Elusive WIMPs

Latest Results from the Cryogenic Dark Matter Search

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* New Collaborators or New Institutions in SuperCDMS

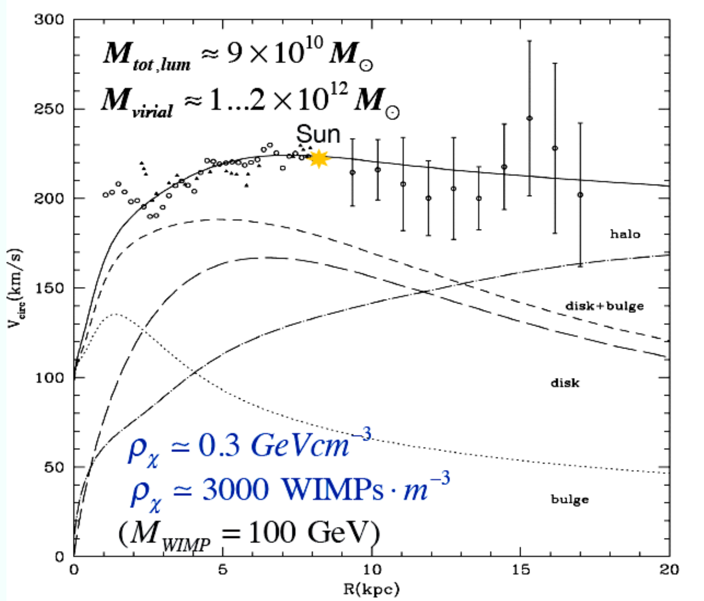
The Nature of Dark Matter

The Missing Mass Problem:

Dynamics of stars, galaxies, and clusters

rotation curves, gas density, gravitational lensing

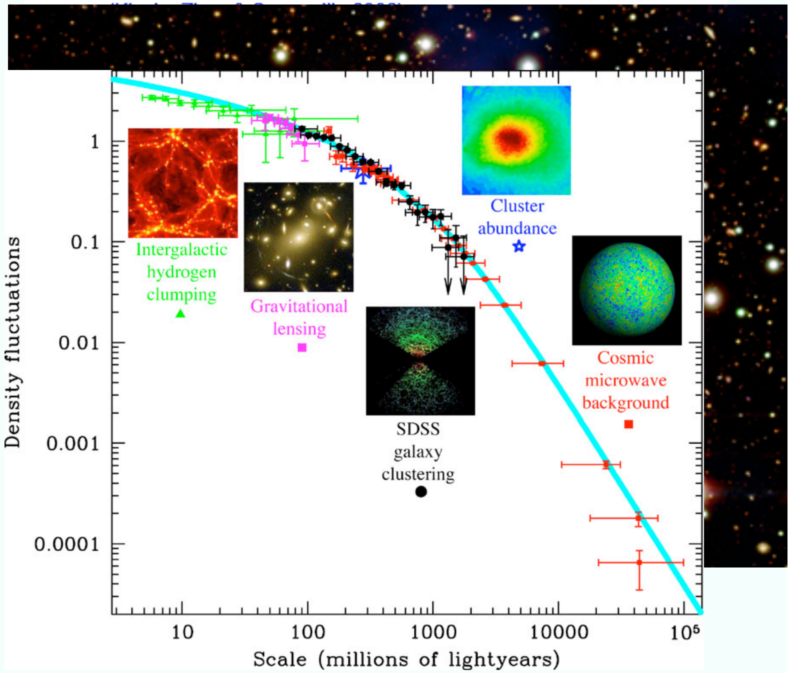
Large Scale Structure formation



Wealth of evidence for a particle solution

No good MOND, Bullet Cluster,

Microlensing (MACHOs) limit < 1 AU



Non-baryonic

Height of acoustic peaks in the CMB (Ω_b)

Power spectrum of density fluctuations (Ω_m)

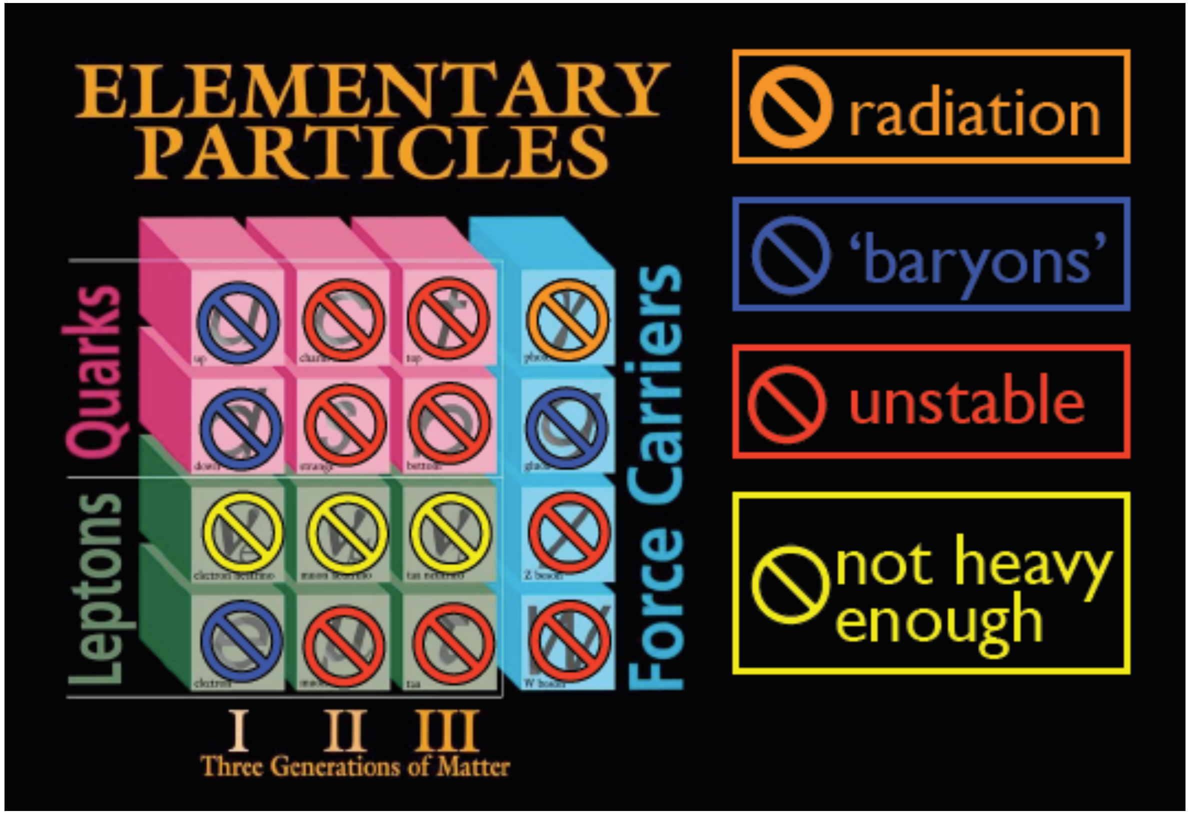
Primordial Nucleosynthesis

And STILL HERE!

Stable, neutral, non-relativistic

Interacts via gravity and/or weak force

The Nature of Dark Matter



(Gondolo, DM Crossroads, Desy 2008)

Thus, we have eliminated all known particles!

We have to turn to Theoretical Models to give us a hint of its properties and to suggest strategies for finding it

Dark Matter Candidates

What particles can we imagine?

WIMPs, axions, Wimpzillas, sterile ν's, gravitinos, KK, and much more!

What particles do we like?

SUSY relics: Solves gauge hierarchy problem: Why is $M_{Pl} >> M_{EW}$?
KK modes: Solve via extra, compact dimensions (unifies gravity with S,EW)
Axions: Restores CP-symmetry in QCD via new (broken) chiral symmetry,

What particles can explain astrophysical mysteries?

511 keV line
positron excess
WMAP haze

What particles can do all that and ALSO

Match relic densities (thermal equil. w/ early Universe ➔ calculable)

Don't violate astrophysical observables

e.g. diffuse γ–ray bkgd , etc.

Dark Matter Candidates in Thermal Equilibrium with the Early Universe

Annihilation stops when number density drops to the point that

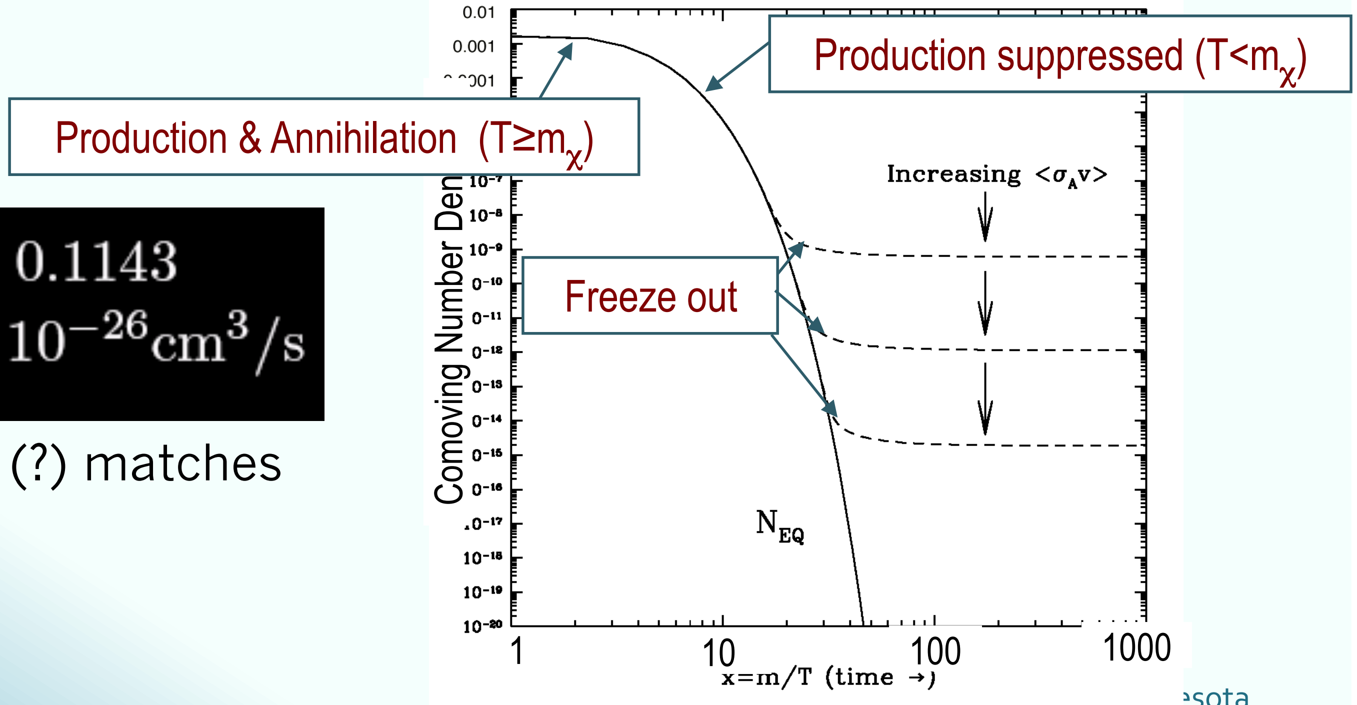
$$H \;>\; \Gamma_A \sim n_\chi \langle \sigma_A v \rangle$$

Freeze-out: annihilation too slow to keep up with Hubble expansion

Leaves a relic abundance: $\Omega_\chi h^2 \approx \dfrac{3 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_A v \rangle_{fr}}$

$$\Omega_\chi h^2 = \Omega_{\rm cdm} h^2 \simeq 0.1143$$
$$\text{for } \langle \sigma v \rangle_{\rm ann} \simeq 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

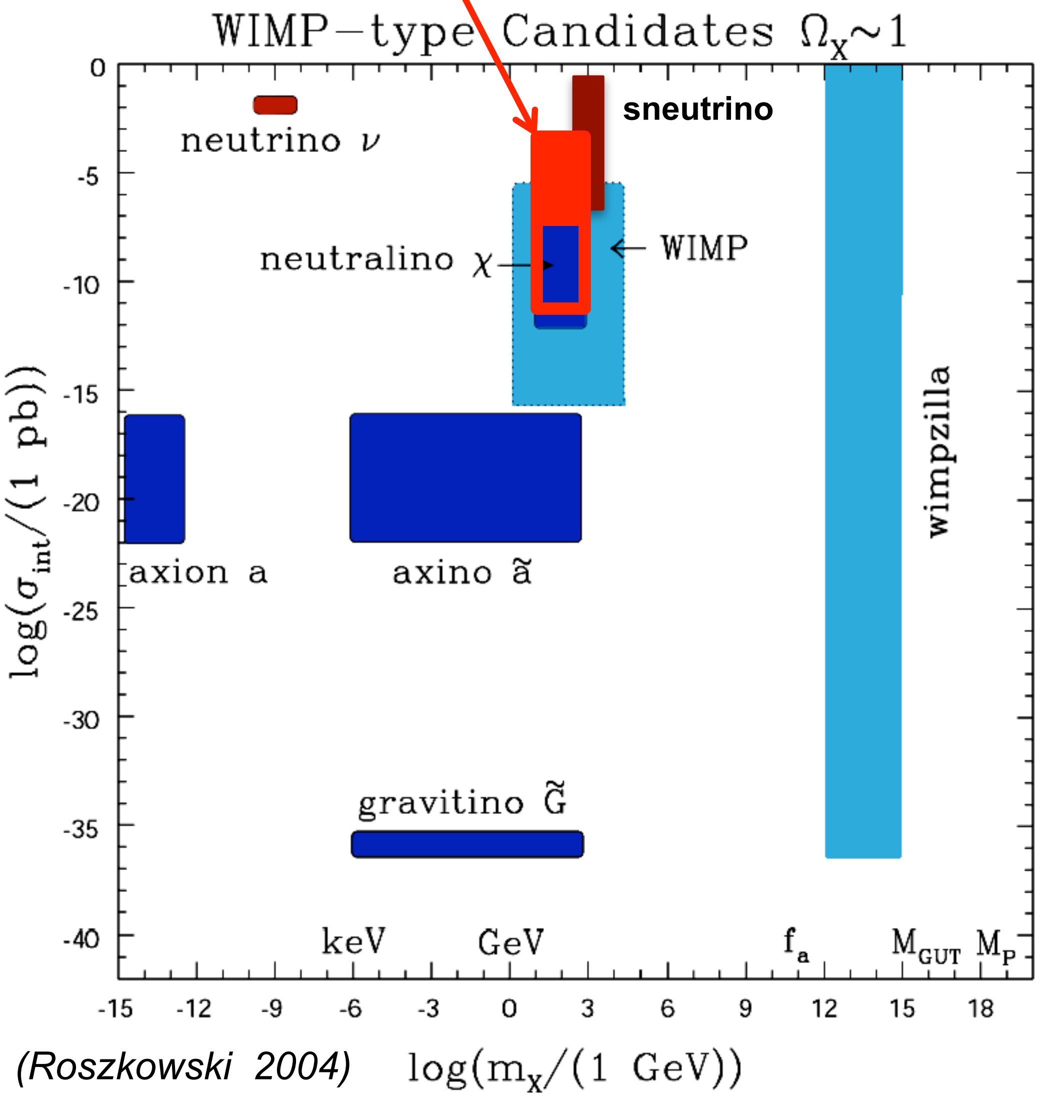
which coincidentally (?) matches the weak scale



Dark Matter Candidates:

HUGE σ - m space

Region we have already excluded



(Roszkowski 2004)

LSP = Lightest Supersymmetric Particle

neutralino:

m_χ > 70 GeV *from LEP*

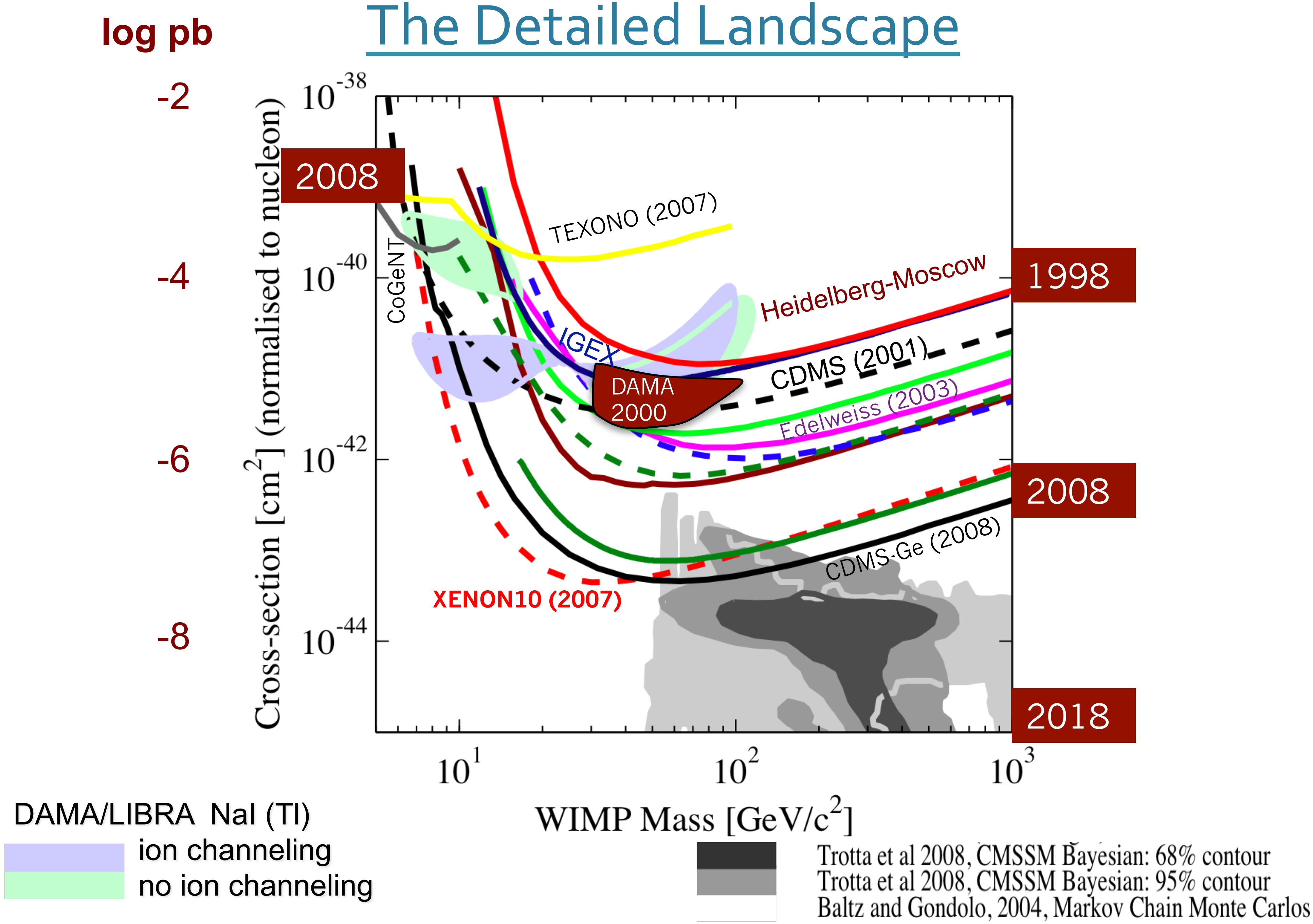
> few GeV *from* $\Omega_\chi h^2 < 1$

< 300 TeV *from unitarity*

tens – 100's GeV fine tuning arguments

weak interaction scale, suppressed by mixing angles in the neutralino couplings

The Detailed Landscape

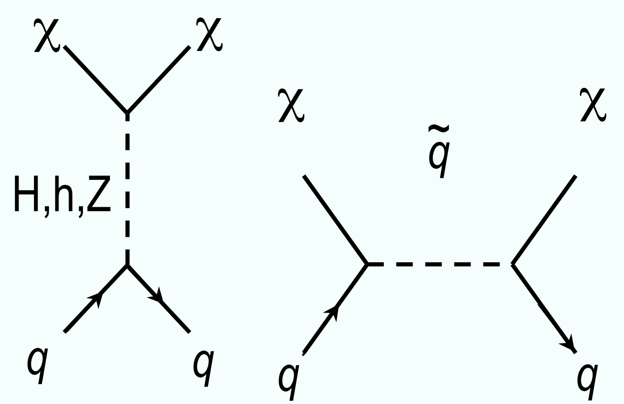


Direct Detection of WIMPs

1. Particle Physics: Interaction cross section with target material

WIMPs elastically scatter off nuclei in targets, producing nuclear recoils.

$$R \propto N \frac{\sigma_{\chi N}}{m_\chi} \rho_\chi \int_{v_{\min}}^{v_{esc}} \frac{f(v)dv}{v}$$



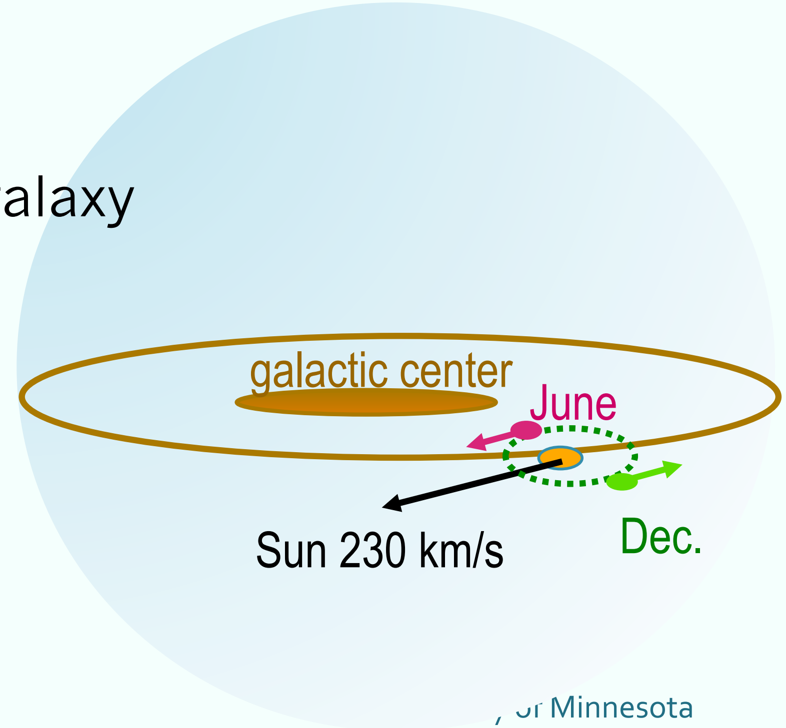
2. Astrophysics: WIMP distribution in our galaxy

Isothermal, spherical halo and M-B velocity dist:

$$f(v)dv = \frac{4v^2}{v_0^3\sqrt{\pi}} e^{-v^2/v_0^2} d^3v$$

$v_0 \sim 230$ km/s $v_{esc} = 650$ km/s

$\rho_\chi = 0.3$ GeV / cm^3



Direct Detection of WIMPs

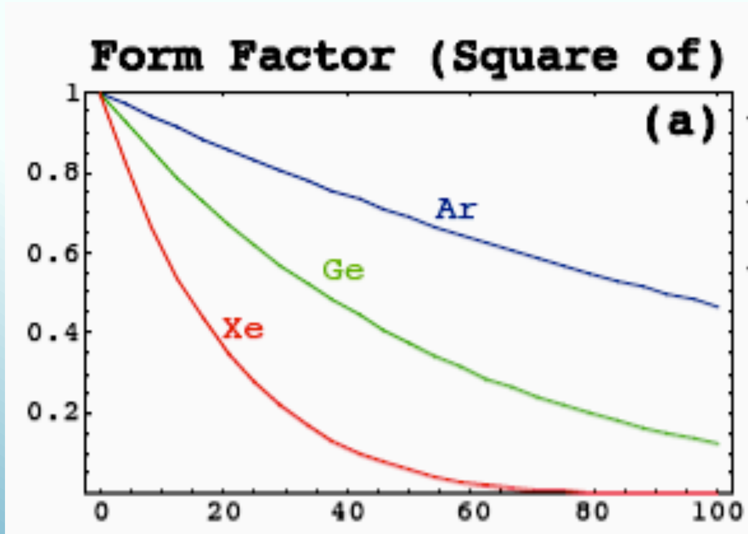
3. Target Material (N):

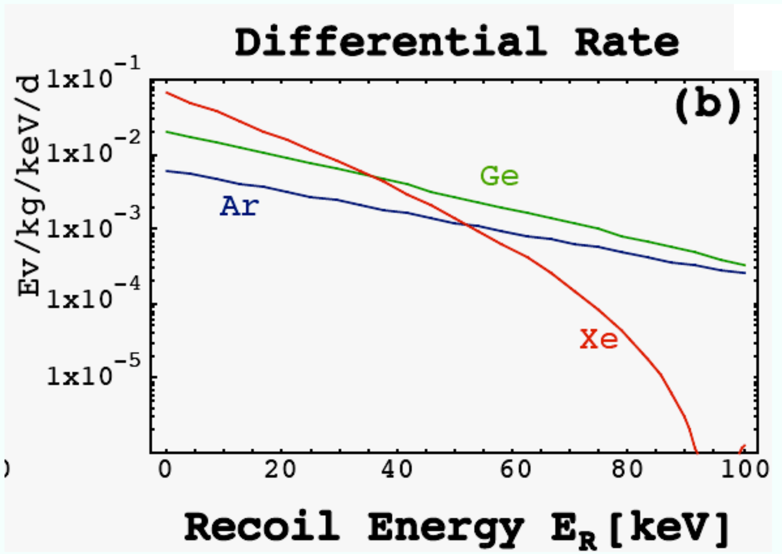
$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{2 m_\chi \mu^2} F^2(E_R) \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv$$

- WIMP-nuclear Reduced Mass (max for $m_\chi \sim m_N$, A^2 enhancement)

- Nuclear Form Factor $F^2(E_R) = \left[\frac{3 j_1(qR_1)}{qR_1}\right]^2 e^{-(qs)^2}$

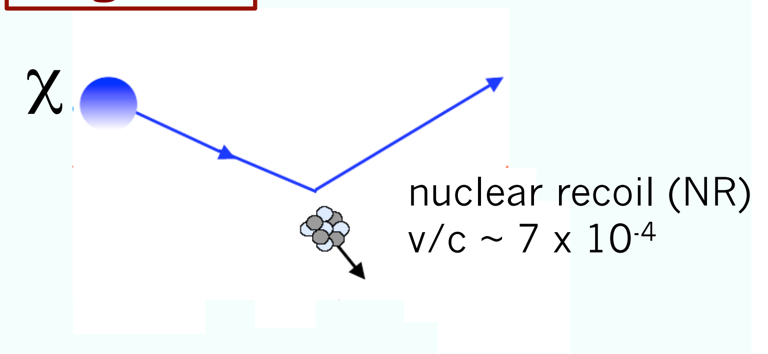
Ar: A = 40
Ge: A = 73
Xe: A = 131

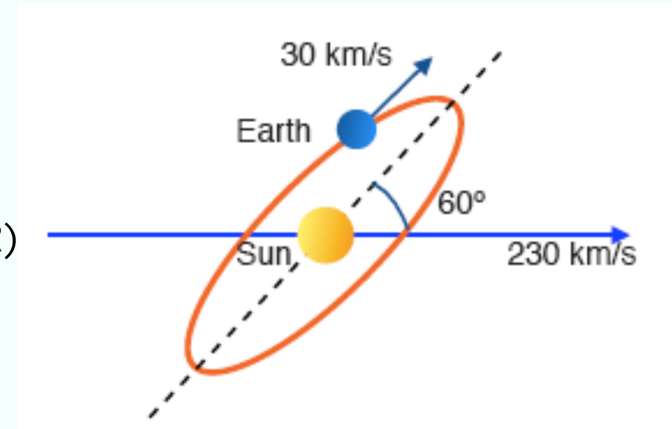


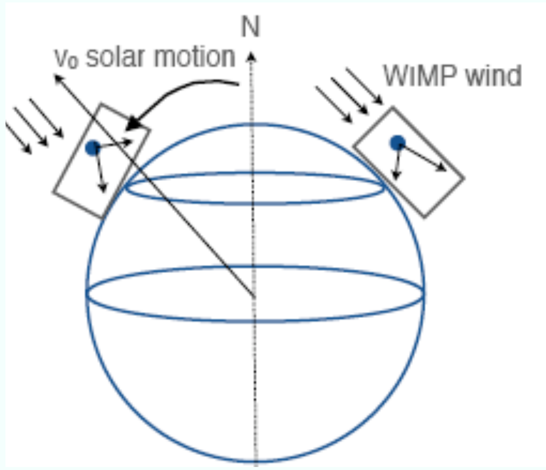


Choose your Technique

Signal





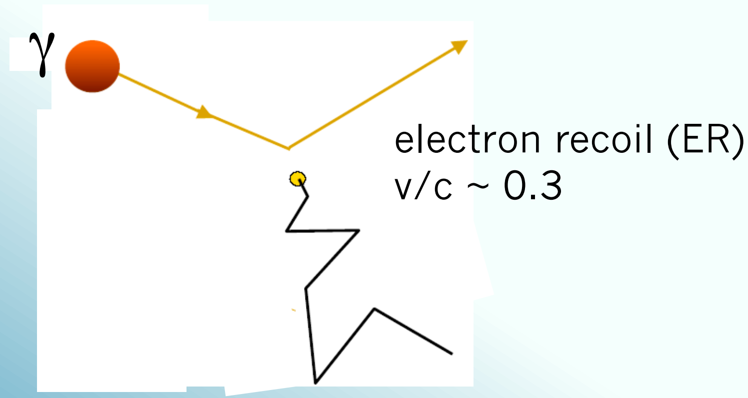


Count nuclear recoils

annual flux variation

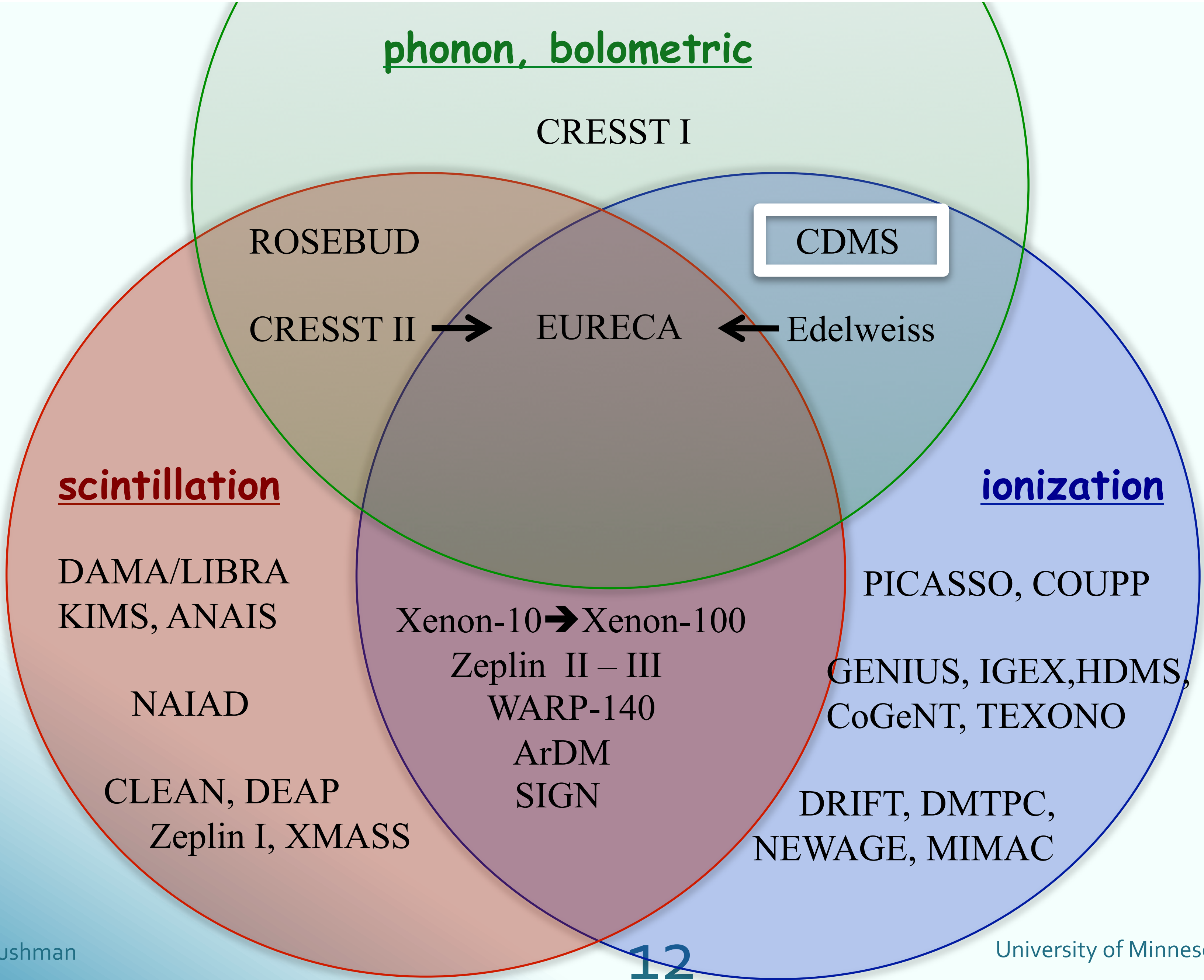
diurnal directional modulation

Background



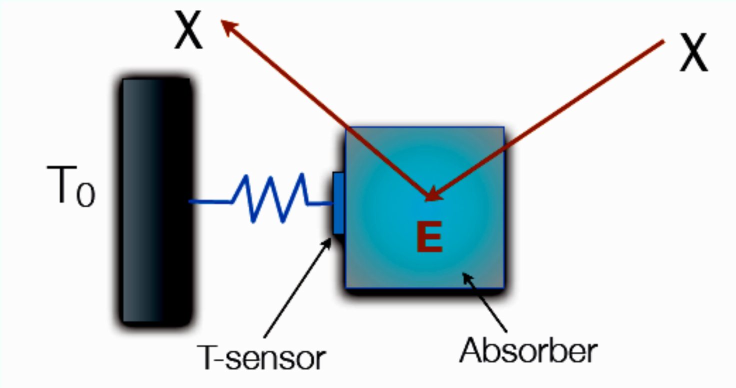
β,γ	discriminate ER vs NR
-or-	eliminate sensitivity to ER
-or-	self-shielding
n	multiple scatters σ varies with target } go deep shielding
α	much higher energy deposit. problem for threshold devices, trackers

Counting Nuclear Recoils: Discrimination Techniques



Cryogenic Techniques at mK Temperatures

Need sensitivity (big ΔT) for small ΔE, so run at T << T_c



$$C(T) = \frac{\Delta E}{\Delta T} \propto T^3$$

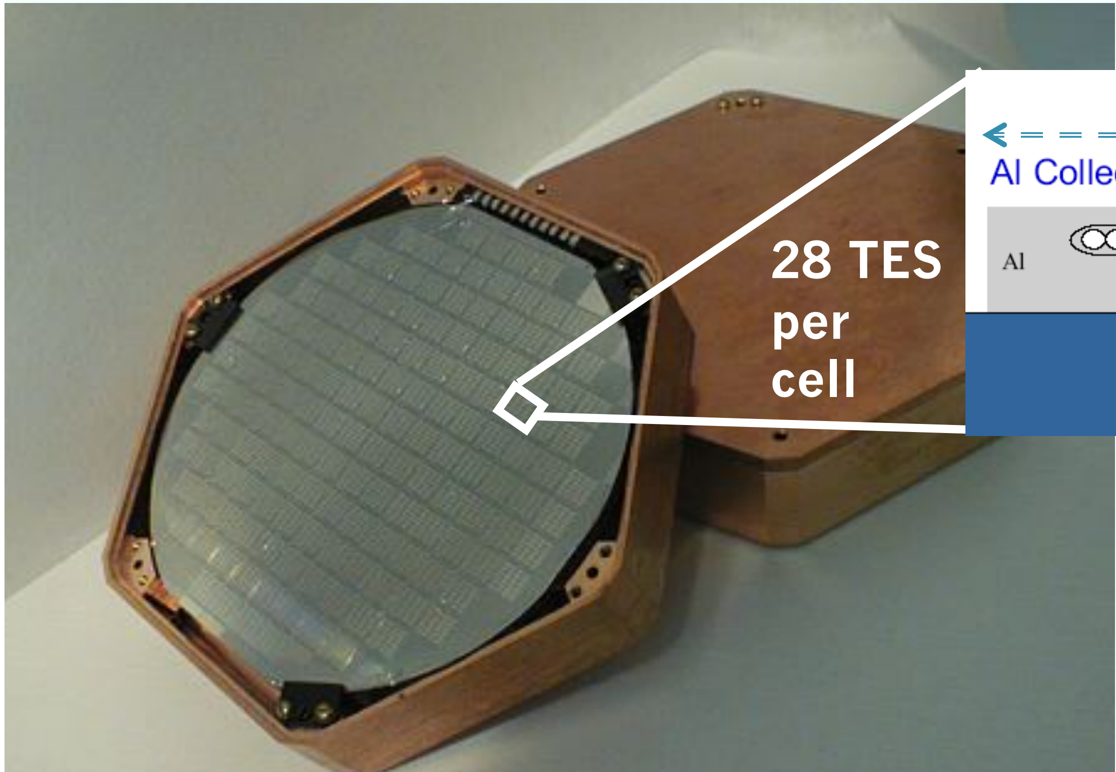
Phonon Signal: Superconducting Transition Edge Sensors
Tungsten TES, Al collection fins or film, SQUID readout
CRESST, CDMS

