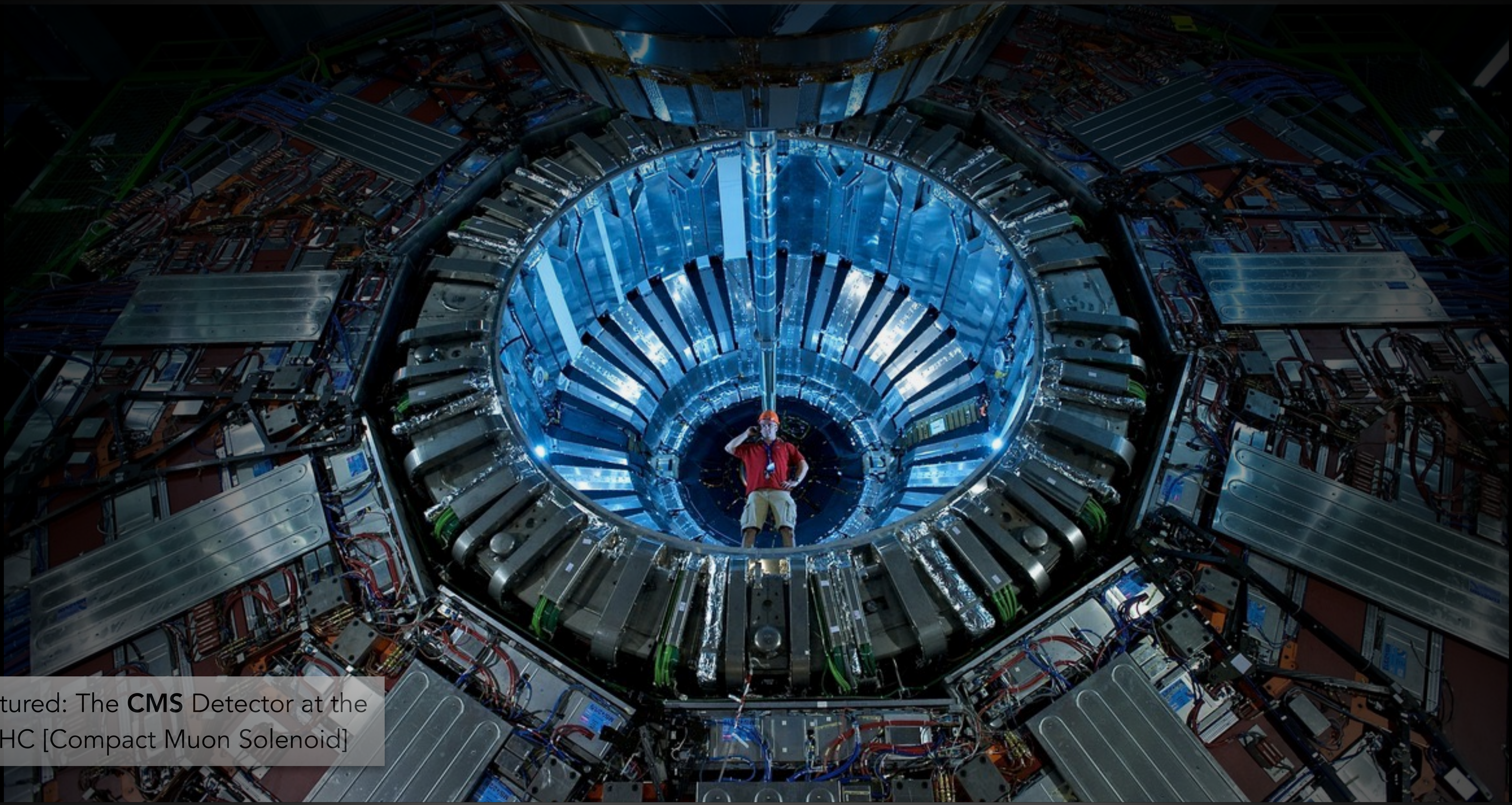
The Large Hadron Collider

& how the game has changed since it switched on in 2008



Pictured: The **CMS** Detector at the LHC [Compact Muon Solenoid]

Dr. Peter Skands

School of Physics and Astronomy - Monash University

& ARC Centre of Excellence for Particle Physics at the Terascale

Why do Science?

Scientia potentia est - knowledge is power

We can improve our lives with it

We can build new things with it

We can solve problems with it

The Real Reasons:

Curiosity and **Fascination**

The Universe is vast, beautiful, and full of mysteries

+ I believe that science is a force for civilisation, without which …

"no knowledge of the face of the earth; no account of time, no arts, no letters, no society, and […] the life of man solitary, poor, nasty, brutish, and short."

On mankind's state without civilisation; Hobbes *Leviathan (1651)*

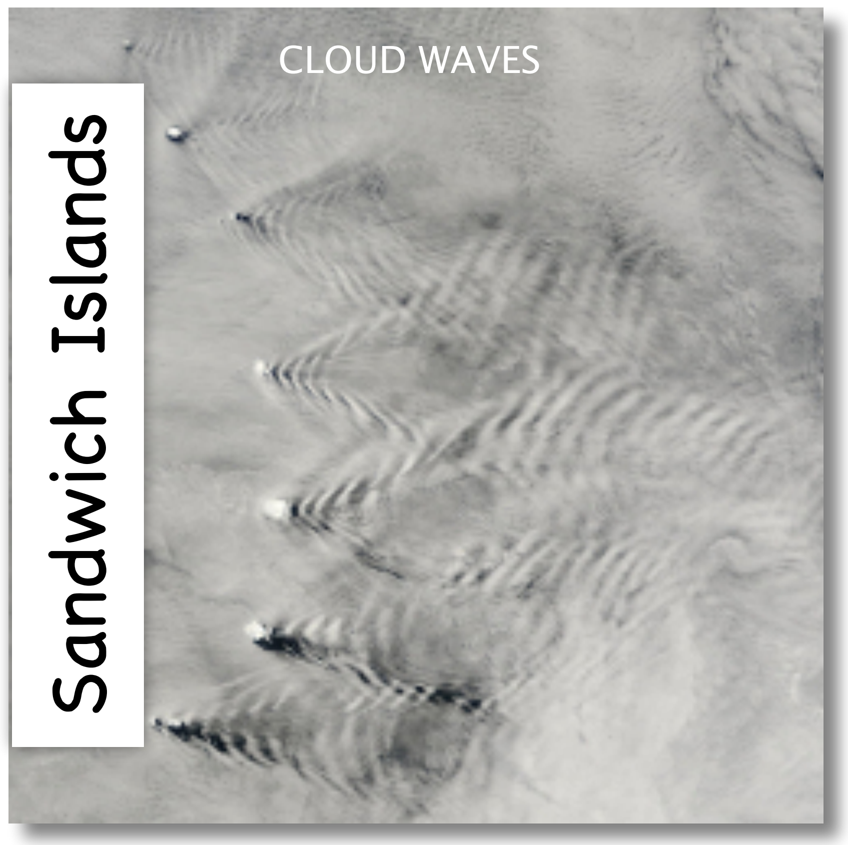
Superstition ain't the way

S. Wonder; *Superstition (1974)*

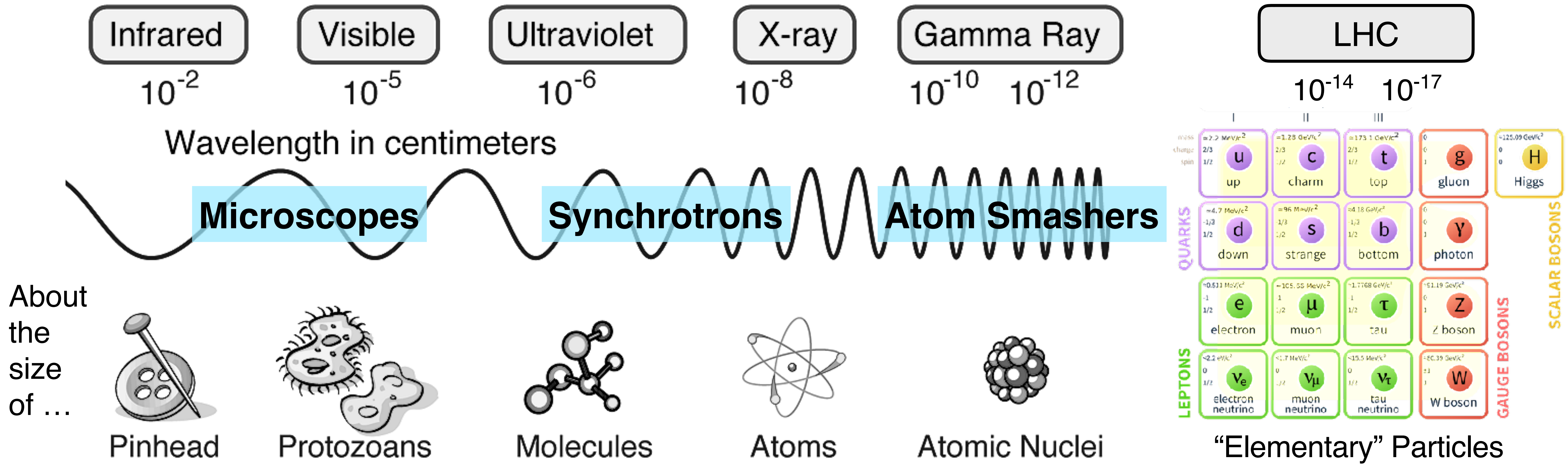
High Energy Physics

How do we see, in the quantum world?

To **see** something small, we need **short-wavelength probes**



NASA – MODIS



What do we need, to resolve a given wavelength with a single quantum (particle)?

"Planck-Einstein" relation

E: Energy $$\mathbf{E} = h\nu = hc / \lambda$$

(The analogy of $\mathbf{E} = mc^2$ for photons)

h: Planck's constant
c: speed of light
ν: frequency
λ: wavelength

Short Wavelengths ➜ **High** Energies

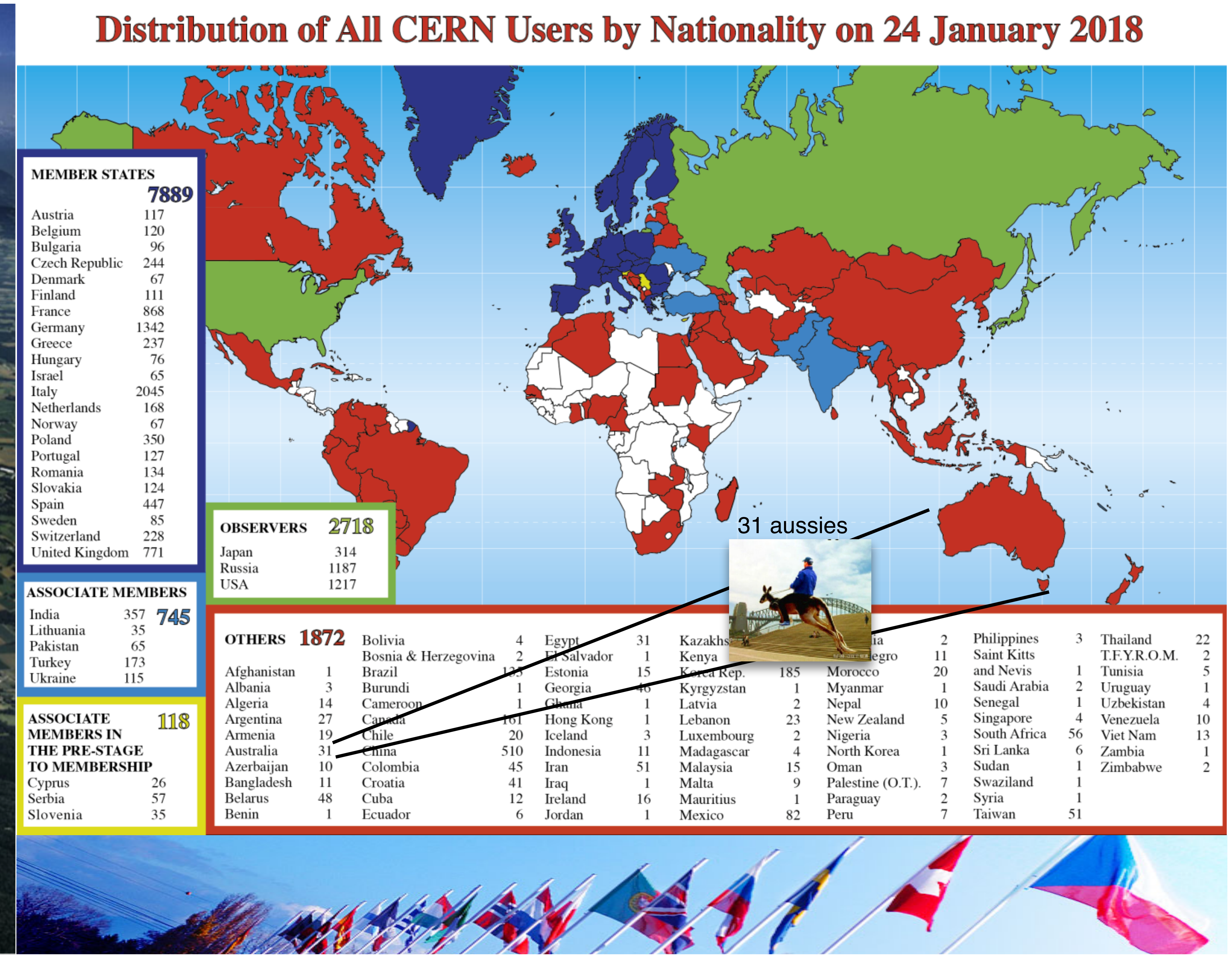
To resolve "a point" (truly fundamental particle?), we would need **infinitely** short wavelengths

In the real world: kick as hard as we can ➜ **accelerators**

CERN: European Organization for Nuclear Research

22 European Member States and around 60 other countries

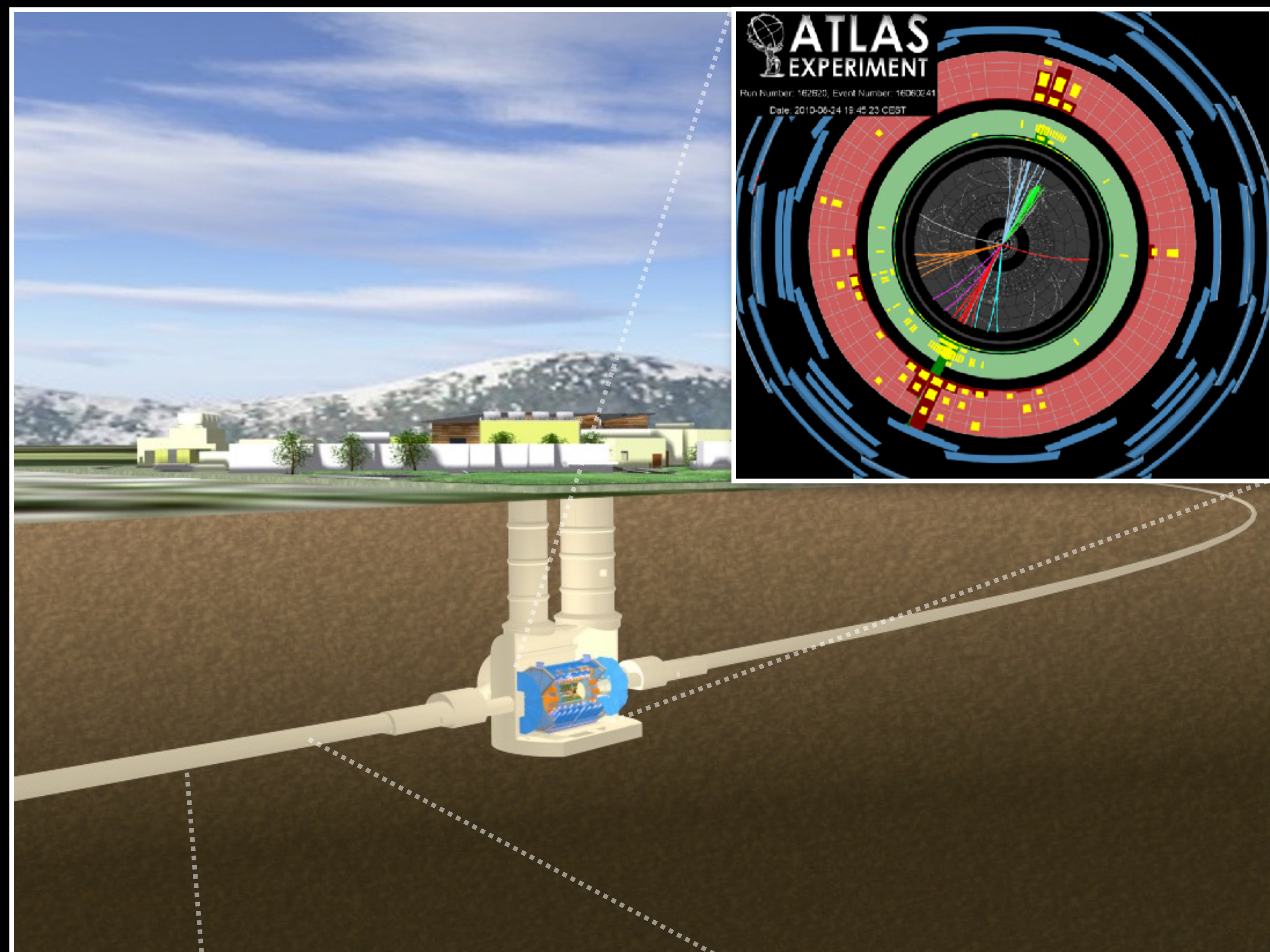
~ 13 000 scientists work at CERN



Founded in **1954** as one of Europe's first joint ventures

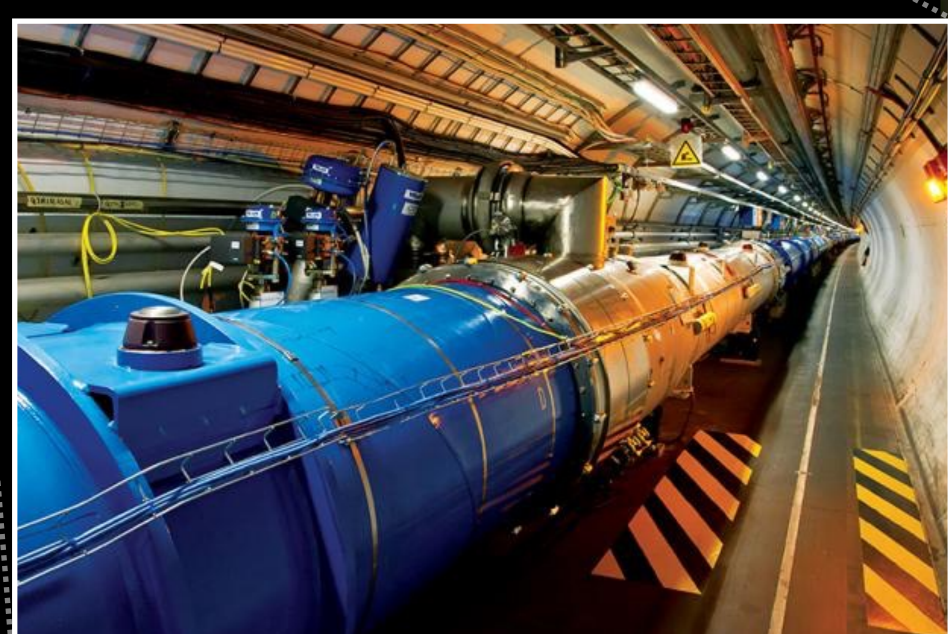
Yearly budget ~ 1 billion CHF ~ 1.4 billion AUD

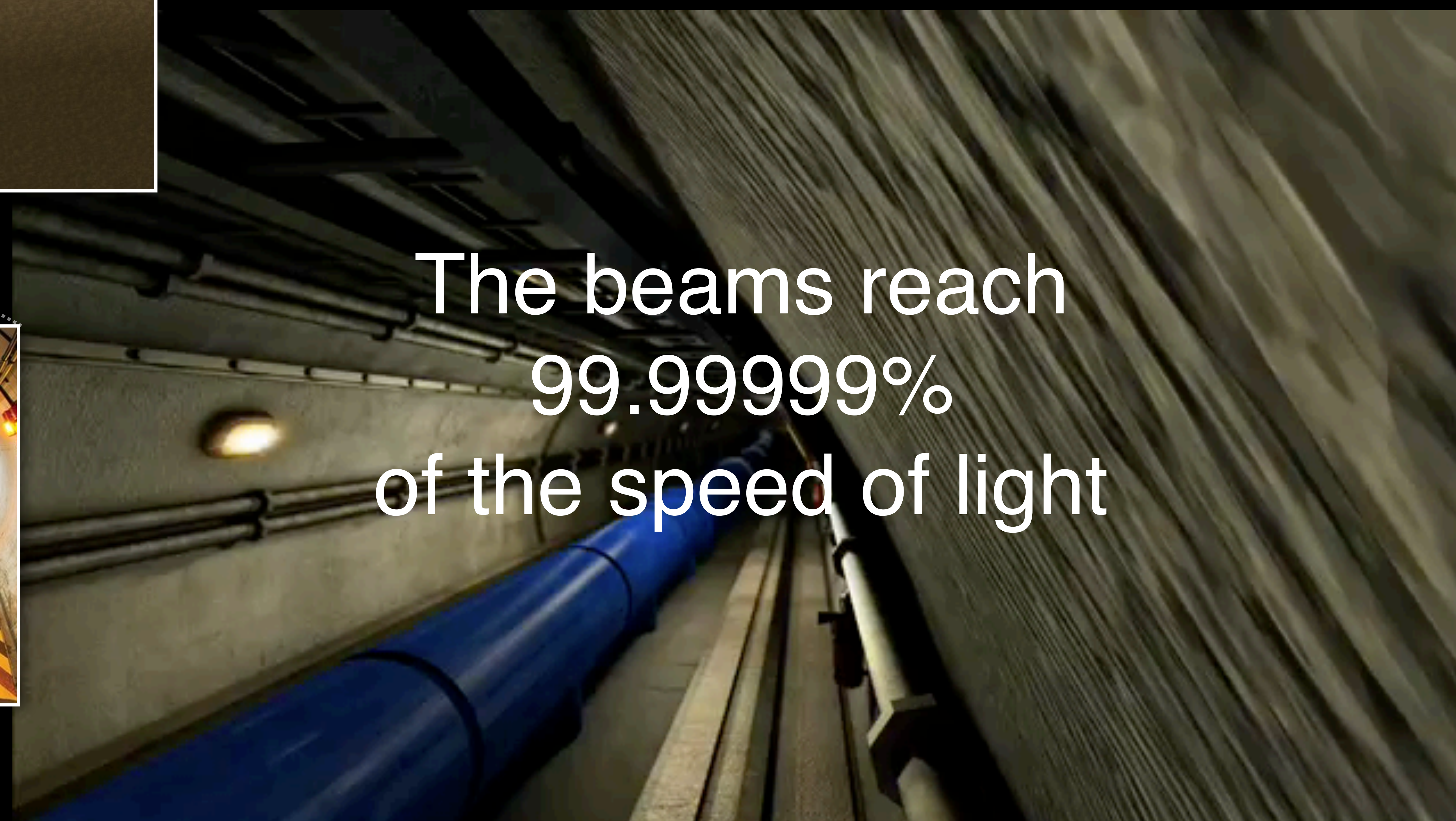
What goes on at CERN?



The LHC is housed in a tunnel
~ 100m underground and 27km long.

