SuperCDMS:

Search for **Dark Matter** with very **Low temperature detectors**

Nader Mirabolfathi

UC Berkeley

Aspen Jan 2014

- Dark Matter: Direct detection challenges
- Advantage of very low temperature detectors
- CDMS solution
- SuperCDMS

Particle detectors: What a progress!

An x-ray picture taken by Wilhelm Röntgen of Albert von

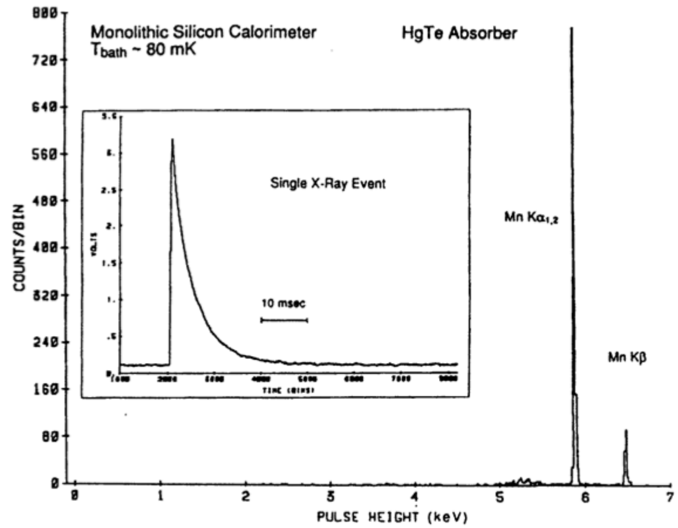
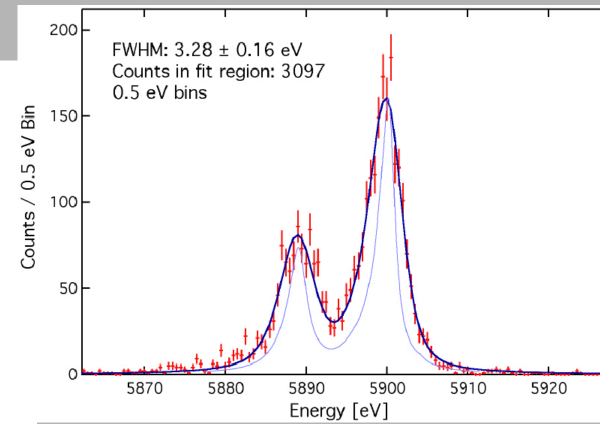
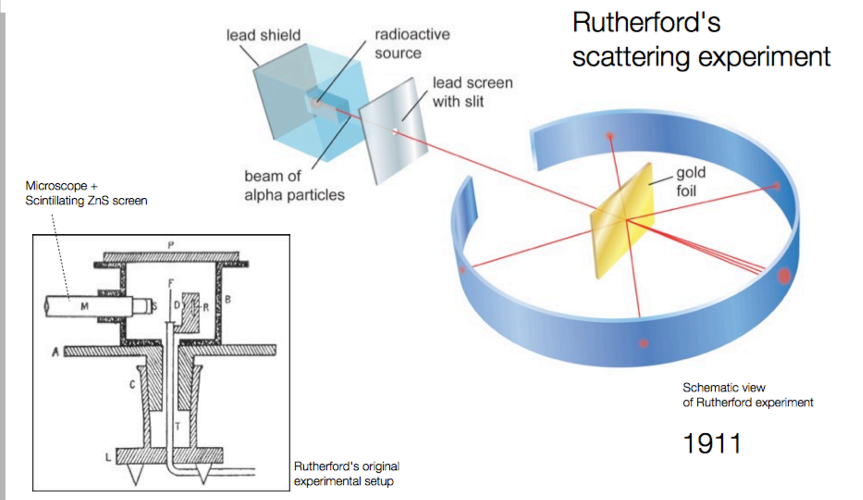
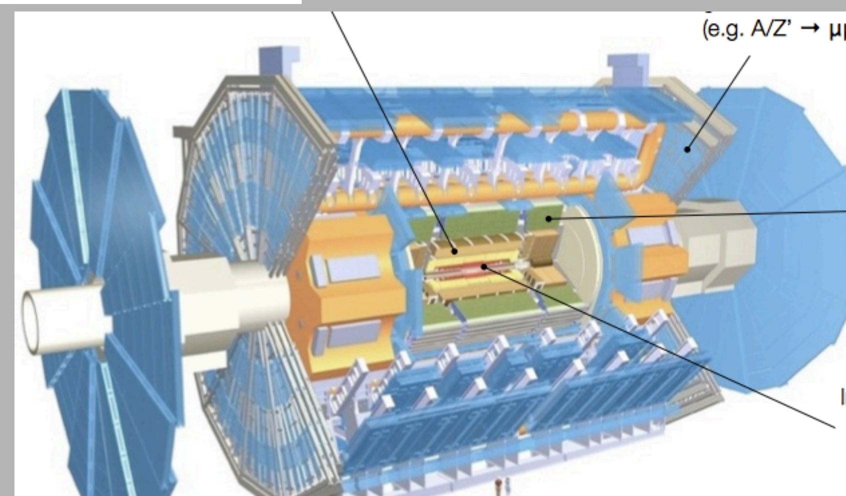


Figure 5. The Mn K_α and Mn K_β spectrum of the Wisconsin/Goddard X-ray microcalorimeter. The FWHM energy resolution for the Mn K_α line is 7.3 eV (figure reproduced from [Mcc93]).







SuperCDMS goal

Directly detect Dark Matter via interactions in Detectors.

Weak scale WIMPs <= hierarchy problem

Freeze out when annihilation rate ≈ expansion rate

$$\Rightarrow \Omega_x h^2 = \frac{3 \cdot 10^{-27} cm^3 / s}{\langle \sigma_A v \rangle} \Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2}$$

coincidence between Cosmology and Particle Physics

Dark Matter Hidden Sector: not necessarily weak scale

Non thermal Dark Matter (Dutta)
Asymmetric Dark Matter (Zurek)
WIMP-less Dark Matter (Feng)
Dark Photon (Arkani Hamed-Finkbeiner-Weiner), atomic DM, Self Interacting etc..

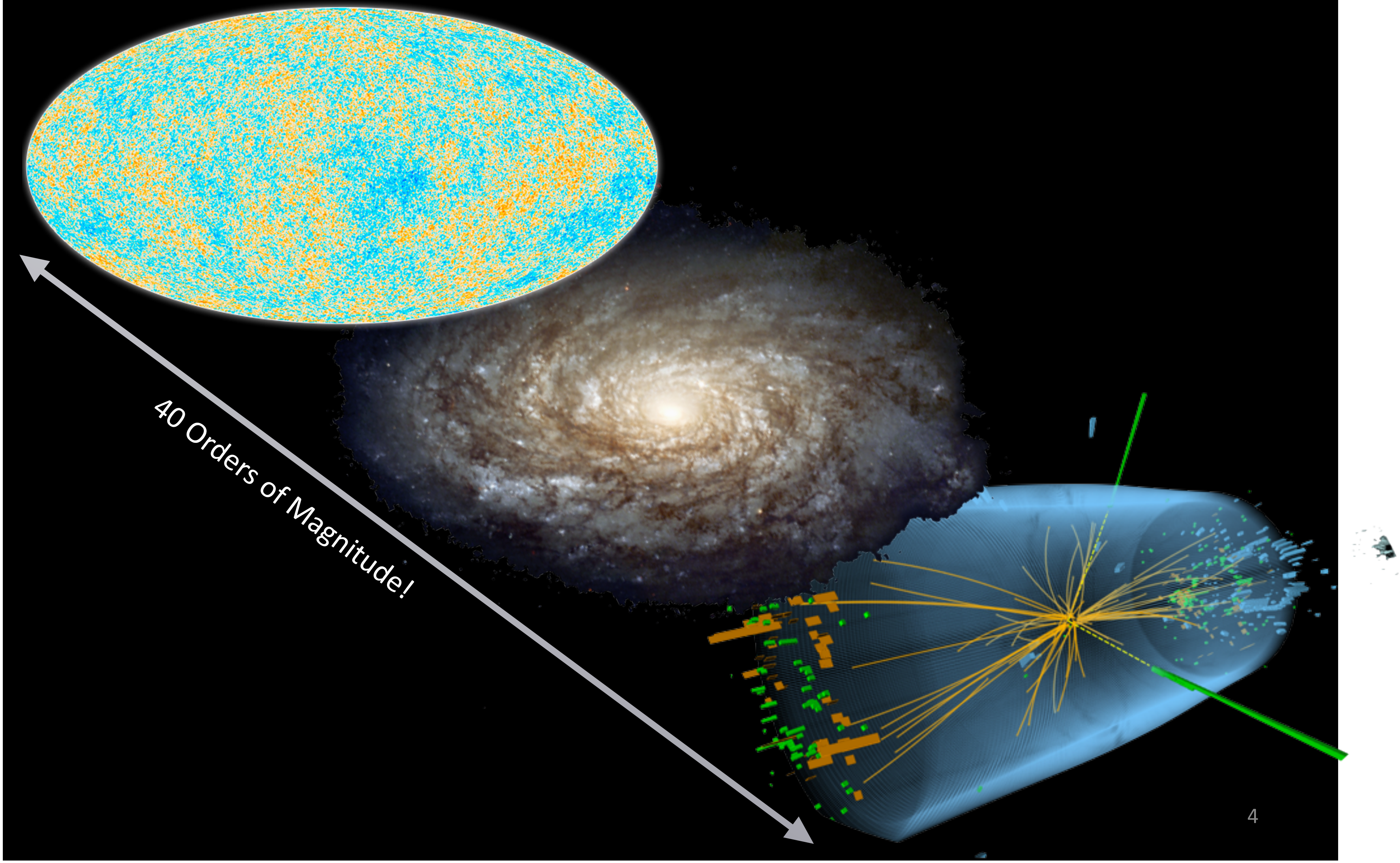
Intriguing but less predictive

Can have low Masses

=>

Direct detection experiments should cover the entire mass spectrum

A Beautiful Problem in Physics




The Hunt for Dark Matter
ALICE
CMS
ATLAS
LHC
LHCb
Production in Colliders
AMS-02
FERMI, Pamela, ATTIC
HESS, VERITAS, Magic
IceCube
1.5 kilometers
2.5 kilometers
Annihilation in the Cosmos
Direct Detection
LUX
SuperCDMS

