# The Road to Zeptobarn Dark Matter and Beyond

Sunil Golwala
Caltech PRC

Feb 4, 2010

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with thanks to Jeff Filippini and SI units:

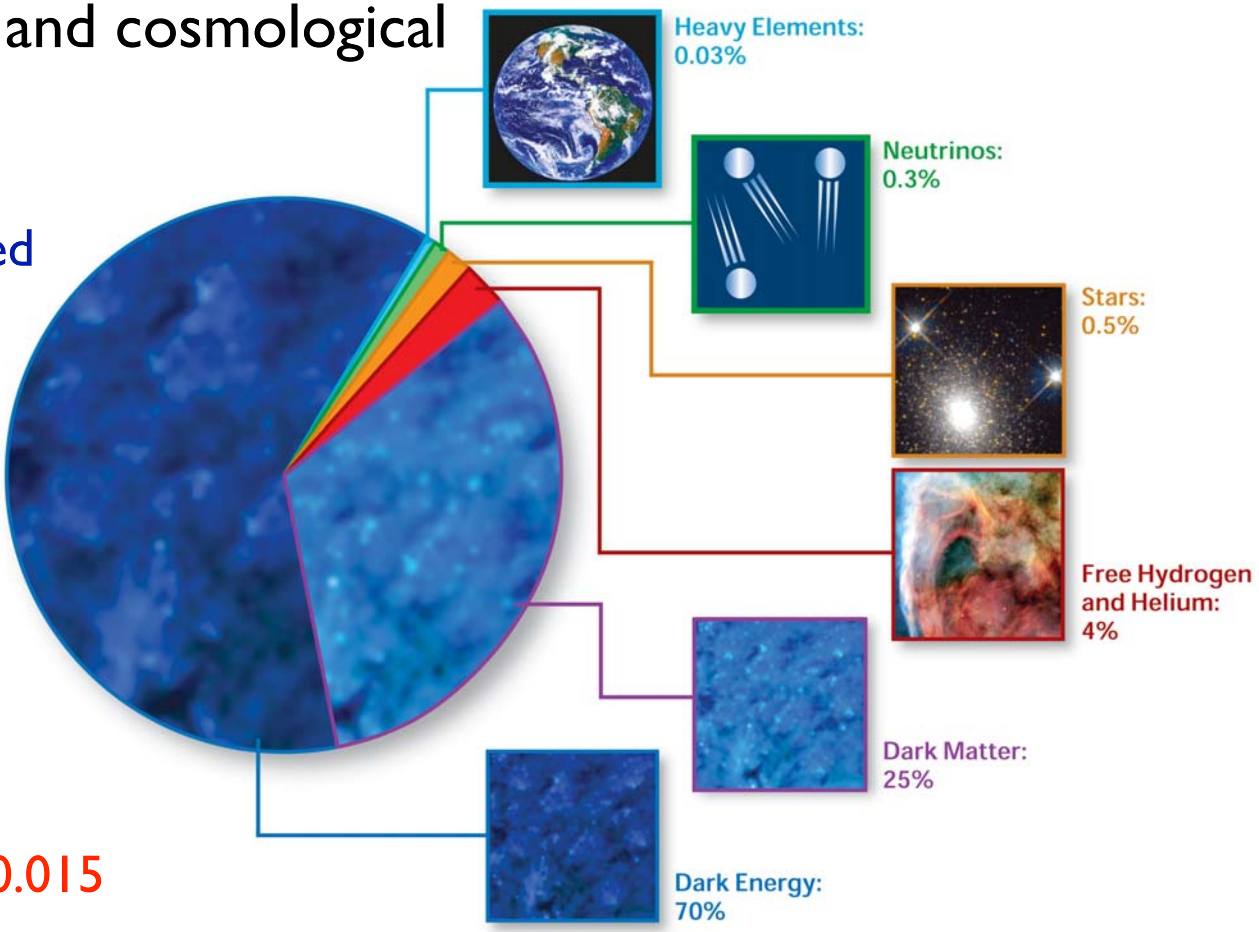
*1 zeptobarn = $10^{-21}$ barn =$10^{-45}$ cm$^2$ cross section for dark-matter/nucleon scattering

# Outline

- Motivation for Weakly Interacting Massive Particle (WIMP) dark matter
- How to look for WIMPs
- Current status of the Cryogenic Dark Matter Search
- Toward the future with SuperCDMS and the Germanium Observatory for Dark Matter (GEODM)
- Review of most favored techniques to search for zeptobarn-scale WIMPs, and one person's scorecard

# Why Dark Matter?

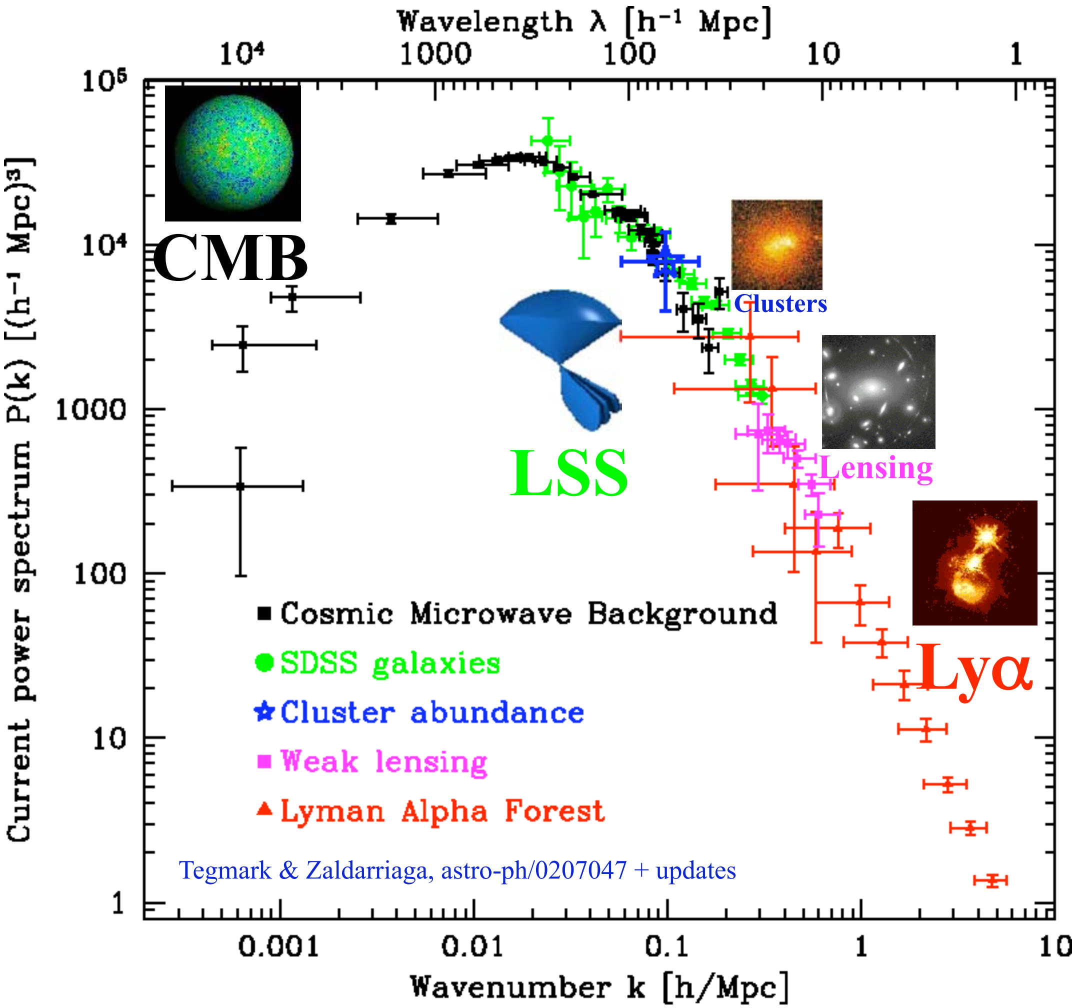
- A host of astronomical and cosmological observations indicate:
  - Total energy density = critical density $\rho_{crit}$ needed for spatially flat universe (within errors)
  - The bulk is in the form of *dark energy*, a fluid that has negative pressure (causes the universe's expansion to accelerate) 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. $M < \text{keV}$ (e.g., $\nu$) 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



Tegmark & Zaldarriaga, astro-ph/0207047 + updates

- 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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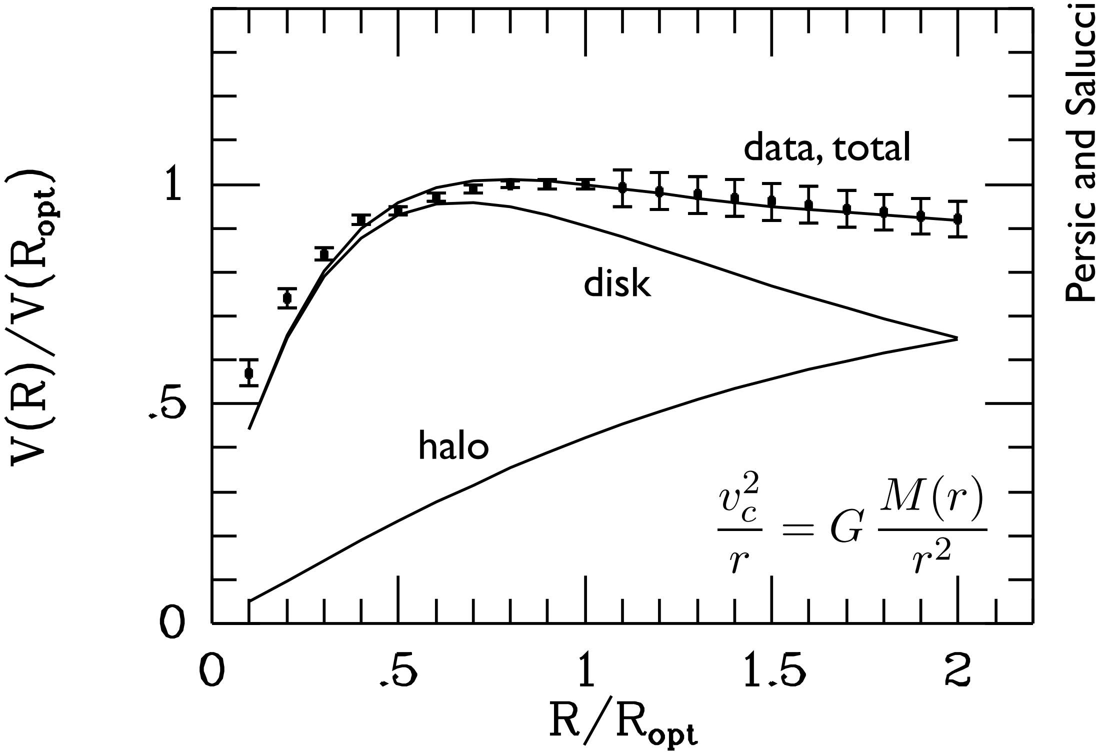

Persic and Salucci

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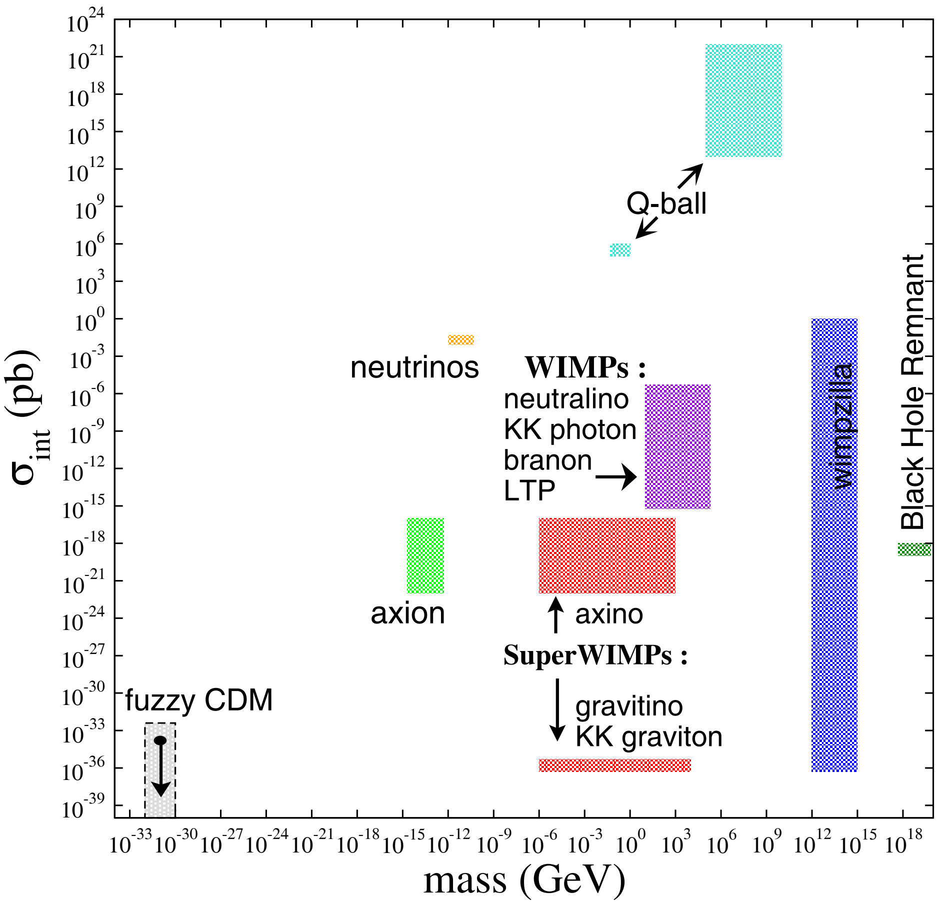
# The Particle Dark Matter Zoo

- Neutrinos
  - massive neutrinos can be cold or warm; low-mass neutrinos are hot
- Axions
  - Form as Bose condensate in early universe: cold in spite of low mass
- Weakly Interacting Massive Particles (WIMPs)
  - new massive (~100 GeV) particle with EW scale interactions
  - SUSY neutralino
  - Lightest Kaluza-Klein particle in universal extra dimensions



Park, in DMSAG 2007 report

- SUSY gravitinos (SuperWIMPs), axinos
- "Data-Driven" candidates: Inelastic dark matter, excited dark matter
- Others:
  - WIMPzillas, SIMPzillas, primordial black holes, Q-balls, strange quark nuggets, mirror particles, CHArged Massive Particles, self interacting dark matter, D-matter, cryptons, brane world dark matter...

# WIMPs

- A WIMP δ is like a massive neutrino: produced when T >> $m_\delta$ 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 $m_\delta$: annihilation continues, production becomes suppressed.
- But, weakly interacting → will "freeze out" before total annihilation if

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

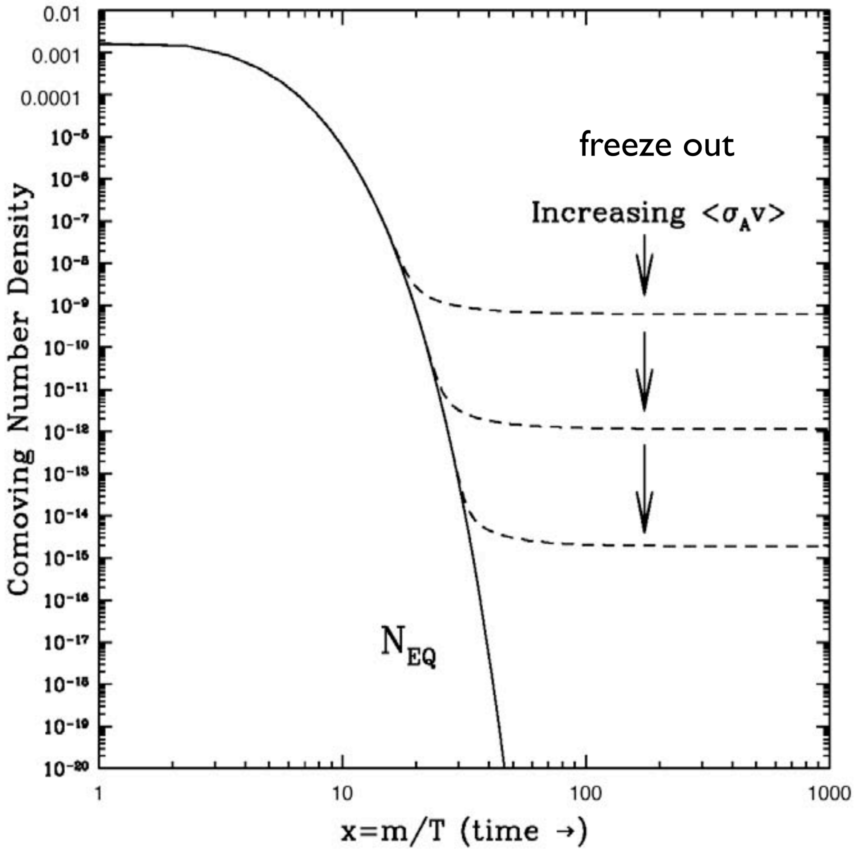
i.e., if annihilation too slow to keep up with Hubble expansion

- Leaves a relic abundance:

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

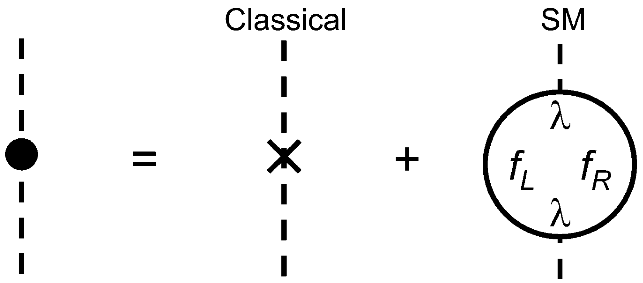
for $m_\delta$ = O(100 GeV)
→ if $m_\delta$ and $\sigma_{ann}$ determined by new weak-scale physics, then $\Omega_\delta$ is O(1)

canonical Kolb and Turner freeze-out plot



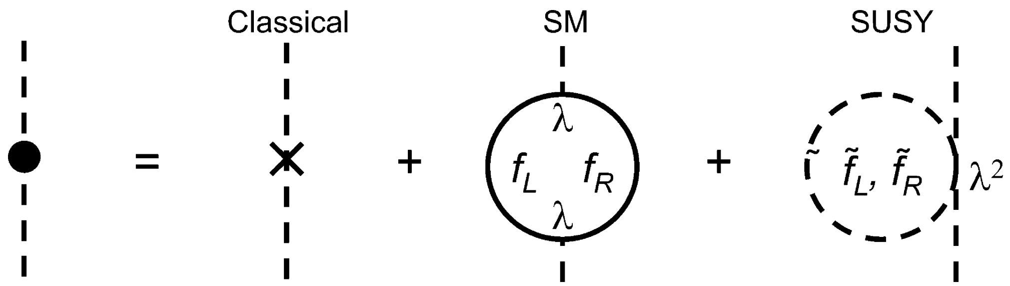
# Supersymmetry and WIMPs

- The Gauge Hierarchy problem: Why is $M_{Pl} >> M_{EW}$?
  - Alternatively: why are Standard Model particle masses so small compared to $M_{Pl}$? Radiative corrections destabilize Higgs boson mass: $\Delta m_H^2 = O(\alpha/\pi)\ \Lambda^2 \quad \Lambda \sim M_{Pl}$



J. Feng

- Supersymmetry provides a solution
  - Standard Model particles in supermultiplets combining particles of different spin
  - stabilizes radiative corrections: every bosonic loop has a corresponding fermionic loop carrying opposite sign
  - SUSY-breaking splits masses so superpartners not yet visible
  - $\Lambda$ given by SUSY-breaking scale: loop cancellation works above $\Lambda$. Need $\Lambda \sim 1$ TeV to keep Higgs light; also provides unification of couplings.

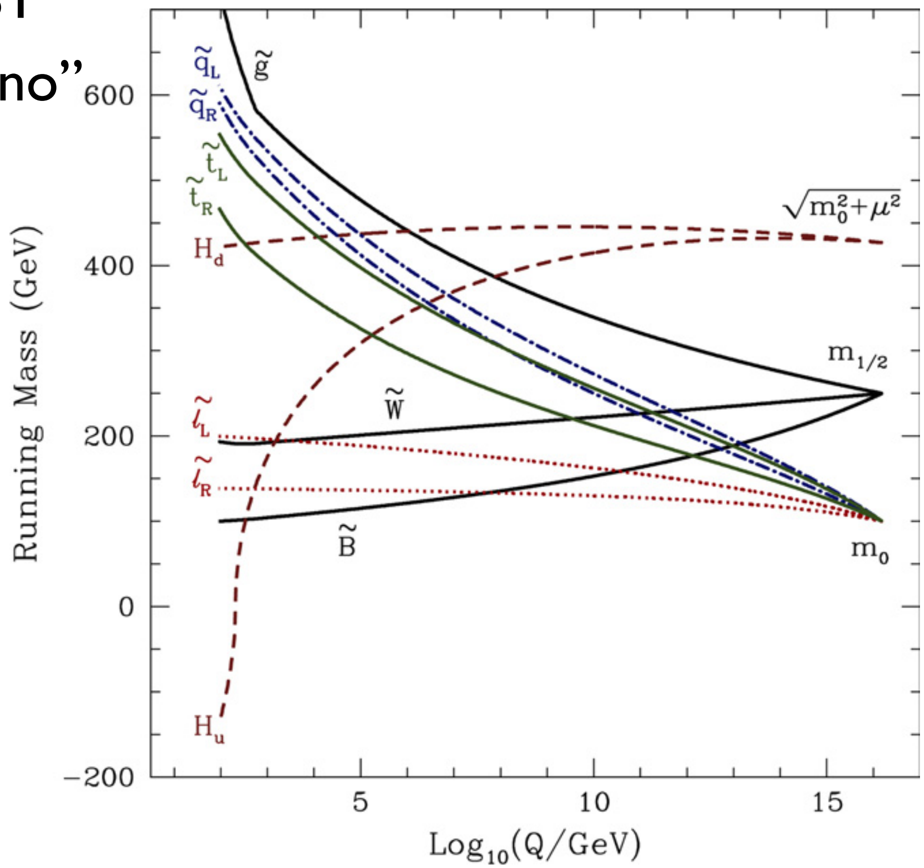


J. Feng

- Lightest superpartner is a good WIMP candidate
  - stable, $m = O(100$ GeV), undetected bec. neutral & interacts only via heavy mediators (EW gauge bosons, Higgs, superpartners of quarks)

# SUSY Particle Content and Parameters

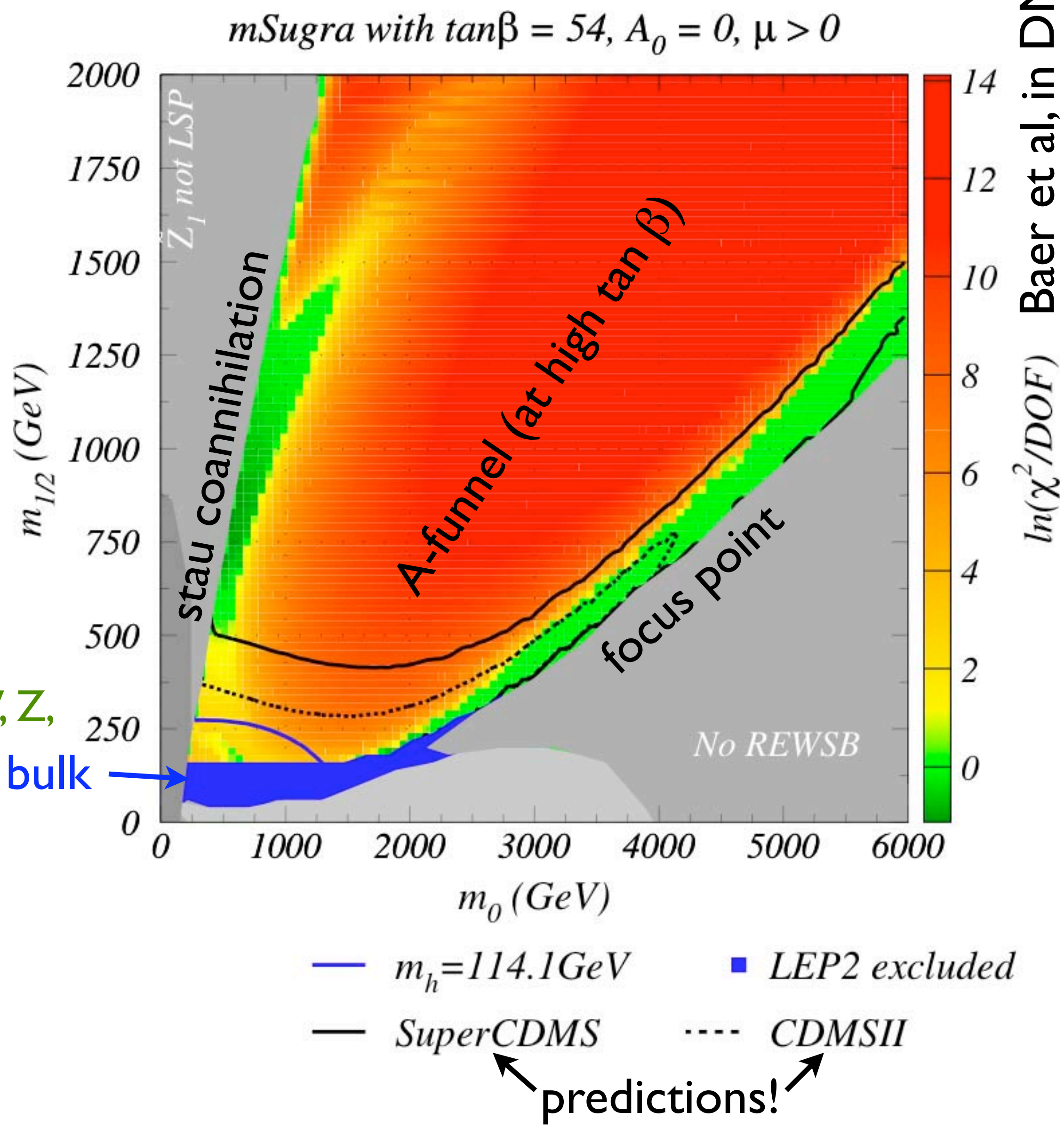
- Every SM fermion (spin-1/2) gets spin-0 "scalar fermion (sfermion)" partner
- Every SM gauge boson (spin-1) gets spin-1/2 "gaugino" partner
- Higgs (spin-0) acquires spin-1/2 "higgsino" partner
- Need a second Higgs to preserve SUSY
- Graviton (spin-2) gets spin-3/2 "gravitino"
- Parameters
  - In unbroken SUSY, all params fixed by SM
  - SUSY breaking results in O(100) params
  - mSUGRA assumption: Masses assumed to be universal at GUT scale: $m_0$ scalar mass, $m_{1/2}$ "ino" mass
  - tan β = ratio of two Higgs vacuum expectation values
  - $\mu$ = Higgs mass parameter
  - Trilinear couplings $A$ (analogue of Yukawa couplings in SM)
- R-parity prevents proton decay and makes lightest superpartner (LSP) stable



# Supersymmetric WIMPs

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

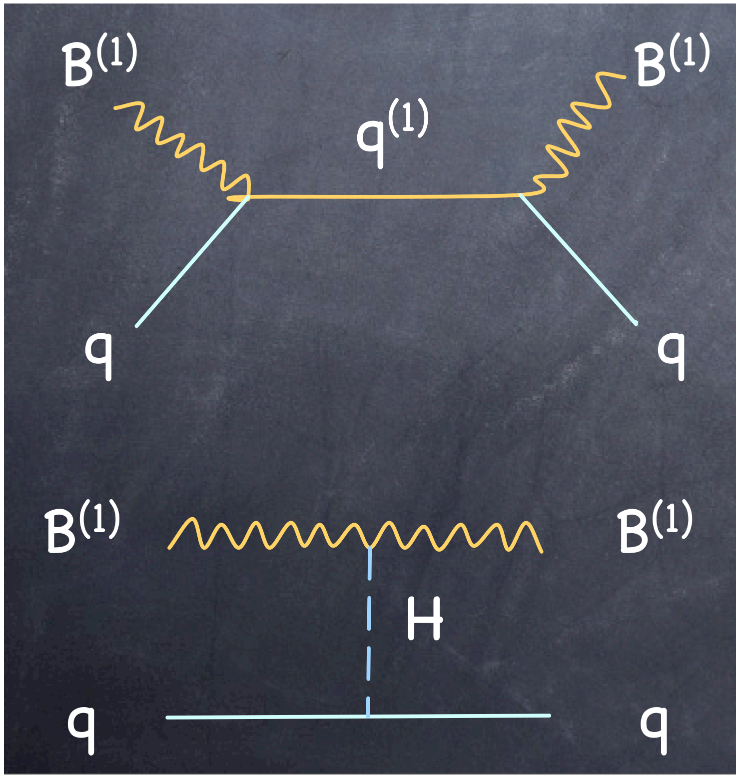
$\chi^2$ of fit to BR($b \rightarrow s\gamma$), muon g-2, and relic density (dominated by relic density: avoid overclosure)



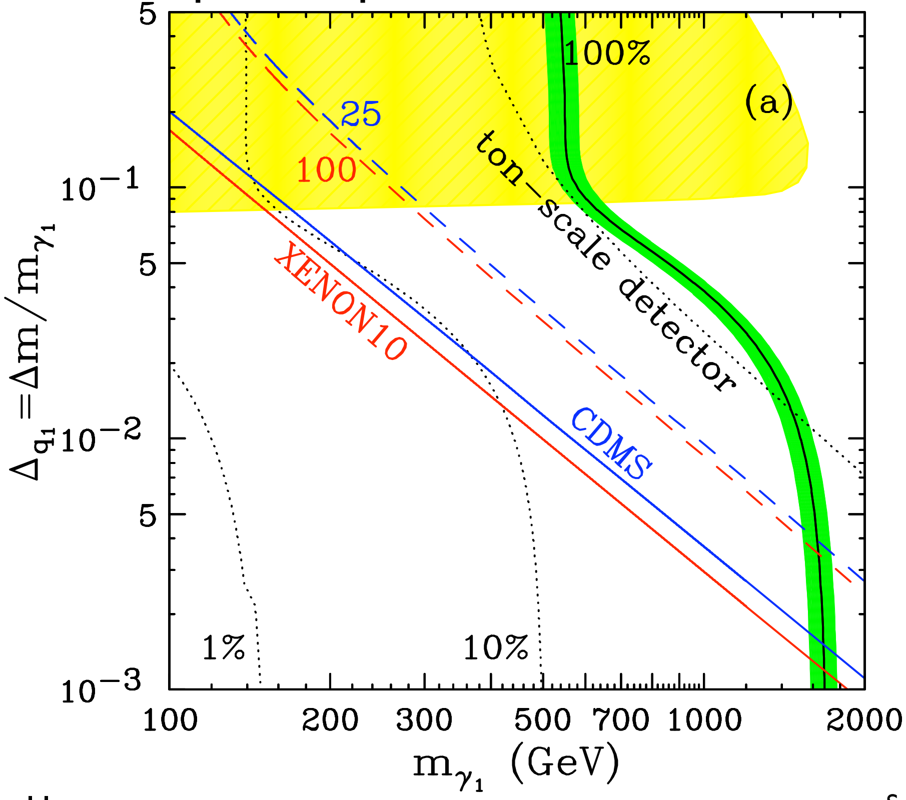
Baer et al, in DMSAG report

# Universal Extra Dimensions WIMPs

- Kaluza-Klein tower of partners due to curled-up extra dimension of radius R
  - $n$ = quantum number for extra dim., $m_n^2 \sim n^2/R^2$, conserved due to mom. cons. in extra dim.
  - compactification of extra dim reduces mom. cons. to discrete parity cons.
  - KK parity $P_{KK} = (-1)^n$ implies lightest KK partner ($n$ = 1) is stable
- $B^{(1)}$, $n$ = 1 partner of B gauge boson, is lightest KK partner in simple cases
- Cross-section on quarks depends on fractional mass difference between $B^{(1)}$ and 1st KK partner of quarks, $q^{(1)}$



spin-independent exclusion limits



1 extra dim, LKP = $B^{(1)}$

yellow = LHC search

Arrenberg et al (2008)

