

The End of Space-Time and Beyond

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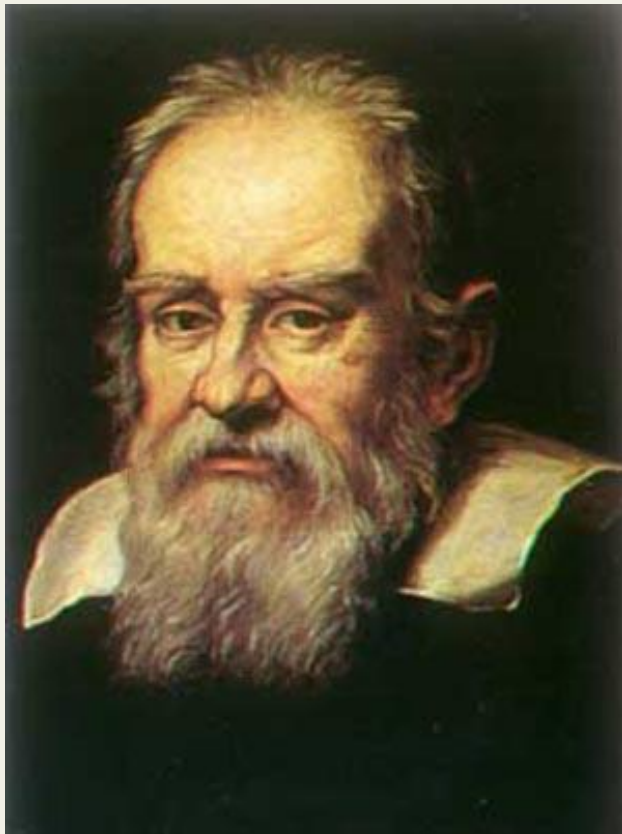
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Galileo

Discovered a new law of Gravity experimentally



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



Newton

Birth of Theory in Science:

**A framework to describe the laws of
Physics**

1687



PHILOSOPHIÆ
N A T U R A L I S
P R I N C I P I A
M A T H E M A T I C A .

Auctore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos
Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. P E P Y S, Reg. Soc. PRÆSES.
Julii 5. 1686.

L O N D I N I,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud
plures Bibliopolas. Anno MDCLXXXVII.

Newton's Laws

- Newton formulated the laws of motion in terms of the flow in time of coordinates of a particle: $(x(t), y(t), z(t))$
- The flow of time is universal and same for all reference frames in uniform motion relative to each other.
- Simultaneity of events is frame independent
- Newton's Law: $F = ma$

Universal Gravitation

$$F_{grav} = G_N \frac{M_1 M_2}{r^2}$$

- Universal law of gravitation (always attractive) Perhaps the first great scientific unification: what applies to apples also applies to the 'heavenly' bodies!
- Instantaneous action at a distance
- In Newton's theory the arena of space is static and time flows independent of the motion of the observer

James Clerk Maxwell (1831-79)

- Maxwell unified electricity and magnetism, in 1861
- Predicted the existence of electromagnetic waves and
- Identified light as an electromagnetic wave moving with a speed in vacuum

$$c = 3.1 \times 10^5 \text{ km/sec}$$



Maxwell's laws of electrodynamics led to a profound revision of the Newtonian view of Space and Time as separate entities

Space and Time became Space-Time in Einstein's Special Relativity

Albert Einstein (1905)

- Speed of light is the same for all observers in relative uniform motion
- Notion of time depends on the state of motion: space and time are mixed up!
- End of Newton's notion of space and time.
- Space-time is born!

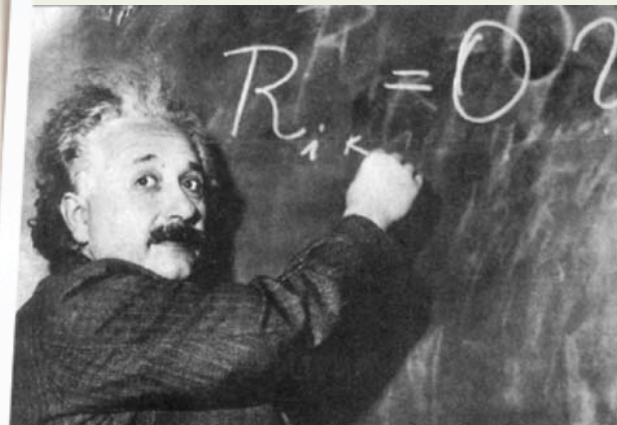


Newton's law of gravity in conflict with space-time of special relativity?

