

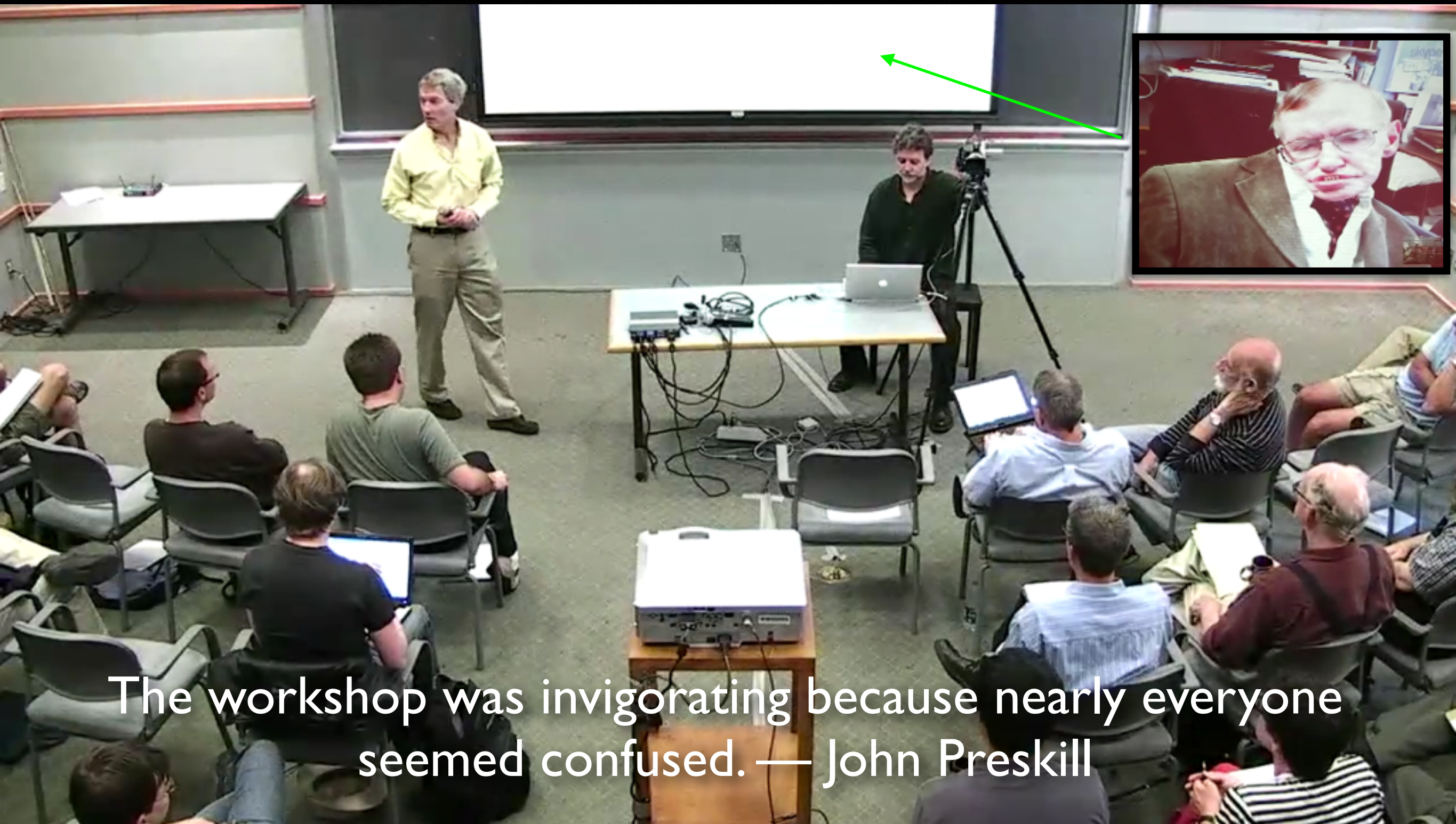
The Black Hole Conundrum

Holograms? Firewalls? Wormholes?

William Koch

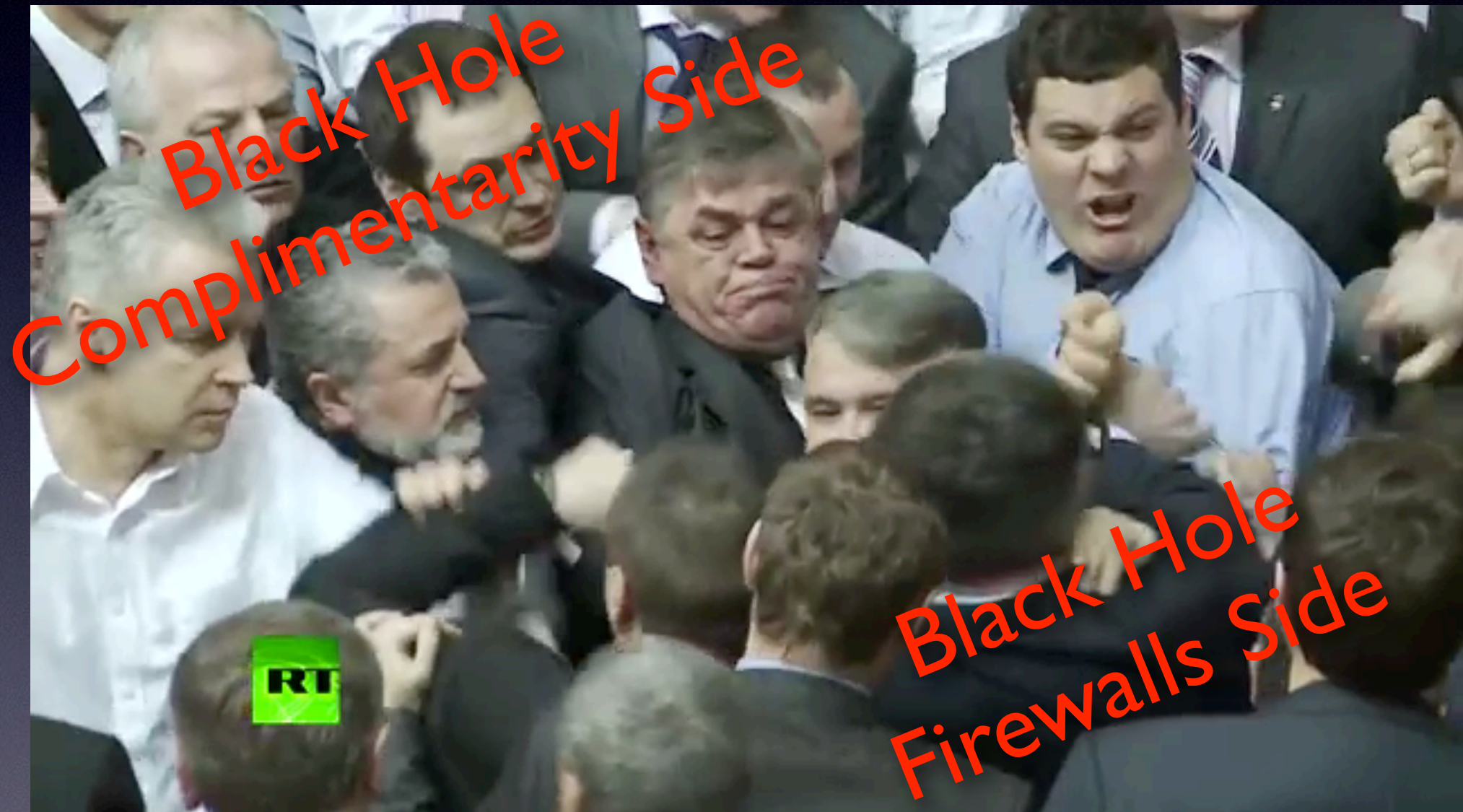
JCCC Astronomy Professor

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

General Relativity

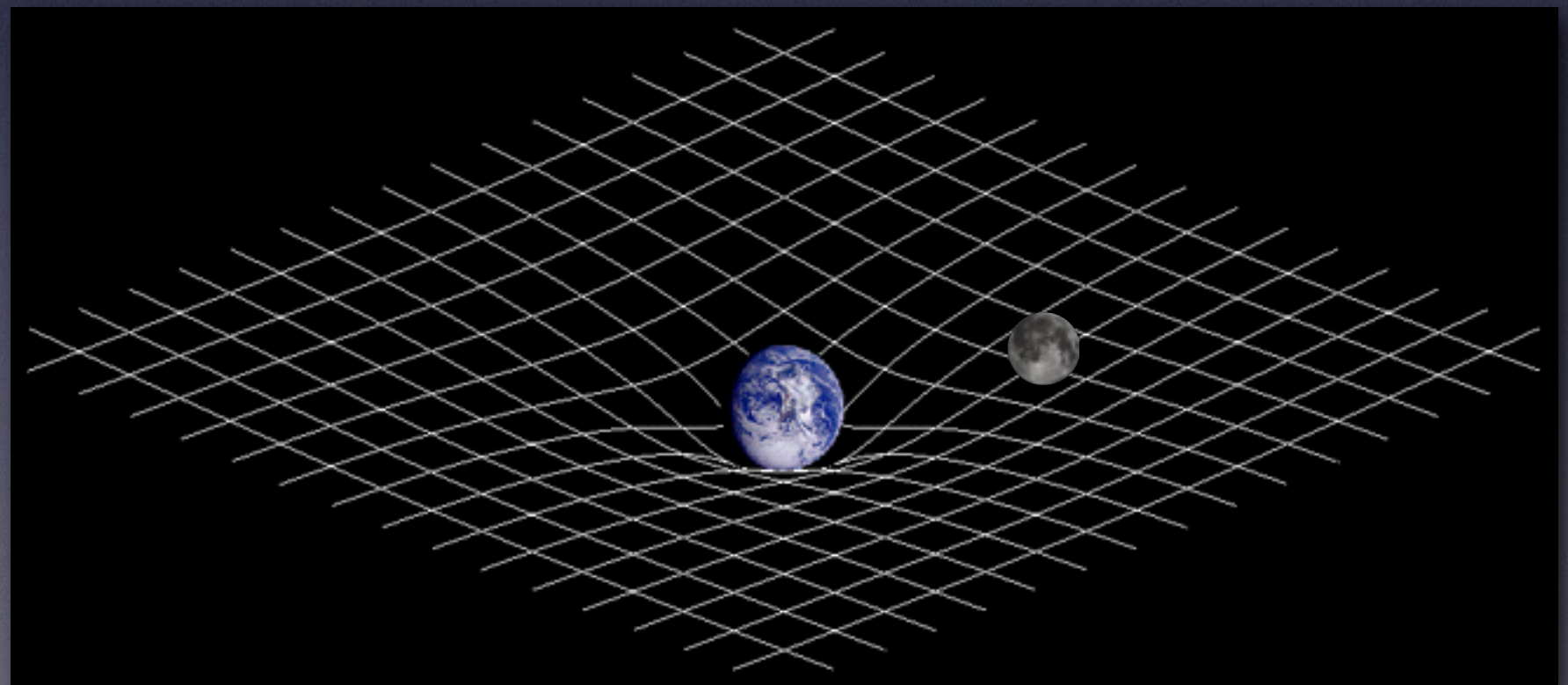
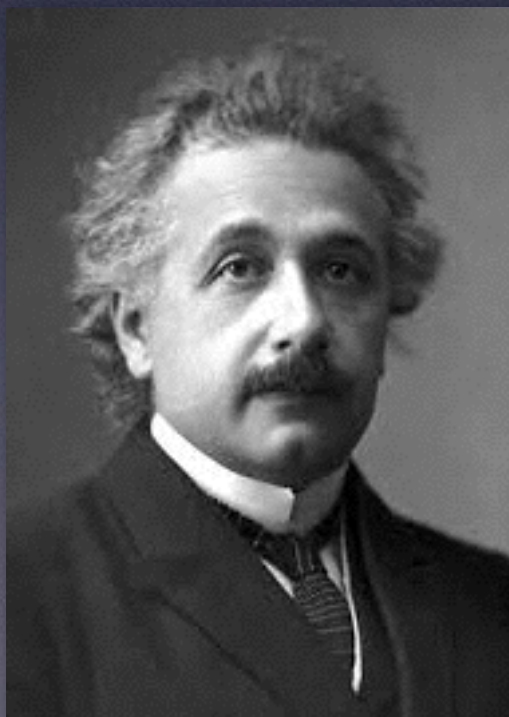
- Principles that should always be obeyed:
 - ➔ **Quantum Mechanics:** microscopic world of atoms.
 - ➔ **General Relativity:** spacetime, gravity

