WIMP Direct Detection: an outlook

Particle Cosmology
Non baryonic dark matter
WIMPs: a generic consequence of new physics at TeV scale

we need three approaches: accelerators, direct detection and indirect detection

Current status
Results
DAMA: tension with other experiments
Immediate plans

The road to larger mass
Comparison of the various technologies

Conclusions
Importance of the science
Complementarity of Direct/Indirect Detection and LHC
We need at least two technologies
Standard Model of Cosmology

A surprising but consistent picture

\[ \Omega_m \gg \Omega_b = 0.047 \pm 0.006 \] from Nucleosynthesis WMAP

\[ \Omega_m h^2 \neq \Omega_b h^2 \approx 15 \sigma \text{'s} \]

Not ordinary matter (Baryons)

Mostly cold: Not light neutrinos≠ small scale structure

1. Particle Cosmology and WIMPs
2. WIMPs: current status
3. The road to high target mass

NASA/WMAP Science Team 2006
Standard Model of Particle Physics

Fantastic success but Model is unstable
Why is W and Z at \( \approx 100 \, M_p \)?
Need for new physics at that scale
supersymmetry
additional dimensions
In order to prevent the proton to decay, a new quantum number
=> Stable particles: Neutralino
Lowest Kaluza Klein excitation

Bringing both fields together: a remarkable concidence

Particles in thermal equilibrium
+ decoupling when nonrelativistic
  Freeze out when annihilation rate \( \approx \) expansion rate

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

Cosmology points to W&Z scale
Inversely standard particle model requires new physics at this scale
(e.g. supersymmetry or additional dimensions)
=> significant amount of dark matter

Weakly Interacting Massive Particles
3 Complementary Approaches

Halo made of WIMPs
1/2 shown for clarity

WIMP scattering on Earth:
e.g. CDMS: currently leading the field

WIMP production on Earth

WIMP annihilation in the cosmos

GLAST/Fermi
Launched 11 June 2008
We need all three approaches

Direct detection
May well provide a detection + \( \approx \) cross section and mass
But what is the fundamental physics behind it?
What can we learn about the galaxy?

LHC
May well give rapidly evidence for new physics: missing energy
But is it stable? \( \Rightarrow \) need direct or indirect detection
Ambiguity in parameters: mass/cross section

Indirect detection
May well provide smoking gun for both dark matter and hierarchical structure formation (subhalos)
But possible ambiguity in interpretation \( \Rightarrow \) need direct detection

Complementary sensitivity to different parameter space region
Complementarity mSugra/CMSSM

Direct Detection:
- Bulk
- Focus point

LHC
- "low energy"

Fermi
- Focus
- + Higgs funnel

cf. J. Ellis’ talk: apologies for inversion of axes
Direct Detection

Elastic scattering

Expected event rates are low
(\ll \text{radioactive background})
Small energy deposition (\approx \text{few keV})
(\ll \text{typical in particle physics})

Signal = nuclear recoil (electrons too low in energy)

\neq \text{Background = electron recoil (if no neutrons)}

Signatures

- Nuclear recoil
- Single scatter \neq \text{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)
Experimental Approaches

A blooming field

Direct Detection Techniques

At least two pieces of information in order to recognize nuclear recoil
extract rare events from background (self consistency)
+ fiducial cuts (self shielding, bad regions)

As large an amount of information and a signal to noise ratio as possible
Scalar couplings: Spin independent cross sections

latest compilation by Jeff Filippini

Gray=DAMA 2 regions(Na, I) from Savage et al.
Spin dependent couplings

$\sigma_{SD}^{ap}$ vs $\sigma_{SD}^{an}$ at mass of $60\text{GeV/c}^2$

Where are we? January 2009
The 2 best experiments so far

**Xenon 10** April 2007

10 background events

**CDMS II** 0802.3530 PRL 102(2009)

0 background event (Expected 0.6±0.5)

Discovery potential

≈5 times Xenon 10
If WIMPs exist, we expect a modulation in event rate.

