Physics Expectations from the Experimental Program

A. Seiden
UCSC

Outline

1) Where were we?

   When? Late 1980's when Tom Banks first came to UCSC. Also, many new facilities about to start: SLC, LEP, Tevatron, HERA.

2) Where are we?

   The Standard Model has been a spectacular success. Its open questions that could be addressed at accelerators have so far been carefully hidden from experimental reach. However, new discoveries have been made based on non-accelerator experiments and studies of the cosmos.

3) Where are we going?

   Several major questions should be addressed in the next decade:

a) Discover the physics underlying electroweak symmetry breaking.

b) Search for and then study the particle corresponding to dark matter.

c) Further quantify dark energy, and its cosmological manifestations.

Where Were We: Some of the Parameters of the Standard Model (Lepton-Photon Conf. 1989)

- Strong Coupling : $\alpha_S(m_Z) = 0.11 \pm 0.01$
- Weak Mixing Angle: $\sin^2(\theta_W) = 0.233 \pm 0.002$
- W mass: $m_W = 80.0 \pm 0.6$
- Z mass: $m_Z = 91.12 \pm 0.16$
- Top Mass: Probably > 70 GeV
- CKM Matrix Does it describe CP violation?
- Neutrinos Most likely massless.

W and Z masses reflected the first data from the SLC and the Tevatron.

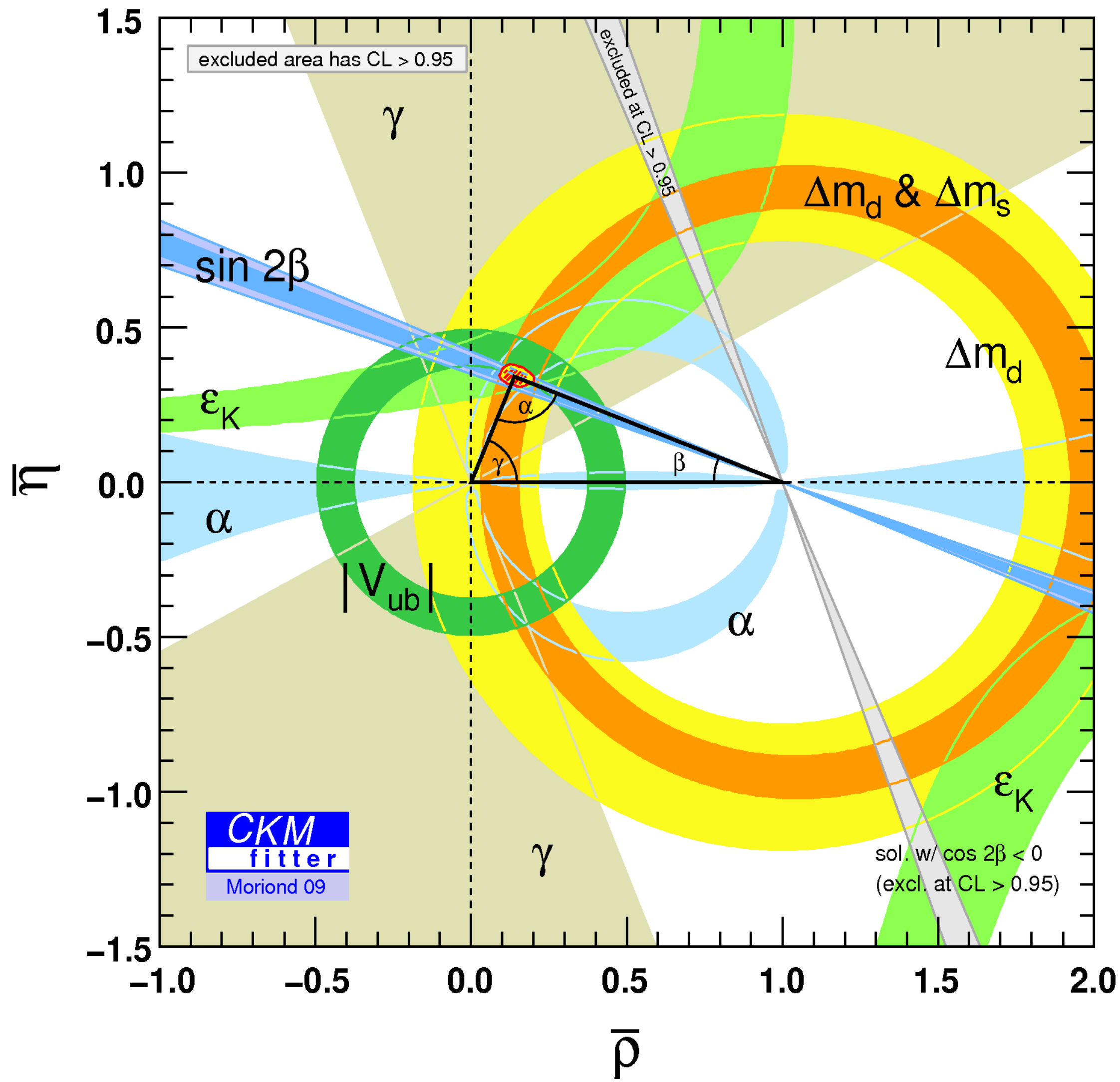
Where Are We: Some of the Parameters of the Standard Model

1989	2009
$\alpha_S(m_Z) = 0.11 \pm 0.01$	$\alpha_S(m_Z) = 0.1176 \pm 0.0020$
$\sin^2(\theta_W) = 0.233 \pm 0.002$	$\sin^2(\theta_W) = 0.2315 \pm 0.0001$
$m_W = 80.0 \pm 0.6$	$m_W = 80.399 \pm 0.025$
$m_Z = 91.12 \pm 0.16$	$m_Z = 91.188 \pm 0.002$
Top Mass > 70 GeV	$m_t = 173.1 \pm 1.3$ GeV
Does CKM describe CP violation?	Is there anything other than the CKM?
Neutrinos are massless	Neutrinos have small masses and a surprising mixing matrix.

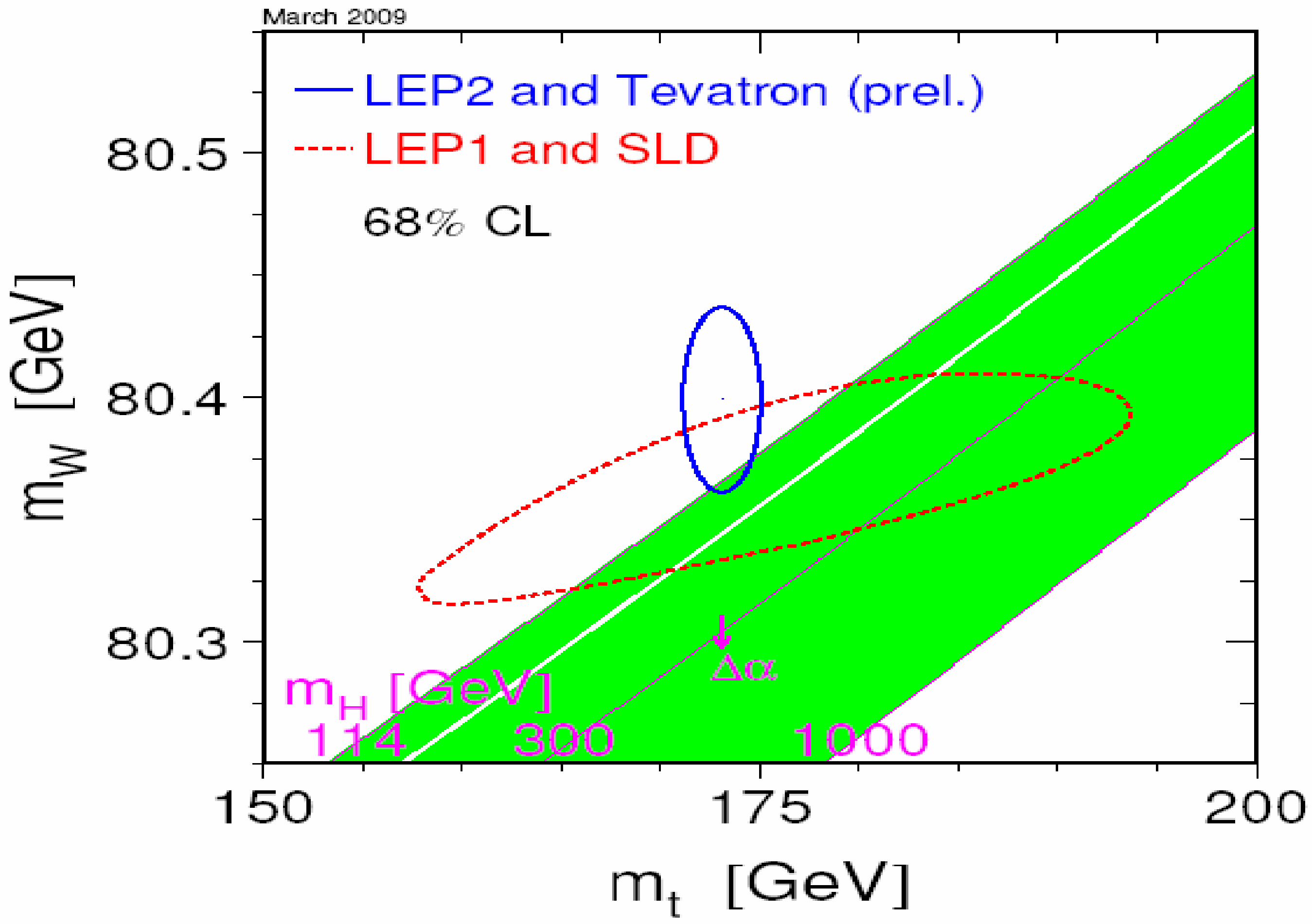
Also the universe in mostly dark matter and dark energy!

