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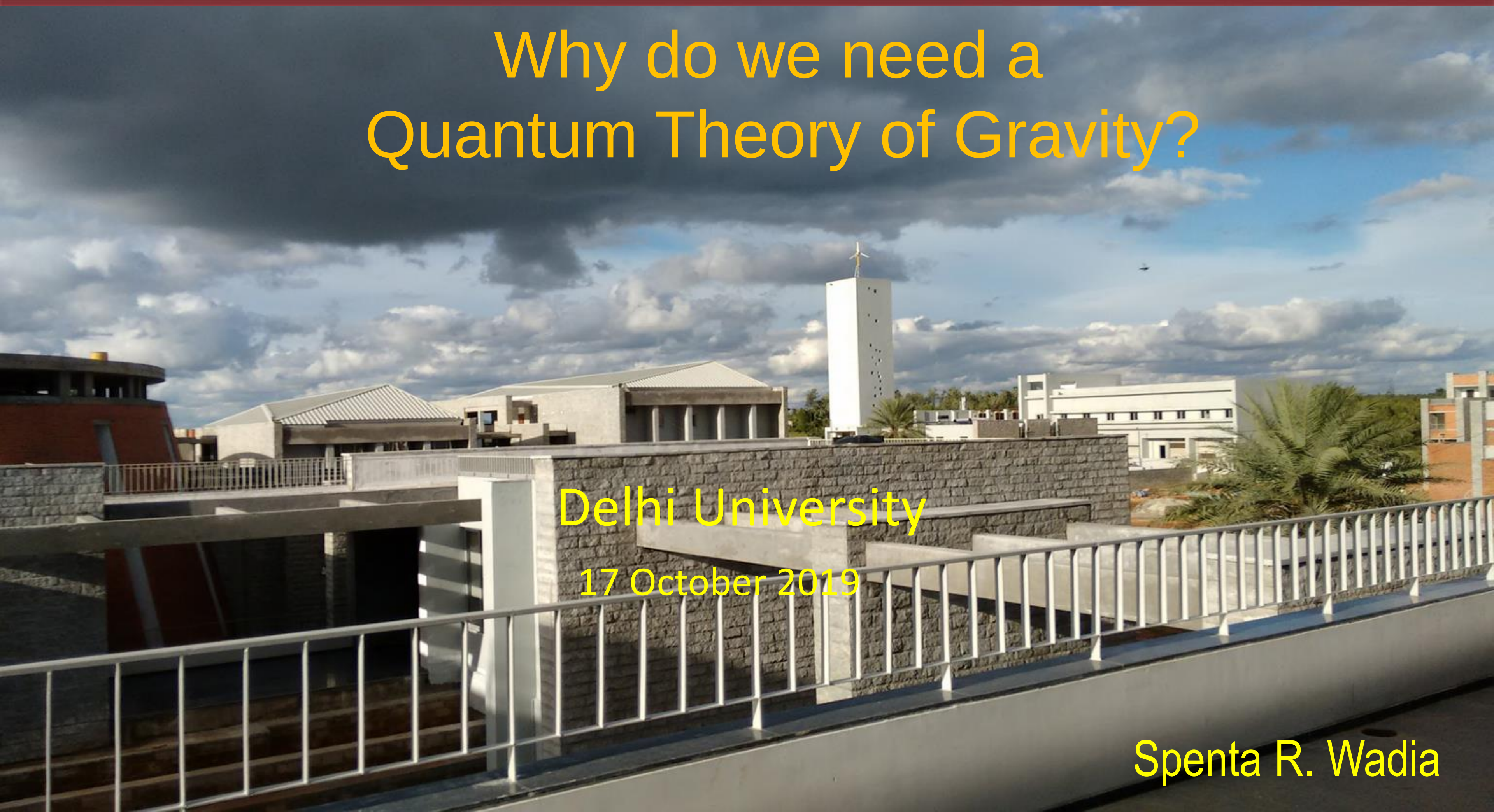
INTERNATIONAL CENTRE *for* THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

Why do we need a Quantum Theory of Gravity?



Delhi University

17 October 2019

Spenta R. Wadia

Galileo (1564-1642)

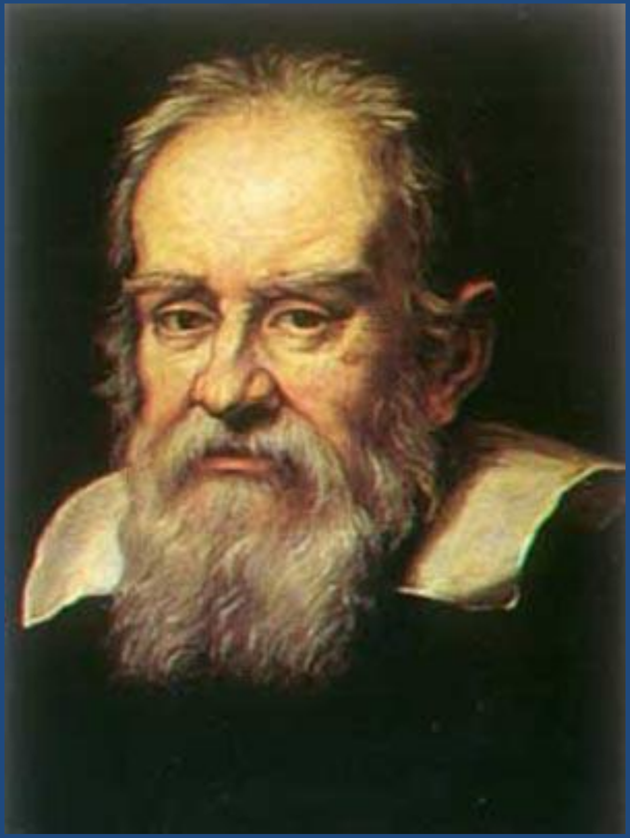
A pioneer of the modern scientific method

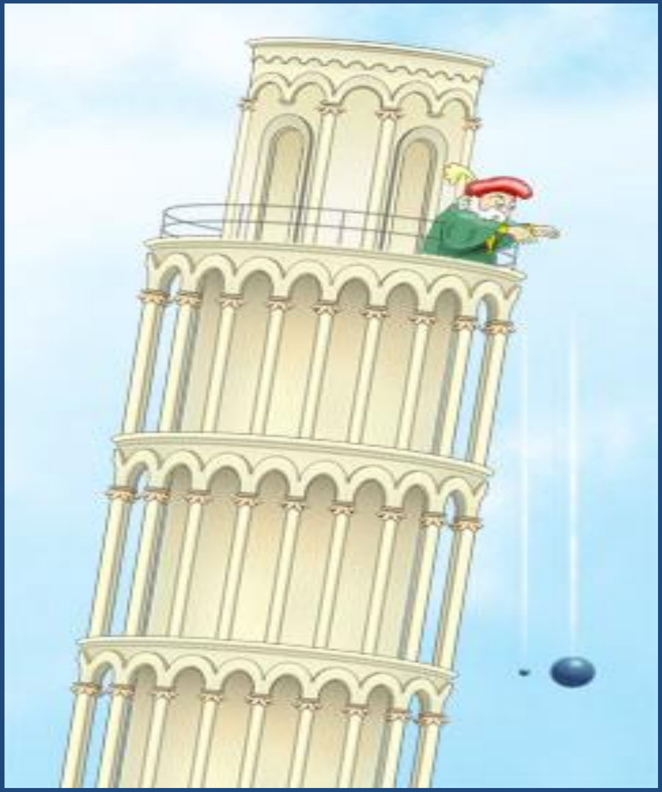
Discovered a new law of gravity

Gravity acts in the same way on all bodies: they all fall in the same way independent of their mass:

$m_{inertial} = m_{gravitational}$

($1/10^{13}$ precision, today) Plays a key role in Einstein's theory of General Relativity





Isaac Newton (Principia Mathematica 1687)

Establishes a framework of mechanics

Newton formulated the laws of motion in terms of the flow in time of the position of a point particle in 3-dims.

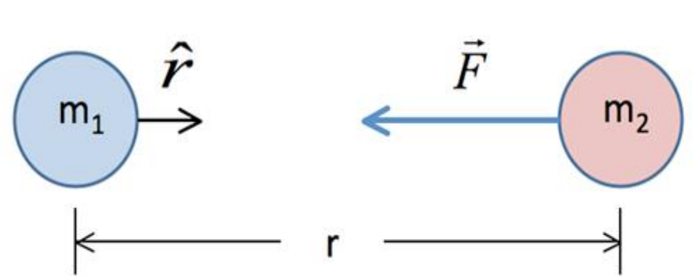
(x(t), y(t), z(t)) is a curve; velocity and acceleration are given by one and two time derivatives

Time is absolute and the same for all observers. Coordinates may be rotated or moved with constant velocity.

Newton's law of motion:

Force = $m_{inertial}$ x **Acceleration**

Newton's law of Universal Gravitation



$$\vec{F} = -\frac{Gm_1m_2}{r^2}\hat{r}$$

Force acts instantaneously at a distance

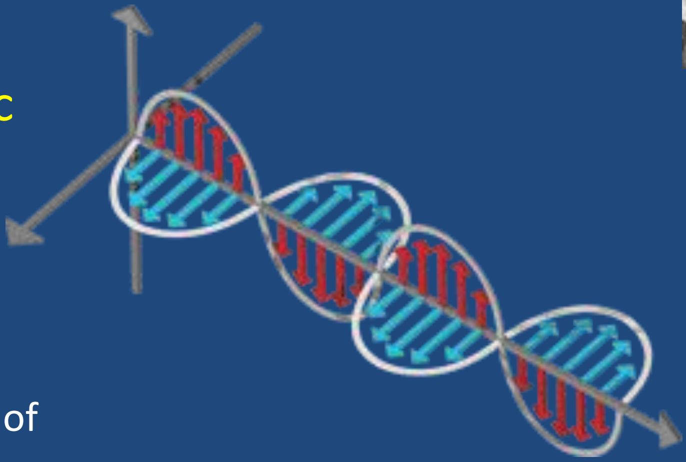
Newton (1692): "That one body may act upon another at a distance through a vacuum without the mediation of anything else, by and through which their action and force may be conveyed from one another, is to me so great an absurdity that, I believe, no man who has in philosophic matters a competent faculty of thinking could ever fall into it."

Newton (1713) "I have not yet been able to discover the cause of these properties of gravity from phenomena and I feign no hypothesis. It is enough that gravity does really exist and acts according to the laws I have explained, and that it abundantly serves to account for all the motions of celestial bodies."