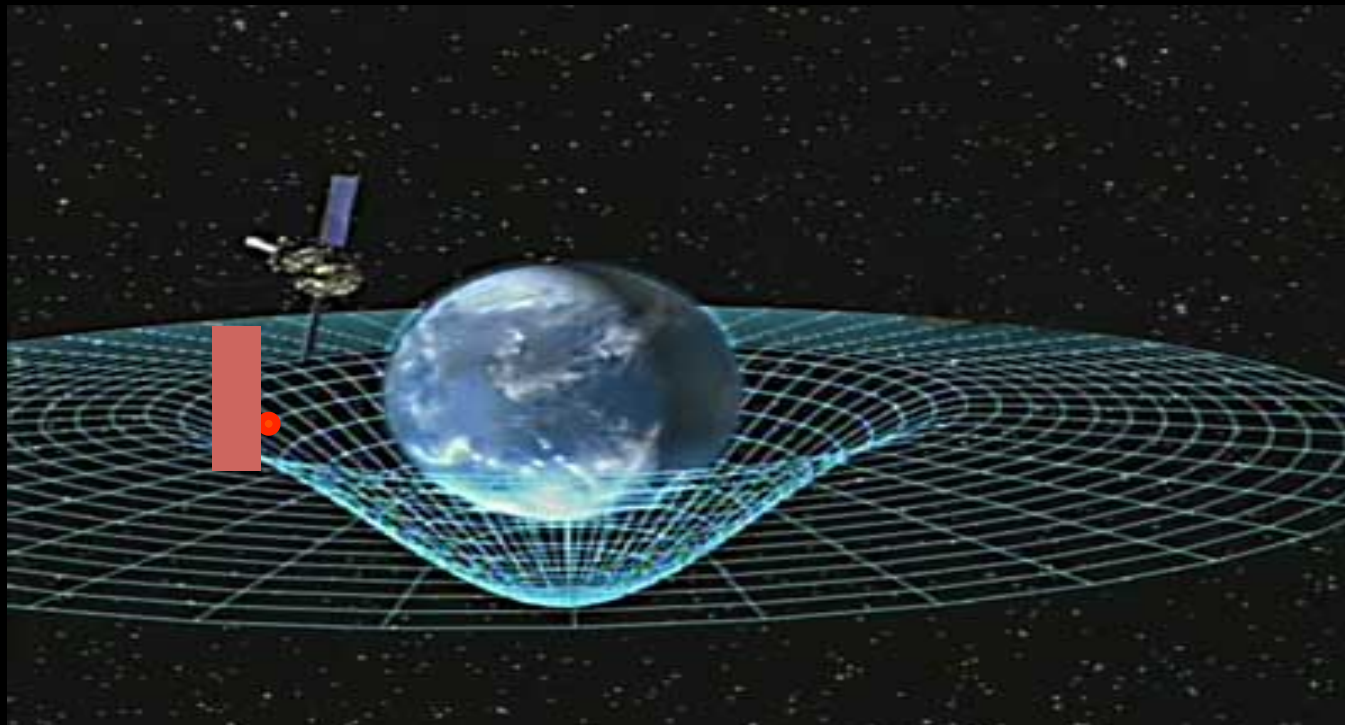
- Newton's laws of gravity involves instantaneous 'action at a distance'
- Conflicts with the finiteness of the speed of light!
- Resolving this puzzle led to the **General Theory of Relativity** in (1915)

General Relativity

- The Principle of Equivalence (1907) is the main physical insight.
- Physical effects of acceleration are indistinguishable from those of gravity: The fall that we attribute to the earth's gravity is no different from the forward fall we experience when we jam the brakes of a car!



In GR Space-time becomes dynamical and explains the gravitational force!



