Direct detection of dark matter

The earth is sitting inside the galactic halo
→ dark matter particles should be streaming past us.
How can we detect them?

SUSY dark matter particles can interact by (at most) weak interactions.
They are typically 10s or 100s of GeV in mass.
→ Look for DM scattering off of atomic nuclei.

Such a scattering event can:

- deposit energy in a detector
  - → look for a small heating-up of a cryogenic detector
- create vibrations
  - → look for a phonon signal
  - → look for a vaporization of superheated liquid
- excite atomic electrons or nucleus (inelastic); ionization in detector

More ideas:

- Earth is orbiting the sun, sun is moving through the galaxy.

There should be an annual modulation in the DM particle velocity
→ annual modulation in (WIMP-velocity-dependent) signal rate.
Chance to learn which direction the WIMPs are streaming from, and their velocity distribution!
But beware: a lot of backgrounds are also annually modulated, like water in the surrounding rock, or temperature-dependent radon emissions.

- Direction of the DM particle: some techniques can tell which way the DM particle was going.

Chance to map out the flux of DM particles!
Look for "streams" in the DM distribution – capture/merger history of our galaxy.

Dark matter direct-detection signal controlled by:

- Particle physics factors

(1) WIMP-nucleon scattering cross section – determines rate
(2) WIMP mass – determines recoil kinematics

- Astrophysics factors

Experiments usually make a “standard” set of assumptions here.

(1) Local WIMP density – determines rate

Pretty well constrained by our galaxy's rotation curve, assuming no major small-scale clumpiness

(2) Local WIMP velocity distribution – determines rate (velocity-dependent cross sections) and signal characteristics (recoil-energy–dependent experimental sensitivity)

Somewhat astrophysics-model-dependent.

– Thermal Boltzmann distribution?

– Tidal streams from past capture of small satellite galaxies by the Milky Way?

– Caustics from the “folding” of infalling fluid of zero-velocity WIMPs?

Chance to use WIMP direct detection to do astrophysics.

WIMP scattering comes from two classes of couplings.

- Spin-independent

Scalar coupling of WIMP to nucleon

e.g. via squark exchange or Higgs exchange

Coherent scattering off multiple nucleons

Cross section increases dramatically with mass of target nuclei – use heavy nuclei

- Spin-dependent

Axial-vector coupling of WIMP to nucleon

e.g. via Z exchange

Cross section proportional to $J(J+1)$ – use nuclei with spin

- If WIMP is not a Majorana fermion, can also scatter by vector interactions.

E.g., heavy Dirac neutrinos, MSSM sneutrinos

(Neutralinos are Majorana fermions.)

