Title: A particle physicist's perspective on dark matter

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Abstract:

A Particle Physicist's Perspective on Dark Matter

M. E. Peskin
April, 2005

Thanks to:

Jonathan Feng, Mark Trodden, Marco Battaglia, Norman Graf, Jim Alexander, Bhaskar Dutta, ...

Ted Baltz, Andreas Birkedal, ...

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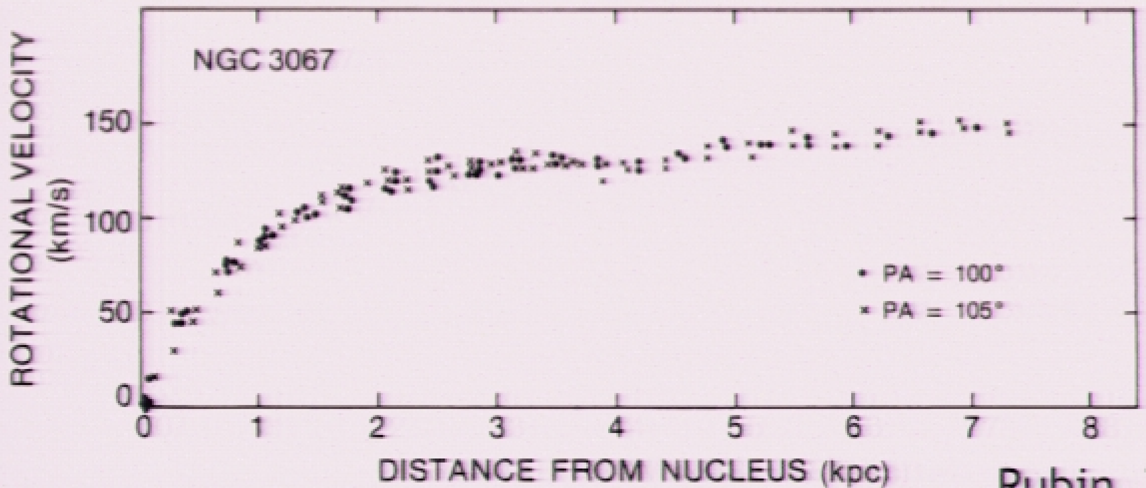
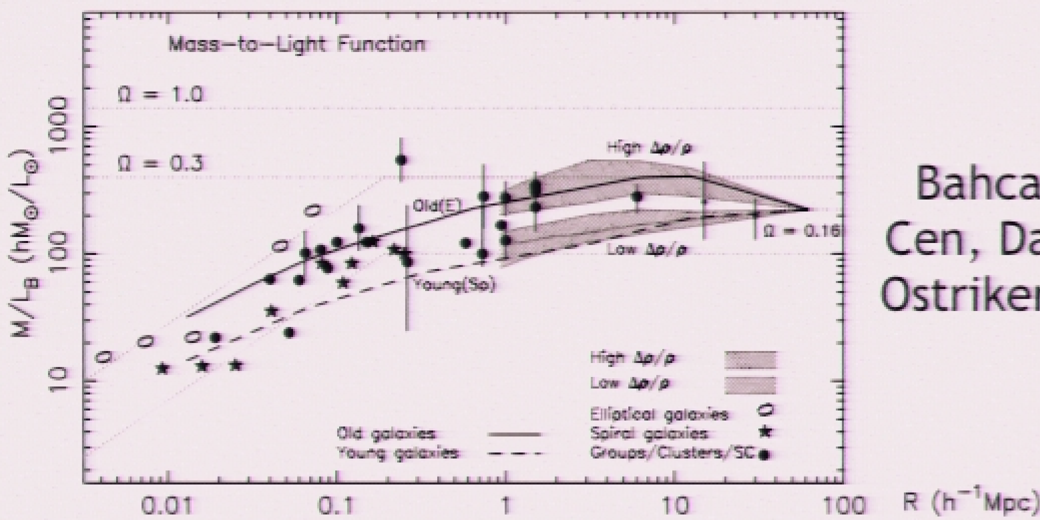
...and now a brief word
from our sponsor ..
the International
Linear Collider
(ILC)

It has been known since the 1930's that stars, gas, and dust account for only a small fraction of the mass of the universe on large scales.



Rubin, Thonnard, Ford



Bahcall,
Cen, Dave,
Ostriker, Yu

From primordial nucleosynthesis (H/D/He abundances) and from the cosmic microwave background, we know that this dark matter is nonbaryonic.

Recent results from the WMAP experiment and the Space Telescope measurent of the Hubble constant imply that

$$\Omega_{DM} = 0.217 \pm 0.027$$

together with

$$\Omega_B = 0.0432 \pm 0.0017$$

$$\Omega_\Lambda = 0.740 \pm 0.034$$

A variety of underground and cosmic ray experiments are now trying to detect dark matter particles.

What do I, as a particle physicist, seek to add to this story ? Don't astrophysicists understand this subject quite well enough?

My answer is that I see a missing ingredient in astrophysics discussions of dark matter. I believe that, on the time scale of experiments that will discover dark matter particles in the cosmos, we particle physicists will supply it. We would like astrophysicists to be aware of what is coming, and perhaps even to help us get the elements of data that they need.

Bertone, Hooper, and Silk:

'This is a typical example of the strong interplay between particle physics, theoretical physics, cosmology and astrophysics. From one side, theoretical particle physics stimulates the formulation of new theories predicting new particles that turn out to be excellent dark matter candidates. On the other side, cosmological and astrophysical observations constrain the properties of such particles and consequently the parameters of the new theories.'

What is missing?

In the study of light from stars and interstellar gas, and in primordial and stellar nucleosynthesis, astrophysicists make direct use of spectra and cross sections measured in the laboratory.

Can we envision a similar interplay between astrophysical and microscopic measurements for the understanding of dark matter ?

On the scale of the galaxy and of distant galaxies and clusters, the existence of dark matter is well established.

However, on scales smaller than the galaxy, there are still many questions:

How did the galaxy assemble itself from the smaller elements predicted by theories of Cold Dark Matter ?

Is dark matter in the galaxy smooth or clumpy? Are there local peaks along caustics ?

How much dark matter resides in the neighborhood of the galactic center ?

How much dark matter is contained in dwarf companions of the Milky Way? Are there companions that are totally dark?

To answer such questions, we rely upon formulae such as

$$\frac{d\Phi_\gamma}{d\log E_\gamma} = \int dr d\Omega \frac{1}{4\pi} n^2(\vec{r}) \; \frac{d(\sigma v)}{d\log E_\gamma}$$

observed gamma-ray flux — uncertain astrophysics — uncertain particle physics

The problem of determining both uncertain pieces is ill-posed.
The experiments are very challenging.

In this situation, there is a temptation to treat every anomaly as a discovery, giving the largest possible values to the uncertain factors.

Can particle physics experiments help?

In the past twenty years, we have failed to discover dark matter candidates, or any new physics beyond the Standard Model.

However, this is likely to change with the beginning of the CERN Large Hadron Collider experiments in 2007.

So I would like to look ahead to what we should learn from these experiments, and what it will take to provide a firm microscopic basis for astrophysical dark matter experiments.

To address this issue, I would like to discuss:

Why the WIMP model of dark matter deserves special attention

Why the LHC should see huge new physics signals

Why--despite this--the LHC is insufficient,
and what we need to complement it.

How we could make microscopic predictions of the
cosmic dark matter density

How such predictions impact the astrophysical detection
of dark matter

There are many models for dark matter, corresponding to particles that range in mass from

$$10^{-4}\ \mathrm{eV}\ \text{(axions)} \quad \text{to} \quad 10^{-4}\ M_{\odot}\ \text{(black holes)}$$

I shouldn't fail to mention the WIMPzilla $(10^{18}\ \mathrm{GeV})$.

The only constraints are that the particle should be "cold" and should have relatively weak interactions.

It is controversial whether dark matter particles interact astrophysically only through gravity, or whether they need to have interaction cross sections in the $\mu\mathrm{barn}$ range to explain the distribution of dark matter in the galaxy.

Most dark matter candidates in the literature fit into a smaller category. They are particles that are neutral and stable but come to thermal equilibrium in the early universe. This constraint leads to a specific value of σ_{NN} to produce the observed dark matter density. That, in turn, fixes the mass scale of the particle and its detection cross sections to interesting values.

I will refer to particles in this class as WIMPs. From here on, I will assume that the dark matter particle is a WIMP.

WIMPs are the only dark matter candidates that appear naturally, with the correct mass scale, in particle physics models.

("Don't trust an experiment until it is validated by theory.")

If dark matter is a WIMP, we will have experimental constraints that could prove its identity. Otherwise, this will be very difficult.

("God is subtle but not malicious.")

Basic formulae for WIMP dark matter

(Turner-Scherrer approximation)

freeze-out: $\xi = T_f / m_N \sim 1/25$

then $$\Omega h^2 = \frac{s_0}{\rho_c/h^2} \left(\frac{45}{\pi g_*} \right)^{1/2} \frac{1}{m_{\rm Pl}} \frac{1}{\langle \sigma v \rangle}$$

putting in numbers:
$$\Omega h^2 = 0.1 \rightarrow \langle \sigma v \rangle = 1 \text{ pb}$$

setting $\langle \sigma v \rangle = \dfrac{\pi \alpha^2}{8 m^2}$ we find m = 100 GeV.

It is amazing that this argument selects the mass scale of the weak interactions !

Particle physicists "know" that there is new physics at the 100 GeV mass scale. With small modifications, any model of this new physics also gives a model of WIMP dark matter.

The most famous examples is supersymmetry

1983 - Weinberg; Goldberg; Ellis, Nanopoulos, Tamvakis

$$R = (-1)^{3B-L+2S}$$

should be conserved to avoid rapid proton decay. This discrete symmetry makes the lightest supersymmetric particle stable.