Largest change of a parameter in units of σ: Cabibbo angle, making data on neutron decay more consistent with theory.

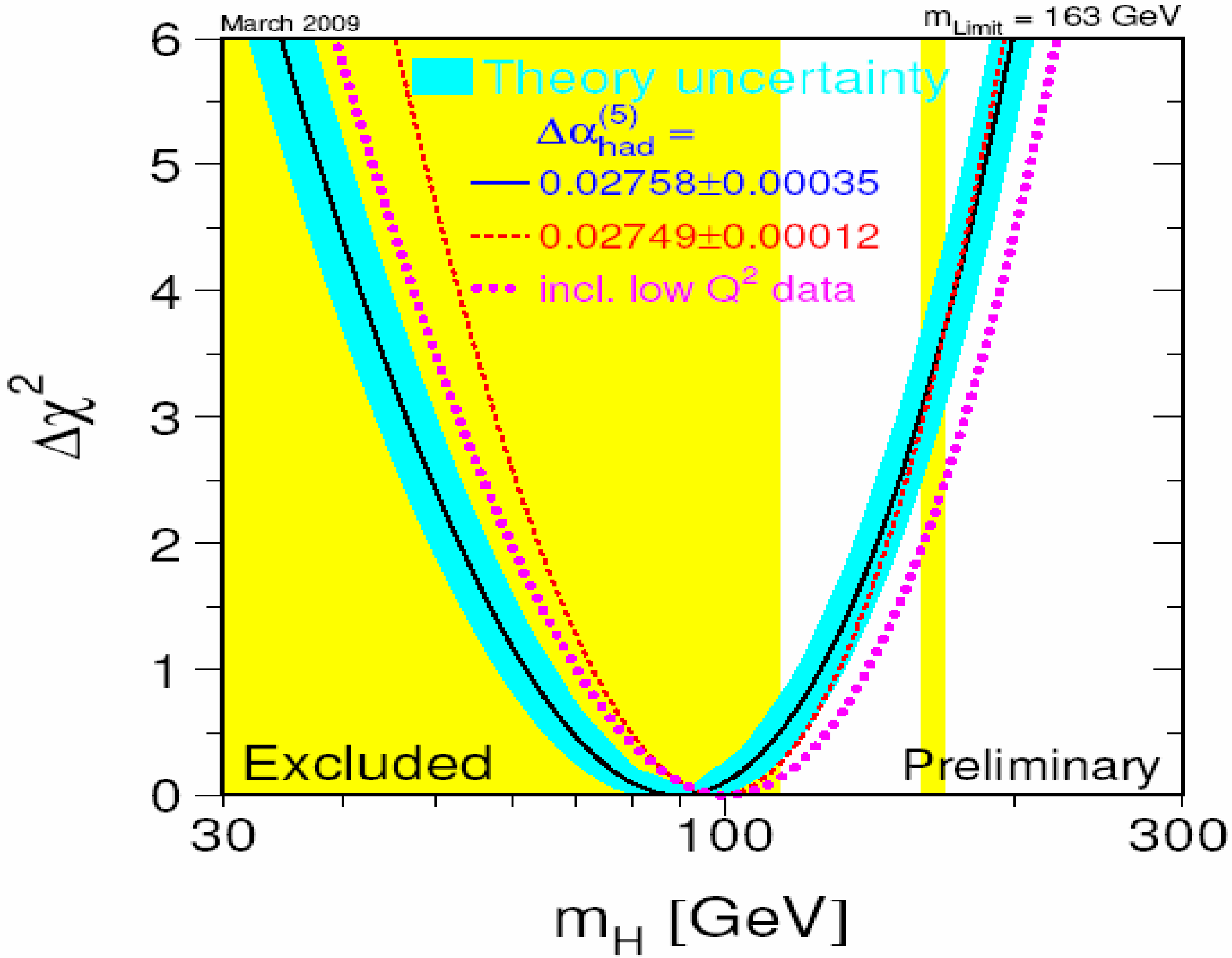
Summary of Results on Quark Flavor Transitions



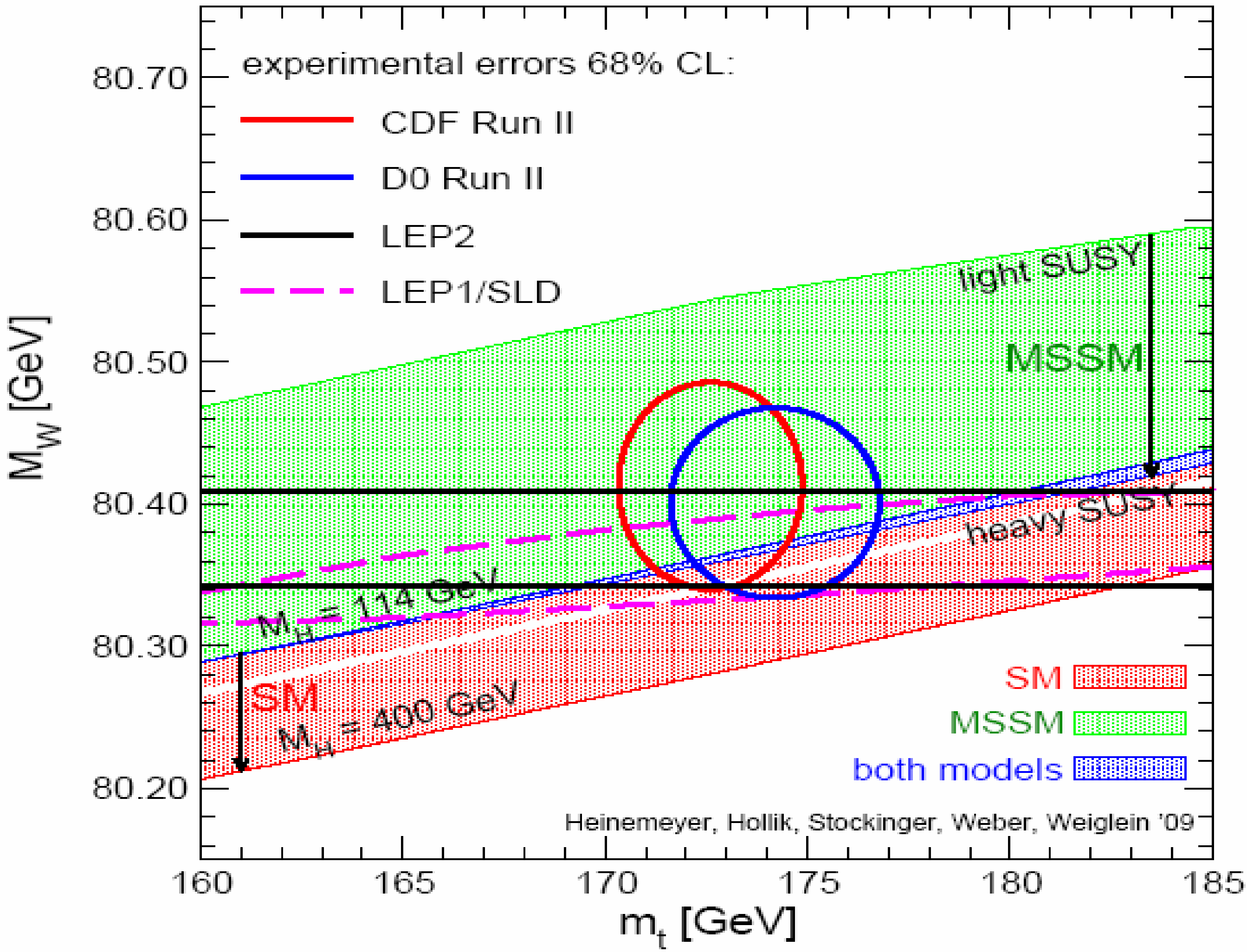
Precision measurements contributing to 1 + $\delta\rho$: the Higgs mass, something from nothing.



