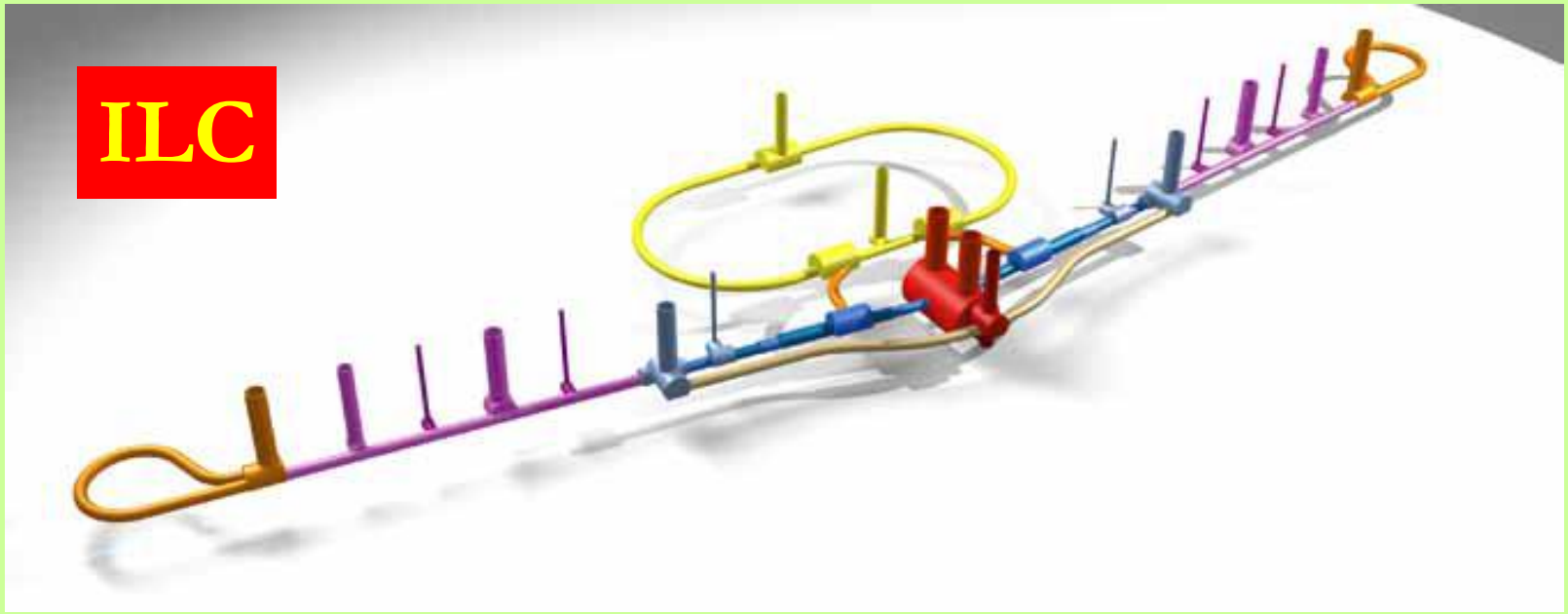
Future Opportunities in Particle Physics



Barry Barish
Caltech

DPF Meeting 13-Aug-2011

What is Particle Physics?

The definition from Wikipedia:

- **"Particle physics is a branch of physics that studies the elementary subatomic constituents of matter and radiation, and their interactions. The field is also called high energy physics, because many elementary particles do not occur under ambient conditions on Earth. They can only be created artificially during high energy collisions with other particles in particle accelerators."**

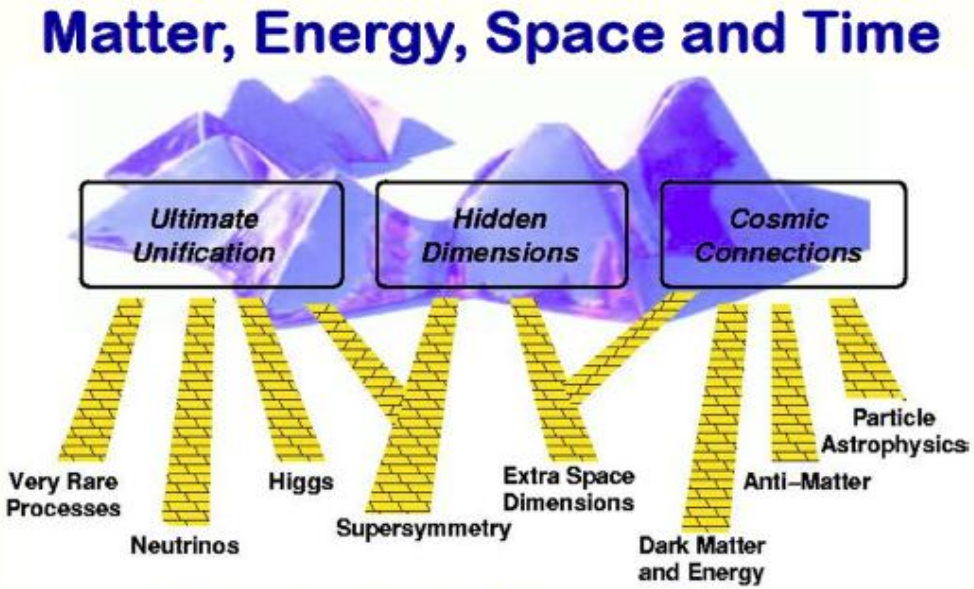
- **"Particle physics has evolved out of its parent field of nuclear physics and is typically still taught in close association with it. Scientific research in this area has produced a long list of particles."**

What is Particle Physics?

The definition from DoE Office of Science:

- **"High Energy Physics explores the most fundamental questions about the nature of the universe. The Office of High Energy Physics supports a program focused on three frontiers of scientific discovery. At the *energy frontier*, powerful accelerators investigate the constituents and architecture of the universe. At the *intensity frontier*, astronomically large amounts of particles and highly sensitive detectors offer a second, unique pathway to investigate rare events in nature. At the *cosmic frontier*, natural sources of particles from space reveal the nature of the universe. Together these three interrelated discovery frontiers create a complete picture, advancing Department of Energy missions through the development of key cutting-edge technologies and the training of future generations of scientists."**

What is Particle Physics?



Path to the Goals of Particle Physics

From each of these goals flows a diverse research program that will be carried out in partnership with colleagues across the globe.

The definition from Bagger-Barish (2001)

Particle Physics: an Inquiry Based Science

1. How can we solve the mystery of dark energy?
2. Are there extra dimensions of space?
3. Do all the forces become one?
4. Why are there so many kinds of particles?
5. What is dark matter?

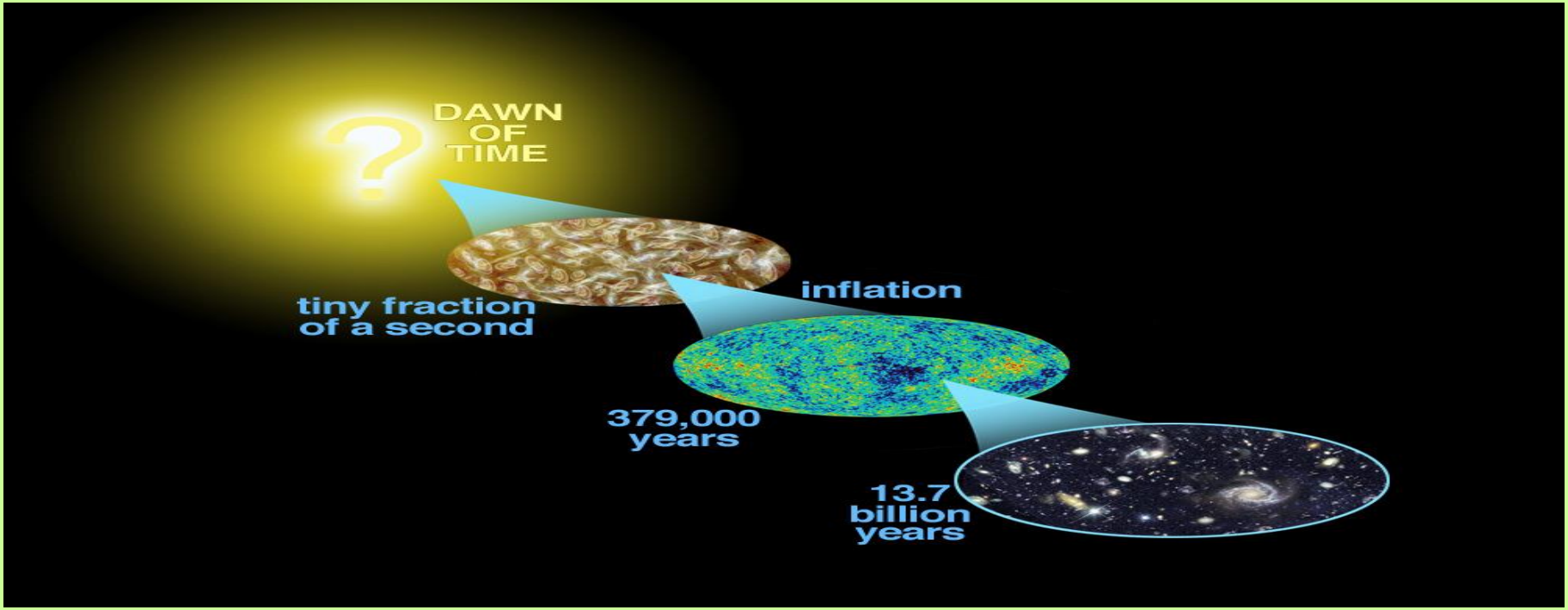
   How can we make it in the laboratory?

