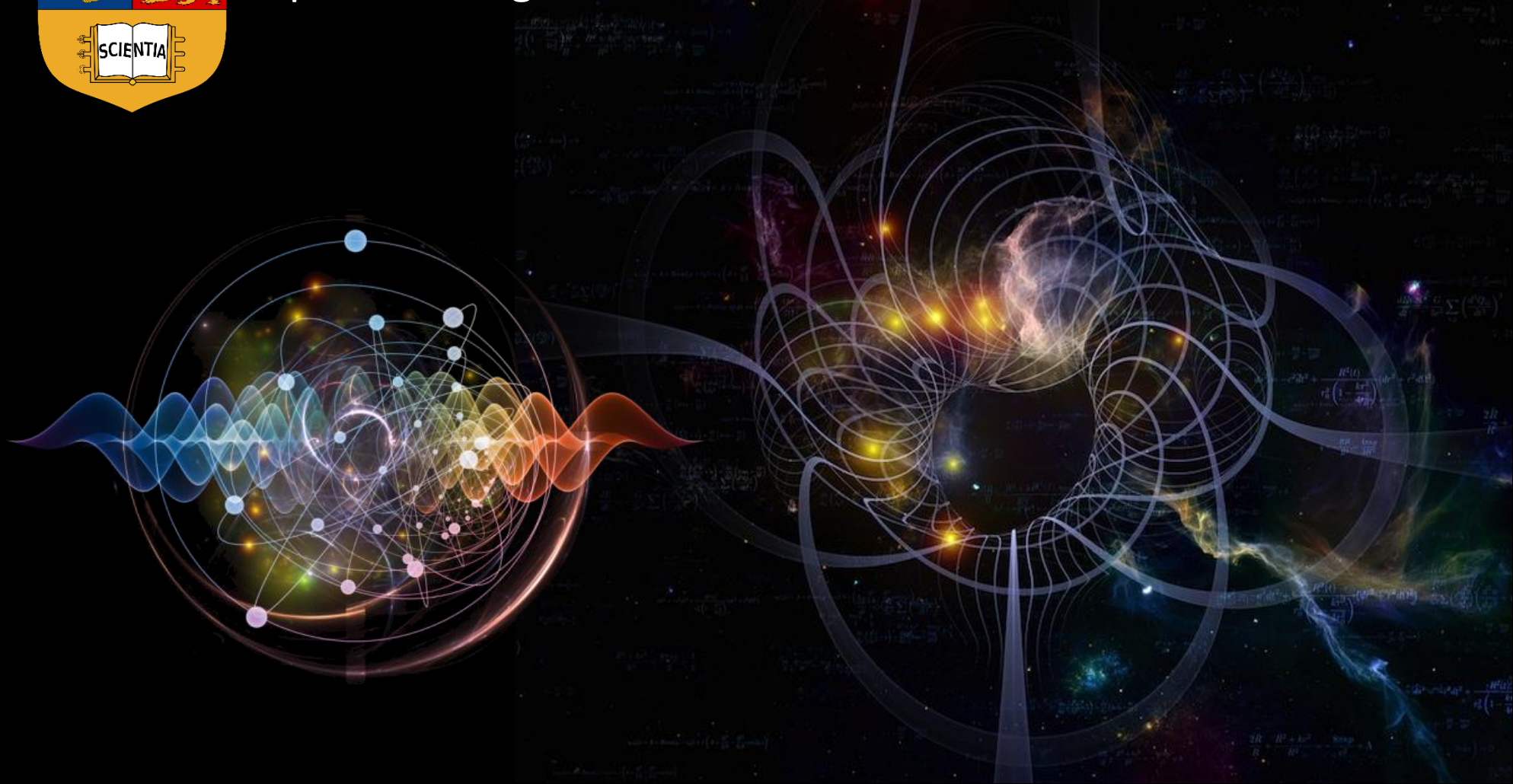




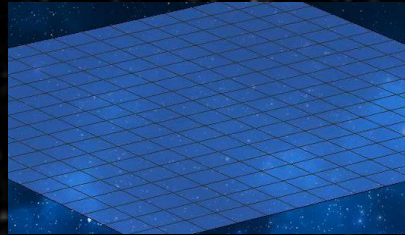
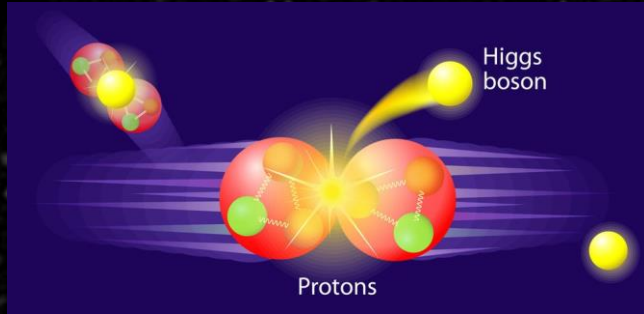
Claudia de Rham
Imperial College London



Higgs all around us

(or Salam&Kibble's legacy)

Higgs has been observed in \sim TeV collisions
 \sim size of a proton (10^{-3} fm= 10^{-18} meters)



Yet implications are present *all around us!*
Including for gravity & structure of whole Universe

ElectroWeak Force

1979 Physics Nobel Prize



Sheldon Lee
Glashow
Prize share: 1/3



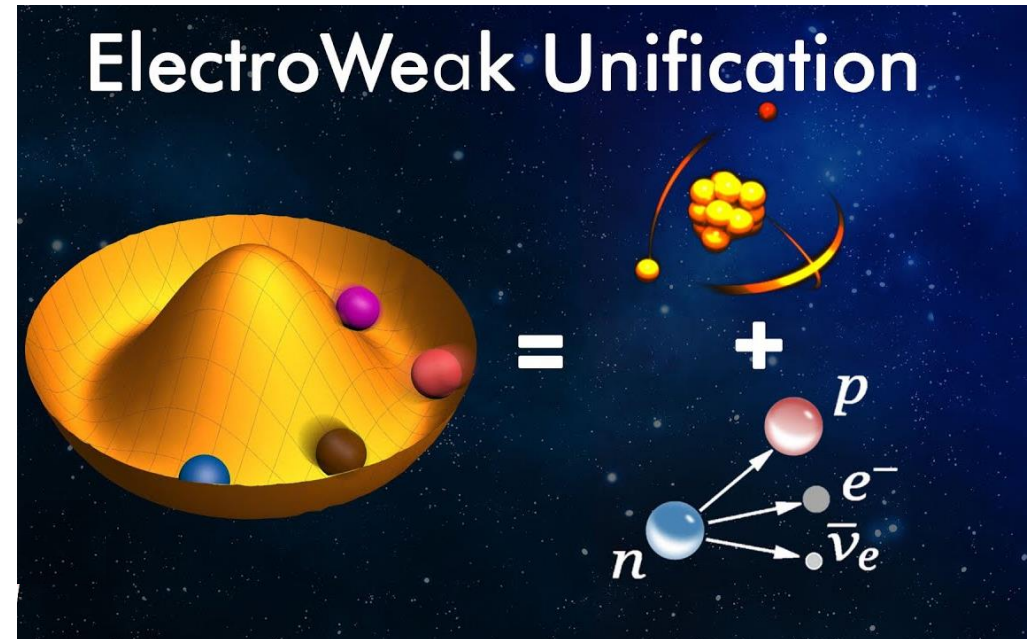
Abdus Salam
Prize share: 1/3



Steven Weinberg
Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current".

