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Light Dark Matter Searches with SuperCDMS and COUPP

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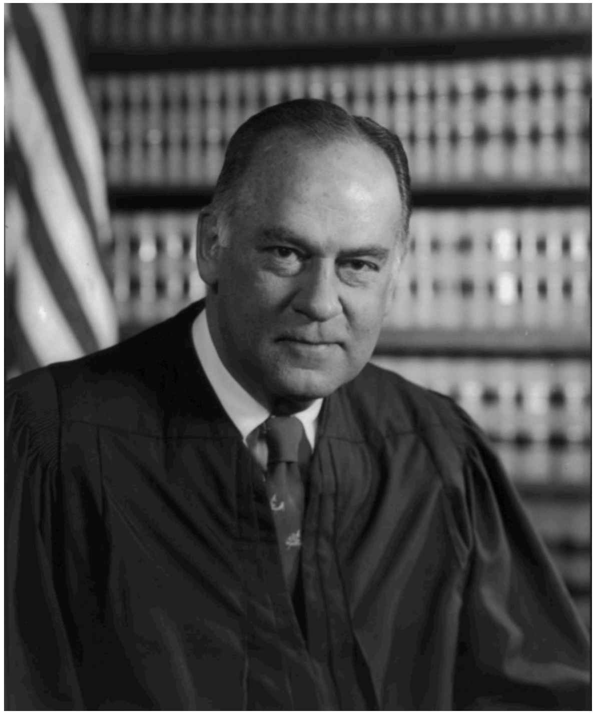
Light Dark Matter Discovery

- Current experiments strive to set better and better limits on the dark matter interaction cross-section
- Is it possible to find a set of criteria that could compose a dark matter discovery?
- How do we remove bias from the process?
- How do we move from the phase of setting limits to experimental techniques with discovery potential?
- Imagine a world with a 8 GeV dark matter discovery. What are the experimental challenges to studying this particle?



Searching for Light Dark Matter with Two Technologies

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- Cryogenic semiconductor detectors (SuperCDMS)
- Superheated liquid detectors (COUPP)

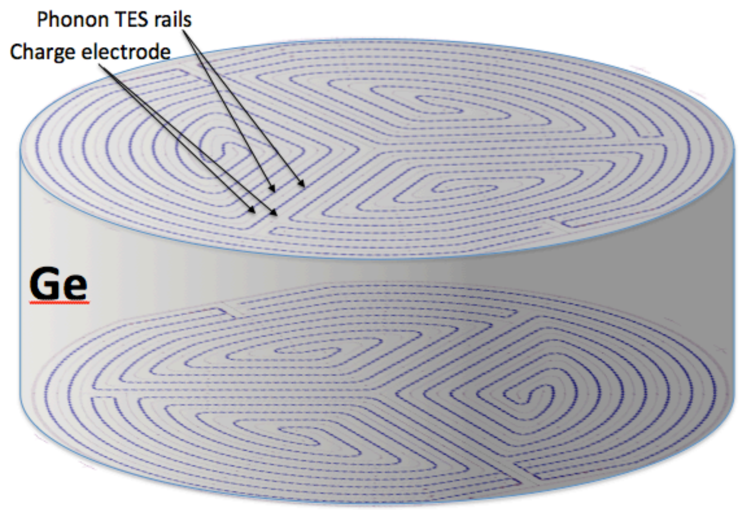
Hot topics and cool physics

SuperCDMS Collaboration

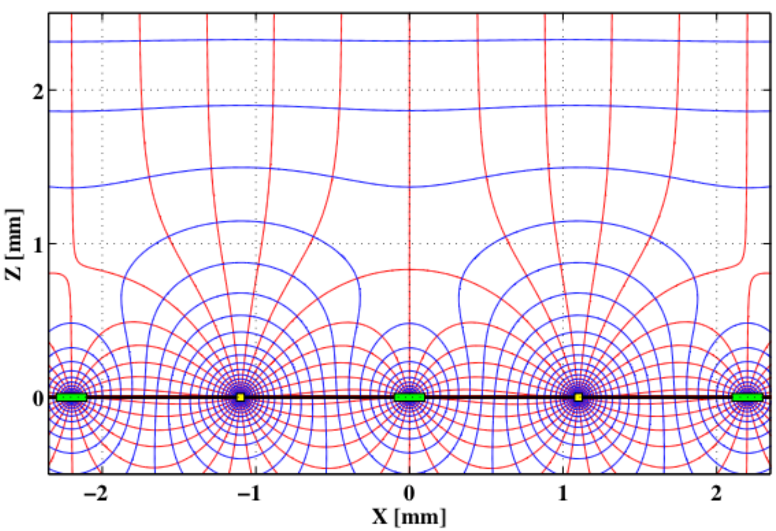
- California Institute of Technology
- Fermi National Accelerator Laboratory
- Massachusetts Institute of Technology
- Queen's University
- Santa Clara University
- SLAC / Kavli Institute for Particle Astrophysics and Cosmology
- Southern Methodist University
- Stanford University
- Syracuse University
- Texas A&M University
- Universidad Autónoma de Madrid
- University of British Columbia
- University of California, Berkeley
- Pacific Northwest National Laboratory
- University of Colorado, Denver
- University of Evansville
- University of Florida
- University of Minnesota

SuperCDMS

- Search with germanium iZIP detectors
- Operating at ~50 mK
  - Enables phonon and charge readout
  - Charge to phonon ratio separates nuclear and electron scatters
- interleaved Z-sensitive Ionization and Phonon sensors on both faces
  - Surface event identification
  - Outer phonon guard ring



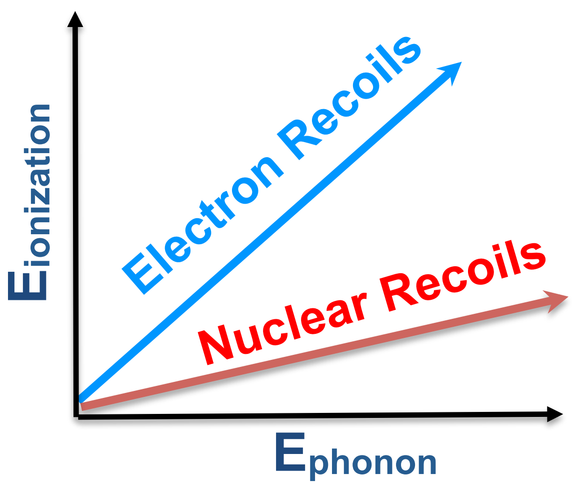
SuperCDMS iZIP detectors have phonon and ionization instrumentation on both faces allowing superior z-sensitivity.