Two proton beams are brought into collision at four points on the ring

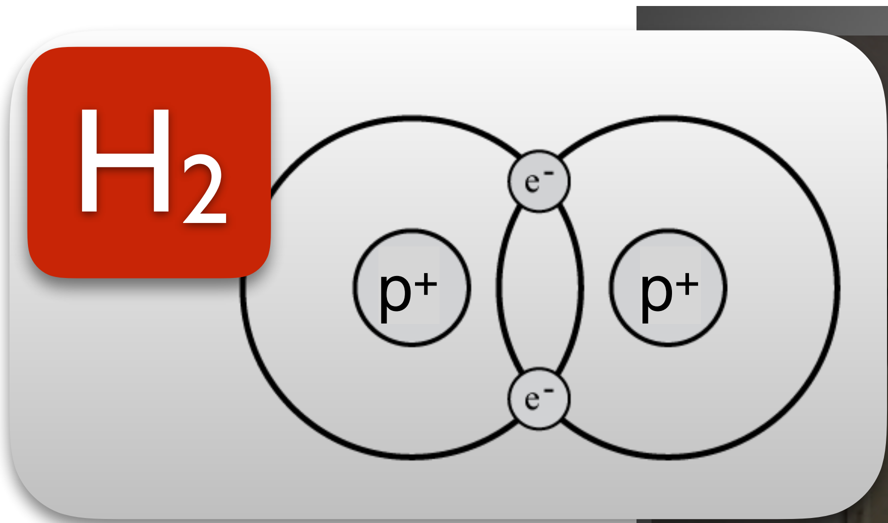


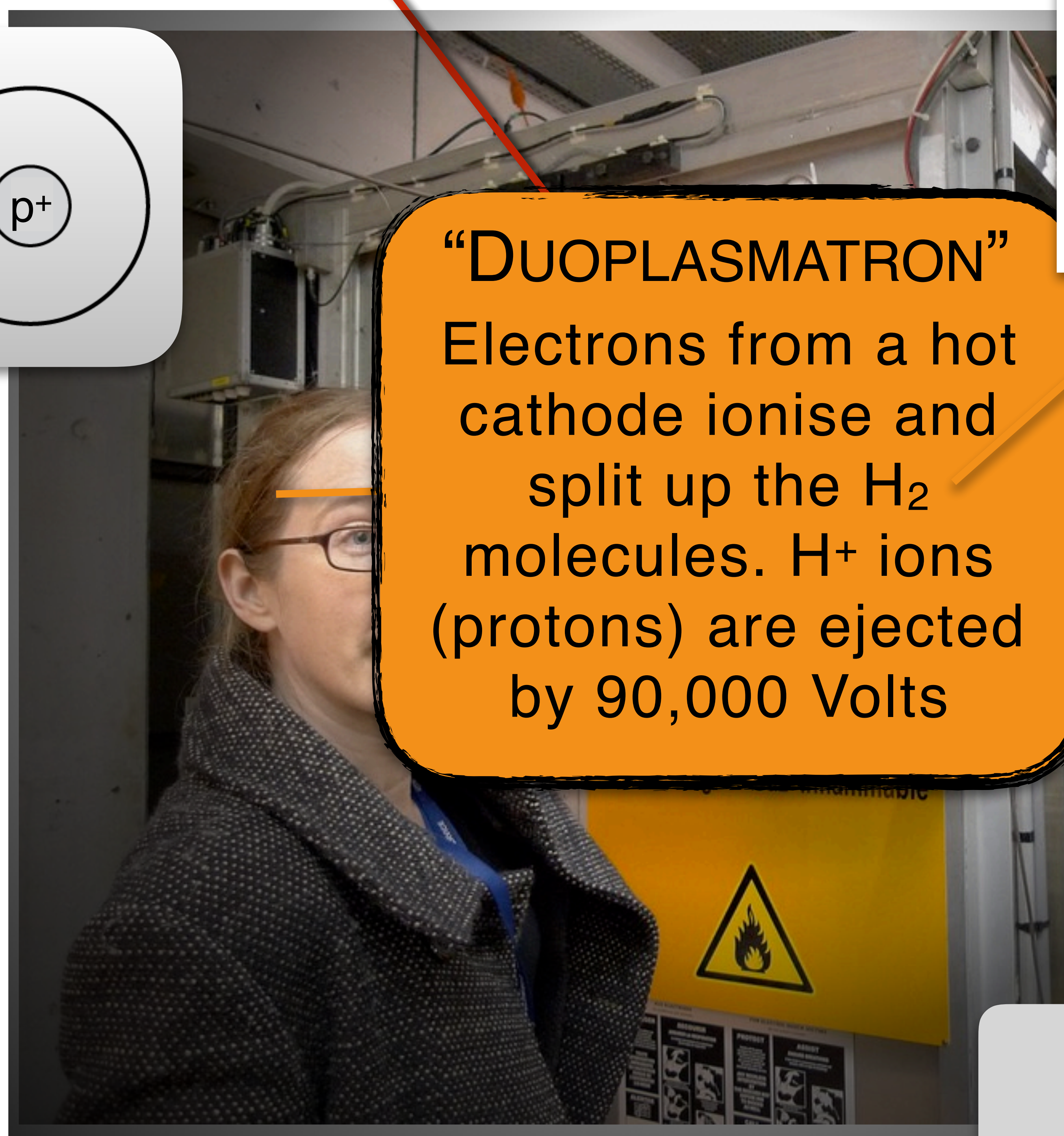


First collisions at 7 TeV in the ATLAS detector at LHC - March 2010

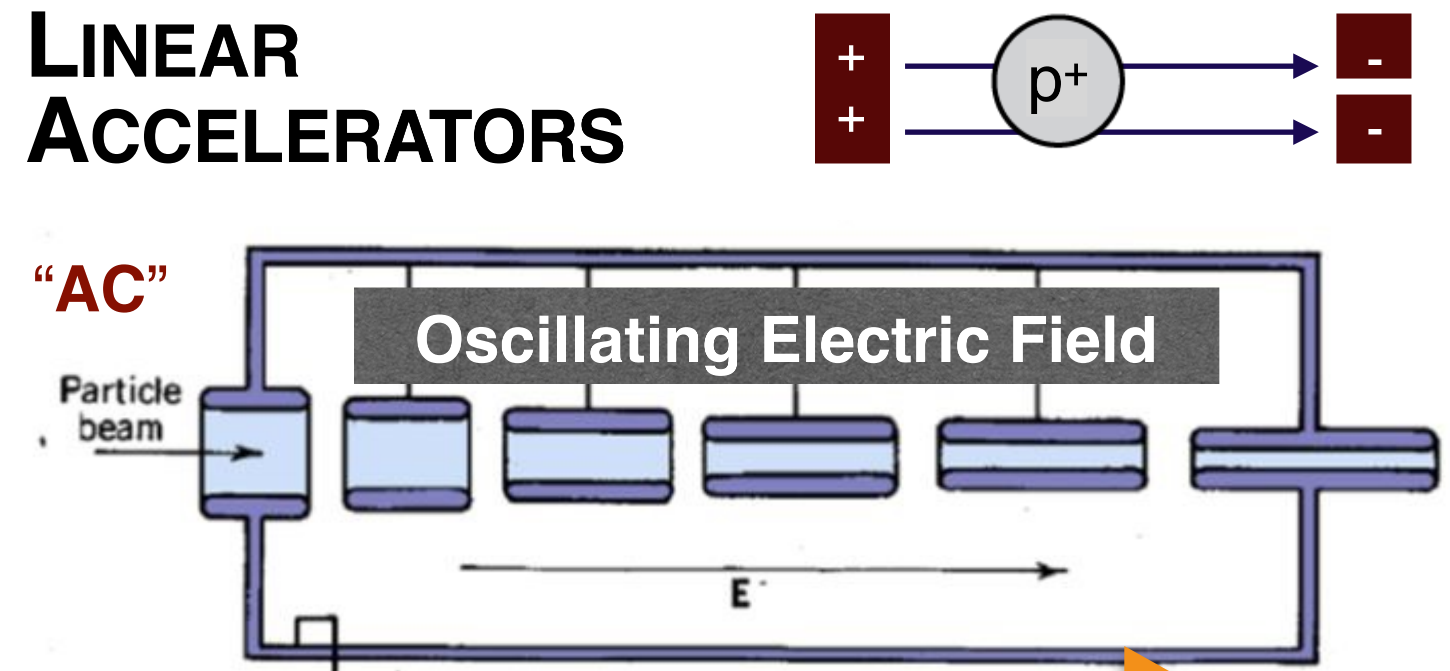
Colliding Protons

The **proton source** is a bottl
gas at one end of the acceler

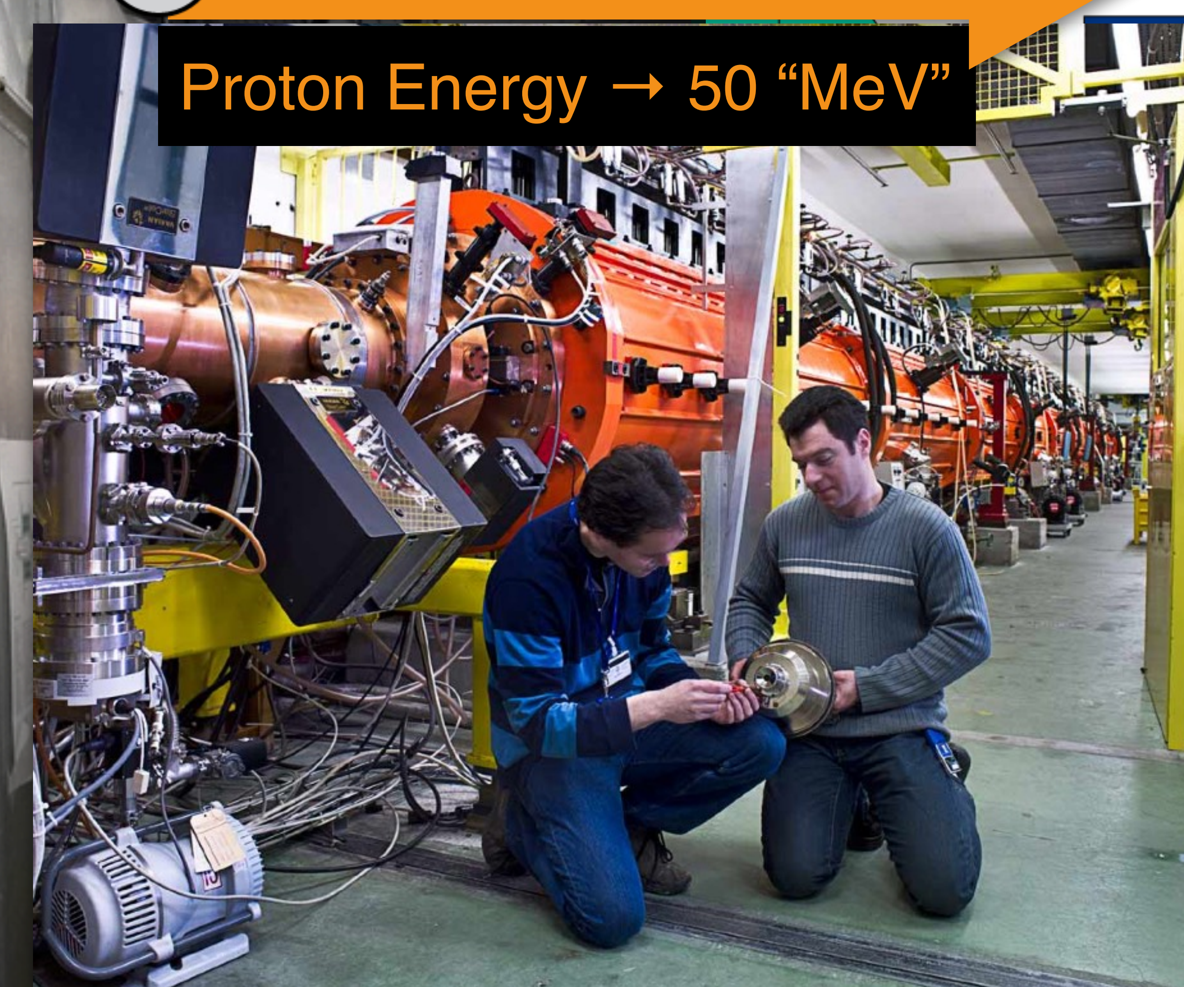




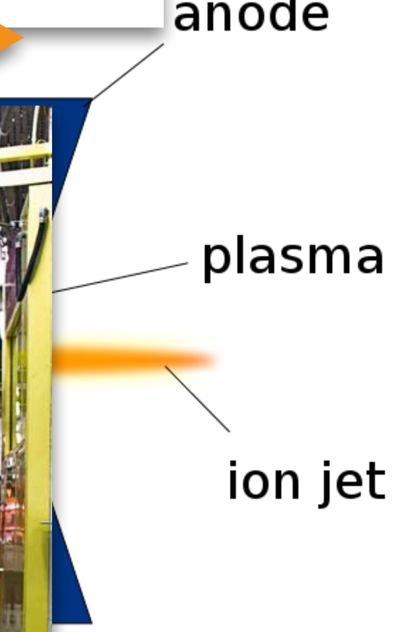
“DUOPLASMATRON”
Electrons from a hot cathode ionise and split up the H_2 molecules. H^+ ions (protons) are ejected by 90,000 Volts



p⁺ LINEAR ACCELERATOR 2



Proton Energy → 50 “MeV”



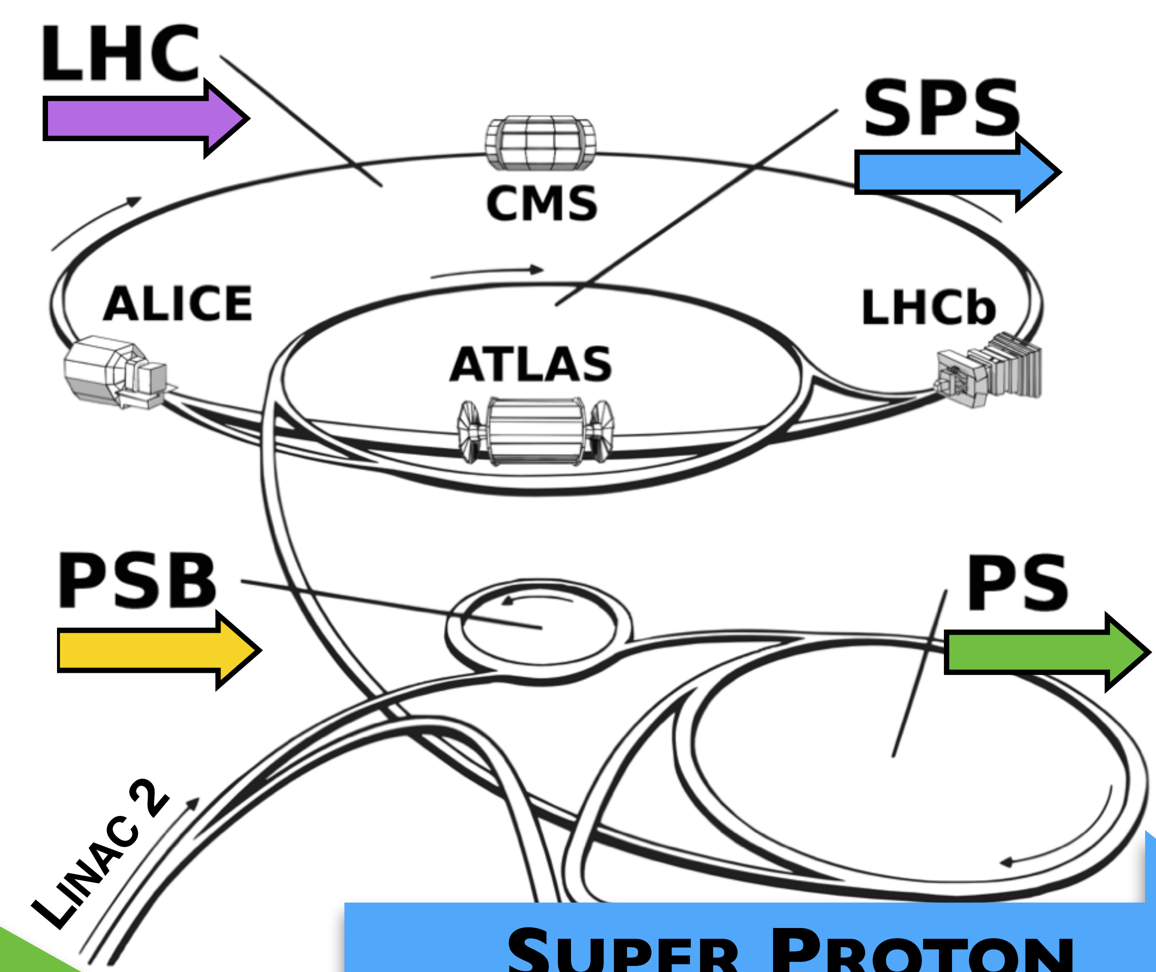
(This bottle is on displa
The real bottle is ~ 1.5m tall. Re

“Electron-Volt”

1 eV = kinetic energy gained by unit-charged particle accelerated by 1 Volt

"Recycling" at CERN

Each decade's top accelerator
→ pre-stage for the next step up



PROTON SYNCHROTRON BOOSTER (4 RINGS)

Length: 160 m
In : 50 MeV
Out: 1.4 GeV

PROTON SYNCHROTRON

(1959)
Length: 628 m
In : 50 MeV - 1.4 GeV
Out: 25 GeV

SUPER PROTON SYNCHROTRON

(1976)
Length: 7 km
In : 25 GeV
Out: 450 GeV

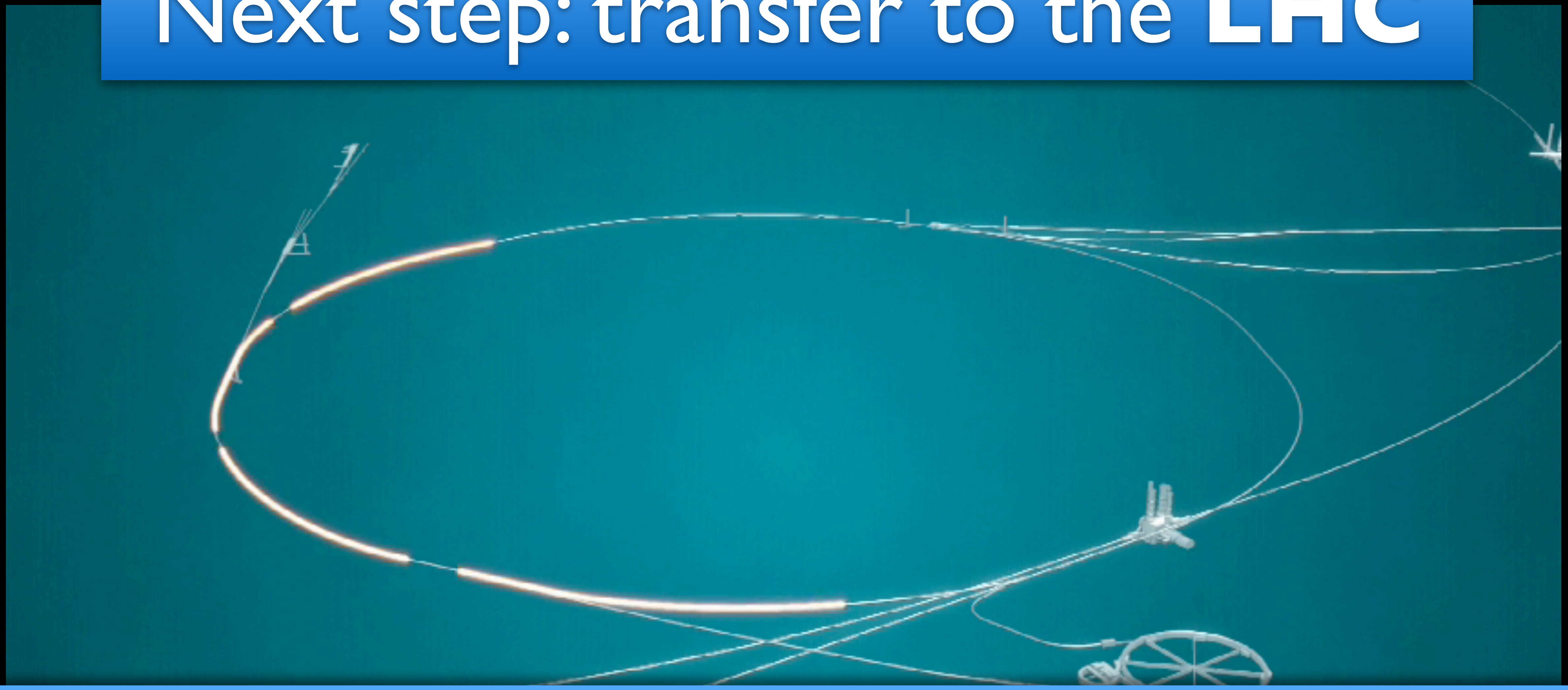
The Last Waypoint

Max energy of Super Proton Synchrotron: **450 GeV**

Corresponding to having been accelerated through a total of 450 billion Volts of potential drop

Operated in the 1980ies; discovered the **W** and **Z** bosons (Nobel Prize 1984)

Next step: transfer to the **LHC**



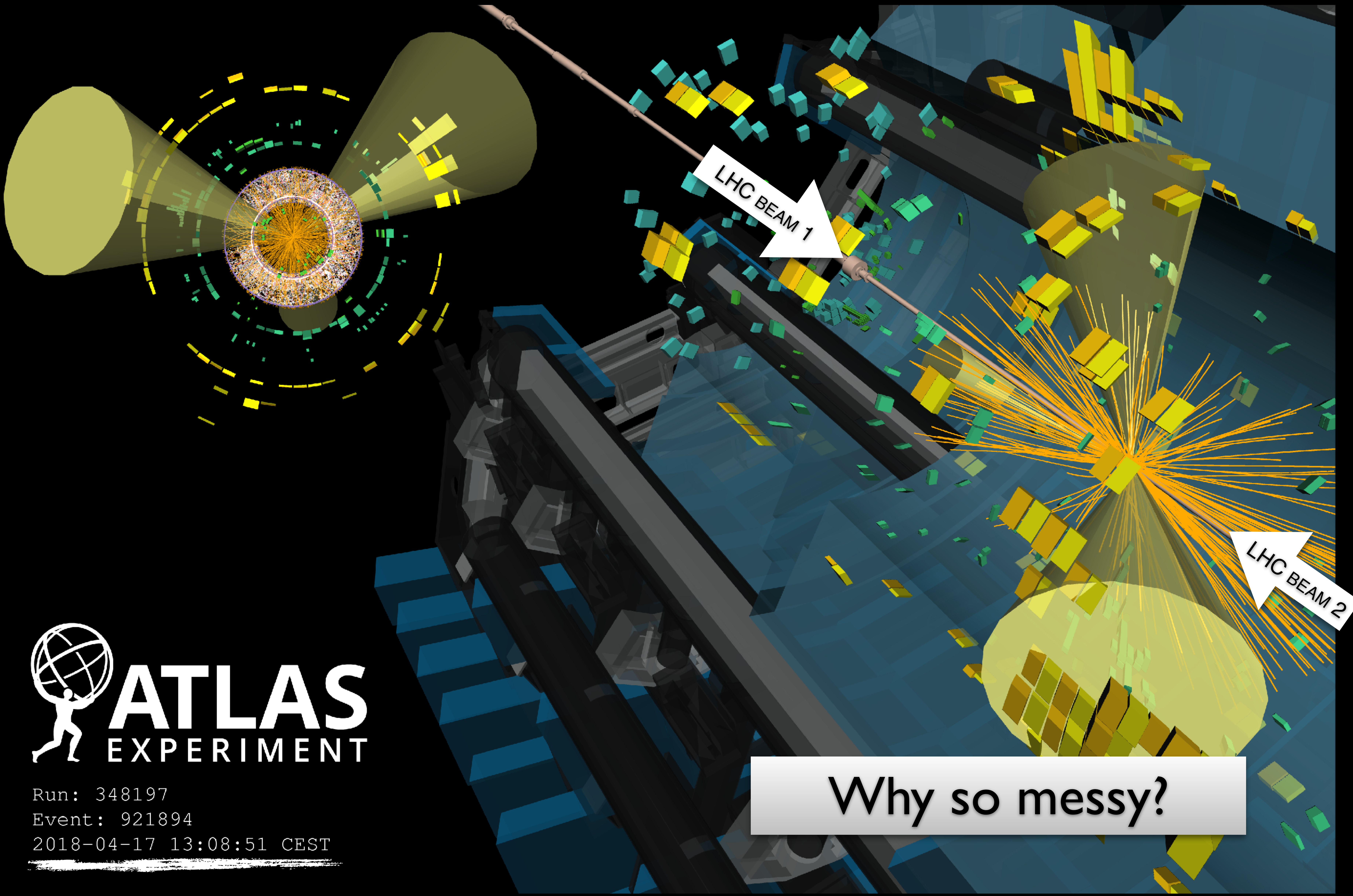
"Stable beams" for 2018 LHC run: **April 17th**

