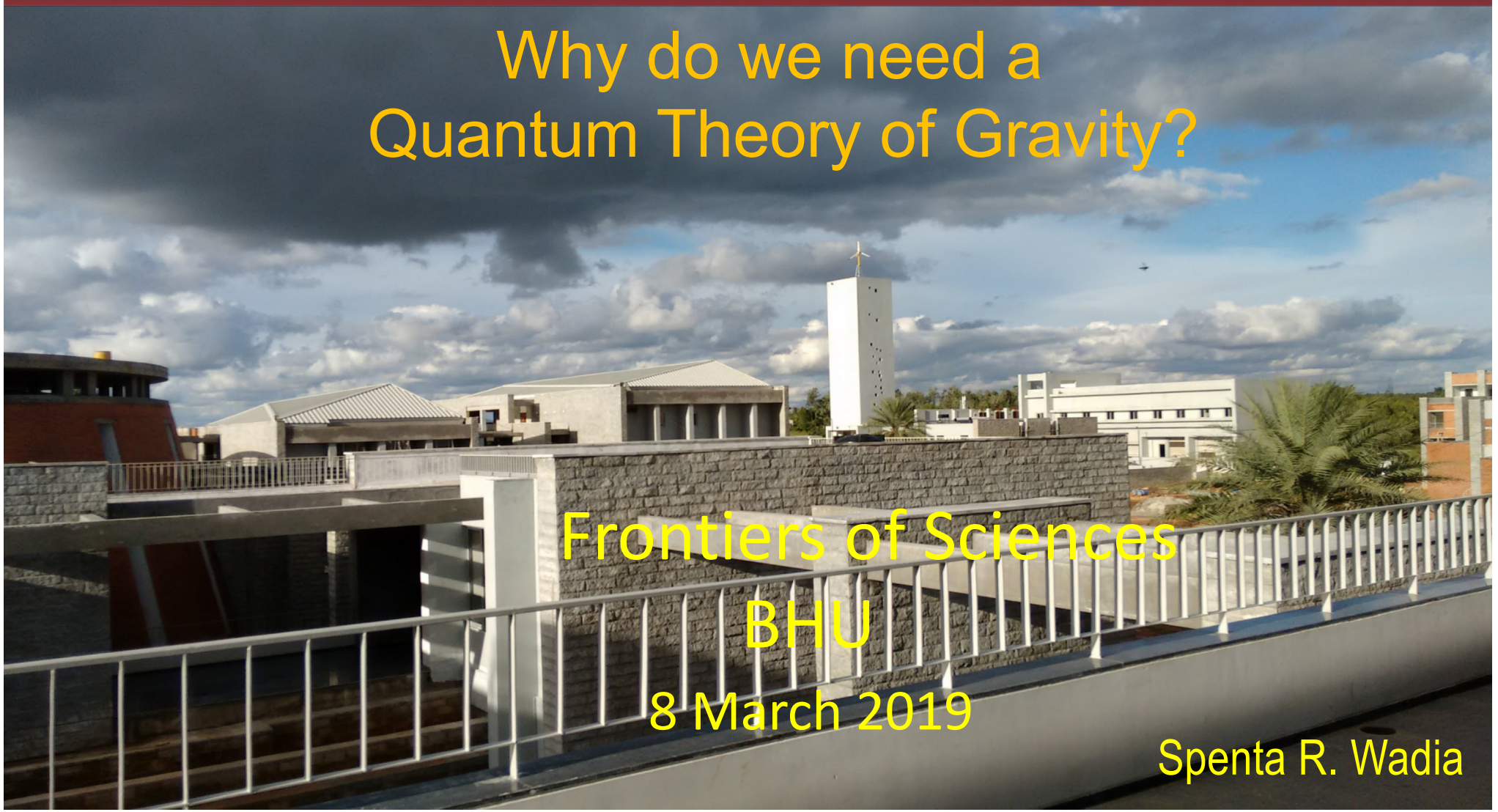
ICTS | INTERNATIONAL CENTRE for THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

Why do we need a Quantum Theory of Gravity?



Frontiers of Sciences

BHU

8 March 2019

Spenta R. Wadia

Galileo (1564-1642)

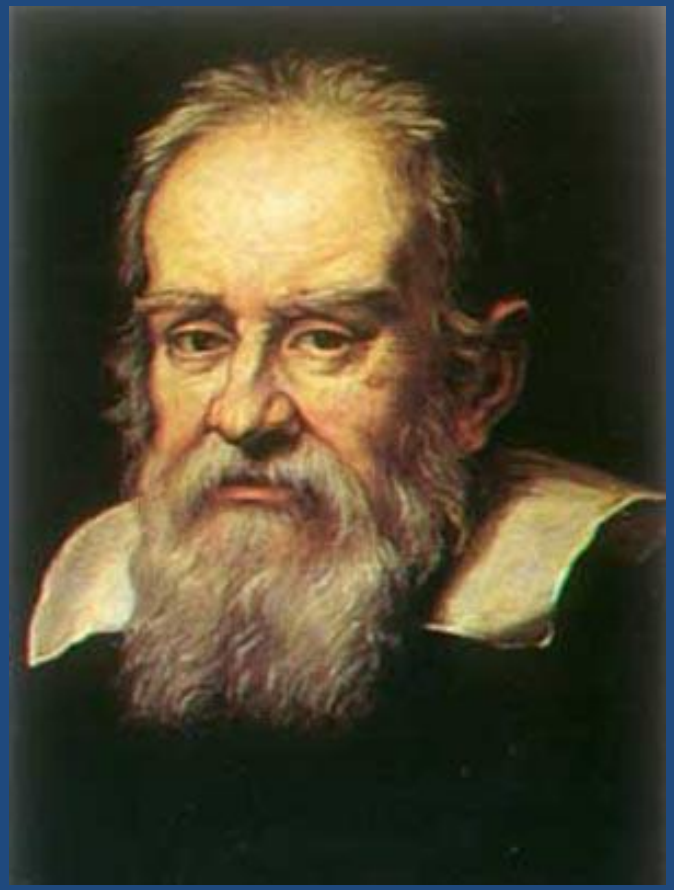
A pioneer of the modern scientific method

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.

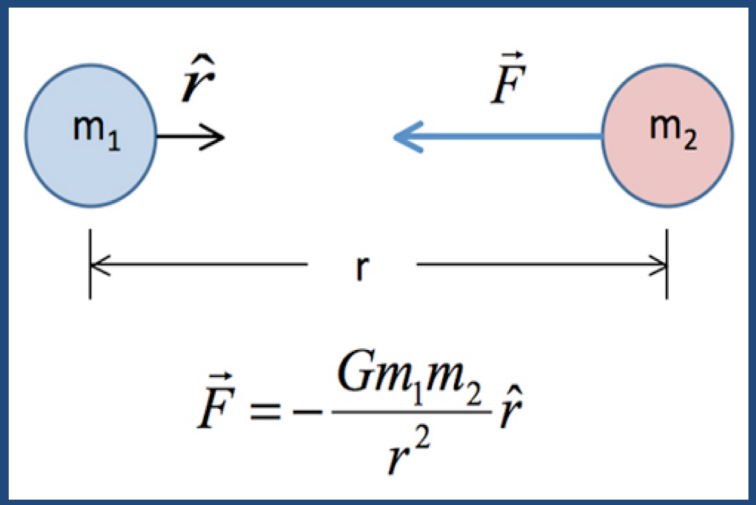
$(x(t), y(t), z(t))$

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



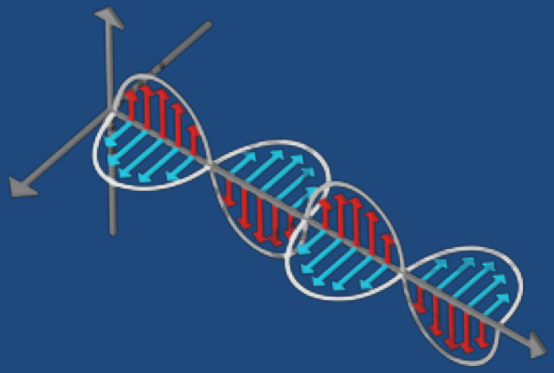
Force acts instantaneously at a distance

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."

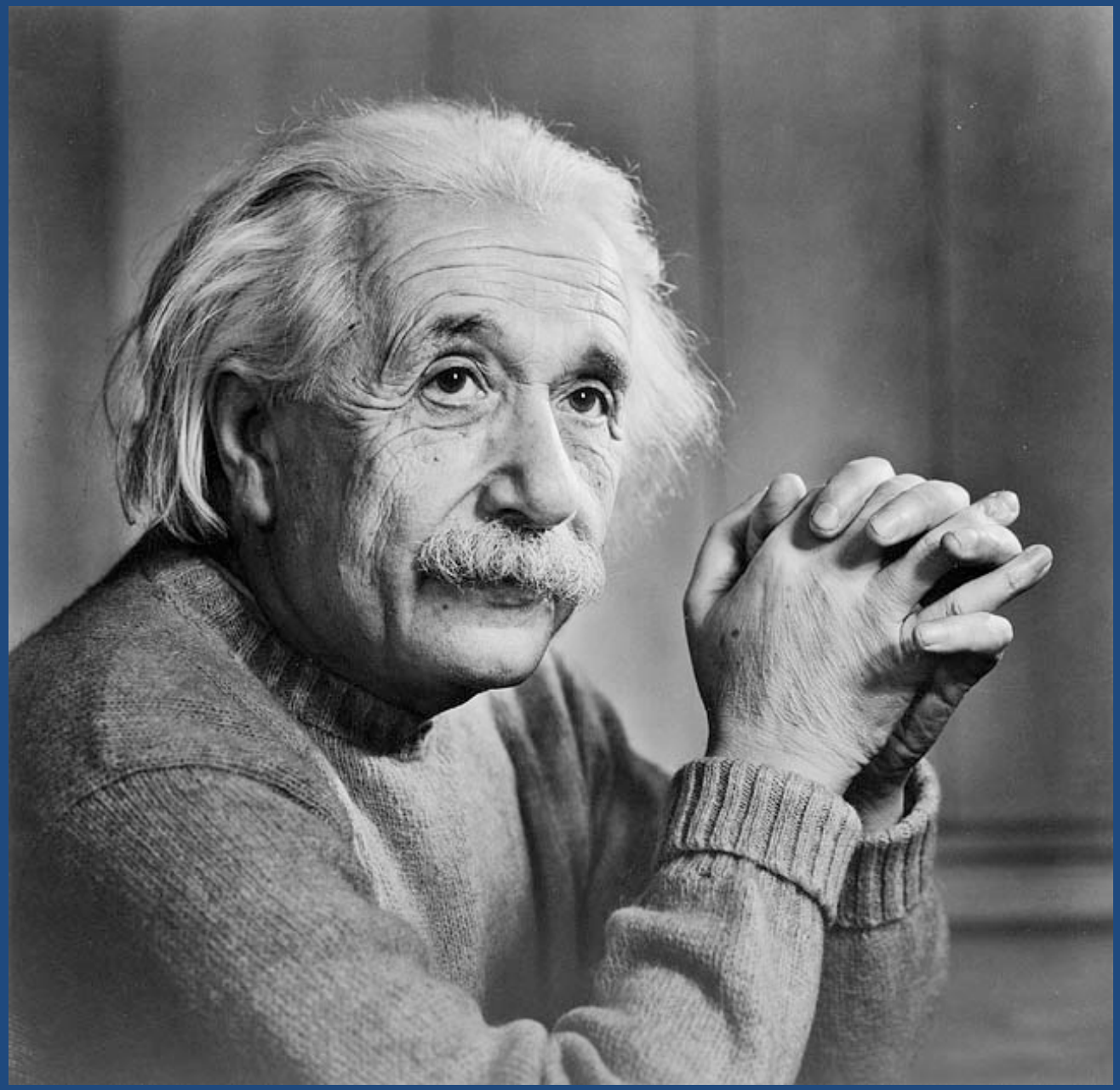
Electric and Magnetic **Fields** and **Waves**

