The CDMS, SuperCDMS, and GEODM WIMP Dark Matter Searches

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UC Davis HEP Seminar

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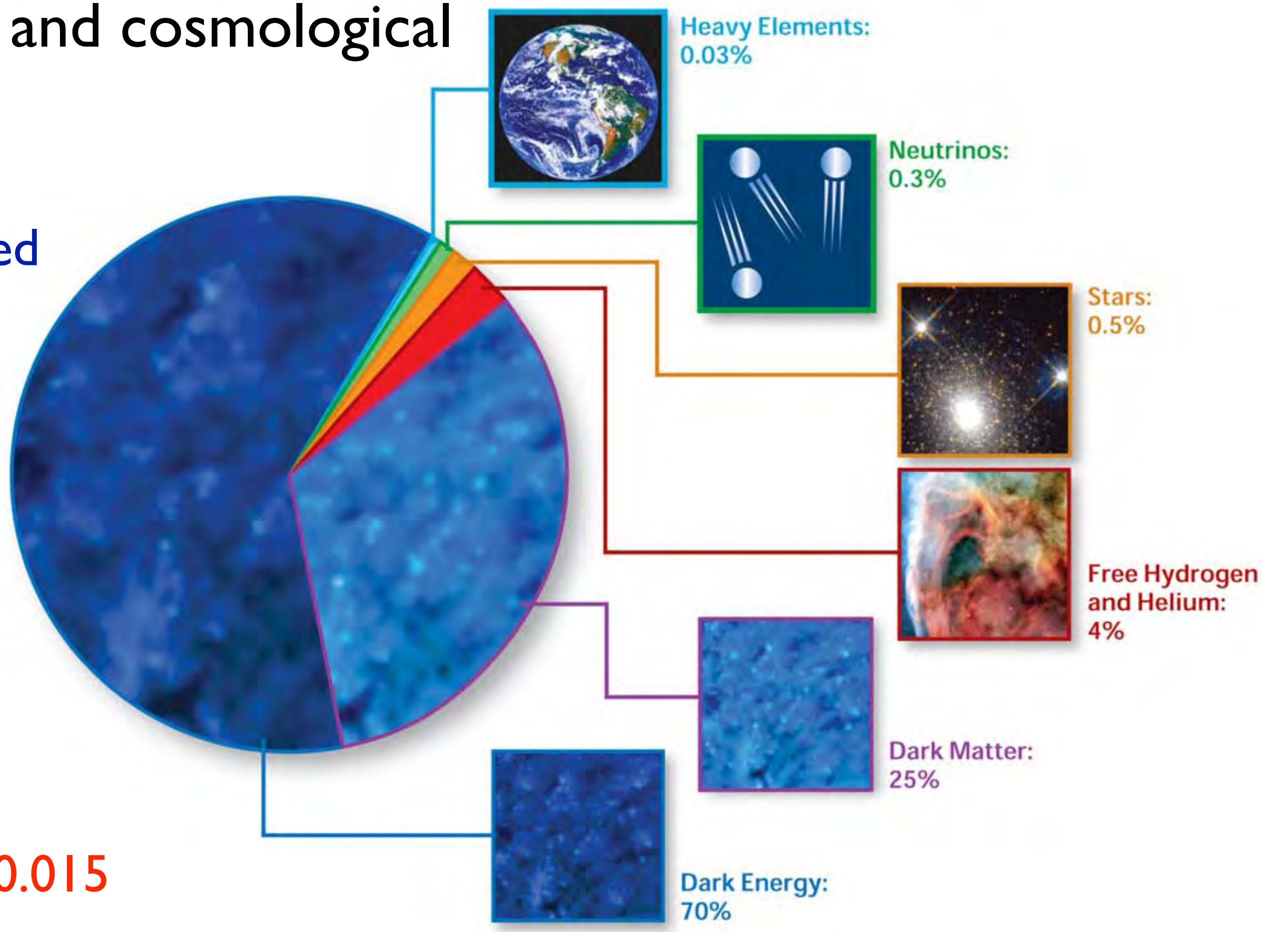
Outline

- Motivation for Weakly Interacting Massive Particle (WIMP) dark matter
- How to look for WIMPs
- Current status of the Cryogenic Dark Matter Search (CDMS)
- Toward the future with SuperCDMS and the Germanium Observatory for Dark Matter (GEODM)

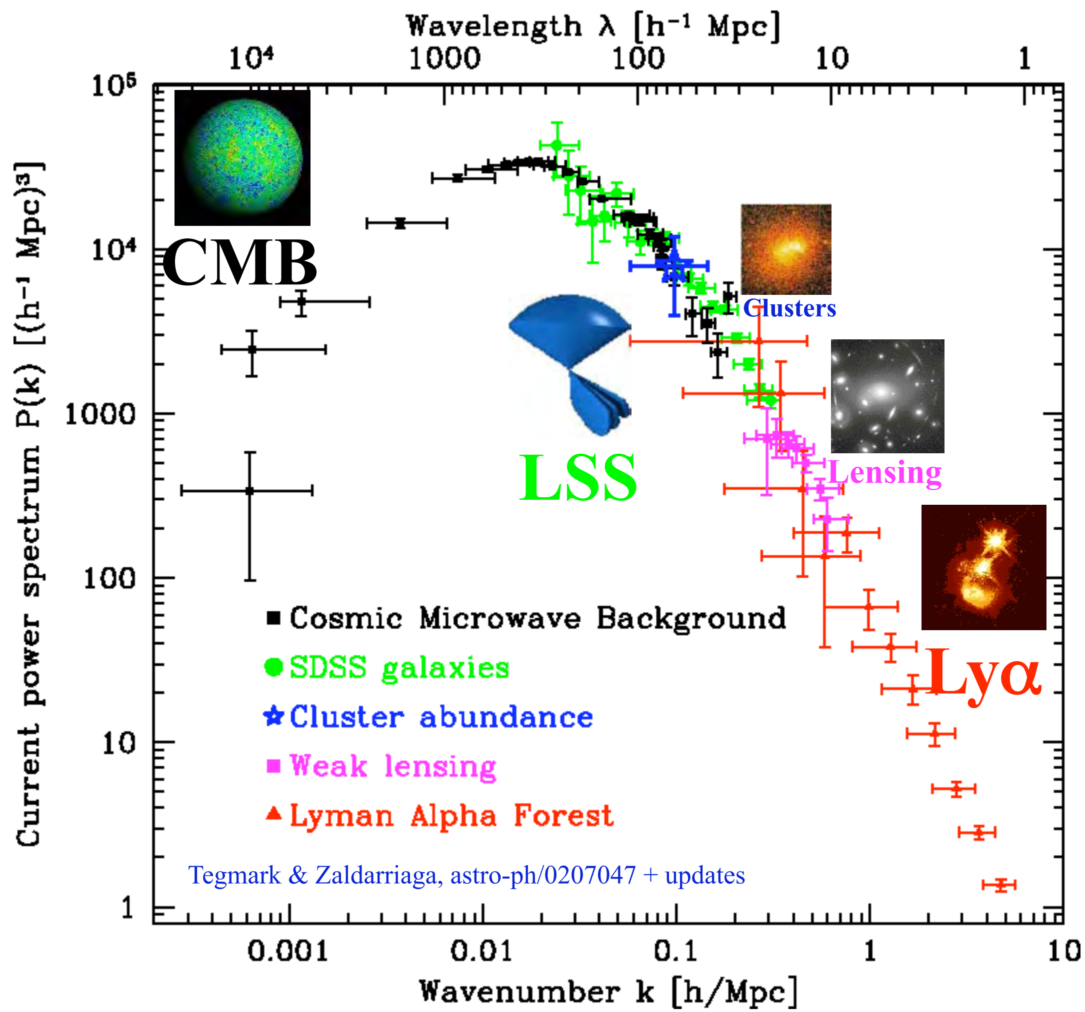
Why Dark Matter?

- A host of astronomical and cosmological observations indicate:
  - Total energy density = critical density ρ_{crit} needed for spatially flat universe (within errors)
  - The bulk is in the form of *dark energy*, a fluid that has negative pressure (causes the universe's expansion to accelerate) and does not clump gravitationally, $\Omega_{DE} = \rho_{DE}/\rho_{crit} = 0.726 \pm 0.015$
  - Most of the matter is in the form of *dark matter*, matter that interacts gravitationally but not electromagnetically, $\Omega_{DM} = \rho_{DM}/\rho_{crit} = 0.228 \pm 0.013$
  - The remaining matter is in the form of baryons, $\Omega_B = \rho_B/\rho_{crit} = 0.0456 \pm 0.0015$ (though much of this has not yet been directly observed!)



Required Dark Matter Characteristics

- Dark matter must be:
  - Cold/warm (not hot):
    - nonrelativistic at matter-radiation equality ($z \sim 3500$) to seed LSS. M < keV (e.g., ν) too hot.
  - Nonbaryonic
    - Light element abundances + Big Bang Nucleosynthesis measure baryon density: too low.
    - Baryonic matter could not collapse until recombination ($z \sim 1100$): too late to seed LSS



- Locally, we know
  - density ~ 0.1-0.7 GeV/cm^3:
    ~1 proton/3 cm^3, ~1 WIMP/coffee cup
  - velocity: simplest (not necessarily most accurate!) assumption is truncated Maxwell-Boltzmann distribution with $\sigma_v \approx 270$ km/s, $v_{esc} = 544$ km/sec

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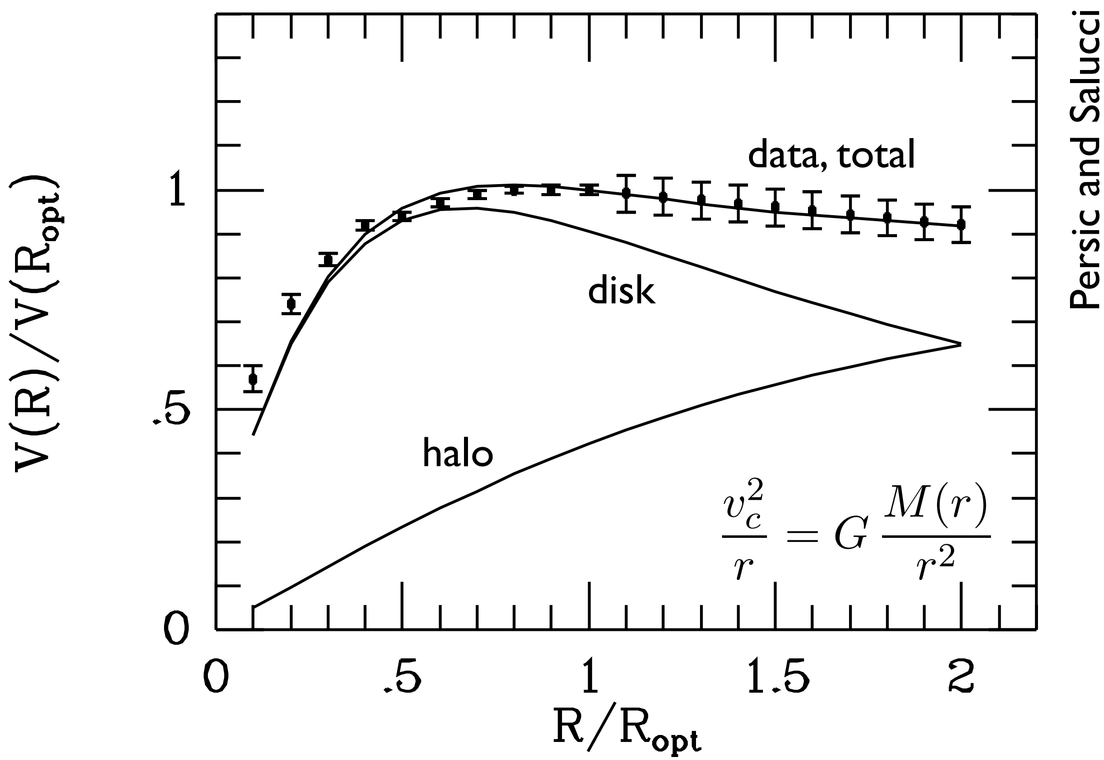

