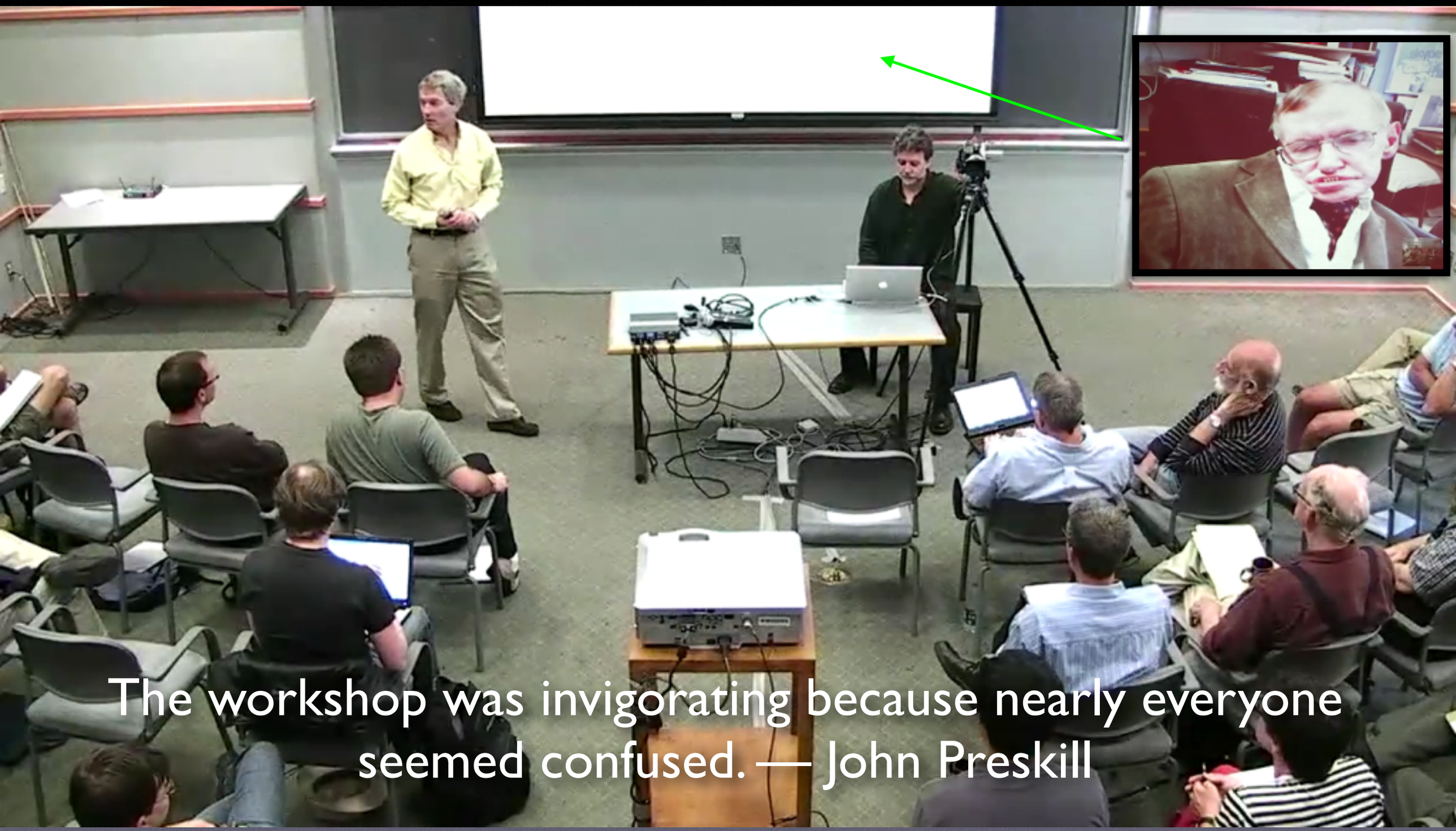
The Black Hole Conundrum

Holograms? Firewalls? Wormholes?

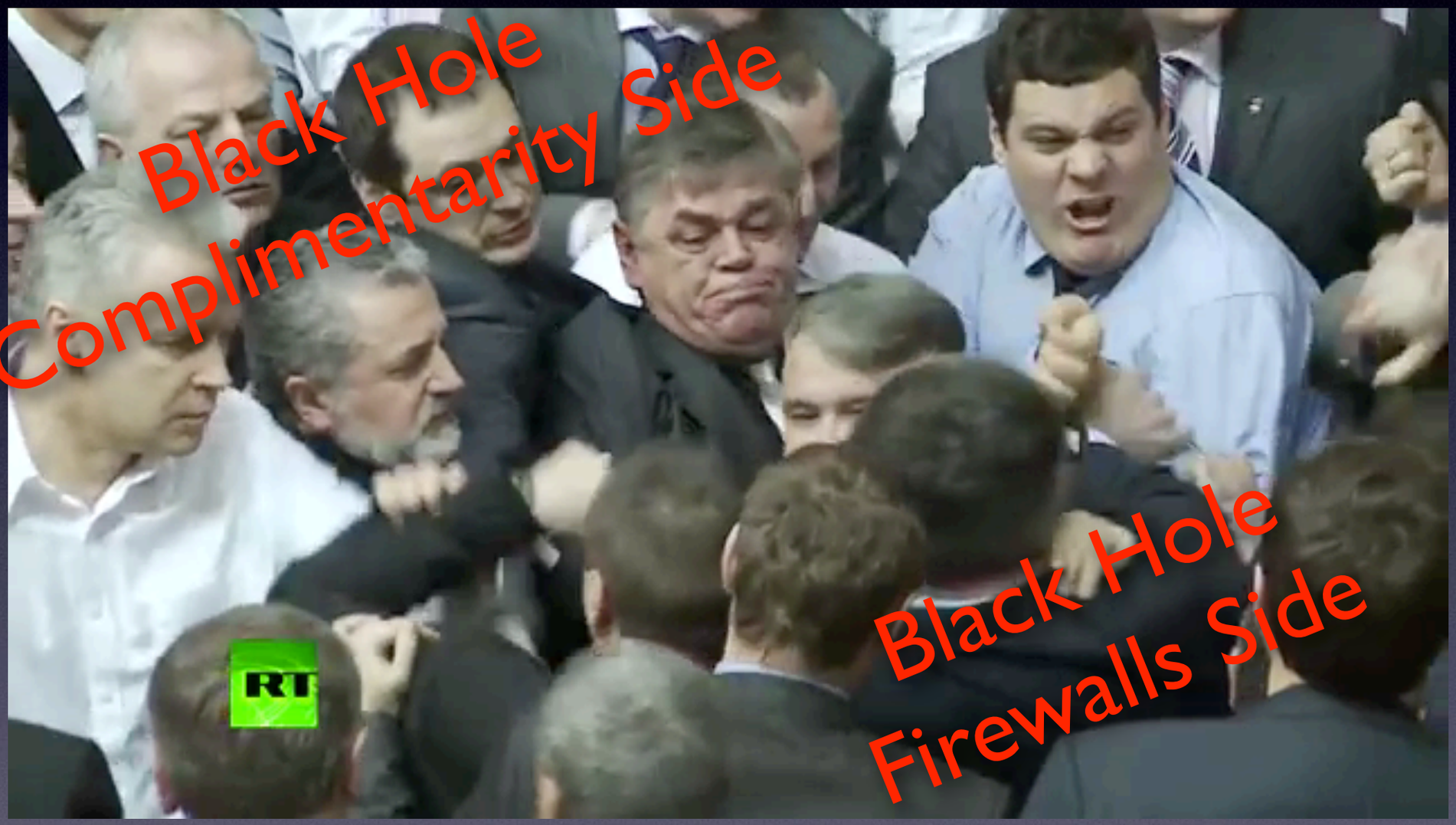
William Koch
JCCC Astronomy Professor

Meeting on Black Holes KITP Aug 2013



The workshop was invigorating because nearly everyone seemed confused. — John Preskill

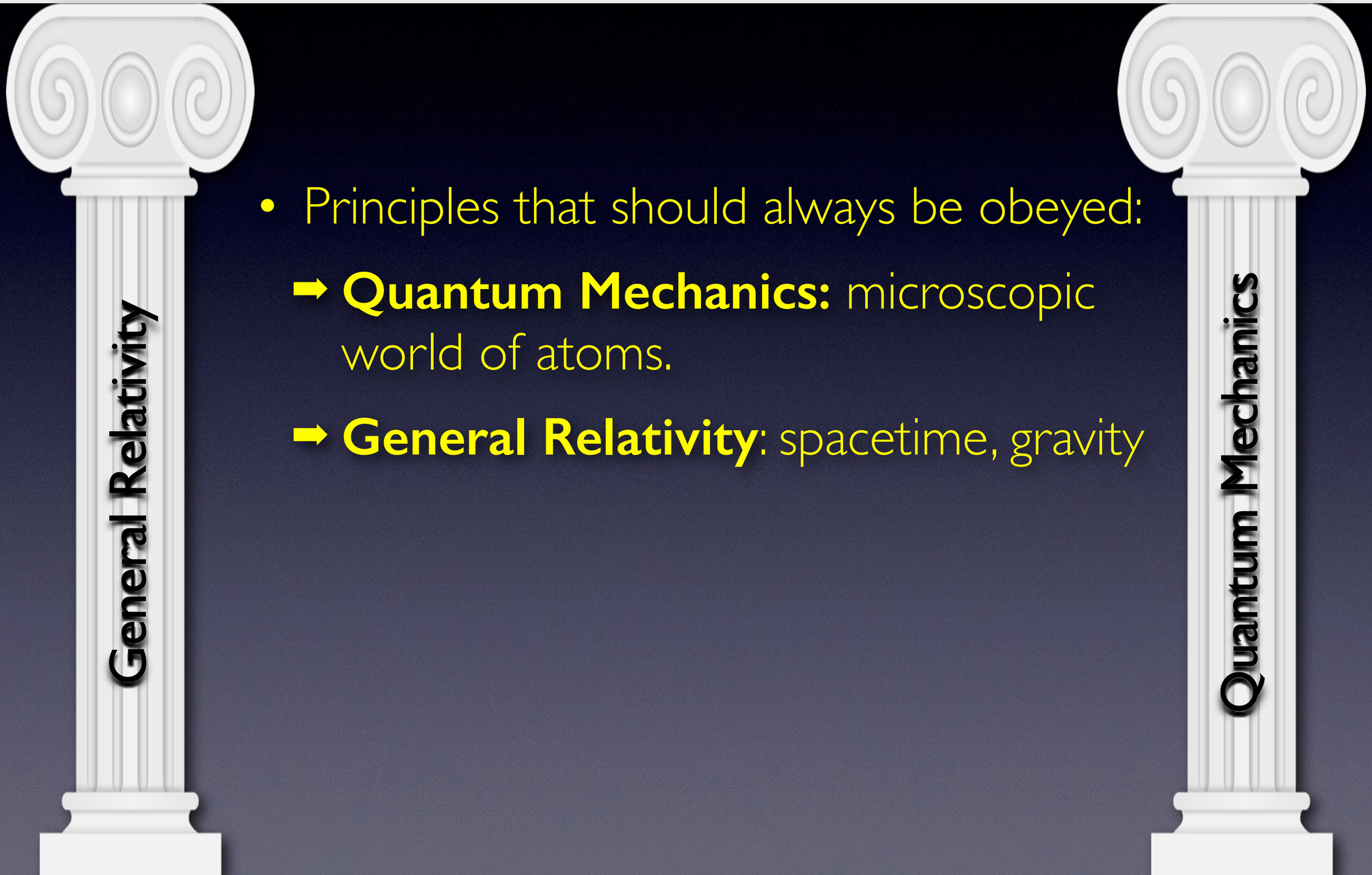
Spirited Disagreements



Motivation

- Black holes are:
  - ➡ real
  - ➡ extreme testing ground for ideas.
  - ➡ forcing deep re-thinking about well-established principles of physics.
  - ➡ giving clues how physics of particles and physics of gravity are connected.
  - ➡ COOL!

Pillars of Modern Physics



- Principles that should always be obeyed:

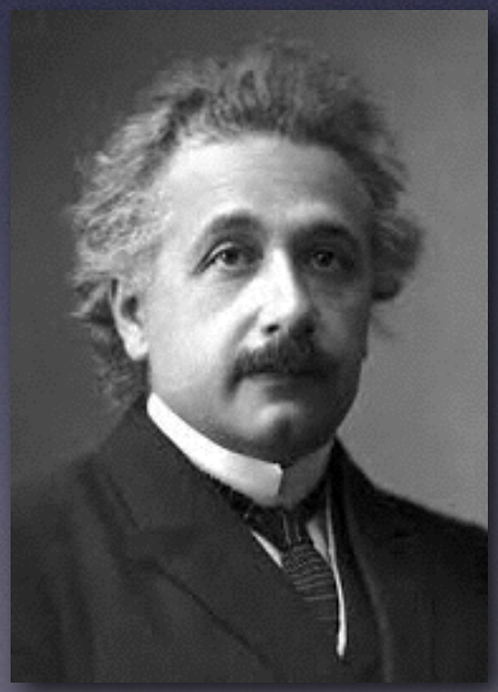
➡ **Quantum Mechanics:** microscopic world of atoms.

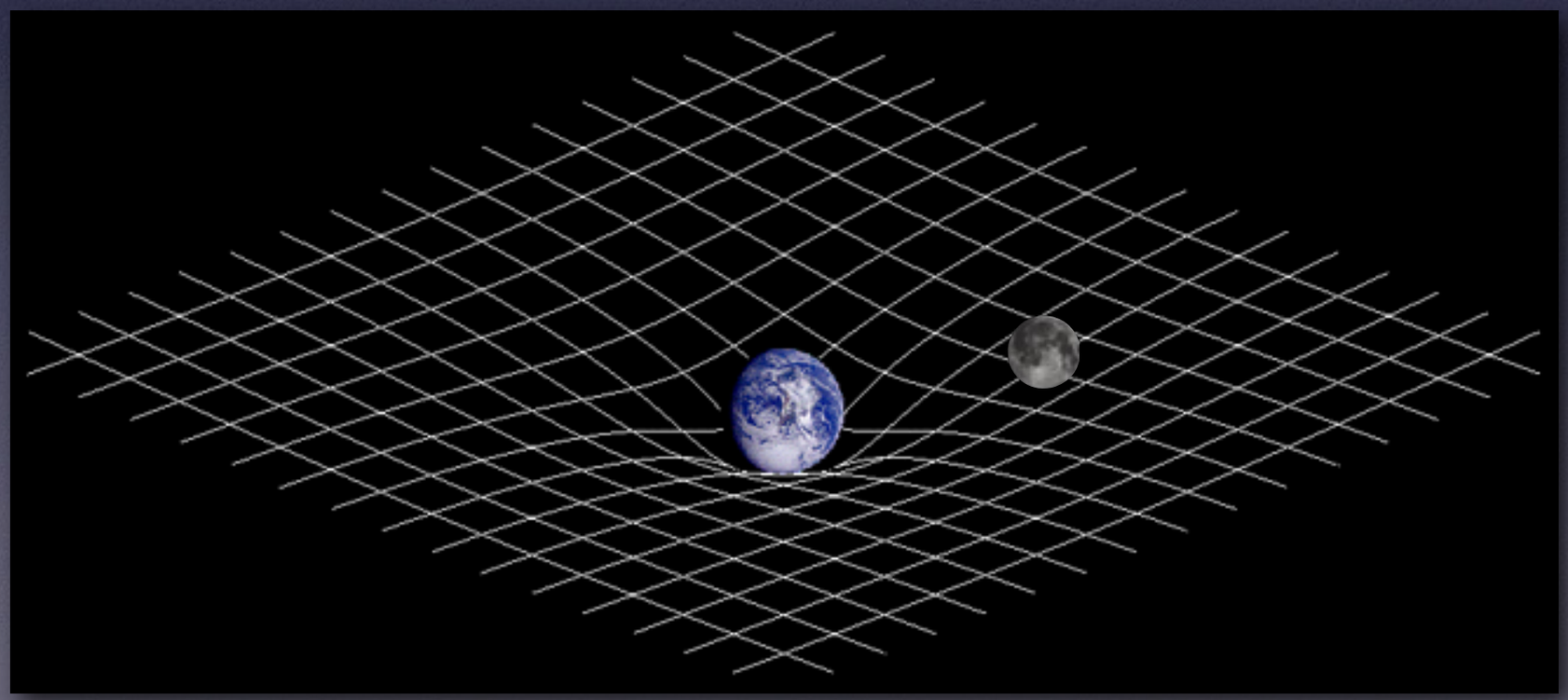
➡ **General Relativity**: spacetime, gravity