Electric and Magnetic **Fields** and **Waves**

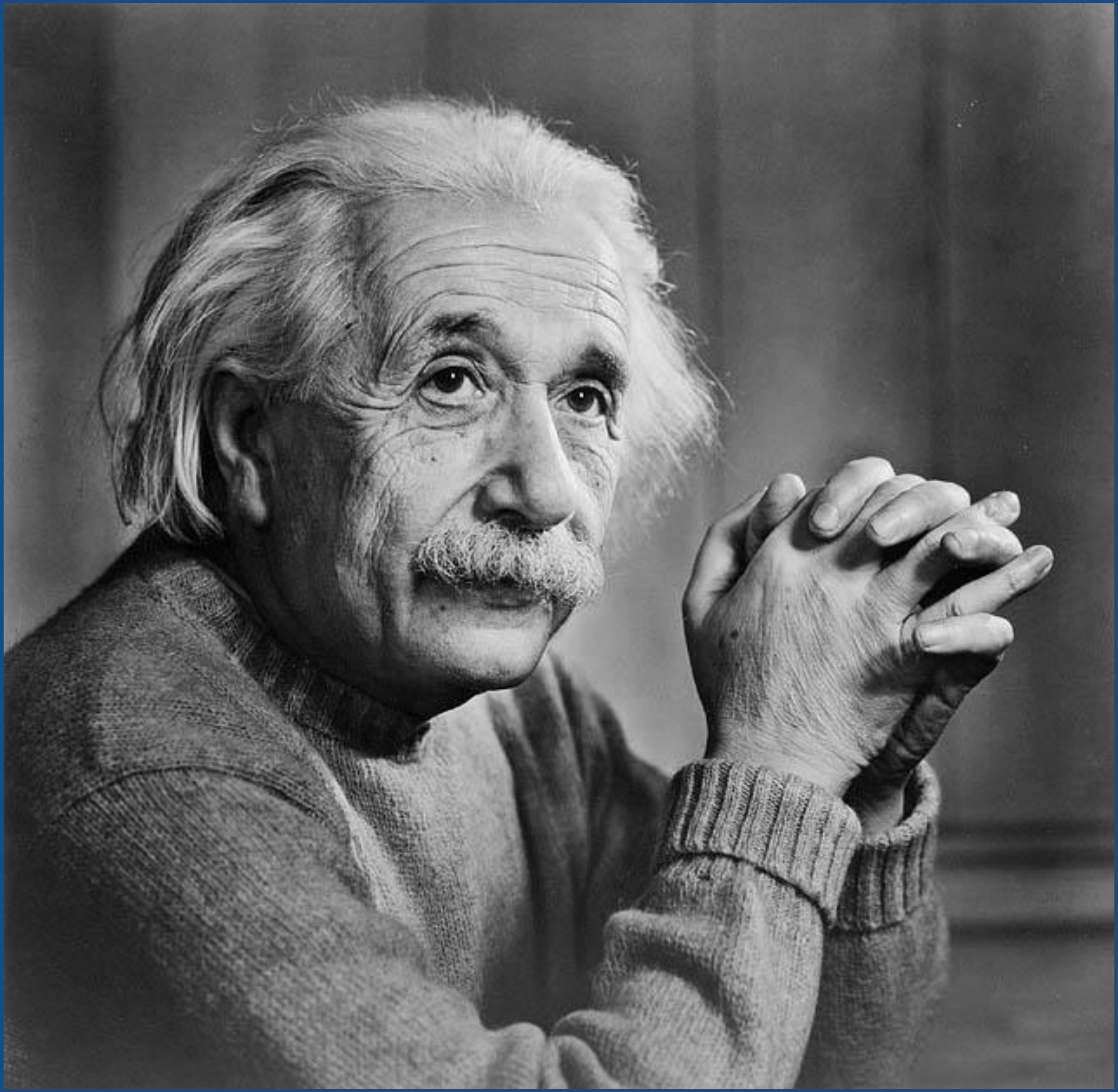
Michael Faraday had demonstrated that light is polarized by a magnetic field.

James Clerk Maxwell unified electricity and magnetism, predicted the existence of electromagnetic waves and identified light as an electromagnetic wave of oscillating electric and magnetic fields moving with a speed c (in vacuum) (1865): $c = 3.1 \times 10^5$ kms/sec



Heinrich Hertz demonstrated existence of radio waves that were predicted by Maxwell's theory with properties exactly the same as visible light (1887) except wavelength is 10^4 times longer.

Albert Einstein (1879-1955)

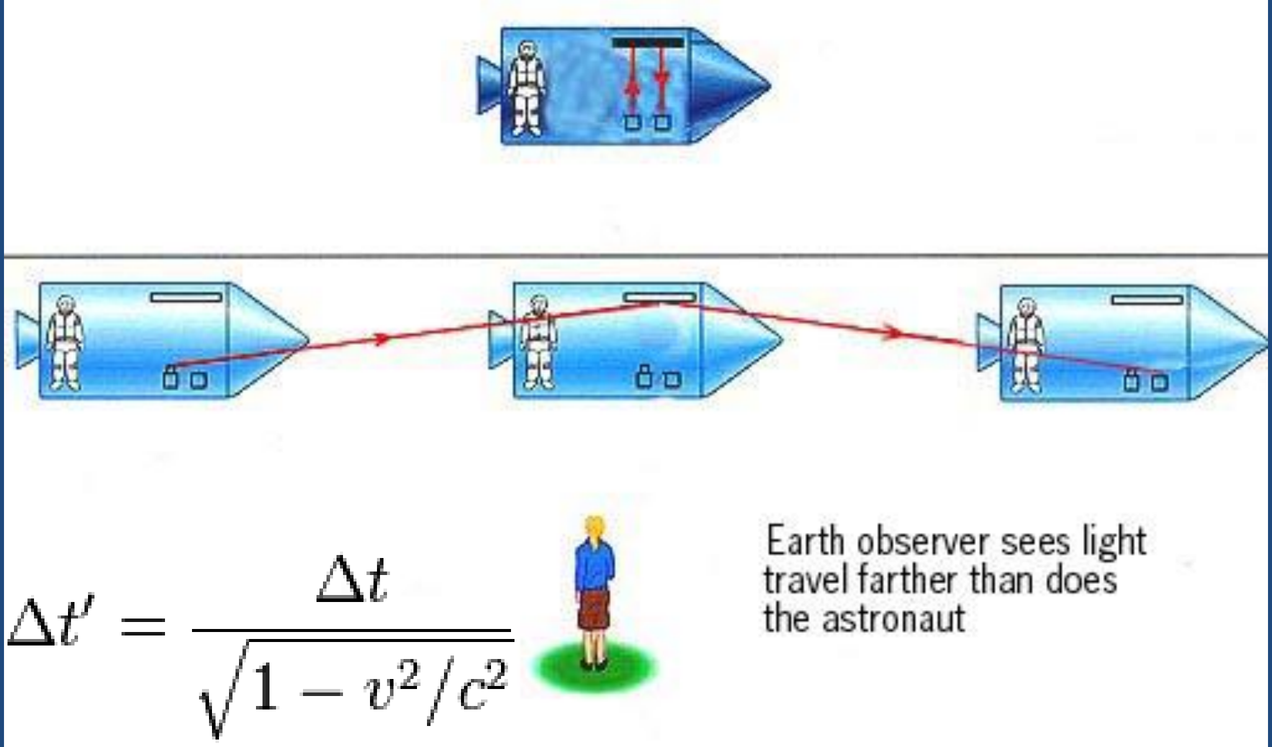


Lorentz, Poincare, Einstein: Special Relativity (1905)

Implications of Maxwell's theory:

Speed of light is the same whether you run towards it or away from it. Space and time have to adjust themselves to ensure this!

Time intervals between events depend on your state of motion; things happen (according to us) more slowly for a moving observer than for us.



$$\Delta t' = \frac{\Delta t}{\sqrt{1 - v^2/c^2}}$$

Minkowski:
space-time geometry

$$ds^2 = (c\Delta t)^2 - (\Delta x)^2$$

Einstein’s Puzzles

Newton’s law of gravity in conflict with special relativity, and why only special relativity?

- That the force of gravity acts instantaneously is not consistent with Special Relativity! Einstein would like to have the force of gravity communicated at the speed of light by a field analogous to the electro-magnetic field of Faraday and Maxwell.
- Special Relativity is restricted to frames with relative constant velocity, but the laws of physics must be valid in any reference frame including those which are accelerating…

Special Relativity, Gravity → General Relativity

The resolution of Einstein's puzzles lead to the General Theory of Relativity

1) Where the gravitational force felt in a small neighborhood of space-time is understood in terms of acceleration of the frame. The `force of gravity' is not instantaneous.
2) Where the simple linear mixing of space and time in special relativity is replaced by a non-linear mixing, called a general coordinate transformation.

Einstein 1915

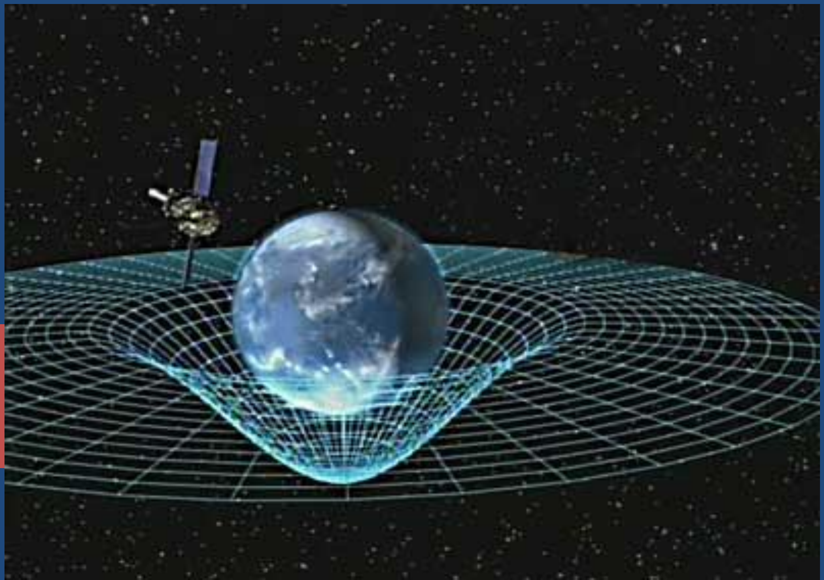
General Relativity: Gravity and Geometry

The equations of GR describe the shape changes of the geometry of space-time caused by massive objects to which other objects respond.

In a curved space-time an object follows a path that maximizes the time in the frame of the object (proper time).