Collision Energy: 13,000 GeV

(~ 1 million times higher than nuclear fusion)

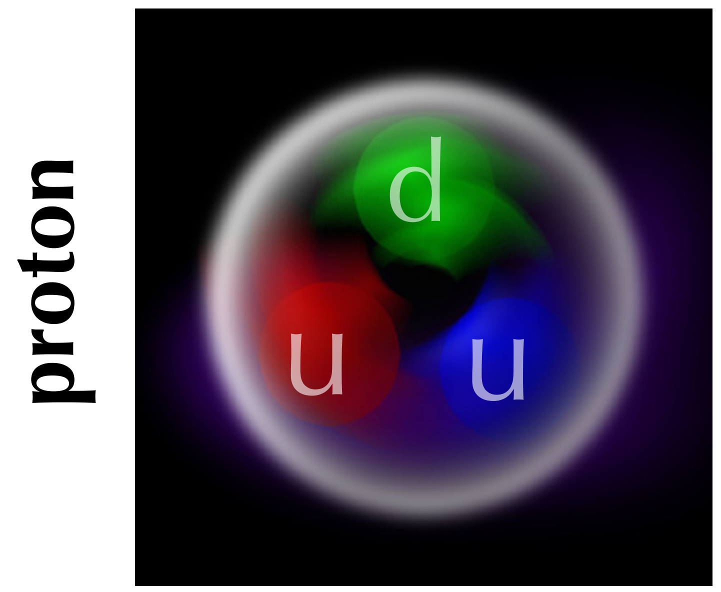
Twice what we had when Higgs boson was discovered **+** more intense beams

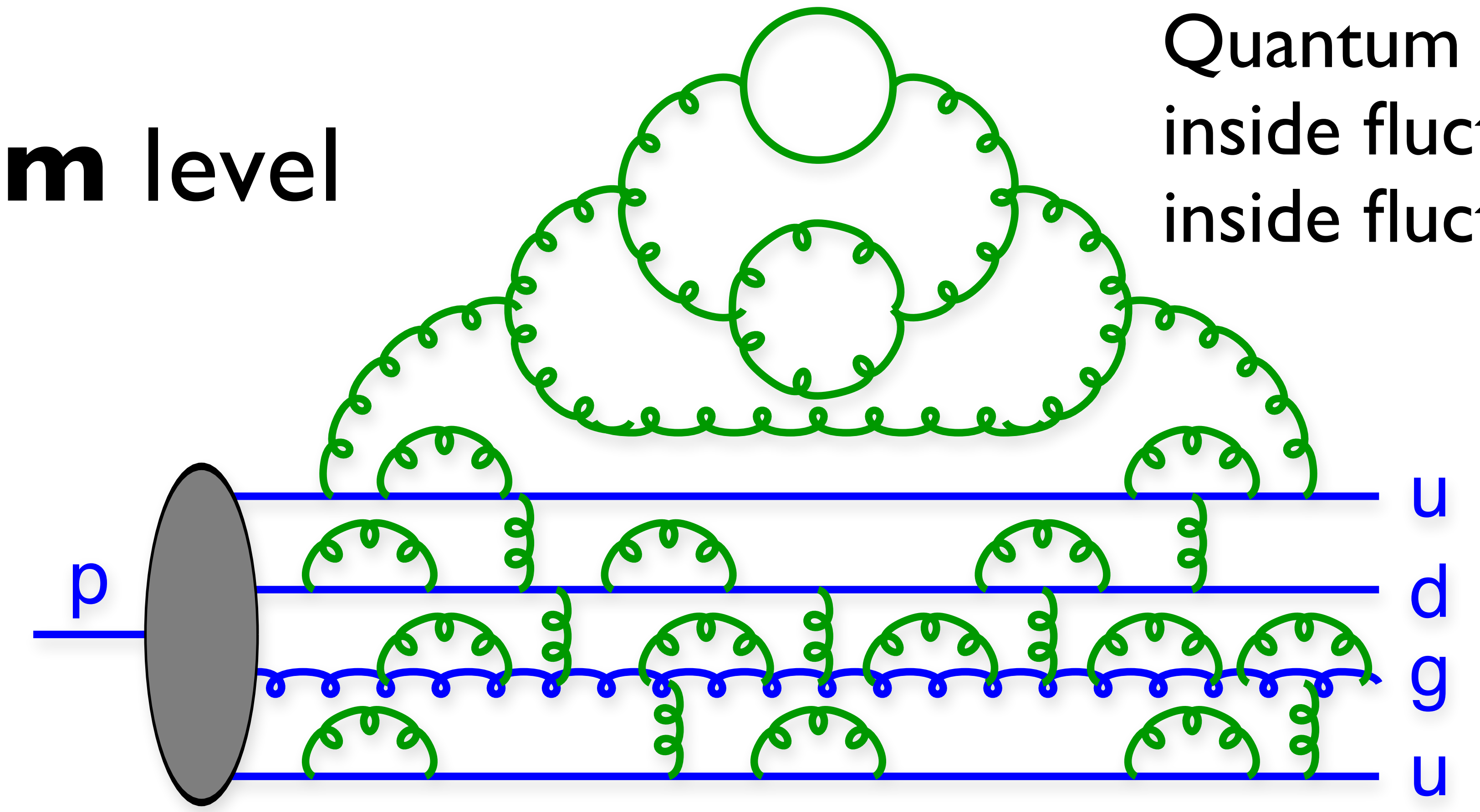
More than **3,000 physics publications** (= new measurement results) from the LHC **so far**



Elementary Particles?

Take a look at the **quantum** level





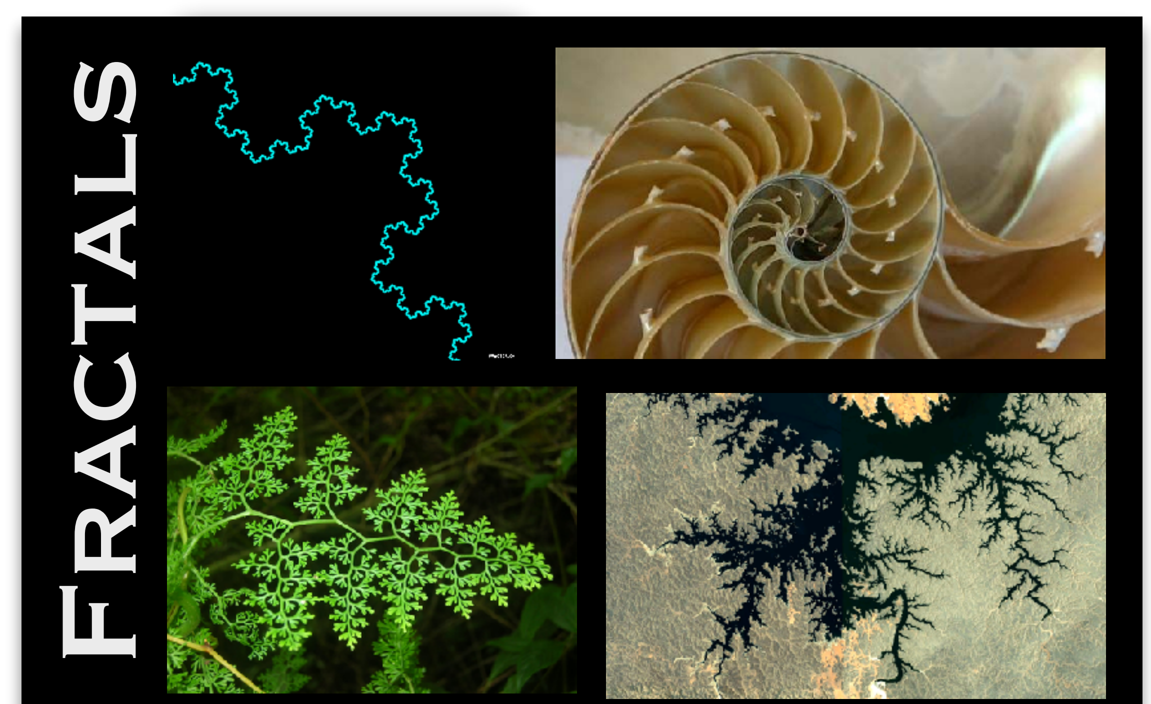
Quantum fluctuations
inside fluctuations
inside fluctuations …

What we see when we look **inside the proton**

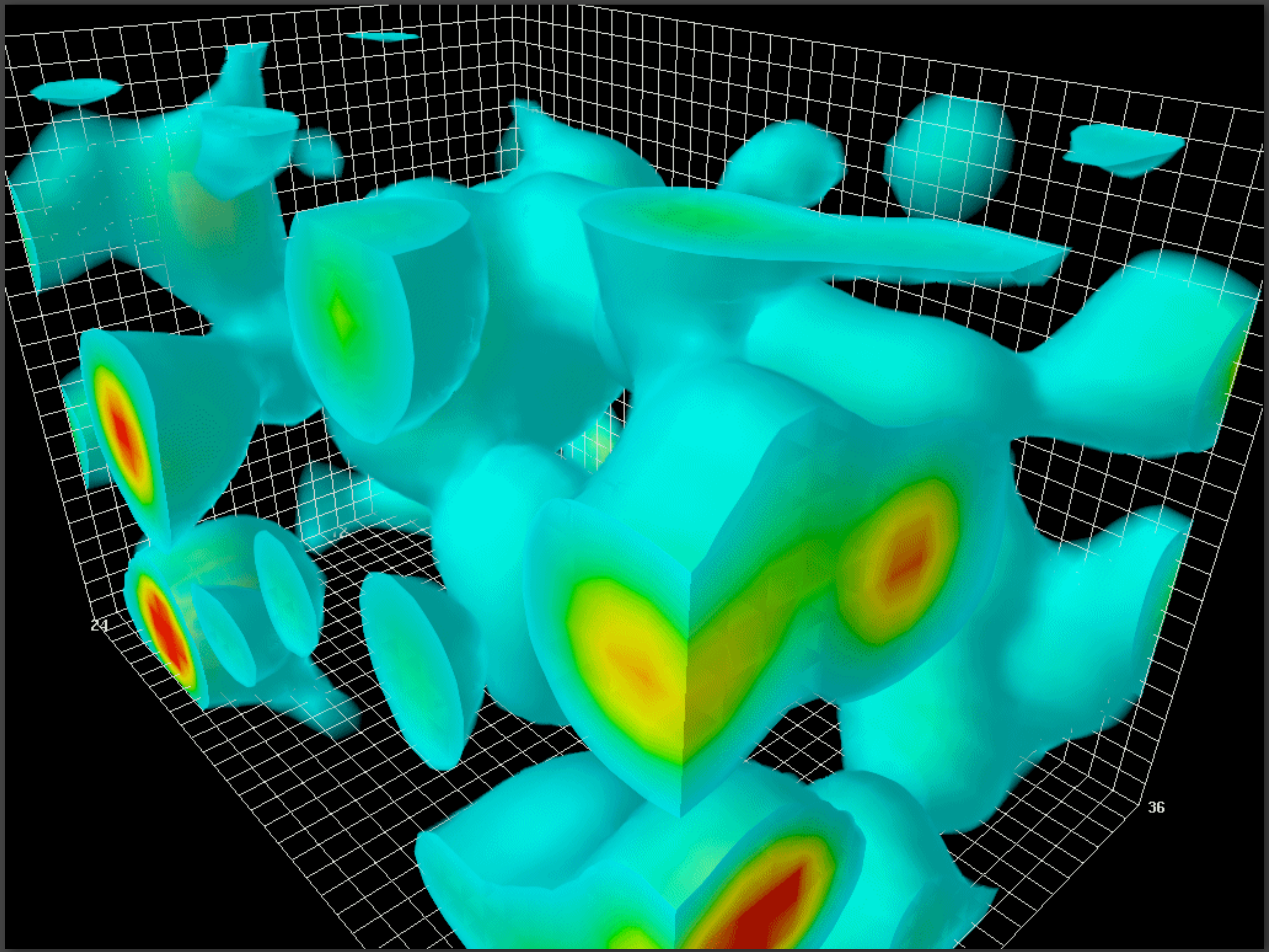
An **ever-repeating self-similar** pattern of quantum fluctuations

At **increasingly smaller distance scales**

To our best knowledge, this is what fundamental ('elementary') particles "really look like"



Quantum Field Theory on a Supercomputer



Simulation of empty space; by D. Leinweber, Adelaide U.

Such Stuff as Beams are Made Of

Lifetime of typical fluctuation ~ r_p/c (=time it takes light to cross a proton)

~ 10^{-23}s; Corresponds to a frequency of ~ **500 billion THz**

To the LHC, that's slow! (reaches "shutter speeds" thousands of times faster)

Planck-Einstein: $E=h\nu$ ➜ ν_{LHC} = 13 TeV/h = **3 million billion THz**

➜ Protons look "frozen" at moment of collision

But they have a lot more than just three quarks inside

Hard to calculate ➠ use statistics to parametrise the structure

Every so often I will pick a gluon, every so often a quark (antiquark)

Measured at previous colliders, as function of energy fraction

Then **compute the probability** for all possible quark and gluon **reactions** and compare with experiments …

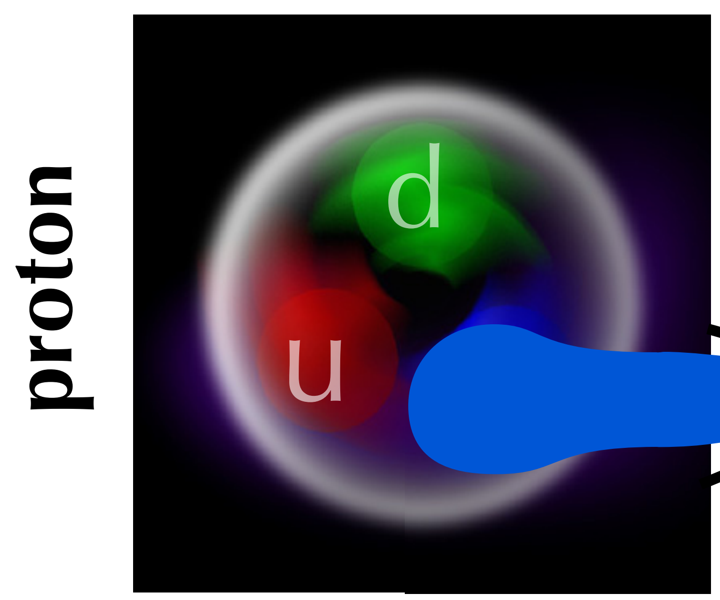
(Part of the work my research team does is writing computer codes that do just that)

Theory vs Data — A Recent Example

Around 2015, a few teams of theorists proposed a new set of measurements to test a fundamental property of the strong nuclear force:

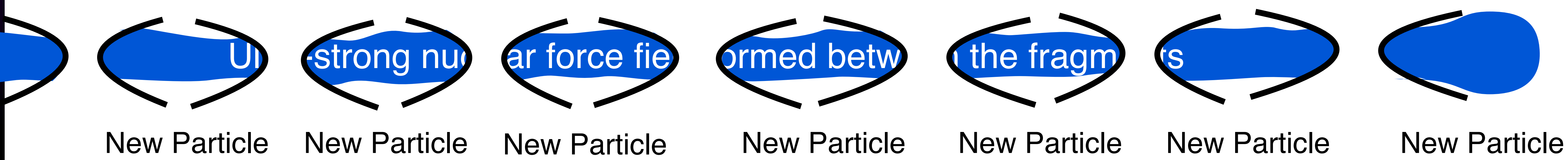
Is the fraction of **“strange”** particles produced in the LHC experiments a constant, or does it depend on how violent the collisions are?

How are 2 colliding protons turned into hundreds of outgoing particles?



Fact: quarks (and gluons) are “confined” inside hadrons (such as protons)

What happens if we give one of them a really hard kick?



Fragmentation: Field energy converted to mass of new quark-antiquark pairs

Strange quarks are heavier (need more energy) → produced less often

What a **strange** world we live in, said Alice [to the queen of hearts]

We wanted to know if "violent" collision events produced higher-strength fields.

The smoking gun would be a higher fraction of strange particles being produced

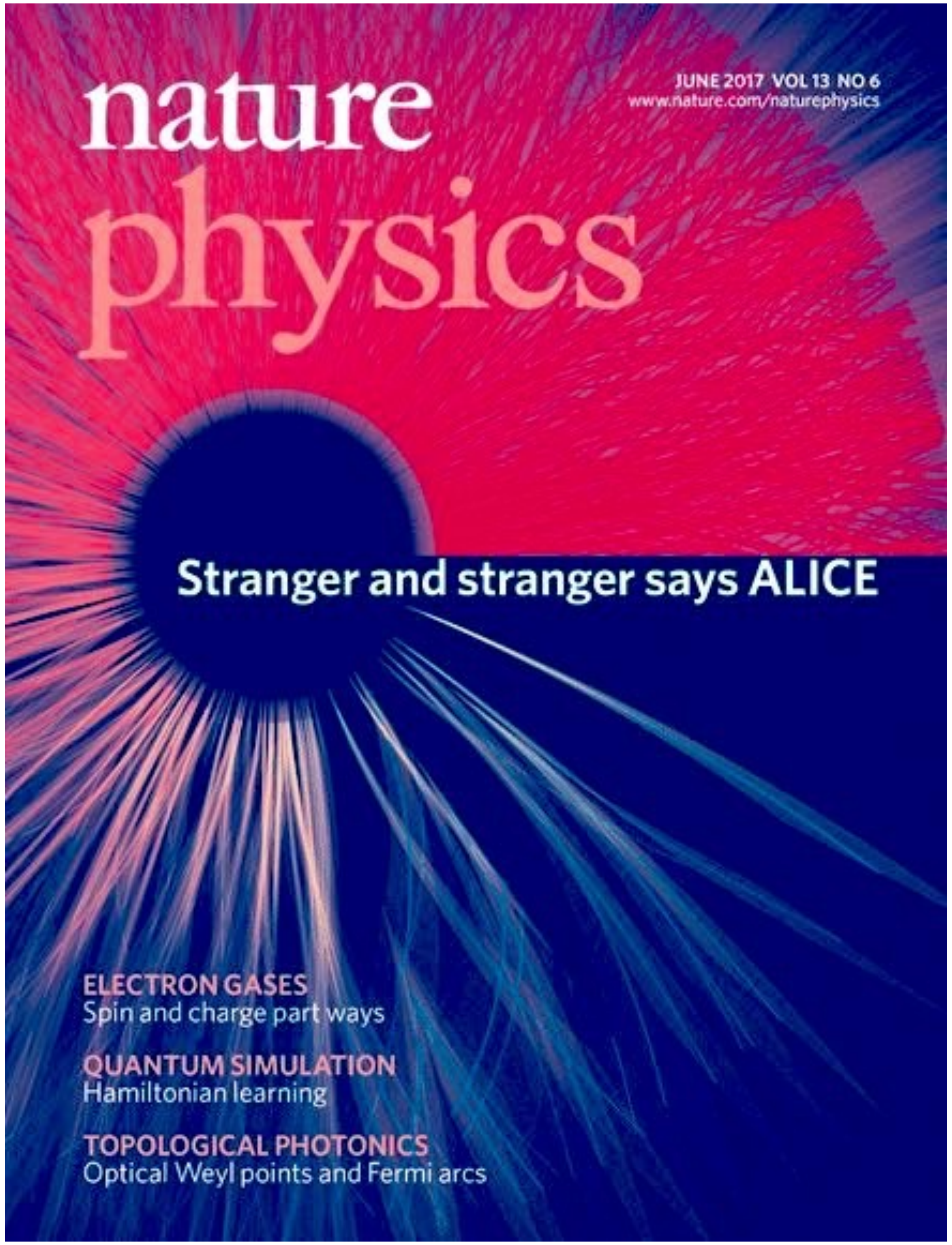
(higher-strength fields would imply more energy per "space-time volume" → easier to produce higher-mass quark-antiquark pairs)

Jackpot!

Now working on models in which nearby fragmenting fields interact with each other, a bit like two wire-carrying currents interact.

Others say the whole thing turns into a liquid which gets heated up.

