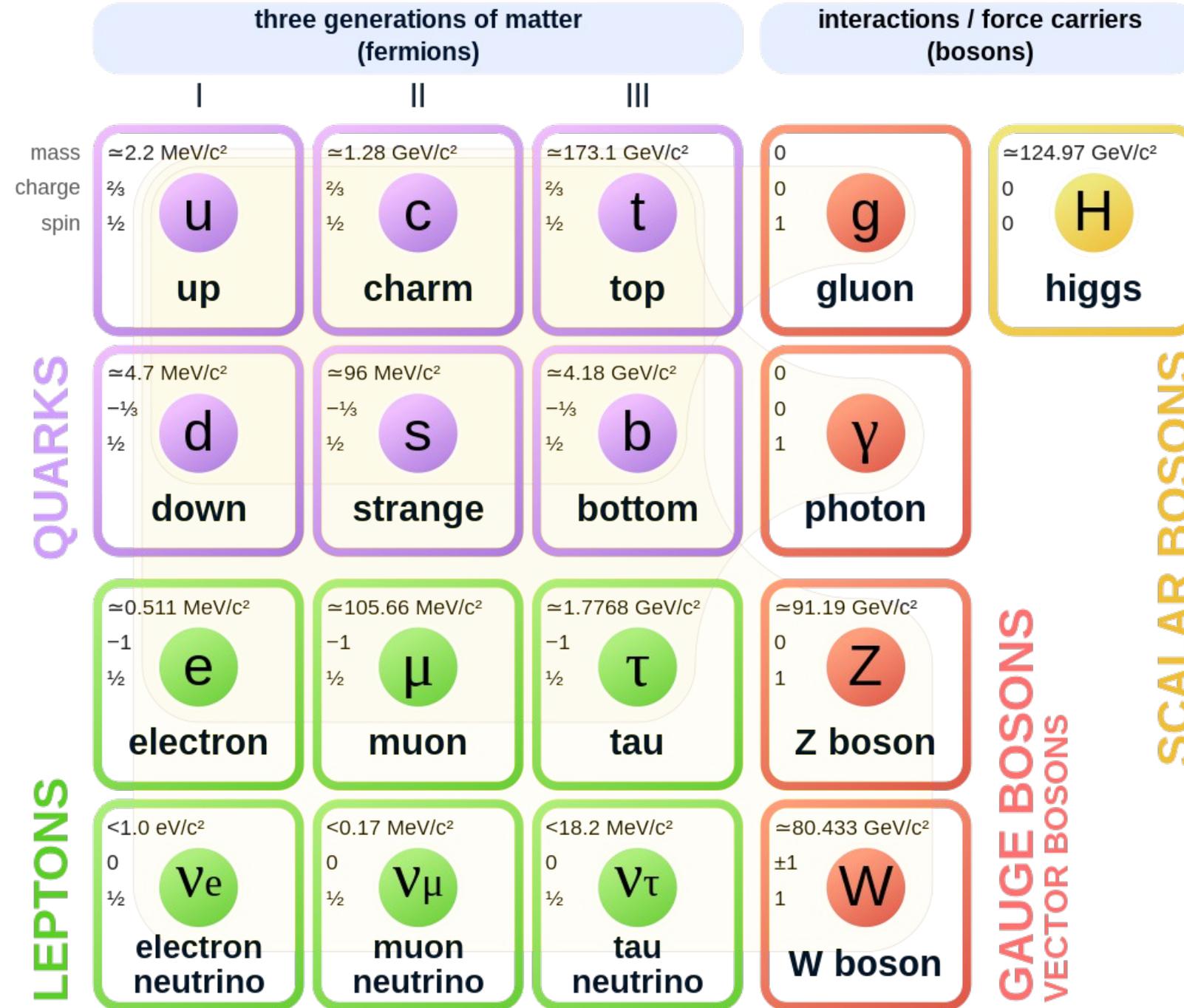




# The Large Hadron Collider

Dr Alison A Elliot – *Rutherford Appleton  
Laboratory*

# Standard Model of Elementary Particles



# Question for you!!

From the Standard Model table you have just seen:  
Which particles make up everything you see around you now?

# What is missing?

- The Standard Model is complete with the addition of the Higgs Boson
- Why do we need new theories if the Standard Model is complete?

# What is missing?

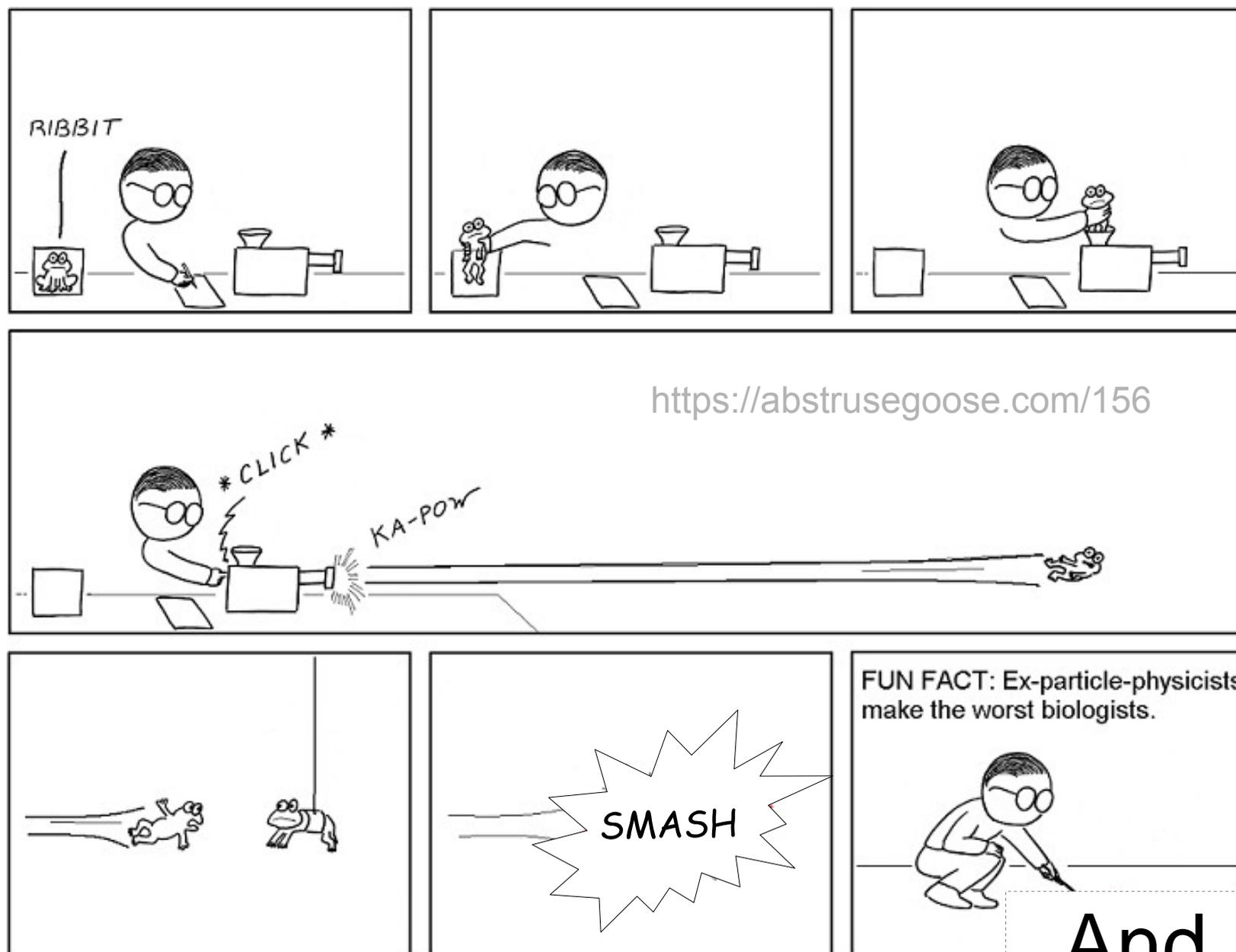
- The Standard Model is complete with the addition of the Higgs Boson
- Why do we need new theories if the Standard Model is complete?
  - Gravity
  - Dark Matter
  - Matter-Antimatter asymmetry
  - Neutrino masses
  - ....

# How to discover if there are more particles!

- Come up with some theories
  - A **graviton** might unify gravitational force with the Standard Model
  - A **dark matter particle** might explain the overabundance of mass in the universe!
  - A **tachyon** sounds really cool? (this theoretical 'faster than light' particle would cause more problems than it would solve)
- Test those theories! But how?



# Disclaimer: I am a particle physicist



And I work on LHC  
experiments...

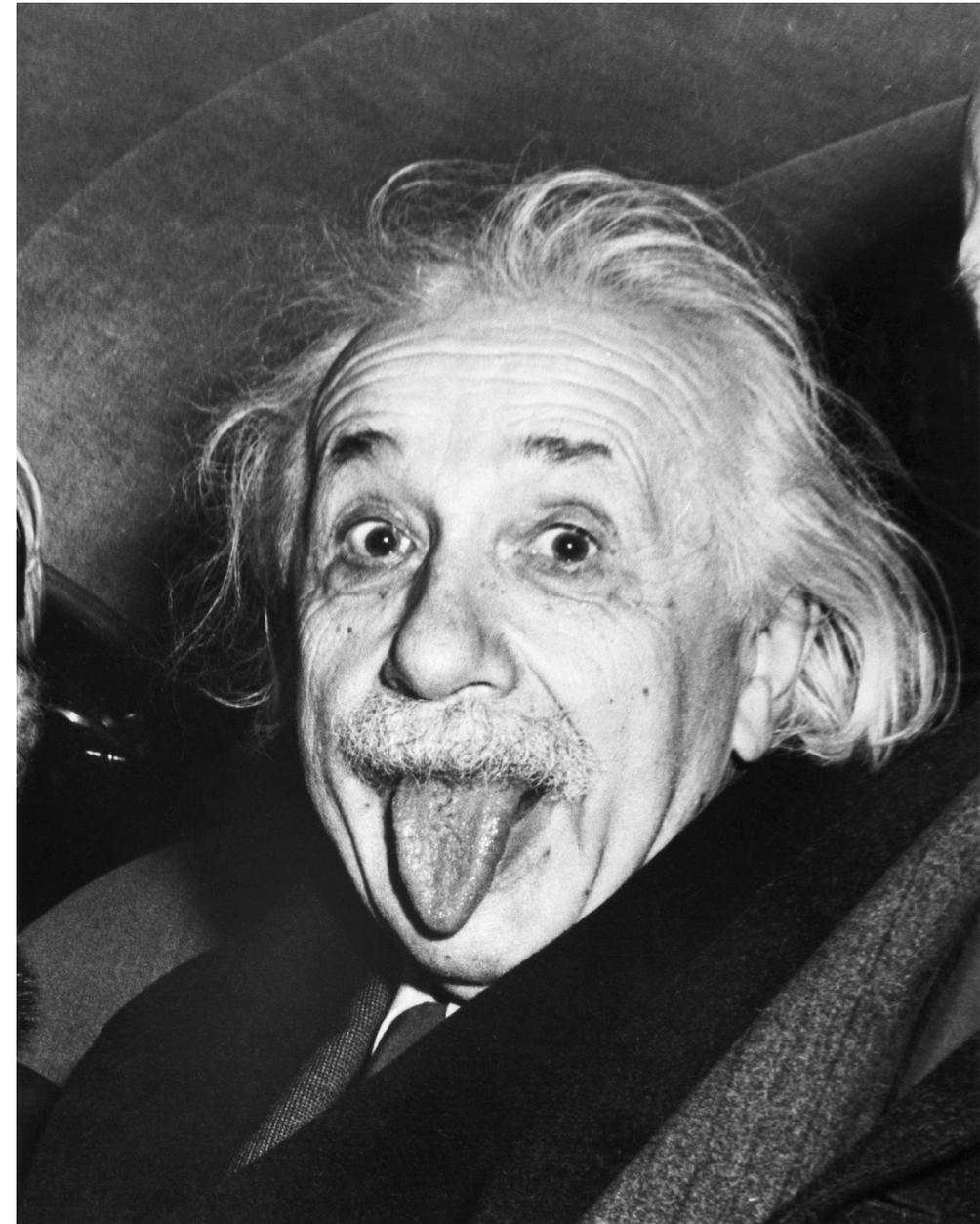
Since I am a particle physicist...

To me, everything is particles

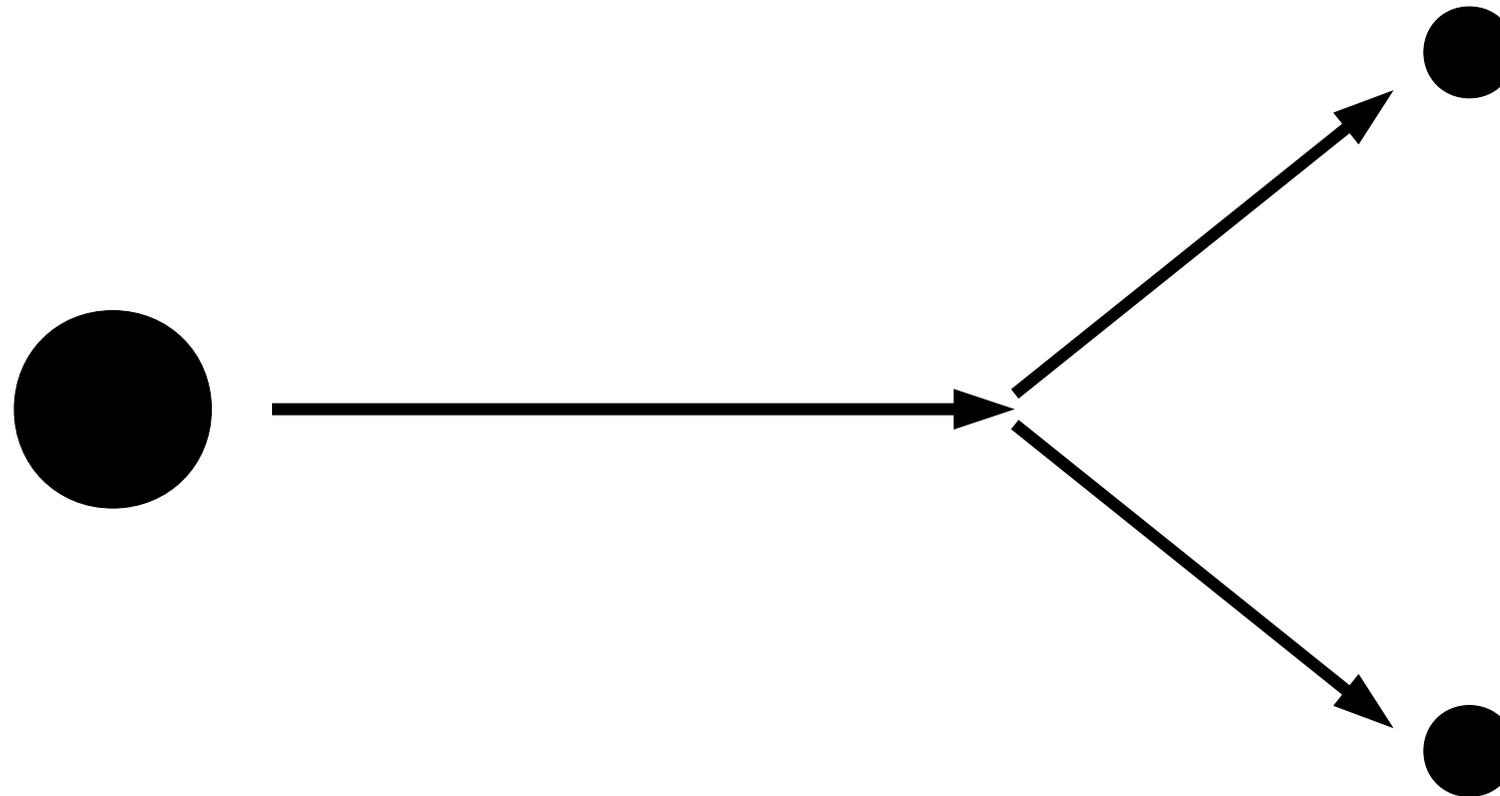
I use something called a **Feynman diagram** to study interactions between the particles I know... and the new particles I am searching for