# Detecting WIMP Dark Matter

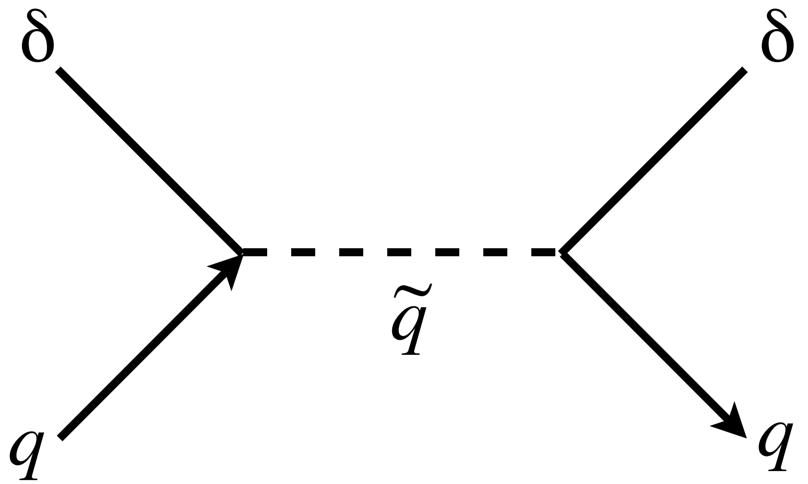
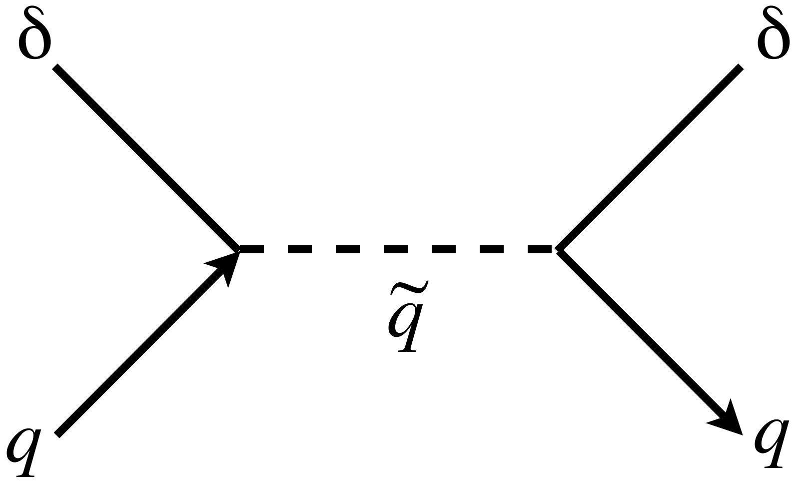


figure à la J. Feng

# Detecting WIMP Dark Matter

WIMP-WIMP
annihilation:
*Indirect Detection*



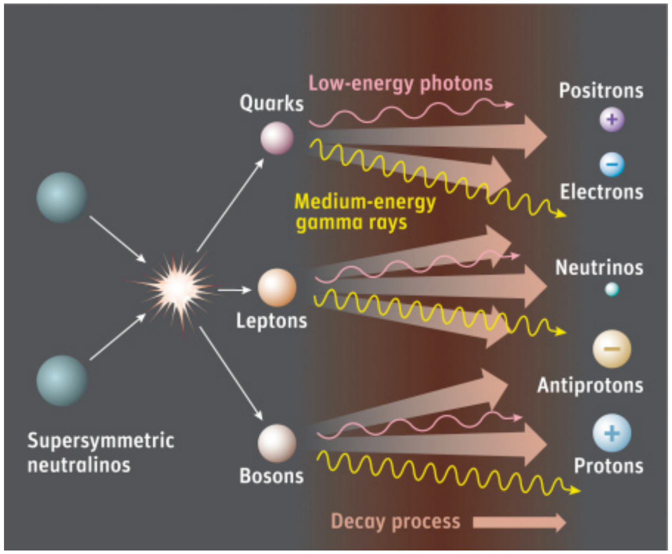
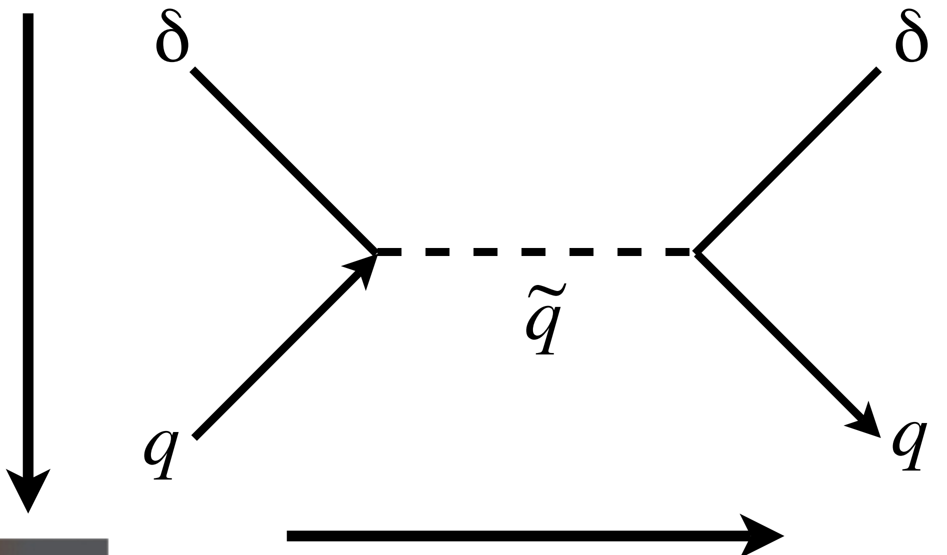


figure à la J. Feng

# Detecting WIMP Dark Matter



WIMP-WIMP
annihilation:
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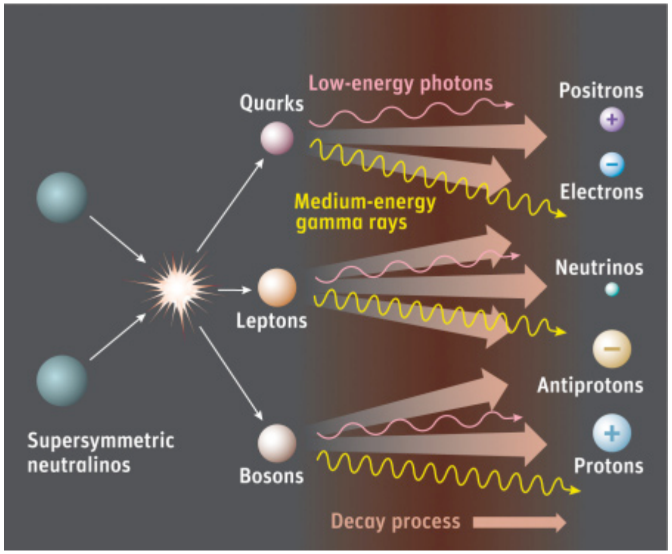


WIMP-quark scattering:
*Direct Detection*

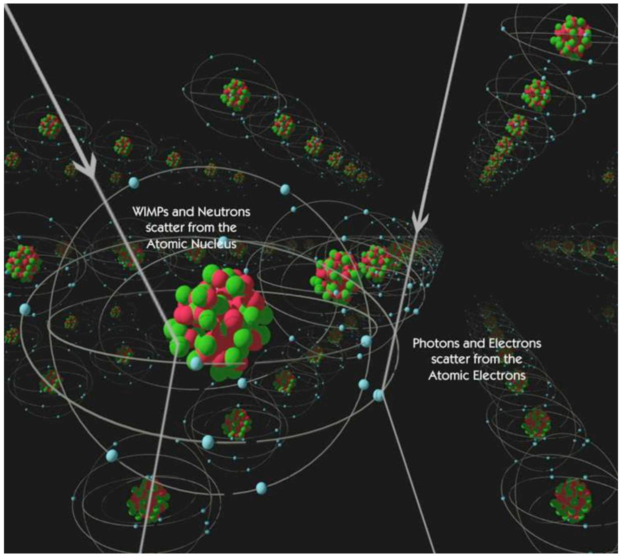
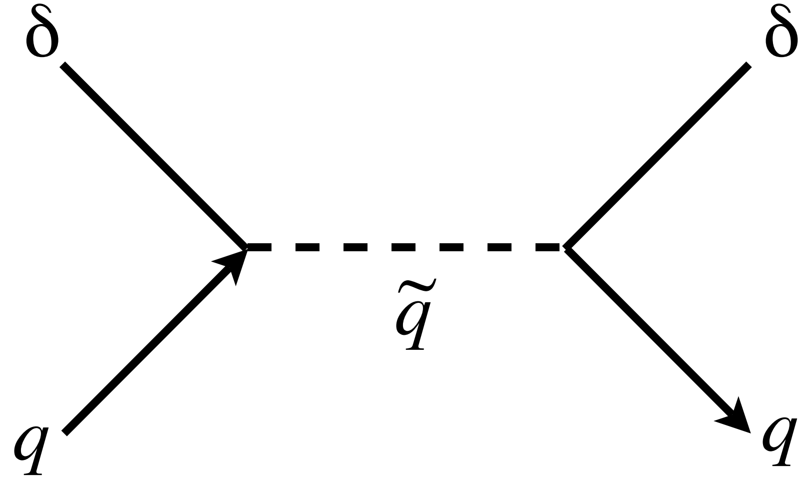


figure à la J. Feng

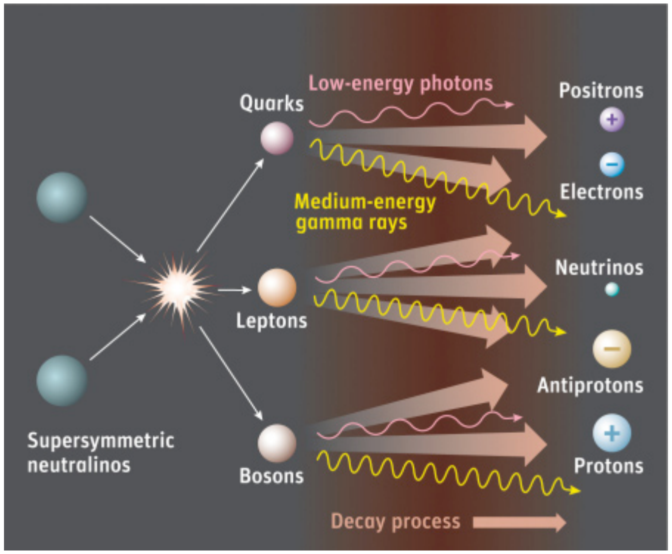
# Detecting WIMP Dark Matter

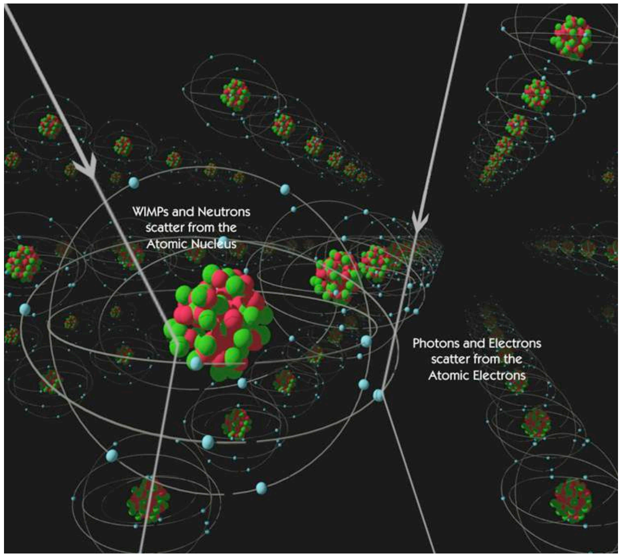
WIMP-WIMP
annihilation:
*Indirect Detection*



WIMP-WIMP
production:
*Collider*
*Production*

WIMP-quark scattering:
*Direct Detection*





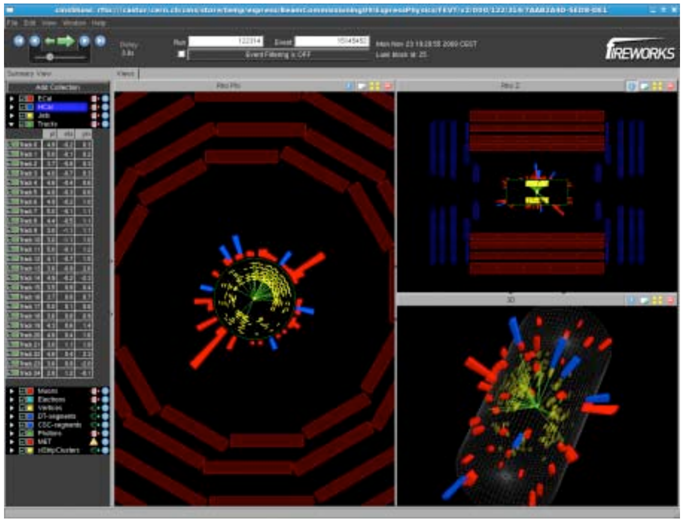
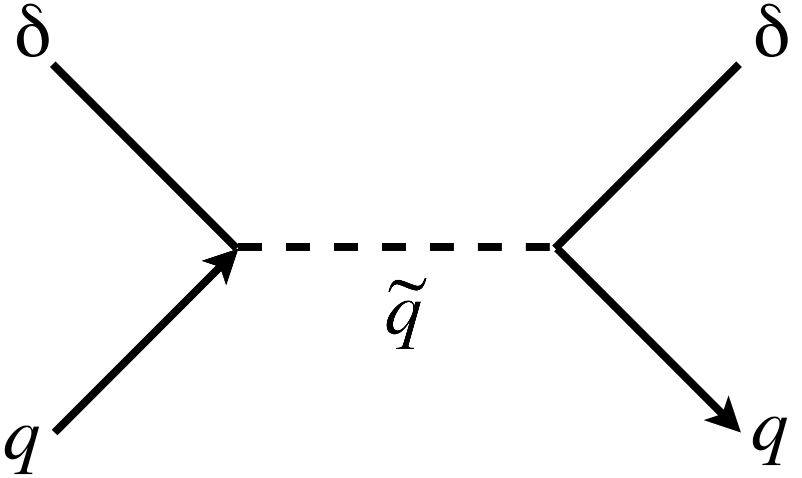


figure à la J. Feng

# Detecting WIMP Dark Matter



WIMP-WIMP
annihilation:
*Indirect Detection*

WIMP-WIMP
production:
*Collider*
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WIMP-quark scattering:
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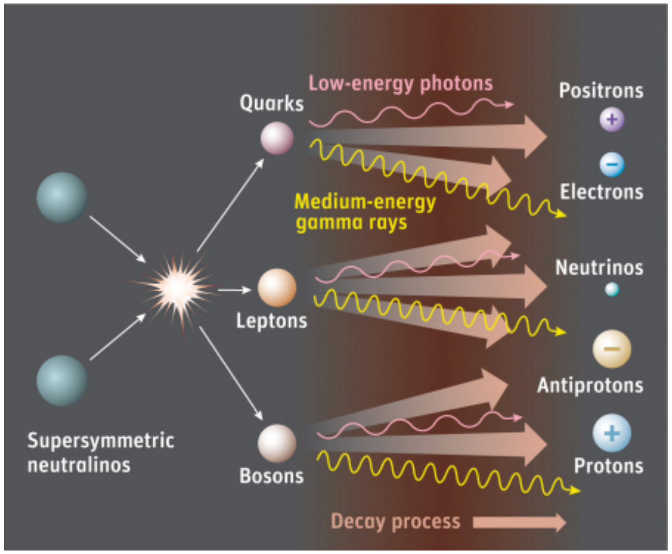
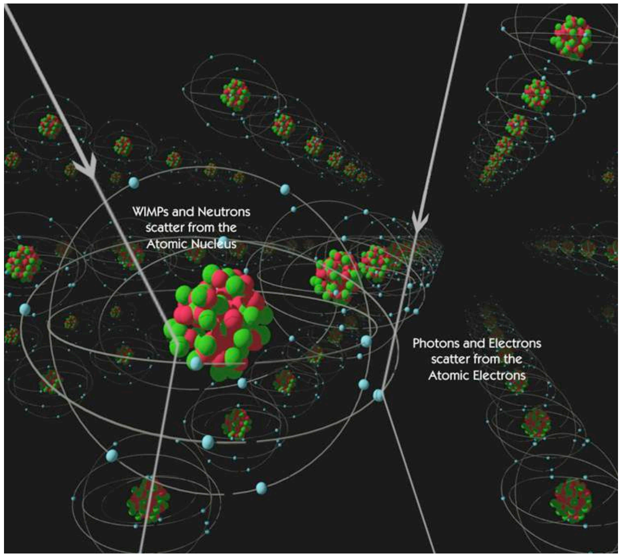
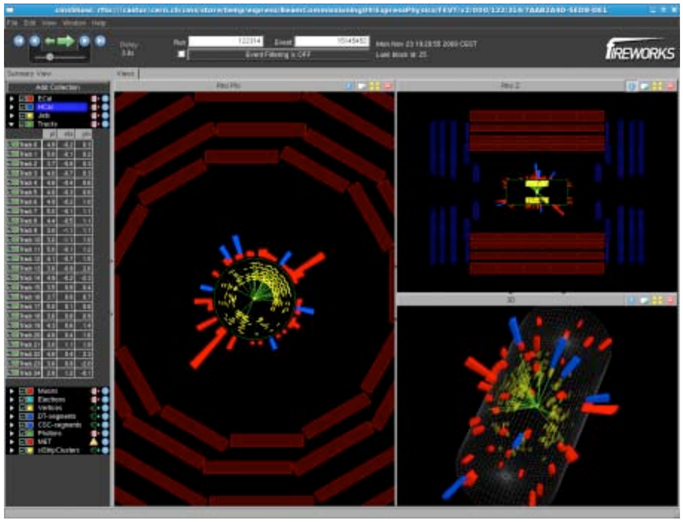






n.b.: colliders are more likely to produce strongly coupled particles that decay to WIMPs

figure à la J. Feng

# What the rest of this talk will *not* be about

- Assorted possible indirect detection signals
  - For those in the know:
    ATIC positron+electron bump, PAMELA positron excess, Fermi bump, WMAP haze, Fermi haze, INTEGRAL 511 keV line from galactic center...
- DAMA annual modulation signal
- Data-driven theories of dark matter
  - Inelastic Dark Matter, Excited Dark Matter, Sommerfeld enhancement, Dark U(1)'s, etc.
- Speculation on how the winoness, binoness, higgsinoness, or other-ness of a WIMP may affect the prospects of one or another search technique.

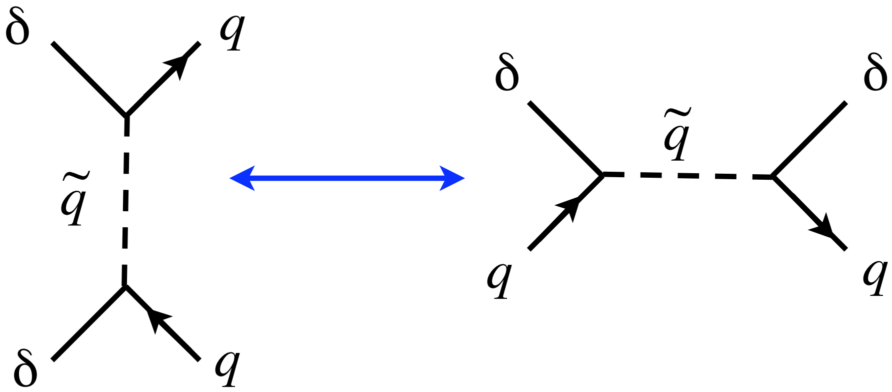
# What the rest of this talk *will* be about

- Where we are now

- How we get to sensitivities of 1 zeptobarn = $10^{-45}$ $cm^2$ for WIMP-nucleon scattering and beyond with multiple techniques so any signal can be robustly verified and high statistics can teach us something about particle physics and/or the galactic halo

# Direct Detection of WIMPs

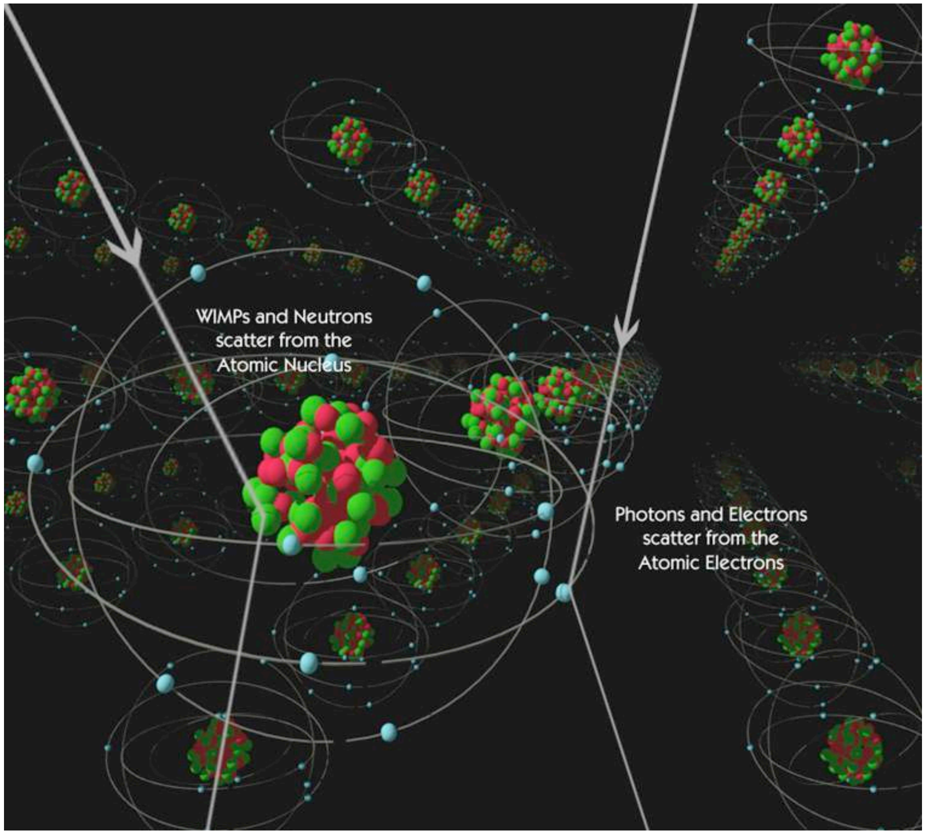
Diagram crossing → detectability?

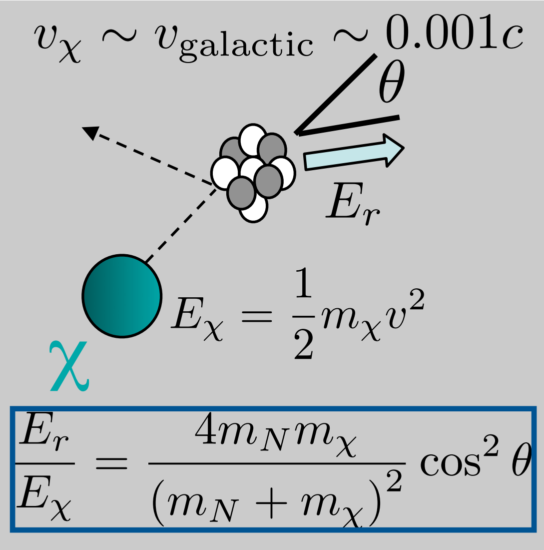


Isothermal halo: $v_0$=270 km/s, $v_{esc}$=544 km/s

Maxwell-Boltzmann velocity dist'n

s-wave scattering

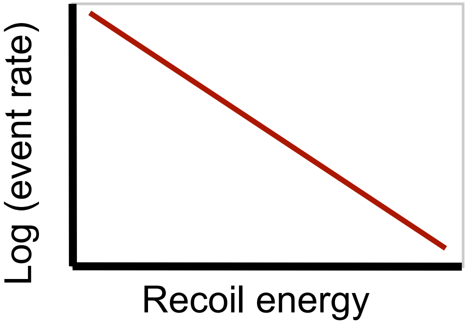




$$v_\chi \sim v_{\mathrm{galactic}} \sim 0.001c$$

$$E_\chi = \frac{1}{2} m_\chi v^2$$

$$\boxed{\frac{E_r}{E_\chi} = \frac{4 m_N m_\chi}{(m_N + m_\chi)^2} \cos^2\theta}$$



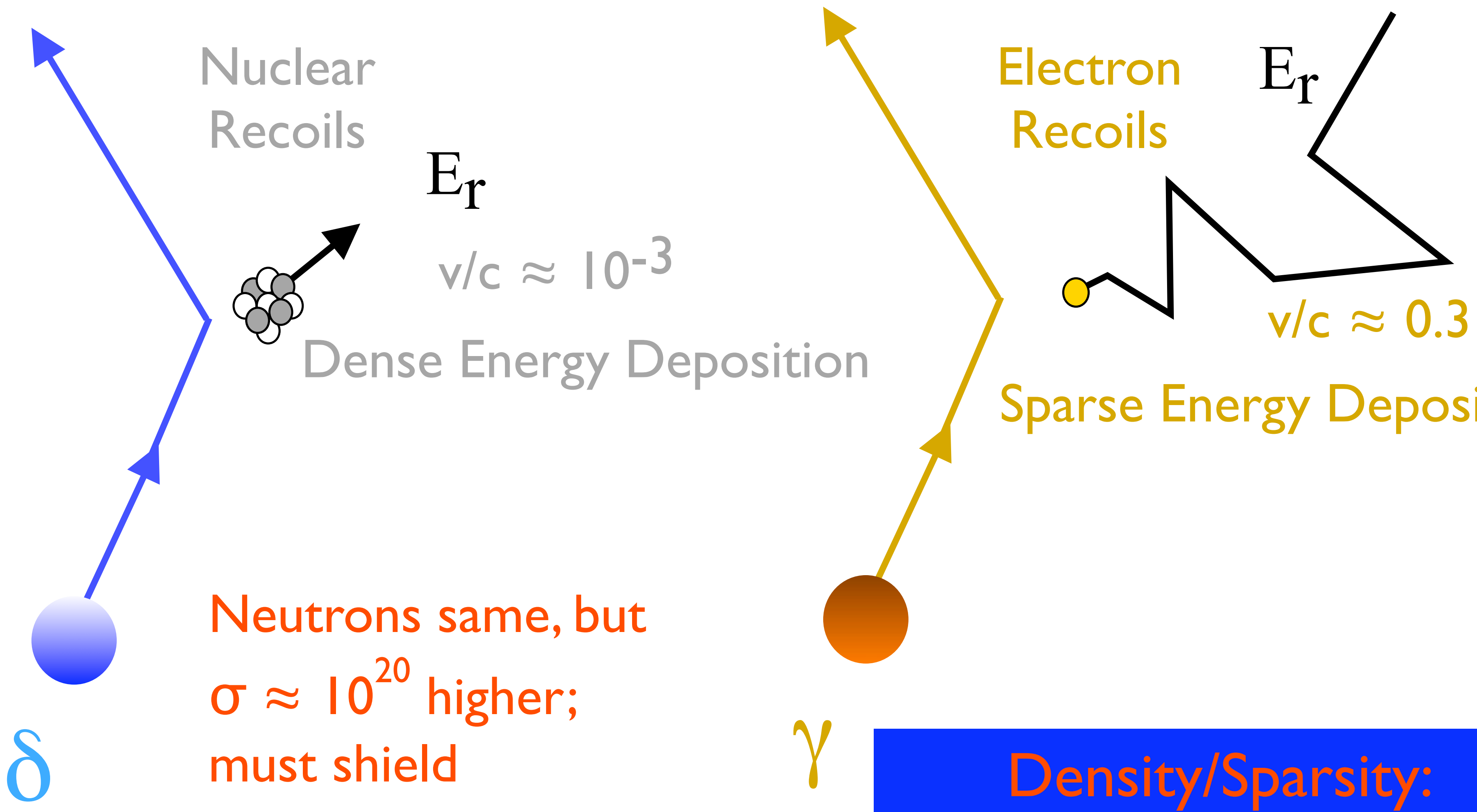
$v_{\mathrm{galactic}} \sim 10^{-3}c$ →

coherent $A^2$ enhancement of scalar (spin-independent) scattering

→

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

# Nuclear Recoil Discrimination



## Signal

Nuclear Recoils

$E_r$

$v/c \approx 10^{-3}$

Dense Energy Deposition

$\delta$

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

## Background

Electron Recoils

$E_r$

$v/c \approx 0.3$

Sparse Energy Deposition

$\gamma$

**Density/Sparsity: Basis of Discrimination**

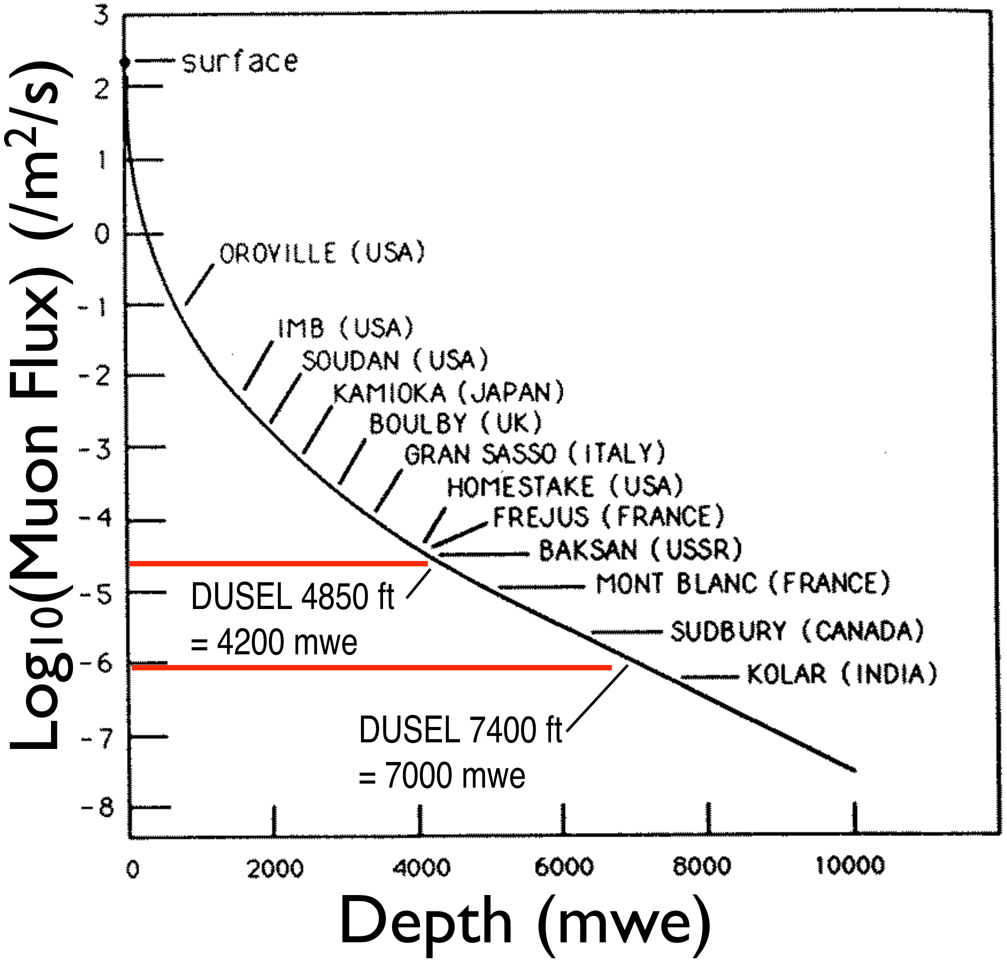
# Deep Underground

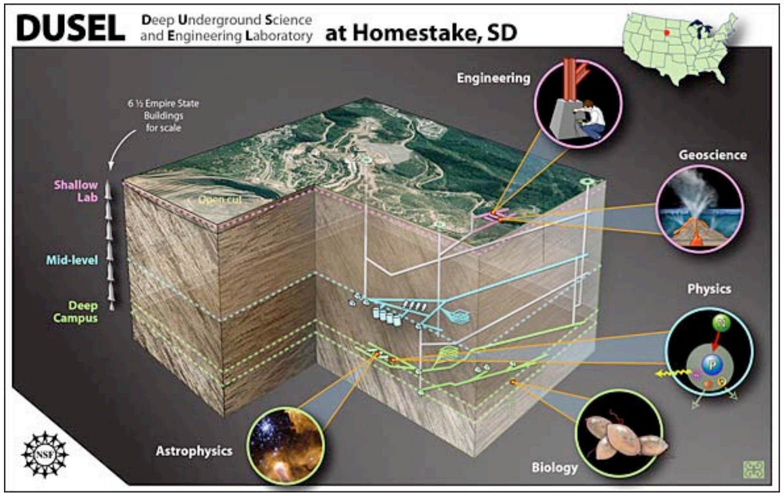
## Low cosmogenic neutron background requisite for any WIMP search

Minnesota (Iron Range)

Italy (Apennines)

Sudbury, Ontario





Homestake, South Dakota
Sanford Lab on existing 4850 ft level
Full lab construction begins 2014?