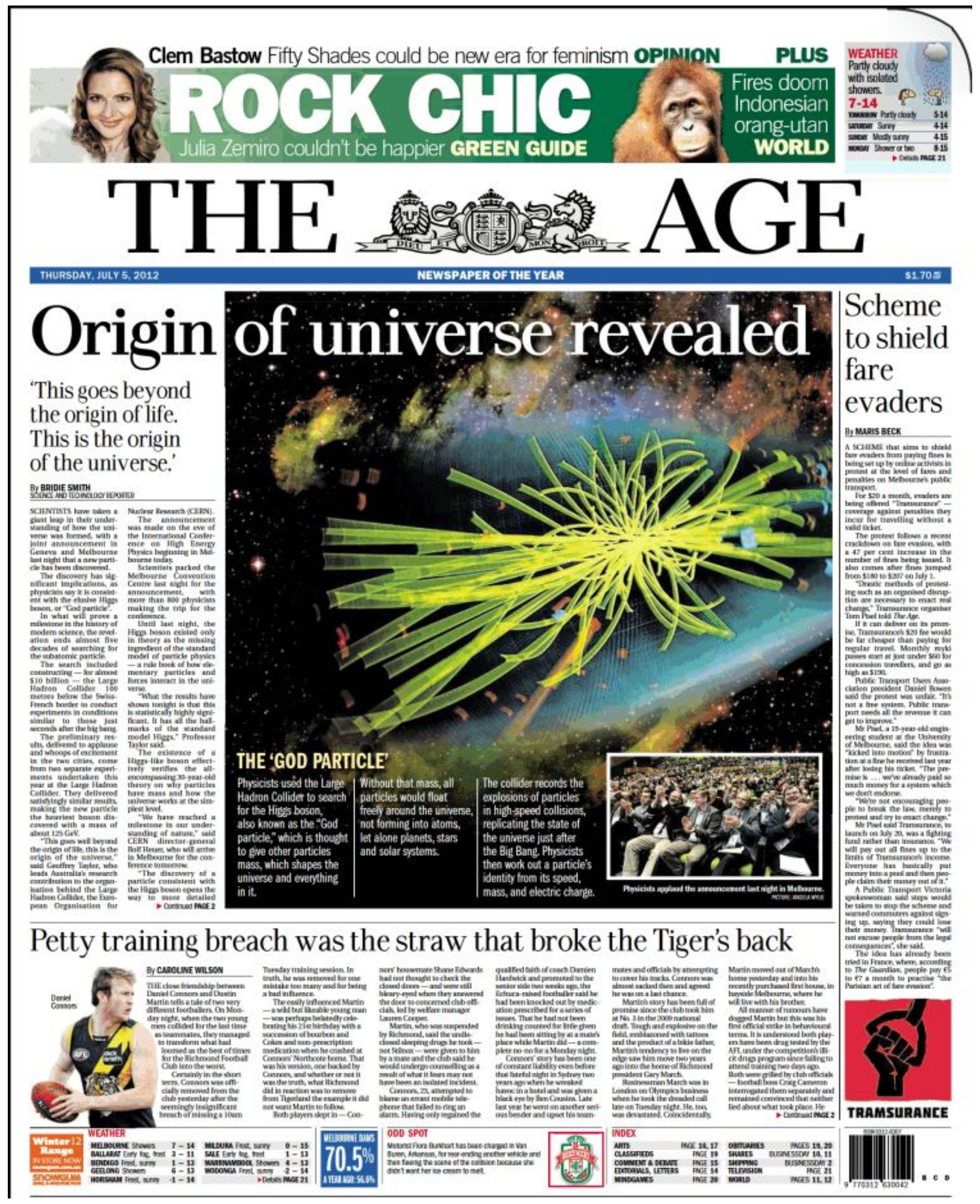
My PhD student is not getting much sleep



Cover of **Nature Physics** *June 2017*

Talking about headlines

July 5th 2012



Clem Bastow Fifty Shades could be new era for feminism OPINION

ROCK CHIC

Julia Zemiro couldn't be happier GREEN GUIDE

PLUS Fires doom Indonesian orang-utan WORLD

THE AGE

THURSDAY, JULY 5, 2012 NEWSPAPER OF THE YEAR

Origin of universe revealed

'This goes beyond the origin of life. This is the origin of the universe.'

Scheme to shield fare evaders

THE 'GOD PARTICLE'

Petty training breach was the straw that broke the Tiger's back

News Science

Key discoveries that changed the world

Higgs boson discovery shines light on secrets of the Universe

Tears for the British hero of particle physics

Q&A

SEAT

Remember when fun was affordable!?

What is "Mass"?

Consider a 'field' distributed evenly across the Universe, of uniform strength (and no preferred direction / polarisation)

Suppose that different particles experience this 'field' as being more or less transparent

- To a photon (light), the field is completely "translucent"
- But an electron (or a proton), will interact with it

Suppose that this field **condenses** around the particles which couple to it, causing an increased energy density around those particles. **Looks like mass** ($E=mc^2$).

We call this field the "**H**" *(or Brout-Englert-Higgs)* **Field**

This hypothesis made one spectacular prediction:
it should be possible to excite waves in the Higgs field itself

The smoking gun

The Higgs Particle

Prediction: there should be a **resonant energy** at which a quasi-stable excitation could be produced: the '**Higgs Boson'** or **'Higgs Particle'**.

But the theory did not predict ***which*** energy; the search was on!

"Quasi-Stable"➜ should quickly dissolve (decay) into other particles, but should be detectable via its decay products

The discovery of a particle consistent with these properties was announced at CERN on July 4, 2012 (at $E = m_H c^2 = 125$ GeV)

2018: we now have a **factor 10 more data**, **+** more on the way

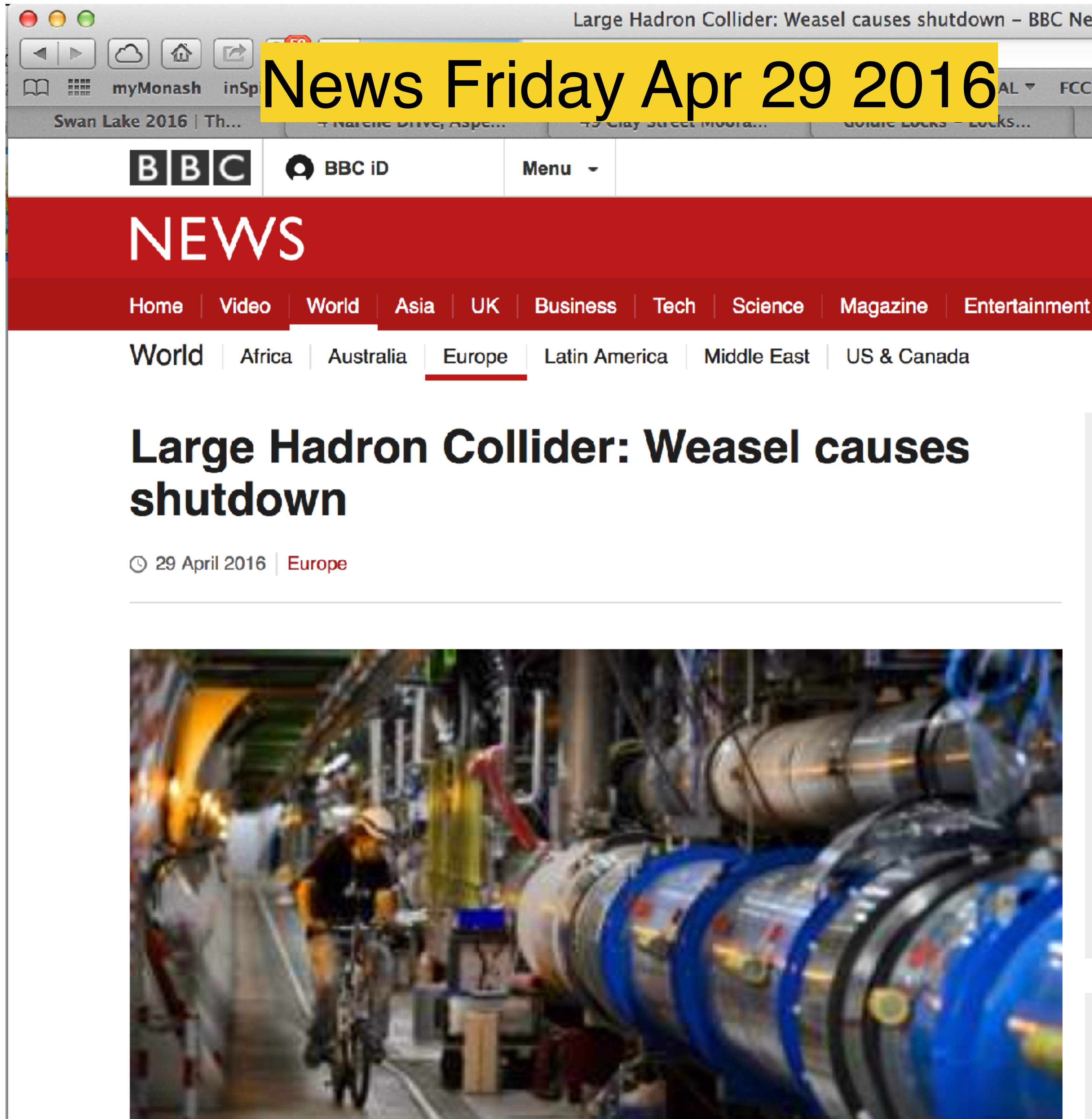
➜ can examine the **quantum properties** of this new H particle

So far, no **major** deviations from 'Simplest Higgs' predictions

This is now the **major puzzle** …

➜ LHC not much in the headlines since then, apart from that time in 2016 …

The Weasel



News Friday Apr 29 2016

BBC NEWS

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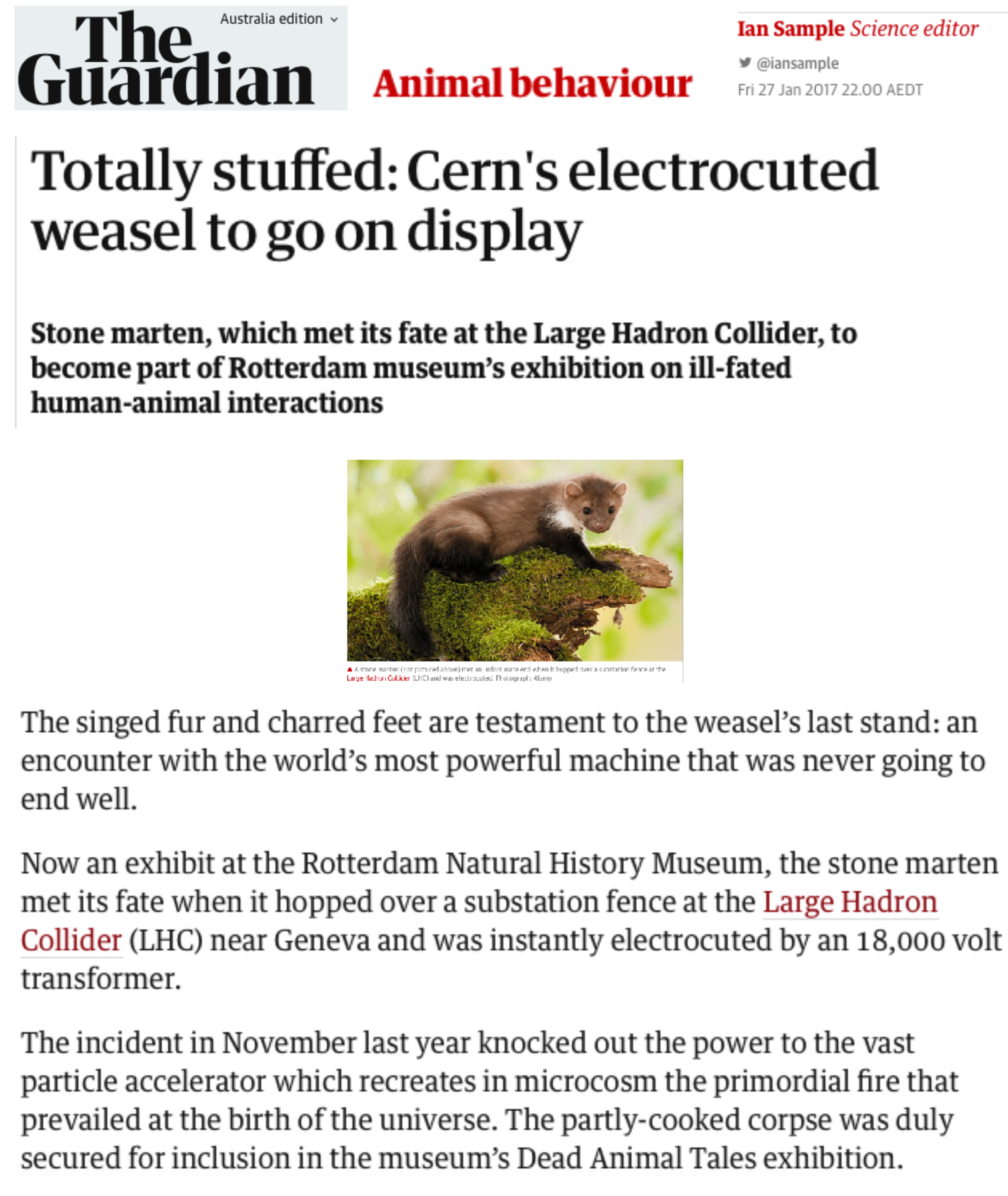
World | Africa | Australia | Europe | Latin America | Middle East | US & Canada

Large Hadron Collider: Weasel causes shutdown

29 April 2016 | Europe



The Guardian — Animal behaviour

Ian Sample *Science editor*
@iansample
Fri 27 Jan 2017 22.00 AEDT

Totally stuffed: Cern's electrocuted weasel to go on display

Stone marten, which met its fate at the Large Hadron Collider, to become part of Rotterdam museum's exhibition on ill-fated human-animal interactions

The singed fur and charred feet are testament to the weasel's last stand: an encounter with the world's most powerful machine that was never going to end well.

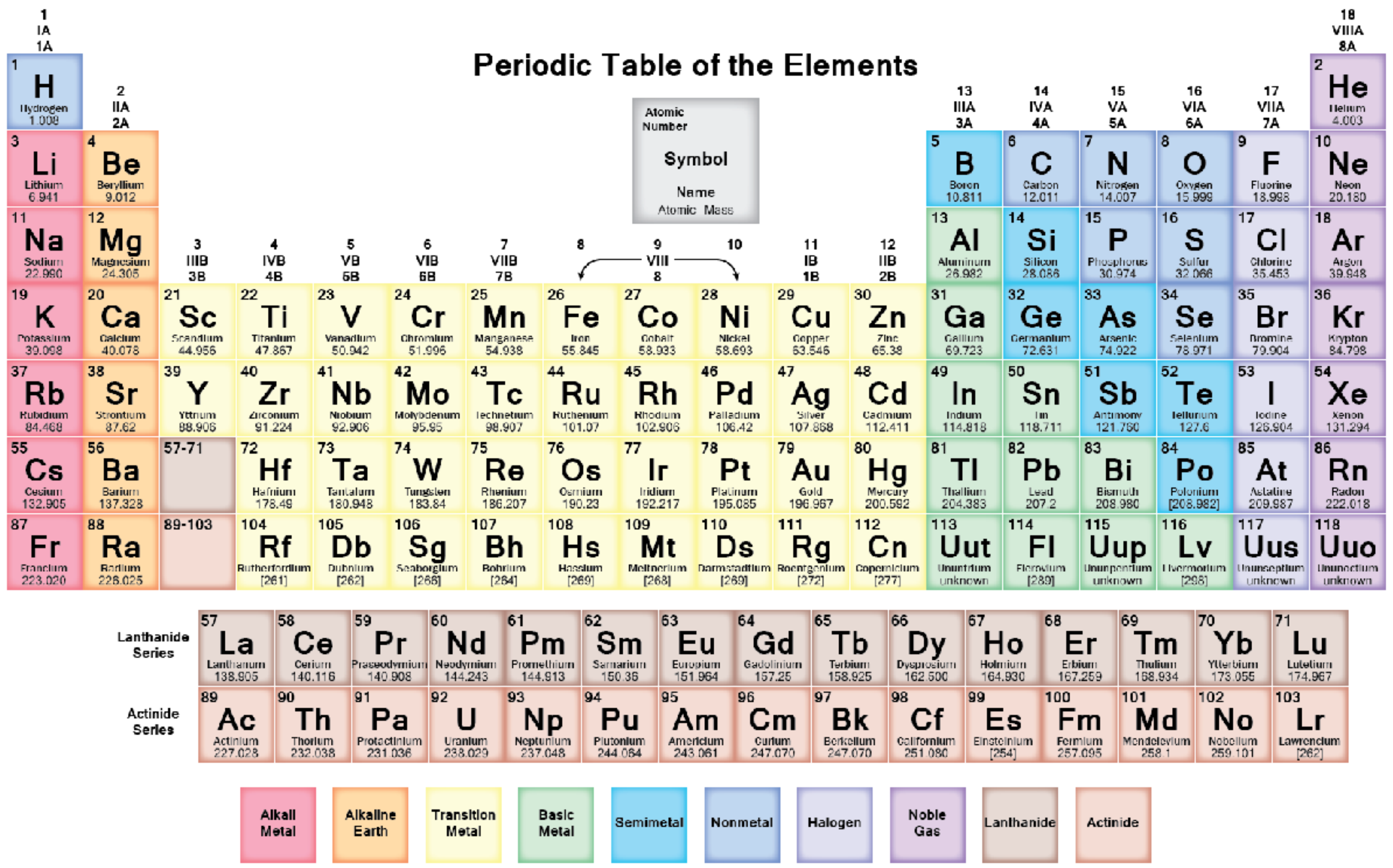
Now an exhibit at the Rotterdam Natural History Museum, the stone marten met its fate when it hopped over a substation fence at the Large Hadron Collider (LHC) near Geneva and was instantly electrocuted by an 18,000 volt transformer.

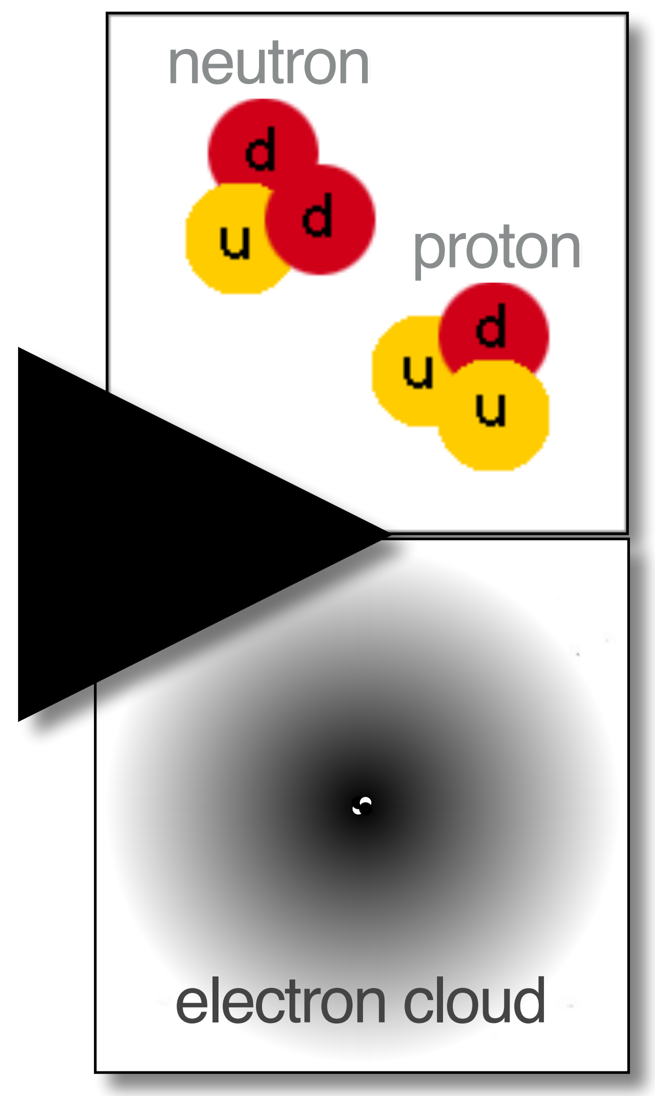
The incident in November last year knocked out the power to the vast particle accelerator which recreates in microcosm the primordial fire that prevailed at the birth of the universe. The partly-cooked corpse was duly secured for inclusion in the museum's Dead Animal Tales exhibition.

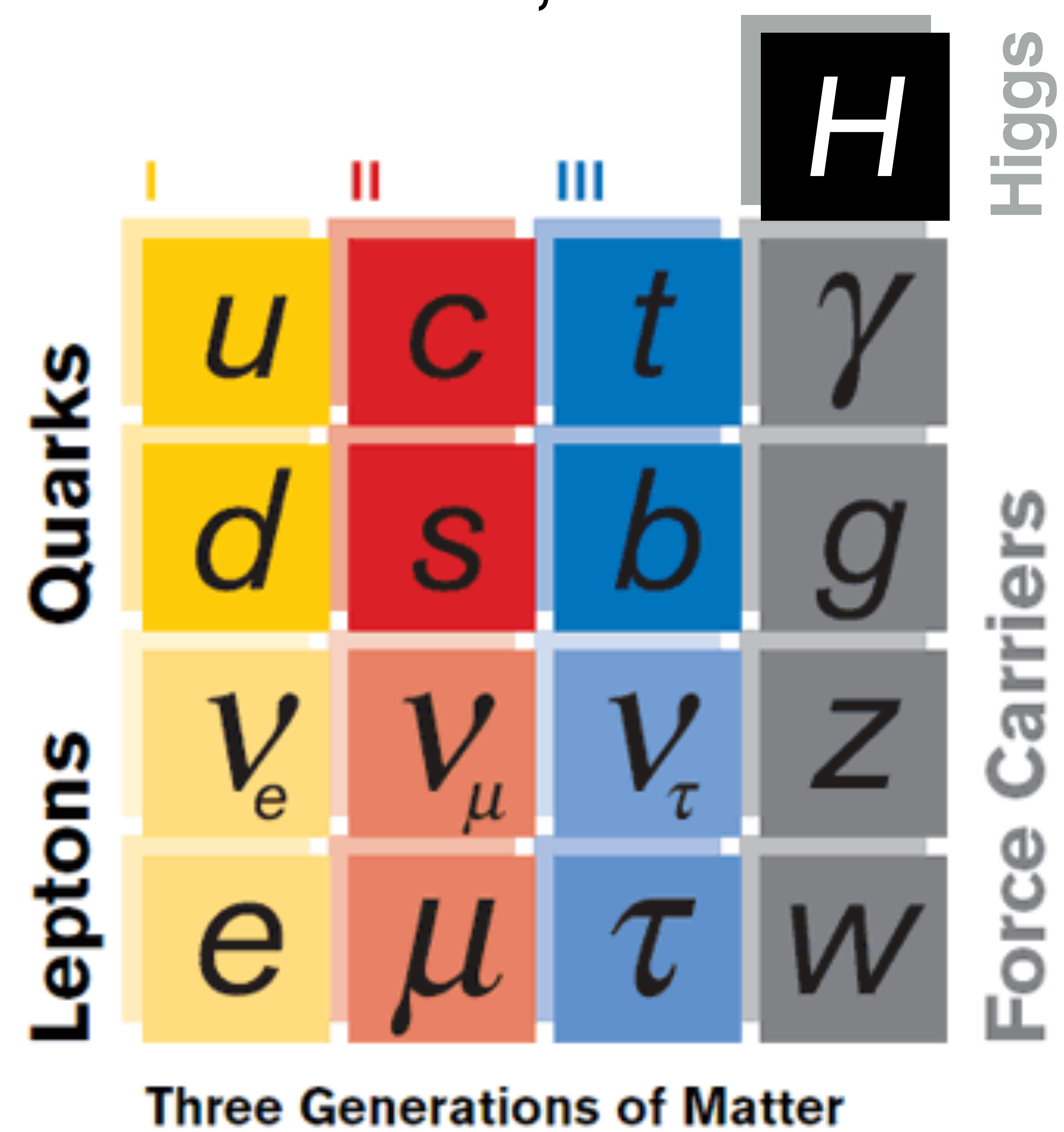
Note: when the LHC is 'fully loaded', the total stored energy in the circulating beams is equivalent to the *HMAS Canberra* moving at 13 knots. (~100 kg TNT equivalent.)

the Last Piece of the puzzle?

In the ~ 100 years since Mendeleev's periodic table, **physics** reduced to just a few **ultra-fundamental constituents**, and the **forces** that act between them







Is there something beyond?

