Dark matter detectors - from low-temperature crystals to cryogenic liquids

CabreraFest
Stanford, October 7, 2012

Laura Baudis
University of Zurich
Modern science has been a voyage into the unknown, with a lesson in humility waiting at every stop (Carl Sagan)
Dark matter in galaxies

Visible galactic disk

Dark matter halo

What could the dark halo be made off?
This story starts in the year 2001...

- when I was fortunate to join Blas’ CDMS group at Stanford (in Dec. 2000)
CDMS in 2001: 35 members

Case Western Reserve University
D.S. Akerib, D. Driscoll, S. Kamat,
T.A. Perera, R.W. Schnee, G. Wang

Fermi National Accelerator Laboratory
M.B. Crisler, R. Dixon,
D. Holmgren

Lawrence Berkeley National Lab
R.J. McDonald, R.R. Ross
A. Smith

Nat’l Institute of Standards & Tech.
J. Martinis

Princeton University
T. Shutt

Santa Clara University
B.A. Young

Stanford University
L. Baudis, P.L. Brink,
B. Cabrera, C. Chang, T. Saab

University of California, Berkeley
S. Armel, V. Mandic, P. Meunier,
W. Rau, B. Sadoulet

University of California, Santa Barbara
D.A. Bauer, R. Bunker,
D.O. Caldwell, C. Maloney,
H. Nelson, J. Sander, S. Yellin

University of Colorado at Denver
M. E. Huber

Brown University
R.J. Gaitskell, J.P. Thomson

The work ahead...
CDMS-II was about to start: first run (Run 20) at SUF with ZIPs

- Full system engineering run: first tower with 3 Ge and 3 Si ZIPs
- New electronics, new DAQ and analysis software, internal n-moderator had been added to the ice-box
Z-ionization and phonon detectors

- ZIPs were being fabricated in Stanford
- T_c measurements in Stanford and Santa Clara
- Calibrations and test at SUF and UCB, CWRU

... and Tarek was still a PhD student
Z-ionization and phonon detectors

- The detectors didn’t just look beautiful, but also gave the position of an interaction, from timing alone: $t_0$ provided by the fast ionization signal.
Z-ionization and phonon detectors

- Moreover, they lead to the identification of different types of interactions in the crystals (neutrons, gamma, betas)
- And to discrimination against surface events
The Radon Scrubbing Facility (RSF)

- The ZIPs needed careful treatment, in particular:
  - surface contamination and radon plate-out were to be avoided
  - thus the construction of RSF, for cleaning and assembly of ZIP detectors and towers, began
It worked, in theory...

* in practice, the charcoal of the temperature swing system would overheat
Luckily, the radon levels turned out low, even without scrubbing....
A physics run (Run 21) at SUF with a 6-ZIP tower

- 4 Ge and 2 Si detectors
Run 21 started in July 2001

Energy distribution (in charge and phonons) of no-signal data traces for the six detectors: sub-keV phonon thresholds!
Energy calibration

Calibrating charge channels with 662 keV line of Cs-137 gamma source:

At low energies: 10.4 keV Ga X-ray

energy resolution:
charge: 0.5 keV @ 10 keV
phonons: 0.7 keV @ 10 keV
The gamma rates were already low

Gamma background rate $\sim 1$ event/(keV kg day) in Ge and $\sim 3$ events/(keV kg day) in Si

With a discrimination ability of $> 99.8\%$ the gamma background is reduced to $< 2 \times 10^{-3}$ events/(keV kg day)
But muon-induced neutrons were dominating the background

Yield plots for background data from the current run (muon coincident!):
gamma background band clearly visible
muon coincident neutrons populate the nuclear recoil band
Nonetheless, the results were competitive...

Yield plots for background data from the current run:

- muon anti-coincident + single scatter cut + risetime cut
- only few events in NR band, consistent with all caused by neutrons

Si-ZIP

Ge-ZIP
The obvious move: to Soudan
The collaboration underground...

The Fellowship of the Phonon
(Berkeley, Brown, Case Western, Fermilab, Florida, Minnesota, NIST, Santa Barbara, Santa Clara, Stanford)
and growing: 67 members

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

California Institute of Technology
Z. Ahmed, S. Golvala, G. Wang

Case Western Reserve University

University of Colorado at Denver
M. E. Huber

Fermi National Accelerator Laboratory

Santa Clara University
B.A. Young

Stanford University

University of California, Berkeley
M. Daal, J. Alvaro-Dean, J. Filippini, P. Meunier, N. Mirabolfathi, B. Sadoulet, D.N. Seitz, B. Serfass, G. Smith, K. Sundqvist

University of California, Santa Barbara

University of Florida, Gainesville
L. Baudis, L. Camarota, I. Diaz, S. Leclercq, T. Saab

University of Minnesota
J. Beaty, P. Cushman, L. Duong, X. Qiu, A. Reisetter
While the (outside) temperature dropped, the plots got fancier...

and new names were invented: ejectrons
The calibrations collected more stats, the Monte Carlos were refined...
and the first tower data was collected

- The neutron background was reduced: from 1 per kg-day to 1 per kg-year
- This run lasted 62 days (53 livedays after cuts), Oct 2003 - Jan 2004
While the background was low, the discrimination power of ZIPs was high...

