Beyond the Standard Model: the next 20 years

2. ILC (and Dark Matter)

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Once we have established the existence of new elementary particles, it will be important to carry out experiments to determine their couplings and quantum numbers.

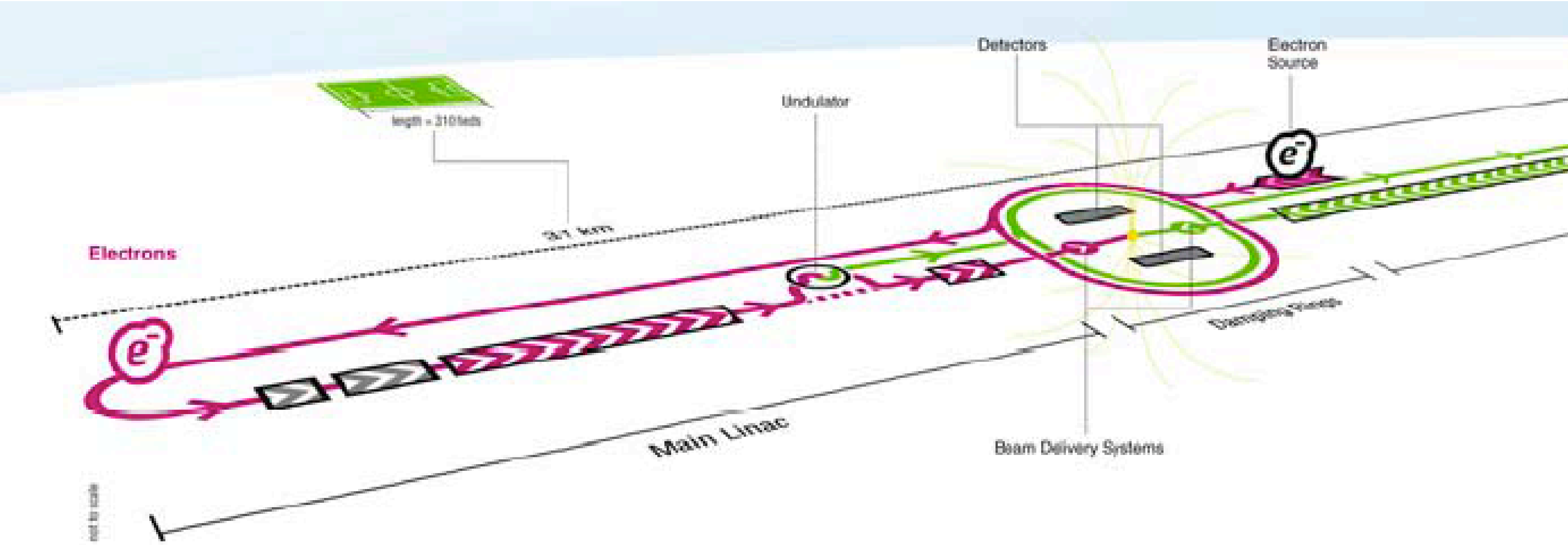
LHC will give the first view of these, through the values of production cross sections and the qualitative observation of spin correlations.

However, it will be the job of e+e- experiments at the ILC to give definitive results for these assignments.

In this lecture, I will review how that will be done, and why it is important.

This subject has a very interesting intersection with the study of cosmic dark matter. Much of the particle physics information that we need to understand dark matter is of this deeper kind that we will only learn from the ILC.

ILC



(figure taken from the 2007 update of the US DOE 20-year plan)

The most interesting results are already found by studying the lightest new particle that is pair-produced in e+e- annihilation.

Thus, to advance beyond the LHC results, the ILC does not need to match the LHC energy.   It only needs to reach the first new particle threshold.

I will first review some of the tools that the ILC gives for the determination of couplings and quantum numbers.

spin identification

chirality assignment

coupling measurents

mixing angle measurements

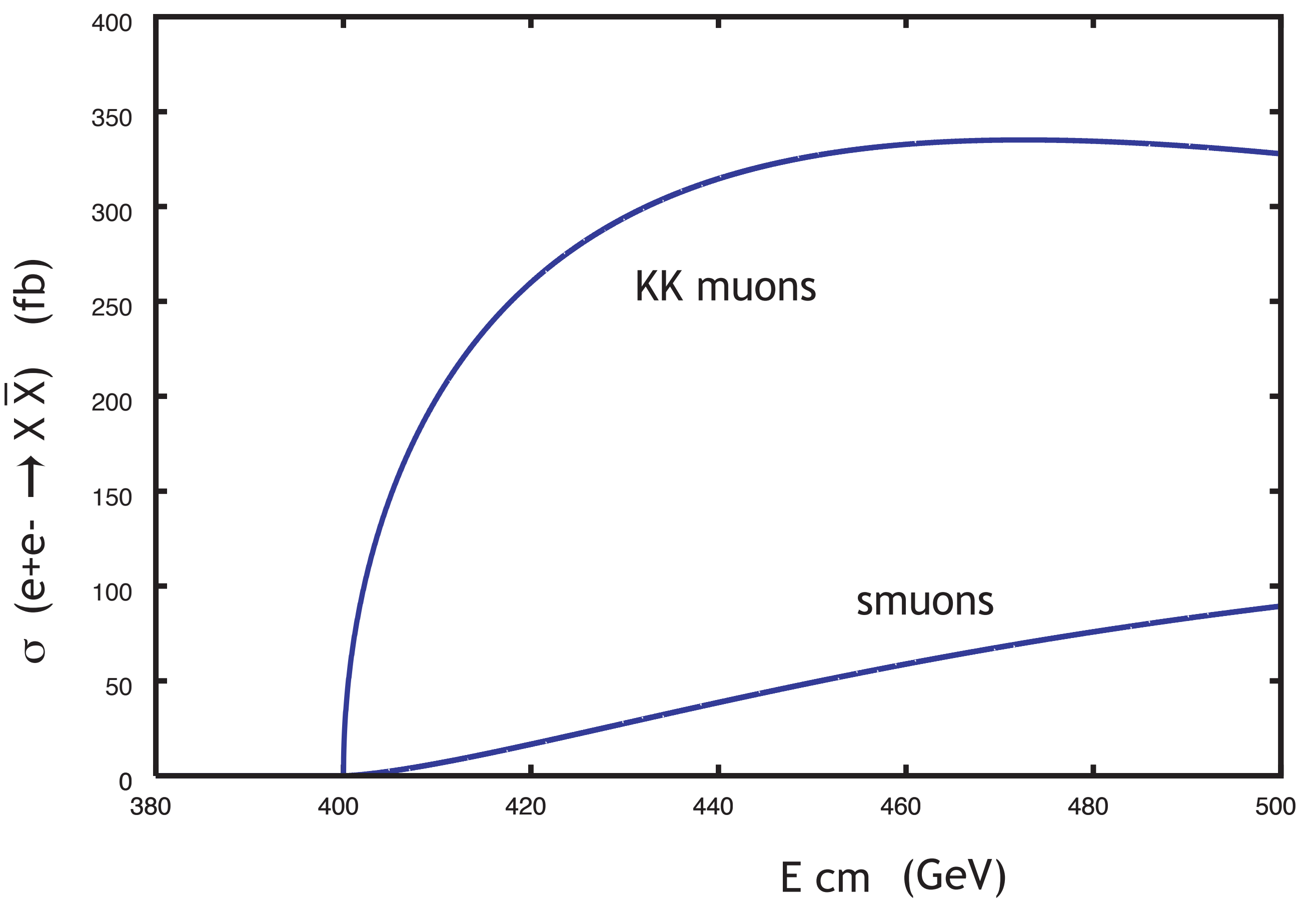
These methods apply to models of all types, but I will give most of the examples in supersymmetry models, where they are worked out most explicitly.

Pair production in e+e- follows very simple formulae, characteristic for each spin:

$$\text{spin-}0 \quad : \qquad \frac{d\sigma}{d\cos\theta} \sim \beta^3 \sin^2\theta$$

$$\text{spin-}\frac{1}{2} \quad : \qquad \frac{d\sigma}{d\cos\theta} \sim \beta(2-\beta^2+\beta^2\cos^2\theta)$$

This already gives definite qualitative identification of models.



The coefficients on the previous slide depend in a simple way on electroweak quantum numbers. These fix the quantum numbers and the chirality assignments. The dependence of the cross sections on e- beam polarization is a crucial test.

$$f_{ab} = -Q + \frac{(I_e^3 + s_w^2)(I^3 + Q s_w^2)}{c_w^2 s_w^2} \frac{s}{s - m_Z^2}$$

Above the Z, all new particles will have distinct SU(2)xU(1) assignments. Their production and decay will show order-1 parity violation.

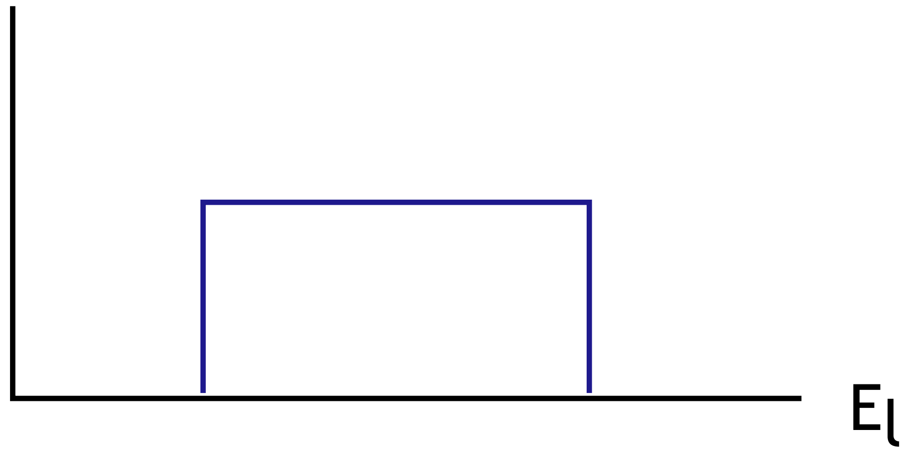
In supersymmetry, there are 2 smuons, the partners of μ_R and μ_L . For these,

$$\begin{aligned} |f_{ab}| &= 1.69 \quad e_R^- e_L^+ \to \widetilde{\mu}_R^+ \widetilde{\mu}_R^- \\ &= 0.42 \quad e_L^- e_R^+ \to \widetilde{\mu}_R^+ \widetilde{\mu}_R^- \\ &= 0.42 \quad e_R^- e_L^+ \to \widetilde{\mu}_L^+ \widetilde{\mu}_L^- \\ &= 1.98 \quad e_L^- e_R^+ \to \widetilde{\mu}_L^+ \widetilde{\mu}_L^- \end{aligned}$$

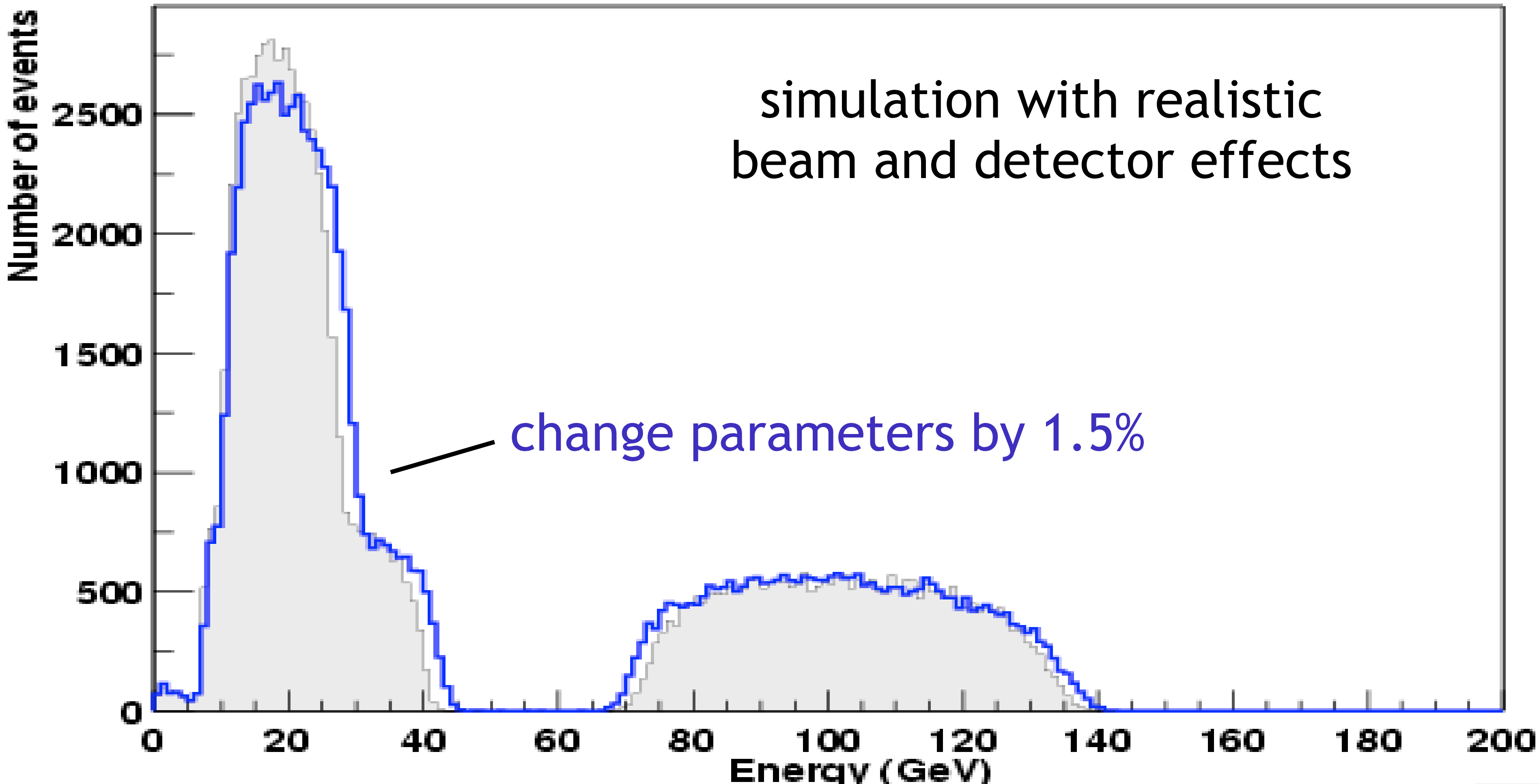
The cross section measurements set us up for high-precision mass measurements of the two states of opposite chirality

A likely slepton decay is $\widetilde{\ell}^- \to \widetilde{N}_1 \ell^-$

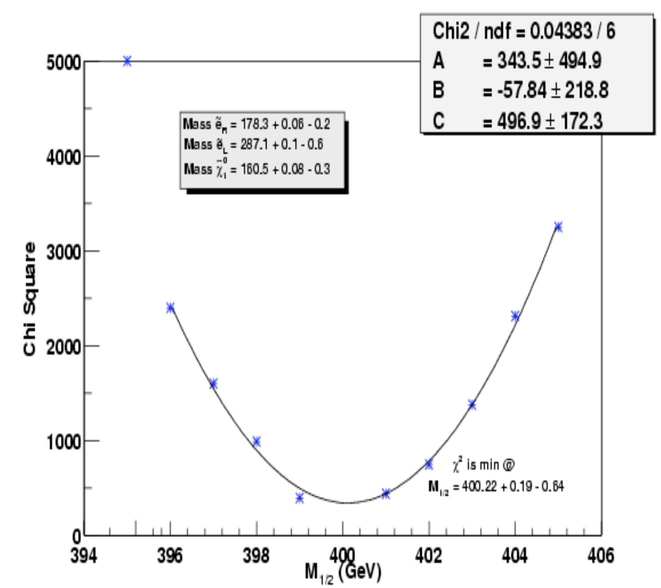
Sleptons have spin 0, so they decay isotropically. Boost, and find a flat distribution in final lepton energy between kinematically-determined endpoints.



Measure the endpoints, and solve for the unknown masses with part-per-mil accuracy.

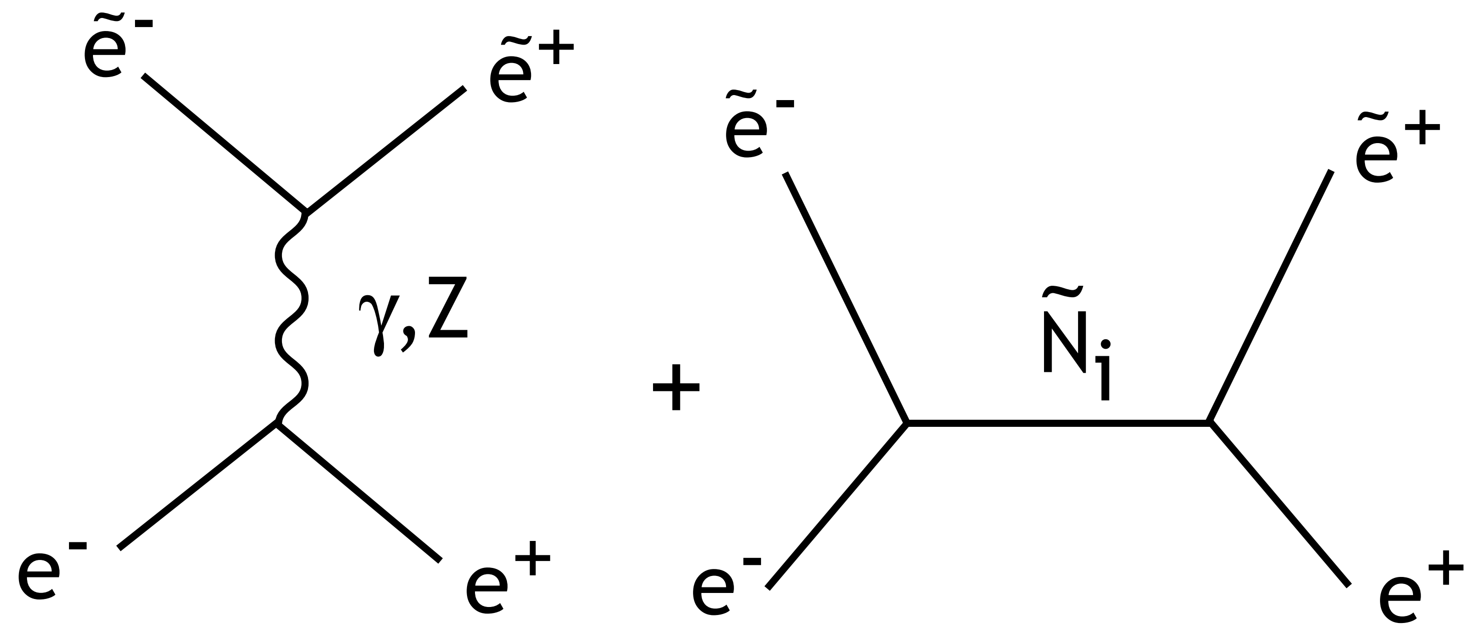


$$m(\widetilde{N}_1) = 160.5^{+0.08}_{-0.3}\ \mathrm{GeV}$$
$$m(\widetilde{e}_R) = 178.3^{+0.06}_{-0.2}\ \mathrm{GeV}$$
$$m(\widetilde{e}_L) = 287.1^{+0.1}_{-0.6}\ \mathrm{GeV}$$



U. Nauenberg et al.

Production of electron partners can involve t-channel exchanges, leading to forward-peaked distributions.   For the selectron,

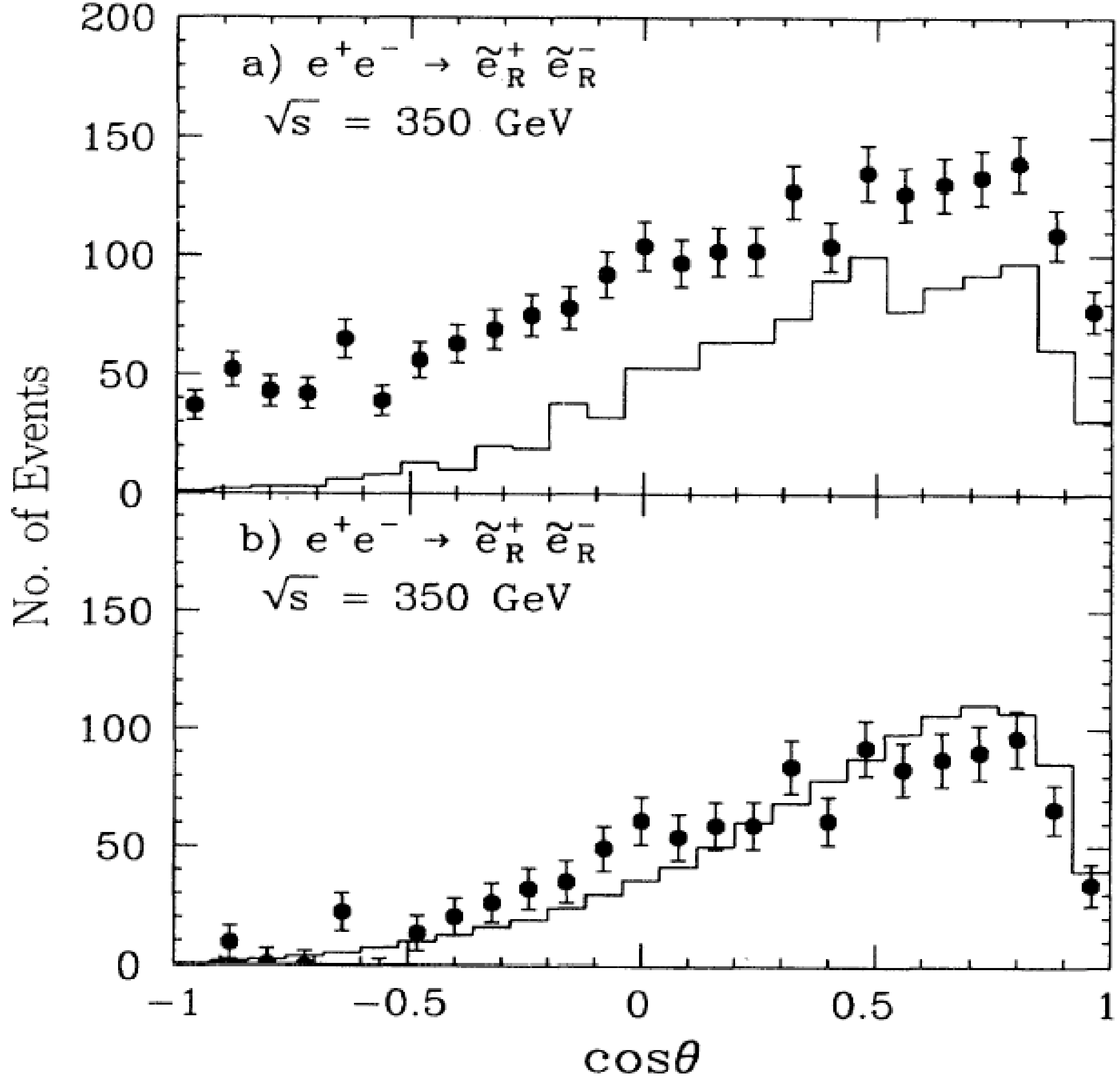


and the second diagram, with neutralino exchange, is typically dominant.

You might worry that, because the selectron decays to an invisible neutralino, the angular distribution might not be measurable.