Photos: Copyright © The Nobel Foundation



Electromagnetic force

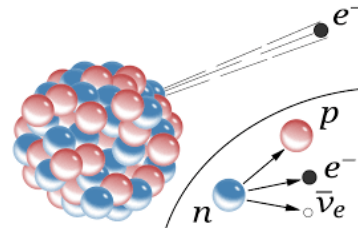


Particle carrier: photon
massless particle



EM has an infinite range

Weak force

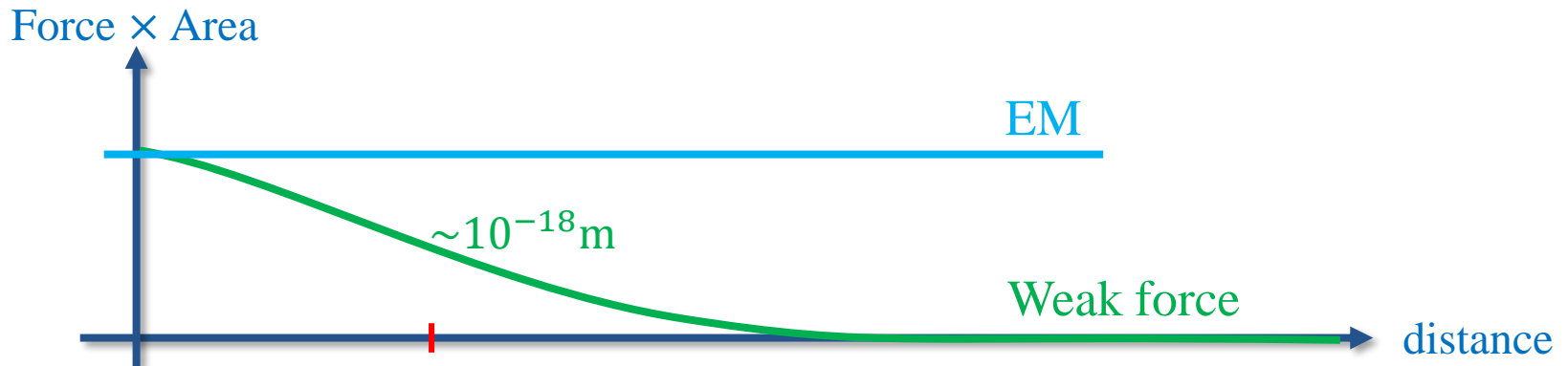


Particles carrier: **W&Z bosons**
Massive particles



Weak force has a short range

Higgs responsible for *weakness* of weak force



Higgs Vacuum

This discovery of the **Higgs confirms** something essential about the **(QUANTUM) VACUUM**

The **VACUUM** is **NOT** empty!

