WIMPs
and Future Gamma-Ray Astronomy
from a Particle Theorist's Perspective

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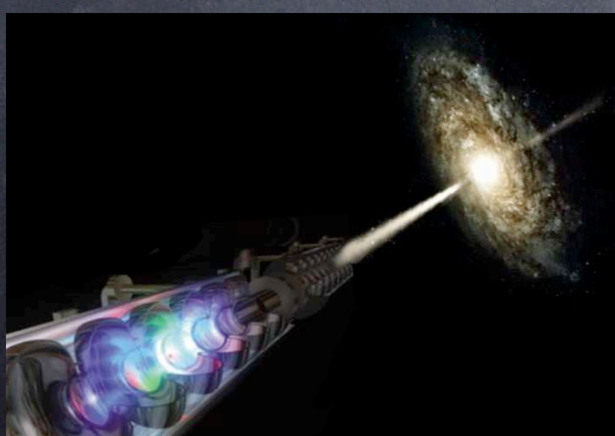
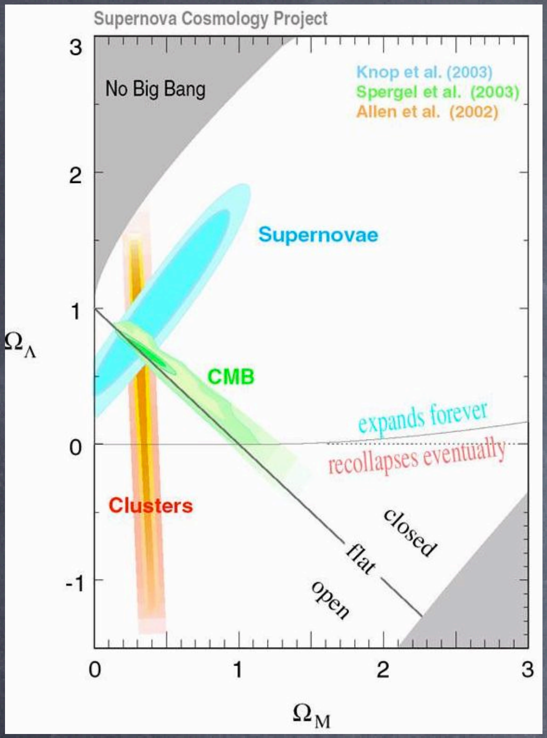


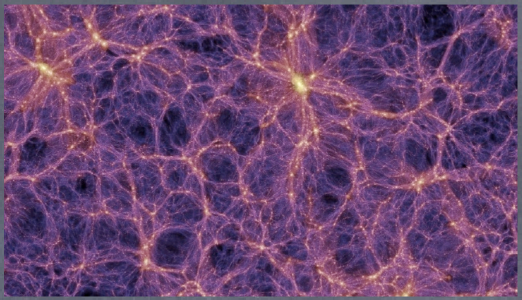
The Future of Very High
Energy Gamma-ray Astronomy
May 13, 2007

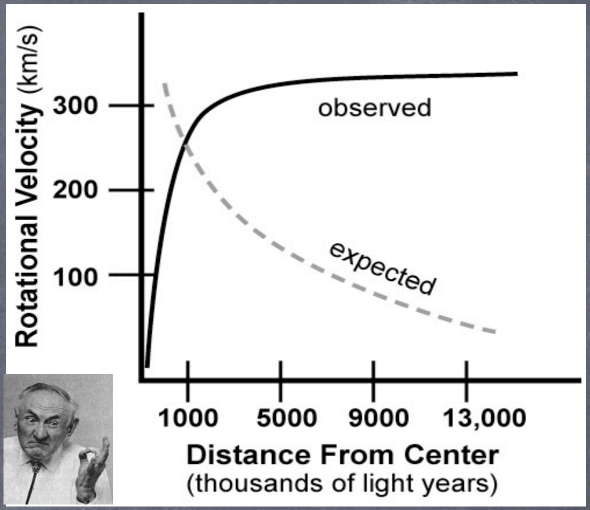
Outline

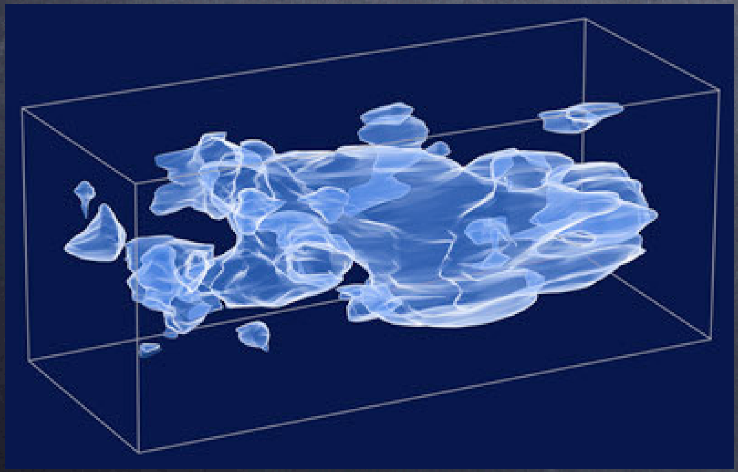
- Dark Matter is real!
- Fitting WIMPs into our view of particle physics
- Thermal Relics
- Indirect Detection
- Interplay with Colliders
- Outlook

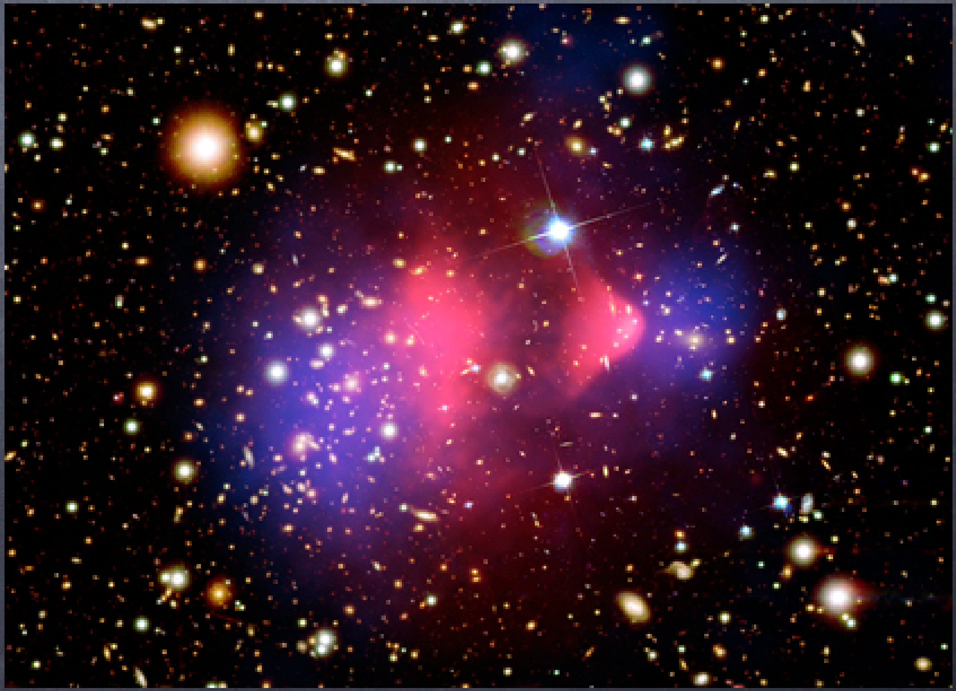
Dark Matter is Real!





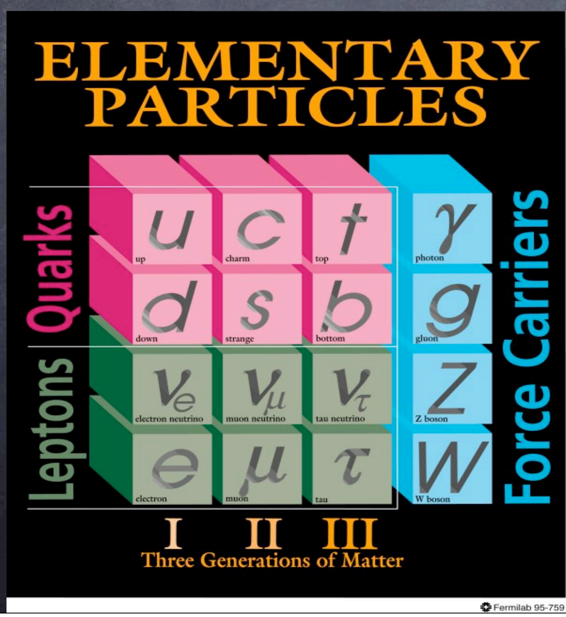






So what is this stuff?

“Cold Dark Matter: An Exploded View” by Cornelia Parker



- What do we know about it?
- Evidence suggests 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).
  - It’s not a part of the Standard Model of particle physics.