Special and General Relativity

Theories of Relativity

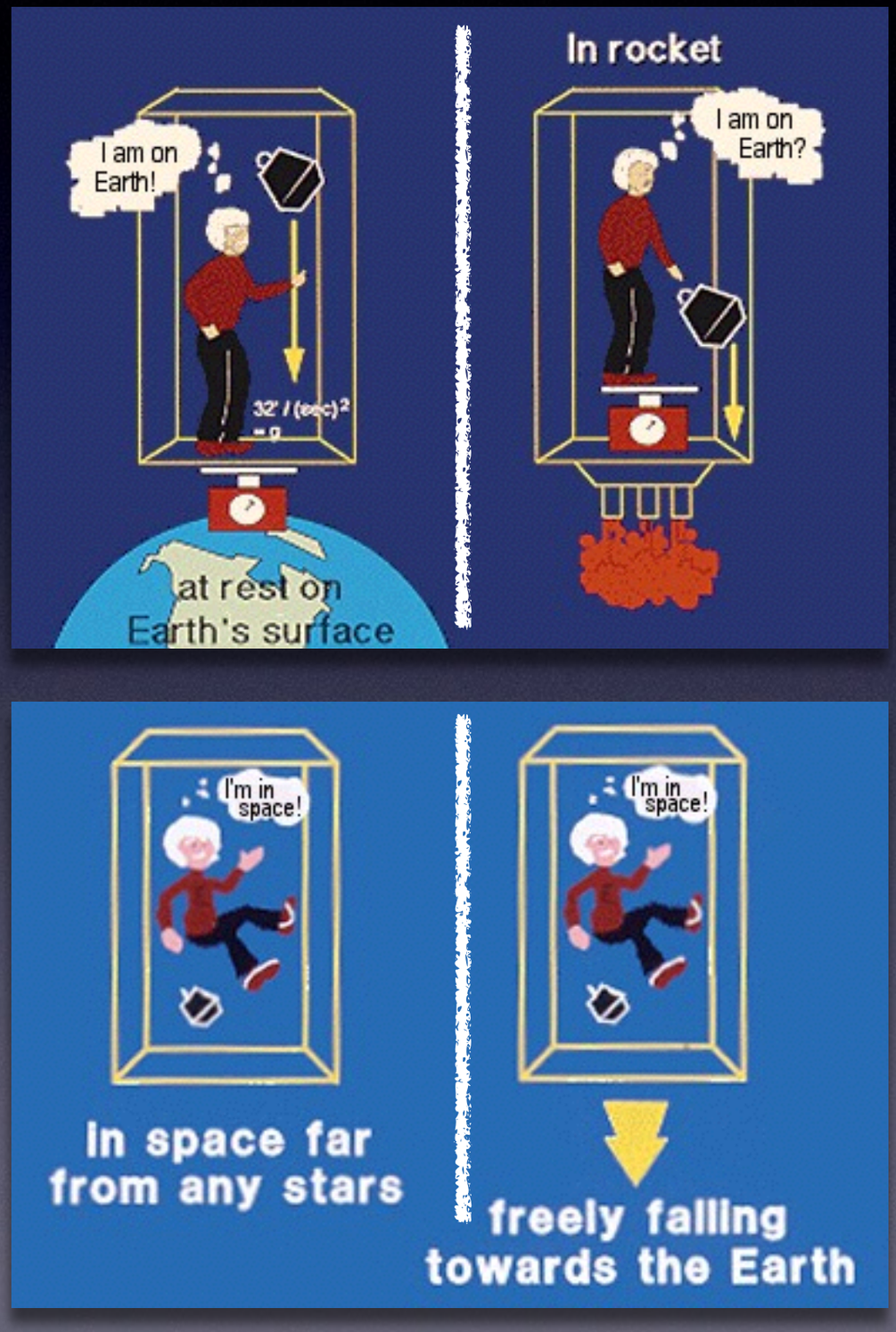
- Special Relativity: (1905)
  - ➡ $E = mc^2$
  - ➡ Speed limit is c
- General Relativity (1915):
  - ➡ Gravity is curvature of spacetime





Equivalence Principle of General Relativity

1. hovering above massive body = acceleration in empty space
2. free-fall = floating in empty space

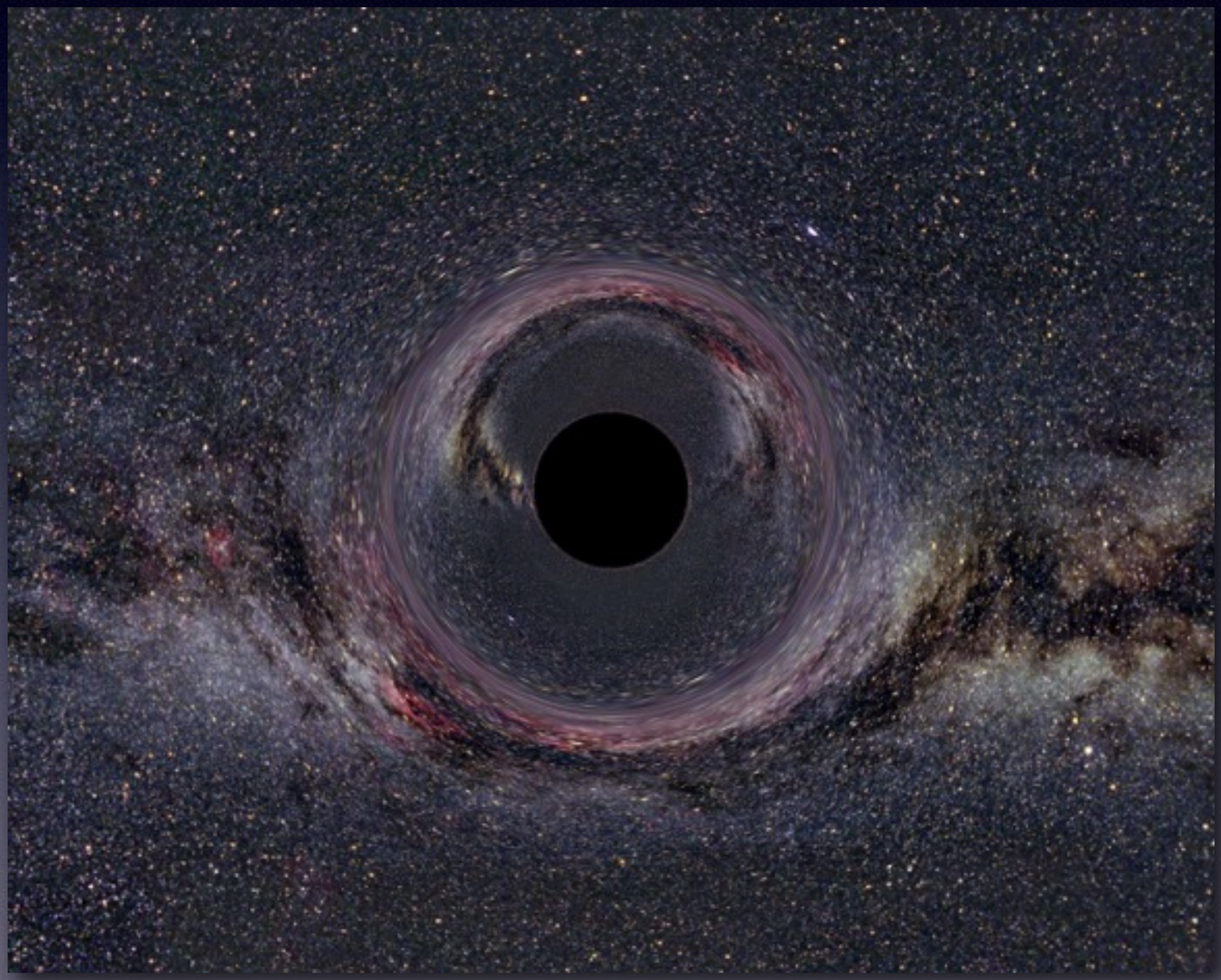


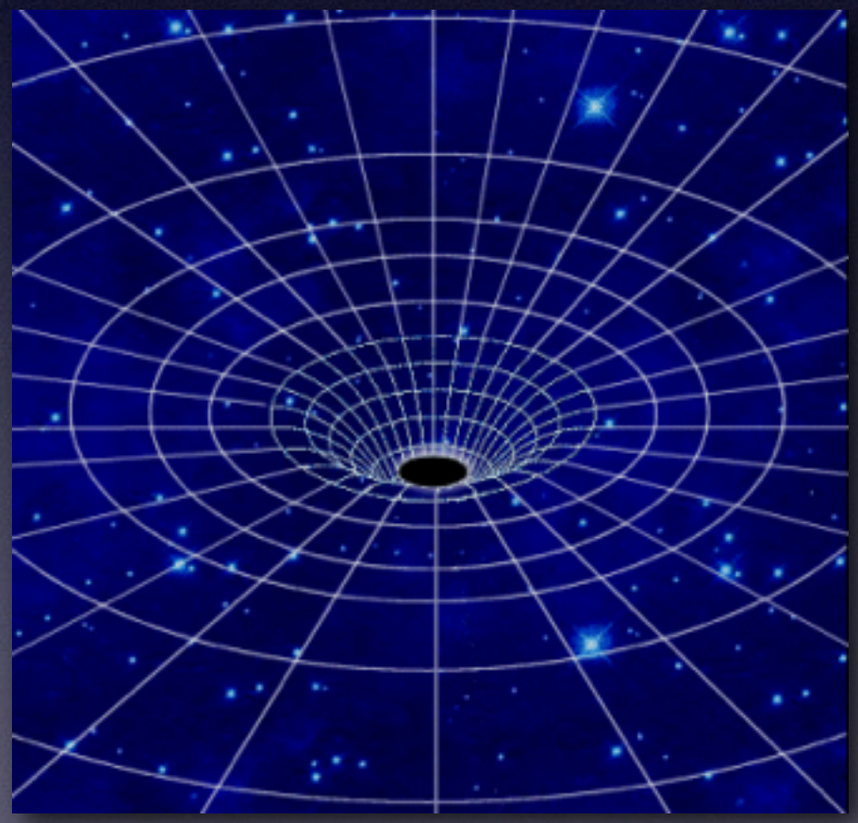
Classical Black Holes

(the kind your grandmother told you about)

Black Holes

- Created by complete gravitational collapse of object.



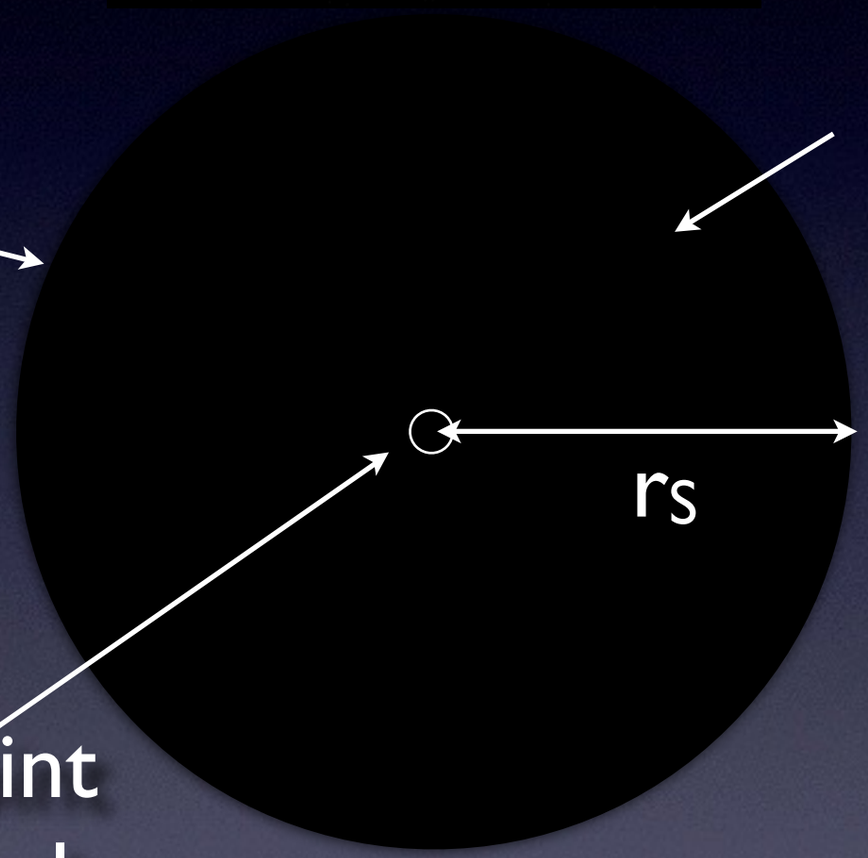


Anatomy of a Non-Rotating Black Hole

Event Horizon is a one-way door!

$v_{esc} = c$

Stuff in here is trapped and will be destroyed at singularity.



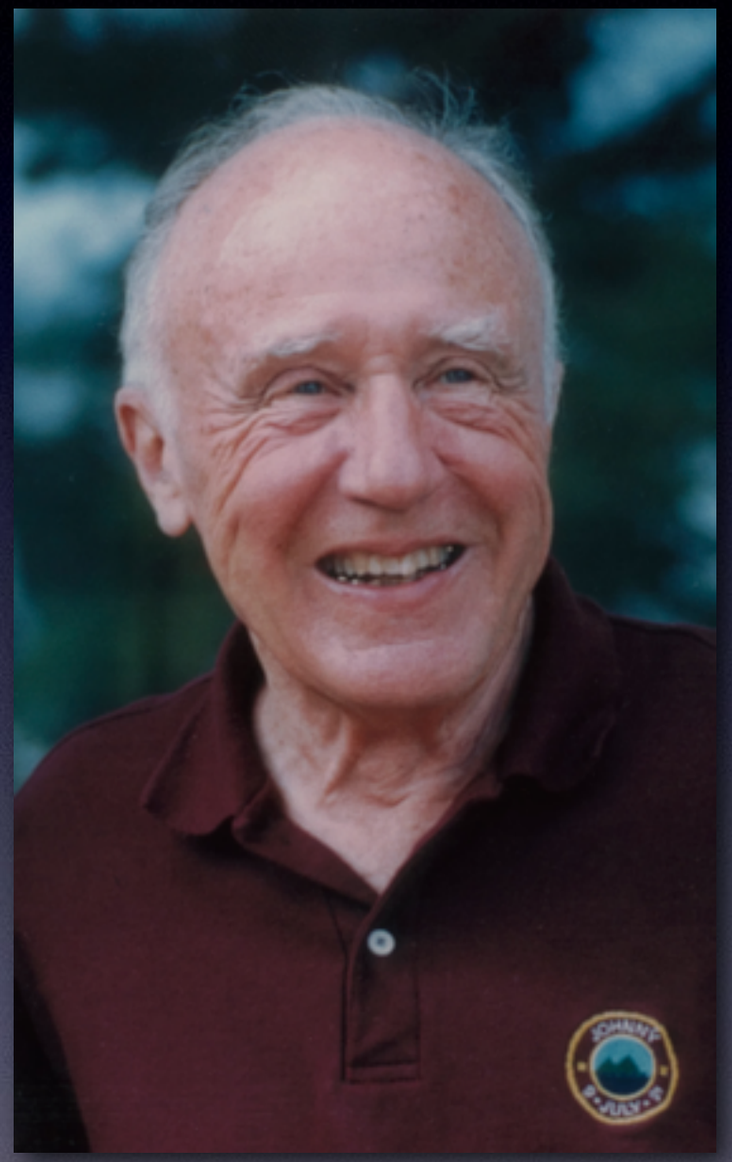
Singularity is a point of infinitely curved spacetime

Information

"Regard the physical world as made of information,
with energy and matter as incidentals.”
— John Archibald Wheeler

Information

- Particle properties (position, speed, spin, etc) are information.
- information is encoded in bits (like computers)
- Information has physical reality and is associated with energy.
- Physical laws describe information change over time.



