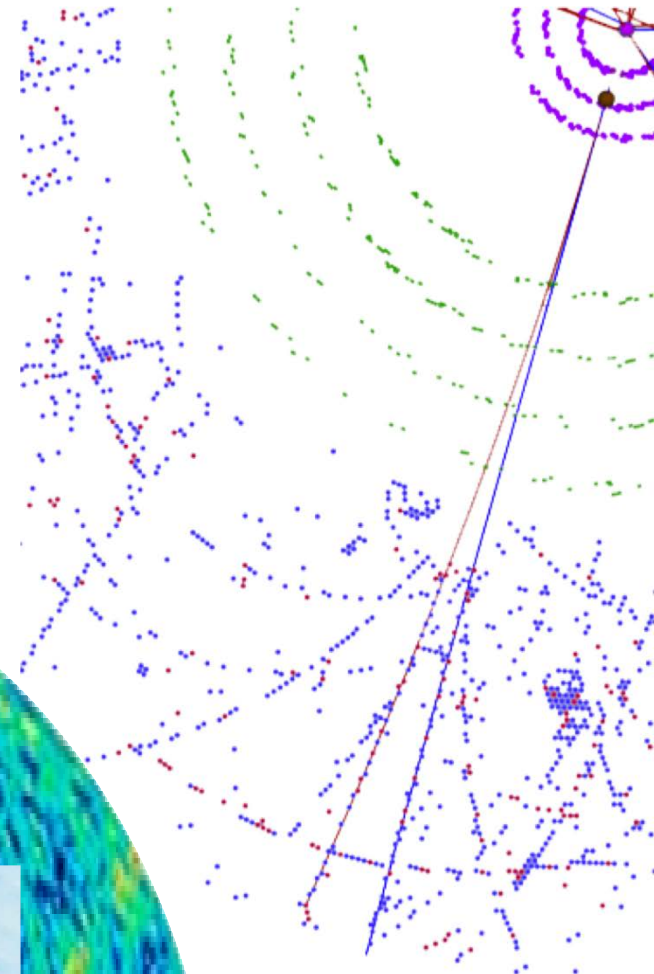
From the infinitesimal to the infinite with high-energy particle colliders



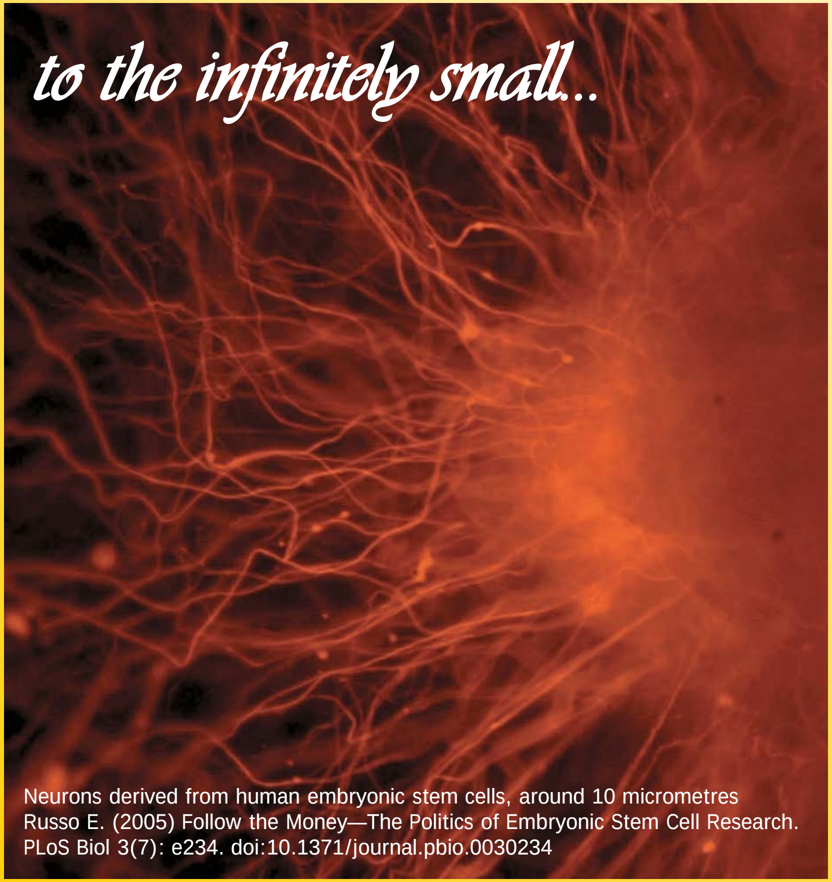
Manuella Vincter

Manuella Vincter

- Professor at Carleton University in Ottawa, Canada
- Experimental Particle Physicist
- Deputy Spokesperson of the ATLAS Collaboration at the CERN Laboratory in Switzerland

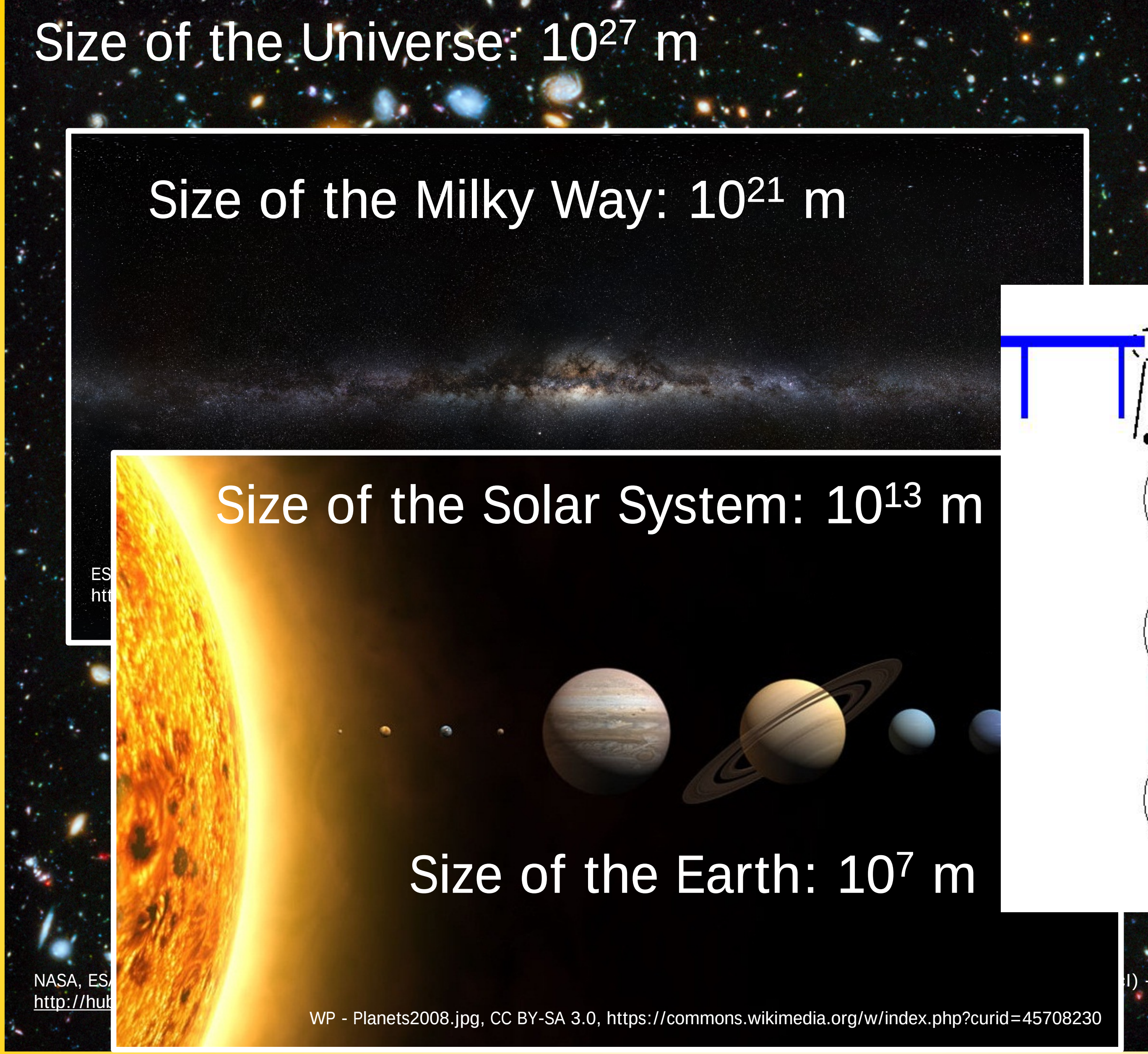
The Universe is beautiful!

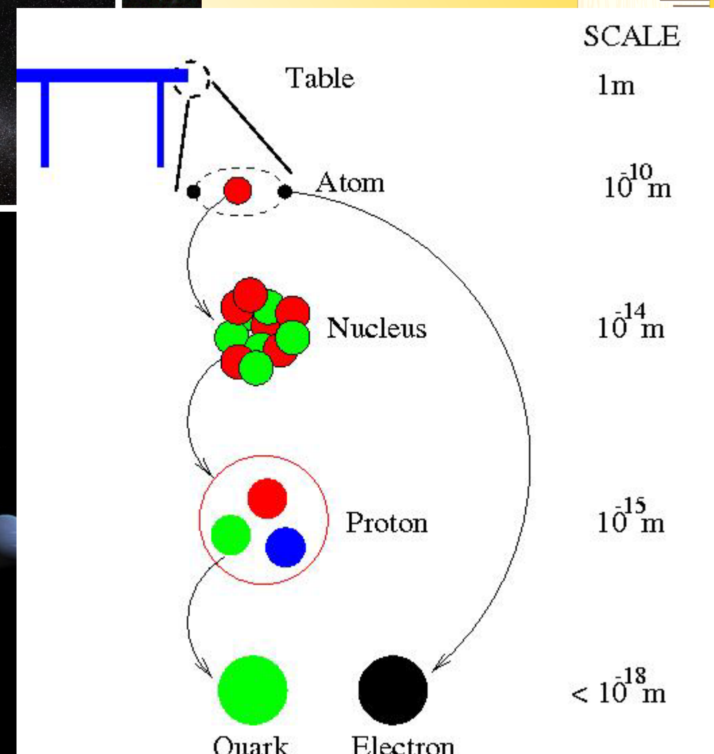
Horsehead nebula 1,500 light years away
By Pablo Carlos Budassi - Own work, CC BY-SA 4.0,
https://commons.wikimedia.org/w/index.php?curid=94313357



Neurons derived from human embryonic stem cells, around 10 micrometres
Russo E. (2005) Follow the Money—The Politics of Embryonic Stem Cell Research. PLoS Biol 3(7): e234. doi:10.1371/journal.pbio.0030234

and the distance scales characterising the Universe are mind boggling...