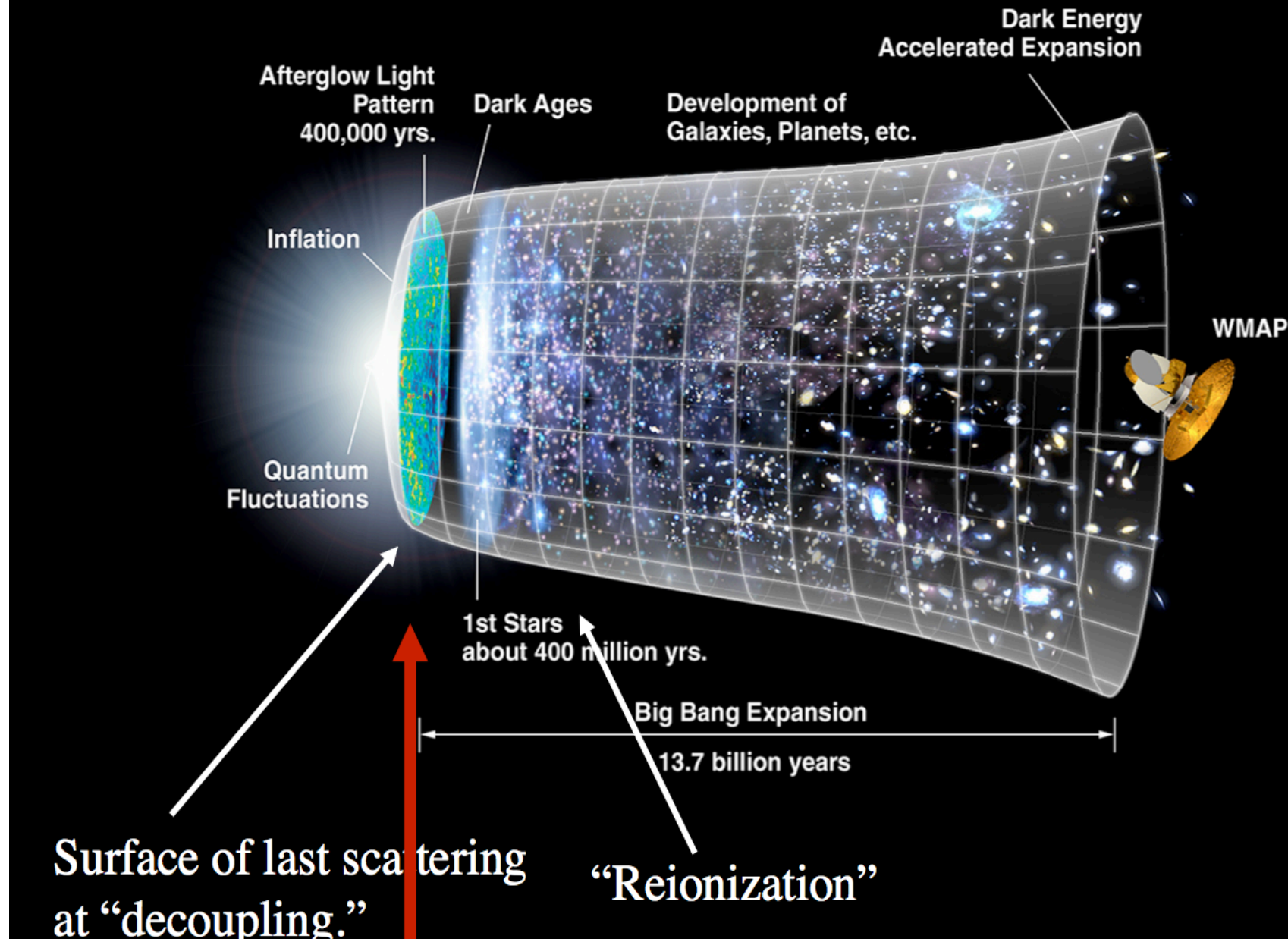
- The gravitational field is described by the warping of the fabric of space-time (1915)
- No action at a distance
"matter tells spacetime how to curve, and curved space tells matter how to move"(John Wheeler)

$$R_{\mu\nu} - \frac{1}{2}G_{\mu\nu}R - \Lambda G_{\mu\nu} = -8\pi G_N T_{\mu\nu}$$