# How does that work, exactly?

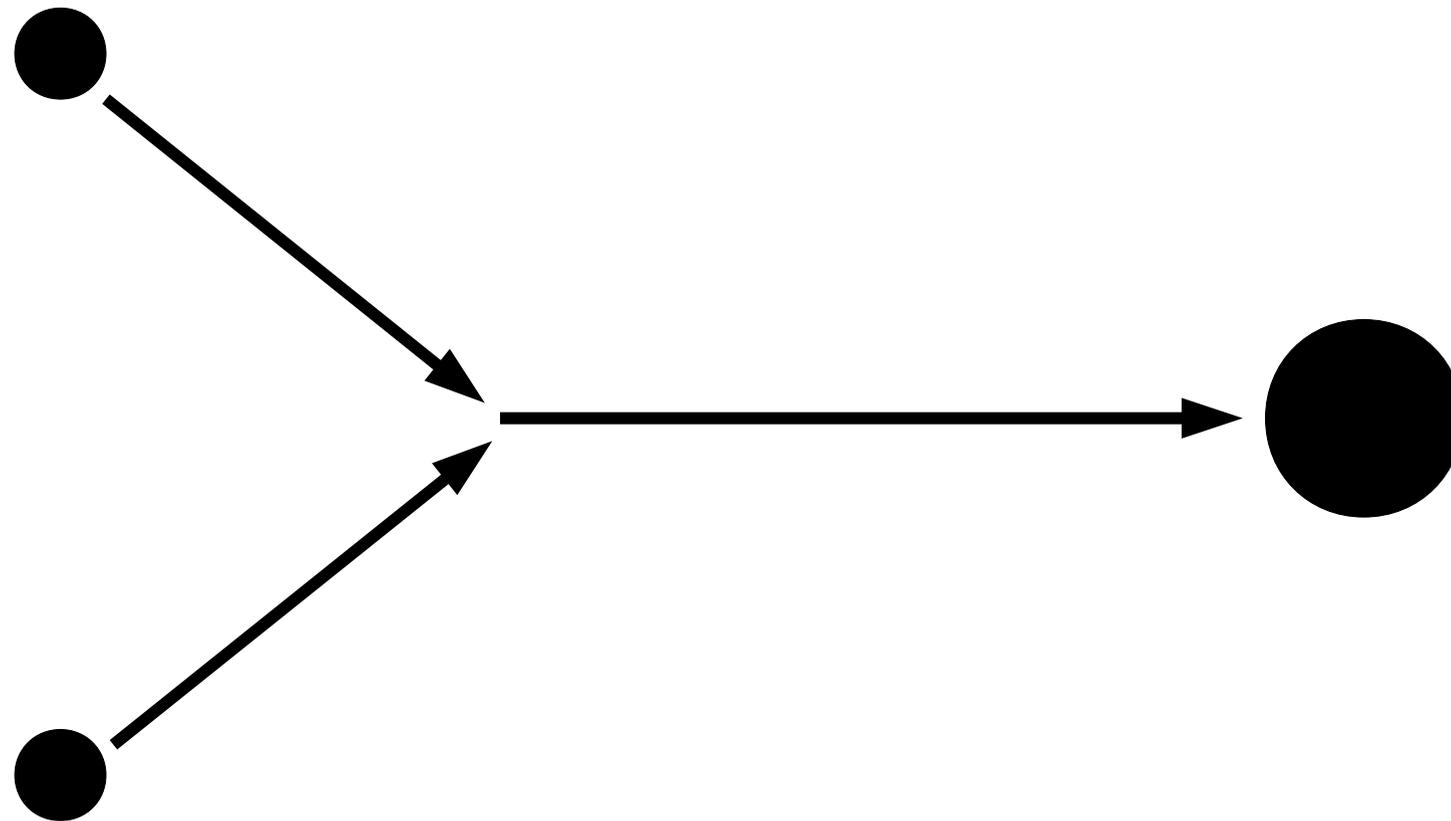
$$E = mc^2$$



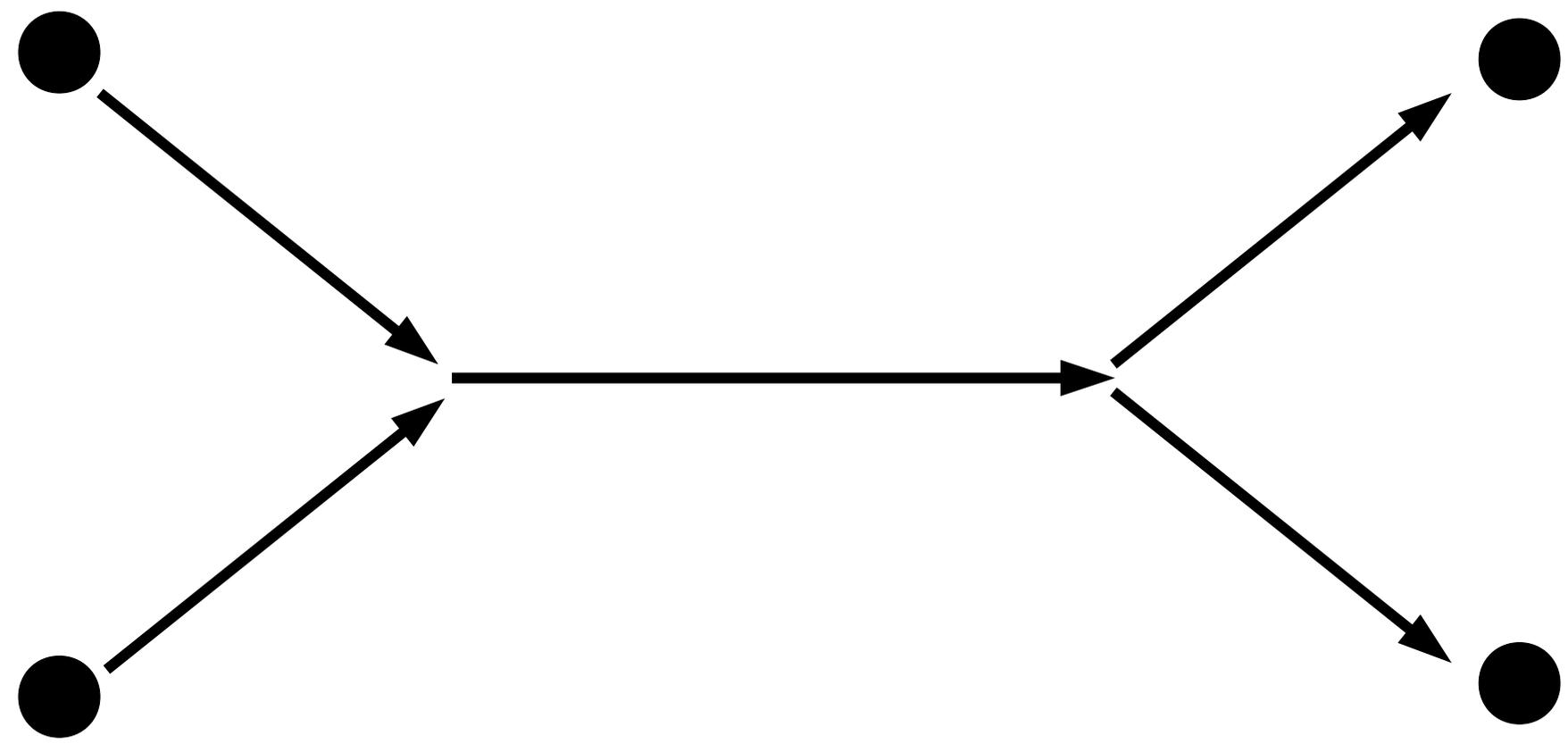
# Particle decay



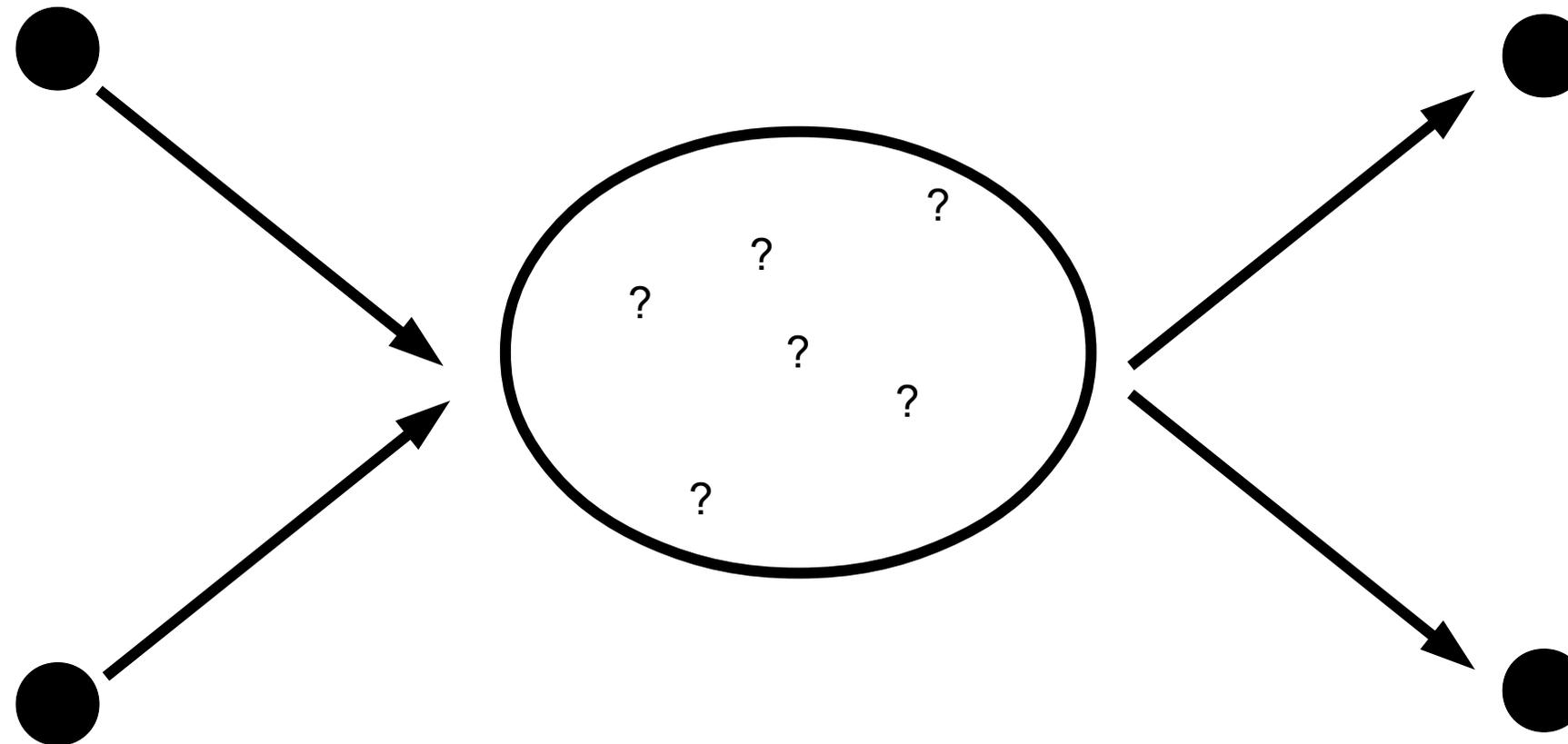
# Particle production



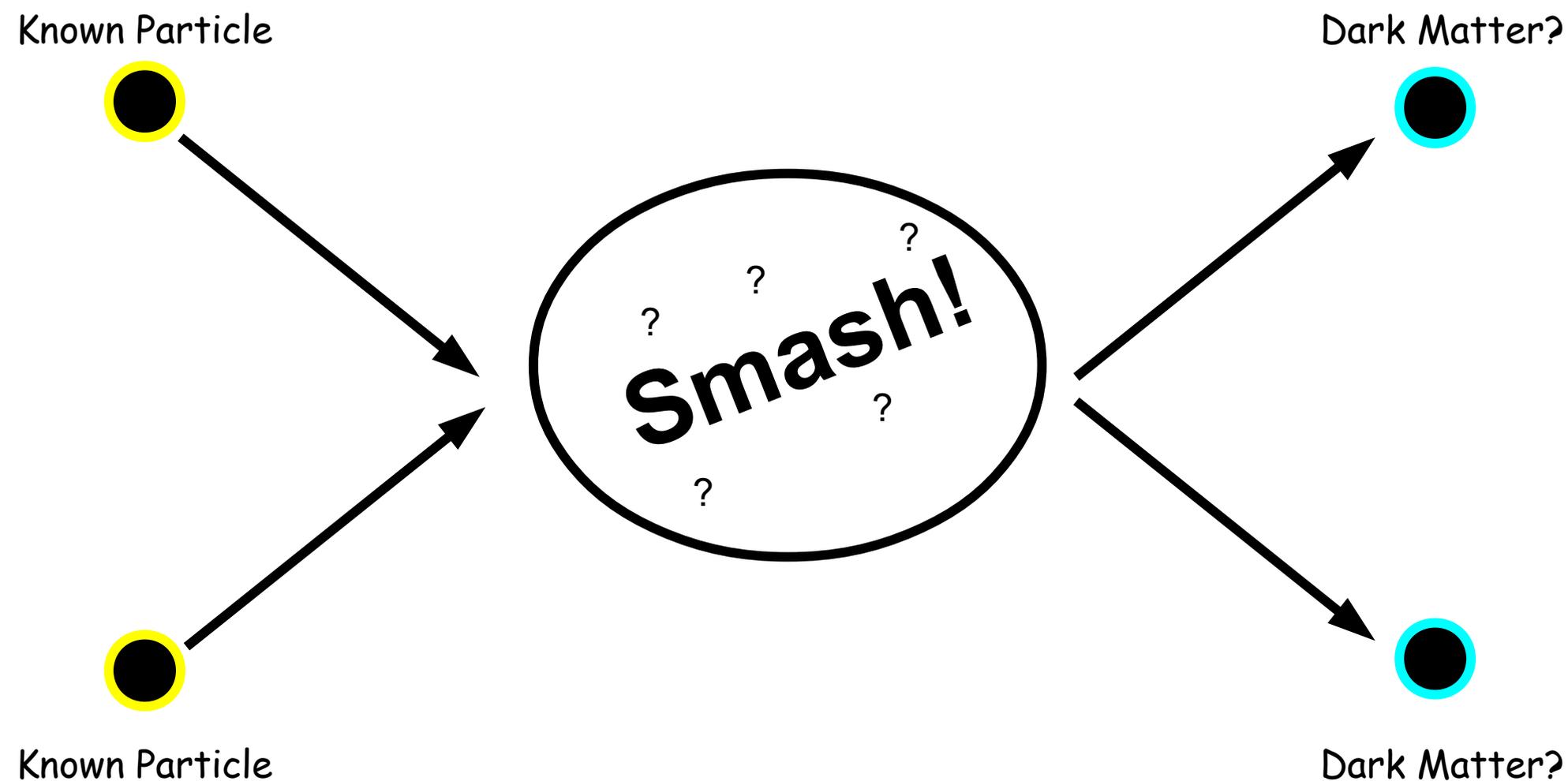
# Particle interaction!



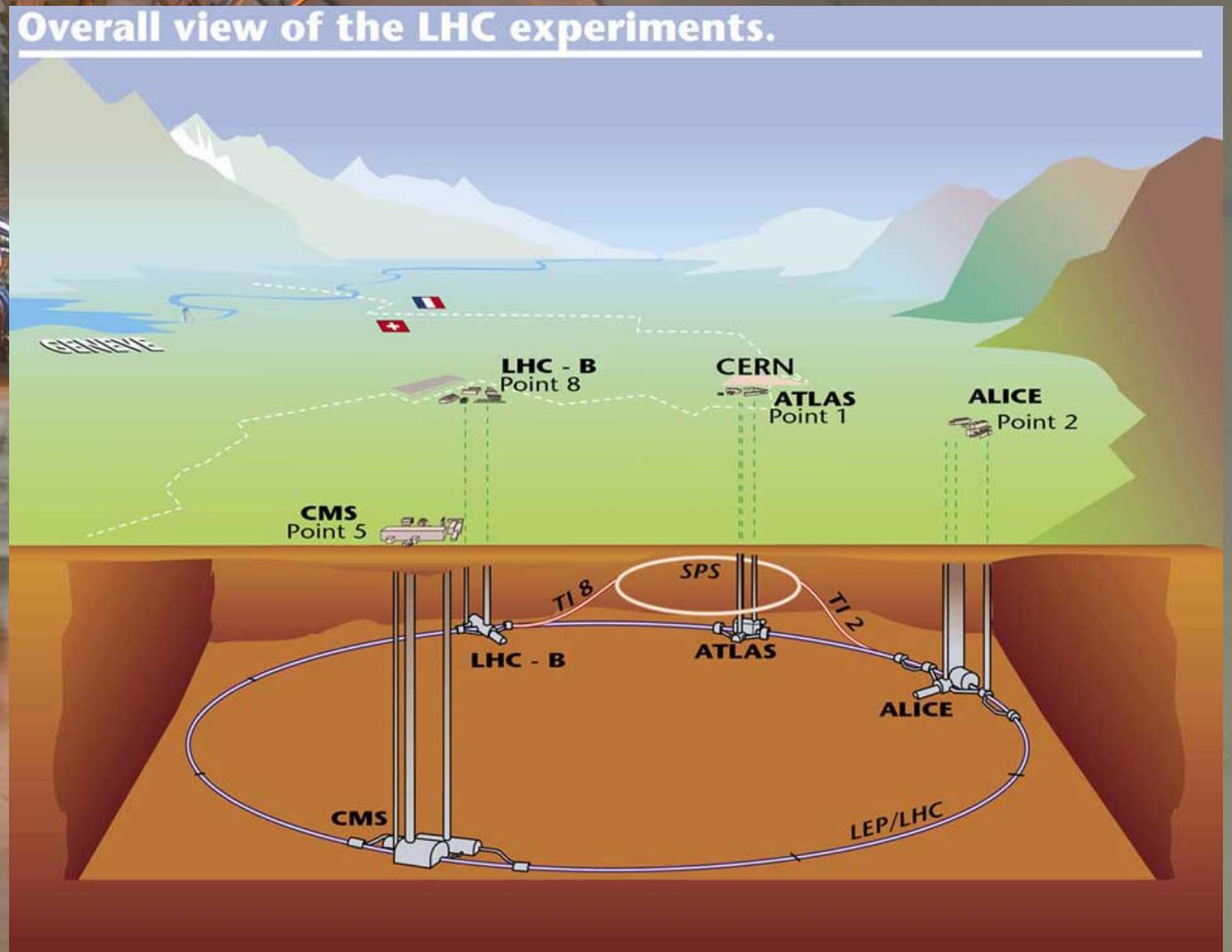
# Interaction we don't know about



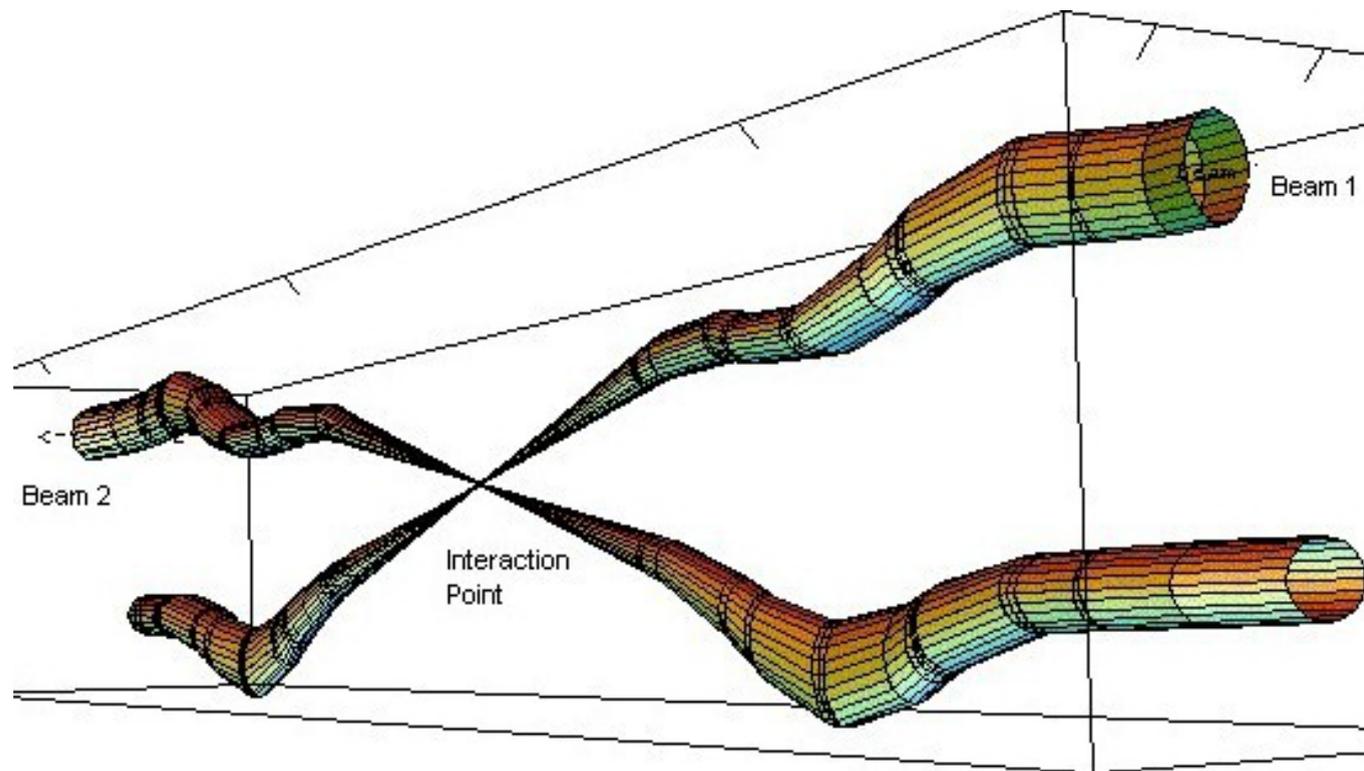
# New particle production: for example - dark matter



# Experimental setup: the Large Hadron Collider



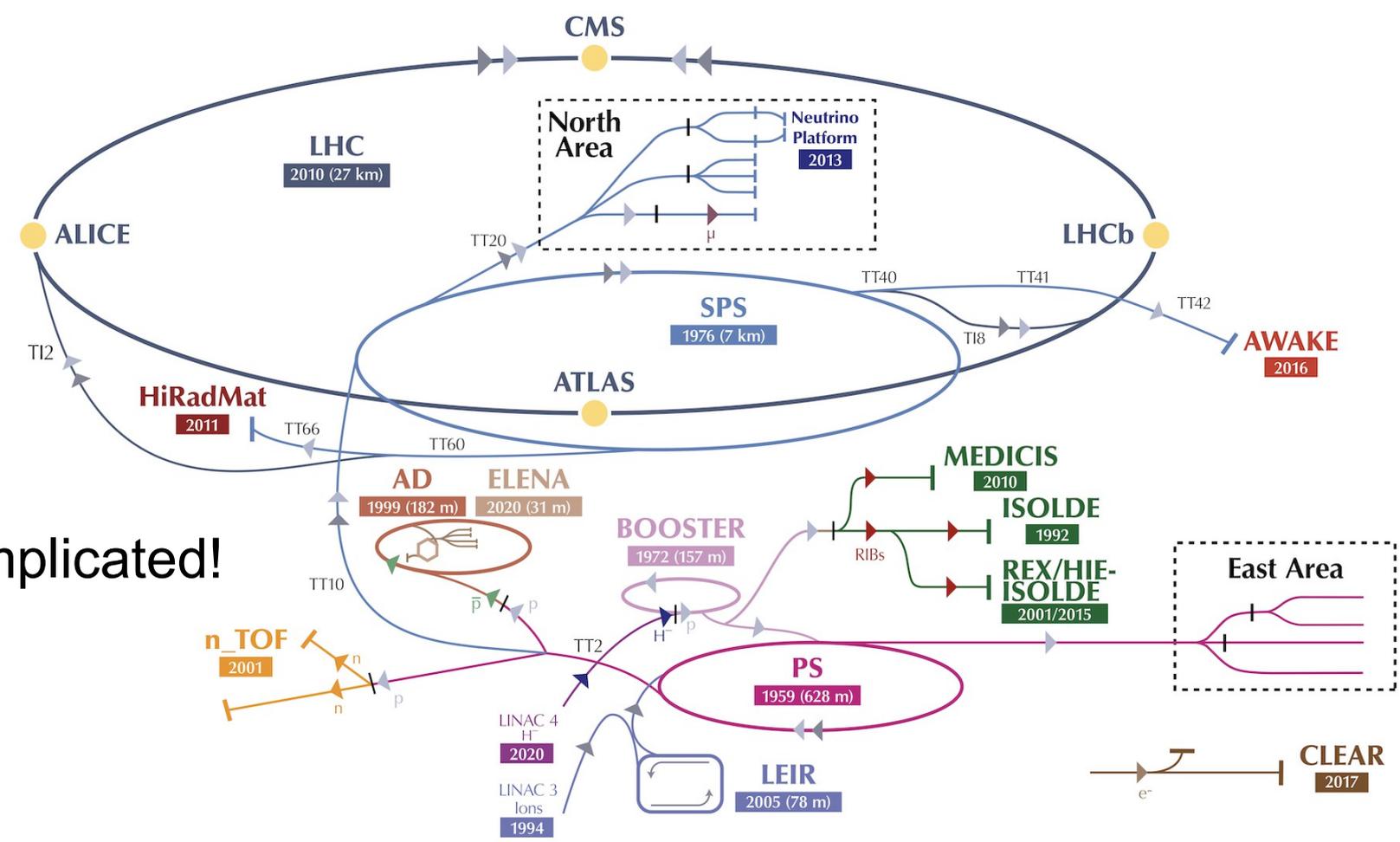
# What happens there



- Beams are made up of bunches of protons (almost 3000 bunches of  $1.2 \times 10^{11}$  protons per bunch)
- The two beams of protons are accelerated in opposite directions at 0.9999999991 times the speed of light.
  - That means a proton in the beam will go around the 27 km tunnel over 11000 times per second!
- Then the beams are steered to collide with each other at specific interaction points in the detector, 40 million times per second.