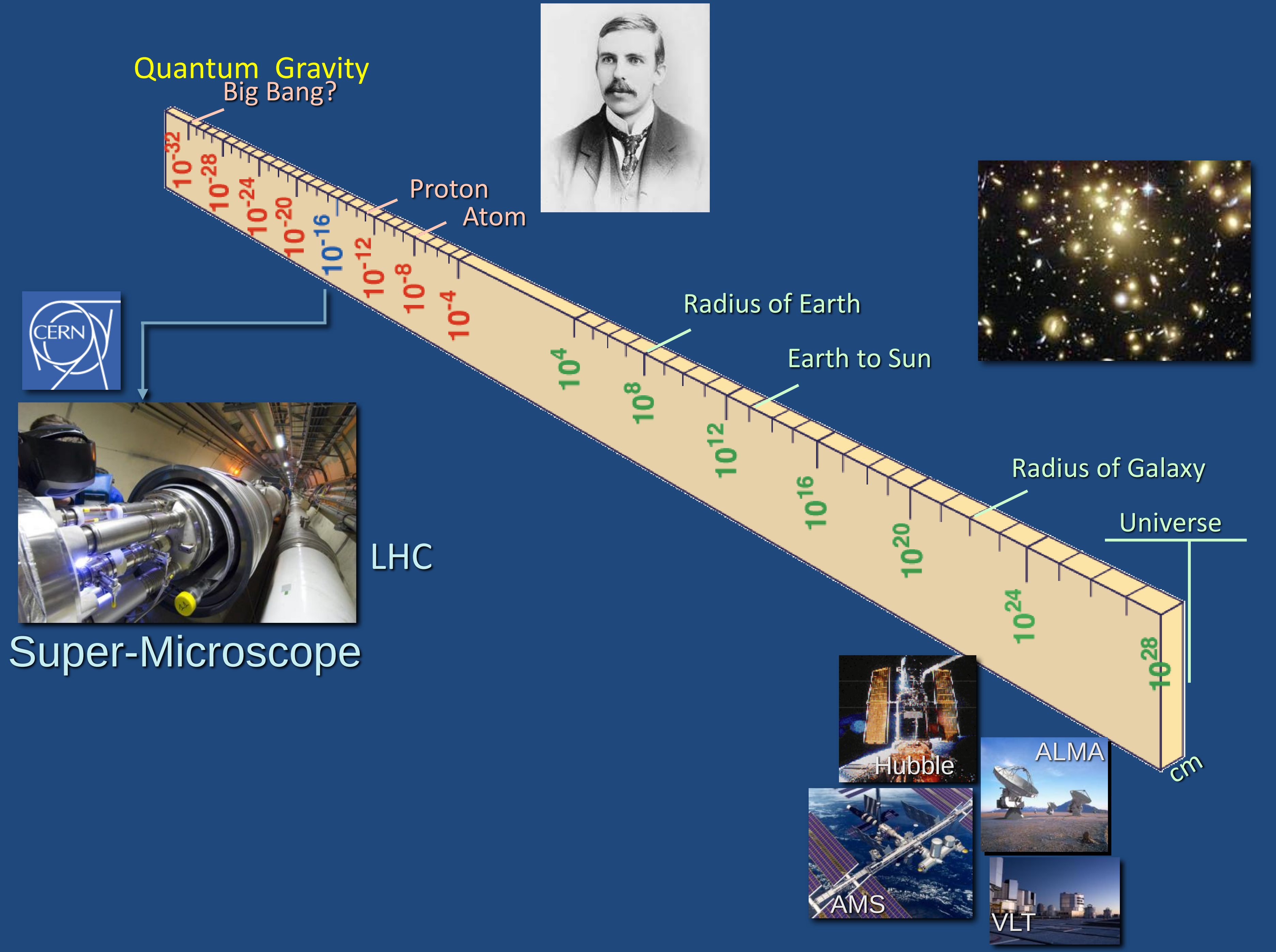
In GR the space-time grid is `elastic', communicative and causal…but very very stiff!

GR is a good theory for physics on large scales

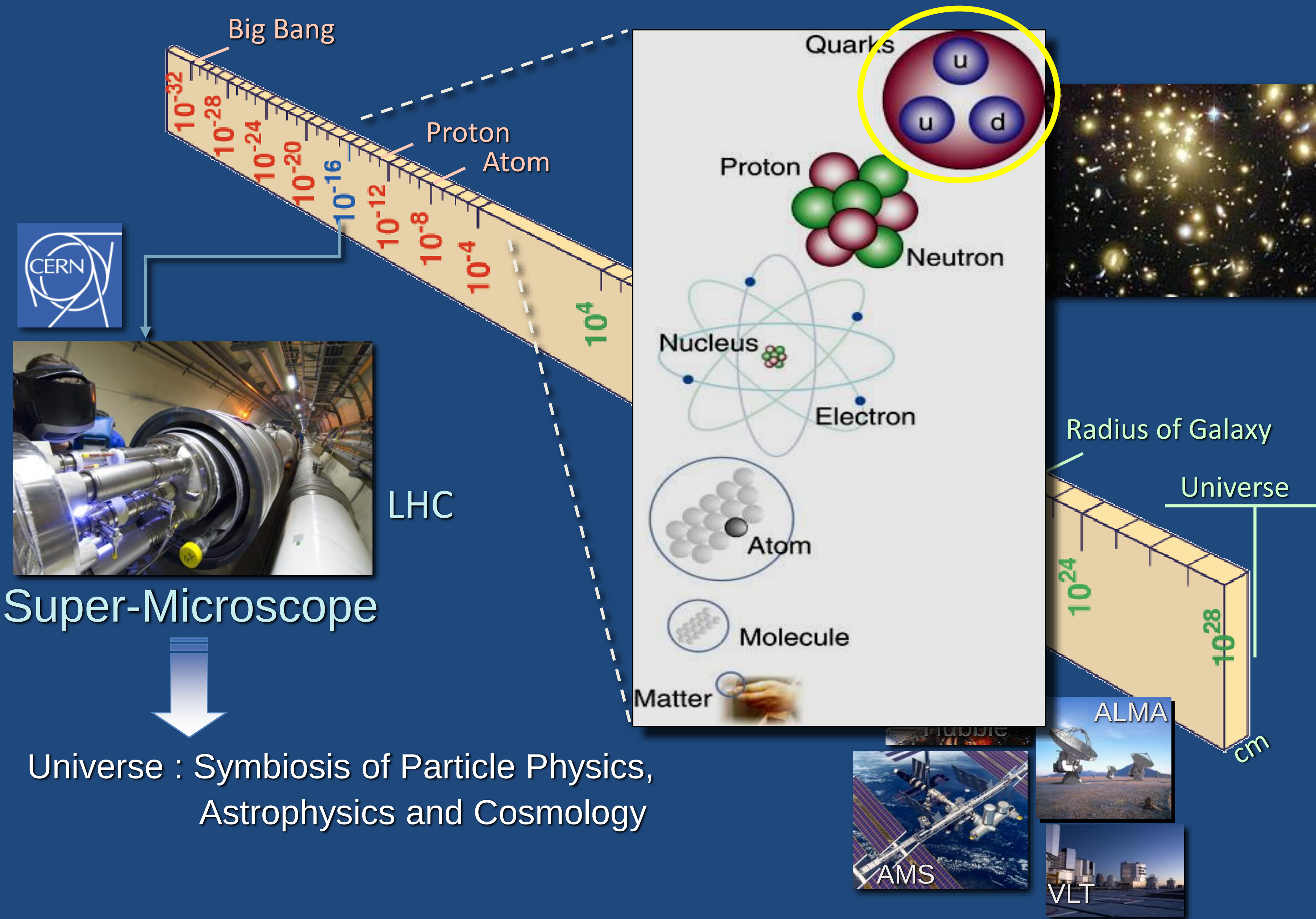


Length scales in the universe:

10^{-32} cms to 10^{28} cms



Quantum Gravity
Big Bang?
10^{-32}
10^{-28}
10^{-24}
10^{-20}
10^{-16}
10^{-12}
10^{-8}
10^{-4}
Proton
Atom
10^{4}
10^{8}
10^{12}
10^{16}
10^{20}
10^{24}
10^{28}
Radius of Earth
Earth to Sun
Radius of Galaxy
Universe
cm
CERN
LHC
Super-Microscope
Hubble
ALMA
AMS
VLT


Big Bang
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10^{-32}
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10^{-4}
10^{4}
CERN
LHC
Super-Microscope
Quarks
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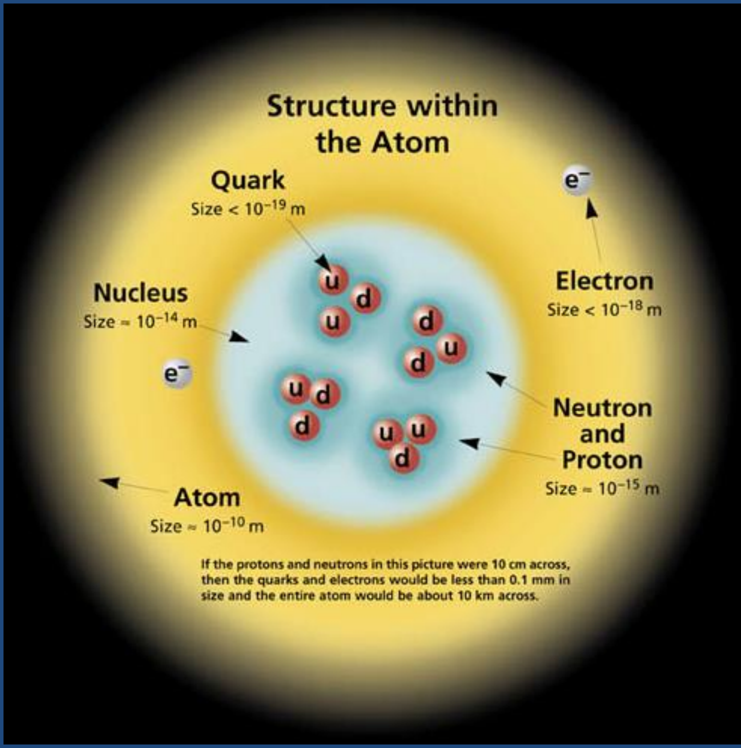
u
d
Proton
Neutron
Nucleus
Electron
Atom
Molecule
Matter
Radius of Galaxy
Universe
10^{24}
10^{28}
cm
ALMA
AMS
VLT
Universe : Symbiosis of Particle Physics,
Astrophysics and Cosmology

Quantum Mechanics



- A 20th century scientific revolution.
- New laws for all particles
  especially below atomic scales.
- Electronic devices, lasers, superconductors
- Colliding elementary particles in the LHC in Geneva all follow the laws of quantum mechanics … tested to 10^{-16} cms.
- Planck, Einstein, Bohr, Heisenberg, Schrodinger, Born, Dirac, Feynman and others