6. What are neutrinos telling us?
7. How did the universe come to be?
8. What happened to the antimatter?
9. Are there undiscovered principles of nature:

   New symmetries, new physical laws?

from the Quantum Universe

The Nature of Particle Physics



"There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy"

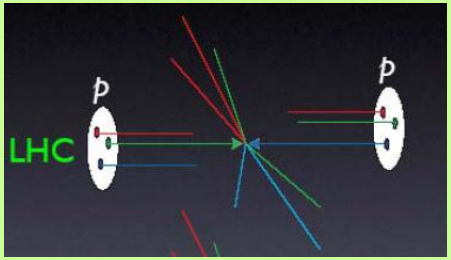
(Hamlet, I.5)

Many Experimental Probes

- Neutrinos
  - » Particle physics and astrophysics using a weakly interacting probe

- Particle Astrophysics/Cosmology
  - » Dark Matter; Cosmic Microwave, etc

- High Energy pp Colliders
  - » Opening up a new energy frontier (~ 1 TeV scale)

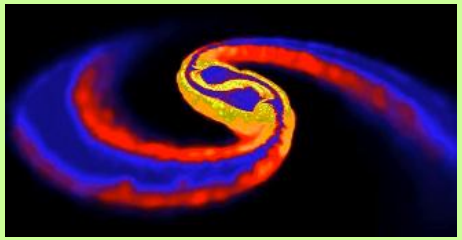


- High Energy Lepton Colliders
  - » Precision Physics at the new energy frontier

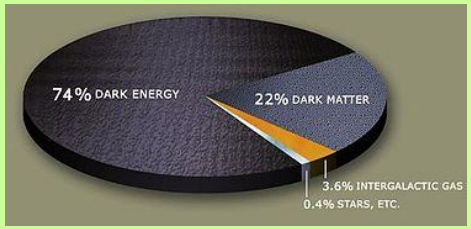
and more Experimental Probes

- **Precision Physics**
  - » SuperB factories
  - » Fermilab: g-2; μ → e; etc.

- **Gravity**
  - » Gravitational waves; quantum gravity



- **Dark Energy**
  - » Space missions



- **New Generations of Accelerators**
  - » Plasma/laser wakefield acceleration

Addressing the Questions

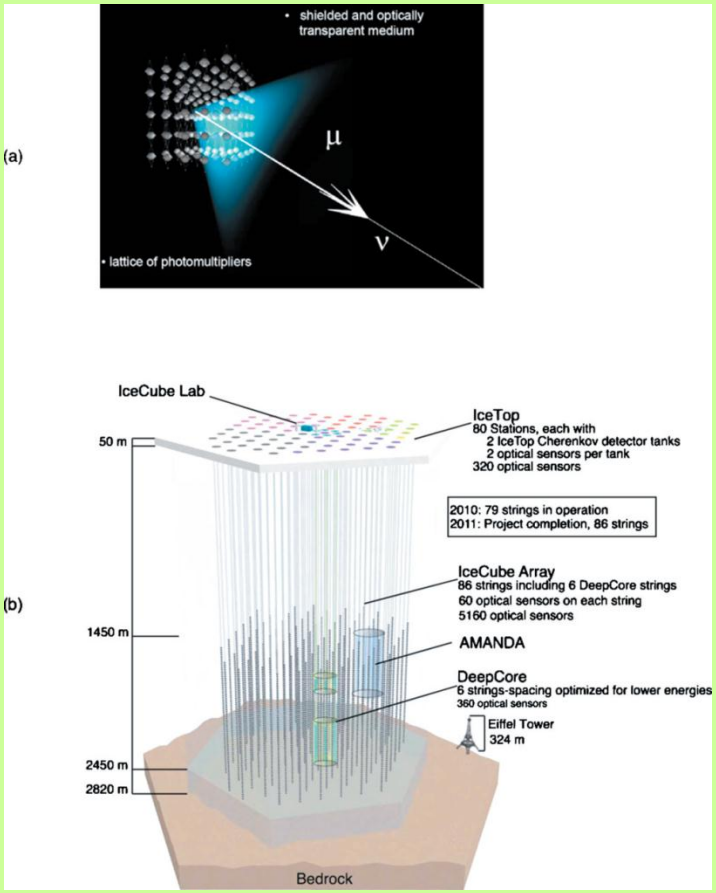
- **Neutrinos**
  - » **Particle physics and astrophysics using a weakly interacting probe**

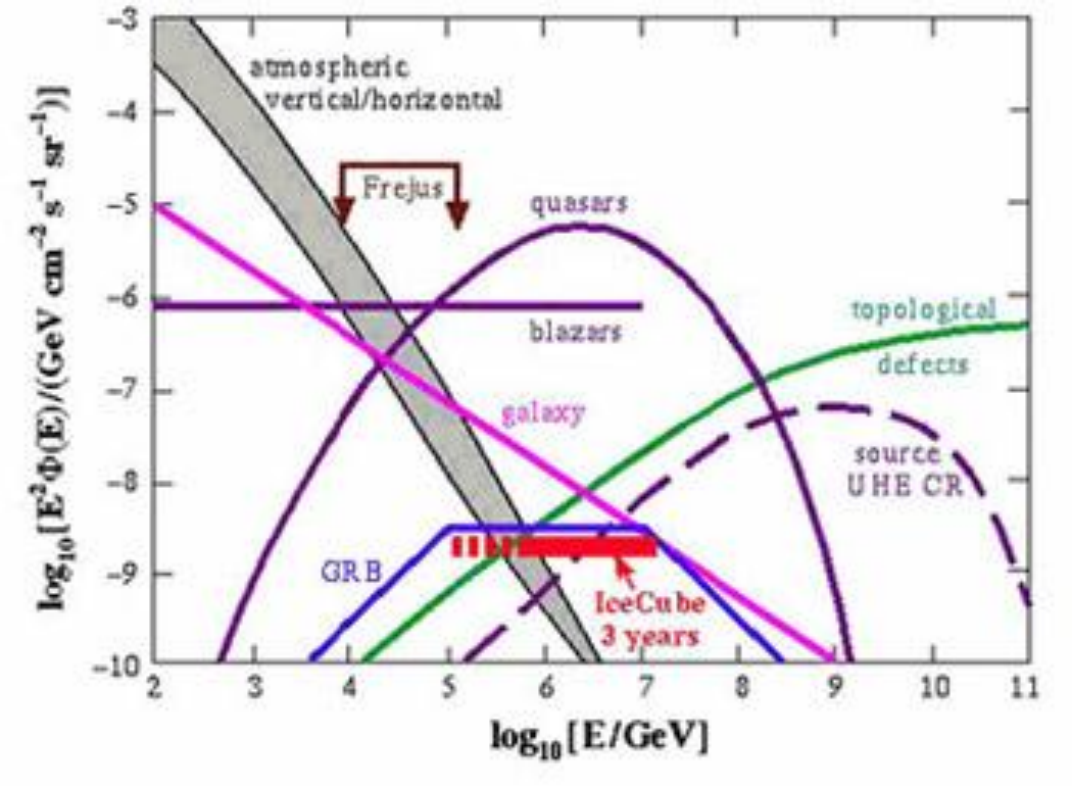
Neutrinos – Broad field; Specialized Expts

- **Neutrino Properties**
  - » Why are neutrino masses so small and what is their mass scale?
  - » Separation and ordering of neutrino masses?
  - » Are neutrinos their own antiparticles?
- **Neutrinos in Astrophysics**
  - » Astrophysical sources of neutrinos, and their contribution to the dark matter?
- **Neutrinos and Fundamental Particle Physics**
  - » CP violation in neutrinos, leptogenesis, possible role in the early universe and in understanding the particle antiparticle asymmetry in nature?

Ice Cube: Neutrino Astronomy

- **Neutrino Astrophysics – Investigating astrophysical sources emitting ultra high energy neutrinos**

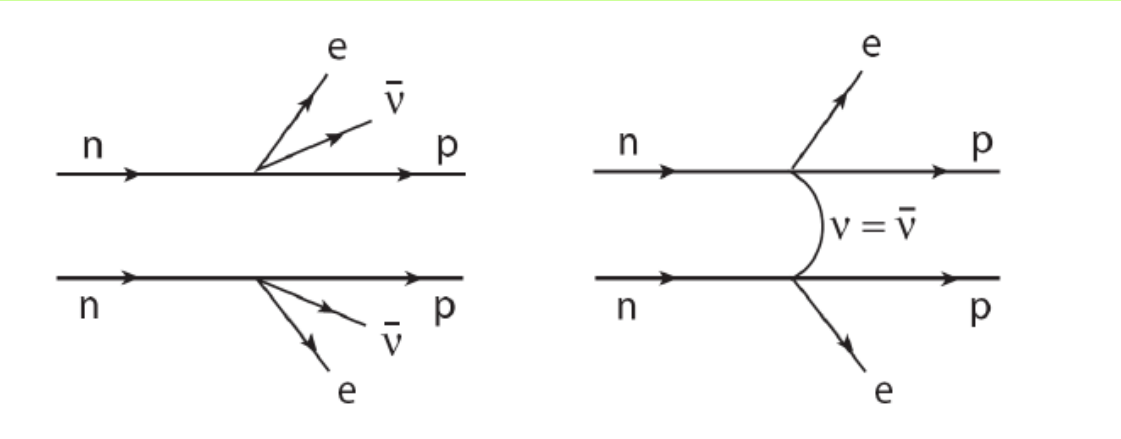




South Pole

Is the neutrino its own antiparticle?

