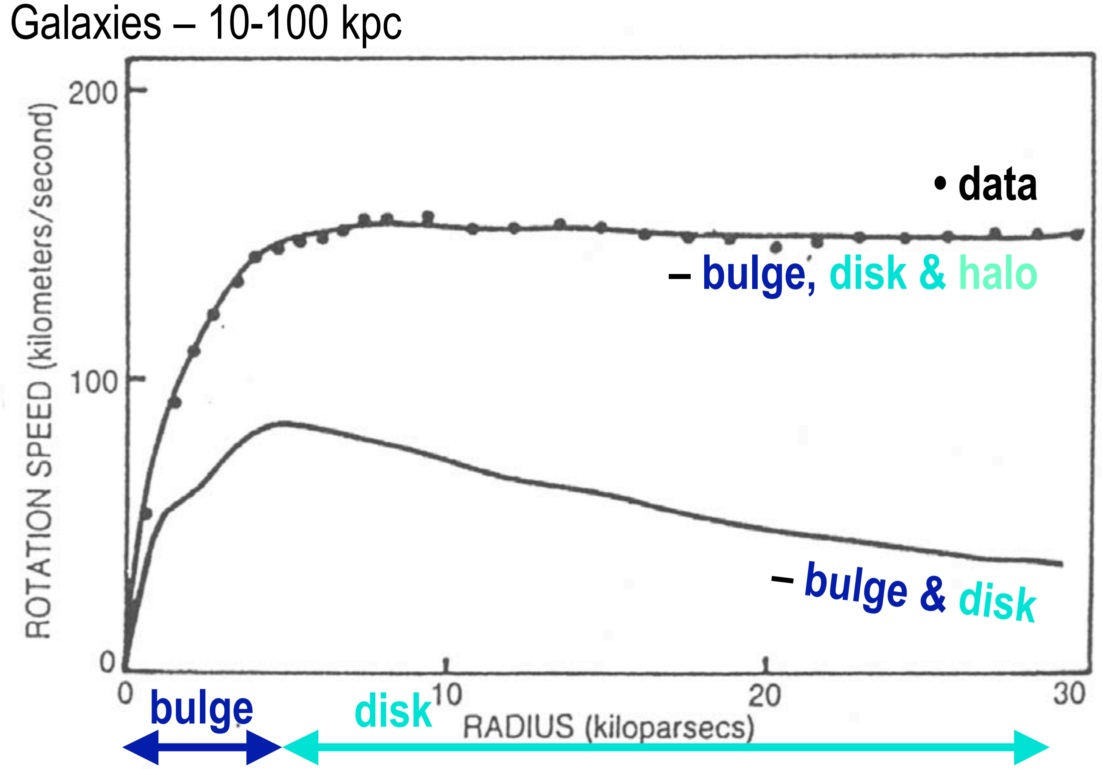
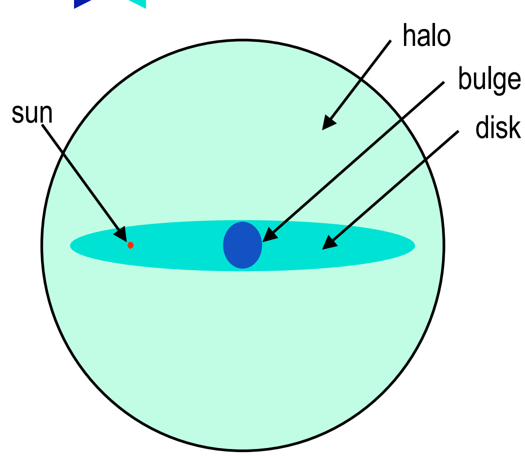
Dynamical Evidence for dark matter: Galactic Halos

Galaxies – 10-100 kpc





$$F_{\text{centripetal}} = F_{\text{gravity}}$$

$$\frac{mV_r^2}{r} = \frac{GmM_{\text{total}}(r)}{r^2}$$

$$V_r = \sqrt{\frac{GM_{\text{total}}(r)}{r}}$$

$$\rho_{\text{dark}}(r) \propto \frac{1}{1 + (r/r_c)^2}$$

$$\Omega_{\text{dark}} \geq 10\Omega_{\text{stars}}$$

$$\Omega \equiv \rho/\rho_{\text{critical}}$$

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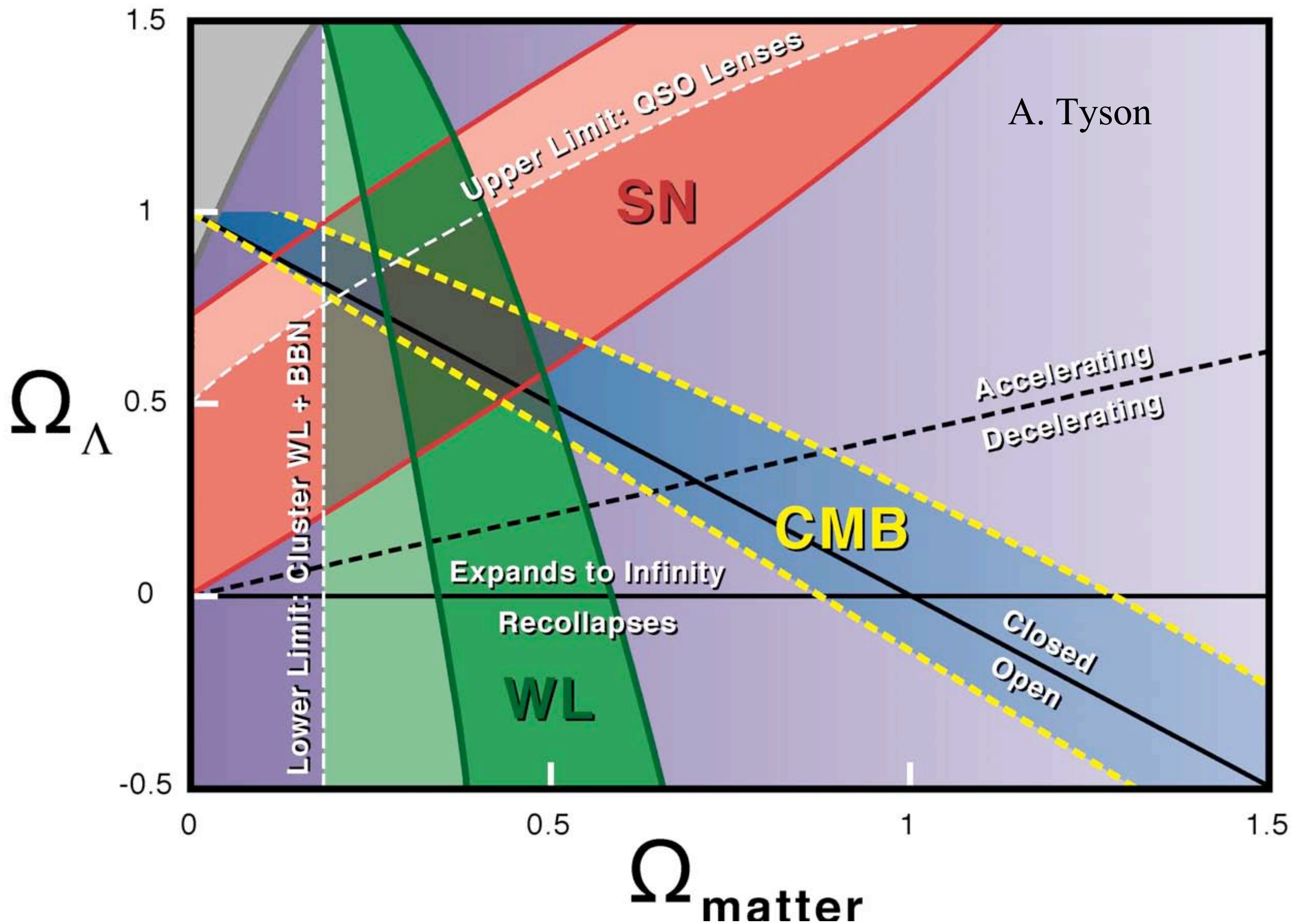
Dark Matter and Recent Cosmology Results



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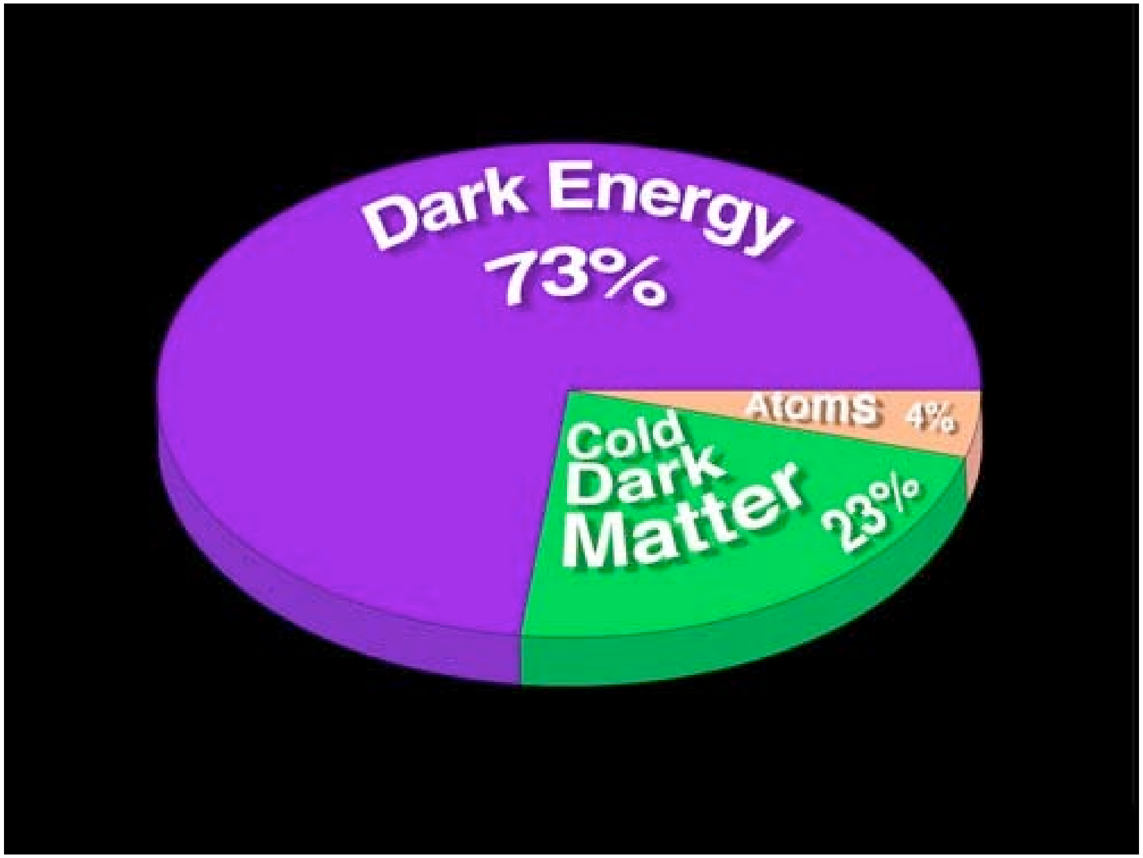
Standard Model of Astrophysics



But what is all this cold dark matter?

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Darth Matter

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Dark Matter is different from normal matter

Big Bang Nucleosynthesis

- Constrain baryon density based on relative abundance of light elements from hot big bang
- Measurements of D/H in primordial gas clouds
  (Burles & Tytler)
  - $\Omega_B = 0.05 \pm 0.005$

No more than 5% of the universe is made of normal matter!

Clusters, CMB, SN1a (Pre-WMAP)

$\Omega_{Matter} = 0.35 \pm 0.05$

Spectacular confirmation from WMAP

- 'Standard Model' confirmed
  - $\Omega_B = 0.047 \pm 0.006$
  - $\Omega_{Matter} = 0.29 \pm 0.07$
- + SDSS further constrain to
  - $\Omega_{Matter} = 0.30 \pm 0.04$

Only about 30% of the universe is made of any kind of matter

Nature of dark matter

- Non-baryonic
- Large scale structure predicts DM is 'cold' – non-relativistic at time of matter-radiation decoupling
  - Required for "early" growth of galaxies

Particle physics – best candidates:

- WIMPs – Weakly Interacting Massive Particles
- Axions – solution to strong CP problem

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WIMPs as Non-Baryonic Dark Matter

Produced in big bang, but also annihilate with each other

Annihilation stops when number density drops to the point that

$$H > \Gamma_A \sim n_\chi \langle \sigma_A v \rangle$$

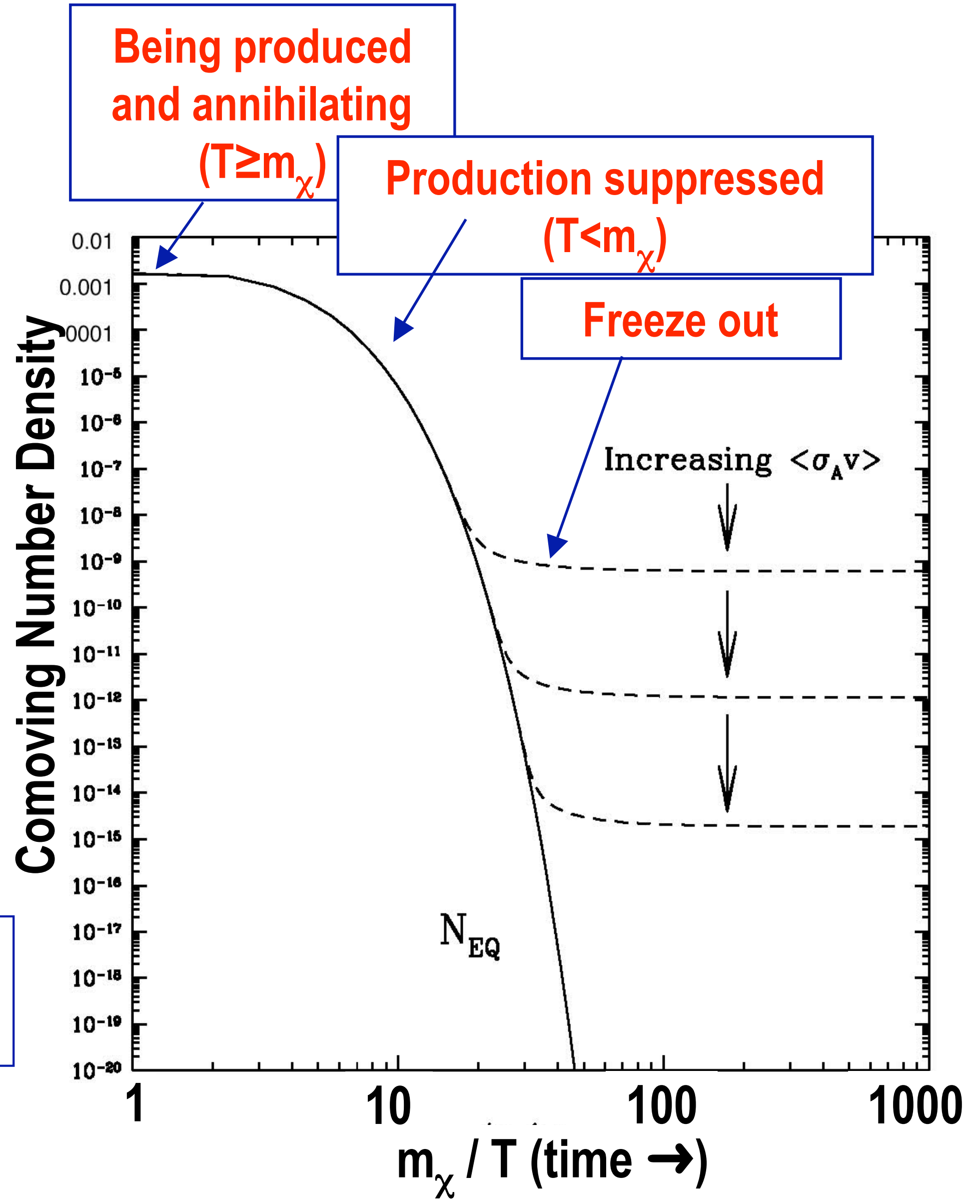
i.e., annihilation too slow to keep up with Hubble expansion ("freeze out")

Leaves a relic abundance:

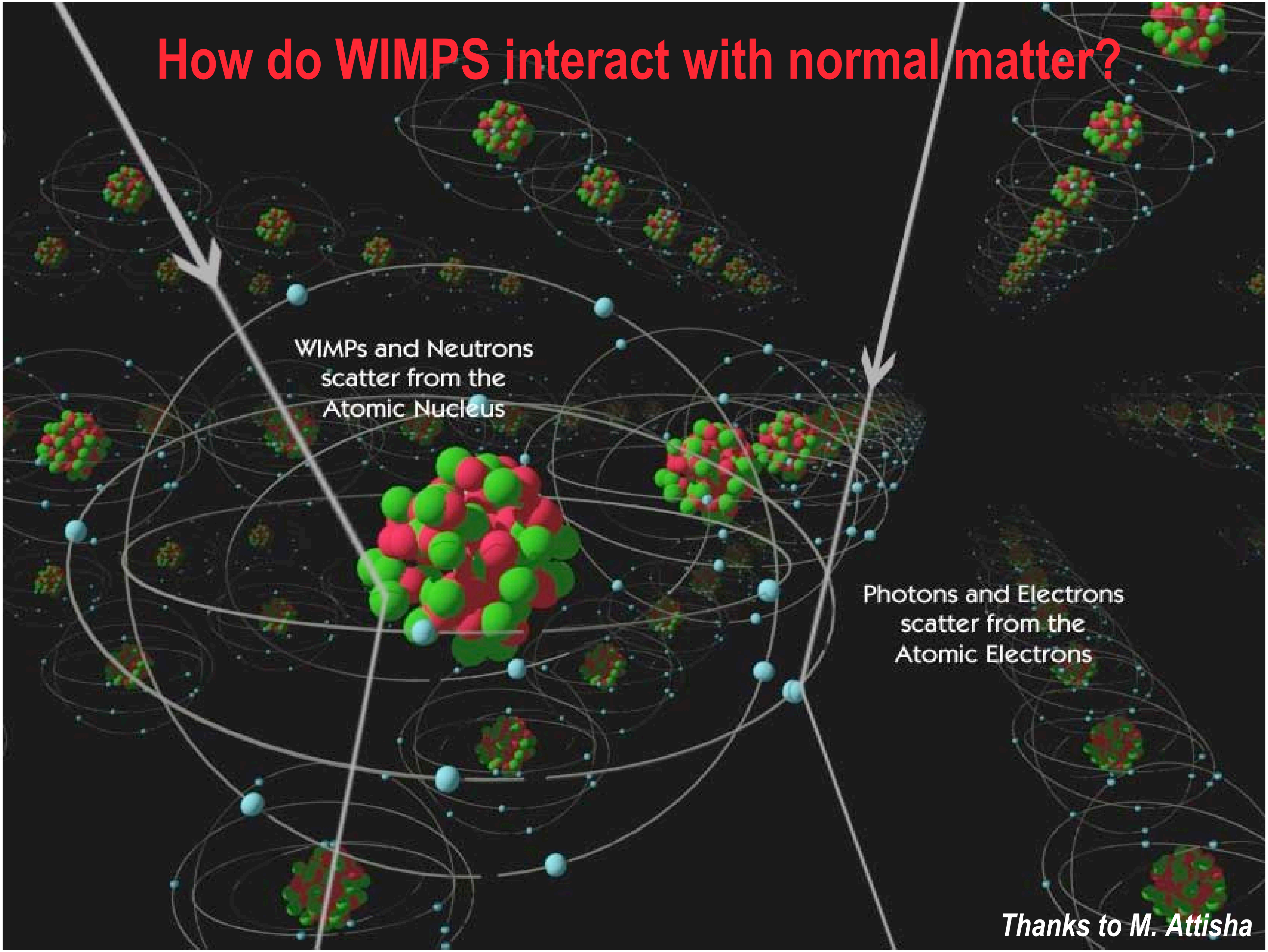
$$\Omega_\chi h^2 \approx 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1} / \langle \sigma_A v \rangle_{fr}$$

$$\Downarrow$$

if m_χ and σ_A determined by electroweak physics, then $\Omega_\chi \sim 0.3$



How do WIMPS interact with normal matter?