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WIMPs

- A WIMP δ is like a massive neutrino: produced when T >> m_δ via pair annihilation/ creation. Reaction maintains thermal equilibrium.
- If interaction rates high enough, comoving density drops as $\exp(-m_\delta / T)$ as T drops below m_δ : annihilation continues, production becomes suppressed.
- But, weakly interacting → will "freeze out" before total annihilation if

$$H > \Gamma_{ann} \sim \frac{n_\delta}{\langle \sigma_{ann}\, v \rangle}$$

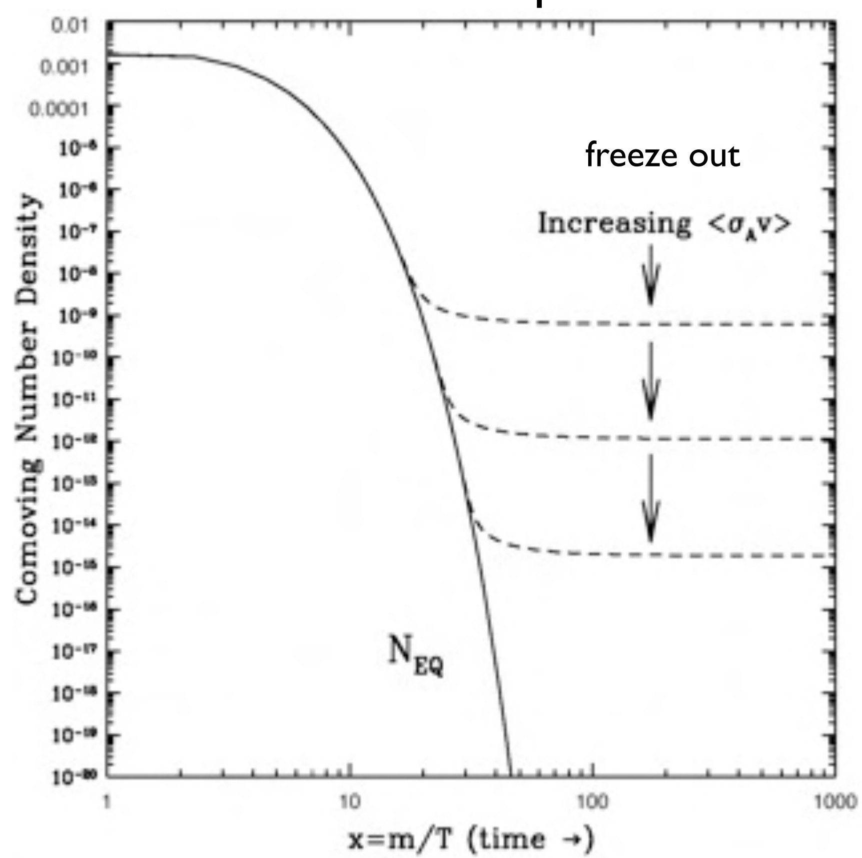
i.e., if annihilation too slow to keep up with Hubble expansion

- Leaves a relic abundance:

$$\Omega_\delta\, h^2 \approx \frac{10^{-27}}{\langle \sigma_{ann}\, v \rangle_{fr}}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

for m_δ = O(100 GeV)
→ if m_δ and σ_{ann} determined by new weak-scale physics, then Ω_δ is O(1)

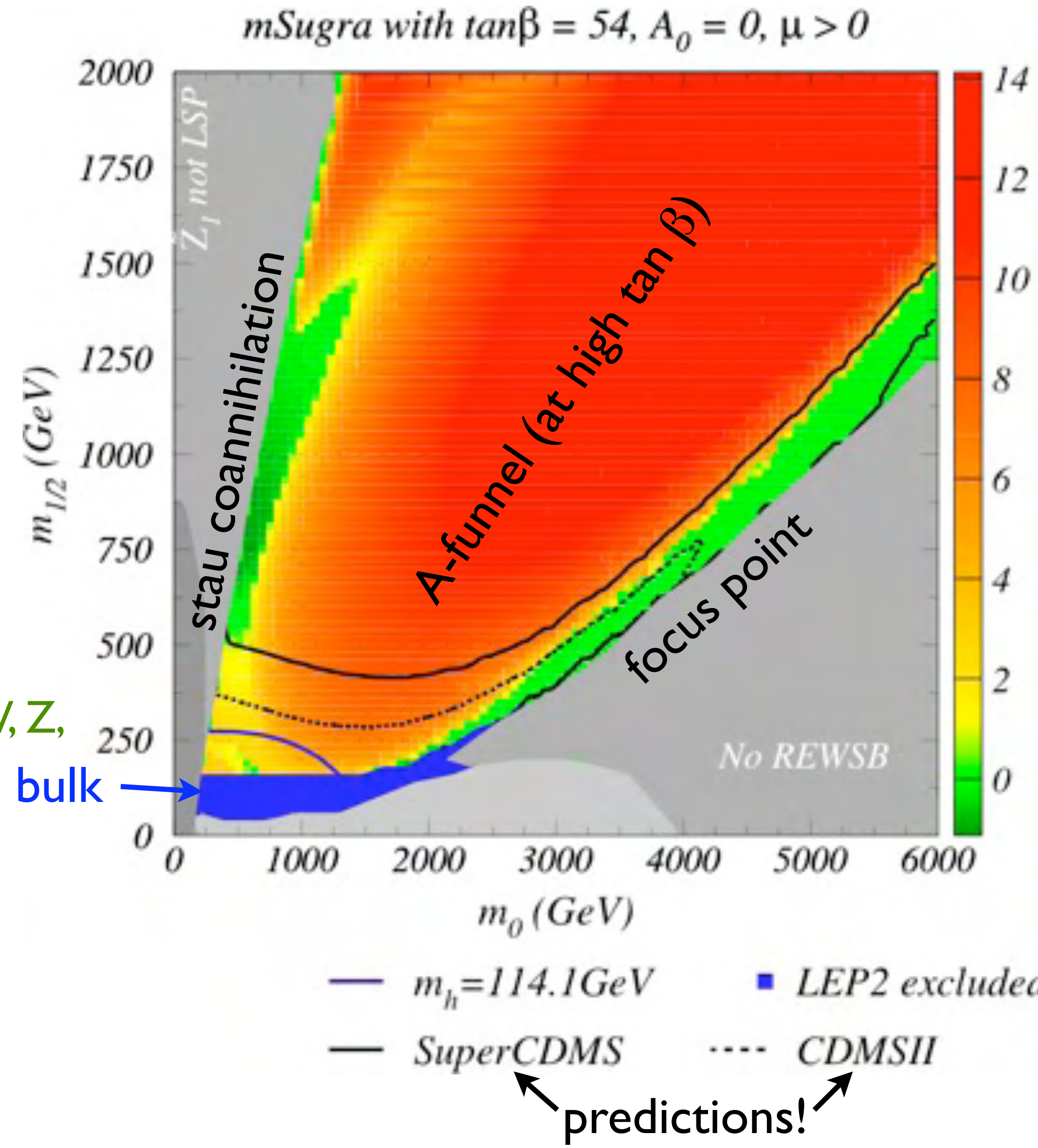
canonical Kolb and Turner freeze-out plot



Supersymmetric WIMPs

- Neutralino LSP δ
  - mixture of bino, wino, higgsinos; spin 1/2 Majorana particle
  - Allowed regions
    - bulk: δ annih. via t-ch. slepton exchange, light h, high BR(b→sγ) and $(g\text{-}2)_\mu$; good DD rates
    - stau coann: δ and stau nearly degenerate, enhances annih., low DD rates
    - focus point: less fine-tuning of REWSB, δ acquires higgsino component, increases annih. to W, Z, good DD rates
    - A-funnel: at high tan β, resonant s-ch. annih. via A, low DD rates

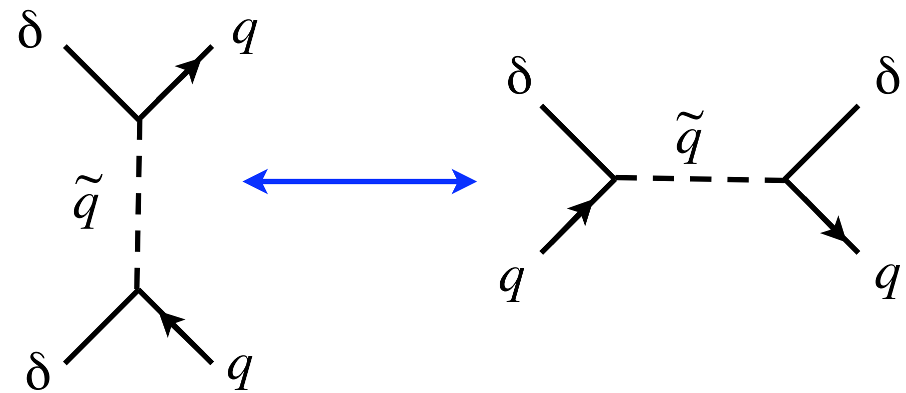
χ^2 of fit to BR(b→sγ), muon g-2, and relic density (dominated by relic density: avoid overclosure)



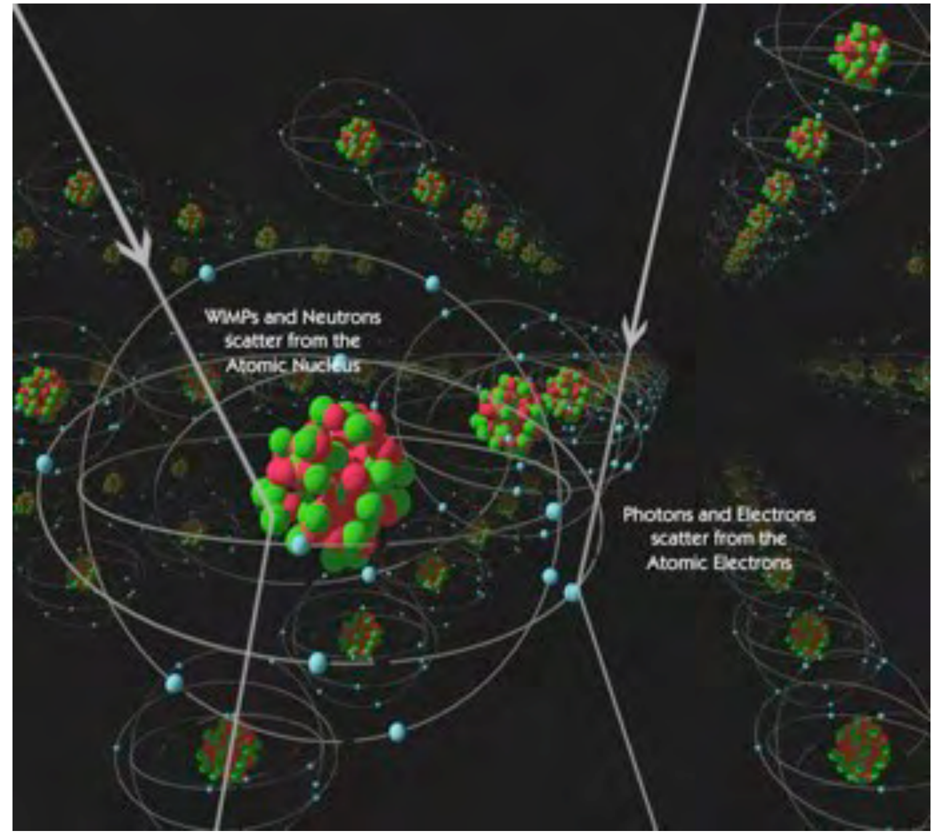
Baer et al, in DMSAG report

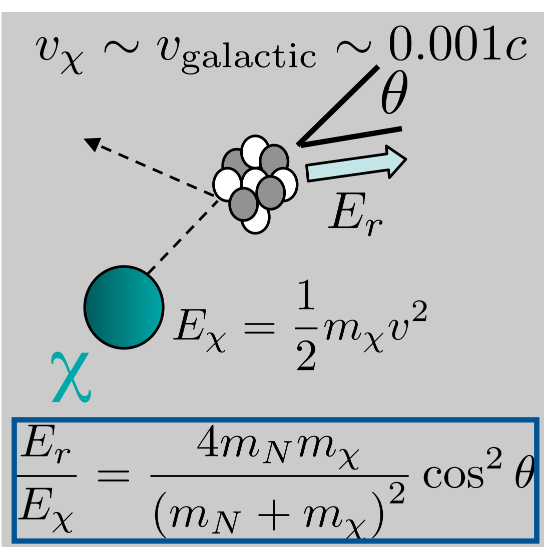
Direct Detection of WIMPs

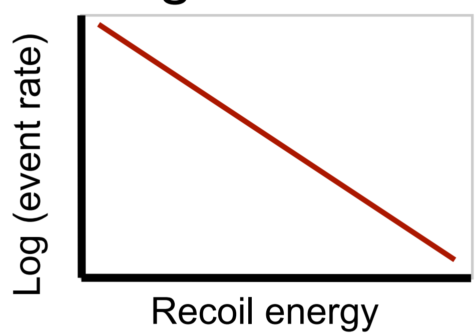
Diagram crossing → detectability?



