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WIMP searches underground  
CDMS and SCDMS

Motivations  
A historical look at field  
Towards event by event discrimination  
New results from CDMS II: increase word sensitivity by 10  
Need for large masses technologies  
SuperCDMS  
Why we choose to go deep
The Dark side

The concordance model

Precision Cosmology

In current paradigm, Dark Matter has to be non baryonic
But “extravagant” universe

\[ \Omega_{\text{tot}} = 1.02 \pm 0.02 \]
\[ \Omega_m = 0.27 \pm 0.04 \]
\[ \Omega_b = 0.047 \pm 0.006 \]
A map of the territory!

Current candidate explanations: systematic mapping

dark matter and energy

baryonic

non-baryonic

Λ Quintessence

? Modification of gravity

Primordial Black Holes

exotic particles

Mirror branes

Energy in bulk

non-thermal

thermal

Light Neutrinos

WIMPs

Axions

Wimpzillas

clumped H₂?

gas

dust

VMO

MACHOs

Einstein Branes
Weakly Interactive Massive Particles

Particles in thermal equilibrium + decoupling when nonrelativistic

Freeze out when annihilation rate $\approx$ expansion rate

$$\Omega x h^2 = \frac{3 \cdot 10^{-27} \text{ cm}^3 / \text{s}}{(\text{MeV})^3} \Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2}$$

Cosmology points to W&Z scale

Inversely standard particle model requires new physics at this scale (e.g. supersymmetry) $\Rightarrow$ significant amount of dark matter

We have to investigate this convergence!

Note: not only supersymmetry

Ex. Additional dimensions Kaluza Klein excitation

K.Agashe, G.Servant hep-ph/0403143

Cross sections also in the same region

Also: Indirect detection

$\delta\delta \rightarrow \gamma\gamma$

$\delta p_{\text{in sun}} \rightarrow \text{trapped} \ \delta\delta \rightarrow \text{high energy } \nu$'s
Direct Detection

Elastic scattering

- Expected event rates are low (<1 evt/kg/week) (<< radioactive background)
- Small energy deposition (∼ few keV) << typical in particle physics
- Signal = nuclear recoil (electrons too low in energy)
- ≠ Background = electron recoil (if no neutrons)

Signatures

- Nuclear recoil
- Single scatter ≠ neutrons/gammas
- Uniform in detector

Linked to galaxy

- Annual modulation (but need several thousand events)
- Directionality (diurnal rotation in laboratory but 100 Å in solids)
Background Limited!

3 fundamental strategies

Decrease the background

State of the art:
Heidelberg Moscow

Extreme proposal:
GENIUS/Genino

Statistical method
background subtraction

• Multiple scattering
• Pulse shape discrim.
• Annual modulation

Event by event
discrimination

Large mass =>
simple detectors e.g. NaI

Active rejection with the best possible discrimination
<= Best technology
signal to noise
no dead region/tails
As much information as possible

Evolution of the field
Direct Detection: Summer 1998

Initially no discrimination

• Ge diodes (1989: USC/PNL, UCSB/LBNL)

  -> Heidelberg/Moscow = most reliable limit at large mass

• Large NaI counters (100 kg -> 250kg installed in Gran Sasso!)

  Spin Independent (Scalar)

  Background limited

  =>Effective mass is small

  mass of background-less detector giving same

  2.5 evt./kg/day

  \((MT)_{\text{eff}} = 1 \text{kg.day}\)
If WIMPs exist, we should observe a modulation in event rate:
Earth adds or subtract 15 km/s to the velocity of the sun going through the halo \(\Rightarrow\) ±4.5% modulation in rate and energy

7 years data with 100kg NaI impressive modulation

Source DAMA
Astro-ph/0307403

DAMA discovery claim
Conventional halo
Scalar coupling
Cryogenic Detectors

Principle: Phonon mediated detectors

Goals

• Sensitivity down to low energy
  Phonons measure the full energy (no ionization yield, quenching factor)