Thanks to M. Attisha

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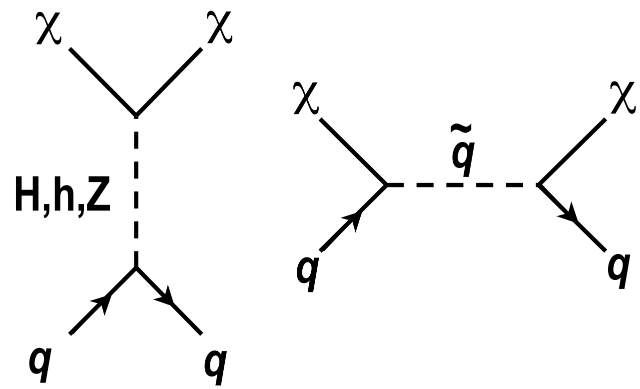
Direct Detection of WIMPs

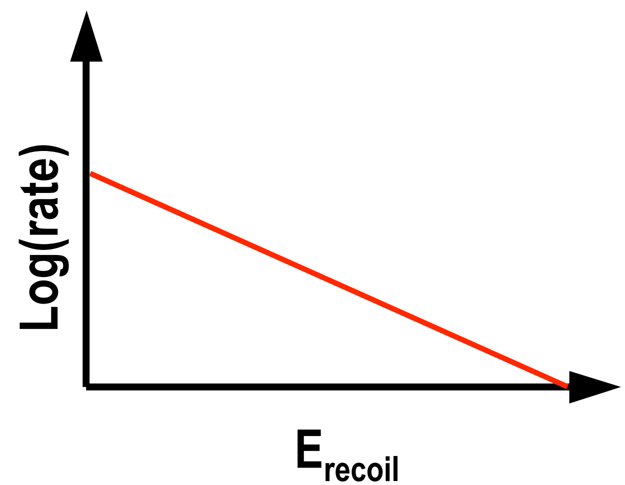


WIMPs elastically scatter off nuclei in targets, producing nuclear recoils, with $\sigma_{n\chi}$ related roughly by crossing to σ_A(~10^{-38} cm^2)

- 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 1 event per kg material per day

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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
    - Cannot contain radioactive impurities
- 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

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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

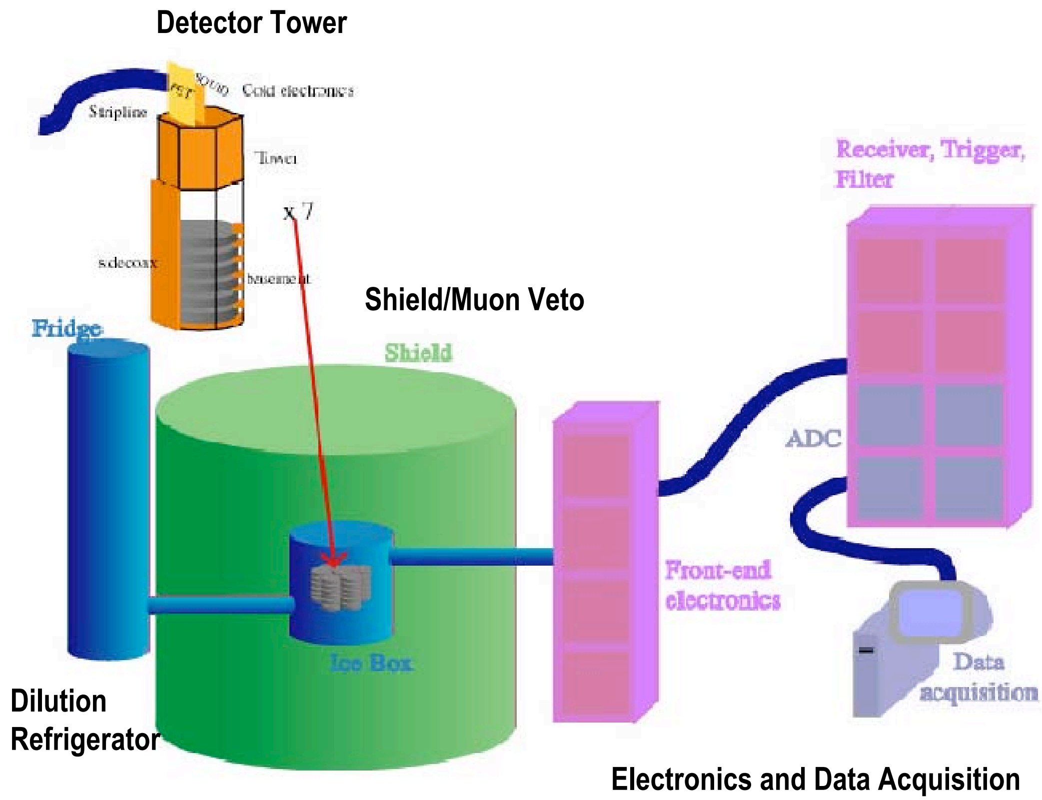
Nuclear recoils produce less charge for the same heat as electron recoils

Deep Underground (Soudan)

Fewer cosmic rays to cause background events

Shielding

Prevent radioactive decay products from reaching detectors



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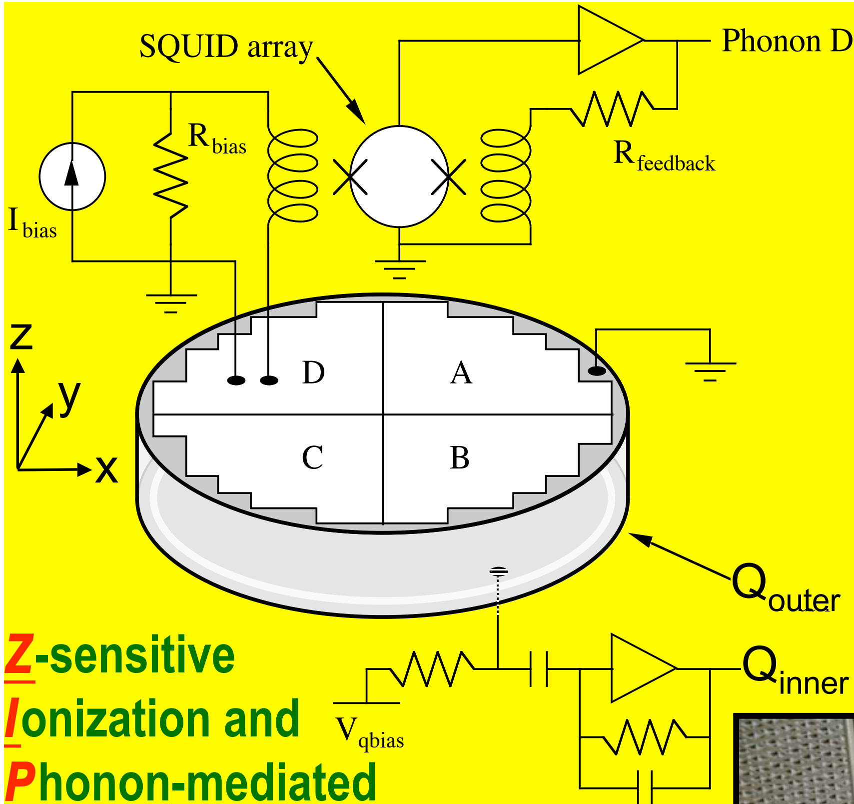
Really Cool Detectors: ZIPs



250 g Ge or 100 g Si crystal

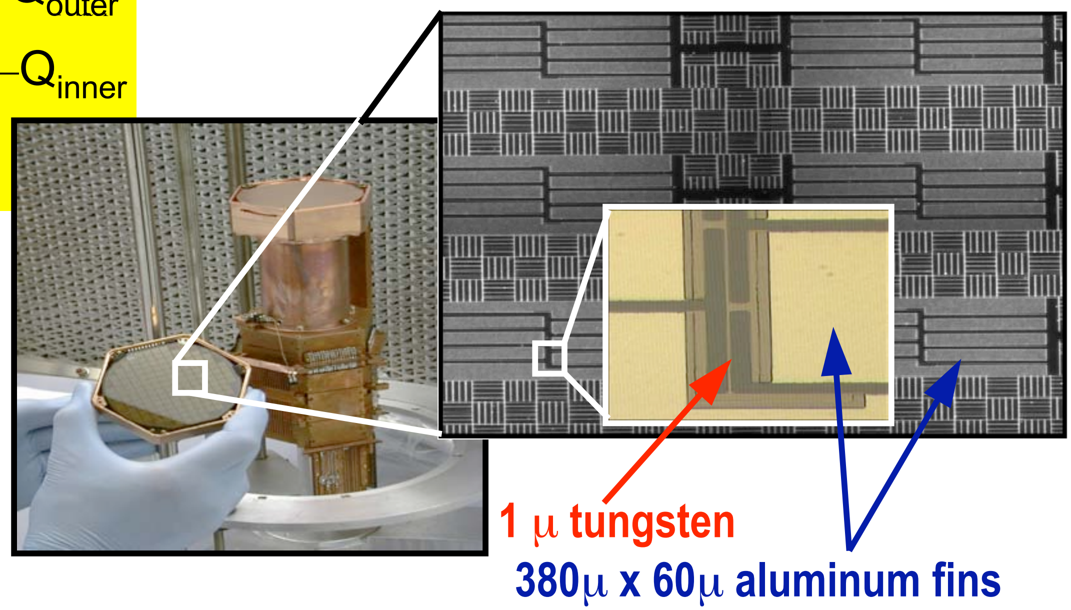
1 cm thick x 7.5 cm diameter

Photolithographic patterning

Collect athermal phonons:

- Crystal lattice vibrations
- Speed of sound in crystal ~ 1 cm/ms results in measurable delays between the pulses of the 4 phonon channels => position sensitivity

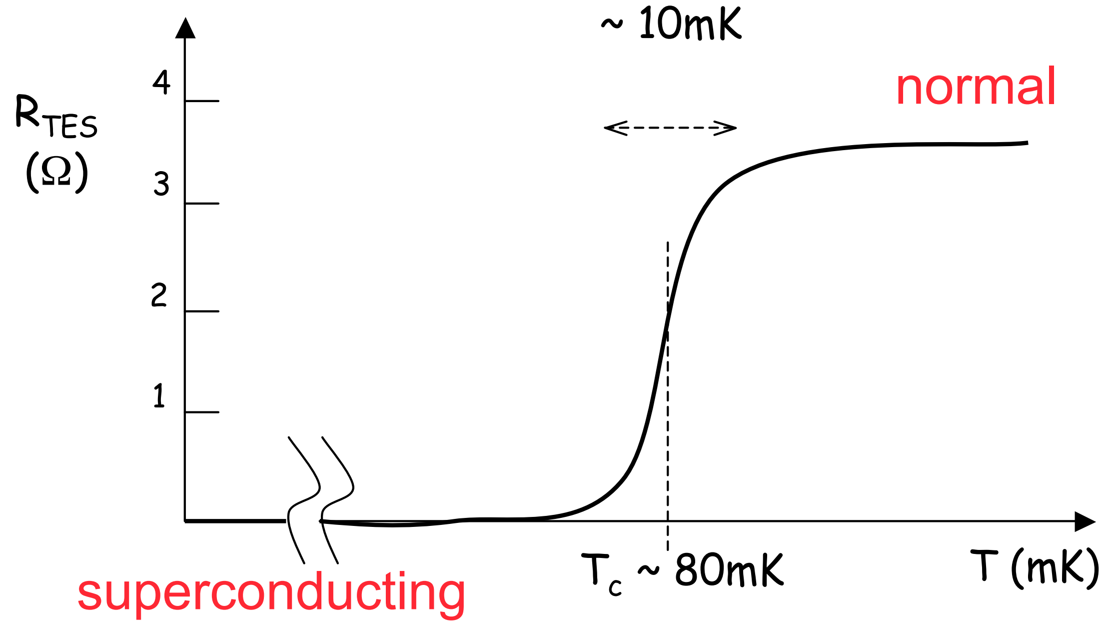
Measure ionization in low-field (~volts/cm) with segmented contacts to allow rejection of events near outer edge



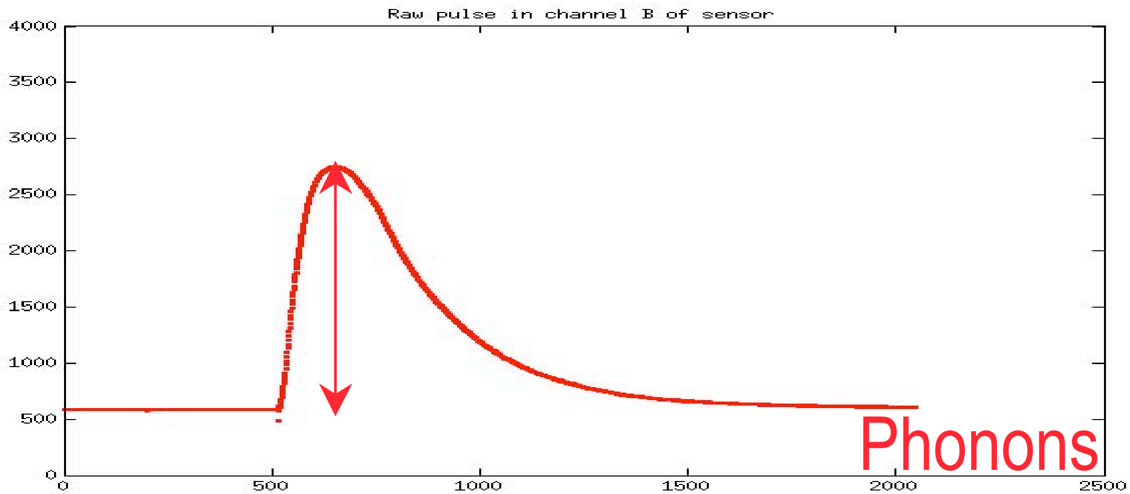
Superconducting Films: Ultrasensitive Thermometers

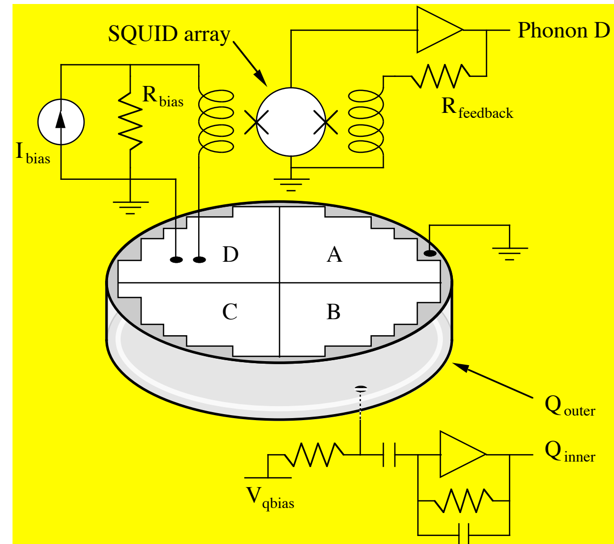
Superconducting films that detect minute amounts of heat

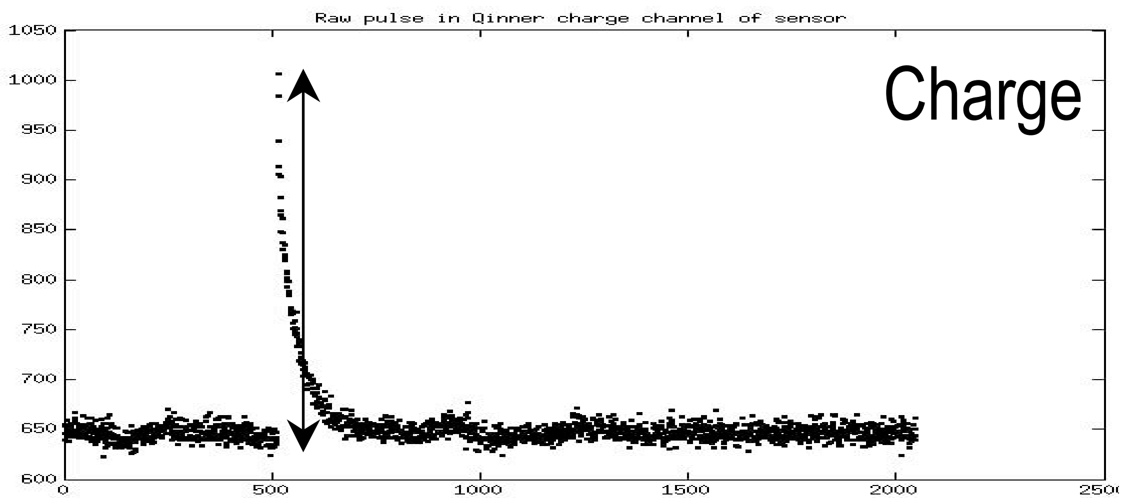
Transition Edge Sensor sensitive to fast athermal phonons

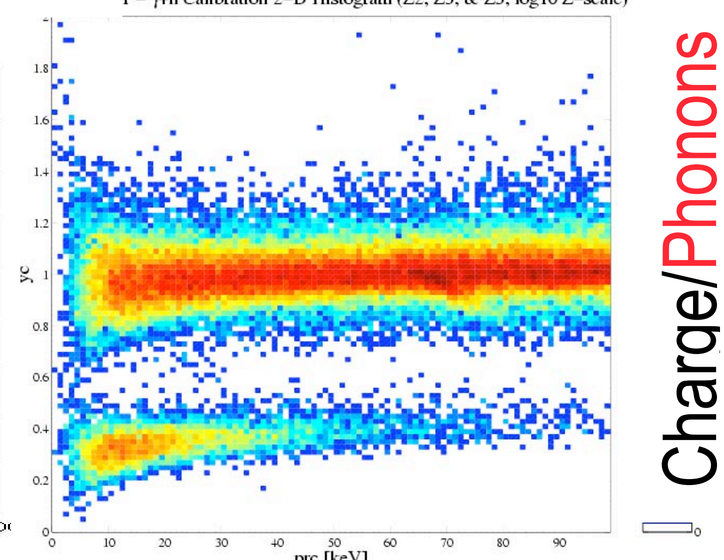


The Voltages We Measure









Phonons – Charge = Recoil energy

CDMS II Background Discrimination

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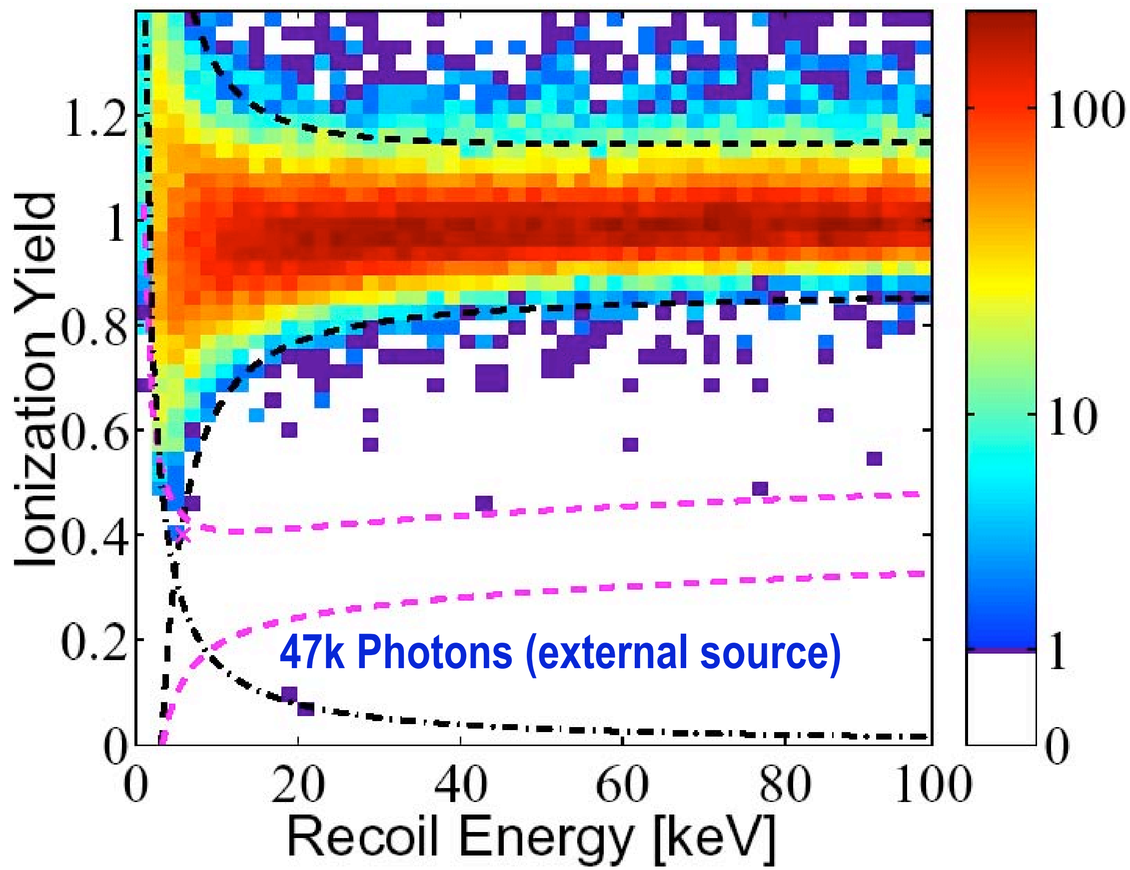
Ionization Yield (charge signal/ phonon signal) depends strongly on type of recoil

