UNVEILING THE ULTIMATE LAWS OF NATURE: DARK MATTER, SUPERSYMMETRY, AND THE LHC

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OUTLINE

- Some things we've learned about the physical universe

- What more do we want to understand about the physical universe?

- What ideas may let us gain that understanding –
  supersymmetry, string theory, extra dimensions

- Coming soon!
  -- Dark matter satellite data!
  -- LHC collider

- String theory – what is it? – why it is so exciting – testing it

- WHAT HAVE WE LEARNED ABOUT THE PHYSICAL UNIVERSE?

  - there is very good evidence for the whole list I'm about to show you
  - not metaphors – summaries of tested, quantitative theories

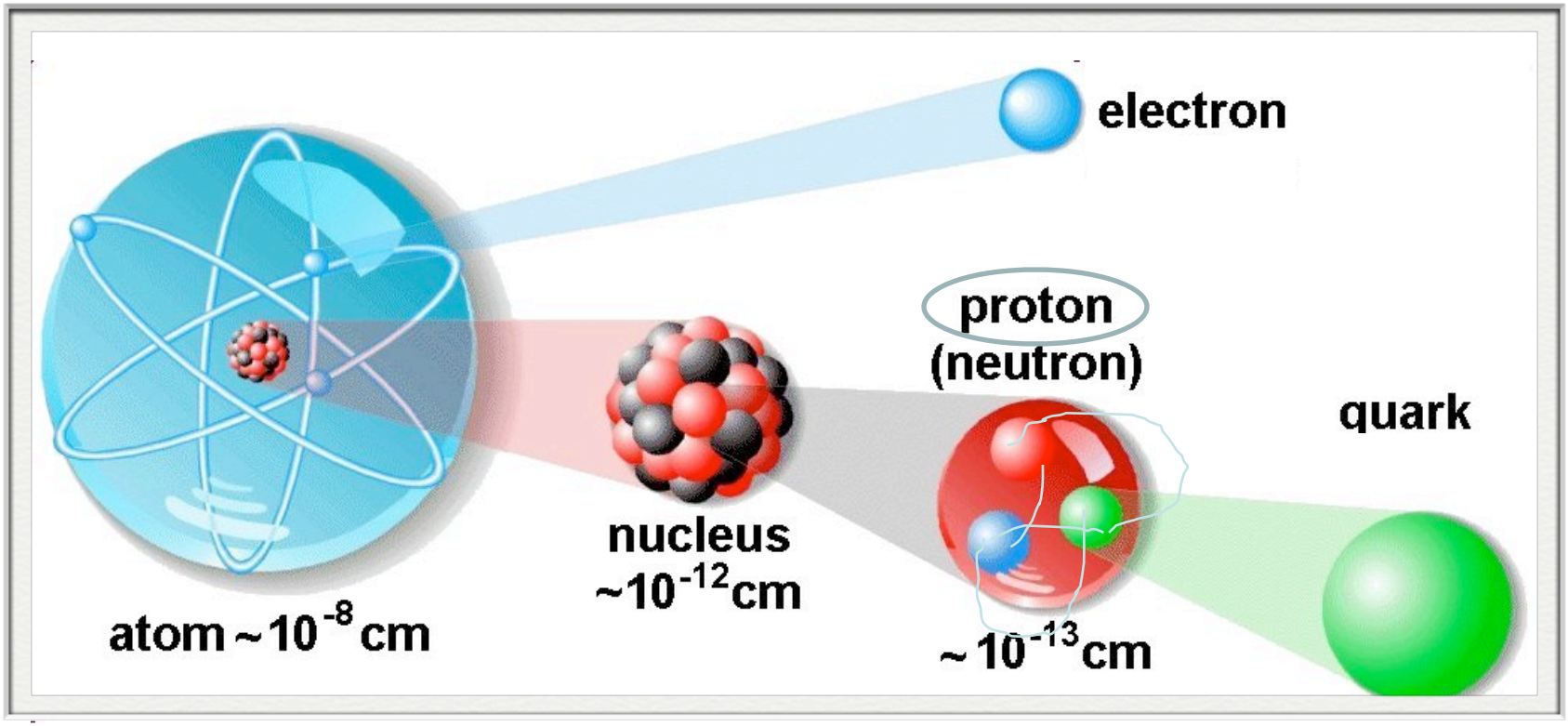
- The universe is governed by a few (or maybe even one) irreducible universal natural laws that describe all there is and all that happens in the natural world – people can discover and understand them 

- The universe formed as a tiny region of energy density, then expanded very rapidly ("inflation") – energy density unstable, turned into matter particles ("Big Bang") – universe expanded and cooled – matter clumped, formed galaxies, stars and planets – carbon, oxygen, and other elements necessary for the chemistry of life on earth were made in stars that exploded before our earth formed

- All we see in the universe ***is*** made of just three fundamental particles (electrons, up quarks, down quarks), interacting via a few forces

- quarks combine via the strong force to make protons and neutrons,
- they combine via the residual strong force to make nuclei
- nuclei and electrons combine via the electromagnetic force to make atoms
- atoms bind via the residual electromagnetic force into molecules, which combine to make people and flowers and chocolate
- Atoms, nuclei make planets and stars

The "Standard Model of particle physics"


electron
proton
(neutron)
quark
nucleus
~10^-12 cm
atom ~10^-8 cm
~10^-13 cm

- The quarks and electrons in us are essentially all from the Big Bang, and many have been in every person who ever lived 

- The universe and the earth and life have histories – each began and developed – we mostly know and understand these histories 

  (began to be known for earth few centuries ago, for life maybe two centuries ago, for universe less than a century ago))

- There is much we do not see – the world is not just the part of it that humans evolved to sense
  - Electromagnetic spectrum extends beyond visible
  - 4 forces, we sense only two
  - Small things – viruses…atoms…quarks
  - Extra dimensions?
  - Many universes?