Isothermal halo: v_0=270 km/s, v_{esc}=544 km/s
Maxwell-Boltzmann velocity dist'n
s-wave scattering







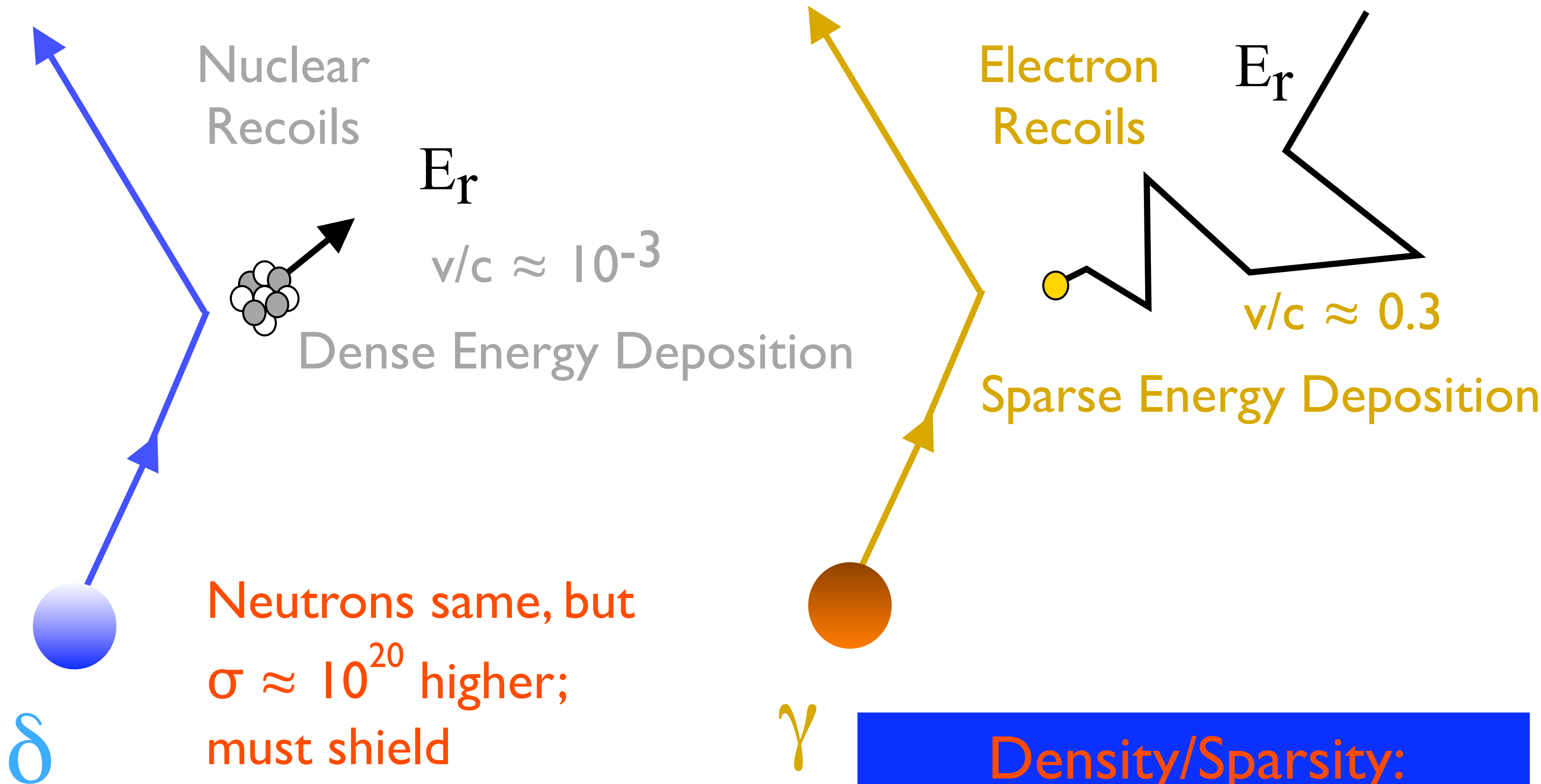
$v_{galactic}$~10^{-3}c →
coherent A^2 enhancement of scalar (spin-independent) scattering

→ Exponential spectrum of ⟨E⟩ ~ 30 keV nuclear recoils, ≪ 1/kg/day

Nuclear Recoil Discrimination

Signal

Background



Neutrons same, but
$\sigma \approx 10^{20}$ higher;
must shield

Density/Sparsity: Basis of Discrimination

Challenges and Techniques

Exponential spectrum of $\langle E \rangle \sim 30$ keV nuclear recoils, $\ll$ 1/kg/day

Challenges

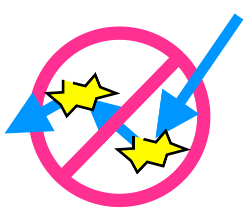
Very **low energy** thresholds (~10 keV)

Large **exposures** (large active mass, long-term stability)

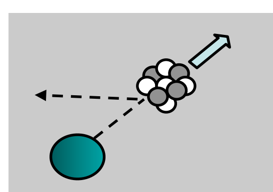
Stringent **background control** (cosmogenic, radioactive)
Cleanliness
Shielding (passive, active, deep site)

Discrimination power

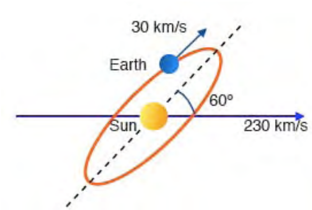
SIGNATURES



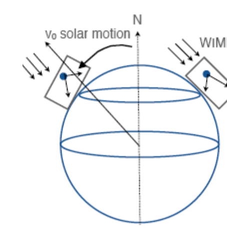
No multiplicity



Nuclear recoils



Annual flux modulation



Diurnal direction modulation

EVENT-BY-EVENT

STATISTICAL

Challenges and Techniques

Exponential spectrum of ⟨E⟩ ~ 30 keV nuclear recoils, ≪ 1/kg/day

the most powerful path to detection: aim for zero background

Challenges

Very **low energy** thresholds (~10 keV)

Large **exposures** (large active mass, long-term stability)

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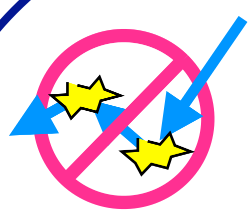

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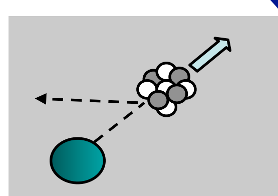

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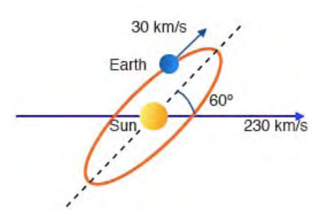

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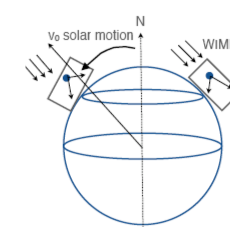
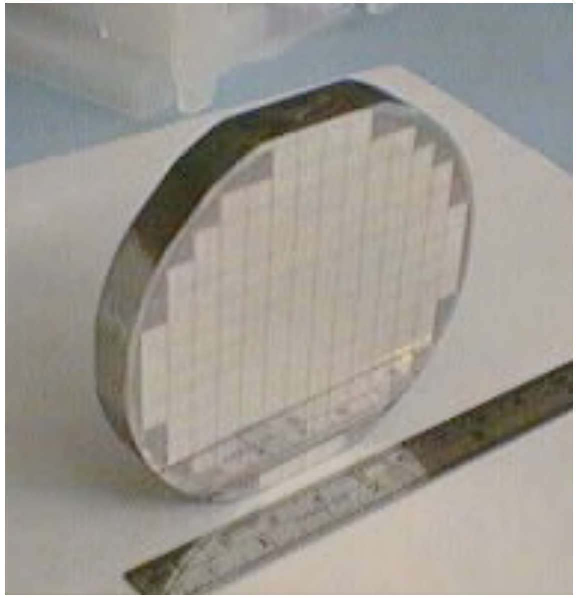


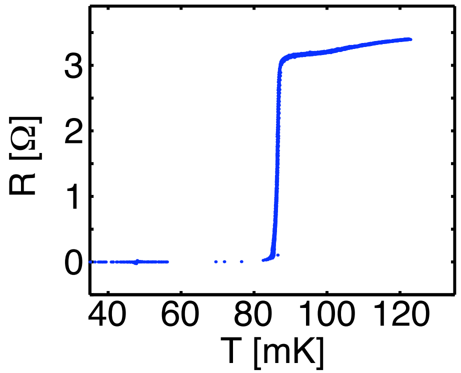
Diurnal direction modulation

STATISTICAL

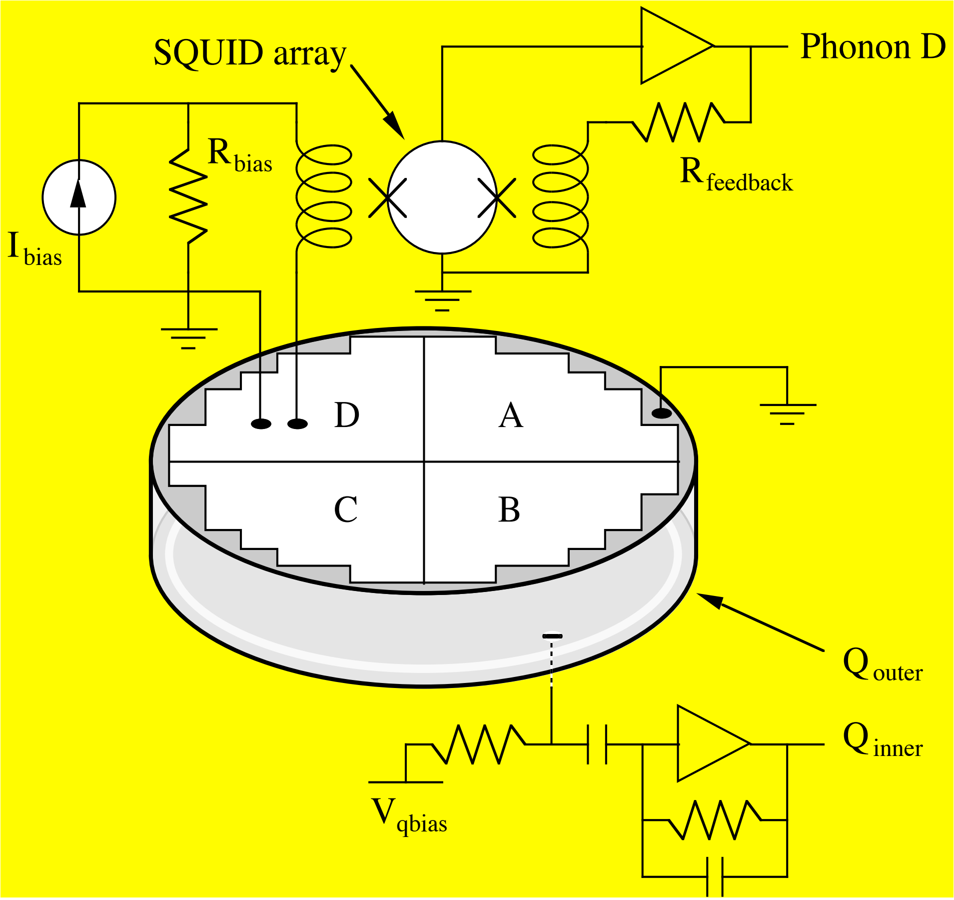
CDMS ZIP Detectors

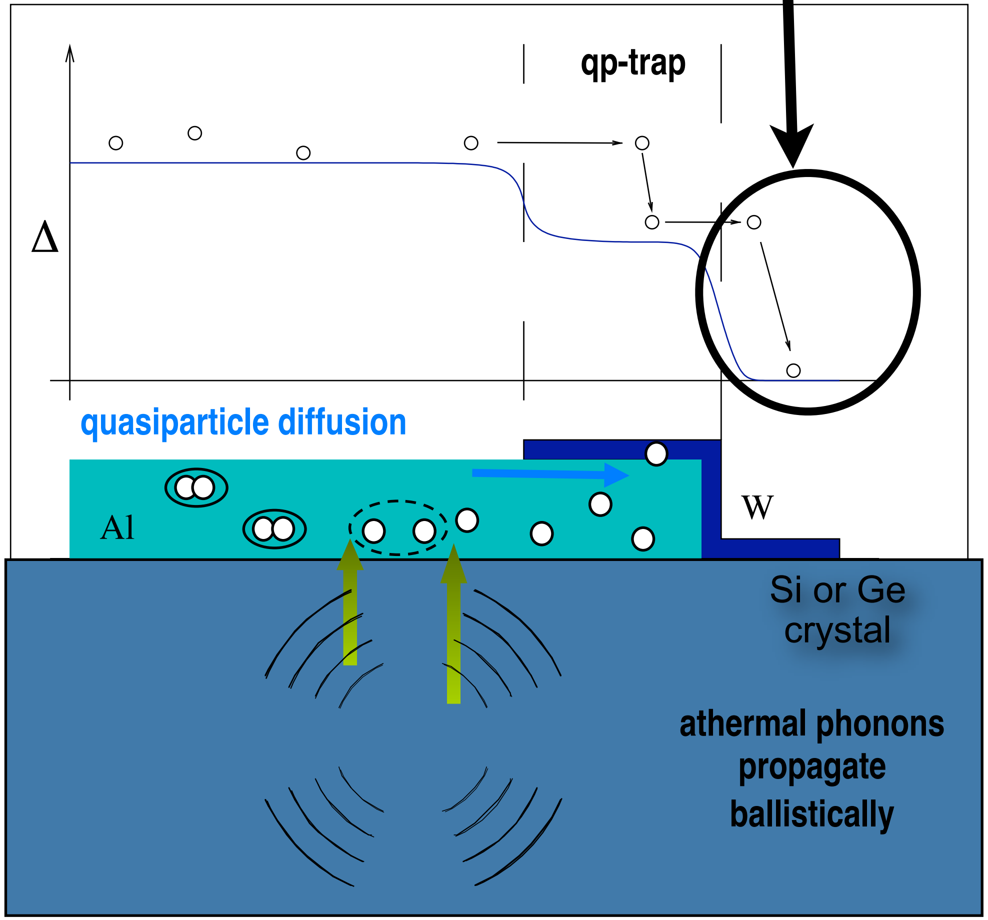


TES = transition edge sensor



Z-sensitive Ionization- and Phonon-mediated detectors: Phonon signal measured using photolithographed superconducting phonon absorbers and transition-edge sensors.