WIMPs in the Halo

isothermal Maxwell-Boltzmann distribution:

Escape velocity=540 Km/s

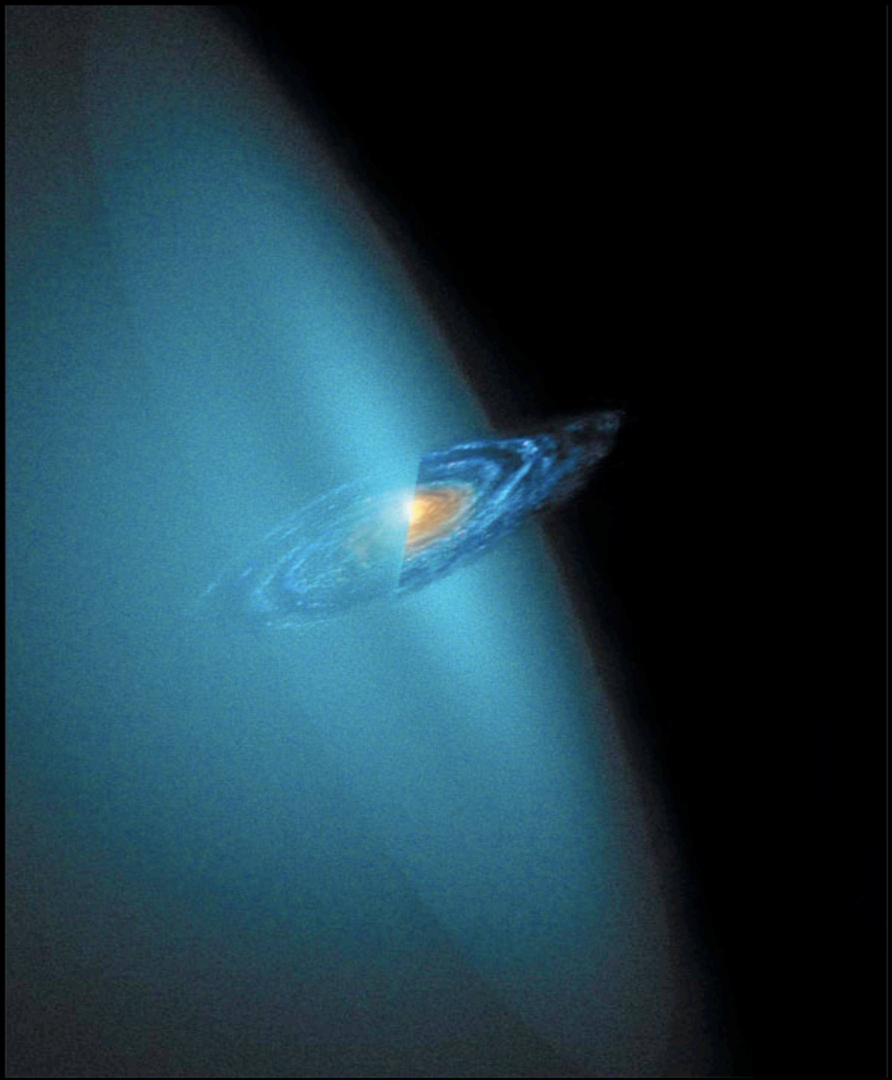
V_0 = 230 Km/s

ρ= 0.3 GeV/cm^3

Rate ~ N n_χ $\langle\sigma_\chi\rangle$

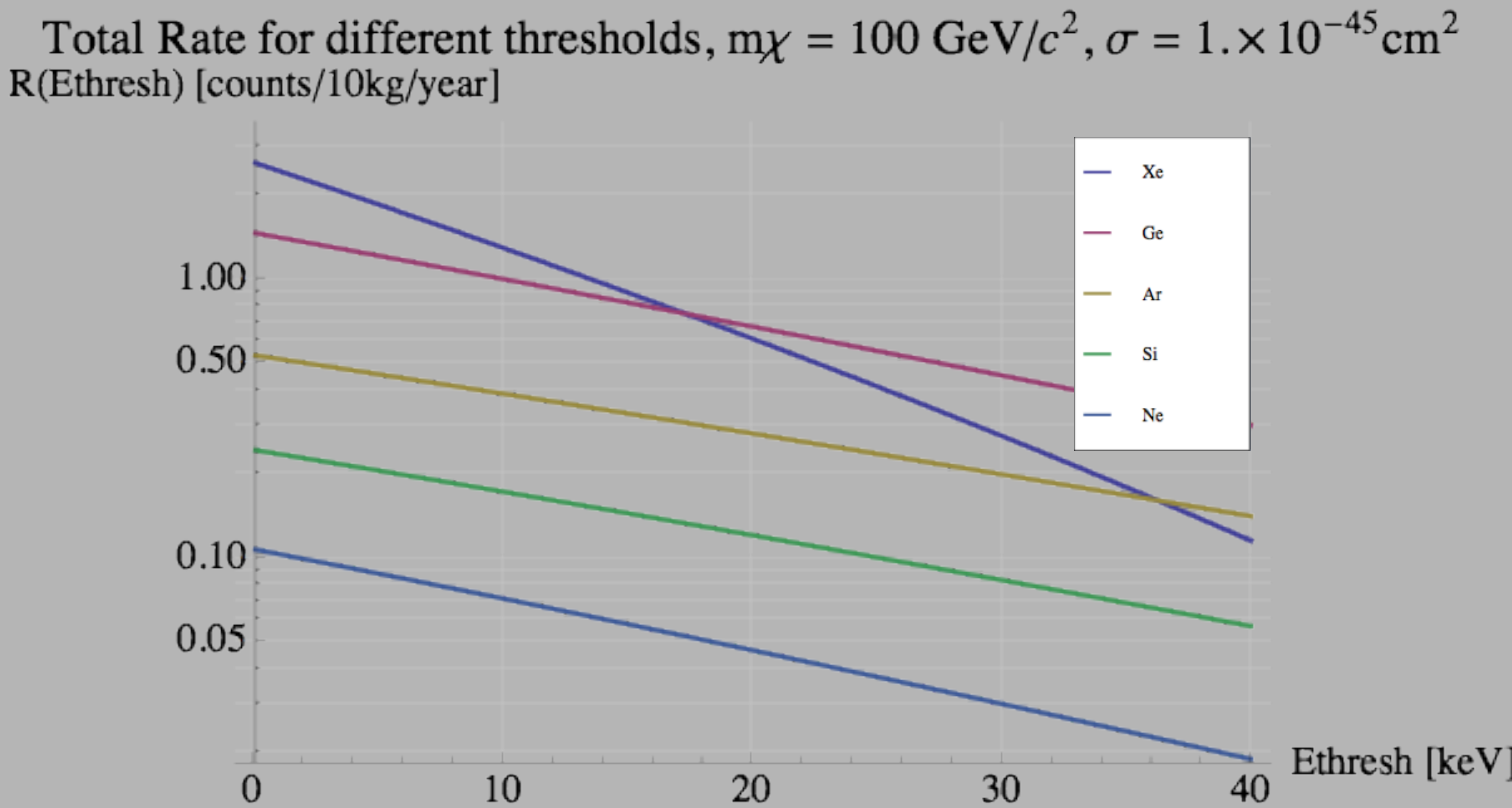
~ keV recoil energy

Rate < 0.1 event/kg/day

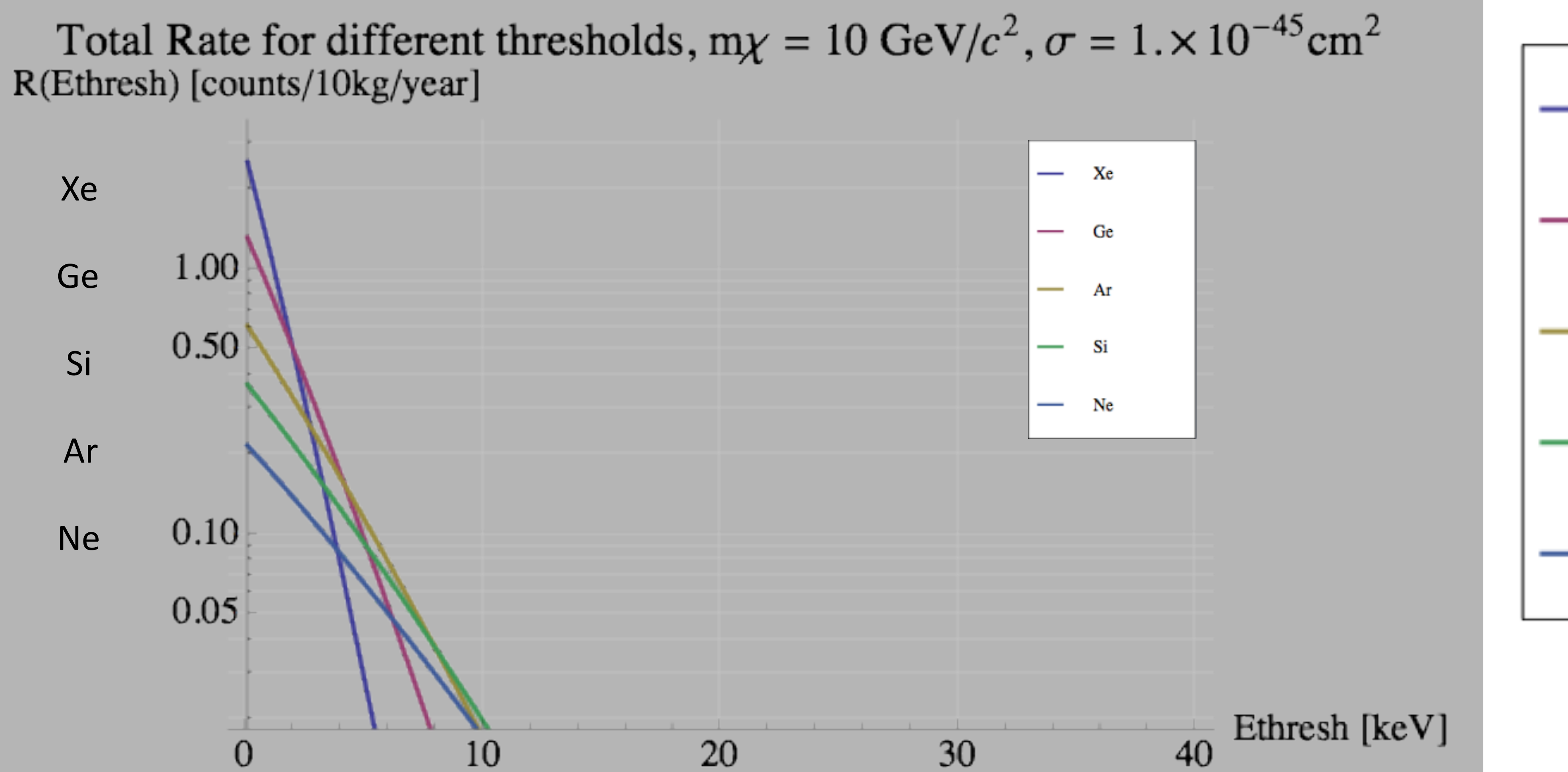


D. Cline, *Scientific American* 2003

Integrated Rate as a function of experimental threshold



Integrated Rate as a function of experimental threshold

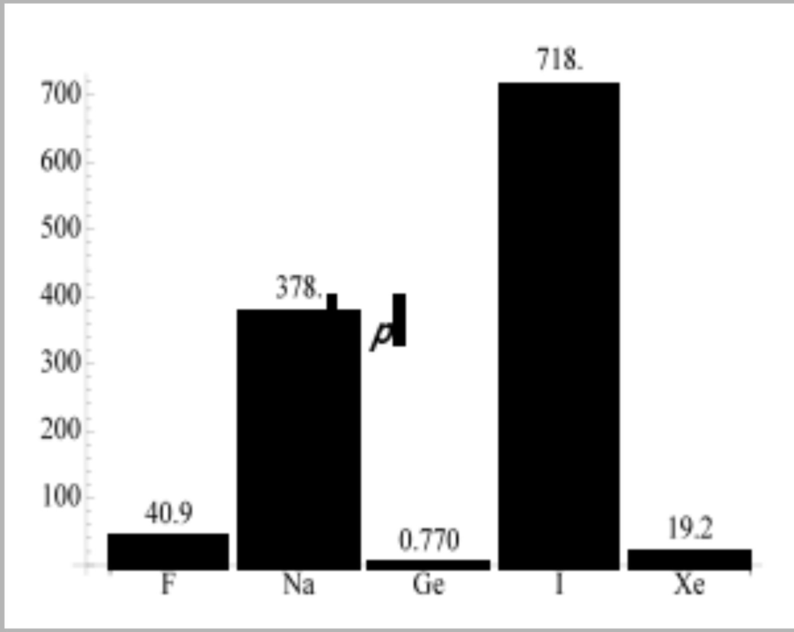


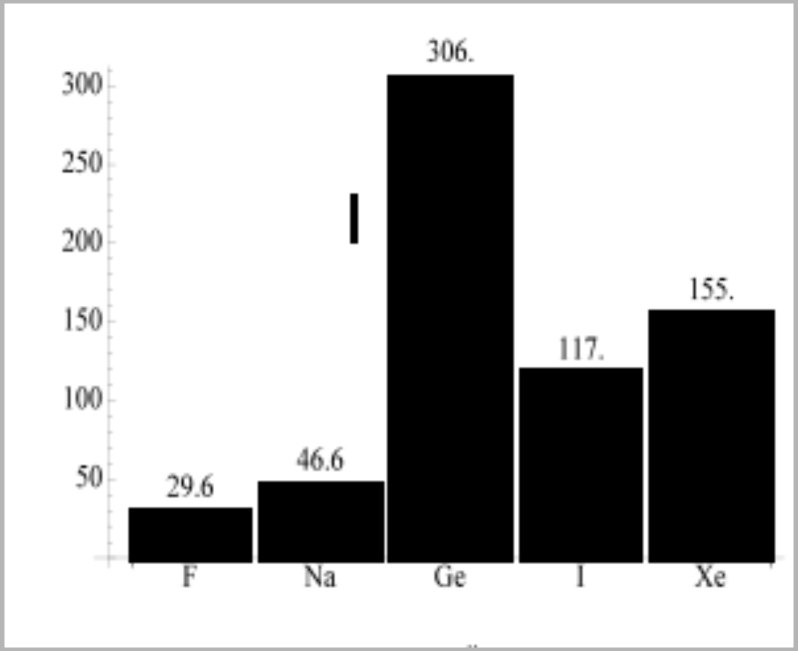
More thoughtful nuclear physics