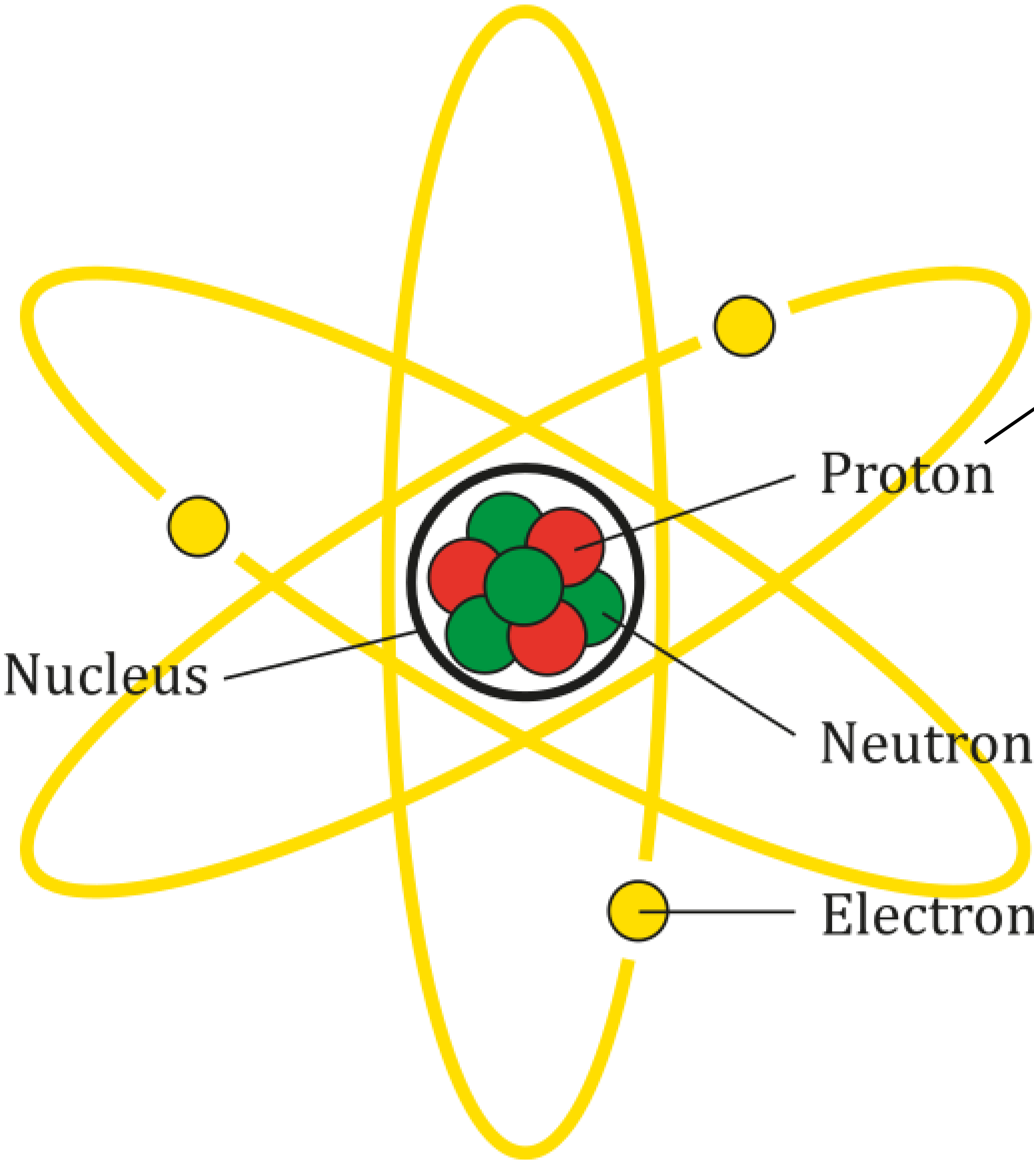


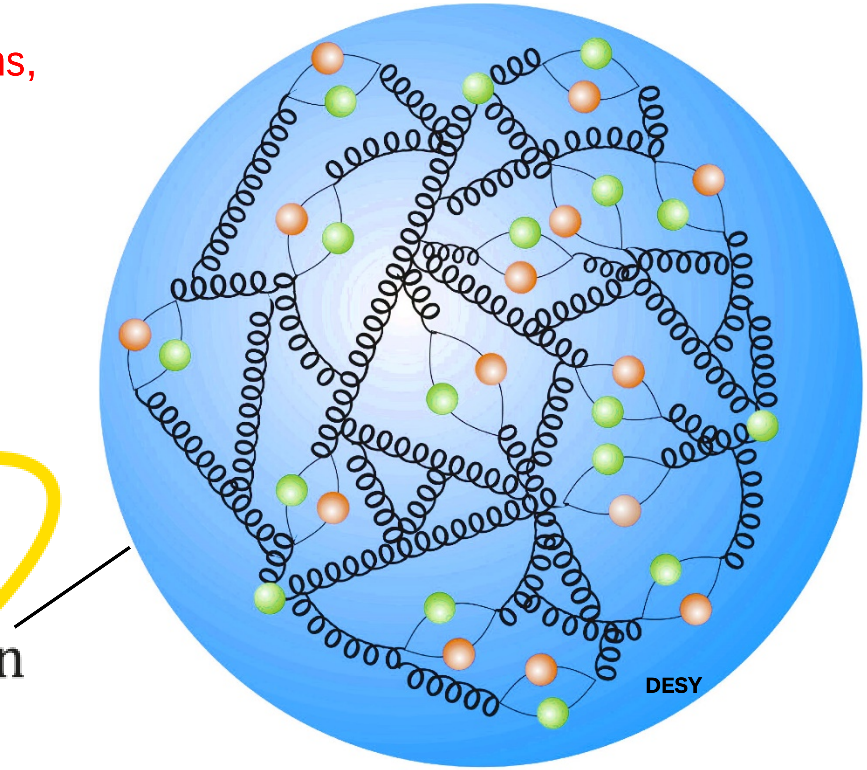
0.000000000000000001 m

1 m

1000000000000000000000000000 m

All of the Universe is made up of atoms (protons, neutrons, electrons)...





Or is it?

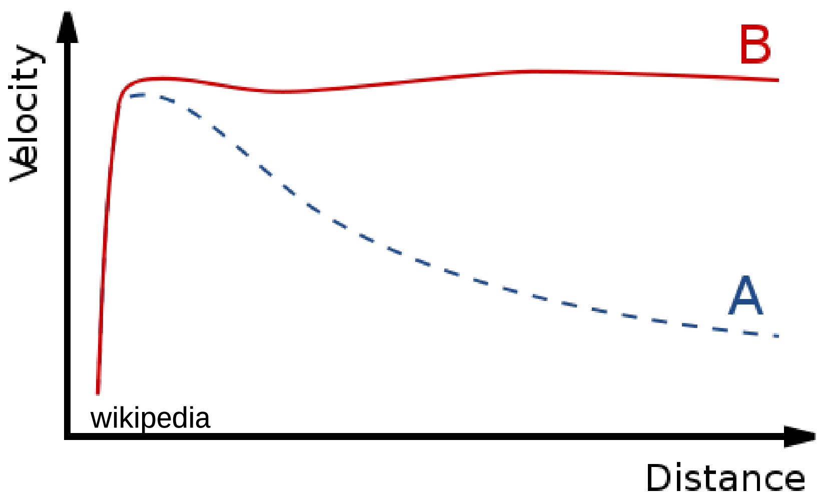
AG Caesar https://bar.wikipedia.org/wiki/Datei:Atom_Diagram.svg

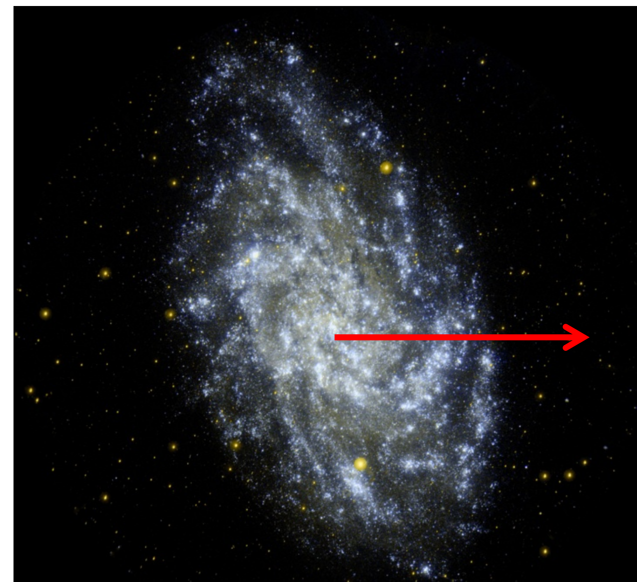
Messier 33 (The Triangulum Galaxy)

spiral galaxy 2.73 million light-years from Earth

Where is all the matter in the universe?

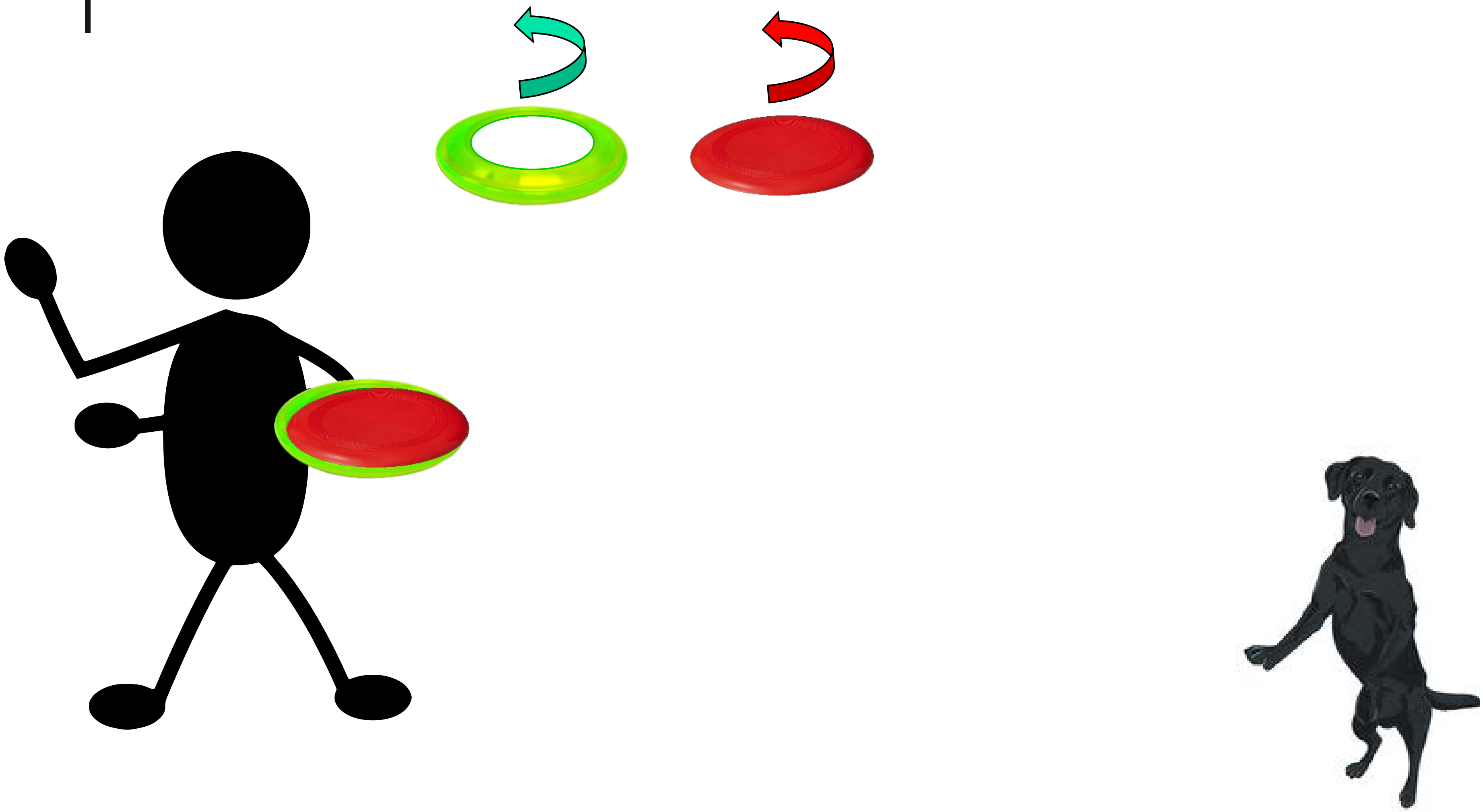
- Louise Volders (1959) measured that a galaxy did not spin according to expected laws of motion
- Orbital velocity of stars&gas (observed matter) in galaxy vs. distance from centre
  - Newtonian mechanics: decreases with distance (see A)
  - Observation: it is flat! (see B)