Most background sources (photons, electrons, alphas) produce electron recoils



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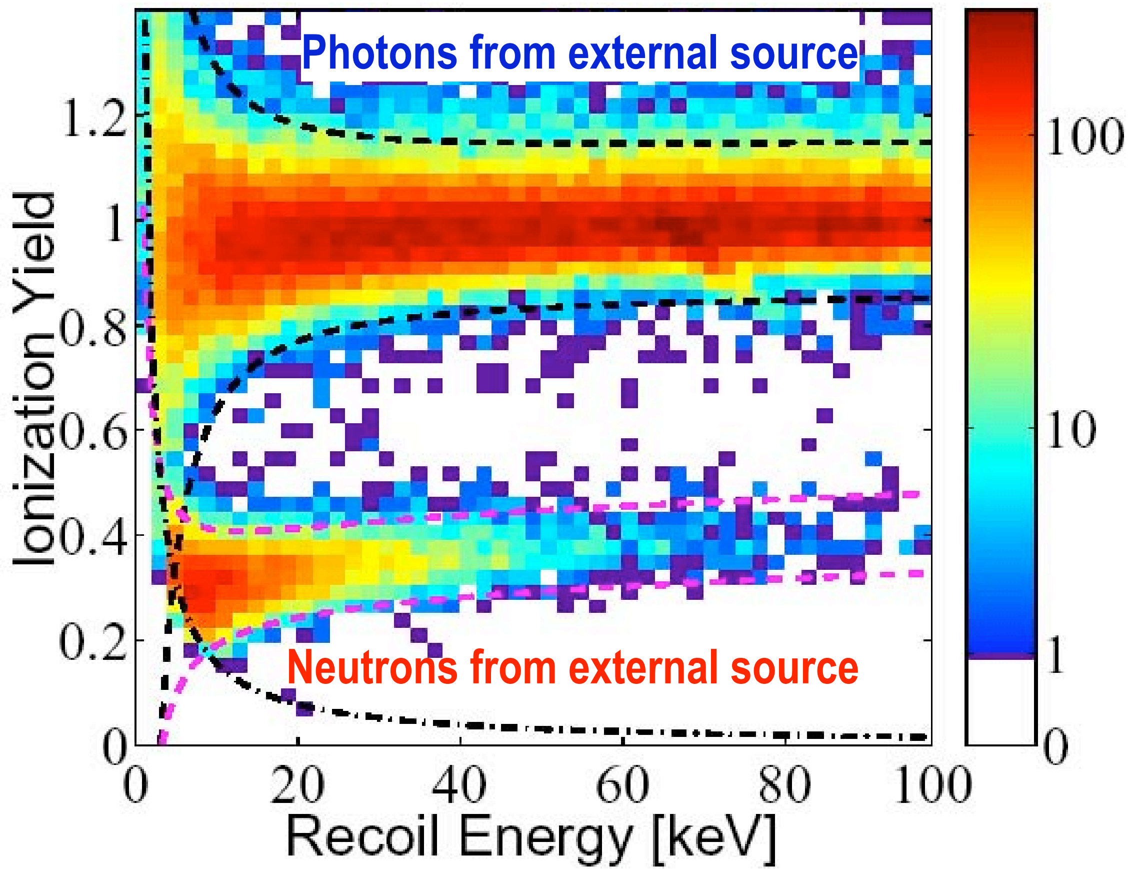
CDMS II Background Discrimination

Ionization Yield (charge signal/ phonon signal) depends strongly on type of recoil

Most background sources (photons, electrons, alphas) produce electron recoils

WIMPs (and neutrons) produce nuclear recoils



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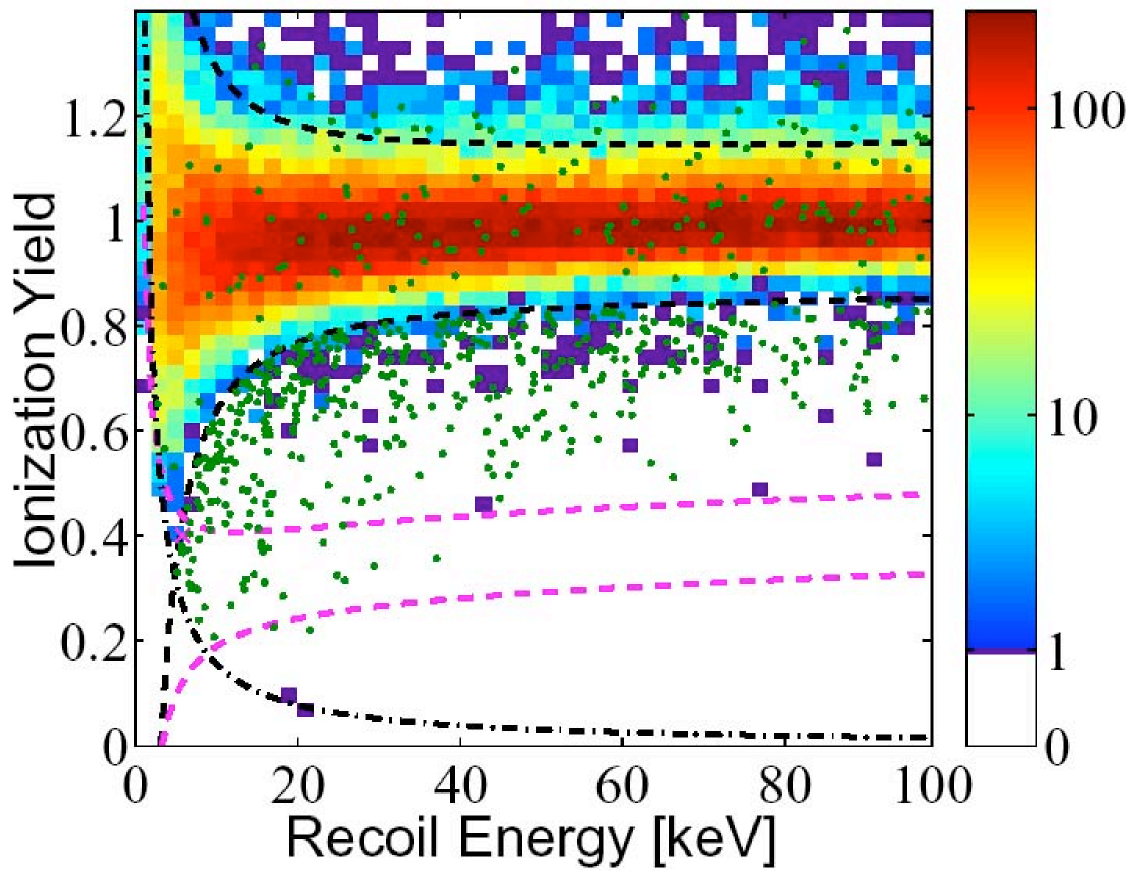

Detectors provide near-perfect event-by-event discrimination against otherwise dominant bulk electron-recoil backgrounds

Particles (electrons) that interact in surface “dead layer” of detector result in reduced ionization yield

The 'Z' in ZIPs: Electron Risetime Discrimination

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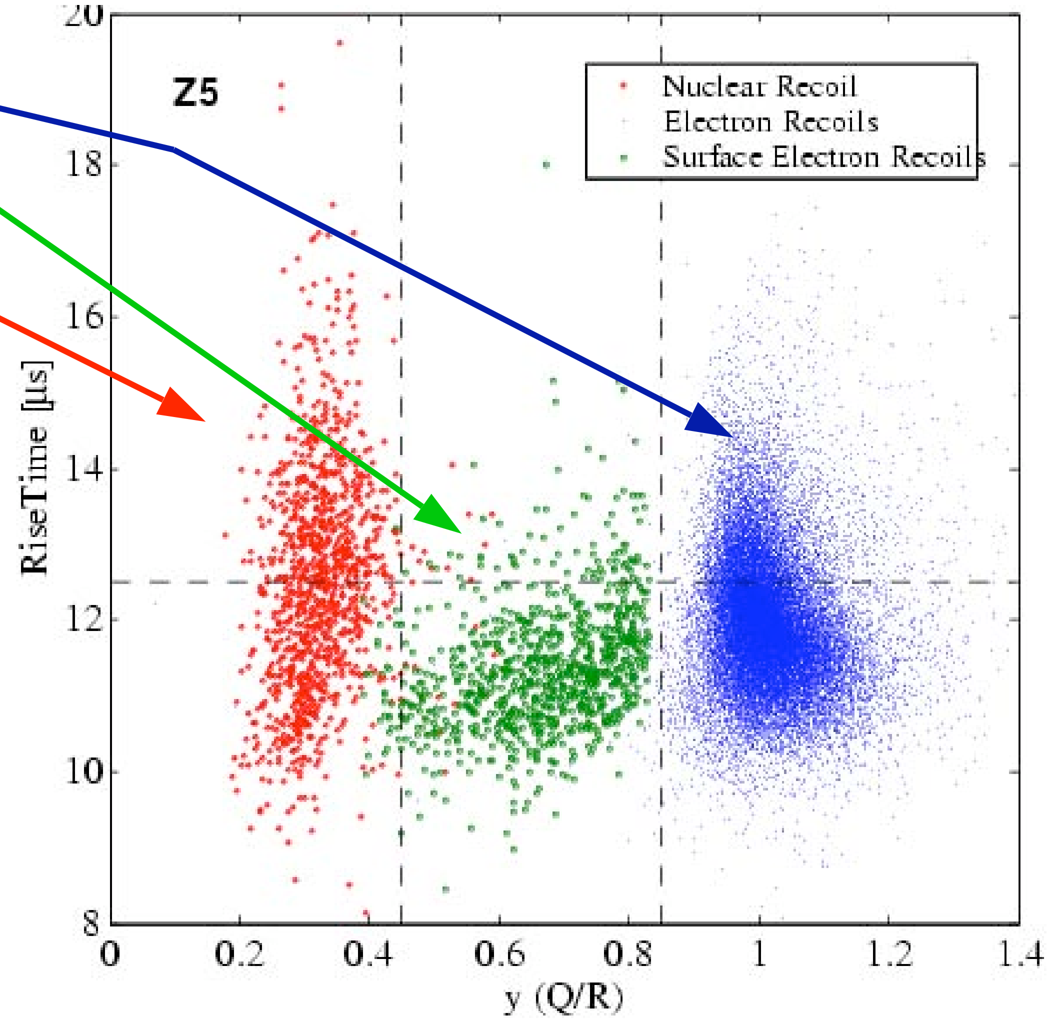
3 populations

- Electron recoils in bulk
- Surface events
- Nuclear recoils in bulk

Surface events produce faster phonons: 2nd discrimination parameter

- Pulse risetime and delay from charge pulse

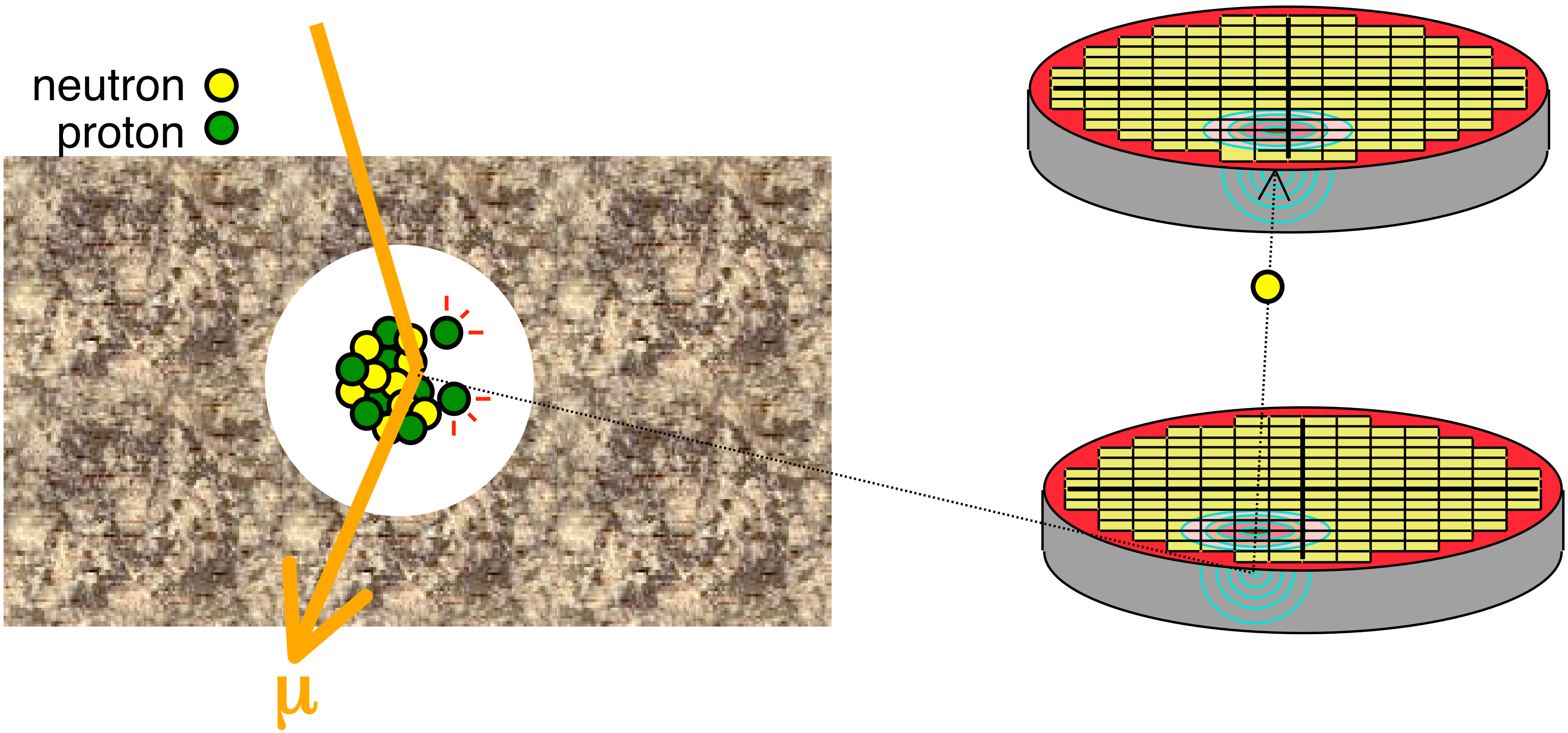
Important second handle on electron backgrounds with 'tail' in charge yield



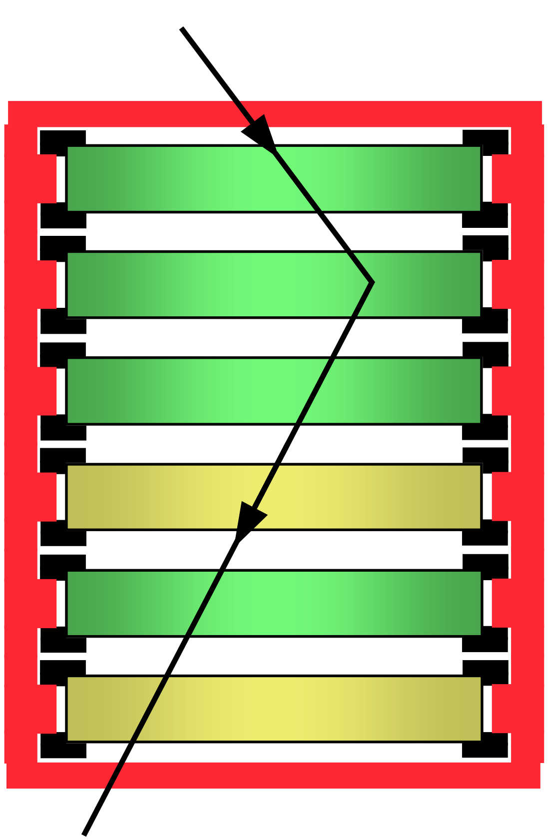
Those pesky little neutrons…

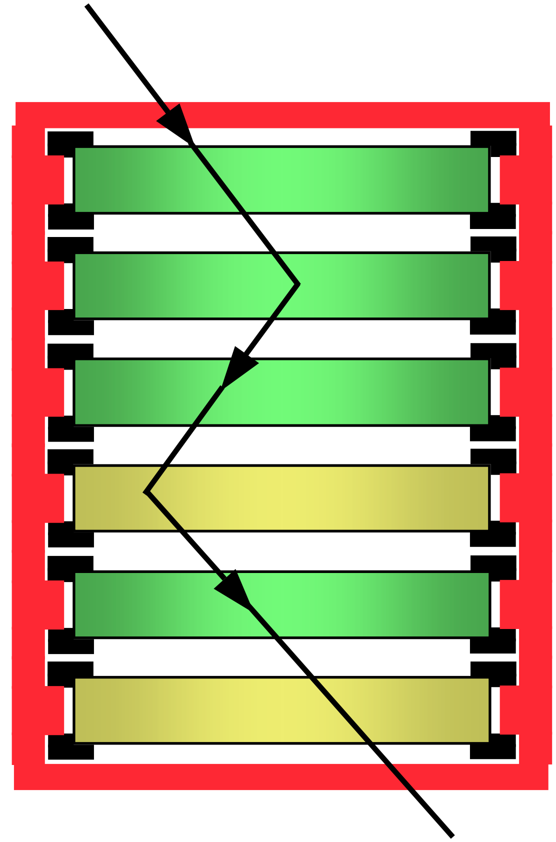
Neutrons produce nuclear recoils

Similar signature to WIMPs



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.

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WIMP vs Neutron Sensitivity of Si and Ge

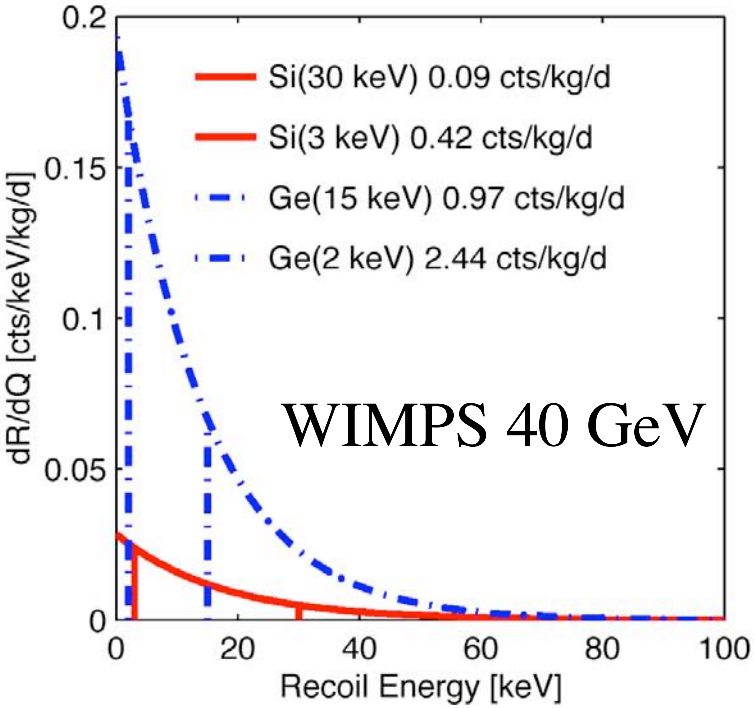
For neutrons 50 keV - 10 MeV

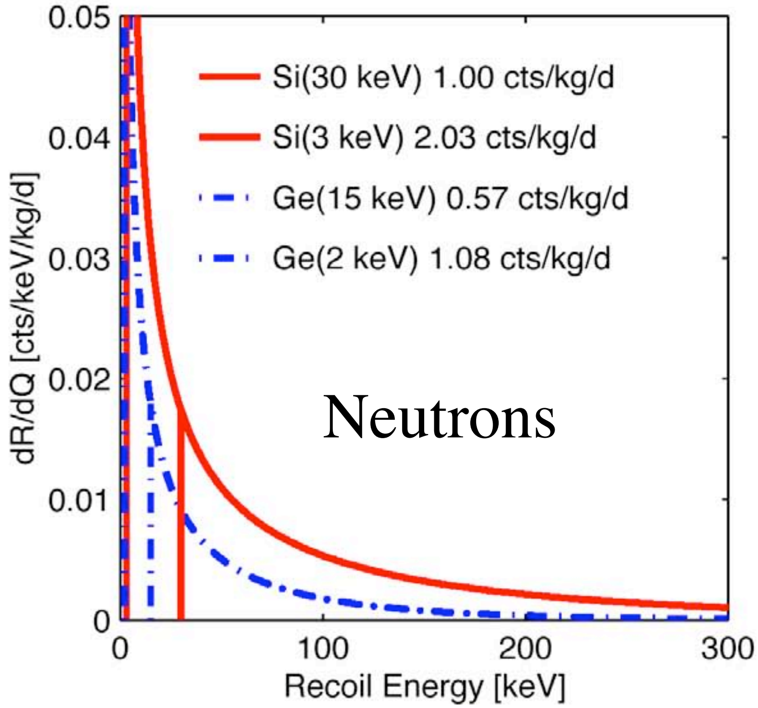
Si has ~2x higher interaction rate per kg than Ge

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!