- **Neutrinoless Double Beta Decay**



- **If neutrino is a Majorana particle (own antiparticle)**
  - » **Determine neutrino mass scale**
  - » **Importance for Grand Unification**
  - » **Lepton number violation**
  - » **Implications for leptogenesis**

Neutrinoless Double Beta Decay

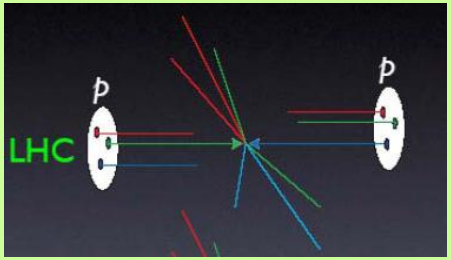
- **Experimental Challenges – What technique?**
  - » **Isotopes decaying to monochromatic electrons over continuum background. No obvious best isotope? Therefore, several large-scale experiments are likely needed.**
  - » **Which technique scales to the needed mass (Xenon, Germaniuim, ???)**
- **Experimental Challenges – Scale required**
  - » **Present experiments – 10 kg → sensitivity to $m_\nu < 1$ eV**
  - » **Need ~ 1 ton detectors to reach atmospheric m_ν ~50 meV**
  - » **Need ~ 50 tons to reach solar m_ν ~ 1 meV scale**
- **Other issues: Low background environment; costs; etc**

Experimental Probes

- Neutrinos
  - » Particle physics and astrophysics using a weakly interacting probe

- Particle Astrophysics/Cosmology
  - » Dark Matter; Cosmic Microwave, etc

- High Energy pp Colliders
  - » Opening up a new energy frontier (~ 1 TeV scale)

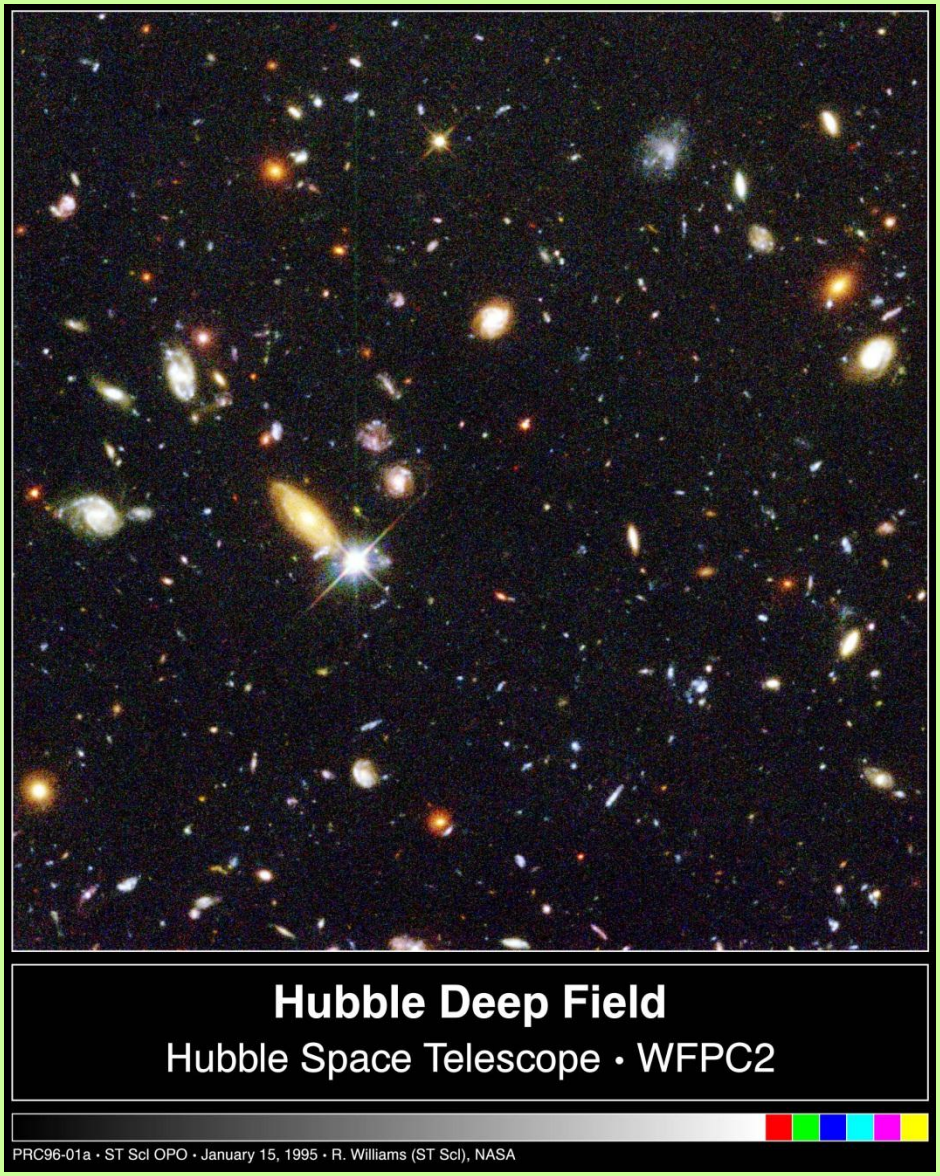


- High Energy Lepton Colliders
  - » Precision Physics at the new energy frontier

Approaches

- **Particle Astrophysics/Cosmology**
  - » **Dark Matter; Cosmic Microwave, etc**

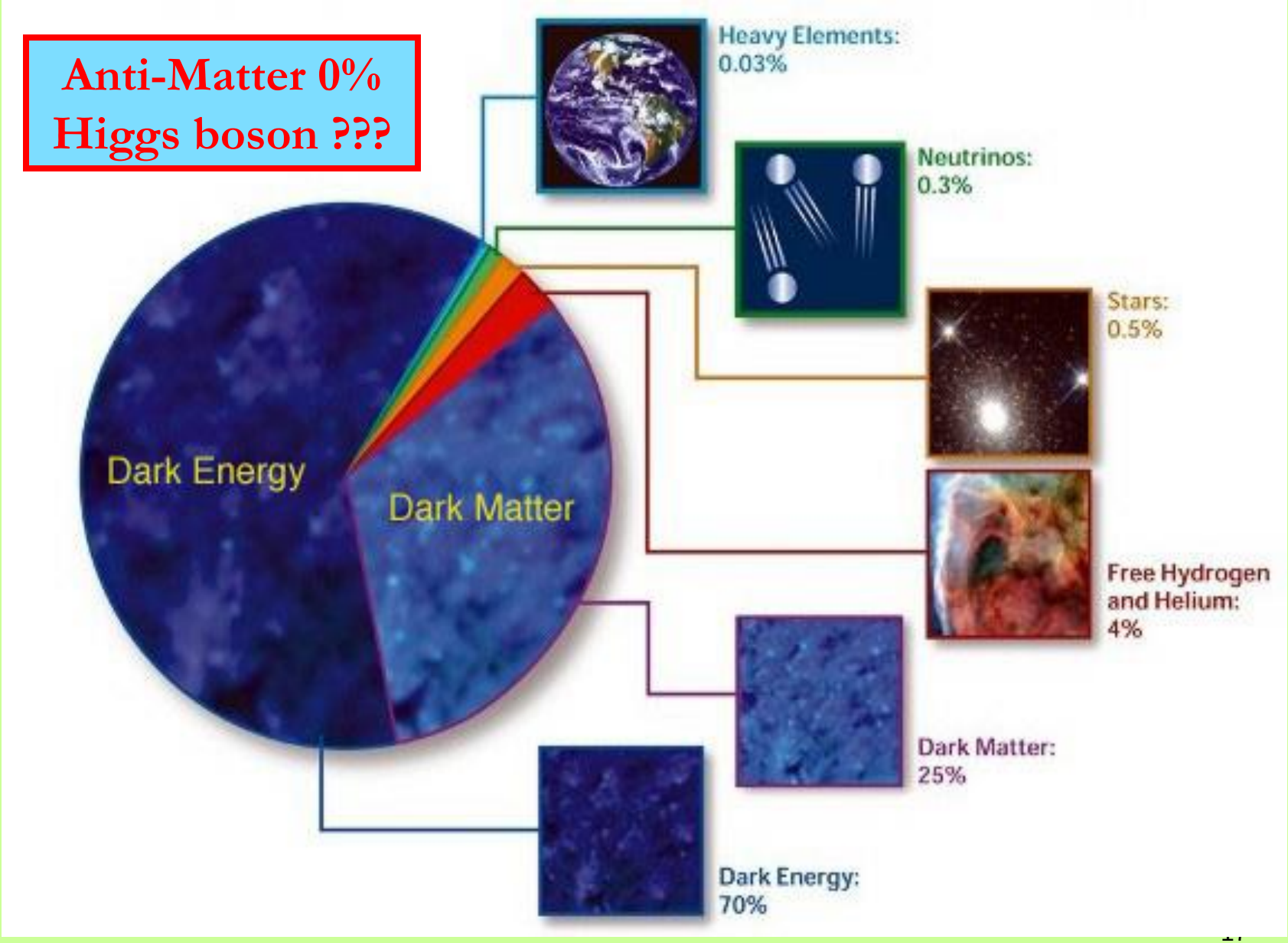
Dark Matter



What don't we see?

Dark Matter
Neutrinos
Dark Energy
…
Higgs Bosons !
Antimatter !!

The Energy Budget of the Universe

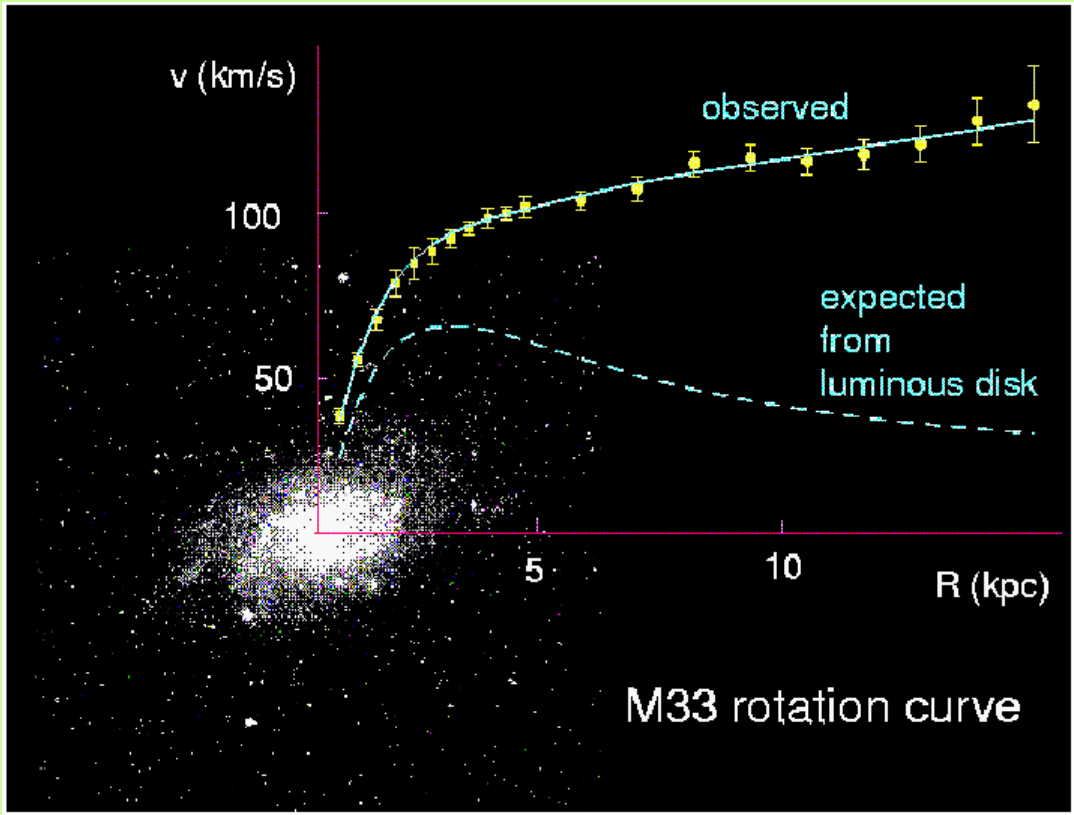


Dark Matter
the evidence

From the Kepler's law, $v_{circ} = \sqrt{\frac{GM(r)}{r}}$ for r much larger than the luminous terms, you should have v α r $^{-1/2}$ However, Instead, it is flat or rises slightly.