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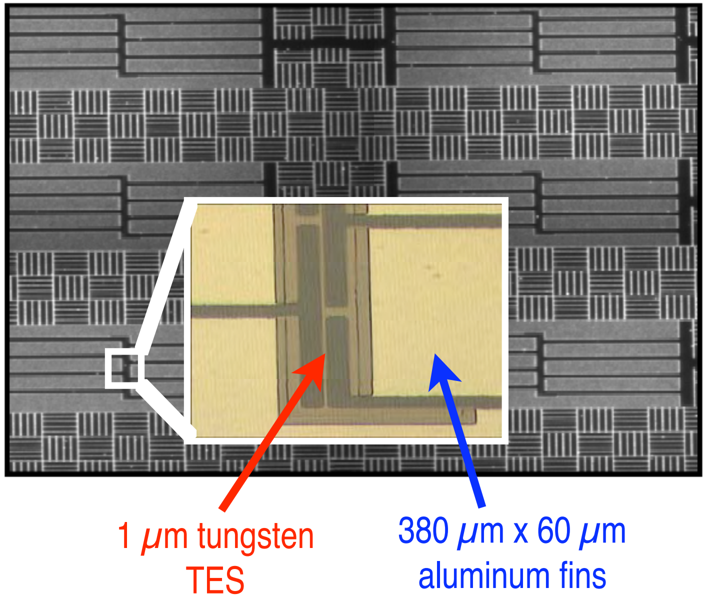

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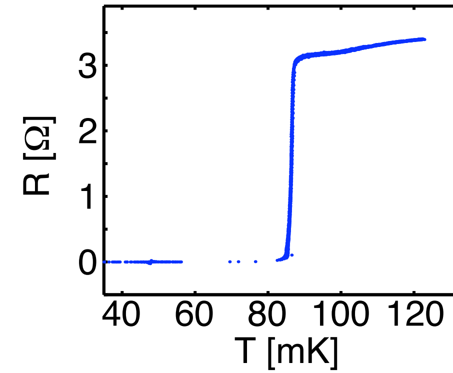

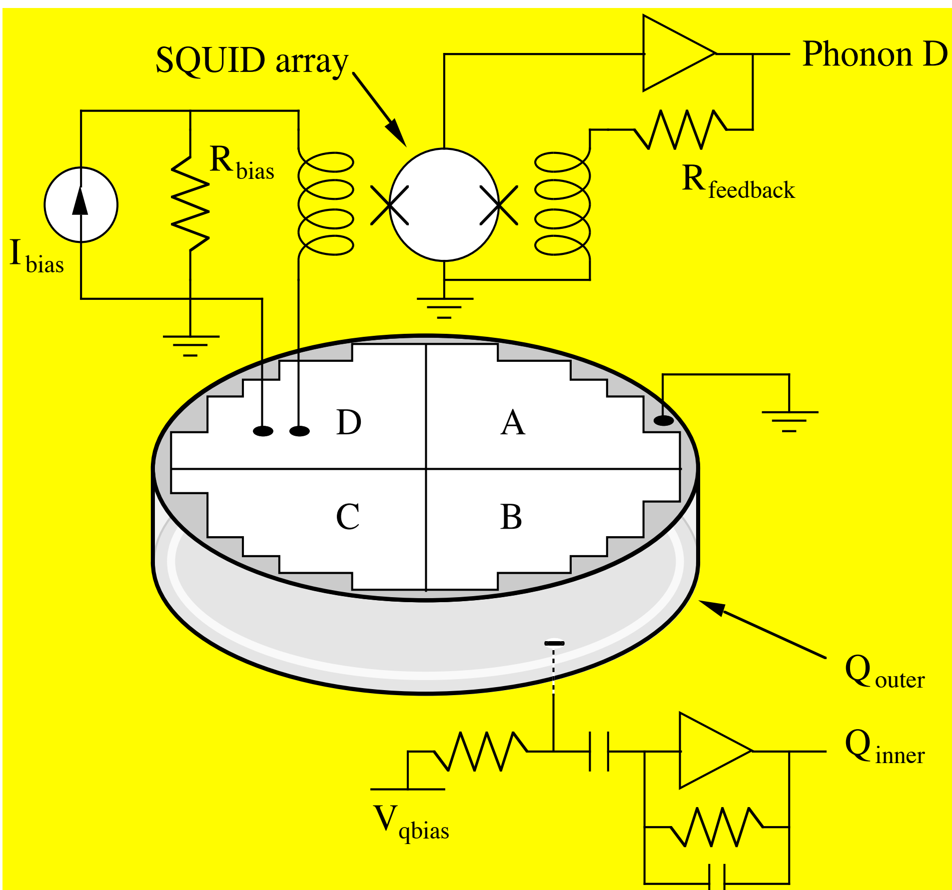

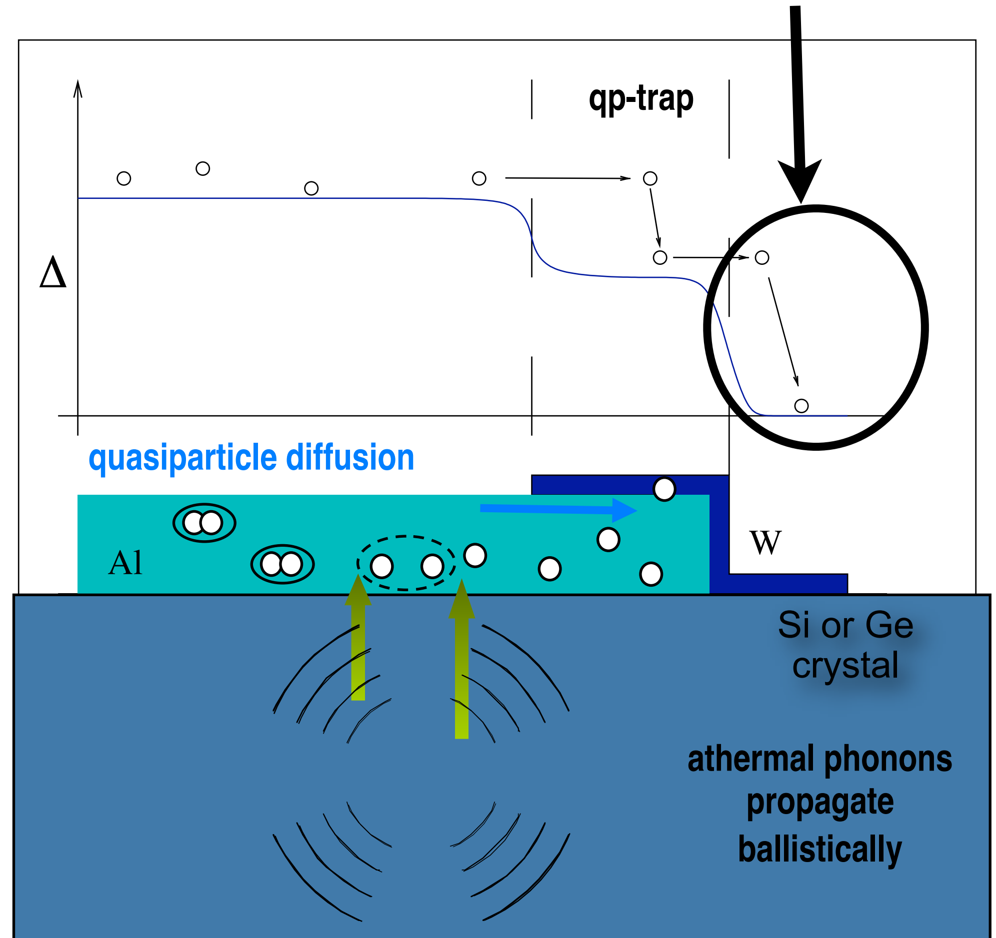

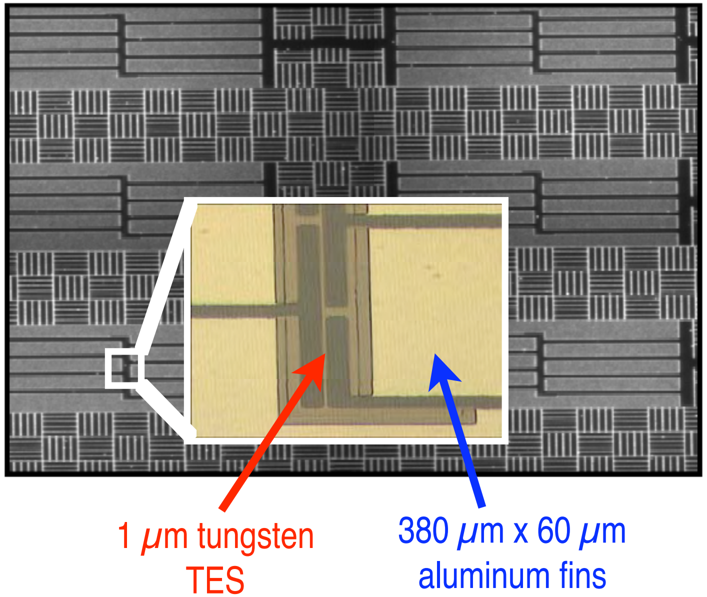

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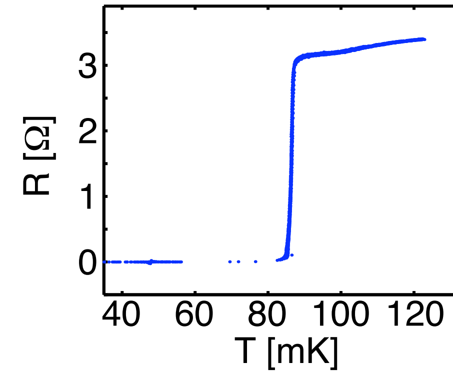

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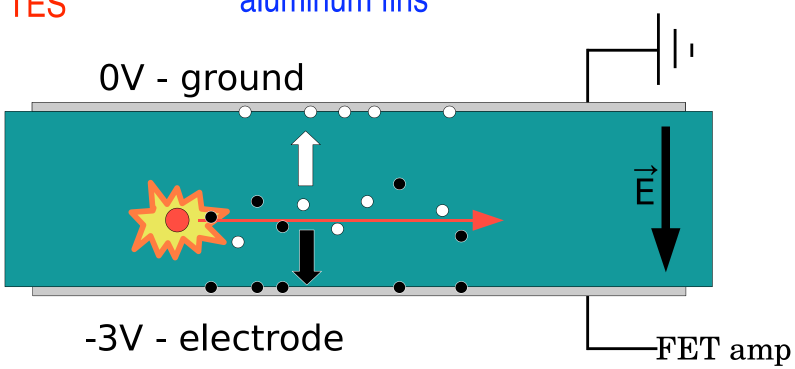