Predictions Robust With Respect to Other Theoretical Uncertainties



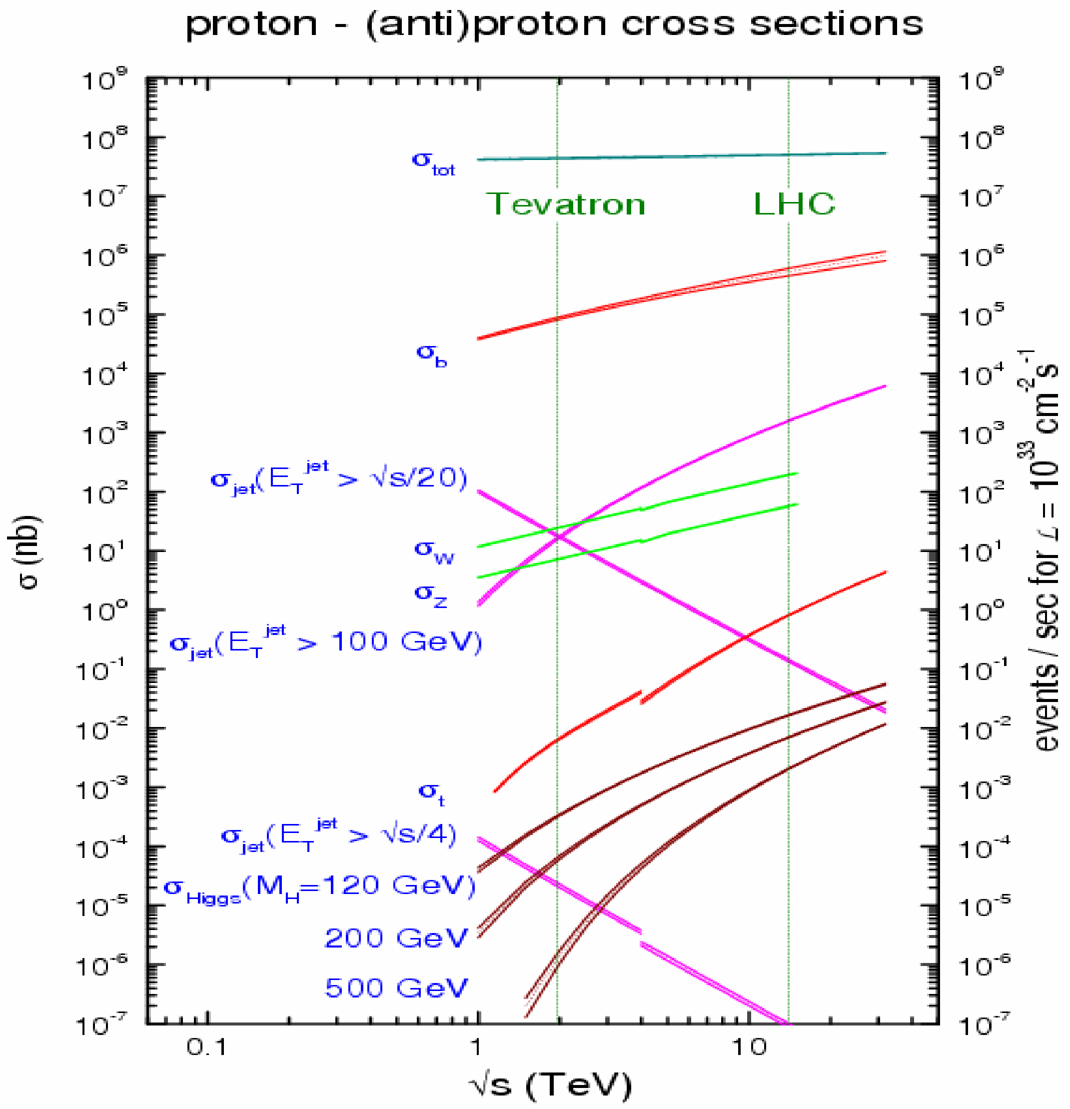
SUSY Provides Lots of Wiggle Room



Where are We Going: Geneva, Switzerland

Angels and Demons at CERN. But will there be a Higgs Boson?

Cross Sections at The Energy Frontier



Very Large Rates for Many Objects

Even at 10% of the design luminosity the rates for various heavy particles is very large, for example:

1 $t\bar{t}$ event per second.

200 W events per second.

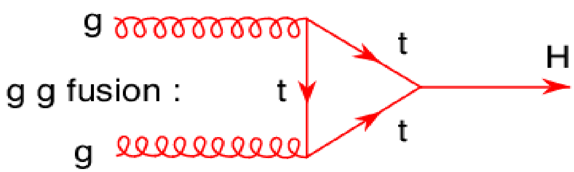
80 Z events per second.

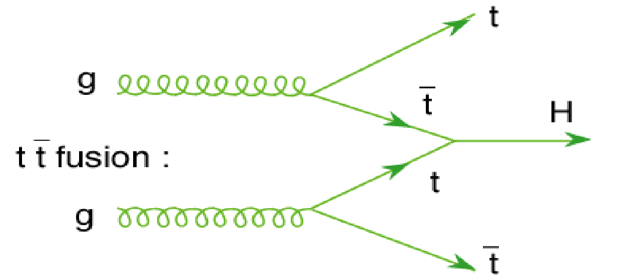
These will be used not only for physics, but also to calibrate the detectors.

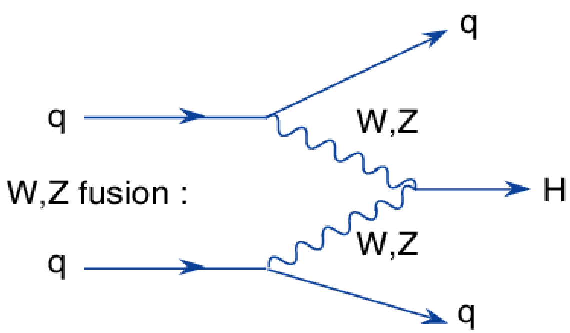
For new physics, the production of any new colored particles within the TeV mass range should have large rates. High rate strong processes are the basis for supersymmetry searches through production of gluinos or squarks at the TeV mass scale. These would cascade down to lighter particles, with the lightest supersymmetric particle escaping the detector – highlights the importance of measuring missing energy! Other possible elements of a signature: jets, leptons, many b or t quarks.

Higgs Diagrams

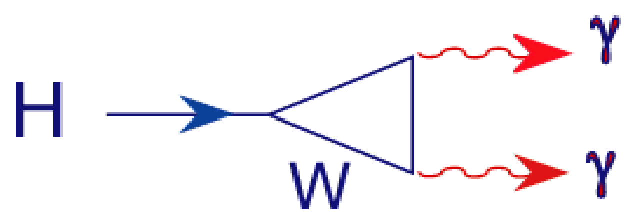
Production diagrams:





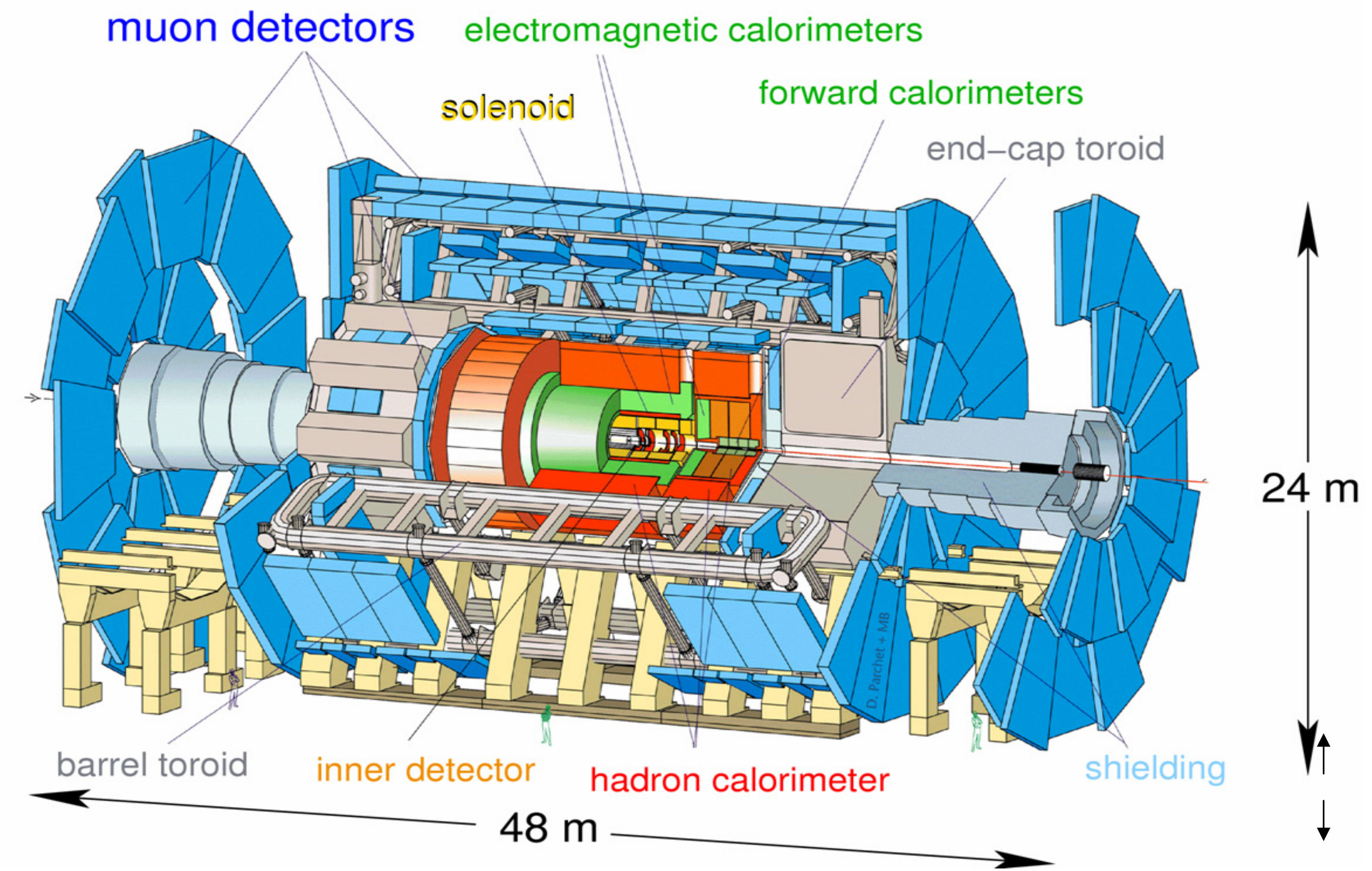


Decay diagram, relevant for light Higgs discovery.

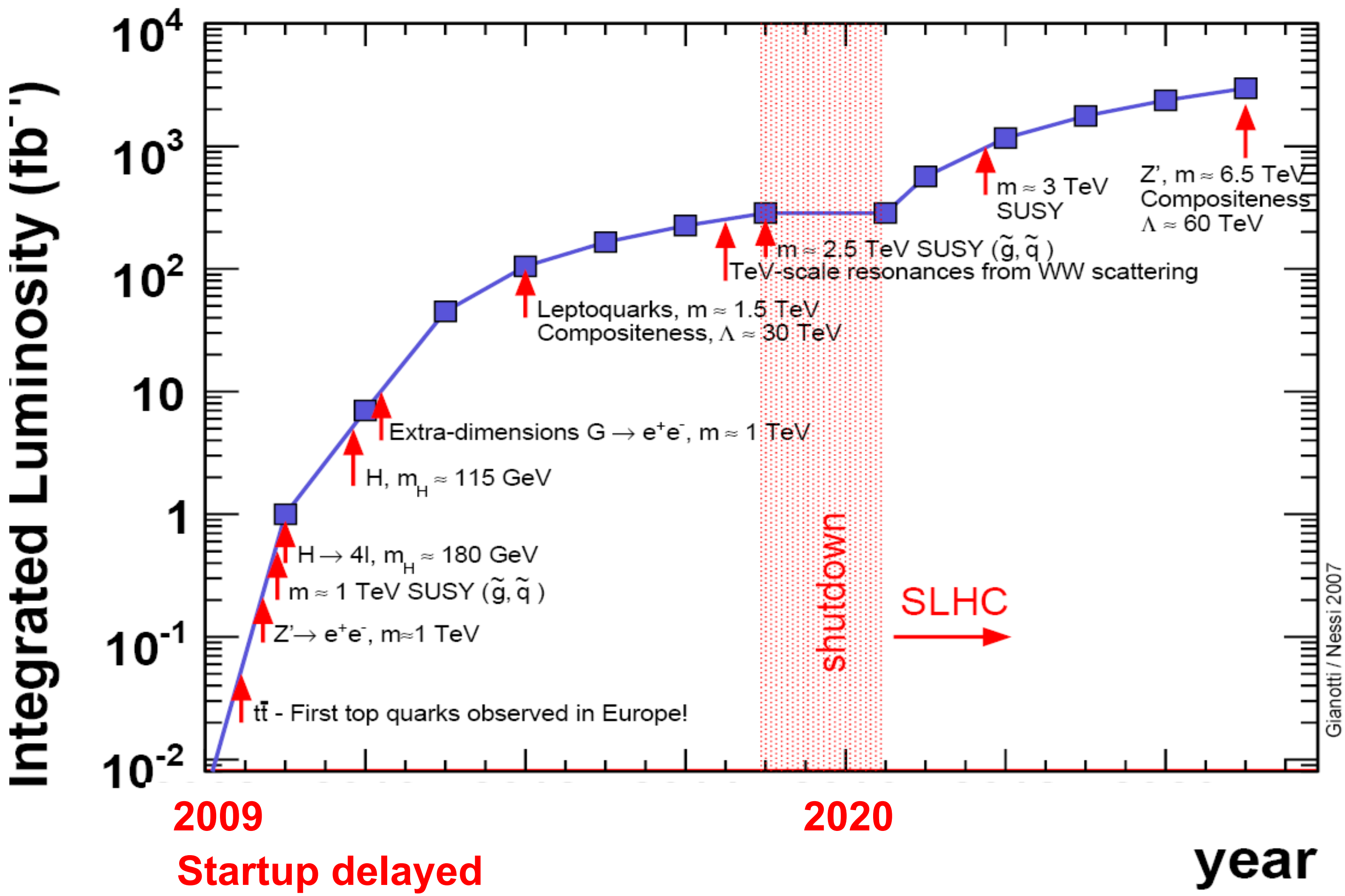


The potential detection of the Higgs, as well as supersymmetric particles, have provided many of the benchmarks for designing the ATLAS and CMS detectors.

