Dark Matter in the Cosmos and in the Lab

M. E. Peskin
October 2007

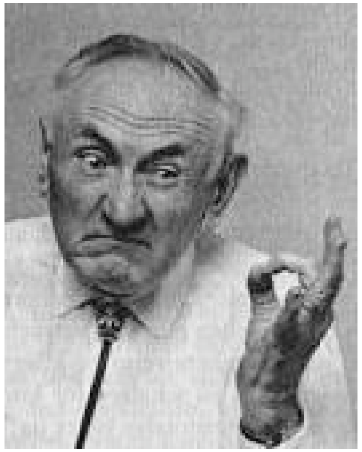
As we look out into the universe, we see stars, galaxies, clusters.

It seems that we can see just where the mass is, and how much there is.

But, in fact, it is just the opposite.

T. A. Rector and B. A. Wolpa - NOAO/AURA/NSF

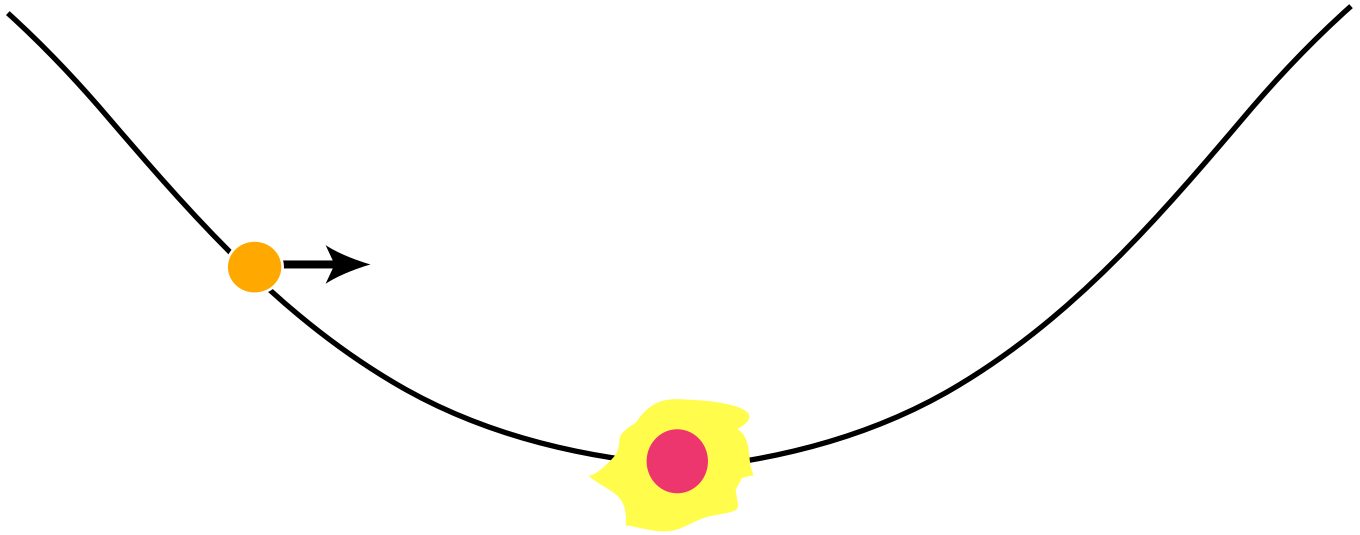
Our story begin in 1933, when Fritz Zwicky measured the mass of the Coma cluster of galaxies.



Fritz Zwicky

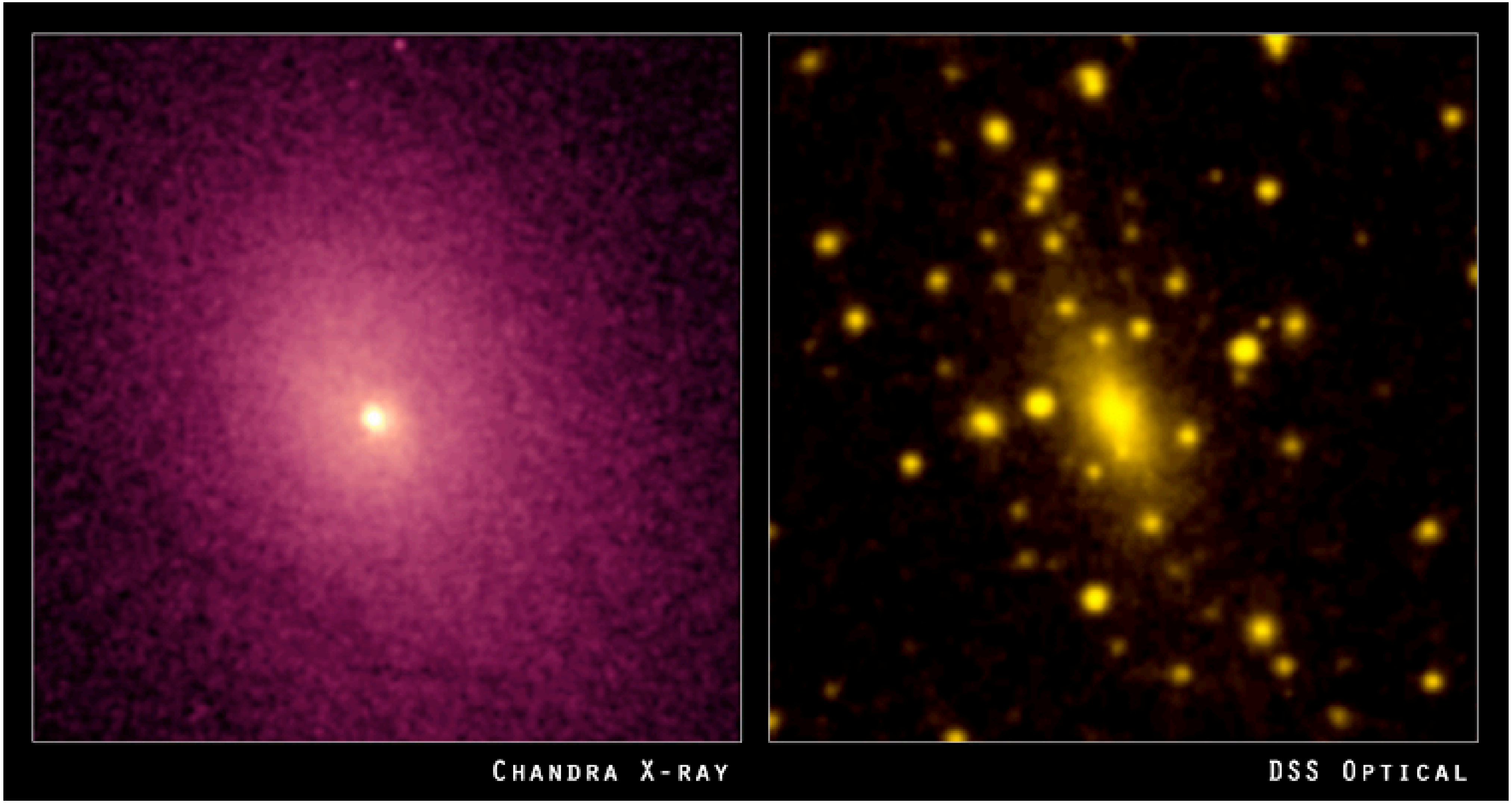
O. Lopez-Cruz and I. K. Sheldon - Kitt Peak from the observed motion of galaxies within a cluster:

use the virial theorem to deduce the gravitational forces, and thus the gravitating mass:



The analysis required 400 times more mass than the total mass of the stars in the galaxies.

We now know that much of this mass takes the form of hot gas radiating X-rays:



Abell 2029

but still only 10-20% of the mass is accounted for.

Many pieces of evidence corroborate this result.

For example, look at the gravitational potential of our galaxy.

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 review

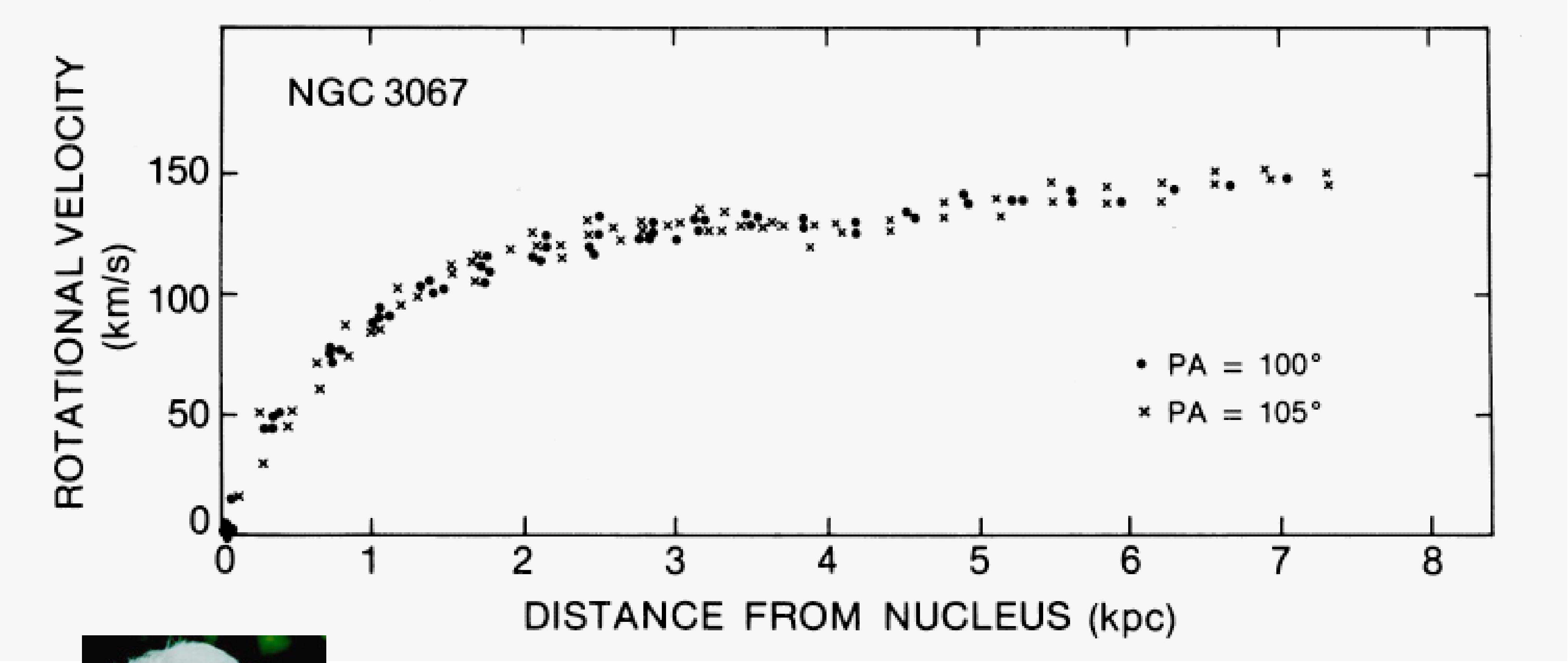
Look at other galaxies. From the Doppler shifts of outlying stars, measure the ‘rotation curve’ v(r).

According to Kepler’s law, we expect

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

if the mass of the galaxy is concentrated in the region where stars are visible.

but for the outlying stars in galaxies, one finds:

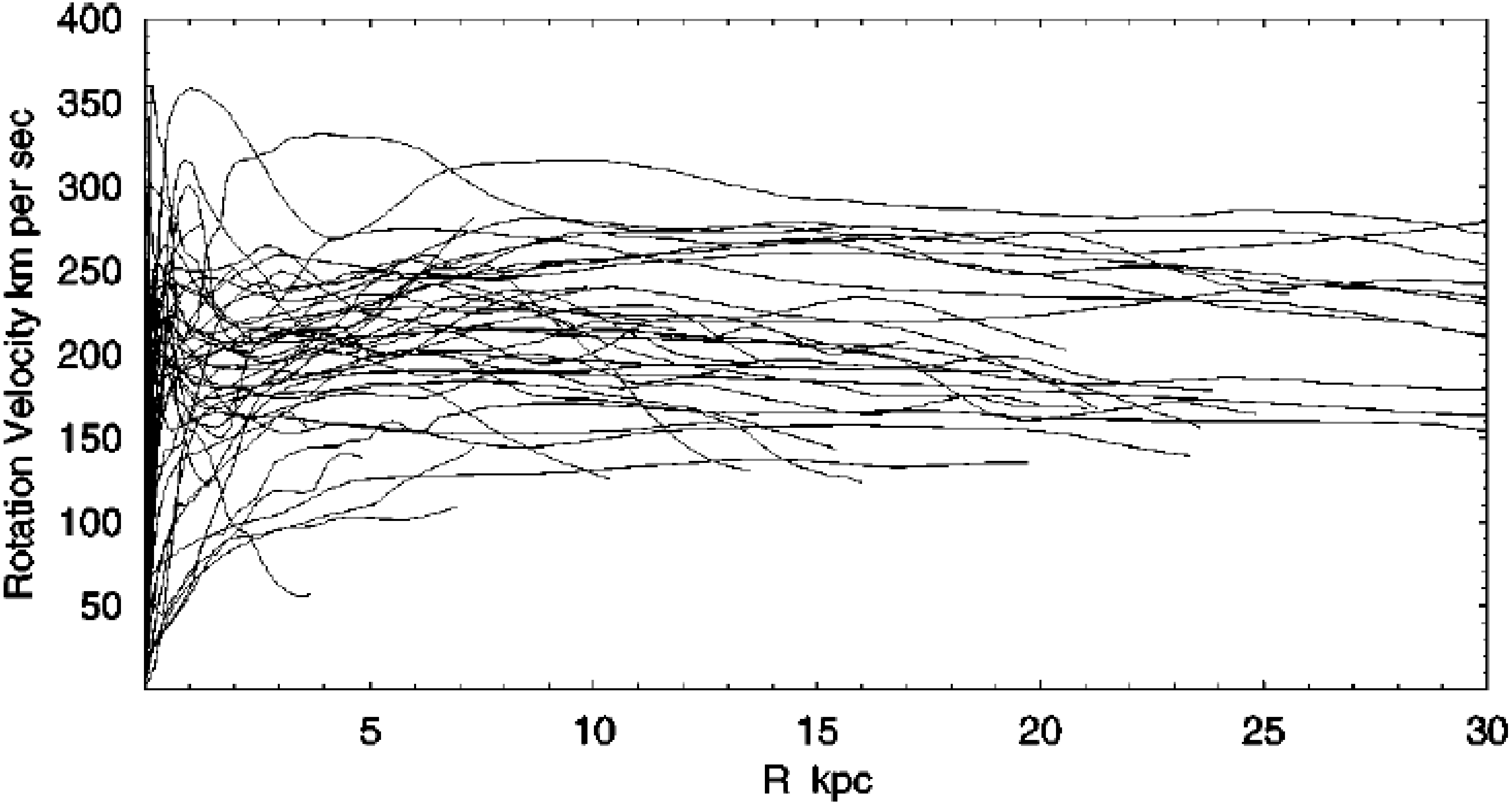


Vera Rubin

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."

Here are the ‘rotation curves’ of 25 more galaxies.



Sofue and Rubin

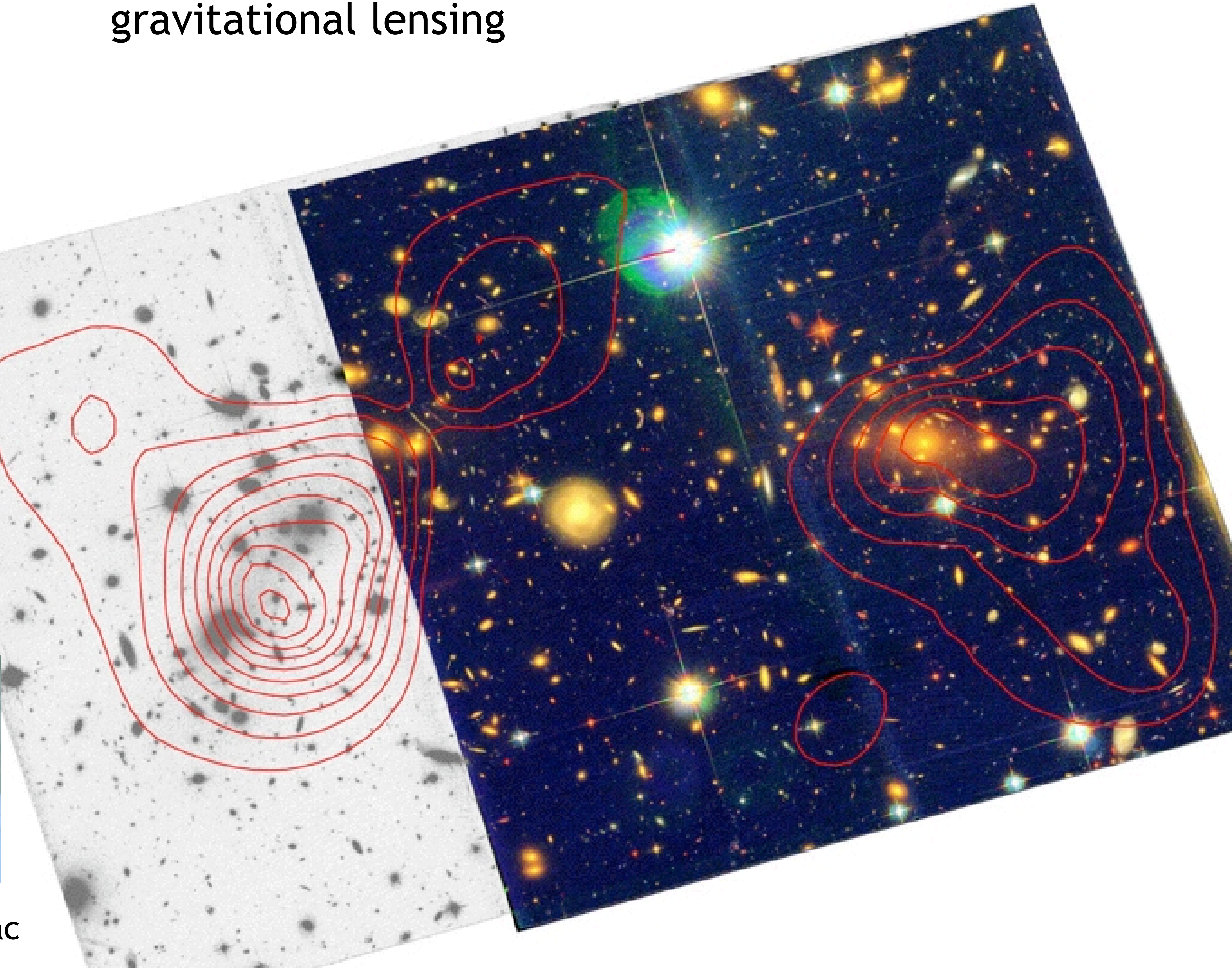
A large concentration of mass such as a cluster of galaxies will bend light, as a ‘gravitational lens’.

If there is a bright galaxy or a quasar behind a cluster, the bending measures the mass of the cluster.

Zwicky actually suggested this technique in 1937.