WIMPs

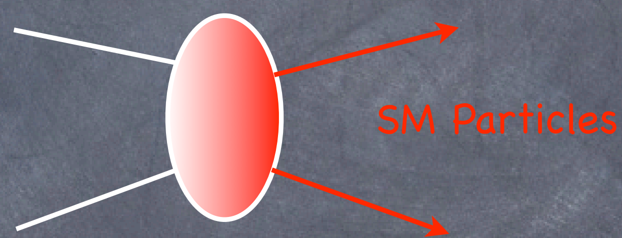
- One of the most attractive proposals for dark matter is that it is a **W**eakly **I**nteracting **M**assive **P**article.
- For a theory of a WIMP, we extend the SM by some new particle ψ that we assume is neutral and heavy. We further assume that some selection rule requires ψ to always interact in 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):

ψ

ψ

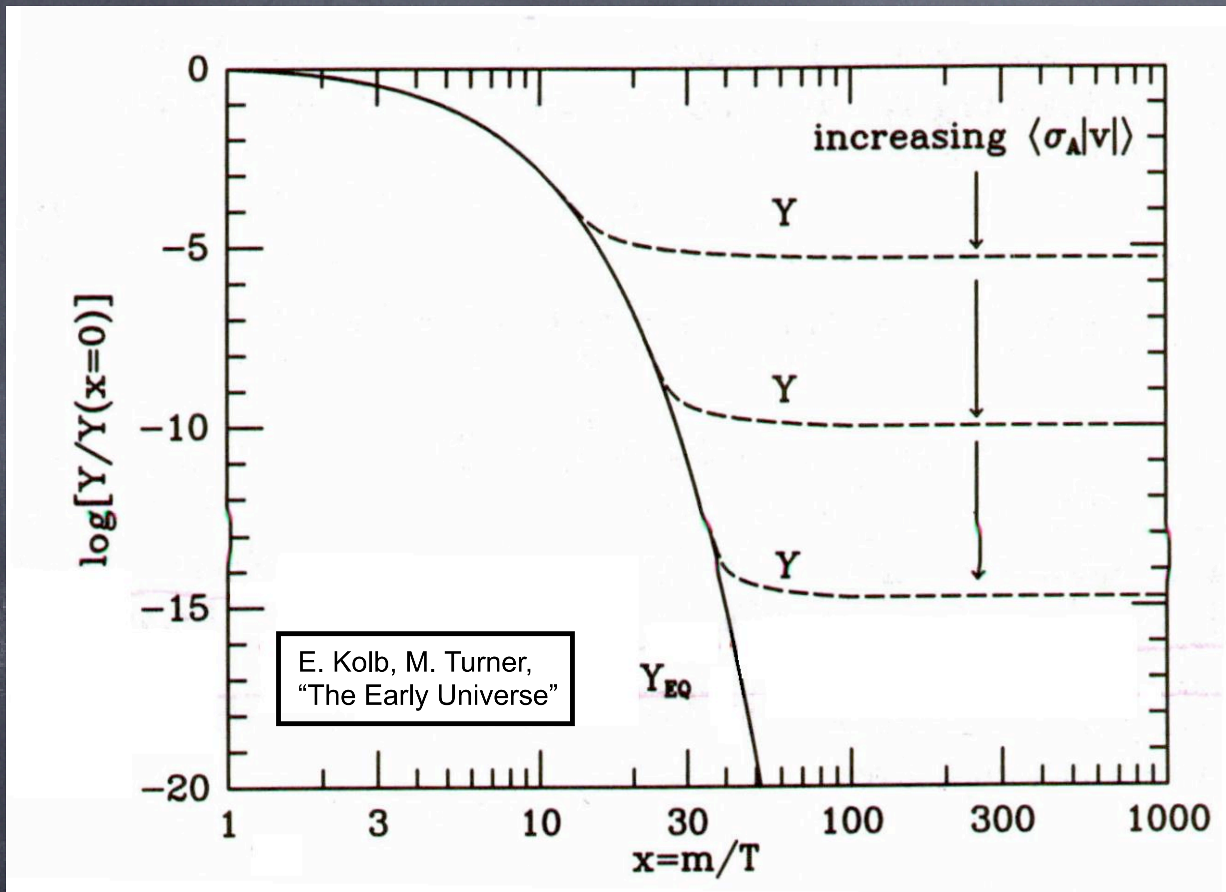


- At temperatures below m, while ψ is in equilibrium, its number density will follow the familiar Boltzmann distribution:

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

- So as the Universe cools, the number density of ψ decreases exponentially for as long as it is in equilibrium.

Freeze Out



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 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 ~ 100 GeV - exactly what we expect for a theory of EW physics!
- Coincidence? Maybe...

The Identity of Dark Matter

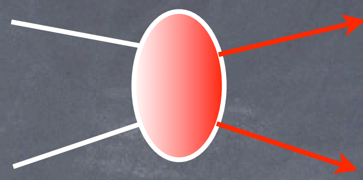
- To verify the WIMP hypothesis, we would like to see some sign that ψ actually exists, and measure σ(ψψ-> SM) to verify that the relic density will match what we actually see in the Universe.

- 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 underlying theory.

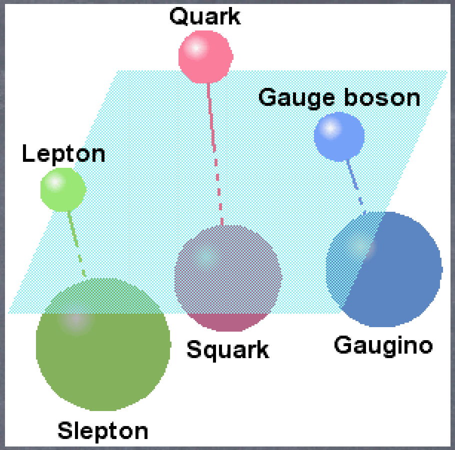
What goes in the blob?

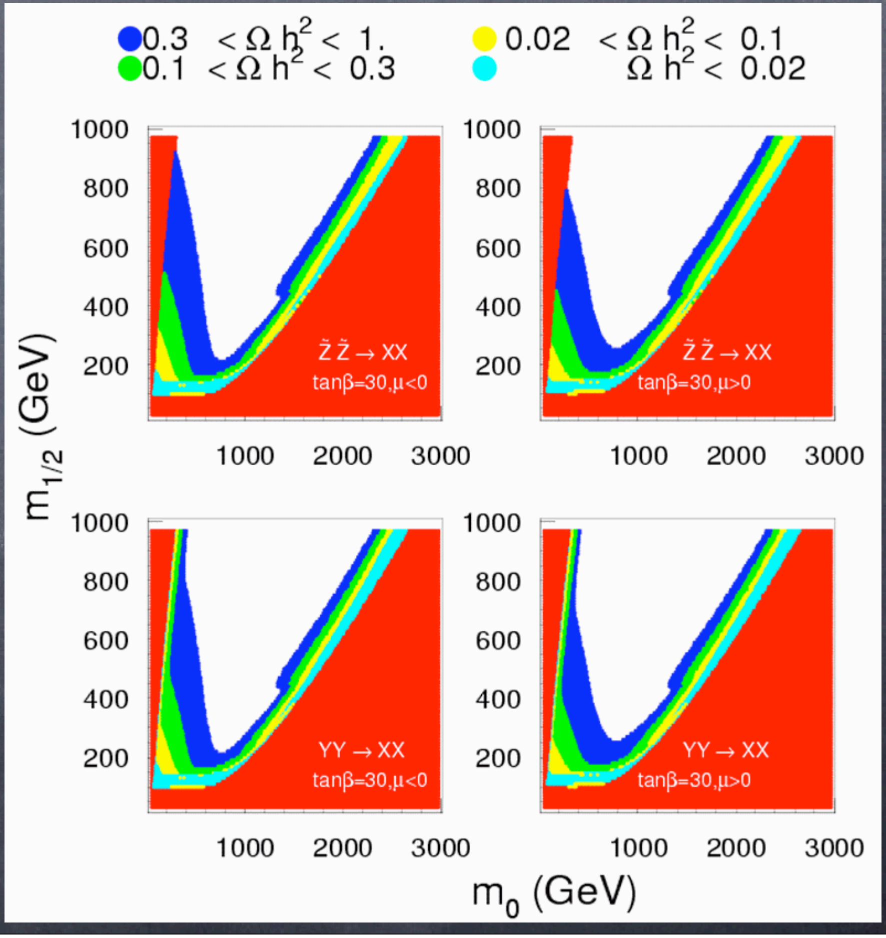


- I wrote a generic representation for the interactions that allow two WIMPs to annihilate into SM particles.
- In a specific theory we can compute this cross section in terms of the parameters of the theory.
- Most theories will have more new particles in addition to the WIMP. The WIMP will be stable 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.

Supersymmetry

- A popular model for dark matter is supersymmetry, which introduces a heavy partner for every SM field.
- These partners carry the same charges as the SM field, but have spin differing by one half unit.
- It nicely explains electroweak symmetry-breaking, and most models contain a potential dark matter particle!