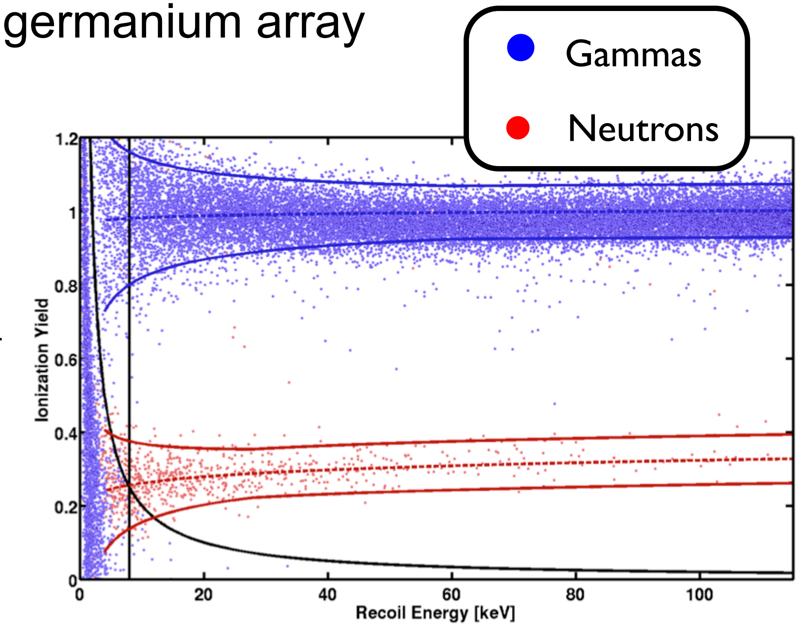
By holding a potential between ionization and phonon electrodes, a more complex electric field is created. Charge near the surface of the detector is collected on only one side. Charge in the bulk of the detector is collected on both faces.

The Cryogenic Dark Matter Search

- The CDMS Collaboration has developed and deployed cryogenic semi-conductor detectors for rare event searches
- CDMS-II at the Soudan Underground Laboratory completed operations in 2009
  - Expect new and interesting results from CDMS-II on LIPs, silicon, annual modulation, …
- SuperCDMS consists of two experiments with substantial detector improvements
  - SuperCDMS-Soudan, an operating ~10 kg germanium array
  - SuperCDMS-SNOLAB, a proposed 200 kg germanium array

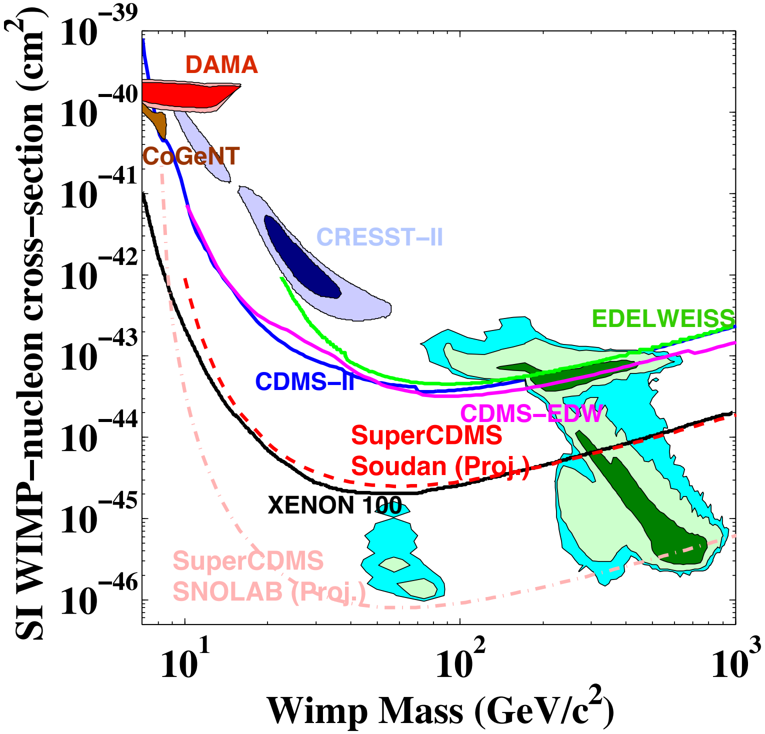


CDMS measures both the heat deposition and the ionization from particle scattering. This allows event-by-event identification the interaction as a nuclear or electron recoil down to energies below 10 keVr.

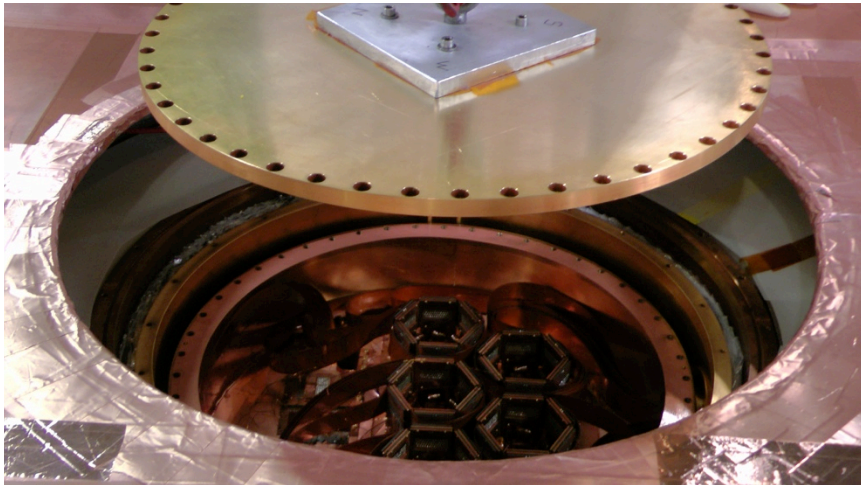


SuperCDMS-Soudan

- Array of 15 iZIPs in the Soudan infrastructure built for CDMS-II
- >X10 sensitivity increase over CDMS-II
  - Larger detector mass (x2.5 thicker detectors)
  - Fiducial fraction improved to 67% from 35%
  - Surface background negligible



Projected WIMP sensitivity for SuperCDMS-Soudan after 3 calendar years (Spring 2015).



