A search for low-mass dark matter with CDMS-II and the development of highly-multiplexed phonon-mediated particle detectors

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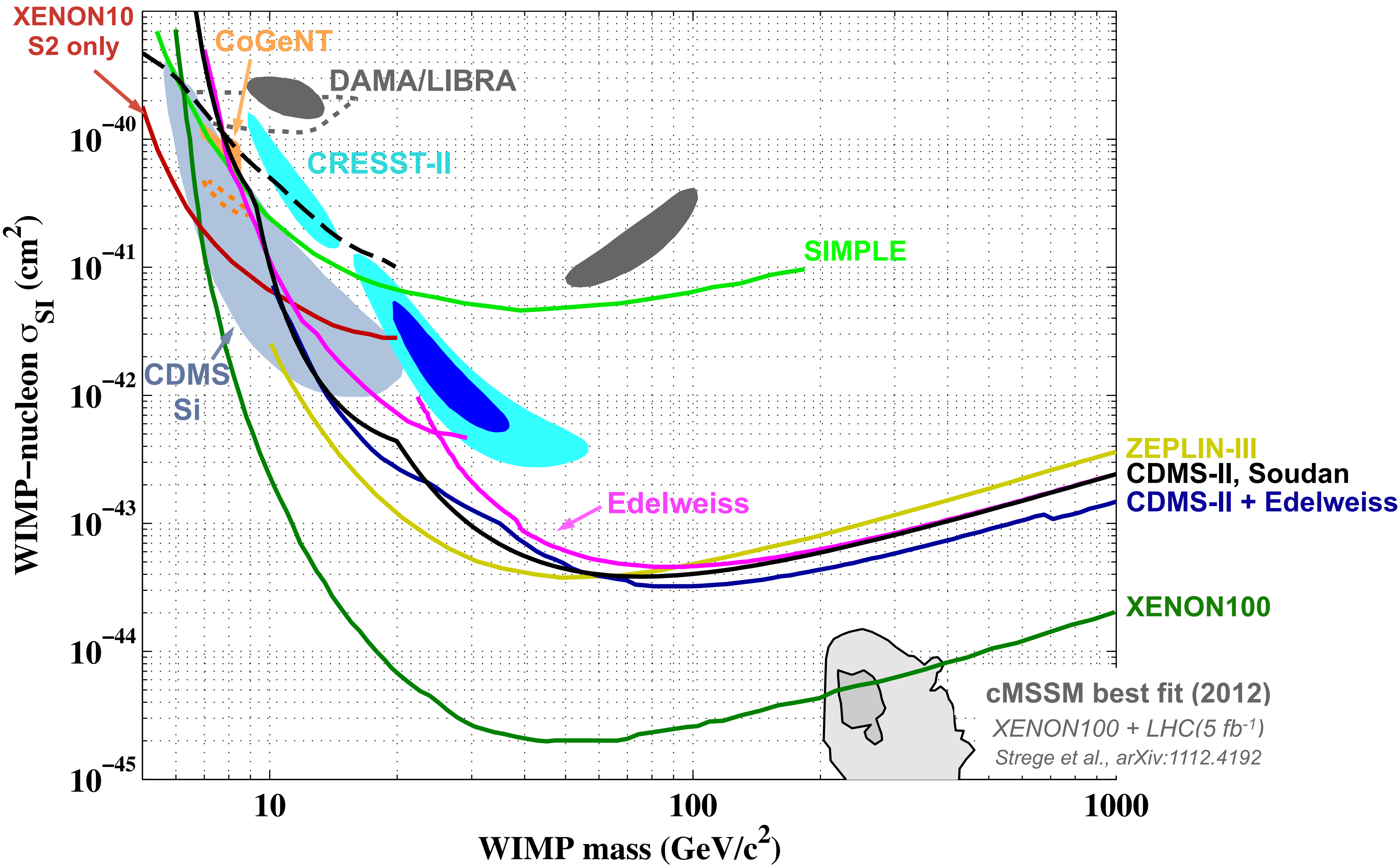
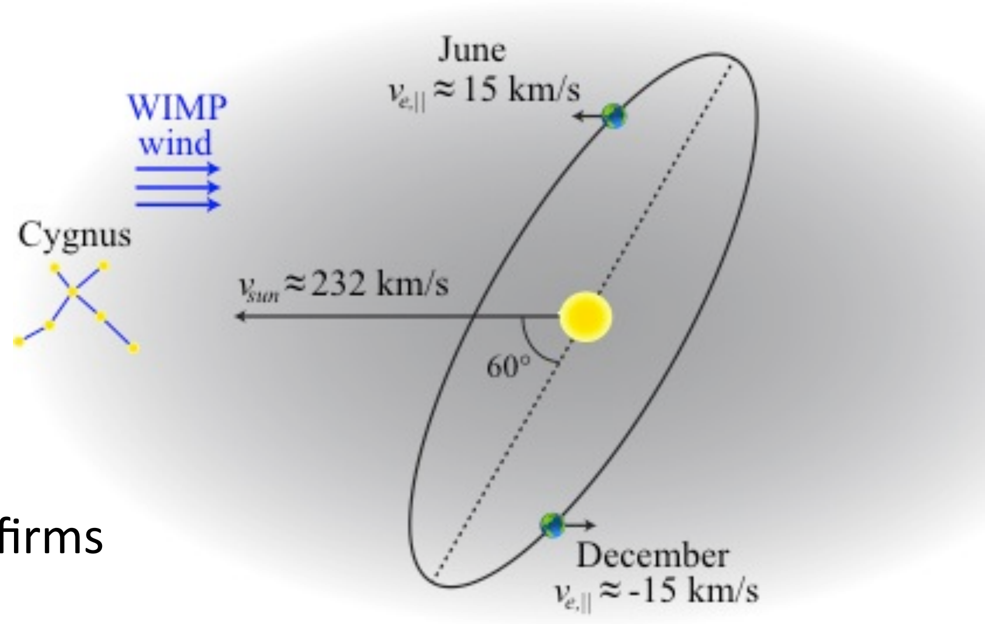
DPF 2013

Direct Detection



DAMA

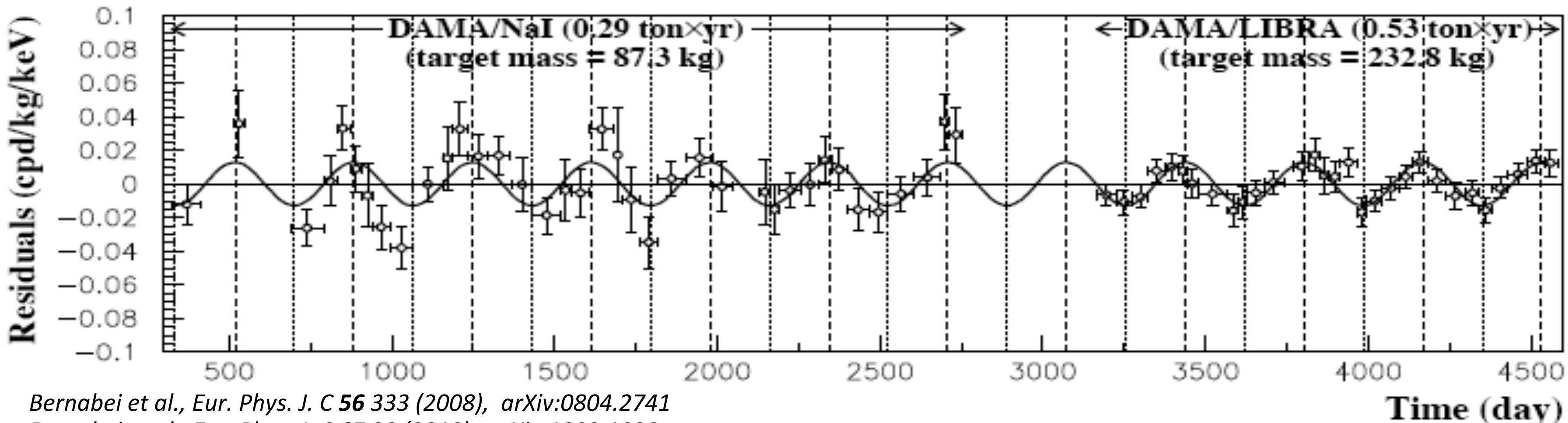
- 250 kg of radiopure NaI scintillator
- Observe annual modulation consistent with dark matter signal



1996-2003: DAMA/NaI reported modulation in count rate over 7 annual cycles

2008: Follow up experiment, DAMA/LIBRA confirms previous results with reported significance ~9σ

Residual rate versus time:



*Bernabei et al., Eur. Phys. J. C **56** 333 (2008), arXiv:0804.2741*
*Bernabei et al., Eur. Phys. J. C **67** 39 (2010), arXiv:1002.1028*

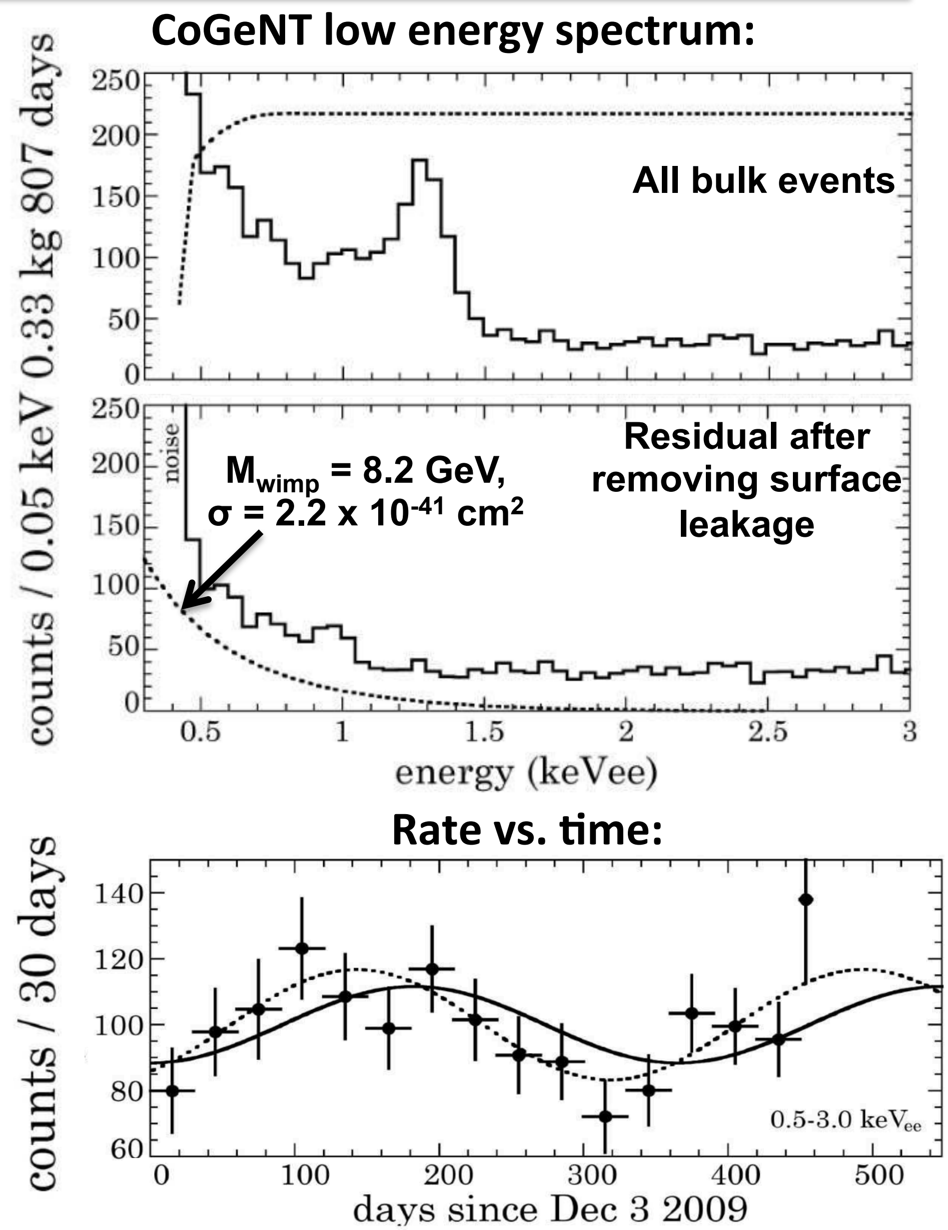
CoGeNT

- 440 g PPC Ge detector with ~0.4 keVee threshold
- Can reject surface interactions using pulse timing
- Observed low-energy excess above known backgrounds

