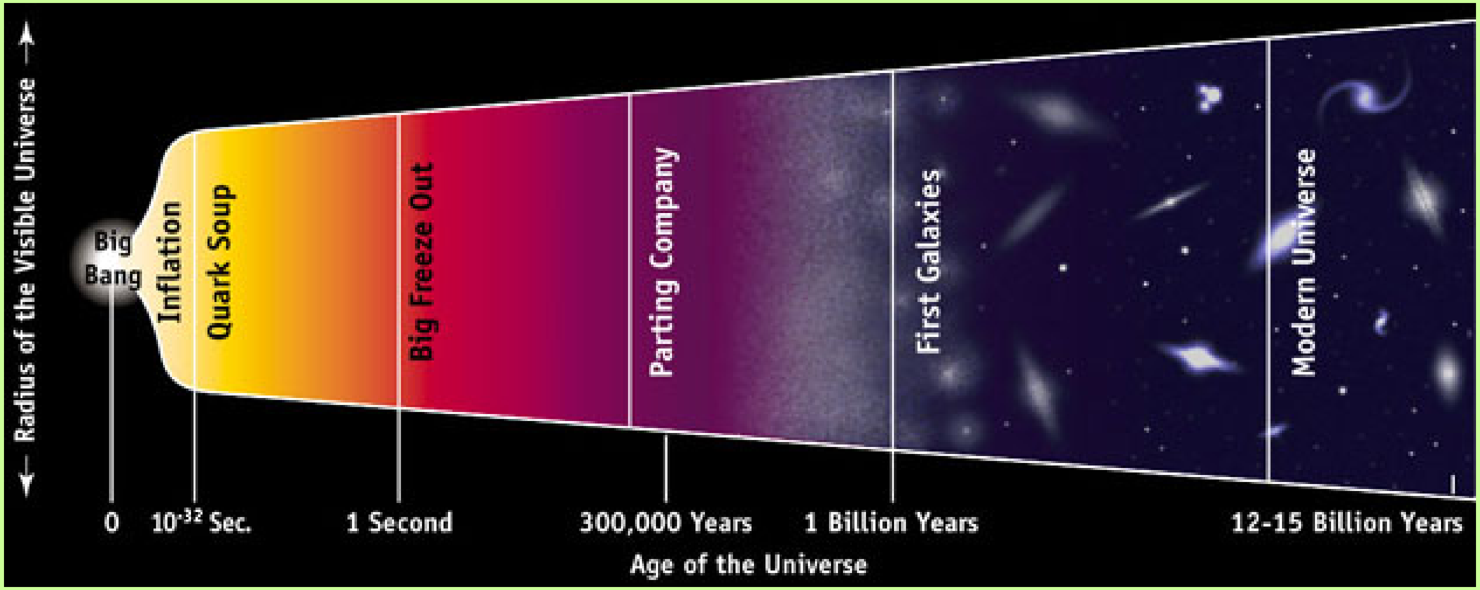
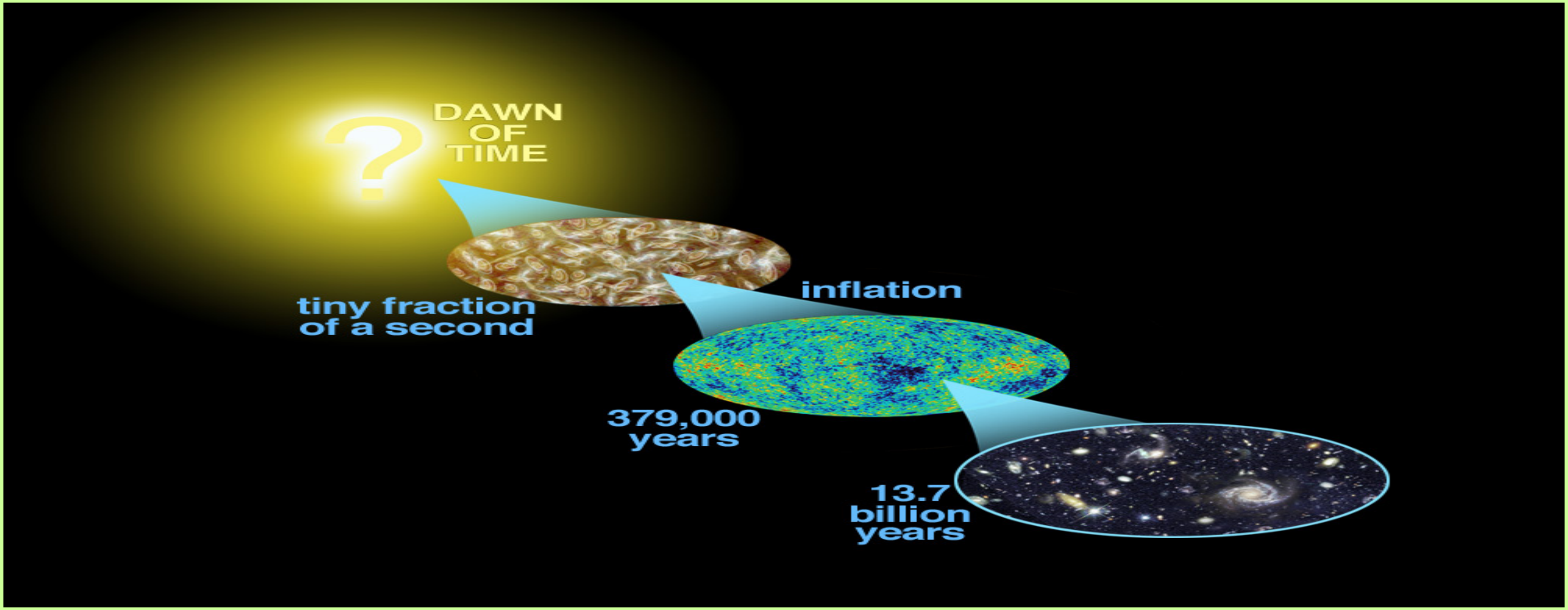
New Frontiers in Particle Physics



Barry Barish
Caltech

AAAS Annual Meeting 22-Feb-2010

The Nature of Particle Physics



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

(Hamlet, I.5)

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?**

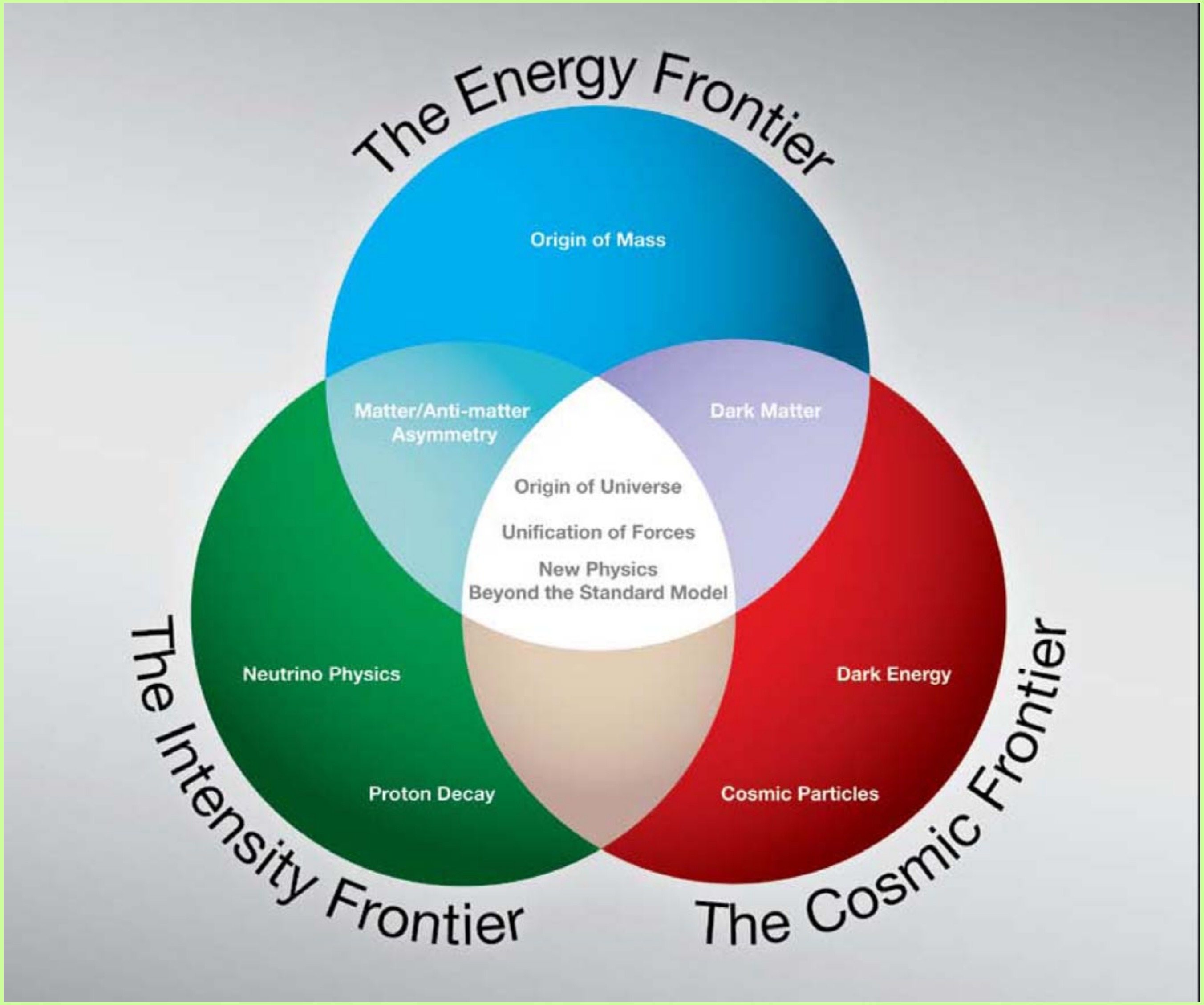
    How can we make it in the laboratory?

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 Frontiers of Particle Physics
(U.S. P5 Report)

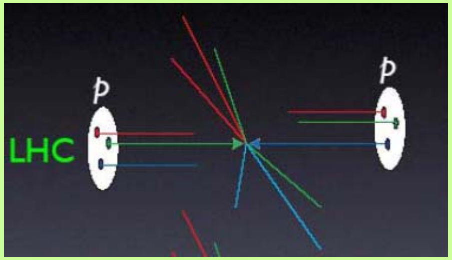


Addressing the Questions

- 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 e^+e^- Colliders
  - » Precision Physics at the new energy frontier

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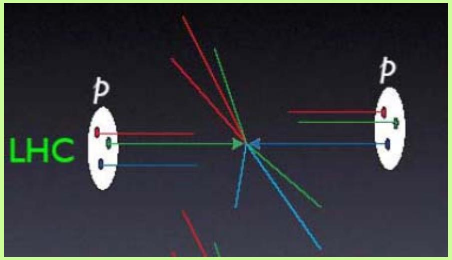

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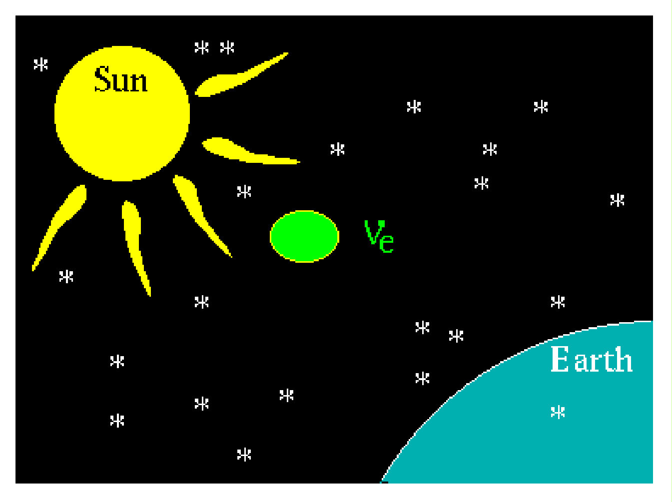
Neutrinos – Many Questions

- Why are neutrino masses so small ?
- Are the neutrinos their own antiparticles?
- What is the separation and ordering of the masses of the neutrinos?
- Neutrinos contribution to the dark matter?

- CP violation in neutrinos, leptogenesis, possible role in the early universe and in understanding the particle antiparticle asymmetry in nature?

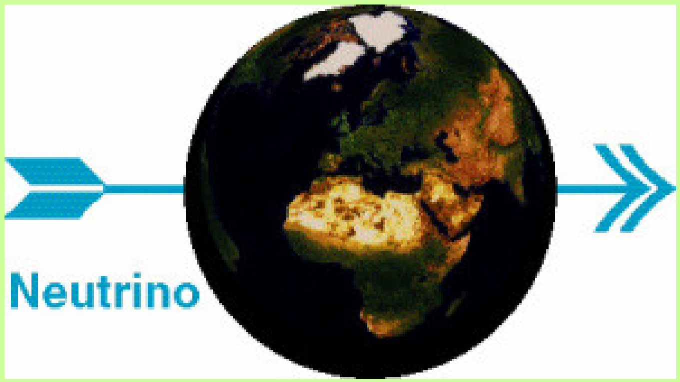
Neutrinos from the Sun

Discovery: Neutrinos coming from the Sun were detected, demonstrating the solar fusion burning process. (Davis / Koshiba Nobel Prize)



Problem: The rate of neutrinos were measured to be only about half the predicted rate. Conclusion: either the sun works differently than theory or half the neutrinos disappear on their journey to the earth.

Neutrinos from the Sun



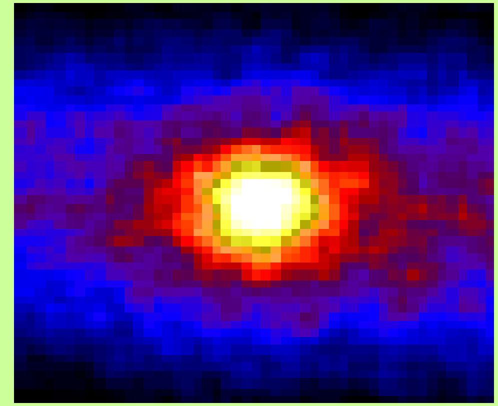
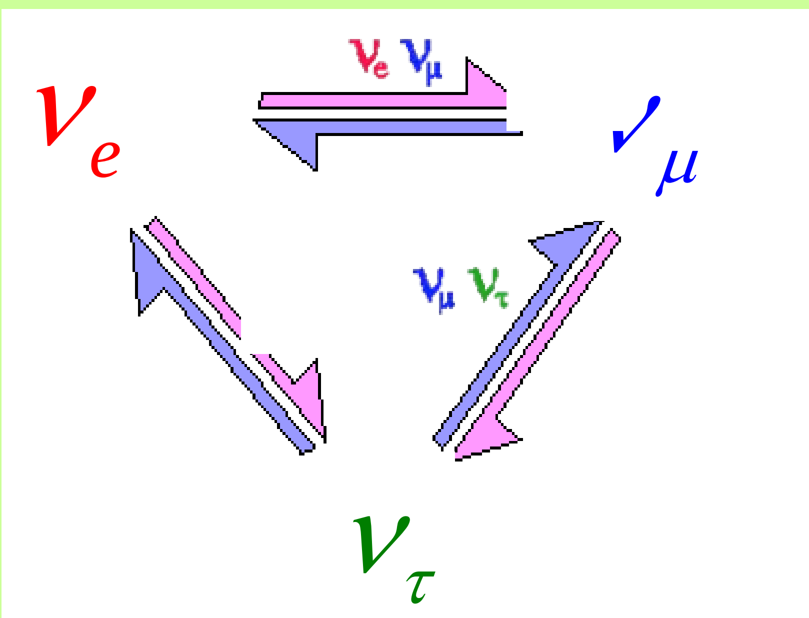
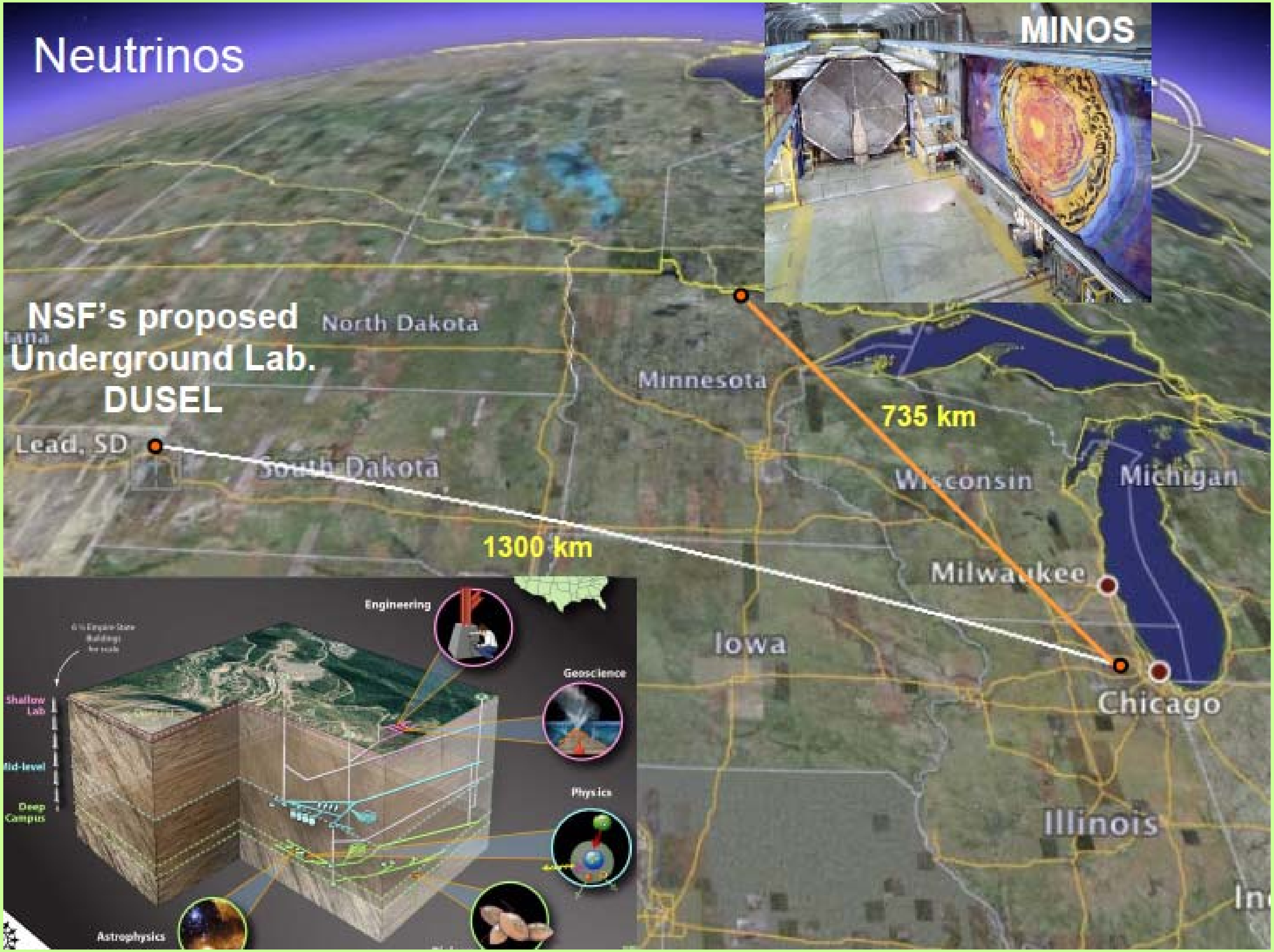


