Black Holes, Information, and String Theory

29 October 2018

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Carlsberg Distinguished Postdoctoral Researcher at the NBIA

Structure of talk: 20th and 21st century physics

1. Gravity and Black Holes(BHs)
- Newton
- Einstein & Democracy
- Schwarzschild & Black Holes
- Hawking

2. Quantum mechanics & Info
- Bohr & Heisenberg
- Dirac & Feynman
- Vacuum fluctuations
- Hawking & Radiation

3. Thermodynamics & Hawking
- Boltzmann & Entropy
- Entropy & Temperature
- Thermo & Quantum for BHs
- (Quantum = Thermodynamics)

4. String Theory & Firewalls?
- Maldacena & Holography
- Quantum Gravity & Strings
- Success: Strings & Black Holes
- Firewalls & (exciting) future!

Structure of talk: 20th and 21st century physics

Sociological disclaimer(s):

There are Heroes here, but... physics is not just by heroes.

Normal people can do physics (for my sake, thank goodness)

Further, the "heroes" who I do list are but a subset of those who've done important work.

EG: Hawking's co-authors!

Part I:
Black Holes, Relativity & Quantum Mechanics

- Lay groundwork for the talk

- Introduce Black Holes

- Introduce Einstein's Relativity

- Introduce Quantum Mechanics
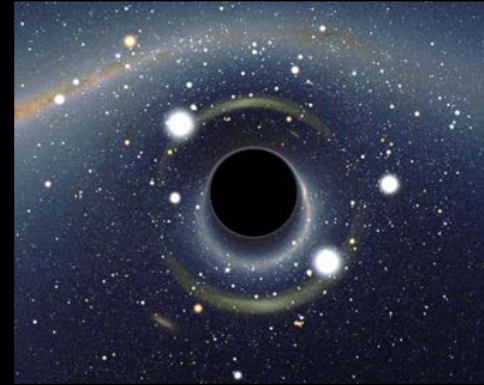
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Newton's Gravity

Any particle of matter in the universe attracts any other with a force varying directly as the product of the masses and inversely as the square of the distance between them
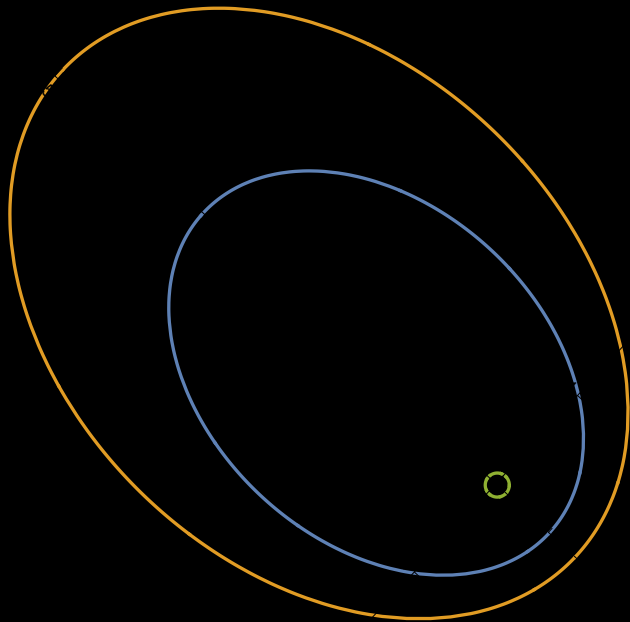
Newton's Gravity

Any particle of matter in the universe attracts any other with a force varying directly as the product of the masses and inversely as the square of the distance between them

$$F(r) = G_N \frac{m\ M}{r^2}$$

Newton's Gravity

- Orbits: closed and elliptic

- Stable solar systems

- Action at distance≠Relativity

- Position and speed well-defined ≠ Quantum Mech

Galileo's Insight (led to Newtonian Physics)

- Bigger masses, bigger forces

- In exact proportion

- Different masses, same acceleration!
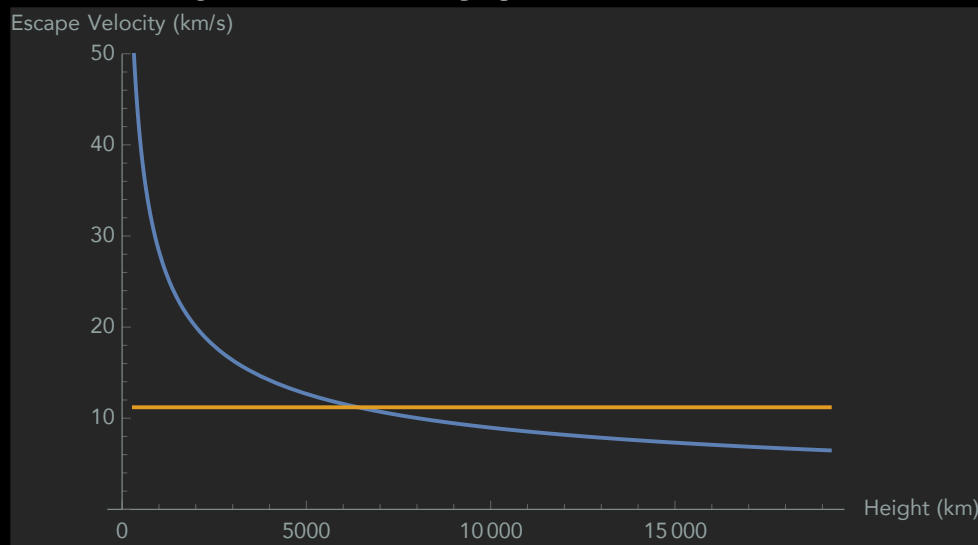
- Speed changes *universally*

"Black Holes" in Newtonian Gravity

- Recall: light-speed is finite

- Recall: "escape velocity"

- Escape velocity > light-speed, then *effectively* a Black Hole

- Simply a picture; will change

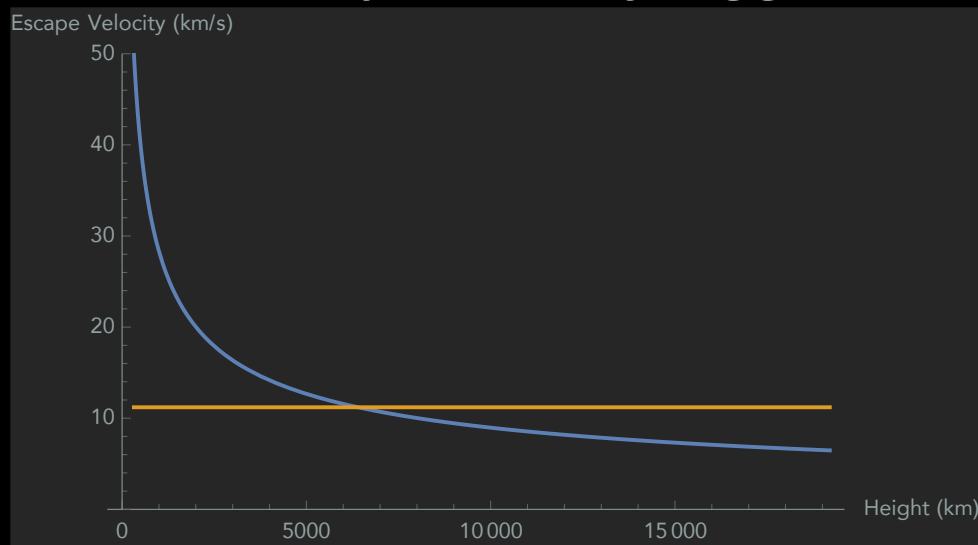# "Black Holes" in Newtonian Gravity

Escape velocity for Earth:


Radius ~ 6400 km; v ~ 11 km/s

- Recall: light-speed is finite

- Recall: "escape velocity"

- Escape velocity > light-speed, then *effectively* a Black Hole

- Simply a picture; will change

"Black Holes" in Newtonian Gravity

Note: escape velocity bigger

for more compact "Earths"!

- Recall: light-speed is finite

- Recall: "escape velocity"

- Escape velocity > light-speed, then *effectively* a Black Hole

- Simply a picture; will change

Einstein: democracy between space & time

- Newton: Light-speed, "c", is not special

- Einstein: Light-speed, "c", **IS** special

- Rocket-flashlights
  - → = normal-flashlights
  - → Can't speed or slow light!

