

ASKING THE BIG QUESTIONS: A JOURNEY INTO PARTICLE PHYSICS

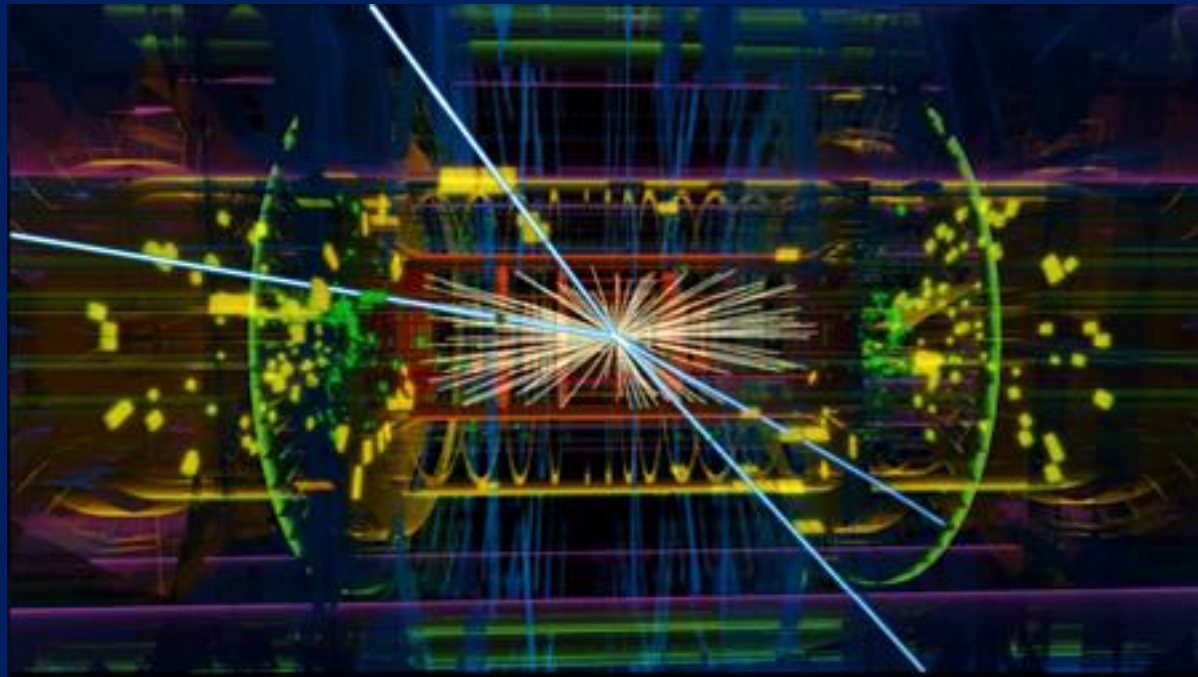
Kate Shaw

**The Abdus Salam International Centre for Theoretical Physics
ATLAS Collaboration**

7th August 2017



ERN International Teacher Weeks Programme 2017





UK Map - ©2006 Destination360







A night sky filled with stars, with a mountain range and a tent visible in the foreground. The text is overlaid on the sky.

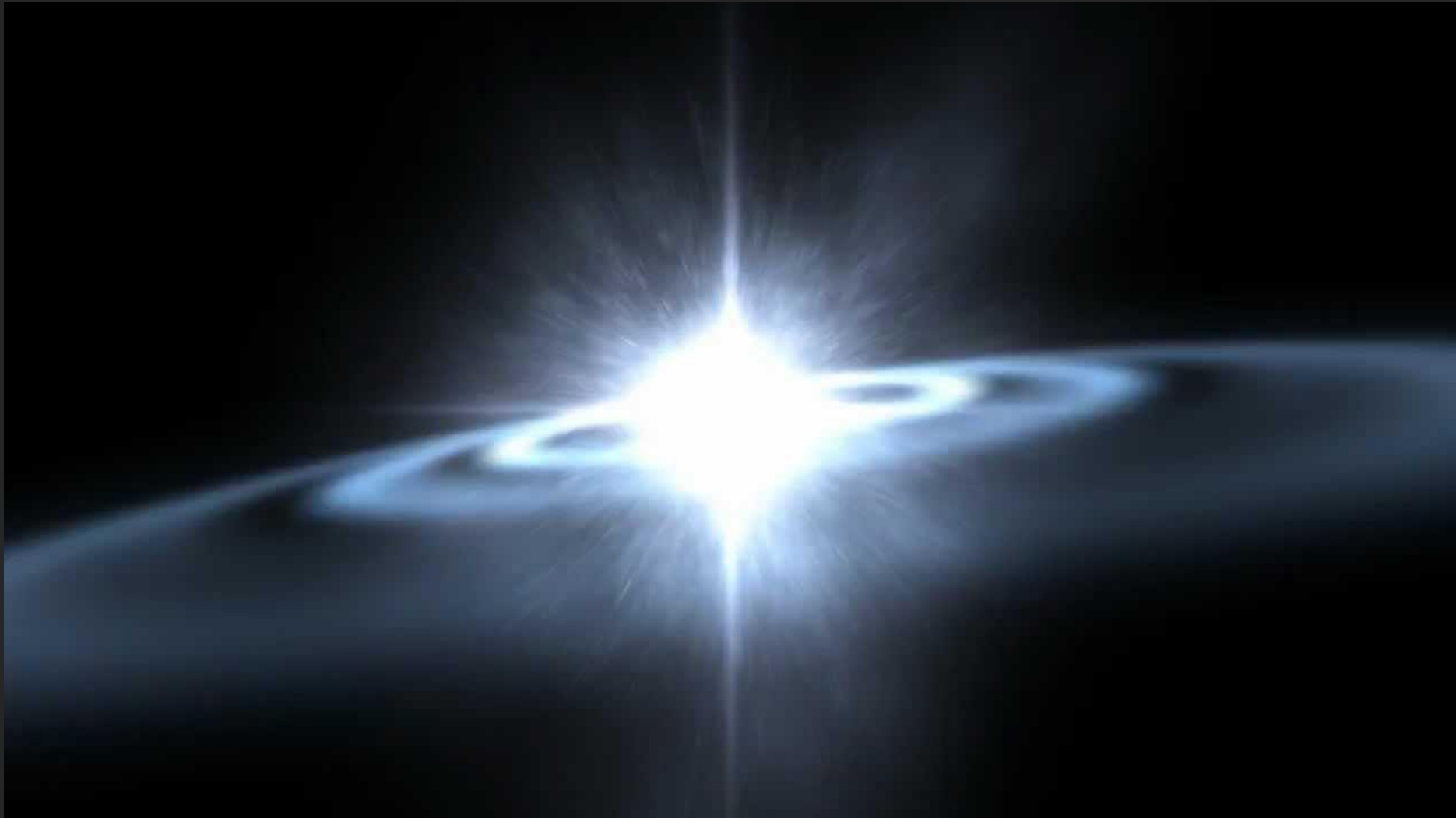
The observable Universe has around **350 billion large galaxies**

It is **90 billion light years across**

Particle Physicists aim to understand what the universe is made out of, how everything interacts and where everything came from!

Physicists are ambitious!

WHERE DID EVERYTHING COME FROM ?



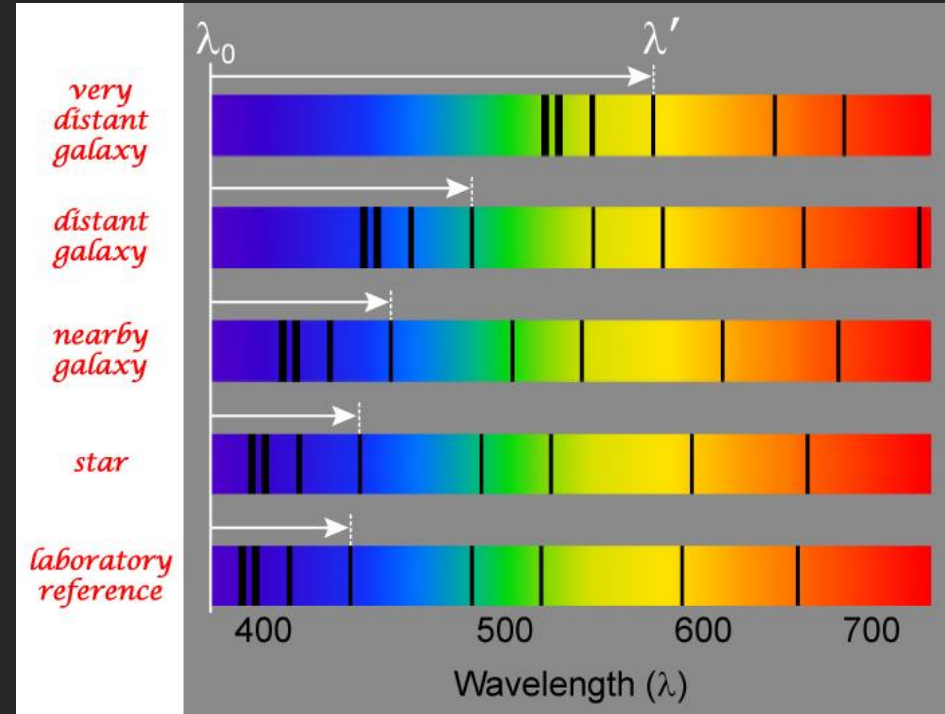
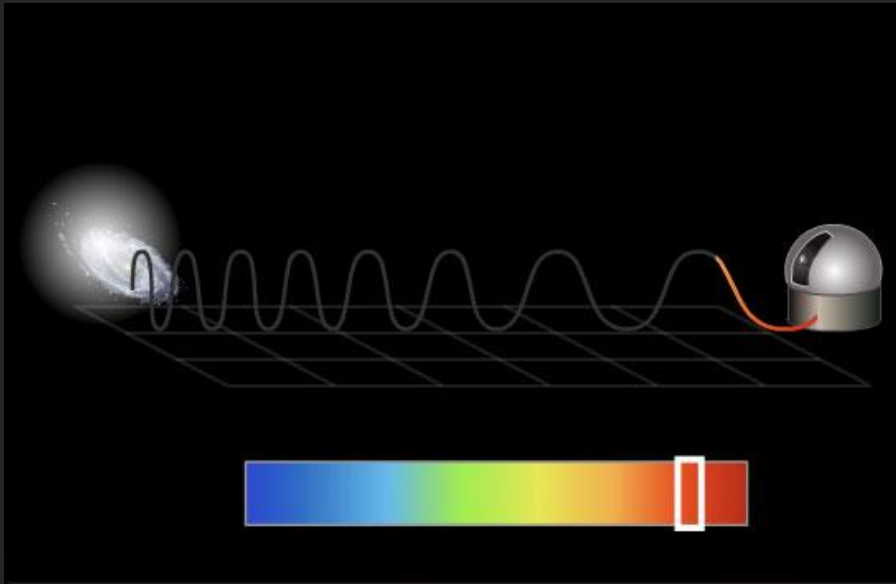
BIG BANG 13.8 Billion years ago

WHERE DID EVERYTHING COME FROM ?



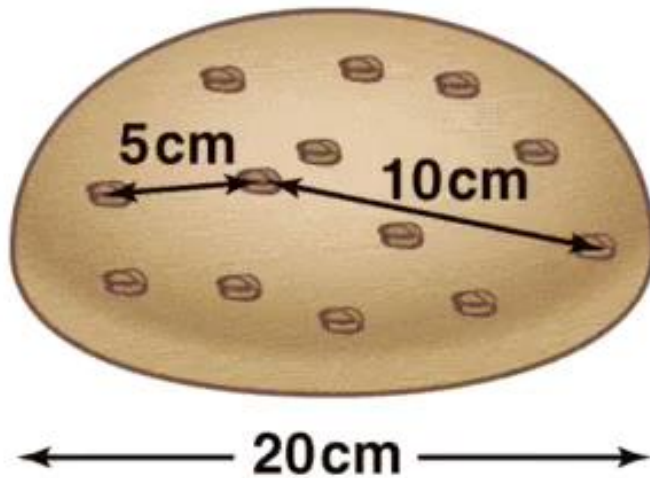
Edwin Hubble, American Astronomer, first to prove there are galaxies outside of the Milky Way (1924)

WHERE DID EVERYTHING COME FROM ?



Hubble showed that the further away a galaxy is from us (or any point in space), the **faster it appears to move** (1929)

WHERE DID EVERYTHING COME FROM ?

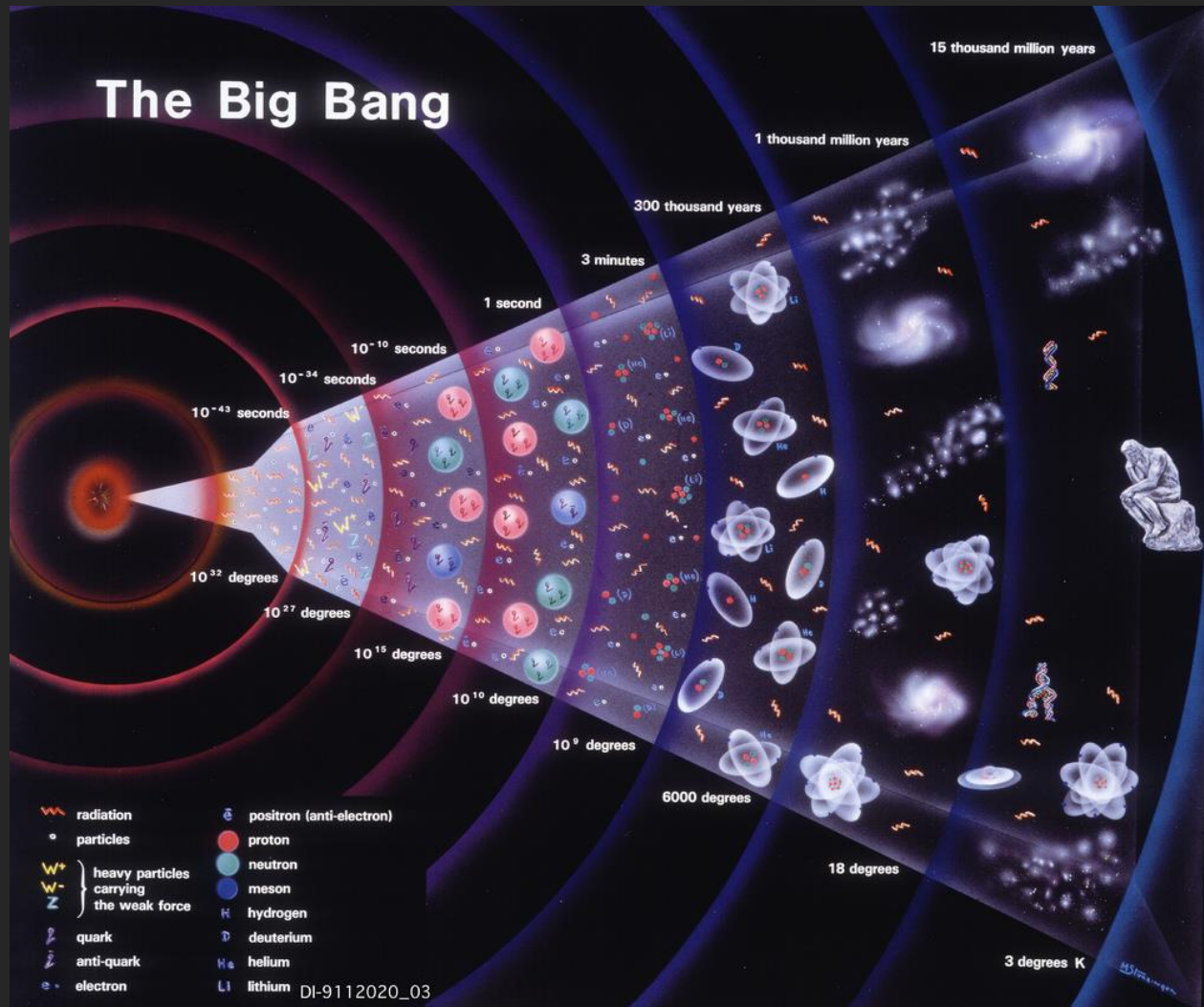


MAP990404

Space is stretching at a constant rate!

Hubble constant: 42 miles/second/3 million light year steps

WHERE DID EVERYTHING COME FROM ?



BIG BANG 13.8 Billion years ago

WHAT IS EVERYTHING MADE OF?



Democritus , Ancient Greek philosopher, ~5 BC

“The universe is composed of two elements: the atoms and the void in which they exist and move.”

‘All matter consists of **invisible particles** called ‘atoms’

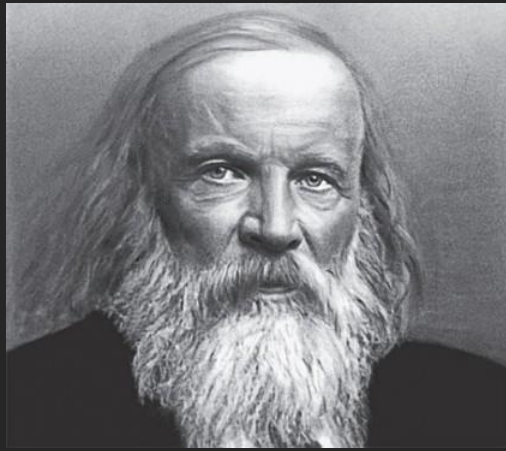
The word *atom* comes from *atomos*, an ancient Greek word meaning *indivisible*



Leucippus , Ancient Greek philosopher, ~5 BC

‘Atoms are **indestructible**, solid but invisible, homogenous, and differ in size, shape, mass, position and arrangement’

WHAT IS EVERYTHING MADE OF?



In 1869 Russian chemist **Dimitri Mendeleev** published the **periodic table**, arranging chemical elements by atomic mass.

~ **80 elements** – WHY SO MANY?
Is there a simpler structure?

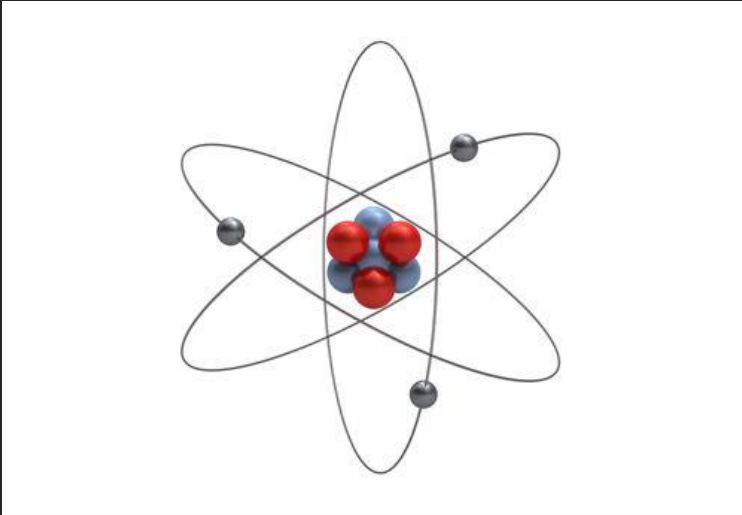
Естественная система элементовъ Д. Менделѣева.