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)

Albert Einstein (1879-1955)

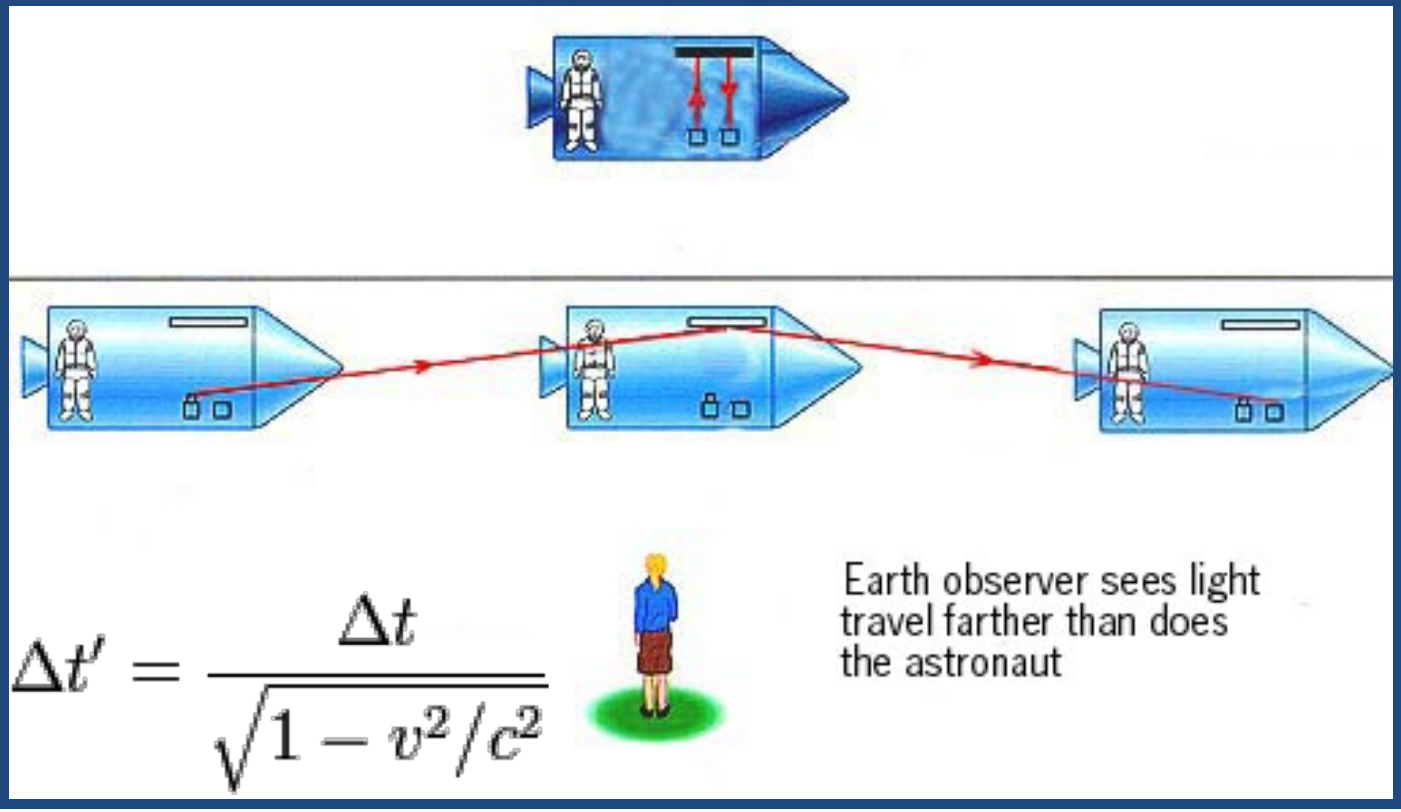


Lorentz, Poincare, Einstein: Special Relativity (1905)

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.



Einstein: Newton's law of gravity in conflict with special relativity and why only special relativity?

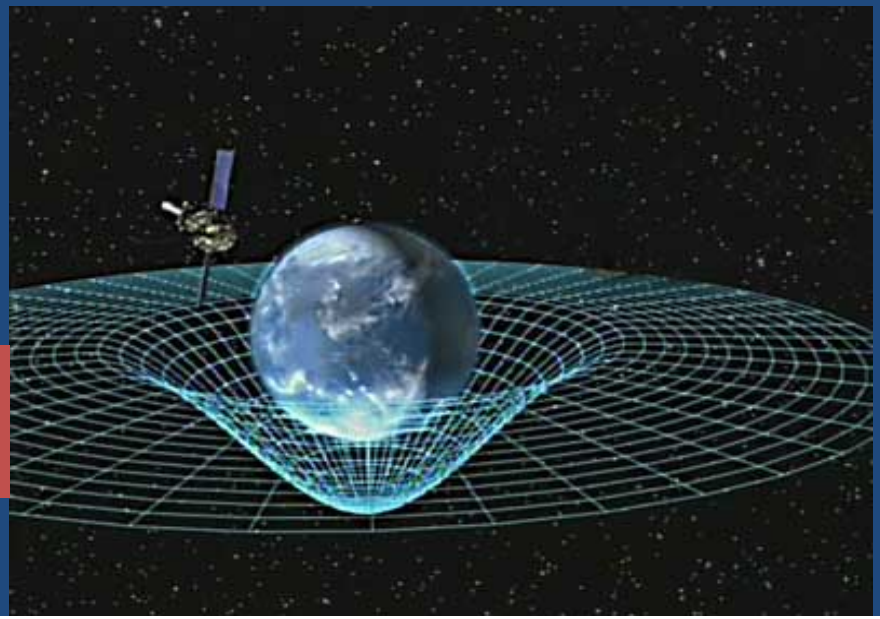
- That the force of gravity acts instantaneously is not consistent with Special Relativity! Einstein would like to have the force of gravity communicated at the speed of light by a field analogous to the electro-magnetic field of Faraday and Maxwell.
- Special Relativity is restricted to frames with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

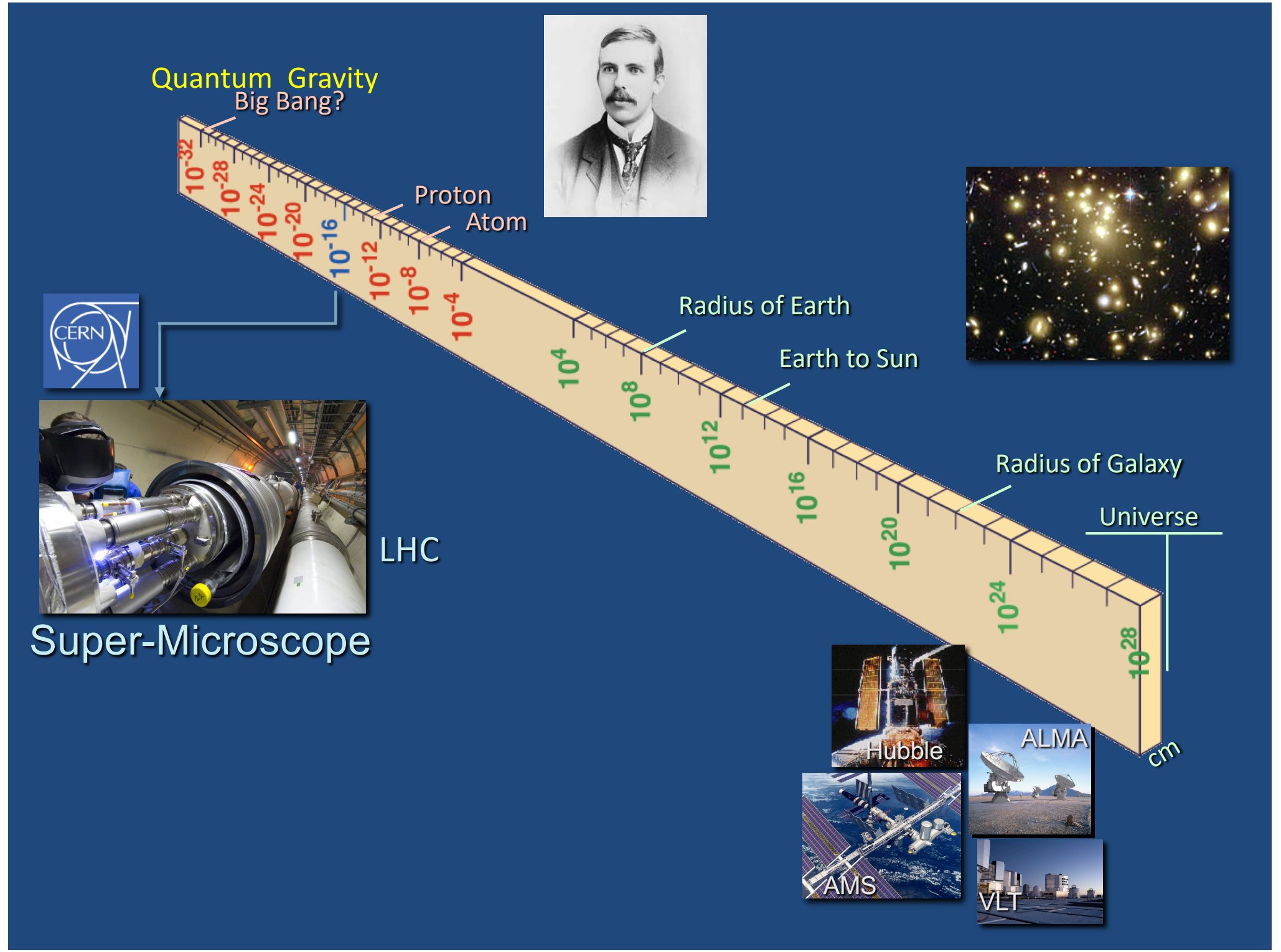
General Relativity

Einstein 1915

The equations of GR describe the shape changes of the geometry or fabric of space-time caused by massive objects in which other objects move.