John Wheeler

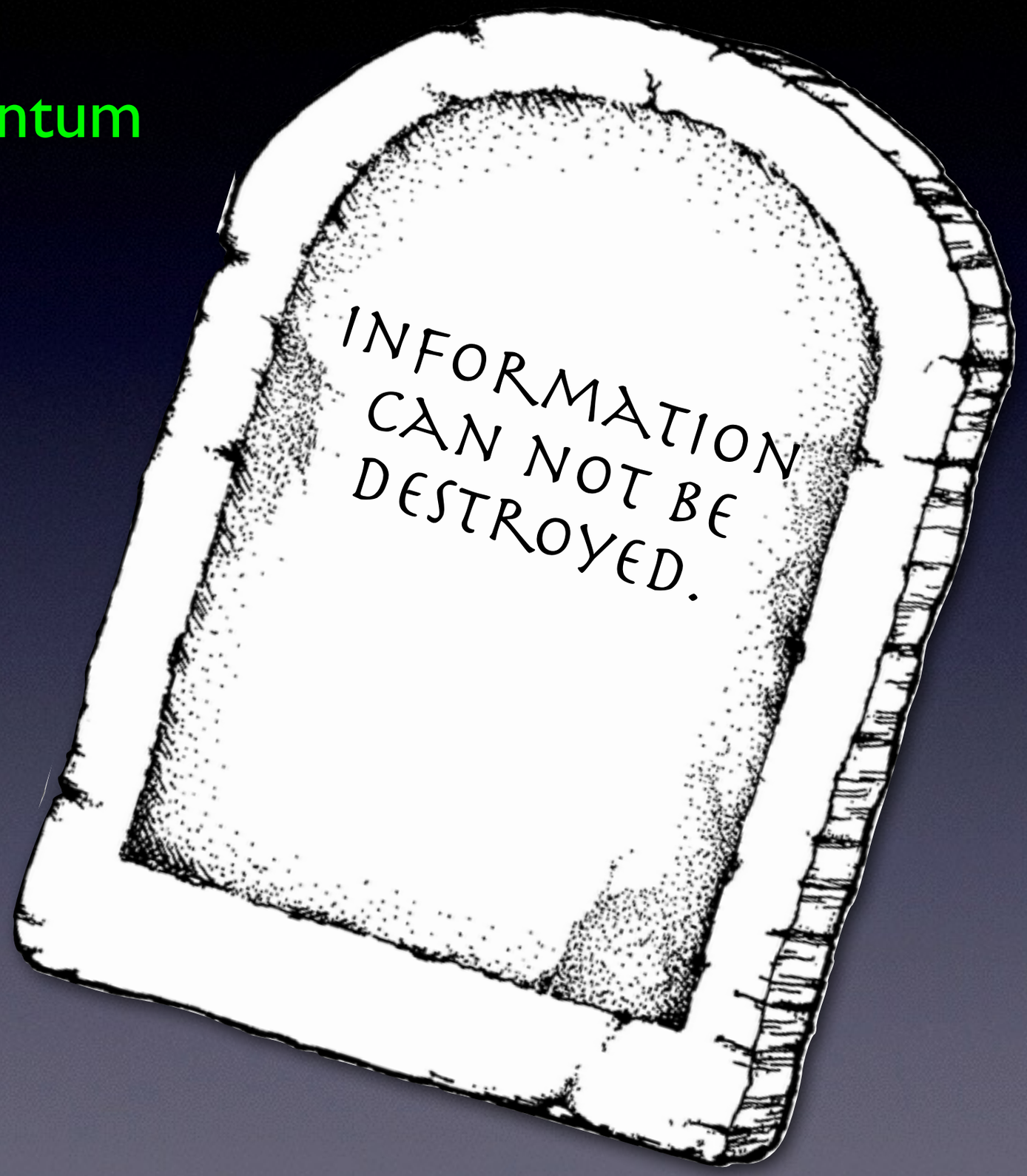
Information

- Objects are huge globs of bits of information.

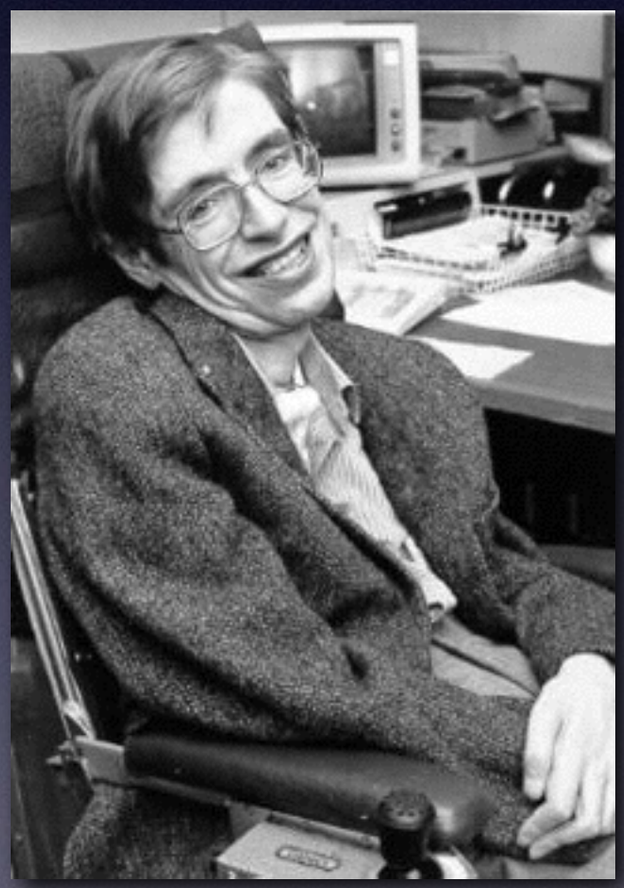
➡ generally hidden due to huge number and tiny size of particles.

Conservation of Information

- Required by quantum mechanics.



- Stephen Hawking, early 70's



Stephen Hawking

Stephen Hawking's Big Question

- What happens to information if it is tossed into a black hole?
- According to GR, information is lost forever behind event horizon.

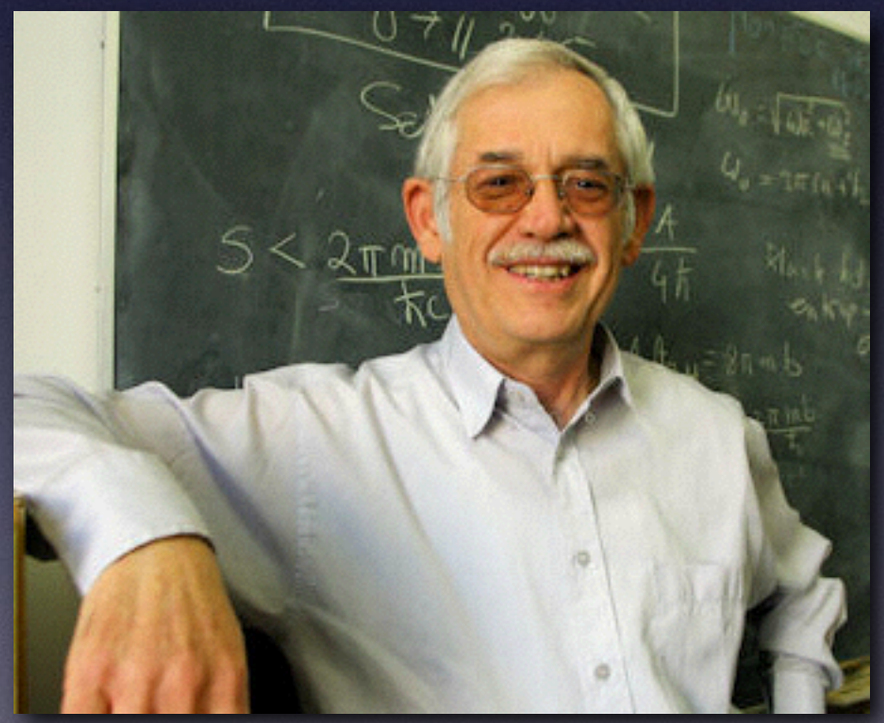
Event Horizon

Information Paradox

- Laws require that information be conserved.
- Laws seem to conspire to *prevent* information from being conserved.
- Hence, the "information paradox"…and triple facepalm!

Black Hole Thermodynamics

- Jacob Beckenstein, 1973 - *Black Holes and Entropy*



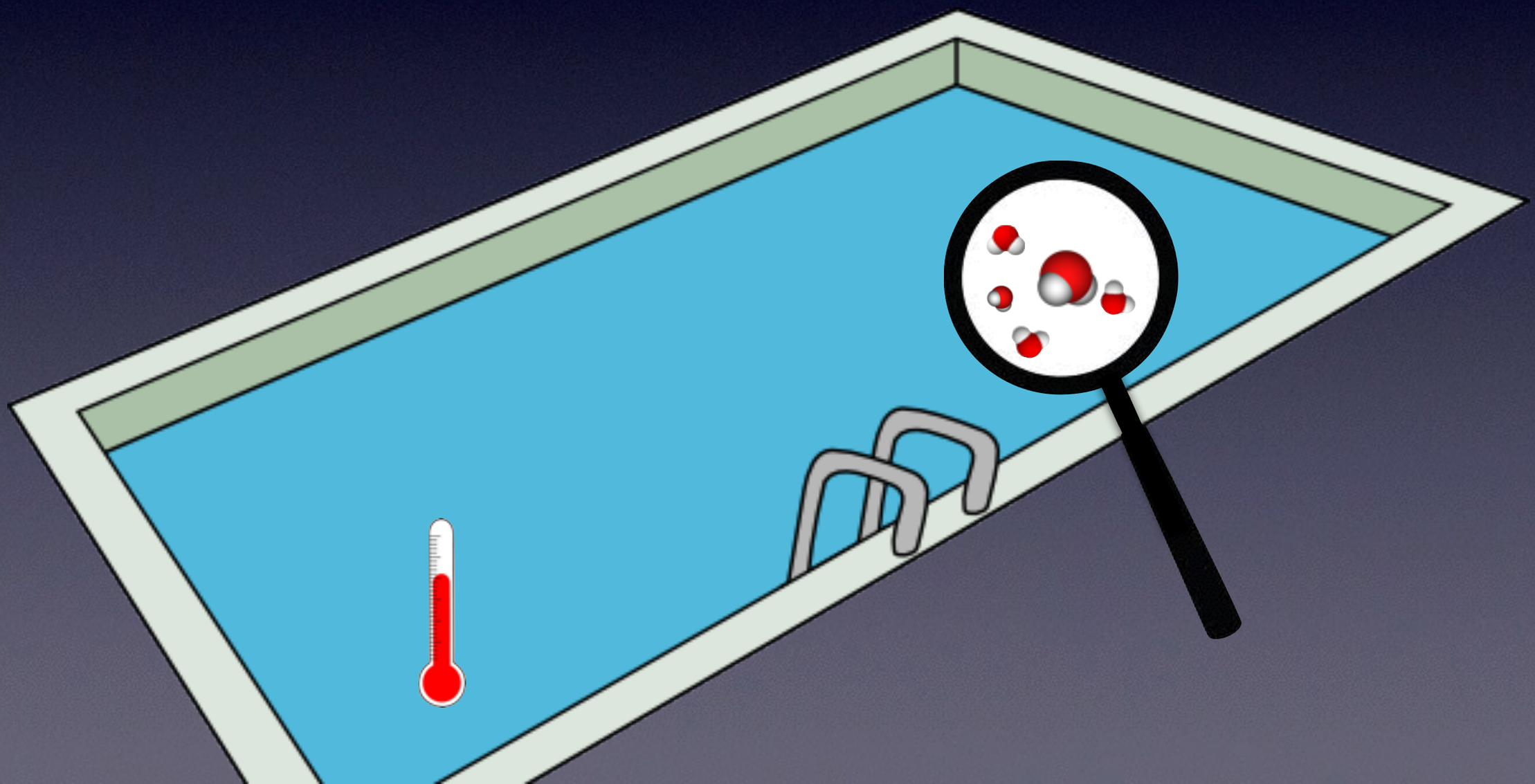
Jacob Bekenstein

Entropy Example

- Clean room (low entropy)
- Messy room (high entropy)

Entropy

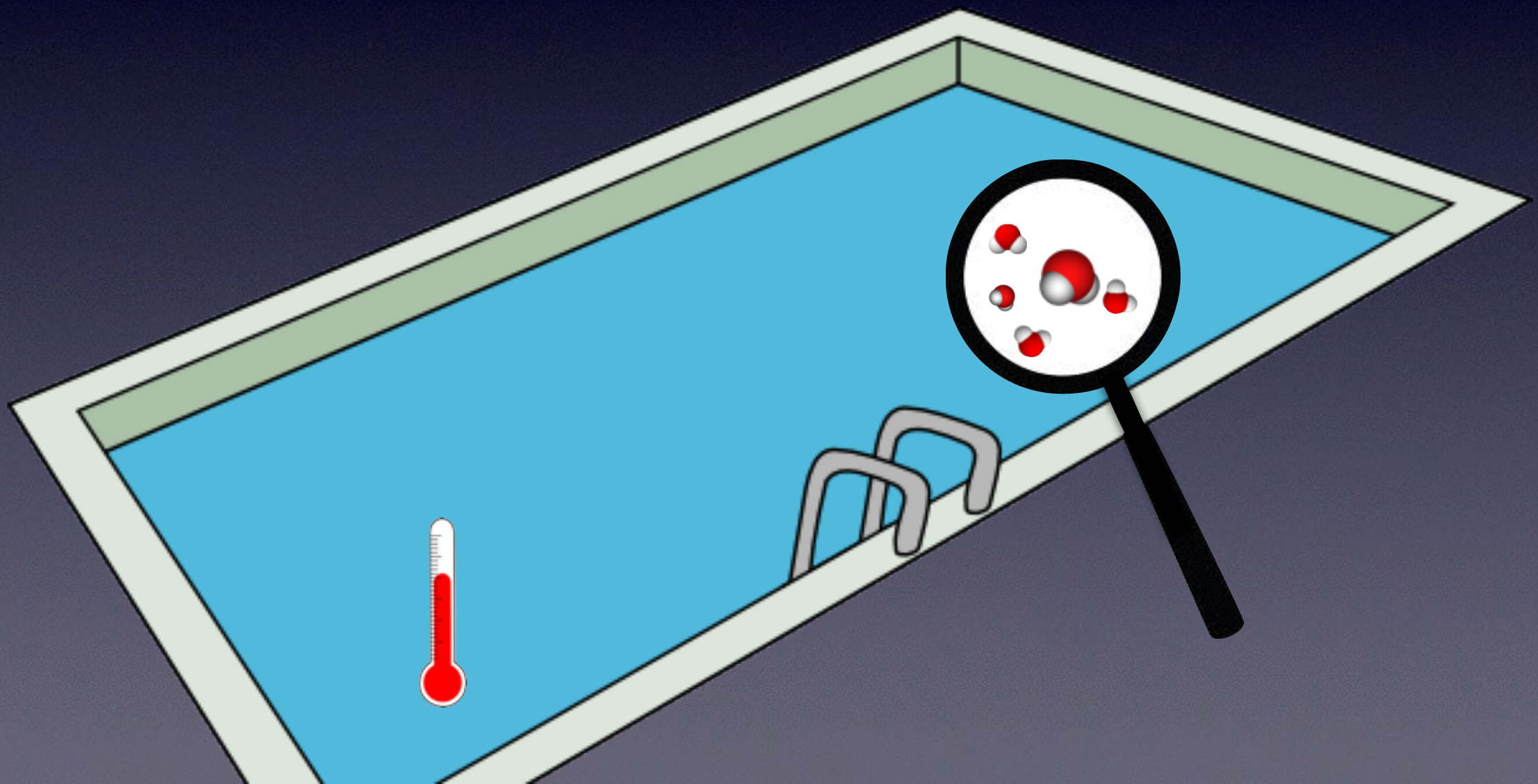
- Swimming Pool
  - ➡ Interesting in temperature and volume.
  - ➡ No knowledge of position & speed of each atom-lots of hidden information.