2010: Observed low energy excess of events consistent with M~10 GeV, σ ~ 5-10x10^{-41} cm^2

2011: Reported 2.8σ annual modulation in residual counting rate from 0.5-3.0 keV

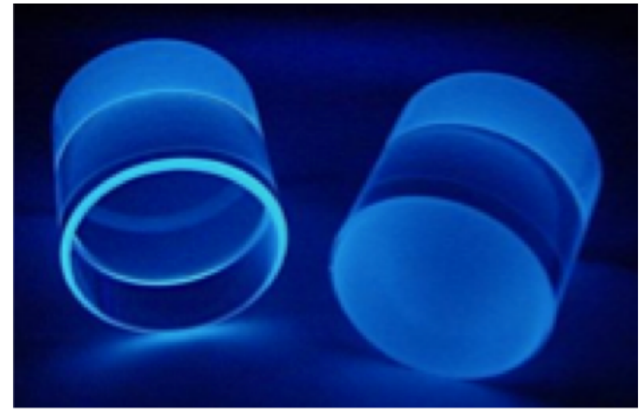
2012: Improved background estimate suggested smaller fraction of events could be due to WIMPs, smaller σ ~ 2x10^{-41} cm^2



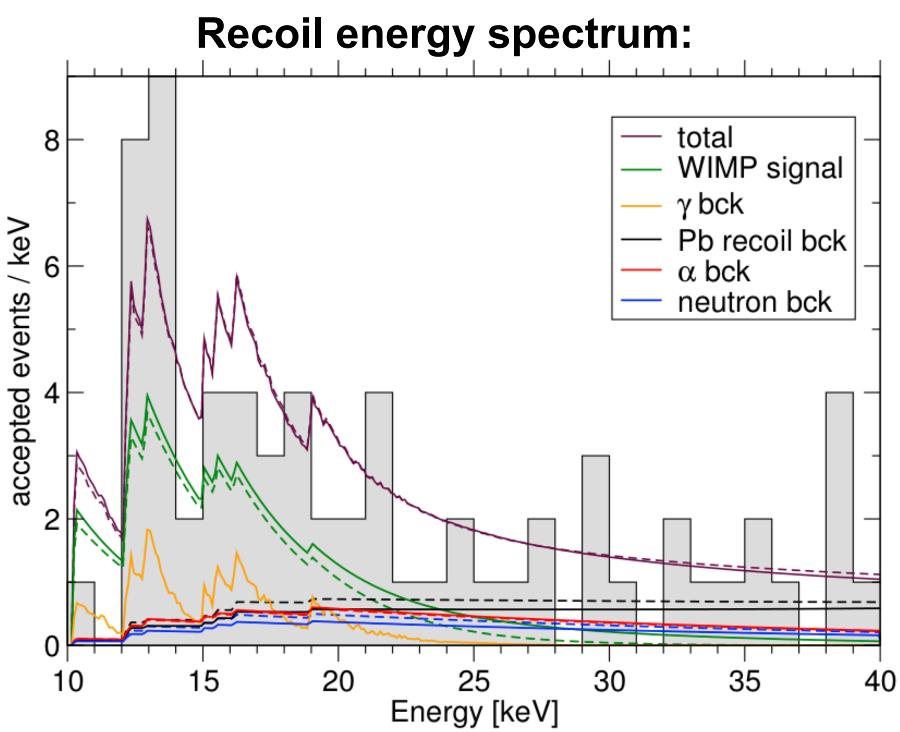
Aalseth et al., Phys. Rev. Lett. ***107****, 141301 (2011), arXiv:1106.0650v3*
Aalseth et al., Phys. Rev. D ***88****, 012002 (2013) arXiv:1208.5737*

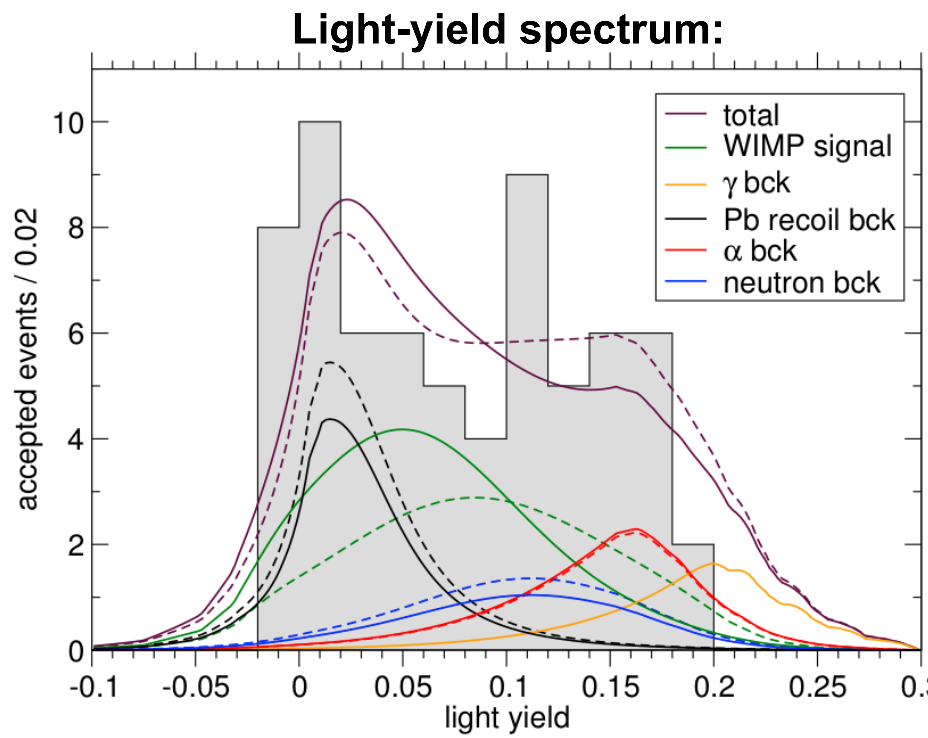
CRESST-II

- 730 kg-days exposure with $CaWO_4$ scintillators
- Measure both light and heat to reject electron recoil backgrounds



2011: Reported >4σ excess of nuclear-recoil like events above known backgrounds





Angloher et al., Eur. Phys. J. C ***72****,1971 (2012) arXiv:1109.0702v1*

The Cryogenic Dark Matter Search (CDMS-II)

CDMS Collaboration

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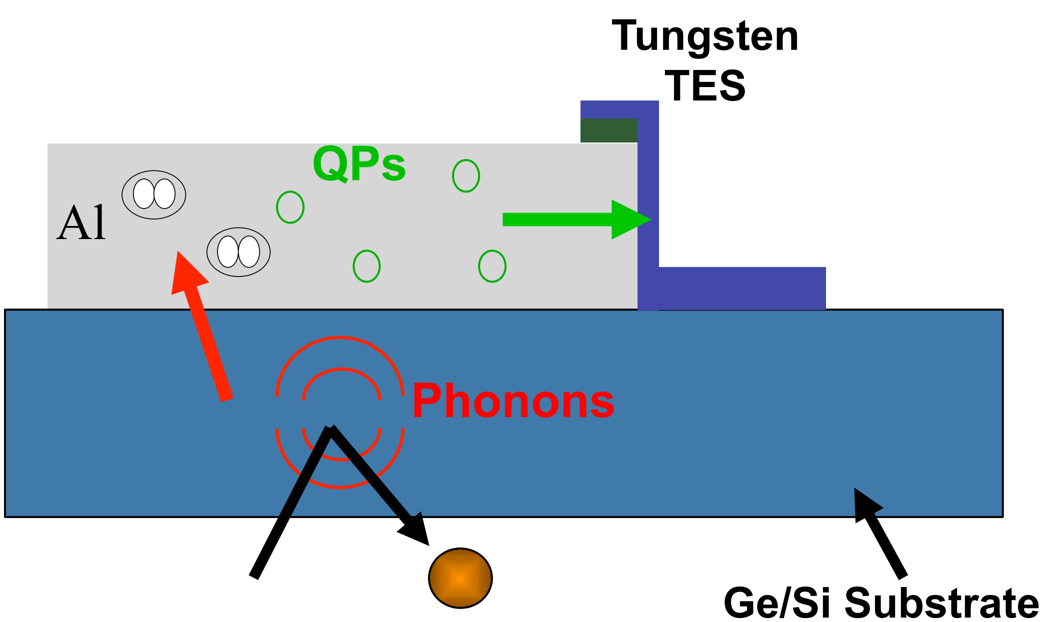
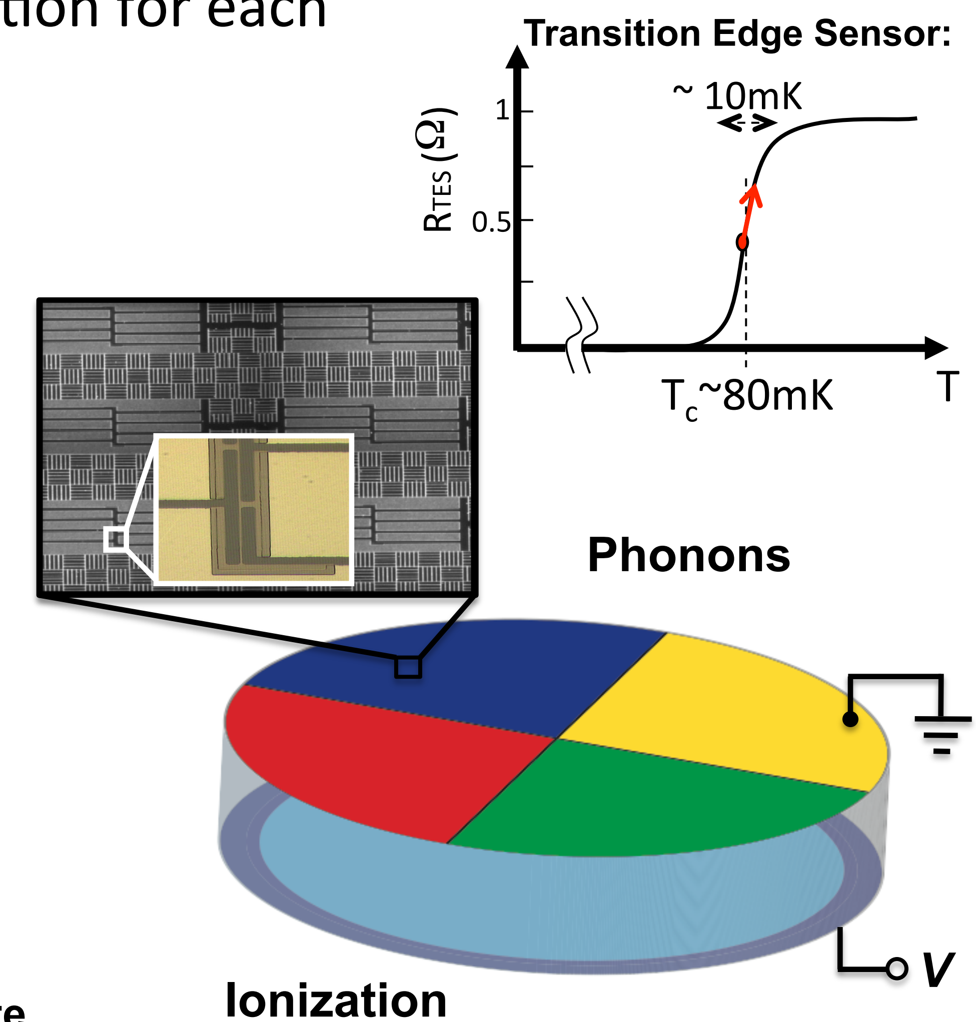
CDMS Detectors