• Active rejection of background: recognition of nuclear recoil
  Combine with low field ionization measurement
  e.g. CDMS I and II
  EDELWEISS or photon (CRESST II)

• More information on rare events

But: operation at very low temperature!

ex: CDMS I
CDMS Background Discrimination

Our main contribution:
Use Ionization Yield (ionization energy per unit recoil energy) to reject the background

Particles (electrons) that interact in surface “dead layer” of detector result in reduced ionization yield

![Graph showing Ionization Energy/Recoil Energy vs Recoil Energy]
1999 Run Ge BLIP Data Set

- all single-scatters
- NR candidates

Entire 45 live days operation Ge BLIPs = 12.4 kg-days
Gamma and electron bands well separated from NR band
NR candidates are truly NR’s
See a total of 13 events > 10 keV
≈ ~ 1 event/kg/day

Even though this event rate is in the region of the DAMA signal, cannot be WIMPs
<= 4 multiple events Neutrons (17 m.w.e.)
CDMS and DAMA Feb 2000

Incompatible at more than 99.98%

Standard scalar interaction
Standard halo velocity distribution

Published in Phys Rev Lett./astro-ph/0002471

B. Sadoulet
2000-2004

**CDMS I**
CDMS confirms its story at shallow depth
- Blue curves
  - Enlargement of fiducial region
  - New detector technology (CDMSII detectors)
  - Additional neutron moderation

**EDELWEISS: same story**
- already located deep Underground, takes the lead at high mass
- But some events begin to appear neutrons?

**ZEPLIN 1**
- Liquid Xenon with scintillation
- No in situ calibration
ZIP Detector Phonon Sensor Technology

Al Collector

W Transition-Edge Sensor

Si or Ge

quasiparticle trap

quasiparticle diffusion

phonons

W Transition-Edge Sensor: a really good thermometer

Measurement of athermal phonon signals maximizes information

$R_{\text{TES}} (\Omega)$ vs $T (\text{mK})$

$T_c \approx 80 \text{mK}$

$\sim 10 \text{mK}$

normal

superconducting
The ZIP Detector Signal

Risetime and delay give information about the 3D position of the event, in particular the proximity to the surface.
Additional CDMS II Discrimination

Use phonon risetime and charge to phonon delay for discrimination of surface electrons "betas" (not possible with equilibrated phonons e.g., EDELWEISS)

Cuts and analysis thresholds determined entirely from calibration data with WIMP search data blinded until after the cuts and thresholds were set.
In Situ Calibrations for “Blind” Cuts

Prior to timing cuts

After timing cuts, set to reject all electron recoils in signal band

Blue points: electron recoils induced by a $^{133}$Ba $\gamma$ source
Yellow points: nuclear recoils induced by a $^{252}$Cf neutron source
**Result with one tower**

In 92 days between October 11, 2003 and January 11, 2004, we collected 52.6 live days - a net exposure of 22 kg-d after cuts.

Below data are shown before (left) and after (right) timing cuts.

(yellow points are from neutron calibration)
2004 CDMS limit from Soudan Lab
Spin Dependent Limits

Preliminary (along the line of Savage et al.)

More and more difficult to accommodate DAMA in conventional models
+ much larger than expected in Supersymmetry
Analysis of 2nd Soudan Run of CDMS II

Included 5 of 6 Ge and 4 of 6 Si detectors (others still blinded)
- 1.25 kg of Ge, 0.4 kg of Si
- 72 live-days WIMP-search data

“Unblinded” on March 31, 2005

Pre-designated “primary” analysis
- Similar to timing cut used previously, but better rejection

4 “secondary” blind analyses with more sophisticated techniques, better rejection of backgrounds
In Situ Calibrations for Setting Cuts “Blind”

