Title: String Theory: Unity in Diversity

Date: Jul 26, 2008 01:00 PM

URL: http://pirsa.org/08070053

Abstract: Amanda Peet received her Ph.D. at Stanford University and currently is Associate Professor at the University of Toronto, her â€œintellectual home base.â€• She is also an Affiliate Member of Perimeter Institute. Amanda's goal is to understand the fundamental dynamics of all forces and particles seen so far in Nature, especially gravity. Broadly: She studies the quantum dynamics of interactions between gravity and matter using string theory, with applications to black holes and cosmology, and links to gauge theory and particle physics. Past work has focused on the black hole information paradox, black hole entropy, D-brane models of black holes, duality, holography, building of new geometries, spacetime singularity resolution, and cosmology. Amanda continues to develop these interests, as well as develop others as new particle accelerator data from LHC and cosmological data (further) influence the field.

0.0

String Theory: Unity in Diversity

by
Amanda Peet
Department of Physics
University of Toronto

these slides are on my Physics web site:

http://pep.to/outreach/pi08

0.1

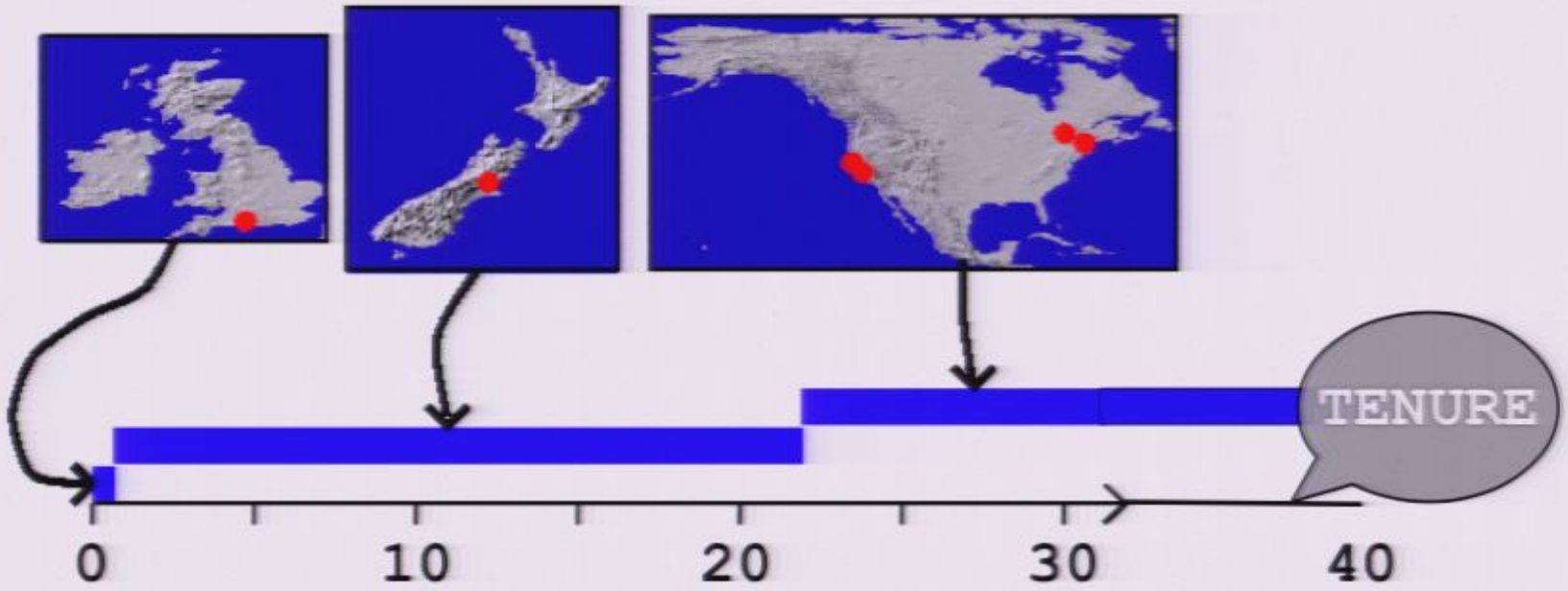
Identity check

This Amanda Peet ...

not that one!

0.2

A brief history of (ti)me



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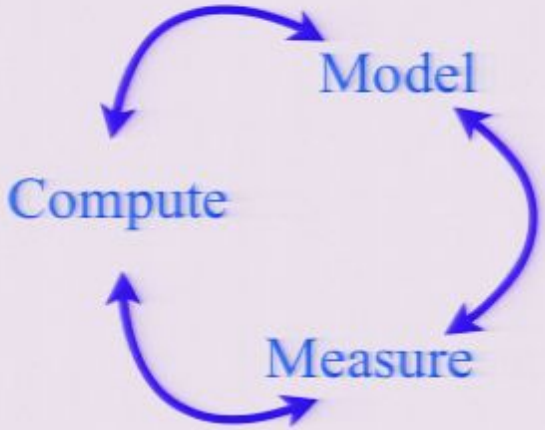
Philosophy: patterns and distance scales

- Physicists: experiment (measure) and theorise (model).
- Traditionally this was a dichotomy for specialization.
- In modern era:



- Want to explain structure - and origin - of fundamental matter and forces, from sub-atomic to cosmological scales!
- Biggest distance imaginable: Hubble (10^{+26}m) *"Macro"*.
- Tiniest distance imaginable: Planck (10^{-35}m) *"Micro"*.

Tools theoretical physicists use

- Computers: hardware and software

- International conferences, workshops, and web sites

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- Discussions with colleagues!
- *Math* is international language.

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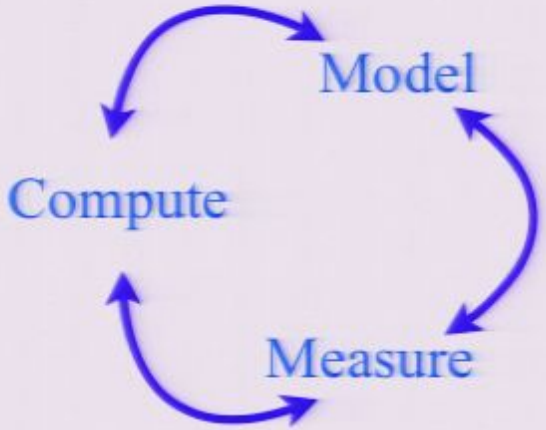

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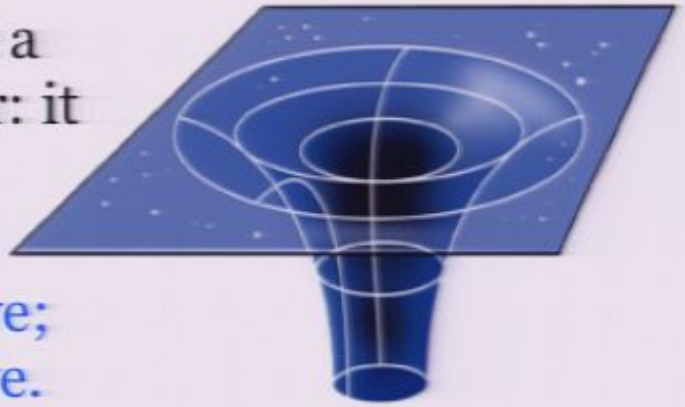
Einstein's GR as intellectual earthquake

