Black Hole Information Loss Paradox

– The War Continues to Rage –

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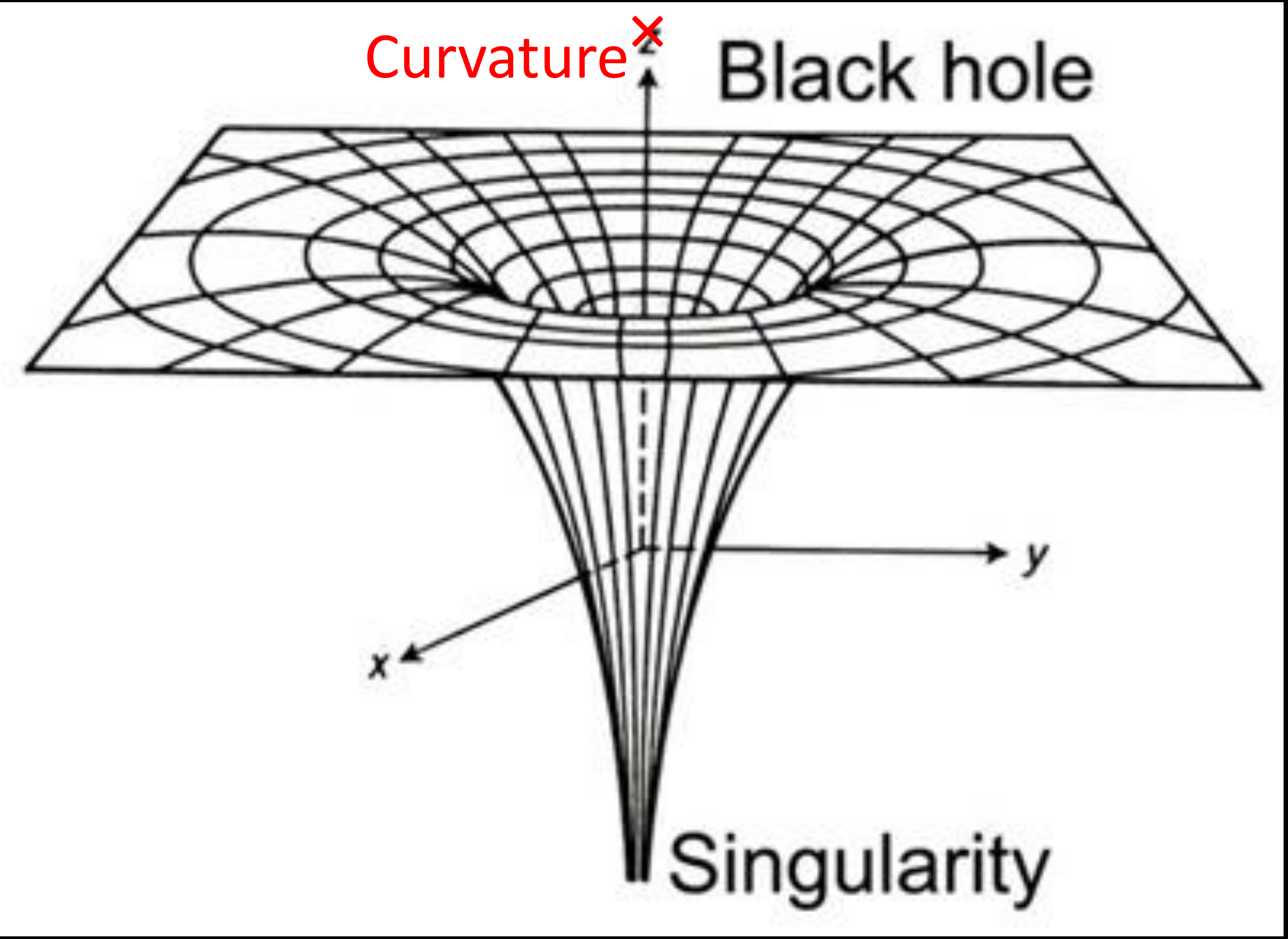
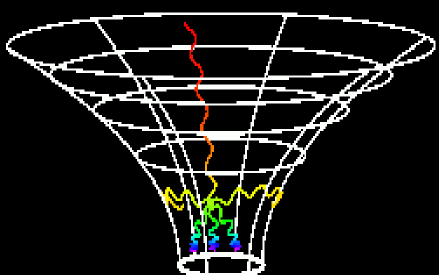
General relativity predicts the existence of black holes



The first black hole solution (1916): Non-rotating BH

$$ds^2 = -\left(1 - \frac{2GM}{c^2 r}\right)c^2 dt^2 + \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)$$

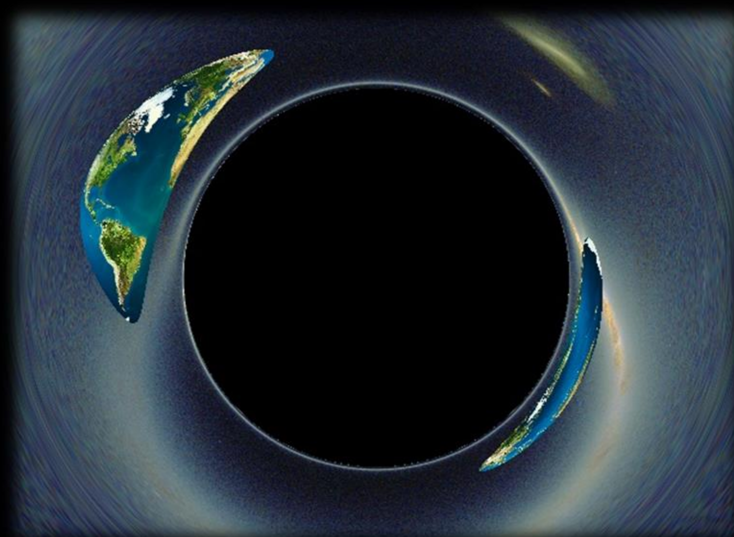
Diverges: $\frac{1}{0} \to \infty$



Event Horizon (事件視界):

$$r_h \equiv \frac{2GM}{c^2}$$

Schwarzschild radius



Schwarzschild = 黑盾

Golden Age of classical black hole
1963 – 1973

Spinning black hole solution (Roy Kerr, 1963)

$$ds^2 = -\frac{\mathrm{D}}{r^2}\left(dt - a\sin^2 q df\right)^2 + \frac{\sin^2 q}{r^2}\left(adt - r_0 df\right)^2 + \frac{r^2}{\mathrm{D}}dr^2 + r^2 dq^2$$

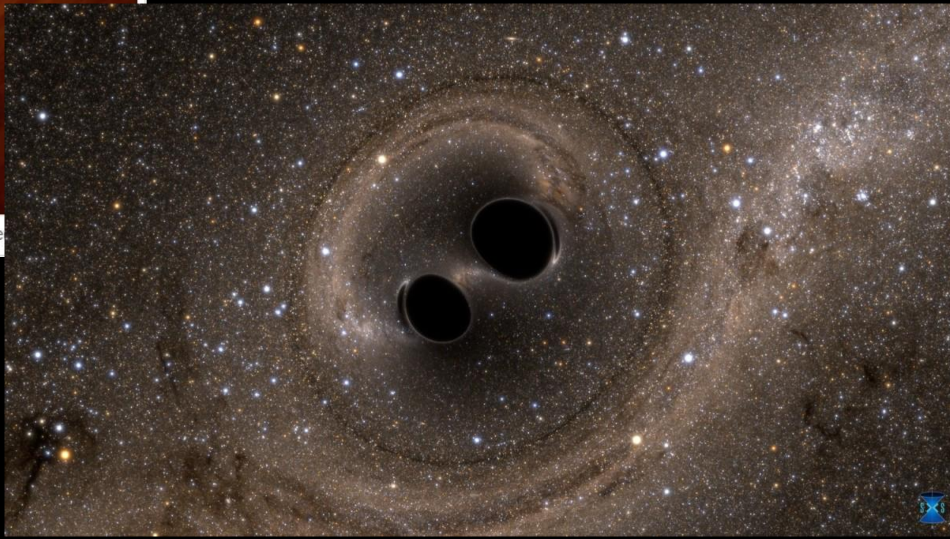
$$r^2 = r^2 + a^2\cos^2 q, \quad r_0^2 = r^2 + a^2, \quad \mathrm{D} = r^2 - 2Mr + a^2$$

Roy Kerr

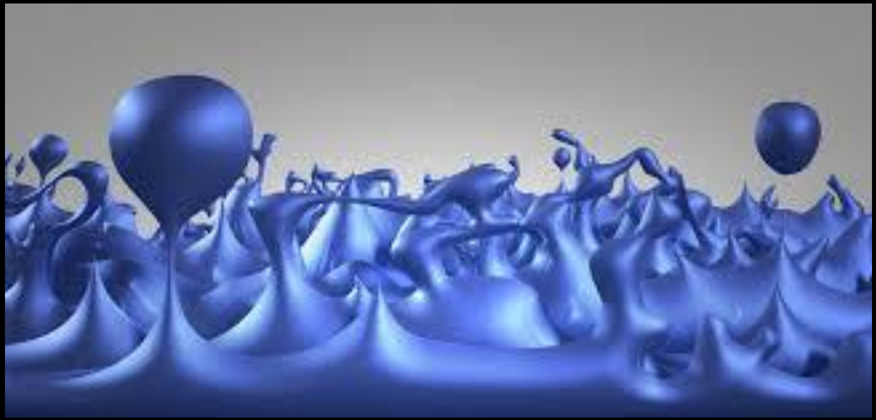
Three types of black holes

Artist's concept illustrating a supermassive black hole with millions to billions times the mass of our sun (Image: NASA/JPL-Calte

Supermassive BH (millions to billions of solar mass)



Stellar size BH (several to tens of solar mass)



Primordial BH (induced around Big Bang)

Black hole thermodynamics
1972 – 1973

"Thermodynamics is a funny subject. The first time you go through it, you don't understand it at all. The second time you go through it, you think you understand it, except for one or two small points. The third time you go through it, you know you don't understand it, but by that time you are so used to it, it doesn't bother you any more." – Arnold Sommerfeld.

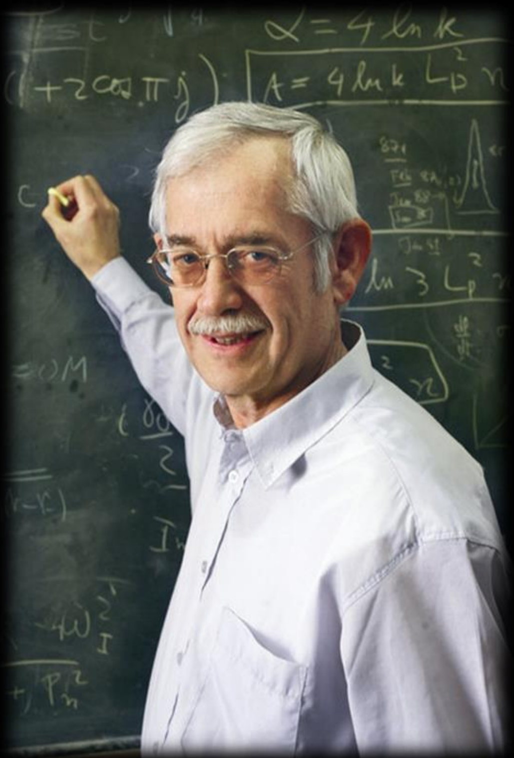
Black hole thermodynamics

- Zeroth Law: The surface gravity of a non-rotating black hole is constant.
- First Law: The change of total energy equals to that of the area, angular momentum, and charge: $dE = \frac{\kappa}{8\pi} dA + \Omega dJ + \Phi dQ$
- Second Law: The area of the BH surface can only increase in time. $\frac{dA}{dt} \geq 0$
- Third Law: Zero surface gravity BH does not exist. In another word, κ cannot be zero.

Black hole entropy

- Bekenstein-Hawking entropy:

$$S_{BH} = \frac{k_B A}{4 l_P^2}$$



Jacob Bekenstein (1947-2015)

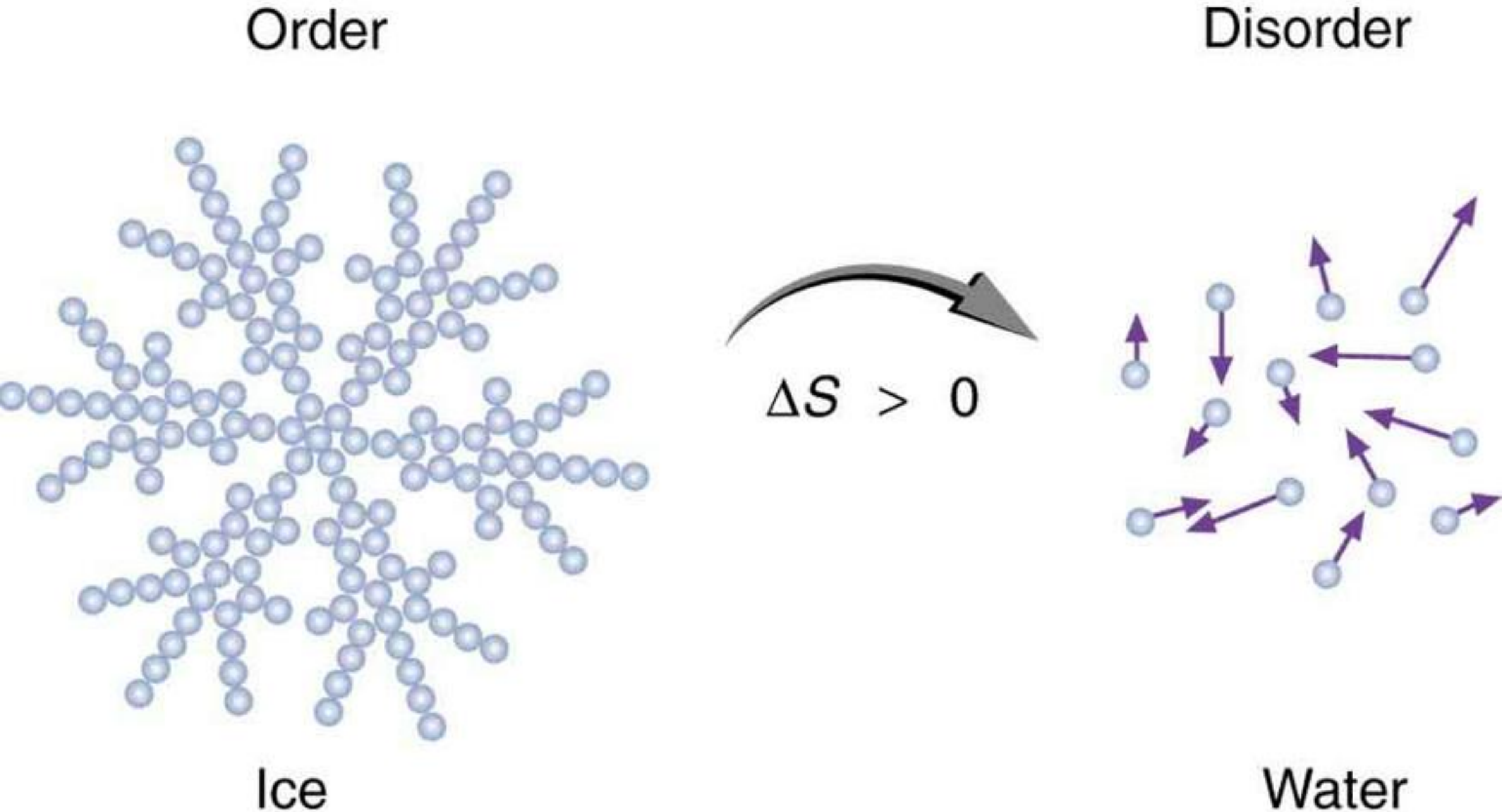
$$E = k_B T$$

Ludwig Boltzmann (1844-1906)

$$S = k \log W$$

Tomb of Boltzmann in Vienna, Austria

Entropy



2nd law of thermodynamics

Black hole entropy: an amazing equation!