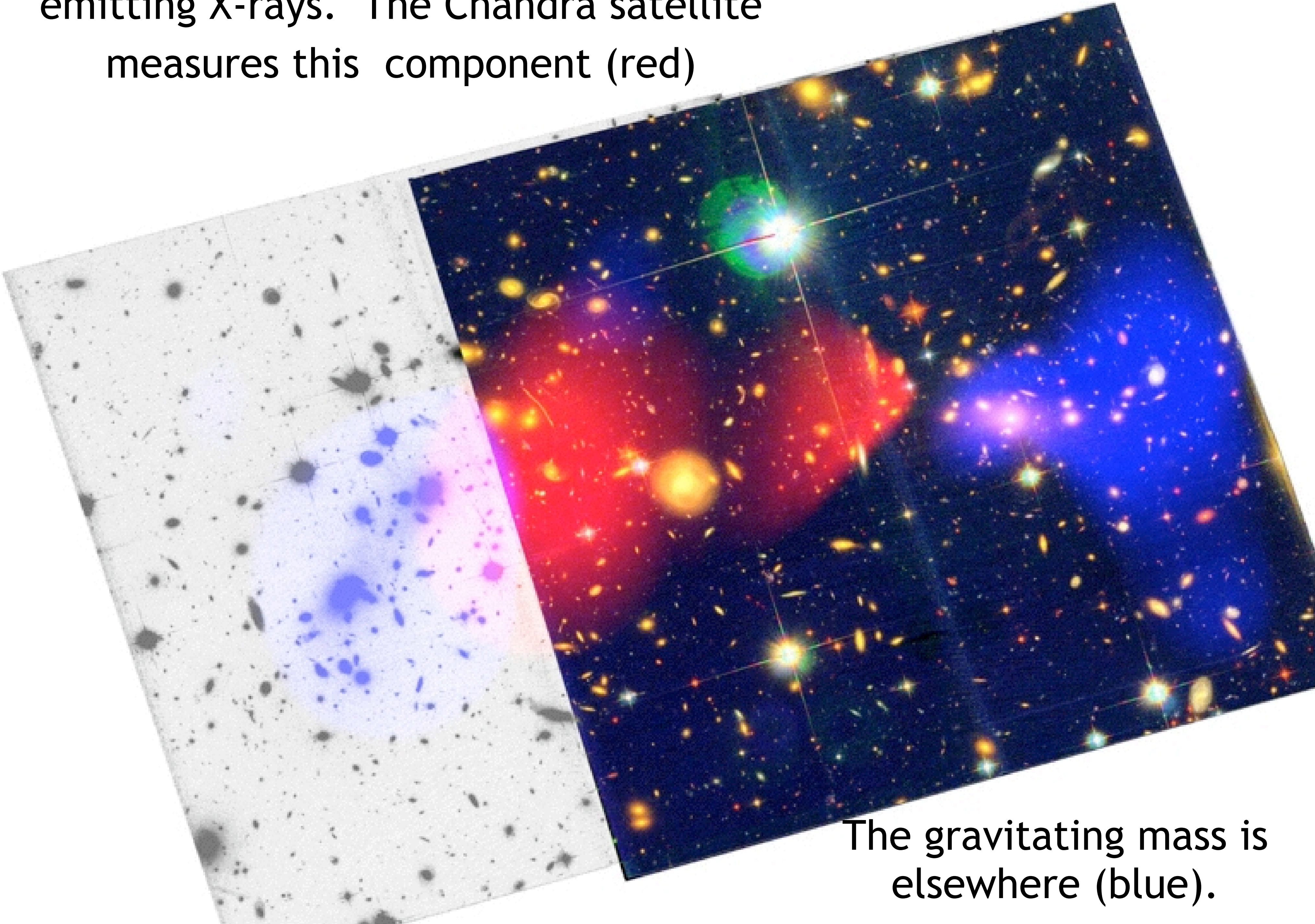
W. N. Colley, E. Turner, J. A. Tyson -- Hubble Space Telescope the bullet cluster (1E0657-56) provides an interesting example. Here is the Hubble Space Telescope Image:

Here is the mass distribution reconstructed from gravitational lensing



Marusa Bradac

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



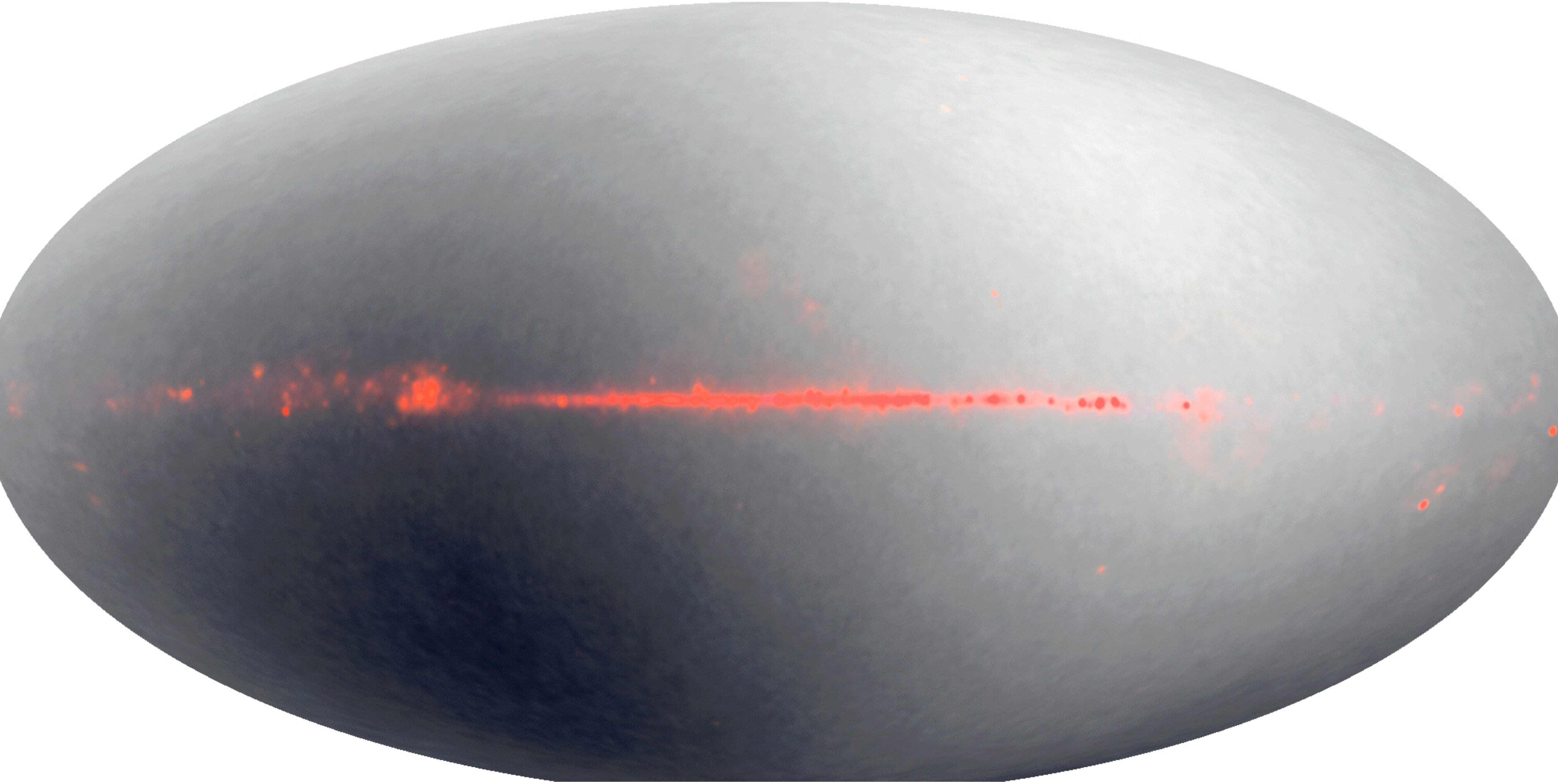
The gravitating mass is elsewhere (blue).

Finally, it is possible to measure the truly primordial density of matter.

Very early in the history of the universe, it was so hot that all hydrogen was ionized.

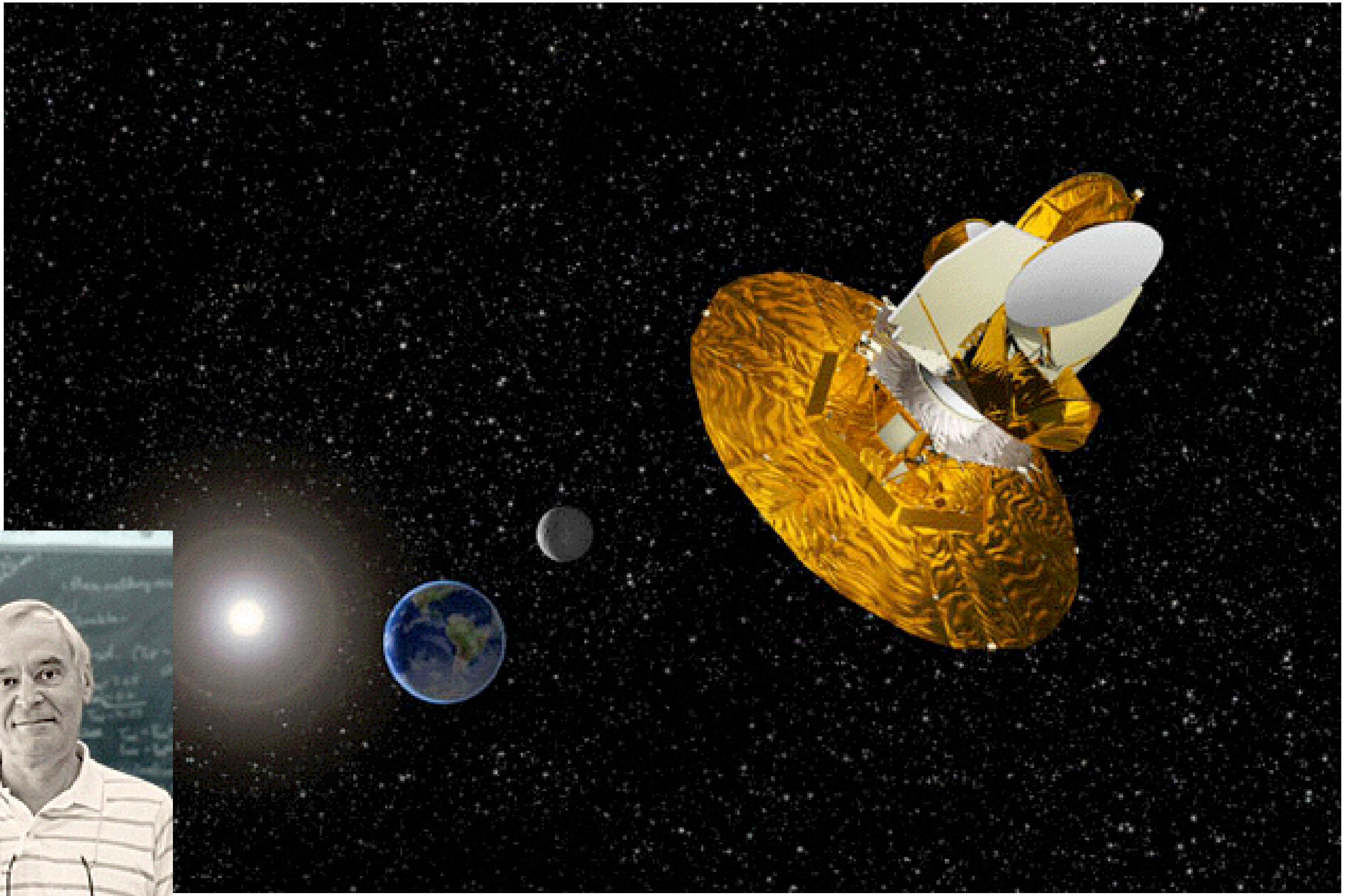
The light emitted when the ionized atoms capture electrons is now visible as a ‘microwave background radiation’ at 2.7 K.

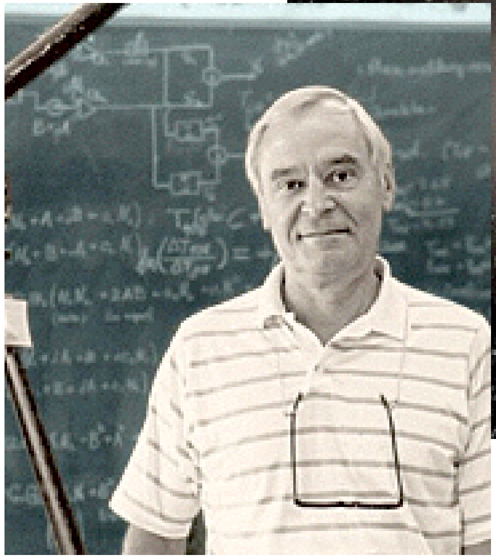
Here is a temperature map of the microwave background



WMAP Science Team

Wilkinson Microwave Anisotropy Probe

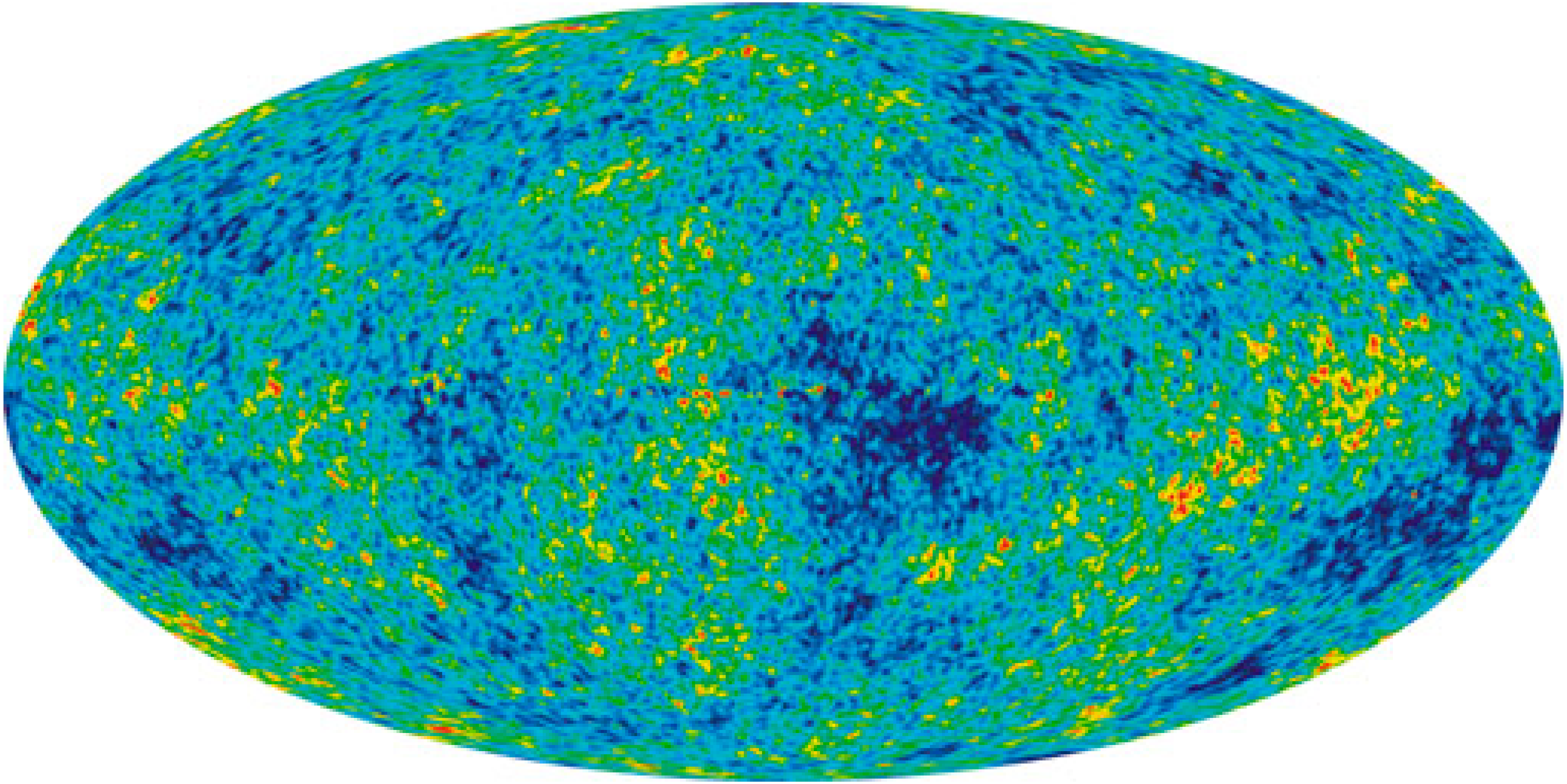




David Wilkinson

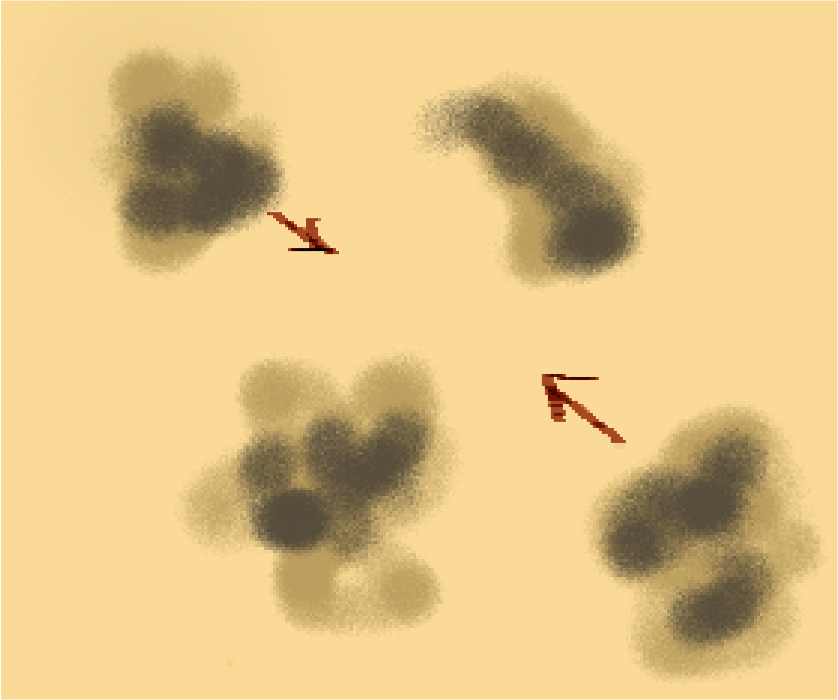
a double microwave receiver,
located at the Lagrange point L2

subtract the Earth’s motion and galactic sources
blow up the residual differences by a factor 100,000



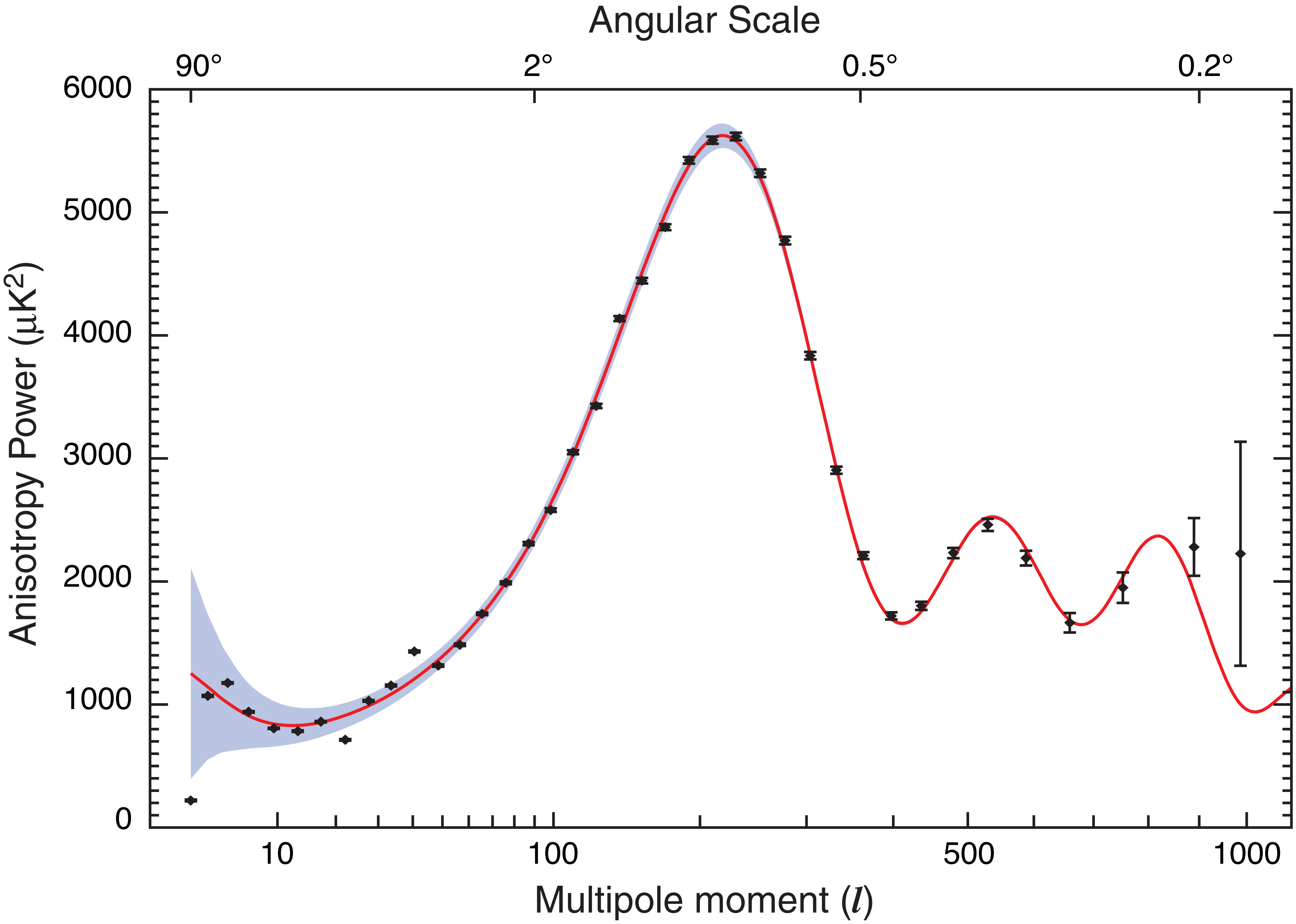
WMAP science team - 2006

The visible peaks and valleys are amplified from the primordial spectrum of fluctations as matter falls into local gravitational potentials.



These regions were of size 100,000 light-years when created; this expands to 100 M light-yr today.

Sound waves are created. Their reverberations measure the dissipation of the cosmic plasma.



WMAP Science Team - 2006

From the first peak position, we learn that the universe is flat when viewed in the large.   So the total energy density in the universe is Einstein's closure density ρ_c.

From the rebounds, we measure a very small dissipation. This implies that only 20% of the matter is atoms; 80% is non-interacting.

In all, the energy of the universe is distributed as:

$\Omega_b = \rho_b/\rho_c = 4.2\%$ atoms

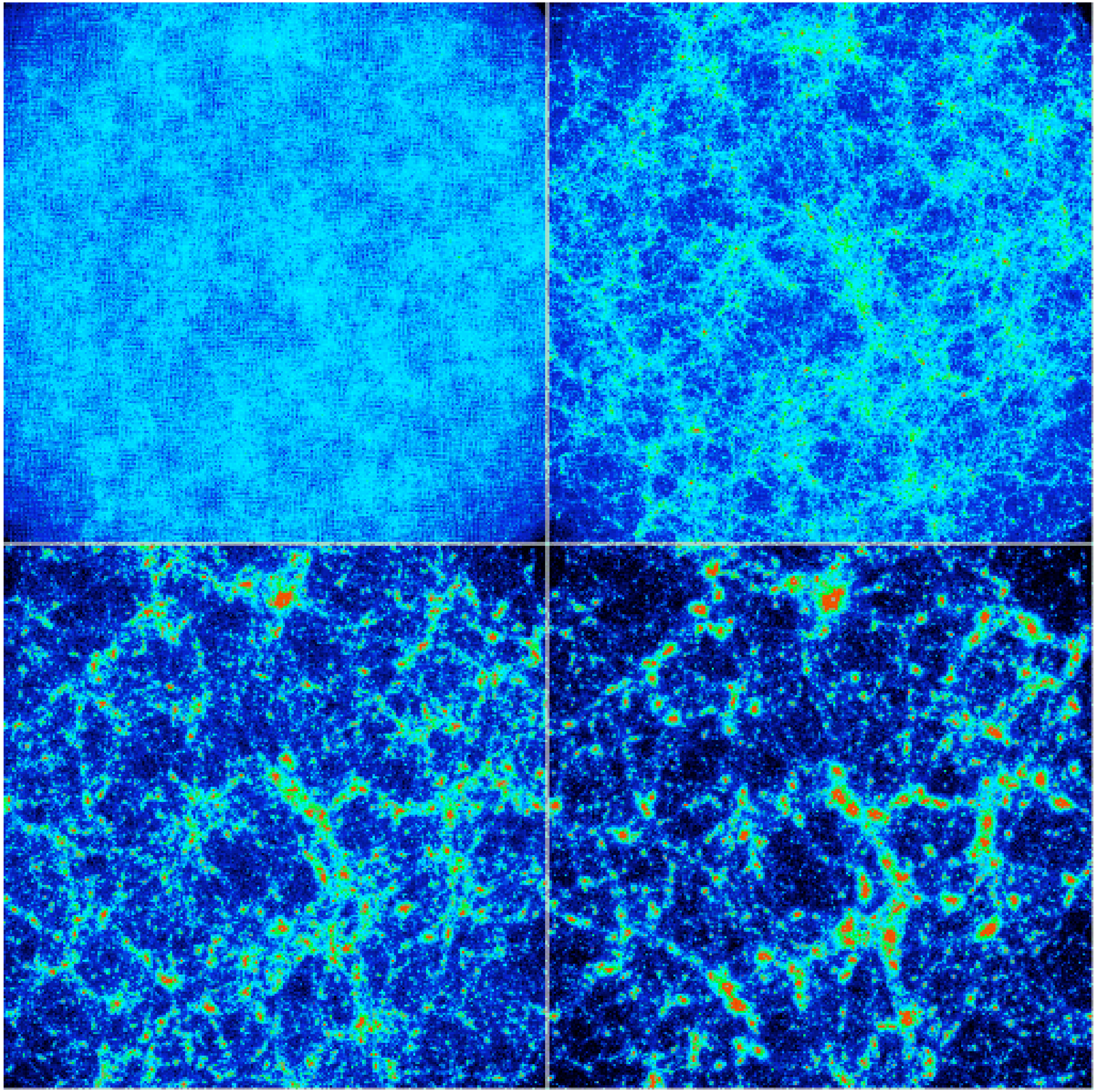
$\Omega_d = \rho_d/\rho_c = 20.\%$ dark matter

$\Omega_\Lambda = \rho_\lambda/\rho_c = 76\%$ dark energy

WMAP 2006

Until very recently, the energy content of the universe was dominated by cold dark matter.