Photo of Sun
taken
underground
using neutrinos



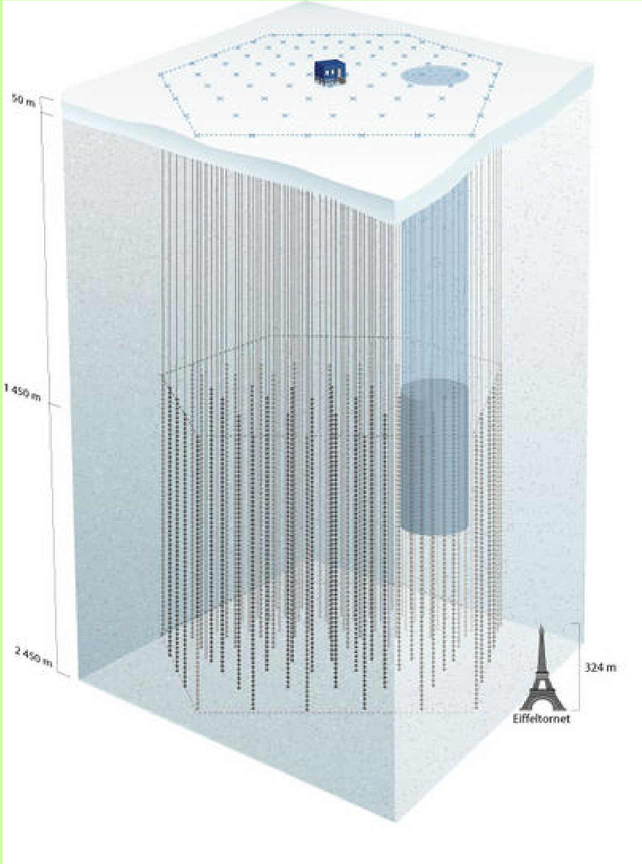
Subsequent experiments at Kamioka mine in Japan and Sudbury mine in Canada demonstrated the reduced rate was due to neutrino oscillations

Neutrino Oscillations in the Lab

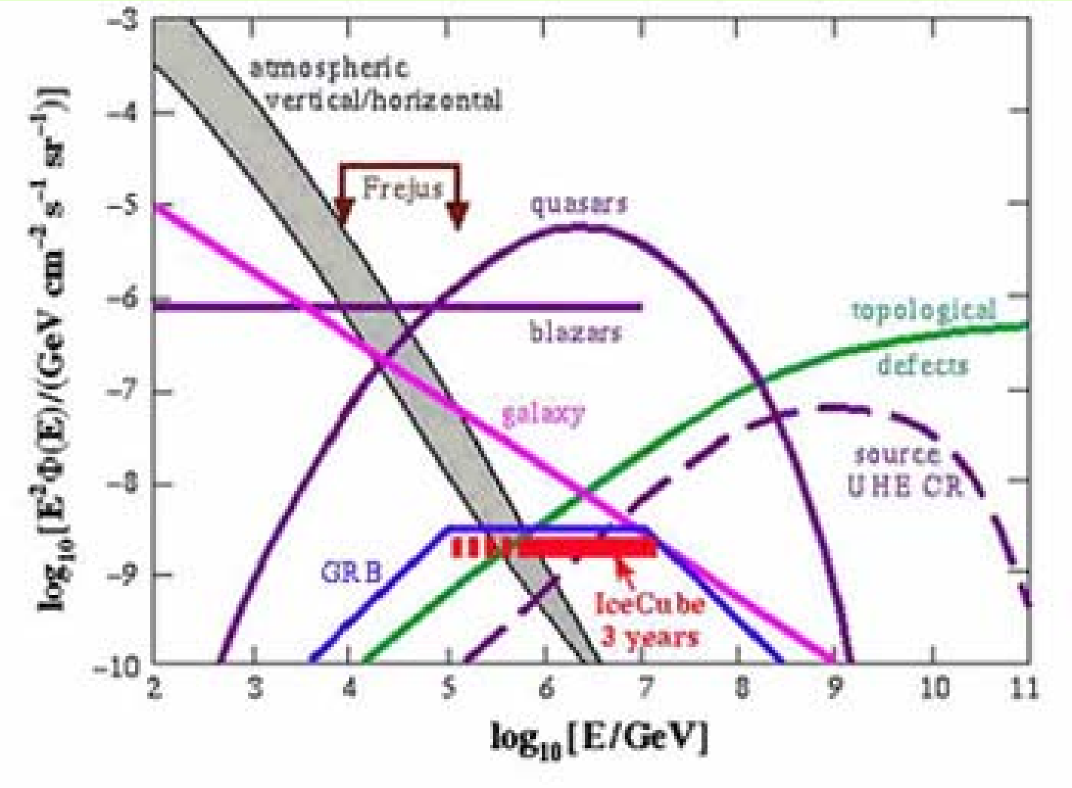


Ice Cube Project

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



South Pole



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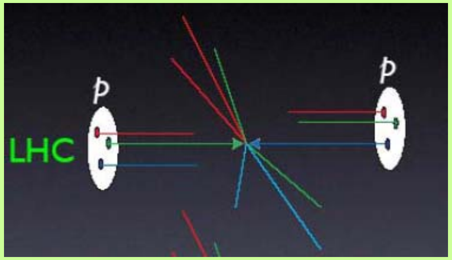

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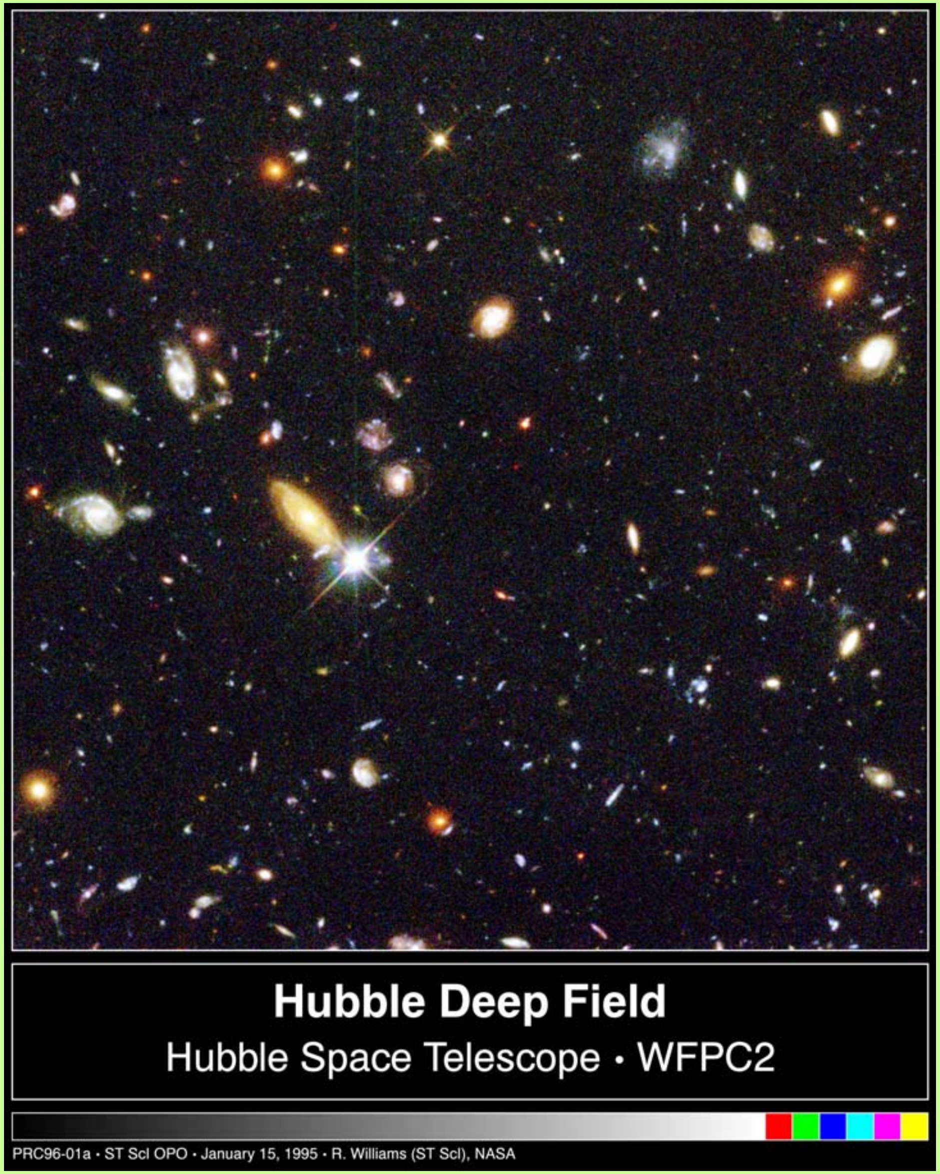
Dark Matter

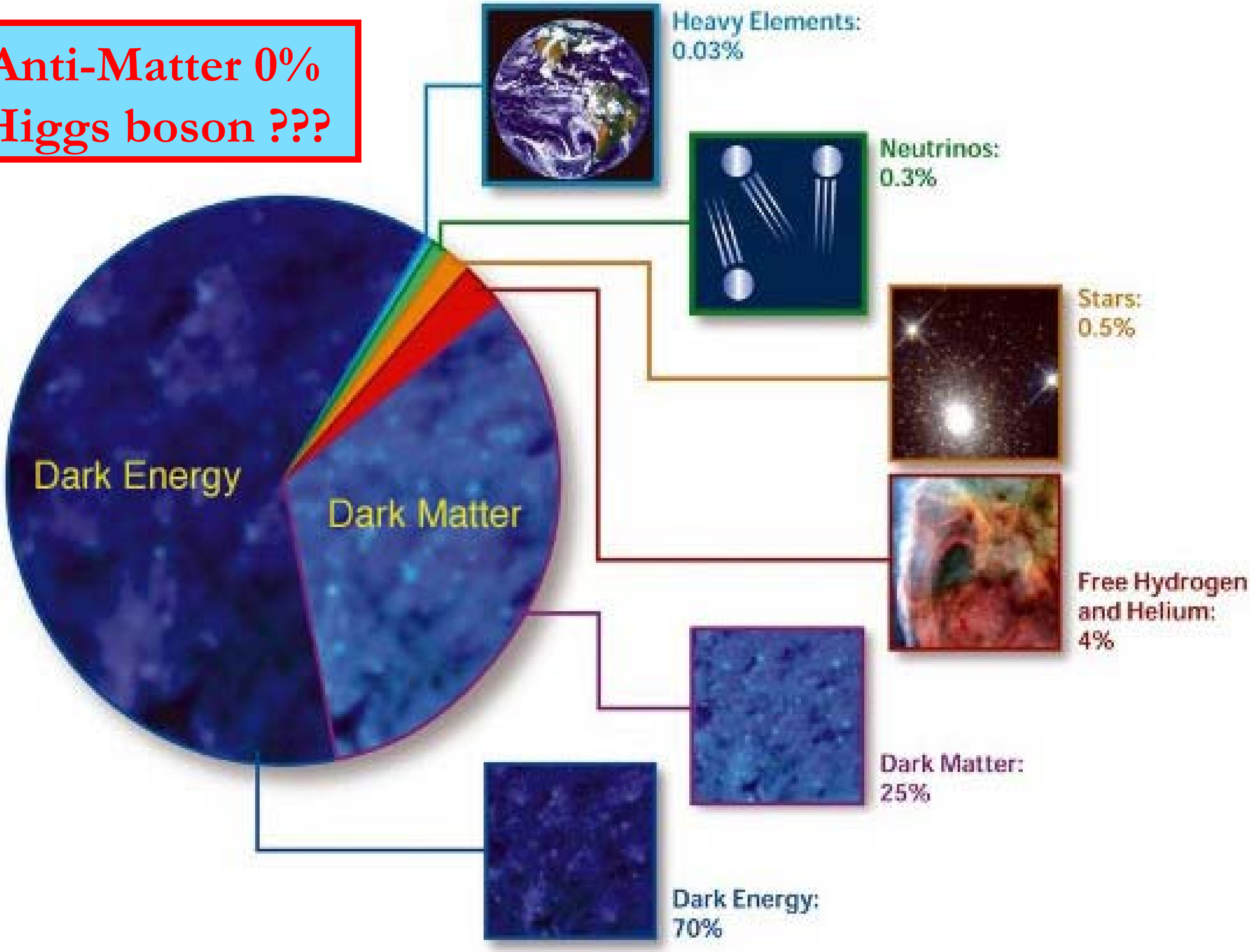


What don't we see?

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

The Energy Budget of the Universe

Anti-Matter 0%
Higgs boson ???



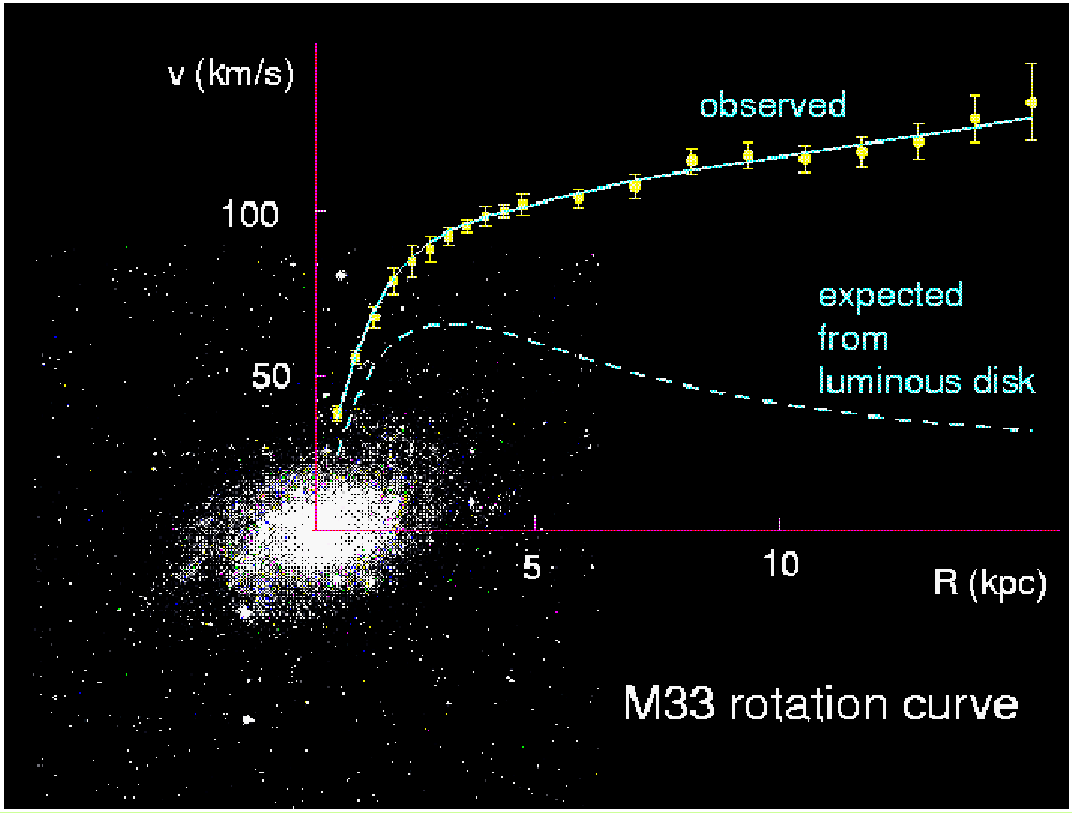
Dark Matter
the evidence

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

This is the most direct evidence for dark matter.