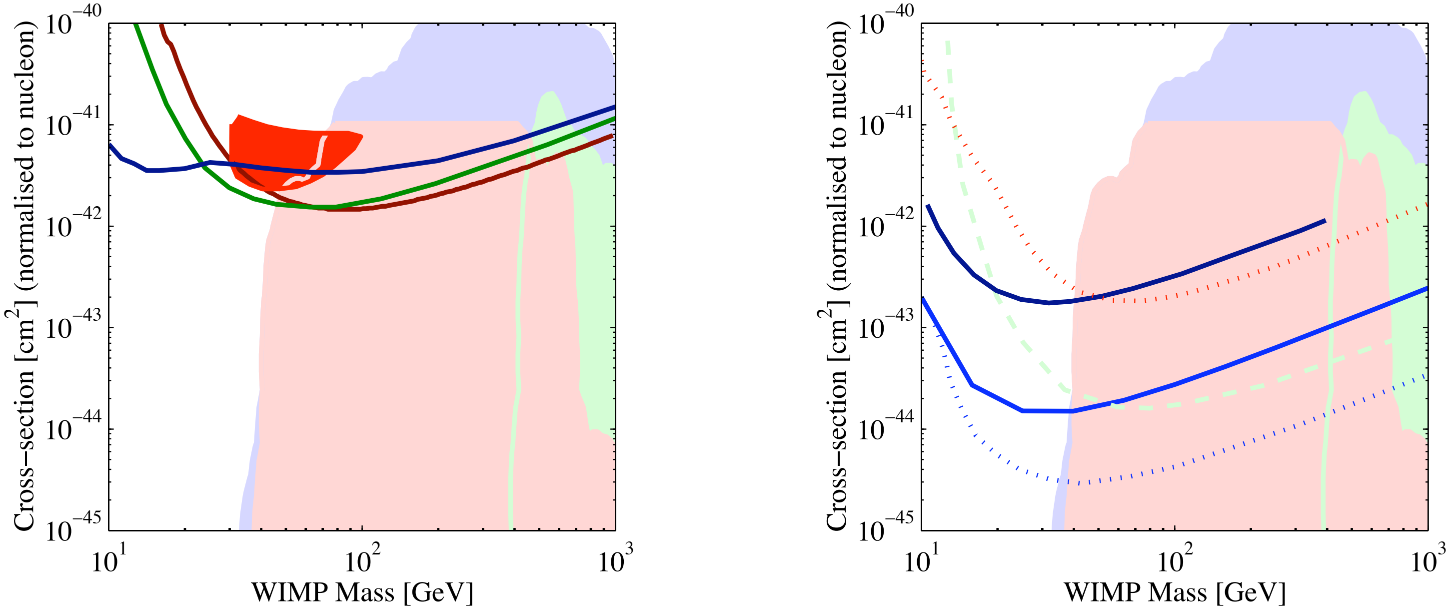
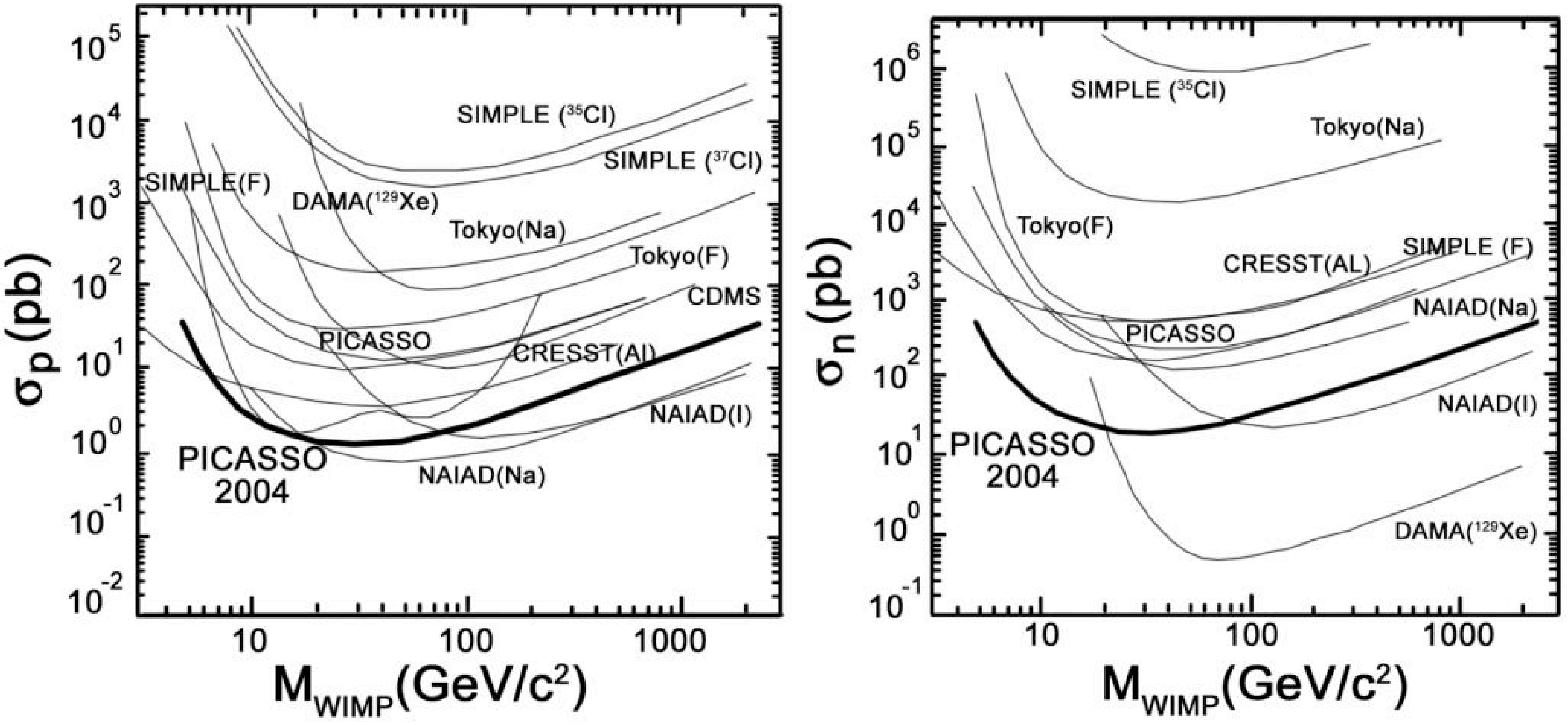