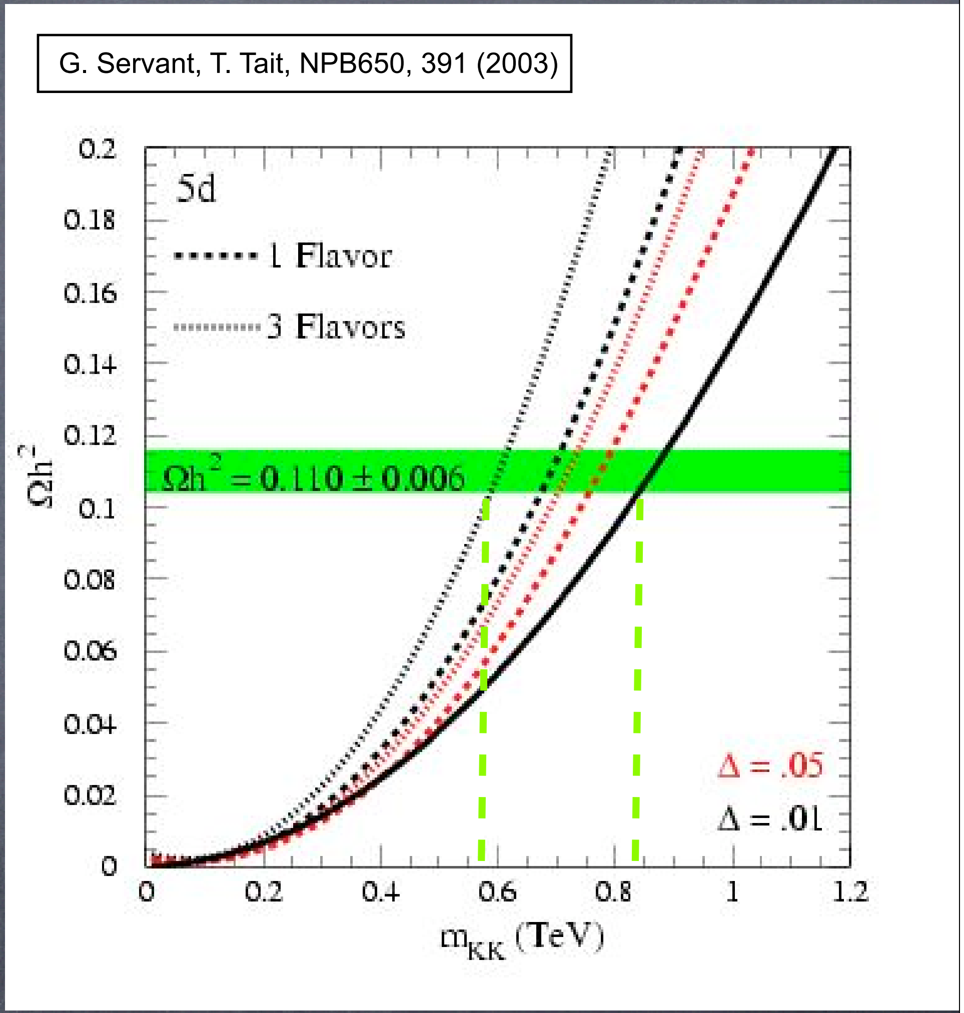


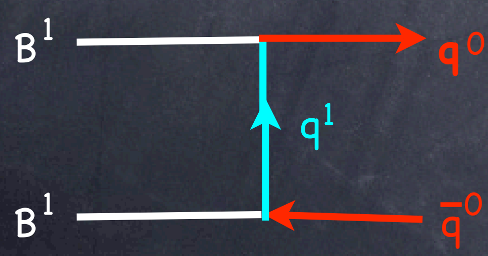
Baer, Balazs, Belyaev JHEP 0203:042,2002

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.

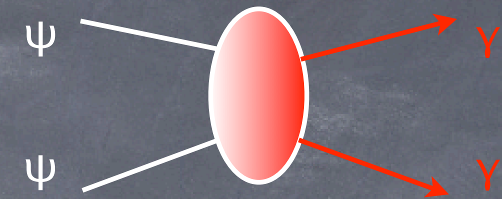




$$P^2 = E^2 - p_x^2 - p_y^2 - p_z^2 - p_5^2 = 0$$

$$E^2 - p_x^2 - p_y^2 - p_z^2 = p_5^2 = M_{eff}^2$$

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 near the Earth.
- Study of high energy photons, neutrinos (and perhaps positrons) could discover dark matter.

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 $\sigma(\psi\psi \rightarrow SM)$. 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

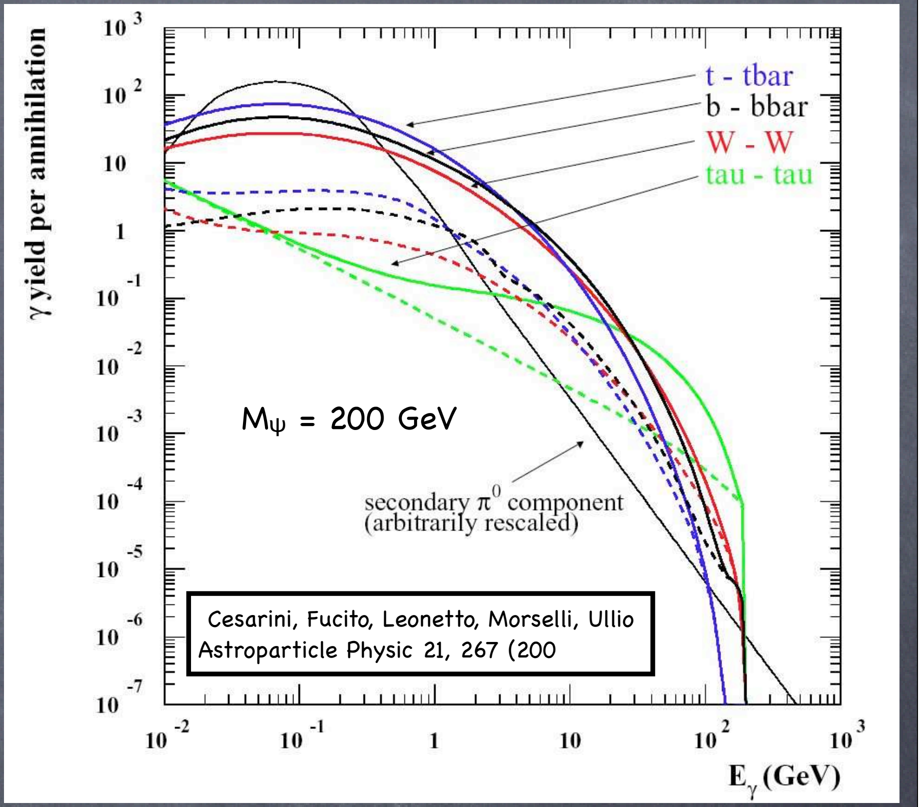
DM density

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

- Models for the galactic structure can disagree about the density by significant factors. So σ will be uncertain.
- The features of the E spectrum do vary from WIMP to WIMP.

From WIMPs to Photons

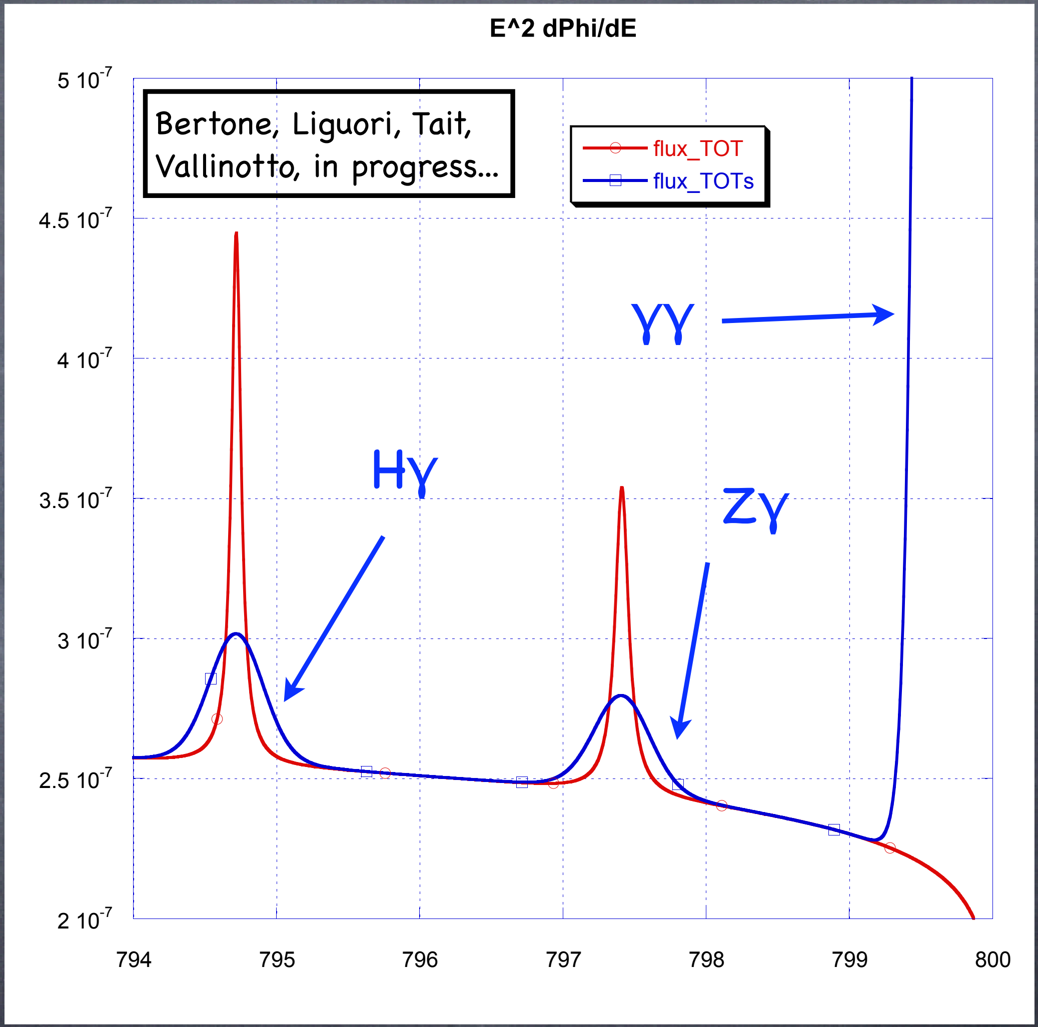
- The details of the energy spectrum depend on the ways in which WIMPs annihilate into photons.
- Annihilations into massive objects such as Ws, Zs, top/bottom quarks, Higgs(es) produce either direct gammas or (more often) lighter quarks and leptons.
- Lighter quarks hadronize and then decay. Leptons experience bremstrahhlung or radiate through acceleration.



A complicated continuum energy spectrum results!