To summarize
the Road Travelled so far…

from Classical Mechanics

to Electrodynamics and Special Relativity

to General Relativity

to Quantum Mechanics

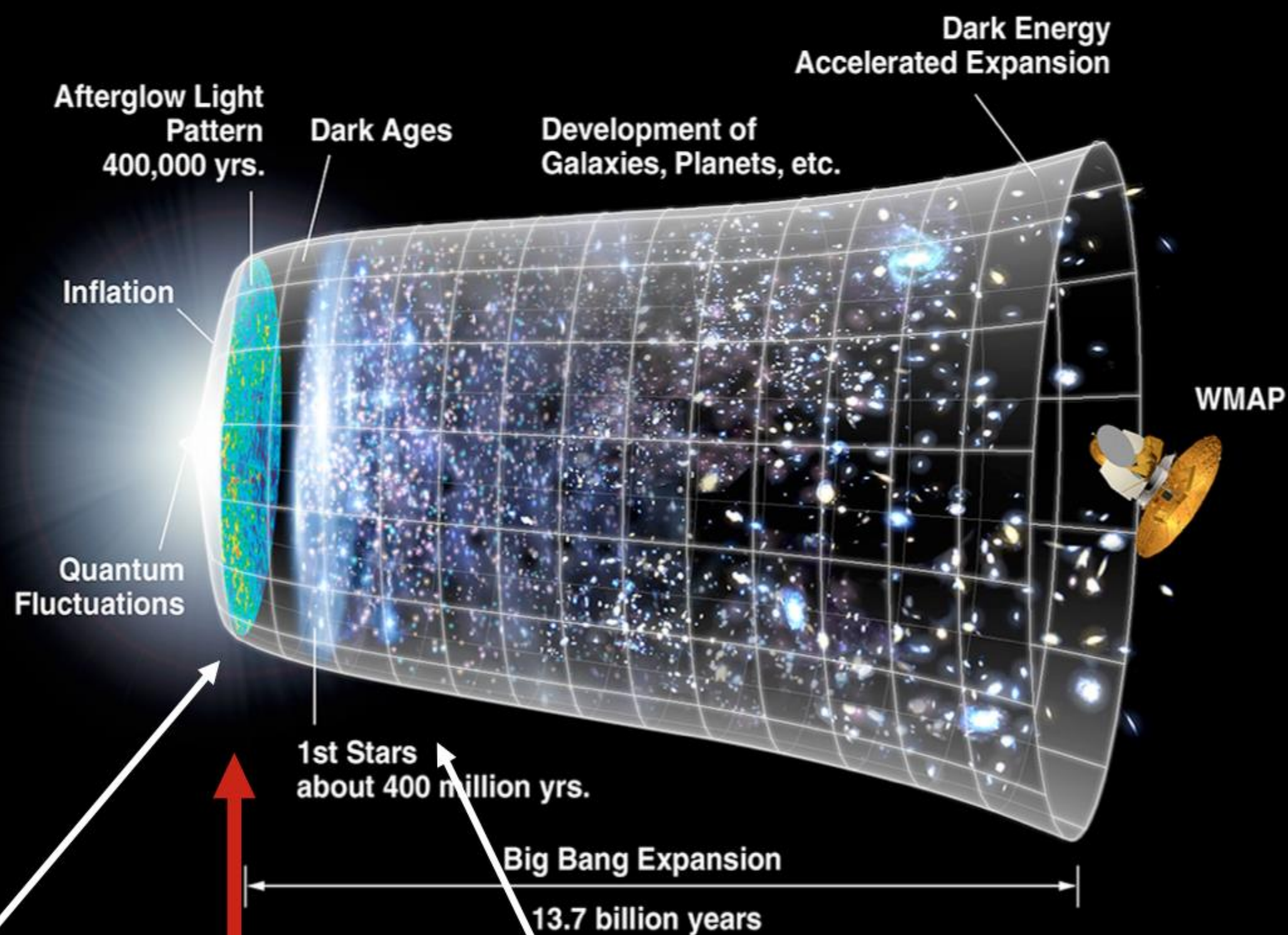
Now back to General Relativity….

Einstein’s equations have surprising and remarkable solutions

- Black Holes (Schwarzschild 1916)
- Gravitational waves (Einstein 1916)
- Expanding and accelerating space-time (+ve cosmological constant) (Friedman 1922, LeMaitre 1927)

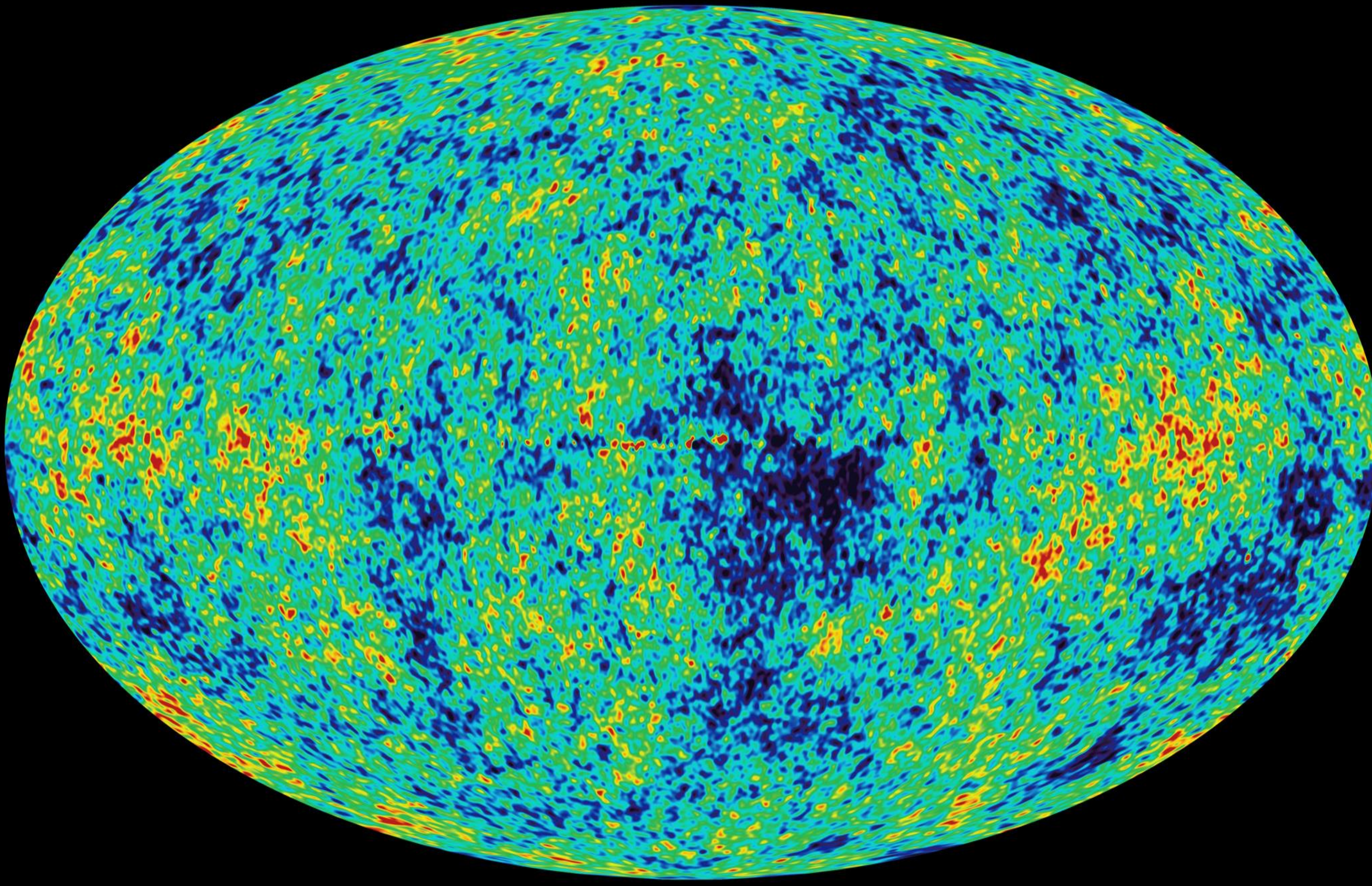
GR becomes a framework to discuss black holes, gravitational waves and cosmology

The Standard Model of Cosmology

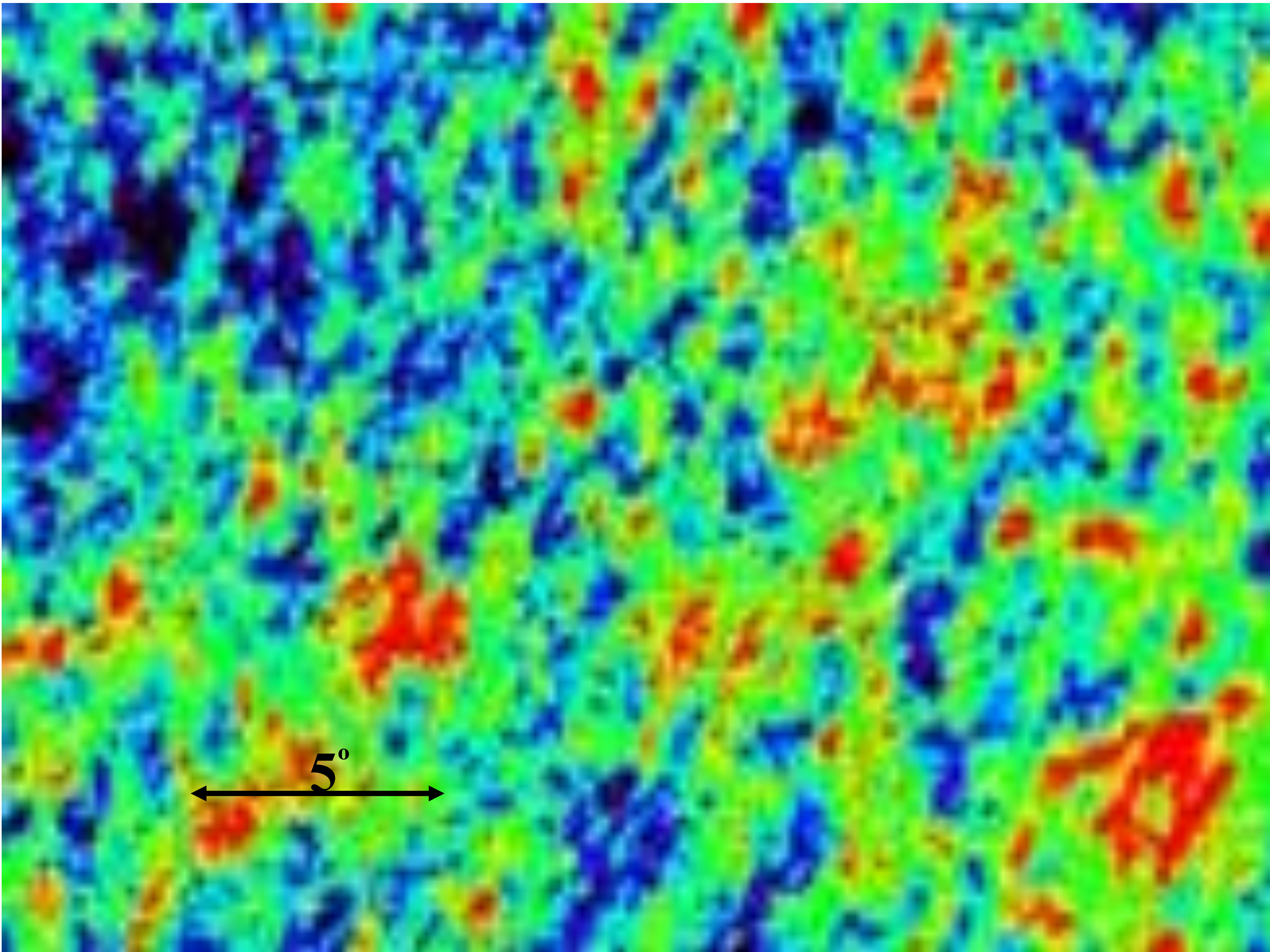


Surface of last scattering
at “decoupling.”