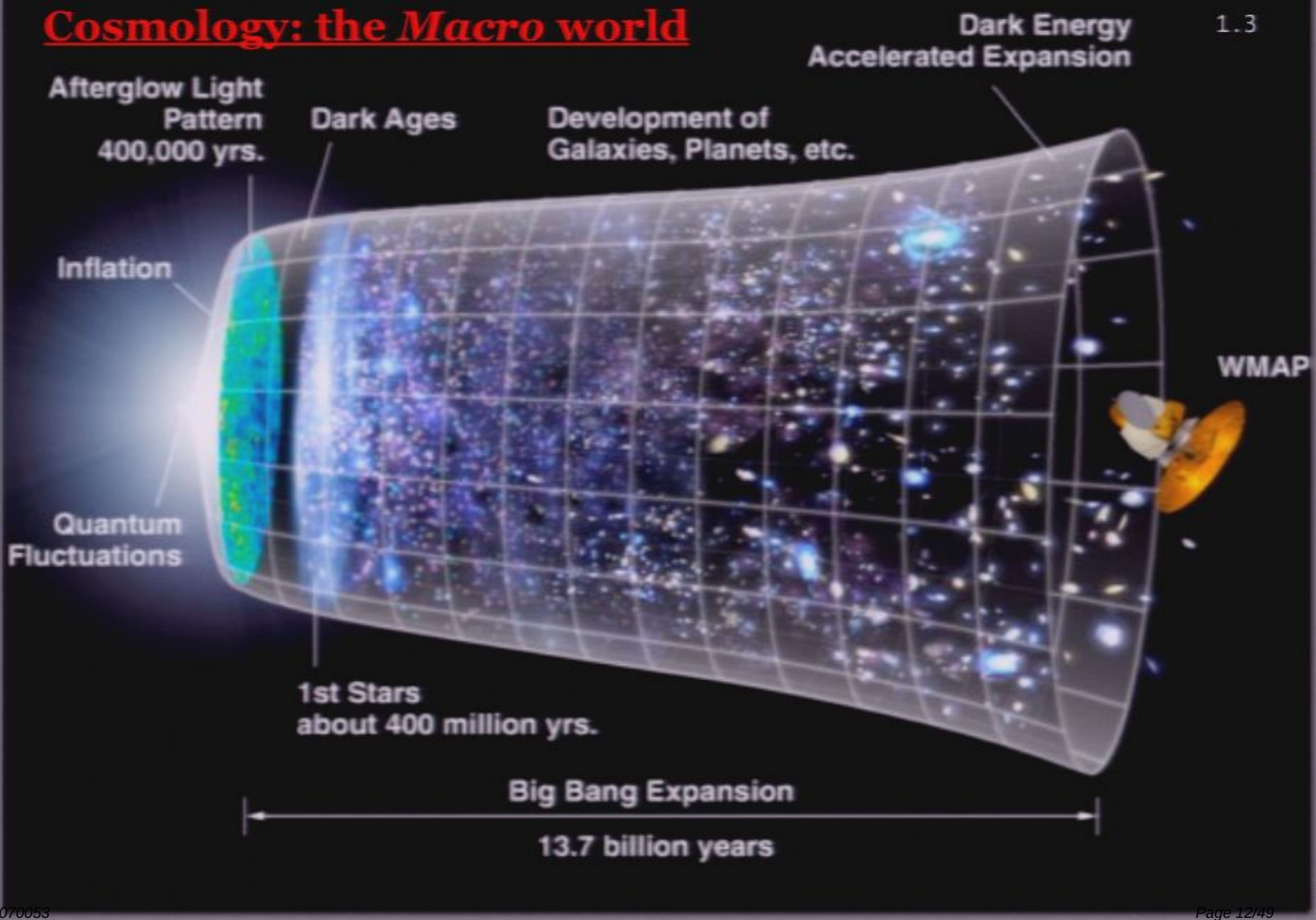
- 350 years after Newton, in 1916, Einstein *finally* finished a new theory of gravity, "General Relativity" (GR).
- Main feature of GR: incorporates unbreakable speed limit. Fastest speed = speed of light = speed of gravity. *Nothing* goes faster than light!

- Einstein's GR theory was a bit like a butterfly coming from a caterpillar: it turned into a beautiful new geometrical thing. "Spacetime."
- Matter tells spacetime how to curve; spacetime tells matter how to move.



Cosmology: the *Macro* world

1.3

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gig-PI.pdf (page 8 of 33)
WMAP and the CMBR
1.4

Relativity: mass, energy and momentum

- Relativistic relationship between $\{m, E, p\}$ is as follows:-

$$\boxed{E^2 - |\vec{p}|^2 c^2 = (mc^2)^2}$$

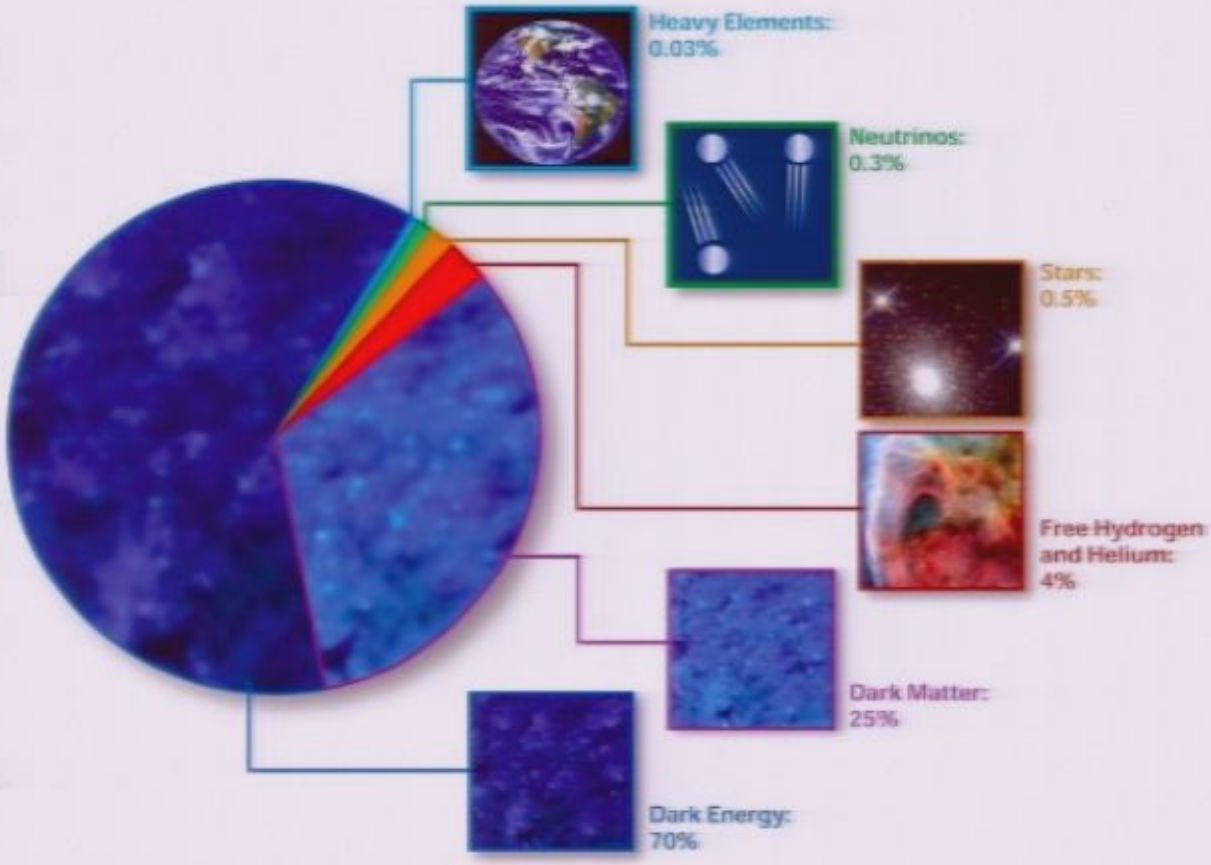
- The beauty of this equation is that it holds in all frames of reference. Mass is *invariant*. It never changes.
- (Kinetic) energy and momentum change under a change of reference frame*, but $\{E, p\}$ keep satisfying the constraint.
- What about *rest frame*? There $\vec{p}_{\text{rest}} = \vec{0}$ so $E_{\text{rest}} = mc^2$.
- What about *massless* particles? $m=0$ so $E_{\text{massless}} = |\vec{p}|c$.
- N.B.: because c is so large in human units, just 1kg of mass converts into a huge explosive energy, equivalent in strength to a *~21.5 Mt* bomb! (Hiroshima was *"only" 5kt!*)

* $$\begin{bmatrix} E \\ p_{\parallel} \end{bmatrix} \to \begin{bmatrix} \cosh\eta & \sinh\eta \\ \sinh\eta & \cosh\eta \end{bmatrix} \begin{bmatrix} E \\ p_{\parallel} \end{bmatrix}; \quad \vec{p}_{\perp} \to \vec{p}_{\perp}; \quad \text{where} \quad \tanh\eta = \frac{|\vec{v}|}{c}$$

1.6

What is our universe made of?