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**




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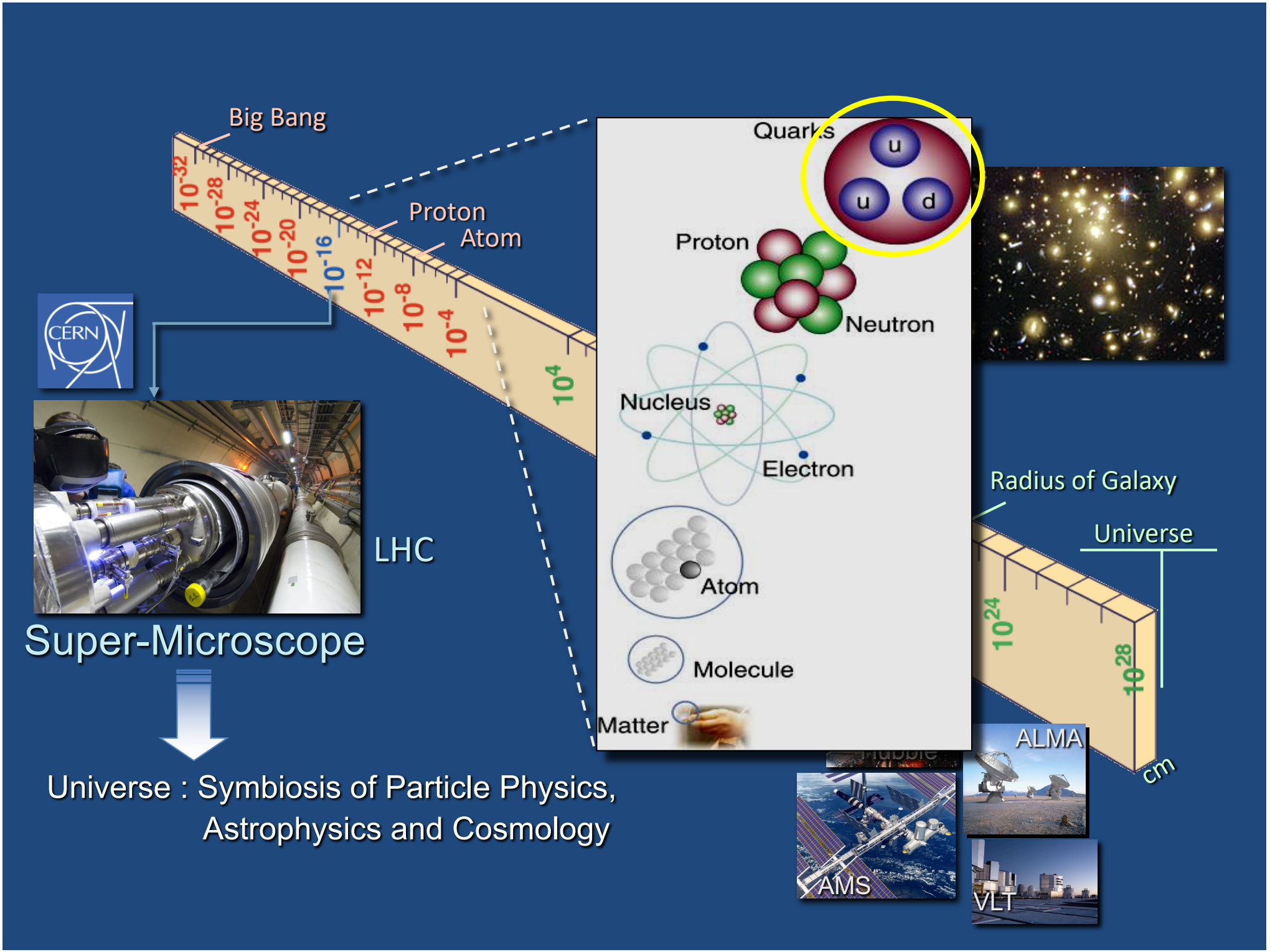
cm
CERN
LHC
Super-Microscope
Hubble
ALMA
AMS
VLT


Big Bang
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Matter
Radius of Galaxy
Universe
10^{24}
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ALMA
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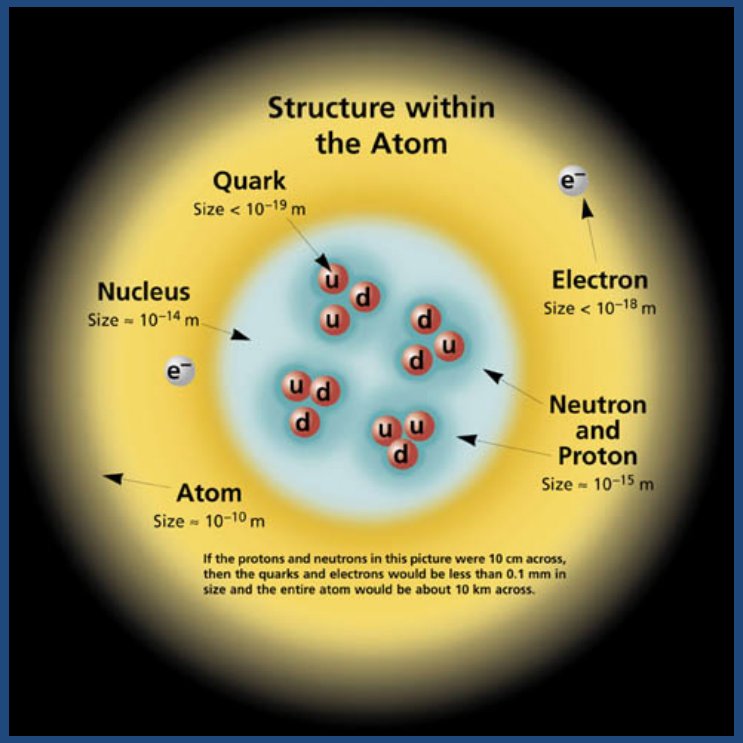
VLT
Universe : Symbiosis of Particle Physics,
Astrophysics and Cosmology

Quantum Mechanics

- A 20th century scientific revolution. New laws for all particles, especially below atomic scales.



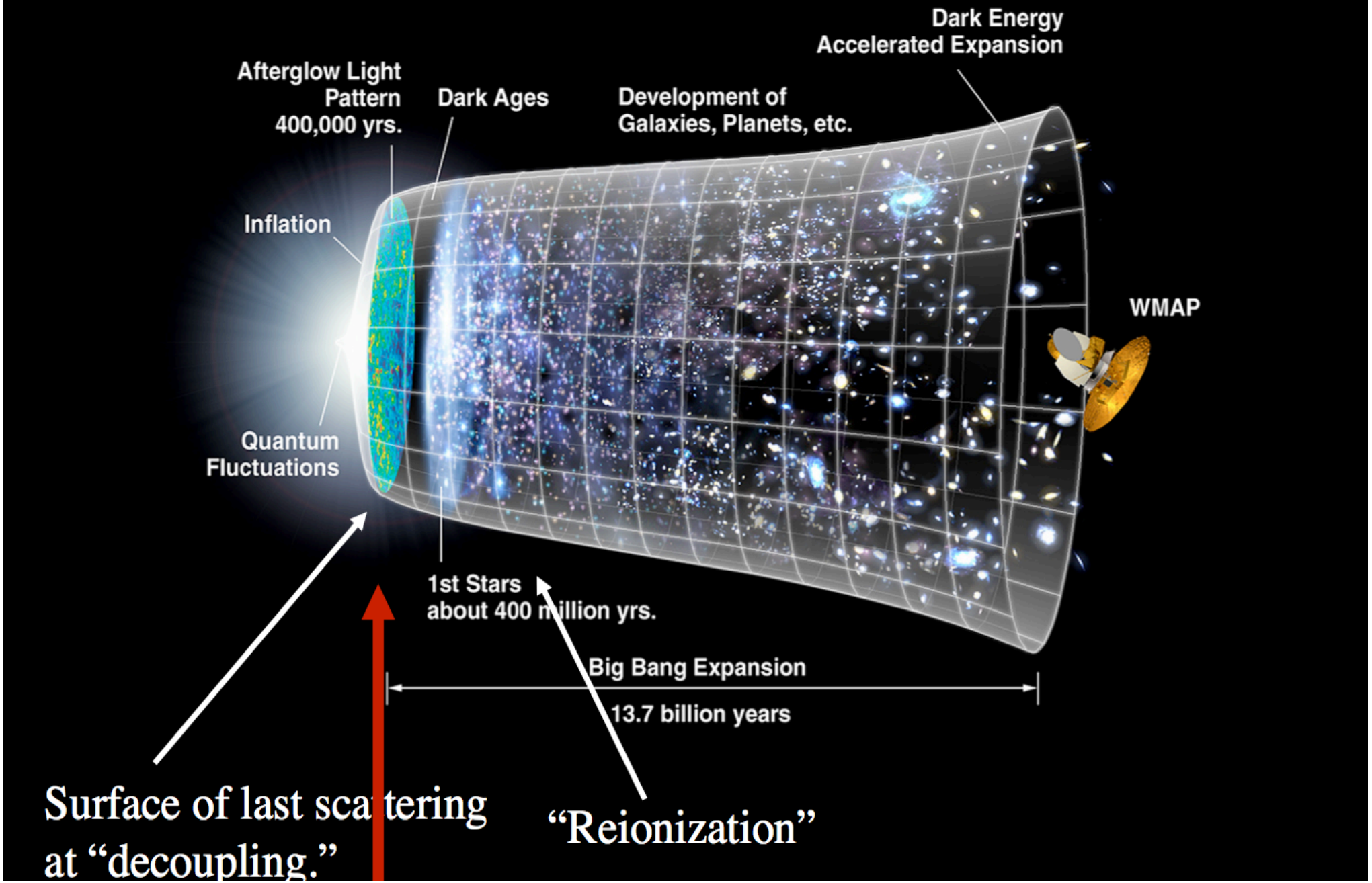
- Electronic devices, lasers, colliding elementary particles in the LHC in Geneva all follow the laws of quantum mechanics … tested to 10^{-16} cms. Macroscopic effects...Superfluidity