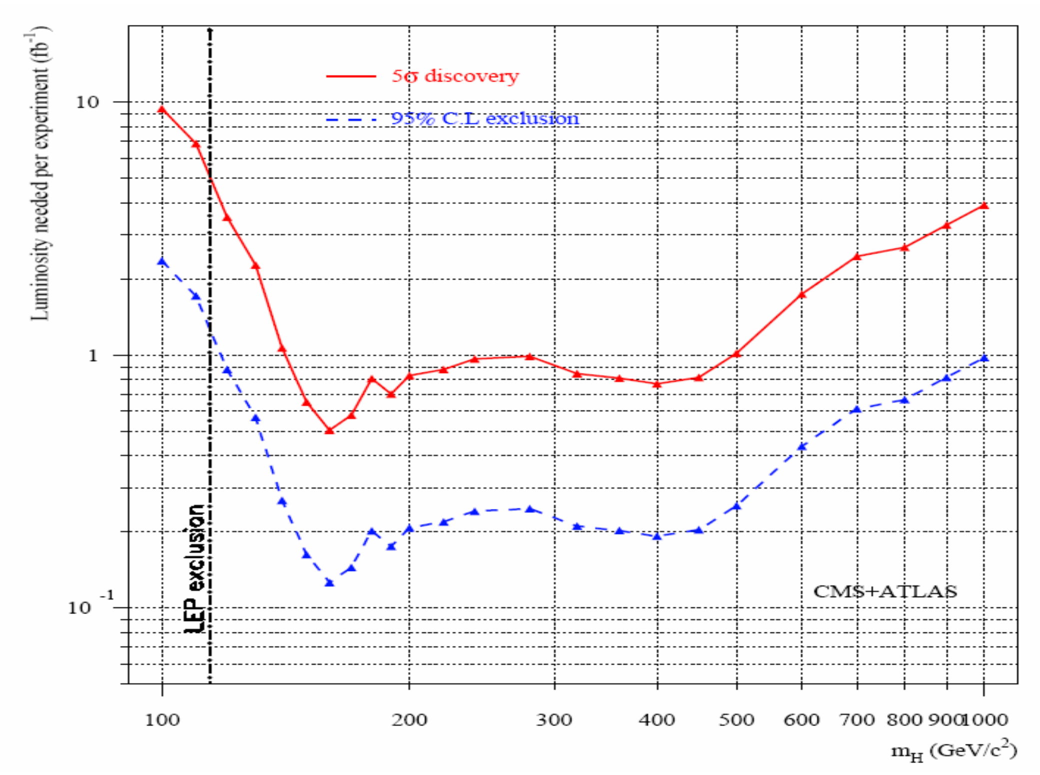
ATLAS Experiment at the LHC



Physics Opportunities at the LHC



Luminosity for Standard Model Higgs Discovery



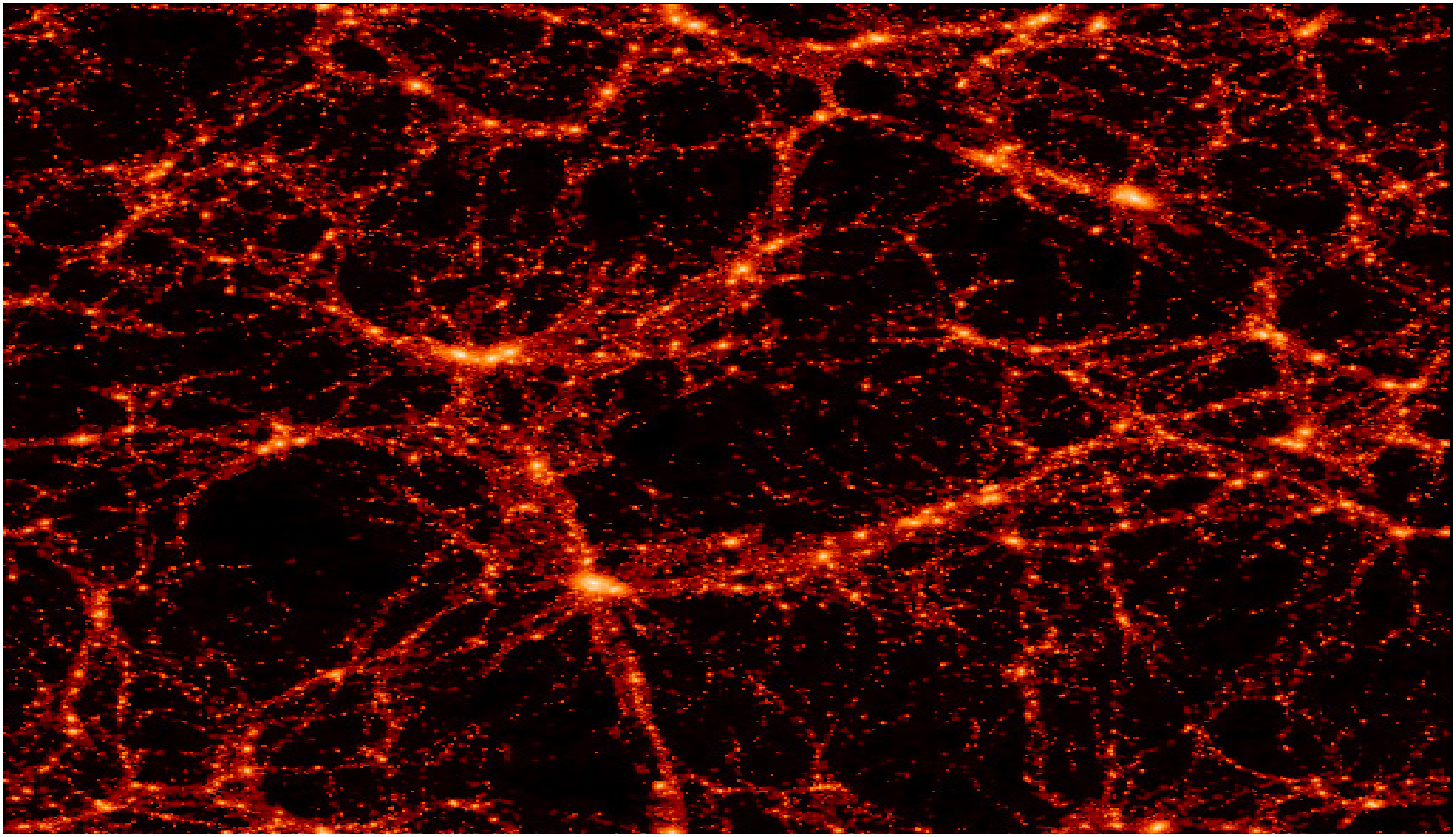
The prospects for discovering a Standard Model Higgs boson in initial LHC running, as a function of its mass, combining the capabilities of ATLAS and CMS.

[Ref: J.-J.Blaising, A.De Reock, J.Ellis, F.Gianotti, P.Janot, L.Rolandi and D.Schlatter, "Potential LHC contributions to Europe's future strategy at the high-energy frontier", contribution to the CERN Council Strategy Group workshop, Zeuthen, May 2006.]

Physics of the Generations

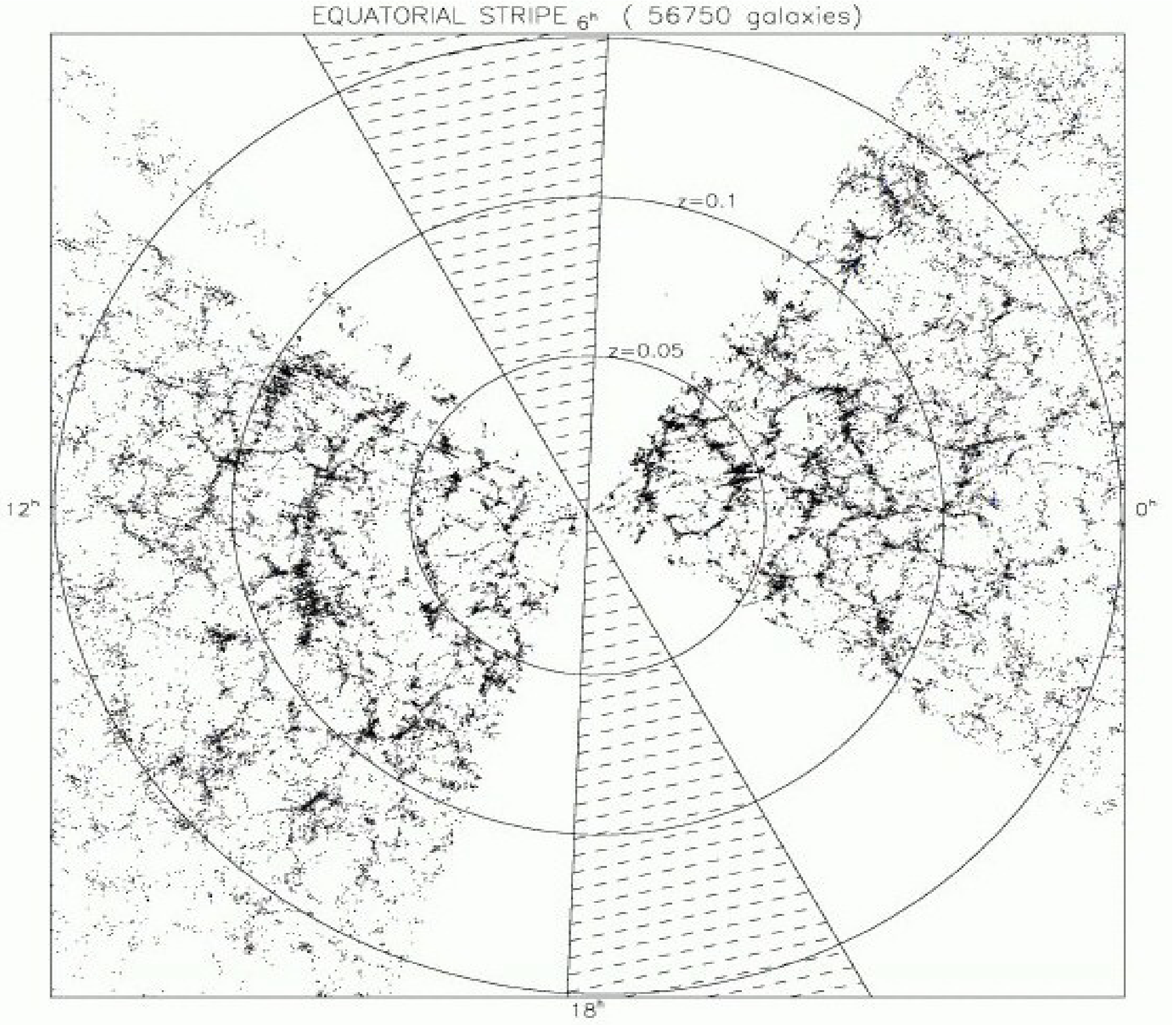
Much of particle physics has focused on studying the three generations of quarks and leptons. If we leave out the Yukawa couplings, the Standard Model has a very large symmetry associated with the various flavors (separate from the gauge symmetries). For example the three left-handed doublets of quarks, the three right- handed down quarks, and three right-handed up quarks generate a global SU(3)xSU(3)XSU(3) symmetry whose origin is not understood. What will we find at the TeV scale? Supersymmetry has particles providing the same group representations as the quarks, but we might see something different. New particles will have additional mass terms beyond the Yukawa couplings. Will these terms shed light on the Physics of the Generations and its origin? For supersymmetry the mass terms might also shed light on the supersymmetry breaking mechanism. Finally, can we get some understanding of the odd pattern of Yukawa couplings, including the origin of CP violation?

Turn to Cosmos: Very small initial fluctuations seen in the cosmic microwave background grow into spectacular structure 13 billion years later due to gravity. Shows a simulation on a large scale.



Scale for plot: 300 million light years on a side.

Sloan Digital Sky Survey: Galaxy Map



Galaxies mapped out to 2 billion light years.

Same pattern seen as in the simulations! These are the luminous components of the universe, dark matter not seen – it is the invisible hand guiding the formation of structure.

Galaxies in collision, many now observed.