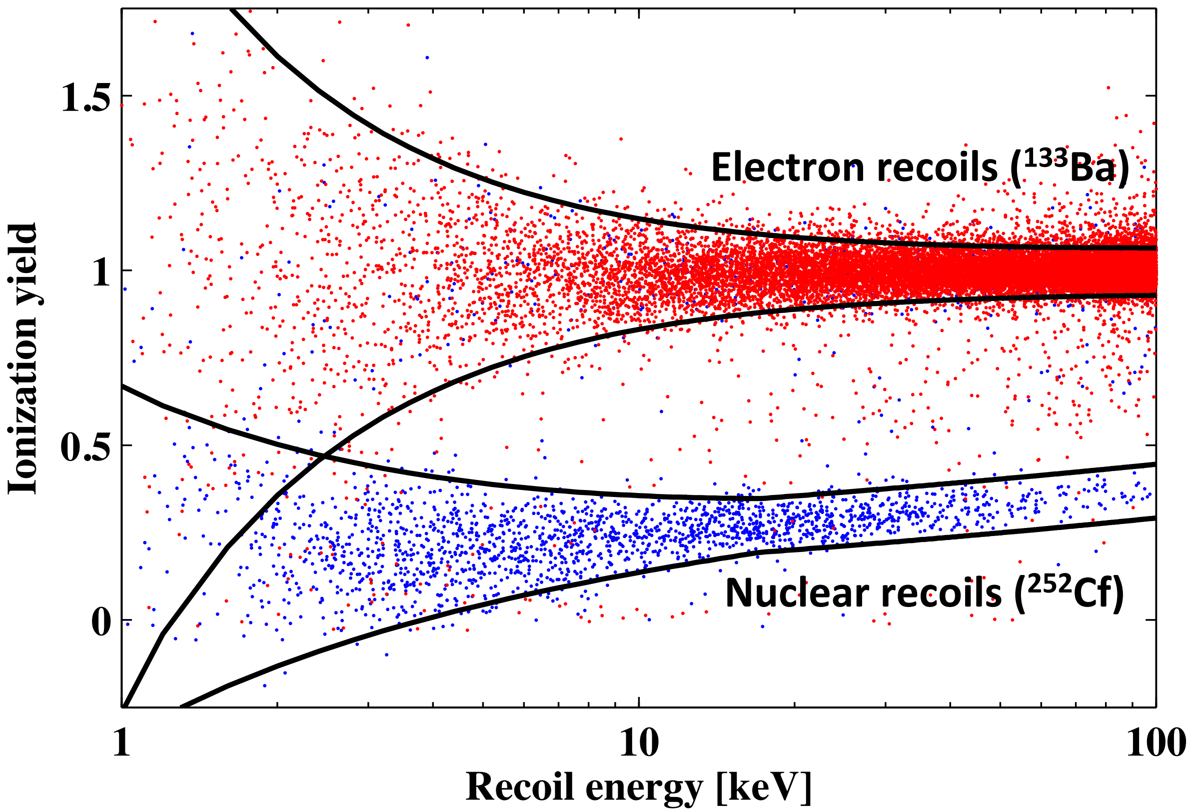
- Measure both phonons and ionization for each particle interaction
  - Four TES-based phonon sensors
  - Two concentric ionization electrodes

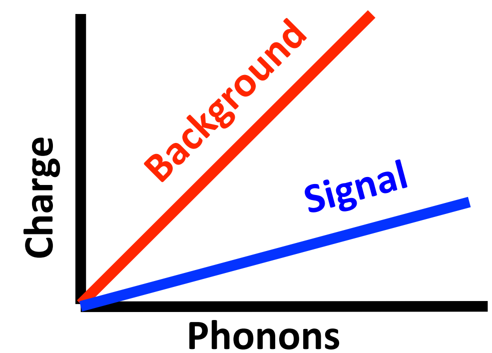




Background Discrimination

- Electron-recoil backgrounds can be eliminated on an event-by-event basis
- Reduced ionization for nuclear recoils (Ionization yield = charge/phonons)





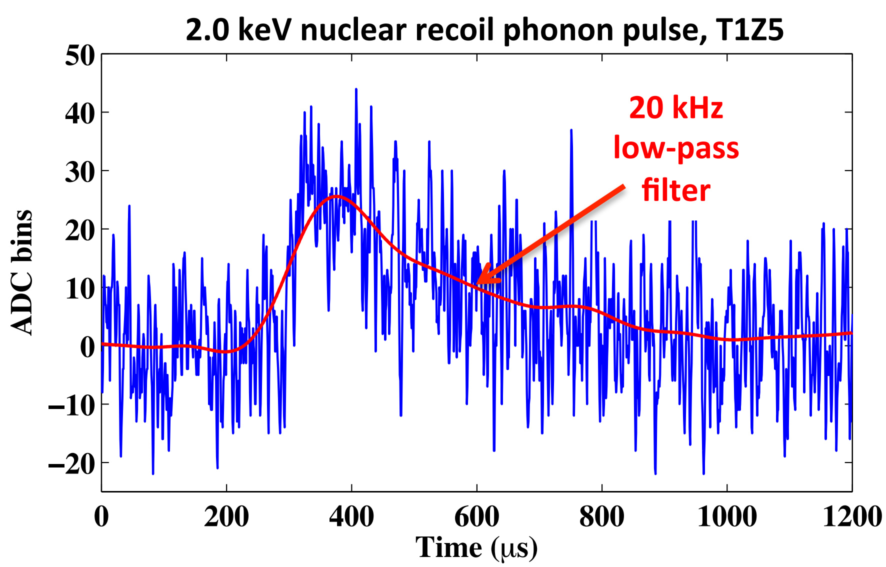
Rejection of calibration gammas:

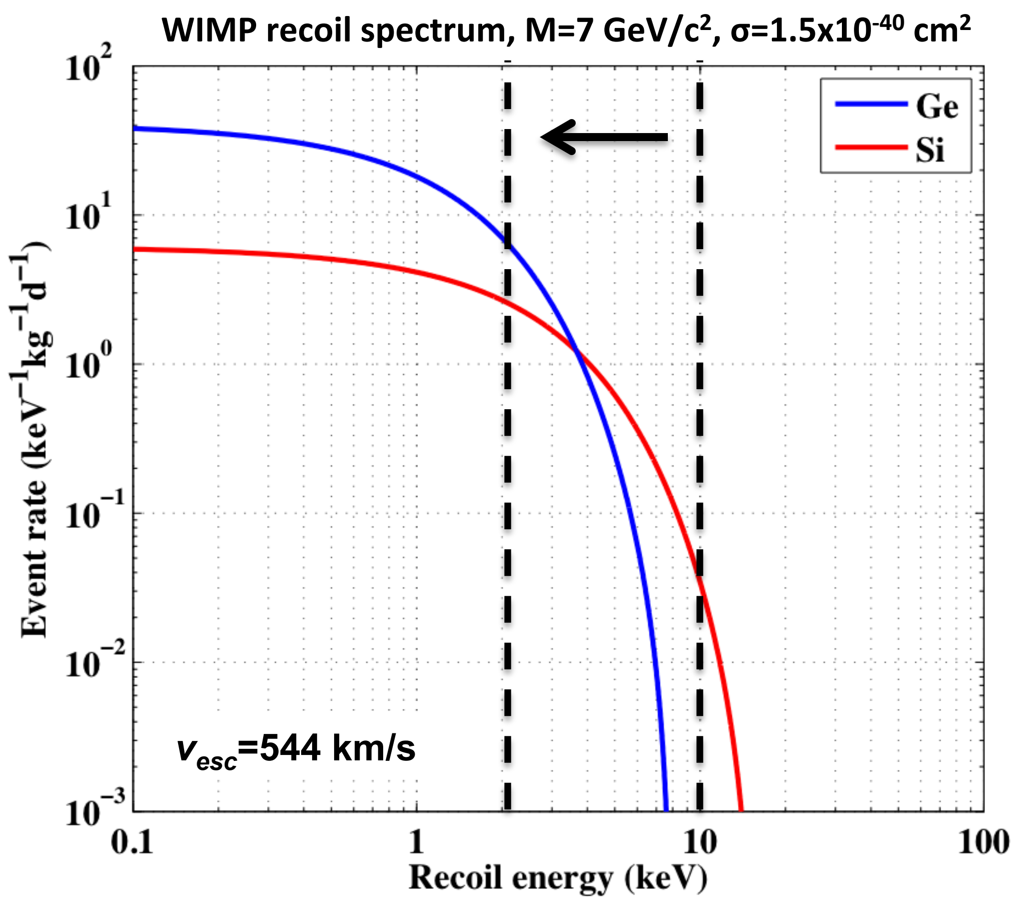
> 10^4:1 above 10 keV

> 10:1 at 2 keV for best detectors

Can CDMS constrain light WIMPs?

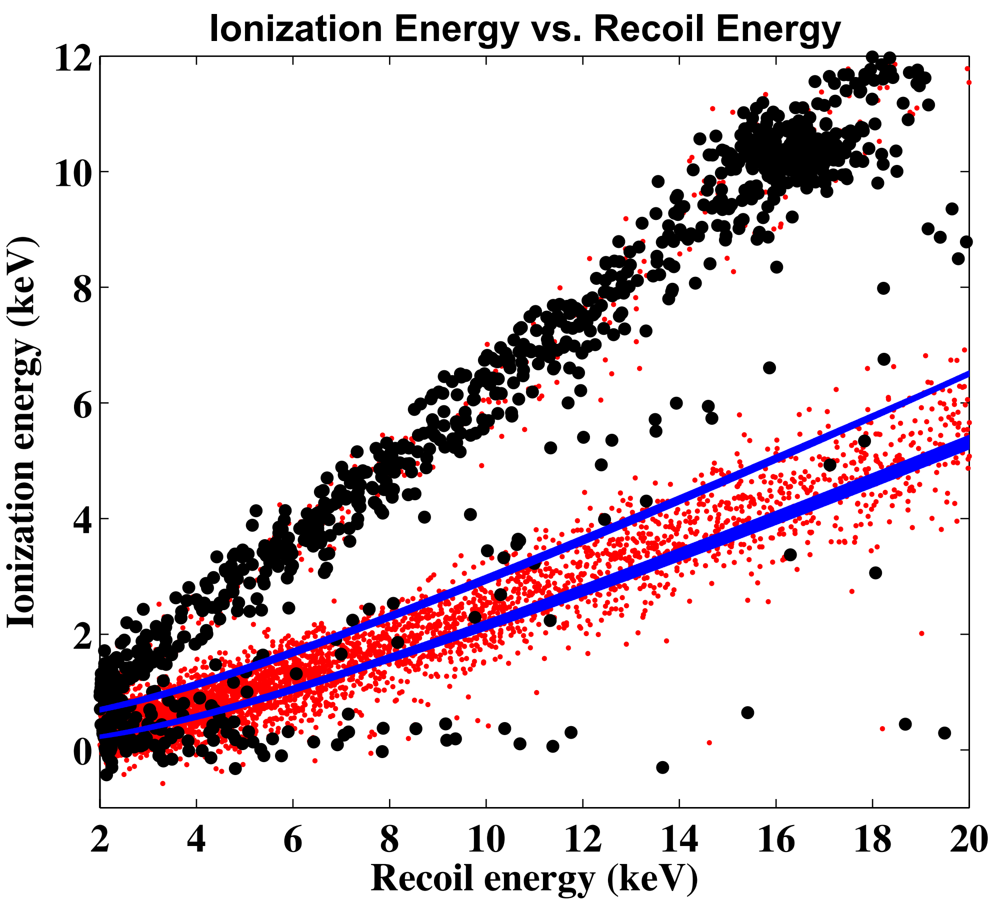
- Previous CDMS Ge results have used ~10 keV thresholds to maintain expected leakages of <1 event
- Can lower energy thresholds significantly, at the cost of higher backgrounds
- Reanalyzed CDMS-II Ge data (taken from 2006-2008) with a 2 keV recoil energy threshold