Quantum Mechanics

SPECIAL AND GENERAL RELATIVITY

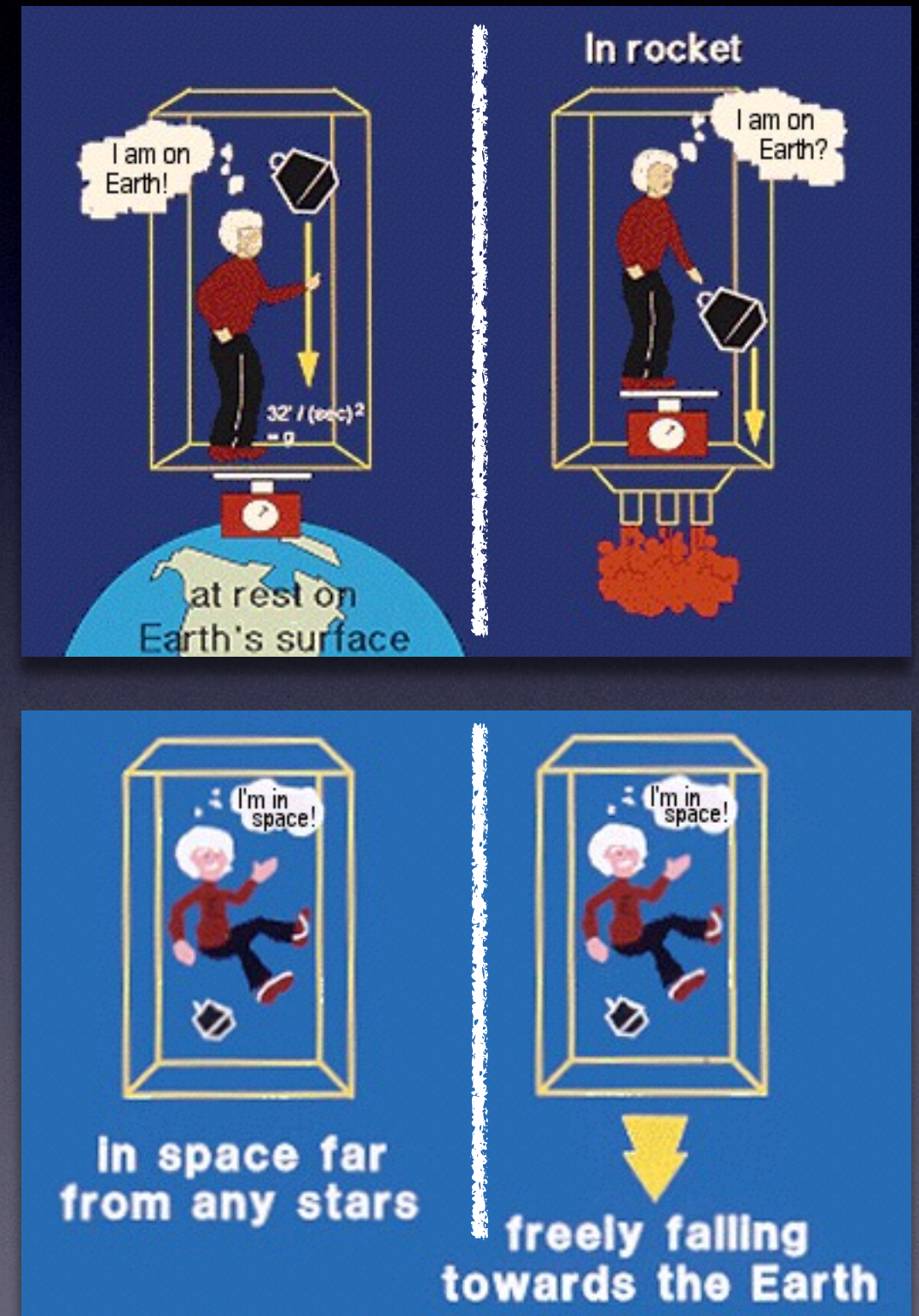
THEORIES OF RELATIVITY

- 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

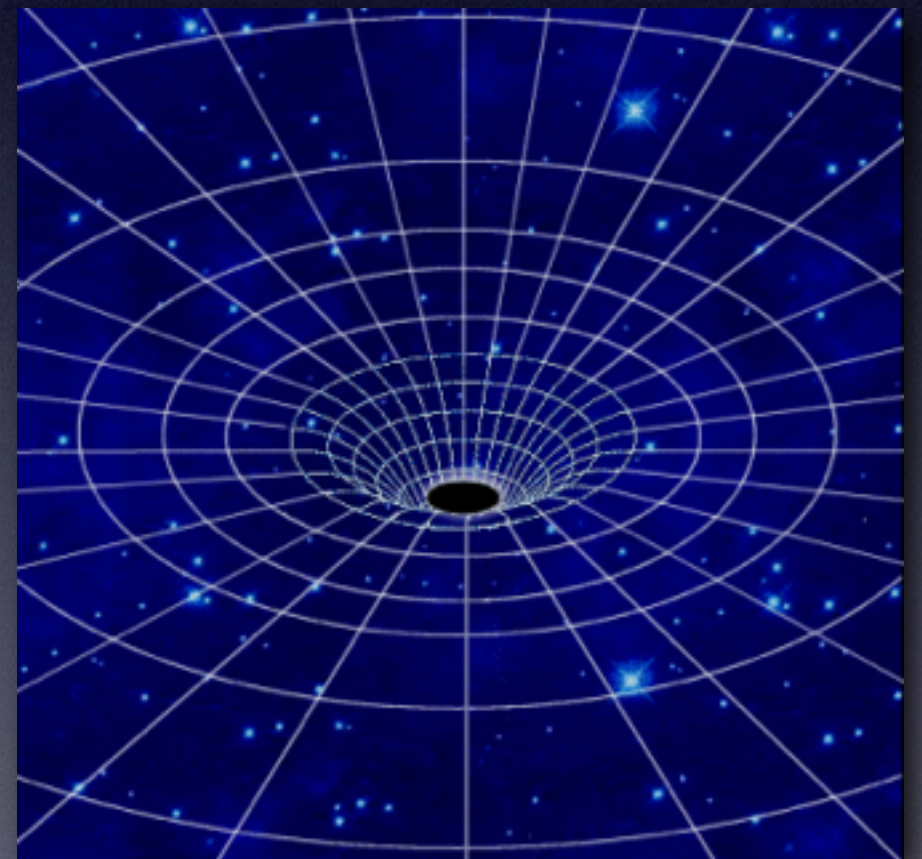
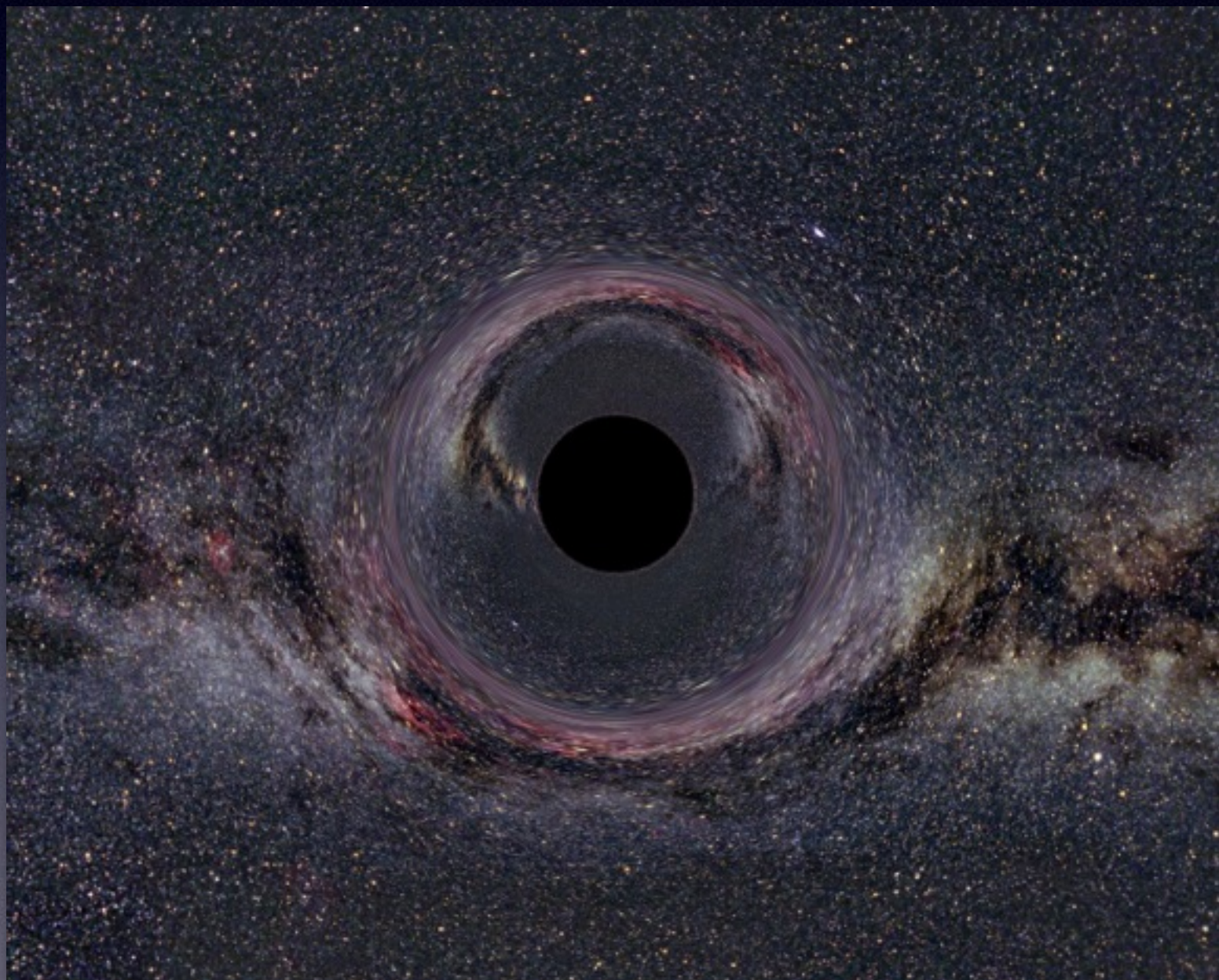


CLASSICAL BLACK HOLES

(THE KIND YOUR GRANDMOTHER TOLD YOU
ABOUT)

BLACK HOLES

- Created by complete gravitational collapse of object.



ANATOMY OF A NON-ROTATING BLACK HOLE

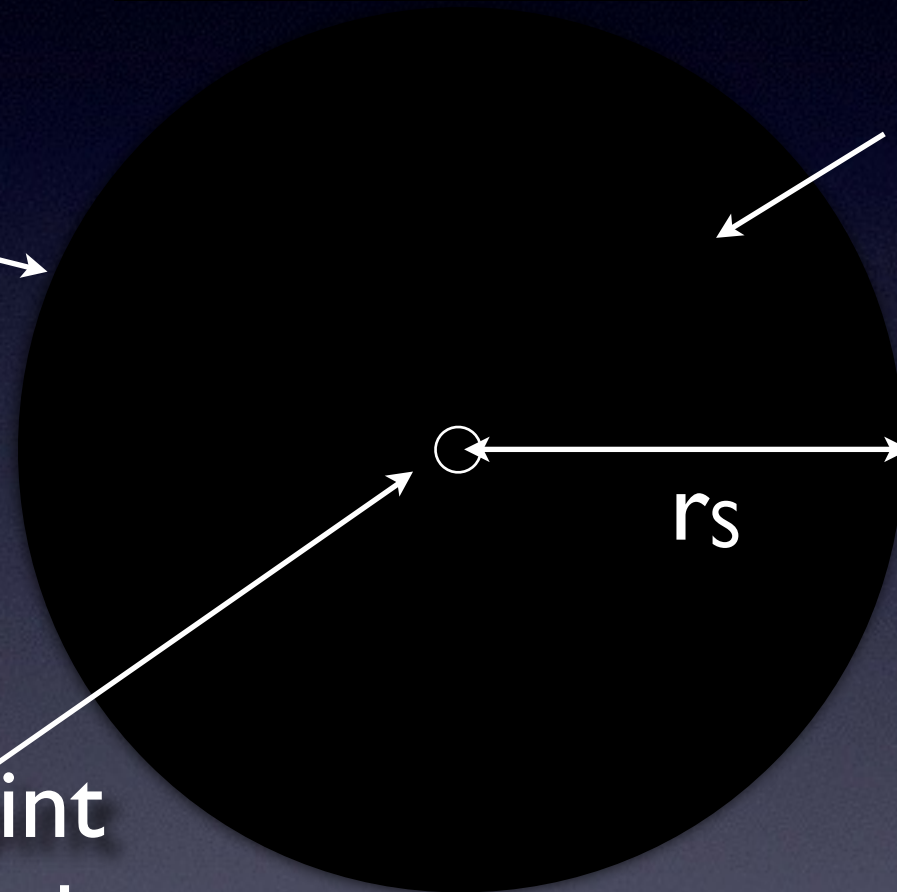


Event Horizon is
a one-way door!