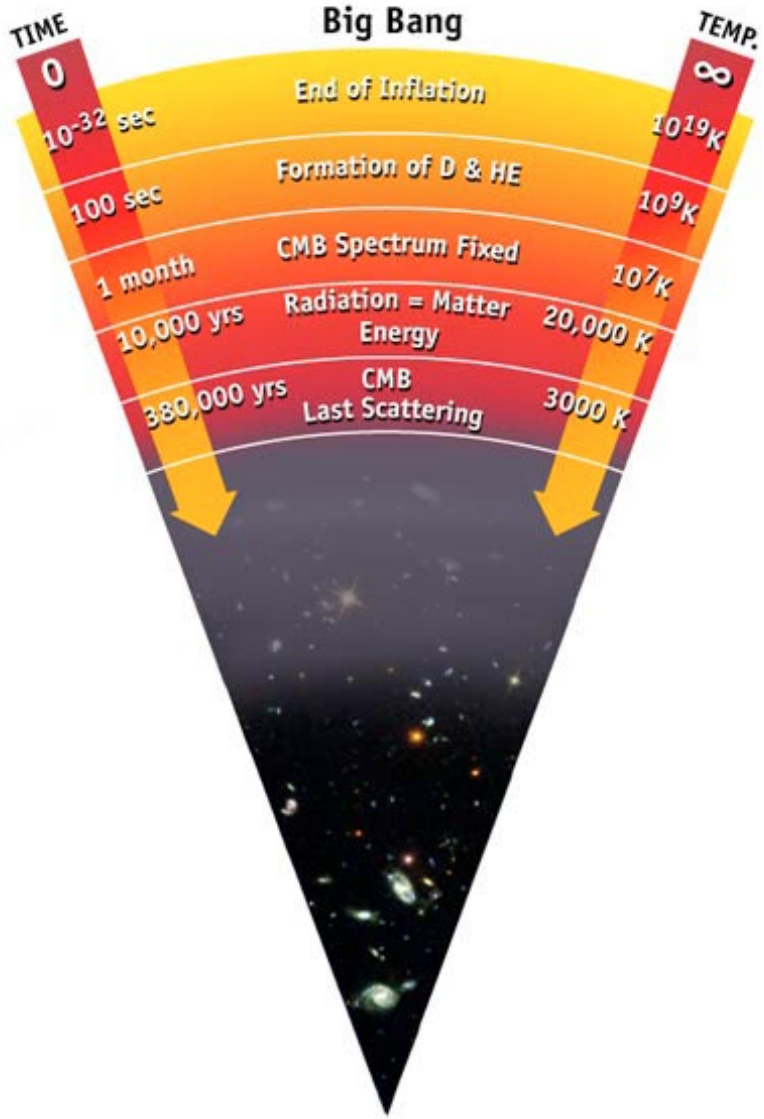
Surprising and remarkable Solutions of Einstein's equations

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

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

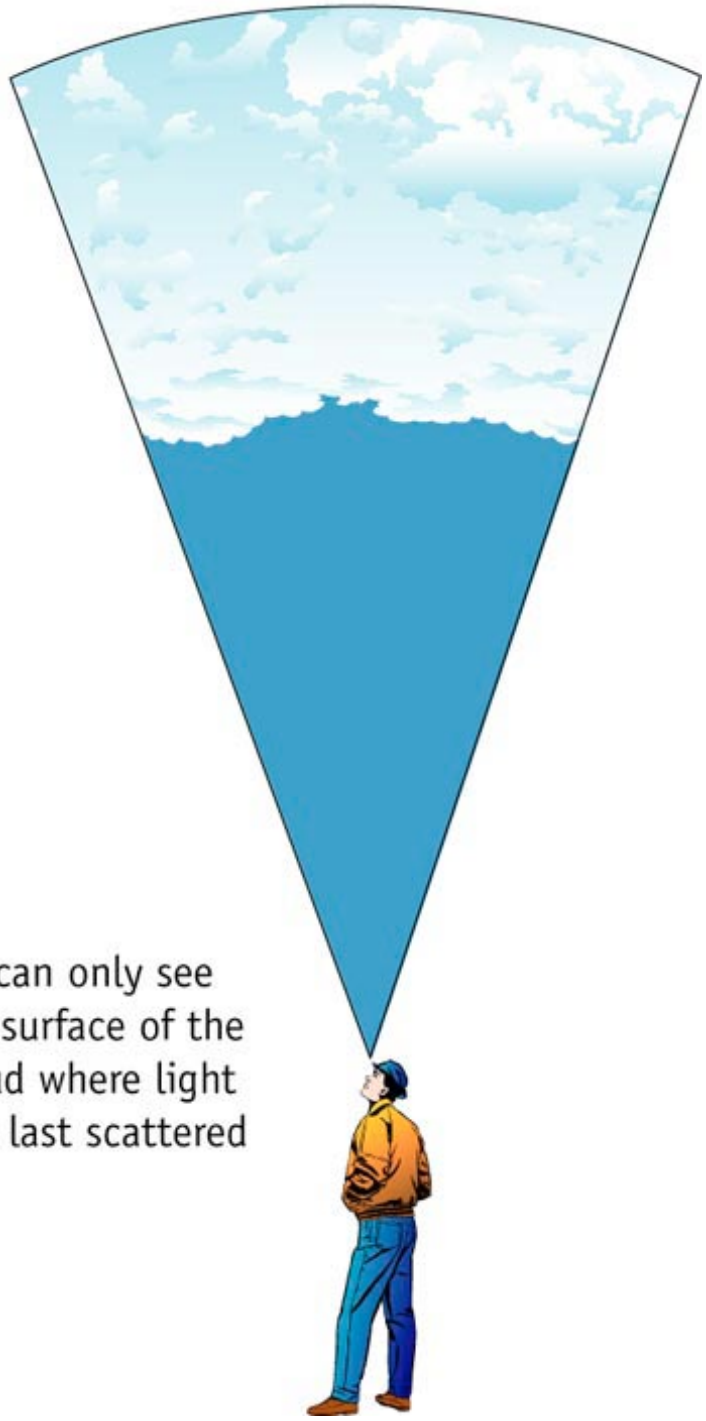
The Standard Model of Cosmology



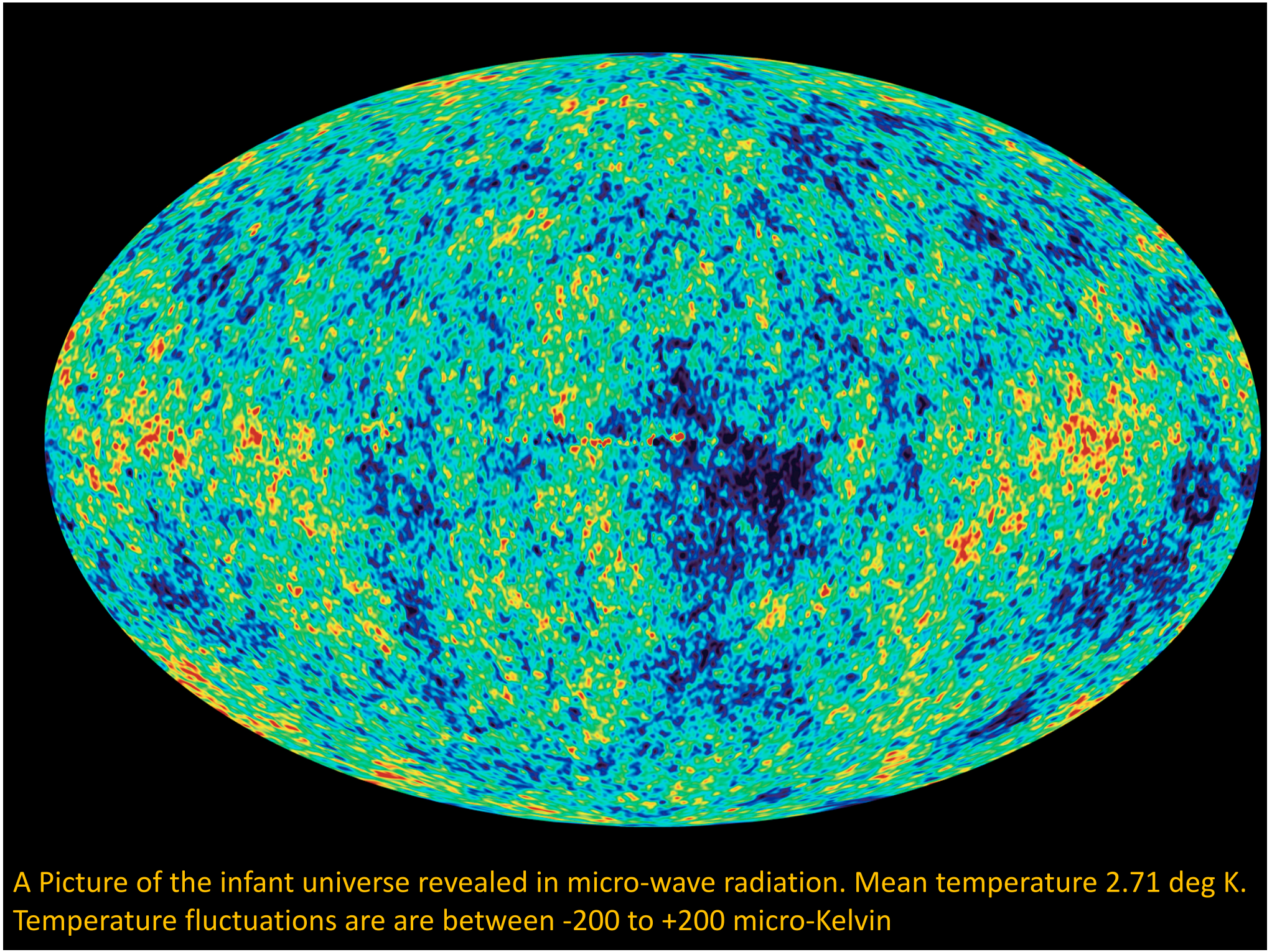


PRESENT
13.7 Billion Years after the Big Bang

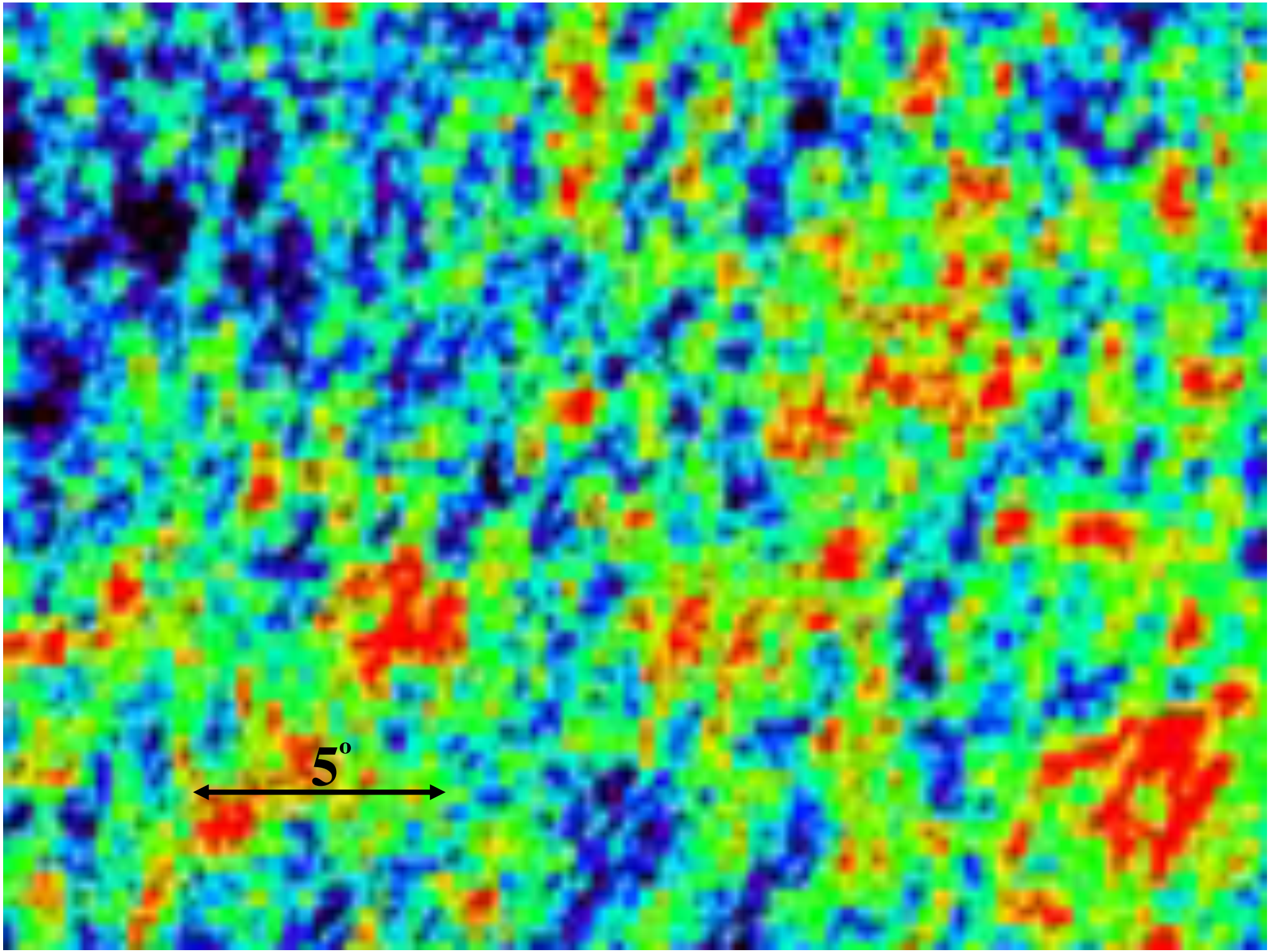
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