“Reionization”

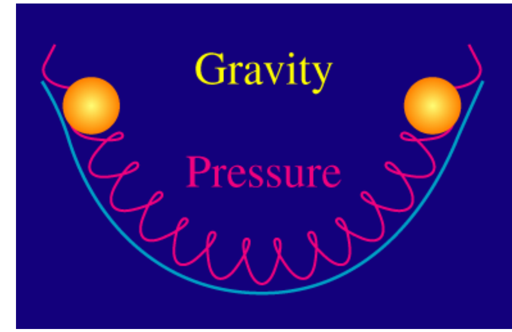


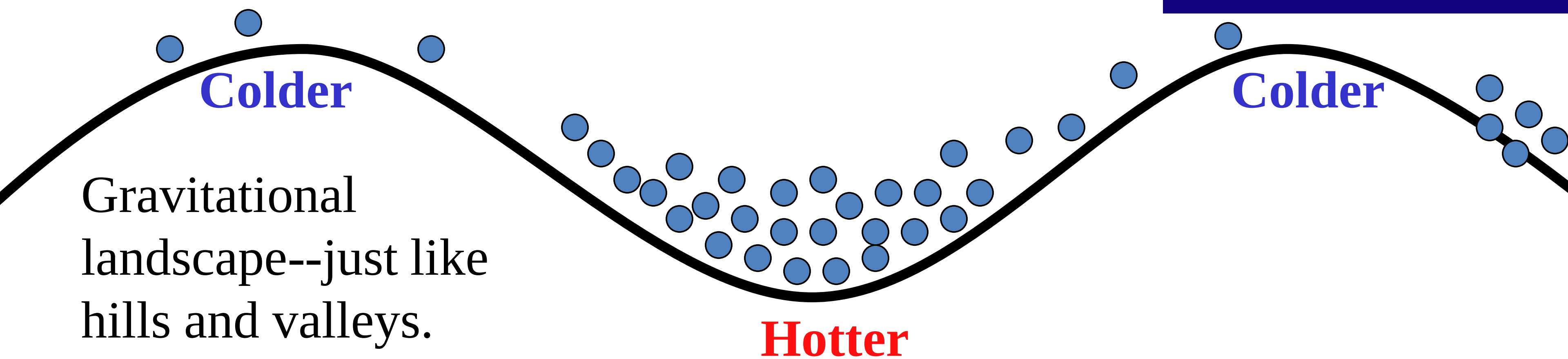
A Picture of the infant universe revealed in micro-wave radiation. Mean temperature 2.71 deg K. Temperature fluctuations are are between -200 to +200 micro-Kelvin


5°

How do we get hot and cold patches?

W. Hu





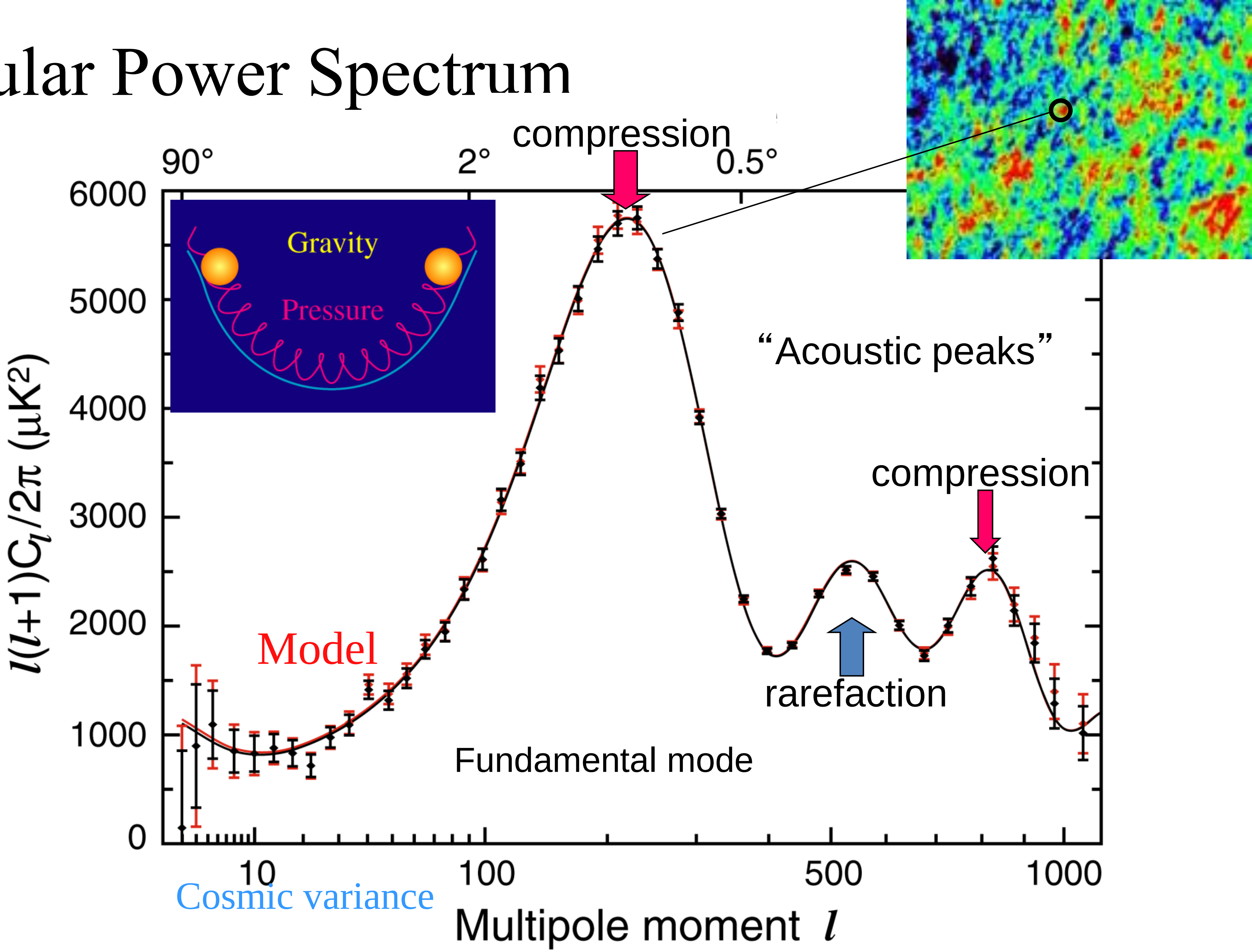
Gravitational landscape--just like hills and valleys.

1 degree in angle

James Peebles awarded the 2019 Nobel Prize for Physics

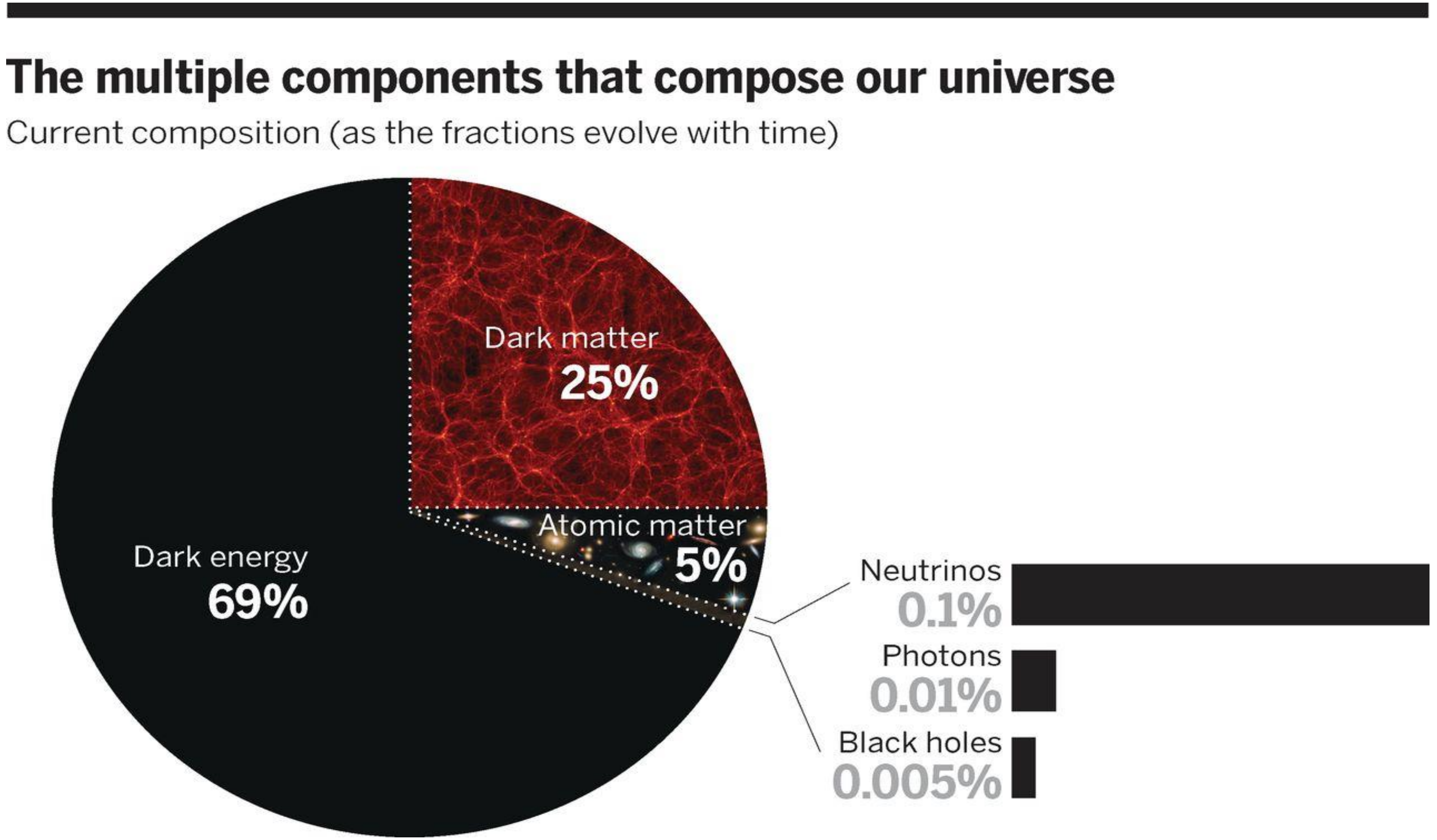
(Lyman Page)