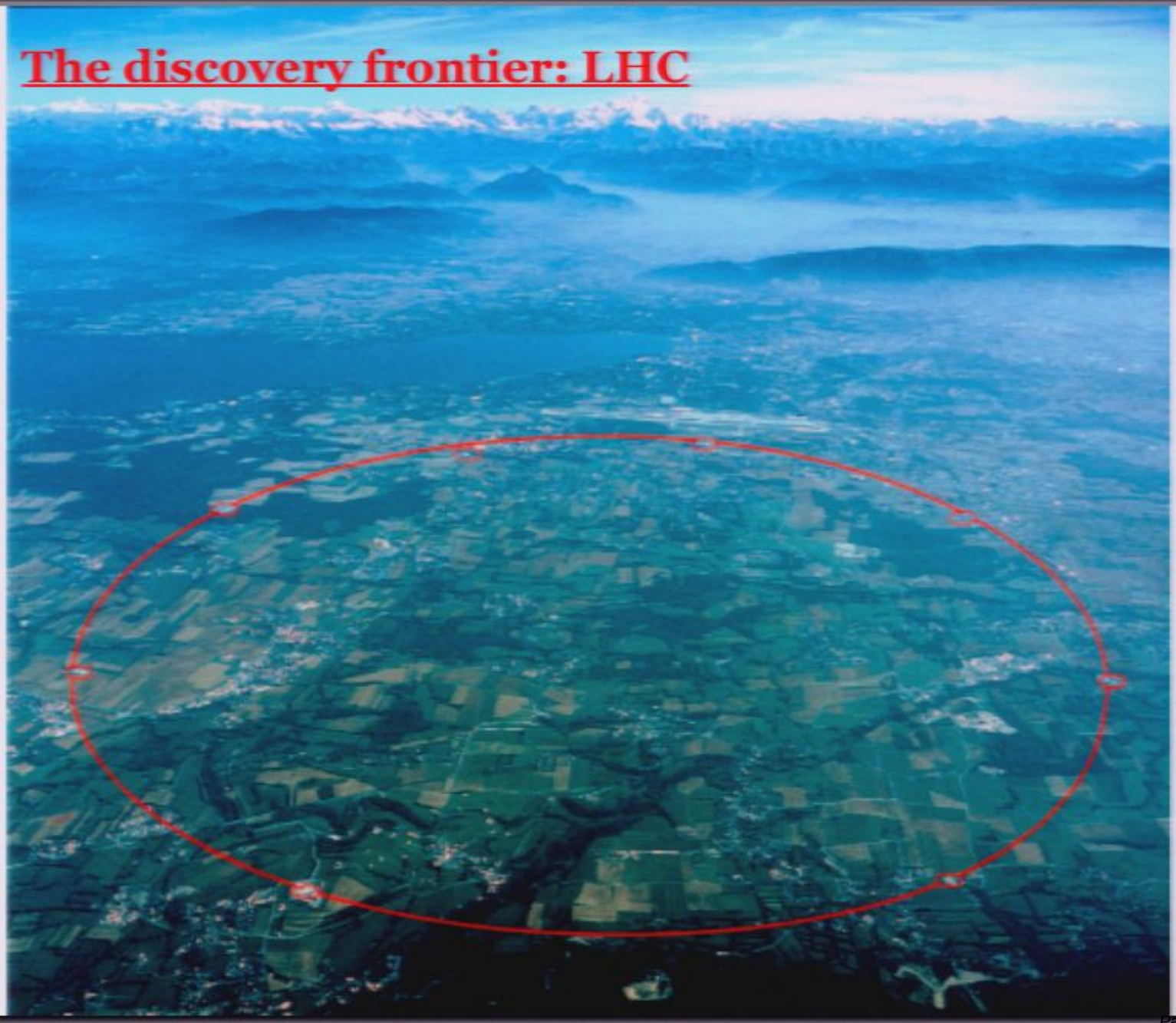
- Survey *stuff* of universe through its gravitational effects.
- CMBR, SNe, lensing, etc. sensitive to different components.



- N.B.: 95% of our universe is made of *unknown* dark stuff!

The discovery frontier: LHC

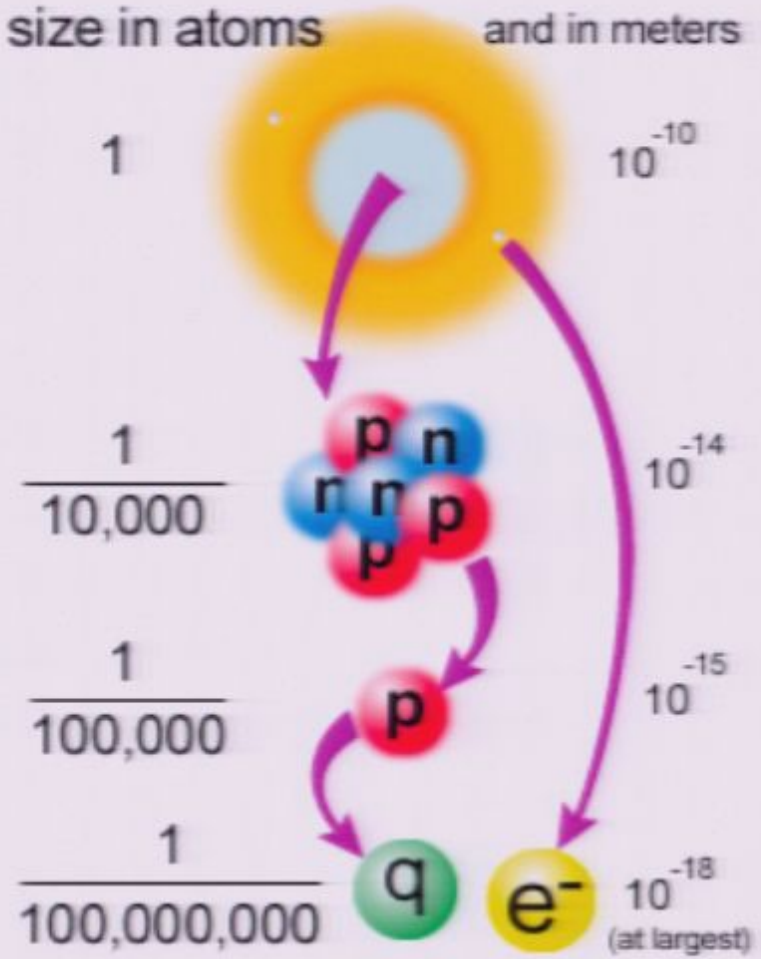
2.2



2.1

Subatomic particles: the *Micro* world

- Molecules are made of atoms.
- Atom has a nucleus and a cloud of electrons around it.
- Nucleus held together by gluons (to counter EM).
- Inside each proton and neutron of nucleus, 3 *quarks*!
- Quarks, and leptons (like e-), are "elementary" particles.
- To probe tiny distance scales, use giant particle accelerator ("atom-smasher").
- Current limit: atto-metre.
- Next step: LHC machine.



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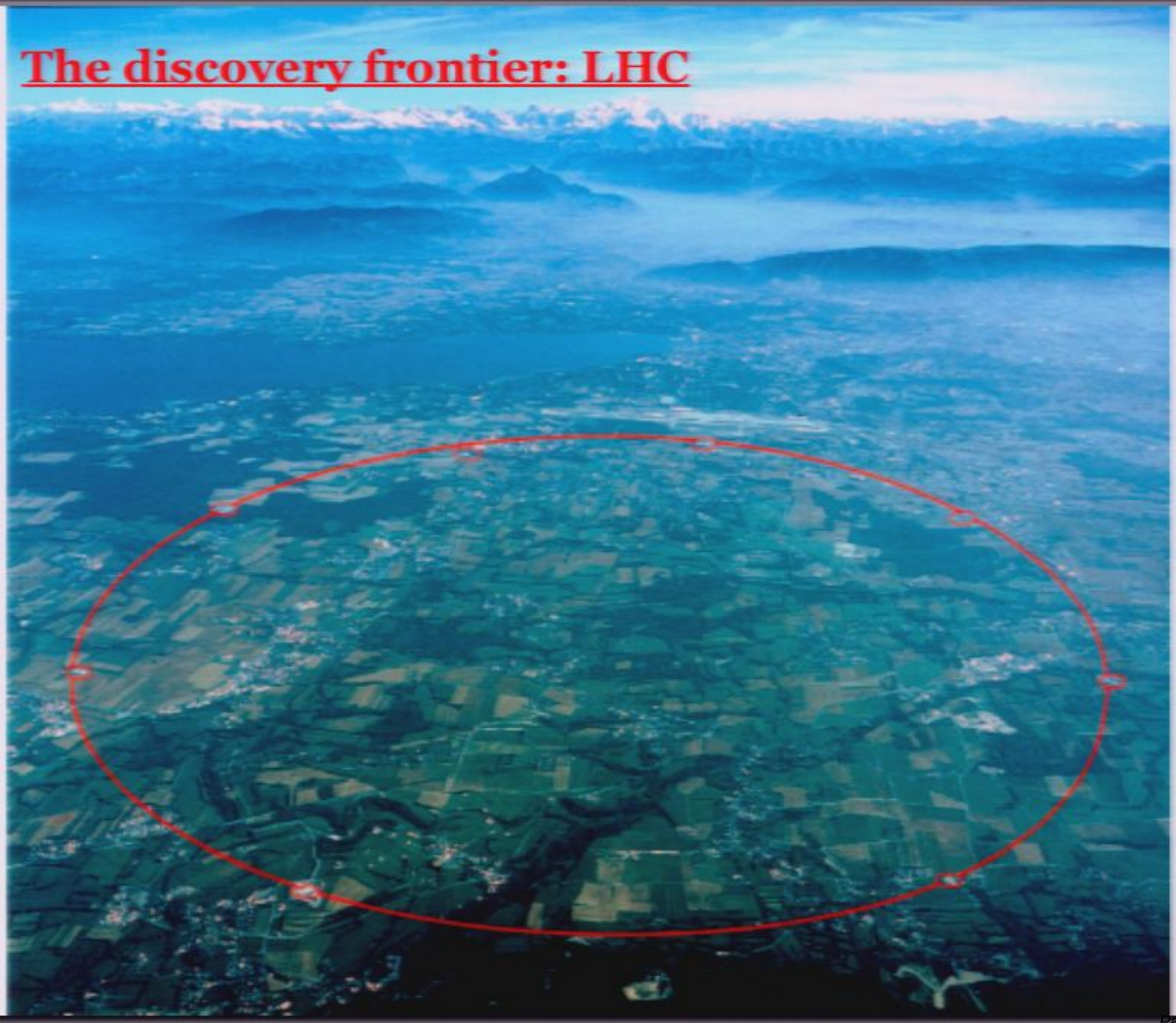

