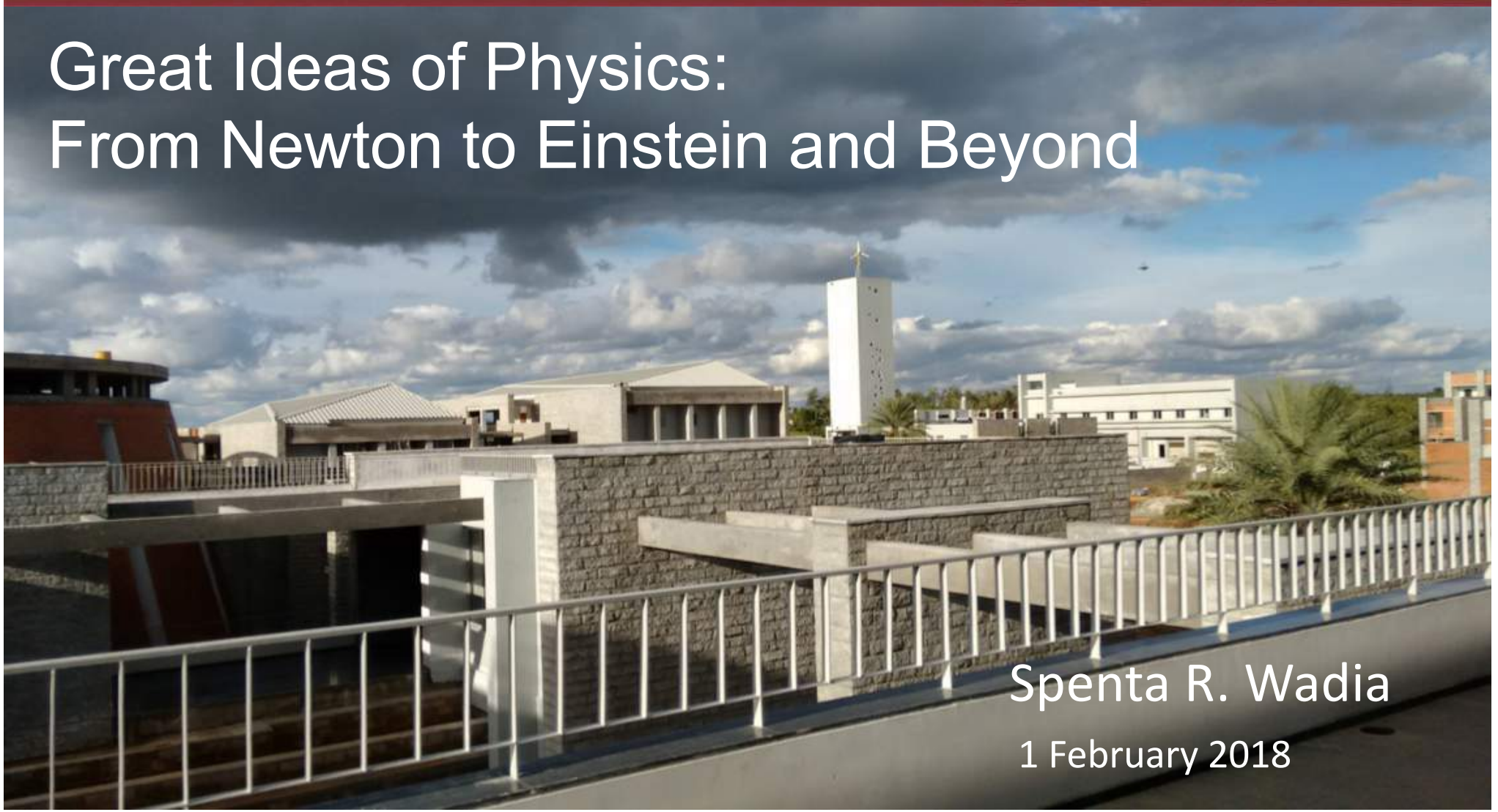
ICTS | INTERNATIONAL CENTRE for THEORETICAL SCIENCES

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

Great Ideas of Physics: From Newton to Einstein and Beyond



Spenta R. Wadia

1 February 2018

Galileo (1564-1642)

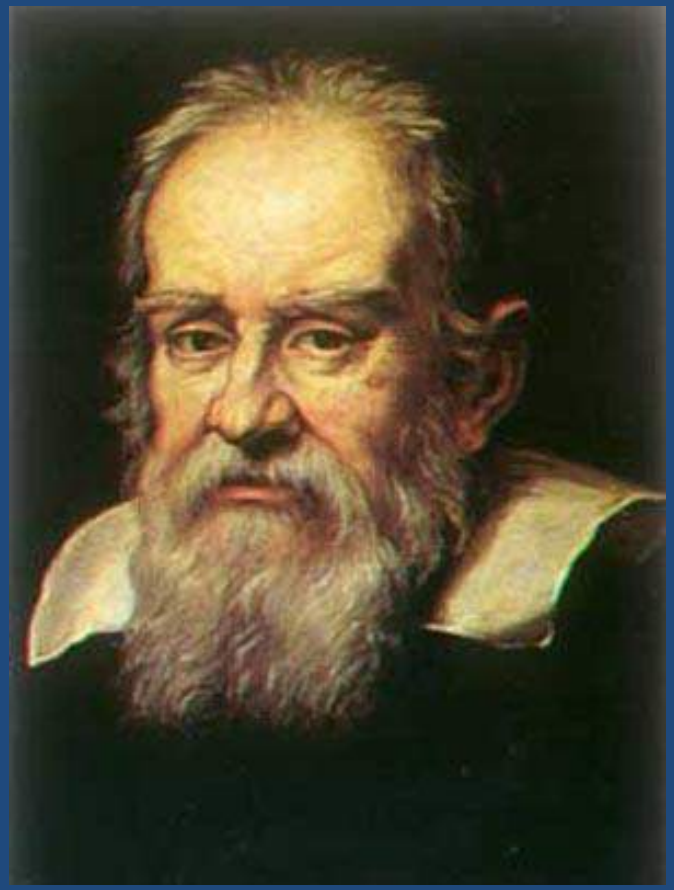
A pioneer of the modern scientific method

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.

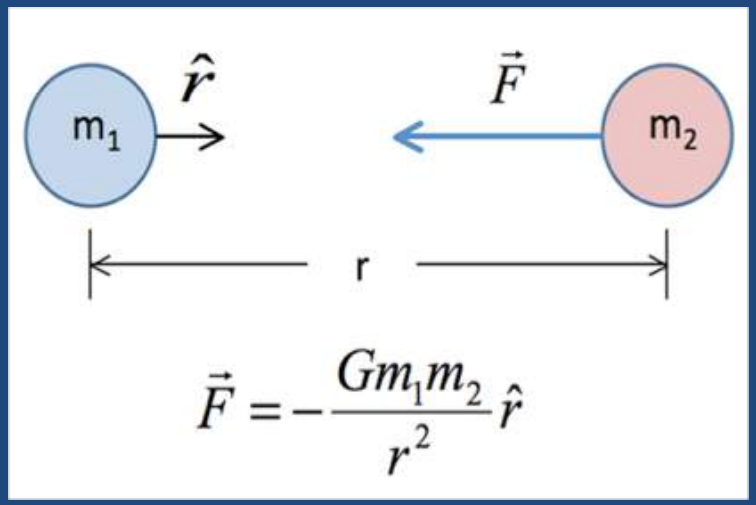
(x(t), y(t), z(t))

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



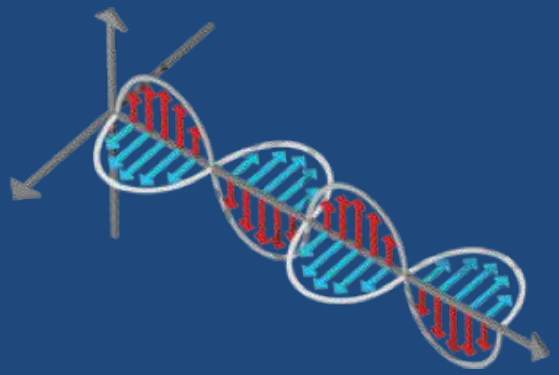
Force acts instantaneously at a distance

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."