This leads to a simple and beautiful picture of structure formation in the universe.



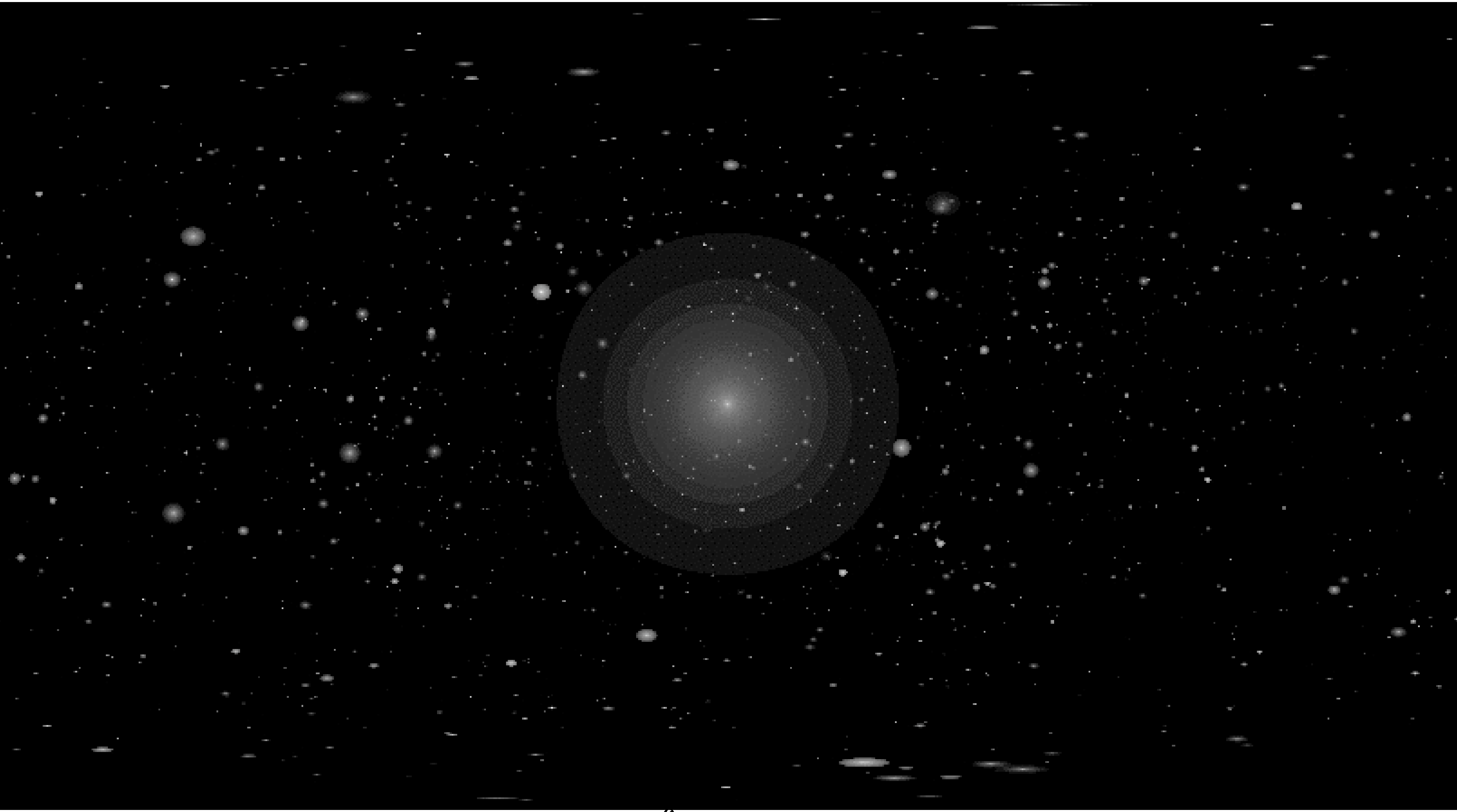
cosmological simulations: M. S. Warran et al. (Los Alamos NL)

The final structures are smaller than galaxies like the Milky Way. Large galaxies should thus contain many layers of substructure.

Some of this is obvious to the eye. But smaller components have been stripped of matter; these are more difficult to detect.

The Large and Small Magellanic Clouds

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



visualization of $\Phi_\gamma \sim \int dz \rho^2$ by Baltz.

This analysis raises many fascinating questions:

Can we see that dark matter in the disk of the galaxy is clumpy rather than smooth?

Is there a dark matter cusp at the center of the galaxy?

Cold dark matter predicts many more dwarf companions of our galaxy. Where did they go ? Could some be completely dark ?

To analyze these questions, we need to learn how to see dark matter.   To understand how to do this, we must answer:

What kind of particle is dark matter made of ?

We need a particle that is stable, neutral, heavy, and very weakly interacting. Bahcall called this a

Weakly Interacting Massive Particle (WIMP)

I will add the property:

WIMPs can be created and annihilated in pairs.

If so, WIMPs were created when the universe was very hot.

In the hot era just after the Big Bang, WIMPs were in thermal equilibrium: Compare

the rate for the WIMP density to be changed by interactions:

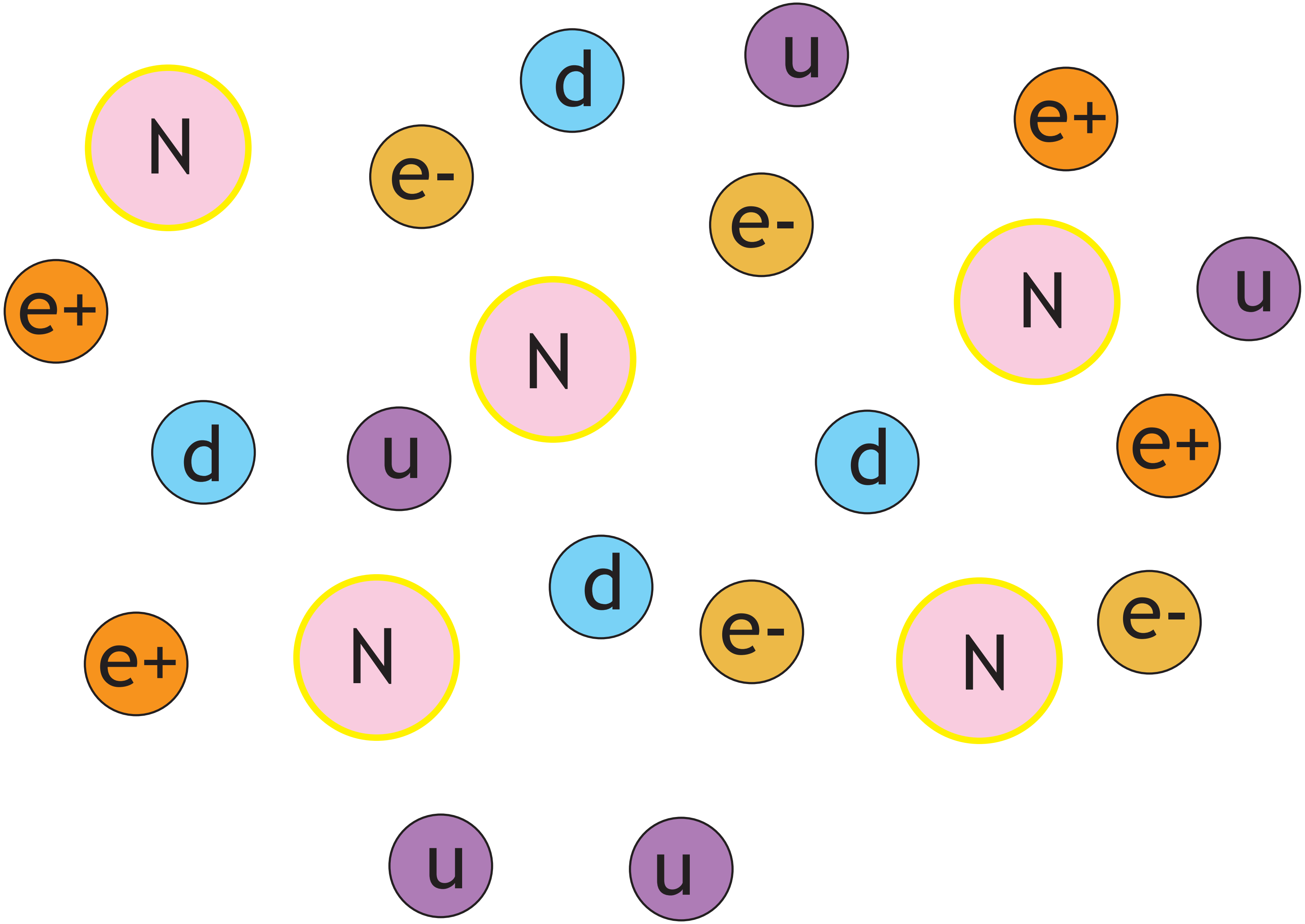
$$\sigma n \sim A\sqrt{\frac{T^3}{m}}e^{-m/T} \qquad \text{with} \qquad A \sim 10^{-4}$$

for electroweak interactions

the rate for the WIMP density to be changed by the expansion of the universe:

$$H \sim \frac{T^2}{m_{\rm Pl}} \qquad \text{with} \quad m_{\rm Pl} = 10^{19}\ \text{GeV} \quad ;$$

so H is smaller for almost any value of A .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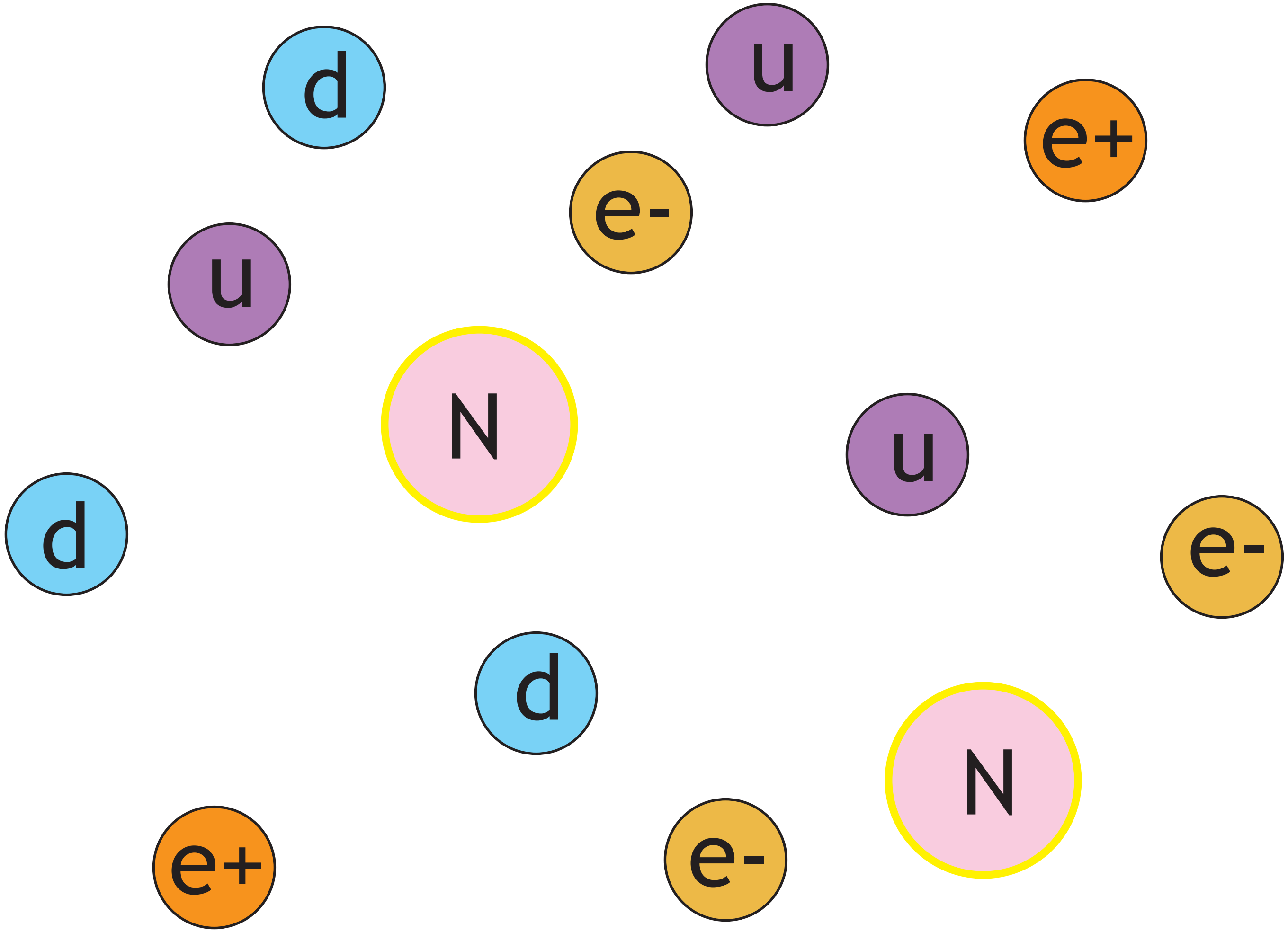
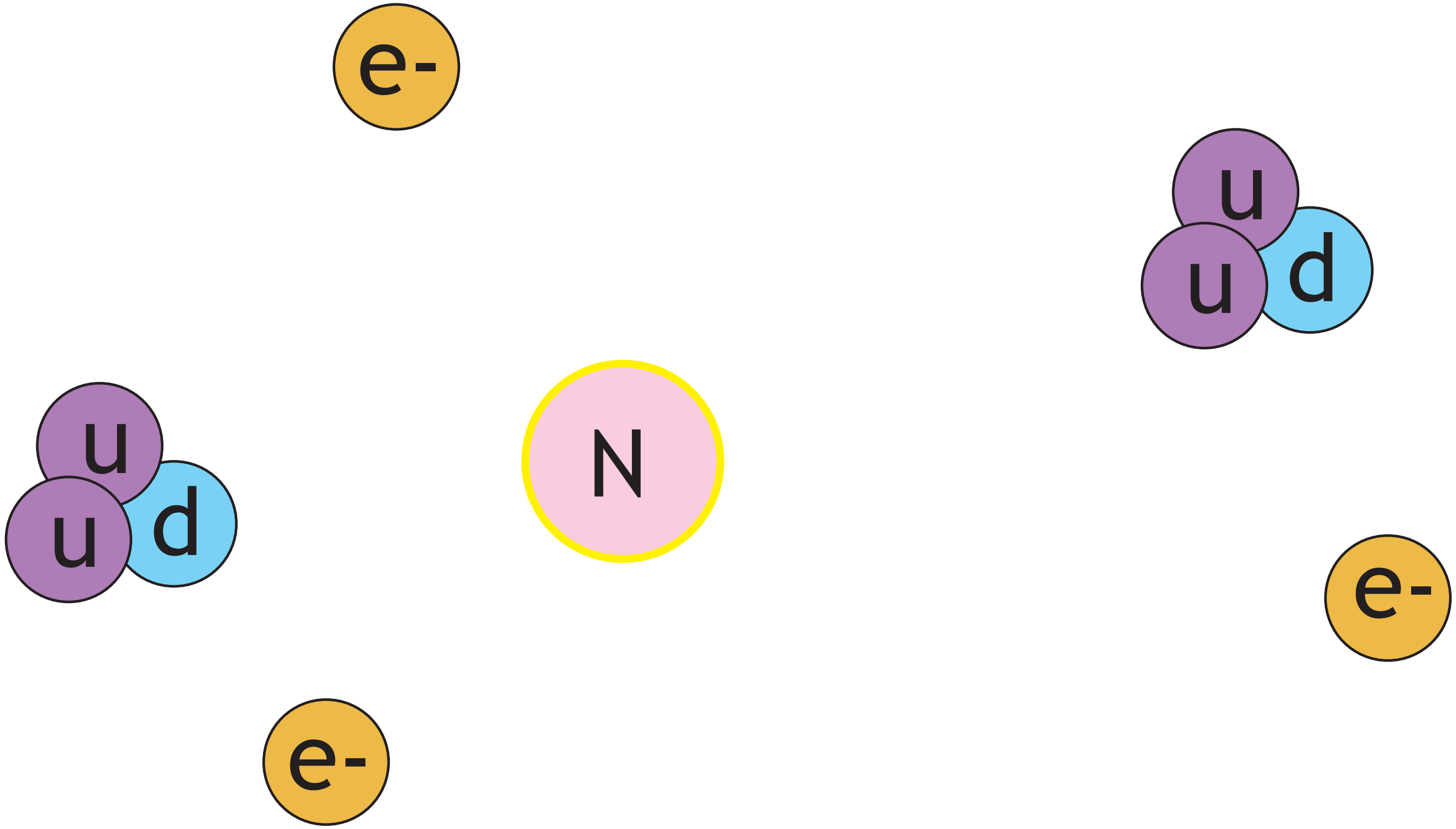
the universe expands and cools ...



until today ...



By integrating the Boltzmann equation for the WIMP density through this era of ‘freeze-out’, it is possible to work out how much WIMP matter is left over:

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

We know the parameters. Put in the numbers:

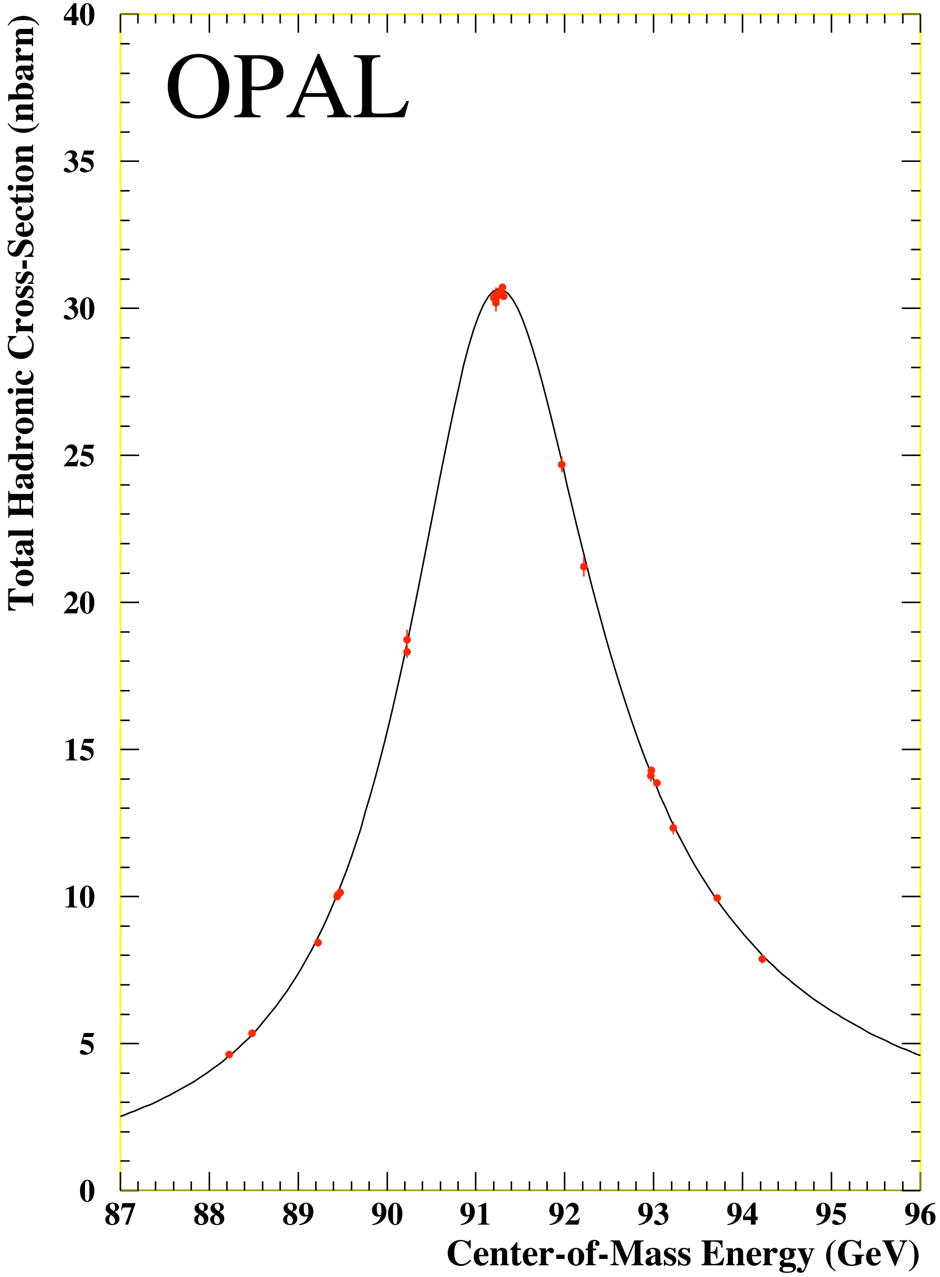
The cross section for WIMP annihilation is

$$\langle \sigma v \rangle = 1 \ \mathrm{pb} = \frac{\pi \alpha^2}{8 m^2} \quad \text{for m = 100 GeV}$$

This points to the length scale of weak interactions.