M33 (Triangulum Galaxy) NASA/JPL-Caltech

- Galaxies are rotating at such a speed that the gravity generated by the observed matter cannot possibly hold them together:
  - Galaxies should have ripped apart a long time ago!
- Possible explanation:
  - Missing matter in the galaxy

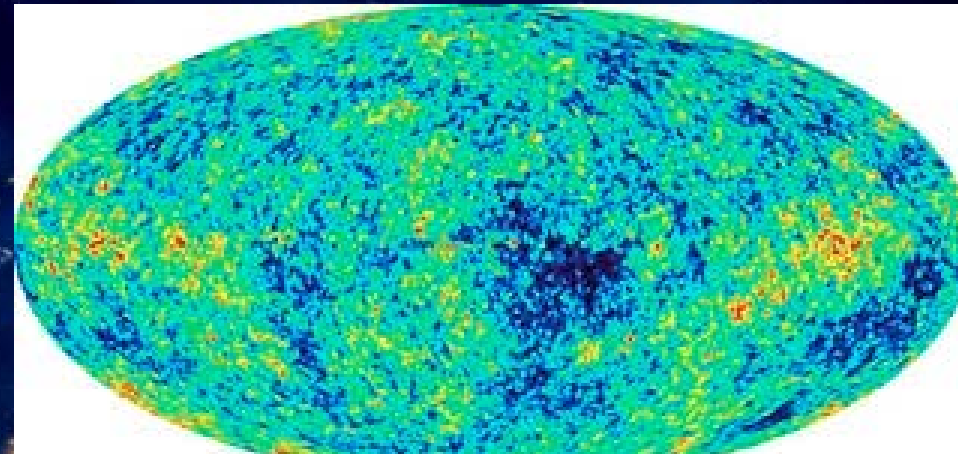
Where is all the matter in the universe?



Where the mass is distributed on the flying disk dictates how it will spin

Open question!

- By looking at the temperature map of the universe:
  - ~30 % of the universe is matter, of which only 4 % is baryonic (i.e. regular everyday stuff). The rest is dark matter!
  - ~70 % of the universe is an unknown dark energy
- We make up but a tiny fraction of the universe!


NASA/WMAP Science Team

What is dark matter?

Can I find it in the universe?

If not, can I make it in a lab?

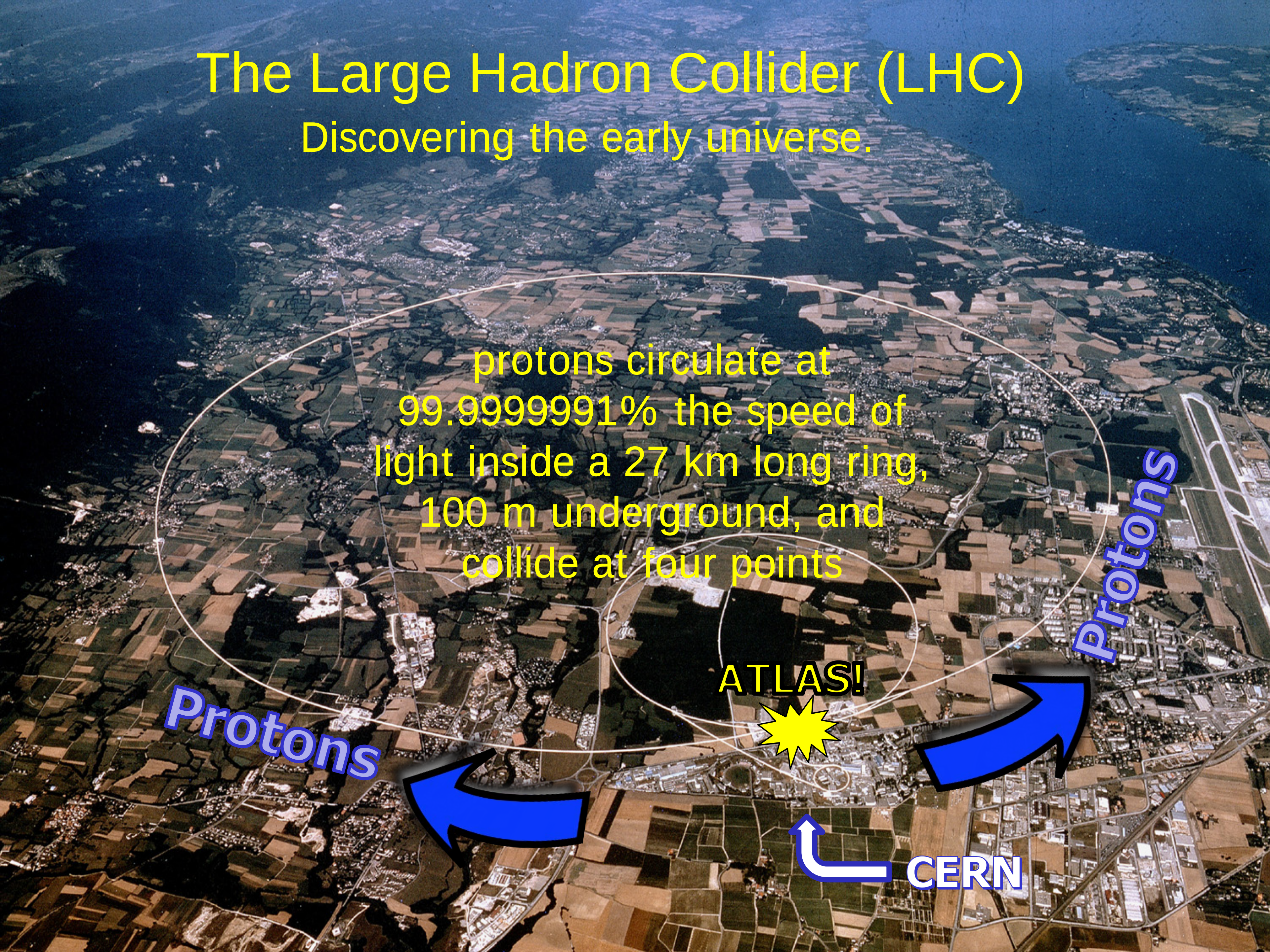
NASA/WMAP Science Team

CERN Laboratory on the Swiss/French border: a paradigm for international cooperation

The Large Hadron Collider (LHC)

Discovering the early universe.

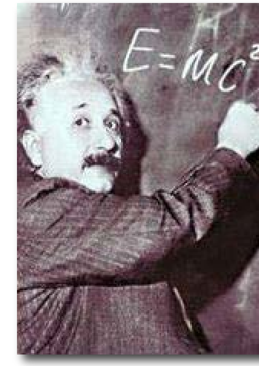
protons circulate at 99.9999991% the speed of light inside a 27 km long ring, 100 m underground, and collide at four points



Study interactions of matter by high energy collisions in a lab

- The early universe was a HOT universe!
- Energy and mass are intimately related!

$E=mc^2$



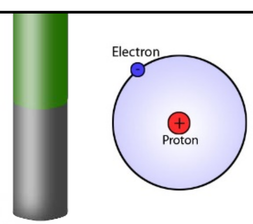
- High energy proton collisions provide the energy which can be converted to new massive objects!

Matter → energy → new matter

- LHC: energy density of collisions like early universe less than a billionth of a second after Big Bang

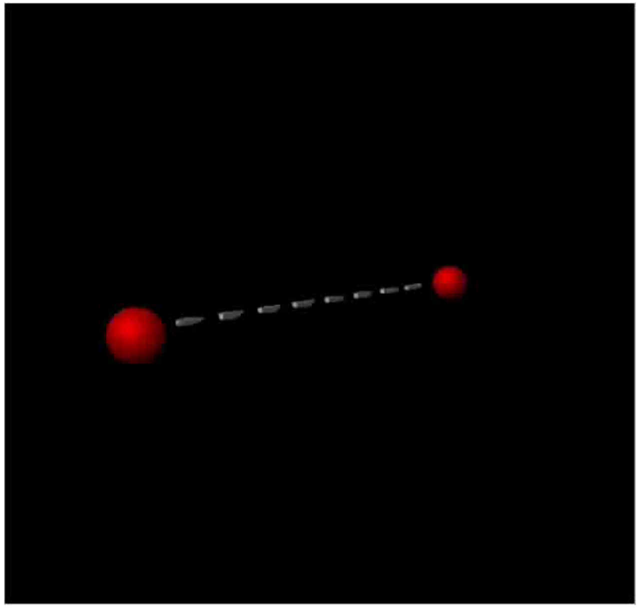
- Energy stored in each LHC beam: 360 mega-joules
  - Kinetic energy: 450 cars at 100 km/h
  - Chemical energy: 70 kg of chocolate (count the calories!)
  - Thermal energy: enough to make “a tonne of tea”