There are many possibilities for the WIMP: $\widetilde{\gamma},\ \widetilde{h}^0,\ \widetilde{\nu}_R, \ldots$

Models with new space dimensions of size $\hbar/200\ \mathrm{GeV}$ lead to WIMP dark matter candidates in many different ways:

"Universal Extra Dimensions" Feng-Matchev, Servant-Tait

Add a flat extra dimension, in which all Standard Model particles move. Parity (P_5) can be a symmetry that makes the lightest Kaluza-Klein particle stable: $\gamma_1,\ \nu_{R1},\ \cdots$

"Warped Extra Dimensions" Agashe-Servant

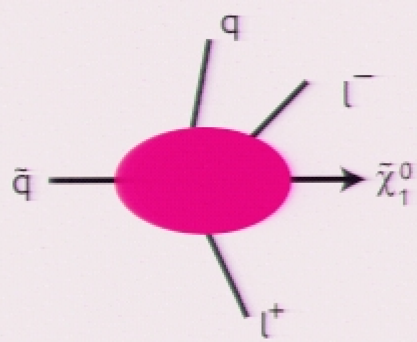
Add an extra dimension of constant curvature, with1/TeV size one one side, Planck sizes on the other. In versions of this theory with grand unification, states that mediate proton decay can be light. Then one must add a Z_2 parity (R) or a Z_3 parity ($\rightarrow \nu_B$).

"Large Extra Dimensions" Cebranos-Dobado-Maroto

Add a large extra dimension, with Standard Model particles on a brane. Then "branons" can be WIMP dark matter.

In most of these models, the conserved quantum number is carried by a new sector of particles that includes states that couple to QCD.

Such particles decay to the dark matter particle,

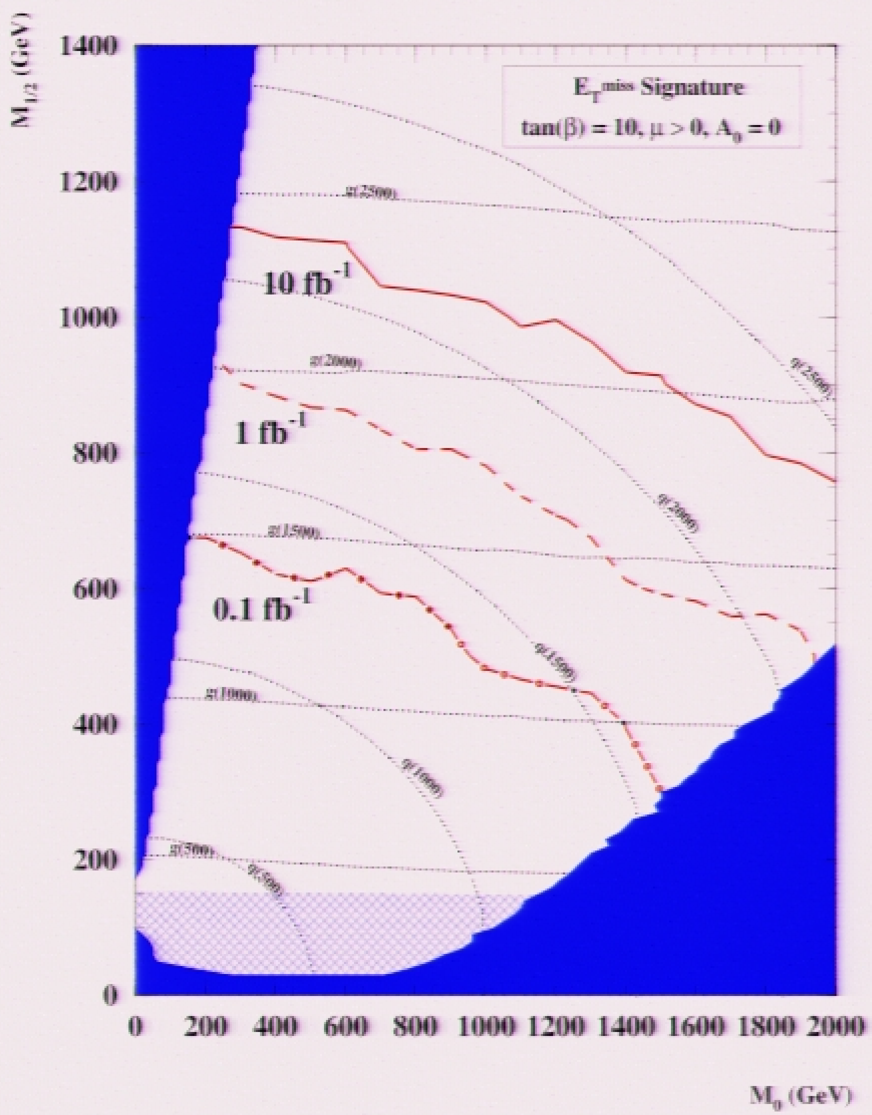


producing events with jets + missing momentum.

The cross section for producing heavy colored particles depends almost only on the mass, and it is very large for masses below 1 TeV:

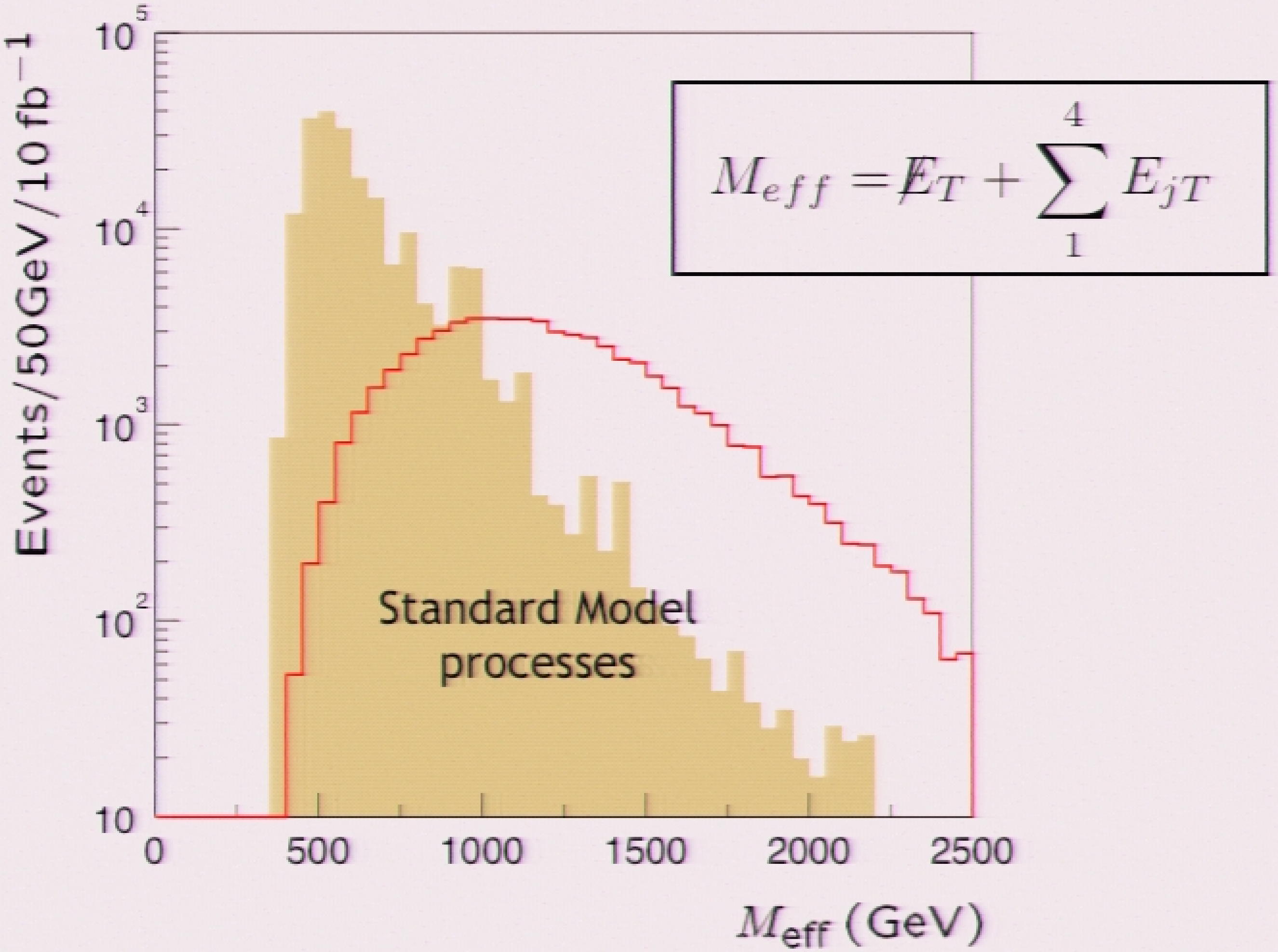
$$\sigma(gg \to \widetilde{q q^*}) \sim 100 \text{ pb}$$

Here are some examples from supersymmetry studies at the LHC. For other models, follow the contours of primary particle mass:



E_T^{miss} Signature
$\tan(\beta) = 10, \mu > 0, A_0 = 0$
$M_{1/2}$ (GeV)
M_0 (GeV)
10 fb^{-1}
1 fb^{-1}
0.1 fb^{-1}

ATLAS


$M_{eff} = \not{E}_T + \sum_{1}^{4} E_{jT}$
Standard Model
processes
Events/50GeV/10 fb^{-1}
10^5
10^4
10^3
10^2
10
0
500
1000
1500
2000
2500
M_{eff} (GeV)