As an elementary particle theorist, this strikes me as an amazing conclusion.

Our precision knowledge of the weak interactions tells us that the correct model of weak interactions is a gauge theory with spontaneous symmetry breaking. The mechanism of symmetry breaking requires new physics at the 100 GeV mass scale.



It is tantalizing that dark matter could be a manifestation of this new physics.

In fact, almost all explicit models of symmetry-breaking mechanisms for the electroweak interactions contain heavy neutral particles with only weak interactions.

These particles are stable if the new particles in the model carry a conserved discrete symmetry. Usually, such a discrete symmetry is required for other reasons, e.g., to prevent rapid proton decay.

One such model is supersymmetry - the idea that all bosons and fermions in Nature have partners with the opposite statistics. In supersymmetry, the fermionic photon is a plausible candidate for the particle of dark matter.

In the past few years, many new models based on extra space dimensions have been studied. All have candidates for WIMP dark matter.

John Ellis

Steven Weinberg

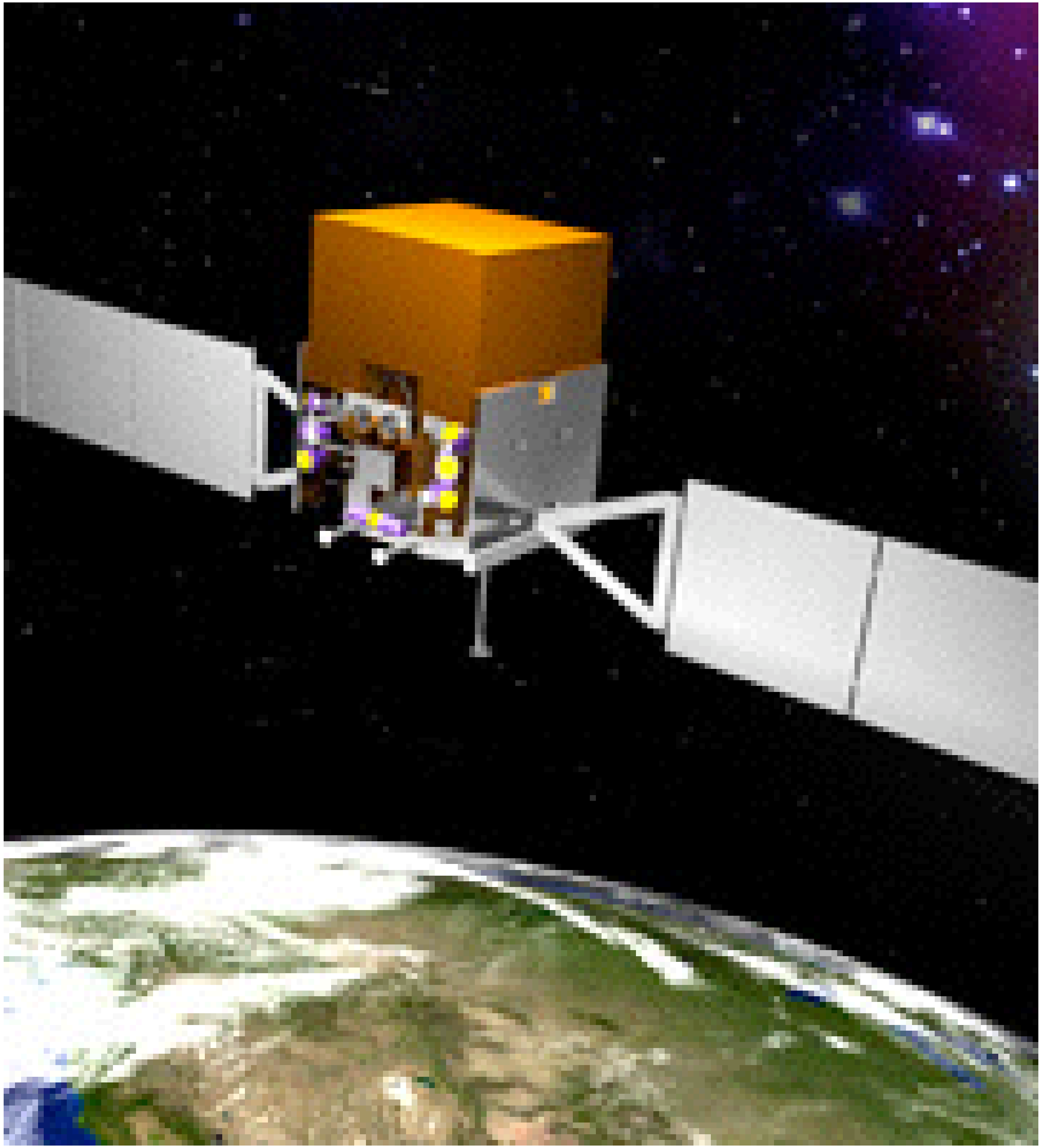
If dark matter is an elementary particle, we can search for it using methods from elementary particle physics.

For example, dark matter annihilation is still going on at some rate. Can we find the signals of this process ?

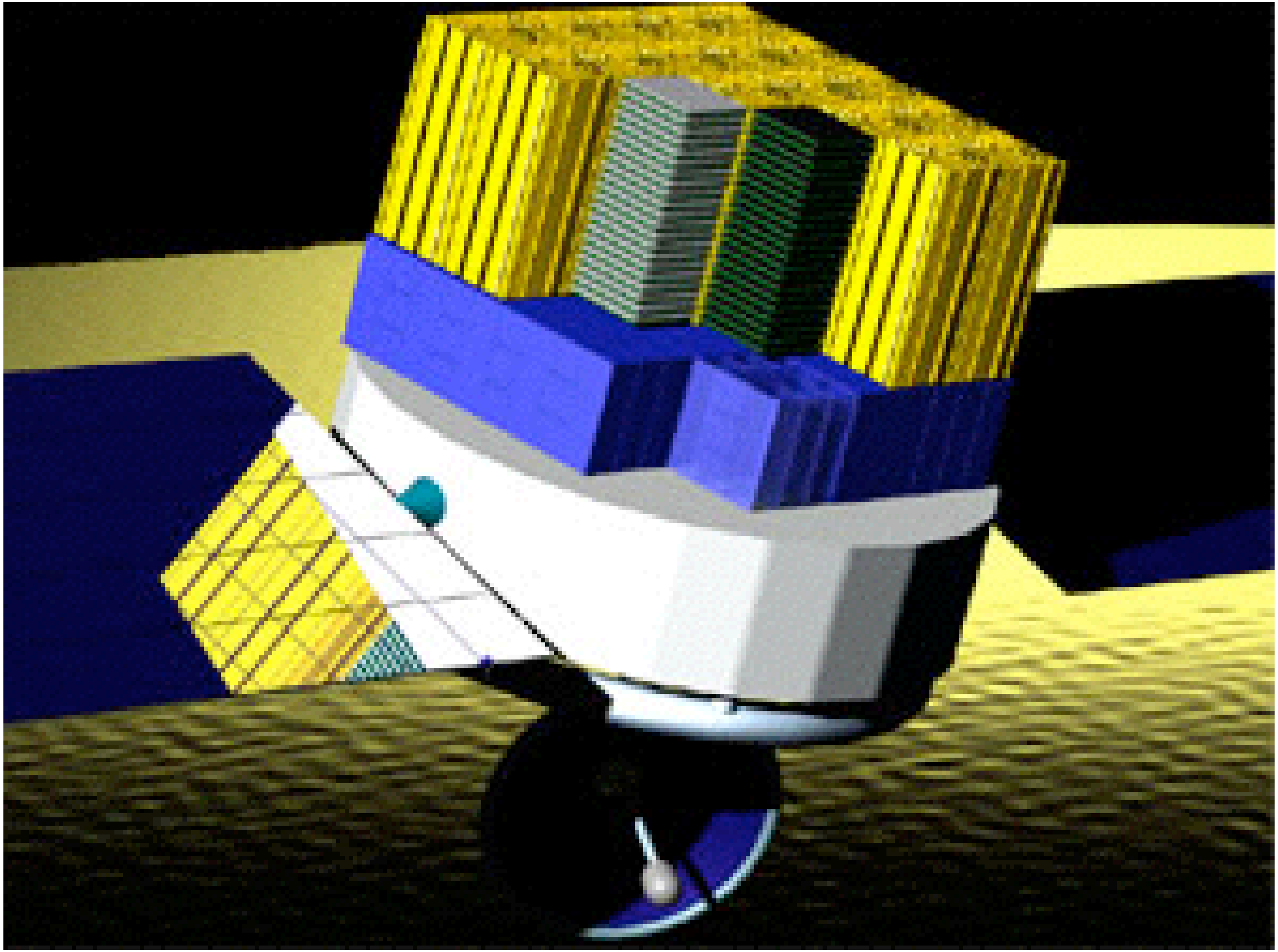
$$N + N \to W \cdots \to \pi^0 \cdots \to \gamma \cdots$$

Gamma rays from space !

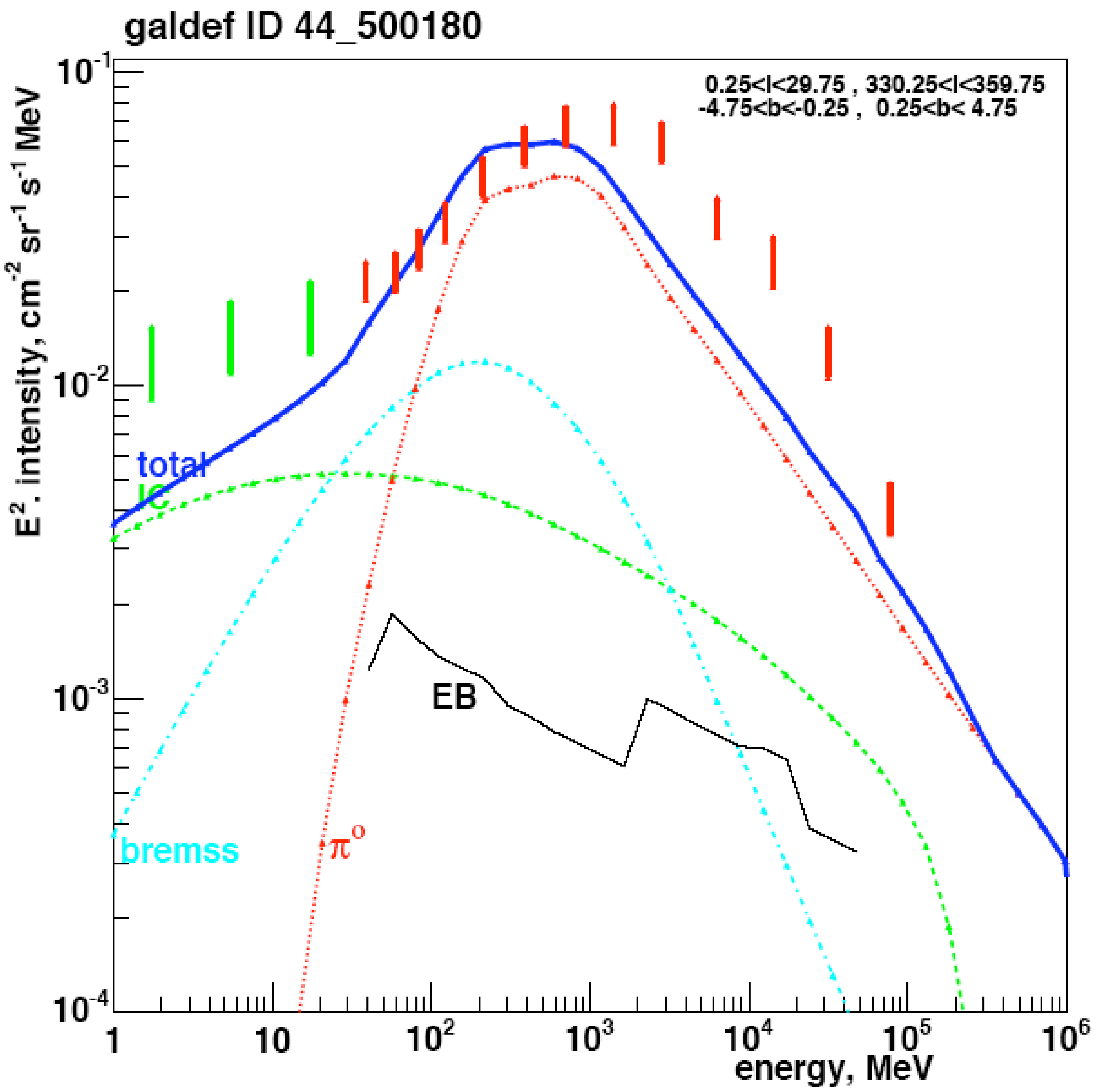
Peter Michelson



the Gamma ray Large Aperture Space Telescope



gamma ray tracker and calorimeter of GLAST



EGRET gamma spectrum vs. "conventional model"
Strong, Moskalenko, and Reimer

We can also look for dark matter particles hitting the earth.

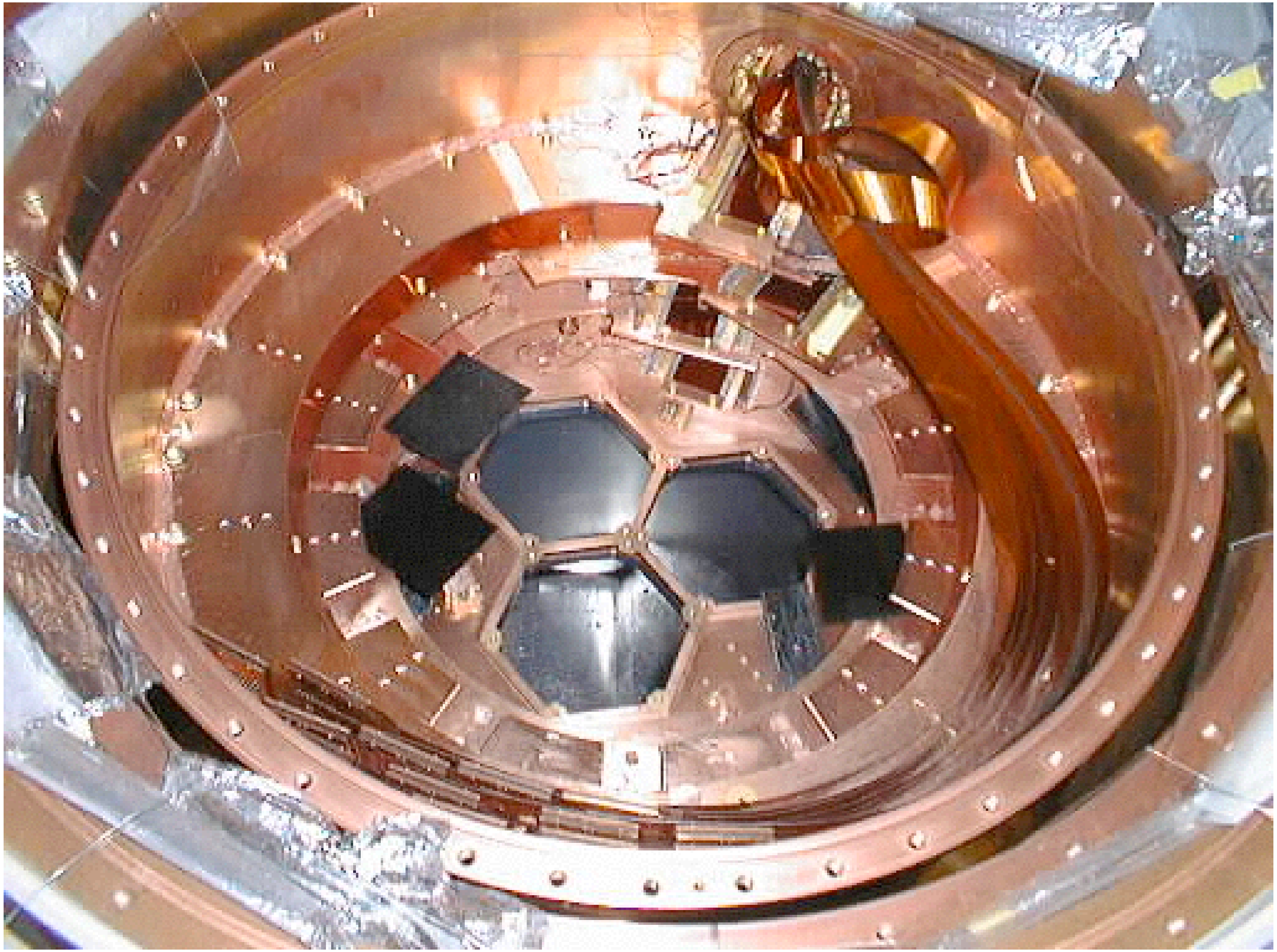
One dark matter particle at a time hits one nucleus, bounces off, and departs.

The energy deposited is tens of keV,

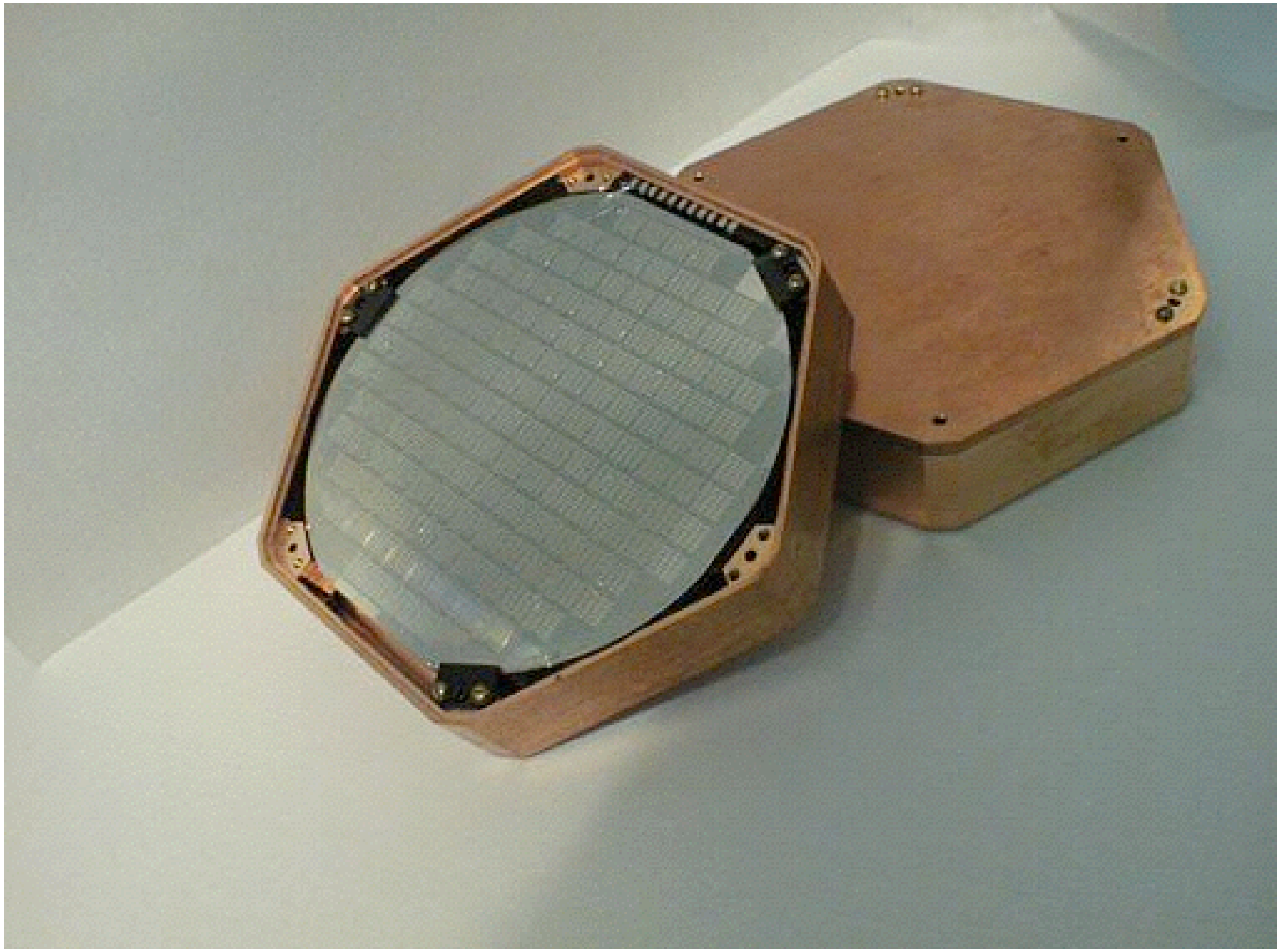
but once a month, say, in a macroscopic amount of material.

So, we had better look in a very quiet place.