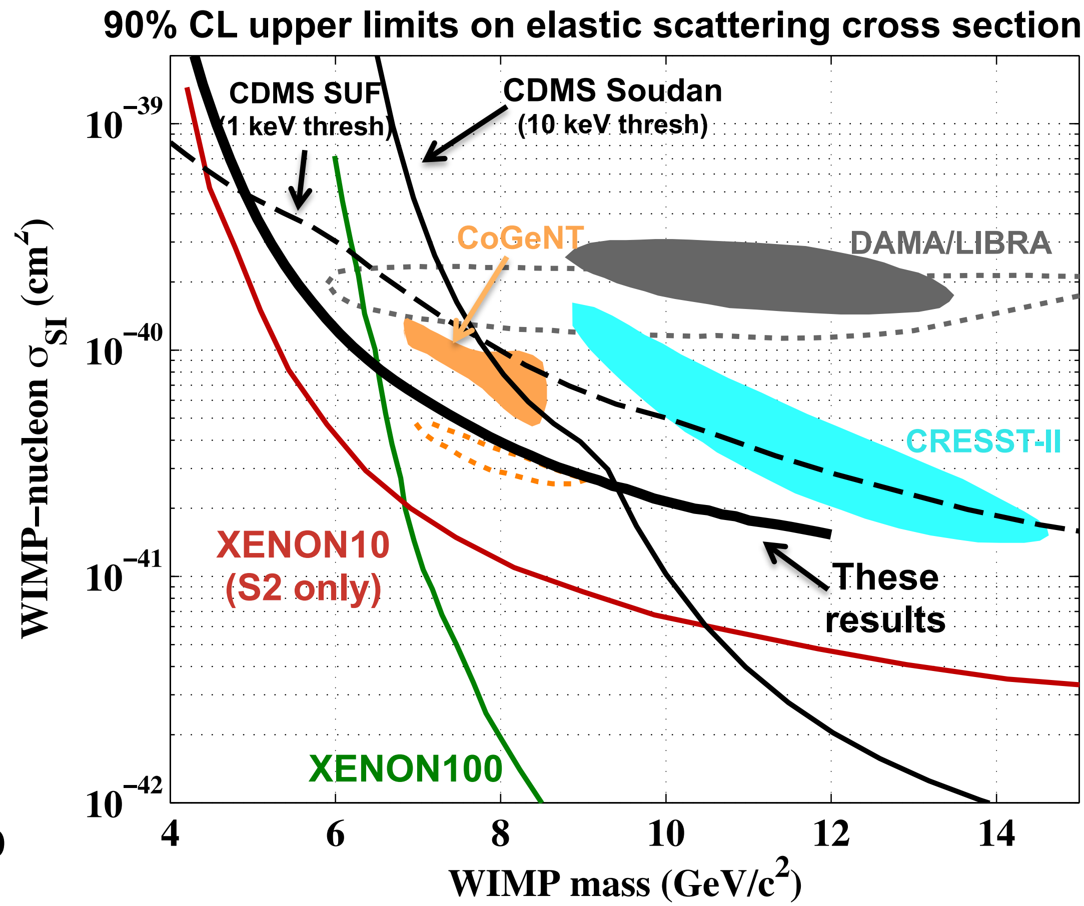




Low-mass constraints

- Select all nuclear-recoil like events in CDMS-II Ge data at low energy
- Conservatively set limits on cross-section assuming all events could be from WIMPs
- Extrapolations of backgrounds from side bands can plausibly account for observed candidates (although significant systematics possible)





Ahmed et al., Phys. Rev. Lett., **106** 131302 *arXiv:1011.2482* (2011)

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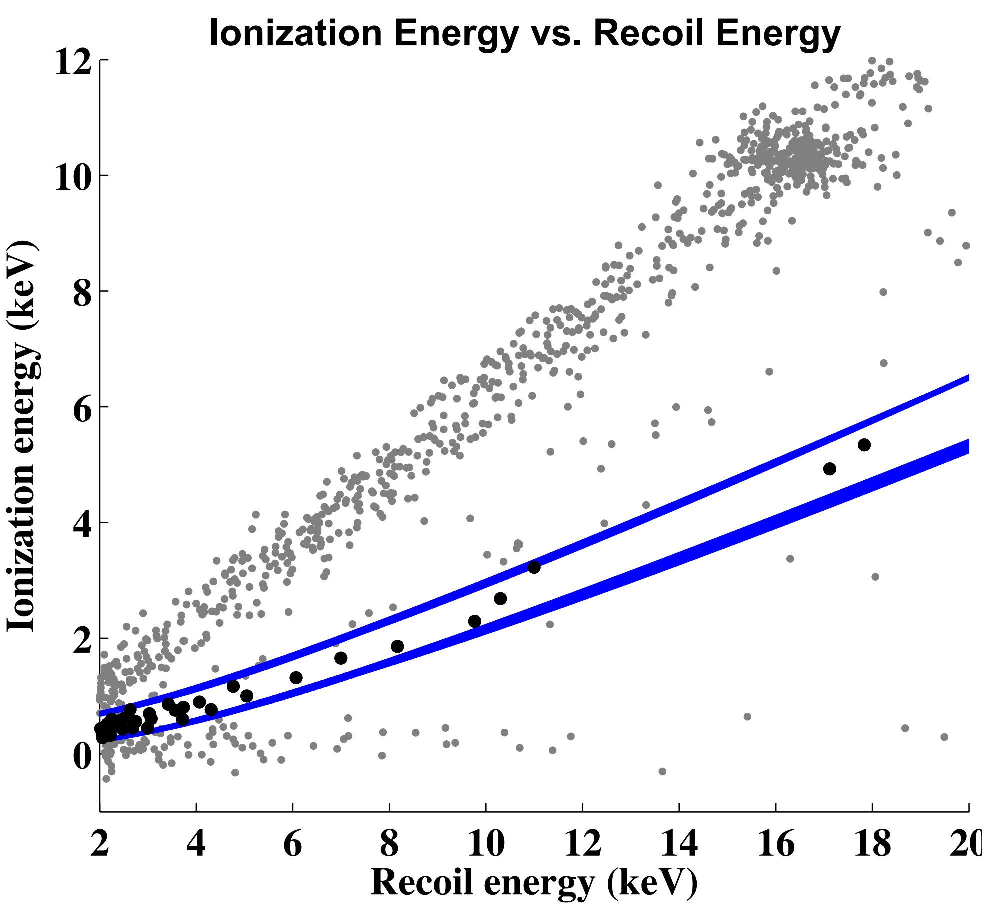
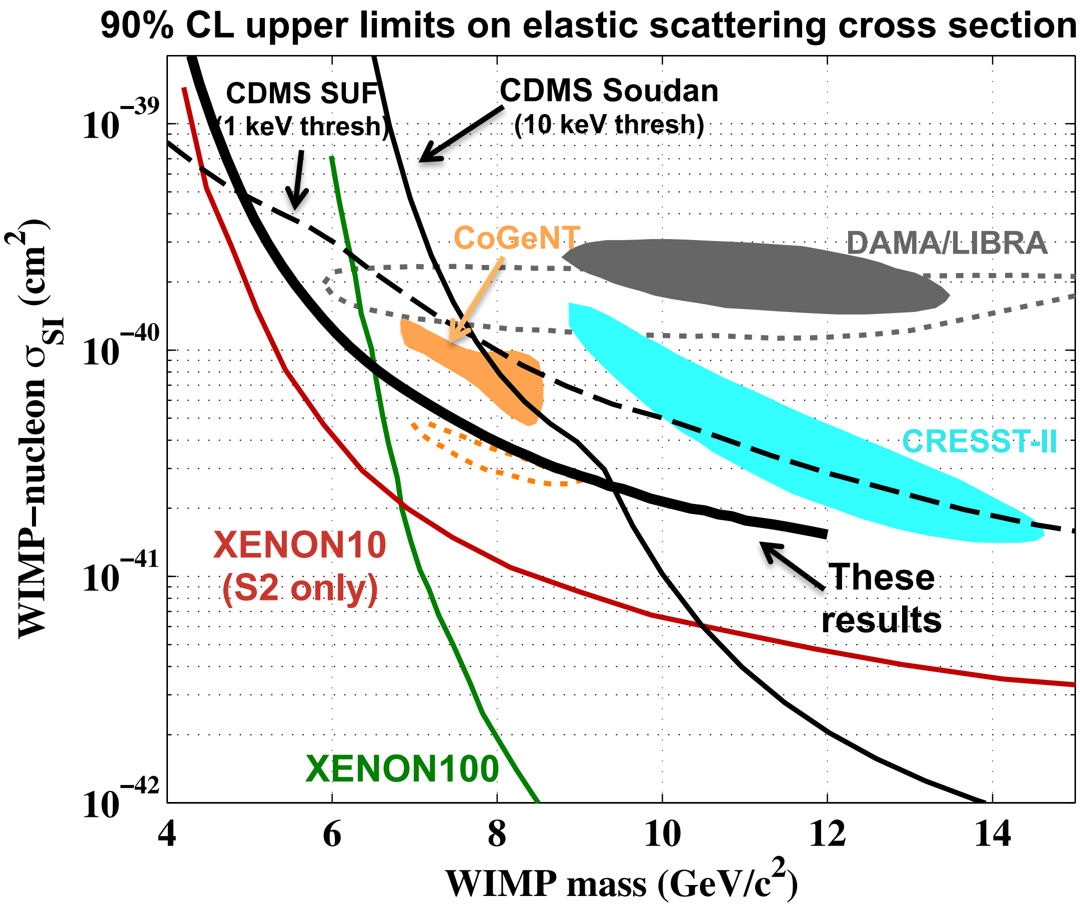




Ahmed et al., Phys. Rev. Lett., **106** 131302 *arXiv:1011.2482* (2011)

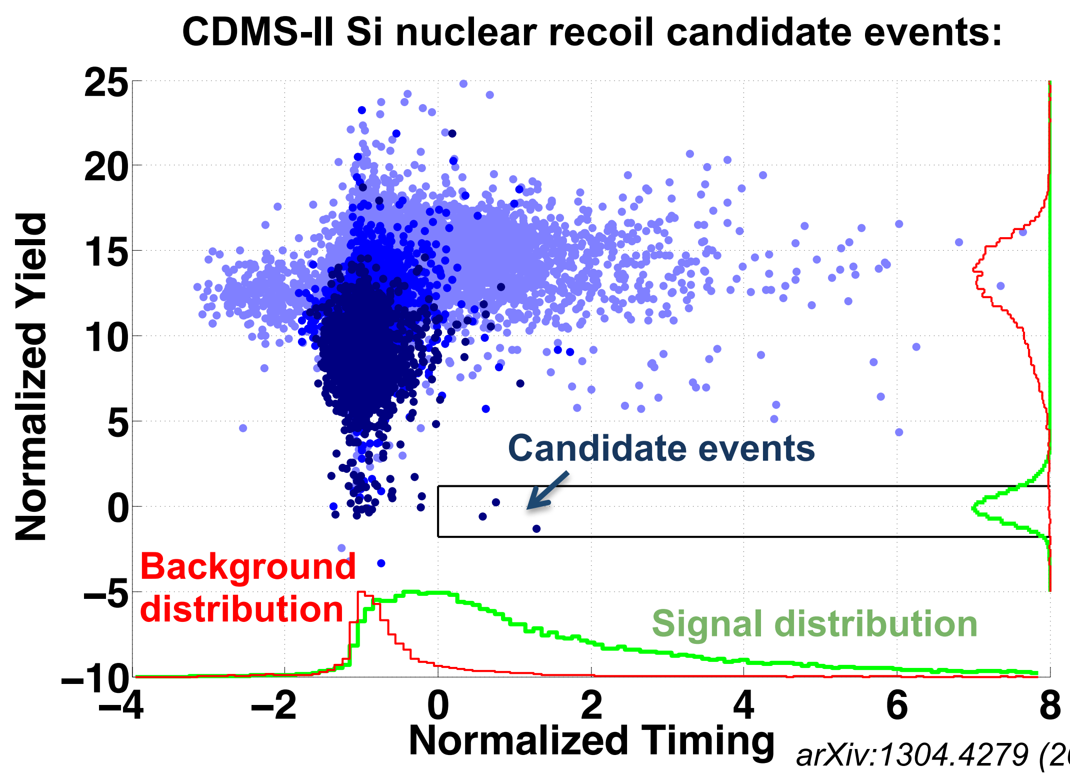
Recent results

- Since publication of these limits, there have been several additional developments:
- CoGeNT has improved background estimates, and low-mass WIMP interpretation now favors σ ≈ 2×10^{-41} cm^2 (compatible with these constraints) *[arXiv:1208.5737 (2012)]*
- Analysis of data from CDMS-II Si detectors found 3 nuclear-recoil candidate events, with expected background:

$$0.41^{+0.20}_{-0.08}(stat.)^{+0.28}_{-0.24}(syst.)$$

- WIMP+background favored over background-only hypothesis at ~3σ
- XENON10 and XENON100 have both published limits which disfavor this region at >90% CL under standard assumptions