# Challenges and Techniques

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

## Challenges

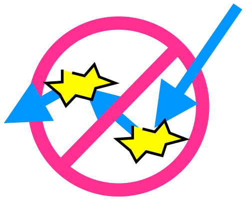
Very **low energy** thresholds (~10 keV)

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

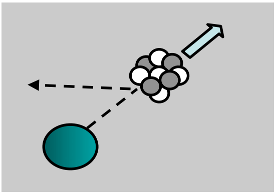
Stringent **background control** (cosmogenic, radioactive)
Cleanliness
Shielding (passive, active, deep site)

**Discrimination power**

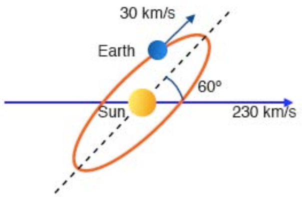
SIGNATURES



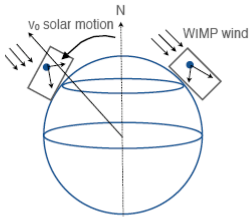
No multiplicity



Nuclear recoils



Annual flux
modulation



Diurnal direction
modulation

EVENT-BY-EVENT

STATISTICAL

# Challenges and Techniques

Exponential spectrum of $\langle E \rangle \sim 30$ keV nuclear recoils, $\ll$ 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)

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

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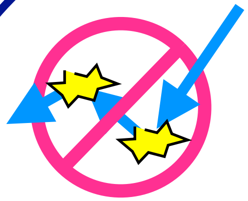
SIGNATURES



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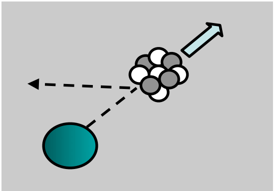
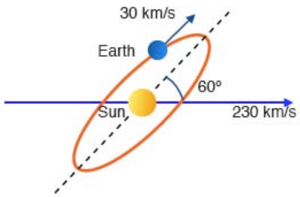
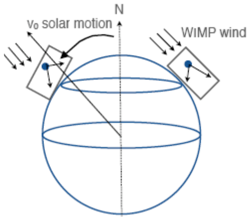


Nuclear recoils

EVENT-BY-EVENT



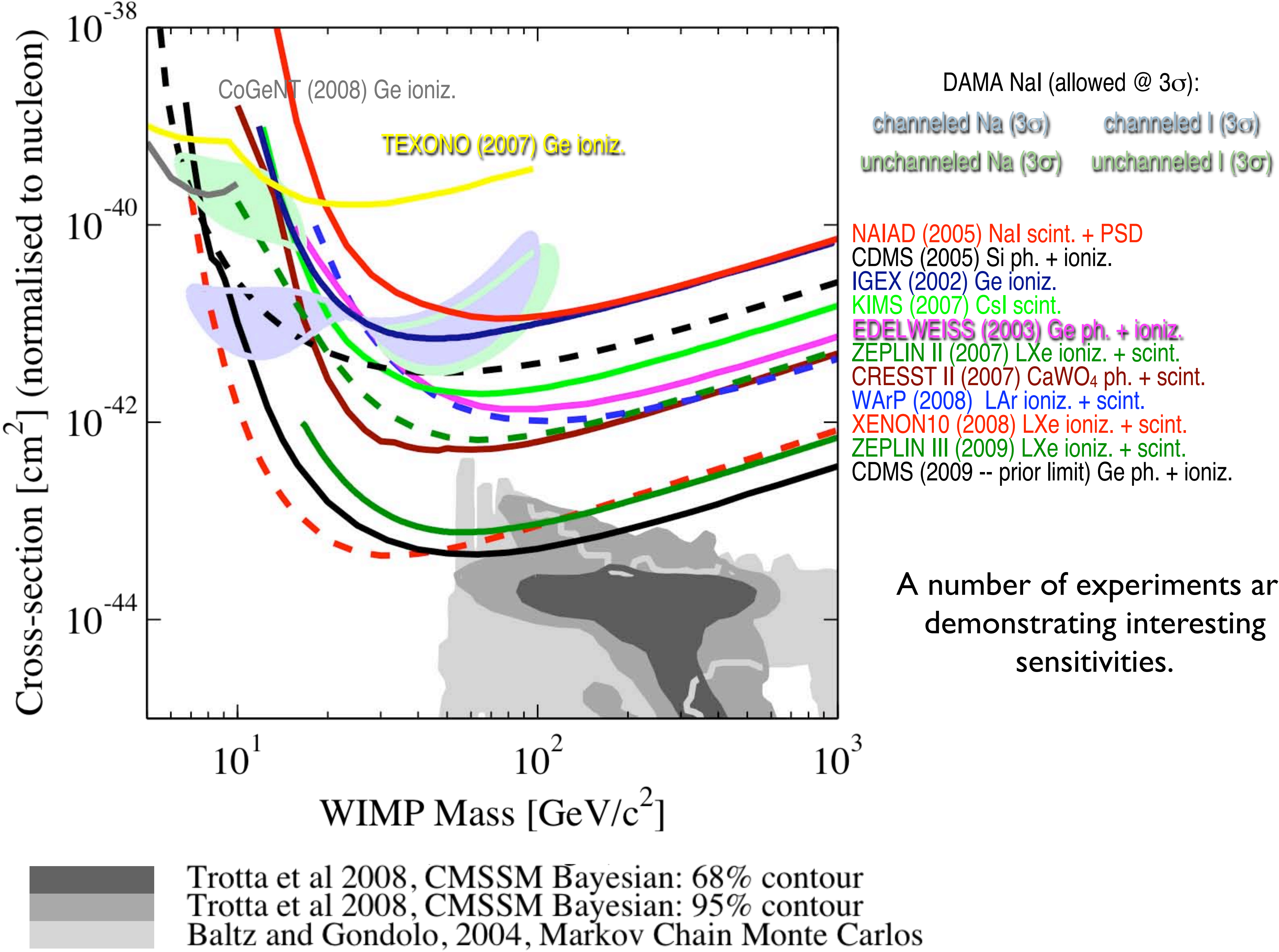
Annual flux modulation



Diurnal direction modulation

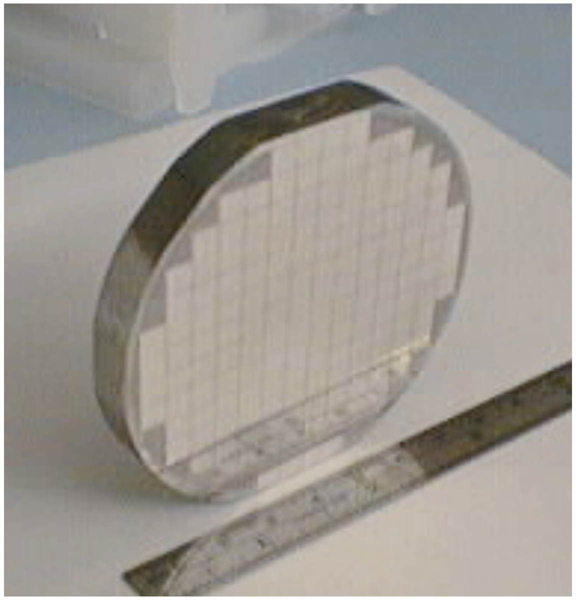
STATISTICAL

# Where We Are Now



plot compiled by P. Cushman using
Gaitskell, Mandic, and Filippini
http://dmtools.brown.edu

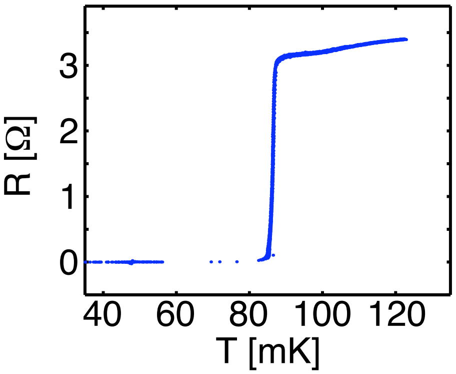
A number of experiments are demonstrating interesting sensitivities.

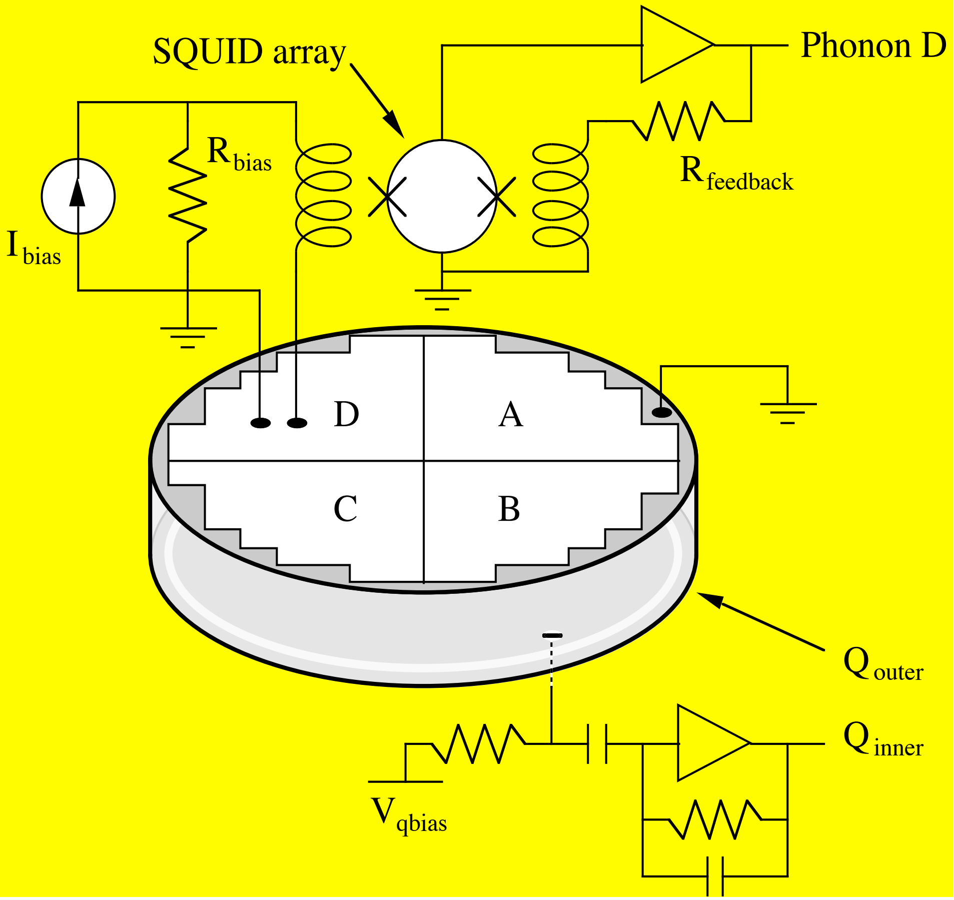


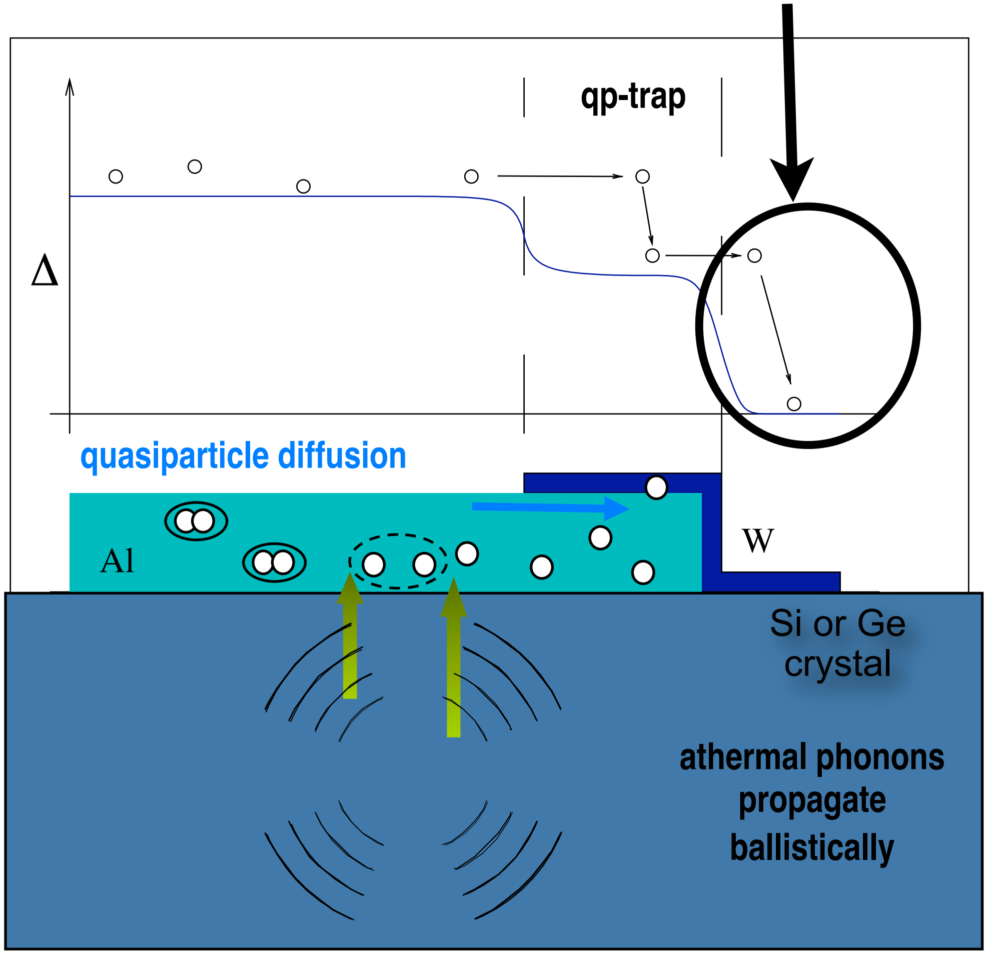
# CDMS ZIP Detectors

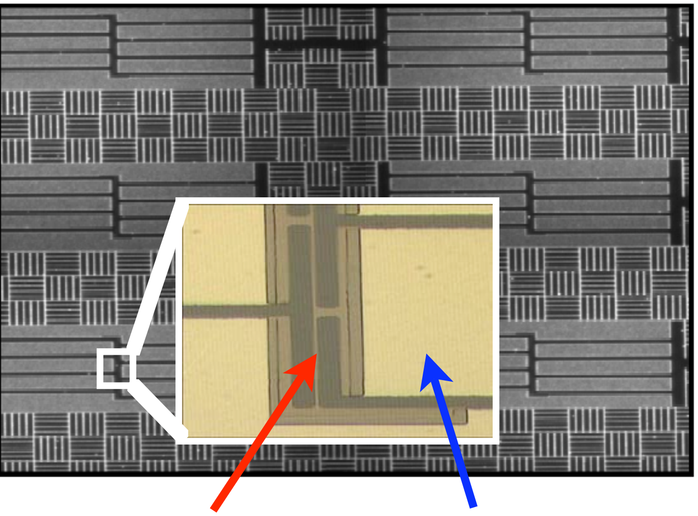
Z-sensitive Ionization- and Phonon-mediated detectors: Phonon signal measured using photolithographed superconducting phonon absorbers and transition-edge sensors.

TES = transition edge sensor









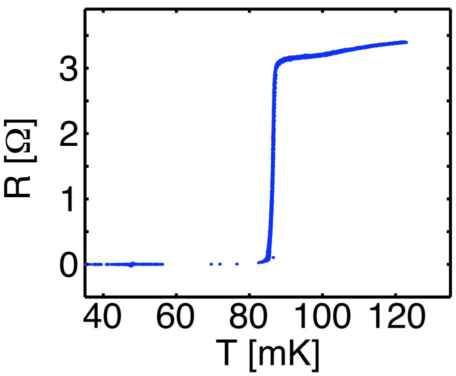
1 $\mu$m tungsten TES

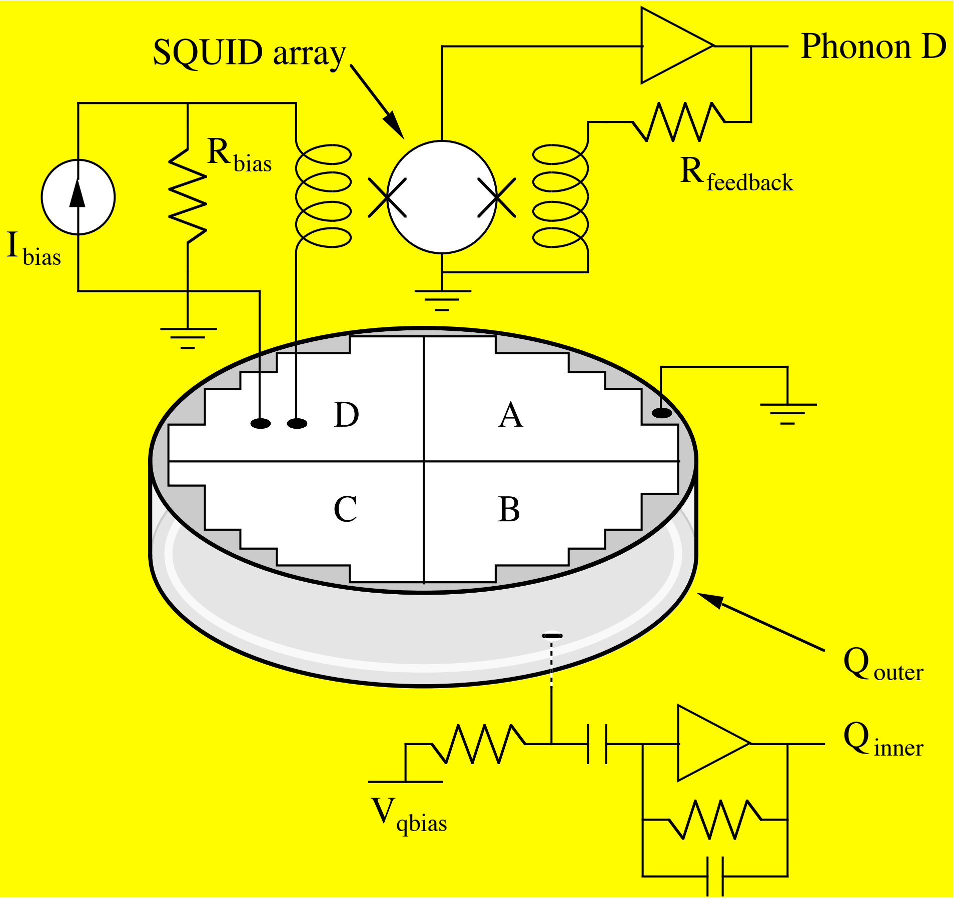
380 $\mu$m x 60 $\mu$m aluminum fins

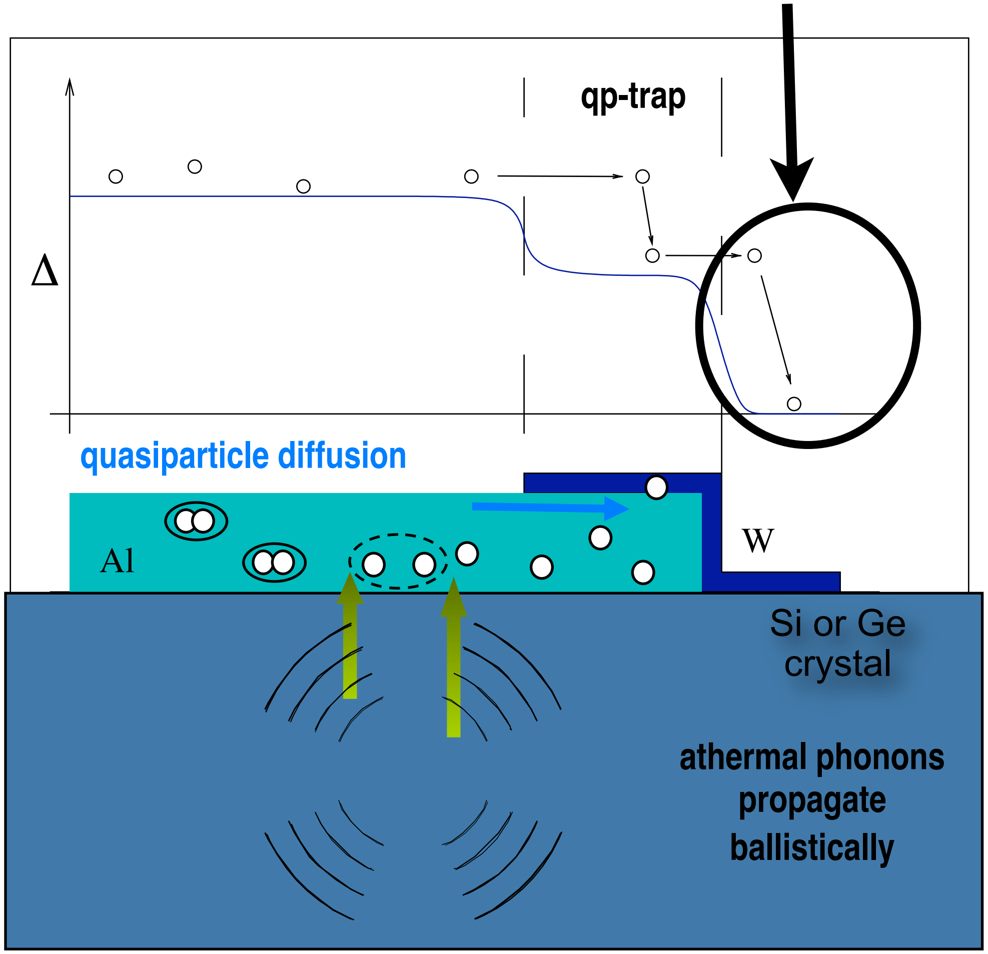
# CDMS ZIP Detectors

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

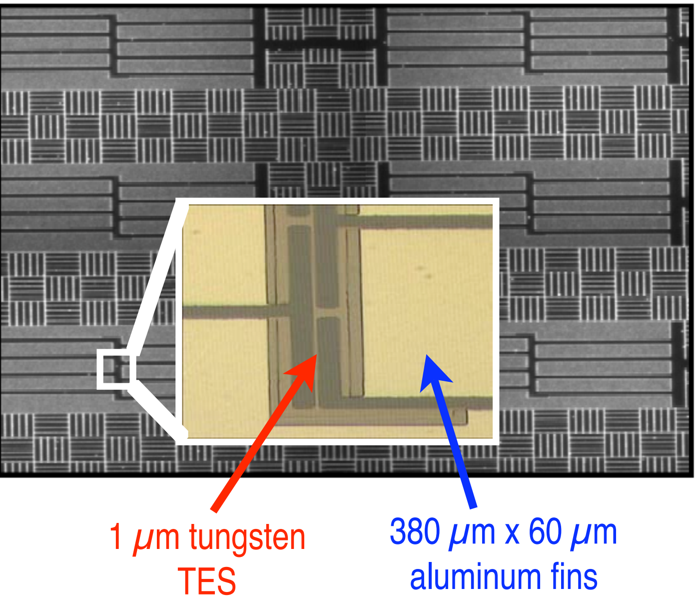
TES = transition edge sensor







# CDMS ZIP Detectors



**Z**-sensitive **I**onization- and **P**honon-mediated detectors: Phonon signal measured using photolithographed superconducting phonon absorbers and transition-edge sensors.

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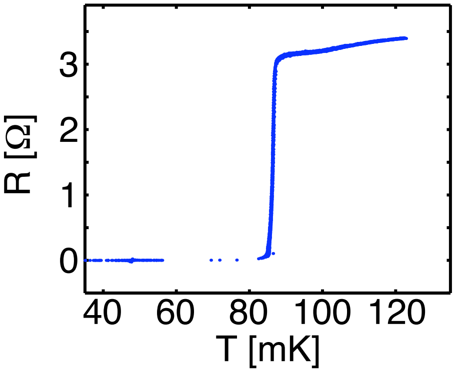
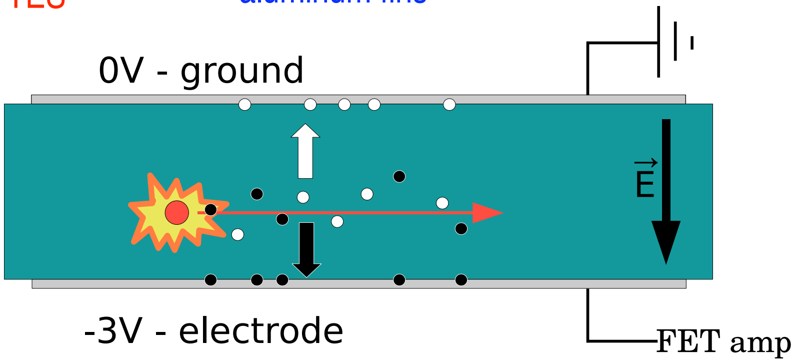
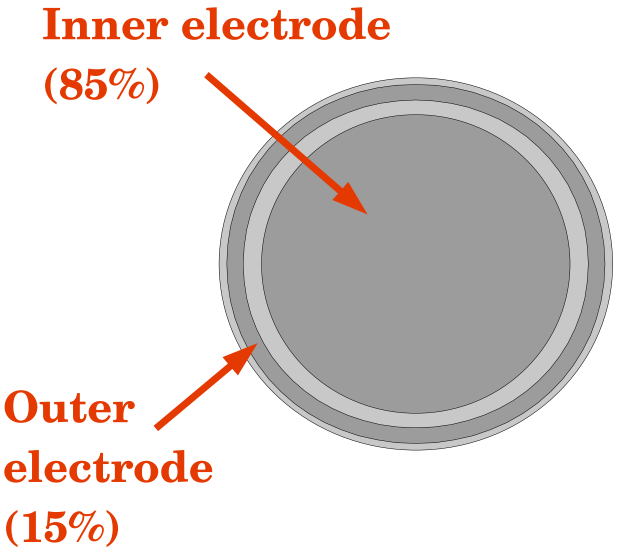
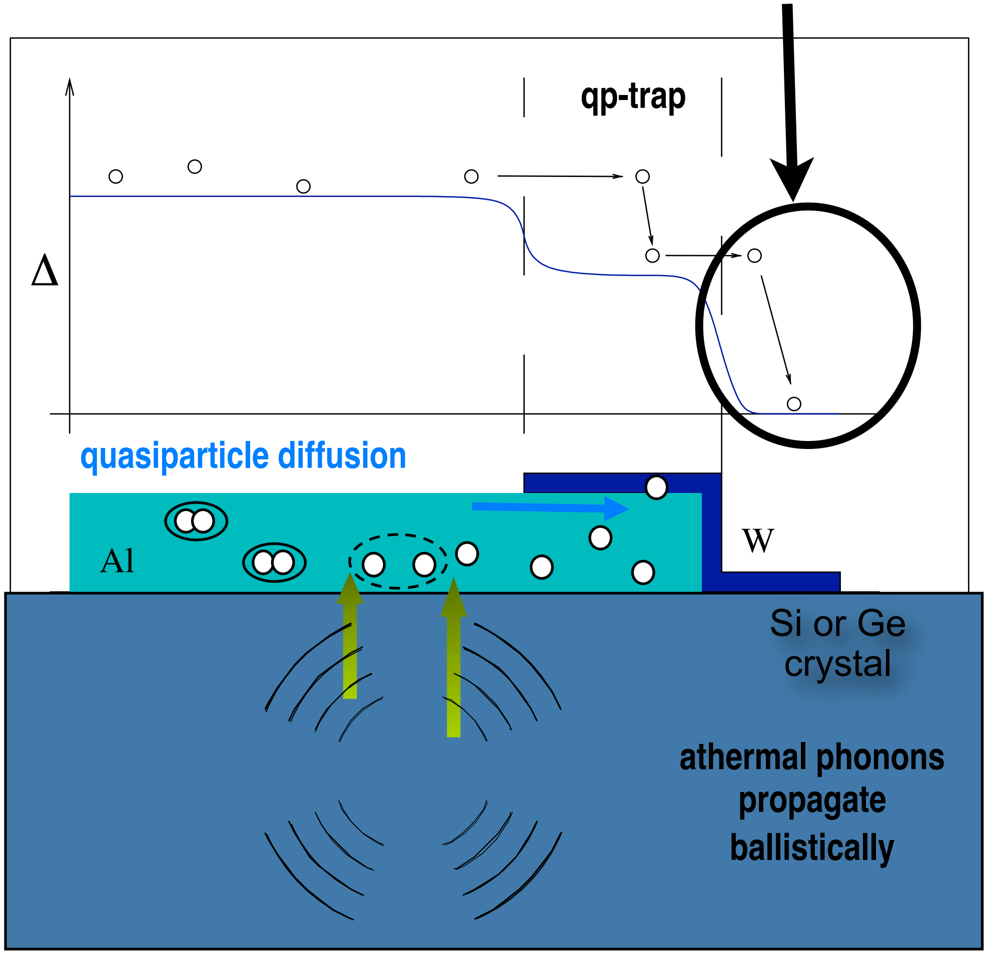
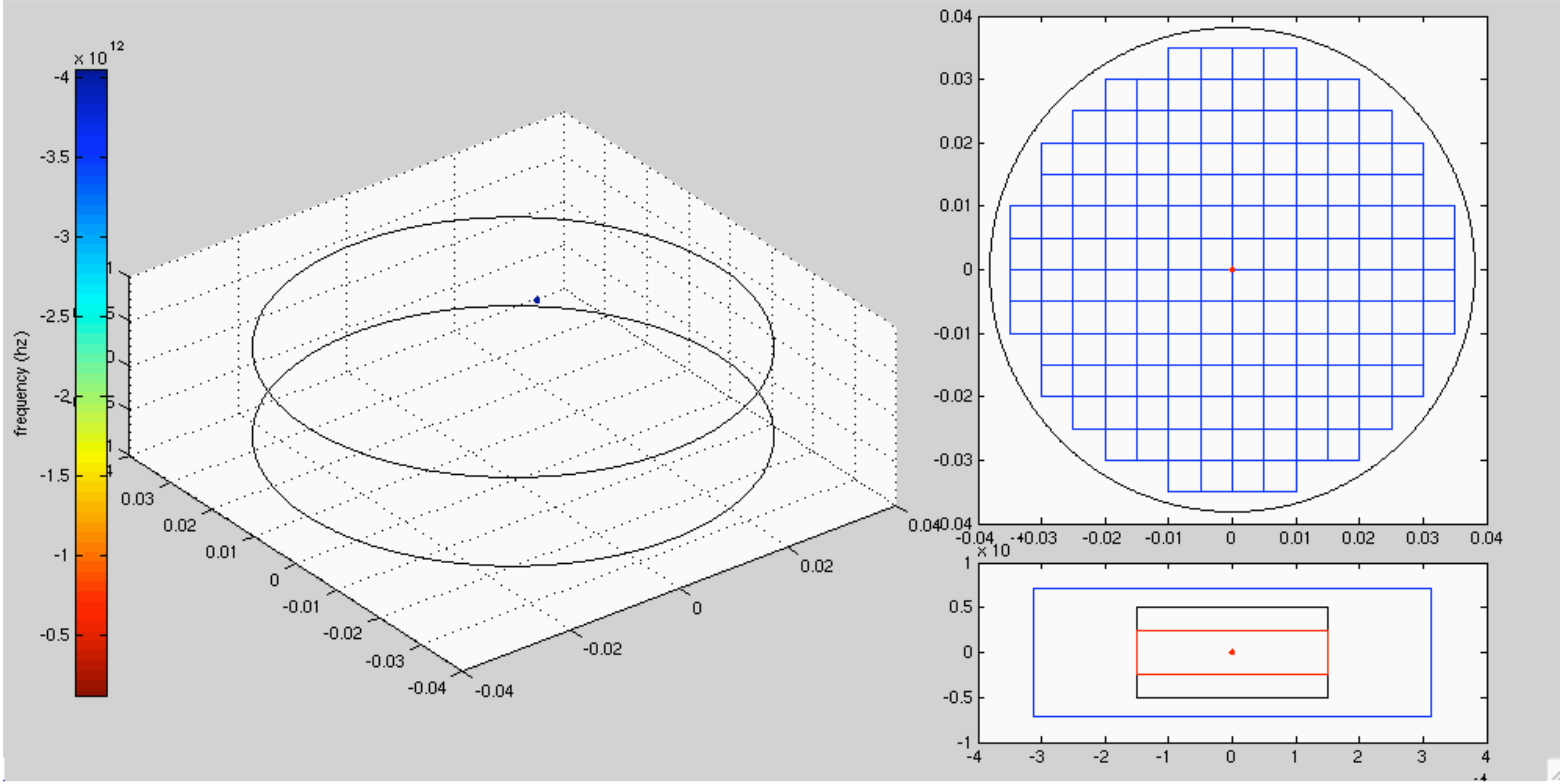








