High Energy Colliders as Tools to Understand the Early Universe

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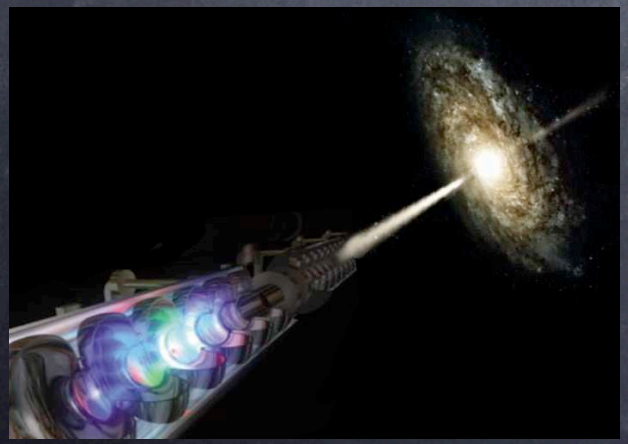
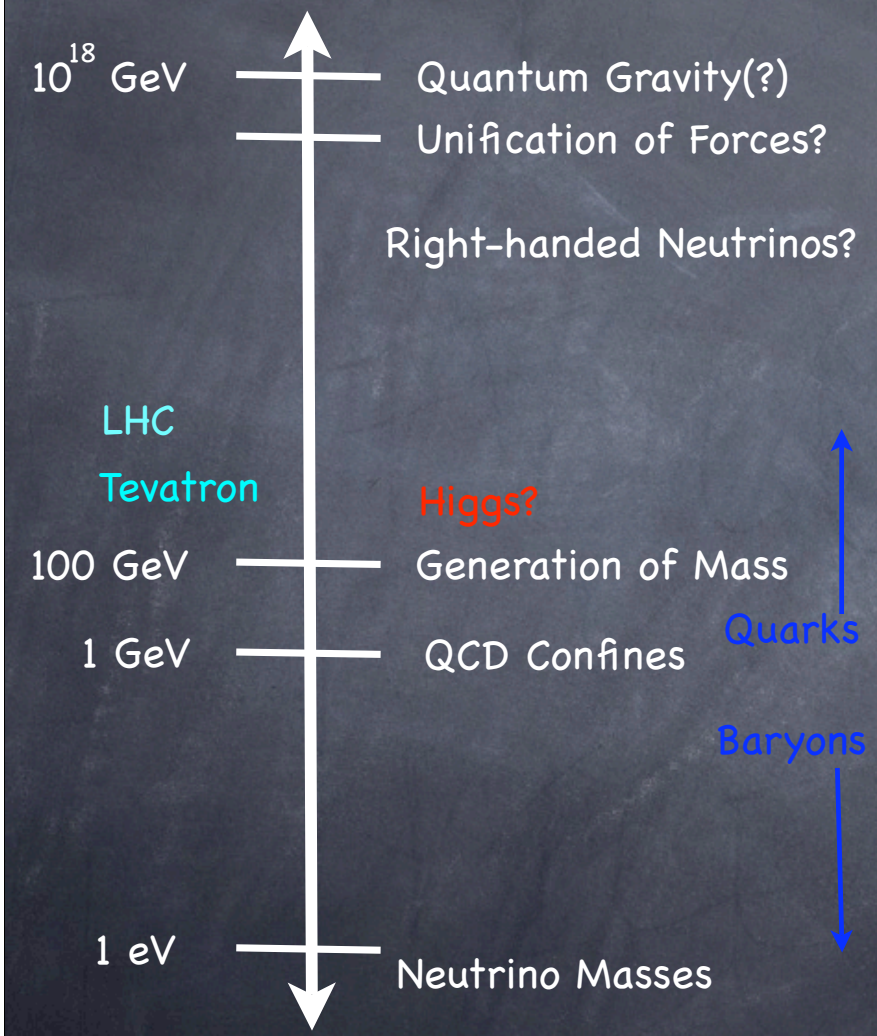


Fermilab
August 16, 2006

Outline

- The Universe is a mysterious place!
  - The Early Universe IS high energy physics.
  - Dark Matter and Dark Energy
- Connections to the mysteries of particle physics?
- Collider experiments and exploring the energy frontier
- Synergy between Observations on Earth and in the Heavens.

The Energy Frontier

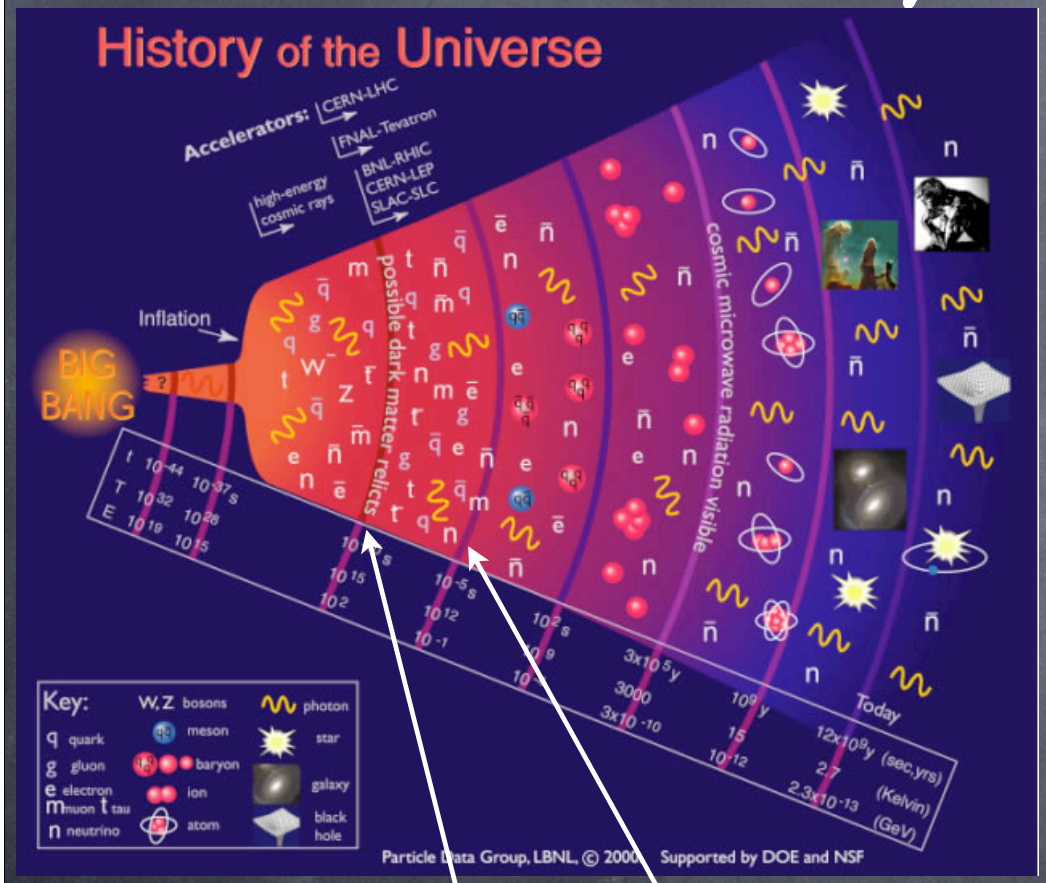


- Particle Physics today explores a very wide range of energies.
- Of particular interest are the highest energies, corresponding to the smallest distances and most massive elementary particles.
- We hope that higher energy physics will reveal more simple organizing principles and a more unified description of nature.
- The TeV scale contains the mystery of Electroweak symmetry breaking.

The Electroweak Scale

- In particular, the electroweak scale is where we hope to make the most progress in the near future of particle physics.
- We still haven't seen the Higgs and so we don't know if the minimal Standard Model is correct or not.
- From a practical point of view, our lack of knowledge of the TeV scale implies that we cannot extrapolate reliably to higher energies. We know that SOMETHING happens at that scale, but we don't know exactly what that something is!
- In fact, the hierarchy and triviality problems are widely considered signs that the minimal model is lacking.

The Early Universe



QCD confines

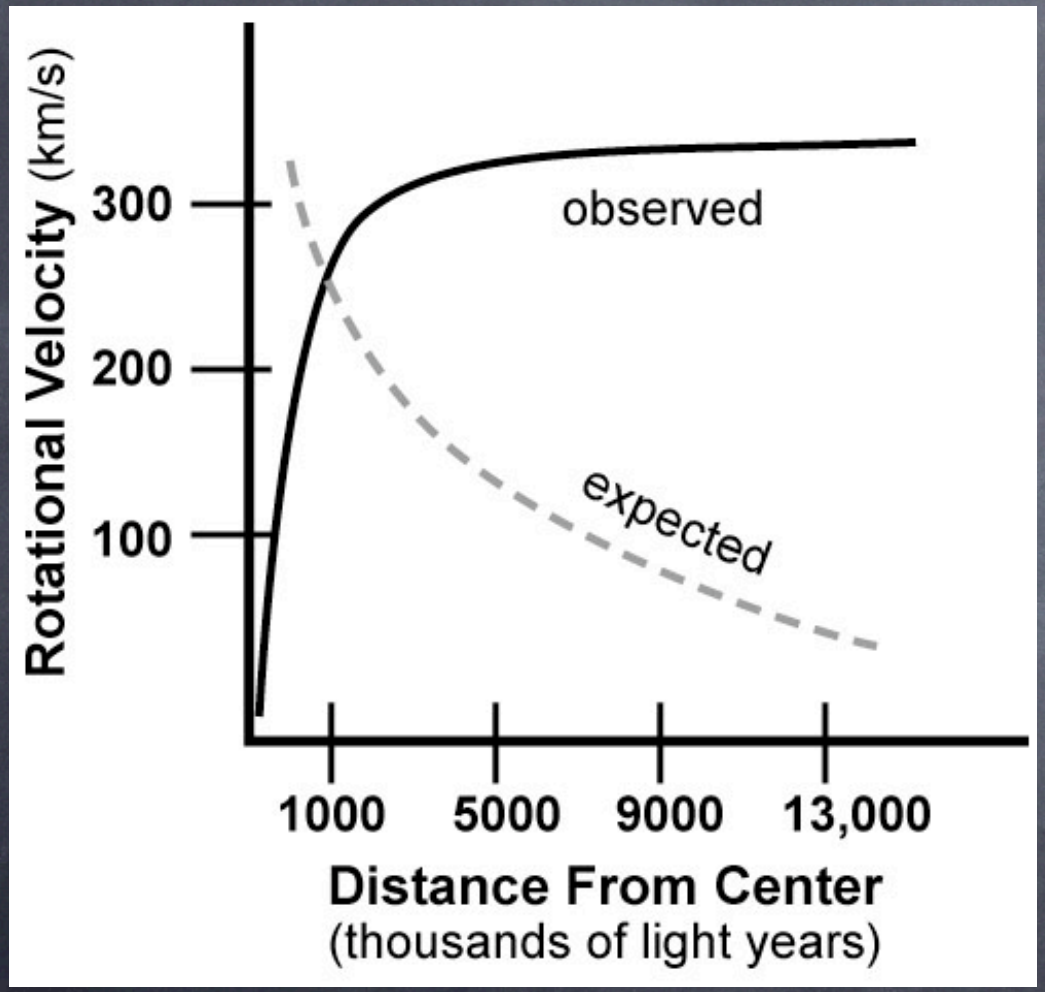
EW scale: Particles Gain Masses

- Understanding the early universe requires us to understand high energy physics.
- The way the universe evolves in a given epoch depends on the dynamics that govern it at that Temperature.
- Without the particle theory to describe those high temperatures, we cannot understand the Universe at those early times.