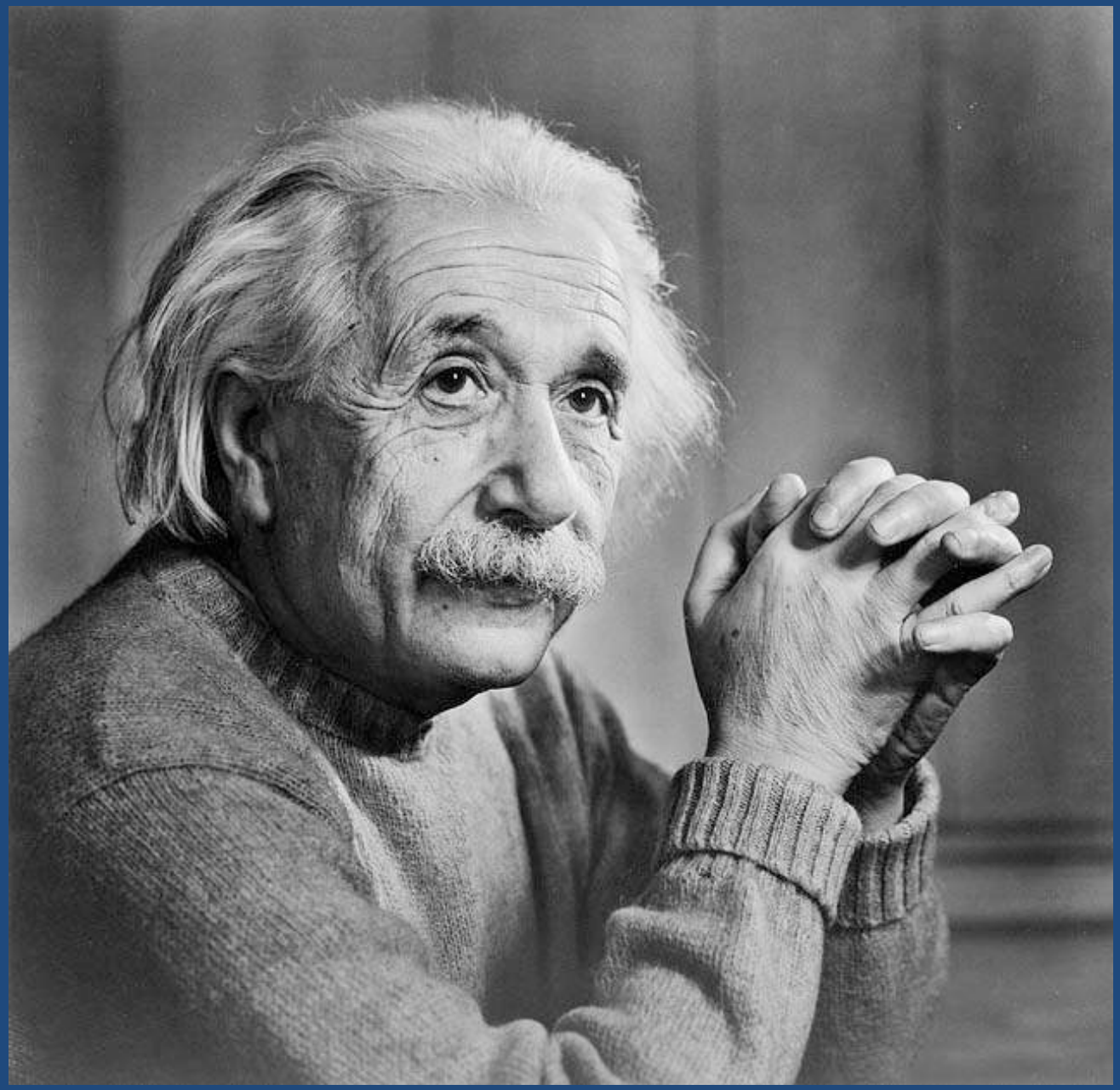
Electric and Magnetic **Fields** and **Waves**

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)

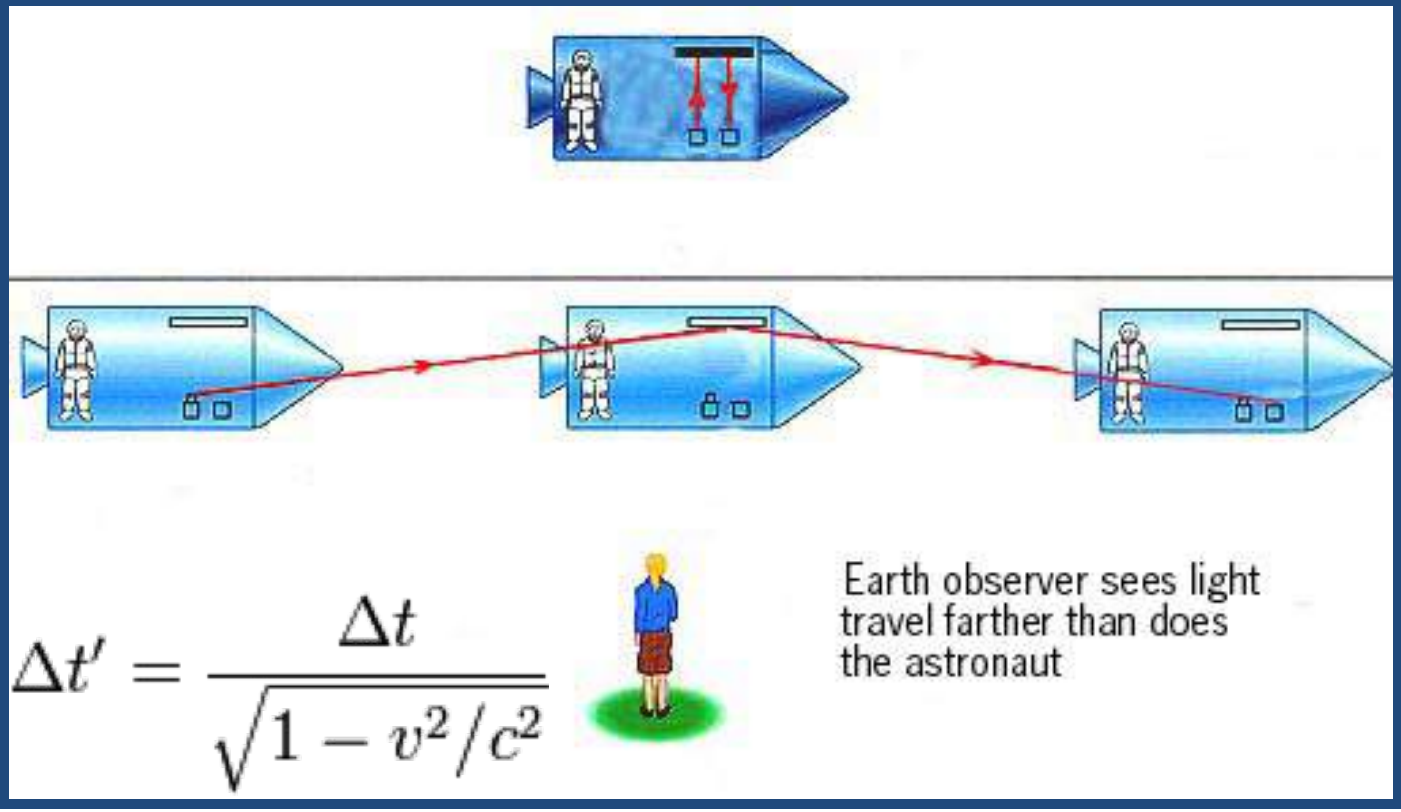


Lorentz, Poincare, Einstein: Special Relativity (1905)

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?

- In Newton's law of gravitation the force of gravity acts instantaneously. 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.
- A possible resolution occurred in 1907: The Principle of Equivalence *(Einstein: "the happiest/luckiest thought of my life").* From here to the discovery of the final equations of General Relativity in 1915 was a tortuous and awe inspiring journey.

100 years ago in Berlin

- In 1915, in a series of weekly (Thursday) presentations to the Prussian Academy in Berlin, (Nov 4, Nov 11, Nov 18, Nov 25, 1915) Albert Einstein put forth his General Theory of Relativity.