Empty space is filled by a FIELD – the **HIGGS FIELD**

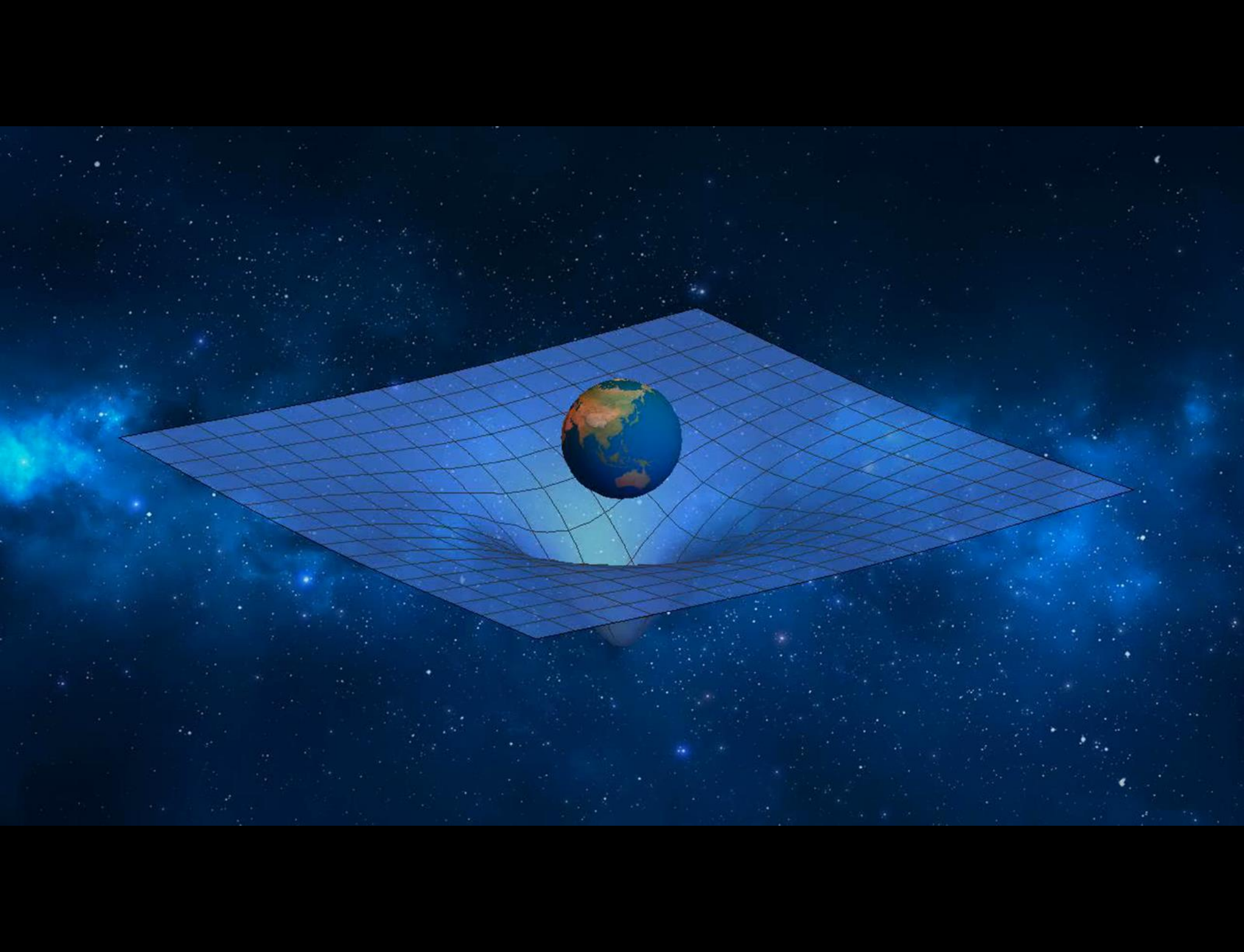
Higgs Vacuum acts as a Medium

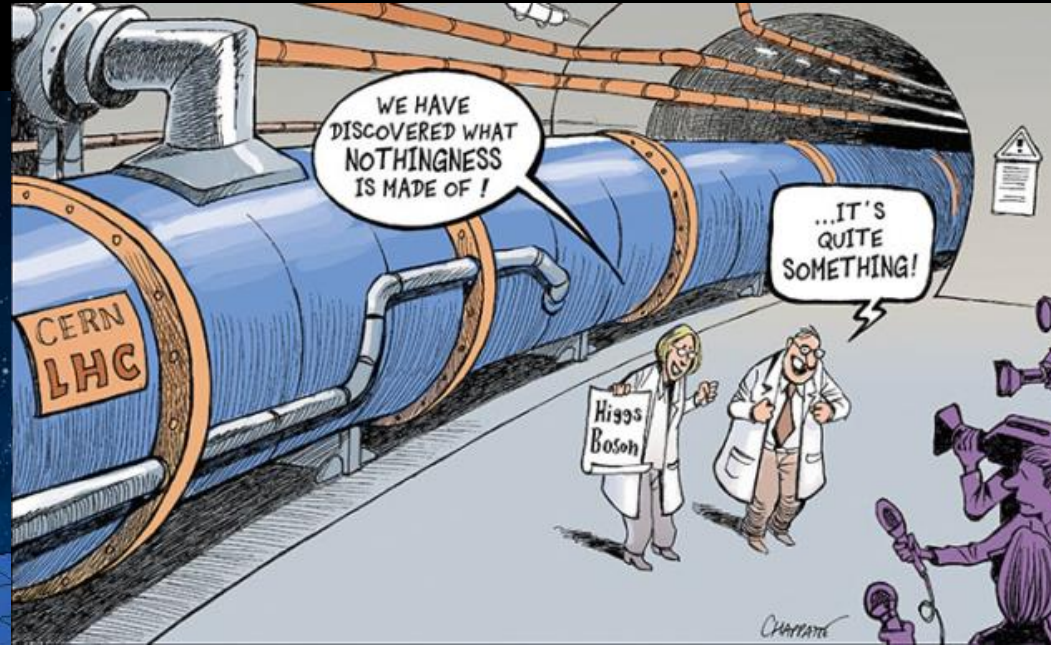


Light particles (like neutrinos) don't interact strongly with the medium, or Higgs vacuum



Heavy particles (like top quark) interact strongly with the Higgs vacuum

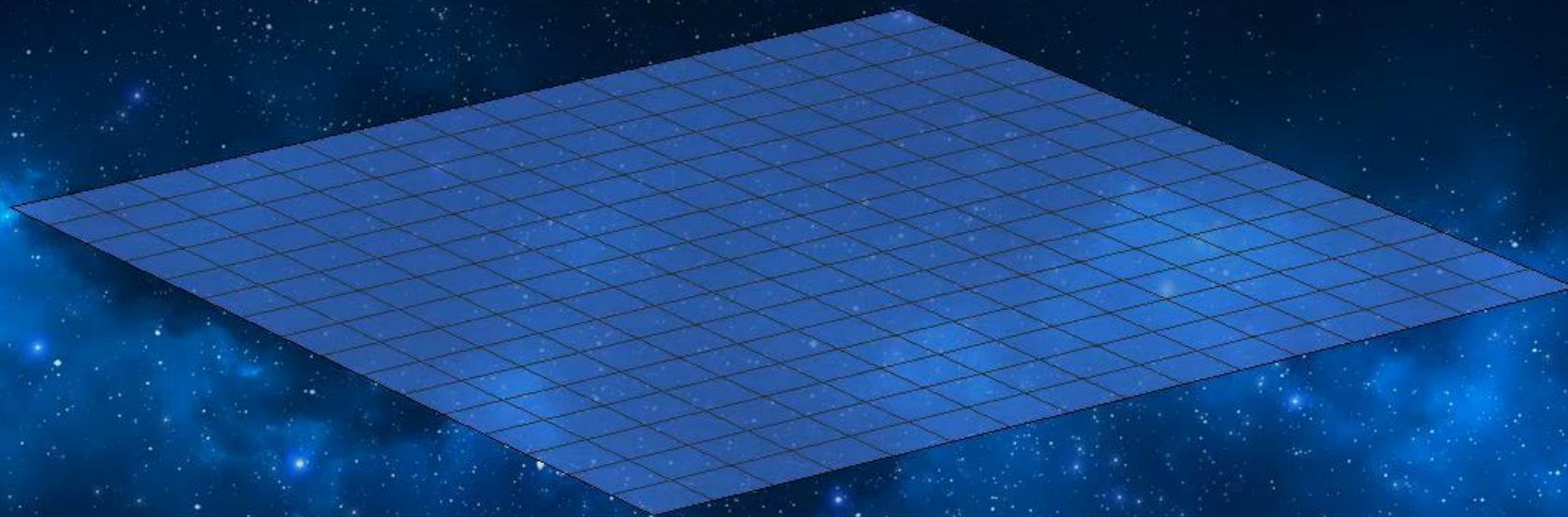




The Higgs mechanism is the proof that the empty space is **filled with a quantum sea** that **HAS an effect** on other particles.

This quantum sea should also have an effect on **GRAVITY!!!**
The whole Universe, (even its most deserted intergalactic voids)
is filled with this quantum sea!

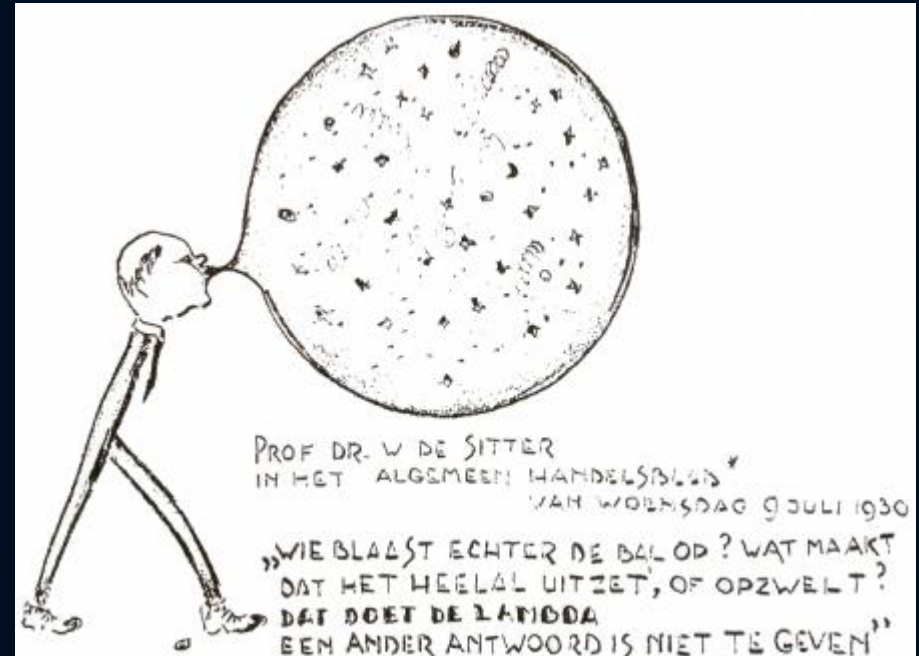
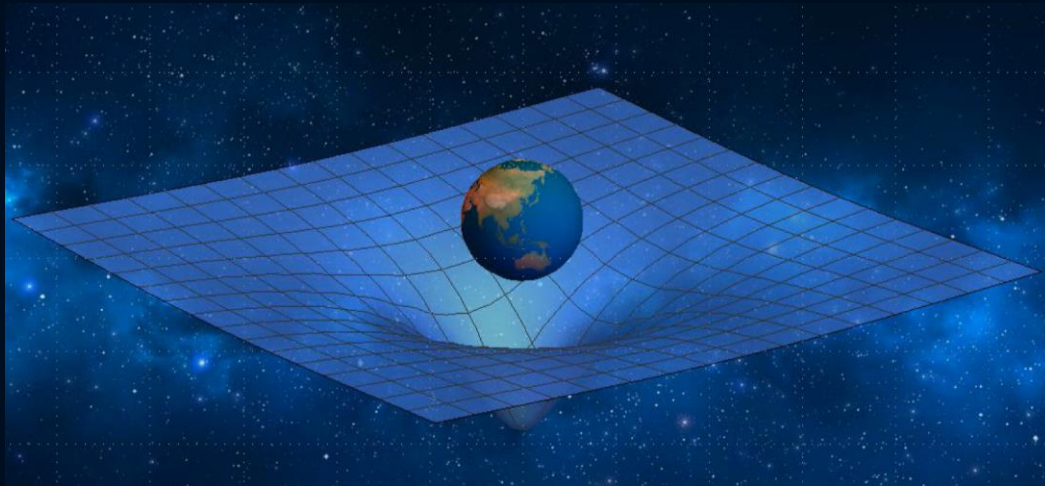
Interacting with gravity means **curving** our spacetime