We can only see the surface of the cloud where light was last scattered

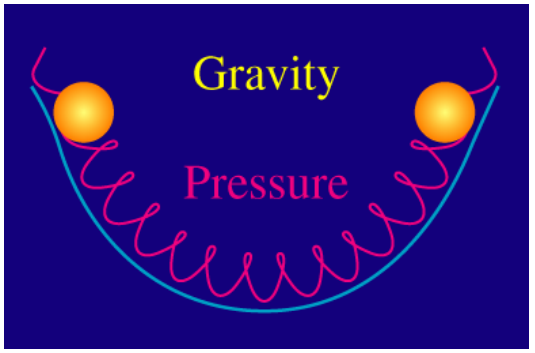


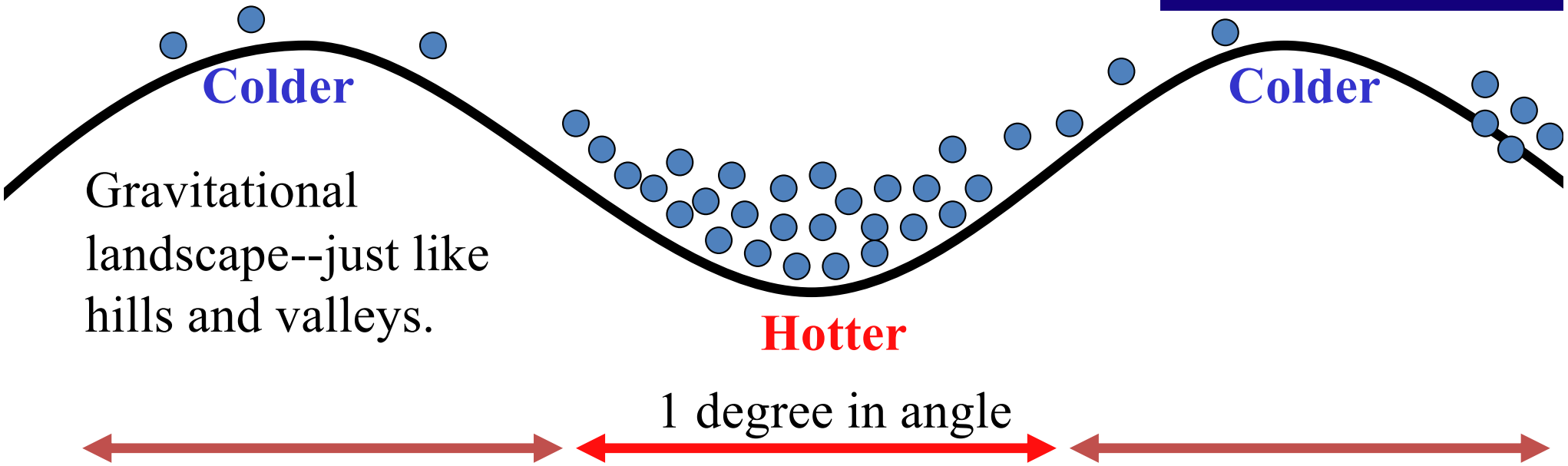
A Picture of the infant universe revealed in micro-wave radiation. Mean temperature 2.71 deg K. Temperature fluctuations are are between -200 to +200 micro-Kelvin


5°

How do we get hot and cold patches?

W. Hu





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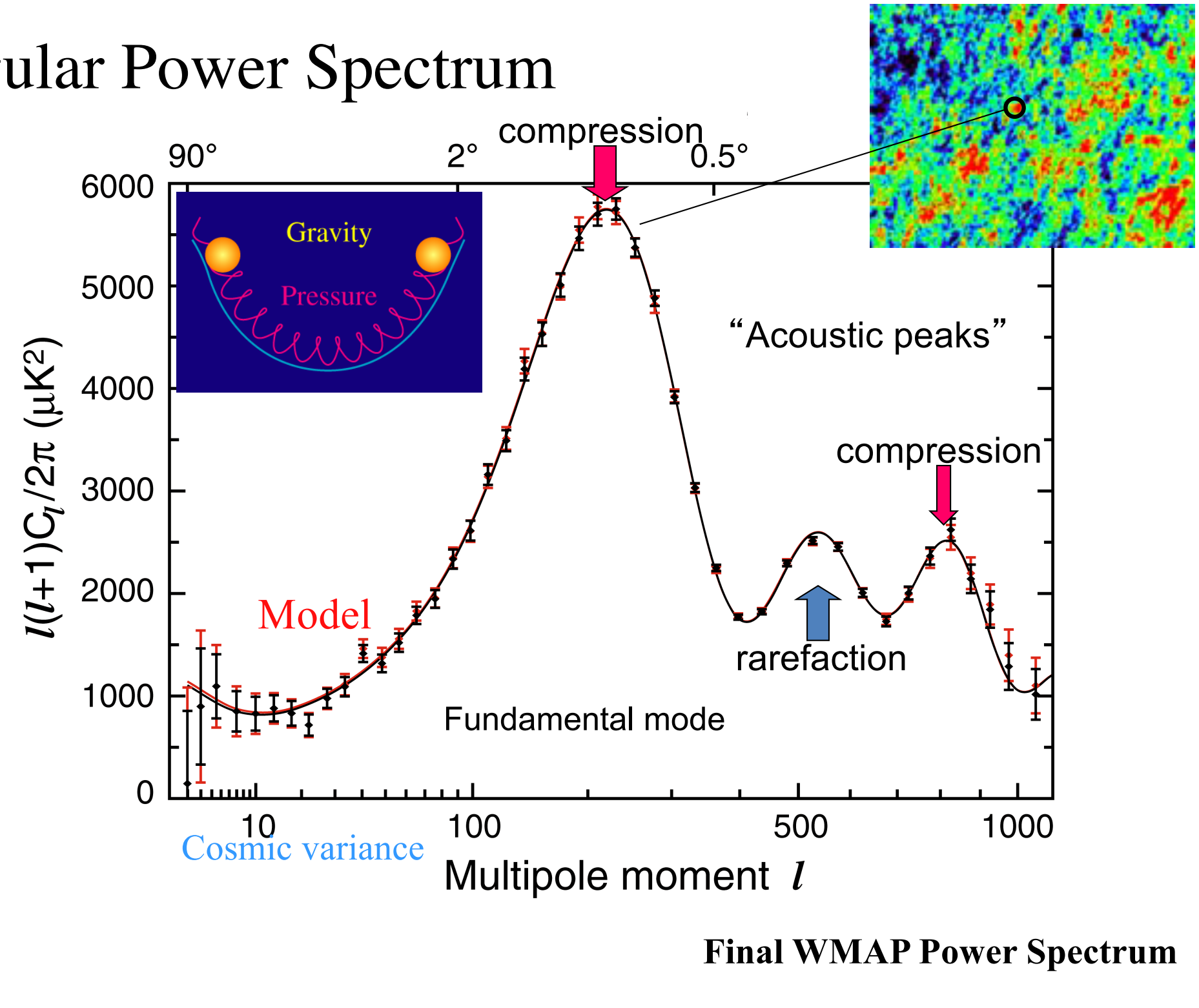
(Lyman Page)