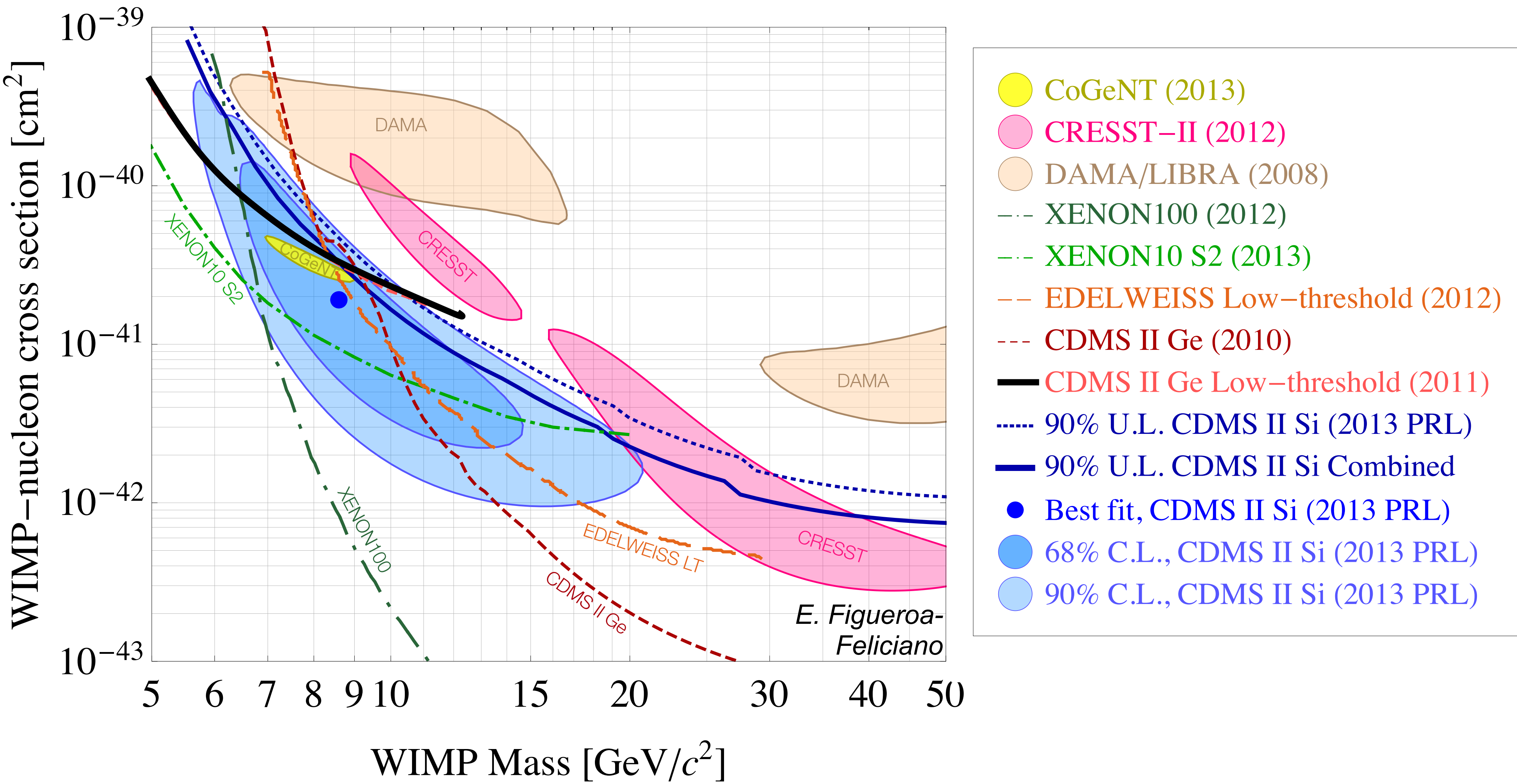
[arXiv:1104.3088 (2013), arXiv:1207.5988 (2012)]



arXiv:1304.4279 (2013)

- Uncertainties in detector response, astrophysical parameters, or WIMP interaction could possibly allow compatibility *[e.g., arXiv:1306.1790 (2013)]*

Current low-mass constraints



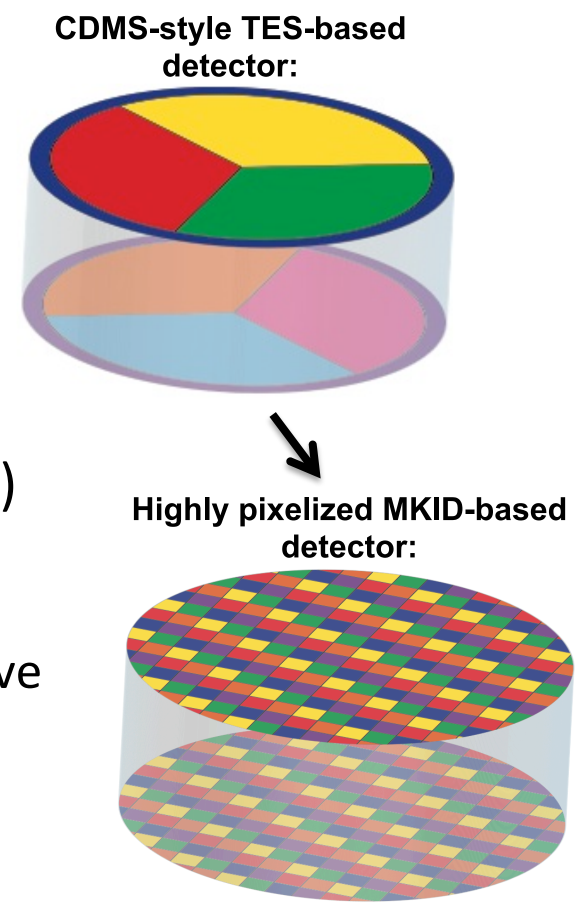
- Stay tuned! While interpretation of low-mass results remains uncertain, many experiments are currently working to eliminate systematics and improve sensitivity to ≈10 GeV WIMPs

Highly-pixelized phonon-mediated particle detectors

B. Bumble, B. Cornell, P.K. Day, S. Golwala,
H.G. Leduc, B.A. Mazin, D.C. Moore, J. Zmuidzinas

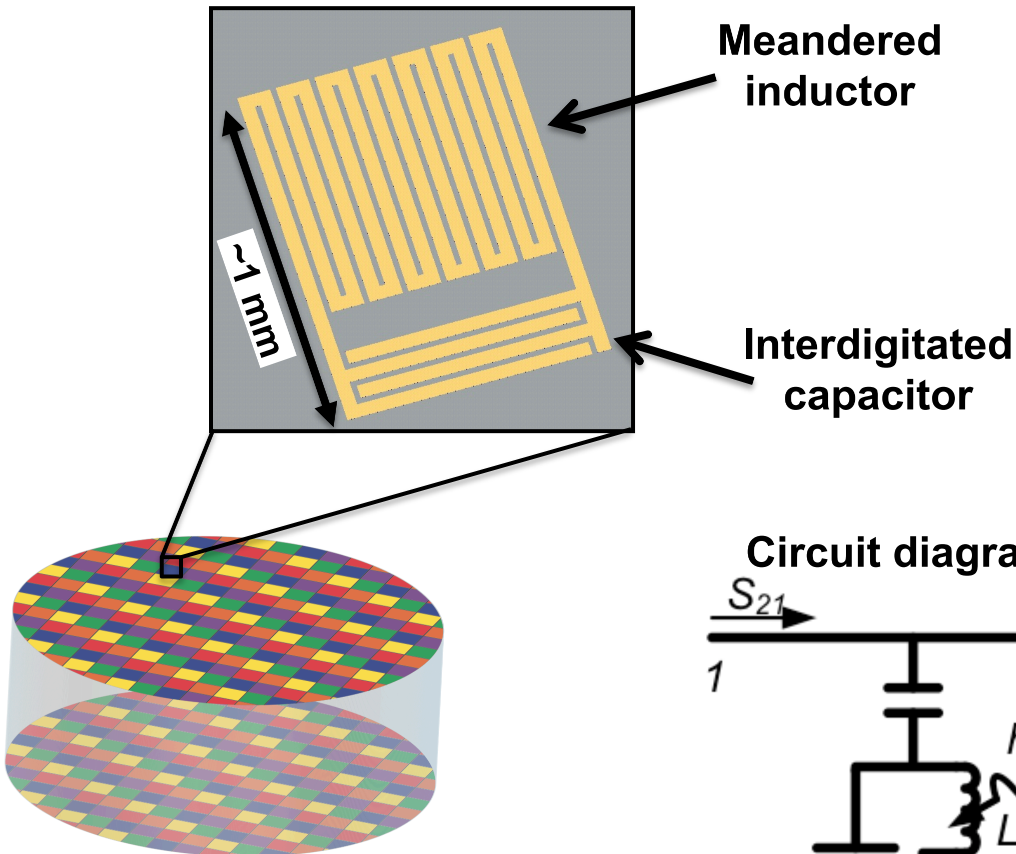
Next-generation detectors

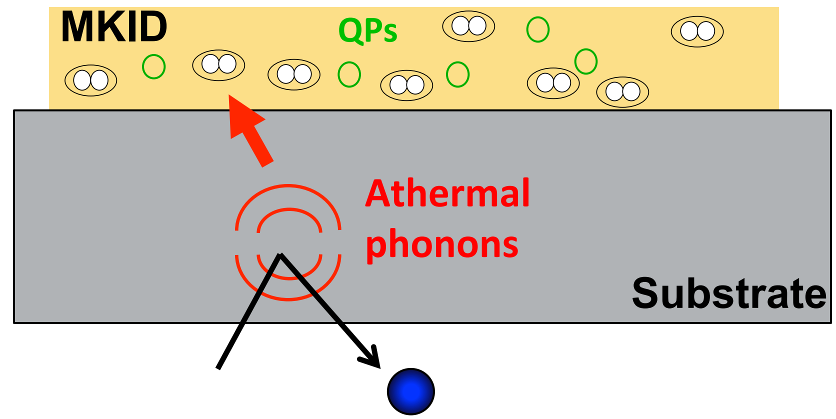
- Ton-scale detectors are required for the next generation of many rare-event searches (e.g. dark matter direct detection, searches for 0νββ)
- Cryogenic detectors currently provide sub-keV energy resolution and excellent background rejection but scaling to large masses is challenging
- Microwave kinetic inductance detectors (MKIDs) may offer several advantages over transition edge sensors (TESs):
  - Simple fabrication (single Al film, >10μm features)
  - Naturally multiplexed
    - More granular phonon sensor expected to improve background rejection
    - Single wire readout per detector
  - No complex cryogenic readout electronics are required