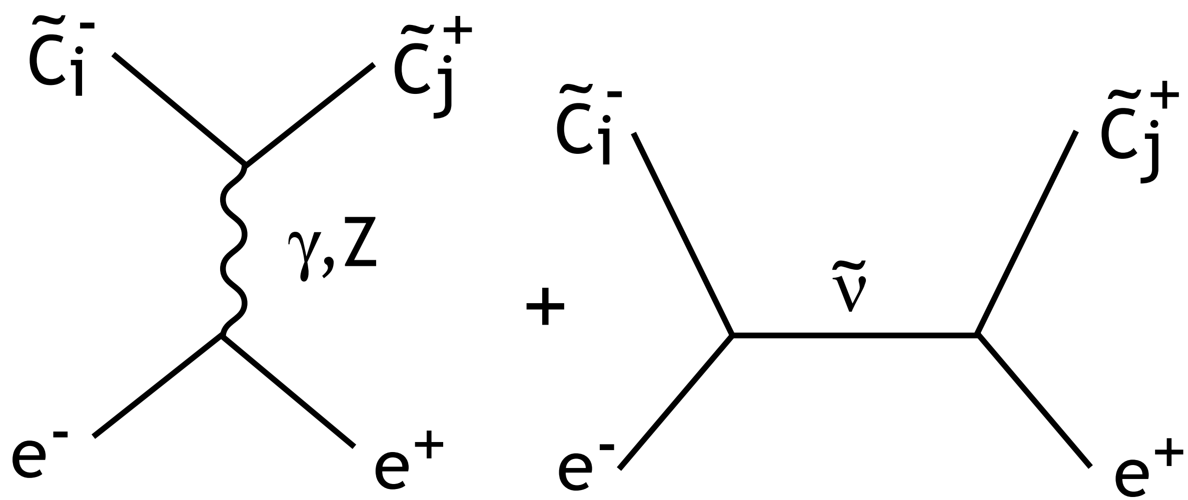
However, this was answered already in the classic work of Tsukamoto et al.

At the ILC, we will measure the residue of the lightest neutralino pole to the 1% level.



In supersymmetry, the W+ and H+ superpartners mix; the mass eigenstates are called charginos.

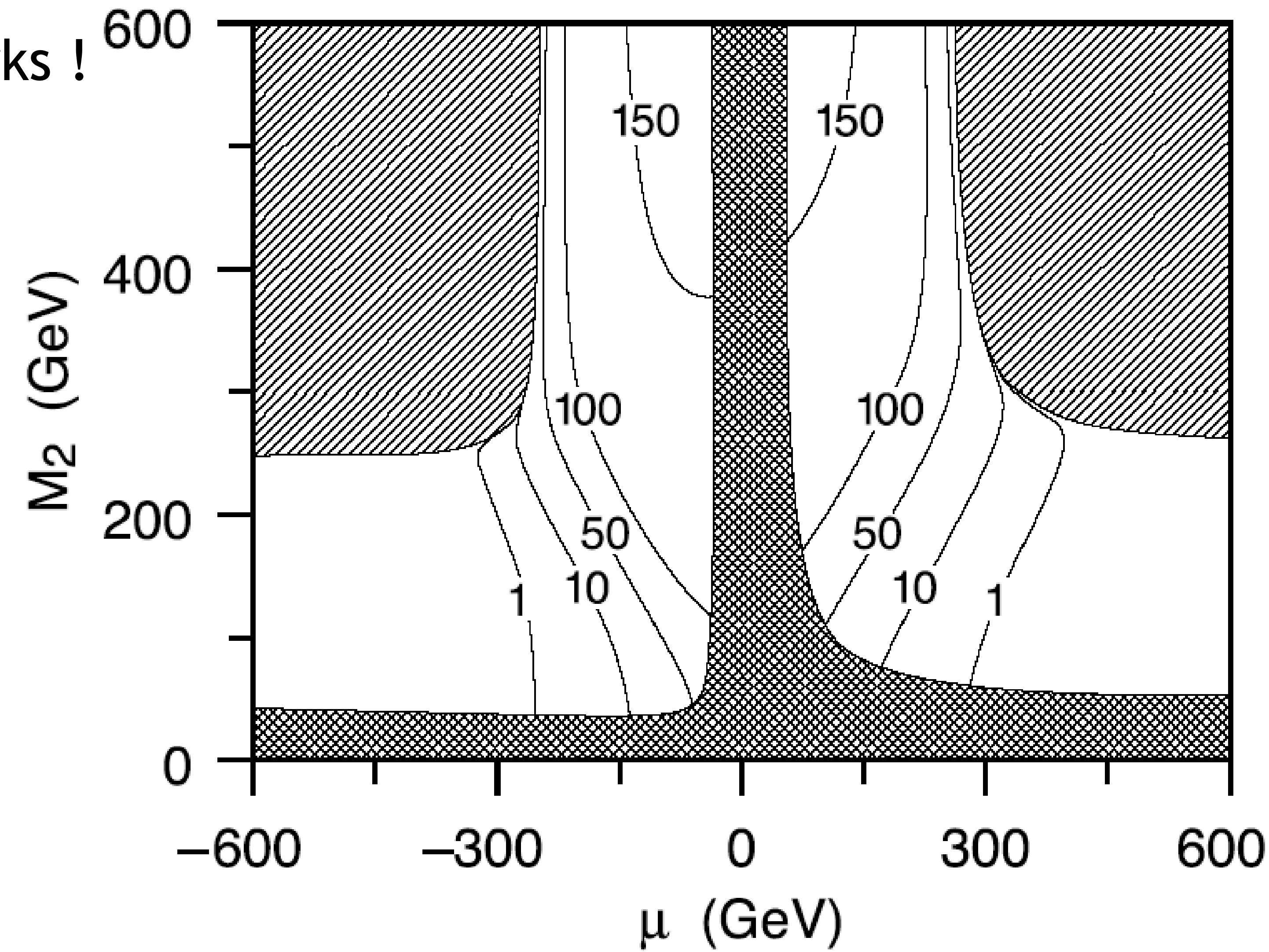
The mixing angles in the lightest chargino are measured by a combination of these techniques (as first described by the JLC group).



For an e_R^- initial state, the second diagram is absent. The first is a pure U(1) exchange. This does not couple to the W partners, so the cross section measures the Higgsino content.

Compare the contours of $\sigma(e^-_R e^+ \to C_1^+ C_1^-)$ plotted in the plane of the supersymmetry parameters μ, M_2.

It works !



This is all very interesting, but why is it so important to know these things ?

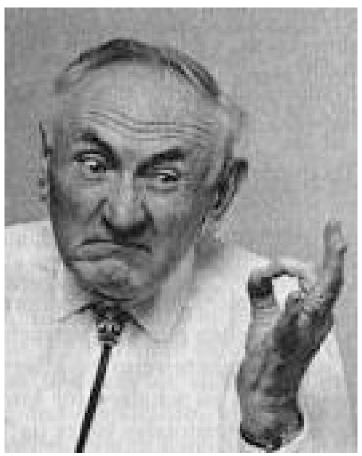
These results give the parameters of the fundamental Lagrangian for the new particle sector. Thus, they will be very important to physicists.

But they have a more tangible importance. They bear in a very direct way on the mystery of cosmic dark matter.

I will now digress and introduce this subject. Then we will come back to the ILC.

The first evidence for dark matter came from the the early period of extragalactic astronomy.

In 1933, Fritz Zwicky measured the mass of the Coma cluster of galaxies.



Fritz Zwicky

O. Lopez-Cruz and I. K. Sheldon - Kitt Peak

By measuring the relative Doppler shifts of galaxies, Zwicky measured the internal kinetic energy of motion of the cluster along the line of sight. Assuming that the the motion is isotropic gives the total kinetic energy. Then, using the virial theorem,

$$\langle V \rangle = -2 \langle T \rangle$$

he could estimate the gravitational potential energy and hence the total mass of the cluster.

The result was 400 times larger than the total mass of the stars in the galaxies of the cluster ($4 \times 10^{11} M_\odot$).

Soon after, Smith found a similar result for the Virgo cluster.

Not all of this missing matter is dark matter.

To get an idea of the magnitudes involved, here is the virial relation:

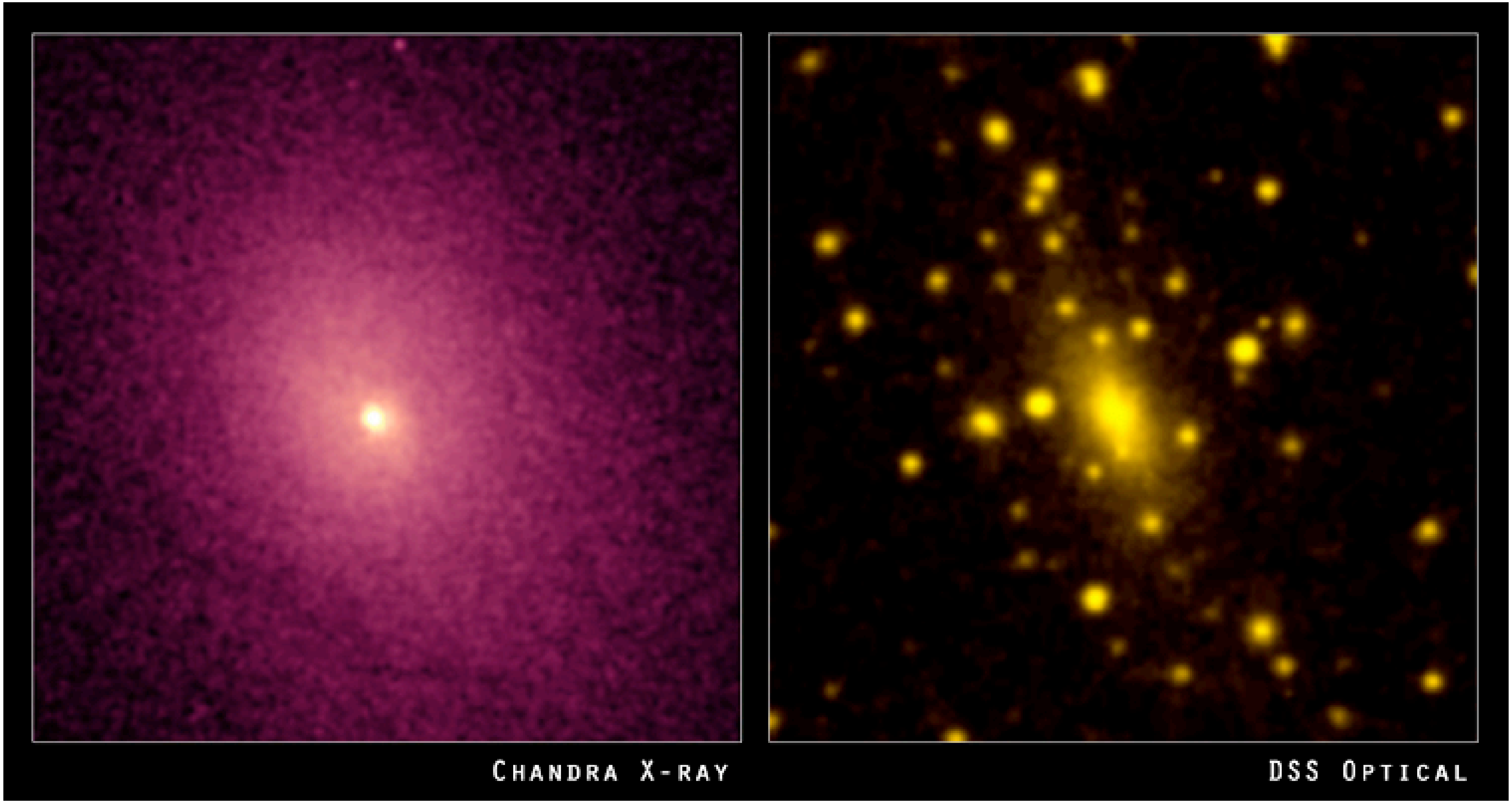
$$M = \frac{Rv^2}{G_N} \sim \left(\frac{R}{1\ \mathrm{Mpc}}\right)\left(\frac{v}{10^3\ \mathrm{km/sec}}\right)^2 \cdot 10^{15} M_\odot$$

Free gas in the cluster will be moving with the same velocity distribution. This implies a temperature

$$kT \sim m_p v^2 \sim 6\left(\frac{v}{10^3\ \mathrm{km/sec}}\right)^2\ \mathrm{k}eV$$

This gas radiates in the X-ray. It is visible (to X-ray satellites) and gives a mass about 15% of the total.

However, (a) this is not 100%; (b) this gas would freely stream out unless a much larger gravitating mass were keeping it in place.



Abell 2029

If we see dark matter on extragalactic scales, can we also see dark matter associated with single galaxies ?

Begin with the Milky Way. Estimate the mass of the Milky Way from the orbital velocities of globular clusters.

As a reference, our sun is 8.5 kpc from the center of the galaxy. Most of the visible stars in the galaxy are within 20 kpc of the galactic center.

Mass of the Milky Way, determined from the orbital velocities of globular clusters

distance (kpc)	result (billion solar masses)
17	200
20	30-200
44	890
50-100	500
50-100	200
100	900
100	1000
118 (one cluster)	< 1000
(total)	1000

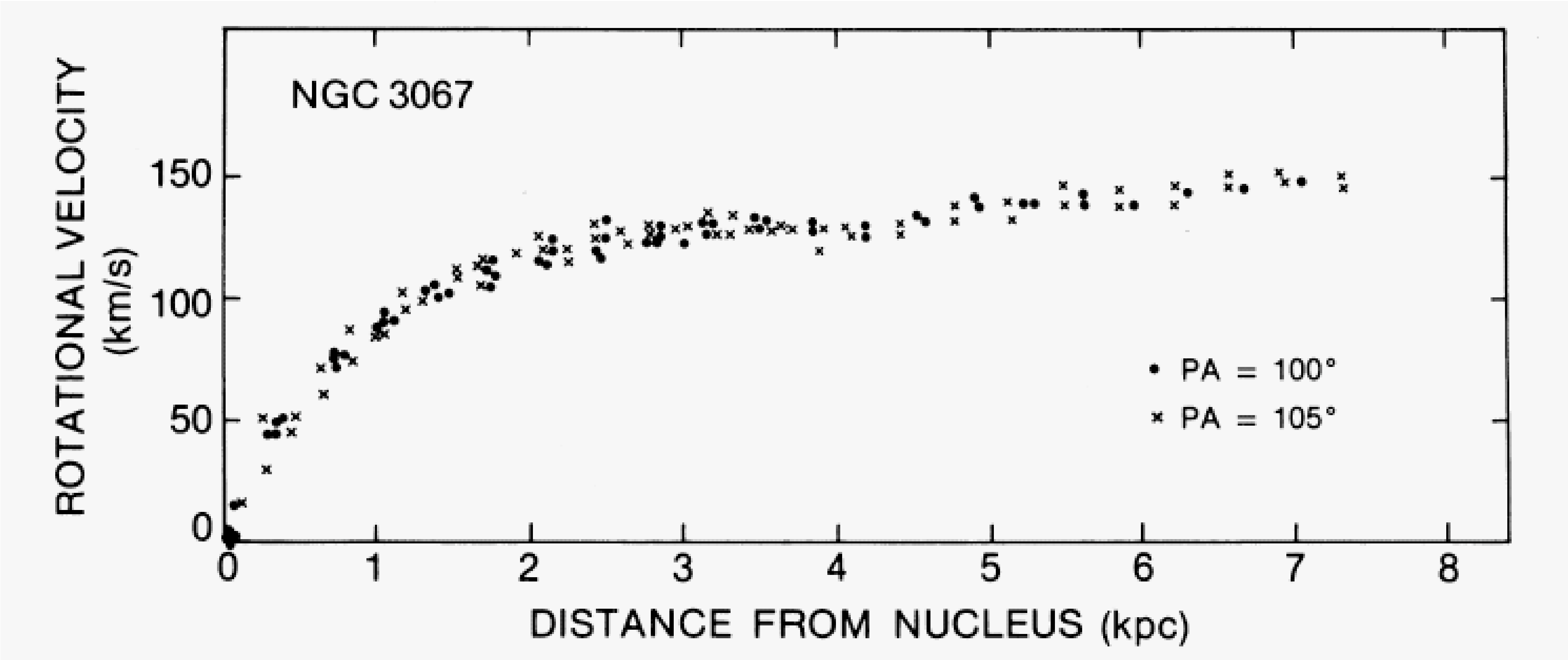
V. Trimble, Ann. Rev. Astro. Astro. (1987)

For other galaxies, it is possible to measure the radial component of the rotation velocities of individual stars and of hydrogen gas cloud (H1 regions).

For objects outside the visible part of the galaxy, the expectation would be Kepler's law:

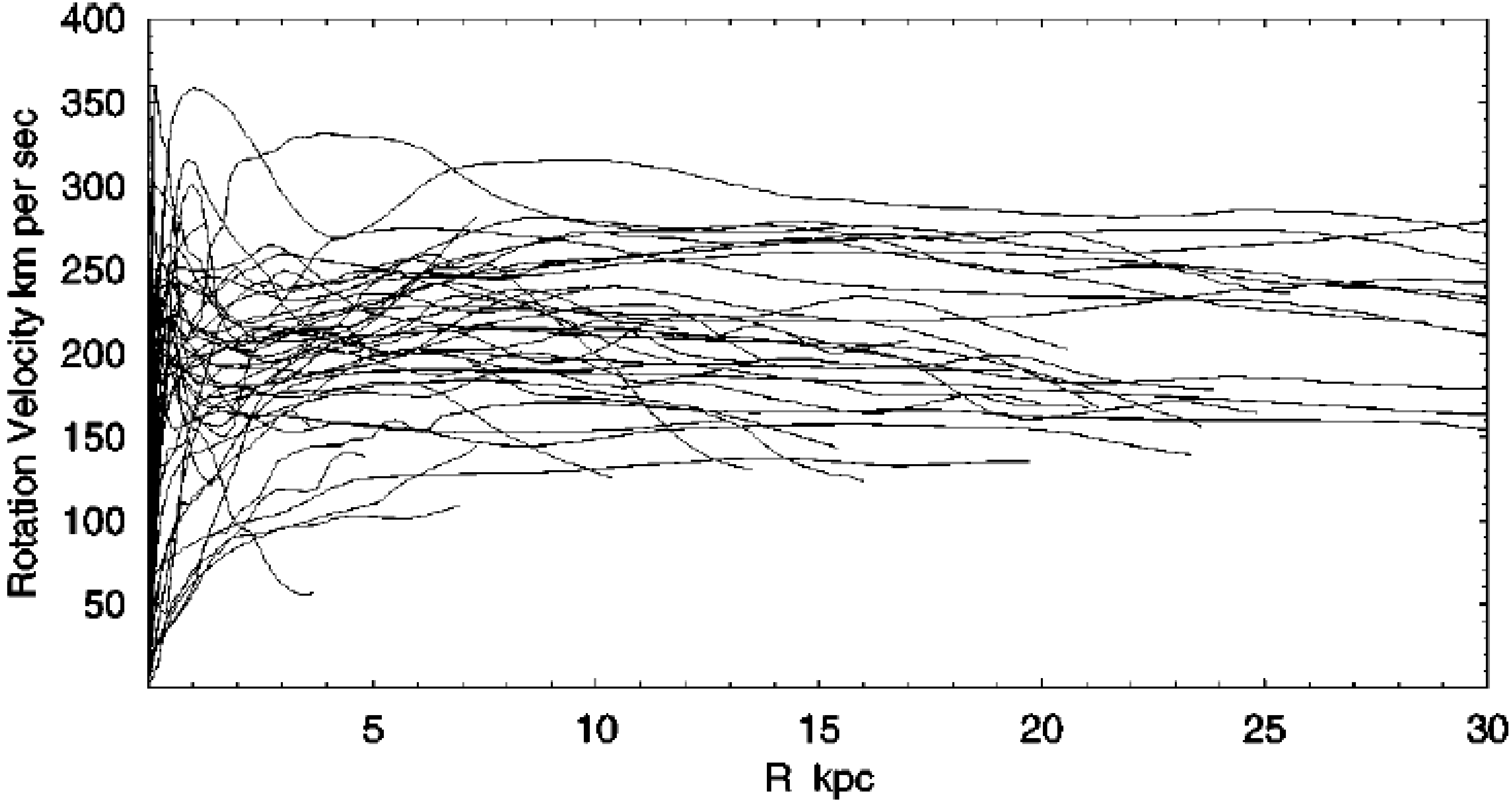
$$T^2 \sim r^3 \text{ or } v \sim 1/\sqrt{r}$$

What is actually seen ?



Rubin, Thonnard, Ford

"Such a velocity implies that 94% of the mass is located beyond the optical image; this mass has a ratio M/L greater than 100."



Sofue and Rubin

The flat rotation curves of galaxies obey a regularity

$$v_{rot}^4 \sim M$$

equivalent to the Tully-Fisher law. Milgrom interpreted this as a requirement for the acceleration of gravity to take the asymptotic form:

$$a = \left(\frac{G_N M}{R^2} \cdot a_0 \right)^{1/2}$$

The theory is called Modified Newtonian Dynamics (MOND).

This is a somewhat dangerous postulate: It is straightforward to modify dynamics at short distances by adding new, higher-dimensional interactions, but modifying dynamics at large distances requires new nonlocal interactions.

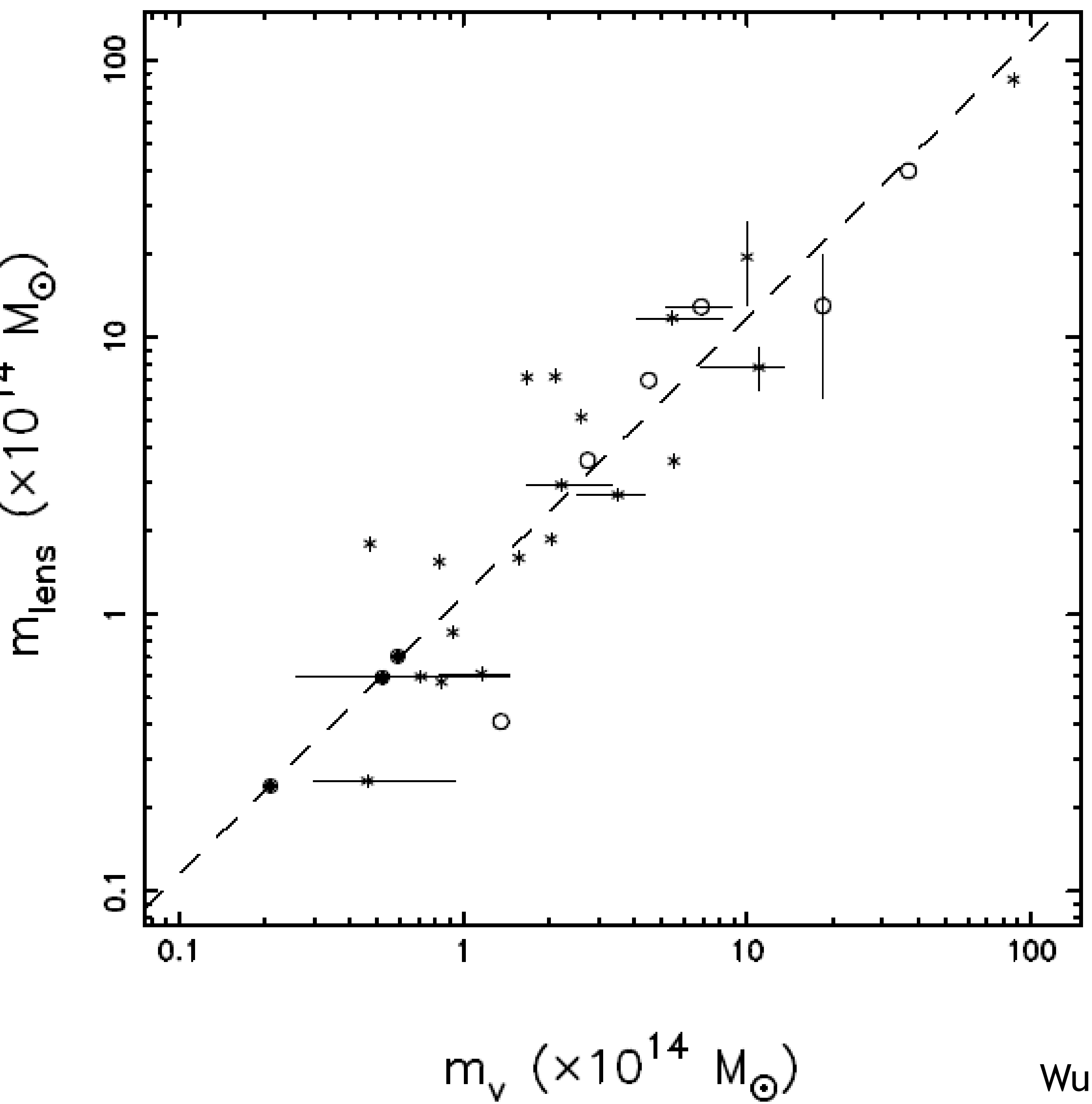
It is not straightforward to make MOND give the correct predictions for cluster size scales (100 x larger than galaxies) or for gravitational bending of light. However, there are generalizations that can fit the data.