Angular Power Spectrum



Final WMAP Power Spectrum

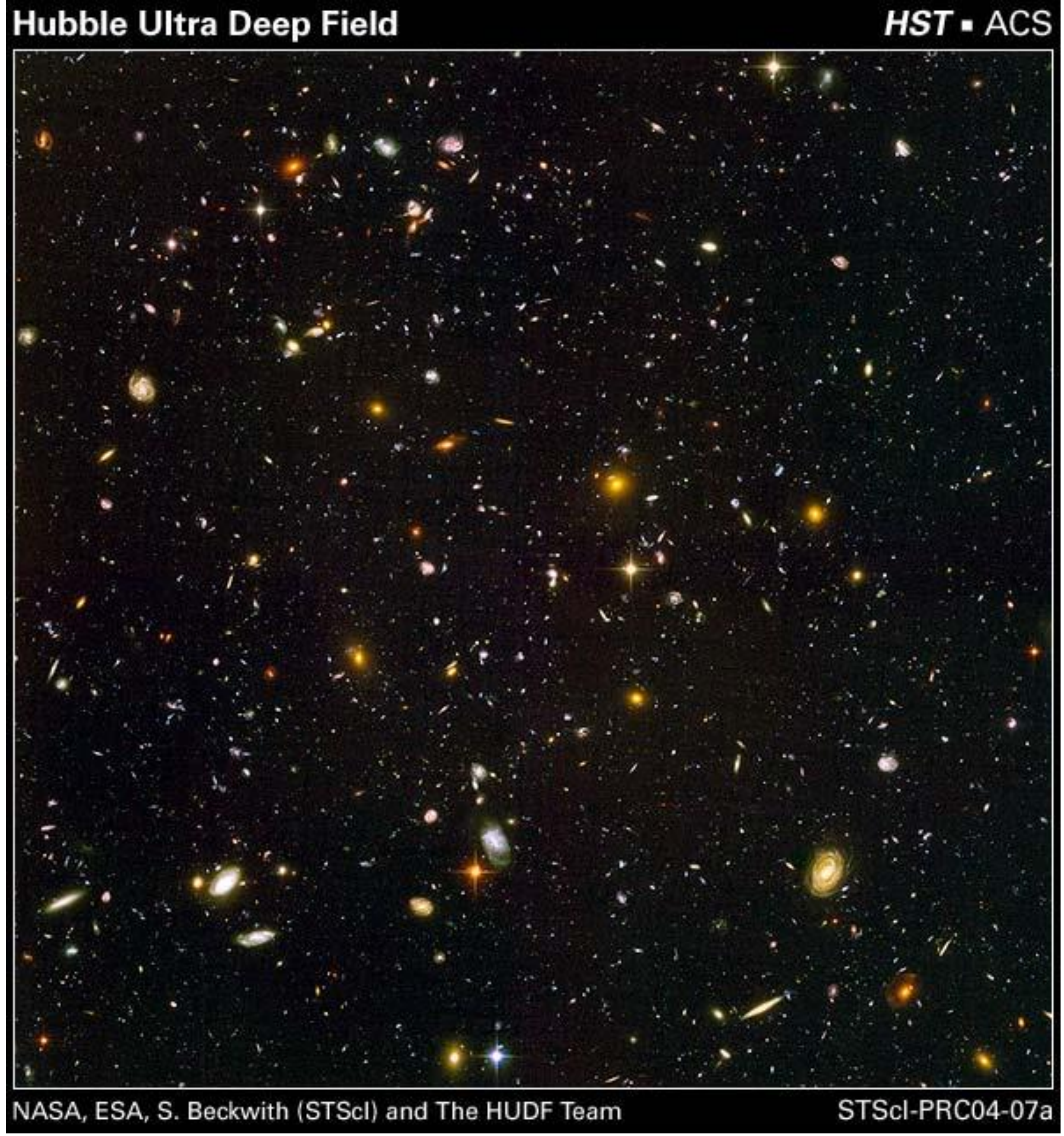
The multiple components that compose our universe. Dark energy comprises 69% of the mass energy density of the universe, dark matter comprises 25%, and “ordinary” atomic matter makes up 5%.



David N. Spergel Science 2015;347:1100-1102

Published by AAAS

The the seeds of observed galaxies are tiny density fluctuations at the surface of last scattering which are in turn imprinted by fluctuations of quantum gravity during inflation.



~10^{11} Galaxies in Observable Universe

STScI/NASA Field & Levay

Summary: Quantum Gravity is needed for the large scale structure of the universe

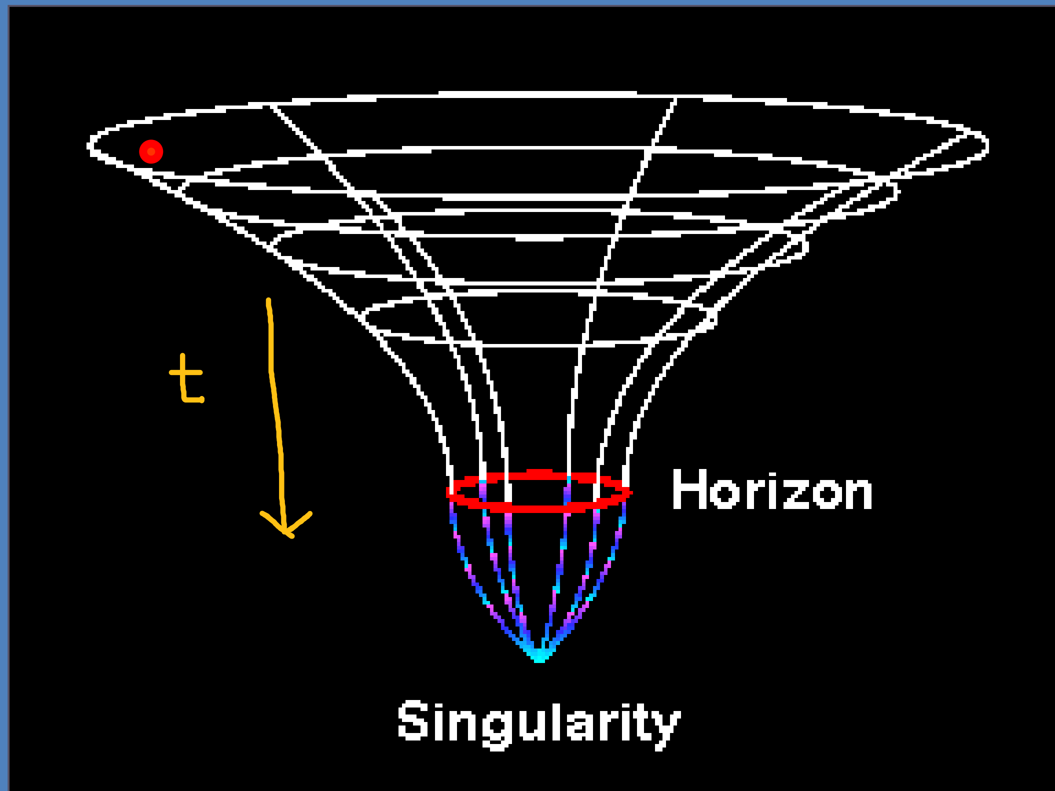
Precision experiments of CMB indicate that a fundamental theory of the large scale structure of the universe requires a quantum theory of gravity which at low energies reduces to Einstein's theory of gravity.

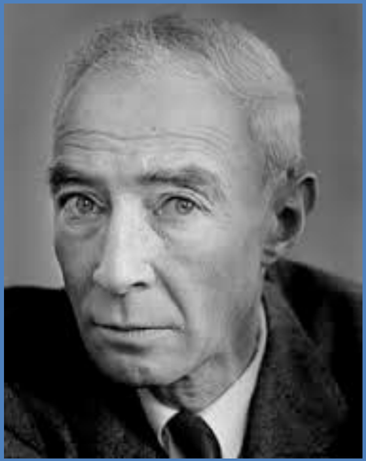
$$g_{\text{eff}}^2 \sim \frac{(\text{energy})^2}{M_{\text{Planck}}^2} = \frac{l_{\text{Planck}}^2}{(\text{distance})^2}$$

$$l_{\text{Planck}} \sim 10^{-35} m \ , \qquad M_{\text{Planck}} = 10^{16} Tev$$

However a quantum version of Einstein's equations leads to divergent answers!