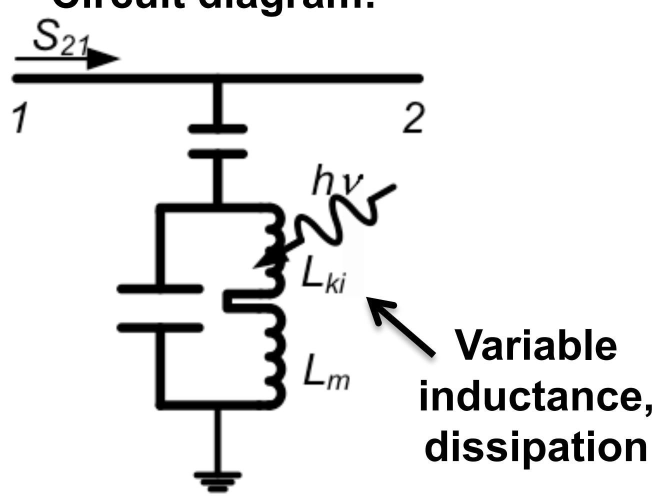
Phonon-mediated MKIDs

- Athermal phonons break Cooper-pairs in MKID giving shift in frequency and dissipation of resonant circuit

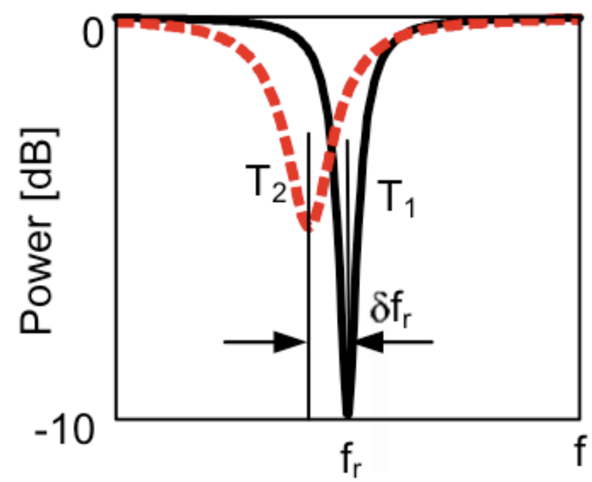




Circuit diagram:



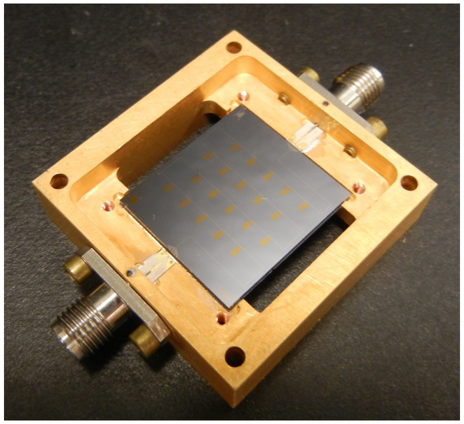
Resonance shift:



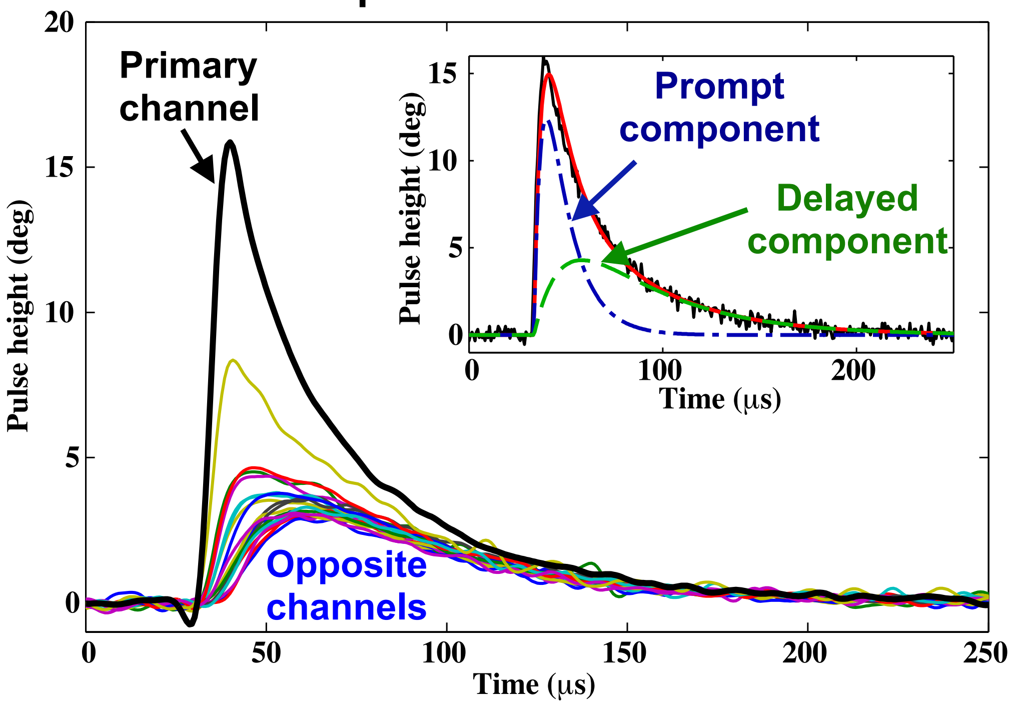
4 cm^2 prototype devices

- Have demonstrated position and energy resolved phonon-mediated particle detection in prototype arrays
- Test devices consist of 2cm x 2cm x 1mm Si substrate patterned with 20 resonators

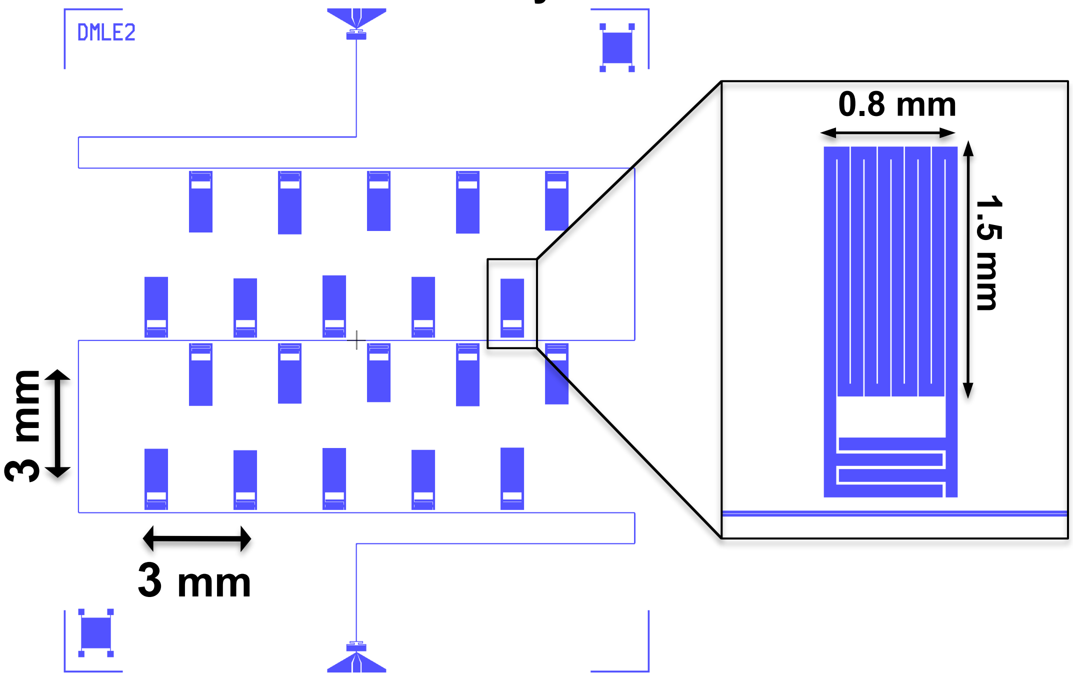
Mounted device:



200 keV phonon-mediated event:



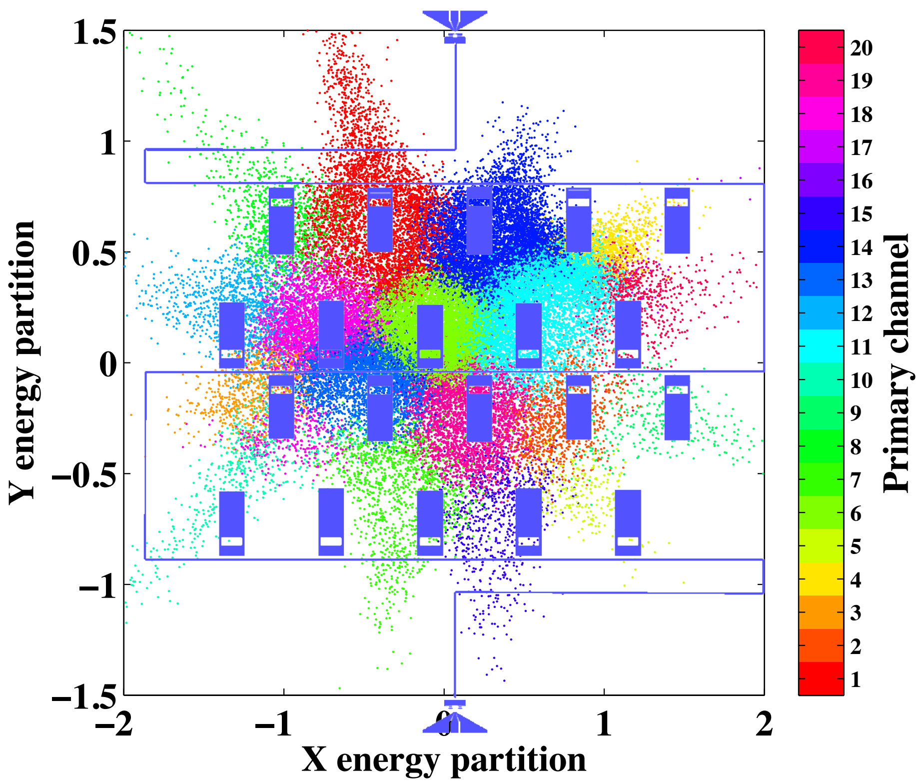
Device layout:



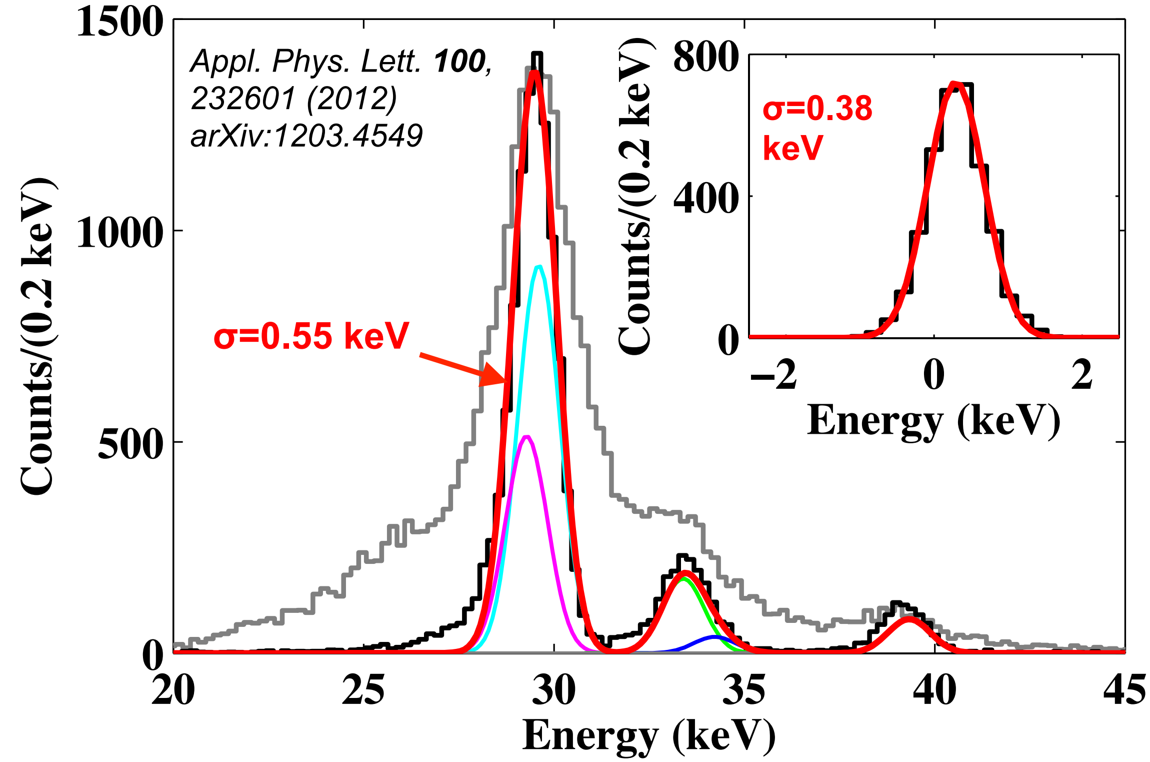
Position and energy reconstruction

- Both position and energy of interactions in substrate can be reconstructed from total phonon amplitude and partitioning of energy between sensors
- Measured energy resolution of σ = 0.55 keV, position resolution <0.5 mm

Position reconstruction:

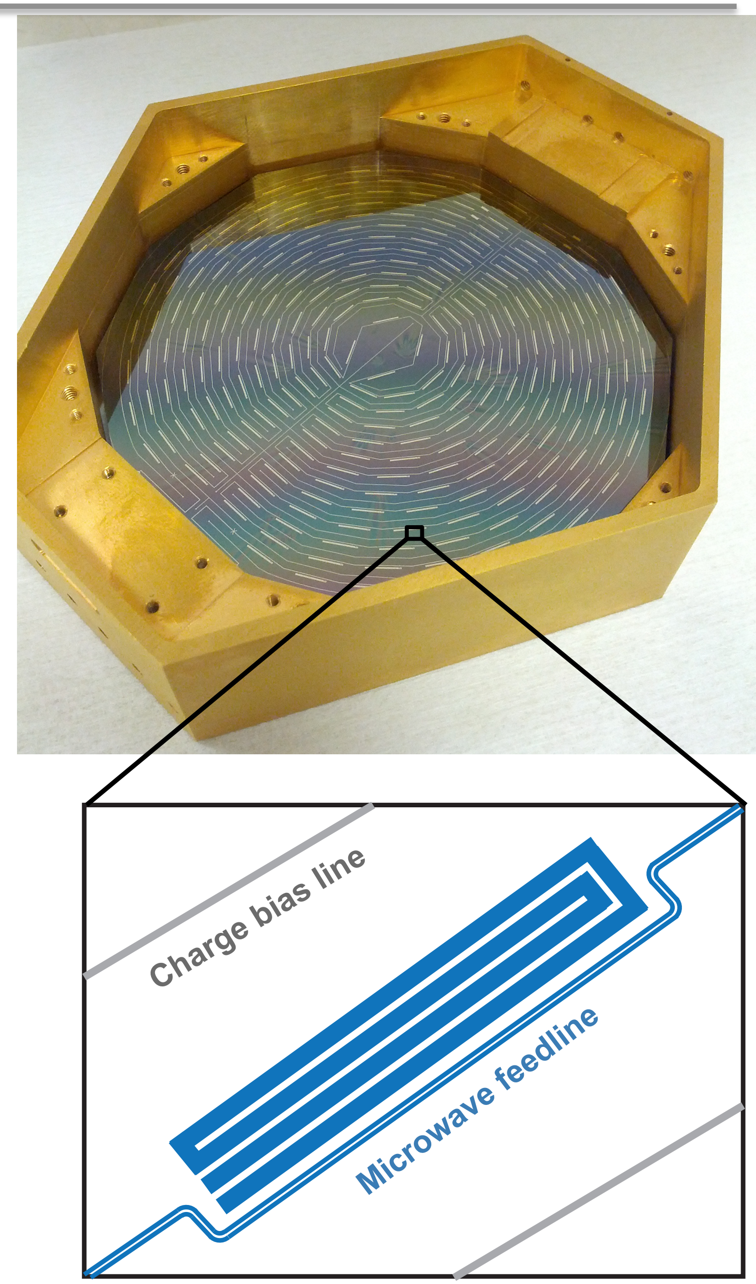


Reconstructed energy spectrum:



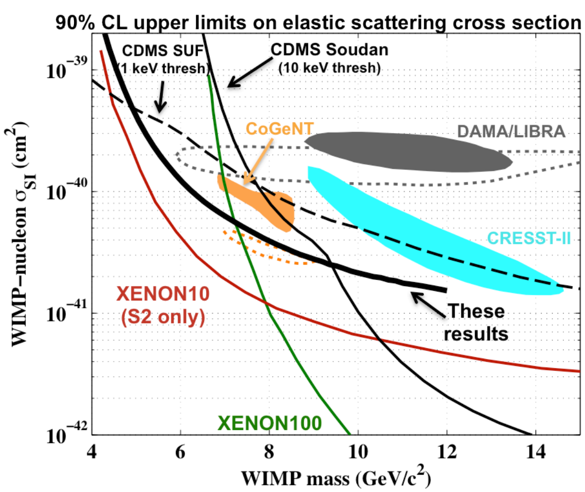
0.25 kg detectors

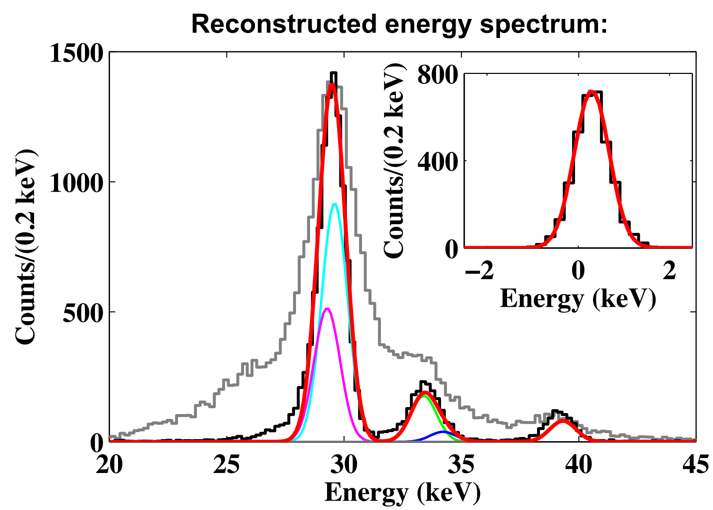
- ~0.25 kg, 3” diameter detectors patterned with array of 250 MKIDs currently being fabricated
- Single microwave feed line per detector
- Also includes interleaved charge electrodes to allow simultaneous measurement of ionization and phonons
- While current energy resolution already competitive with existing detectors, but significant improvement may be possible by improvements to:
    - Phonon collection efficiency
    - Kinetic inductance fraction
    - Quasiparticle lifetime
    - Amplifier noise



Conclusions

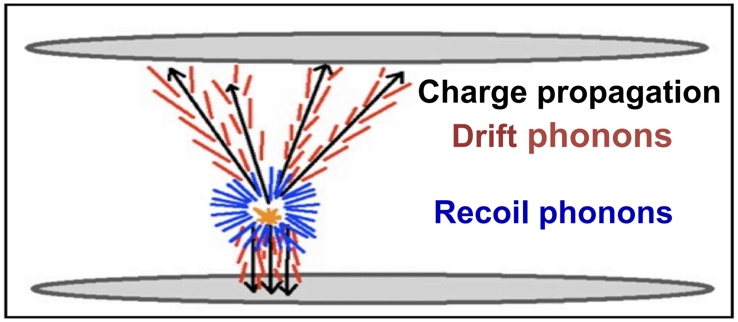
- Reanalysis of CDMS II data has with a 2 keV recoil energy threshold disfavored low-mass WIMP interpretations for DAMA/LIBRA, CRESST-II, and the entire CoGeNT excess, under standard assumptions
- Compatible with recent CDMS-II Si and revised CoGeNT WIMP interpretations that predict smaller interaction cross-section ($\sigma \approx 2 \times 10^{-41}$ cm^2)
- While the interpretation of possible signals remains unclear, many experiments are working to improve sensitivity
- Demonstrated MKID-based particle detectors, offering a promising technology for extending cryogenic detectors to future rare event searches





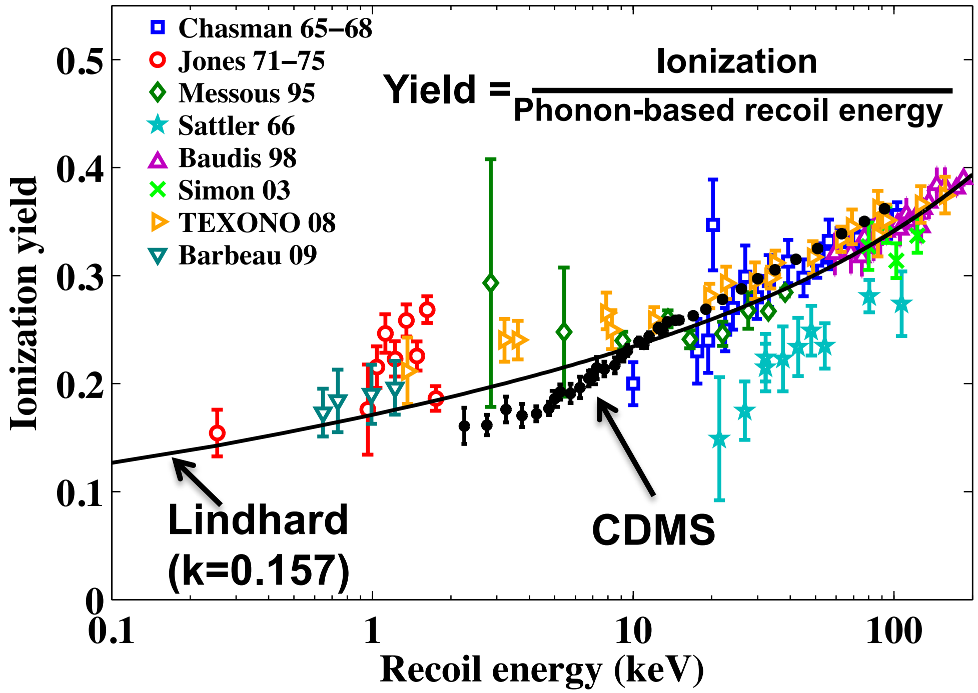
Calibration of Energy Scales

- Nuclear recoil energy reconstructed from phonon signal alone
- Must correct for difference in Neganov-Luke (NL) phonons relative to electron recoils
- Measure ionization yield for nuclear recoils using ^{252}Cf calibration data
- NL phonons only ~15% of signal, so 10% error on yield gives <2% error on recoil energy