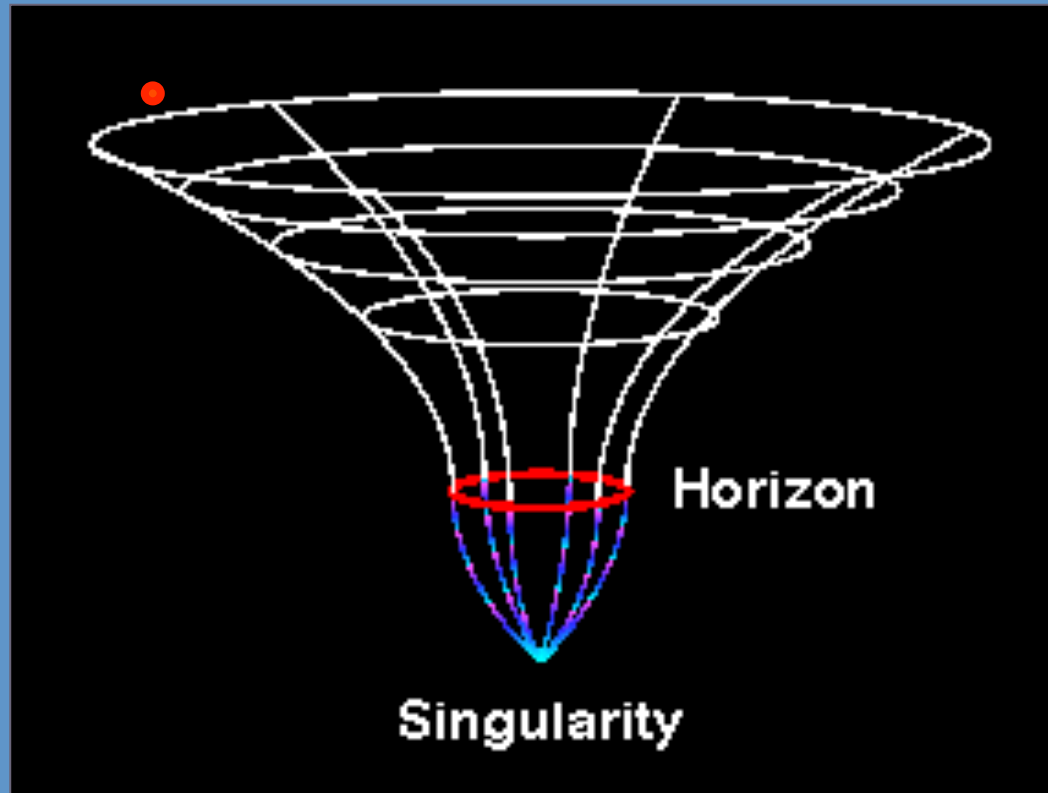
Forms the basis of the

Standard Model of Cosmology

The Standard Model of Cosmology



Einstein's theory also predicts Black Holes



Study of black holes will help unravel the
'new structure of space-time'
Primordial cosmology too difficult at present

Bekenstein: Black holes have entropy

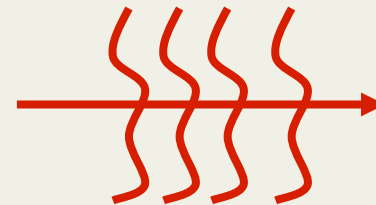
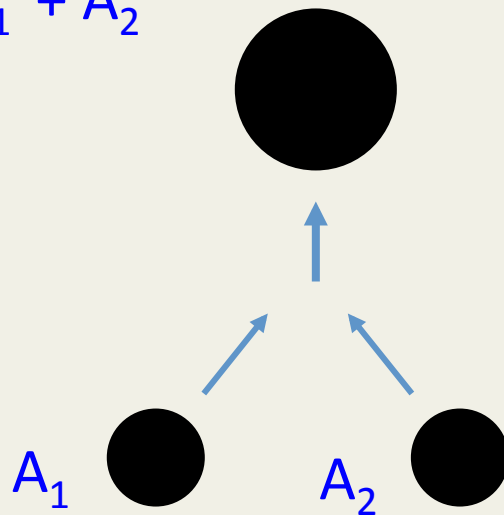
- If you throw a bucket of hot water into a black hole you will contradict the second law of thermodynamics unless you assume that the black hole has an entropy!
- Entropy is proportional to the area of the horizon of the black hole
- $S_{\text{BH}} = aA_h$
- Area theorems of GR justify this choice