Vacuum sea is everywhere
Affects spacetime uniformly
everywhere

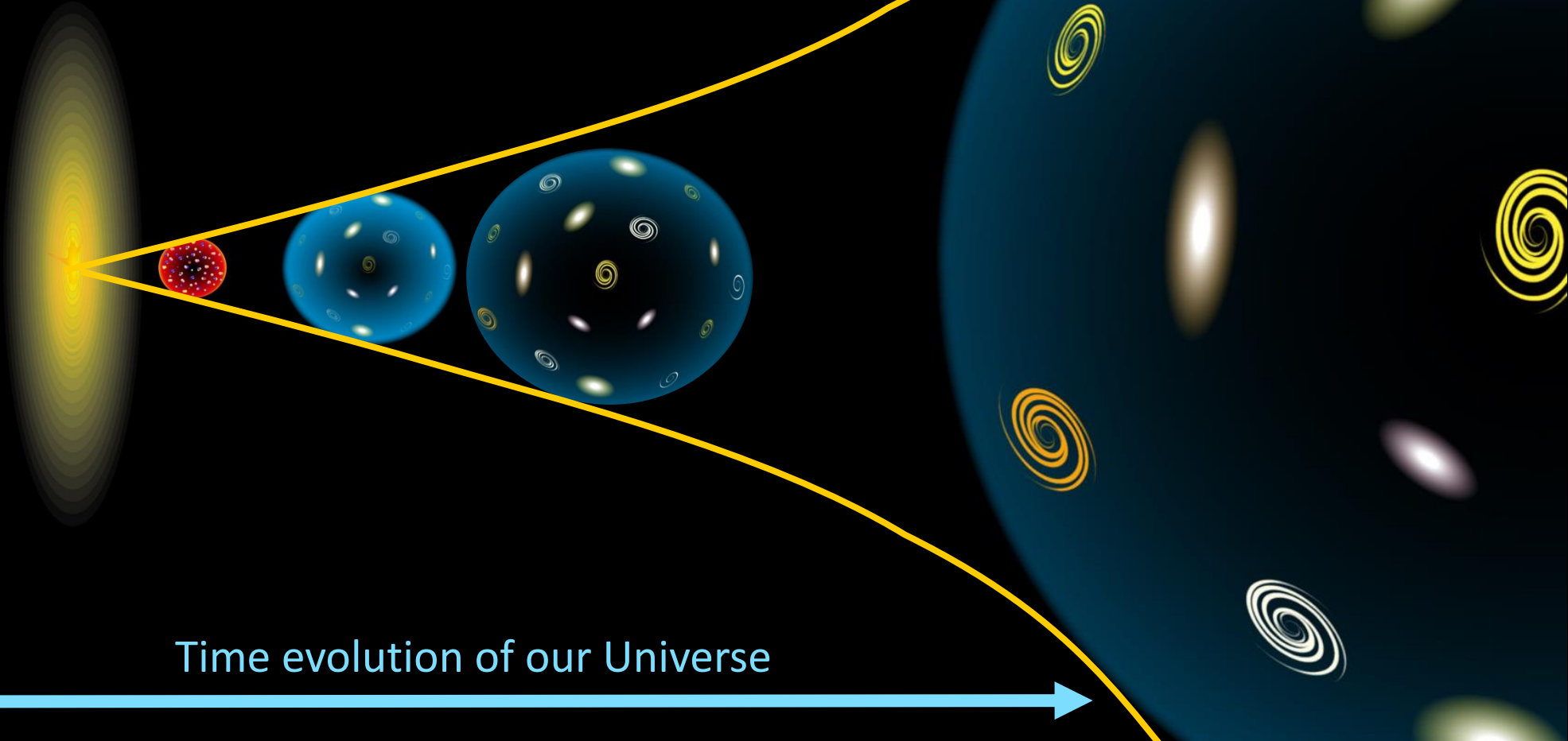
Local effect of a Planet



Affects evolution of Universe
as a whole

Higgs vacuum should accelerate
expansion of Universe
Precisely what we observe today!

Big Bang

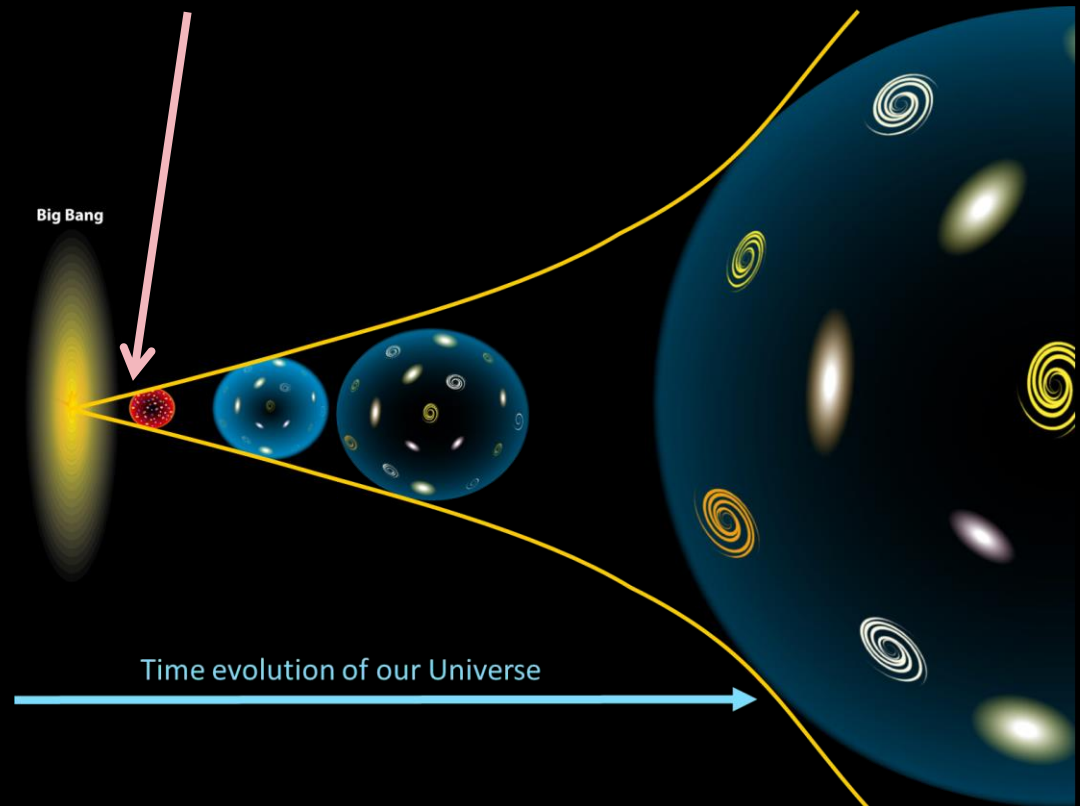


Time evolution of our Universe

Higgs vacuum should accelerate
expansion of Universe
Precisely what we observe today!