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$$v_1 \oplus v_2|_{\text{Newton}} := v_1 + v_2$$
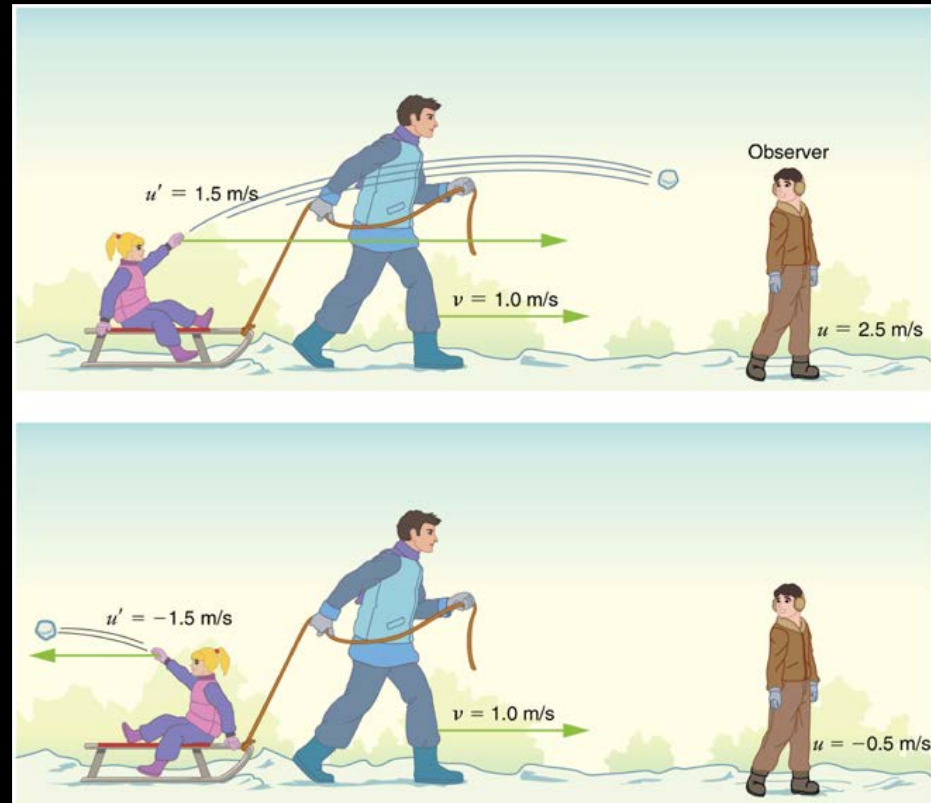
$$v_1 \oplus v_2|_{\text{Einstein}} := \frac{v_1 + v_2}{1 + (v_1 v_2 / c^2)}$$

$$v \oplus c|_{\text{Einstein}} = c$$

Einstein: democracy between space & time

- Space and time interwoven

- Relative motion: durations, lengths appear different
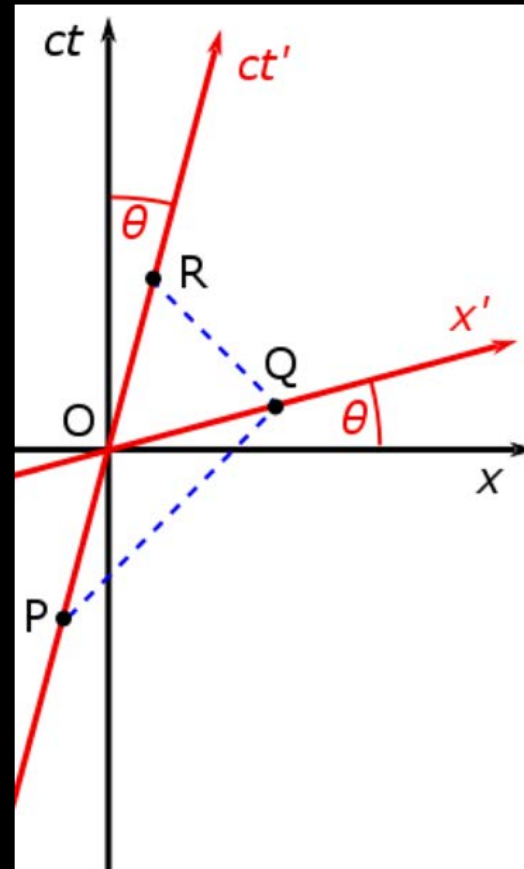
Einstein: democracy between space & time

- Gravity accelerates things

- Velocities change with time

- Space and time are *warped*, stretched by gravity

- Einstein's equations say how
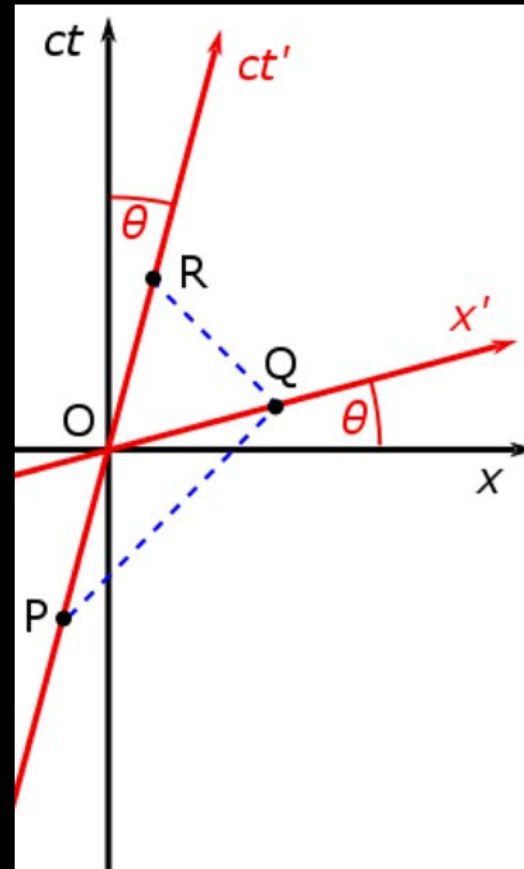
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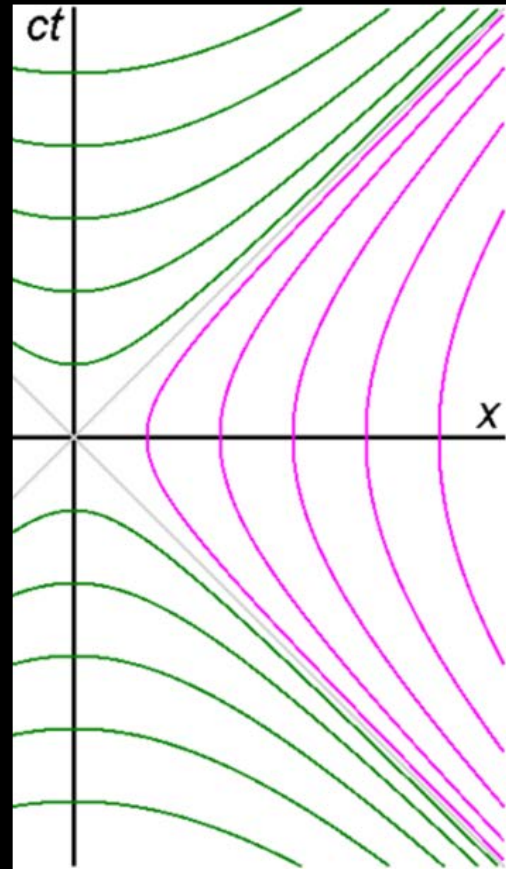
Black Holes in Einstein Gravity: Schwarzschild

$$R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$
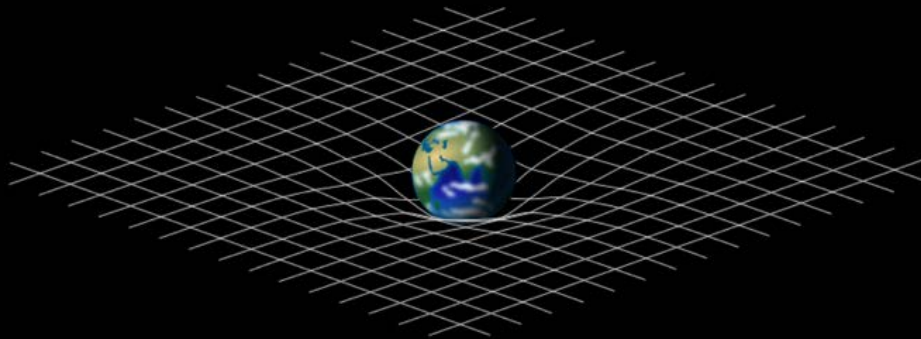
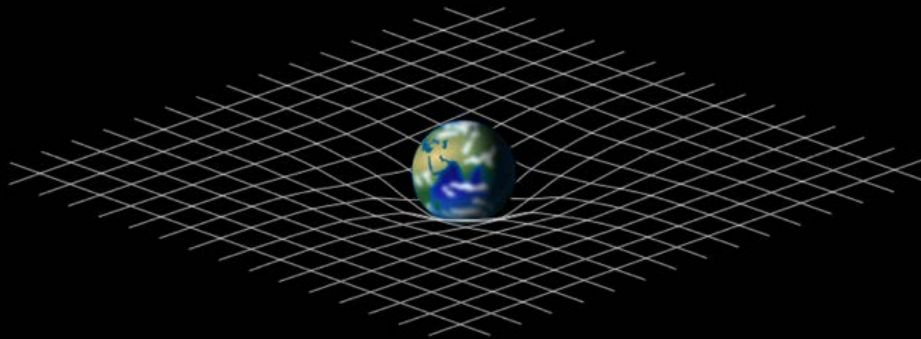**SCHWARZSCHILD'S SOLUTION**

- Schwarzschild: "gravity" for a star in General Relativity (GR)

- Far away, it gives the result in Newton's gravity. Good!

- Close in, it has **new features!**
   → First, simplest solution to GR
   → New stuff! Still mysterious!!

Black Holes in Einstein Gravity: Schwarzschild
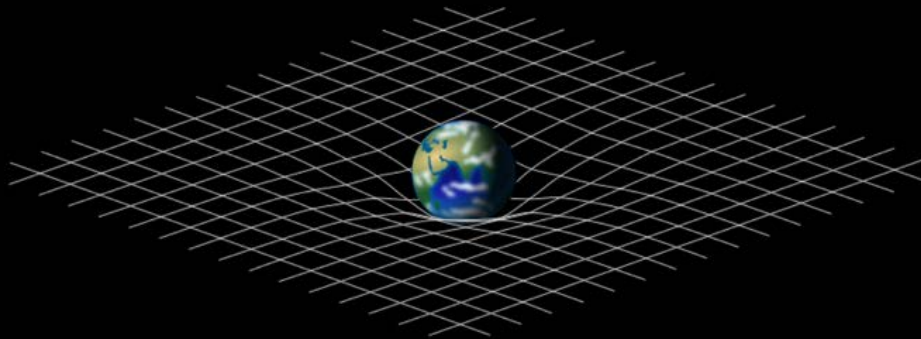
$$R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

SCHWARZSCHILD'S SOLUTION

- Einstein's Equations = "GR"
  - →Winter 1915-1916

- Schwarzschild: first solution!
  - →WWI German Artilleryman
  - →Found time to study GR
  - →Famous solution ALSO 1916!