Line Detection

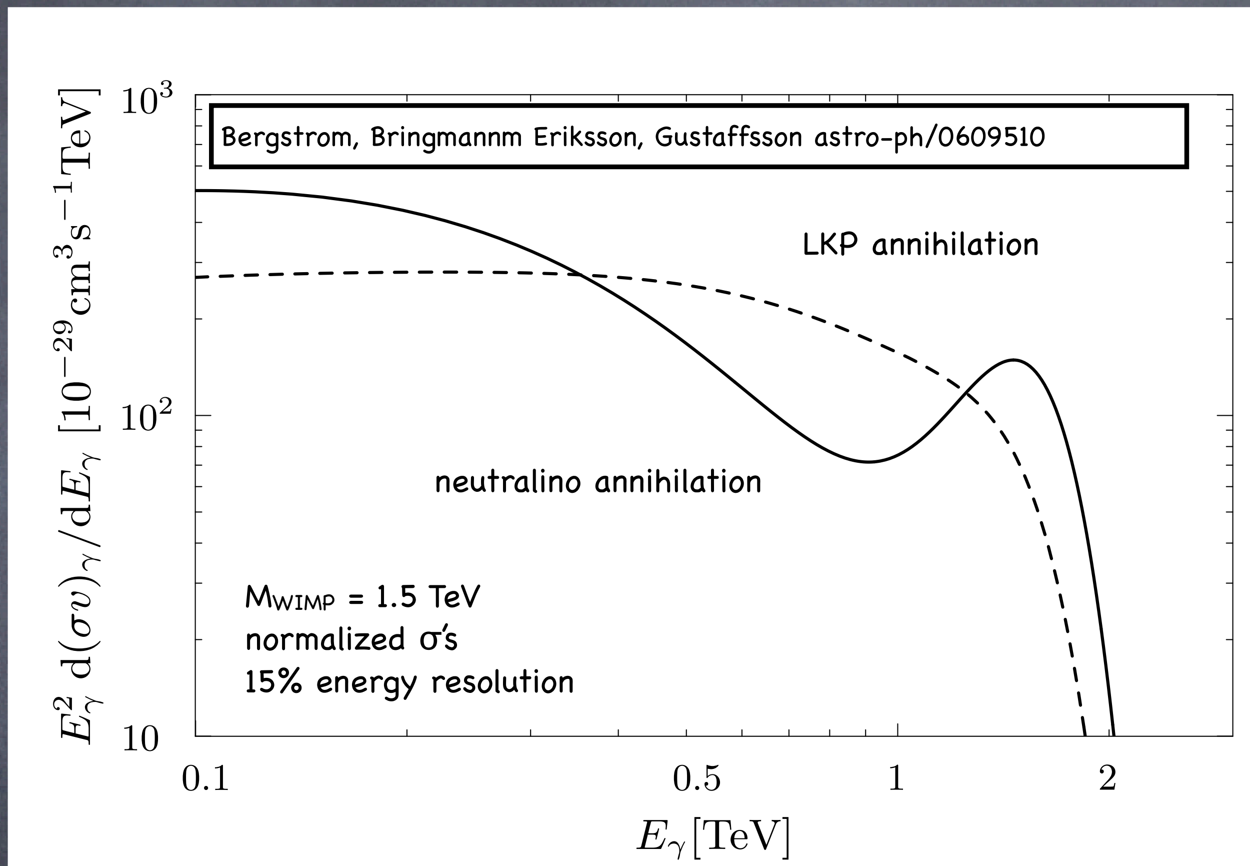
- Loop processes can also produce γ's in two-body annihilation modes, with sharp energy distributions.
- Let's take an example of the UED theory with the LKP as dark matter.
- Sharp lines from BB->γγ, BB-> Zγ, and BB->Hγ.
- BB->Hγ does **NOT** occur in Supersymmetric theories!



γγ line: Bergstrom, Bringmannm Eriksson, Gustaffsson PRL94, 131301 (2005)

γ continuum: Bertone, Servant, Sigl PRD68, 044008 (2003)

Information in the Spectrum



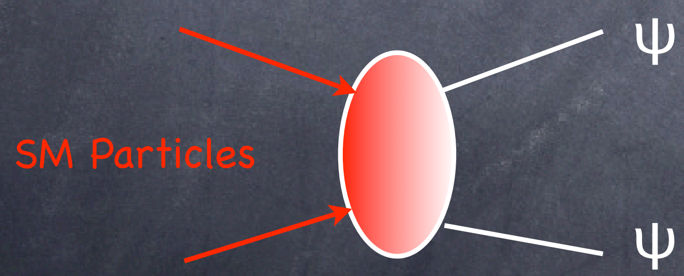
- The different interplay in the cocktail of processes which lead to gamma rays can help distinguish one theory from another.

- It can also help distinguish different parameter choices within the same theory (see i.e. discussions in Baltz, Battaglia, Peskin, Wizansky PRD74, 103521 (2006) for discussion of some supersymmetric models).

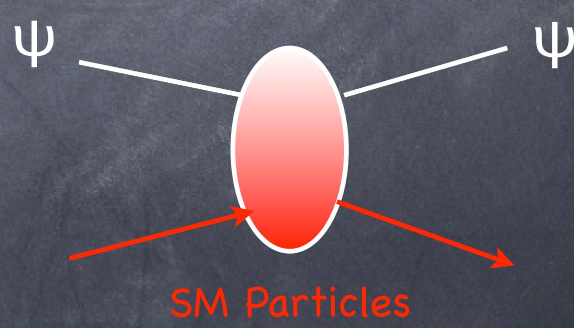
Other Processes

- 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



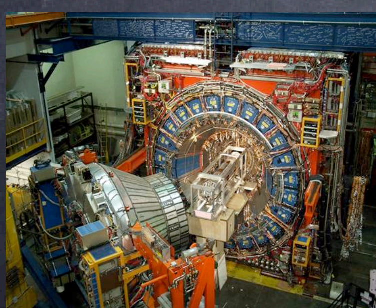
WIMPS scatter with ordinary matter.

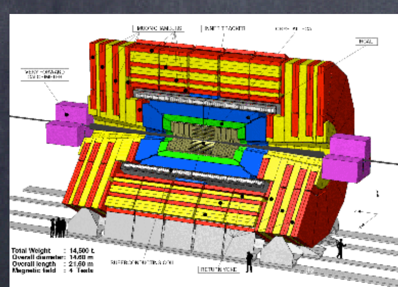
Collider Production

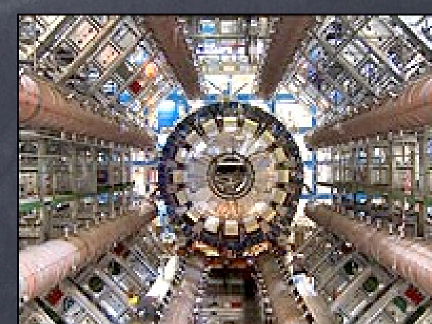
- Which brings me to the way in which high energy colliders can tell us something about dark matter.

- 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.

- 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.

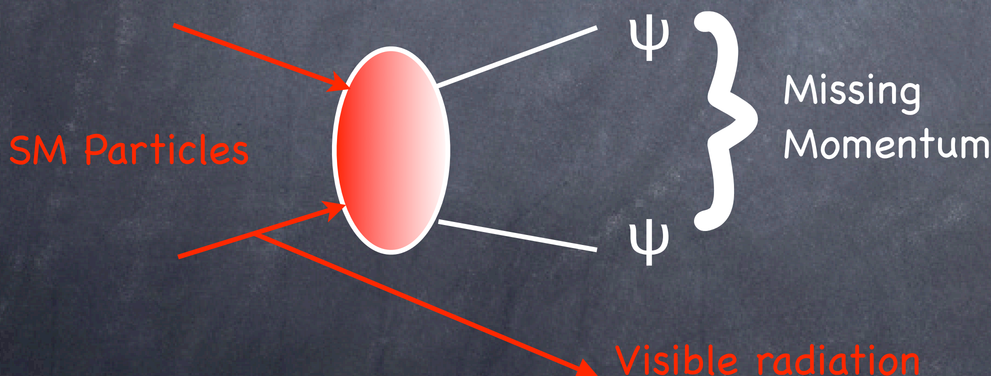


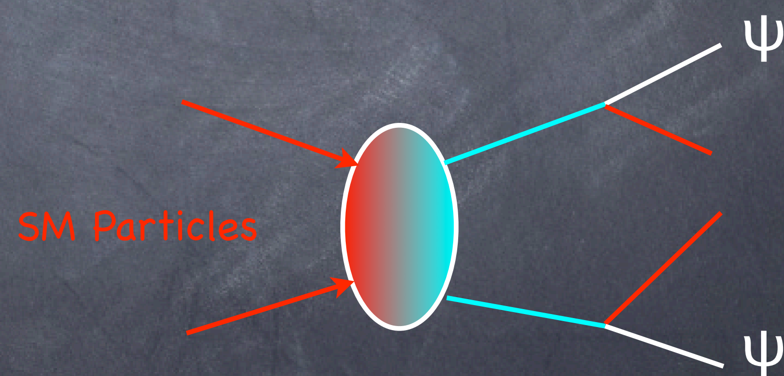




Seeing the Invisible?