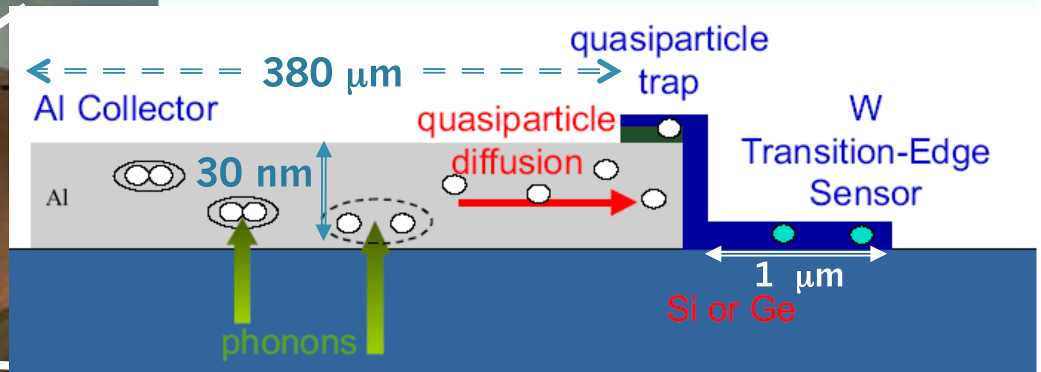
Bolometric: Superconductor Thermistors
Neutron Transmutation Doped-Ge
ROSEBUD, EDELWEISS

CDMS Detectors (phonon readout)

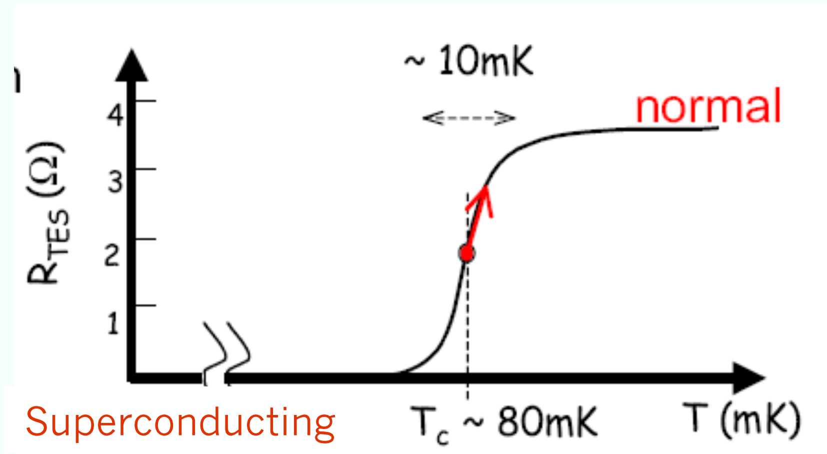
photolithographic patterning produces 4144 “thermometers”

(quasi-particle-assisted electrothermal-feedback transition-edge sensors)





1 cm thick x 7.5 cm diam crystals of
250 g Germanium or 100 g Silicon



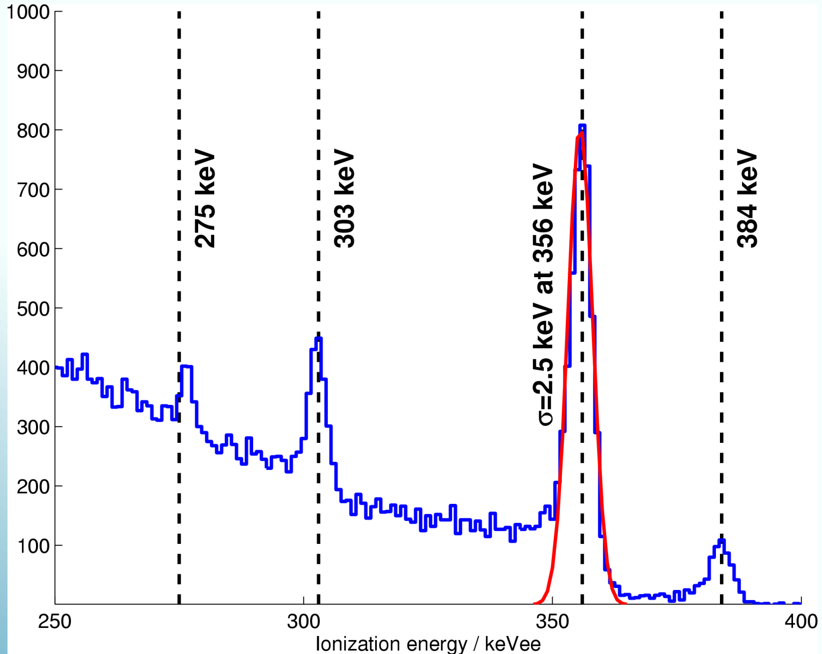
CDMS Detectors (ionization readout)

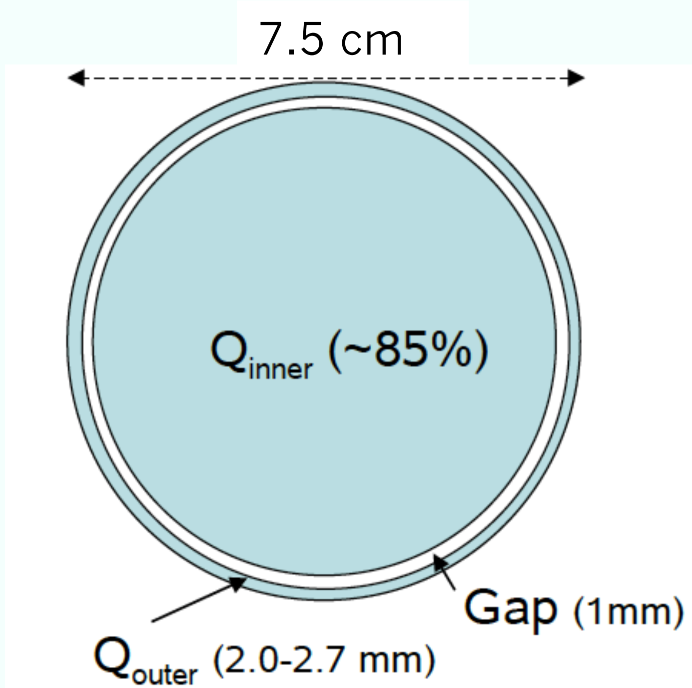
Concentric electrodes define a fiducial volume

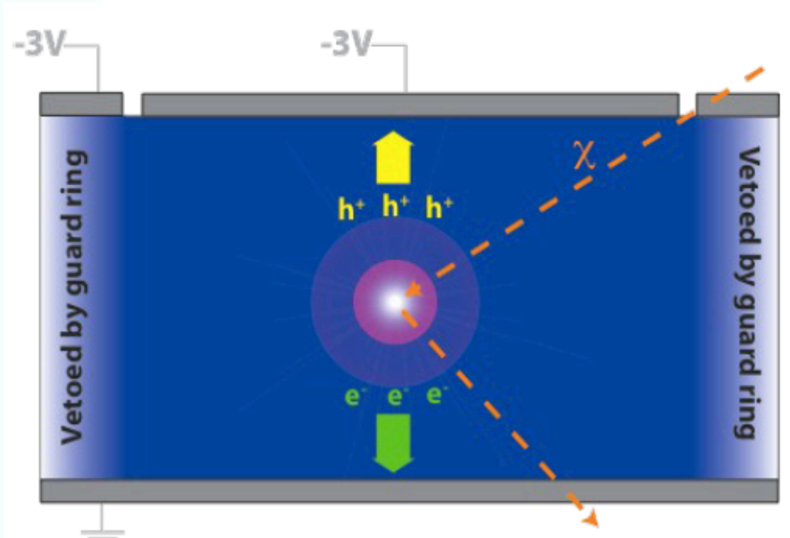
Charge traps neutralized by
LED flashing on a regular basis

Good Energy Resolution

^{133}Ba peaks in a Ge ZIP





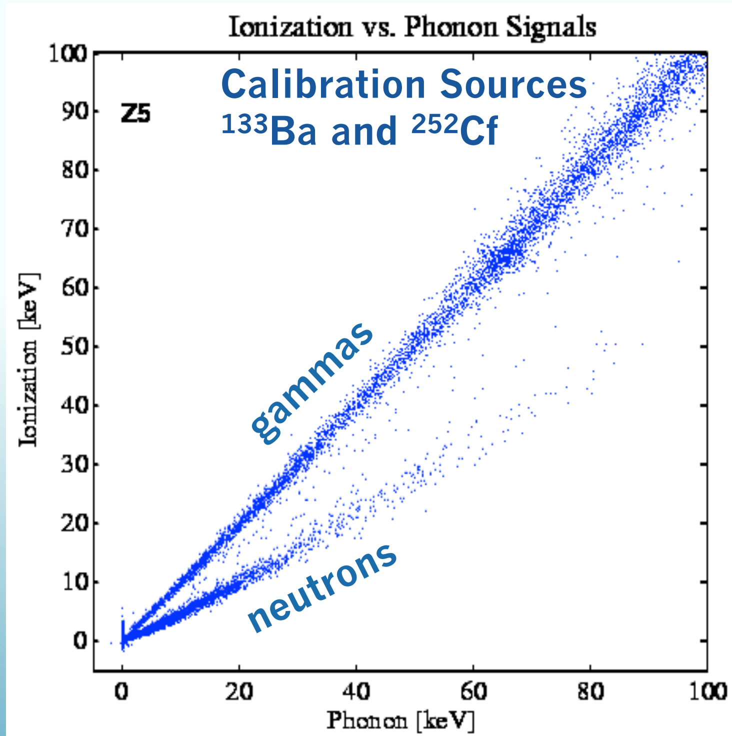


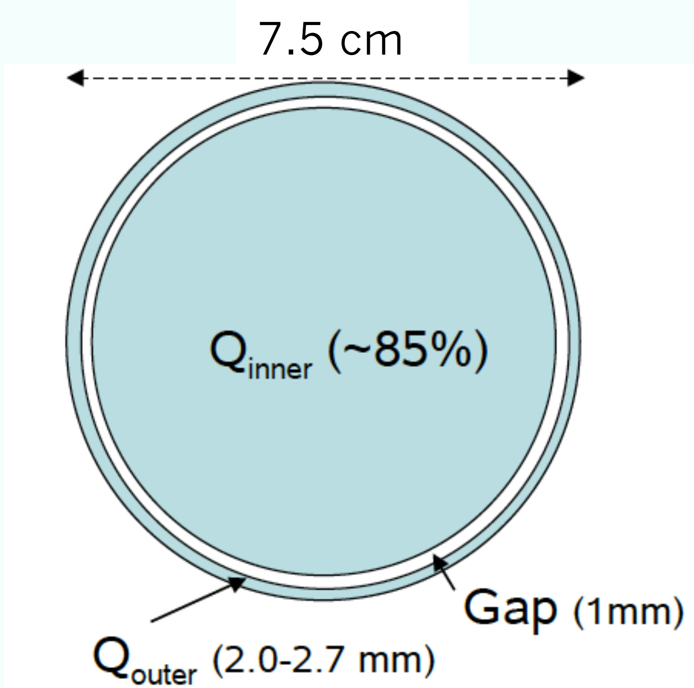
CDMS Detectors (ionization readout)

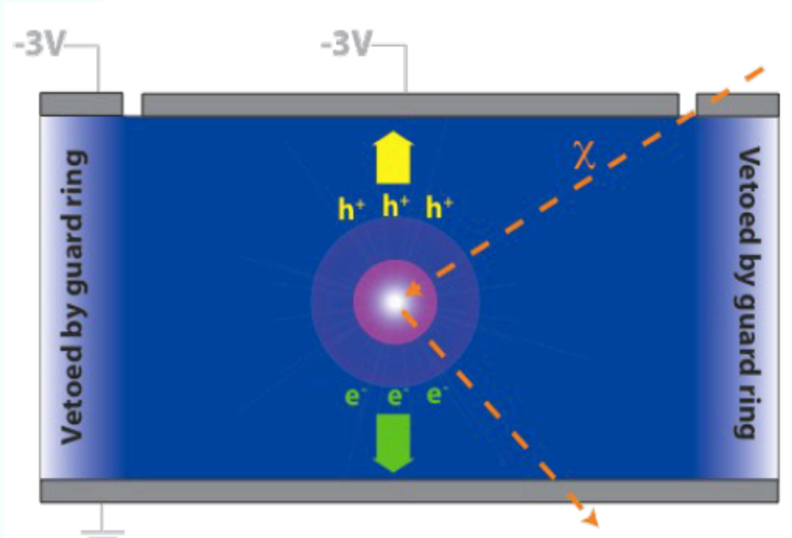
Concentric electrodes define a fiducial volume

Charge traps neutralized by LED flashing on a regular basis

Combine with Phonon Signal to get Discrimination between ER and NR



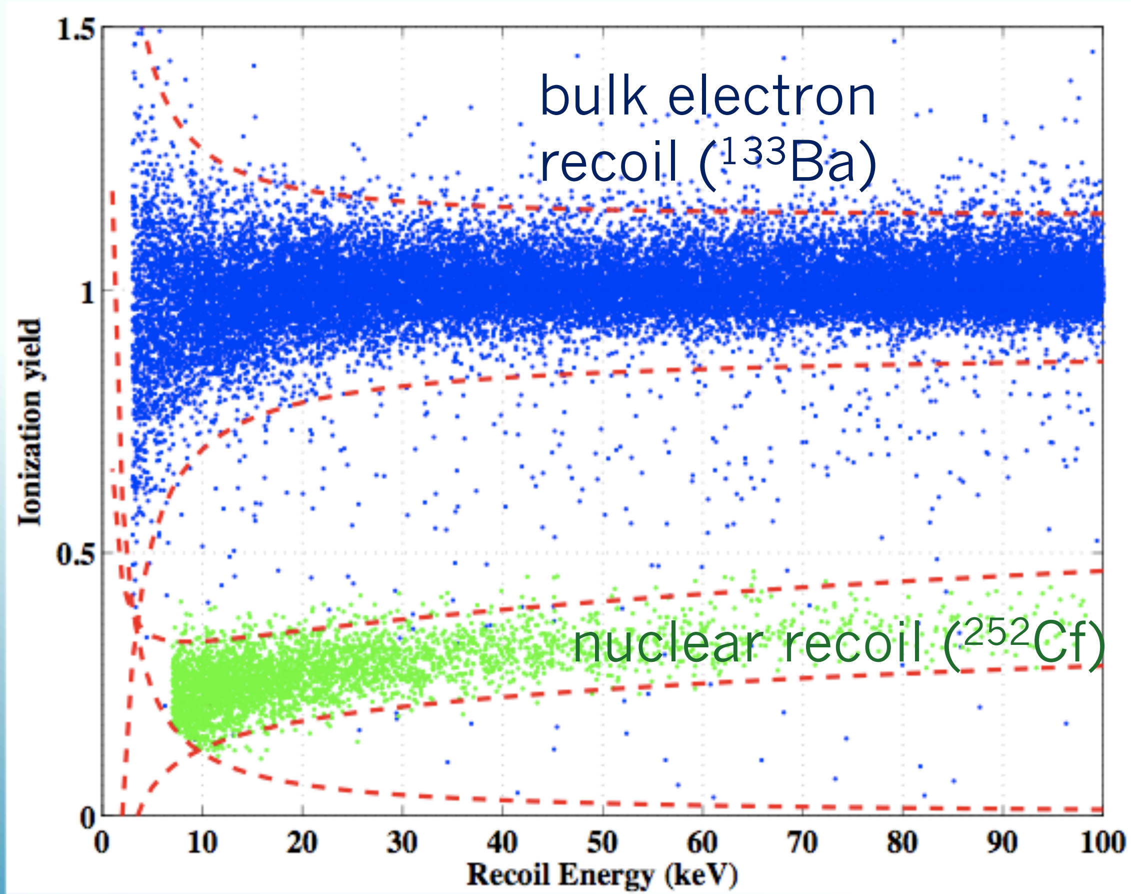


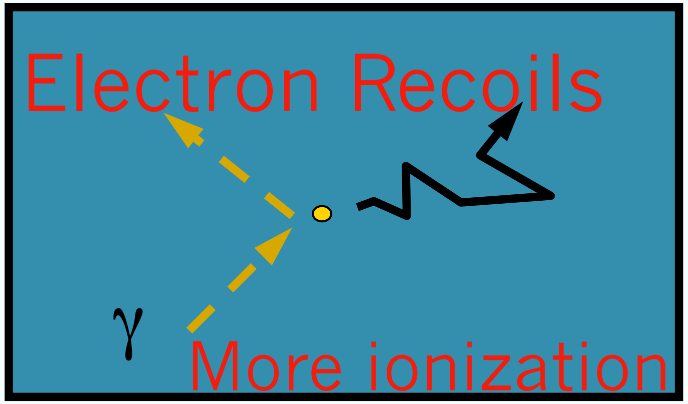


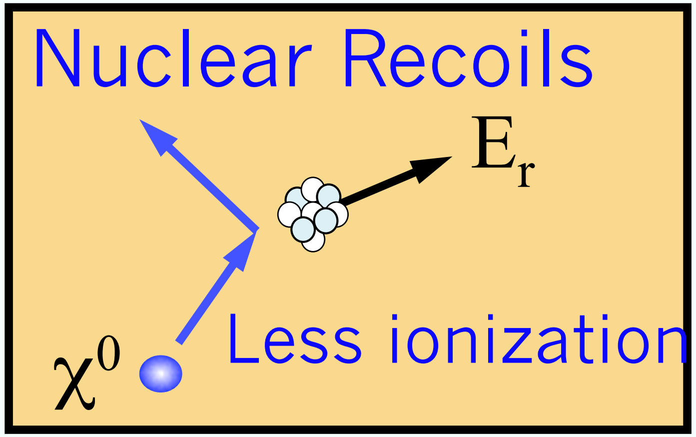
Bulk Gamma Rejection

$$= \frac{\text{ionization energy}}{\text{phonon energy}}$$

Primary electron recoil rejection >10,000:1

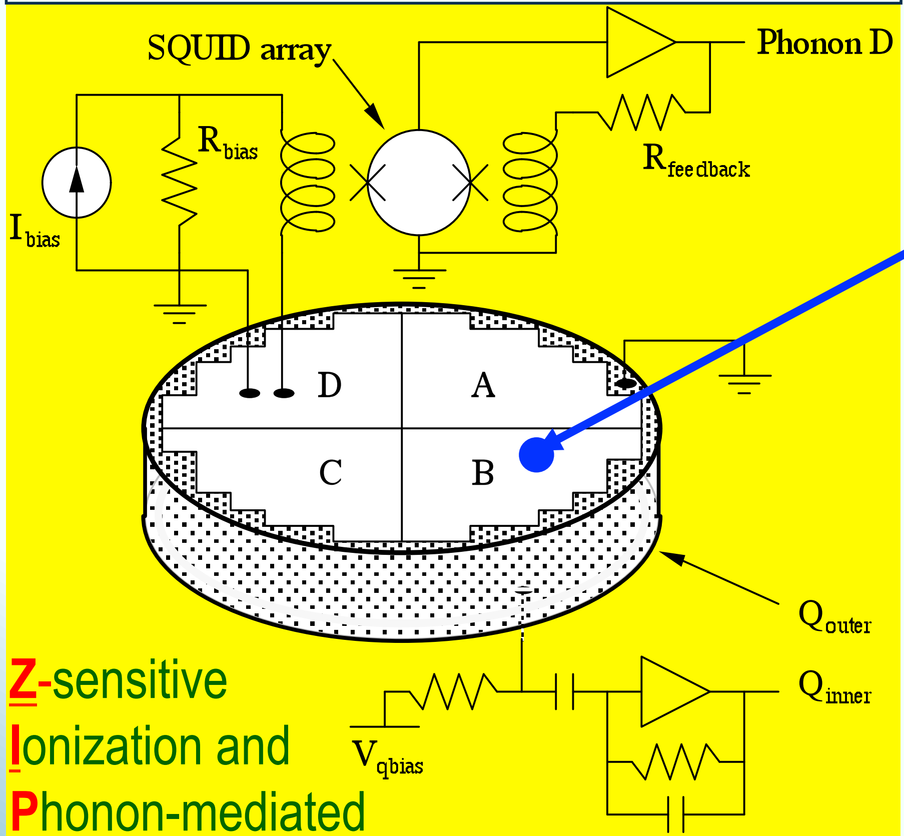




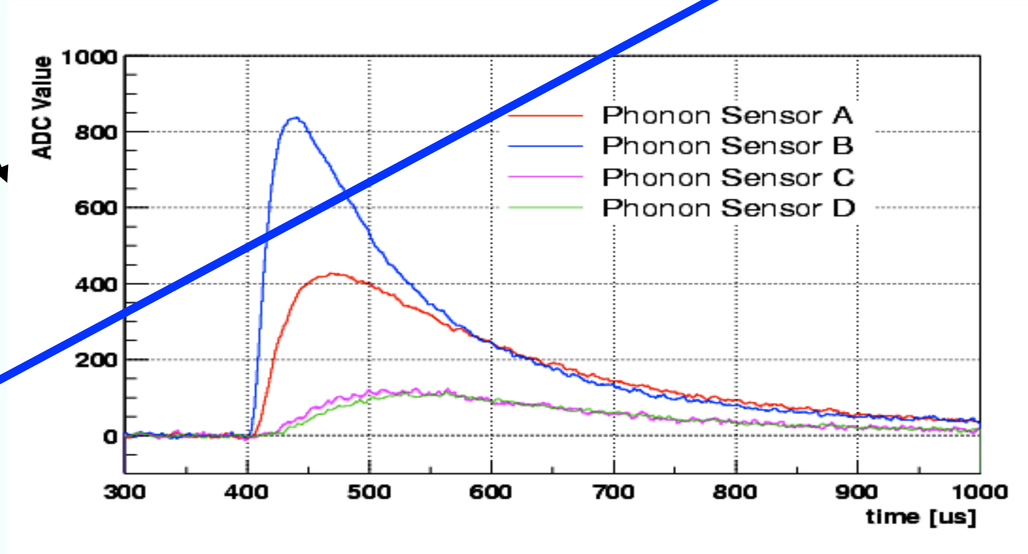


SIGNAL Pulses

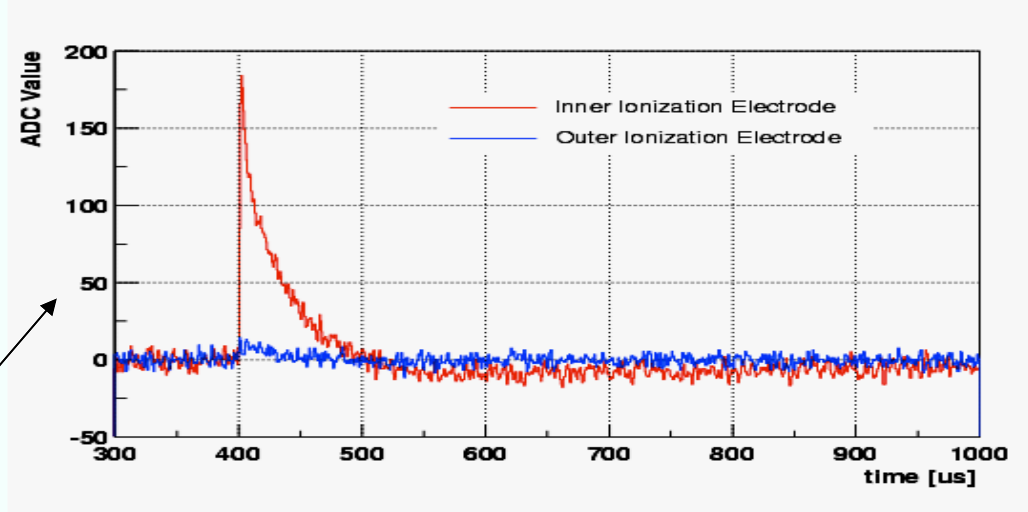
TOP SURFACE
Measure phonon signal with 4 quadrants of Transition Edge Sensors



Z-sensitive
Ionization and
Phonon-mediated

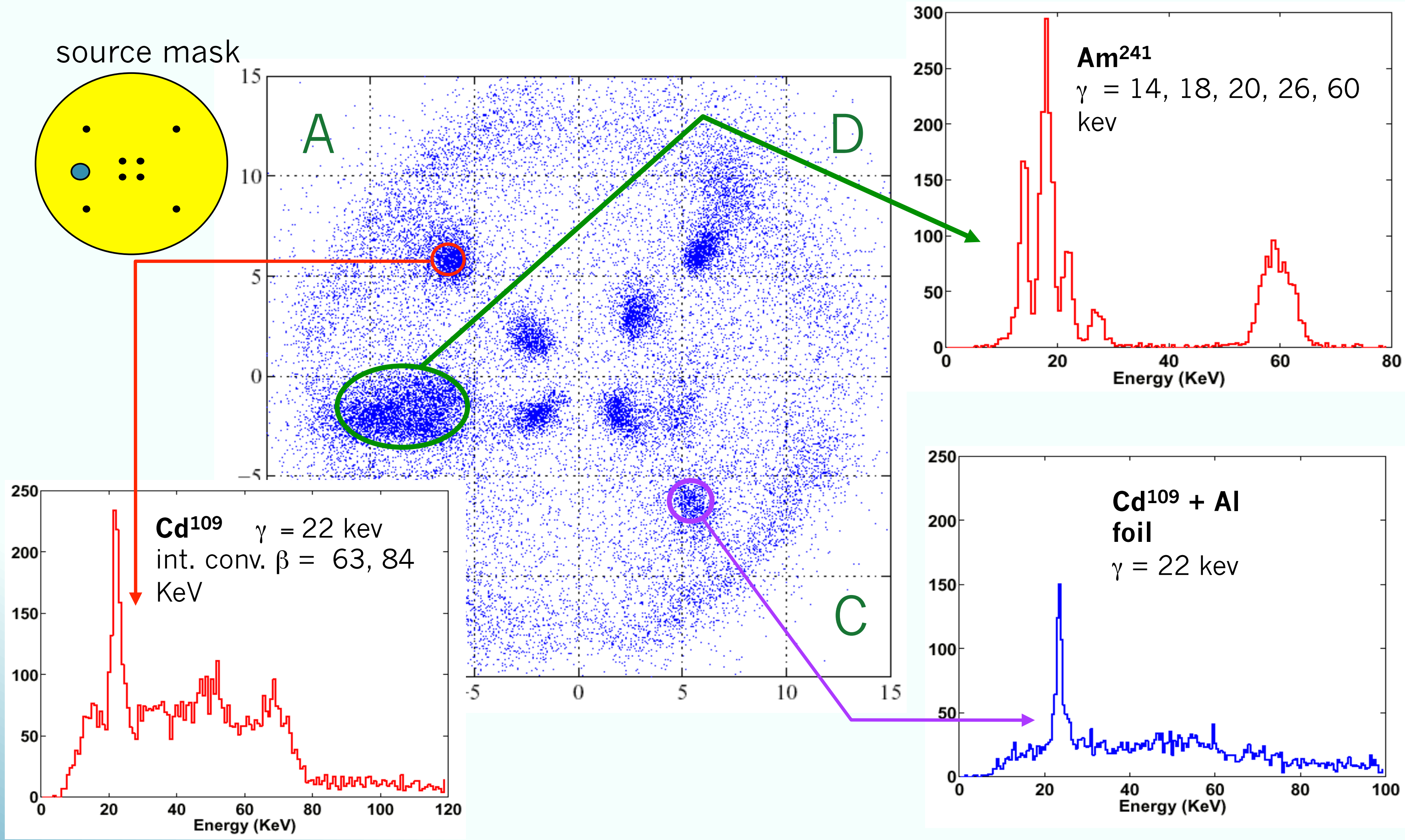


BOTTOM SURFACE
Measure ionization with Q-inner and Q-outer to allow rejection of events near outer edge



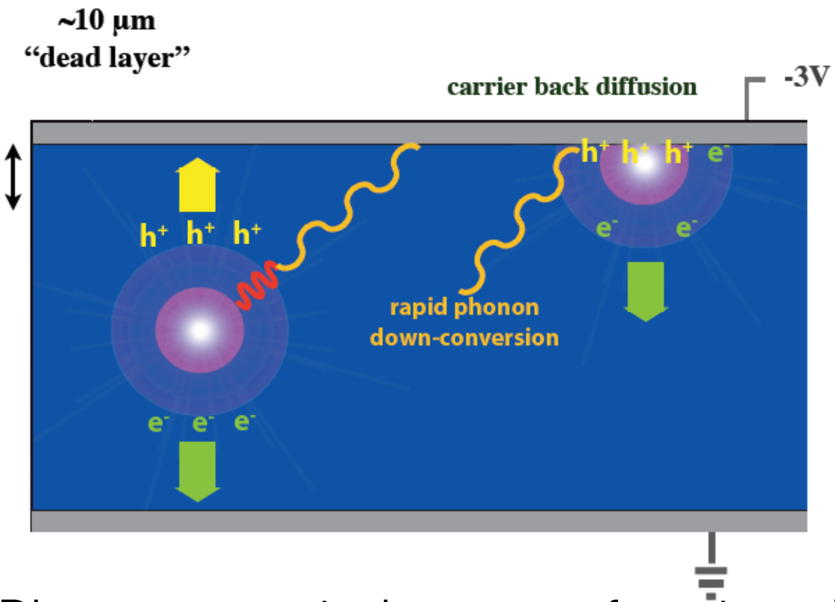
XY - Position Information

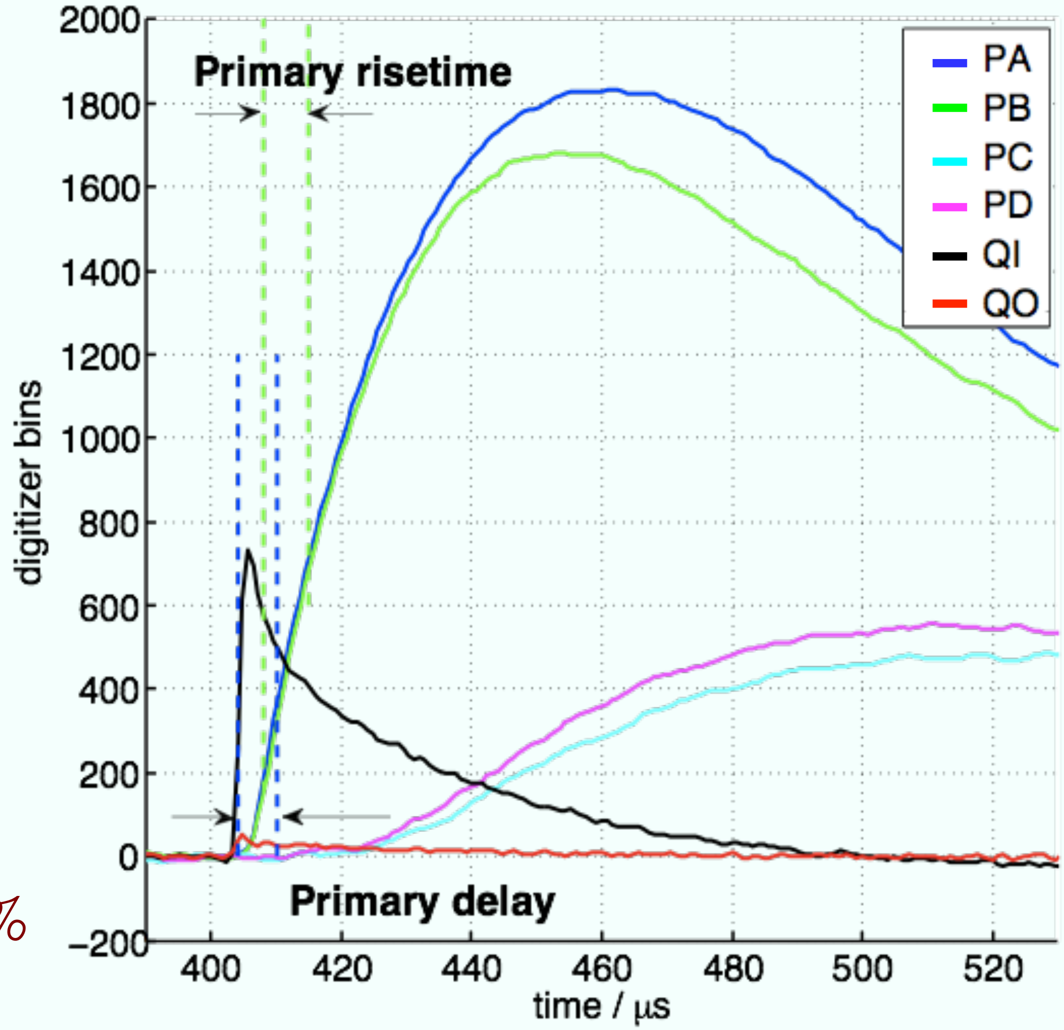
from phonon quadrant relative amplitudes and delays



Z-Position Information

from phonon and ionization relative timing





Phonons created near surface travel faster through crystal (ballistic)

Construct a Timing Parameter from a linear combination of

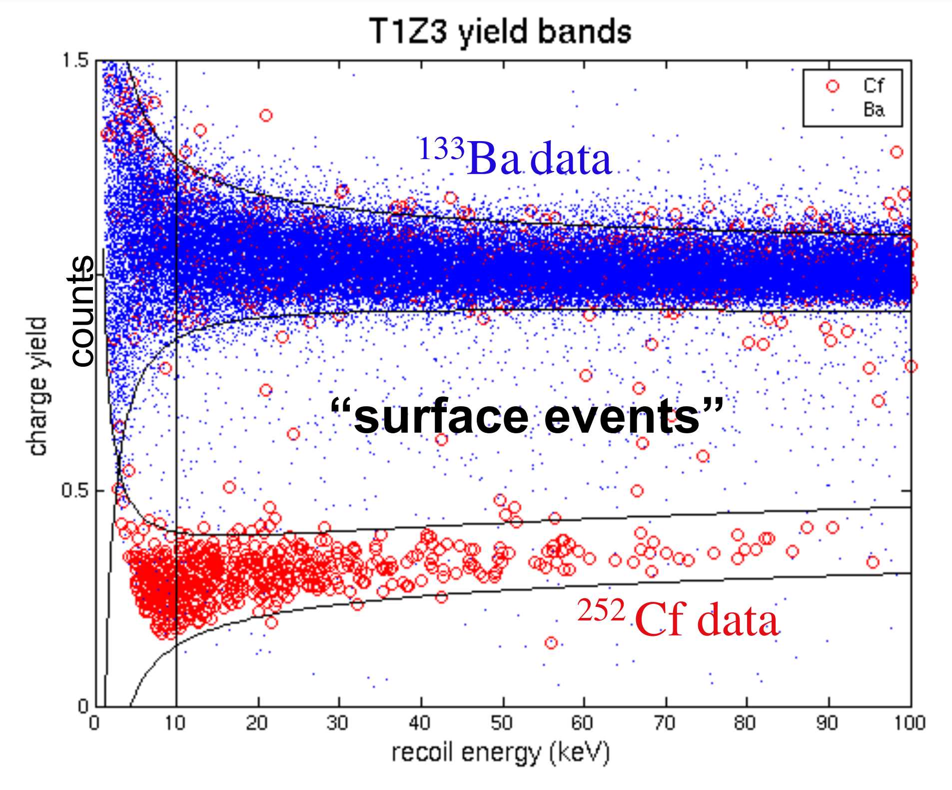
Risetime = phonon RT from 10-40%

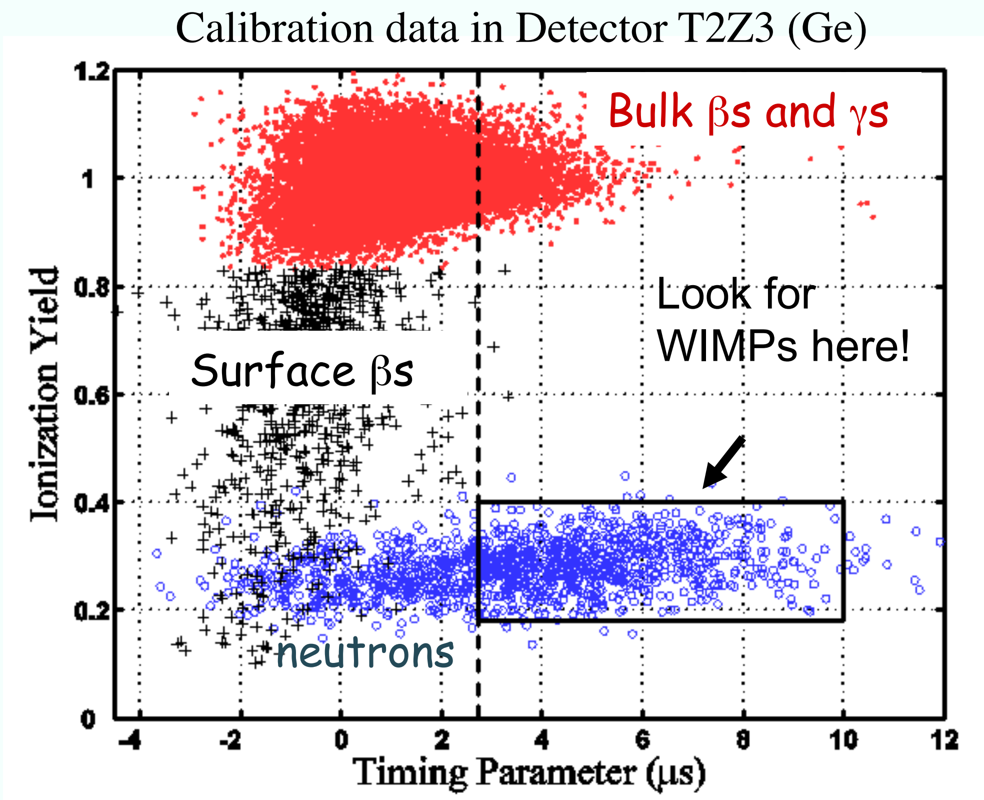
Delay = Δt between phonon at 20% and charge at 20%

Z-Position = Surface Event Rejection

Any trace β-emitters on detector surface have incomplete ionization and can fake a nuclear recoil.