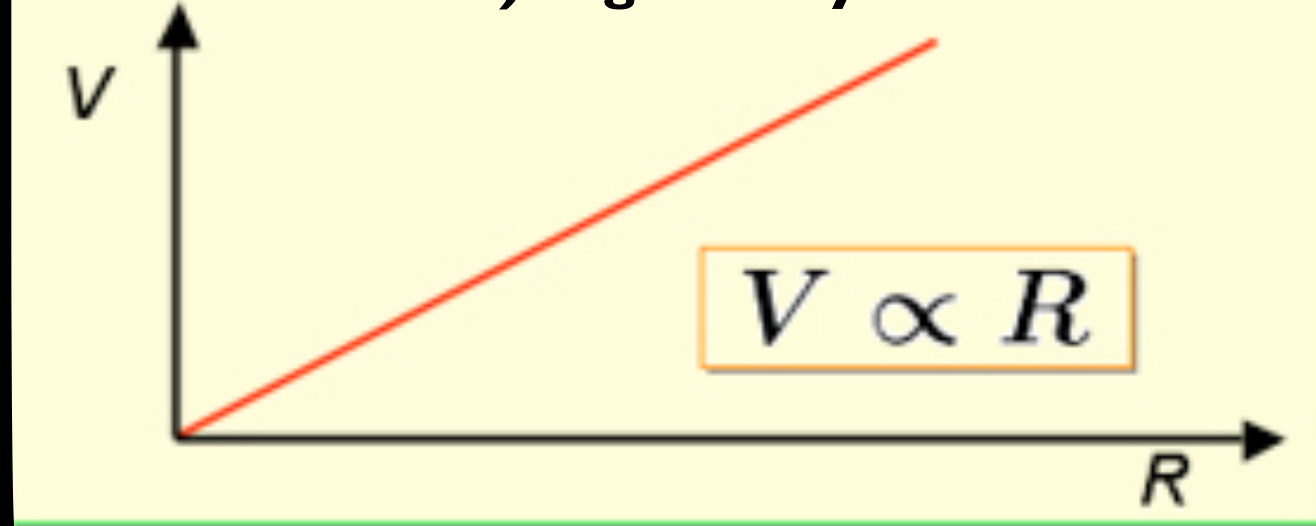
Dark Matter, Matter vs Antimatter, Higgs Origins, Grand Unification, Quantum Gravity …

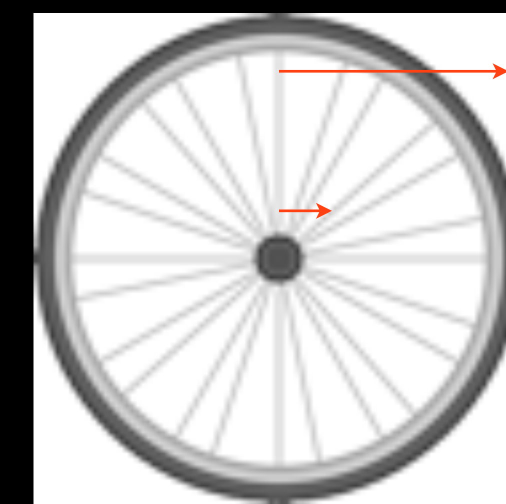
What we know ...

Physics Lesson: Rotation Curves

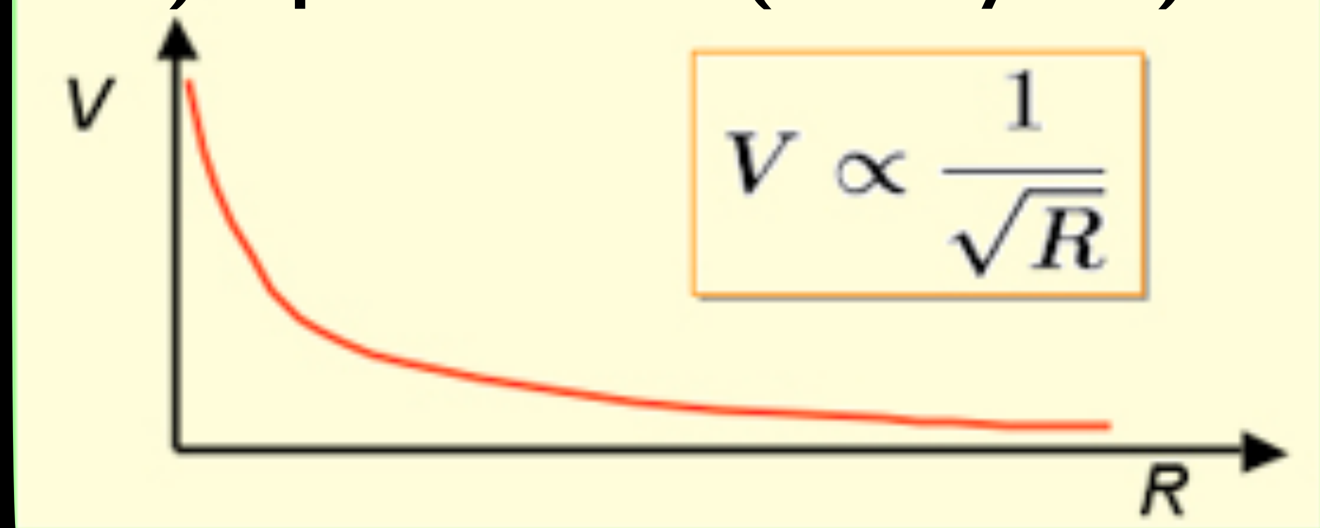
Rotation Curves

1) Rigid Body



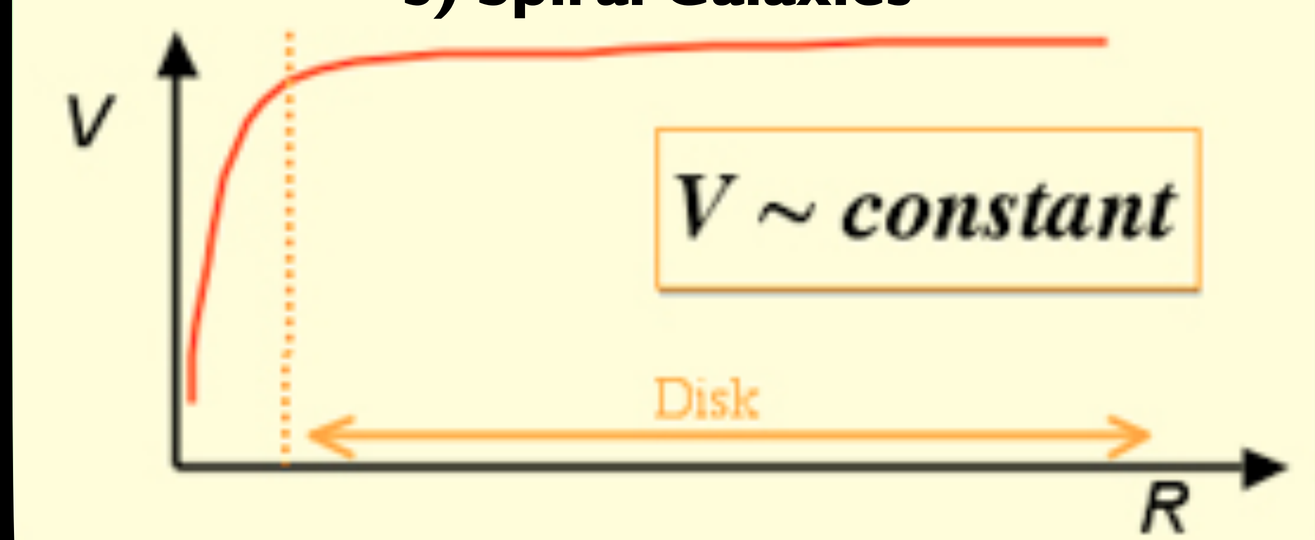


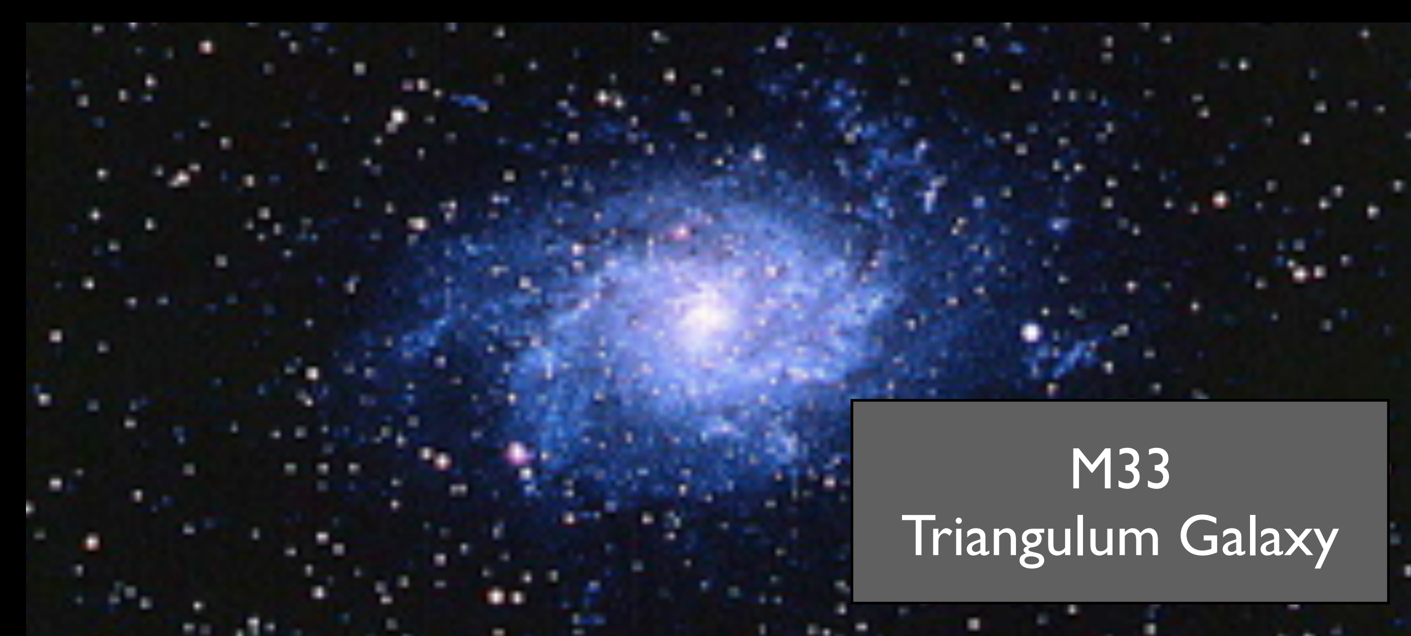
2) Keplerian Motion (Solar System)



Mercury: 48 km/s Earth: 30 km/s Neptune: 5 km/s

3) Spiral Galaxies

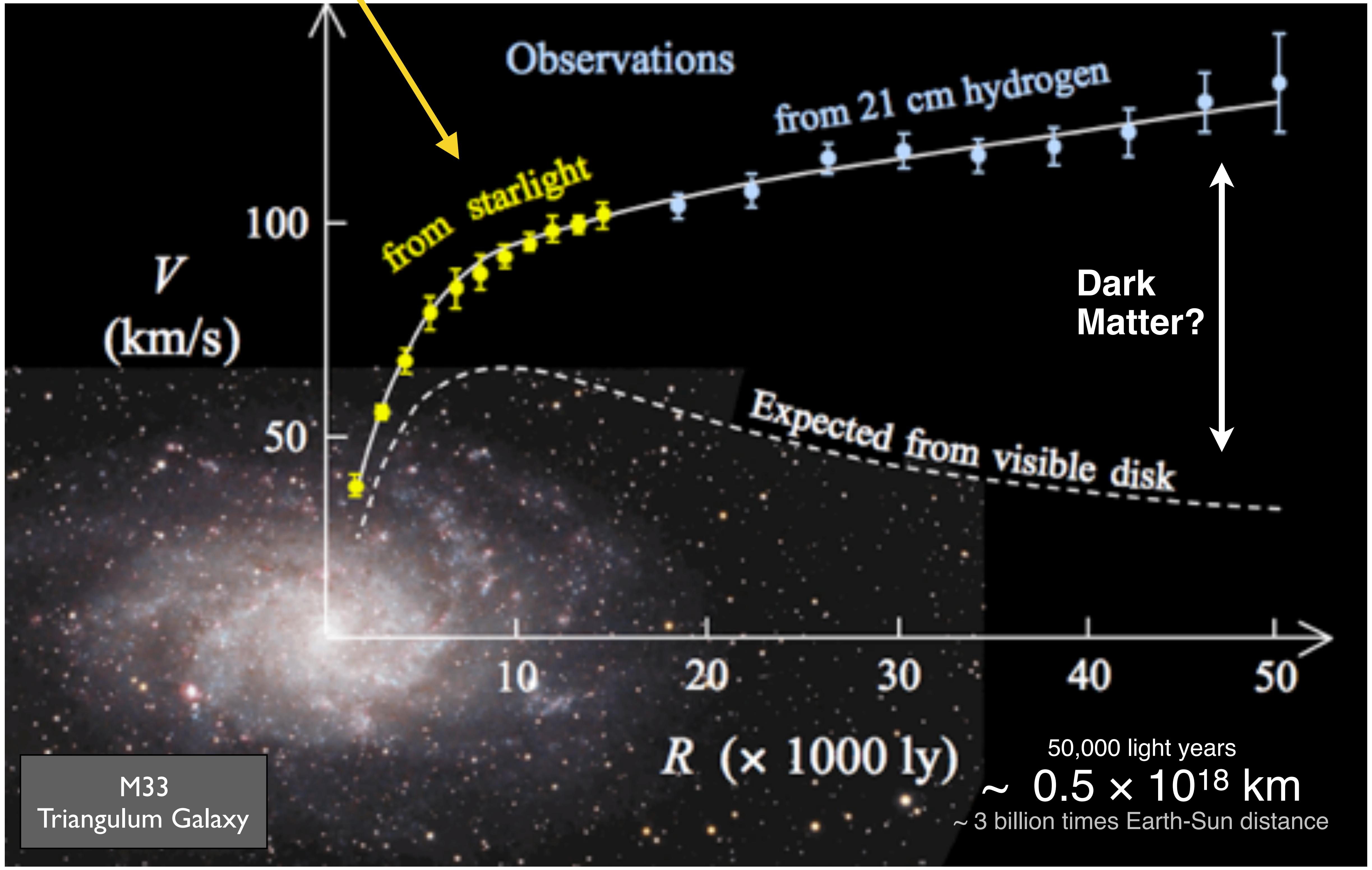




The case for Dark Matter

Something is making galaxies spin like crazy

(1932: Jan Oort)
1933: Fritz Zwicky:
1960s-1970s: Vera Rubin



+ Several other independent indications

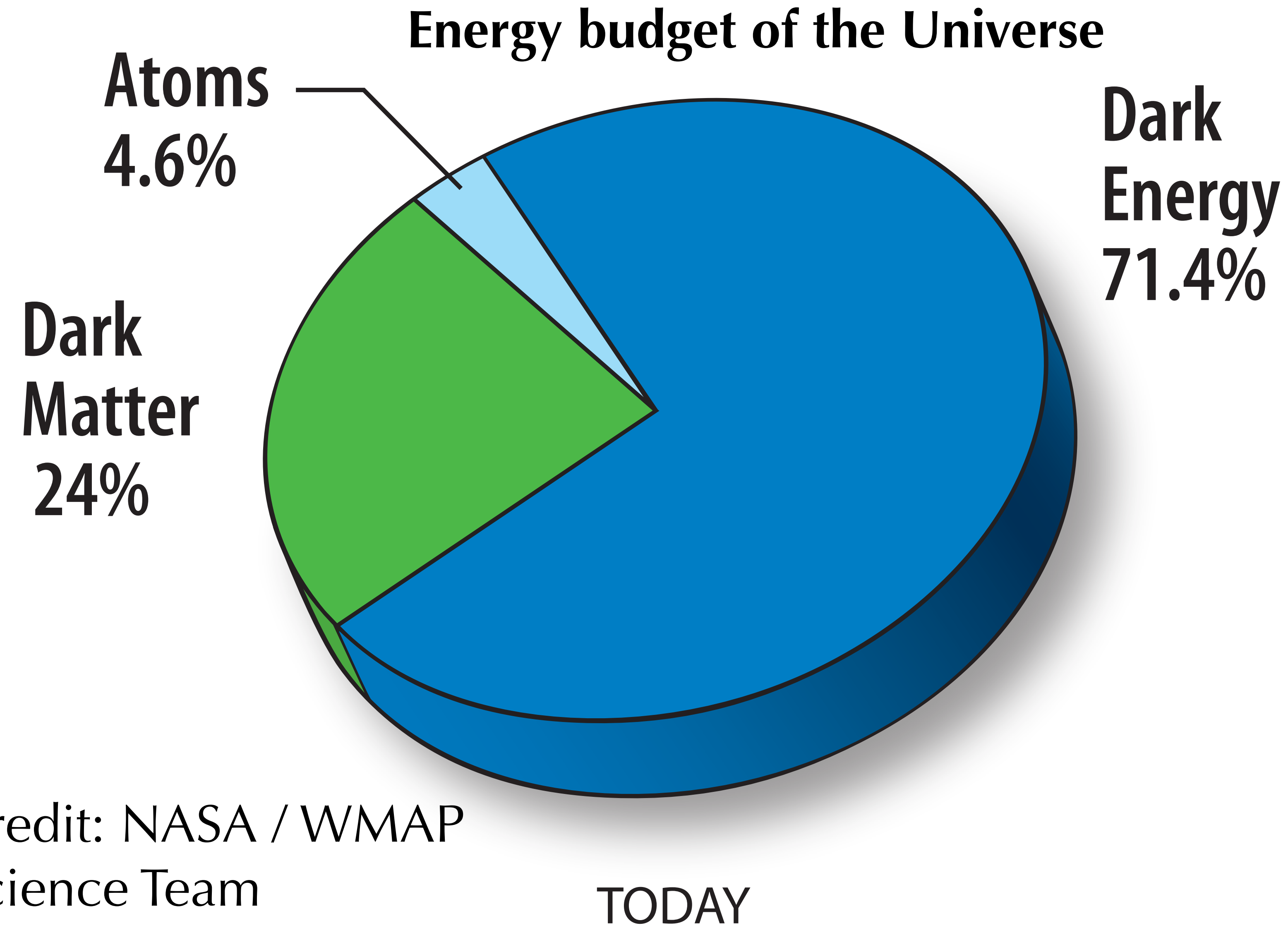
Structure formation

Computer simulations of how galaxies form require large amounts of dark matter to act as “seeds” of galaxy formation

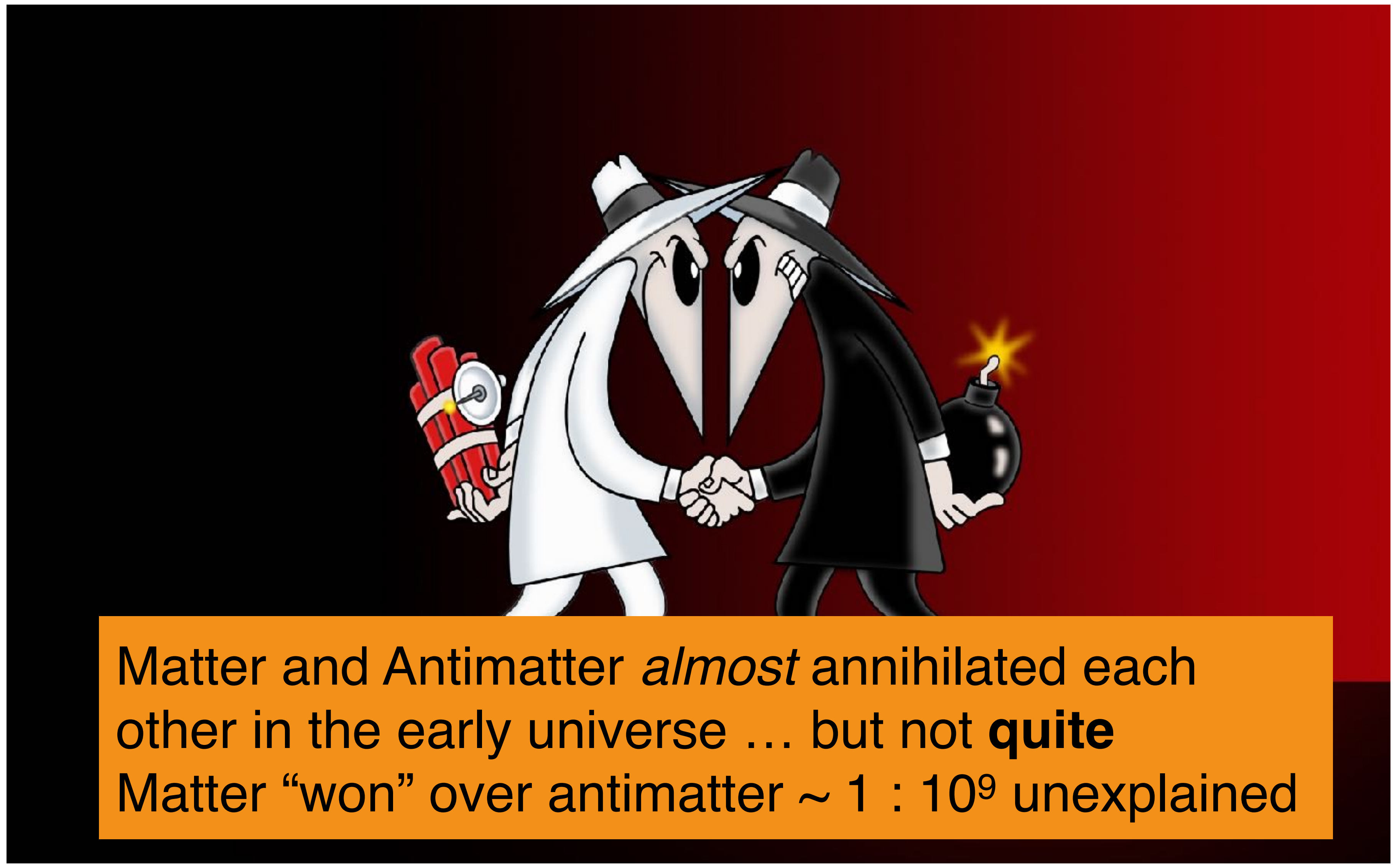
Microlensing (bullet cluster)

Looking at the aftermath of collisions of clusters of galaxies. Gravitational bending of background light shows sources of gravity ‘passed straight through’, not concentrated in the middle where most of the visible matter is.