$$v_{\text{esc}} = c$$

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

Singularity is a point
of infinitely curved
spacetime

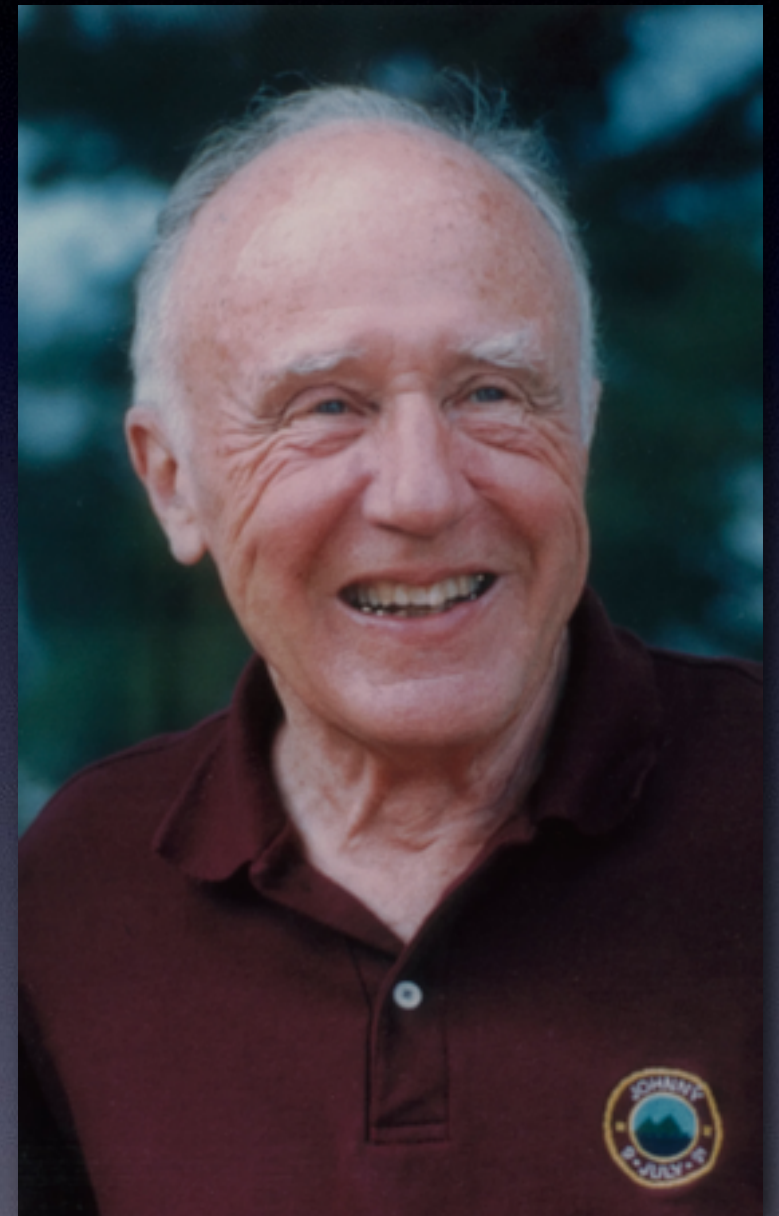


INFORMATION

"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

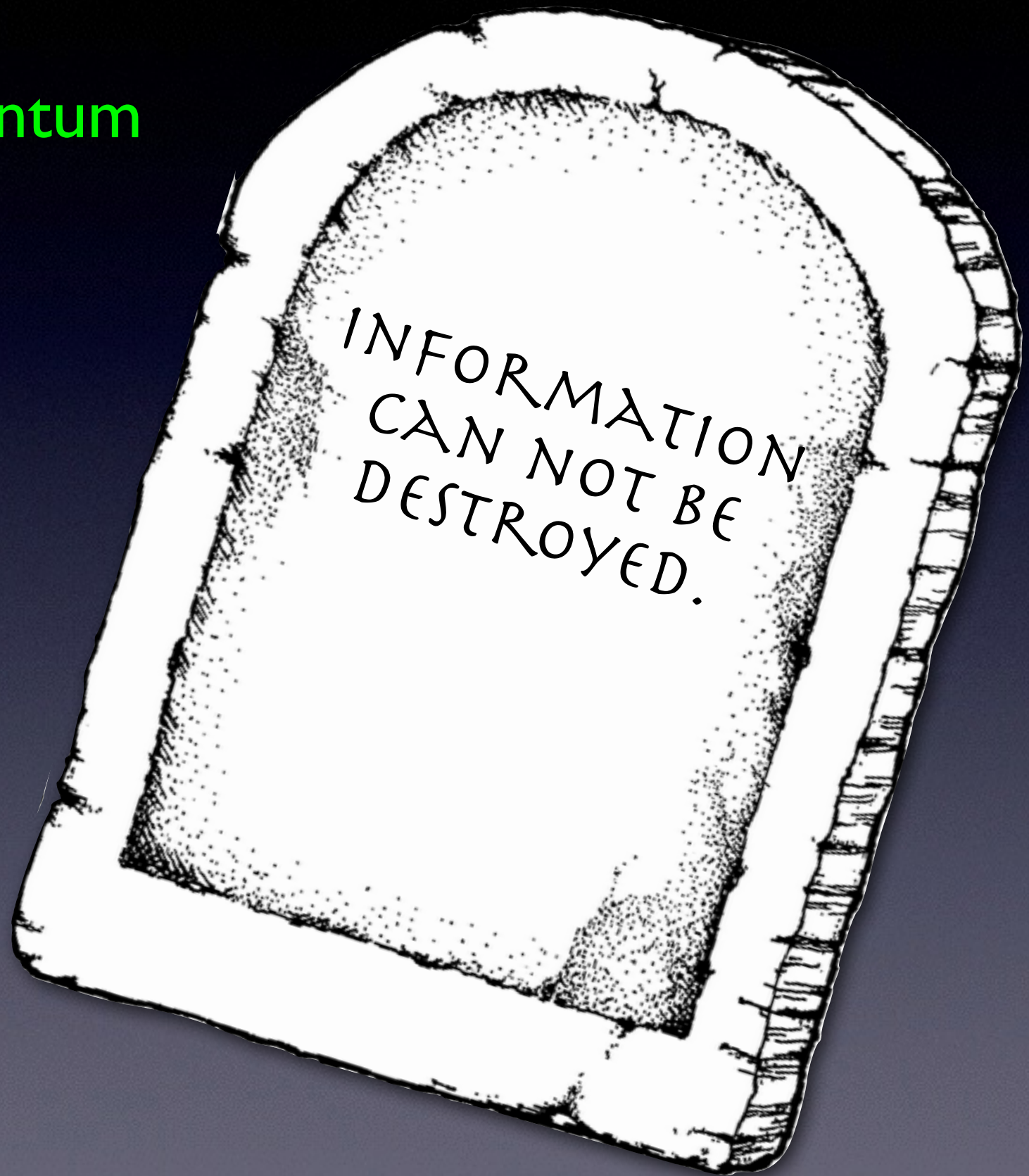
INFORMATION

- Objects are huge globs of bits of information.
 - ➡ generally hidden due to huge number and tiny size of particles.