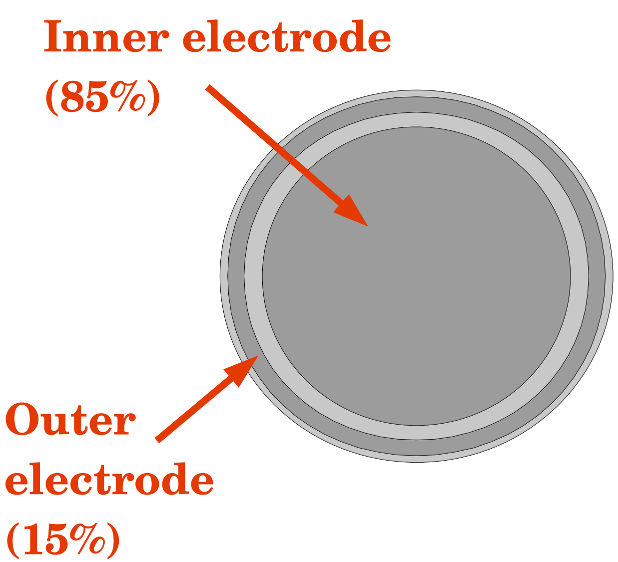

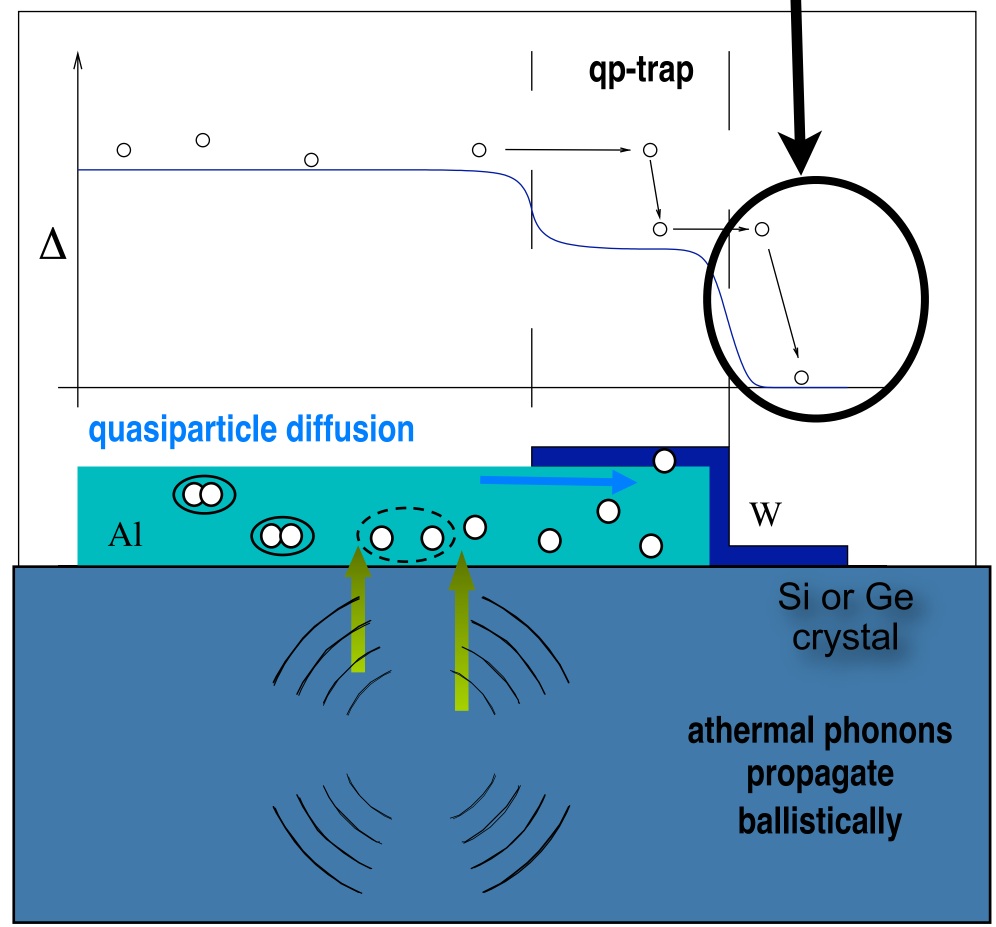

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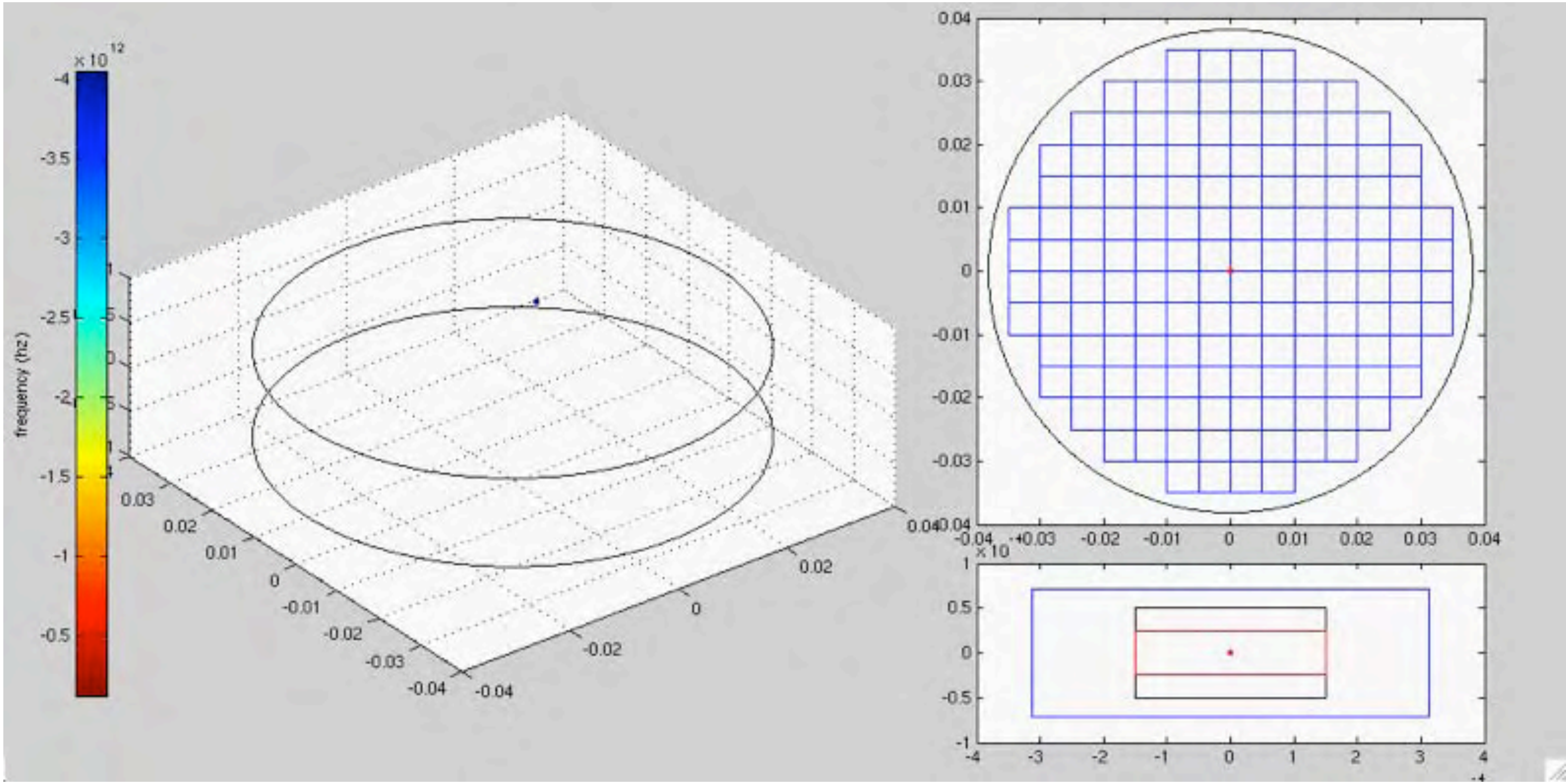


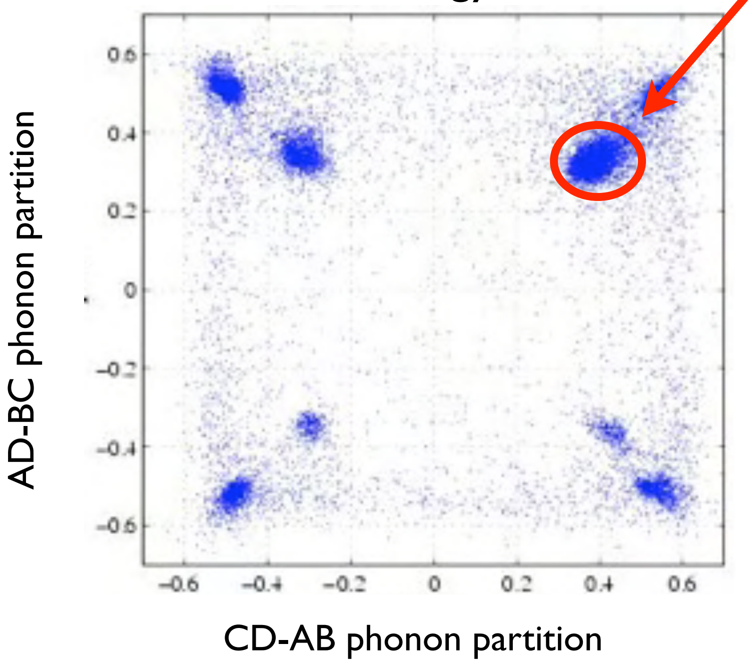
Position Reconstruction

Sound speed ~ 1 cm/μs

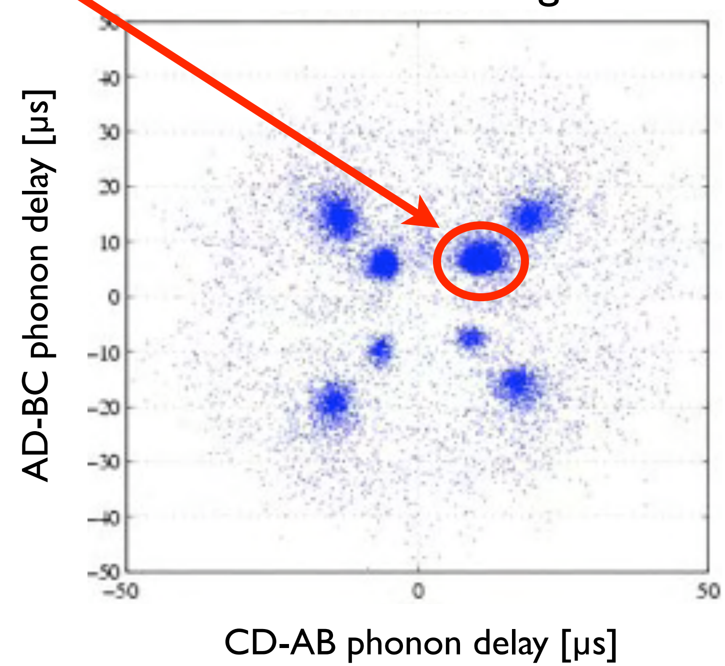
Crucial to
correct for position dependence
of athermal phonon signals

Collimated ^{109}Cd sources (β, 22 keV γ)

Phonon Energy Partition

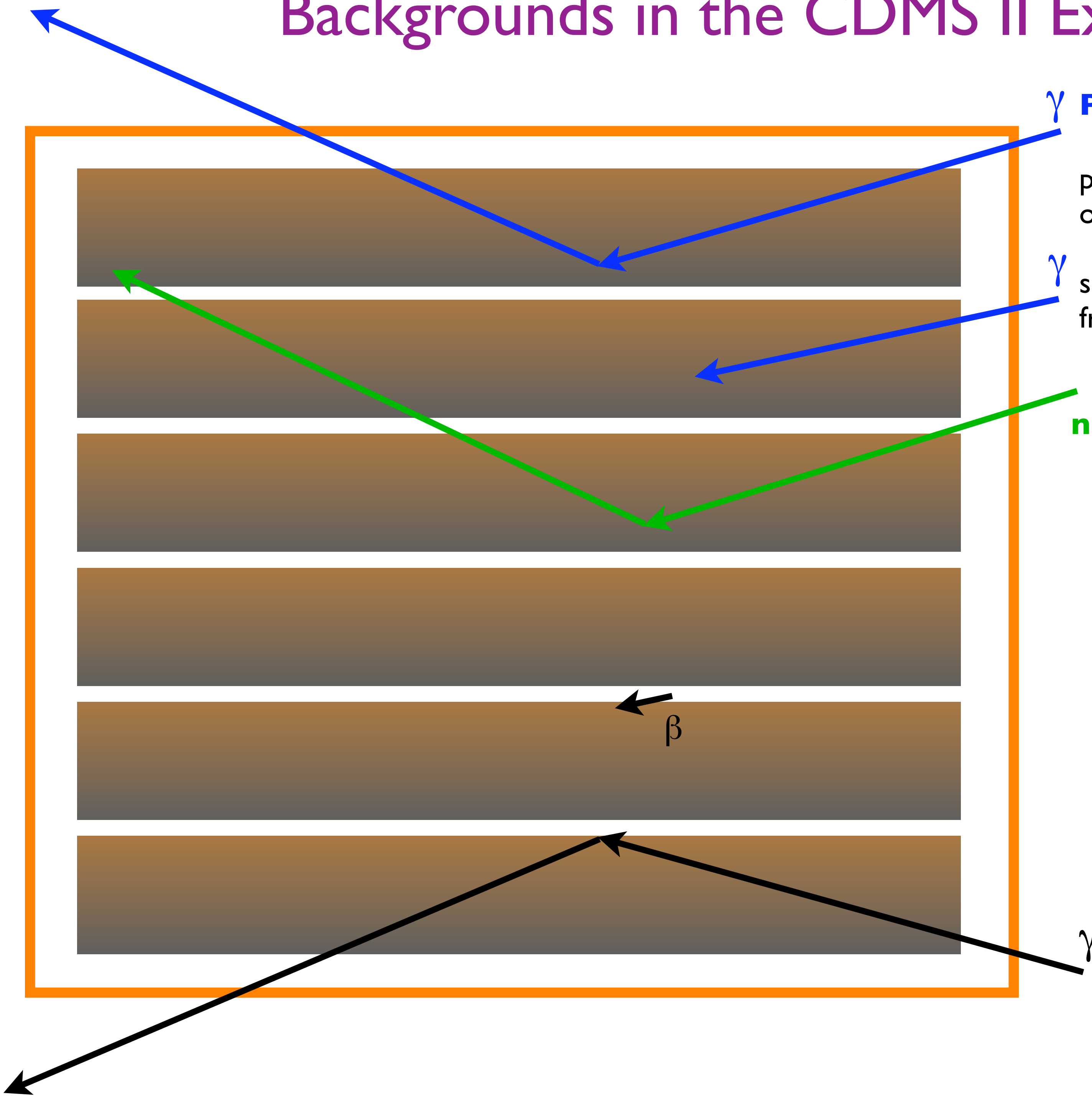


Phonon Timing



Data from UC Berkeley calibration of T2Z5, née G31
V. Mandic et al., NIM A **520**, 171 (2004)

Backgrounds in the CDMS II Experiment



Photons (γ)

primarily Compton scattering
of broad spectrum up to 2.5 MeV

small amount of photoelectric effect
from low energy gammas

Neutrons (n)

radiogenic: arising from fission and (α,n) reactions in surrounding materials (cryostat, shield, cavern)

cosmogenic: created by spallation of nuclei in surrounding materials by high-energy cosmic ray muons.