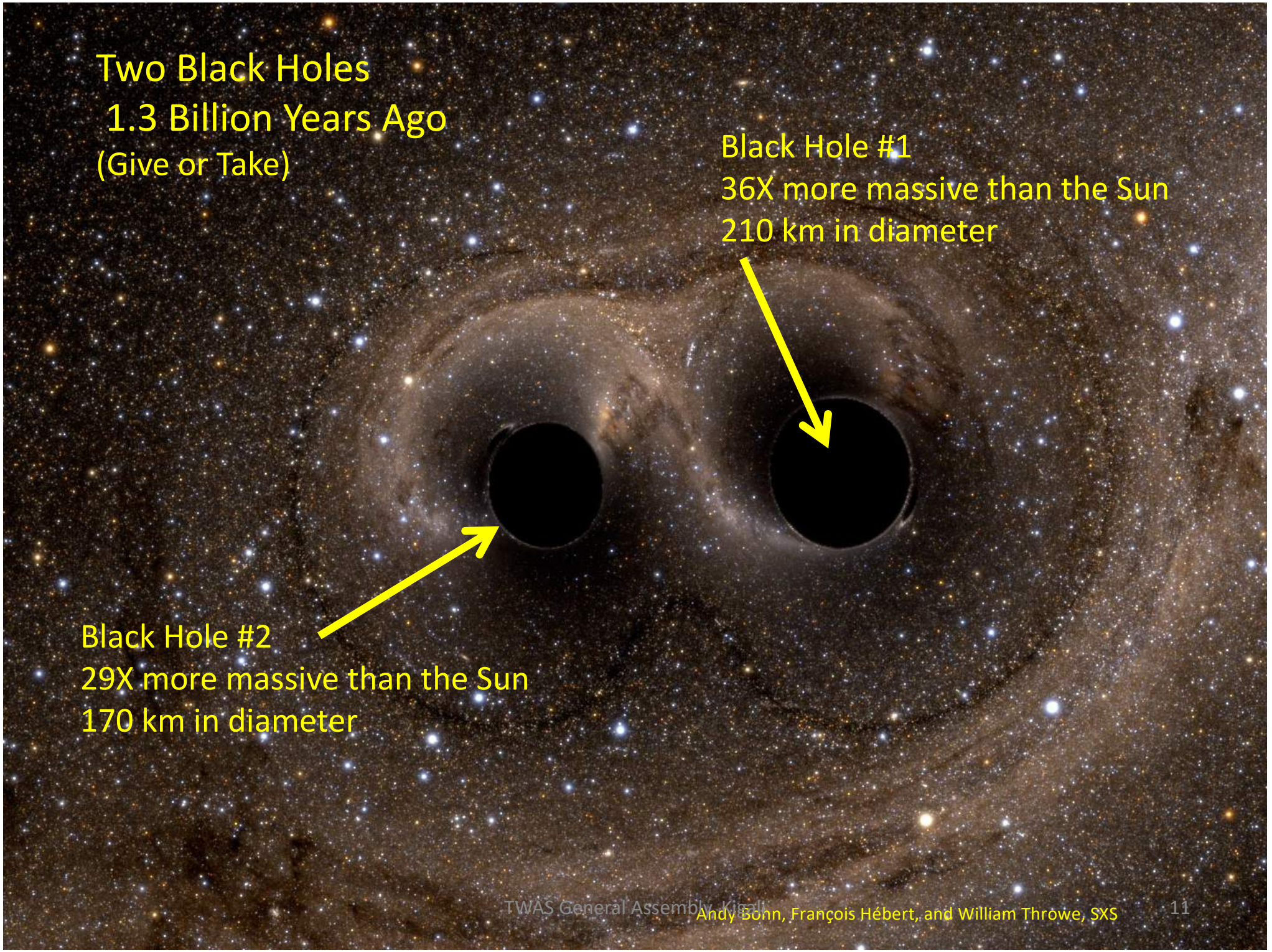
- Nov 25, 1915 is significant because it is on this day the complete and correct equations were presented for the first time:

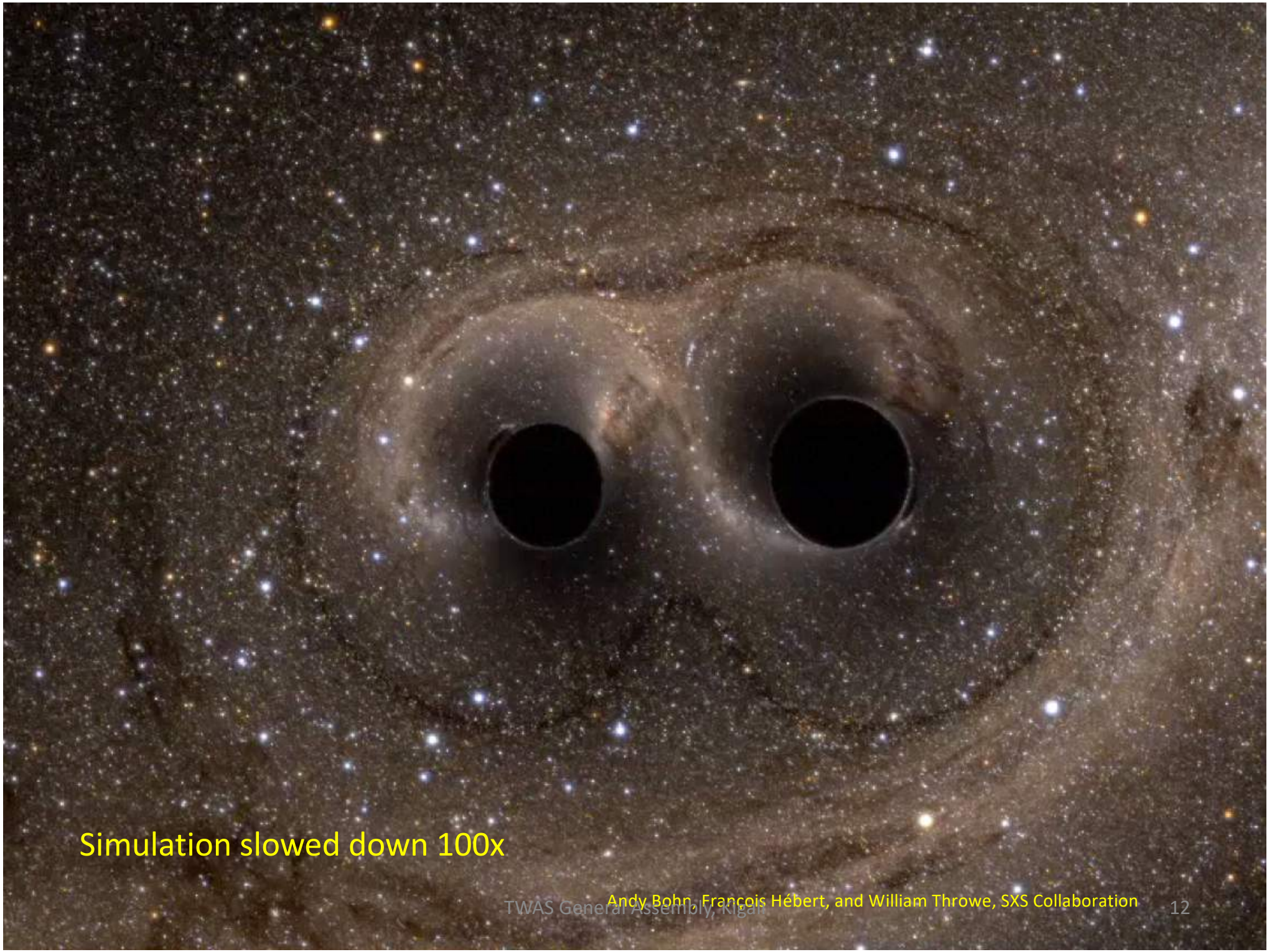
A. Einstein, Die Feldgleichungen der Gravitation. Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin) 1915, 844–847 (1915)

- GR overturned the Newtonian view where space is a static arena and time is absolute and unchanging. In GR space-time is a dynamic arena and gravitation is a consequence of the curvature of space- time.

- Einstein's theory has passed many tests in the 100 years of its existence but the most spectacular test happened in 2015…

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


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
Andy Bonn, François Hébert, and William Throwe, SXS



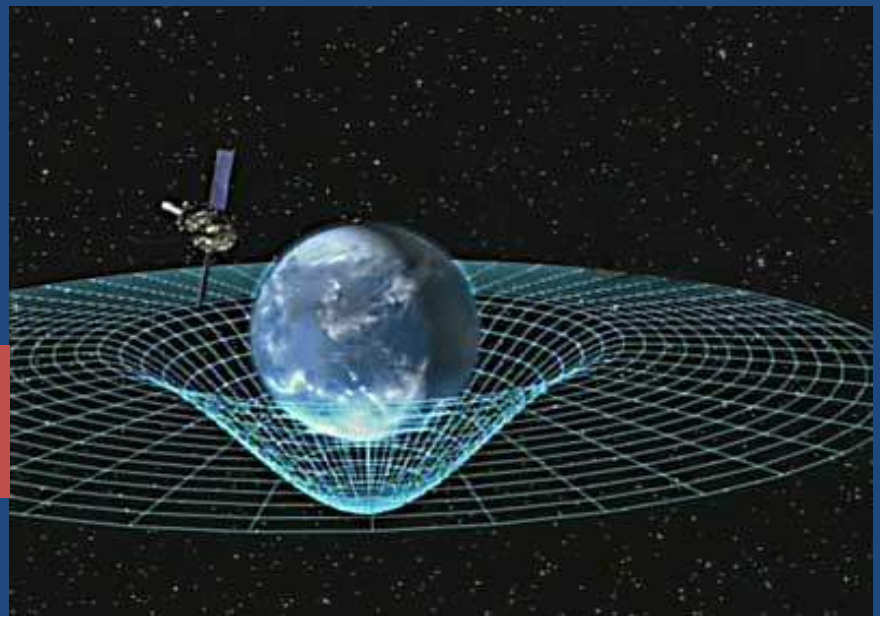
Andy Bohn, François Hébert, and William Throwe, SXS Collaboration

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!