SuperCDMS detector installation was completed 8 Nov 2011. Detectors have been operating with final settings since March 2012.

Low Mass WIMP Search

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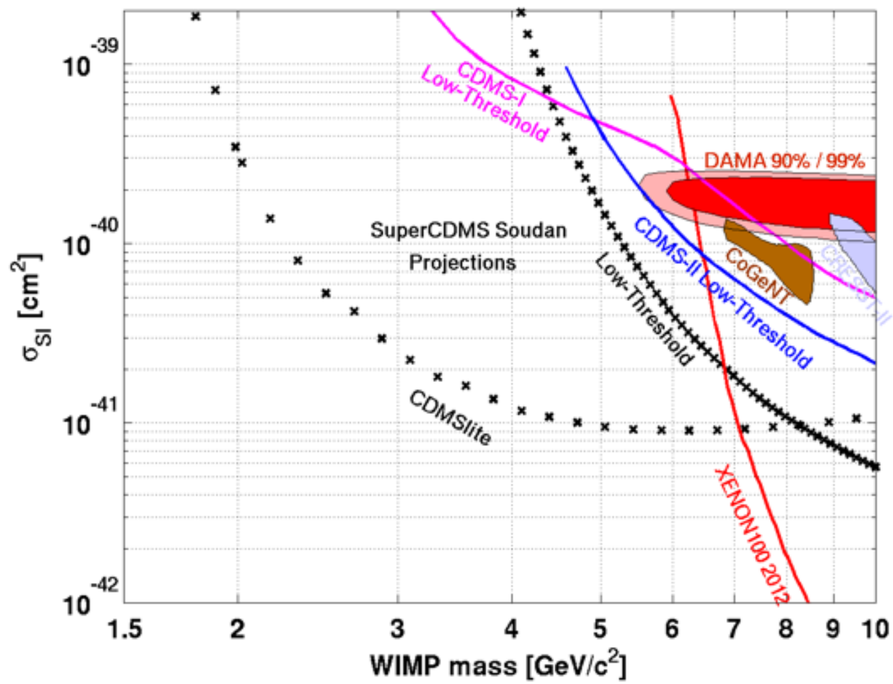
- Low mass WIMP search based on two strategies
- ‘Low-Threshold’ search, optimizing the analysis to approach the hardware trigger threshold
  - Nuclear recoil discrimination down to 2 keVr, but significant overlap of electron and nuclear recoil distributions
  - Note that this projection assumes fewer events with no ionization detected
- ‘CDMSlite’ search, an ionization only search strategy with lower threshold
  - Use Neganov-Luke amplification to increase the signal-to-noise for low-energy events
  - Note this projection assumes a 85 eVee threshold

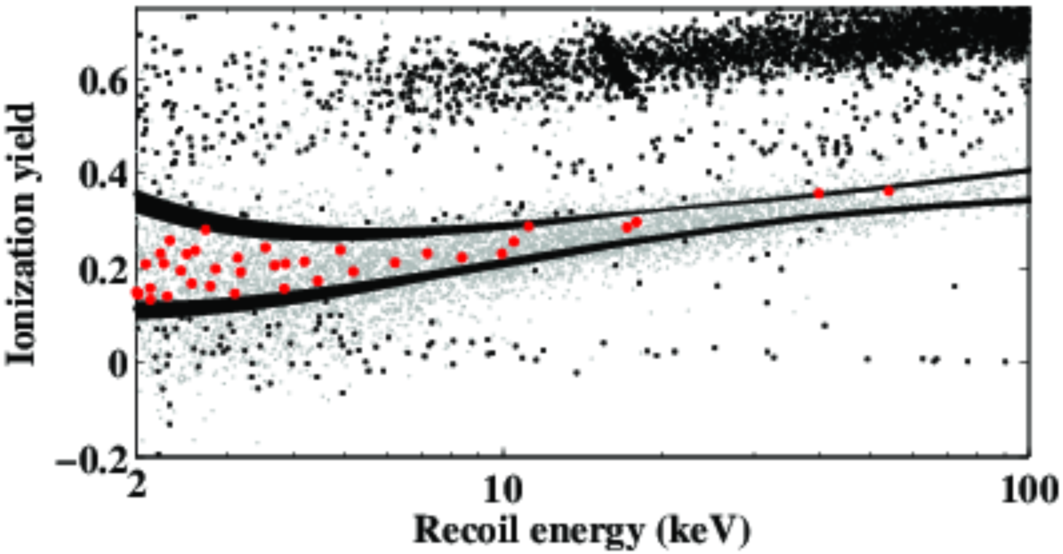


SuperCDMS-Soudan is pursuing a two-fold strategy to search for light dark matter (WIMPs with masses below 10 GeV.) The ‘Low-Threshold’ and ‘CDMSlite’ projections show the expected sensitivity of these two search strategies.

SuperCDMS Low-Threshold Search

- Thresholds were recently tuned by optimizing the trigger filtering
  - Lowered thresholds by factors of 1.5-2
- Four detectors operating with thresholds of ~2 keVr
- The new iZIP design has significantly reduced the quantity of interactions with no charge detected (based on a study of a multi-detector interactions)
  - Double sided readout allows improved position resolution for events in regions of poor charge collection
  - Surface field reduces the 'dead-layer' significantly

PRL 106, 131302 (2011)



Extending the analysis of traditional WIMP search data to the trigger threshold shows that discrimination is reduced, but not eliminated at nuclear recoil energies as low as 2 keV. This figure is from CDMS-II data and the limiting background was from events where the charge signal was consistent with noise. Preliminary results show that the iZIPs have significantly reduced the quantity of events with no charge signal while retaining 2 keVr thresholds.