Area law:

The area of the horizon always increases just like entropy in thermodynamics

Hawking
(1970)

$$A > A_1 + A_2$$



Gravitational waves

We have discussed black holes according to Einstein's theory of general relativity, which is a classical theory

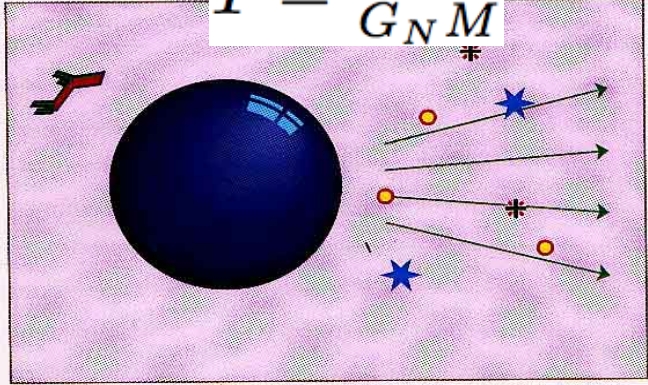
When we include quantum mechanics we find a new surprise:

Quantum Mechanics and Black Holes

- In the quantum theory black holes radiate (Hawking radiation)
- Temperature is proportional to Planck's constant
- Black holes obey the laws of thermodynamics

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BLACK HOLES AREN'T BLACK !

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

$$S_{bh} = \frac{A}{4A_{Pl}}$$
$$A_{Pl} = \hbar G_N / c^3$$
$$A_{Pl} \approx 2.6 \times 10^{-70} \text{ m}^2.$$

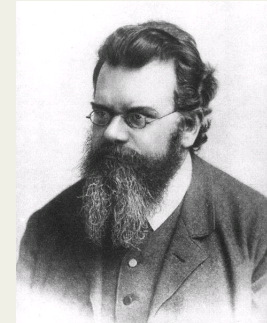
Thermodynamics and Statistical Mechanics

- Statistical Mechanics explains thermodynamics in terms of 'microscopic degrees of freedom'... 'the building blocks'.
- Boltzmann's formula for thermodynamic entropy:

$$S_B = k_b \log W$$

W= number of accessible micro-states of the system

k_b is Boltzmann's constant



Played a fundamental role in establishing the corpuscular nature of matter around the turn of the 20th century

Atoms and Molecules exist!

“Much of the physics establishment did not share his belief in the reality of atoms and molecules — a belief shared, however, by Maxwell in Scotland and Gibbs in the United States; and by most chemists since the discoveries of John Dalton in 1808. He had a long-running dispute with the editor of the preeminent German physics journal of his day, who refused to let Boltzmann refer to atoms and molecules as anything other than convenient theoretical constructs. Only a couple of years after Boltzmann's death, Perrin's studies of colloidal suspensions (1908–1909), based on Einstein's theoretical studies of 1905, confirmed the values of Avogadro's number and Boltzmann's constant, and convinced the world that the tiny particles really exist.”

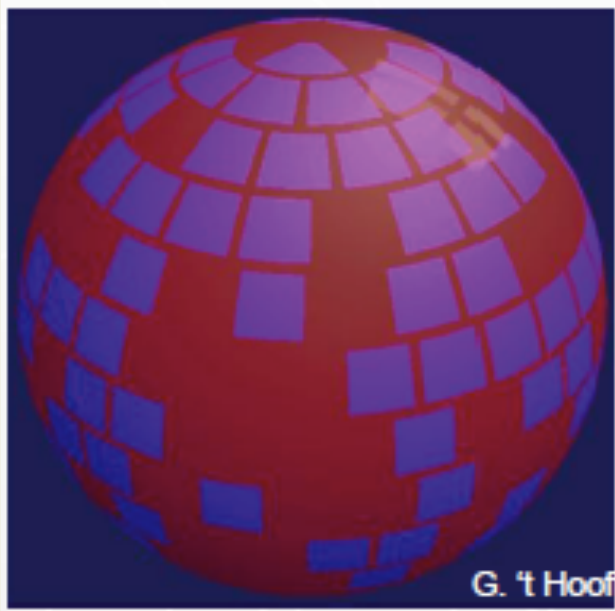
Is $S_{\text{BH}} = \text{Area}/4A_{\text{pl}} = k_b \log W = S_B$?

