ICTS | INTERNATIONAL CENTRE for THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

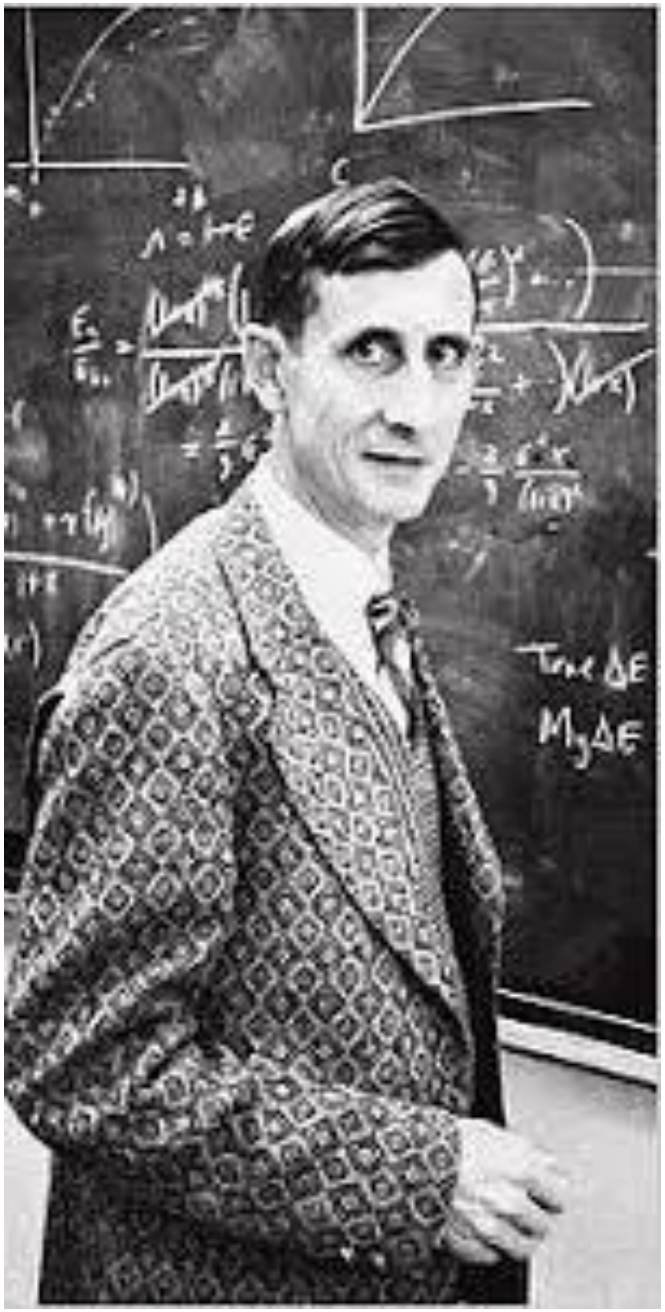
Black holes: Beacons in our search for a quantum theory of space-time

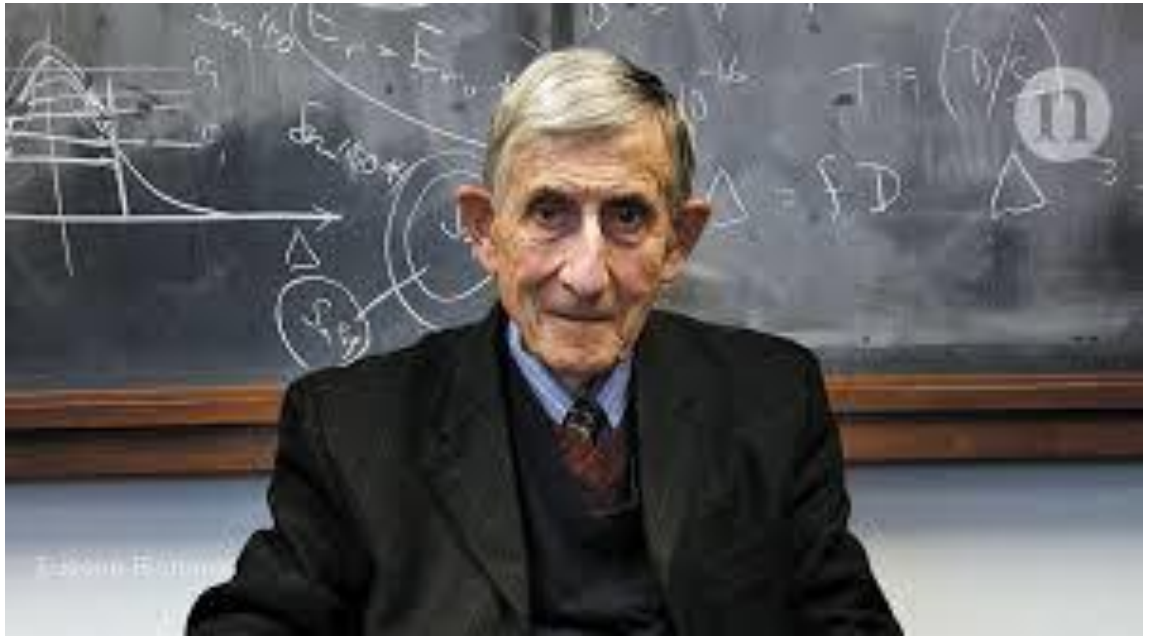
Dayal Bagh Educational Institute

Diamond Jubilee Memorial Lecture

29 February 2020

Spenta R. Wadia





Freeman Dyson (1923-2020)

Dedicated to the memory of Freeman Dyson

Galileo (1564-1642)

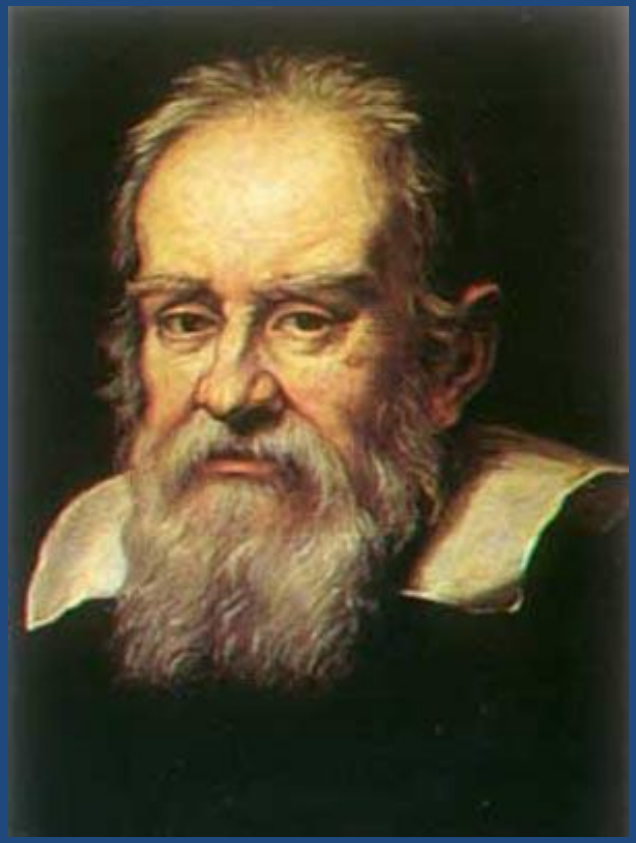
A pioneer of the modern scientific method

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:

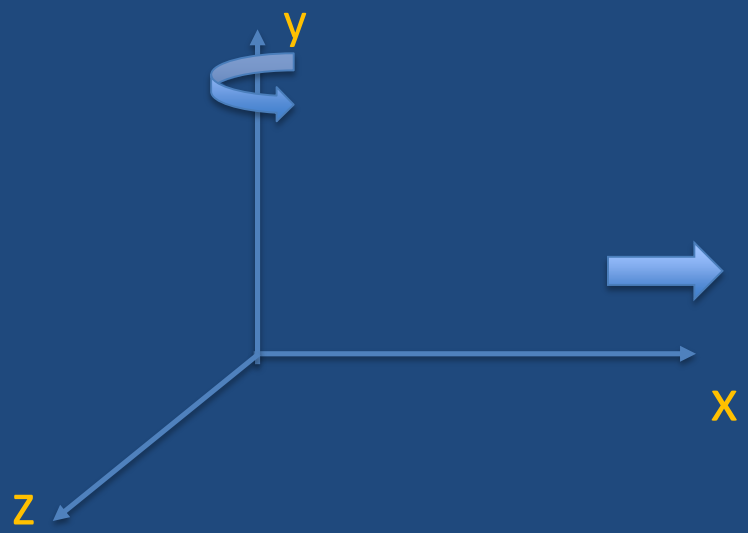
$m_{inertial} = m_{gravitational}$

($1/10^{13}$ 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 particle in 3-dims.

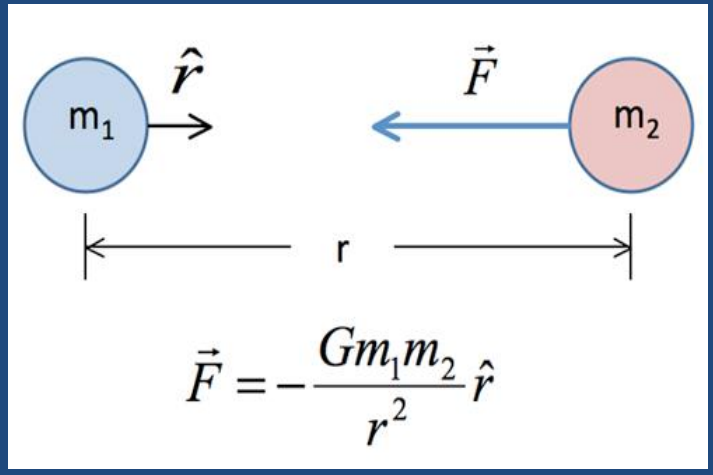


(x(t), y(t), z(t)) is a curve; velocity and acceleration are given by one and two time derivatives. Coordinates may be rotated or moved with constant velocity

Newton's law of motion:
Force = $\text{mass}_{\text{inertial}}$ x acceleration

Time is absolute and the same for all observers.