Entropy

- **Entropy** (S) is a measure of how may ways the positions and speeds of atoms could be arranged to yield same temperature and volume.

➡ A measure of the amount of hidden information.



First Law Thermodynamics

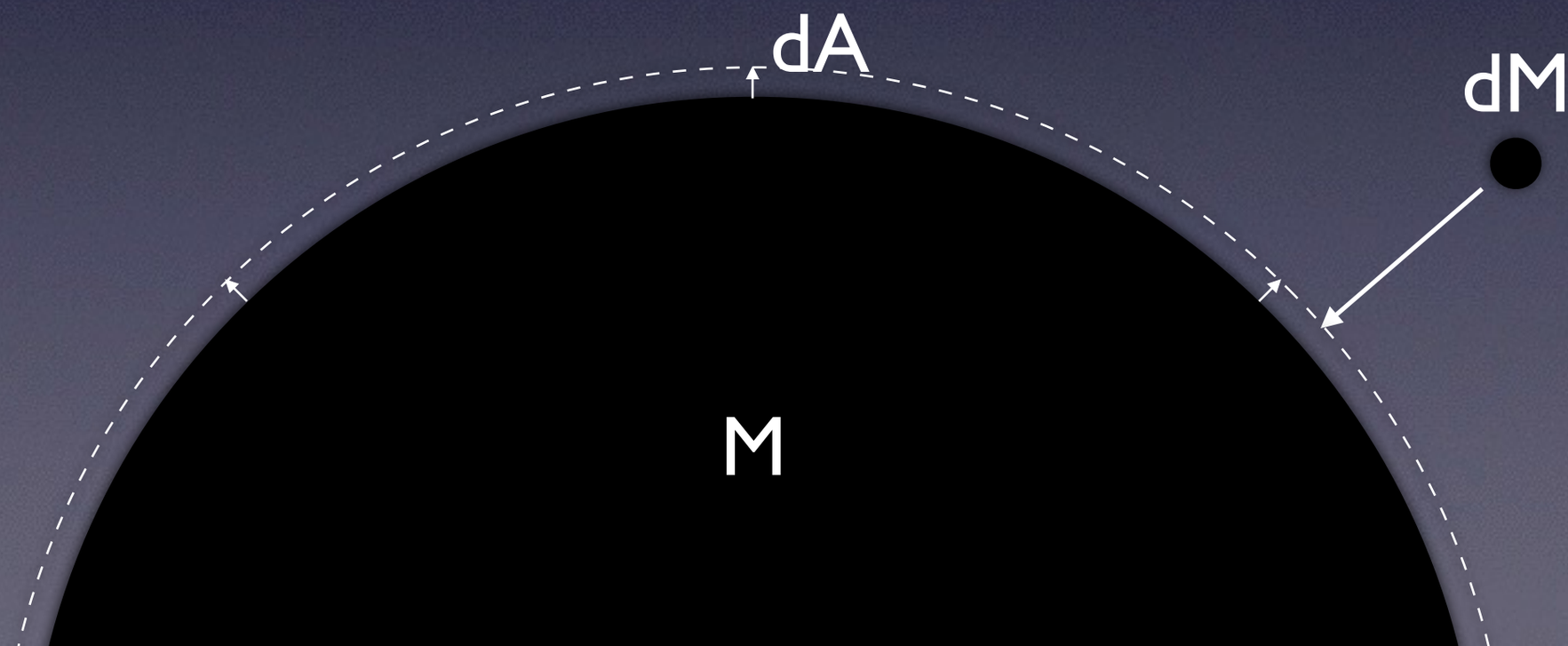
$$dE = TdS - W$$

- Basically a statement of the conservation of energy.

Black Hole Thermodynamics

$$dM = \frac{\kappa}{8\pi M} dA - W$$

- Bekenstein imagined building black hole piece at a time



Black Hole Entropy

$$dE = TdS - W \qquad dM = \frac{\kappa}{M} dA - W$$

- Work (W) has same meaning in both equations
- Mass & Energy are equivalent ($E = mc^2$).
- Black hole temperature: $T \sim \frac{1}{M}$
- Black hole entropy: $dS \sim dA$
- Entropy (hidden information, in bits) of black hole is proportional to its surface area (in Plank-areas)!

Hawking Radiation

- Stephen Hawking, 1974 - *Particle Production by Black Holes*

Hawking Radiation

- Black holes must radiate.
- Quantum fluctuations spontaneously create particles and radiation outside event horizon that radiate out into space.

- Comes at cost of gravitation energy of black hole.
- Black hole slowly evaporates away!

Event Horizon

A Problem

Information Loss in Hawking Radiation

- Hawking argues that the radiation contains NO information of anything that is tossed in.
- Black hole evaporates with that information trapped inside.

➡ **Information is irretrievably destroyed!**

Pillars of Modern Physics

- Principles that should always be obeyed:

➡ ~~**Quantum Mechanics:** microscopic world of atoms.~~

➡ **General Relativity**: spacetime, gravity

Information Lost

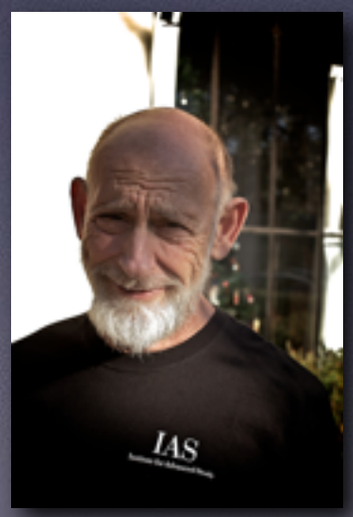
General Relativity

Quantum Mechanics

Black Hole Complimentarity

Leonard Susskind, Lárus Thorlacius, and John Uglum, 1993 - *The stretched horizon and black hole complementarity*

Juan Maldacena, 1997 - *AdS/CFT Correspondance*

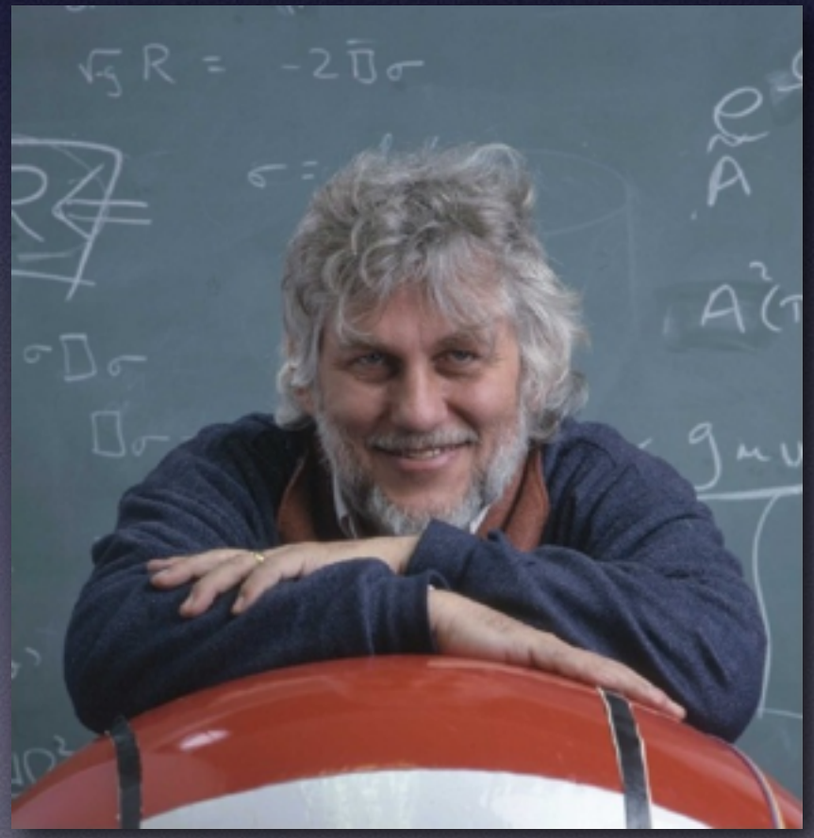


Leonard Susskind

Juan Maldacena

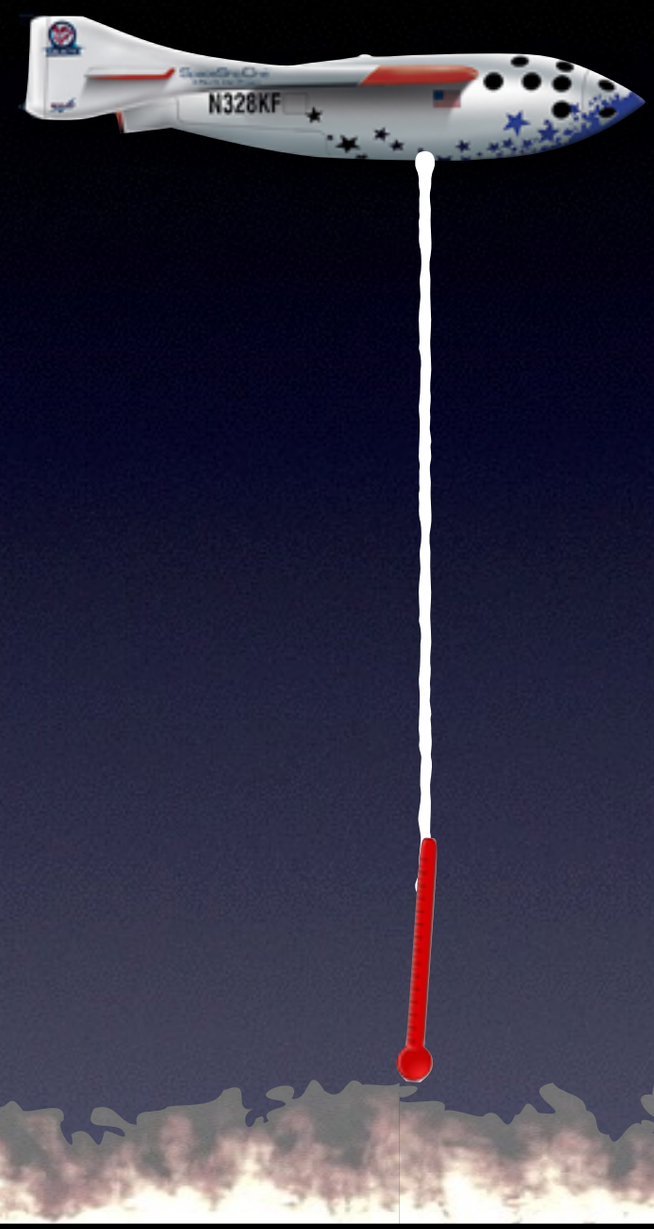
Unruh Effect

- Unruh Effect: An accelerating observer will observe thermal radiation even when a non-accelerating observer would observe none.



William Unruh

Hot "Stretched Horizon"



- Hovering = Acceleration

No Hot "Stretched Horizon"

- Free-fall = Empty space

Event Horizon

What Observer Sees

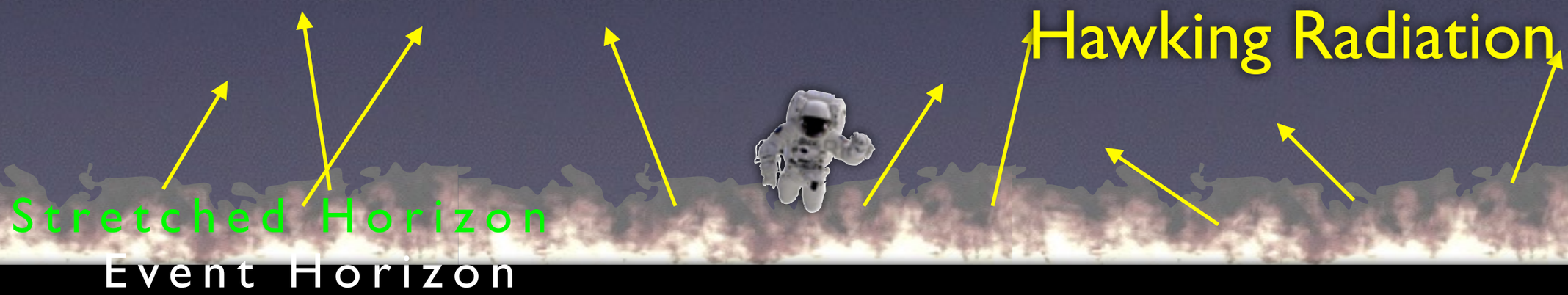
- Hot stretched horizon 1 Plank-length above event horizon.
- Information (astronaut) gets thermalized and scrambled, but not destroyed!

  ➡ Never sees information cross horizon!

- Bits of information come out later as Hawking radiation.

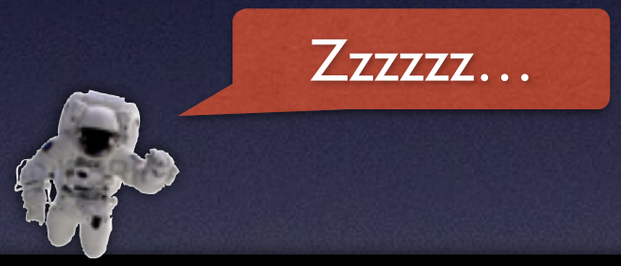
  ➡ NO INFORMATION LOSS!

Ah Ha!