Particle Physics and Cosmology

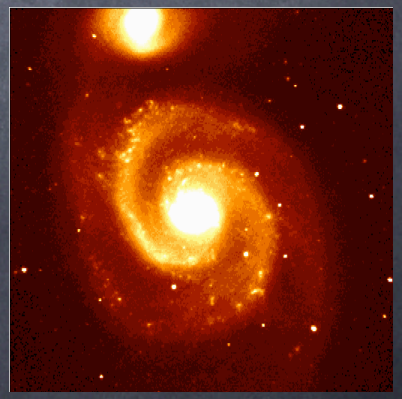
- We've already seen that even without making reference to any of the observations of the Universe, cosmology requires an understanding of high energy physics.
- Of course, the synergy goes in the other direction as well.
- The mapping of particle physics onto cosmology implies that interesting features of cosmology may be telling us about features of high energy physics currently beyond the reach of colliders.

The Missing Mass



- In the 1930s it was observed that visible stars do not account for enough mass to explain the rotation curves of galaxies.

F. Zwicky, 1933



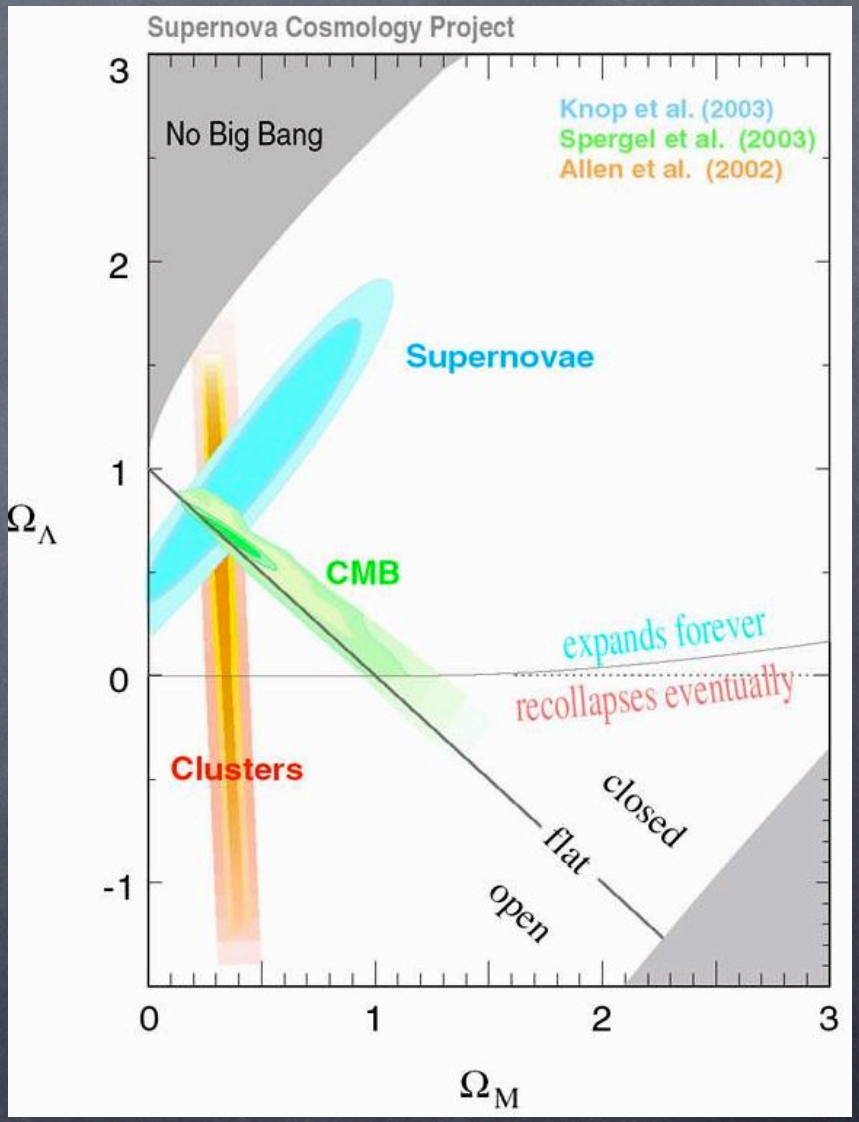
Spiral Galaxy M51

What's going on?

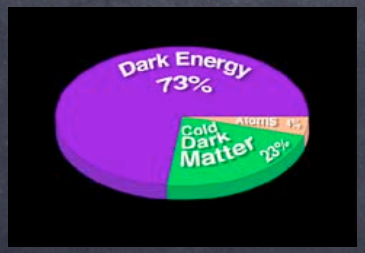
- Either there is mass in some non-luminous form, or the force of gravity is modified at large distances.
- Further data favors the first explanation.
- Structure formation favors a non-relativistic component of the Universe.
- Gravitational lensing occurs because large quantities of matter between us and a luminous source bend light and distort the image.
- That doesn't mean a modification of gravity can't be the answer, but it implies that the simplest solution is that there are dark components to the Universe.

CMB and Supernovae

- Today, the best determinations of dark matter come from the CMB (which shows the Universe is very flat) and super-novae, which show that the expansion is accelerating.
- Models of structure formation favor the same amount of dark matter as well!
- The data also favors a large component of dark energy.



$$\Omega_M h^2 = 0.126 \pm 0.01$$



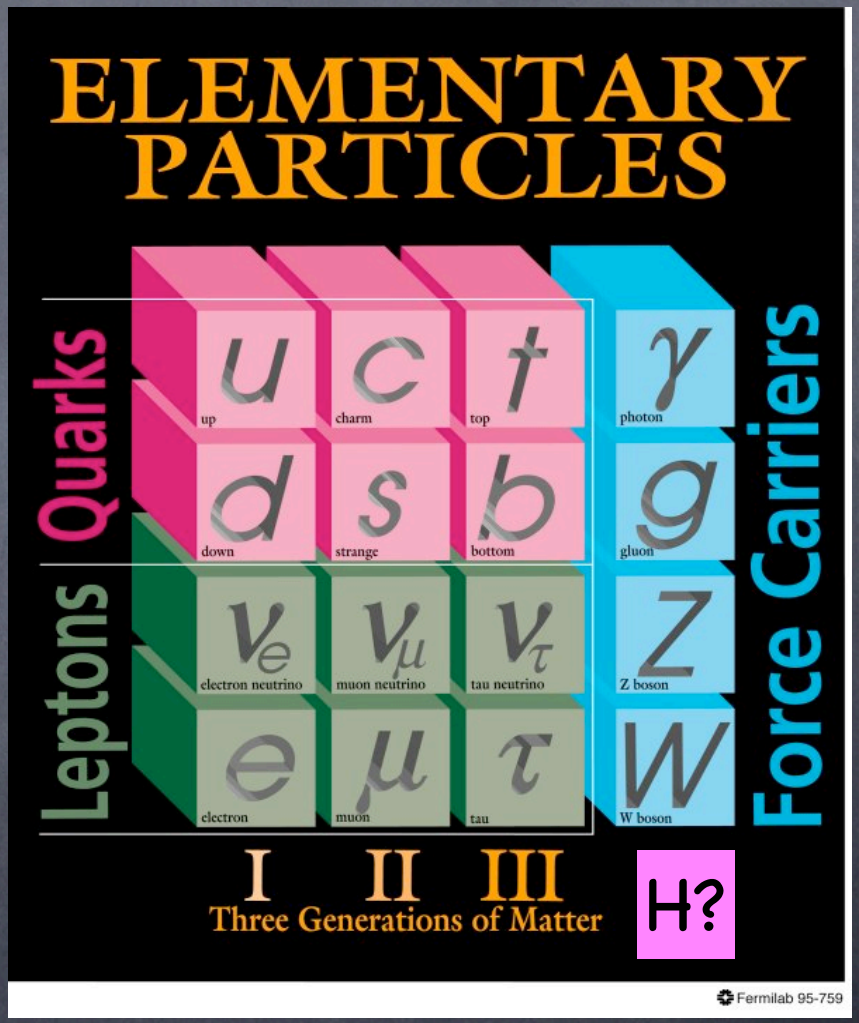
So what is this stuff?

"Cold Dark Matter: An Exploded View" by Cornelia Parker

- What do we know about it?
- It is:
  - Dark (neutral)
  - Non-relativistic (massive)
  - Still around today (stable or with a lifetime of the order of the age of the Universe itself).

Physics Beyond the SM

- The Standard Model has nothing with the right properties:
  - Photons, leptons, hadrons: too bright!
  - Neutrinos: too light!
  - Ws, Zs, and Higgs bosons: too short-lived!
- Dark matter is a manifestation of physics beyond the Standard Model!



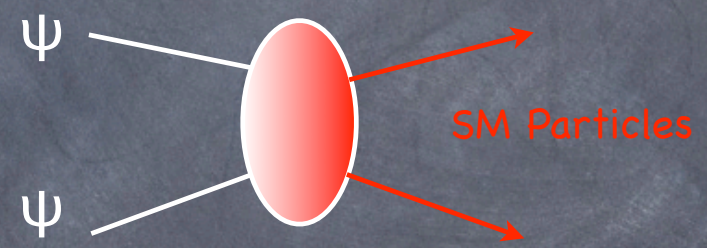
WIMPs

- One of the most attractive proposals for dark matter is that it is a **W**eakly **I**nteracting **M**assive **P**article.
- So for a theory of a WIMP, we extend the SM by some new particle ψ that we assume is neutral and heavy. We further assume that some selection rule requires ψ to always interact in pairs, so that no interaction will allow it to decay all by itself into SM particles, and thus it will be stable.
- The main attraction is that the amount of WIMPs in the Universe can be understood purely by assuming that at some early time they were in equilibrium with the hot plasma of SM particles. The **relic density** of ψ today doesn't depend in great detail on the early universe, but just on some of the microscopic properties of the WIMP itself.

Relic Density

- The energy density of ψ, as a non-relativistic particle, is just given by its mass m times its density in the Universe today.