• General non-relativistic effective theory of dark matter direct detection has been developed. [Fitzpatrick, Haxton, Katz, Lubbers, Xu 2013]

• Couplings depending on large nucleons velocity in addition to standard SD, SI.

• Couplings to: $\vec{J}$ $\vec{L}\cdot\vec{s}$ change the expected rates significantly

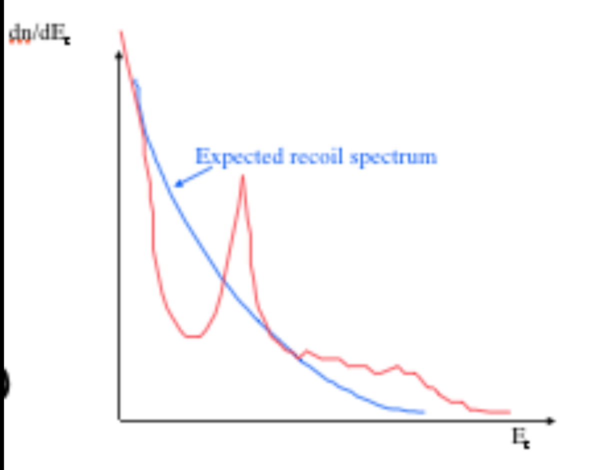




Need multiple targets to pinpoint the specific couplings

Direct detection challenges:

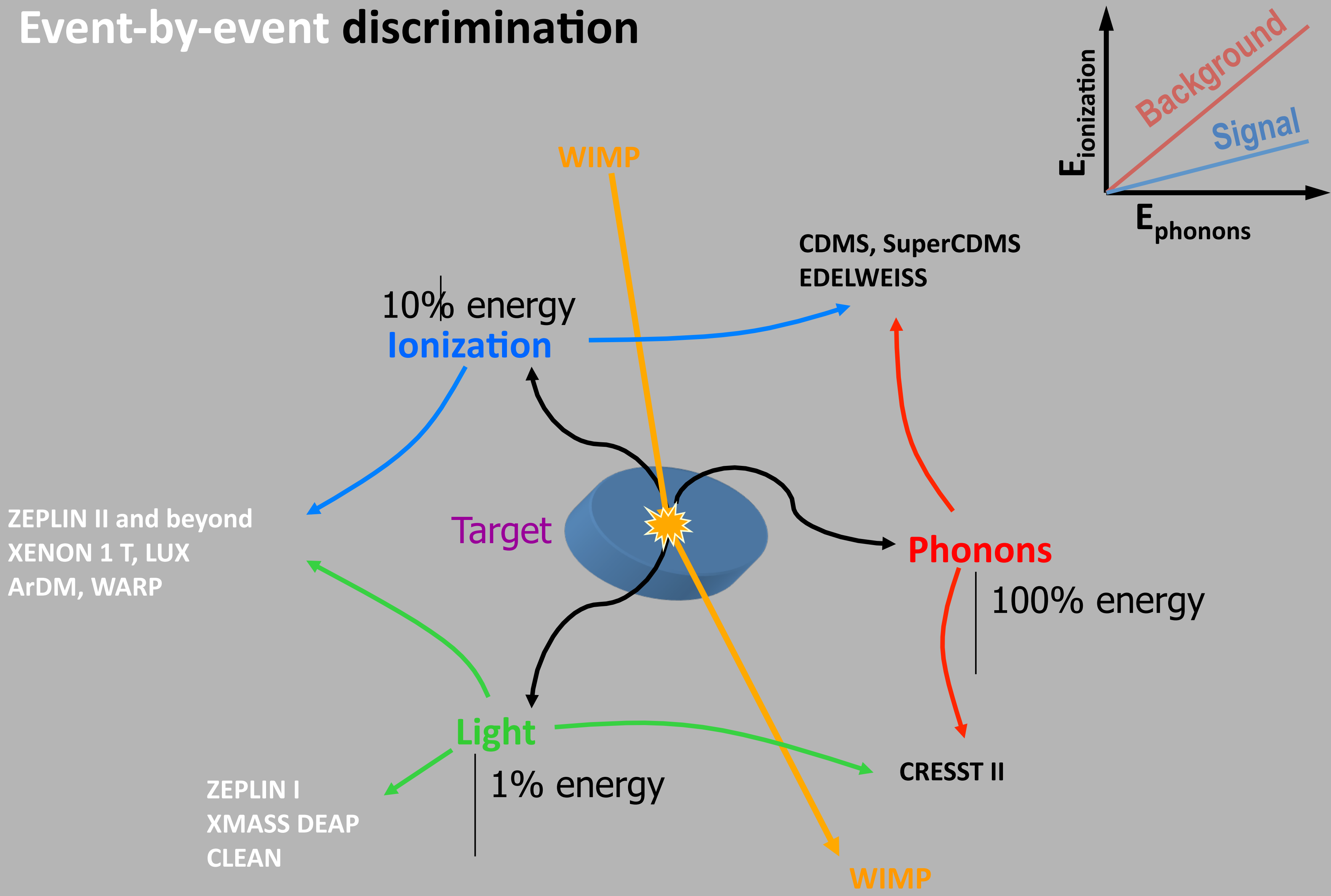
- Search sensitivity (low energy region <<100 keV)
  - ❑ **Current Exp Limit < 1 evt/ 10kg/year, ~< 10^{-4} evt/kg/day**
  - ❑ **Goal < 1 evt/tonne/year, ~< 10^{-5} evt/kg/day**