# ZIP Detectors

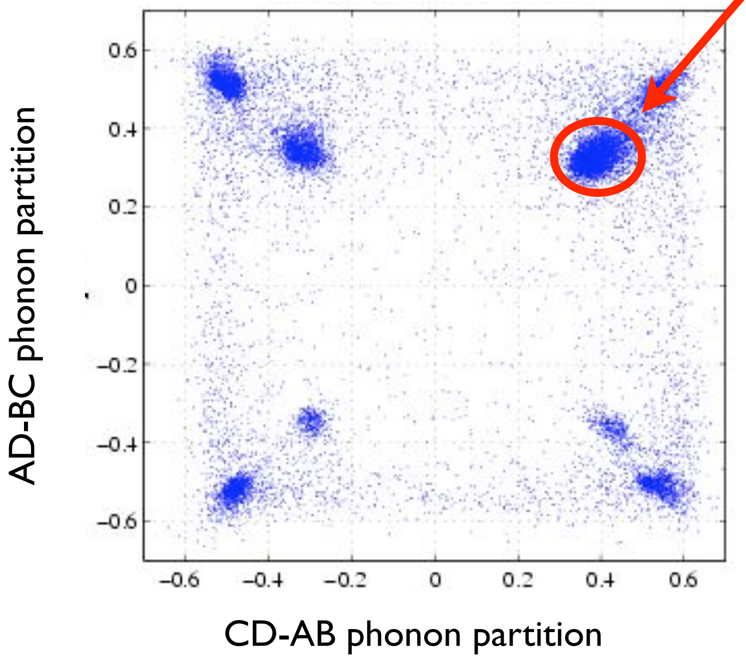


# Position Reconstruction

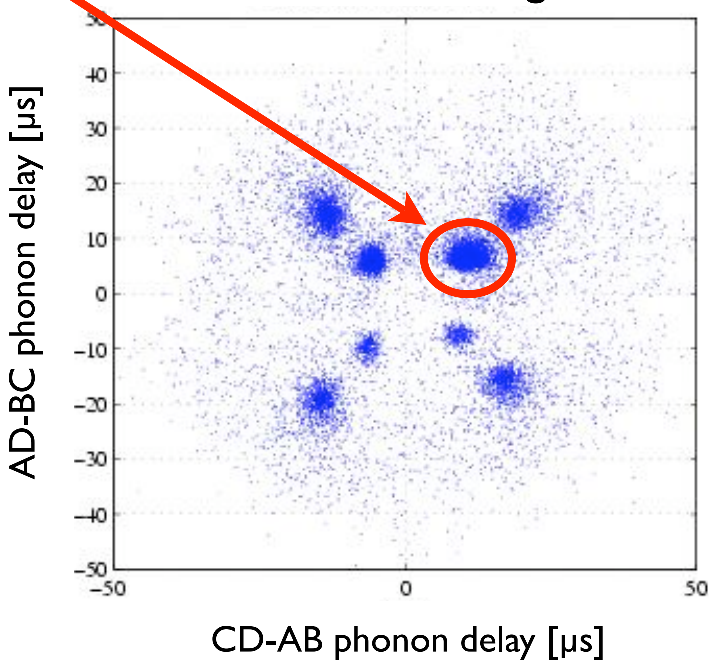
Sound speed ~ 1 cm/μs

Crucial to
*correct for position dependence*
of athermal phonon signals

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



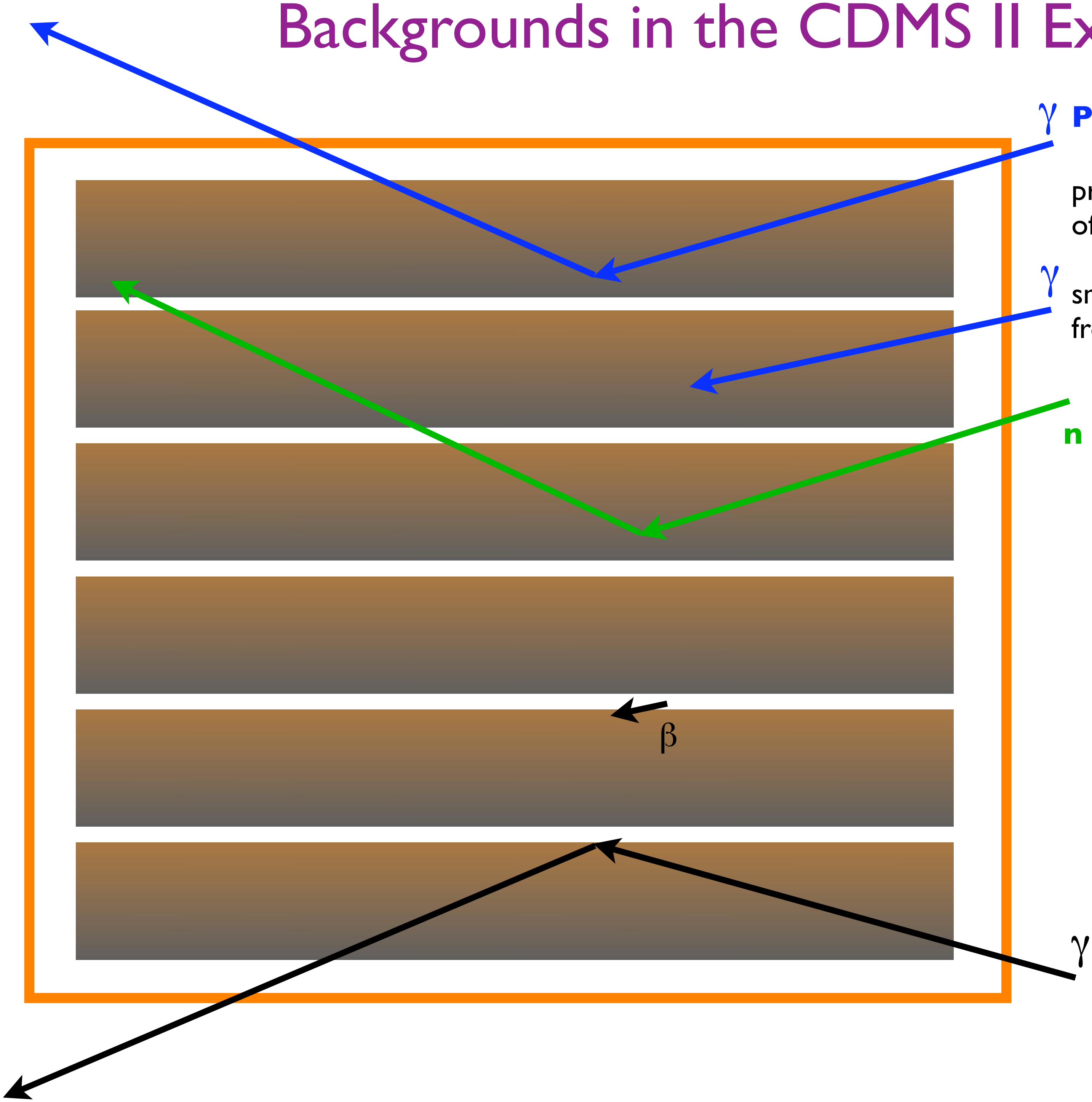
Phonon Energy Partition



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.

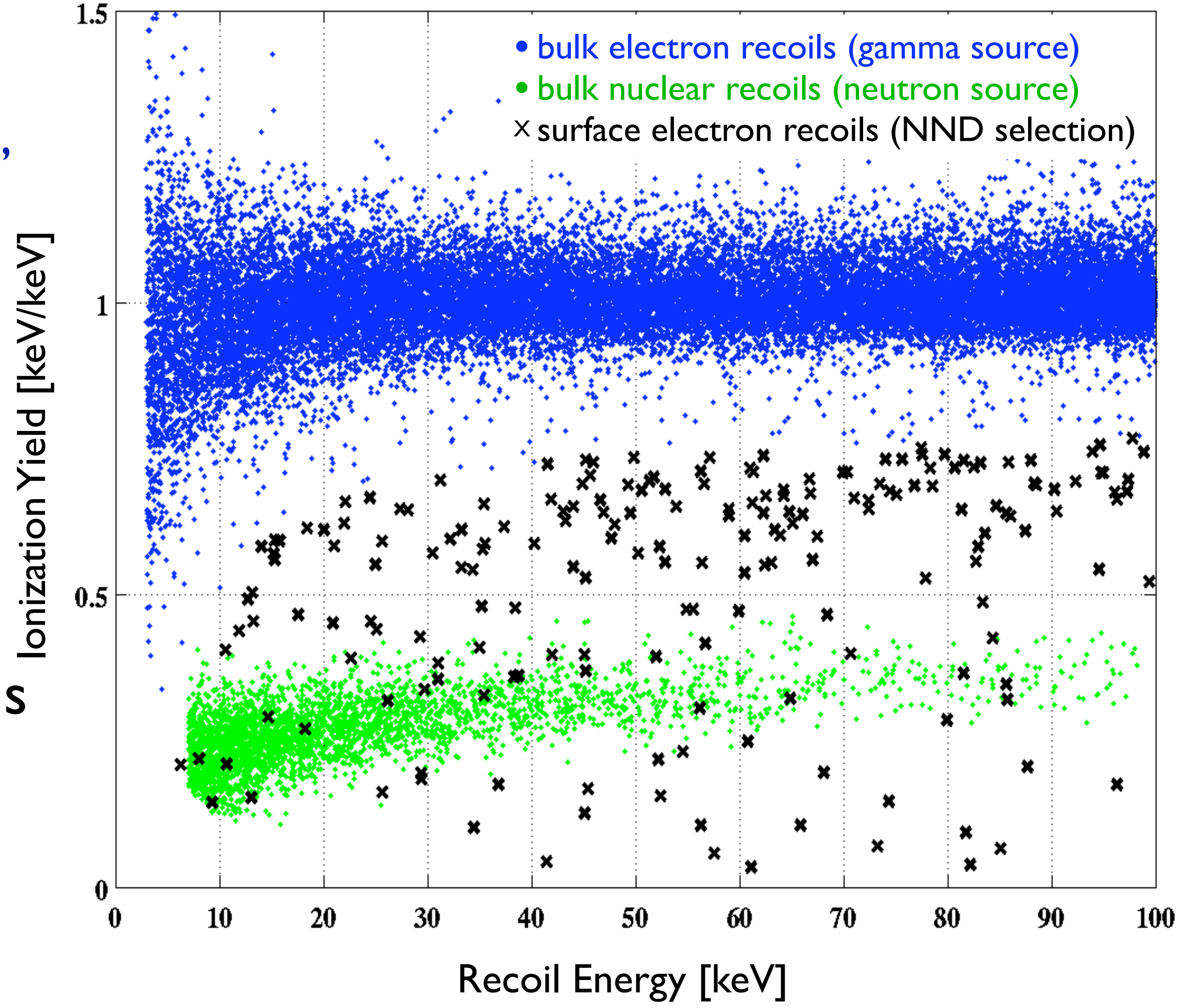
**Surface events (“β”)**

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

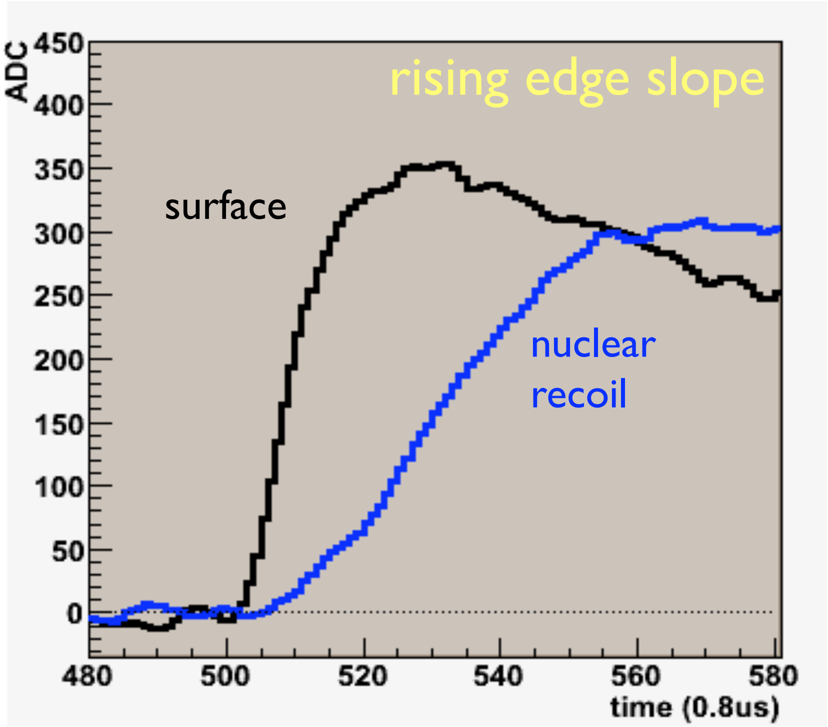
- Recoil energy
  - Phonon (acoustic vibrations, heat) measurements give full recoil energy
- Ionization yield
  - ionization/recoil energy strongly dependent on type of recoil (Lindhard)
- Excellent yield-based discrimination for photons
- Ionization dead layer:
  - low-energy electron singles (all 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)

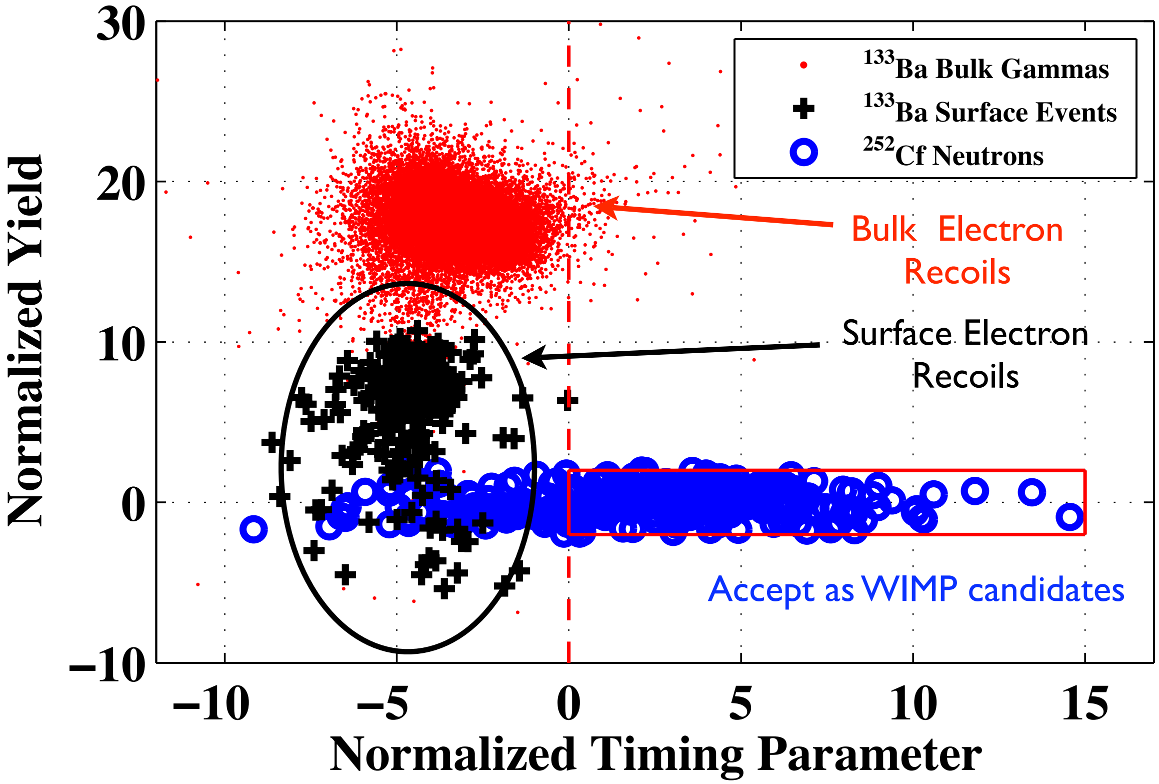


# ZIP z Position Sensitivity

- 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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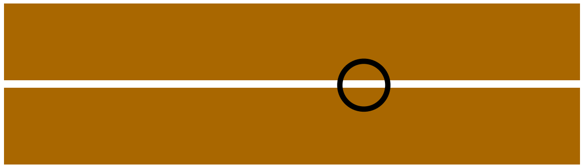
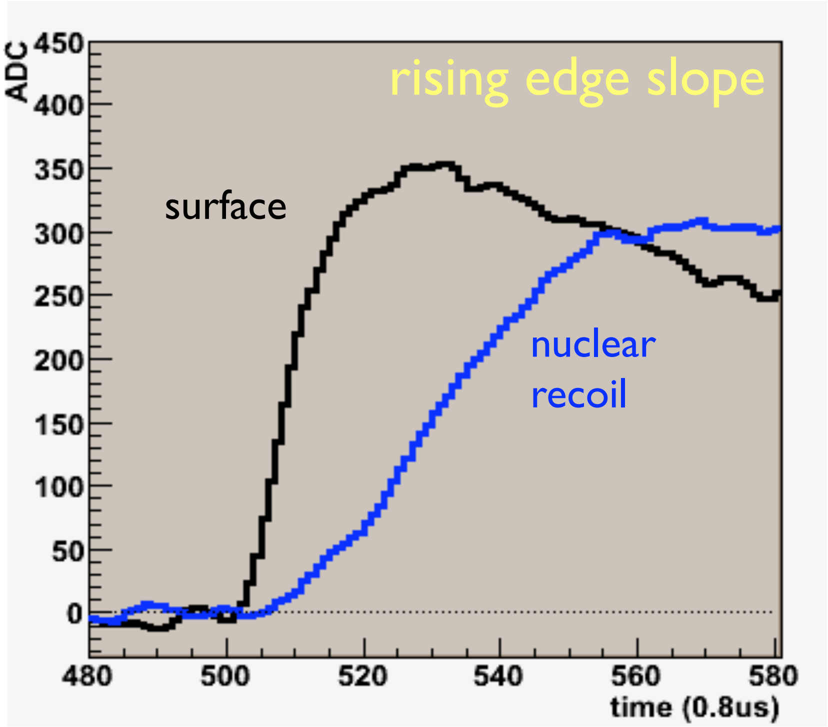
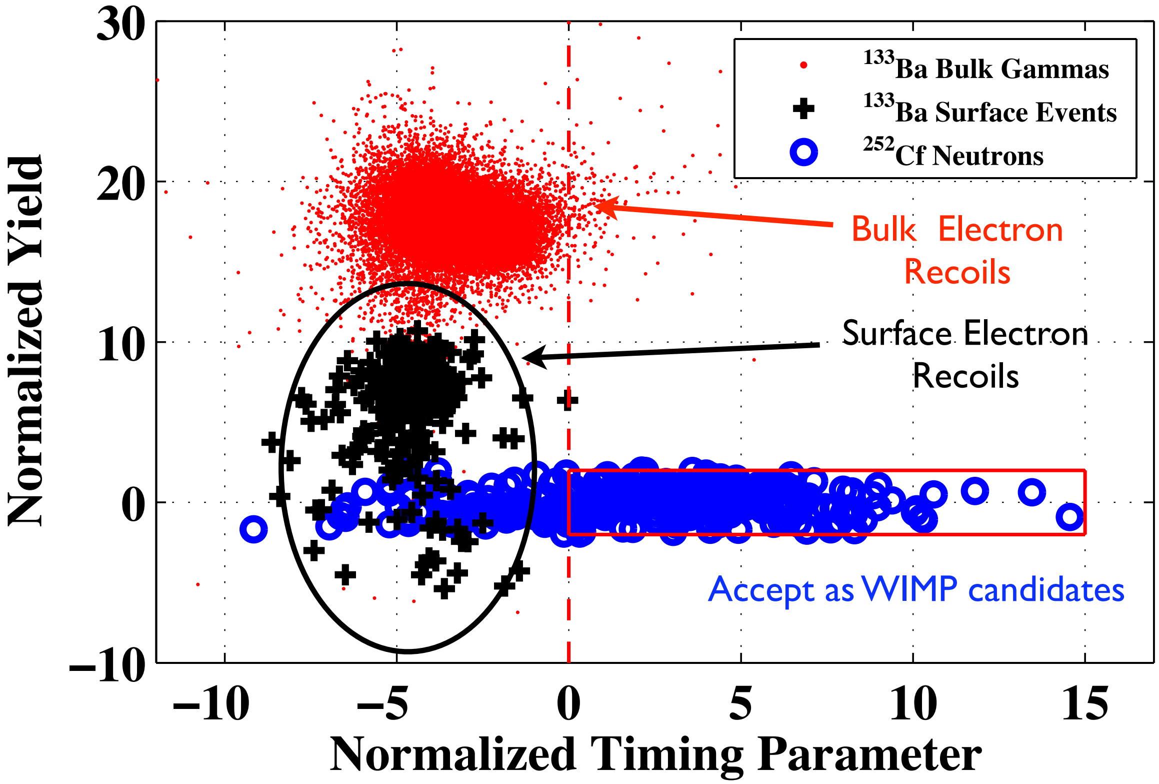


1:1 scale: 3 in. x 1 cm, 1 mm separation





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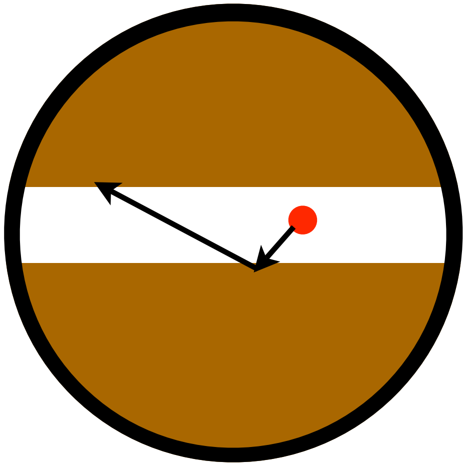
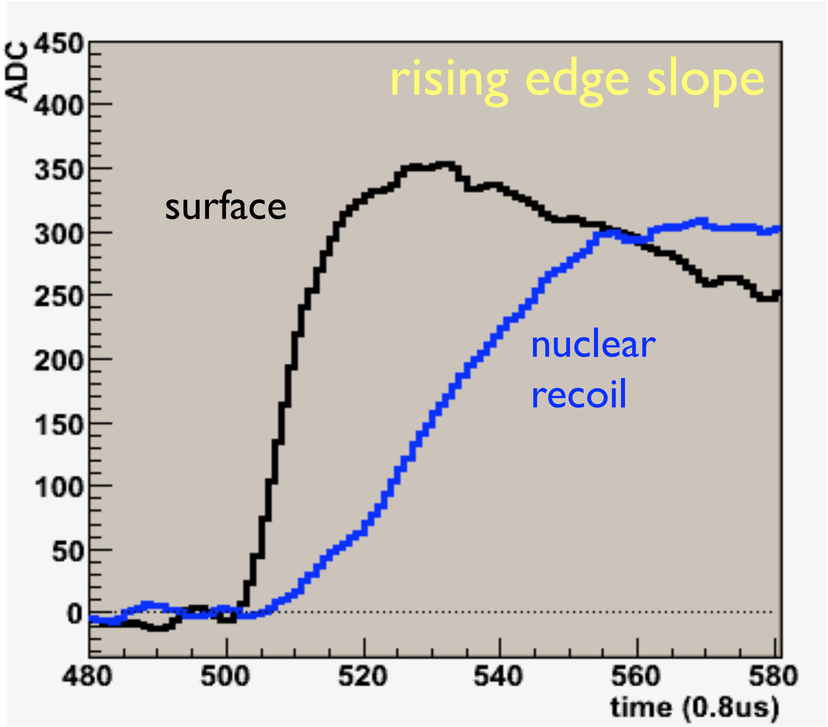
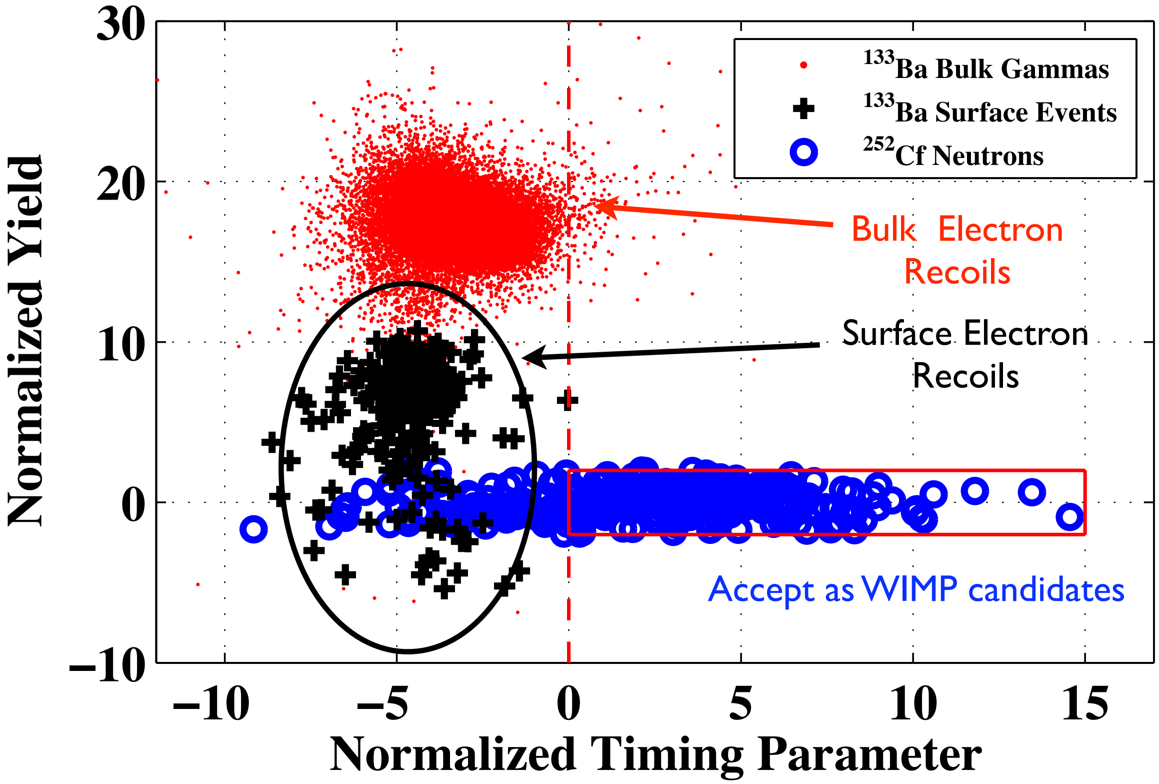






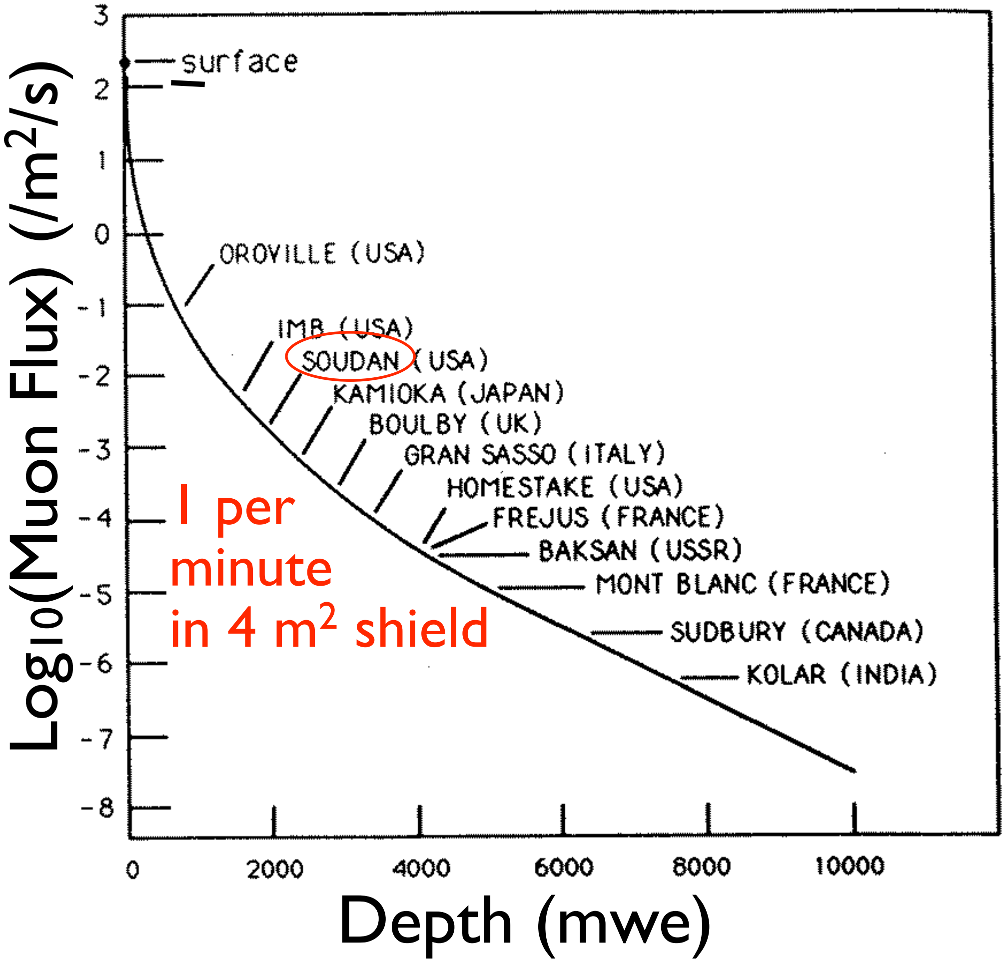
Bulk Electron Recoils

Surface Electron Recoils

Accept as WIMP candidates

# 2002–2008: 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



LEVEL NO. 27

2341 FEET BELOW THE SURFACE
689 FEET BELOW SEA LEVEL

# The CDMS II/SuperCDMS/GEODM Collaborations

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

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

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, J. Yoo

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

NIST
K. Irwin

Queens University
W. Rau, P. di Stefano

Santa Clara University
B. A. Young

SLAC National Accelerator Lab
E. do Couto e Silva, J. Weisand

Southern Methodist University
J. Cooley

Stanford University
P.L. Brink, B. Cabrera, M. Pyle,
S. Yellin

St. Olaf College
A. Reisetter

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

Texas A&M
R. Mahapatra, M. Platt

University of California, Berkeley
M. Daal, N. Mirabolfathi, B. Sadoulet, D. Seitz,
B. Serfass, K. Sundqvist