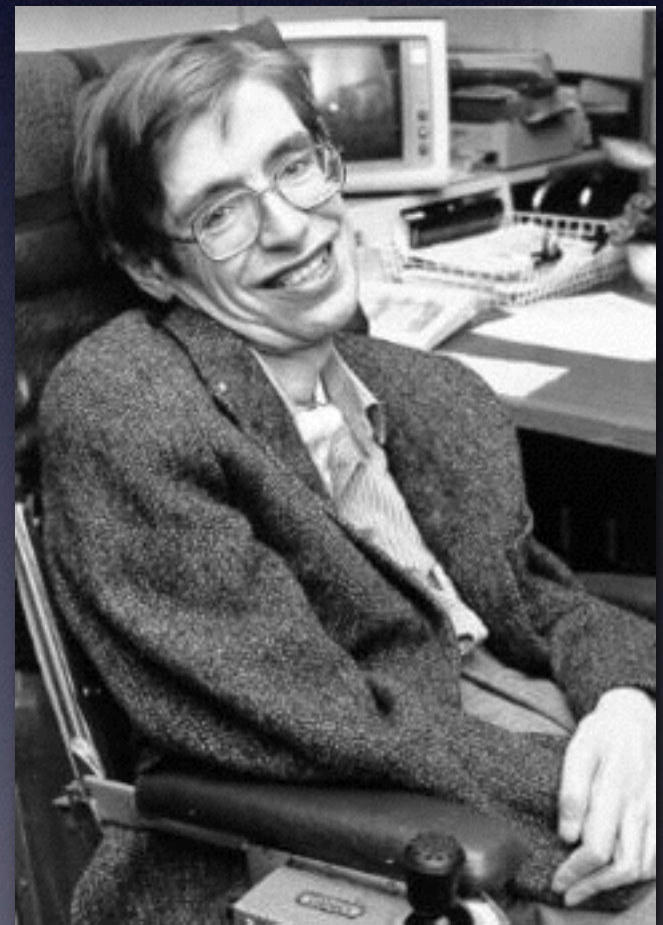


CONSERVATION OF INFORMATION

- 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

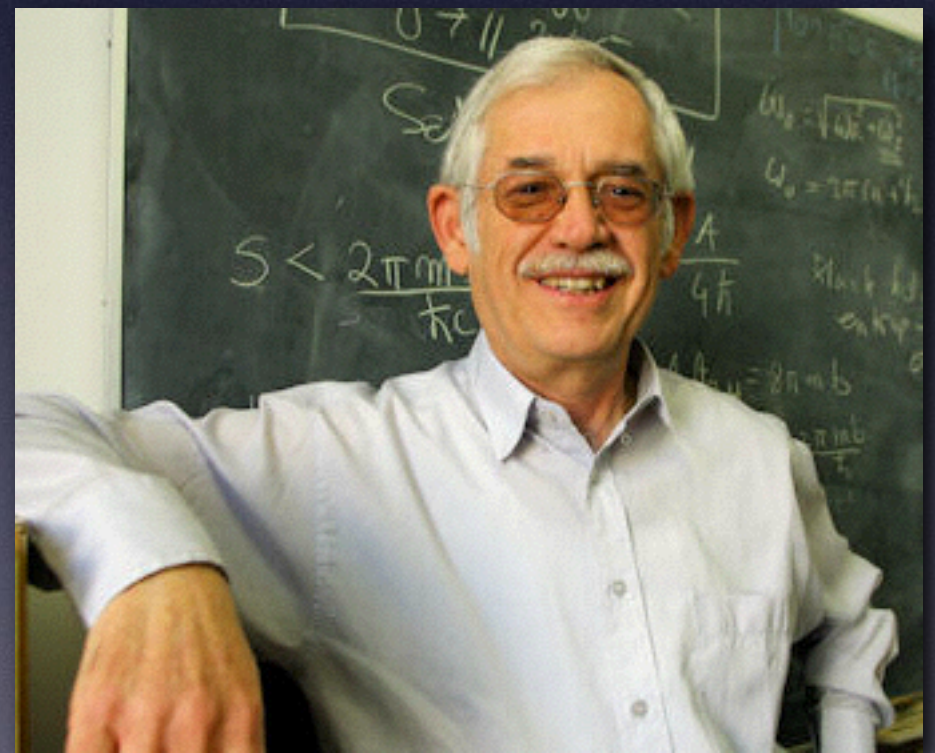
INFORMATION PARADOX

- 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

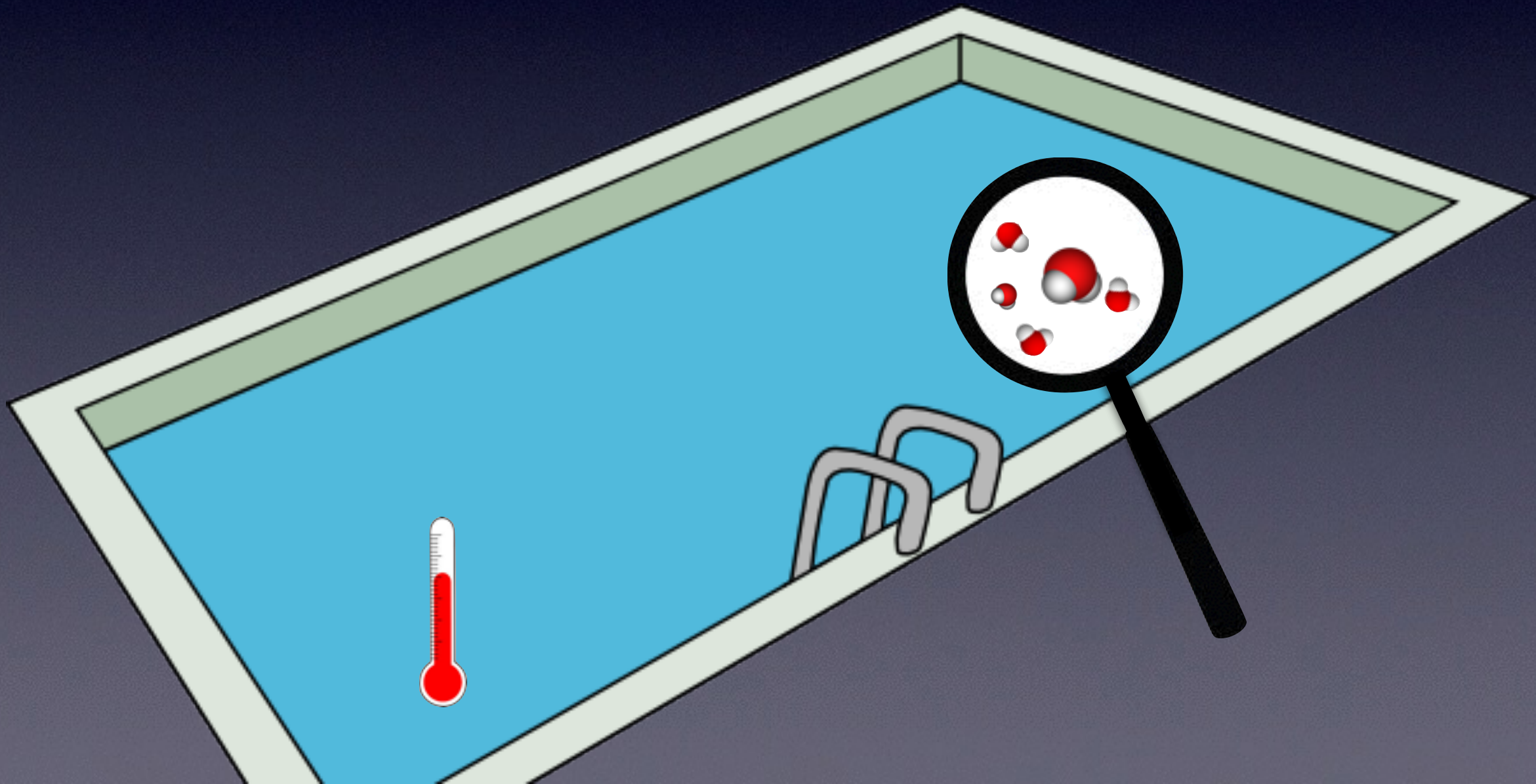
ENTROPY EXAMPLE

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



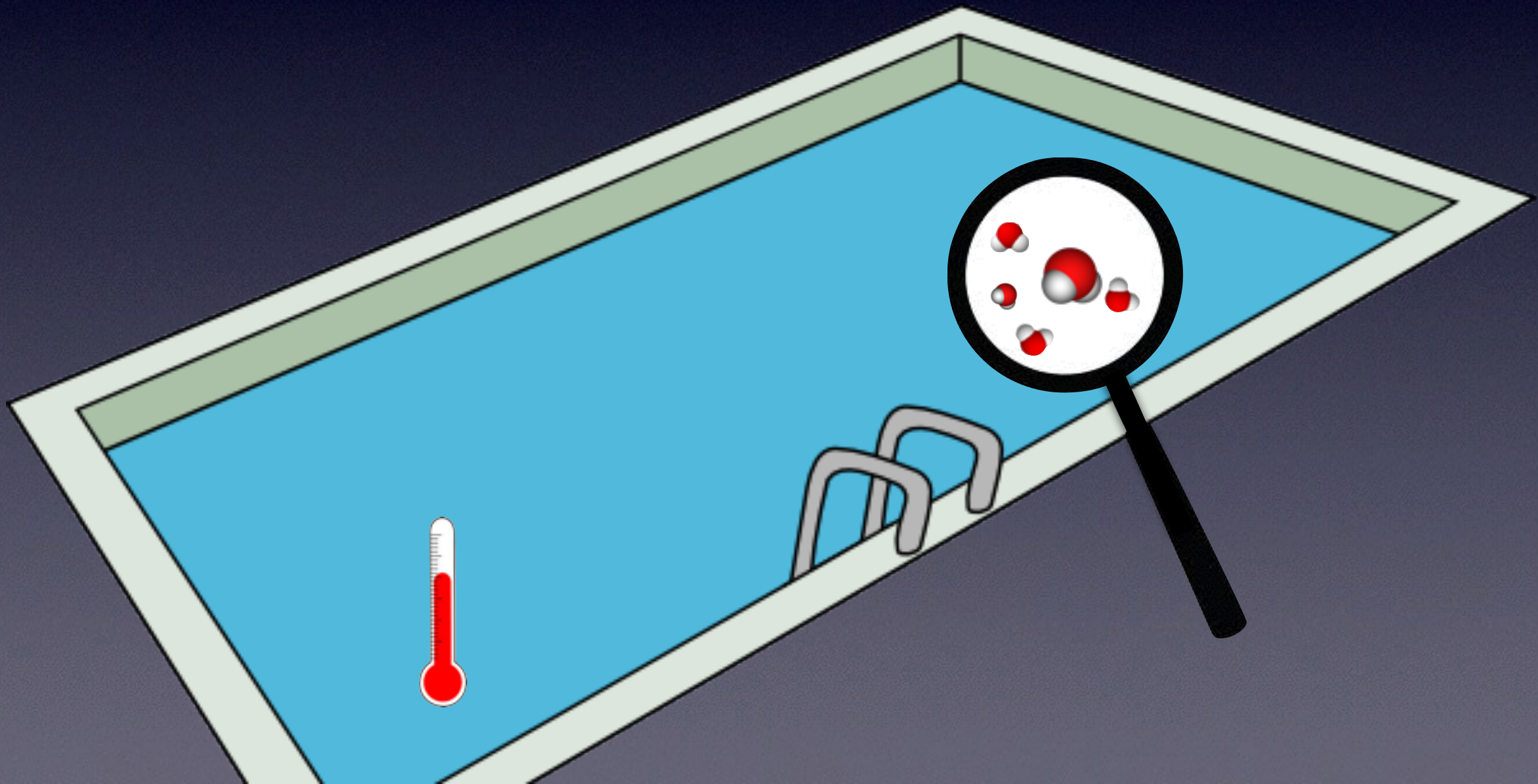
ENTROPY

- 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 many 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

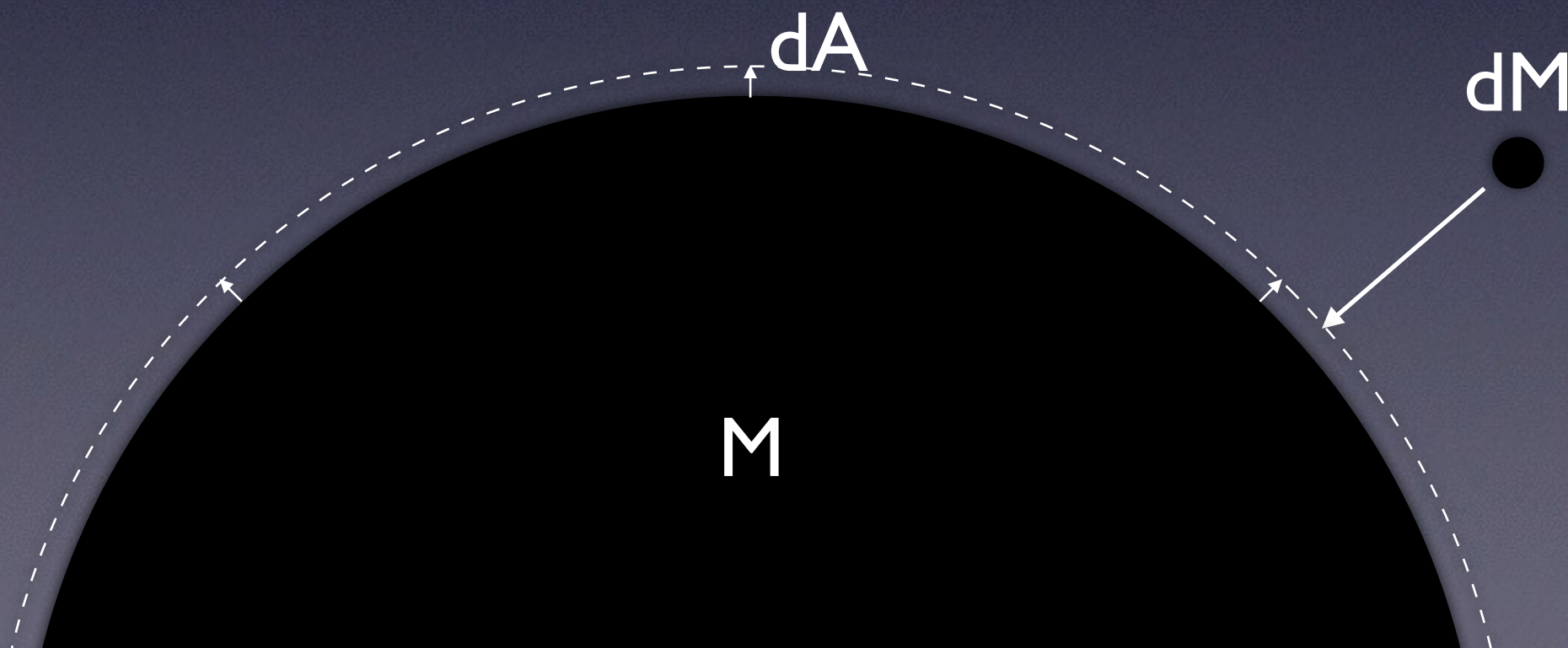
$$dE = TdS - W$$

- 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

$$dE = TdS - W$$

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

- 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

General Relativity

- Principles that should always be obeyed:
 - ➔ ~~Quantum Mechanics~~: microscopic world of atoms.
 - ➔ **General Relativity**: spacetime, gravity

Quantum Mechanics

BLACK HOLE COMPLIMENTARITY

Leonard Susskind, L  rus Thorlacius, and John Uglum, 1993 -
The stretched horizon and black hole complementarity

Juan Maldacena, 1997 - *AdS/CFT Correspondance*



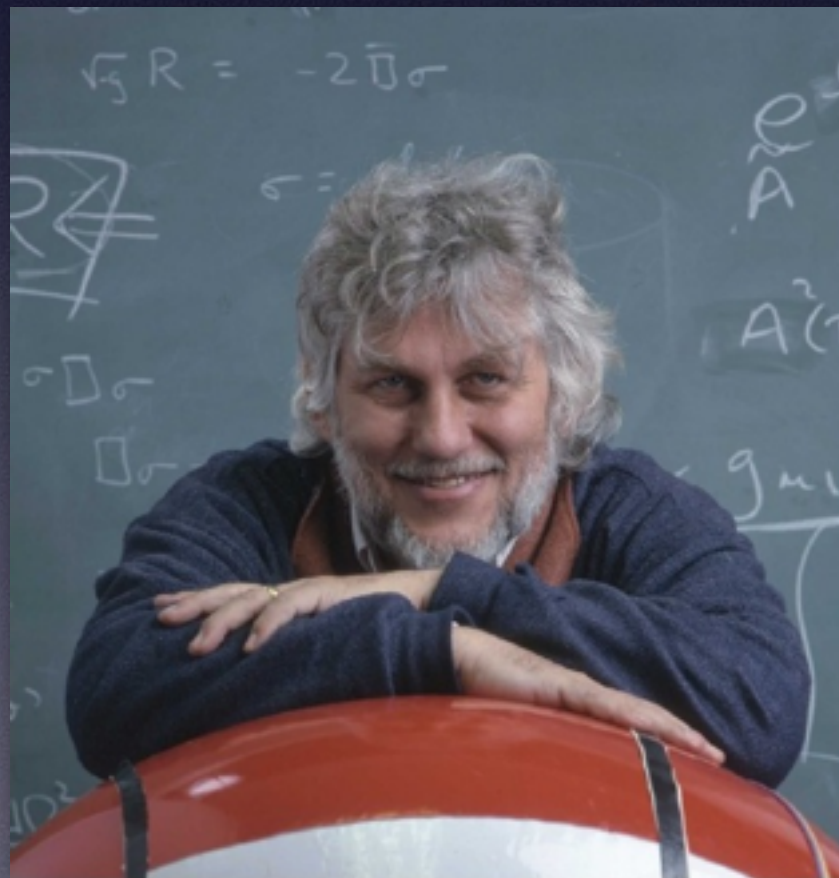
Leonard
Susskind



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”

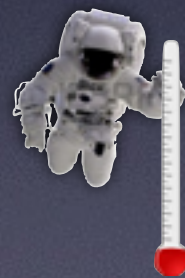
- Hovering = Acceleration



Event Horizon

NO HOT “STRETCHED HORIZON”

- Free-fall = Empty space



Event Horizon

WHAT OBSERVER SEES

- Hot stretched horizon | 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!