We extend our awareness with technology – telescopes, microscopes, cameras, detectors

And we extend it with scientific theories!

TODAY SOME BIG QUESTIONS ARE ANSWERED, THE REST ARE BEING *ADDRESSED* SCIENTIFICALLY

-- first time in history – exciting time

-- usually when topics become subjects of scientific research they become understood within few decades

-- while developing, an area changes, maybe a lot, then eventually settles down

- sound and heat are motion of atoms
- everything around us is made of atoms
- age of visible universe
- sun works by fusion
- origin of 92 chemical elements

-- while an area is changing there are lots of ideas that are tested, and data that needs confirmation

Research **I**n **P**rogress

[Rest In Peace??]

Science is about ***understanding***

What do we want to understand?

- What are we and the things around us made of?
- Why are there protons and nuclei and atoms?
- Where do stars and galaxies and the universe come from, how do they work
- What makes life possible?
- Etc.

Today, after about 400 years (Copernicus, Kepler, Galileo …), we have achieved the "Standard Model(s) of particle physics and of cosmology" – actually answers many questions!

Amazing progress

- When Shakespeare wrote there was no understanding of how *any* aspect of the natural world worked!
- Today a full quantitative description of the world around us, of all that we see!

We have *description*, and *how*, but **why** missing

There is much more we want to understand

- What is the dark matter
- Why is the universe made of matter, not antimatter?
- What is the dark energy?
- What causes inflation?
- Why are there the forces (gravity, strong, weak, electromagnetic) and can we relate them?

All being addressed

And even – are the underlying laws of nature inevitable? – is our world unique?

The goals of science have changed in past ~20 years!

- *Now that we have the Standard Models we can formulate the "why" questions*
- *Because of Supersymmetry and String Theory and extra dimensions, which allow us to **address** these questions*

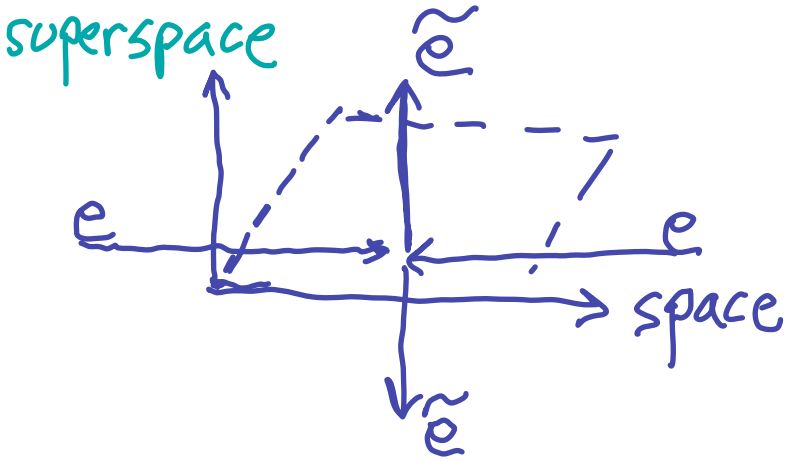
SUPERSYMMETRY

We know our world is described by the rules of quantum theory

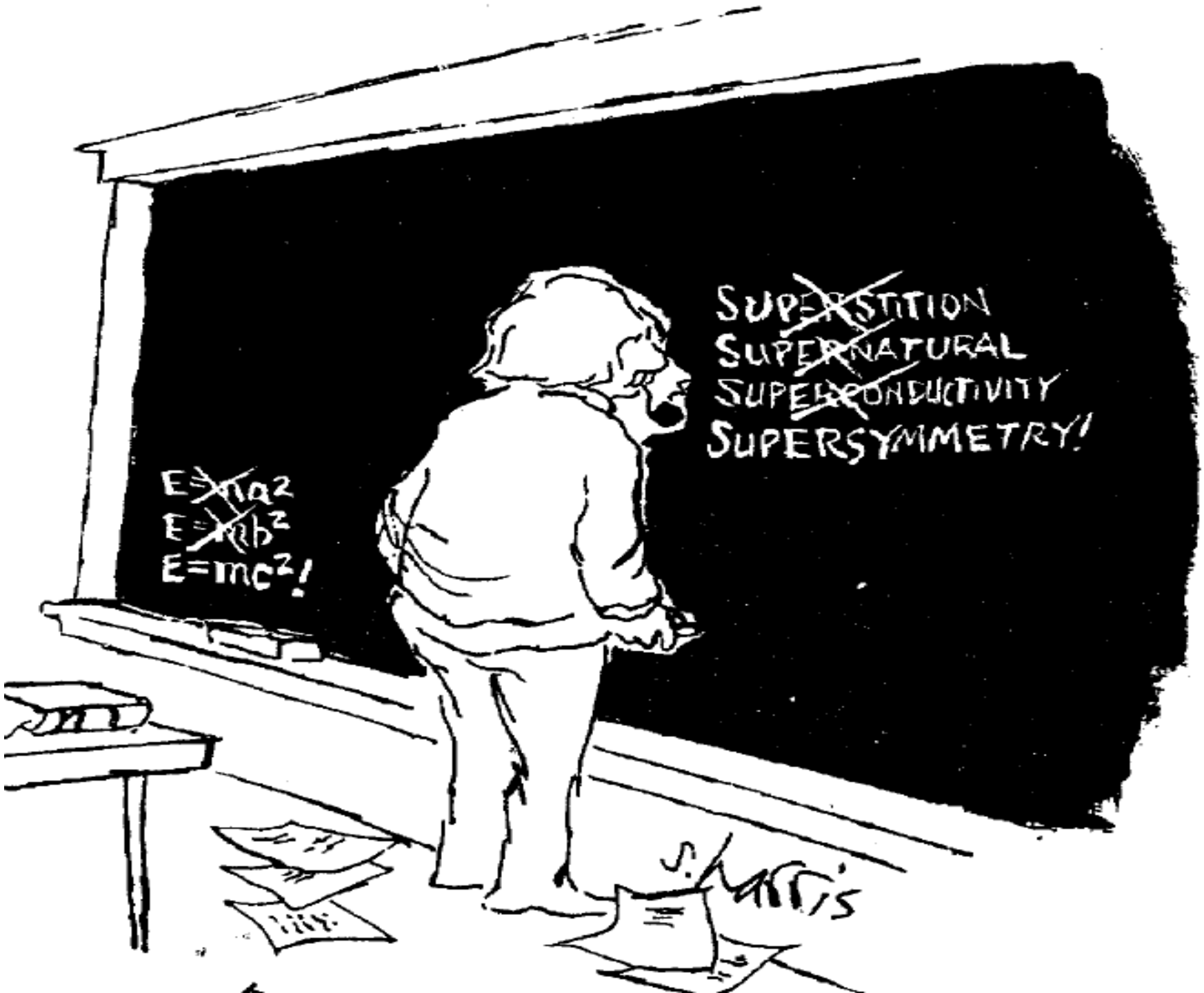
But we don't describe our space dimensions by those rules