- 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:



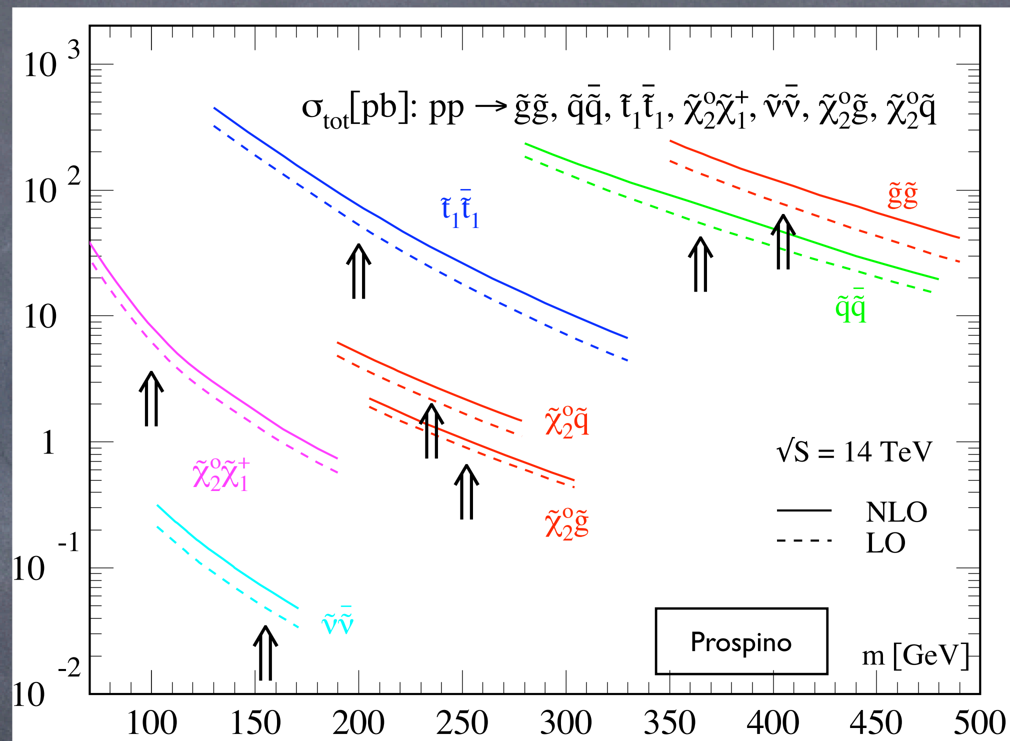


Radiation from the SM side of the reaction.

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.



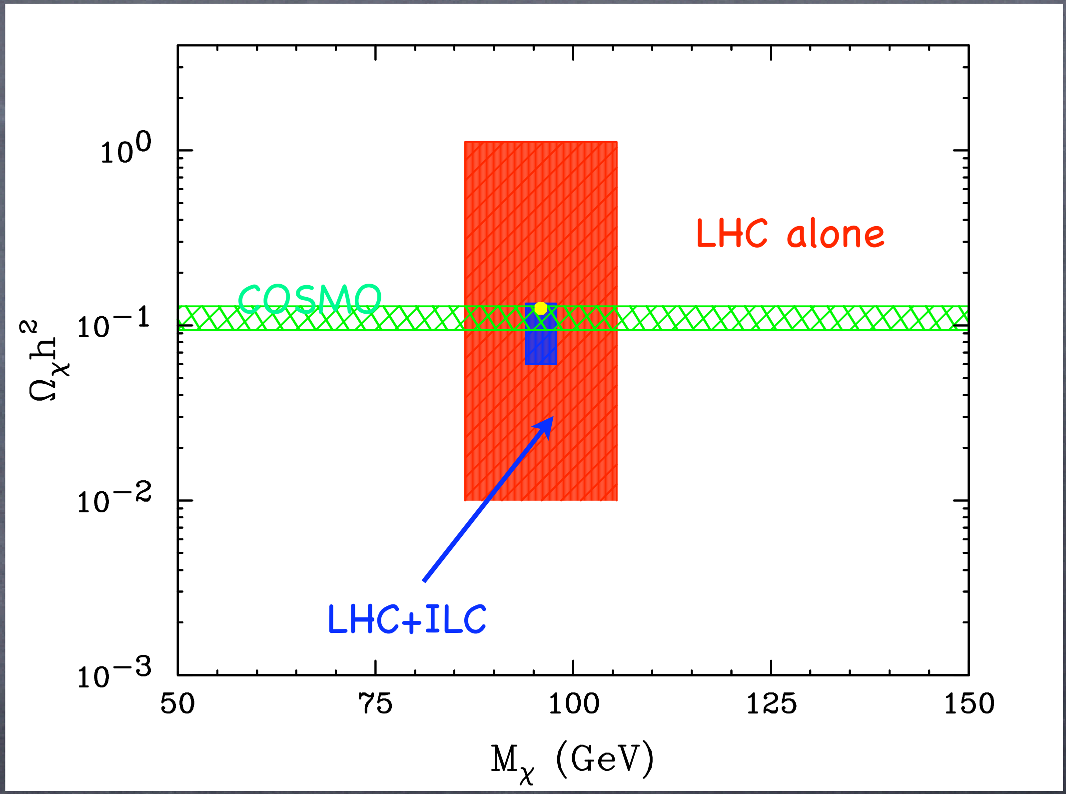
Supersymmetric particle production cross sections at the LHC

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.
- Still, correlation with (in)direct observation in the cosmos will be required to confirm the identification.

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.
- Combining 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

Synergy

- There's a lot of room for indirect observation of dark matter, and colliders to play off of one another.
- For example, we have seen that the energy spectrum of gamma rays from annihilation is giving us hints about the interactions of Dark Matter with SM particles.
- We can also use measurements from colliders to understand more deeply the microphysics of dark matter.
- Controlling this unknown then allows direct detection to map the distribution of dark matter!

Get this from colliders...

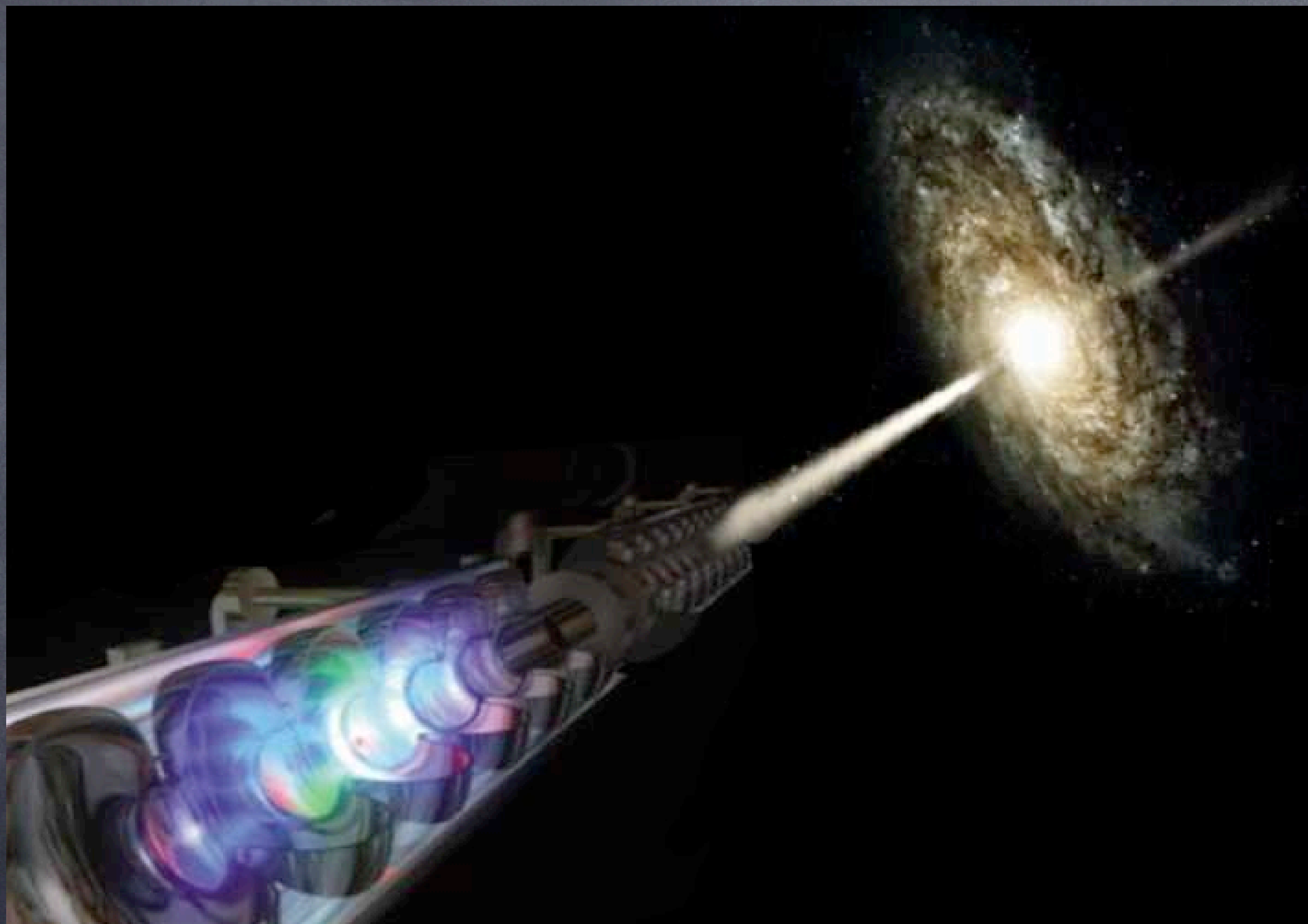
...and measure this from gamma rays!

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

Outlook

- Dark matter is a clear signal of physics beyond the standard model. It is imperative to particle physics that we understand what it is, and how to incorporate it into our understanding of a fundamental theory.
- The current generation of high energy gamma ray observatories have great potential to observe dark matter annihilation either as a first discovery, or in tandem with future laboratory experiments.
- Either way, both fields should be enriched by a deeper understanding, and information from either source will open up new opportunities to both understand particle physics and the Universe!