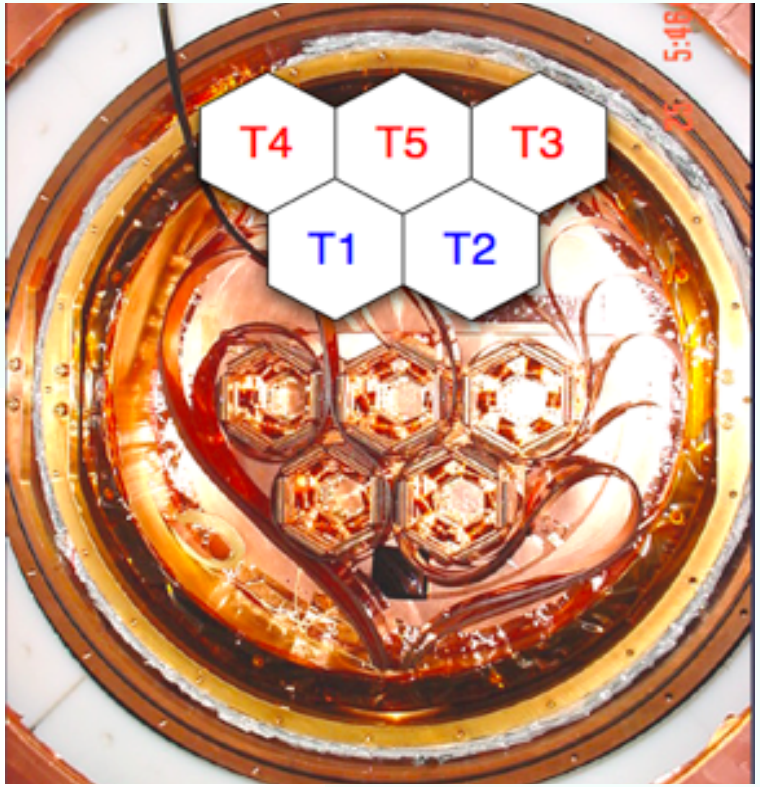
Yield = Normalized and position-corrected Ionization to Phonon ratio

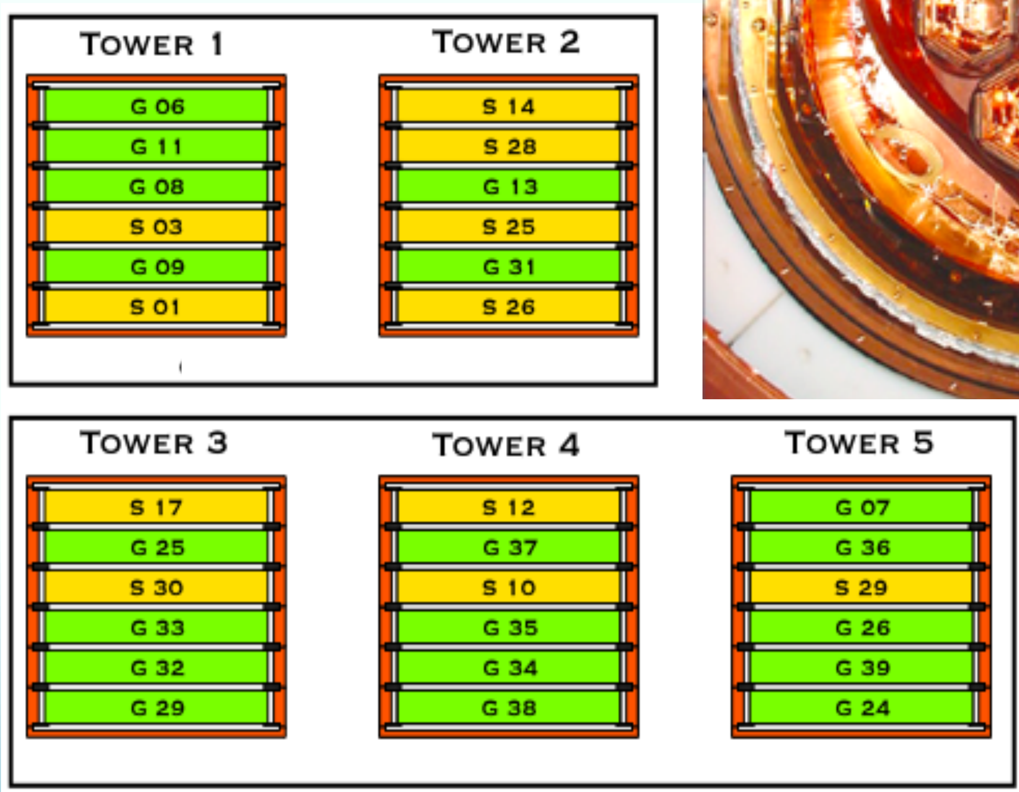




5-Tower CDMS Runs

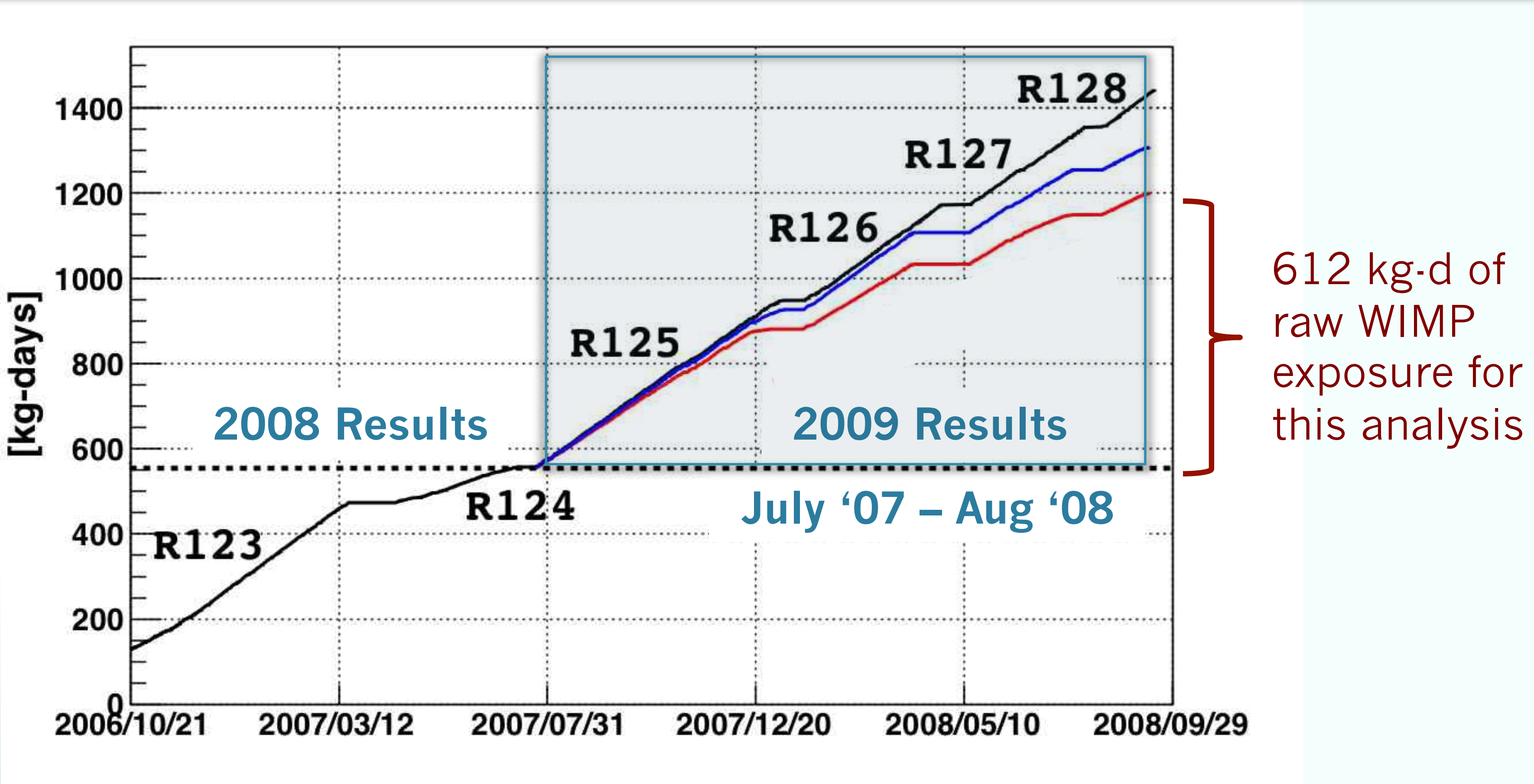
30 ZIPs installed in Soudan since June '06
19 ZIPs + 11 ZIPs
Ge (4.4 kg) Si (1.1 kg)





CDMS Livetime and Exposure

70% Livetime, 10 M WIMP search events, 225 M ^{133}Ba calibration events



Blue: remove some detectors from WIMP single scatter search (still used to reject multiples)

Red: remove periods of poor data quality

Further cuts on the data to define WIMP "box"

194.1 kg-days exposure in "box" after further cuts

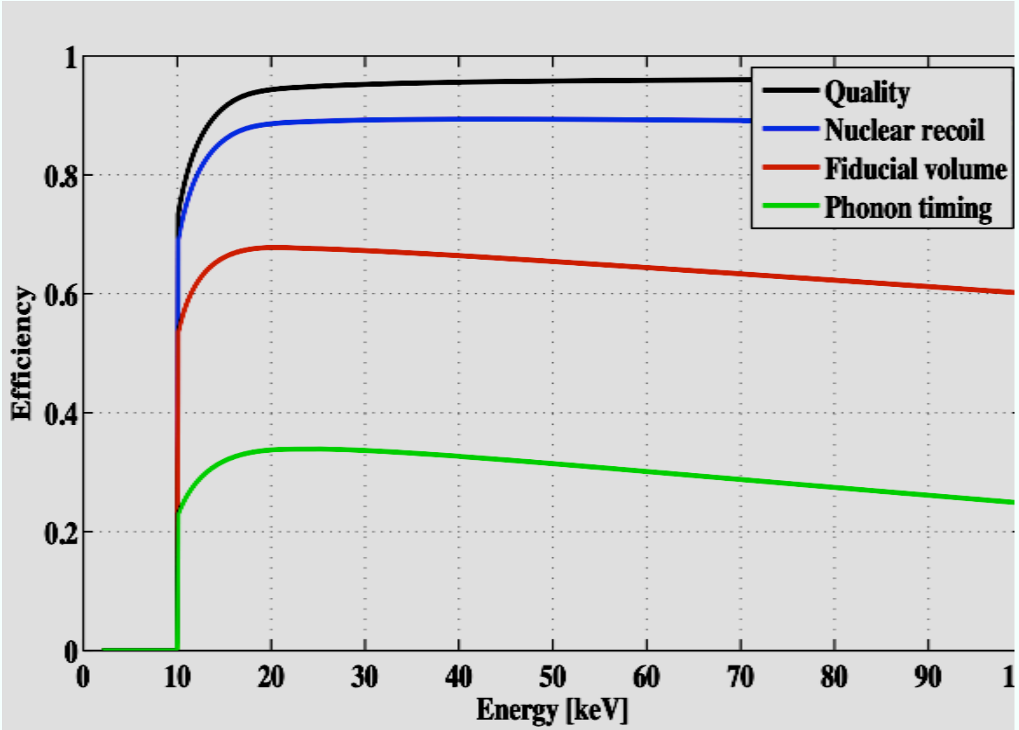
Veto Anti-coincident

Within 2σ of nuclear recoil band

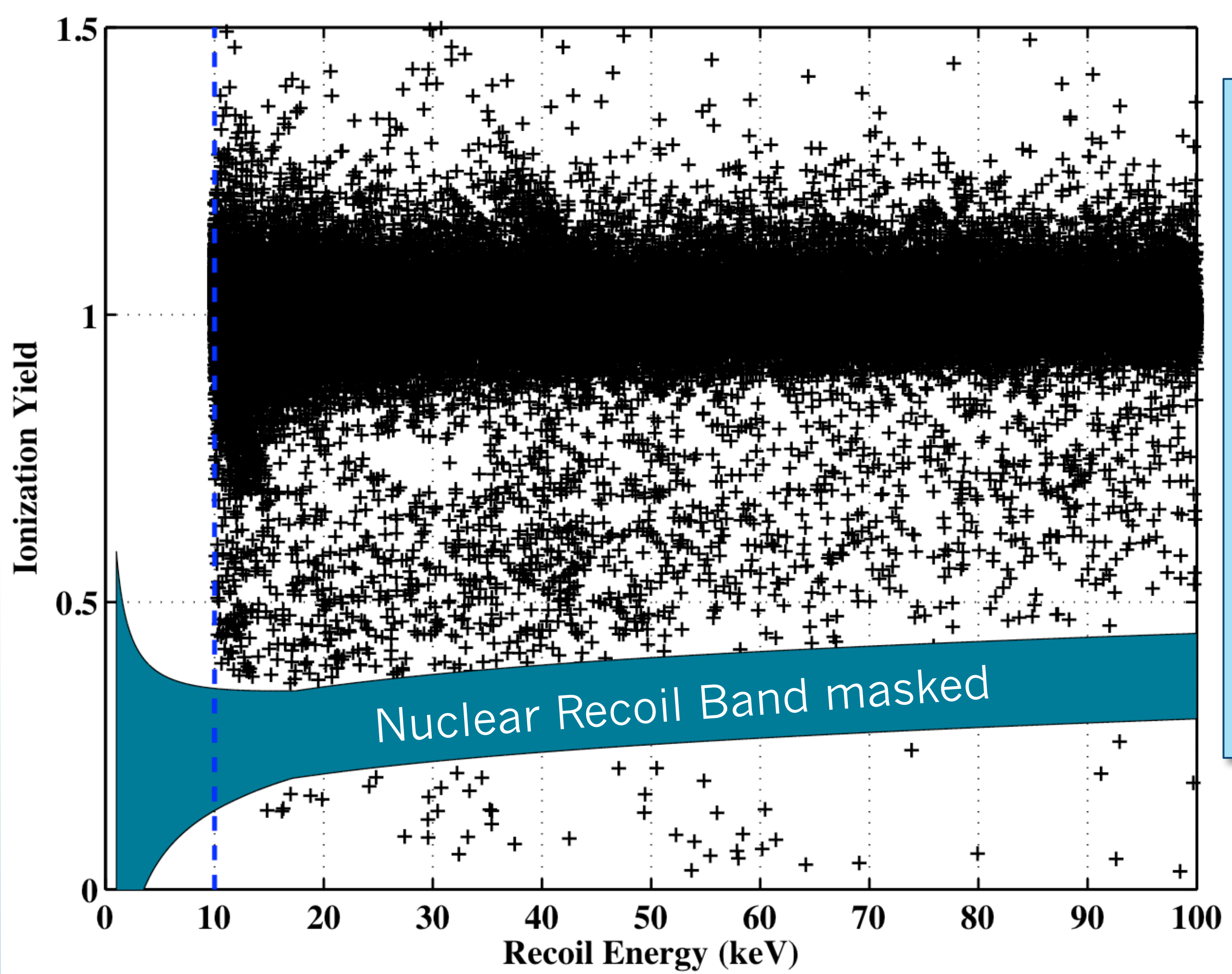
Fiducial cut (Qinner)

Single Scatters

Surface (timing) cut



Opening the Box - November 4, 2009



Blinded Data after all cuts except timing cut

Don't look at single scatters in NR band

Next Step:

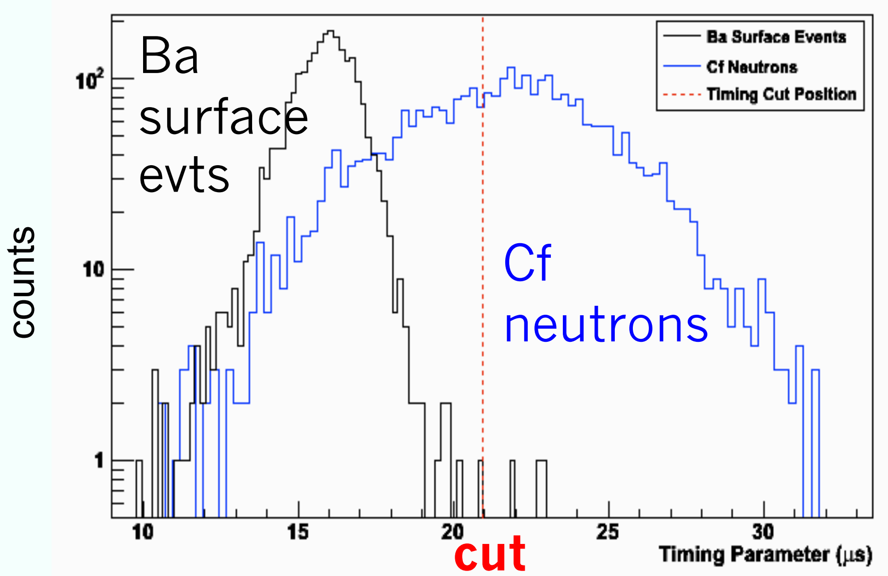
Decide on Timing Cut for each detector

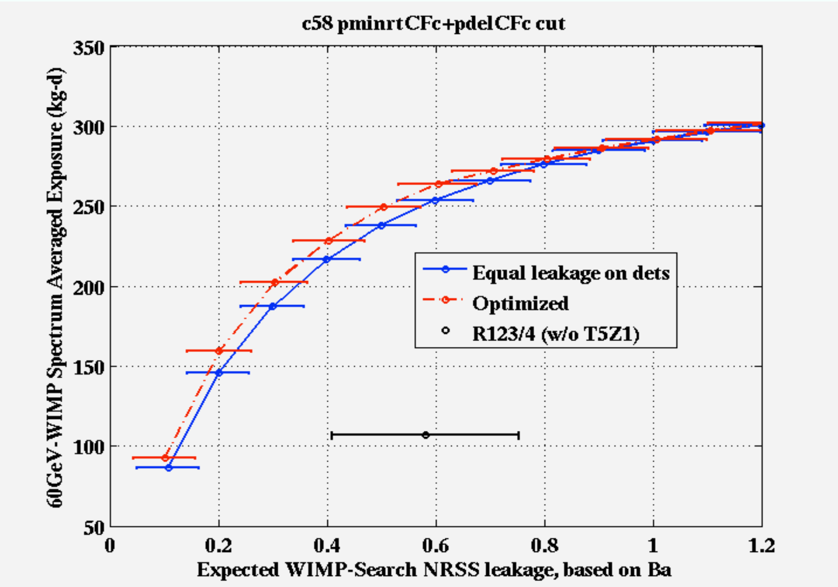
Tuning the surface cut to < 1 background event

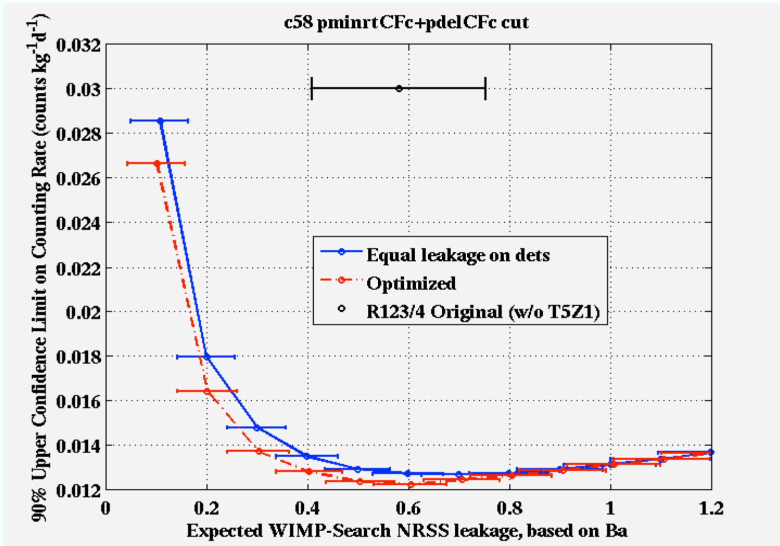
Our timing cut is a choice.
Trade-off between
Exposure and Leakage.

Use a 60 GeV WIMP spectrum
averaged exposure

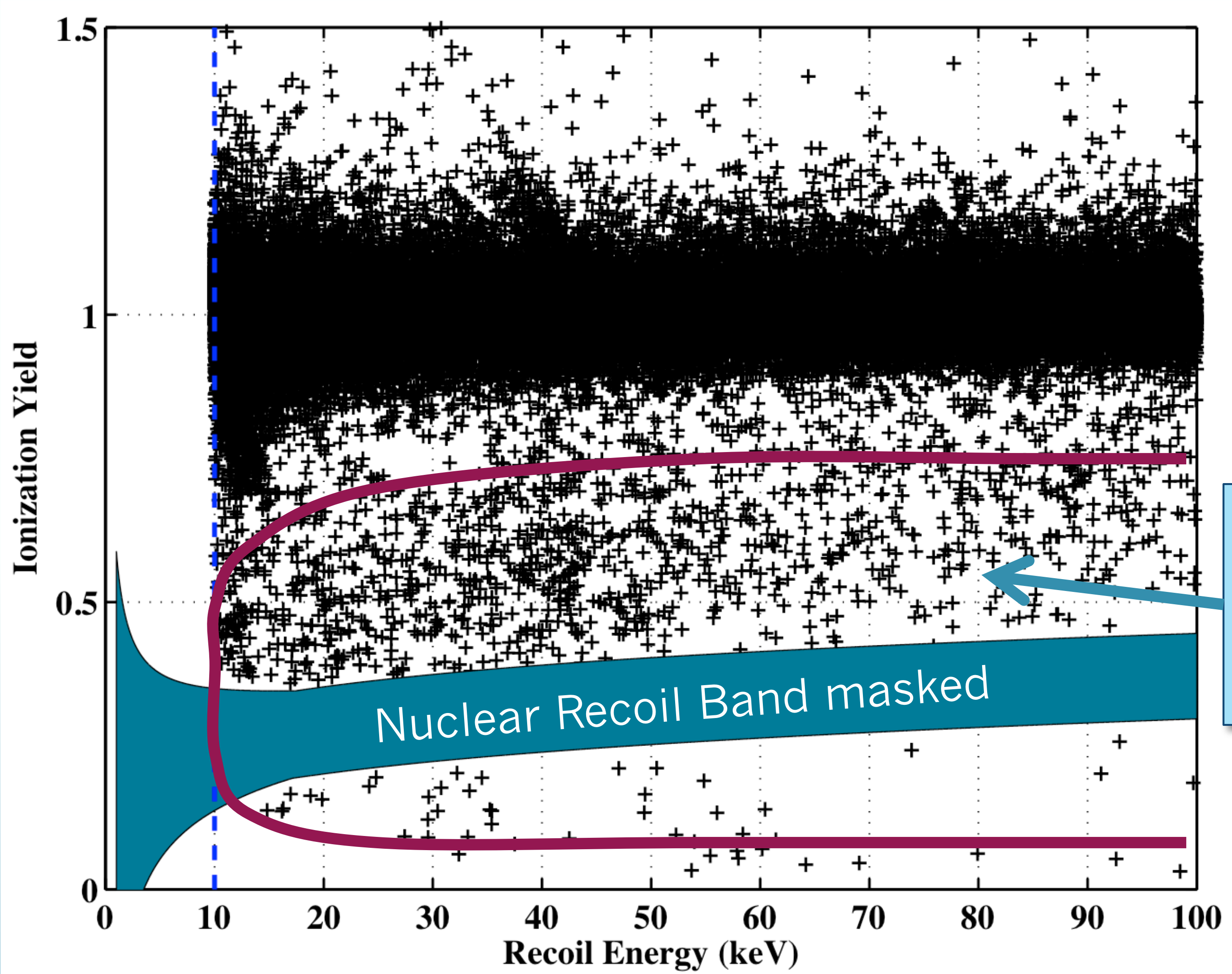
0.6 evt is optimum leakage
Fairly flat minimum







Estimate Leakage without looking in box
3 Independent distributions

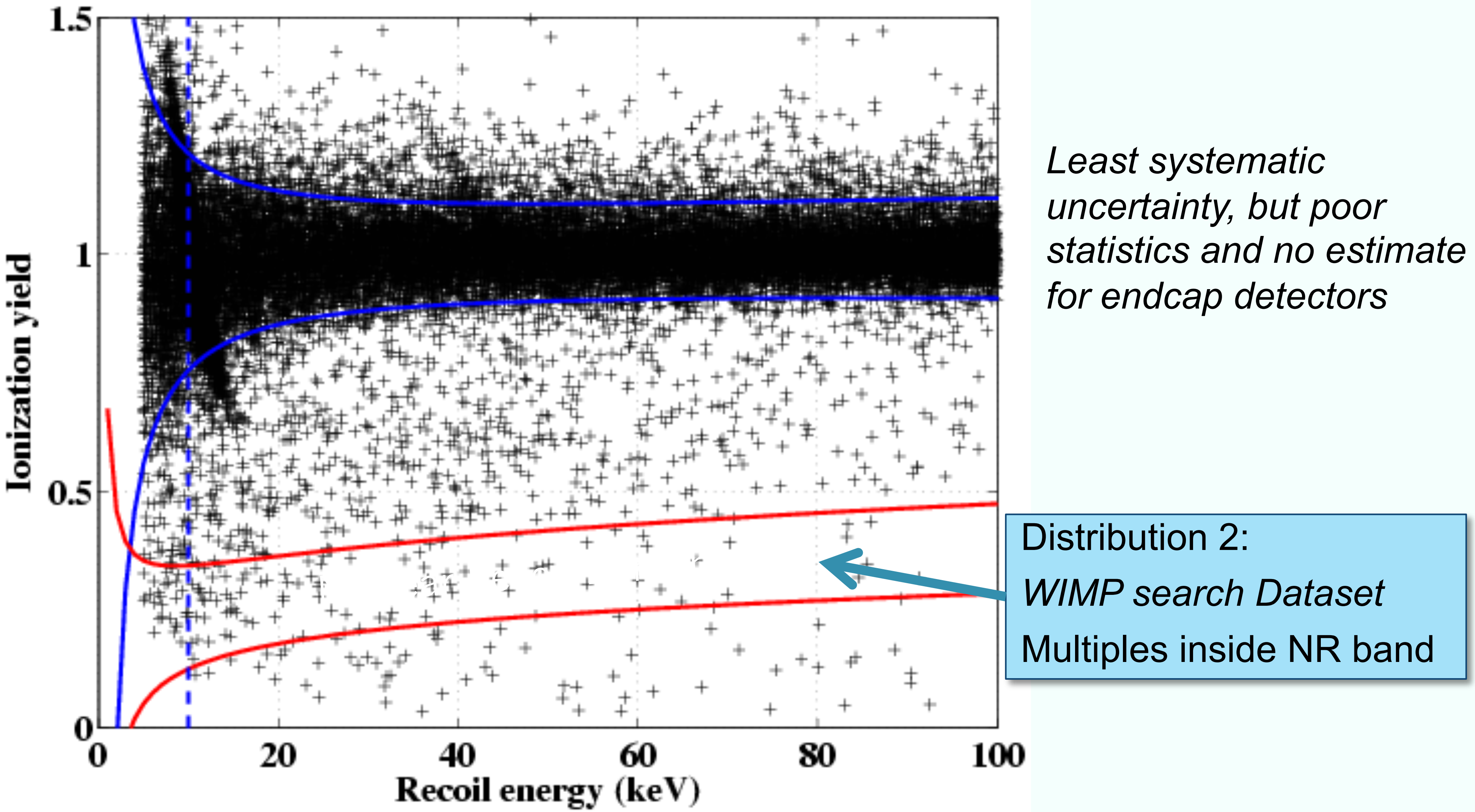


Distribution 1:

WIMP search Dataset

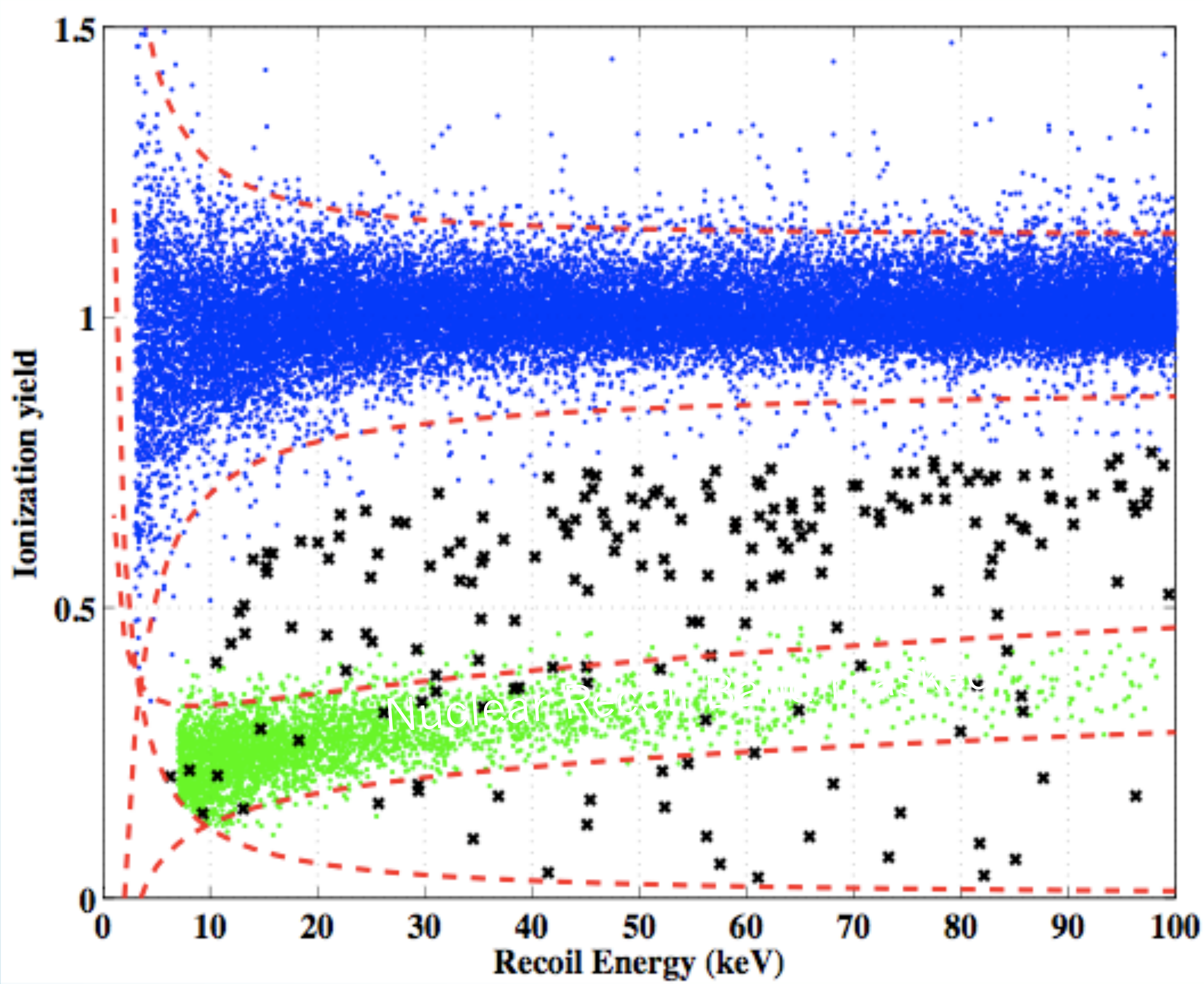
Singles and multiples just outside NR band

Estimate Leakage without looking in box
3 Independent distributions



Least systematic uncertainty, but poor statistics and no estimate for endcap detectors

Estimate Leakage without looking in box
3 Independent distributions



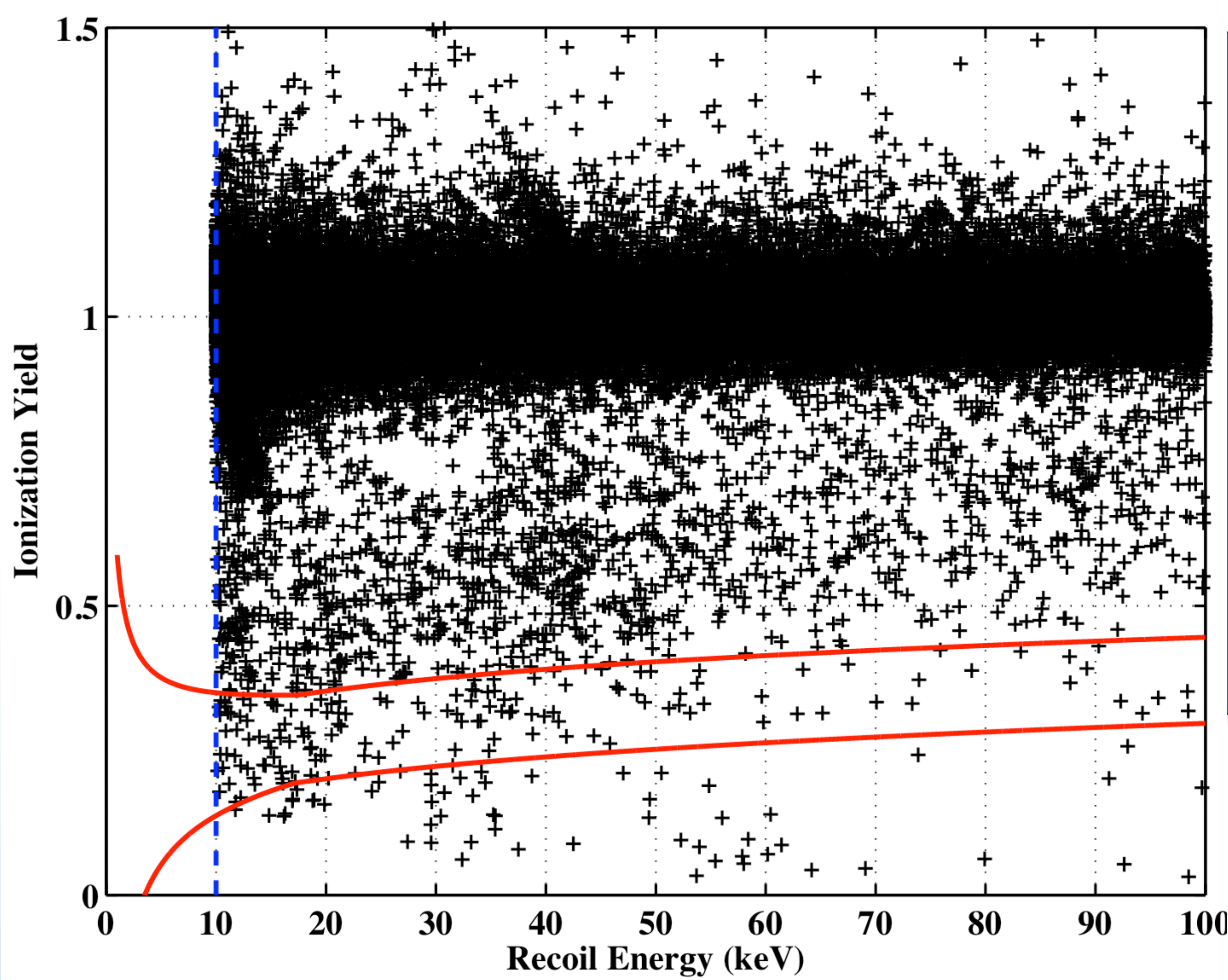
Best statistical power, but most systematic uncertainty. Need to correct for differences in source energy & position

Distribution 3:

Barium dataset

Singles and Multiples inside wide region around (and in) NR band

Opening the Box - November 4, 2009



Blinded Data

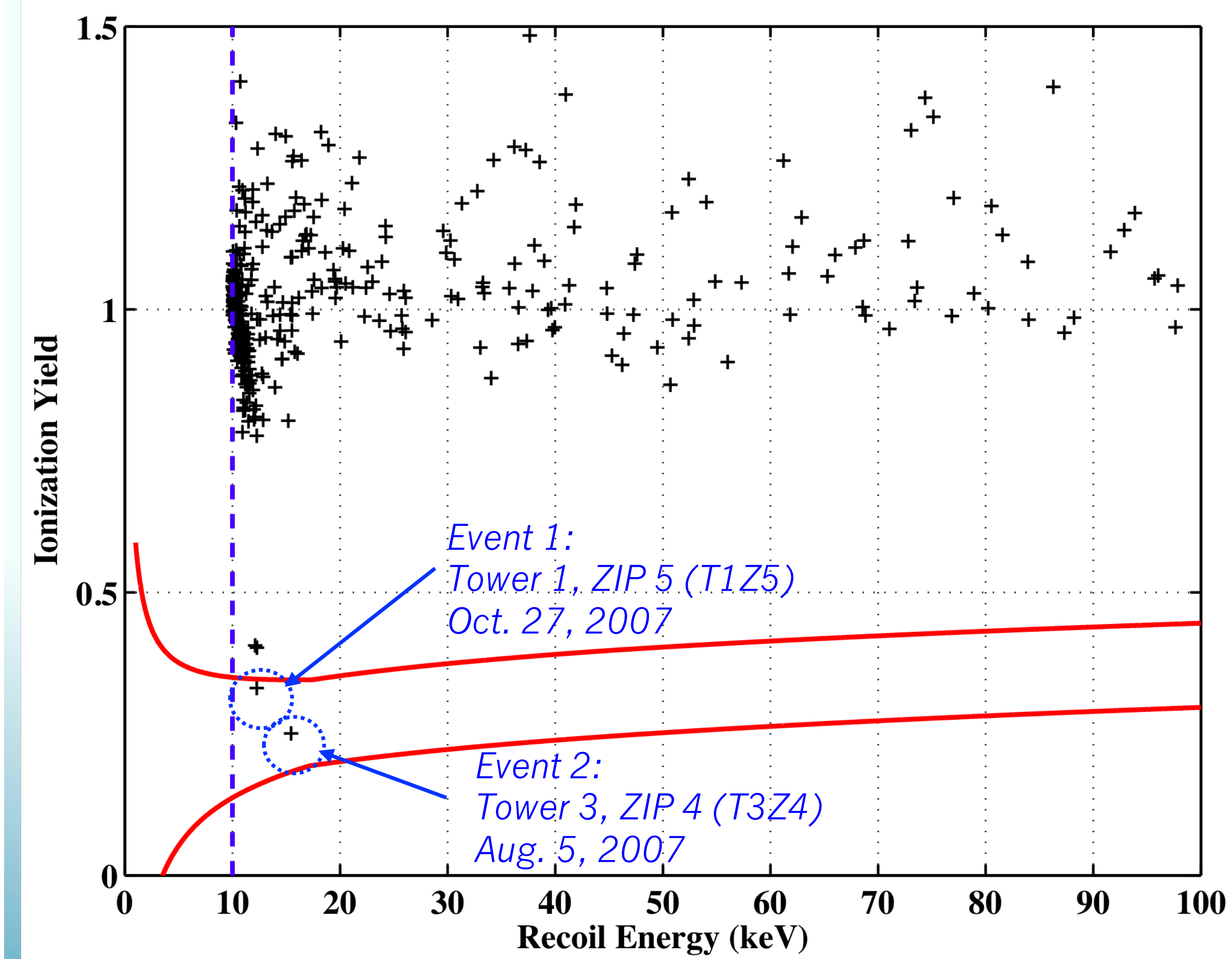
Unmask events in NR band that FAIL surface cut

150 events appear

Compare to our Leakage Estimates to see if there are systematics issues.