Einstein's Equations of General Relativity

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi\frac{G}{c^4}T_{\mu\nu}$$

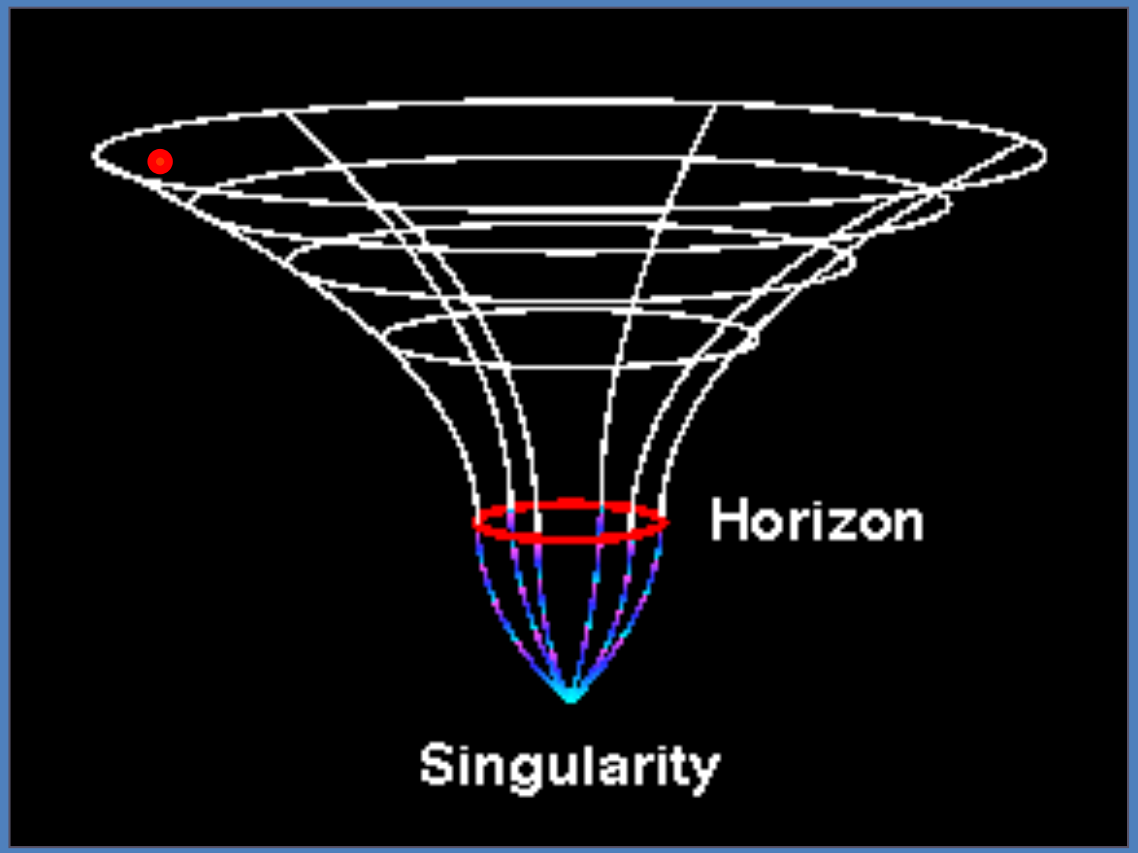
Note: $G/c^4 \sim 10^{-43}$ in appropriate units

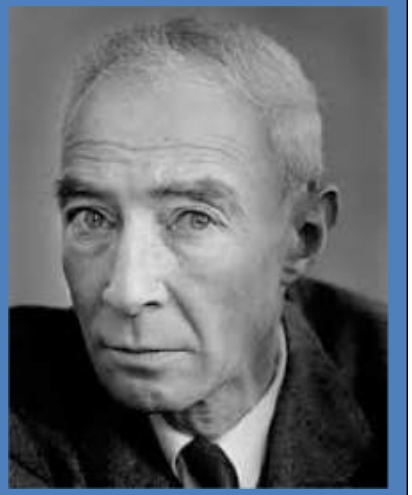
Solutions of Einstein's equations

- Black Hole solution (Schwarzschild; 1916)
- Expanding and accelerating space-time (Friedman, LeMaitre, Robertson, Walker; 1922, 1927)
- Gravitational waves (Einstein; 1916)