Figure 21: Current (left) and future (right) sensitivities of direct detection experiments. In the left frame, from top to bottom along the right side of the figure, the current limits from the CDMS, ZEPLIN-I and Edelweiss experiments are shown. The filled region near 30-100 GeV and 10^{-41} cm^2 is the parameter space favored by the DAMA experiment. In the right frame, from top to bottom along the right side of the figure, the projected reach of the GENIUS test facility (solid), CRESST-II (dots), CDMS-Soudan (solid), Edelweiss-II (dashed) and ZEPLIN-MAX (dots) are shown. In each frame, as filled regions, the space of models predicted by supersymmetry are shown [258]. The narrow region along the right side of the figure represents higgsino-like models, the region that reaches to the top of the figure represents mixed higgsino-gaugino models and the largest region represents gaugino-like models. These figures were made using the interface found at http://dendera.berkeley.edu/plotter/entryform.html.

from hep-ph/0404175

Example: PICASSO (a potential SNOLab experiment)
Uses superheated droplets containing fluorine (nucleus with large spin)
Sensitive to spin-dependent coupling
WIMP scattering causes superheated fluid to vaporize – listen for the "ping".



from hep-ex/0502028

Indirect detection of dark matter

"Indirect detection" means looking for the annihilation byproducts of DM particles.
Annihilation rate is proportional to WIMP number density squared