Группа I.	Группа II.	Группа III.	Группа IV.	Группа V.	Группа VI.	Группа VII.	Группа VIII. (переходъ къ I)	Группа IX.		
R'O	R'O или RO	R'O ³	R'O ⁴ или RO ²	R'O ⁵	R'O ⁶ или RO ³	R'O ⁷	R'O ⁸ или RO ⁴	H=1 HX		
Типичес. H=1 H ² O, NH ₃ , HCl, H ² N, H ² C, ROH.	Be=9,4 BeCl ₂ , BeO, Be ² Al ³ Si ⁴ O ¹¹	B=11 BCl ₃ , B ² O ₃ , B ² N ₃ , H ² Na ⁺ O ⁻ , BF ₃	C=12 CH ₄ , C ₂ H ₂ , C ⁺ , C ⁻ , CO, CO ₂ , CO ⁺ , CO ⁻	N=14 NH ₃ , N ₂ O, N ² O ₄ , NO, NO ⁺ , M, MN ₂	O=16 OH, H ₂ O, C, O ⁺ , O ⁻ , OM ⁺ , O ⁻ , R, HOK	F=19 FH, BF ₃ , SF ₆ , CaF ₂ , K ₂ HF ₂	Cl=35,5 CH ₃ , ClM, ClCl, ClOH, ClO ⁺ , H, AgCl			
Рядъ 1. Li=7 LiCl, LiOH, Li ² O, LiX, Li ² CO ₃	Na=23 NaCl, NaOH, Na ² O, Na ² SO ₄ , Na ² CO ₃	Mg=24 MgCl ₂ , MgO, MgCO ₃ , MgSO ₄ , Mg ² NH ⁺ PO ₄	Al=27,3 Al ³ Cl ₃ , Al ³ PO ₄ , KAlS ² O ₇ , Al ³ H ⁺ O ⁻	Si=28 SiH ₄ , SiCl ₄ , SiH ₃ F, KAlS ² O ₇ , SiO ₂	P=31 PH ₃ , PCl ₃ , P ⁺ O ⁺ P ⁺ O ⁺ , Ca ⁺ P ⁺ O ⁺	S=32 SH ₂ , S ⁺ M ⁺ , SO ₂ , S ⁺ X, Ba ⁺ SO ₄	Br=80 BrH, BrM, Br ⁺ O ⁻ , BrAg ₂			
Рядъ 2. K=39 KCl, KOH, K ² O, KNO ₃ , K ² PtCl ₆ , K ² SF ₆	Ca=40 CaSO ₄ , CaOnSiO ₄ , CaCl ₂ , CaO, CaCO ₃	Zn=65 ZnCl ₂ , ZnO, ZnCO ₃ , ZnSO ₄ , ZnEt ₂	Ti=48(50?) TiCl ₃ , TiO ₂ , Ti ⁺ O ₂ , FeTiO ₃ , TiOSO ₄	V=51 VOCl ₃ , V ⁺ O ⁺ , VO ₂ , Cr ⁺ O ⁺ K ⁺ Cr ⁺ O ⁺ , Cr ⁺ O ⁺ Cl	Cr=52 CrCl ₃ , CrCl ₂ , Cr ⁺ O ⁺ , Cr ⁺ O ⁺ K ⁺ Cr ⁺ O ⁺ , Cr ⁺ O ⁺ Cl	Mn=55 FeK ⁺ O ⁺ , FeS ₂ , FeO ₂ , Fe ⁺ O ⁺ , FeK ⁺ Cy ⁺	Co=59 CoX ⁺ CoX ⁺ , CoX ⁺ 2N ⁺ H ⁺ , CoK ⁺ Cy ⁺	Ni=59 NiX ⁺ NiO ⁺ , NiSO ⁺ 4H ⁺ O ⁺ , NiK ⁺ Cy ⁺	Cu=63 CuX, CuX ₂ , CuH, Cu ⁺ O, CuO, CuKCy ⁺	
Рядъ 3. Cu=63 CuX, CuX ⁺	Sr=87 SrCl ₂ , SrO, SrH ⁺ O ⁺ , SrSO ₄ , SrCO ₃	In=113 InCl ₃ , In ⁺ O ⁺	Zr=90 ZrCl ₃ , ZrO ₂ , ZrX ⁺	Nb=94 NbCl ₃ , Nb ⁺ O ⁺ , Nb ⁺ O ⁺ 2H ⁺ O ⁺ , NbK ⁺ F ⁺	Mo=96 MoCl ₃ , MoS ₂ , MoO ₂ , M ⁺ Mo ⁺ O ⁺ n ⁺ Mo ⁺ O ⁺	Br=80 BrH, BrM, Br ⁺ O ⁻ , BrAg ₂	Ru=104 RuO ₄ , RuCl ₃ , RuO ₂ , RuCl ₂ , RuK ⁺ Cy ⁺	Rh=104 RhCl ₃ , RhCl ₂ , Rh ⁺ O ⁺ RhX ⁺ , RhK ⁺ Cy ⁺	Pd=106 PdH, PdO, PdCl ₂ , PdCl, PdK ⁺ Cy ⁺	Ag=108 AgX, AgX ₂ , AgCl, Ag ⁺ O ⁺ , AgKCy ⁺
Рядъ 4. Rb=85 RbCl, RbOH, Rb ⁺ PtCl ₆	Cd=112 CdCl ₂ , CdO, CdS, CdSO ₄	Sn=118 SnCl ₃ , SnCl ₄ , SnO, SnX ⁺ SnNa ⁺ O ⁺	Sb=122 SbH ₃ , SbCl ₃ , Sb ⁺ O ₂ , Sb ⁺ O ₃ , Sb ⁺ S ₂ , SbOX	Te=125(?)128? TeH ₄ , TeCl ₄ , TeO ₂ , TeO ⁺ M ⁺ TeM ₂	I=127 IH, IAg, IHO, IHO ⁺ HgI ₂ KI					
Рядъ 5. Ag=108 AgX, AgCl ₂	Ba=137 BaCl ₂ , BaH ⁺ O ⁺ , BaO, BaSO ₄ , BaSiF ₆	Ce=140 CeCl ₃ , Ce ⁺ O ⁺ , CeO ₂ , CeX ⁺ CeX ⁺ CO ⁺ K ⁺ X ⁺	Ta=182 TaCl ₅ , Ta ⁺ O ₅ , TaK ⁺ F ⁺	W=184 WCl ₆ , WCl ₅ , WO ₂ , K ⁺ WO ⁺ n ⁺ WO ₂						
Рядъ 6. Cs=133 CsCl, CsOH, Cs ⁺ PtCl ₆	Pb=207 PbCl ₂ , PbO, PbO ₂ , Pb ⁺ SO ₄ , Pb ⁺ CO ₃ , Pb ⁺ Et ⁺ SO ₄ , Pb ⁺ Et ⁺ CO ₃	Bi=208 BiCl ₃ , Bi ⁺ O ⁺ , Bi ⁺ OH ₃ , BiX ⁺ BiOX, BiNO ⁺ (HO) ₂								
Рядъ 7. 153	168	160	162	164	166	168				
Рядъ 8. 175	177	217=Er ⁺ 7(109) ?E ⁺ O ⁺ ErX ⁺ ?	2180=Di ⁺ 7(La187) ?DiO ⁺ DiX ⁺ ?				199? Os=193 OsO ₄ , OsH ⁺ O ⁺ , OsCl ₃ , OsCl ⁺ , OsK ⁺ Cy ⁺	198? Ir=195 IrCl ₃ , IrCl ⁺ , IrCl ₂ , Ir ⁺ O ⁺ , IrK ⁺ Cy ⁺	197 Pt=197 PtCl ₂ , PtCl ⁺ X ⁺ , PtK ⁺ Cy ⁺	198 Au=197 AuCl ₃ , AuCl, Au ⁺ O ⁺ Au ⁺ O ⁺ , AuKCy ⁺
Рядъ 9. Au=197 AuX, AuX ⁺	Hg=200 HgCl ₂ , HgCl ⁺ Hg ⁺ O ⁺ , Hg ⁺ O ₂ , HgX ⁺ nHg ⁺ O ⁺	Tl=204 TlCl ₃ , Tl ⁺ O ₂ , Tl ⁺ SO ₄ , Tl ⁺ SO ₃ , TlCl ⁺	Pb=207 PbCl ₂ , PbO, PbO ₂ , Pb ⁺ SO ₄ , Pb ⁺ CO ₃ , Pb ⁺ Et ⁺ SO ₄ , Pb ⁺ Et ⁺ CO ₃	Th=231 ThCl ₃ , ThO ₂ , ThX ⁺ ThSO ⁺	U=240 UCl ₃ , UO ⁺ UO ⁺ X ⁺ , UO ⁺ M ⁺ O ⁺					
Рядъ 10. 230	235	227	235	235	245	245	246	248	249	250

WHAT IS EVERYTHING MADE OF?

Particle Physics seeks to understand fundamental particle and forces

The atom



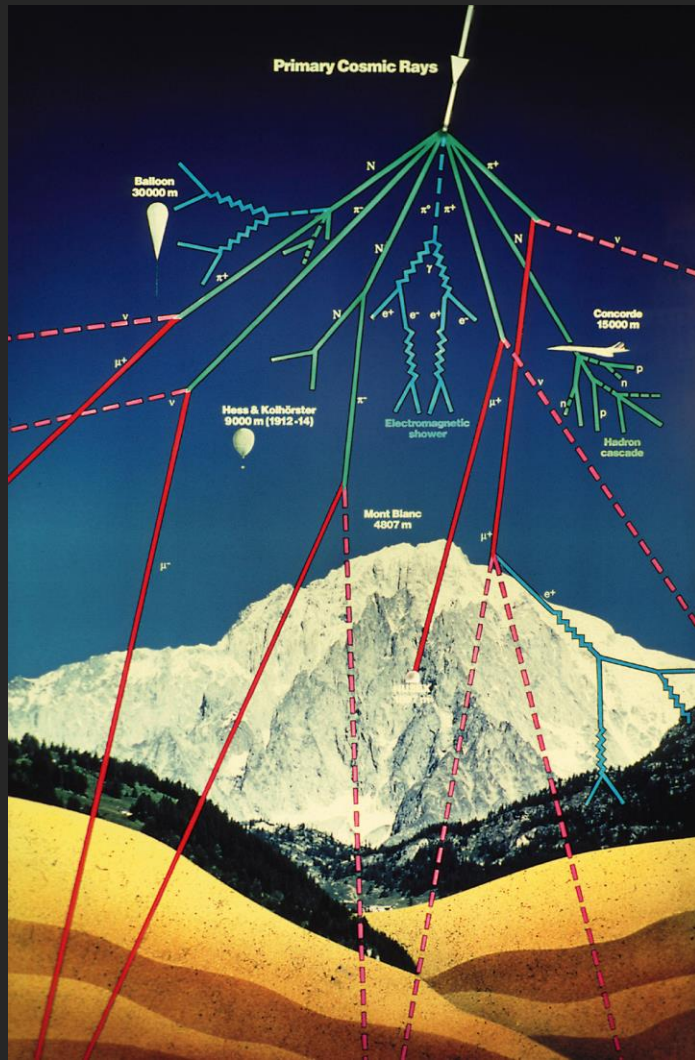
- 1897 electron discovered by J.J. Thompson
 - 1911 nucleus of the atom discovered by Ernest Rutherford, and nucleus of hydrogen a proton
 - 1932 neutron discovered by James Chadwick
- Photon – particle of the electromagnetic force suggested by Einstein in 1905

However other particles not part of the atom seemed to appear!

- 1932 positron detected (predicted by Dirac in 1928)
- 1934 neutrinos established in theory – detected in 1956

WHAT IS EVERYTHING MADE OF?

Cosmic rays



- 1937 muons were discovered in cosmic rays

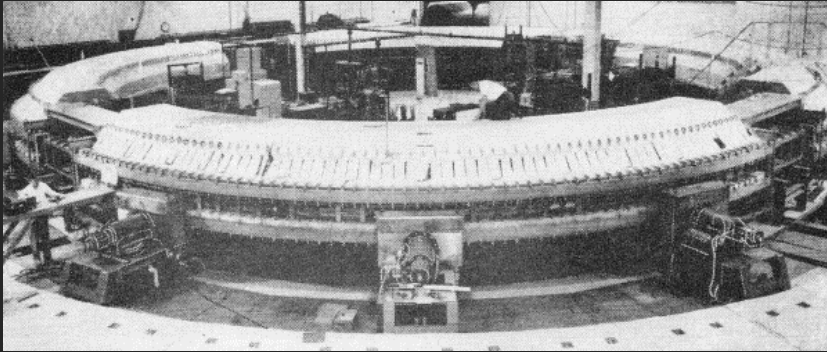
Who ordered that?

- 1947 pions (a type of meson) were also discovered!!

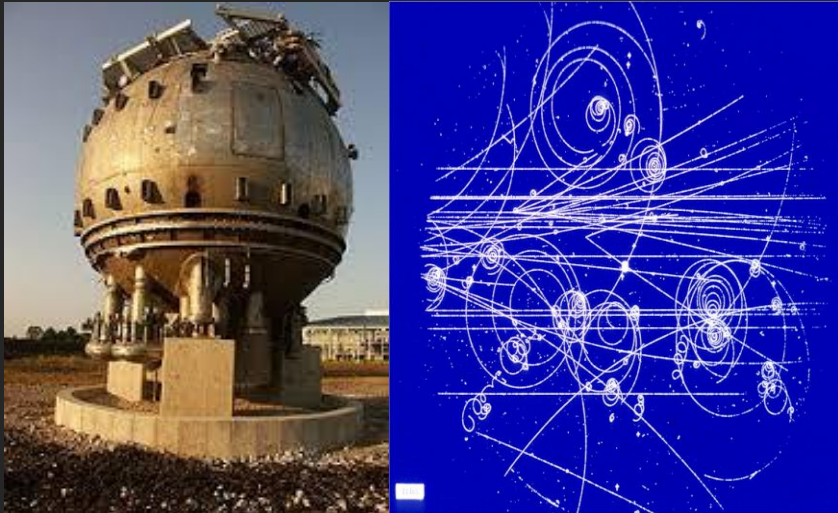
Things were getting out of hand! What were all these particles?

WHAT IS EVERYTHING MADE OF?

Atom smashers (1950s)



The Brookhaven Cosmotron, at 1.3 – 3.3 GeV accelerator



Plethora of NEW particles started coming out of these atom smashers!

Sigma particles, rho particles, Delta particles, kaons, Lambda...

Some of the Particles in the "Particle Zoo"

p^+ n^0 $\Sigma^- \Sigma^0 \Sigma^+ \Sigma^{++}$ $\Delta^- \Delta^0 \Delta^+ \Delta^{++}$
 Λ^0 $e^+ e^-$ $\pi^+ \pi^0 \pi^-$
 $\Xi^- \Xi^0 \Xi^+ \Xi^{++}$ $\Omega^- \Omega^0 \Omega^+$ $\tau^+ \tau^-$
 $\eta \eta'$ $\mu^+ \mu^-$ ω $\rho^+ \rho^0 \rho^-$
 $\nu_e \nu_\mu \nu_\tau$ ϕ γ $K^+ K^0 K^-$

WHAT IS EVERYTHING MADE OF?

Particle Zoo

HADRONS

Particle Zoo (1950s, 1960s)

BARYONS		MESONS		LEPTONS		PHOTON	
Symbol	Charge	Symbol	Charge	Symbol	Charge	Symbol	Charge
p	+1	π^+	+1	e^-	-1	γ	0
\bar{p}	-1	π^-	-1	e^+	+1		
n	0	π^0	0	ν_e	0		
Δ	0	K^+	+1	$\bar{\nu}_e$	0		
		K^-	-1				
		K^0	0				

Over 100 'elementary' particles

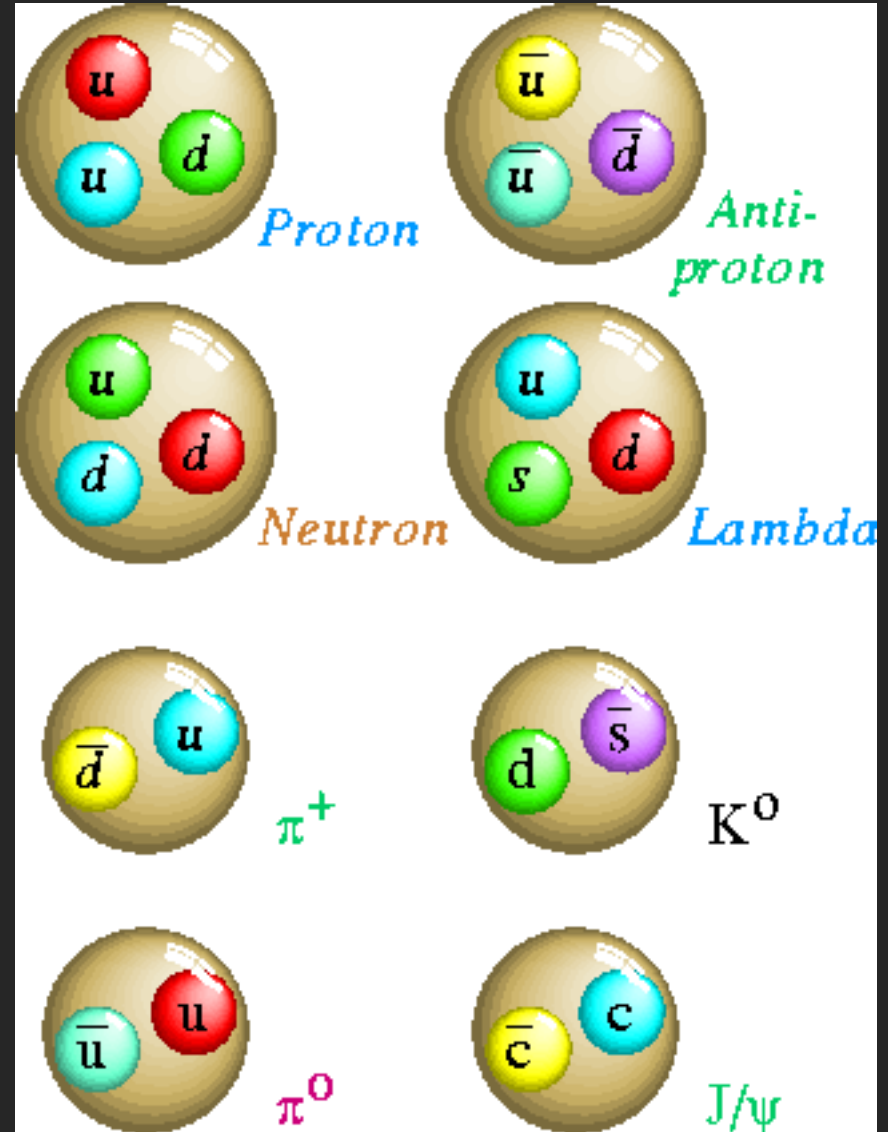
WHAT IS EVERYTHING MADE OF?