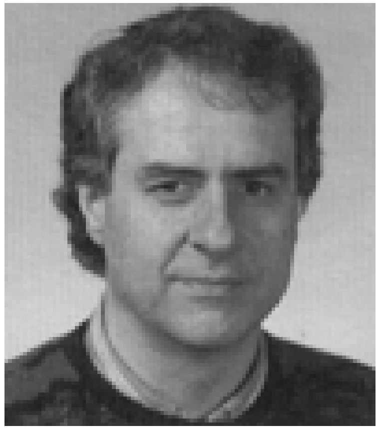
Soudan mine, northern Minnesota



cryostat of the CDMS detector

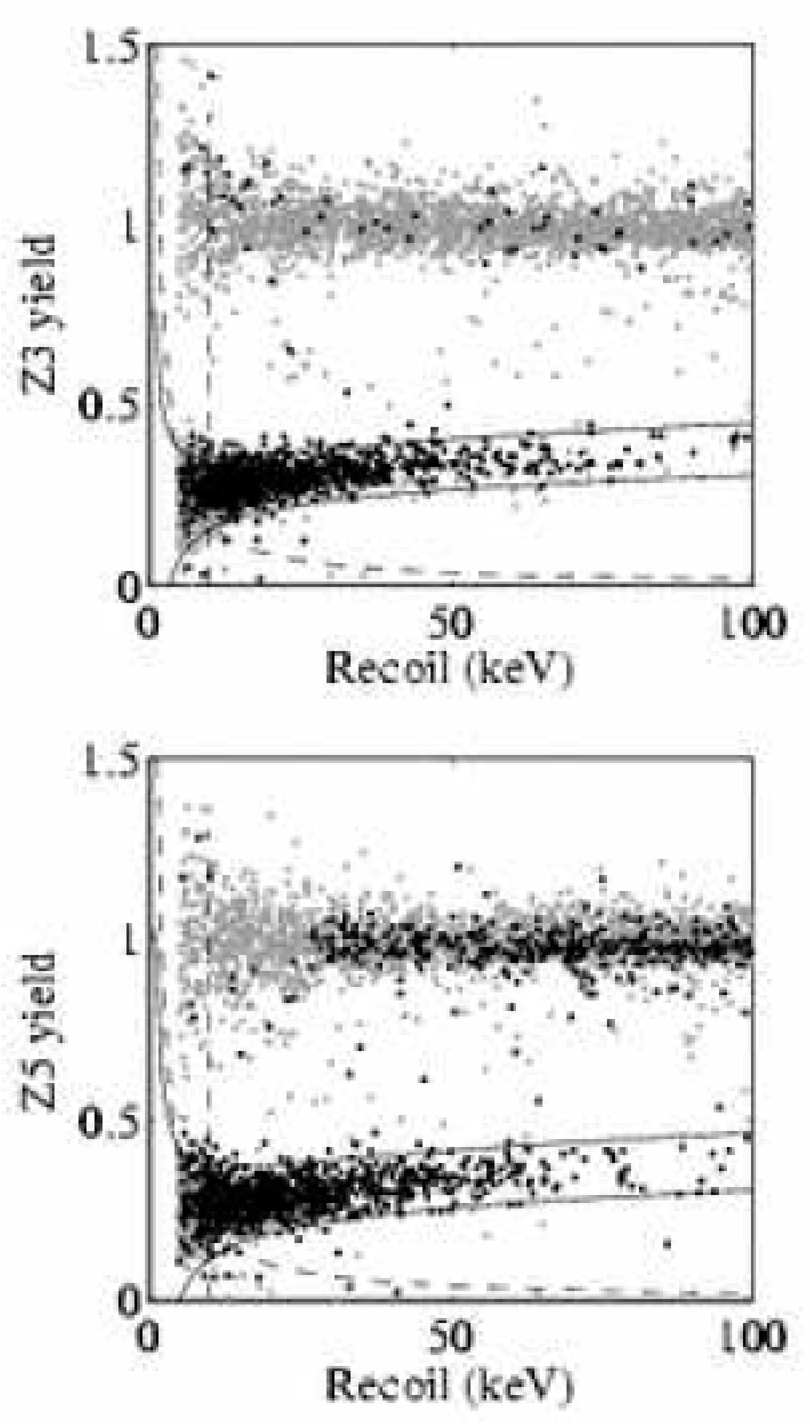


A ZIP detector (100 g Si)
from the CDMS experiment

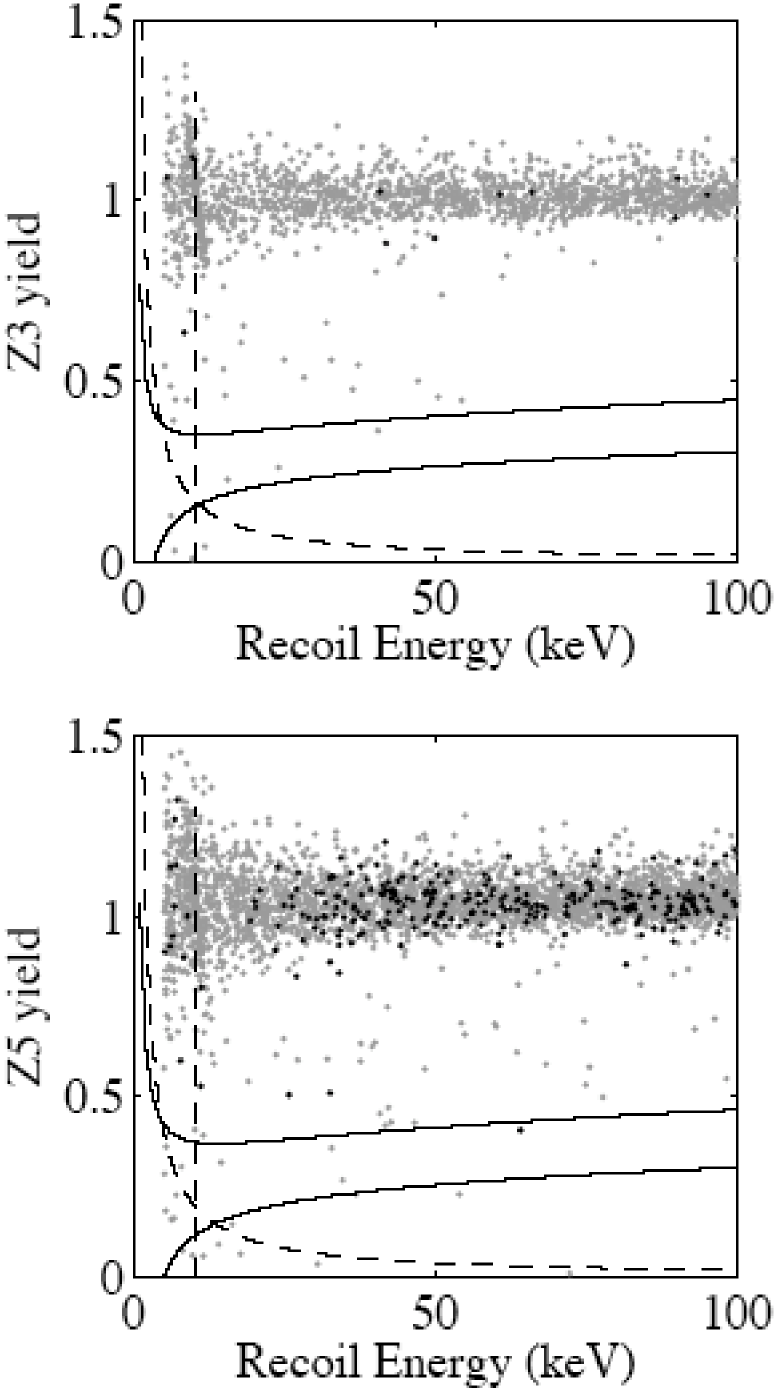


Blas Cabrera

calibration with Cf-252/Ba-133



real data



The current bounds on the WIMP-nucleon cross section approach

$$10^{-7} \text{ pb} = 100 \ \ \text{zeptobarn}$$

for some range of masses. Supersymmetry models can give this value, but more commonly this cross section is

$$1 - 10 \ \ \text{zeptobarn}$$

or even below.

Larger solid-state devices and large liquid argon/xenon detectors could reach the 1 zb level.

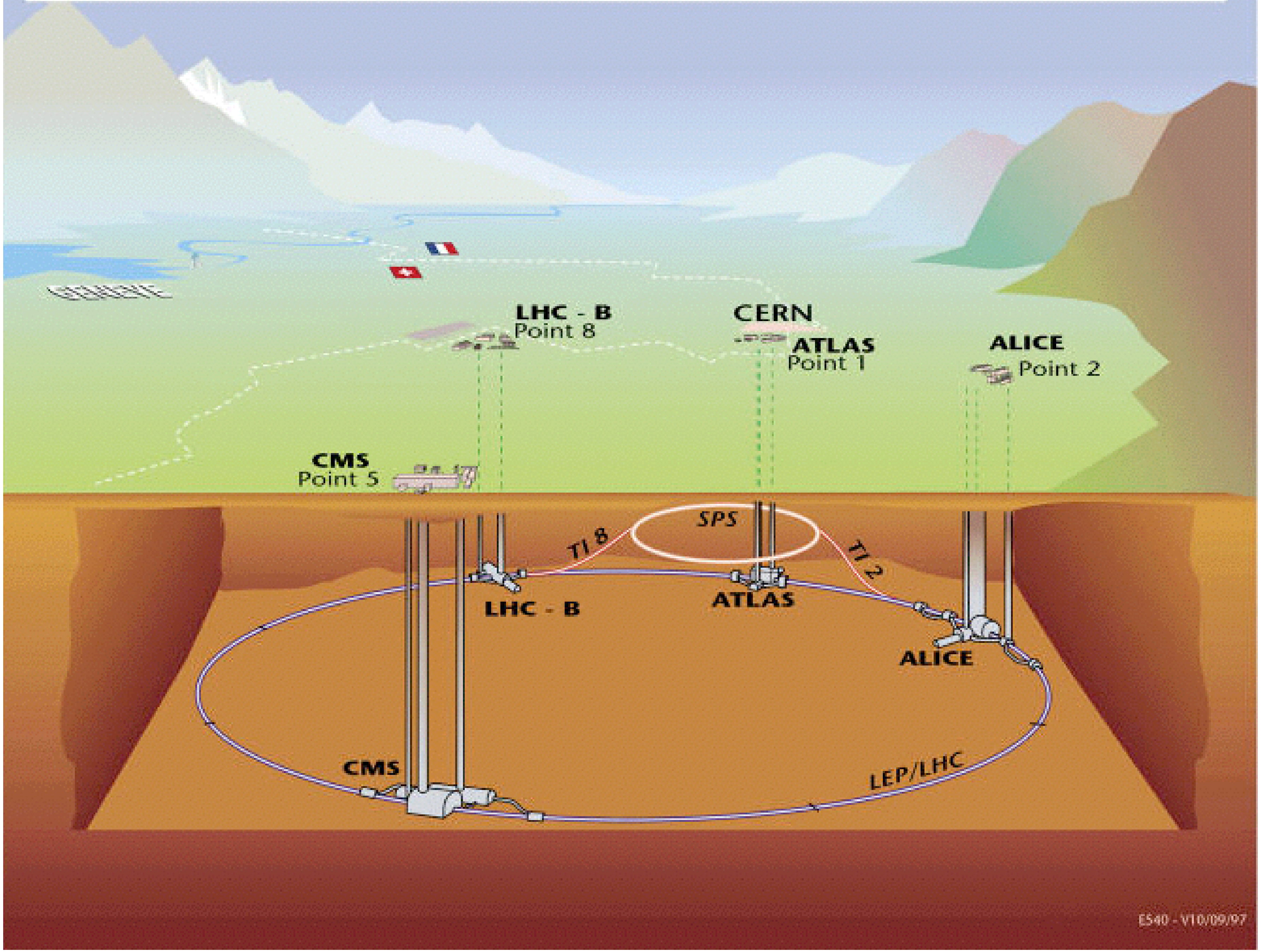
Finally, if it is possible for WIMPs to annihilate in pairs, they can also be produced in pairs. We only have to collect enough energy in one place.

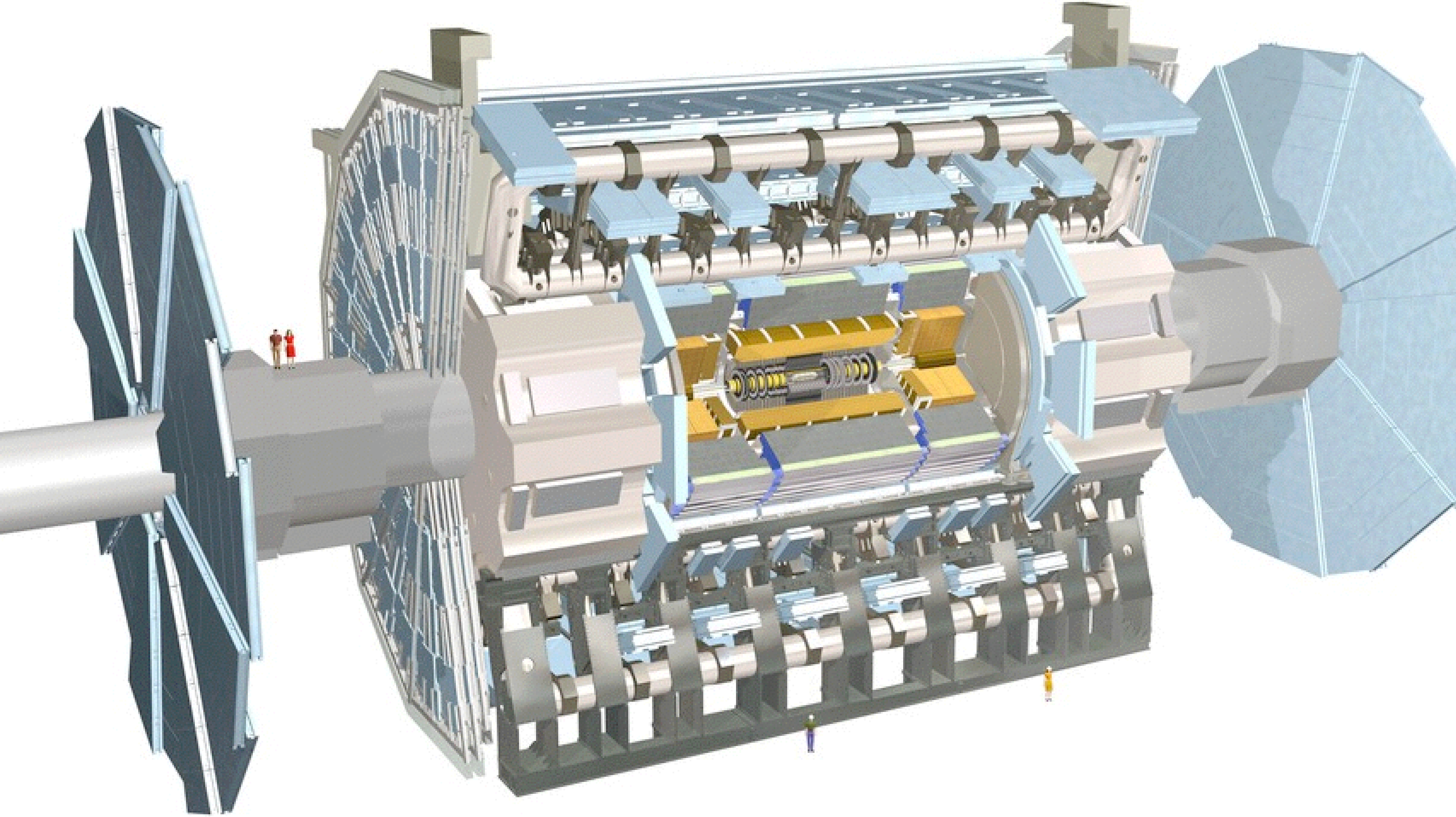
Hopefully, this is within the capability of the world's highest energy particle accelerators.

the Geneva region

with the CERN Large Hadron Collider

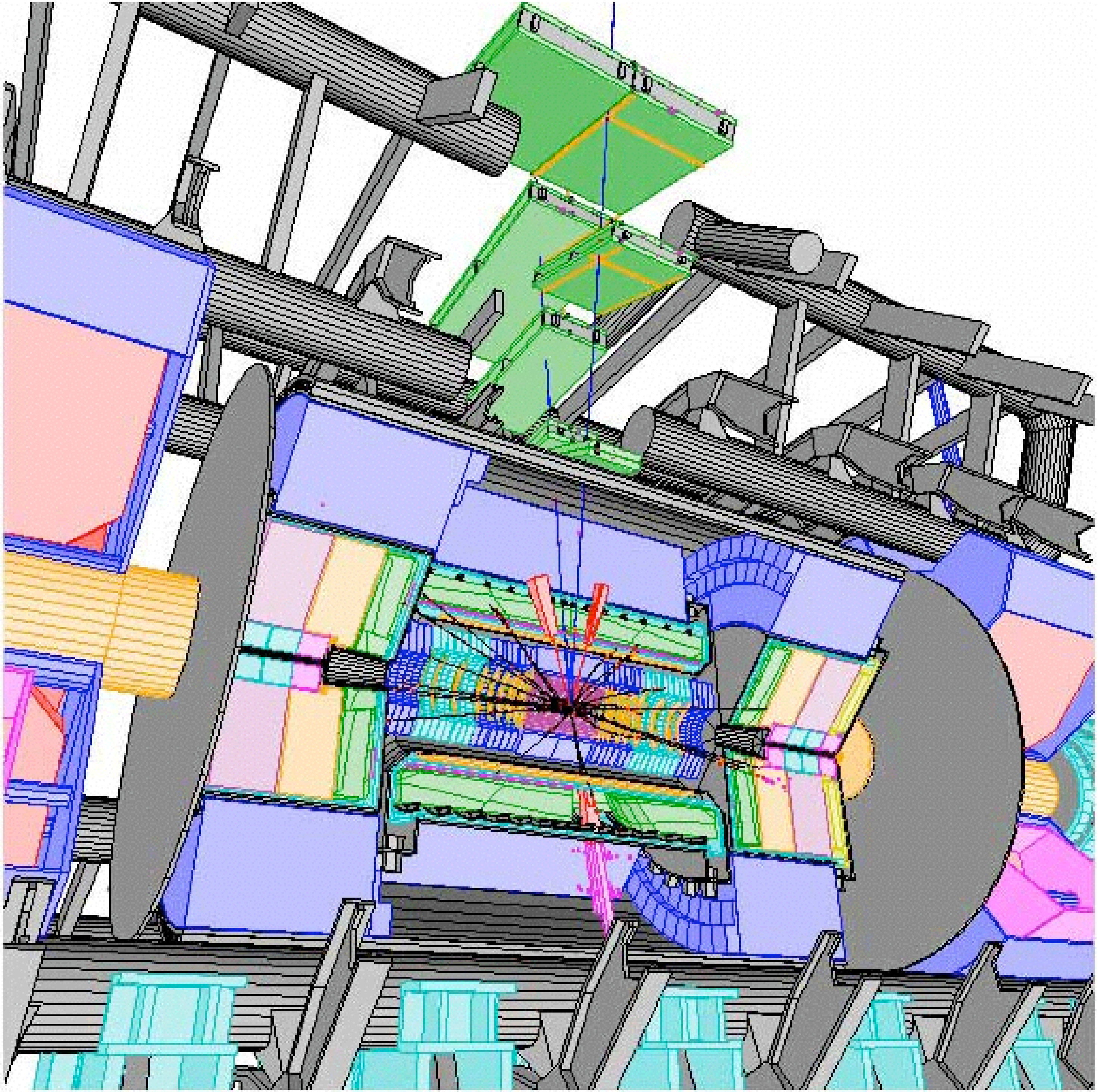
Overall view of the LHC experiments.





the ATLAS experiment

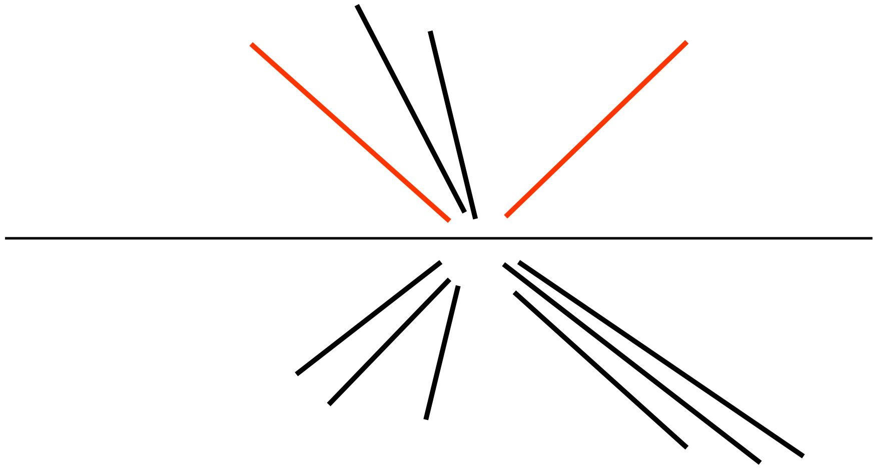
arrival of a superconducting muon toroid at CERN



simulated high-energy event in ATLAS

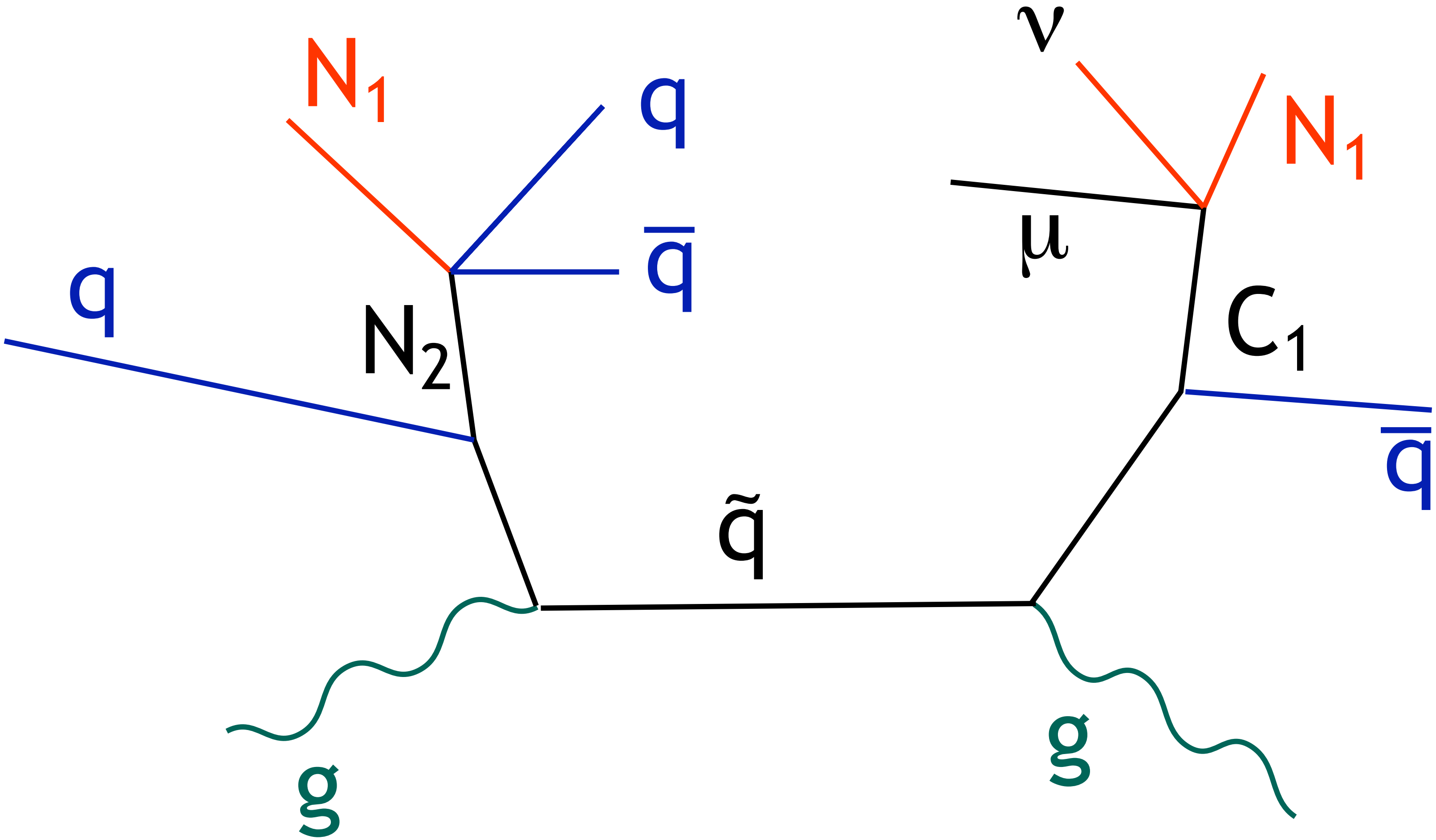
A WIMP produced at the LHC would penetrate the detector and escape, leaving no trace.