- To understand the final density of WIMPs, to see if it matches the requirements of cosmology, all we need to specify is how effectively two WIMPs can scatter into SM particles, σ(ψψ -> SM):



- At temperatures below m, while ψ is in equilibrium, its number density will follow the familiar Boltzmann distribution:

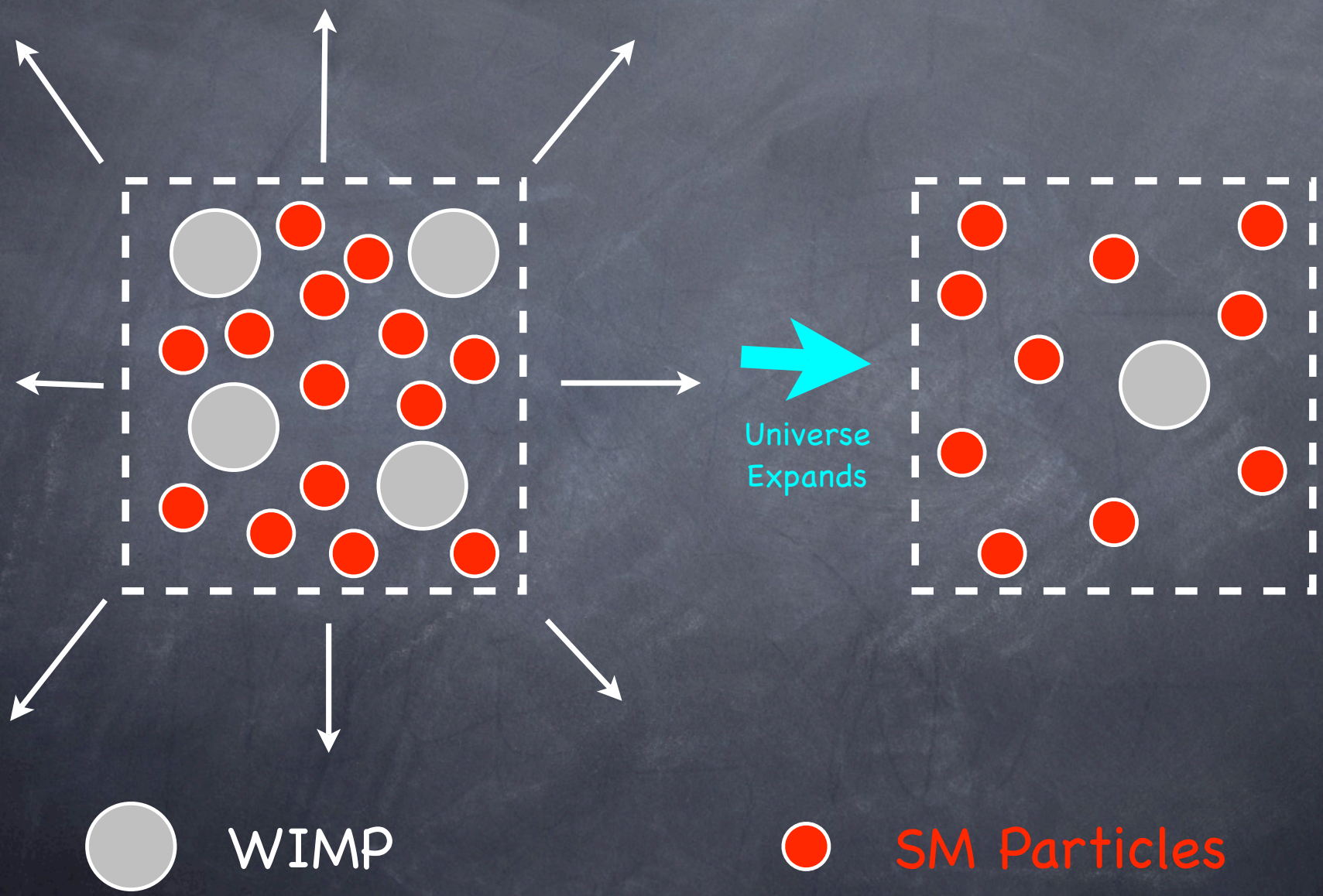
$$n_{eq} = g\left(\frac{mT}{2\pi}\right)^{3/2} \mathrm{Exp}\left[-m/T\right]$$

- So as the Universe cools, the number density of ψ decreases exponentially.

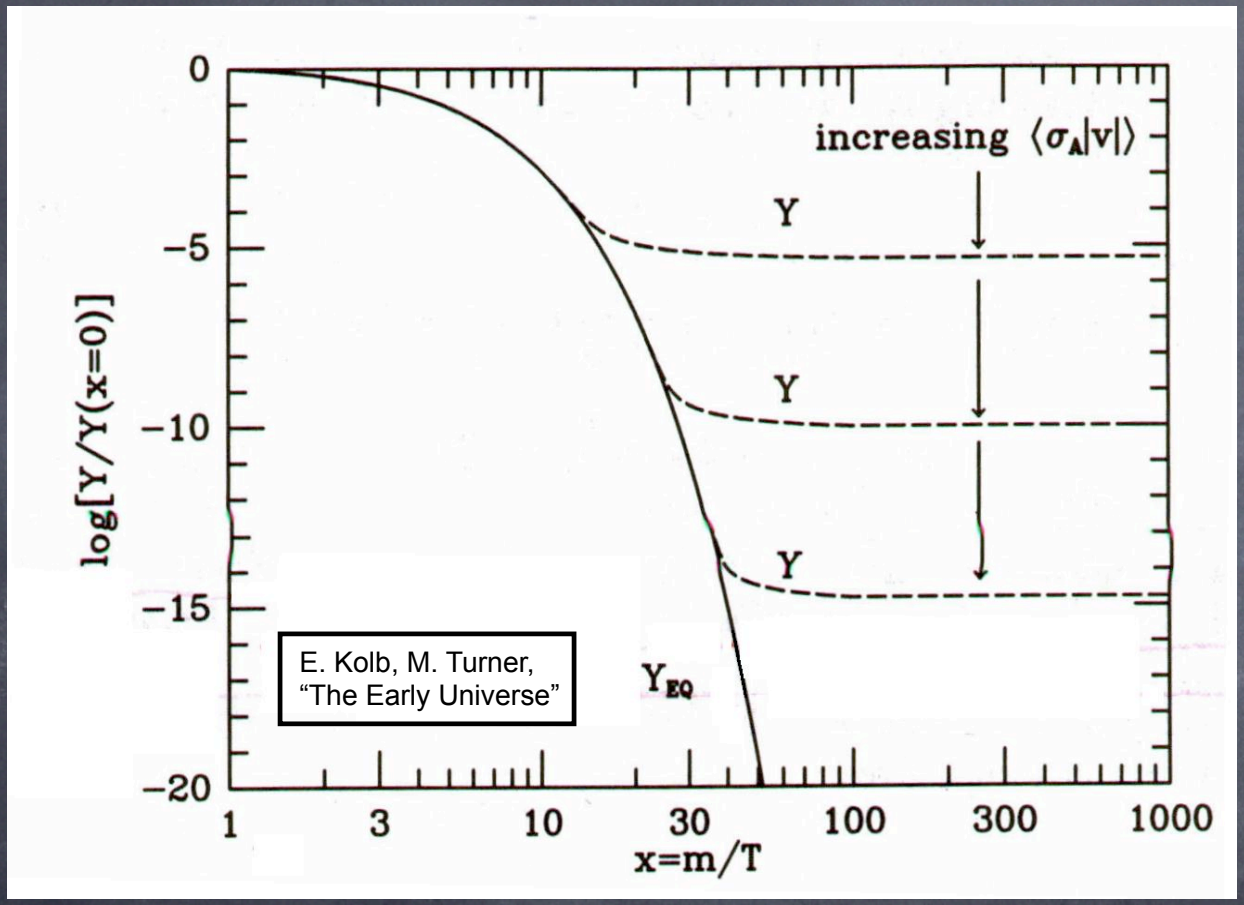
Freeze-Out

- However, an important modification to the picture occurs because the Universe is expanding.
- At the "freeze-out" temperature, the WIMPs are sufficiently diluted that they can no longer find each other to annihilate. At that point, they fall out of equilibrium with the SM plasma, and the number density ceases to fall.
- The temperature at which this occurs depends quite sensitively on σ: more strongly interacting WIMPs will stay in equilibrium longer, and thus end up with a smaller relic density than more weakly interacting WIMPs.

Freeze-Out



Relic Density



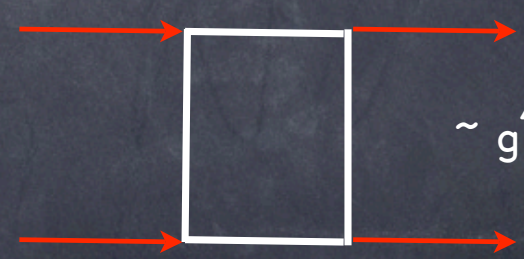
x=m/T increasing
is
T decreasing
is
time increasing

- So, for any WIMP, once we know its mass m and cross section into SM particles <σv>, we can predict its relic density.

TeV Scale Dark Matter

- We already expect new physics at the weak scale, and it is interesting to ask if models of electroweak symmetry-breaking could also contain dark matter.
- Such theories almost always include heavy objects, and neutral objects are easy enough to arrange. Thus, the trick is to have these objects be stable.
- Many theories for EWSB **do** have this property, by imposing a symmetry that forces the new particles to couple in pairs.
- This makes it much easier to agree with precision EW data from LEP and SLAC by suppressing SM -> SM processes.

$\sim g^2 / m^2$



$\sim g^4 / (4\pi\, m)^2$

TeV Dark Matter?

- Using the preferred amount of dark matter, we can extract the cross section which will result in the correct relic abundance.

$$\Omega_\psi h^2 = \frac{s_0}{\rho_C}\sqrt{\frac{45}{\pi g_*}}\frac{1}{m_{Pl}\langle\sigma v\rangle}$$

- We find that $\langle\sigma v\rangle \sim 1$ pb works well. This is an interesting number, first because this magnitude of σ is currently being explored at colliders.

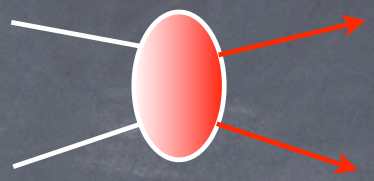
- Also, if we assume $\sigma \sim g^4/(128\pi\, m^2)$, the mass which leads to the right relic density is $m \sim 100$ GeV - exactly what we expect for a theory of EW physics!

- Coincidence? Maybe...

The Identity of Dark Matter

- To verify the WIMP hypothesis, we would like to see some sign that ψ actually exists, and measure $\sigma(\psi\psi \to SM)$ to verify that the relic density will match what we actually see in the Universe.
- That would at least be circumstantial evidence that we have divined the identity of dark matter.
- To really understand how it fits into a theory of EW scale physics, we need to understand in detail how it interacts with the SM.
- These details will depend on the specific model of dark matter, and thus truly pins down the theory of dark matter.

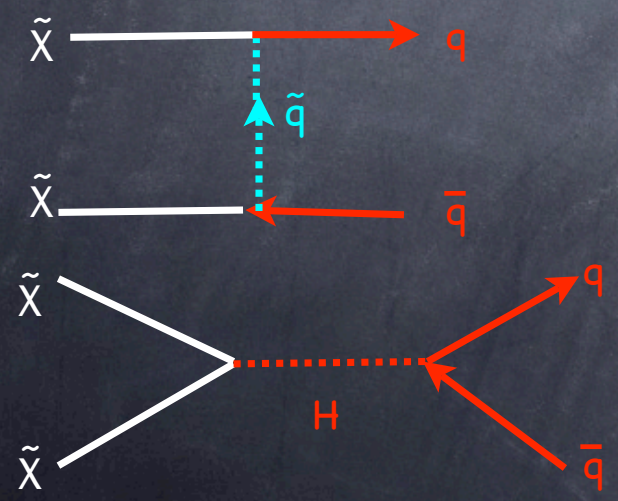
What goes in the blob?