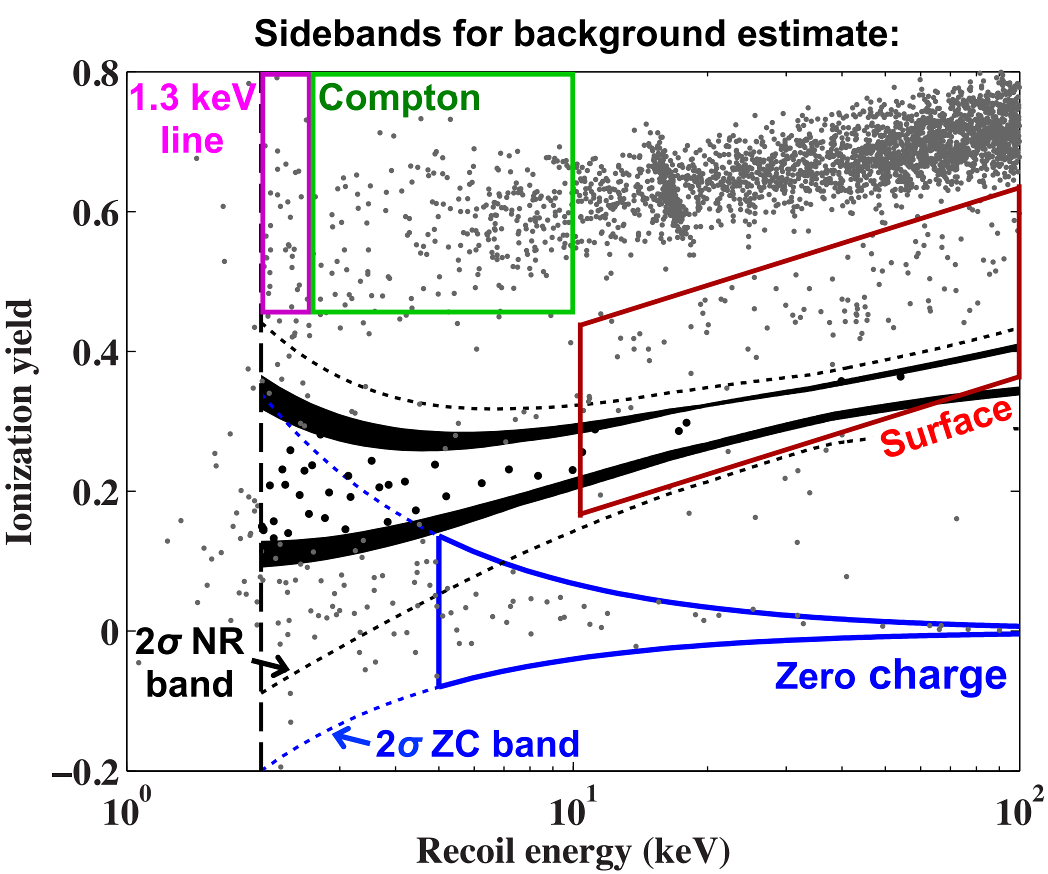
*Neganov and Trofimov, Otkryt. Izobret., **146**, 215 (1985)*
*Luke, J. Appl. Phys., **64**, 6858 (1988)*

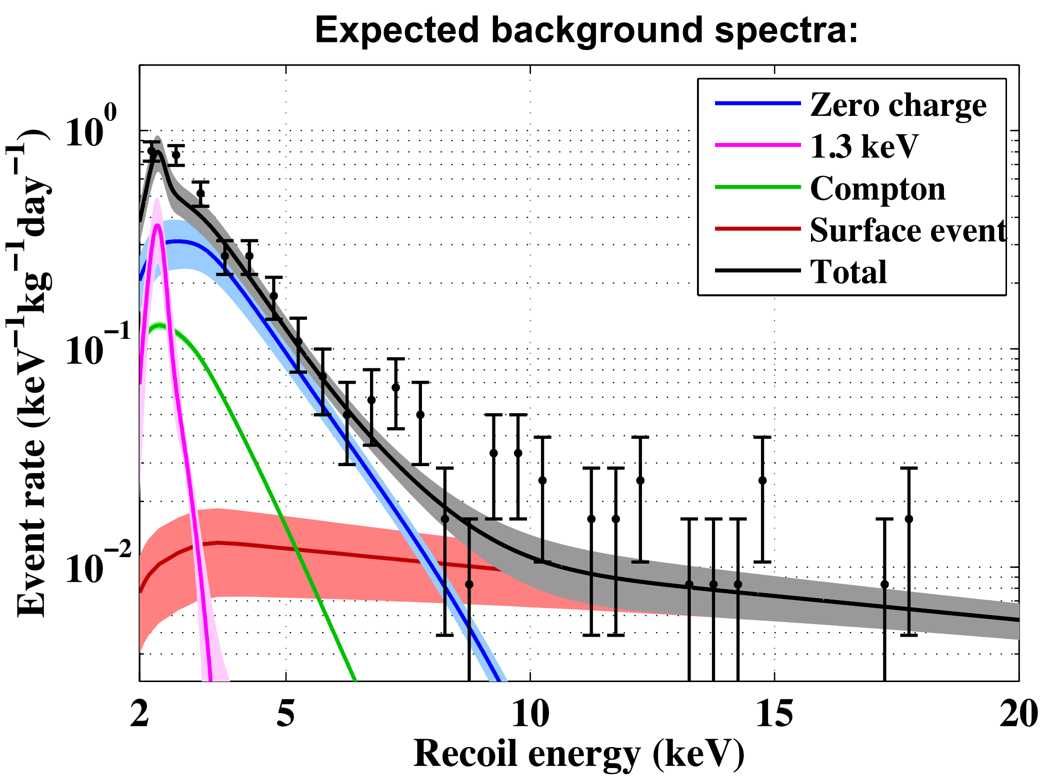
Nuclear recoil ionization yield:



Electron Recoil Backgrounds

- Candidates can be explained by extrapolations of backgrounds from sidebands
- Possibly significant systematic errors due to extrapolations to low energy
- Do not subtract these backgrounds when setting limits





Expected sensitivity

- S. Golwala has calculated expected sensitivity for athermal phonon mediated detector with direct absorption in MKIDs
- Assumes phase readout (amplifier limited), $Q_c << Q_i$ to resolve ~few μs rising edge of pulse, quasiparticle population dominated by readout power
- Expected energy resolutions as good as ~40 eV for massive, ~0.5 kg detectors:

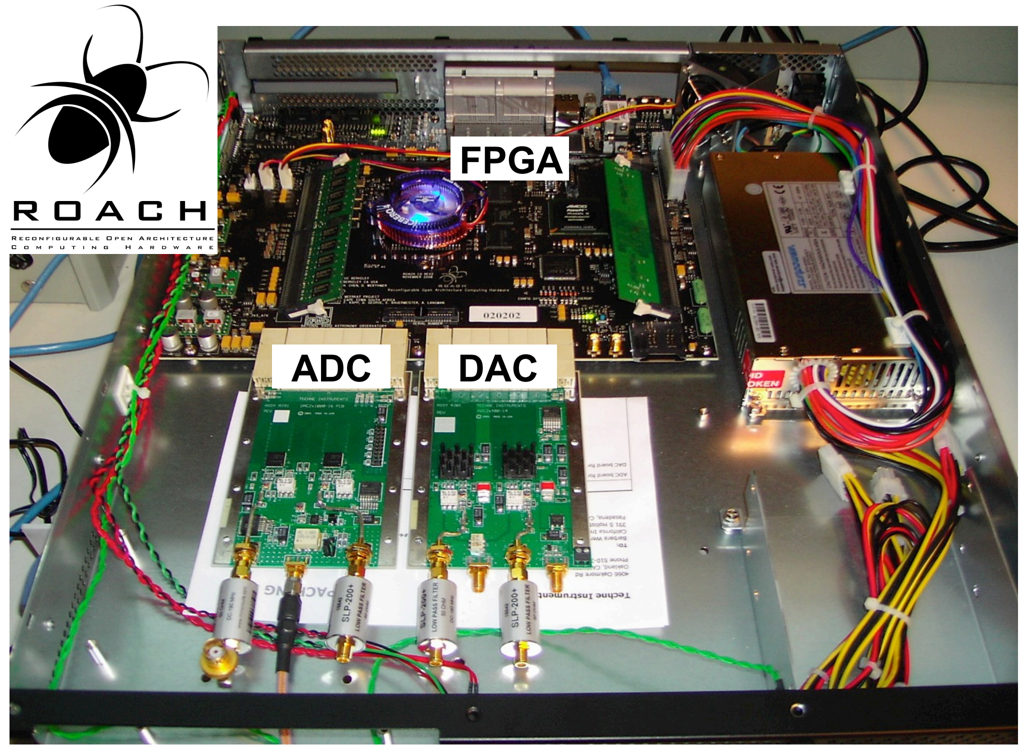
$$\sigma_E = (38\ \mathrm{eV}) \left(\frac{0.3}{\eta_{ph}} \frac{2.1}{\beta(\omega,T)} \frac{\Delta}{115\ \mu\mathrm{eV}} \right) \sqrt{ \frac{\eta_{read}}{1} \frac{0.75}{\alpha} \frac{0.5}{p_t} \frac{A_{sub}}{100\ \mathrm{cm}^2} \frac{T_N}{5\ \mathrm{K}} \frac{3\ \mathrm{GHz}}{f_0} \frac{\lambda_{pb}}{1\ \mu\mathrm{m}} \frac{100\ \mu\mathrm{s}}{\tau_{qp}} \frac{1.2}{S_1(\omega,T)} }$$

Readout QP generation efficiency (η_{read})
Substrate area (A_{sub})
HEMT noise temperature (T_N)
Cooper pair breaking length (λ_{pb})
Phonon absorption efficiency (η_{ph})
Kinetic inductance fraction (α)
Phonon transmission probability (p_t)
Quasiparticle lifetime (τ_{qp})

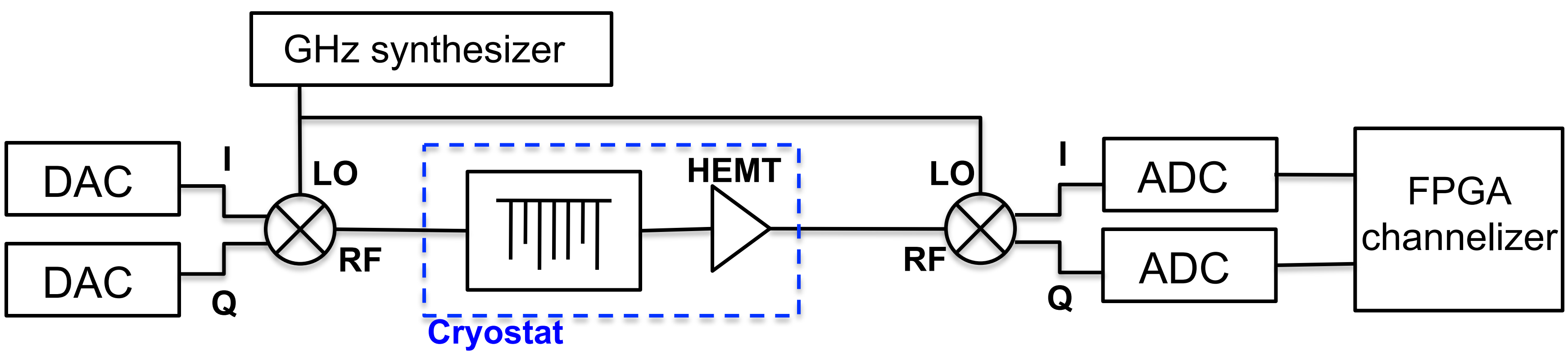
- For amplifier noise limited readout, resolution would improve with better amps (e.g., TiN paramp, Eom et al., arXiv:1201.2392)

Readout electronics

- Room temperature electronics used to demultiplex resonator tones
- Open source ROACH board (developed by CASPER at Berkeley) provides FPGA, interface to custom DAC/ADC boards
- Custom firmware with onboard trigger provides 2048 samples at 1.3 MHz for each channel, for each event



R. Duan et al., *Proc. SPIE 7741*, 7741V (2010)



Position reconstruction

- Interaction location can be determined from:
  - Partitioning of energy between sensors
  - Timing delays