CDMS low ionization threshold experiment

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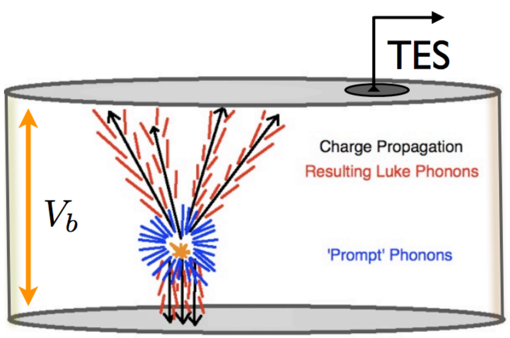
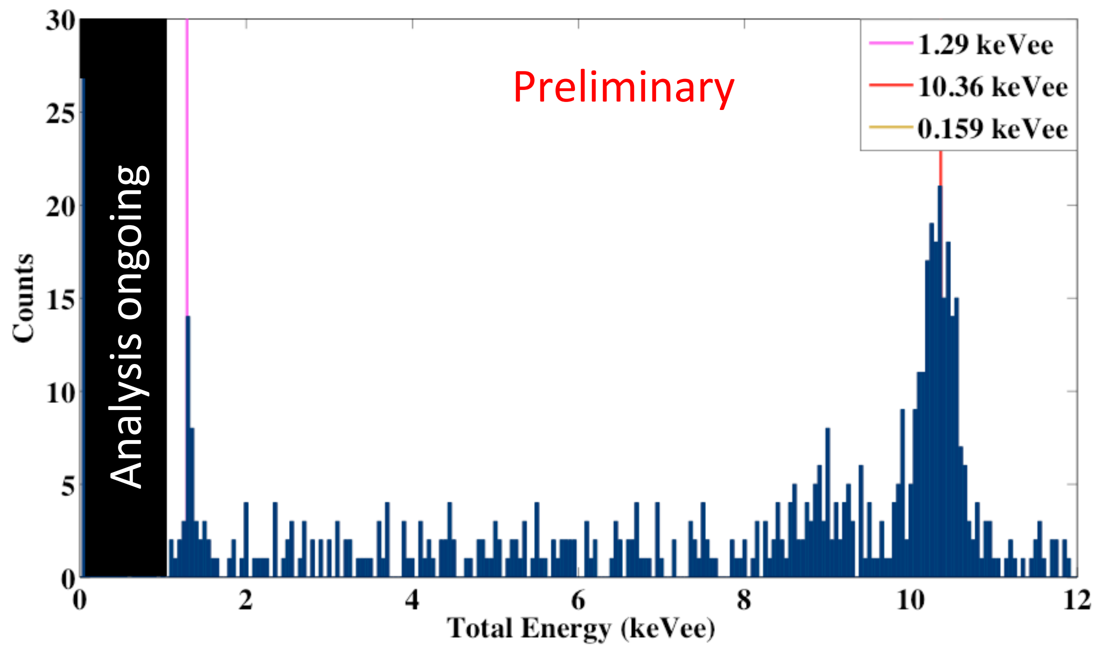
- CDMSlite strategy leverages Neganov-Luke amplification to realize low thresholds with high-resolution
  - Ionization only, no event-by-event discrimination of nuclear recoils
- Drifting N_e electrons across a potential, V, generates N_eV electron volts of heat
- Low background data taken Fall 2012
- First results expected May 2013





This spectrum shows the low-energy performance of SuperCDMS detectors with increased voltage. The applied bias was 69V corresponding to an order of magnitude gain in the signal. The energy resolution for the 1.29 keV gallium L-shell line is ~40 eV. The increase at 9 keV is due to cosmic ray activation of ^{65}Zn. Note that this spectrum has not been corrected for the efficiency of the cuts used.