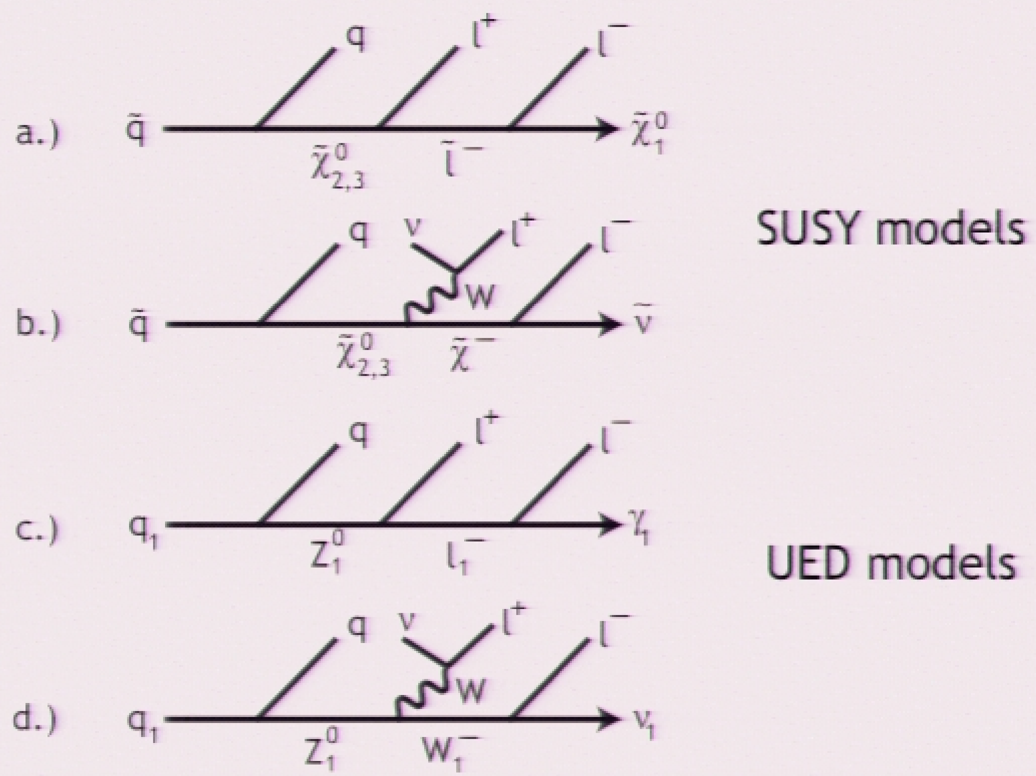
If this logic is correct, the LHC must discover the new physics signal of jets + missing energy very early in its program. Kinematic analysis of these events can also give the mass of the missing neutral particle to about 10% accuracy.

To obtain further information that would be relevant to dark matter searches, we should try to obtain the cross sections of this particle.

But, it is not so easy to learn the cross sections of an unobservable particle.

One strategy is to identify it qualitatively, then built the phenomenology of its reactions and couplings.

The discovery of missing momentum events at the LHC does not necessarily indicate for supersymmetry or any other particular WIMP dark matter model. Rather, we have to look for characteristic properties of a particular model. These will be hard to find at the LHC:

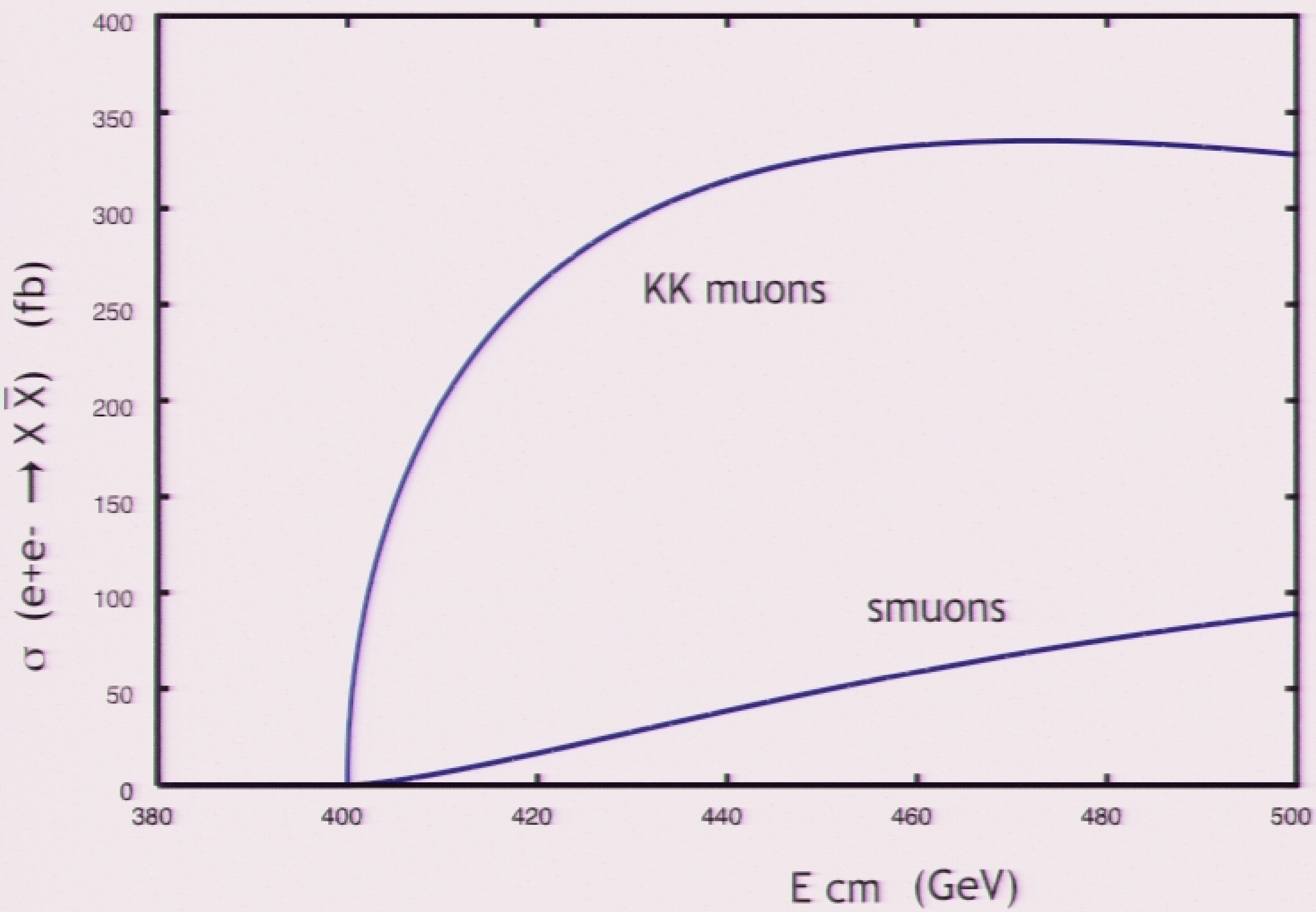


How do we qualitatively identify the WIMP dark matter model?

The key is to measure the spin and EW quantum numbers of particles that carry the conserved quantum number of the WIMP.

Often, it is sufficient to measure the properties of the lightest charged particle in this sector.

That is very straightforward at a Linear e+e- Collider of sufficiently high energy.


400
350
300
250
200
150
100
50
0
380
400
420
440
460
480
500
σ (e+e- → X X̄) (fb)
KK muons
smuons
E cm (GeV)

How do we qualitatively identify the WIMP dark matter model?

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Often, it is sufficient to measure the properties of the lightest charged particle in this sector.

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Once we have qualitatively identified the dark matter particle, the next step is to see whether we can quantitatively account for the relic density.

This is nontrivial. The relic density depends on the annihilation cross section σ_{NN}, but that is typically very model-dependent.

Fortunately, σ_{NN} depends mainly on the masses and couplings of the lightest states of the new sector.

The determination of these quantitites is a particular strength of the Linear Collider.

Should a microscopic calculation of Ωh^2 agree with the cosmic value determined from the CMB ?

The issues are similar to those in primordial nucleosynthesis. Agreement constrains, disagreement argues for entropy production or late-decaying particles.

Alternatively, the WIMP could decay to a 'super-WIMP' with extremely weak interactions, giving

$$\Omega h^2 = \Omega_W h^2 \cdot \frac{m_{SW}}{m_W}$$

Feng, Takayama, Rajaraman, and Smith studied the case of supersymmetry. The option

$$\widetilde{\chi}^0 \rightarrow \gamma + \widetilde{G}$$

is excluded by its late energy release. The option

$$\widetilde{\ell} \rightarrow \ell + \widetilde{G}$$

is acceptable, with roughly $\tau_{\widetilde{\ell}}$ ~ 1 yr.

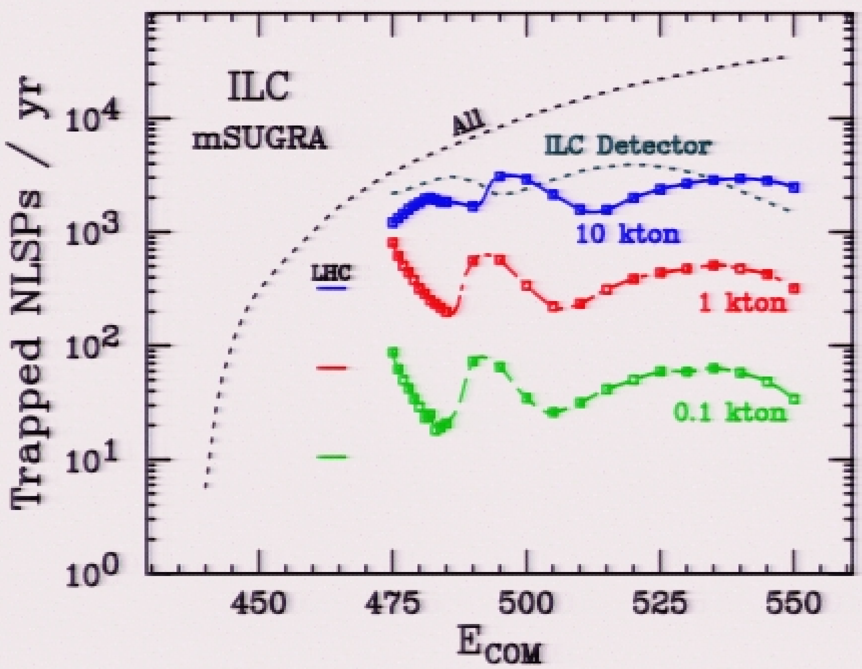
In this scenario, all astrophysical searches for dark matter fail.

However, it is possible to observe $\widetilde{\ell}$ at colliders as a stable massive charged particle.