Hawking Radiation

Stretched Horizon
Event Horizon



WHAT IN-FALLING ASTRONAUT SEES



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

Event Horizon



Zzzzzz...

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.

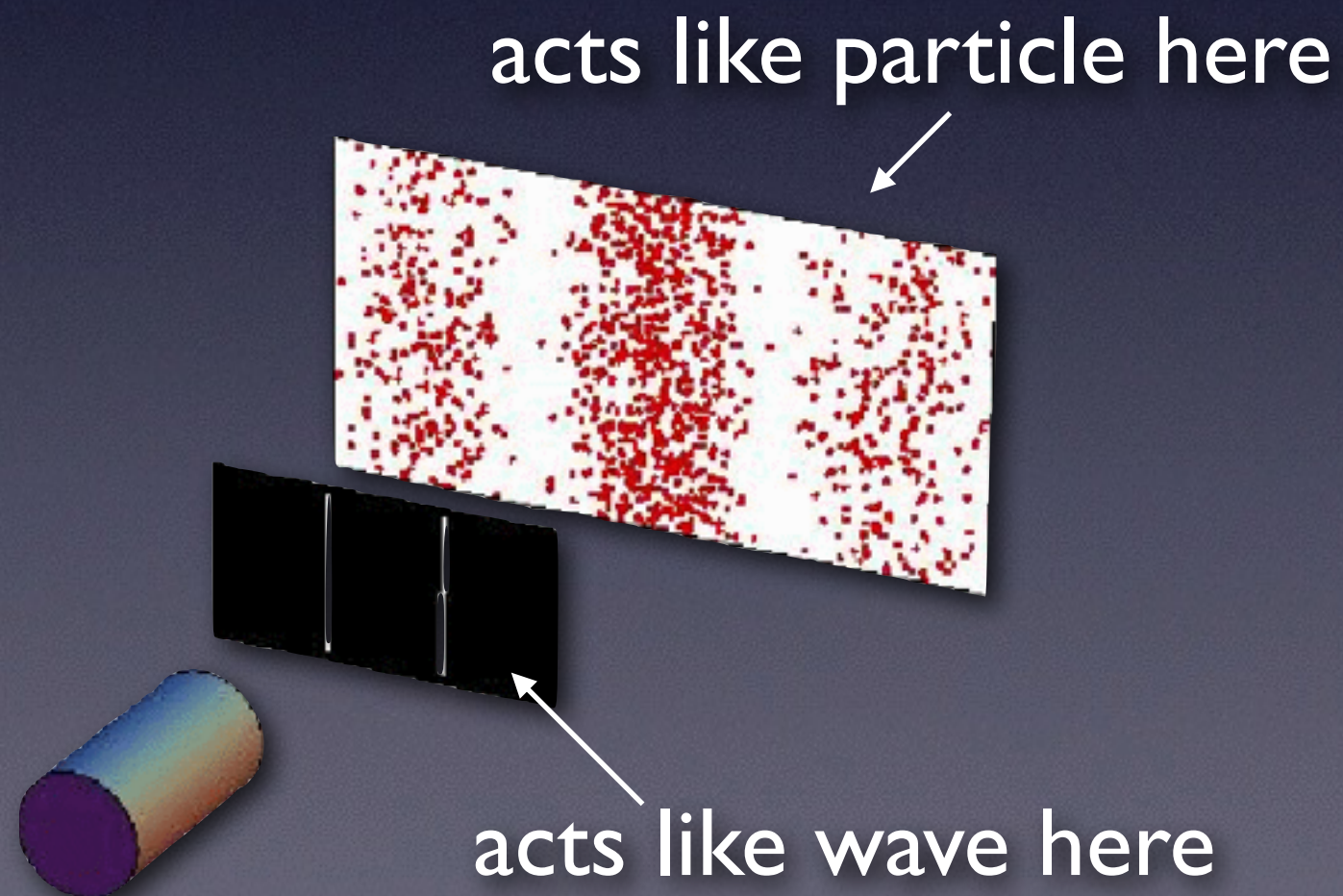
Event Horizon



Hello?...
HELLO?!!

COMPLIMENTARITY

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

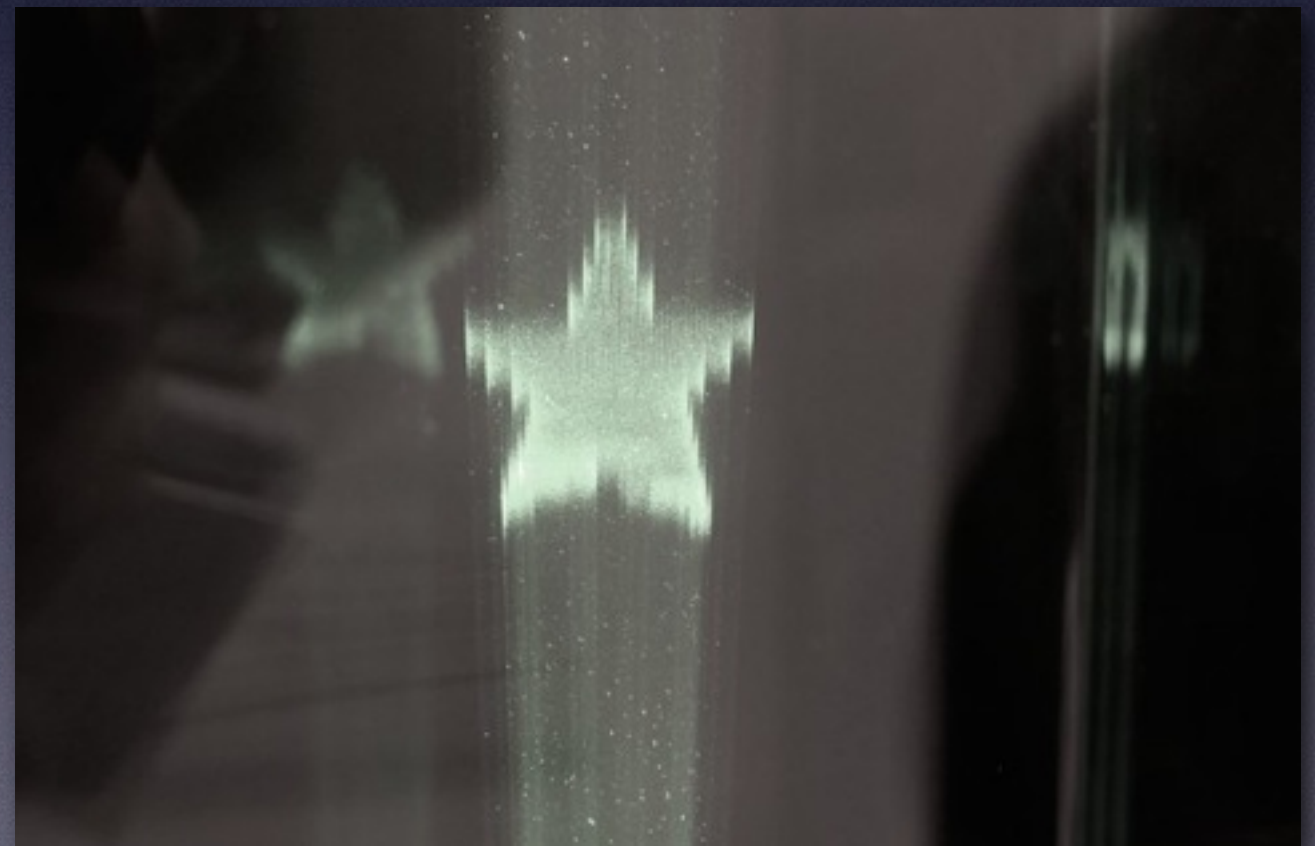
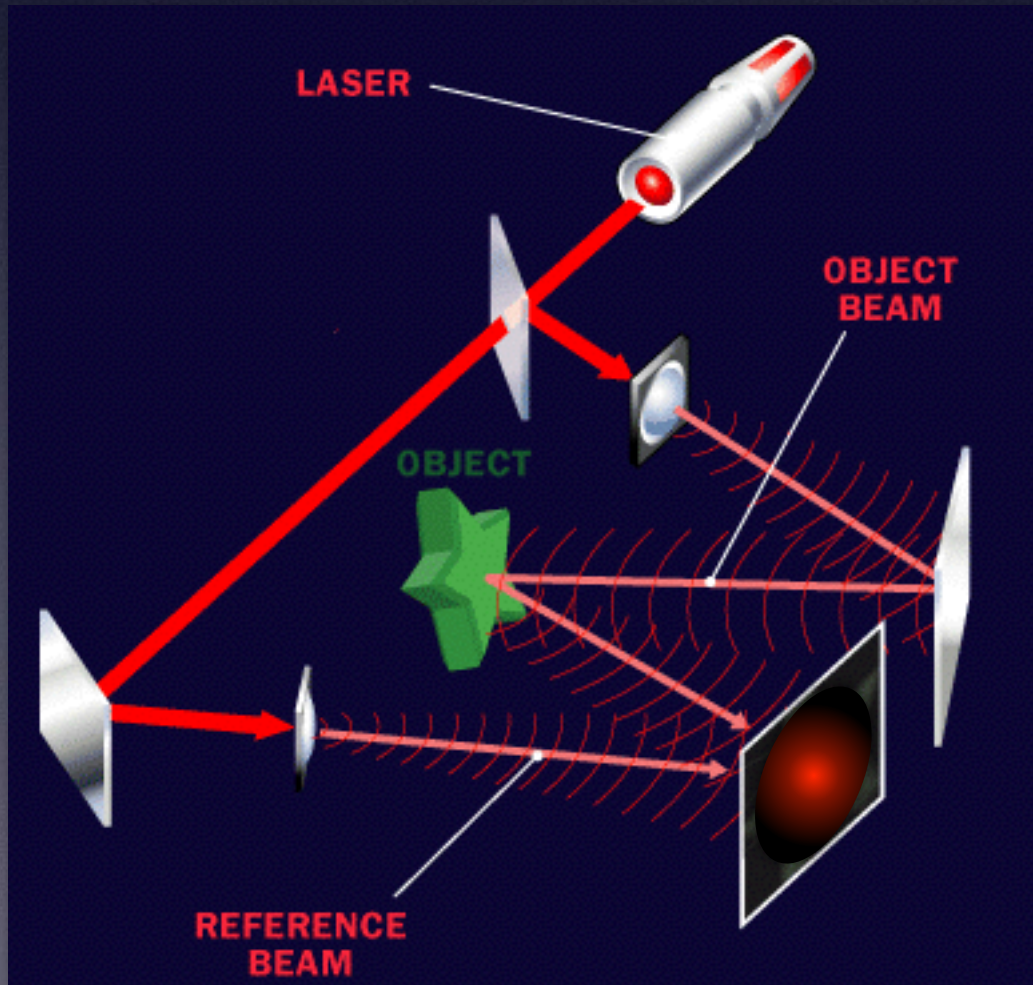