Future Cryogenic Capability

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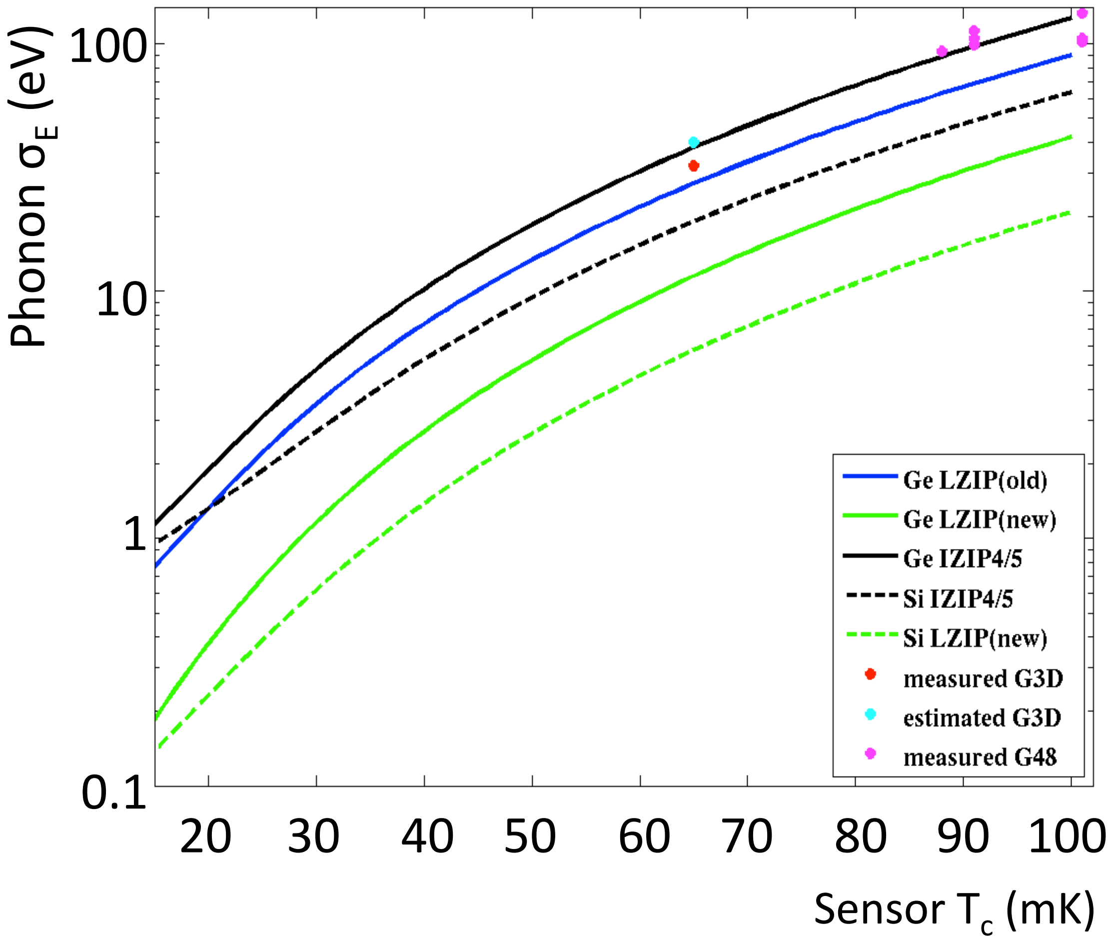
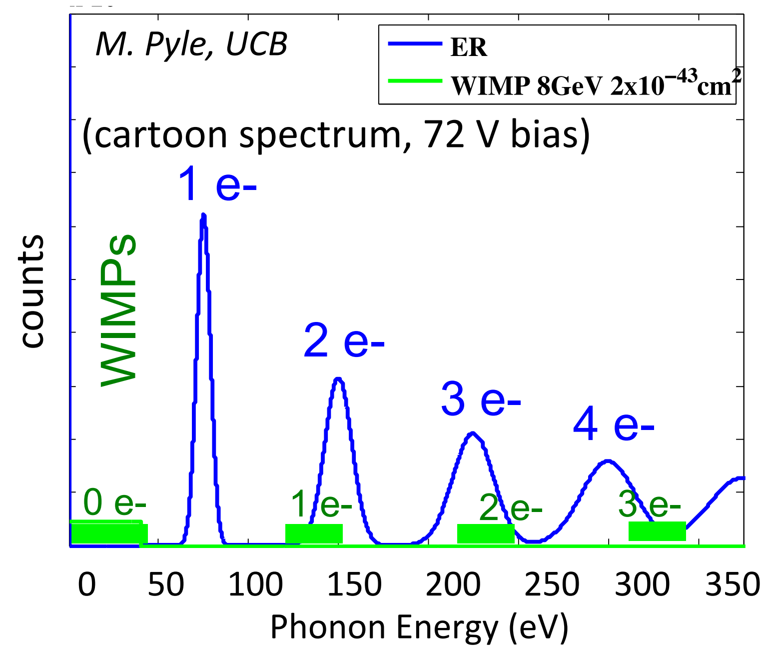
- Lower transition temperatures (Tc) could lead to dramatically better sensor resolution
- Tc's of 20 mK could improve the resolution by x125
- Cryogenics will be more difficult
  - Some tension with the desire to scale to massive 100s kg Ge arrays
- Sensitivity to single charge carrier pairs possible (3 eV)



It was recently realized how our phonon resolutions are scaling with the transition temperature ($\sigma_E \propto T_c^3$). By reducing the Tc and operating temperature, dramatic gains in resolution could be realized.

Recovering Recoil Discrimination at Low E

- By combining high voltage amplification with higher resolution phonon sensors, the electron recoil spectrum should resolve into a 'forest' of charge peaks
- Nuclear recoils could be the only events between the electron recoil peaks



When the resolution becomes much smaller than the energy from each electron-hole pair, an ionization spectrum will resolve into a series of peaks corresponding to the quantization of charge. Discrimination between nuclear and electron recoils could be possible by studying events between the peaks. For example, only nuclear recoils should exist between zero and the first electron-hole peak.