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

Einstein's theory predicts Black Holes

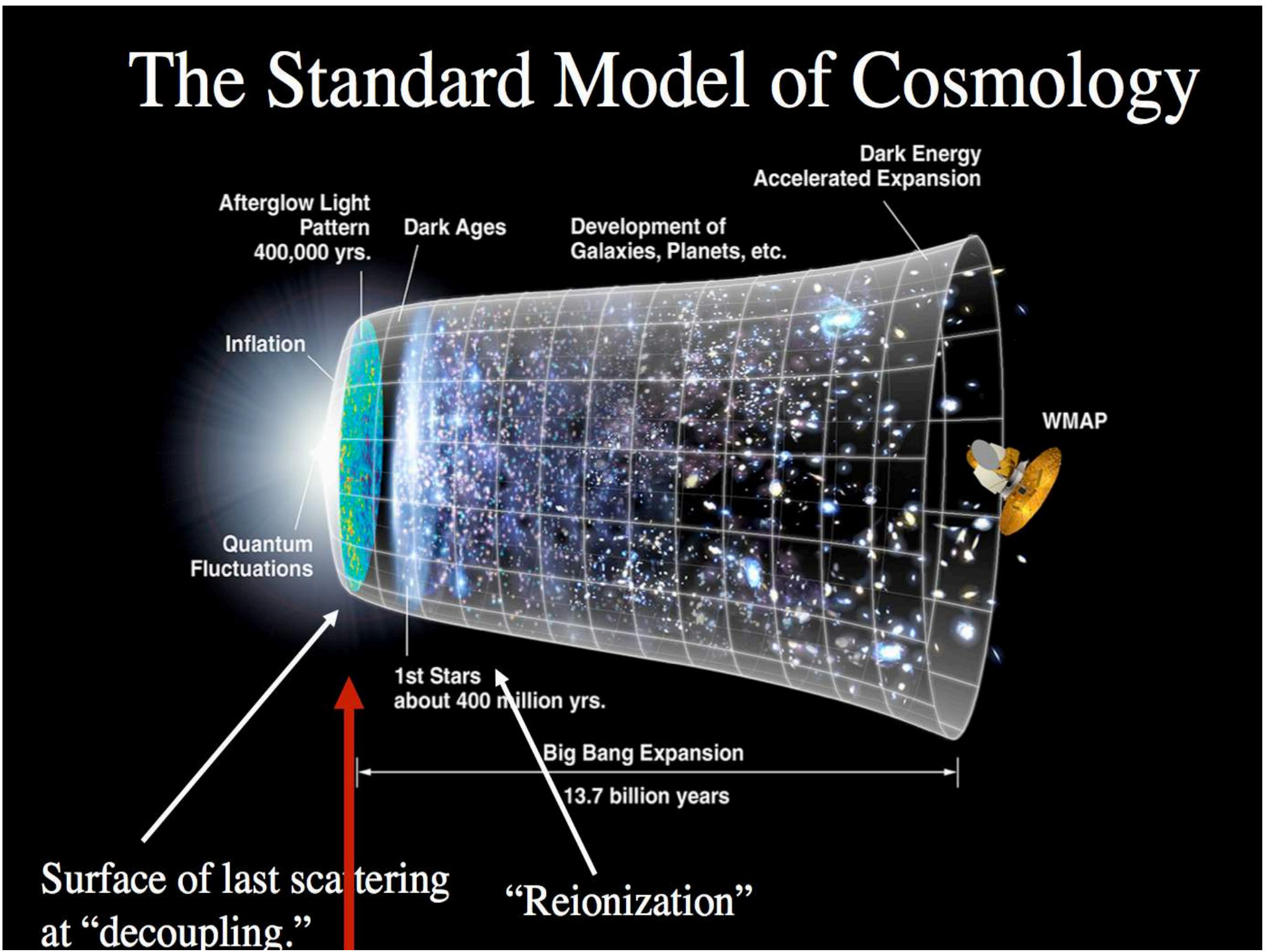




Schwarzschild

Chandrasekhar & Oppenheimer

The Standard Model of Cosmology

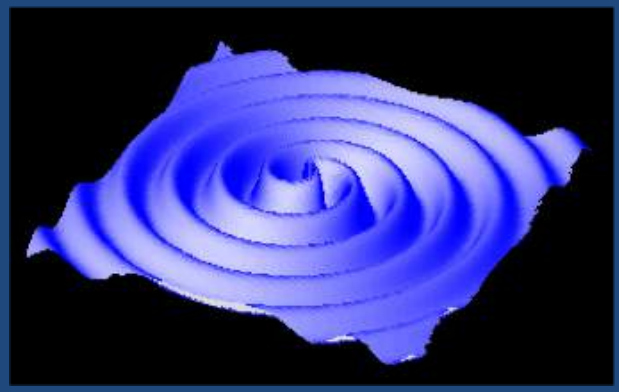


Gravitational Waves

- Gravitational waves (GWs), ripples in the fabric of space-time, were predicted by Einstein in 1916 and detected in 2015.
- Indirect observation in binary pulsar (Hulse & Taylor, 1974)
- GWs will profoundly influence our knowledge of the universe and its past…it will see what `light' cannot.
- Waves need to be understood in terms of `gravitons'.

accelerating charges (time-varying dipole moment) → electromagetc waves -> photons

accelerating masses (time-varying quadrupole moment) → gravitational waves -> gravitons



The observations by LIGO verified two spectacular predictions of classical General Relativity:

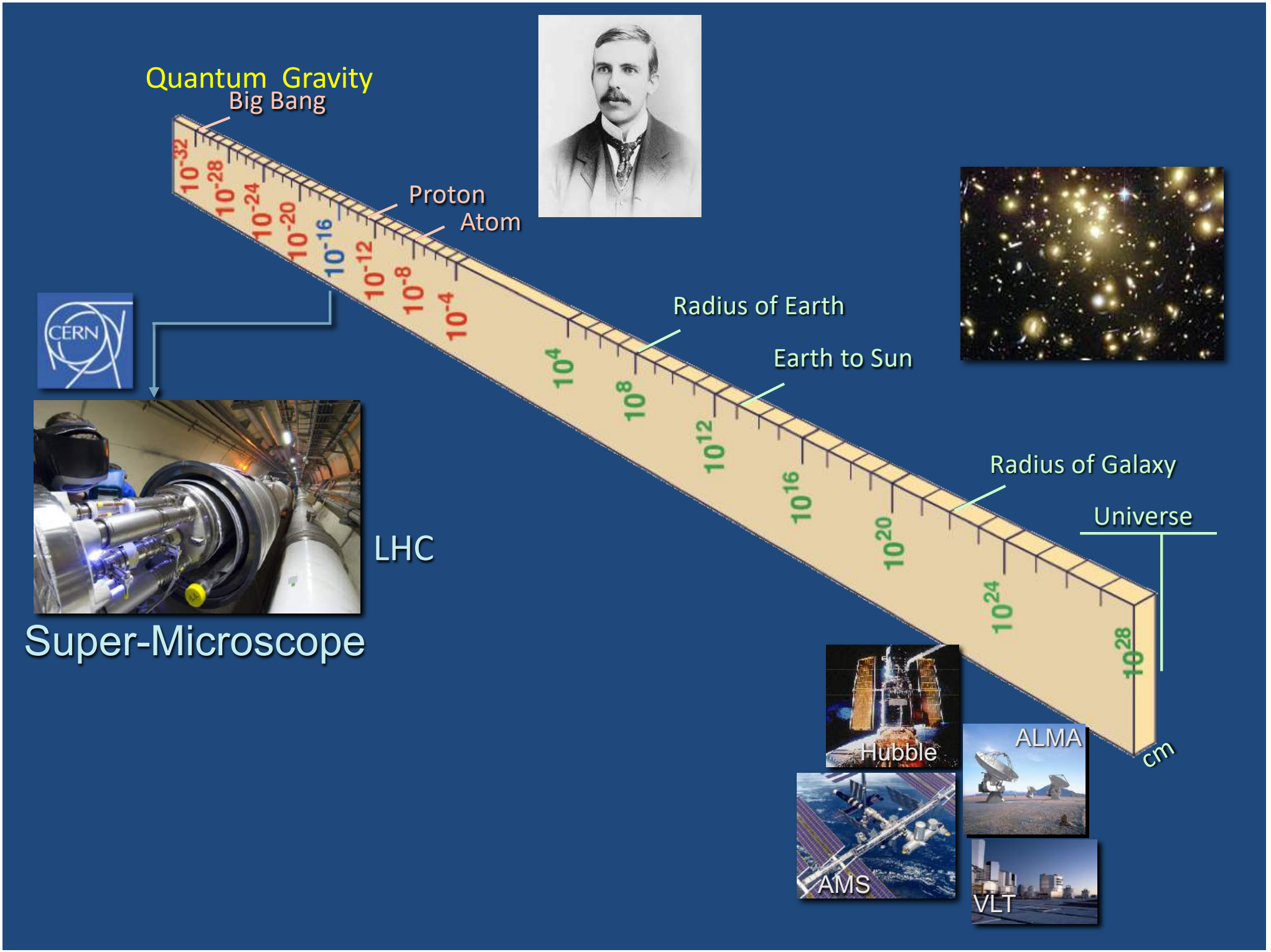
Gravitational waves … ripples in the fabric of space-time …

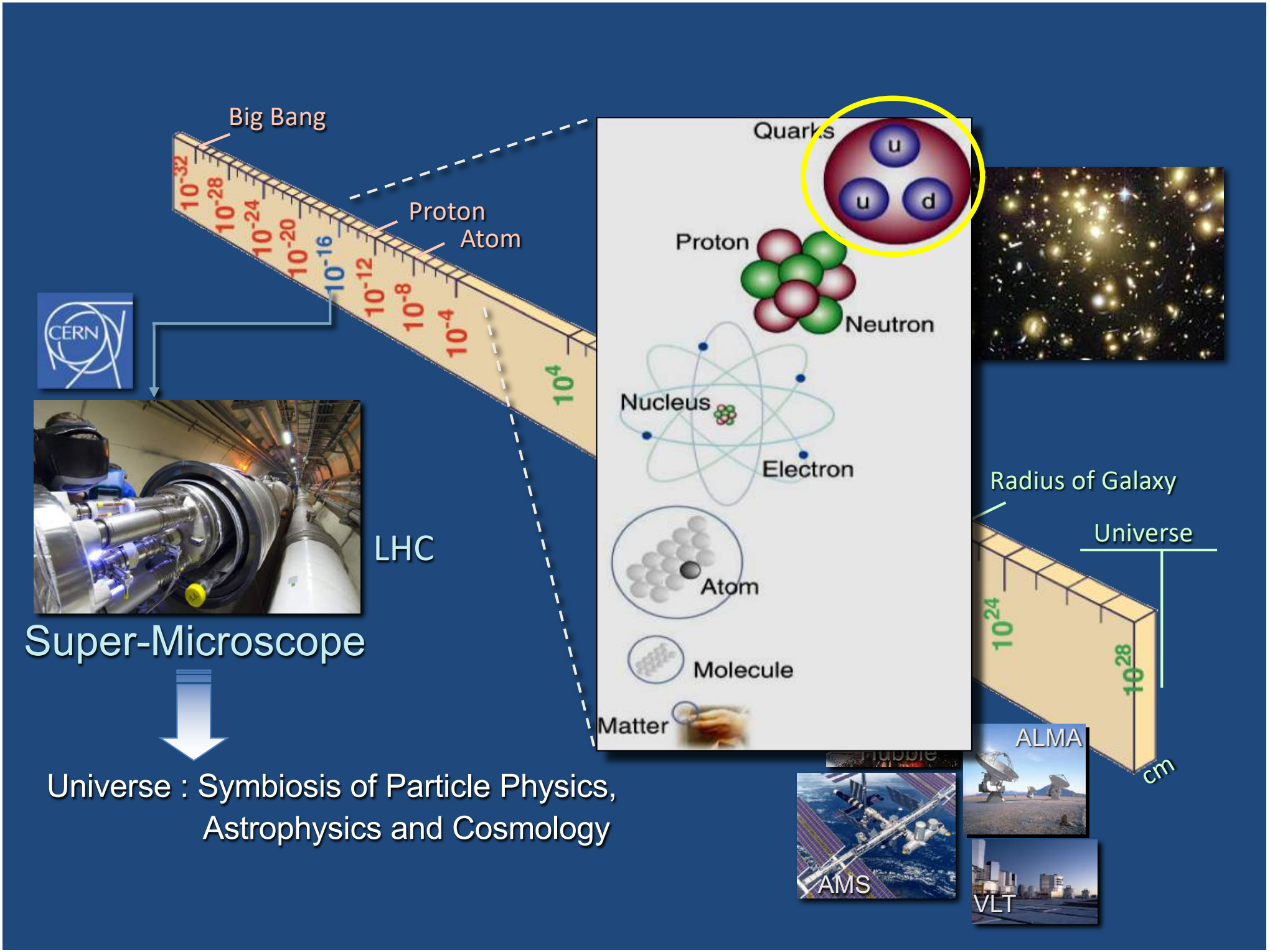
and

Black Holes

Quantum Mechanics (early 20th century)