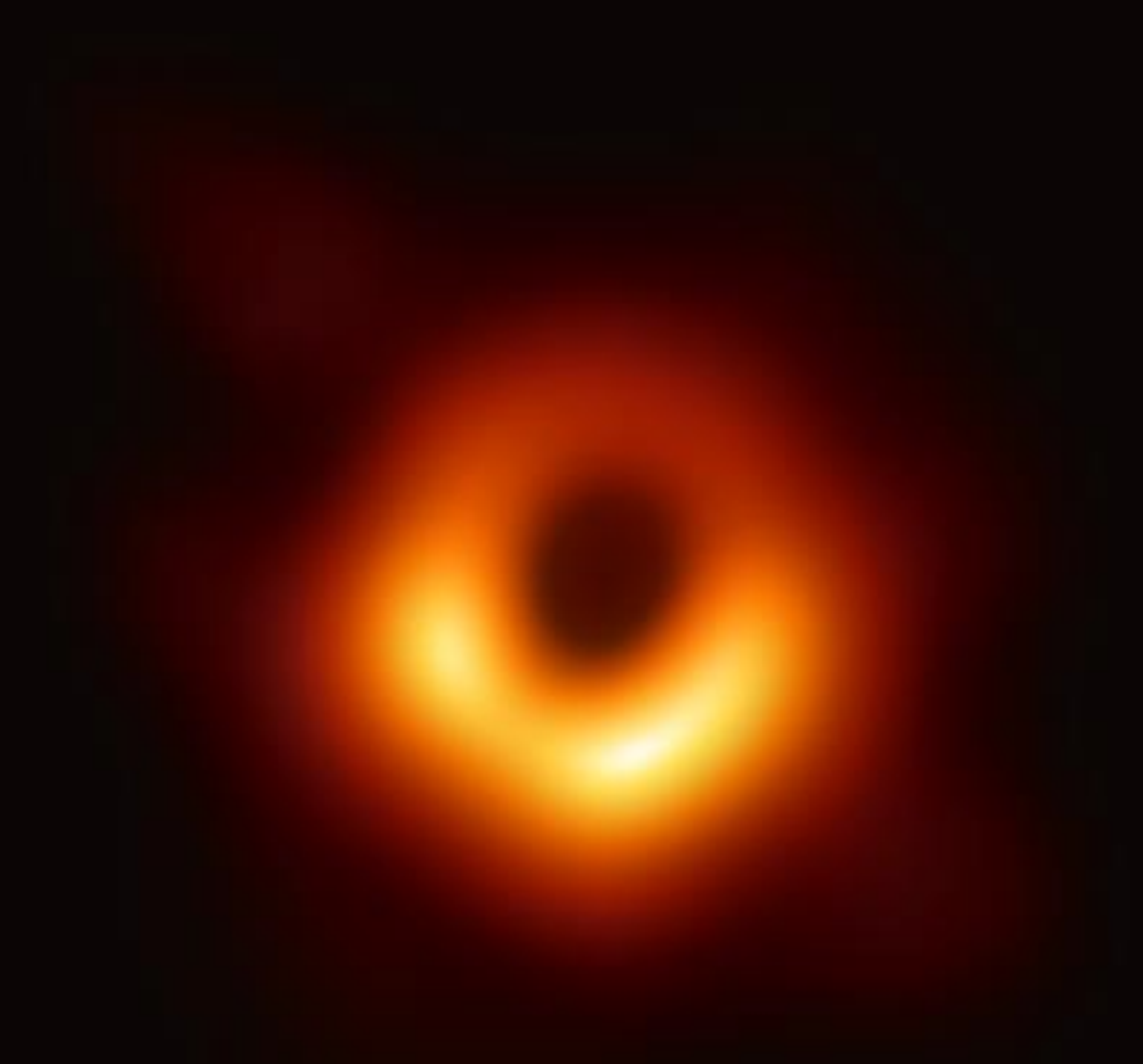
General Relativity predicts Black Holes





Black holes are characterized by
a horizon and a singularity. They exist in Nature!

Schwarzschild Chandrasekhar & Oppenheimer



The first image of a supermassive black hole and its shadow in the Messier 87 galaxy , in the Virgo cluster. (Event Horizon Telescope collaboration)

Simulation slowed down 100x

Andy Bohn, François Hébert, and William Throwe, SXS Collaboration

Till now we were discussing the classical physics of black holes

In Quantum Mechanics black holes are hot due to the presence of a HORIZON

Hawking calculated the temperature of the black hole

$$T_{\mathrm{H}} = \frac{\hbar c^3}{8\pi G k_{\mathrm{B}} M}$$

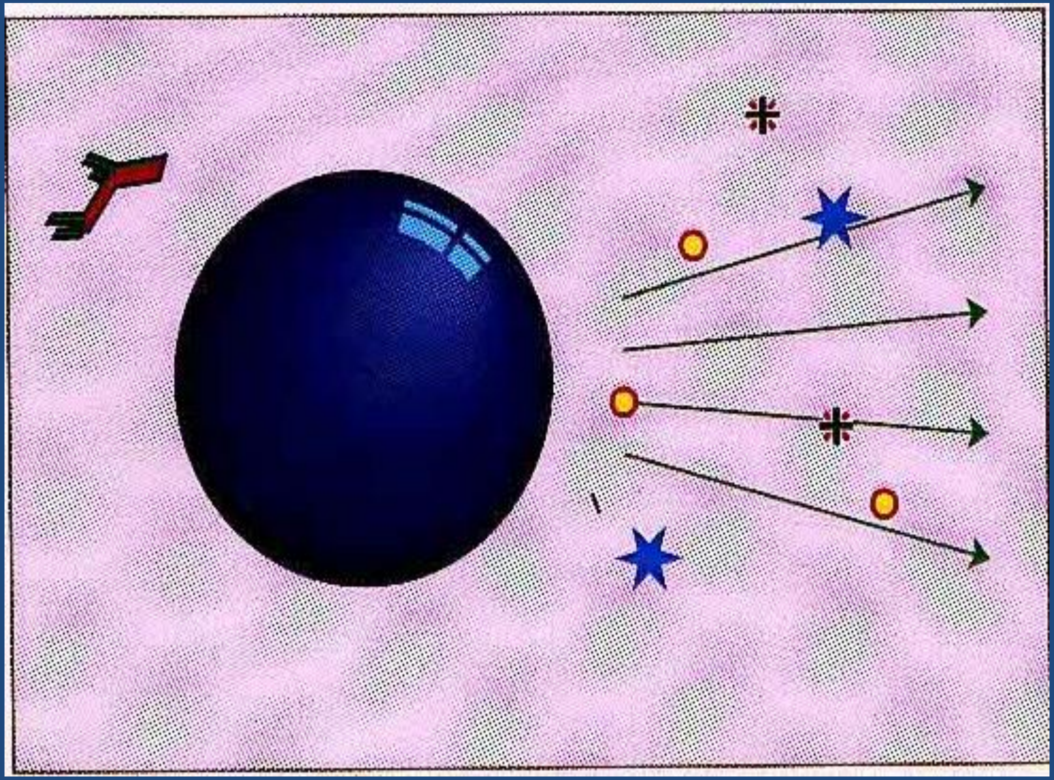
- T_{sun} = 3.6 x 10^{-7} K
- T_{earth}= 0.1 K
- $T_{M=10^{18}kg}$= 7000 K (white light)
- Hot bodies have energy in the form of heat which is measured by a quantity `S' called `Entropy'.
- Bekenstein-Hawking: $$S = \frac{Area}{(10^{-33}\,cm)^2}$$
- `Area' is of the horizon of the black hole

Hawking Radiation and Information Loss

Like all hot bodies black holes radiate.

A black hole forms in various ways, but it always evaporates in the same way leading to **information loss**

as there is no memory of its initial state!



Area theorems of GR:

Bh1+Bh2 -> Bh(12)

$A_{12} \geq A_1 + A_2$

$$S_{BH} = \frac{kc^3}{4\hbar G} A$$

Black holes + radiation satisfy all the laws of thermodynamics

Information Loss by Hawking radiation is not allowed by Quantum Mechanics!

Since the black hole radiation is thermal the initial information about the details of the formation of a black hole is lost.

This violates a fundamental principle of Quantum Mechanics where information is never lost, except if we do statistical averages, as in quantum statistical mechanics.

When a block of wood burns, there is no conflict with quantum mechanics!

Can information loss for black holes be understood as due to an averaging process when there are a large number of internal states?

Is there a theory of quantum gravity in which black hole entropy $S_{BH} = k \log(N)$?

(Bekenstein-Hawking formula =Boltzmann formula)

What are the internal states of the BH, that would account for bh entropy?

Conclusion: **The large scale structure of the universe and black holes both require a quantum theory of gravity!**

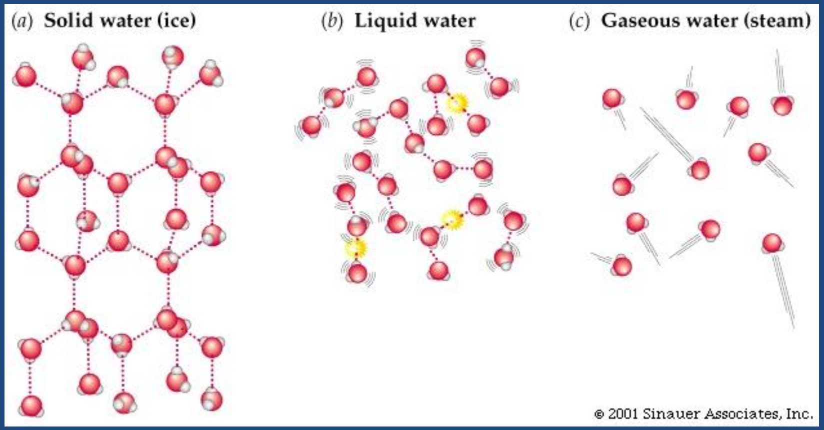
But gravity cannot be quantized in the standard way. Einstein's equations area long wavelength manifestation of an underlying theory.

Fundamental question: What is this underlying theory?

The situation is similar to hydrodynamics which is described by velocity and density fields. However there is an underlying fundamental theory comprising of interacting molecules of water.

The hidden structure of water/space-time?

- Water has a molecular structure underlying its smoothness… and various phases!



What is the hidden structure underlying the `smooth' geometry of space-time?

- What are the analogues of the molecules of water in Einstein's theory gravity?

- **Clue** in the study of **black holes (which are predicted by Einstein's theory and exist in nature)… in String Theory**

String Theory

For quantum gravity the most promising theory is string theory as it is a finite theory and also contains general relativity at long distances.

String theory

can compute the gravitational fluctuations from inflation and can possibly provide a theory of the pre-inflation era…and the origin of the universe.

and

It provides new degrees of freedom besides the graviton that can account for the entropy of black holes using Boltzmann’s formula.

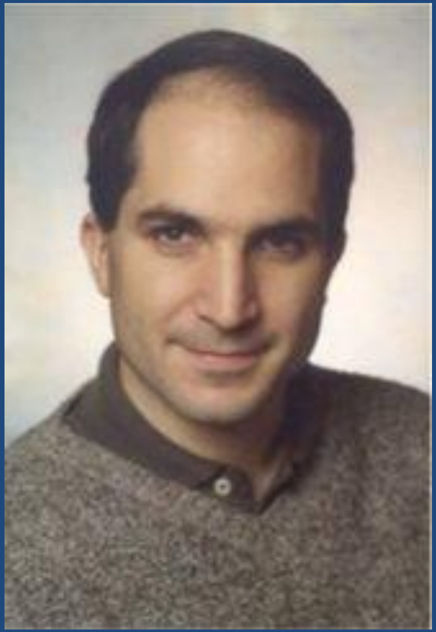
Black holes micro-states

In 1996 Strominger and Vafa provided the first concrete evidence in a calculable model that the black hole space-time is a sort of a hydrodynamic description of more basic underlying constituents!

