Dark Matter



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Motivations for non-baryonic Dark Matter Search - 1 Astrophysical measurements





- - "Dark" matter halo around the galaxies
 - Local density: ρ_{DM} ~ 0.3 - 0.5 GeV/cm3





Motivations for WIMPs

- Large scale structures
 - CMB precision observations
- SN1a observations...
 - Rotation curves



N-Body Simulation of the Cold Dark Matter Cosmology





Natural WIMP candidate: SUSY LSP neutralino

 $\tilde{\chi}_{1}^{0} = N_{11}\tilde{B} + N_{12}\tilde{W}^{3} + N_{13}\tilde{H}_{1}^{0} + N_{14}\tilde{H}_{2}^{0}$ gaugino fraction: $Z_g = \left| N_{11} \right|^2 + \left| N_{12} \right|^2$

Indirect detection:

- Detection of WIMP annihilation products
- SuperK, ANTARES, AMANDA...

 \rightarrow Stable if SUSY exists and R-parity is conserved

- Direct detection:
 - WIMP scattering off nuclei





Possible WIMP Signatures

Nuclear vs electronic recoil

- (discrimination almost required now)
- Recoil energy spectrum shape
 - (exponential, rather similar to background ...)
- Annual flux modulation

- (tricky, most events close to threshold, small effect)

- Diurnal direction modulation
 - (nice signature, but requires low pressure gaseous target)
- No multiple interactions
 - (removes limited fraction of background)
- Consistency between targets of different nuclei
 - (essential once first signal is clearly identified)





Direct detection techniques





Experimental challenges

- Background suppression
 - Deep underground sites
 - Radio-purity of components
 - Active/passive shielding
 - Large target mass required
 - ~ few keV energy threshold
 - Stability and reproducibility

- Discriminate recoil populations
 - Photons scatter off electrons
 - WIMPs/neutrons off nuclei
 - radon heavy nuclear recoils, alpha tails...



Current direct detection experiments

Discrim.	Name	Location	Technique	Target	Status
	CUORICINO	Gran Sasso	Heat	41 kg TeO2	running
	GENIUS-TF	Gran Sasso	Ionization	42 kg Ge in N2	running
1 Prove	HDMS	Gran Sasso	Ionization	0.2 kg Ge diode	running
Ì	IGEX	Canfranc	Ionization	2 kg Ge Diodes	stopped
3/	DAMA	Gran Sasso	Light	100 kg NaI	stopped
XX XX	LIBRA	Gran Sasso	Light	250 kg NaI	running
Sx	NaIAD	Boulby mine	Light	65 kg NaI	running
	ZEPLIN-I	Boulby mine	Light	4 kg Liquid Xe	running
7× 1	CDMS-I	Stanford	Heat + Ionization	1 kg Ge + 0.2 kg Si	stopped
, je	CDMS-II	Soudan mine	Heat + Ionization	5 kg Ge + 1 kg Si	running
Leeker Leeker	CRESST-II	Gran Sasso	Heat + Light	0.6 to 9.9 kg CaWO4	starting
	EDELWEISS-I	Modane	Heat + Ionization	1 kg Ge	stopped
	EDELWEISS-	Modane	Heat + Ionization	10-35 kg Ge	starting
	ROSEBUD	Canfranc	Heat + Light	0.2 kg BGO	running

Wimps direct detection experiments

- CDMS-I (cryo Ge and Si @ Stanford), CDMS-II @ Soudan Mine
- EDELWEISS (cryo Ge @ Fréjus)
- CRESST (cryo CaWO₄) @ Gran Sasso
- ZEPLIN, DRIFT, NaIAD @ Boulby Mine)
- DAMA/LIBRA (NaI, Xe @ Gran Sasso)
- IGEX @ Canfranc, HDMS/GENIUS-TF (Ge) @ Gran Sasso
- ROSEBUD (cryo BGO), ANAIS (NaI)
- CUORICINO/ CUORE (TeO₂) @ Gran Sasso
- SIMPLE, MACHe3, ORPHEUS (Bern)
- ELEGANT, LiF @Japan
- + Future experiments: SDMS, EURECA, XENON, XMASS