What we know …



Credit: NASA / WMAP
Science Team



What we know …

The laws of nature embodied by the Standard Model are indeed **slightly** different between matter and antimatter

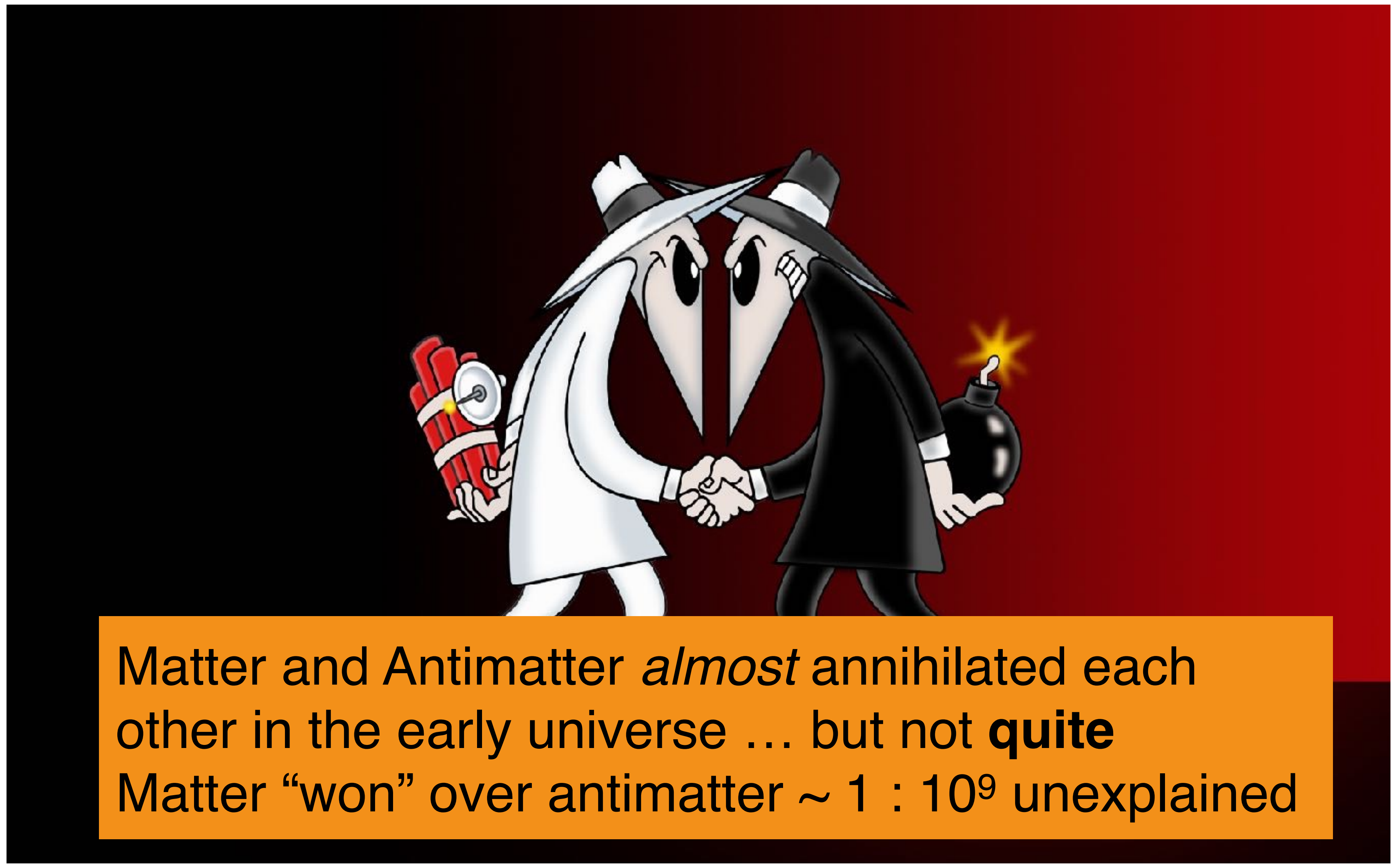
(Called CP violation; discovered in 1964, Nobel Prize 1980)

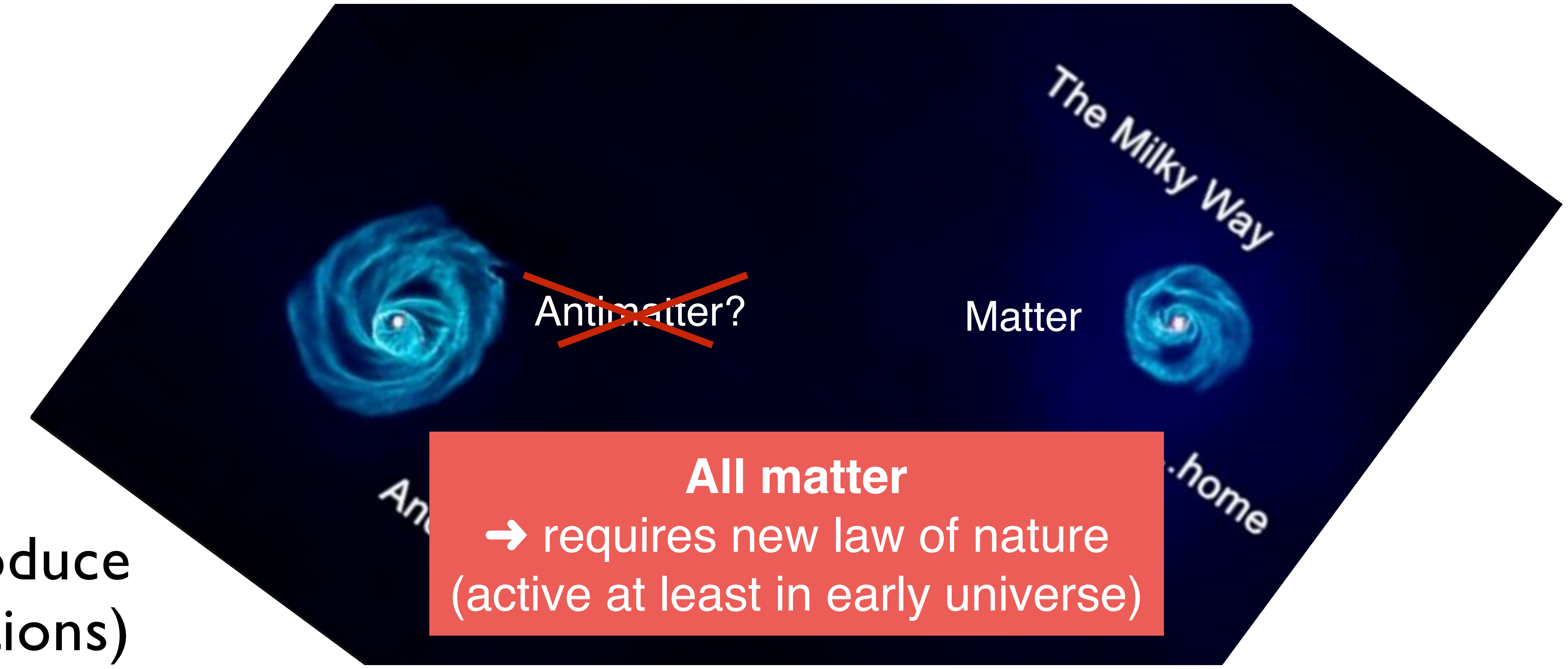
But the difference is **far too small** (by a factor ~ 100 billion) to explain the observed dominance of matter over antimatter in the universe

Could we be living in a "matter pocket", with other "anti-matter pockets" around?

No.

(border regions & mergers would produce observable gamma rays from annihilations)





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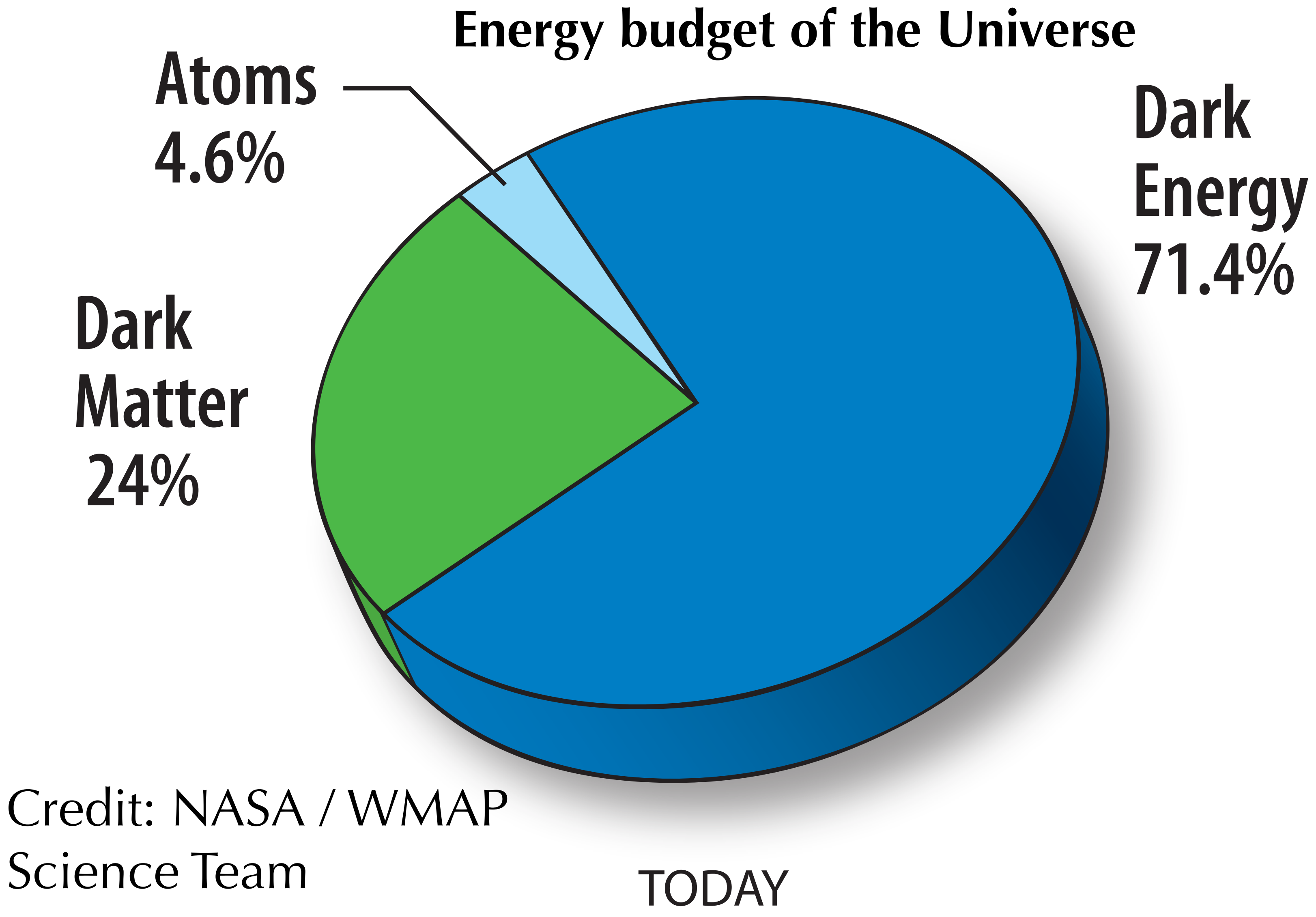
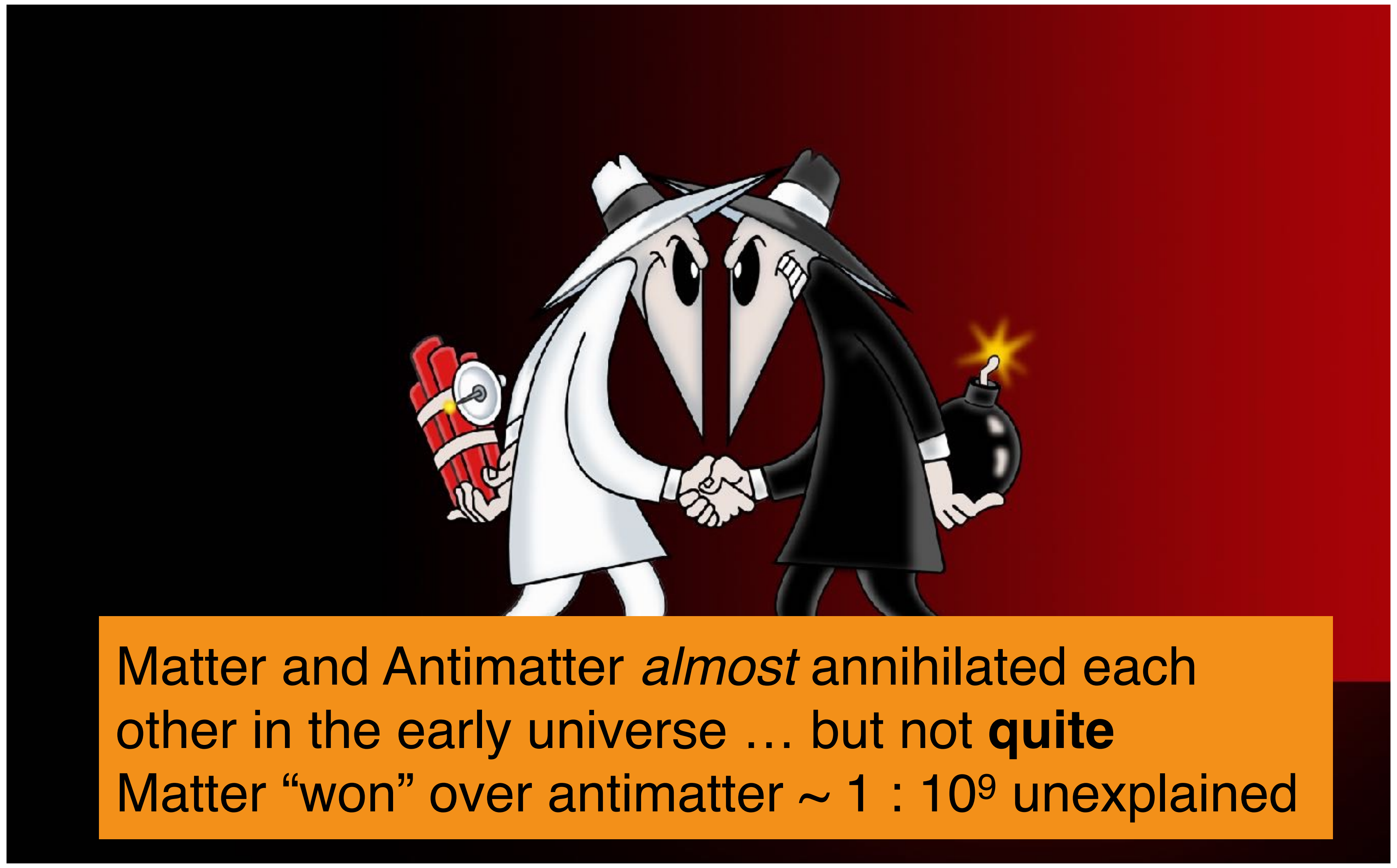




Sir William of Occam* may like the Higgs …

But theoretical physicists do **not**

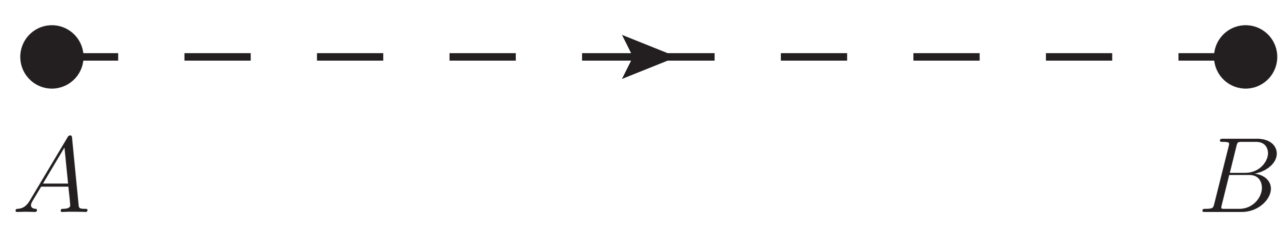
Educated guess ~ factor 10^{16} wrong

➜ Call that educated ?!

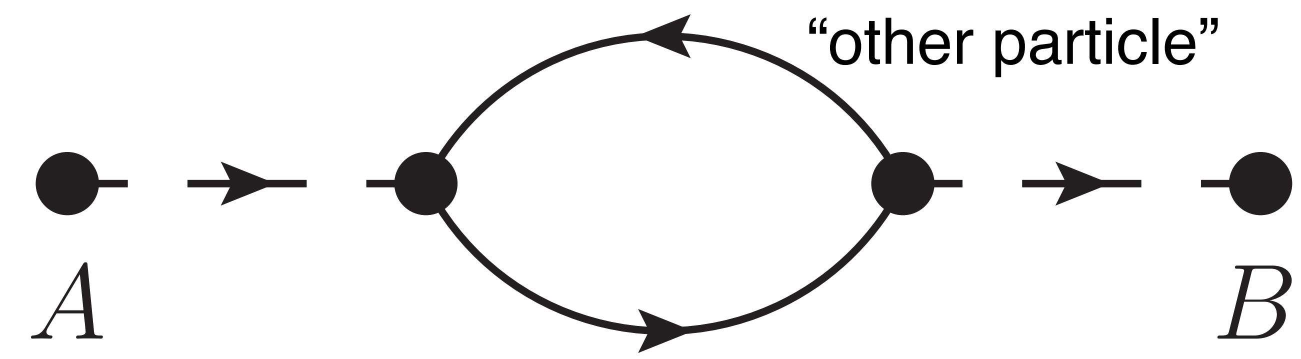
*Occam's Razor: among competing explanations to fit the same facts, the simplest tends to be the correct one

The problem with the Higgs

Here is a Higgs boson propagating from point A to point B:



Another quantum history for the same thing:



In quantum field theory, the fact that particles can "fluctuate" and exist briefly as other particles has to be included, and produces important "quantum corrections"

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"Hierarchy problem":

the 2^{nd} diagram "resets" effective Higgs mass to whatever the mass of the "other particle" is.

➜ If there is new particle physics at the "Planck scale", we would guess $m_H \sim m_{Planck} \sim 10^{18} - 10^{19}$ GeV

LHC measured $m_H \sim 120$ GeV

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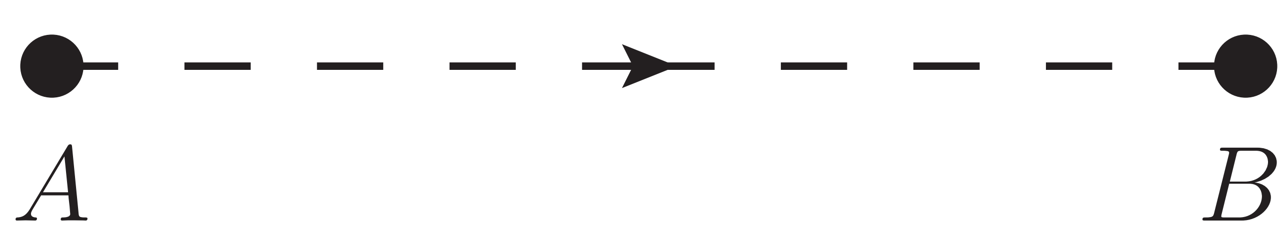

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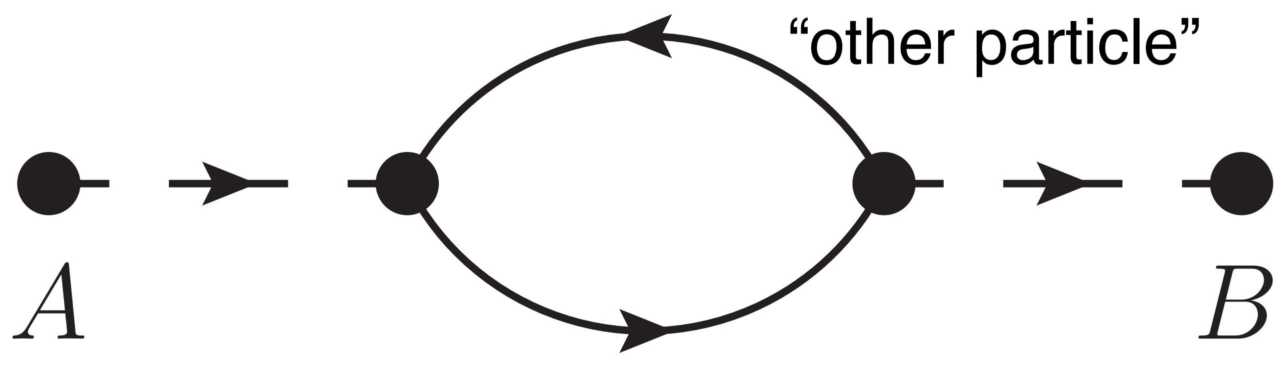

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...

Better guesses all based on new principles, like **supersymmetry**

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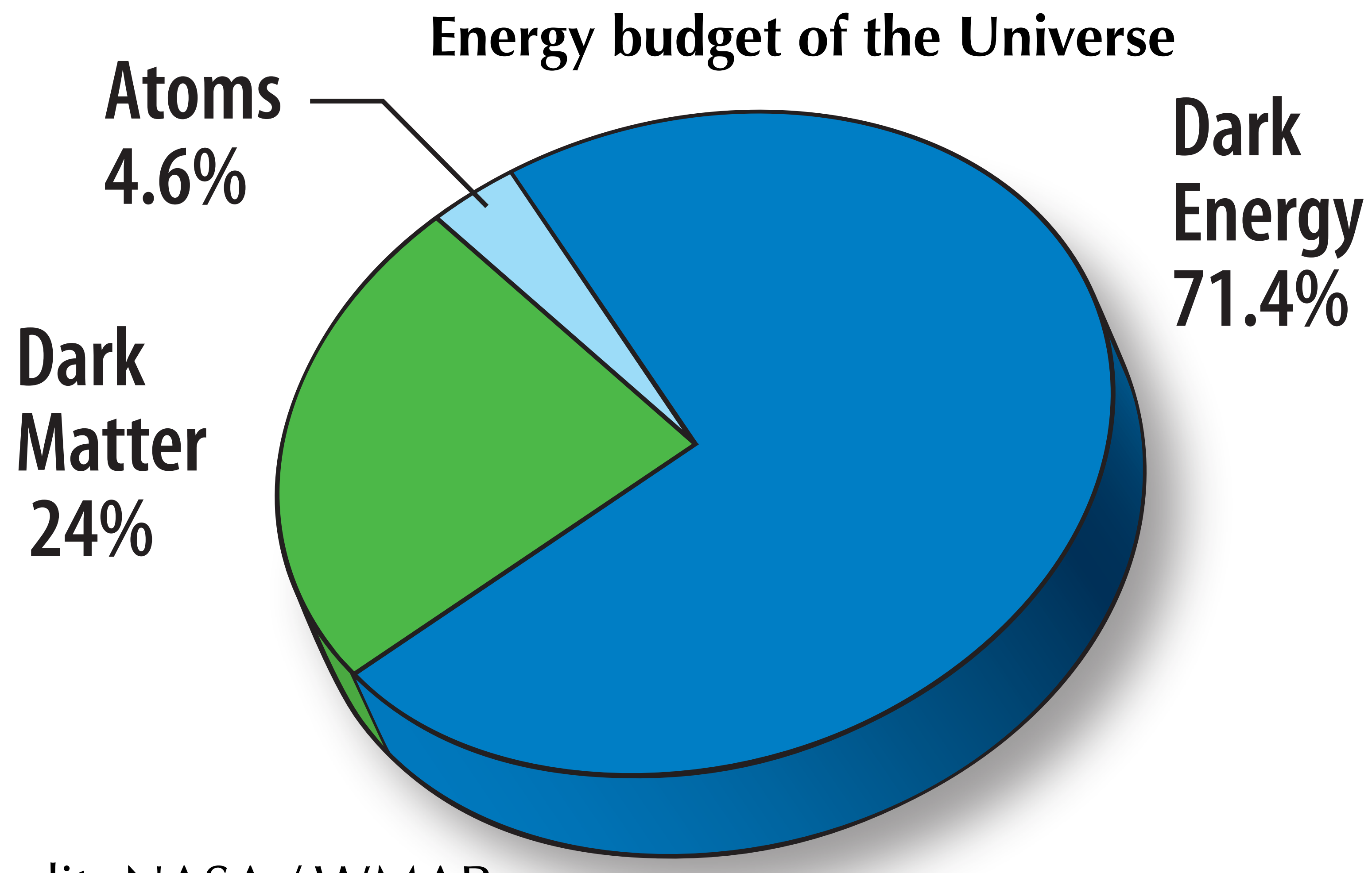
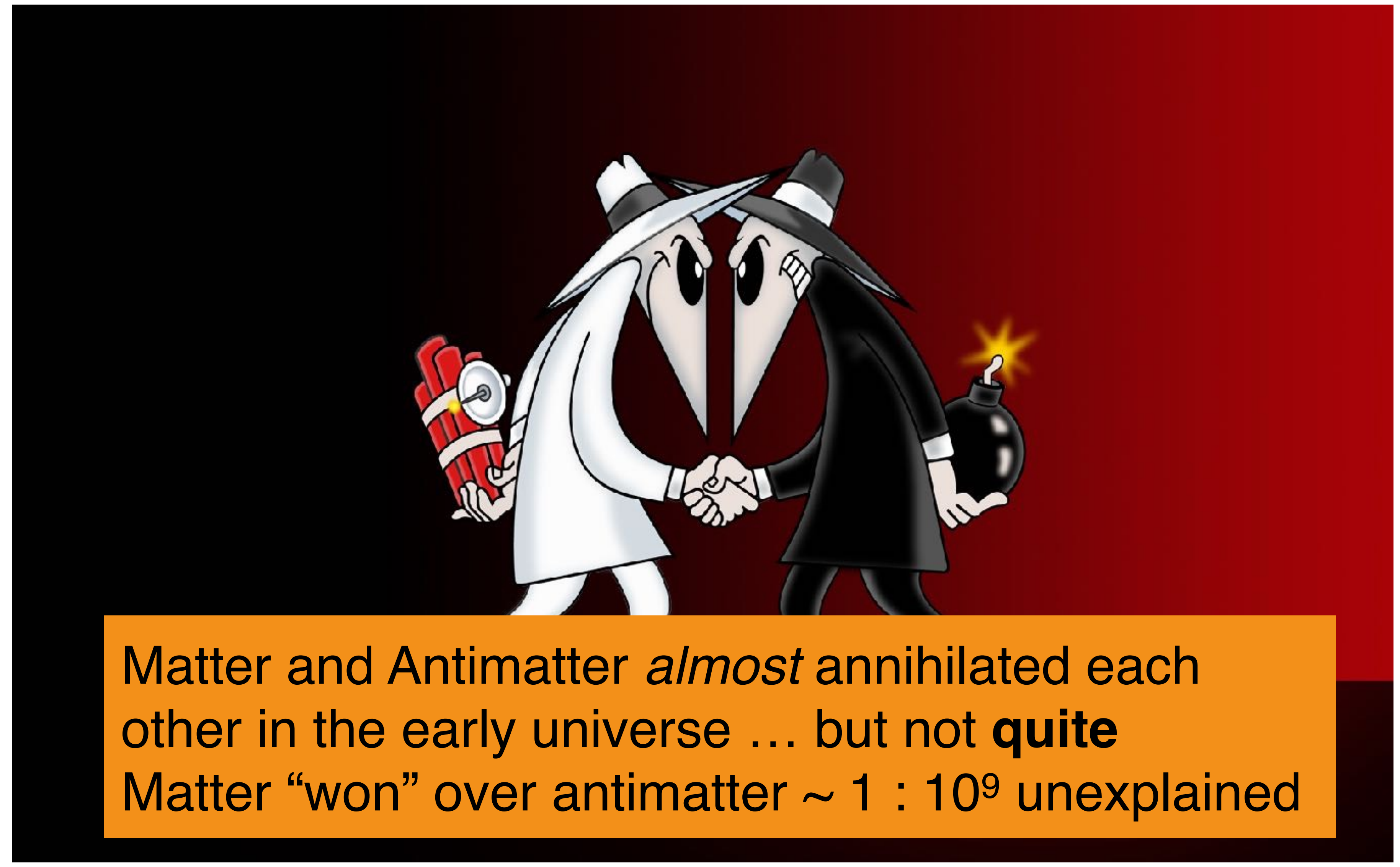
➜ If there is new particle physics at the "Planck scale", we would guess $m_H \sim m_{Planck} \sim 10^{18} - 10^{19}$ GeV