Newton's law of Universal Gravitation



Force acts instantaneously at a distance

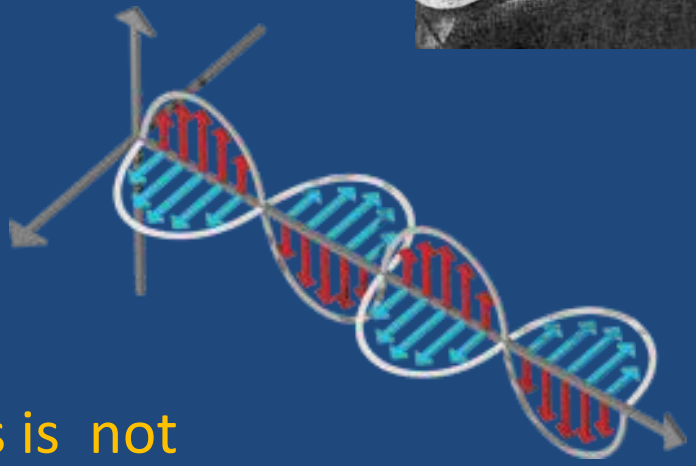
Newton (1692): "That one body may act upon another at a distance through a vacuum without the mediation of anything else, by and through which their action and force may be conveyed from one another, is to me so great an absurdity that, I believe, no man who has in philosophic matters a competent faculty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

Faraday introduced the idea of Electric and Magnetic fields.

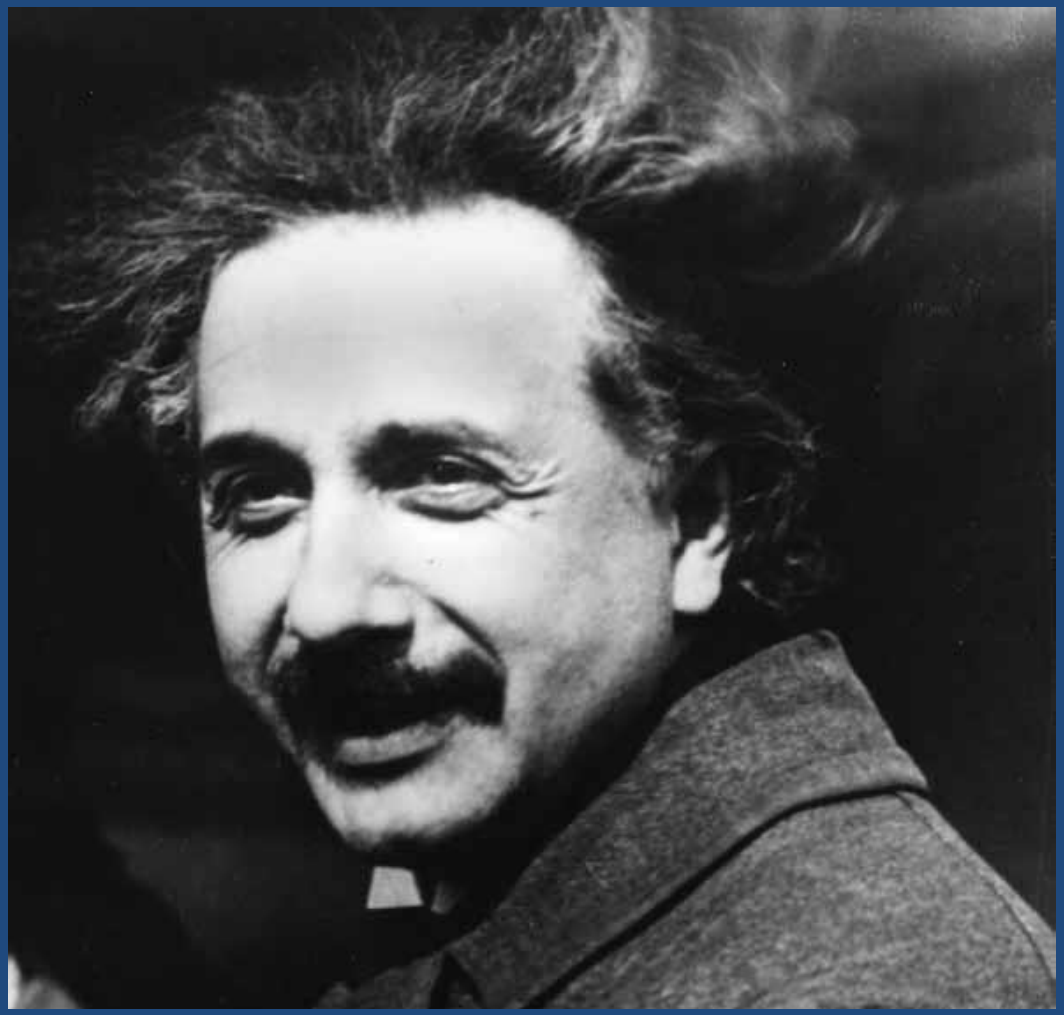
Maxwell unified electricity and magnetism, predicted the existence of electromagnetic waves and identified light as an electromagnetic wave of oscillating electric and magnetic fields moving with a speed $c = 3.1 \times 10^5$ kms/sec (in vacuum) (1865)



Hertz demonstrated existence of radio waves with properties exactly the same as visible light (1887) except wavelength is 10^4 times longer.

Interaction between electric charges is not instantaneous and is mediated by electric and magnetic fields moving at the speed of light

Albert Einstein
Special Relativity 1905



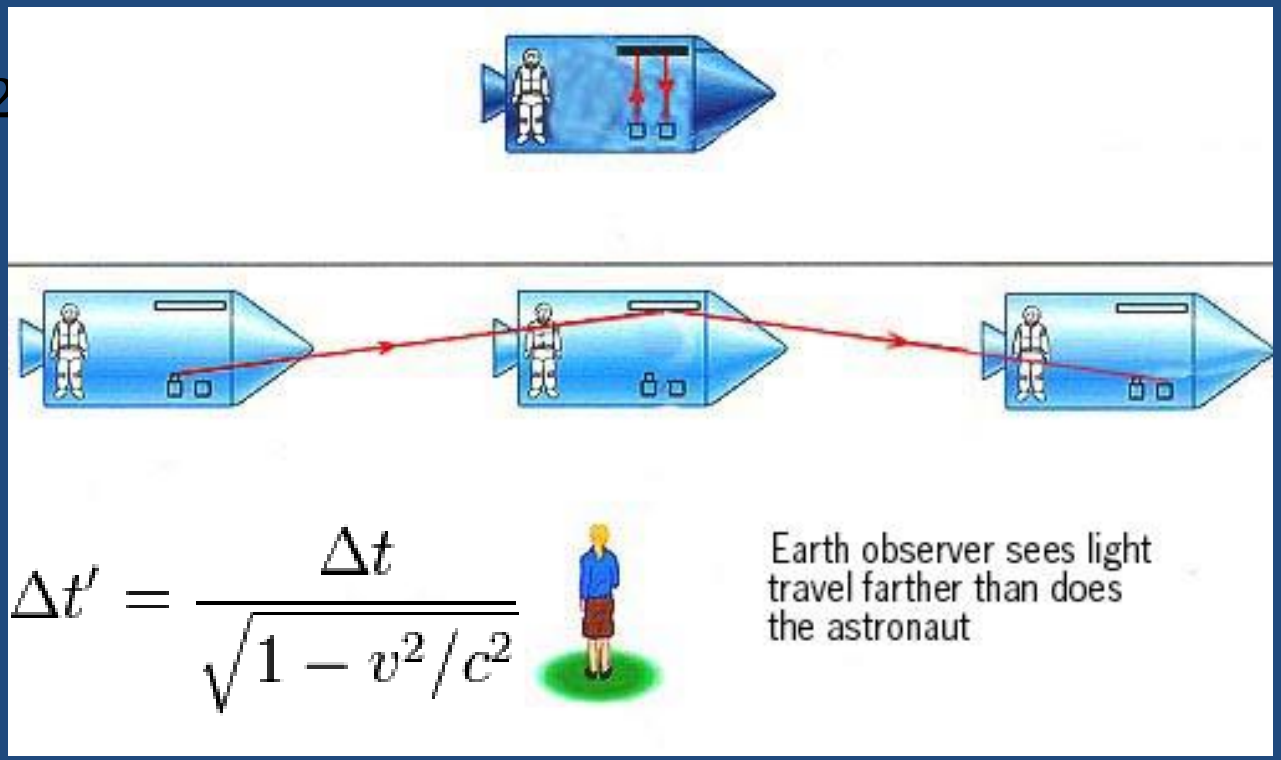
Lorentz, Poincare, Einstein: Special Relativity (1905)

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.

- x^2



Einstein's Two 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 spacetime 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 "Principle of Equivalence"… the fall when a car suddenly brakes

2) Where the linear mixing of space and time in special relativity is replaced by a non-linear mixing, called a general coordinate transformation.