DAMA claims 3 keV peak cannot be fully explained by $^{40}$K escape peak.

Clearly a modulation.

Not a WIMP: incompatible with other experiments.
Spin independent interactions

Spin dependent
What could it be: Physics?

An axionic type particle of 3 keV converting its mass into electromagnetic energy in detector

Modulation by flux Electron recoil line at 3 keV
Checked by other detectors: CoGeNT, CDMS!

3 keV peak excluded cf. CDMS arXiv:0907.1438

3 keV peak in DAMA single rate is not physical (if $Z^2$ scaling)
Probably $^{40}$K escape (1.46MeV missed)
Excludes as modulation signal as big as DAMA (even in optimistic case of ±6%)

Note that cross sections of exothermic radiations tend to be inversely proportional to velocity => modulation very much suppressed (Pospelov et al. 2008)
What could it be?

Most likely very subtle detector problem

- Modulation is basically summer-winter
- Example of the cosmic muon rate which is modulated with the same phase (decay path of the pions change with temperature)
- Many things change: temperature, water in mountain, humidity, electric voltage

What seems excluded

- Neutron from muons
- Direct effect of muons on detector

Examples of effects which have not been excluded convincingly

- Modulation of the efficiency
  - e.g. of the PM noise rejection algorithm
- Modulation of the $^{40}$K 1.46 MeV gamma detection efficiency
  - (e.g. varying humidity in purge gas => modulation of dead layer => 3 keV escape)

Not blind analysis!

Sociological problem:

Nobody finds the result plausible enough to repeat the experiment!
However, as a field we need to cross check the only claim.

A different team has to redo the experiment in Southern Hemisphere

- e.g. NaI detectors in a hole in Antarctic Ice (Stubbs, Fisher, IceCube, B.S.)
Noble Liquids: Current Plans

Single phase detectors
Xenon: Rely on self shielding + position reconstruction:
  XMASS 800kg
Argon: Rely on pulse shape discrimination:
  Mini Clean 150kg fiducial Ar 2010 6-7 pe/keV
  DEAP-3600 1000kg fiducial 2011

Dual phase Xenon
Xenon 100: Assembled in Gran Sasso.
  Currently purifying (100kg-30kg fiducial)
LUX 300kg -> 100kg fid : SUSEL (Homestake)
  Surface: Summer 2009
  4850 ft: early 2010?

Dual phase Argon
WARP 140kg: Commissioning 1.7pe/keV
  result 2010 Goal: $10^{-44}$cm
ArDM: 500kg commissioning at CERN
  Liquid Ar run May 09
  Purity difficulties

Depleted $^{39}$Ar
Underground source: Princeton: <1/25
Immediate Future (cryogenic)

CDMS: Finished data this winter 09
≈ 4kg Ge  750 kg day after quality cuts being analyzed
=> 1370 kg day total
Hope to be still background free
Sensitivity ≈ 2 \times 10^{-44} \text{ cm}^2/\text{nucleon: This Summer 09!}
New 1” thick detectors => 1 Supertower of 3kg => 15kg in 2010

Edelweiss
Switching to interdigitated detectors
(Concept initially proposed by CDMS)
Underground demonstration of excellent rejection of the surface events <1/40000 >50keV
12 such detectors 400g
2010 -> 9kg with 800g detectors

CRESST II
Major upgrade 66 SQUIDs for 33 detectors + neutron shield
Commissioning run with 3 detectors 2007-2008
9 detectors ≈300g currently (July 09) cooling down
COUPP: Bubble chamber
Long duration metastable state broken by large ionization events
nuclear recoil or nuclear recoil from alpha (purity level ≈ Borexino)
2.5 kg prototype CF$_3$I bubble chamber at Fermilab (300 mwe)

Next stage 60 kg: to be installed @ 300 mwe this fall (cf M. Szydagis)

Likely to be an excellent way to lower upper limit.
Much more difficult to get a convincing positive signal
The road to larger masses

Three Challenges

- Understand/Calibrate detectors
- Be background free
  - much more sensitive than background subtraction
  - eventually limited by systematics
- Increase mass while staying background free