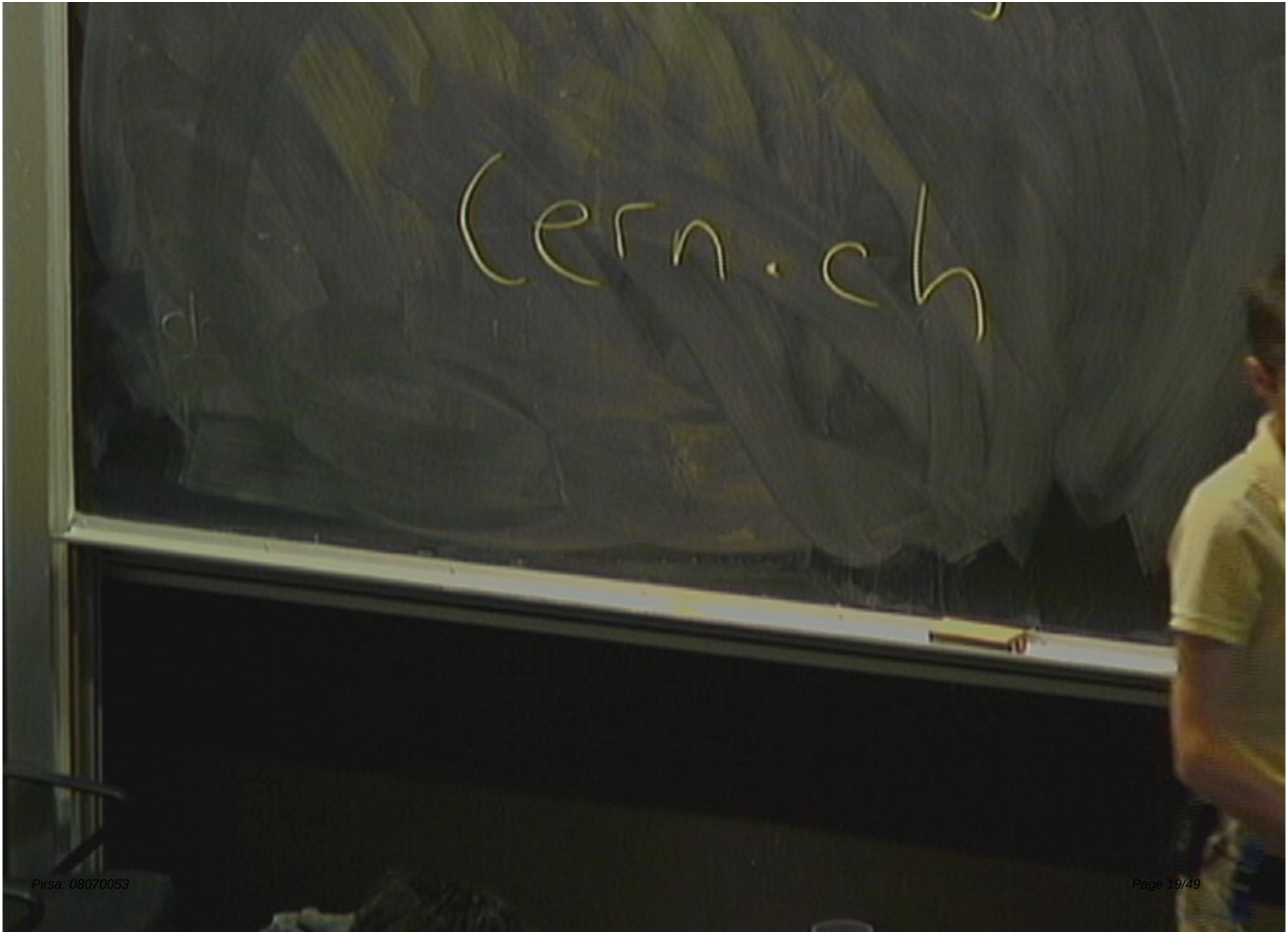
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The discovery frontier: LHC