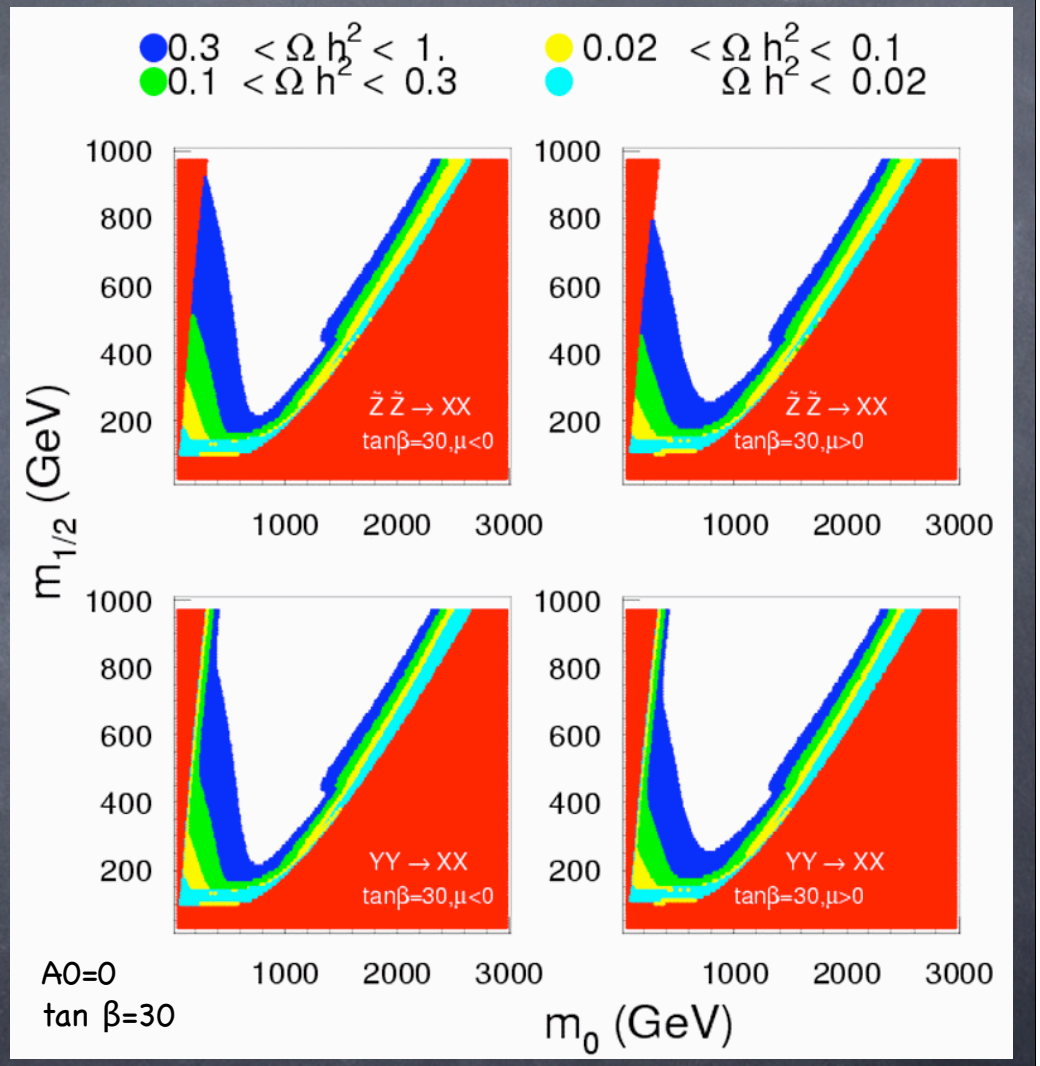


- I wrote a generic representation for the interactions that allow two WIMPs to annihilate into SM particles.
- In a specific theory we can compute this cross section in terms of the parameters of the theory.
- Most theories will have more new particles in addition to the WIMP. The WIMP will be stable so long as all of the new states couple in pairs, and the WIMP is the lightest of the new states.
- Then, we can compute the relic density as a function of those parameters, and the requirement that we get the right amount of dark matter puts constraints on those parameters.

SUSY: The Neutralino

- A popular theory of EW breaking is supersymmetry. These theories have a super-partner for every SM field with the same gauge charges, but spin different by 1/2.
- The lightest of these new states is usually a super-partner of the EW bosons, the neutralino. Pairs can annihilate into SM particles by exchanging the heavier super-partners.



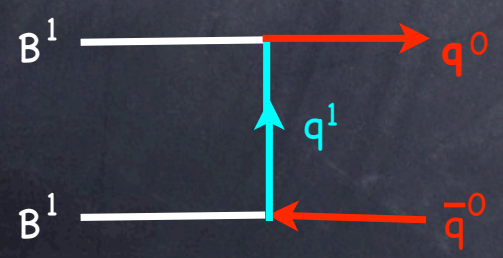


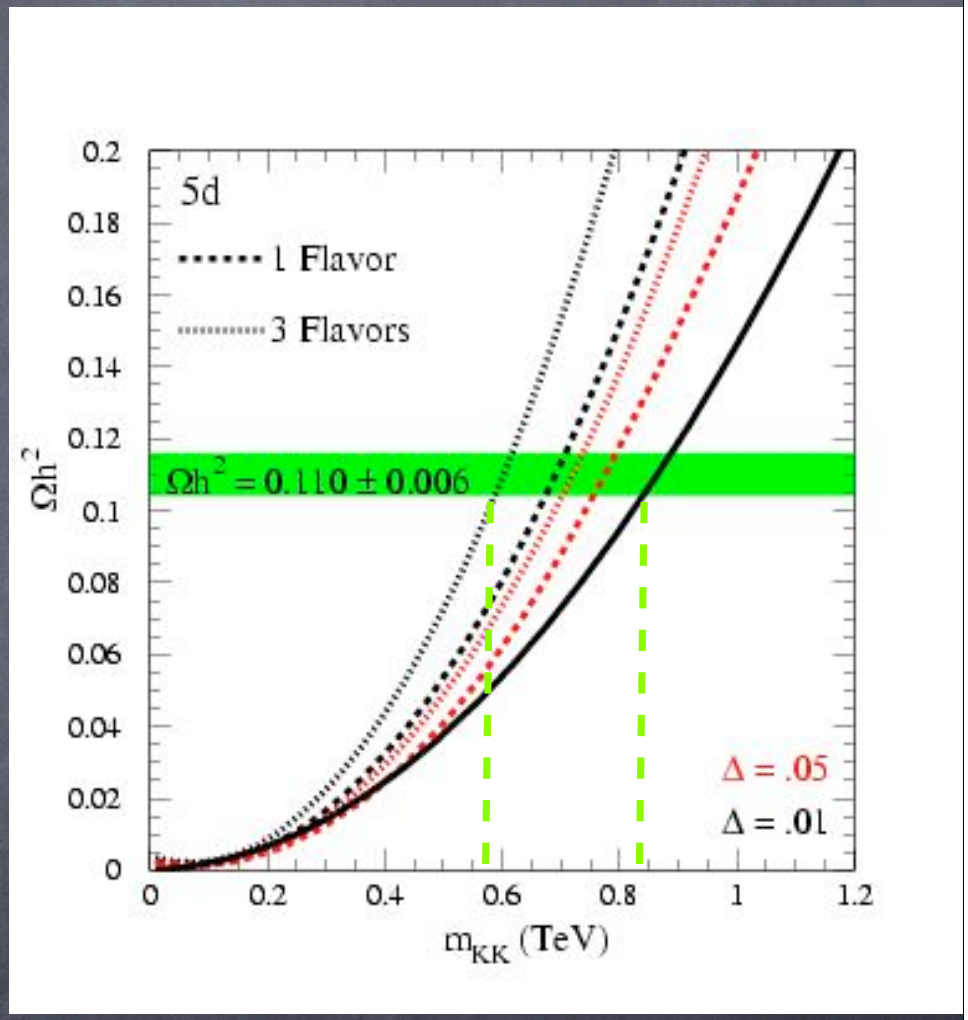
Baer, Balazs, Belyaev JHEP 0203:042,2002

UED: The LKP

- Another interesting theory has extra spatial dimensions that we don't see because they are curled up. The SM is identified as the particles not carrying extra dimensional momentum. When a SM particle carries momentum in the extra dimension, it looks like a copy of the original SM field with a larger mass. These KK modes couple in pairs to SM fields because of a space-time symmetry of the theory (Universal Extra Dimensions). The lightest KK particle (LKP) is stable.

- The LKP is usually the KK mode of an EW boson, and thus is neutral and a good DM candidate.





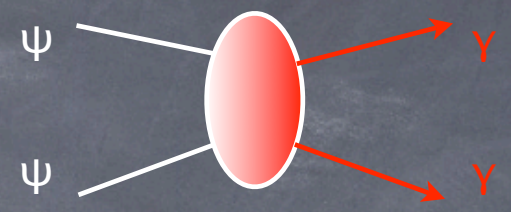
Useful Bounds?

- A quote from M Strassler who lectured earlier this week:

> In general, I suggest you listen politely to a theorist giving you a list of cosmological constraints, but ignore the constraints when doing collider analyses!

- In fact, I completely agree with him!
- Bounds are useful in the context of a specific theory. Those SUSY plots assume a pattern of SUSY-breaking (mSUGRA) which we might hope contains elements of truth, but most would agree probably is not literally true to the exclusion of all else.
- In the case of mSUGRA, it is known that a small change of parameters which may leave many collider signatures unchanged can drastically affect the dark matter density prediction.
- I think a better viewpoint is that we should see these sources of information as complementary. They enrich each other, not exclude each other.

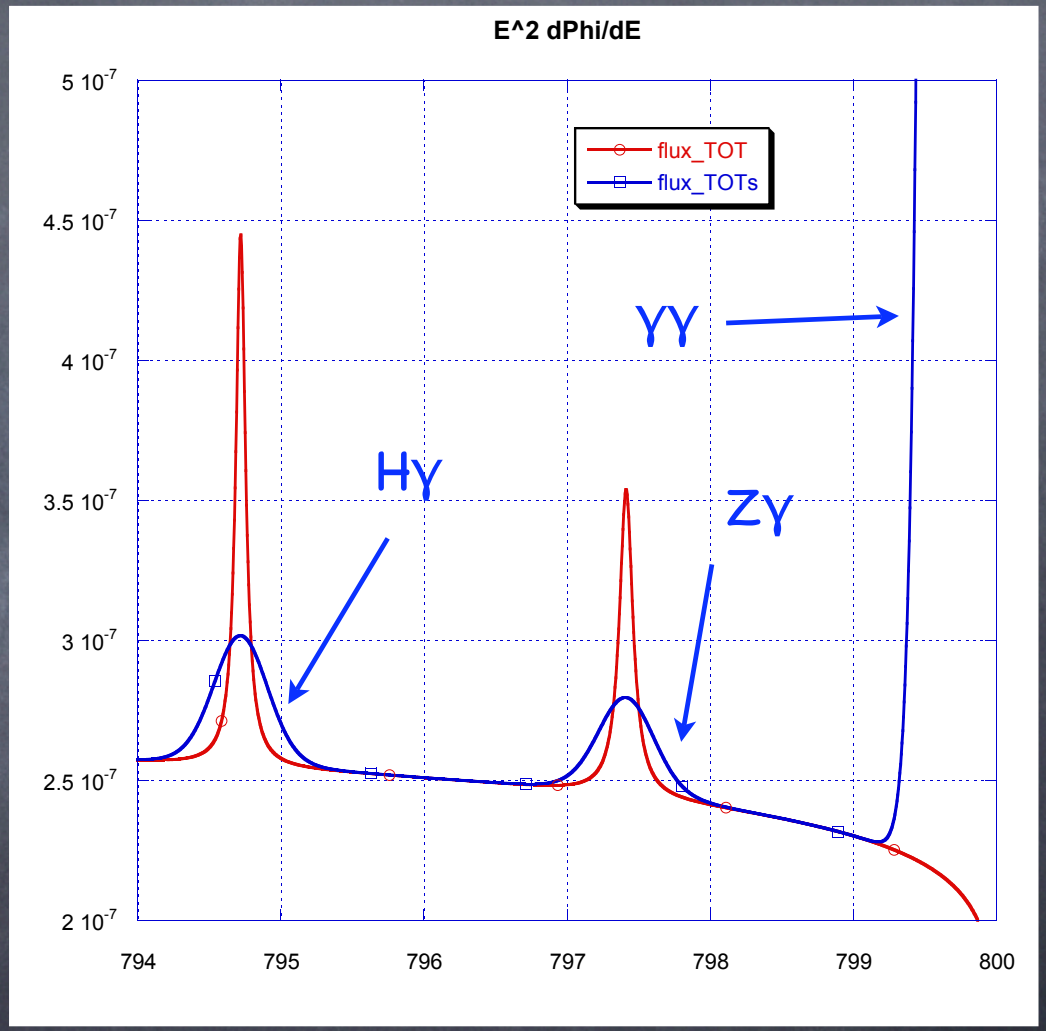
Indirect Detection



- In fact, there is a process which allows us to see (at least part of) the process ψψ-> SM directly.
- WIMPs in the galaxy can occasionally encounter one another, and annihilate into SM particles. Some of those particles can make their way to the Earth where we can detect them.
- In particular, photons and neutrinos interact sufficiently weakly with the interstellar medium, and might be detected on the Earth.
- Future experiments like GLAST, MAGIC, AMANDA, and ICECUBE all might discover dark matter this way.