Black Holes in Einstein Gravity: Schwarzschild

$$R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

SCHWARZSCHILD'S SOLUTION

- Light moving away from star:
  - →Does not "slow down"
  - →But does lose *energy*

- Compact → "Black Holes"
  - →Photon energy > 0
  - →Bounds radius
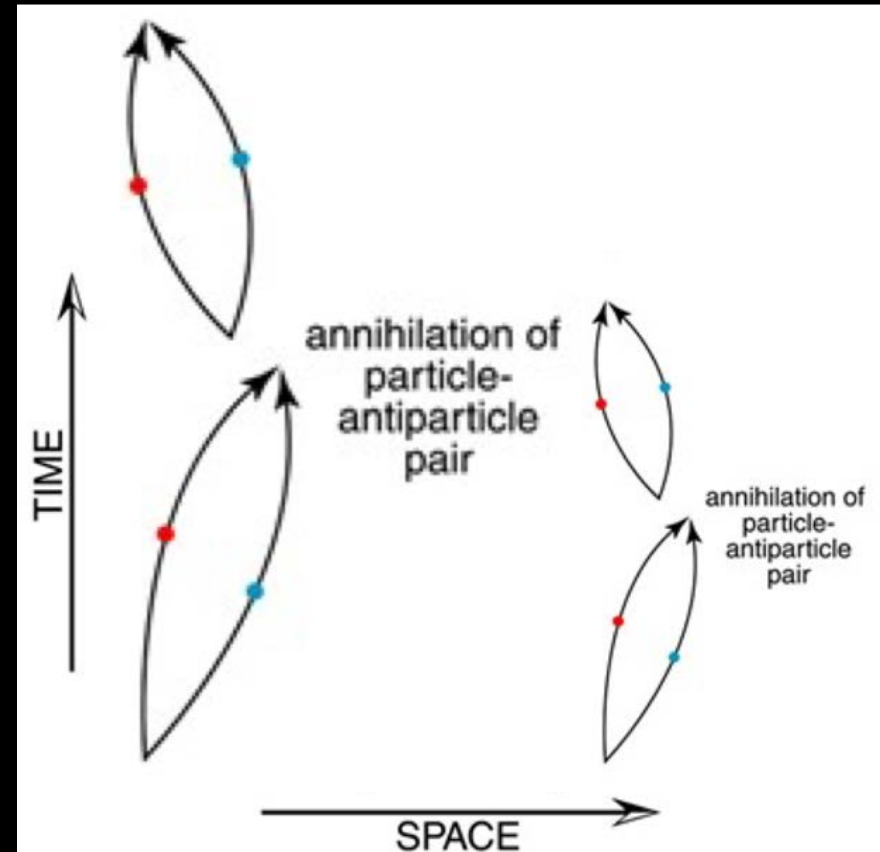 - →Below it, light trapped!

Black Holes in Einstein Gravity: Schwarzschild

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$$r_{\mathrm{Sch}} = 2G_N M/c^2$$

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  - → Photon energy > 0
  - → Bounds radius
  - → Below it, light trapped!

Black Holes in Einstein Gravity: "No Hair"!

- Compact star = _**Black**_

- Very few features = "No Hair"
  - →Mass (of course)
  - →Spin = conserved
  - →Charge = conserved

- That's it! BH = "Featureless"!

Black Holes in Einstein Gravity: Hawking

- **Thermal** radiation from Black Holes!

- Simple picture:

- Fluctuations are inherently quantum (next part of talk)!

Black Holes in Einstein Gravity: Hawking

- **Thermal** radiation from Black Holes!

- Simple picture:

- Fluctuations are inherently quantum (next part of talk)!

Black Holes in Einstein Gravity: Hawking

- **Black Holes Evaporate!**

- Conserved quantities
  - →Mass
  - →Charge
  - →Angular momentum

- Radiation removes mass (and charge etc.): evaporation.

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Electrons, Protons & Atoms: Maxwell
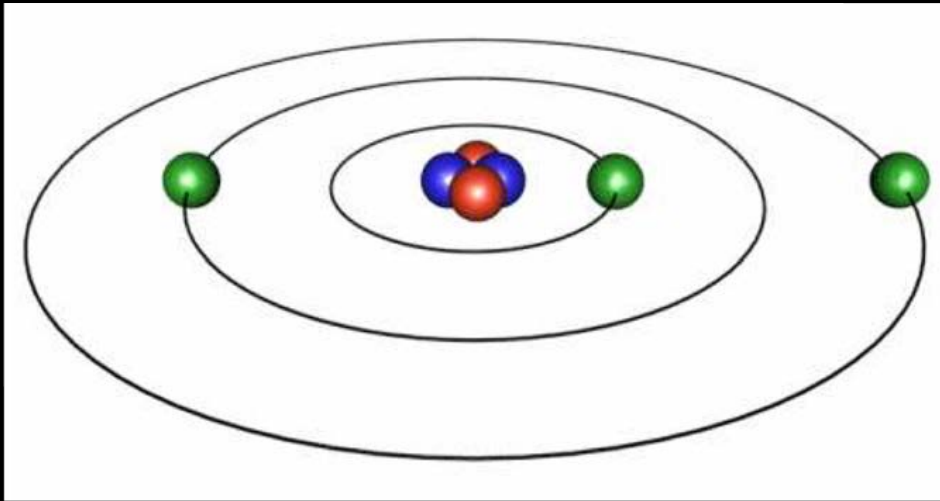
- Circular motion
  - →Continuous
  - →Swinging bricks = heavy
  - →Heavy = force = accelaration

- Accelerating charges radiate
  - →Old style TVs (sort of)
  - →X-rays

- Classical picture of atoms = constant radiation, unstable

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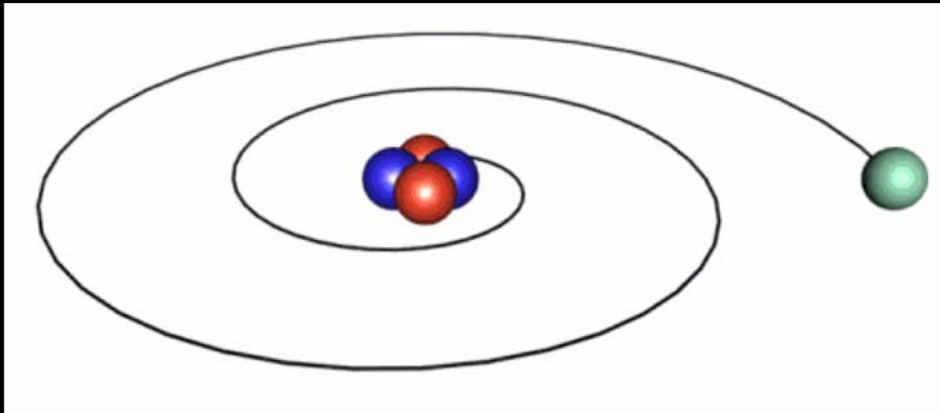
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Electrons, Protons & Atoms: Bohr
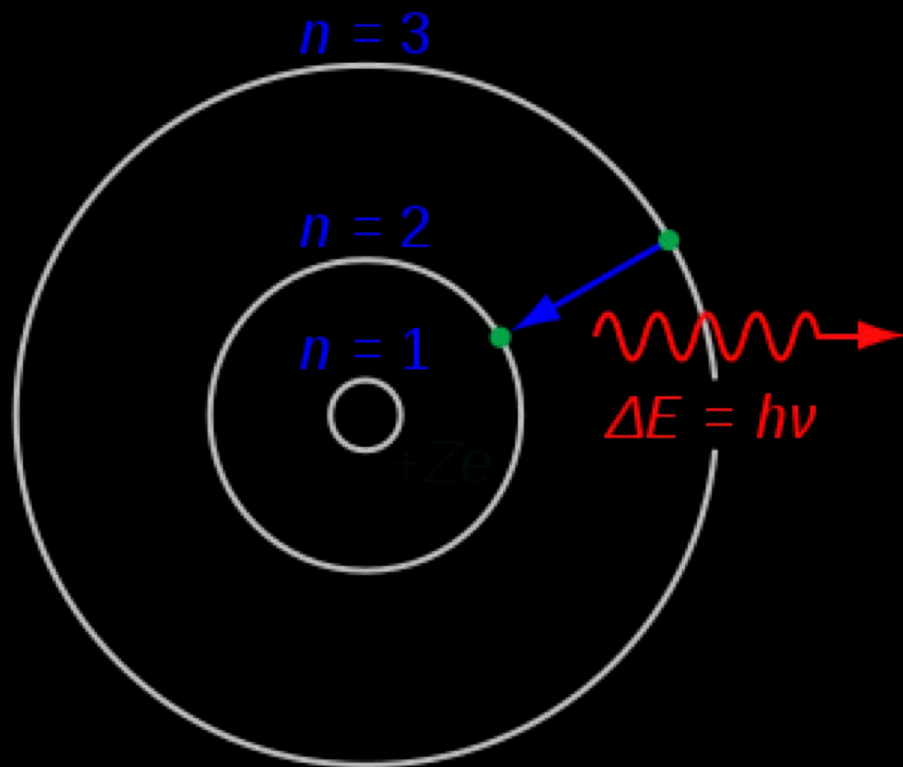
- Maxwell Atom: continuous

- Bohr Atom: *quantized*

- Orbits quantized, thus stable!