Bonus Material



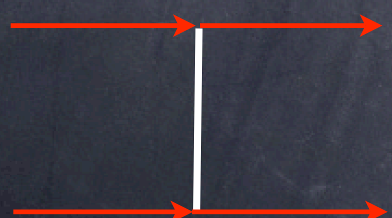
TeV Scale Dark Matter

- 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.

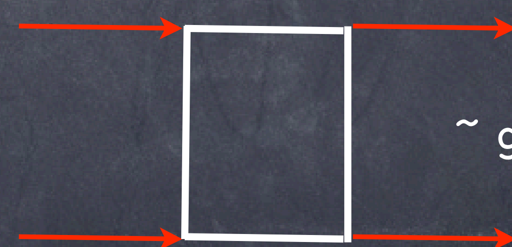
- Such theories almost always include heavy objects, and neutral objects are easy enough to arrange. Thus, the trick is to have these objects be stable.

- 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.

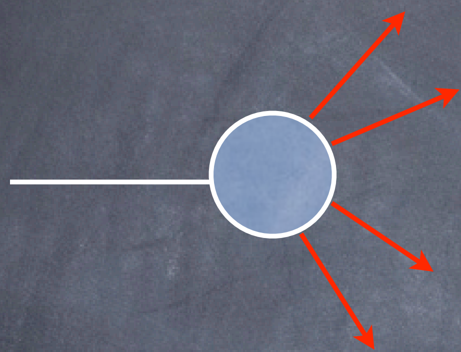


$\sim g^2 / m^2$

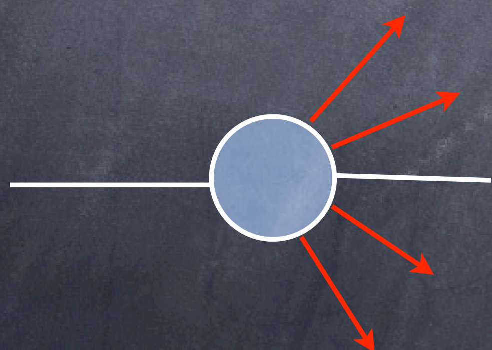


$\sim g^4 / (4\pi\, m)^2$

Interacting in Pairs



ψ decays

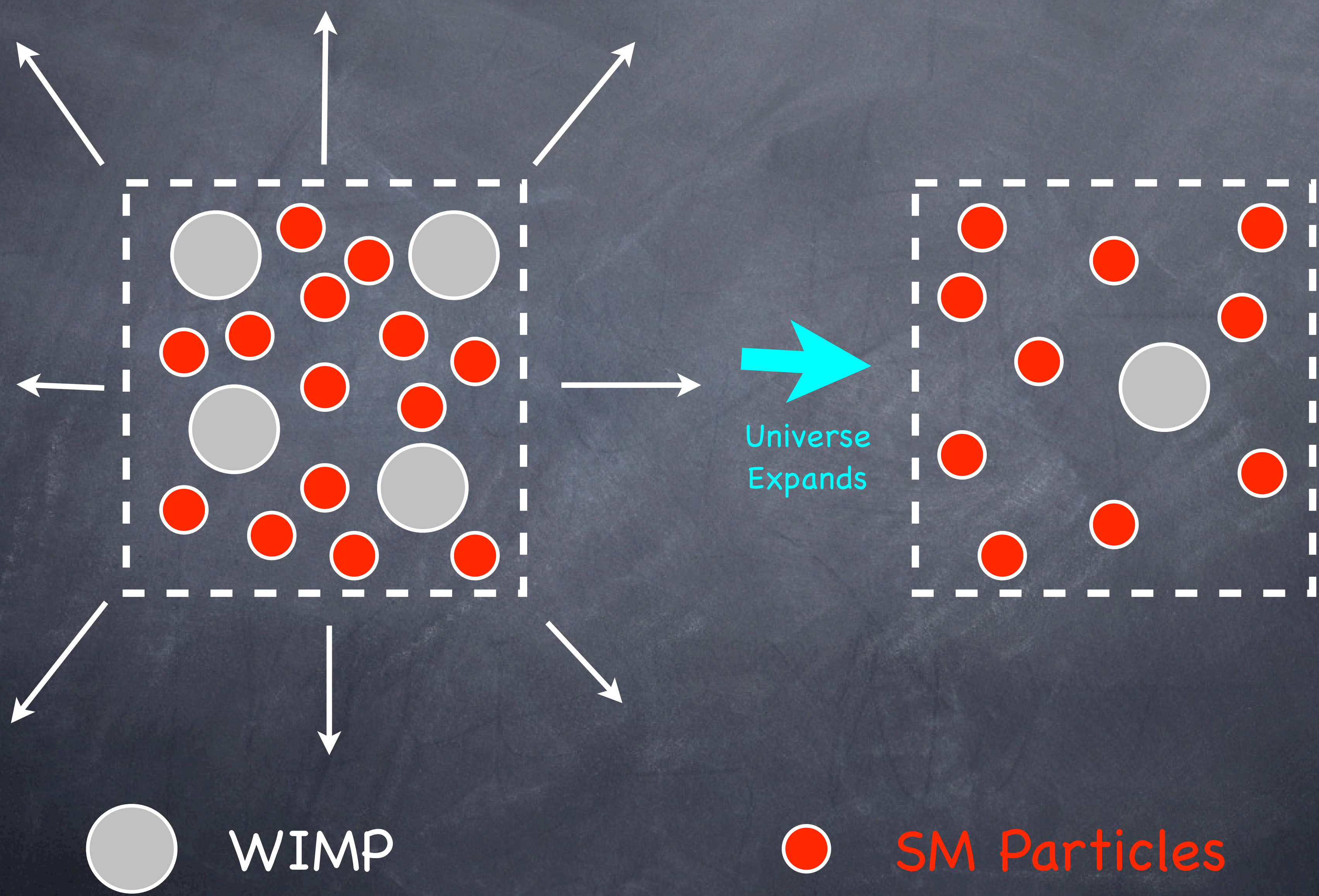


The number of ψs is conserved

Freeze-Out

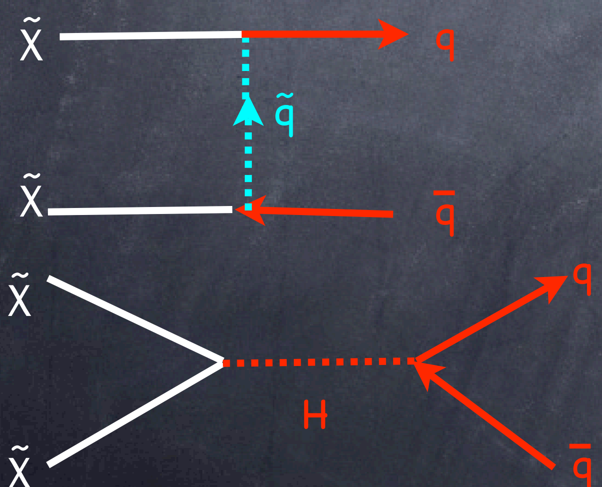
- However, an important modification to the picture occurs because the Universe is expanding.
- At the "freeze-out" temperature, the WIMPs are sufficiently diluted that they can no longer find each other to annihilate. At that point, they fall out of equilibrium with the SM plasma, and the number density 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.

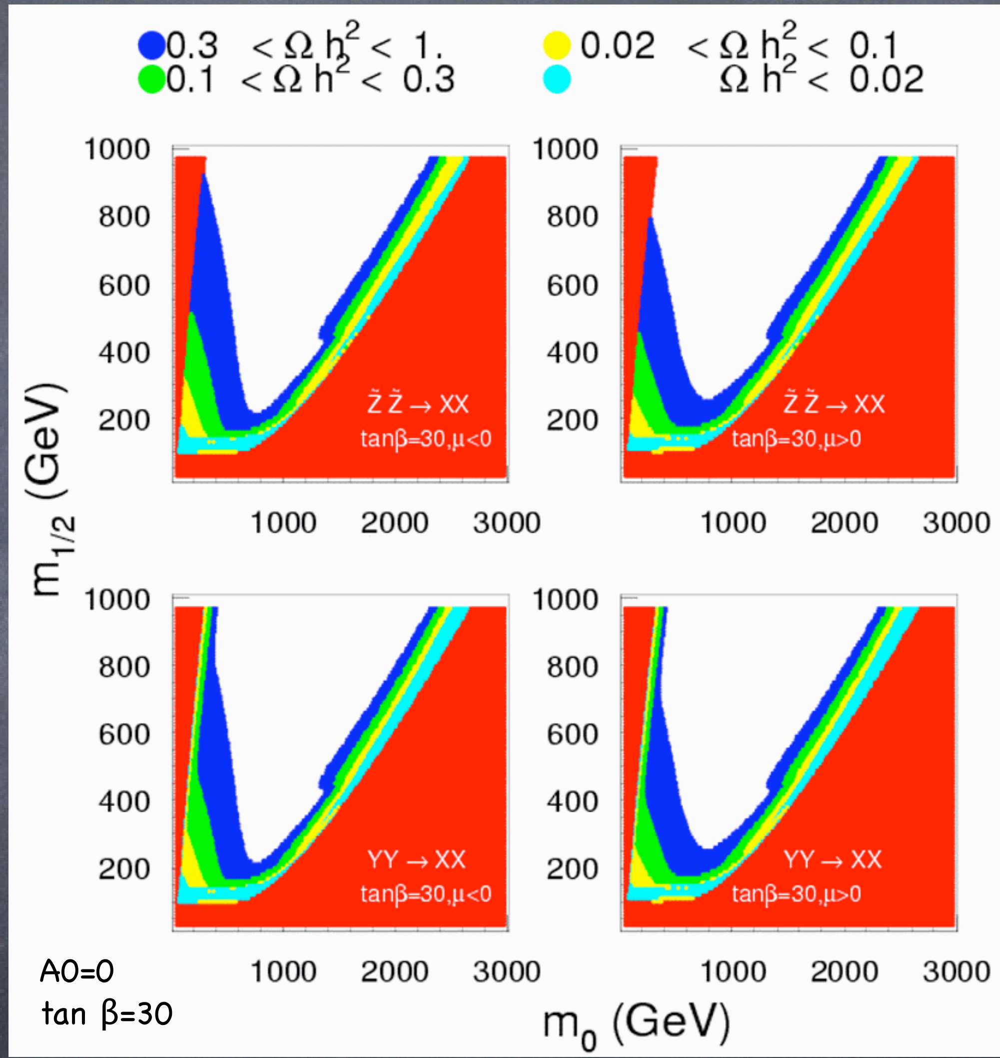
Freeze-Out



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.