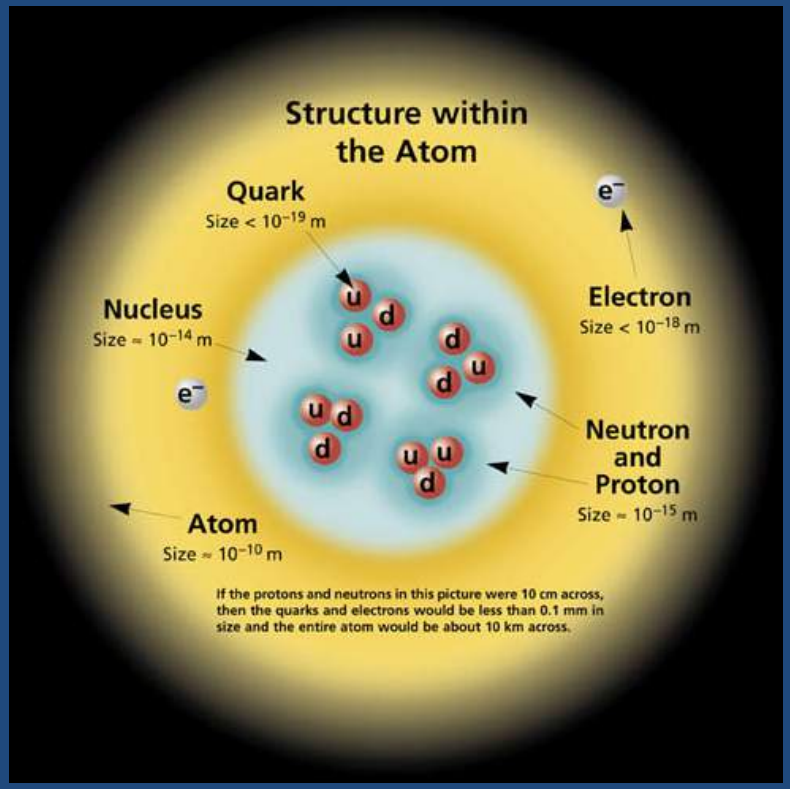
Physics at small scales


Quantum Gravity
Big Bang
Proton
Atom
Radius of Earth
Earth to Sun
Radius of Galaxy
Universe
cm
CERN
LHC
Super-Microscope
Hubble
ALMA
AMS
VLT


Big Bang
Proton
Atom
10^{-32}
10^{-28}
10^{-24}
10^{-20}
10^{-16}
10^{-12}
10^{-8}
10^{-4}
10^{4}
CERN
LHC
Super-Microscope
Quarks
u
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 microscopic particles



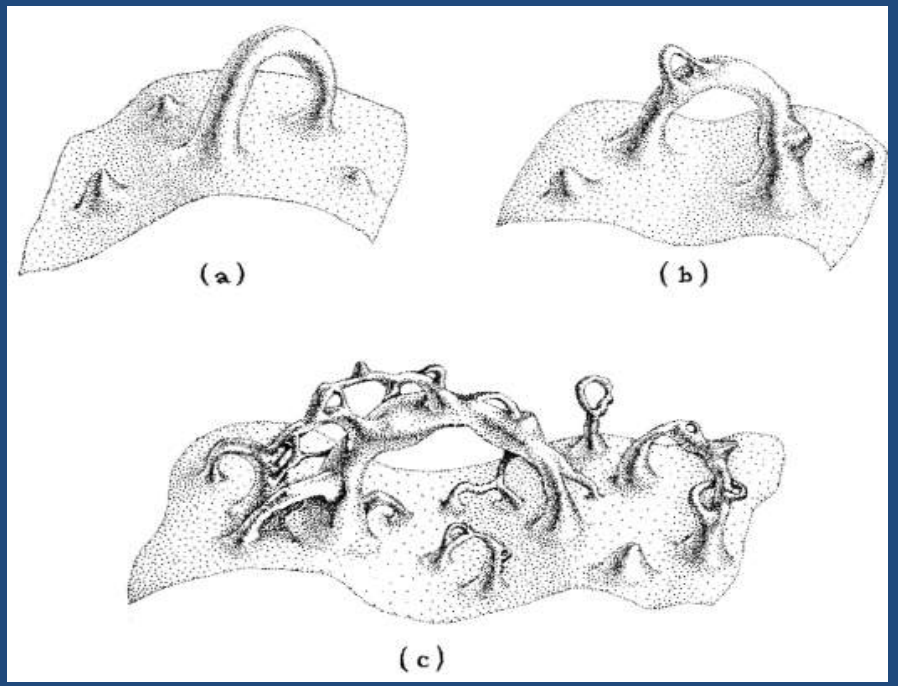
- Electronic devices, lasers, colliding elementary particles in the LHC in Geneva all follow the laws of quantum mechanics … tested to 10^{-16} cms

GR and Quantum Mechanics

QM (the uncertainty principle) implies that the fabric of space-time cannot be smooth at Planck space-time scales, and the Einstein theory breaks down at extremely short distances (10^{-33} cm) and short times (10^{-44} s). Quantum fluctuations (jitters) do not allow sensible calculations in GR!

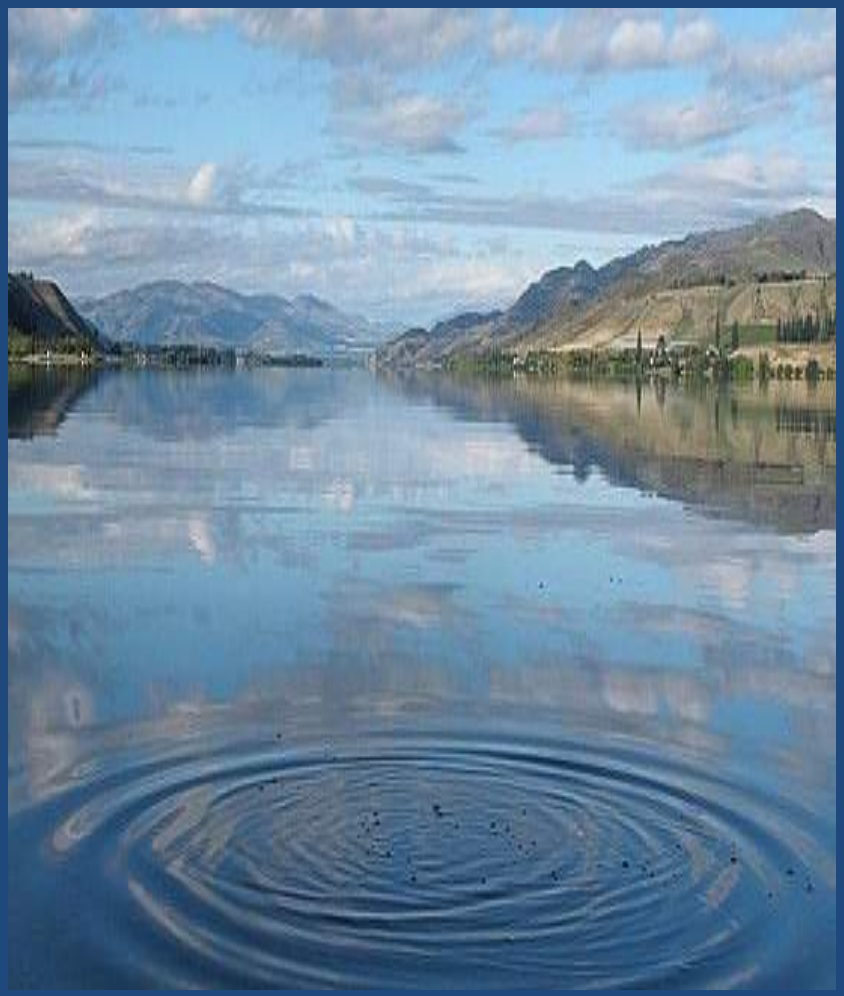
We need a quantum theory of gravity to understand: the big bang and gravity waves that will carry messages from the earliest times in the universe when there was no light; to resolve black hole conundrums; to address the energy budget of the universe …which is mostly dark energy ...