Supersymmetry is the idea that for every space dimension there is an associated quantum dimension, and that the laws that describe nature don't change if you interchange those dimensions

If you collide two particles, e.g. electrons, with enough energy, you can knock them into the quantum dimensions, where they become their "superpartners" – e.g., selectrons



Every particle should have a superpartner if this is right


SUPERSTITION
SUPERNATURAL
SUPERCONDUCTIVITY
SUPERSYMMETRY!
E=mc²!

Supersymmetry invented (about 1973) as a beautiful theory – not to solve any puzzles or explain data

Turned out to explain a lot!

- Allow our energy scale and fundamental Planck scale to co-exist in theory (1979) – differ by 10^{17} – cannot separate in SM
- Allows description of forces to unify (1992) – could not in SM
- Provides dark matter candidate (1983) – none in SM – lightest superpartner
- Can explain "Higgs physics" (1982) – SM cannot explain it
- Can explain matter asymmetry of universe (1993) – cannot in SM

And more

The lightest superpartner may also be the dark matter of the universe!

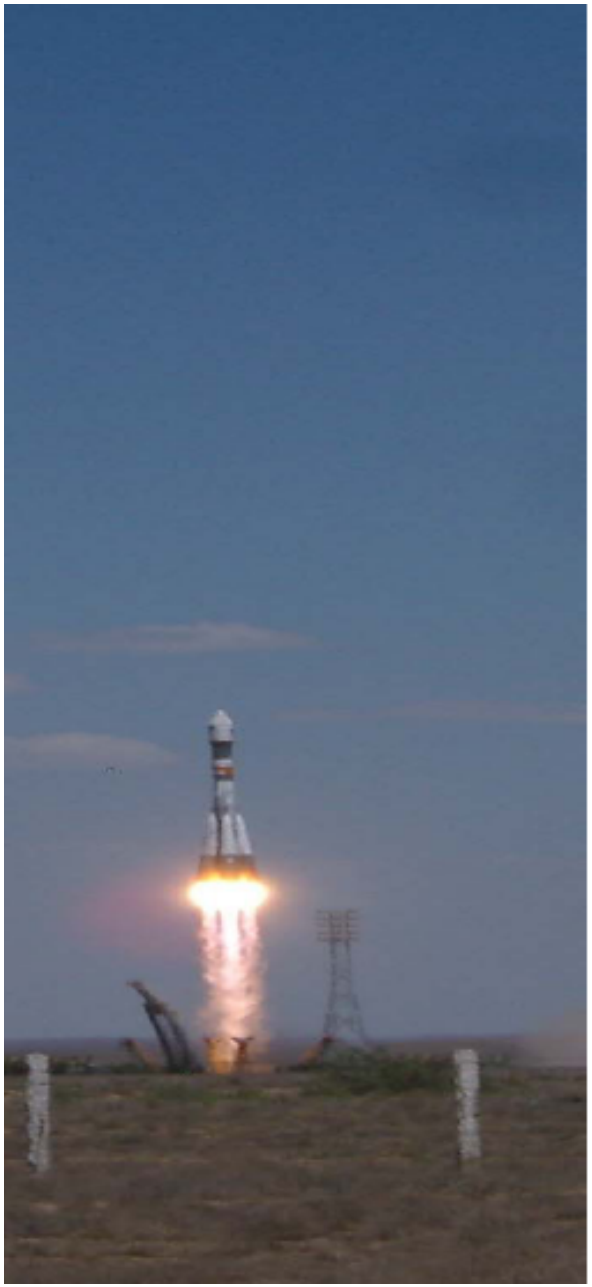
- Big Bang, universe cools, unstable particles decay – after a while left with only

γ, e, u, d, n, LSP

n, p, nuclei

atoms

Dark matter spread throughout galaxy – two DM particles can annihilate, into all Standard Matter particles and antimatter – antimatter less common so easier to see, search for it – positrons, antiprotons, gammas