- Rough question: Why? Fixed in Quantum Mechanics.

Space and Time in Quantum Mechanics

- Quantum Mechanics = "QM"

- Positions are probabilistic

- Probabilities evolve in time
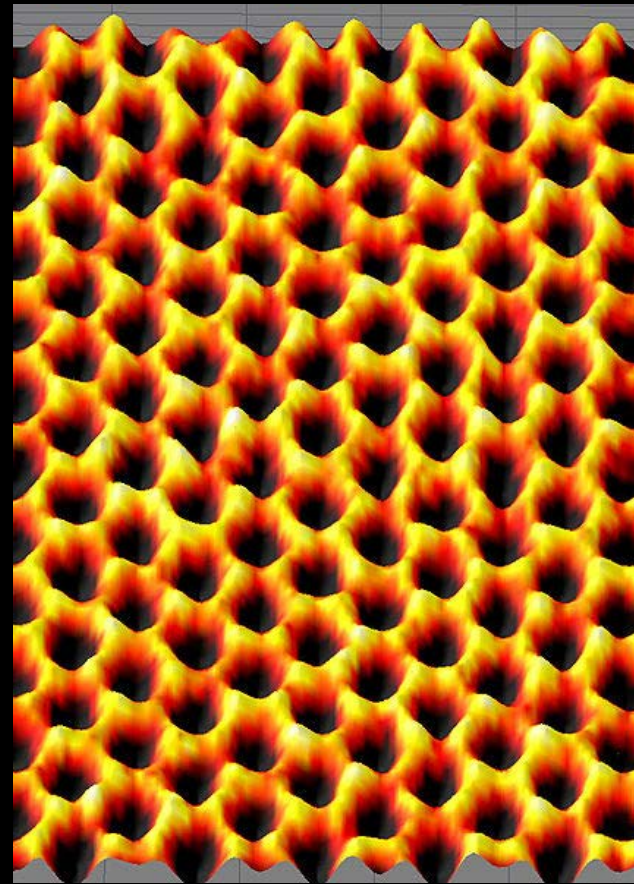
Space & Time: Quantum Mech vs Relativity

- "Where will it be?"
  - →Probabilistic
  - →Given by Schrodinger Eq
- "How old is it?"
  - →An input into Schrodinger Eq
  - →Time marches on...
  - →...but positions don't
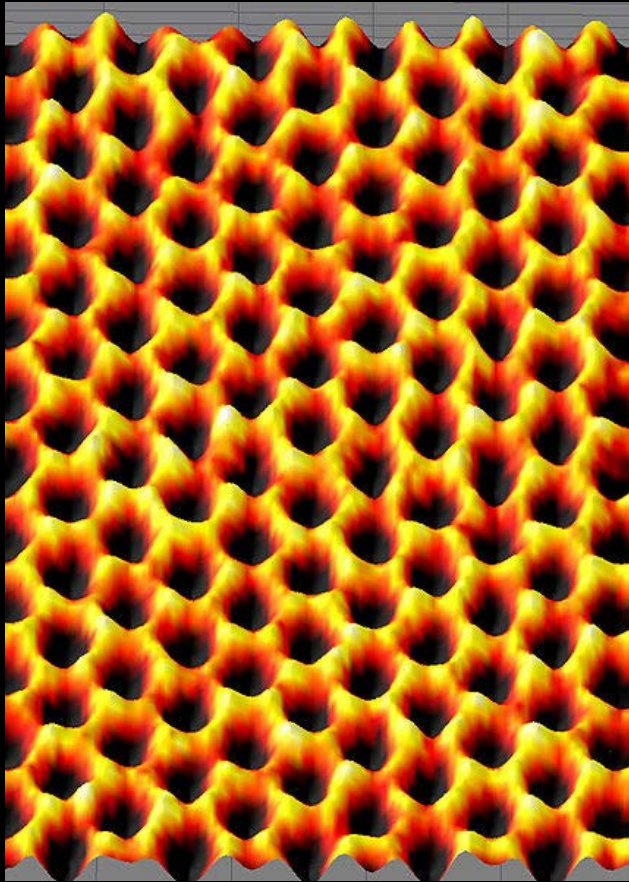- QM: space-time asymmetry!
- GR: space-time symmetry!
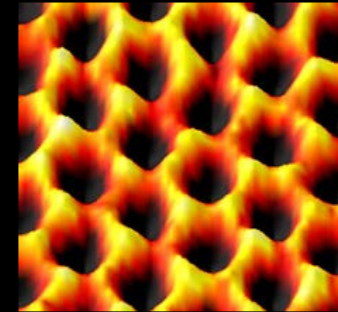
QM: $\hat{\mathbf{x}} \longleftrightarrow\!\!\!\!/ \ \mathbf{t}$

GR: $x \longleftrightarrow t$
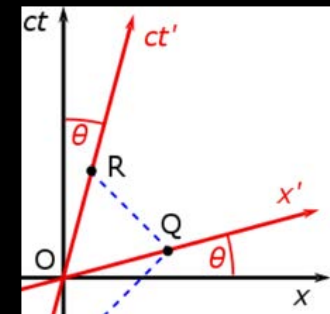
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QM: $\boxed{\hat{\mathbf{x}} \longleftrightarrow\!\!\!\!/ \ \mathbf{t}}$

$$i\hbar\frac{\partial}{\partial t}\psi(\hat{\mathbf{x}},t) = \left(-\frac{1}{2m}\partial_{\hat{\mathbf{x}}}^2 + V(\hat{\mathbf{x}})\right)\psi(\hat{\mathbf{x}},t)$$

GR: $\boxed{x \longleftrightarrow t}$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

Electrons, Protons & Atoms: Heisenberg

- Uncertainty Principle

- Apply to electrons and atoms

- Position vs. Momentum

- Time vs. Energy

Electrons, Protons & Atoms: Heisenberg

Real AFM image of single-layer graphite:

Note: Electrons and atoms are *really* "smeared"!
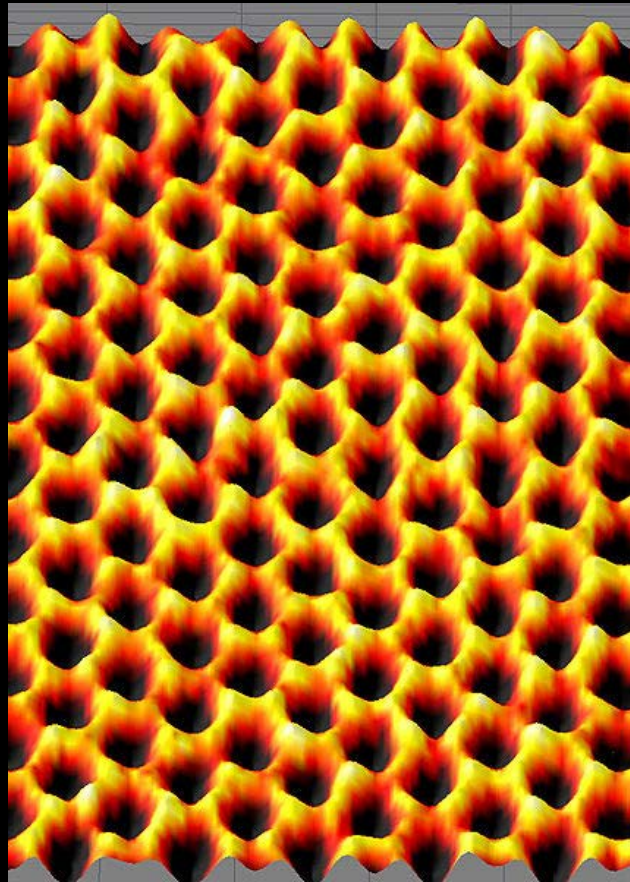
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Electrons, Protons & Atoms: Heisenberg

Idealized picture for single-layer graphite:

Note: ***naive*** idealized pic differs from ***real image***!
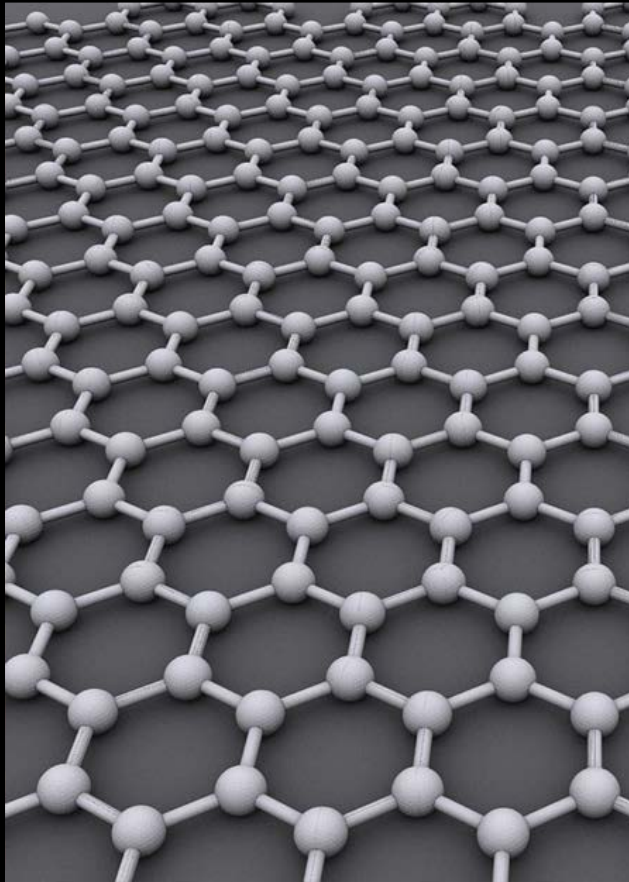
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Electrons, Protons & Atoms: Dirac & Feynman

$$E = mc^2$$

- Relativistic Quantum Mech?!