BREAK THROUGH

1960s Murray Gell-Mann of Caltech said hadrons are composed of more fundamental particles which he called quarks.

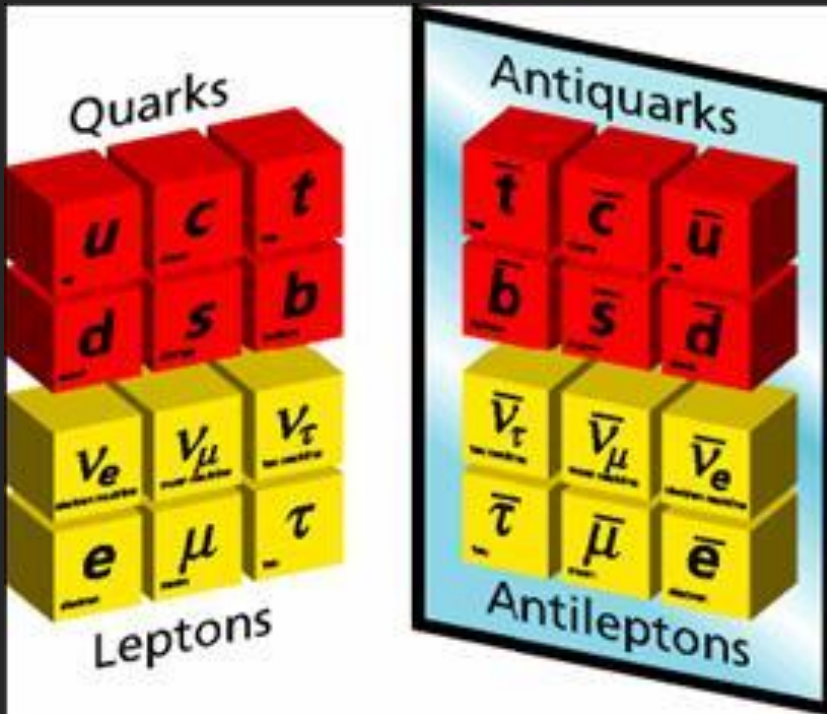


The word comes from a line in Finnegans Wake, a book written by James Joyce.

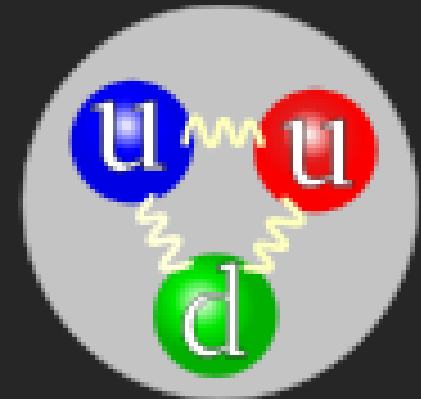


WHAT IS EVERYTHING MADE OF?

Fundamental matter particles



Quarks lived together in twos or threes, making up hadrons like the proton



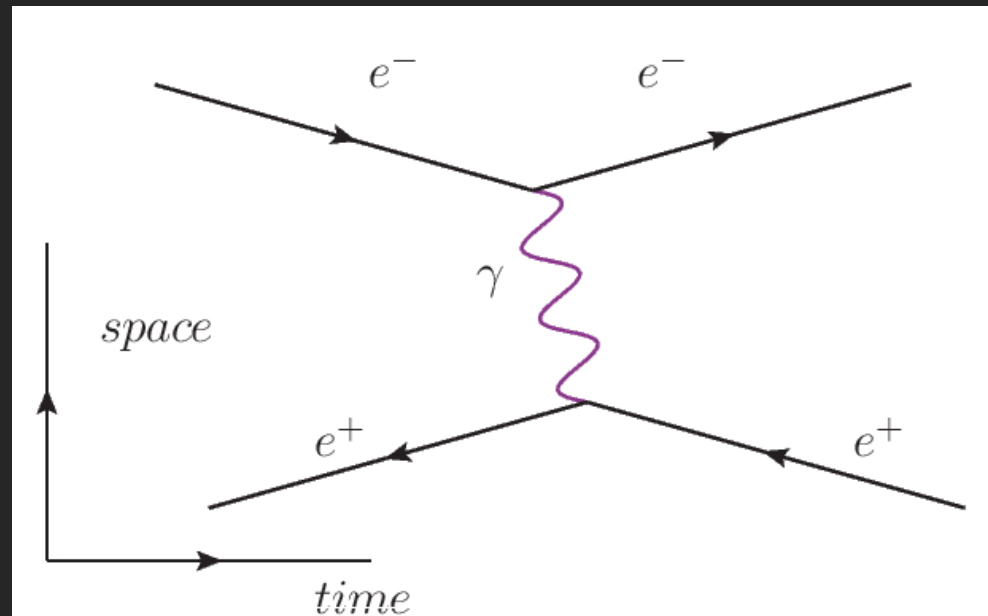
WHAT IS EVERYTHING MADE OF?

Fundamental forces described using relativistic quantum field theories

Electromagnetism: Quantum electrodynamics describes how light and matter interact

Extremely successful theory!

e.g. measurements of the fine structure constant show agreement to within ten parts in a billion (10^{-8})



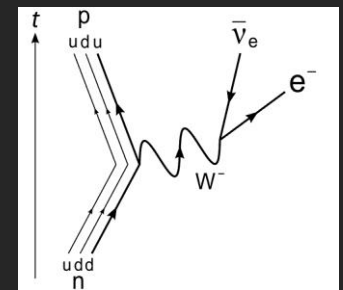
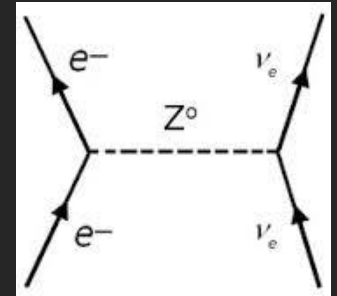
When electrically charged particles interact they exchange a photon

WHAT IS EVERYTHING MADE OF?

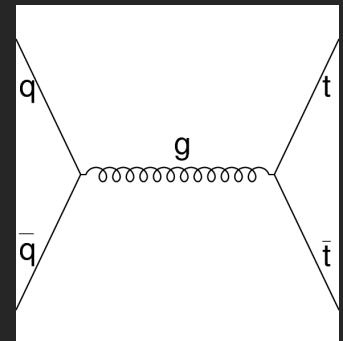
Fundamental forces described using relativistic quantum field theories

A unified theory with electromagnetism was obtained in 1968 – the electroweak theory

W and Z predicted and discovered at CERN 1983



Finally the Strong Force – a very much more complicated force – was described in Quantum Chromodynamics



WHAT IS EVERYTHING MADE OF?

The Standard Model

MATTER

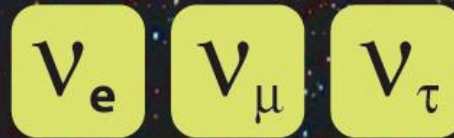
FORCE



Quarks



Gauge Bosons



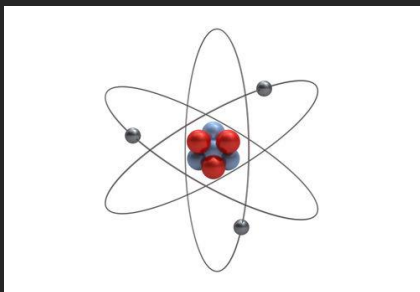
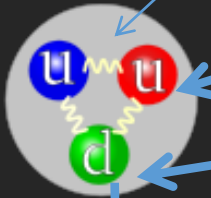
Higgs Boson?



Leptons

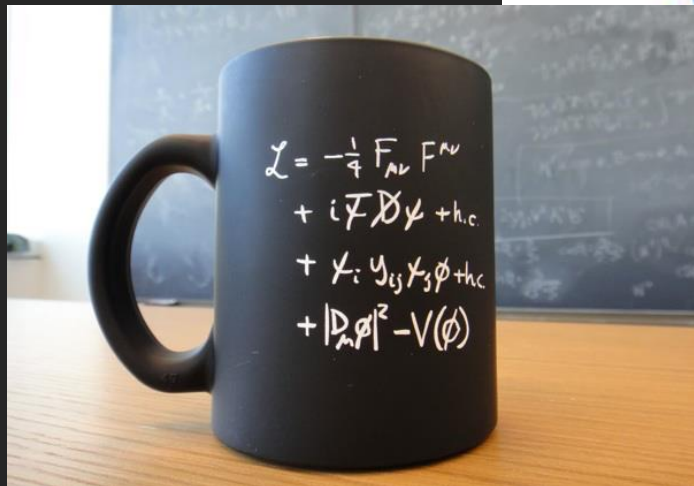
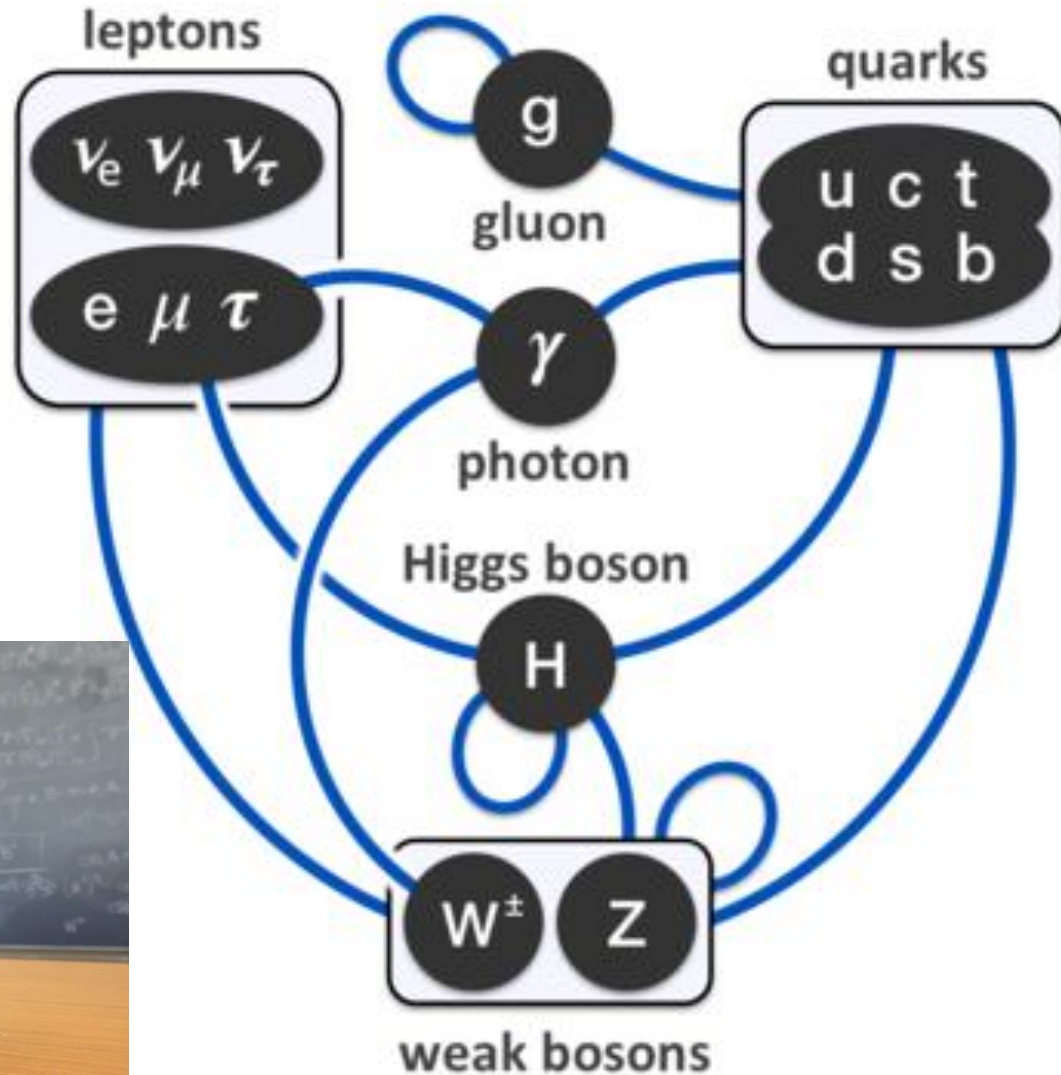
THE STANDARD MODEL OF
PARTICLES AND FORCES

IS THIS ALL THAT EXISTS?

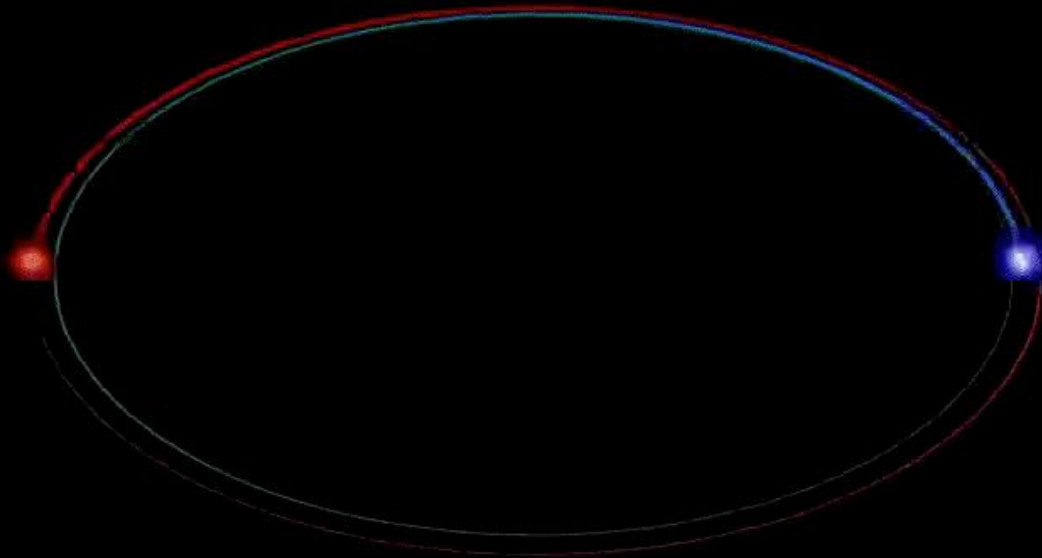


WHAT IS EVERYTHING MADE OF?

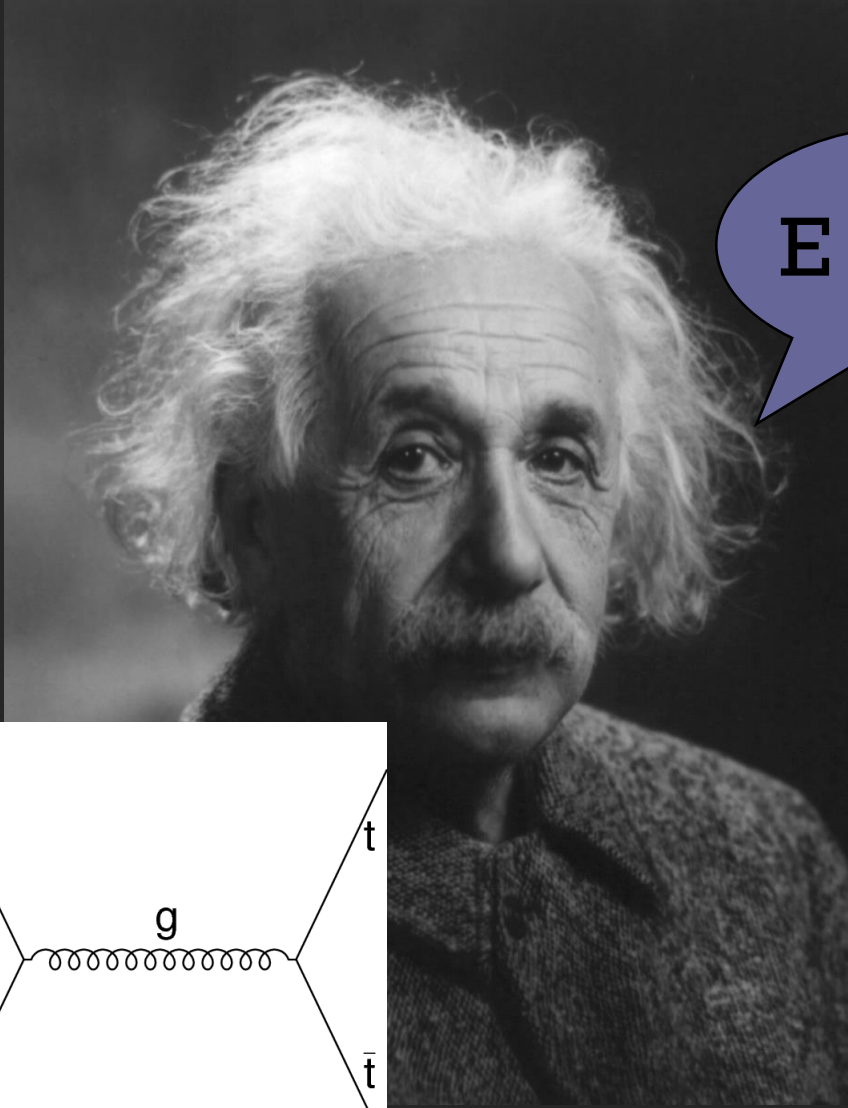
The Standard Model



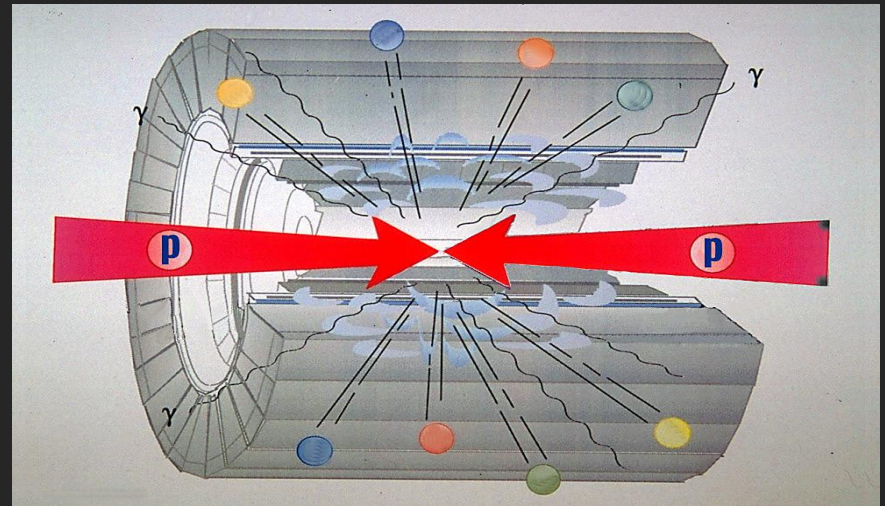
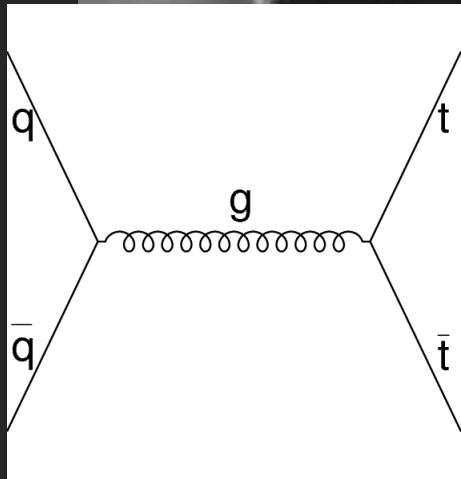
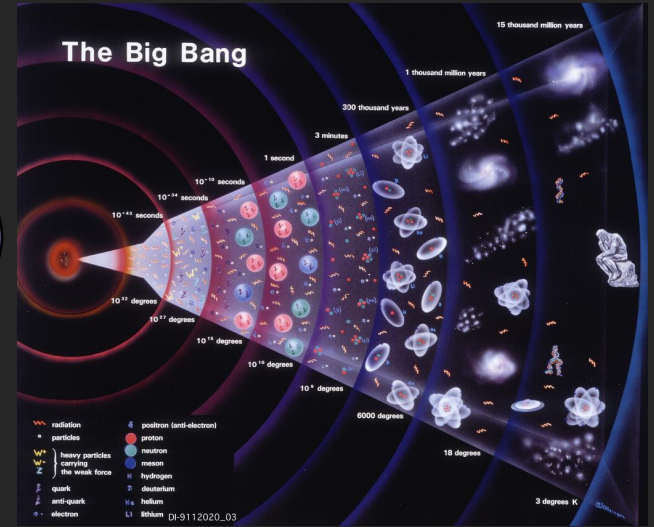
HOW DO WE STUDY PARTICLE PHYSICS?