- WIMP annihilation in the galactic centre

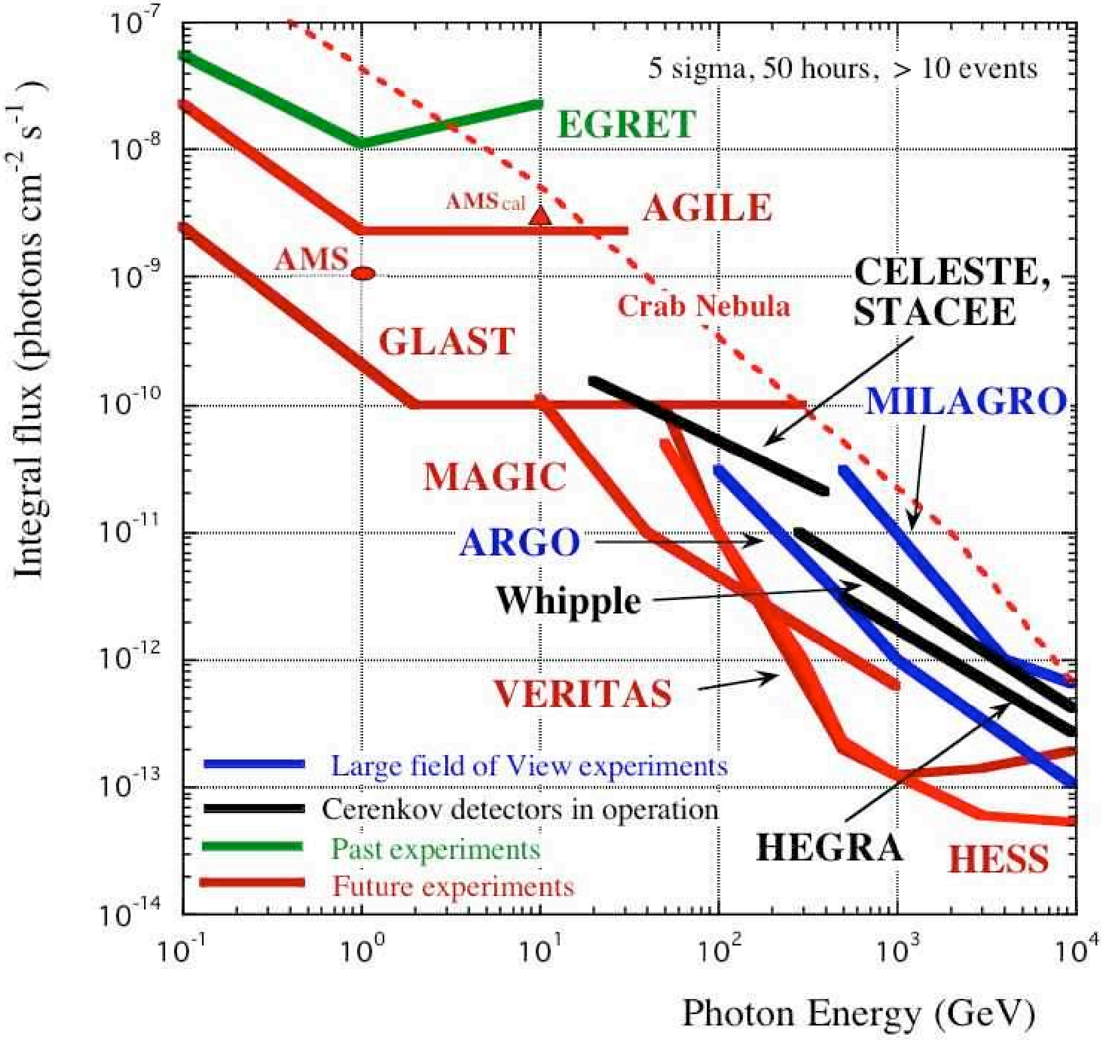
High number density – but depends strongly on the astrophysics model for the core of the halo!
Annihilation byproducts: gamma rays are easiest to see.
Electrons/positrons/hadrons get bent by galactic magnetic fields; neutrinos hard to detect (but see later)
Look for signal coming from gravitational centre of the galaxy.

- Gamma ray spectrum:

– $\widetilde{N}_1 \widetilde{N}_1 \to \gamma\gamma$ would give monochromatic γ-ray line at energy equal to $m_{\widetilde{N}_1}$ a smoking gun! Plus we get $m_{\widetilde{N}_1}$ for free!
– Other annihilation processes give γs from the showering. Spectrum depends on annihilation branching fractions and $m_{\widetilde{N}_1}$. Given these, can simulate it with PYTHIA.

- Gamma ray detection:

– From the ground: γs shower in the atmosphere. Have to separate them from cosmic ray protons.
– From space: detect γs directly. Good pointing capability, energy resolution. EGRET (past) only up to 30 GeV; GLAST (future) up to several hundred GeV. An EM calorimeter in space!