Opening the Box - November 4, 2009

surface event leakage estimate = **0.8 ± 0.1(stat) ± 0.2(sys)**



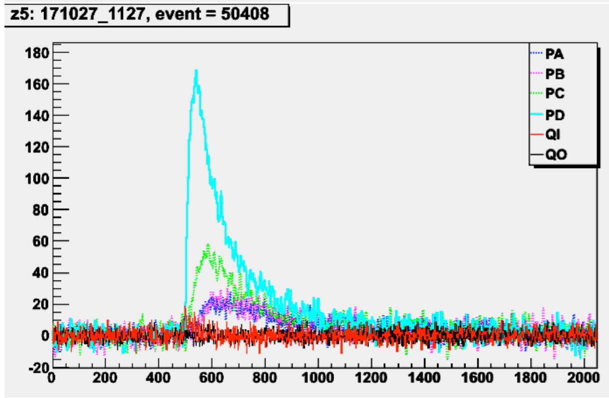
Apply Timing CUT

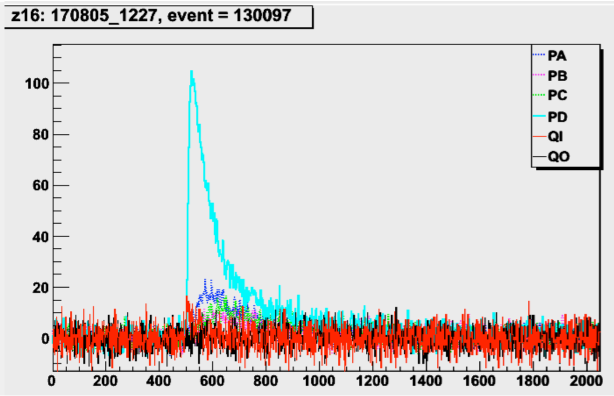
and two events are left

Recall that our previous dataset had ZERO events.

6 or more events already starts to be inconsistent with our previous result

Check to make sure these are good events





Event itself

Individual Pulses and fits
Noise baseline
All analysis parameters
(e.g. position, energy, etc)

Typical, Far from edges

Check Other Detectors in same event

How many sigma away from baseline noise? **True Single Events**
Only typical noise in Veto Pane? **True Anti-Coincident Event**

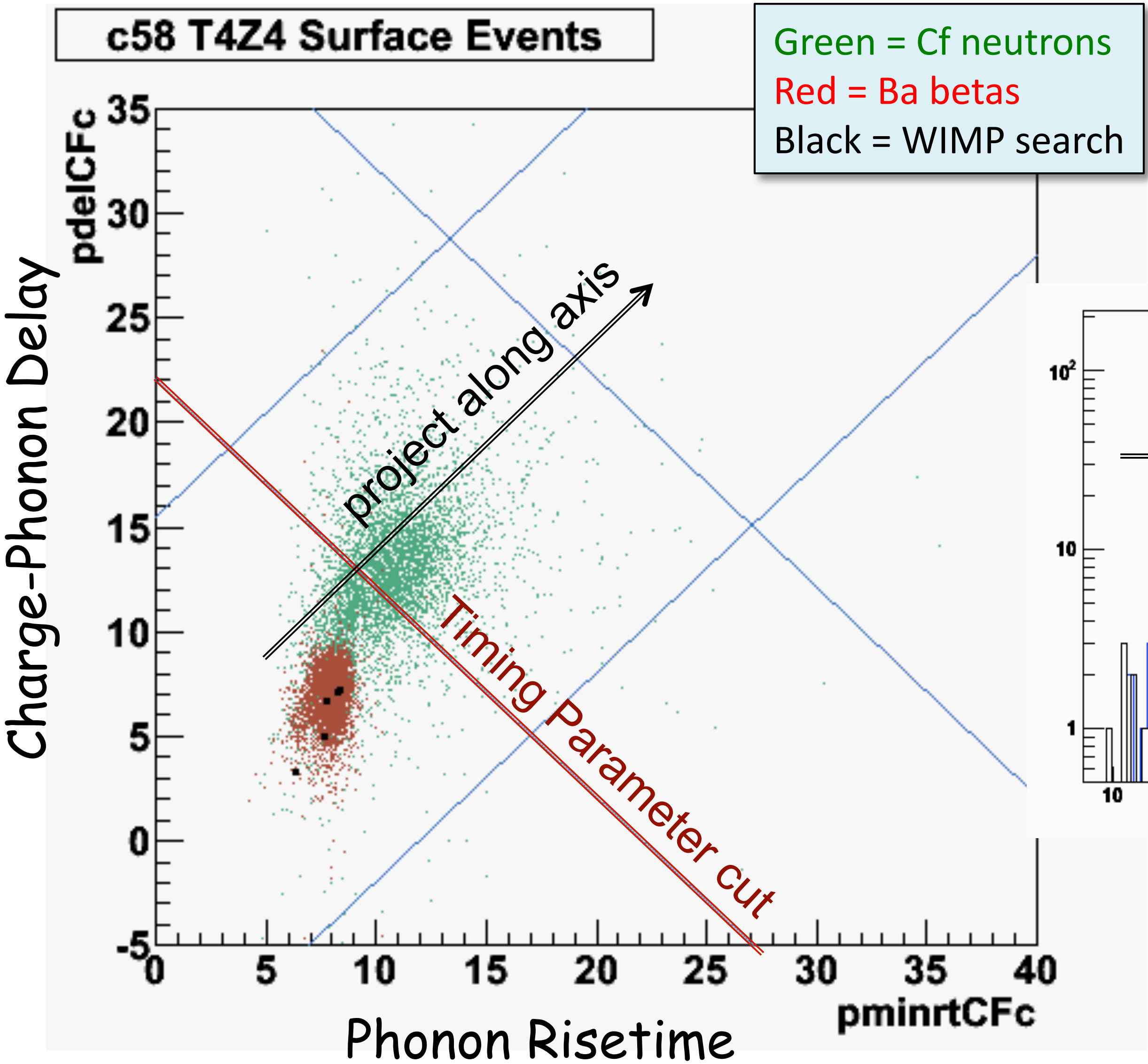
Check run series in which event occurs

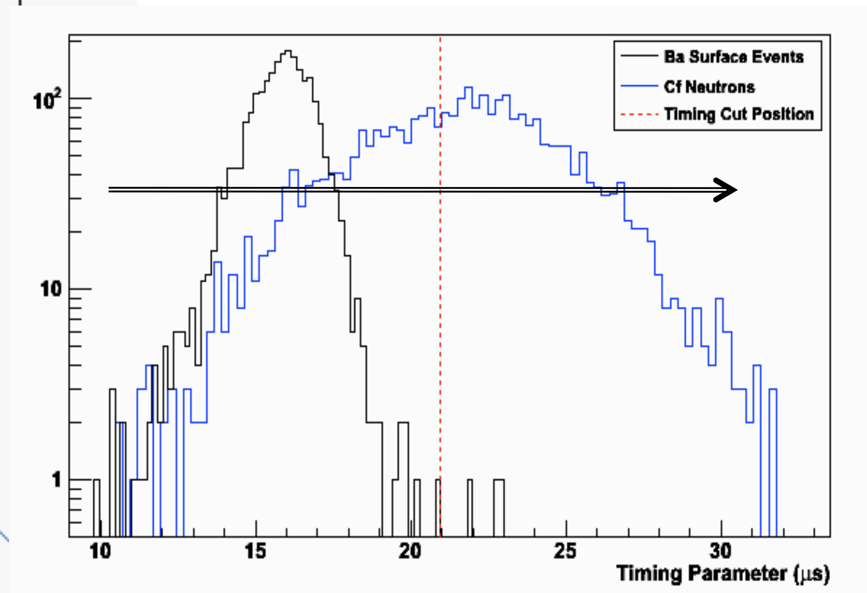
Neutralization: Fraction of low-yield events & size of run series. **Typical**
Check Kolmogorov-Smirnov tests for series. **Valid, good scores**
EM Rates (gamma and beta bands) **Typical**

Could they be a Surface Event?

Look at Timing Parameter in detail

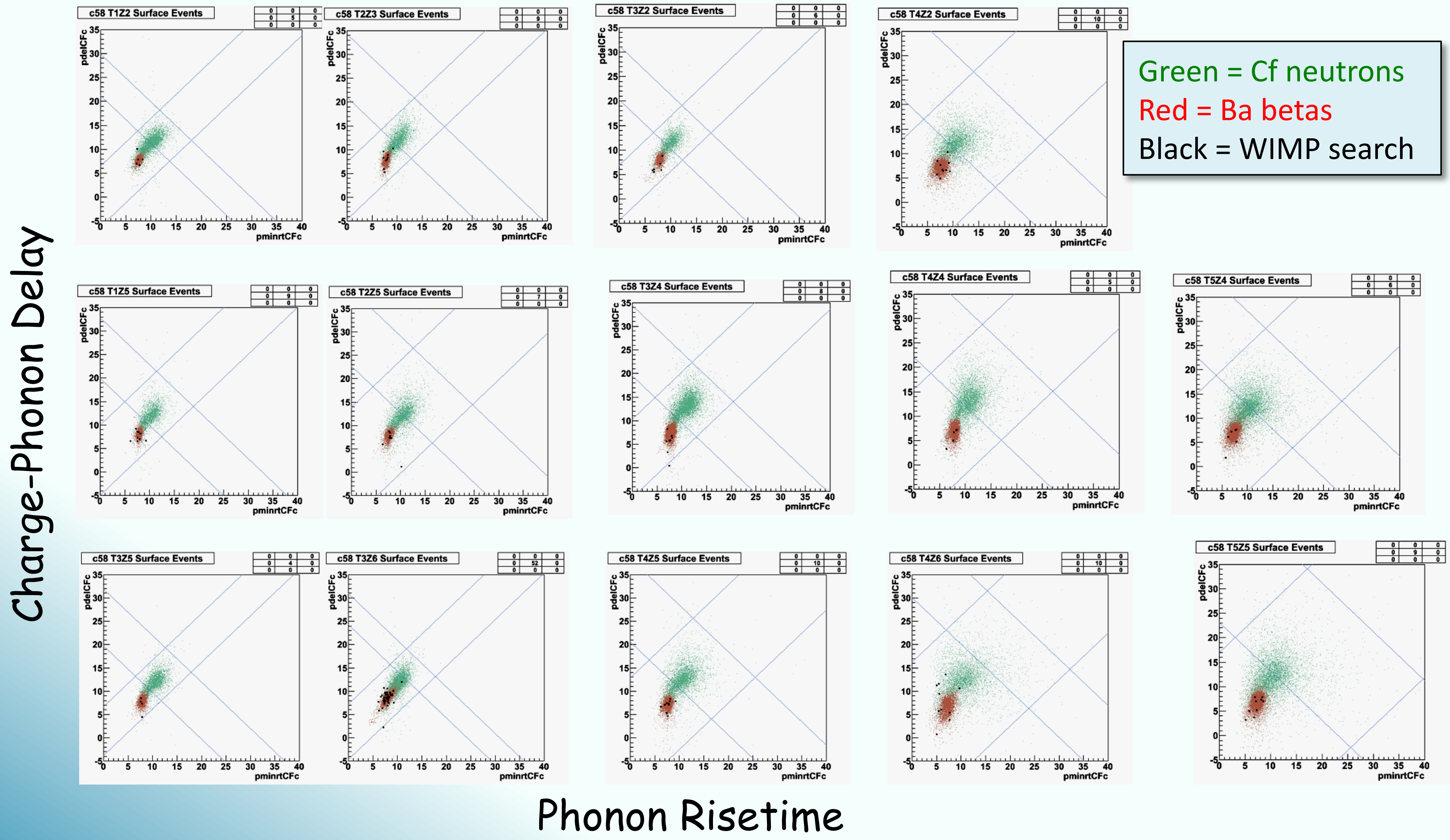
Calibration data in green and red; WIMP Search data in black



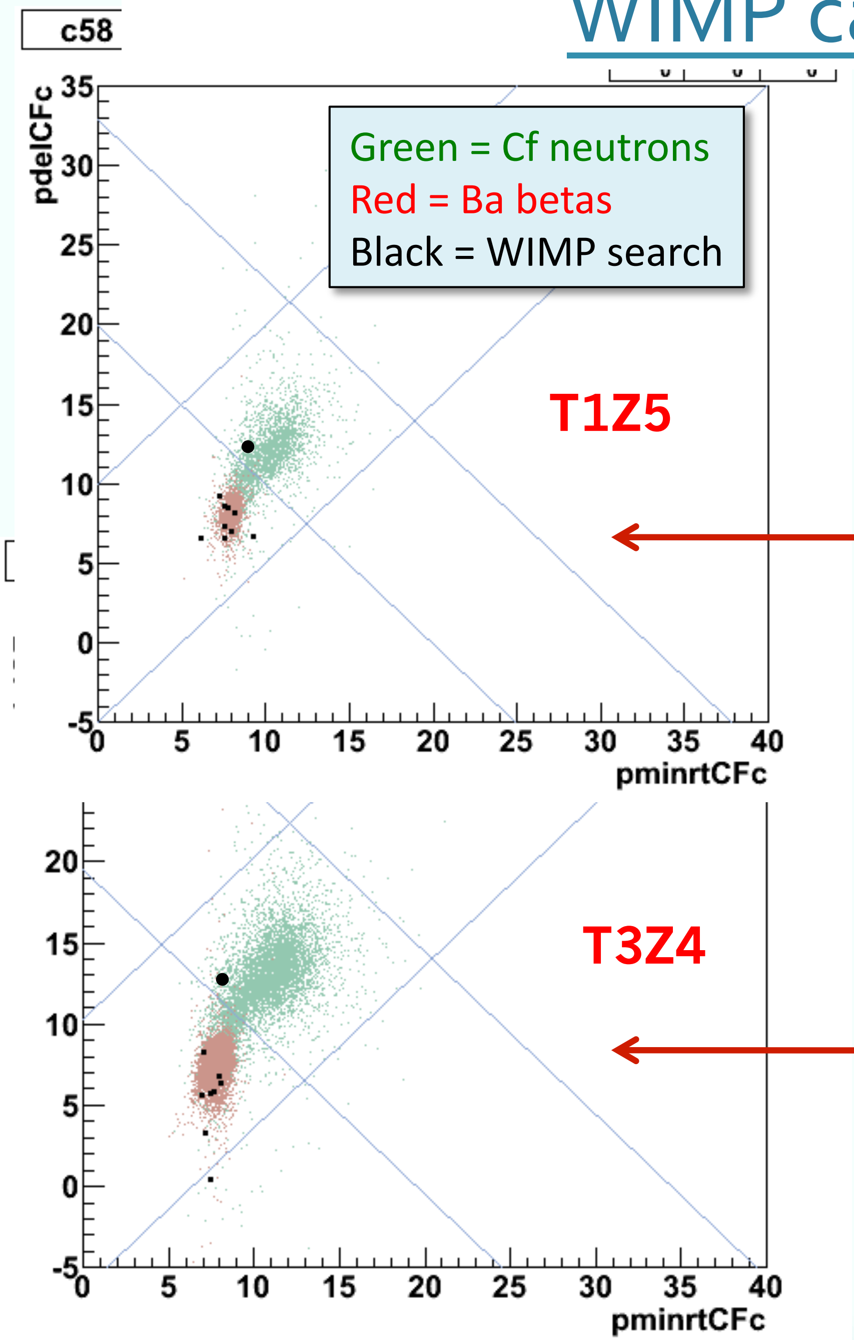


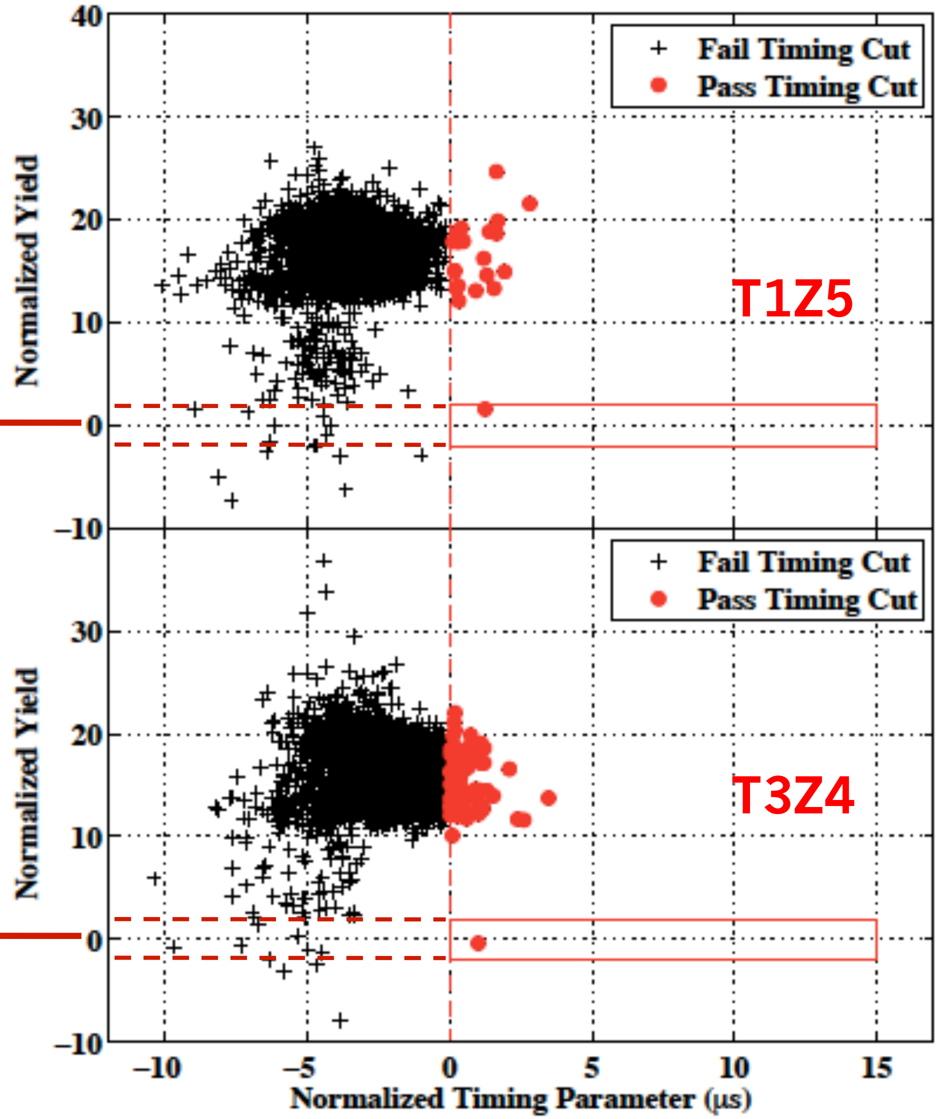
Yield Band events for all detectors in Delay vs Risetime Space

Timing parameter cut chosen for each detector



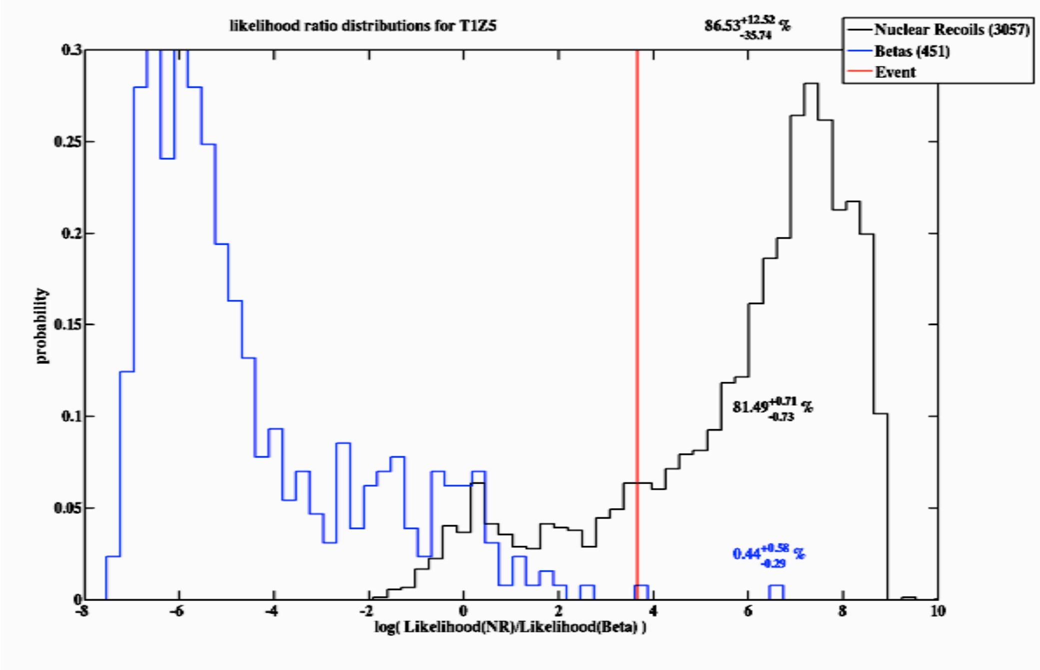
WIMP candidate events

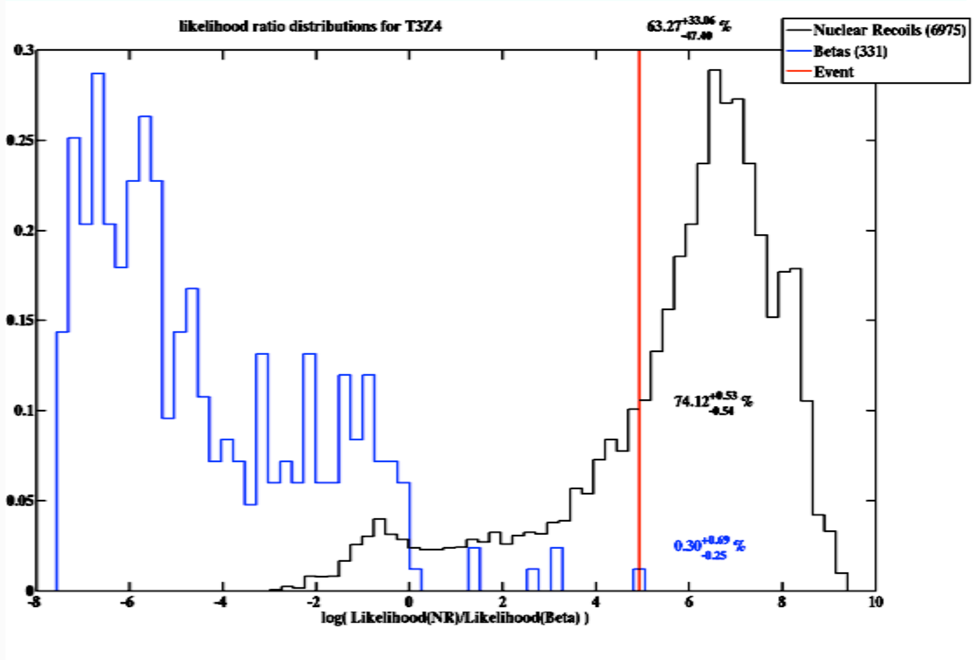




Likelihood Analysis

allows us to determine how much candidate events resemble neutron distribution (WIMP-like) or beta distribution (surface evt)

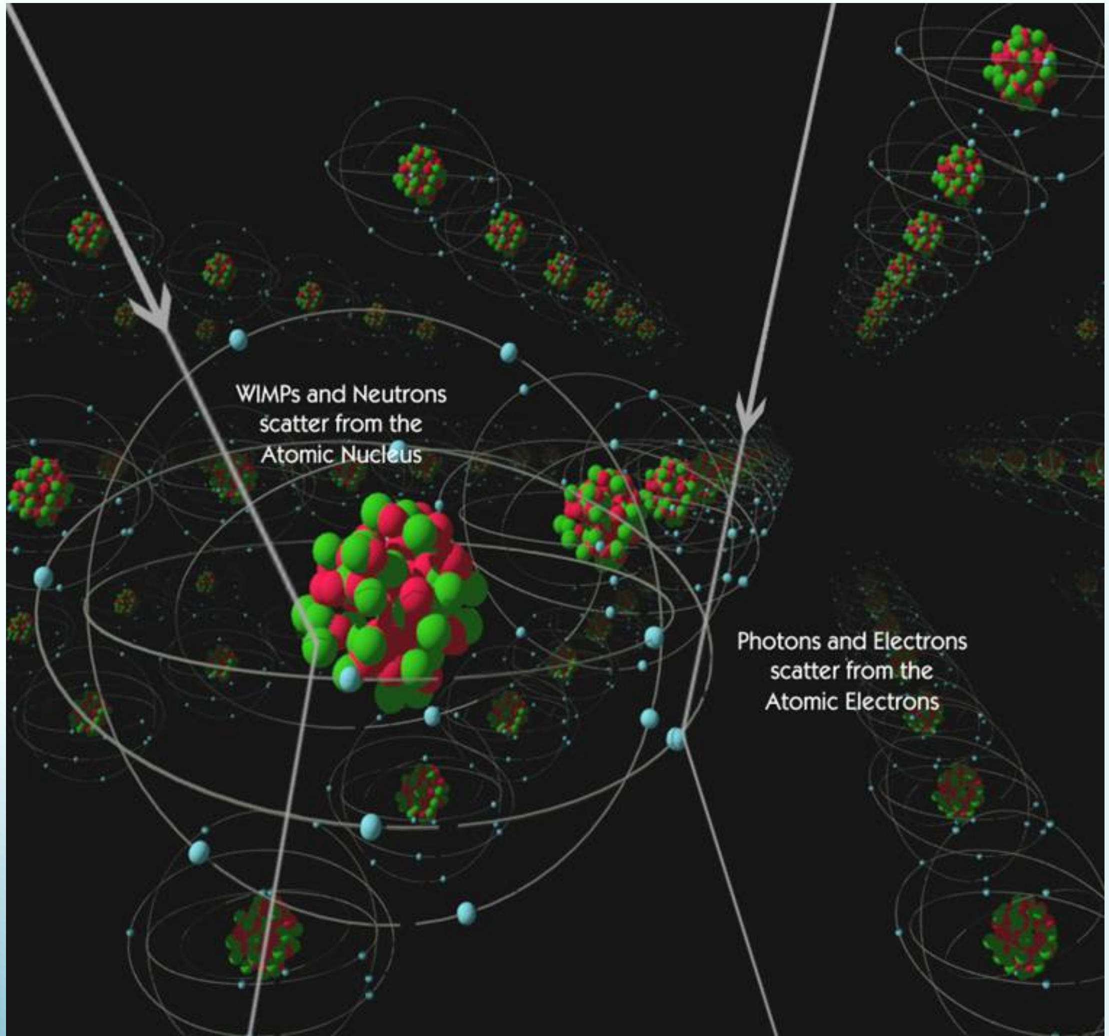




T1Z5
81% Nuclear Recoil
0.4% Surface Event

T3Z4
74% Nuclear Recoil
0.3% Surface Event

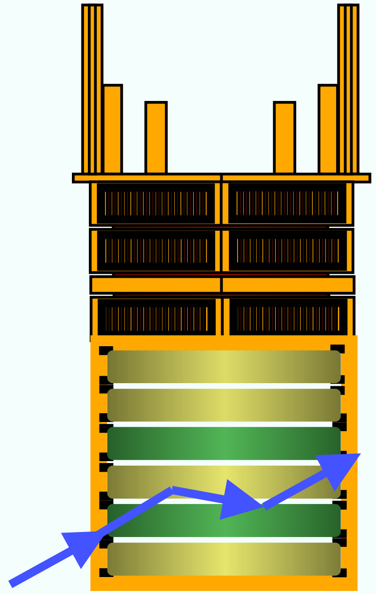
Could they be neutrons?



M. Attisha

Neutrons normally produce multiple-scatter Nuclear Recoils, but our stack is not infinitely large or hermetic!