HOW DO WE STUDY PARTICLE PHYSICS?



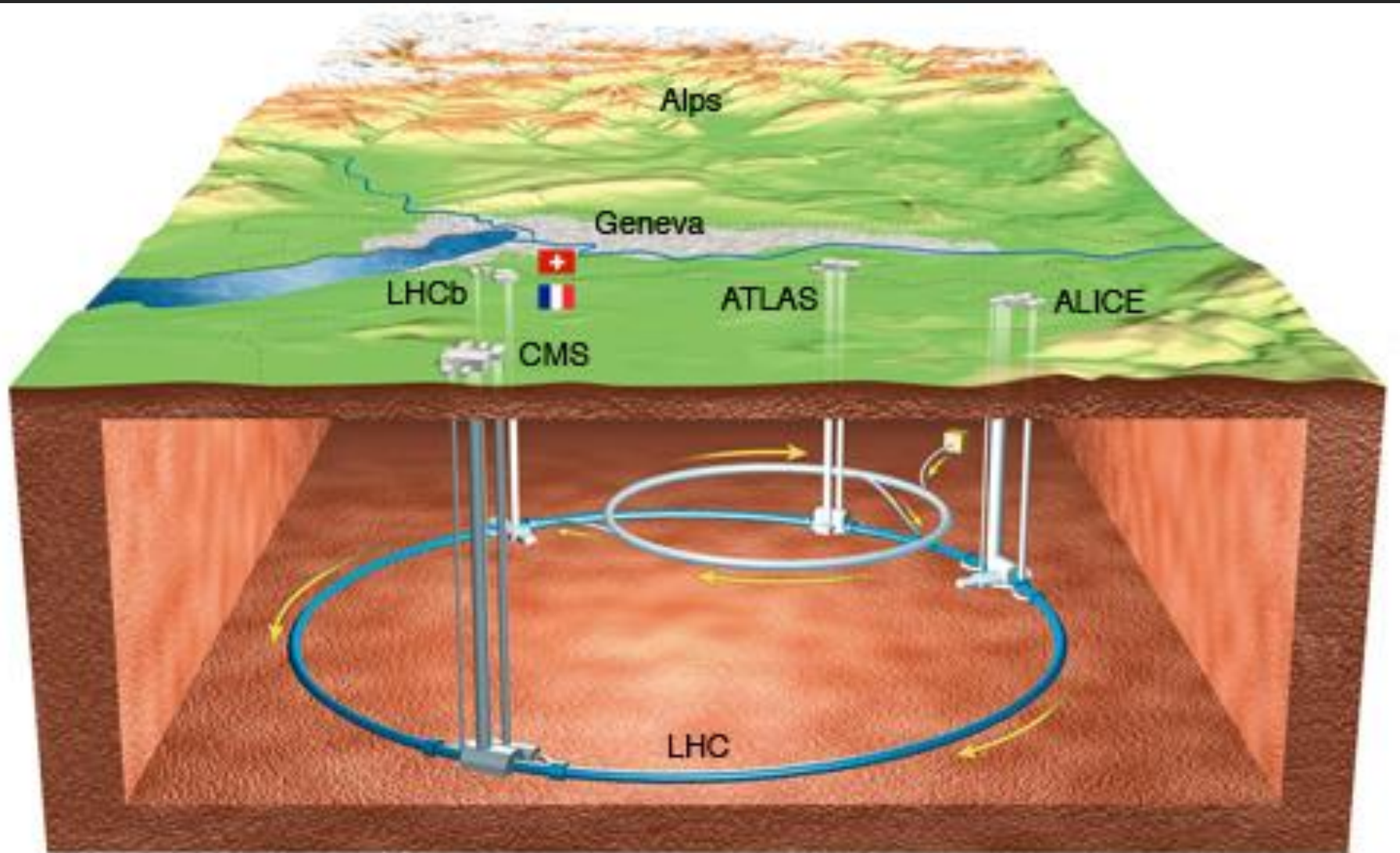
$E = mc^2$



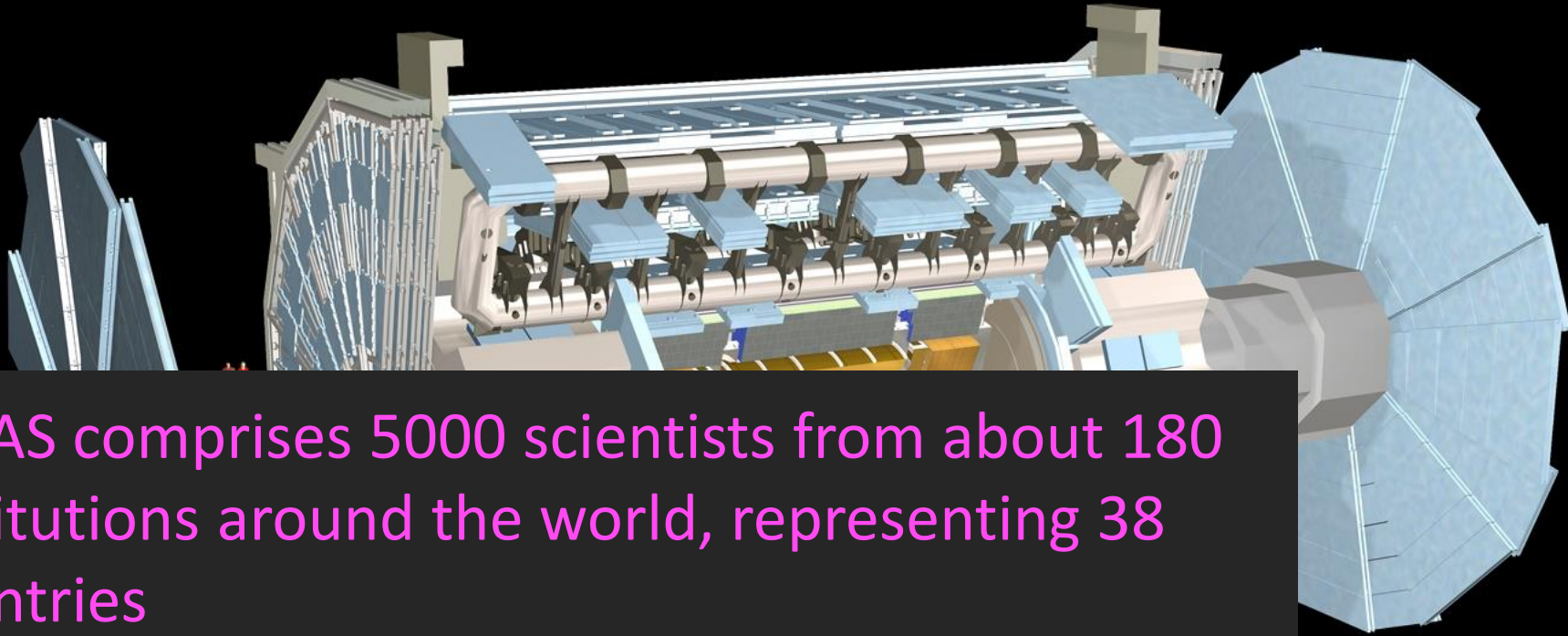
THE LARGE HADRON COLLIDER



THE LARGE HADRON COLLIDER



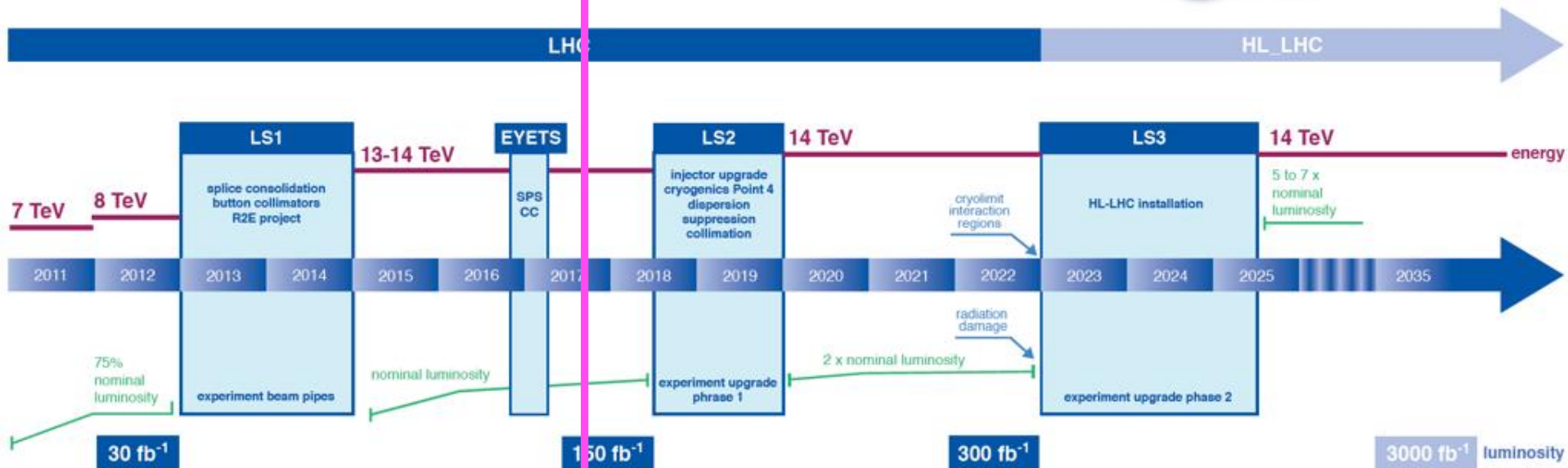
THE ATLAS EXPERIMENT



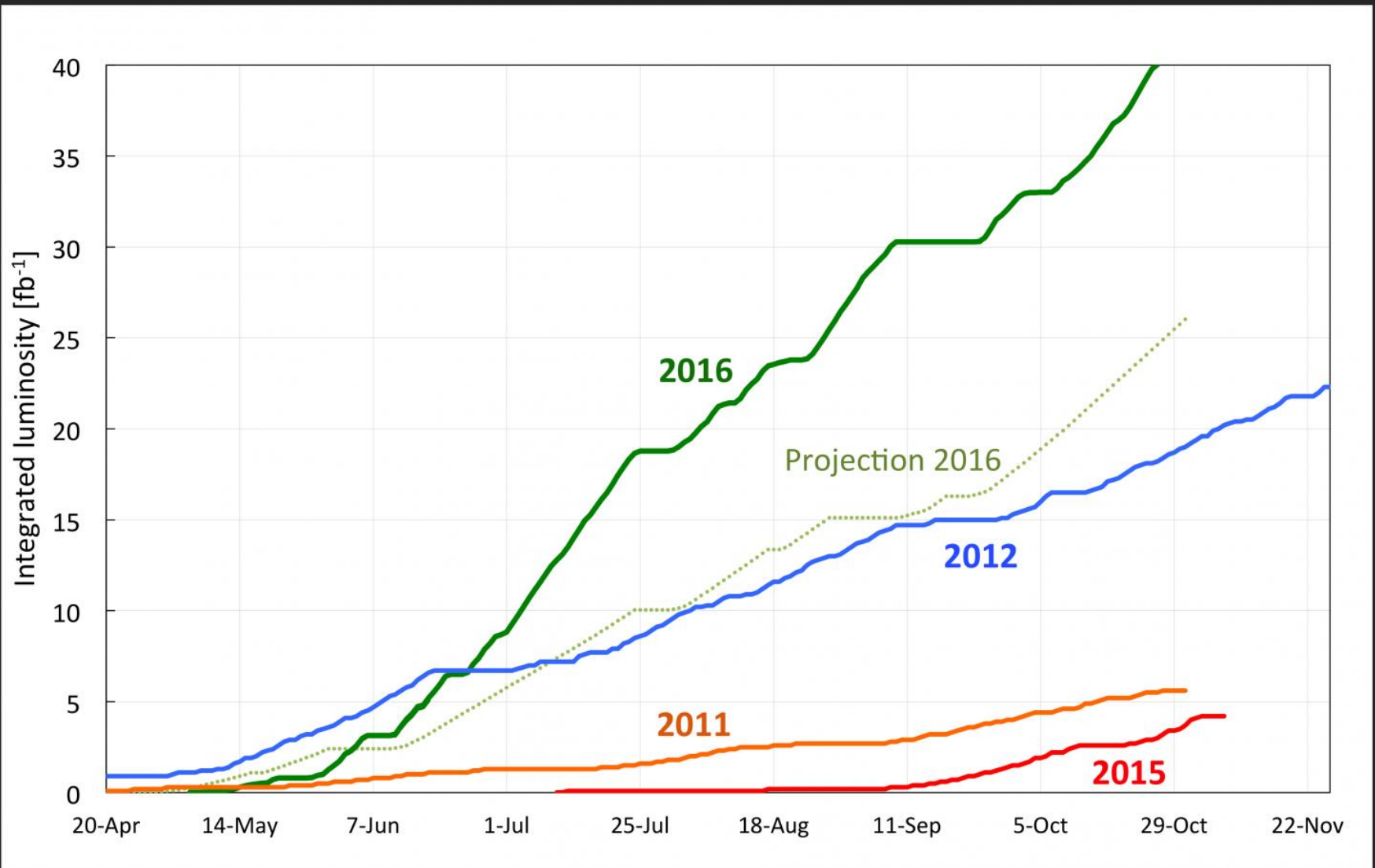
ATLAS comprises 5000 scientists from about 180 institutions around the world, representing 38 countries

THE LARGE HADRON COLLIDER

LHC / HL-LHC Plan

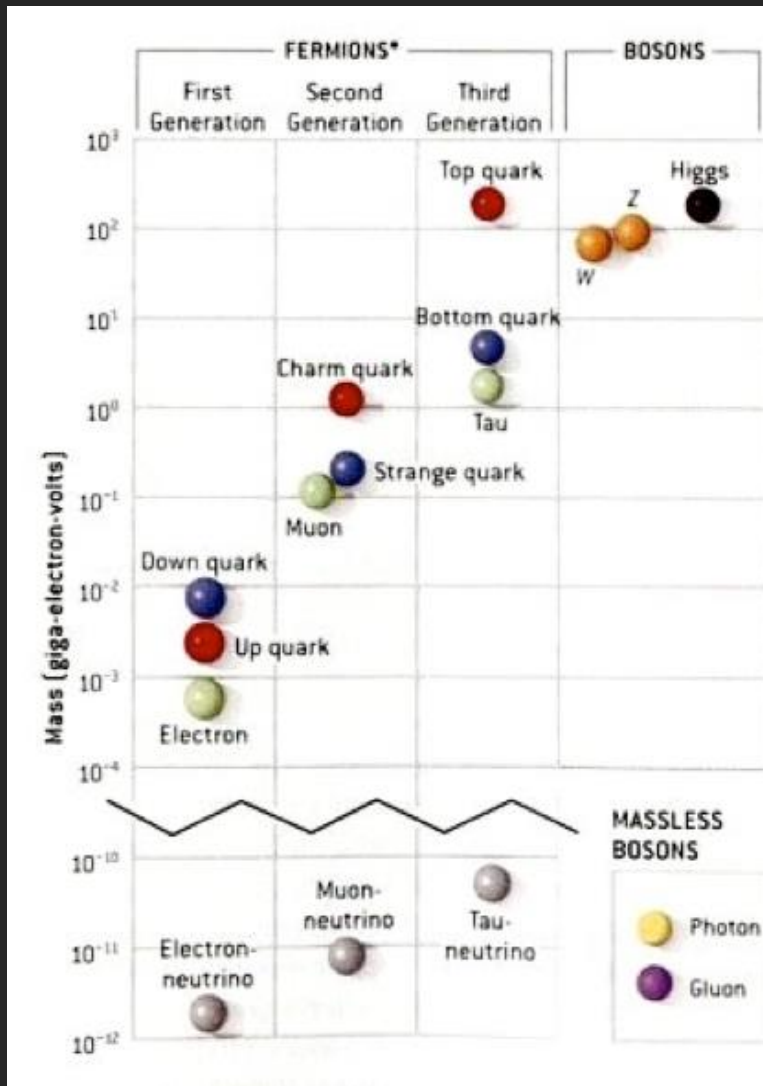


THE LARGE HADRON COLLIDER



THE ATLAS EXPERIMENT

How do we find new particles?