Satellite detector

Indirect Detection of Dark Matter with PAMELA

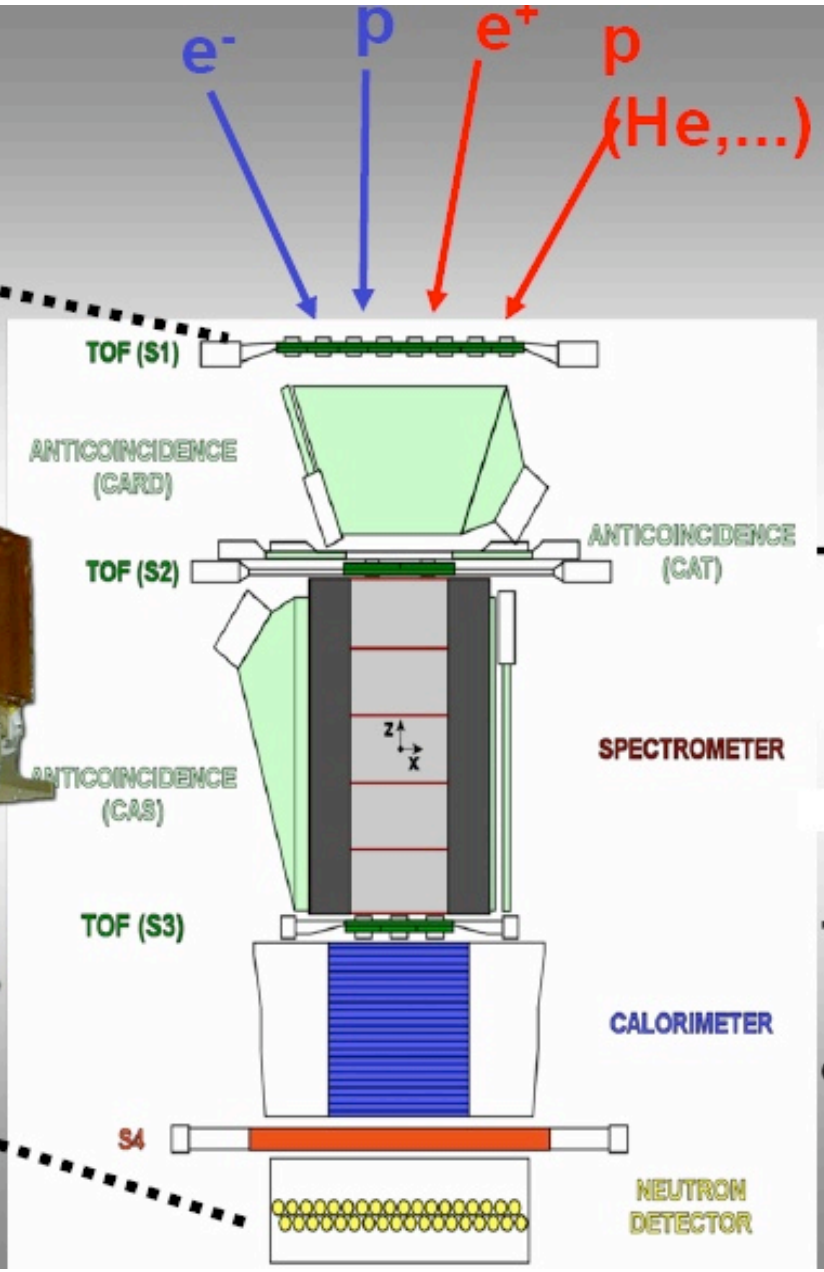
Mirko Boezio
INFN Trieste, Italy

On behalf of the PAMELA collaboration

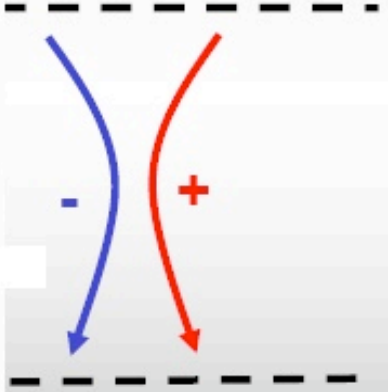
LHC and Dark Matter Workshop

January 6th 2009

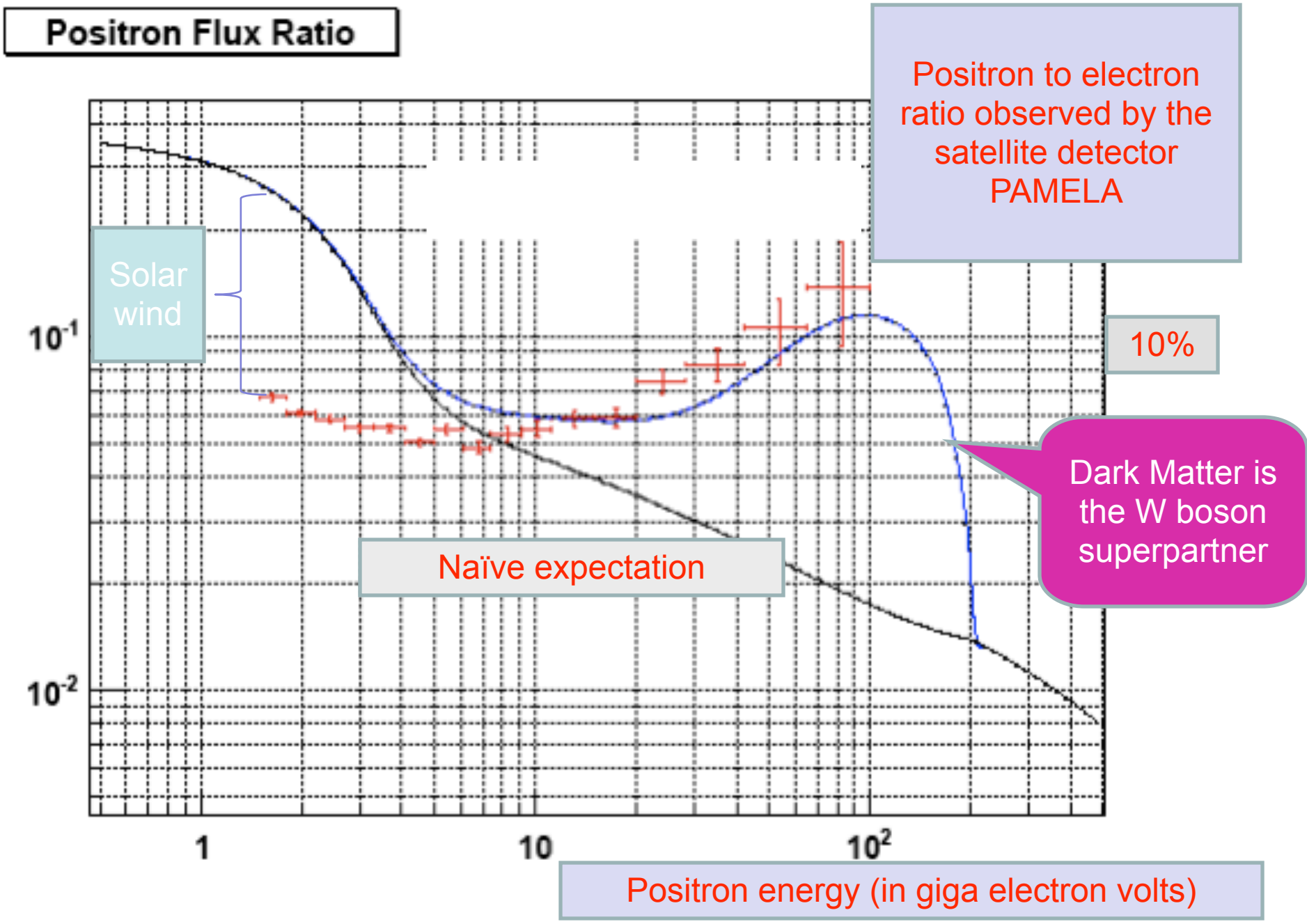
GF ~21.5 cm²sr
Mass: 470 kg
Size: 130x70x70 cm³