Soudan, Minnesota :
The place to look for cold dark matter

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Life in the mine

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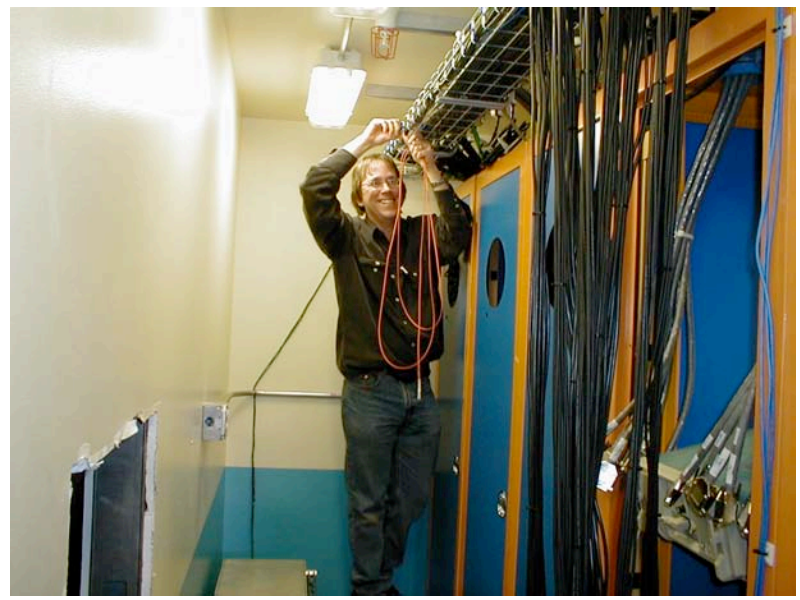
Pictures from the front lines



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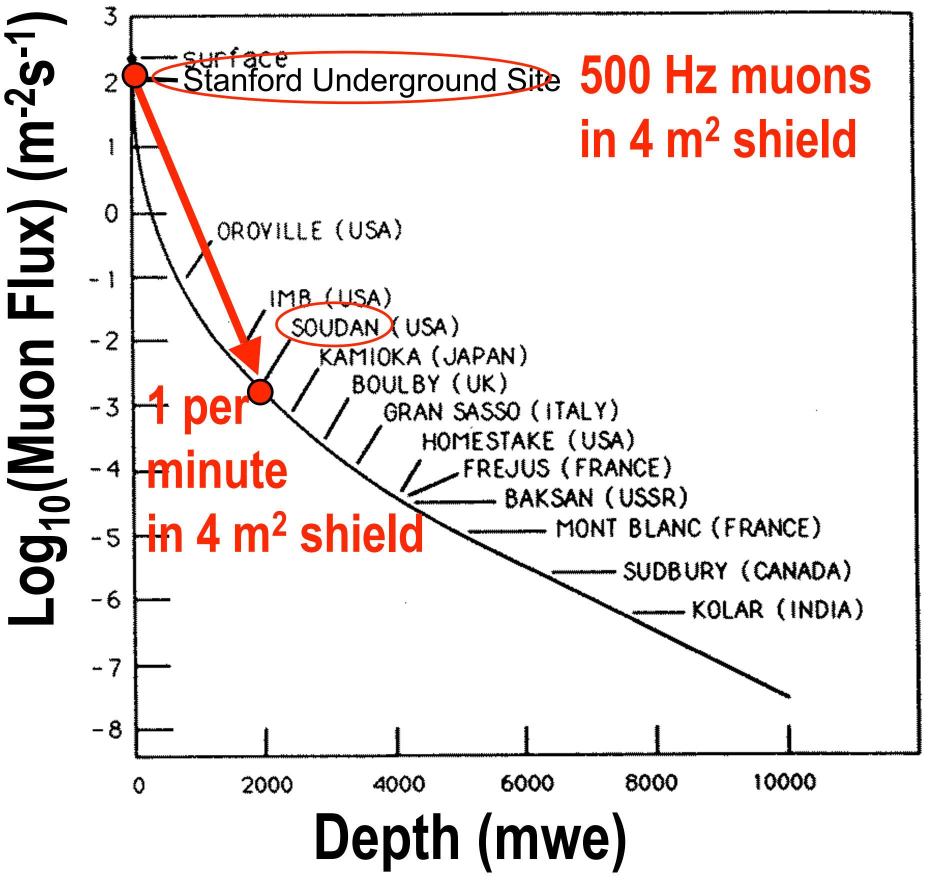
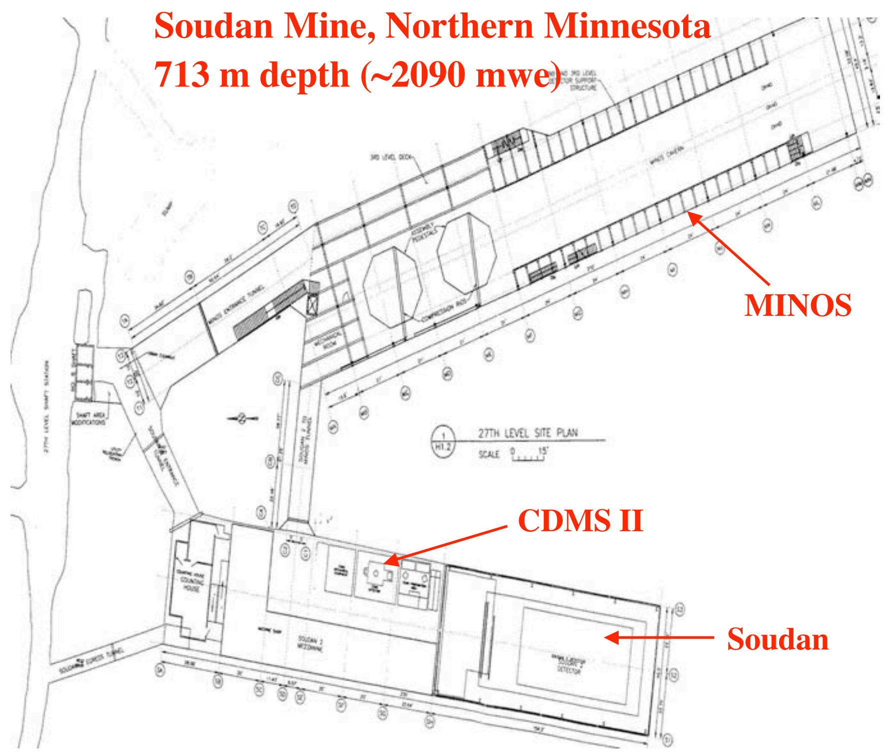
Why are we at Soudan?

Depth reduces neutron background to ~1 / kg / year (< 5 neutrons/year)

WIMP sensitivity goal is 0.01 events / kg / kev / day (~ 20 WIMPS/year)





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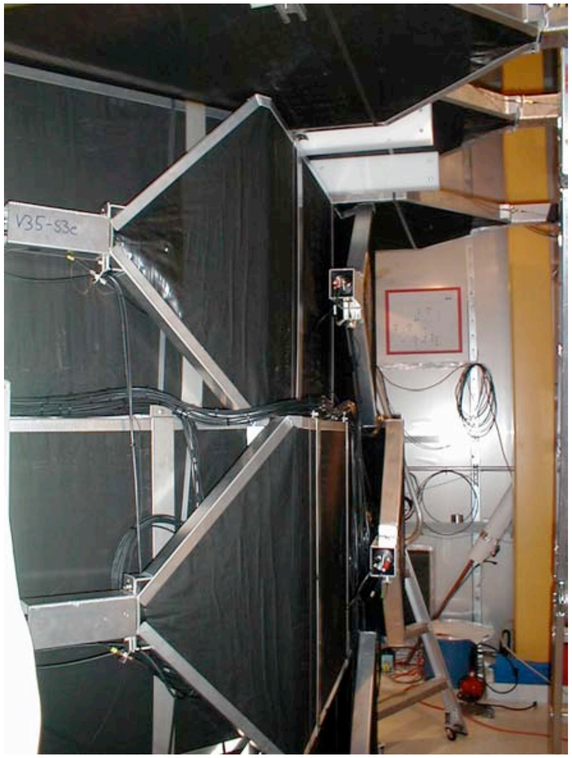
Shielding, Veto

Layered shielding (reduce γ, β, neutrons)
~1 cm Cu walls of cold volume (cleanest material)
Thin "mu-metal" magnetic shield (for SQUIDs)
10 cm polyethylene (further neutron moderation)
22.5 cm Pb, inner 5 cm is "ancient" (low in ^{210}Pb)
40 cm polyethylene (main neutron moderator)



Active Veto (reject events associated with cosmics)
Hermetic, 2" thick plastic scintillator veto wrapped around shield
Reject residual cosmic-ray induced events
Information stored as time history before detector triggers
Expect > 99.99% efficiency for all μ, > 99% for interacting μ
MC indicates > 40% efficiency for μ-induced showers from rock

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Cryogenics - How to get really cold

Dilution refrigerator

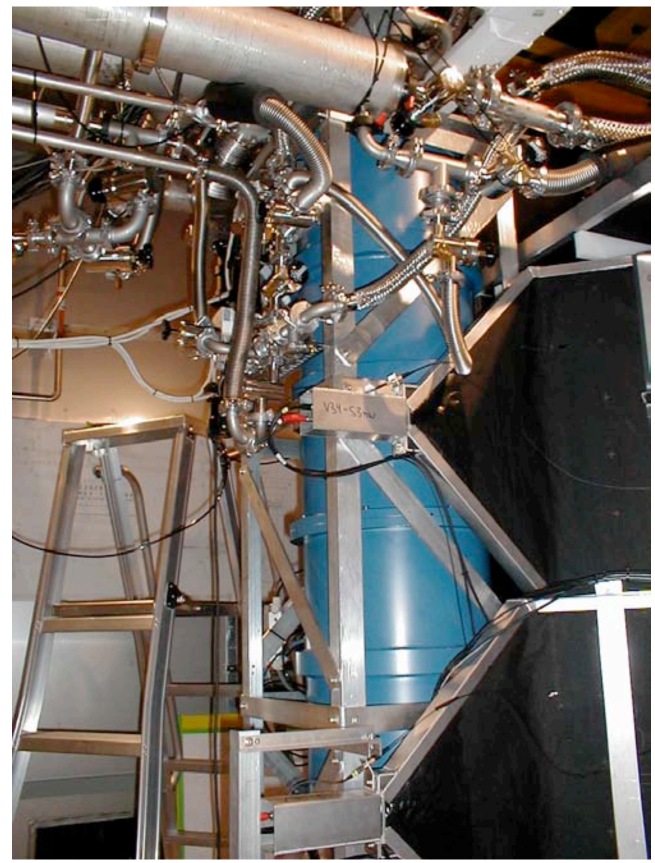
- Combination of vacuum insulation, liquid nitrogen (77K) and liquid Helium (4K)
- Pump on liquid Helium => 1.5 K
- Evaporate and condense 3He/4He mixture => 0.1 K

Icebox

- Copper cold volume offset from refrigerator
- Allows hermetic shielding against radioactive contamination, cosmic rays

Fridge

Icebox



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How to build a cryogenic experiment

The long road to setting up a new underground experiment
(> 1 year of work compressed to ~30 seconds)

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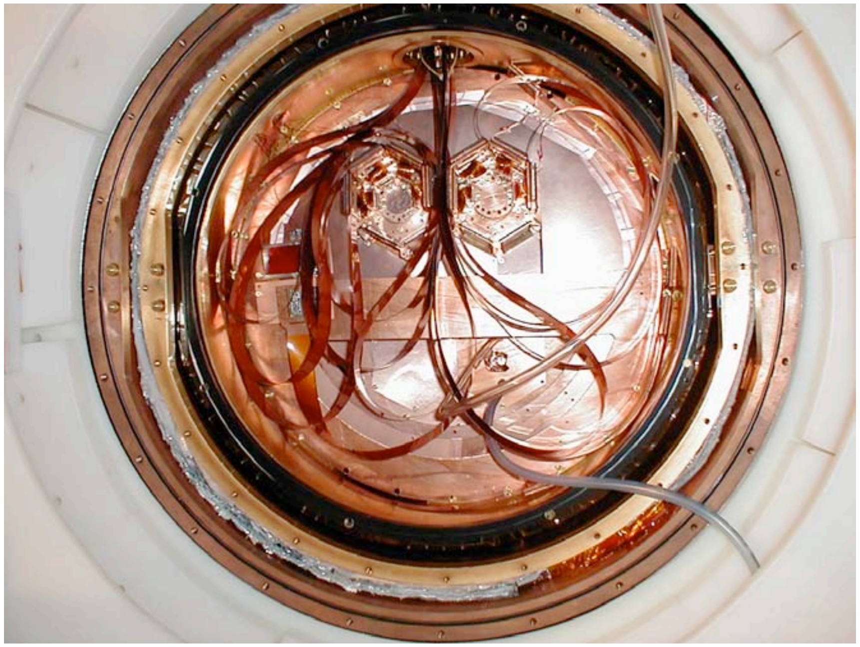
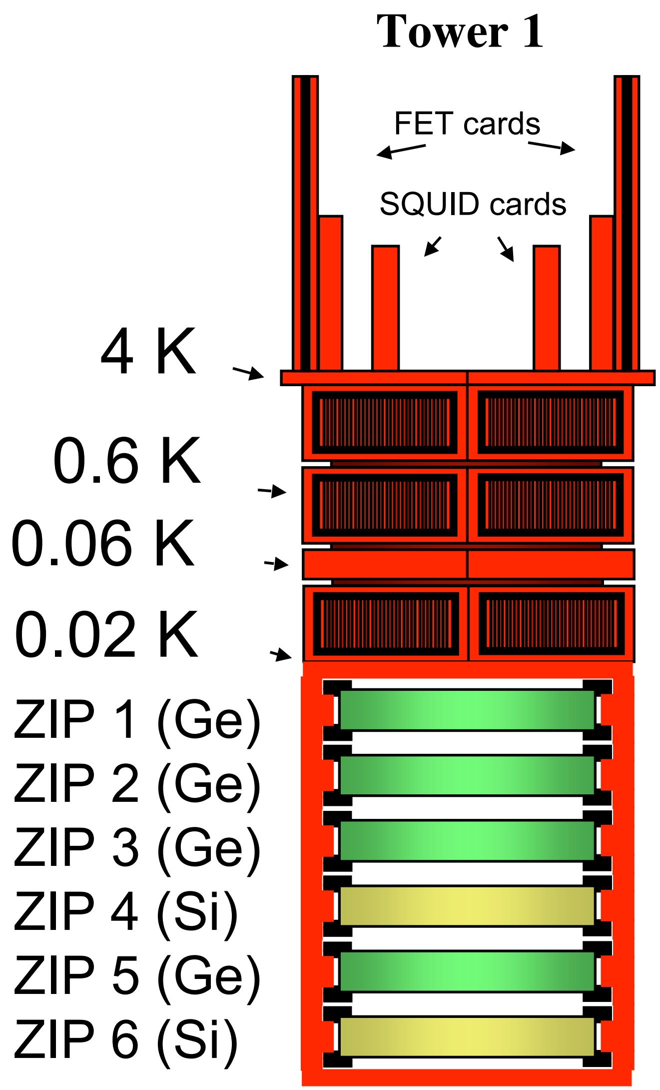
Installing detectors in the icebox

- Two Towers currently installed (6 Ge, 6 Si detectors)
  - Tower structure allows connection to thermal layers and path for electrical signals to room temperature
  - First stage preamplifiers at 4K to minimize noise
- About to install three more towers (12 Ge, 6 Si)
  - Requires clean room conditions and steady nerves!
  - Checkout of new towers takes many weeks
- Room for two more towers later





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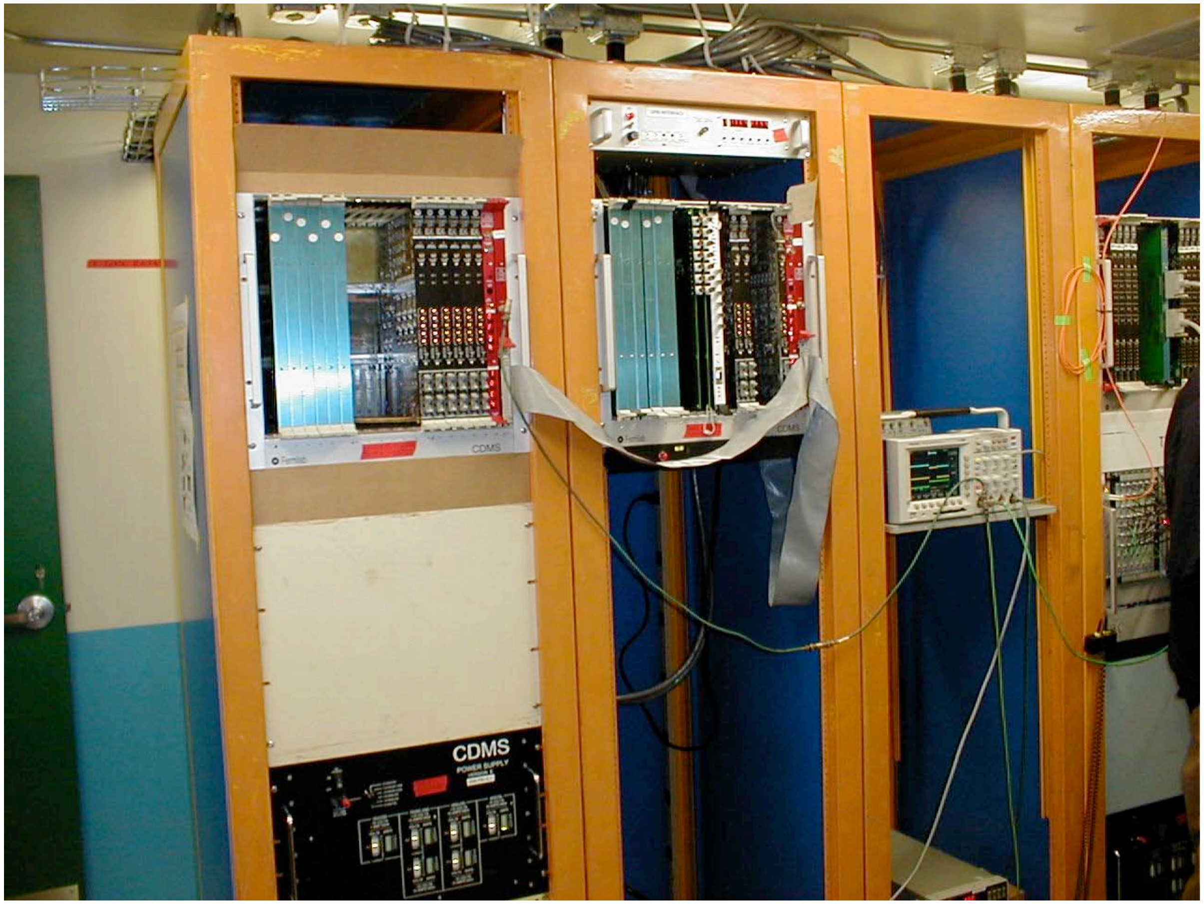
Electronics, DAQ



Taking data in a mine requires remote control and monitoring capabilities

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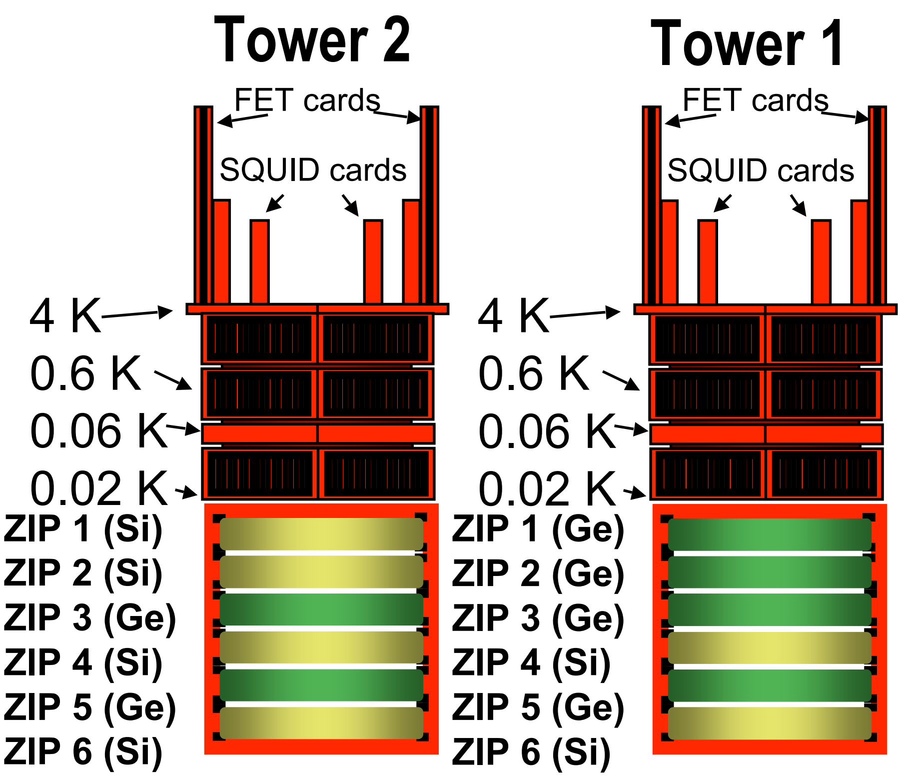
First Data from CDMS II at Soudan

October 2003- January 2004 run of "Tower 1"

- 4 Ge (0.85 kg) and 2 Si (0.17 kg) detectors
- 62 "raw" livedays, 53 livedays after cutting times of poor noise, etc.
- Shield and veto effective at rejecting most conventional backgrounds
- Paper submitted to Physical Review Letters

February 2004 - summer 2004 run of Towers 1 & 2

- 6 Ge (1.5 kg) and 6 Si (0.6 kg) ZIPs
- Similar backgrounds to Tower 1
- 75 live days accumulated
- Data being analyzed