LHC measured $m_H \sim 120$ GeV

What we know …



Credit: NASA / WMAP Science Team



Sir William of Occam* may like the Higgs

…

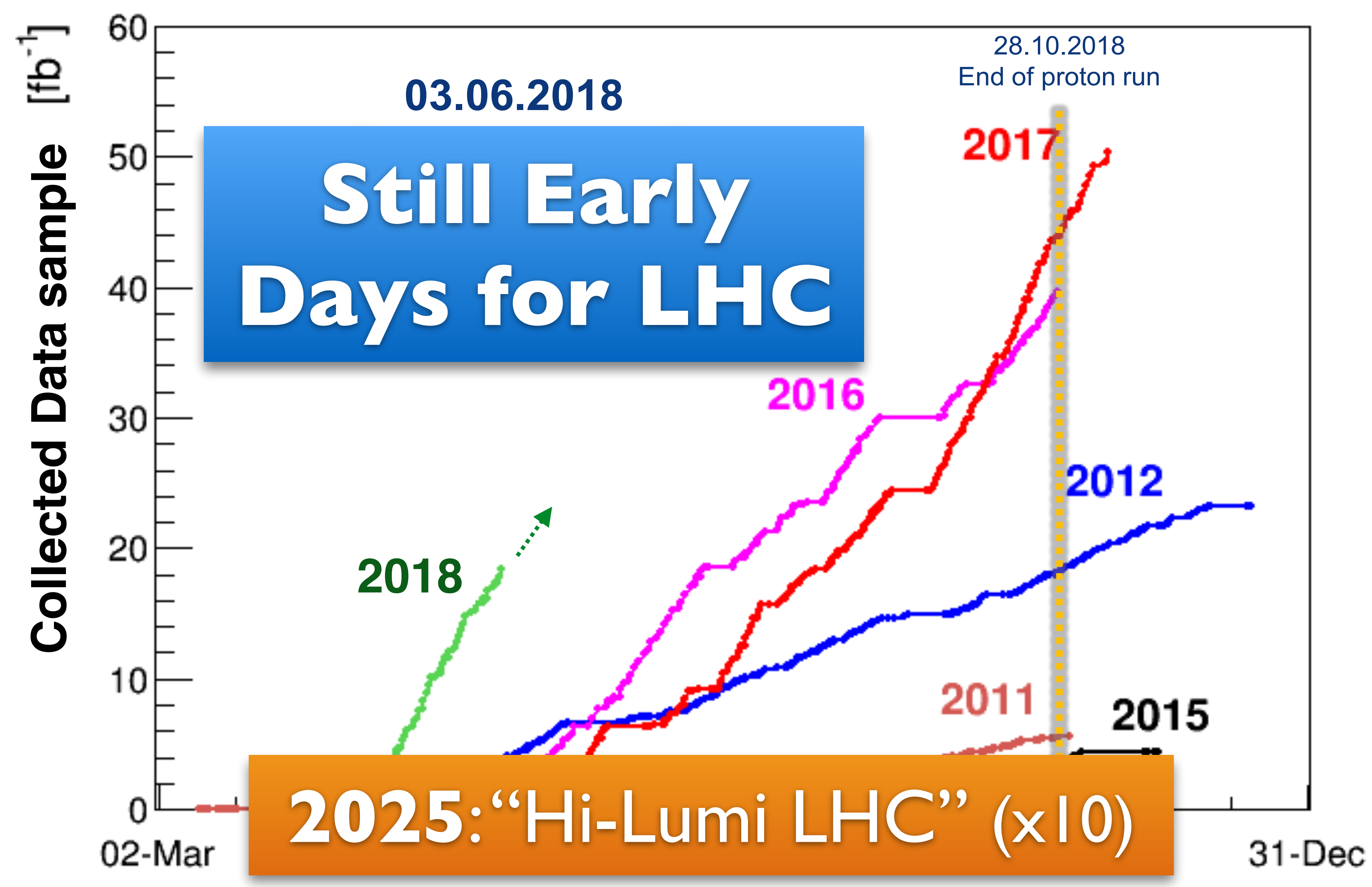
But theoretical physicists do **not**

Educated guess ~ factor 10^{16} wrong

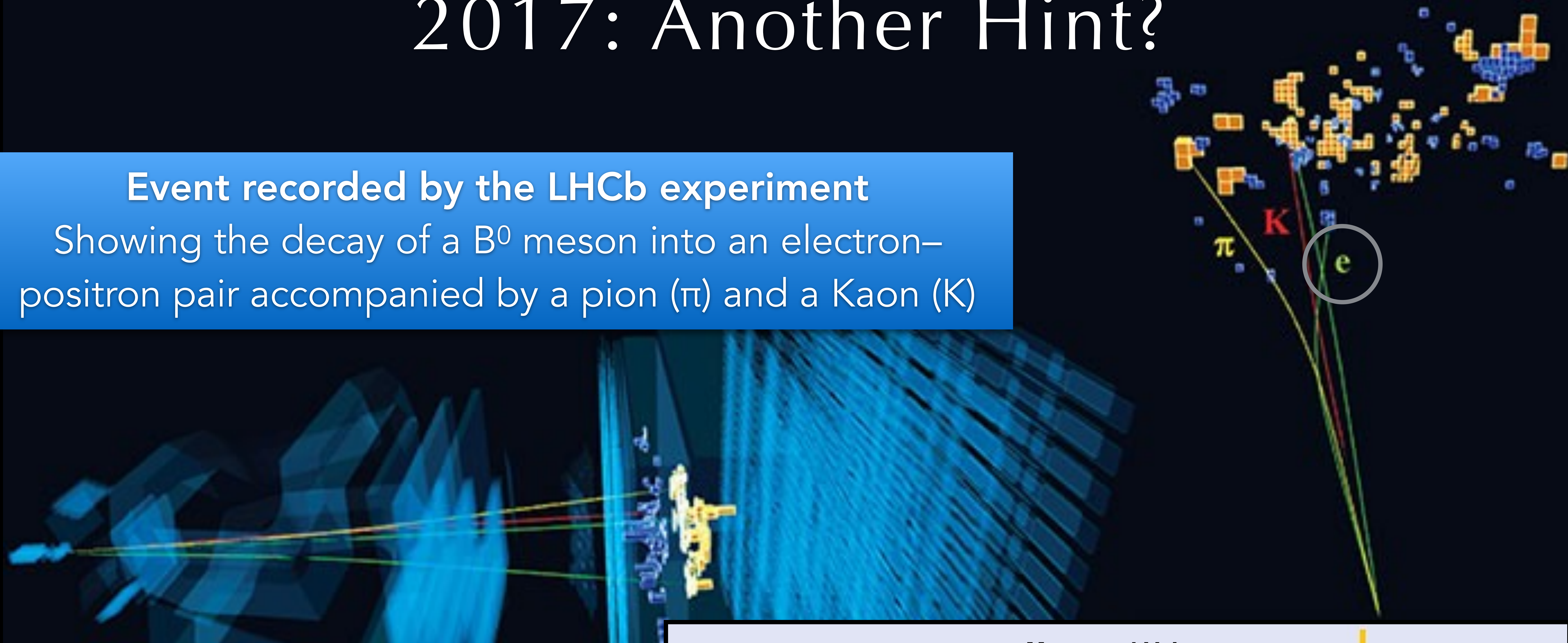
➜ Call that educated ?!

…

Better guesses all based on new principles, like **supersymmetry**



2017: Another Hint?



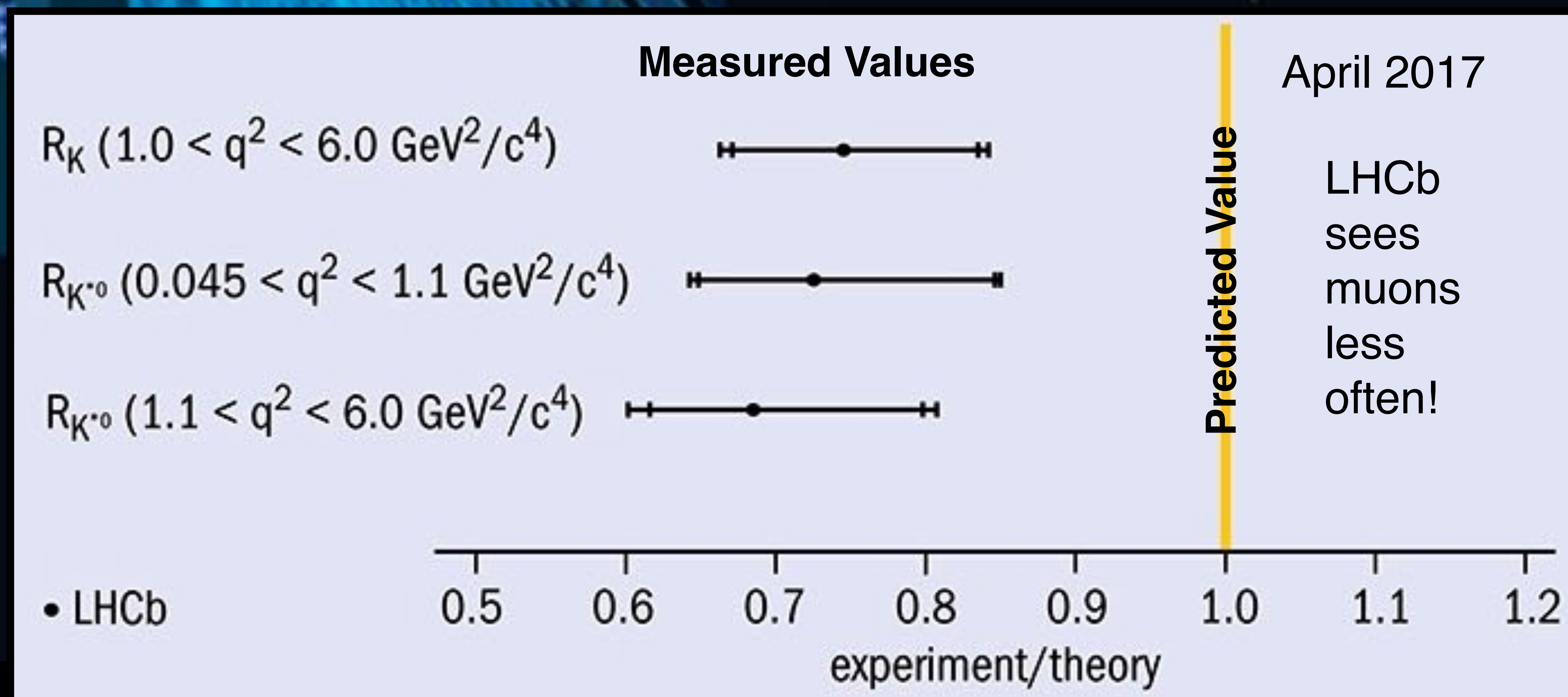
Event recorded by the LHCb experiment

Showing the decay of a B^0 meson into an electron–positron pair accompanied by a pion (π) and a Kaon (K)

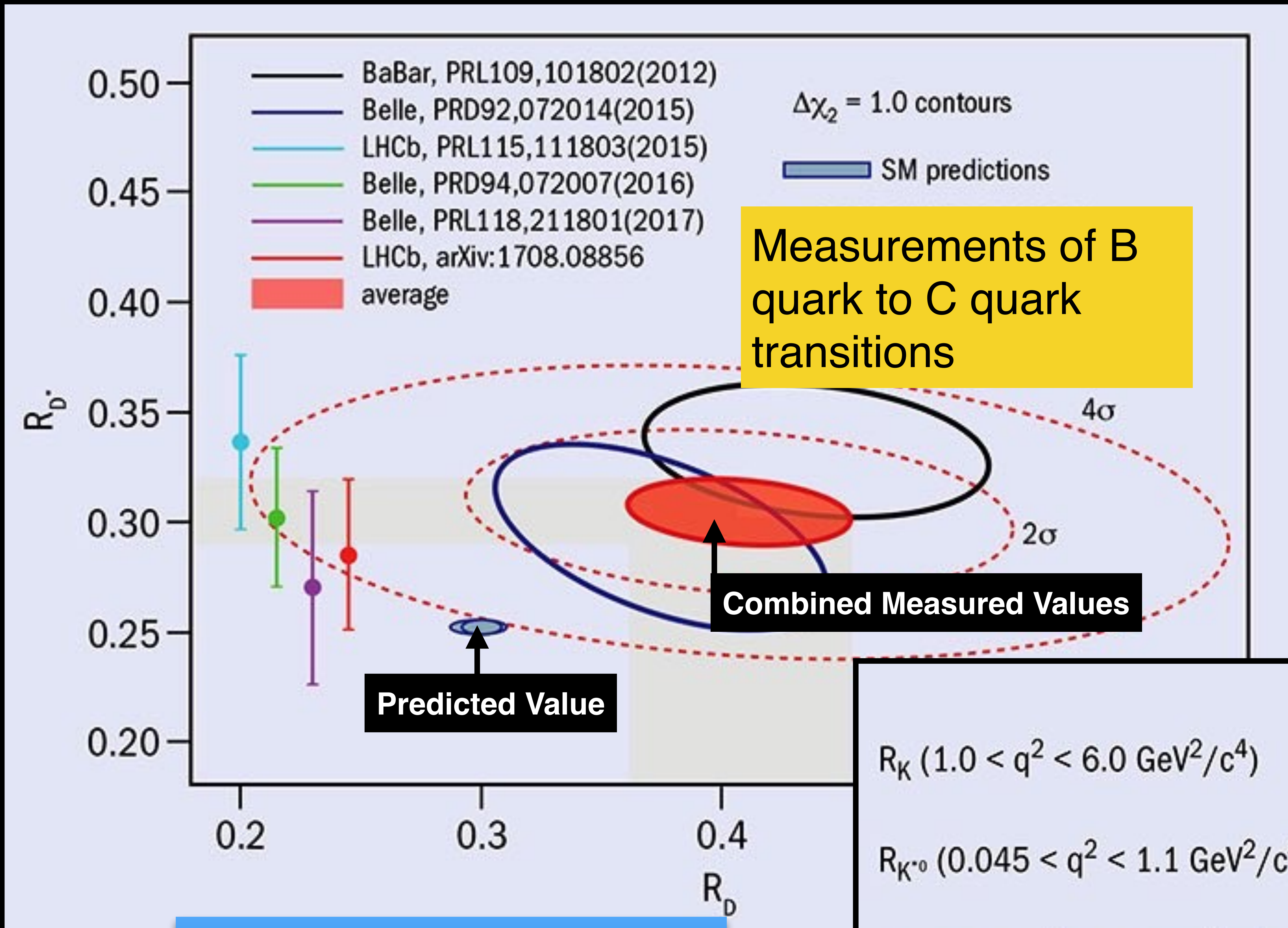
Firm prediction of the Standard Model:

Should see electrons and muons equally often in this decay : **R = 1**

*(called **Lepton Universality**)*



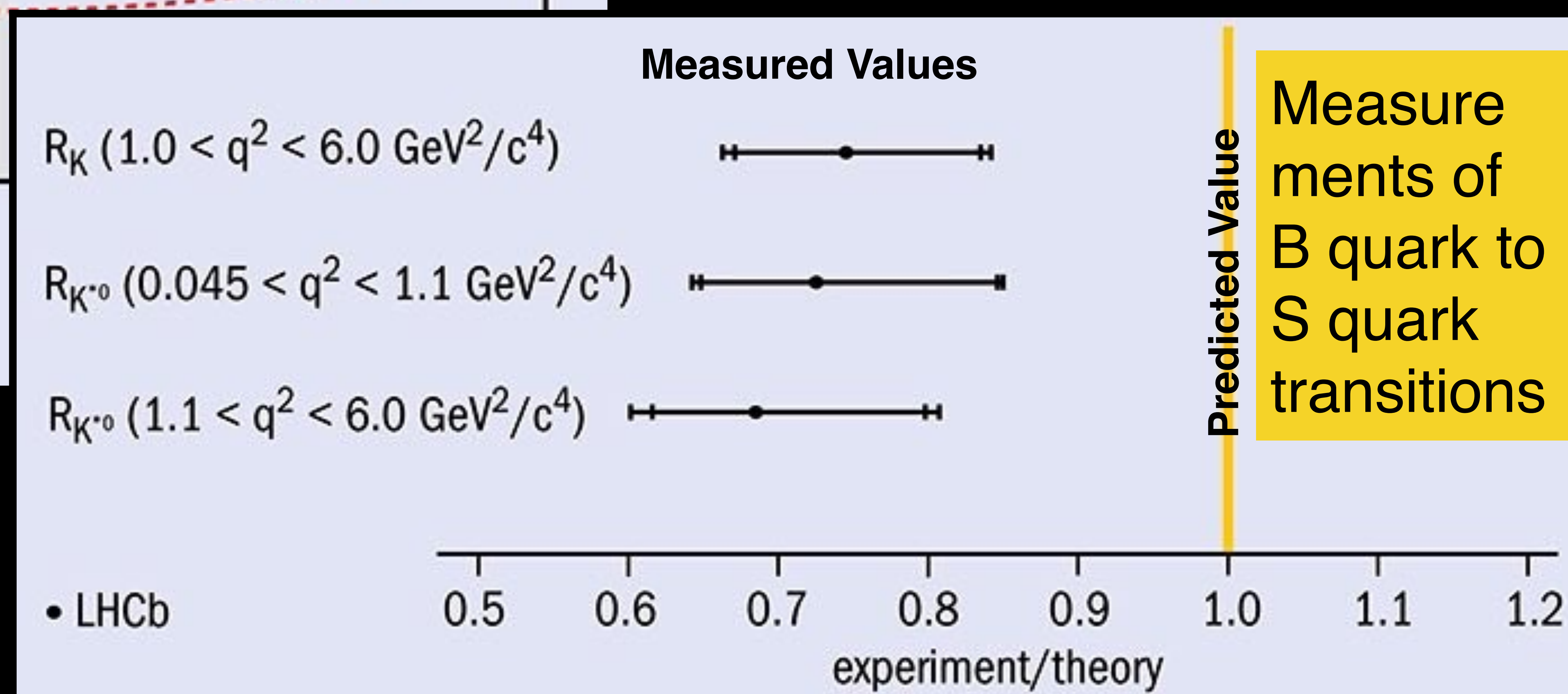
Related measurements also show discrepancies



Note: this is research going on right here at Sydney U.

Taking part in the Belle II experiment hosted by the KEK laboratory in Japan.

First collisions in early 2018, aiming at 50 times more data than its predecessor



Follow-up measurements now eagerly awaited

Stay Tuned

Thank you for your attention!

Stay Tuned

Thank you for your attention!

Rates and Triggers

We get ~ 40 million collisions / sec.

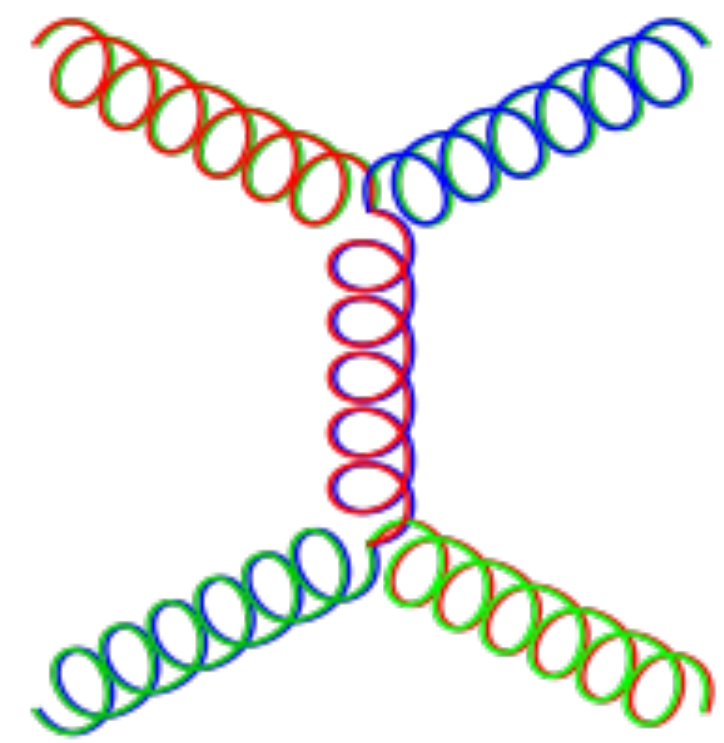
We can save ~ 100 / sec to disk.