# The CERN accelerator complex

## Complexe des accélérateurs du CERN



Actually... it's really complicated!

- ▶  $H^-$  (hydrogen anions)
- ▶ p (protons)
- ▶ ions
- ▶ RIBs (Radioactive Ion Beams)
- ▶ n (neutrons)
- ▶  $\bar{p}$  (antiprotons)
- ▶  $e^-$  (electrons)
- ▶  $\mu$  (muons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKEfield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive Experiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n\_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

# It all starts with a bottle of hydrogen



- Contains about 5 kg of hydrogen, or about  $3 \times 10^{27}$  atoms of hydrogen.
- If we completely refilled the two beams in the LHC every ten hours, we could keep it going for over a billion years.
  - With only one bottle!

# Stages of acceleration

The protons are accelerated in stages

- The hydrogen atoms are accelerated in the linear accelerator Linac4 to 160 MeV, and their electrons stripped away
- The protons are injected into the Proton Synchrotron Booster (PSB), and accelerated to 1.4 GeV
- Next, they are injected into the Proton Synchrotron (PS), where they are sent into bunch packets, and accelerated to 25 GeV
- Finally in the pre-acceleration chain, the protons are sent in batches to the Super Proton Synchrotron (SPS), and they are accelerated up to 450 GeV.

At last.... these bunches are sent into the LHC and ramped up to collision energy.... But how does this acceleration actually work?

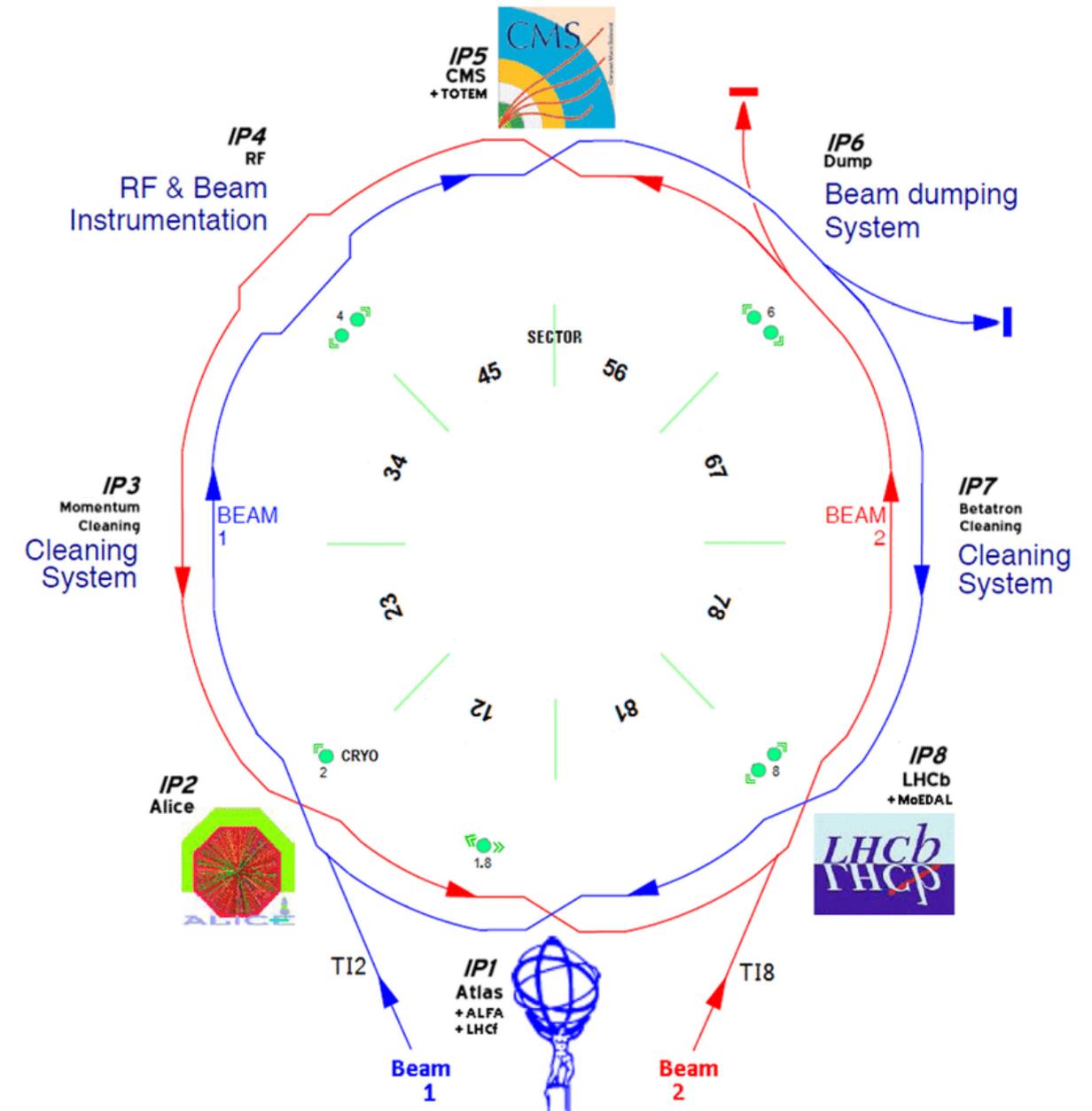
# RF cavities and Magnets!



- The radiofrequency cavities accelerate the beam every time it passes by
- The magnets steer the beams, which would otherwise leave the LHC ring

# Acceleration

- Every time the beams pass through the RF cavities, they are accelerated
- There are also two injection 'kickers' which steer the beam into the LHC rings in opposite directions

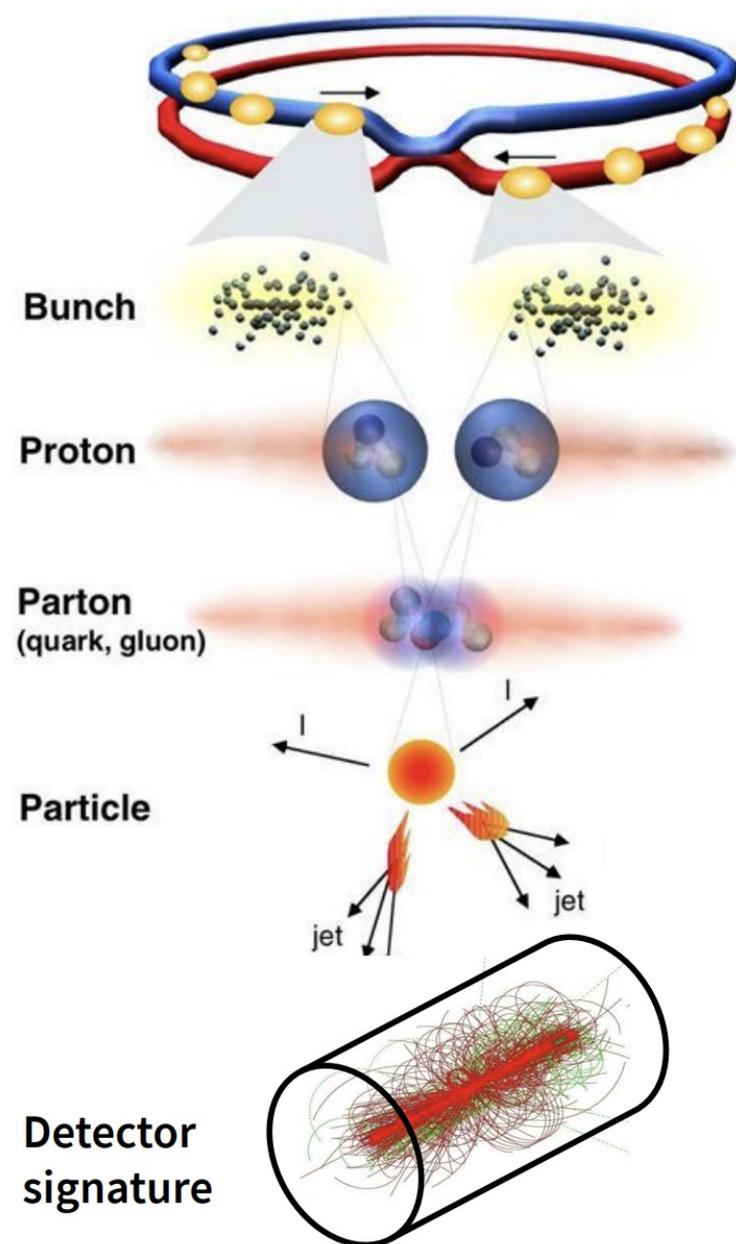


# When a magnet goes wrong...

- The more acceleration you give a beam, the stronger the magnets have to be to steer.
- The LHC magnets were designed to run at superconducting temperatures ( $-271^{\circ}\text{C}$ ) with huge currents running through them.
  - When they were first being commissioned, there was what LHC physicists like to call 'the incident'.
  - The incident was caused by a bad connection that suddenly caused resistance, leading to damage.
  - 53 magnets needed replacement! But in less than a year, we were back doing physics



# The collisions



- Beams circulate at full energy
- Bunches of protons brought together at interaction points
- Protons from that bunch might collide at 13.6 TeV
- But really it's the 'partons' inside the protons that interact!
- New particles are created from  $E = mc^2$
- These particles and/or their decay products are recorded in detectors

How do we see what has happened? - Detectors!

# Question for you!!

Can you name any of the four detectors around the LHC?

# Detector: CMS

## CMS DETECTOR

Total weight : 14,000 tonnes  
Overall diameter : 13.0 m  
Overall length : 23.7 m  
Magnetic field : 3.8 T

STEEL RETURN YOKE  
12,500 tonnes

## SILICON TRACKERS

Pixel (100x150  $\mu\text{m}$ ) ~16m<sup>2</sup> ~66M channels  
Microstrips (80x180  $\mu\text{m}$ ) ~200m<sup>2</sup> ~9.5M channels

SUPERCONDUCTING SOLENOID  
Niobium 0.9 mm coil carrying ~13,000A

## MUON CHAMBERS

Barrel: 250 Drift Tube, 480 Resistive Plate Chamber  
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chamber

## PRESHOWER

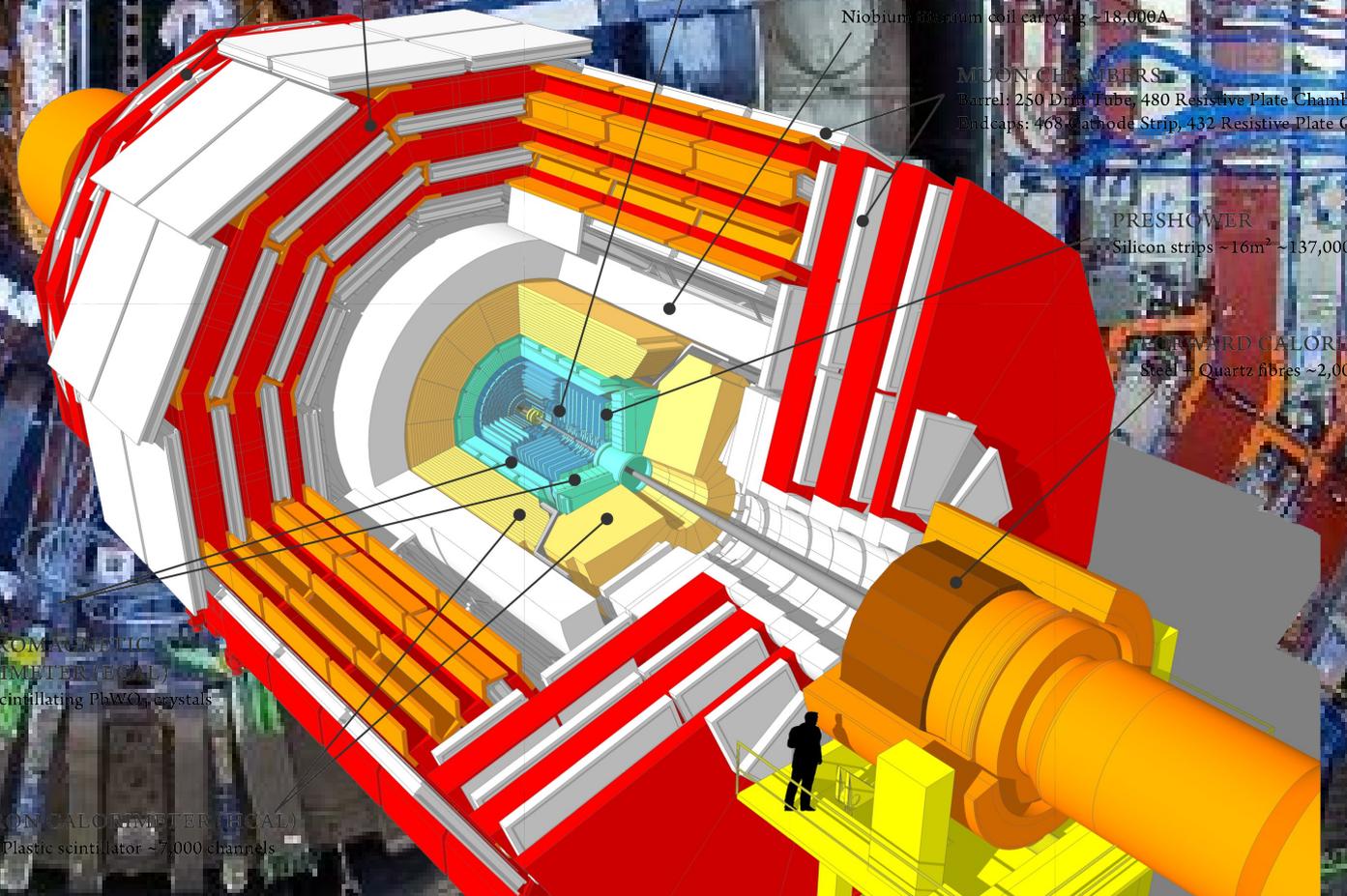
Silicon strips ~16m<sup>2</sup> ~137,000 channels

## FORWARD CALORIMETER

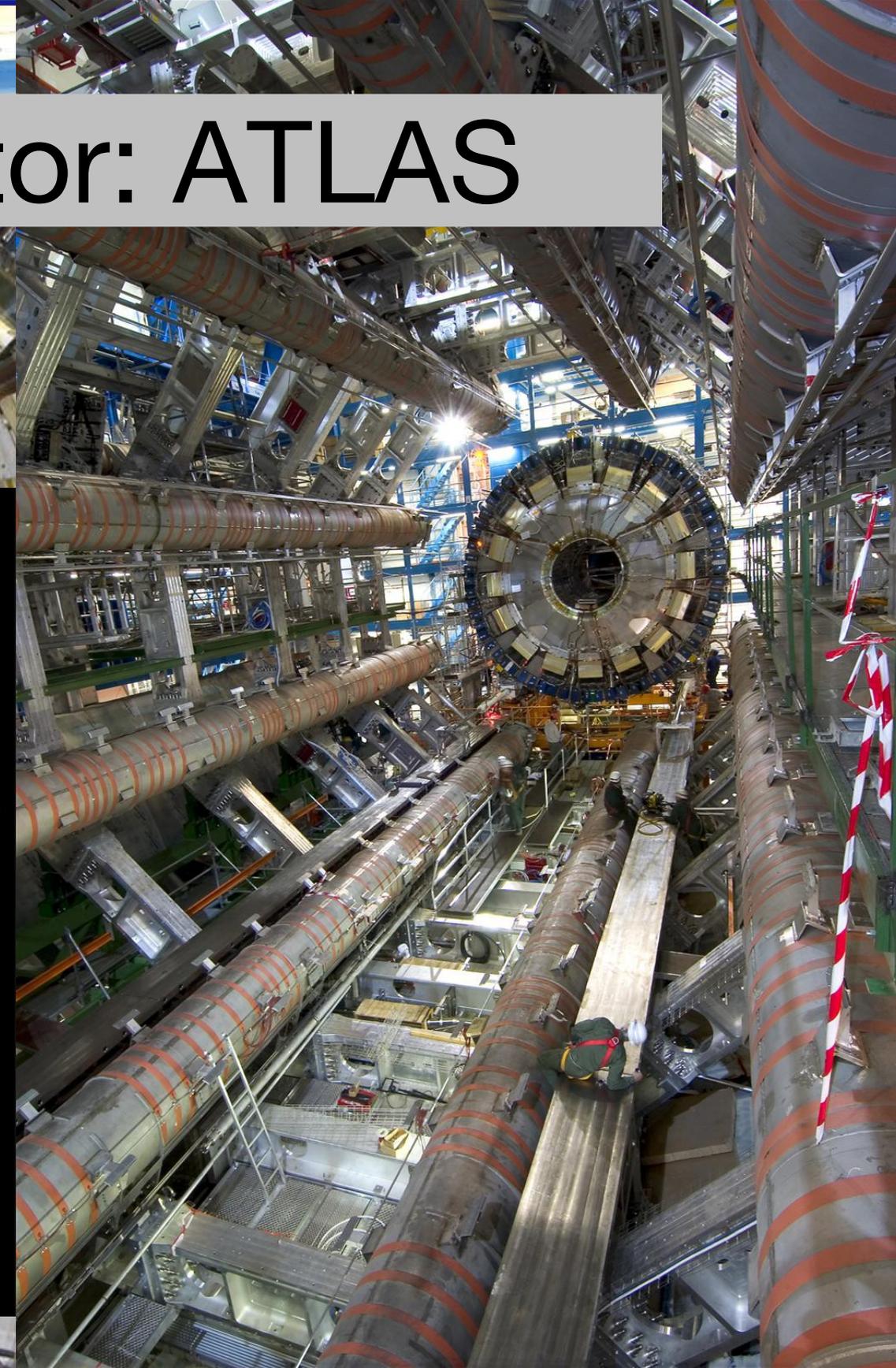
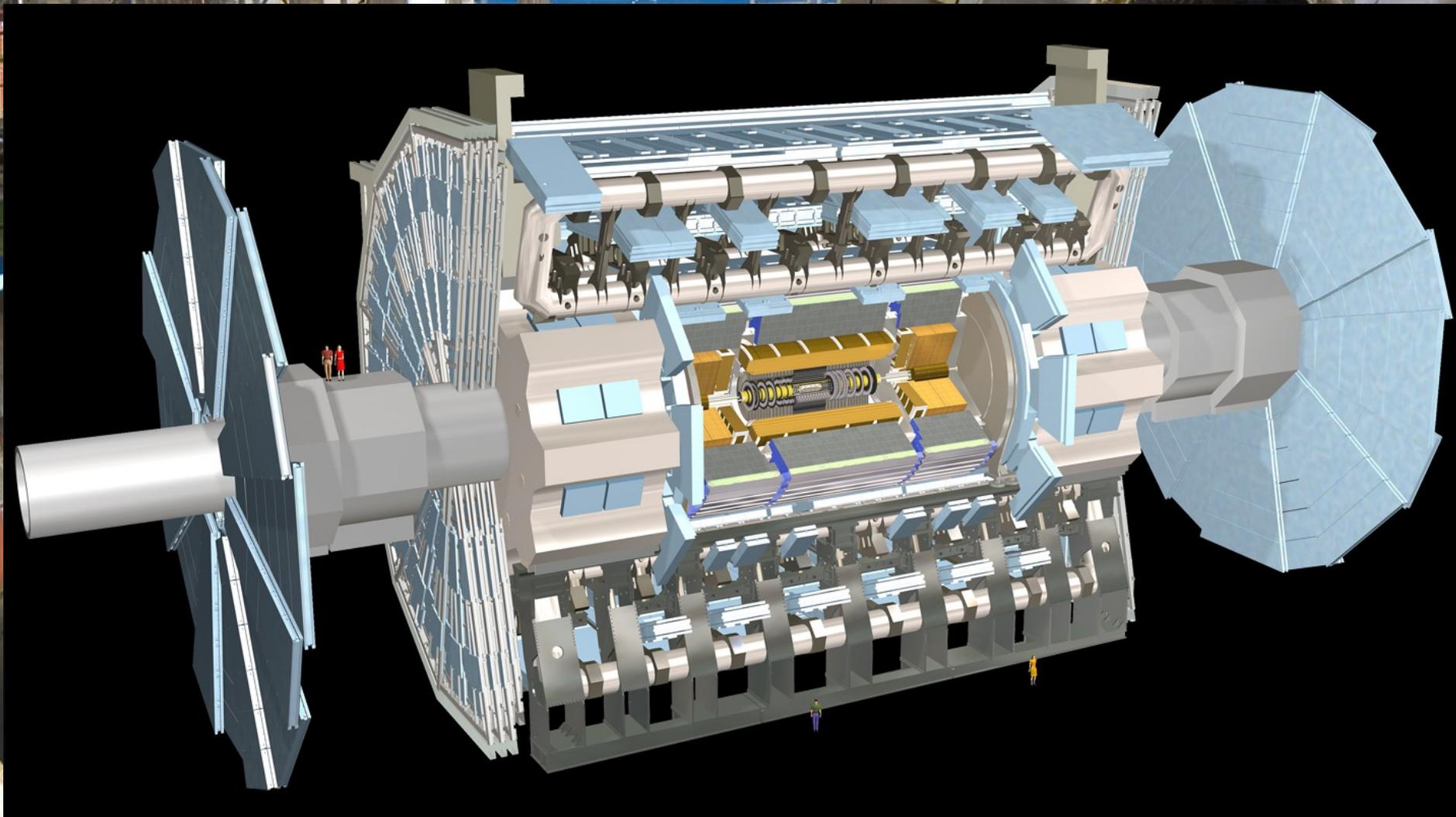
Steel + Quartz fibres ~2,000 channels