- Einstein's theory CANNOT be quantized consistently!



- What is to be done?

Emergent Picture: Einstein's theory is an effective geometrical theory analogous to a fluid 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.

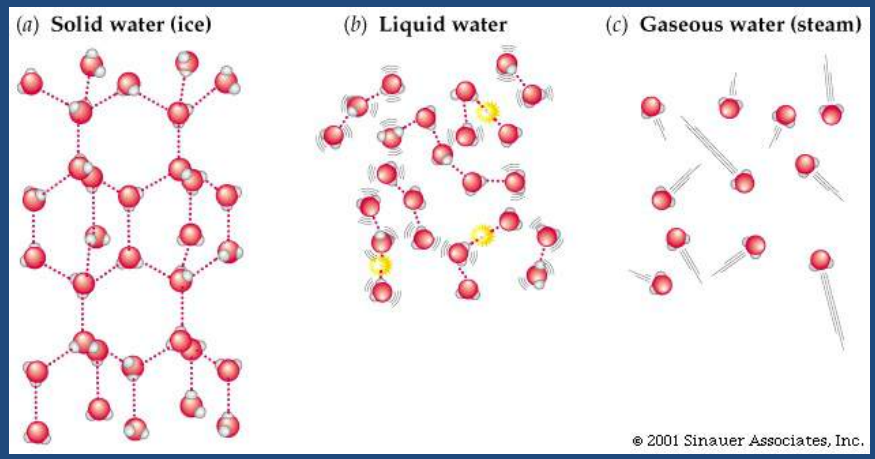
The wave will travel at the speed of sound in water and its effect will be felt a distance away.

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 in the gravity theory of Einstein?

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

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

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

$$T = \frac{\hbar c^3}{G_N M}$$

- Hot bodies have energy in the form of heat which is measured by a quantity `S' called `Entropy'.
- Bekenstein-Hawking:

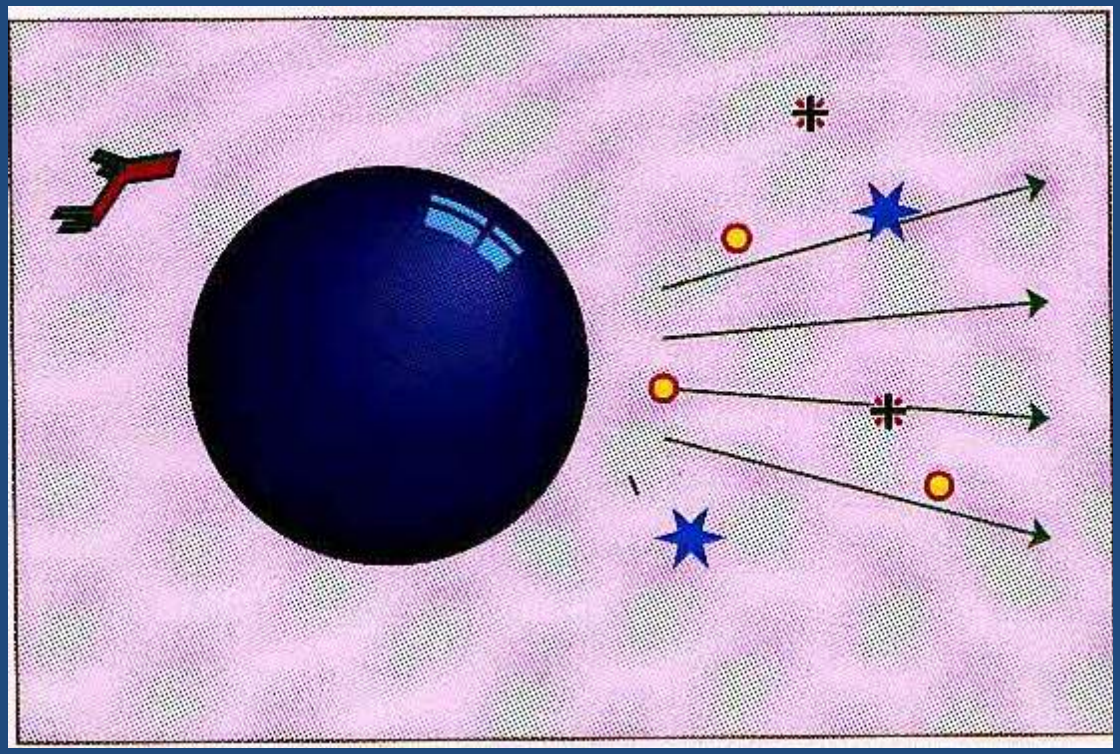
$$S = \frac{Area}{(10^{-33}\ cm)^2}$$

- `Area' is of the horizon of the black hole

Hawking Radiation

Like all hot bodies black holes radiate.

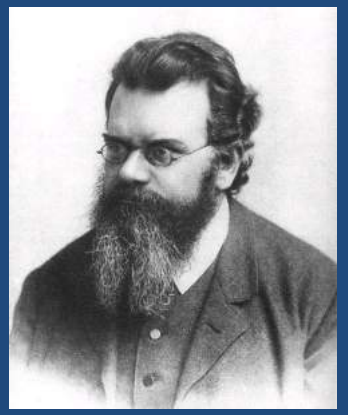
A black hole forms in various ways, but it always evaporates in the same way leading to **information loss**



Black holes + radiation satisfy all the laws of thermodynamics

Information loss

Boltzmann



Statistical Mechanics:

Information loss is not consistent with quantum mechanics. It is understood as due to a averaging process when there are a large number of internal states N.

Entropy is a measure of the number of internal states that make up the system: $\mathbf{S_{boltzmann} = klogN.}$

Is it true that $S_{blackhole} = \dfrac{Area}{(10^{-33}\,cm)^2}$ = klogN ? **YES**

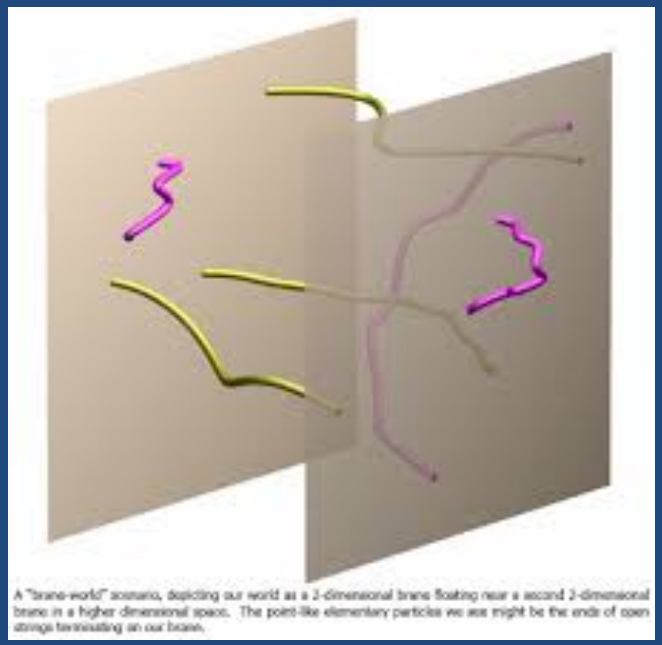
String Theory…1960…1996…2016

- In the 1960s a framework was serendipitously discovered in attempts to understand the spectrum of strongly interacting elementary particles….it's basic degrees of freedom are extended objects the simplest being the one dimensional string…
- String theory is consistent with quantum mechanics

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 `mem-branes' 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.

Black holes can be built out of more elementary degrees of freedom: branes

Andrew Strominger and Cumrun Vafa found this astonishing fact in 1996 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!