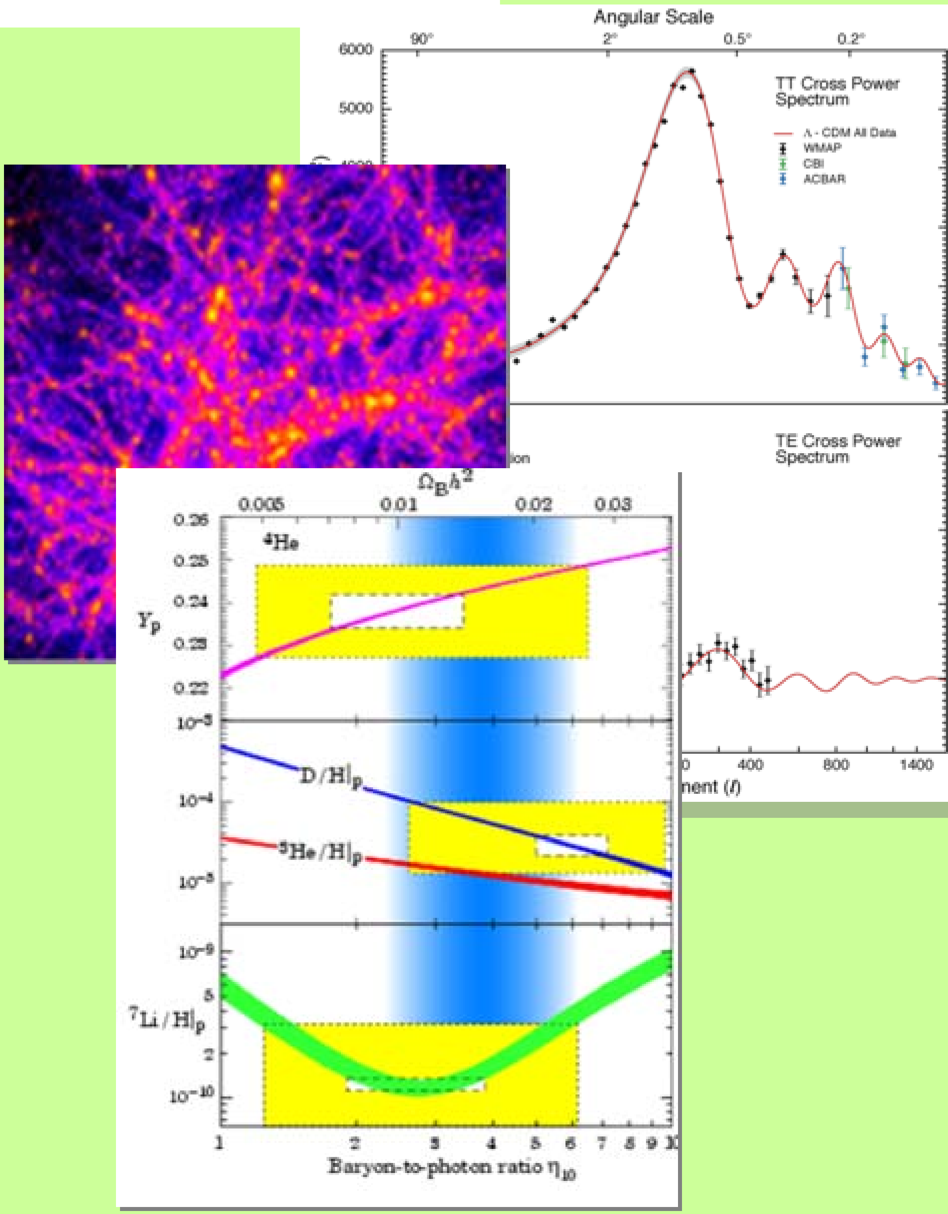
There are many complementary measurements at all scales

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

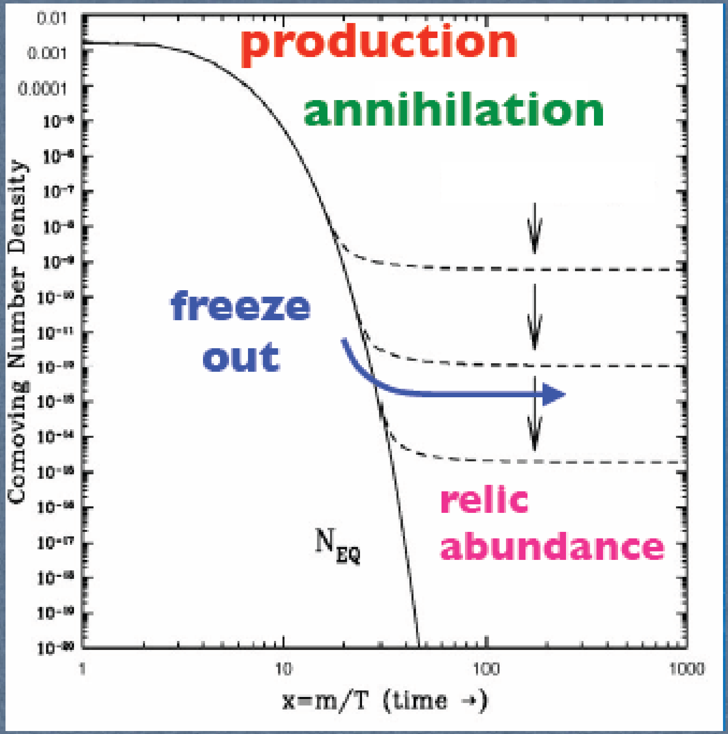
Weakly Interacting Massive Particles (WIMPs)

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."

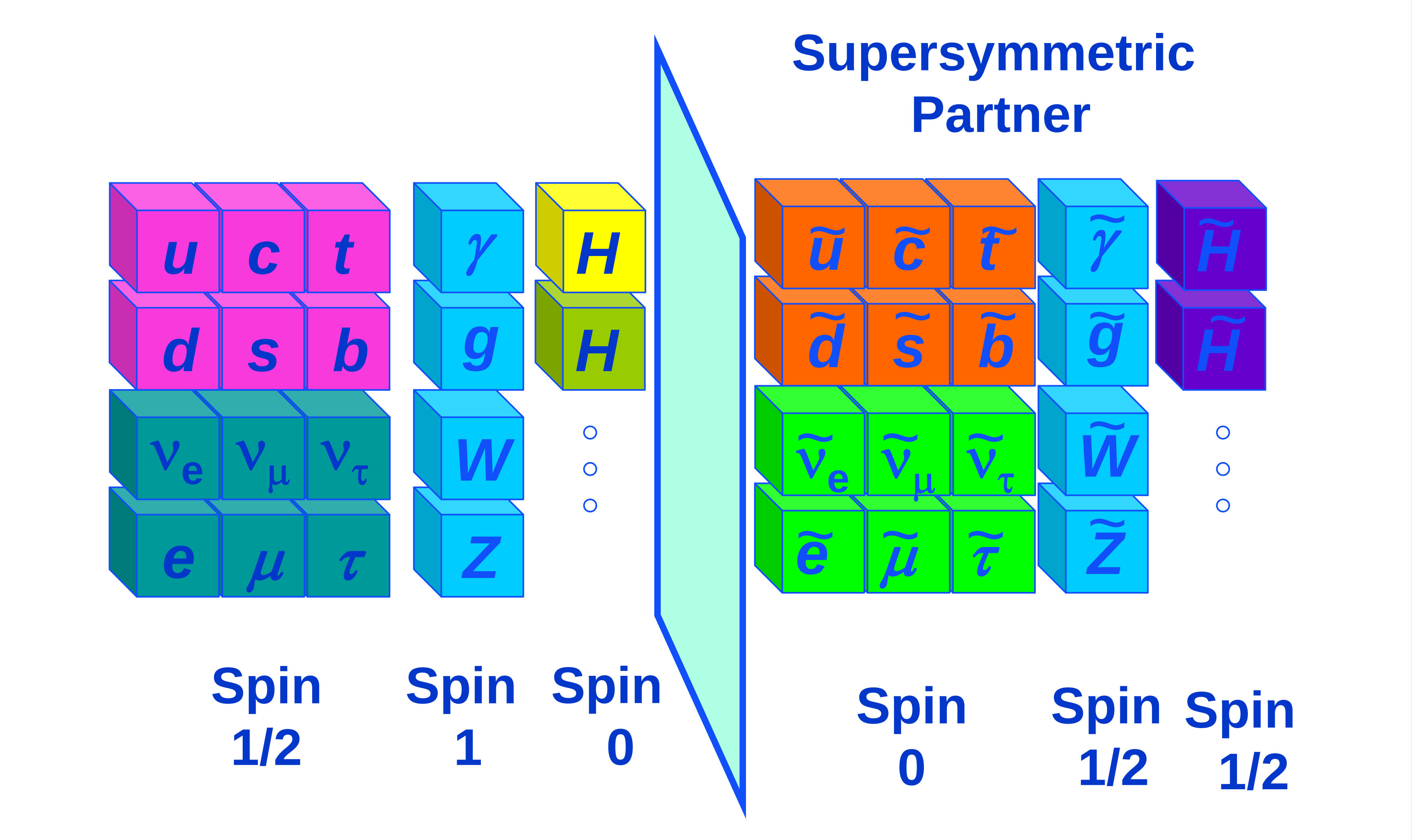
Leading candidate –
"Supersymmetric Particles"



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

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

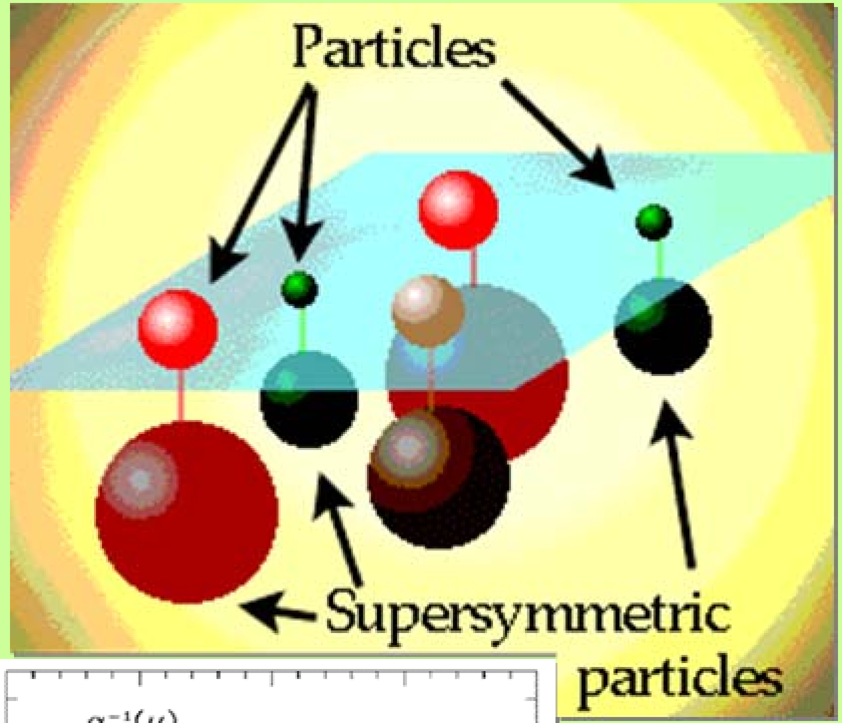
What is Supersymmetry?

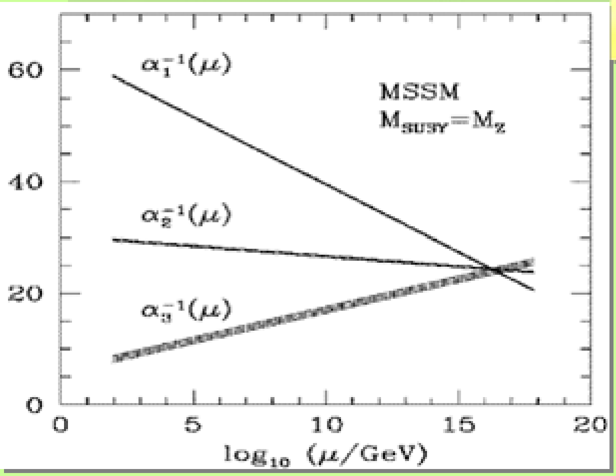


Supersymmetry

- The most theoretically appealing extension of the Standard Model
- Natural solution to hierarchy problem (stabilizes quadradic divergences to Higgs mass)
- Restores unification of couplings
- Vital ingredient of string theory
- Naturally provides a compelling candidate for dark matter

$\tilde{\gamma}$, $\tilde{Z}$, $\tilde{h}$, $\tilde{H}$



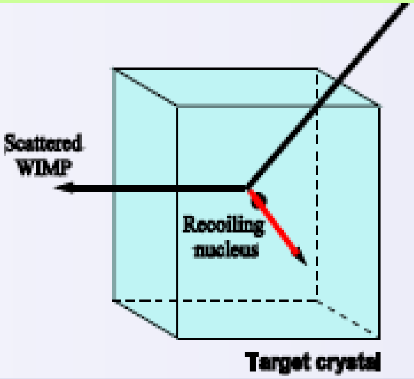


Searching for Dark Matter

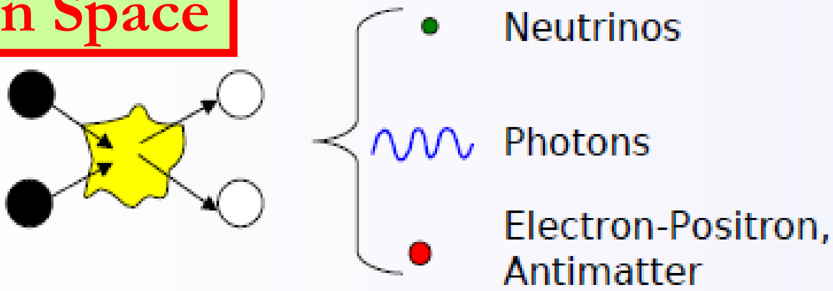
Underground

- Direct Detection:

Look for the elastic scattering of dark matter with nuclei



In Space

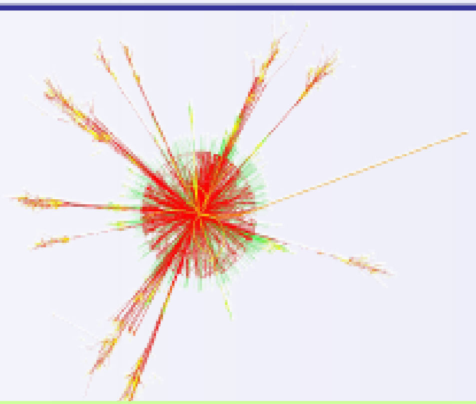


- Indirect Detection:

Look for the annihilation products

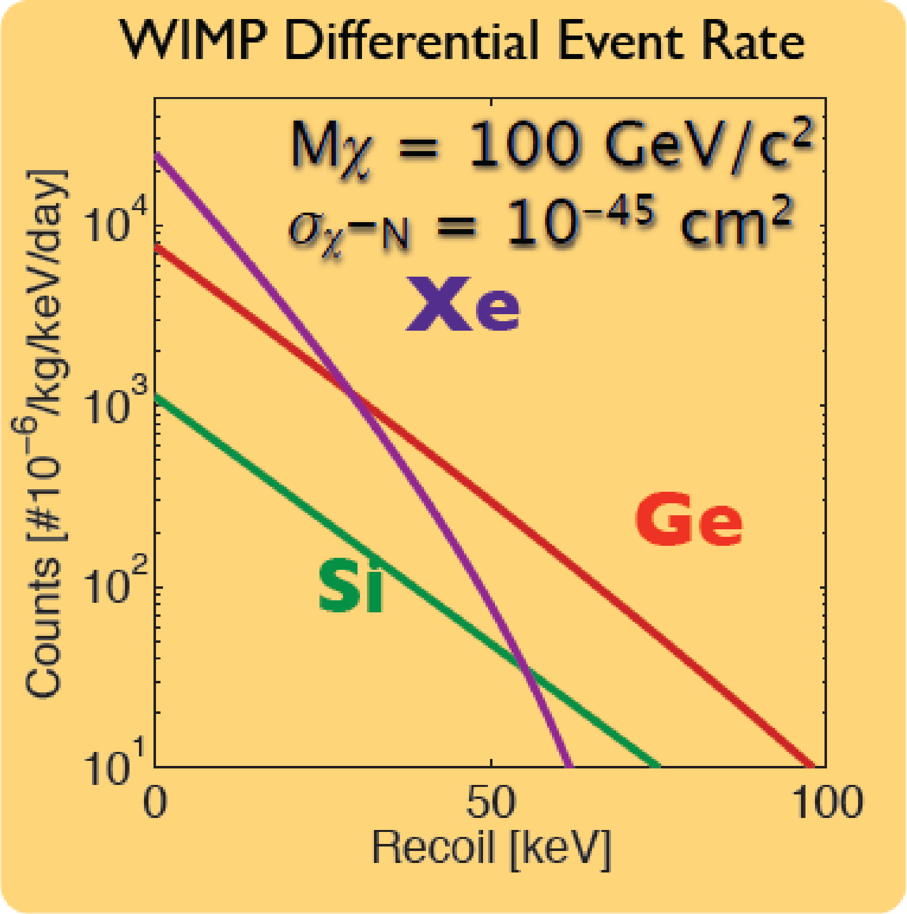
On Accelerators

Look for signals of new physics

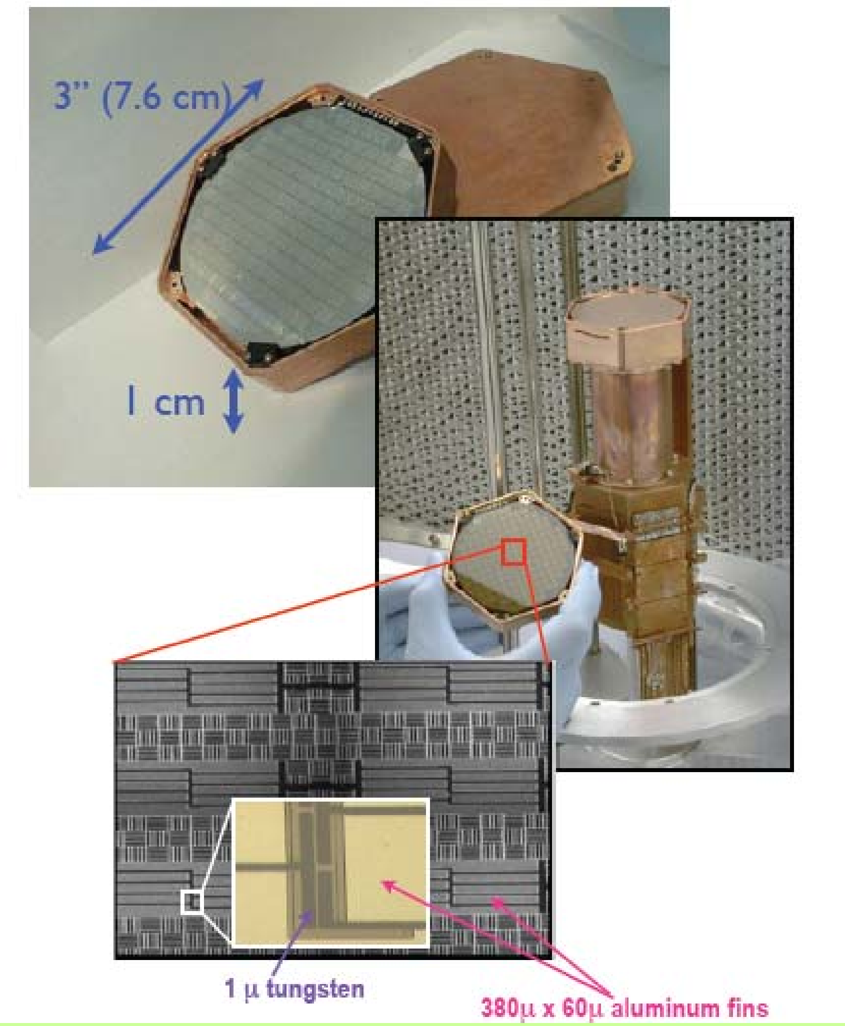


Direct Detection of Relic WIMPS

- Elastic scattering of a WIMP deposits small amounts of energy into recoiling nucleus (~ few 10s of keV)
- Featureless exponential spectrum
- **Expected rate: < 0.01/kg-d**
- Radioactive background of most materials higher than this rate.