Second run’s calibration data, prior to timing cuts

After timing cuts, set to reject nearly all low-yield electron recoils

Blue points: electron recoils induced by a $^{133}$Ba $\gamma$ source

Yellow points: nuclear recoils induced by a $^{252}$Cf neutron source

53% acceptance of neutrons

23x our WIMP-search background

Seattle 6/23/05
WIMP-search data

Prior to timing cuts

After timing cuts, which reject most electron recoils

10.4 keV Gallium line

**Preliminary Estimate:** 0.37 ± 0.20 (sys.) ± 0.15 (stat.) electron recoils, 0.05 recoils from neutrons expected
1st Year CDMS Soudan Combined Limits

90% CL upper limits assuming standard halo, $A^2$ scaling

Upper limits on the WIMP-nucleon cross section are $1.7 \times 10^{-43}$ cm$^2$ for a WIMP with mass of 60 GeV/c$^2$

- Factor of 2.3x below CDMS Soudan 1st run
- Factor 10 lower than any other experiment

Excludes large regions of SUSY parameter space under some frameworks

- Bottino et al. 2004 in yellow
- Kim et al. 2002 in cyan
- Baltz & Gondolo 2004 mSUGRA in red

Combined Soudan limits

DAMA NaI/1-4 $3\sigma$ region

http://dmtools.brown.edu/Gaitskell&Mandic
CDMS II Short Term Plans

5 Towers installed
  4 kg of Ge
  2 kg of Si

Plug identified in cooling down
  Solved, fridge successfully cooled by itself, reassembly complete
  Hope to be cold by end of the month

NSF and DOE approved extension of CDMS II operation to Sept 07
  Should allow another factor of 10 in sensitivity
Will CDMS be background-limited soon?

No! More sophisticated analyses show better rejection of electron recoils

⇒ Adjust expected background at ≈0.5 evt without losing too much efficiency

Additional discrimination parameters
  e.g. Ratio of energy in sensor with largest signal to energy in sensor with smallest signal

Better combining of parameters
  e.g. $\chi^2$ with full correlation matrix
CDMS and Supersymmetry

CDMS II is starting to put significant limits on unconstrained minimum supersymmetry and will extend the search down by factor 10 in cross section.

Important: “close” supersymmetry complementary to Tevatron/LHC

But still above the constrained minimum supersymmetry e.g. mSUGRA

Need to extrapolate to 25 or 100 kg to get in this region

=> additional factor 10-50
Complementarity for LHC

In order to fully exploit complementarity with LHC we need more reach: SuperCDMS

Example of mSUGRA regions where LHC can measure most of parameters and CDMS provides consistency: mass + presence as dark matter

May even detect SuperSymmetry in regions which would be difficult to LHC
Theory summary and SCDMS reach
What is needed?

**No surface electron background**
- Improve already excellent performance of our detectors
- Identification of contaminants and elimination: Radon control

<table>
<thead>
<tr>
<th>Improve</th>
<th>Phase A</th>
<th>Phase B</th>
<th>combined</th>
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<tbody>
<tr>
<td>Detector rejection</td>
<td>×5</td>
<td>×2</td>
<td>×10</td>
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<tr>
<td>Analysis discrimination</td>
<td>×4</td>
<td>×2</td>
<td>×8</td>
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<tr>
<td>Background reduction</td>
<td>×5</td>
<td>×2</td>
<td>×10</td>
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<tr>
<td>Total Improvement</td>
<td>×100</td>
<td>×8</td>
<td>×800</td>
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<tr>
<td>Production rate per kg</td>
<td>×5</td>
<td>×10</td>
<td>×50</td>
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**No neutron background**
- Soudan may become limited by neutrons at ≈ 1/3 CDMS II goal level
  => Move to SNOlab

**More mass:** 25kg 150kg → 1 ton
- Thicker detectors
- More detectors: streamline tests, industry involvement
- Bigger IceBox
≈ Background Free
Conclusions