University of California, Santa Barbara
R. Bunker, D. O. Caldwell, H. Nelson

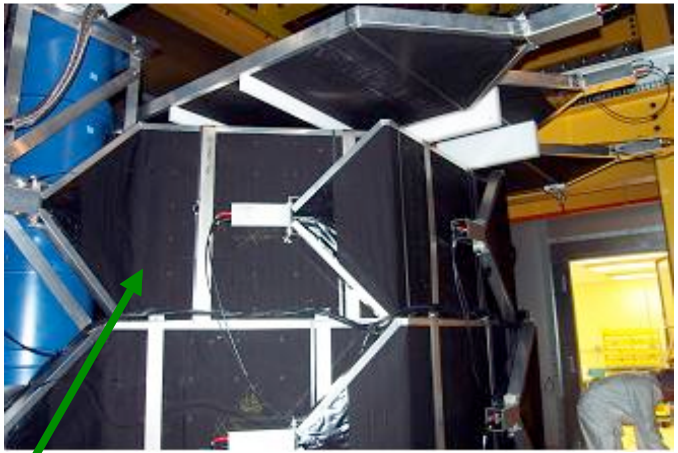
University of Colorado at Denver
M. E. Huber, B. Hines

University of Florida
T. Saab, D. Balakishiyeva

University of Minnesota
P. Cushman, M. Fritts, V. Mandic, X. Qiu, O. Kamaev

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

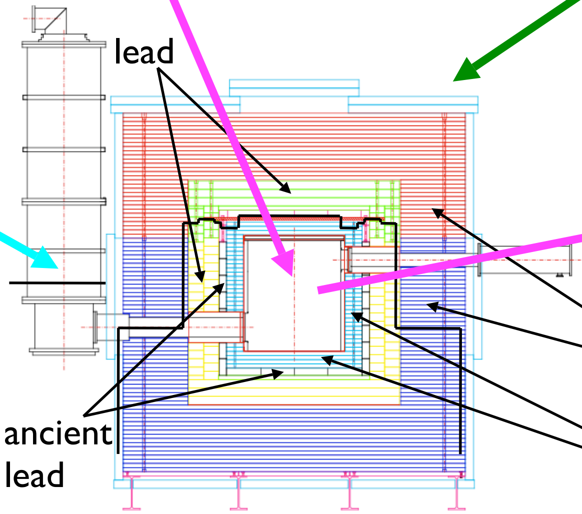
# CDMS II Soudan Installation



Plastic scintillator

Oxford Instruments 400 μW dilution refrigerator

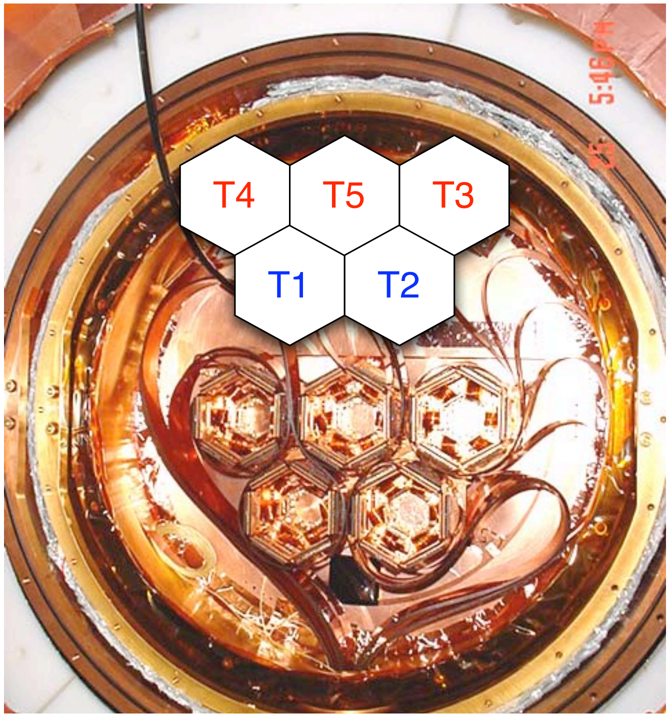
detector cold volume (“icebox”)



outer polyethylene

inner polyethylene

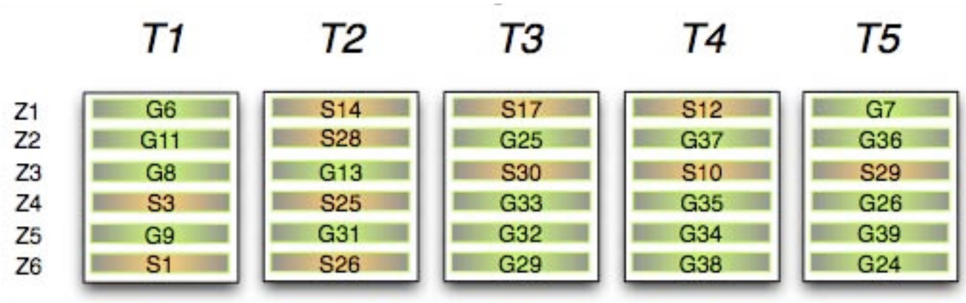
RF shielded class 10,000 clean room



detectors operate @ 40 mK

# Five Tower Runs (2006-9)

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



|  | T1 | T2 | T3 | T4 | T5 |
|---|---|---|---|---|---|
| Z1 | G6 | S14 | S17 | S12 | G7 |
| Z2 | G11 | S28 | G25 | G37 | G36 |
| Z3 | G8 | G13 | S30 | S10 | S29 |
| Z4 | S3 | S25 | G33 | G35 | G26 |
| Z5 | G9 | G31 | G32 | G34 | G39 |
| Z6 | S1 | S26 | G29 | G38 | G24 |

- Runs 123 - 124
  - Acquired: Oct06-Mar07, Apr07-Jul07
  - Exposure: ~400 kg-d (Ge "raw")
- Runs 125 - 128 RECENT WORK
  - Acquired: Jul07-Jan08, Jan08-Apr08, May08-Aug08, Aug08-Sep08
  - Exposure: ~600 kg-d (Ge "raw")
- Run 129 (Nov08-Mar09)
  - Engineering run, some detector problems

- Results:
  - See D. Moore HEP seminar Mon Feb 8 for details
  - Quick summary:
    - Blind analysis
      - Cuts on data to define WIMP candidates based on calibration or non-signal band data to avoid bias
      - Cuts set to optimize sensitivity, ~ exposure/expected background
    - Expected background:
      - 0.8 ± 0.1 (stat.) ± 0.2 (syst.) surface events
      - radiogenic neutrons: 0.03-0.06
      - cosmogenic neutrons: < 0.1
    - Observed 2 events
      - 23% chance of ≥ 2 background events
      - no significant evidence for WIMP interactions
    - Set upper limit **without** subtraction of expected background

# The Happy Analyzers

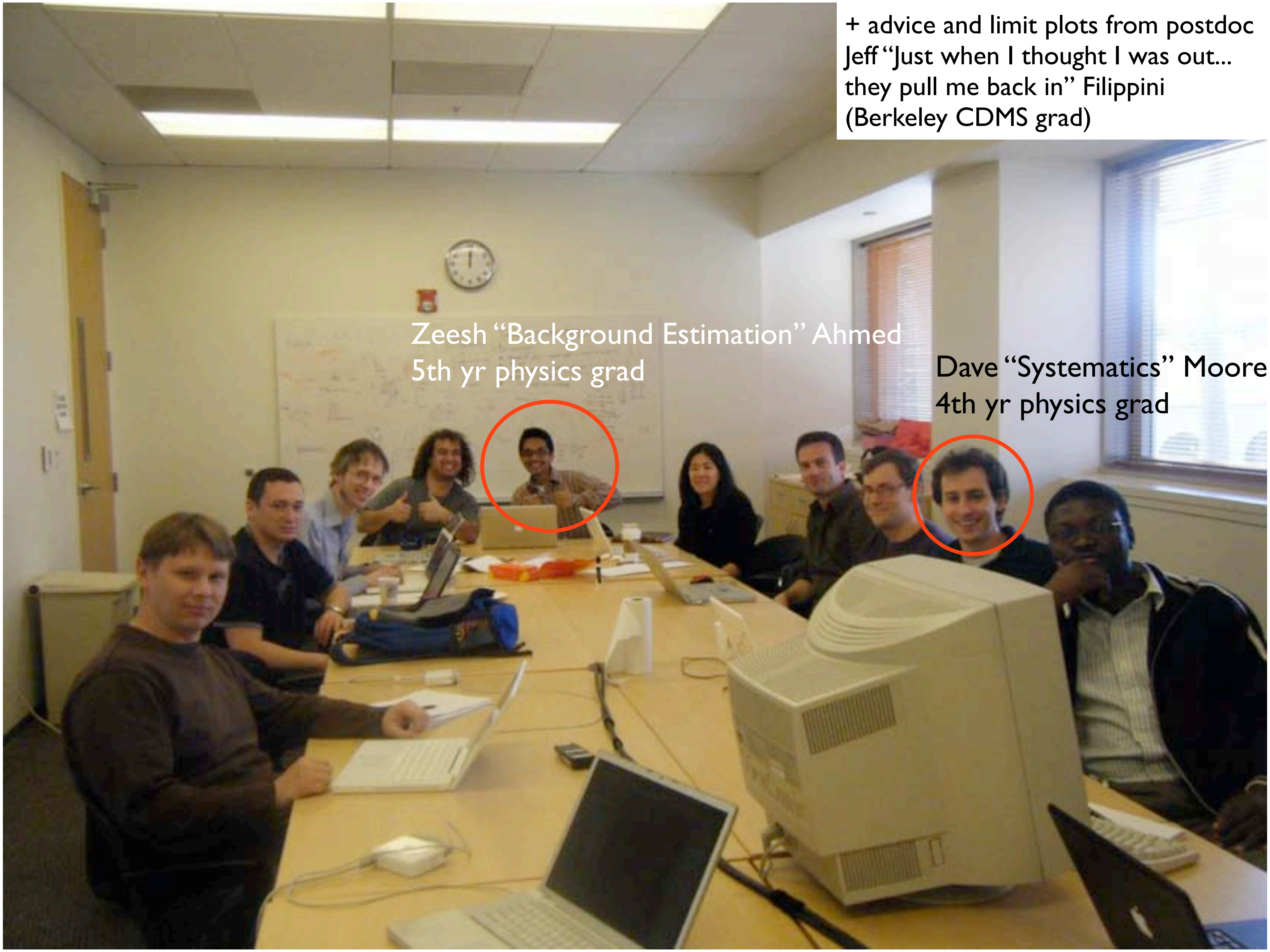
# The Happy Analyzers

Zeesh “Background Estimation” Ahmed
5th yr physics grad

Dave “Systematics” Moore
4th yr physics grad

# 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)



Zeesh "Background Estimation" Ahmed
5th yr physics grad

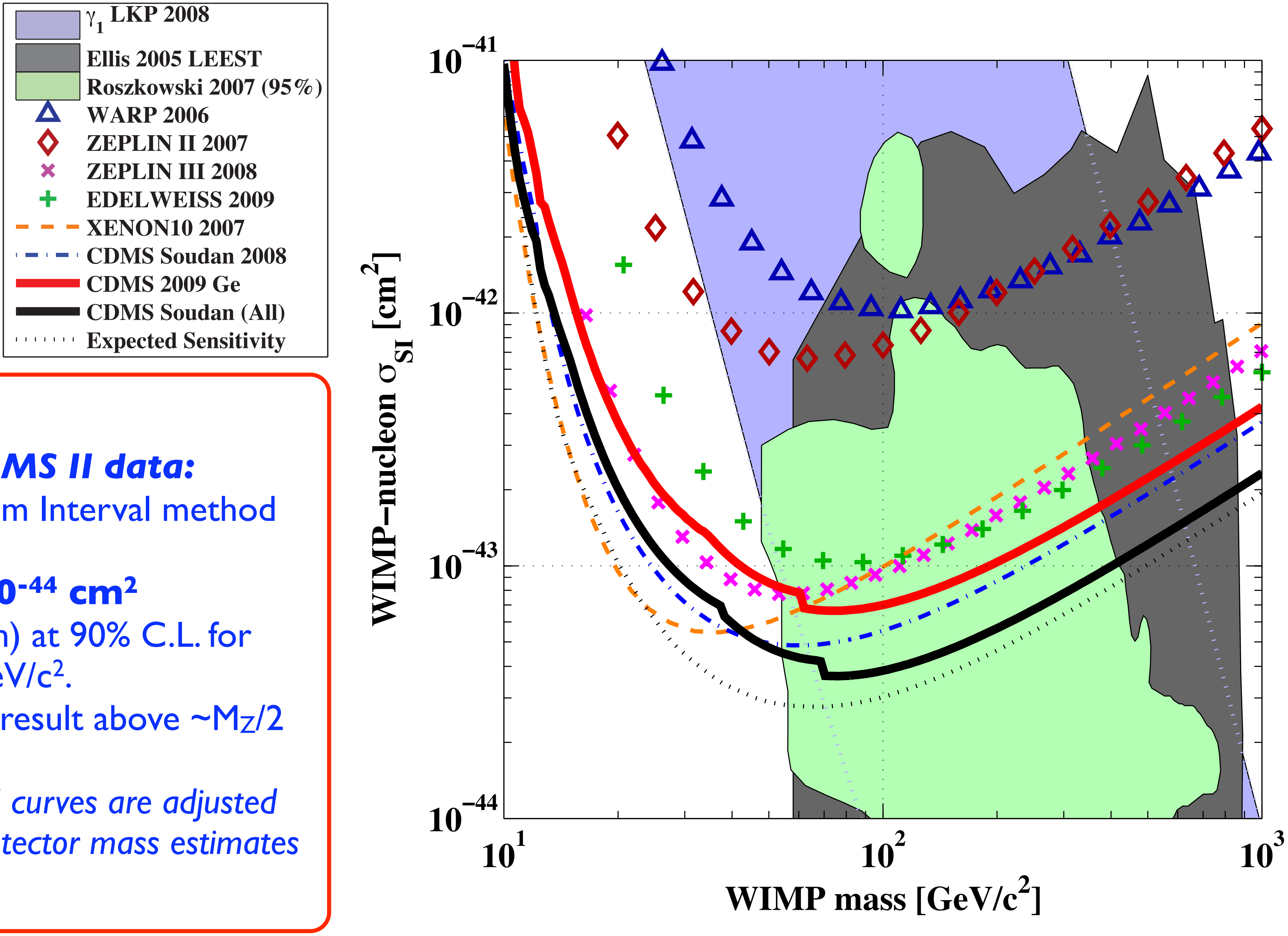
Dave "Systematics" Moore
4th yr physics grad

# Spin-Independent Limits

KK/SUSY theory

Other searches

CDMS II results



***Combined CDMS II data:***

- Yellin's Optimum Interval method (no bkg. subt.)
- **$\sigma_{SI} > 3.8 \times 10^{-44}$ cm$^2$** (>38 zeptobarn) at 90% C.L. for $M_{WIMP}$ = 70 GeV/c$^2$.
- World-leading result above ~$M_Z/2$

***Note:*** *All CDMS curves are adjusted for ~9% lower detector mass estimates*

# From CDMS II to SuperCDMS and GEODM

**CDMS II**

∅7.5cm x 1cm ZIP
0.25 kg/detector

16 detectors = 4 kg
2 yr, 1700 kg-d

**SuperCDMS Soudan**

∅7.5cm x 2.5cm mZIP
0.64 kg/detector

25 detectors = 15 kg
2 yr, 8000 kg-d

**SuperCDMS SNOLAB**

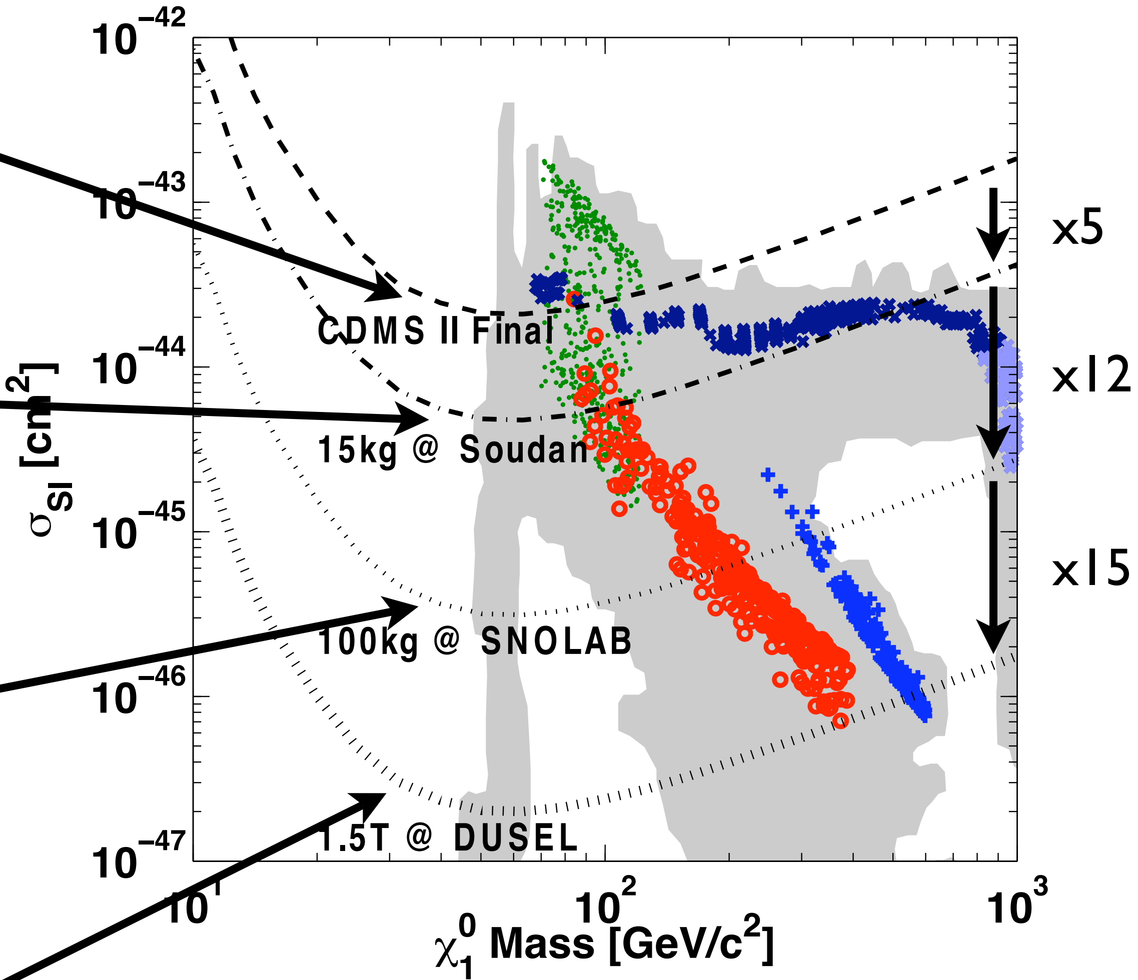
∅10cm x 3.5cm iZIP
1.5 kg/detector

70 detectors = 105 kg
3 yr = 100,000 kg-d

**GEODM DUSEL**

∅15cm x 5cm iZIP
5.1 kg/detector

300 detectors = 1.5 T
2 yr, 1.5 M kg-d



Staged three-prong program to explore MSSM or study a signal:

- decreased backgrounds
- improved background rejection
- increase in mass/detector and decrease in cost/detector

< 1 event misid'd bgnd at each stage

# Larger Substrates

- Larger substrates provide gains in bgnds and in cost/time per kg
- Step 1: 10-cm HPGe substrates
- Step 2: Dislocation-free Ge
    - deep (Ev + 0.080 eV) $V_2H$ impurity ruins 77K HPGe γ spectrometers; inhibited via dislocations at $10^{2\text{-}4}$ cm$^{-3}$ created by thermal gradients during crystal pulling
    - impurity no problem for CDMS: impurities are neutralized
    - dislocation-free xtals available up to 30 cm diameter!

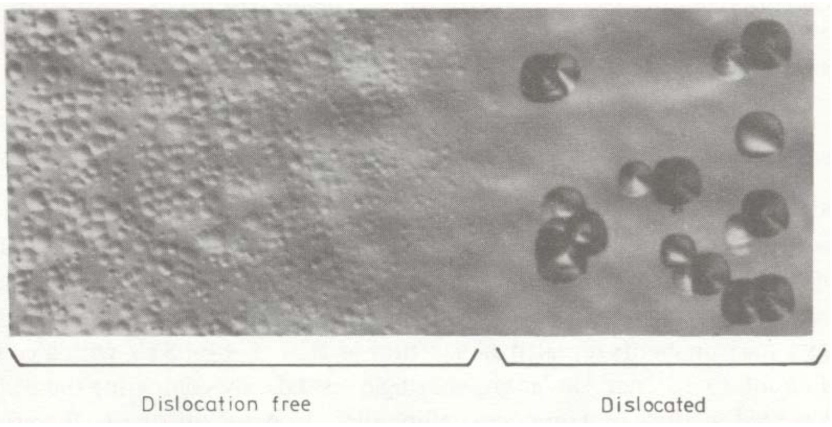
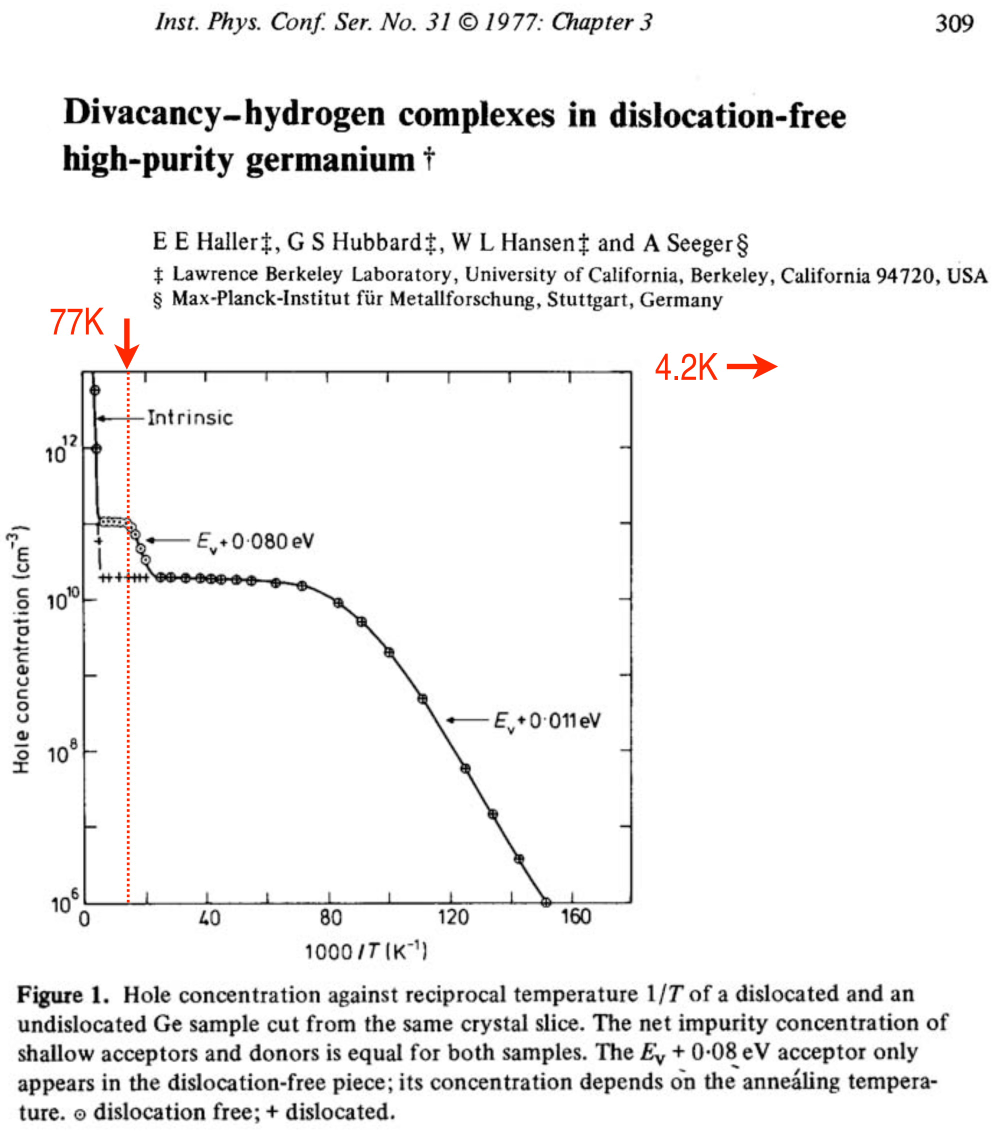


**Figure 2.** Photograph of a partially dislocated (100) surface of a hydrogen-grown Ge crystal. The large etch pits with four-fold symmetry in the right half of the picture are due to dislocations. The hemispherical pits in the left half of the picture are attributed to vacancy and hydrogen complexes.



*Inst. Phys. Conf. Ser. No. 31 © 1977: Chapter 3* 309

**Divacancy–hydrogen complexes in dislocation-free high-purity germanium** †

E E Haller‡, G S Hubbard‡, W L Hansen‡ and A Seeger§

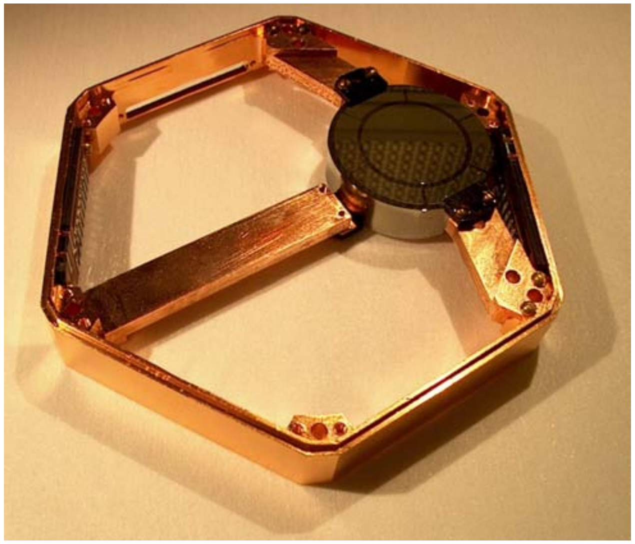
‡ Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, USA

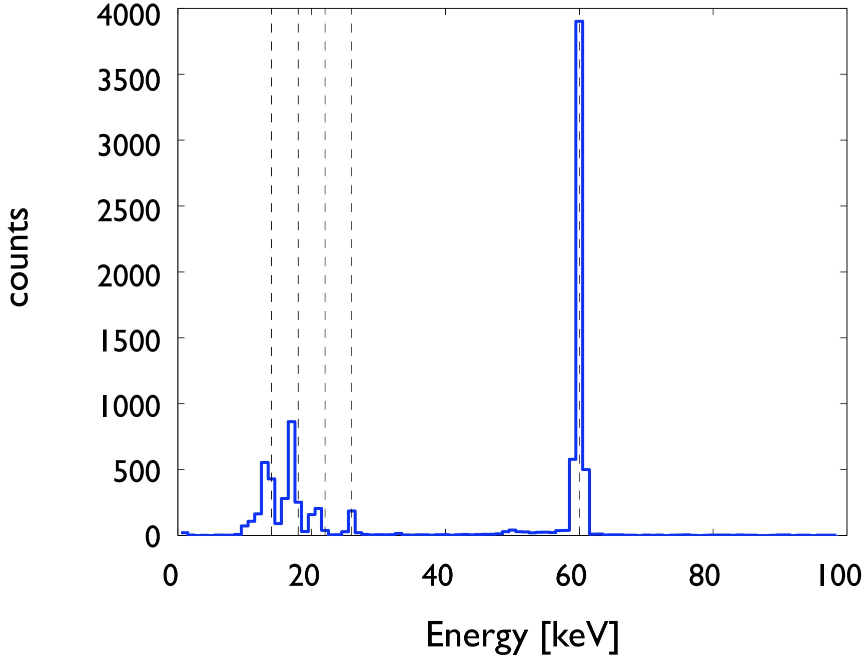
§ Max-Planck-Institut für Metallforschung, Stuttgart, Germany

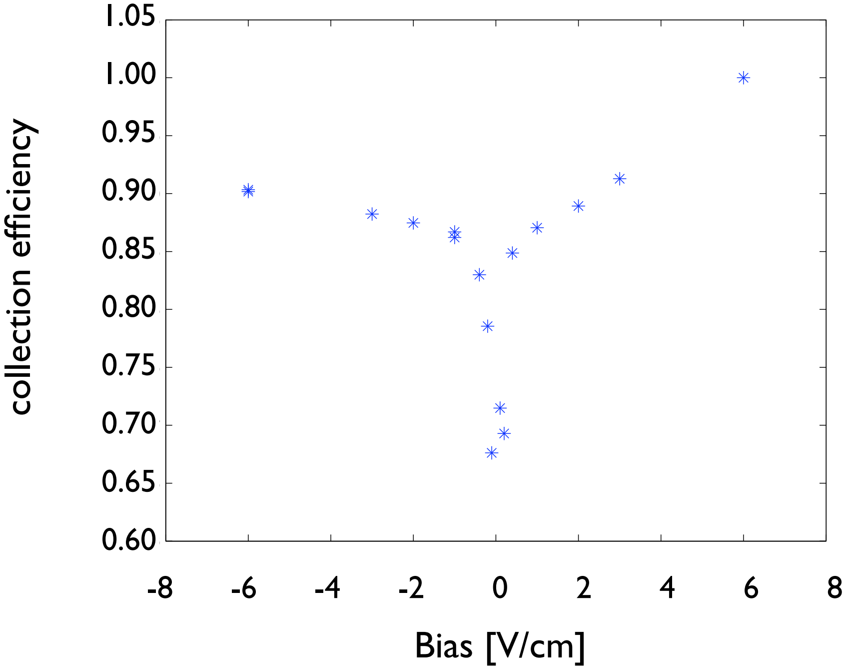
**Figure 1.** Hole concentration against reciprocal temperature $1/T$ of a dislocated and an undislocated Ge sample cut from the same crystal slice. The net impurity concentration of shallow acceptors and donors is equal for both samples. The $E_V + 0{\cdot}08$ eV acceptor only appears in the dislocation-free piece; its concentration depends on the annealing temperature. ⊙ dislocation free; + dislocated.