MATTER

u

c

t

d

s

b

Quarks

ν_e

ν_μ

ν_τ

e

μ

τ

Leptons

FORCE

γ

g

W

Z

Gauge Bosons

H

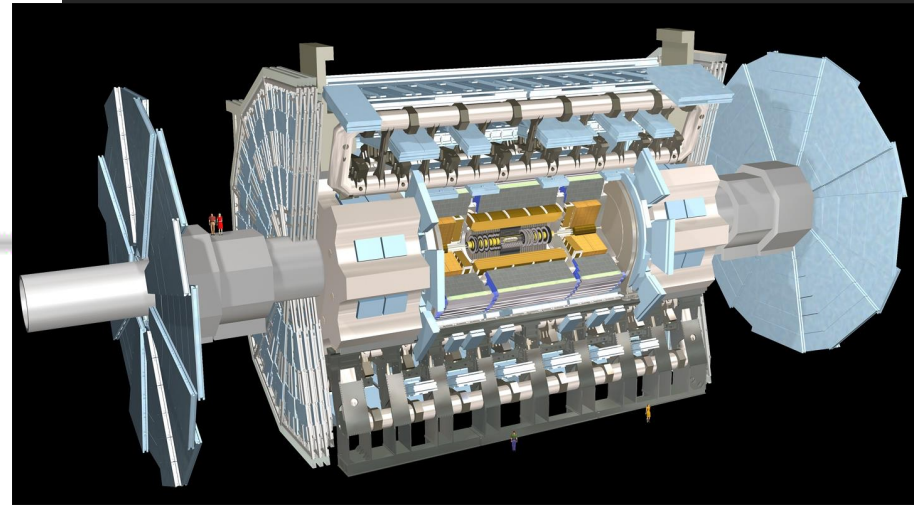
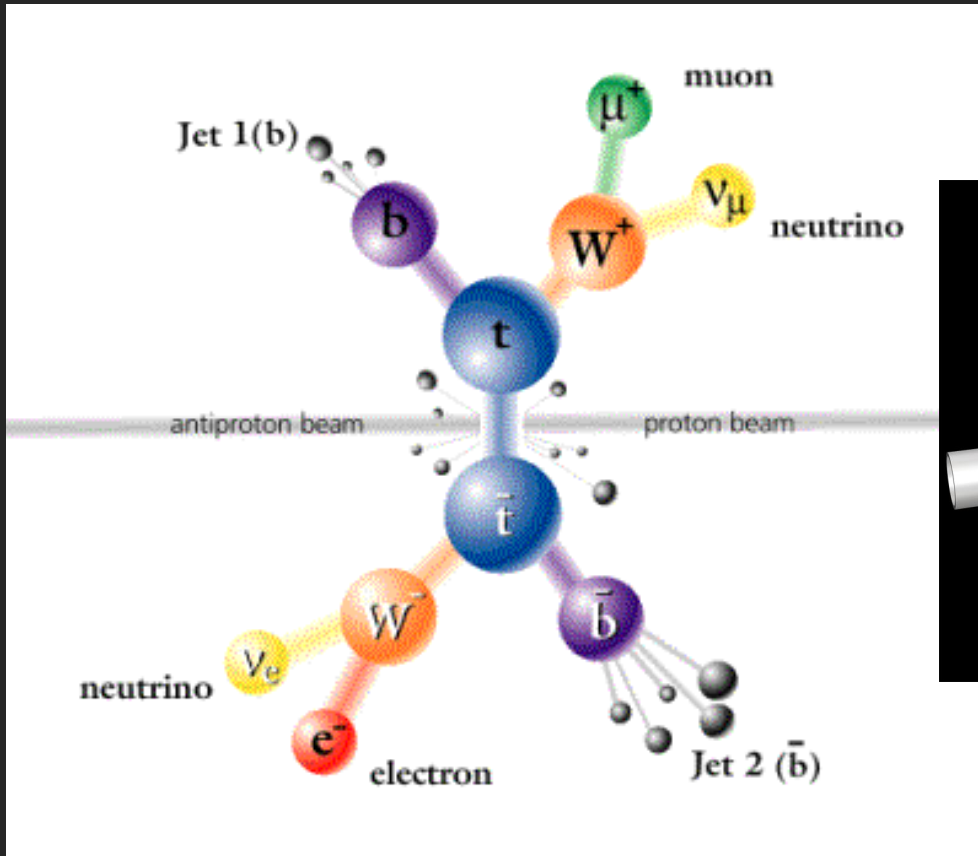
Higgs Boson?

THE STANDARD MODEL OF PARTICLES AND FORCES

IS THIS ALL THAT EXISTS?

THE ATLAS EXPERIMENT

How do we find particles?

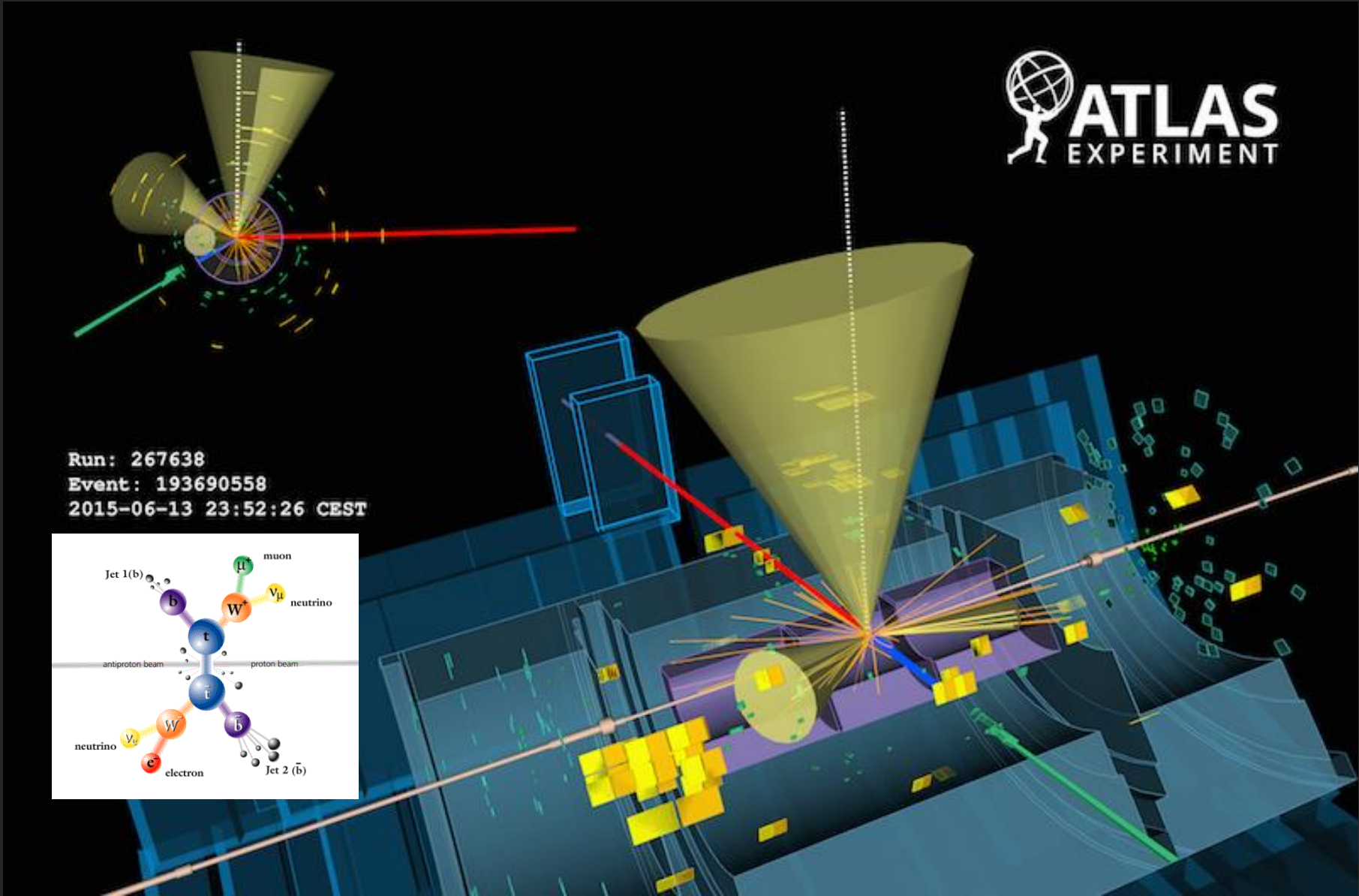
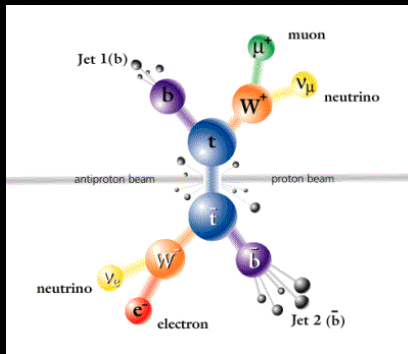


THE ATLAS EXPERIMENT

How do we find particles?

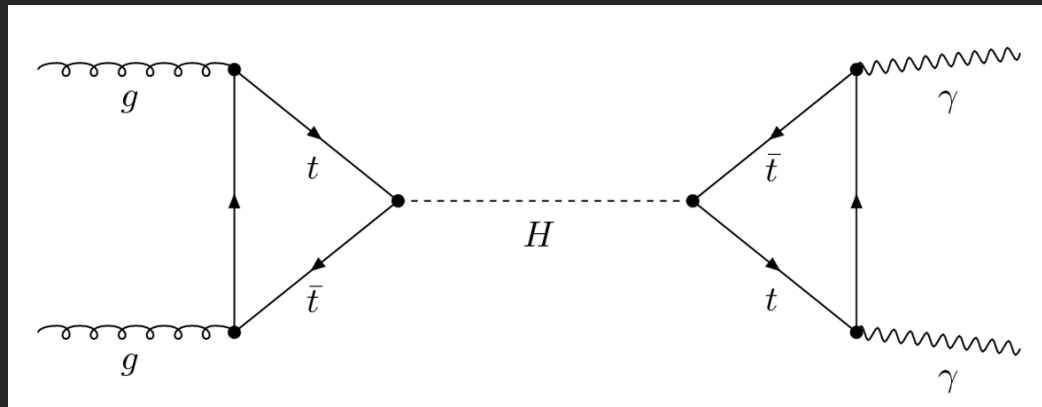


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THE ATLAS EXPERIMENT

How did we find the Higgs?

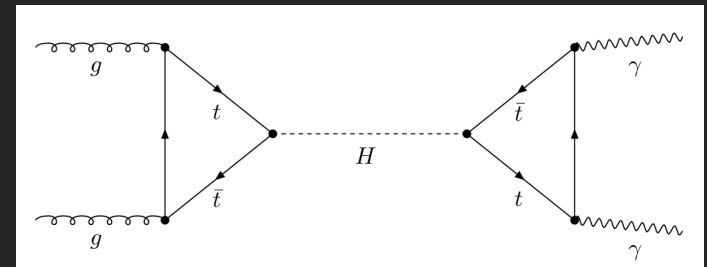
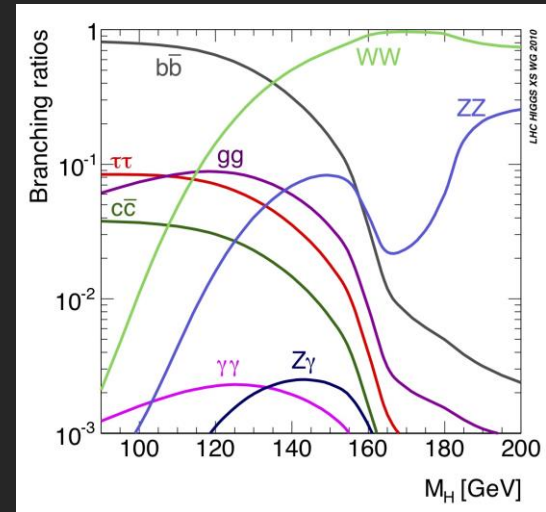
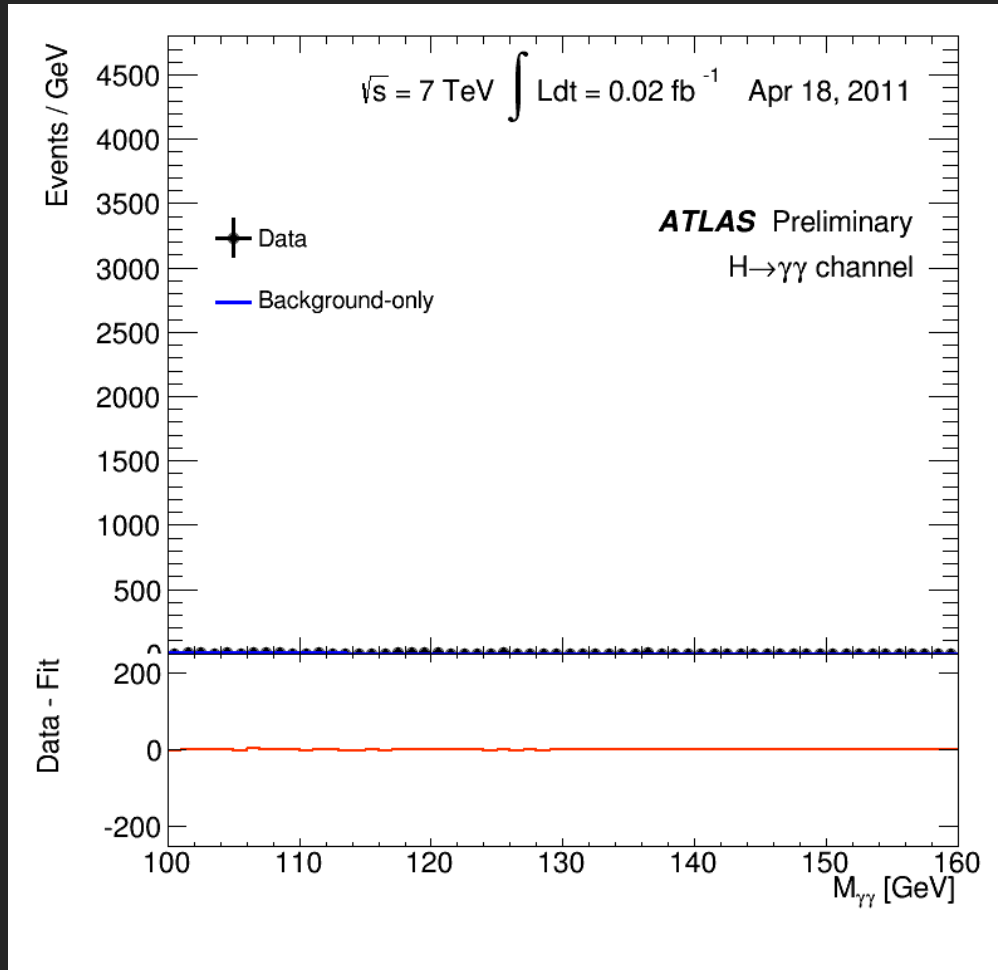


Example: Higgs decays into two photons



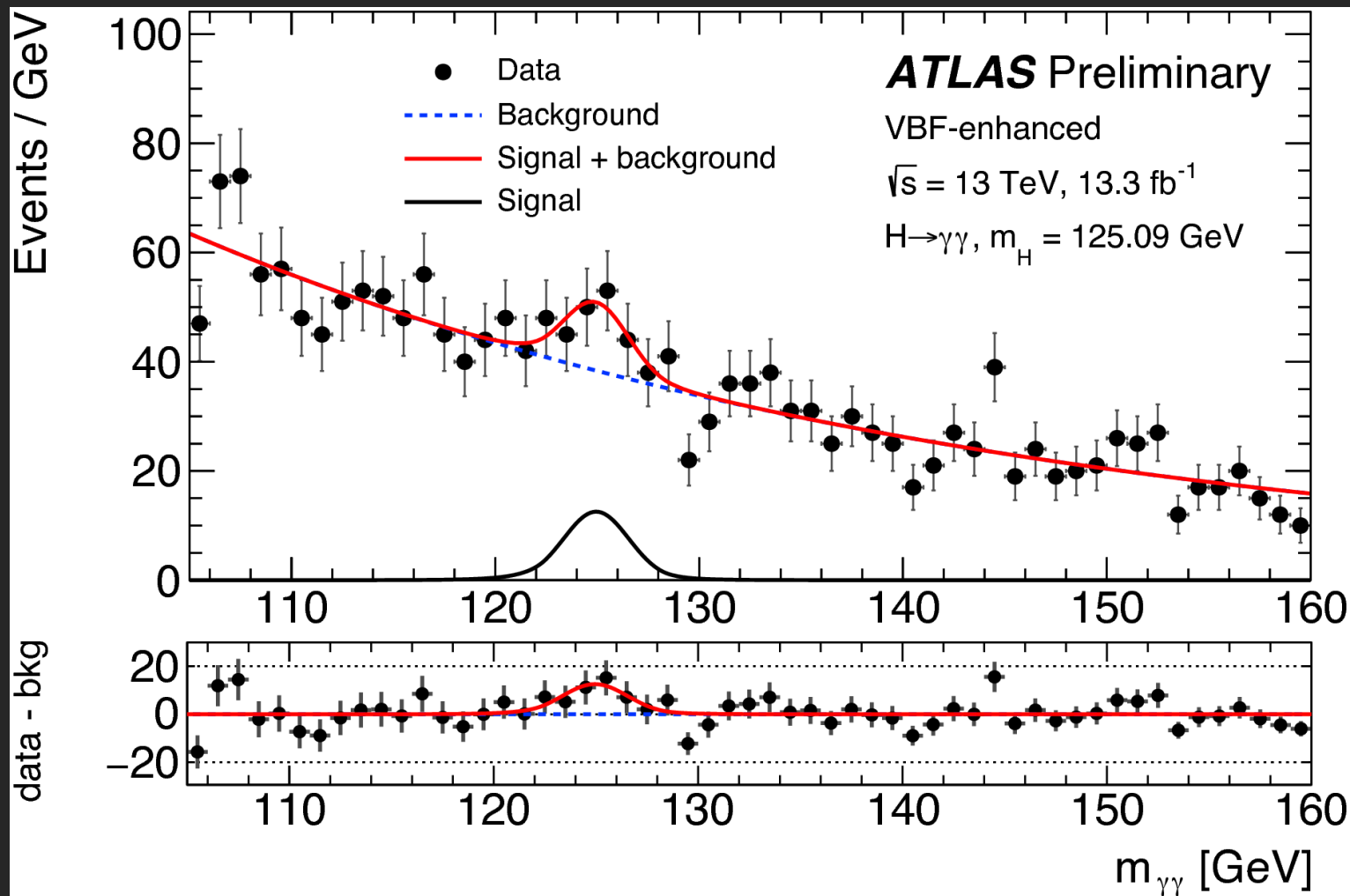
THE ATLAS EXPERIMENT

How did we find the Higgs?



THE ATLAS EXPERIMENT

How did we find the Higgs?