- Uncertainty for "empty" "vacuum"

- Vacuum fluctuations

- "Empty" space roils and boils
  → …must conserve energy!

Electrons, Protons & Atoms: Dirac & Feynman

$$E = mc^2$$

"VACUUM" = "NOTHING"

= "NO PARTICLES"

= "NO ENERGY"

"Empty" depends on distance!

- Relativistic Quantum Mech?!

- Uncertainty for "empty" "vacuum"

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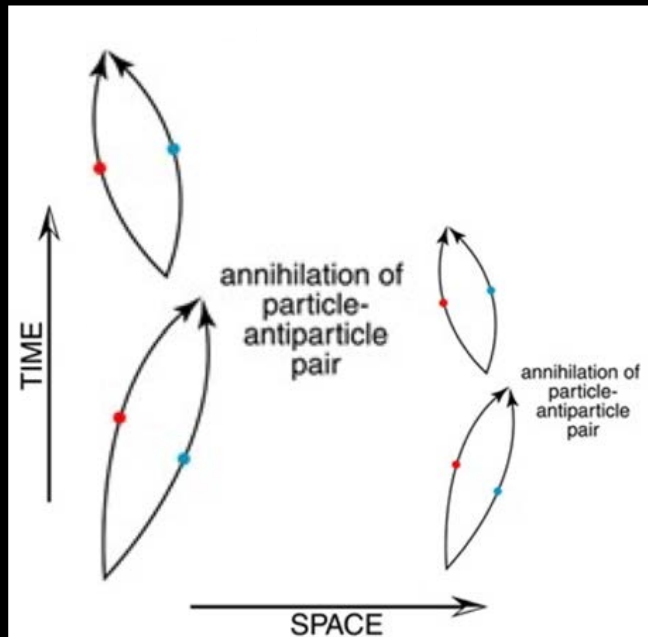
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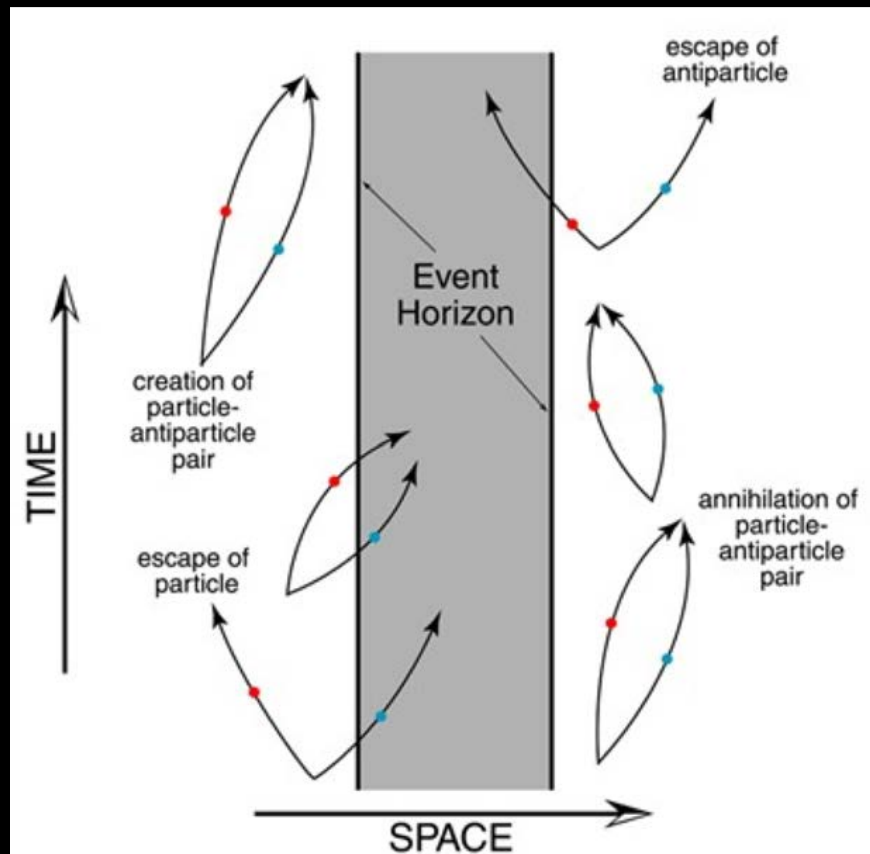
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Hawking Radiation → BH Evaporation

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- Radiation removes mass (and charge etc.): evaporation.
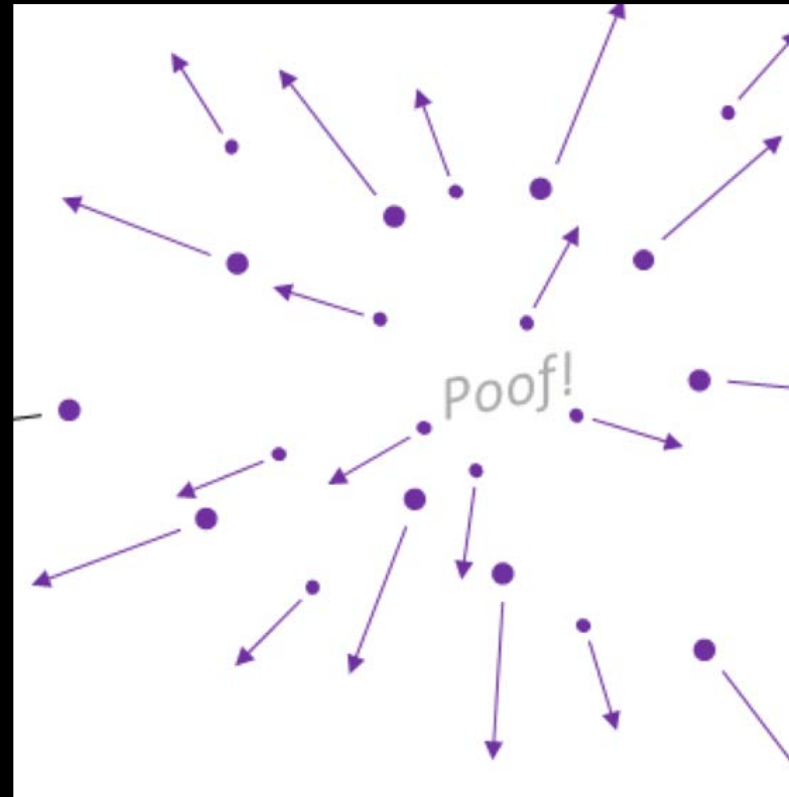
Ageing Atoms in Quantum Mechanics
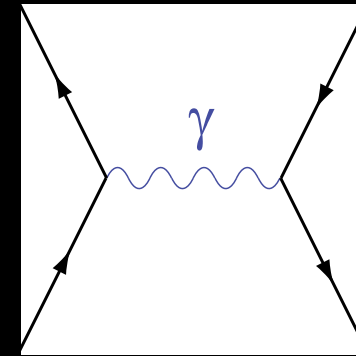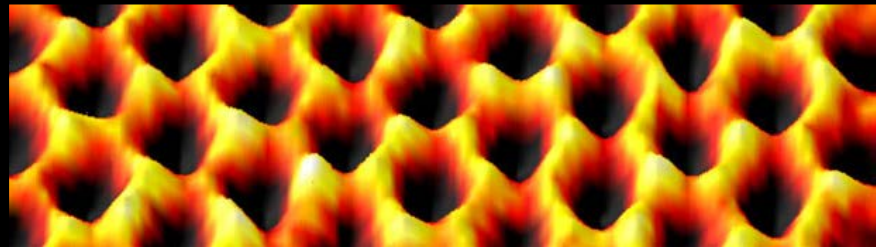
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- Experimentally verified

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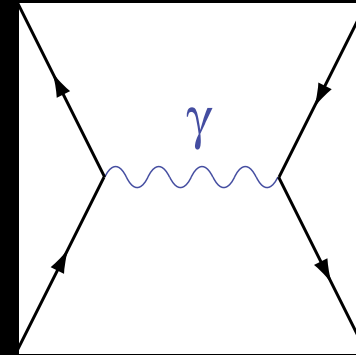
Ageing Atoms in Quantum Mechanics

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Ageing Black Holes in Quantum Mechanics

- Many quantum systems =
a bigger quantum system

- Stars: **huge** quantum systems

- Stars: burn-out and collapse,
form Black Holes (BHs)

- BHs evaporate and…vanish?!
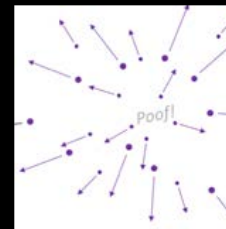
Ageing Black Holes in Quantum Mechanics

- Black holes are "unstable"

- Is information preserved???

- Hard to think about...