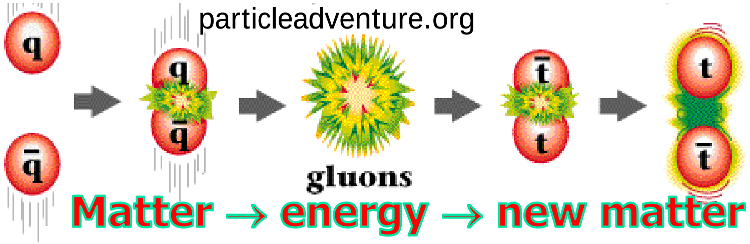
LHC accelerator chain

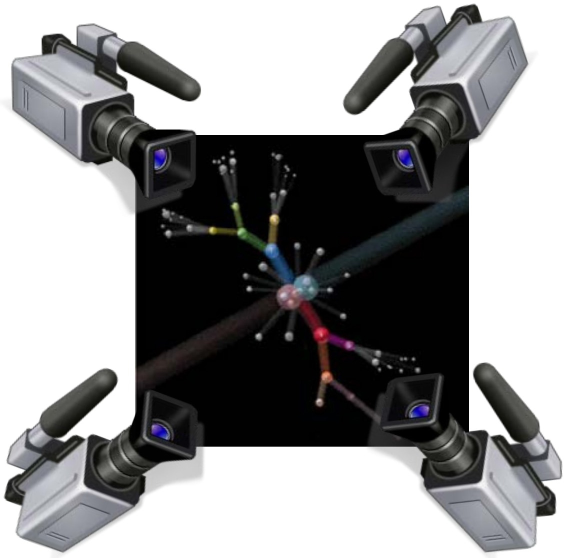


Hydrogen

LHC's cameras





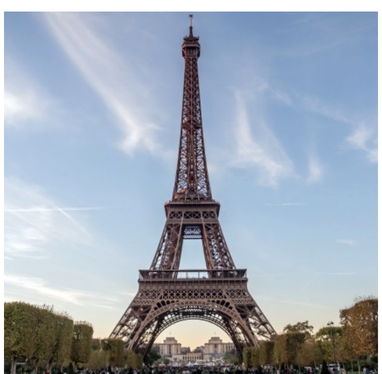


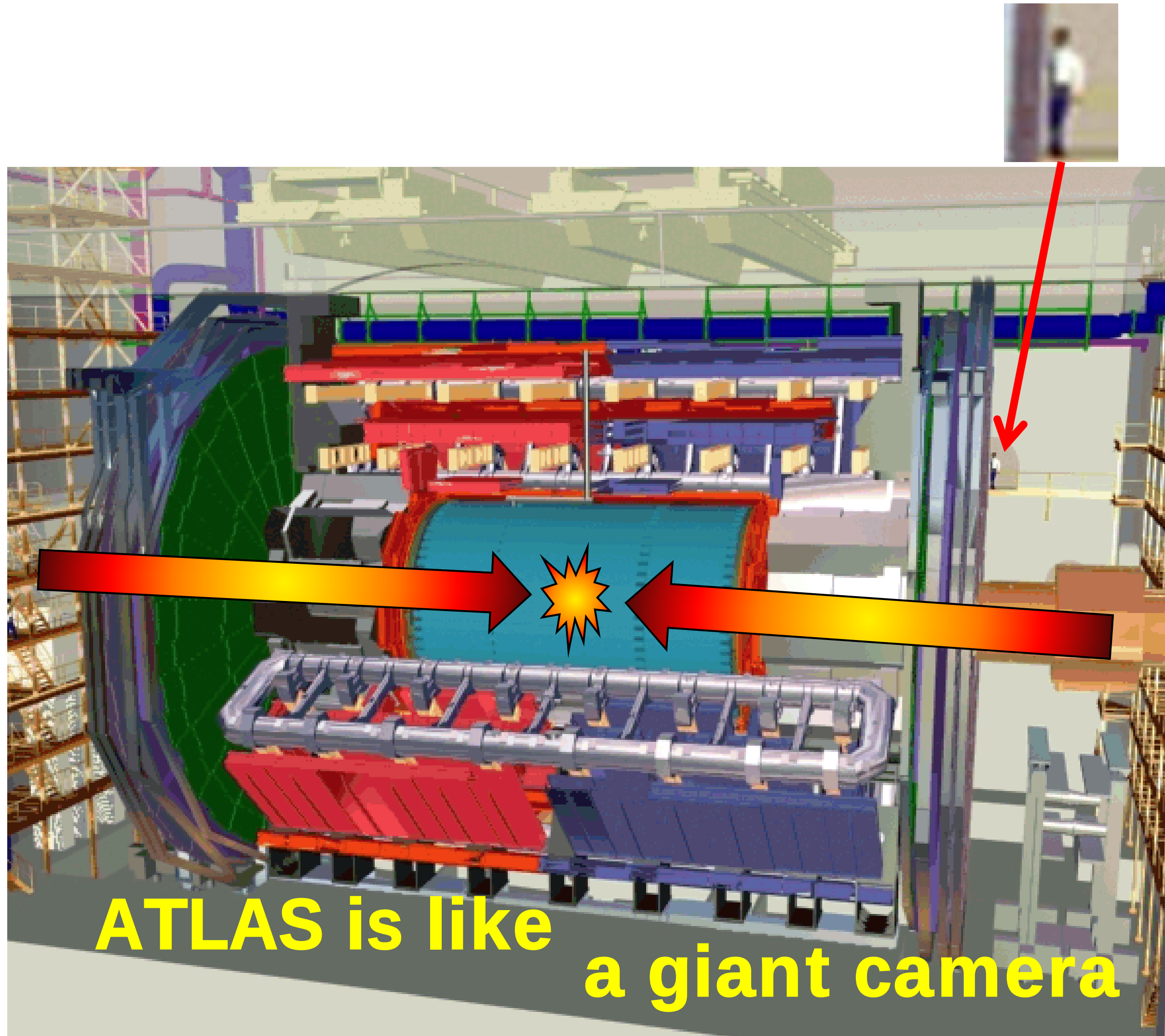
- You need some sort of "camera" to record the passage of the collision products
  - Needs to take ~40 million pictures per second, for about 9 month every year!
- Four such "cameras" at the LHC
  - ATLAS, CMS, LHC-b, ALICE

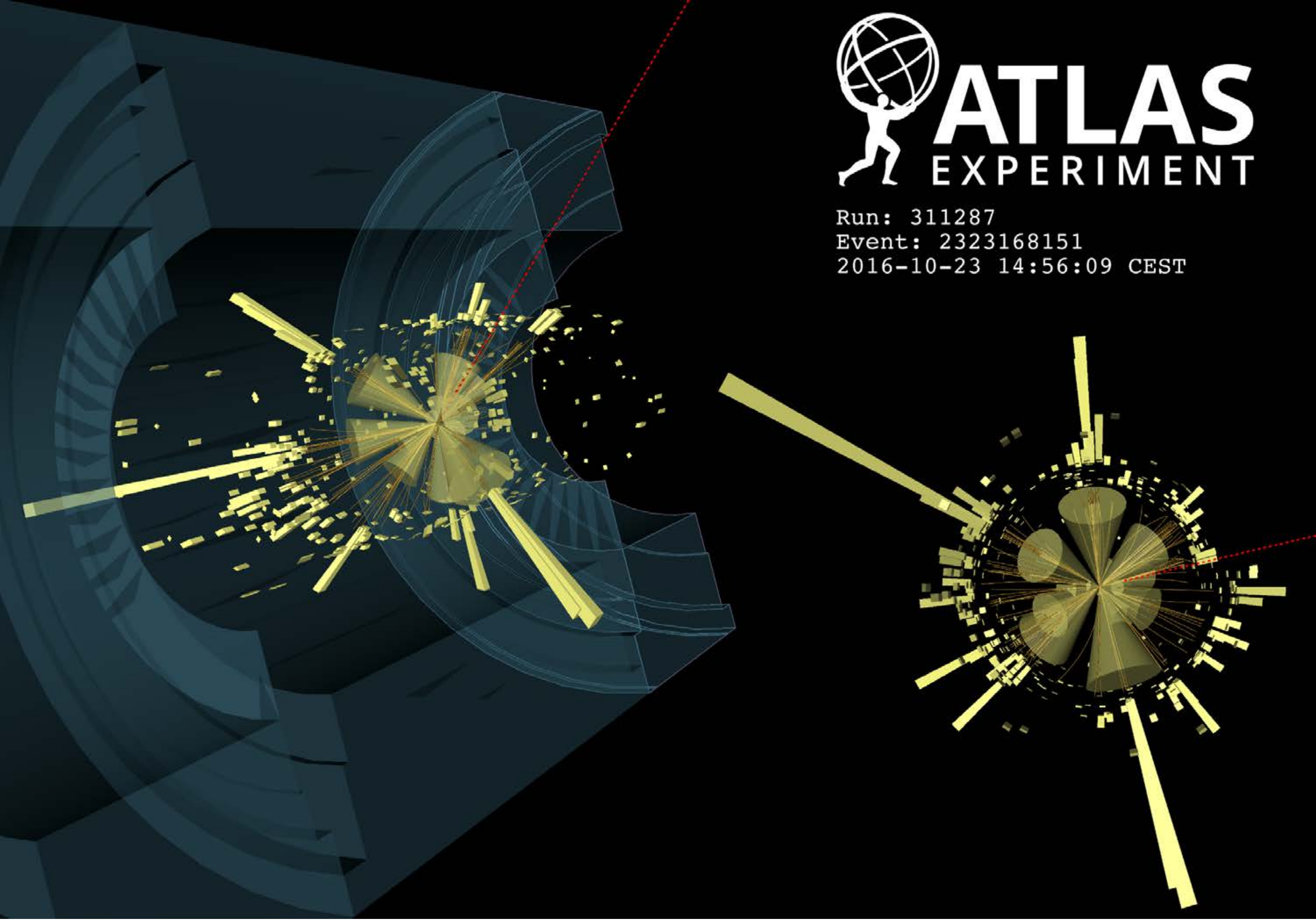
The ATLAS Detector

ATLAS is

- ... a detector capable of identifying the particles produced in pp collisions
  - ~80m underground
  - As tall as a 7 storey building!
  - 25m diameter
  - Total length 44m
  - Weight of 7000 Tons ... Same as wrought iron of:



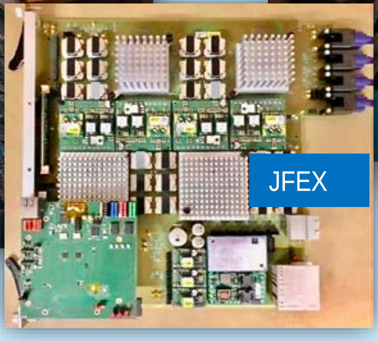


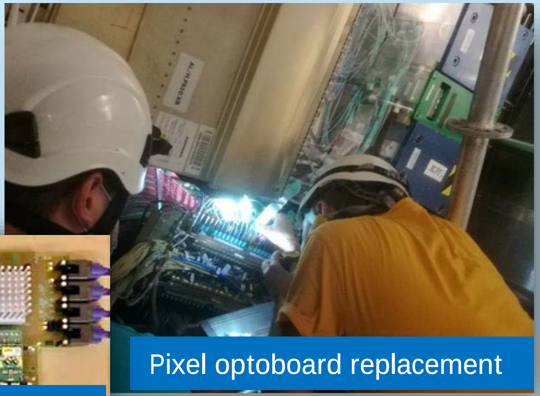


Search for new phenomena in final states with large jet multiplicities and missing E_T [pub]