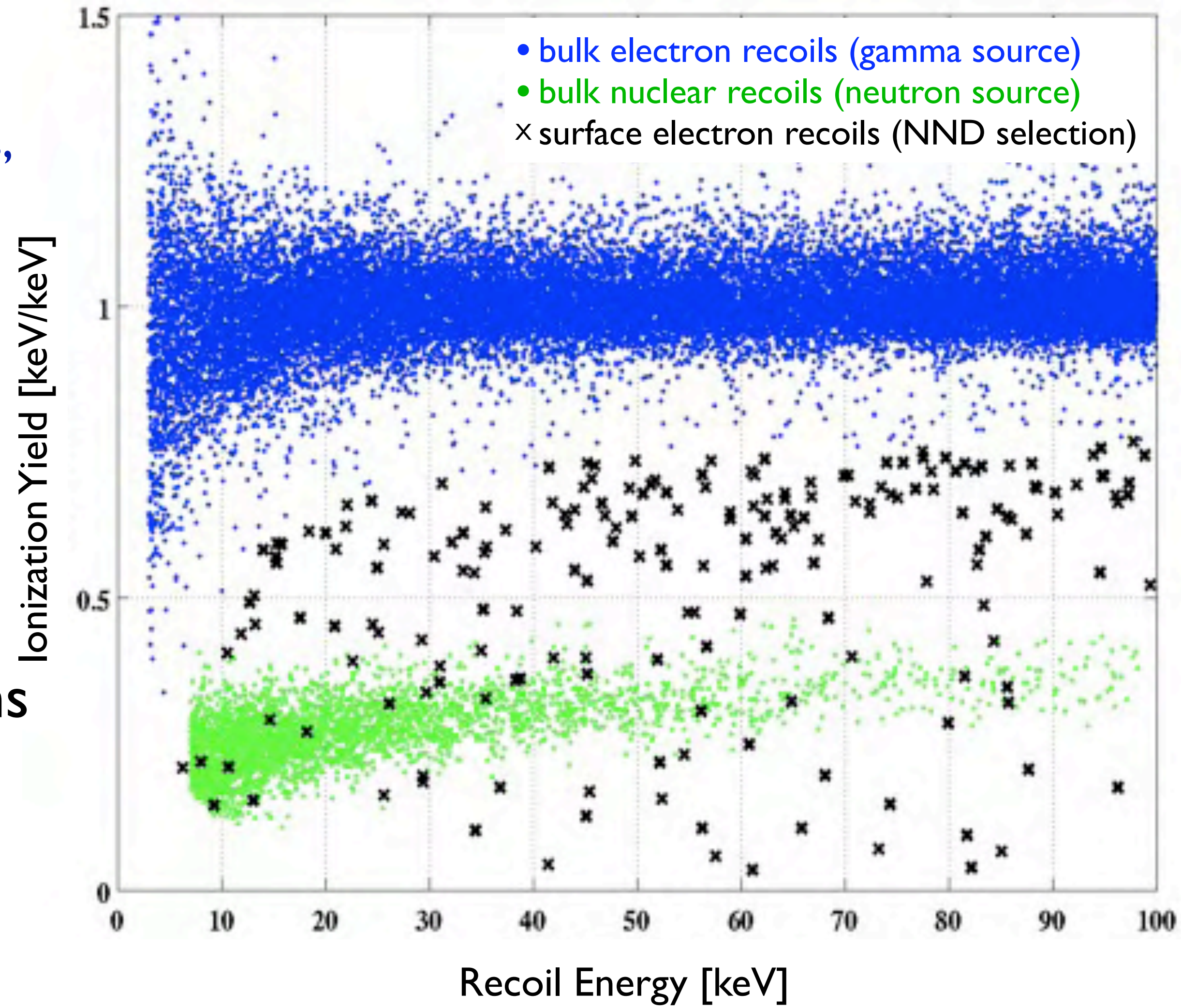
Surface events ("β")

radiogenic: electrons/photons emitted in low-energy beta decays of ^{210}Pb or other surface contaminants

photon-induced: interactions of photons or photo-ejected electrons in dead layer

Nuclear Recoil Discrimination in CDMS II

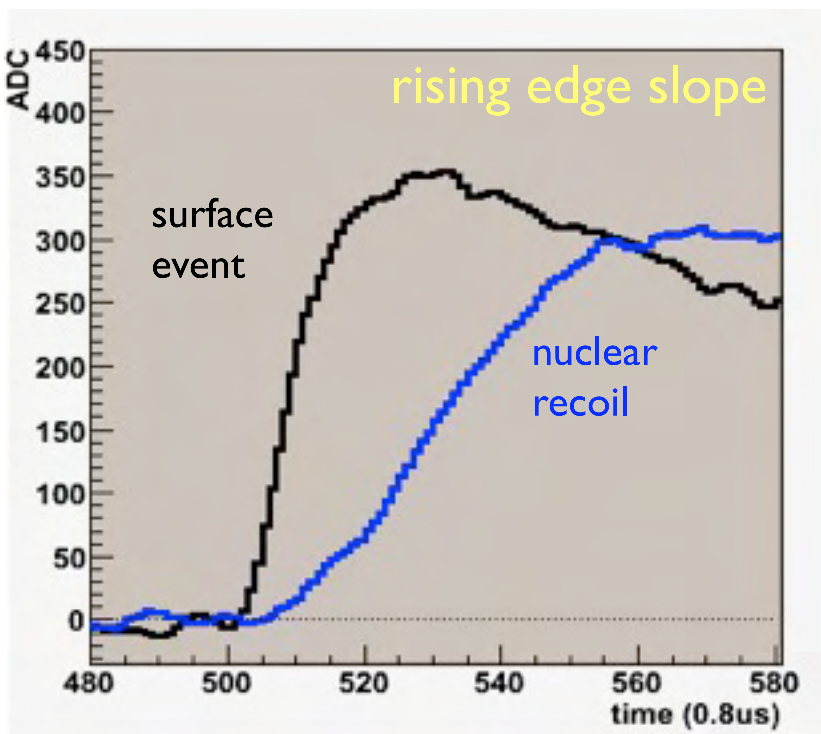
- Recoil energy
  - Phonon (acoustic vibrations, heat) measurements give full recoil energy
- Ionization yield
  - ionization/recoil energy strongly dependent on type of recoil (Lindhard)
- Excellent yield-based discrimination for photons
- Ionization dead layer:
  - low-energy electron singles (all surface ER): 0.2 misid
  - 1.2 x 10^{-3} of photons are surface single scatters, 0.2 of those misid'd (⇒ 2 x 10^{-4})
  - also, radiogenic low-energy electrons from decay of ^{210}Pb on surface (radon daughter)

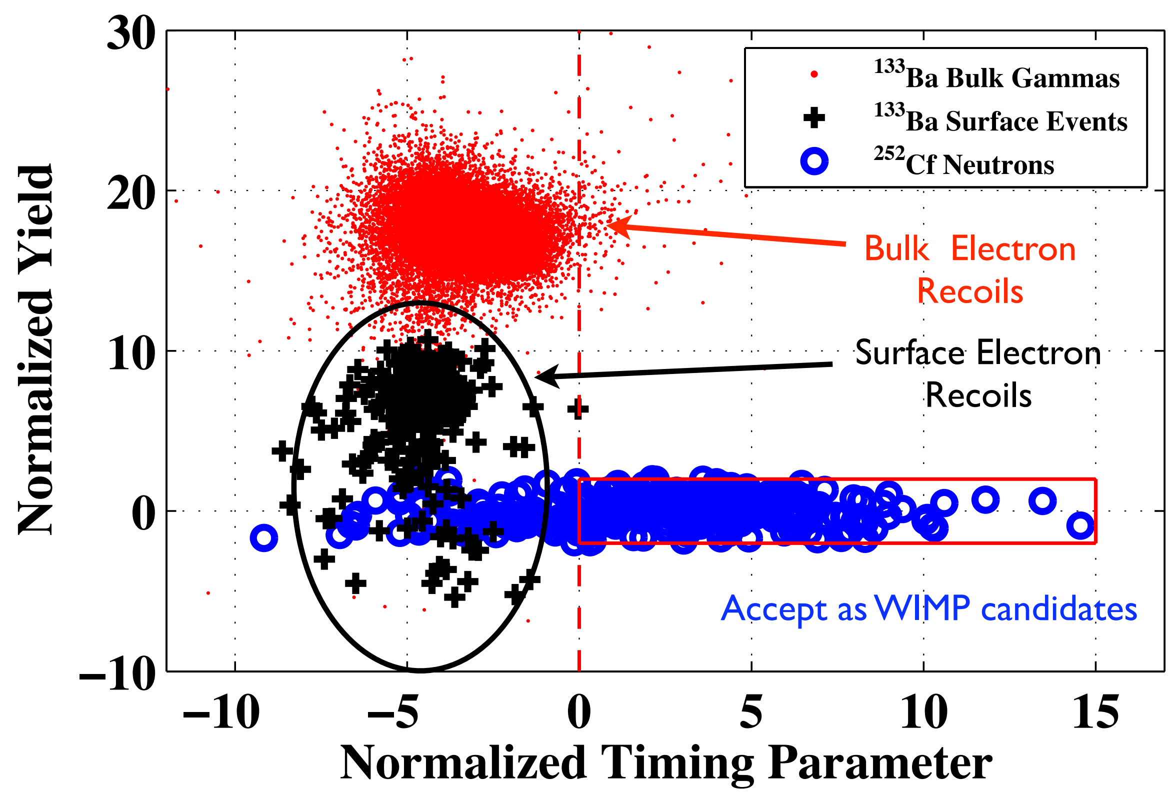


ZIP z Position Sensitivity

- Surface events produce faster phonon pulses (test sample: nearest neighbor low-yield doubles (NNDs)): provides discrimination

1:1 scale: 3 in. x 1 cm, 1 mm separation





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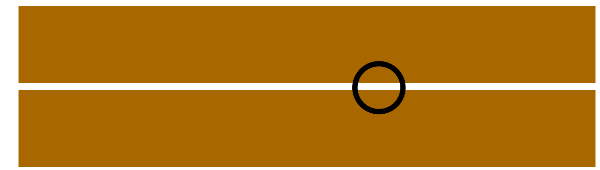

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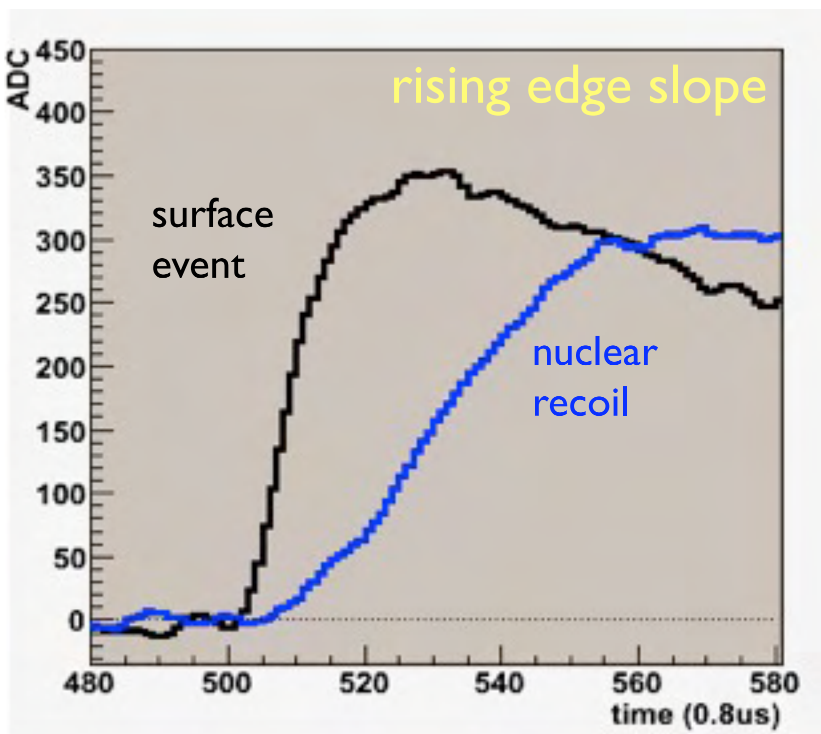