- ...without Quantum *Gravity*
  (very hard)
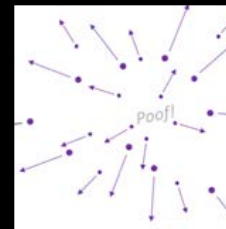
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Relativity, Black Holes & Quantum Mechanics

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- We have introduced Quantum Mechanics

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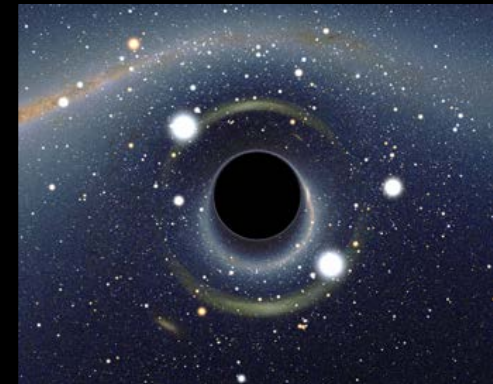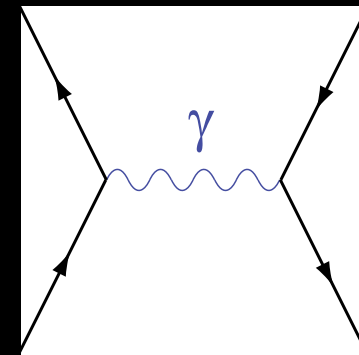
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   - Einstein & Democracy
   - Schwarzschild & Black Holes
   - Hawking

2. Quantum mechanics & Info
   - Bohr & Heisenberg
   - Dirac & Feynman
   - Vacuum fluctuations
   - Hawking & Radiation

3. Thermodynamics & Hawking
   - Boltzmann & Entropy
   - Entropy & Temperature
   - Thermo & Quantum for BHs
   - (Quantum = Thermodynamics)

4. String Theory & Firewalls?
   - Maldacena & Holography
   - Quantum Gravity & Strings
   - Success: Strings & Black Holes
   - Firewalls & (exciting) future!

Part II:
Black Holes, Quantum Gravity & Firewalls

- Introduce Thermodynamics & Entropy

- Entropy/quantum info & the Horizon

- Holography, String Theory & Maldacena
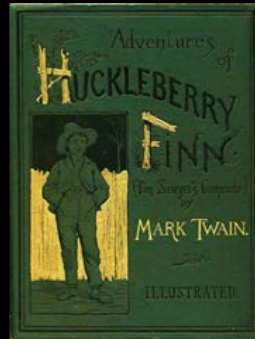
- Recent controversy & Polchinski's "Firewalls"

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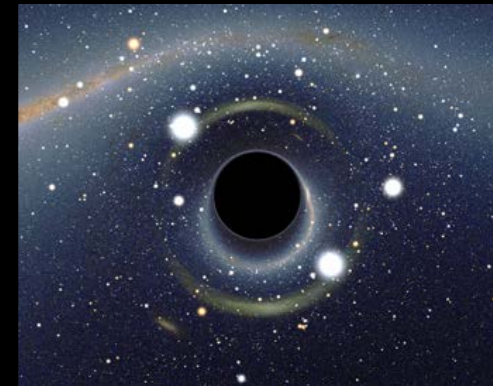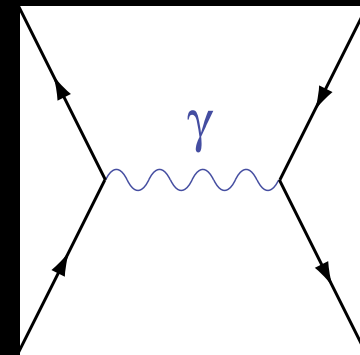
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"To Destroy a Book"/"BH Info Paradox in QM"

- Burning book scrambles info

- "Book" = "complex QM state"

- "Just" time evolution of a complicated QM "state"

- Information is (in principle) preserved

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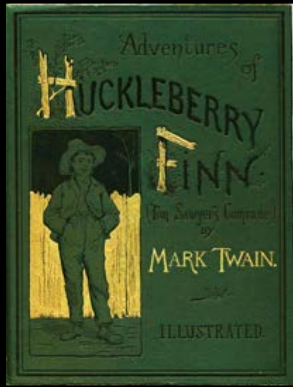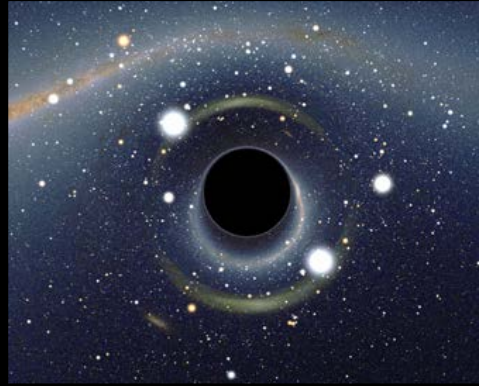- Information is (in principle) preserved
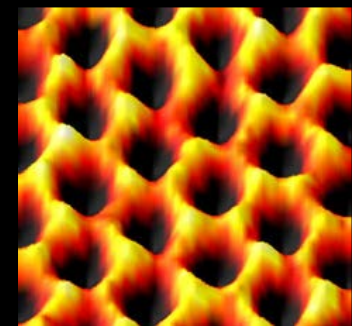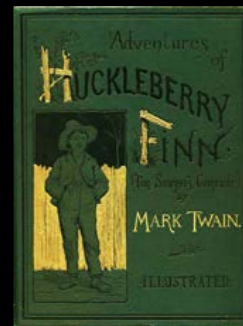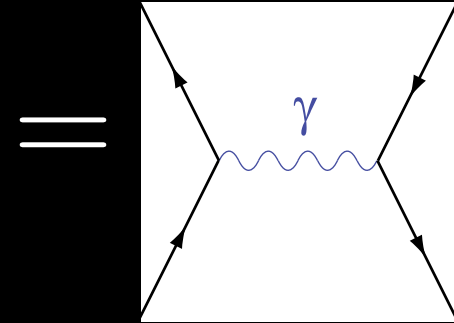
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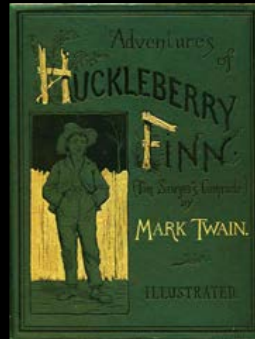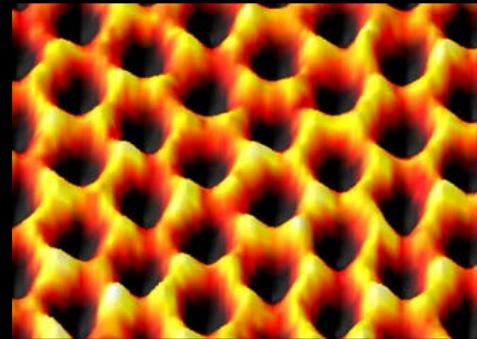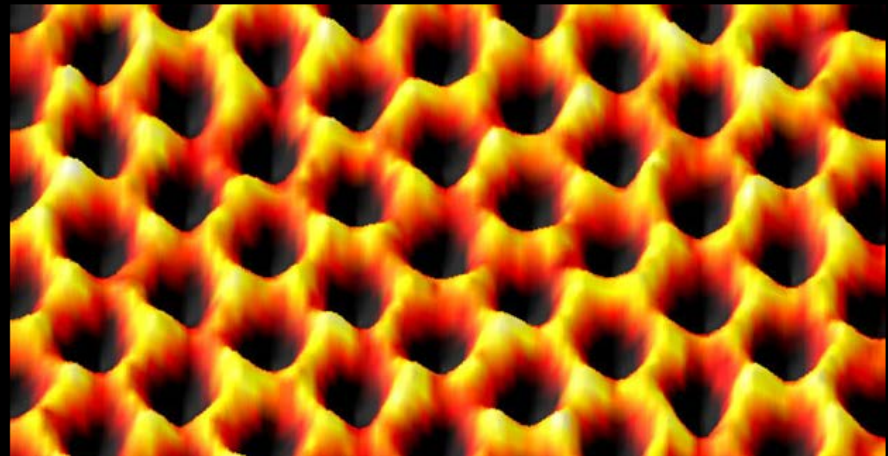
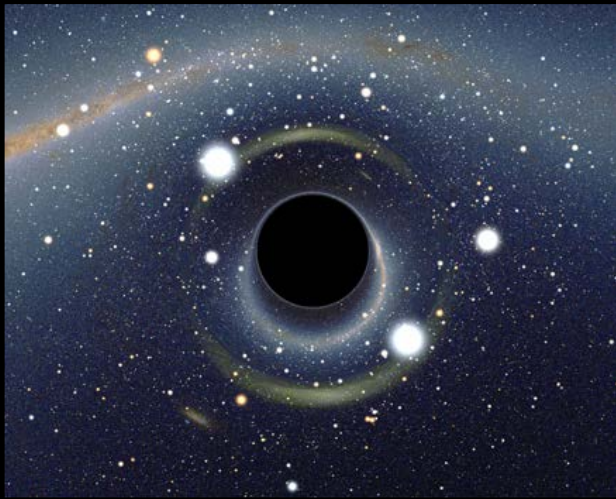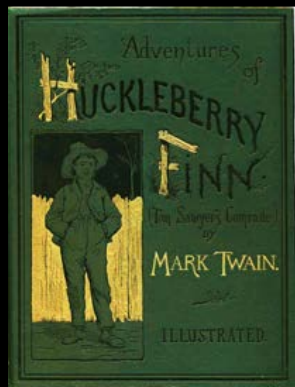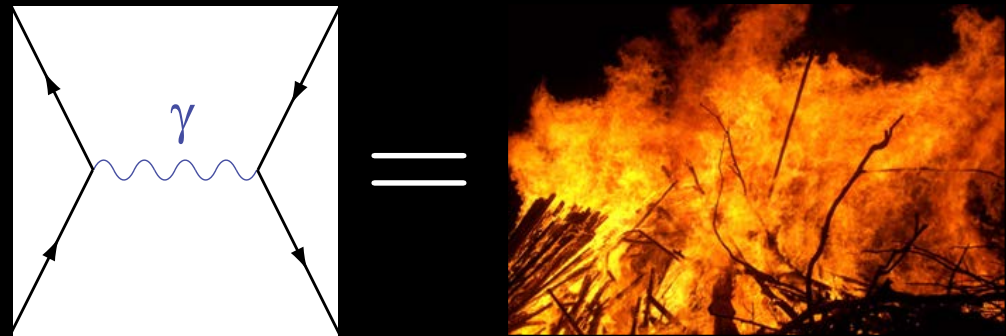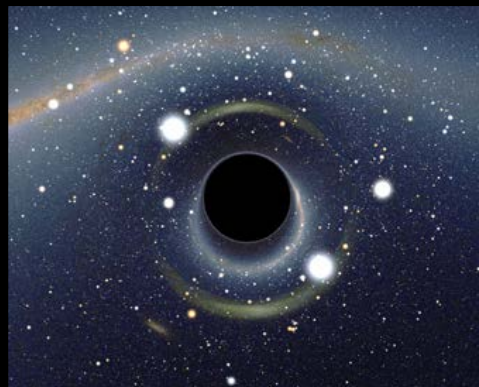# "To Destroy a Book"/"BH Info Paradox in QM"

- Black magic for Black Holes

- Also time evolution of a complicated QM "state"

- Can't look "past the curtain"!