ATLAS-CONF-2016-067

PARTICLE PHYSICS

MATTER

u	c	t
d	s	b

Quarks

ν_e	ν_μ	ν_τ
e	μ	τ

Leptons

FORCE

γ	g
W	Z

Gauge Bosons

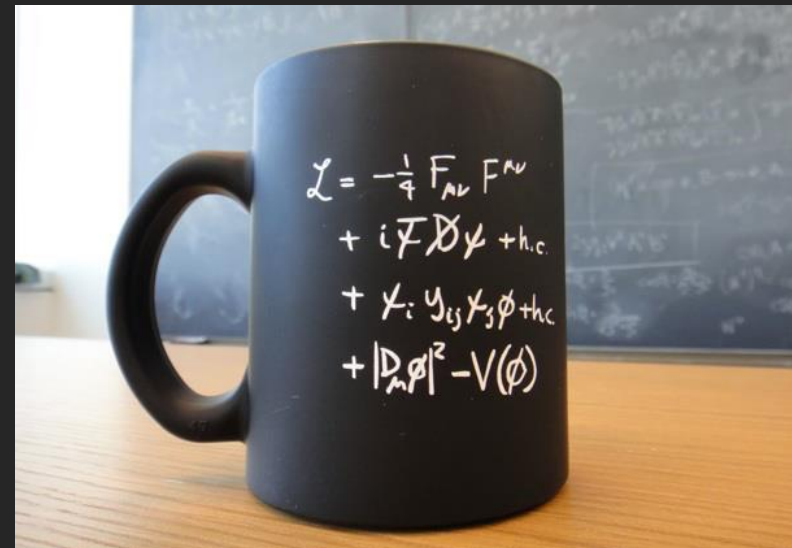
H

Higgs Boson?

THE STANDARD MODEL OF PARTICLES AND FORCES

IS THIS ALL THAT EXISTS?

GREAT JOB PARTICLE PHYSICIS!!!!



$$\begin{aligned} \mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi}\not{D}\psi + \text{h.c.} \\ & + \bar{\psi}_i \gamma_3 \psi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi) \end{aligned}$$

PARTICLE PHYSICS

MATTER



Quarks



Leptons

FORCE



Gauge Bosons



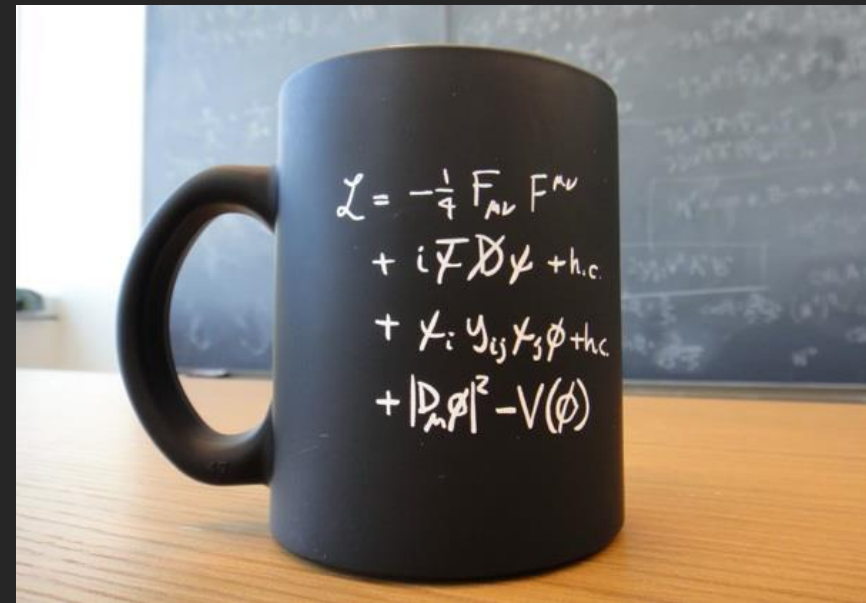
Higgs Boson?

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PARTICLES AND FORCES

IS THIS ALL THAT EXISTS?

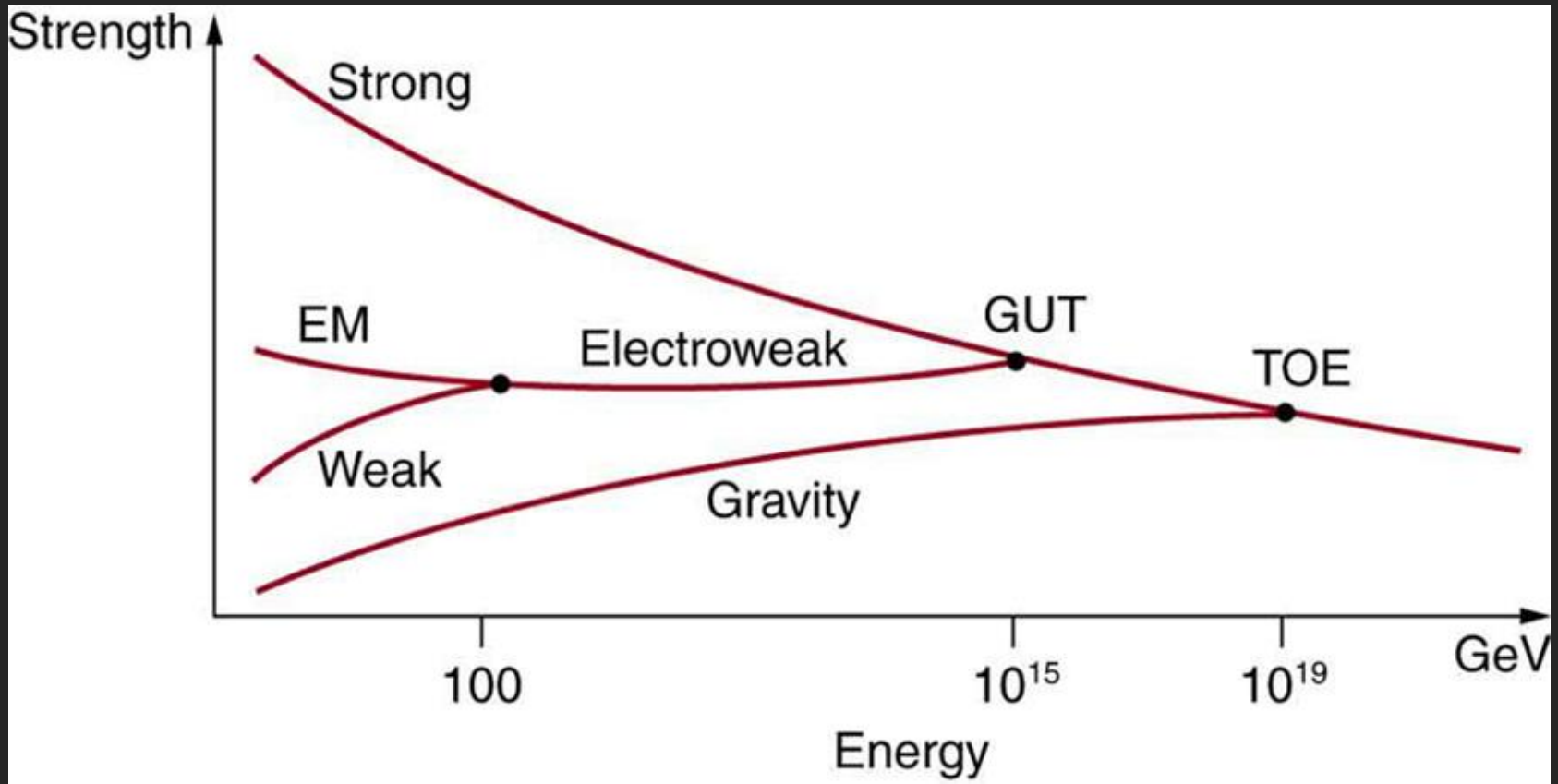
Issues:

- Gravity
- Dark Energy, Dark Matter
- Neutrino masses
- Matter-antimatter asymmetry
- Hierarchy problem



PARTICLE PHYSICS

Fundamental forces described using relativistic quantum field theories



Today

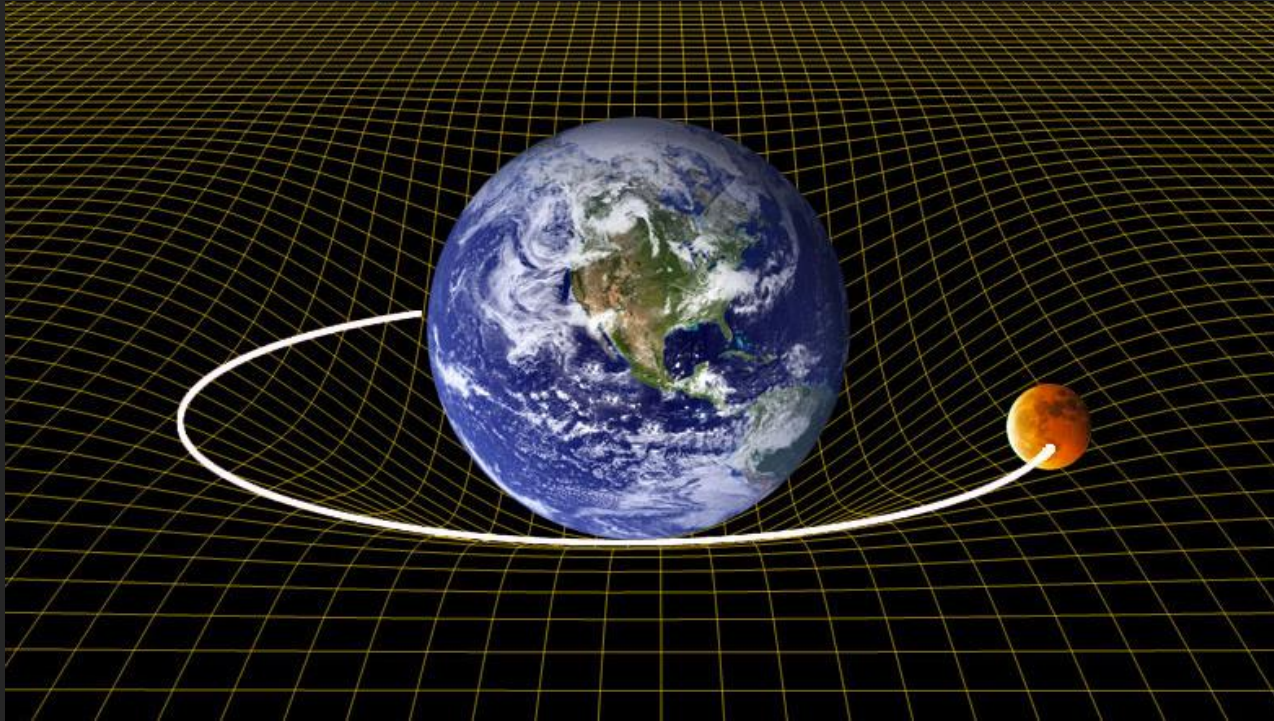


Time

THE PROBLEM WITH GRAVITY

Gravity is described by **General Relativity!**

We currently don't have a **quantum theory of gravity!**



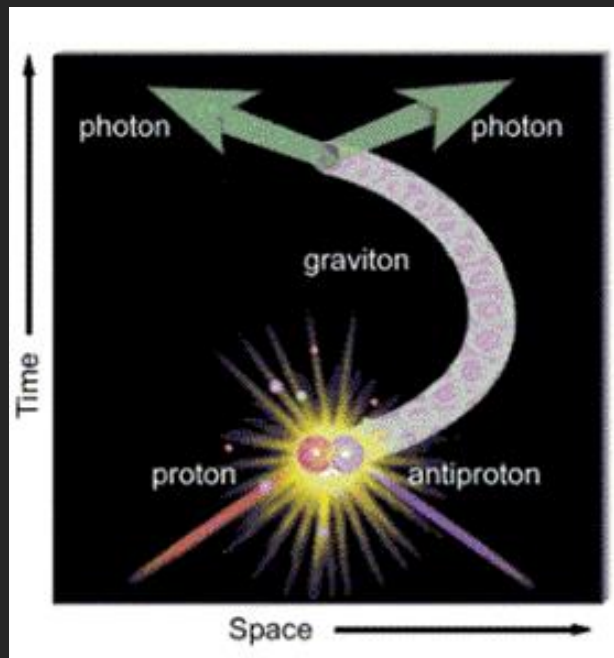
Problem in making a quantum theory of gravity due to something called renormalisation – **infinities occur!**

Other approaches include **string theory** and **loop quantum gravity**

THE PROBLEM WITH GRAVITY

Hypothetical force carrier for Gravity: **The Graviton**

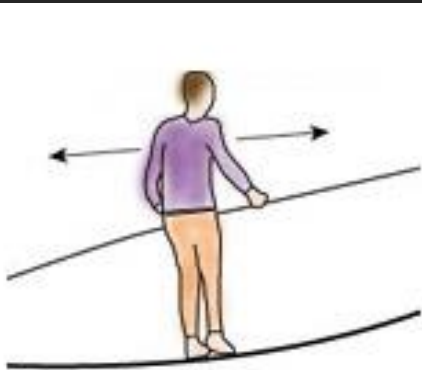
- **Graviton**: spin 2 massless (tensor) boson
- Cross-section would be **very low!**
- ATLAS and CMS are still searching for it!



EXTRA DIMENSIONS?

Einstein's general theory of relativity tells us that space can expand, contract, and bend.

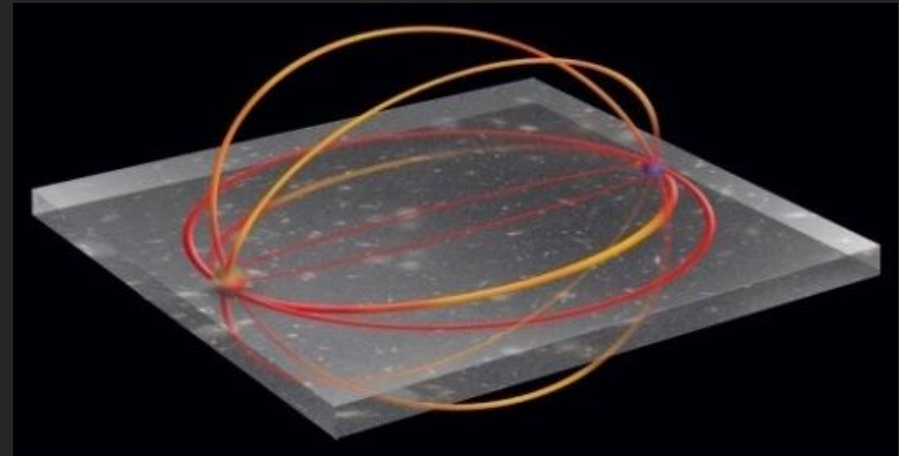
If one dimension were to contract to a size smaller than an atom, it would be hidden from our view.



An acrobat can only move in one dimension along a rope..



...but a flea can move in two dimensions.

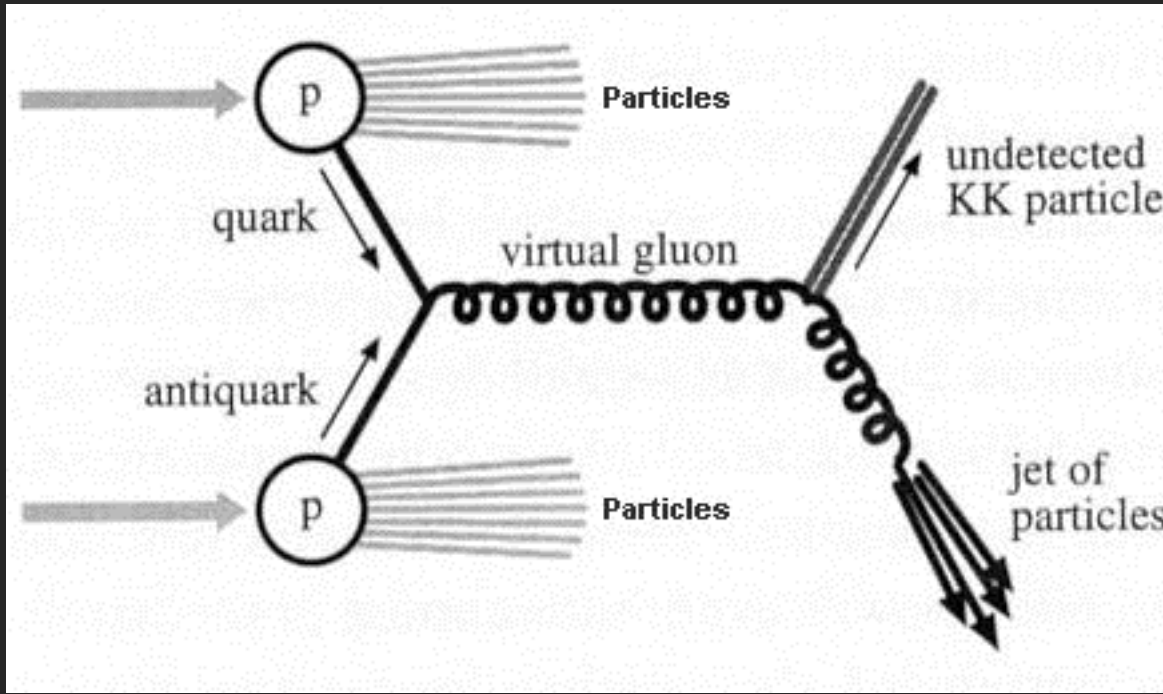


One possibility for gravity being so weak is because part of it spreads to extra dimensions

THE GRAVITON & EXTRA DIMENSIONS?

If gravitons exist, it should be possible to create them at the LHC, but they would rapidly disappear into extra dimensions.

Example – Graviton produced in association with a jet



The Graviton propagates in the extra dimensions

Only one jet of hadrons would be observed in our four-dimensional world.

We would see of monojet events at colliders.

NEUTRINO MASSES

Neutrinos are the least understood particles in the standard model. They come in 3 flavours, were found to oscillate between these flavours in the 90's and 00's, indicating they have a **non-zero mass!**

This is not predicted by the Standard Model.

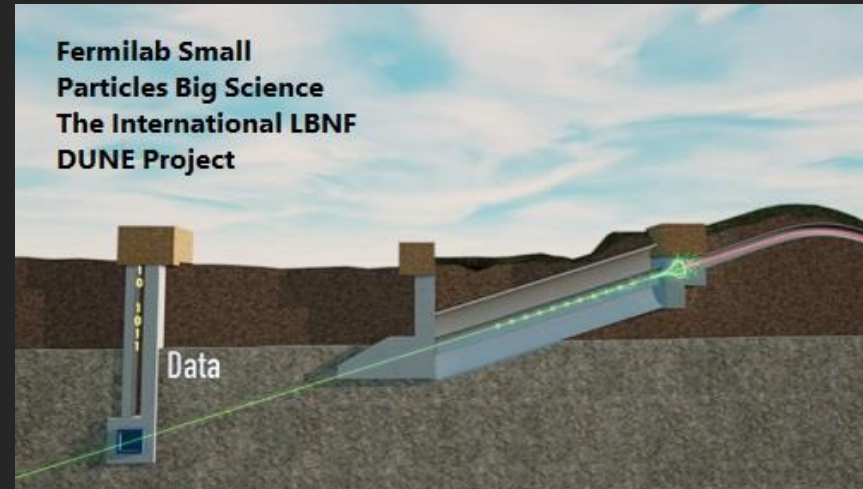
Scientists are studying these elusive particles in numerous experiments.