6000 people from around the world doing science with leading-edge technology

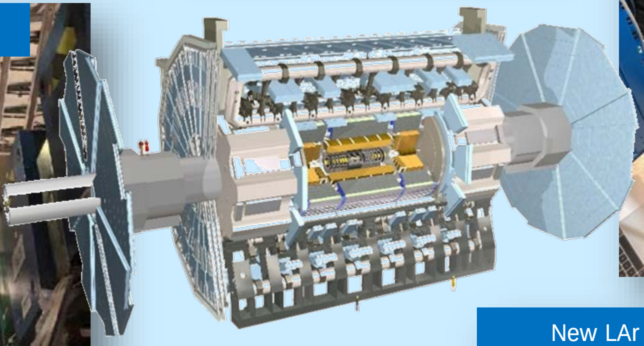

Muon New Small Wheels

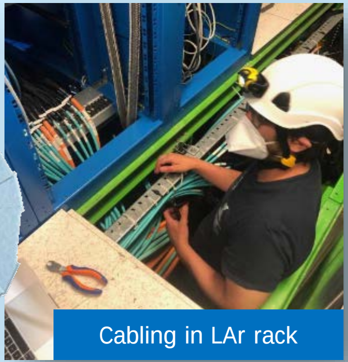

JFEX


Pixel optoboard replacement

Run-3 Trigger Workshop


Tile Calorimeter maintenance



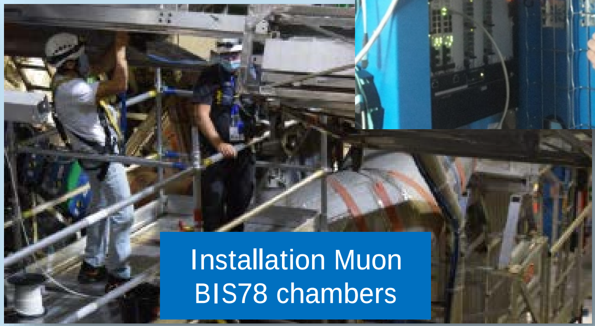

Cabling in LAr rack

New LAr processing blade

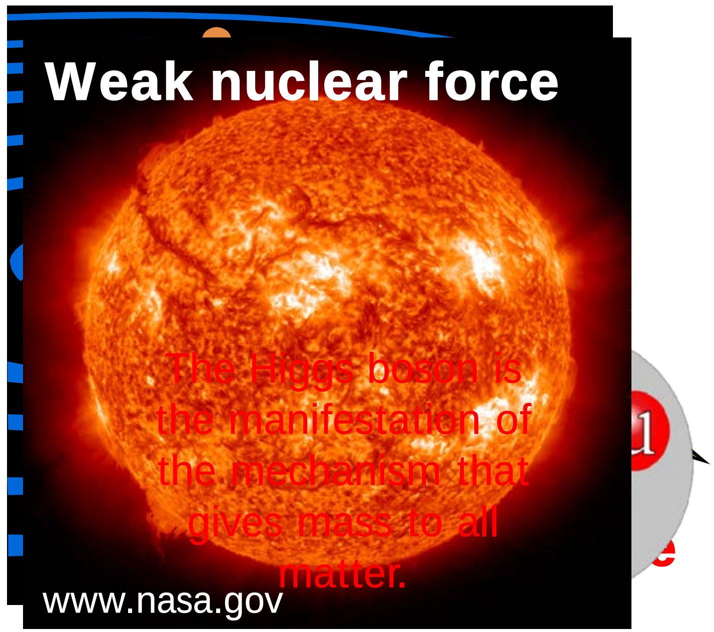

Just before COVID ☹


FELIX


Milestone Weeks in ATLAS Control Room


Installation Muon BIS78 chambers

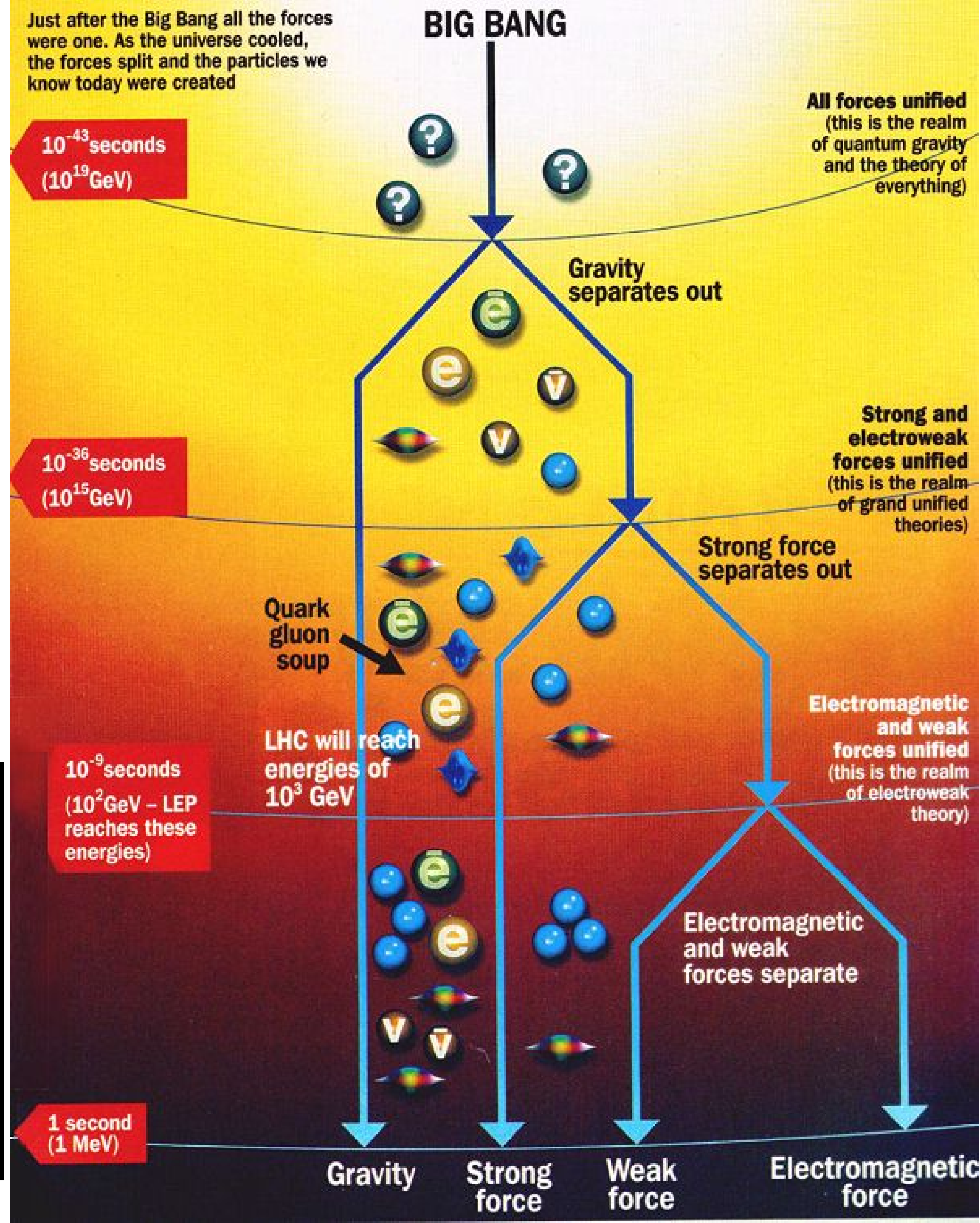
The four fundamental forces of nature



Matter & the messengers of the forces

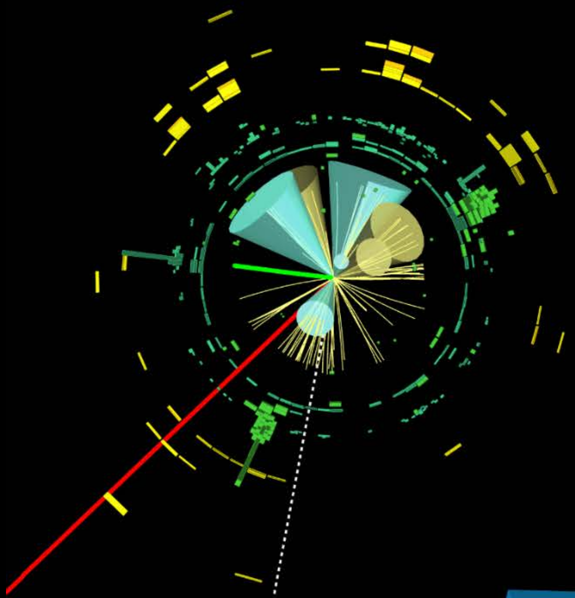
- Matter feels the four fundamental forces of nature by exchanging little “messengers”
- Observed mass and distance travelled by messenger depends on the force

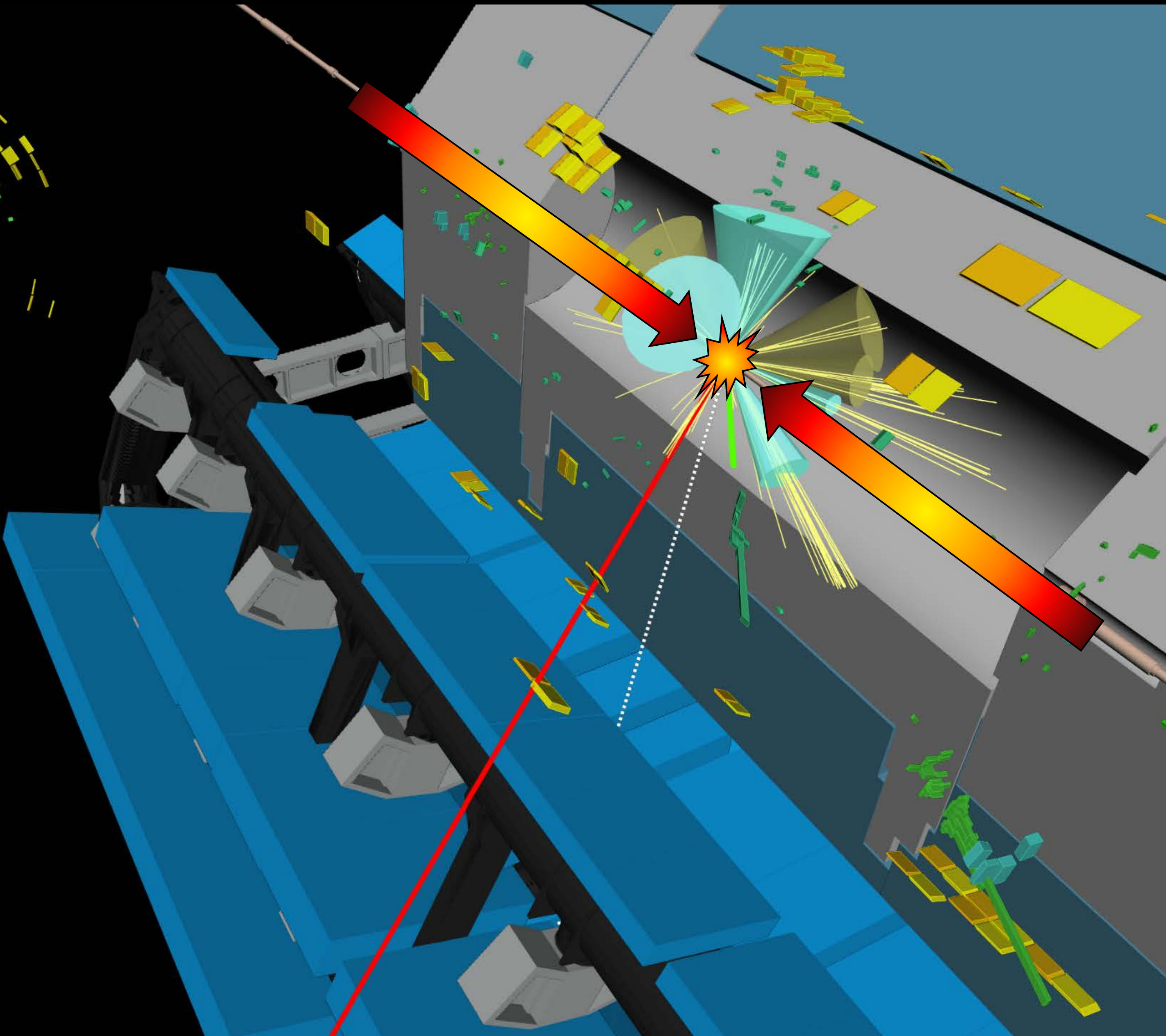
Force	Messenger	Range
EM	γ	infinity
Weak	$W^{\pm}$, Z^{o}	$\sim 10^{-18}$ m
Strong	gluons	$\sim 10^{-15}$ m
Gravity	gravitons?	infinity



What kind of LHC physics results might you see at a conference like PANIC?

Nearly 600 physicists from around the world meeting online this week...