- Activity of typical Human
  - ❑ **~10 kBq (10^4 decays per second, 10^9 decays per day)**
- Environmental Gamma Activity in unshielded detector
  - ❑ **10^7 evt/kg/day (all values integrated 0–100 keV)**
  - ❑ **This can be reduced to ~10^2 evt/kg/day using 25 cm of Pb**

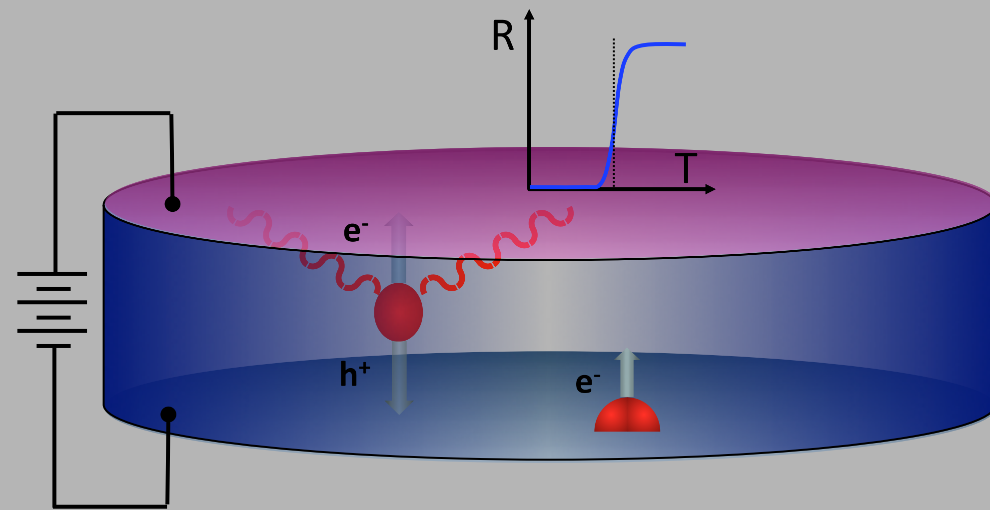
Need large detectors with low threshold and excellent background rejection!

Event-by-event discrimination



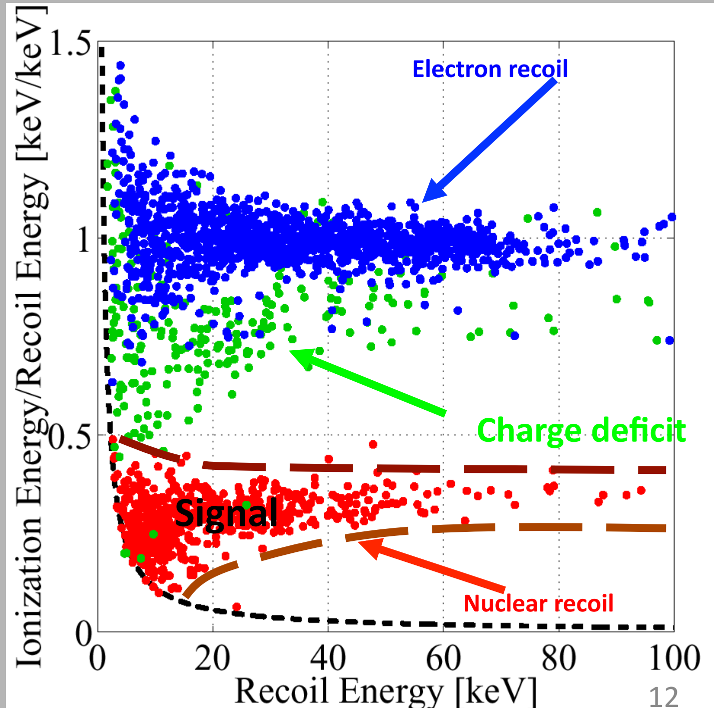
CDMS Principle

- Large (~ 1 kg) Semiconductor crystals (Ge or Si) **cooled to T < 0 .04 K.**
- Measure **recoil** energy via Lattice vibrations: **Phonons.**
- Simultaneously Measure the Ionization.
- Ionizing power i.e. Ionization Yield:
  - $Y_{electron\text{-}recoil} > Y_{nuclear\text{-}recoil}$
  - Event-by-event discrimination
- Near surface events
  - Electron recoil but poor charge collection.
  - Near geometrical boundaries.



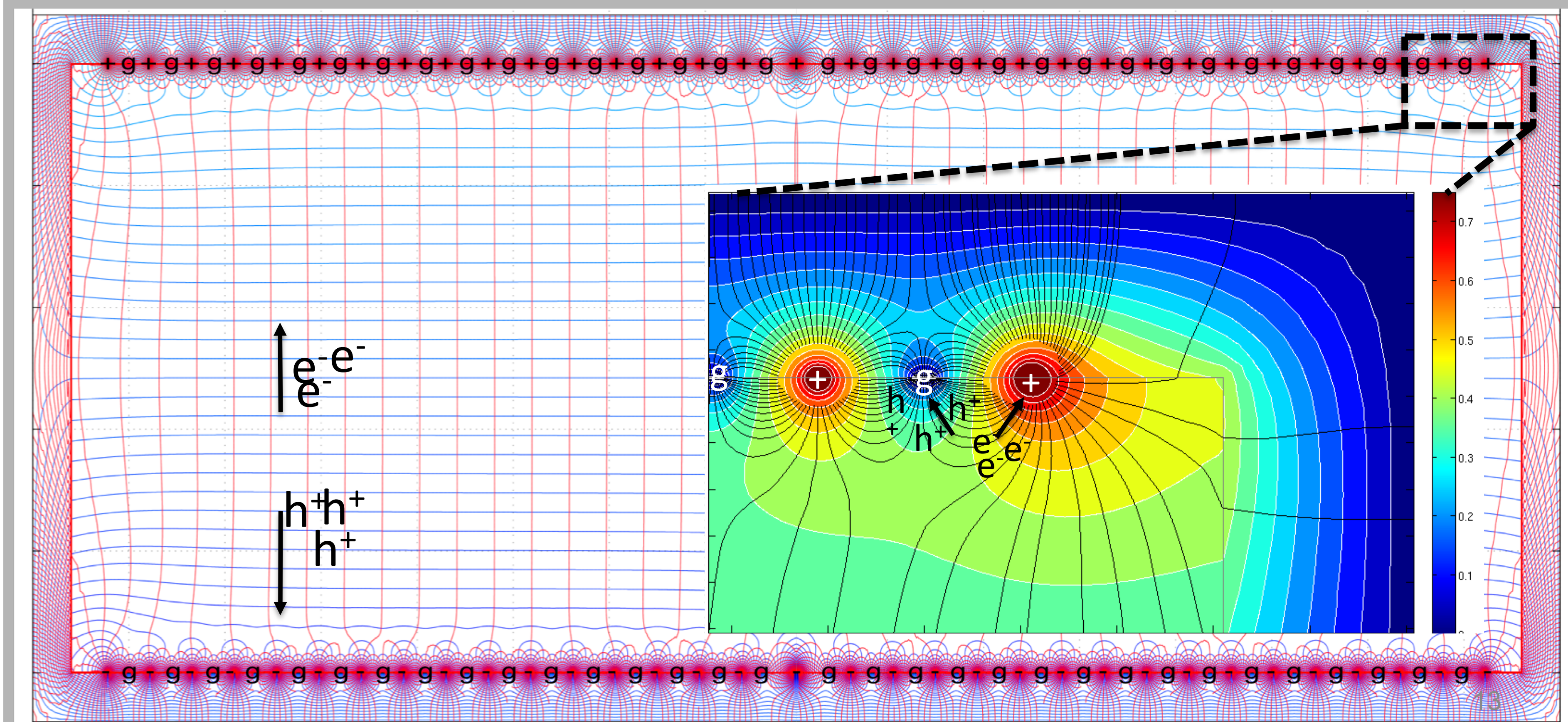
CDMS II solution:

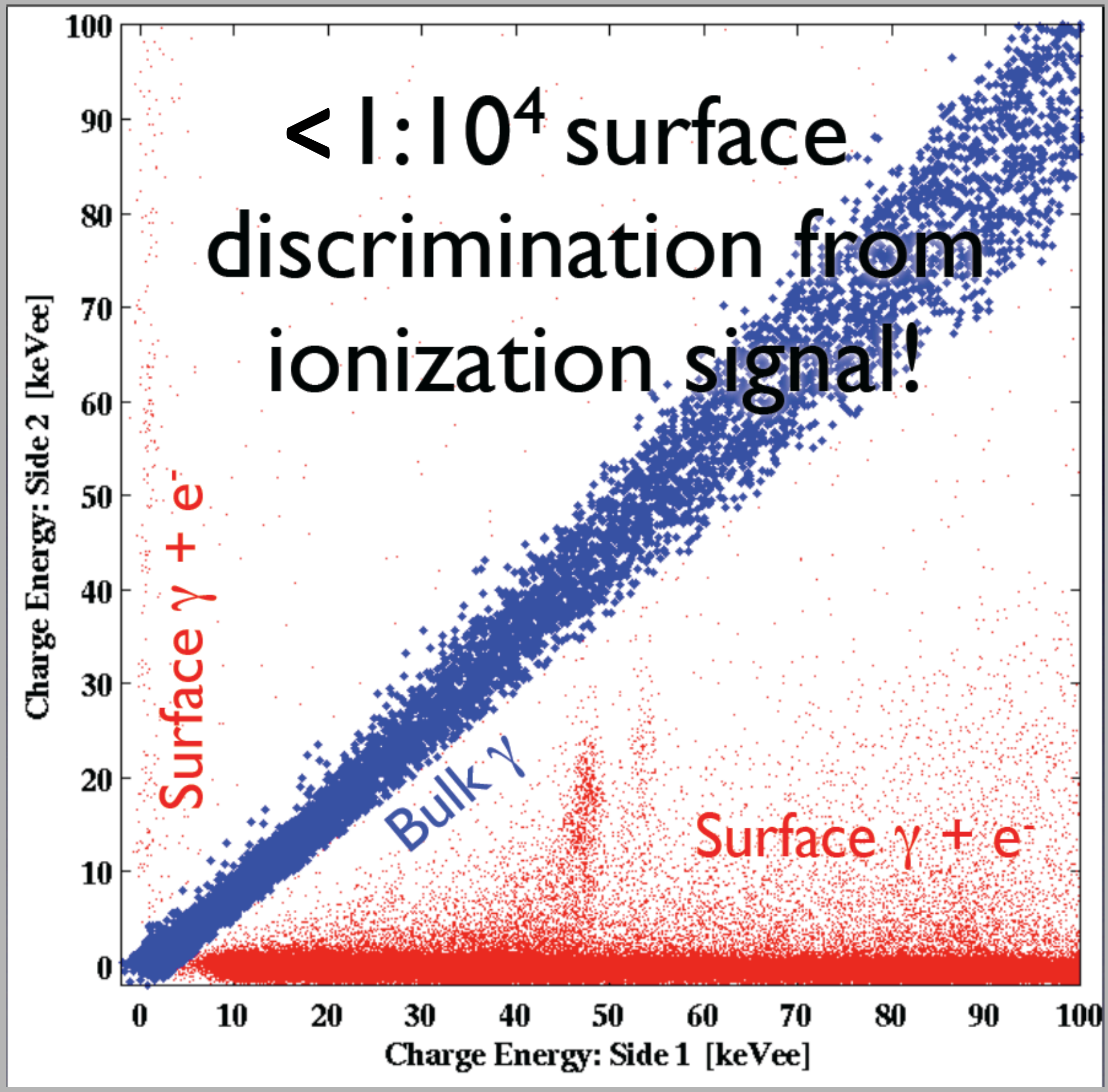
- Detect phonons before they reach equilibrium.
- reconstruct position of events=>Reject Near surface