It is not clear how else to challenge MOND quantitatively. But recently MOND has been challenged by interesting qualitative observations. This comes from another way to measure the mass distribution in cluster-size objects: gravitational lensing.

Zwicky first proposed this technique in 1937. It has come of age with the Hubble Space Telescope images.

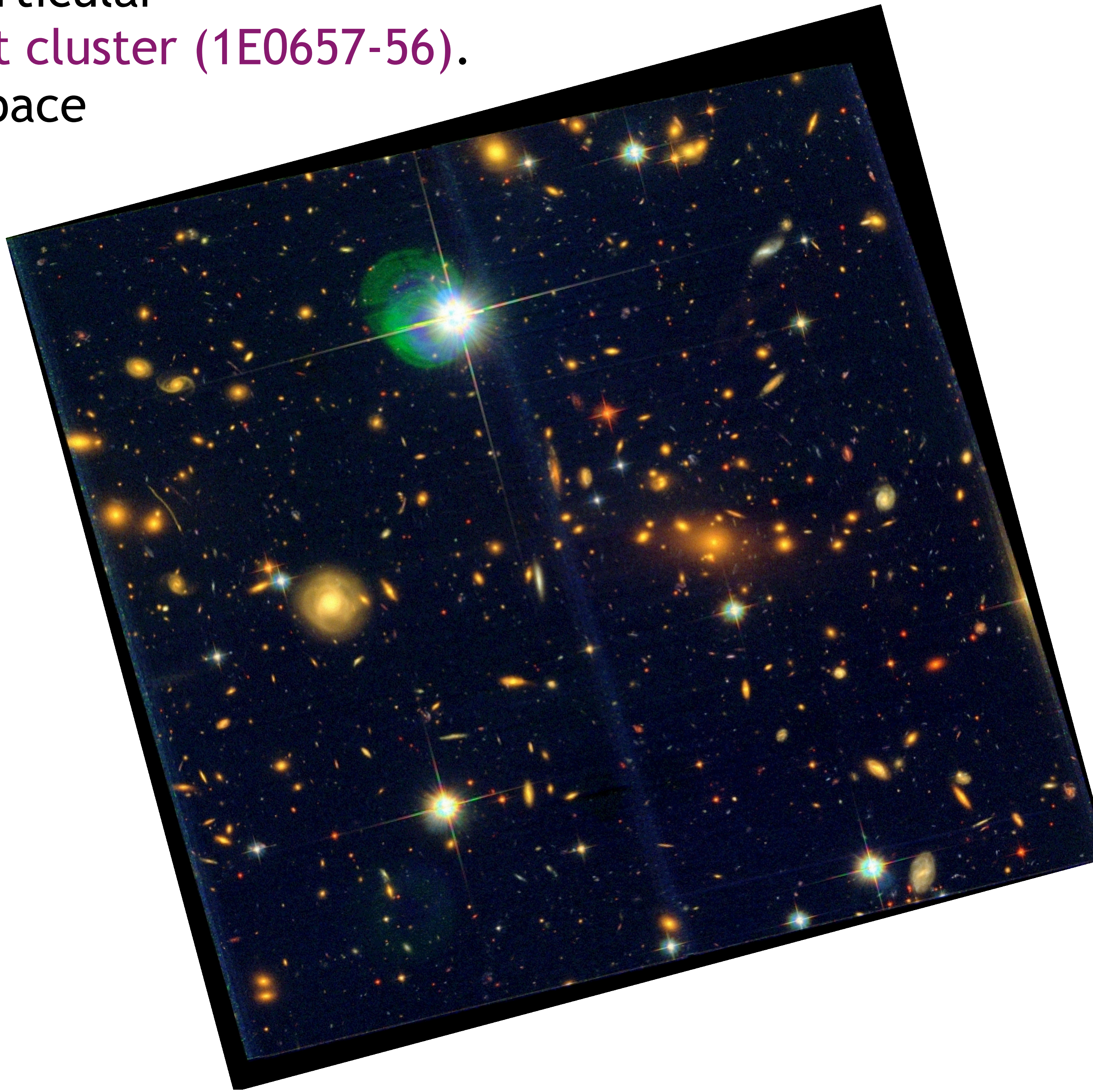
In general, gravitational lensing estimates of cluster mass are in good agreement with virial estimates.

0024+1654 W. N. Colley, E. Turner, J. A. Tyson -- Hubble Space Telescope


0.1
1
10
100
0.1
1
10
100
m_{lens} $(\times 10^{14}\ M_\odot)$
m_v $(\times 10^{14}\ M_\odot)$

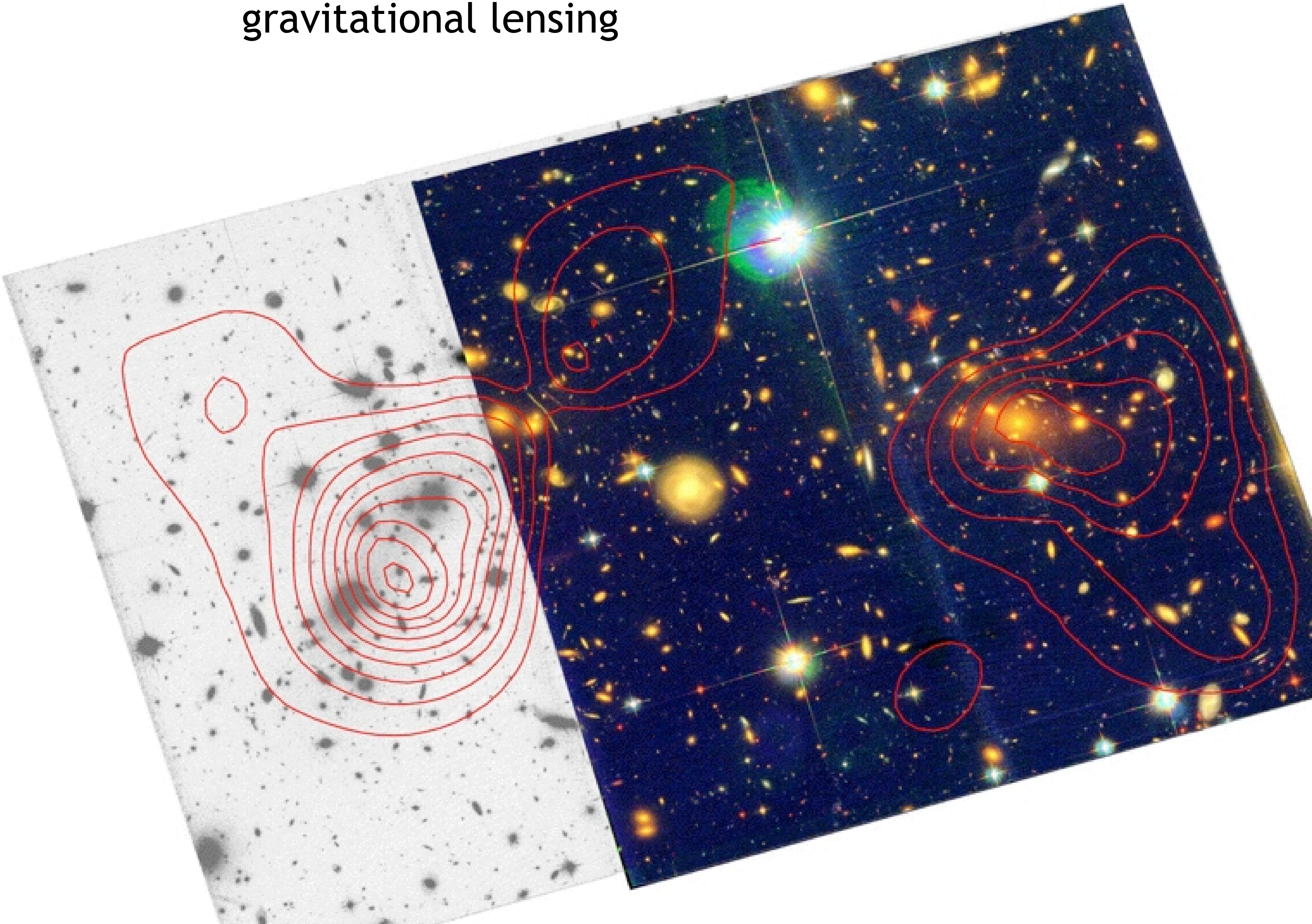
Wu and Fang

Let’s examine the particular example of the bullet cluster (1E0657-56). Here is the Hubble Space Telescope Image:

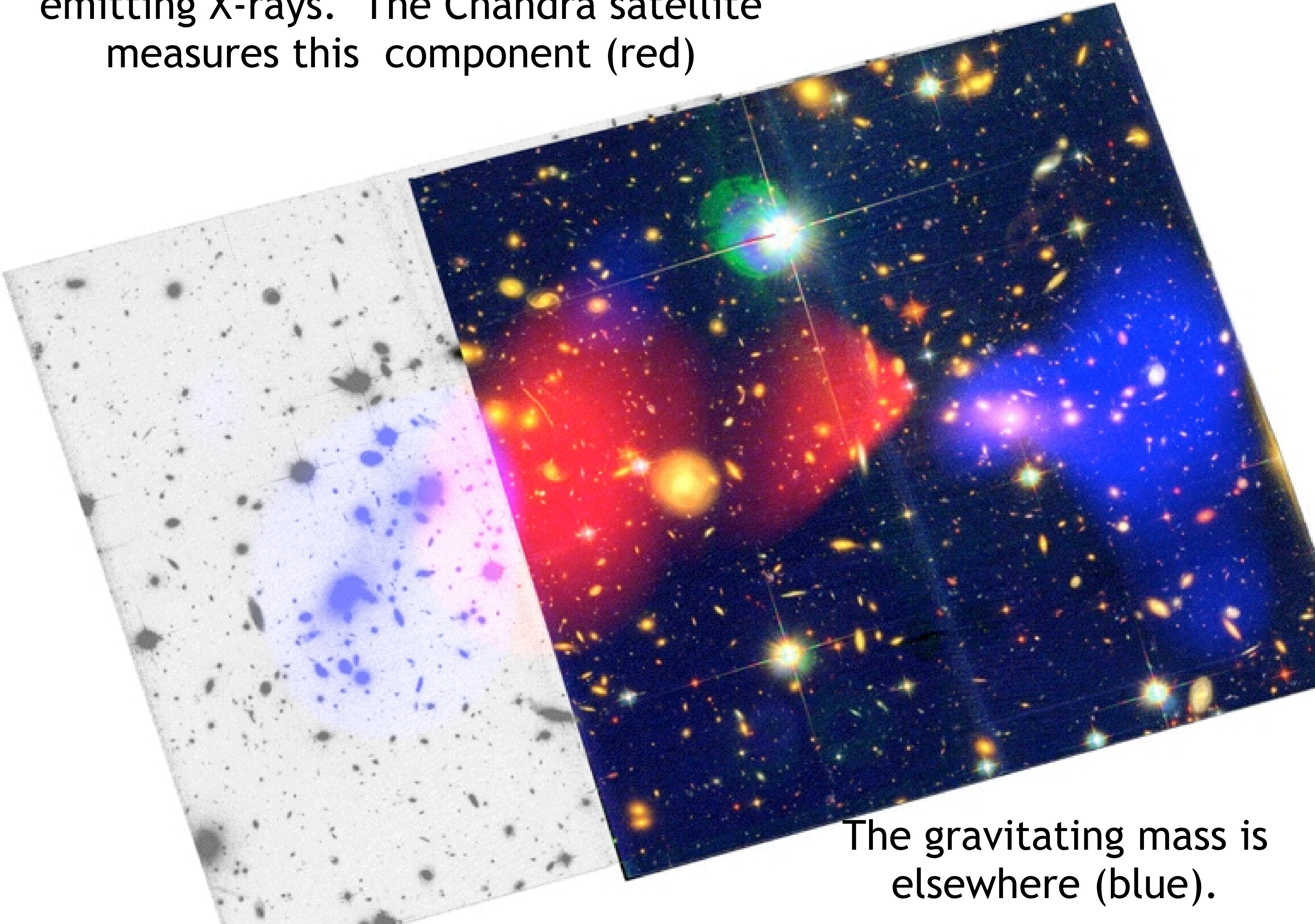


analysis of Bradac, Clowe, Gonzalez, Marshall, Forman, Jones, Markevitch, Randall, and Schrabback

Here is the mass distribution reconstructed from gravitational lensing



The atomic matter is mainly in hot gas, emitting X-rays. The Chandra satellite measures this component (red)



The gravitating mass is elsewhere (blue).

Our best understanding of the cosmic density of dark matter, however, comes from none of these sources, but, rather, from studies of the early universe through the cosmic microwave background.

In the early universe, structures could grow by gravitational collapse only after matter-radiation equality, which occurred at red shift

$$z \sim 2900$$

The radiation from the cosmic microwave background originated at the time of `recombination'

$$z \sim 1300$$

and thus gives evidence of a very early period in the growth of structure.

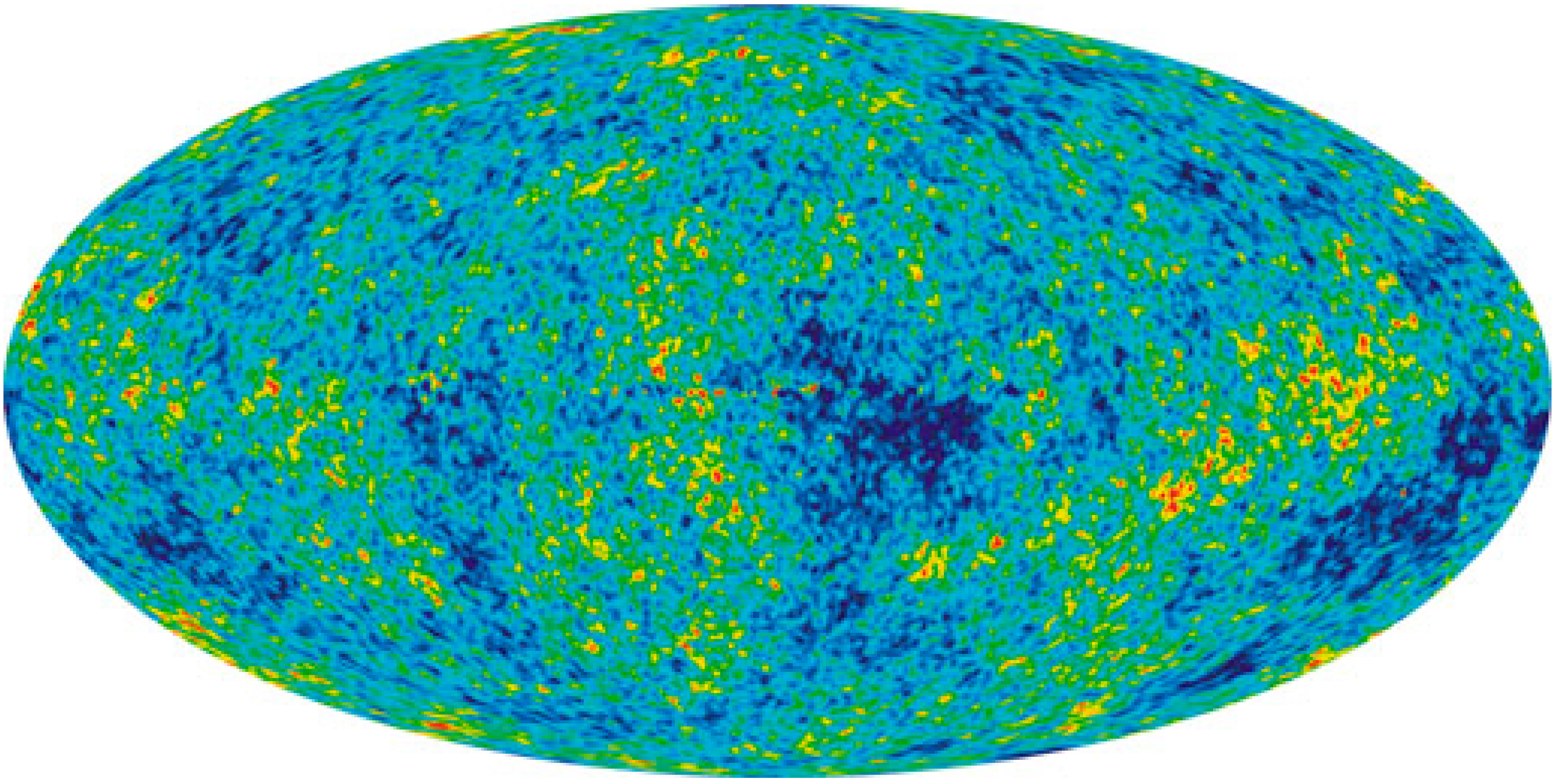
Key features of the CMB radiation are:

the radiation is approximately thermal black-body radiation. The local fluctuations in T are of the order of 10^{-5}

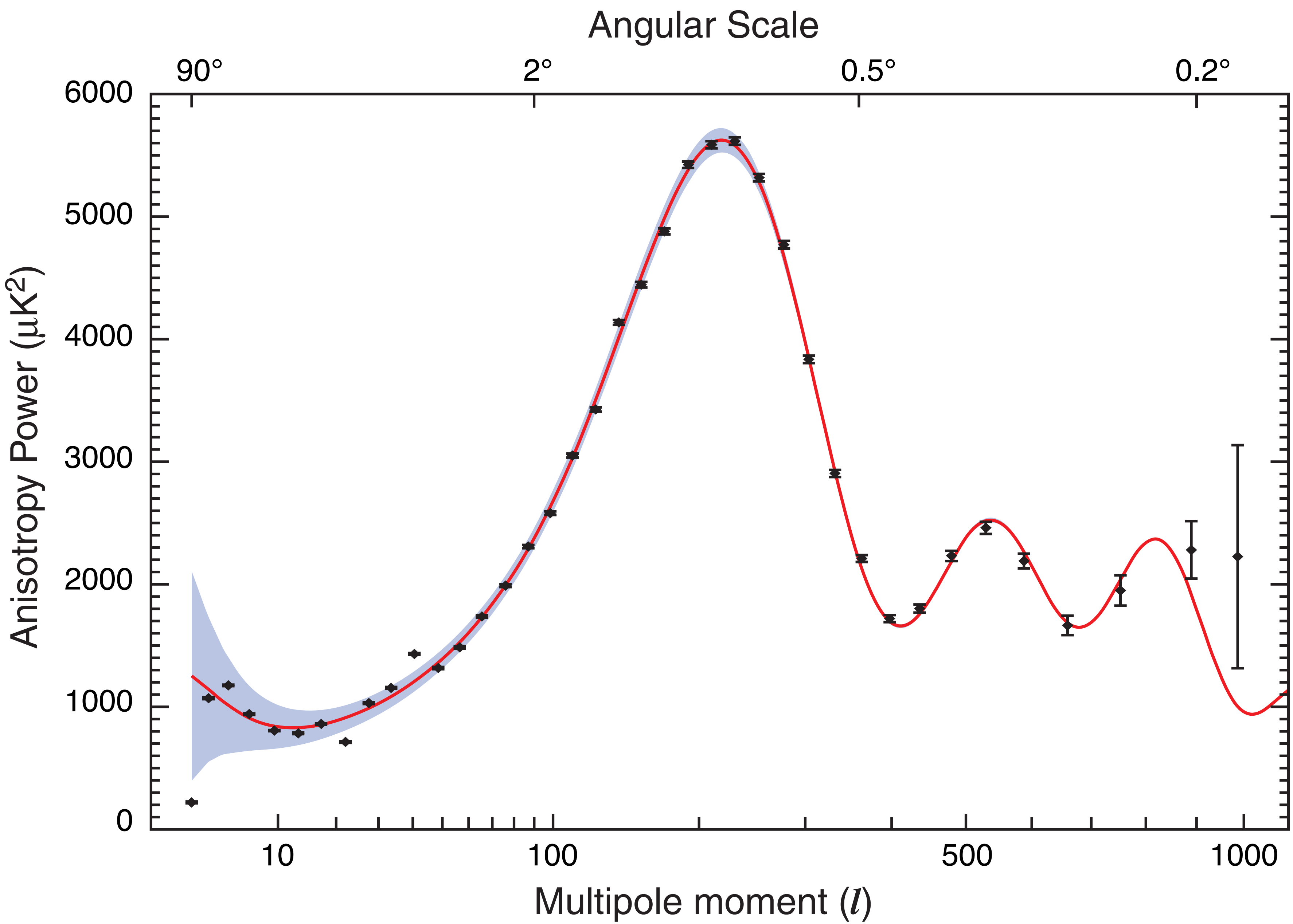
the fluctuation spectrum has an 'acoustic' peak at angular sizes of 1°. This should correspond to the beginning of the collapse of matter into gravitational potential wells The size of the structure should be approximately the size of the sound horizon at recombination, expanded with the universe:

$$10^5 \text{ l-yr} \cdot z_{rec} = 10^8 \text{ l-yr}$$ (for a flat universe)

the fluctuation spectrum has additional peaks corresponding to the overtones of the acoustic oscillations. The relative sizes of these peaks measure the equation of state and the dissipation in the primordial medium.



WMAP science team - 2006



WMAP Science Team - 2006

If one models the CMB as being generated by a medium composed of hydrogen gas plus noninteracting dark matter, it is possible to extract the curvature of the universe and the fraction of each component. With the notation

$$\Omega_i = \rho_i/\rho_c \qquad h = H_0/(100\ \mathrm{km/sec/Mpc})$$

the results are: (WMAP 2006)

1. The universe is flat: $\Omega_{tot} = 0.99 \pm 0.01$

2. The density of matter is much larger than that of baryons

$$\Omega_m h^2 = 0.126 \pm 0.01$$
$$\Omega_b h^2 = 0.0223 \pm 0.0008$$

Using $h^2 = 0.50 \pm 0.06$ from the Hubble space telescope, we find that 80% of the mass and 20% of the total energy density of the universe is in the form of dark matter.

What do we know about dark matter at this stage ?

It is a new species of matter that is stable and has interactions that are negligible in astrophysics (< barn). It is present at a density of 20% of the critical density:

$$\rho_{DM} = 1 \ \mathrm{GeV/m}^3$$

A huge range of hypothetical particles fit this description. Some examples are

the axion	m = $10^{-5}\mathrm{eV}$
the WIMPzilla	m = $10^{18}\mathrm{GeV}$
black holes of	< $10^{-2} \ M_\odot$

It is a major channel to elementary particle physicists to discover the particle identity of dark matter.