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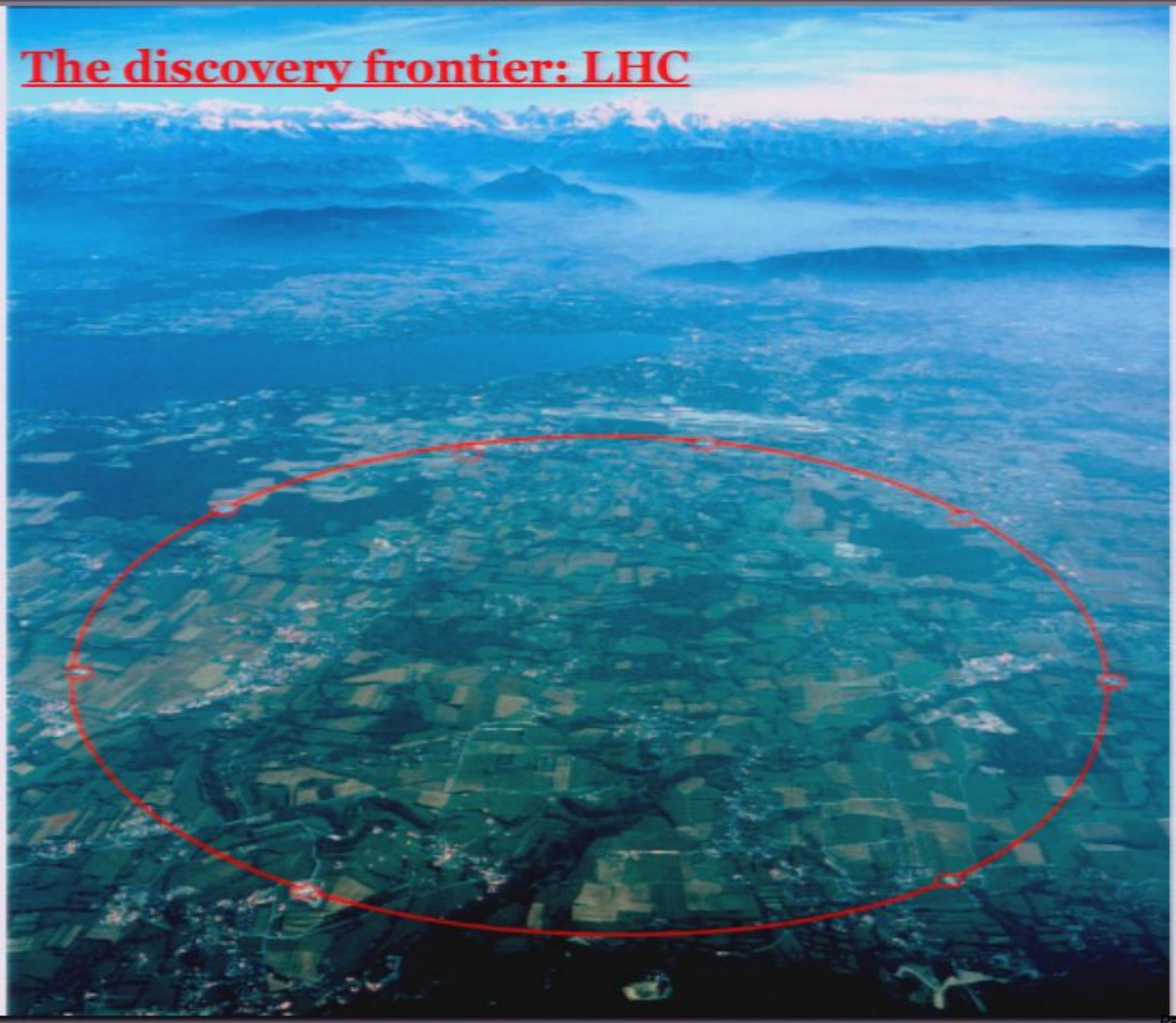
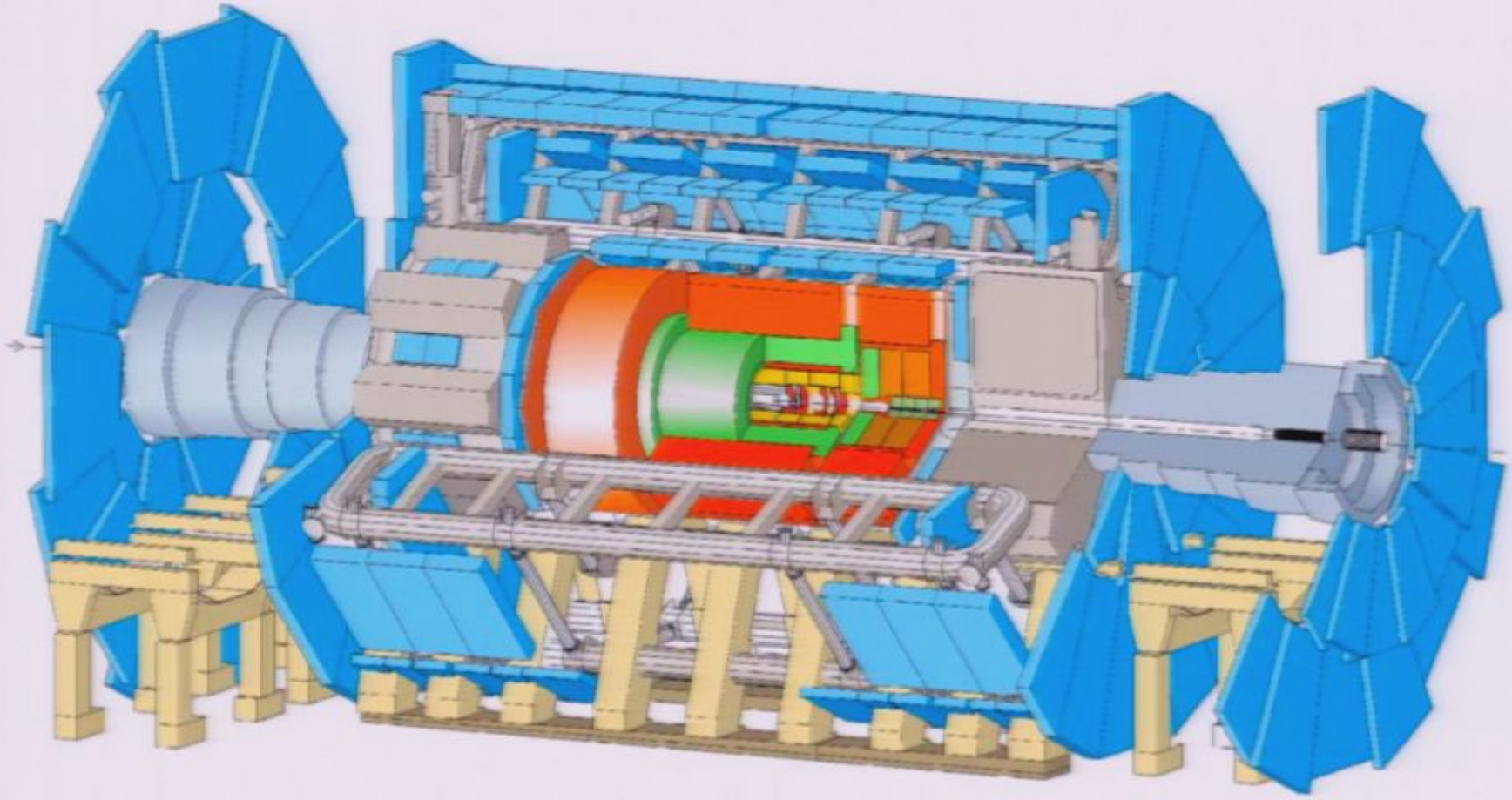
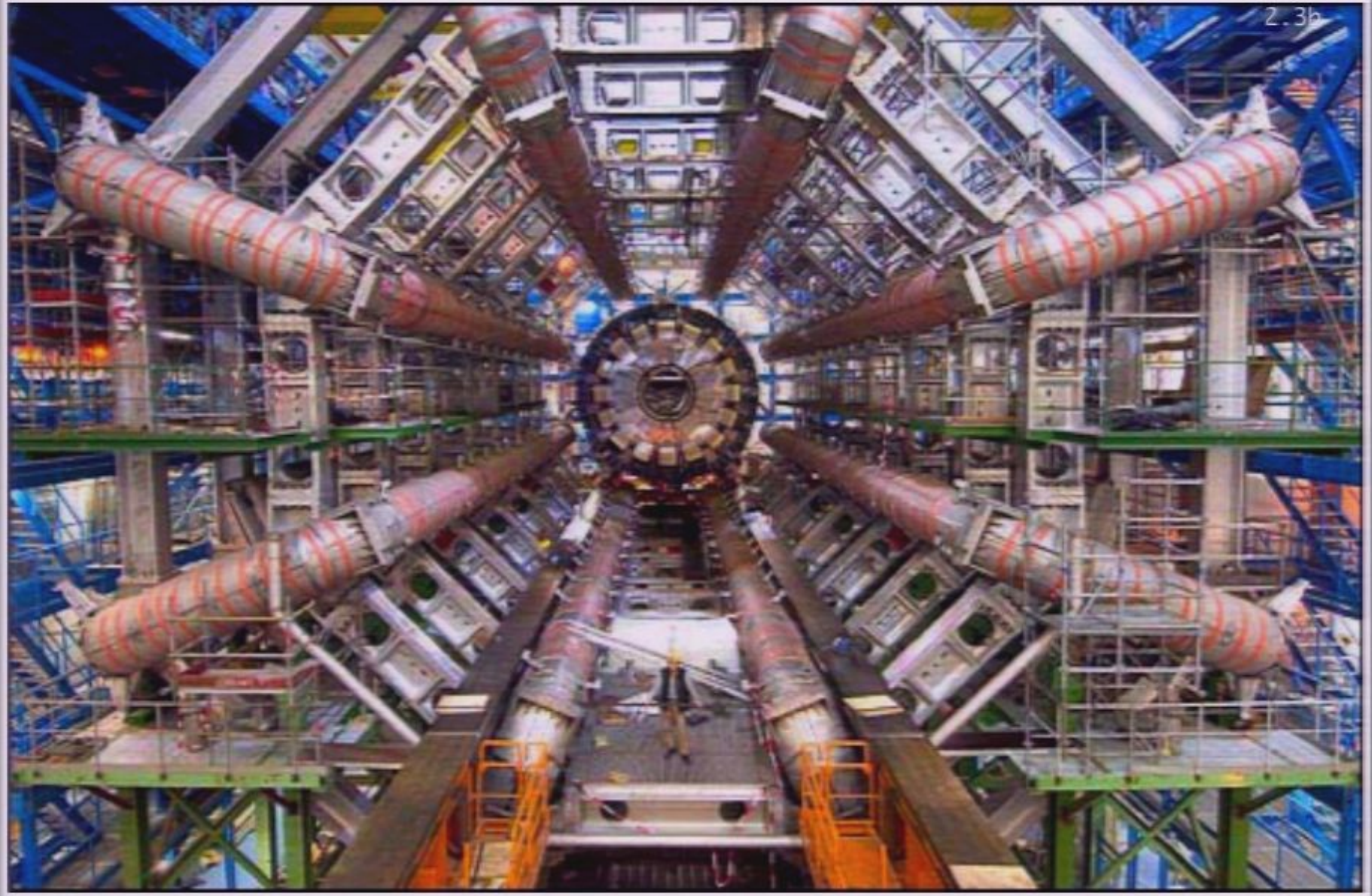


2.3a

The ATLAS detector part of LHC




2.3b

Quantum uncertainty

- The Heisenberg Uncertainty Principle is deep and fundamental; it describes *tradeoffs in precision* for pairs of physical observables. Examples:-
  - time versus energy: $\Delta t \Delta E \geq \hbar$
  - spatial position versus momentum: $\Delta x \Delta p \geq \hbar$
- Every quantum has fundamental jitter about it, called "zero point energy". Can *never* turn this off - even at absolute zero temperature. Intrinsic; fuzzes things out.
- If we have high enough energy in our system, its energy uncertainty can translate into uncertainty about particle number via $E = mc^2$.

Quantum behaviour rules the *Micro* world

- Everyday objects have "definite" properties, e.g. size, speed. This "fact" is actually an *idealization*, valid only if the object is heavy and slow (e.g. hockey puck)!
- In real life, *quanta (wavicles), not particles or waves.*
- Quanta sometimes behave like pointy things, sometimes like wavy things. *Quantum weirdness real*: seen in lab.
- Quantum physics insists that we give up on determinism. We are left instead with the knowledge that what we *can* calculate to high precision are *probabilities*.
- Einstein remained uncomfortable with this, even to the very end. However, as Stephen Hawking said, "It was Einstein who was confused, not the quantum theory!"