But, there is plenty of other activity in the events that produce WIMPs.



The rates are expected to be large -- 10^5 events/ year.

So we have the opportunity to shed light on dark matter from high-energy particle physics.



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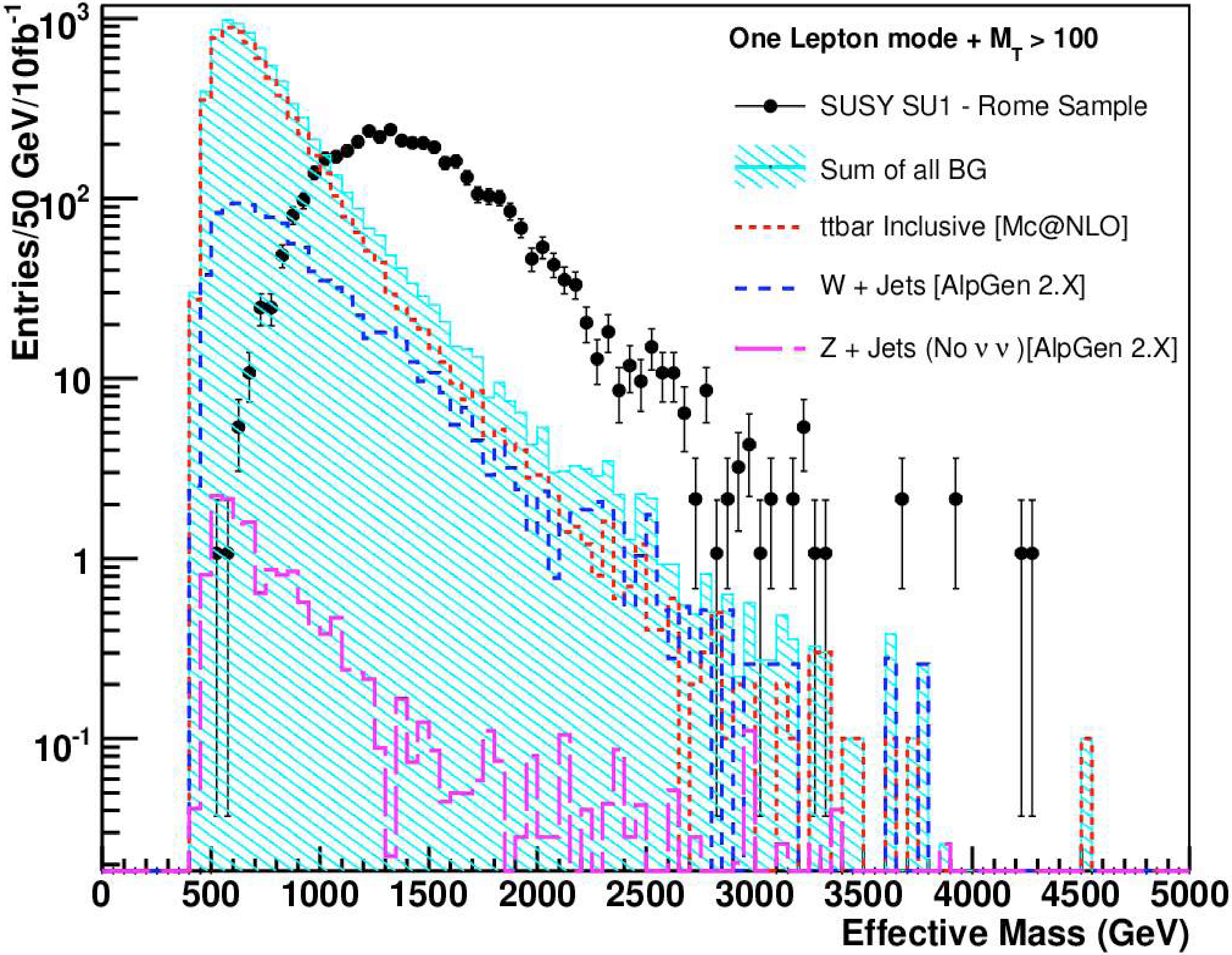
It is complex to evaluate the Standard Model backgrounds. Nevertheless, these events are highly characteristic for large jet activity and large missing energy.



Padhi
ATLAS

However, it is not sufficient to observe these events. We need to use them to make precision measurements of the properties of dark matter particles.

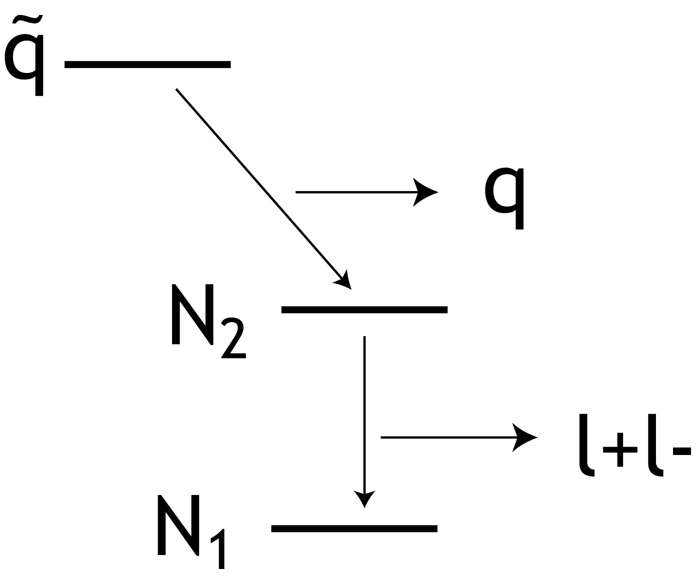
It is not so obvious that this can be done:

We do not know the momenta of the quarks or gluons that initiate the reaction.

We do not observe the (two) outgoing dark matter particles.

Still, it is possible to work from the observed final-state particles.

A feature of many supersymmetry spectra is the decay chain



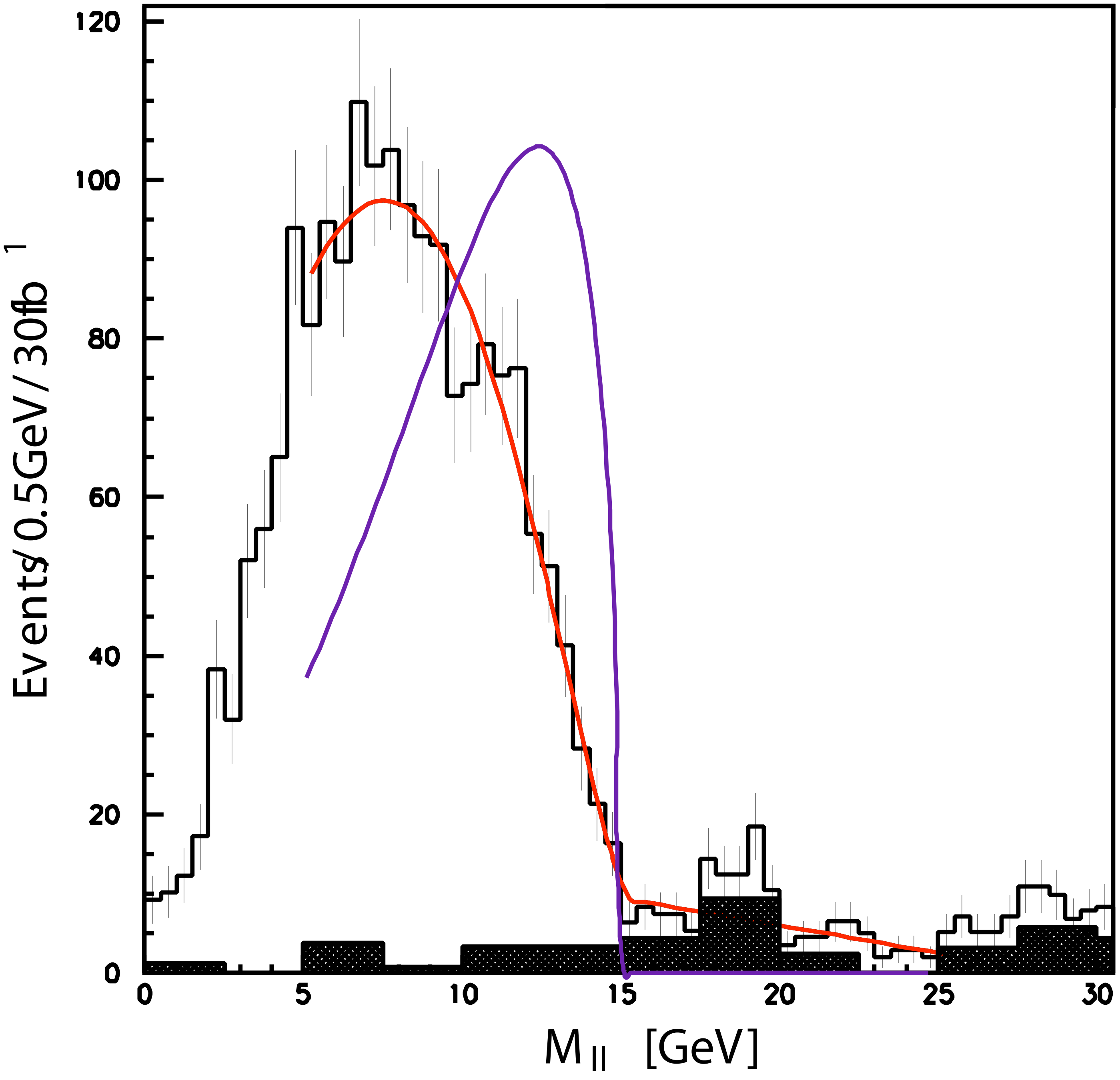
The lepton moment are measured completely, and we can construct their spectrum of invariant masses. If

$$m(N_2) - m(N_1) < m_Z$$

this spectrum terminates at

$$m(\ell^+\ell^-)_{max} = m(N_2) - m(N_1)$$

Here is a worked example that makes use of this effect.



Kitano-Nomura

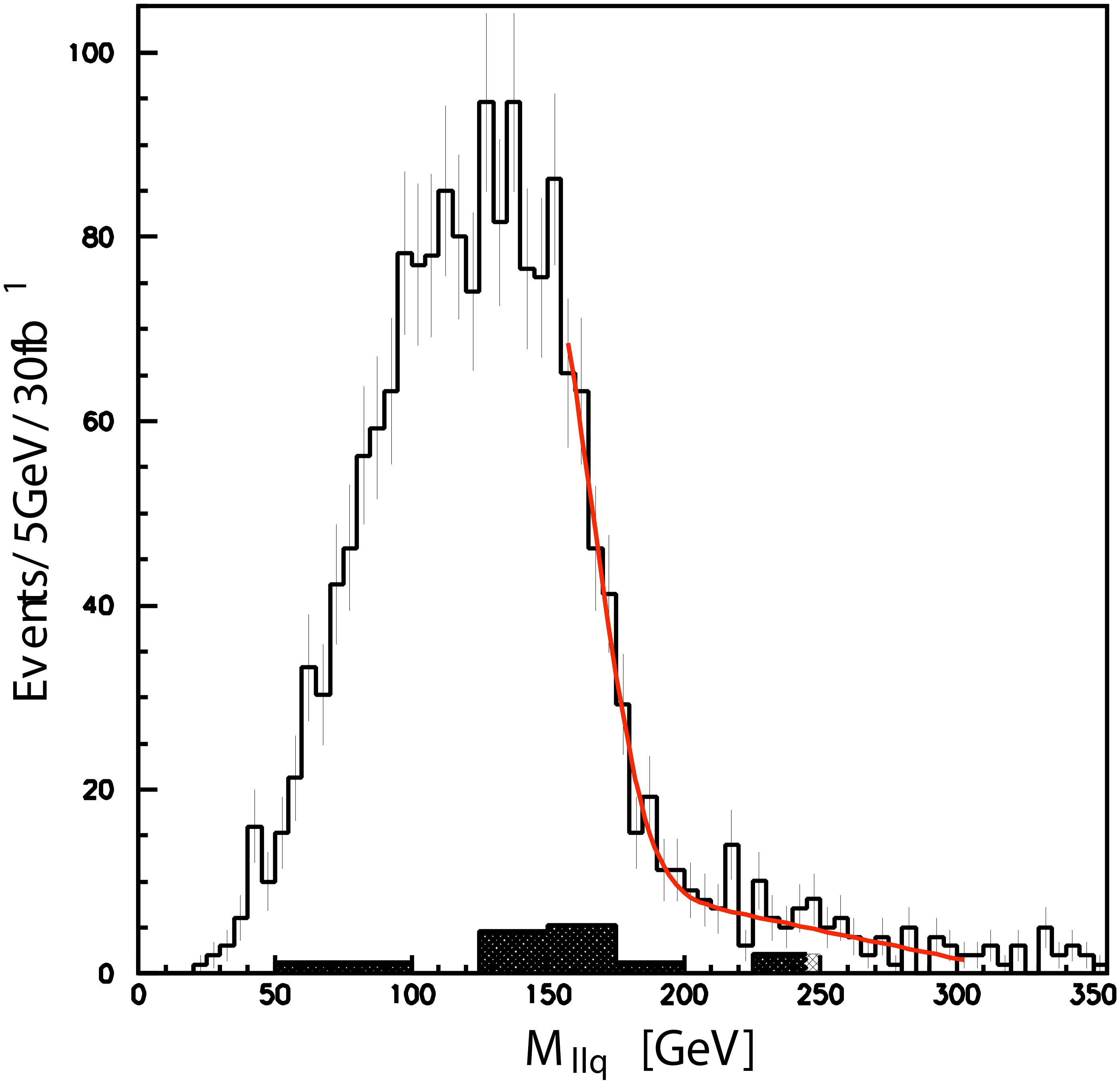
Now try to combine a quark with the lepton pair. Find the two hardest jets of particles observed in the event, and try to combine one with the lepton pair.

Some useful variables are:

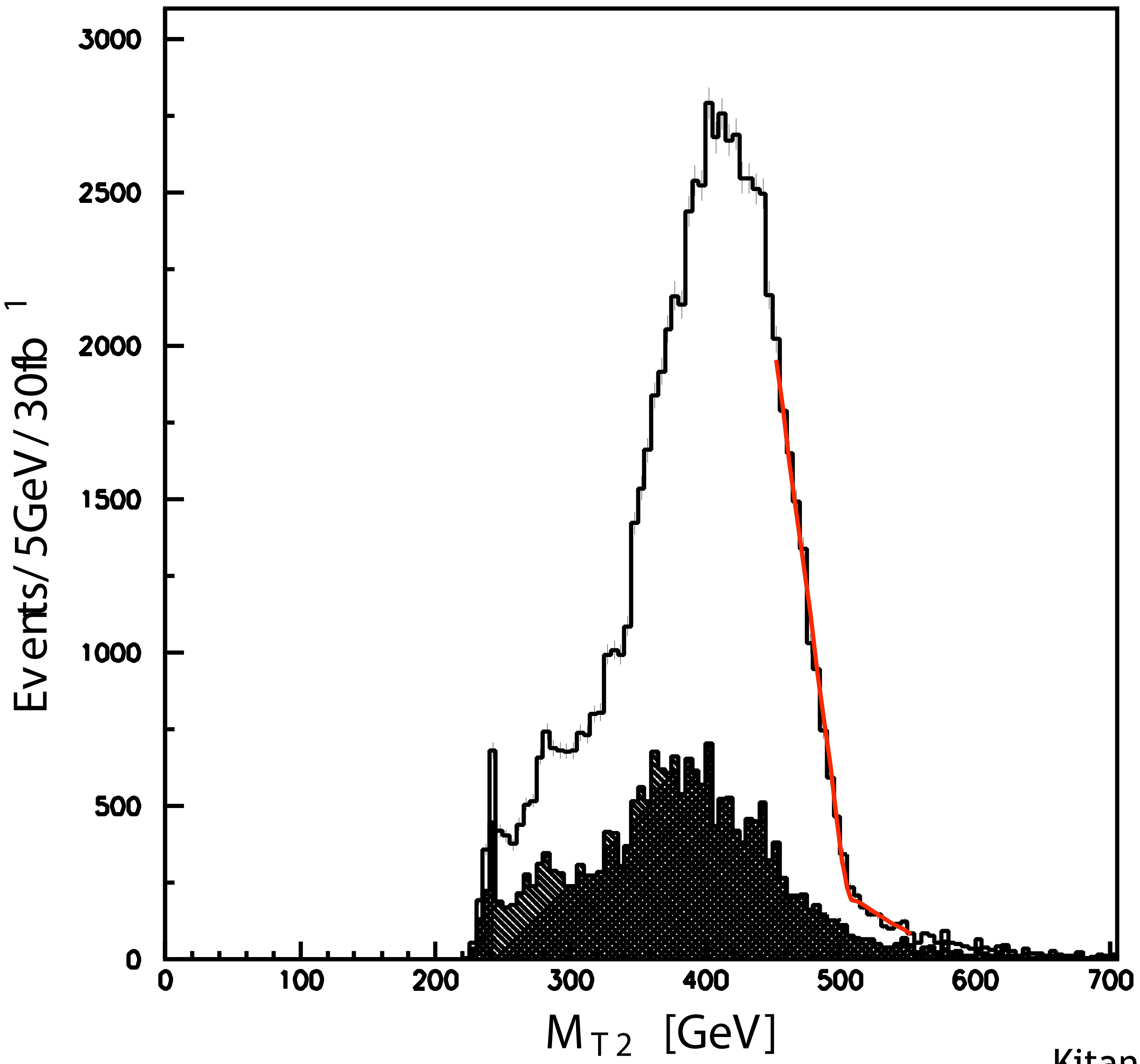
$$min_{1,2}\{m(\ell\ell j)\}$$

$$M_T^2 = min_{(\not{p}_{T1}+\not{p}_{T2}=\not{p}_T)}\ max\{m_T^2(p_1\ \not{p}_1), m_T^2(p_2\ \not{p}_2)\}$$

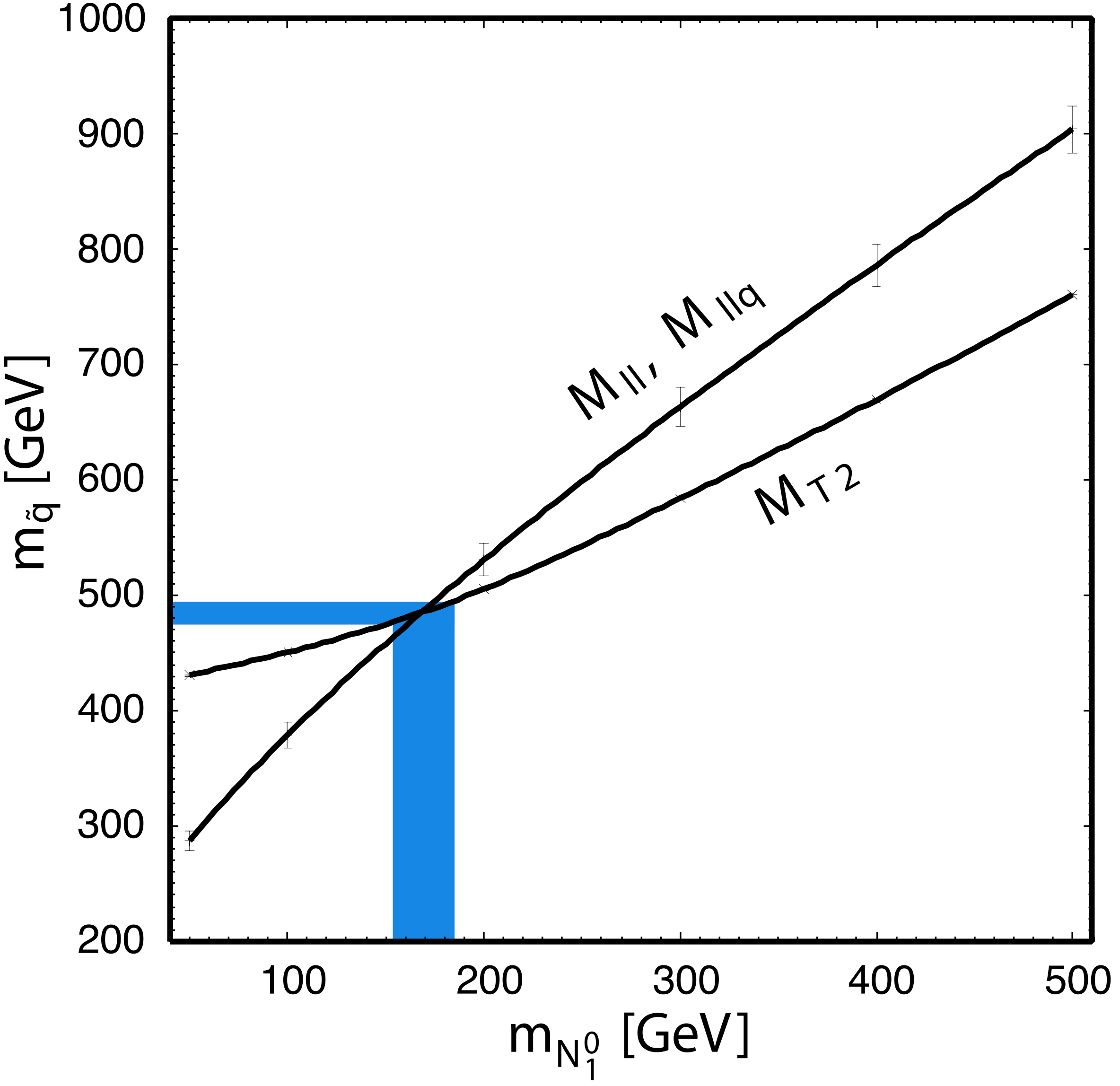
Lester and Summers



Kitano-Nomura



Kitano-Nomura



$$m_{N_1} = 169 \pm 17 \text{ GeV} \quad m_{\tilde{q}} = 486 \pm 11 \text{ GeV}$$

Kitano-Nomura

With these and other tricks, one can determine the WIMP mass at the level of 10% or below. 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.