HOLOGRAPHIC PRINCIPLE

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

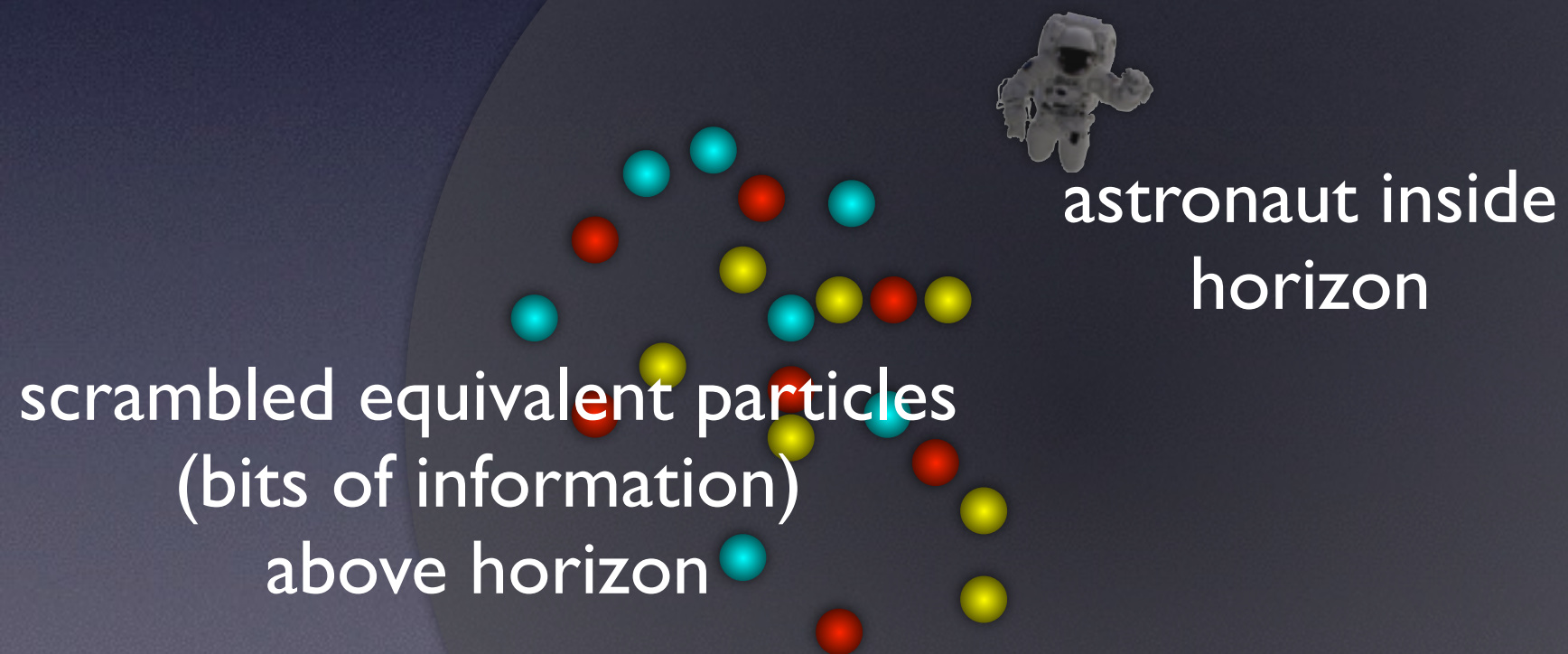
HOLOGRAMS

- 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.



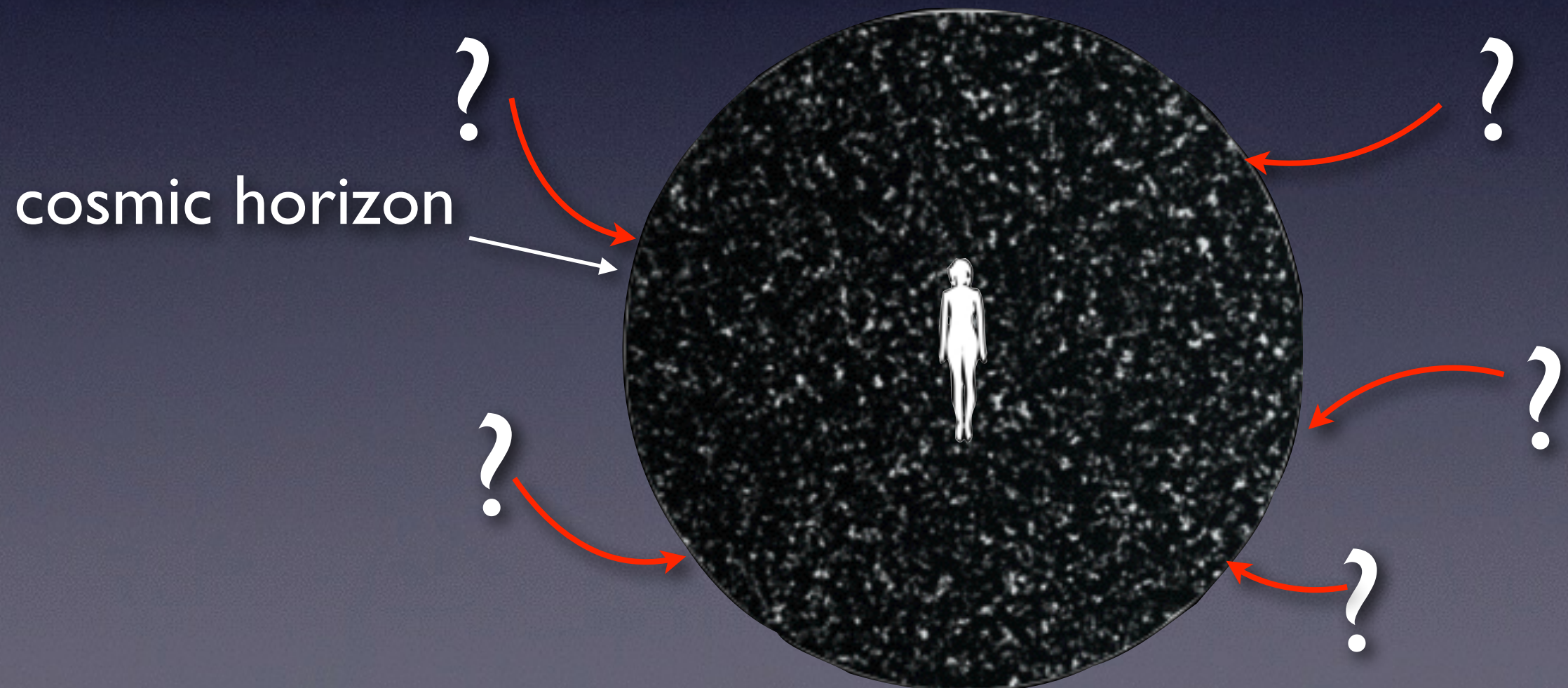
HOLOGRAPHIC EVENT HORIZON

- 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?

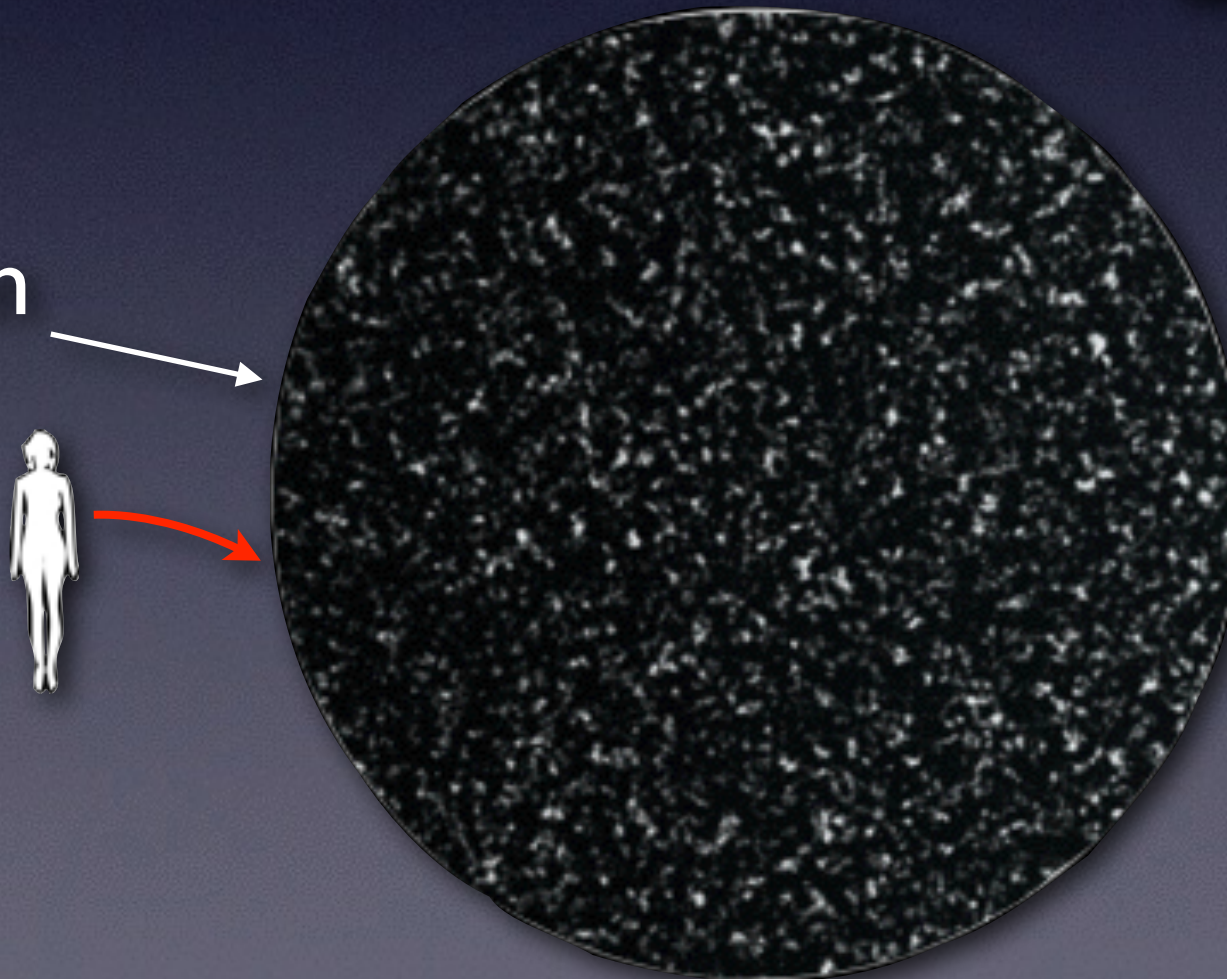


HOLOGRAPHIC UNIVERSE

- We are outside cosmological horizon of other regions of the universe.
 - ➔ Are we also encoded on a 2-d surface?
- Are we and the 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