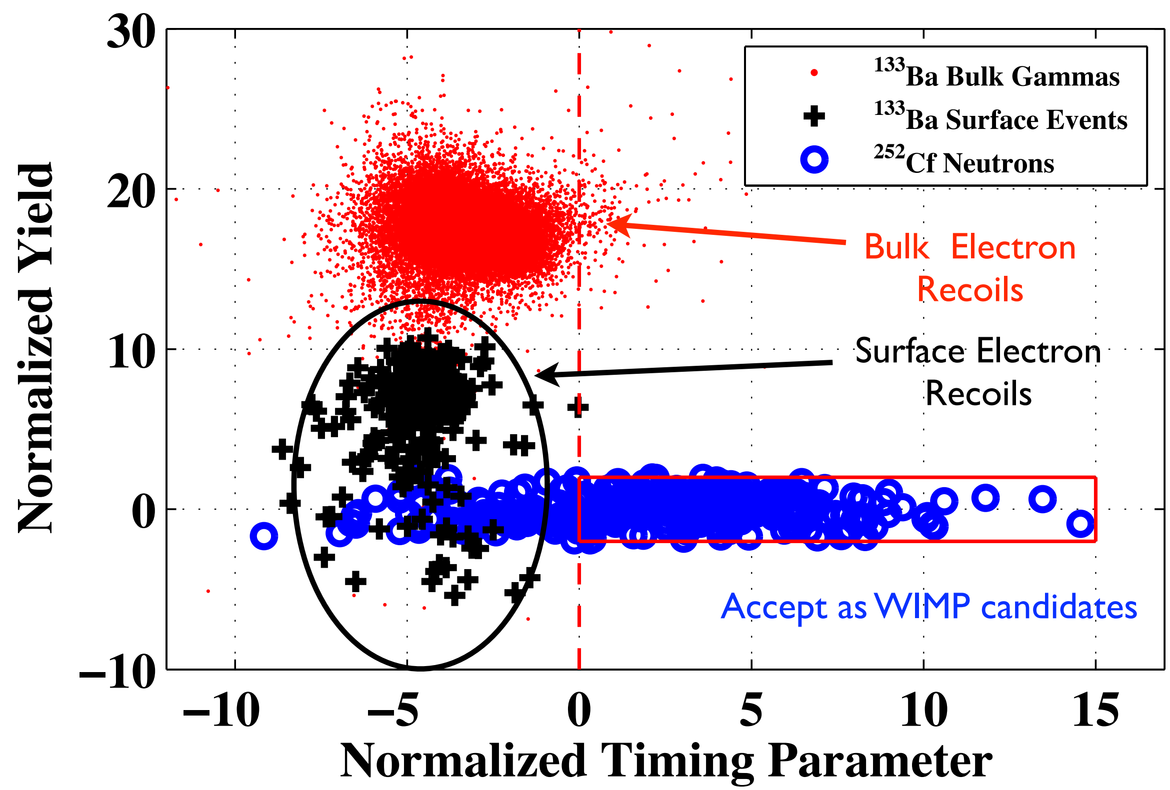

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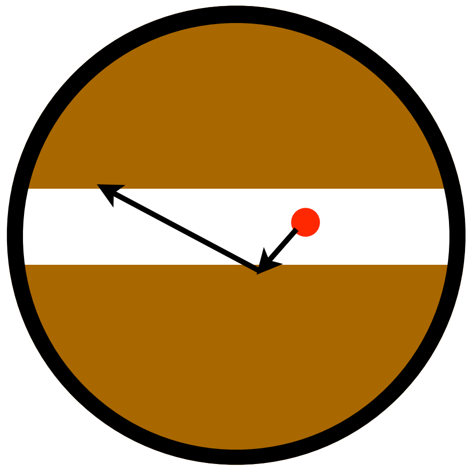
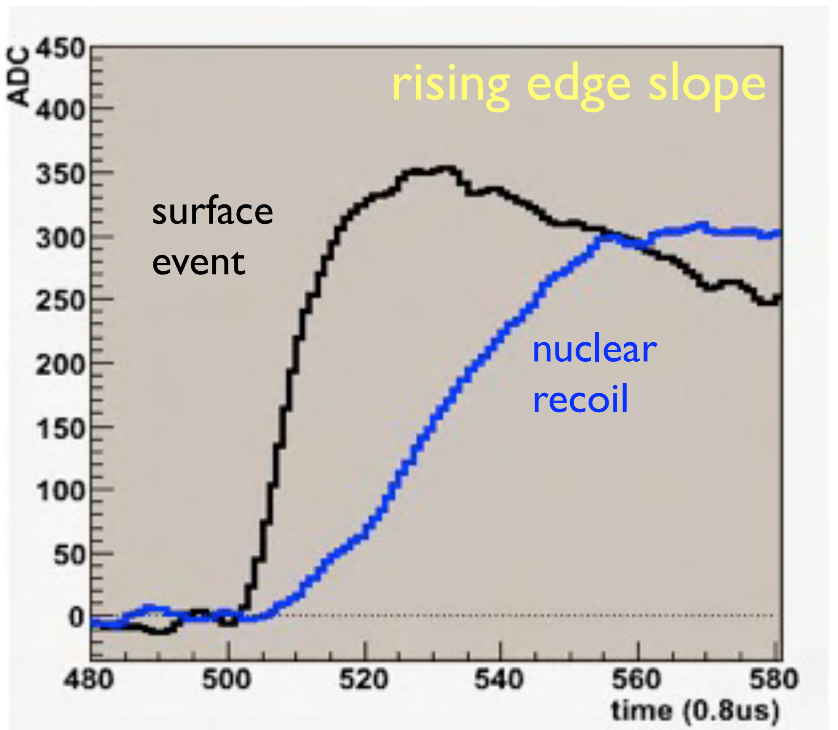
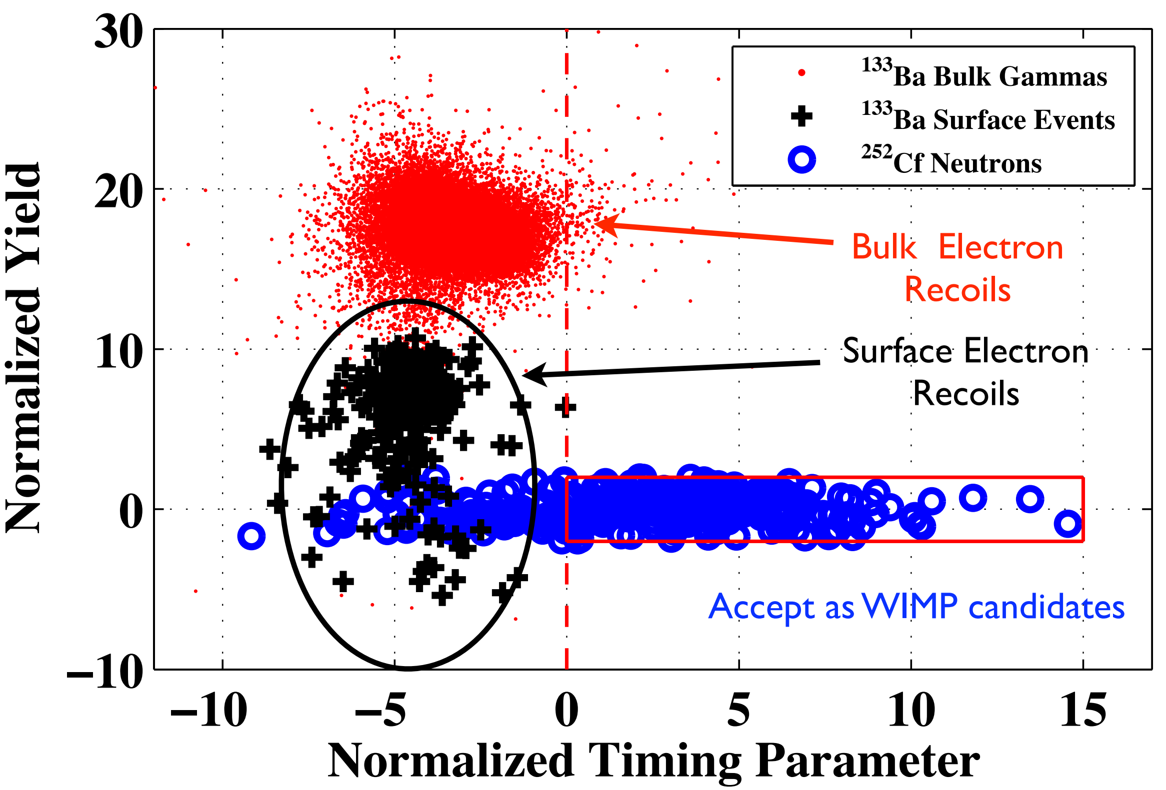
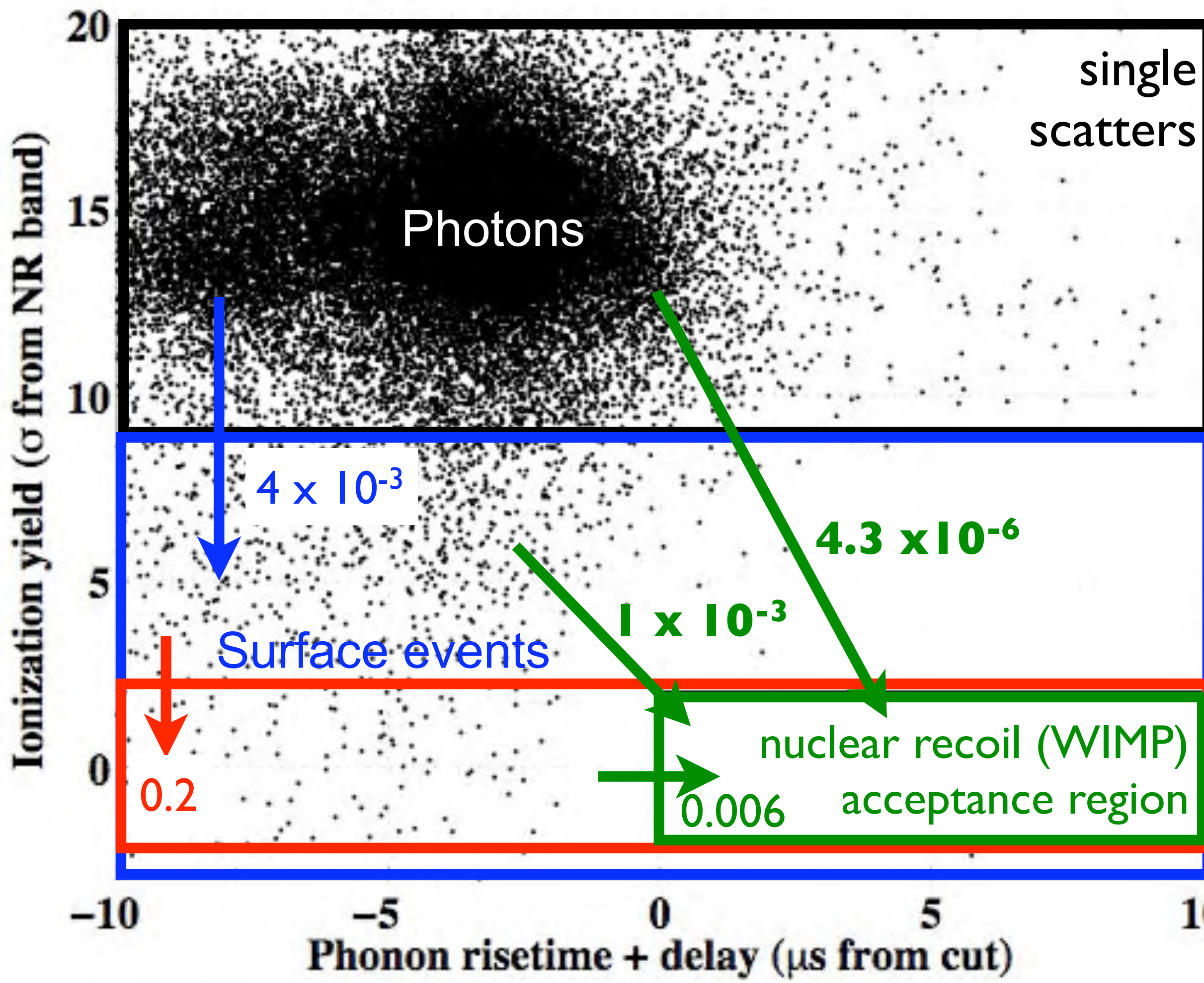