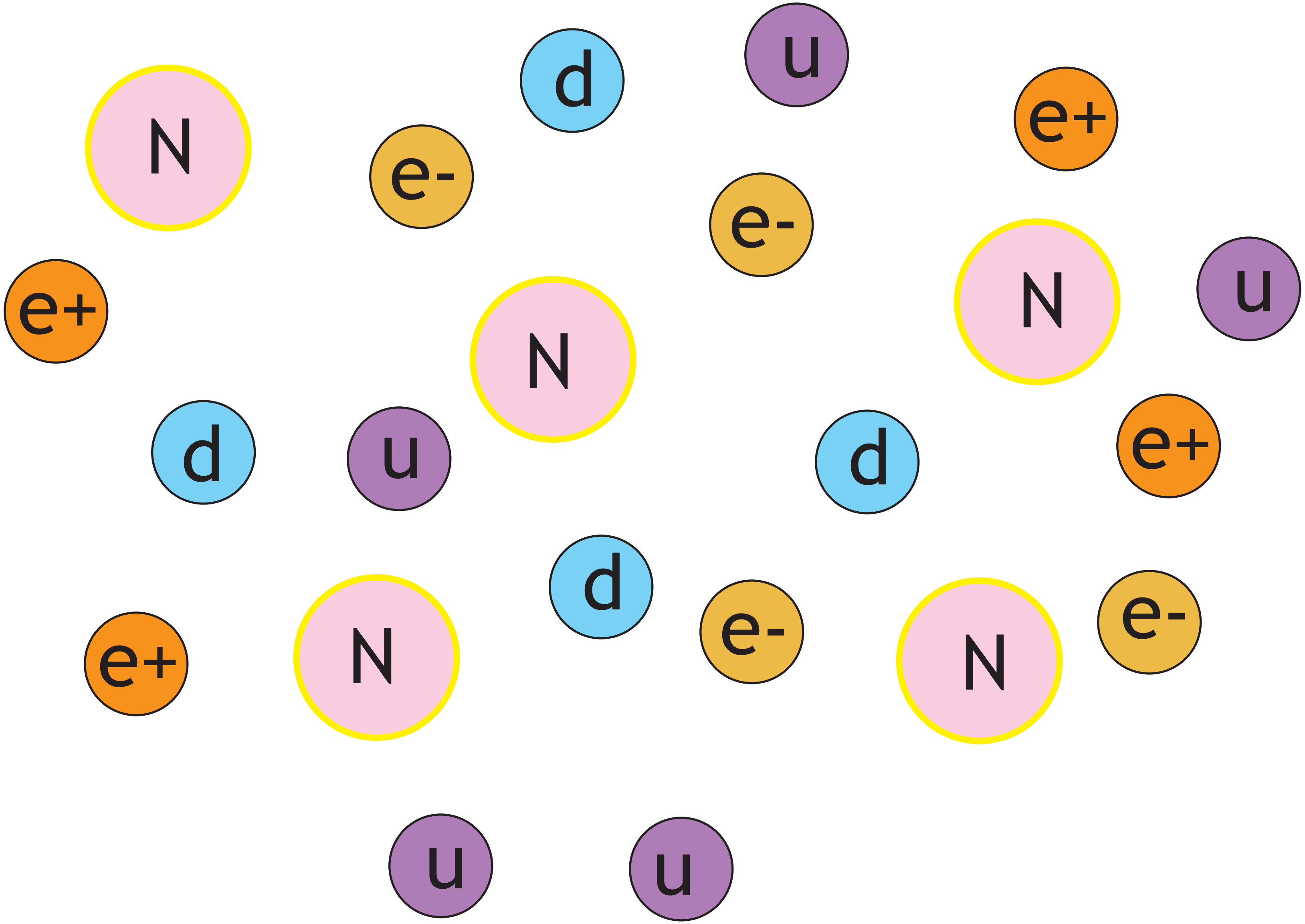
To make progress, we need to add further assumptions. Here is one that I consider weak (although the models on the previous slide are counterexamples):

Dark matter particles were in thermal equilibrium at some time in the early universe.

I will call a neutral, stable, weakly-interacting particle that satisfies this assumption a WIMP. Even if the particle is stable, it can be maintained in equilibrium if it can be created or annihilated in pairs.

This assumption allows us to compute the cosmic density of dark matter:

Start from the initial condition of thermal equilibrium. As the temperature decreases, the density of WIMPs decreases. Eventually, as the universe expands, WIMPs cannot find their partners, and a residual 'relic' density is 'frozen out'.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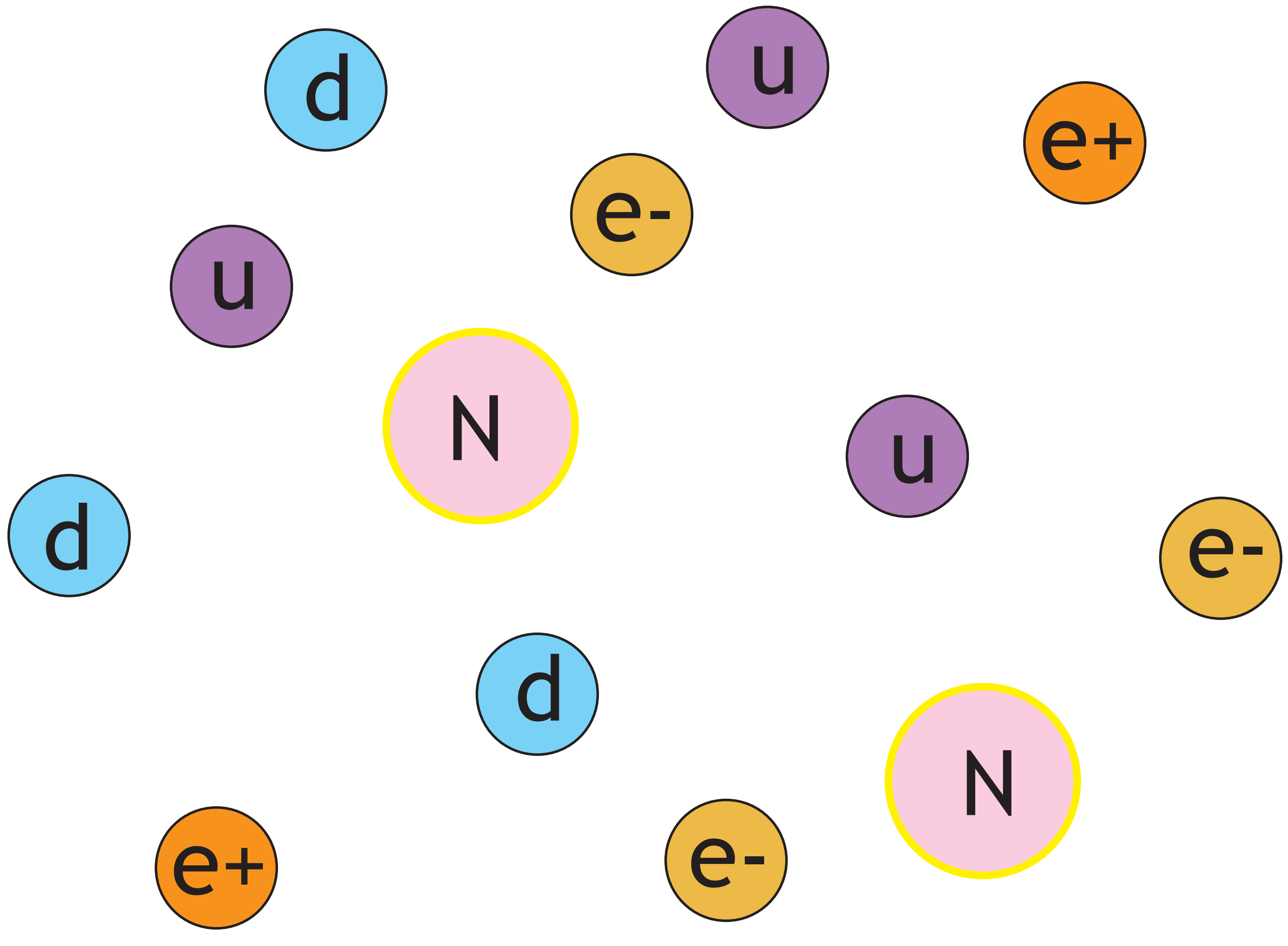
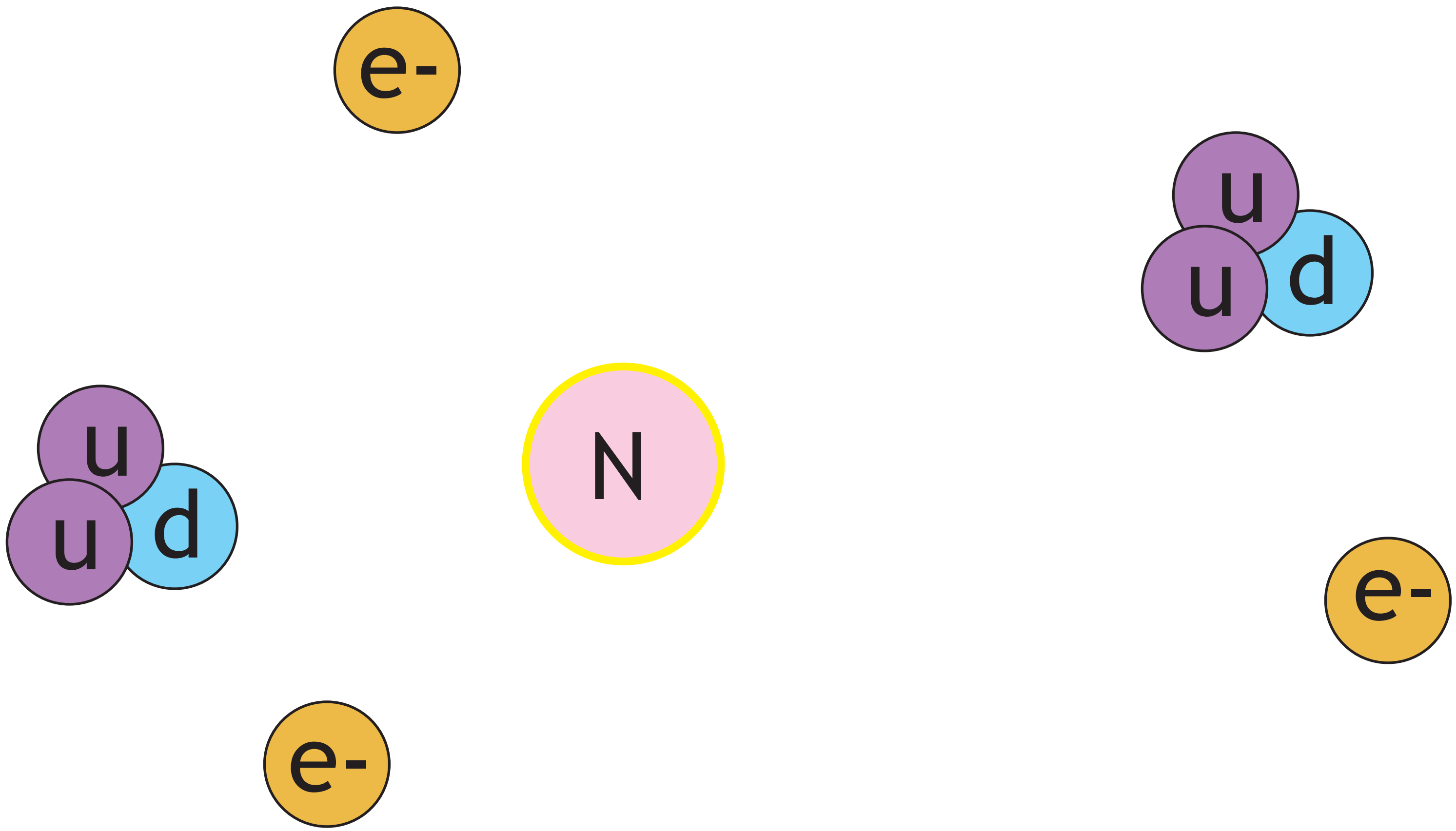
the universe expands and cools ...



until today ...



Discuss this quantitatively:

Pair creation and annihilation and the expansion of the universe are accounted by the Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2\right)$$

where the expansion rate (still radiation-dominated) is

$$H = \frac{1}{2t} = \left[\frac{8\pi^3}{90} g_*\right]^{1/2} \frac{T^2}{m_{\mathrm{Pl}}}$$

where, e.g., g_* = 86.25 for the Standard Model at 10 GeV. The annihilation term dominates until the WIMPs become very nonrelativistic and

$$e^{-m_N/T} \sim \frac{T^{1/2}}{m_N^{3/2} m_{\mathrm{Pl}} \langle \sigma v \rangle}$$

This is the condition for freeze-out. Numerically, for any electroweak cross section, $\xi_f = T_f/m_N = 1/25$.

Since the universe is expanding so slowly, the expansion is approximately adiabatic, that is, entropy is conserved. Define $Y = n/s$ and use the entropy as a reference point. In a radiation-dominated universe,

$$s = \frac{2\pi^2}{45} g_* T^3$$

so the Boltzmann equation becomes

$$\frac{dY}{dt} = -\frac{2\pi^2}{45} g_* T^3 \langle \sigma v \rangle (Y^2 - Y_{eq}^2)$$

$$\frac{dY}{d\xi} = -C(Y^2 - Y_{eq}^2)$$

where

$$\xi = T/m_N \ , \ C = (\pi g_*/45)^{1/2} m_N m_{\mathrm{Pl}} \langle \sigma v \rangle$$

Now there is a nice approximation (Turner-Scherrer): Assume that Y equals its thermal value until freezeout; after freezeout, drop the second term on the right. This approximation is good to 5-10%.

$$\frac{dY}{Y^2} = -C d\xi$$

Integrate from freezeout to T = 0:

$$\frac{1}{Y(0)} - \frac{1}{Y(\xi_f)} = C\xi_f$$

The second term on the left is small, so we can write, finally,

$$Y(0) = \left(\frac{45}{\pi g_*}\right)^{1/2} \frac{1}{m_N m_{\rm Pl}} \frac{1}{\xi_f \langle \sigma v \rangle}$$

If $\langle \sigma v \rangle$ depends strongly on temperature as $T \to 0$, replace

$$\xi_f \langle \sigma v \rangle \to \int_0^{\xi_f} d\xi \, \langle \sigma v \rangle$$

I'll rewrite the final result in terms of $\Omega_N = \rho_N/\rho_c$, taking the normalization to be set by the current entropy density of the universe. The result becomes

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

Putting in measured values, we can extract the value of the WIMP annihilation cross section:

$$\langle\sigma v\rangle = 1 \text{ pb}$$

This is, amazingly, the characteristic size of cross sections at the LHC ! Alternatively, parametrize

$$\langle\sigma v\rangle = \frac{\pi\alpha^2}{8m^2}$$

Then m = 100 GeV.

Is this a coincidence ? Most astrophysicists think so.

I have just the opposite opinion. We know that we need new physics at the 100 GeV mass scale to explain electroweak symmetry breaking. If we want a mechanism for EWSB, we need new interactions, not just one Higgs boson.

So we should be asking, do such theories contain WIMPs ?

Generically, models of EWSB contain new neutral particles. These have weak-interaction cross sections. The only nontrivial question is, are these particles stable ?

The lightest new particle will be stable if there is an exact discrete symmetry P such that this particle, and some or all new particles, carry the discrete quantum number.

Almost every model of EWSB either can contain or must contain such a discrete symmetry:

Supersymmetry: Generically, proton decay is very rapid.

$R = (-1)^{B-L+2S}$ removes the dangerous operators.

Flat extra dimensions: $P_5 \ : \ x^5 \to -x^5$ is naturally present.

Warped extra dimensions: proton decay is again a problem.

Katz-Nelson advocate applying R-parity
Agashe-Servant advocate a Z_3 parity

Little Higgs: T-parity alleviates problems with precision electroweak measurements
(though Hill and Hill warn that T-parity is often violated!)

All of the models on the previous page contain one more very interesting feature:

There exist particles with QCD color that carry the conserved discrete quantum number and have masses comparable to the WIMP mass.

Thus, dark matter gives a second, independent motiviation to search for new heavy particles at the hundred-GeV mass scale.

In the previous lecture, we discussed that, from the LHC data, we will obtain the mass of the invisible decay product of new particles to about 10% accuracy.

If we could measure the mass of the astrophysical dark matter particle to similar accuracy, we could obtain a first piece of evidence that the invisible particles seen at the LHC and in the galactic halo are the same.

This is likely to be available in next five years, as experiments on dark matter detection mature. We will obtain mass estimates

from the recoil energy spectrum in direct detection

from the gamma ray spectrum in dark matter anhilation

from the positron spectrum in dark matter annihilation

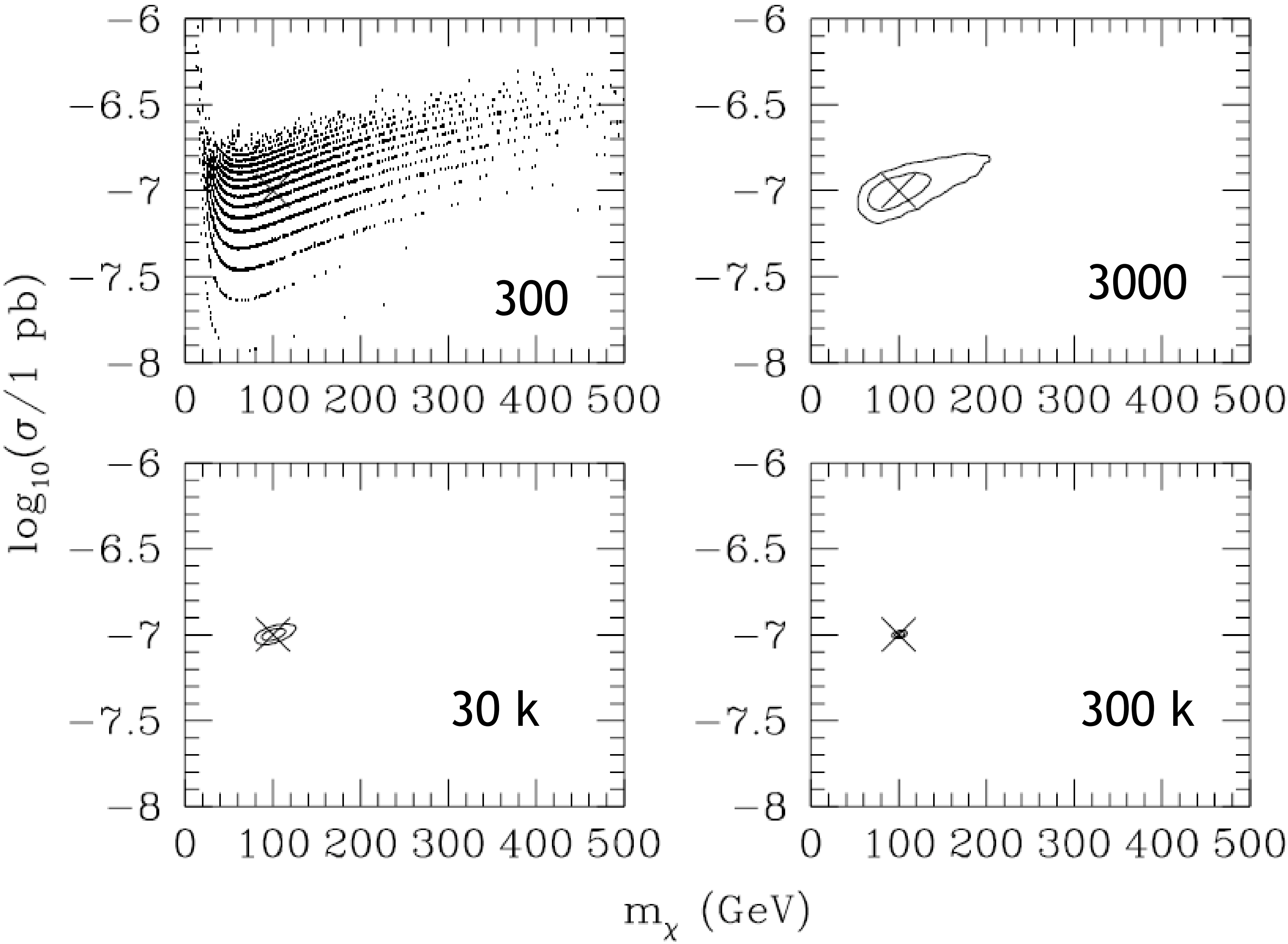
In direct detection, if the WIMP mass is well matched to the target mass, we expect billiard-ball-like collisions. Then the energy spectrum in recoil is a good measure of the WIMP mass.

$$\langle E_R \rangle = \frac{2v^2 m_T}{(1 + m_T/m_\chi)^2}$$

Then for a WIMP of mass about 100 GeV, we expect a 20% measurement of the WIMP mass with 100 direct detection events.

Recently, Green has done a detailed study of this measurement for super-CDMS.

exposure kg-d



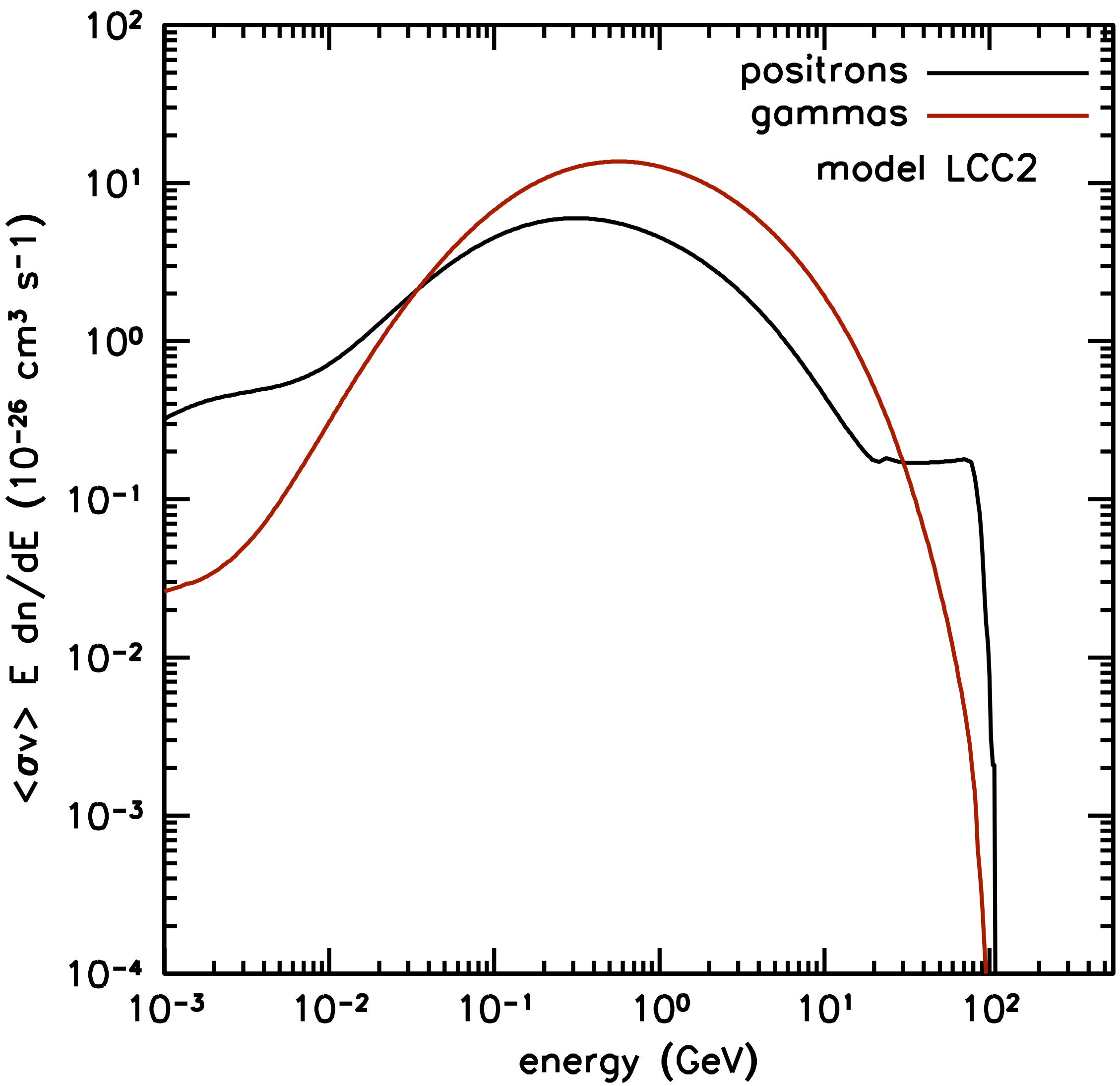
Green

In indirect detection, we measure the spectrum of gammas or other products in WIMP pair annihilation.   This spectrum has a sharp kinematic endpoint at the mass of the WIMP.