Germanium diodes (IGEX, Heidelberg-Moscow)

High purity: best intrinsic background level ~ 0.05 evt/kg/keV/day (Heidelberg-Moscow) ~ 0.21 evt/kg/keV/day (IGEX), lower E threshold BUT, no electron recoil background rejection possible



Running: Genius-TF

- Based in Gran Sasso
- 14 x 2.5 kg enriched HPGe crystals in N₂
- Extreme radiopurity of all components
- Expected BG: 0.01 count/kg/keV/d
- Expected threshold: 12 keV recoil
- 20 years to see a 4-σ modulation compatible with CDMS limit !



- Tritium
- Cosmogenesis (⁶⁸Ge)
- Radon decay products



First WIMP candidate: DAMA

- Gran Sasso Lab, 3500 mwe
- 9 crystals for ≈ 100kg NaI(Tl)
- Scintillation detectors with N₂ flow
- Limited discrimination (not used after 1996 exclusion analysis)
- Looking for annual modulation





A first WIMP candidate: DAMA



WIMP candidate under standard halo parameters: M_{γ} = (52 +10) GeV and $\sigma_{\gamma-N}$ = (7.2 -2094) .10-6 pb

Rather opaque analysis (raw spectrum, cuts, calibration) Nevertheless, checking this result remains important 2nd phase 250 kg LIBRA running...



"DAMA energy resolution at low energies is better than the resolution measured for much smaller crystals and better than poissonian limit with a light yield of 10 photoelectrons per keV" (UKDMC, Robinson et al. 2002)

Note: DAMA measures ≤ 6 photoelectrons/keV (visible energy)

CDMS-II detectors: ZIPs



250 g Ge or 100 g Si crystal 1 cm thick x 7.5 cm diameter

Collect athermal phonons: XY position imaging Surface (Z) event veto based on pulse shape





CDMS II Background Discrimination

Ionization Yield
 (ionization energy
 per unit recoil
 energy) depends
 strongly on type of
 recoil

 Most background sources (photons, electrons, alphas) produce electron recoils



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First CDMS-II run @ Soudan



astroph/0405033, · submitted the PRLts and blind analysis new benchmark $\cdot \approx$ factor 10 increase in sensitivity expected in near future powerful rejection of surface events

using charge/phonon

second run analyzed

The Modane Underground Laboratory



1700 m depth under the Fréjus Tunnel (4800 we)
 4 μ/m²/day (≈ 2 × 10⁶ less than at the surface)
 1500 neutrons (>1 MeV)/m²/day (rock radioactivity)



EDELWEISS-I

- Modane Lab: 4800 mwe → muons / 2.10⁶ Low radioactivity dilution cryostat 17 mK Shielding:
 - 30cm paraffin, 20cm Pb, 10cm Cu
- 3 x (Heat + Ionization) 320 g Ge detectors
 - Charge collection 4V polarisation
 - Guard ring electrode
 - Amorphous Ge or Si sub-layer (surface events)











EDELWEISS thermal detectors: excellent energy resolution

Sub-keV energy resolution on phonon channels (down to 250 eV baseline, 350 eV FWHM at 10 keV)
≈1 keV FWHM on

charge channelsBackground

comprehension down to a few keV e.e.



EDELWEISS-I : 2002 data from GGA1 detector

1.5

 3 months data taking: 0 event (1?)
 Sensitivity: ≈ 1.4 × 10⁻⁶ picobarn
 Nuclear recoil calibrations at start and end of data

taking



200

A. Benoit et al., astro-ph/0206271/, Phys. Lett. B 545 (2002) 43



2003 Edelweiss data

- Additional ~45 kg.d recorded with 3 new detectors
- 2 phases with 2 different triggers
 - On the ionization signal
 - On the phonon signal
- 2000-2003 data represent ~ 60 kg.d
- Results :
 - Events observed in nuclear recoil band (33 for E_{rec} > 15 keV)