2.6

Why quantum physics doesn't rule the *Macro* world

- De Broglie wavelength of quantum: $\lambda = \frac{h}{p}$
- For a photon (massless), $p = \frac{E}{c}$, $E = hf$
  e.g. a green photon has wavelength ~550nm.
- For massive particles at low speed a good approximation is: $p = mv$
- Therefore, a 60kg Amanda moving at ~1m/s has a de Broglie wavelength of approximately ... the Planck length!

- This is so small as to be completely irrelevant.
- Typically: if de Broglie wavelength is of same order as apparatus size, *see* quantum weirdness.

3.1

Graviton scattering in quantum theory

- The tug by gravity on anything with energy - like an electron, or even another graviton- can be computed in terms of exchanging gravitons. [c.f. ice skaters]

- Quantum physics applied directly to Einstein's theory gives - for the scattering probability of gravitons -

$$\text{Probability} \propto \left(\frac{E}{E_{\text{Planck}}}\right)^2$$

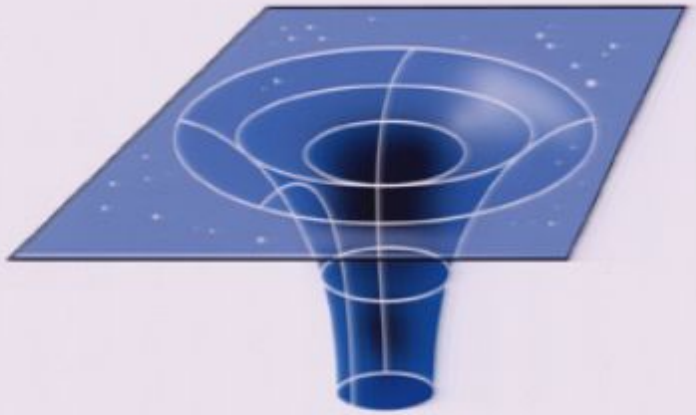
- This becomes *nonsensical* at energies higher than

$$E_{\text{Planck}} \sim \sqrt{\frac{c^5\hbar}{G}}$$

- which is about a Gigajoule (a.k.a. 10^{19}GeV) - a big kick!

Twin pillars of 20th Century physics

- Quantum Field Theory "QFT" - quantum toolbox - gave us Standard Model of particle Lego: 3 forces + matter.
- In particle Legoland, gravity is classical, weak, & *ignored*.
- Einstein's General Relativity "GR" is relativistic classical theory of gravitational force. Supersedes Newton's.
- Toolbox is geometrical; very different math than QFT of other 3 forces.
- GR describes space-time as a dynamical fabric – which is warped by matter – and which causes matter to move.



A theoretical emergency

- Twin pillars of 20th Century Physics - GR and QM - are fundamentally incompatible: at high-energy, physical questions get nonsensical answers. *oops!*
- Need new theory, with softer high-energy behaviour, that
- reduces to known physics in well-understood regimes: ➠ GR in classical limit (Correspondence Principle);
- has no internal mathematical inconsistencies (ie, is anomaly-free);
- describes quantum gravity.

- Want to *calculate* physics of big bang and black holes.

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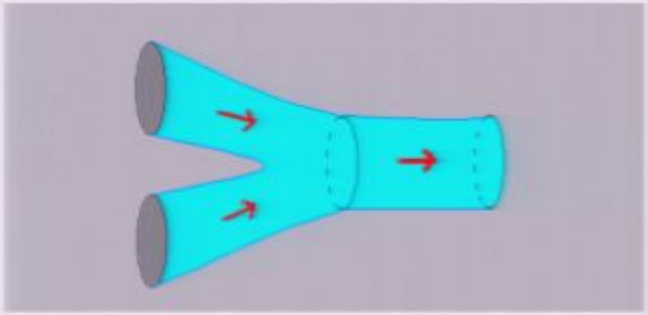
3.4

String = Lego

- All 'particles': matter and force-carriers (e.g. electron, quark, photon) are really tiny vibrating "superstrings" or "strings".

- Forces described naturally via splitting and joining of strings. Smooth process.



- If assume strings are basic lego, consistent (quantum!) theory of gravity comes out *automatically*.
- *Calculability* is ST's great advantage.

- String is simplest complication needed to solve puzzles⇛

Particle ID

- How does a physicist tell particles apart?
  - By mass and (intrinsic) spin, which are the *only* labels invariant under space-time symmetry.

- Two major types of particles:-
  - matter: spin ½ (fermions),
  - interaction-transmitter: spin 0,1,2 (bosons).

- Two kinds of fundamental matter seen, so far:
  - Leptons: $(e, \nu_e), (\mu, \nu_\mu), (\tau, \nu_\tau)$
  - Quarks: $(u, d), (c, s), (t, b)$
  - Puzzles: why 3 generations? why mass hierarchies?

- Four fundamental forces seen, so far ➡

3.6

Force ID

Force:	Gravity	EM	Weak nuclear	Strong nuclear
carrier particle:	h	γ	W^+, W^-, Z	g
felt by leptons:	yes	yes, if charged	yes	no
felt by quarks:	yes	yes	yes	yes
range:	infinite	infinite	sub-nuclear	nuclear
strength today:	weakest	weak	weaker	strong

Puzzles: How do Z,Ws get mass? Why different strengths?

Forces and coupling constants

- How do physicists get a handle on how strong a force is? By measurement... and also by modelling it, using quantum principles to do calculations.

- For electromagnetism, force strength is the "fine structure constant":

$$\alpha_{\mathrm{EM}} = \frac{e^2}{\hbar c}$$

- Weak and strong nuclear forces have a similar story.

$$\alpha_{\mathrm{W}} \quad , \quad \alpha_{\mathrm{S}}$$

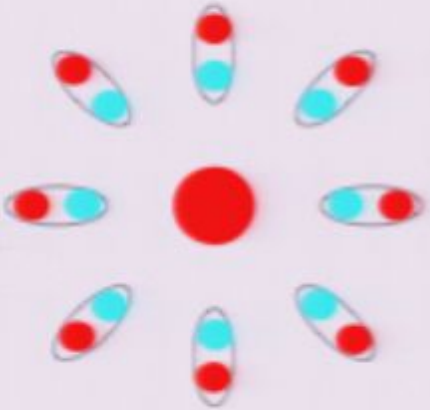
- For gravity, the situation is different (!):

$$\alpha_{\mathrm{G}} = \frac{G}{c^5 \hbar} E^2$$

- Notice how energy E appears. * What if E gets huge?!?

3.8

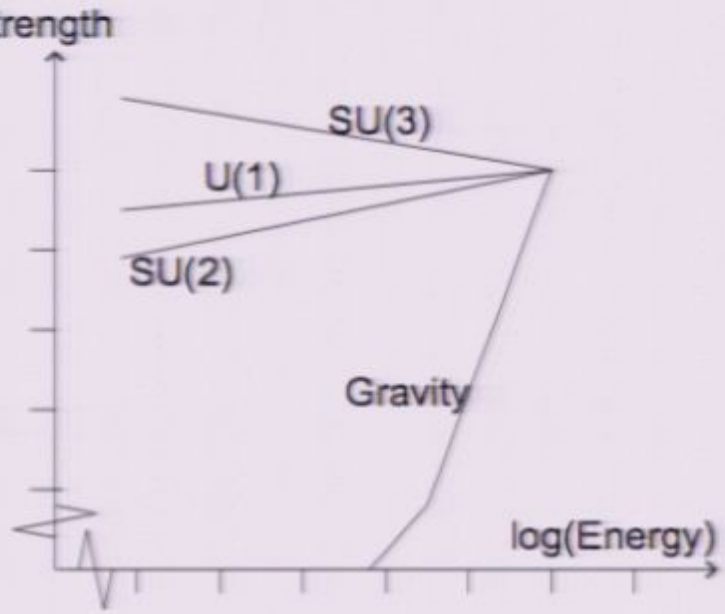
Unification



- Fundamental constants describing strength of forces *not* actually constant: "coupling constants" vary with energy!

- Screening relies on relativity (so making virtual pairs isn't prohibitively expensive) and quantum uncertainty (so pairs in cloud aren't real).
- Strong nuclear force gets *weaker* at higher energy (!);
- EM, weak nuclear, gravity get stronger at high energy.

- Wildly extrapolating strengths upwards suggests all 4 forces unify into one force at 10^{32} K!