Thermodynamics

Geometry

General relativity

$$S_{BH} = \frac{k_B A}{4 l_P^2}$$

Gravity

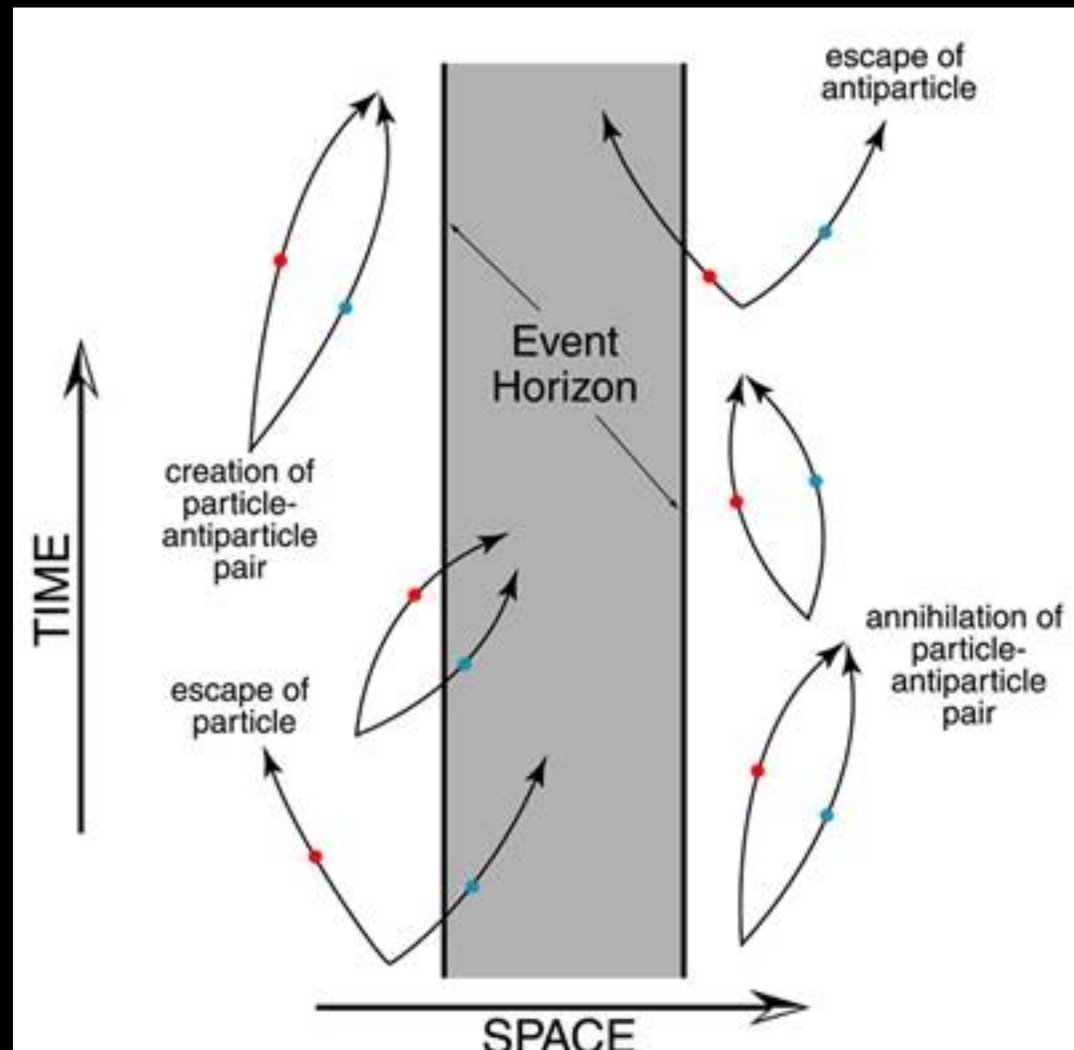
Quantum mechanics

Worse yet, S is NOT proportional to the BH volume, but its surface area!

Hawking evaporation: Linking GR, QM, and Stat Mech in one stroke

$$r_s = \frac{2GM}{c^2} \qquad g = \frac{GM}{r_s^2}$$

$$k_B T_H = \frac{\hbar c^3}{8pGM} = \frac{\hbar g}{2pc}$$



Black hole evaporation

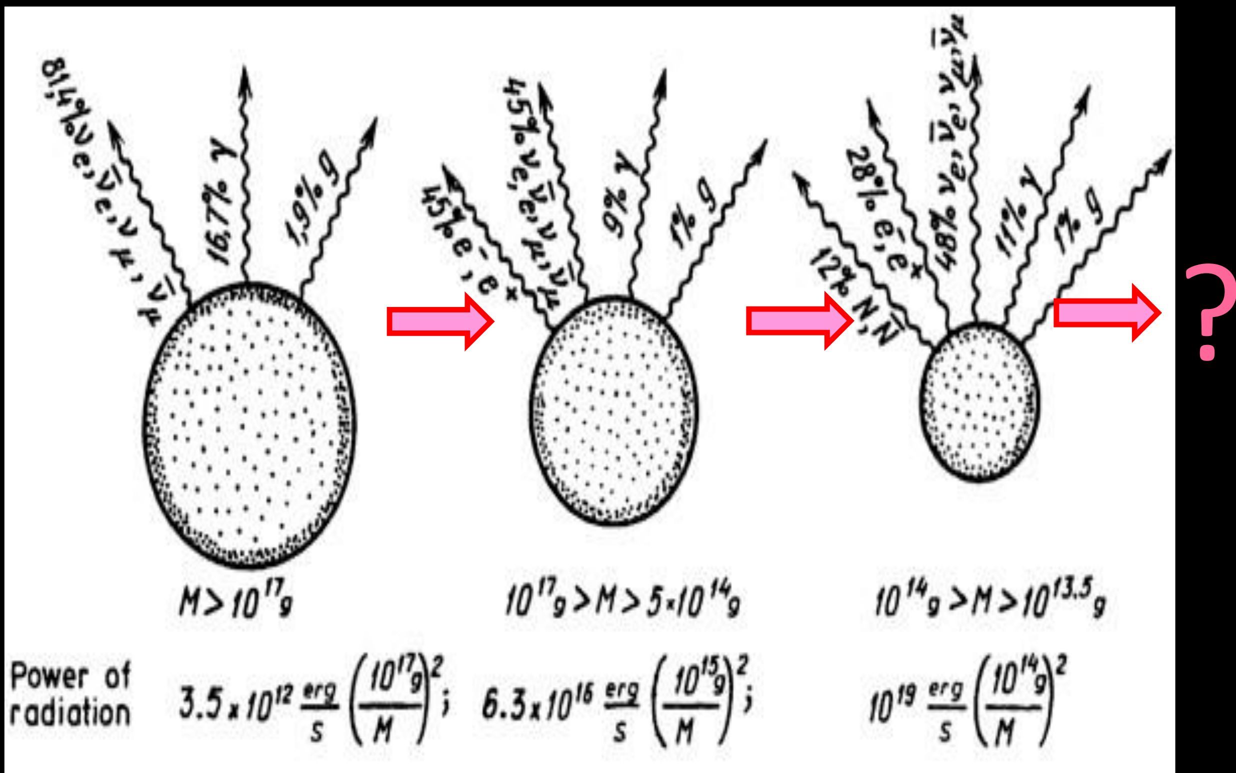
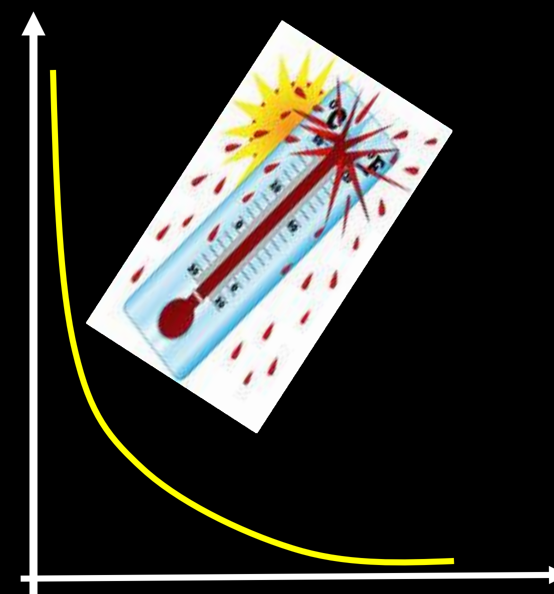


Figure 10.7: Quantum decay of a non-rotating black hole. The fractions of gravitons (g), photons (γ), neutrinos (ν) and other elementary particles are given in percent of the total number of particles emitted by black holes of different masses.

$$T_{BH} = \frac{\hbar c^3}{8\pi k_B G M}$$



Frolov, V. V. P., Novikov, I. D. (1998). Black hole physics: basic concepts and new developments (Vol. 96). Springer

Lifetime of black holes

- Hawking temperature:

Planck's Constant [Quantum Mechanics]

Relativity

$$T = \frac{\hbar c^3}{8\pi G M \, k_B}$$

Boltzmann's Constant [Thermodynamics]

Newton's Constant [Gravity]

- Stefan-Boltzmann law: $$\frac{E}{A} = s T^4 \mu \frac{1}{M^4}$$

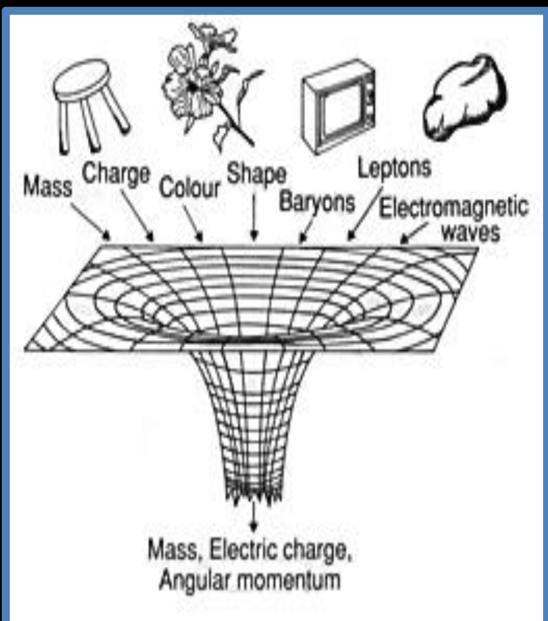
Black hole surface area: $$A = 4 p r_h^2 \mu M^2$$

BH evaporation rate inversely proportional to mass squared:

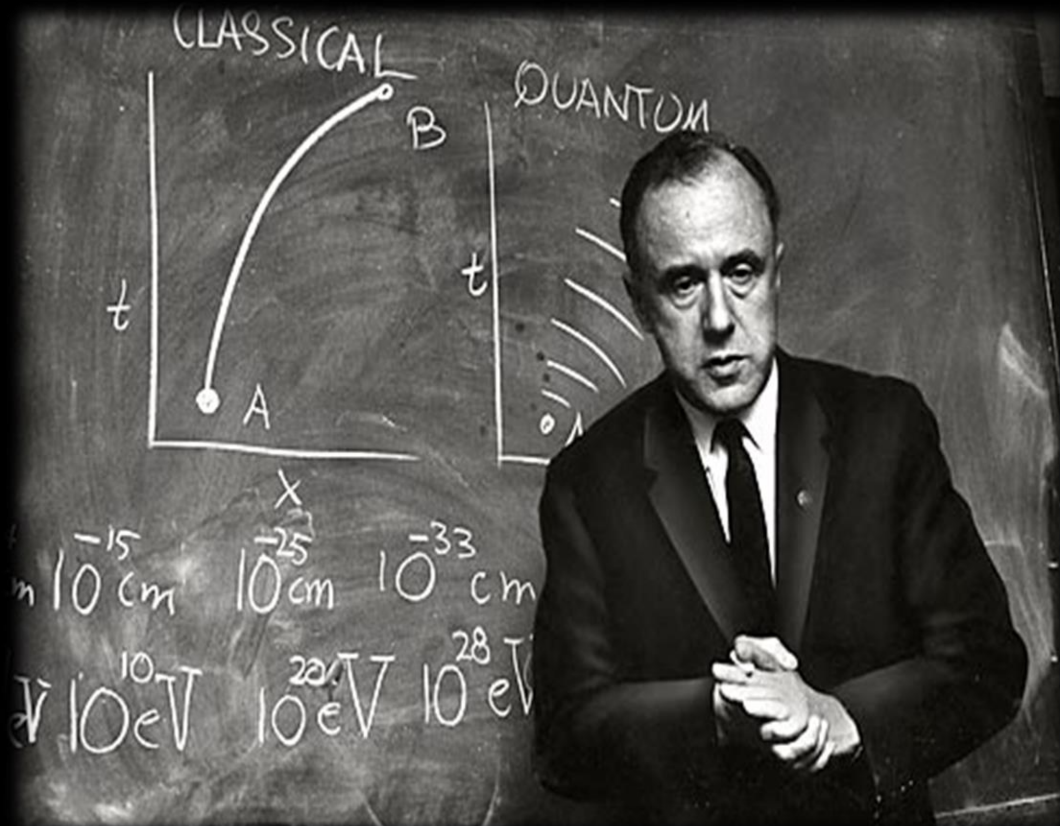
$$\frac{dM}{dt} \mu \frac{1}{M^2}$$

Lifetime of BH: Solar mass BH=10^{67} years

Age of the universe = 1.38 x 10^{10} years

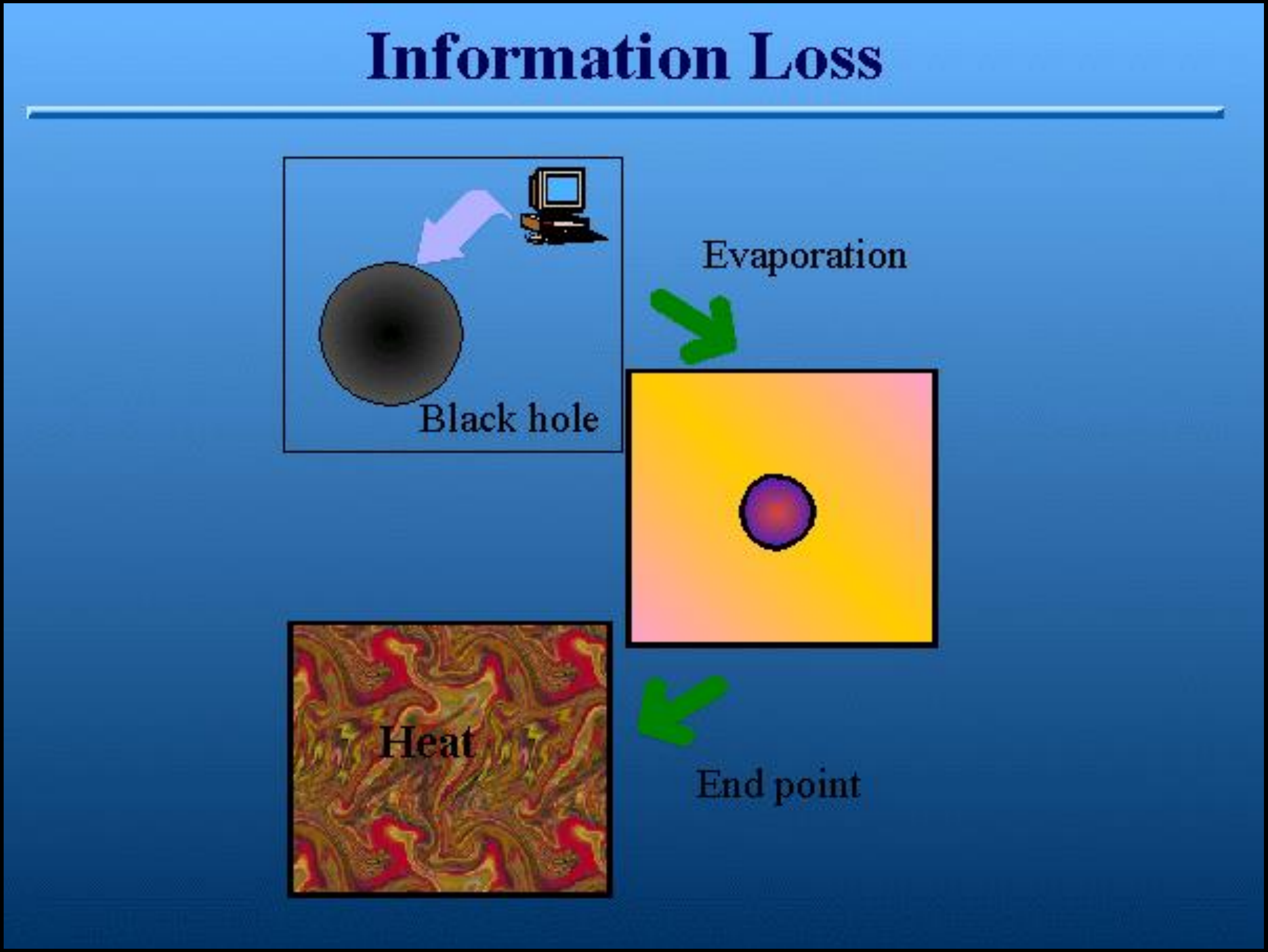


No-hair theorem

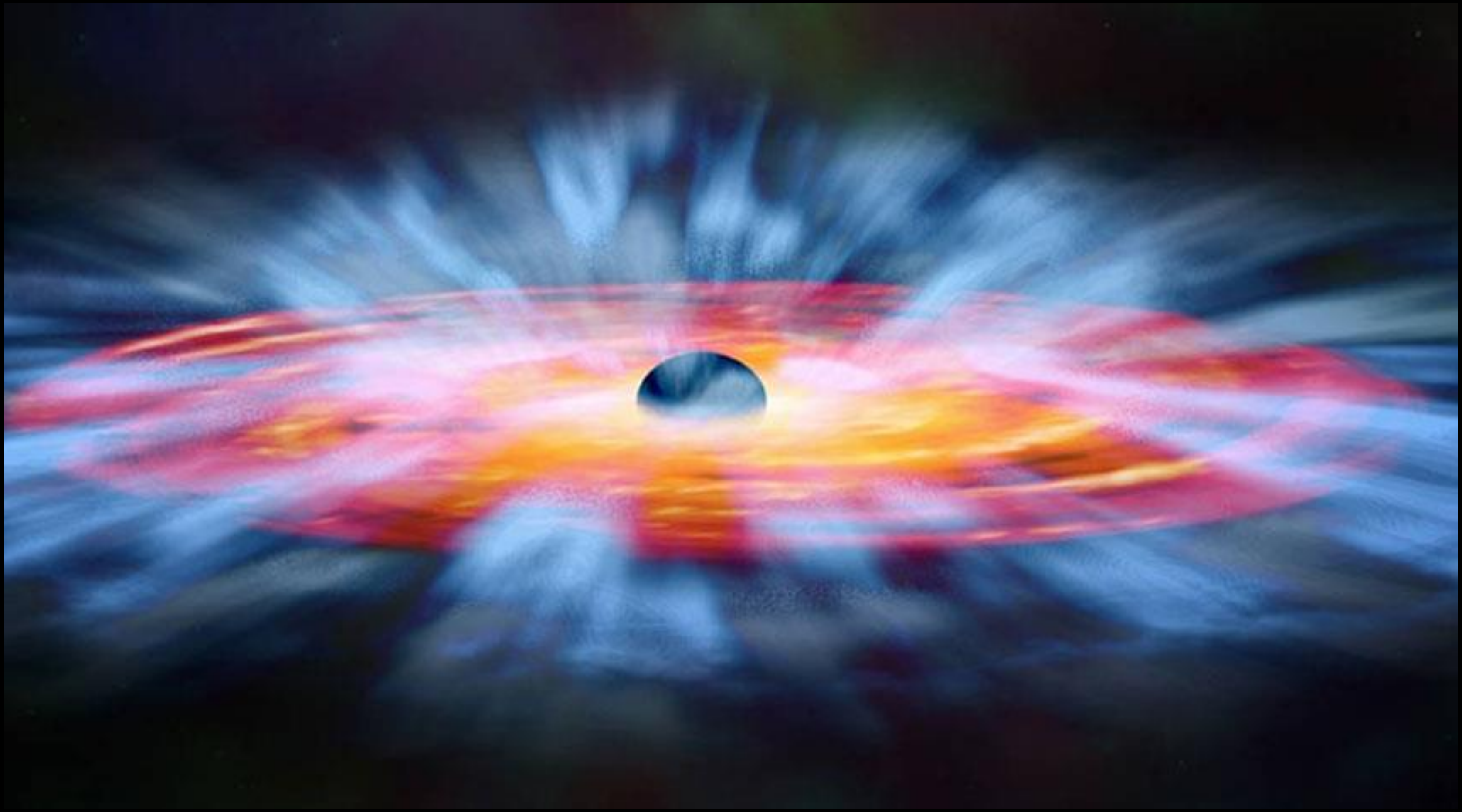


John Wheeler (who invented the name Black Hole):
"What would happen if I drop my coffee into a black hole?"