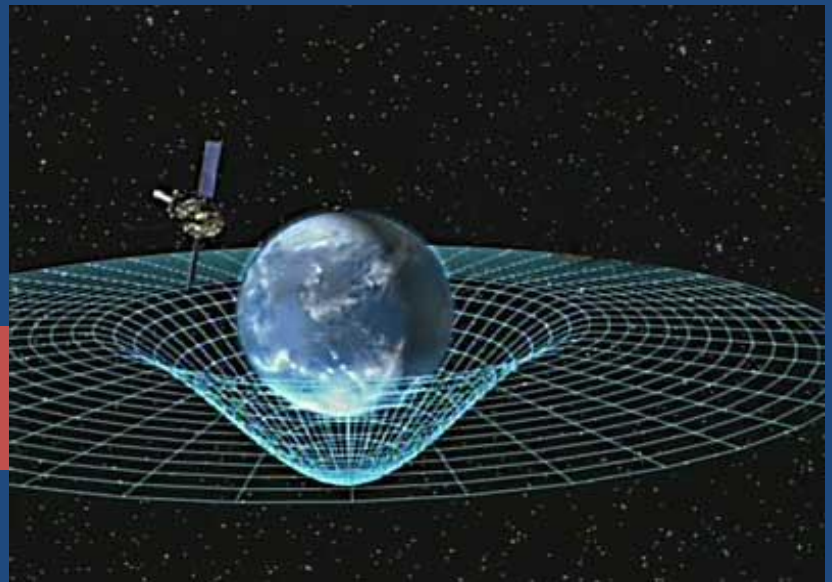
Einstein 1915

General Relativity: Gravity as 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).

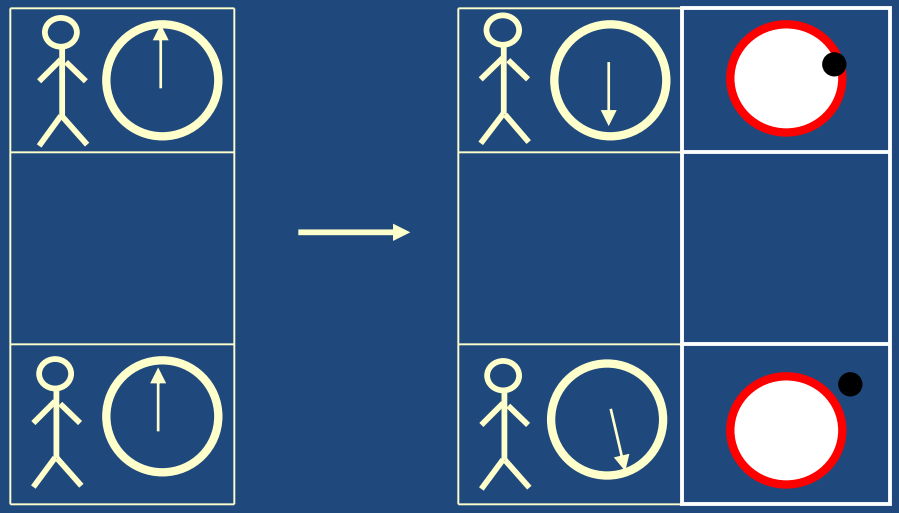
In GR the space-time grid is `elastic', communicative and causal…but very very stiff! **GR is a good theory for physics on large scales**



Einstein's theory implies that time flows different for two observers in a gravitational field

Upper floor

Lower floor



Time flows more slowly

(A part in 10^{15}) for a height of 100 meters.

This effect is relevant for GPS!

Einstein's equations have surprising and remarkable solutions describing different space-times

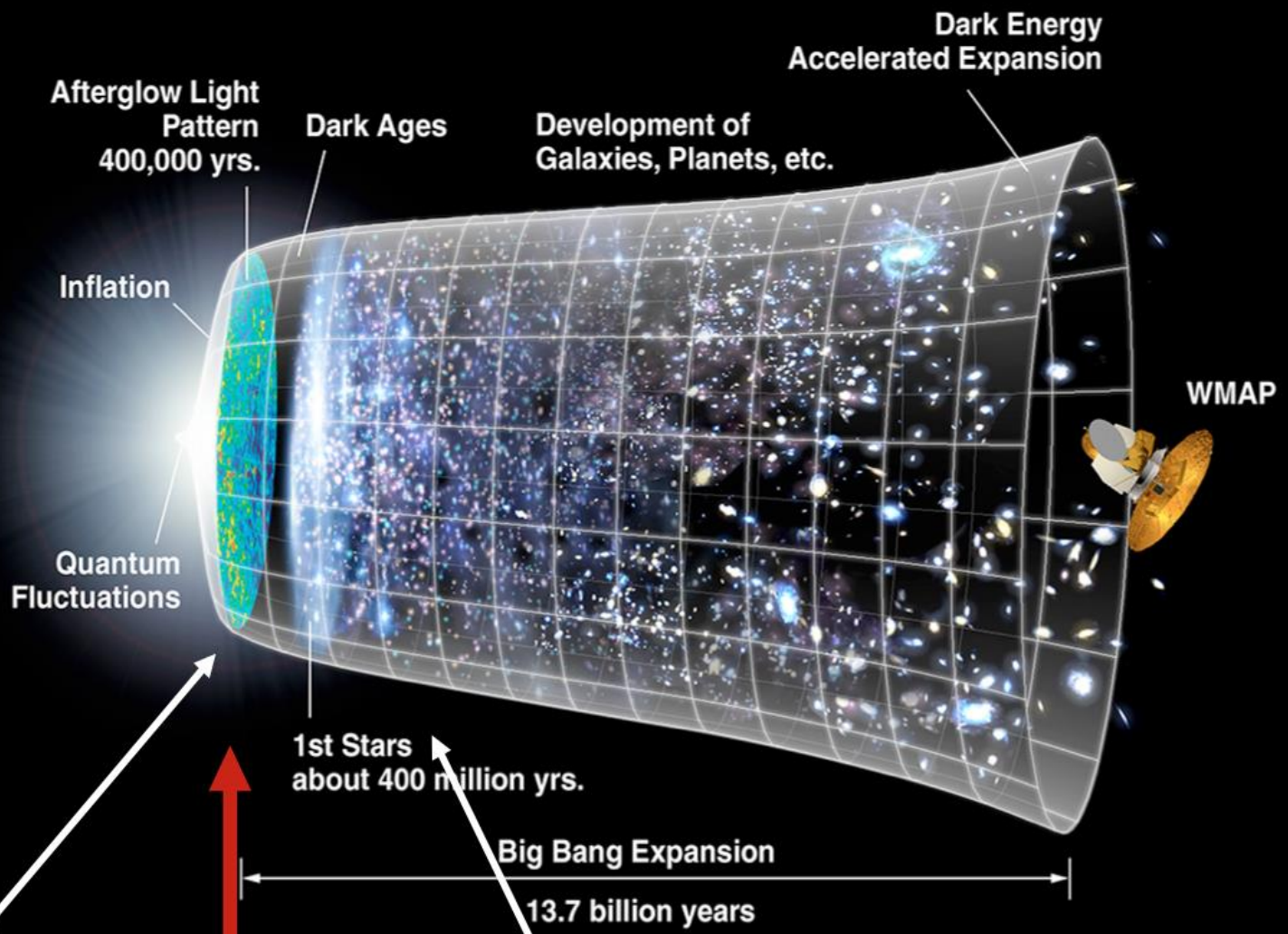
1. Expanding and accelerating space-time (+ve cosmological constant) (Friedman 1922, LeMaitre 1927)
2. Gravitational waves (Einstein 1916)
3. Black Holes (Schwarzschild 1916; Kerr 1963)