Indirect Detection

- The spectrum of γ's comes from many processes.
- Let's take an example of the UED theory with the LKP as dark matter.
- Sharp lines from BB->γγ, BB-> Zγ, and BB->Hγ.
- Continuum spectrum from BB-> charged particles followed by radiation.



Bertone, Liguori, Tait, Vallinotto, in progress...

Is Indirect Detection Enough?

- Indirect detection would be a great discovery of a dark component of the Universe. But that isn't enough to pin down dark matter's nature.
  - From a theoretical point of view, we don't get all of σ(ψψ -> SM). Just the part into γ's and maybe ν's.
  - The signal depends on the DM density squared along the direction we are looking:

Distance along line of sight

DM density

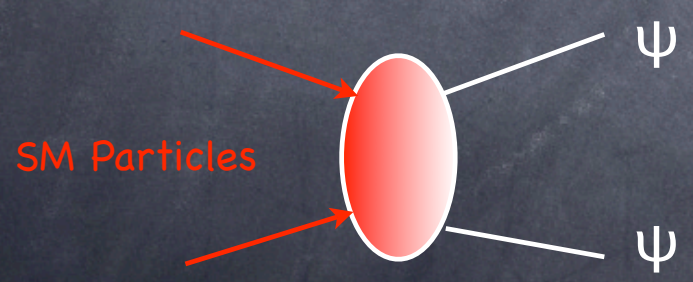
$$\frac{dN}{E} = \frac{d\langle\sigma v\rangle}{dE} \int dl\, \rho_{DM}^2(l)$$

- Models for the galactic structure disagree about the density by as much as an order of magnitude. So σ will be uncertain.
- The features of the spectrum do vary from WIMP to WIMP, but not very strongly. Mostly the mass controls the shape.

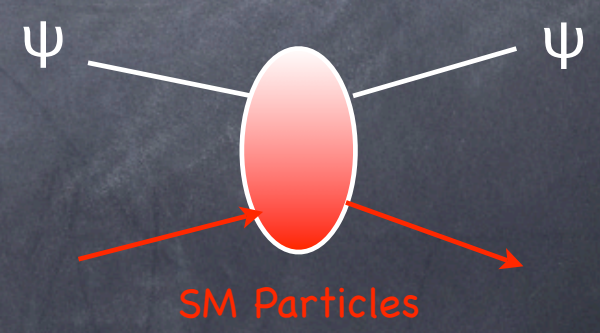
Other Processes

- Indirect detection is very interesting because it probes (a subset) of the processes directly responsible for the WIMP abundance. But we saw that it is limited as to how much information we can extract and by our knowledge of the WIMP density in our galaxy.

- Fortunately, we can predict more phenomena by just rearranging the annihilation diagram!



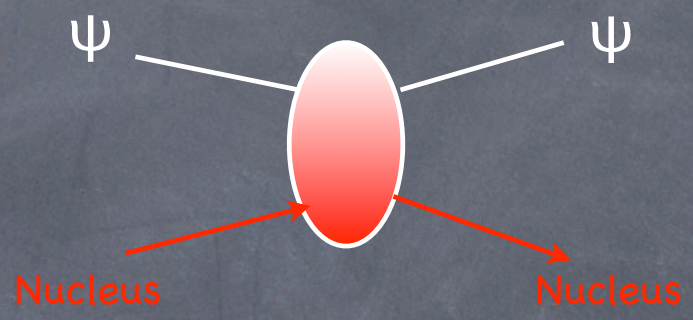
High energy collisions of ordinary matter produce WIMPS

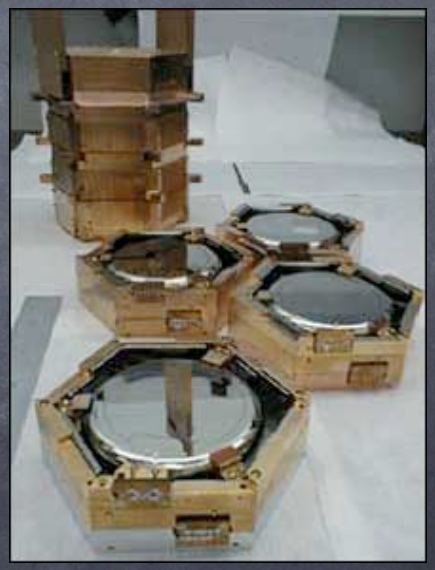


WIMPS scatter with ordinary matter.

Direct Detection

- Direct detection attempts to discover dark matter through its collision with heavy nuclei.
- This is a rare process, since WIMPs don't interact strongly with ordinary matter.
- Heavily shielded detectors such as CDMS or DAMA look for a WIMP which easily passes through the shielding, but happens to interact with the detector.





CDMS

Direct Detection

- Unlike indirect detection, the rate of a direct detection experiment depends on one power of the WIMP density (close to the Earth).

DM density

Nuclear Physics

$$\frac{dN}{dE} = \sigma_0 \frac{\rho}{m} \int dv f(v) F(E)$$

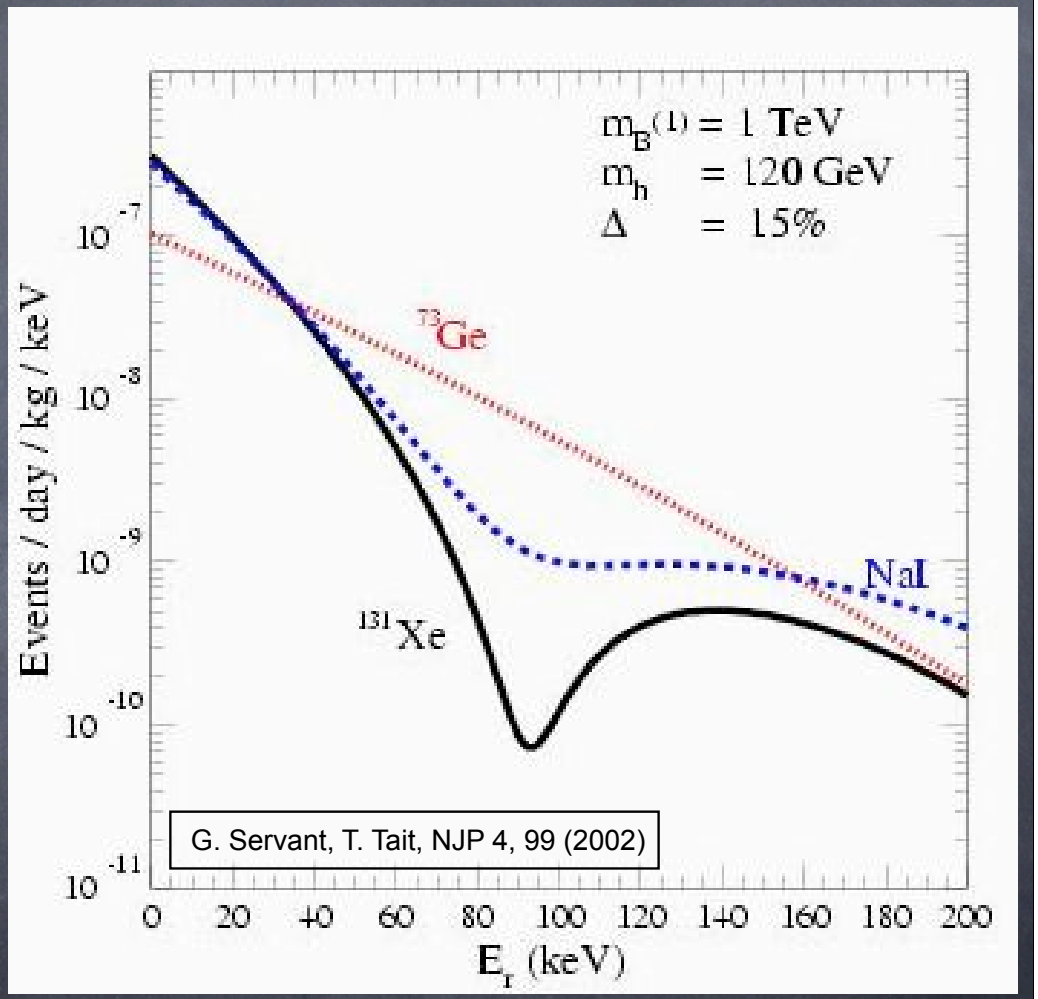
WIMP velocity distribution

- The energy spectrum of the recoiling nucleus depends on the WIMP mass, and nuclear physics. (There is some interplay between the form factor for "scalar" compared to "spin-dependent" WIMP interactions with nuclei which IS WIMP-dependent - but usually the first is so completely dominant that it is difficult to see the second.

- The cross section is dominated by the effective WIMP interactions with quarks and gluons.

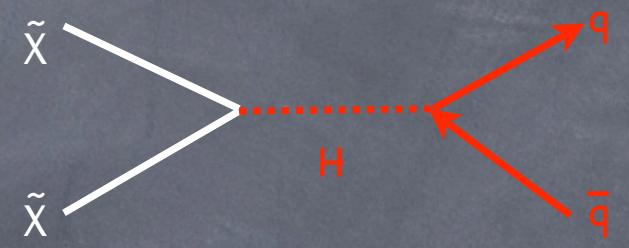
Recoil Energy

- The recoil energy spectrum depends on the mass of the WIMP and some details of how it interacts with the target.
- The nuclear physics of the target is very important.
- However, most direct detection experiments are not sensitive to the recoil spectrum, and statistics are likely to be limited.