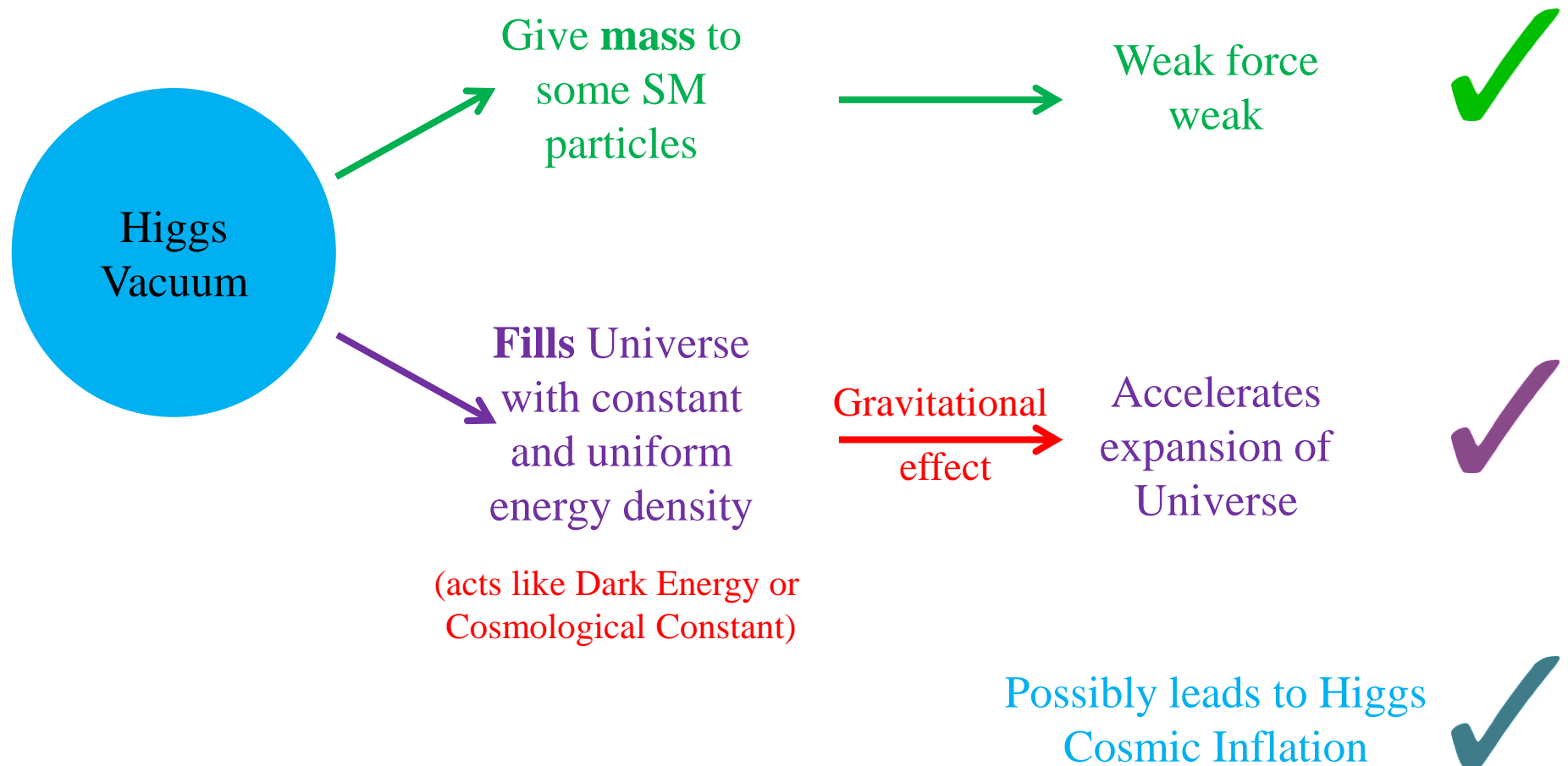
Higgs may even be responsible for the period
of cosmic Inflation at beginning of Universe

work by
Arttu Rajantie



Higgs & Gravity

So far so good between Higgs and Gravity.



Higgs & Gravity

So far so good between Higgs and Gravity.

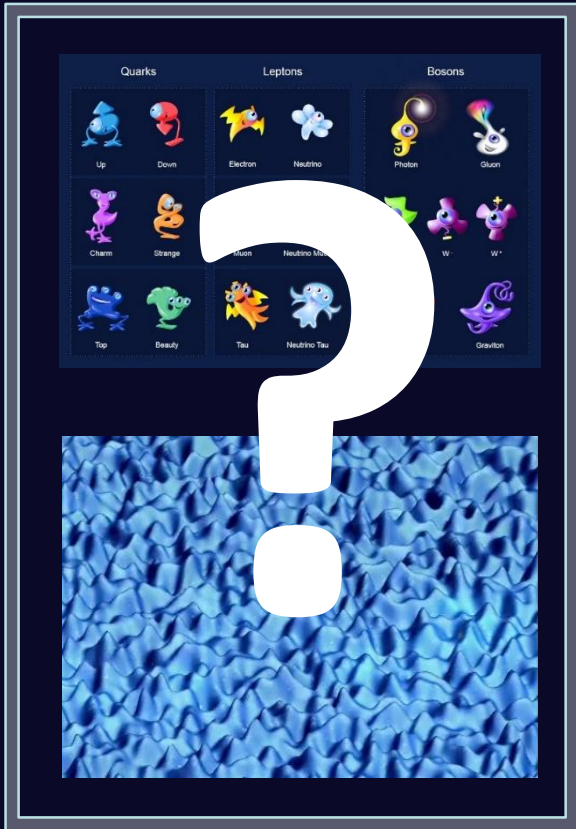
The **issue** is that the Higgs is **too good** at what it does!
It would stretch the structure of spacetime way too fast.

At least

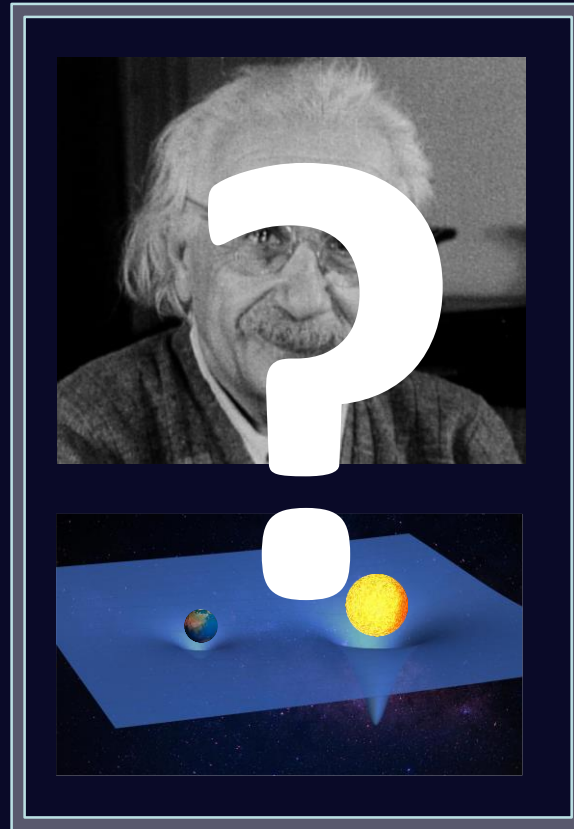
10,000,000,000,000,000,000,000,000,000,000

times too fast...