The COUPP-PICASSO Collaboration

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PICASSO

Laurentian University
Université Laurentienne

Saha Institute of Nuclear Physics

UNIVERSITY OF ALBERTA

Czech Technical University in Prague

Université de Montréal

Queen's UNIVERSITY

INDIANA UNIVERSITY SOUTH BEND

SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

THE UNIVERSITY OF CHICAGO

Fermilab

NORTHWESTERN UNIVERSITY

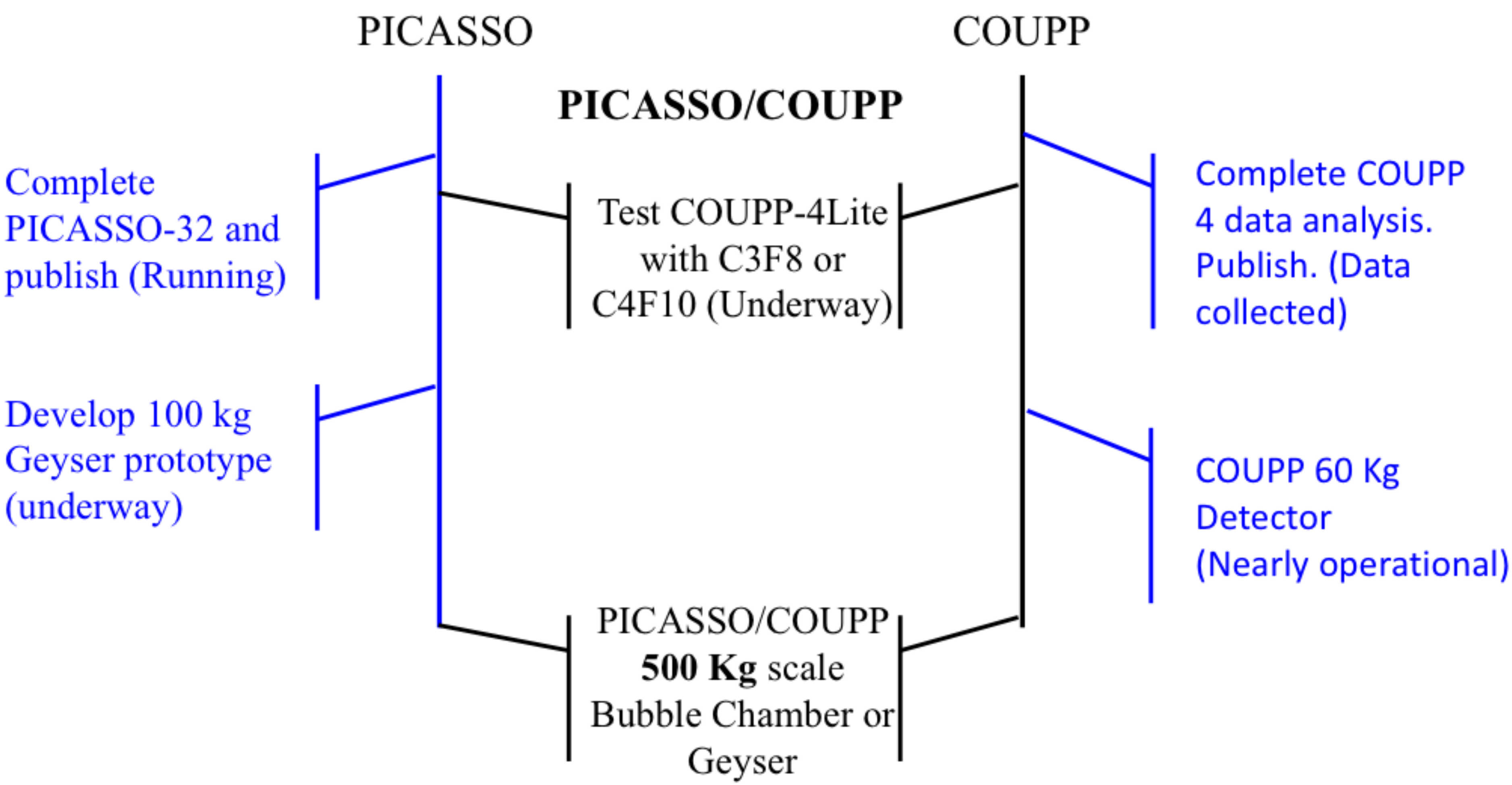
Pacific Northwest National Laboratory

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

VirginiaTech *Invent the Future®*

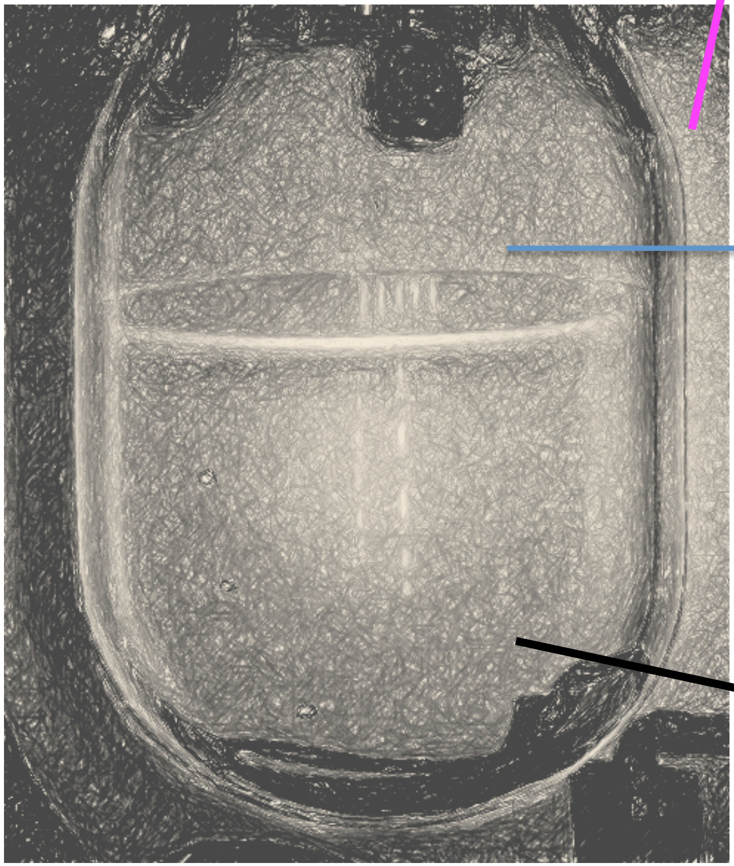
COUPP

COUPP-PICASSO Future Plans



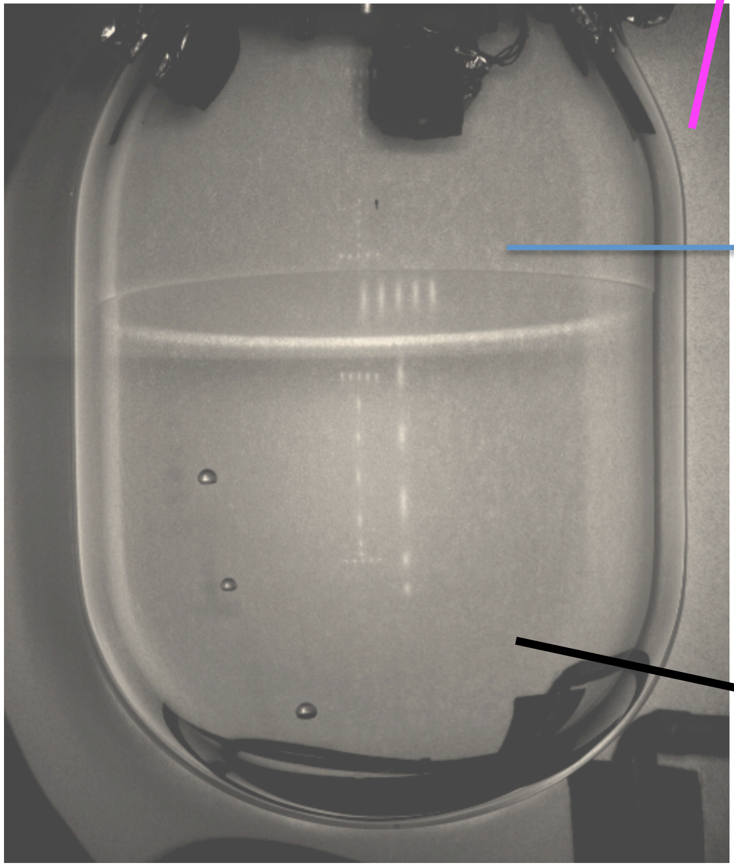
Dark Matter Bubble Chambers

- Superheated CF_3I target
- Depositions of enough energy ($>E_T$) in a small enough volume ($<R_c$)create bubbles
  - F. Seitz, Phys. Fluids **1**, 2 (1958)
- Cameras watch and issue a trigger
- The target is re-liquefied with 60 second compression