iZIP: A new detector design

- Interleaved electrodes (1 mm pitch) on both sides.
- Alternating +V ground (i.e. phonon sensors) on one side -V & ground on the other side.
- Bulk events see the average Voltage on each side: Uniform Field in the bulk.
- In contrast the problematic Near-surface events sense the big transverse field at the surface.





Negligible surface background for SuperCDMS run: Soudan, SNOLAB

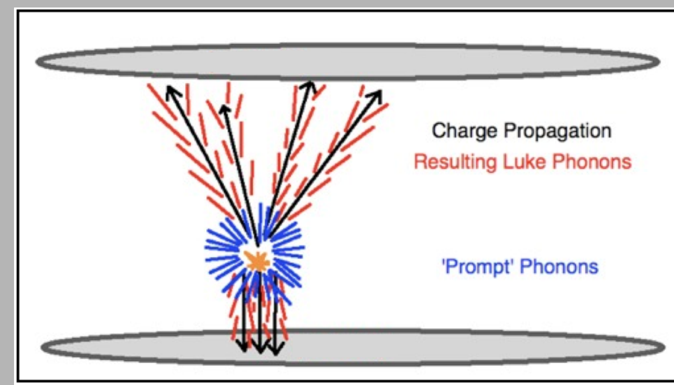

0.625 Kg

Luke-Neganov amplification

Luke et al., Nucl. Inst. Meth. Phys. Res.A 289, 406 (1990)

- **Luke**-Neganov Gain

$$
\begin{aligned}
E_{tot} &= E_r + E_{luke} \\
&= E_r + n_{eh} e V_b \\
&= E_r \left(1 + \frac{eV_b}{\epsilon_{eh}}\right)
\end{aligned}
$$



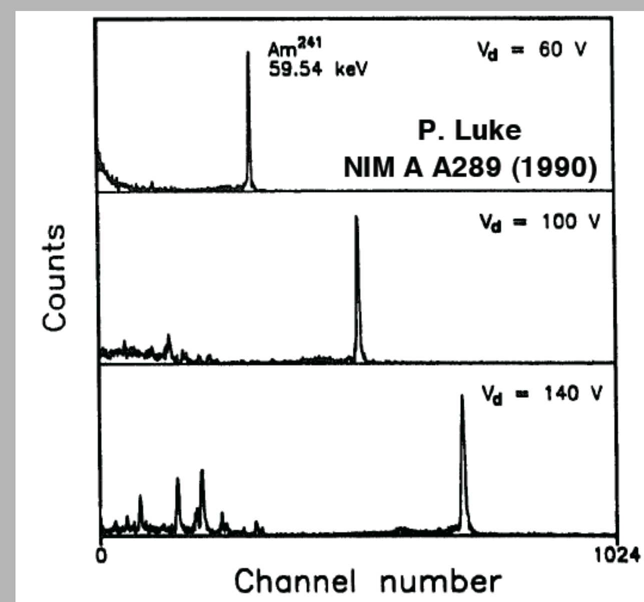
• Phonon noise doesn't scale with the ionization bias:

=> **S/N ⇧**

• In theory one can increase Bias to reach Poisson fluctuation limit:

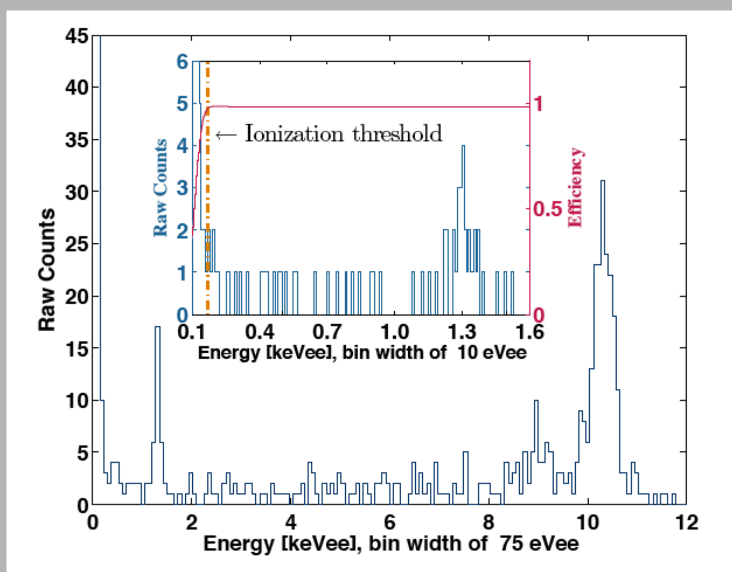
$$\sqrt{F \varepsilon E}$$

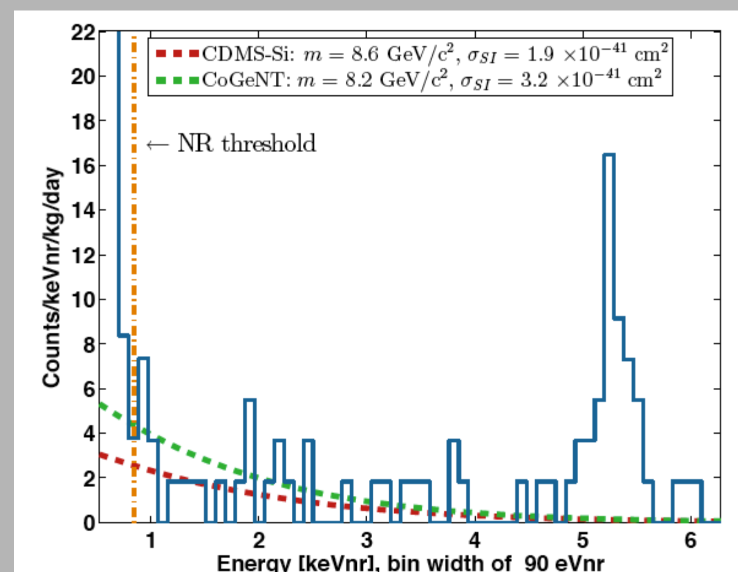
limitation: Ge Breakdown



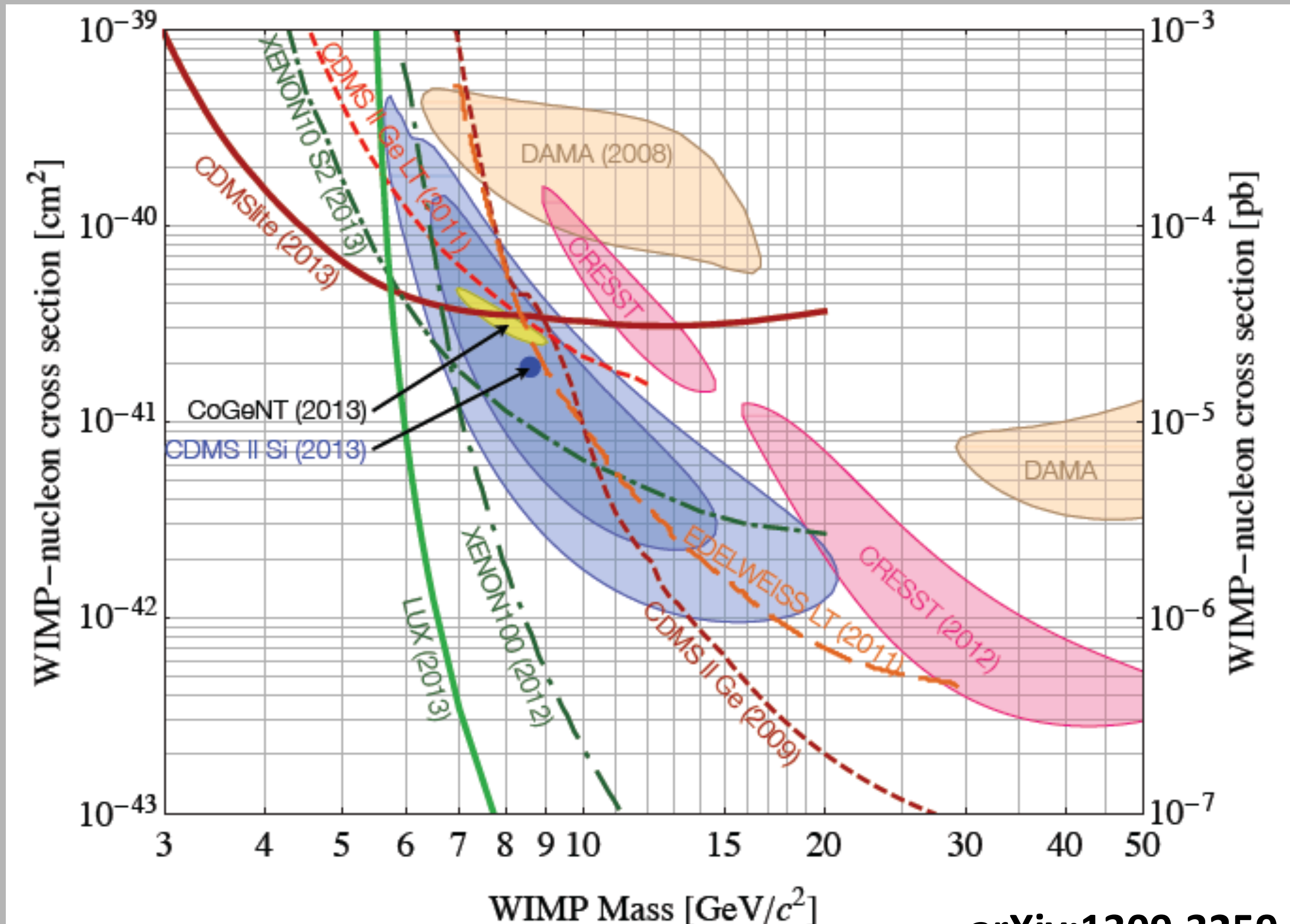
CDMSlite

- Use the Luke phonon amplification to indirectly measure ionization using very good phonon resolution.
- One iZIP (0.6 kg) used for this data
- ~6 kg.day exposure
- Impressive 14 eV_{ee} resolution for Vbias=69 Volts.
- Due to low frequency noise DAQ threshold =100 eV_{ee} and analysis threshold 170 eV_{ee}.





CDMSlite limit



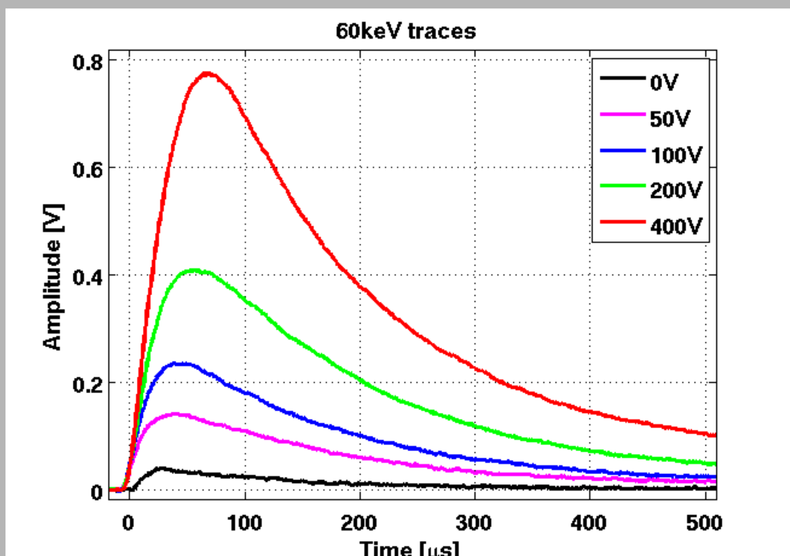
arXiv:1309.3259

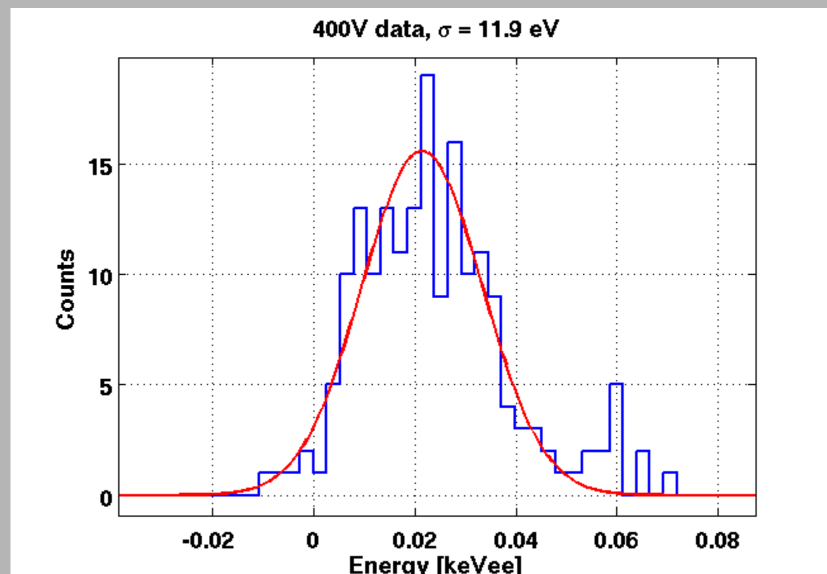
- **Included (Blue region) results from CDMS silicon blind analysis 140 kg.d.**
- **Revealed 3 WIMP-candidate events.**
- **Highest likelihood for WIMPs:**

  Mass= 8.6 GeV/c^2 and cross section 1.9x10^{-41} cm^2 [Phys. Rev. Lett. 111, 251301]

Improving CDMSlite threshold

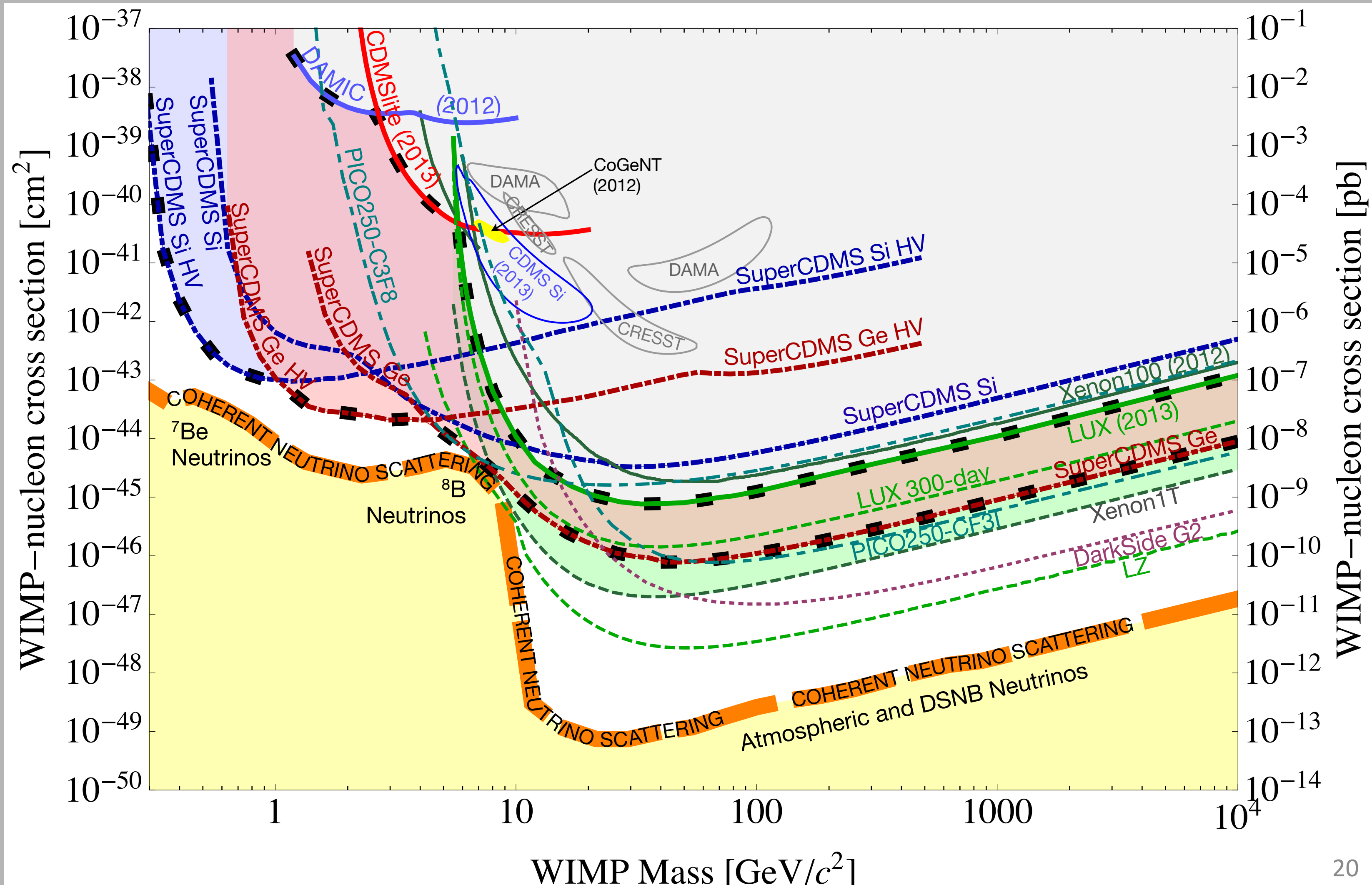
- Mainly crystal breakdown or leakage at V>60.
- Very low compared to standard 77K Ge detectors e.g. CoGeNT, Majorana…
- Recent studies at UCB in collaboration with LBNL Majorana group and Texas A&M suggest:
  - No inherent problem associated to < 1K operations
  - Mainly due to carrier injection at the contacts.
  - A careful engineering of the contacts between electrodes to Ge allow higher V and lower threshold.