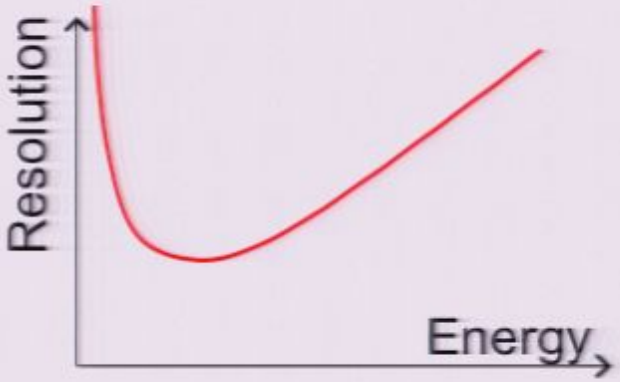


Where does the buck stop?

- If we keep looking deeper and deeper, will there be more and more layers of the onion?

- For particle accelerators, higher energy (more $$) gives better resolution.
- What about string accelerators?

- Pumping energy up beyond string scale turns out to pump up size of probe!



- Minimum physical size indicates no need - or meaning - to looking 'deeper'. So maybe this (string) really is *it*!

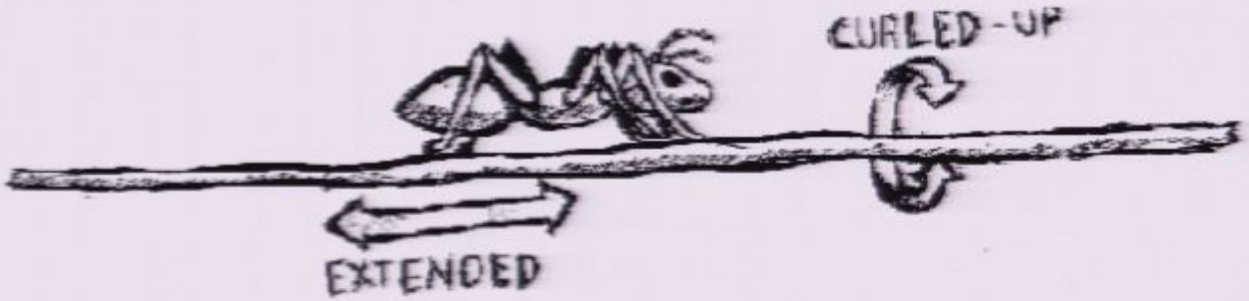
Supersymmetry

- Theoretical boson-fermion pairing.
- Logical extension of known symmetries of Nature.
- Useful for helping explain unsolved puzzles.
- Supersymmetry, if it exists in Nature, must be *broken* at today's energy scales: no sparticles seen to date.
- Super-stuff may be discovered at LHC accelerator; may explain dark matter - perhaps even dark energy!

Particle	Superpartner
leptons, quarks	sleptons, squarks
Higgs	Higgsino
photon, Ws, Z, gluon	photino, Winos, Zino, gluino
graviton	gravitino

Extra dimensions of space

- Theories incorporating this idea go back over 80 years, but string theory is new in requiring more dimensions.

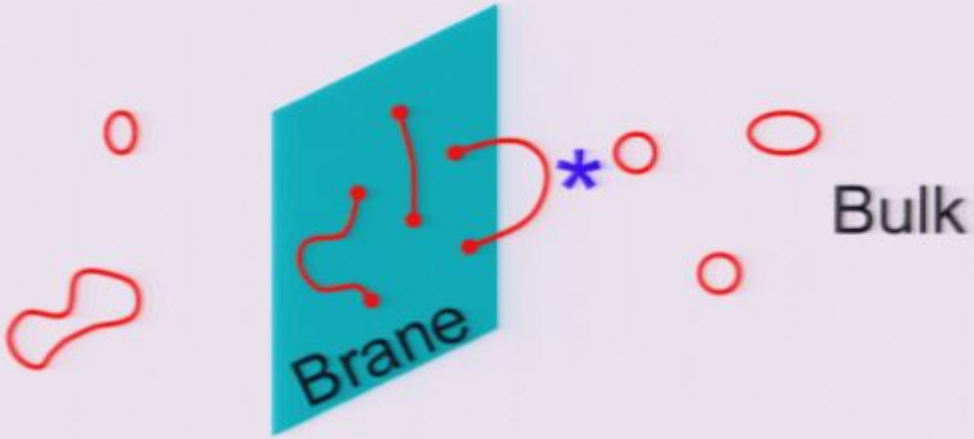


- Big ant can walk in only *one* direction - the circular (small) dimension is just curled up so small it goes unnoticed.
- Tiny ant would think twig surface is *two*-dimensional.

- State-of-the-art experiment says:
  - if all are allowed in, extra dimensions must be <0.01fm
  - if only gravity is allowed in, they must be <0.15mm

D-branes (new in 1995)

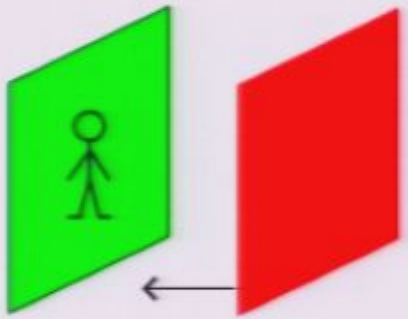
- Strings not the only extended objects in string theory!
- "D-brane" := hypersurface where open strings end



- D-branes carry generalization of electric charge
- Gravity fields (etc.) live in $D=9+1$: "in bulk"
- Gauge fields (e, γ, etc.) live in $d=p+1$: "on brane"

Origin of our universe

- Special challenge for any unified theory: must explain origin of matter+spacetime from scratch, *magic-free!*
- String theory gives new options for creating the initial hot tiny fireball that expanded to eventually create Earth+us.
- Imagine car crash (with eyes, ears shut) ➡
- Was the Big Bang really a Big Brane Crash?



New dualities between particle & string theories

- Emergent gravity examples occur in "large-N" systems.
- Take lots of D-branes:

$$N \to \infty$$

- Special low-energy limit ⇛ massive simplifications! actions between closed & open strings go away.

Open strings: large-N particle gauge theory living on branes	⟷	Closed strings: living in *near-core* region of bulk spacetime

- Stunning new dualities (equivalences) between gravitational/stringy theories & particle field theories.
- *Explicit, computable* example of emergent gravity.

Spacetime - quantum, dynamical, emergent

- Spacetime used to be known as just a *stage* on which the real actors - particles and forces - played out the drama.
- In modern string theory, we can smoothly
  - tear the fabric of space, change its topology;
  - change the number of dimensions of space.
- So spacetime as a fundamental idea is probably doomed!
- Big fat classical space-time must be dynamically *emergent*. How does this happen? Need to work out more examples.
- Some remaining, intriguing questions:
  - Why does time run forwards?
  - Was there anything before the Big Bang?
  - Should quantum theory be applied to the whole universe?
  - Is our universe a lucky cosmological accident or unique?

4.8

Join in: undiscovered country awaits you!

- Even as progress continues - in bits and fits - big Qs remain!

- What is the nature of quantum gravity?
- Why is there an arrow of time?
- What, exactly, lies at the heart of a black hole?
- What are the limits of scientific knowledge?

- Remember David Gross maxim: "when in doubt, *calculate*!"