- 20 kg.d
- Energy threshold : 20, 30 keV
- 3 events observed in the nuclear recoil band



2003 data (phonon trigger)



Lower energy threshold : 15 keV

- 30 events observed in nuclear recoil band, most below 30 keV in 22 kg.d
- 1 coincidence n-n observed between detectors
- Stable behavior of 3 detectors over total exposure



Edelweiss new limit

Unknown backgrounds

"Yellin method"* used to derive exclusion limit *(PRD 66,032005 (2002))

No background subtraction

New (prel.) limit consistent with the previous publication *(Phys. Lett. B 545 43 (2002))





Experimental spectrum

 Low energy spectrum inconsistent with Wimp mass > ~ 20 GeV
 A n-n coincidence has been observed

> Possible backgrounds

- neutrons
- miscollected charge events

(surface events)



Recoil energy (keV)

Energy Spectrum

Lessons from Edelweiss-I

With 3 new detectors and an extended exposure, the preliminary 2003 exclusion limit confirms the previous published one

Surface events :

- Improved radiopurity in Edelweiss-II
- Identification (or suppression) possible with NbSi thin film sensor
- Neutron background :
 - Improved shielding against neutron
 - Anti-coincidences more efficient with increased number of detectors

Identification of surface events

- 2 NbSi athermal phonon sensors for surface event rejection
- Two components :
 - Thermal (energy)
 - Athermal/transitory (nearsurface tag)
- For this surface event, the athermal component is higher in NbSi 1
- First tests of 200g modules in Edelweiss-I promising :
 - 10 x less background while retaining 50 % efficiency



Transitory

thermal





Perspectives : Edelweiss-II

- Aim : x 100 improvement in sensitivity
- 1st phase :
 - 21*320g Ge bolometers with NTD heat sensor
 - 7*400g Ge bolometers with NbSi thin film sensor
- Installation started in April 2004
- Data taking in 2005





March 2004: EDELWEISS-I ended Install EDELWEISS-II with 21 x 320-g + 7 x 400-g Ge detectors (≈ 10 kg germanium) 120 detector capacity (35 kg Ge)

Dilution : 8-10 mK obtained on several runs Wiring and cold electronic test : mid 2004



Edelweiss II : new setup

- Clean room
- Efficient shielding against neutron and gamma ray background
 - 20 cm lead
 - 50 cm PE
 - Muon veto
 - Sensitivity
 - Edelweiss I :0.2 evt/kg/day
 - Edelweiss II :
 - 0.002 evt/kg/day



CRESST-II experiment (Gran Sasso)

Background discrimination by simultaneous detection of phonons



Works with many absorber materials CaWO₄, PbWO₄, BaF, BGO (other tungstates and molybdates)



CRESST II - Detector Module



phonon channel 300g CaWO₄ Ø = 40mm, h = 40mm W-SPT 4 x 6 mm²

light channel Si 30 × 30 × 0.4 mm³ W-SPT

reflector polymeric foil, teflon





Direct detection summary

- Background discrimination is now essential
- Sensitivity of CDMS, EDELWEISS and CRESST one order of magnitude better than present competitors
- Optimistic SUSY models are now tested





ZEPLIN-I: light time constants



 Xe^*

Xe₂*

Triplet

27ns

2Xe

175nm

+Xe

Singlet 3ns

2Xe

175nm







ZEPLIN-I: some caveats



- Sensitivity claimed by ZEPLIN: 10⁻⁶ picobarn at M_W = 60 GeV requires very large background subtraction: > 99.9 %
- No calibration in range of interest for WIMP recoils (< 40 keV)
- In presence of a neutron source, no low-energy nuclear recoils are observed !
- Instead "ambient neutrons" (when neutron source is removed !) are used as calibration
- No demonstration that "ambient neutrons" are indeed neutrons
- Conservative ZEPLIN-I sensitivity: 10⁻³ picobarn, not 10⁻⁶ picobarn