GR becomes a framework to discuss

black holes, gravitational waves and cosmology…

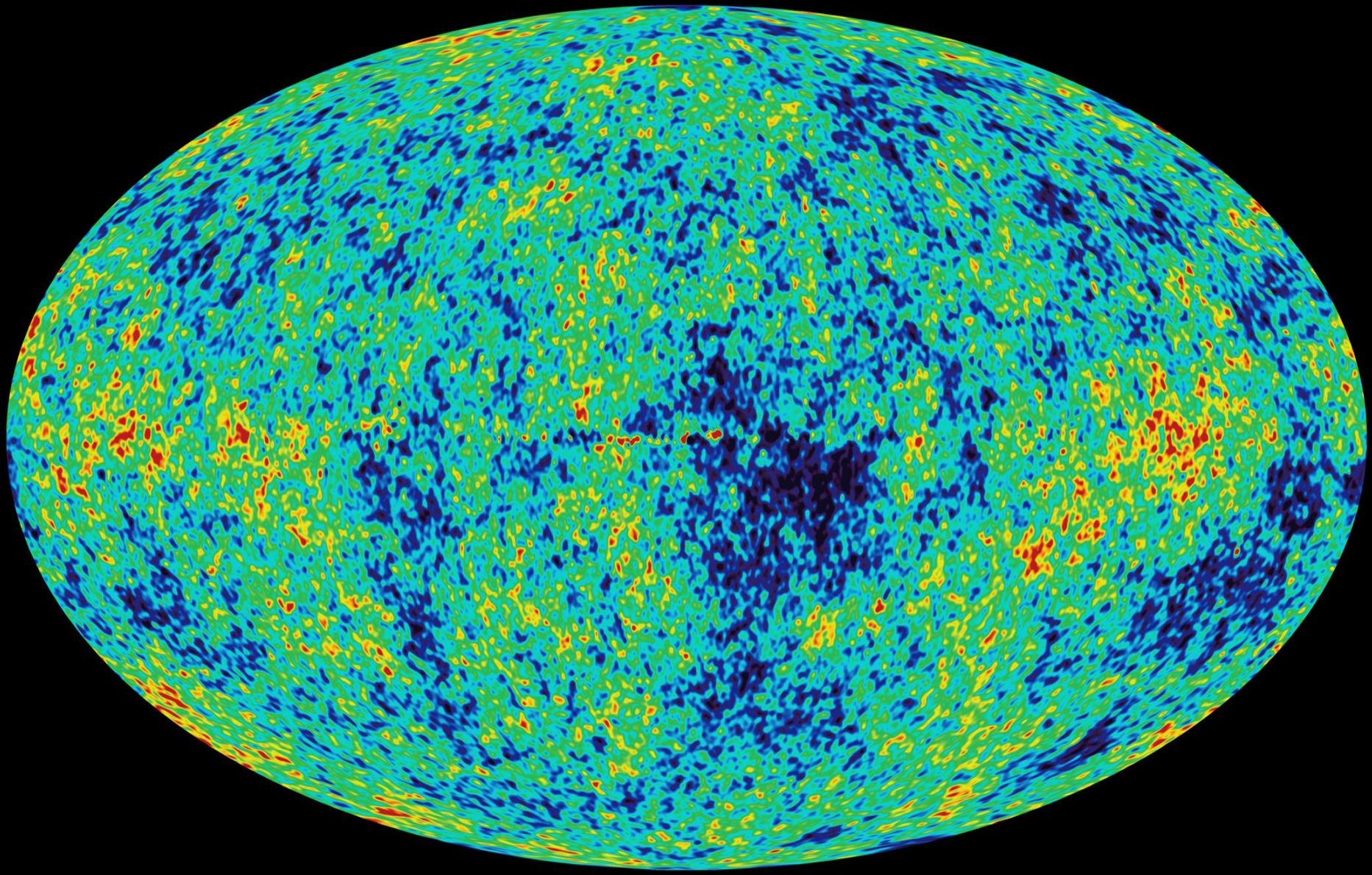
by now these applications are experimentally confirmed!

The Standard Model of Cosmology

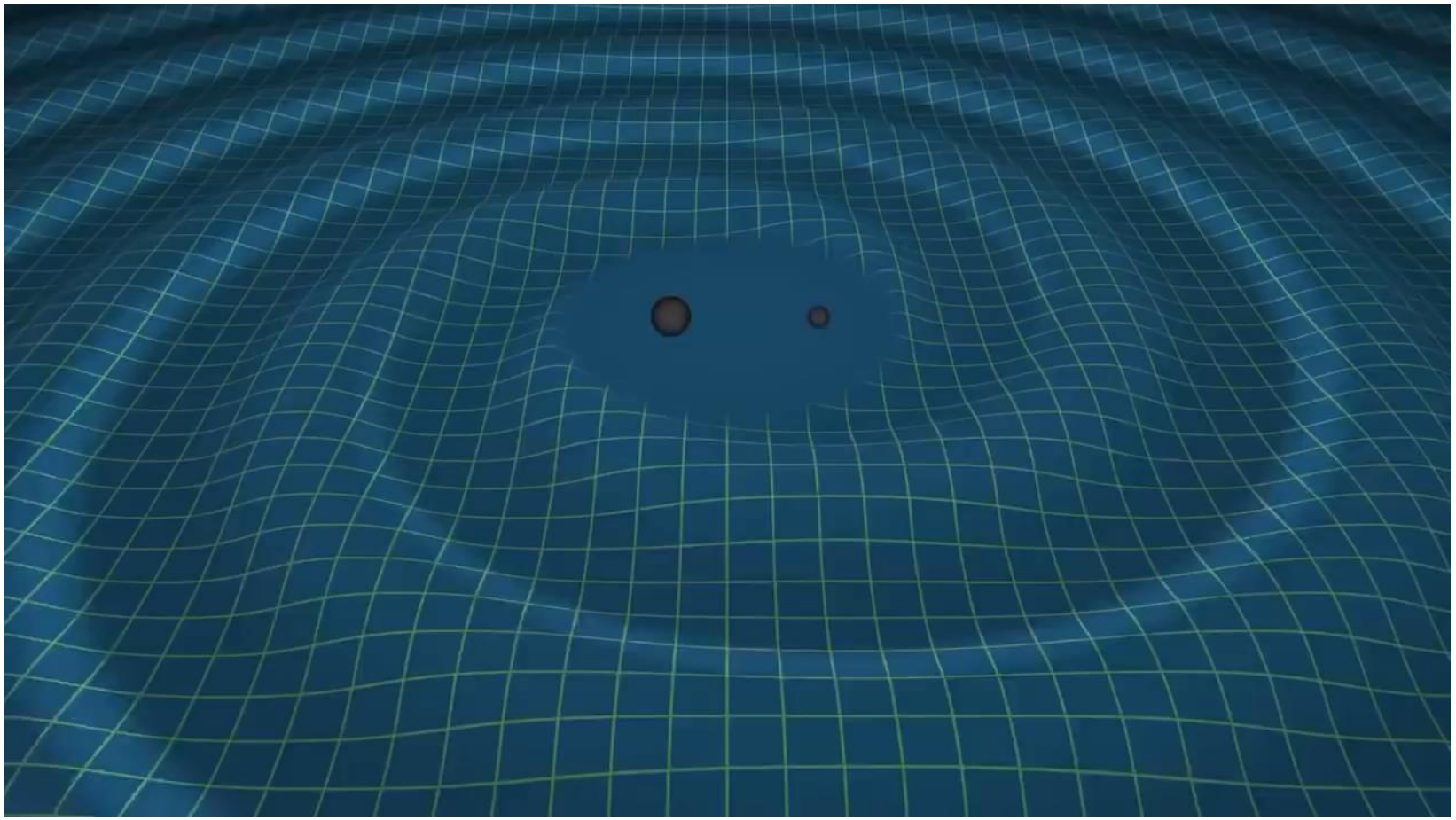


Surface of last scattering at "decoupling."

"Reionization"

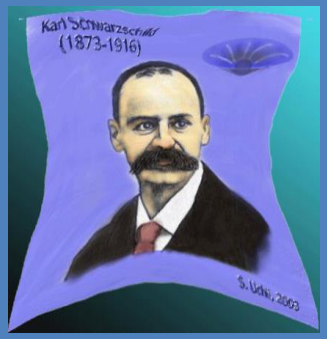


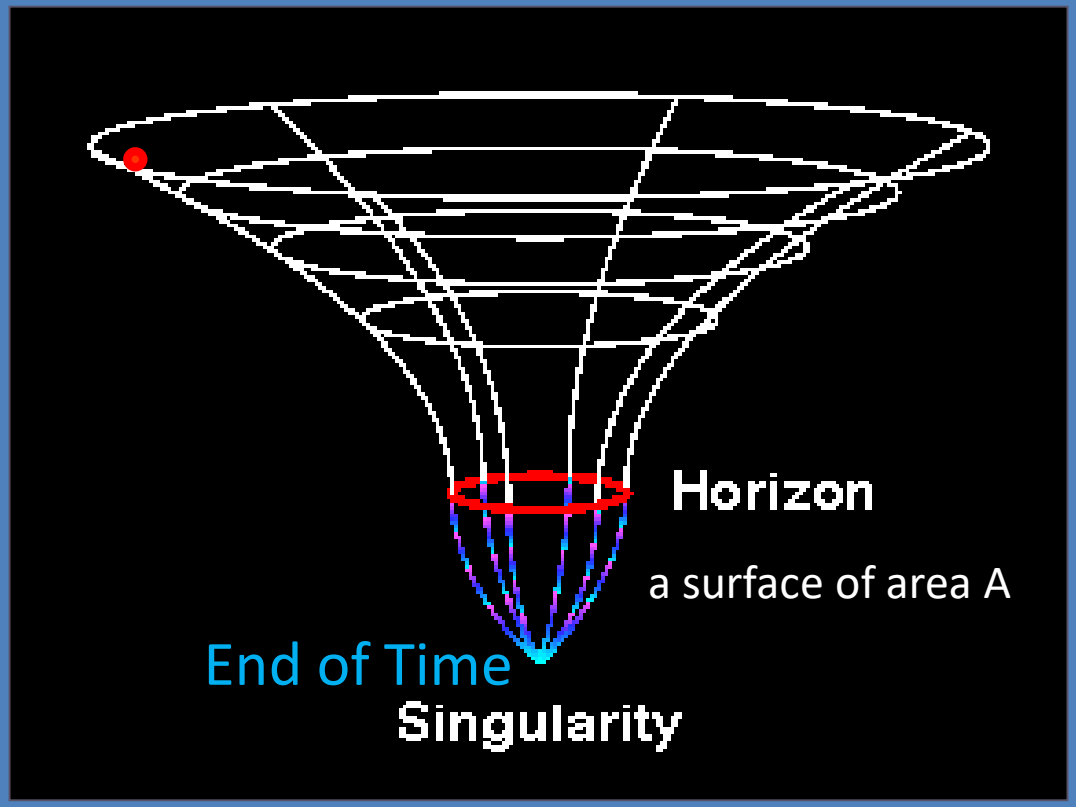
A Picture of the infant universe revealed in micro-wave radiation. Mean temperature 2.71 deg K. Temperature fluctuations are are between -200 to +200 micro-Kelvin