This is the most direct evidence for dark matter.

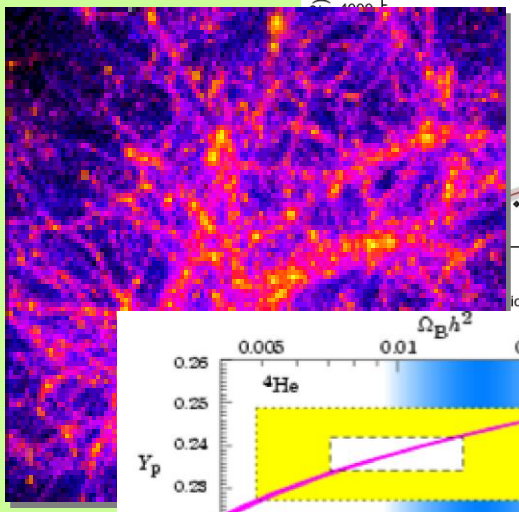
There are many complementary measurements at all scales

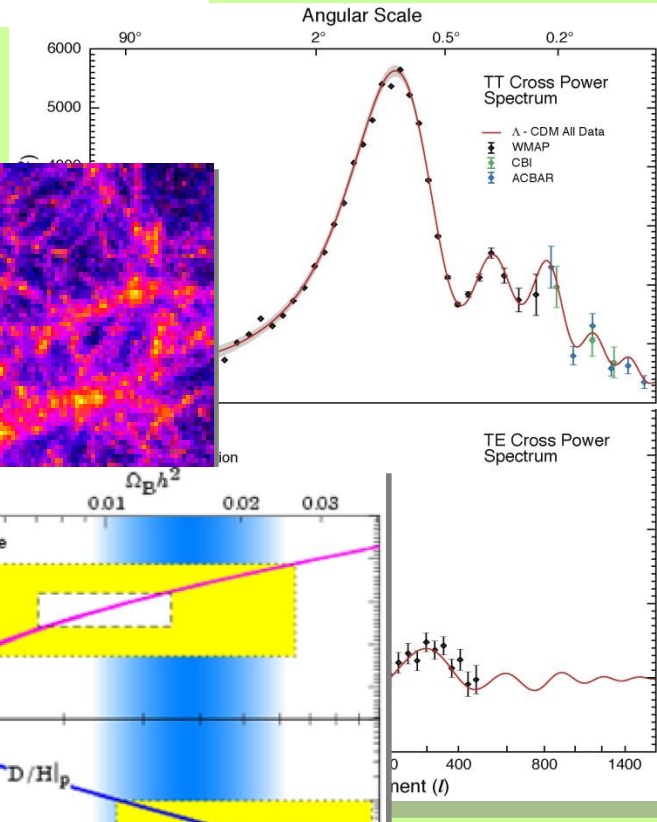


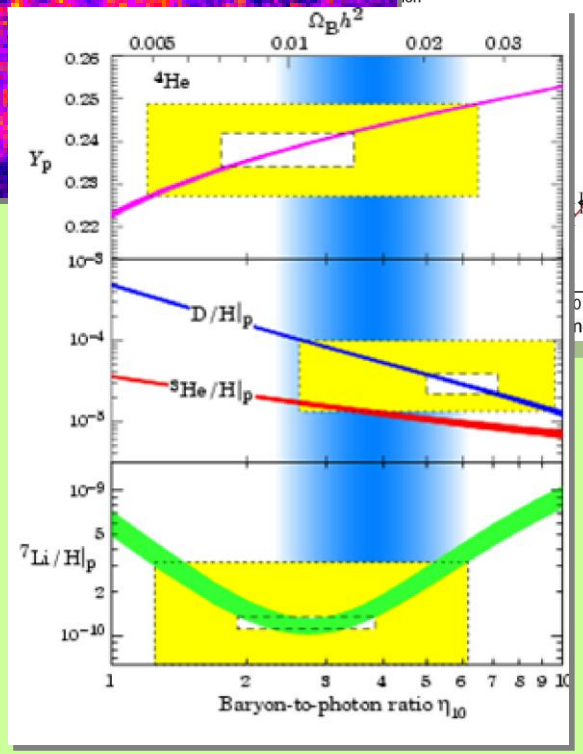
Corbelli & Salucci (2000);
Bergstrom (2000)

Other Dark Matter Evidence

- Evidence from a wide range of astrophysical observations including rotation curves, CMB, lensing, clusters, BBN, SN1a, large scale structure
- Each observes dark matter through its gravitational influence
- Still no (reliable) observations of dark matter's electroweak interactions (or other non-gravitational interactions)
- Still no (reliable) indications of dark matter's particle nature







Dark Matter Particle Candidates

Axions, Neutralinos, Gravitinos, Axinos, Kaluza-Klein Photons, Kaluza-Klein Neutrinos, Heavy Fourth Generation Neutrinos, Mirror Photons, Mirror Nuclei, Stable States in Little Higgs Theories, WIMPzillas, Cryptons, Sterile Neutrinos, Sneutrinos, Light Scalars, Q-Balls, D-Matter, Brane World Dark Matter, Primordial Black Holes, …

EVIDENCE STRONGLY FAVORS NON-BARYONIC COLD DARK MATTER

Leading Dark Matter Candidate

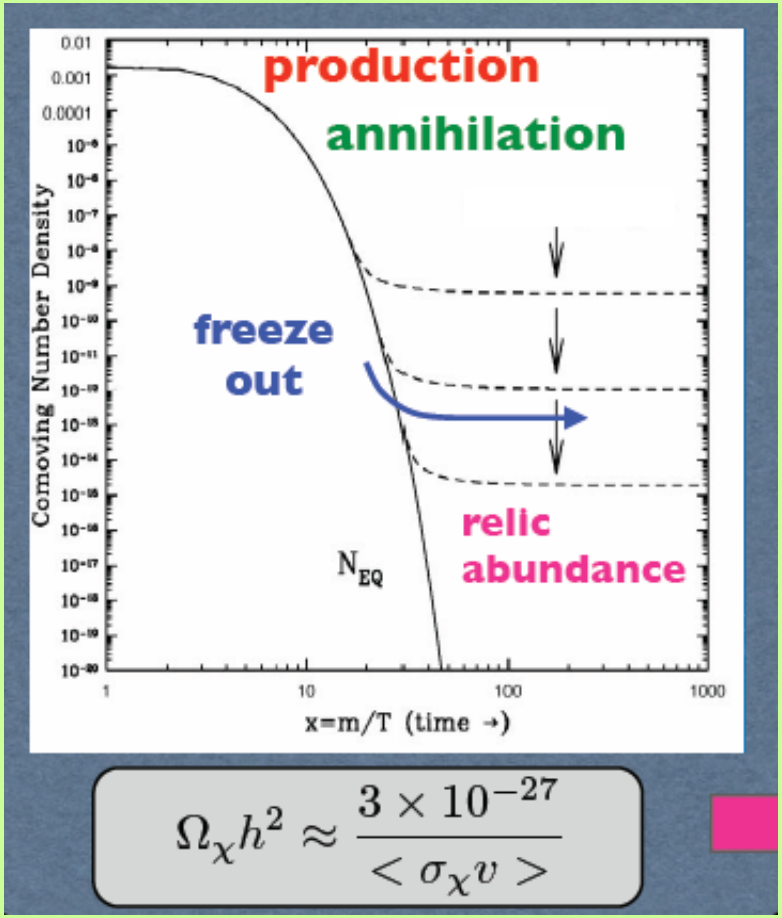
Weakly Interacting Massive Particles (WIMPs)

Weakly interacting particles produced thermally in the early universe

Large mass compared to standard particles.

Due to their large mass, they are relatively slow moving and therefore "cold dark matter."

Leading candidate – "Supersymmetric Particles"



$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27}}{< \sigma_\chi v >}$$

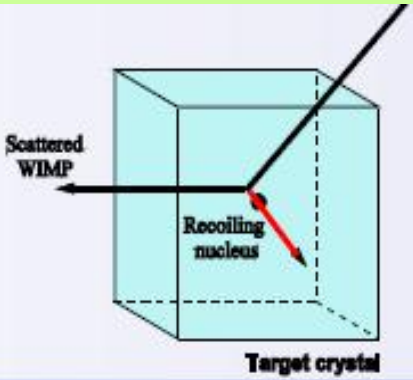
Supersymmetric dark matter would solve one of biggest problems in astrophysics and particle physics at the same time !