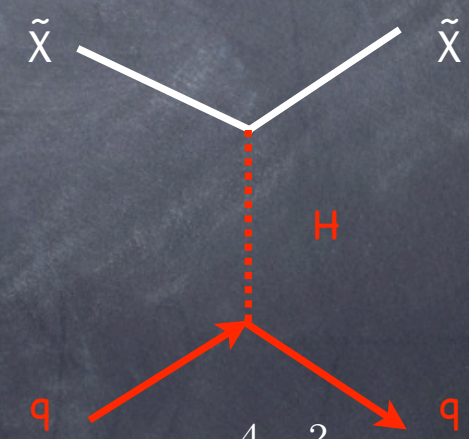


Crossed Sections

- As with indirect detection, a positive result from a direct detection experiment would be an exciting sign of dark matter.
- However, direct detection also does not provide enough information to verify the WIMP hypothesis by reconstructing the relic density.
- The rate is sensitive only to the cross section into quarks, and further, the crossing of one WIMP and one quark from initial to final state can have a large effect which is difficult to extract if direct detection is the only DM signal at hand.
- As an example of how this works, consider the supersymmetric case where neutralinos annihilate into quarks through an s-channel Higgs.
- The annihilation rate can have a large enhancement when the Higgs is close to on shell. The direct scattering cannot.



$$\sigma \sim \frac{g^4 m_\chi^2}{\left(2m_\chi^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2}$$

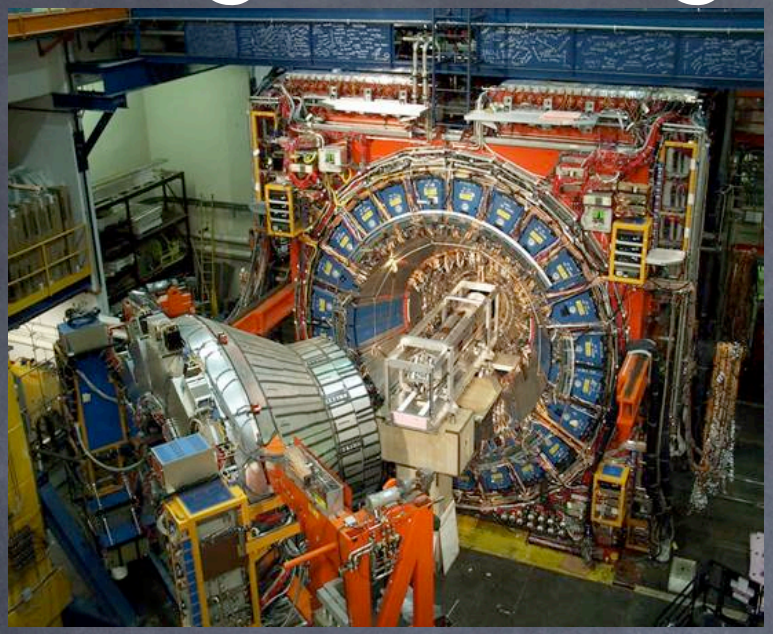


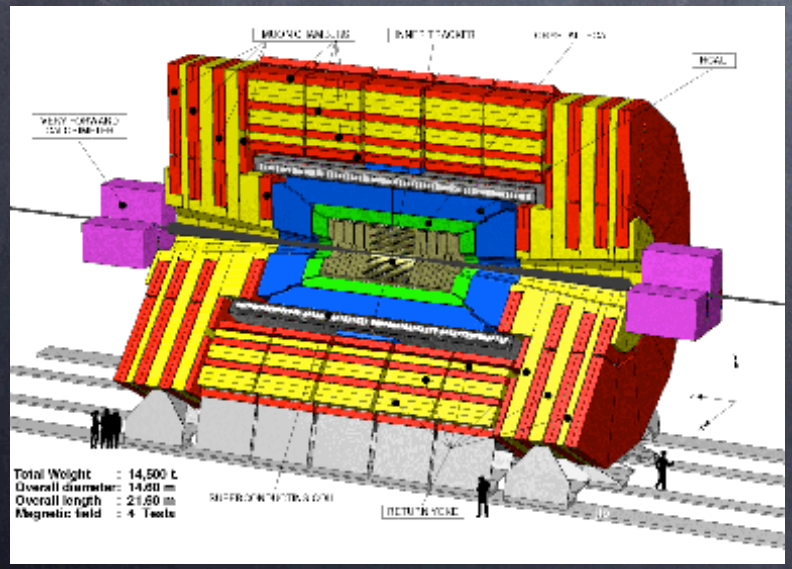
$$\sigma \sim \frac{g^4 m_\chi^2}{\left(2m_\chi^2 + m_H^2\right)^2}$$

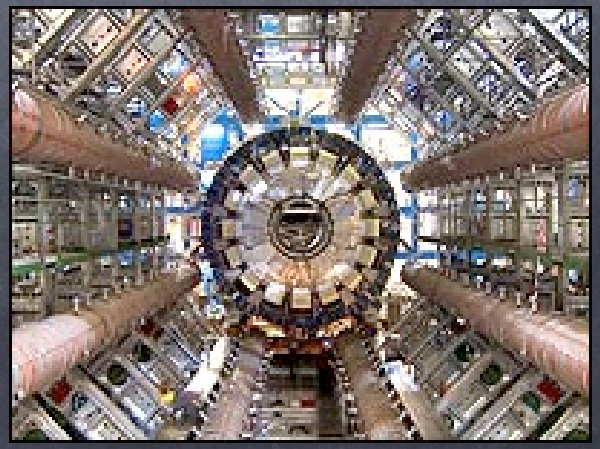
Collider Production

- Which brings me to the way in which high energy colliders can tell us something about dark matter.
- By studying the production of WIMPs in collisions of SM particles, we are seeing the inverse of the process which kept the WIMPs in equilibrium in the early Universe.
- The crossing which switches the initial and final states is not likely to change the cross section as dramatically as the move from s- to t-channels that took place in going to direct detection.
- Finally, provided they have enough energy to produce them, colliders allow us to study the "partners", which are no longer present in the Universe today.

High Energy Detectors

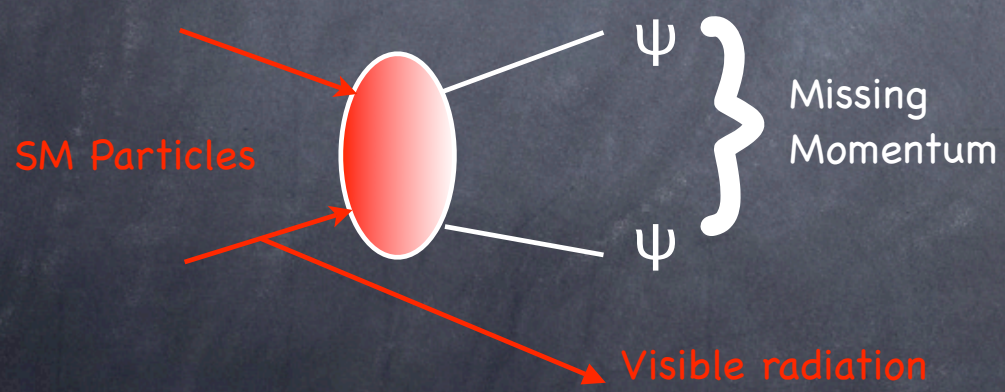


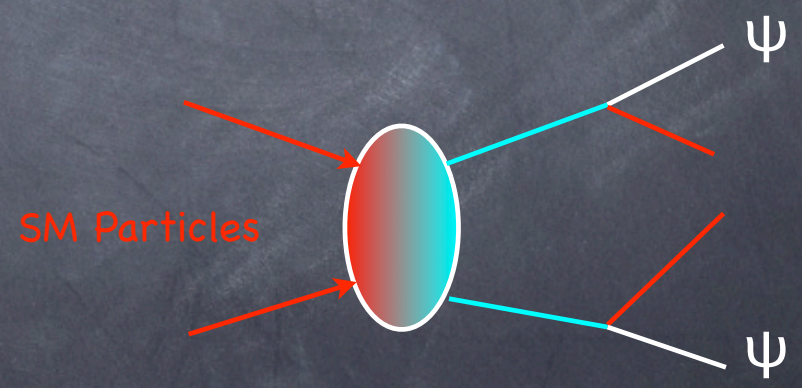




Seeing the Invisible?

- WIMPs interact so weakly that they are expected to pass through the detector components without any significant interaction.
- Thus, they are invisible.
- There are two ways we can try to "see" them nonetheless:



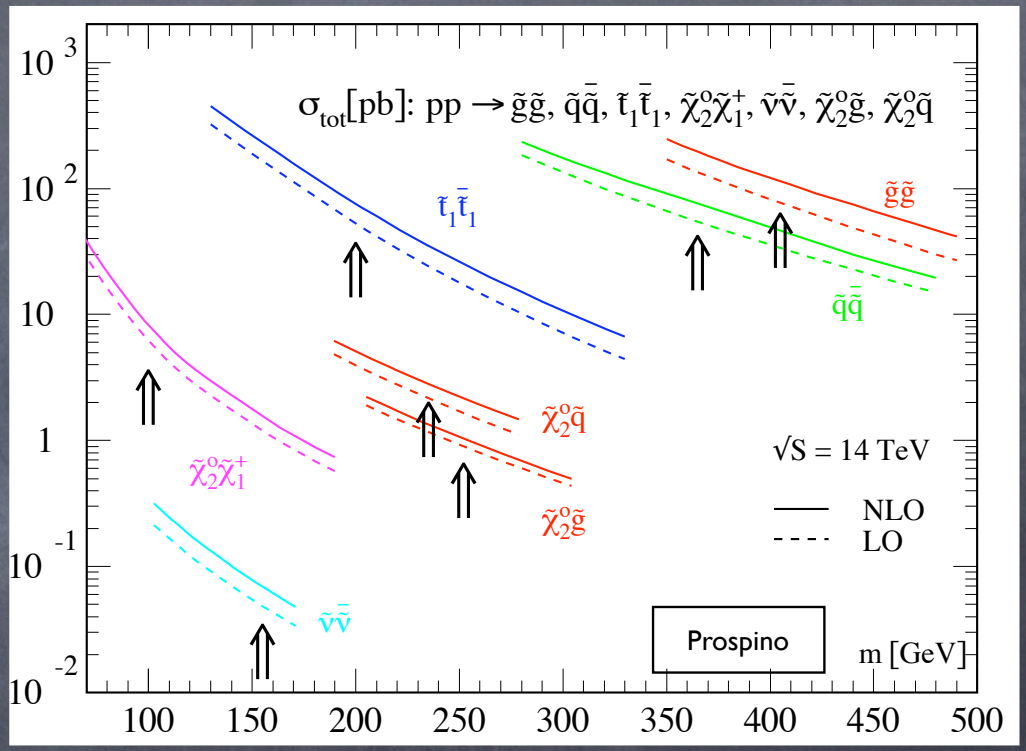


Radiation from the SM side of the reaction.

Production of "partners" which decay into WIMPS + SM particles.

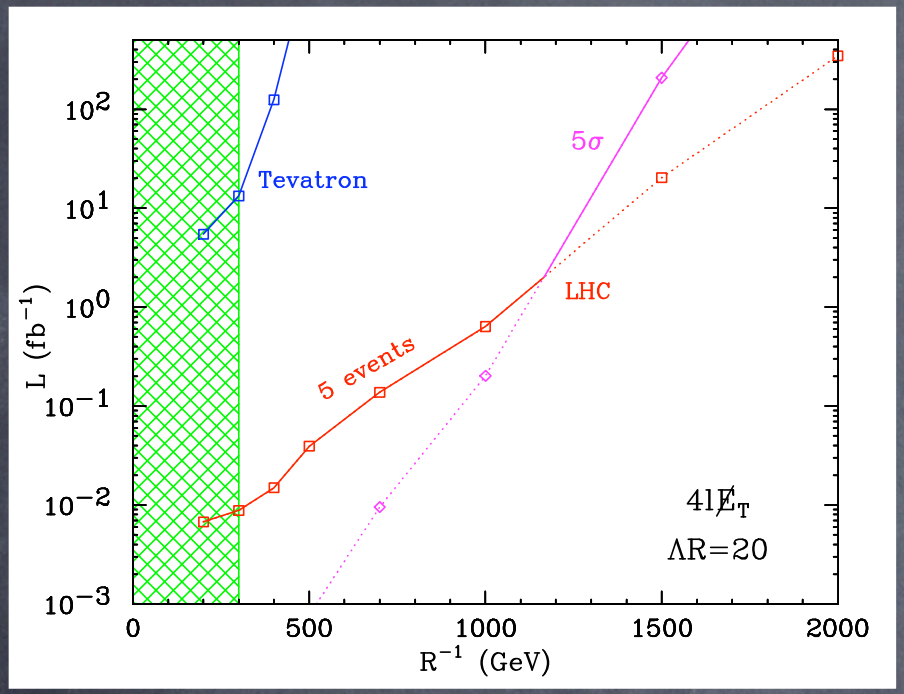
Rates and Processes

- Which particles are accessible depends on the collider.
- At a hadron collider like the Tevatron or LHC, rates to produce new colored particles are large because of the strong coupling.
- These particles are often less important to understand dark matter, but they decay into the EW particles which are important.
- At a future e+e- collider such as the ILC, the heavist states may not be accessible because of more limited energy; but the precision with which accessible states can be measured is unparalleled.