A Linear Collider operating near threshold can collect $\tilde{\ell}$'s in a water tank and measure $\tau_{\tilde{\ell}}$ and $m(\tilde{\ell}) - m(\tilde{G})$

Spontaneously broken supersymmetry makes a precise prediction, which can be checked:

$$\tau = \frac{6}{G_N} \frac{m_{\tilde{G}}^2}{m_{\tilde{\ell}}^5} \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\ell}}^2}\right)^{-4}$$



Feng and Smith

c.f. Hamaguchi, Kuno, Nakaya, and Nojiri

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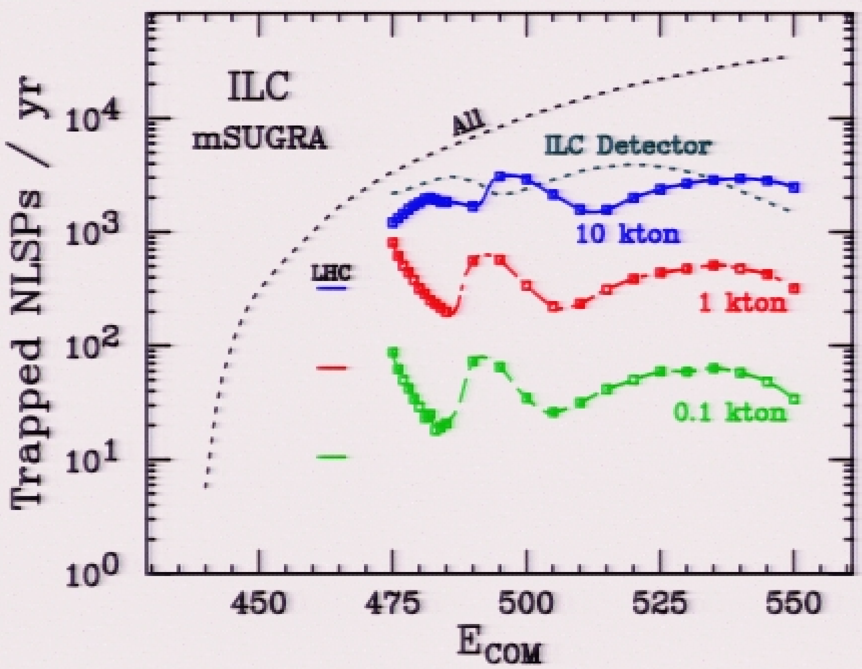

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Now return the focus to more conventional supersymmetry scenarios, with neutralino dark matter. For these well-understood models, can we collect experimental data that can predict the dark matter relic density ?

The study of this question brings us into the intricacies of supersymmetry models.

Begin from the simplest situation in which the neutralino is the supersymmetric partner of the U(1) gauge boson of the Standard Model (the 'bino').

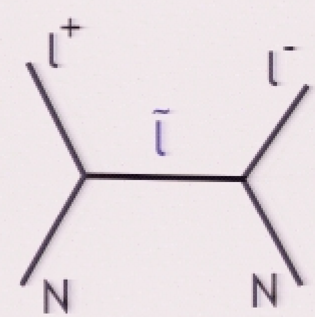
In this case, the dominant annihilation channels are:

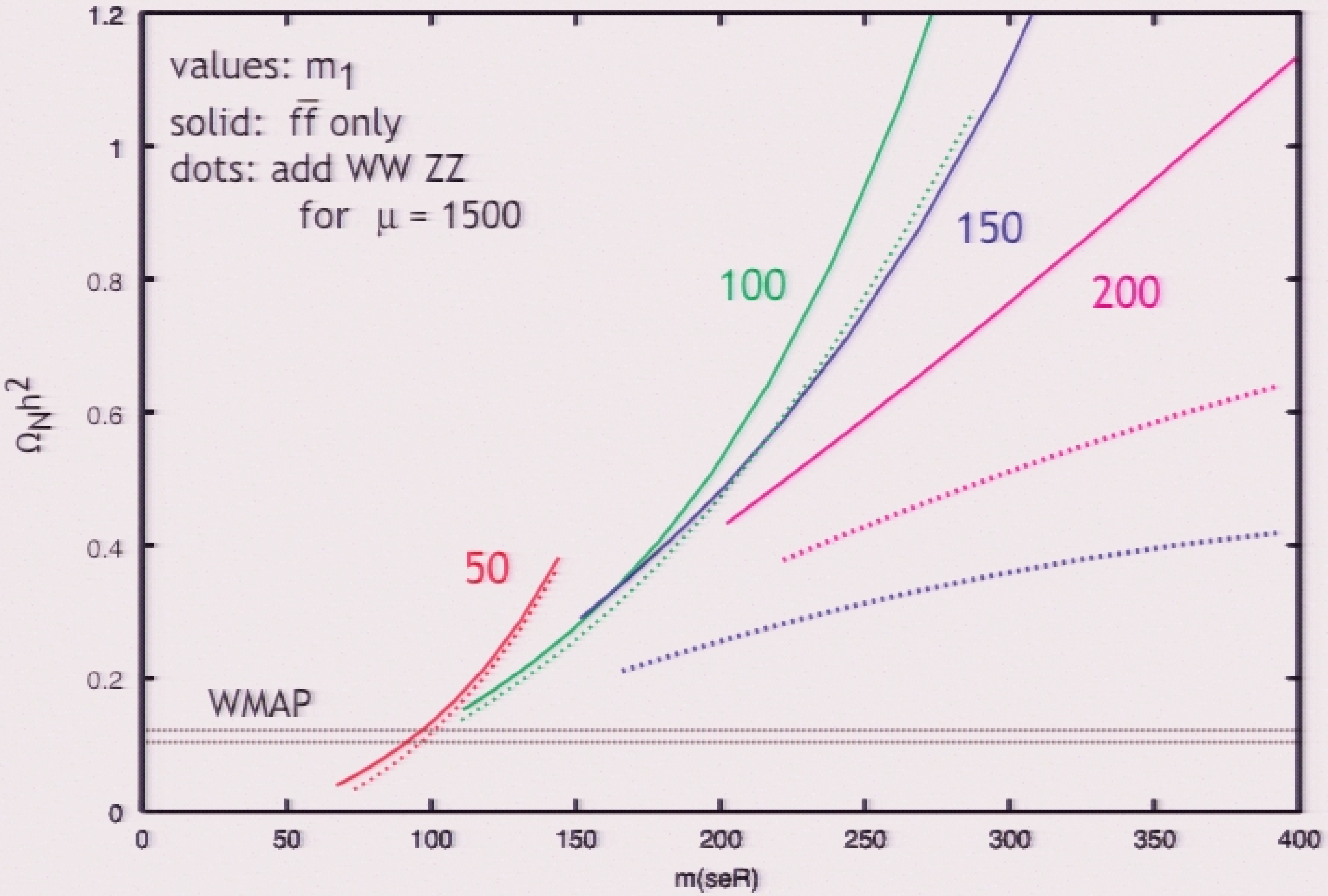
$$N\,N \to \ell^+\ell^-,\ q\bar{q}$$

Goldberg: annihilation in the S-wave is helicity suppressed, so the leading term of annihilation is in the P-wave

but $\xi = \frac{T_f}{m_N} \sim \frac{1}{25}$

so 8 x larger cross sections are needed





W-Y Chuang, E.-H.Yong, MEP

In the 1980's, $\Omega_N \sim 1$

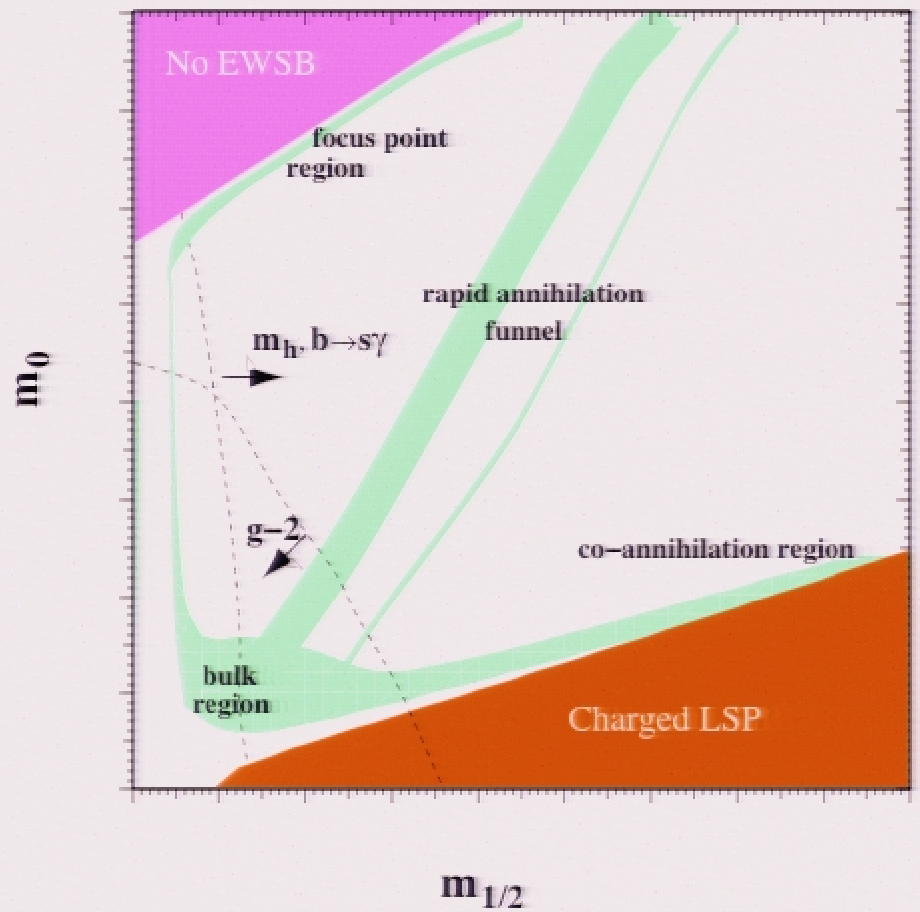
it worked !

Today, $m_{\tilde{\ell}} > 100 \text{ GeV} \quad \Omega_N \sim 0.2$

it does not work any more, except for a range of slepton masses very close to the current limit.

To obtain the density required from the CMB, we must go to this region, or to other special regions of the parameter space.