Searching for Dark Matter

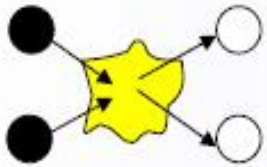
Underground

- Direct Detection:

Look for the elastic scattering of dark matter with nuclei



In Space



- Neutrinos
- Photons
- Electron-Positron, Antimatter

- Indirect Detection:

Look for the annihilation products

On Accelerators

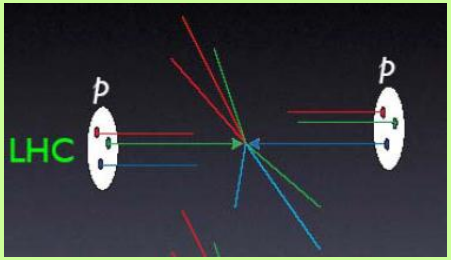
Look for signals of new physics

Experimental Probes

- **Neutrinos**
  - » Particle physics and astrophysics using a weakly interacting probe

- **Particle Astrophysics/Cosmology**
  - » Dark Matter; Cosmic Microwave, etc

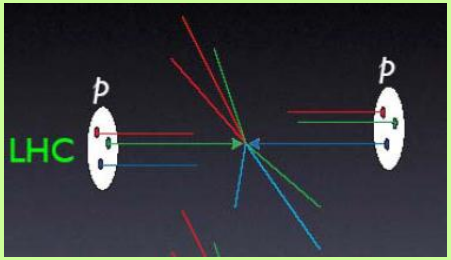
- **High Energy pp Colliders**
  - » Opening up a new energy frontier (~ 1 TeV scale)



- **High Energy Lepton Colliders**
  - » Precision Physics at the new energy frontier

Addressing the Questions

- **High Energy pp Colliders**
  - **Opening up a new energy frontier (~ 1 TeV scale)**



- **High Energy e^+e^- Colliders**
  - **Precision Physics at the new energy frontier**

Exploring the Terascale

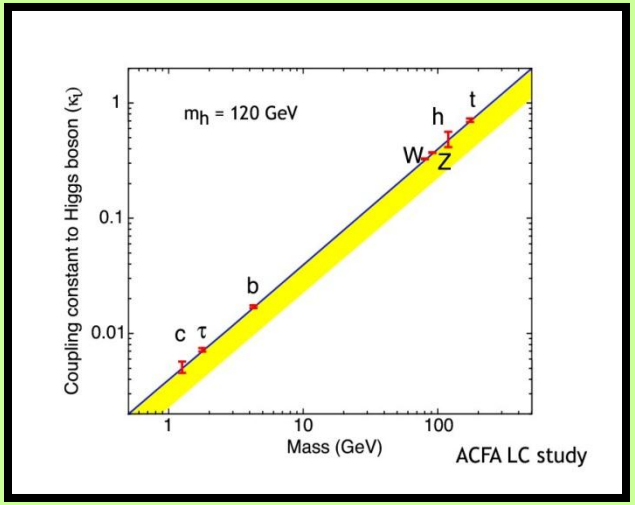
the tools

- **The LHC**
  - » **It will lead the way and has large reach**
  - » **Quark-quark, quark-gluon and gluon-gluon collisions at 0.5 - 5 TeV**
  - » **Broadband initial state**
- **A Lepton Collider (e.g. ILC or ?)**
  - » **A second view with high precision**
  - » **Electron-positron collisions with fixed energies**
  - » **Well defined initial state**
- **Together, these are our tools for the terascale**

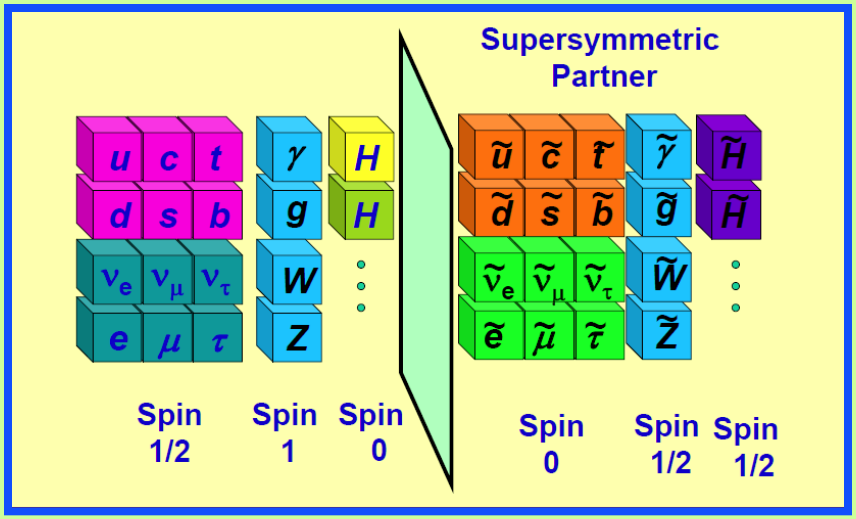
LHC

The machine and detectors work very well and results are emerging

- **Higgs**



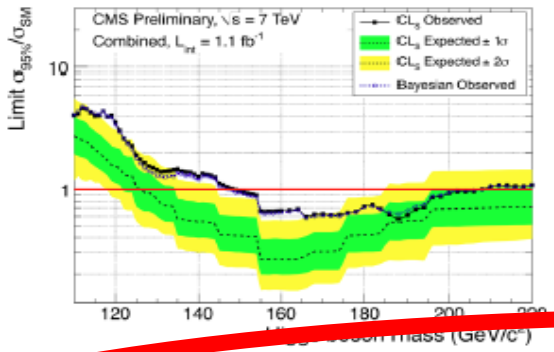
- **Supersymmetry**



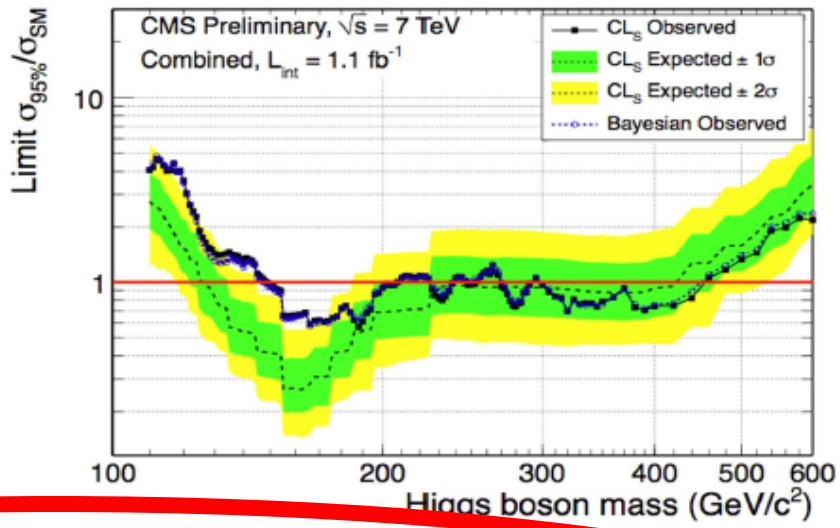
LHC/CMS: Higgs Search

SM Higgs exclusion limits

Expected exclusion: 127-420 GeV
Observed exclusion: 149-206 GeV + 300-440 GeV + parts in between



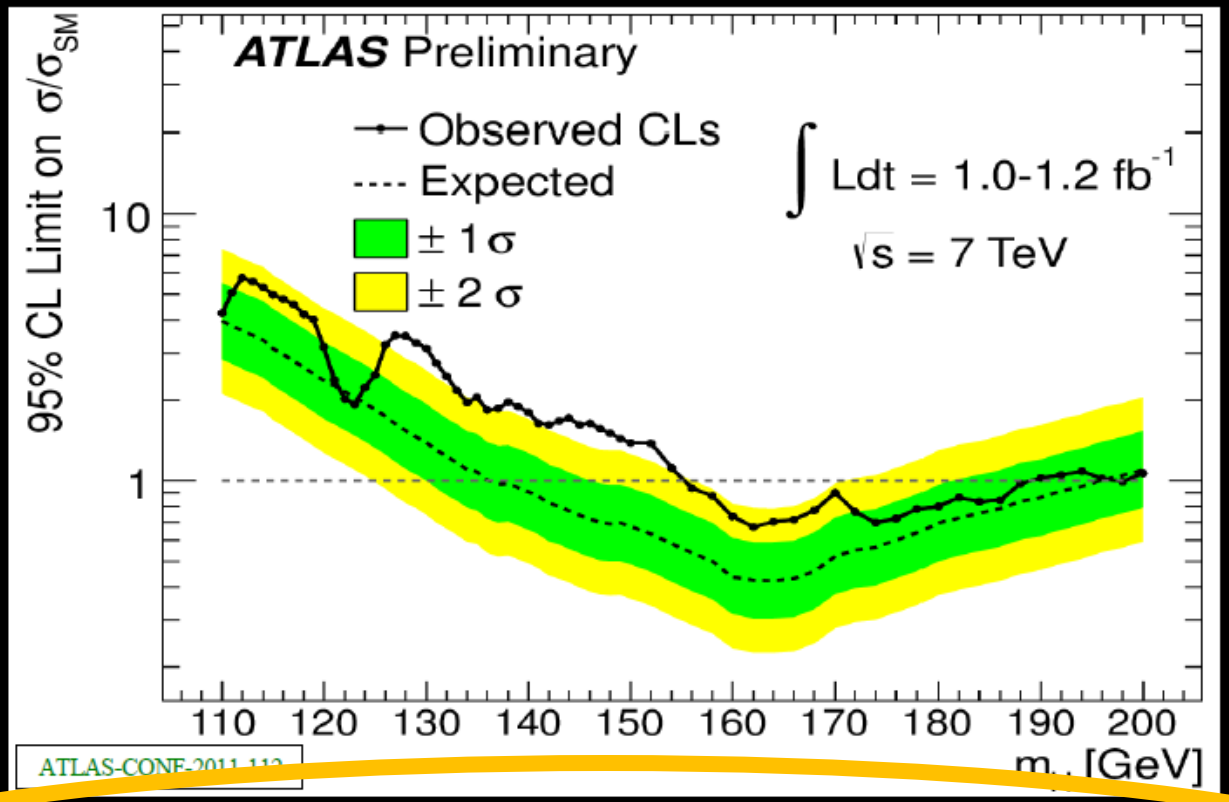
CMS PAS-HIG-11-011



In the low mass part (114-149 GeV) we see a couple of interesting regions showing excesses larger than 3σ (local significance without correction for LEE effects). Further study with the new data we are collecting will hopefully tell us if we are seing a background fluctuation or a first sign of the Higgs boson.