Biggest discrepancy in the whole history of physics...



+



+



= Slower acceleration

Higgs & Gravity & Mass



Could Gravity itself carry a mass?

Could there be another Higgs Mechanism for Gravity?

1915: Einstein's theory of General Relativity (graviton massless) → answer no!

1939: Fierz&Pauli provides first framework for massive graviton → answer maybe?

1970: vDV&Z raised issue related to massless limit → answer no!

1970: Vainshtein solved issue → answer maybe?

1971: **Chris Isham, Abdus Salam, and J. Strathdee** (previously from Imperial)

work out how massless and massive gravitons could work together → answer maybe?

1972: Boulware and Deser prove fatal instability → answer no!

90s: question *reinvestigated* → answer no!! no!!

2000s: question *re...reinvestigated* → answer no!!! no!!! no!!! ... no !!!

2010: question *rerereinvestigated*, loophole in previous arguments → answer maybe?

2011: Theory of massive gravity constructed → answer yes!!!



Andrew Tolley (Imperial)

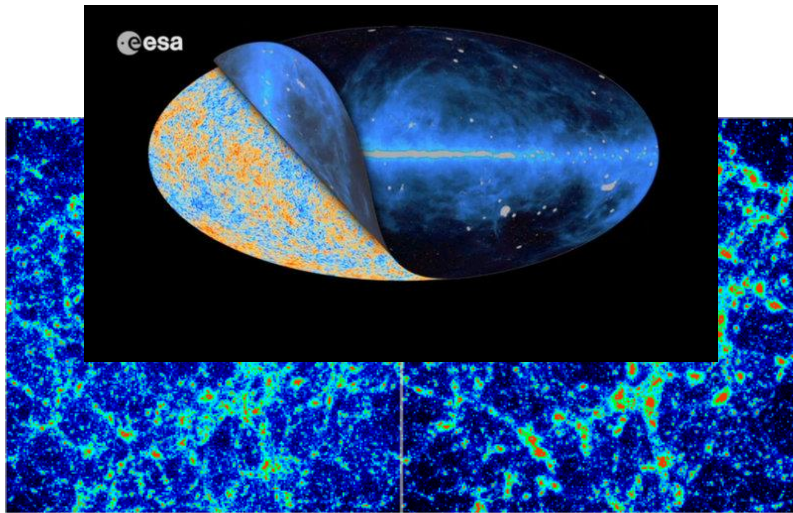


Gregory Gabadadze (NYU)

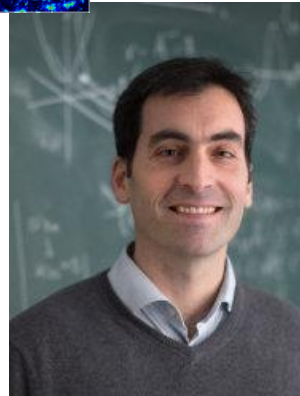
Observational & Exp Signatures?

Cosmology

- Evolution of Universe
- Structure Formation
- Primordial Gravitational Waves



Work on Cosmological Constraints
& constraints of fundamental physics
from GWs led by Carlo Contaldi
& astrophysics group



Gravitational Waves

GWs using atom interferometry
AION led by
Oliver Buchmuller (PI)



Tests of Equivalence Principle

Imperial led efforts with atomic clocks

Oliver Buchmuller



Mike Tarbutt

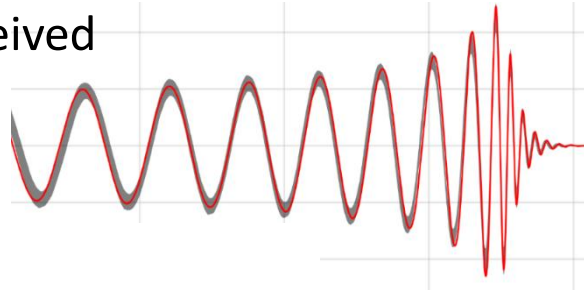
Search for Higgs Mechanism for Gravity



With colleagues at
Imperial College
London and beyond

Waves at different frequencies

Signal Received



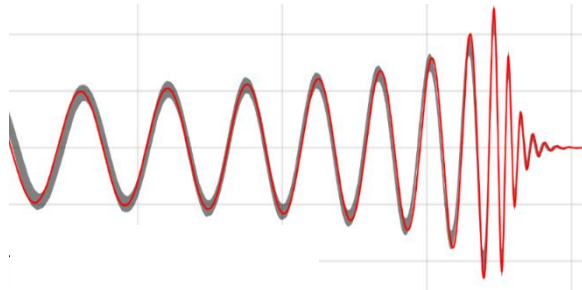
By looking at the shape of the wave, we can put a constraint on the speed of the different frequencies (ie determine the *dispersion relation*)

Put a bound on the mass of the graviton

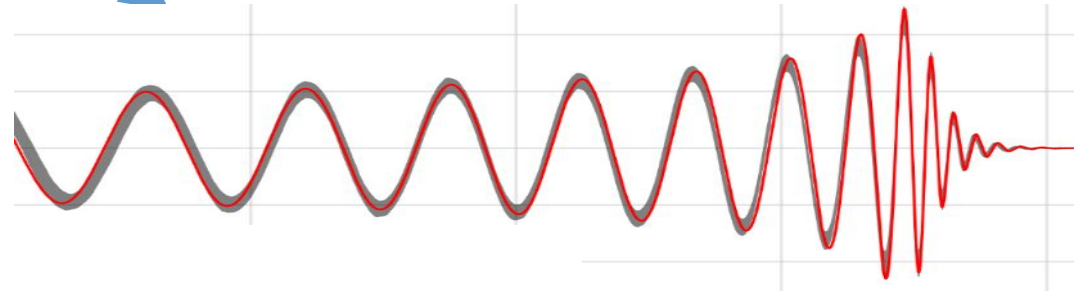
$$m_{\text{graviton}} < 10^{-22} \text{ eV } (\sim 10^{-58} \text{ kg } \dots)$$

If all frequencies travel at the same speed

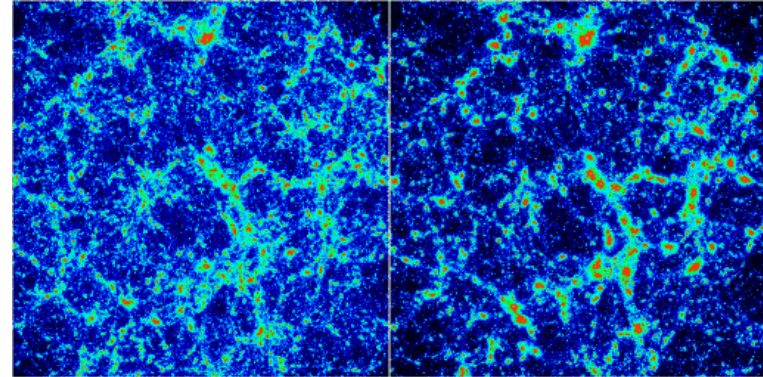
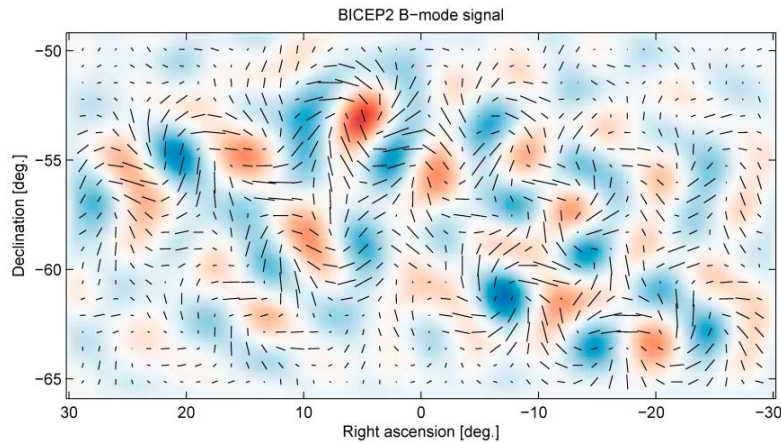
Long wavelengths slower than shorter wavelengths