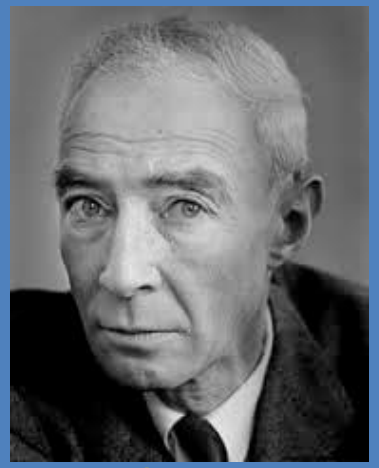


On 14 September 2015, at the LIGO sites gravitational waves were detected

General Relativity predicts Black Holes





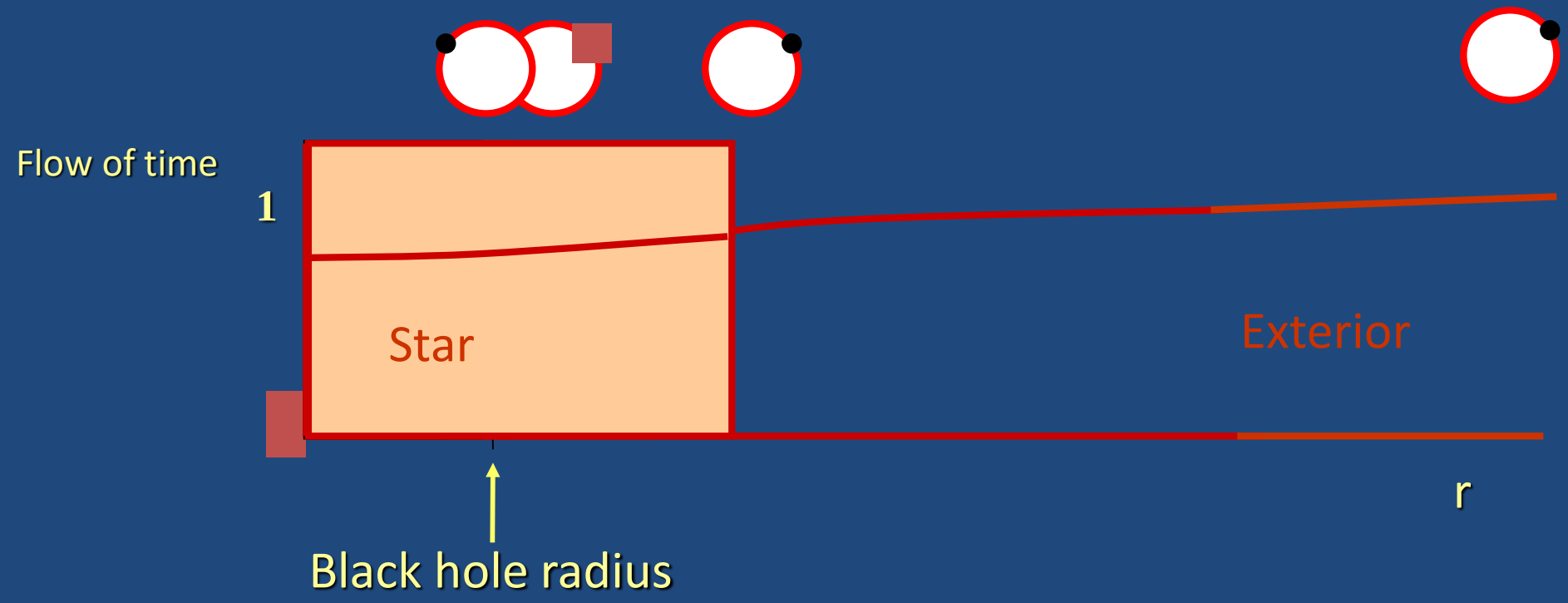


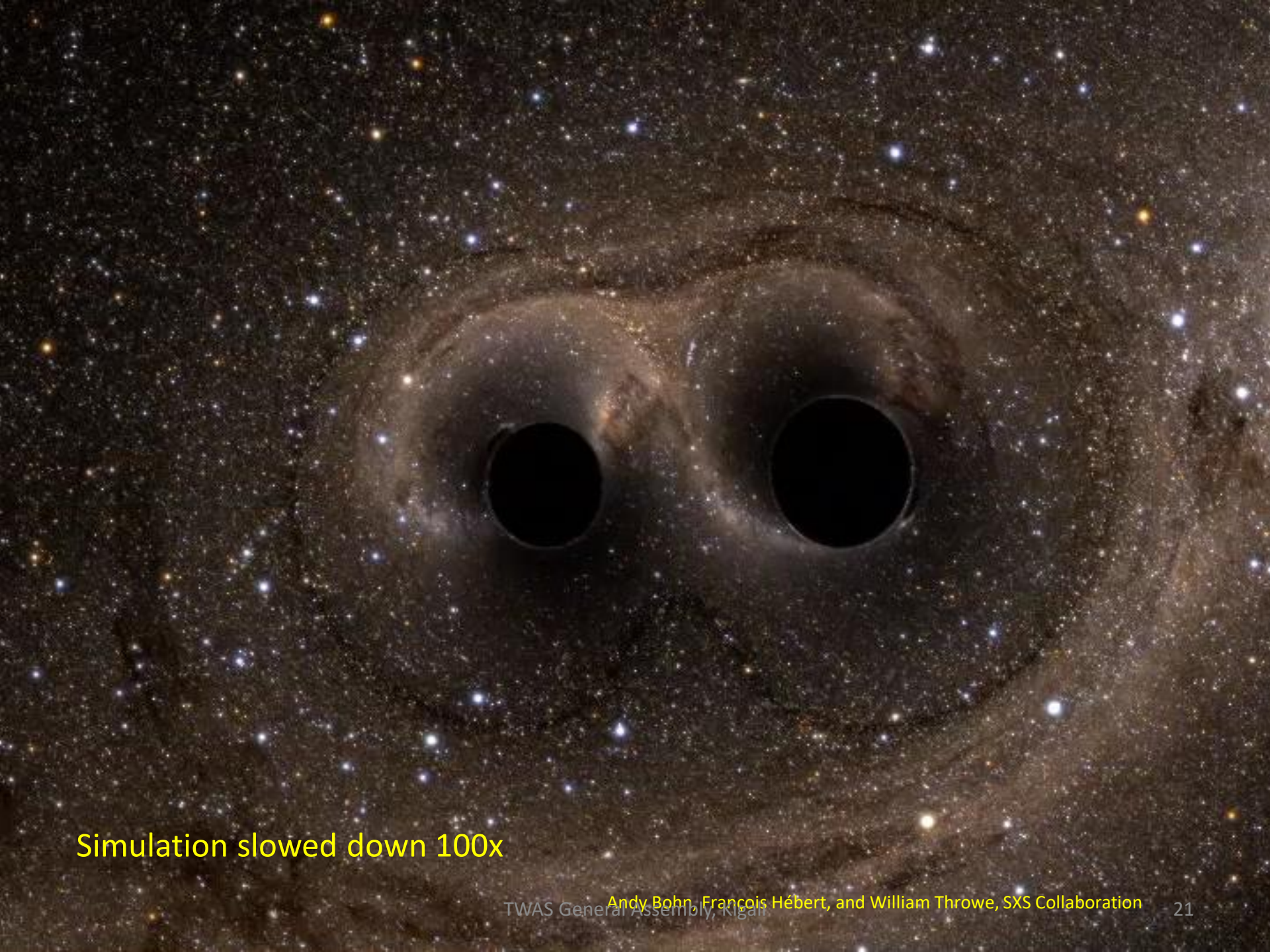
Black holes are characterized by
a horizon and a singularity. They exist in Nature!