LHC/ATLAS: Higgs Searches

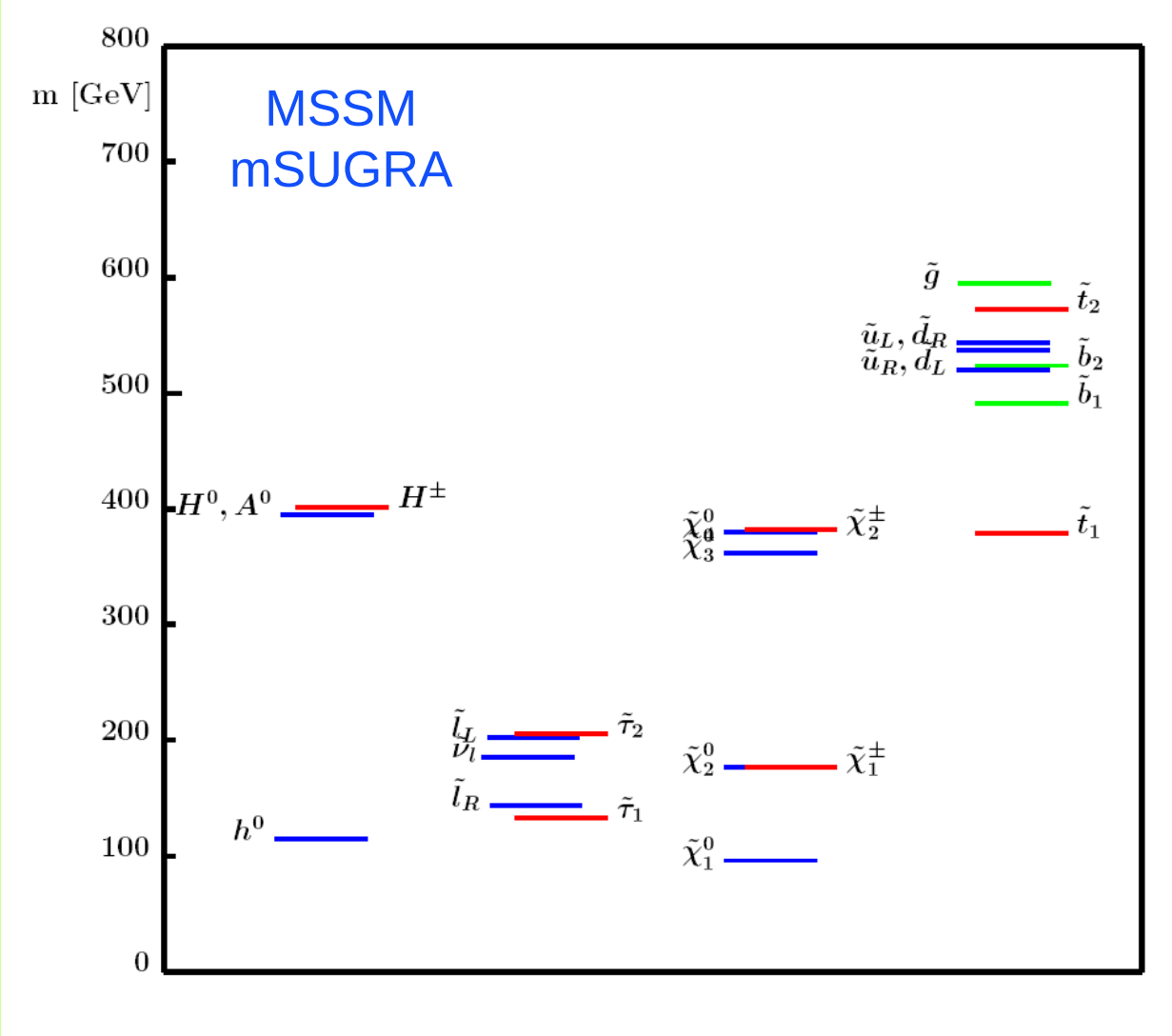
The Low Mass Region Is there more to say yet?



Limit on σ/σ_{SM} from data is generally rather poorer than median expectation if no Higgs

Is it a fluctuation, or a background, or something else?

Spectrum of Supersymmetric Particles

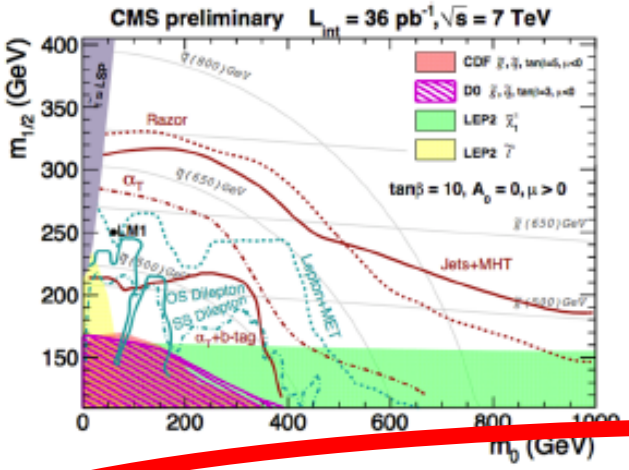


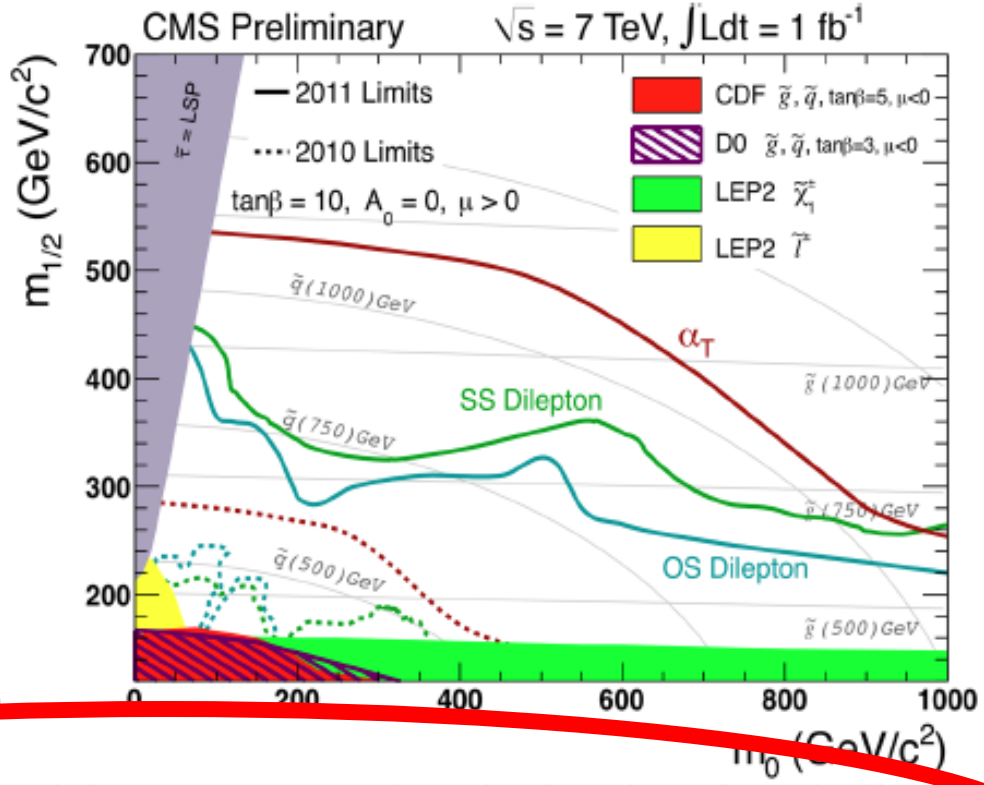
squarks and sgluons heavy yielding long decay chains ending with LSP neutrilino

LHC/CMS Supersymmetric Particles

Progress on SUSY

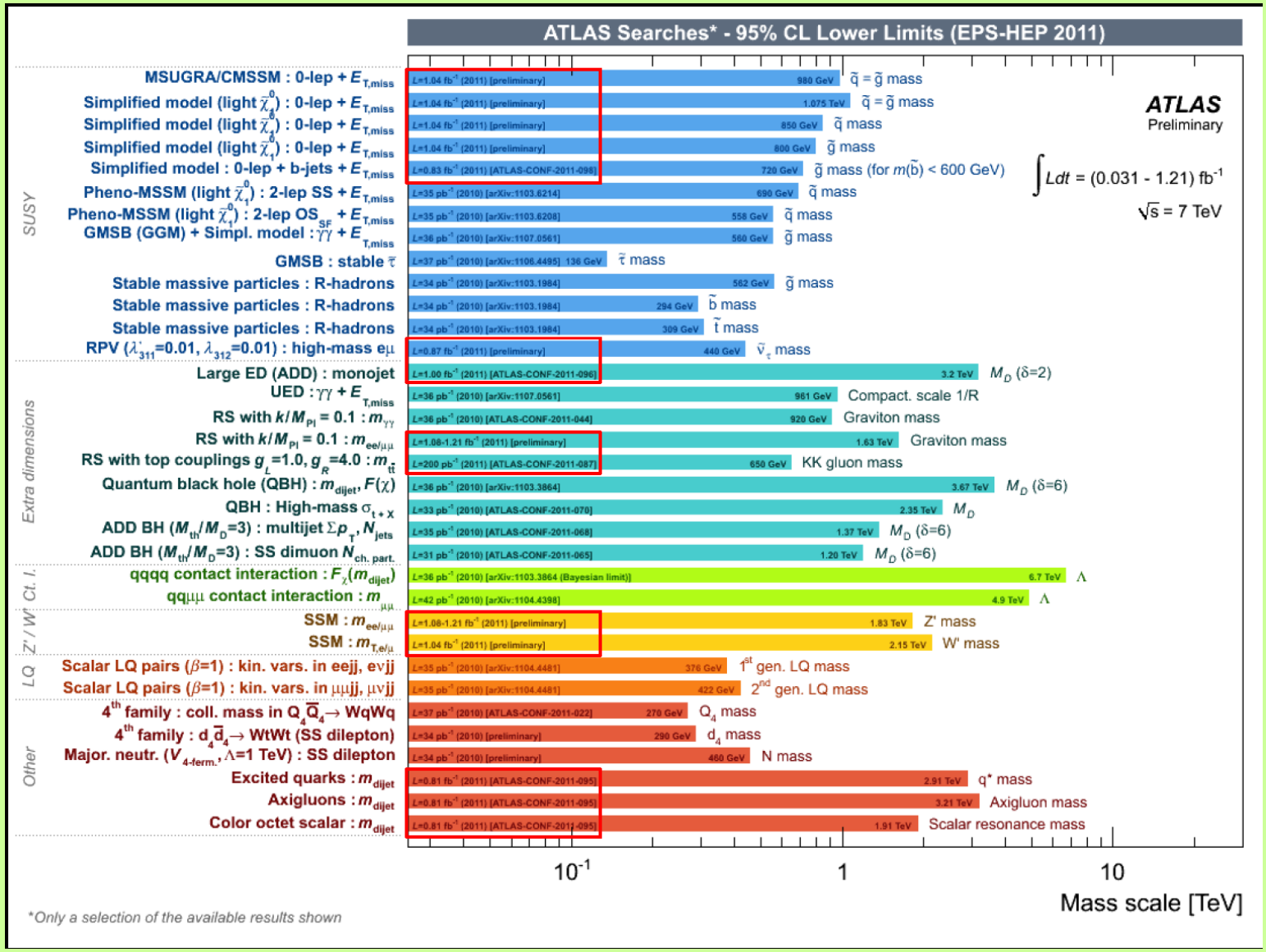
Results of the first three SUSY analyses completed on 2011 data (α_T , Same Sign and Opposite Sign dileptons).