Dark Matter Searches

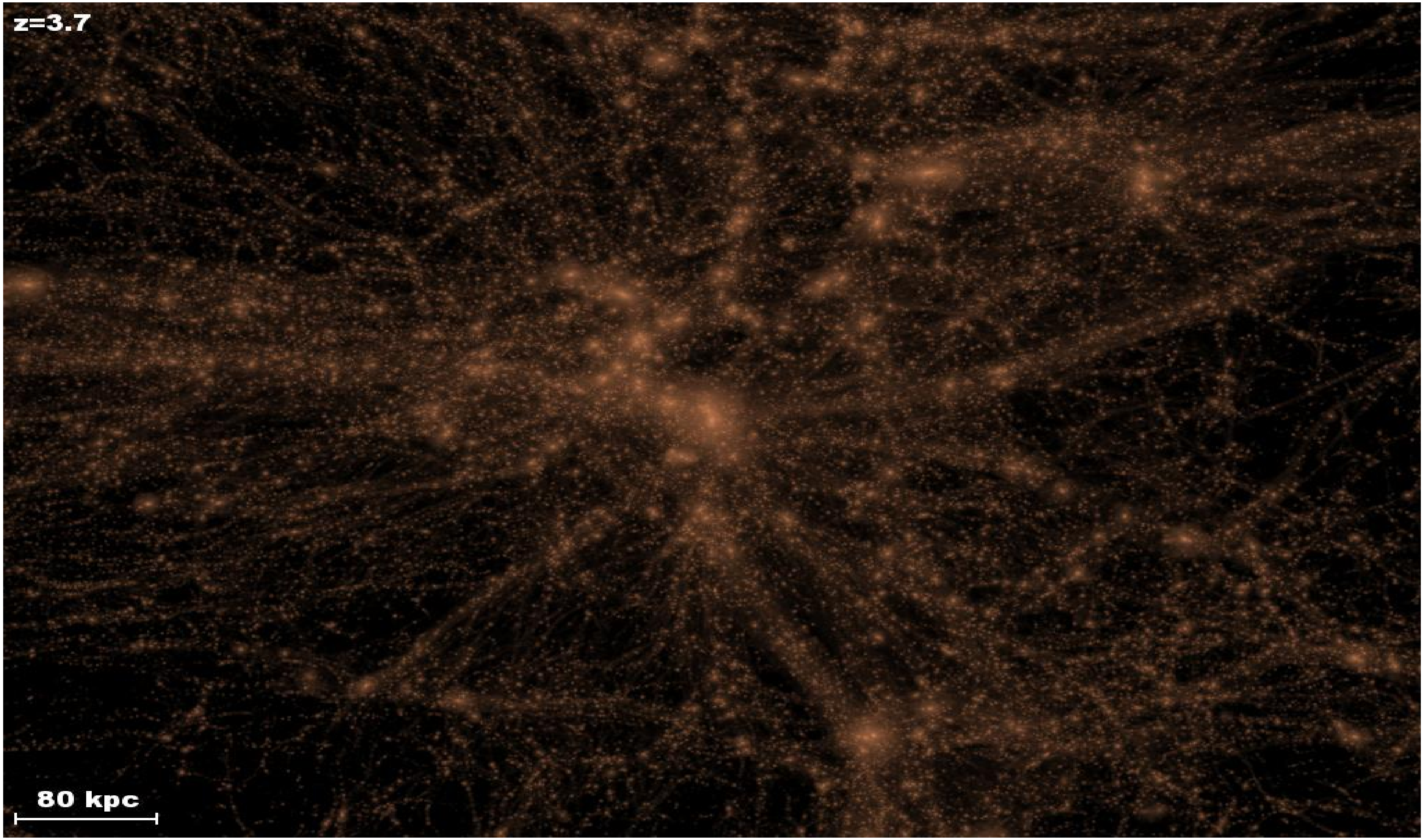
This is an area with great promise as we have developed a number of very capable experiments to search in several ways for dark matter. Leading candidate for the dark matter are WIMPs, which in various theories have the correct cross sections to be relics of the big bang yielding the presently observed density. The experiments are:

- The LHC will allow direct production of WIMPs in a number of new physics scenarios. The most favorable cross sections occur when a new colored particle can be produced, cascading through related particles to a lightest stable particle. Signal: Missing energy (WIMP) plus whatever the cascade produces (for example jets, leptons, photons, many b or t quarks). The lightest supersymmetric particle provides an excellent candidate for dark matter.

- If WIMPs have interactions beyond gravity then perhaps they annihilate in space. New satellite (Fermi experiment) is looking at γ rays and electrons and positrons in space with vastly better capabilities than previous experiments. Fermi can't measure charge, however, Pamela experiment has reported a surprising excess in the positron to electron ratio. What is this due to? The search for γ rays requires understanding conventional sources. An intriguing place to look – small galaxies near our own that are enhanced in dark matter.

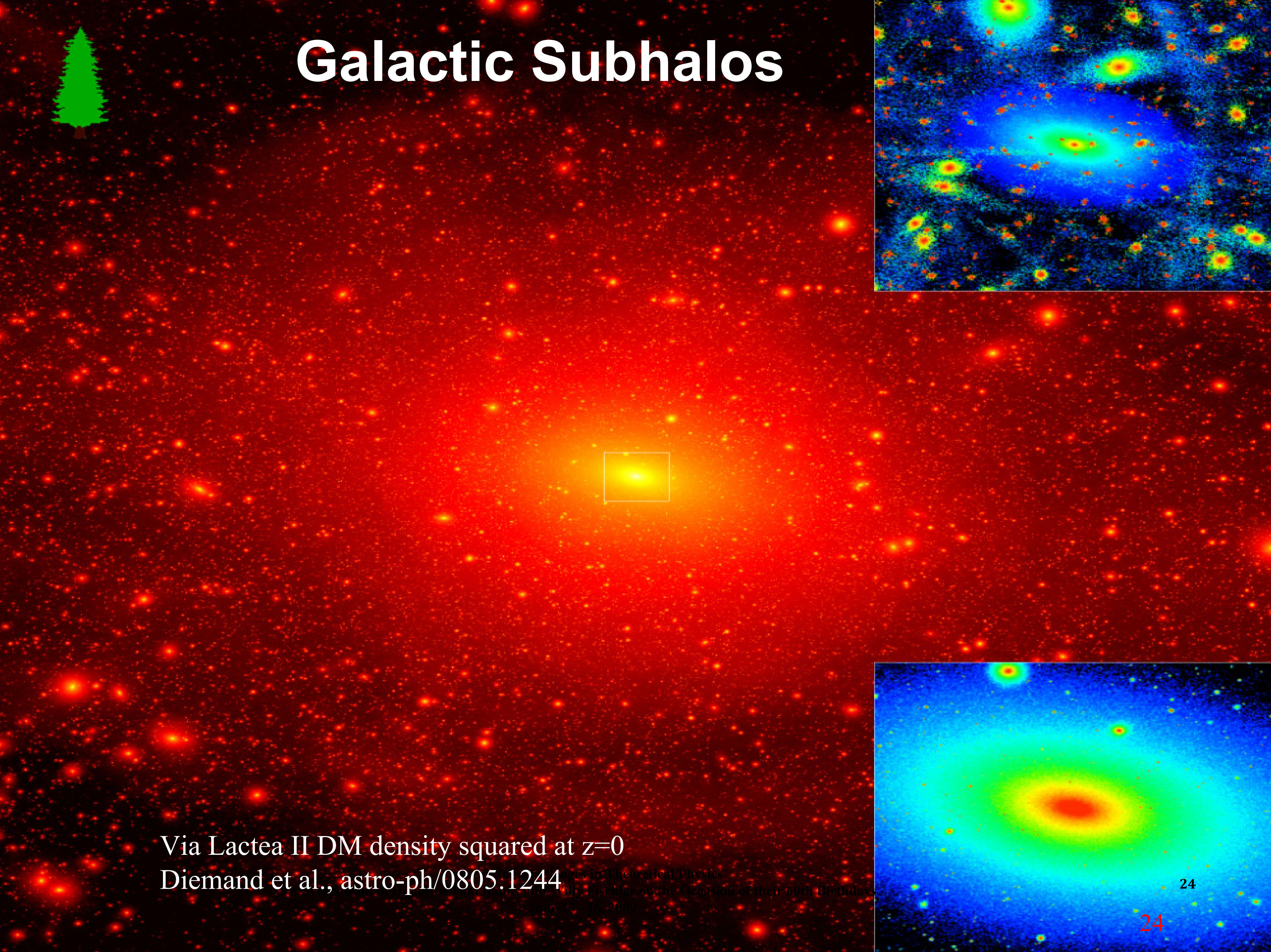
- Scattering on materials of the WIMPs present all around us.

Simulation of Region of the Early Universe, about the Size of our Own Galaxy, in its Early History (12 Billion Years Ago).