What In-falling Astronaut Sees

- From General Relativity, notices "no drama" as he passes event horizon



Event Horizon

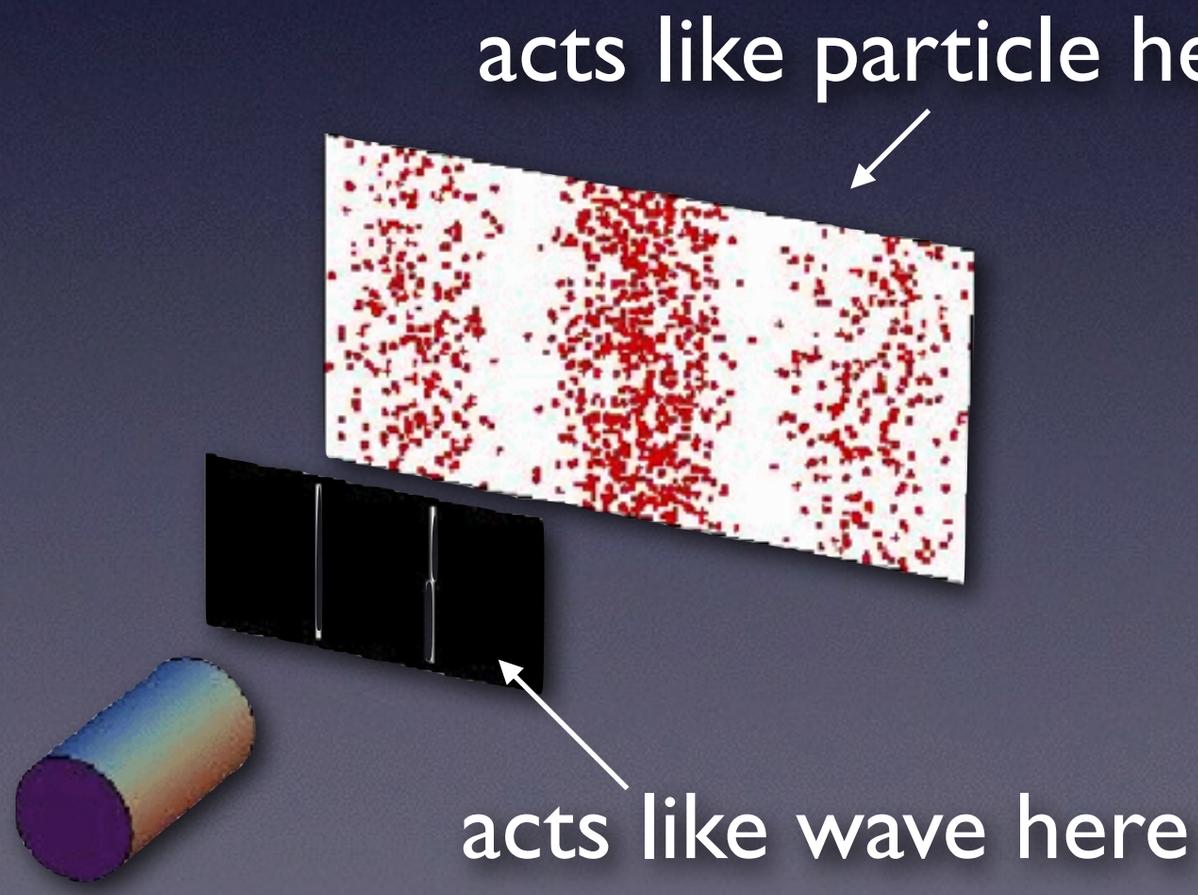
What In-falling Astronaut Sees

- From General Relativity, notices "no drama" as he passes event horizon
- Information goes in with him.
- Cannot communicate his arrival inside to outside horizon.

Event Horizon

Complimentarity

- Stories seem contradictory, but are consistent in observation.
- Neither sees information both places.
- Neither sees information destroyed!



Holographic Principle

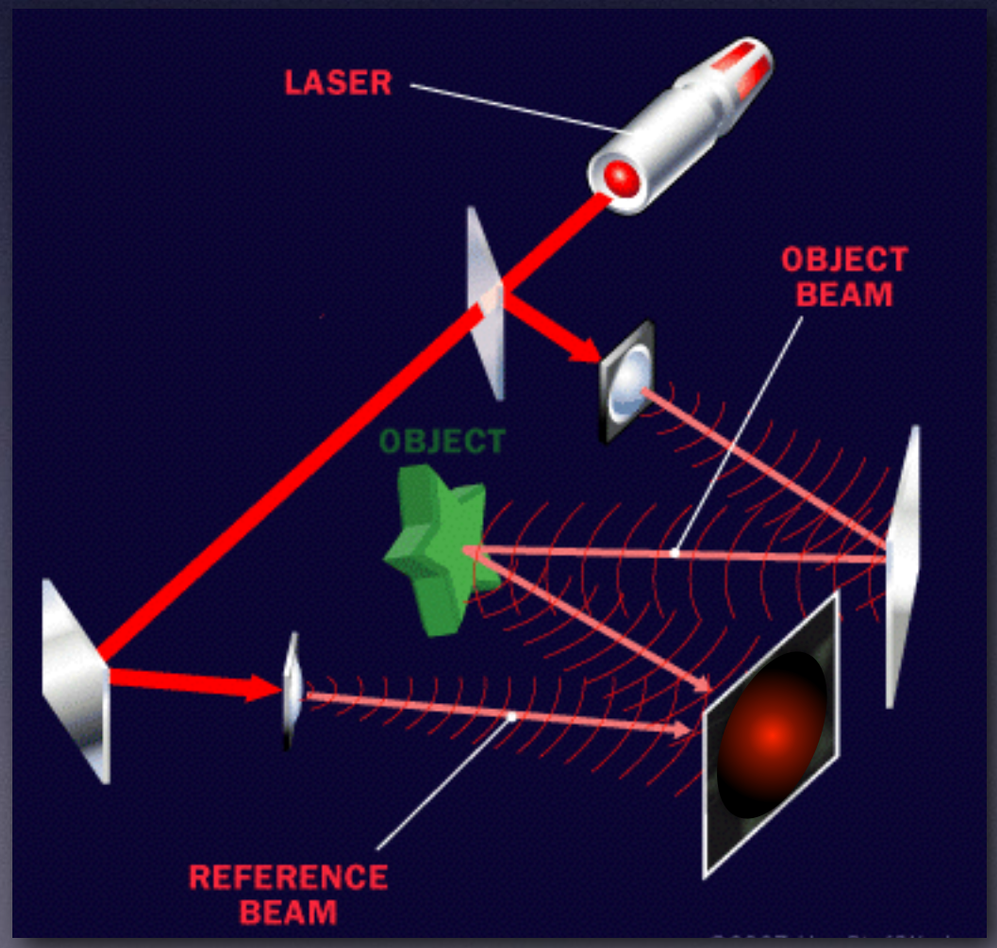
- Leonard Susskind, 1994 - *The World as a Hologram*

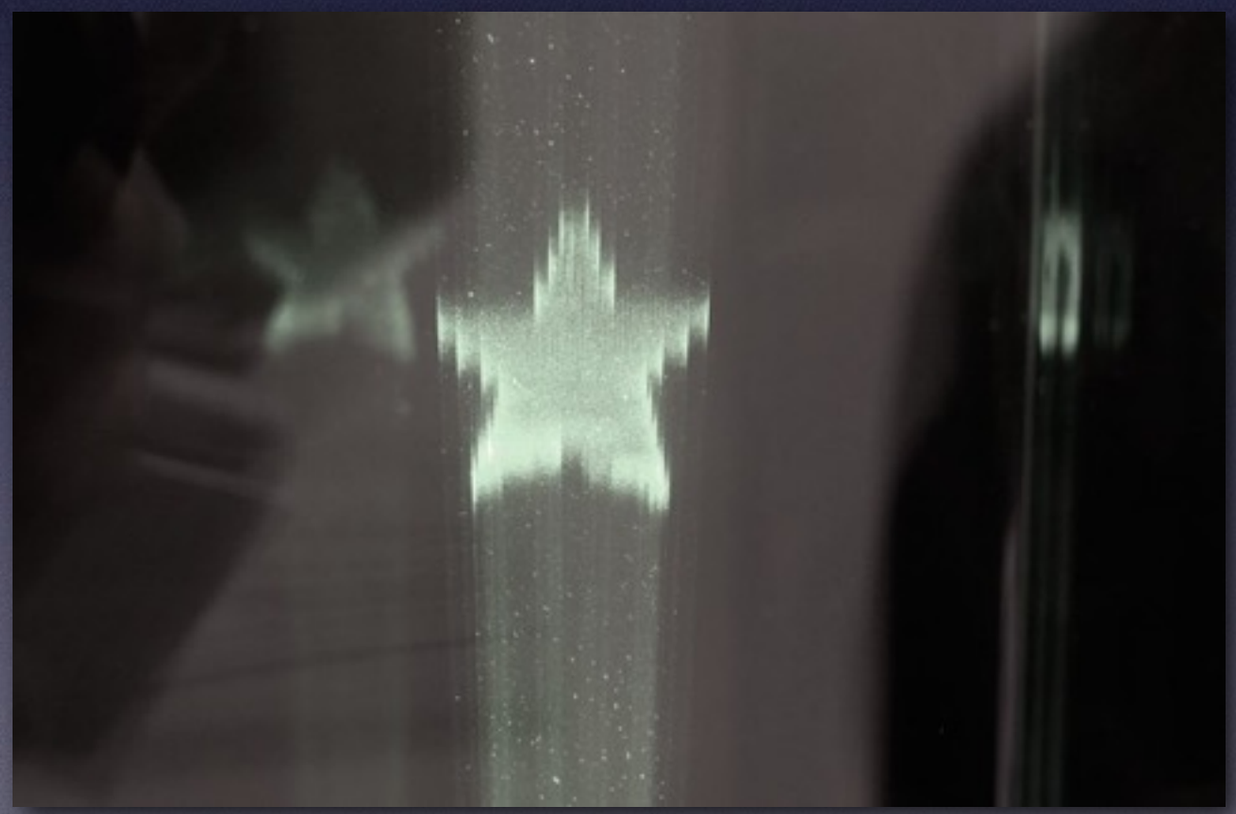
Holograms

- 3-d volume of information can be entirely encoded on 2-d surface.

➡ 2-d encoding scrambles 3-d information

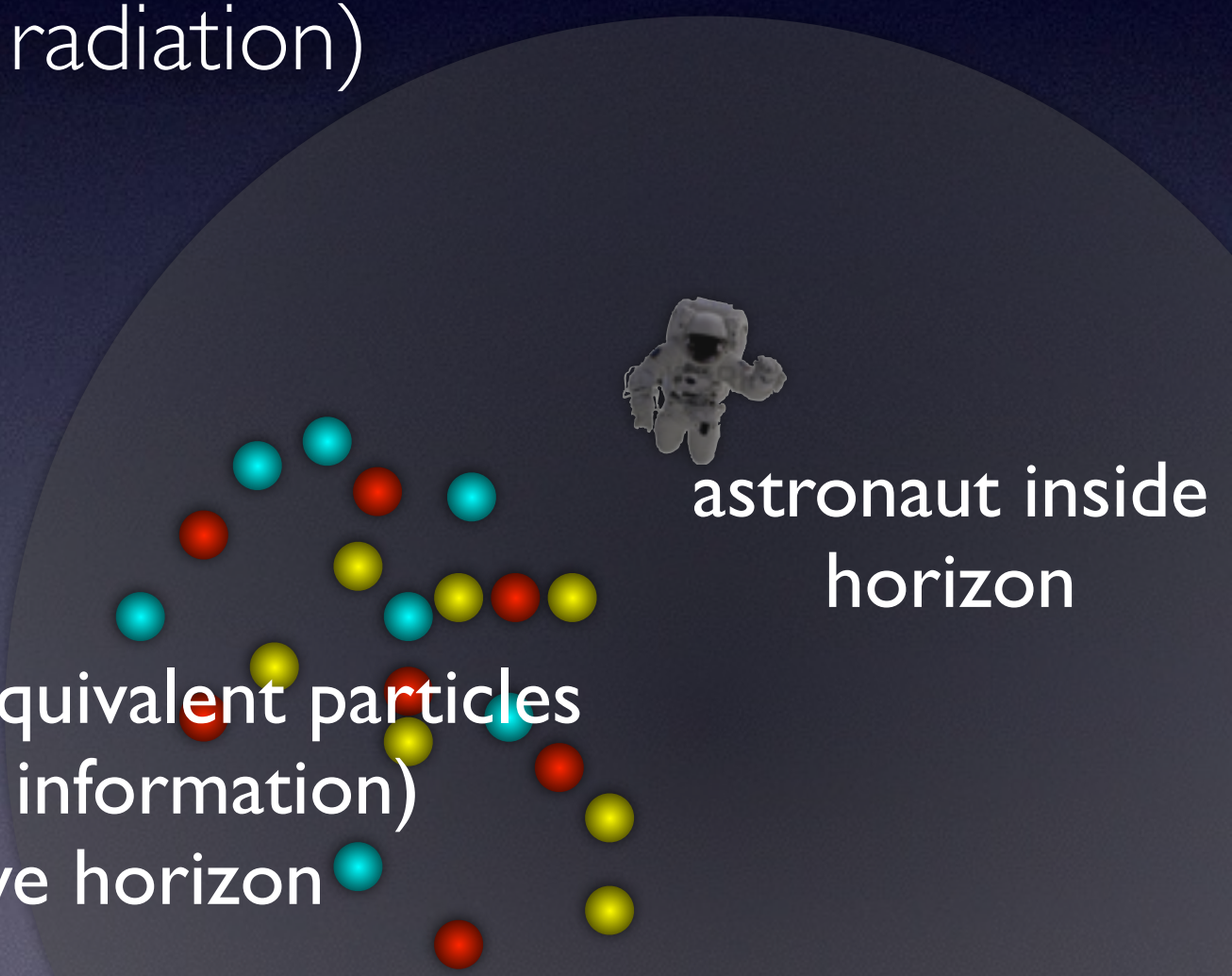
➡ Need to know rule to descramble it and create image.





Holographic Event Horizon

- Observer sees in-falling information scrambled & stored on "stretched horizon"
- Like a 2-d hologram of everything that has fallen in (later emitted as Hawking radiation)

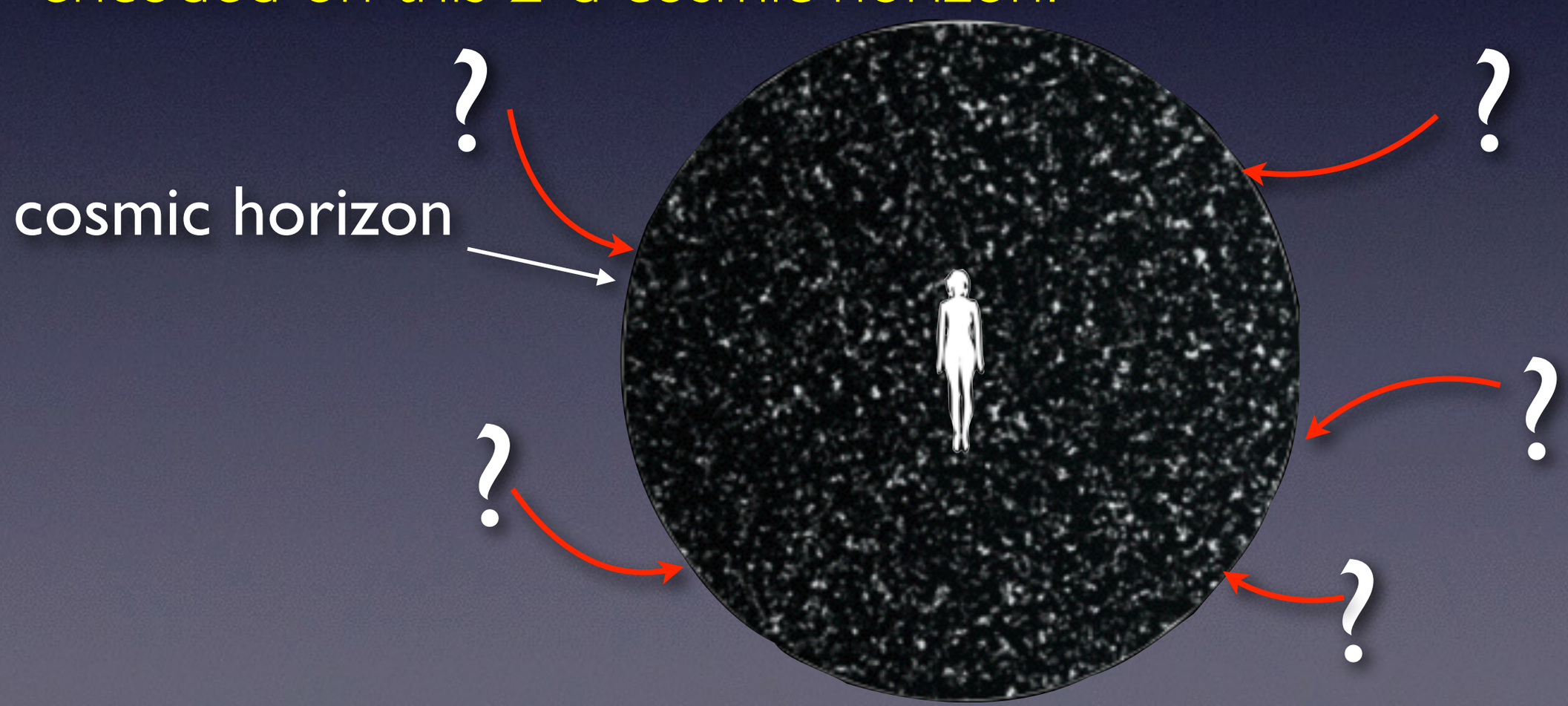


Accelerating Universe

- Expansion of universe is accelerating!
- Creates point of no return around us (46.6 Bly).