This is useful even if the WIMP does not decay directly to gammas or positrons.

I will show examples in a model in which

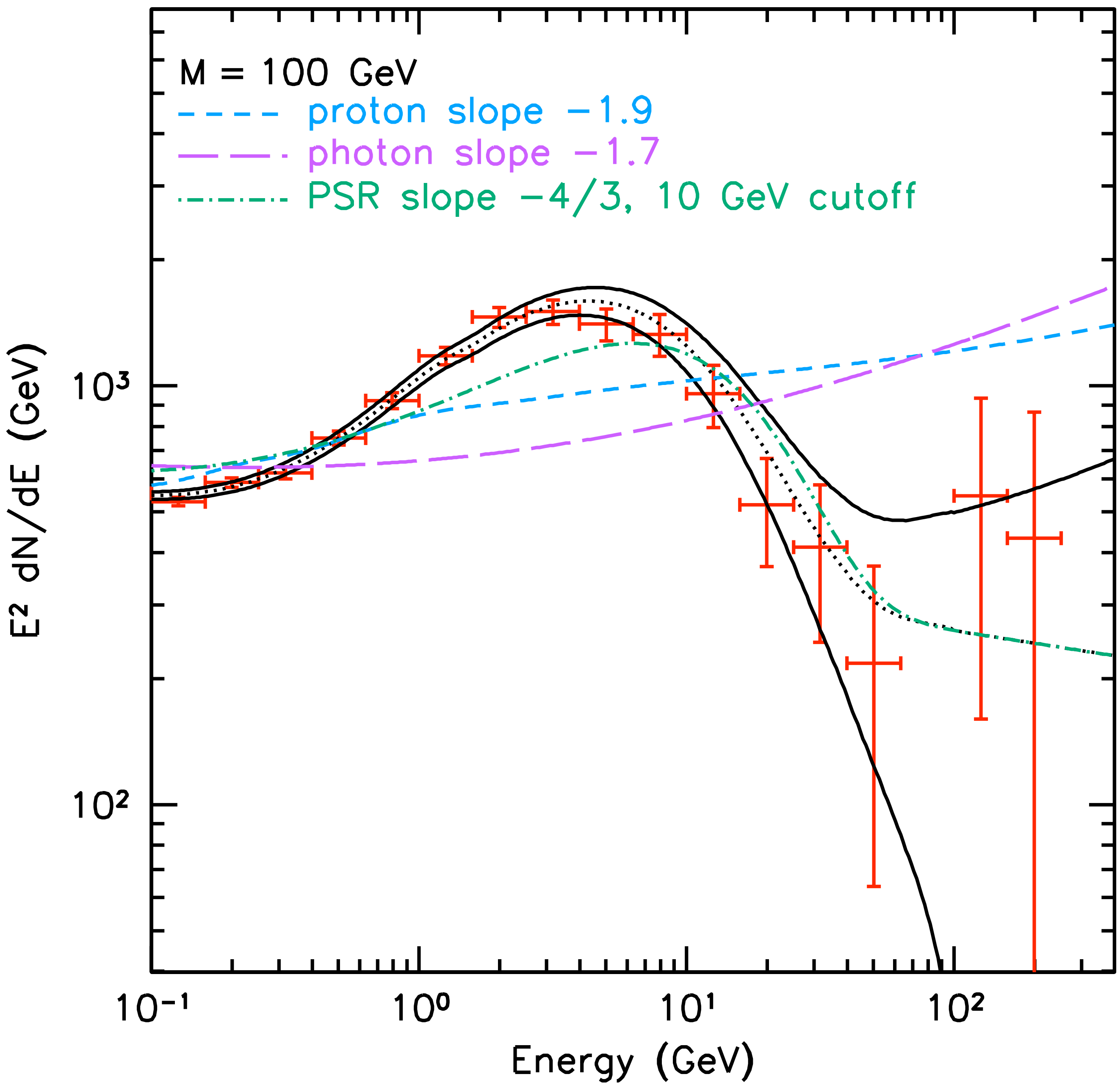
$$\chi + \chi \to W^+W^- \ , Z^0 Z^0$$



gamma ray spectrum, including extragalactic background. The error bars correspond to a 5 year GLAST observation of a dark matter subhalo clump of mass

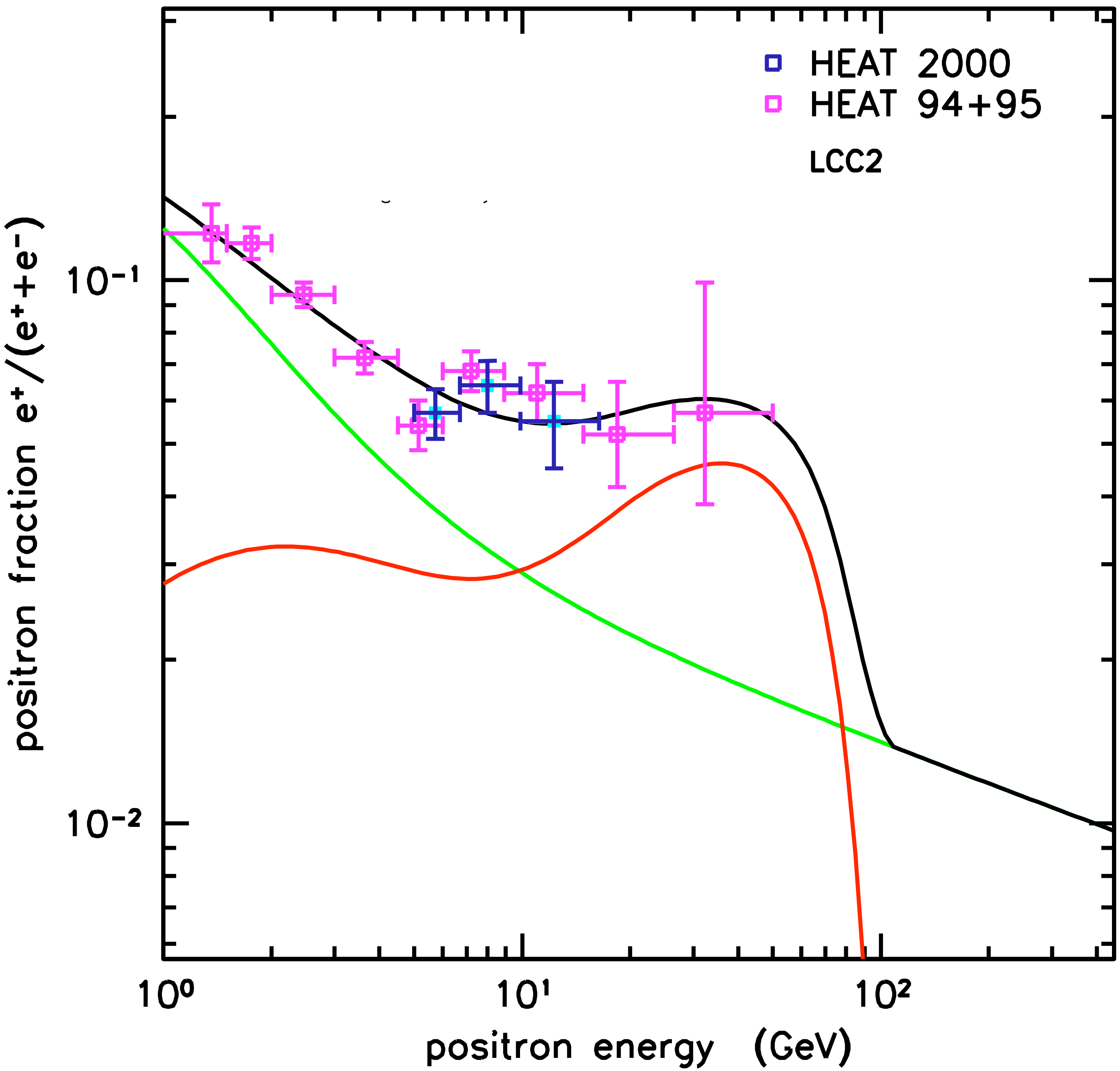
$$2 \times 10^6 M_\odot$$

at 3 kpc.



Baltz, Taylor, and Wai

Here is the positron spectrum from the same model, propagated with the code of Baltz and Edsjo. The comparison with HEAT data is for your amusement only.



So at least we can see our way through the first step in the program of proving that a massive stable neutral particle seen at the LHC is the particle that makes up dark matter.

The next problem would be to measure other specific properties of the dark matter particle, for example, $\langle \sigma v \rangle$, and check these against the values predicted by collider data.

This program turns out to be very difficult. The results for $\langle \sigma v \rangle$ and other relevant cross sections depend on the mass spectrum, but also on many more properties. At the highest level, they depend on the model of electroweak symmetry breaking and on the scenario that is chosen within this model. In detail, they depend on mixing angles and specific particle assignments.

Thus, we find that the results of the ILC experiments discussed at the beginning of this lecture become crucial inputs into the discussion.

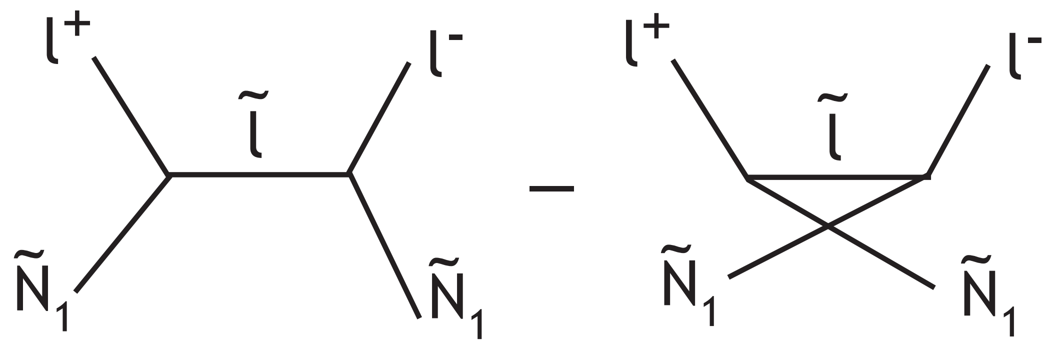
In the next section of this talk, I will concentrate on the problem of predicting $\langle \sigma v \rangle$ in supersymmetry models in which the dark matter particle is the lightest neutralino, the lowest-mass combination of the superpartners of $(\gamma, Z^0, H_u^0, H_d^0)$

From our previous discussion, we would like to find

$$\langle \sigma v \rangle = 1 \ \mathrm{pb}$$

What is required to obtain this value ?

The simplest mechanism for NN annihation is annihilation through t-channel slepton exchange. For simplicity, I ignore slepton masses and Higgs couplings. Then



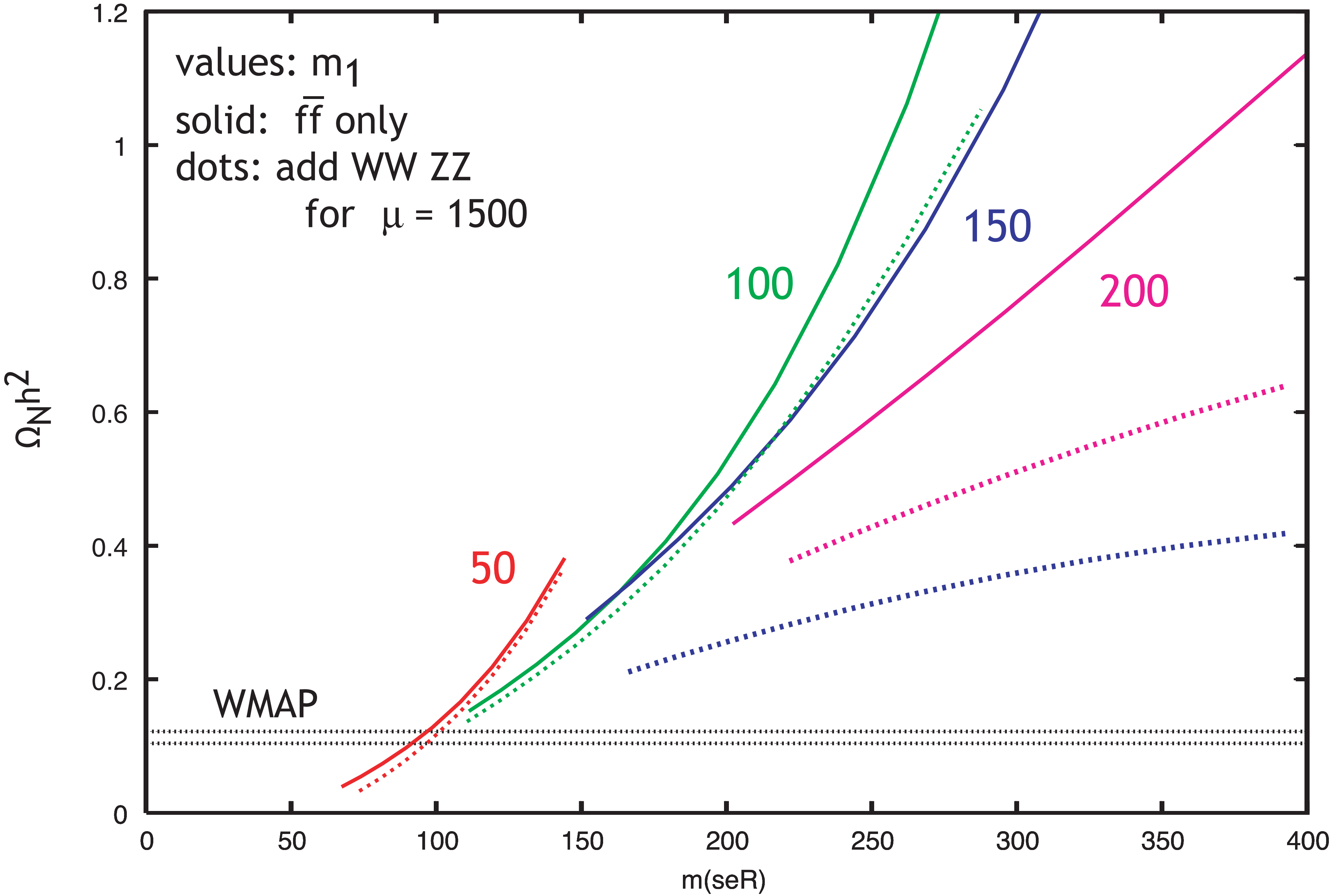
$$v \frac{d\sigma}{d\cos\theta_{CM}} = \frac{\pi\alpha^2}{8m^2} \left|\frac{V_{011}}{c_w}\right|^2 \left| \frac{m_N^2}{|t| + m_{\tilde{\bar{l}}}^2} - \frac{m_N^2}{|u| + m_{\tilde{\bar{l}}}^2} \right|^2$$

This is excellent, except for the unfortunate final factor , which vanishes at threshold. Since $\xi = T/m_N \sim 1/25$, we pay a severe penalty, about a factor 8 in $\langle \sigma v \rangle$, if we need to rely on P-wave rather than S-wave annihlation.

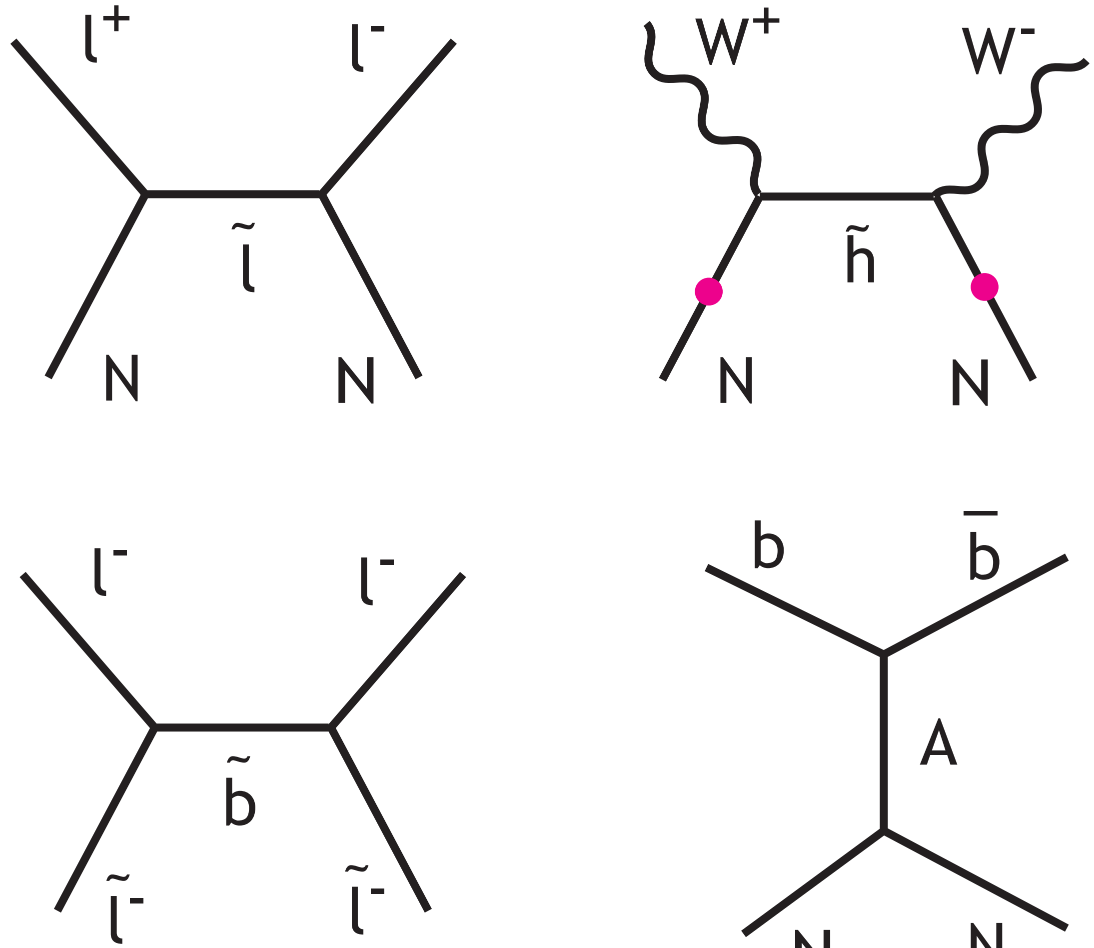
The cancellation occurs because Fermi statistics requires the N's to annihilate in the S-wave in a spin 0 configuration

while the final state, for massless leptons, has spin 1.

With this suppression, $\langle \sigma v \rangle$ can be large enough to give the observed value of Ω_N only if the sleptons masses are just above the LEP2 lower limit of about 90 GeV.


values: m_1
solid: $f\bar{f}$ only
dots: add WW ZZ
for μ = 1500
100
150
200
50
WMAP
$\Omega_N h^2$
m(seR)
0
0.2
0.4
0.6
0.8
1
1.2
0
50
100
150
200
250
300
350
400

Fortunately, more general models of supersymmetry contain a variety of mechanisms for generating a large enough neutralino annihilation cross section:



Baltz, Battaglia, Wizansky and I recently did a detailed study of how our improving knowledge of the supersymmetry spectrum from collider experiments could affect our understanding of the dark matter problem. We chose several model points in the space of MSSM couplings at which people had worked out the expected accuracy of collider measurements, constructed MSSM parameter sets consistent with these measurements, and then evaluated the properties of dark matter at these points using the program DarkSUSY.

Let me show you a few results from that study, first for the evaluaton of $\langle \sigma v \rangle$.

Begin with the model LCC2 in our study, for which the dominant neutralino annihilation channels are

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

This model has very heavy squarks and sleptons, and a gluino at 800 GeV. At the LHC, there is copious SUSY production by

$$gg \to \widetilde{g}\widetilde{g}$$

There will be a large like-sign-dilepton signal, from the decay

$$\widetilde{g} \to u\overline{d}C_1^- \to u\overline{d}\ell^-\nu N_1$$

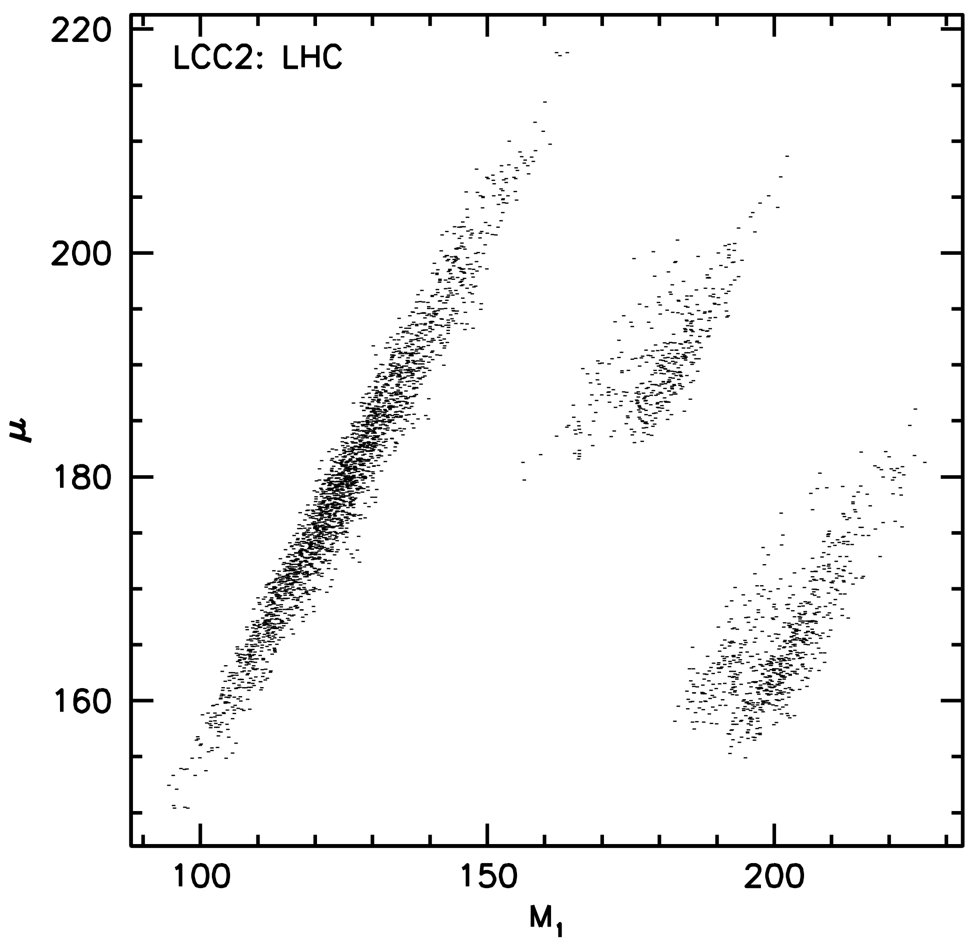
on both sides of the reaction. It will be obvious that there is new physics ! This signal will argue for the Majorana nature of the gluino mass.