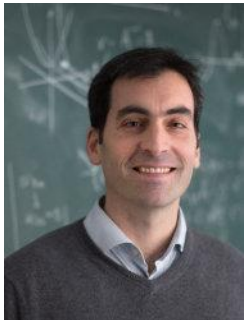
Signal Emitted



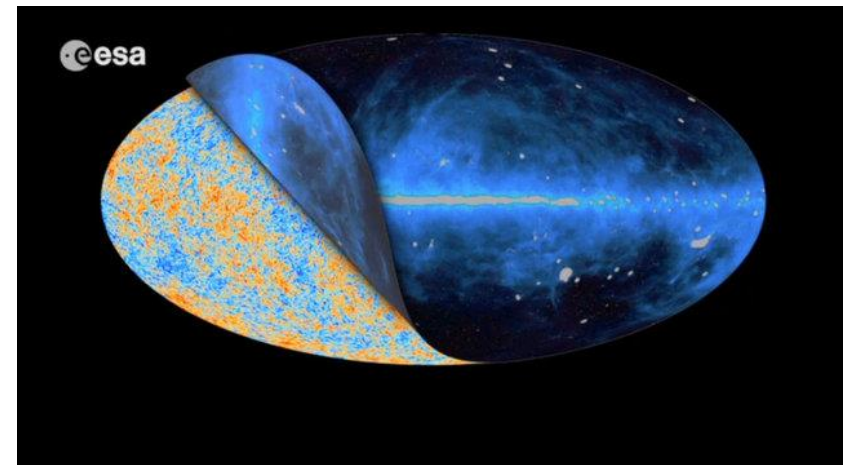
Bounds from Primordial Gravitational Waves & Cosmology



if primordial GWs are detected would imply the graviton is effectively massless at the time of recombination $m_{\text{eff}} \ll 10^{-29} \text{eV}$
Would also affect structure formation

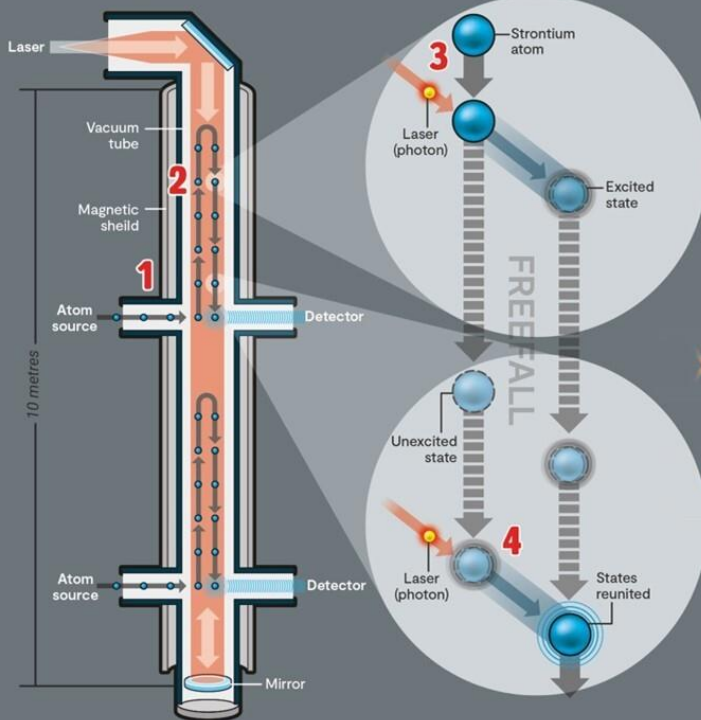


Connects with work on Cosmological Constraints and constraints of fundamental physics from Gravitational Waves led by **Carlo Contaldi**

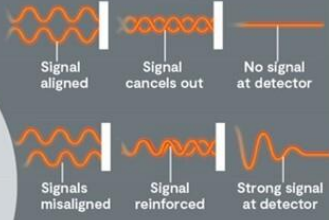


Detecting GWs using atom interferometry

AION Atom Interferometer Observatory and Network

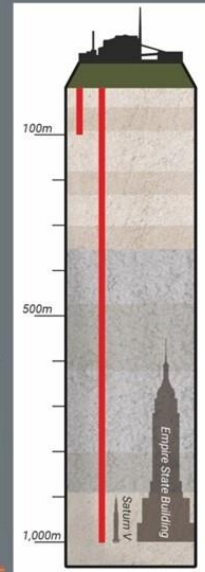


- 1 Strontium atoms are cooled to a fraction above absolute zero and then transported to the centre of a vacuum system.
- 2 The atoms are launched upwards and spend around a second in freefall.
- 3 As an atom falls, a laser pulse is fired at it. Because of its quantum properties, the atom splits into two states – one that absorbs the energy and momentum of the laser photon and receives a kick – and one that does not and carries on falling. This creates two 'beams' of falling atoms.
- 4 A second laser pulse reunites the atom in the excited state with its slower counterpart. A final laser pulse is used to measure the atom.
- 5 If nothing interacted with the atoms as they fell, their signals will align. However, if something has delayed one of the falling atoms, altered its path, or its properties, the signals will not align and an interference pattern will be measured.



In the case of gravitational waves, this would involve a change in the shape of the space through which the atom is falling. In the case of dark matter, it would involve a change in the properties of the atom itself.

In effect, the two falling atoms act like the two arms of a laser interferometer like LIGO. Any changes in the wavelength of one atom 'arm' will become apparent when the signals are recombined.



Once the technique is proven at the 10 metre scale, the project will be scaled up to a 100 metre facility that will be constructed within an existing mineshaft at the Boulby Underground Laboratory. The hope is that the project can then be scaled up to 1,000 metres, which will require a new underground facility.