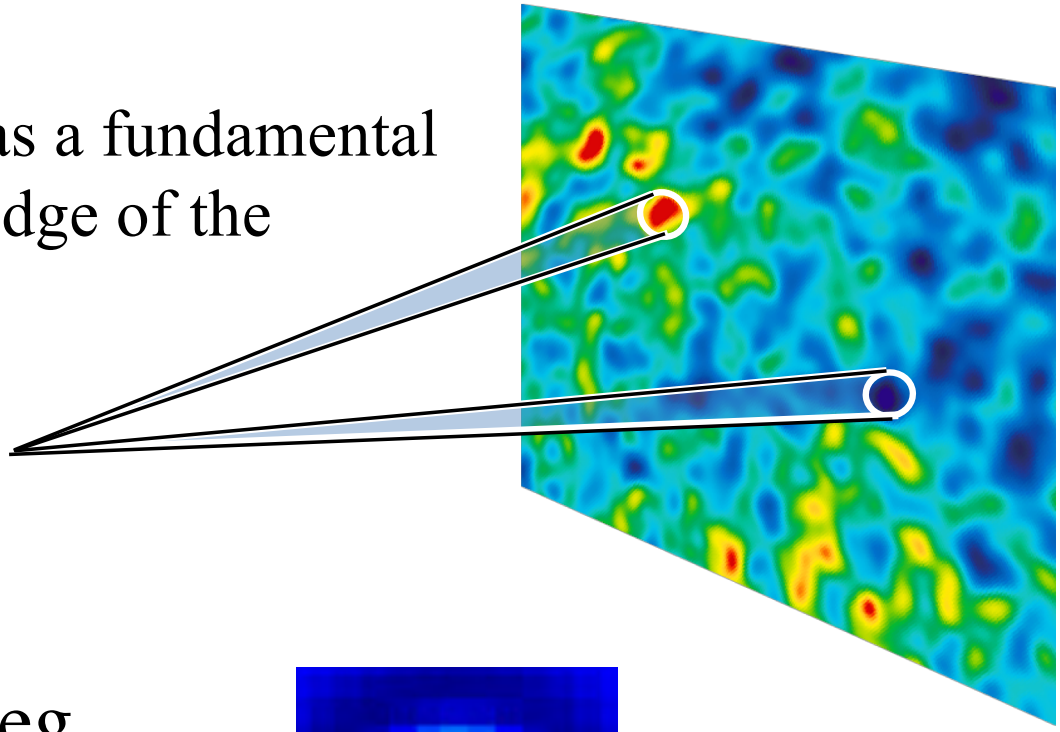
Angular Power Spectrum



Final WMAP Power Spectrum

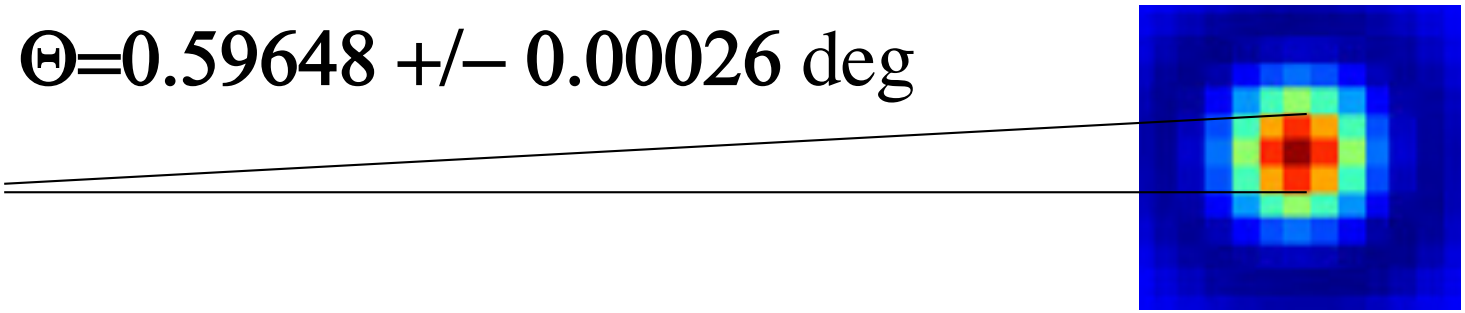
(Lyman Page)

The “fundamental mode” acts as a fundamental “footprint” or yardstick at the edge of the observable universe.



from Planck:

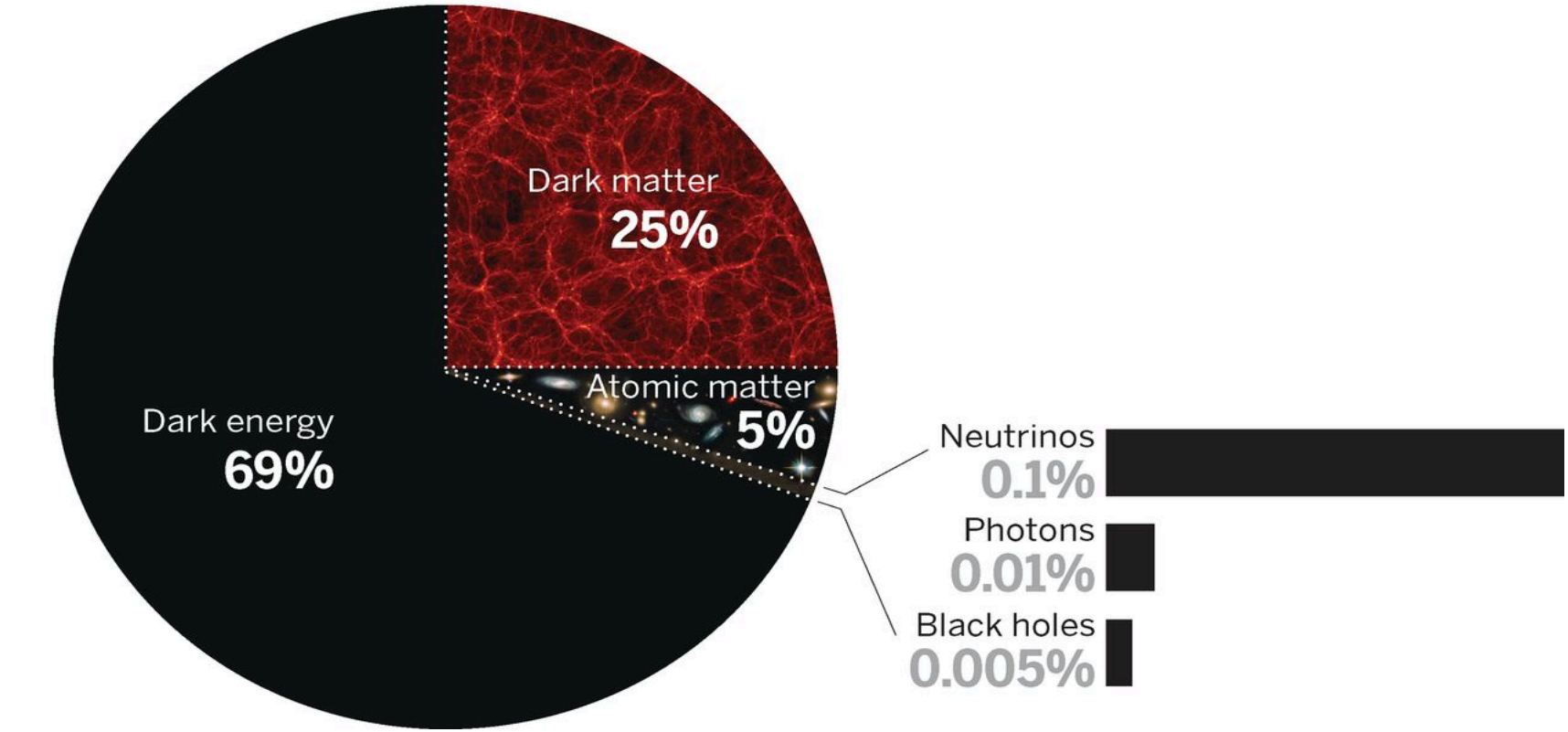
$\Theta = 0.59648 \pm 0.00026$ deg



Stacked hot spots.

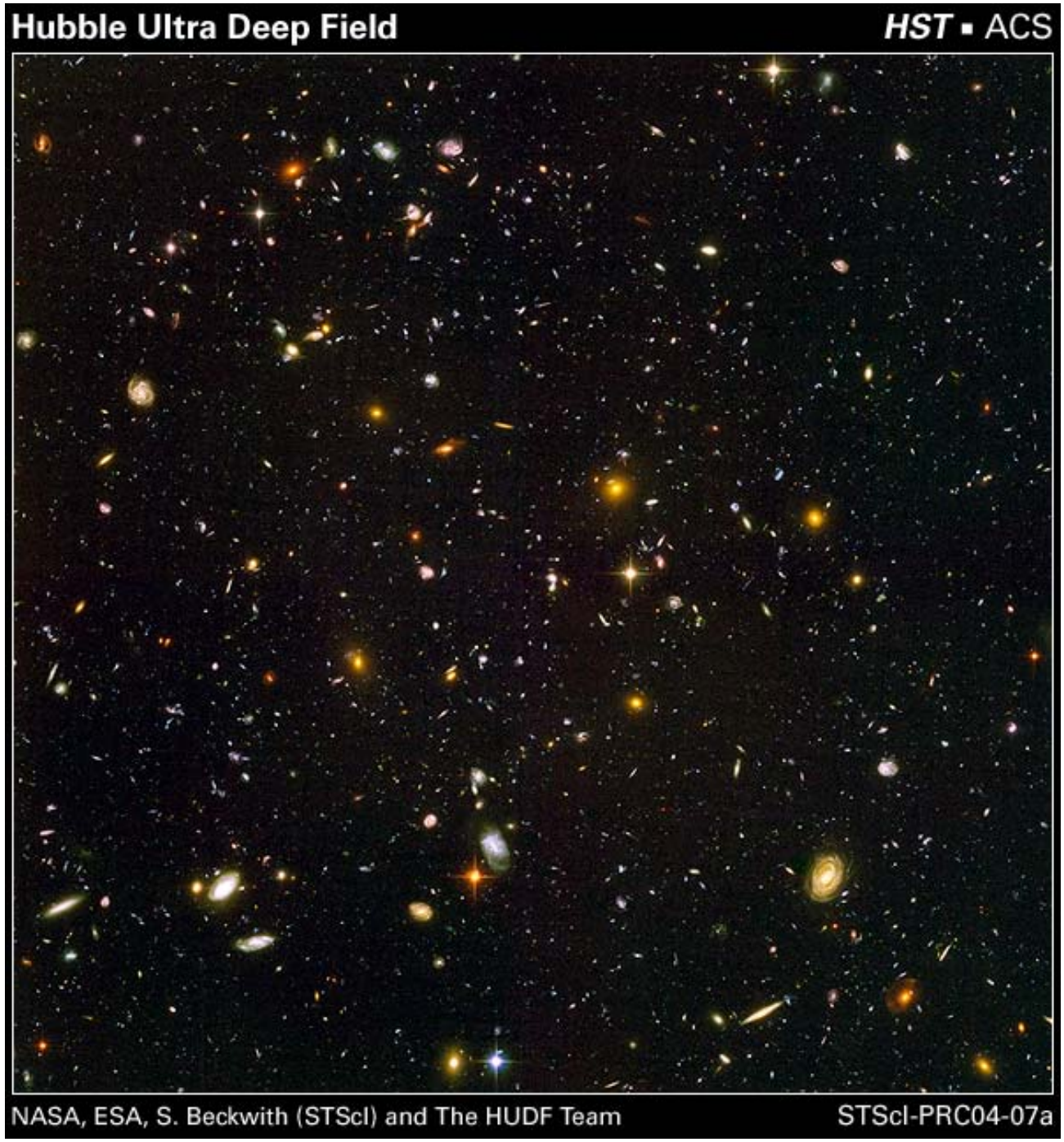
This allows us to determine the size of the observable universe.

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

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 need 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.