There will be 3-body dilepton cascades from the decays

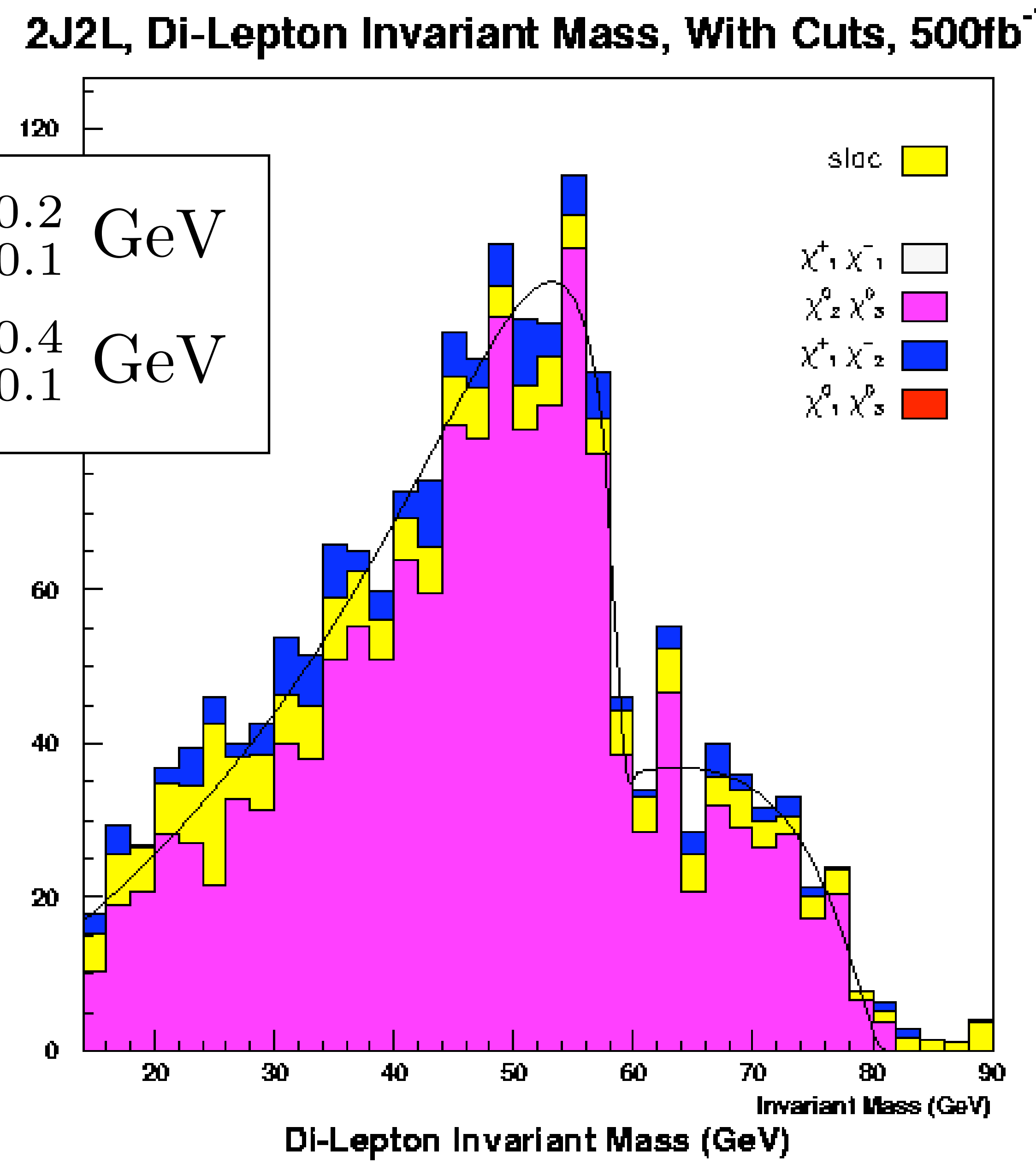
$$\widetilde{g} \to q\overline{q}N_{1,2,3} \qquad N_{2,3} \to N_1\ell^+\ell^-$$

So we will know two neutralino mass differences to 1% accuracy.

Unfortunately, the mass splittings alone do not tell us whether the LSP is mainly bino, wino, or Higgsino. Here are out parameter sets, in the plane of m_1 vs μ. The Higgsino case can be excluded from the shape of the dilepton mass distribution.



$$m(\widetilde{N}_2) - m(\widetilde{N}_1) = 58.7^{+0.2}_{-0.1}\ \mathrm{GeV}$$
$$m(\widetilde{N}_3) - m(\widetilde{N}_1) = 82.0^{+0.4}_{-0.1}\ \mathrm{GeV}$$



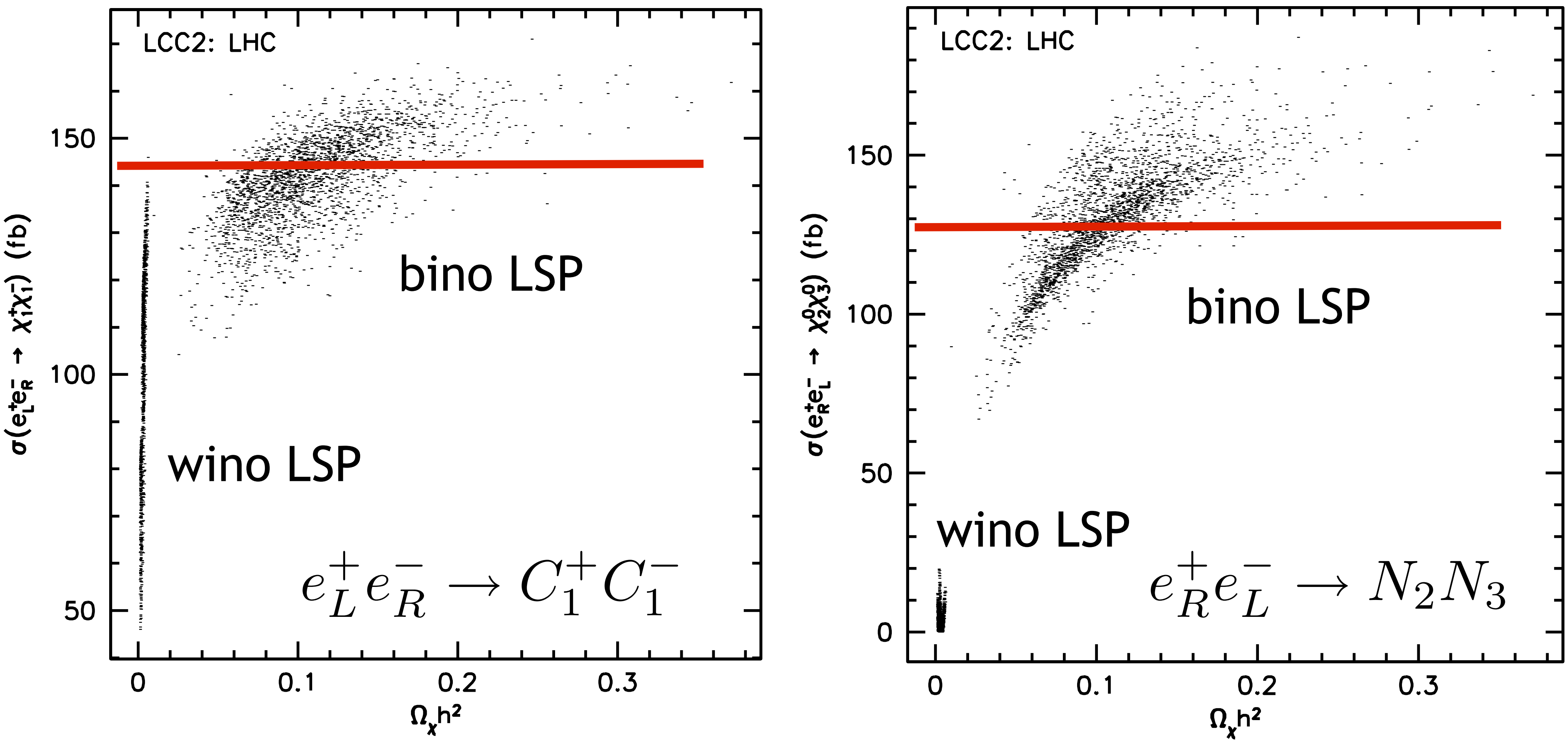
The values of the mass splitting are improved to the per mil level at the ILC.

The detailed shape of the distribution is a nontrivial test of supersymmetry.

However, this is not enough.

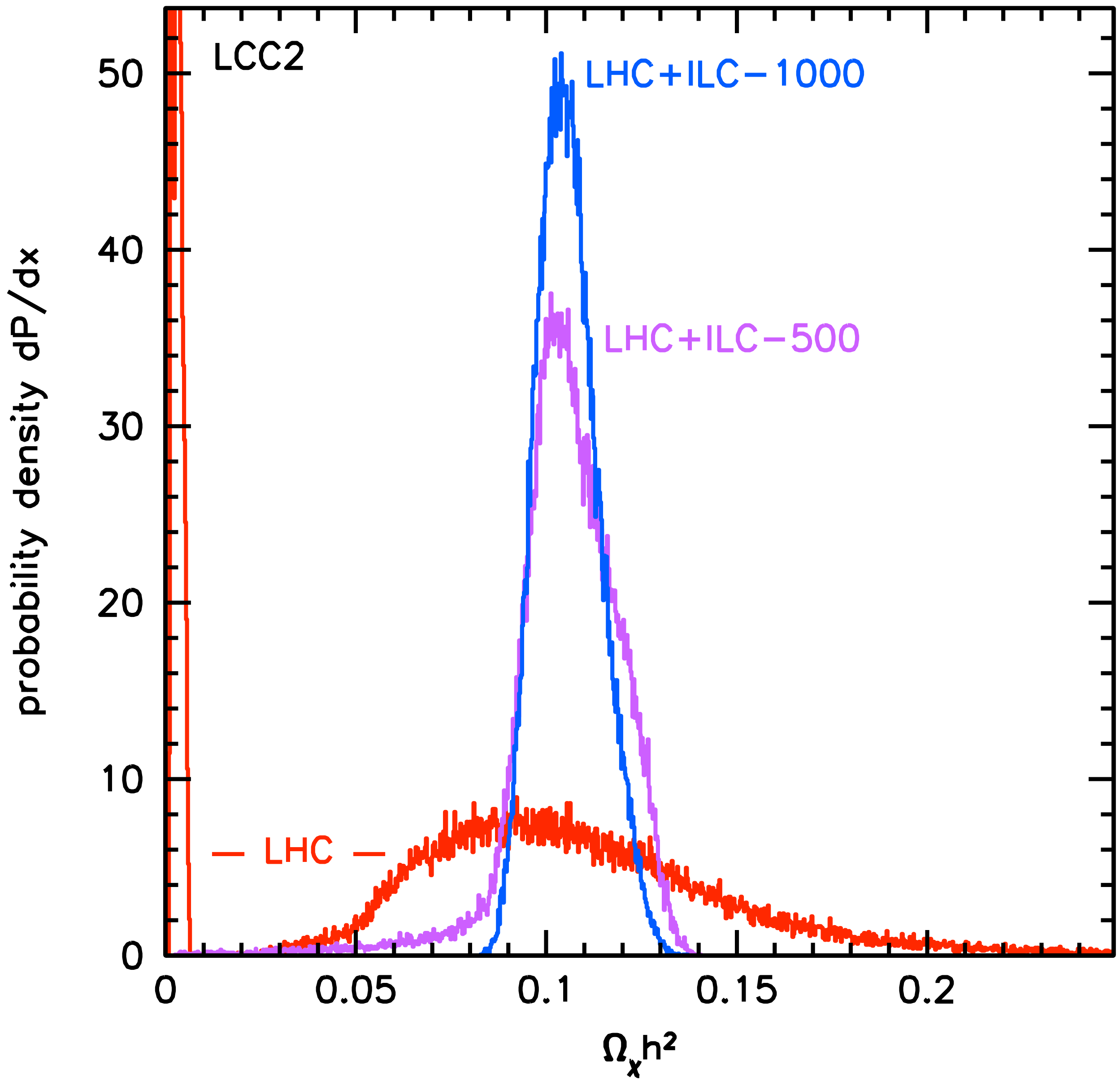
J. Alexander, et al.

Clearly, we need to measure the neutralino and chargino mixing angles. I argued at the beginning of the lecture that this could be done by measuring cross sections for pair production with polarized initial states. Here is the result:



Here are the implications for the dark matter properties.

Here is the prediction of the neutralino relic density from collider physics. This can be compared to the measurement of Ω_N from the CMB.
Do neutralinos make up 100% of the dark matter ?

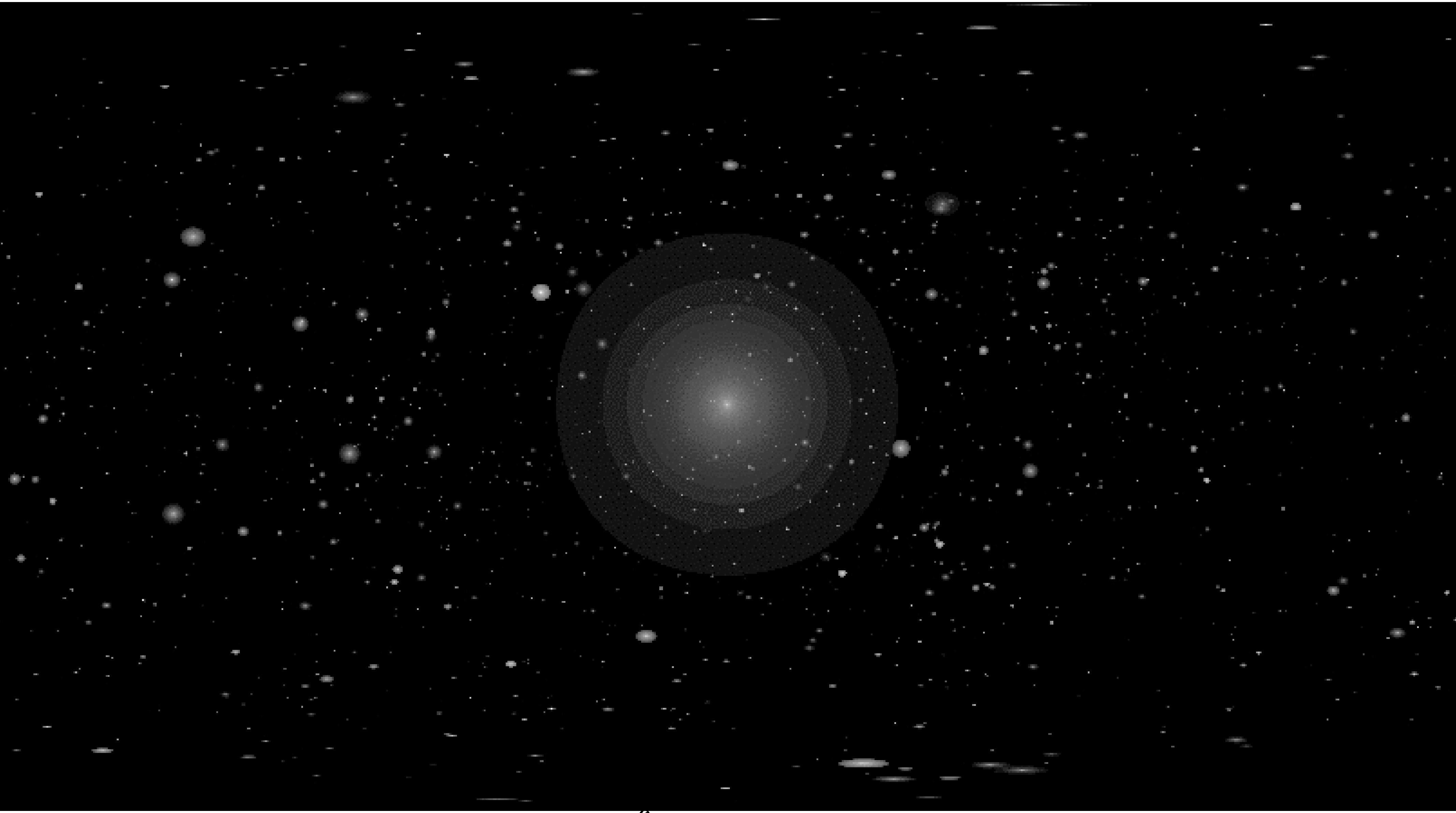


Other interesting astrophysical issues can also be addressed by this measurements.

The distribution of dark matter in the galaxy is expected to be clumpy, since, in cold dark matter evolution, the galaxy was built by hierarchial clustering of dark matter.

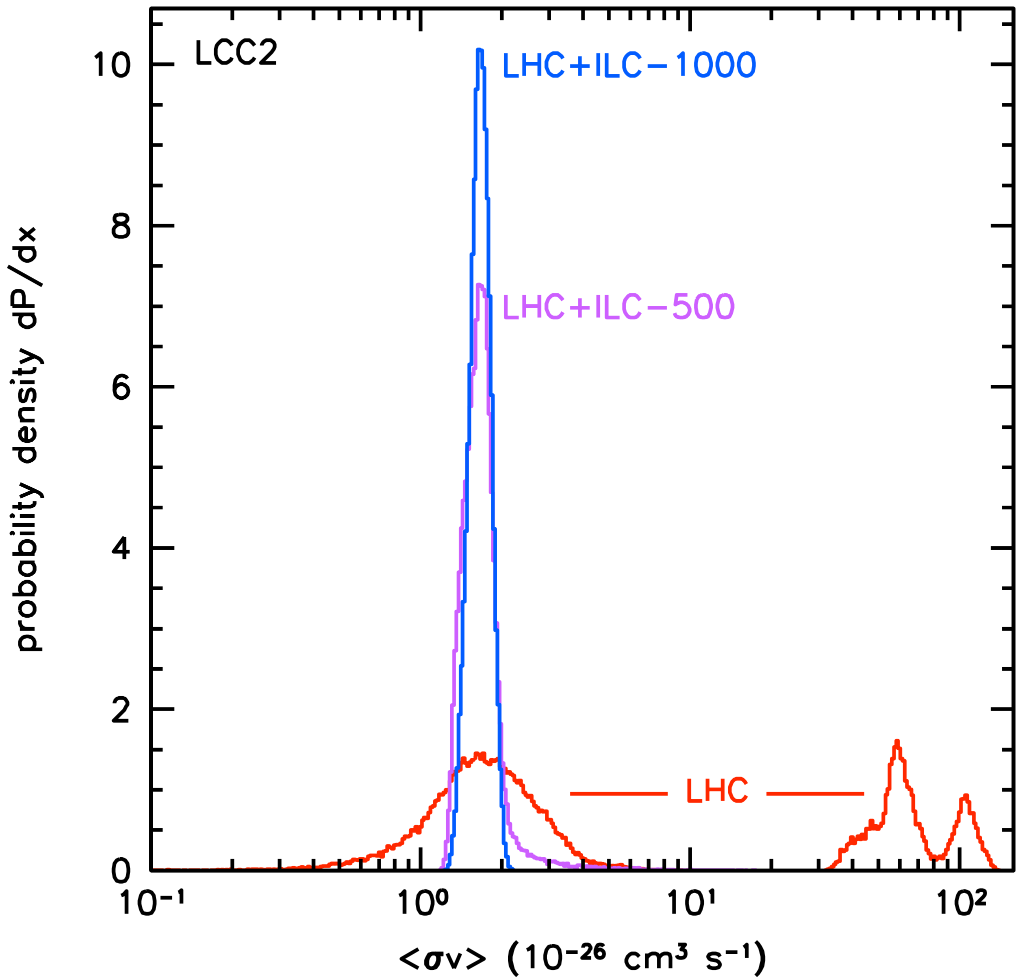
The clumps are expected to shine in gamma rays from dark matter annihilation.

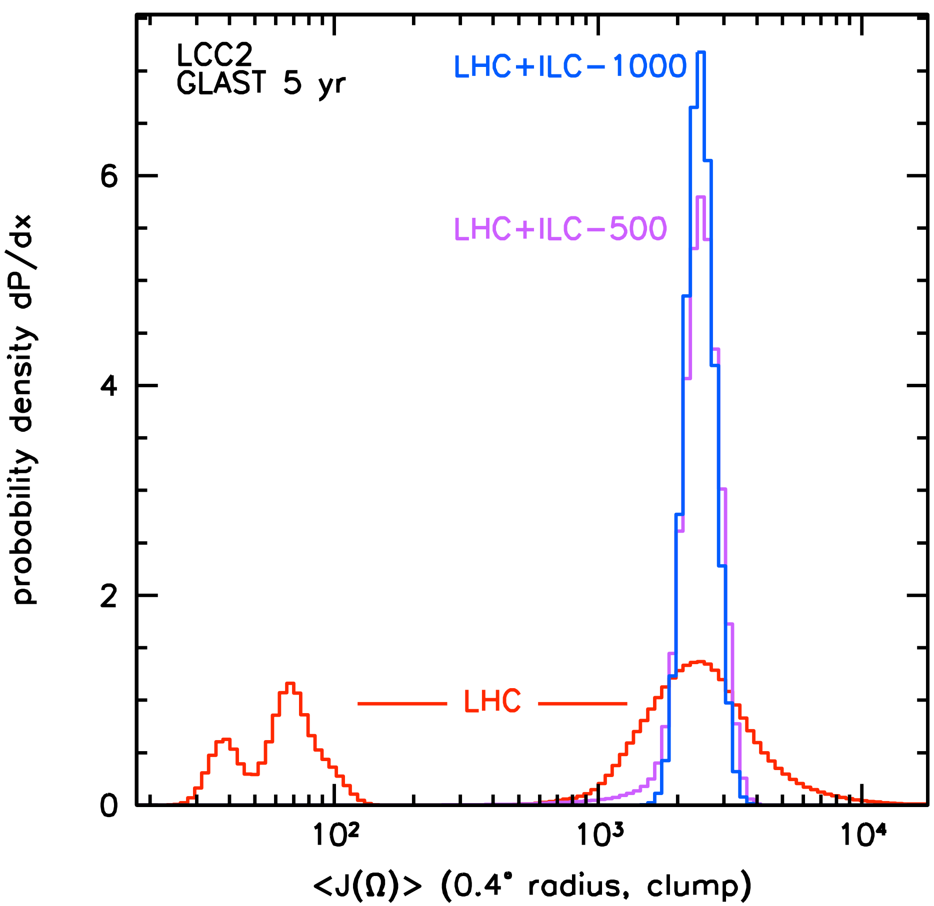
Dark matter structure of a model galaxy, with hierarchial clustering, from simulations of Taylor and Babul



visualization of $J \sim \int dz \; \rho_N^2$ by Baltz.

The collider data also determines the neutralino annihilation cross section at threshold. This can be used to normalize signals of dark matter annihilation in the galaxy, e.g., in gamma rays.





By this method, we can directly determine the density of neutralinos in clusters of dark matter in the galaxy.

Another mechanism to enhance $\langle \sigma v \rangle$ is co-annihilation.

In principle, many species carry the conserved parity of the dark matter particle. Transitions between species are mediated by light particles, which are plentiful in the thermal plasma

$$N + \ell^- \leftrightarrow \widetilde{\ell}^- + \gamma$$

So, relative densities are in thermal equilibrium

If $\quad m_{\widetilde{\ell}} - m_N \sim T_f \quad$ or $\quad \dfrac{m_{\widetilde{\ell}} - m_N}{m_N} \sim \xi \sim 4\%$

then $n(\widetilde{\ell})$ is comparable to $n(N)$.