We need to shield from them



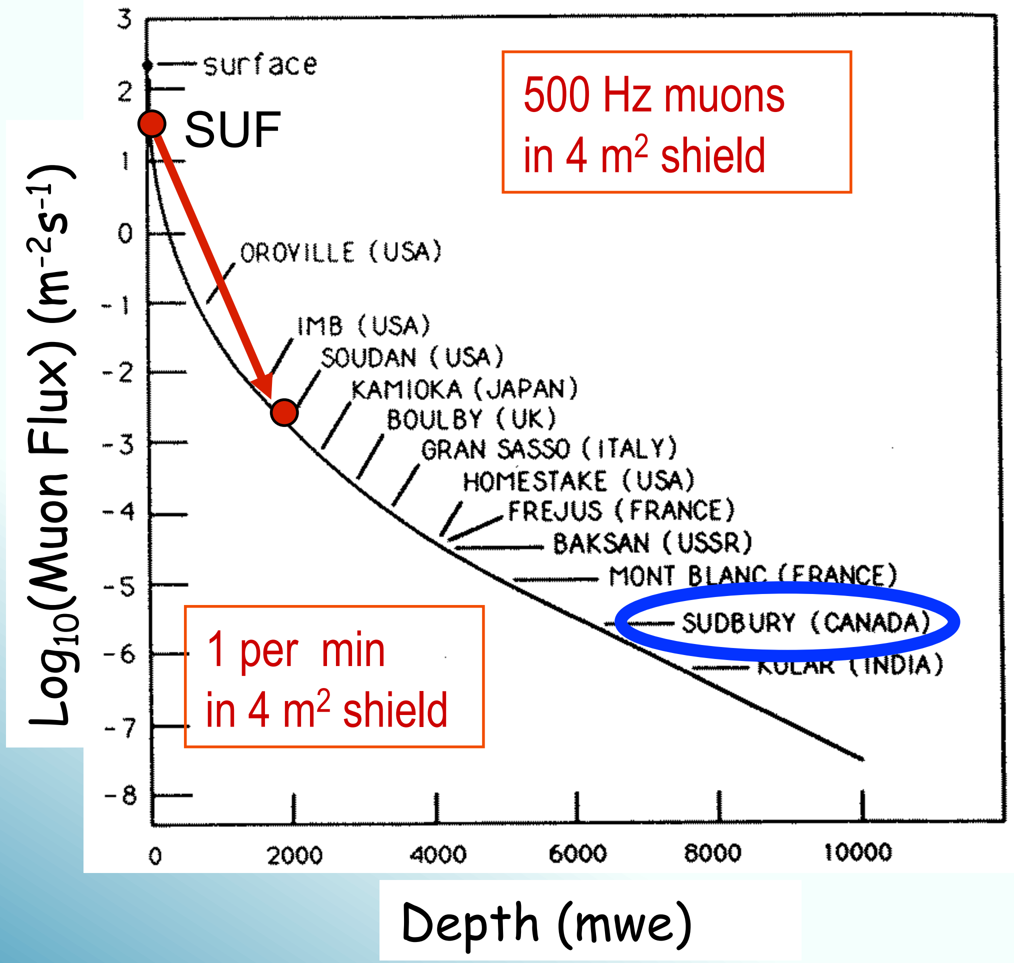
Sited at the Soudan Underground Lab (Minnesota, USA)

which sometimes seems like just outside Moscow

Cosmogenic Neutron Bkgd

2090 mwe reduces muon flux by ~30,000

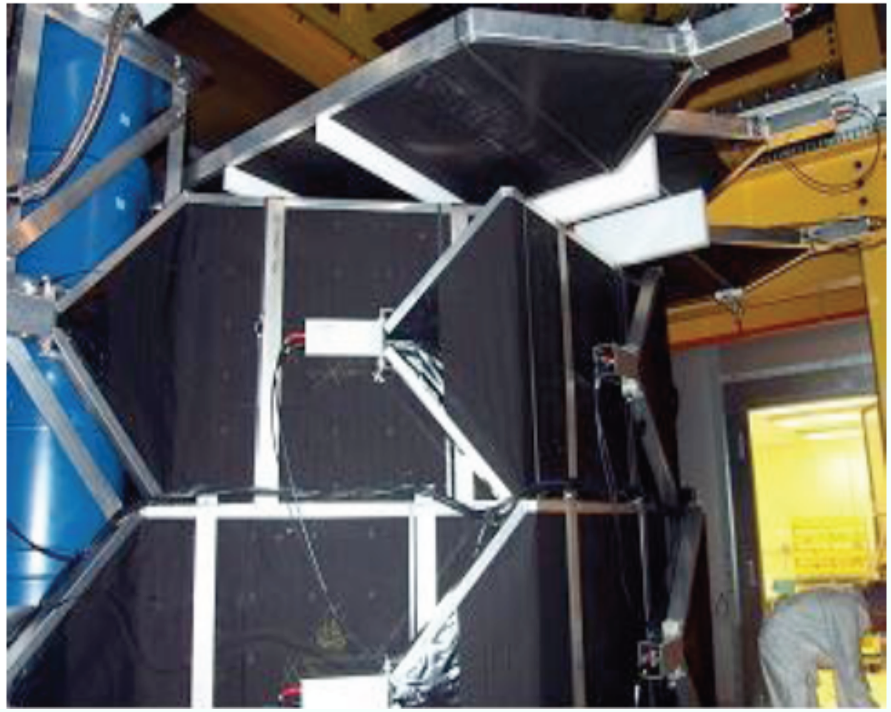
Reduces neutron background from ~1 / kg / day to ~1 / kg / year



Scintillator Panels = active muon veto

100% efficient for Muons
96% efficient for NR in detectors

17% of the neutron events come from parent muons that do NOT intersect shield



Cosmogenic Neutron Bkgd

Tool kit for establishing the cosmogenic background

Full Simulation of 5 tower run starting from muon files matched to Soudan geography and Soudan2/MINOS angular muon flux data

29 live years of GEANT4
42 live years of FLUKA/MCNPX

Handful of Veto-coincident nuclear recoils over entire 5-tower running
16 multiples 3 singles

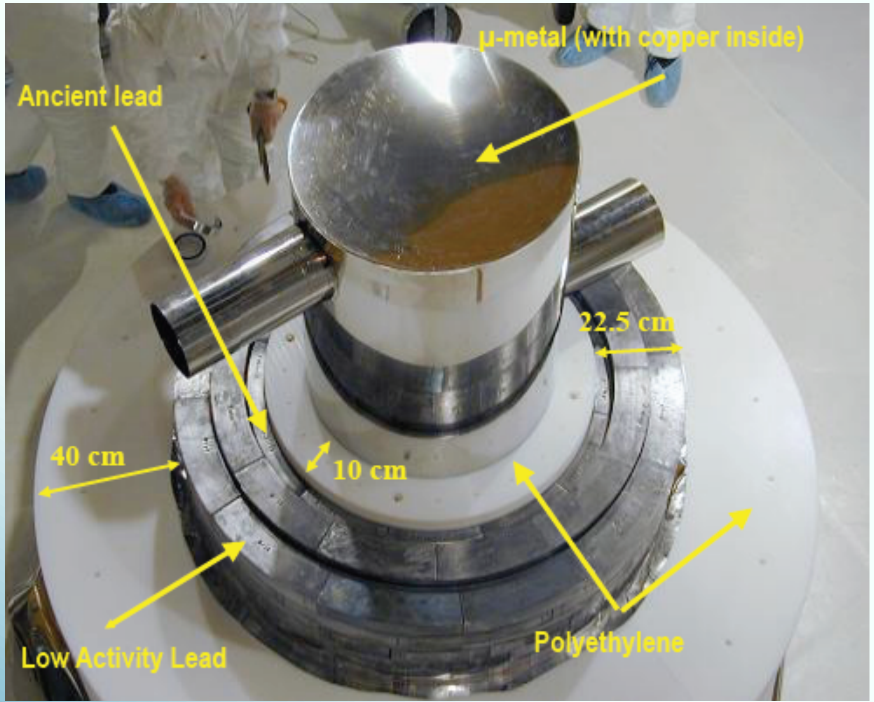
Multiple ways to combine these, all were consistent. (except absolute MC flux)

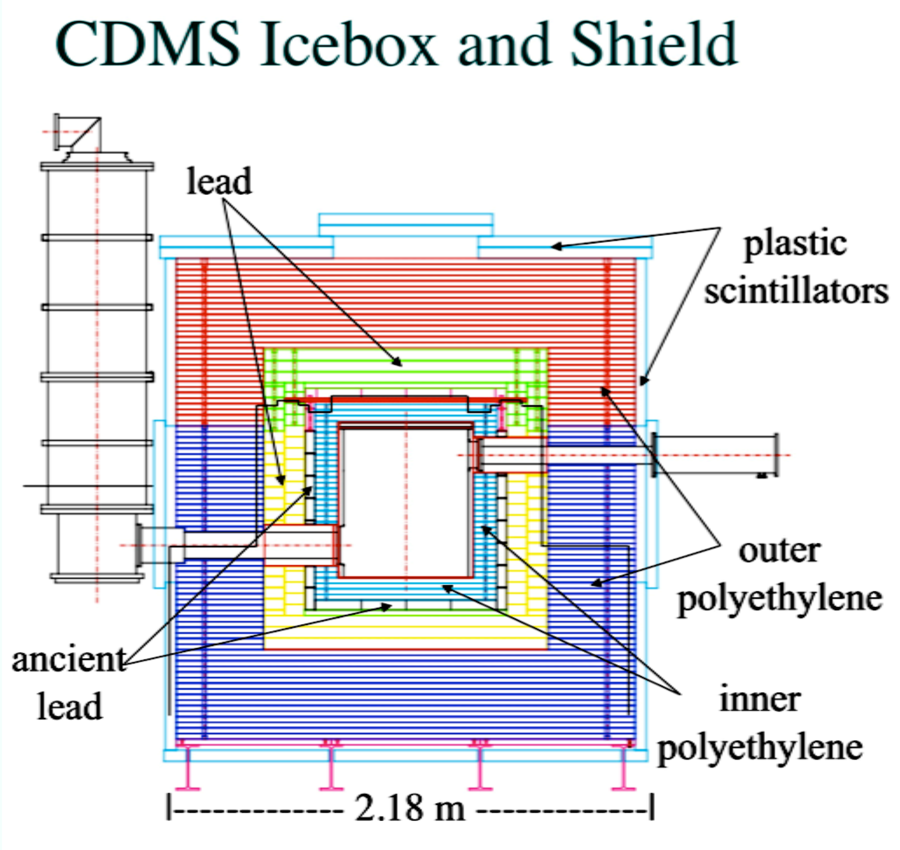
Chose $\left[\text{3 NR singles, vetoed} \right]_{\text{data}} * \varepsilon_{\text{neutron}} * \left[\dfrac{\text{NR singles, unvetoed}}{\text{NR singles, vetoed}} \right]_{\text{MC}}$

$0.04^{+0.04}_{-0.03}$ (stat) events

Spontaneous fission and (α-n) reactions

Lead/Poly Shielding
Effective shielding of low energy neutrons from rock radioactivity
But
Generates neutrons via SF and (α-n)





Spontaneous fission and (α-n) reactions

GEANT4 MC determines # single NR based on U/Th (and $^{40}K/^{60}Co$) content in lead, poly, copper cans, tower assemblies

MC Input

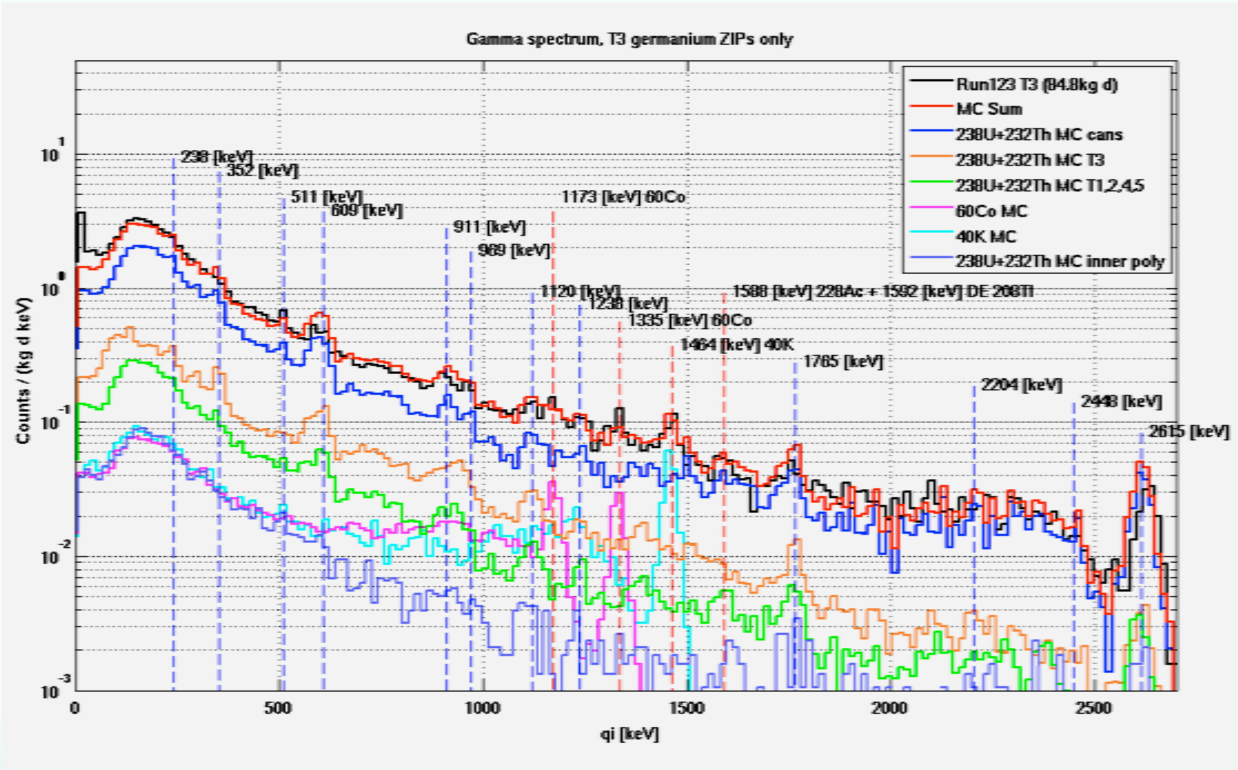
(1) Screening of materials using γ detectors

(2) Match detector γ spectrum to global fit of contaminant spectra

Estimated background in this data set

(dominated by Cu cans)

.03 - .06 events



So what can we say about these 2 events?

- for the Blind Analysis

The probability to observe 2 or more surface events based on the estimated background is
20%

After including the neutron background, the probability to observe 2 or more events is
23%

We would have to reduce our exposure by 28%
and leakage to 0.4 events to get rid of both candidates

No additional events would enter the signal region until we increase the revised surface event estimate to 1.7 events

Our results cannot be interpreted as significant evidence for WIMP interactions. However, we cannot reject either event as signal either.

Spin Independent Limit (90% CL)

Optimum Interval Method (Yellin) with 2 events
Not background subtracted

CDMS 2009

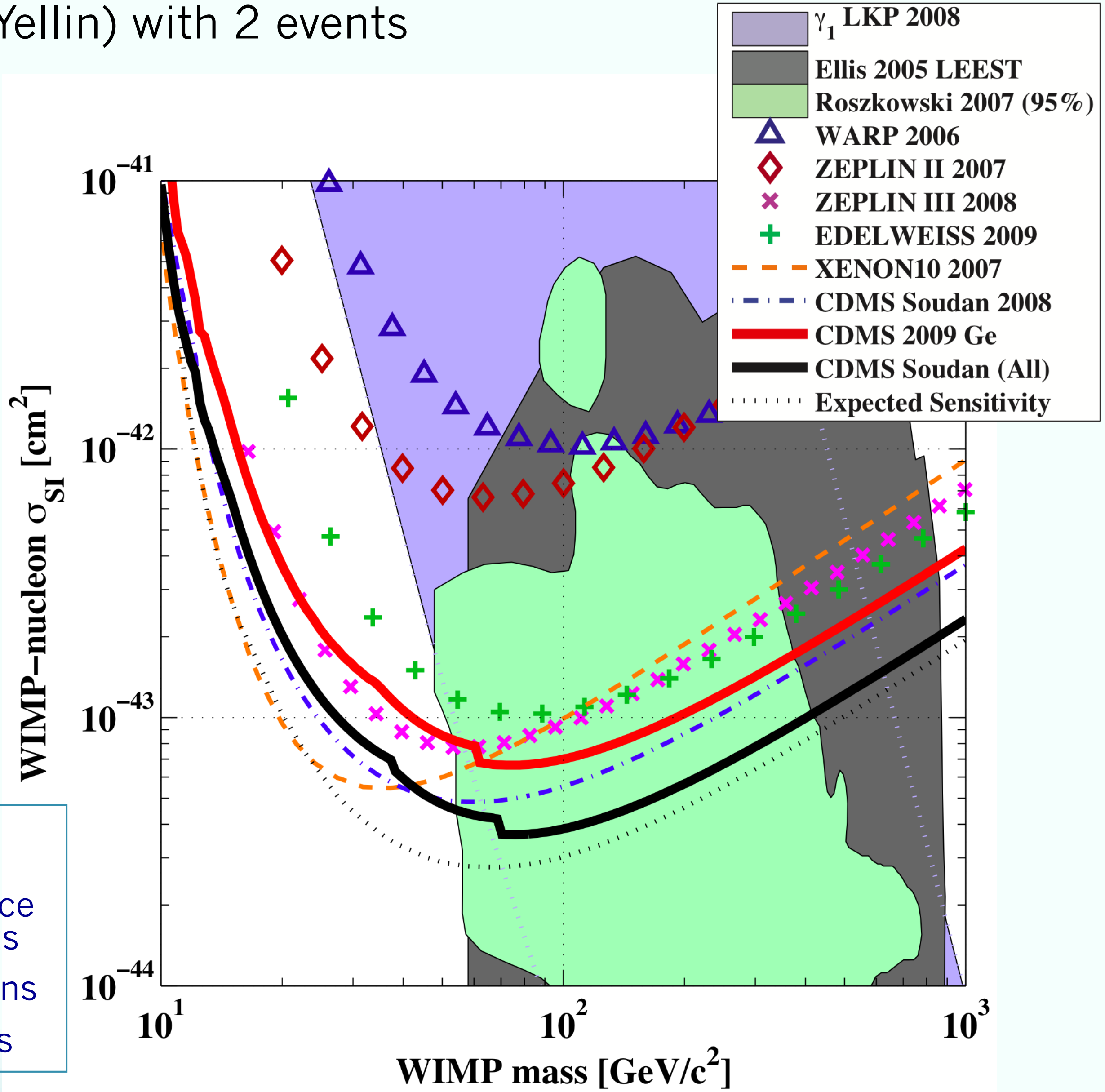
$\sigma = 7.0 \times 10^{-44}\ cm^2$
@ $m_\chi = 70$ GeV

CDMS Combined Soudan

$\sigma = 3.8 \times 10^{-44}\ cm^2$
@ $m_\chi = 70$ GeV

Sensitivity curve assuming:

0.8 ± 0.1(stat.) ± 0.2(sys.) surface events
0.01 - 0.08 cosmogenic neutrons
0.03 - 0.06 radiogenic neutrons



What's Next?

We were committed to presenting a Blind Analysis of our Results.

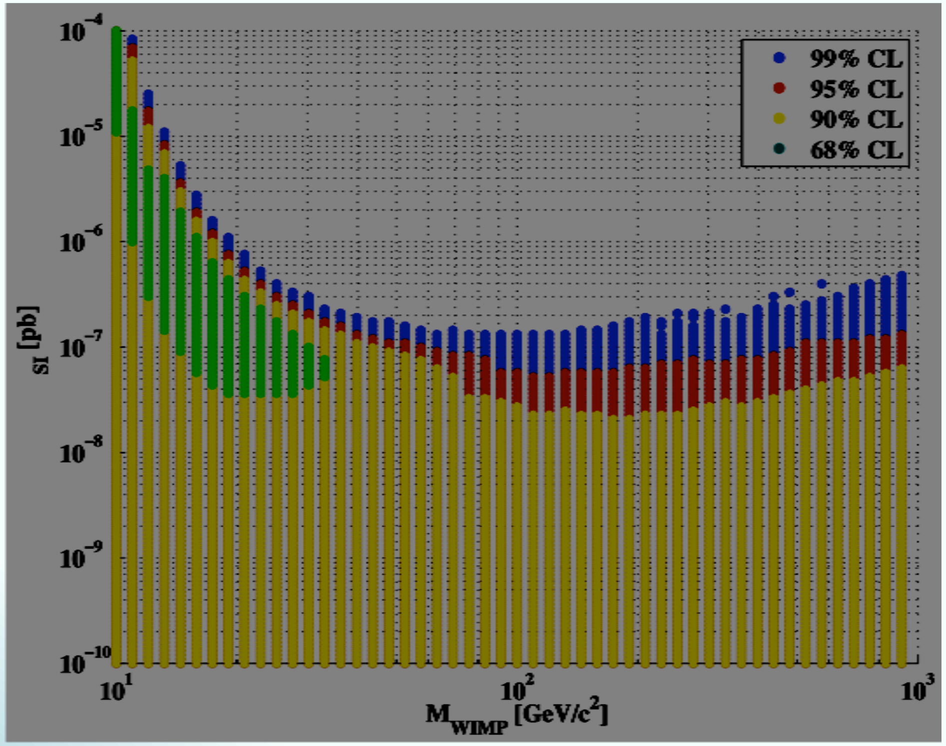
1. Define a "box" in an unbiased manner
2. Count number of events inside
3. Form limit without background subtraction
   Optimal Interval or Maximum Gap

Now we are reanalyzing the data – Summer 2010

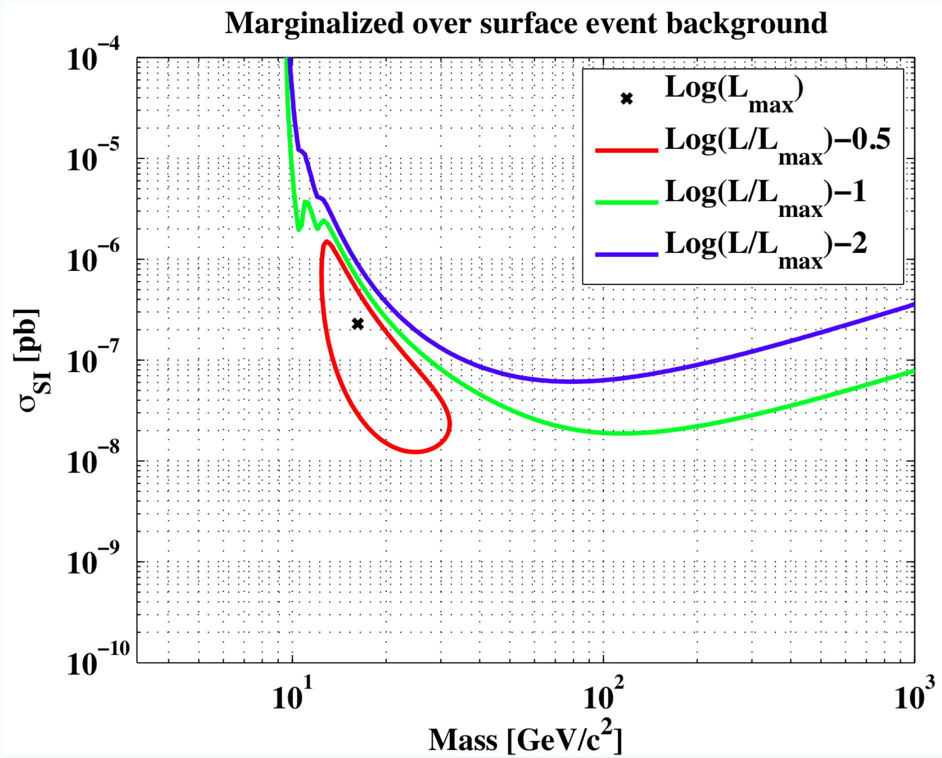
1. Revise our optimal filter routine (min ChiSq)
2. Fit backgrounds into our signal region
3. Re-optimize exposure vs timing cut
4. Do full Feldman-Cousins and Likelihood Analysis
5. Possibly over the entire set of runs 123-128

Preview of Coming Attractions

Feldman-Cousins

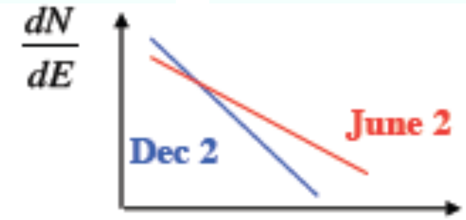


Log-Likelihood

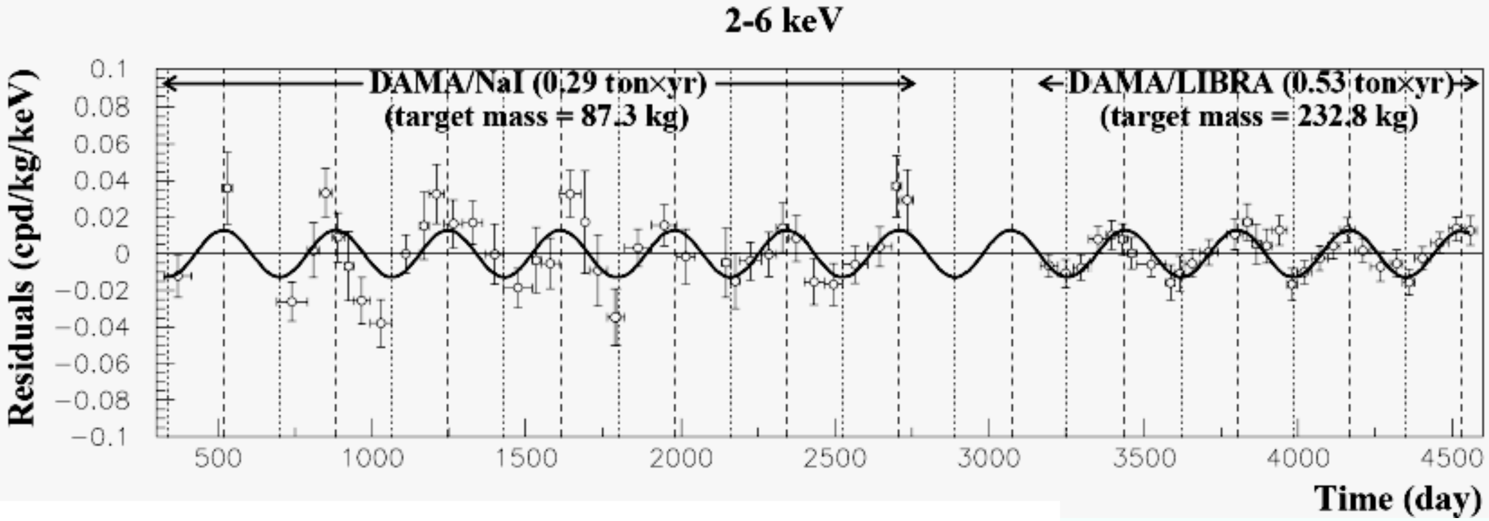


Caution – we are now moving away from a Blind Analysis.
This requires a full study of our backgrounds in the region of the candidate events. Preliminary work has started on this.

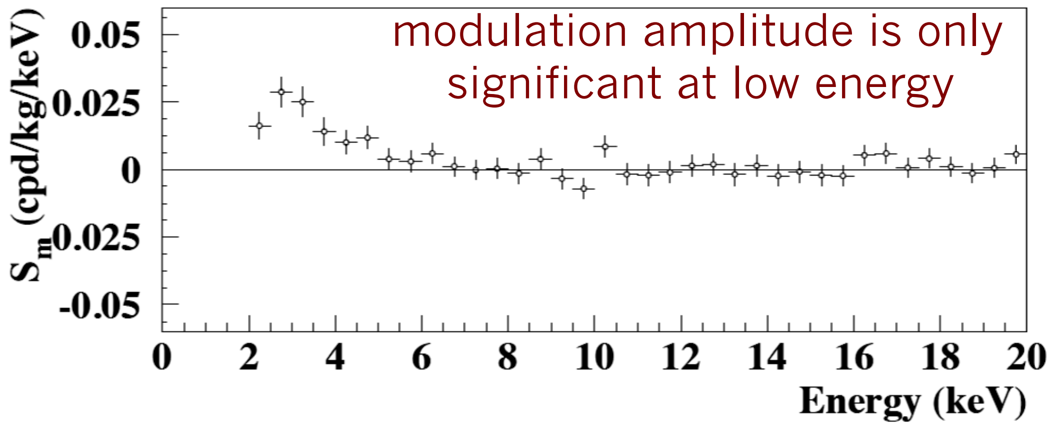
Annual Flux Variation



DAMA/LIBRA exposure = 0.82 ton-years of NaI(Tl) at LNGS



arXiv:0804.2741
arXiv:0804.2738



modulation amplitude is only significant at low energy

an amplitude $A_m = 0.0131 \pm 0.0016$
a period of $\omega = 0.998 \pm 0.003$ years
a phase max at $t_0 = 144 \pm 8$ days
with significance C.L. = 8.2σ

DAMA **Not Compatible** with other experiments:
Try modifying your assumptions

Non-standard halos, DM streams, caustics

Light WIMPs that interact with electrons

Axion-like relic particles

XDM, IDM help explain Integral 511 keV line, Pamela antimatter excess

XDM: Exciting DM $\chi^* + N \rightarrow \chi + N$

range of possible downscatters, rich spectrum, heavy WIMPs

IDM: Inelastic DM $\chi + N \rightarrow \chi^* + N$

Low energy recoils suppressed
Heavier tgt has smaller threshold velocity
Enhanced modulation

For a given E_r, need min v for a heavier χ^* ($\delta \sim 100$ keV)

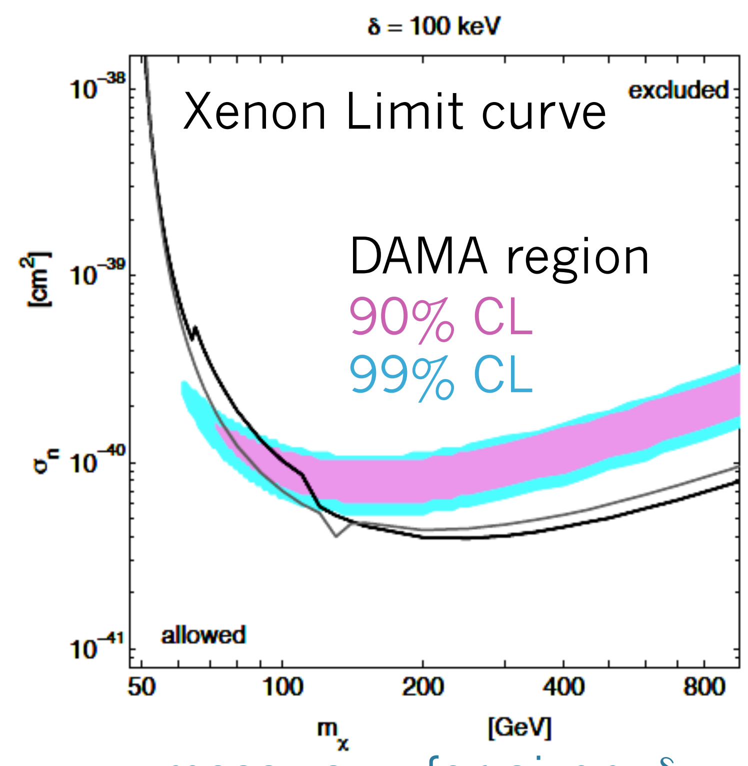
$$v_{min} = \sqrt{\frac{1}{2m_N E_R}}\left(\frac{m_N E_R}{\mu_1} + \delta\right)$$

Inelastic Dark Matter: χ+N→ χ^* + N with mass difference δ

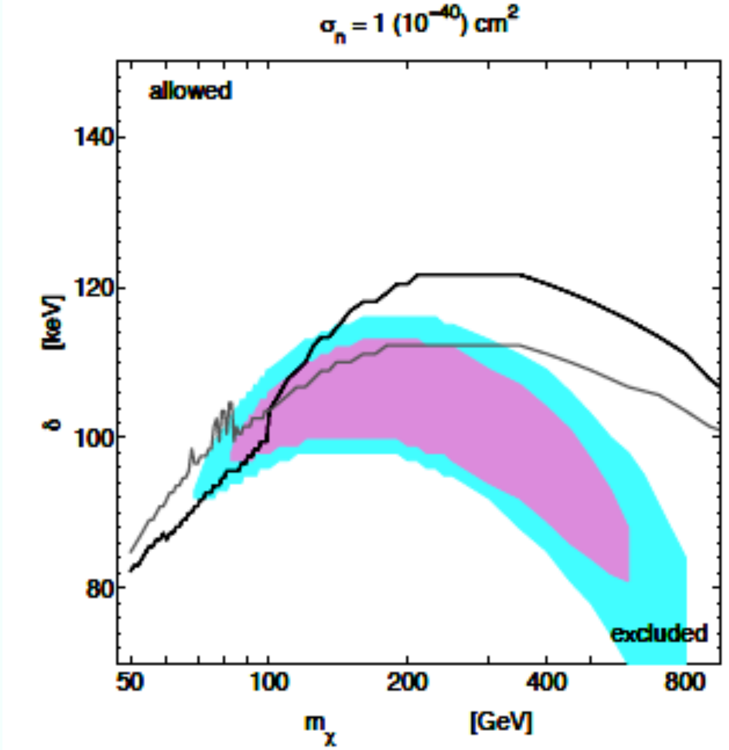
Range : δ = 0 (elastic scatter) to δ =170 keV for m_χ = 100 GeV and v_{esc} = 500 km/s

R. Bernabei et al., Eur. Phys. J. C. 56 333 (2008).
S. Chang, G. Kribs, D. Tucker-Smith and N. Weiner, Phys. Rev. D 79, 043513 (2009)

Example plots from XENON10 *Phys. Rev. D 80, 115005 (2009)*



mass vs σ for given δ

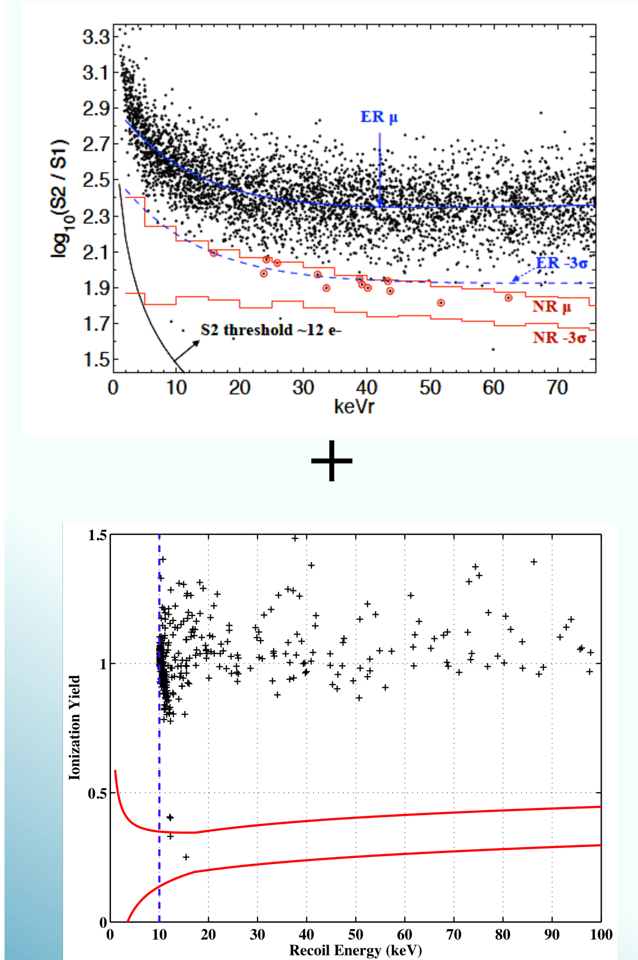


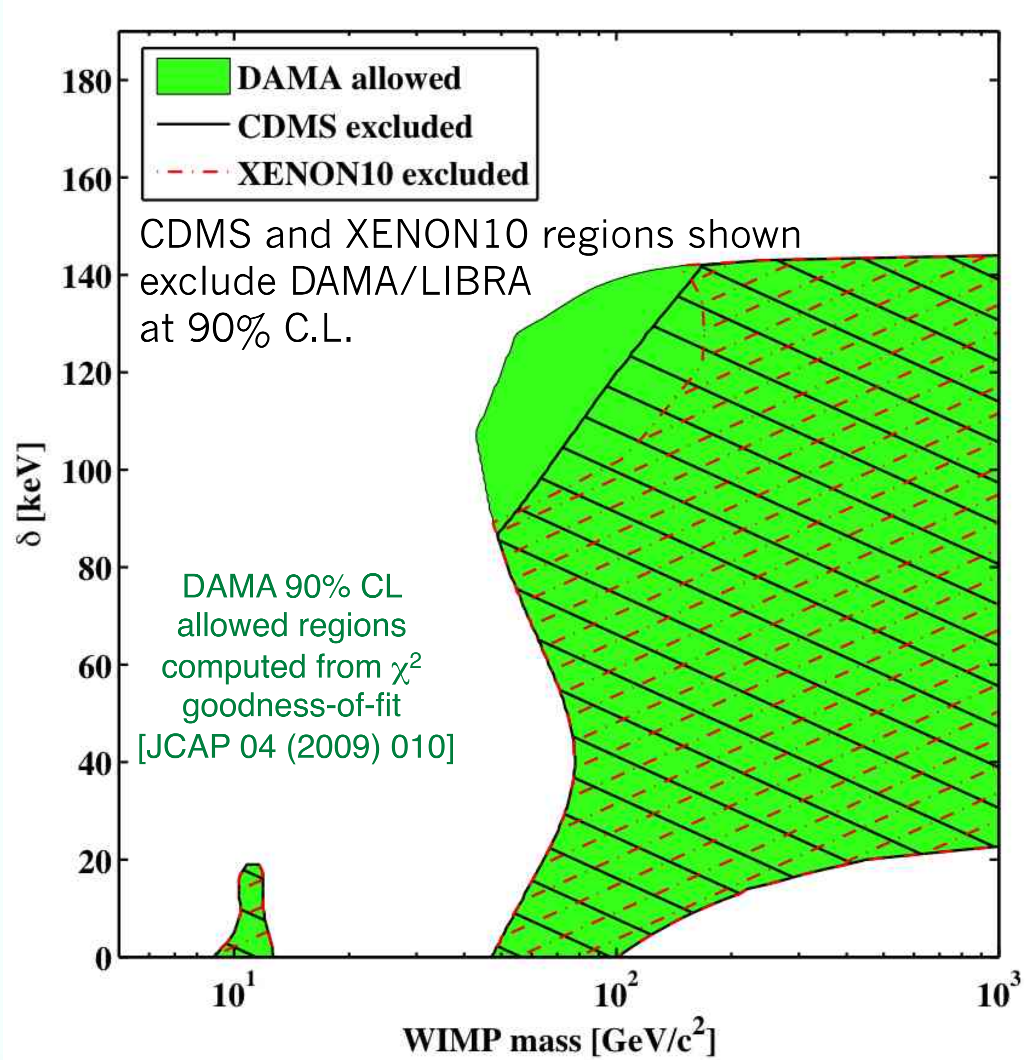
mass vs δ for given σ

Scan over the range of allowed δ, m_χ

Inelastic Dark Matter: χ+N→ χ^* + N with mass difference δ

This disfavors all DAMA/LIBRA allowed region except for WIMPs of mass ~100 GeV with δ ~80-140 keV





Cryogenic Techniques at mK: Future

CDMS ➔ SuperCDMS Soudan (15 kg, 2010)

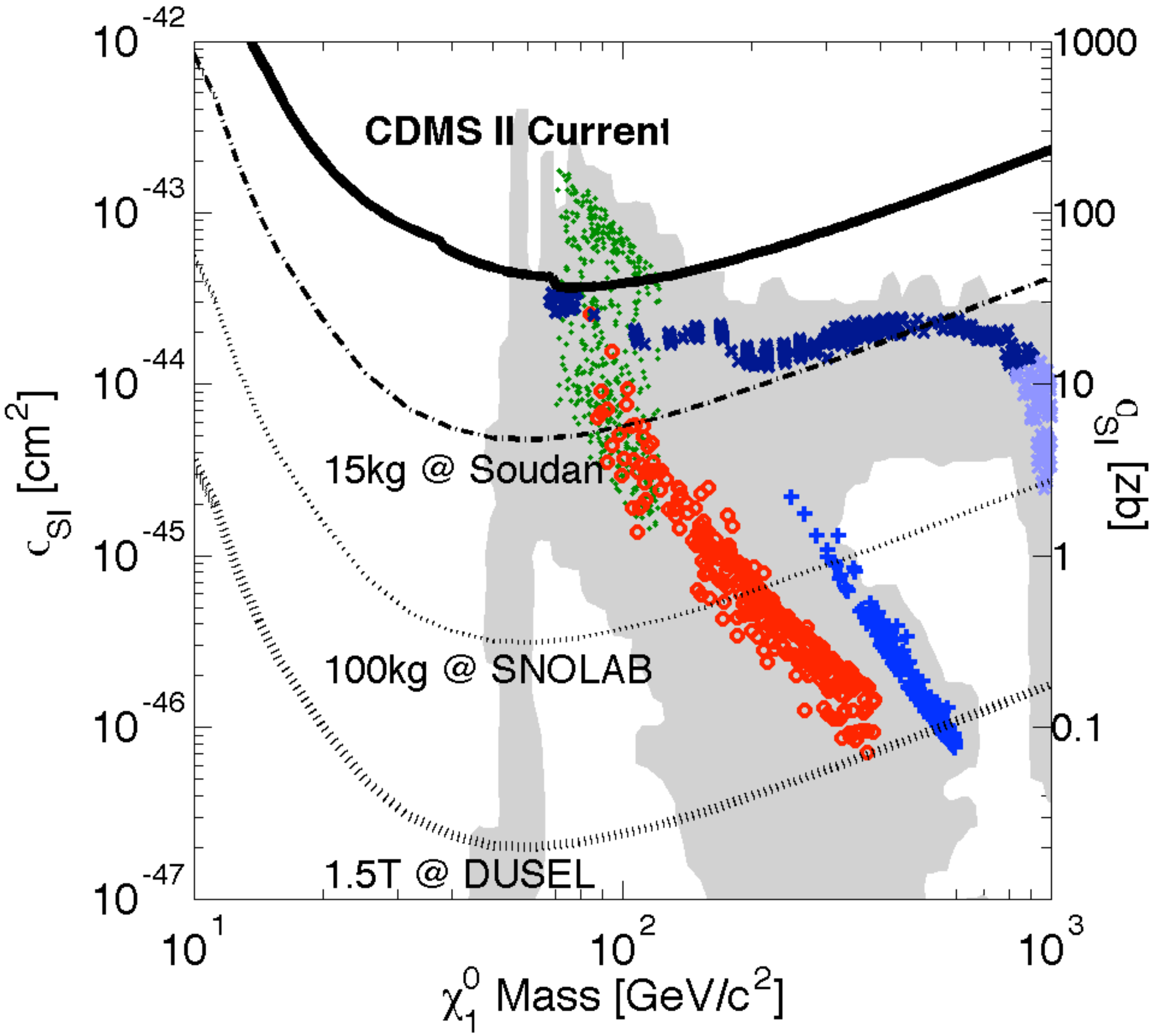
➔ SuperCDMS SNOLab (100 kg, 2012)

Cleaner and Deeper, SuperCDMS detectors and R&D on GEODM crystals.