T2K, Japan

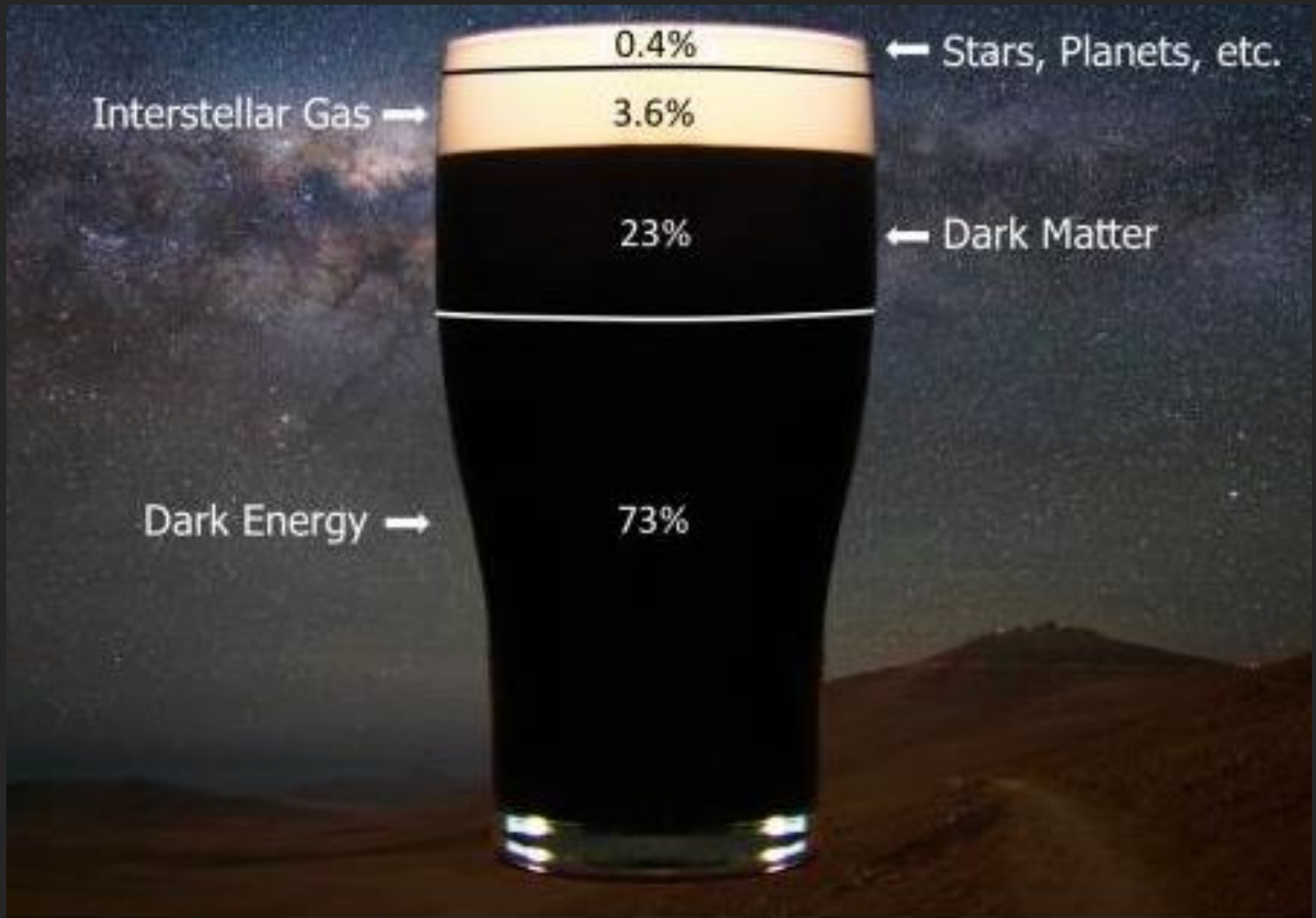


SNO+, Canada

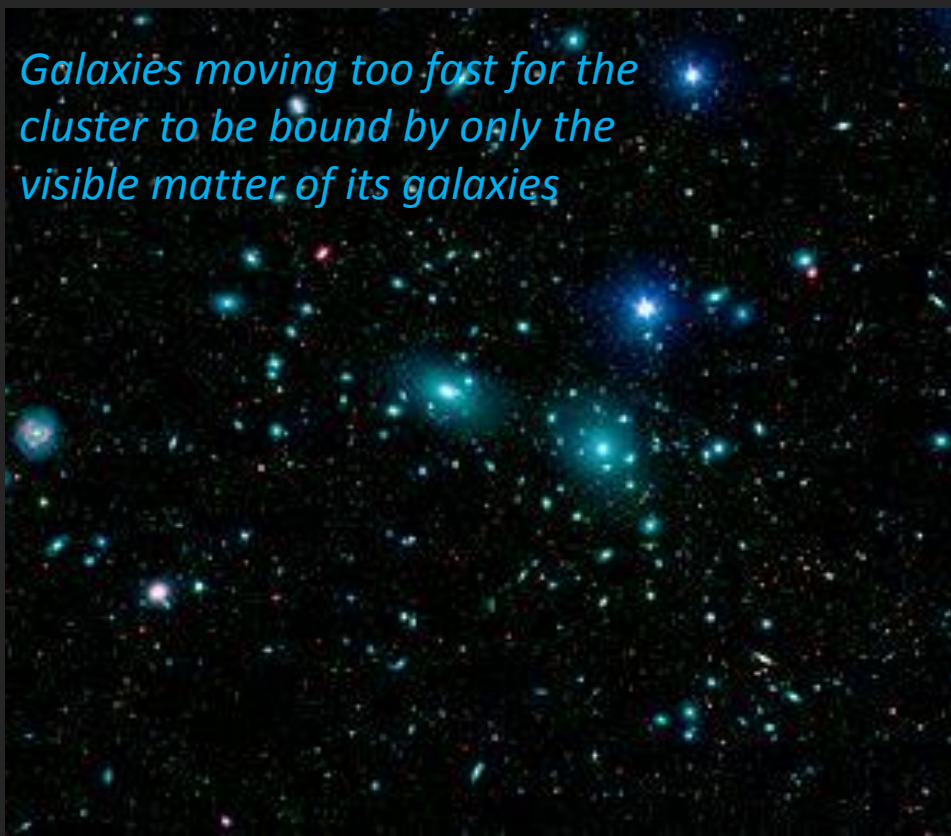


Dune, US

DARK ENERGY & DARK MATTER

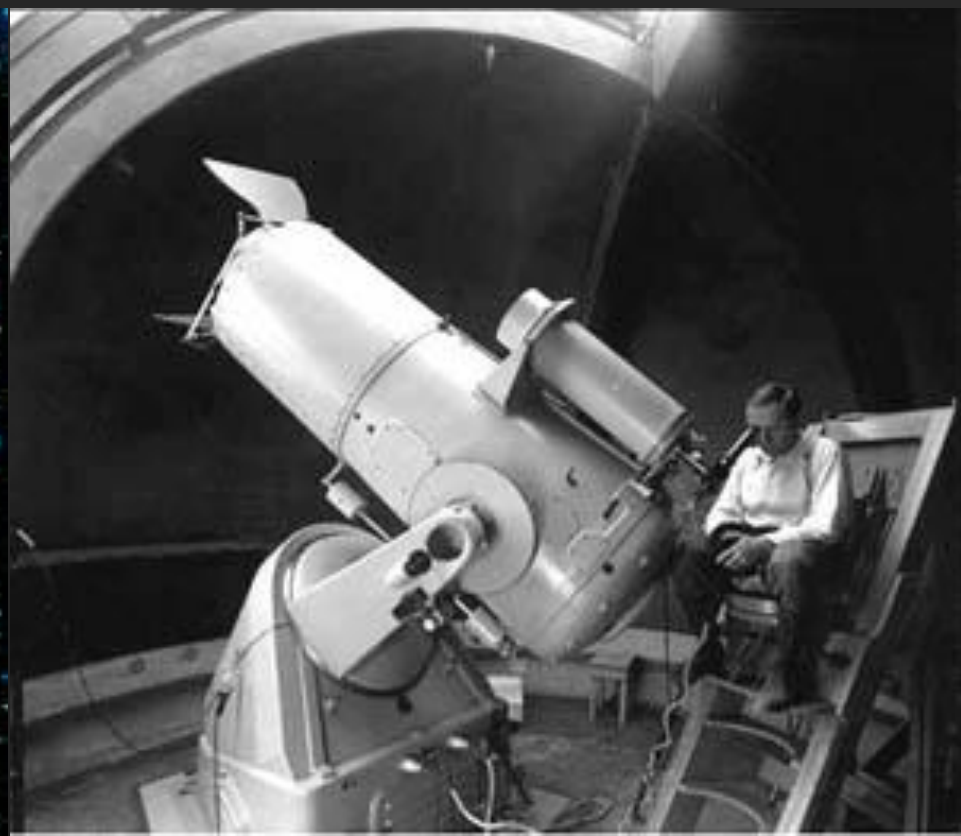


DARK MATTER



Galaxies moving too fast for the cluster to be bound by only the visible matter of its galaxies

Coma Cluster, contains over 1000 identified galaxies, 321 million light years away from Earth, ~ 90 % dark matter



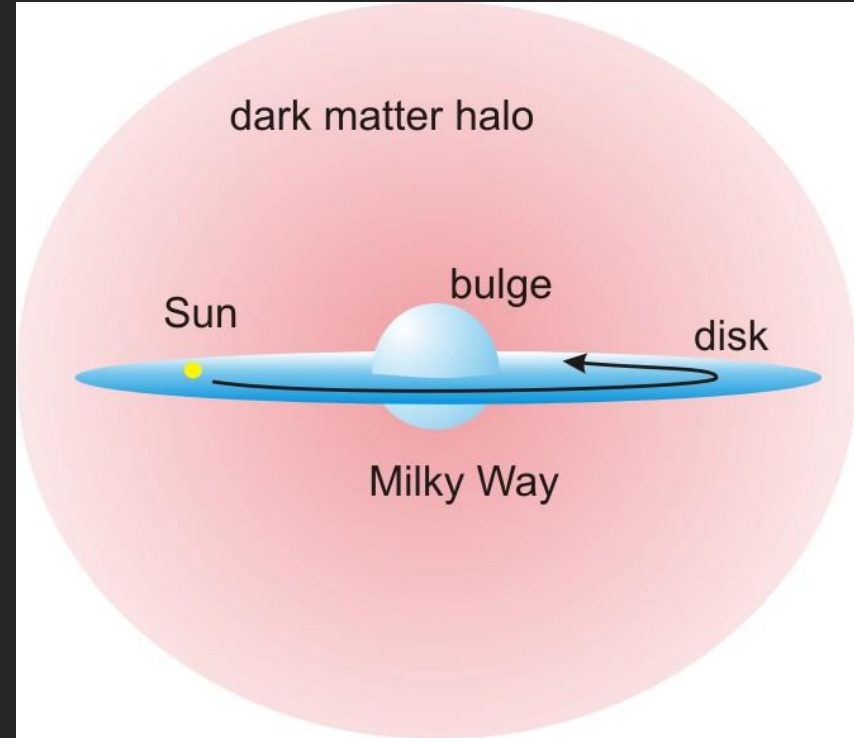
Fritz Zwicky, Swiss Astronomer
In 1933 inferred existence of *dunkle Materie*

Galaxies must be held together by some dunkle Materie

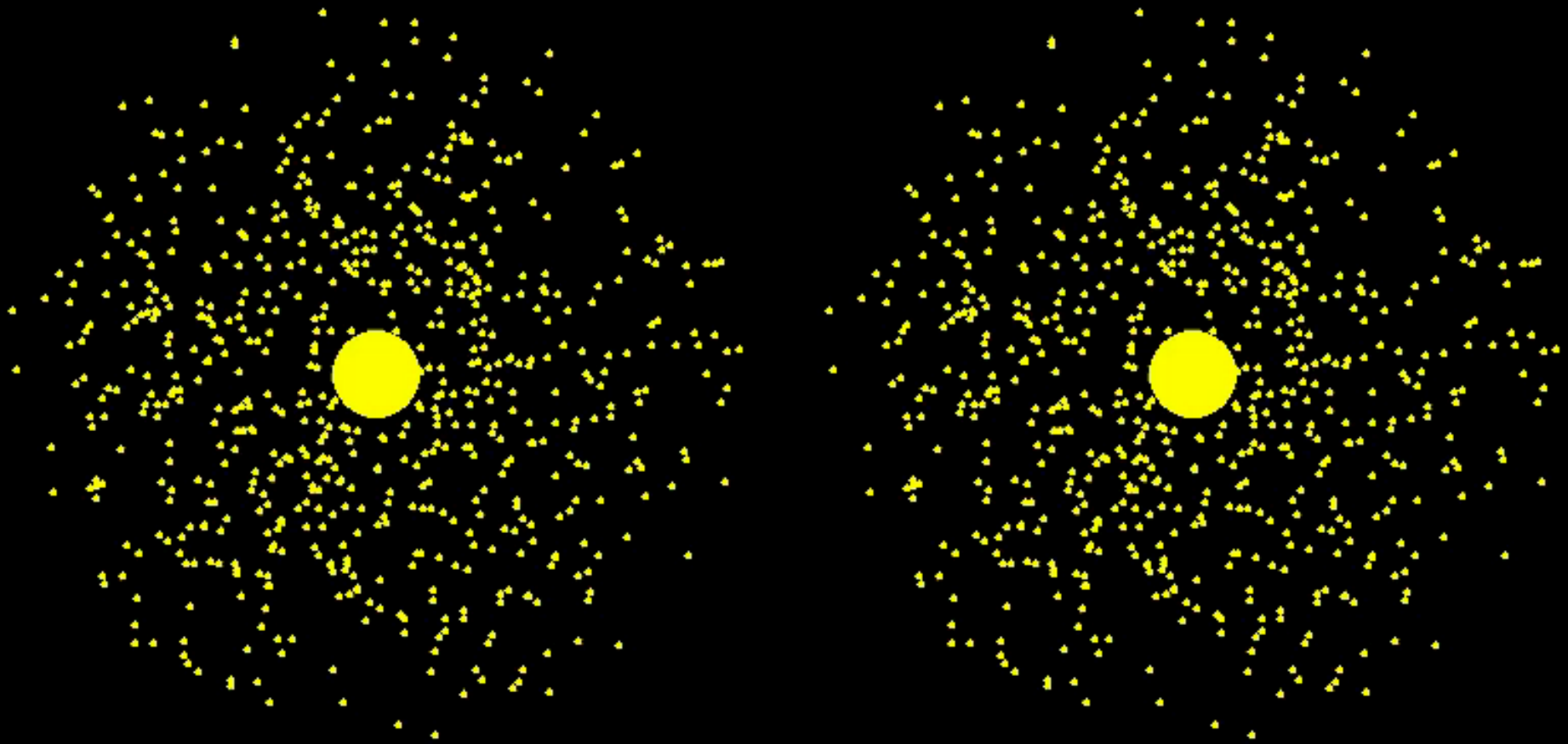
DARK MATTER



1970s Vera Rubin: Investigated rotational curves of spiral galaxies



DARK MATTER



Galaxies must be held together by some dunkle Materie

DARK MATTER

By 1980 Dark Matter was widely recognised as an unsolved problem in astronomy

What do we know about dark matter?

- Its **dark**, it does not absorb, reflect or emit light! This means it does not interact with the electromagnetic force
- It interacts with **Gravity**



We know what it is **not**:

- clouds of normal matter without stars
- antimatter – which produces unique gamma rays when it interacts with normal matter
- made of black holes - as these are confined objects, dark matter is scattered

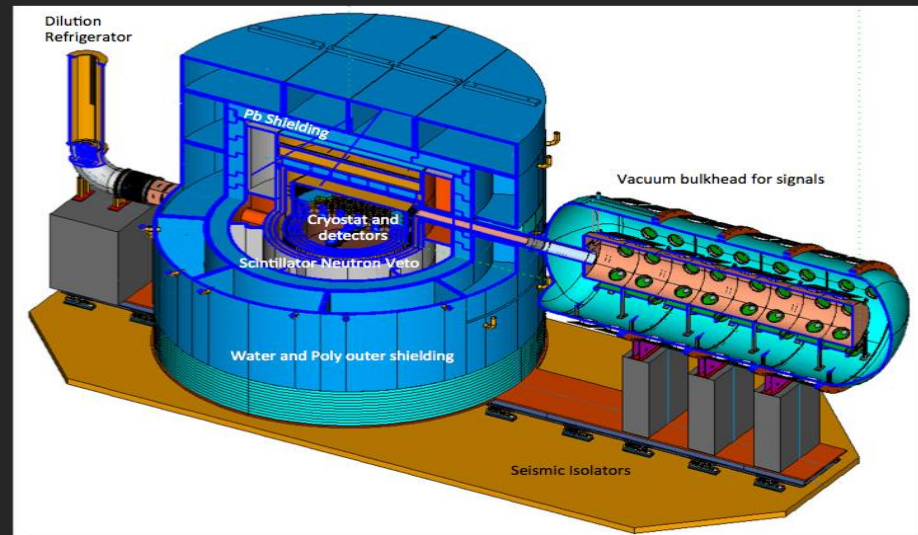
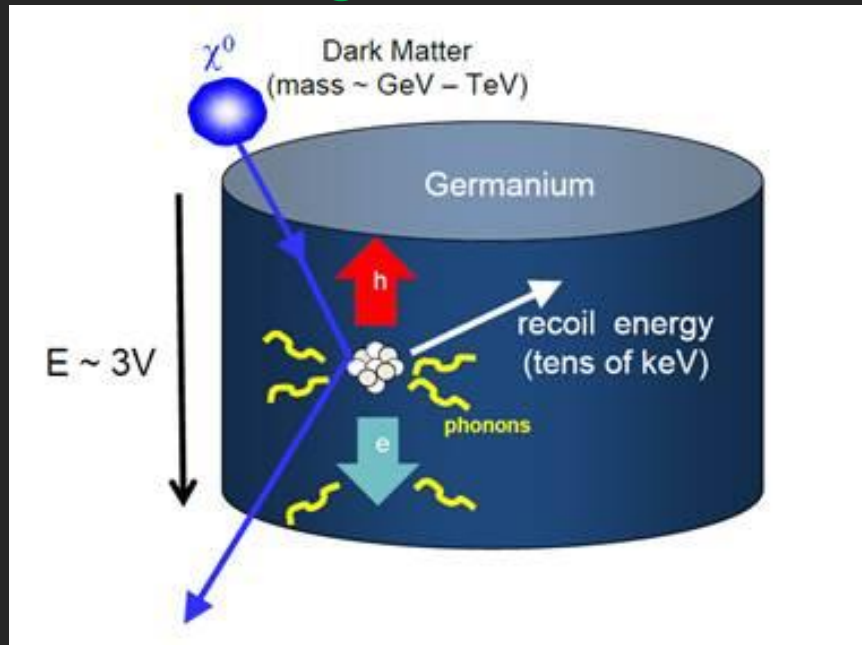
DARK MATTER

A heavy candidate is the **WIMP**: Weakly Interacting Massive Particles

- If not too massive these should be detectable at the LHC
- A theory named **SUPERSYMMETRY** which solves the hierarchy problem provides a **neutral, heavy, weakly interacting particle**, which is an ideal candidate for the WIMP!