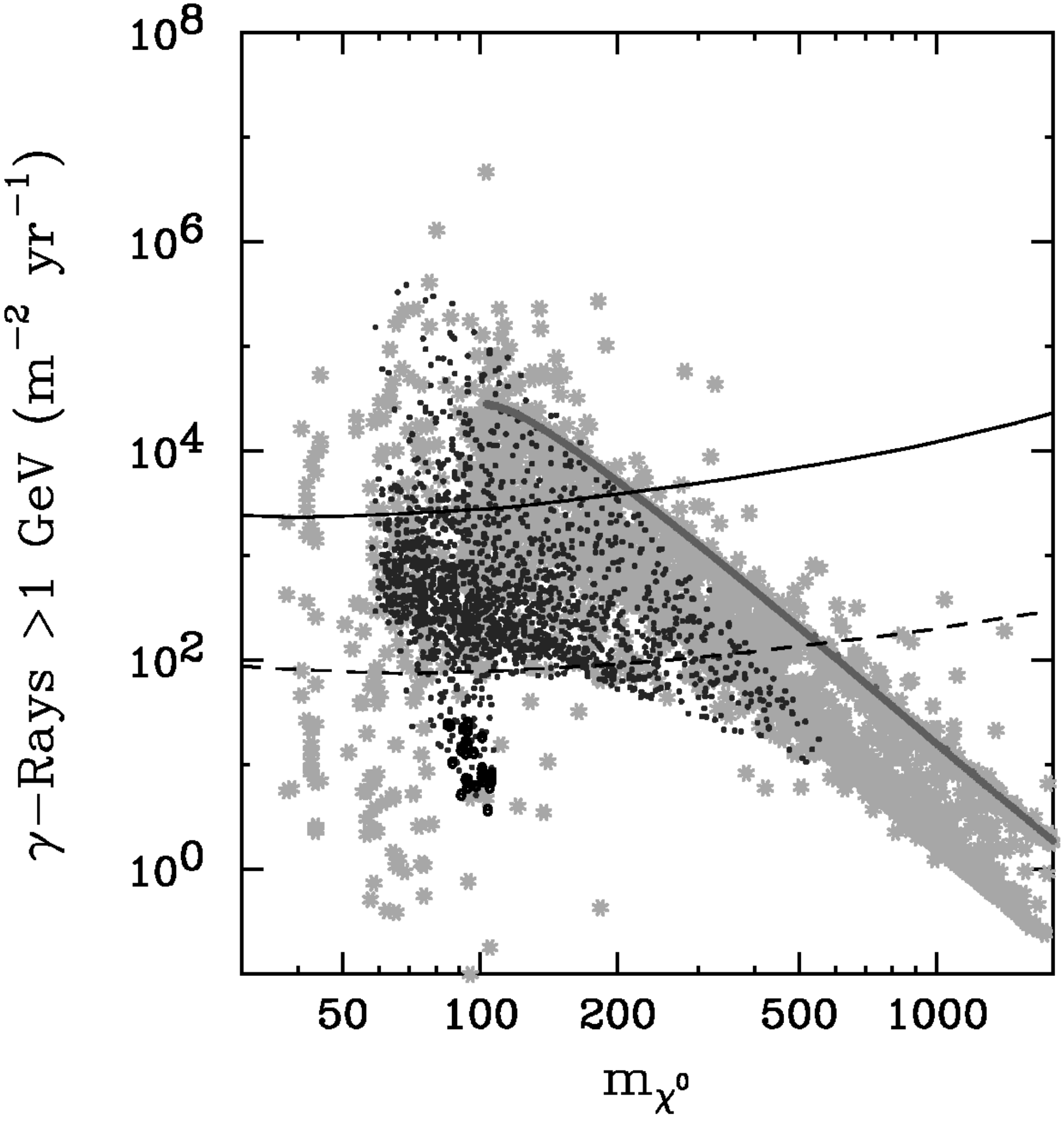


from hep-ph/0404175

Space-based detectors are small – need higher integral flux; can go to lower energies

Ground-based detectors are large – can go to lower integral flux; need higher energies (mainly to separate from background)

Dark matter indirect detection by gamma-rays from the galactic centre
(for one particular halo profile)



from hep-ph/0404175

- Solid line: present limit from EGRET
- Dashed line: predicted sensitivity of GLAST
- Points: various SUSY models

- WIMP annihilation in the sun

WIMPs get gravitationally captured in the sun – eventually annihilation rate equals capture rate → equilibrium depends only on capture rate

– Capture rate depends on WIMP-nucleon scattering cross section (must scatter to lose energy and get gravitationally captured) and local WIMP density (less sensitive to halo models).

Annihilation byproducts: neutrinos are the only thing we can see

The sun is opaque to electrons/positrons/hadrons.

Look for neutrinos coming from the sun

- Neutrino spectrum:

– WIMP annihilation gives higher energy neutrinos than solar fusion processes.