CDMS II Background Discrimination

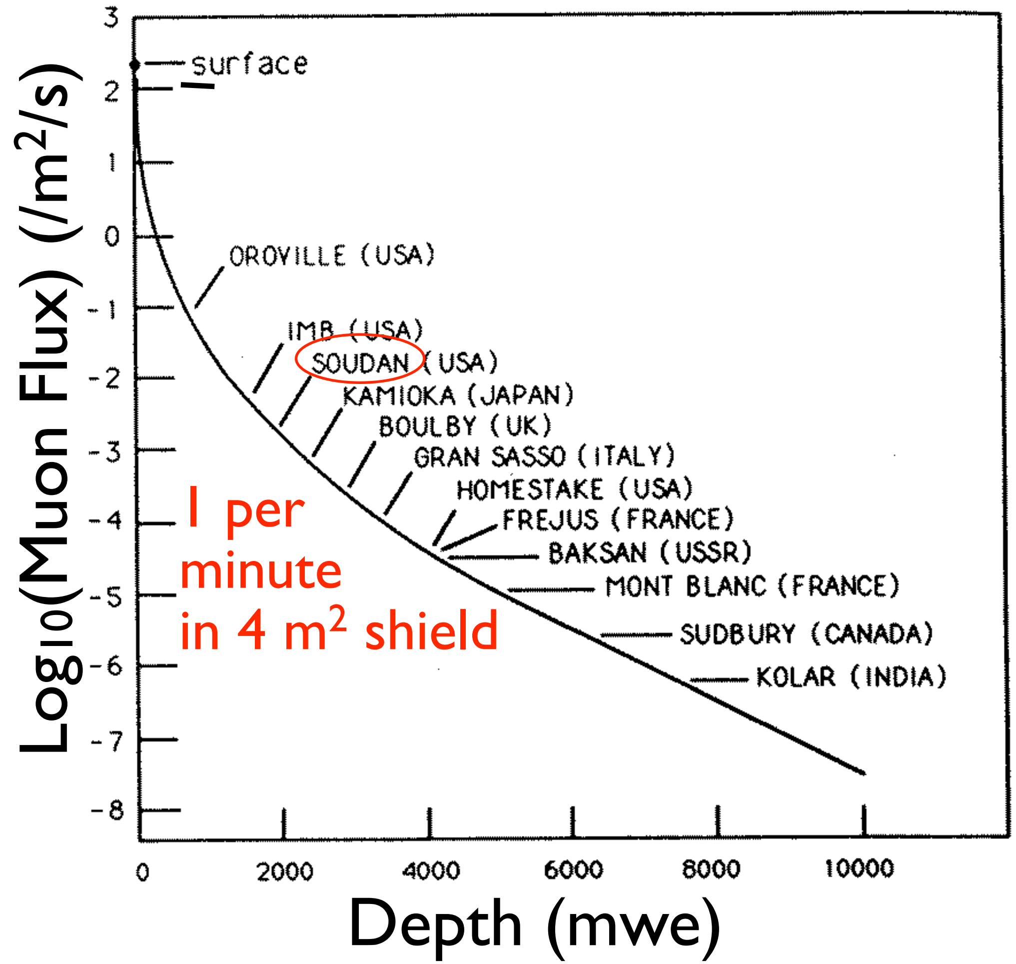
- Photon rejection
  - Bulk photon rate (bulk ER) = 300/kg/day. Single-scatters = 90/kg/day
  - Single-scatter surface ERs = 0.3/kg/day
  - Surface ER singles/ bulk ER singles = 4 x 10^{-3}
  - Surface ER singles misid'd as nuclear recoils (NRs) /surface ER singles = 0.2 (ionization dead layer)
  - Phonon timing rejects surface events: 0.006 misid. prob.
  - Overall misid probability: 1.4 x 10^{-6} for bulk ER, **4.3 x 10^{-6}** for single-scatter bulk ER



- Beta rejection
  - Comparable single-scatter ER rate of low-energy beta emitters (mainly ^{210}Pb)
  - 0.2 misid by yield and 0.006 misid by timing: **1 x 10^{-3}** misid probability

2002–2009: CDMS II at Soudan

Depth of 2000 meters water equivalent reduces neutron background to ~1 / kg / year; veto down to 0.008 sgl / kg / yr



The CDMS II/SuperCDMS/GEODM Collaborations

CDMS II through to GEODM. Not all collaborators are participating in every stage

Brown University
M. Attisha, R. J. Gaitskell, J.-P. Thompson

Caltech
Z. Ahmed, J. Filippini, S. R. Golwala, D. Moore

Case Western Reserve University
D. S. Akerib, C. N. Bailey, D. R. Grant, R. Hennings-Yeomans, M.R. Dragowsky

Fermilab
D. A. Bauer, M.B. Crisler, F. DeJongh, J. Hall, D. Holmgren, L. Hsu, E. Ramberg, R. L. Schmitt, J. Yoo

MIT
E. Figueroa-Feliciano, S. Hertel, K. McCarthy, S. Leman, P. Wikus

NIST
K. Irwin

Queens University
C. Crewdon, P. di Stefano, J. Fox, S. Liu, C. Martinez, P. Nadeau, W. Rau,

Santa Clara University
B. A. Young

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Southern Methodist University
J. Cooley

Stanford University
P.L. Brink, B. Cabrera, M. Cherry, L. Novak, R.W. Ogburn, M. Pyle, M. Razeti, B. Shank, A. Tomada, S. Yellin, J. Yen

St. Olaf College
A. Reisetter

Syracuse University
R.W. Schnee, M. Kos, J. M. Kiveni

Texas A&M
K. Koch, R. Mahapatra, M. Platt, K. Prasad, J. Sander

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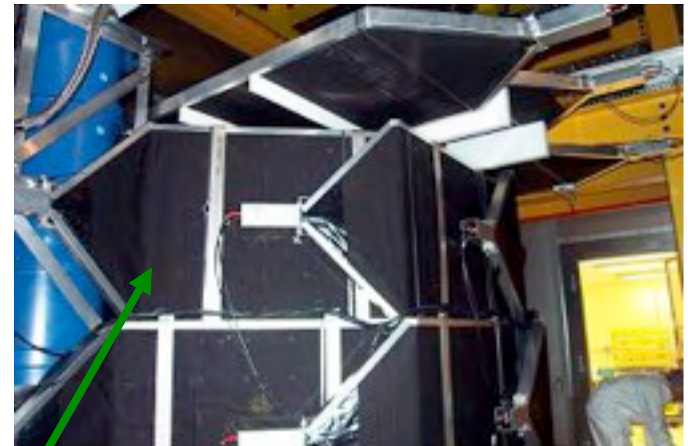
University of Colorado at Denver
B. Hines, M. E. Huber

University of Florida
D. Balakishiyeva, T. Saab, B. Welliver

University of Minnesota
J. Beaty, H. Chagani, P. Cushman, S. Fallows, M. Fritts, T. Hoffer, O. Kamaev, V. Mandic, X. Qiu, R. Radpour, A. Villano, J. Zhang

University of Zurich
S. Arrenberg, T. Bruch, L. Baudis, M. Tarka

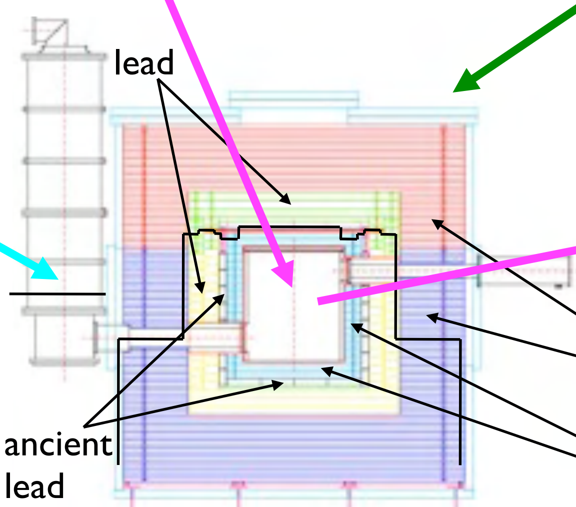
CDMS II Soudan Installation

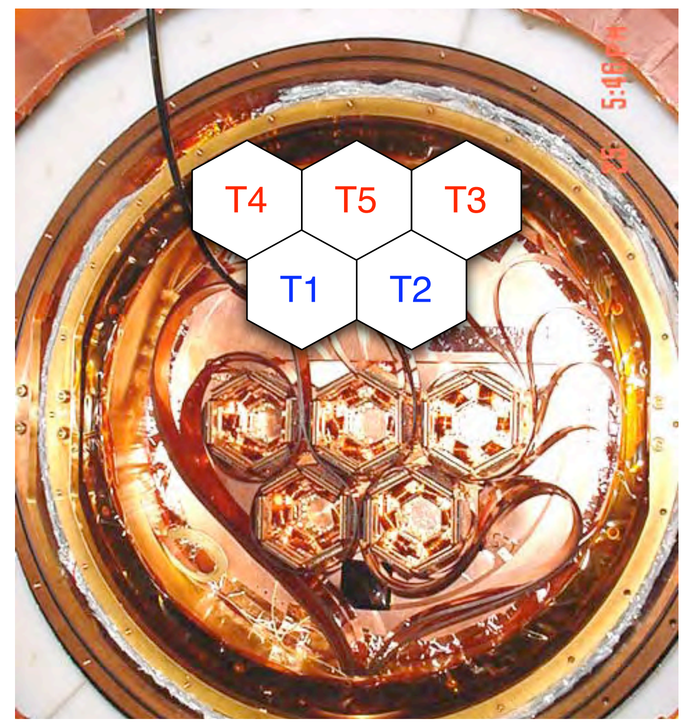


Plastic scintillator

Oxford Instruments 400 μW dilution refrigerator

detector cold volume (“icebox”)





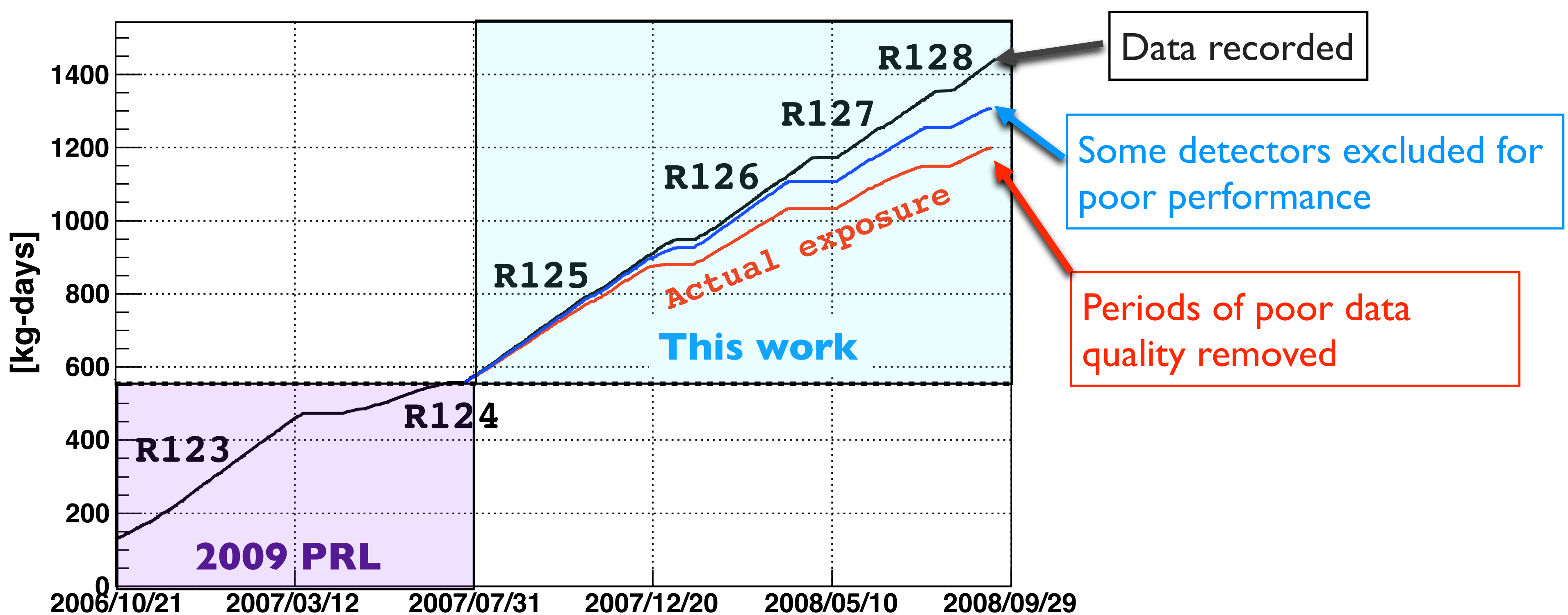
RF shielded class 10,000 clean room

detectors operate @ 40 mK

Five Tower Runs (2006-9)

- 30 ZIPs (5 Towers) installed:
  4.75 kg Ge, 1.1 kg Si

- Runs 123 - 124
  - Acquired: Oct06-Mar07, Apr07-Jul07
  - Exposure: ~400 kg-d (Ge "raw")
- Runs 125 - 128 THIS WORK
  - Acquired: Jul07-Jan08, Jan08-Apr08, May08-Aug08, Aug08-Sep08
  - Exposure: ~600 kg-d (Ge "raw")



The Happy Analyzers

The Happy Analyzers

The Happy Analyzers

+ advice and limit plots from postdoc Jeff "Just when I thought I was out... they pull me back in" Filippini (Berkeley CDMS grad)

Blind Analysis

- Quarantined signal-like events during data reduction
  - Single-scatter
  - No activity in veto shield
  - Ionization yield near nuclear recoil band
- These events have no effect on the definition of our signal criteria
- Quarantine broken only when all cuts are finalized: "unblinding"
- Avoids statistical bias: cut on independent event distributions, not observed candidate events