- Are there micro-states whose counting gives rise to W and hence S_{BH} ?
- If the answer is YES, then we have found a 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.

The answer is YES!

- In the `framework' of `string theory' it is indeed possible to build black holes out of basic building blocks called `branes' which are solitons of `string theory'
- 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!
- Avinash Dhar, Gautam Mandal and SRW explained Hawking radiation and BH thermodynamics in the framework of statistical mechanics in this corpuscular model of the black hole.

Holographic interpretation of S_{BH}



Entropy = number of cells of Planck area

$$\Omega \sim \exp (M/M_{\text{pl}})^2 ,$$

$$M_{\text{pl}} \sim 10^{-8} \text{ kg}, M \sim 10^{30} \text{ kg}$$

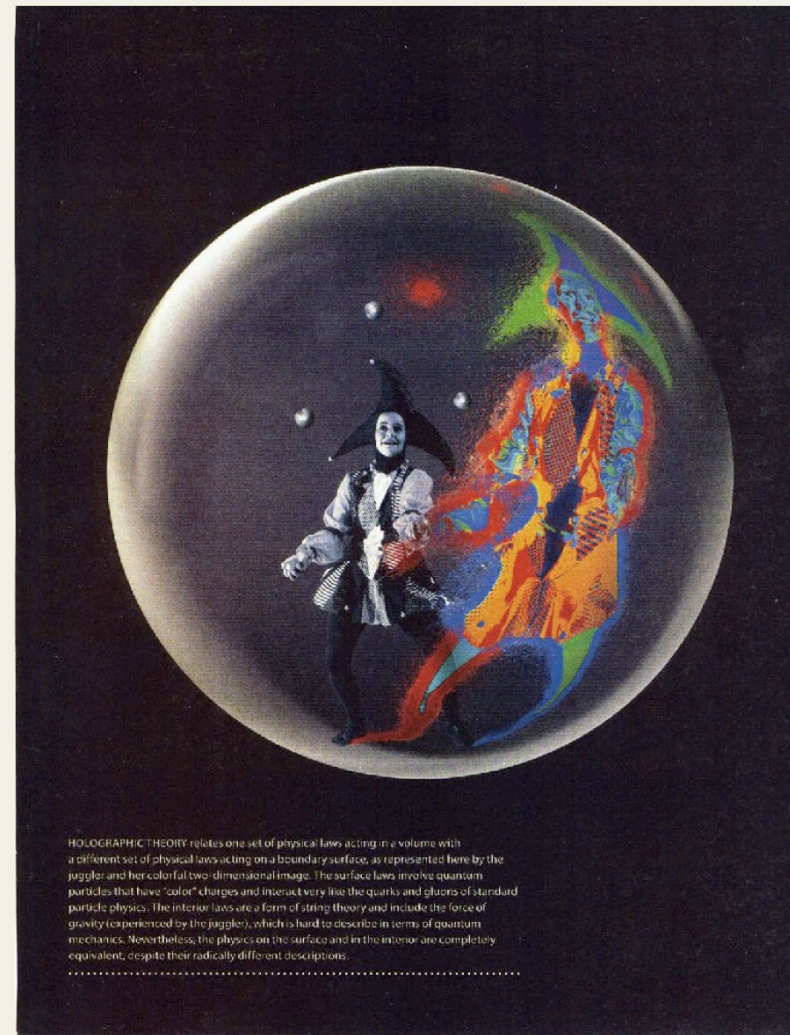
$$\Omega \sim \exp (10^{76}), \text{ for solar mass bh}$$

$$T \sim 3.6 \times 10^{-7} \text{ K}$$

The fact that the entropy is proportional to the area of the horizon and not the volume it encloses, gives a clue that even though the degrees of freedom of the black hole are apparently behind the horizon, they seem to leave an imprint (hologram) on the horizon.