  ➡ Like event horizon of black hole *inside-out*.

- Is information about rest of 3-d universe somehow encoded on this 2-d cosmic horizon?

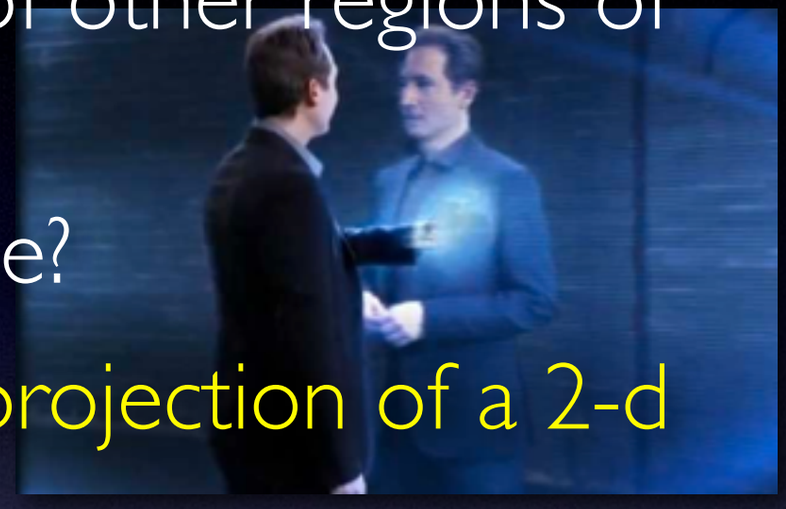


Holographic Universe

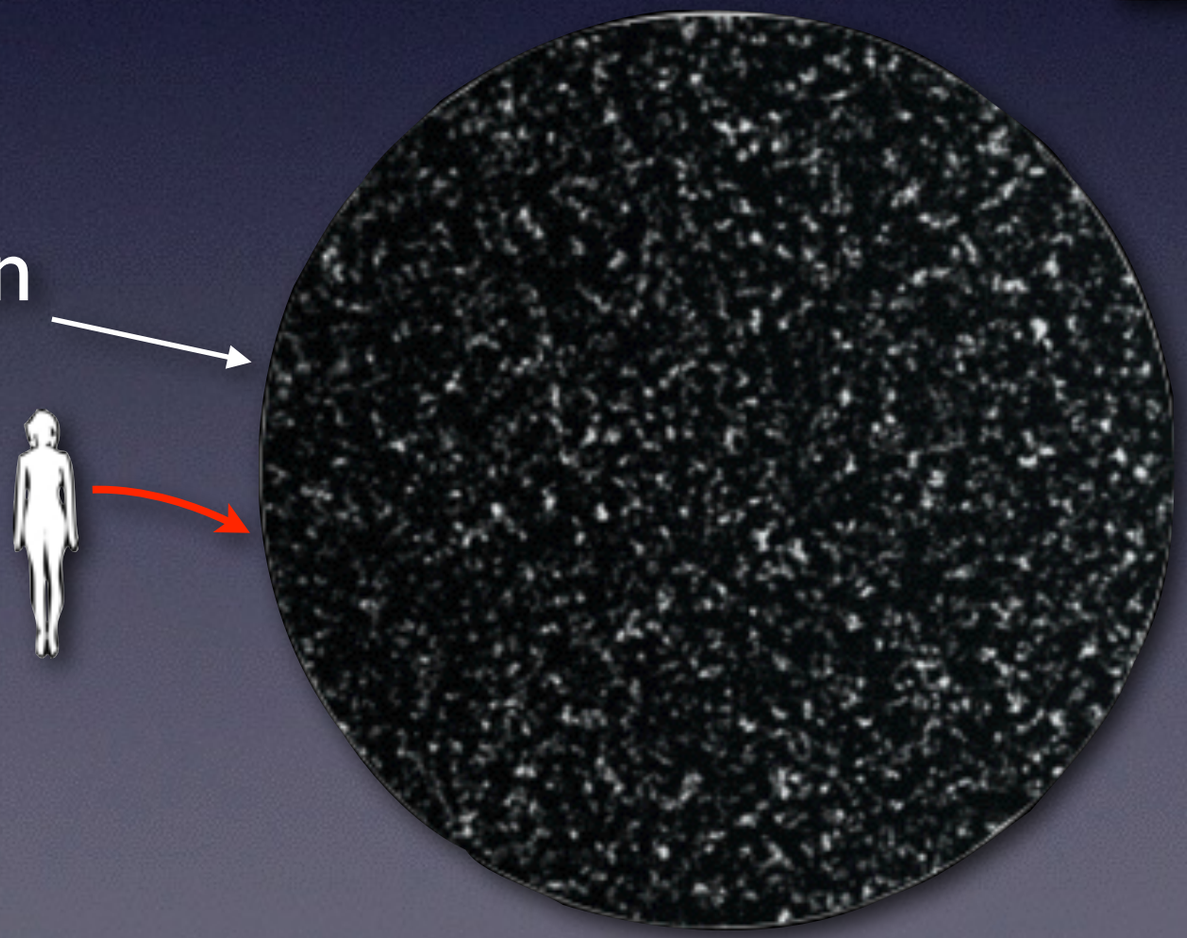
- We are outside cosmological horizon of other regions of the universe.

  ➡ Are we also encoded on a 2-d surface?

- Are we and the the whole universe a projection of a 2-d surface?



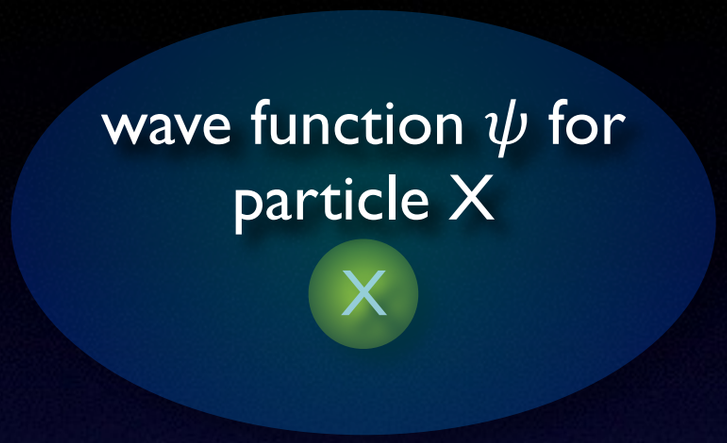
cosmic horizon



A Problem

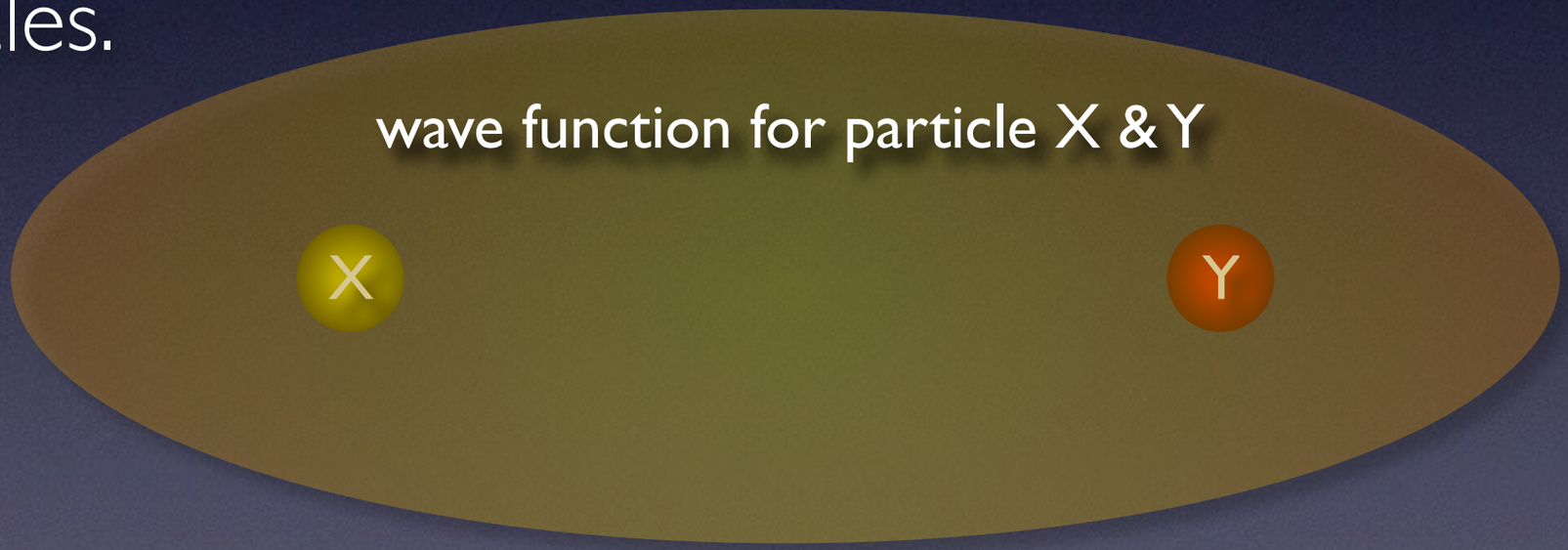
- *Information in Black Hole Radiation*, Don Page, Phys Rev Letters,1993
- *Complementarity or Firewalls?*, A. Almheiri, D. Marolf, J. Polchinski and J. Sully, (AMPS) 2012

Quantum Wave Functions



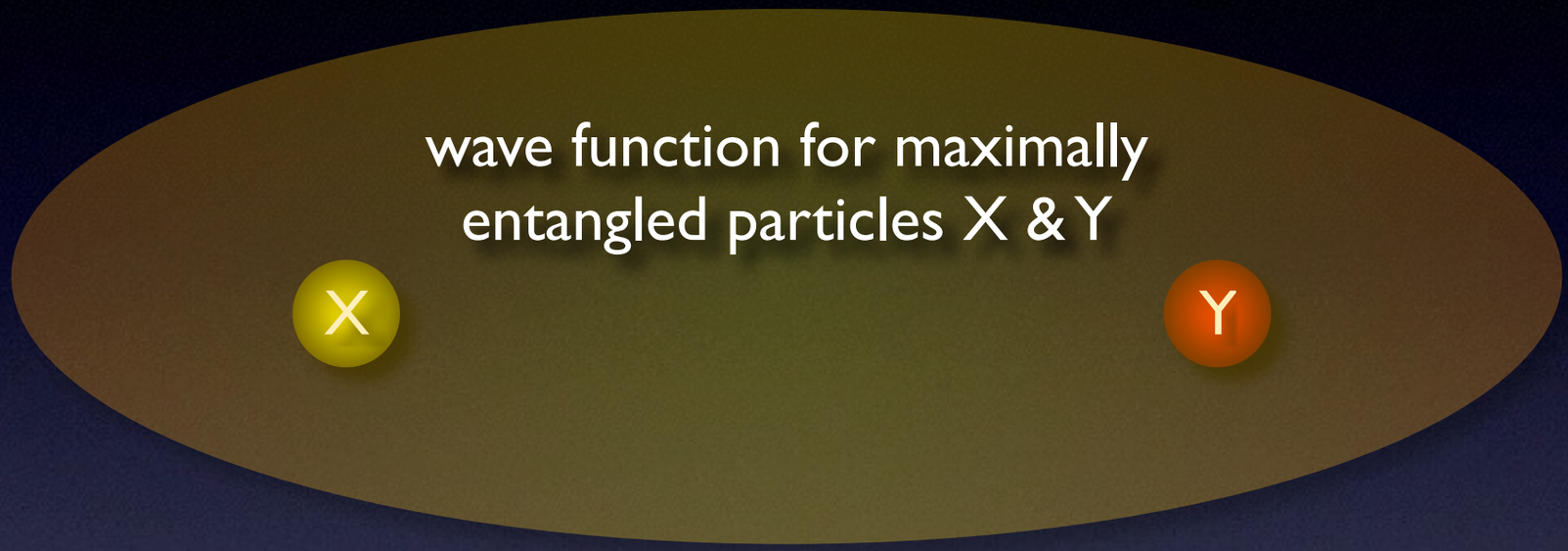
$$ih\frac{\partial}{\partial t}\psi = \hat{H}\psi$$

- Quantum mechanics assigns a wave function (ψ) for particles.



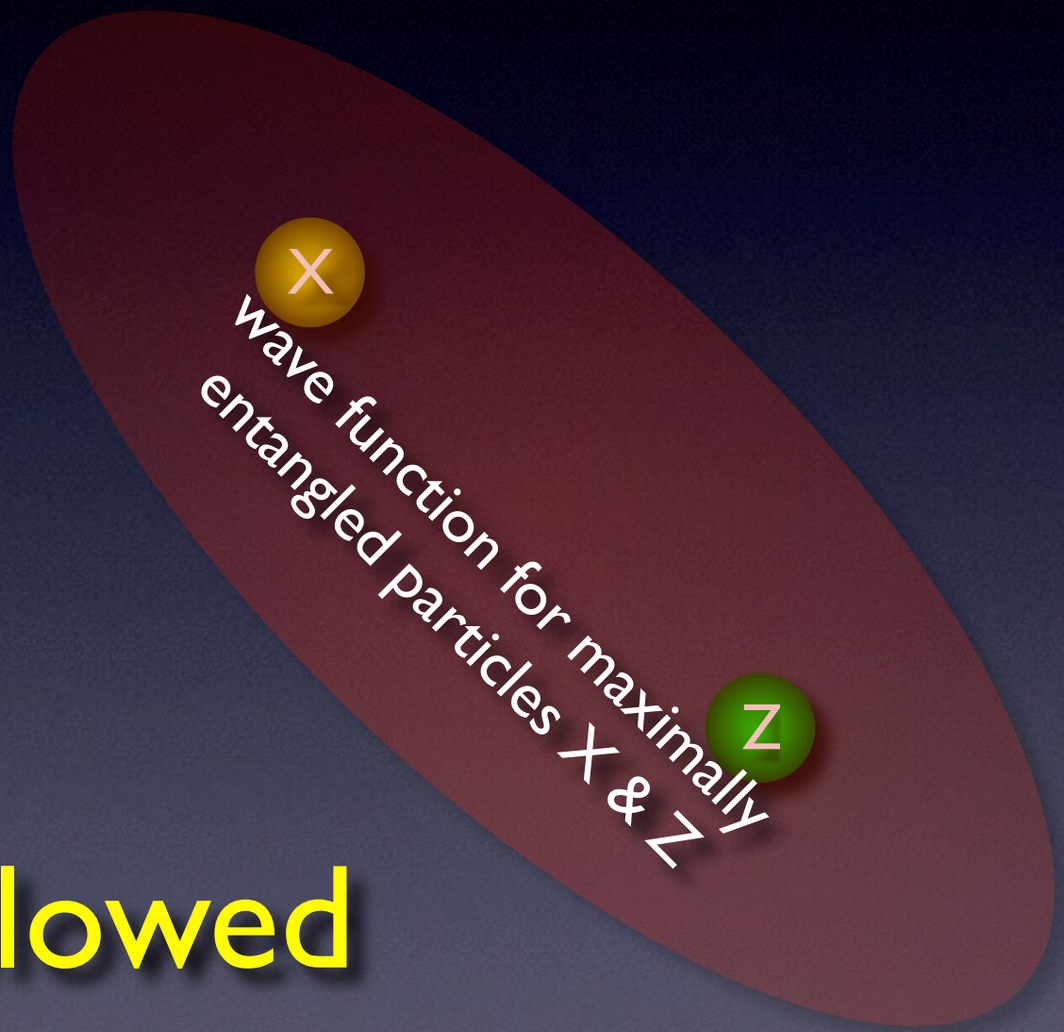
- Entangled particles described by single inseparable wave function-each particle carries information about the other.