CRYSTAL  
ELECTROMAGNETIC  
CALORIMETER (ECAL)  
~76,000 scintillating PbWO<sub>4</sub> crystals

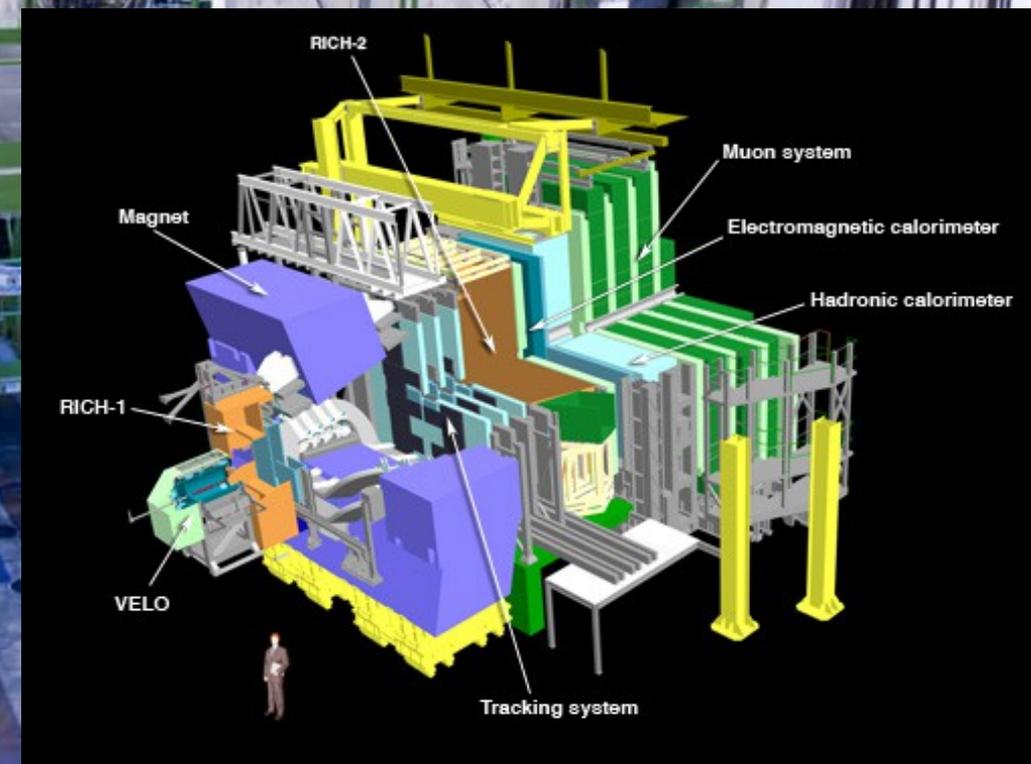
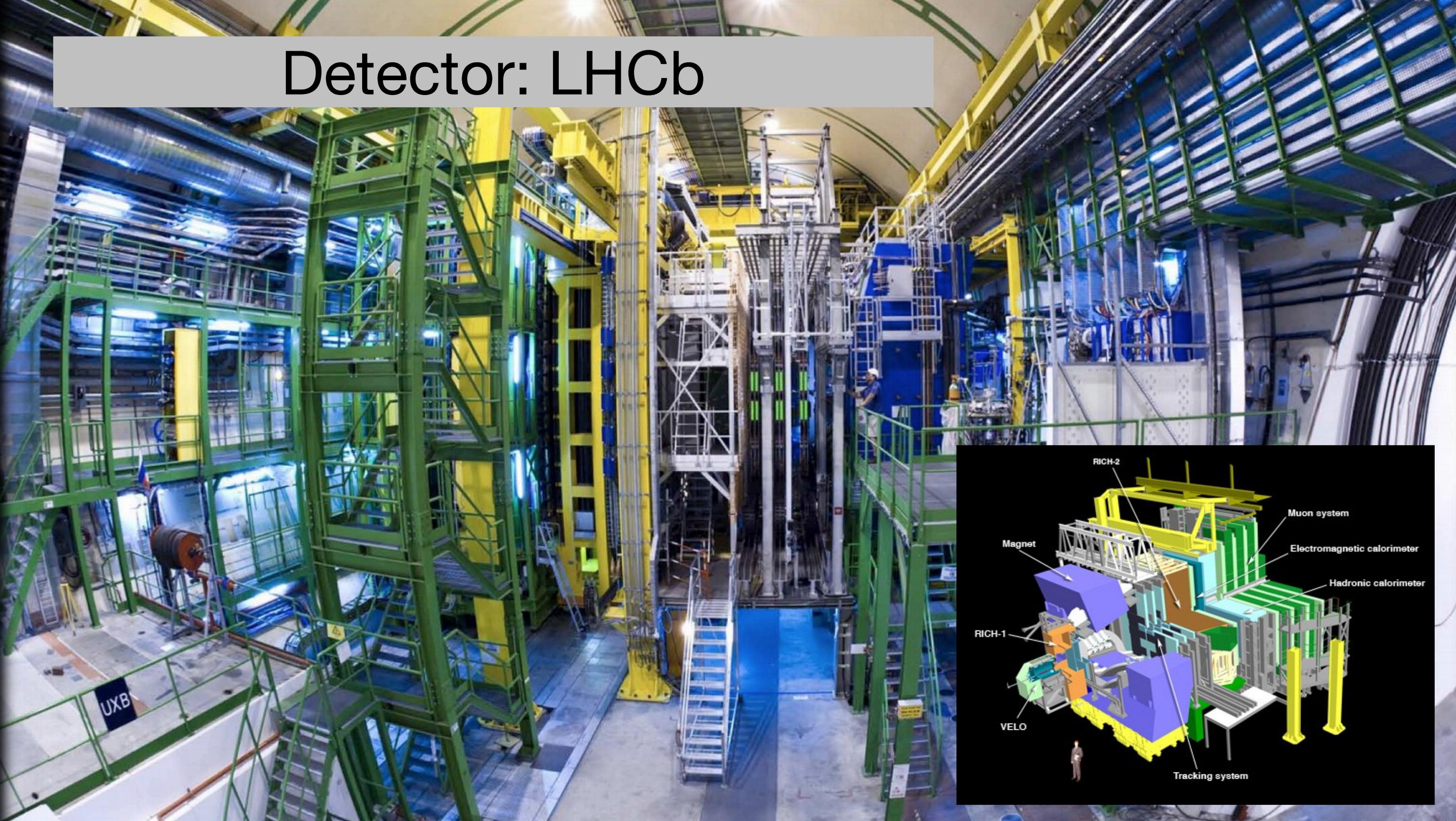
HADRON CALORIMETER (HCAL)  
Brass + Plastic scintillator ~7,000 channels



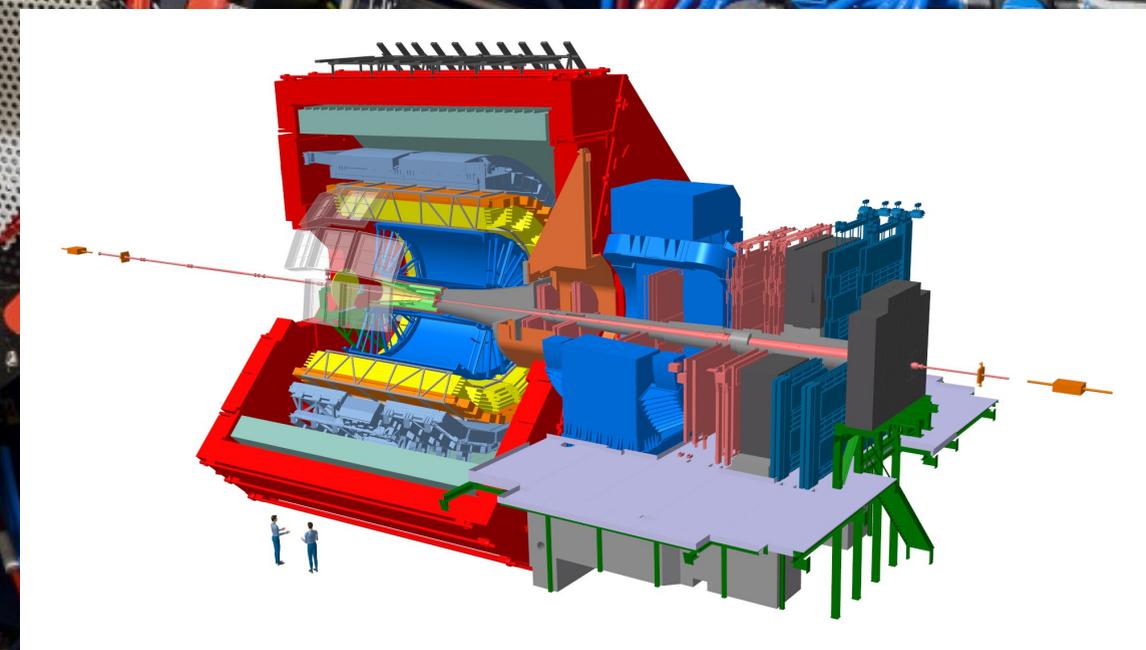
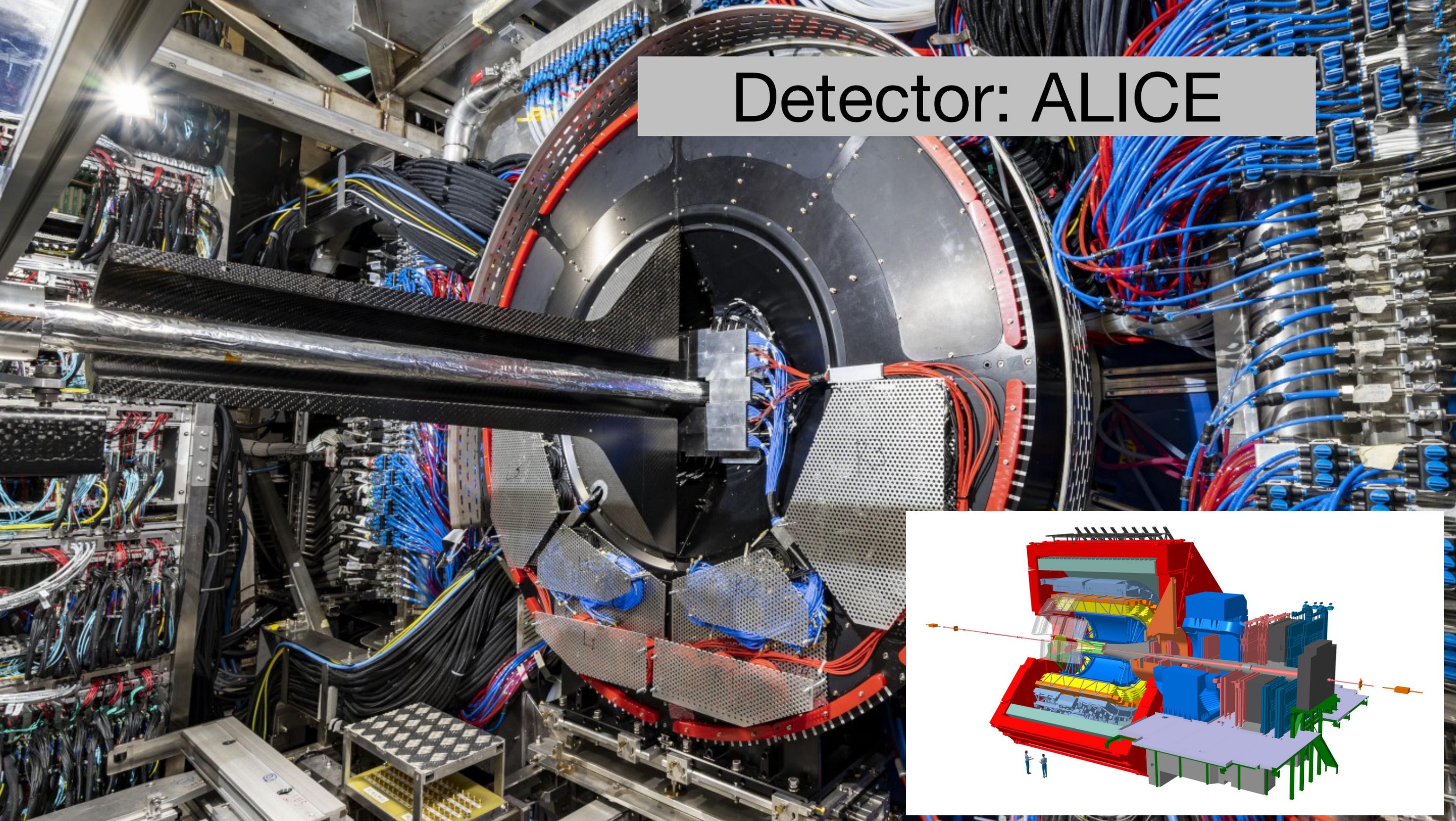
# Detector: ATLAS