The "Cryogenic Dark Matter Search" (CDMS)



The CDMS experiments measures the recoil energy imparted to detector nuclei through WIMP-nucleon collisions by employing sensitive phonon detection equipment coupled to arrays of cryogenic germanium and silicon crystals.

WIMP Direct Searches

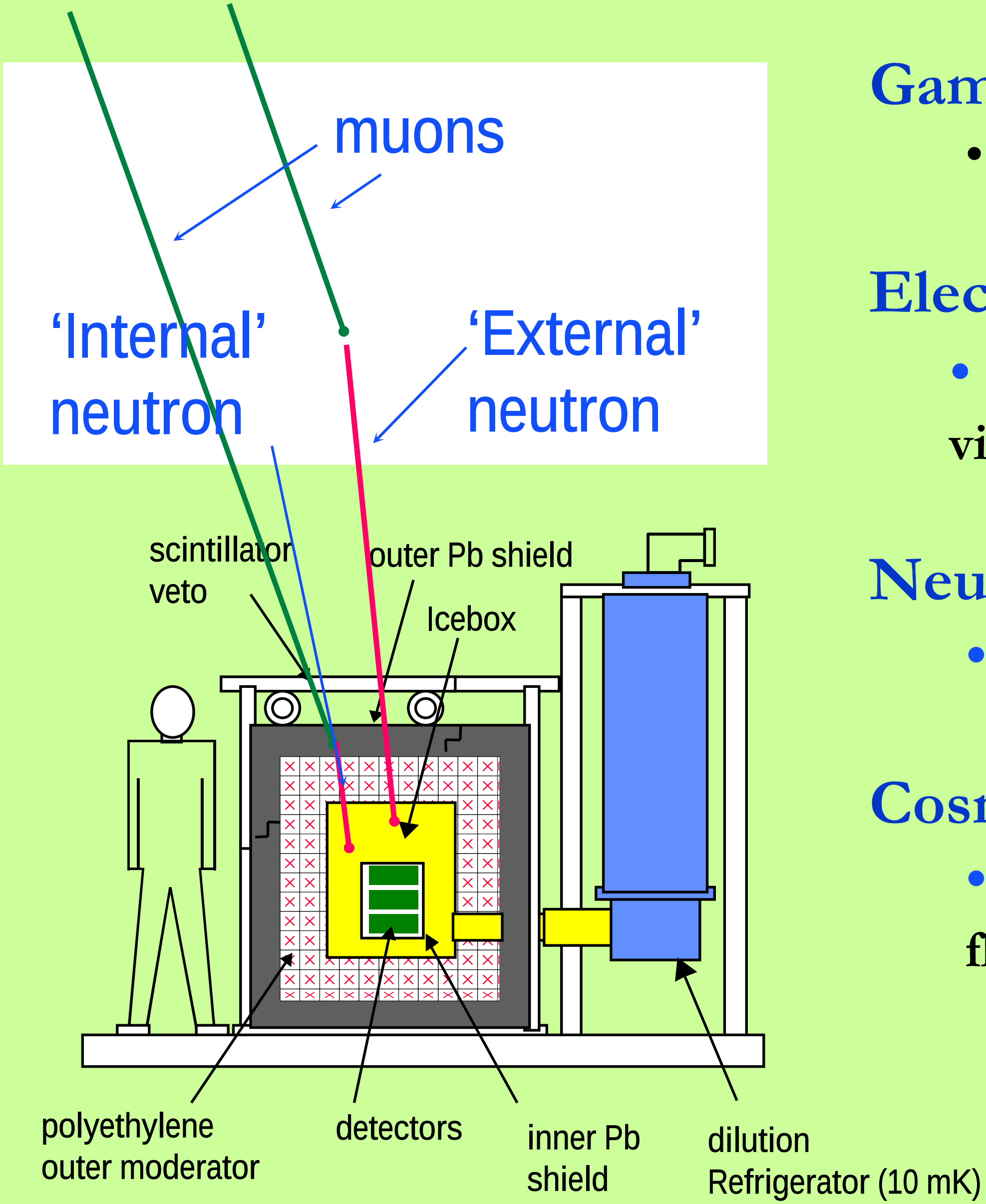
- Located at the Soudan mine in sunny Minnesota
- CDMS II is 2341 feet below the surface (2090 mwe)

CDMS

Cryogenic

Dark Matter Search

Sources of Background



Gammas / X-Rays

- Reject using additional shielding

Electrons

- Produced in the detector – rejected via analysis

Neutrons

- Reject by additonal scintillator veto

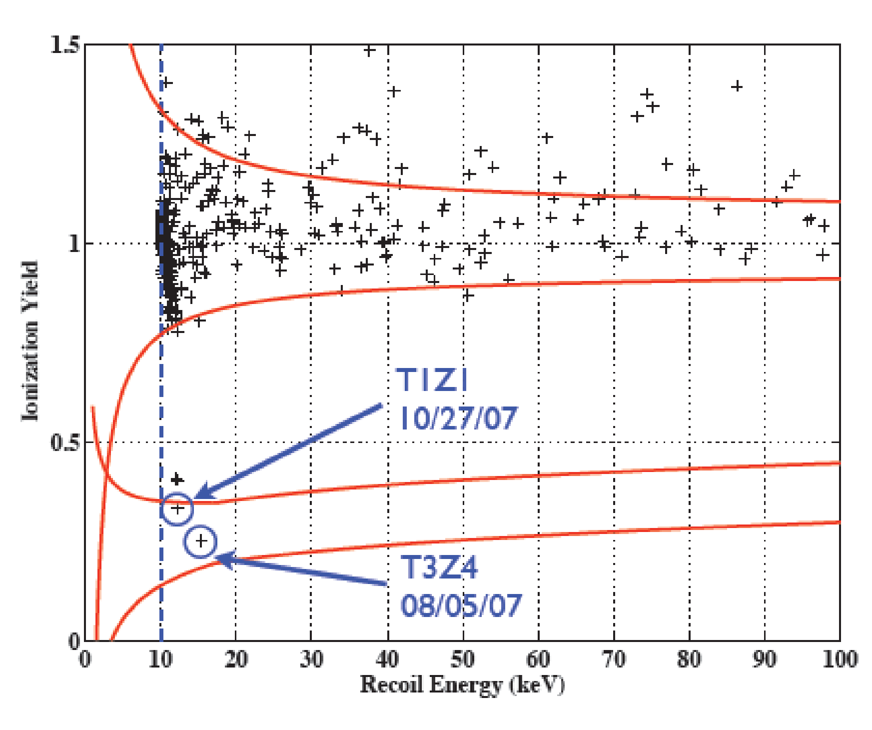
Cosmic Ray Muons

- Depth (2090mwe) reduces muon flux by a factor of ~50,000

Recent CDMS Result

"The final exposure of our low-temperature Ge particle detectors at the Soudan Underground Laboratory yielded two candidate events, with an expected background of 0.9 ± 0.2 events."

"The combined CDMS II data place the strongest constraints on the WIMP-nucleon spin-independent scattering cross section for a wide range of WIMP masses and exclude new parameter space in inelastic dark matter models."



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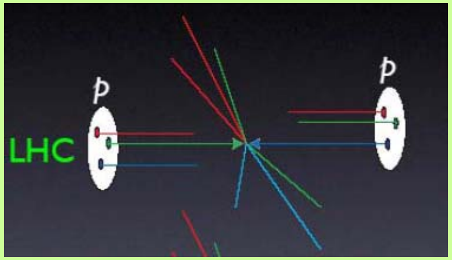

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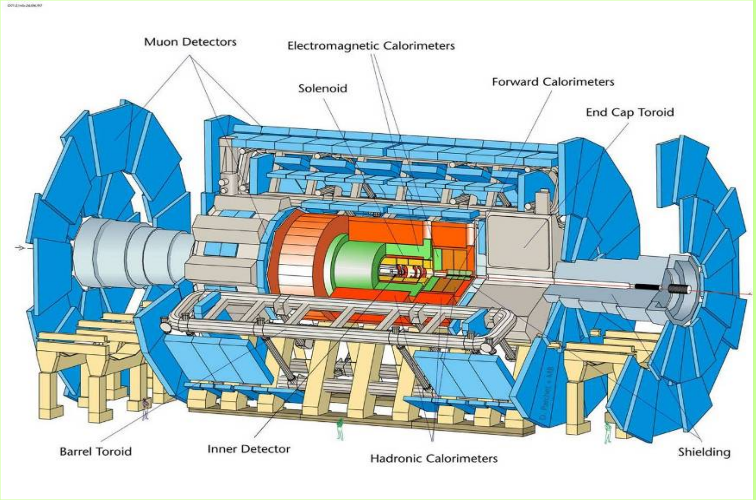
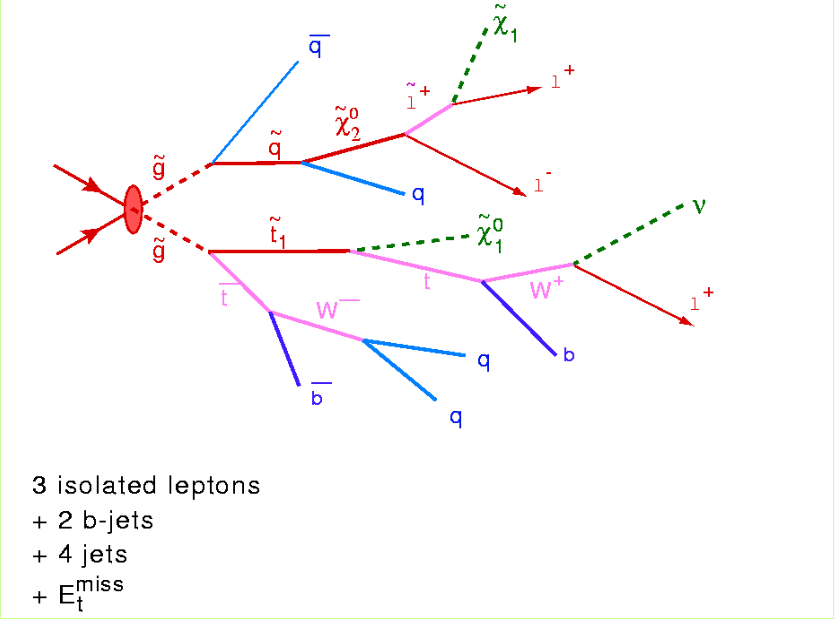
  - » Precision Physics at the new energy frontier

Megascience project --- LHC

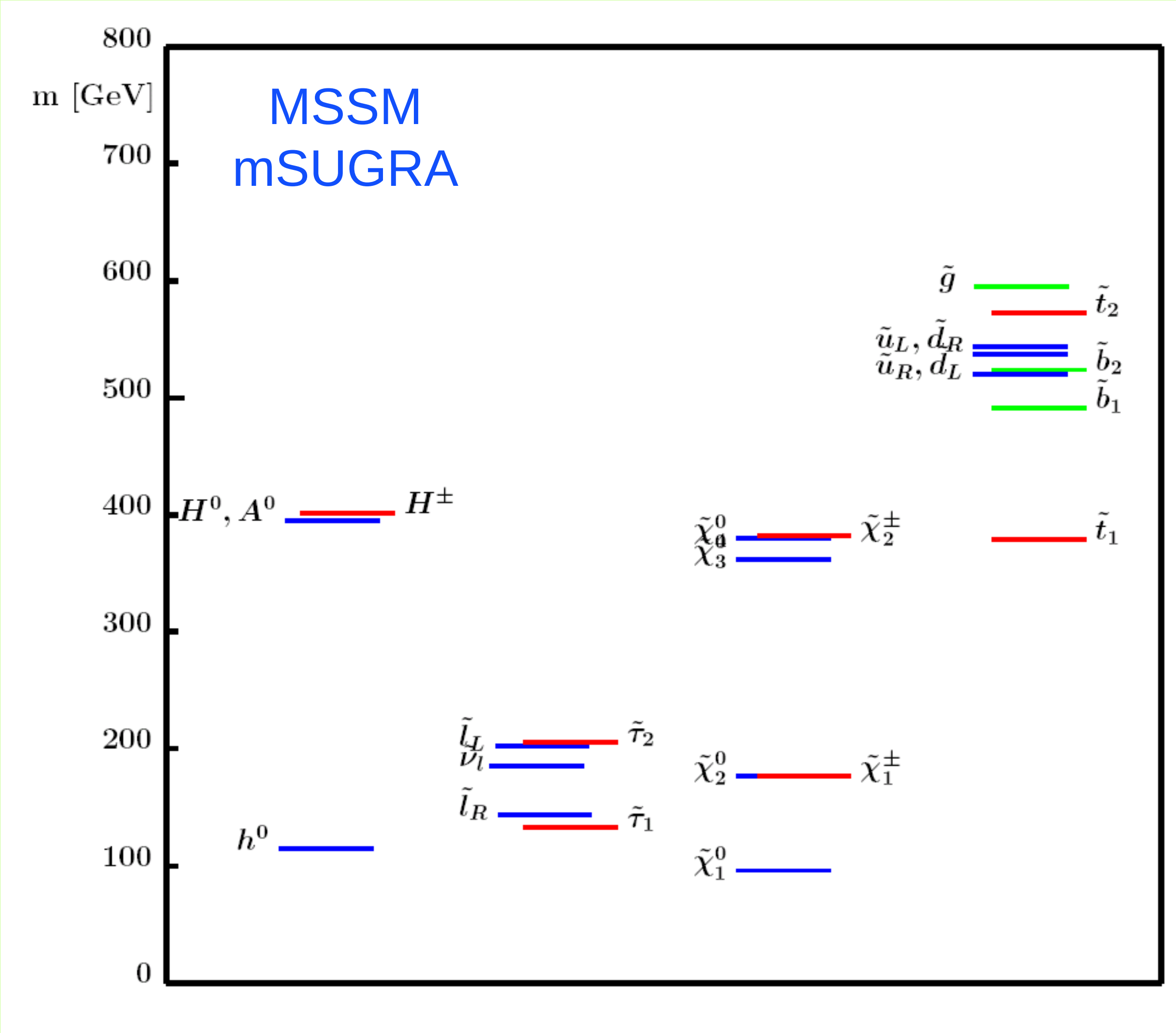




Exploring the Terascale
the tools

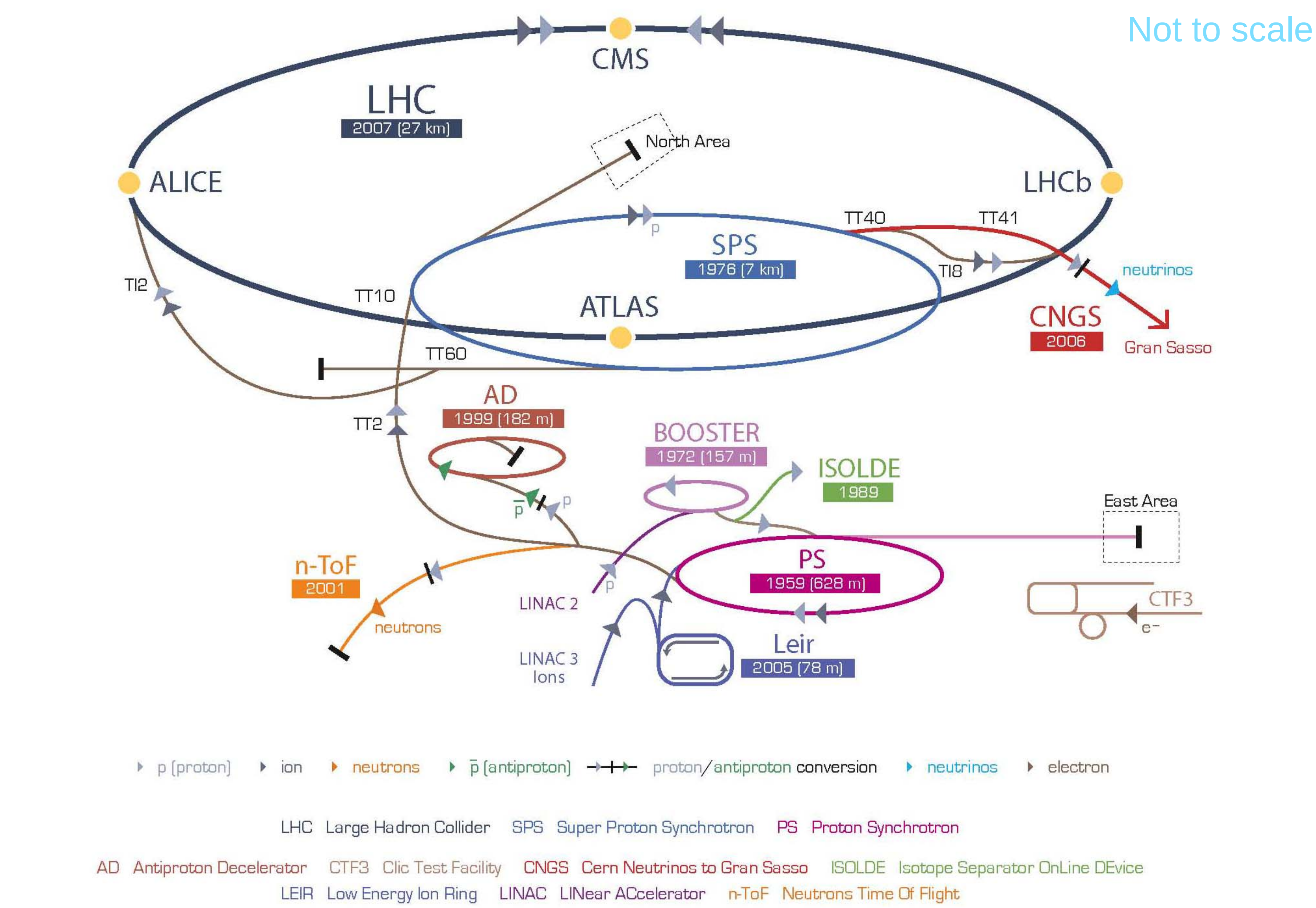
- **The LHC**
  - » It will lead the way and has large reach
  - » Quark-quark, quark-gluon and gluon-gluon collisions at 0.5 - 5 TeV
  - » Broadband initial state
- **The ILC**
  - » A second view with high precision
  - » Electron-positron collisions with fixed energies, adjustable between 0.1 and 1.0 TeV
  - » Well defined initial state
- **Together, these are our tools for the terascale**