# Larger Substrates

- Proof-of-principle from Haller sample of dislocation-free Ge (3 cm x 1 cm)
  - Good collection at 1 V/cm (reasonable field)
- Working with Umicore and Photonic Sense to demonstrate 15-cm fab at necessary purity/compensation levels
  - DUSEL R&D grant, DUSEL S4 grant
  - Germanium workshop in Berkeley this fall

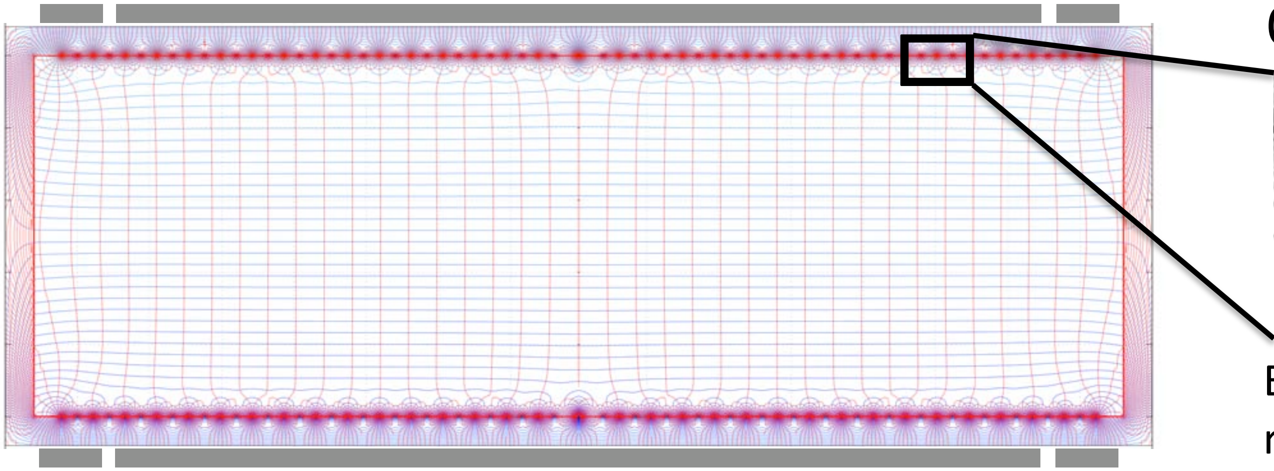


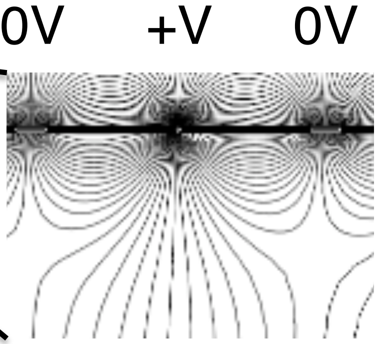




# Improving Background Rejection

- Interdigitated ZIP (iZIP) design meets needs for SuperCDMS SNOLAB and GEODM



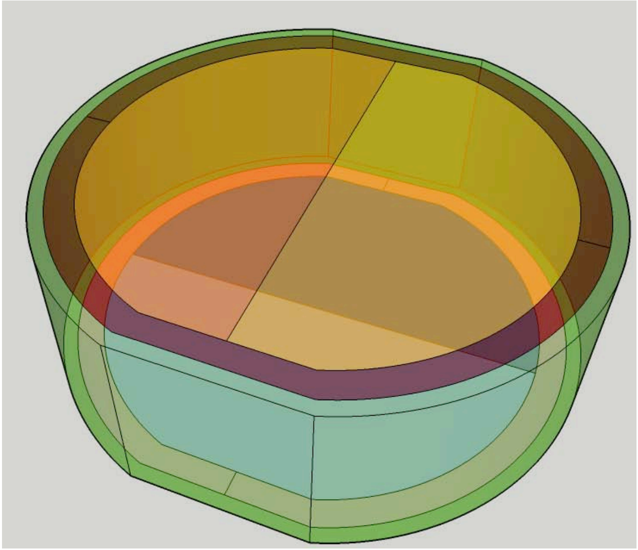


negative version on other face

Edelweiss proved low field regions not a problem

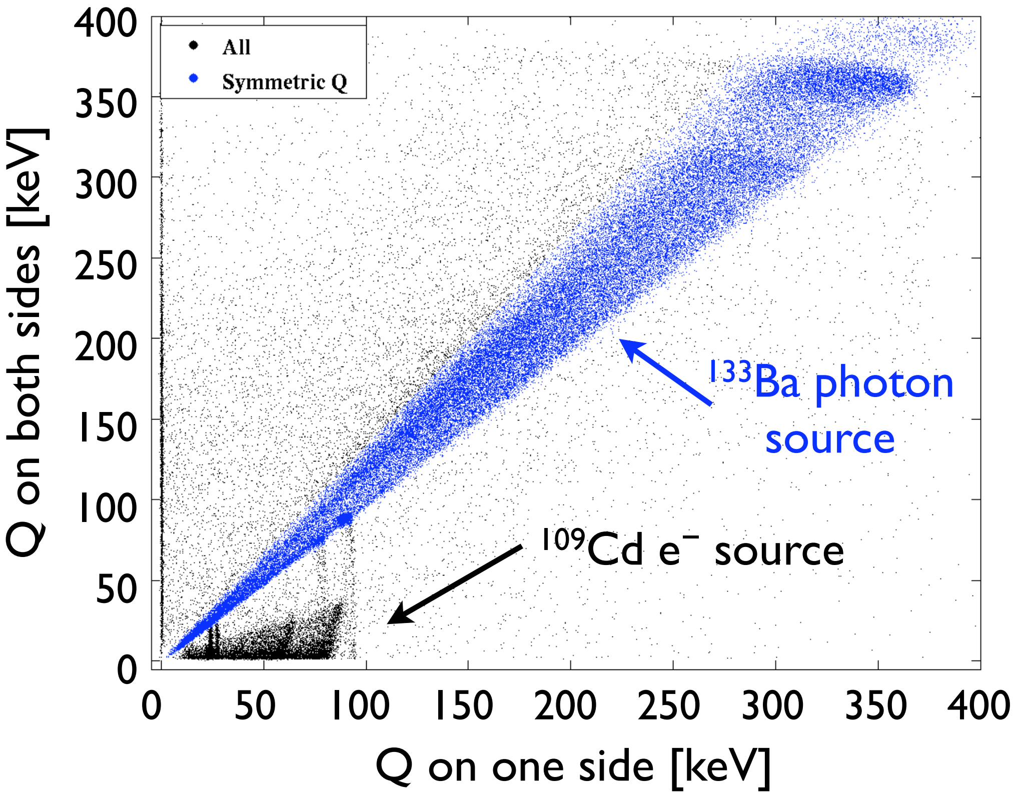
M. Pyle

- Interleaved ionization electrodes cause ionization to partition differently for surface and bulk events
- High field near surface increases ionization yield for surface events
- Top/bottom phonon sensors (ground rails) provide simpler, more direct z information



# Improving Background Rejection

- Interdigitated ZIP (iZIP) design appears to meet needs of SuperCDMS SNOLAB and GEODM
  - Surface events share charge differently than bulk events: < $10^{-3}$ misid
  - High field at surfaces increases ionization yield: 0.2 misid → < $3 \times 10^{-4}$ misid
  - Phonon partition and timing z position: < $10^{-3}$ misid



M. Pyle, B. Serfass

  - All measurements limited by neutron background in surface test facilities
  - Ionization yield and Q/P asymmetry likely uncorrelated; if true, then overall misid $10^{-4}$ → < $3 \times 10^{-7}$, far better than needed for GEODM

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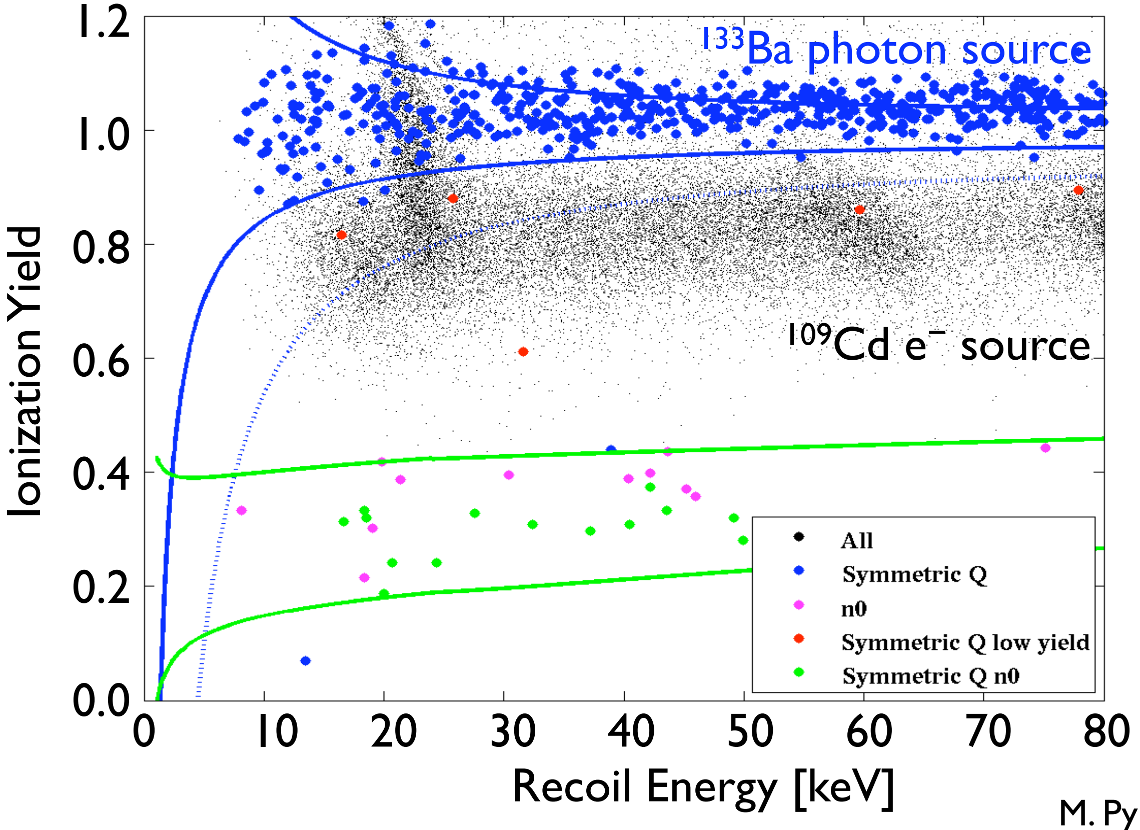

M. Pyle, B. Serfass

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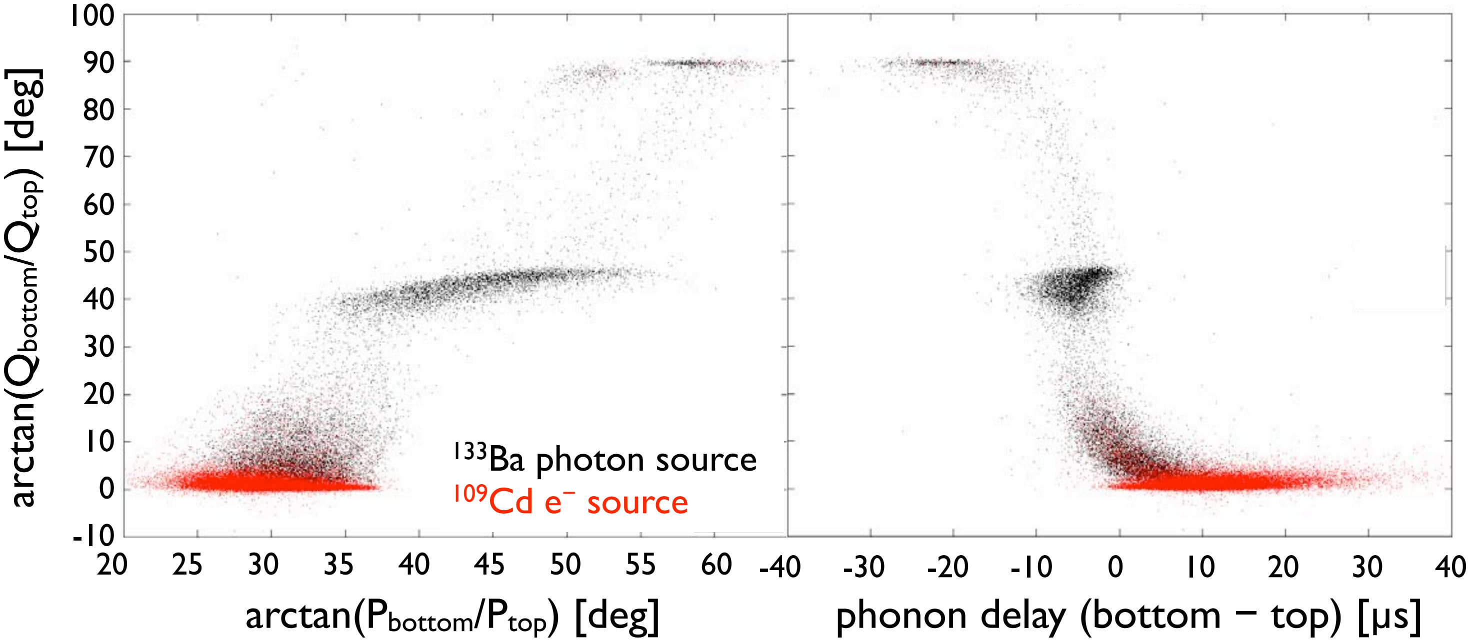
  - High field at surfaces increases ionization yield: 0.2 misid → < $3 \times 10^{-4}$ misid
  - Phonon partition and timing z position: < $10^{-3}$ misid

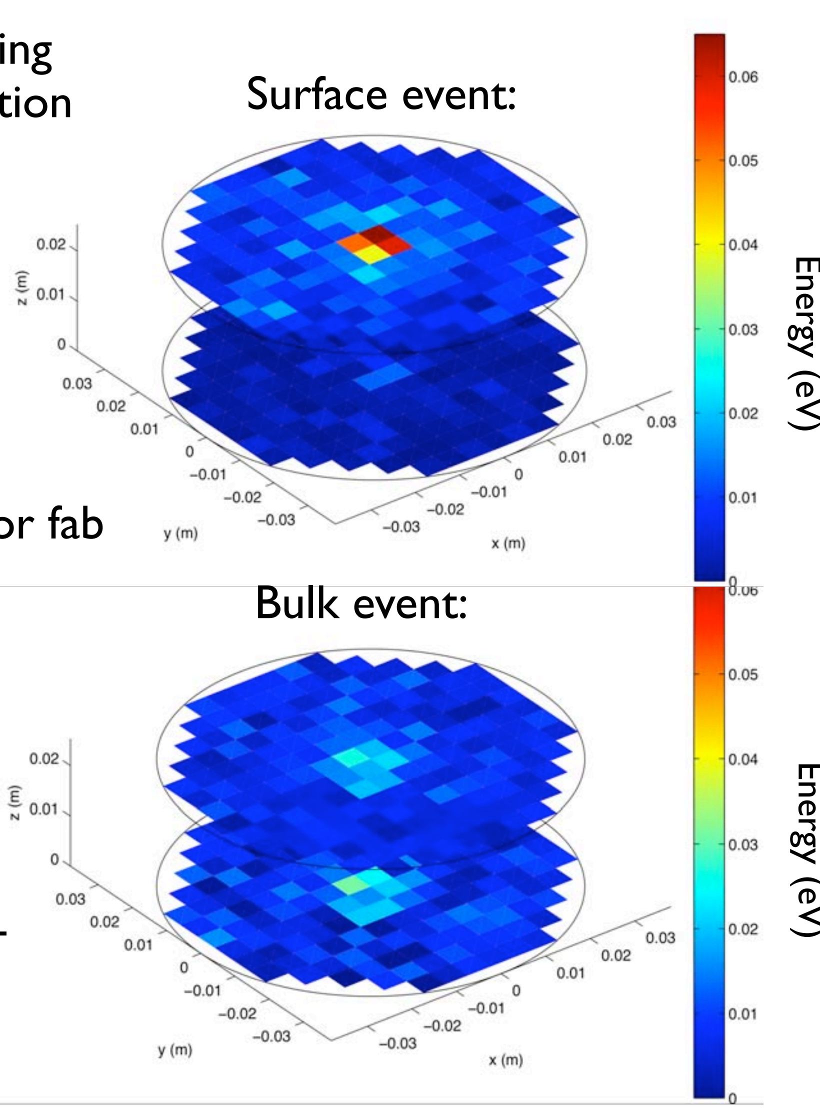


M. Pyle, B. Serfass

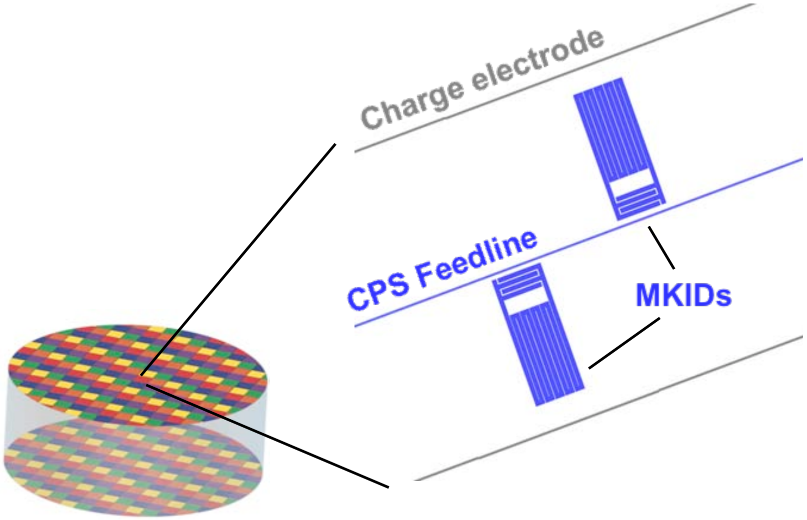
  - All measurements limited by neutron background in surface test facilities
  - Ionization yield and Q/P asymmetry likely uncorrelated; if true, then overall misid $10^{-4}$ → < $3 \times 10^{-7}$, far better than needed for GEODM

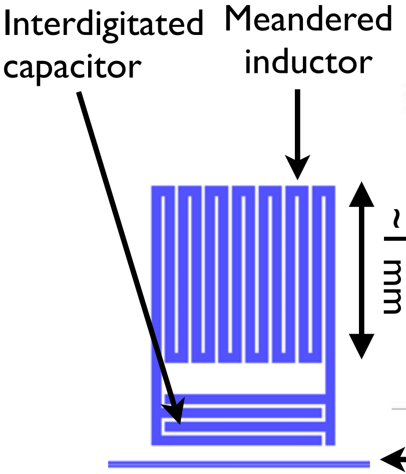
# Phonon Detection Using MKIDs

- Microwave kinetic inductance detectors (MKIDs, Zmuidzinas et al) can detect phonon energy: meV phonons break Cooper pairs, change L of superconductor
- Multiplexable: Form LC resonator w/single superconducting film. Readout like FM/AM radio with digital signal generation and demodulation.
- Recent development of lumped-element designs having low susceptibility to dielectric constant fluctuation noise and using large penetration depth materials enables large-area resonators for phonon sensing (Day, Gao, LeDuc, Noroozian, Zmuidzinas)
- Single film, 5 μm features would simplify GEODM detector fab
- Finer pixellization of phonon sensor provides additional surface event rejection



Figures by D. Moore

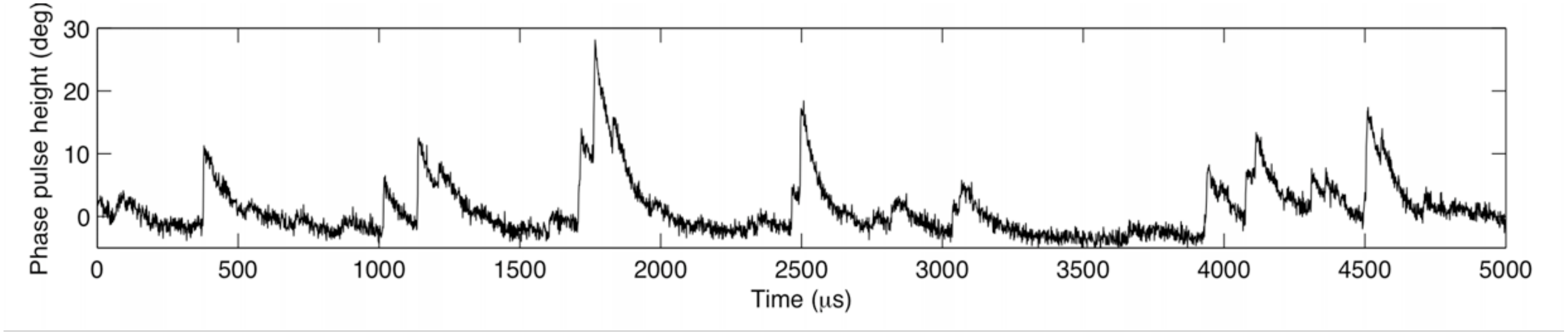




coplanar stripline (CPS) feedline to excite/probe resonator

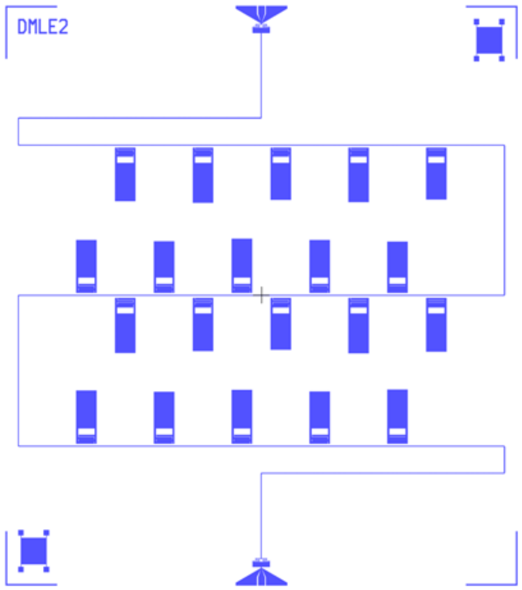
# Expected Sensitivity

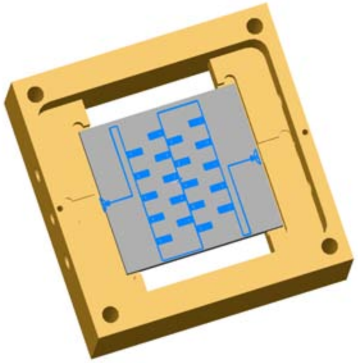
- Phonon-mediated 6 keV X-rays observed with ~100 µs lifetimes in mm$^2$ resonators:



D. Moore

- Using measured noise and responsivities, calculate a noise-equivalent power (NEP)
- Converting to an energy resolution gives: $\sigma_E$ = 46 eV for A = 1.5 mm$^2$ and $\sigma_E$ = 14 eV for A = 0.64 mm$^2$ (single-resonator resolution)
- Numbers agree with measured resolution for 5 eV photons in ~0.1 mm$^2$ resonators, scaled by responsivity
- An MKID-based detector with 500 one mm$^2$ resonators would have similar energy resolution as current designs, but would be much easier to fabricate and read out
- 12 mm x 16 mm array of 20 resonators soon to be tested with collimated source to demonstrate position reconstruction!

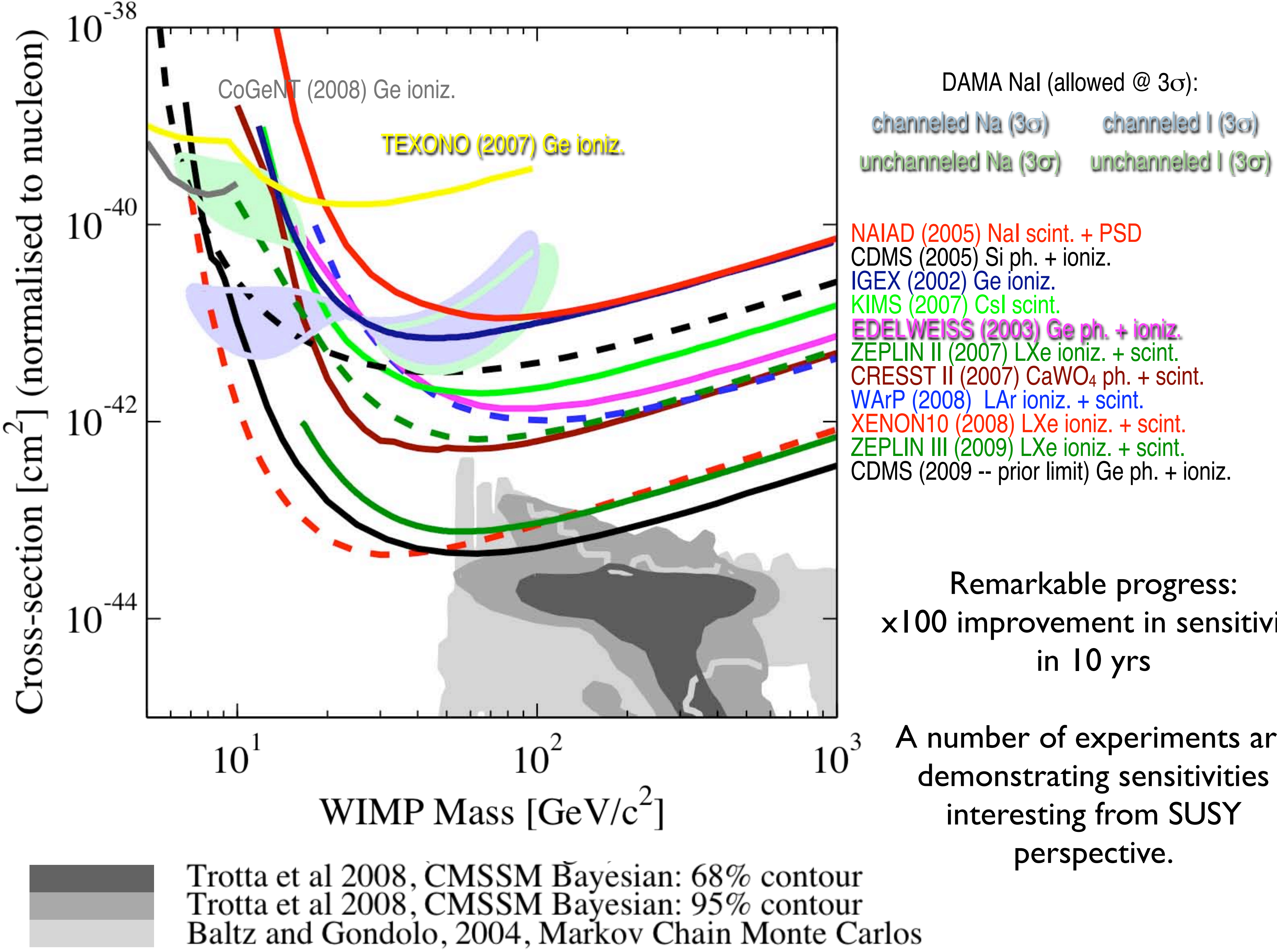




# Project(s) Status

- SuperCDMS Soudan
  - Fully approved (review Aug 2009); preparing final project execution plan
  - First detectors running underground since mid-2009, installing new detectors this year/next year, interesting exposure by end 2011
- SuperCDMS SNOLAB
  - iZIP + 100 kg total mass received substantial endorsement from PASAG
  - SLAC has joined experiment
  - requesting R&D funds this year, project proposal next year, hope for FY13 construction start
  - SNOLAB test facility being assembled to demo iZIP rejection underground ASAP
- GEODM DUSEL
  - iZIP + 15 cm x 5 cm to provide 1.5 T detector mass
  - "S4" DUSEL engineering study proposal funded
  - Working on production of large crystals and automation of fab using evolution of current detector design
  - Caltech working on simplified phonon sensors using MKIDs
  - SNOLAB test facility will provide underground demonstration of rejection

# Where We Are Now



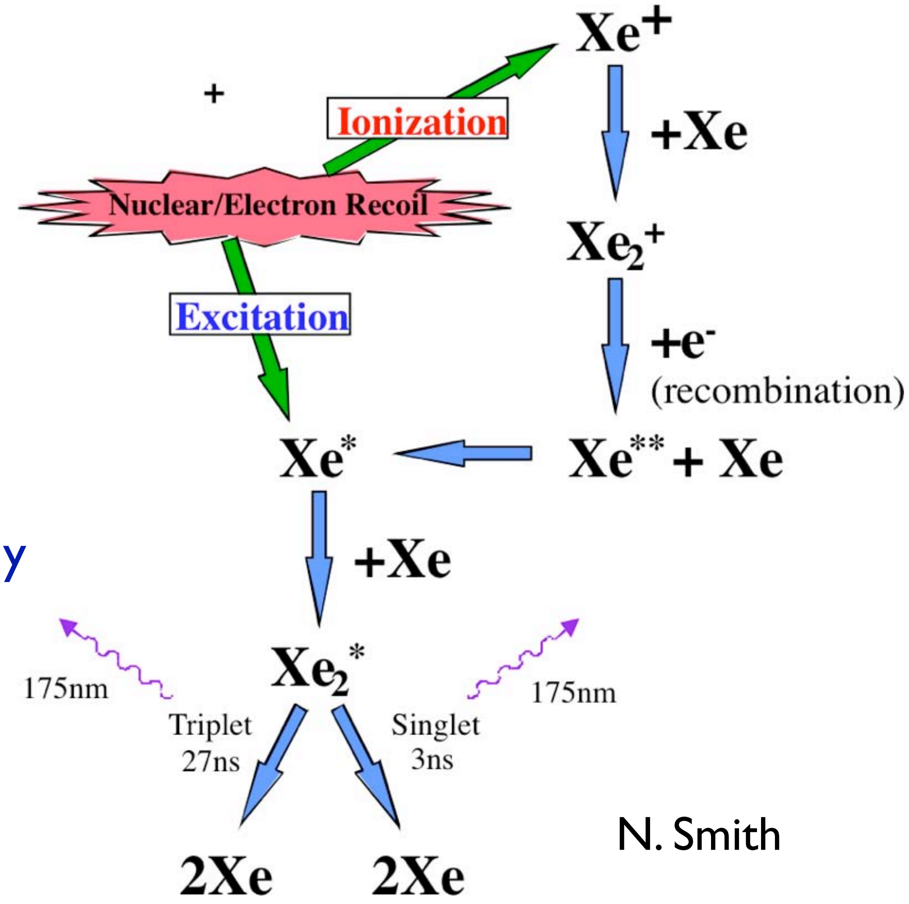
plot compiled by P. Cushman using Gaitskell, Mandic, and Filippini
http://dmtools.brown.edu

Remarkable progress:
x100 improvement in sensitivity in 10 yrs

A number of experiments are demonstrating sensitivities interesting from SUSY perspective.