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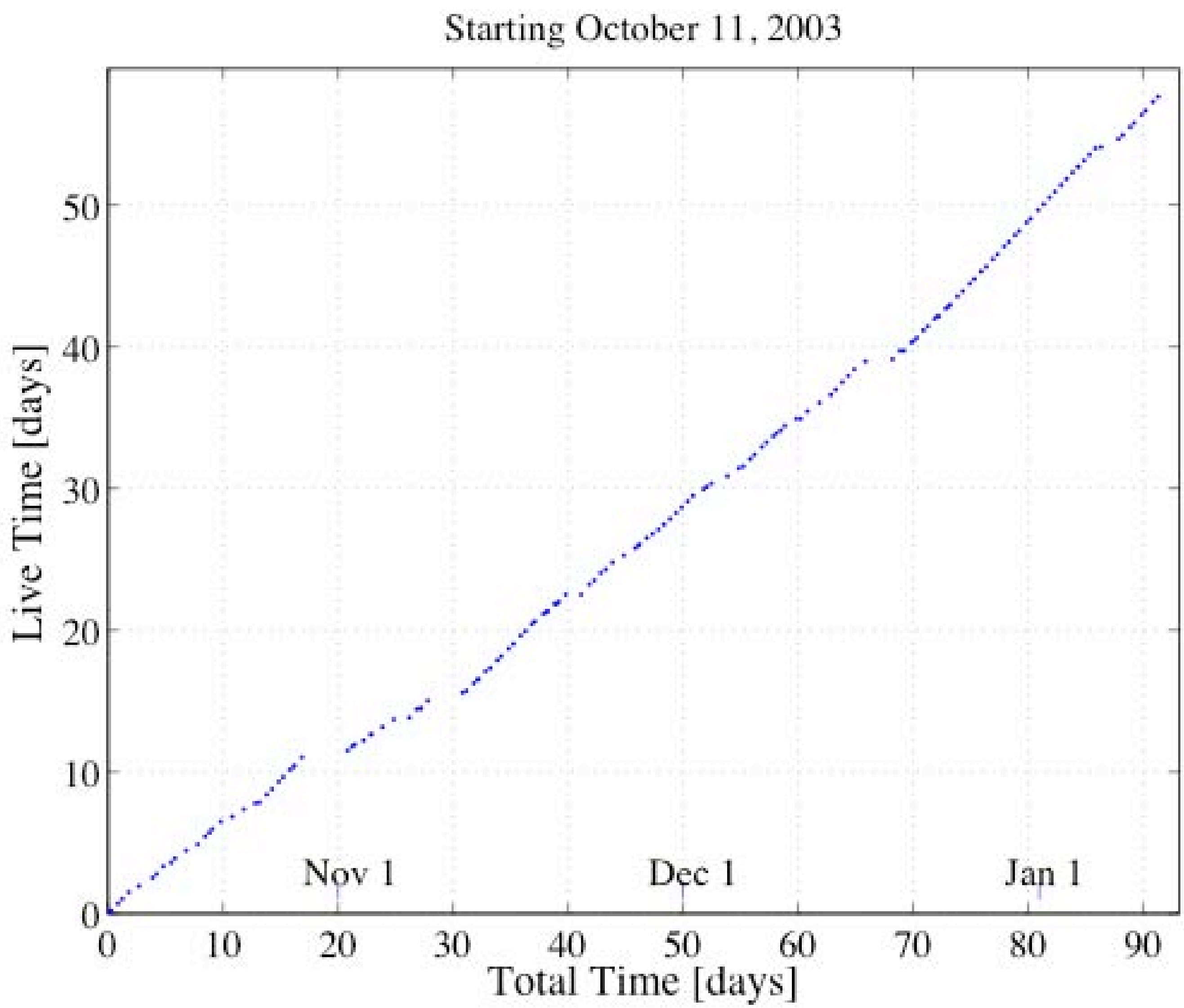
Staying alive

- Collected 53 live days during 92 calendar days
- Efficiency nearly 85% for last six weeks
- Downtime mainly for cryogen transfer



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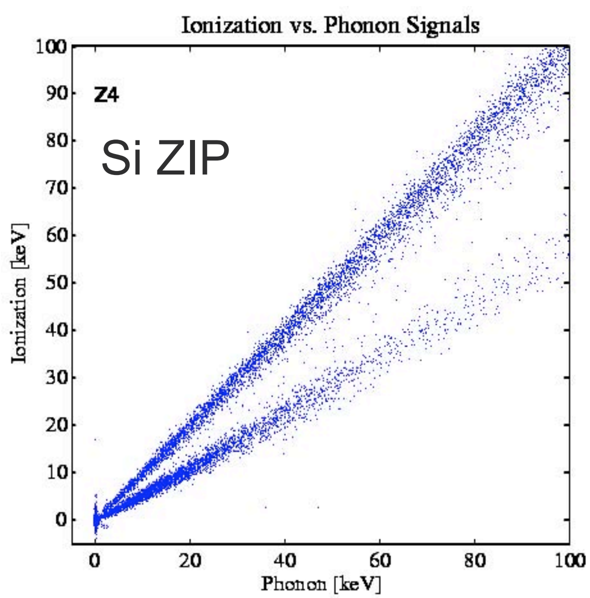
Calibration

The response of the detectors is best understood by using gamma (133Ba) and neutron (252Cf) calibration sources.

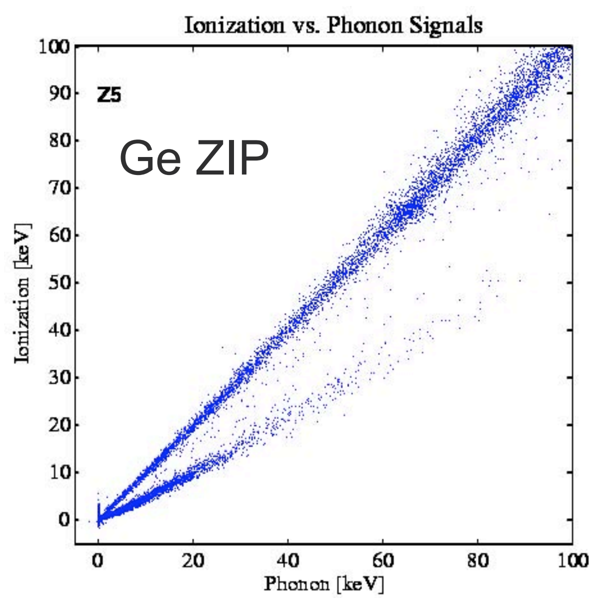
Gamma calibration: Energy scale, phonon uniformity corrections, defines betas ejected from gamma scattering, leakage into nuclear recoil band

Neutron calibration: Defines nuclear recoil band (where WIMPs will appear)

Ionization [keV]



Phonon [keV]



Phonon [keV]

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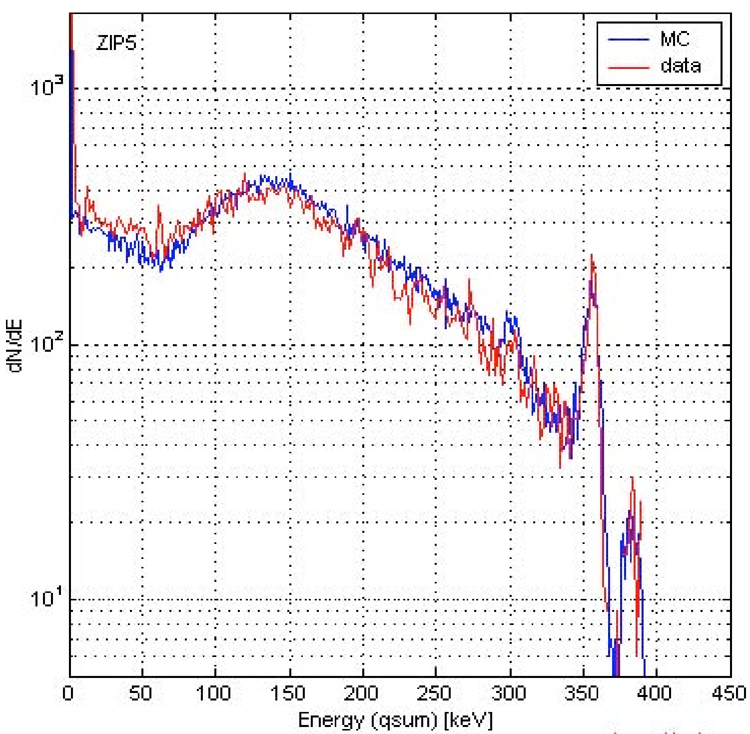
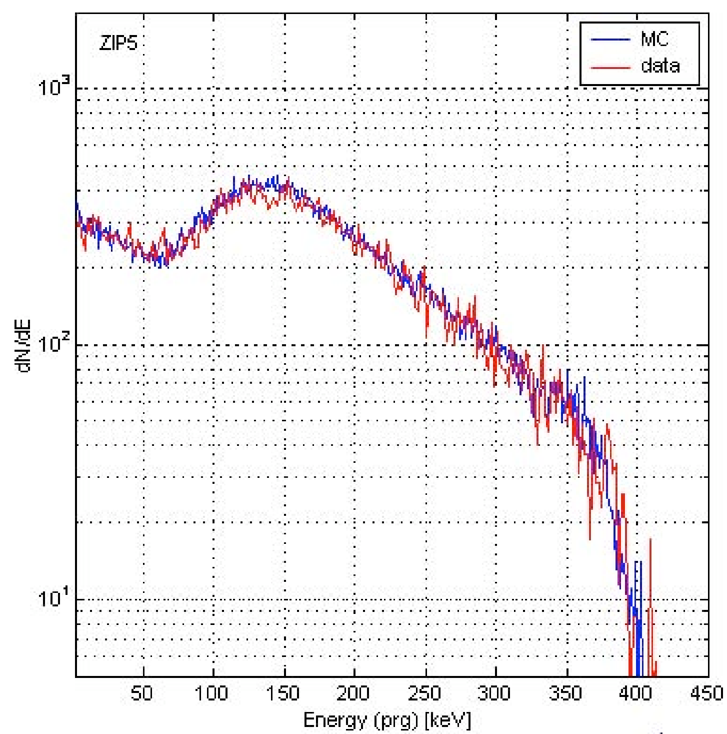
Understanding the data

Ionization energy in keV



Phonon energy (prg) in keV



Excellent agreement between data and Monte Carlo

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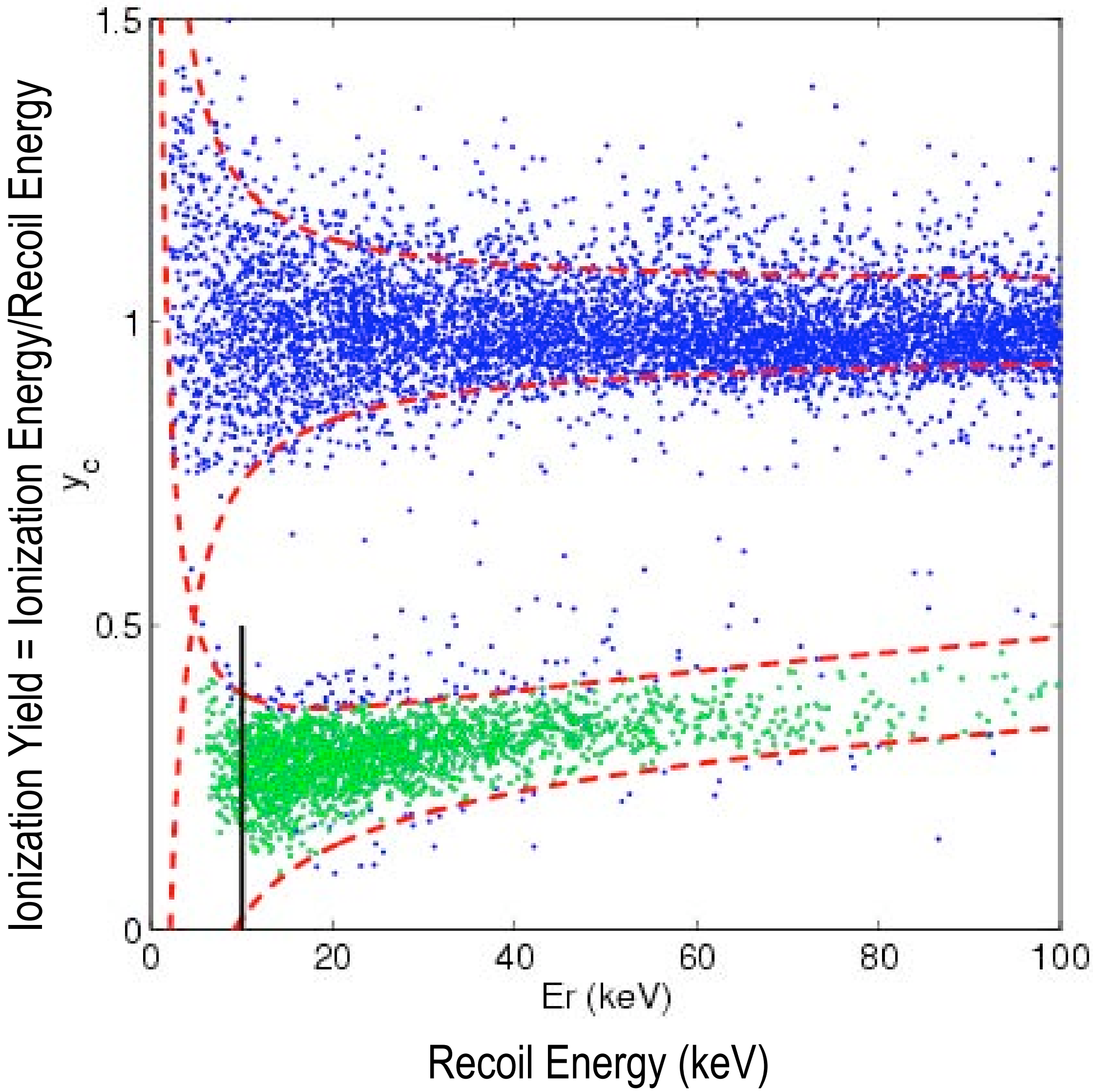
Searching the data for WIMPs

- Upper red dashed line are +/- 2 σ gamma band
- Lower red dashed line are +/- 2 σ nuclear recoil band
- Phonon non-uniformity corrected with high statistics gamma calibrations
- Bands and cuts determined with calibration data as was the analysis threshold energy



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Avoiding bias

“Blind” Analysis

- Cuts and energy threshold based on *calibration data*
- WIMP-search data blinded until analysis ‘fixed’
- Simplest possible cuts

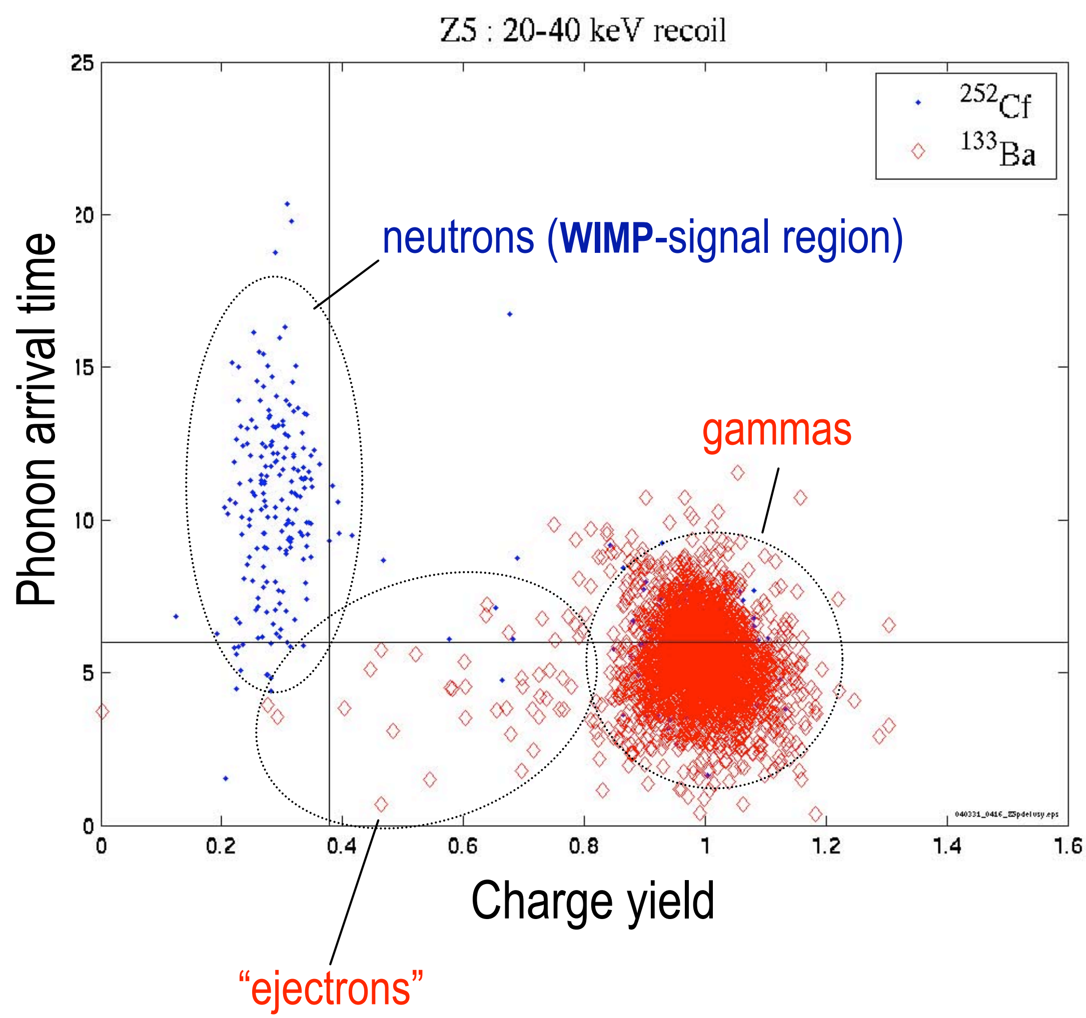
Rejection of surface electrons (low energy betas)

- Use phonon risetime and charge-to-phonon delay

NOT yet optimized

- We already can do better on both background rejection and nuclear recoil acceptance.
- Find the best balance between keeping WIMPS and not keeping backgrounds!

^{252}Cf neutron & ^{133}Ba gamma calibrations



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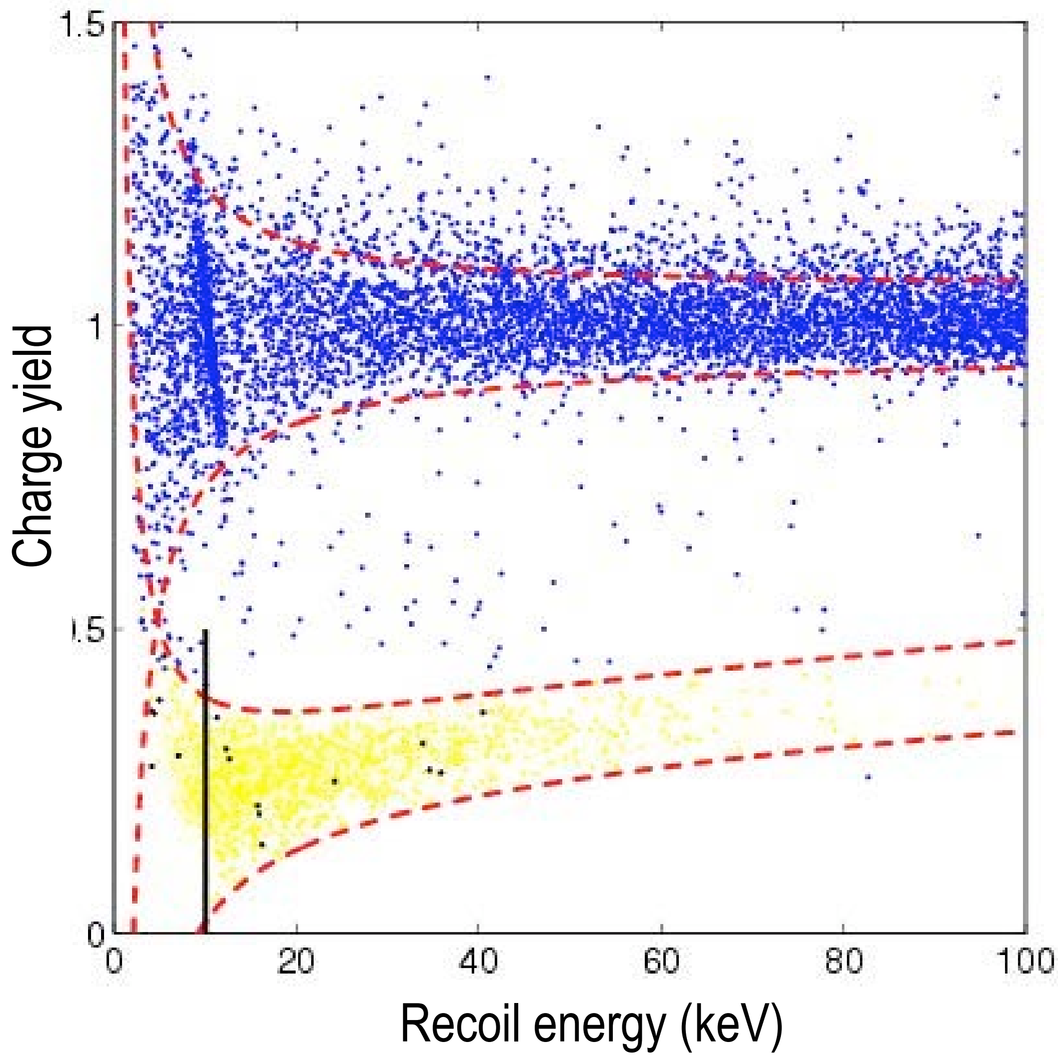
And the answer is…

Exposure

- 92 days (October 11, 2003 to January 11, 2004)
- 52.6 live days
- 20 kg-d net (after cuts)