Within the constrained SSM models we are crossing the border of excluding gluinos and squarks up to 1TeV and beyond. The air is getting thin for constrained SUSY. More conclusive results after summer.

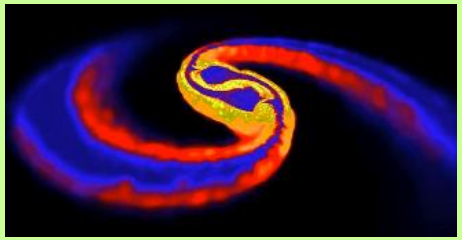
LHC/ATLAS Supersymmetric Particles



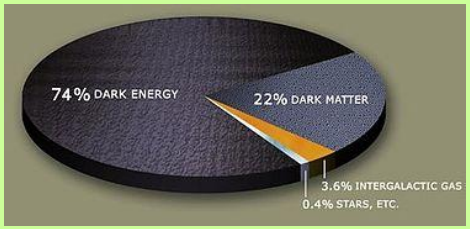
more Experimental Probes

- **Precision Physics**
  - » SuperB factories
  - » Fermilab: g-2; μ → e; etc.

- **Gravity**
  - » Gravitational waves; quantum gravity



- **Dark Energy**
  - » Space mission (Europe)



- **New Generations of Accelerators**
  - » Plasma/laser wakefield acceleration

Addressing the Questions

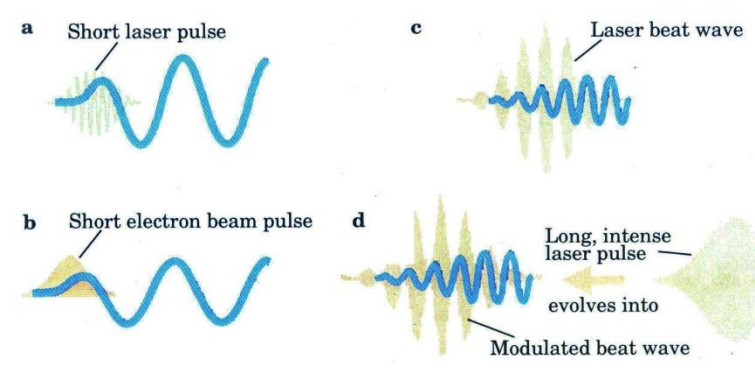
- New Generations of Accelerators
  - » Plasma/laser wakefield acceleration

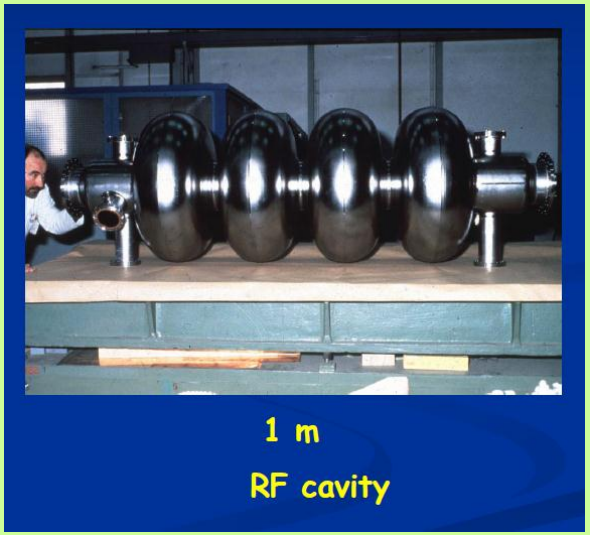
Future of Accelerator Based Particle Physics?

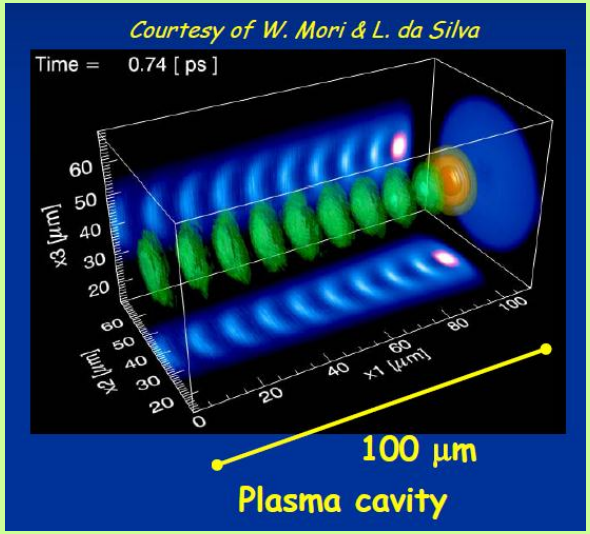
Future of Accelerators (eliminate materials!)