Spectrum of Supersymmetric Particles

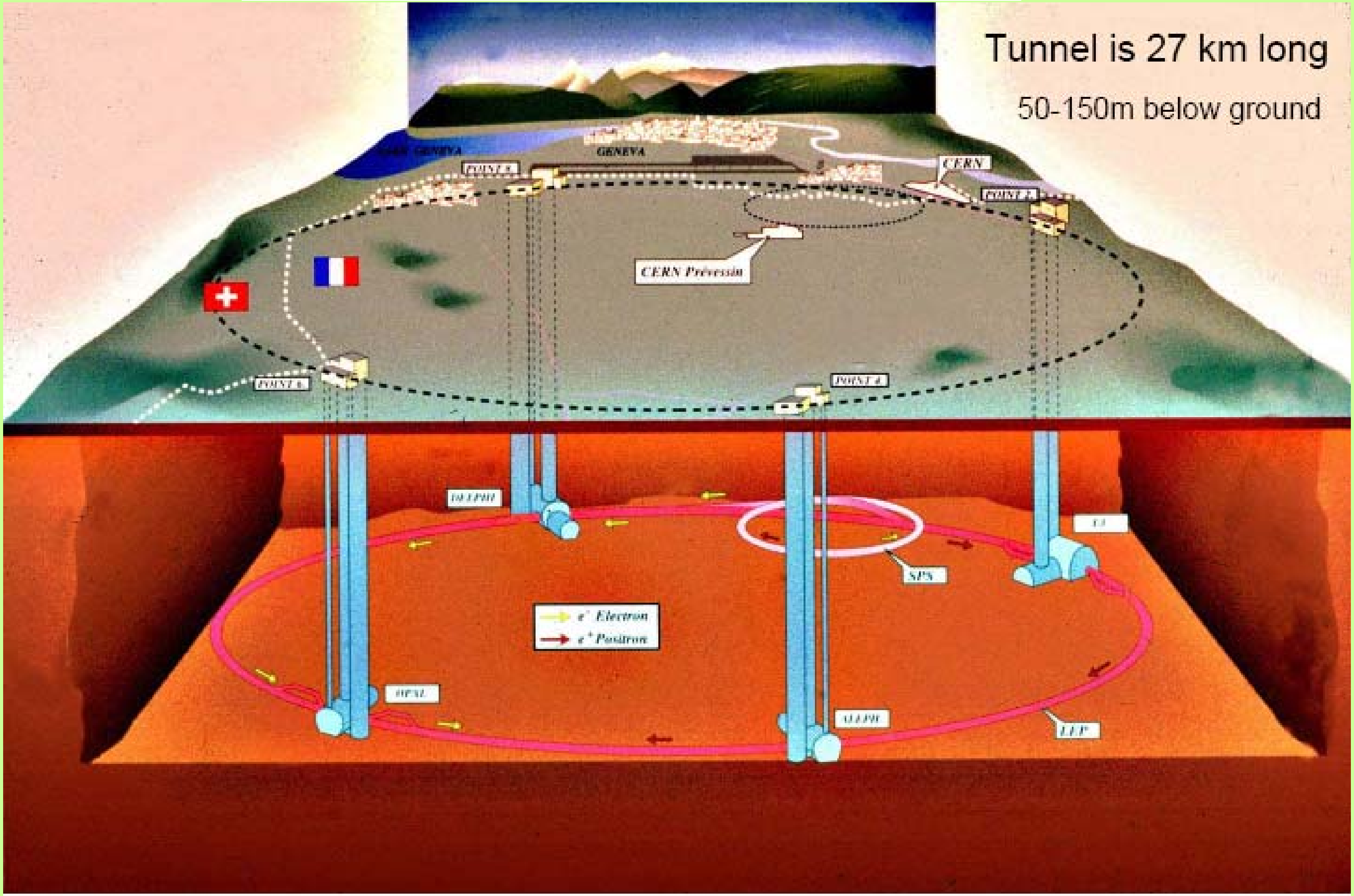


squarks and sgluons heavy yielding long decay chains ending with LSP neutrilino

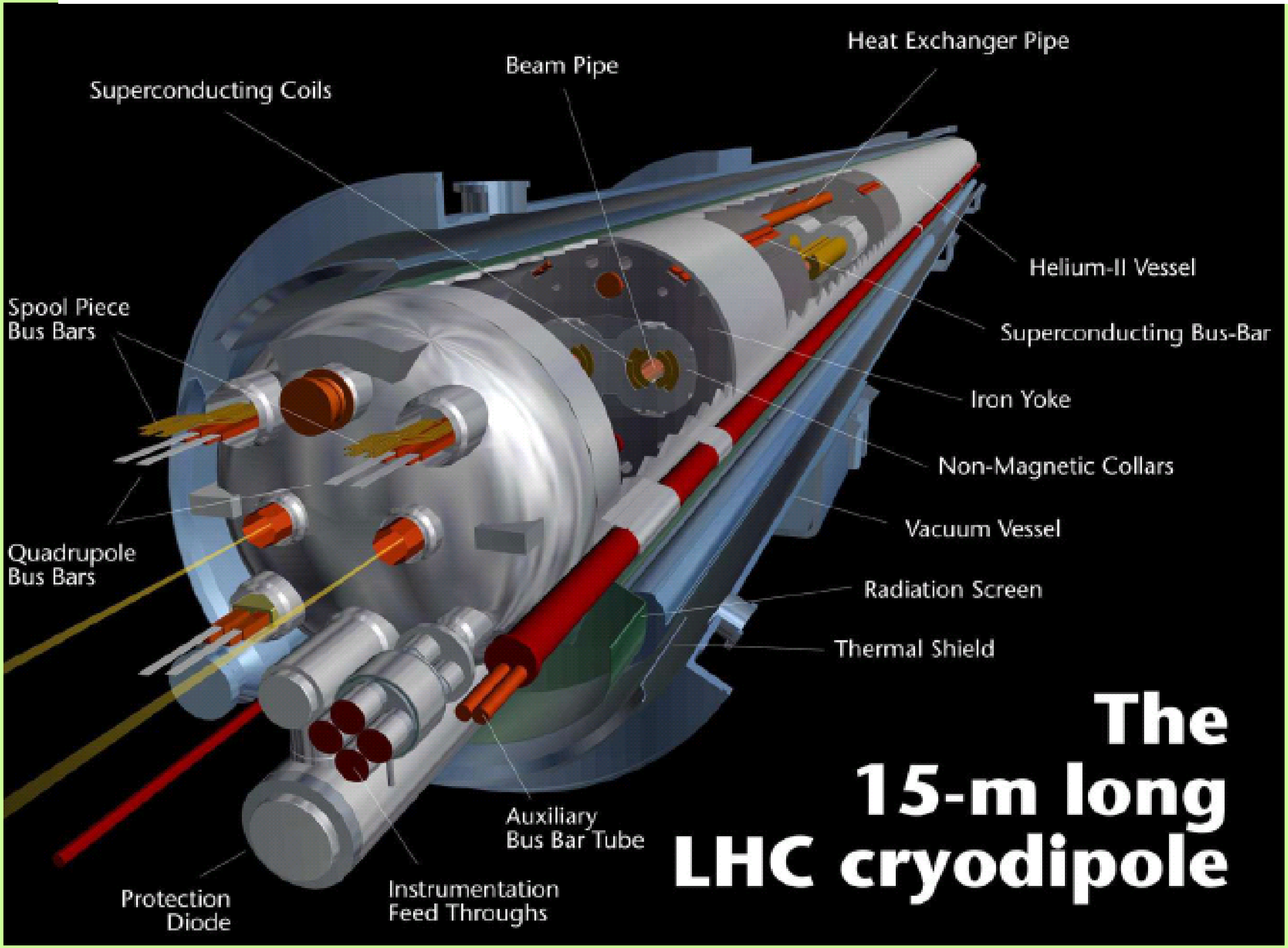
CERN Accelerator Complex



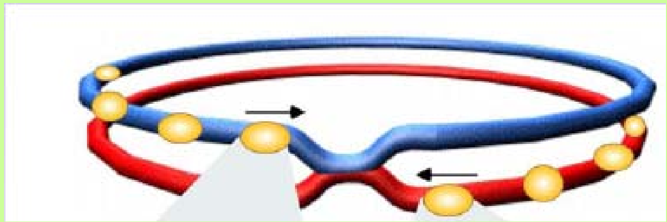
LHC is deep underground

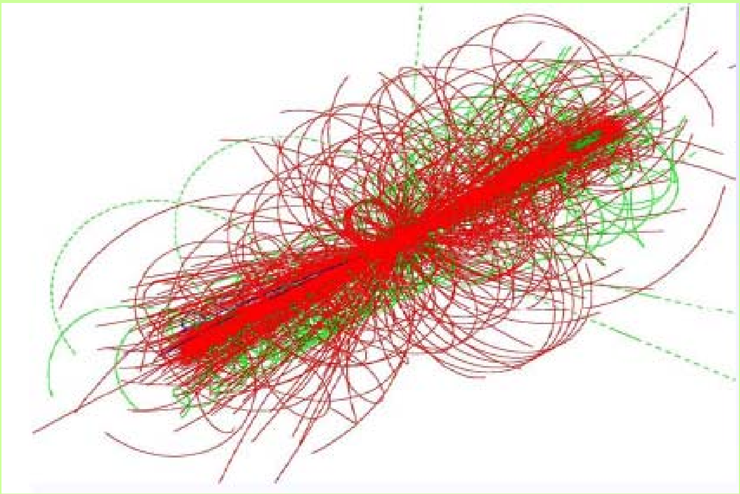


LHC --- Superconducting Magnet



Proton-Proton collisions at the LHC





- 2835 + 2835 proton bunches separated by 7.5 m

$\rightarrow$ collisions every 25 ns
= 40 MHz crossing rate

- 10^{11} protons per bunch

- at $10^{34}/cm^2/s$
$\approx$ 35 pp interactions per crossing
pile-up

$\rightarrow \approx 10^9$ pp interactions per second !!!

- In each collision
$\approx$ 1600 charged particles produced

Enormous challenge for the detectors

The LHC Accelerator

Tests of superconducting magnets
(3 years, 24 hours per day)


Teams from India at the CERN test facility

The LHC Accelerator

Transfer line magnets from SPS to LHC (~5km)

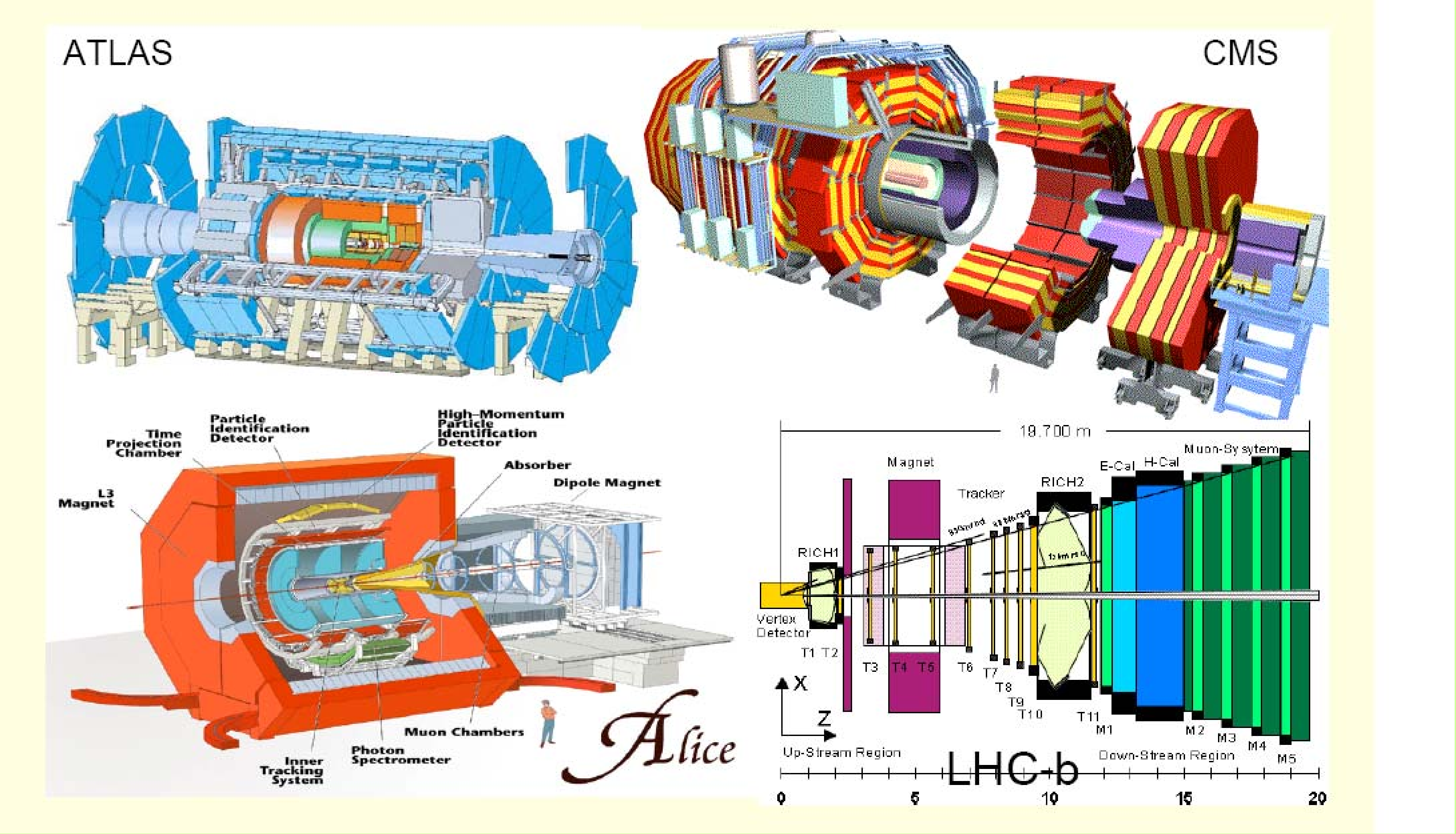
Transfer Line: main quadrupole (blue), followed by a corrector (green) and a series of main dipoles (red). All built by Budker Institute for Nuclear Physics (BINP) in Novosibirsk, Russia

The LHC Accelerator

Inner triplet magnets from US and Japan
focusing the LHC beams towards the collision points