- Different for QM w/ BH? Is information still preserved?

"To Destroy a Book"/"BH Info Paradox in QM"

- Time evolution "normal" for a few quantum states

- "Burning" keeps information

- BHs "destroy" information!

- Different evolution for TONS of quantum states in BH??

Entropy, Energy & Temperature: Boltzmann

- Thermodynamics

- Entropy (S) = disorder

- Entropy/disorder increases

- Fundamentally: macroscopic measure of micro-states
  → Boltzmann's tombstone:

Entropy, Energy & Temperature: Boltzmann

- Thermodynamics

- Entropy (S) = *COMPLEXITY*

- Precisely: ("k" = a number)
  - →W counts states with energy E
  - →Boltzmann's tombstone:

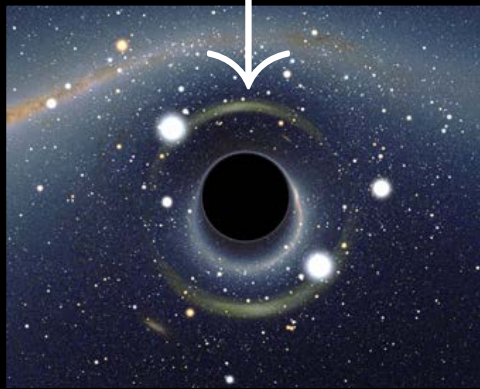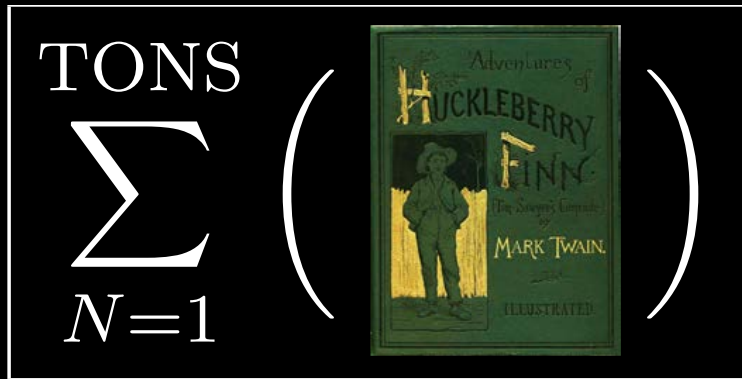- Entropy/complexity increases

$S = k. \log W$
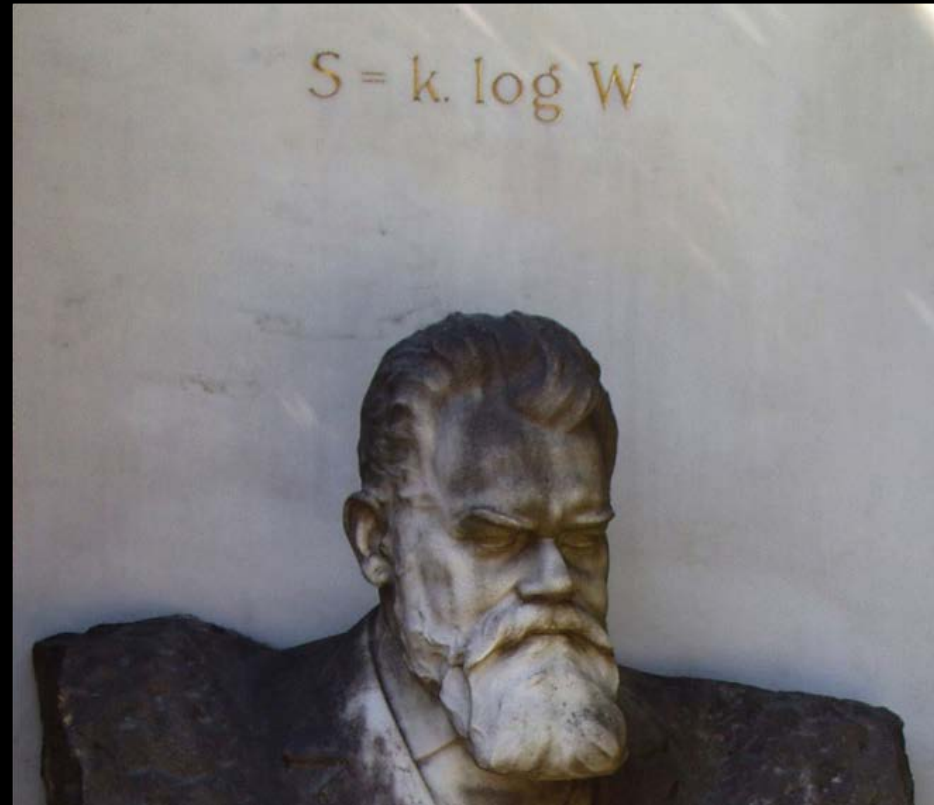
Entropy, Energy & Temperature: Hawking

- Temperature, Energy, and Entropy: deeply related

- Precisely: *Rate of entropy increase with energy gives inverse temperature*
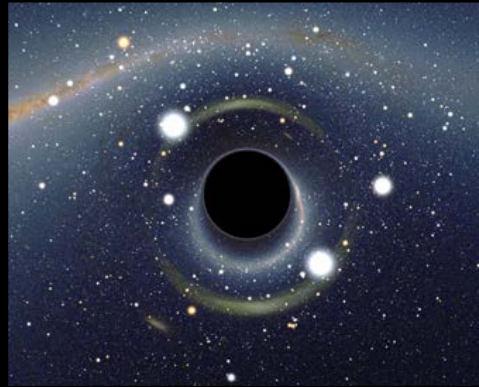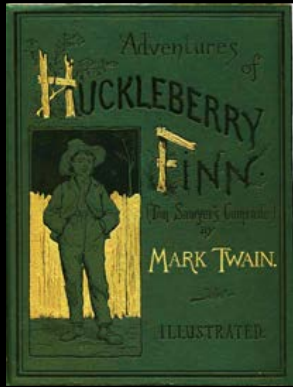
- Thus, temperature>0 means entropy *grows* with energy

$$\frac{1}{T} = \frac{\partial S}{\partial E}$$

Entropy and Black Hole "Hair"

$$\sum_{N=1}^{\text{TONS}} \left(\text{} \right)$$

- Normal matter has entropy

- Entropy cannot decrease

- Pre-collapse material for Black Holes is normal matter

- Pre-collapse material for Black Hole has entropy > 0!
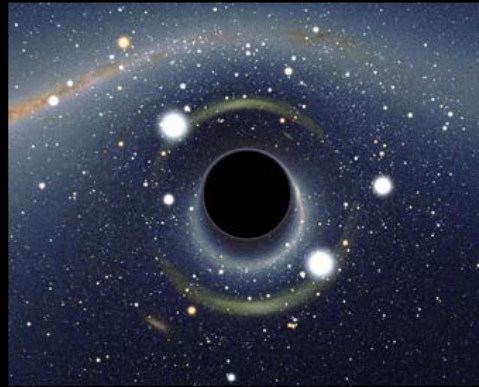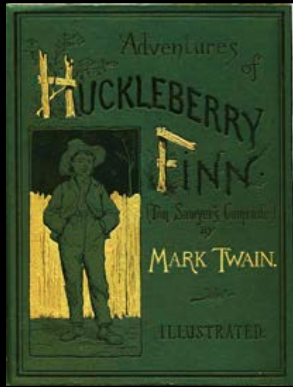
Entropy and Black Hole "Hair"

$$S(\text{Book}) > 0$$

$$S(\text{Black Hole}) > \text{TONS} \times S(\text{Book}) \gg 0$$

- Normal matter has entropy

- Entropy cannot decrease

- Pre-collapse material for Black Holes is normal matter

- Post-collapse Black Holes *must* have entropy >> 0!!!
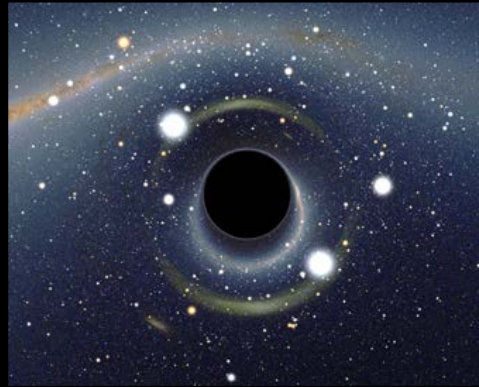
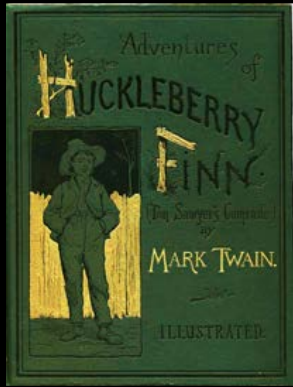# Entropy and Black Hole "Hair"

Q: How books many is "TONS" of books, i.e. will form a BH?