Data: Yield vs Energy

- Timing cut off
- Timing cut on
- Yellow points from neutron calibration



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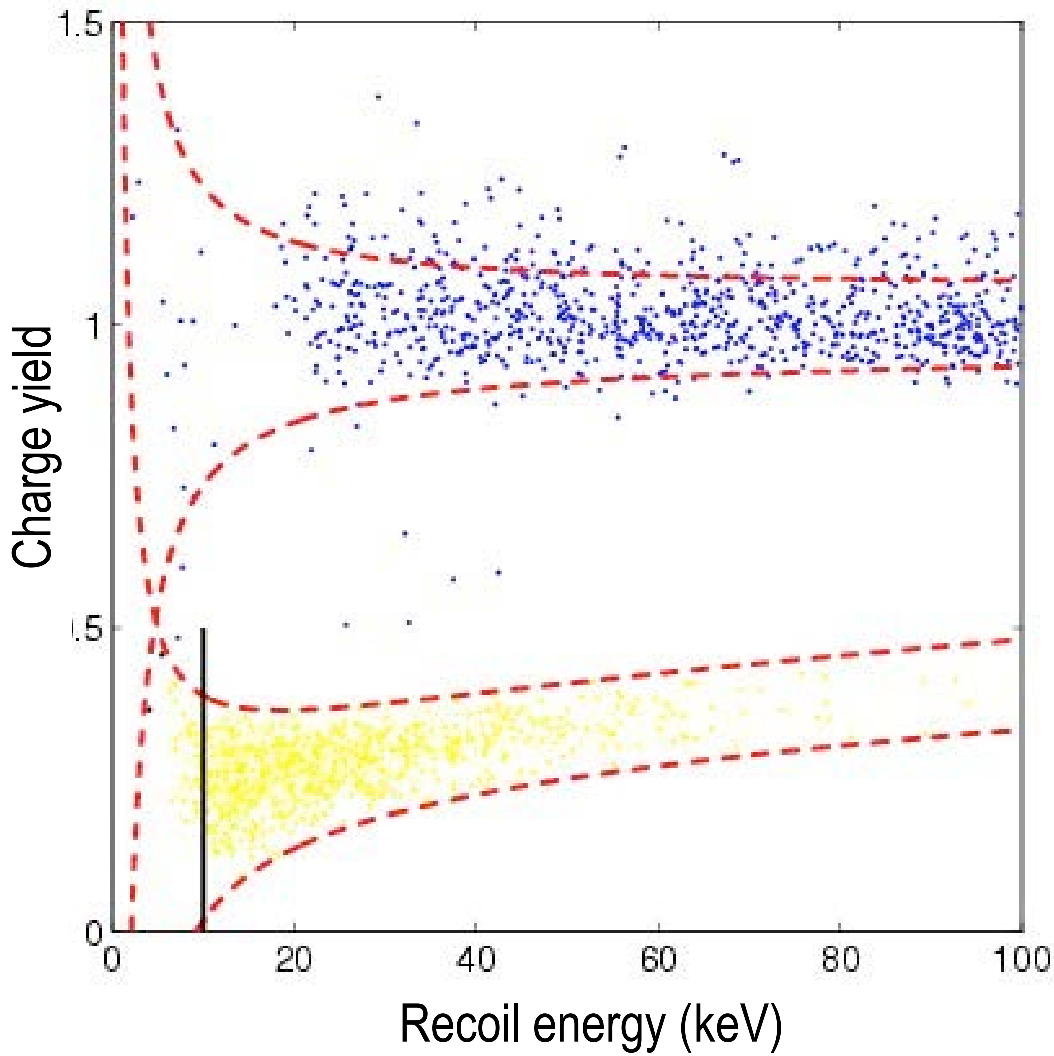
And the answer is …

Exposure

- 92 days (October 11, 2003 to January 11, 2004)
- 52.6 live days
- 20 kg-d net (after cuts)

Data: Yield vs Energy

- Timing cut off
- Timing cut on
- Yellow points from neutron calibration



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Fermilab
August 9, 2004

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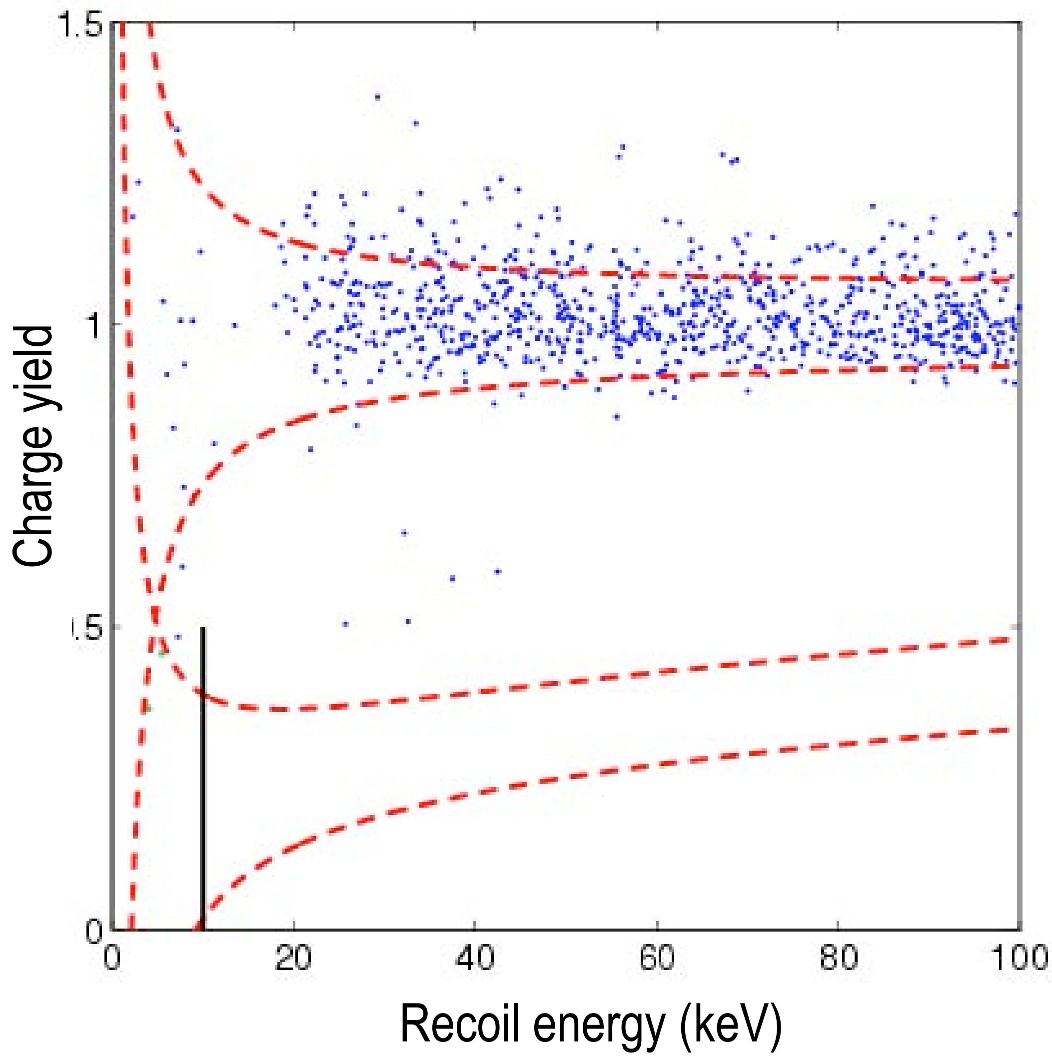

No nuclear-recoil candidates

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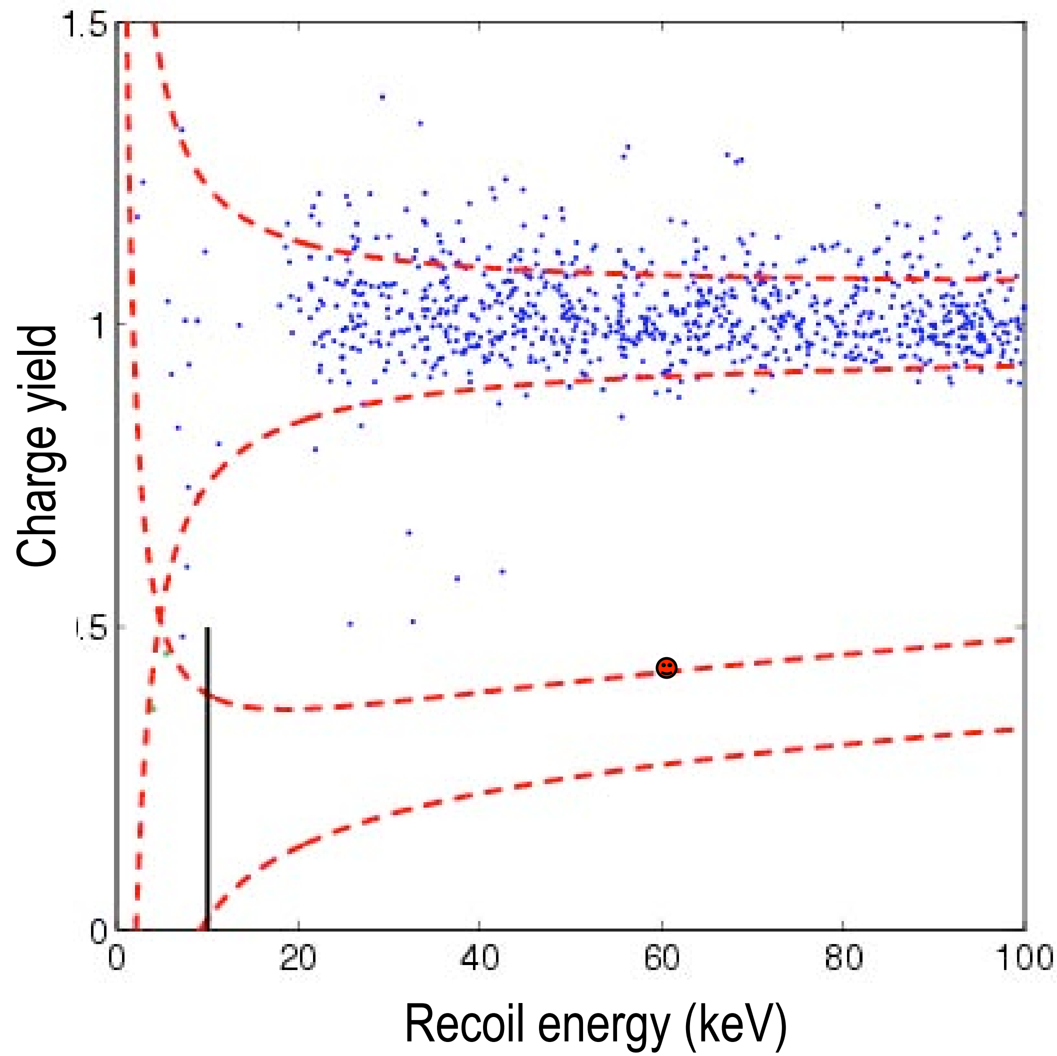
Well, maybe 1….



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The perils of blinding

After ‘opening the box’, found an analysis mistake:

- Inadvertently used pulse fitting algorithm designed for saturated pulses for most of the data, instead of algorithm optimized for low-energy pulse
  - Algorithms give similar results for most detectors, except:
    - Z5 has low-frequency baseline noise in outer charge electrode
    - Saturated pulse algorithm doesn’t handle this as well as optimal algorithm
    - Net effect is that one event was rejected in blind analysis but would have survived all cuts without the mistake
    - Exhaustive search reveals no other events close to boundaries

Is this surprising? NO!

- Our best estimates of beta leakage => 0.7 +/- 0.3 beta events SHOULD have been seen.
- Event has ionization yield suggestive of betas, although phonon timing is closer to neutrons (but still consistent with betas)
- Improved beta cuts we are developing reject this event (no longer blind though, so watch out for bias)

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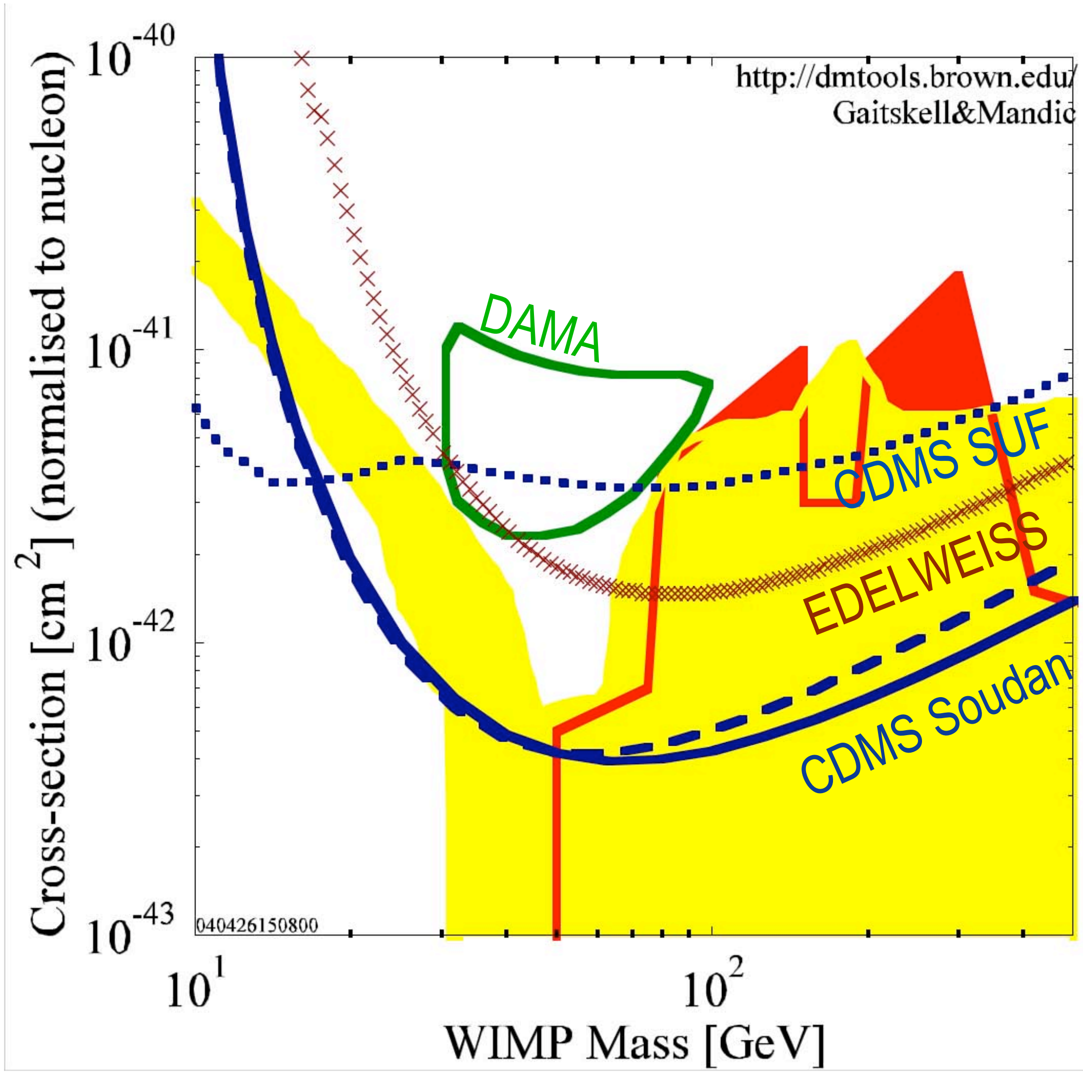
NEW CDMS limit from Soudan

- Exposure after cuts of 52.6 kg-d raw exposure with Ge ≈ 20 kg-days for 60 GeV/c² WIMP
- No nuclear-recoil candidates
- Expect ~1 mis-identified beta
  - Second non-blind analysis has 1 candidate (dashed limit curve show effect of this)
- Expect 0.1 unvetoed neutrons (1.0 muon coincident neutron)

- Upper limit on WIMP-nucleon cross section as a function of WIMP mass

- New limit ~4x (x10) better than EDELWEISS (CDMS SUF) at a WIMP mass of 60 GeV/c²



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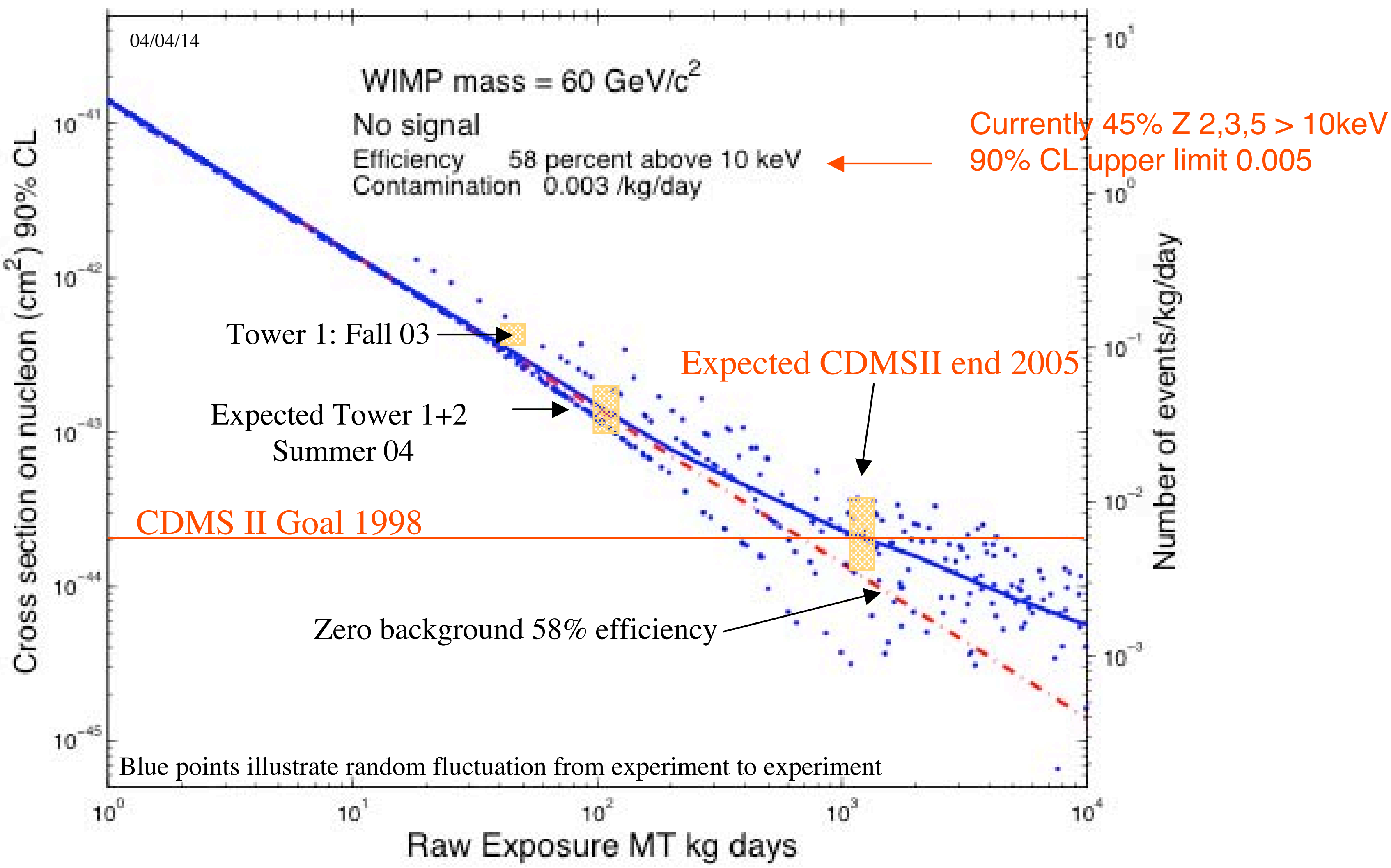
Run longer (T), with more detectors (M)

Improvement linear until background events appear



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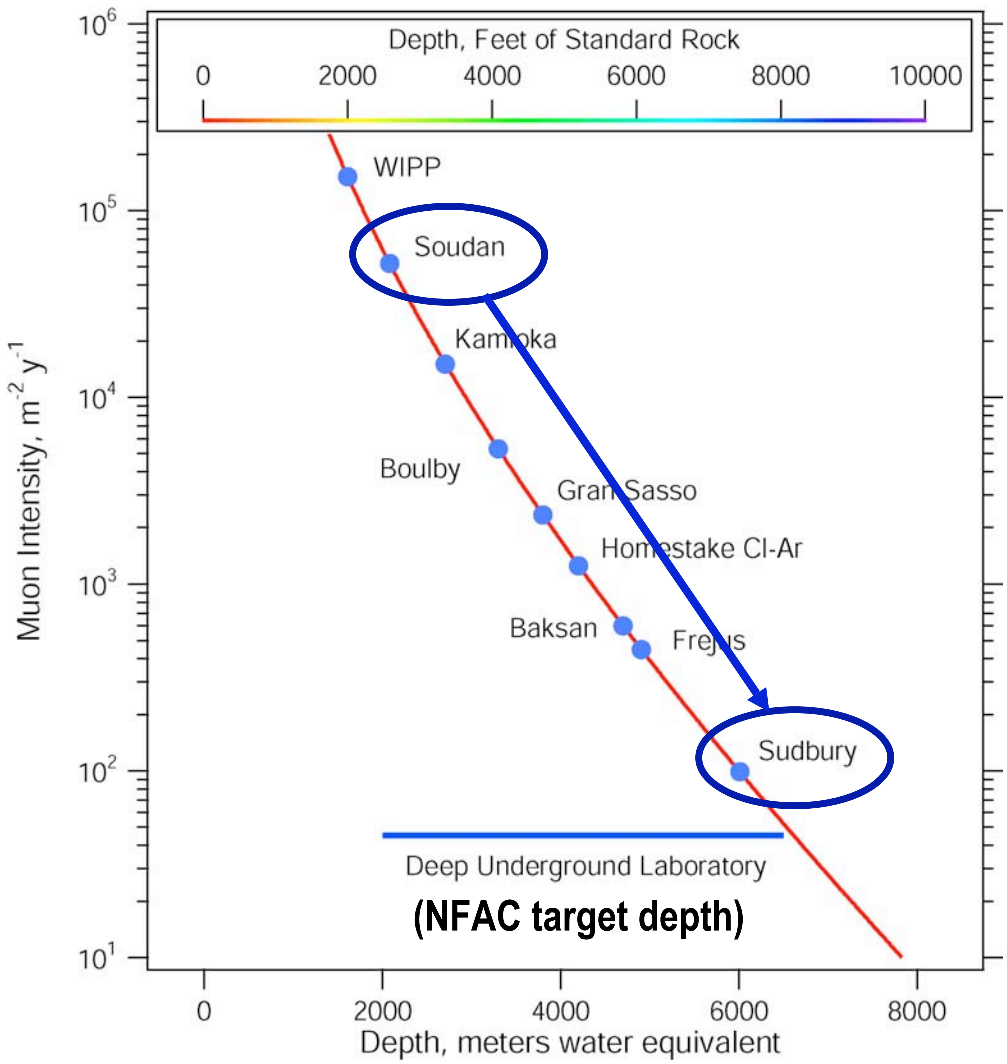
Avoid neutrons, go deep - CDMS@SNOLAB