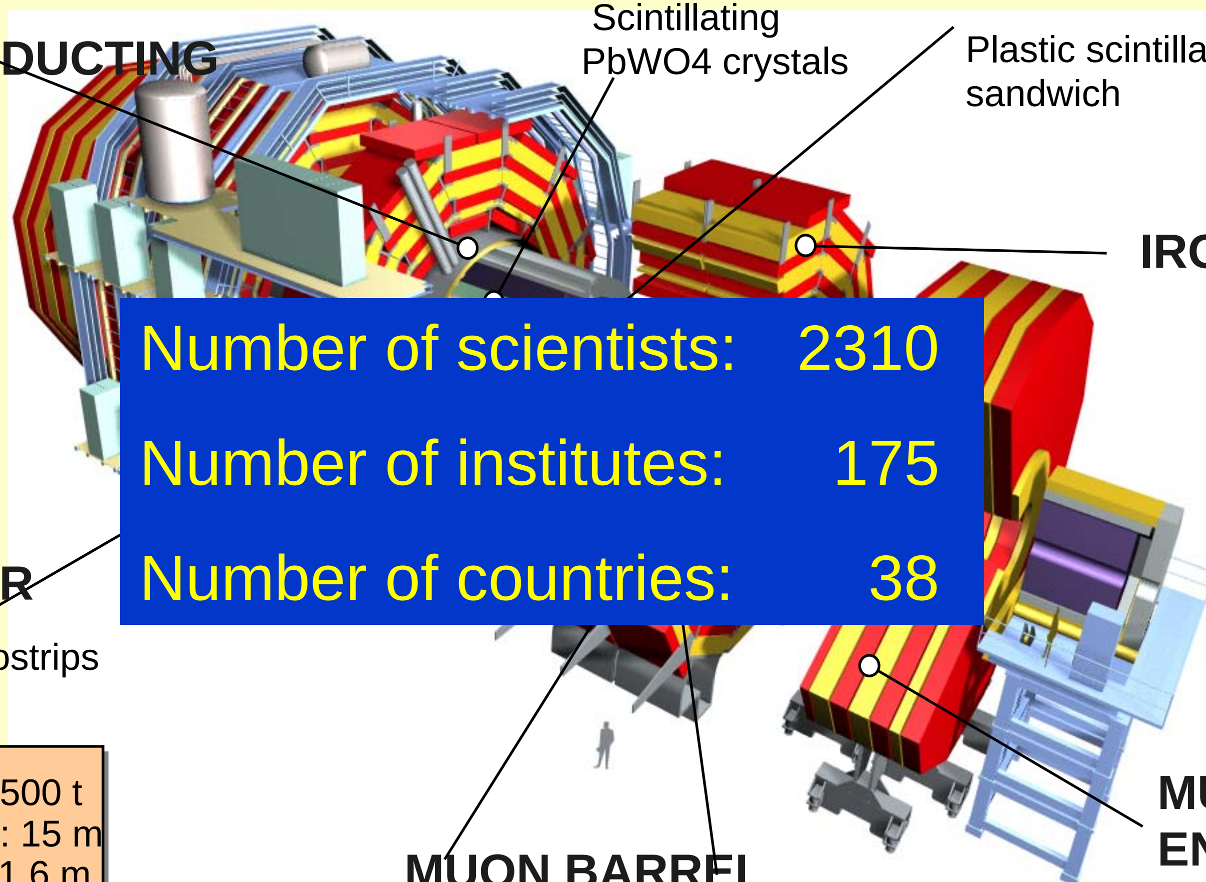
The LHC Experiments

- Each experiment has its own independent management and governance structure



LHC Experiments

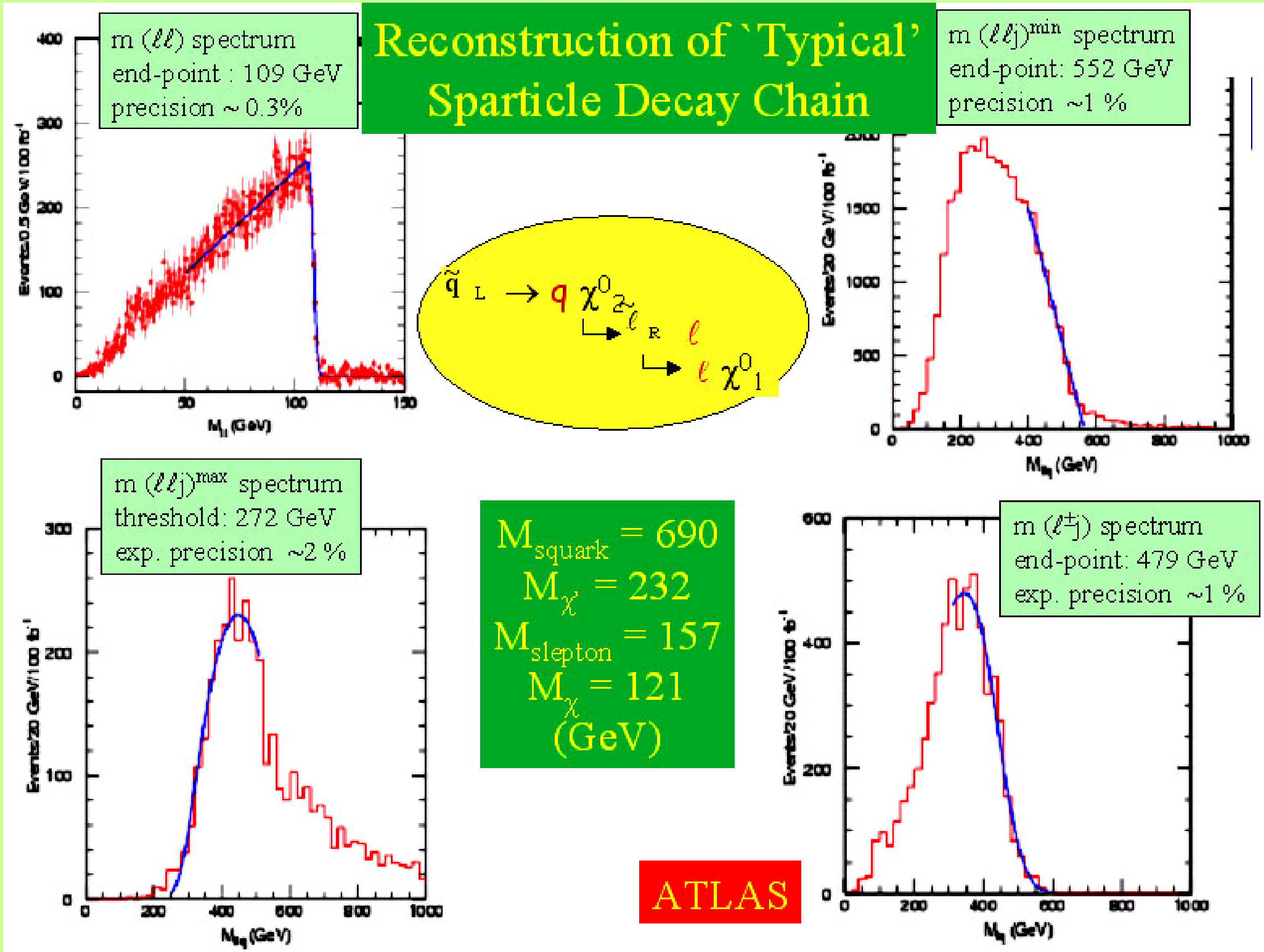
Compact Muon Solenoid - CMS



Number of scientists:	2310
Number of institutes:	175
Number of countries:	38

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

Supersymmetric Detection at LHC



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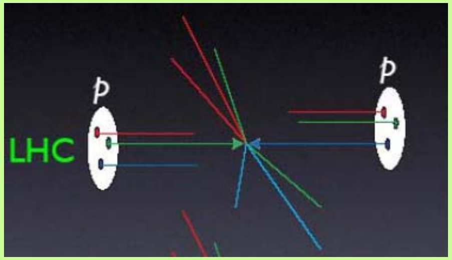
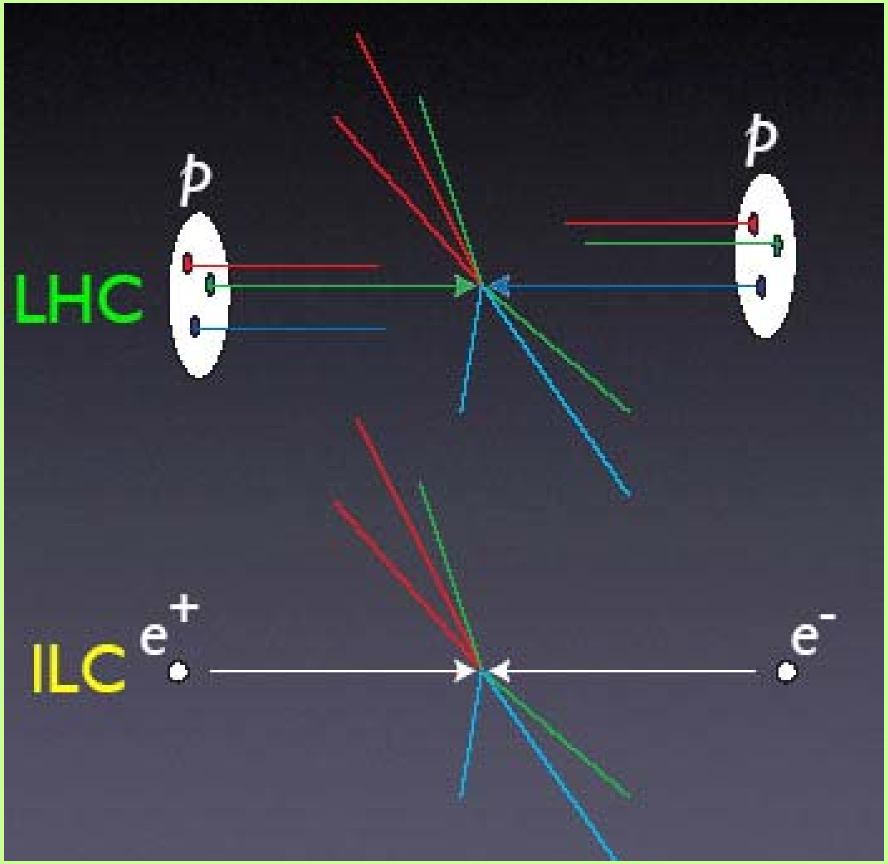


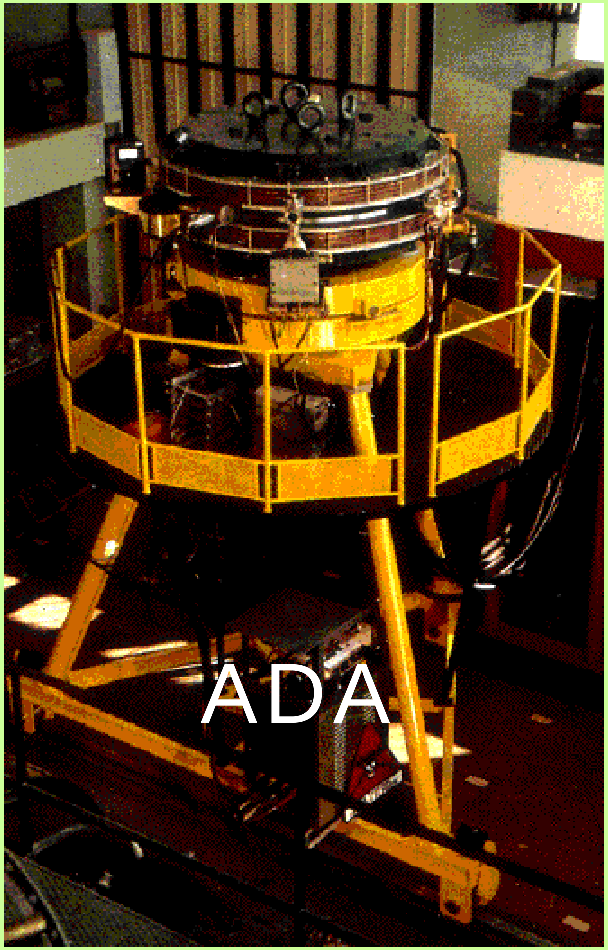
- High Energy e^+e^- Colliders
  - » **Precision Physics at the new energy frontier**

Why e^+e^- Collisions ?

- elementary particles
- well-defined
  - » energy,
  - » angular momentum
- uses full COM energy
- produces particles democratically
- can mostly fully reconstruct events



Electron-Positron Colliders



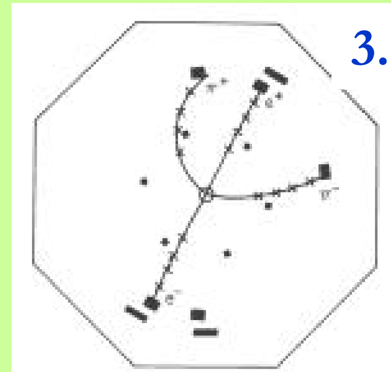
Bruno Touschek built the first successful electron-positron collider at Frascati, Italy (1960)

Eventually, went up to 3 GeV

But, not quite high enough energy ….