# Detector: LHCb

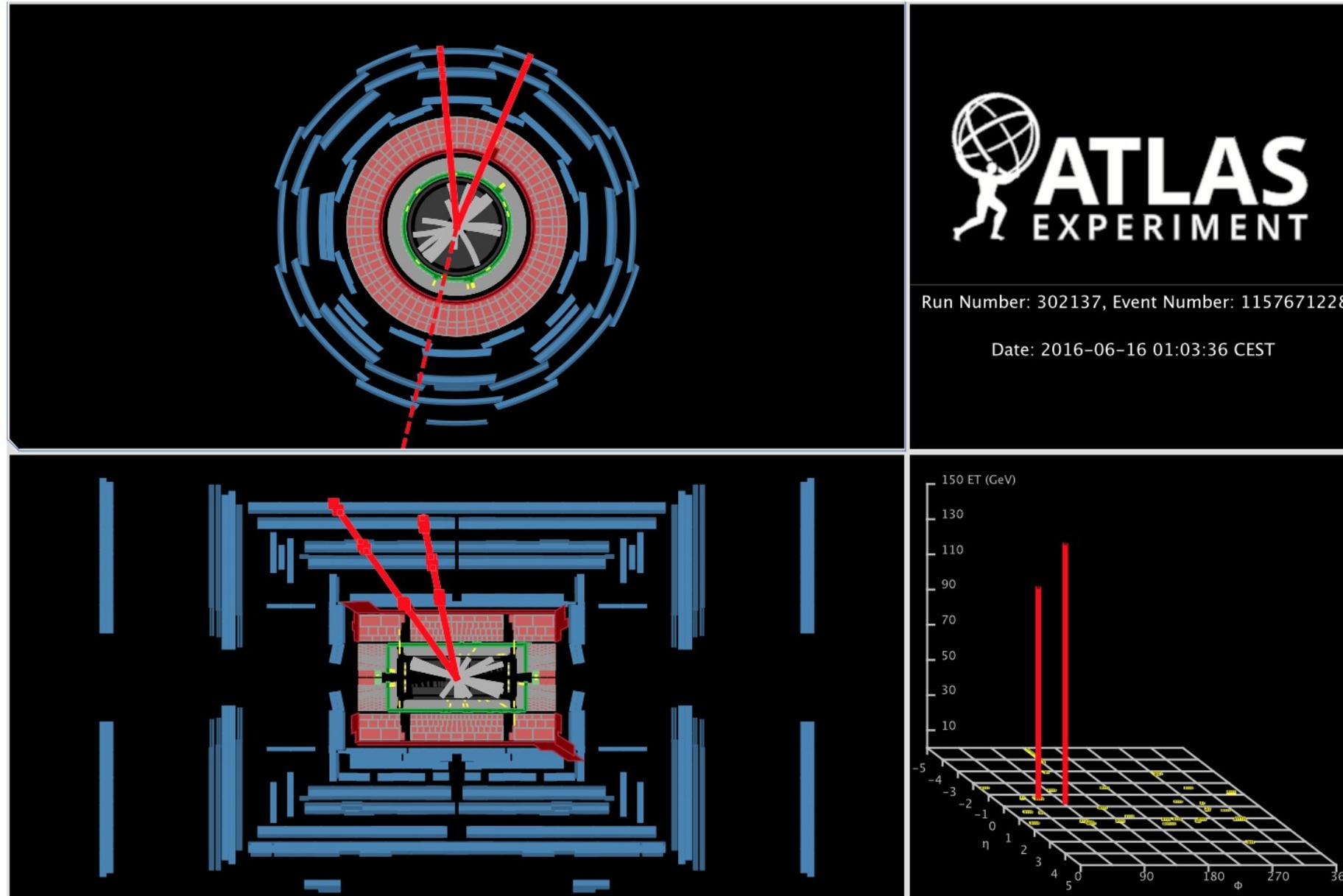


# Detector: ALICE





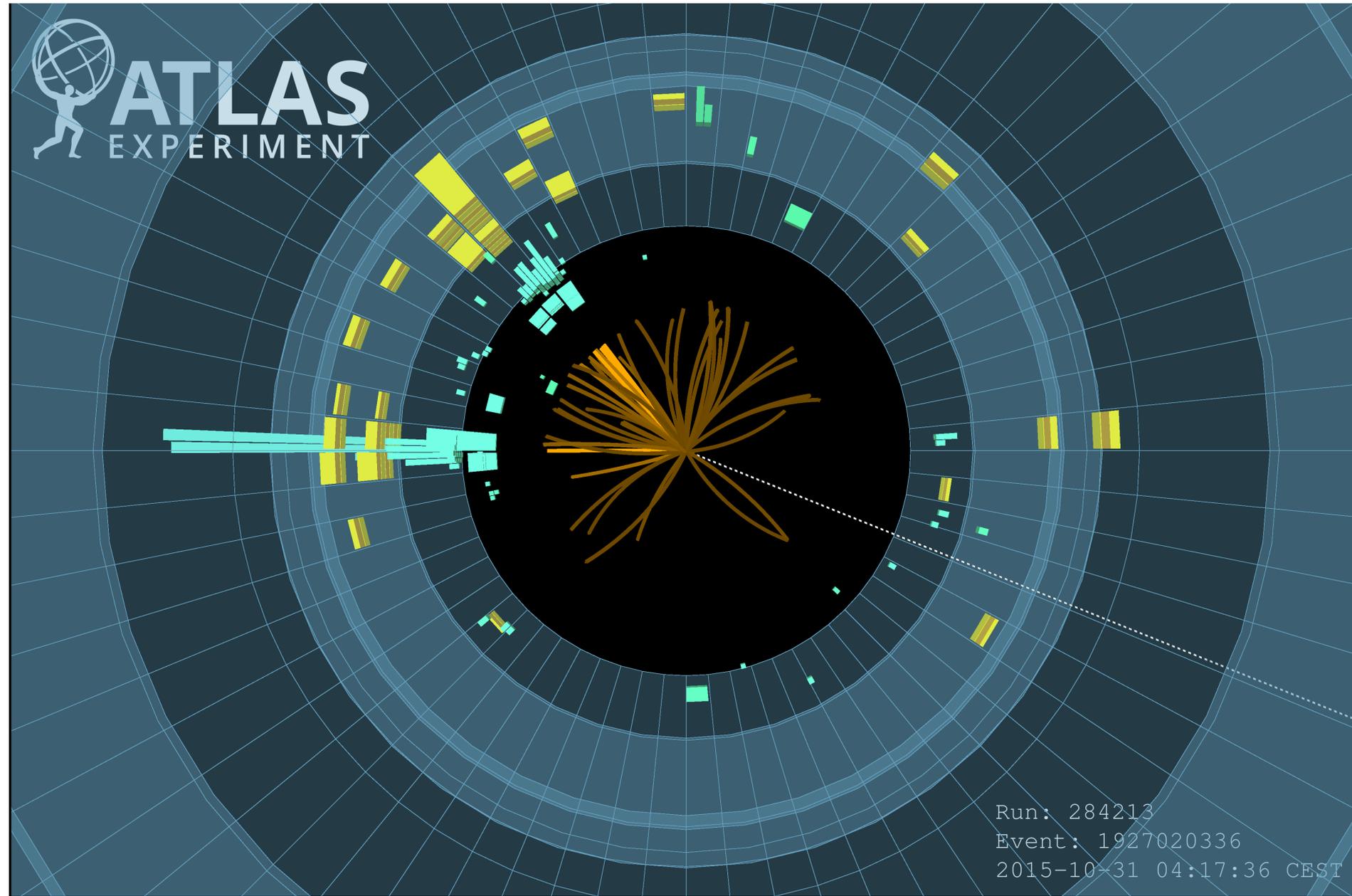
# Potential dark matter event in ATLAS



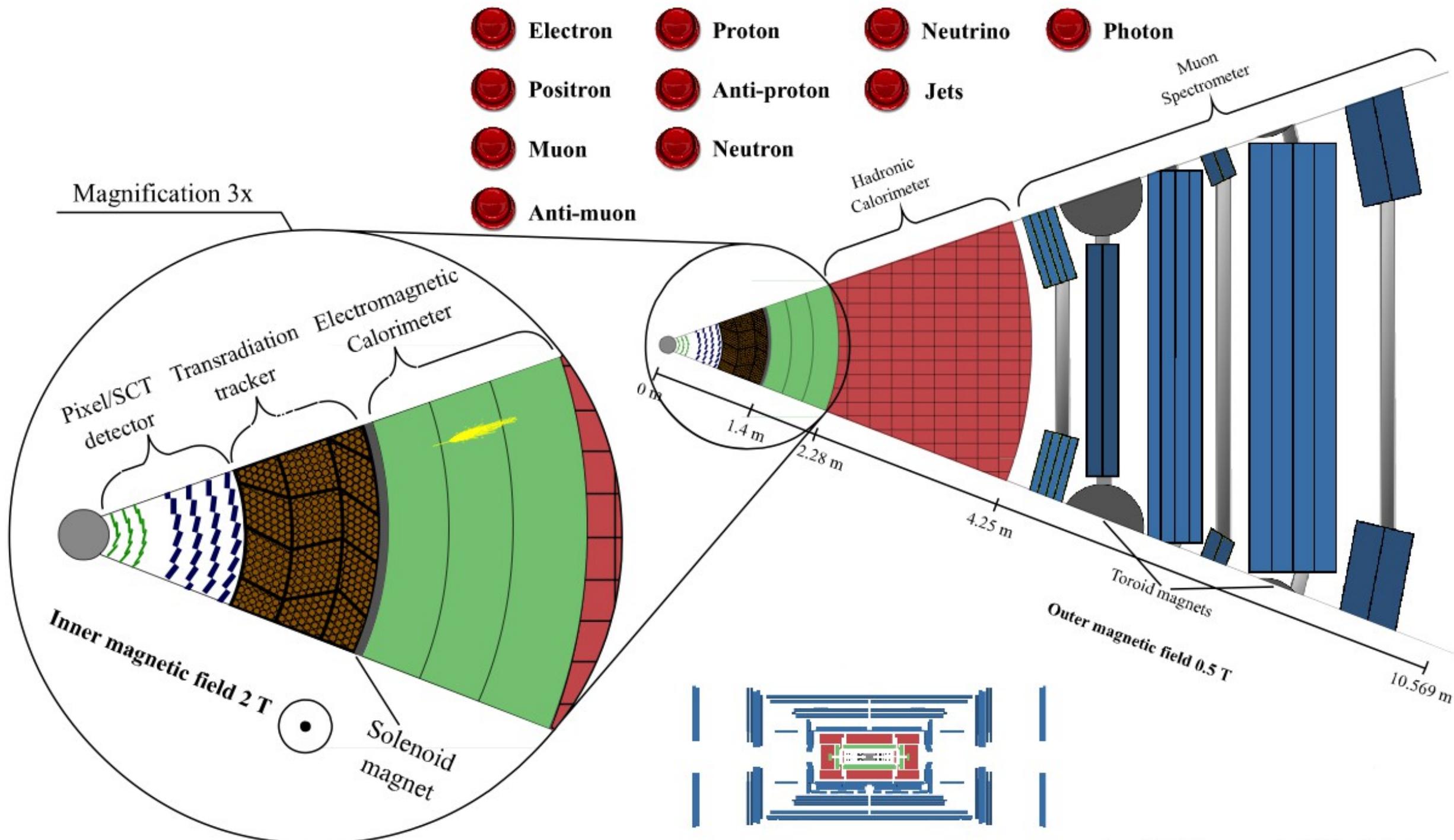
[Link to Plot](#)

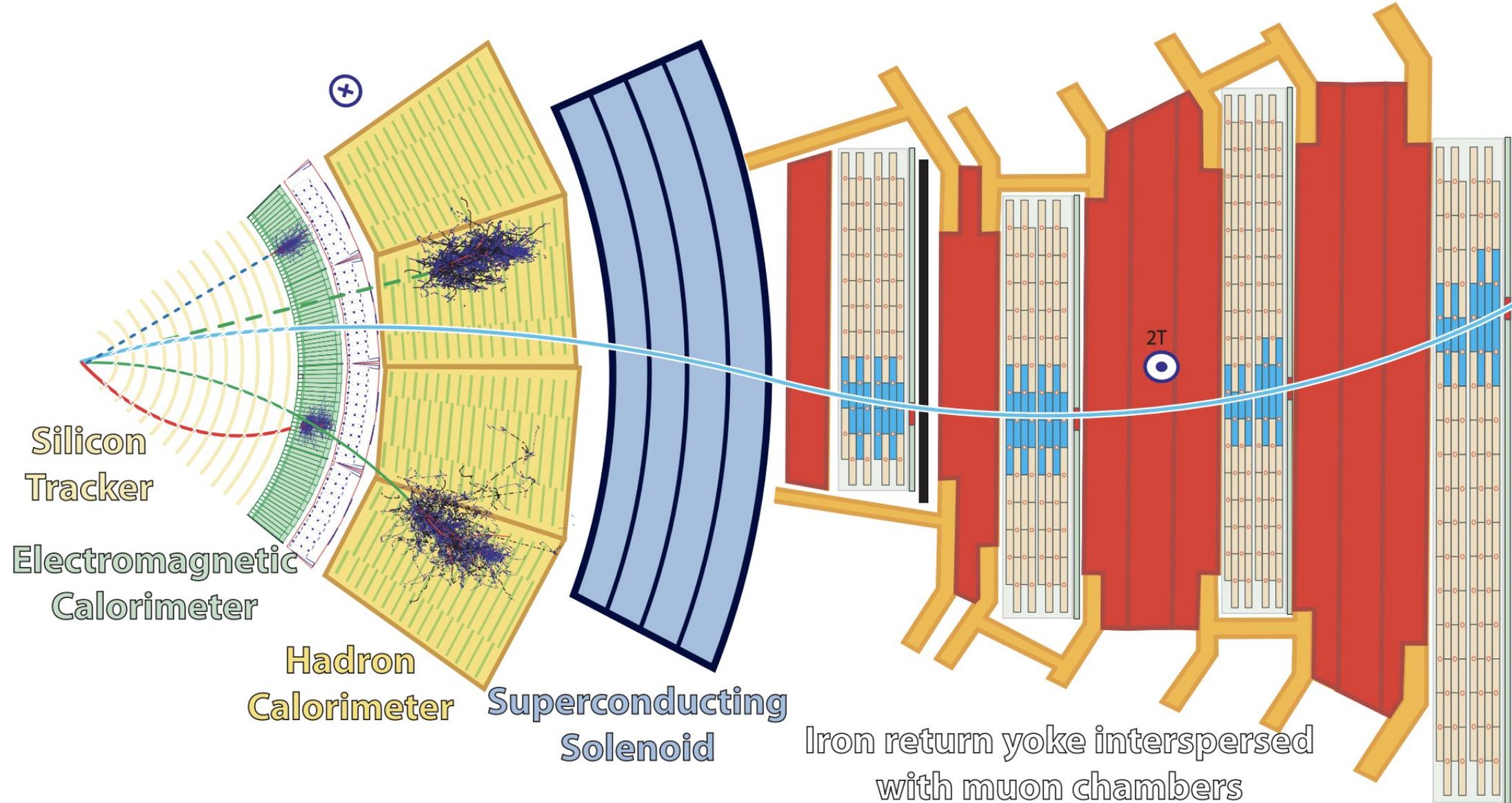
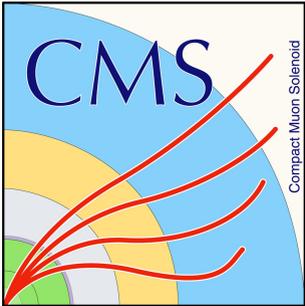


# Potential dark matter + b-quarks



[Link to Plot](#)



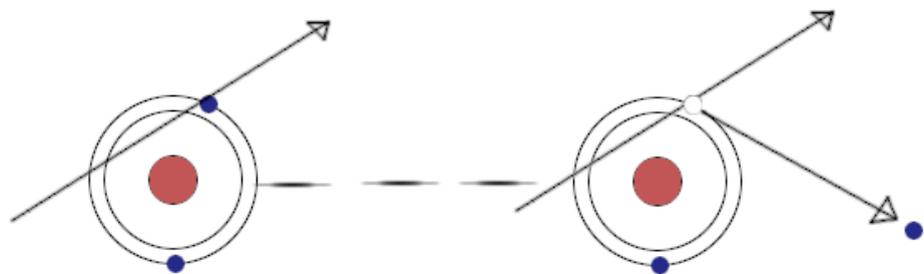


- Muon
- Electron
- Charged hadron (e.g. pion)
- - - Neutral hadron (e.g. neutron)
- - - Photon

# Particle identification – the mathematics

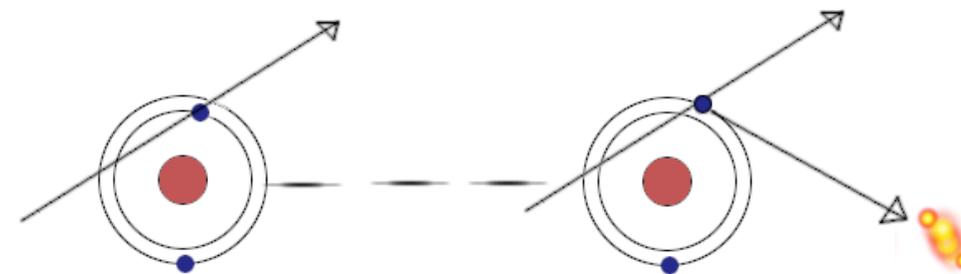
- Centripetal force:
  - $F = mv^2/r$ ,  $m$  is the mass of the particle,  $v$  is its velocity, and  $r$  is its radius of curvature
- Magnetic force:
  - $F = qvB$ , where  $q$  is the charge of the particle,  $v$  is its velocity, and  $B$  is the magnetic field
- Balancing them:
  - $m v^2 / r = q v B$  .... the centripetal force is balanced by the forces coming from the magnetic field, so lets rearrange and solve for  $r$  ...
  - $r = m v / q B$  .... where  $m$  and  $q$  are intrinsic to the particle,  $v$  is the speed of light, and  $B$  is a known quantity. Now you just measure the radius to give you a clue of the identity of the particle!

# What is signal? (Physics perspective)



Incoming light or particle interacts with outer electron

Electron is torn away from its nucleus, leaving a charged ion



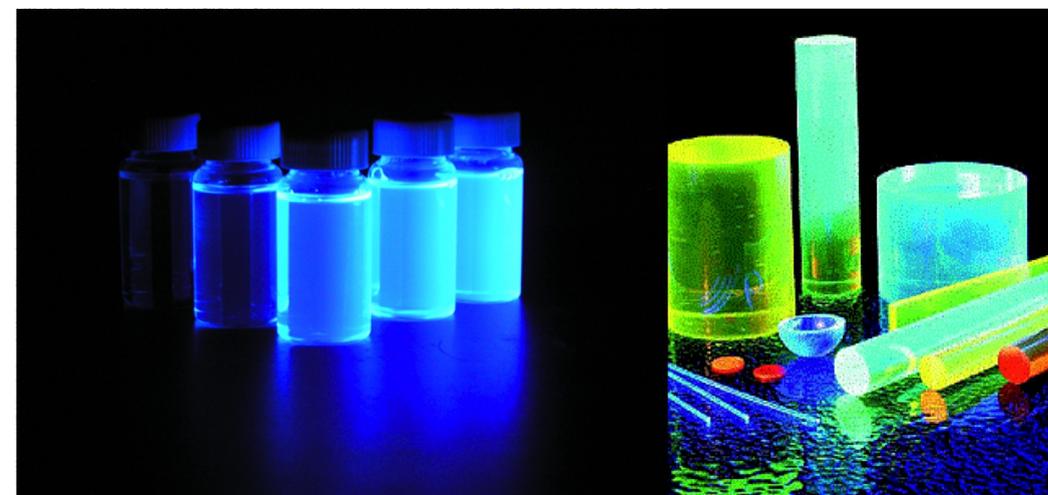
Incoming light or particle interacts with outer electron

Electron absorbs some of the energy but soon releases it in the form of light

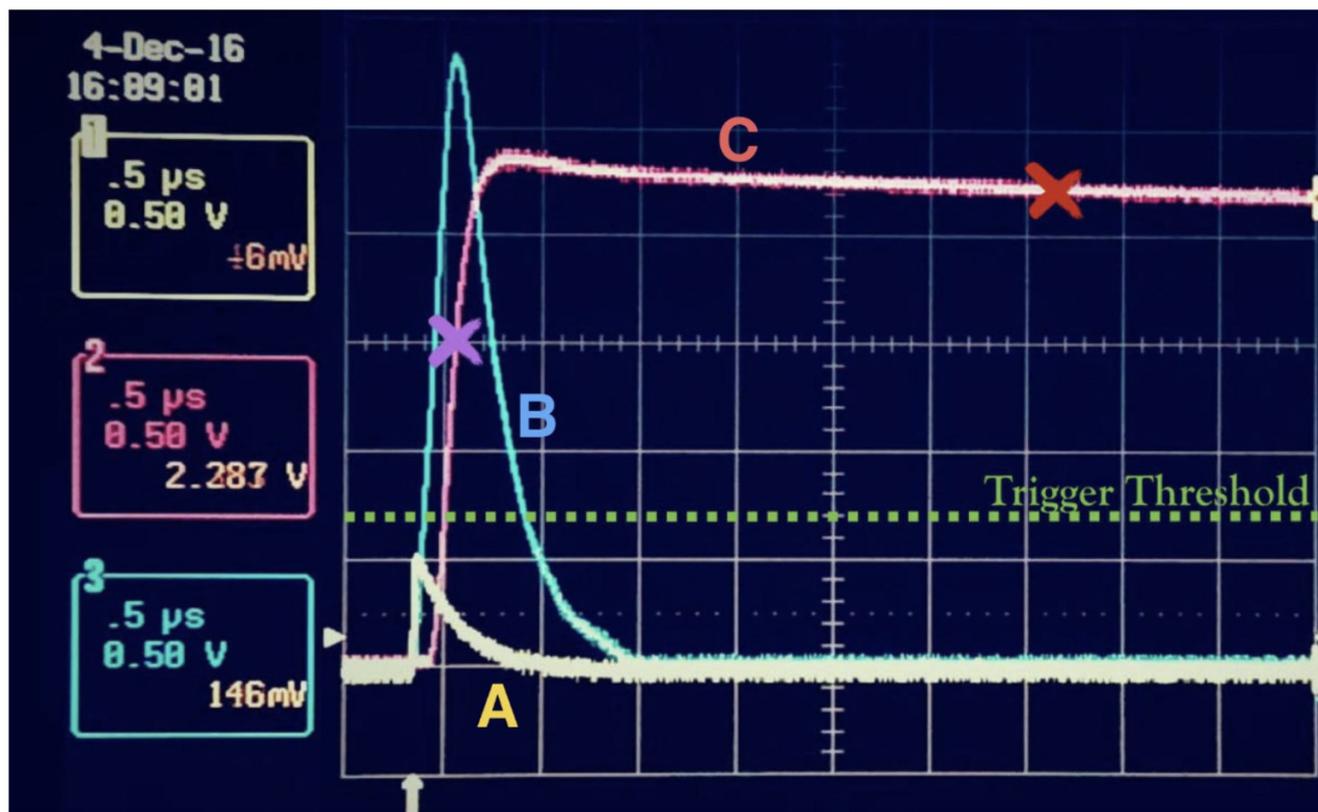
## Ionising radiation



## Scintillation



# How to trigger physics signals?

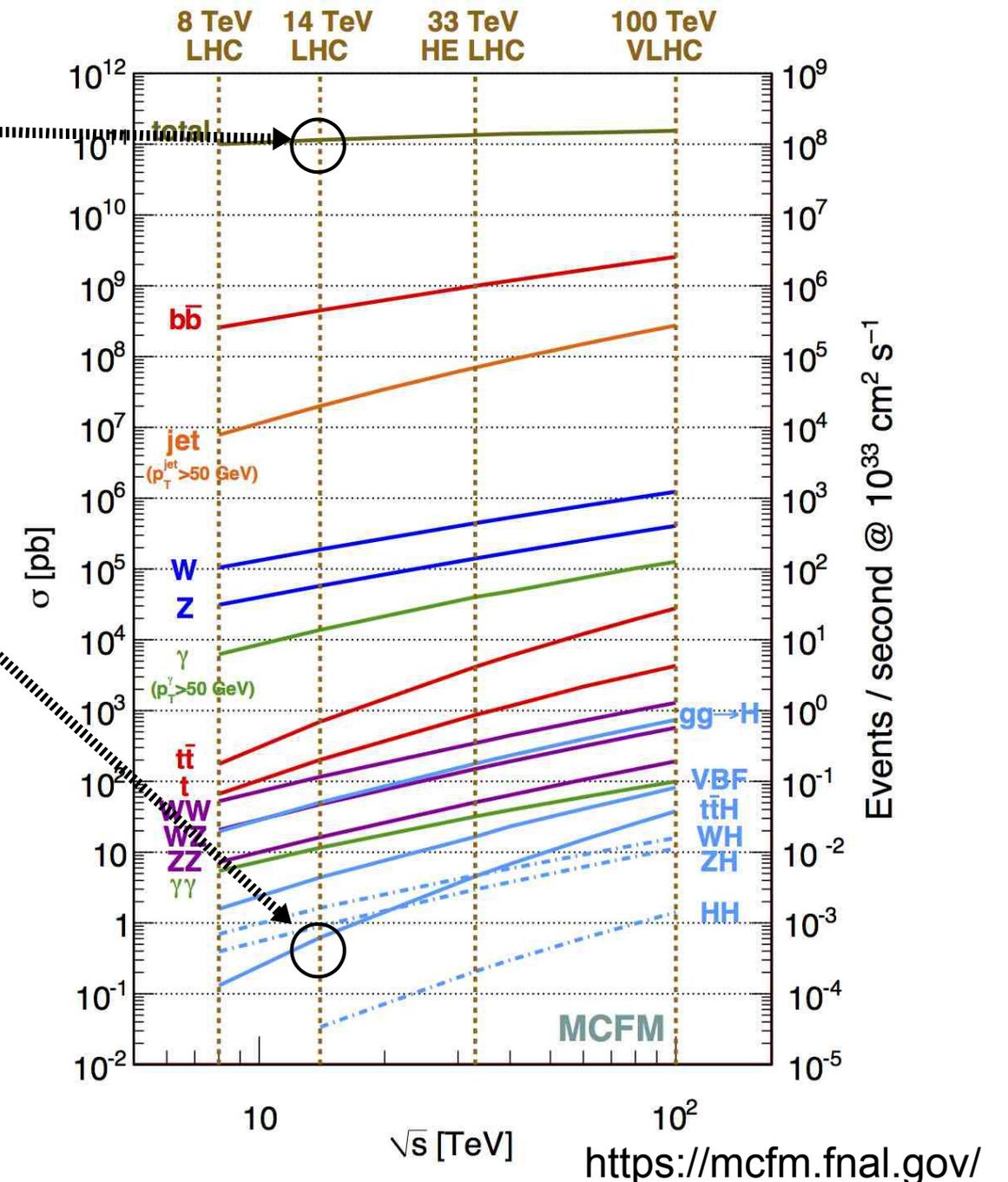


<http://cosmicwatch.lns.mit.edu/detector>

- Read a pulse
- Amplify the pulse
- Check if it is above a threshold
- Send the trigger signal to the system if it is
- Record data from the system
- Prepare to do it again