wave function ψ for
particle X

X

$$i\hbar \frac{\partial}{\partial t} \psi = \hat{H} \psi$$

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

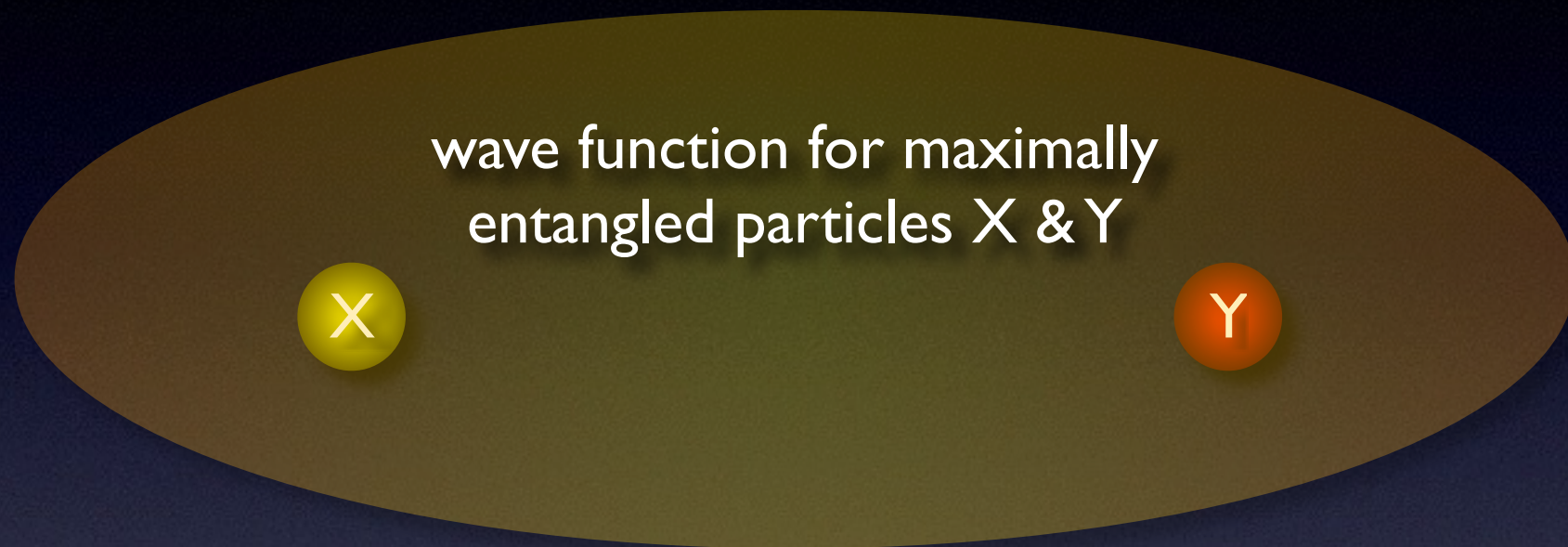
wave function for particle X & Y

X

Y

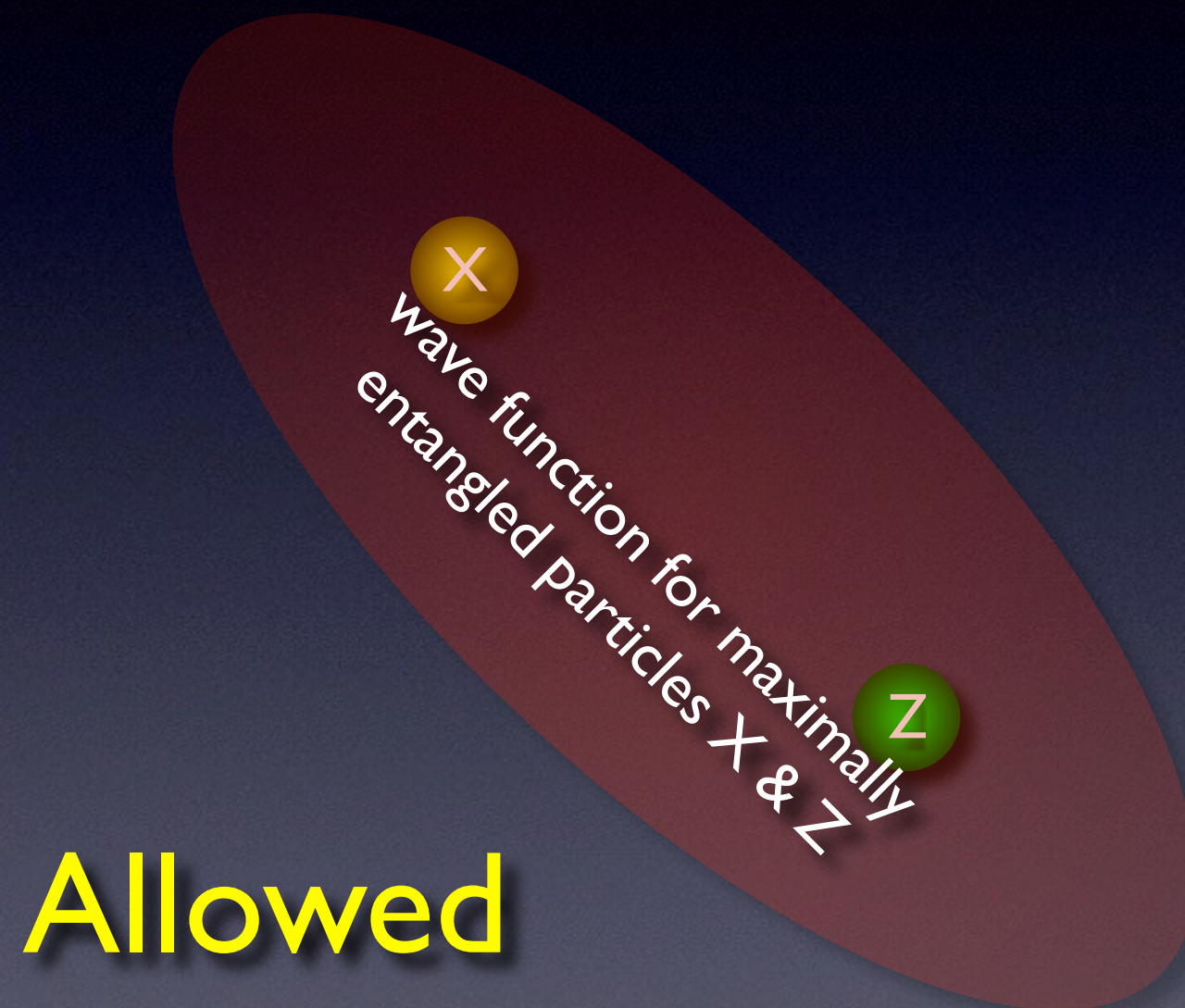
- Entangled particles described by single inseparable wave function—each particle carries information about the other.

ENTANGLEMENT MONOGAMY

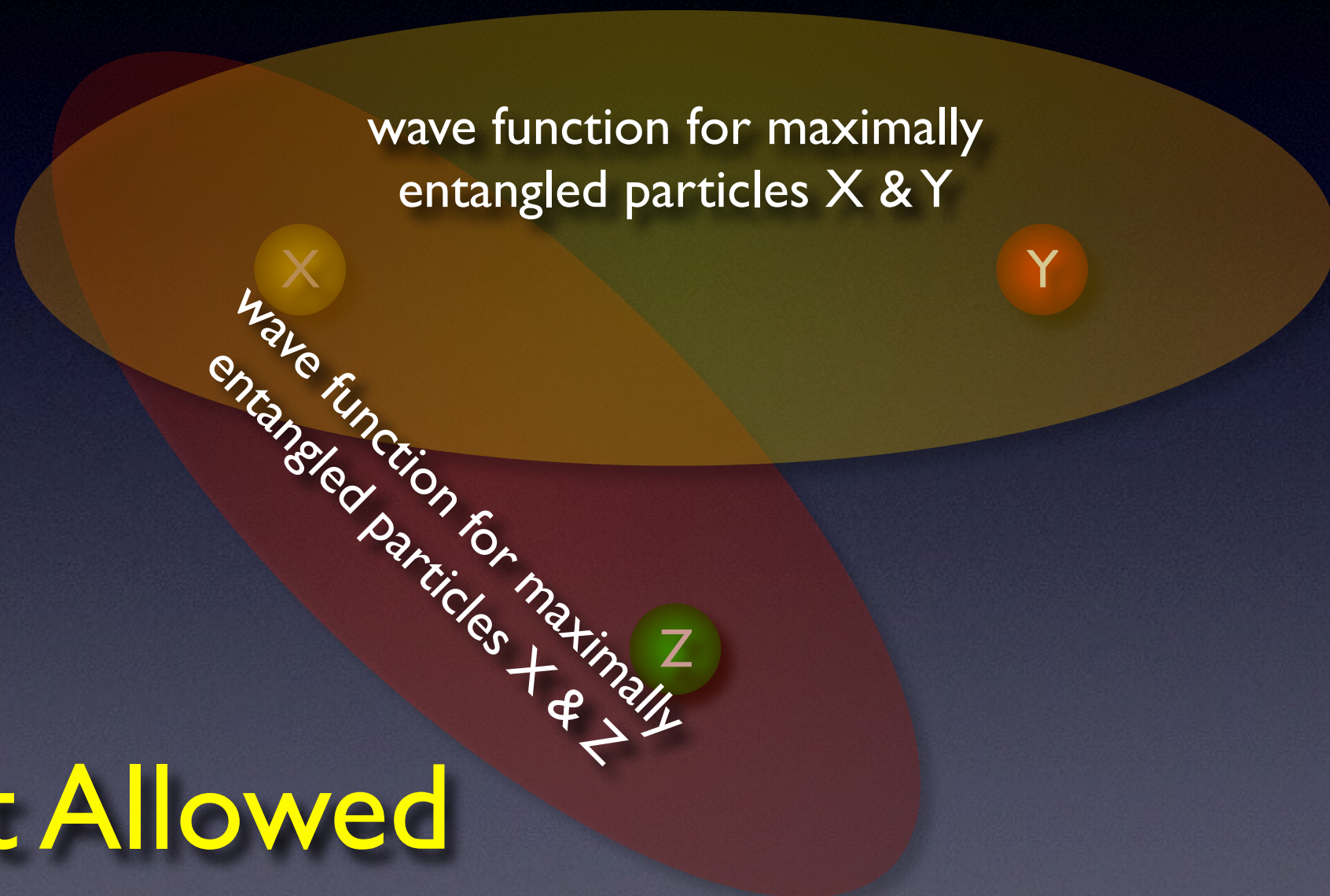


Allowed

ENTANGLEMENT MONOGAMY



ENTANGLEMENT MONOGAMY

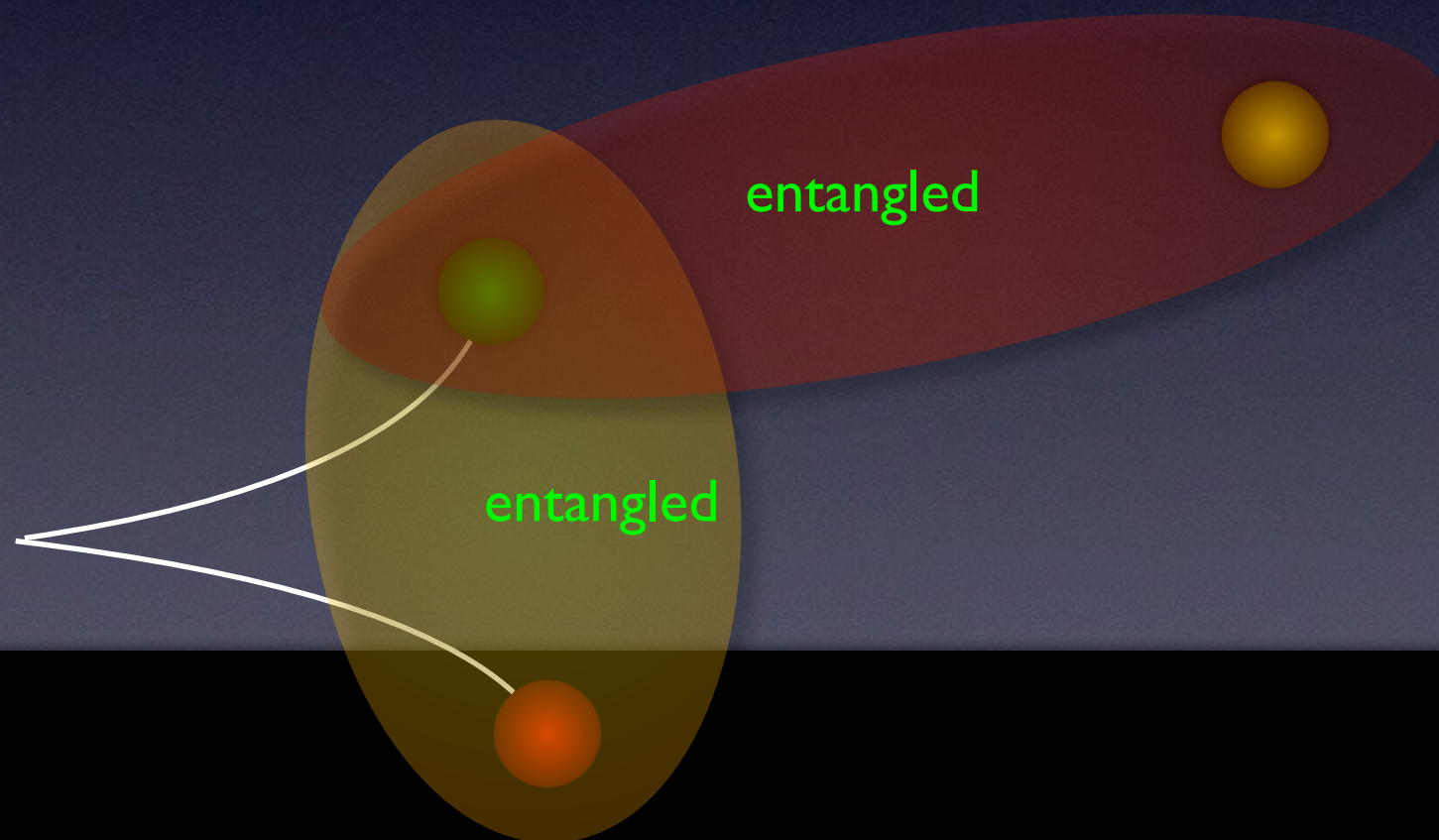


Not Allowed

- 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!



Event Horizon

PILLARS OF MODERN PHYSICS

General Relativity

- Principles that should always be obeyed:

→ ~~Quantum Mechanics~~: microscopic world, atoms.