Some $\widetilde{\ell}$ processes, notably

$$\ell N \to \ell + \gamma, Z^0 \qquad \widetilde{\ell}^- \widetilde{\ell}^- \to \ell^- \ell^-$$

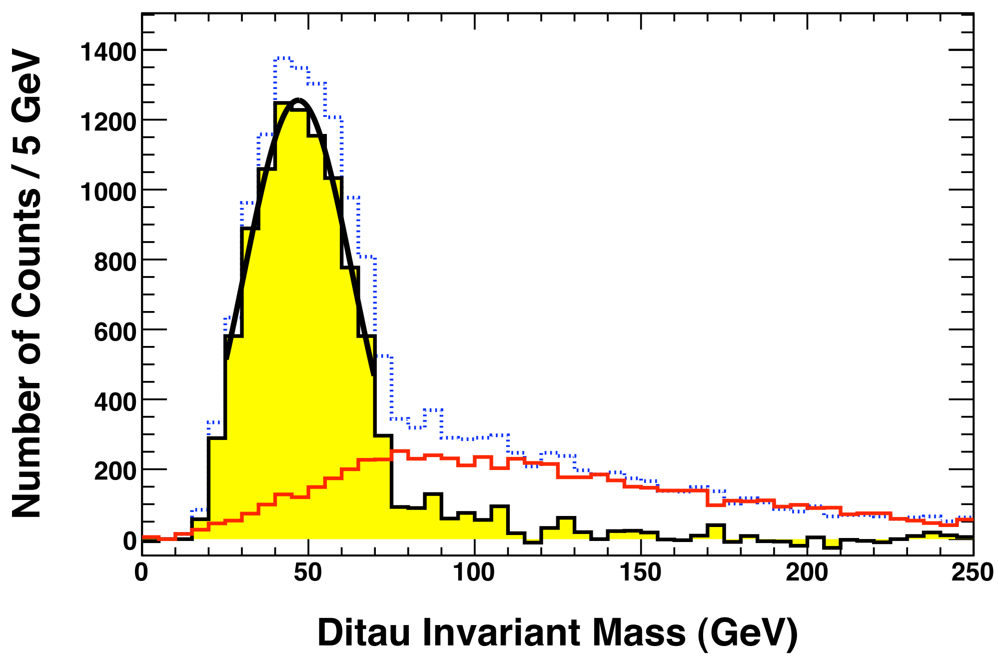
proceed in the S-wave. Then we easily obtain $\langle \sigma v \rangle = 1 \text{ pb}$ for $m_N \sim m_{\widetilde{l}}$ of 100-300 GeV.

In our study, we chose a point LCC3 at which co-annihilation is the dominant mechanism of supersymmetry annihilation in the early universe. The co-annihilating particle is the $\widetilde{\tau}_R$.

You might think that that $\langle \sigma v \rangle$ is strongly dependent on

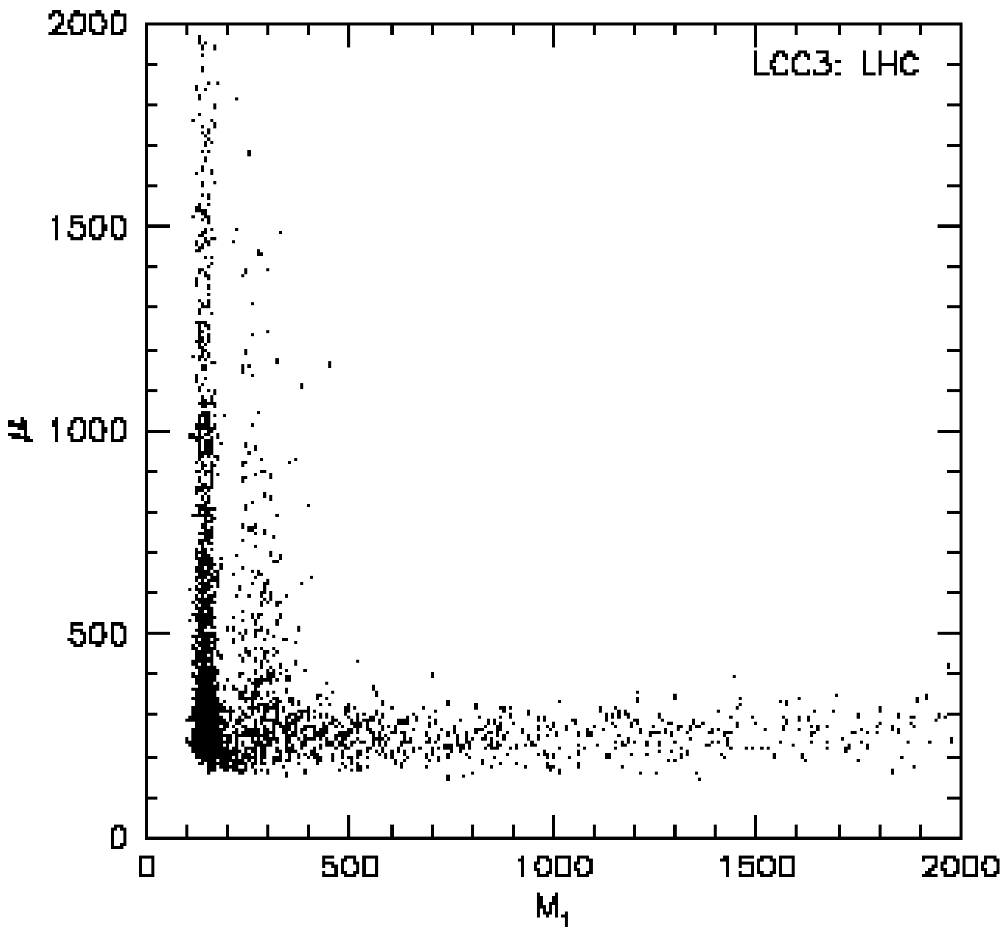
$$m(\widetilde{\tau}_R) - m(\widetilde{N}_1^0)$$

Arnowitt et al. studied this measurement both at LHC and at ILC. At ILC, the mass difference could be measured to better than 1 GeV. At LHC, it is possible to measure the mass difference to a few GeV from the endpoint of the $\tau\tau$ invariant mass spectrum.



However, this is not the whole story. The annihilation cross sections also depend strongly on the content of the lightest neutralino, and on the value of $\tan\beta$.

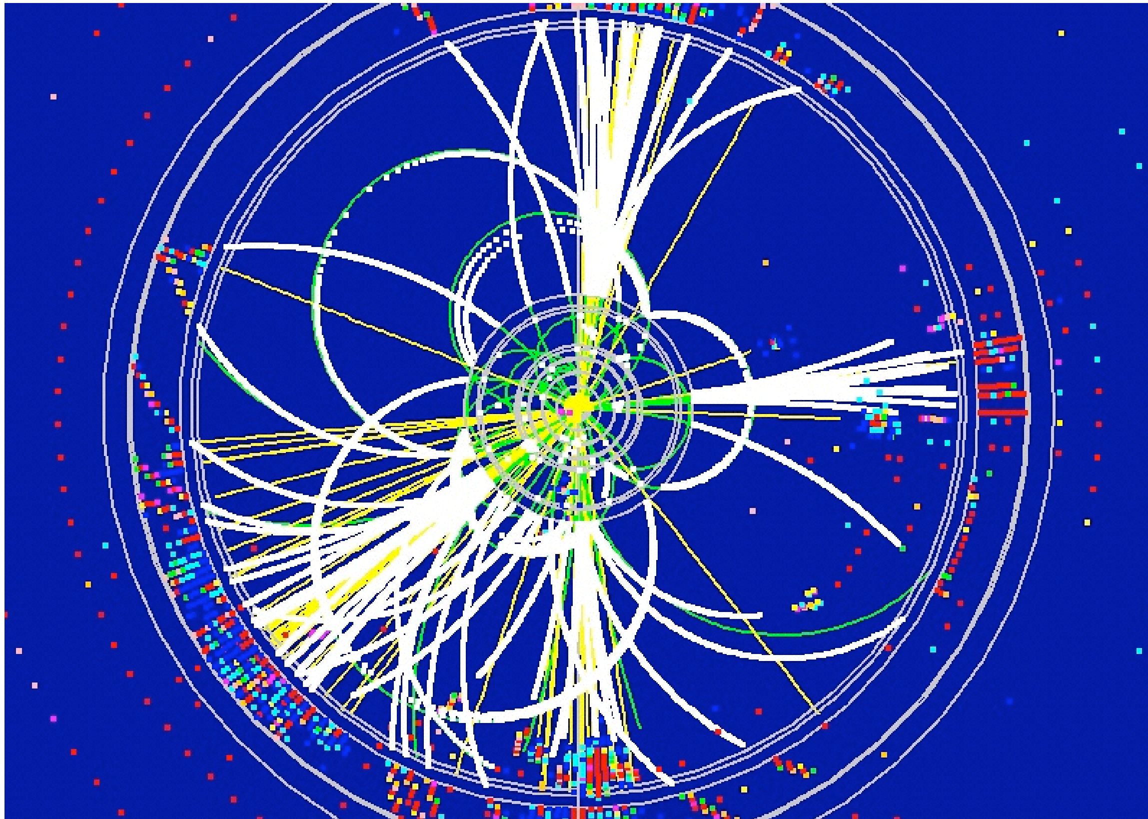
At LCC3, this information is not available at the 500 GeV ILC, but it can be found from measurements at 600-800 GeV.

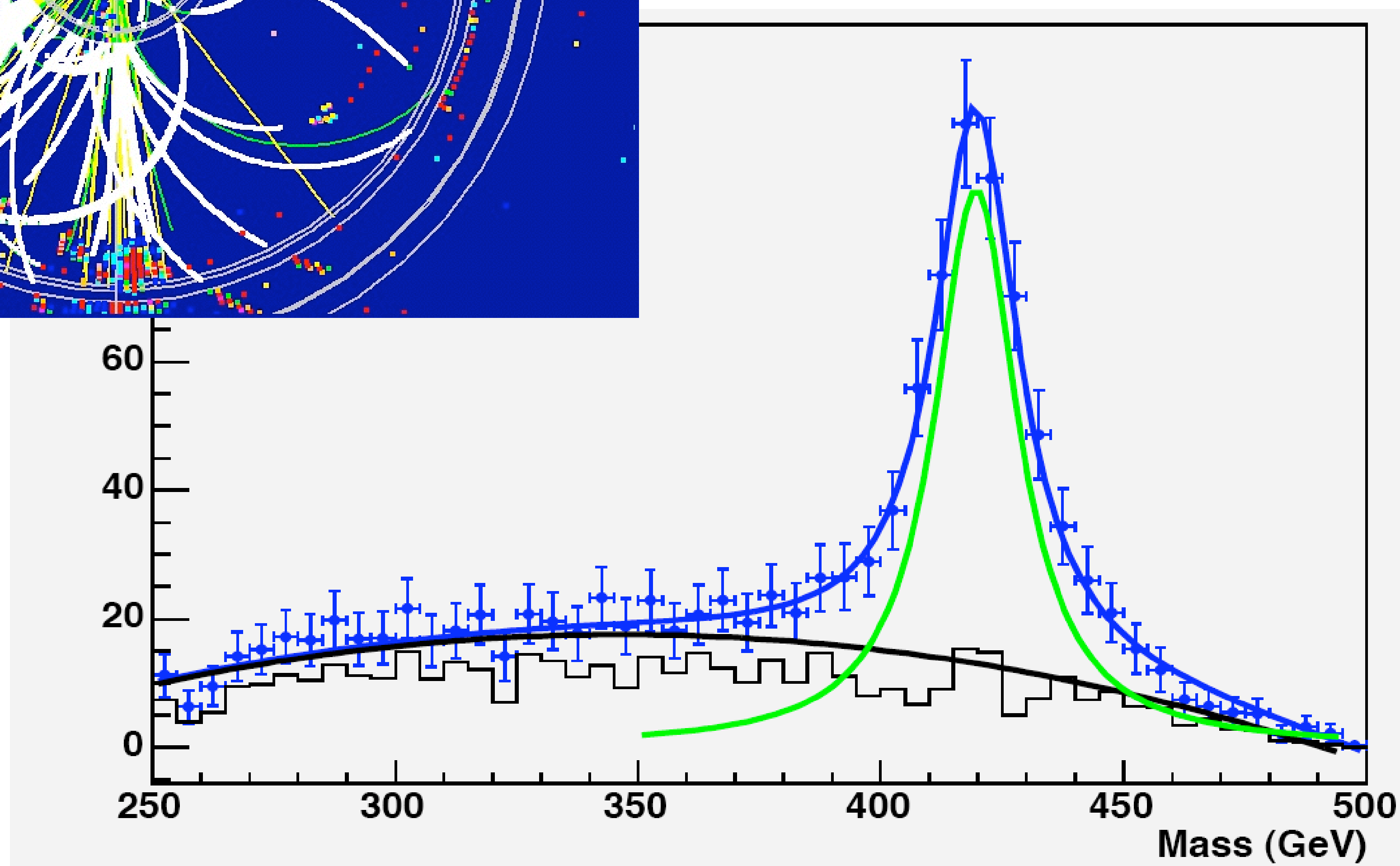


$\tan\beta$ is determined from the observation of

$$e^+e^- \to H^0 A^0 \to 4b$$

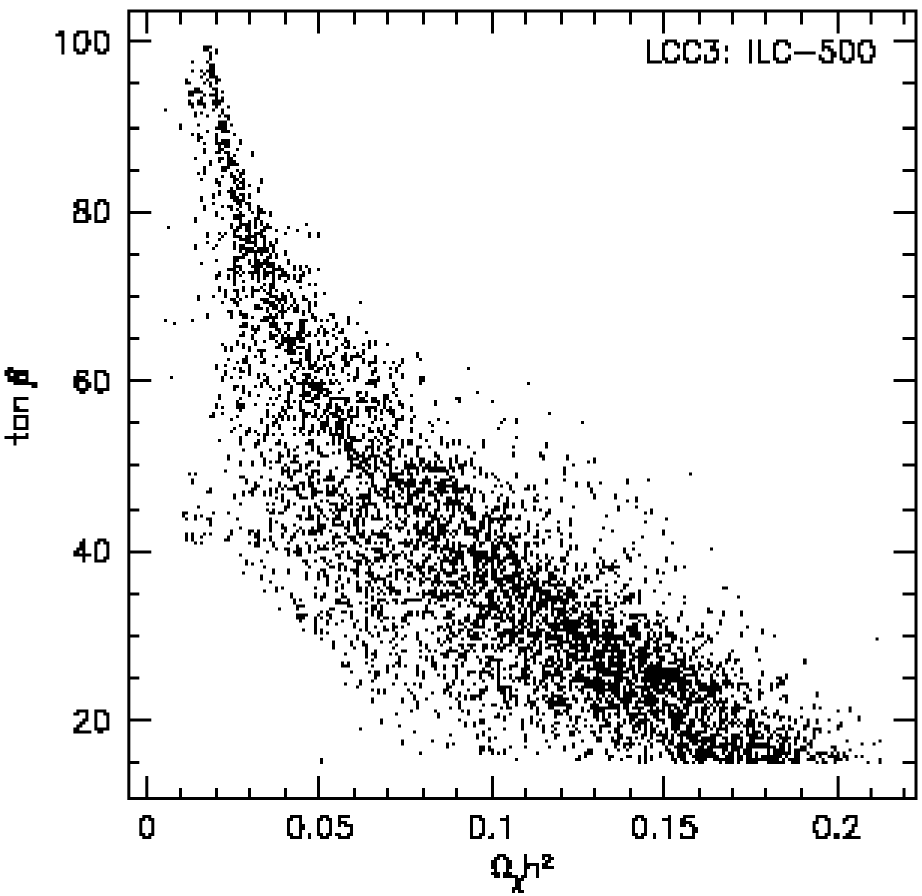
at the ILC, and measurement of the H, A width.



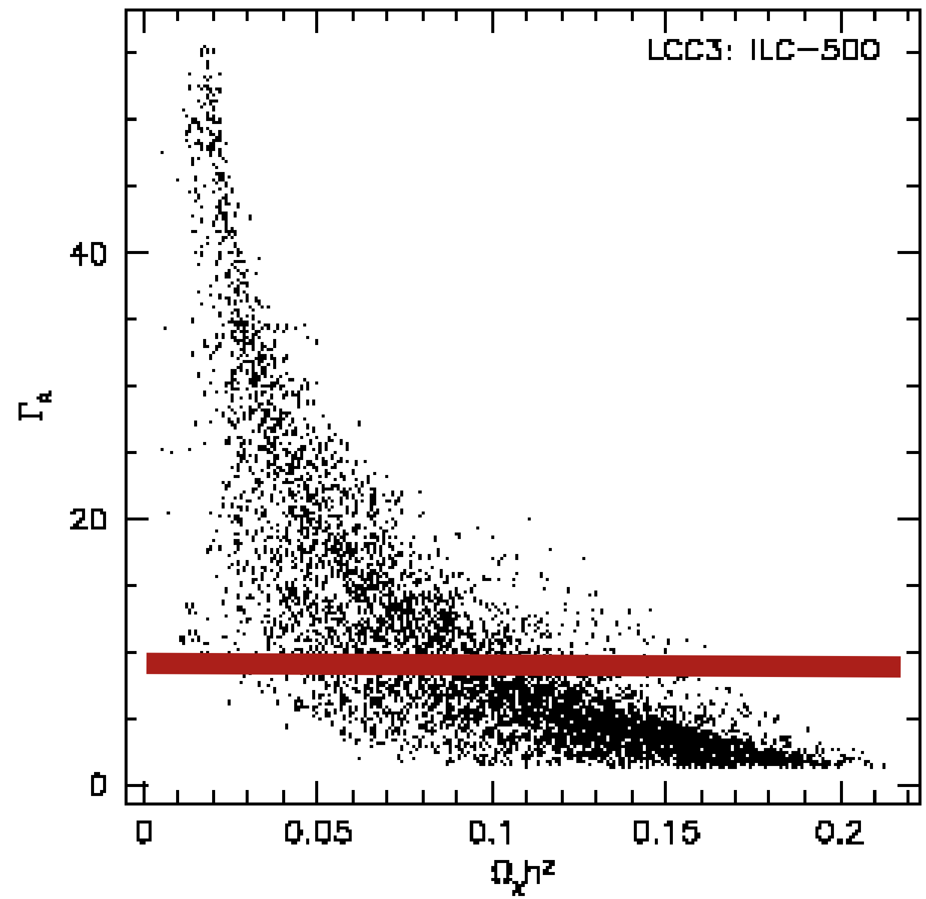


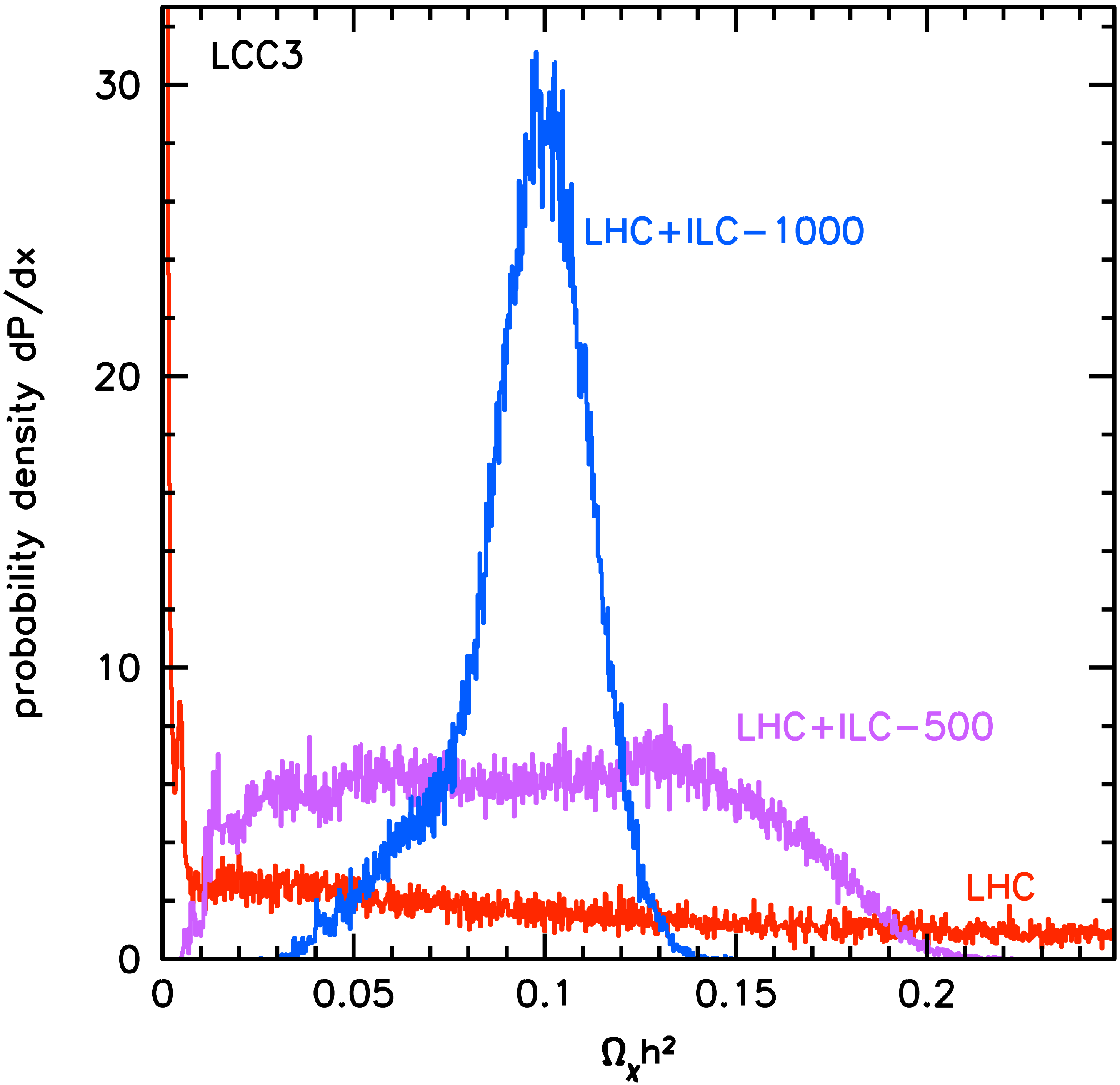
M. Battaglia

$\Omega_N h^2 \ vs. \ \tan\beta$



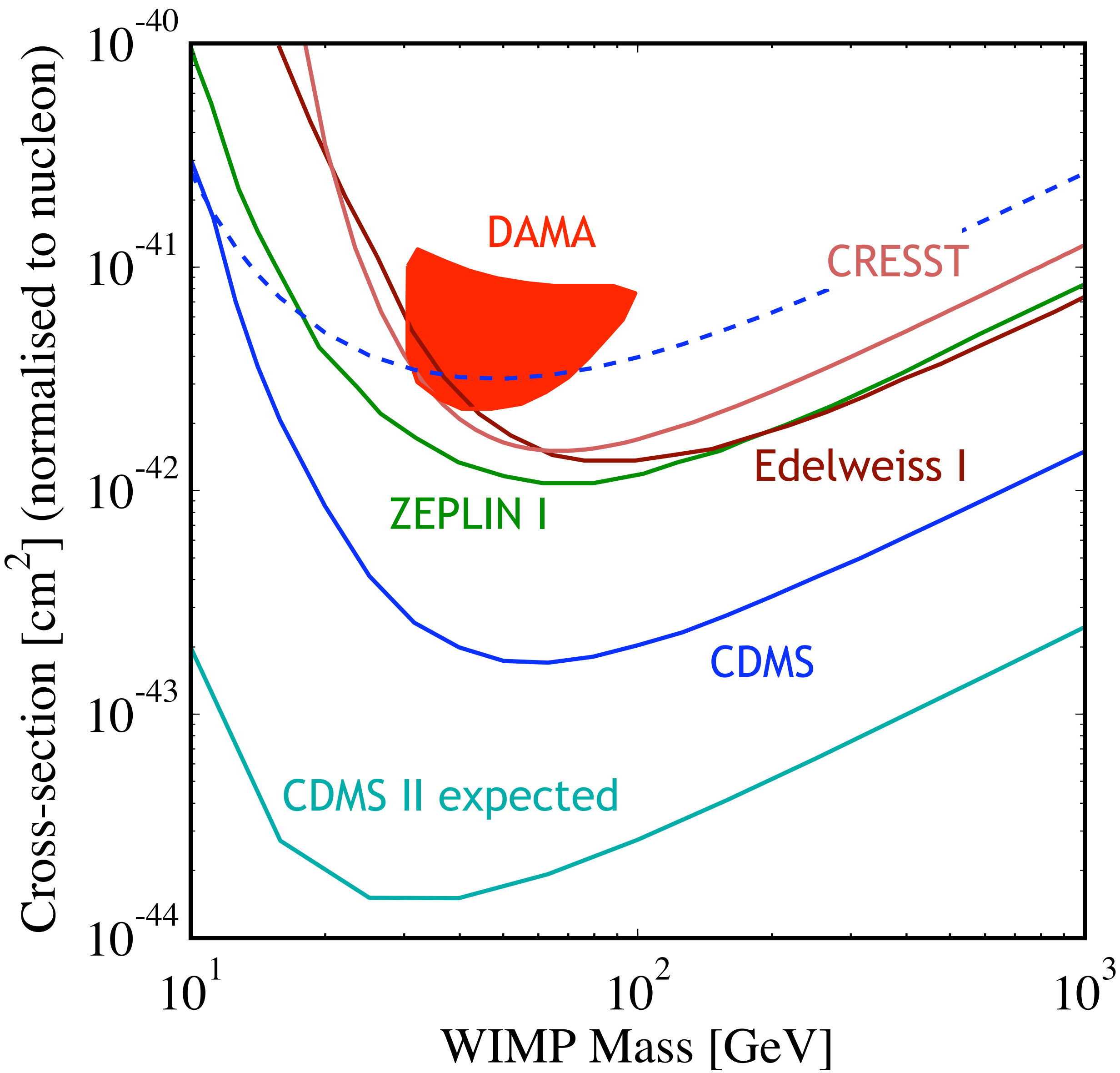
$\Omega_N h^2 \ vs. \ \Gamma_A$




LCC3
LHC+ILC−1000
LHC+ILC−500
LHC
probability density dP/dx
$\Omega_\chi h^2$
0
10
20
30
0.05
0.1
0.15
0.2