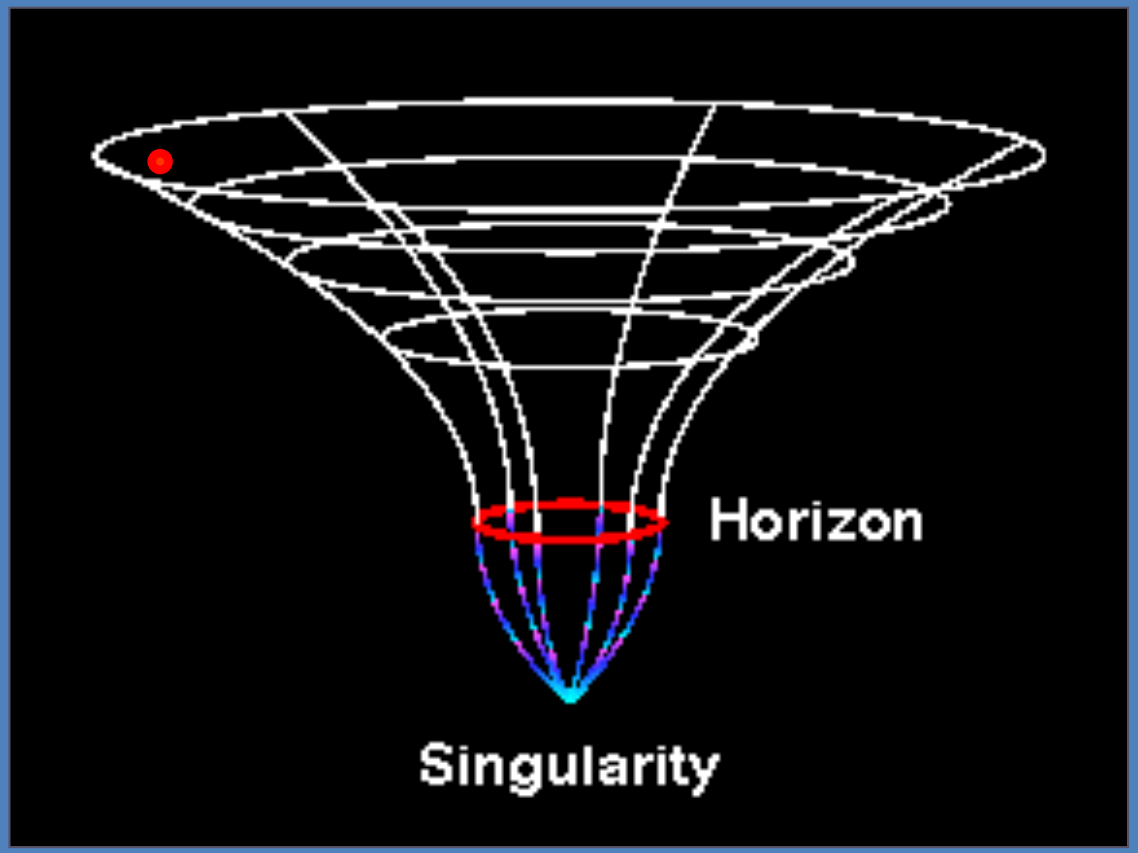
$$g^2_{\text{eff}} \sim \frac{(\text{energy})^2}{M^2_{\text{Planck}}} = \frac{l^2_{\text{Planck}}}{(\text{distance})^2}$$

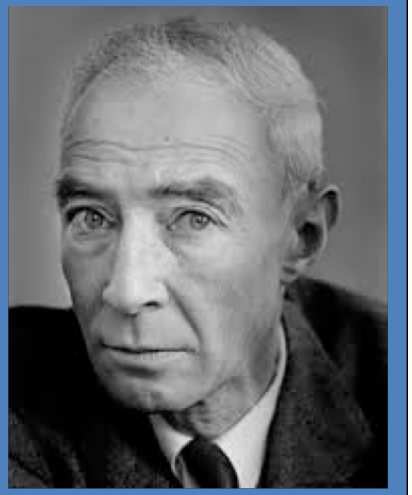
$$l_{\text{Planck}} \sim 10^{-35} m \ , \qquad M_{\text{Planck}} = 10^{16} Tev$$

Quantizing Einstein's equations leads to

divergent answers!

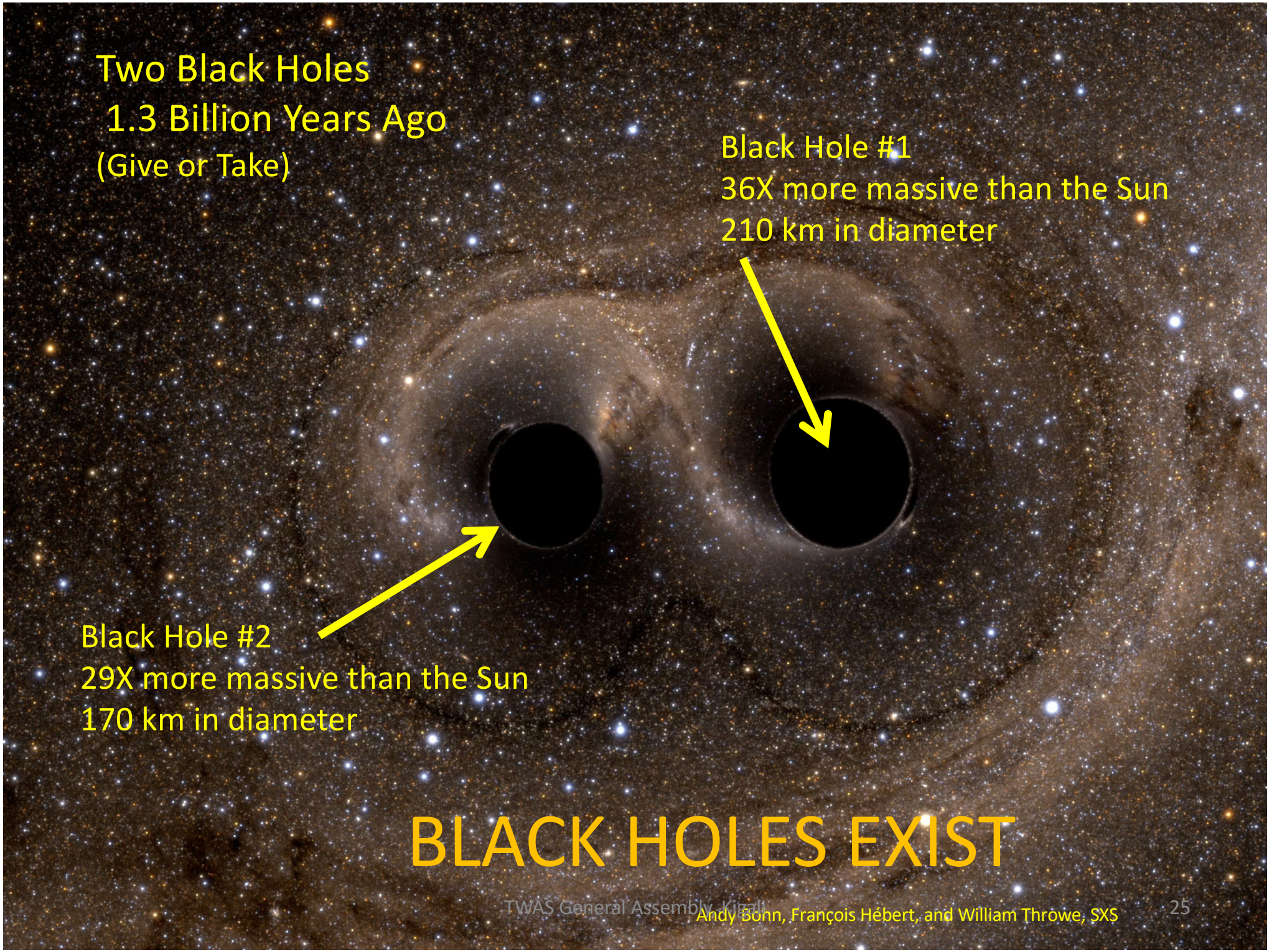
Einstein's theory predicts Black Holes





Black holes exist and abound in nature

Schwarzschild **Chandrasekhar & Oppenheimer**


Two Black Holes
1.3 Billion Years Ago
(Give or Take)
Black Hole #1
36X more massive than the Sun
210 km in diameter
Black Hole #2
29X more massive than the Sun
170 km in diameter
BLACK HOLES EXIST
Andy Bonn, François Hébert, and William Throwe, SXS

In Quantum Mechanics black holes are hot due to the presence of a HORIZON (Hawking):

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

- $T_{sun} = 3.6\ 10^{-7}$ 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

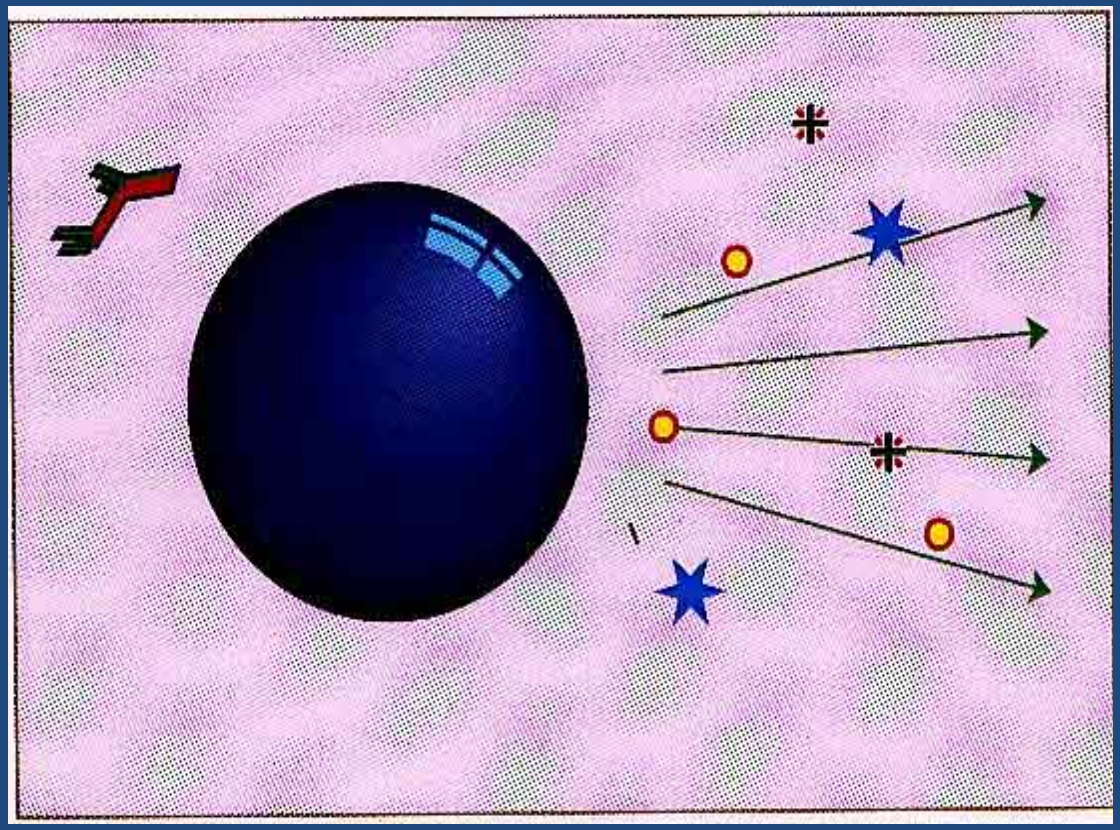

HERE LIES WHAT WAS MORTAL OF
STEPHEN HAWKING
1942-2018

Hawking Radiation

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 how it was formed!



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

Since the black hole final state is a radiating thermal state the initial information about 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. Information is lost when a block of wood burns, but there is no conflict with quantum mechanics.

Boltzmann's entropy formula: $S = k \log(N)$, N is the number of internal states of the system, $N>>1$

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 = k log(N) ?

i.e. $S_{BH} = \frac{kc^3}{4\hbar G} A$ = k log(N) ?

What are the internal states of the BH?