The next big step: Gravity is Holographic

- Black hole entropy is proportional to Area rather than Volume!
- Gravity is holographic and the interior is faithfully reflected on the boundary where the micro-states are easily understood, well defined and calculable in principle.

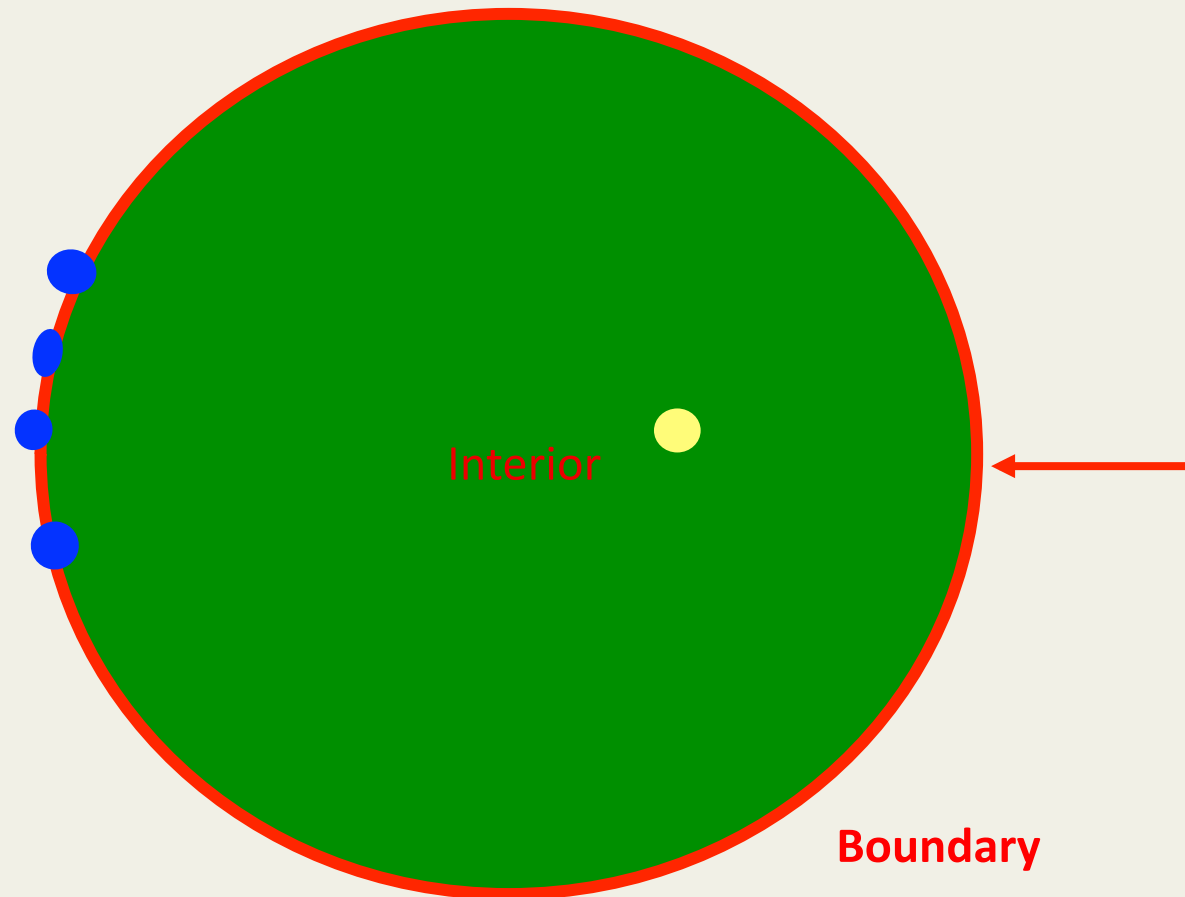


Precise Holography conjecture: A conceptual and computational tool

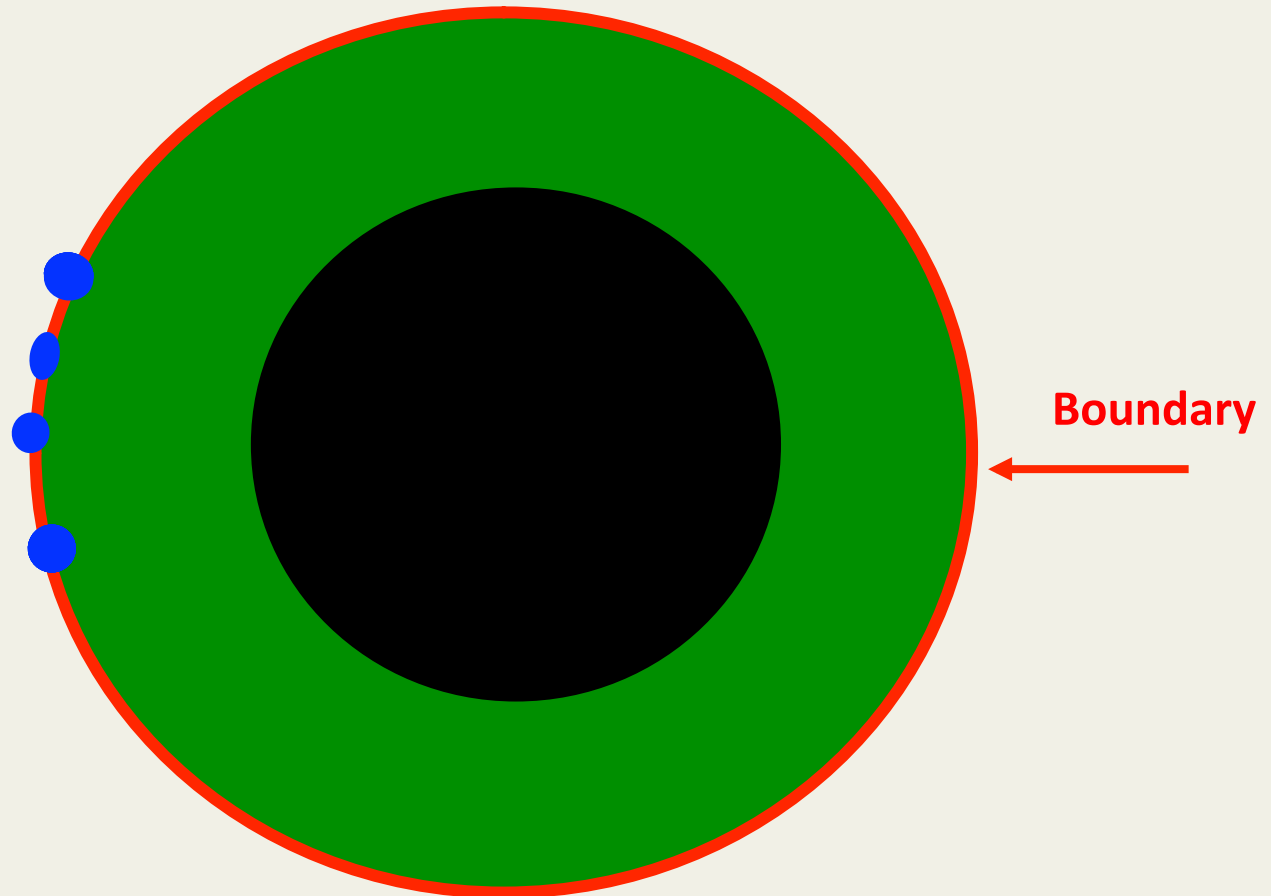
Juan Maldacena (1996)



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

Conclusions

- Newton's static space and time where gravitational force acts between particles
- Replaced by Einstein's space-time in special relativity
- In GR space-time becomes dynamical and mediates the force of gravity
- Black hole entropy in Quantum Mechanics begs the question: Is $S_{\text{BH}} = S_{\text{B}}$?
- Yes there are 'constituent building blocks' which satisfy the above formula.
- End of smooth space-time. There are discrete microstates that evaluate S_{BH}
- Gravity is 'holographic'

Thank you!

The Big Bang

PHYSICS

Chemistry starts
around here

CHEMISTRY

BIOLOGY

Life on
Earth / years

Thought

- radiation
- particles
- W^+ } heavy particles
- W^- } carrying
- Z } the weak force
- quark
- anti-quark
- electron
- positron (anti-electron)
- proton
- neutron
- meson
- hydrogen
- deuterium
- helium
- lithium