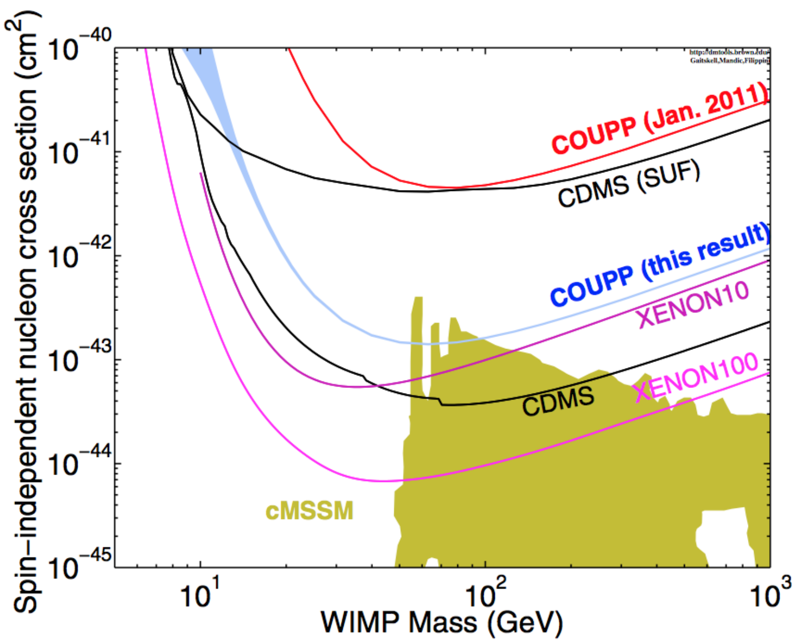
Continuously Heated Bubble Chambers

- Superheated CF_3I target
- Depositions of enough energy ($>E_T$) in a small enough volume ($<R_c$)create bubbles
  - F. Seitz, Phys. Fluids **1**, 2 (1958)
- Cameras watch and issue a trigger
- The target is re-liquefied with 60 second compression

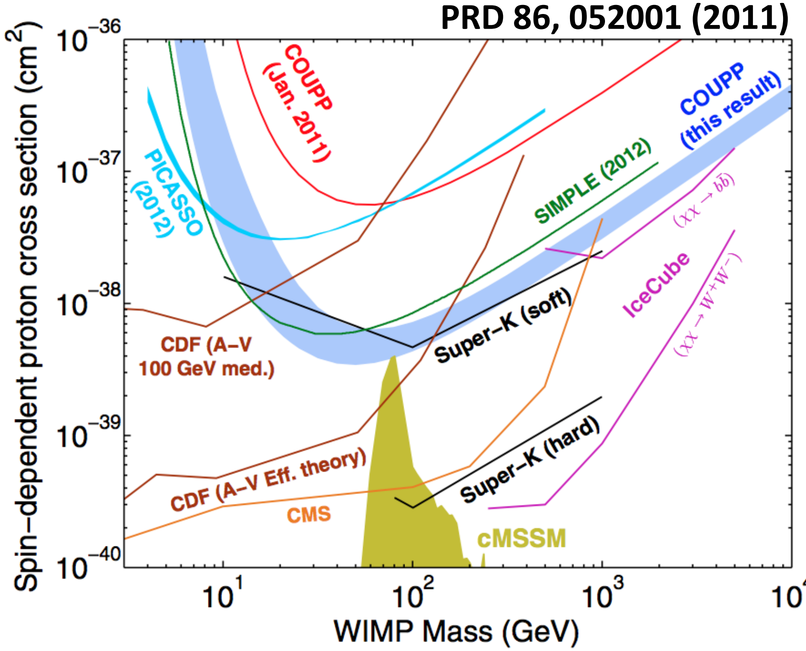


Trouble Down Under (Sudbury)

- First indications of tension between low energy Fluorine efficiency and nuclear recoil calibration came with the COUPP4 SNOLAB results



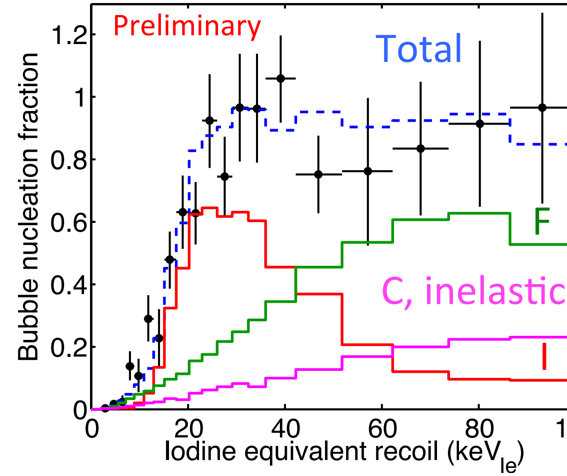
PRD 86, 052001 (2011)



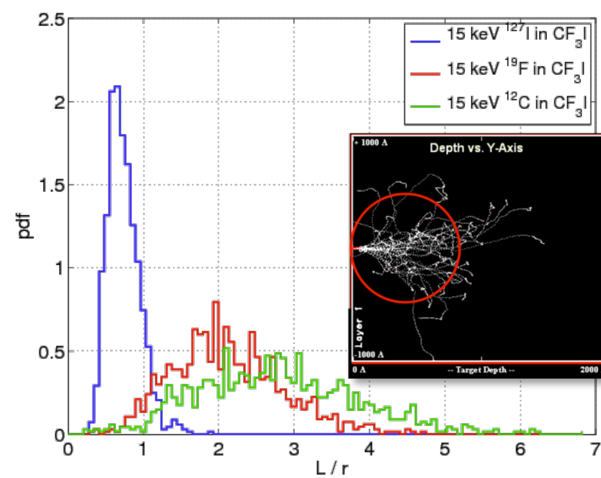
The COUPP4 results from SNOLAB included two threshold models to account for the systematic uncertainties in the detector threshold. The main uncertainty was the response of the detector to recoils of the light elements Carbon and Fluorine. This effects the spin-dependent sensitivity and the light dark matter sensitivity more significantly than the high mass spin-independent sensitivity.