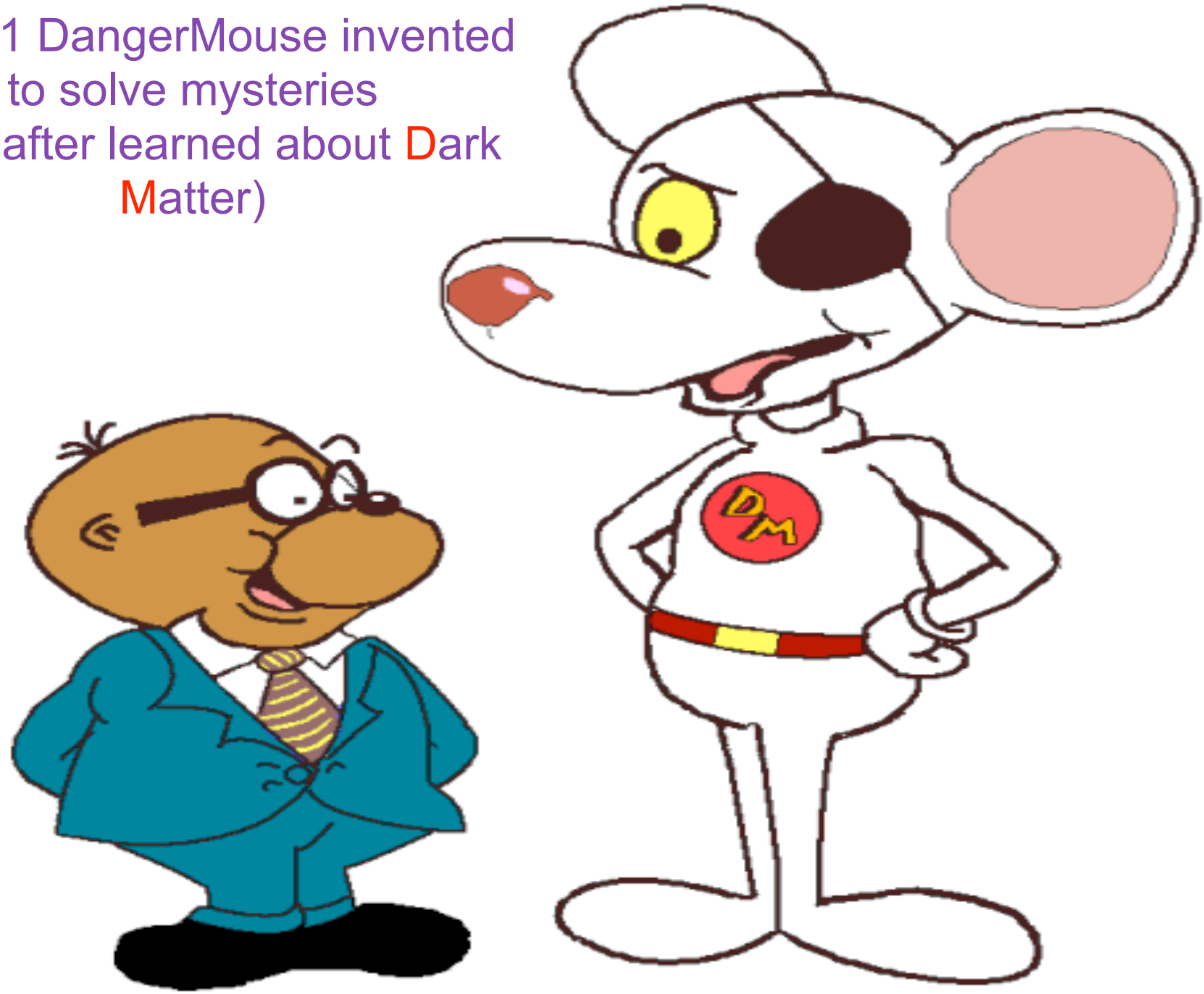
Trigger, ToF, dE/dx



Electron energy, dE/dx, lepton-hadron separation


Positron Flux Ratio
Positron to electron ratio observed by the satellite detector PAMELA
Solar wind
10%
Dark Matter is the W boson superpartner
Naïve expectation
10^{-1}
10^{-2}
1
10
10^2
Positron energy (in giga electron volts)