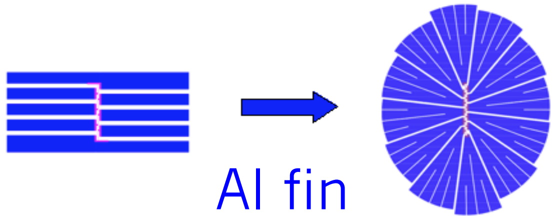
➔ GEODM (1.5T, DUSEL-2017)

Cost-effective scaling of TES via larger crystals, multiplexing, mass production, cryogen-free fridge

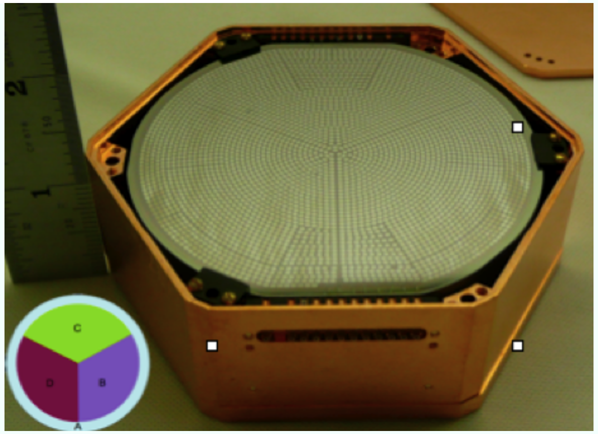
Sensitivity Reach



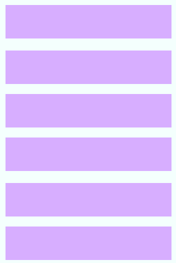
Al fin



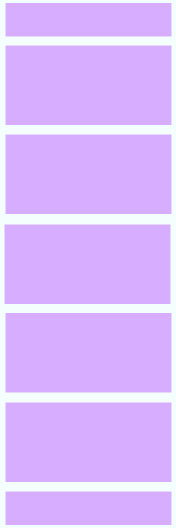
SuperCDMS underway



"mercedes" ZIP = mZIP



CDMSII Tower



SuperTower

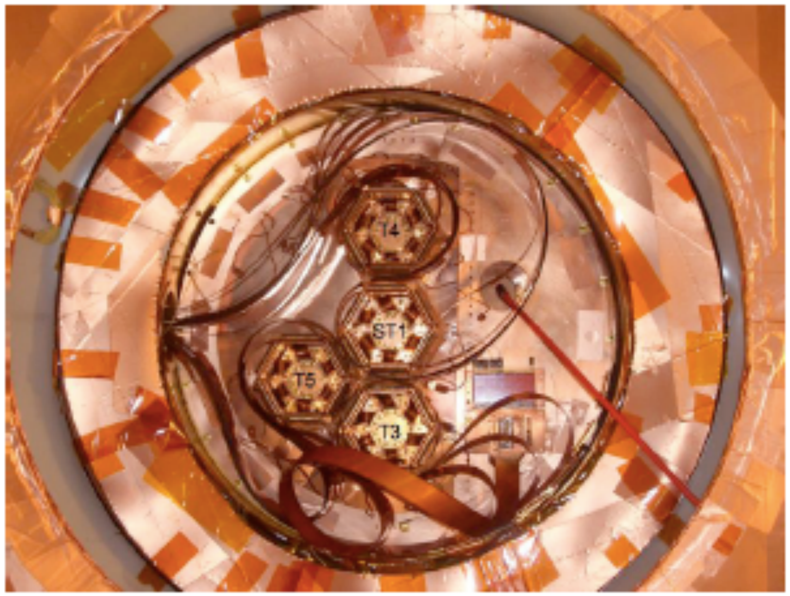
15 kg of Ge at Soudan in 5 SuperTowers

2.5X thicker (1-inch) Ge

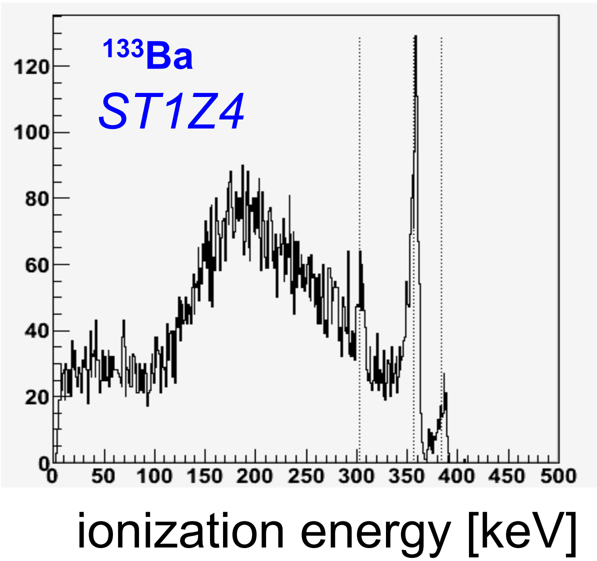
"endcap" Ge veto detectors

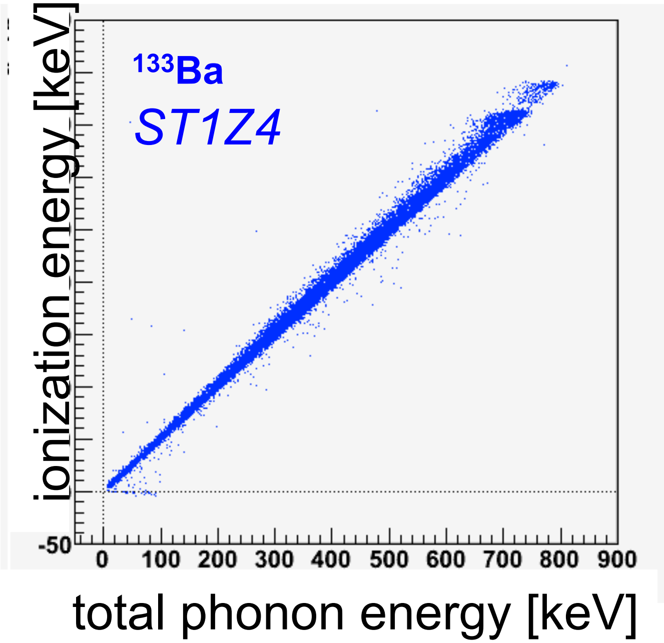
new Al fin pattern

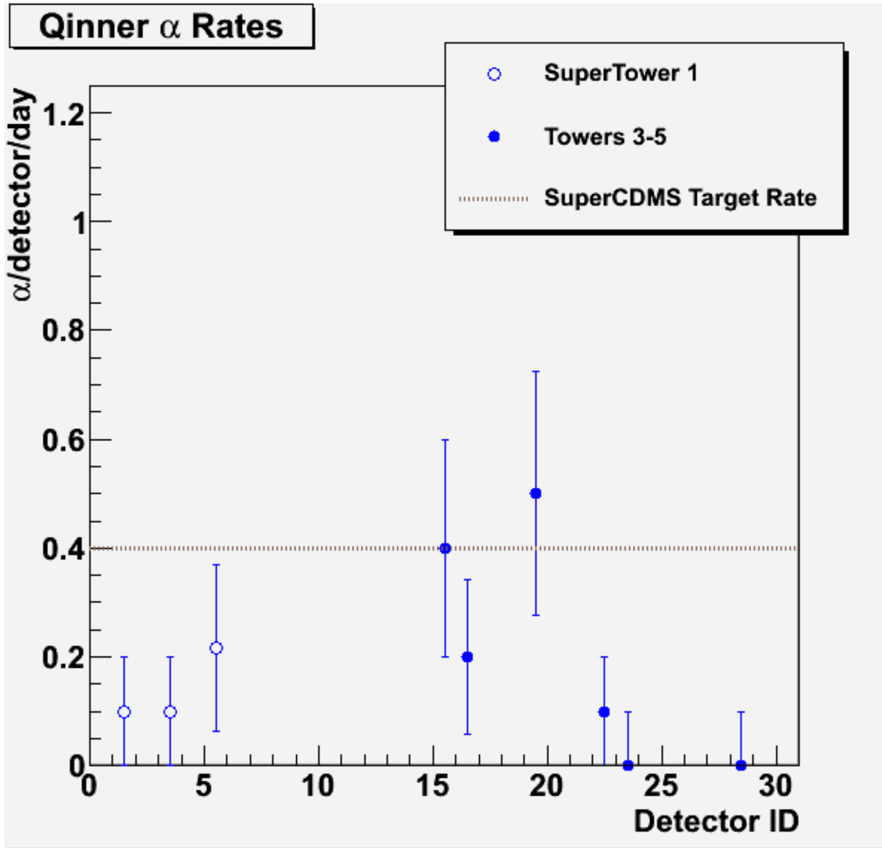
new channel configuration



SuperTower1 Performance





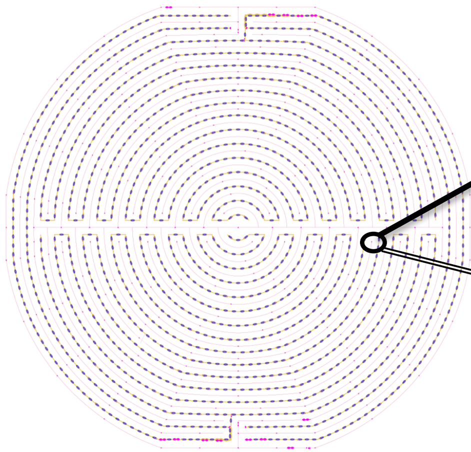


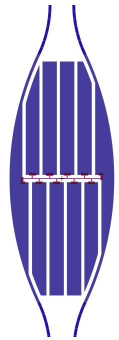
Backgrounds from Rn daughters lower than targeted goal

Even better detectors = iZIPs

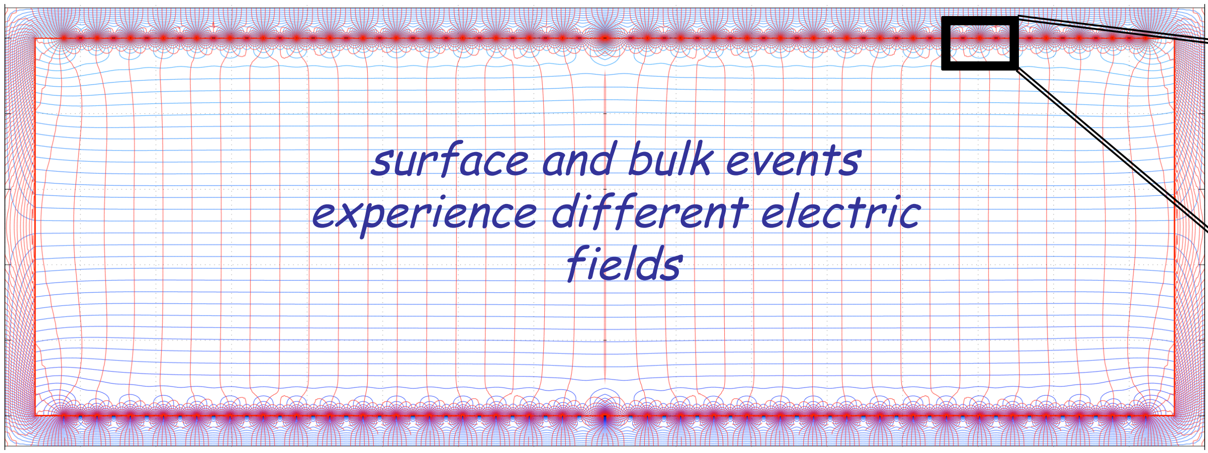
Interleavened charge and phonon channels

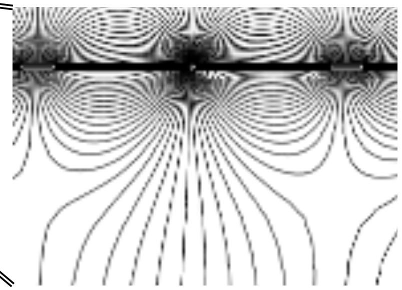
- first demonstration by CDMS in 2005 - *NIM A559 (2006)*
- EDELWEISS characterization of bkg rejection - *0905.0753*
- CDMS characterization of bkg rejection - *July 2009*





Closeup of phonon sensor

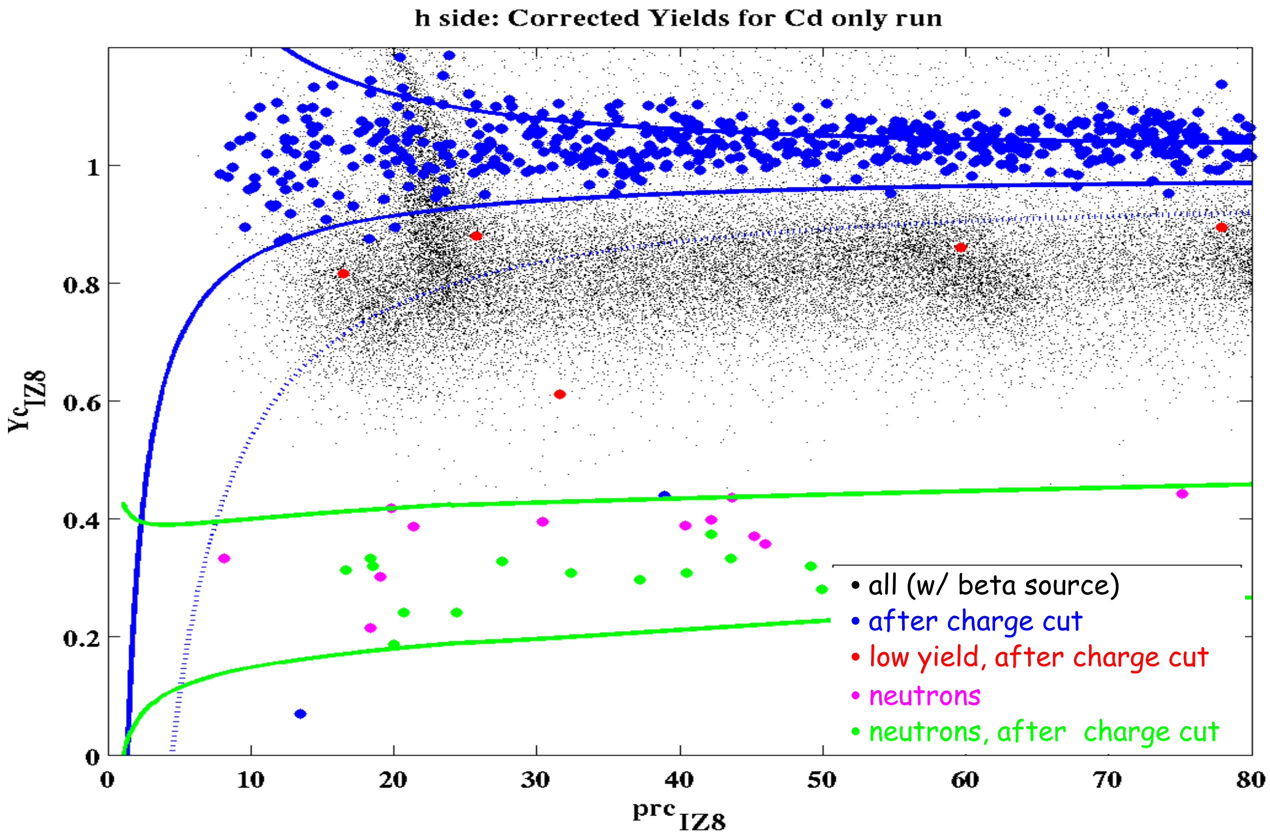




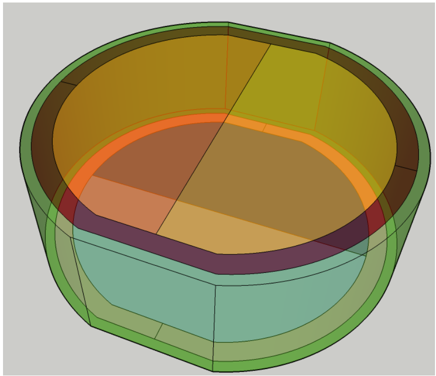
Charge near surface is collected by electrodes on ony one side

iZip Surface Event Rejection

1/3000 rejection of surface events in NR band based only on charge collection



- roughly X10 better than CDMS-II style detectors !
- efficiency for neutrons passing charge cut is ~55%



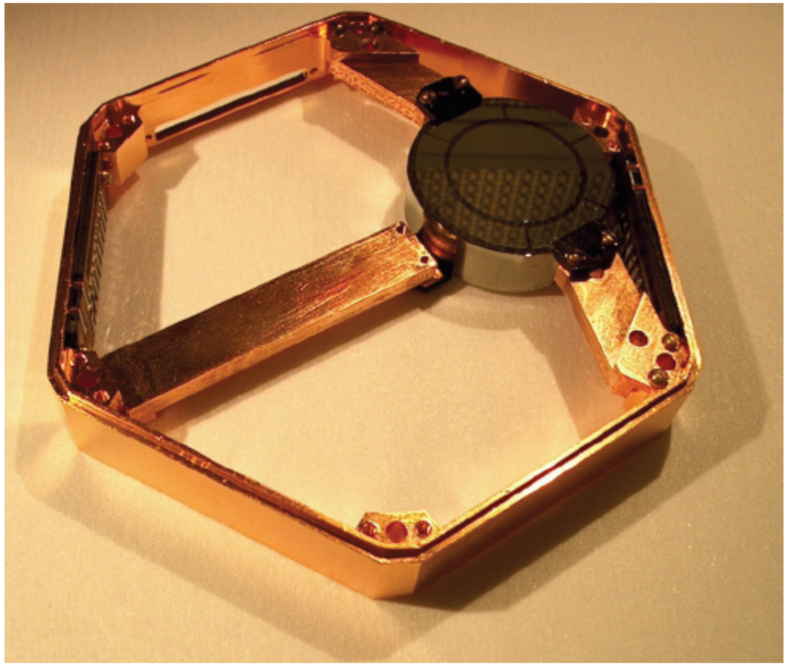
bonus: phonon sensors on both sides provides additional depth information

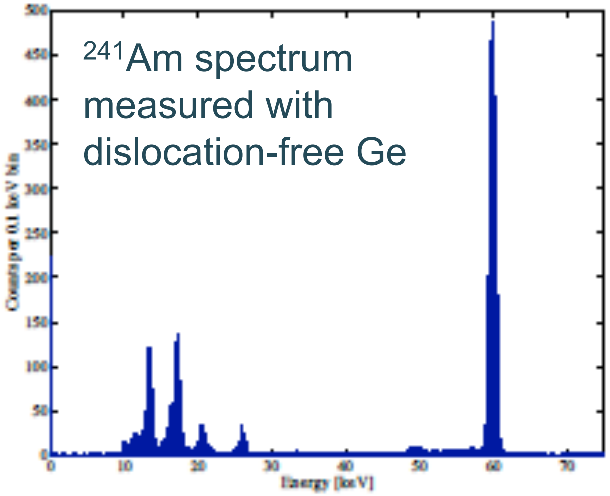
GEODM Detectors
large and cheaply mass-produced by industry

Why dislocation free?

dislocation-free Ge is available in larger diameters than “detector-grade”

CDMS is investigating possibilities for 6-inch diameter or larger substrates





UCB TF demonstration of ionization collection with dislocation-free Ge crystal

Wired Magazine got it right last year

"The discovery of dark matter will not be a eureka moment. It will almost certainly start off as a contentious, tentative sighting that scientists argue about for years."

Let There Be Light! *by Hazel Muir - 04 August 2009*

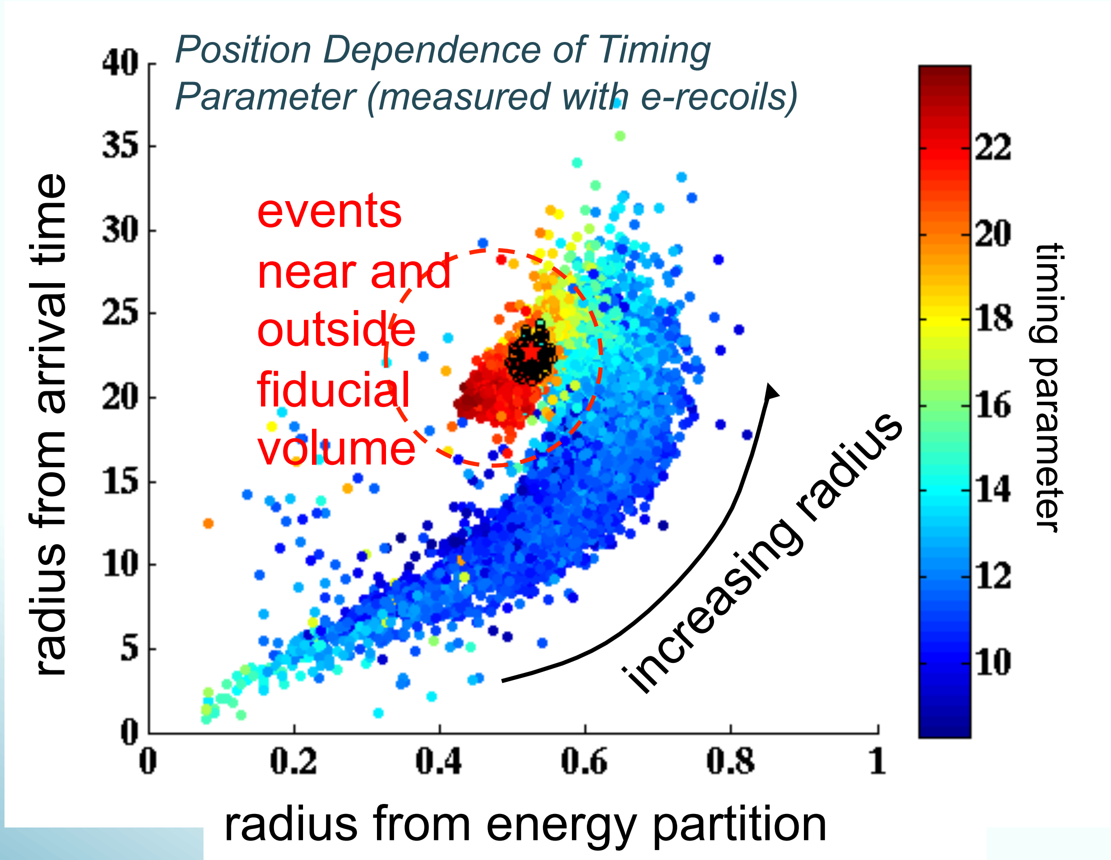
http://www.wired.co.uk/wired-magazine/archive/2009/09/features/let-there-be-light!-the-search-for-dark-matter.aspx

CDMS in Real Life

Phonon Position Correction

Timing and energy response vary across the detector

Construct a lookup table from ^{133}Ba data to correct the variation



Neither partition nor arrival time provide a unique measurement of position at high radius. Together, they unfold the degeneracy.

2009 Improvement:

Include events just outside the fiducial volume to better correct events at high radius.

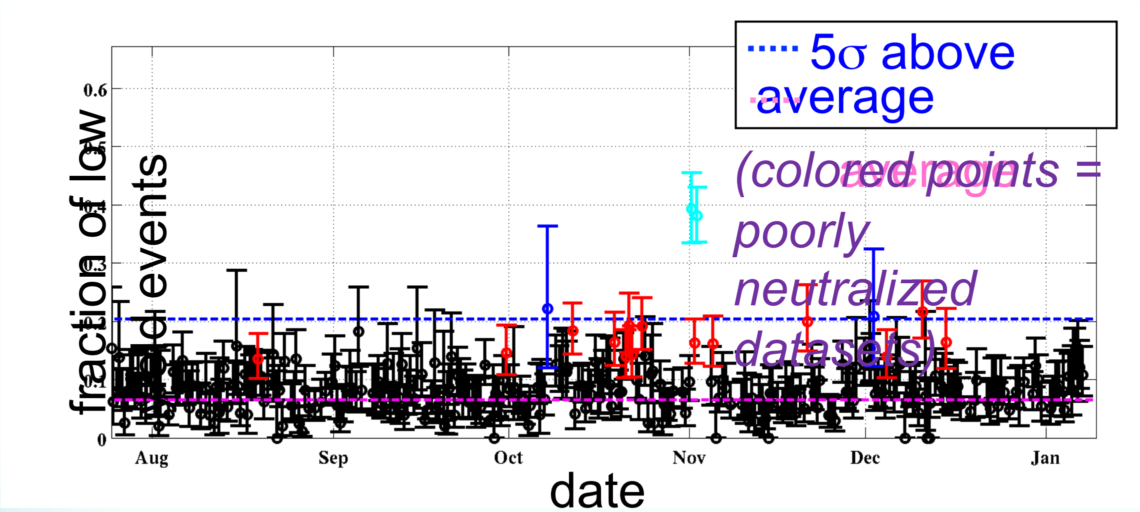
→ Significantly reduces timing outliers (we cut on the tails)

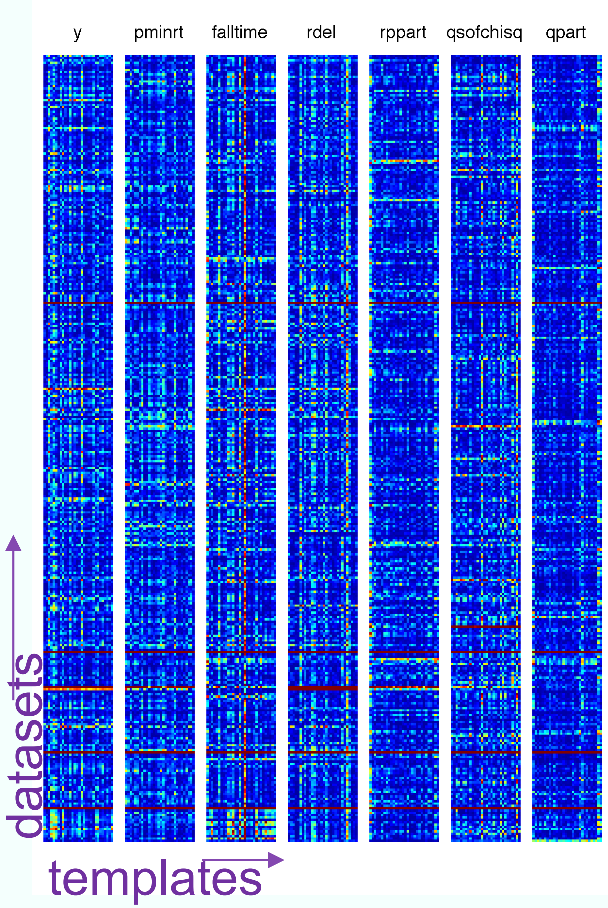
Data Quality Monitoring

sounds mundane, but its important!

checking data consistency against 7 reconstructed parameters

Regular flashing with LED's "neutralizes" ion trapping centers.





Visual representation of KS-tests

Data quality checks ensure the data was taken during good periods of neutralization.

Surface Event "Leakage" (3 ways)

3 independent methods to estimate the number of expected surface events

CDMS Vocabulary Lesson:

SS = single scatter event

MS = multiple scatter in adjacent detector

NR = event within 2σ nuclear-recoil band

WB = low yield events surrounding nuclear-recoil band

f = fraction of events passing surface-event rejection cut

METHOD 1

(*f* - from WIMP search dataset)

$$\text{leakage}_1 = N_{NR,SS} * f_{NR,MS}$$

METHOD 2

(*f* - from WIMP search dataset)

$$\text{leakage}_2 = N_{NR,SS} * f_{WB,MS}(\text{face}, E_{recoil})$$

METHOD 3

(*f* - from Ba dataset)

$$\text{leakage}_3 = N_{NR,SS} * f_{NR+WB,MS}(\text{face}, E_{recoil})$$

Surface Event Leakage Estimate

Method 1: least systematic uncertainty, but poor statistics and no estimate for endcap detectors

$\text{leakage}_1 = 0.5 \pm 0.3$ *(stat.)*

Method 2: includes endcap detectors, but added systematic uncertainty and poor statistics

$\text{leakage}_2 = 0.8 \pm 0.6$ *(stat.)*

Method 3: best statistical power, but most systematic uncertainty

$\text{leakage}_3 = 0.5 \pm 0.1$ *(stat.)*

$\text{leakage}_{\text{combined}} = 0.6 \pm 0.1$ (stat.)

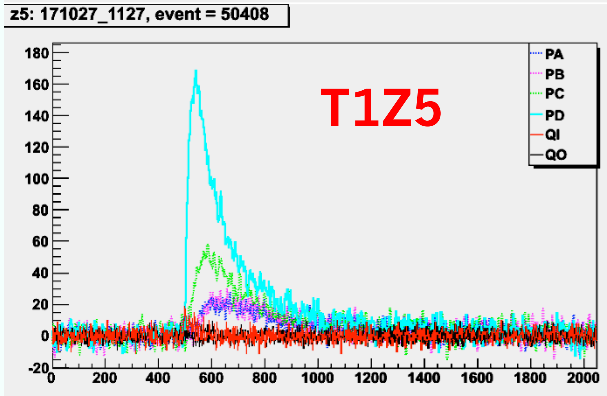
Check to make sure these are good events

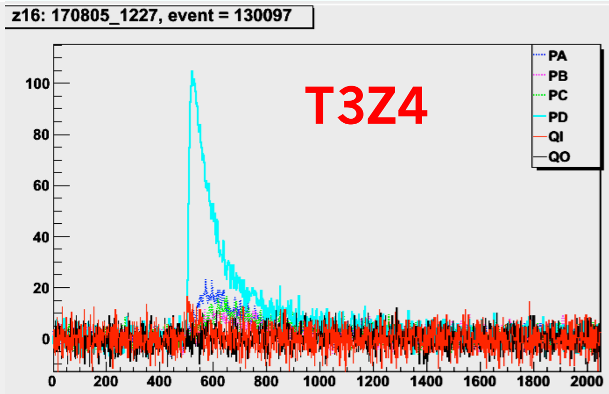
Check the event itself

Individual Pulses and fits

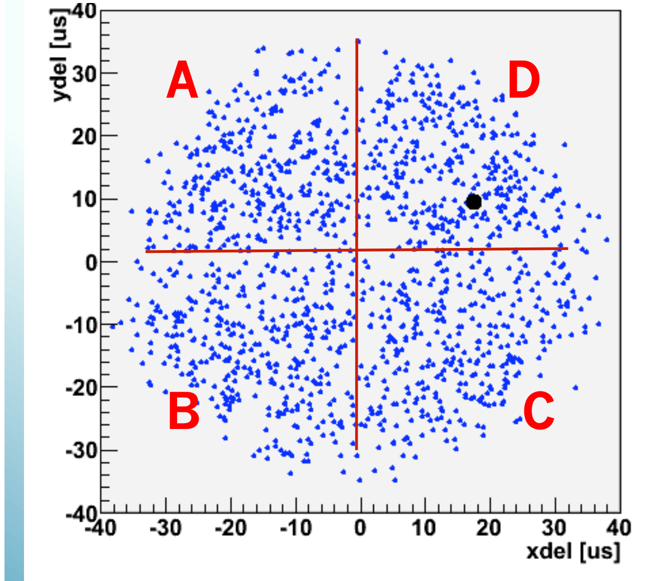
Noise baseline

All analysis parameters
(e.g. position, energy, etc)

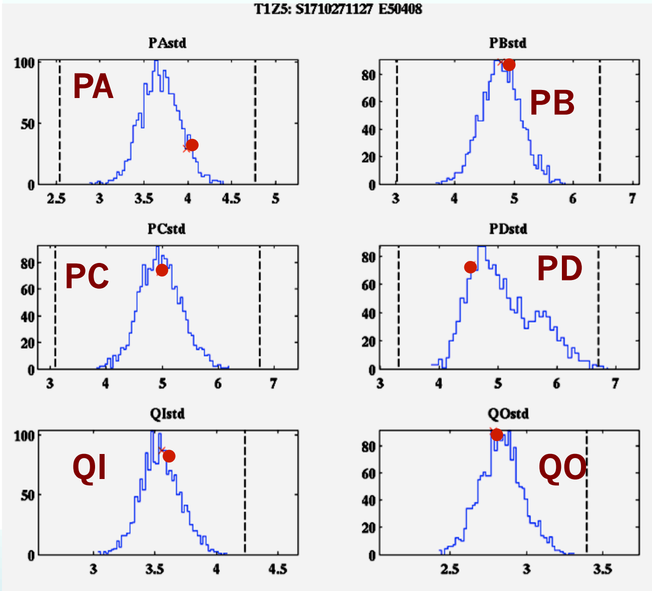


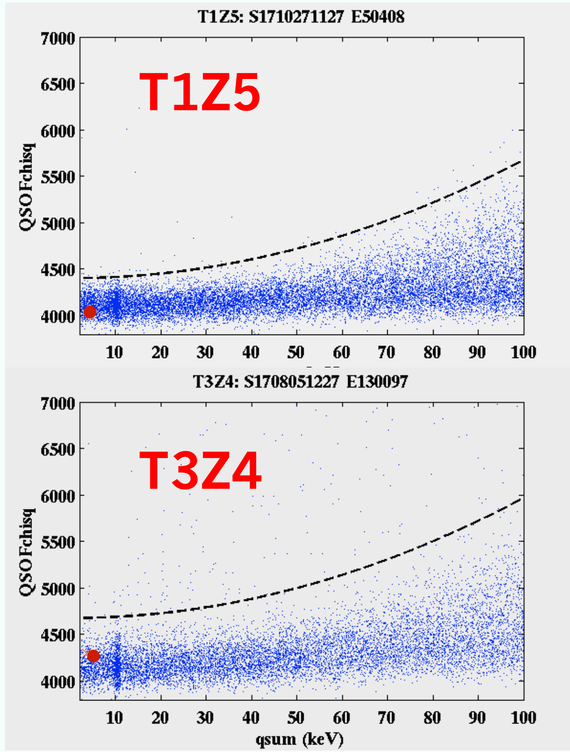


T1Z5 Position (Delay Plot)



prepulse baseline width

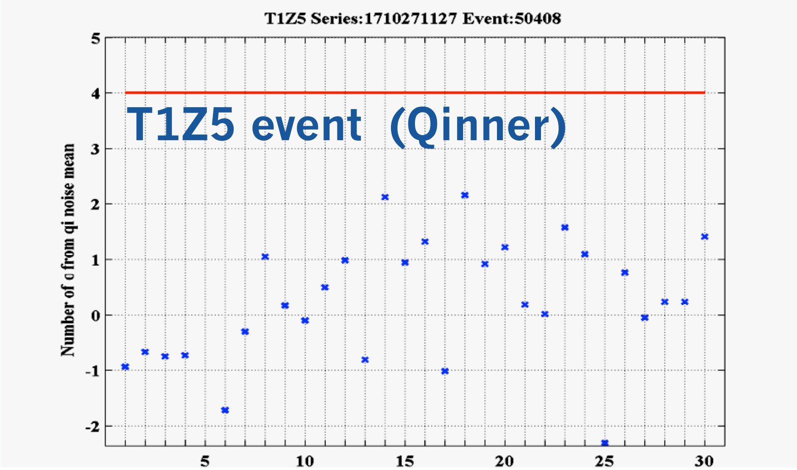


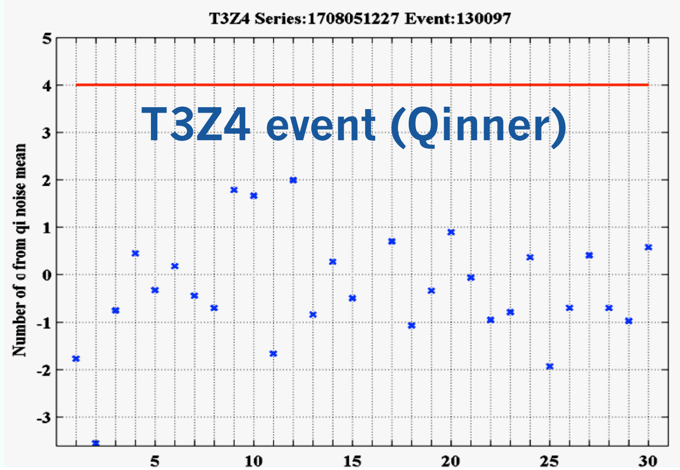


Check to make sure these are good events

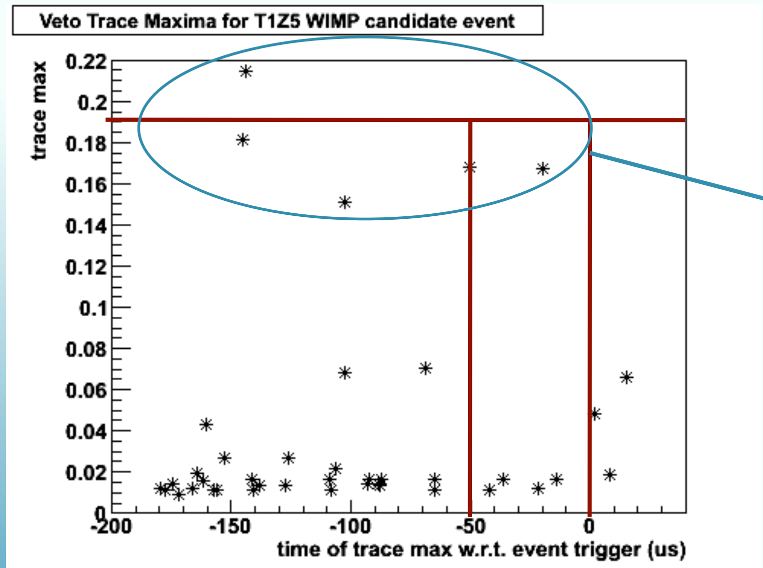
Check Other Detectors in same event $(Q_i, Q_o, P_{A\text{-}D})$