We will soon have three possible ways to do this:

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

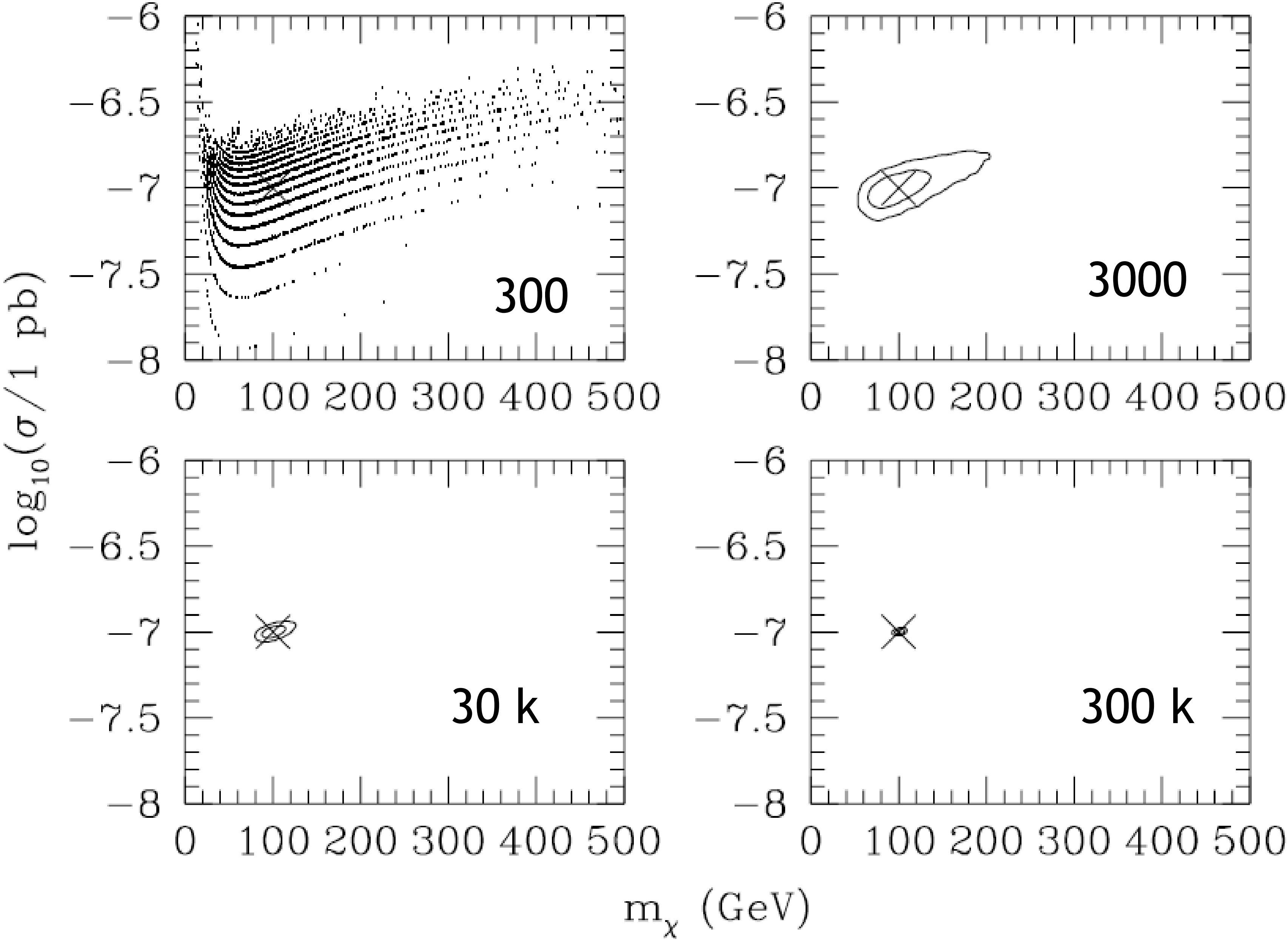
In direct detection, if the WIMP mass is well matched to the target mass, we expect billiard-ball-like collisions. Then the energy spectrum in recoil is a good measure of the WIMP mass.

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

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



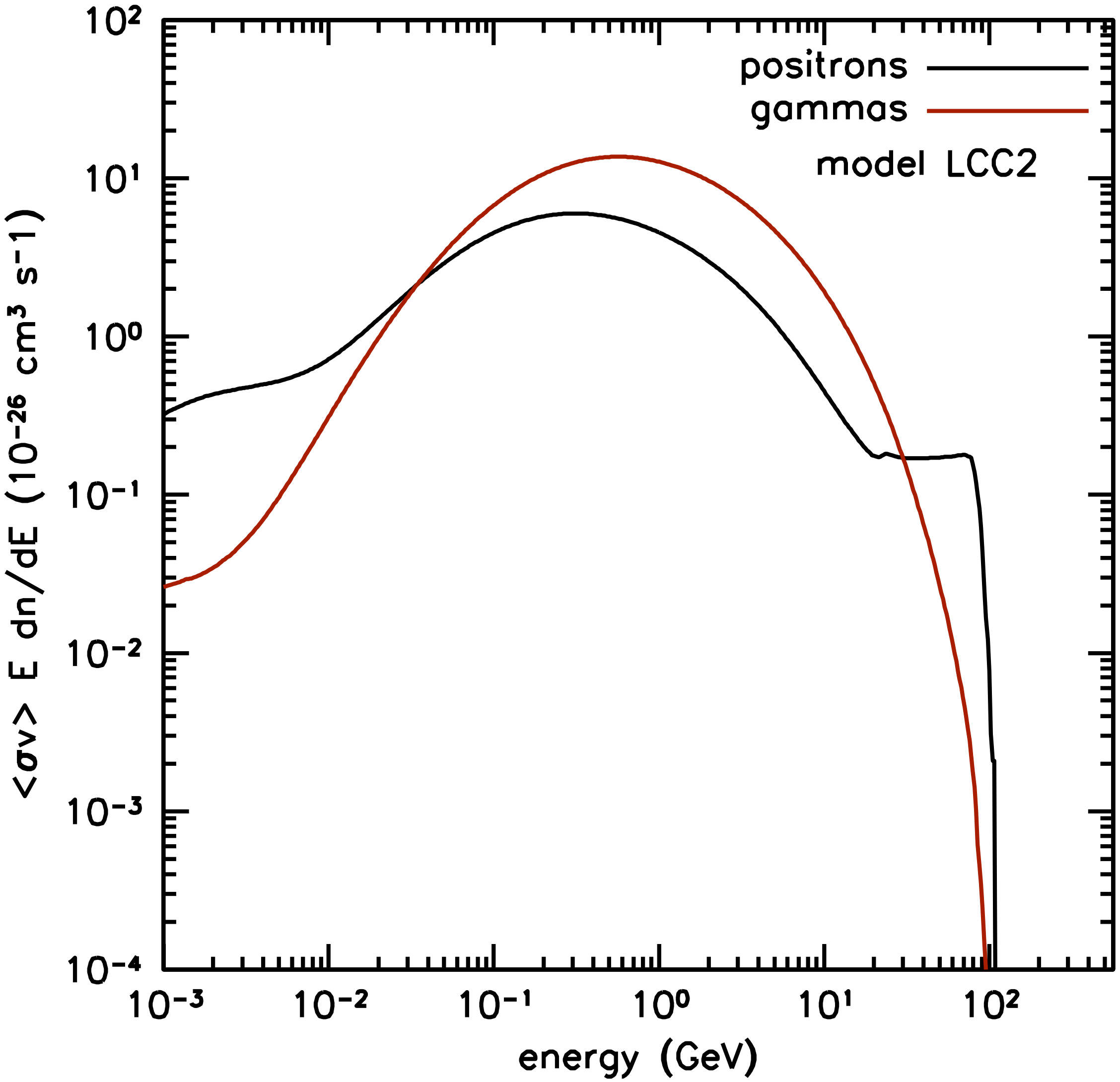
Green

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

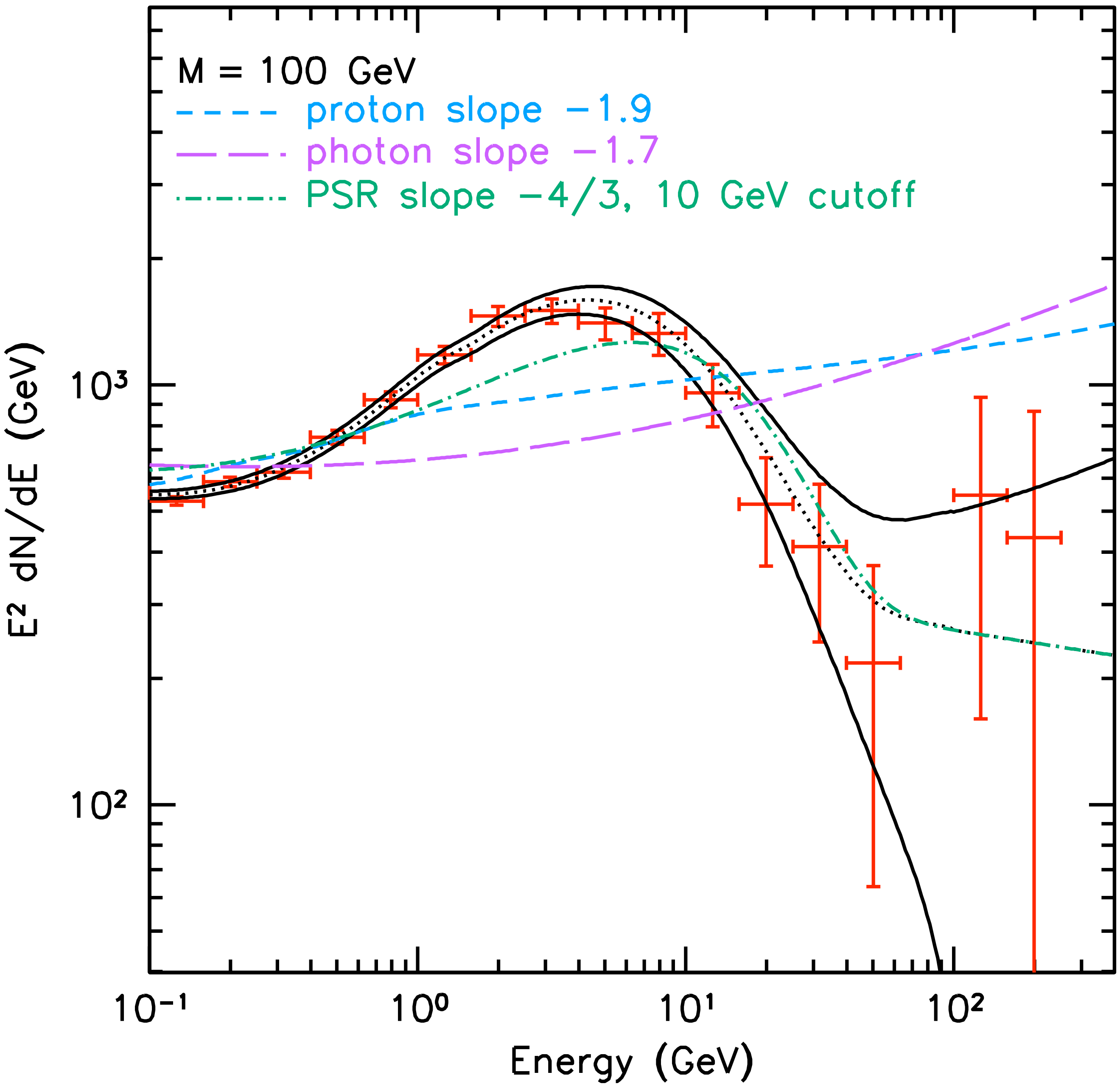
$$\chi + \chi \to W^+W^- \; , Z^0 Z^0$$



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

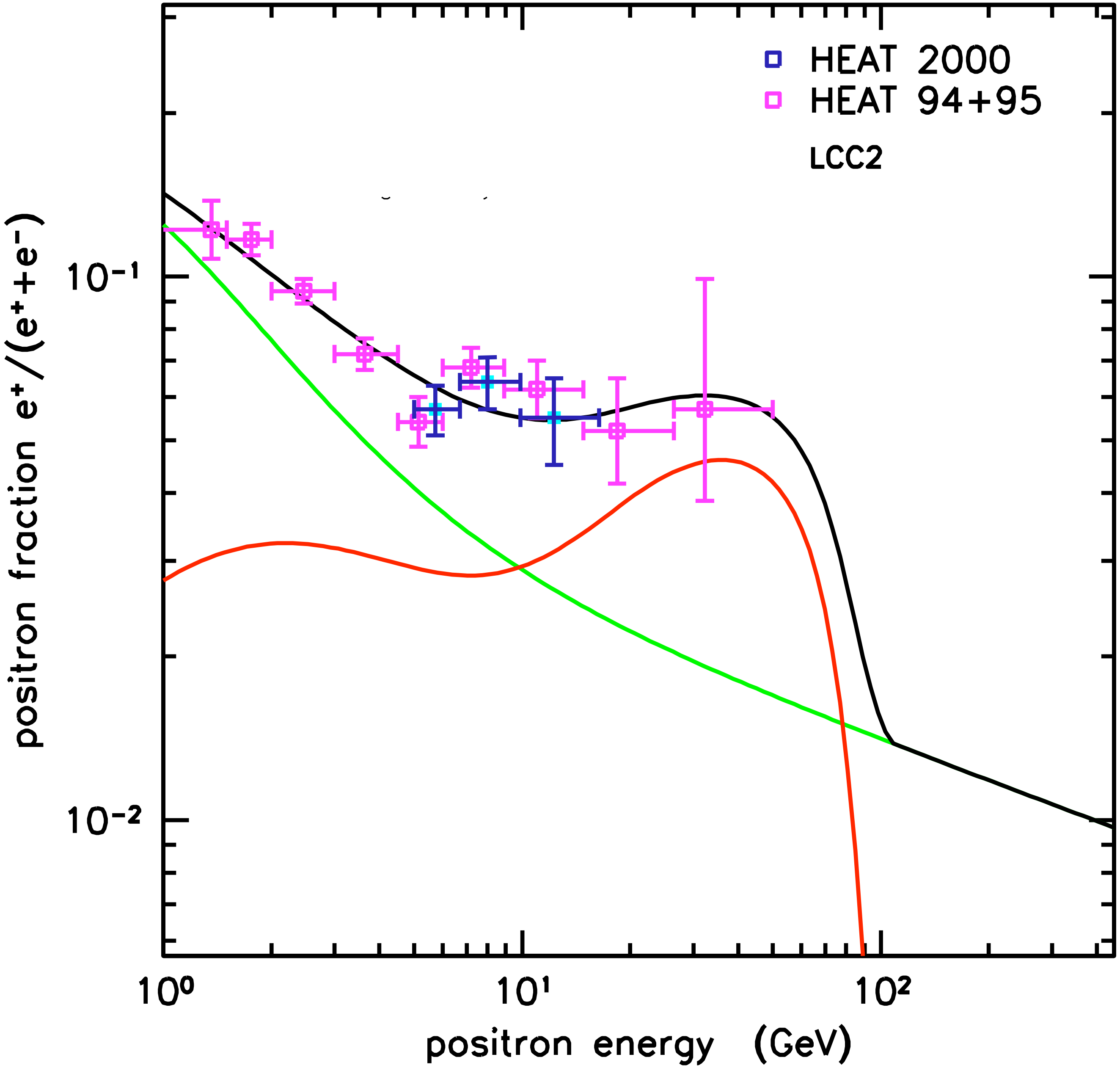
$$2 \times 10^6 M_\circ$$

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. A new experiment PAMELA will confirm or refute the presence of an endpoint.



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.

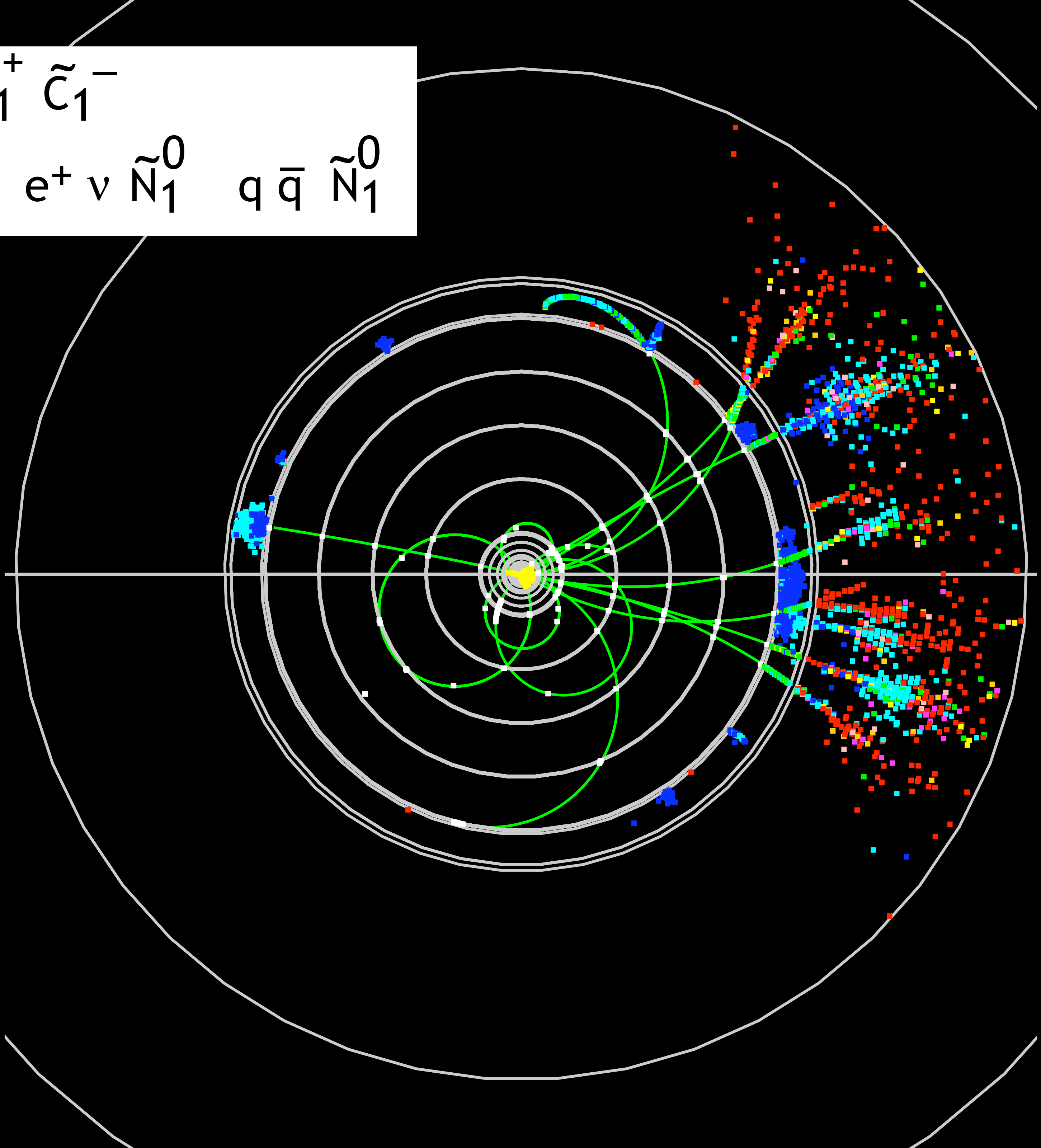
To complete this program requires measurements that go beyond the capabilities of the LHC. This will be possible with parallel experiments using electron-positron annihilation. For this, we propose another giant accelerator, the International Linear Collider (ILC).

The ILC will take us, not to higher energy, but to a higher level of precision in the study of the WIMPs.

It will allow us to tune the annihilation energy to pick out the simplest reactions that produce WIMPs, and to extract the detailed cross sections, including dependence on initial- and final-state polarization.