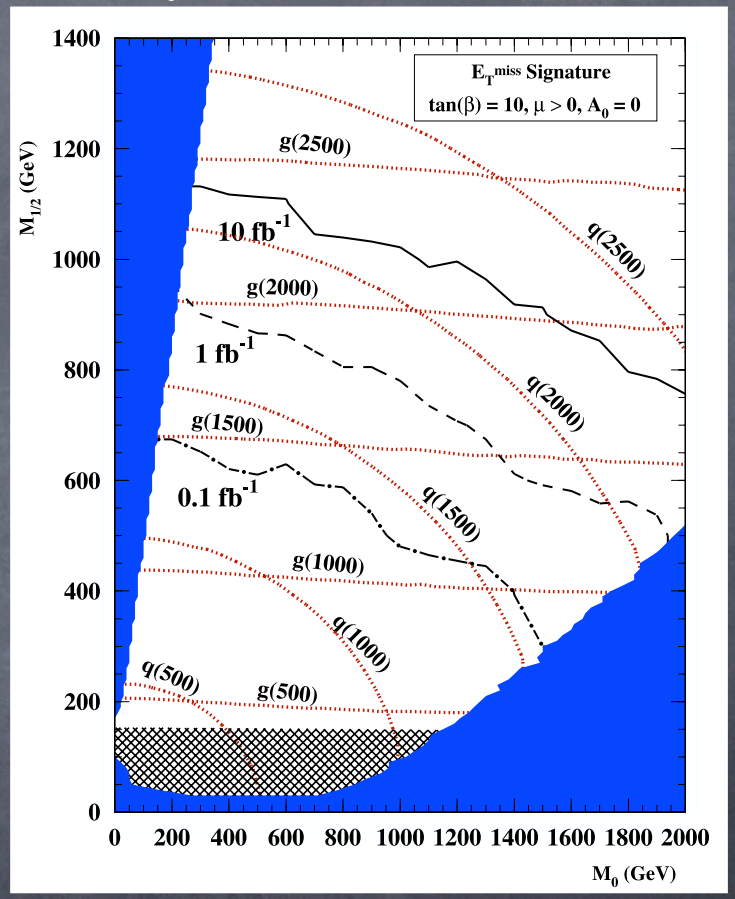
Supersymmetric particle production cross sections at the LHC

Discovery Prospects



Kaluza-Klein Quarks decaying into LKPs+jets

Cheng, Matchev, Schmaltz
Phys.Rev.D66:056006,2002

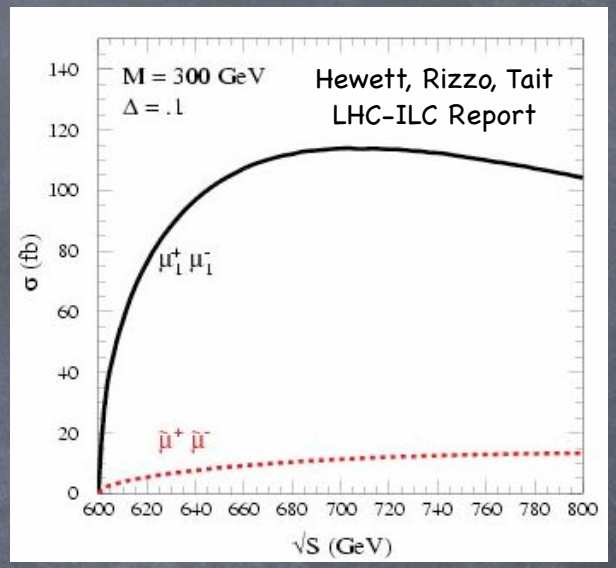


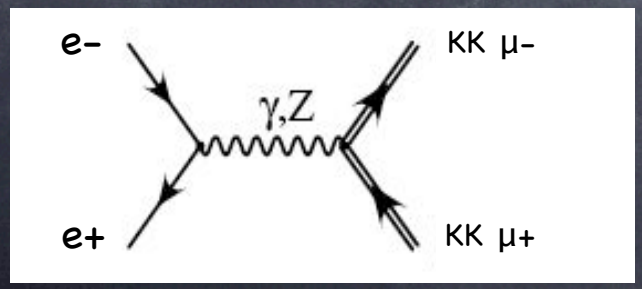
Squarks + Gluinos into Neutrlino+jets

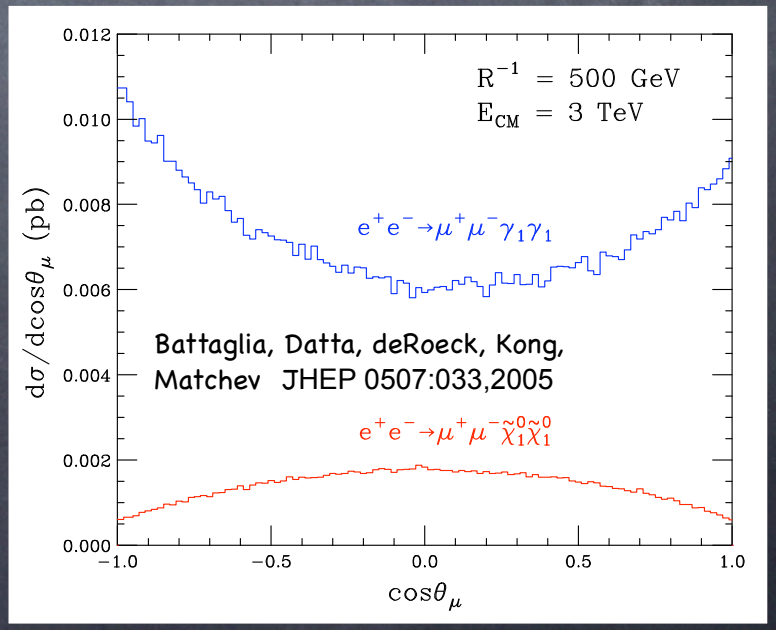
ATLAS study

Distinguishing SUSY from UED

- SUSY and UED can be very tricky to distinguish.
- Both theories contain new states that look like heavy copies of the SM fields.
- They primarily differ by their spins, but the fact that we miss the WIMPs makes it difficult to reconstruct spin.
- So the first task in unravelling the true theory is to be able to understand something about the spins of the new states.







Reconstructing the Relic Density

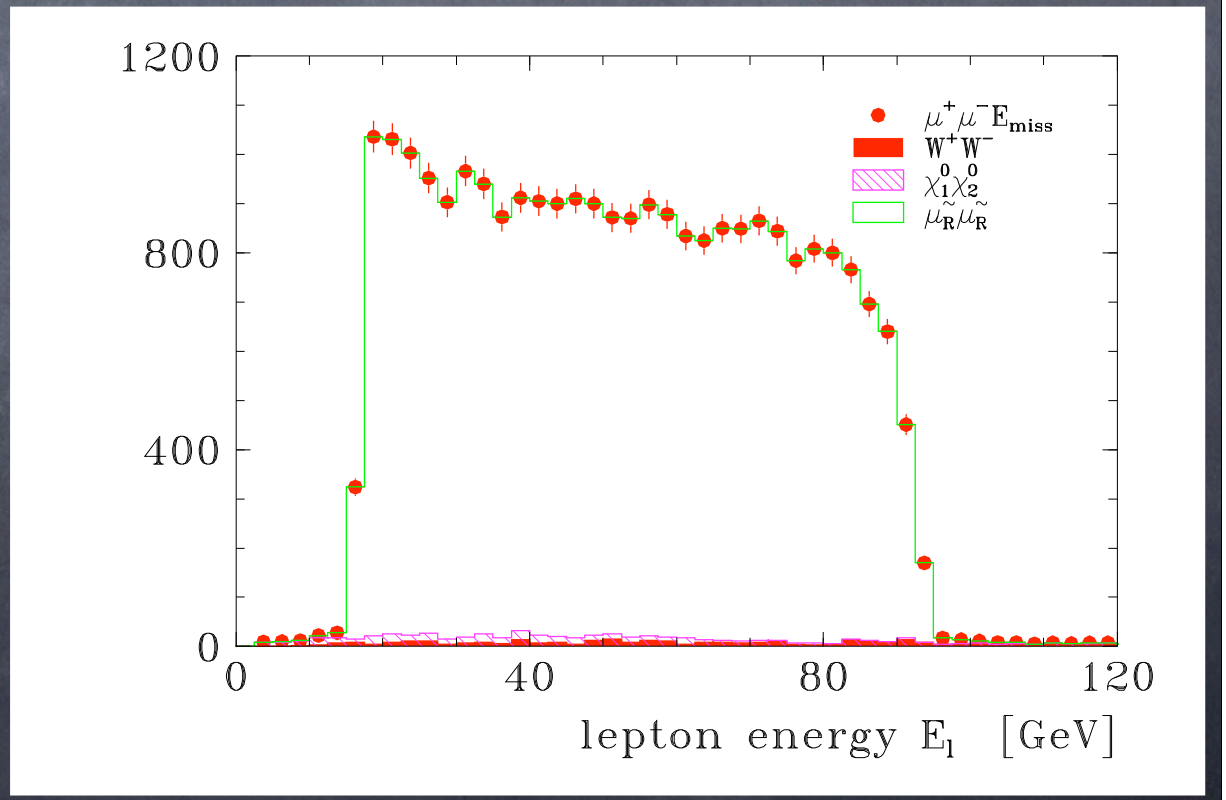
- The hope is that by discovering enough of the new states, and measuring the right quantities, we will have everything we need to reconstruct the relic density.
- Eventually, with enough measurements to teach us how WIMPs interact with the Standard Model, we could hope to reconstruct the relic density.
- That would be a (circumstantial) clue that we have identified dark matter, and that we understand why it is present in the observed quantity in the Universe.

Measuring Masses

- Masses can be measured at colliders, for example from kinematic distributions.
- As an example, consider e+e- -> super-muons.
- The smuon decays into a regular muon and a neutralino.
- The distribution of muon energies reflects an upper limit related to the smuon mass and collider center of mass energy, and a lower limit related to the fact that enough energy must be left-over to make a massive neutralino.