Differences in Nuclear Recoil Efficiency

- The differences in threshold efficiency have been carefully verified in calibration detectors using a low energy neutron source (YBe) and a high energy pion beam (CIRTE)
- TRIM simulations of nuclear scattering in CF_3I shows Iodine tracks at threshold are almost always contained in the critical radius for making a bubble whereas a most Fluorine recoils near threshold deposit energy outside the critical radius



The COUPP Iodine Recoil Threshold Experiment (CIRTE) measures efficiency to nuclear recoils from pion scattering in the Fermilab test beam.



TRIM simulations of nuclear recoils shows that most Fluorine and Carbon tracks are larger than the critical radius for bubble formation.

Switching Target Fluids for Better Light Dark Matter Sensitivity

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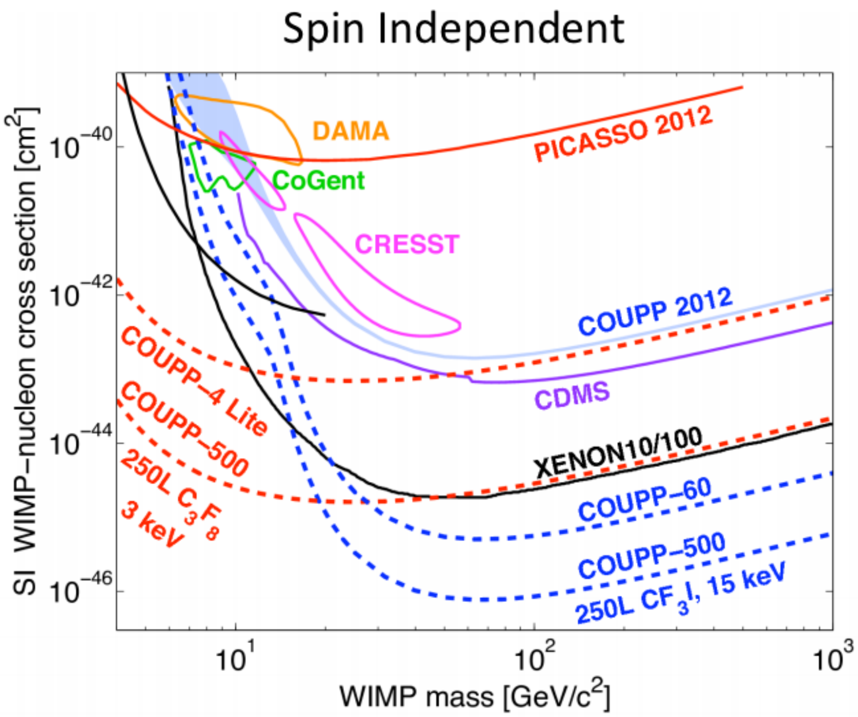
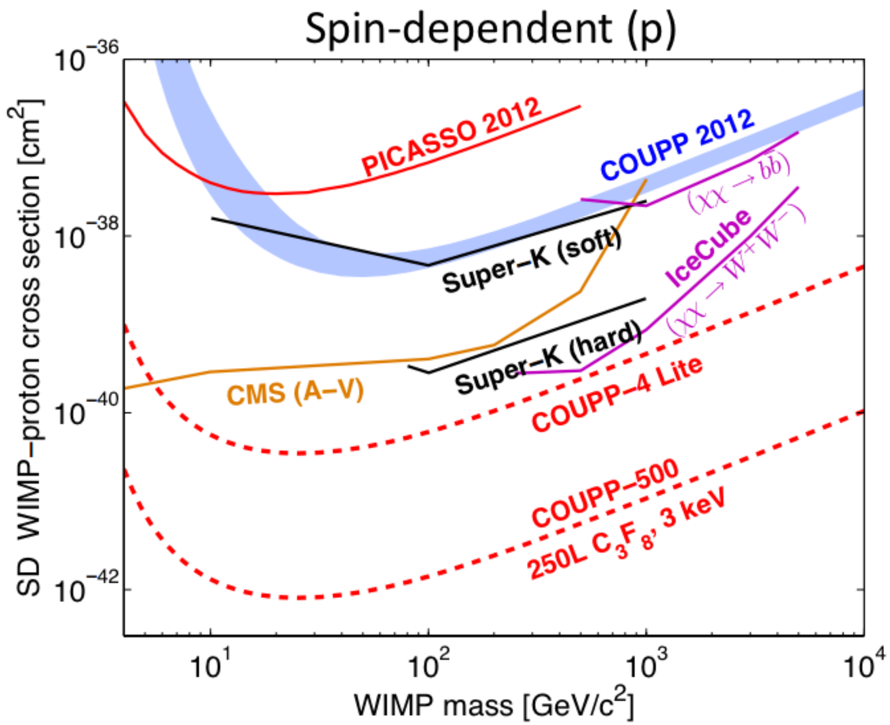
- The next run of a 2L class bubble chamber in SNOLAB will use C_3F_8 (COUPP-4Lite)
- Considering C_3F_8 as the baseline target fluid for COUPP500
- Simulations and calibrations by PICASSO show improved fluorine efficiency for perfluorocarbons
- Lower threshold operations expected (~3 keV)
- Lower toxicity is a bonus

The COUPP-PICASSO Collaboration is betting on light dark matter and spin-dependent sensitivity. Changing the bubble chamber active fluid to C_3F_8 will improve the efficiency to low-energy Fluorine recoils.

COUPP-PICASSO Future Sensitivity

- Using perfluoropropane in future bubble chambers will increase the sensitivity to spin-dependent interactions and light dark matter





Conclusions

- SuperCDMS-Soudan is running and current results are promising for light dark matter using a traditional low threshold search (2-3 keVnr) with electron-nuclear recoil discrimination and a lower threshold (~150 eVee) search leveraging Neganov-Luke amplification
  - Lowering the transition temperatures can improve the resolution and could allow for recoil discrimination at extremely low energies (~3 eVee/50 eVnr)

- COUPP-PICASSO is going 'all-in' on light dark matter (and spin-dependent interactions) by switching target fluids to perfluoropropane
  - PICASSO has a decade of experience with superheated perfluorobutane
  - The increase in the number of fluorine targets, the decrease in the energy threshold, and the increase in the nucleation efficiency will dramatically improve the sensitivity for dark matter with masses below 10 GeV