Infographic: Ben Gilliland, STFC

Led by Oliver Buchmuller (PI)

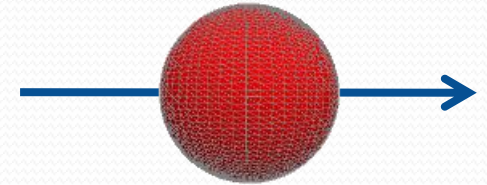


Gravitational Waves in General Relativity

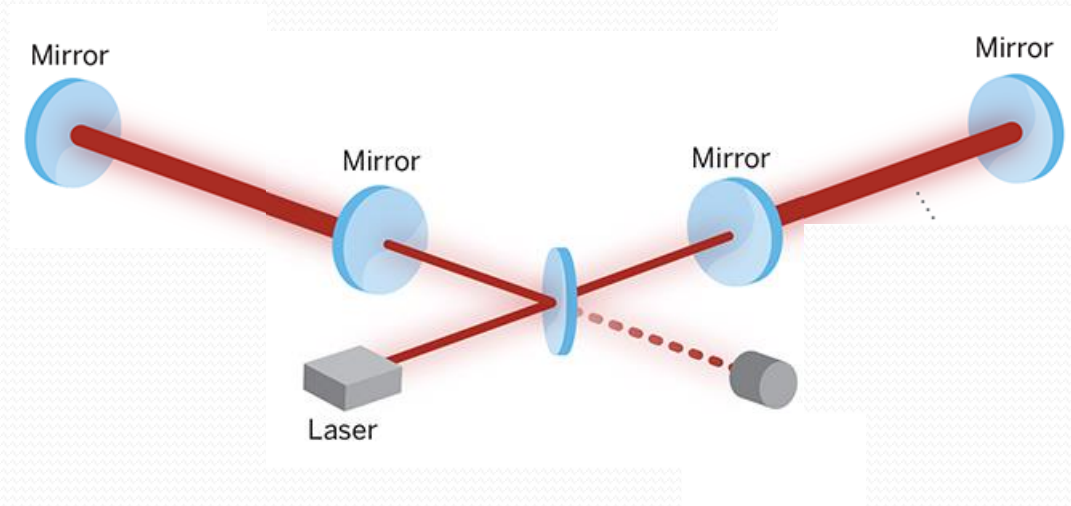
± 2 tensors



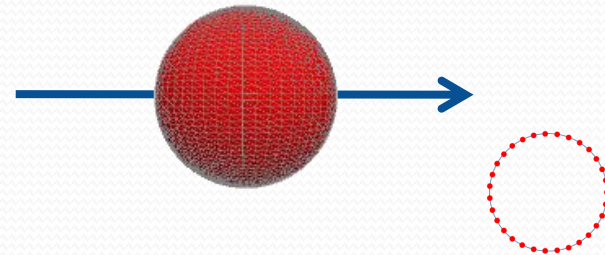
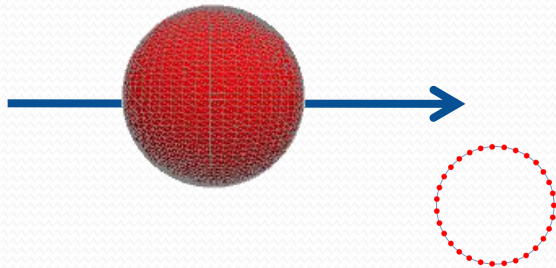
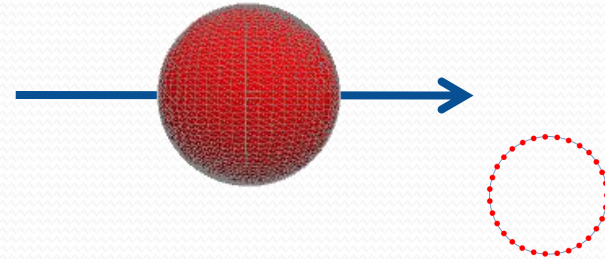
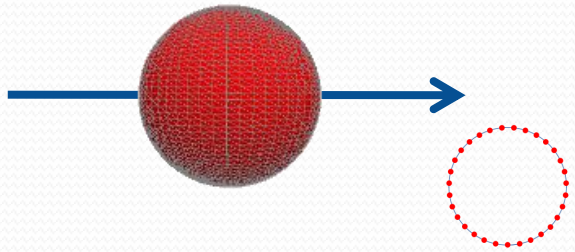
Straight on view



Side view



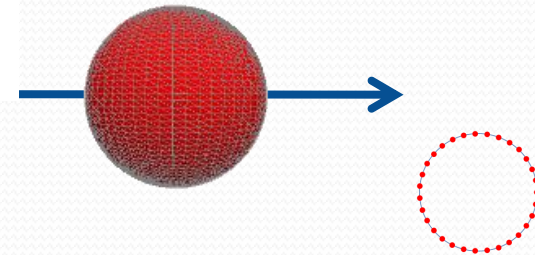
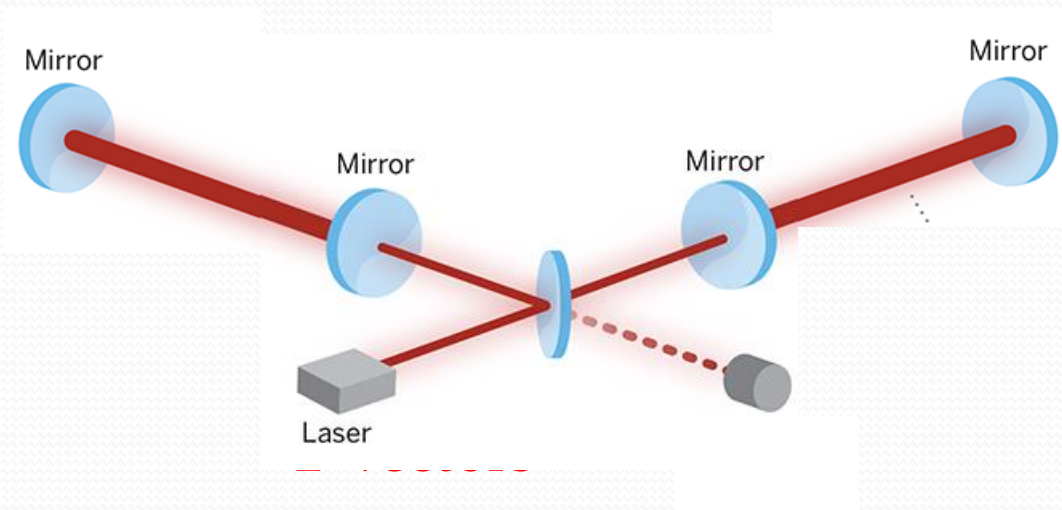
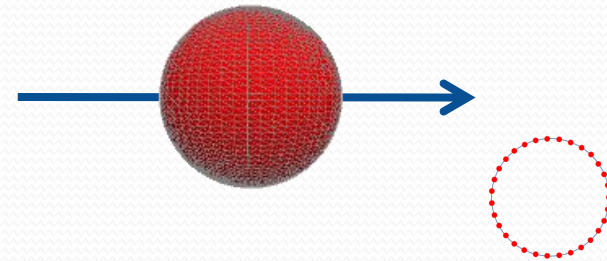
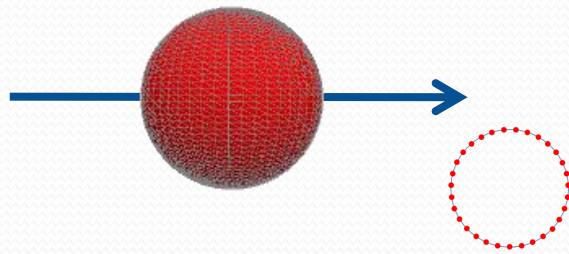
In principle GW could have 4 other polarizations



2 'vectors'

2 'scalars'

In principle GW could have 4 other polarizations



2 'scalars'

(Slightly) Breaking Equivalence Principle



GR tensor
modes



Additional
Massive
Gravity
mode



Imperial led efforts
with atomic clocks and
other tests of equivalence principle



Mike Tarbutt



Oliver Buchmuller