Plasma/Laser

Wakefield Acceleration



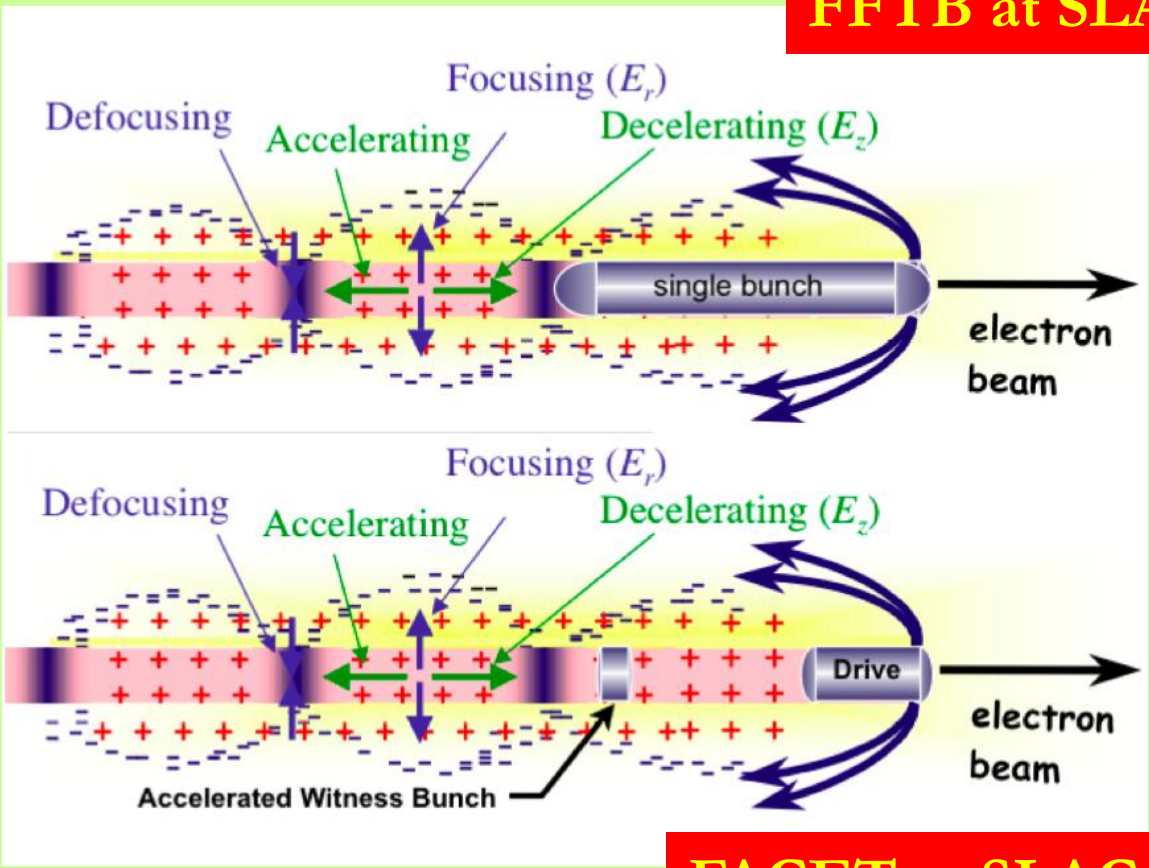


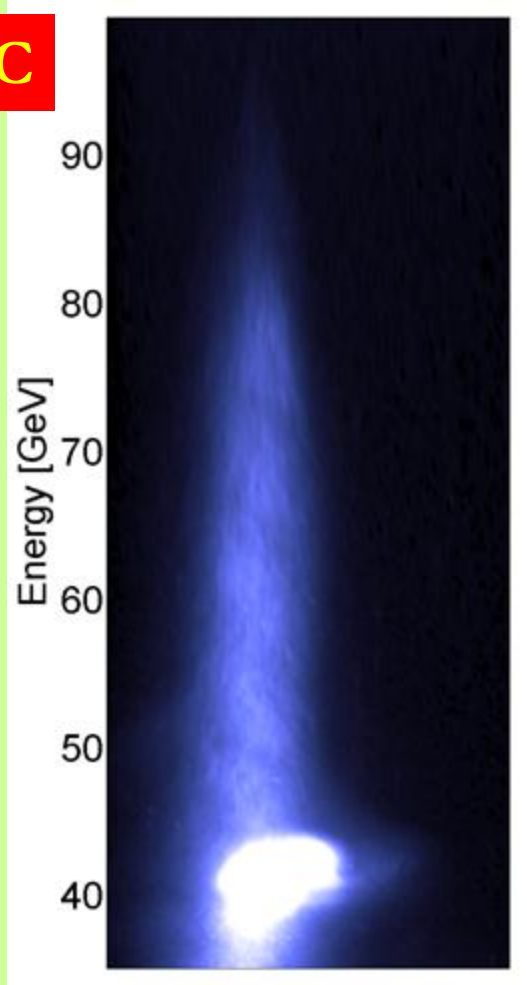


Compact Acceleration

50 GeV/meter has been achieved

FFTB at SLAC

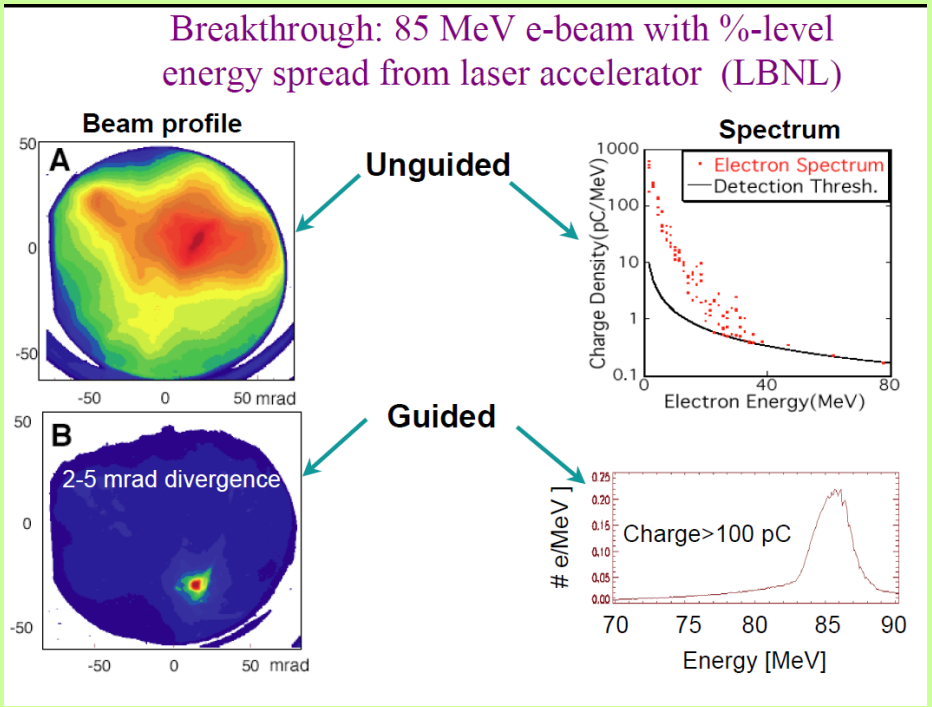




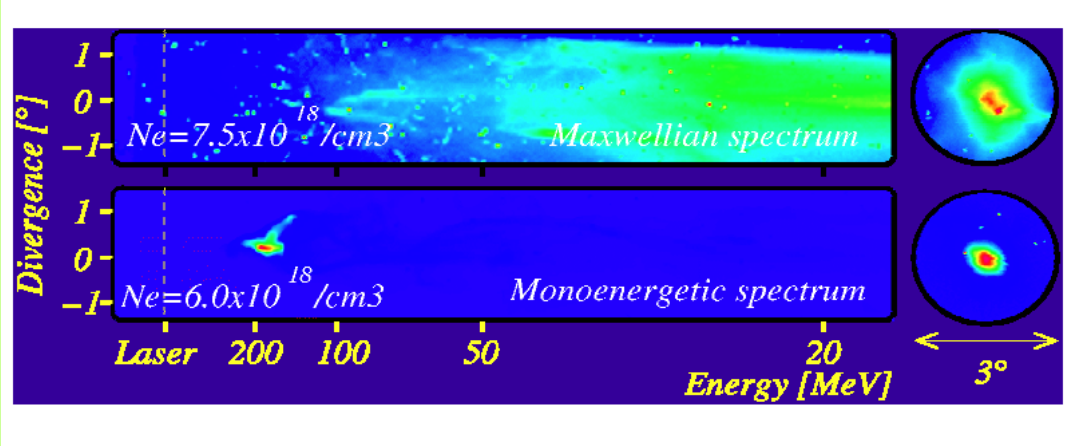
FACET at SLAC

Controlling the beams

LBNL



Reducing energy spread to ~ percent level



Reducing angular divergence (< 1 degree)

Advanced Accelerator R&D projects

FACET

Location
SLAC National Accelerator Laboratory

Creates electron wake using an electron beam in a plasma

Based on previous experiments that doubled the energies of a few electrons—from 42 billion to 85 billion electron volts—in 84 centimeters

Stimulus funds
$14.5 million

Next step/midterm goal:
is to create tighter electron bunches and accelerate them from 23 billion to 46 billion electronvolts in 40 centimeters

BELLA

Location
Lawrence Berkeley National Laboratory

Creates electron wake using a laser beam in a plasma

Based on previous experiments that accelerated tightly packed electron bunches—the kind needed for physics experiments—from zero to 1 billion electron volts in 3 centimeters

Stimulus funds
$20 million

Next step/midterm goal:
is to accelerate already-tight electron bunches to higher energies, from zero to 10 billion electronvolts in 80 centimeters

Lots of fundamental questions

1. How can we solve the mystery of dark energy?
2. Are there extra dimensions of space?
3. Do all the forces become one?
4. Why are there so many kinds of particles?
5. What is dark matter?

   How can we make it in the laboratory?

6. What are neutrinos telling us?
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9. Are there undiscovered principles of nature:

   New symmetries, new physical laws?

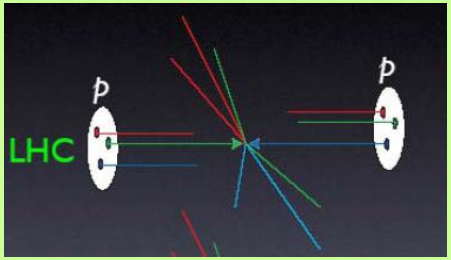
from the Quantum Universe

Many Opportunities

- Neutrinos
  - » Particle physics and astrophysics using a weakly interacting probe

- Particle Astrophysics/Cosmology
  - » Dark Matter; Cosmic Microwave, etc

- High Energy pp Colliders
  - » Opening up a new energy frontier (~ 1 TeV scale)

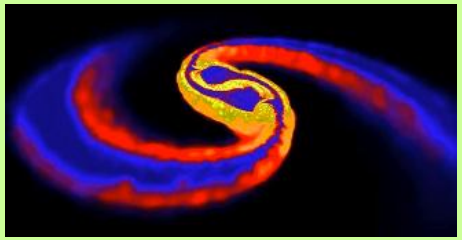


- High Energy Lepton Colliders
  - » Precision Physics at the new energy frontier

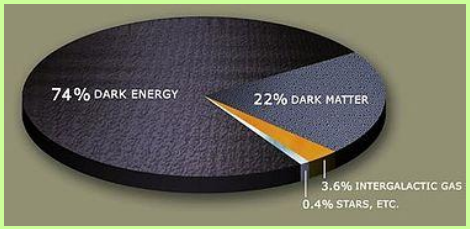
and more Opportunities

- **Precision Physics**
  - » SuperB factories
  - » Fermilab: g-2; μ → e; etc.

- **Gravity**
  - » Gravitational waves; quantum gravity

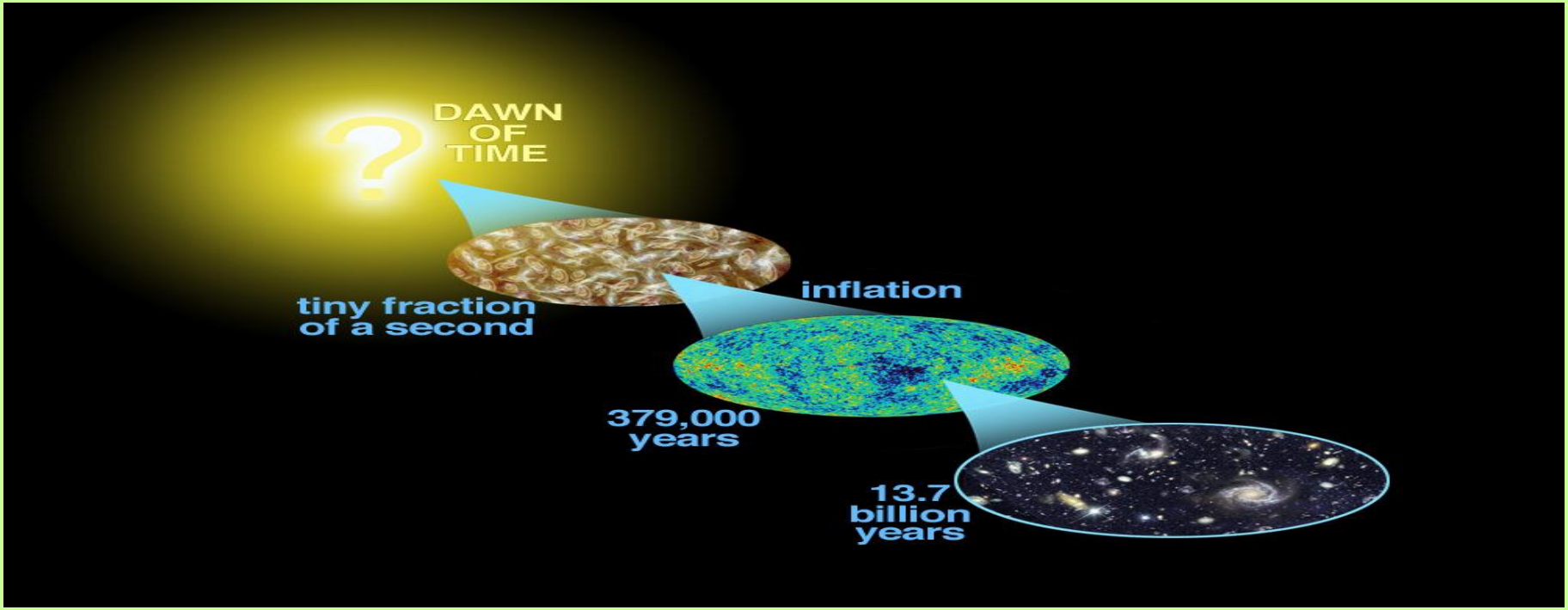


- **Dark Matter, Dark Energy**
  - » Accelerators; underground; space missions



- **New Generations of Accelerators**
  - » Plasma/laser wakefield acceleration

What will we discover by DPF2021 or DPF 2031 ??



"There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy"

(Hamlet, I.5)