– Spectrum depends on annihilation branching fractions and $m_{\widetilde{N}_1}$.

– Neutrinos can come from $\widetilde{N}_1\widetilde{N}_1 \to \nu\bar{\nu}$ (typically very rare), $\widetilde{N}_1\widetilde{N}_1 \to W^+W^-$ with semileptonic decays, or annihilation to heavy quarks followed by semileptonic decays. Showering can be simulated with PYTHIA.

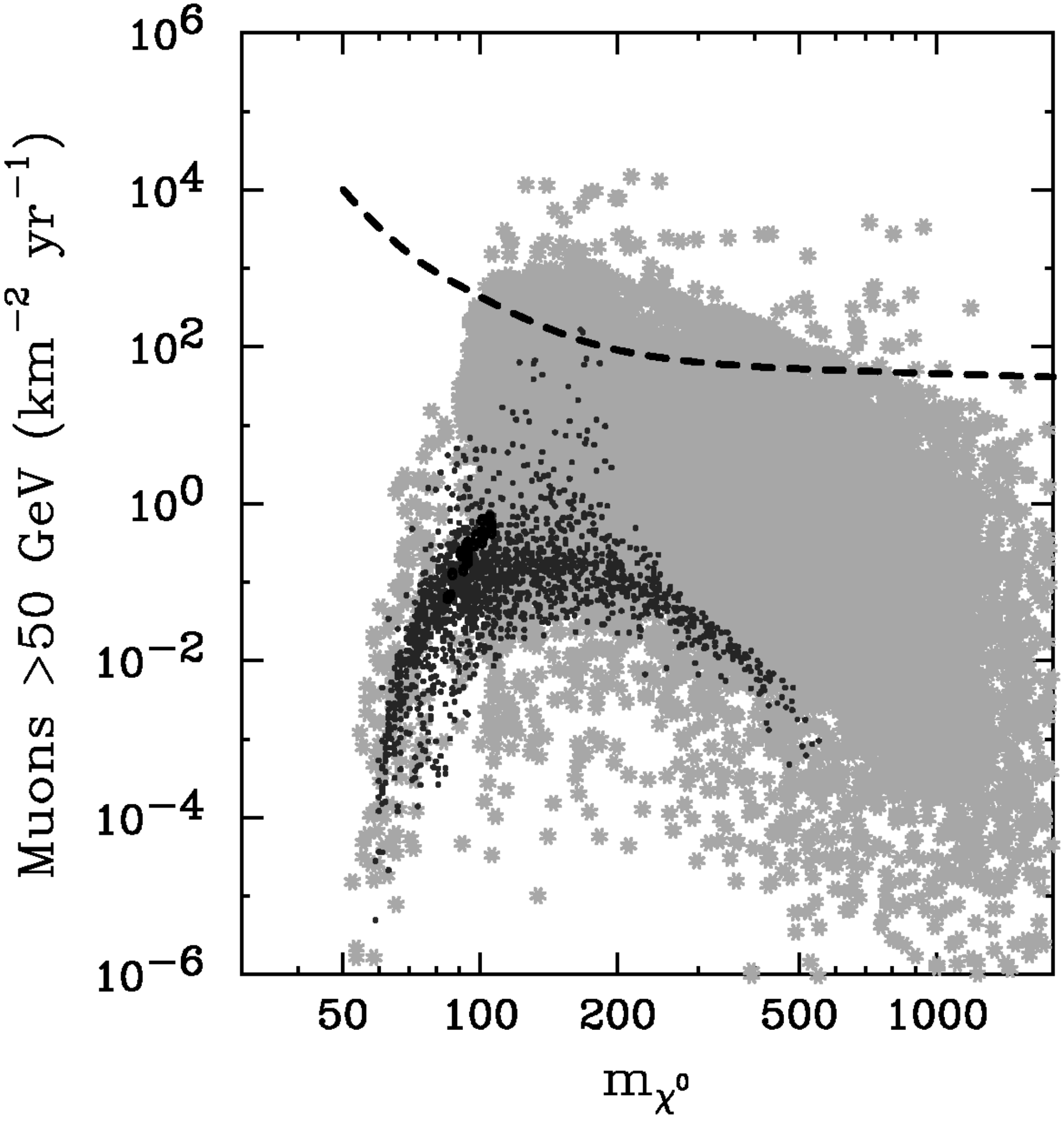
- Neutrino detection:

High energies, low rates. Need big detector.