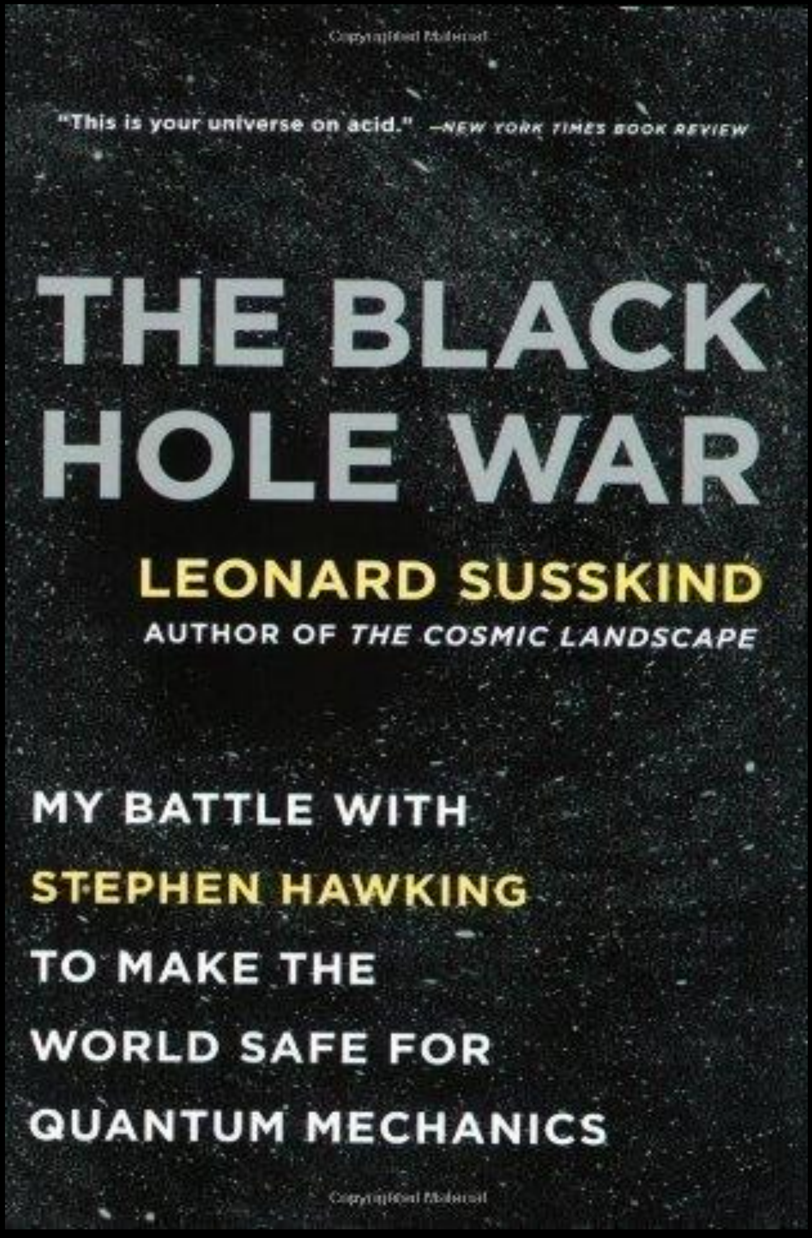
The information loss problem



Can Hawking radiation carry out information after all?

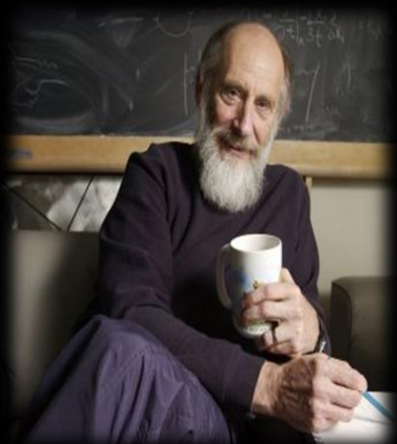


Recommend reading

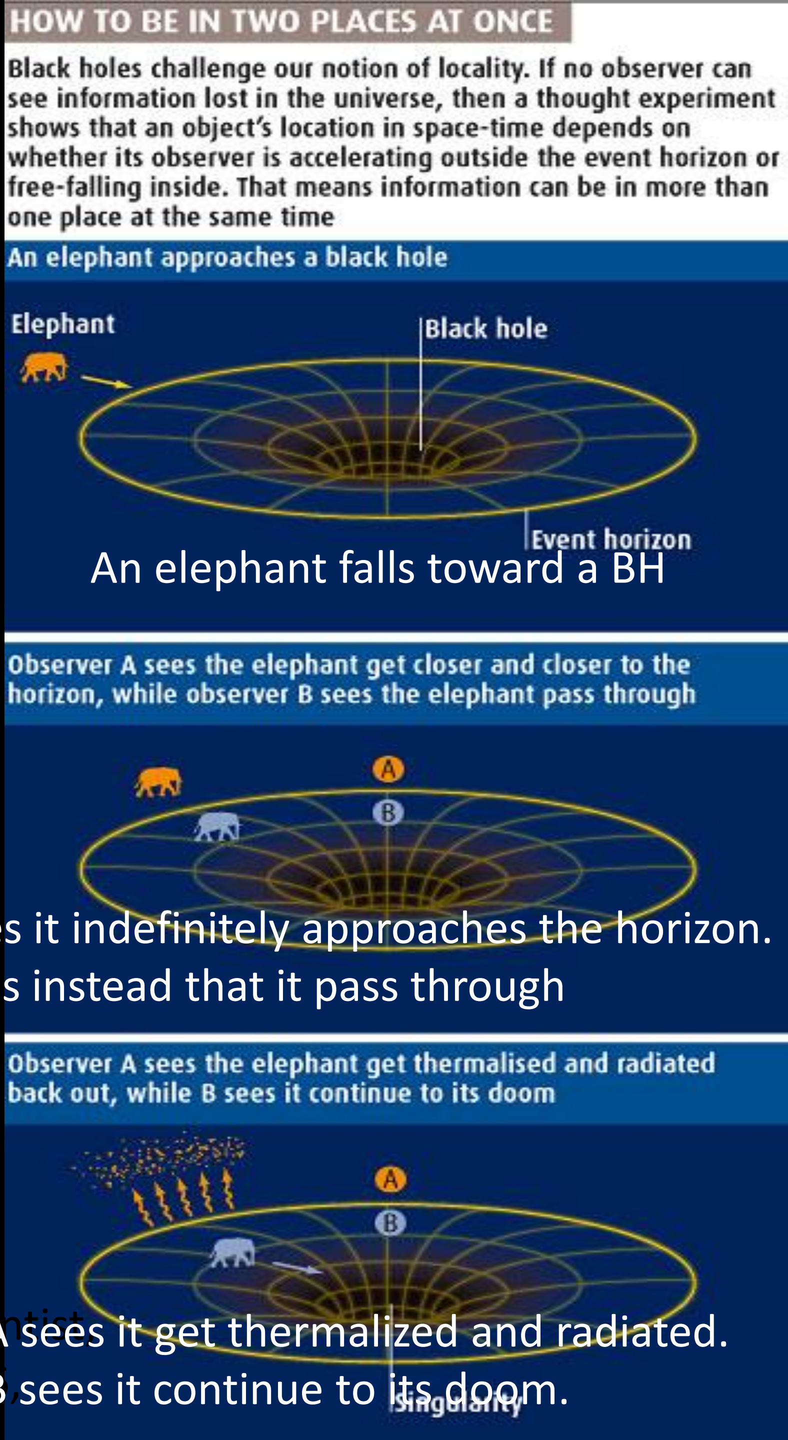


BH Complementarity Principle

The basic requirement of natural law is that it is *consistent with causality*.



Leonard Susskind, Lárus Thorlacius, John Uglum, “The Stretched Horizon and Black Hole Complementarity”



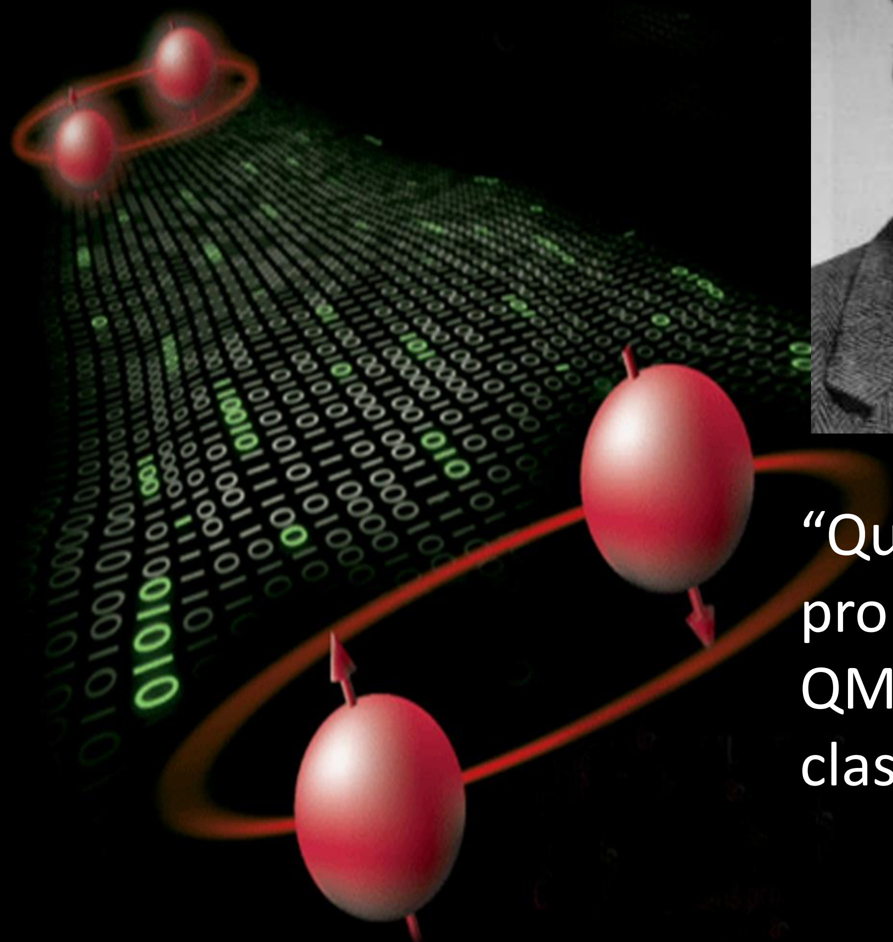
An elephant falls toward a BH

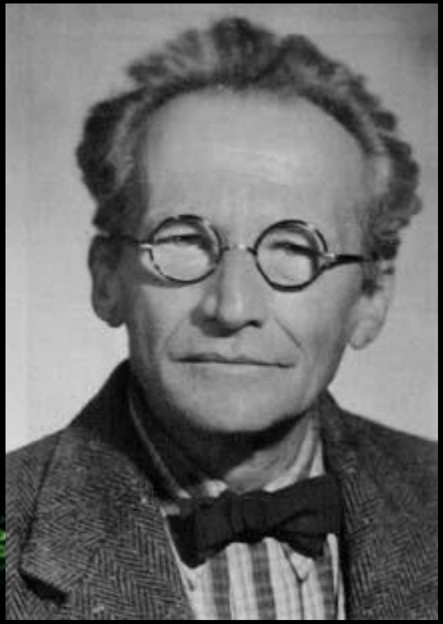
A sees it indefinitely approaches the horizon.
B sees instead that it pass through

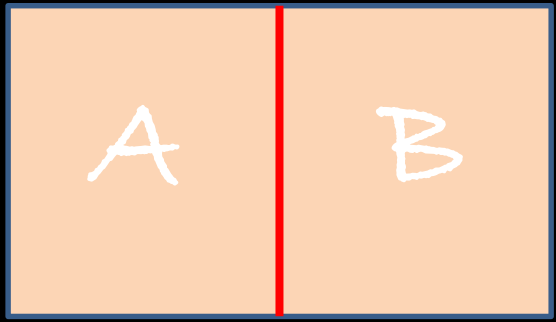
A sees it get thermalized and radiated.
B sees it continue to its doom.

Quantum entanglement

Schrödinger: *"Verschrankung"* (1935) as a result of discussing with Einstein

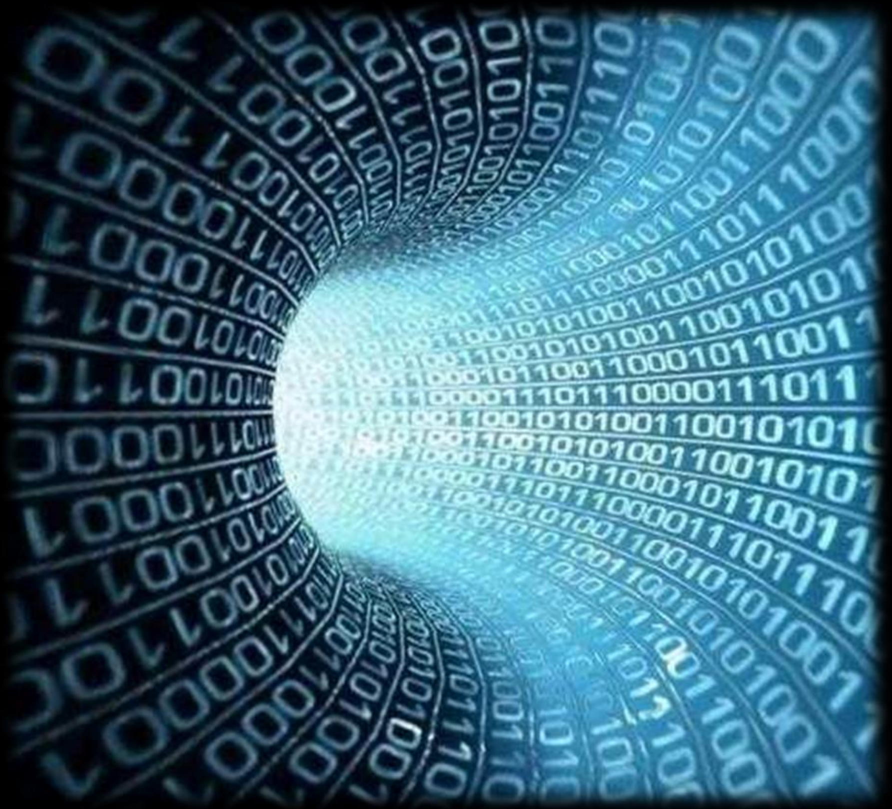






"Quantum entanglement is not just a property of QM, it is THE character of QM. It fundamentally breaks QM from classical physics.

What is quantum entanglement?