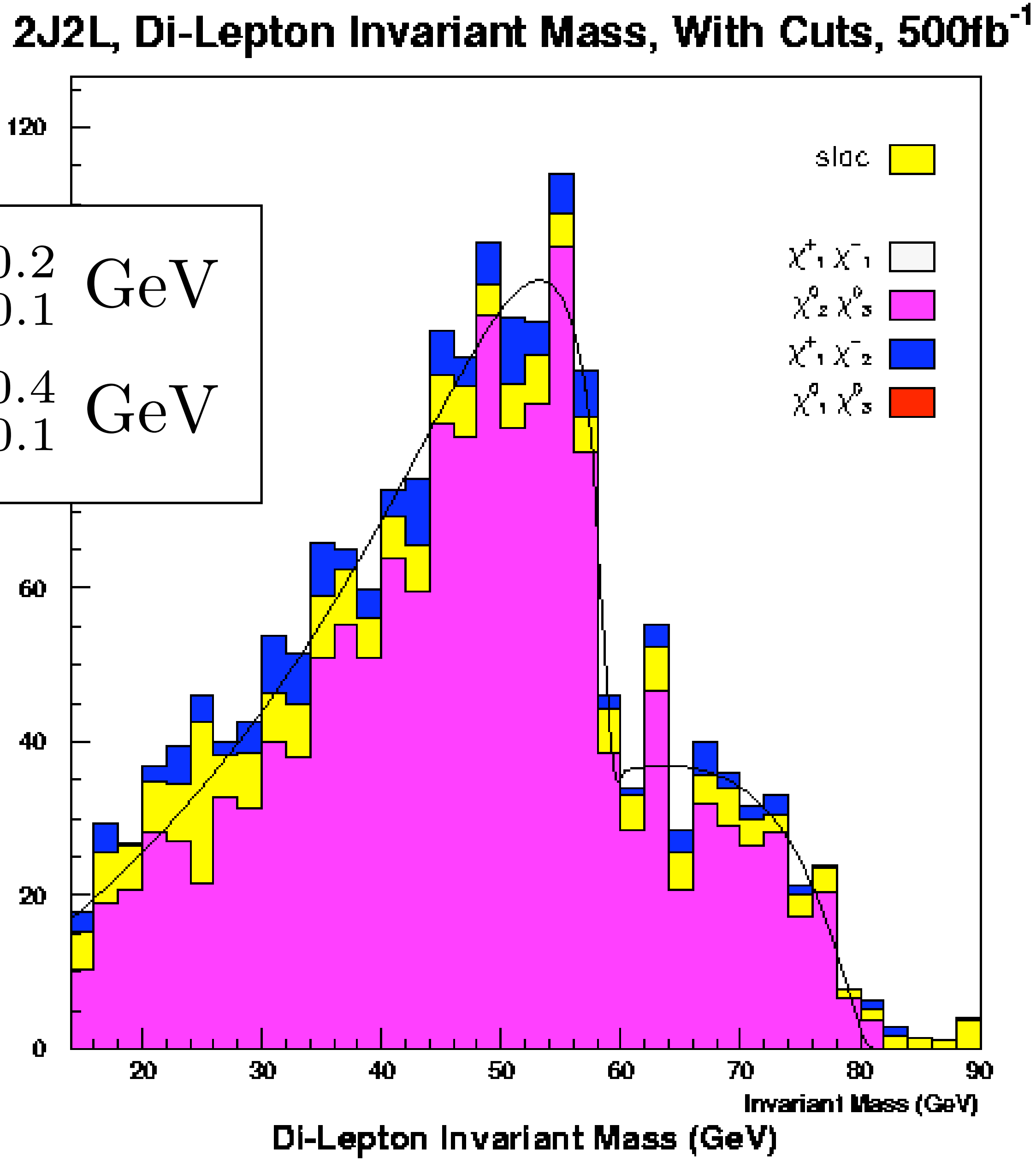
$$e^+e^- \rightarrow \tilde{C}_1^+ \, \tilde{C}_1^-$$

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



precision determination of mass differences from the dilepton spectrum:

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



The detailed shape of the distribution is predicted by supersymmetry

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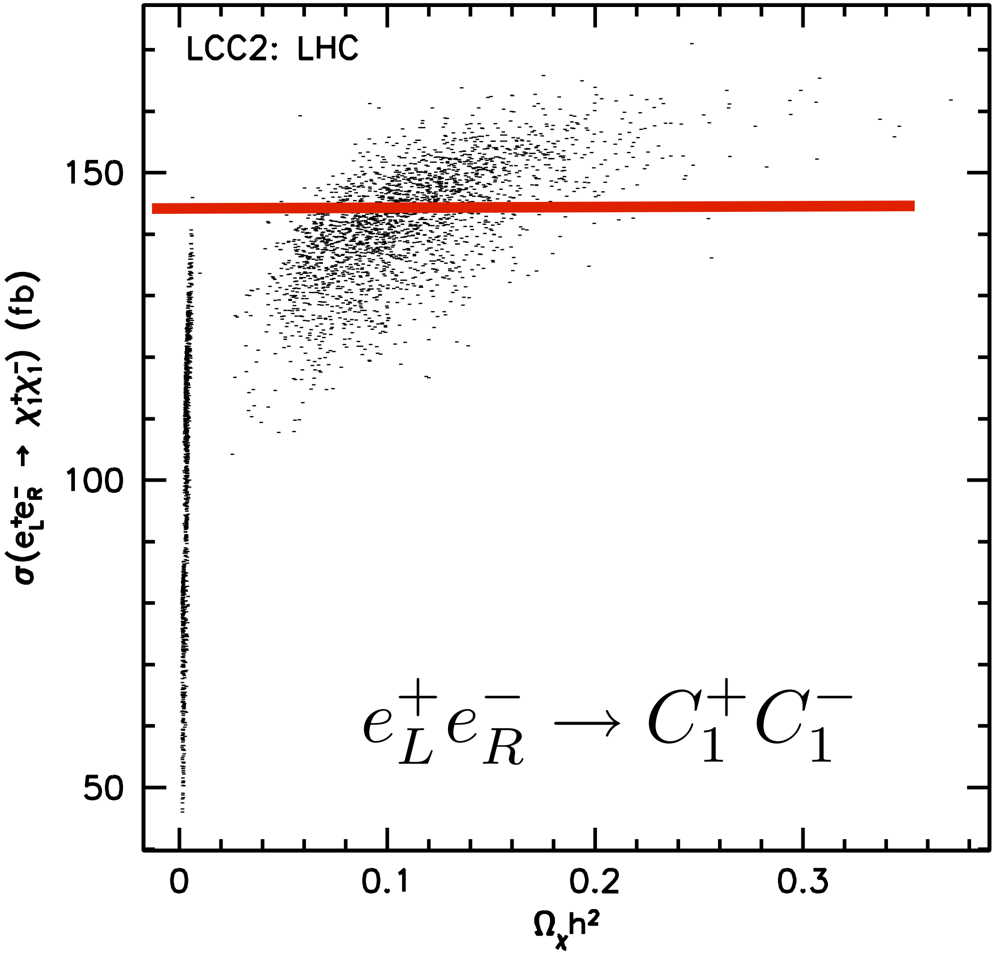
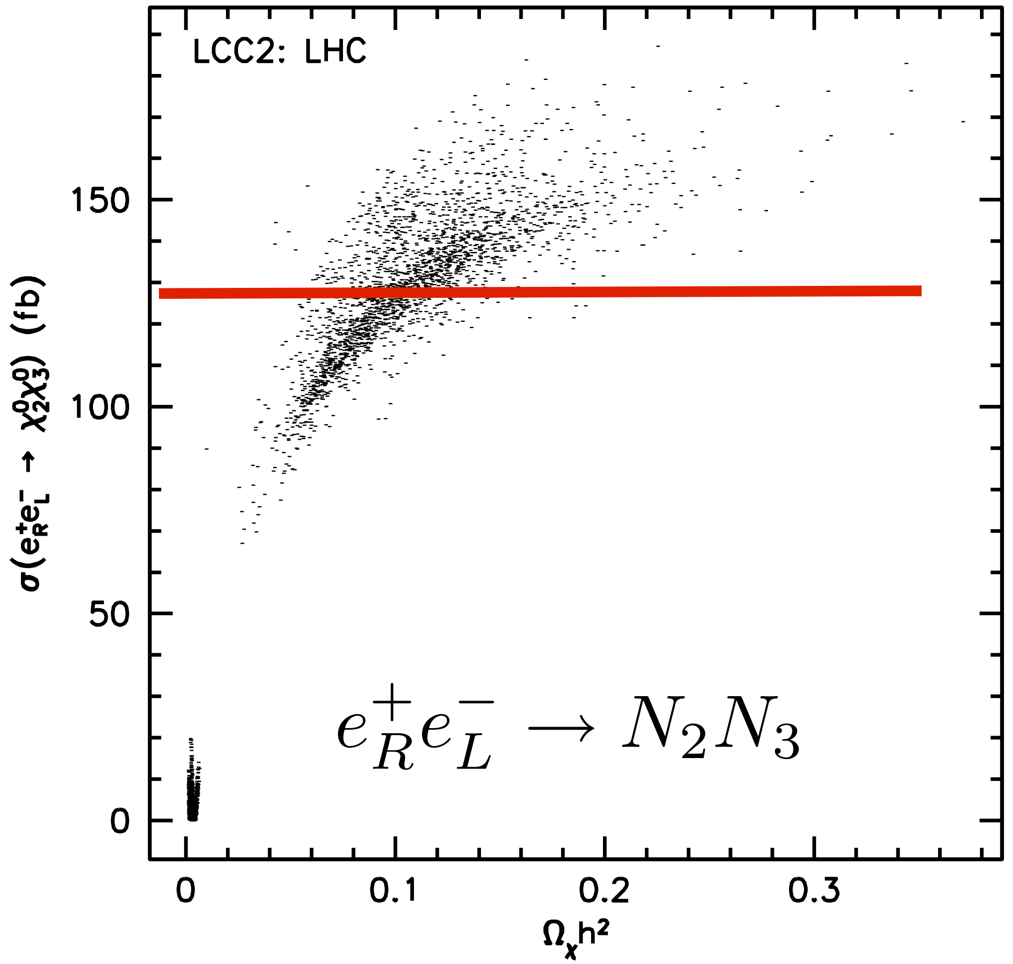
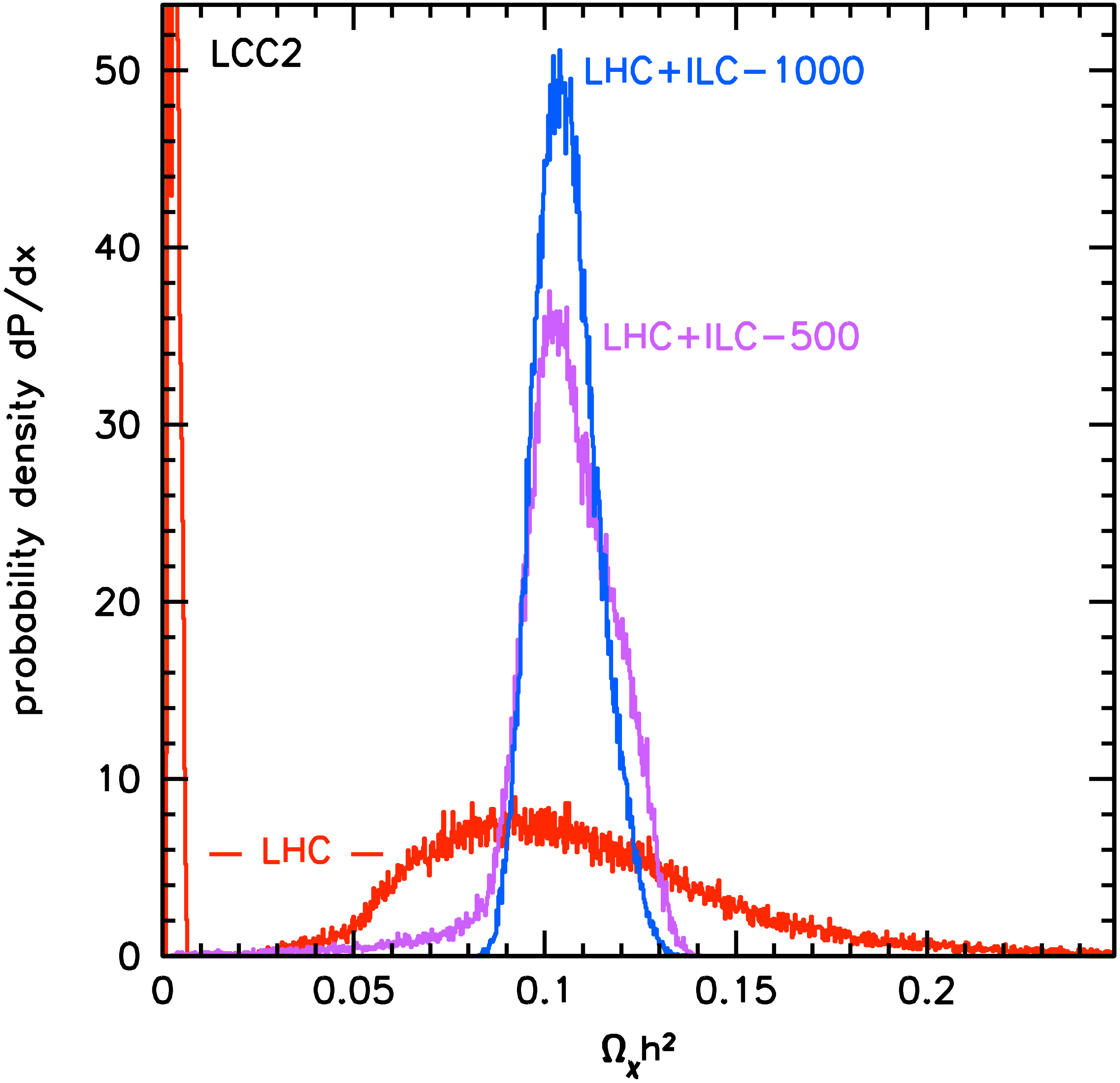
For this model, the spectrum constraints from the LHC alone give multiple solutions with different WIMP properties. The ambiguity is resolved by measuring polarization-dependent production cross sections at the ILC:



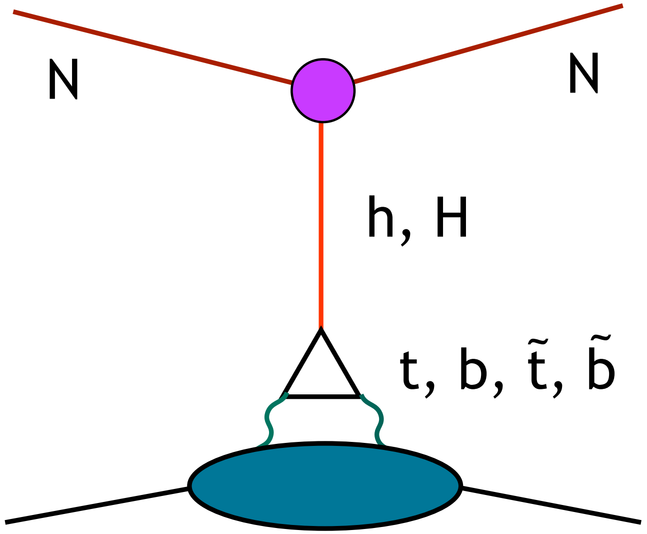


from the parameter determination, we obtain a microscopic predition of the cosmic dark matter density

to be compared to the measurement from the cosmic microwave background.



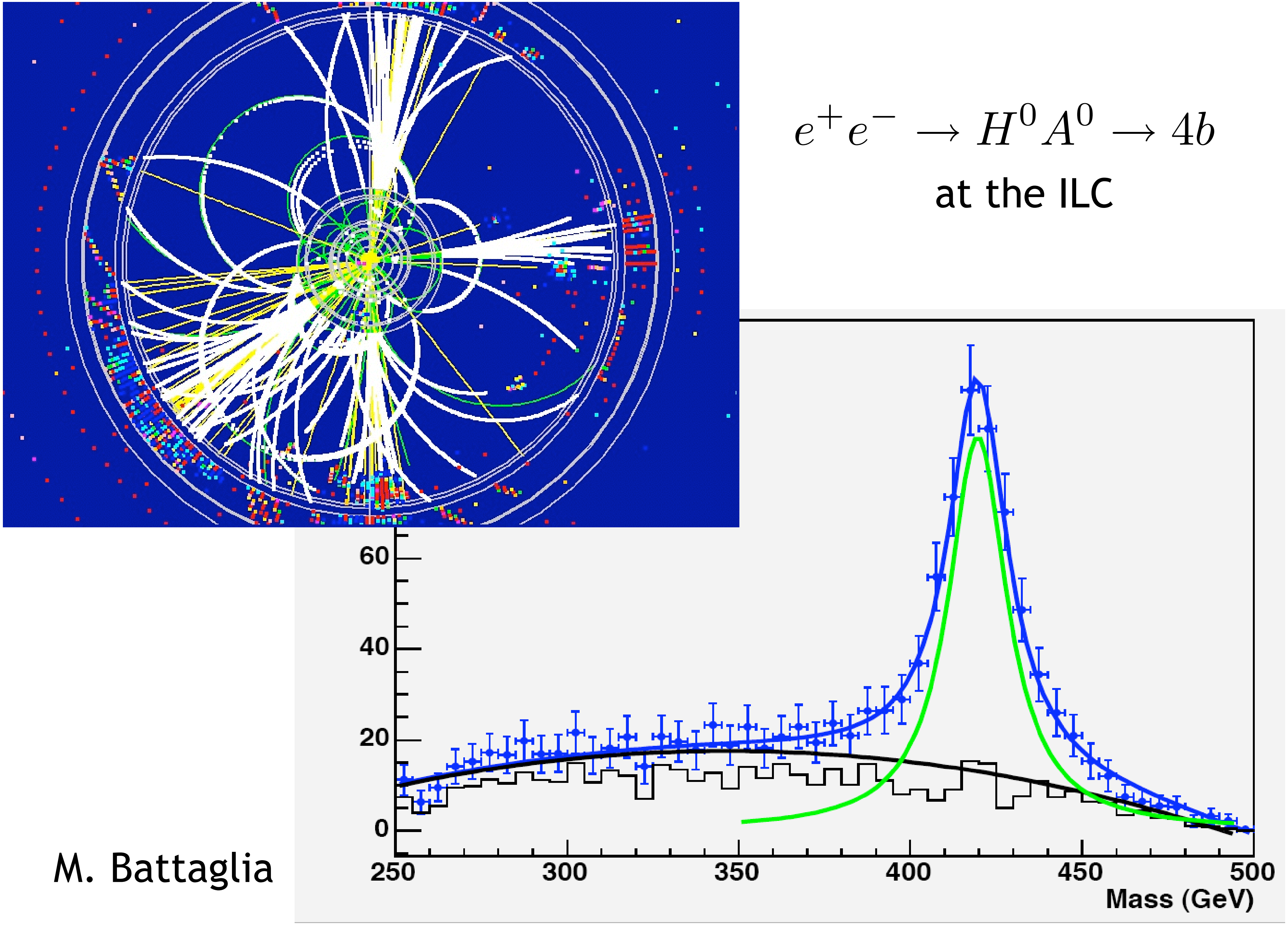
In supersymmetry, the direct detection cross section is typically dominated by Higgs exchange:



Precise measurements of the properties of the Higgs bosons at the ILC will provide the essential data to evaluate this cross section.

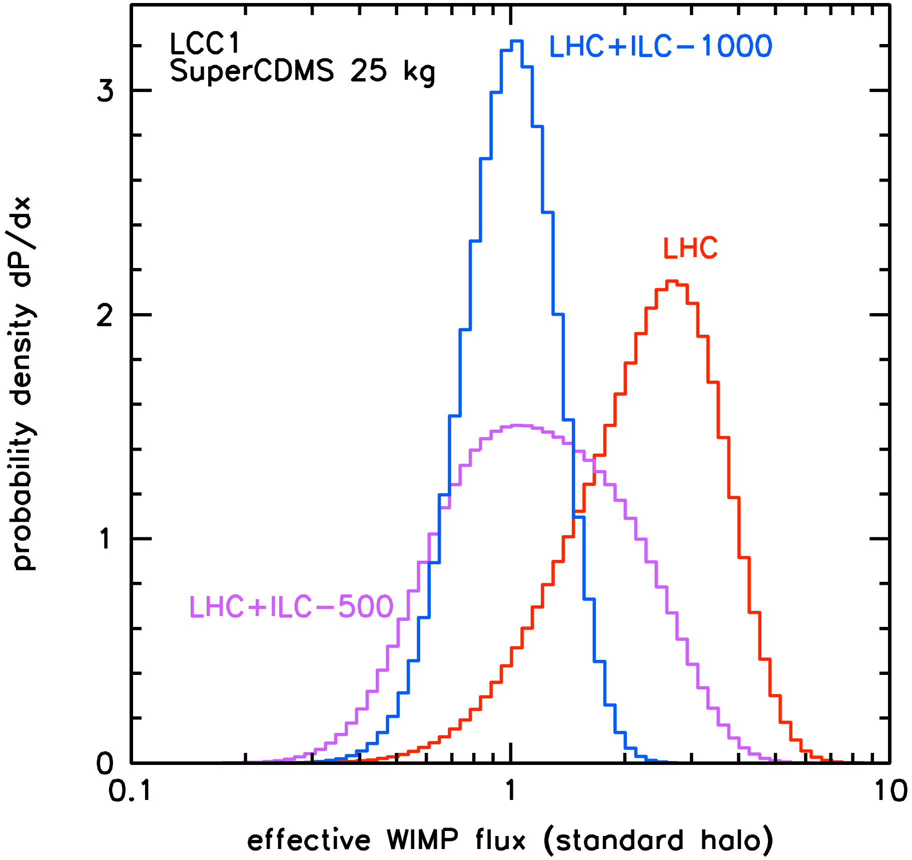
$$e^+e^- \to H^0A^0 \to 4b$$

at the ILC



M. Battaglia

Combining this cross section and the counting rate from a direct detection experiment, we will be able to measure the absolute flux of WIMPs at our position in the galaxy.



Similarly, by combining collider measurements and deteection rates for annihilation gamma rays, we can map the WIMP substructure of the galaxy.

This is the future of the study of cosmic dark matter:

The LHC and the ILC will give precision data on the spectrum of new particles that is in its own right important information about the fundamental interactions.

These data will constrain the WIMP properties so that astrophysicists can determine the distribution of WIMPs in the galaxy.

Thus, over the next 5-15 years, we can expect a new chapter to be written in our knowledge of physics, with insights for both the smallest and the largest distance scales in the universe.