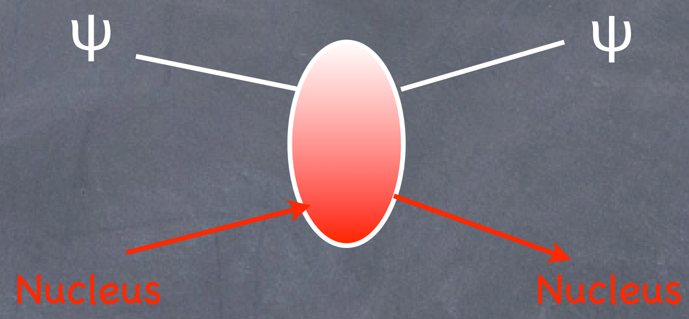




Baer, Balazs, Belyaev JHEP 0203:042,2002

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, DAMA, or DRIFT 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).

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

DM density

Nuclear Physics

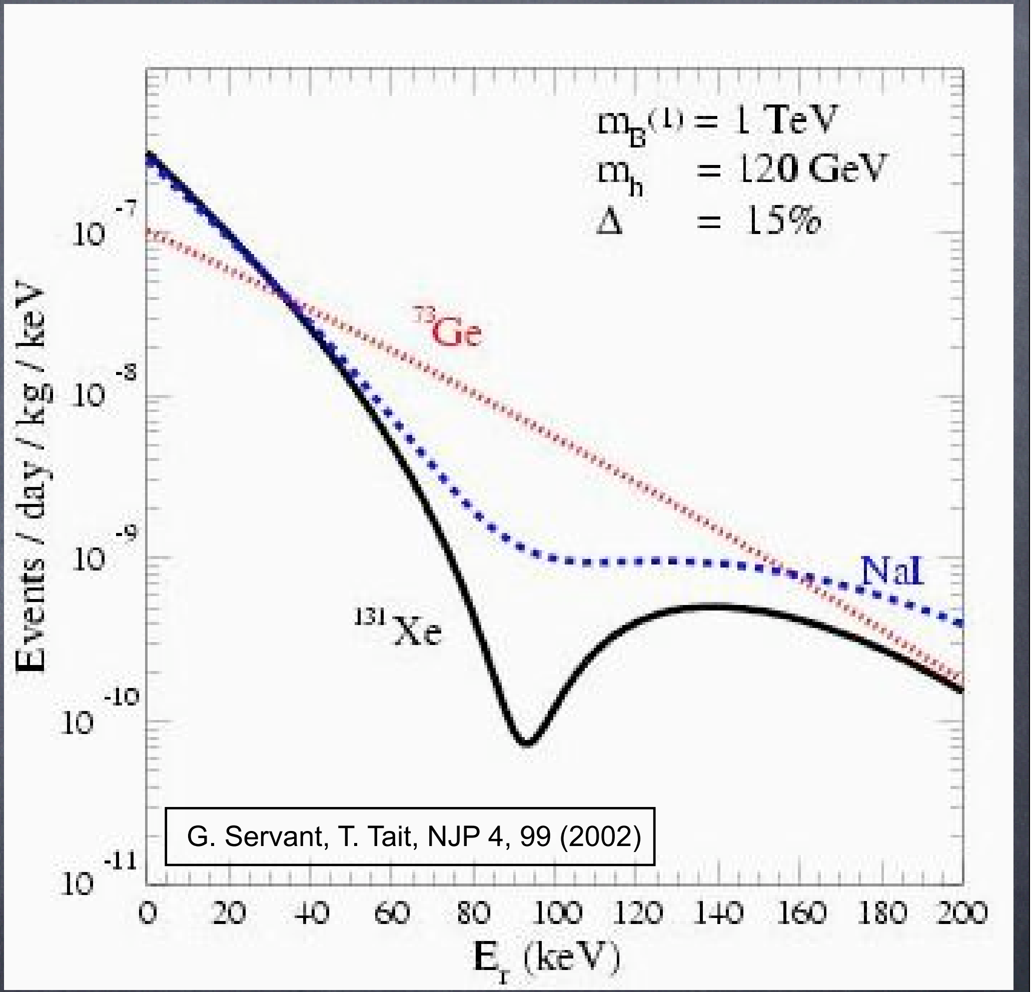
WIMP velocity distribution

- 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.



UED

Crossed Sections

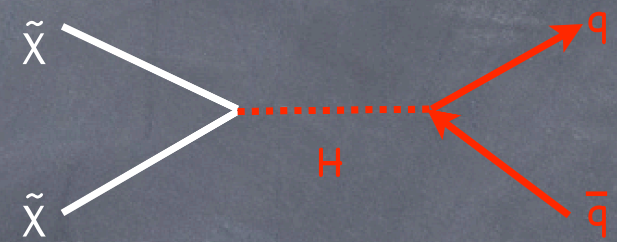
- As with indirect detection, a positive result from a direct detection experiment would be an exciting sign of dark matter.

- However, direct detection also does not provide enough information to verify the WIMP hypothesis by reconstructing the relic density.

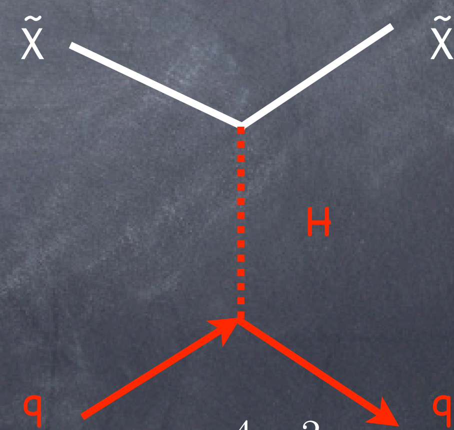
- The rate is sensitive only to the cross section into quarks, and further, the crossing of one WIMP and one quark from initial to final state can have a large effect which is difficult to extract if direct detection is the only DM signal at hand.

- 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.

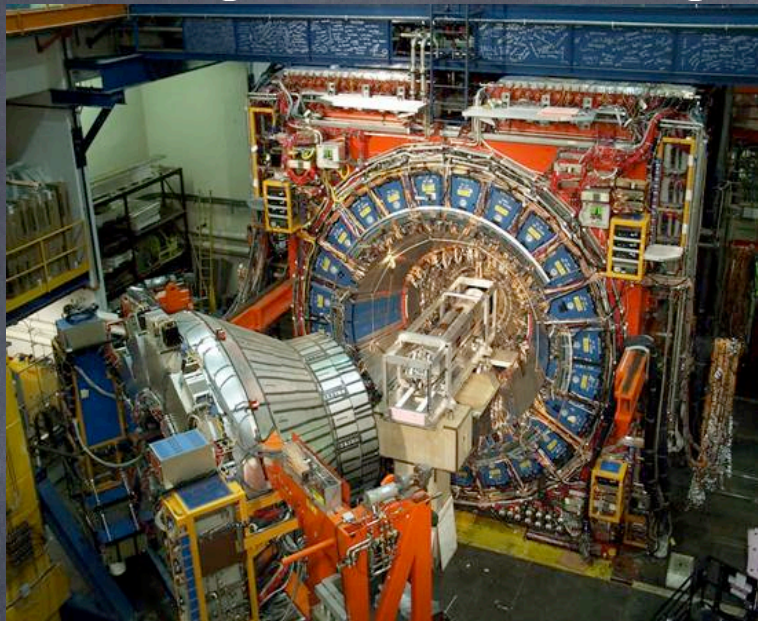


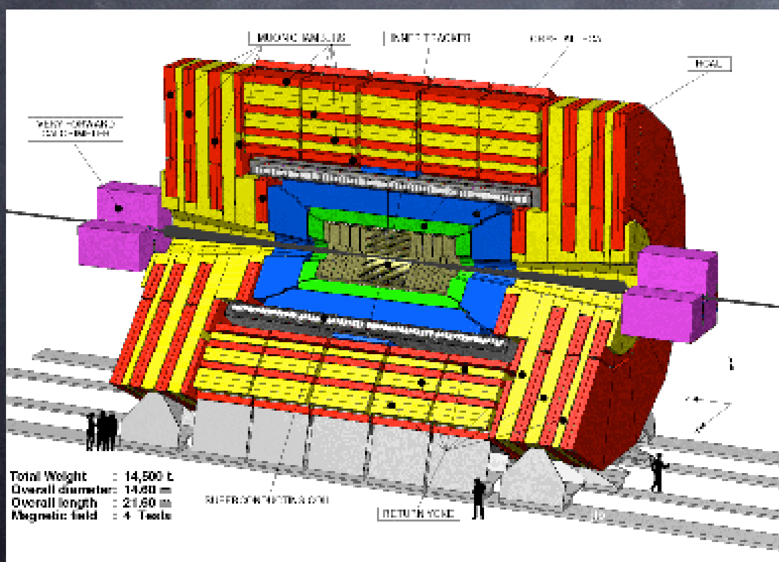
$$\sigma \sim \frac{g^4 m_\chi^2}{\left(2m_\chi^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2}$$