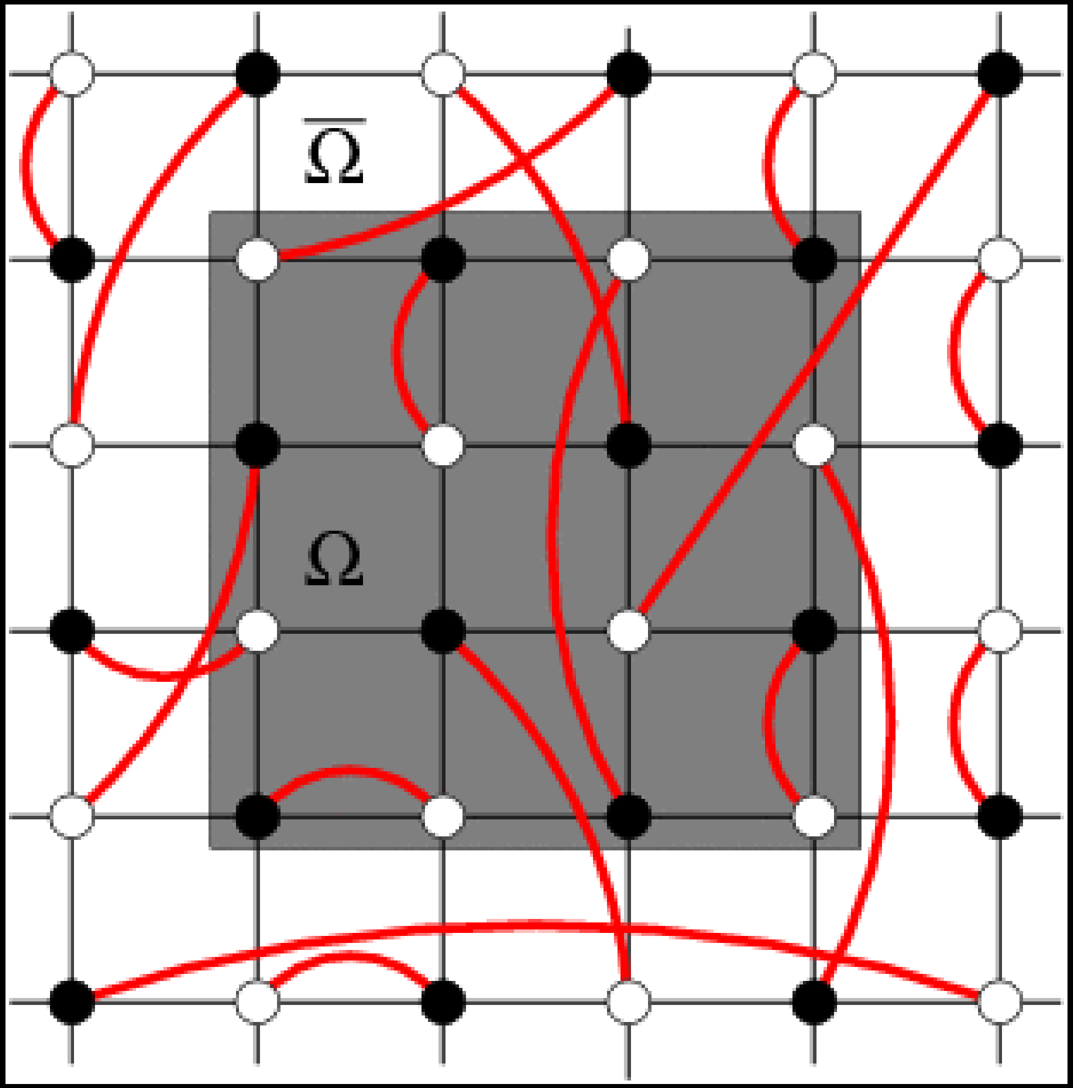
Thermodynamics:

Entropy ⟺ Disorder

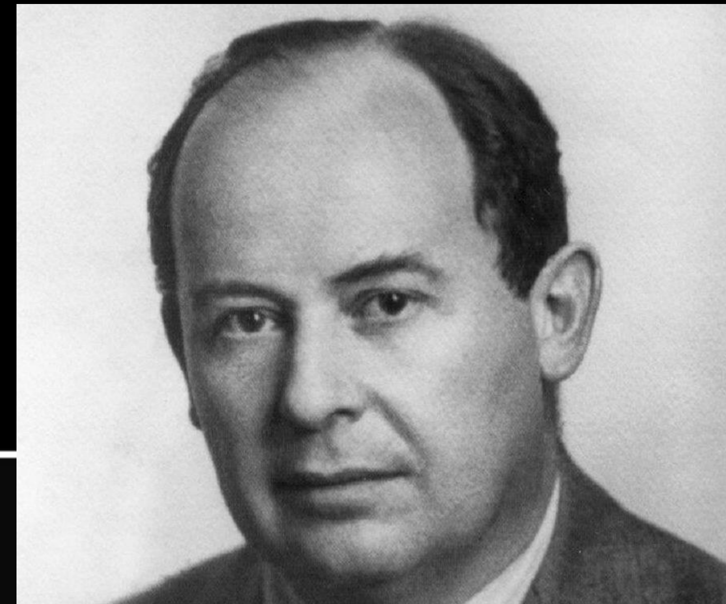
Quantum Informatics:

Entanglement Entropy ⟺ How tangled the system is

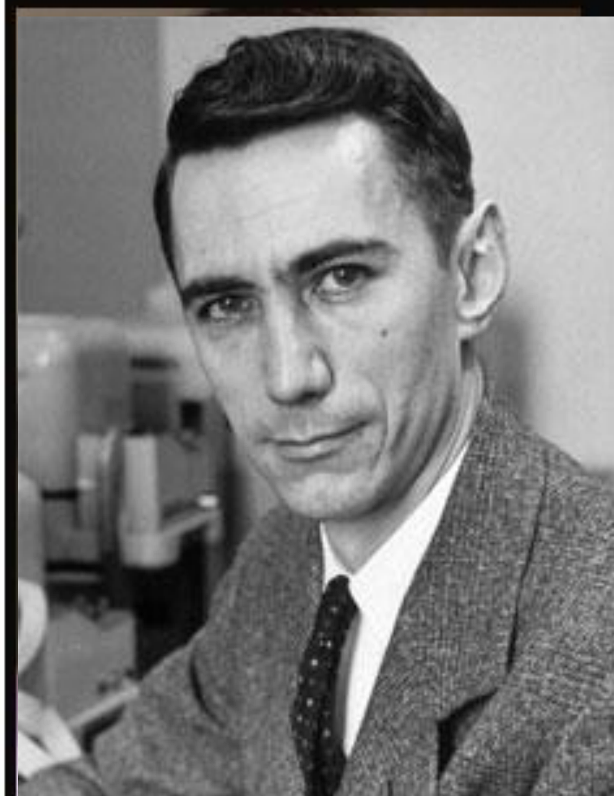
Monogamy of quantum entanglement



From Shannon entropy to von Neumann entropy



John von Neumann



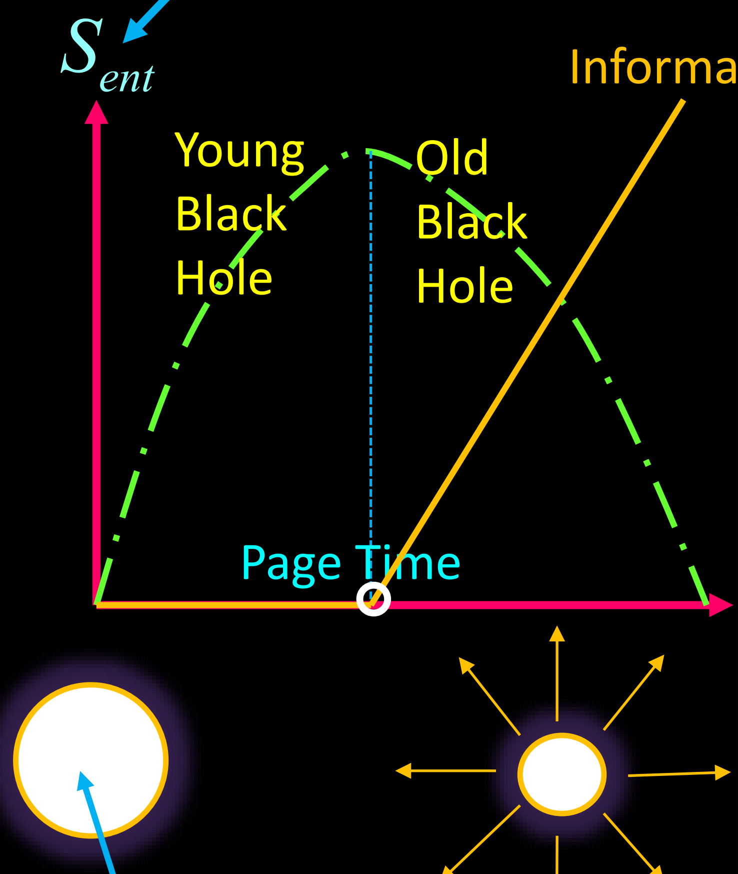
Use entropy and you can never lose a debate, von Neumann told Shannon - because no one really knows what entropy is.

(William Poundstone)

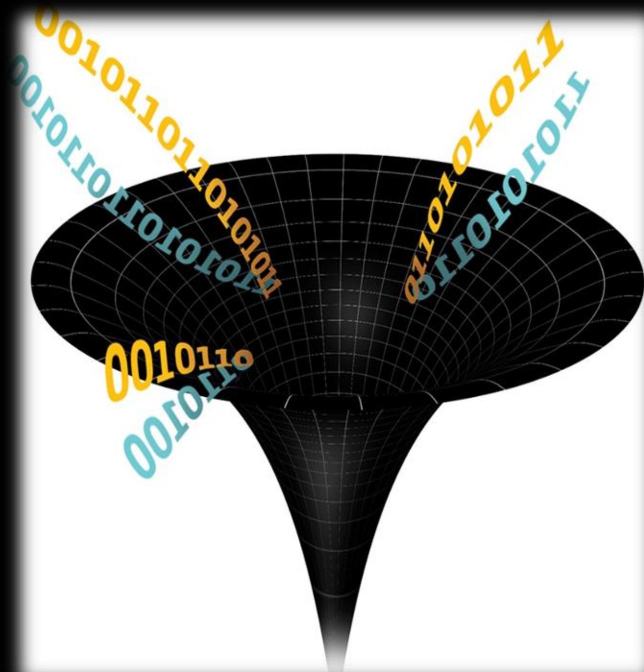
Claude Shannon (1916-2001)

When would BH entanglement entropy come out?

Entanglement entropy



Pure state black hole



Don Page

AMPS firewall paradox

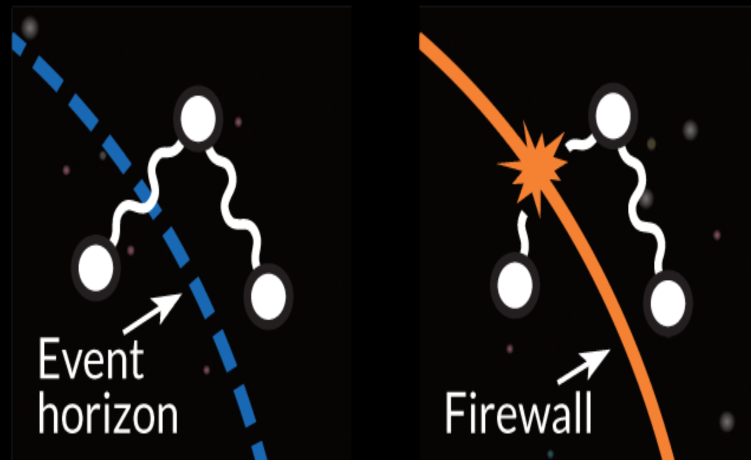
In 2012, four physicists (AMPS) argued that the 3 basic assumptions that led to the BH complementarity principle, namely,

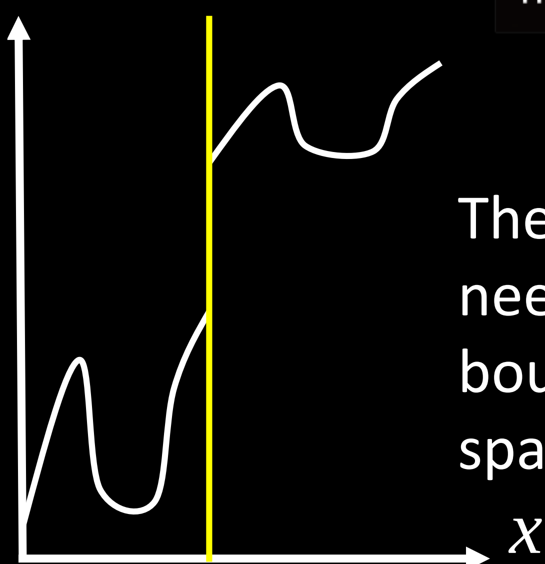
1. Unitarity
2. Local quantum field theory
3. No drama

cannot be all consistent. They suggested that the "most conservative" solution would be that there exists a firewall on the BH surface, anything falls into BH would be burned into ashes.

AMPS firewall paradox

The energy of a quantum field at a location x depends on the variation of the field value there.





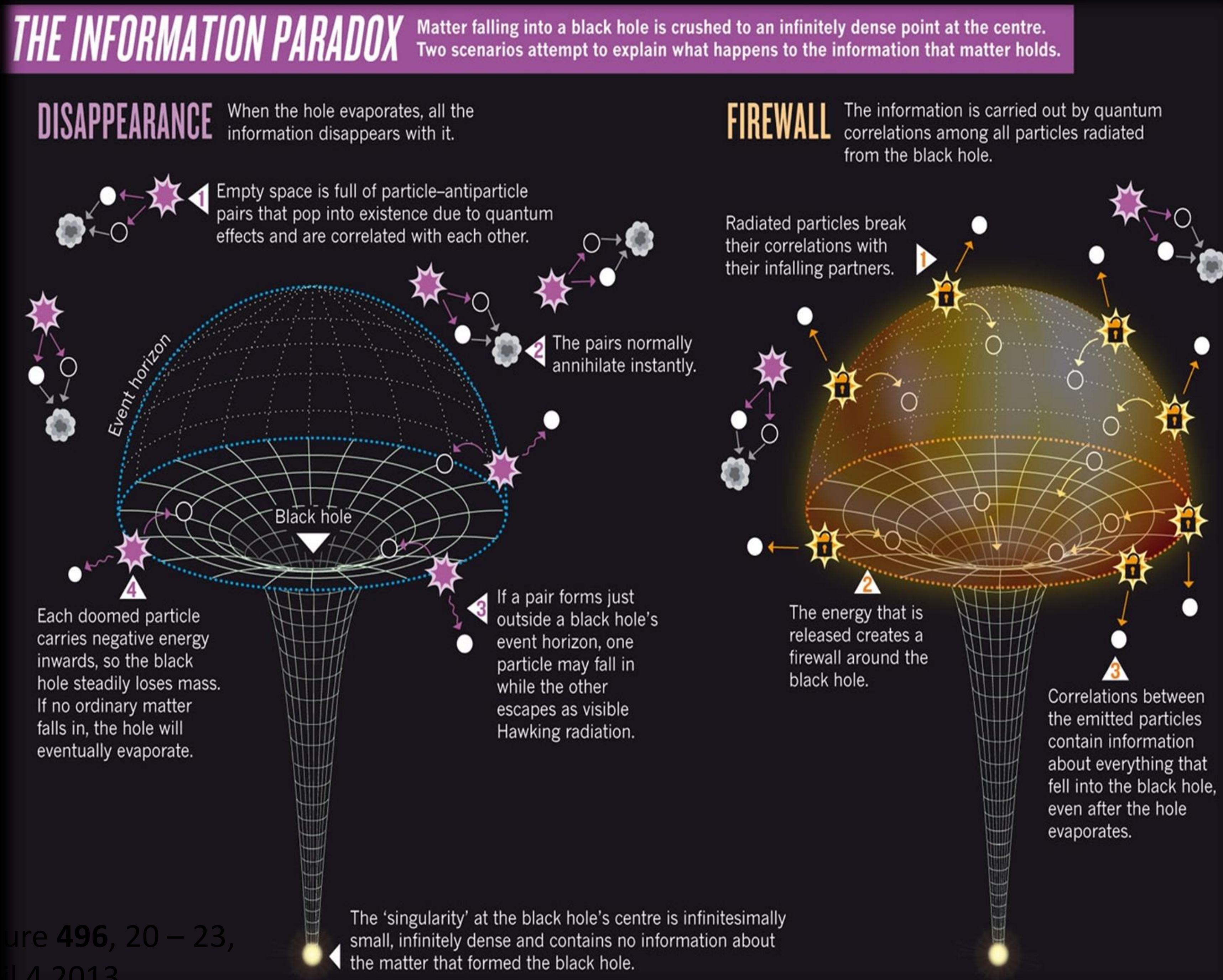
The value of the quantum field needs not be continuous on a boundary across which the spacetime is not continuous.

- Ahmed Almheiri, Donald Marolf, Joseph Polchinski, James Sully,

  "Black Holes: Complementarity or Firewalls?", JHEP 1302 (2013) 062.

- Ahmed Almheiri, Donald Marolf, Joseph Polchinski, Douglas Stanford, James Sully,

  "An Apologia for Firewalls", JHEP 1309 (2013) 018.