ZEPLIN I Energy Resolution





Perspective: XENON

- Dual phase Xe experiment using TPC
- Light/Ionization detector
- Very-low BG photomultipliers
 - 10 kg prototype underway
 - 100kg phase : 1 TPC
 - Real 3-D measurement if CsI photocathode is efficient enough
 - Goals:
 - 1 ton scale (10 LXeTPC)
 - 16 keV recoil threshold
 - > 99.5% BG discrimination
 - Reach few 10⁻¹⁰ pb within 3 years

(See E. Aprile's talk)



XMASS: 100KG TEST DETECTOR



Low background setup Vertex, energy reconstruction self-shielding purification system

- Demonstration of selfshielding at high energies (> 150 keV)
- High energy threshold
- No DM limits derived



Wimps indirect detection experiments

- AMANDA, ICECUBE (South Pole)
- ANTARES (Mediterranean), ANTARES-1km2
- NESTOR
- Superkamiokande, Hyperkamiokande
- Gamma-ray telescopes: CANGAROO, MAGIC, HESS, ...
- Satellite experiments: AMS-02, GLAST, ...



WIMP indirect detection

- WIMP elastic scattering: in average, loss of energy;
 v < v_{escape} capture
 → WIMPs will gather at center of Sun, galaxy, Earth
- Neutralino: Majorana particle → its own antiparticle if massive → must annihilate
- Annihilation τ ; b, c, t quarks; gauge bosons; Higgs bosons ν ; γ ; e^+ ; antiprotons
- Main signatures:
 - Search for excess of up-going muons from direction from center of Sun, galaxy, Earth
 - Search for annihilation lines
 (galactic center, cosmological, ...)

Mostly neutrinos from the Center of the Sun and the Earth

Indirect WIIMP search

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 Dark matter in Galaxy due to neutralinos (self annihilate)

 $\sim c + \mu + v_{\mu}$

Density ~
 0.3 GeV/cm³

 $\chi + \bar{\chi} \rightarrow b + \bar{b}$



Amanda-II: **677 PMTs** at 19 strings (1996-2000)

2005-2010

~ 0.1-1 km² detectors ICECUBE, ANTARES, NESTOR...

(see review talk by A. Kouchner)







WIMP indirect searches : best present limit from Super-K



Combined analysis for sun, earth and galactic center: no excess over atmospheric neutrino expectation in any cone angle.

Conservative limit within a factor \approx 5-10 of CDMS



Super-Kamiokande:

50 kT water Cherenkov detector (22.5 kT fiducial) 11146 inward-facing 20 in. PMTs 1885 outward-facing veto PMTs

HEAT, PAMELA, AMS-02...

- Charged antiparticles : antiproton; e+ (detection requires large enhancement factors)
- Charged ⇒ no directionality
- S/B discrimination difficult, spectral shape prediction (over background E^{-γ})
- Directionality on gamma-ray flux
- S/B discrimination via on/off sources of high density : galactic centre, but signature ?
- Energy up to m_c, resonance at E = m_c

The AMS-02 Project (see talks by S. Gentile and T. Siedenburg) AMS-02



Aachen Physics Ib



Frank Raupach - p.5/25

Positron DM signal: HEAT vs. AMS-02





Direct/indirect: μ flux from the Earth

strictly after J. Edsjö, review paper at Neutrino'2004

Direct detection definitely more sensitive







Conclusions

- Direct detection WIMP experiments (CDMS, EDELWEISS and CRESST) are at last sensitive to (optimistic) SUSY models (≈ 10⁻⁶ pbarn)
- Next generation experiments (CDMS-II, CRESST-II, EDELWEISS-II, XENON, ...) should bring factor $\approx x$ 10-50 improvement in sensitivity
- (\approx few 10⁻⁸ pbarn) and begin to test more realistic models
- Testing the bulk of SUSY parameter space (down to 10⁻¹⁰ pbarn) will require experiments in the one-ton range and extreme background rejection
- Indirect detection is complementary (spin-dependent couplings), but hardly competitive for detection of low σ scalar interaction models
- LHC together with direct/indirect detection experiments will hopefully allow to pinpoint WIMP DM within the next ≈ 10 years