SPEAR at SLAC

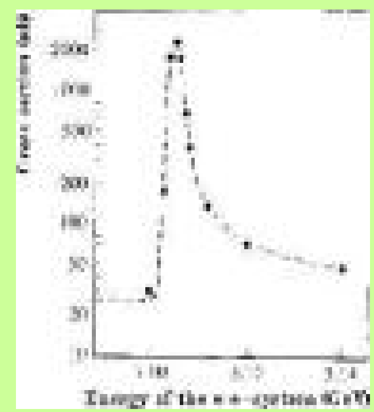
3.1 GeV



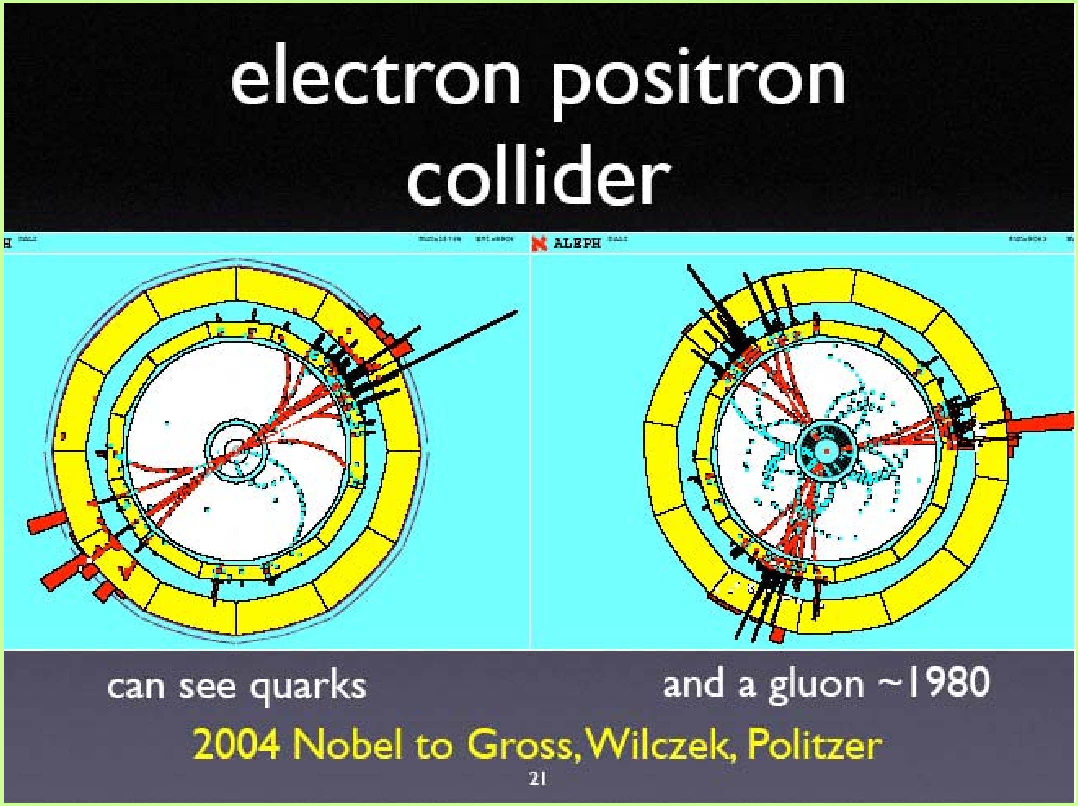
Burt Richter
Nobel Prize

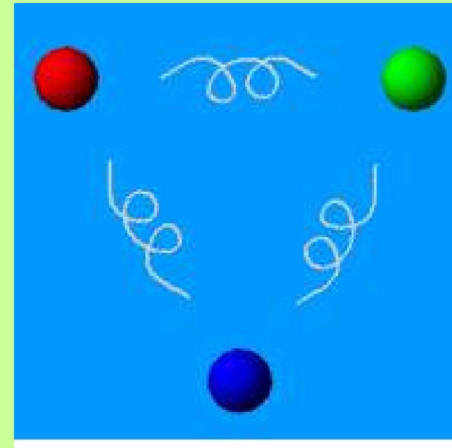
and

Discovery
Of
Charm
Particles



The rich history for e^+e^- continued as higher energies were achieved …

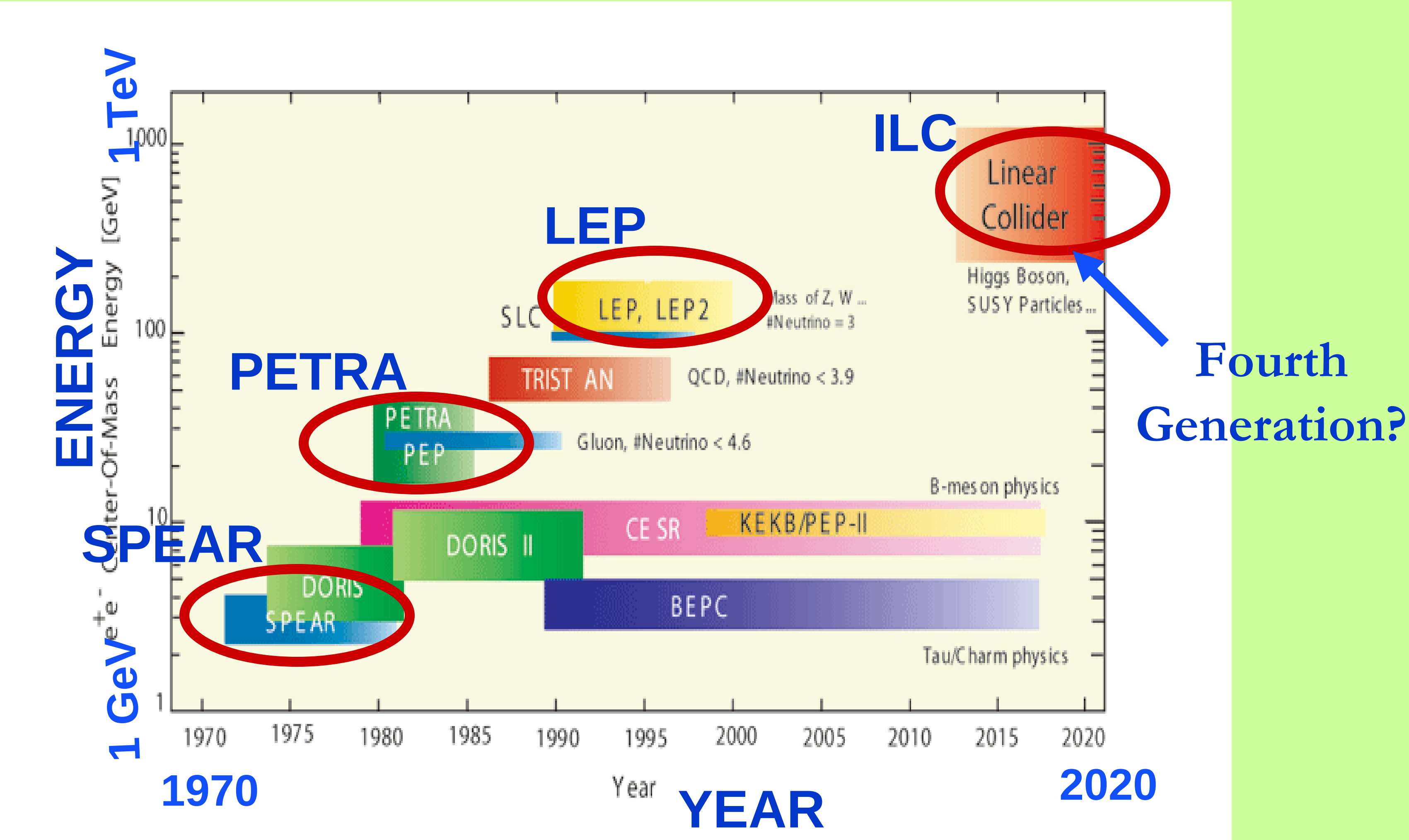




DESY PETRA Collider

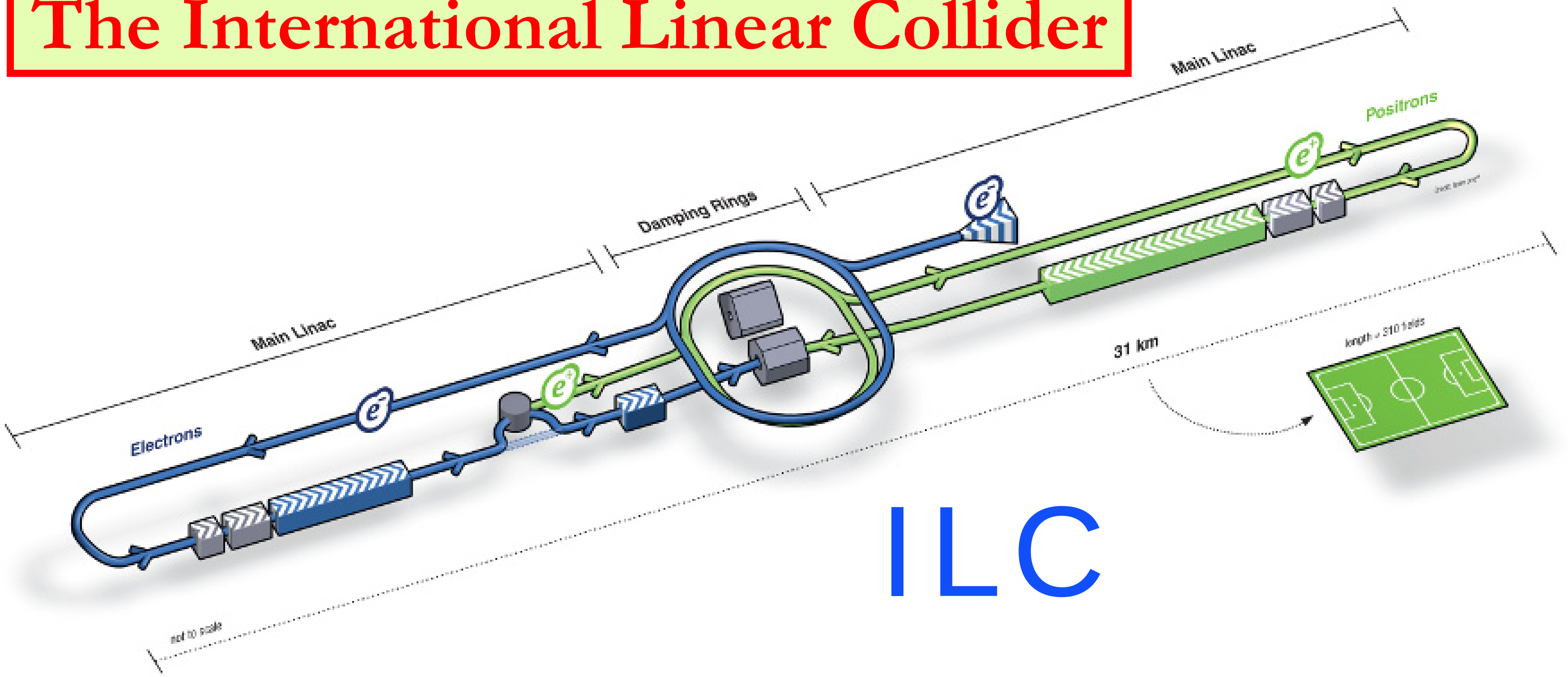
Three Generations of e^+e^- Colliders

The Energy Frontier



The next great particle accelerator

The International Linear Collider

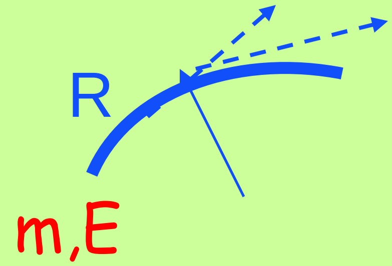


ILC

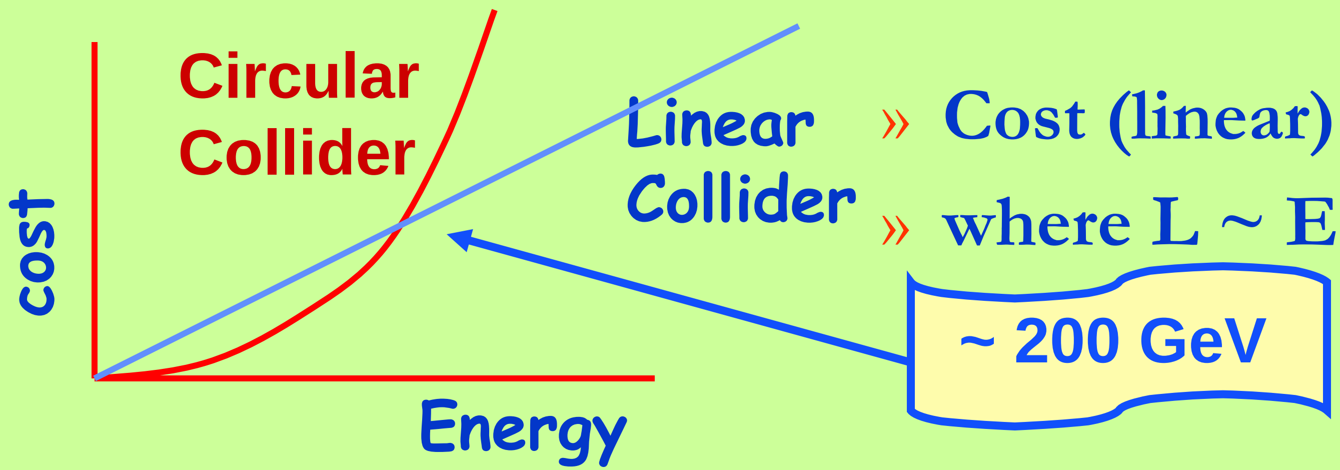
Why Linear?

- **Circular Machine**
  - $\Delta E \sim (E^4 / m^4 R)$
  - Cost $\sim a R + b \Delta E$

    $\sim a R + b (E^4 / m^4 R)$
  - Optimization : $R \sim E^2 \Rightarrow$ Cost $\sim c E^2$



Synchrotron Radiation



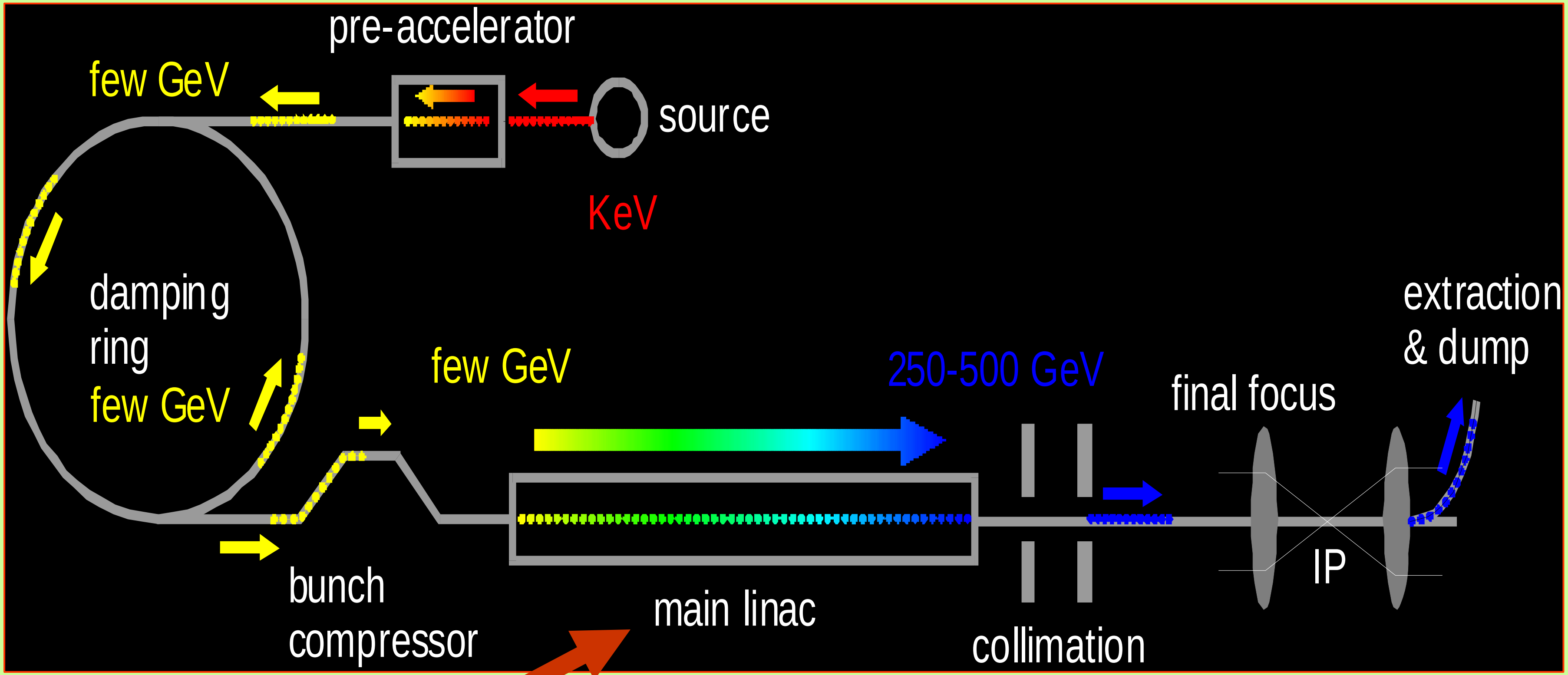
- Cost (linear) $\sim a' L$
- where $L \sim E$

Superconducting RF Technology

- **Forward looking technology for the next generation of particle accelerators: particle physics; nuclear physics; materials; medicine**

- **The ILC R&D is leading the way Superconducting RF technology**
  - » **high gradients; low noise; precision optics**

Designing a Linear Collider



Superconducting RF Main Linac

Luminosity & Beam Size

$$L = \frac{n_b N^2 f_{rep}}{2\pi\sigma_x\sigma_y} H_D$$

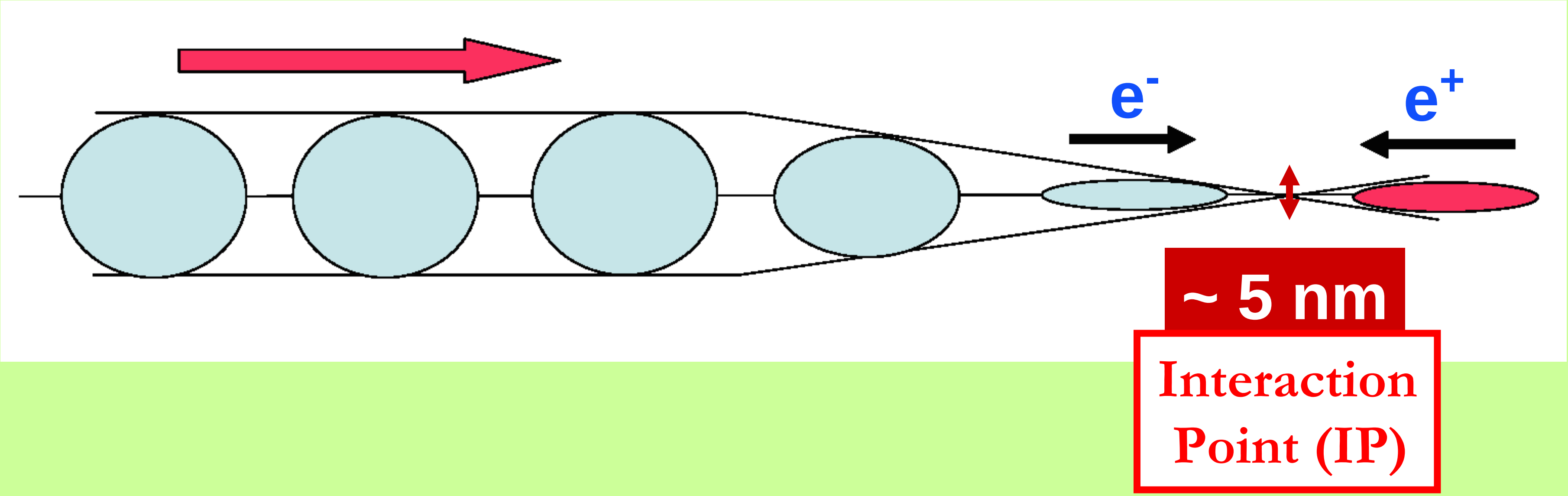
- f_{rep} * n_b tends to be low in a linear collider

	L	f_{rep} [Hz]	n_b	N [10^{10}]	σ_x [μm]	σy [μm]
ILC	2×10^{34}	5	3000	2	0.5	0.005
SLC	2×10^{30}	120	1	4	1.5	0.5
LEP2	5×10^{31}	10,000	8	30	240	4
PEP-II	1×10^{34}	140,000	1700	6	155	4

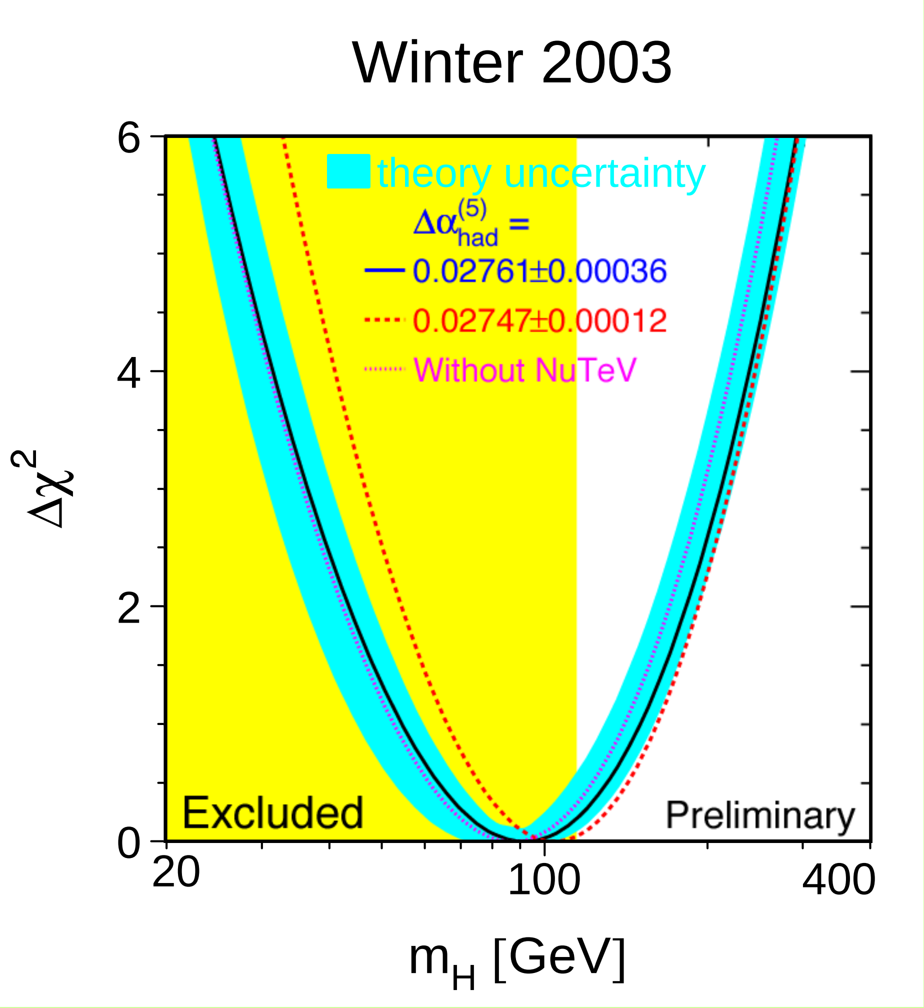
- Achieve luminosity with spot size and bunch charge

Achieving High Luminosity

- Low emittance machine optics
- Contain emittance growth
- Squeeze the beam as small as possible

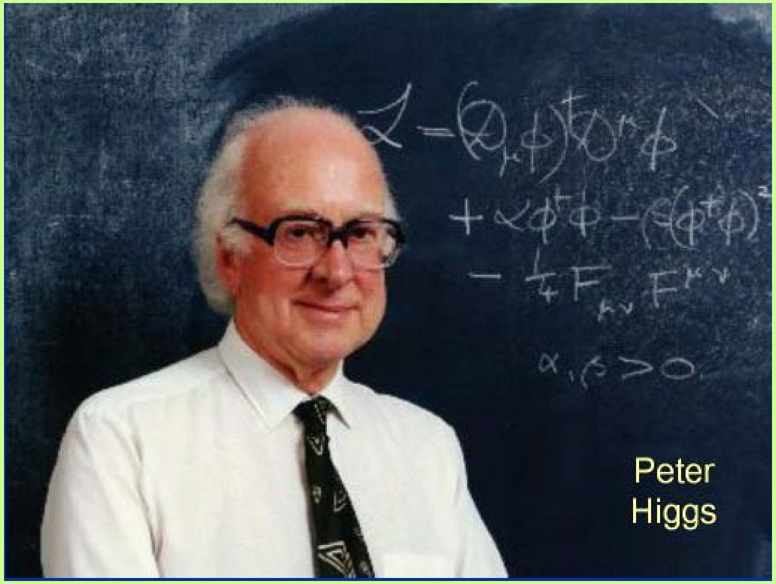


LEP has set the stage for terascale physics



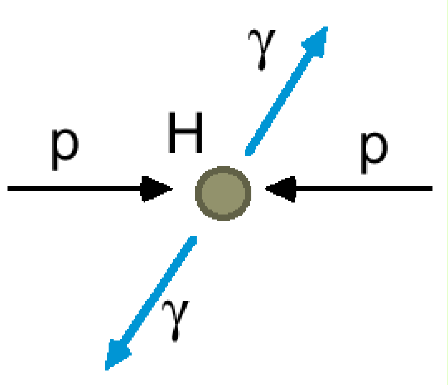
What causes mass ??