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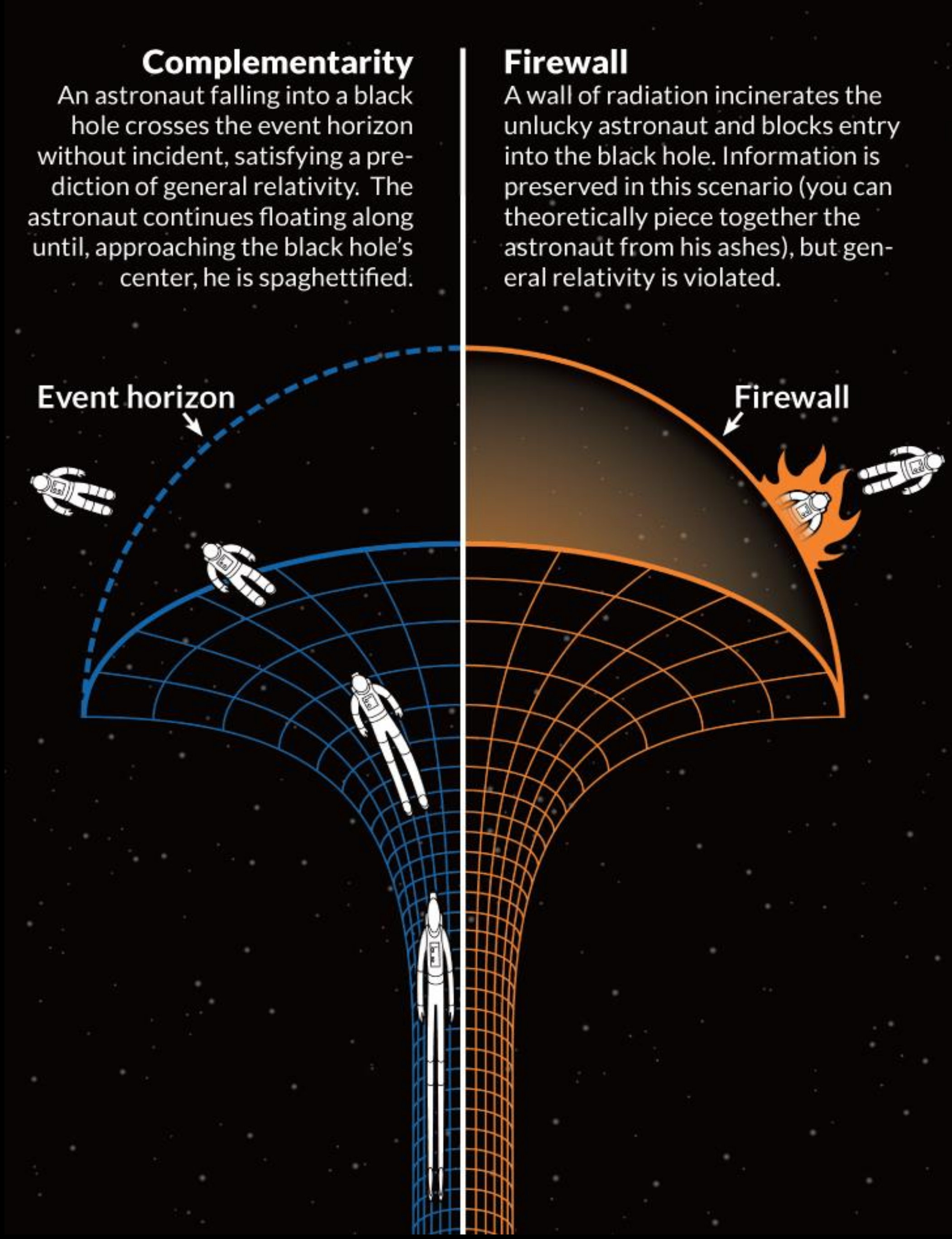


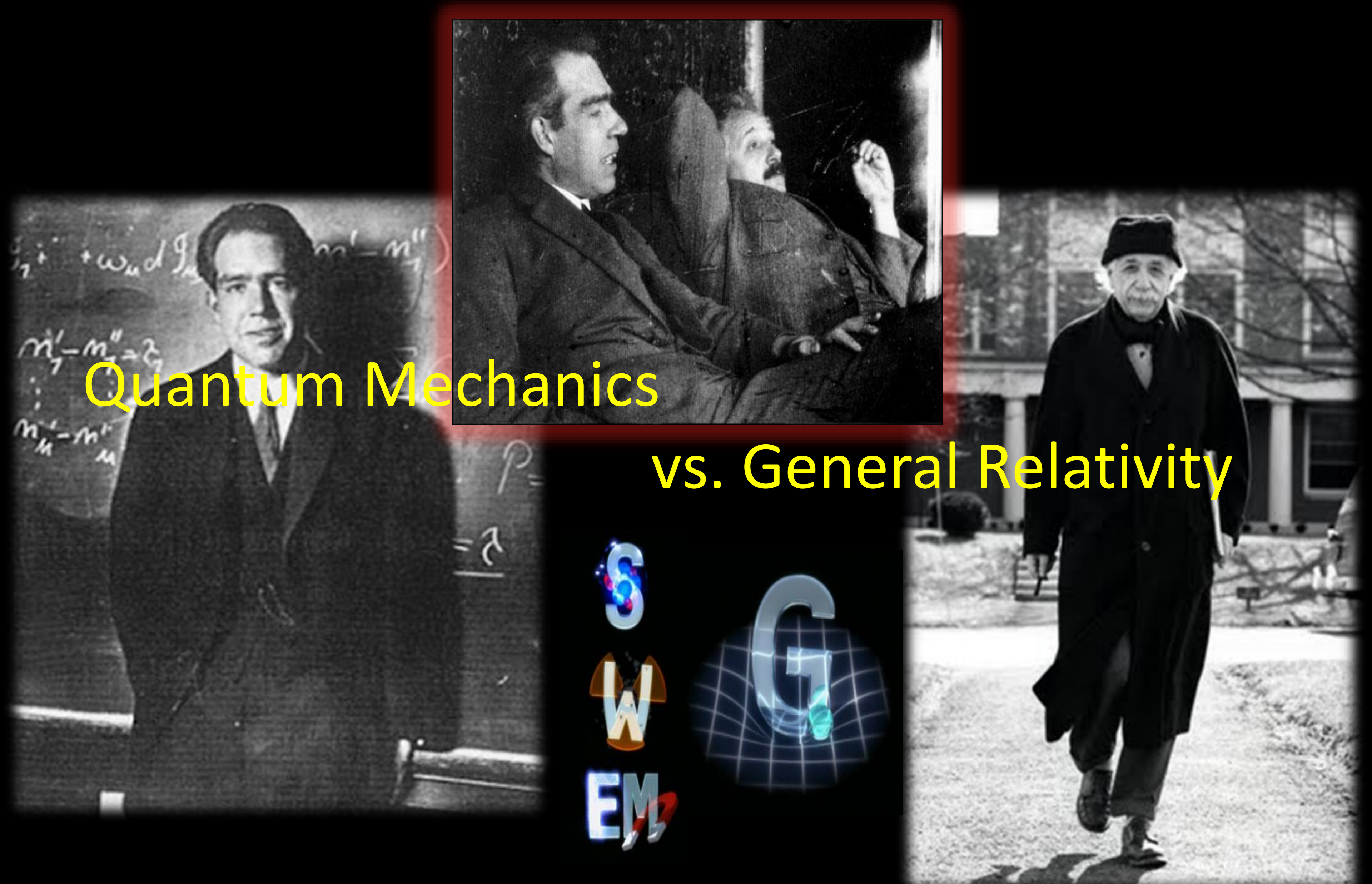
General relativity:

For a sufficiently large BH, whose curvature is small, objects should pass its horizon uneventfully — “No Drama”

AMPS firewall:

The requirement that Hawking radiation can bring information out from BH would result in the notion of firewall.

Conflict between QM and GR!



Quantum Mechanics

vs. General Relativity


Solutions to the Paradox

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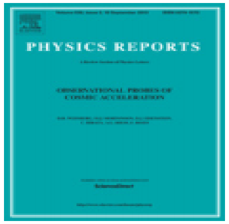

Black hole remnants and the information loss paradox☆

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Singularity in general relativity and quantum gravity

ABSTRACT

Forty years after the disc
If Hawking radiation doe
hole, it seems that unita
the other hand, attempts
firewall controversy. Amic
with a "remnant" has rem
properties" of such an ob
of any proposal must be
providing a timely review
thoughts regarding the c
information loss paradox
importance of understand
there remains a possibilit
In this context a black hol
that a remnant remains a
interior geometry, may he
controversy. We hope tha
remnants more critically but also more thoroughly.

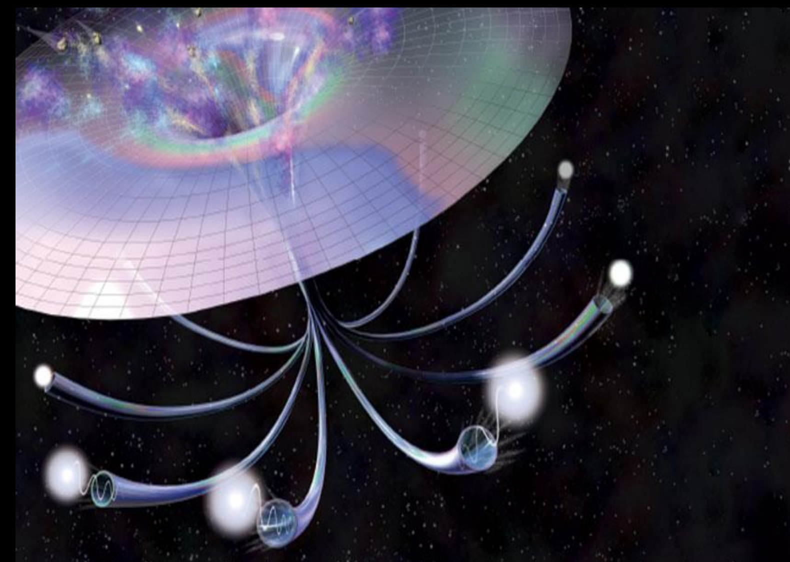
Solution 1: Horizon does not exist

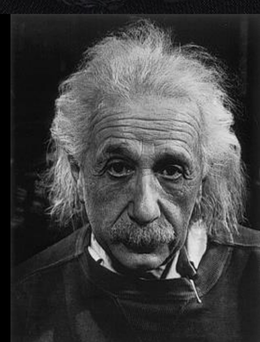
- Media: Hawking said BH does not exist (2014).
- Actually what Hawking said was, Event Horizon may not exist, the only thing real is the Apparent Horizon.
- Apparent horizon can trap matter and lights, but as the BH evaporates, they will be released.
- However, the notion of apparent horizon depends on the choice of the coordinates, and so it's not an invariant statement.

Solution 2: Quantum entanglement is actually equivalent to wormholes

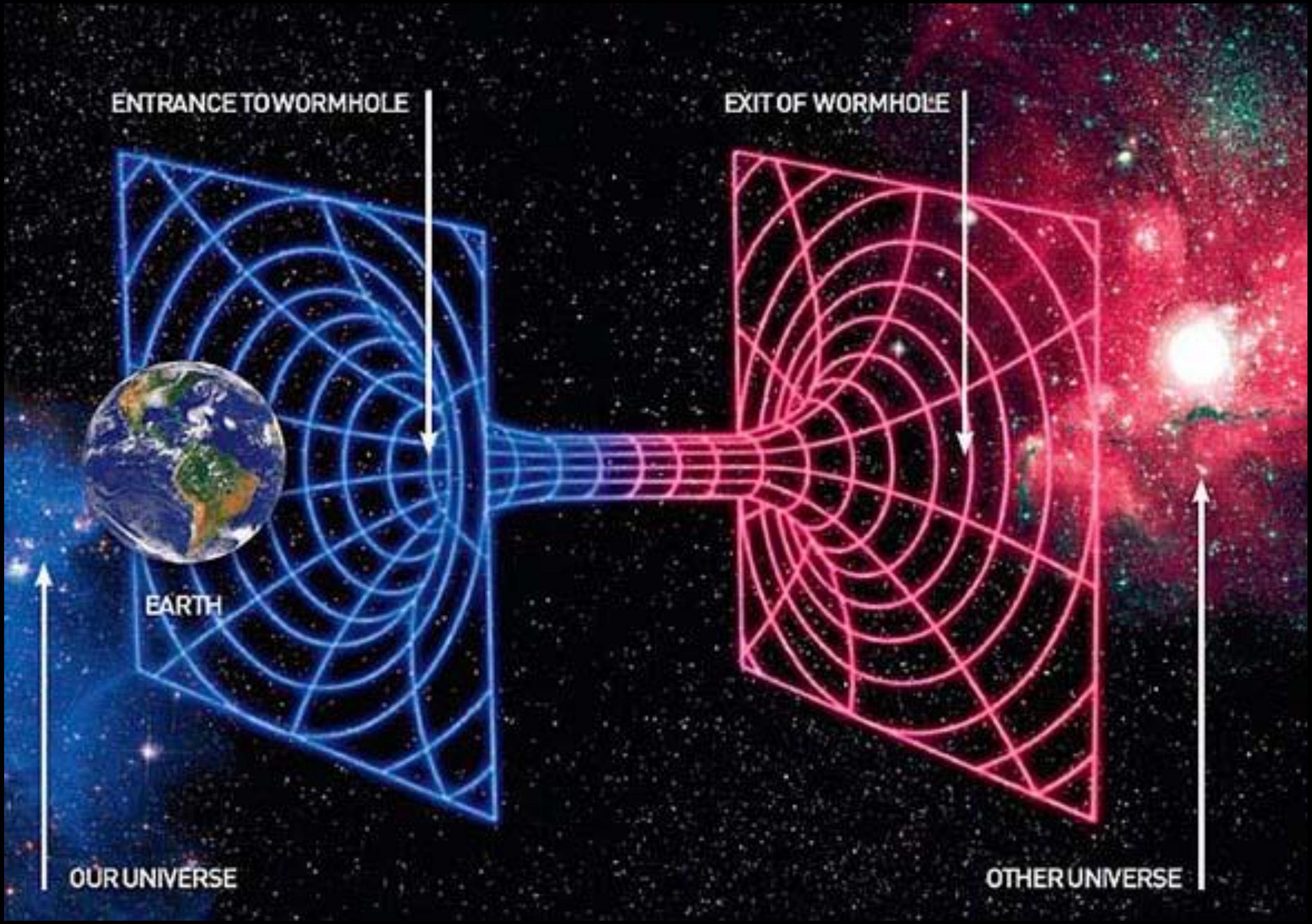
ER (Einstein–Rosen) =EPR (Einstein–Podolsky–Rosen)

=





Wormhole

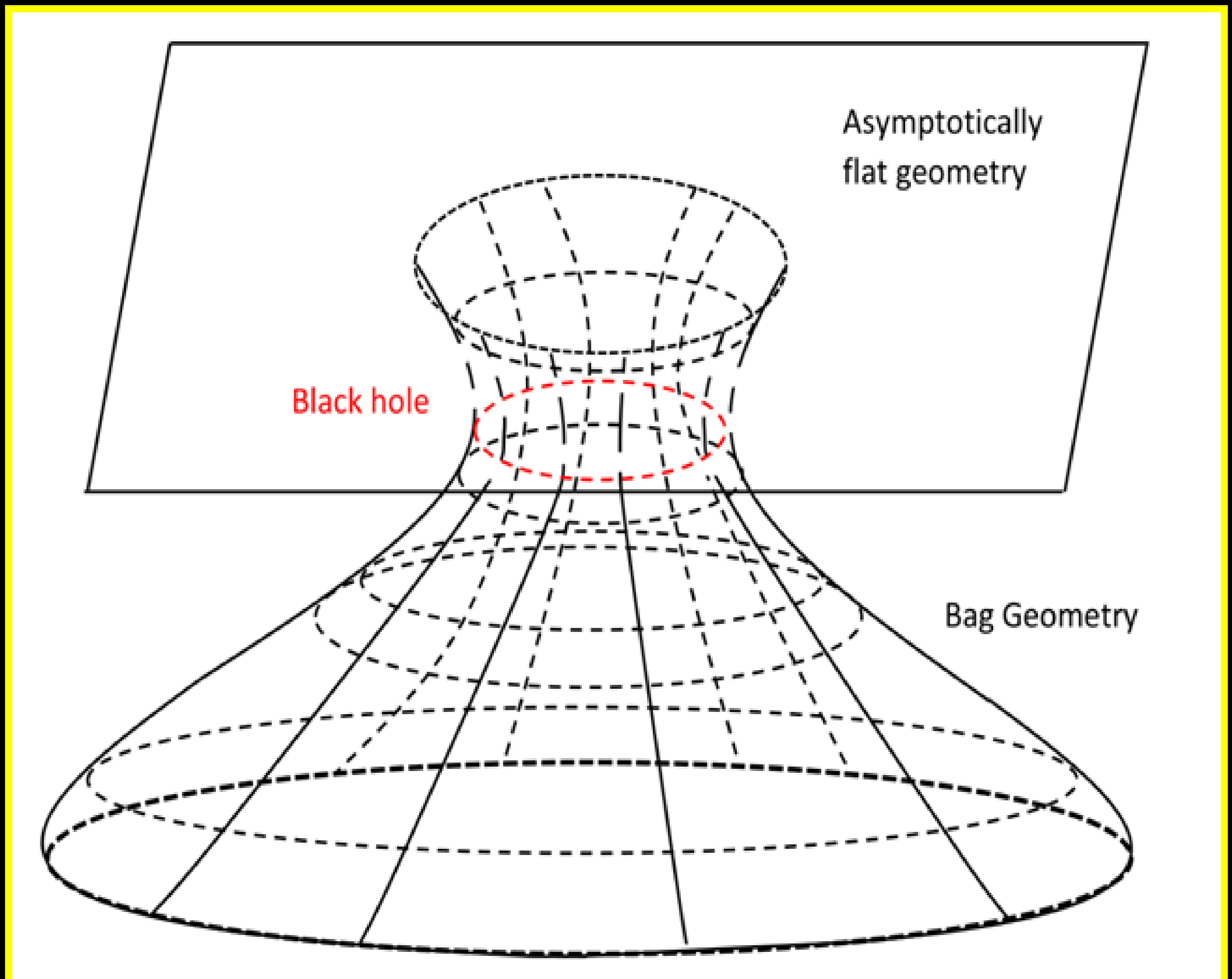

ENTRANCE TO WORMHOLE
EXIT OF WORMHOLE
EARTH
OUR UNIVERSE
OTHER UNIVERSE

Solution 3: Decoding BH information would take extremely long time

D. Harlow, P. Hayden, "**Quantum Computation vs. Firewalls**", JHEP 06 (2013) 085, [arXiv:1301.4504 [hep-th]].

The existence of firewall can only be revealed when the BH information is decoded, but thqt will take a time longer than BH's lifetime.