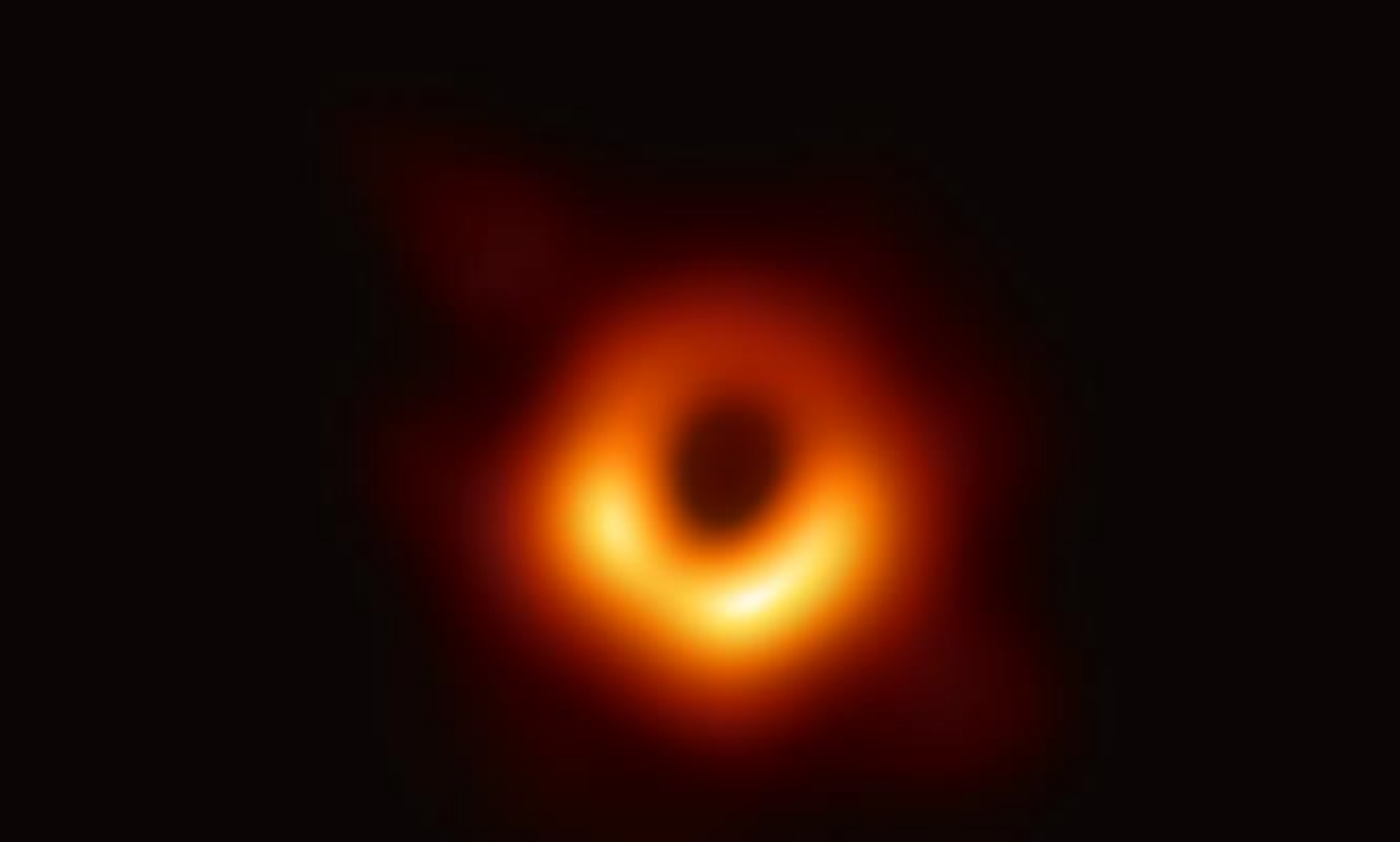
Schwarzschild

Chandrasekhar & Oppenheimer

Flow of time in the presence of a massive Star and a Black Hole

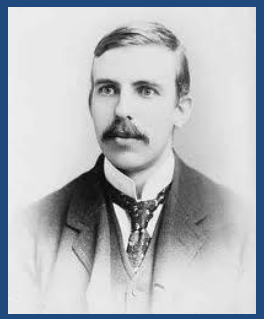



Simulation slowed down 100x
Andy Bohn, François Hébert, and William Throwe, SXS Collaboration



The first image of a supermassive black hole and its shadow in the Messier 87 galaxy , in the Virgo cluster. (Event Horizon Telescope collaboration, (April 2019)

Length scales in the universe



Quantum Gravity

Big Bang?

Proton

Atom

10^{-32} 10^{-28} 10^{-24} 10^{-20} 10^{-16} 10^{-12} 10^{-8} 10^{-4} 10^{4} 10^{8} 10^{12} 10^{16} 10^{20} 10^{24} 10^{28} cm

Radius of Earth

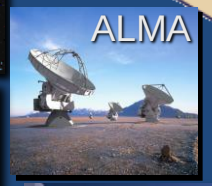
Earth to Sun

Radius of Galaxy

Universe

LHC

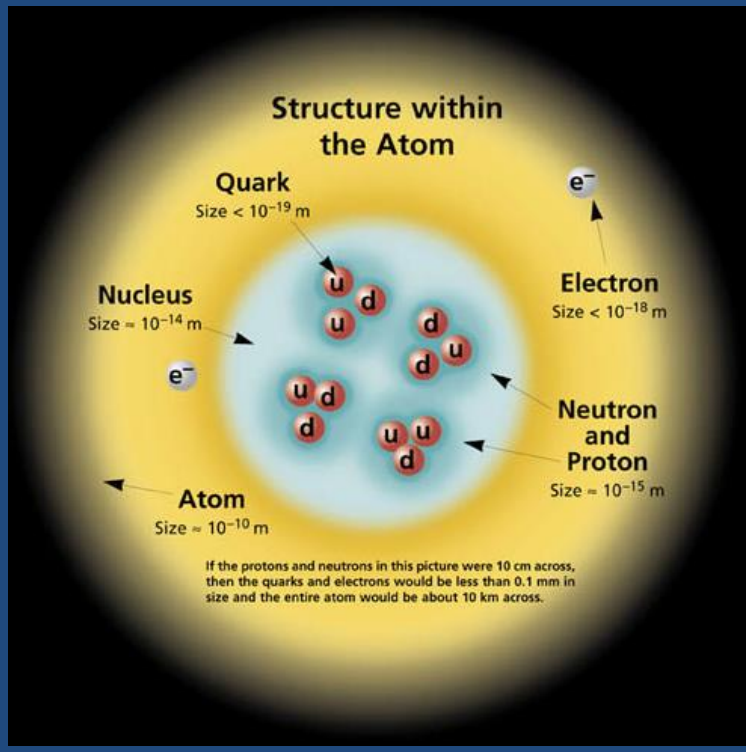
Super-Microscope



Enter Quantum Mechanics

- A 20th century scientific revolution:

(Planck, Einstein, Bohr, Heisenberg, Schrodinger, Born, Dirac, Feynman and many many others)



- New laws for all particles
  especially below atomic scales.

- Electronic devices, computers, lasers, superconductors, superfluids, quantum computing…

- Colliding elementary particles in the LHC in Geneva all follow the laws of quantum mechanics …
  tested to 10^{-16} cms

Quantum Mechanics Rules

- QM assigns a complex number for an event; e.g. the motion of a particle from one point to another

- $A(a , b; C)$ $A(b , a; C)$
- $A(b , a; C) = A(a , b; C)^*$
- The PROBABILITY of the event is given by

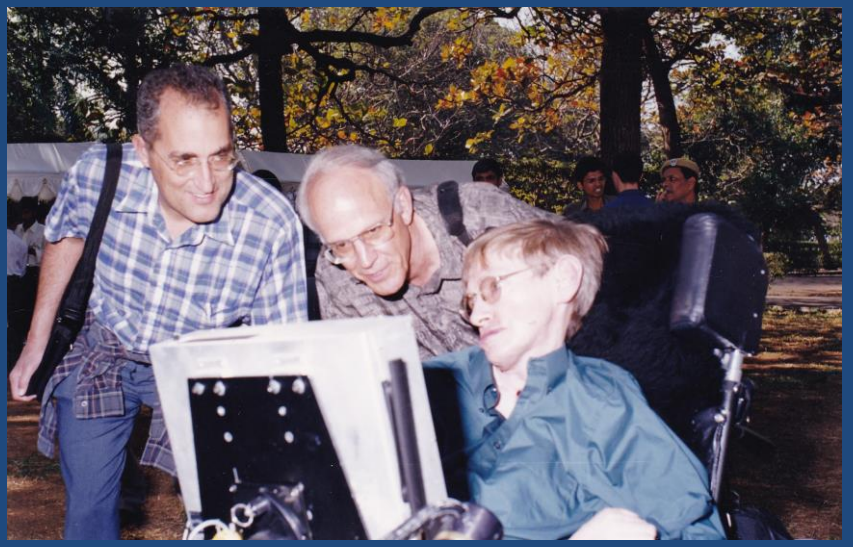
  $P(a , b; C) = A(b , a; C)\, A(a , b; C)^*$

Quantum Mechanics and Black Holes

In QM if a particle to falls into a BH with a certain *probability*, then there is an *equal probability* for it to be emitted.
Hence quantum mechanics requires that
black holes must radiate! (Hawking 1974)

Hawking calculated the temperature of the black hole and argued that the end point of BH evaporation is purely thermal radiation.

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



- $T_{sun} = 3.6 \times 10^{-7}$ K
- $T_{earth} = 0.1$ K
- $T_{M=10^{18}kg} = 7000$ K (white light)

Temperature formula + 1st law of thermodynamics =>

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

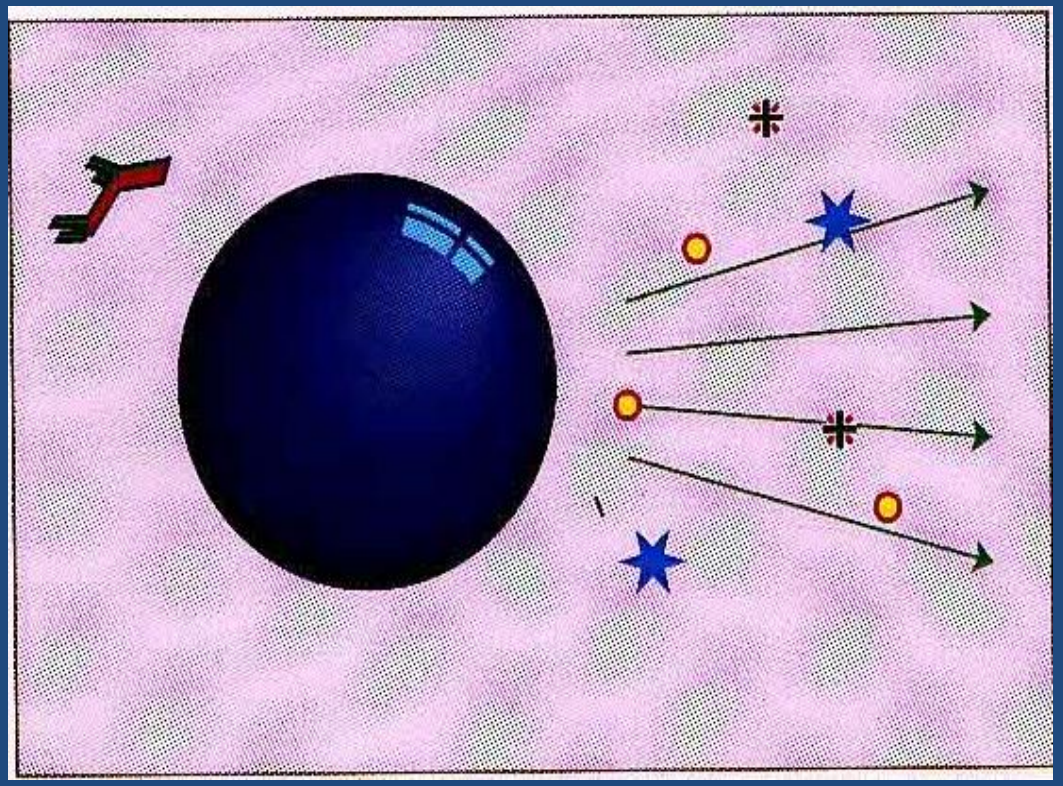
One of the important formulas of 20th century physics that contains all three fundamental constants!