Light candidates: Axion, Gravitino, light moduli, dilatons

BUT – nothing has been seen in direct searches!



Cryogenic Dark Matter Search (CDMS)

DARK MATTER

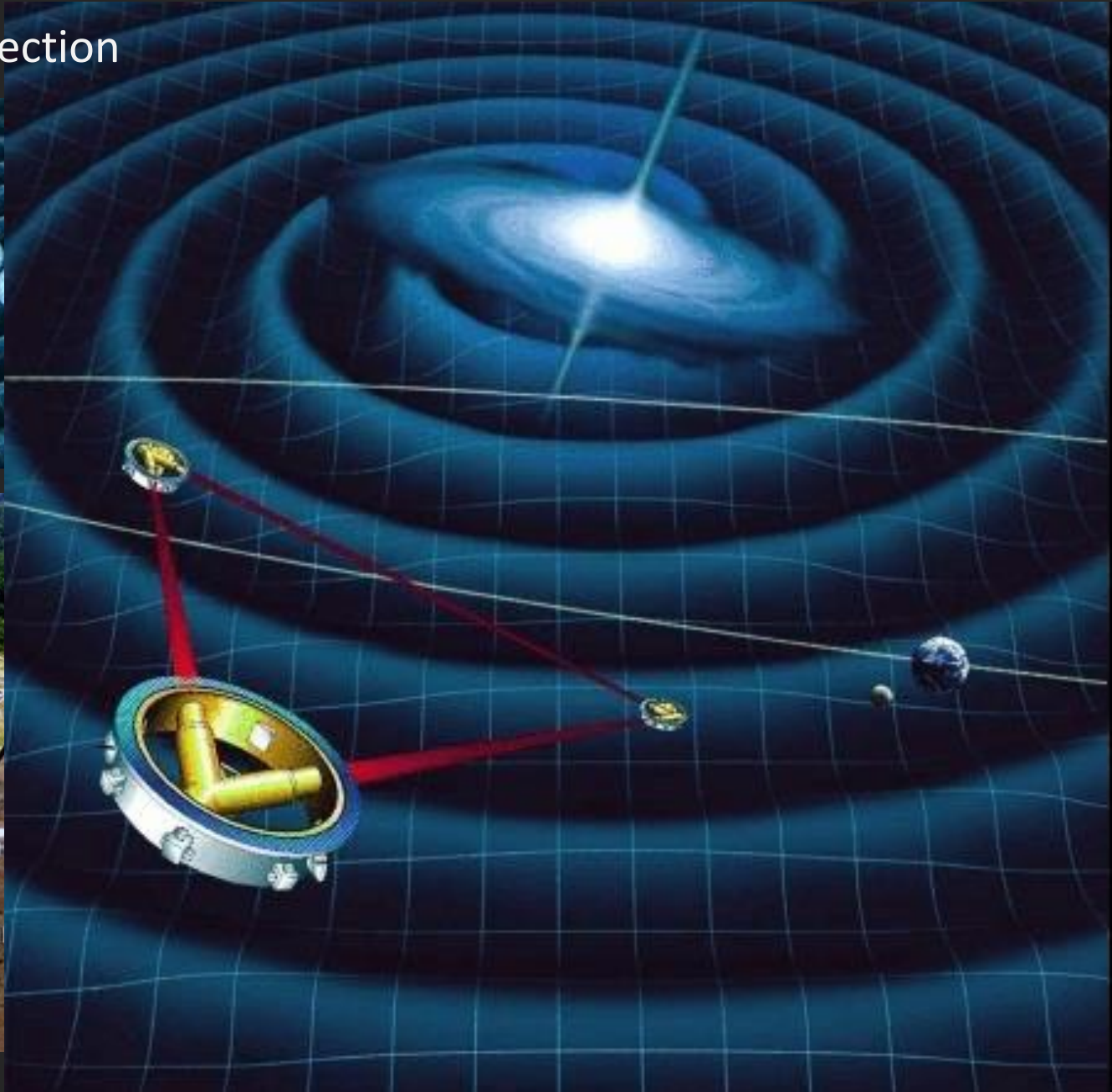
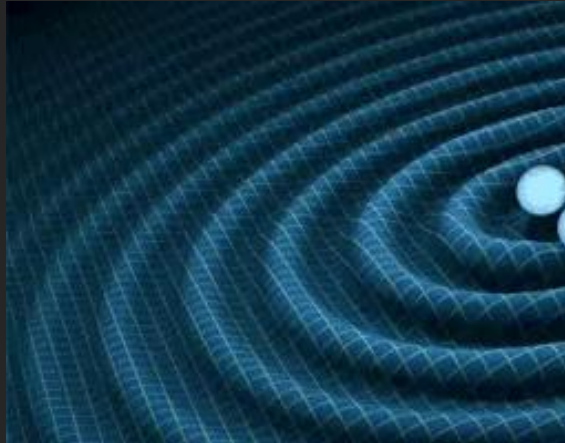


Asimina Arvanitaki, Stavros Niarchos
Foundation Aristarchus Chair in Theoretical
Physics at Perimeter Institute, Canada

- Suggests novel method to search for **ultra light Dark Matter**
- Using a type of **gravitational wave detector** (that use differential measurement of two atom interferometer)

DARK MATTER

Gravitational wave detection



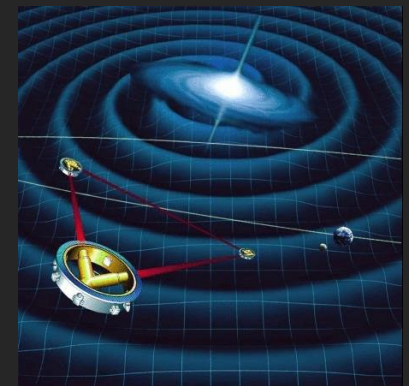
DARK MATTER

arXiv:1606.04541



Asimina Arvanitaki, Stavros Niarchos Foundation Aristarchus Chair in Theoretical Physics at Perimeter Institute, Canada

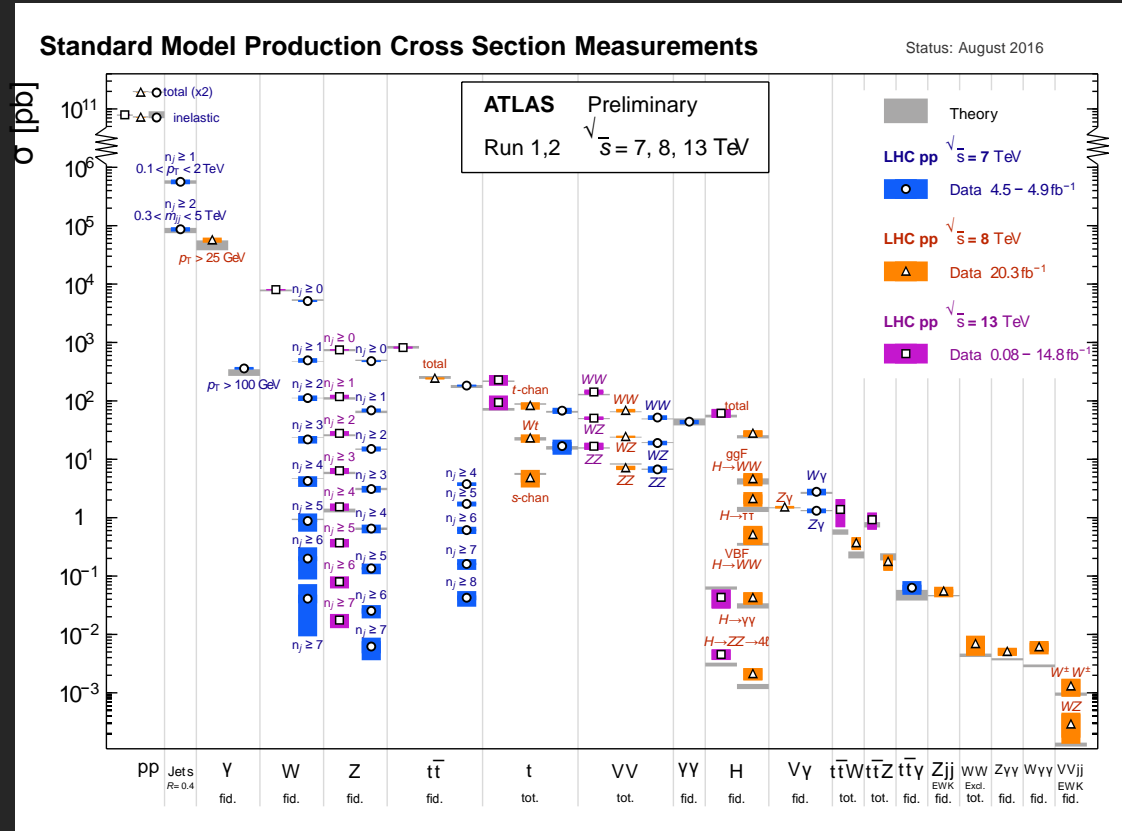
- Packed particles, specifically bosons, in a given space will overlap and begin **to behave like a wave**
- Ultra light dark matter can cause temporal oscillations in fundamental constants
- Frequency set by DM mass, amplitude set by local DM density



Looking for cracks in the SM

Testing Standard Model predictions at the LHC

Using the Higgs, the Top and others and a probe for New Physics!



Looking for cracks in the SM



Dirac famously predicted that, for electrons and muons, the factor relating the magnetic moment to spin would have a value of 2.

A recent measurement for the muon differs with a significance of 3.5σ

The muon $g-2$ experiment at Fermilab, US, aims to measure the anomalous magnetic moment of the muon to unprecedented accuracy

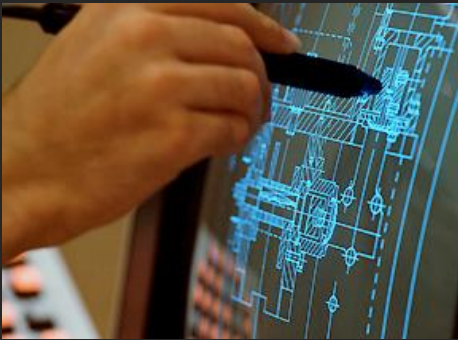
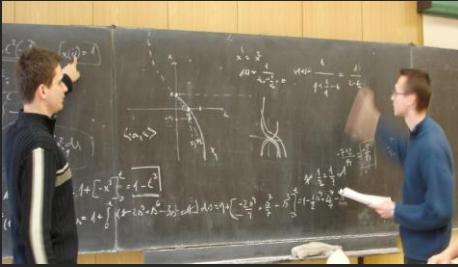
UK institutes include Liverpool, UCL, Lancaster, Oxford

WORLD OF PARTICLE PHYSICS

Particle Physics for Society

Because particle physics asked **BIG questions** we need new **unique** and **innovative** ideas and equipment which has had a huge impact in society!

WORLD OF PARTICLE PHYSICS



Fundamental Science



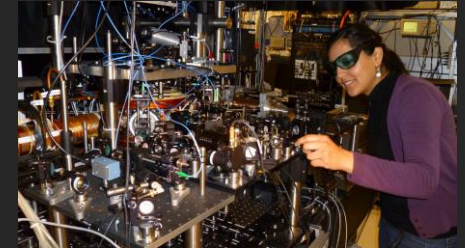
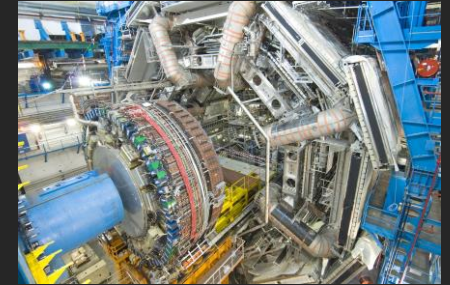
Applied Science



Technology, Engineering and Innovation



Sustainable Development

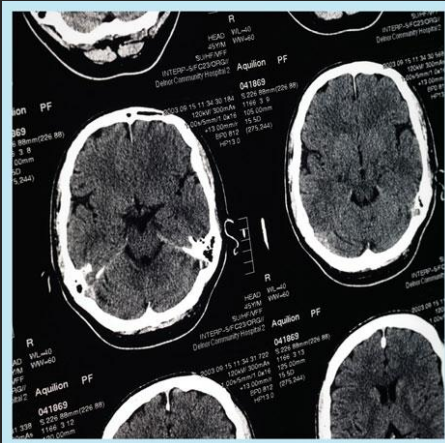


WORLD OF PARTICLE PHYSICS

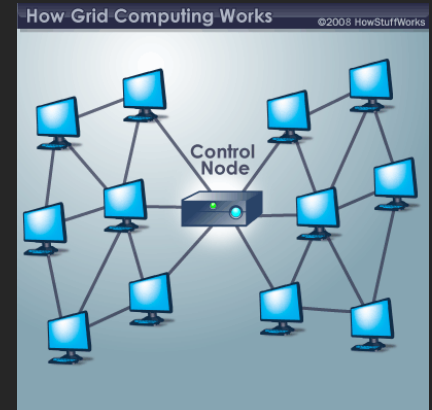
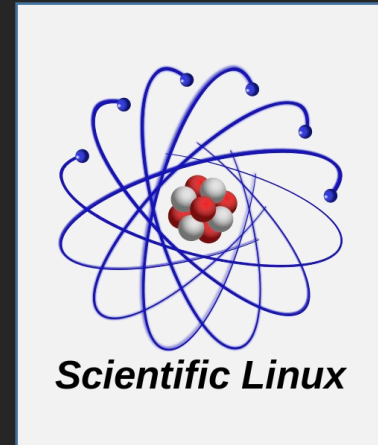
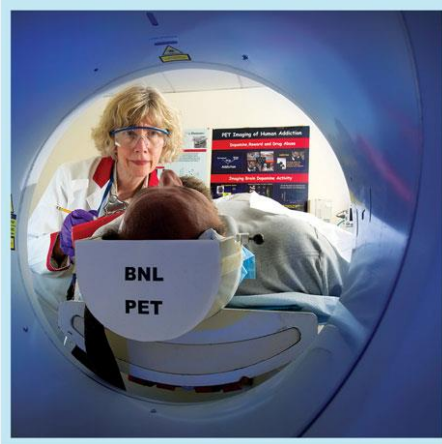
Technology



World Wide Web developed at CERN



MRI and PET



GRID Computing

WORLD OF PARTICLE PHYSICS

Education – physics/science undergraduates / PhDs



The need to solve **environmental** and **developmental** problems requires **scientists**

Education and investment into educational, technological and cultural institutions play a key role in growing a **knowledge-based economy**

Higher education, research and innovation fuel national development

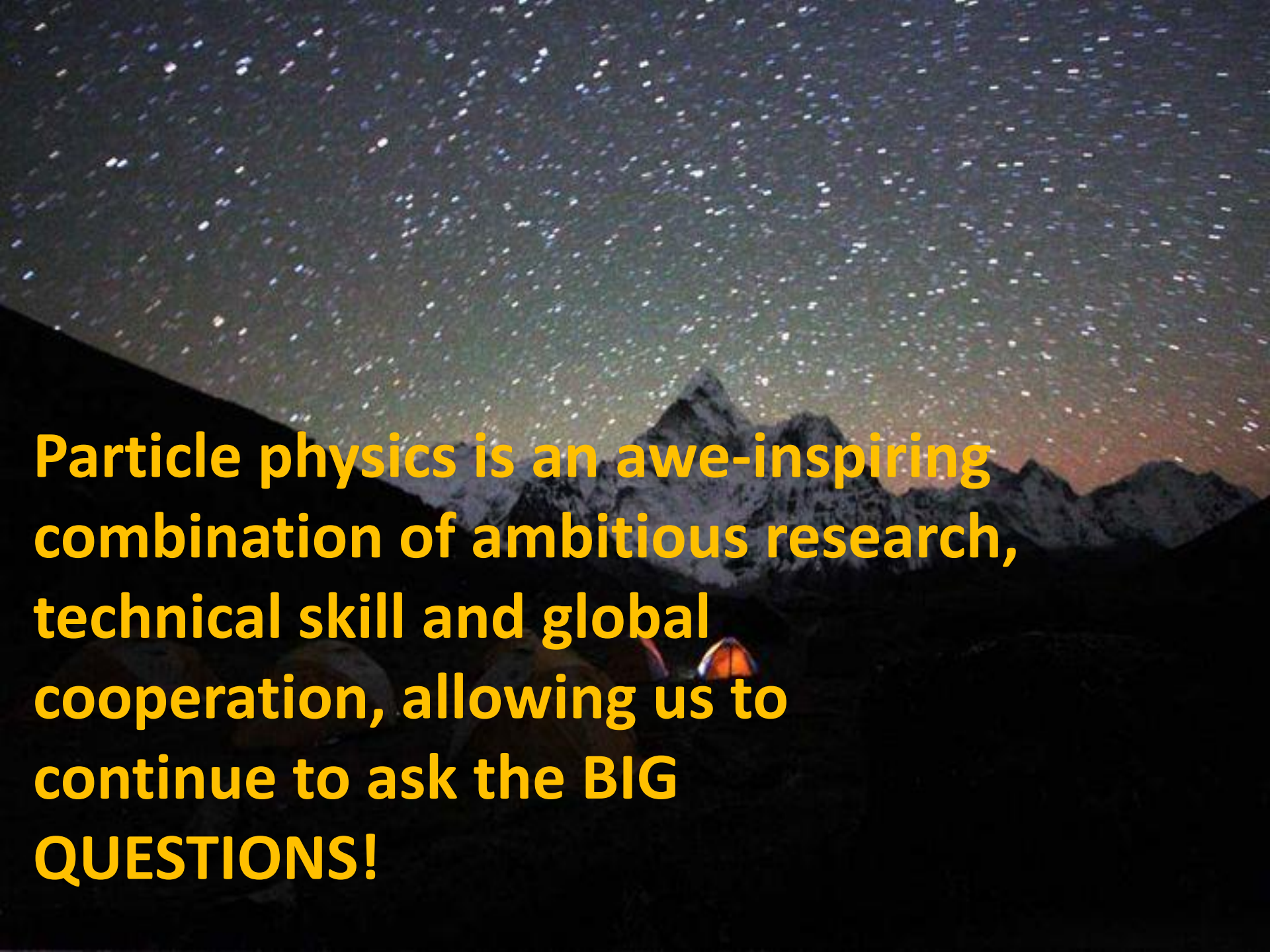


WORLD OF PARTICLE PHYSICS

Education – Particle Physics can inspire young people!



Science teaches young people to think for themselves, ask questions, query assumptions!

A night sky filled with stars over a mountain range with a tent.

Particle physics is an awe-inspiring combination of ambitious research, technical skill and global cooperation, allowing us to continue to ask the BIG QUESTIONS!



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THANK YOU