WHICH ONES?

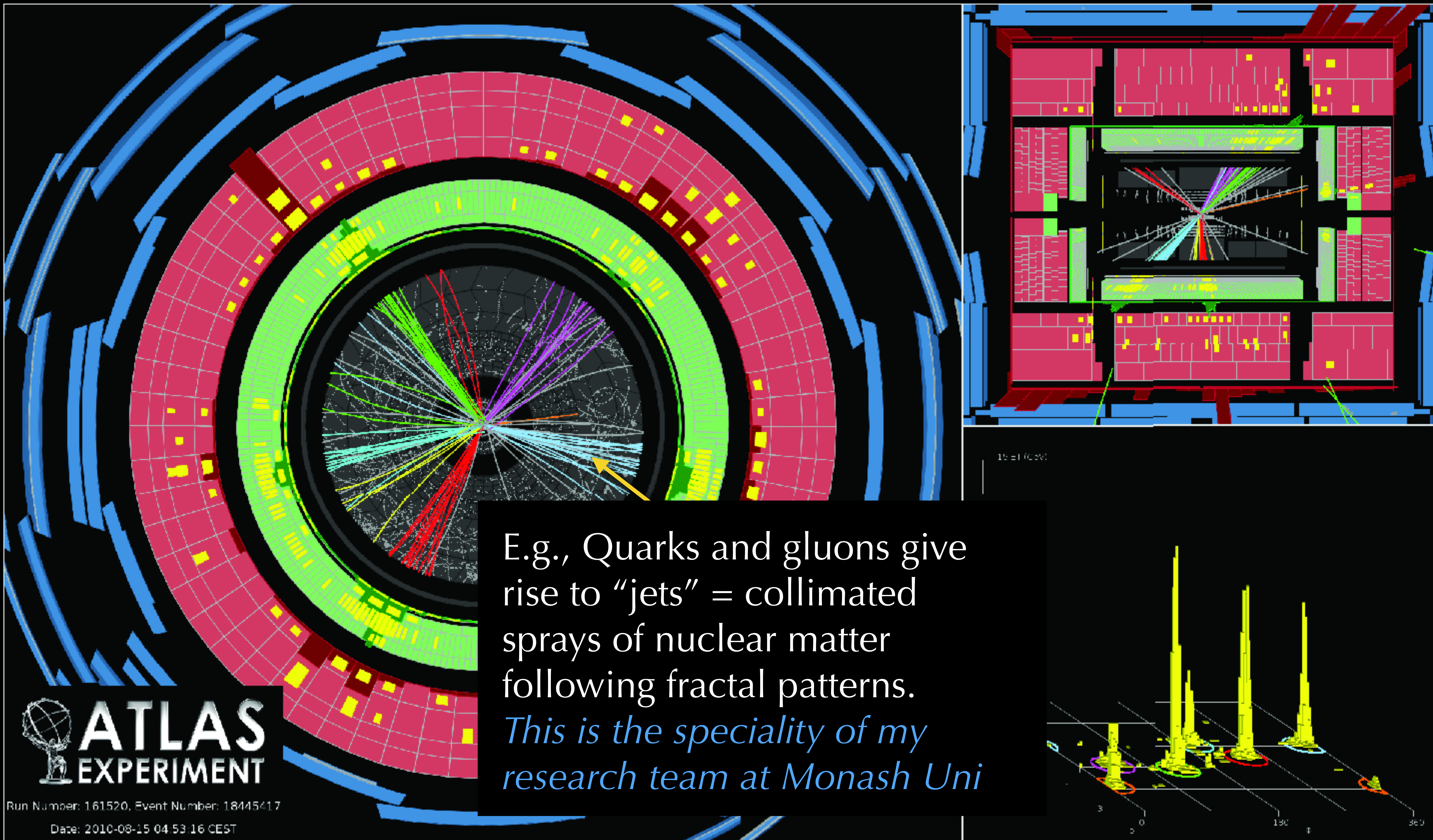
Automated "trigger" systems decide which collisions may be interesting

Not all reactions are created equally

- The most likely collision type is gg → gg
- The top quark is the heaviest elementary particle
  - Discovered in 1995 by Fermilab's Tevatron accelerator.
  - The LHC can make ~ 1 top quark / second.
- The reaction gg → Higgs will happen ~ 1 / minute
  - We don't want to loose too many of them …



+ Complications: *Bremsstrahlung radiation, confinement (quarks/gluons→**hadrons**), probabilities, …*



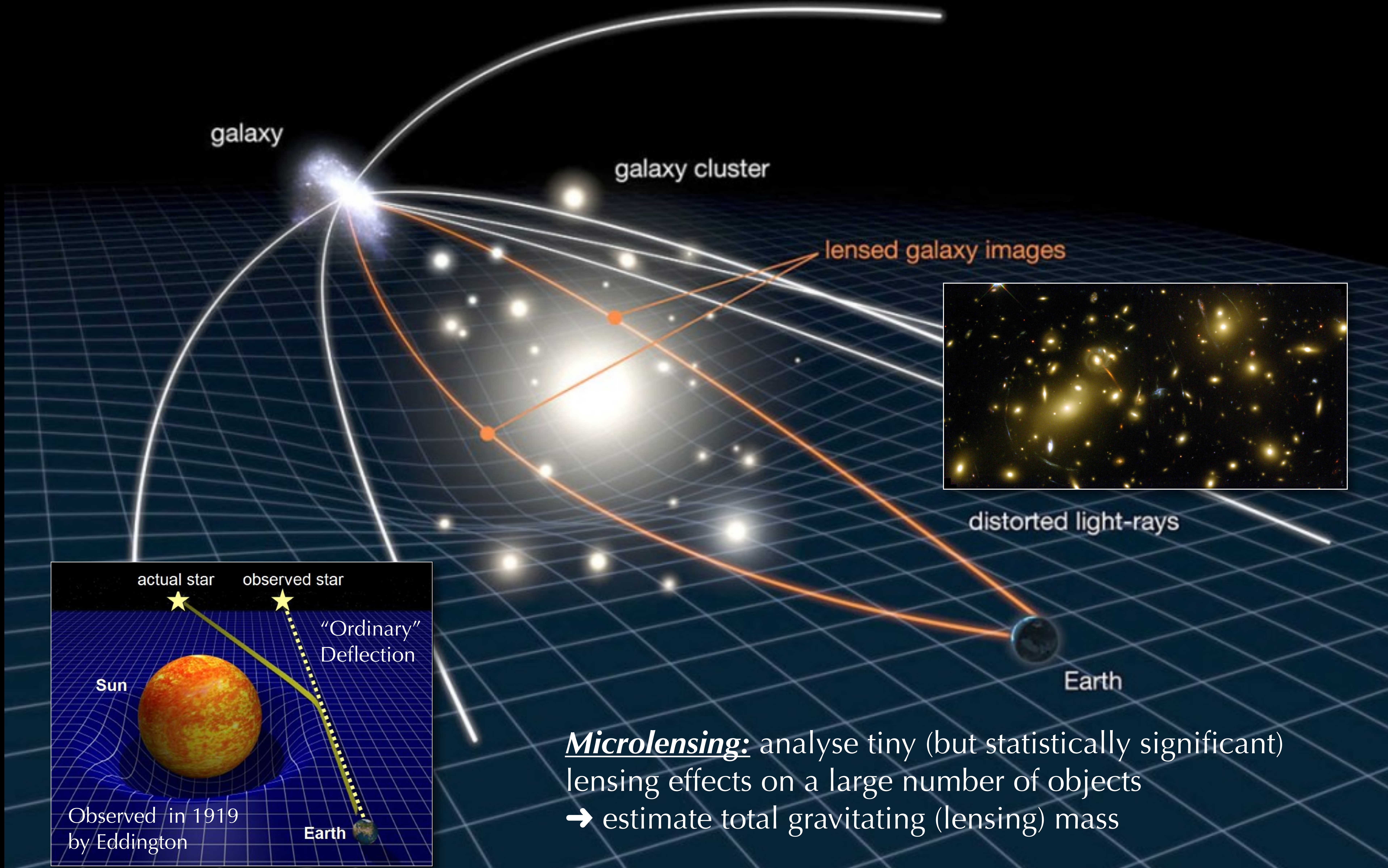
E.g., Quarks and gluons give rise to "jets" = collimated sprays of nuclear matter following fractal patterns.

This is the speciality of my research team at Monash Uni

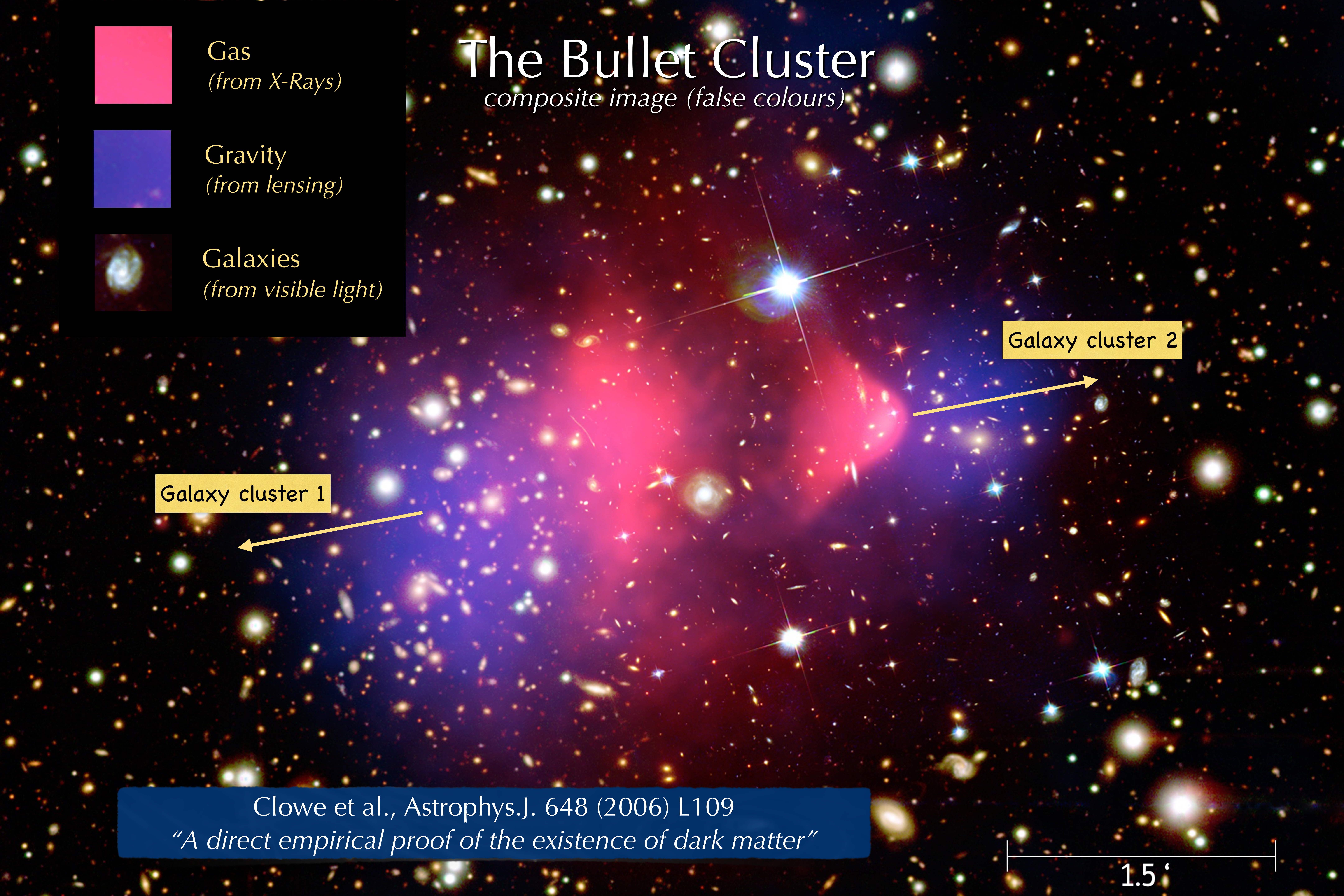
The basic law of quantum mechanics: anything that ***can*** happen ***will*** happen

Gravitational Lensing

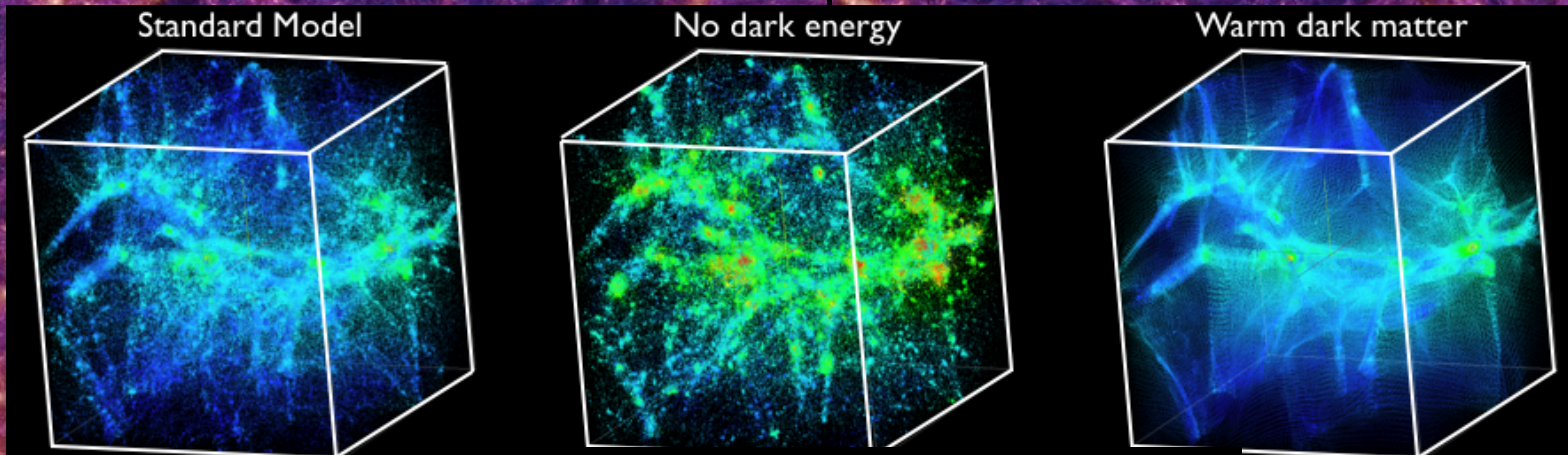
1912: Predicted by Einstein
1979: First Lens
1988: First Ring



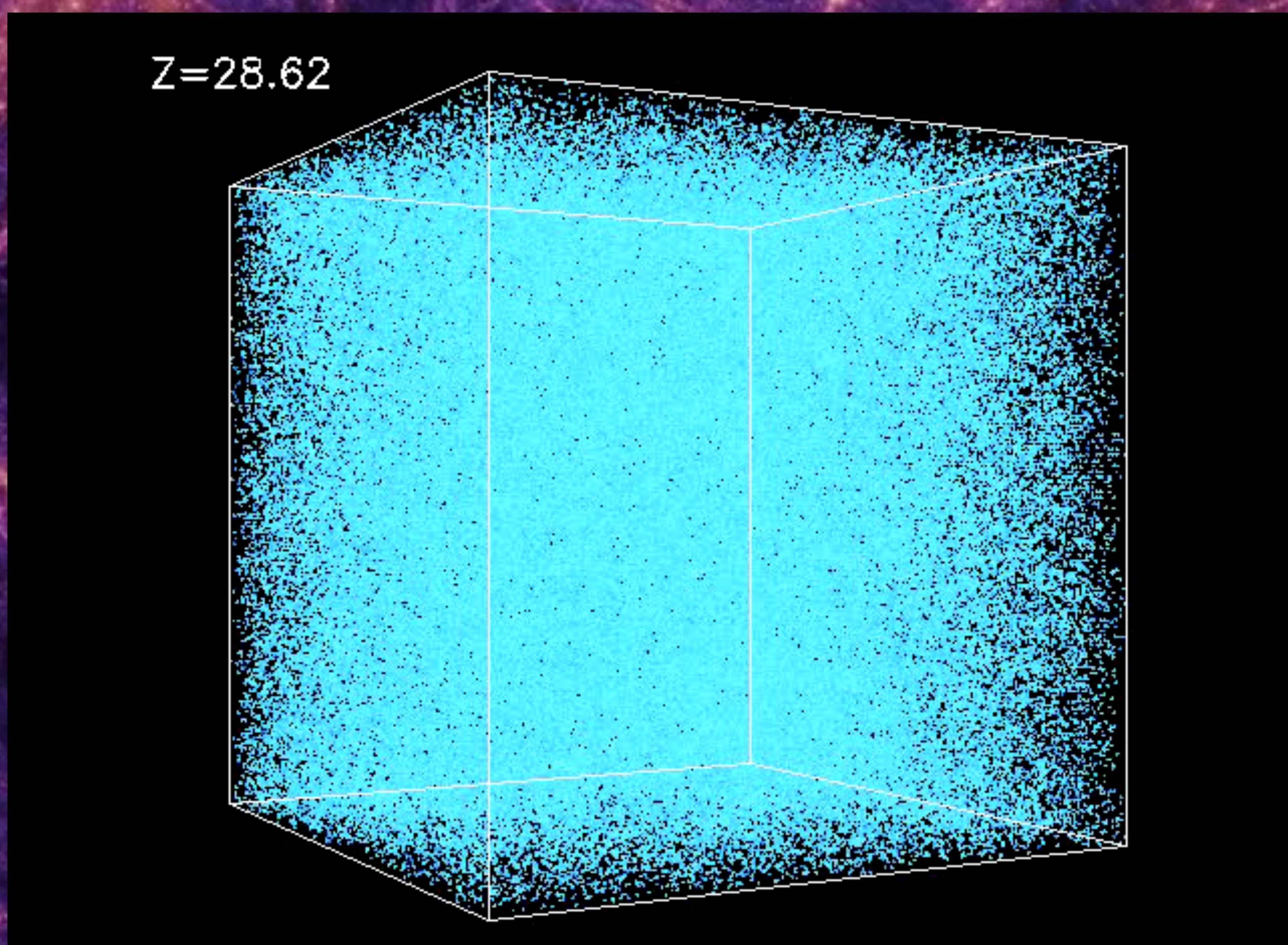
Microlensing: analyse tiny (but statistically significant) lensing effects on a large number of objects
➜ estimate total gravitating (lensing) mass


The Bullet Cluster
composite image (false colours)
Gas
(from X-Rays)
Gravity
(from lensing)
Galaxies
(from visible light)
Galaxy cluster 2
Galaxy cluster 1
Clowe et al., Astrophys.J. 648 (2006) L109
"A direct empirical proof of the existence of dark matter"
1.5 '

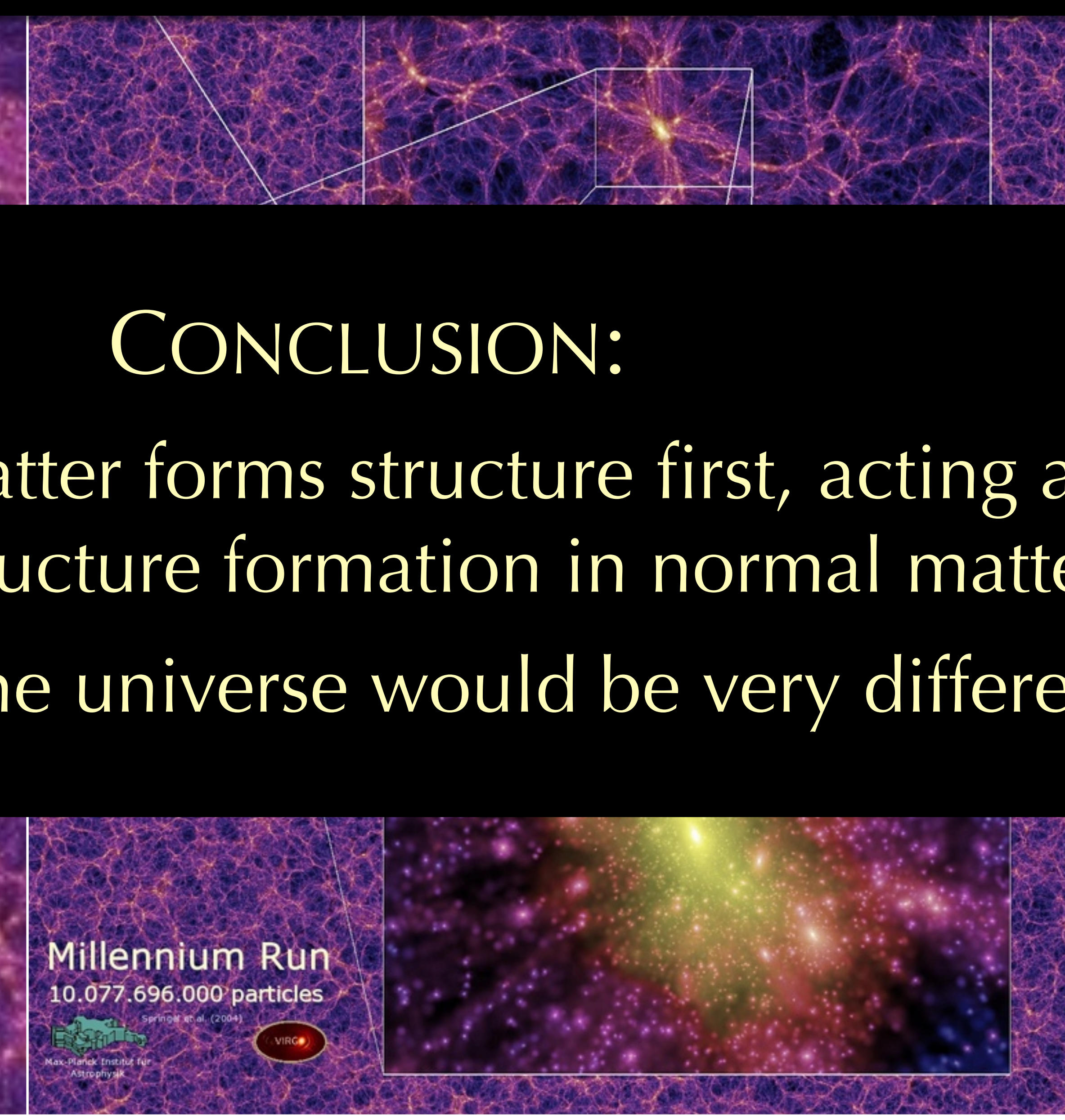
The *Millennium Simulation*: largest N-Body Simulation ever carried out, containing over 10 billion particles. [Virgo Consortium]



Simulations performed by K. Heitmann, at Argonne Leadership Computing Facility



Simulations performed at the National Center for Supercomputer Applications by A. Kravtsov (U Chicago) and A. Klypin (New Mexico State U). Visualizations by Andrey Kravtsov.



Conclusion:

(Cold) Dark Matter forms structure first, acting as the seeds for structure formation in normal matter.

Without it, the universe would be very different.

(+ illustrates another frontier: the **computational** one)