SuperCDMS projection

- x 100 better than CDMSII sensitivity to WIMP-nucleon interaction for 50 GeV/c^2
- Unique sensitivity at low mass



SuperCDMS Collaboration

California Inst. of Tech.
B. Cornell, S.R. Golwala, D.C. Moore, R.H. Nelson

Fermi Nat. Accelerator Lab
R. Basu Thakur D.A. Bauer, D. Holmgren, L. Hsu, B. Loer,

Massachusetts Inst. of Tech.
A.J. Anderson, J. Billard, E. Figueroa-Feliciano, S.A. Hertel, K.A. McCarthy

Pacific Northwest National Laboratory
J. Hall

Queen's University
C.H. Crewdson, P.C.F. Di Stefano, O. Kamaev, C. Martinez, P. Nadeau, K. Page, W. Rau, Y. Ricci

Santa Clara University
B.A. Young

SLAC Nat. Accelerator Lab.
M. Asai, A. Borglund, D. Brandt, P.L. Brink, G.L. Godfrey, M.H. Kelsey, R. Partridge, K. Schneck, D.H. Wright

Southern Methodist University
J. Cooley, B. Kara, H. Qiu, S. Scorza

Stanford University
B. Cabrera, D.O. Caldwell*, R.A. Moffat, P. Redl, B. Shank, S. Yellin, J.J. Yen

Syracuse University
M.A. Bowles, R. Bunker, Y. Chen, M. Kiveni, R.W. Schnee

Texas A&M University
H.R. Harris, A. Jastram, R. Mahapatra, K. Prasad, J. Sander

U. Autónoma de Madrid
D. G. Cerdeno, L. Esteban, E. Lopez Asamar

Univeristy of British Columbia
S.M. Oser, H. Tanaka

U. of California, Berkeley
M. Daal, T. Doughty, N. Mirabolfathi, A. Phipps, M. Pyle, B. Sadoulet, B. Serfass, D. Speller

U. of Colorado, Denver
M.E. Huber

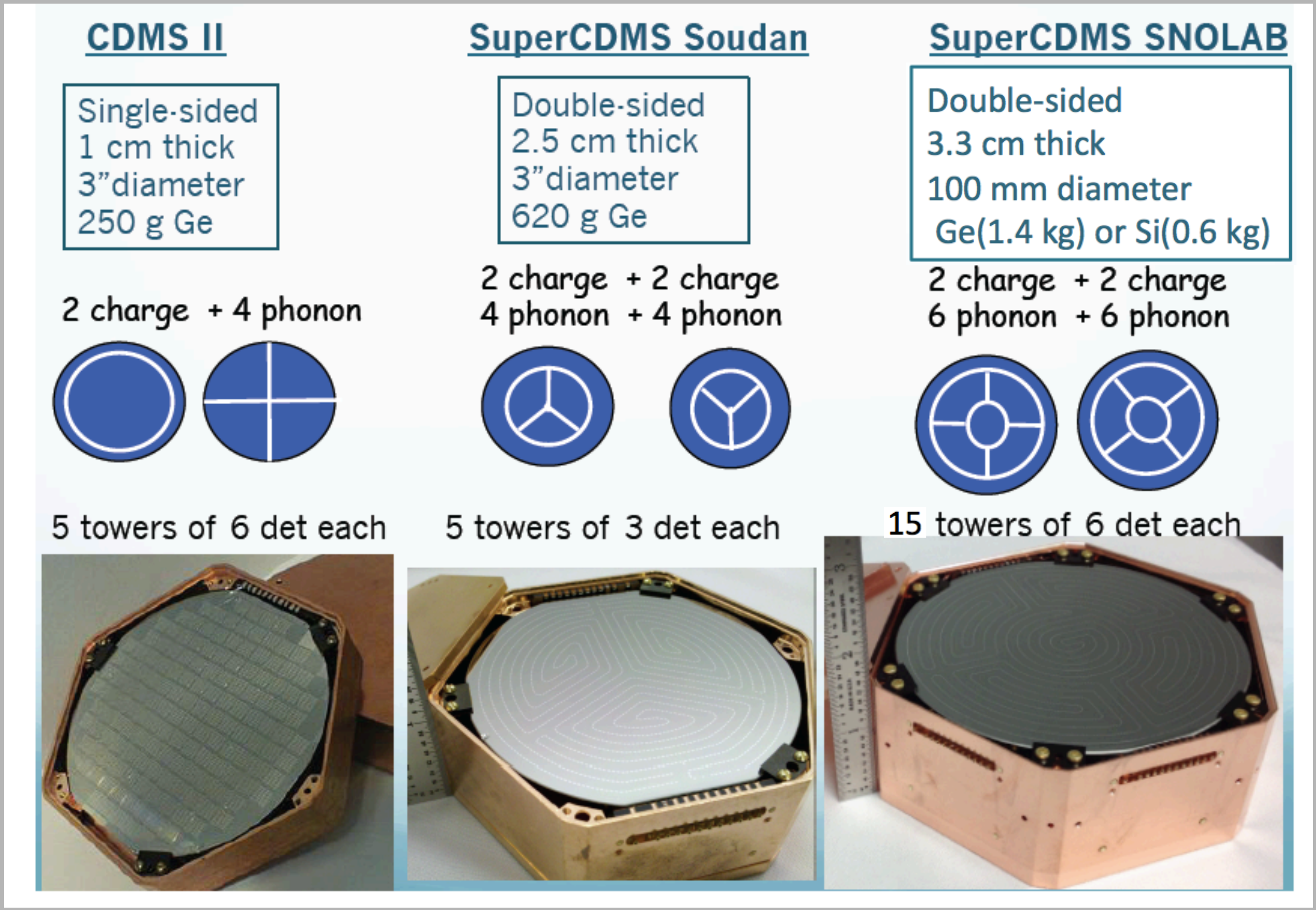
University of Evansville
A. Reisetter

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

University of Minnesota
H. Chagani, P. Cushman, S. Fallows, M. Fritts, T. Hofer, A. Kennedy, K. Koch, V. Mandic, M. Pepin, A.N. Villano, J. Zhang

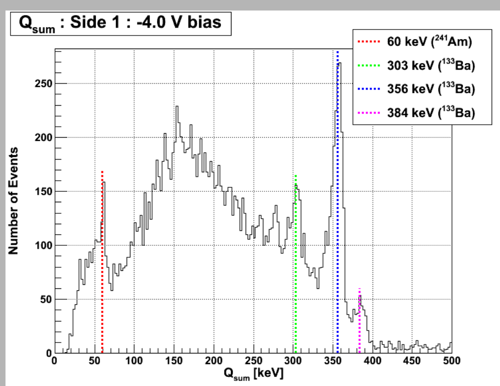
http://cdms.berkeley.edu

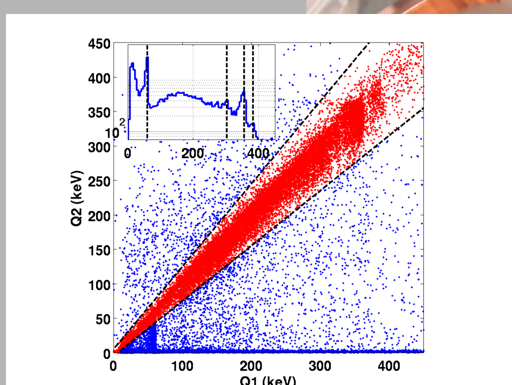
CDMSII to SuperCDMS SNOLAB

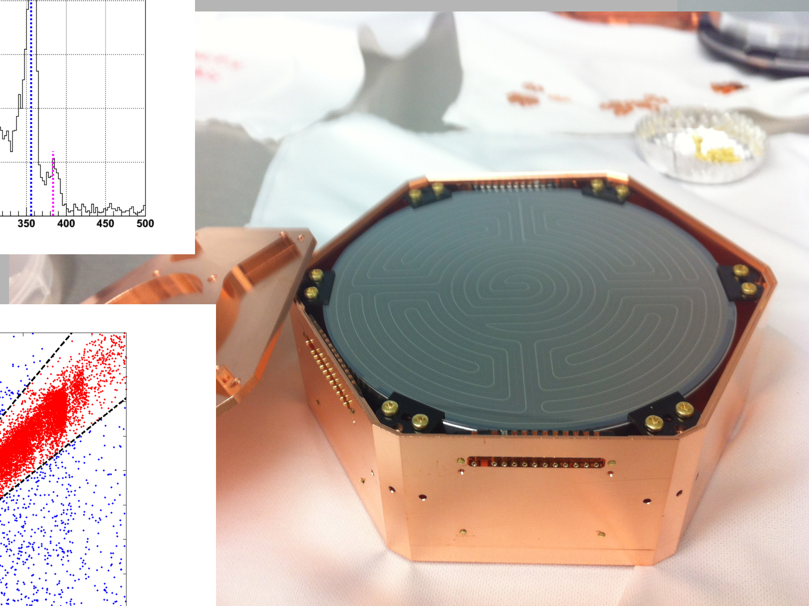


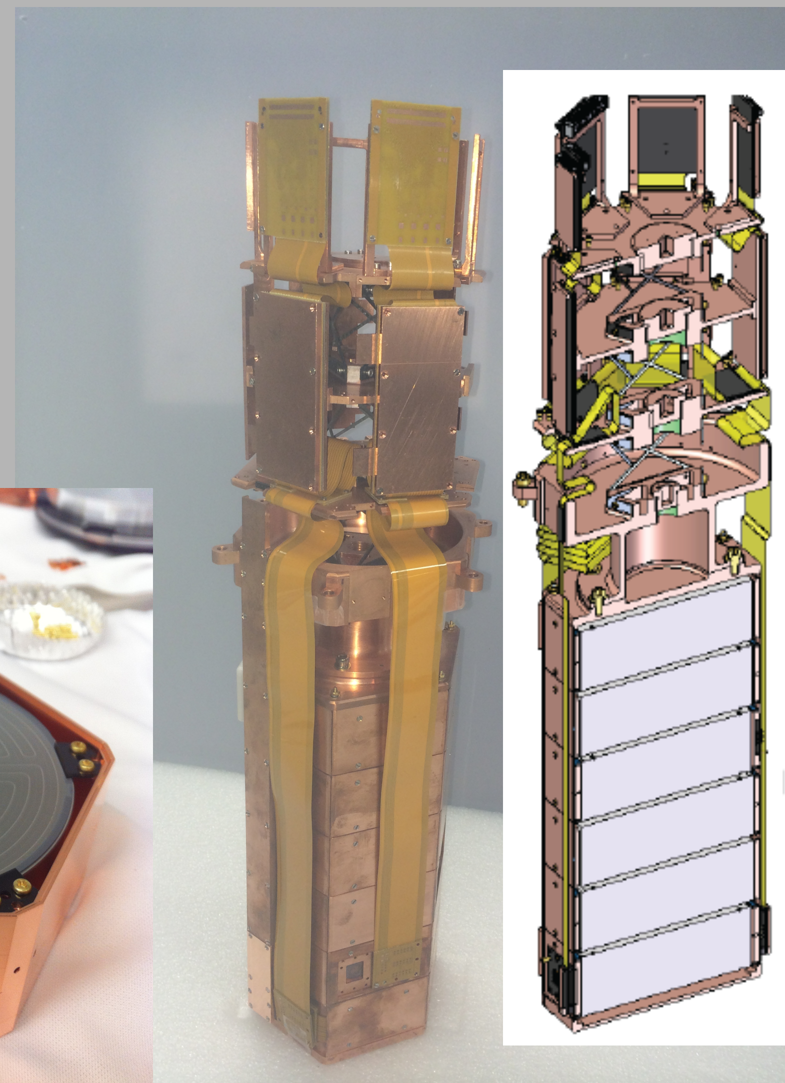
SuperCDMS SNOLAB Detectors

- Demonstrated performance at UMN Test Facility.
- Modular payload: 6 detectors per tower.
- Each detector fully tested before installation.
- Improved Ionization and Phonons Readout:
    - Using HEMTs for Ionization readout
    - Lower T_c phonon sensors: σ scales with T_c^3