Searches for WIMPs are essential

- Cosmology
- Particle Physics and Gravitational Physics

Roadmap

- Elastic scattering identifying event by event nuclear recoil
- + linking to galaxy
- Phonon mediated detectors are leading the pack
- challenge: extrapolate to 100kg/1 ton
- Importance => Development of other large mass technology
- liquid Xe is best candidate but fundamental response measurements still poorly known

Essential of have large mass technology ready to complement LHC

Best route to connection to galaxy is low pressure TPC: Particle Physics technology: we should be ready to make \( \approx 10000 \text{ m}^3 \) chambers + shielding if we see a signal

DUSEL:

- Deep site is much better
- Availability is crucial: SNOLab only possibility before DUSEL
- R&D important for the field (+ low background counting facility)
DAMA claim

If we interpret the modulation as evidence for WIMPs

In conventional halo model
+ scalar scaling of matrix element

Note: $\approx$ Incompatible with rate
  • Heart shape + best fit close to top
  • Half of the modulation fitted
Technical Questions about DAMA

**Efficiency?**

The signal is a region of sharply increasing efficiency

*Method of determining and monitoring efficiency*
- Local source
- Spectrum of gammas

**Shape of the spectrum?**

- Spectrum before cut?
- Detailed explanation of shape: e.g. why does it decrease at threshold?

**Stability?**

- Is threshold stability sufficient? (<1%)
- DAMA: No modulation of multiples
- Monitoring of other quantities (noise etc...)

Claimed signal
Have They Discovered the WIMPs?

Unfortunately ambiguous
Many things vary between the summer and the winter
DAMA: “We have not found any cause for our modulation”
They may just not have found the culprit yet

A number of technical questions are still unanswered
Internal consistency
Determination and stability of their efficiency in signal region

Incompatible with new generation of WIMPs searches
At least in conventional scaling on target atomic number
and standard halo model
If DAMA is right, something unexpected!
Other groups are gearing up to check their result
CDMS II should reach its goal!

Simulation of limits based on our extended Cousin-Feldman likelihood ratio test

Currently 45% Z 2,3,5 > 10keV
Contamination 0.008±.003

Blue points illustrate random fluctuation from experiment to experiment

Tower 1: Fall 03
Expected Tower 1+2 Summer 04
CDMS II Goal 1998
Zero background 58% efficiency

Expected CDMSII end 2005 mid 2006

Currently 45% Z 2,3,5 > 10keV
Contamination 0.008±.003

Blue points illustrate random fluctuation from experiment to experiment
First Year of Running CDMS II at Soudan

October 2003 - January 2004 run of “Tower 1”
62 “raw” livedays, 53 livedays after cutting times of poor noise, etc.

March-August 2004 “The Two Towers”
1.5 kg of Ge, 0.6 kg of Si
76 “raw” livedays, 74 livedays
Nearly doubled exposure, expected sensitivity, and calibration data

Livetime (days)

Calibration runs

Nearly 85% livetime for last six weeks

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Extra calibration runs

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Towers 1 & 2

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Extra calibration runs

Livetime (days)

Towers 1 & 2
EDELWEISS

Similar technology to CDMS I

Deep underground (Frejus)
30 cm parafine, 20 cm Pb, 10 cm Cu
No active veto
2 events which limit their sensitivity (neutrons?)
04-05 Installation of 21 + 7 detectors in new cryostat
**Neutrinos from Sun/Earth**

**Capture by sun & earth**
- Trapped
- => annihilation in center

Observable: high energy neutrino

\[ \frac{dn}{dt} = \Gamma_{\text{elast}} n - \Gamma_{\text{ann}} n^2 \Rightarrow \text{in equilibrium} \quad \Gamma_{\text{ann}} n^2 = \Gamma_{\text{elast}} n \]

\[ \Rightarrow \text{measure elastic scattering} \]

**More or less proportional**
- **Sun** (also spin dependent)
- **Earth**

**Elastic scatter**

Capture by sun & earth
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