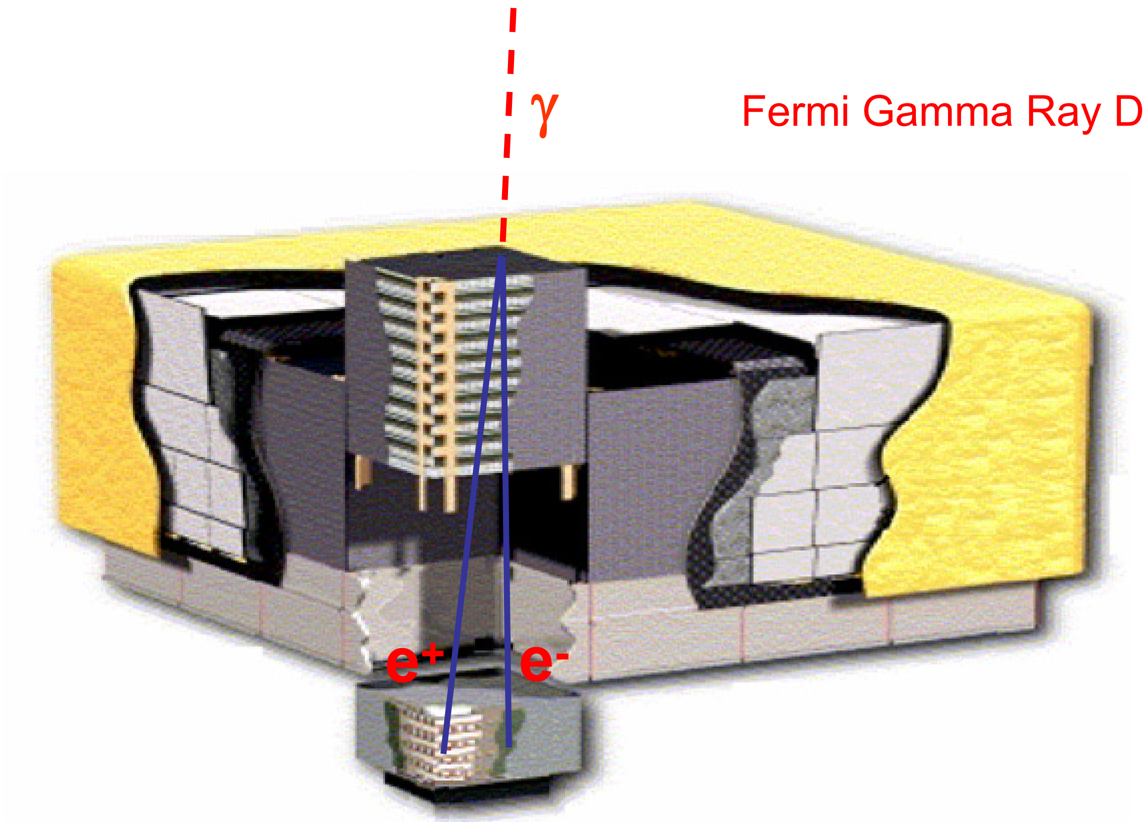
Galaxies Today

Galactic Subhalos



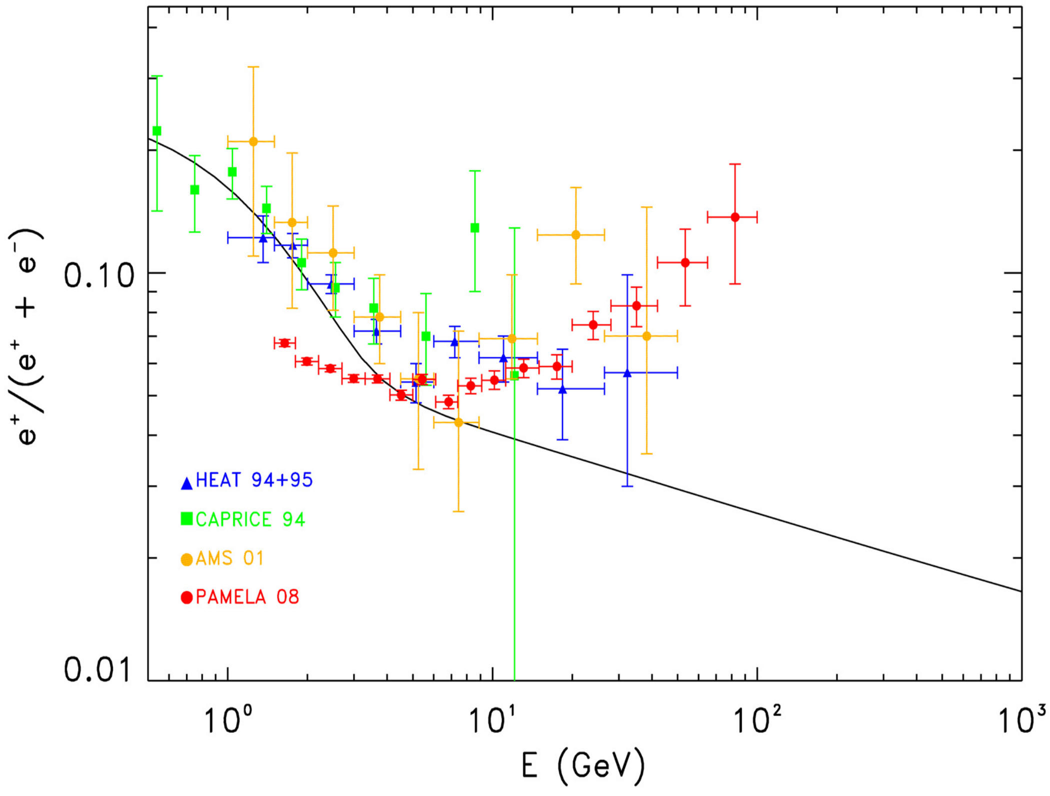
Via Lactea II DM density squared at z=0
Diemand et al., astro-ph/0805.1244

Gamma Ray Space Telescope



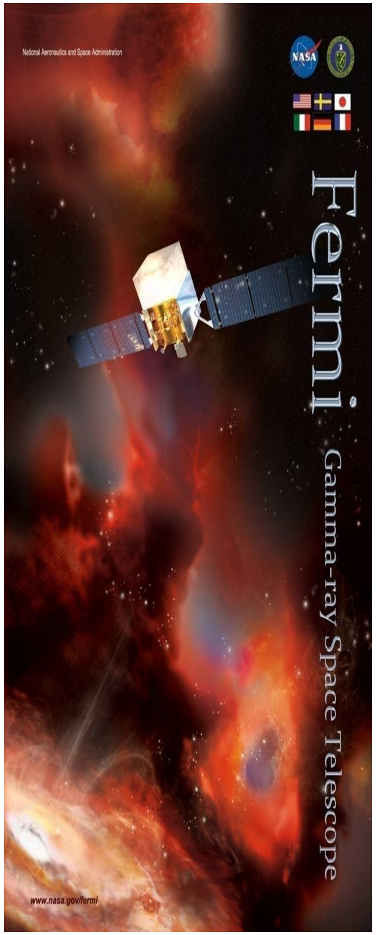
Satellite launched last June to look at Gamma Rays from Space. Will it see the annihilation of dark matter leading to gamma rays or perhaps electrons and positrons? It is taking data and the scientists are studying the energetic particle sources in space.