# Liquid Nobles

- Method:
  - ionization and direct excitation paths have different populations for nuclear and electron recoils
  - *independently*, different paths populate fast singlet and slow triplet states differently
- Implementations:
  - LXe: observe scintillation and drift $e^-$
  - LNe: observe slow and fast scintillation
  - LAr, GXe: both



N. Smith

| | Liquid density (g/cc) | Boiling point at 1 bar (K) | Electron mobility (cm$^2$/Vs) | Scintillation wavelength (nm) | Scintillation yield (photons/MeV) | Long-lived radioactive isotopes | Triplet molecule lifetime ($\mu$s) |
|---|---|---|---|---|---|---|---|
| LHe | 0.145 | 4.2 | low | 80 | 19,000 | none | 13,000,000 |
| LNe | 1.2 | 27.1 | low | 78 | 30,000 | none | 15 |
| LAr | 1.4 | 87.3 | 400 | 125 | 40,000 | $^{39}$Ar, $^{42}$Ar | 1.6 |
| LKr | 2.4 | 120 | 1200 | 150 | 25,000 | $^{81}$Kr, $^{85}$Kr | 0.09 |
| LXe | 3.0 | 165 | 2200 | 175 | 42,000 | $^{136}$Xe | 0.03 |

D. McKinsey

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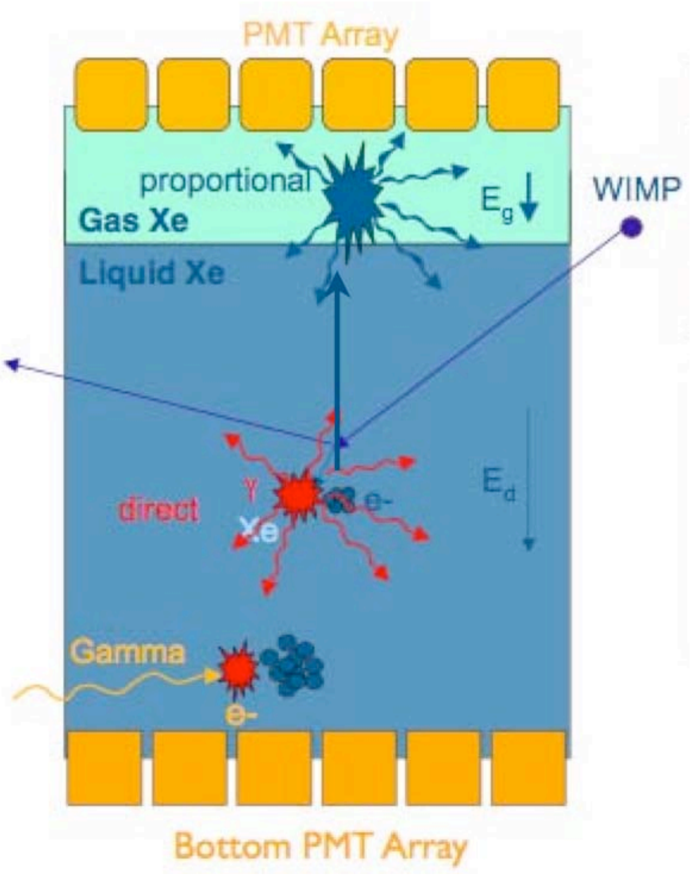

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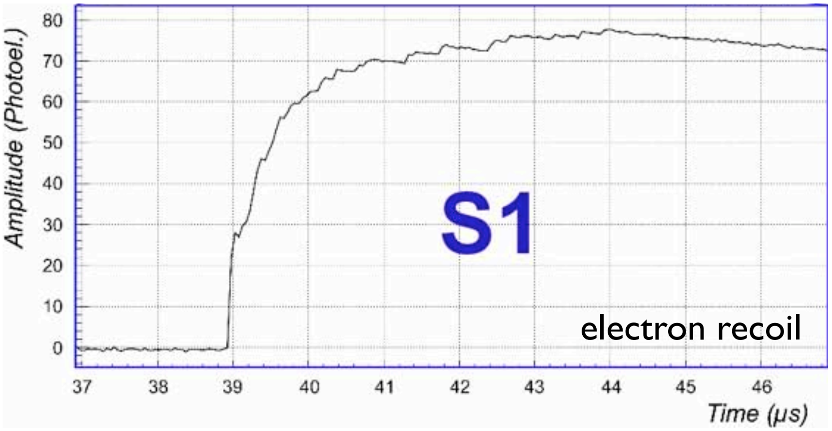

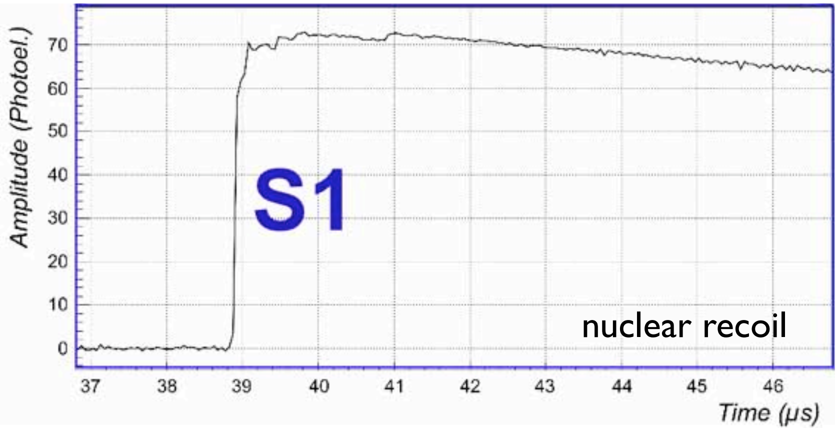

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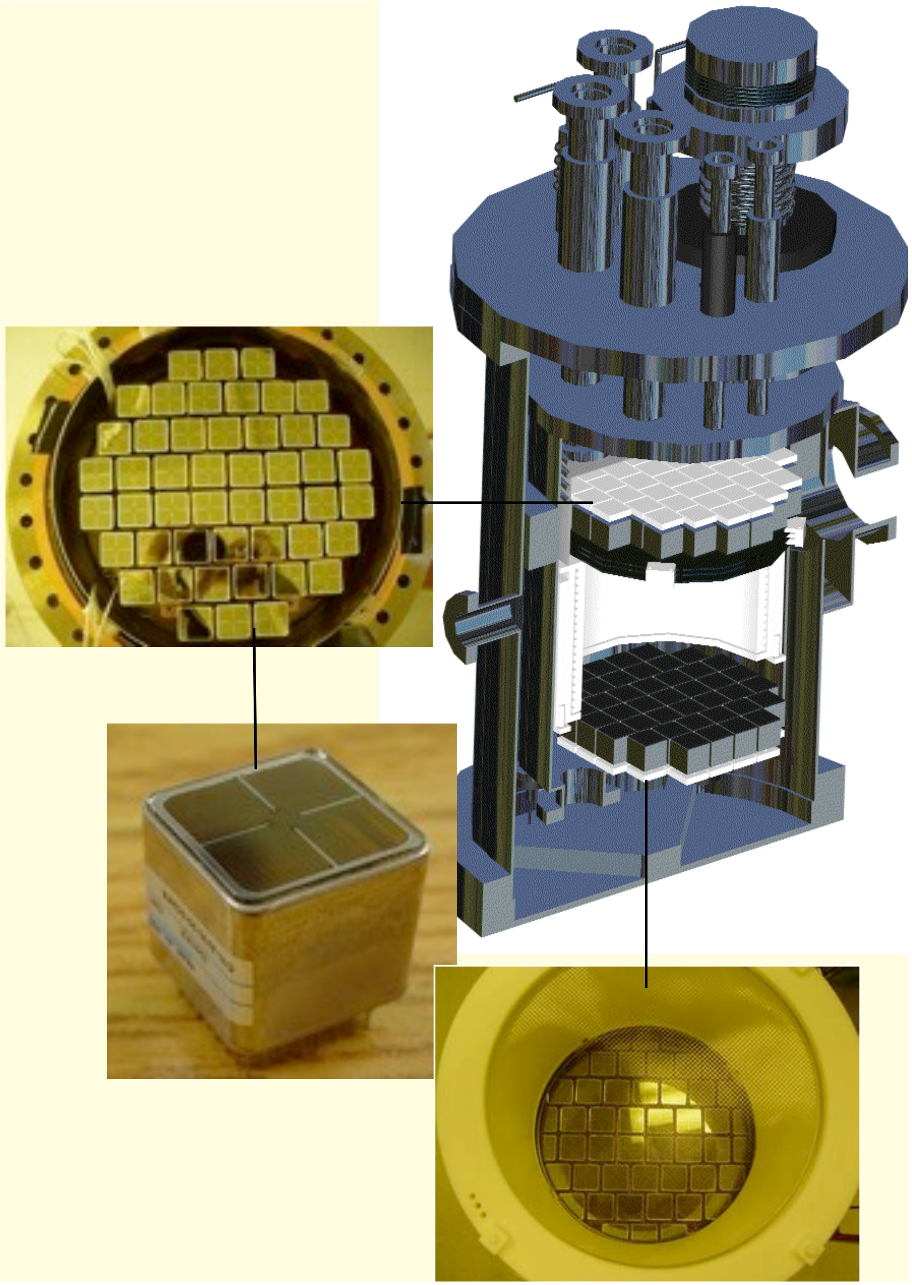
  - First competitive LXe expt
    - 5.4 kg fiducial
    - good light collection (5 pe/keV)
    - good bgnds in in prototype
  - 2007 results limited by bgnd consistent with tail of EM into WIMP acceptance region
  - cutting harder will reduce NR acceptance from 50%
  - Scale-up needed to reduce bgnd by self-shielding, need to maintain ionization and light collection efficiency
- ZEPLIN III (Boulby)
  - similar idea, higher bgnds, less self-shielding



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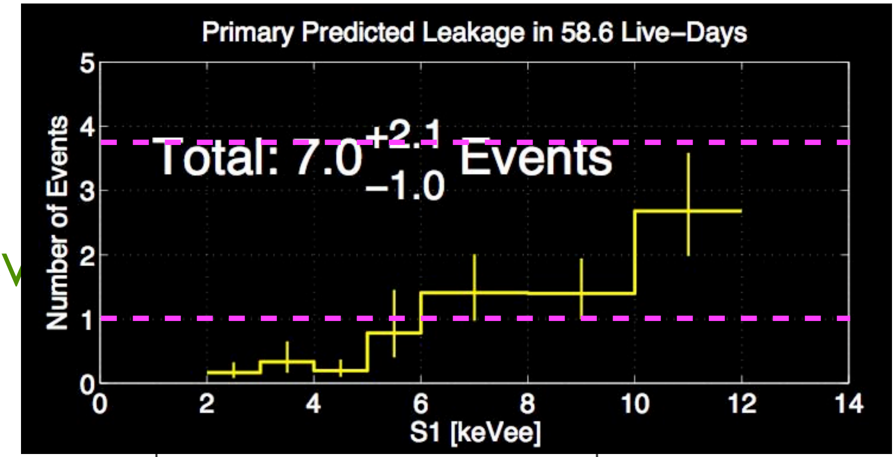
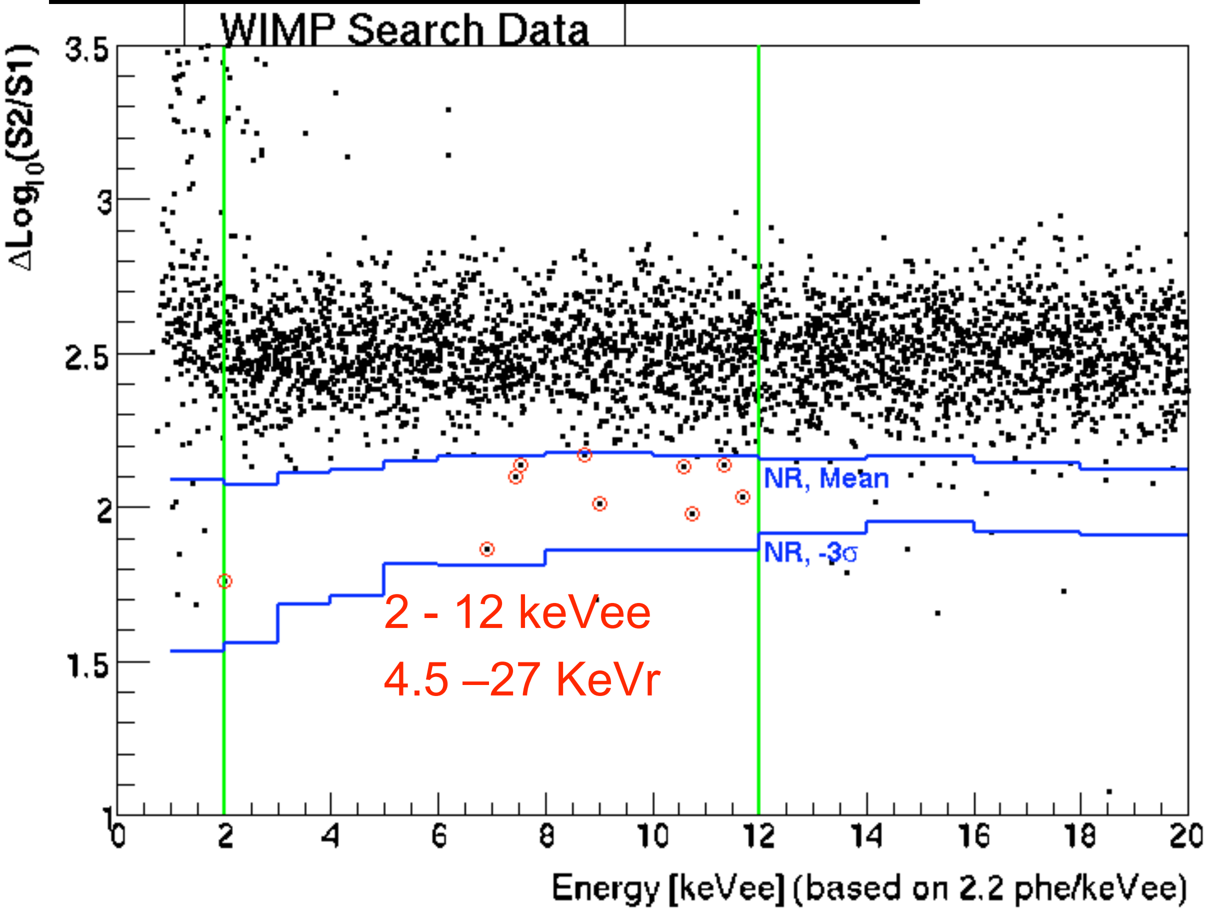


99.0% rejection

99.9% rejection



2 - 12 keVee

4.5 –27 KeVr

# Liquid Xenon

- XENON100 (Gran Sasso)
  - upgrade of XENON10, 50 kg fiducial, 170 kg total
  - cold and operating since mid-2008, working on light yield and e⁻ drift issues, physics running began at end 2009
  - XENON 100+: 100-kg fiducial w/QUPIDs
- LUX (Sanford/Homestake)
  - LUX: 100 kg fiducial, 350 kg total
  - demonstrated functionality above-ground with 60 kg LXe, 0.5 kg active
  - installing now at surface
  - installing in Davis cavern mid/late 2010
- XMASS
  - single-phase: self-shielding only, shielding built, detector in process, commissioning ~start 2010

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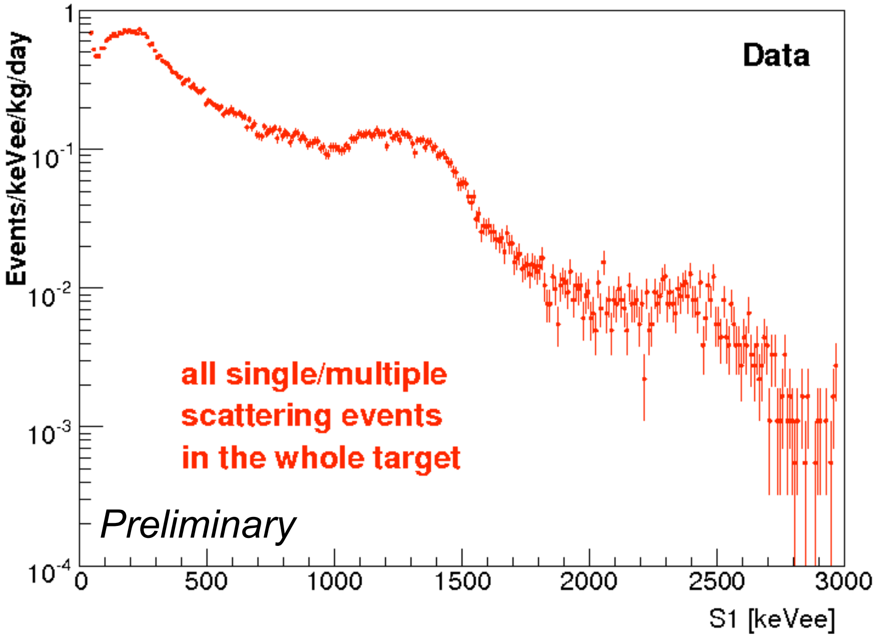

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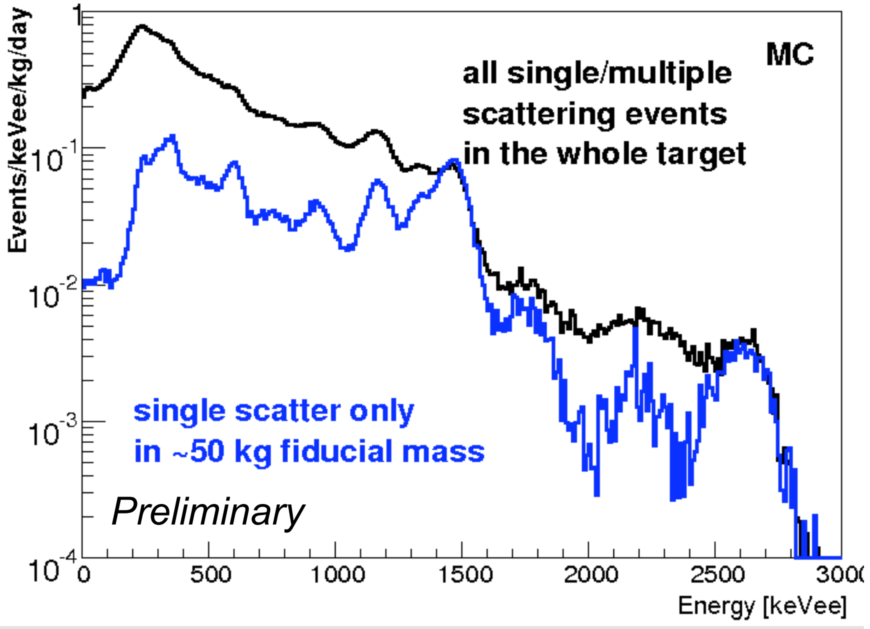

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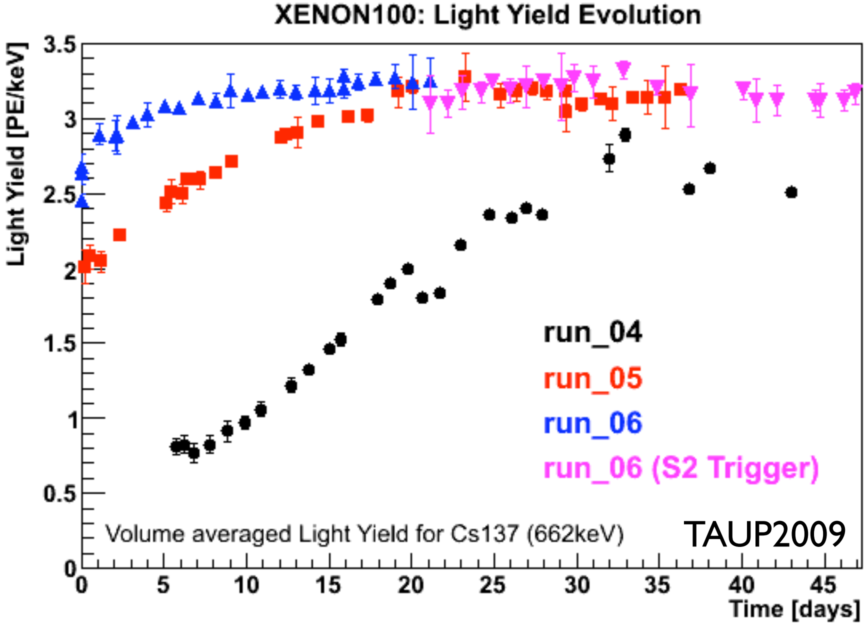

3 pe/keV at 662 keV = 5 pe/keV at low energy

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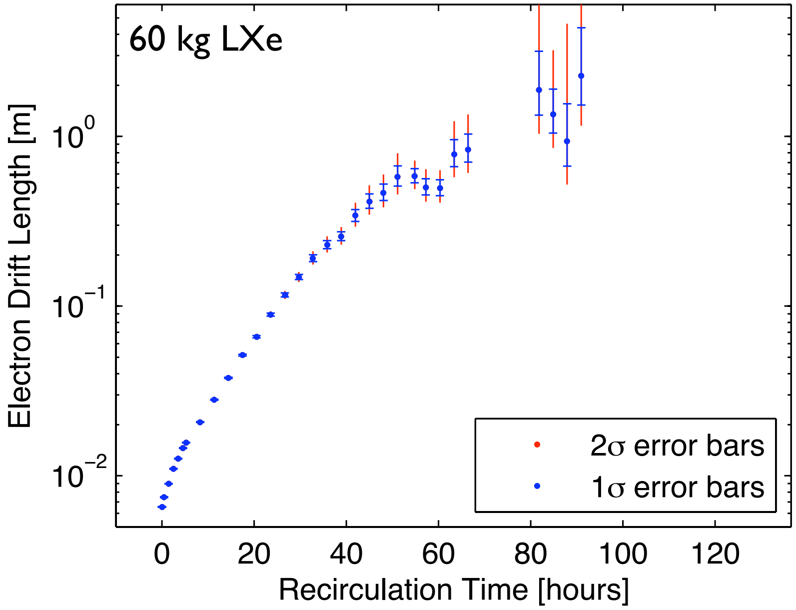

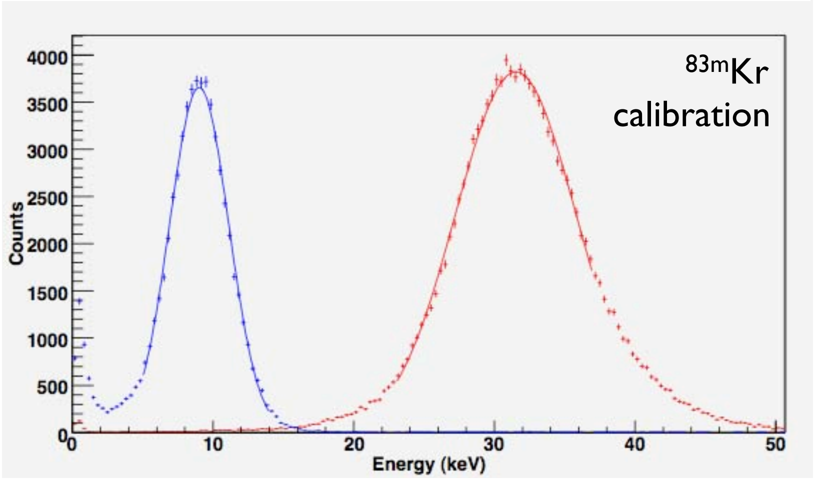

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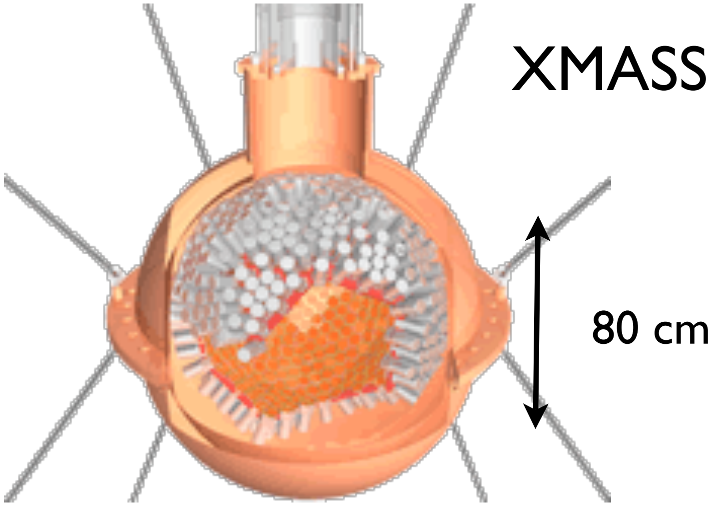
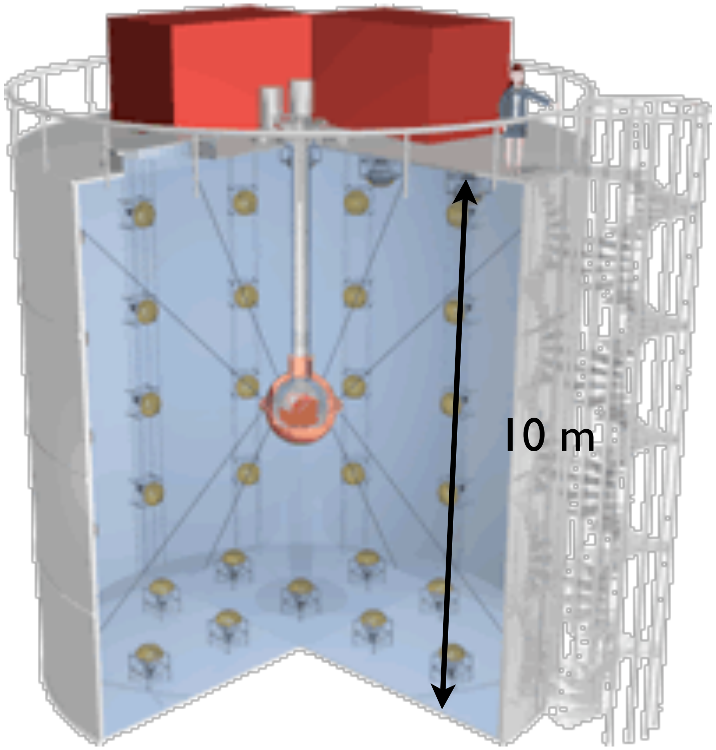


100 kg fiducial, 800 kg total



# Liquid Argon

- $^{39}$Ar: 1 Bq/kg. Must deplete!
- 2-phase
  - WArP (Gran Sasso)
    - 140-kg detector being commissioned inside passive water shield, active LAr shield
  - ArDM
    - still in R&D phase, but 1-ton R&D detector constructed and filled, uses fewer larger PMTs, uses LEMs for ionization gain
  - DarkSide
    - Proposed for SNOLAB, depleted Ar
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  - miniCLEAN (SNOLAB):
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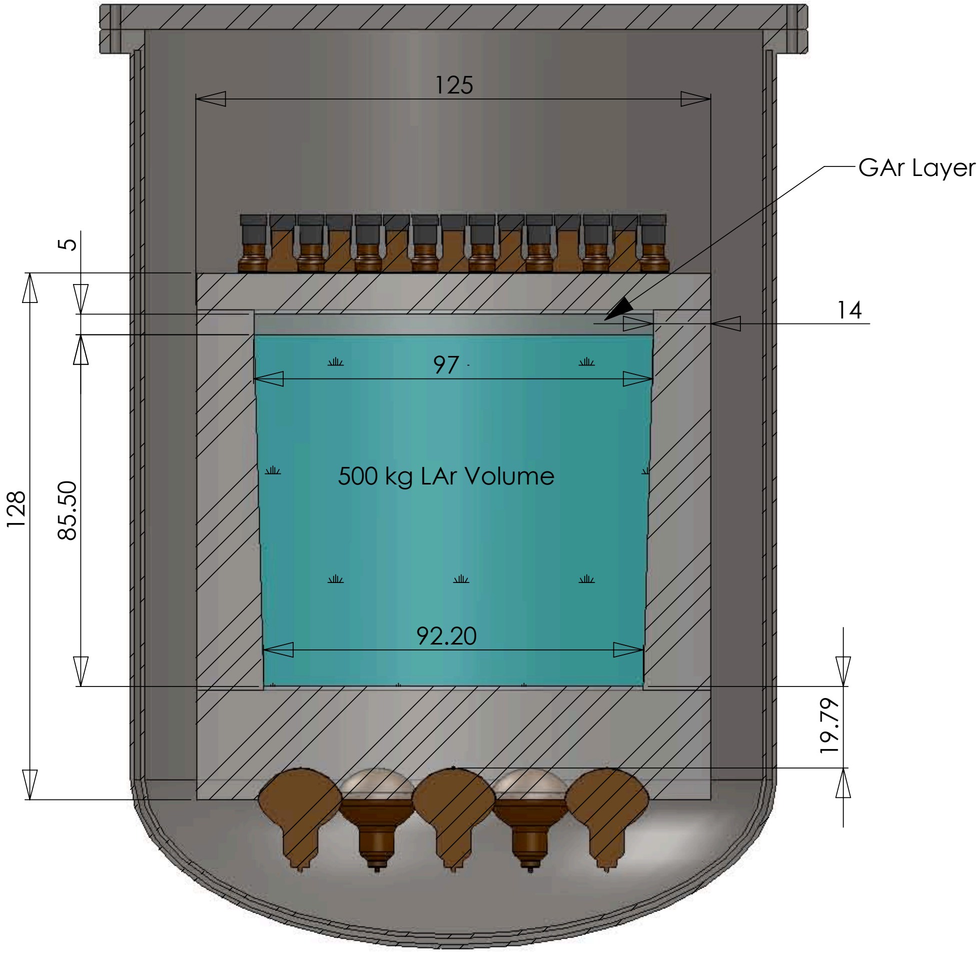

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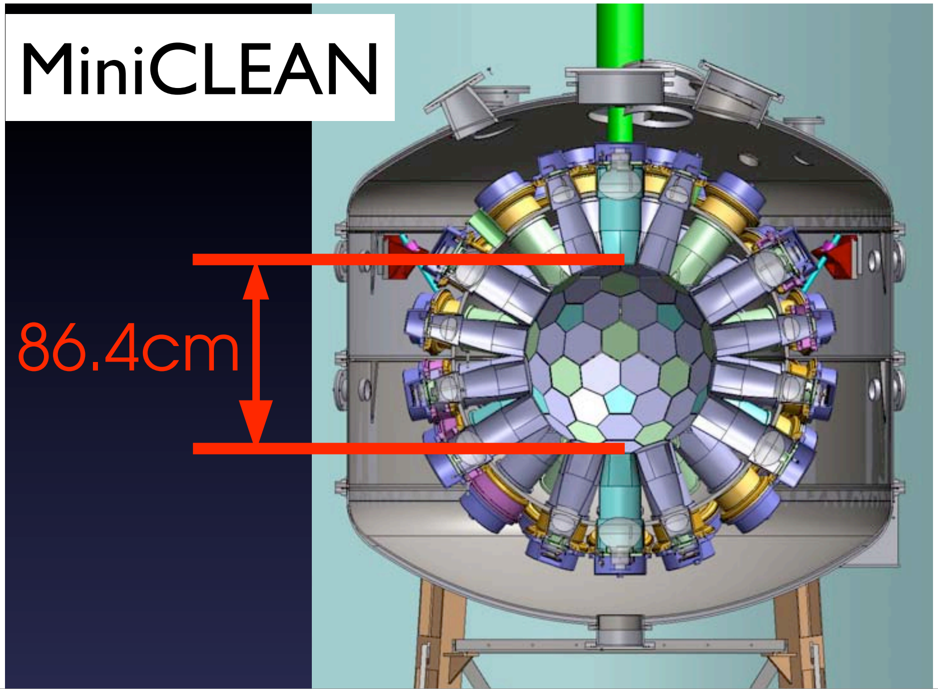

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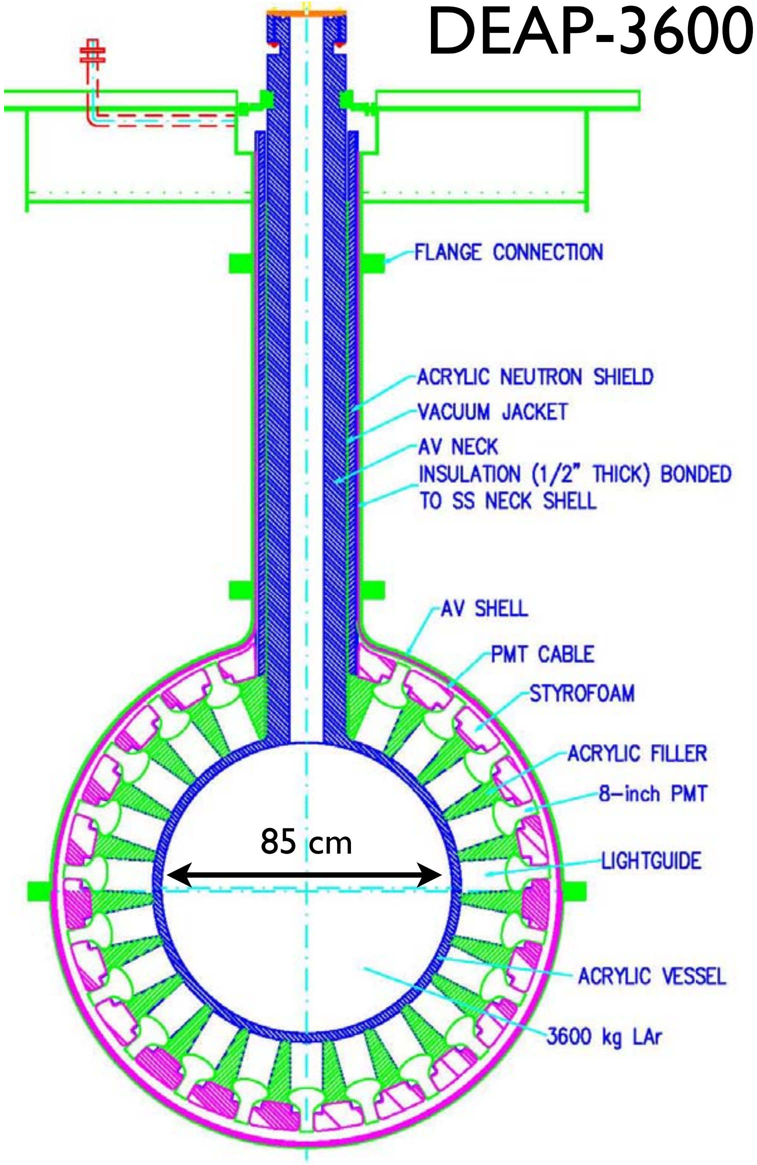
DEAP-3600