- 10.4 keV Gallium x-ray
- 10 keV threshold (1@20 keV)
- 0.7 ± 0.2 misidentified electrons, 0.07 recoils from neutrons expected
- Timing Cuts for Surface Rejection:
  - Omitted
  - Applied

1 NR candidate consistent with background
resulting in the world’s best limits in 2004

Next: The two towers
... and the blind analysis method was introduced to the field

![Graph showing cross-section vs WIMP mass](Image)

- DAMA 1996
- Edelweiss 2003
- Zeplin-I
- CDMS (Si)
- CDMS (Ge) 2-Tower
- CDMS (Ge) combined

**Physical Review Letters 96 (2006)**

- 74.5 live days
- 96.8 (31.0) kg-days
- Ge (Si) before cuts

Laura Baudis, University of Zürich, Cadenarafest Stanford 2012
Finally five towers were installed: commissioning in early 2006

5 towers in Soudan icebox:
19 Ge (4.75 kg) detectors
11 Si (1.1 kg) detectors

Entrance to the Soudan Mine
Box with CDMS tower -> elevator
In parallel with plans for SuperCDMS and a new icebox

- Phased approach with 25 kg - 150 kg - 1 t of ultra-cold Ge detectors

SuperCDMS

SuperCDMS Phase A
25 kg of Ge 2011

SuperCDMS Phase B
150 kg of Ge 2014

SuperCDMS Phase C
1000 kg of Ge
Runs at Soudan continued, and Stanford produced first SuperZIPs... with the plan to operate 2 super-towers at Soudan, and 7 at SNOLAB.
Back to prediction for the future

From R. Gaitskell, Annual Reviews Vol. 54, 2004

not quite there yet....
First liquid xenon detectors ~2003

**ZEPLIN-I (single phase)**

- 3.1 kg fiducial mass, 3 PMTs
- 293 kg-days
- Light yield = 2.5 photoelectrons/keV
followed by dual-phase detectors

ZEPLIN-II 30 kg at Boulby/UK

XENON 3kg fiducial demonstrator at Columbia

Time projection chambers with 3D position resolution

xy-position

<table>
<thead>
<tr>
<th>Time Difference between Primary (S1) and Proportional (S2) Light</th>
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<tbody>
<tr>
<td>$\Delta t$ between primary (S1) and proportional (S2) light</td>
</tr>
</tbody>
</table>

S1

S2

65 µs
and plans for XENON10 at Gran Sasso

The XENON10 time projection chamber

48 top PMTs, 41 bottom PMTs

light (S2) hit pattern top PMT array
XENON10 installed in spring 2006, first run in August 2006

Gran Sasso Laboratory, May 2006

XENON10 in its shield at Gran Sasso
The WIMP landscape in 2007-2008

CDMS-II: a ‘zero background’ experiment

Ge: 121.3 kg d (after cuts)
XENON100 starts operation in 2008 in the same shield as XENON10 at LNGS.

- XENON100 in its shield
- Time projection chamber
- 98 top PMTs, 80 bottom PMTs
The WIMP landscape in 2010-2012

SuperCDMS will strike back!
The five SuperTowers

- First iZIPs are at Soudan, cold and taking science data!

<table>
<thead>
<tr>
<th>Period</th>
<th>Sensor Size</th>
<th>Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>~2000-'09</td>
<td>7.6cm x 1cm CDMS II iZIP</td>
<td>4 phonon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 charge</td>
</tr>
<tr>
<td>~2011-'13</td>
<td>7.6cm x 2.5cm SuperCDMS iZIP</td>
<td>8 phonon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 charge</td>
</tr>
<tr>
<td>~2014-???</td>
<td>10cm x 3.8cm SNOLAB prototype iZIP</td>
<td>12 phonon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 charge</td>
</tr>
</tbody>
</table>

Surface Events from $^{210}\text{Pb}$
“Bulk” γ events
“Bulk” nuclear recoils from $^{252}\text{Cf}$

- Dark matter signal region is well separated from bulk and surface background
SuperCDMS sensitivity: Soudan and SNOLAB

10cm x 3.8cm, 1.4 kg
SNOLAB prototype iZIP
SuperCDMS: a much larger collaboration