Solution 4: BH Remnant stores the missing information

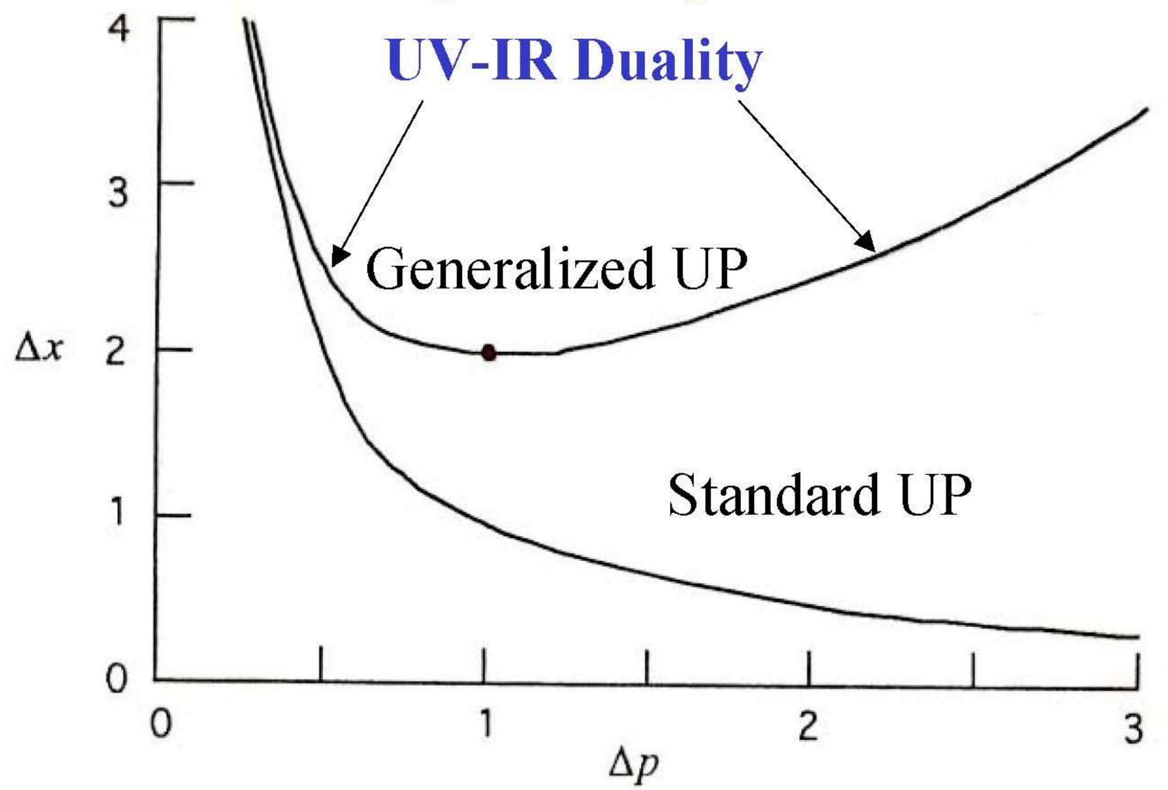


Generalized uncertainty principle - Gravitational correction to QM

$$\Delta x > \hbar/\Delta p + \xi^2 l_P{}^2(\Delta p/\hbar)$$

$$\hbar/\Delta p \longleftrightarrow \Delta p/\hbar$$

UV-IR Duality



GPU leads to BHR

- Generalized uncertainty principle argues for the existence of a minimum length (Planck length)
- Repeating what Hawking did using standard UP, invoking GUP to BH evaporation.

  → Hawking evaporation would come to a stop when BH radius reaches Planck length

  → Black hole remnant
- BHR can be a throat to the "bag of gold", a wormhole, a large interior volume.

- BHR is stable against further collapse due to its dynamics via GUP, not by symmetry principle.
- Analogy: Stability of Bohr atom protected by the standard uncertainty principle, not by symmetry.

Standard Uncertainty Principle

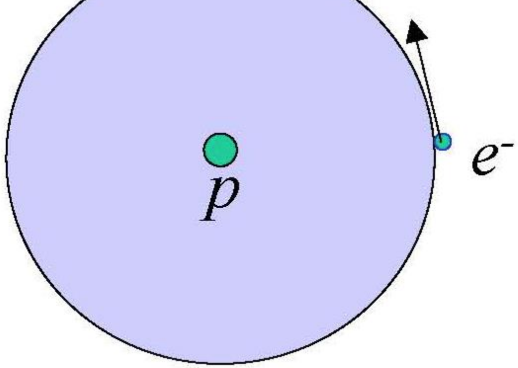
$$\left.\begin{array}{c}\Delta x \Delta p > \hbar \\ E = p^2/2m - e^2/r\end{array}\right\}$$

$$\delta E = 0 \longrightarrow r_{min} \sim \hbar^2/me^2 = r_{Bohr}$$

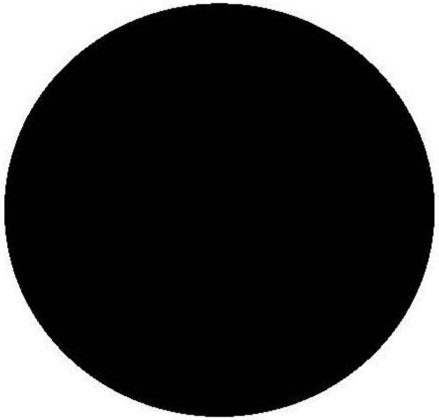
Generalized Uncertainty Principle

$$\left.\begin{array}{c}\Delta x > \hbar/\Delta p + \xi^2 l_P^2 (\Delta p/\hbar) \\ M_{BH} = c^2 r_s/2G\end{array}\right\}$$

$$\delta M_{BH} = 0 \longrightarrow r_{min} \sim 2\xi G m_P/c^2 = \xi l_P$$



Bohr Atom



Black Hole Remnant


Naked Black Hole Firewalls

Naked Black Hole Firewalls


臺大校訊

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中華民國 105 年 4 月 20 日 星期三 http://host.cc.ntu.edu.tw/sec/schinfo/schinfo_asp/show.asp 電話 33662041 E-mail:albert@ntu.edu.tw

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首次學界人士獲獎

第二屆 總统創新獎
R.O.C. (Taiwan) Presidential Innovation Award
頒獎典禮

物理系陳丕燊教授跨國團隊〈正面全裸的物理 赤裸的黑洞火牆〉發表 *Physical Review Letters* 期刊

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Molecular-type Workshop on Black Hole Information Loss Paradox, YITP, Kyoto, May 2015

Hideki Yukawa Memorial Hall

Yukawa Institute for Theoretical Physics

The five authors of the paper with another colleague during the discussion at the Yukawa Institute for Theoretical Physics: (L to R) Dong-han Yeom, Yen Chin Ong, Pisin Chen, Don Page, Yasusada Nambu, and Misao Sasaki.

$\Delta M \sim \sqrt{N}\,\omega \sim \sqrt{fM^2}\,\frac{1}{M} = \sqrt{f}$

At $f \sim \frac{1}{M}$, $\Delta M \sim \frac{1}{\sqrt{M}}$

$\sim 10^{-19} \sim \text{GeV}$

$\Delta R \sim \Delta M \sim \sqrt{f}$

Each particle localizes to

$\tilde{\delta} R \sim M$; N to $\delta R \sim \frac{M}{\sqrt{N}} \sim \frac{1}{\sqrt{f}}$

In this case $\Delta R = \delta R$ at $f=1$,

where $\Delta R \sim \delta R \sim 1$

$\Delta t_{evap} \sim M^2$

$\boxed{BH}\boxed{LHR}\boxed{EHR}$

Each particle has $p \sim \frac{1}{M}$.

$M \to (1-f)M$, fraction f evaporated

Number of particles $N \sim fM^2$

$\Delta P \sim \sqrt{N}\,p \sim \sqrt{fM^2}\,\frac{1}{M} \sim \sqrt{f}$. $\Delta v \sim \frac{\Delta P}{M} \sim \frac{\sqrt{f}}{M}$

$t \sim fM^3$. $\Delta x \sim \Delta v\, t \sim f^{3/2} M^2$

Each particle localizes to $\tilde{\delta} x \sim M$

N particles " " $\delta x \sim \frac{M}{\sqrt{N}} \sim \frac{M}{\sqrt{fM^2}} = \frac{1}{\sqrt{f}}$

$\Delta x \sim \delta x$ at $f^{3/2} M^2 \sim f^{-1/2} \Rightarrow f^2 M^2 \sim 1$, $f \sim \frac{1}{M}$.

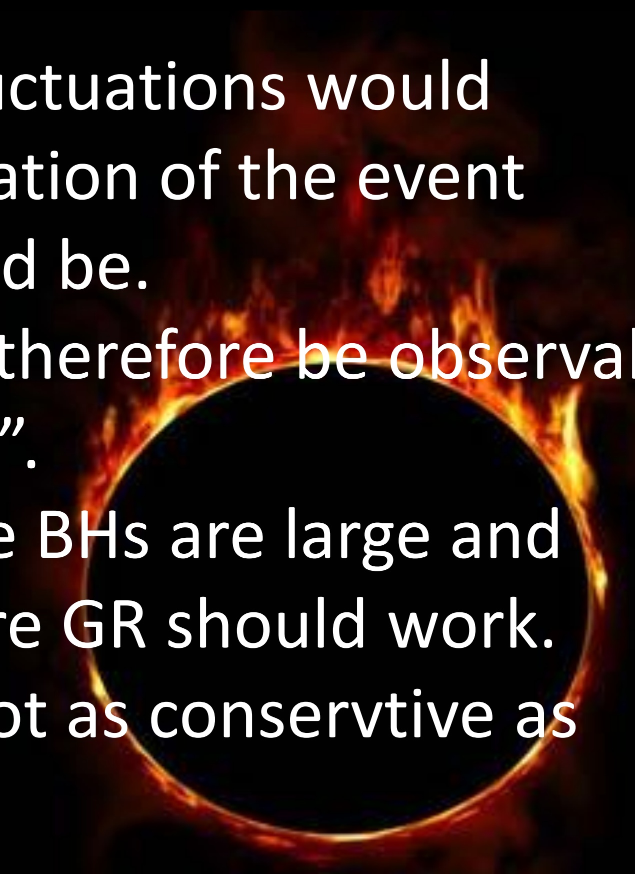
There $\Delta x \sim M^{-3/2} M^2 = M^{1/2}$

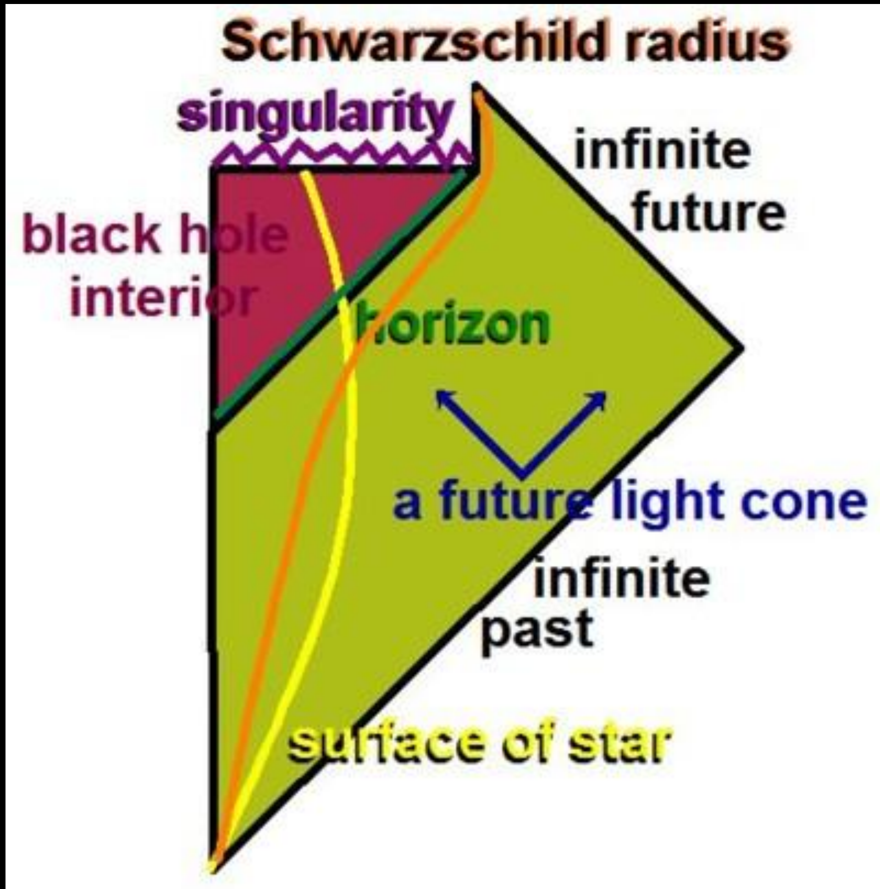
$\delta x \sim \frac{1}{\sqrt{f}} \sim M^{1/2} \to M_\odot^{1/2} \sim 10^{\frac{38}{2}} = 10^{19} \sim 10^{-14}\ \text{cm}$

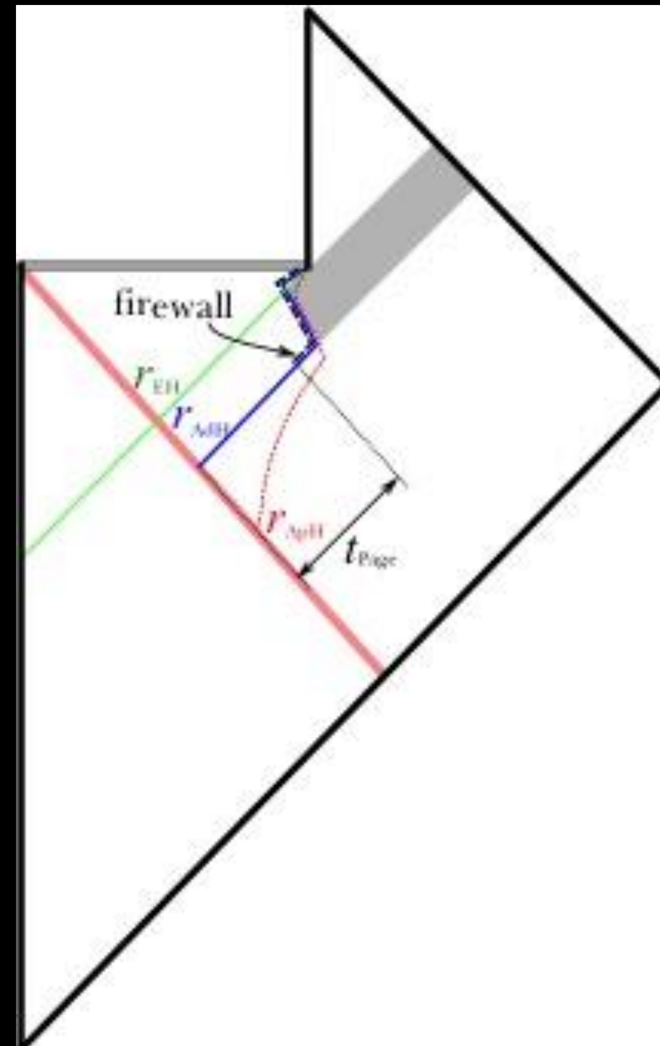
$N \sim fM^2 \sim M \sim 10^{38}$ $\quad \frac{\delta x}{M} \sim \frac{1}{\sqrt{fM}} \ll 1$ for $f \gg \frac{1}{M^2}$, $N \gg 1$

How would firewalls become naked?

- As a quantum process, fluctuations are inevitable in Hawking radiation.
- BH’s backreaction to these fluctuations would “teleologically” cause the migration of the event horizon inside of where it would be.
- The supposed firewall would therefore be observable to distant observers, or “naked”.
- On the other hand, stellar size BHs are large and have small curvatures; therefore GR should work.
- So the notion of firewalls is not as conservtive as AMPS argued.