- Deepest laboratory now in operation
  - Soudan (2000 mwe) -> Sudbury (6000 mwe)
- Neutron background due to cosmic rays reduced to insignificance
- Must work even harder to reduce other backgrounds (gammas, betas)



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Ultimate goal: 1000 kg of detectors at SNOLAB

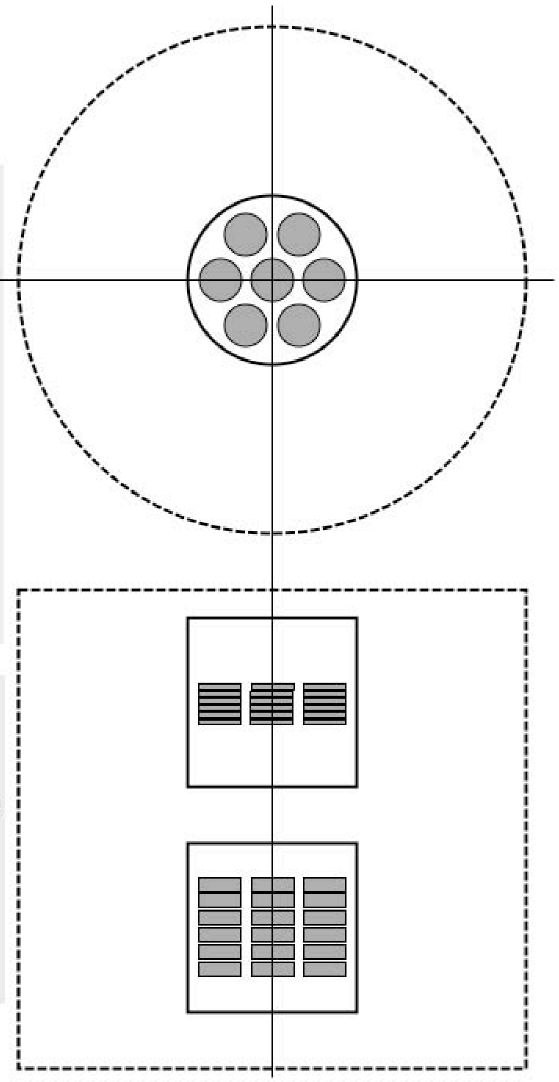
CDMS II – Phase A:
3"x1 cm => .25 kg Ge
1 x 6 Det Towers =>
1 kg Ge + 0.2 kg Si
SUF -> Soudan

CDMS II – Phase B:
3"x1 cm => .25 kg Ge
2 x 6 Det Towers =>
1.5 kg Ge + 0.6 kg Si
Soudan

CDMS II – Phase C:
3"x1 cm => .25 kg Ge
5 x 6 Det Towers =>
4.5 kg Ge + 1.2 kg Si
Soudan

CDMS III – Phase A:
3"x1 cm => .25 kg Ge
5 x 6 Det Towers =>
4.5 kg Ge + 1.2 kg Si
x3 exposure at Soudan

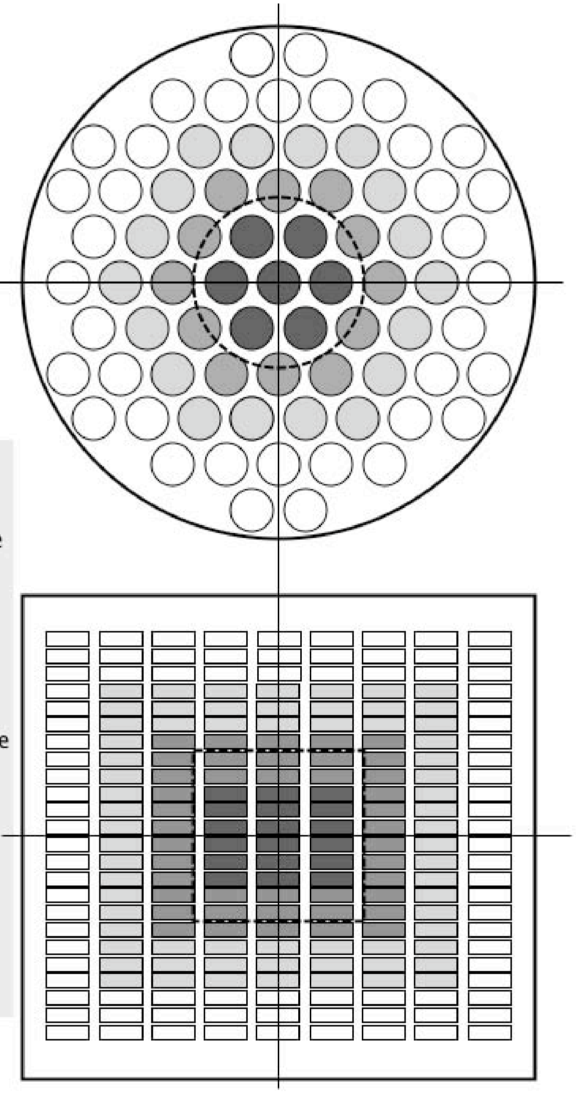
CDMS III – Phase B:
3"x1" => .64 kg Ge
2 x 6 Det Towers =>
up to 7.6 kg Ge
x10 less n's at Soudan



CDMS SNOLAB – Phase A:
3"x1" => 0.64 kg Ge
7 x 6-Det Towers =
42 Dets =>to 26.7 kg Ge
Soudan -> SNOLAB
SUF testing (2 batches)

CDMS SNOLAB – Phase B:
3"x1" => 0.64 kg Ge
19 x 12-Det Towers =
228 Dets =>to 145 kg Ge
Soudan/SUF testing
(6 batches)

CDMS SNOLAB – Phase C:
3"x1" => 0.64 kg Ge
73 x 24 Det Towers =
1752 =>to 1,113 kg Ge
Soudan/SUF testing
(45 batches)



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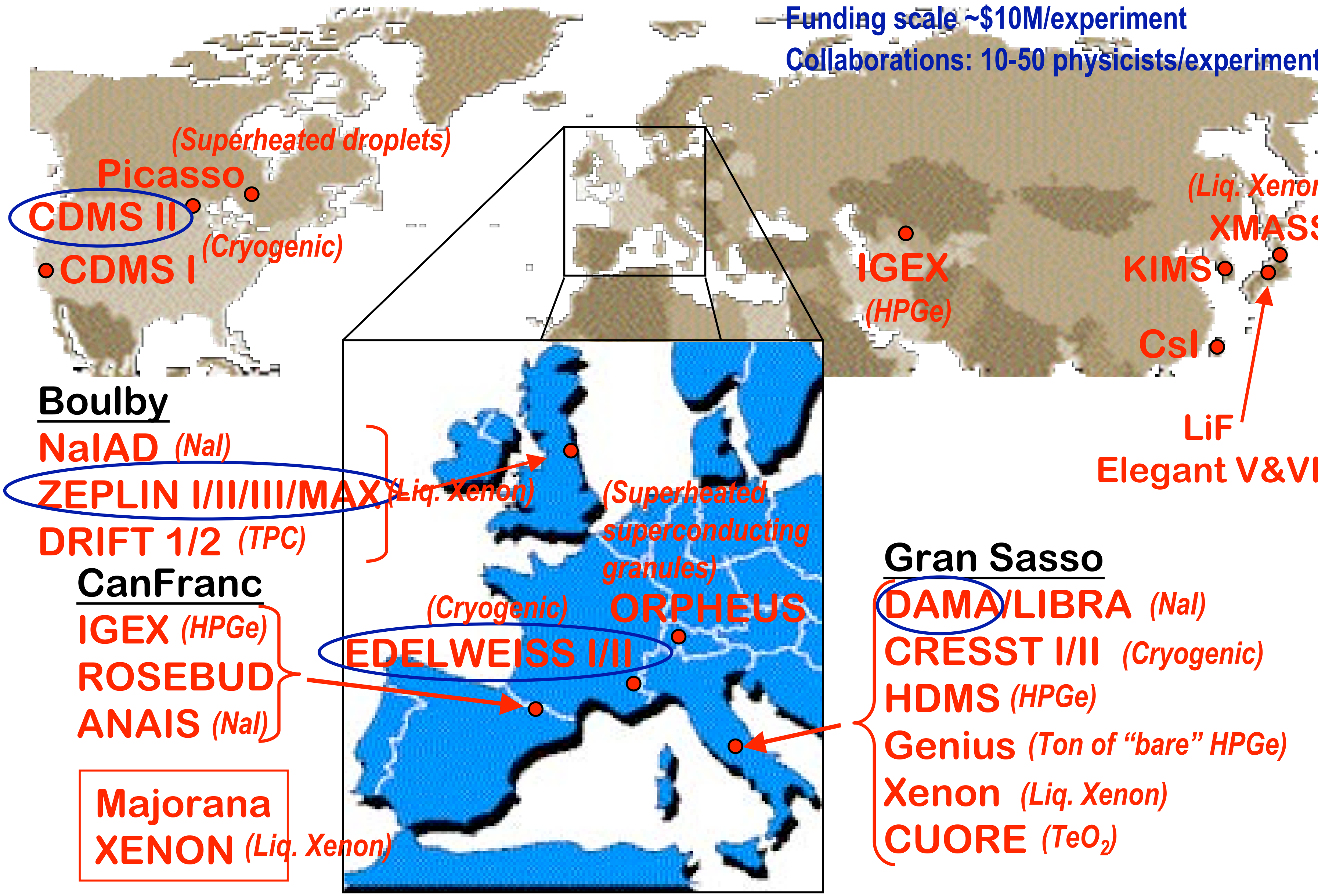
WIMP-detection Experiments Worldwide



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DAMA NaI Experiment

(Huge target mass, little background discrimination)

Very elegant experimental setup - 1996-2002

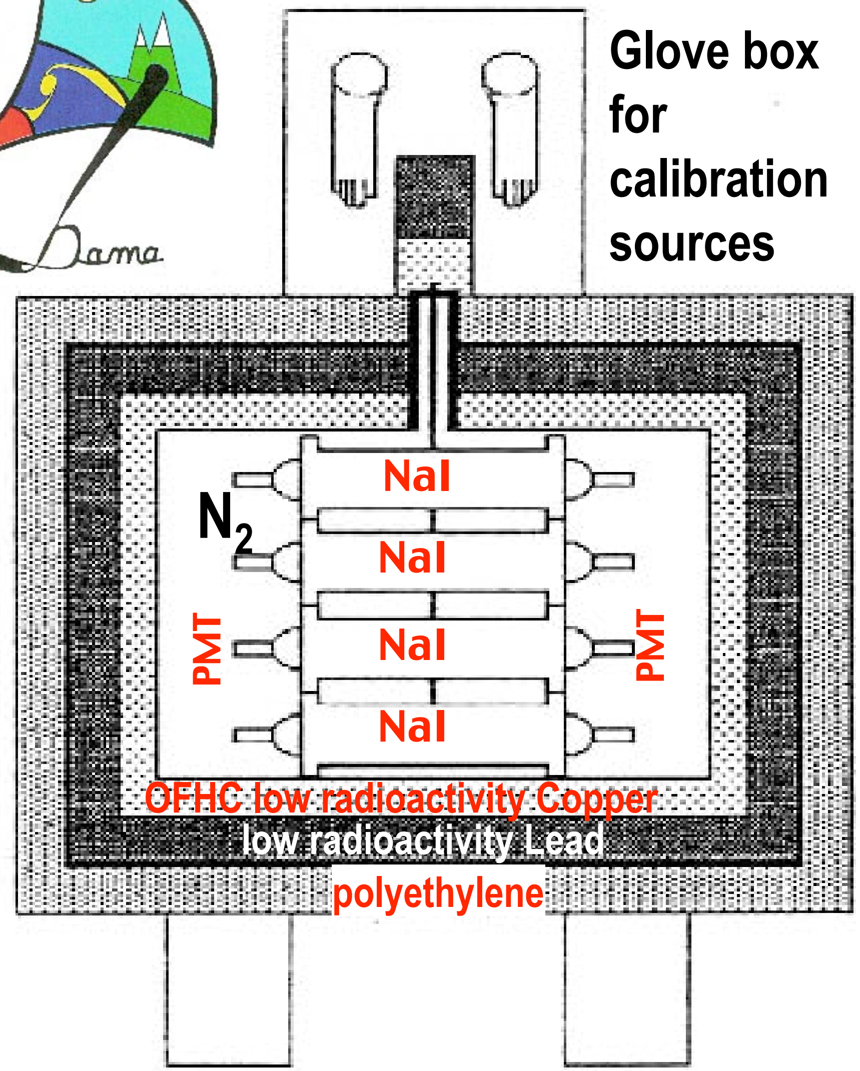
Located at Gran Sasso Underground Lab (4000 mwe)
+ Photon and Neutron shielding

9 × 9.7 kg low-activity NaI scintillator crystals, each viewed by 2 PMTs

- Known technology
- Low cost
- Large mass
- Spin-dependent interactions

107,731 kg-days total exposure

See annual modulation signal (6.3σ)!



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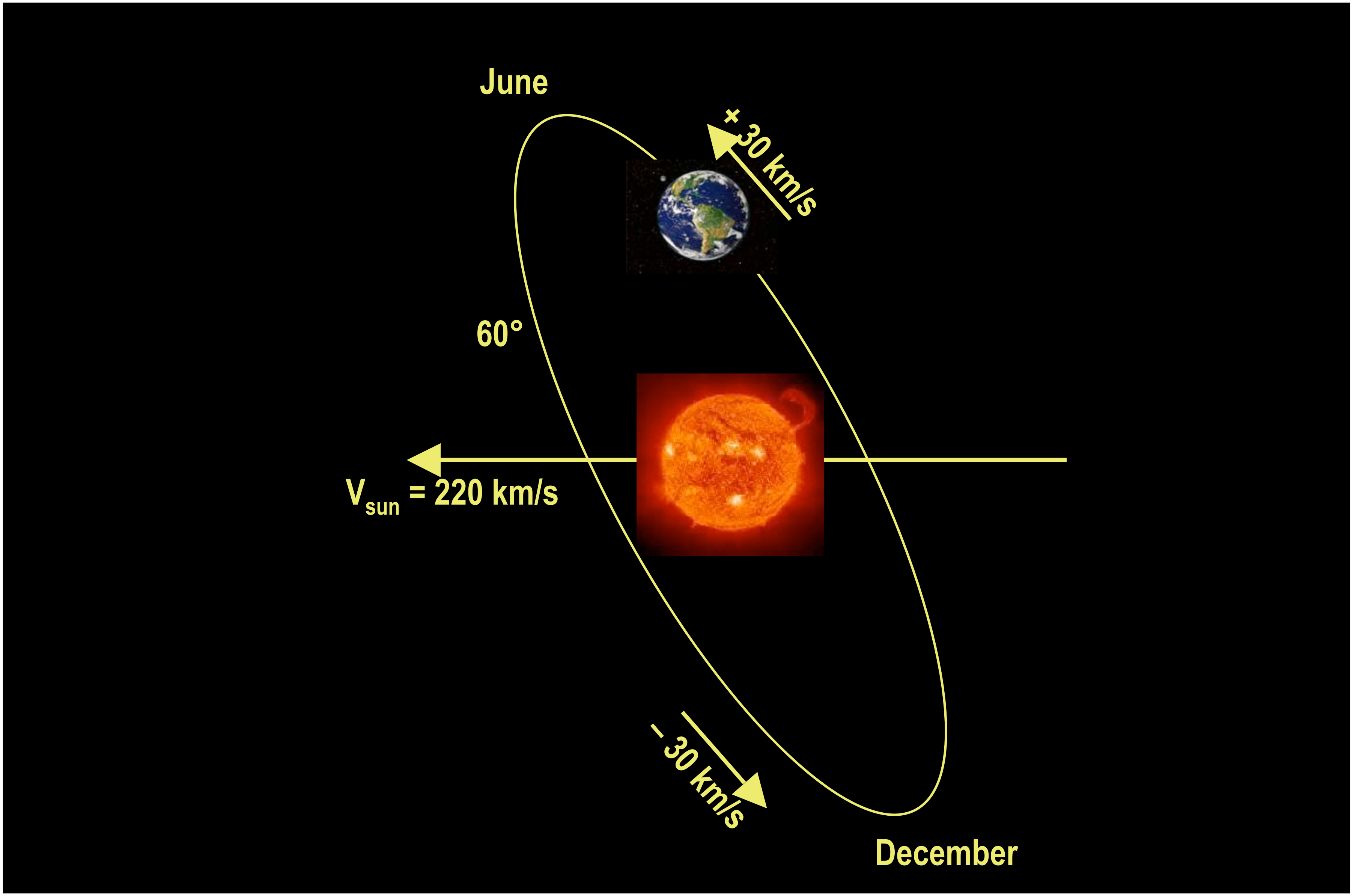
Annual Modulation = More WIMPs in the summer



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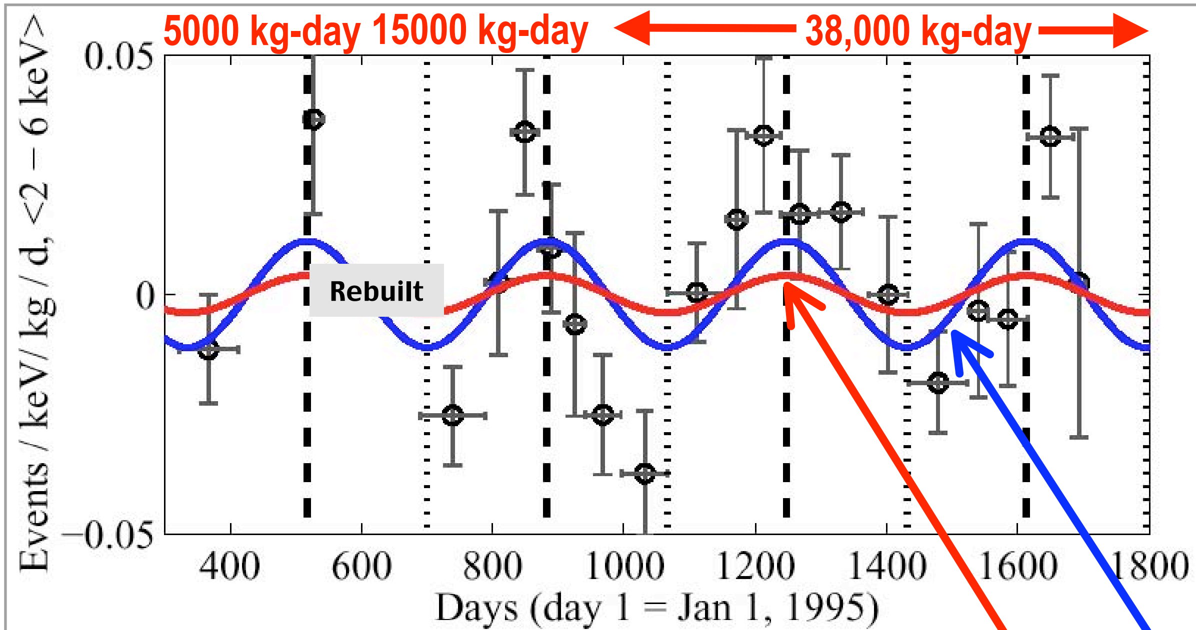
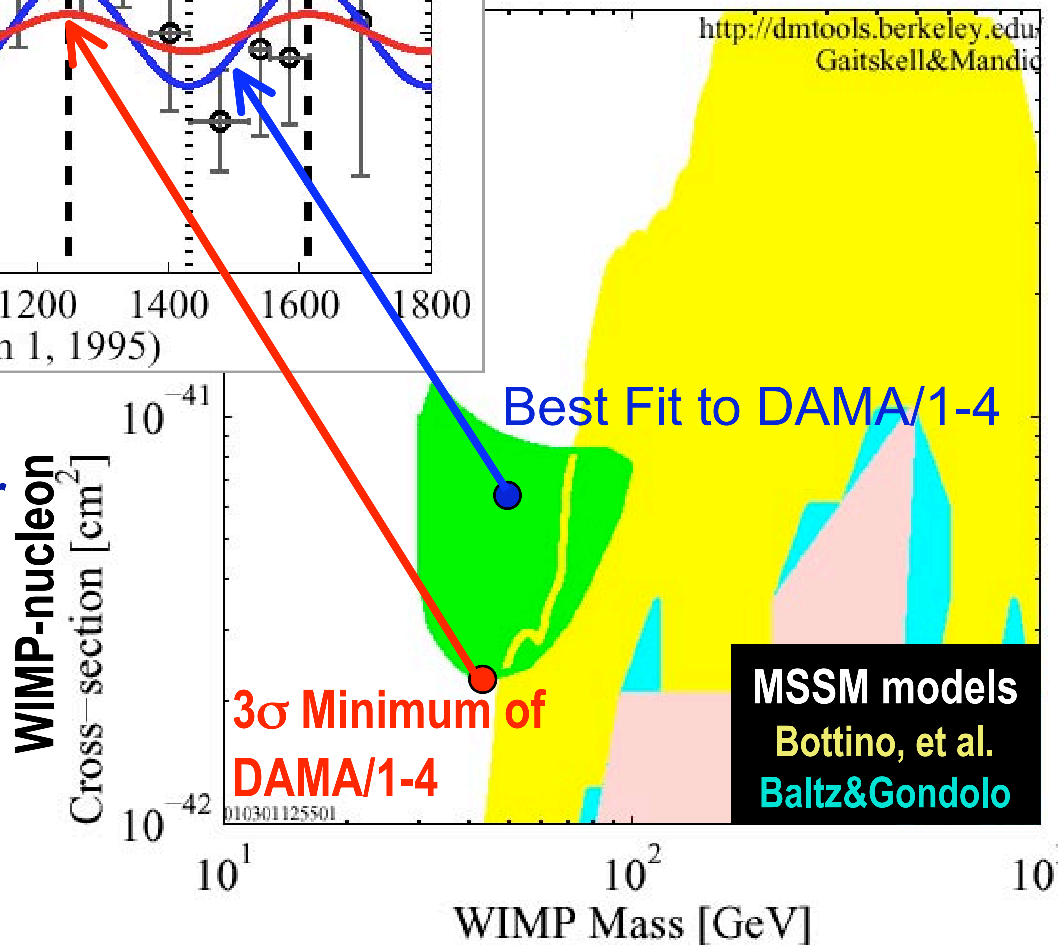
DAMA 4-year Annual Modulation Results