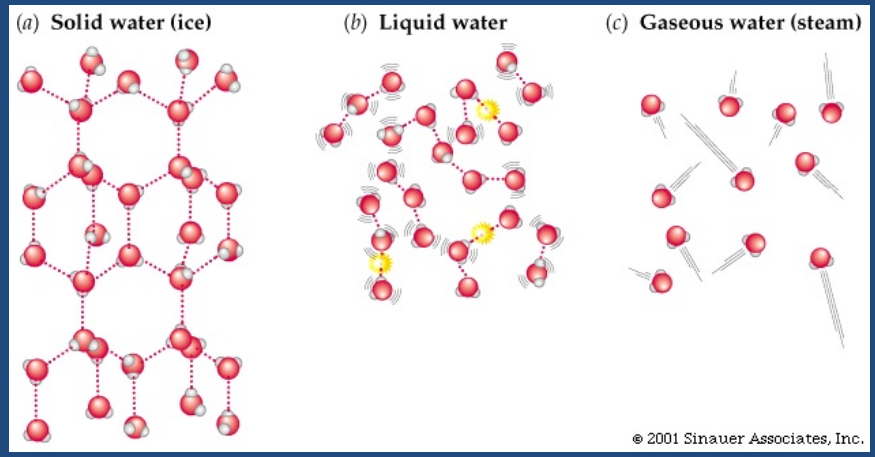
The large scale structure of the universe and black holes both require a quantum theory of gravity!

Gravity cannot be quantized in the standard way. It turns out to be a long wavelength manifestation of an underlying theory. What is this theory?

The situation is similar to hydrodynamics which is described by the 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 gravity the most promising underlying theory turns out to be string theory.

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

It provides new degrees of freedom besides the graviton that can account for the entropy of black holes.

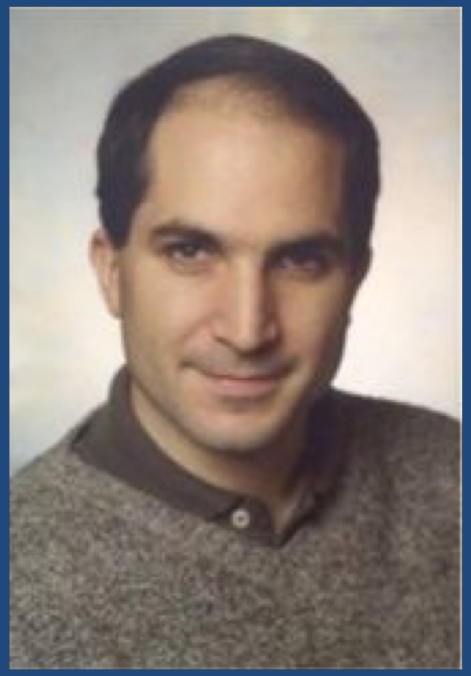
Black holes micro-states

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!

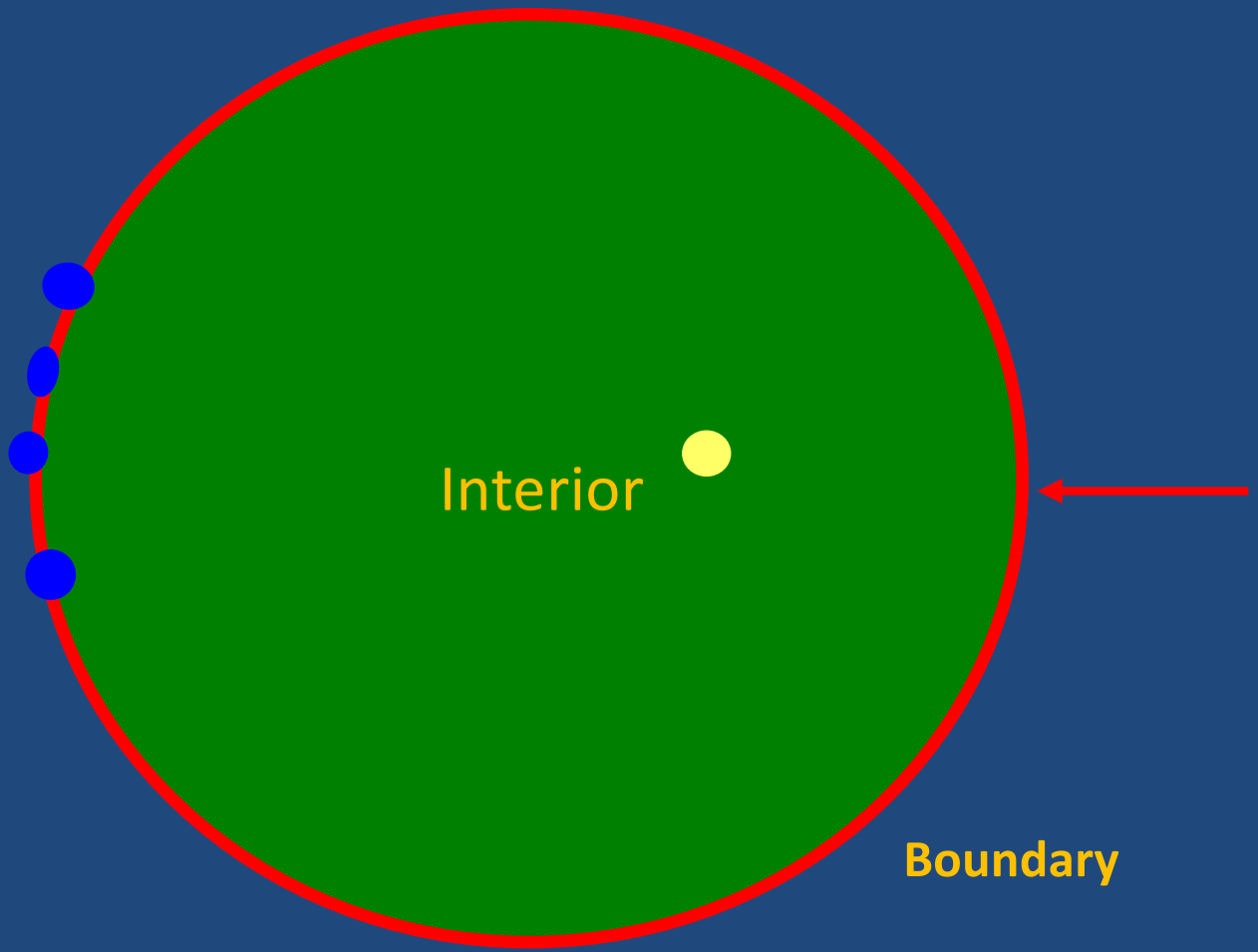
Hawking radiation and BH thermodynamics can be calculated in the framework of statistical mechanics in this constituent model of the black hole! (Dhar, Mandal, SW; Das, Mathur; Callan, Maldacena)

Precise Holography conjecture: A conceptual and computational tool for Quantum Gravity

Juan Maldacena (1997)

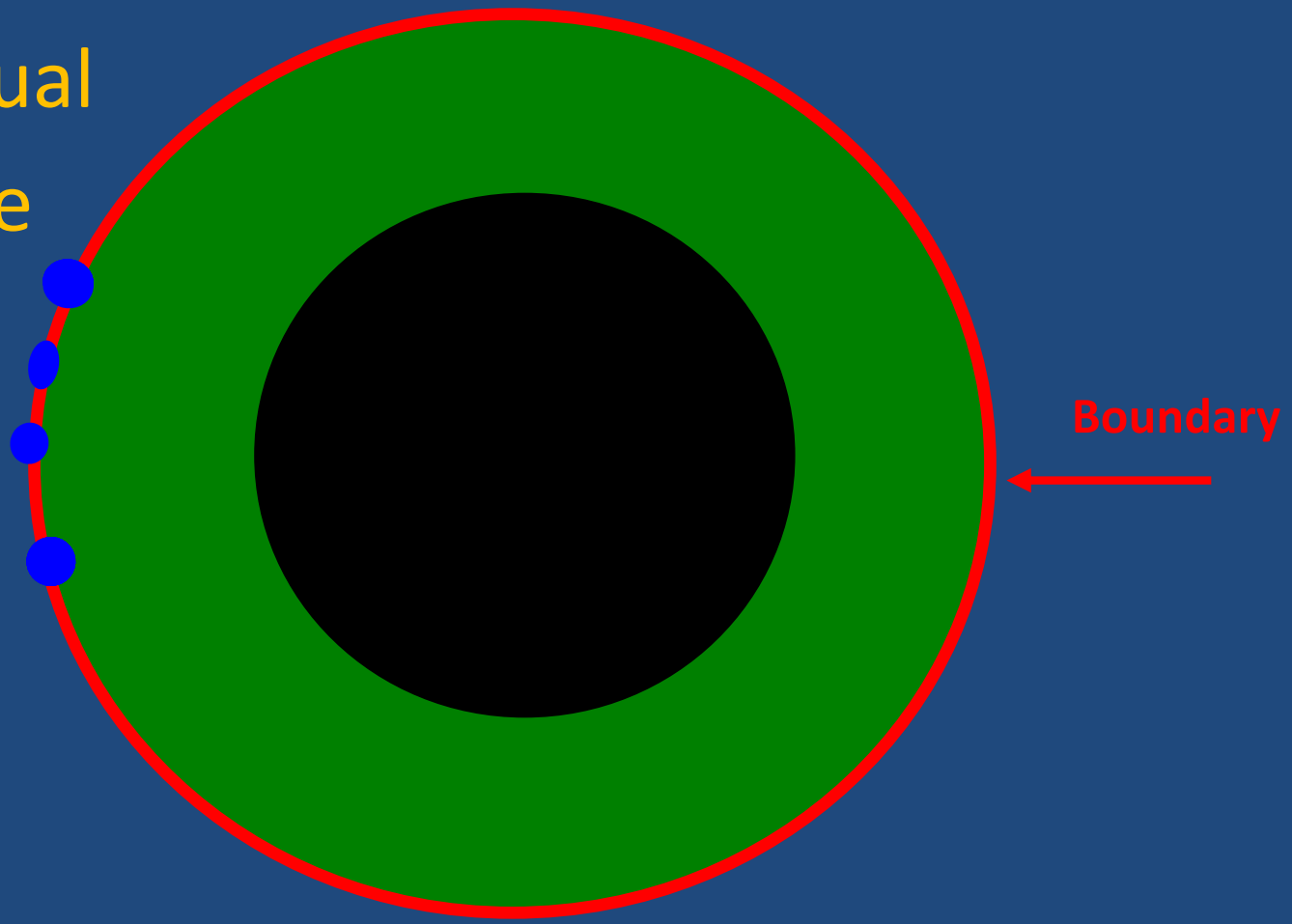


Gravity in the interior →
Described by interacting particles on the boundary.



Black holes correspond to a large number of particles on the boundary

BH in AdS is dual to QFT at finite temperature



Temperature and entropy → motion of particles on the boundary

Applications of AdS/CFT

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

$\eta/s = (1/4\pi)\hbar/\mathrm{k_b}$ (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 and Ryu-Takayanagi formulas

Applications to quantum chaotic systems: $\lambda \leq 2\pi kT/\hbar$ (Maldacena, Shenker, Stanford, Kitaev…)

Concluding remarks

In string theory, there is a possibility to understand the fundamental theory of 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

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

- 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