# Physics motivation

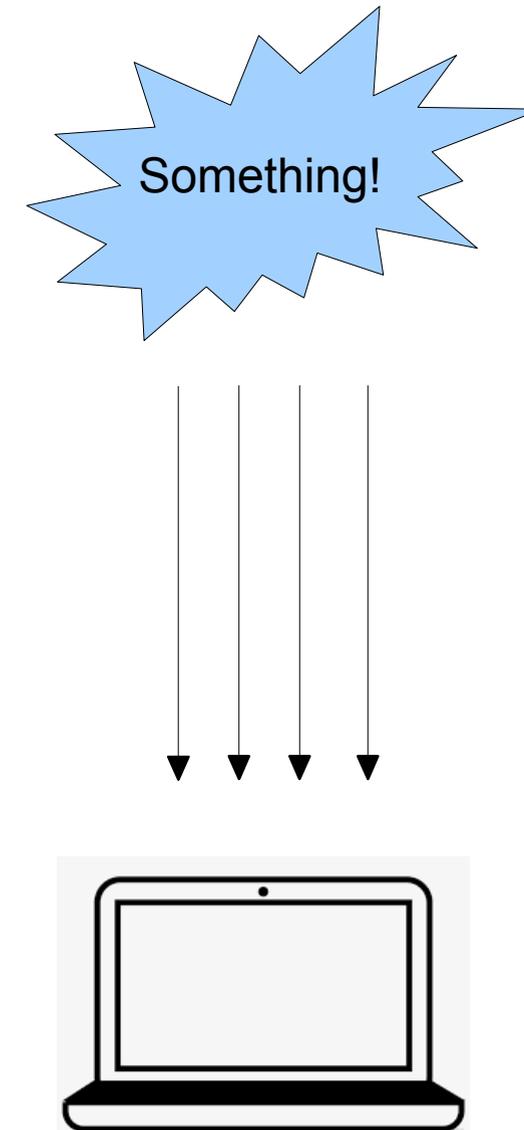
- So much rate in proton interactions!
- So little of interest.
- There are 100 billion ( $10^{11}$ ) events happening every second, this is very challenging
- Most of these interactions are low-energy, and not very interesting to study if you're looking for new particles.



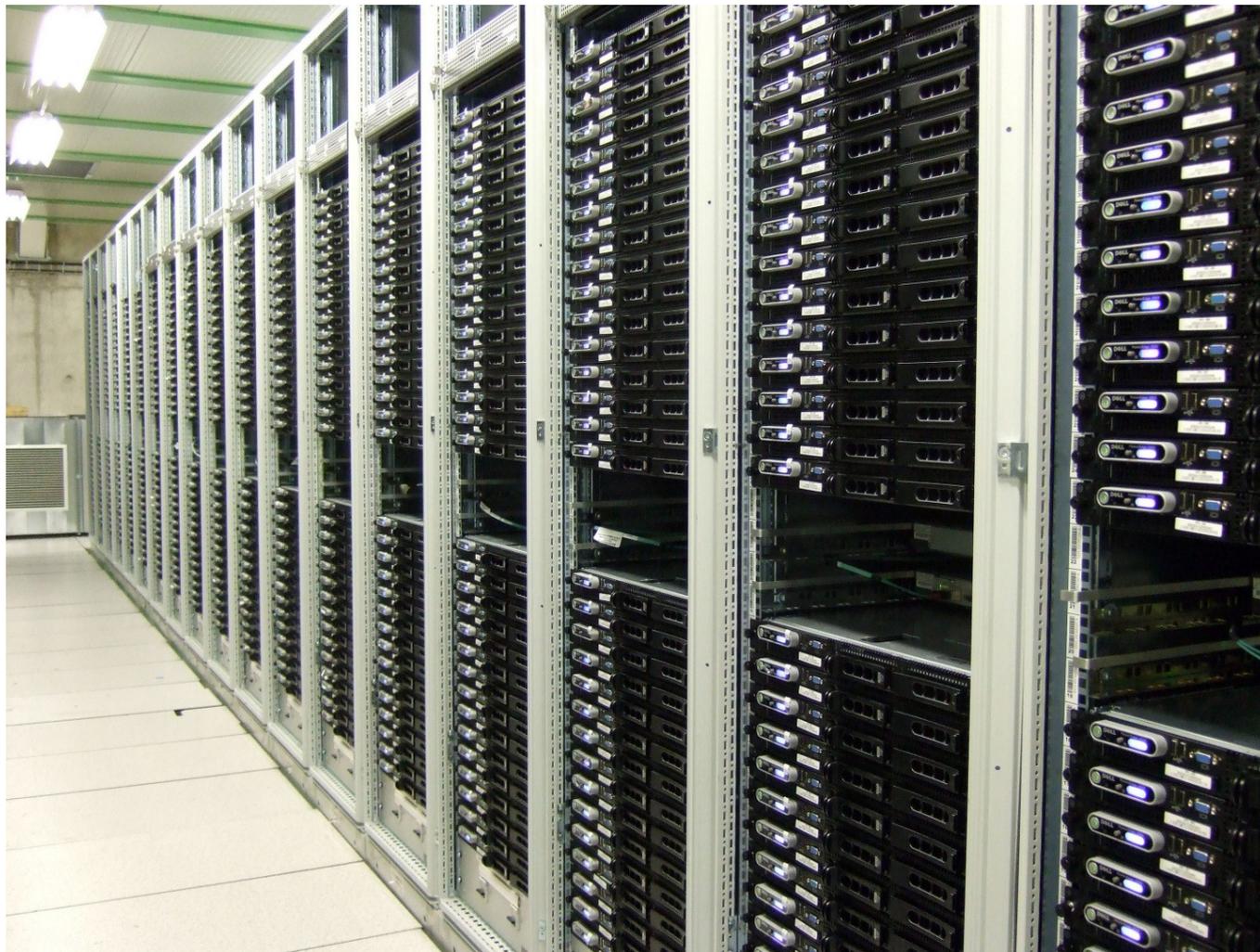
# Data acquisition

Measure and record some real world quantity or quantities by:

- Receiving signal information from sensors
- Converting that data into a form that can be understood:
  - Quantifying the signal
  - This can include digitising the signal, if it came in an analogue form
- Storing relevant information
  - Output saved onto a permanent storage, where it can be accessed again later



# Data readout and recording



- An event passes trigger.
- A signal goes to the system buffering holding the event
- The buffered event is released, and recorded
- The recorded information is likely digitised to save space
- The information will be in a raw format



# Data!

```

00000004 00000001 0000c89c aa1234aa 00003227 0000001c 04000000 00793c29 00000001 00000000
00000000 50753e27 0ab16f70 00097a2b 00000000 00033dac 00000063 920117d5 00000aa8 00000081
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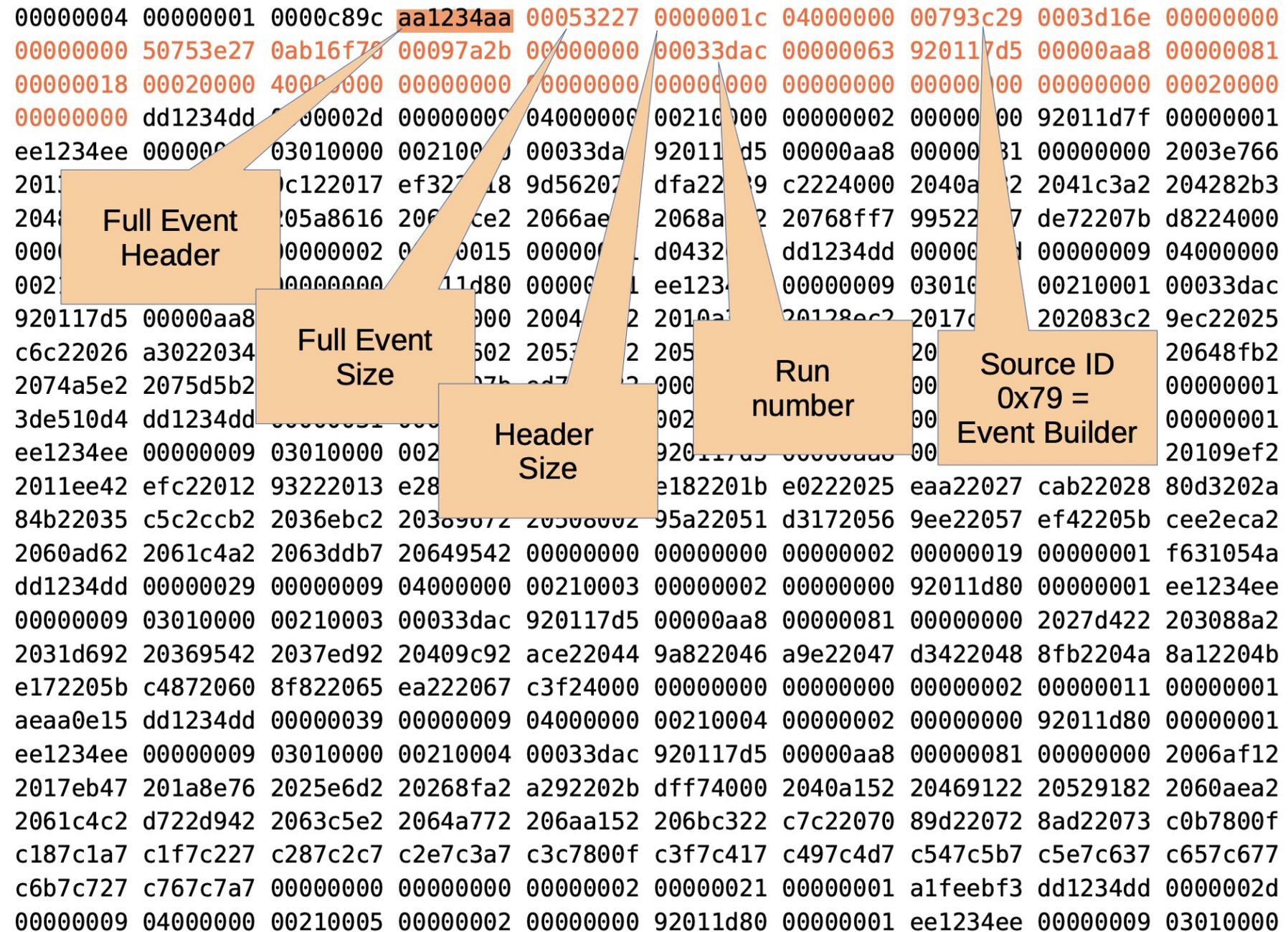
# Okay, lets see what we're looking at

```
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```





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2074a5e2	2075d5b2	207aa892	ad322017	00000000	00000000	00000002	00000015	00000001	00000001
3de510d4	dd1234dd	00000031	00000000	1600 fragments	00610002	00000002	00000000	92011d80	00000001
ee1234ee	00000009	03010000	00610000	920117d5	00000aa8	00000081	00000000	20109ef2	00000000
2011ee42	efc22012	93222013	e2822017	00000000	e182201b	e0222025	eea22027	cab22028	80d3202a
84b22035	c5c2ccb2	2036ebc2	20389672	20508002	95a22051	d3172056	9ee22057	ef42205b	cee2eca2
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dd1234dd	00000029	00000009	04000000	00610003	00000002	00000000	92011d80	00000001	ee1234ee
00000009	03010000	00610003	00033dac	920117d5	00000aa8	00000081	00000000	2027d422	203088a2
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e172205b	c4872060	8f822065	ea222067	c3f24000	00000000	00000000	00000002	00000011	00000001
aeaa0e15	dd1234dd	00000039	00000009	04000000	00610004	00000002	00000000	92011d80	00000001
ee1234ee	00000009	03010000	00610004	00033dac	920117d5	00000aa8	00000081	00000000	2006af12
2017eb47	201a8e76	2025e6d2	20268fa2	a292202b	dff74000	2040a152	20469122	20529182	2060aea2
2061c4c2	d722d942	2063c5e2	2064a772	206aa152	206bc322	c7c22070	89d22072	8ad22073	c0b7800f
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```