Candidate four-top-quark event

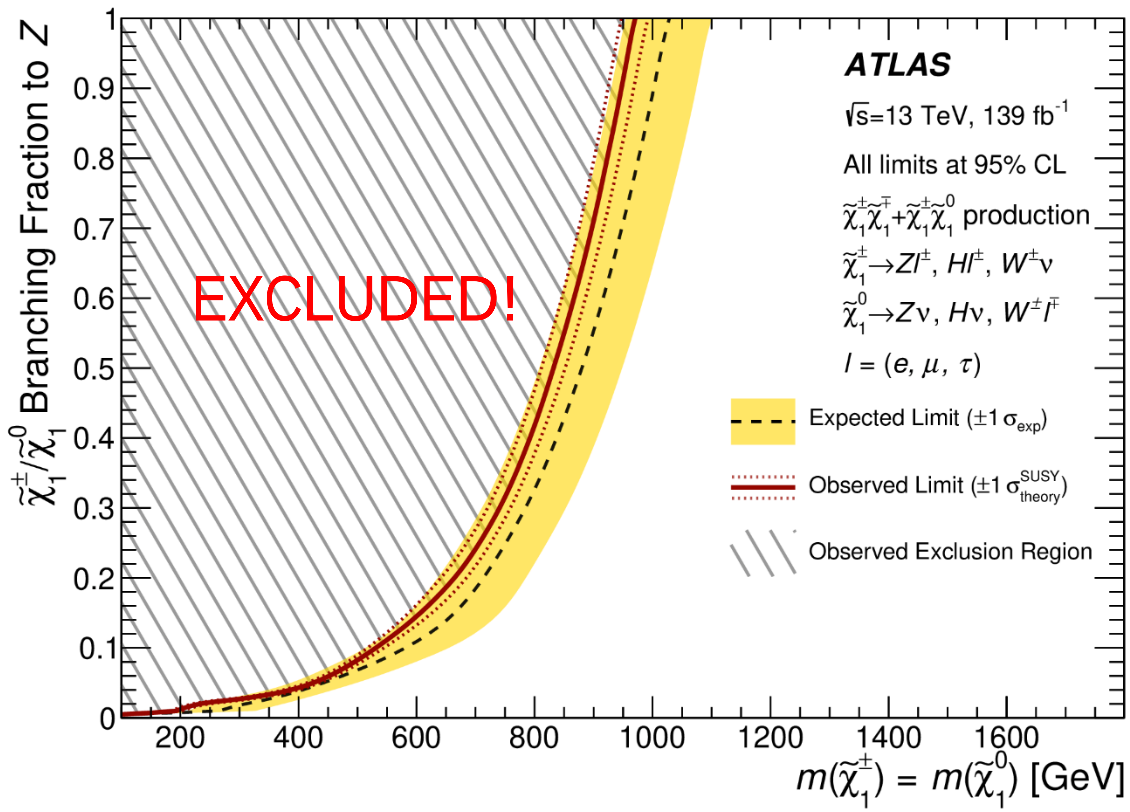
Run: 349114
Event: 1280053930
2018-04-29 10:53:24 CEST

To search…

[Search for trilepton resonances from chargino and neutralino pair production in √s =13 TeV *pp* collisions with the ATLAS detector]

- We search for new particles, and if none found, exclude the range of mass that the new particles could have.
  - “If such a particle exists, then its mass must be greater than XXXX”

Some other property of the new particle



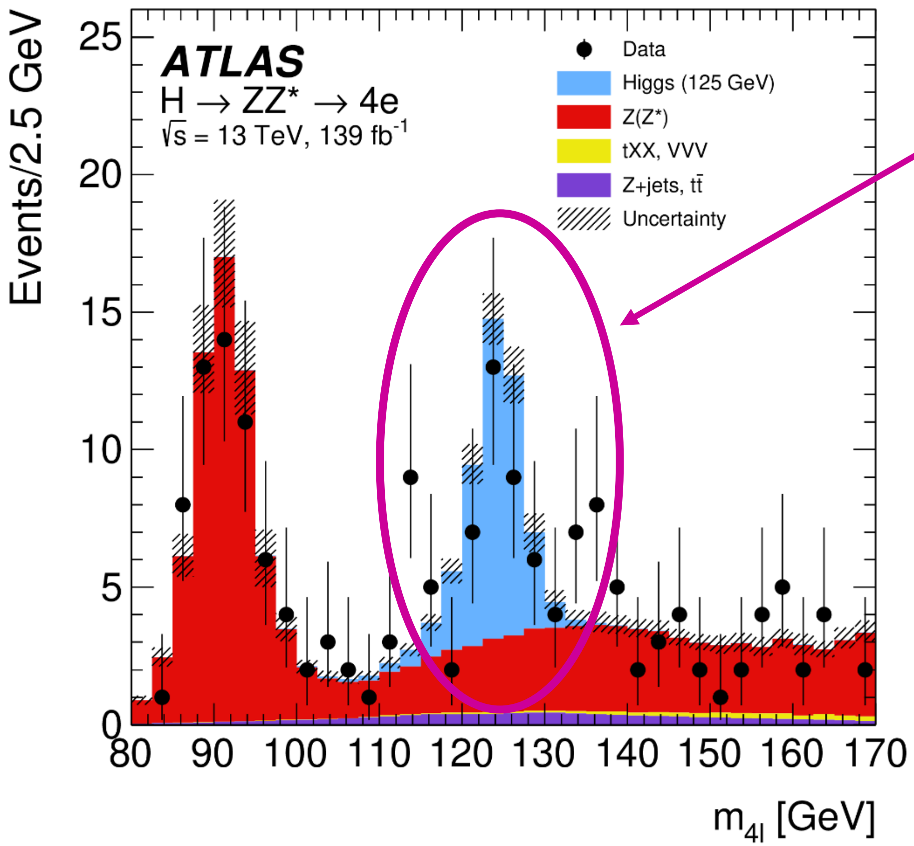
Mass of the hypothetical particle

To discover…

[Measurements of the Higgs boson inclusive and differential fiducial cross sections in the 4ℓ decay channel at √s = 13 TeV]

- We search for new particles, and if one is found, we determine its properties
  - "We found a new particle and we measured its mass to be XXX"

How many times we saw the new particle



The Higgs boson!

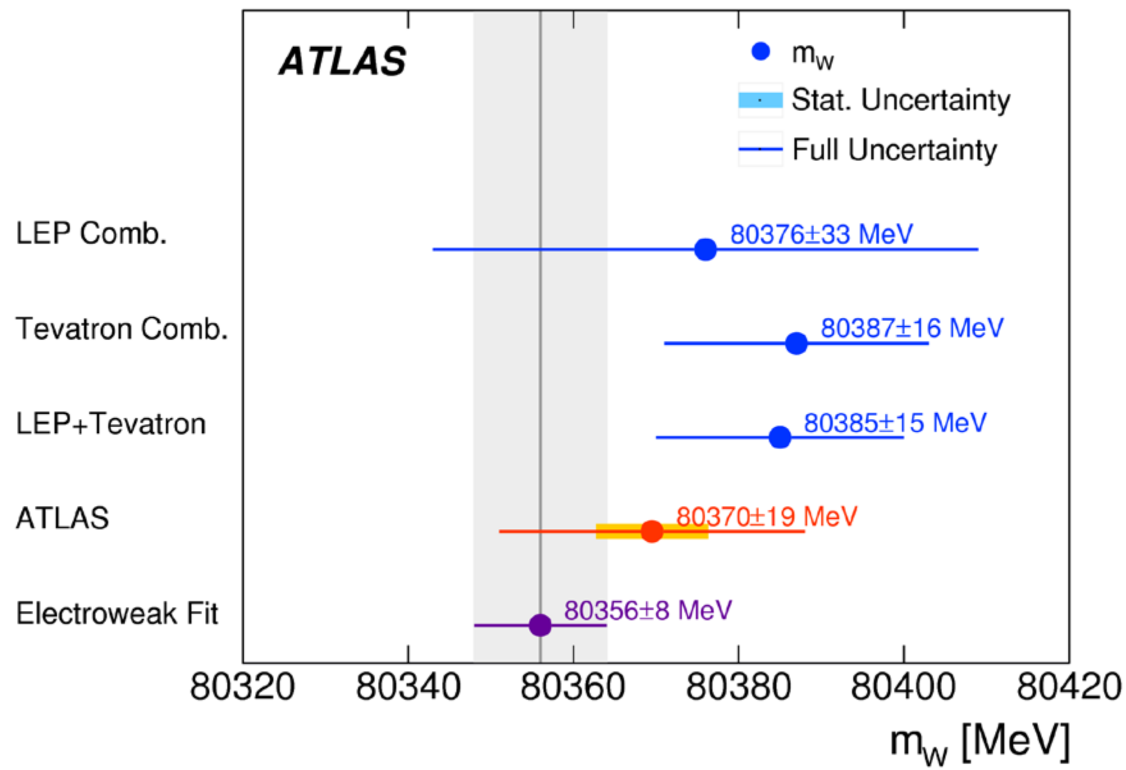
Mass of the new particle

To measure…

Measurement of the W-boson mass in pp collisions at √s =7 TeV with the ATLAS detector

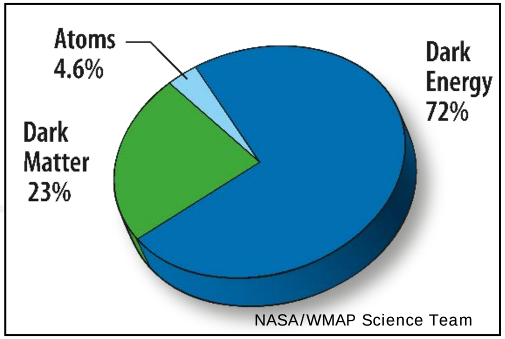
- We study with precision the properties of known particles, to look for deviations from the theoretical predictions.
  - "We measured the properties of this particle with precision, and it agreed with theoretical predictions"