→ ~~General Relativity~~: spacetime, gravity

Quantum Mechanics

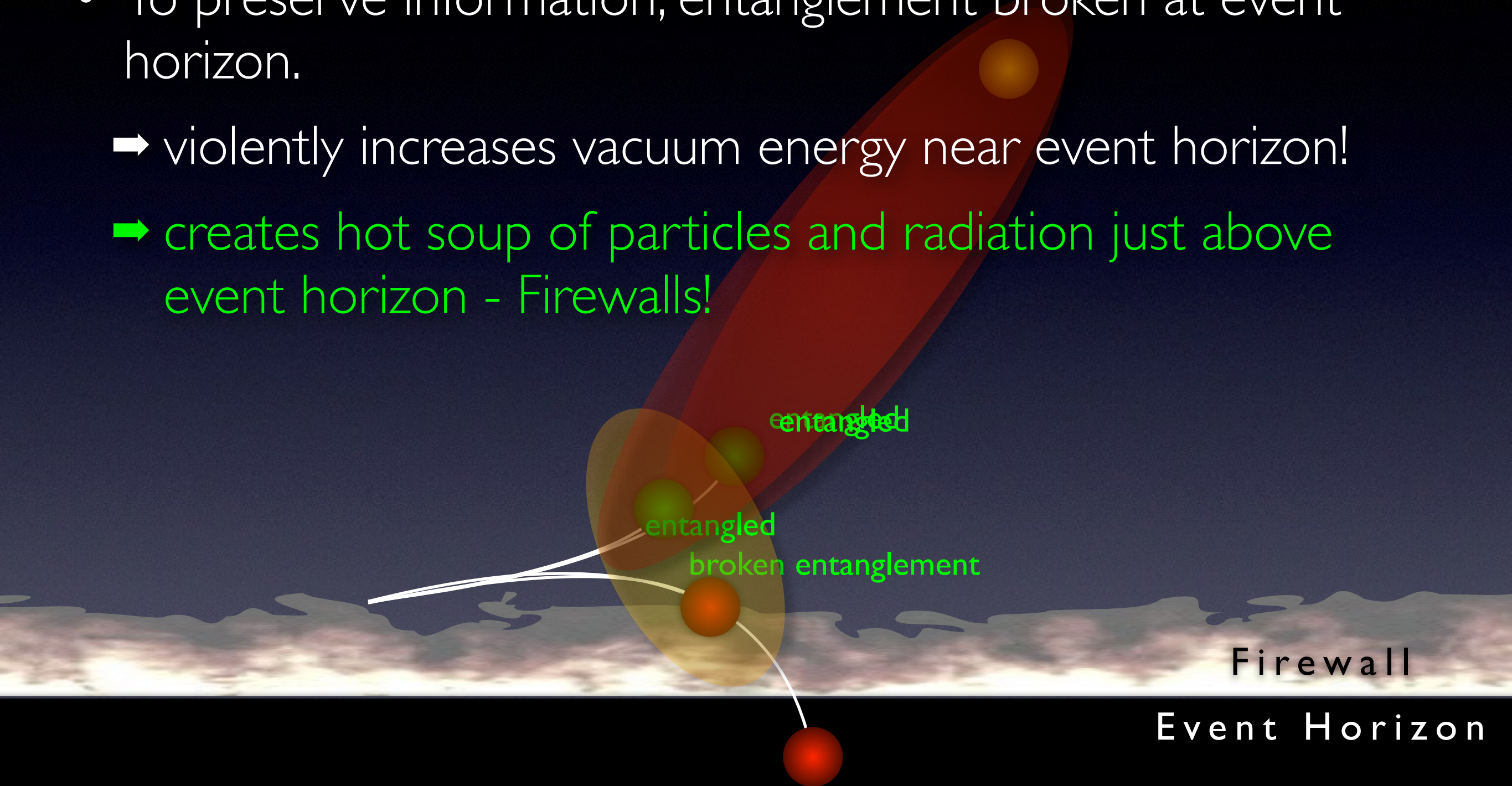
Entanglement Monogamy Broken!

A NEW PICTURE - FIREWALLS

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

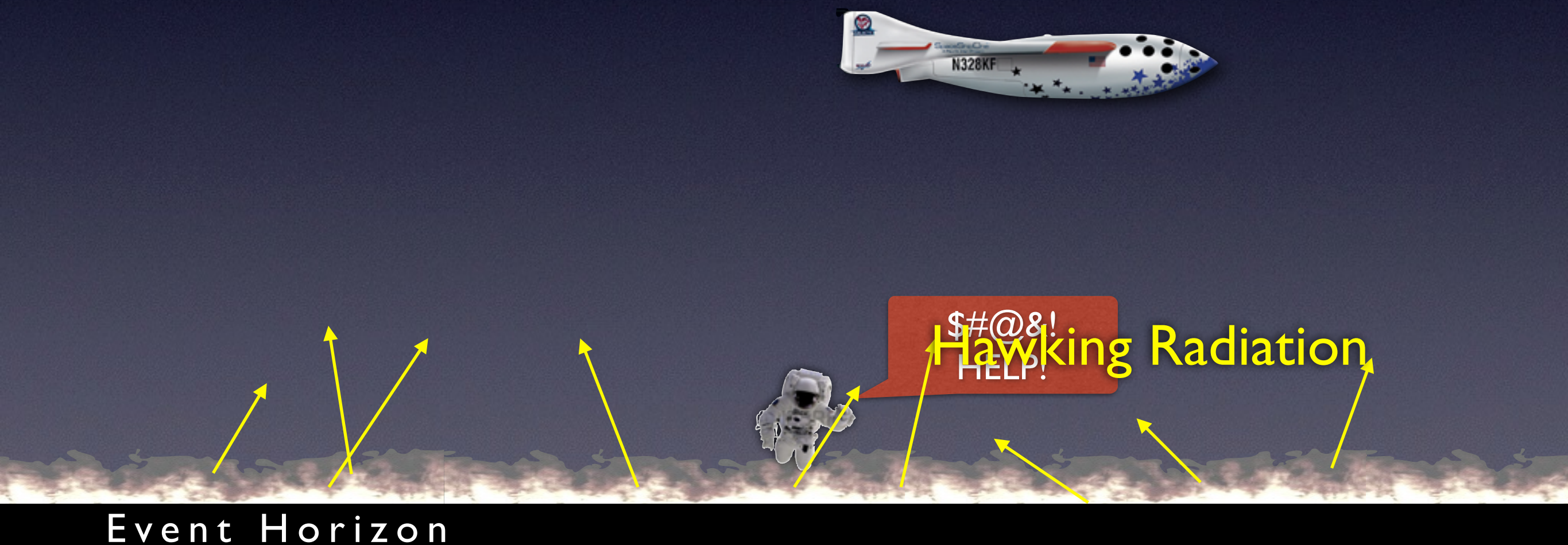
FIREWALLS

- 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!



Zzzzzz...

PILLARS OF MODERN PHYSICS

General Relativity

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Quantum Mechanics

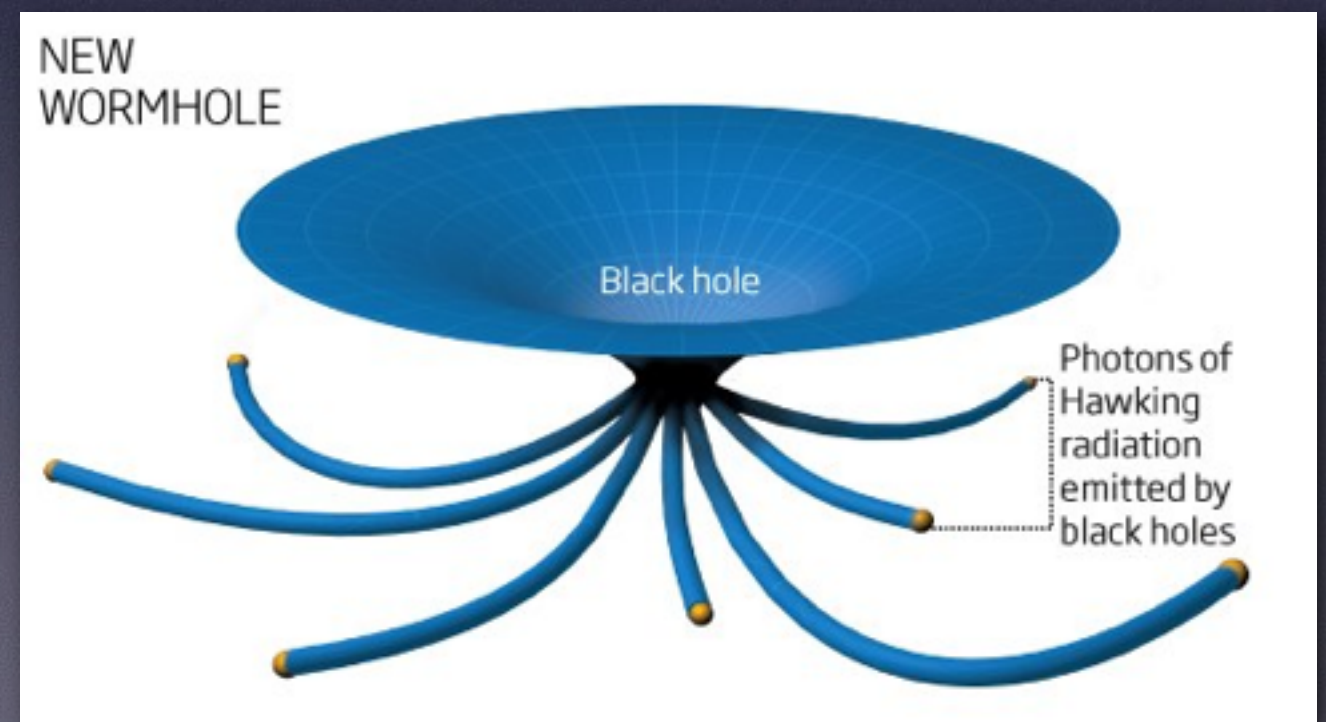
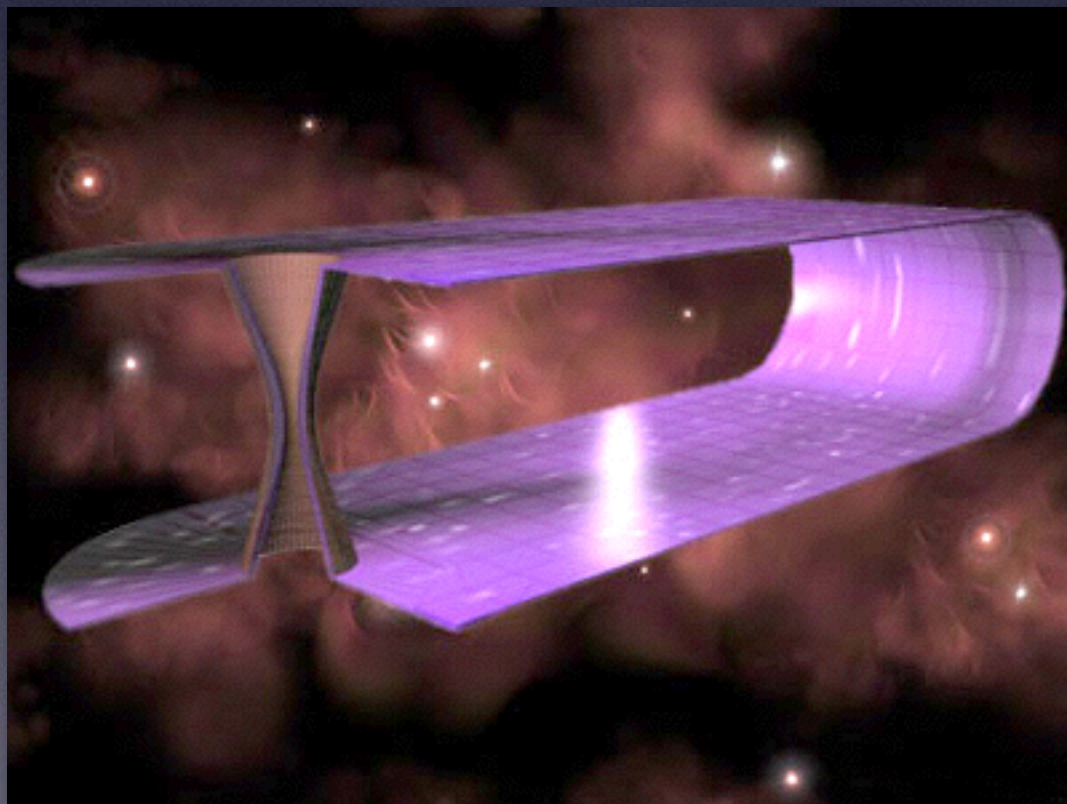
Loss of Equivalence Principle!

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