Various possibilities appear in the parameter space of 'minimal supergravity'; we choose some points in this space as examples:



The physics of the WIMP annihilation cross section is different in each region:

'bulk region'

annihilation through slepton exchange

σ_{NN} depends on the light slepton masses and couplings

'focus point region'

annihilation to WW, ZZ

σ_{NN} depends on $m_1, m_2, \mu, \tan\beta$

'coannihilation region'

annihilation of $\widetilde{\tau}$ is actually dominant

σ_{NN} depends on $m(\widetilde{\chi}_1^0), m(\widetilde{\tau}), \theta_\tau$

'A funnel region'

annihilation through A resonance

σ_{NN} depends on $m(\widetilde{\chi}_1^0), m(A), \Gamma(A), \tan\beta$

Our study group (Feng, Trodden, et al.) selected four representative points for more detailed study. I will now present some (preliminary) results.

Point	Region	m_0	$m_{1/2}$	$\tan\beta$	A_0	m_χ	m_{ch}
LCC1	bulk	100	250	10	-100	96.1	133.2
LCC2	focus pt.	3280	300	10	0	107.7	159.4
LCC3	coann.	210	360	40	0	142.5	152.0
LCC4	funnel	380	420	53	0	169	195

LCC2 gives a nice example:

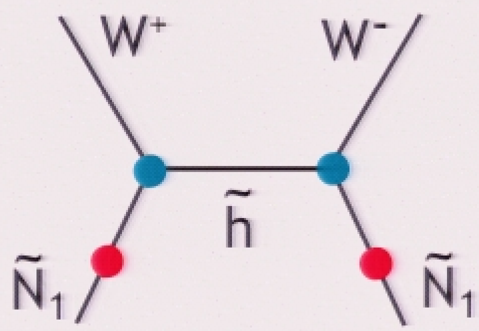
Squarks and sleptons are heavy, so the dynamics depends on the four supersymmetry parameters

$$m_1,\ m_2,\ \mu,\ \tan\beta$$

NN annihilation is dominated by

$$NN \to W^+W^-\ ,\ Z^0Z^0$$

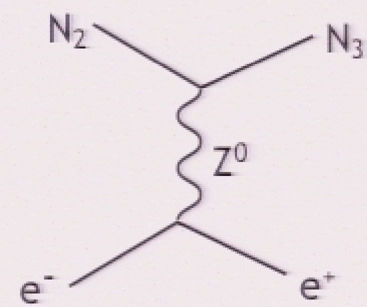
which in turn depends on the mixing of gauge and Higgs supersymmetry partners:



To measure this mixing, determine the mass spectrum and the polarized cross sections.

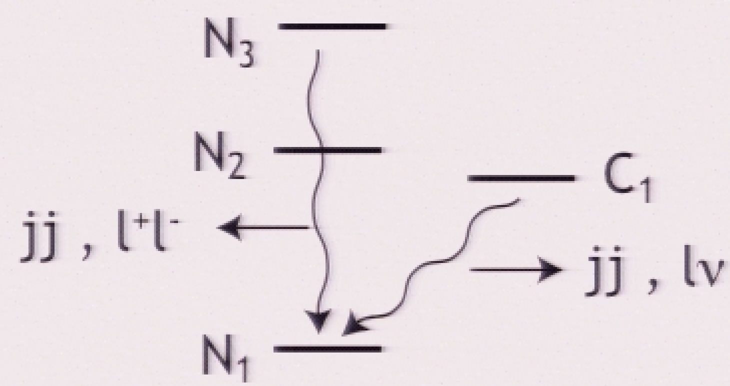
A particularly important reaction at this point is

$$e^+e^- \to N_2 N_3$$



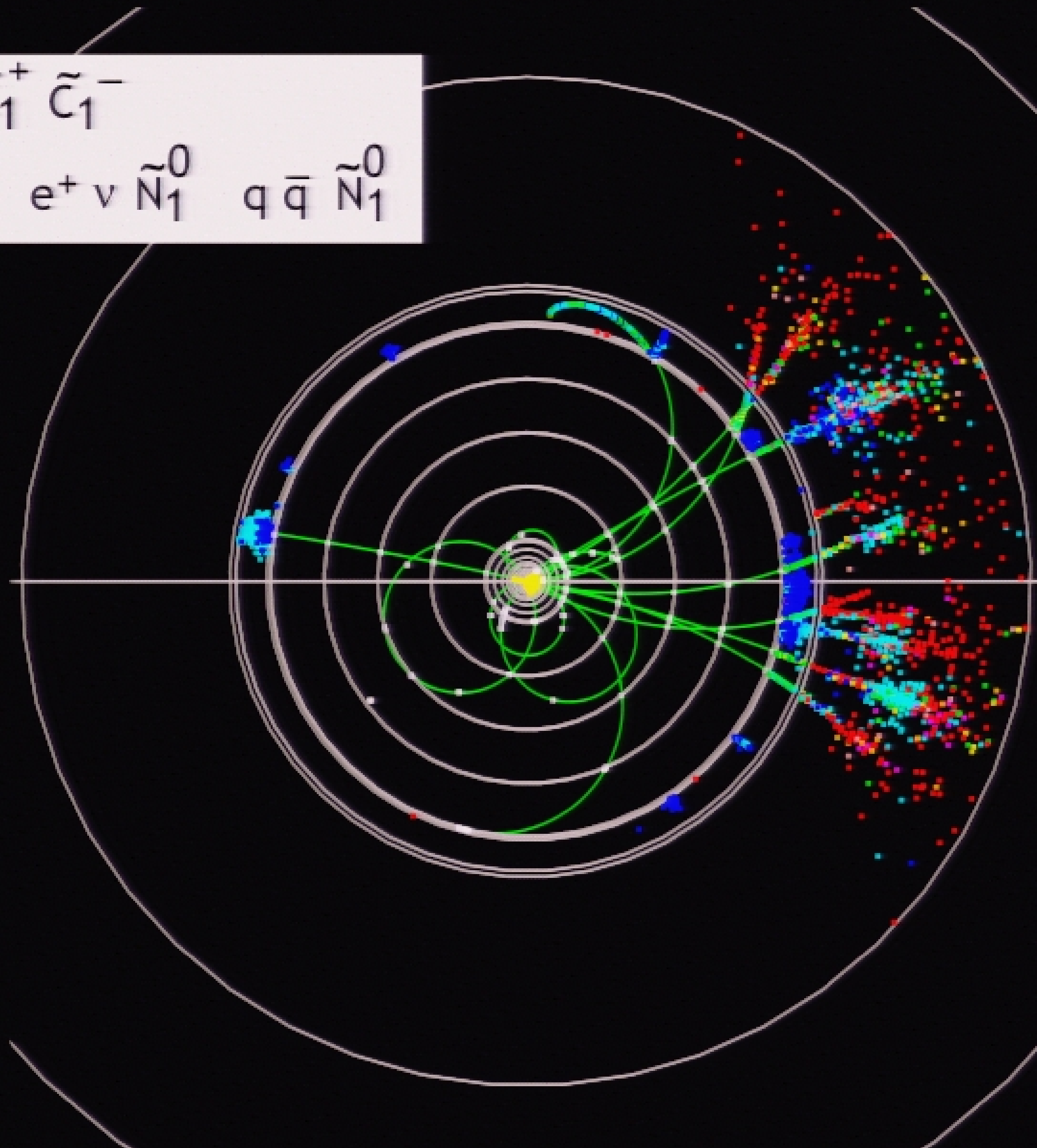
The cross section from e^-_R depends specifically on $\widetilde{w}^0 - \widetilde{h}^0$ mixing.

Observe the final particles through the transitions to the lightest neutralino



$$e^+e^- \rightarrow \tilde{C}_1^+ \, \tilde{C}_1^-$$

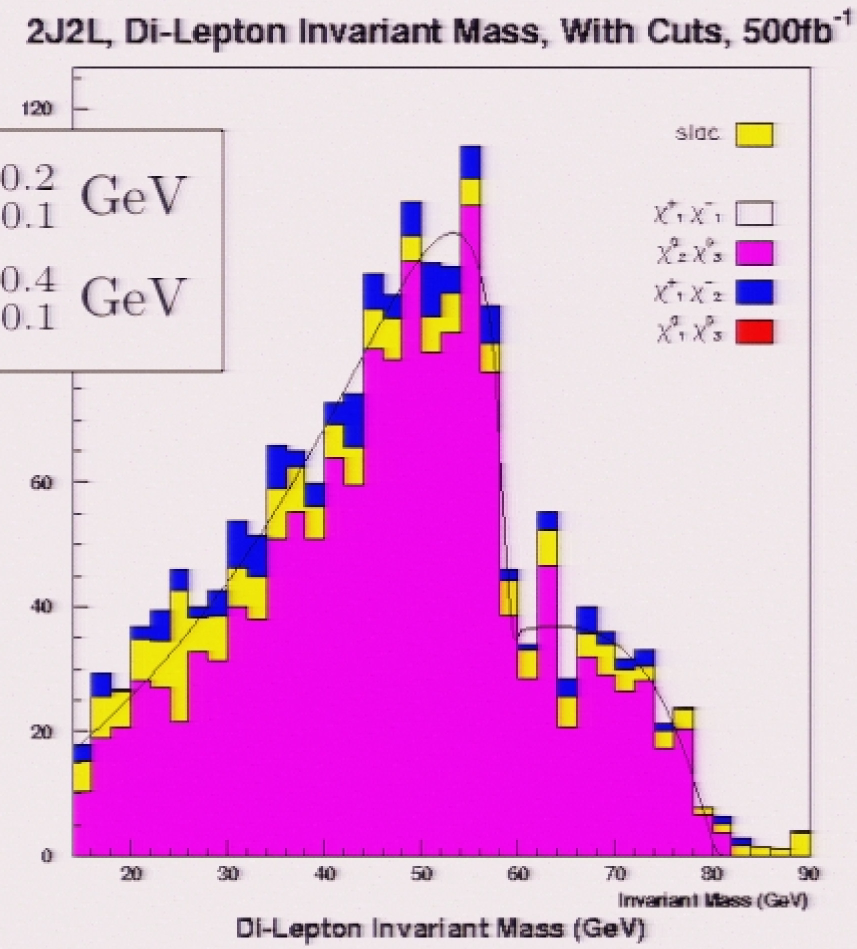
$$\rightarrow \quad e^+ \, \nu \, \tilde{N}_1^0 \quad q \, \bar{q} \, \tilde{N}_1^0$$



$$m(\widetilde{N}_2) - m(\widetilde{N}_1) = 58.7^{+0.2}_{-0.1}\ \mathrm{GeV}$$

$$m(\widetilde{N}_3) - m(\widetilde{N}_1) = 82.0^{+0.4}_{-0.1}\ \mathrm{GeV}$$

The detailed shape of the distribution is predicted by supersymmetry



J. Alexander, et al.

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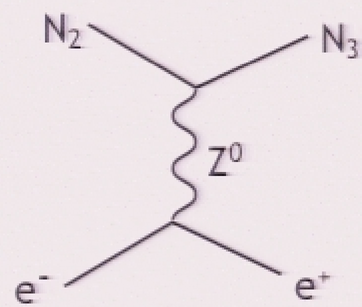