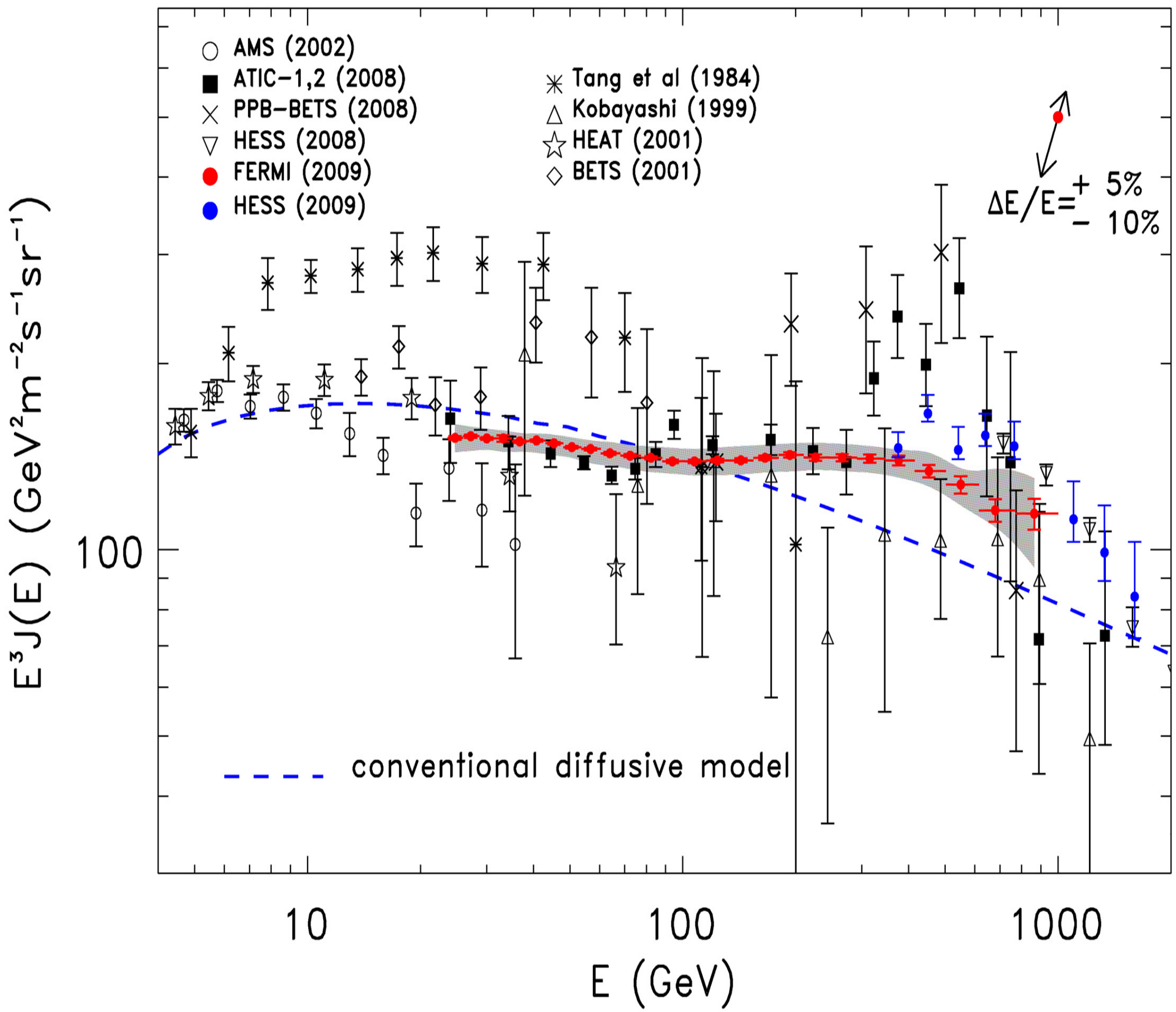
New High Energy Measurement in 2008



- PAMELA measures an increase in the $e^+/(e^-+e^+)$ fraction

New: 2009 Fermi Data on Electrons + Positrons





Dark Matter Scattering Search - DUSEL

Lots of dark matter is zipping through us; does it very occasionally scatter when it hits matter (like neutrinos)? Specially designed experiments have begun to look for this. They have to be deep underground. The rock above the experiments filters out other particles whose interactions would swamp the dark matter signal above ground. These particles interact before getting to large depths underground.

Homestake mine in South Dakota. Planned location for a new underground laboratory for research in physics, geology, engineering, and biology (called DUSEL). Will host experiments searching for WIMP dark matter about 1 mile below ground.

Wimp Dark Matter Detectors, Very Active Field

Detection limits governed by how big a volume we can make for a detector that has no background. Want large atomic number to exploit coherent scattering in the case of spin independent cross sections. Last generation of detectors about 10kg in mass, have deployed a next generation typically in the 100kg range, working on design of multi-ton detectors. Limits for the cross section from the 10 kg detectors typically around 10^{-43} cm^2 (normalized to a nucleon) out to 1 TeV mass WIMPs. One detector claims a signal, not consistent with others but perhaps we don't understand what dark matter is.

Some of the choices for detection material:

Liquid Xenon, liquid Argon, Ge crystals, NaI crystals, bubble chamber filled with heavy liquid (CF_3I).

Multi-ton detectors (for example 20 tons of liquid Xenon) will increase cross section sensitivity by about 5 orders of magnitude. Calculations of cross sections in the case of supersymmetry indicate that this will allow exploration of a significant fraction of the supersymmetry space.

Dark Energy – The Big Surprise

Dark Energy described by a small cosmological constant: doesn't fit with standard expectations of being either zero or enormous. Both now disagree with measurements. Mostly irrelevant for first few billions of years after the big bang, dark matter was major actor then, after photon decoupling. Since then, dark energy has been a growing part of the energy balance, as seen in the table below

z	Age of Universe in Years	Energy Fraction in Matter	Fraction in Dark Energy
3	2.2 Billion	.96	.04
2	3.3 Billion	.91	.09
1	5.9 Billion	.75	.25
0	13.7 Billion	.25	.75

The only way we know how to study dark energy is through measurements of the cosmos using telescopes. The data for probably the next decade will come from telescopes on earth. Hope to eventually deploy a telescope in space. The telescopes use a number of measurements and analysis techniques under active development.

Some of the Challenges for Dark Energy Studies

Goal is to measure the evolution of the universe's geometry over time since the Big Bang and the growth of structure in the universe, which is affected by the geometry. Can the dark energy component be described just in terms of w(z), the ratio of pressure to energy density for the dark energy? Is the measured parameter the same in all directions? Will we find w = -1 for all z, which is just a cosmological constant. Four flagship measurements have been identified.

- Baryon Acoustic Oscillations: relatively new technique, measures expansion history of the universe. Should be easiest method to model. Requires spectroscopic data for many galaxies.
- Cluster studies: measures expansion history and the growth of large-scale structure. Potentially very small statistical uncertainties compared to other techniques, systematic uncertainties still being understood, but provides a powerful, independent constraint.
- Weak lensing: could be most powerful individual technique providing a direct measurement of mass, but requires use of photometric measurement of the redshift. What will be the systematic limit here, not yet a mature technique?
- Supernova measurements: most prominent technique to date, measures the geometry. What is the systematic limit here?

Telescopes to Study Dark

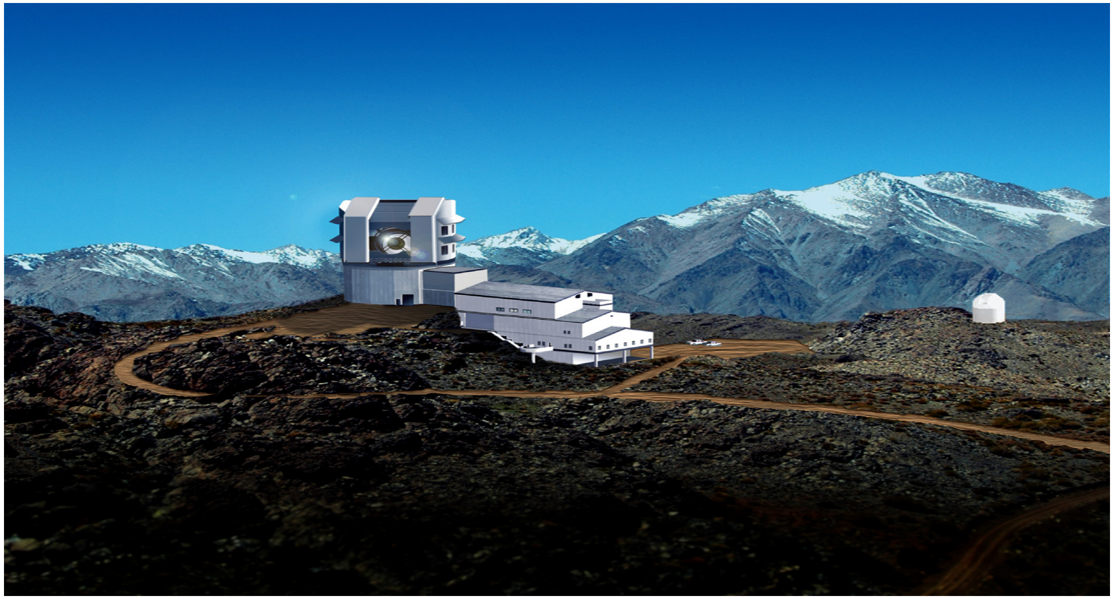
Approved Projects:

The **BOSS** extension of the Sloan Digital Sky Survey, using its re-instrumented 2.5 m telescope, to start studying dark energy later this year. Will study Baryon Acoustic Oscillations.

The **Dark Energy Survey**, using a re-instrumented 4m telescope, will take data, starting in 2011. This experiment will use the other three techniques.

These experiments will measure w to about 10% for each of a number of techniques and begin to see whether w depends on z and whether the techniques give a fully consistent picture (that is, is it just w).

LSST, 8.4 meter telescope proposal for a very large survey of the cosmos around the middle of next decade – study effects of Dark Energy, but also Dark Matter distribution in much more detail. Would be a joint NSF-DOE project.



Artists conception of the LSST, to be located in Chile.

Concluding Comments

- If the Angels defeat the Demons we should finally have the information you really want from the LHC. Is there a Higgs, is there Supersymmetry, are there Extra Dimensions, or do we have a complete surprise?
- If it is a WIMP, the upcoming generation of experiments should have a very good chance of discovering Dark Matter as a particle that has a mass and that does more than just interact via gravity. An initial discovery would probably lead to a vigorous experimental program to better pin down the WIMP properties and understand more about its local distribution.
- So far Dark Energy is fully consistent with a cosmological constant. We will be getting much more information on this and also check carefully whether this simple assumption works for all kinds of measurements. If yes, then understanding the presence of a small cosmological constant will be one of the major challenges for those of you in the audience.