The mechanism – Higgs or alternative appears around the corner

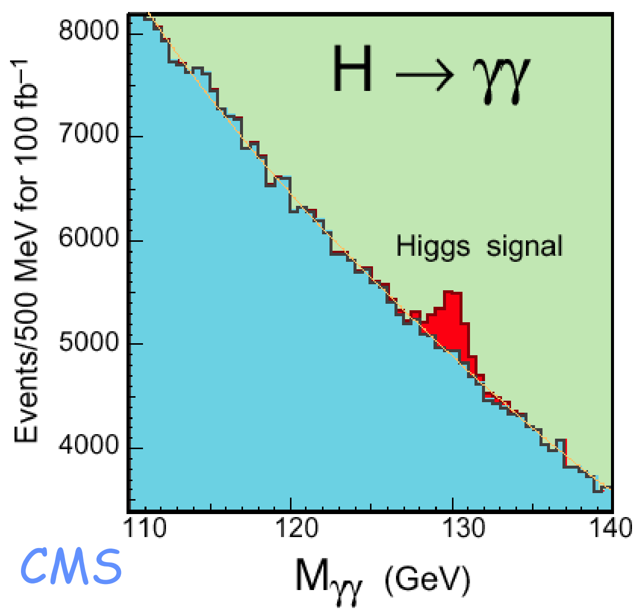


LHC: Low mass Higgs: $H \rightarrow \gamma\gamma$

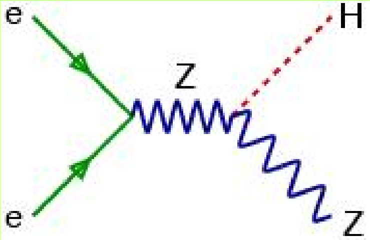
$\mathcal{M}_{\mathcal{H}} < 150$ GeV/c^2

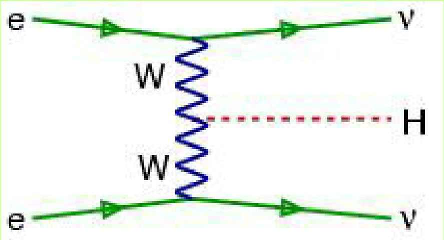


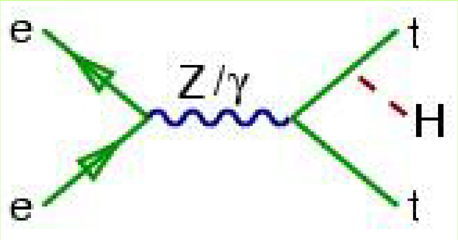
- Rare decay channel: BR ~ 10^{-3}
- Requires excellent electromagnetic calorimeter performance
    - acceptance, energy and angle resolution,
    - γ/jet and γ/π^0 separation
    - Motivation for LAr/$PbWO_4$ calorimeters for CMS
- Resolution at 100 GeV: $\sigma \approx$ 1 GeV
- Background large: S/B $\approx$ 1:20, but can estimate from non signal areas

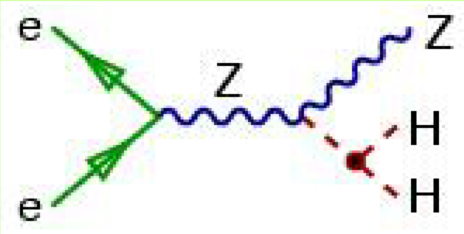


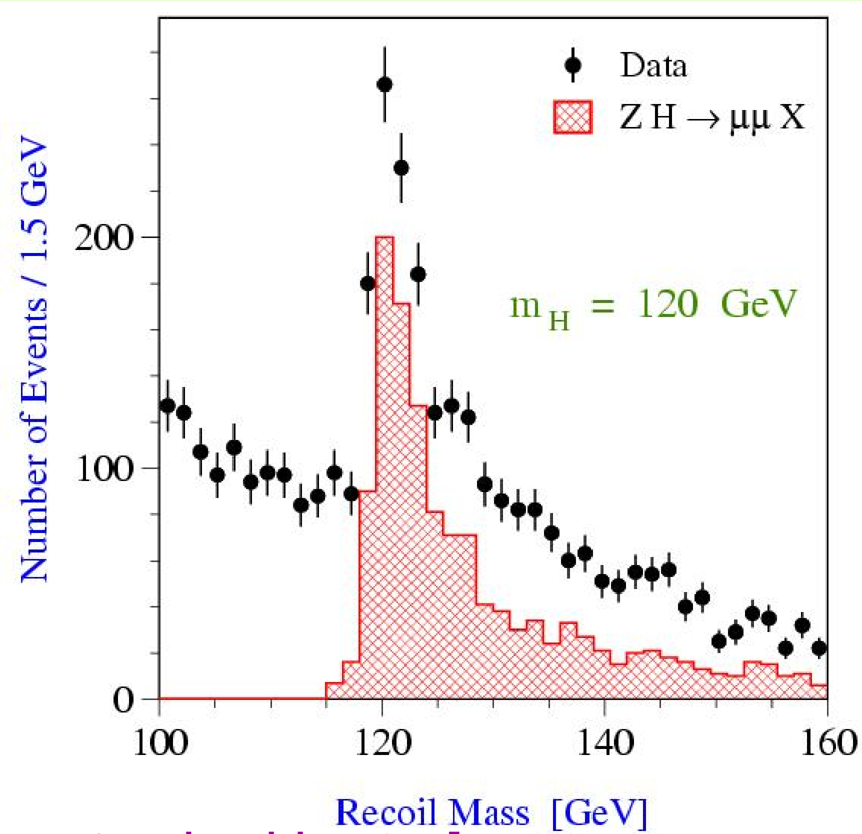
ILC: Precision Higgs physics









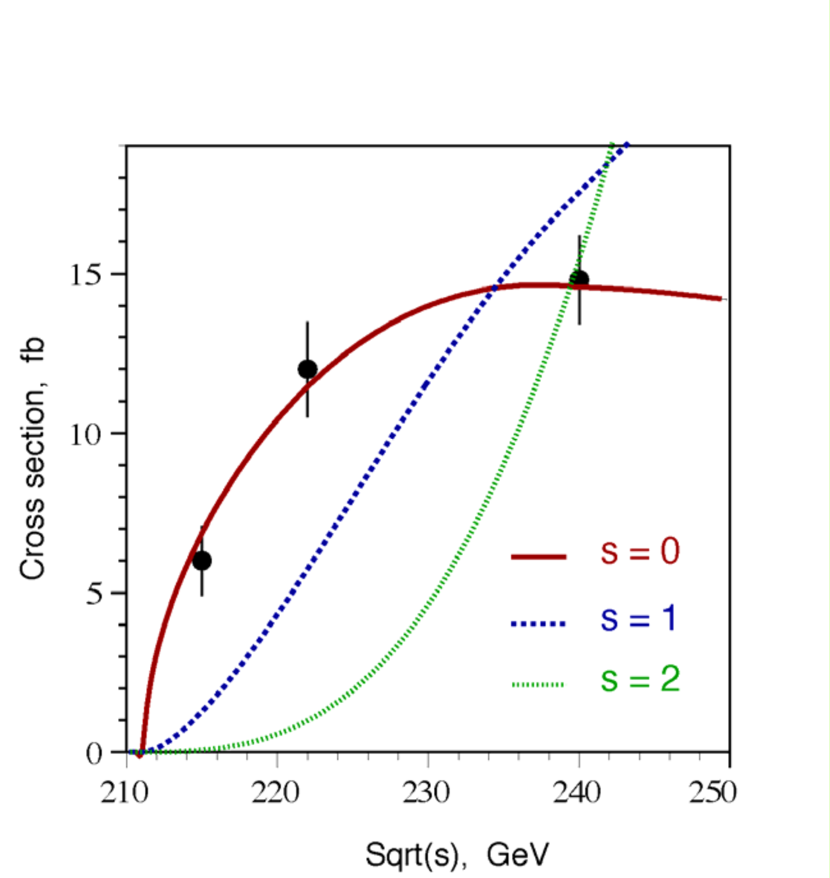


Garcia-Abia et al

- **Model-independent Studies**
  - **mass**
  - **absolute branching ratios**
  - **total width**
  - **spin**
  - **top Yukawa coupling**
  - **self coupling**
- **Precision Measurements**

How do you know you have discovered the Higgs ?

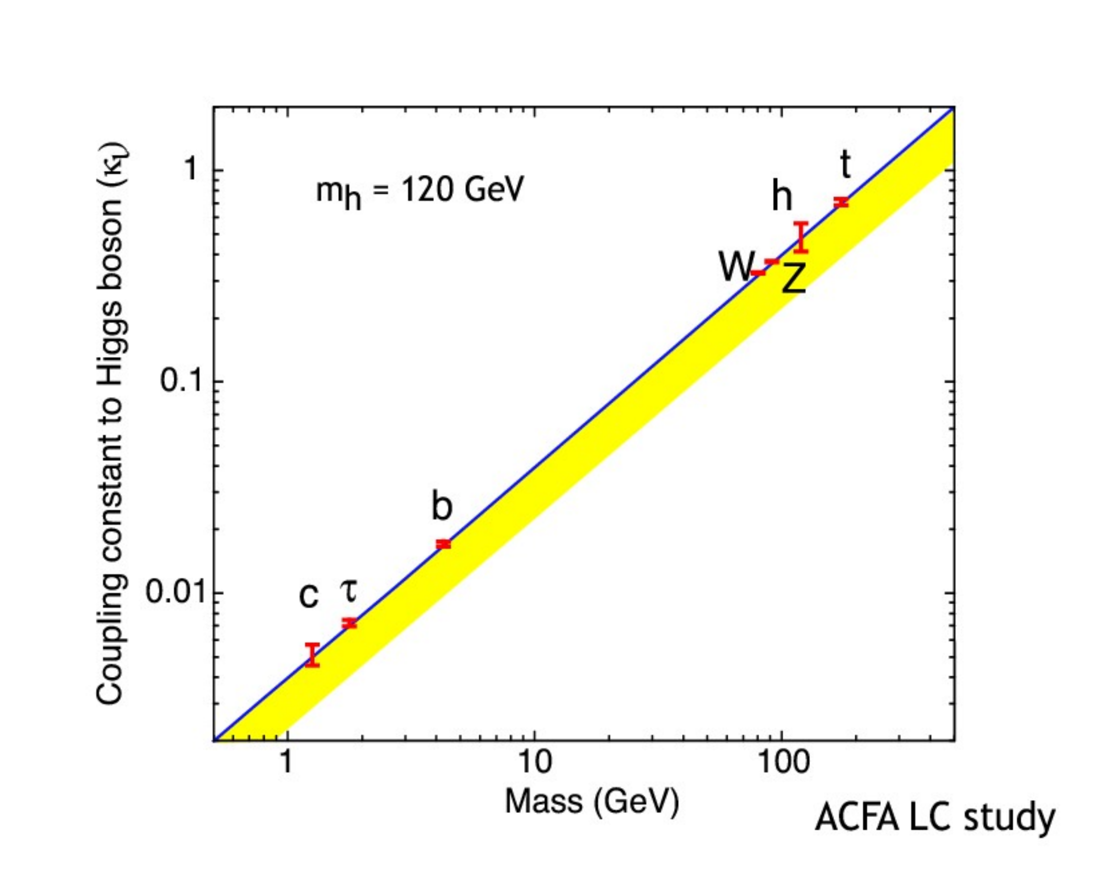
Measure the quantum numbers. The Higgs must have spin zero !



The linear collider will measure the spin of any Higgs it can produce by measuring the energy dependence from threshold

What can we learn from the Higgs?

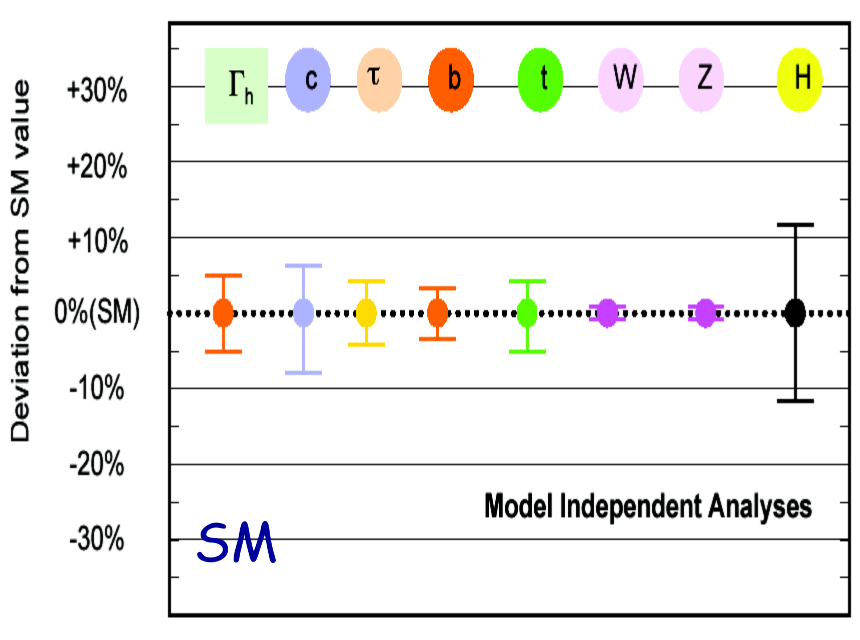
Precision measurements of Higgs coupling



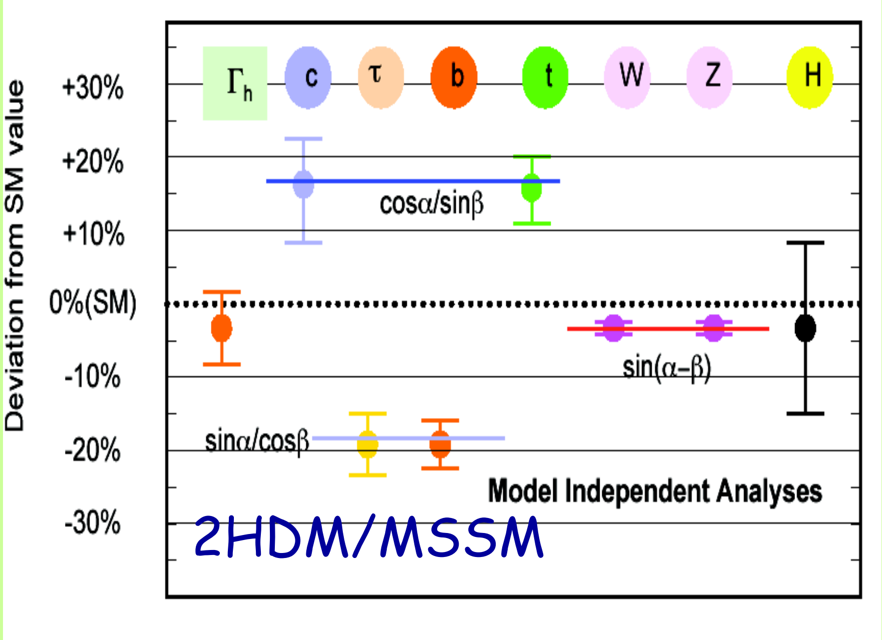
Higgs Coupling strength is proportional to Mass

e^+e^- : Studying the Higgs

determine the underlying model



Yamashita et al



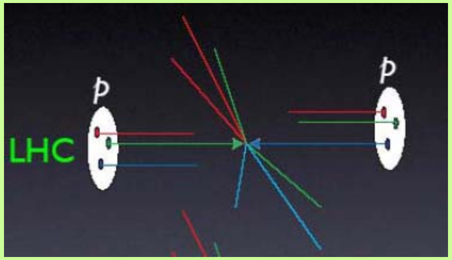
Zivkovic et al

Today's New Frontiers

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

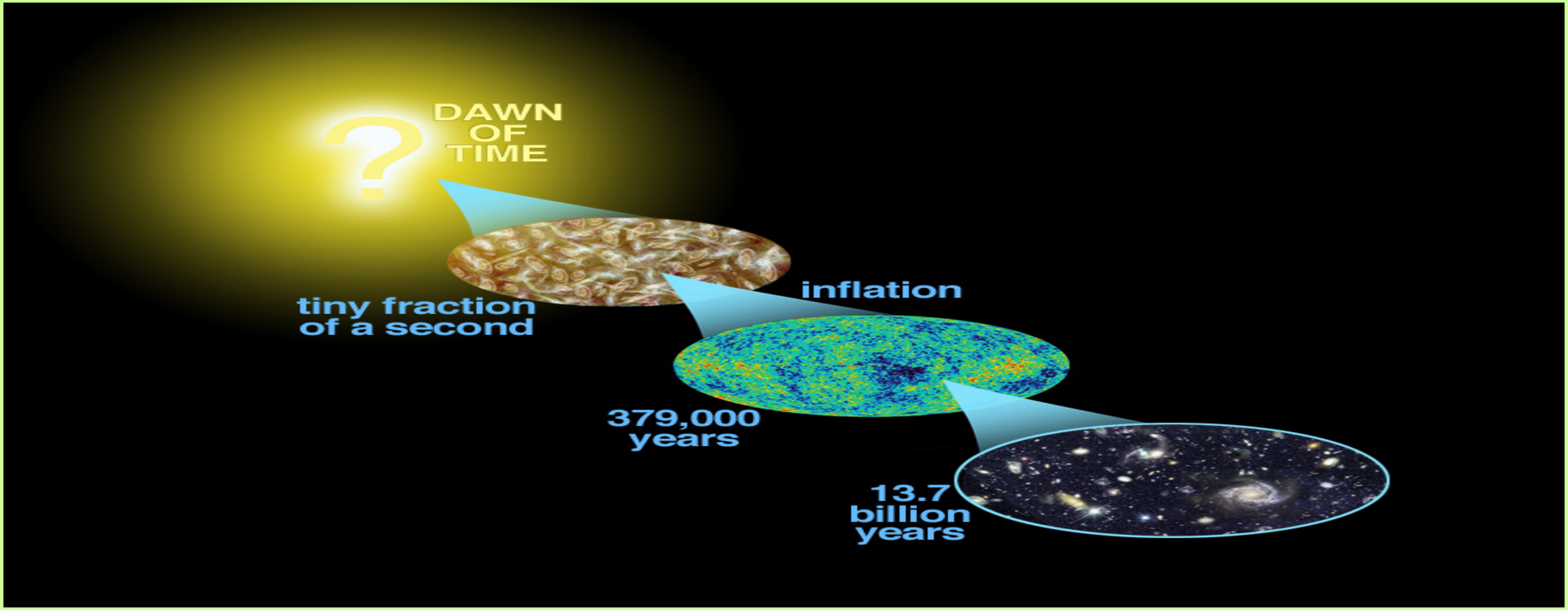
- **Particle Astrophysics/Cosmology**
  - » Dark Matter; Cosmic Microwave, etc

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



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

What will we discover? Where will it lead us?



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

(Hamlet, I.5)