$(\hbar G/c^3)=(10^{-66})$ cm^2, is the `Planck area' in 3-dims.
k is Boltzmann's constant

Hawking Radiation and Information Loss

Hawking: BHs radiate

A black hole forms in various ways, but it always evaporates in the same way. The final state is thermal radiation leading to **information loss** as there is no memory of the initial state!



The Information Paradox

Since black hole radiation is thermal with a Planck spectrum at temperature T, the initial information about the details of the formation of a black hole are lost.

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

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

Hawking's calculation created a crises in theoretical physics.

Many Questions

1. Is there a theory of quantum gravity with degrees of freedom (states) that would account for black hole entropy using Boltzmann's formula for entropy?

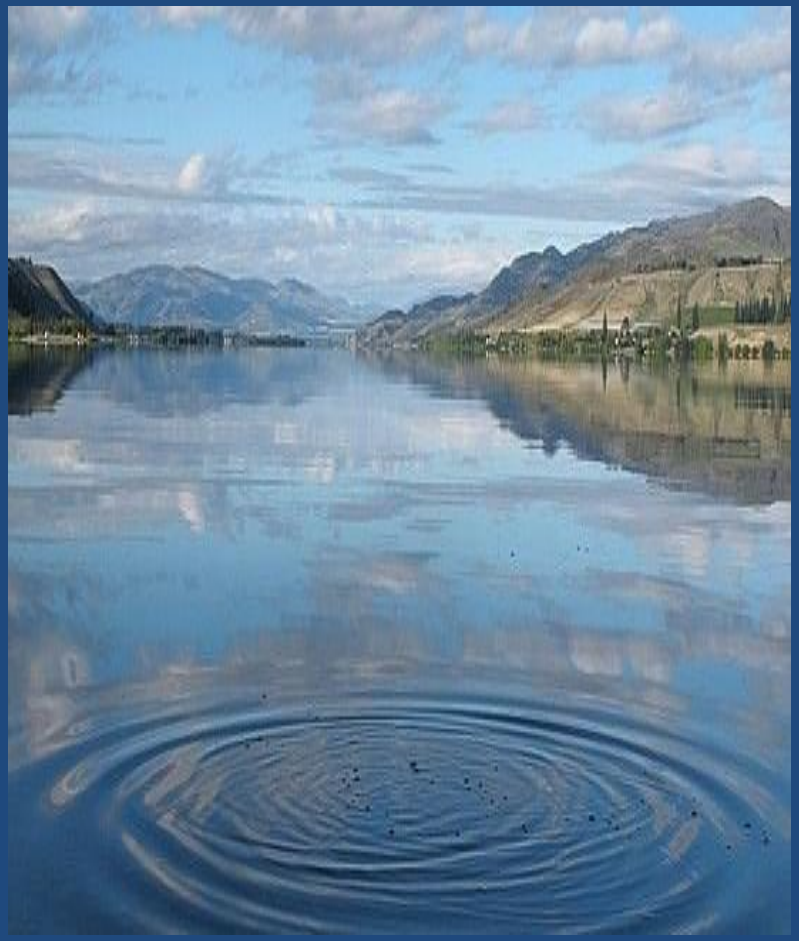
   $S_{BH} = k \log(N)$ N= number of internal states

2. Can one calculate Hawking radiation by averaging over the very large number of internal states of a quantum black hole?

3. Is there an exact formulation of a non-perturbative string theory (quantum gravity)?

4. Where is the error in Hawking's calculation that creates a conflict with QM?

Emergent Picture: Einstein's theory is an effective geometrical theory analogous to a fluid dynamics description of water



Drop a big pebble in a calm lake

It will cause a wave (distortion) to travel outwards from where it was dropped.

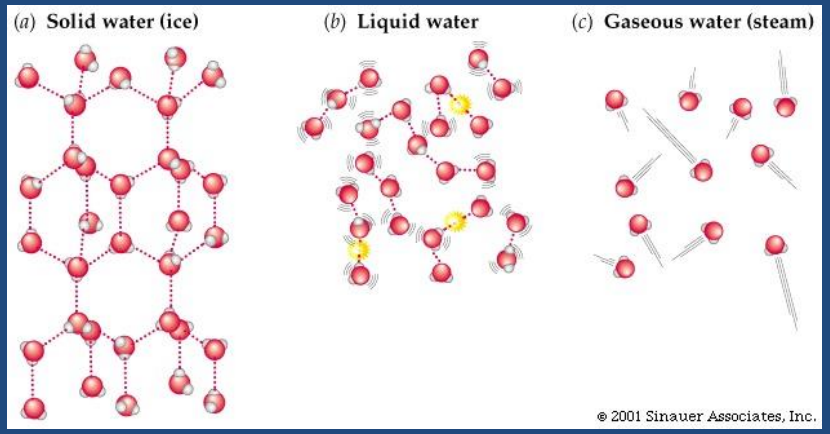
The wave will travel at the speed of sound in water and its effect will be felt a distance away.

The passing wave will wiggle a small sized object floating in the water!

There is a cause and an effect communicated by a wave traveling at a definitive speed…analogous to gravitational waves set off by colliding black holes.

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 and their interactions in gravity?

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

String theory is a new framework of physics that can provide answers to these questions

It is consistent with quantum mechanics and contains general relativity at long distances…if one does not look too closely.

It provides new degrees of freedom besides the graviton that can account for the entropy of black holes using Boltzmann's formula and one can calculate Hawking radiation. (This is demonstrated for a class of black holes)

In the special case of anti-de Sitter spacetimes that have a boundary it provides an exact holographic formulation of quantum gravity on the boundary of AdS (More later)

Most recently in lower dimensions one can point to the error in Hawking's calculation. Information theoretic ideas and holography have played an important role in this understanding.

Partial answers

Q1. Is there a theory of quantum gravity with degrees of freedom (states) that would account for black hole entropy:

$$S_{BH} = k \log(N)?$$

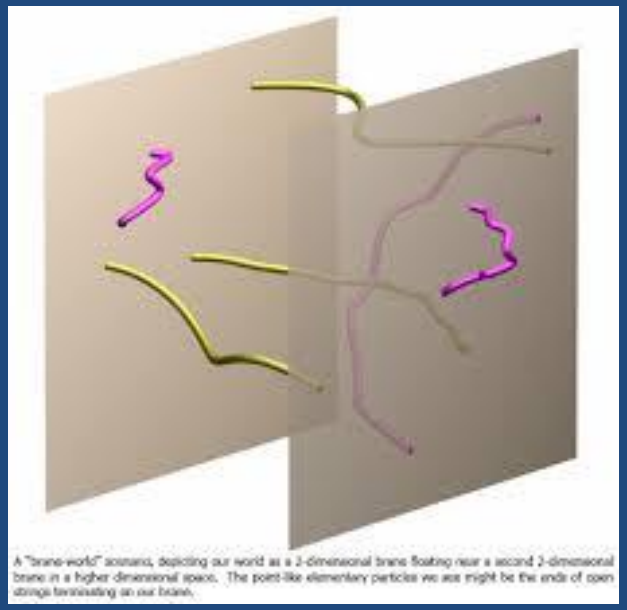
(Bekenstein-Hawking formula = Boltzmann formula)

A1: Strominger and Vafa (SV) calculated BH entropy and 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 (of string theory) called discovered earlier by Polchinski. The SV BH is extremal and has zero temperature.

Black Hole Micro-states

- String theory has the degrees of freedom beyond the gravitons of Einstein's theory that underlie the smooth geometric description. These are `membranes' of various dimensions: 0, 1,2,….,9. Special ones are D-branes (Polchinski)

e.g. 2 D-branes interacting via open string exchange.



A "brane-world" scenario, depicting our world as a 3-dimensional brane floating near a second 3-dimensional brane in a higher dimensional space. The point-like elementary particles we see might be the ends of open strings terminating on our brane.

- They are `analogous' to the molecules of water which are the underlying bits of the smooth fluid.

Q 2. Can information loss for black holes be understood as due to an averaging of a very large number of internal states, like in quantum statistical mechanics?

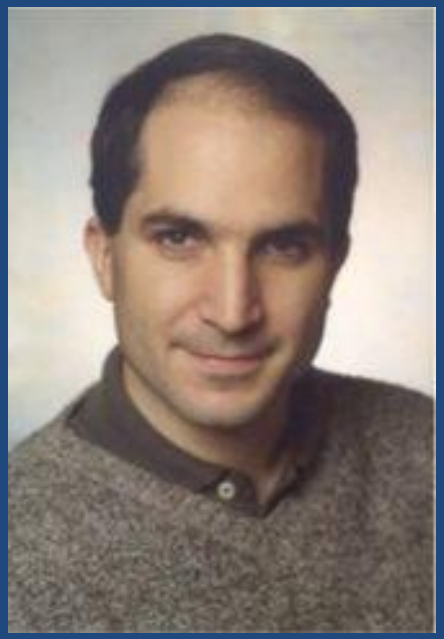
Q3. Can one calculate Hawking radiation in such a theory?