Collider experiments can also give information important for understanding the direct detection of WIMPs. The current situation is the exclusion plot

$\sigma(Np)\ \mathrm{cm}^2$



from DMtools - Gaitskell & Mandic

The next generation of detectors

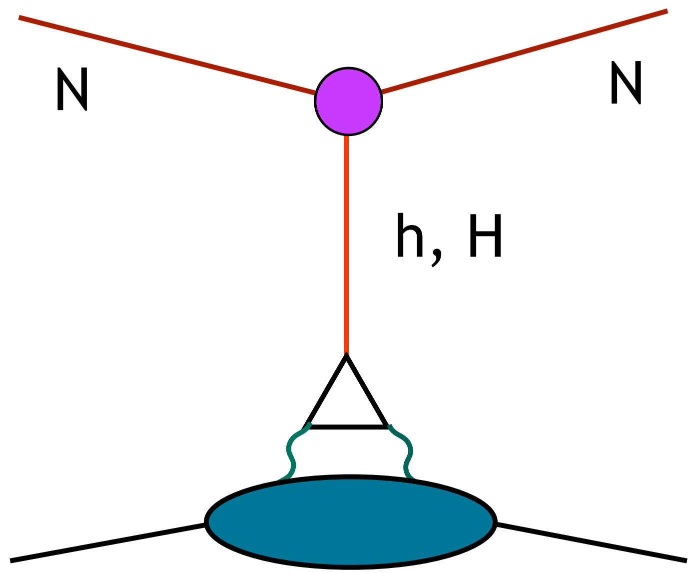
superCDMS (Germanium), Xenon, WARP (Liquid Argon)

and others should reach a sensitivity of

$$\sigma(Np) \sim 10^{-45}\ \mathrm{cm}^2 = 1\ \mathrm{zeptobarn}$$

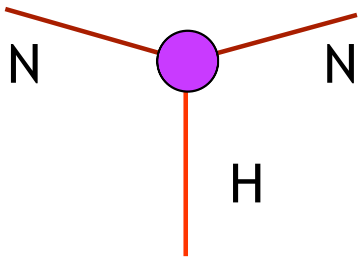
If (when) a detection is observed, how will we analyze it ?

The full expression for the Np cross section in SUSY is quite complicated. However, if squarks are sufficiently heavy, this cross section is typically dominated by the diagram:



To evaluate the cross section, we need to know the mass and couplings of the Higgs bosons h and H.

The neutralino-Higgs coupling



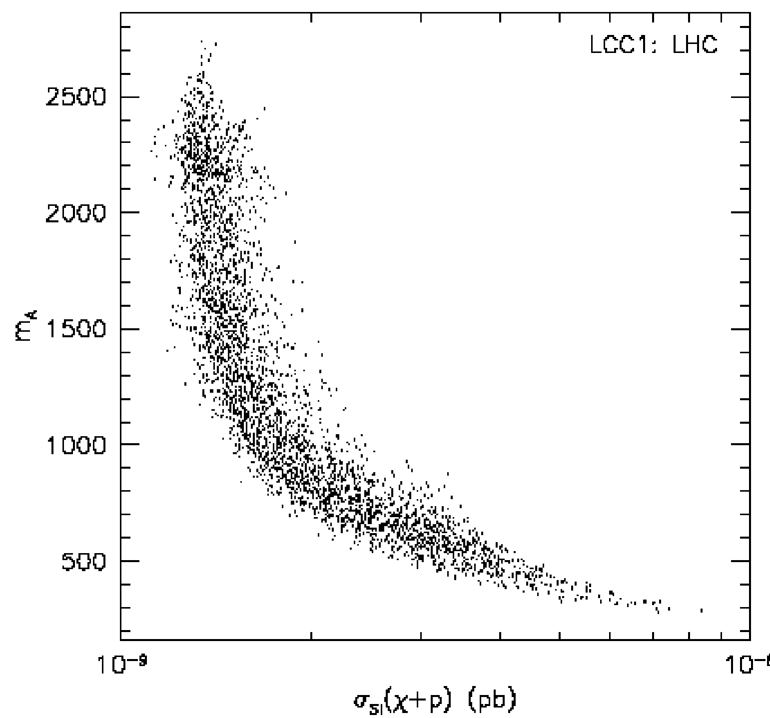
$$= \frac{ie}{2}\left(\frac{V_{11}}{c_w} - \frac{V_{21}}{s_w}\right)(V_{31}\cos\alpha - V_{41}\sin\alpha) + (i \leftrightarrow j)$$

depends both on $\tan\beta$ and on the neutralino mixing angles.

The Higgs mass is a crucial parameter. The heavy Higgs can be found at the LHC only if $\tan\beta$ is sufficiently large.

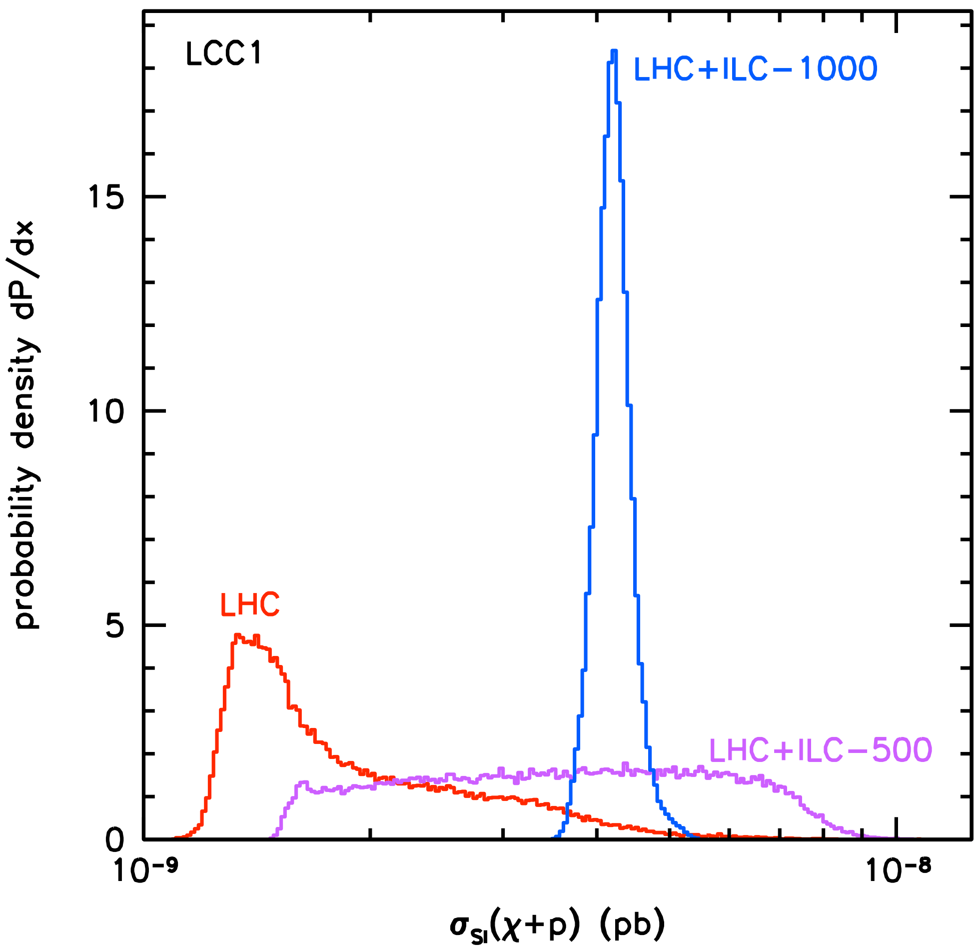
Otherwise, we need to measure this mass at the ILC.

$$\sigma(Np)\ vs.\ m_A$$

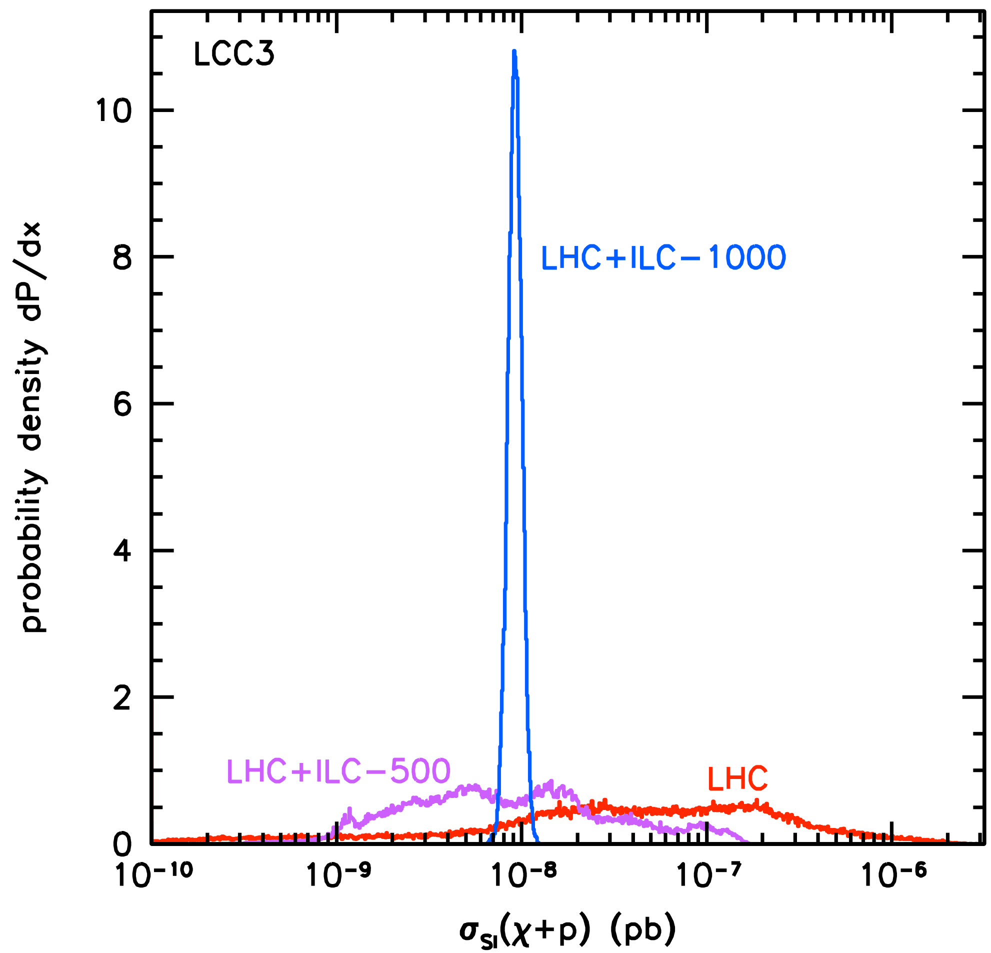


Here are estimates of the accuracy with which colliders will determine the Np cross section, from Baltz et al. (ignoring the f_{Ts} uncertainty)

SPS1a:
the H boson cannot be discovered at LHC; this needs the ILC-1000

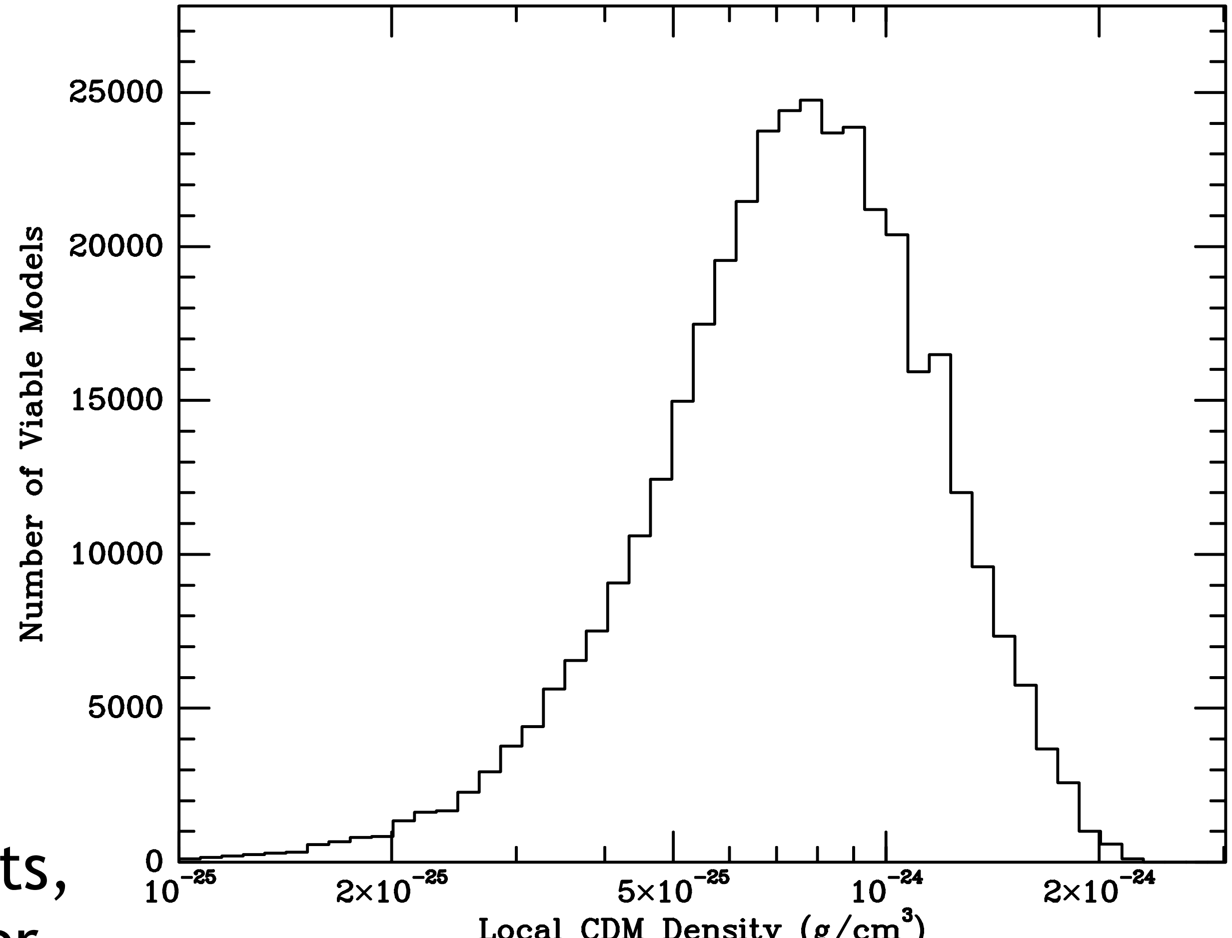


Arnowitt et al point:
the H boson should be discovered at LHC, but mixing angles need the ILC-1000



The direct detection rate also depends on the local density of WIMP dark matter. More specifically, the direct detection rate is proportional to the local flux of WIMPs.

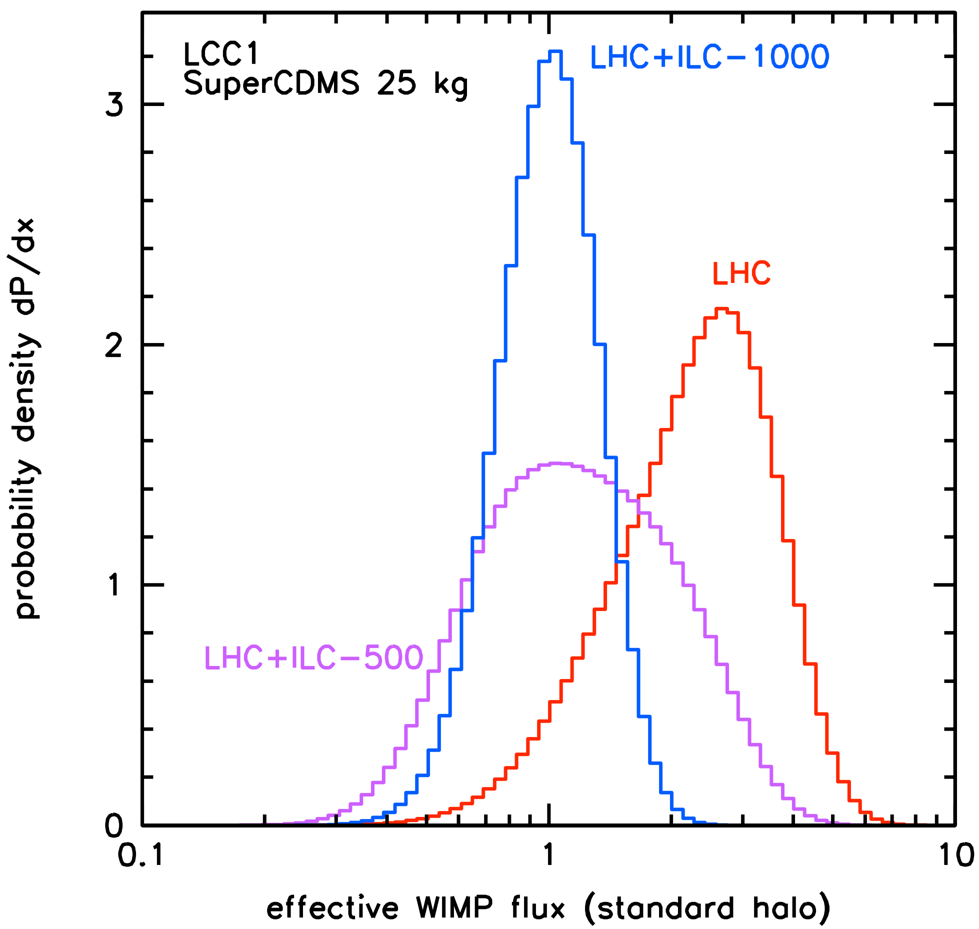
Gates, Gyuk, and Turner constructed a large number of models consistent with the galactic rotation curve. Here is the distribution of the local WIMP density:



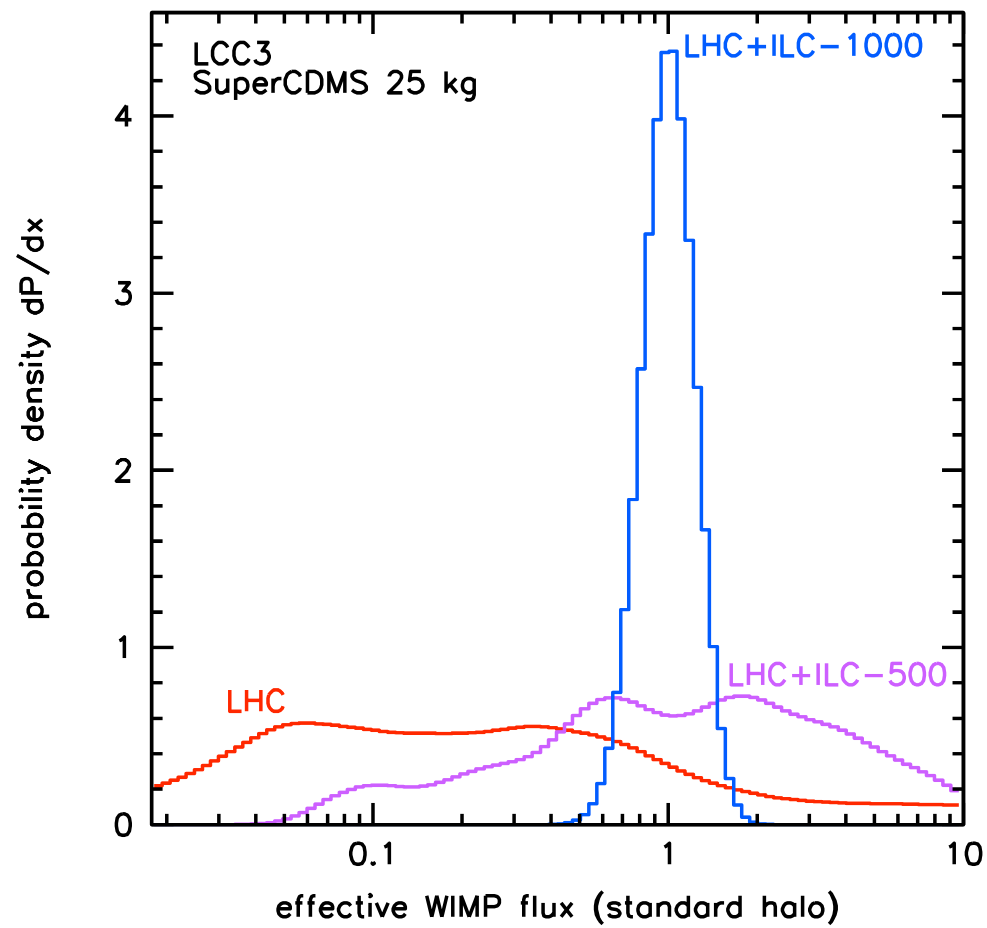
Other models of the galactic halo predict mutliple WIMP components, some of which have higher velocity than the standard one.

If the LHC and ILC measurements would determine $\sigma(Np)$, we could turn the story around: measure the detection rate, divide by the known cross section, and learn the value of the local WIMP flux. Here is how well it should be done, combining the previous estimates with the counting rates from super-CDMS:

LCC1: 16 events



LCC3: 29 events



It is remarkable how the fine details of new particle interactions that the ILC makes available to us become the key inputs from particle physics to the astrophysical exploration of dark matter.

Astrophysicists, then, need the ILC,

and we can accurately say that we need the ILC to understand the universe on large scales as well as small ones.

The important information begins at the first new particle threshold, though in the examples we studied it was also important to run the ILC above 500 GeV.

There is much more to say about precision measurement of the Lagrangian parameters of new particle at the ILC.

But, again, please excuse me if I skip ahead, to the era beyond the ILC.