In 1981 DangerMouse invented to solve mysteries (right after learned about Dark Matter)




PAMELA
DangerMouse working
to check data and
detector
→ OK!

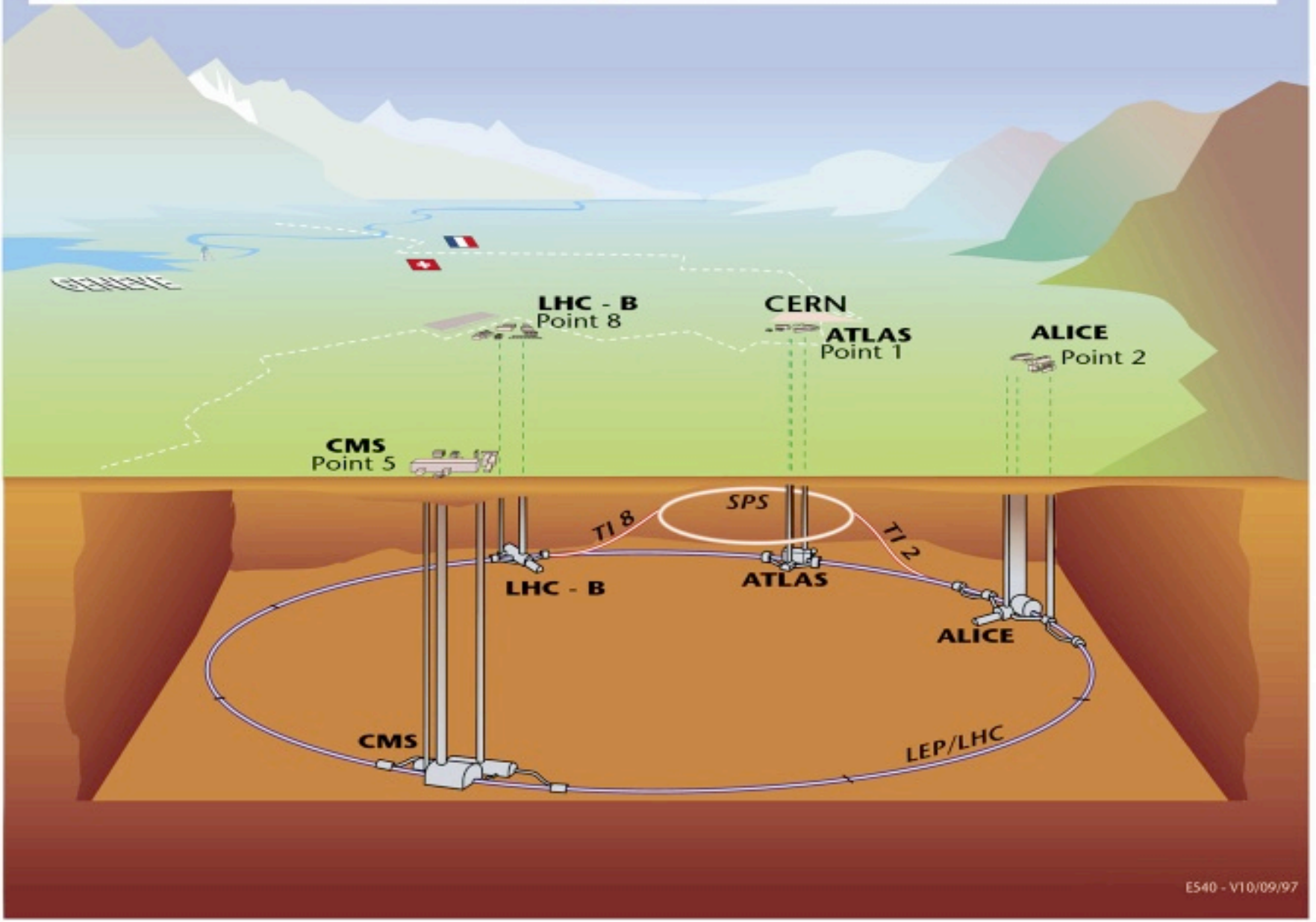
LHC (Large Hadron Collider, CERN, Geneva)