All measurements and predictions

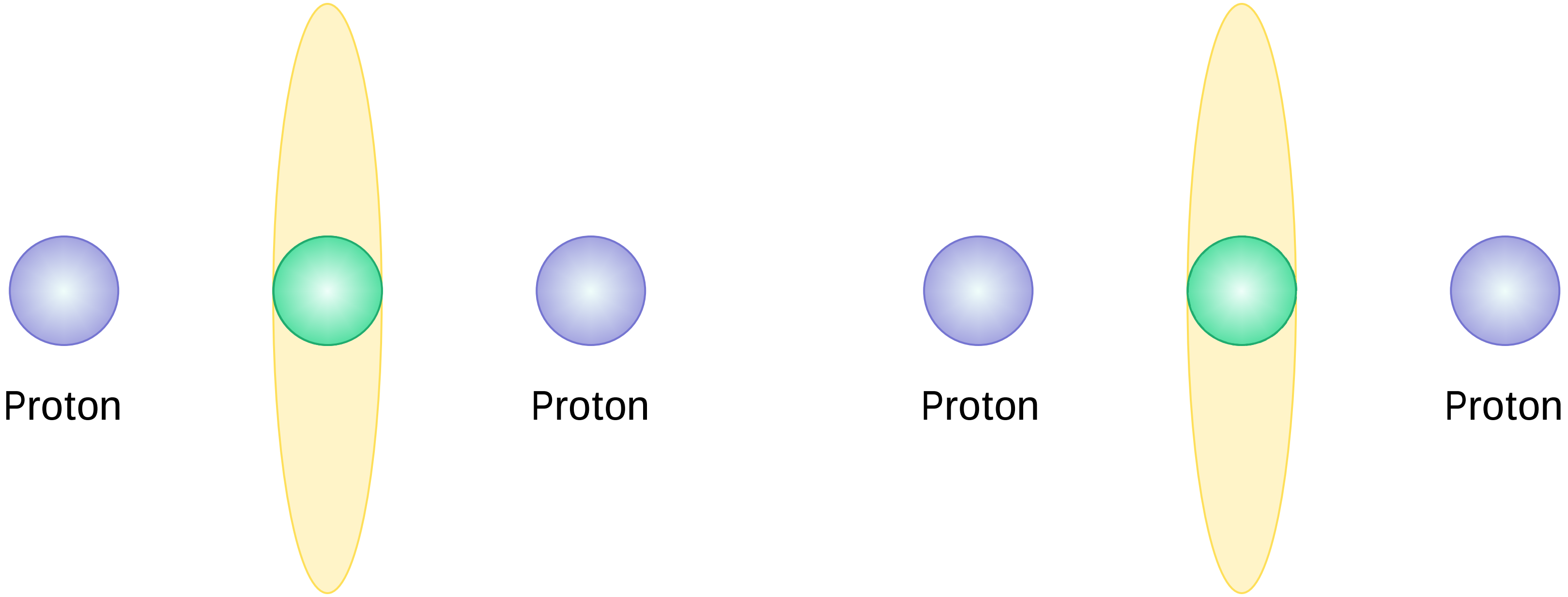


Mass of the known particle

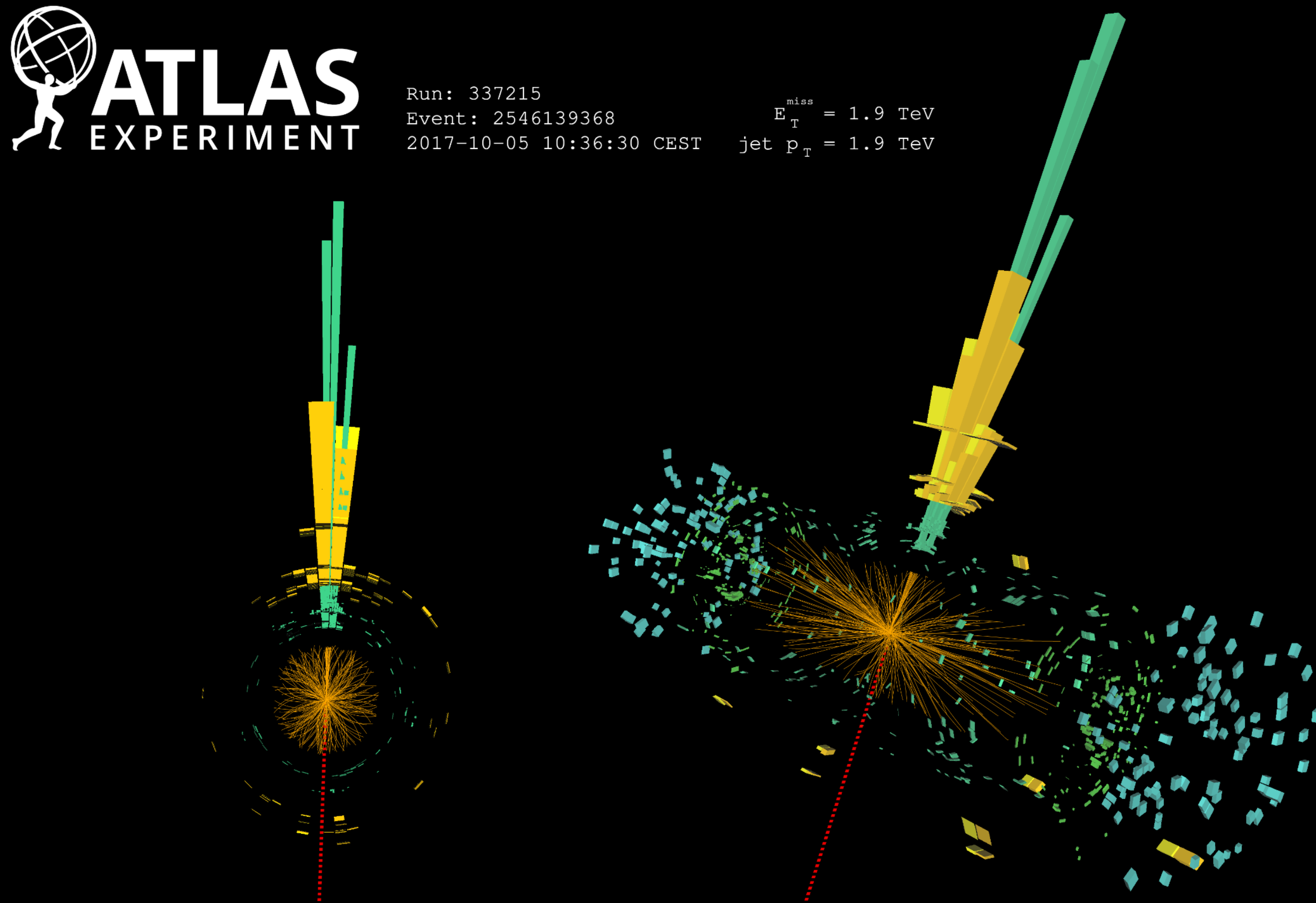
Dark Matter: how can we see something that we can't "see"?



- Dark Matter is thought to be "weakly interacting"
  - Doesn't emit light and doesn't interact with most of the fundamental forces.
- Even if we can't see it, it can have an effect on other particles, through the conservation of fundamental laws of physics like conservation of energy and momentum.



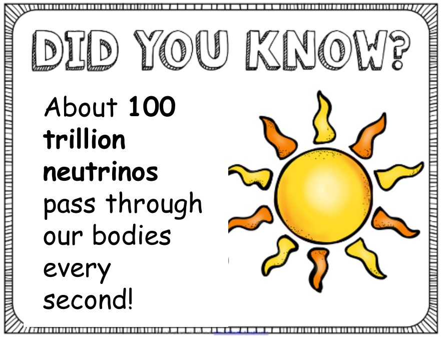
- Can look for particles that seem to recoil against *nothing*
- One example of a search for Dark Matter...

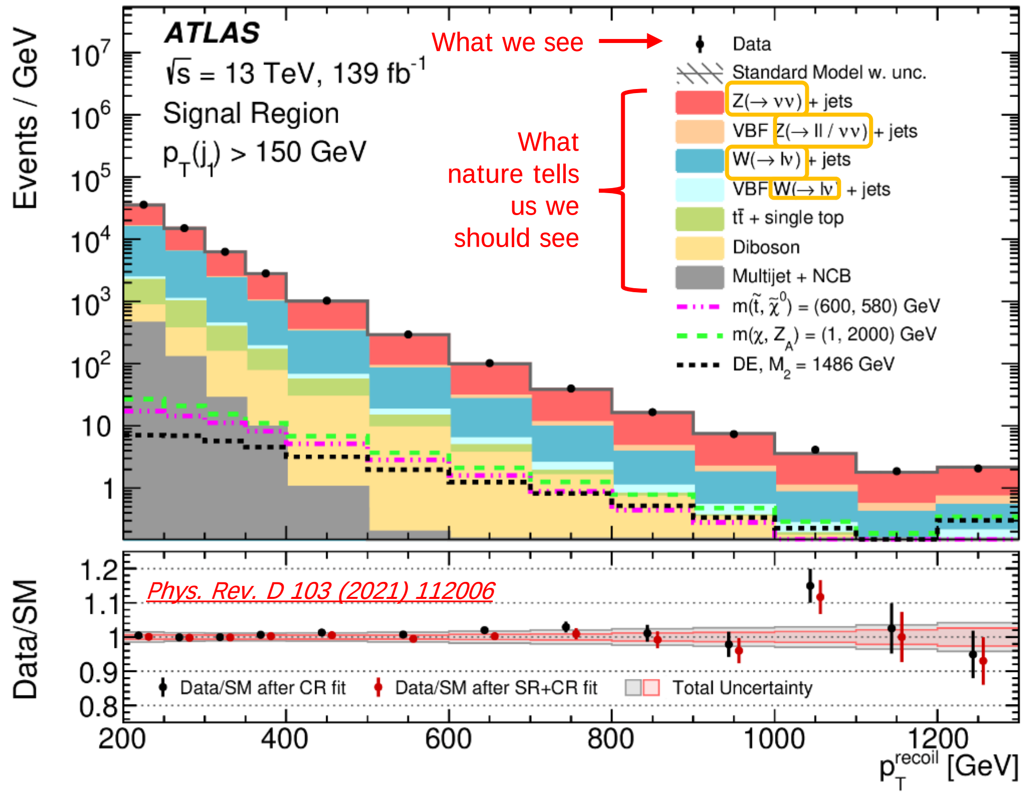


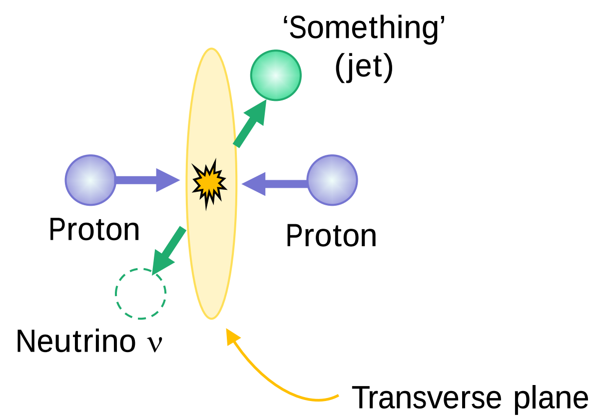
Candidate Dark Matter: production of a monojet

Excluding all plausible causes for such events...

- Nature already produces particles that “we can’t see”!
  - Neutrinos ν (e.g. produced in the Sun but also in LHC collisions)
- Momentum in the transverse plane of the recoiling “something”



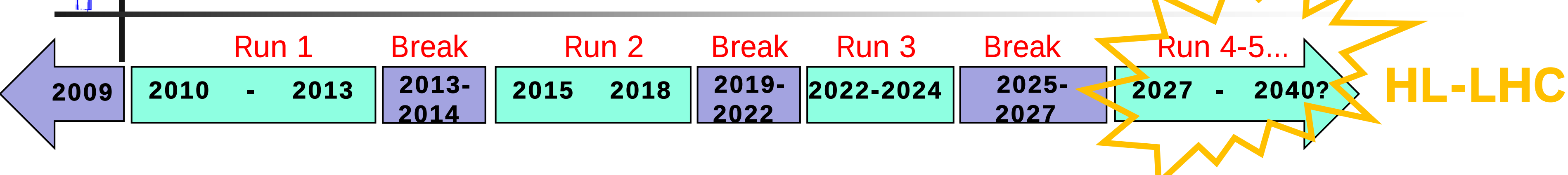




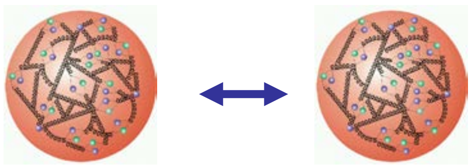
We don’t see anything “extra” beyond what our interpretation of Nature (‘Standard Model’) tells us we should see.

No Dark Matter observed yet at LHC.

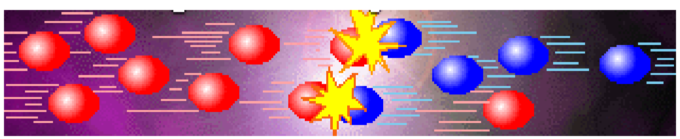
What's next for the LHC?



- So far, the LHC has only produced a few percent of all the collisions it plans to make!
  - To get there, it must collide more protons simultaneously!
- Protons are not point-like objects and they are really small! 10^{-15} m.