00000004 00000001 0000c89c aa1234aa 00053227 0000001c 04000000 00793c29 0003d16e 00000000
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20745e2 2075d5b2 207aa892 a12207b ed72ee7 00000000 00000000 00000002 00000015 00000001
3de510d4 dd1234dd 00000031 00000009 04000000 00610002 00000002 00000000 92011d80 00000001
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c6b7c727 c767c7a7 00000000 00000000 00000002 00000021 00000001 a1feebf3 dd1234dd 0000002d
00000009 04000000 00610005 00000002 00000000 92011d80 00000001 ee1234ee 00000009 03010000

```

Fragment  
Header

0x61: MDT  
Barrel side A  
(module 2)

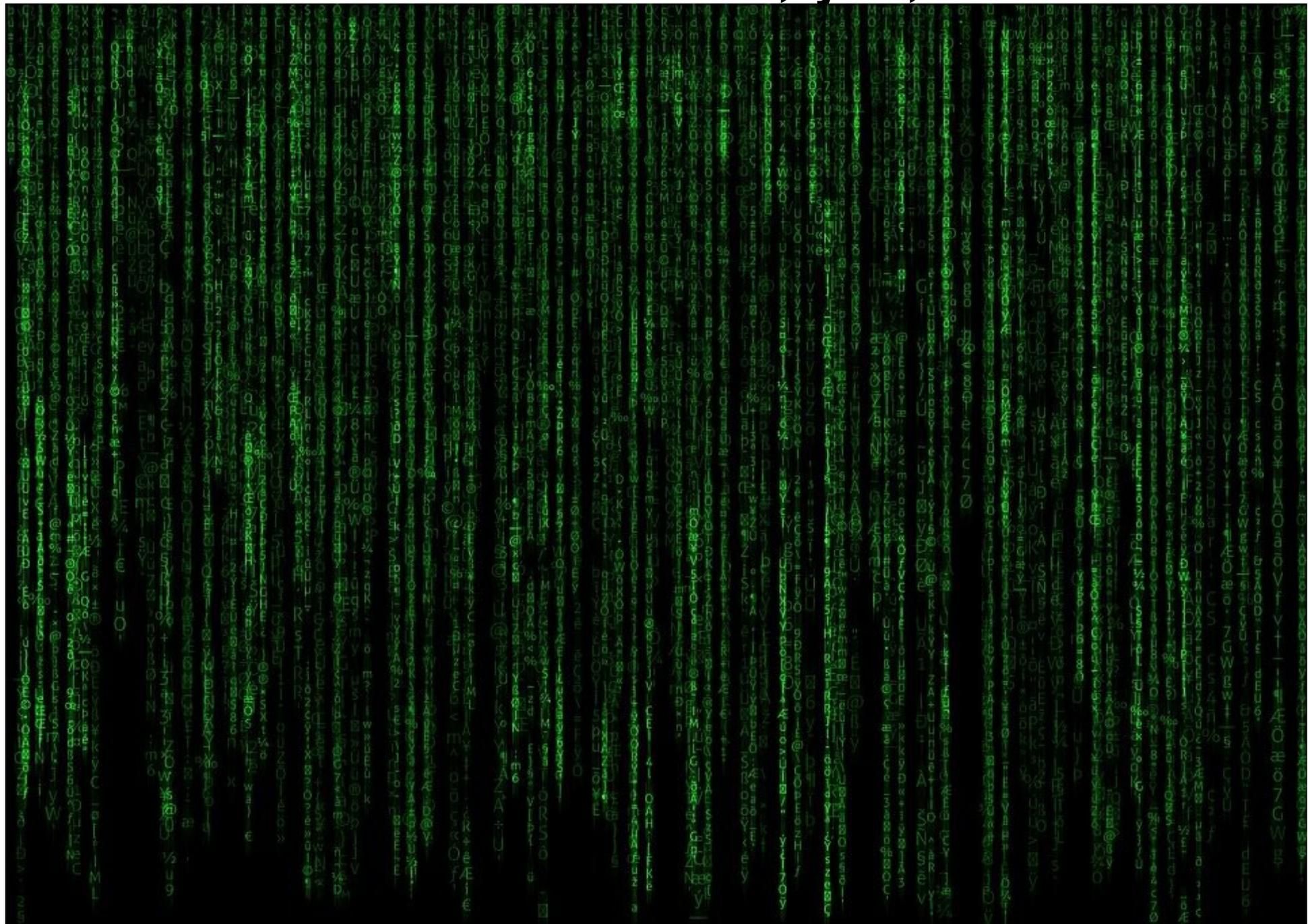
Run  
number

data

Trailer



# All I see is electron, jet, tau...



# Data processing and distribution

- Luckily, we don't have to understand streams of bit files from the LHC.
- Data gets reconstructed into computer and human friendly formats!
- In our computer exercises we are using Open Data from the CMS detector
  - We will be looking at real collisions from the LHC and see if we can spot a Higgs boson
  - Data has been reconstructed to give collections of muons and electrons, with their charge, energy, position, mass, and momenta



In summary....

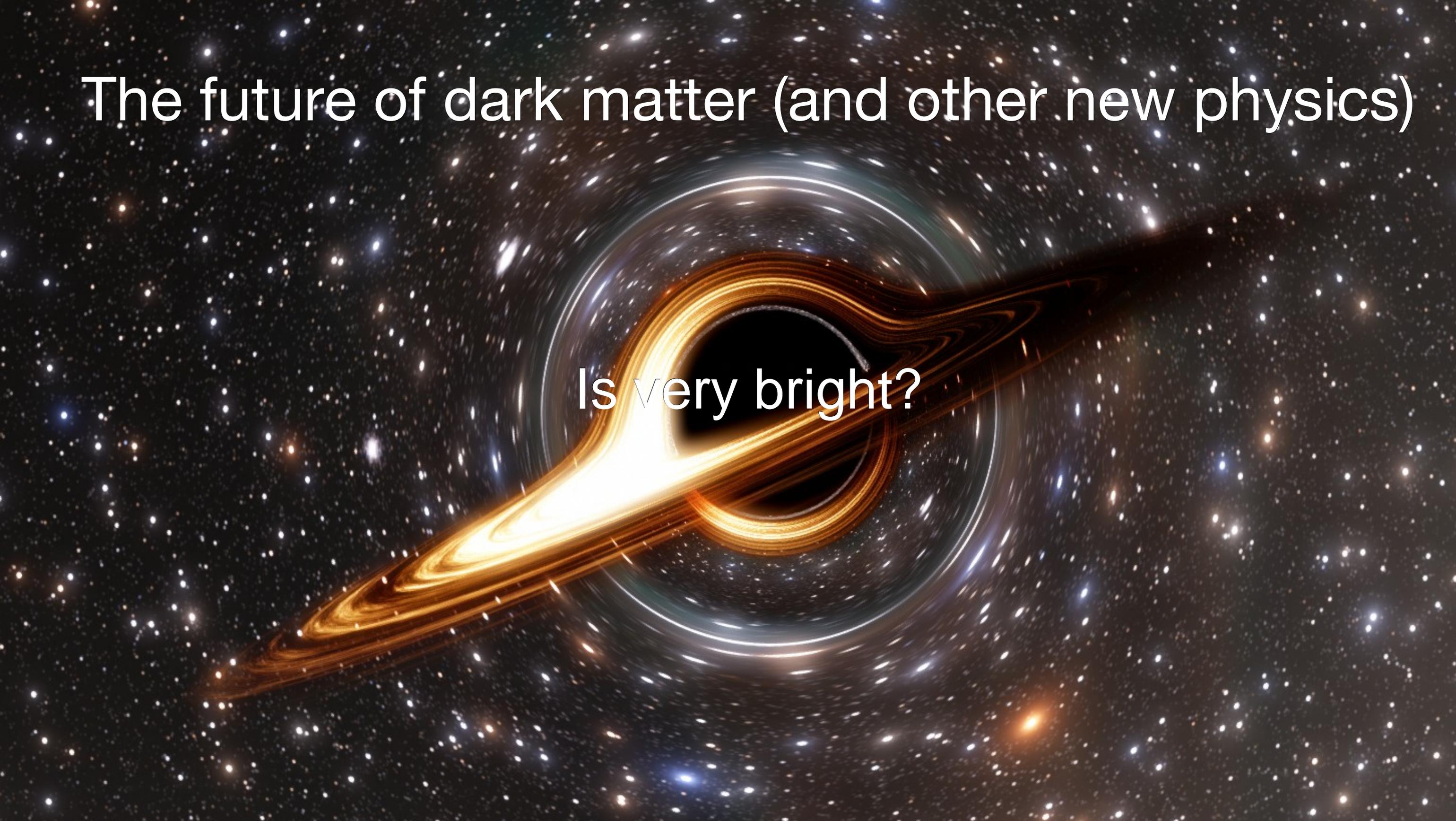
A visualization of the cosmic web, showing a complex network of dark matter filaments and clusters. The filaments are represented by thin, purple lines, while the clusters are shown as bright, yellowish-orange points. The background is a deep purple color.

The search for new particles  
... like cold dark matter

**Is just heating up?**

# The future of dark matter (and other new physics)

Is very bright?



Around 1900, prevailing thought that there wasn't more to be discovered, and 'just had to wrap up a few things'.

Discovery of the electron

General relativity

Quantum mechanics

*What's around the corner for us?*



# Thank you for listening!

For more details on....

- ... The ATLAS detector: <https://atlas.cern/Discover/Detector>
- ... The CMS detector: <https://cms.cern/detector>
- ... The particles we are looking at: <https://particleadventure.org/>
- ... More fun with particle identification:  
[https://atlas.physicsmasterclasses.org/en/zpath\\_playwithatlas.htm](https://atlas.physicsmasterclasses.org/en/zpath_playwithatlas.htm)



## Additional slides

# Which information should be stored?

- Only relevant to record when the signal occurs. Otherwise have to sift through recorded data for the relevant information
  - Expensive to store!
  - Waste of processing resources!
- How do we decide what to record?



(Getty Images/iStockphoto)

- Say I wanted to take a picture of lightning ⚡
- I could go outside taking pictures right now... eventually, I might get a picture of lightning.
- I would probably fill up my memory first. And then some more.