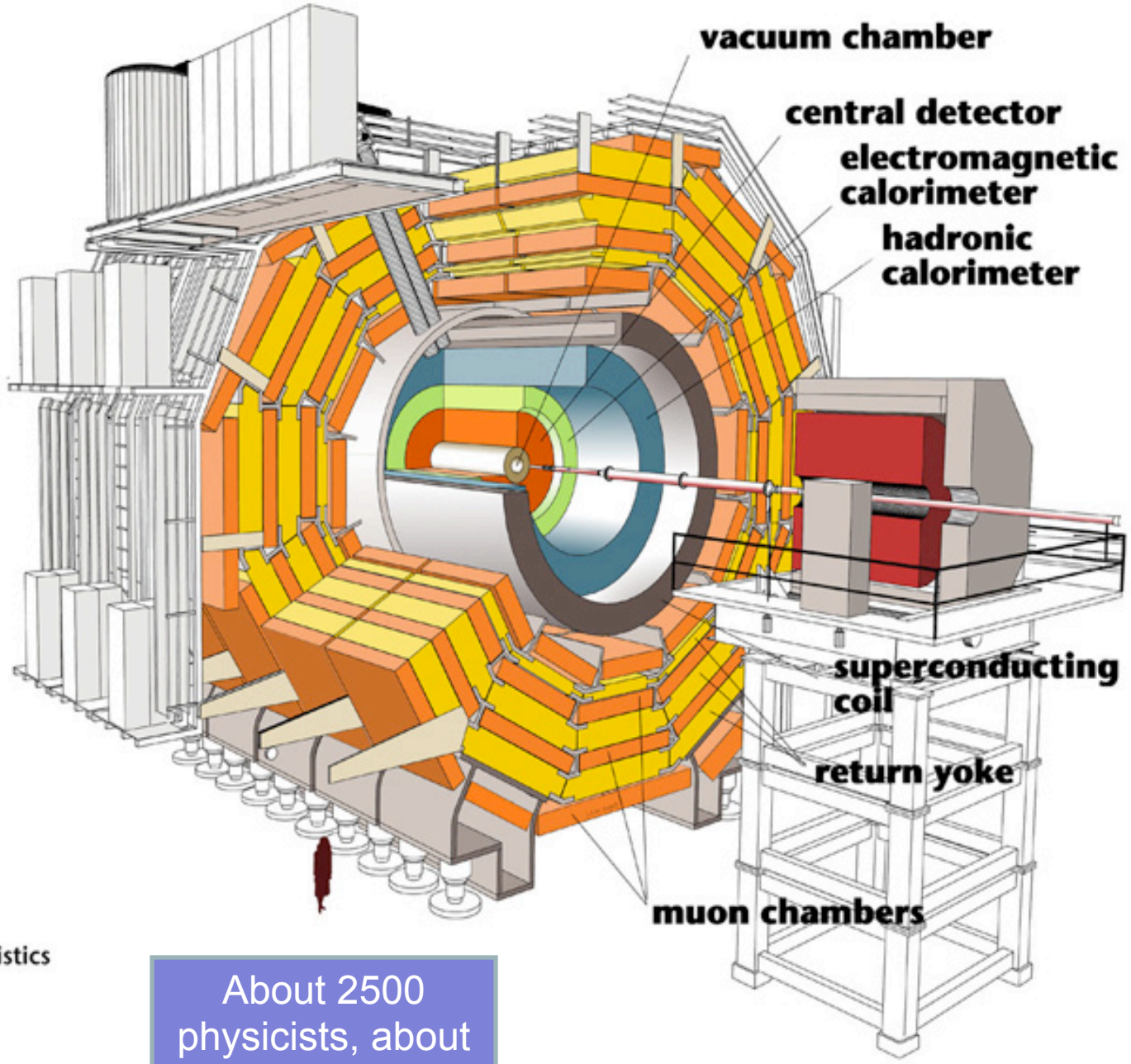
-- extraordinary scientific device – "why" machine

- Accelerate protons, collide them, inside a "detector" – take a picture of what comes out, look for new things
- Billions of collisions a second, less than one "interesting" – need very fast decisions, pushes frontier of hardware and software
- 10^{11} bytes a second, more than all telecommunications on earth – every second for years → Grid computing
- Hopefully find superpartners (2010-2011), [Higgs bosons (2011-2012)]


27 km

Overall view of the LHC experiments.





Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

About 2500 physicists, about $1B

IF SUPERSYMMETRY RELEVANT, SUPERPARTNERS MUST BE DISCOVERED AT COLLIDERS, SUCH AS LHC

Selectron $\tilde{e}$

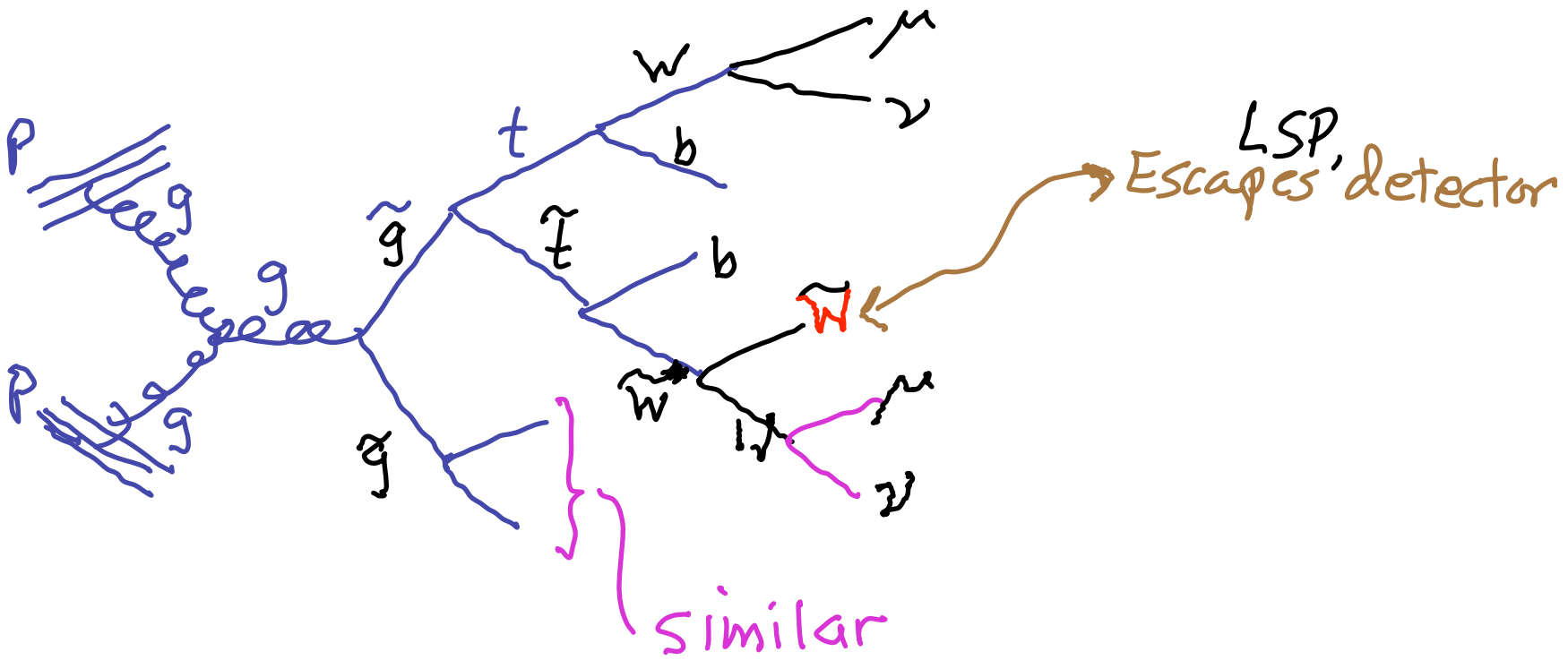
photino $\tilde{\gamma}$

gluino $\tilde{g}$

stop squark $\tilde{t}$

sneutrino $\tilde{\nu}$ etc

POSSIBLE LHC EVENT



→ 4 b's, 4 $\mu^{\pm}$, large missing P_{Trans}

No similar Standard Model events!

(such events predicted by same theory that predicts PAMELA dark matter LSP)

STRING THEORY

(International meeting here this week)

String theory is:

A quantum theory consistent with general relativity, and incorporating the electromagnetic, strong, and weak forces, and the particles these forces act on are leptons and quarks, and the theory requires all of these to exist

--Possible to write such a mathematical theory, IF ten dimensions! – those we don't see are small, "Planck scale" size – 10^{-33} cm

--Reinterpret electron as a string of energy density instead of a point particle, but still an electron

--Contains Supersymmetric Standard Model

What do we mean by "explain"? – property emerges without being put in – constructing a different and equally arbitrary approach that gives the result being "explained" does not count

If didn't know about proton, Standard Model would predict it, and all it's properties

If didn't know about dark matter, supersymmetry would have predicted it, made us look for it

– that's what actually happened for dark matter not made of protons and neutrons

If didn't know about gravity, families of particles, Standard Model forces, string theory would have suggested them

SOME QUESTIONS
Beyond SM

	Standard Model	*Supersymmetric* Standard Model	*String theories*
What form is matter?	√		√ √
What *is* matter			√ √
What is light?	√√		
What interactions give our world?	√		√ √
Gravity	~	~	√√
Supersymmetry?			√ √
How is supersymmetry broken?			√ √
Stabilize quantum hierarchy?		√√	
Explain hierarchy?			√ √
Unify force strengths?		√√	√ √
Higgs physics?	~	√√?	√ √
What is dark matter?	~	√	√ √
Matter asymmetry (no antimatter)?	~	√	√ √

– √ ***address*** √√ ***explain*** ~ ***accommodate***

Test string theory?

- Test Newton's Second Law, F=ma? No, not directly, must specify F. Pick a force, test for lots of forces
  - -- Do similar thing for string theory – 10D → 4D, etc
  - -- Make predictions, test them → tests theory
  - -- Major focus of our meeting

- Don't need to be at Planck scale to test – always relics – Big Bang, speed of light, dinosaurs

- Test, "see" extra dimensions?
  - Total energy of world is zero, but for 10D world or 4D?
  - Cosmology of 4D world different from that of 10D world
  - Energy conserved in 10 D or 4D? Maybe particles escape into other D

Time scale to test theory? Usually few decades

– best tests often come after have theory, e.g. for electromagnetism light outside visible spectrum, radio waves

– for Big Bang, helium abundance, cosmic microwave background radiation

I think a major thing we have learned in the past two decades or so is that to ***explain*** our world beyond the Standard Model(s) we have to formulate our theories in more than four dimensions!

- ***Quantum dimensions for supersysmmetry***
- ***Extra space dimensions for string theory, each with a quantum dimension***

ANOTHER PERSPECTIVE – UNIFICATIONS

-- 400 years ago many forces, phenomena – then science unified our understanding of:

- Motion on earth and in heavens
- Motion and heat
- Motion and sound
- Electricity and magnetism
- Different forms of energy
- Everything we see made of atoms
- Chemistry and physics
- Everything we see made of electron and quarks
- Electromagnetism and light
- Space and time
- Special relativity and quantum theory
- Electromagnetism and weak interactions
- “Grand” unification of strong, weak, and electromagnetic interactions?
- String theory – grand unification plus gravity plus quarks and leptons?

Einstein’s goals of understanding achieved (if correct…)

All cultures addressed big questions – for thousands of years invented myths – no myth considered idea that science has led us to: the universe and life could arise in an extremely simple form and evolve over a long time into a beautiful and complex system

Myths are satisfying -- science testable, and right or wrong -- and satisfying too! – understanding *why* 

-- string theory and testing it with LHC, dark matter is taking us to new levels of understanding 

-- universe is old and cold and dark, and maybe has extra dimensions – but now we understand that life only possible if universe old and cold and dark (and has extra dimensions?) 

Humans evolved to need to understand – understanding the world can be a source of confidence and dignity