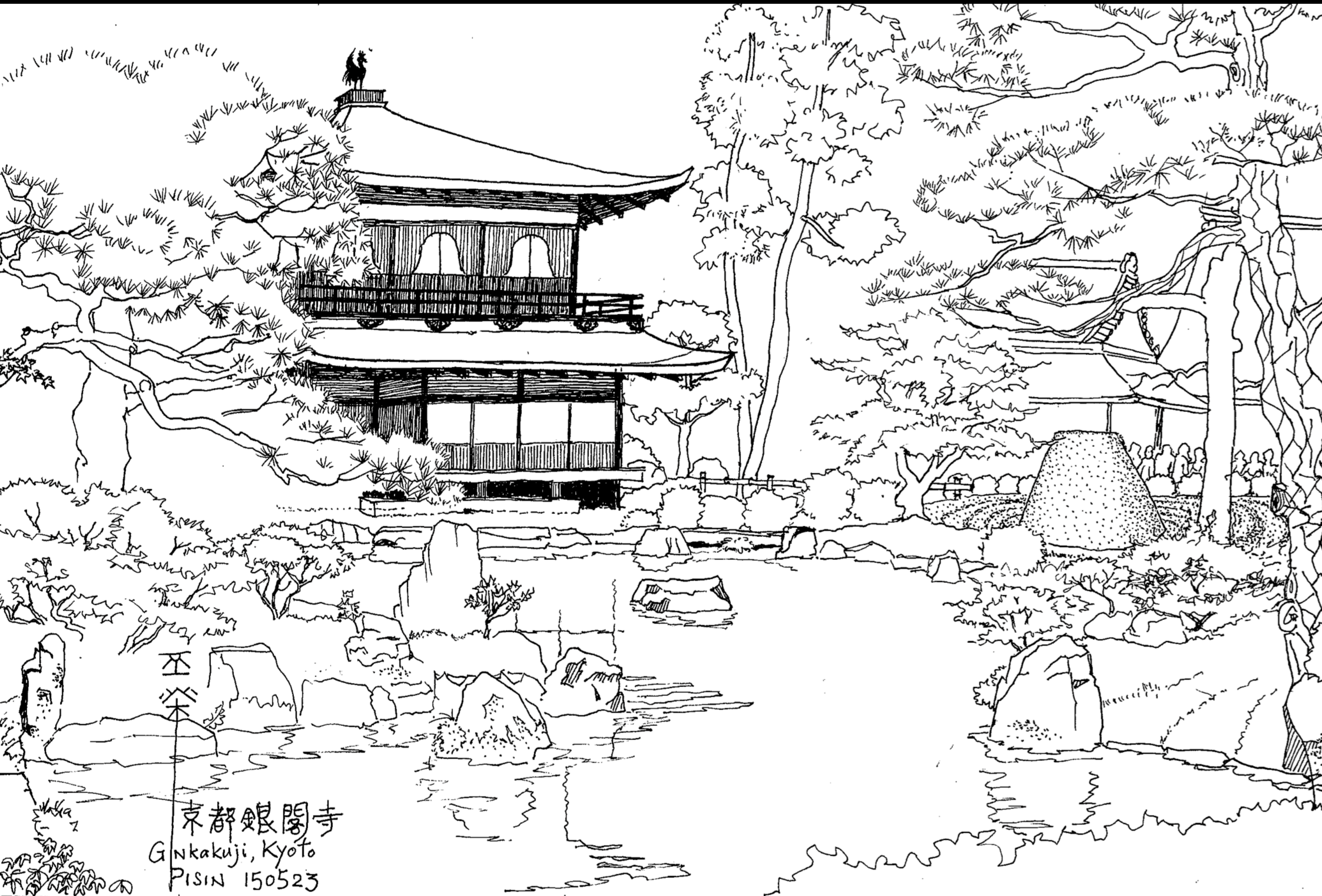




A conceptual Penrose diagram illustrating the formation of a Schwarzschild black hole from a collapsing null shell, and its subsequent Hawking evaporation. Here, the event horizon (r_{EH}) has been shifted inward some distance from the adiabatic horizon (r_{AdH}) due to a quantum fluctuation. This renders the firewall (denoted by the dashed curve that appears after the Page time t_{Page}) naked. The apparent horizon (r_{ApH}) is also shown for comparison, but light rays can escape from inside it, since the black hole is shrinking.


Kyoto Ginkakuji Temple (銀閣寺)

Kyoto Ginkakuji Temple (銀閣寺)

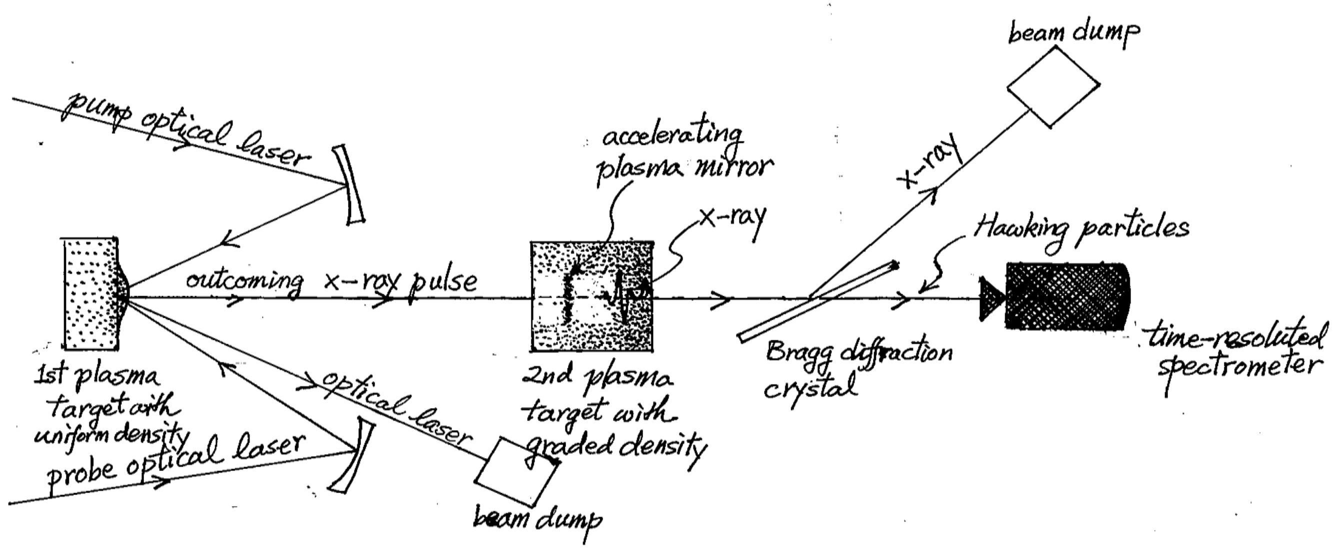



Kyoto Philosopher Path (哲學之道)

Kyoto Philosopher Path (哲學之道)

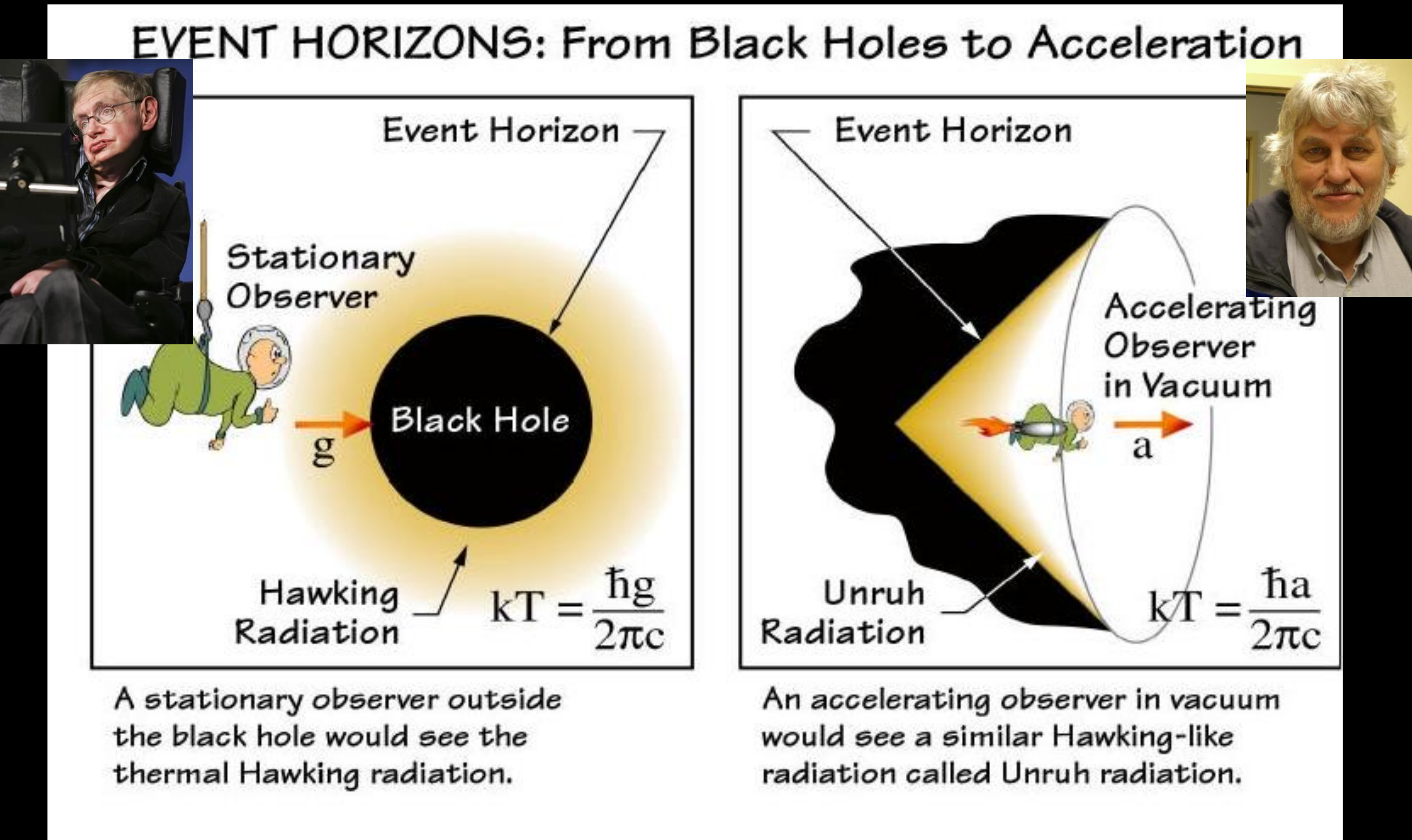

Accelerating Plasma Mirror

A conceptual design of the accelerating plasma mirror experiment

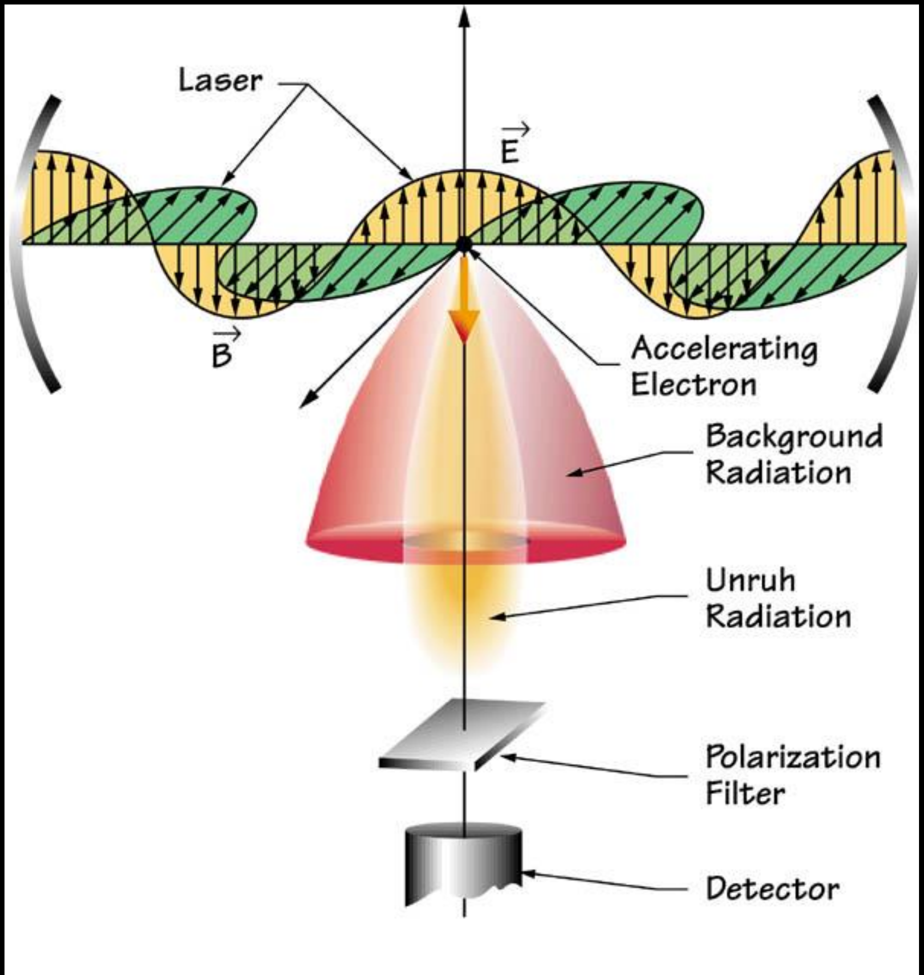


Schematic diagram for an accelerating plasma mirror experiment to investigate black hole information loss paradox

Unruh Effect vs. Hawking Effect



Proposed Unruh effect experiment (Chen-Tajima, 1999)



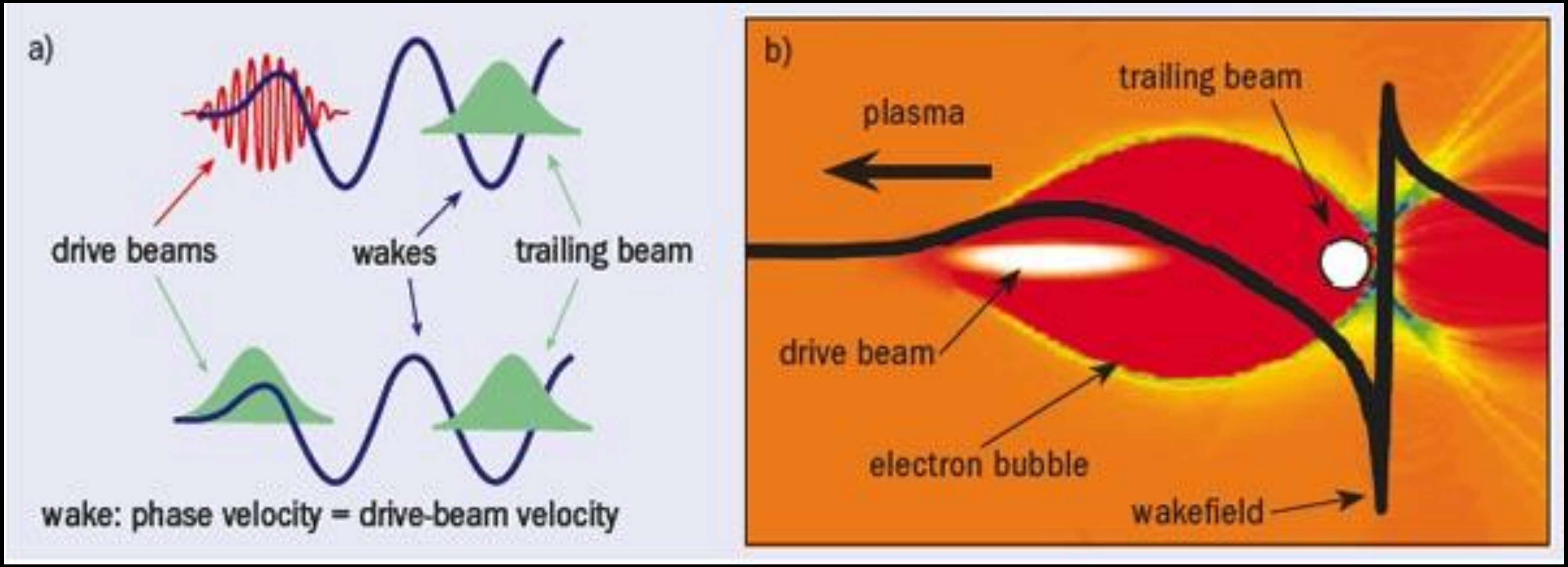
Schematic Diagram for Detecting Unruh Radiation