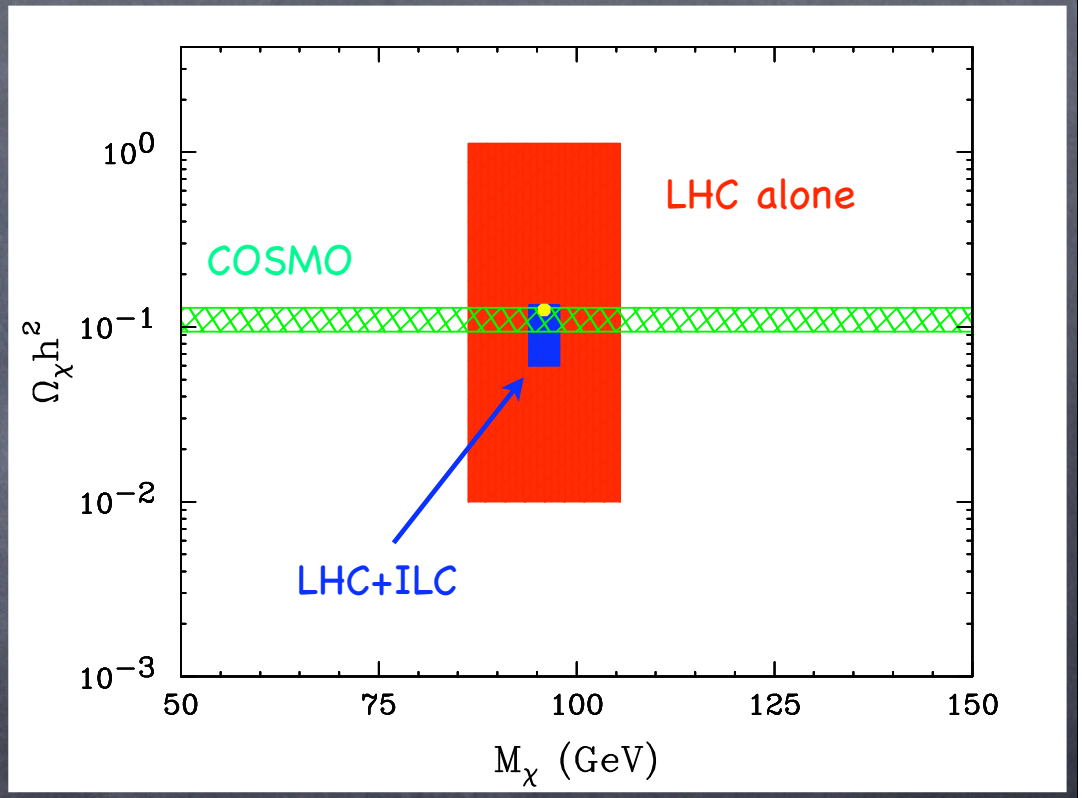
$$
\begin{aligned}
E_{+/-} &= \frac{\sqrt{s}}{4}\left(1-\frac{m_{\tilde{\chi}}^2}{m_{\tilde{\ell}}^2}\right)(1\pm\beta)\,, \\
m_{\tilde{l}} &= \frac{\sqrt{s}}{E_- + E_+}\sqrt{E_-\,E_+}\,, \\
m_{\tilde{\chi}} &= m_{\tilde{l}}\sqrt{1-\frac{E_- + E_+}{\sqrt{s}/2}}
\end{aligned}
$$

Martyn, LHC-ILC report



Tevatron / LHC / ILC

- There is a large complementarity between the information from hadron colliders, and that from a future lepton collider.
- Hadron colliders typically have access to heavier states, but lose precision because of we can't reconstruct the parton CoM system, and from the hadronic environment.
- Comining the two can lead to a very precise reconstruction of the DM relic density, as shown for an example SUSY model here.



Birkedal, Matchev, Alexander, Ecklund, Fields, Gray, Hertz, Jones, Pivarski hep-ph/0507214

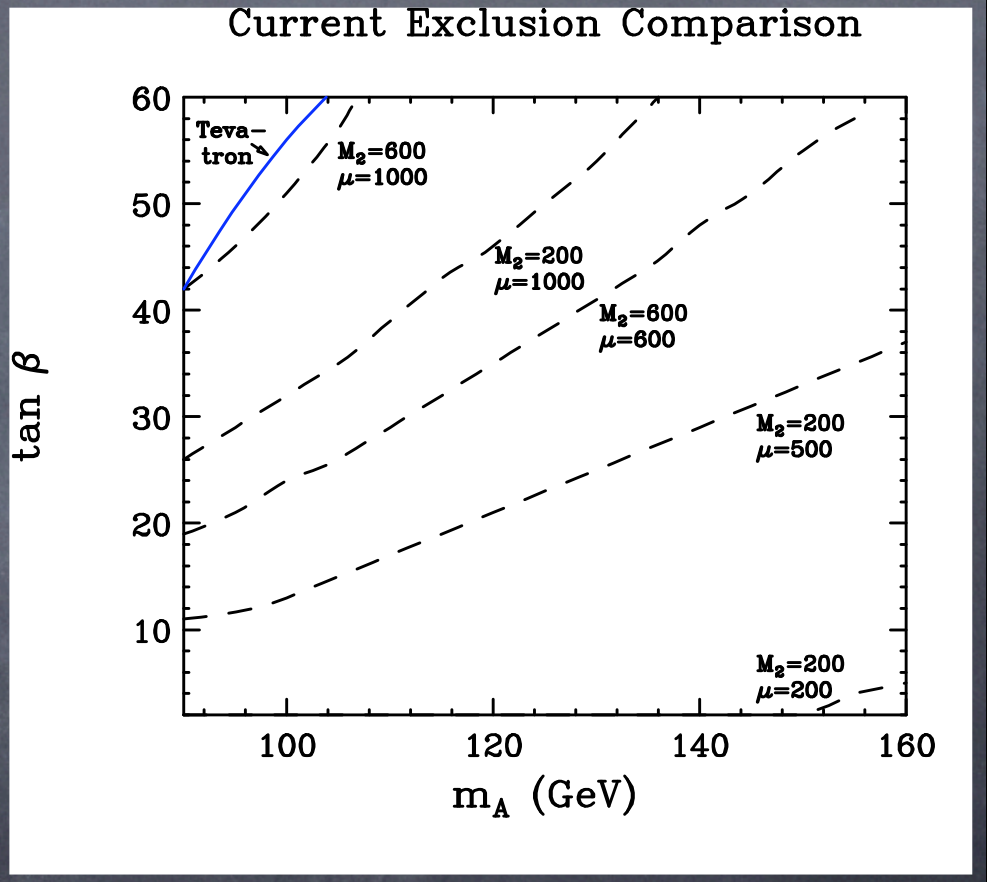
Are Colliders Enough?

- Personally, if we can reconstruct the relic density, I will be fairly satisfied that the circumstantial evidence is quite strong.
- Of course, it might be that we will already have indirect and/or direct detection results at the time of a collider discovery, or soon afterwards.
- Some people would probably want one of these signs that the new particles being seen at colliders really are the stuff that is actually in the Universe before being convinced.
- This would allow us to correlate measurements at colliders with predictions for heavenly observations.

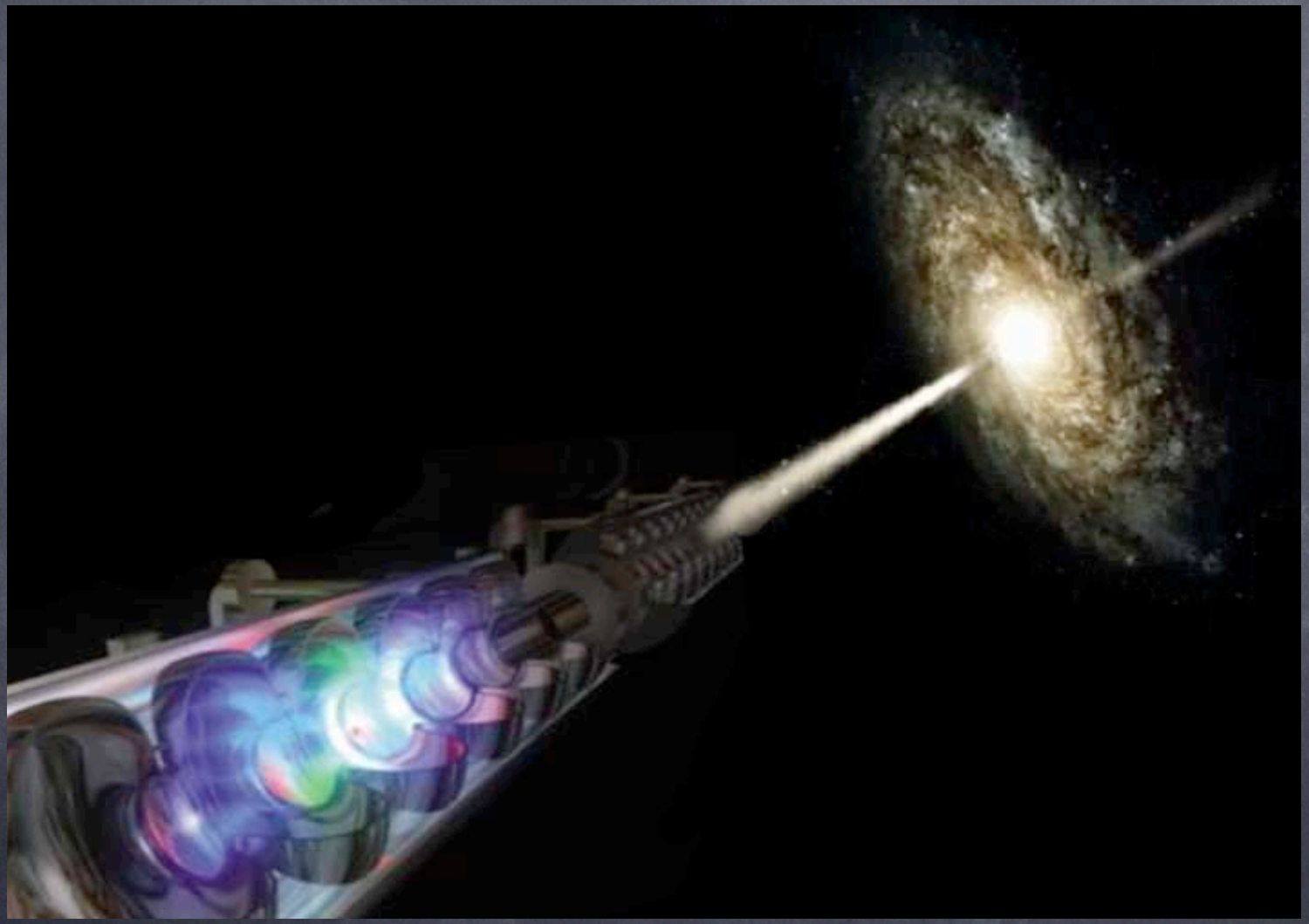
Synergy

- I see a lot of room for interplay between all three types of processes: collider, indirect, and detect.
- Collider processes start with a well-understood initial state. By controlling the initial conditions, we have an advantage in extracting the parameters which determine the microscopic physics.
- Direct detection represents a clearer indication that what we are dealing with IS really the WIMP!
- Once we understand the microphysical reactions, Indirect detection tells us about the profile of dark matter in the galaxy, something that will help a lot in understanding galactic structure and dynamics.

- There may also be sectors of the theory which are more difficult to test at colliders.
- For example, a study of super-symmetric theories concluded that the CDMS bound from the lack of a direct signal is currently more constraining than the Tevatron search on the CP odd Higgs A0 - but subject to assumptions about the local DM density, other model parameters, etc.



Carena, Hooper, Skands hep-ph/0603180

Conclusions

- The mysteries of the Universe require information from accelerators in order to be properly understood.
- There is every reason to believe that both fields can continue this fruitful relationship.
- I have specifically drawn on the example of dark matter as a case in which we see evidence for the existence of something in cosmology that we would like to understand. Detailed understanding probably requires a controlled environment such as collider in order to reliably extract a clear picture.
- Combined with direct and indirect searches, we can maximize our understanding of the Universe and the Energy frontier!