<table>
<thead>
<tr>
<th>The Super CDMS Collaboration</th>
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</thead>
<tbody>
<tr>
<td>Caltech</td>
</tr>
<tr>
<td>Instituto de Fisica Teorica, Universidad Autonoma de Madrid</td>
</tr>
<tr>
<td>Fermilab</td>
</tr>
<tr>
<td>MIT</td>
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<tr>
<td>NIST</td>
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<tr>
<td>Queens University</td>
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<tr>
<td>Santa Clara University</td>
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<tr>
<td>SLAC/KIPAC</td>
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<tr>
<td>Southern Methodist University</td>
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<td>Stanford University</td>
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<td>Syracuse University</td>
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<td>University of Colorado at Denver</td>
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<tr>
<td>University of Florida</td>
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<tr>
<td>University of Minnesota</td>
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<tr>
<td>University of Texas A&amp;M</td>
</tr>
</tbody>
</table>

Enectali Figueroa-Feliciano - UCLA Dark Matter 2012
The future: SuperCDMS at SNOLAB, XENON1T at LNGS

- SuperCDMS: 15 kg to 1.5 tons Ge
- iZIP Ge detectors with improved charge and phonon readout
- First phase at Soudan, next phase at SNOLAB

- XENON1T: 3 t (1t) total (fiducial)
- 300 Hamamatsu R11410-21 PMTs for light/charge readout
- In 10 m x 10 m water Cherenkov shield in Hall B at LNGS

10cm x 3.8cm, 1.4 kg SNOLAB prototype iZIP

3 R11410 PMTs at UZH
Neutrinos might be our ‘ultimate background’

- R&D and design study for next-generation noble liquid detector
- Physics goal: build the “ultimate WIMP detector”, before the possibly irreducible neutrino background takes over; probe WIMP cross sections down to $\sim 10^{-48}$ cm$^2$

20 t LXe (and/or LAr) cryostat in large water Cherenkov shield

2vbb: EXO measurement of $^{136}$Xe $T_{1/2}$
Assumptions: 50% NR acceptance, 99.5% ER discrimination
Contribution of 2vbb background can be reduced by depletion
Ge and Xe: complementary targets to reconstruct WIMP properties

- Different targets are sensitive to different directions in the $m_X - \sigma_{SI}$ plane

<table>
<thead>
<tr>
<th>target</th>
<th>$\epsilon$ [ton(\times)yr]</th>
<th>$\eta_{cut}$</th>
<th>$\bar{A}_{NR}$</th>
<th>$\epsilon_{eff}$ [ton(\times)yr]</th>
<th>$E_{thr}$ [keV]</th>
<th>$\sigma(E)$ [keV]</th>
<th>background events/(\epsilon_{eff})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe</td>
<td>5.0</td>
<td>0.8</td>
<td>0.5</td>
<td>2.00</td>
<td>10</td>
<td>Eq. (7)</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Ge</td>
<td>3.0</td>
<td>0.8</td>
<td>0.9</td>
<td>2.16</td>
<td>10</td>
<td>Eq. (6)</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Ar</td>
<td>10.0</td>
<td>0.8</td>
<td>0.8</td>
<td>6.40</td>
<td>30</td>
<td>Eq. (8)</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

reconstruction probabilities for Xe, Xe + Ge, Xe + Ge + Ar

includes galactic uncertainties

fixed galactic model $m_X$ [GeV]
The world wide wimp search

- SNOLAB
- DEAP/CLEAN
- Picasso
- COUPP
- SuperCDMS
- Boulby
- ZEPLIN
- DRIFT
- Soudan
- SuperCDMS
- CoGeNT
- Homestake
- LUX
- Modane
- EDELWEISS
- Canfranc
- ArDM
- Rosebud
- ANAIS
- South Pole
- DM Ice
- Gran Sasso
- XENON
- CRESST
- DAMA/LIBRA
- DarkSide
- WARP
- YangYang
- KIMS
- Kamioka
- XMASS
- Newage
- Jinping
- Panda-X
- CDEX
- Boulby
- ZEPLIN
- DRIFT
WIMP search evolution in time

Factor ~10 every two years:
thanks to mk-crystals and noble liquids

~1 event kg^{-1}yr^{-1}

This is steeper than Moore’s law!
Summary

- Cold dark matter is *still here with us*
- New, heavy, neutral, stable and weakly interacting particles (WIMPs) *still offer an attractive scenario*
- *We have entered the era of data*: direct detection, indirect detection, the LHC
- The field of direct dark matter detection had taken off with the advent of mk crystal detectors, *in particular with CDMS, which set examples for all*
- Today, direct detection experiments have reached unprecedented sensitivity and can probe WIMP with masses from a few GeV to a few TeV
- Germanium and xenon targets offer complementary information, both can probe spin-independent and spin-dependent WIMP-nucleon couplings
- In the event of a signal from a dark matter particle they will allow to constrain its mass and cross section
I believe I don’t have to convince you that Blas and his group have played and continue to play a major role in CDMS, SuperCDMS and in the dark matter field as a whole.

I would personally like to thank Blas for his guidance, for his profound knowledge and wisdom that he was never tired to share - he was and remains a truly inspiring mentor!

‘The constitution of the universe may be set in first place among all natural things that can be known. For coming before all others in grandeur by reason of its universal content, it must also stand above them all in nobility as their rule and standard.’

Galileo Galilei, Dialogue