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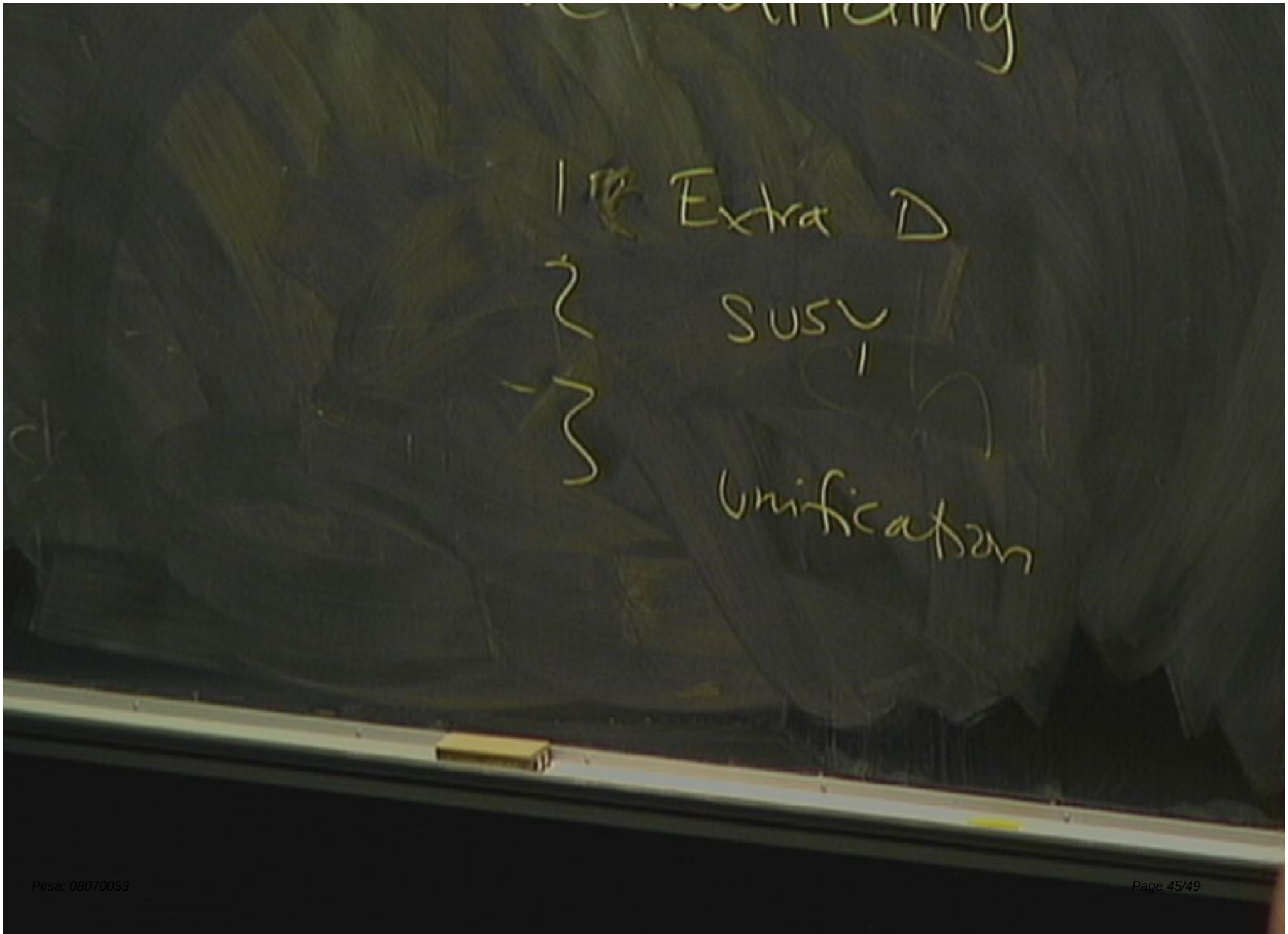
1 Extra D
2 SUSY
3 Unification

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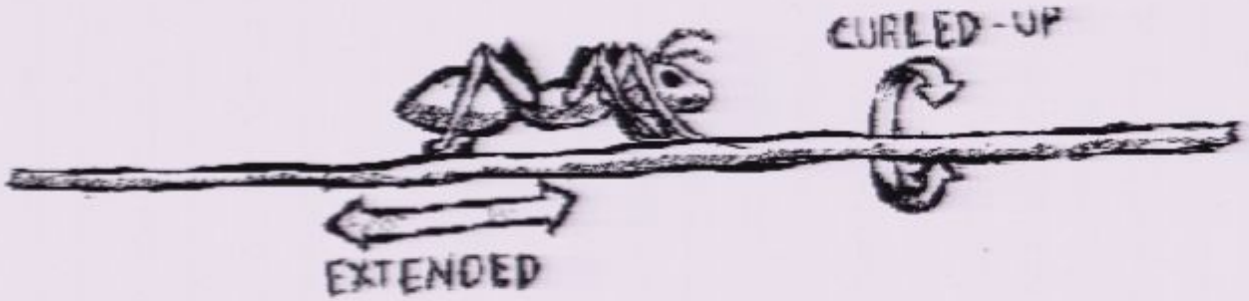

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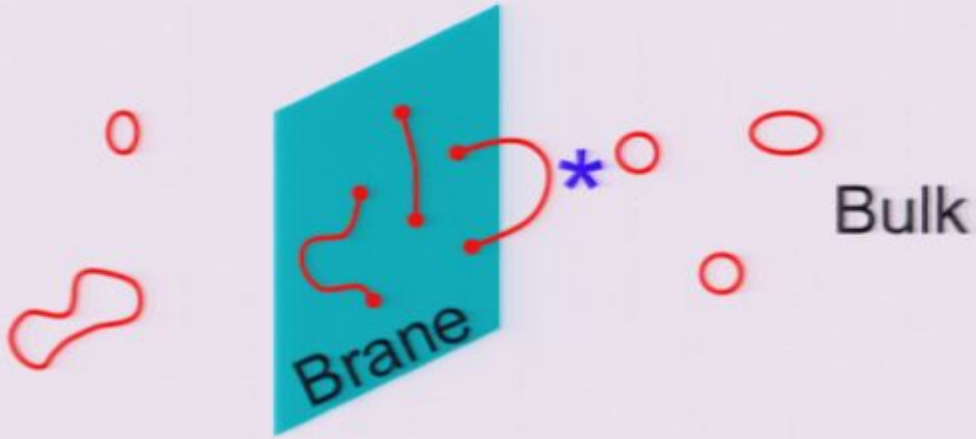

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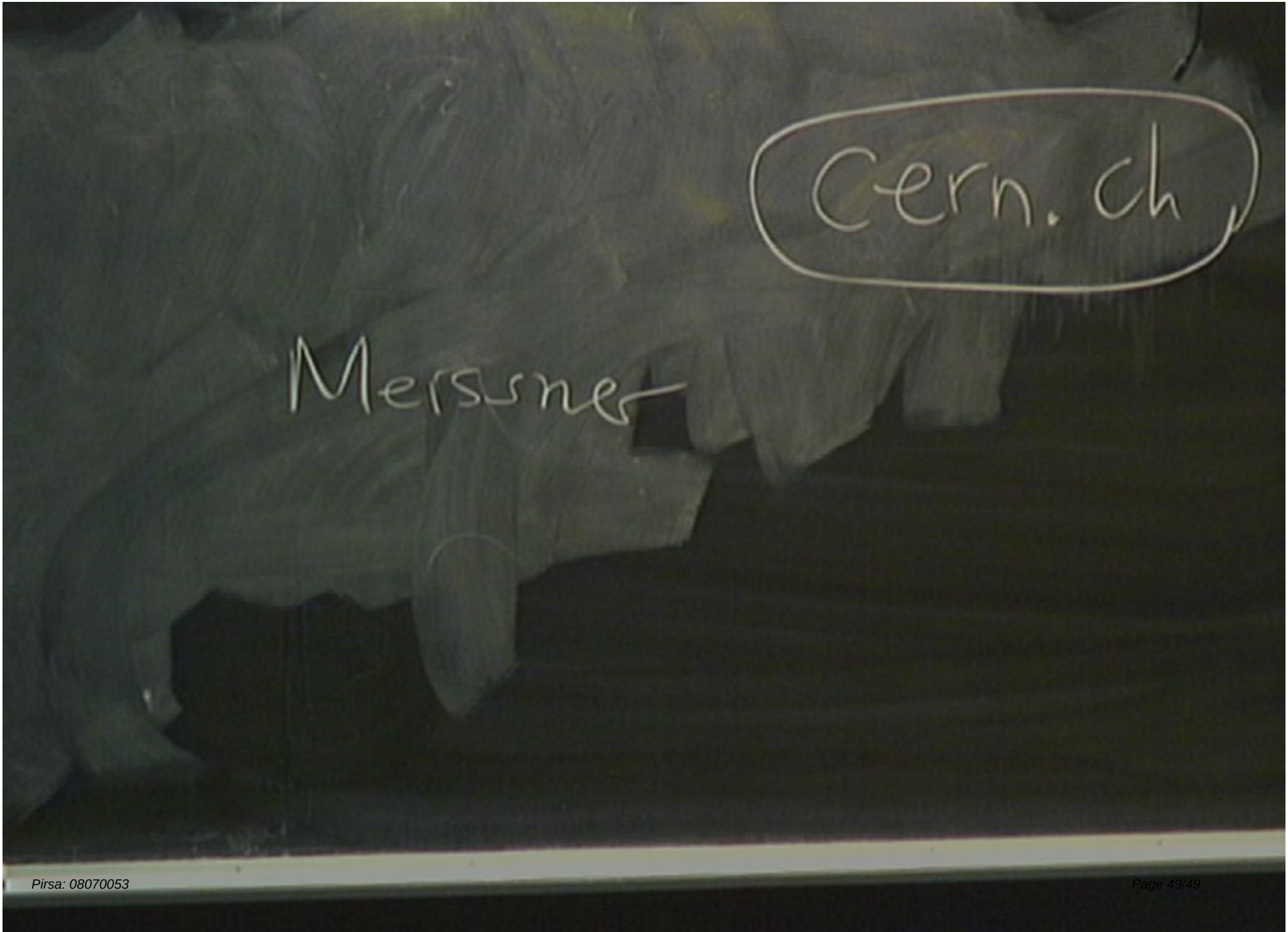
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