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)

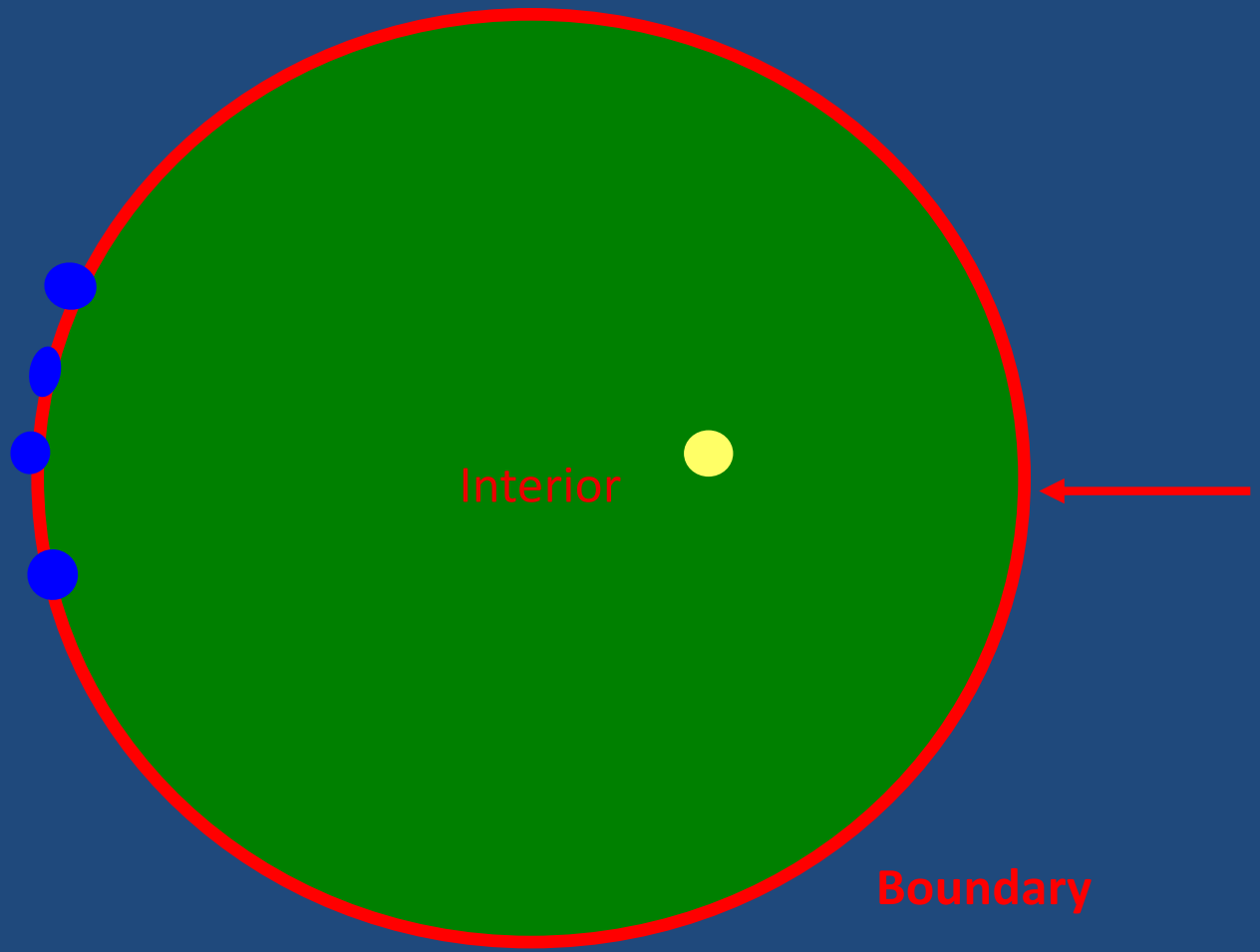
S_{BH}= Area/$4A_{pl}$ = $k_b$logN = S_B is true!

- Micro-state counting gives rise to N and hence $S_{BH.}$ Slightly excited black holes Hawking radiate due to interaction of micro-states with elementary string quanta like gravitons…
- We have found a model microscopic theory in which Einstein's space-time is a coarse grained and long wavelength description!! Just like flowing water is a coarse grained description of a large number of water molecules.
- It is in this sense quantum mechanics and the new degrees of freedom of quantum gravity make Einstein's theory an approximation to an underlying reality that we have just begun to explore.
- Insights from black holes paved the way for another development which provides a powerful conceptual and calculational tool: the Holographic Principle.

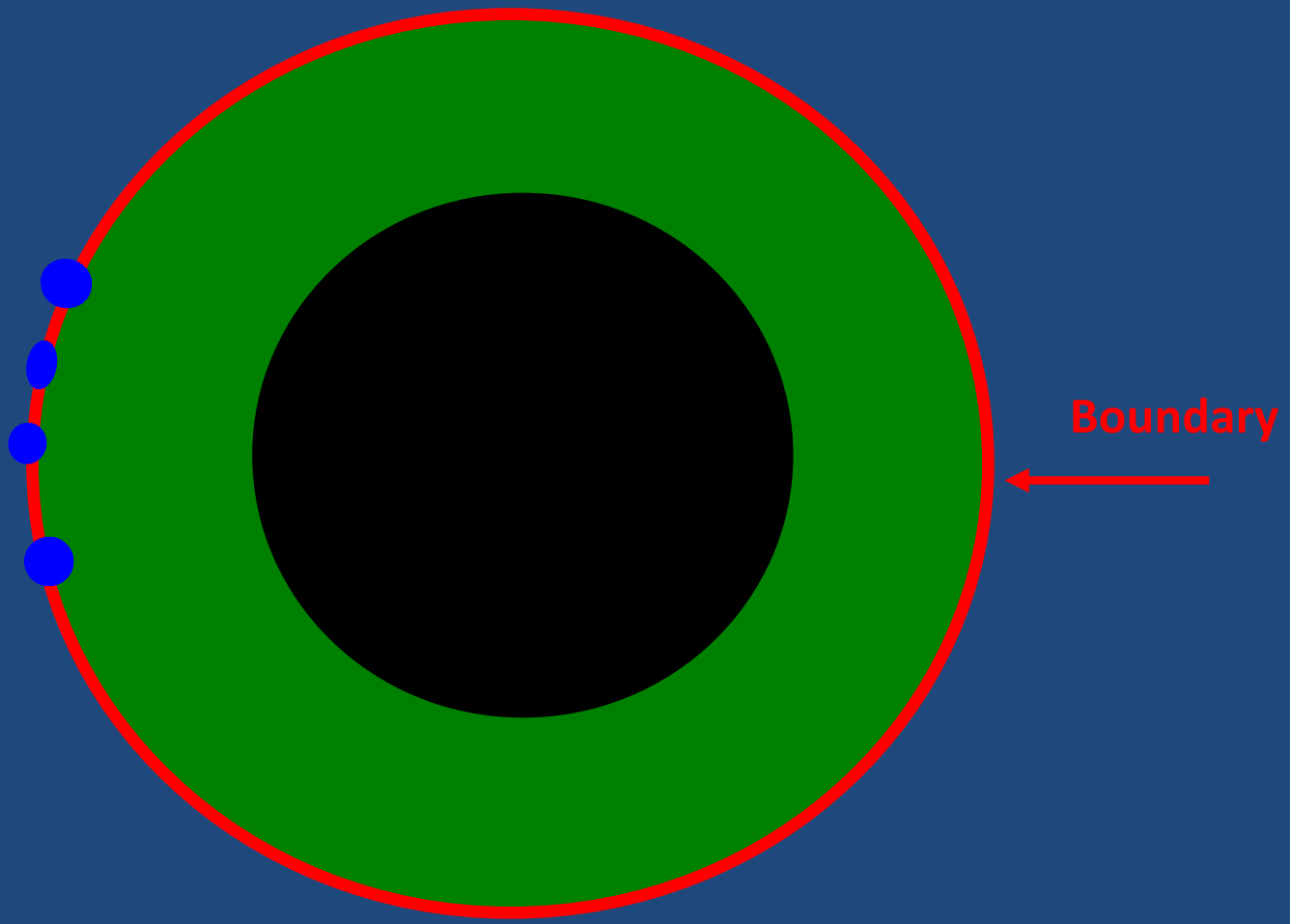
Precise Holography conjecture: A conceptual and computational tool

Juan Maldacena (1996)

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



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



Temperature and entropy → motion of particles on the boundary

Concluding remarks

In string theory, quantum mechanics of black holes points to a revolutionary fact that space-time has more degrees of freedom than the metric. This fact leads to intriguing connections of string theory with different parts of physics and mathematics.

In particular the `holographic' description of Maldacena besides providing an exact description of quantum gravity enables the string theory framework to make contact and contribute to fluid dynamics, superfluidity, thermalization in large systems, strongly coupled quark gluon plasma, condensed matter systems…and mathematics.

It also has the tenet to present a unified theory of the physical world and the universe at large.

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

- Stan Whitcomb for slides pertaining to LIGOß
- Juan Maldacena for the animation about black holes
- Various sources, including `Einstein Online' of MPI, Albert Einstein Institute for illustrations.

Thank You