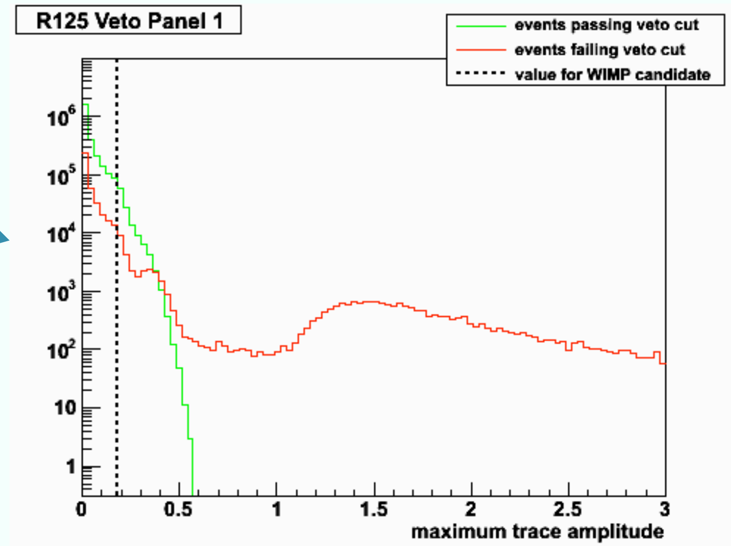
How many sigma away from baseline noise? ➔ True Single Events





Only typical noise in Veto Panel ➔ True Anti-Coincident Event

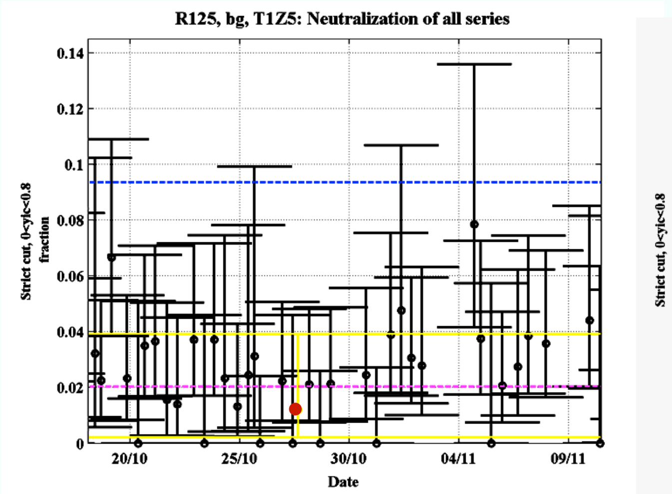


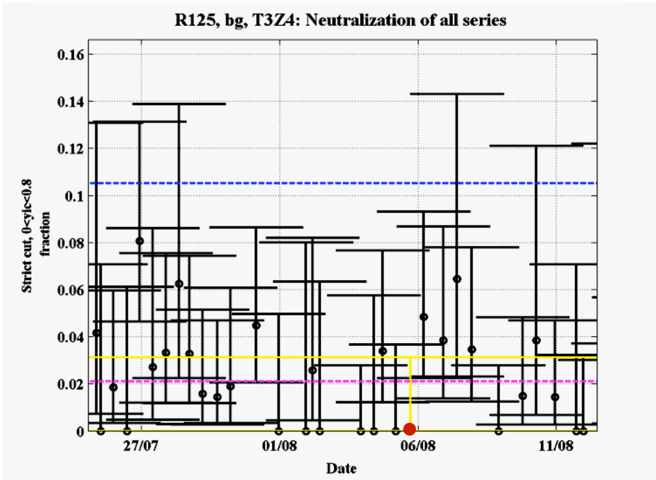


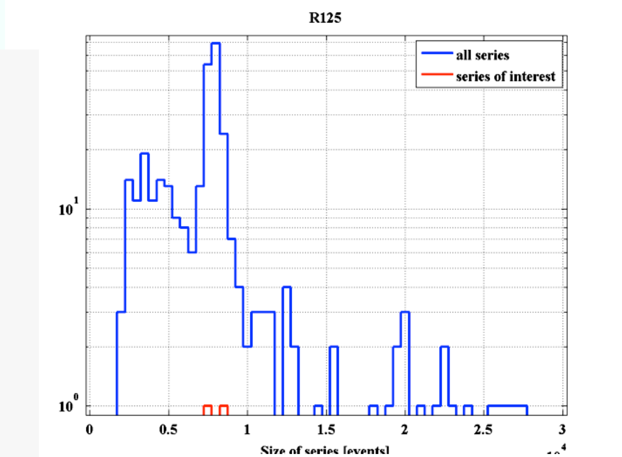
Check to make sure these are good events

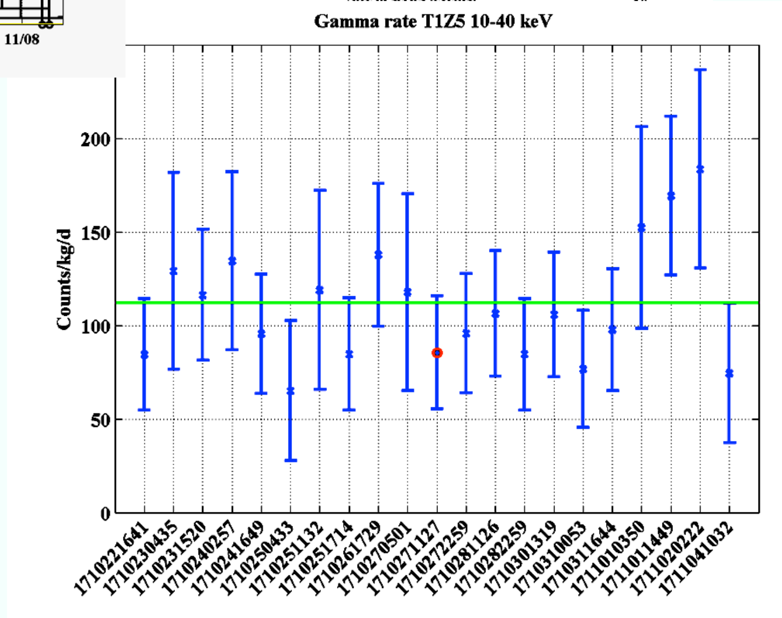
Check run series in which event occurs

Neutralization: Fraction of low-yield events & size of run series. **Typical**









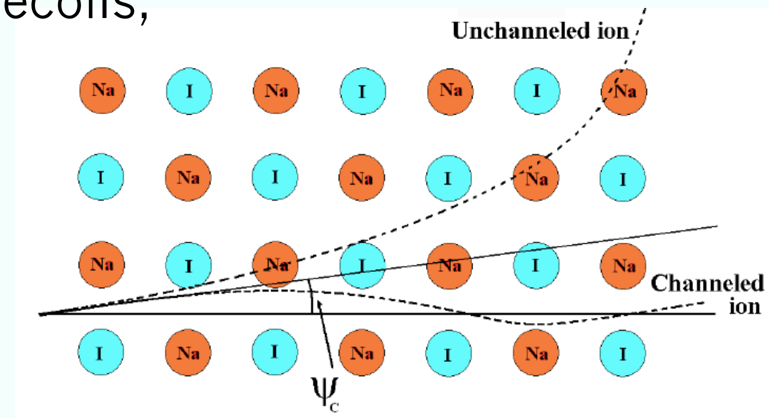
Check Kolmogorov-Smirnov tests for series.
Valid, good scores

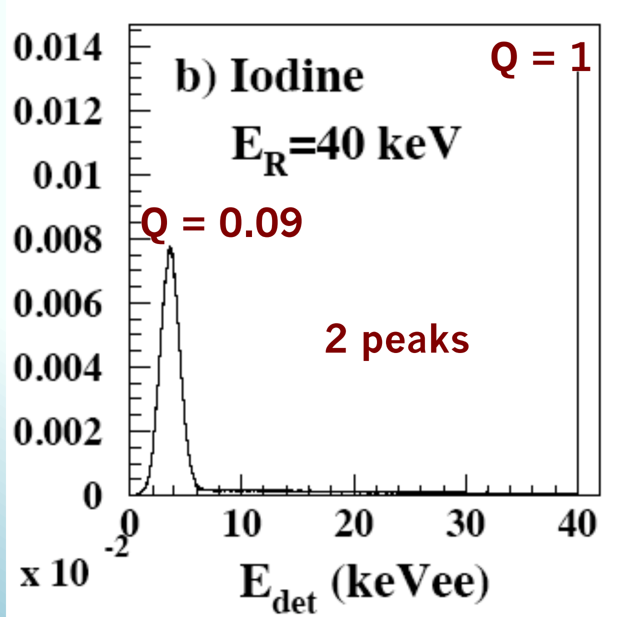
EM Rates (gamma and beta bands)
Typical

DAMA **Not Compatible** with other experiments:
Try Channeling

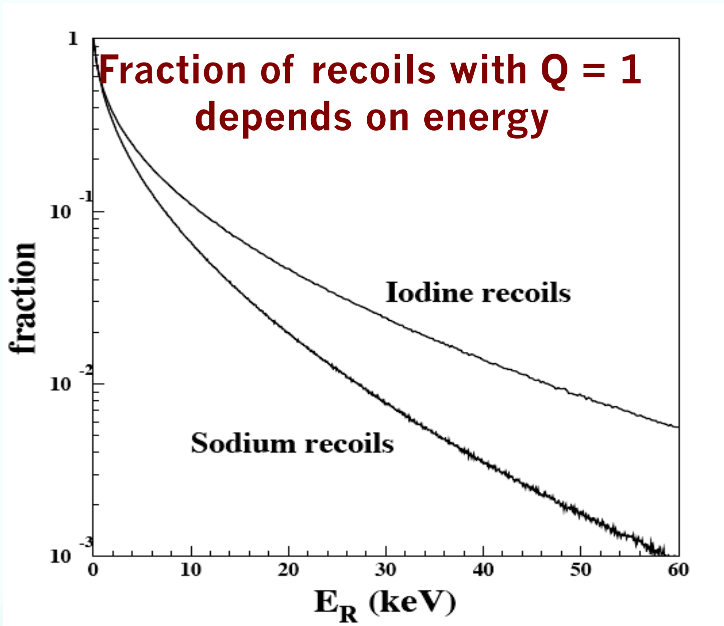
Q (light yield) = 0.09 for I recoils and 0.3 for Na recoils,

but Q = 1 if the ion (recoiling neutron) travels along lattice axis. Energy deposition is found in the ER channel





arXiv:0710.0288 (astro-ph)



DAMA gets extra sensitivity to low E and NR cuts eliminate signal.

Scattering Cross Sections

Spin Independent vs Spin Dependent

In general, a Lorentz invariant Lagrangian $\mathscr{L}$ has S, P, V, A interactions.
The WIMPs can be a fermion or a boson or a scalar particle
However, galactic WIMPs are non-relativistic ➔ divide into two categories

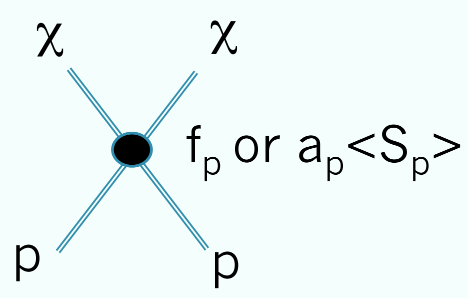
(a) $\mathscr{L}_{S+V}$: Scalar interaction as μA^2
(large λ_{dB} ➔ coherent interaction)

$$\sigma_{SI} = \frac{m_N^2}{4\pi(m_\chi + m_N)^2}\left[Zf_p + (A-Z)f_n\right]^2$$

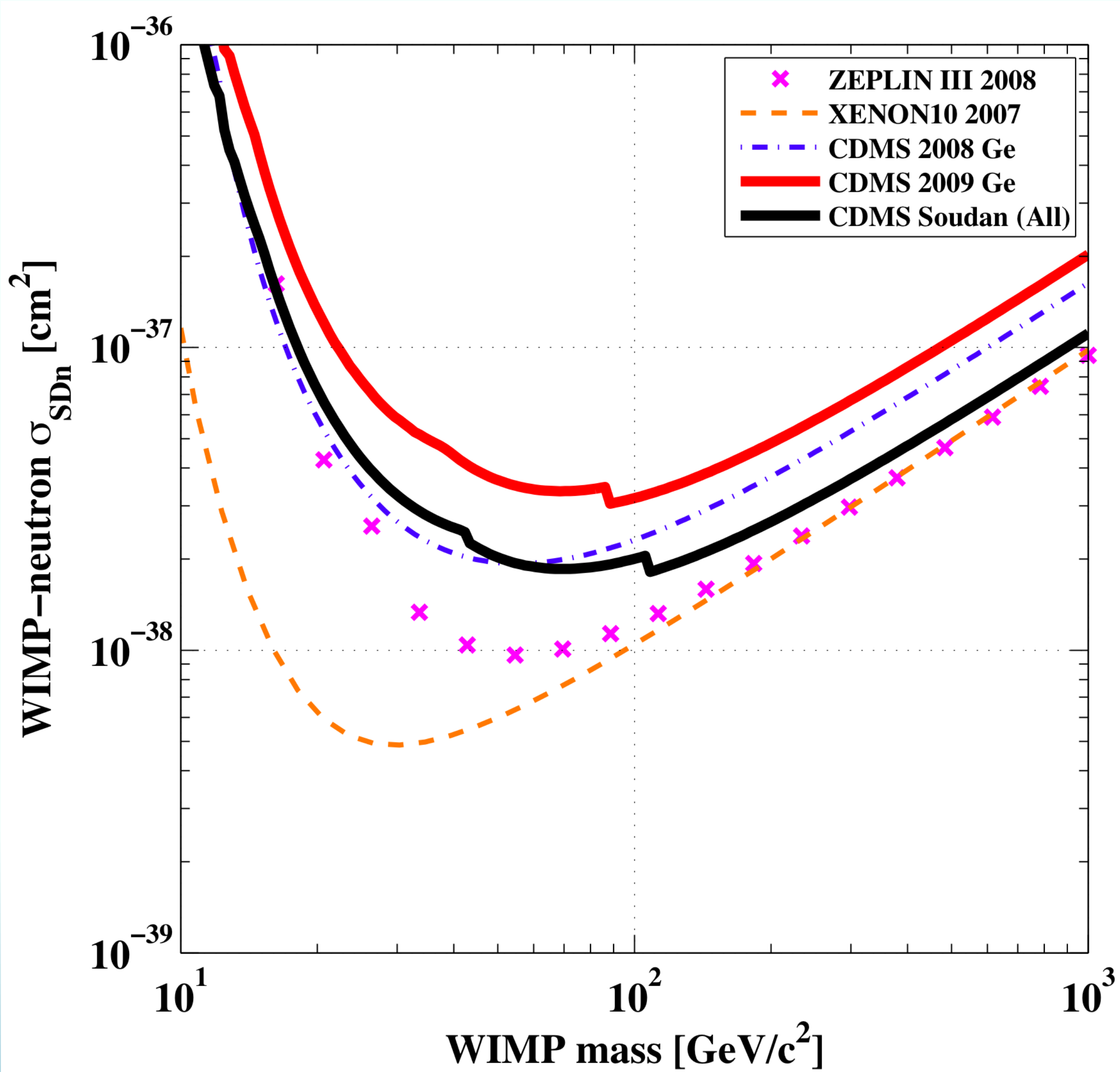
(b) $\mathscr{L}_A$ Spin-spin interaction couples to net nuclear spin J_N

$$\sigma_{SD} = \frac{32}{\pi}G_F^2 \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2}\frac{J_N+1}{J_N}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2$$

f and a are effective couplings and <S> gives the spin content

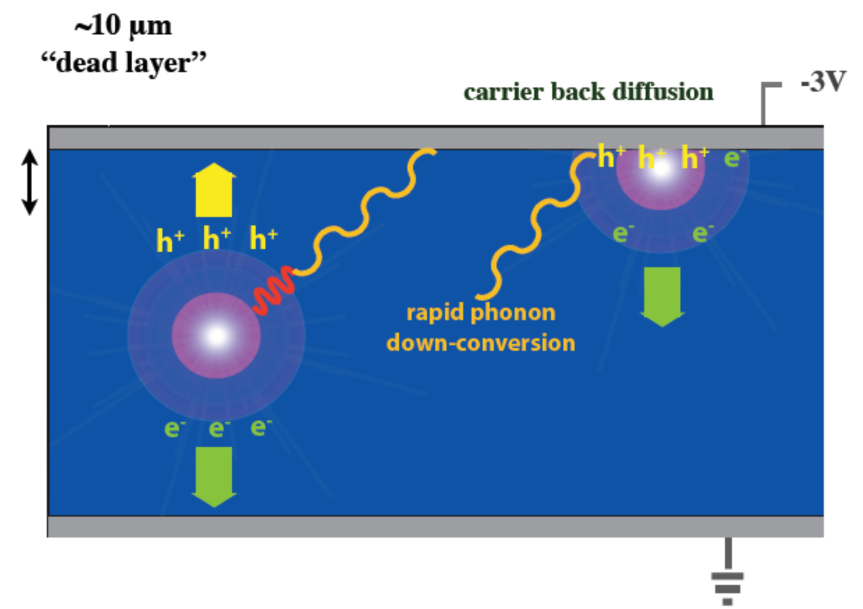


Spin Dependent Limit (90% CL)



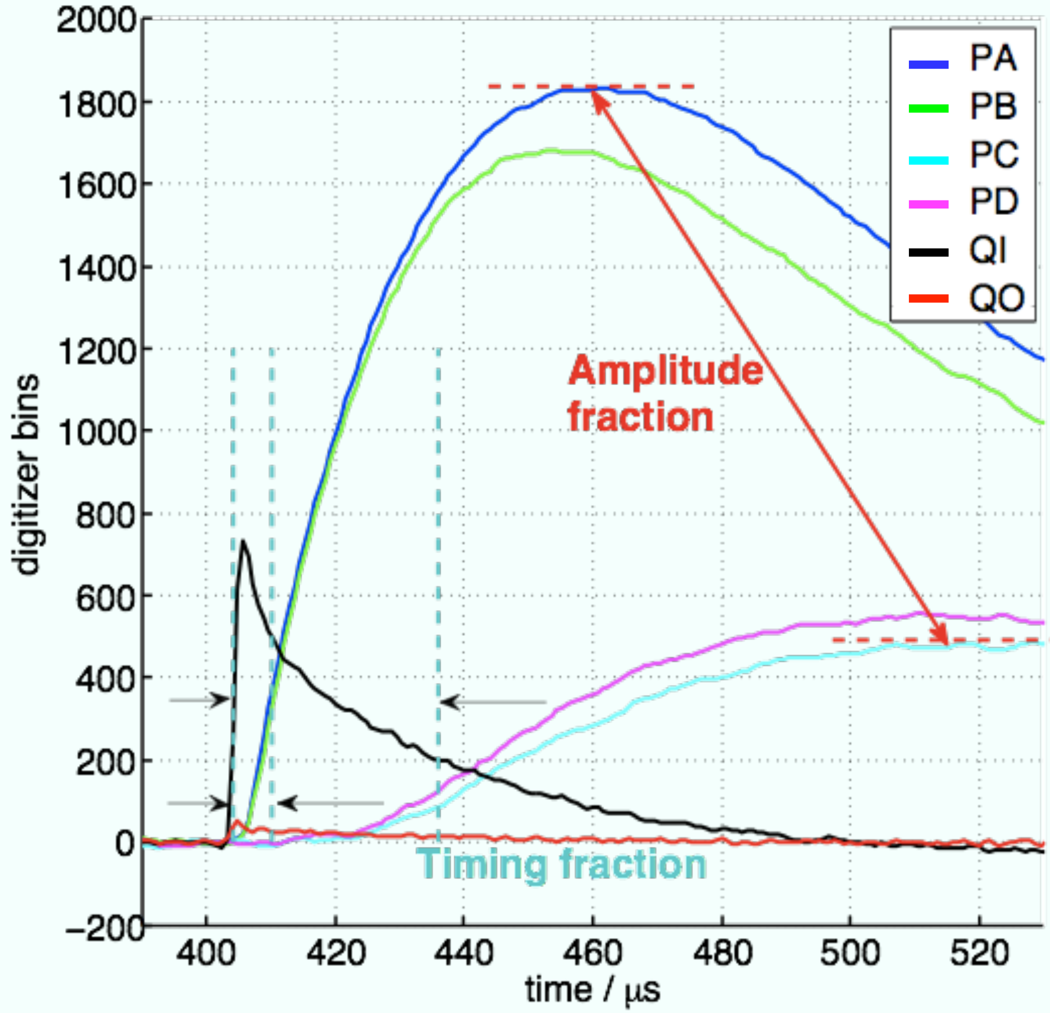
Z-Position Information

Other timing parameters have been explored

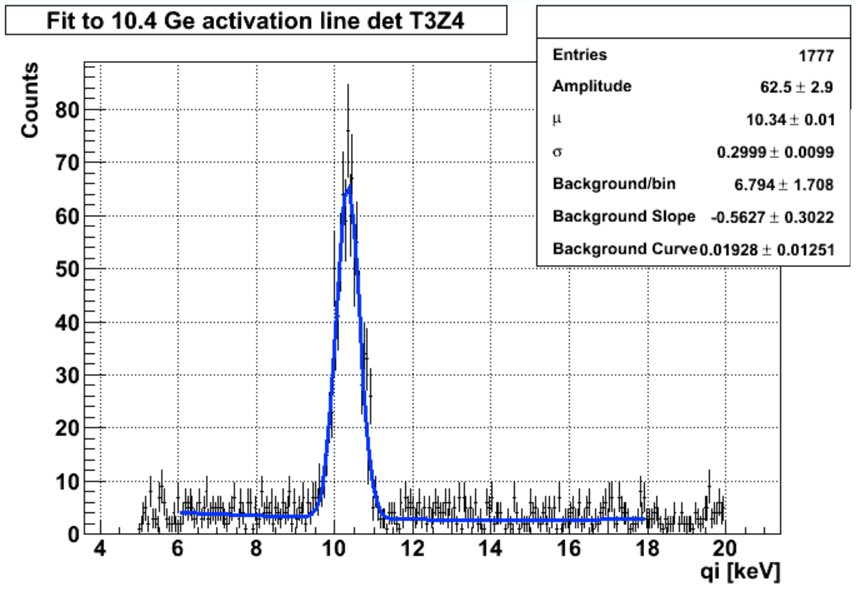


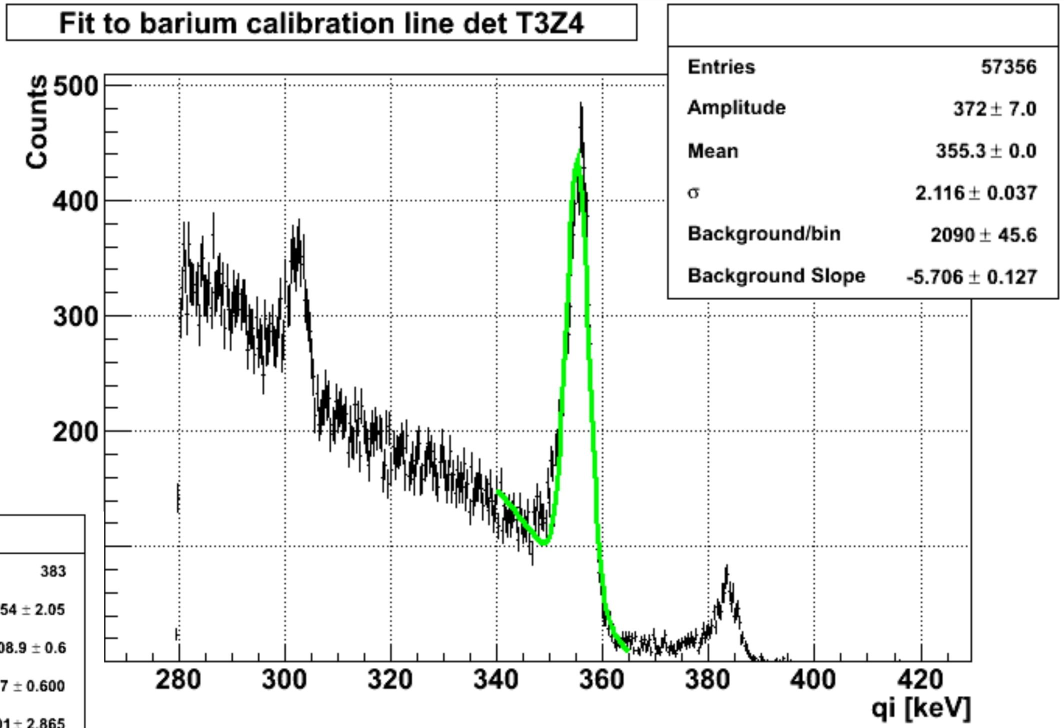
Ratio of Primary/Opposite channel

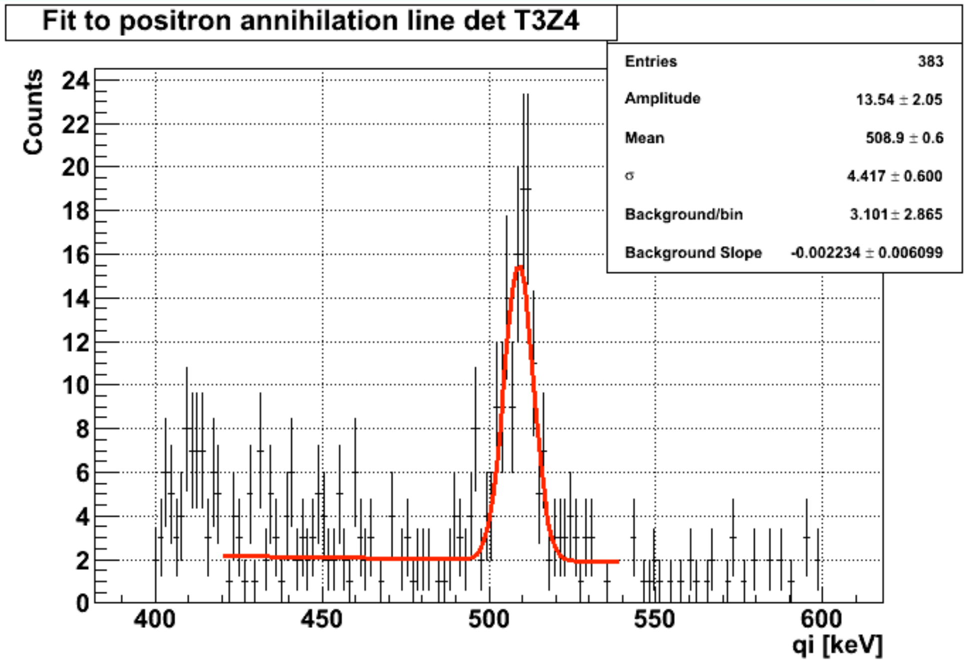
both in Amplitude and Timing



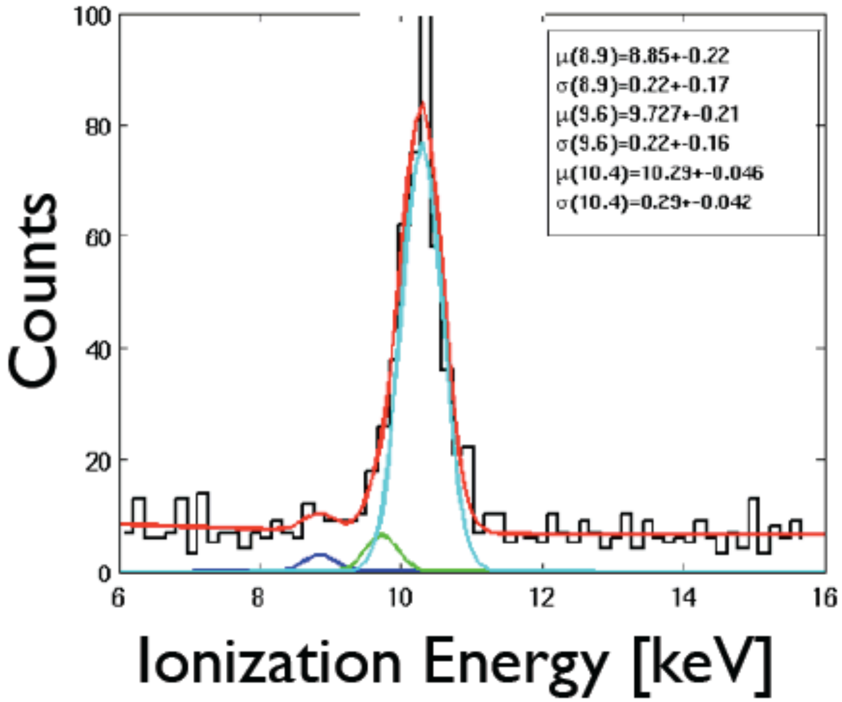
Energy Resolution from current data

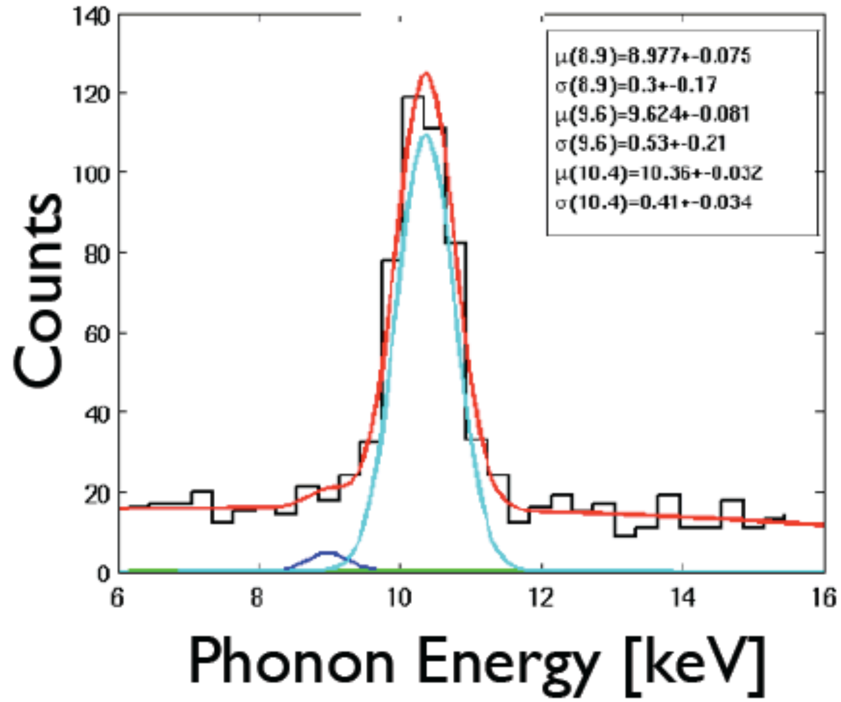






Energy Resolution





Fits of the lines 10.36 keV, 8.9 keV and 9.7 keV in the phonon and ionization channels for a single detector.