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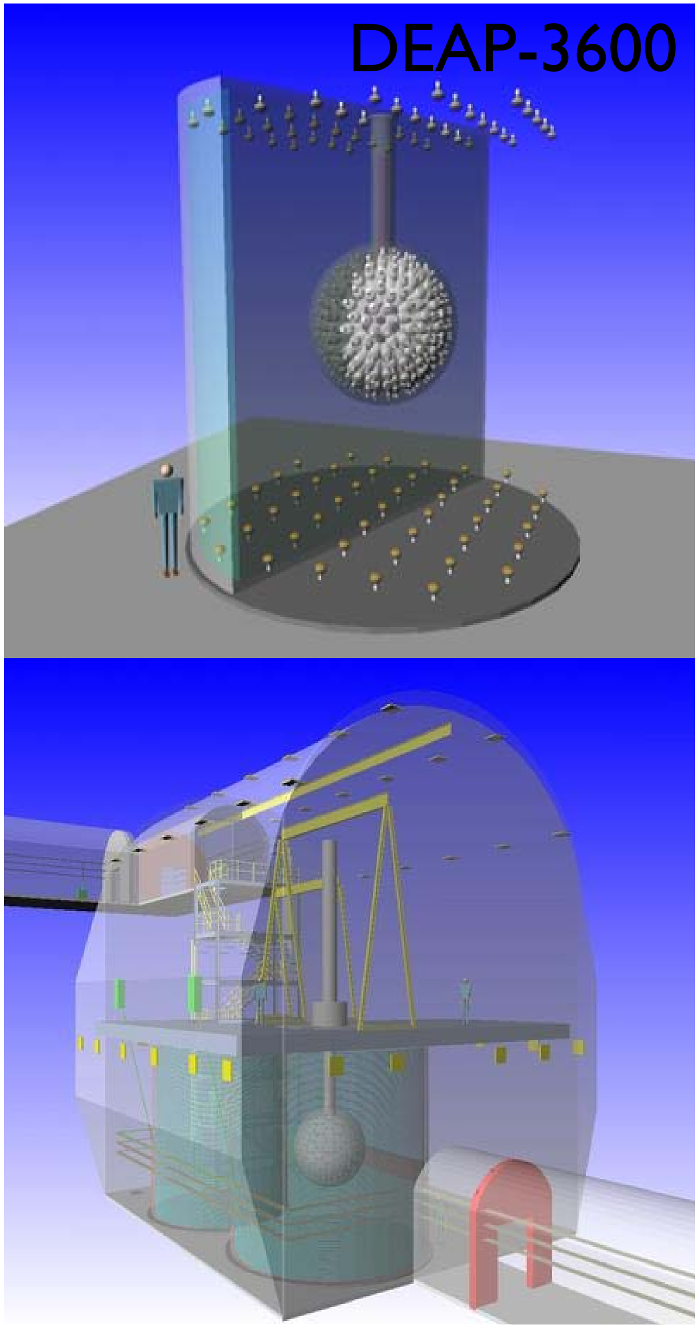
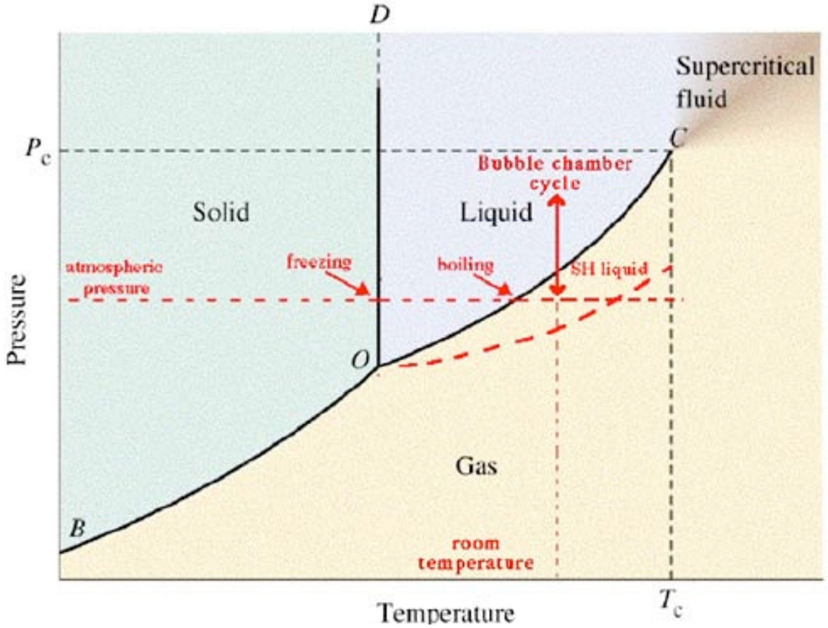
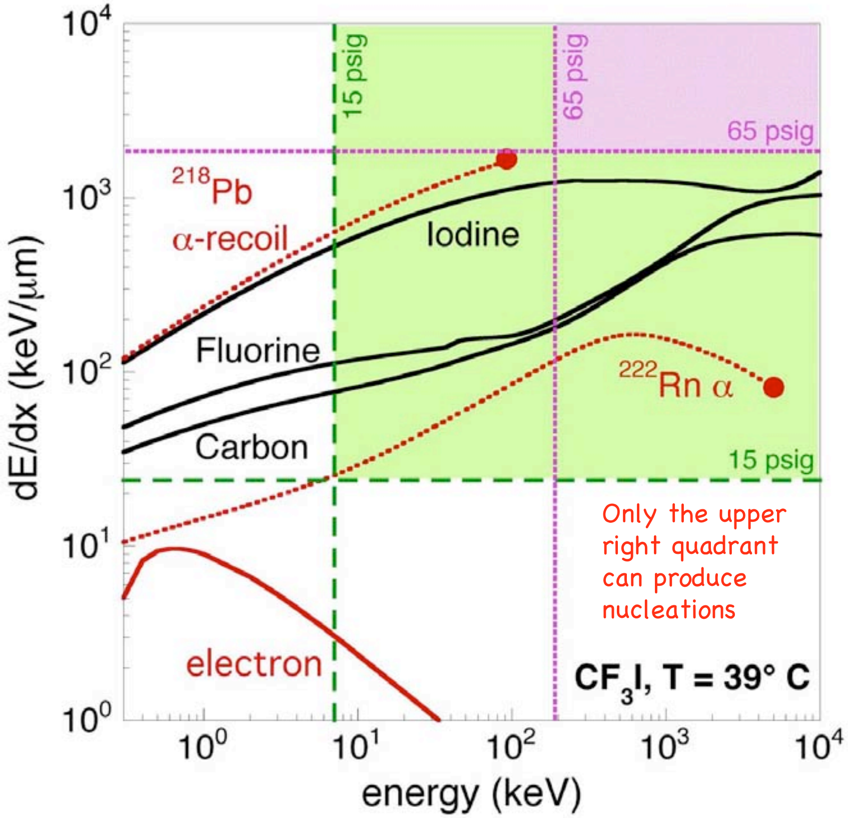


# Metastable Bubble Chamber Detectors

- Bubble chamber
  - Superheated liquid or gel + energy density effect: ER deposition density too small to nucleate bubbles
  - Excellent rejection of ERs: $>10^{13}$ @ 10 keVr threshold (COUPP)

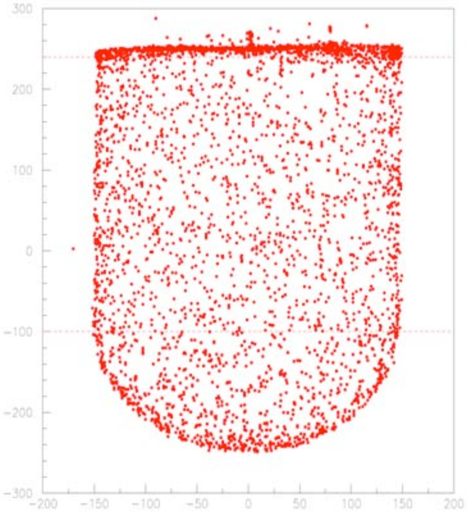




  - Threshold detector, controlled by temperature & pressure.
  - Video and acoustic readout
- Assorted nuclei, spin-indep (I and Br) and spin-dep (F)
- Inexpensive, but must scan threshold and/or have multiple detectors

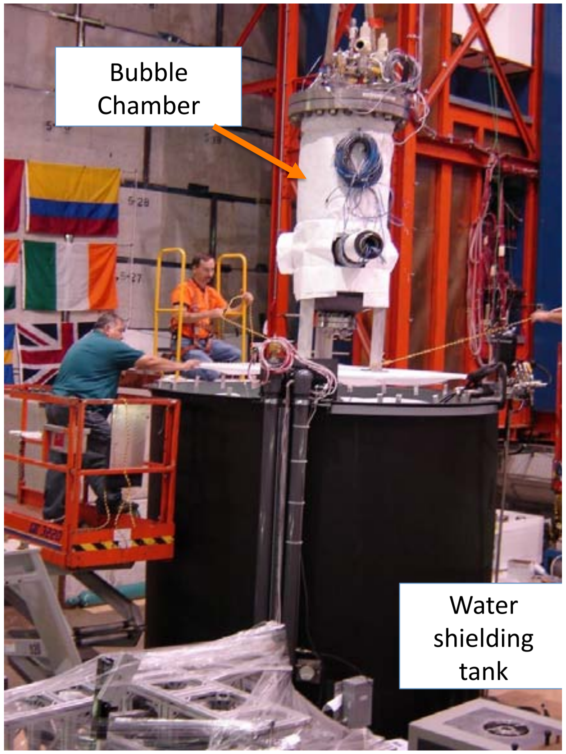
# Metastable Bubble Chamber Detectors

- COUPP
  - video readout
  - run of 2 kg at 300 mwe limited by α bgnd from vessel and α's from radon emanation into bulk
  - 60 kg tested at surface, running underground at 300 mwe with water shield; aim to demonstrate alpha bgnd at Borexino levels
  - alphas will still be a problem
- PICASSO (SNOLAB)
  - acoustic (piezo) readout
  - 14 kg-d from 0.12 kg provides new spin-dep constraints
  - 1.9 kg running since start 2009
  - demonstrated NR/α discrim. via acoustic pulse height



COUPP
2-kg detector

COUPP
60-kg detector
surface test



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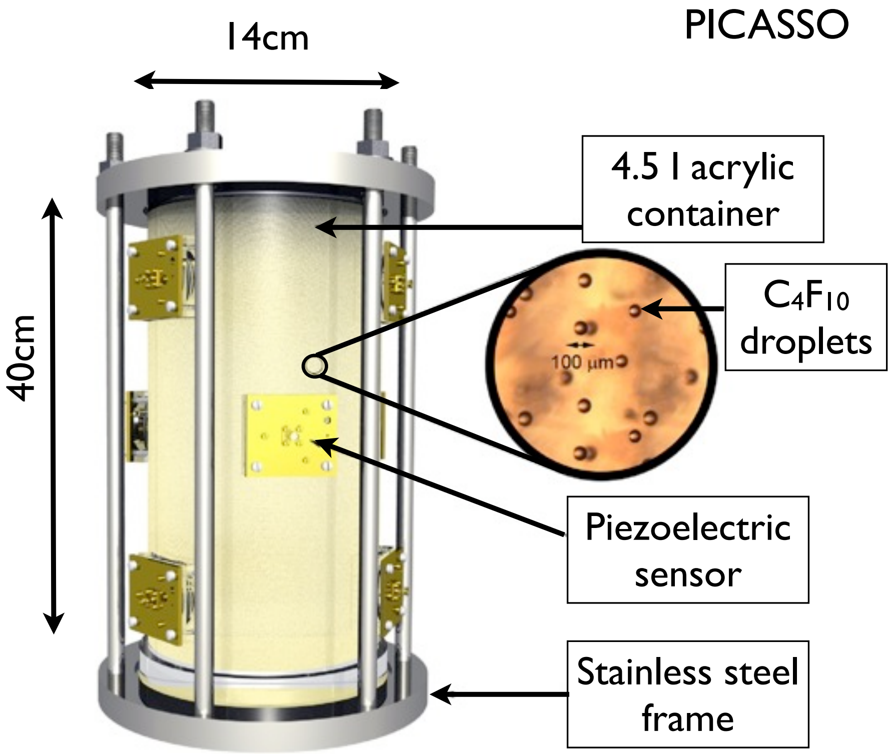
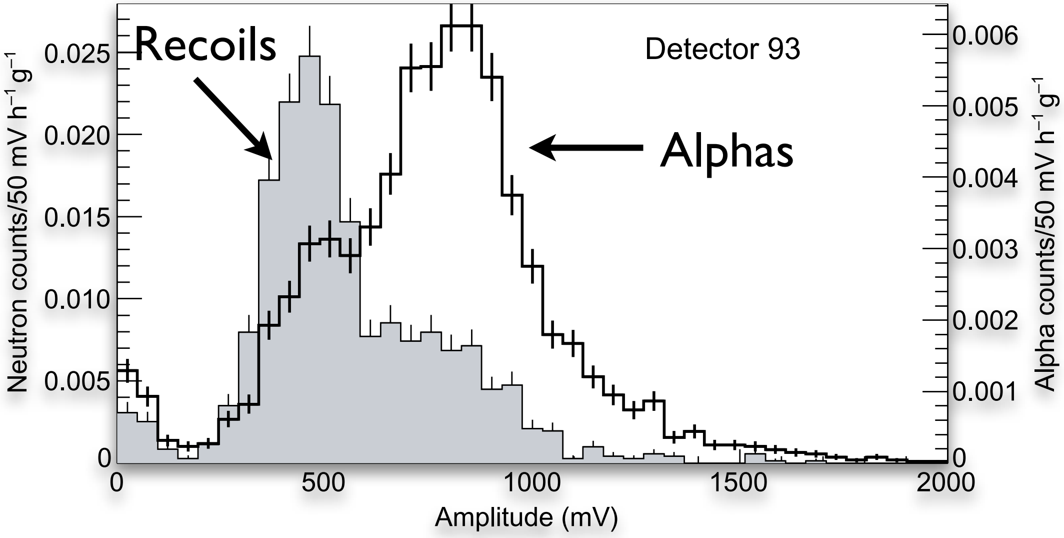
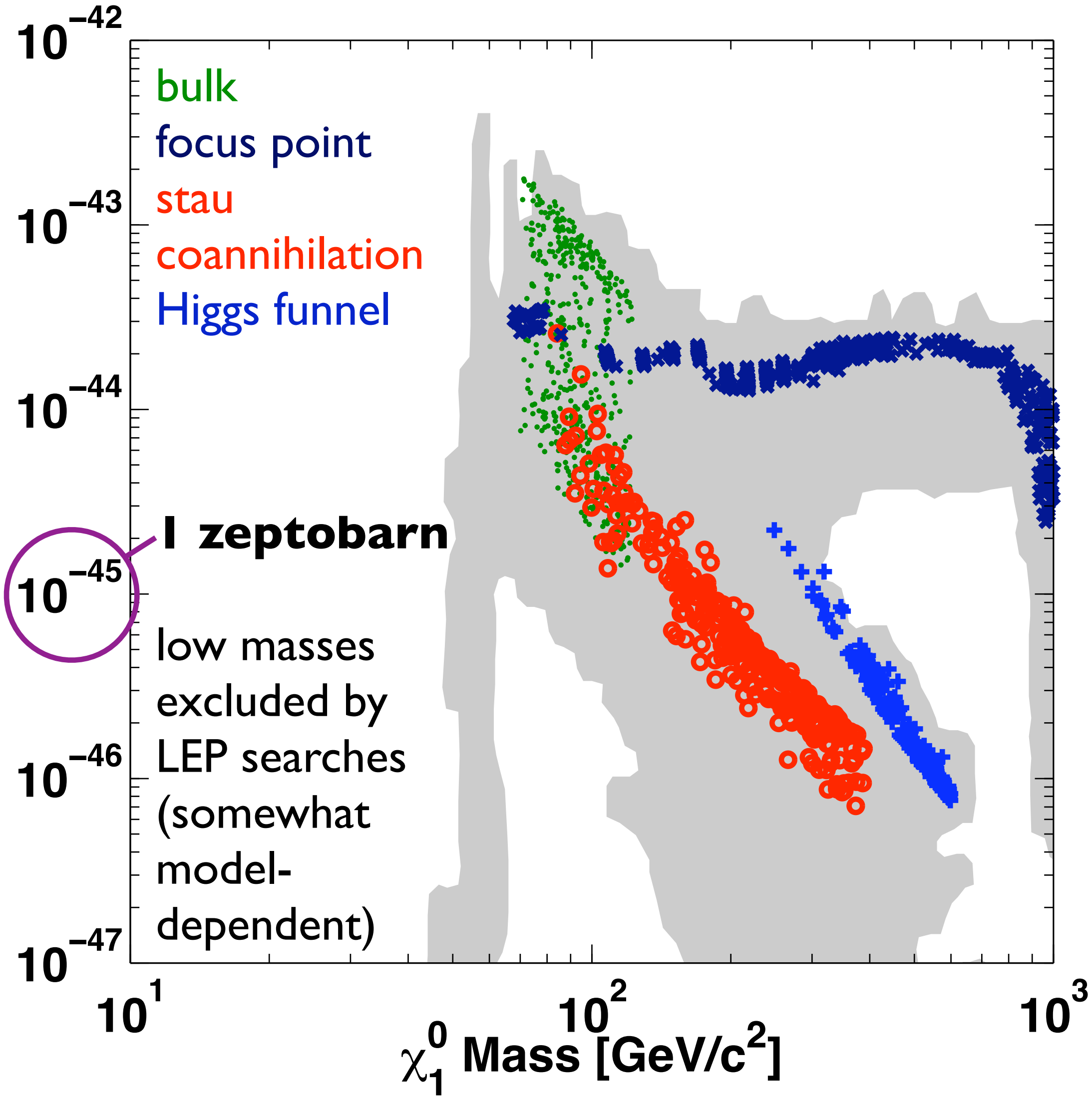
- PICASSO (SNOLAB)
  - acoustic (piezo) readout
  - 14 kg-d from 0.12 kg provides new spin-dep constraints
  - 1.9 kg running since start 2009
  - demonstrated NR/α discrim. via acoustic pulse height



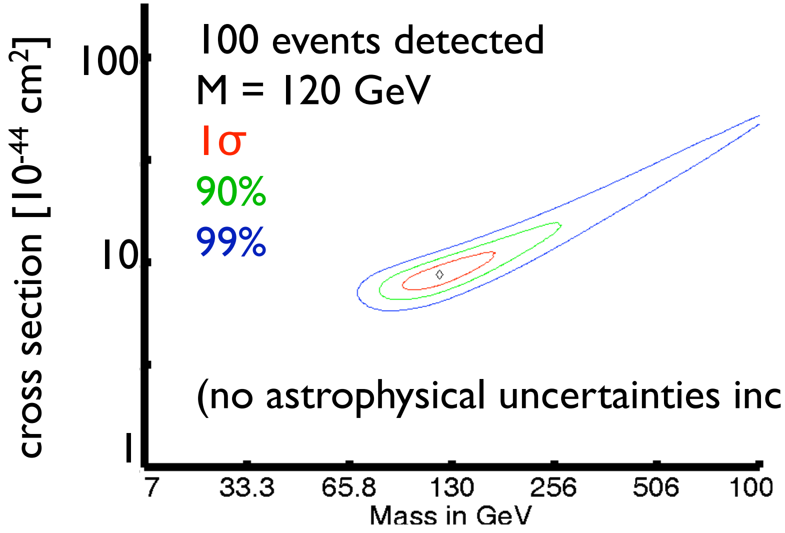


# Where We Are Going: the Zeptobarn Scale

- Why 1 zeptobarn?
  - focus point largely above 1 zb except at v. high mass
  - enter region of extreme fine tuning of SUSY if WIMPs not seen by 1 zb
- 0.01 zb sensitivity would give 100 events at 1 zb: constrain WIMP mass!



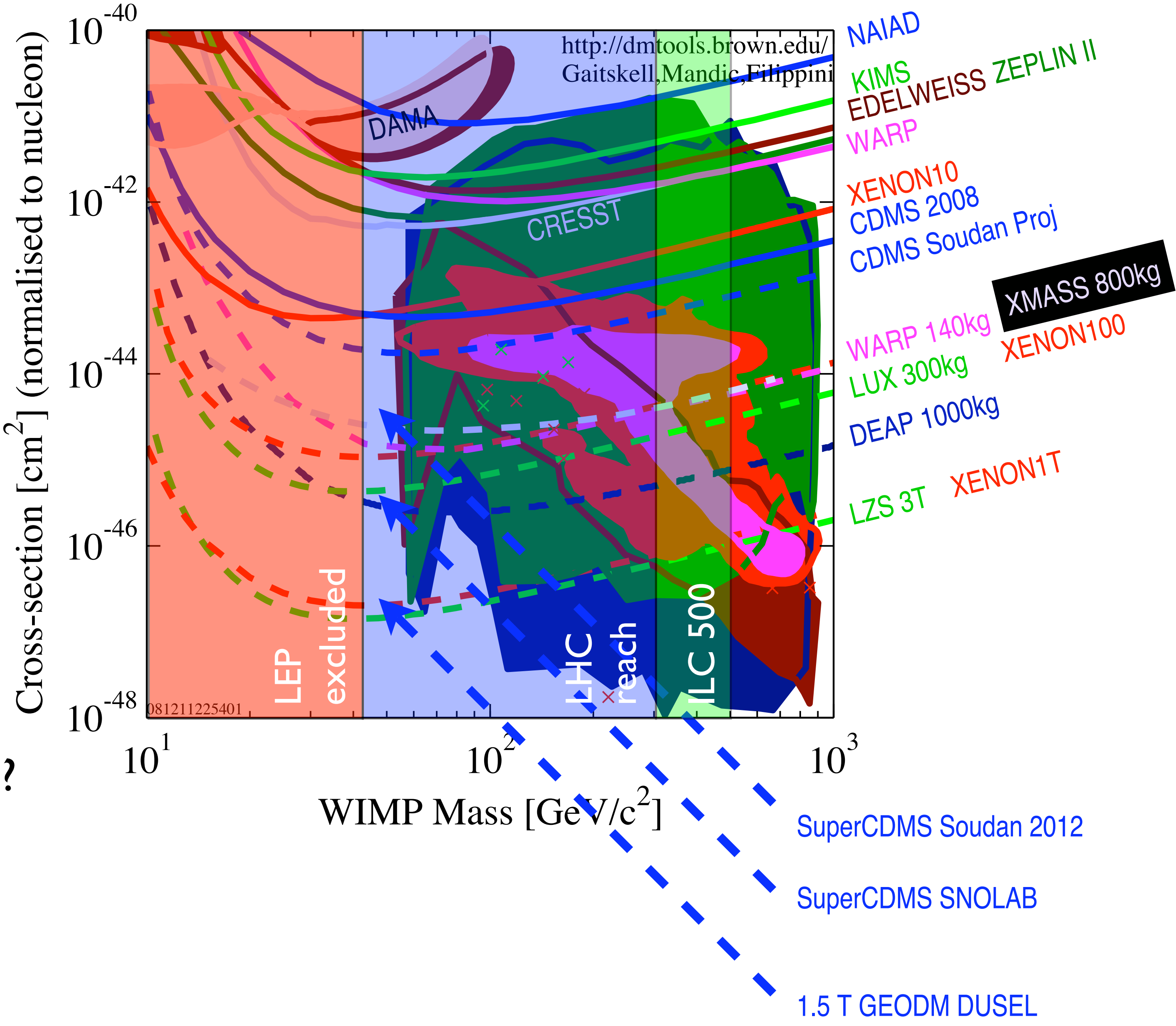
grey: Baltz & Gondolo Markov Chain Monte Carlo scan of mSUGRA space, requiring relic density in 95% CL allowed region



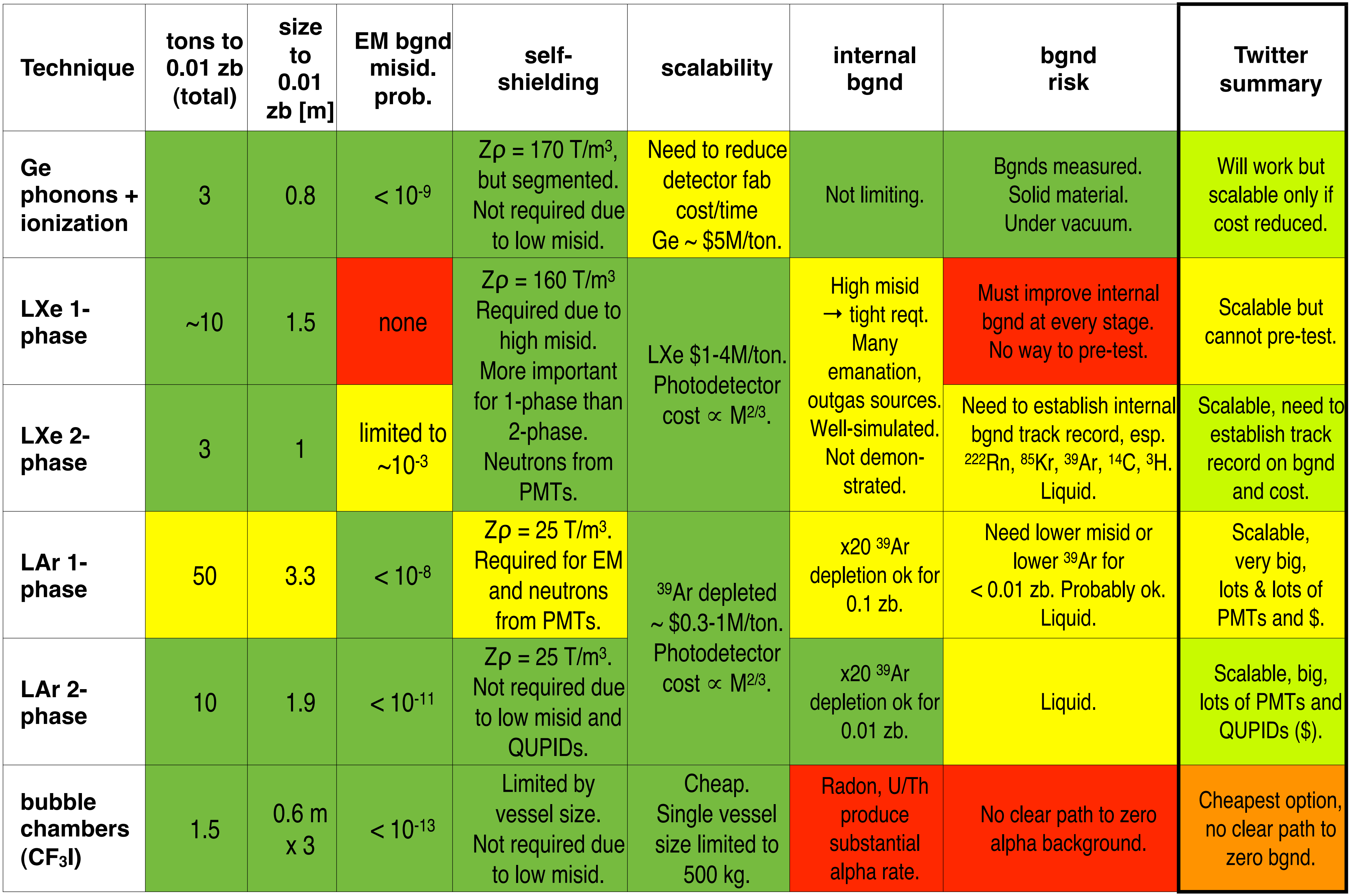
(no astrophysical uncertainties included!)

# To the Zeptobarn Scale and Beyond

- Fortunately, we have a wide range of techniques promising sensitivity to 1 zb and beyond
- Simultaneously, LHC turning on and will march upward in mass.
- How to assess promise of various techniques?



# Direct Detection Technique Scorecard



| Technique | tons to 0.01 zb (total) | size to 0.01 zb [m] | EM bgnd misid. prob. | self-shielding | scalability | internal bgnd | bgnd risk | Twitter summary |
|---|---|---|---|---|---|---|---|---|
| **Ge phonons + ionization** | 3 | 0.8 | $< 10^{-9}$ | $Z\rho = 170$ T/m$^3$, but segmented. Not required due to low misid. | Need to reduce detector fab cost/time Ge ~ \$5M/ton. | Not limiting. | Bgnds measured. Solid material. Under vacuum. | Will work but scalable only if cost reduced. |
| **LXe 1-phase** | ~10 | 1.5 | none | $Z\rho = 160$ T/m$^3$ Required due to high misid. More important for 1-phase than 2-phase. Neutrons from PMTs. | LXe \$1-4M/ton. Photodetector cost $\propto M^{2/3}$. | High misid → tight reqt. Many emanation, outgas sources. Well-simulated. Not demon-strated. | Must improve internal bgnd at every stage. No way to pre-test. | Scalable but cannot pre-test. |
| **LXe 2-phase** | 3 | 1 | limited to ~$10^{-3}$ | | | | Need to establish internal bgnd track record, esp. $^{222}$Rn, $^{85}$Kr, $^{39}$Ar, $^{14}$C, $^{3}$H. Liquid. | Scalable, need to establish track record on bgnd and cost. |
| **LAr 1-phase** | 50 | 3.3 | $< 10^{-8}$ | $Z\rho = 25$ T/m$^3$. Required for EM and neutrons from PMTs. | $^{39}$Ar depleted ~ \$0.3-1M/ton. Photodetector cost $\propto M^{2/3}$. | x20 $^{39}$Ar depletion ok for 0.1 zb. | Need lower misid or lower $^{39}$Ar for < 0.01 zb. Probably ok. Liquid. | Scalable, very big, lots & lots of PMTs and \$. |
| **LAr 2-phase** | 10 | 1.9 | $< 10^{-11}$ | $Z\rho = 25$ T/m$^3$. Not required due to low misid and QUPIDs. | | x20 $^{39}$Ar depletion ok for 0.01 zb. | Liquid. | Scalable, big, lots of PMTs and QUPIDs (\$). |
| **bubble chambers ($CF_3I$)** | 1.5 | 0.6 m x 3 | $< 10^{-13}$ | Limited by vessel size. Not required due to low misid. | Cheap. Single vessel size limited to 500 kg. | Radon, U/Th produce substantial alpha rate. | No clear path to zero alpha background. | Cheapest option, no clear path to zero bgnd. |

# Zeptobarn Redux

- How will we get to zeptobarn dark matter and beyond?
  - By pursuing a number of techniques until we have a much clearer *empirical* understanding of their pros and cons
  - By building *more than one* experiment capable of having near-zero background to WIMP interactions and with sensitivity to the most interesting portions of SUSY parameter space.
    - Must establish a signal is present with extreme confidence that it cannot be caused by misidentified backgrounds.
    - Must establish that the signal characteristics are consistent between different nuclei and detection techniques.
- Eventually, we will need directional detectors to observe diurnal modulation to tie the signal to our motion through the galaxy.
  - But not an efficient way to search.

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- The last decade was an exciting time for the development of multiple new search techniques.

- In the next decade, we'll see the rubber hit the road to zeptobarn dark matter and beyond.