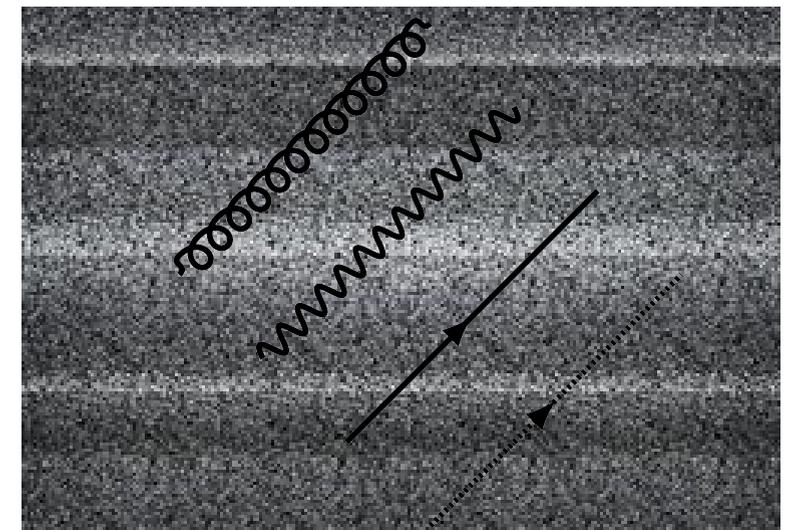
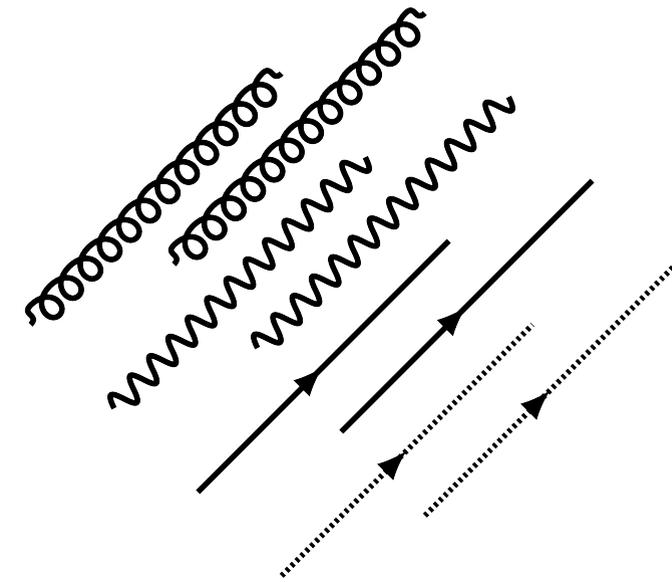
# Trigger

- A Trigger is a time-based and signal-based criteria for recording data
  - Time-based: **when** interesting things could happen
  - Signal-based: **what** interesting thing does happen
- Back to our thought experiment: what if you wanted to take a picture of lightning?
  - Find a storm: time window
  - Continuous pictures? ... would run out of space
  - Regular pictures? ... would miss most strikes
  - Longer exposures, or picture bursts could help...
  - Or maybe you have really quick reactions!
  - Apparently a 'lightning trigger' for cameras exists!
    - This is an ideal solution :)

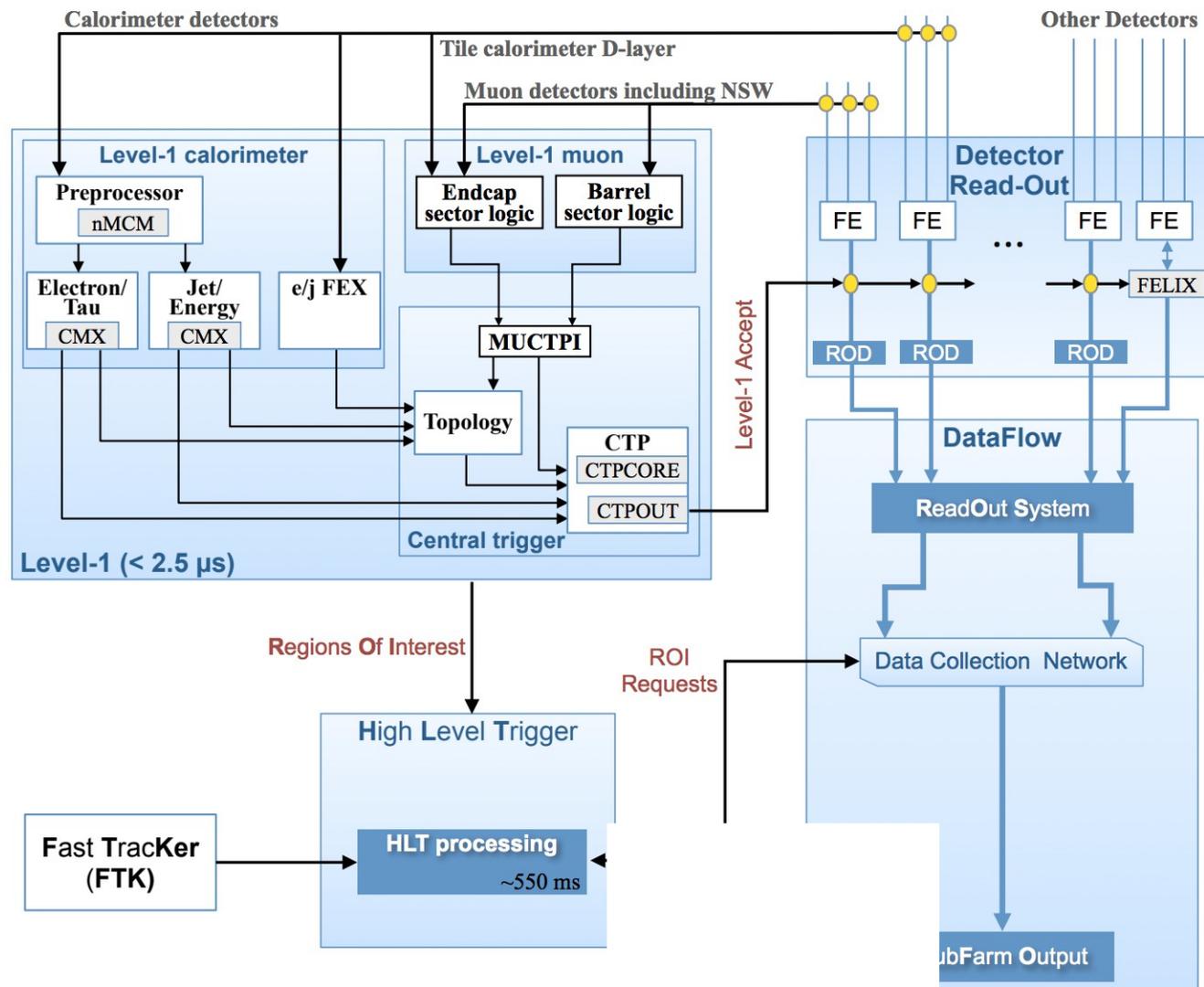


# Trigger for physics

- Detector design has to take into account:
  - What kinds of particles?
  - What energy?
  - What momentum?
  - How many of each?
- Trigger has to distinguish further between:
  - Similar signals
  - Rare processes
  - Noise and detector problems



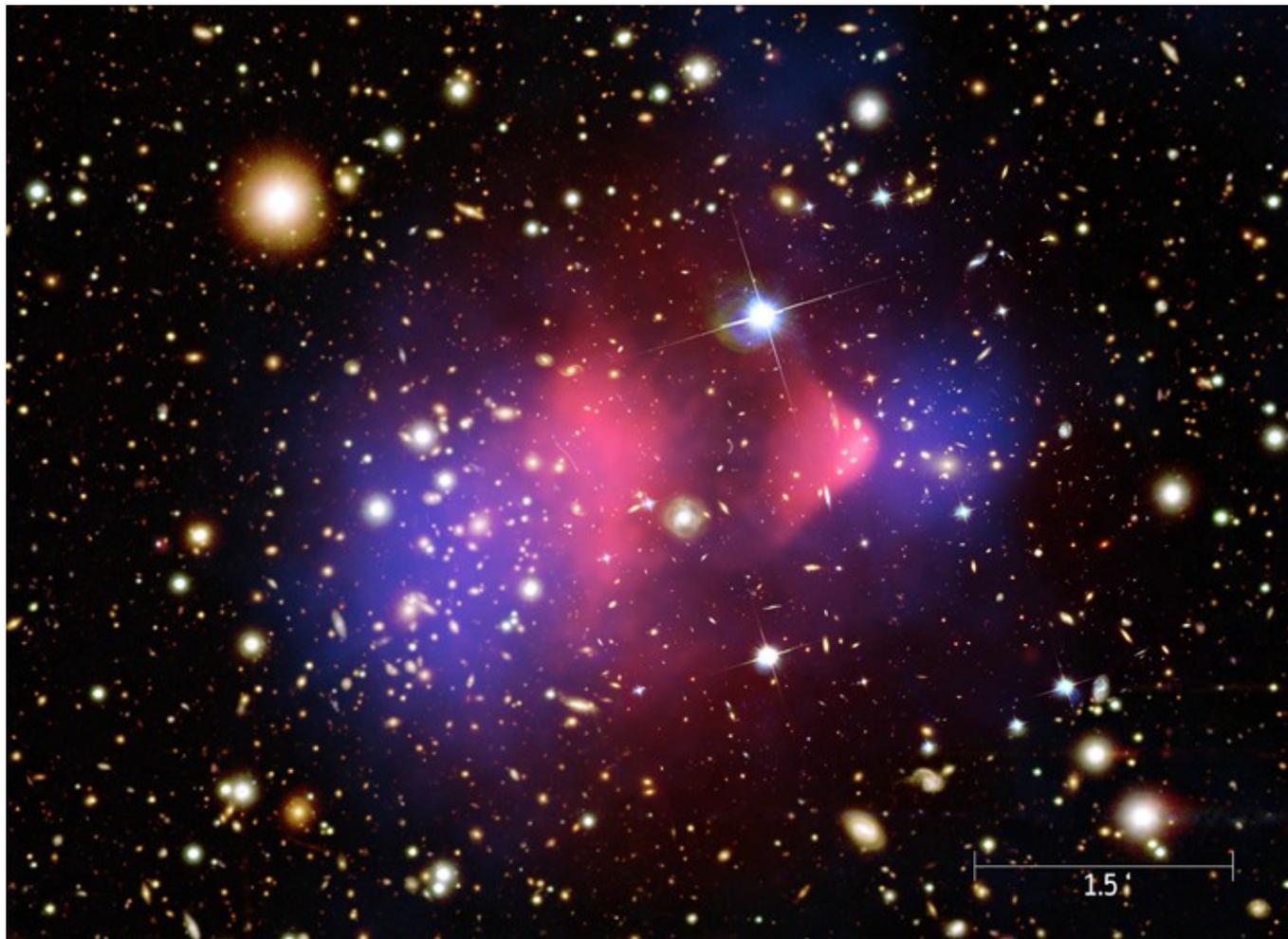
# Triggering summarised



It looks very complicated! But the idea is very simple, we just:

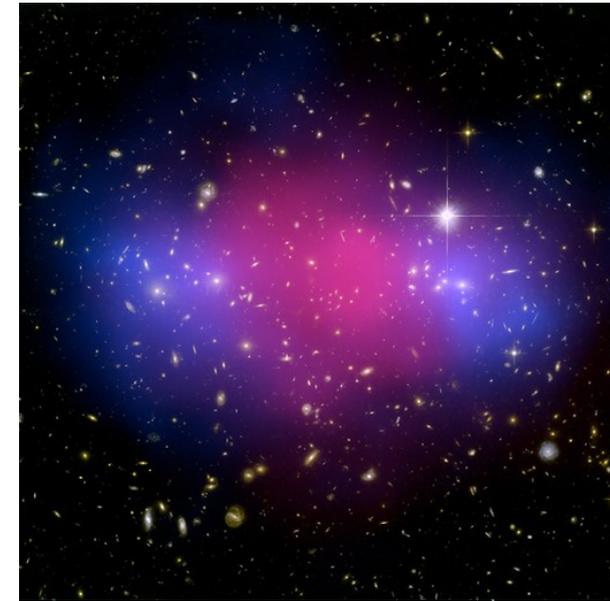
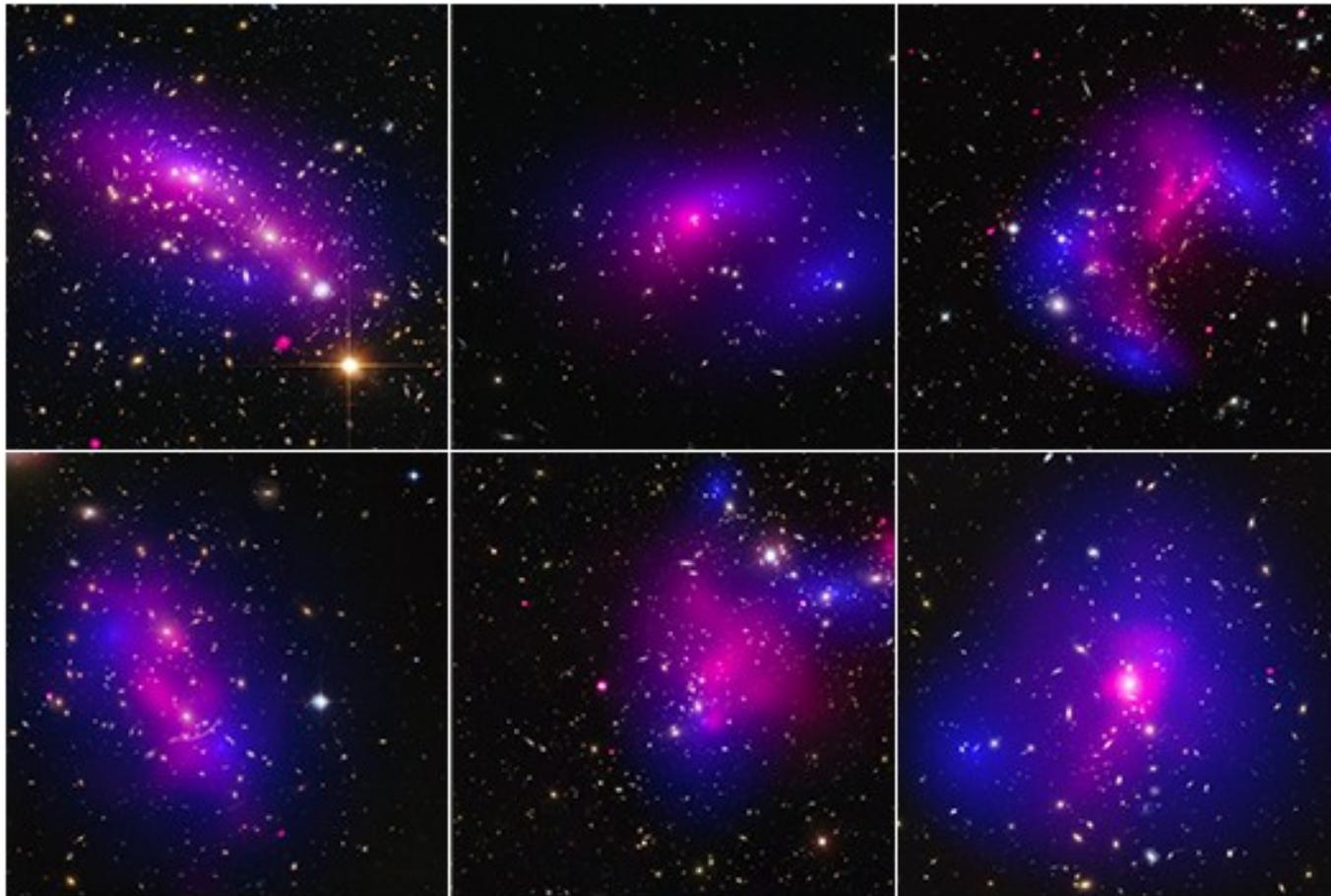
- Identify the particle
- See if it has a high energy
- Then record it!

# Are we sure about Dark Matter?



- The Bullet Cluster
- This is my least favourite evidence for dark matter in astronomy (sorry!)
- Can one example prove a systematic overabundance of material in the universe? Can it determine the nature of that material?

# Bullet Cluster continued



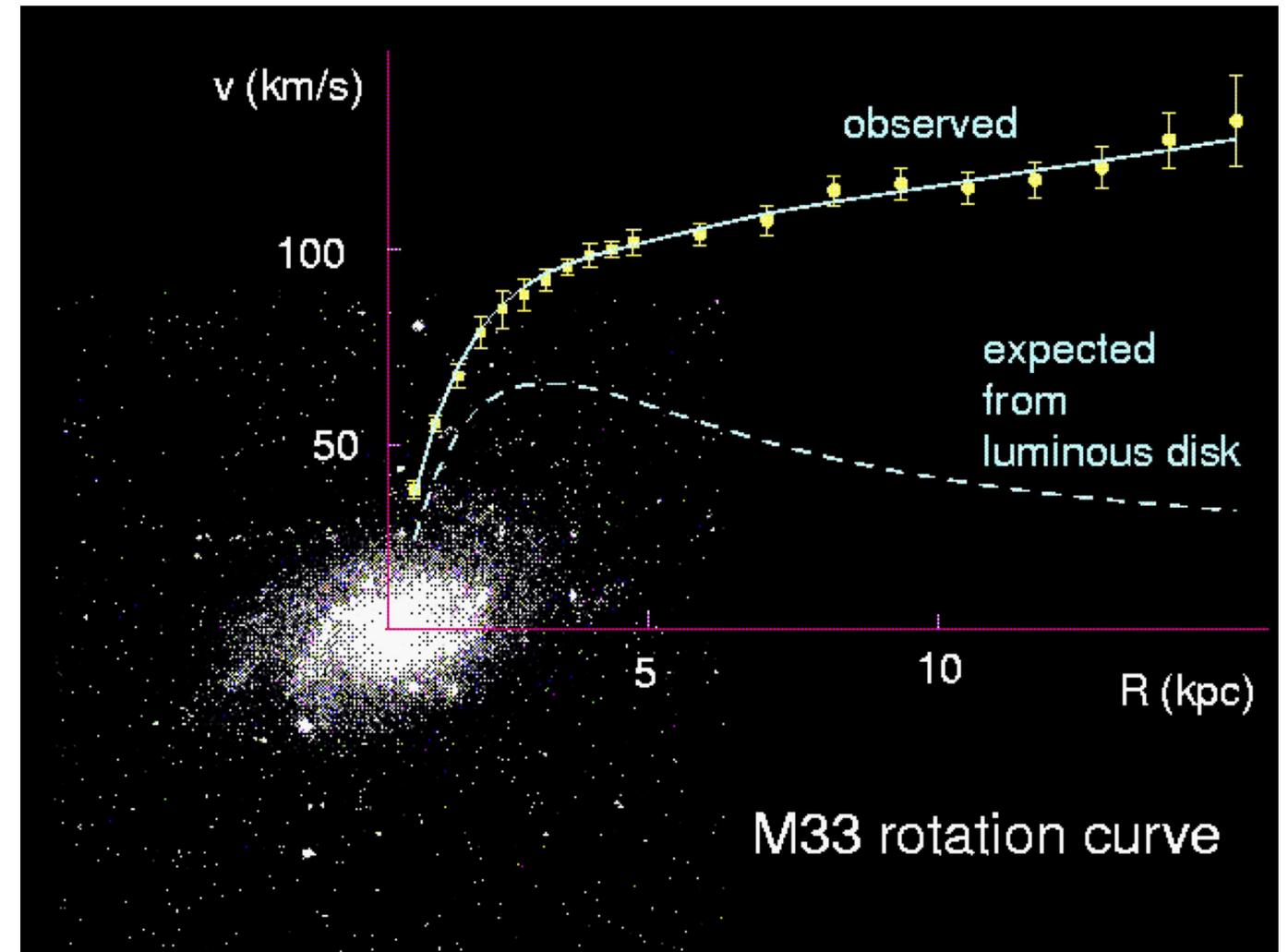
- Actually, there are a lot of colliding clusters like the bullet cluster.
- 72 similar clusters being studied by NASA & Chandra
- Giving a more systematic look at dark matter distributions on cluster scales

[http://chandra.harvard.edu/press/15\\_releases/press\\_032615.html](http://chandra.harvard.edu/press/15_releases/press_032615.html)

# Galactic rotation curves

- As a random thought analogy:

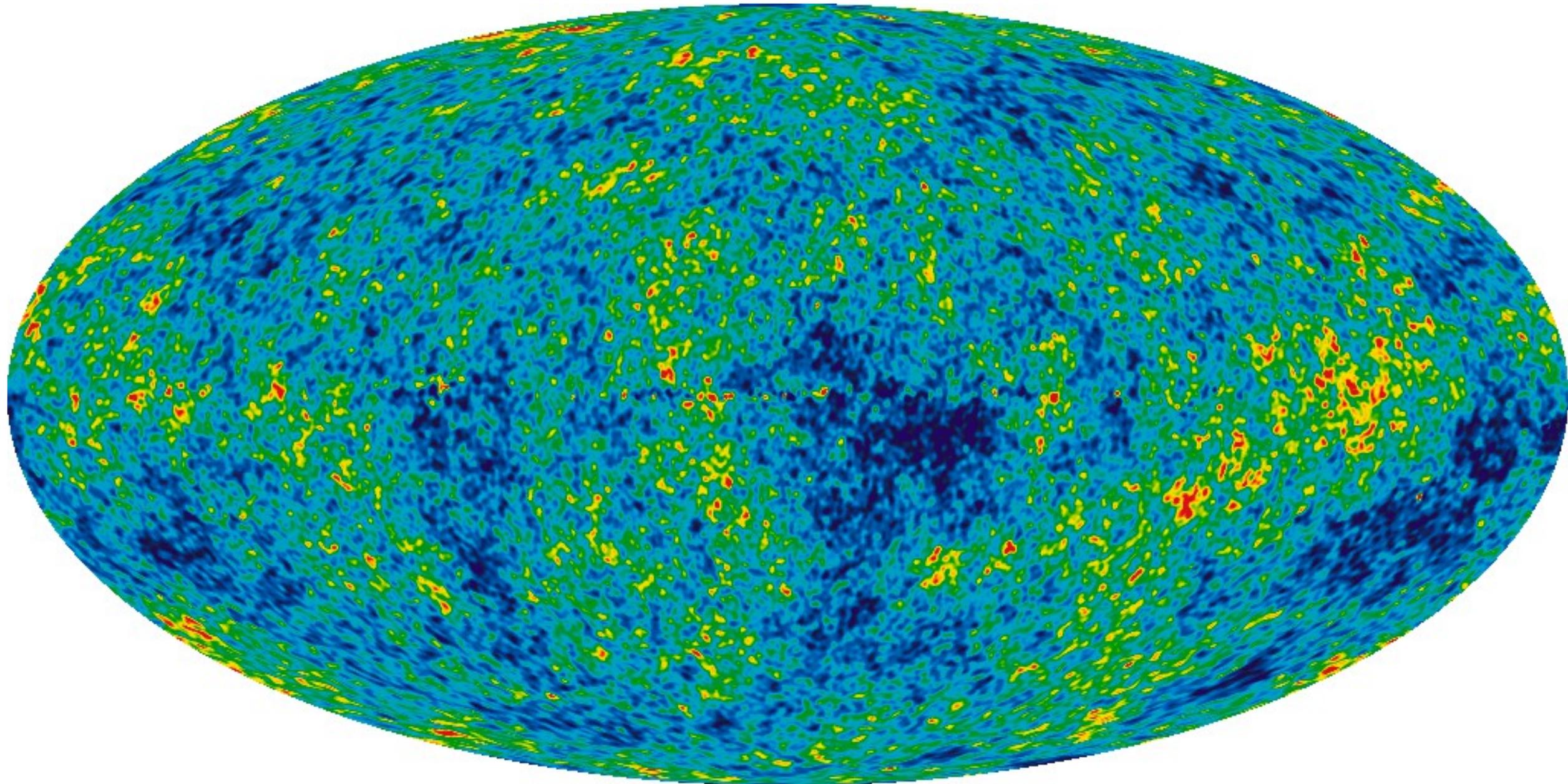
Think about riding your bike around a roundabout – the faster you go, the more grip (force) you need to keep you from being thrown out of the roundabout at a tangent.
- If the stars are going that speed and not being hurled out of rotation, there is some extra force keeping them in there
- Much more mass from non-luminous matter than luminous material is indicated by the observations



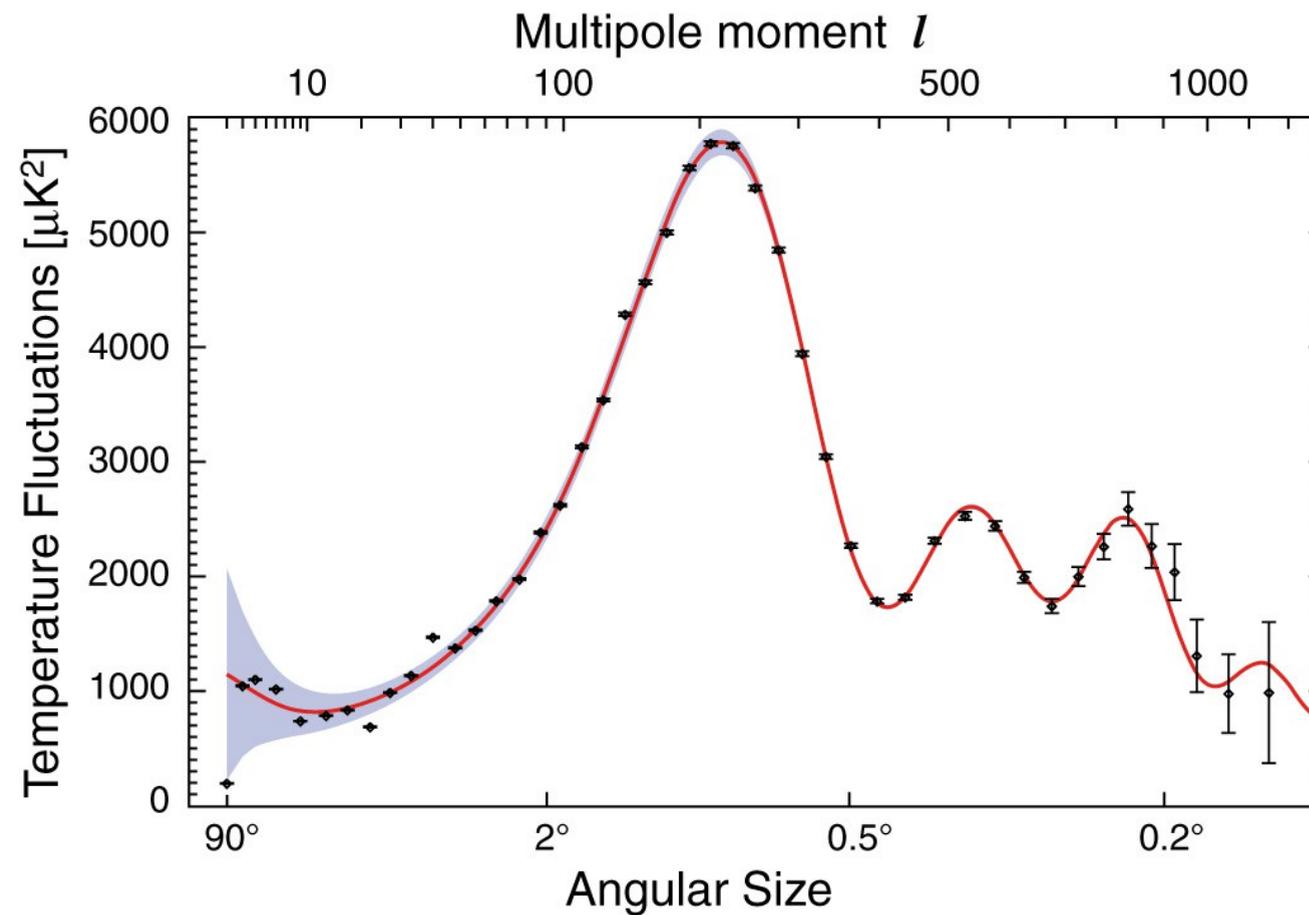
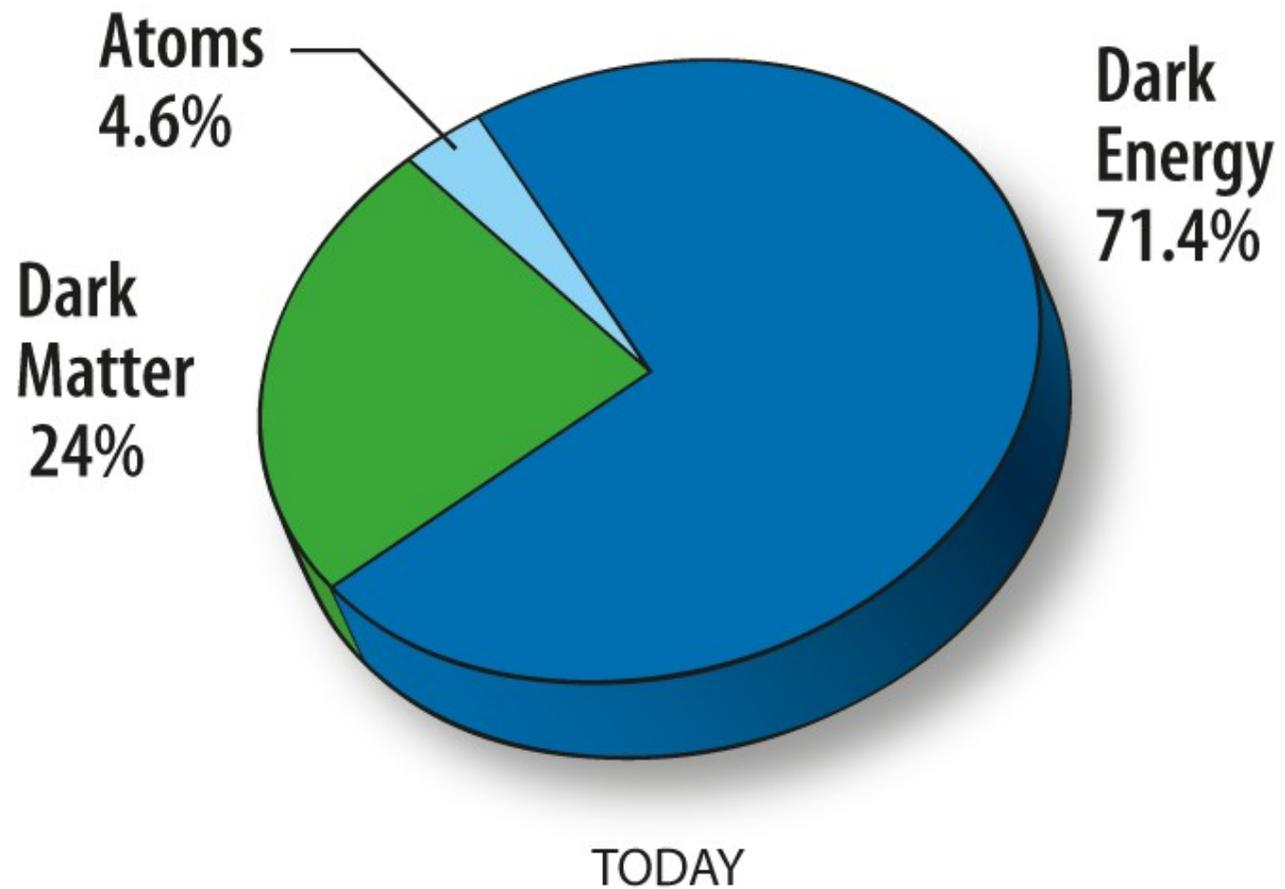
# Galaxy Cluster lensing



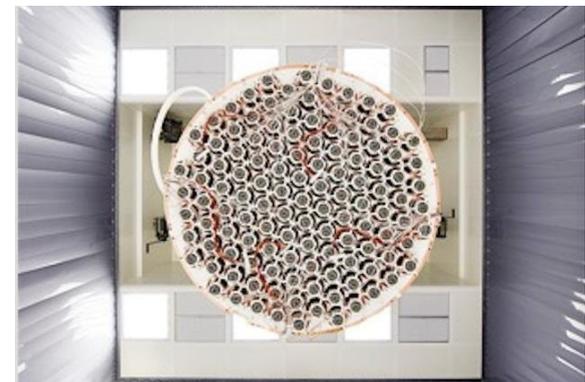
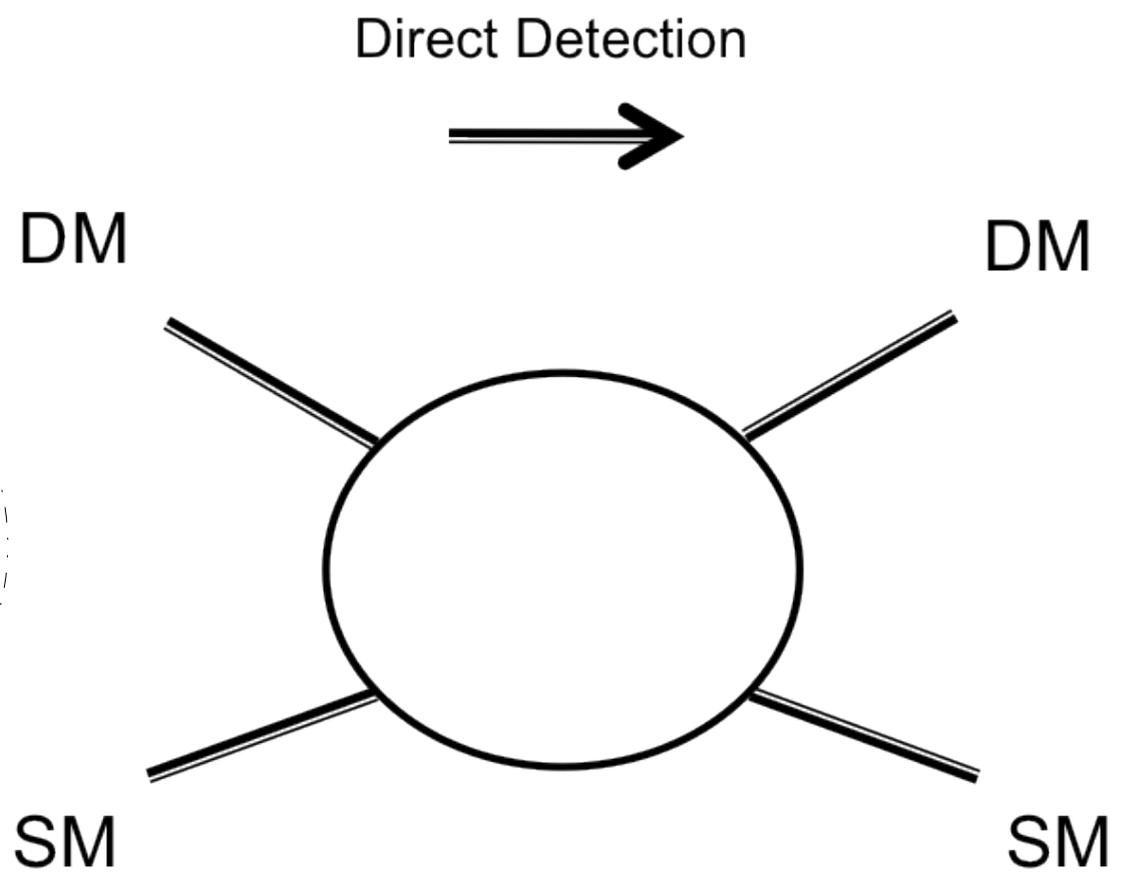
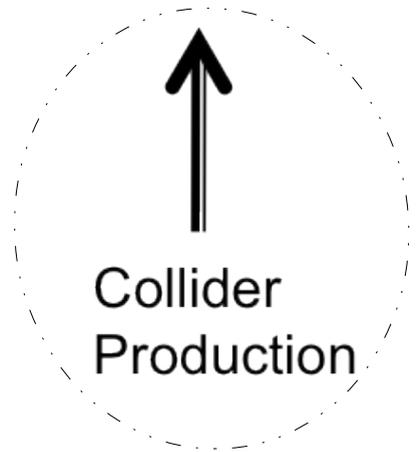
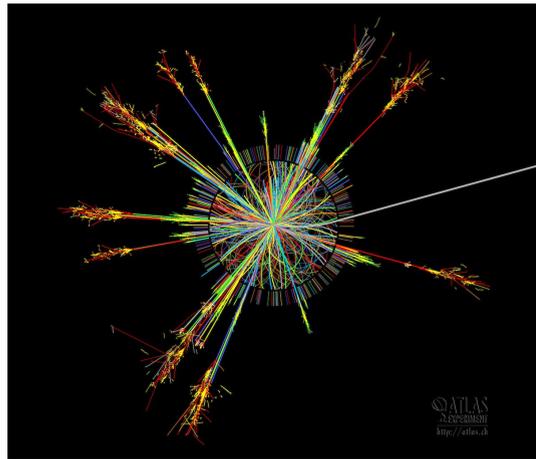
# Large scale structure and the CMB



# What does it all add up to?



# Detecting Dark Matter



Dark Matter Annihilation