– Amanda / IceCube: photodetectors in the Antarctic ice! Look for Cherenkov light from high-energy muon from $\nu_\mu \to \mu$ charged-current interaction in the earth. Measure muon direction and energy.

– Antares, Nestor: same idea, but photodetectors located in the water of the Mediterranean.

Dark matter indirect detection by neutrinos from the sun



from hep-ph/0404175

- Dashed line: IceCube sensitivity
- Grey points: general MSSM
- Black points: mSUGRA

- Positrons or anti-protons

From WIMP annihilation in the galactic centre or nearby

Charged particles: bent by galactic magnetic fields. Don't point back to their origin.

Need to tell antimatter apart from huge matter cosmic-ray background

→ Need space- or balloon-based experiments

Current experiments: statistics not very good, systematic uncertainties large; don't know "standard" backgrounds very well.

– "Smoking gun" signal would be $\widetilde{N}_1\widetilde{N}_1 \rightarrow e^+e^-$ (typically very rare) giving monochromatic positron; positron energy gets downshifted by scattering, but has a high-end cutoff. (Can get a feature like this in Extra Dimension theories with KK dark matter.)

– More likely: get positrons from showering; spectrum depends on $m_{\widetilde{N}_1}$ and branching fractions, convolved with energy downshifting from propagation through the galaxy.

- Gravitino dark matter: the “super-WIMP”

Meaning, “super-weakly interacting” massive particle

The gravitino interacts very weakly – remember only the NLSP with no other possible decays will decay to a gravitino LSP with any appreciable branching fraction.

- Production:

– SUSY particles thermally produced as usual in early universe

but not gravitino, since it interacts too weakly

– NLSP freezes out in the usual way

– Later, NLSP decays to gravitino.

“Cosmology at colliders” would lead us to think that thermal freeze-out would produce too much NLSP dark matter, or maybe even sneutrino dark matter (would have too large a direct-detection rate), or maybe even charged or coloured dark matter (wouldn’t be “dark”)!

– Gravitino is lighter than NLSP, so same number density can give correct mass density.

- Detection:

– Direct detection? No, scattering cross section is way too small.

– Indirect detection? No, annihilation rate is way too small.

– Our only chance is detection at colliders (if decay length is short enough) or, if NLSP is charged, we could produce them in colliders, capture them, and watch them decay.

NLSP decay rate is fixed by gravitino interaction strength, which is fixed by gravitino mass! Can finally test DM abundance.

One other hope:
– NLSP is cold dark matter: $\sim$ zero velocity. Computer simulations expect it to clump gravitationally into more "cuspy" distributions than are observed.
– NLSP decay to gravitino could produce gravitinos with a velocity distribution: warm dark matter.
– Nonzero velocities: gravitinos "free-stream" more, smear out clumpiness in distribution.
– Fine-scale clumpiness measurements of DM mass density could detect "warm" nature.

There might even be something to this:
http://news.bbc.co.uk/2/hi/science/nature/4679220.stm

They measured the mass distributions of a bunch of small satellite galaxies of the Milky Way, using star orbit trajectories.

Last Updated: Sunday, 5 February 2006, 23:25 GMT

Dark matter comes out of the cold

By Jonathan Amos
BBC News science reporter

Astronomers have for the first time put some real numbers on the physical characteristics of dark matter.

The DM "comes in a 'magic volume' which happens to correspond to an amount which is 30 million times the mass of the Sun. It looks like you cannot ever pack it smaller than about 300 parsecs - 1,000 light-years; this stuff will not let you. That tells you a speed actually - about 9km/s - at which the dark matter particles are moving because they are moving too fast to be compressed into a smaller scale."

Time will tell if it's right.