R. Bernabei et al., Phys. Lett. B 480, 23 (2000)



- Residual modulation in events/keVee/kg/day averaged over 2-6 keVee range (most is expected in 2-3 keVee bin)

- 3 more years analyzed (astro-ph/0307403) consistent results
- New 250 kg LIBRA installation started August 2002

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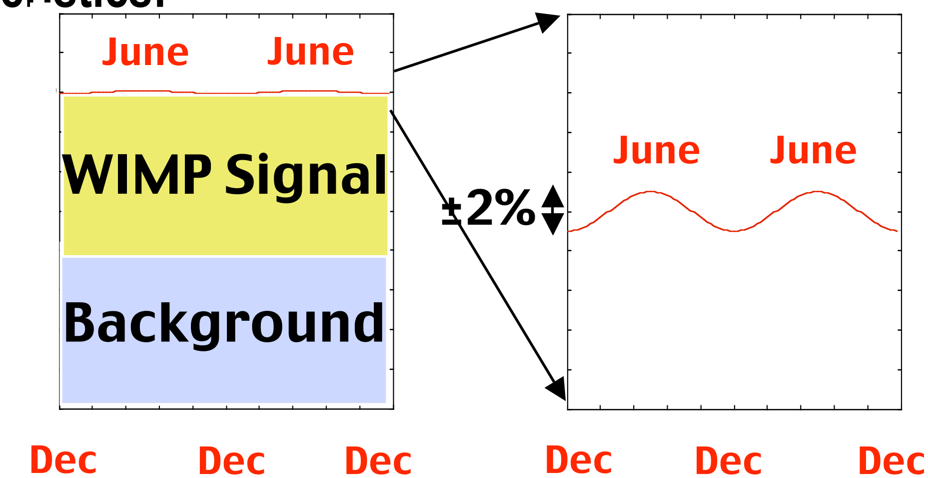
DAMA Search for Annual Modulation

Do not distinguish between WIMP signal and background directly

- Calculate the WIMP interaction rate from the amplitude of the modulation

WIMP annual modulation signal characteristics:

- Rate = cos(t)
- Low energies (hard to measure)
- 1 year period
- Known phase (summer/winter)
- Single hit (but only analyzed)
- Amplitude < 7% at maximum



Careful control of possible sources of background modulation

- Temperature variation (<<0.1%)
- Rn (no air)

(See Eur. Phys. J. C18 (2000), 283

Control of all possible systematic effects still difficult

- Near-threshold behavior of efficiency, energy linearity, and noise stability

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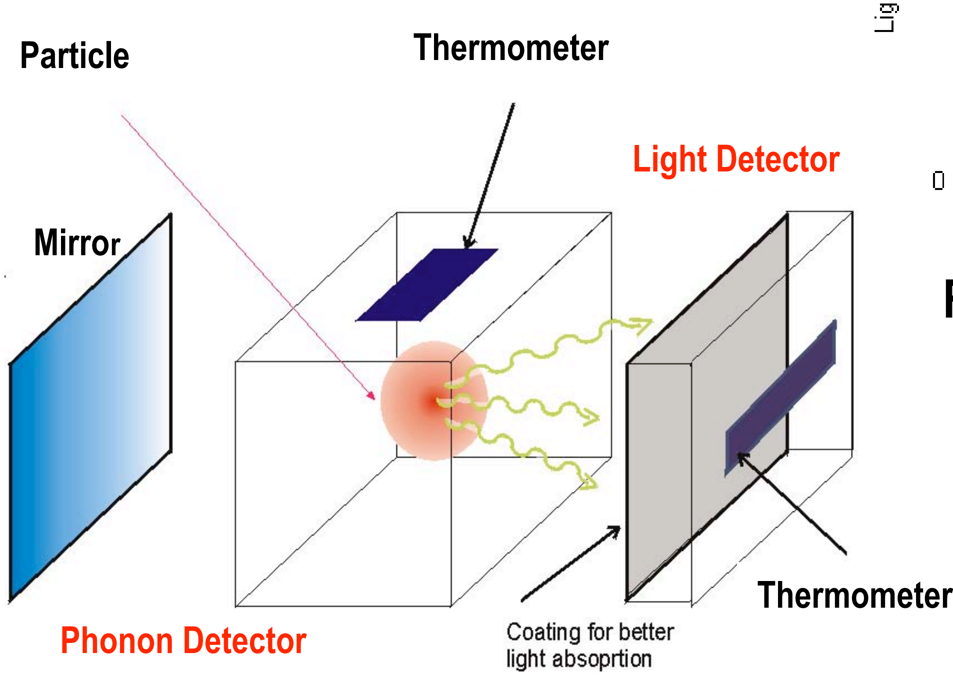
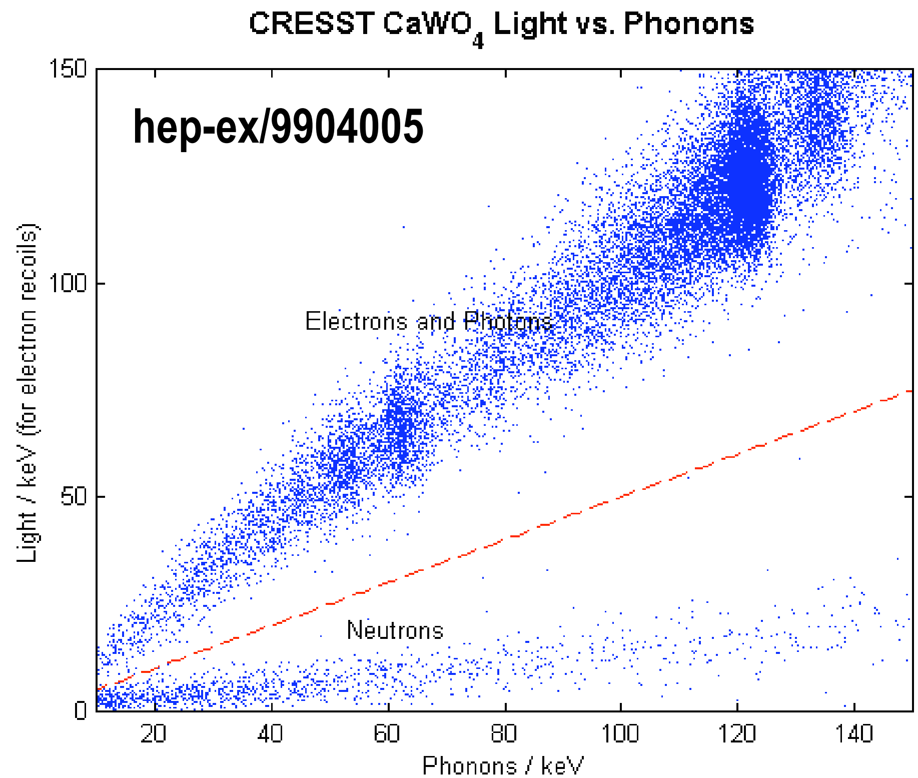
CRESST: Phonons and Scintillation

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





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

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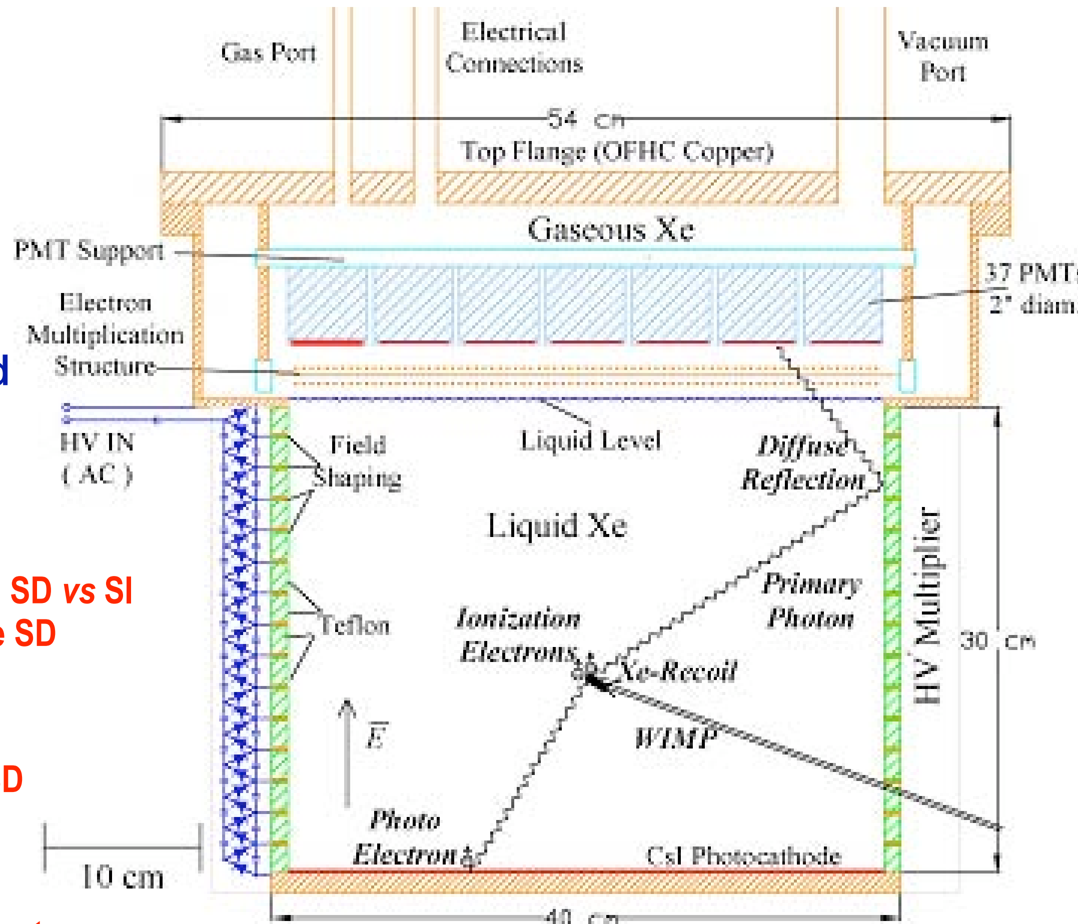
Liquid Xenon Detectors:

Compromise between large mass and background rejection

Potential to challenge cryogenic detectors
- Background rejection
  - Pulse shape discrimination now
  - R&D towards scintillation + ionization
- Scales more readily to high mass

Challenges
- Implement “dual-phase” to improve scintillation signal
- Ionization signal/noise poor near threshold

Several programs
- DAMA collaboration
  - Developed PSD in LXe
  - ^{129}Xe *vs* ^{136}Xe by using PSD → comparing SD *vs* SI signal to increase the sensitivity to the SD component
- Zeplin (UK/UCLA et al)
  - Preliminary results from 5 kg Xe using PSD
  - R&D proceeding towards 1 ton detector
- XENON expt (Columbia et al)
  - R&D phase I study towards 1 ton experiment
  - Based on earlier developments for LXeGRIT x-ray astrophysics



Columbia Univ.

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GENIUS

(Ultimate in background reduction, but no discrimination)

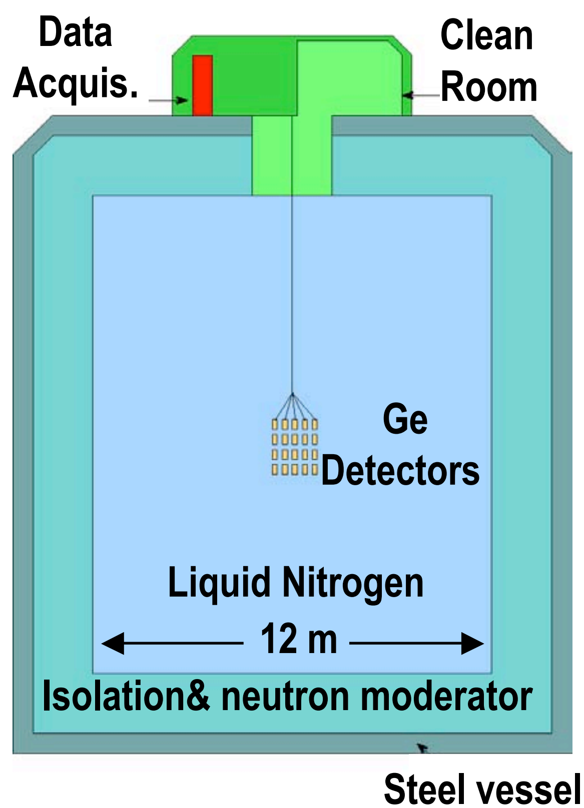
Eliminate ~ALL material near detectors

- Suspend 100-kg naked Ge diodes in a LN_2 tank
- Backgrounds dominated by surface activation of Ge detectors

Goal: 0.01 eV / kg / y E<100 keV (hep-ph/9910205)

GENINO - proposed similar set-up with 5-m diameter tank, external shielding

GENIUS Test Facility ($0.064 m^3$ LN_2) to be installed this year at Gran Sasso
(hep-ex/0012022)



CUOPP (Heavy Liquid Bubble Chamber)
Ultimate in background rejection?

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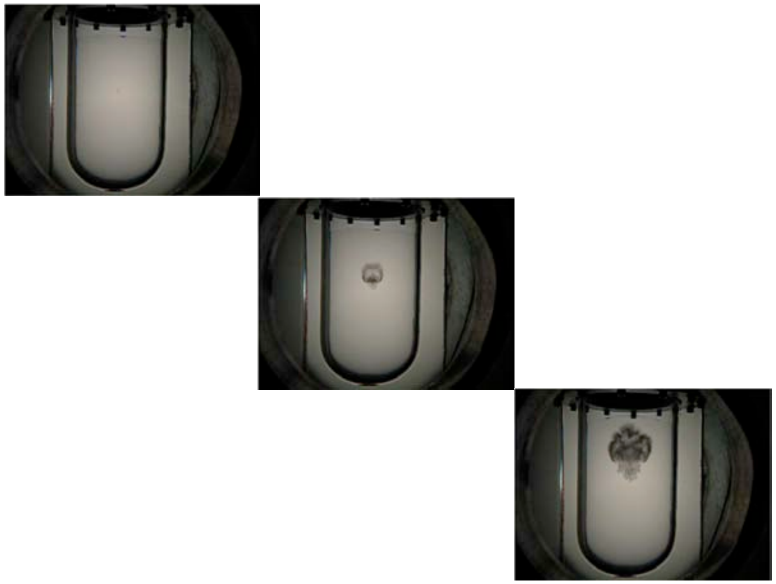
August 9, 2004

Superheated heavy liquid (e.g. CF_3I)
- 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

Challenges
- No energy information
- Possible backgrounds from materials surrounding liquid
- 1 liter prototype operating in shallow site - need to demonstrate at deep site
- Operational stability



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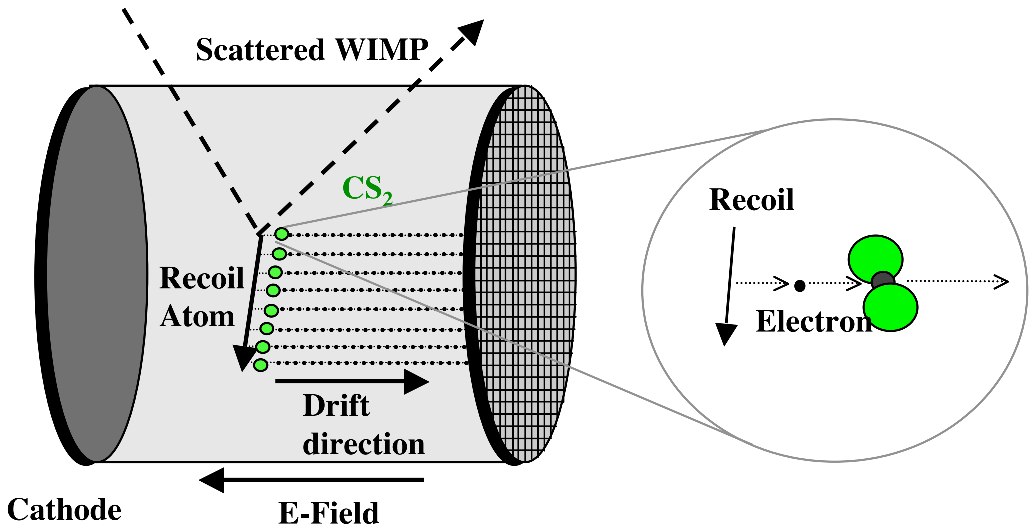
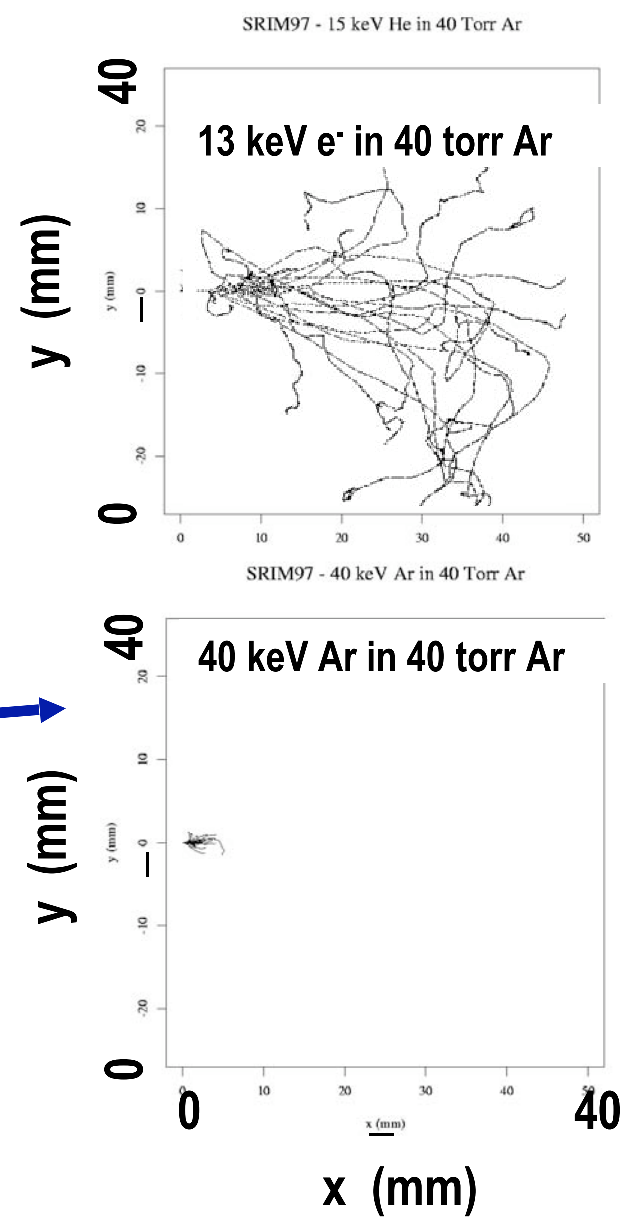
DRIFT: Look for signal directionality





- Sensitive to direction of recoiling nucleus
  - Diurnal modulation signal – galactic origin of signal
- Drift negative ions in TPC
  - No magnet
  - Reduced diffusion
- Electron recoils rejected via dE/dx, range
- DRIFT I
  - Cubic meter in Boulby since 2001
  - Engineering runs completed
- DRIFT II extension to 10 kg module proposed

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Summary and Projections

WIMPs

- Look for 23% of the universe!
- New particle physics (SUSY neutralino)
  - Sensitive to 10-10000 GeV masses
  - Challenging MSSM models
  - Complementary to LHC searches

Broad range of experimental approaches/efforts

- CDMS II at Soudan leads the chase
- Significant competition from other techniques

Expansion towards ton-scale experiment

- Several approaches possible
- Competitive reach for SUSY with LHC!
  - And we're sensitive to higher mass WIMPs!

Growing scale of experiments

- Larger and deeper => $$
- DUSEL - Deep Underground Science and Engineering Laboratory

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