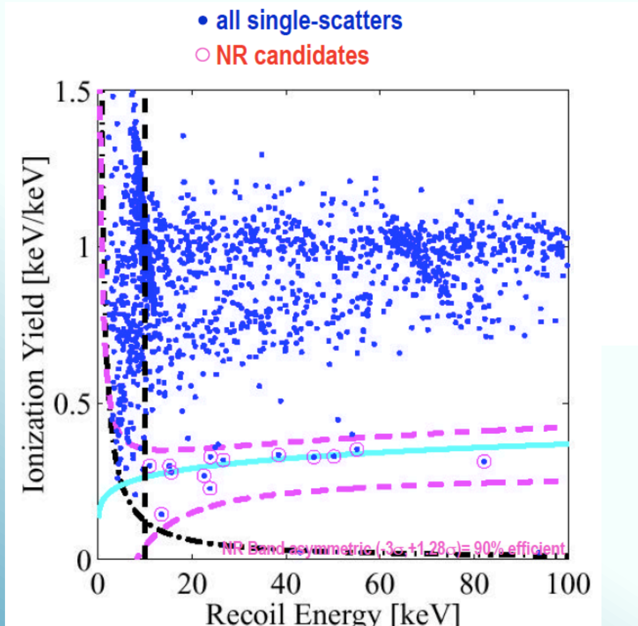
A Brief History of CDMS: Late 90's

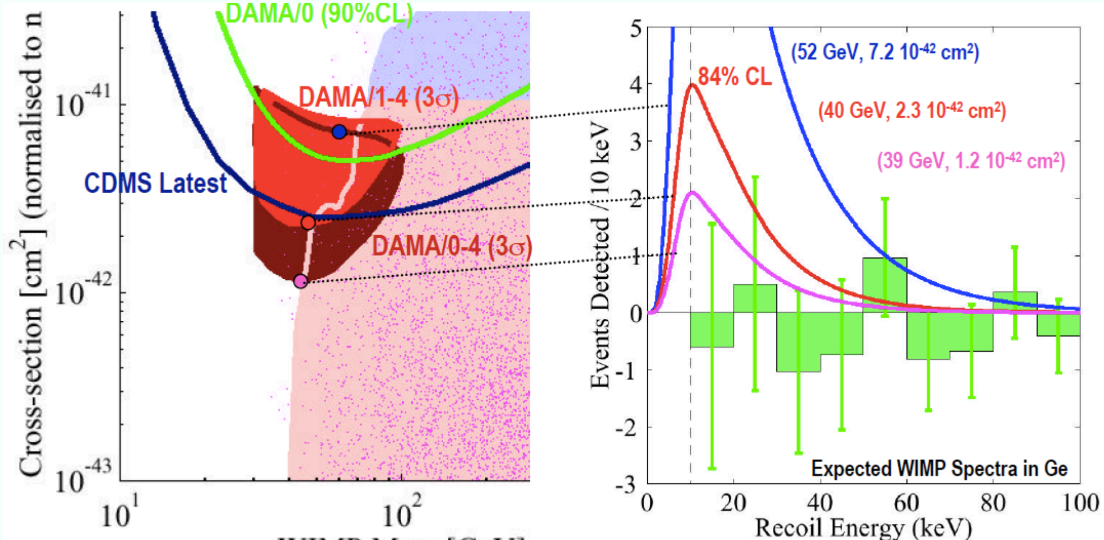
1997 DAMA signal: consistent with HDMS but surprisingly high

Run at Stanford (17 mwe)

- 10.6 kg-d with four 165 g Ge BLIP (thermal phonon calorimetry)
  13 NR singles, all neutrons: MC, right # of multiples

- 1.6 kg-d with 100 g Silicon ZIP (TES readout of athermal phonons)

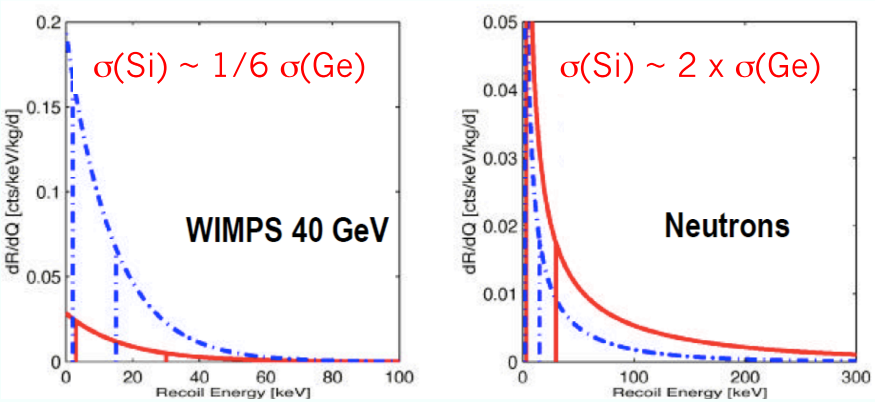




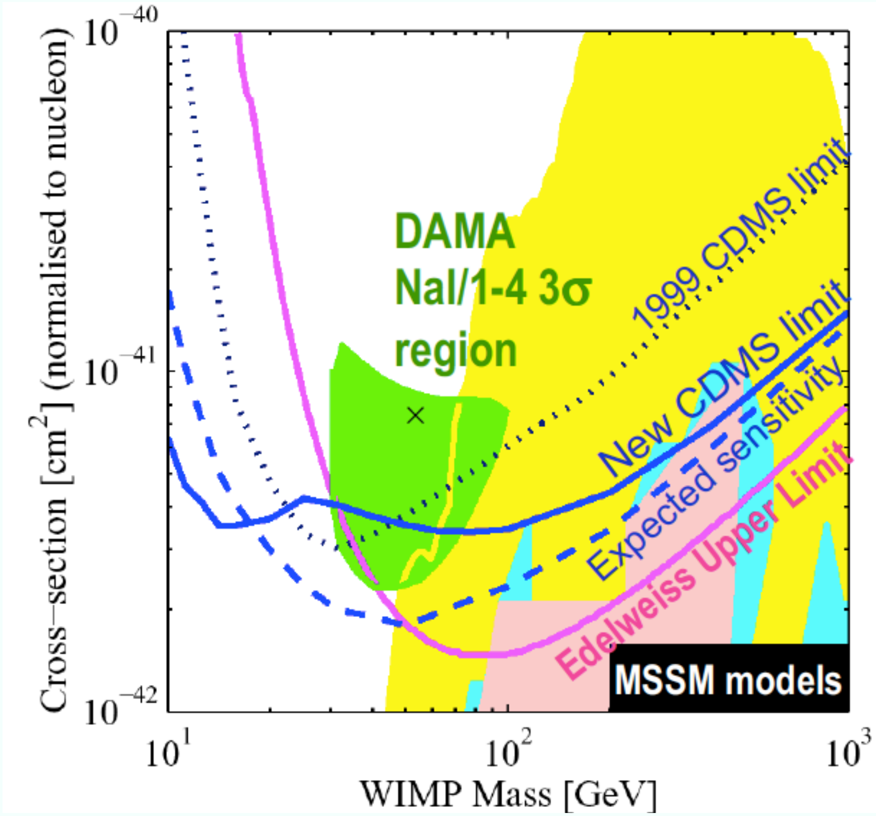
CDMS events after subtraction of measured neutron background seen at SUF

A Brief History of CDMS: early 2000's

Still think we will see a signal soon, so build both Si and Ge ZIPs
to distinguish neutrons from WIMPs



Silicon means less exposure,
but low mass WIMP sensitivity



Run a "tower" of 6 ZIPs (CDMS II)
Stanford, neutron bkgd

The competition (Edelweiss) with
BLIPs at a deeper site

Move tower at Soudan (2100 mwe)

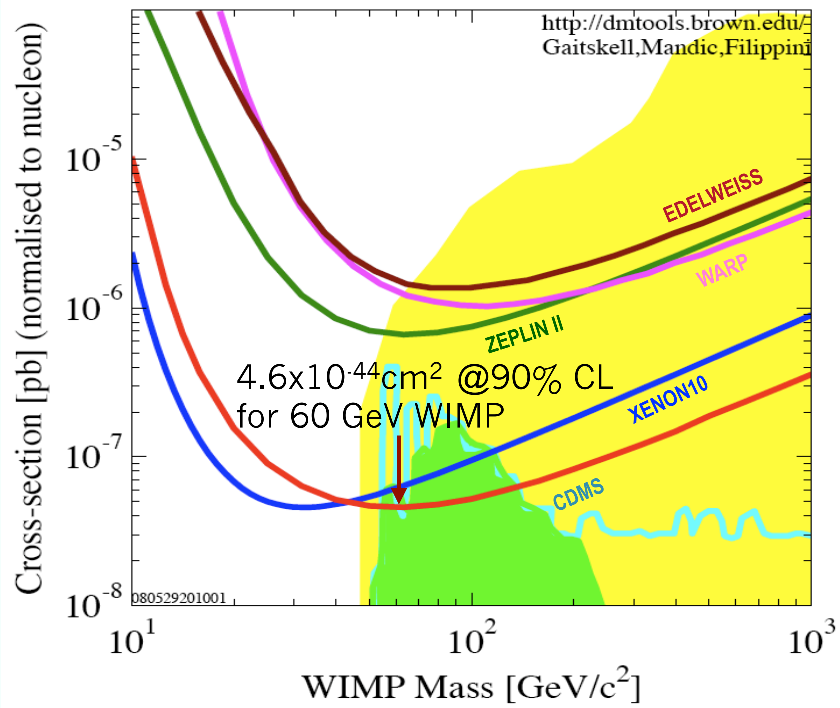
A Brief History of CDMS: 2004-2008

CDMS continues to add more towers
2008 Results: Zero events in 5-tower run
398 raw kg-d (121 kg-d after cuts)

Directional Detection (DRIFT) is on
R&D hold until someone sees a signal

Noble Liquids become "the competition"
because scaling to huge volumes
may be necessary

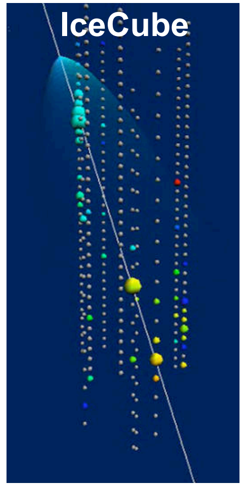
WARP, ZEPLIN, XENON, ArDM, DEAP,
LUX, CLEAN, XMASS
Best Noble Liquid limit: Xenon10
(a dozen NR singles are background)



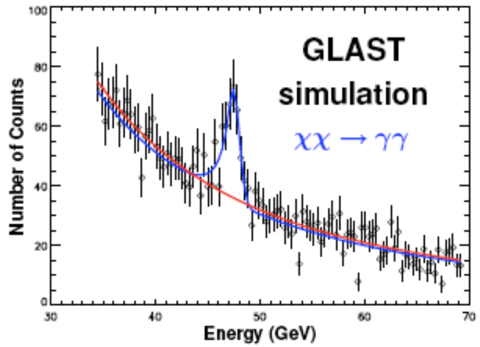
DAMA/LIBRA result confirms DAMA, but interpretations now vary widely

Indirect Detection of WIMPs: *How*

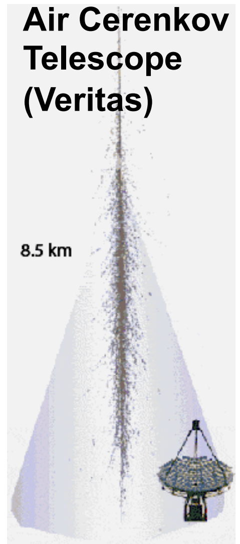
WIMP pair annihilation: **the same σ_A used to determine relic density also fixes astrophysical annihilation rate**



Trap WIMPs in Sun core, only high energy ν's escape
- Large č detectors for μ-tracks from CC interactions
- AMANDA➔ ICE CUBE (South Pole), ANTARES (also sees GC)



Observe gamma rays from GC
- Possible gamma line
- Directional gamma excess



Space-based: EGRET➔ Fermi (GLAST)
Ground-based: Veritas, HESS, Cangaroo, MAGIC

Find excess antimatter in cosmic rays
- e+ from annihilation in the neighborhood (< few kpc)
- antiprotons from most of the galaxy

Synchrotron Radiation: Any e+e− excess + galactic B-fields

WIMP Annihilation: *Hints*

PAMELA confirms HEAT positron excess (10-100 GeV)
Needs a large boost factor for DM,
nearby pulsars might do it

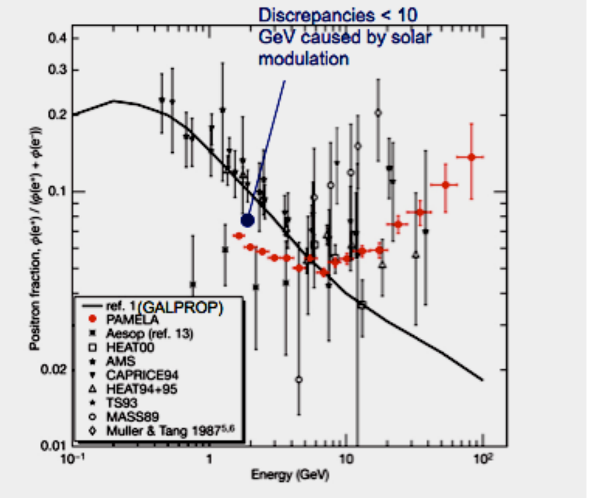
PAMELA measures an anti-proton flux (1-100 GeV)
No "excess"

ATIC e+e− (300-800 GeV) excess
is NOT confirmed by Fermi

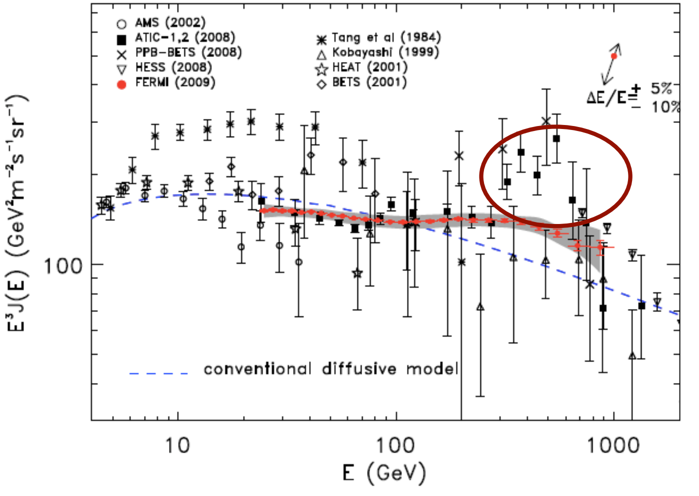
HESS (and others) excess TeV γ's from Galactic Center
but lots of processes could do that

INTEGRAL 511 keV line from galactic center
actually off-center,
points toward low mass X-ray binaries

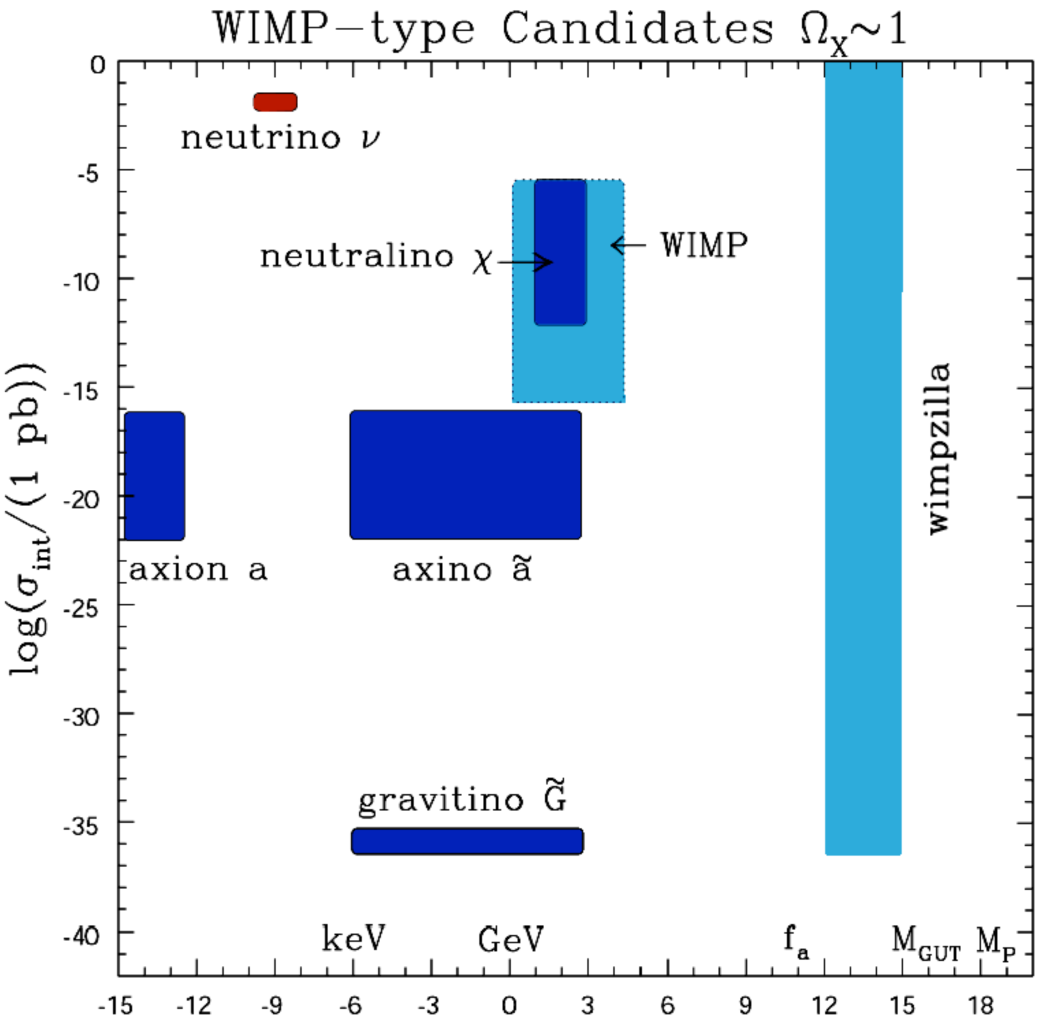
WMAP "haze" (harder than expected GC spectrum
interpreted as synchrotron radiation
but not by WMAP!



O Adriani *et al.* *Nature* **458**, 607-609 (2009) doi:10.1038/nature07942



Dark Matter Candidates: *HUGE σ - m space*



(Roszkowski 2004) $\log(m_\chi/(1\ GeV))$

Standard Model Neutrinos

neutrinos exist!

But their mass is too small

$$\Omega_\nu h^2 = \sum_{i=1}^{3} \frac{m_i}{93eV} \leq 0.07$$

$\Omega_\nu h^2 < 0.007$ from CMB anisotropies, LSS

Relativistic – Hot dark matter

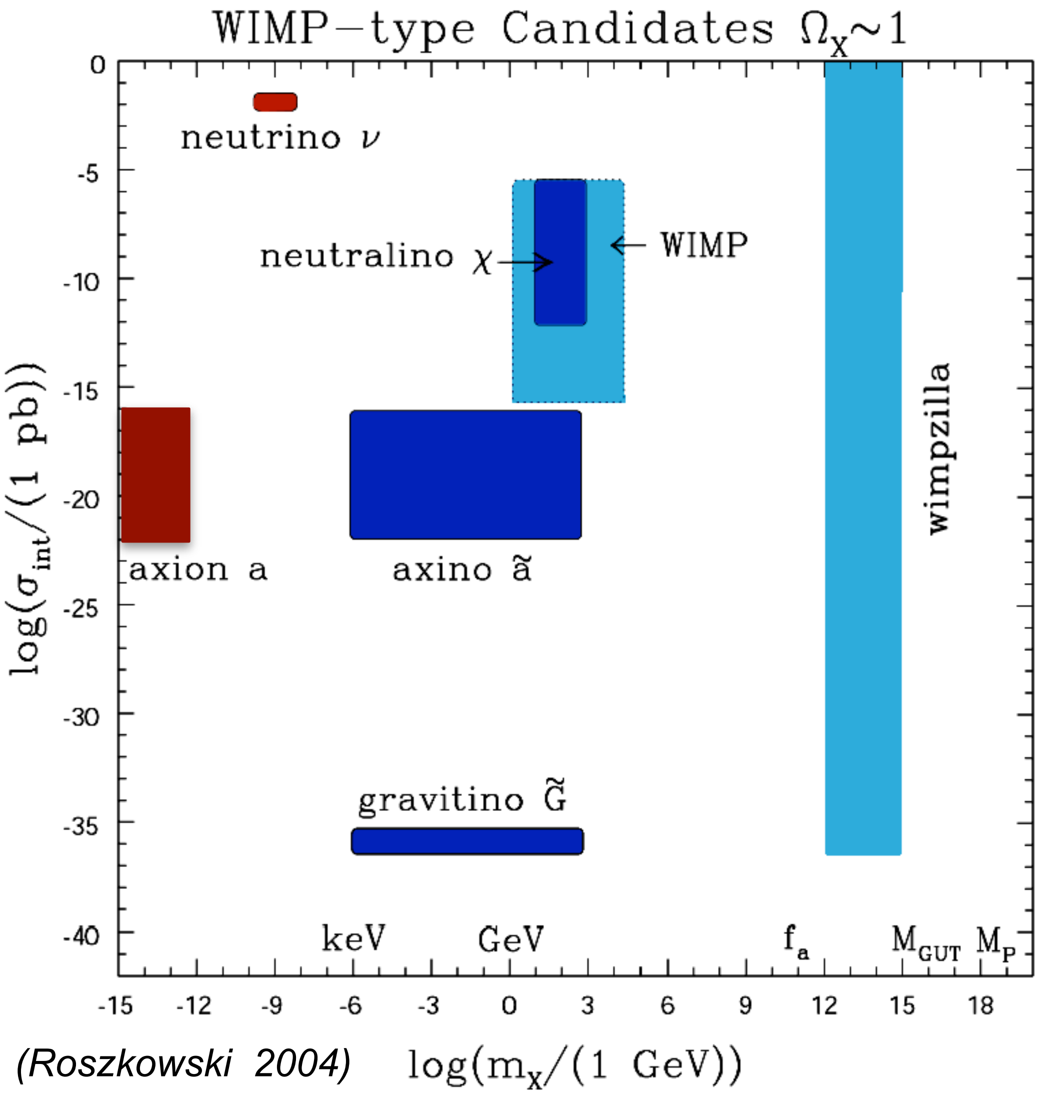
Sterile ν

m > few keV: abundance, decay products

m > 10 keV: WMAP re-ionization optical depth

wreaks havoc with reionization unless it occurs via decaying particles

Dark Matter Candidates



(Roszkowski 2004)

Axions

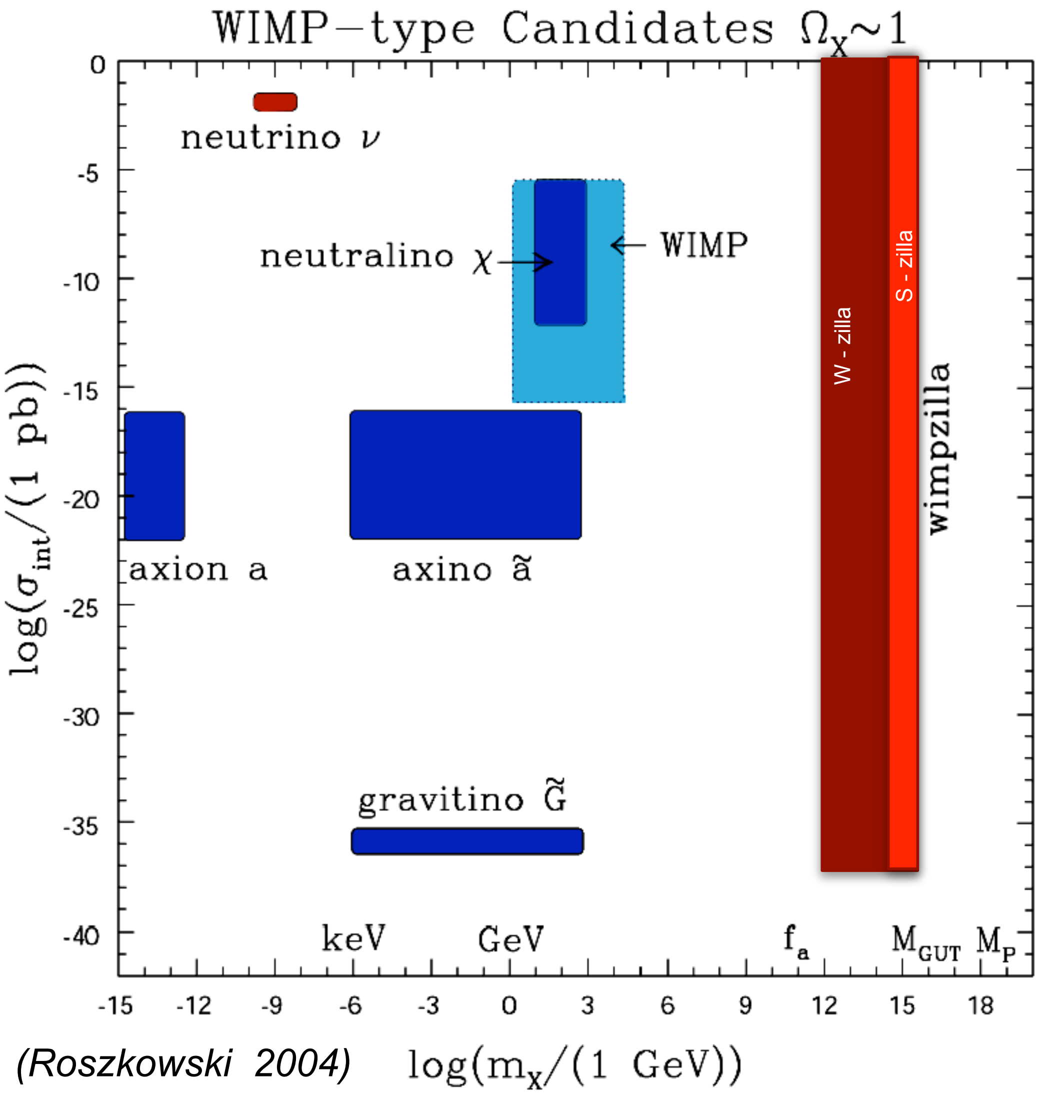
m < 0.01 eV
lab searches, stellar cooling, SN 1987A

Very weak: *not in thermal equilibrium with early universe.*

Born non-relativistic (*cold dark matter*)

Thermally produced in stars
strong astrophysics limits

Dark Matter Candidates



(Roszkowski 2004)

Wimpzillas and Simpzillas

m > 10^{10} GeV

Provides solution to GKZ cosmic rays

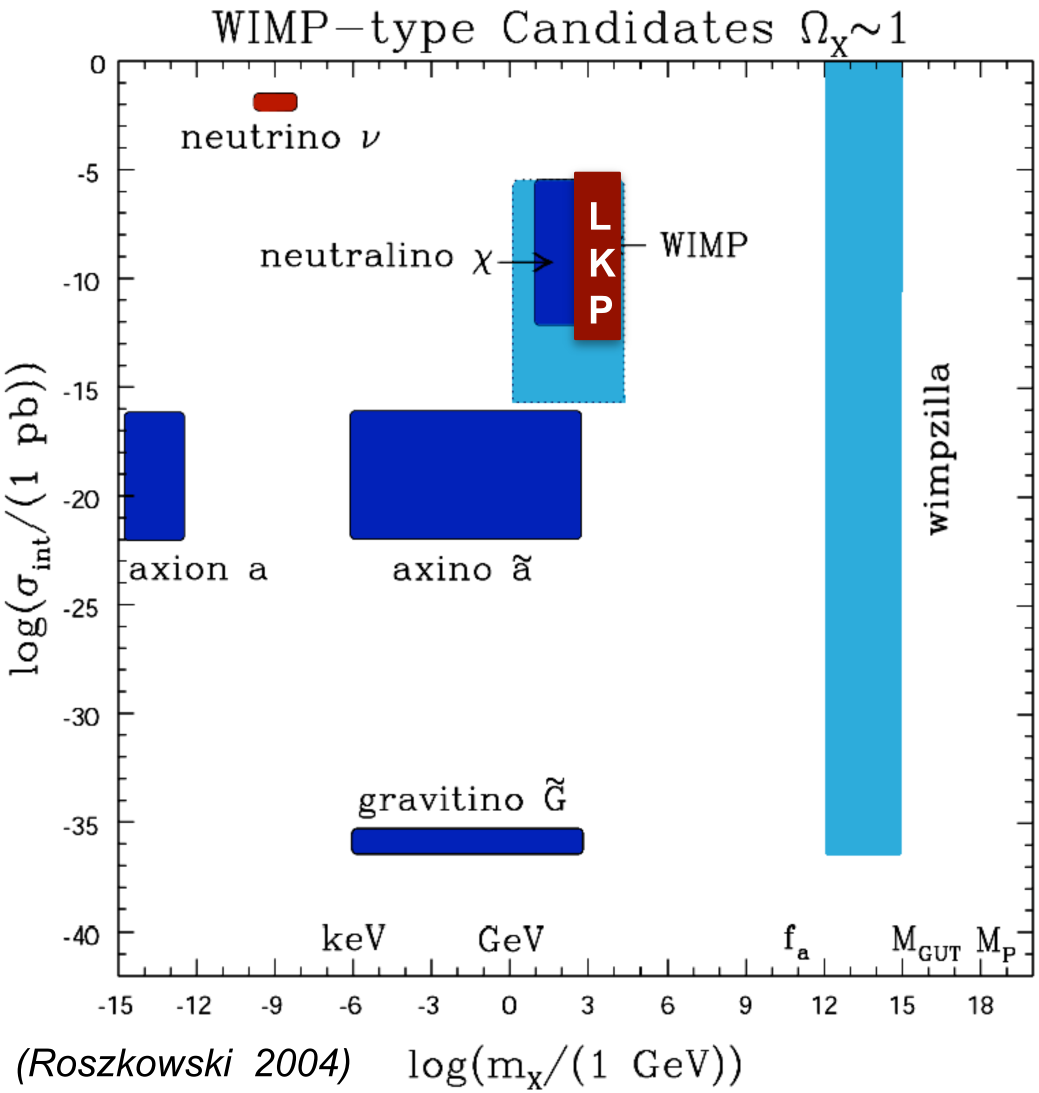
Gravitationally produced: *inflaton, GUT scale, curvature perturbation*

Avoids unitarity bound

no early universe thermal equilibrium

Ωh^2 depends on $\sigma_{production}$ not $\sigma_{annihilation}$

Dark Matter Candidates



(Roszkowski 2004)

Kaluza-Klein modes

m ~ 400 – 1200 GeV *Relic Density*
m > 300 GeV *Compactification Scale R^{-1}*

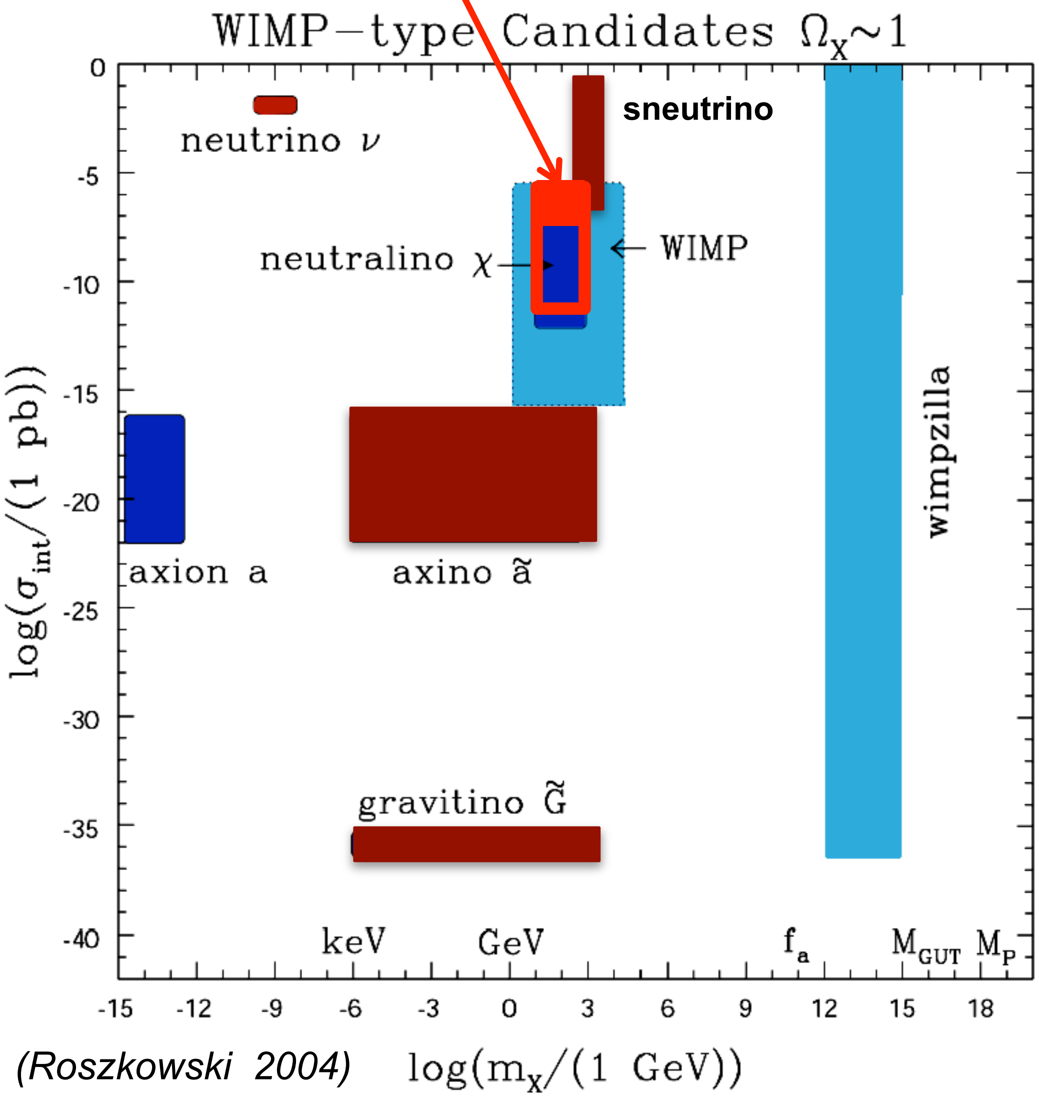
mass splitting can be small $m_n = n/R$
coannihilation large
may be difficult signature for LHC

LKP is a WIMP

many models: *UED, MUED, warped dimensions*

Dark Matter Candidates

Region we have already excluded



(Roszkowski 2004)

Supersymmetric particles

neutralino:

m_χ > 70 GeV *from LEP*

> few GeV *from* $\Omega_\chi h^2 < 1$

< 300 TeV *from unitarity*

tens – 100's GeV fine tuning arguments

weak interaction scale, suppressed by mixing angles in the neutralino couplings

axino: *mass not directly determined by SUSY breaking scale, light (warm DM)*

gravitino: *No direct detection*

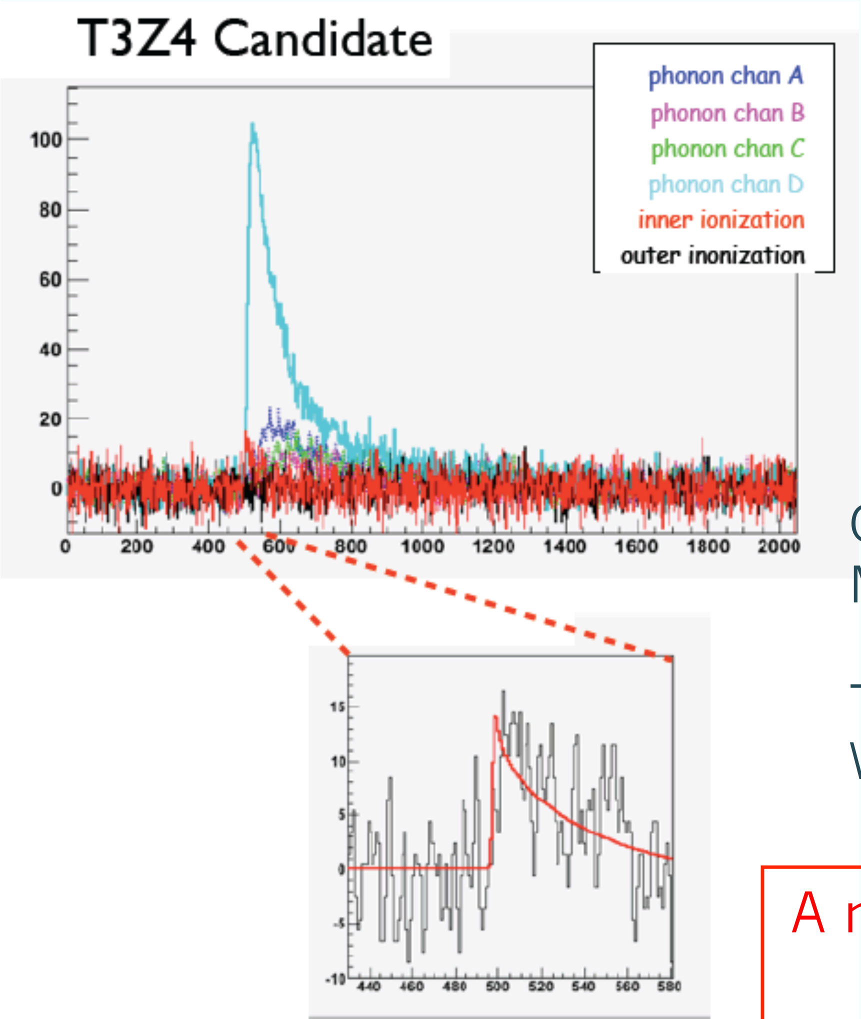
Tension between BBN and relic density

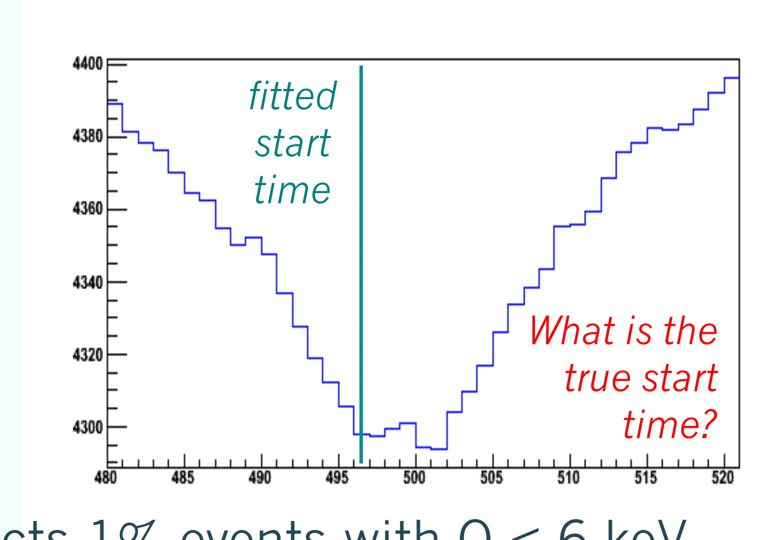
sneutrinos: *550 – 2300 GeV (relic density)*

large σ ➔ *eliminated by direct searches*

OK – Good Event. But is it a Nuclear Recoil?

Look in detail at the timing parameters





Only affects 1% events with Q < 6 keV
Mostly accounted for in the pre-unblinding leakage estimate.
T1Z5 not affected, for example
We know a better algorithm and will reanalyze for unblind analysis

A more careful accounting revised the surface event leakage to

0.8 ± 0.1(stat) ± 0.2(sys)