Direct Detection Techniques
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**The Competition** *(a simplified/biased view)*

**COUPP:**
- Bubble chamber 2 kg -> 100 kg

**Liquid Xenon:**
- scintillation+ionization
- self shielding ≈ 2.5 cm
- 10 kg -> 100 kg -> 20 tonne

**Liquid Argon:**
- scintillation+ionization
- pulse shape discrimination
- 2 kg -> 100 kg -> 50 tonne

**Low temperature Ge:**
- phonons+ionization
- Zero background so far
- 5 kg -> 15 kg -> 150 kg -> 1.5 tonne

**Many new ideas**
- Single phase -> simplicity
- High or low pressure gas TPCs

**Excellent upper bound machine?**
- sensitive to alpha contamination
- not enough information for discovery

**Promising but not proven background**
- mediocre discrimination 99%
- can be defeated by Rn diffusion
- cosmogenics at DUSEL 4850 ft
- not cheap 1 ton of Xenon = $10M

**Promising**
- need $^{39}$Ar depletion (underground source)
- far UV -> wave shifter, high threshold

**Promising extrapolation path**
- large 150 mm Ø, 50 mm thick crystal
- large scale multiplexing (e.g. RF)
- automation of TES process or KIDs separated function
- simplification of testing
e.g. Larger Ge Detector Mass

SuperCDMS 15 kg detectors: 1cm→1” 250g→635 g

Much larger detectors → SCDMS@SNOLAB

Liquid N2 Ge crystals limited to 3” ≈ 100 dislocation/cm
But we showed recently that dislocation free Ge works at low temperature!
Umicore grows (doped) dislocation free 8” crystal
6”x2” or 8”x1” ≈ 5kg + Multiplexing

1.5 tonne GEODM@ DUSEL for $5OM
Detector mass +automation+ simplified testing
We do not know yet...
Likely to take some time of systematic work
Need strong R&D basically at full scale

Go beyond propaganda
“My detector is bigger than yours!”
Not the whole story: Detailed understanding of the phenomenology
Zero background!
One background can/will hide another one!

In any case we need at least two different technologies (may be three worldwide)
Cross checking each other
Protection against unexpected background
Physics! e.g.
Coherence additive quantum number: $A^2$ dependence (scalar coupling)
spin dependence
Threshold in target mass=>$\text{dark matter excited state}$
Next 6 years (Pre DUSEL) program

Current WIMP searches

Next generation

1 generation beyond

Finer and finer tuning to get right density!

Next generation Large Hadron Collider 09

Significant chance of discovery

few $10^{-45}$ cm$^2 \leq 2010$  
$10^{-46}$ cm$^2 \leq 2015$

Science complementary to LHC and Fermi-GLAST/ Ice Cube

What are the technologies of the future?
Conclusions

Essential to detect Dark Matter
  A key ingredient of the standard model of cosmology
  WIMPs is the generic thermal model

Complementarity of direct detection, indirect detection and accelerators
  The next 3 years may well allow a spectacular discovery
  B.Sadoulet, Science 315 (2007) 61

  Direct detection at a few $10^{-45}$ cm$^2$/nucleon
  Large Hadron Collider; production of Supersymmetric Particles but stable?
  Fermi/GLAST + ICE Cube could be a smoking gun (Dark Matter + Hierarchical merging)

Direct detection
  Entering the interesting (generic) territory with a variety of methods
  at a few $10^{-45}$ cm$^2$/nucleon
  - Phonon mediated detectors (SuperCDMS, EDELWEISS)
  - Liquid Xenon 2 phase
  - Liquid Ar 2 phases+pulse shape
  maybe other simpler technologies (XMASS, MiniCLEAN, COUPP)

At the same time explore the best technologies onto which to converge
  for the next generation (we need at least two technologies)
  If no discovery: explore corners of parameter space with low elastic scattering
  If/when we have a discovery:  
    - Get better statistics => dark matter observatory
    - Link to/study galaxy (low pressure TPC≈5000 m$^3$)