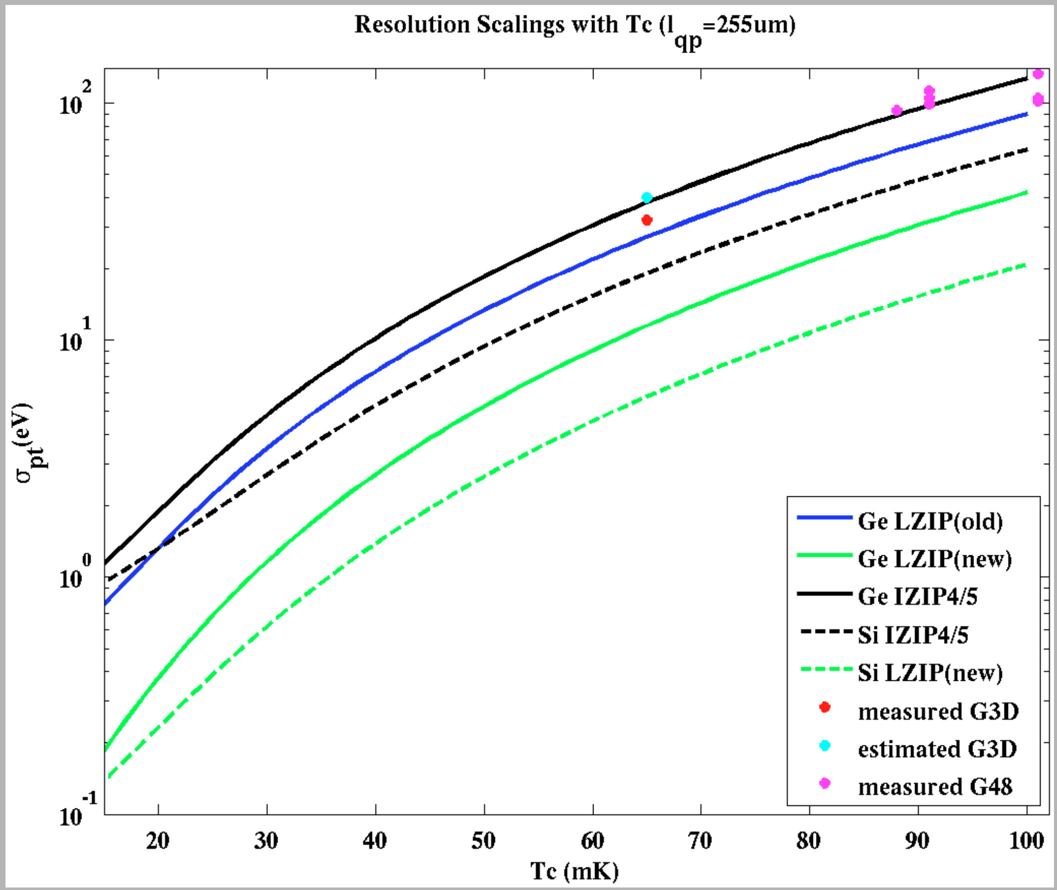






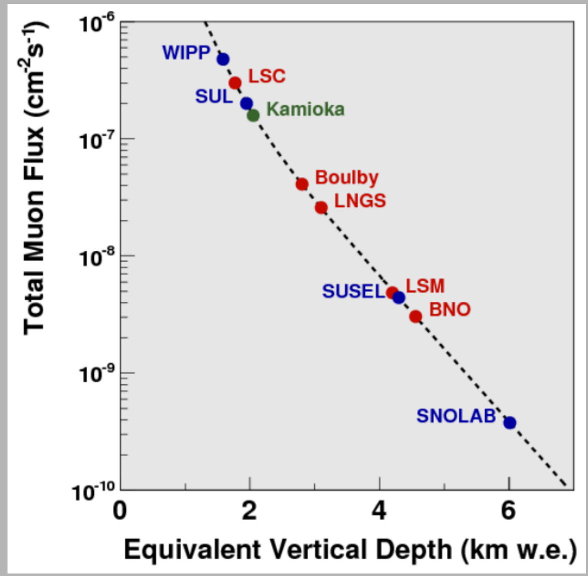
Detector Resolution

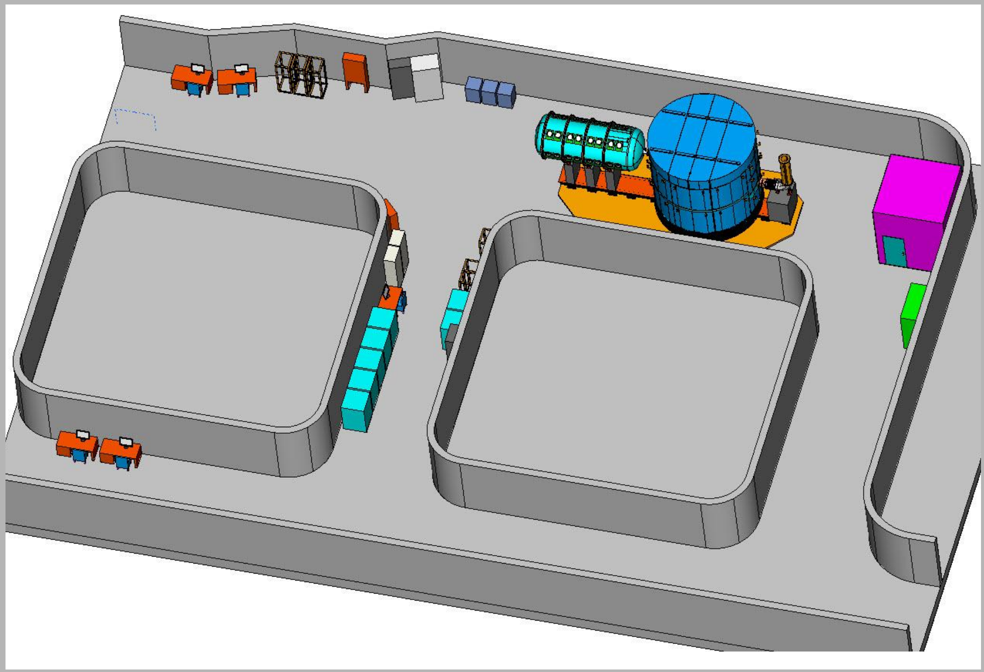
- Improved Ionization and Phonons Readout:
  - Using HEMTs for Ionization readout mounted at 4K.
  - A new readout less sensitive to environmental noise.
- CDMS phonon already demonstrated (42 eV) sufficiently low for SuperCDMS SNOLAB
  - Can further improve Lower T_c phonon sensors: σ scales with T_c^3

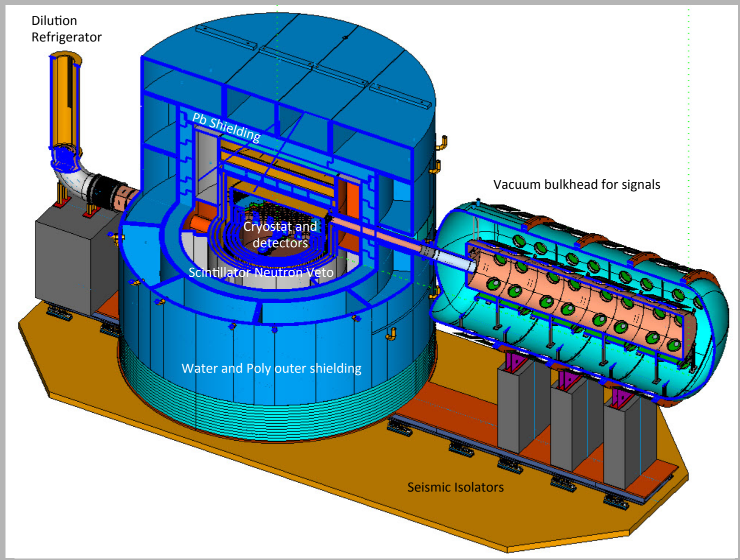


SuperCDMS SNOLAB Setup

- Deeper than Soudan=> less cosmogenic neutron.
- New cryogenic design and lower background.
- The experimental design can accommodate up to 400 kg payload.
- Improved radioactive shielding.







Conclusion

- Multiple target nuclei necessary for Dark Matter direct detection.
  - Different experiments have different backgrounds and systematics.
  - Different targets are necessary to pinpoint the DM coupling.
- Ionization-phonon technique offers excellent background discrimination and CDMS historically proved to be near background free.
- New models extend DM candidate masses down to < 1 GeV.
  - Low temperature Phonon detectors offer unique resolution => low detection threshold.
  - SuperCDMS Soudan has set the lowest limit for WIMPs of mass < 7 GeV; ongoing run will improve sensitivity at low and high masses.
- SuperCDMS SNOLAB will provide unique sensitivity to low-mass WIMPs near or down to the neutrino floor while extending sensitivity at high masses by x10.