Fig. 2

Plasma wakefield acceleration

Tajima-Dawson (1979)- Laser driven

Chen-Dawson-Huff-Katsouleas (1985)- Particle beam driven



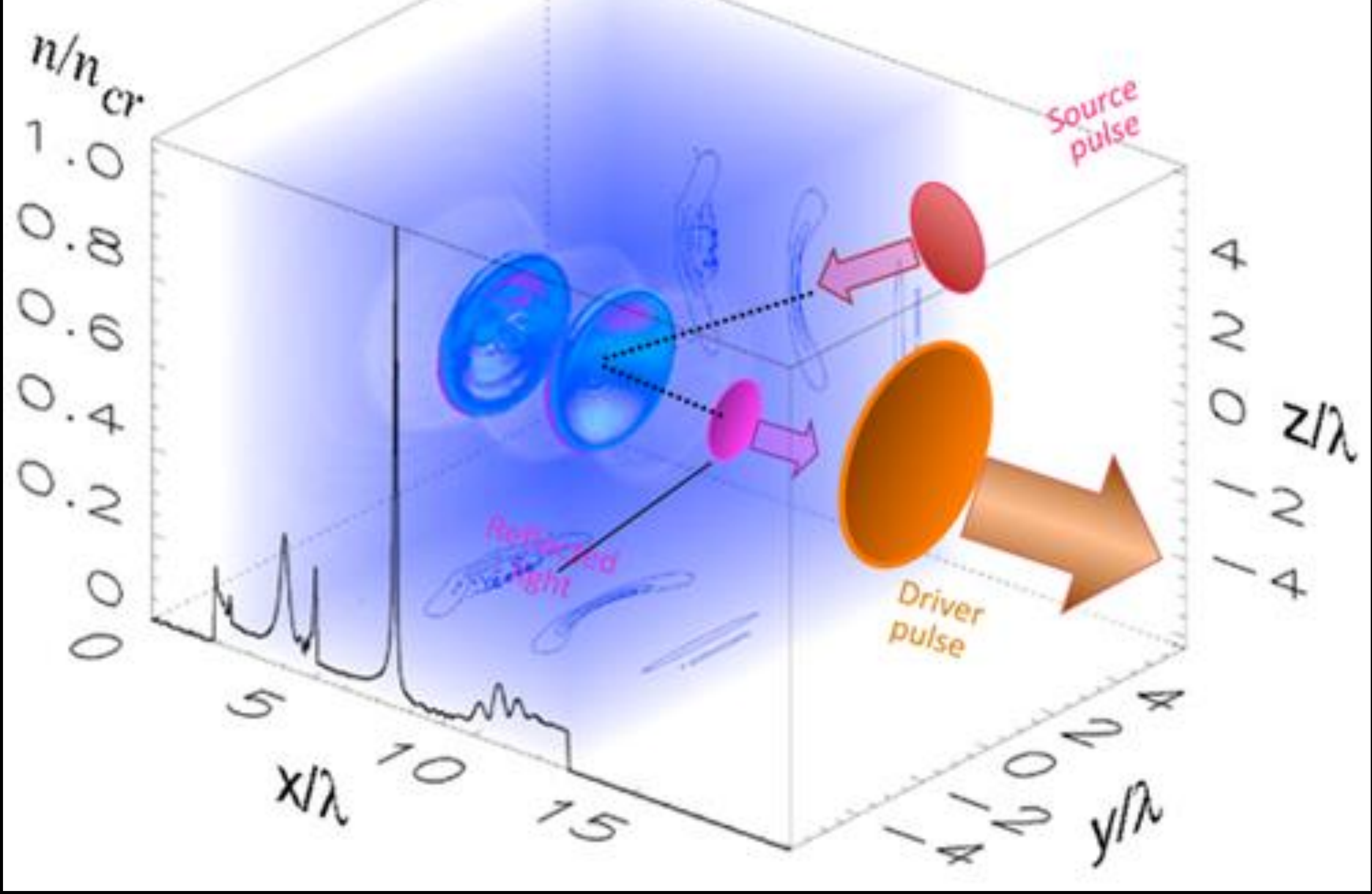
SLAC & LBL- Acceleration of O(100) GeV/m observed!

AWAKE- A new experiment at CERN

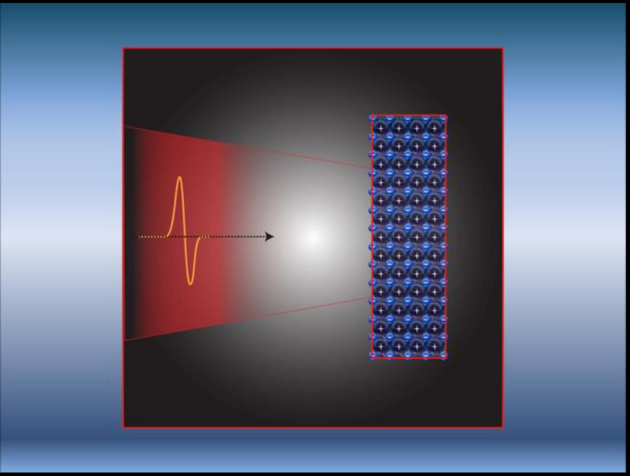
Relativistic Plasma Mirror

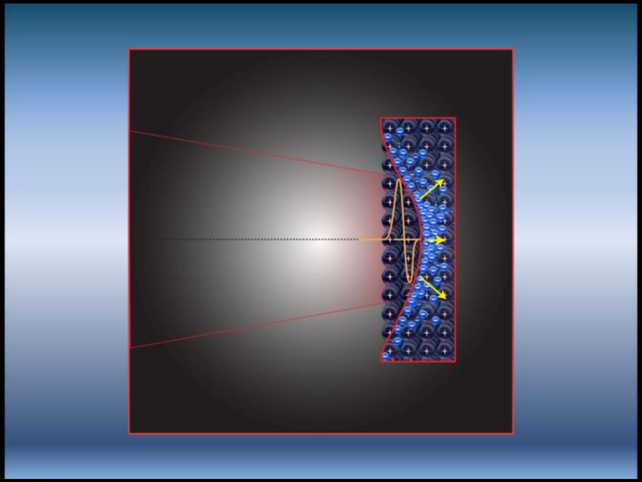
Bulanov, Esirkepov, Tajima (2003)

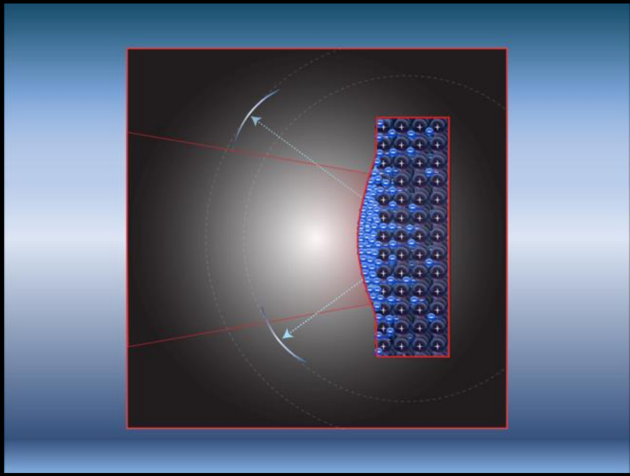
Reflected laser pulse Lorentz-boosted and tighter-focused.

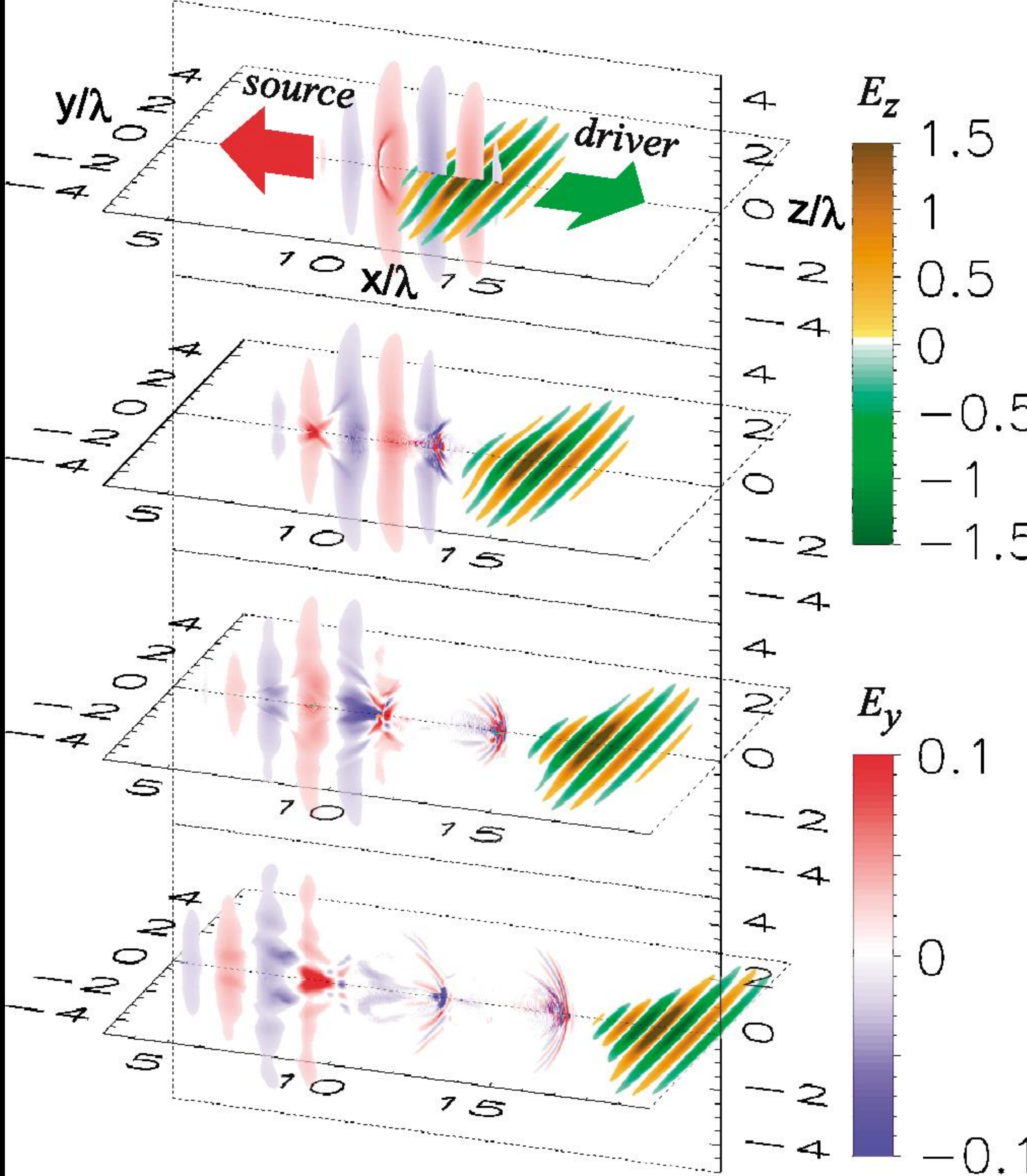


Plasma mirror can also be created by laser bouncing off the target









source
driver
y/λ
x/λ
z/λ
E_z
1.5
1
0.5
0
−0.5
−1
−1.5
E_y
0.1
0
−0.1

Plasma wakefield in the nonlinear regime acts like a tunami

Accelerating plasma mirror

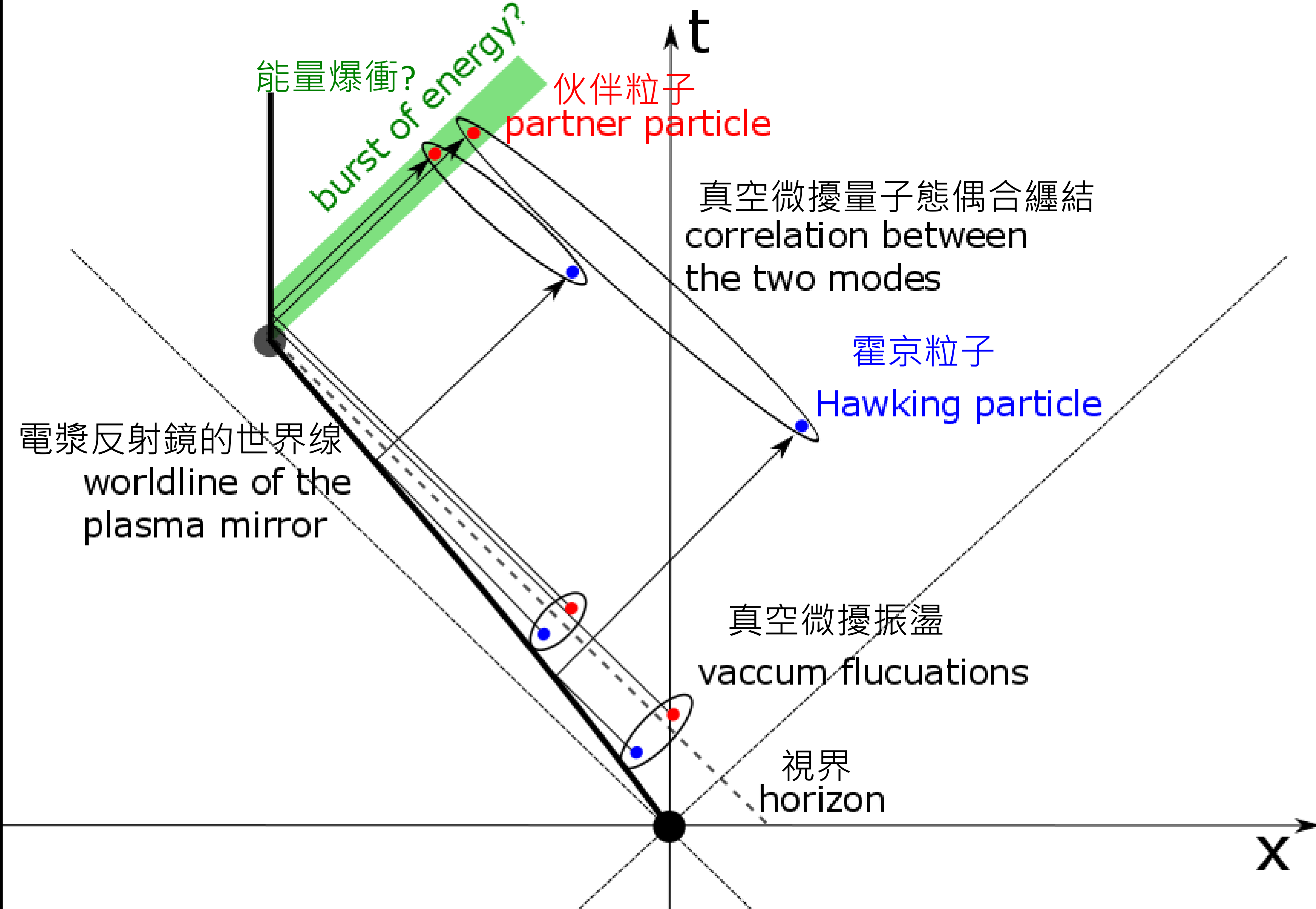
- Born relativistic
- Laser velocity in plasma can be accelerated and therefore its wakefield
- Acceleration can increase in time and stop abruptly

What can it offer?

- Investigation of correlation of partner modes and possible final outburst of energy

What it cannot offer?

- Being in flat space, unitarity preserved: no loss of information
- No singularity either

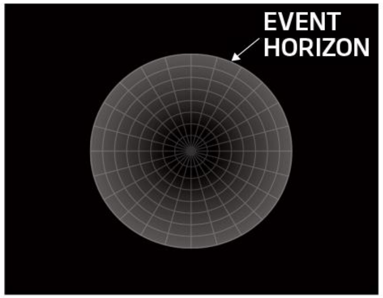


How would accel. plasma mirrors reveal the secrets of black hole information loss paradox?

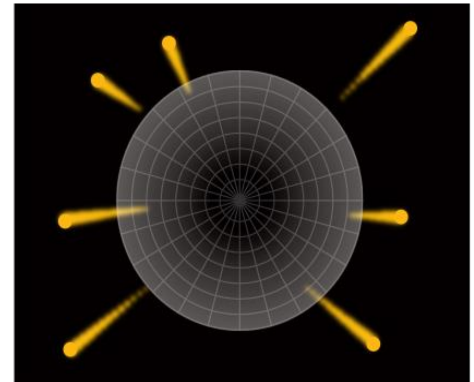
Summary – The war continues to rage

Brief history of black holes

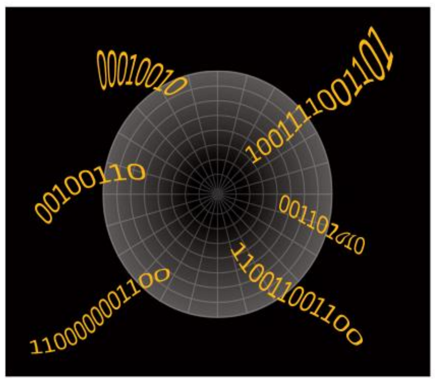
1916
Black holes emerge from general relativity: nothing, not even light, escapes the event horizon



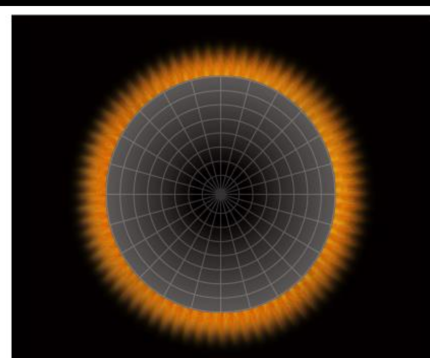
1974
Black holes emit **Hawking radiation** thanks to quantum mechanics



2004
Hawking accepts that **information escapes** from black holes



2012
Escaping information ignites **firewall,** which can't be reconciled with general relativity



2016
Firewalls would be naked

?