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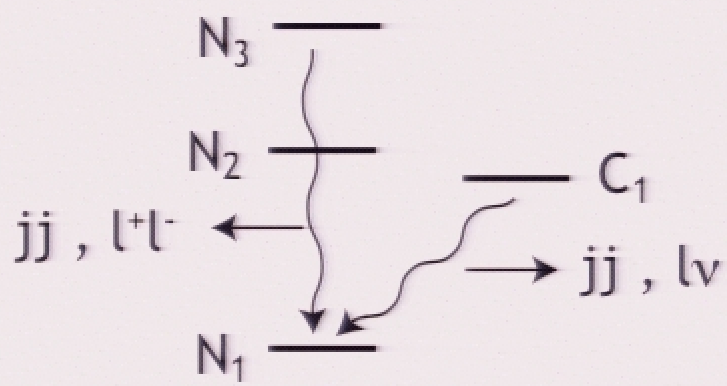

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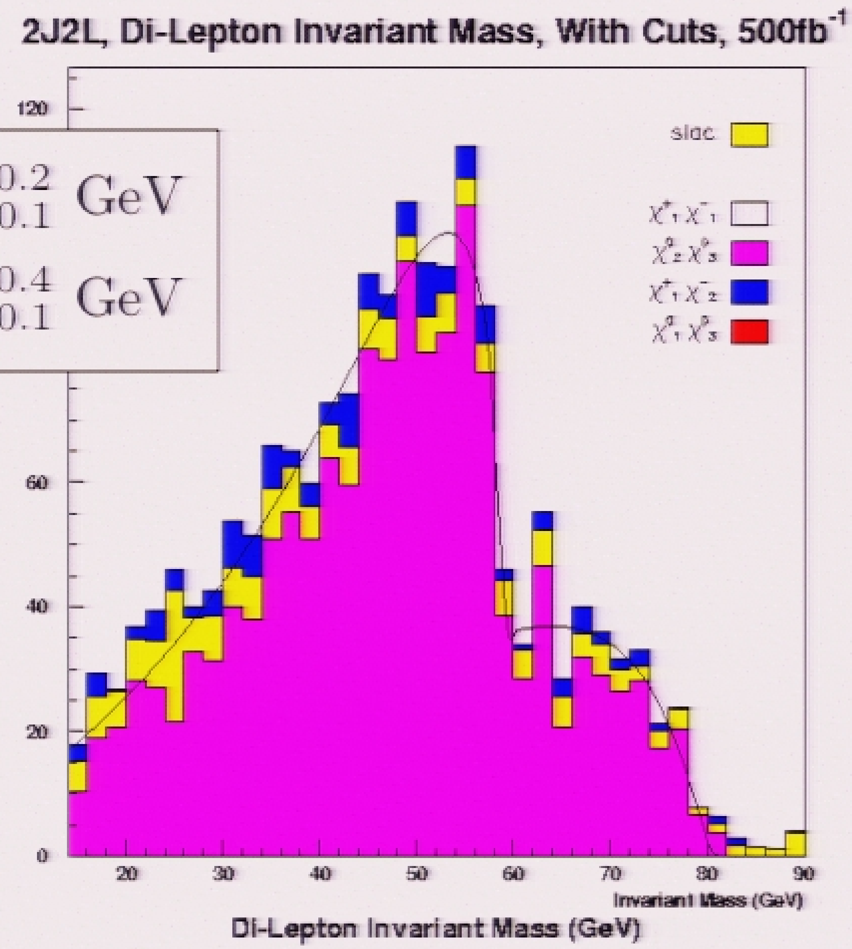

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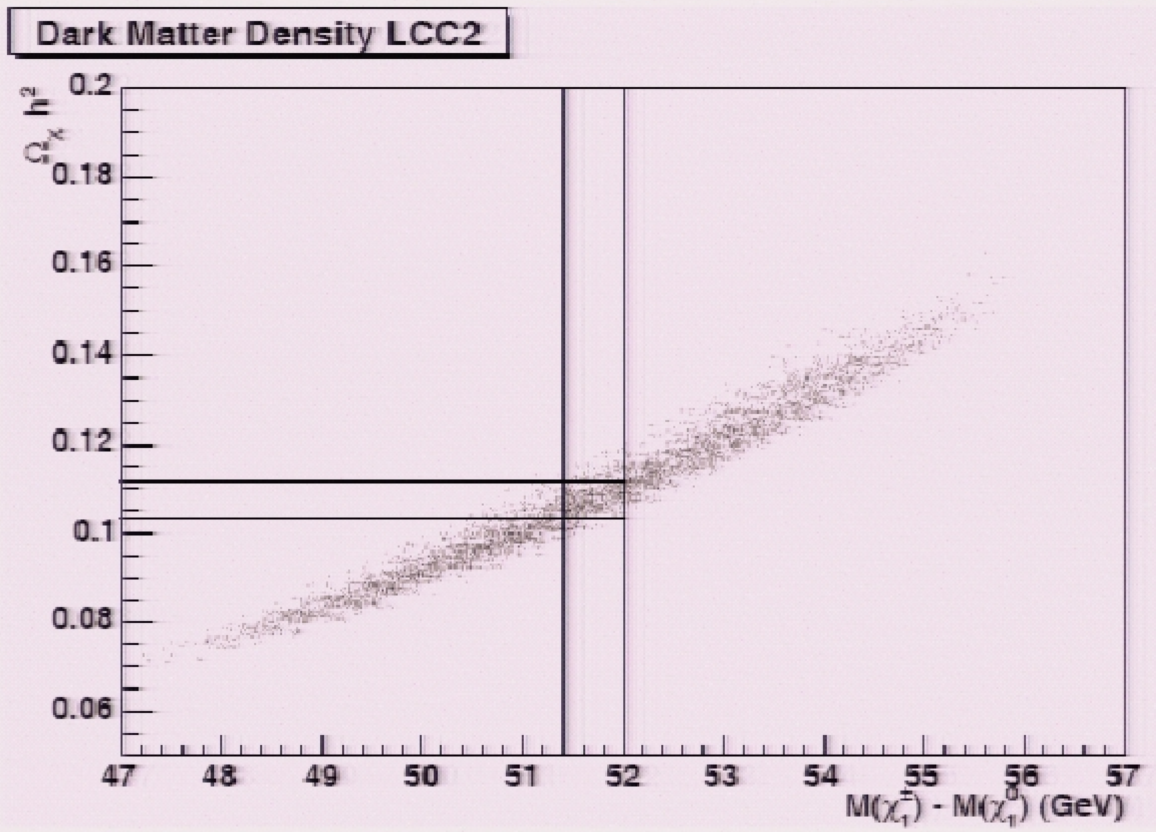
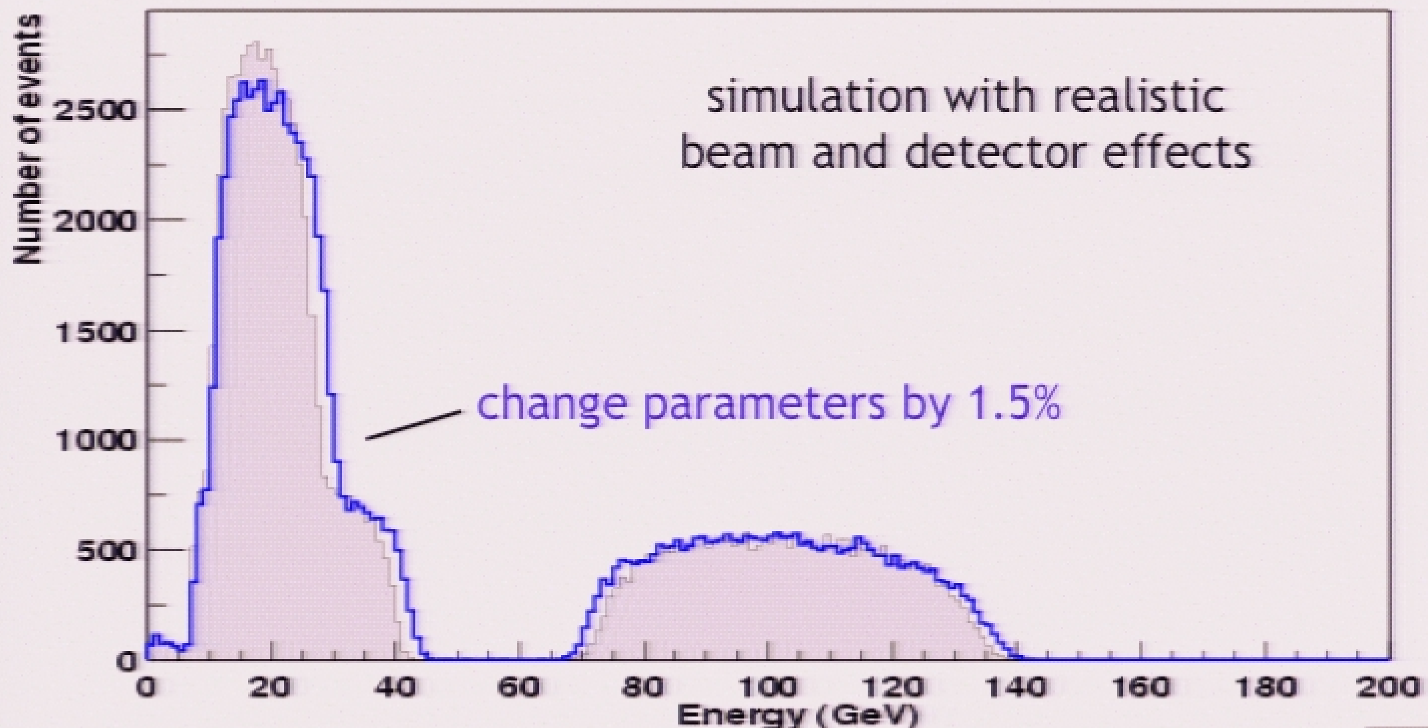
J. Alexander, et al.