A2 and A3:
Exciting a BH gives it a low and non-zero temperature. Hawking radiation rates and BH thermodynamics can be calculated in the framework of statistical mechanics in the constituent model of the black hole! (Dhar, Hassan, Mandal, David, Wadia (1996; 2002)

Insights from black holes paved the way for another development which provides a powerful conceptual and calculational tool: the Holographic Principle, partial answer to Q3.

Next big step: Holography and a precise formulation of Quantum Gravity…the AdS/CFT correspondence

-Juan Maldacena (1997)

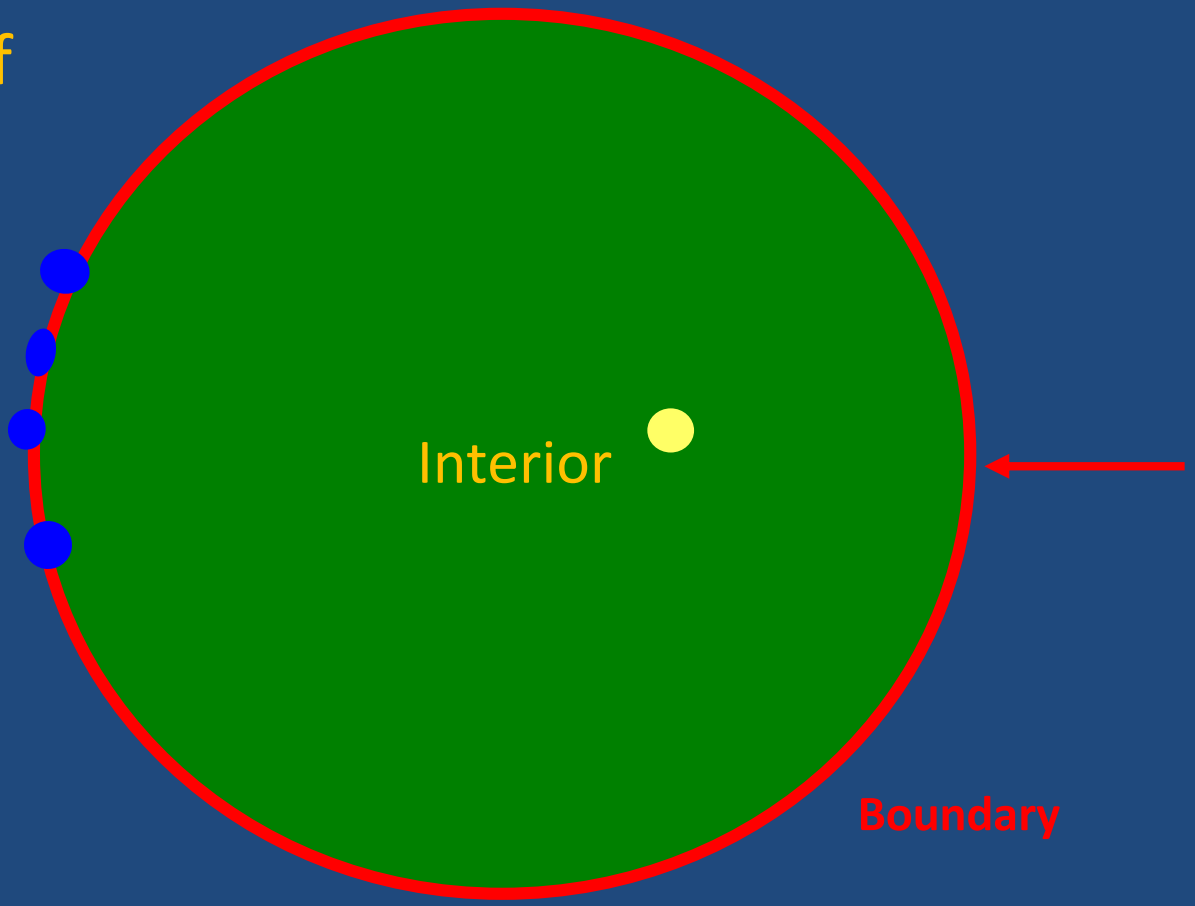


This development has led to enormous activity over the last 20 years…brought together people working in string theory, mathematics, condensed matter physics, quantum information, chaotic systems…

Many important contributions from various groups in India.

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

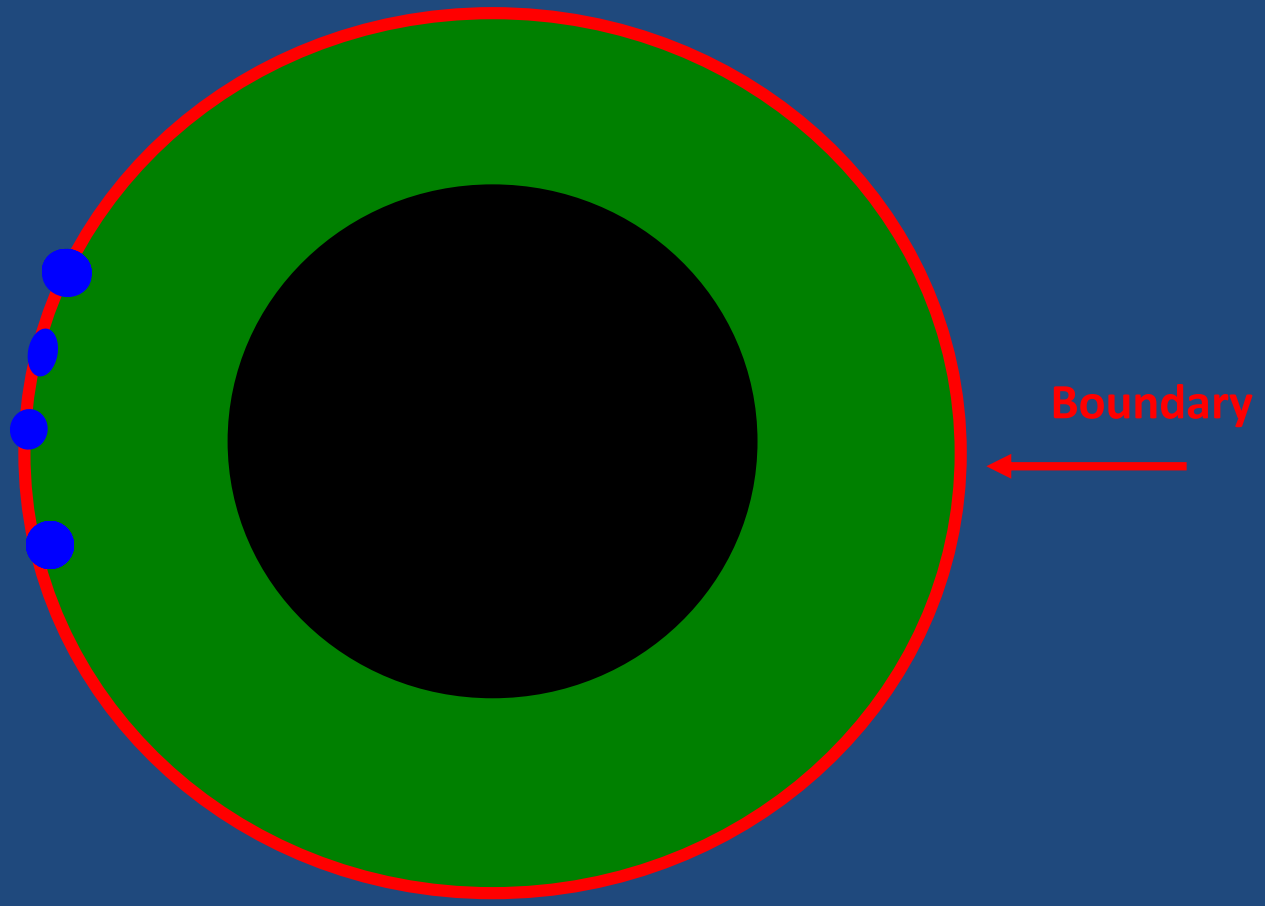
In the interior of
AdS space-time
is gravity



On the AdS
boundary
lives a unitary
Quantum Field Theory

BH physics in AdS is coded into a unitary QFT at finite temperature on the boundary

Temperature and entropy → motion of particles on the boundary.



This correspondence in principle resolves the information puzzle

Missing piece in Hawking's calculation?

Using holography and ideas of quantum information, the time dependence of the quantum entanglement entropy of the Hawking radiation can be calculated in low dimensional models …(Maldacena, Almheiri, Mahajan, Zhao, Stanford, Shenker, Pennington, Yang, …)

Hawking had missed out an important piece in this formula, which crucially reflects the unitarity of the evaporation process.

Concluding remarks

Pursuing the resolution of the `information paradox' presented by the work of Hawking has led us to unearth deep facets of the quantum theory of space-time and gravity…and led to the discovery of the AdS/CFT holographic correspondence and information theoretic ideas for the resolution of the information paradox.

Many deep questions remain, e.g. an explicit understanding of the singularity of a black hole, where time ends. This could enable an understanding of the beginning of time…how the universe began…

Acknowledgement

- The Infosys Foundation Homi Bhabha Chair

- Juan Maldacena for the animation about black holes

Thank You