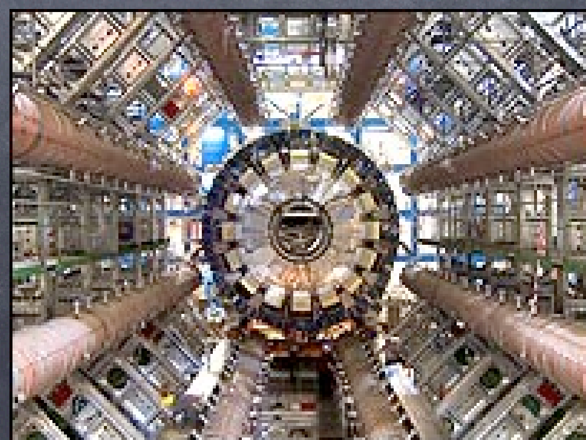


$$\sigma \sim \frac{g^4 m_\chi^2}{\left(2m_\chi^2 + m_H^2\right)^2}$$

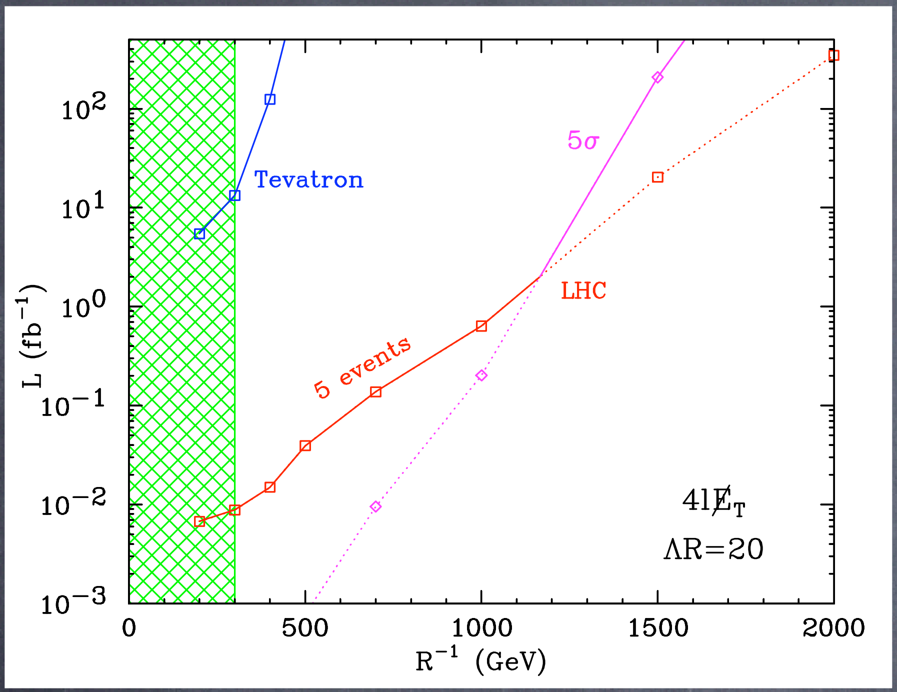
High Energy Detectors







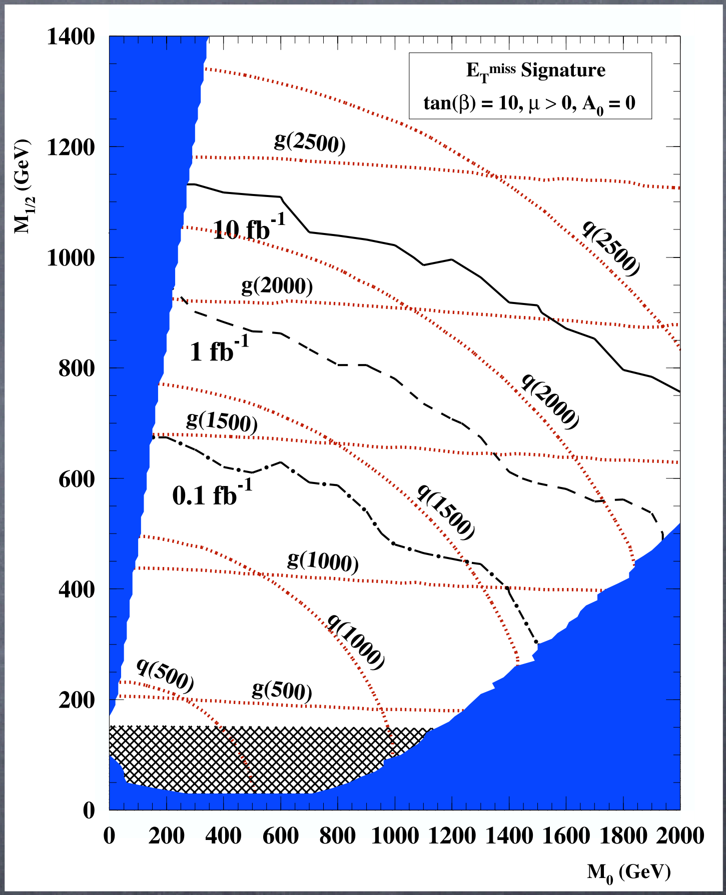
Discovery Prospects



Kaluza-Klein Quarks decaying into LKPs+jets

Cheng, Matchev, Schmaltz

Phys.Rev.D66:056006,2002

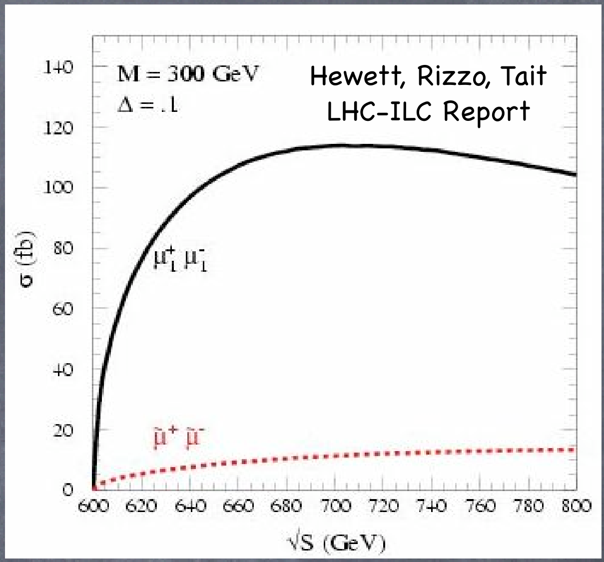


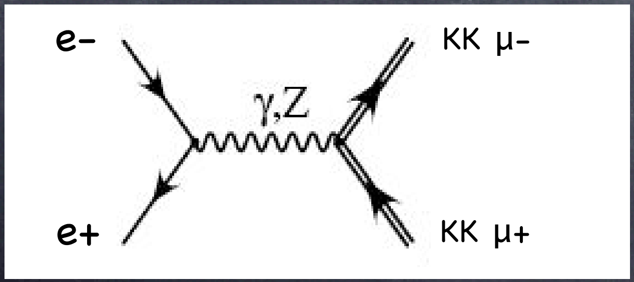
Squarks + Gluinos into Neutrlino+jets

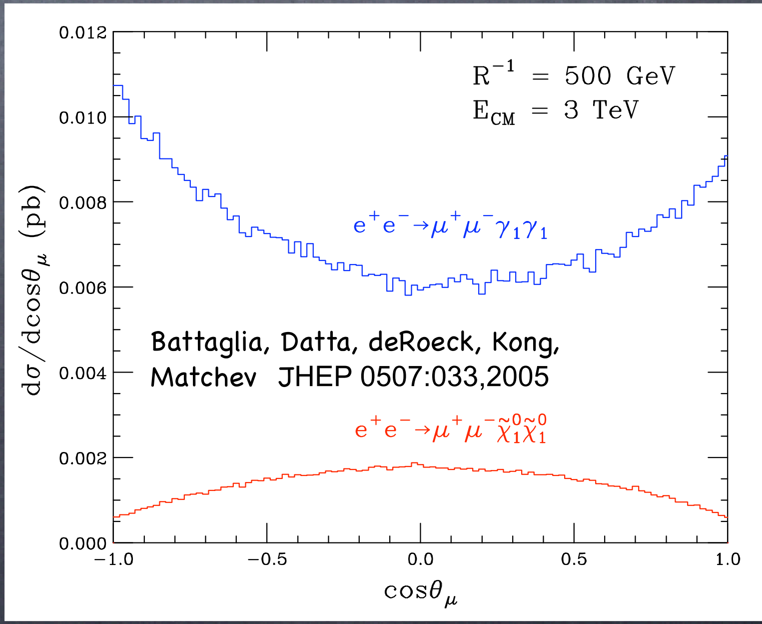
ATLAS study

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.







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.

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

$$m_{\tilde{l}} = \frac{\sqrt{s}}{E_- + E_+}\sqrt{E_- E_+}\,,$$

$$m_{\tilde{\chi}} = m_{\tilde{l}}\sqrt{1 - \frac{E_- + E_+}{\sqrt{s}/2}}$$

Martyn, LHC-ILC report