Entanglement Monogamy



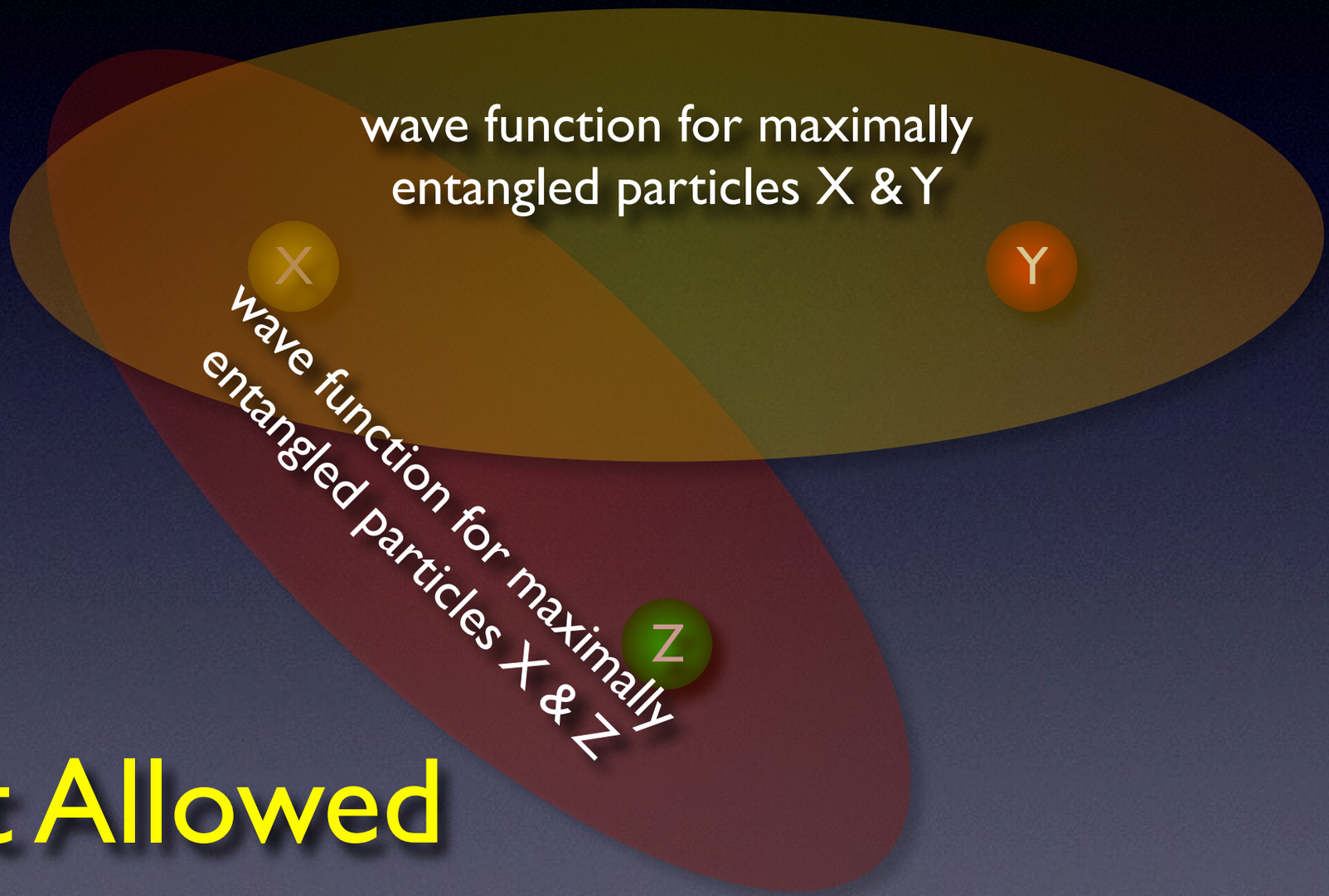
Allowed

Entanglement Monogamy



Allowed

Entanglement Monogamy

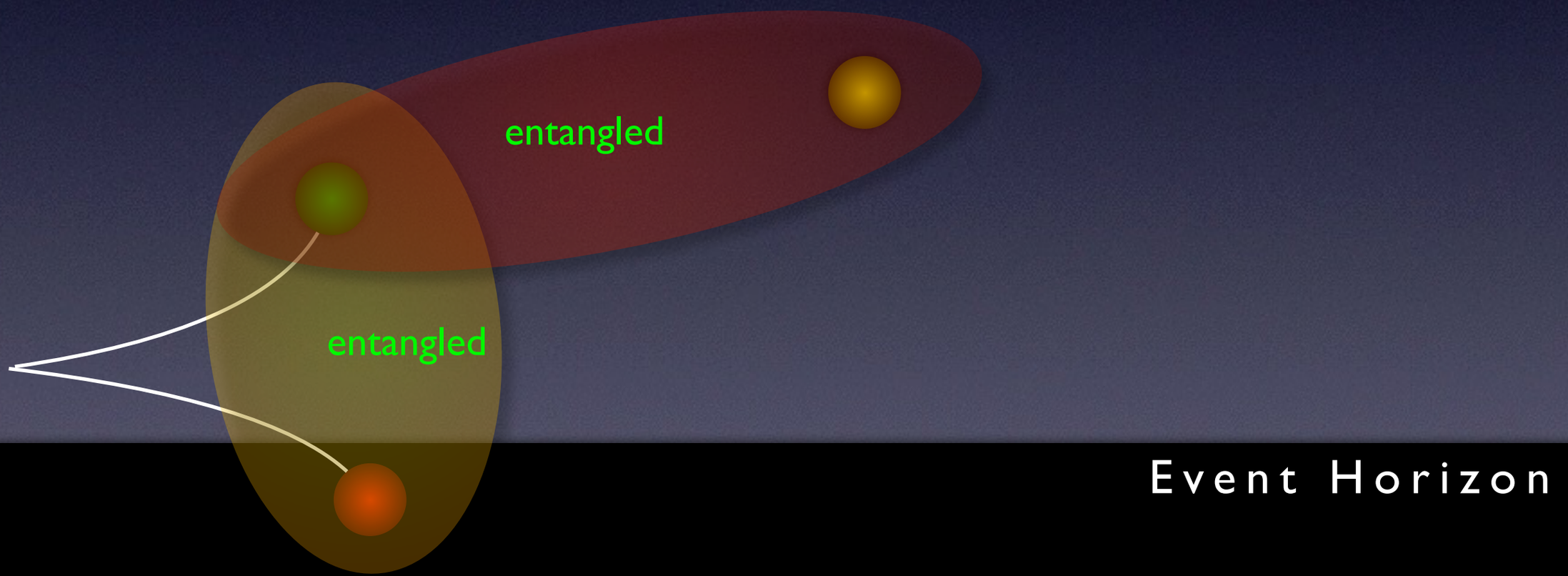


Not Allowed

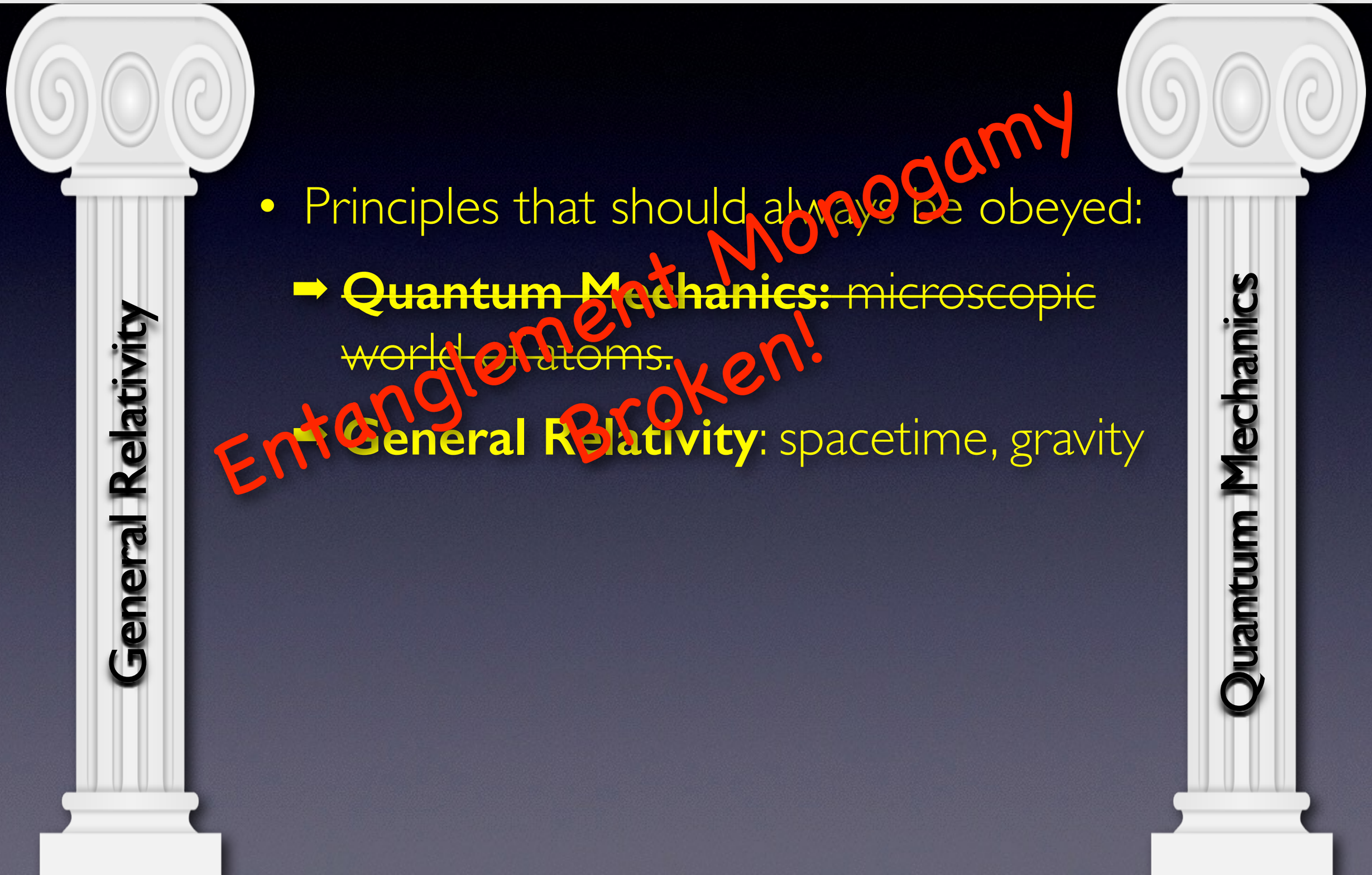
- Cannot have X maximally entangled with both Y and Z!

Problem With Complementarity

- For information to escape and obey "no drama" rule, Hawking radiation has to be multiply entangled!



Pillars of Modern Physics



A New Picture - Firewalls

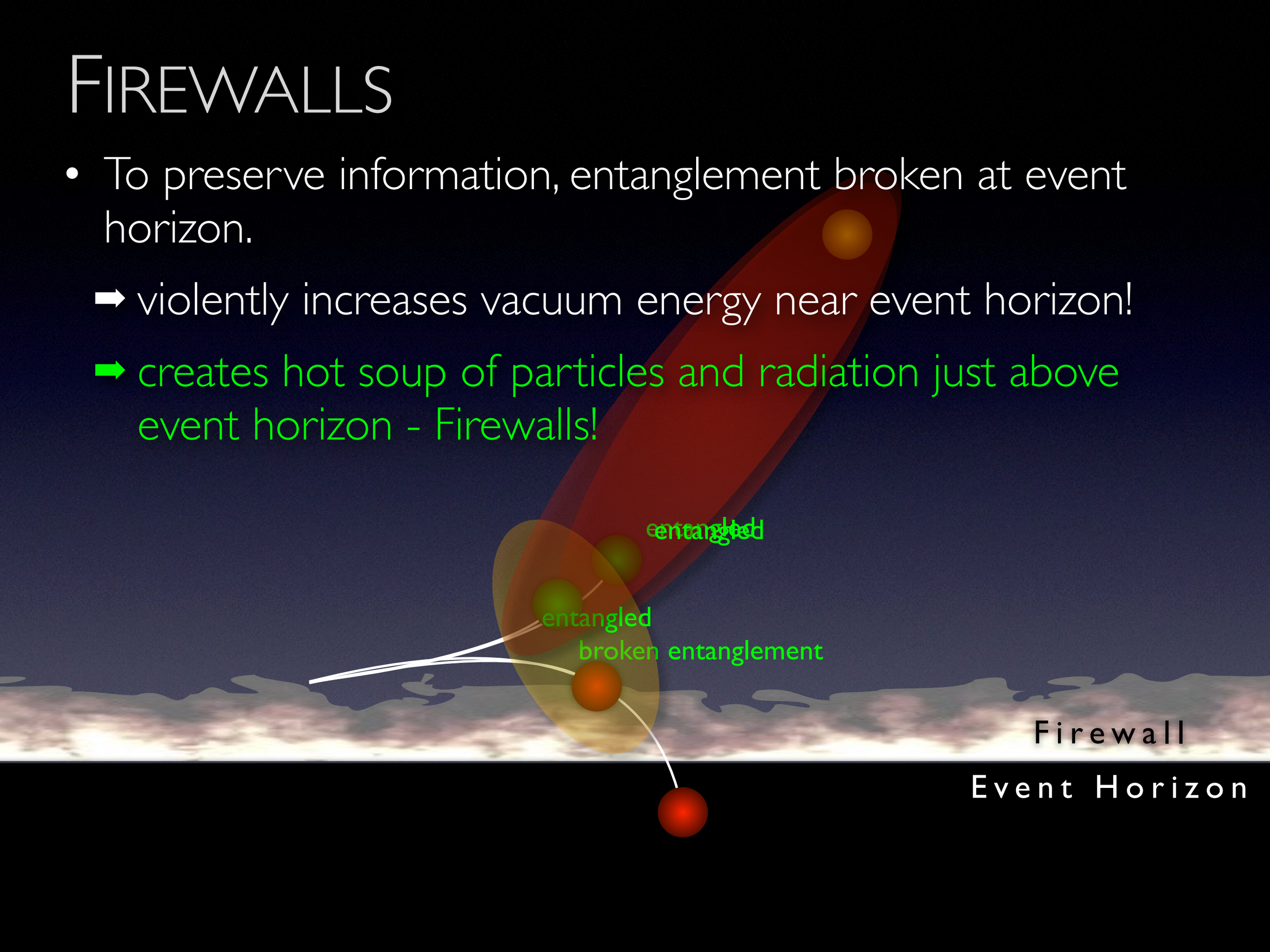
- A. Almheiri, D. Marolf, J. Polchinski and J. Sully, (AMPS) 2012 (same paper)

FIREWALLS

- To preserve information, entanglement broken at event horizon.