Hawking radiation and BH thermodynamics can be calculated in the framework of statistical mechanics in this constituent model of the black hole! (Dhar, Mandal, Wadia; Das, Mathur; Callan, Maldacena)

Holography conjecture provides a precise formulation of Quantum Gravity…

Juan Maldacena (1997)



Gravity in the interior → described by interacting particles on the boundary.

Interior is a

Gravity/String Th

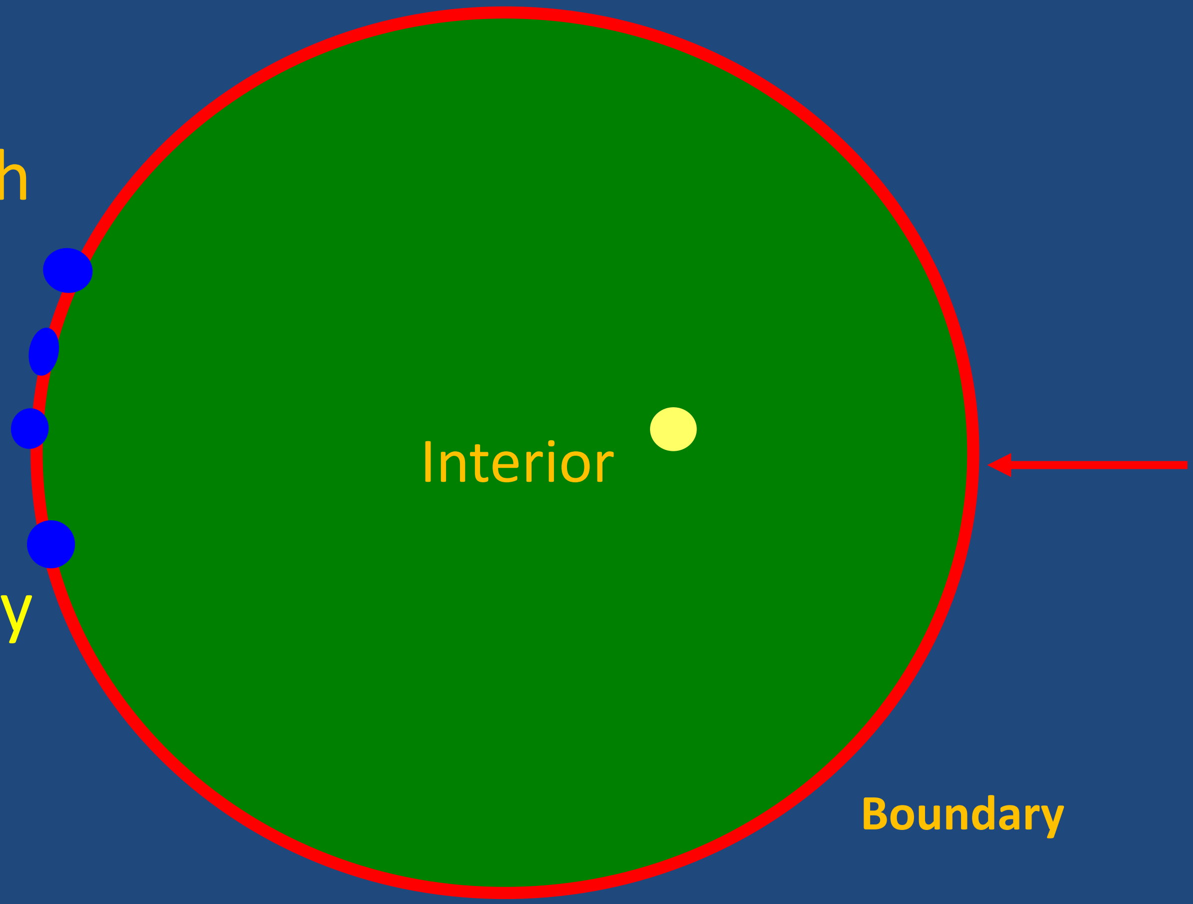
In AdS

space-time

On the boundary

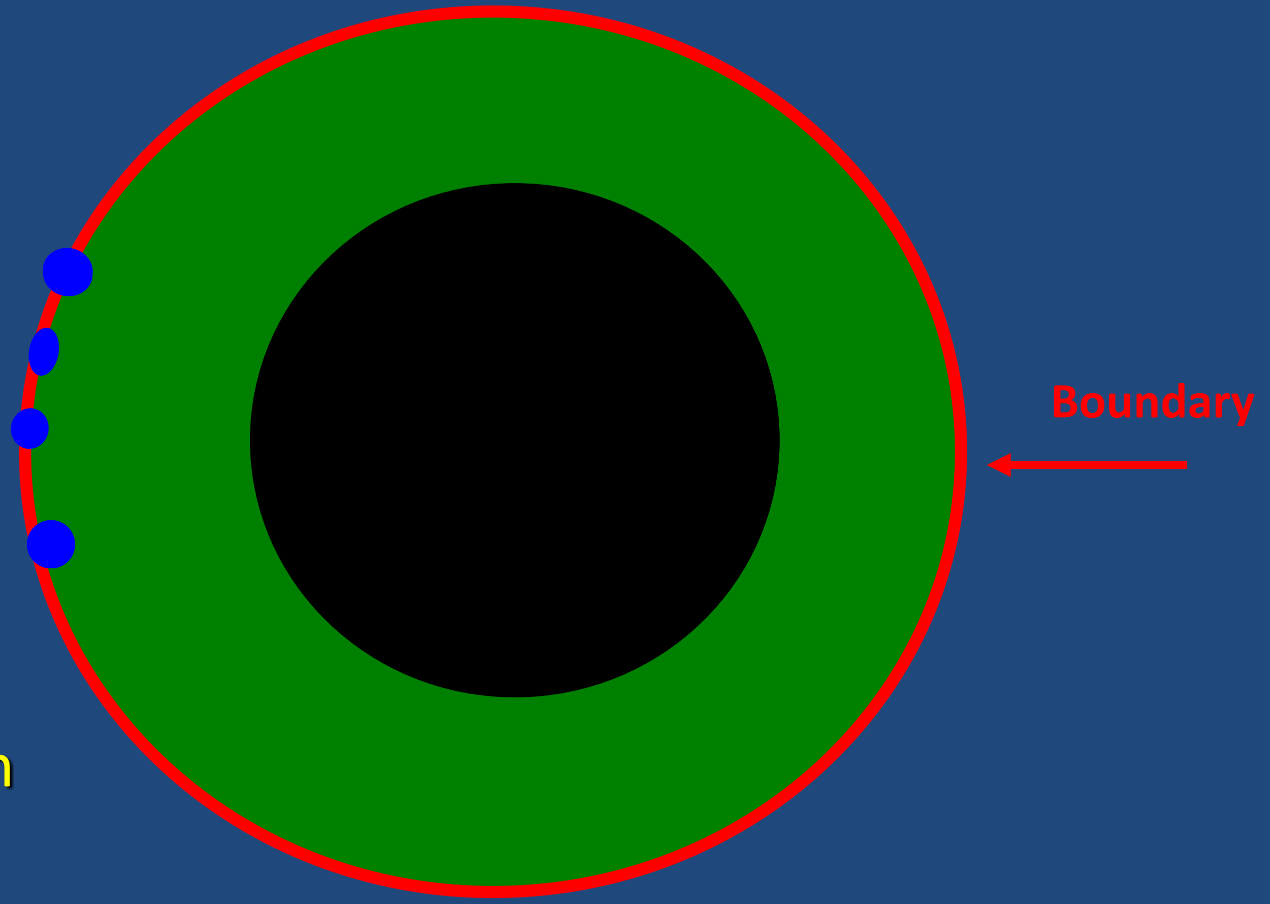
lives a unitary

QFT



BH in AdS is dual to a unitary QFT at finite Temperature.

Temperature and entropy → motion of particles on the boundary.



In principle solves information puzzle

BH formation is thermalization of the QFT.

Applications of AdS/CFT

Strongly coupled systems and fluid dynamics correspond to dynamics of BH horizons:

$\eta/s = (1/4\pi)\hbar/k_b$ (Policastro, Starinets, Son)

Fluid dynamics equations are derivable from small motion of black hole horizon (Bhattacharya, Minwalla, Rangamani and Hubney)

Entanglement entropy of strongly coupled systems is computed by the geometrical Ryu-Takayanagi formula

Connection to quantum information theory (Almiehiri, Dong, Harlow)

Applications to quantum chaotic systems: $\lambda \leq 2\pi kT/\hbar$

(Maldacena, Shenker, Stanford, Kitaev…)

Status of information paradox

The AdS/CFT correspondence solves the information paradox in principle, but we do not yet have a convincing understanding of this resolution in the bulk.

In particular

1) how does one describe using boundary CFT the experience of an observer falling into the horizon of the black hole. Progress here is due to Kyriakos Papadodimas and Suvrat Raju.

2) How does one explain the error in Hawking's calculation and restore unitarity. Progress here is due to Almiehiri, Mahajan, Maldacena, Zhao

3) Explicit calculation of bh formation in the SYK model.

Progress here is due to Dhar, Gaikwad, Joshi, Mandal and Wadia

Concluding remarks

Observations in cosmology and the fact that black holes exist require a quantum theory of gravity which at large distances gives rise to General Relativity. String theory is a candidate framework that can has the tenets to be a theory of quantum gravity.

It provides a framework to understand quantum gravity fluctuations responsible for the large scale structure of the Universe.

It provides new degrees of freedom that makes black hole physics consistent with quantum mechanics. This fact leads to intriguing connections of string theory with different parts of physics and mathematics.

The Legacy of Einstein for Theoretical Physics

The Herbert Spencer Lecture, delivered at Oxford, June Io, I933.

i) The fundamental role of symmetry in the formulation of the laws of physics. This was an important motivation in arriving at the gauge principle which is at the foundation of the standard model of elementary particles.

i) The discovery of the laws of nature by **logical invention based on general principles**, which can subsequently meet the test of experiment. e.g. the Dirac equation for the electron.

i) String theory carries forward the legacy of Albert Einstein. Its goal is to present a unified theory of all elementary physical laws that govern our universe (or even other universes!)

Acknowledgement

- The Infosys Foundation Homi Bhabha Chair
- Juan Maldacena and Stan Whitcomb for the animation about black holes
- Lyman Page for slides on CMB
- Various sources, including `Einstein Online' of MPI, Albert Einstein Institute for illustrations.

Thank You