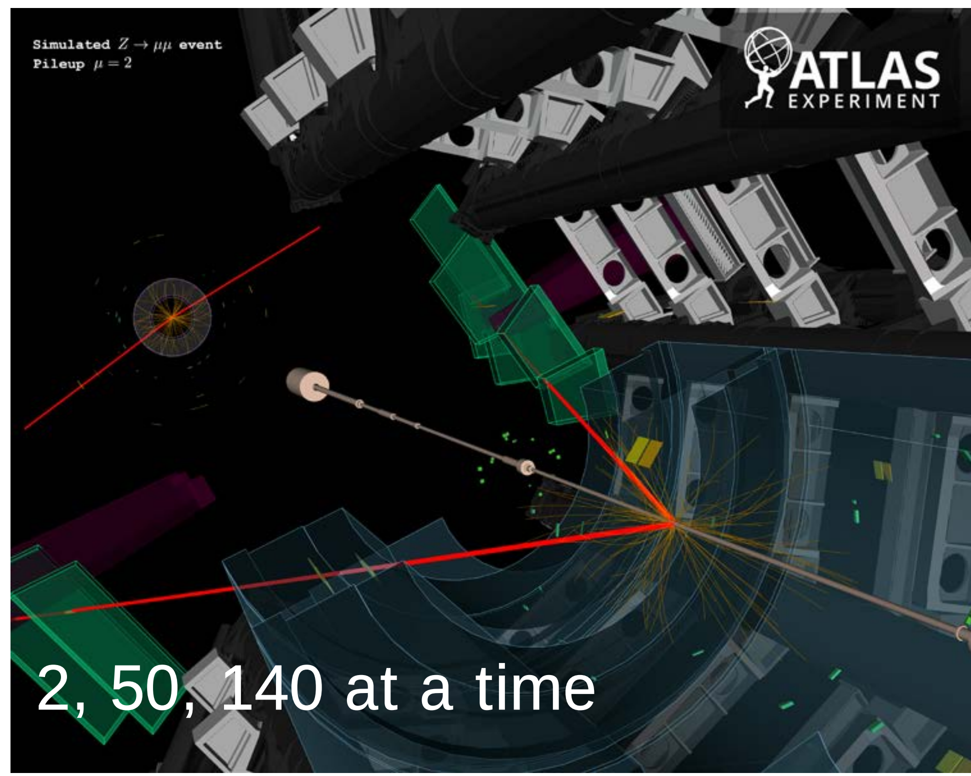
- Collide many protons simultaneously in the hopes that one or more collide



- Run 1: 10-20 at a time
- Run 2: 25-40 at a time
- Run 3: up to 50-60 at a time?
- Run 4-5: up to 200!

High-Luminosity LHC (HL-LHC)

- Hope to accumulate per year what we accumulated in all of Run 1-3



The *future* of high-energy collider physics

Projects in particle physics have very long timescales…

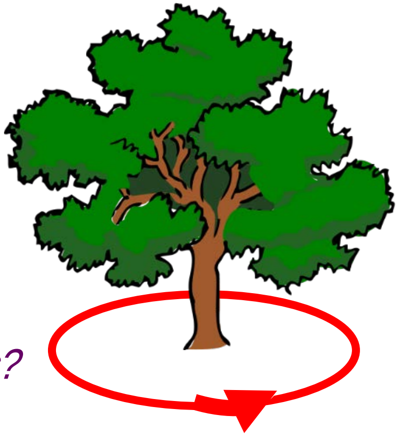
LHC & experiments: *first thoughts in mid 1980s*

LHC experiments (like ATLAS): *approved in mid 1990s*

First ATLAS equipment underground: *early 2000s*

25 years

First high-energy LHC collisions: *2010*



First high-luminosity LHC (HL-LHC) collisions: *late 2020s*

30 years

Final high-luminosity LHC collisions (HL-LHC): *late 2030s?*

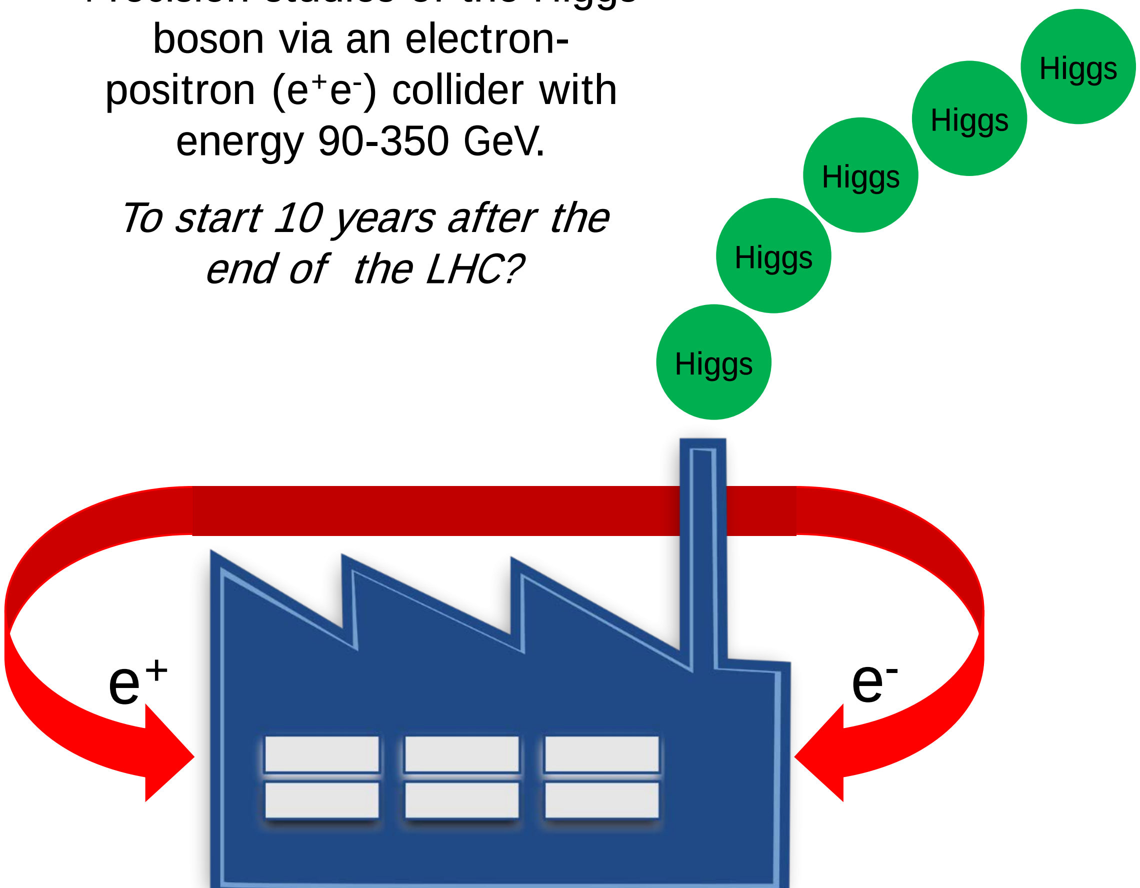
The successor to the LHC is already being planned right now!

European Community comes together to plan the future of collider physics

High-priority future initiatives: the possibilities

A Higgs boson ‘factory’!
Precision studies of the Higgs boson via an electron-positron (e^+e^-) collider with energy 90-350 GeV.

To start 10 years after the end of the LHC?



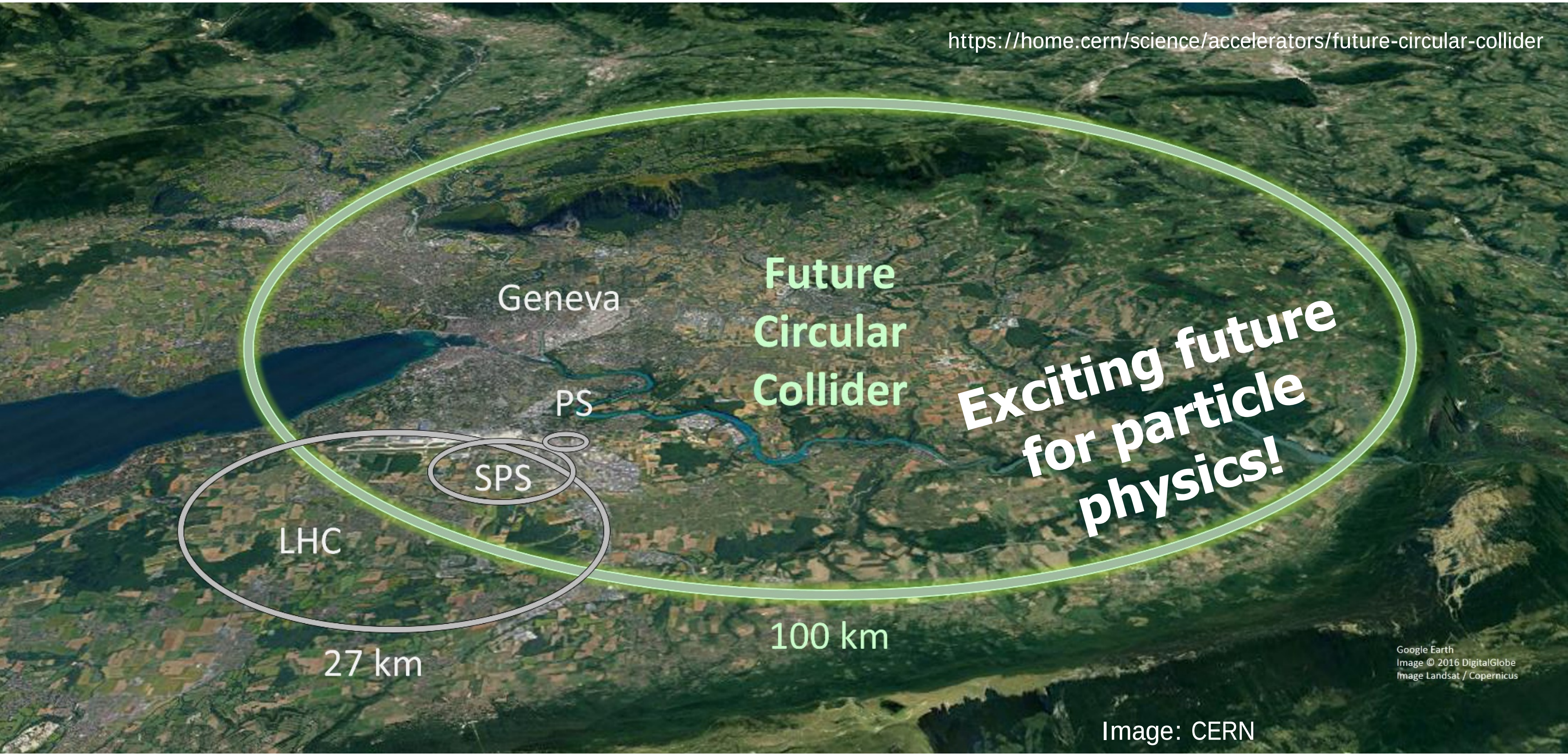
A discovery machine!
Proton collisions at the highest achievable energy
(100 TeV? = 7 x LHC)
Study the nature of Dark Matter.


X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

To start after e^+e^-?

FCC: Future Circular Collider at CERN

- 80-100 km e^+e^- and/or pp collider with its own new experiments
- New international collaborations proposed to build accelerator and detectors



Visit the ATLAS website

Public lectures around once per month:
ATLAS YouTube Live

See inside the
ATLAS cavern!
Google Street View

Great video of
ATLAS in action!