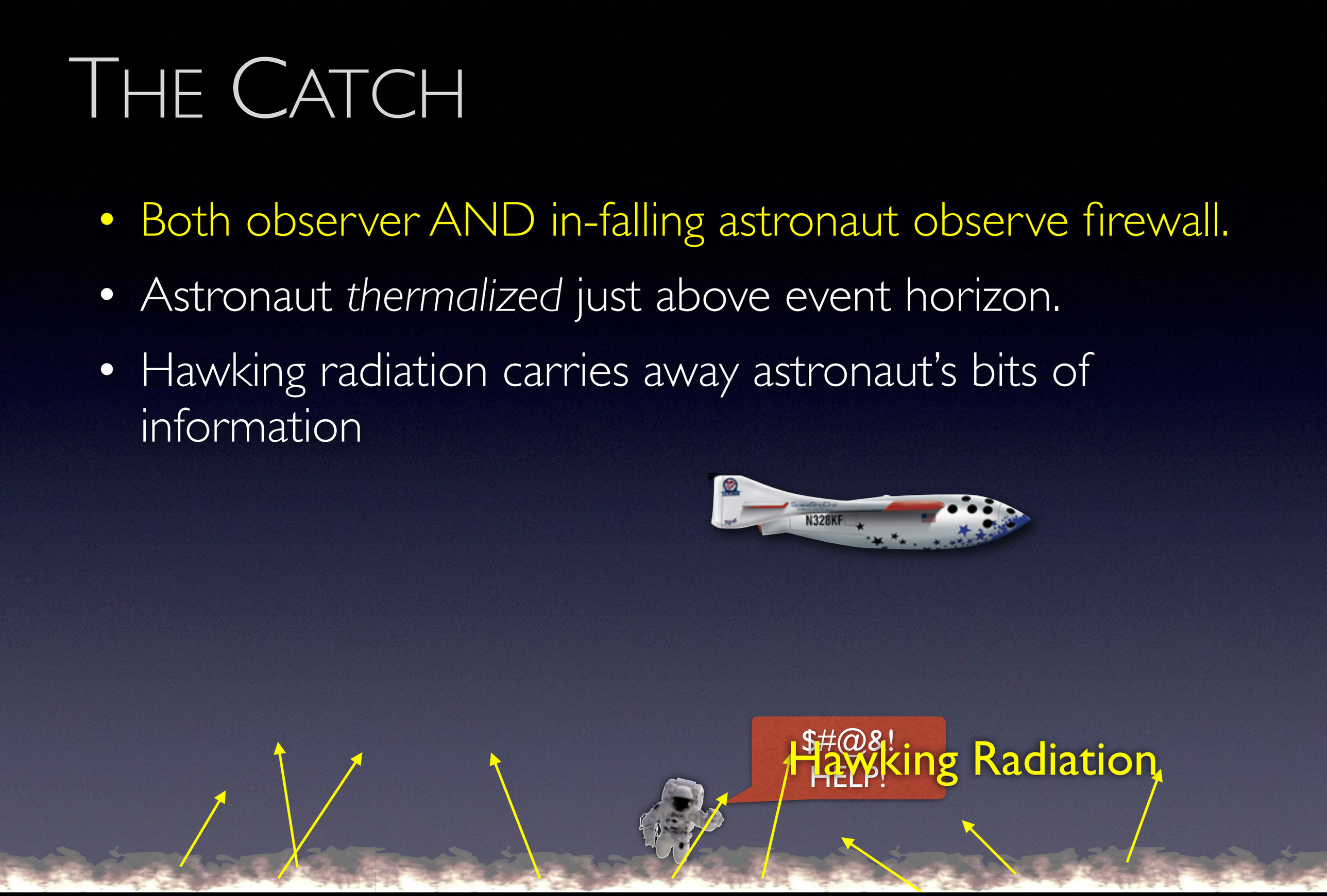
➡ violently increases vacuum energy near event horizon!

➡ creates hot soup of particles and radiation just above event horizon - Firewalls!



The Catch

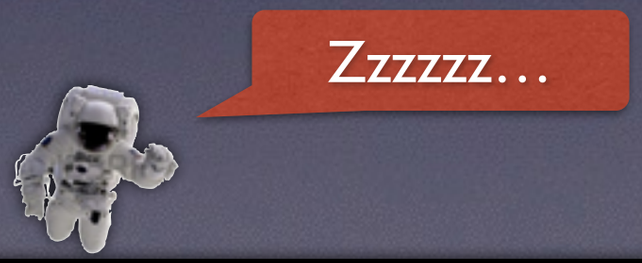
- Both observer AND in-falling astronaut observe firewall.
- Astronaut *thermalized* just above event horizon.
- Hawking radiation carries away astronaut's bits of information



A Problem

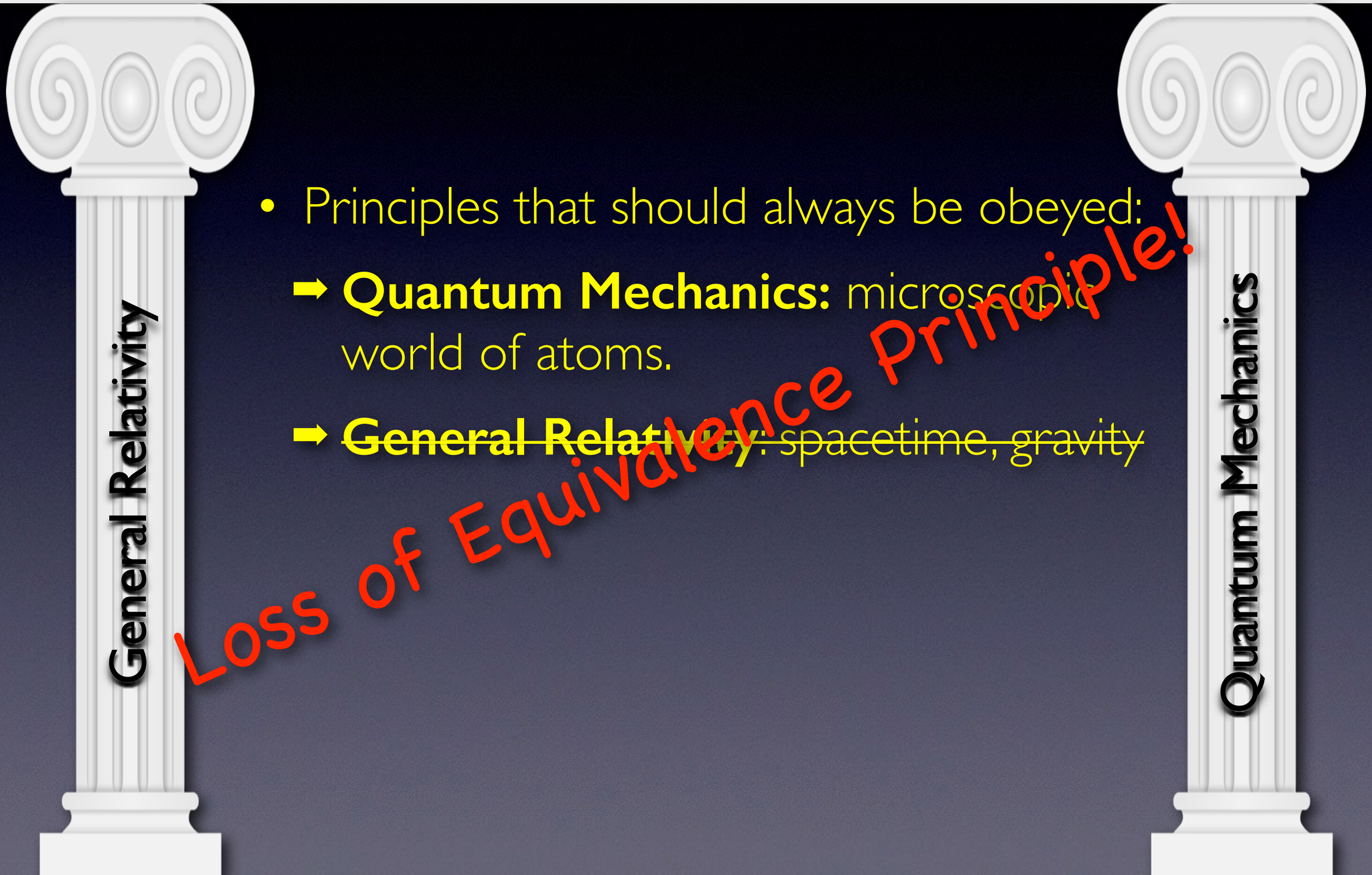
Problem With Firewalls

- According to Equivalence Principle, astronaut should see "no drama" (i.e. no fire)!
- Astronaut sees no cause for firewall any more than he would in empty space!



Event Horizon

Pillars of Modern Physics



Wormholes

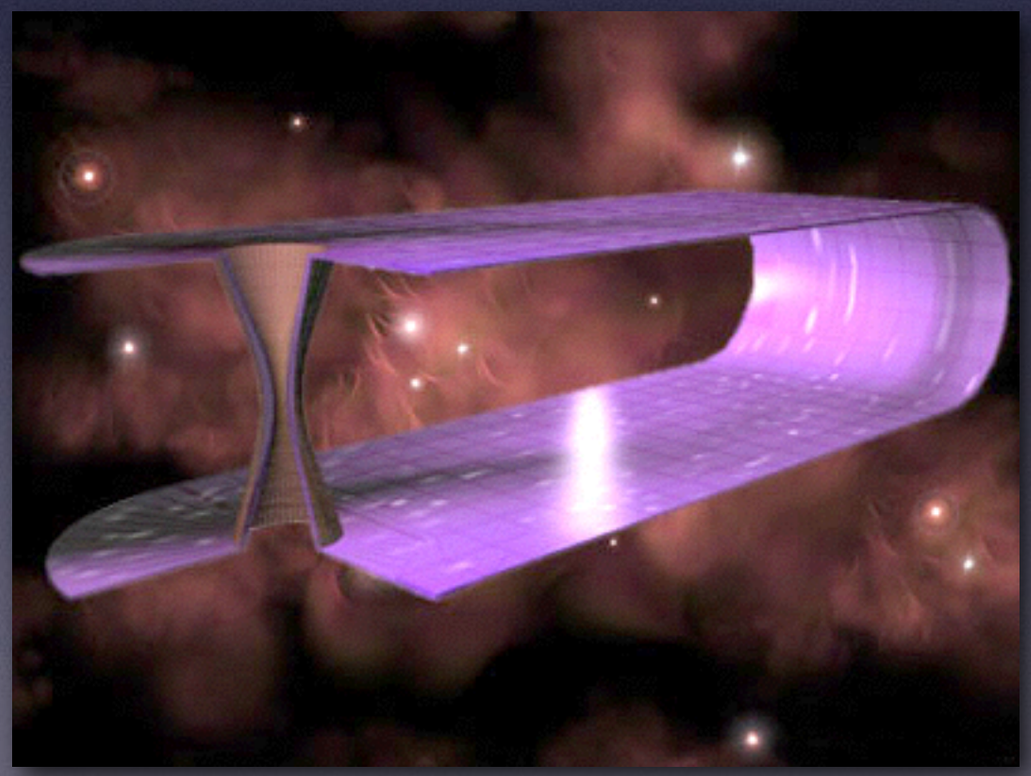
- Juan Maldacena, Leonard Susskind, 2013 - *Cool horizons for entangled black holes*

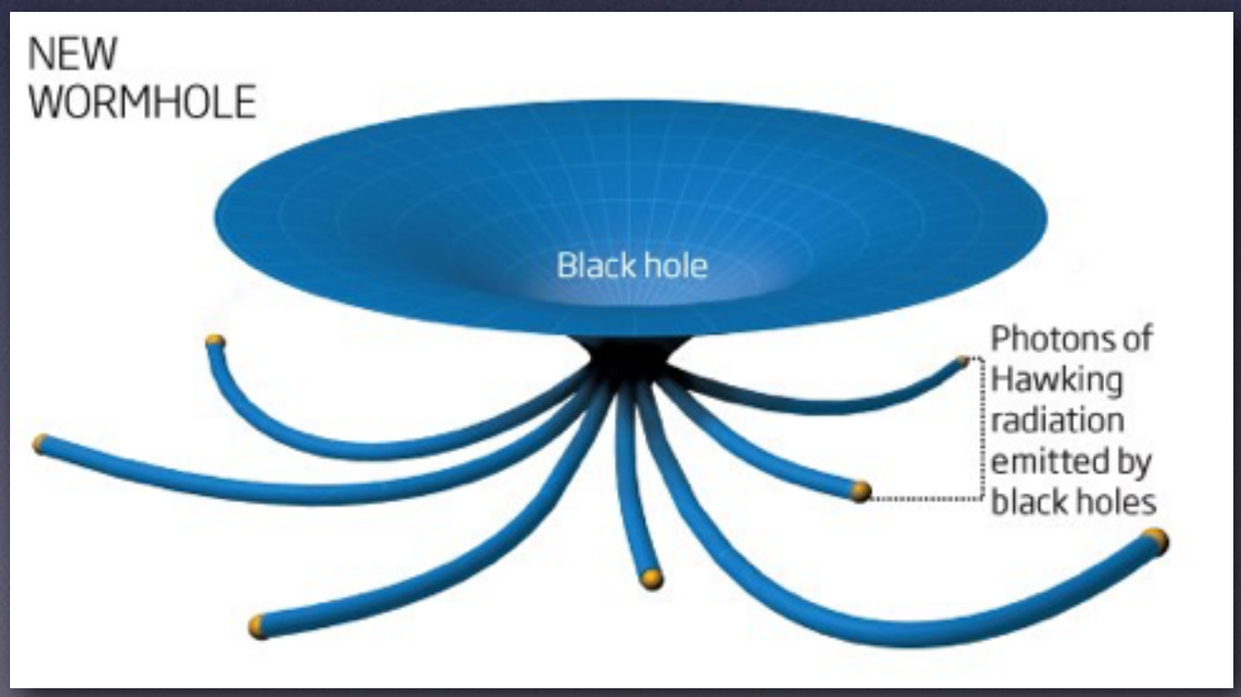
Microscopic Wormholes

- Mathematics of wormholes seem to be mathematically similar to quantum entanglement!
- In-falling particles and Hawking radiation are connected by wormholes through additional dimension of space.

➡ Side-steps entanglement monogamy problem.

➡ Preserves information and equivalence principle.





No Black Hole Interiors?

- Stephen Hawking, 2014 - *Information Preservation and Weather Forecasting for Black Holes (non-technical)*

Event Horizons as End of Spacetime

- Space & time may NOT be fundamental entity.
  - ➡ Emergent property of quantum entanglement.
- Entanglement mechanism, and thus spacetime, may stop before event horizon.
  - ➡ no "inside" of the event horizon
  - ➡ no Firewall!
  - ➡ no information loss

The Upshot

What This Research Tells Us

- Finding apparent inconsistencies with existing laws.
  - ➡ Is information NOT conserved?
  - ➡ Does quantum mechanics work differently than we thought?
  - ➡ Is the Equivalence Principle of General Relativity wrong?
  - ➡ Is faster-than-light information transfer possible?
- Confusion can be GOOD!
  - ➡ Generally believed that resolution likely to profoundly affect our understanding of fundamental physics.
  - ➡ Presents opportunity for fresh sharp minds to make major contributions.

Suggested Sources

- *Black Hole Wars* by Leonard Susskind
- *Entanglement* by Amir D. Aczel
- Black holes, quantum information, and the foundations of physics, Steven B. Giddings, Physics Today, 2013
- iTunes/Youtube interviews and talks
  - ➡ *Falling into a Black Hole* (Google hangout discussion with Maldacena, Susskind, Bousso, Polchinski)
  - ➡ Susskind popular talk on Holographic Principle.
  - ➡ Fuzz or Fire Conference at KITP 8/13
- Papers at arxiv.org