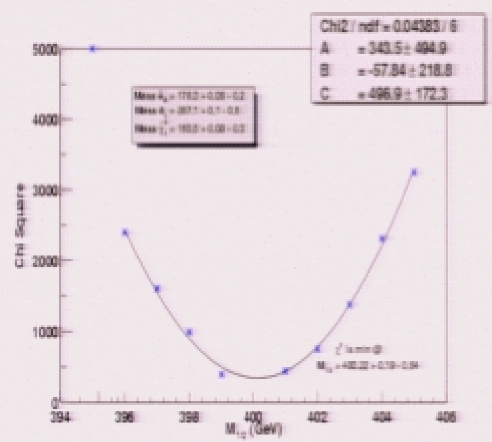
This scan of the parameter space shows that it is necessary to determination the masses to a few hundred MeV.



M. Battaglia

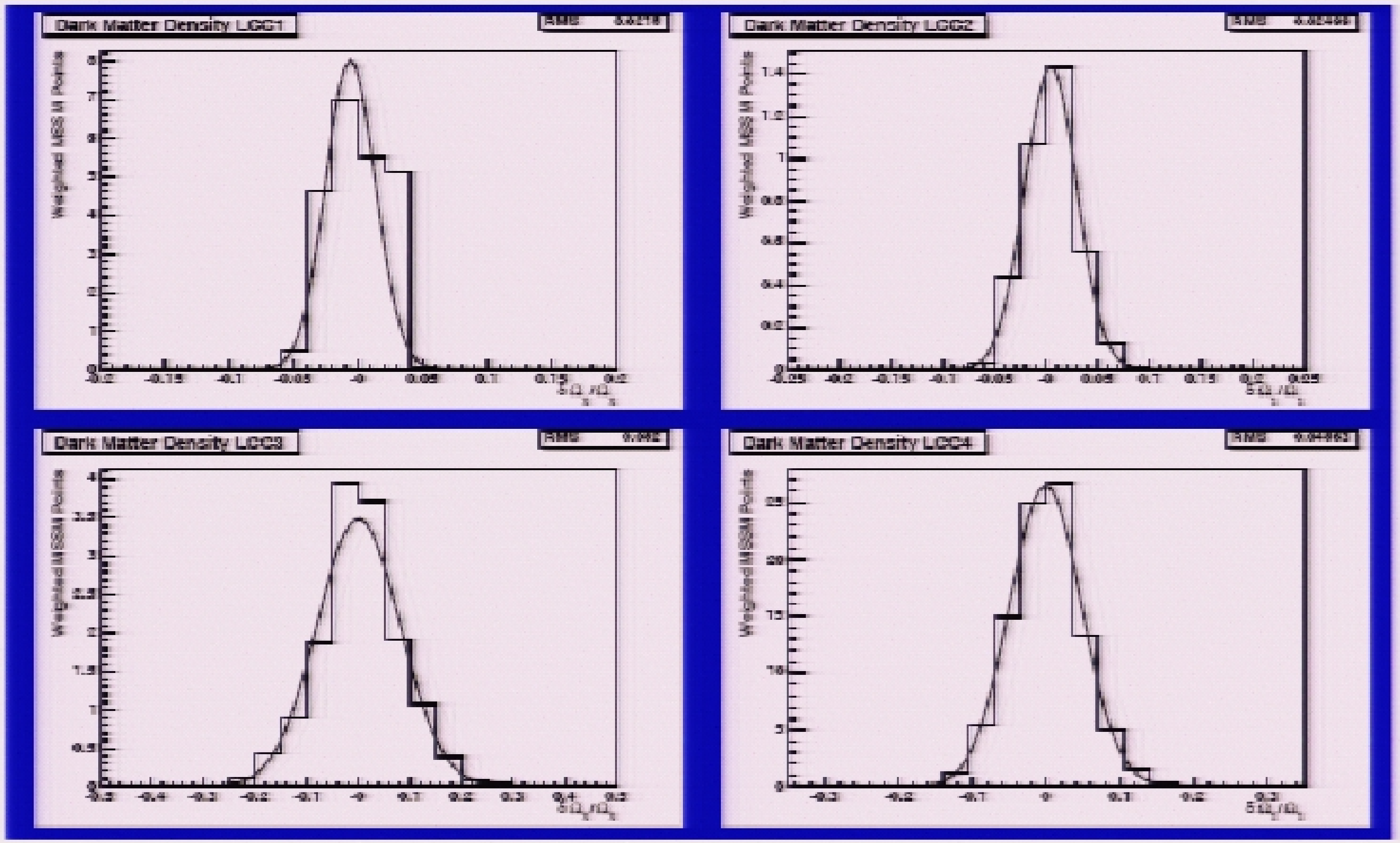


$$m(\widetilde{N}_1) = 160.5^{+0.08}_{-0.3}\ \mathrm{GeV}$$
$$m(\widetilde{e}_R) = 178.3^{+0.06}_{-0.2}\ \mathrm{GeV}$$
$$m(\widetilde{e}_L) = 287.1^{+0.1}_{-0.6}\ \mathrm{GeV}$$



U. Nauenberg et al.

Preliminary results for Ωh^2 determinations at the four points:



M.Battaglia

Finally, I will briefly discuss the implications of the detailed supersymmetry physics for astrophysical searches for dark matter.

The analysis is simplest for the gamma ray signal from dark matter annihilation, for which I wrote earlier

$$\frac{d\Phi_\gamma}{d\log E_\gamma} = \int dr d\Omega \frac{1}{4\pi} n^2(\vec{r}) \; \frac{d(\sigma v)}{d\log E_\gamma}$$

This can be written in a way that factorizes astrophysical from particle physics uncertainties

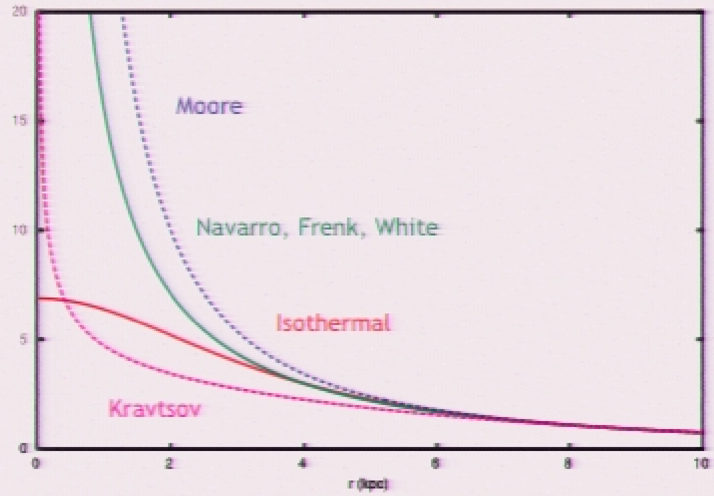
$$\frac{d\Phi_\gamma}{d\log E_\gamma d\Omega} = \rho_0^2 r_0 J(\Omega) \cdot \frac{1}{4\pi m_\chi^2} \frac{d(\sigma v)}{d\log E_\gamma}$$

with

$$\rho_0 = 0.3 \text{ GeV/cm}^3 \; , \; r_0 = 8.5 \text{ kpc} \; , \; J = \int dz/r_0 \; (\rho/\rho_0)^2$$

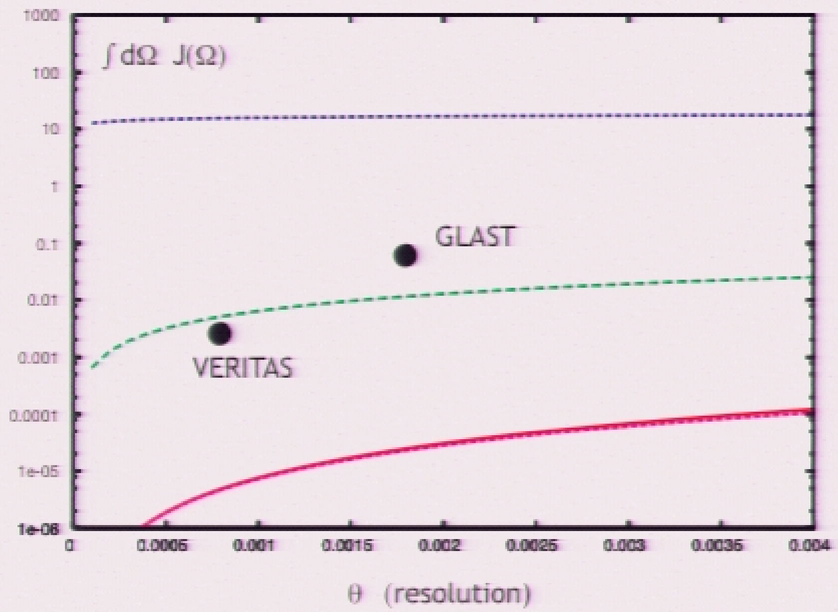
and we can estimate: $\frac{d(\sigma v)}{d\log E_\gamma} \sim 3 \cdot 1 \text{ pb} \cdot c \sim 10^{-26} \text{ cm}^3/\text{sec}$

Models of the dark matter distribution near the galactic center vary widely:



For the canonical cross section,

$$m_\chi = 100 \text{ GeV}$$

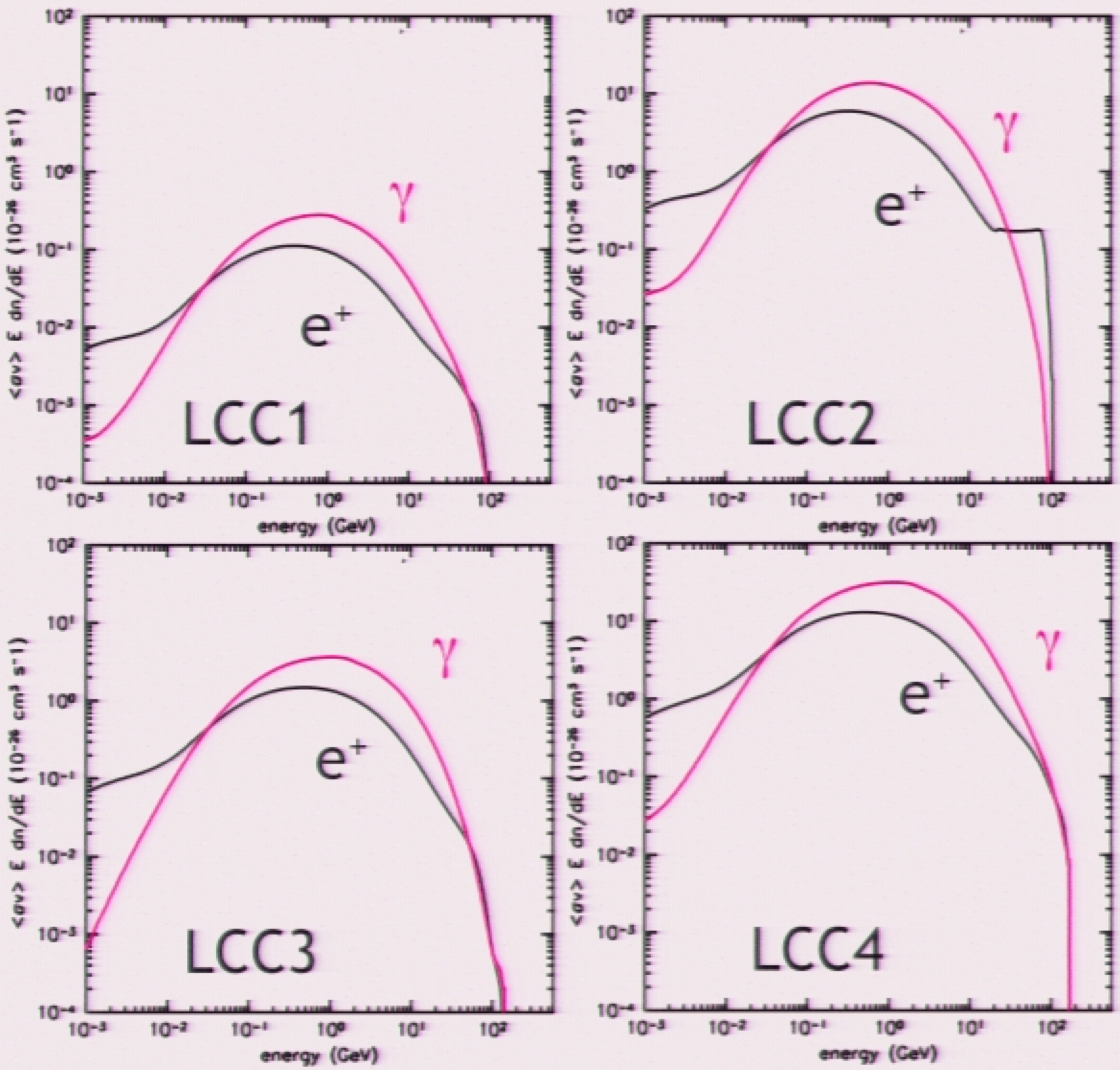


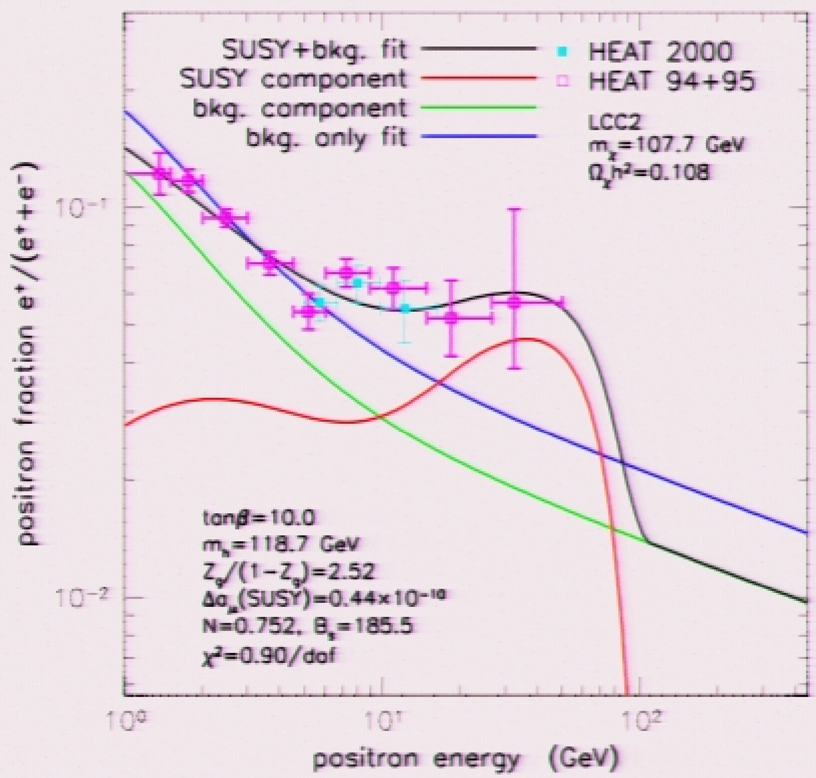
How reliable is the estimate of the cross section that I used?

That depends strongly on the physics scenario.

The relic density measures the effective annihilation cross section at the freeze-out temperature. If the annihilation is in the S-wave, this same cross section applies to the gamma spectrum. If the annihilation is P-wave or from coannihilation, it does not.

Here are the gamma and positron spectra from neutralino annihilation at the four model points (from Ted Baltz):

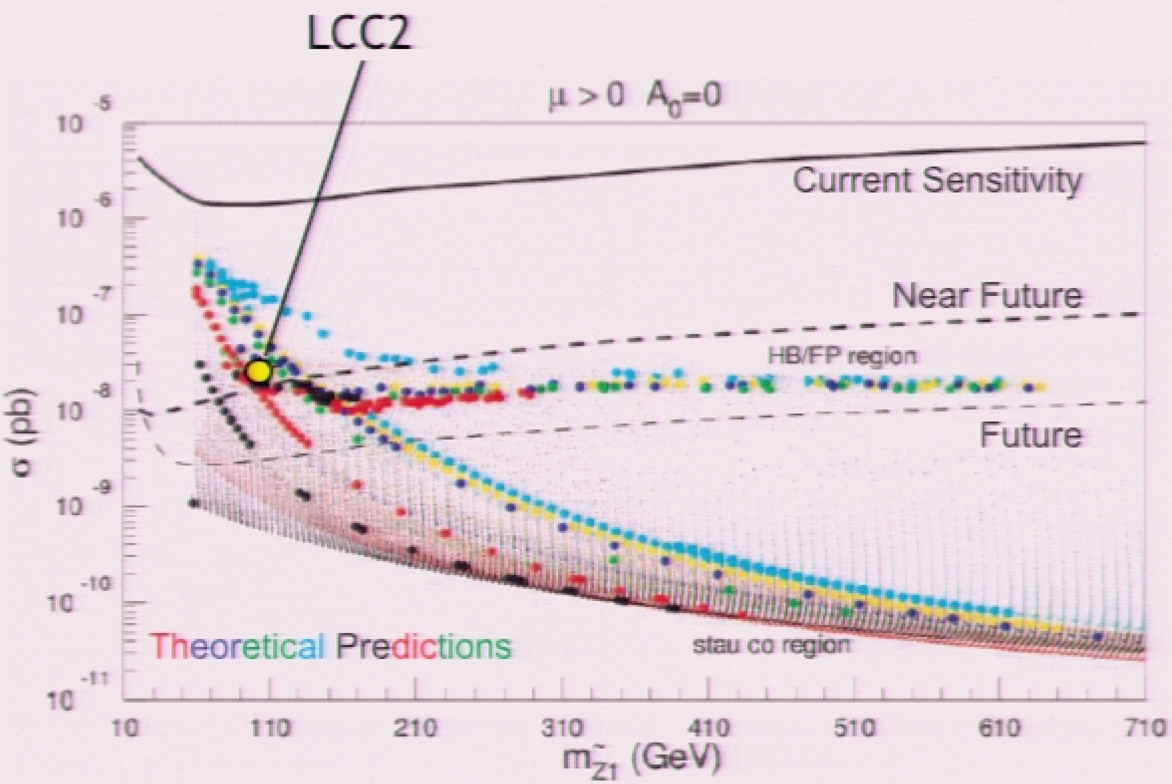

LCC1
LCC2
LCC3
LCC4
γ
e+
<σv> E dn/dE (10⁻²⁶ cm³ s⁻¹)
energy (GeV)



LCC2; assumes B = $\langle \rho^2 \rangle / \langle \rho \rangle^2$ = 185.5

In UED dark matter, a similar signal appears for B = 1.

Direct detection cross sections also depend on the scenario. The (often leading) contribution from Higgs exchange requires measurement of the neutralino mixing angles.



Baer, Balazs, Belyaev, O'Farrill (2003)

Conclusions:

There are good reasons to give special attention to WIMP models of dark matter. These models gives us the chance to resolve both the particle physics and the astrophysics questions about dark matter experimentally. As part of this program, we should:

1. Observe dark matter as missing energy at a collider.
2. Determine qualitatively which model is correct.
3. Determine whether that model quantitatively explains the relic density.
4. Determine the cross sections relevant to astrophysical dark matter observations.

The LHC is not sufficient. We also need experiments at an e+e- Linear Collider (ILC) to achieve these goals.