A (roughly): A library from the Sun to Pluto!

- Normal matter has entropy

- Entropy cannot decrease

- Pre-collapse material for Black Holes is normal matter

- Post-collapse Black Holes *must* have entropy >> 0!!!

Entropy and Black Hole "Hair"

Pluto = God of Underworld

Hellish library

- Normal matter has entropy

- Entropy cannot decrease

- Pre-collapse material for Black Holes is normal matter

- Post-collapse Black Holes *must* have entropy >> 0!!!

Entropy and Black Hole "Hair"

Laws of Thermodynamics

$\updownarrow$

Black Hole Thermodynamics

- BHs vs Thermodynamics

- So: Black Holes have entropy!

- Black Holes must have "hair"!

- Accords with Hawking:
  → Entropy vs Energy...
  → gives Temperature (Hawking)!

Entropy and Black Hole "Hair"

Laws of Thermodynamics $\longleftrightarrow$ Black Hole Thermodynamics

$$T_{\mathrm{BH}} = \frac{1}{8\pi M_{\mathrm{BH}}} \quad , \quad S_{\mathrm{BH}} = 16\pi M_{\mathrm{BH}}^2$$

1st Law for Thermo : $dE = TdS$ $\longleftrightarrow$ 1st Law for BHs : $dE = T_{\mathrm{BH}} \, dS_{\mathrm{BH}}$

2nd Law for Thermo : $\dfrac{dS}{dt} \geq 0$ $\longleftrightarrow$ 2nd Law for BHs : $\dfrac{dS_{\mathrm{BH}}}{dt} \geq 0$
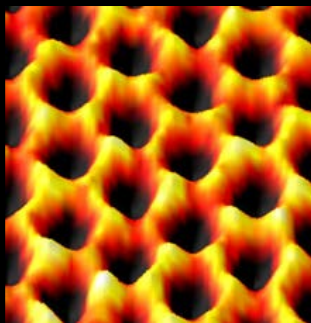
An Aside: Black Holes vs "Everything"

vs
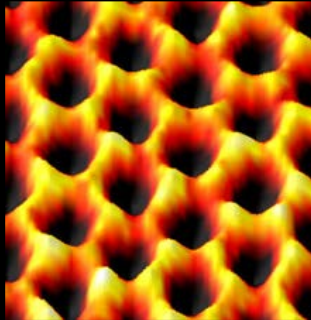
vs

= ?!

- BHs vs Quantum Mechanics!
  →BH = many quantum systems
  →Quantum systems & info

- BHs also vs Thermodynamics!
  →BH = many statistical systems
  →Statistical systems & entropy

- Thermo = Quantum? Whoa!

An Aside: Black Holes vs "Everything"

The Schrodinger Equation:

$$i\partial_t\psi(x,t) \propto \partial_x^2\psi(x,t)$$

The Heat Equation:

$$-\partial_t\phi(x,t) = \partial_x^2\phi(x,t)$$

- BHs vs Quantum Mechanics!
  - →BH = many quantum systems
  - →Quantum systems & info

- BHs also vs Thermodynamics!
  - →BH = many statistical systems
 - →Statistical systems & entropy

- Thermo = Quantum? Whoa!

A Bulk-Boundary Duality for Black Holes?

- Black Holes *should* retain info
  - →Quantum Mechanics says so!
  - →Thermodynamics says so!

- GR: *But how?* Can't look into the middle (bulk)!!!!

- 't Hooft: Store the info on the outer surface (boundary)?!
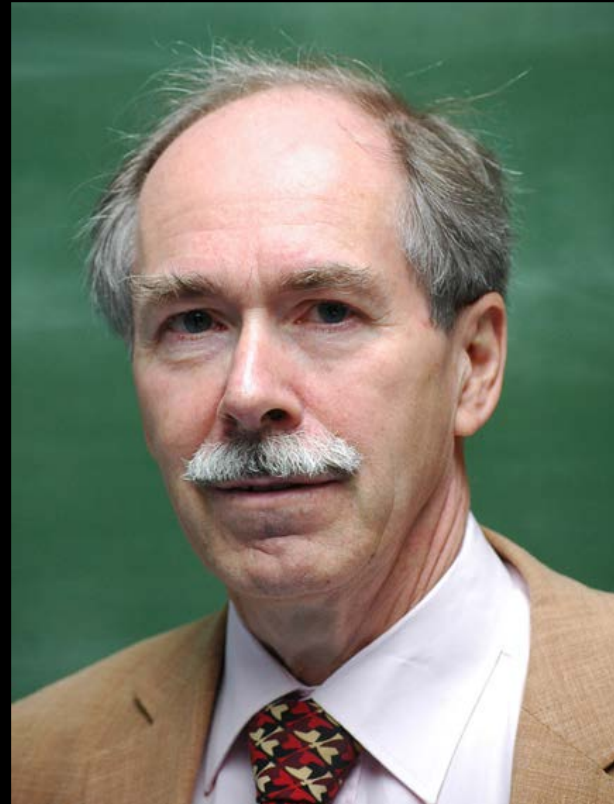
A Bulk-Boundary Duality for Black Holes?

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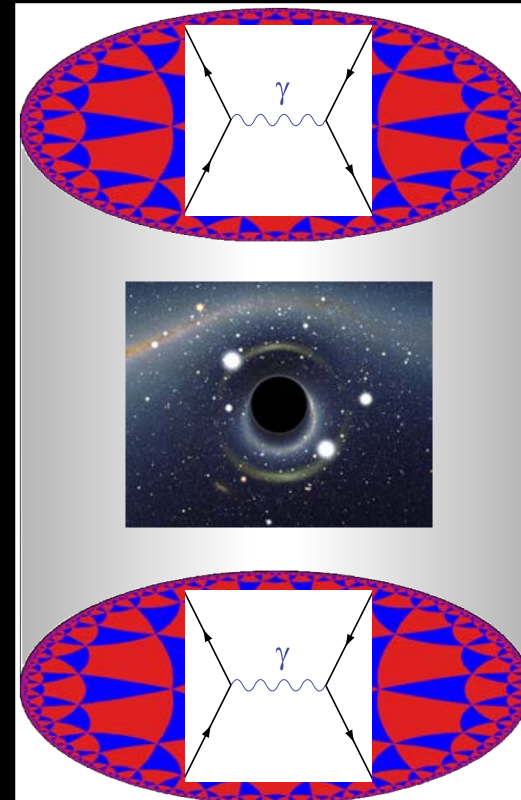
A Bulk-Boundary Duality for Black Holes?

- Maldacena's example:
    - →GR in "the middle"
    - →QM on "the edge"
    - →Inside GR = Edge QM

- First "real" example of bulk-boundary duality
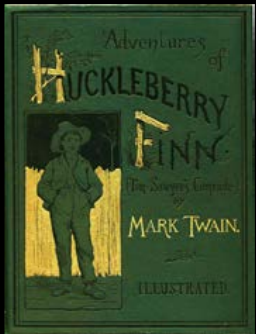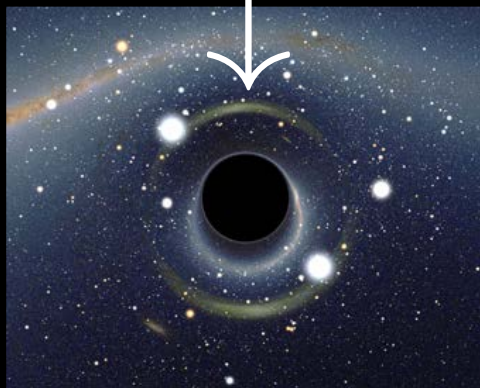
- Details technical

A Bulk-Boundary Duality for Black Holes?

- Maldacena's ex.: AdS/CFT
  - →GR in "the middle": AdS
  - →QM on "the edge": CFT
  - →AdS-Inside = Edge-CFT

- First "real" example of bulk-boundary duality
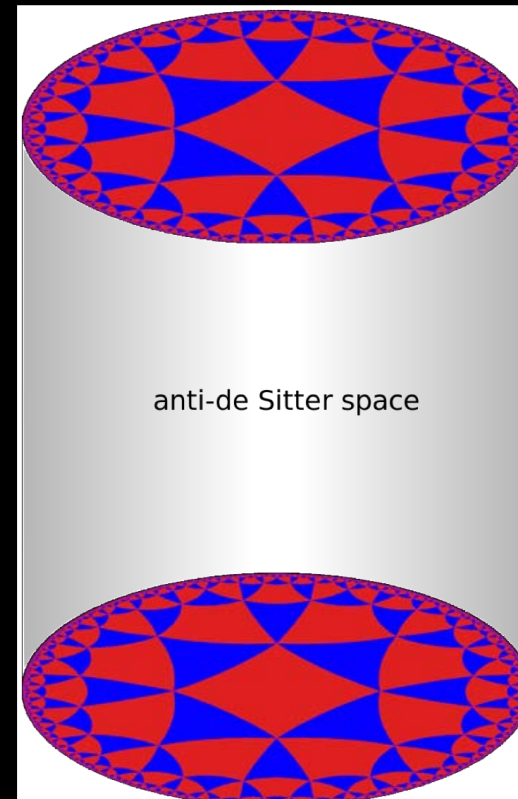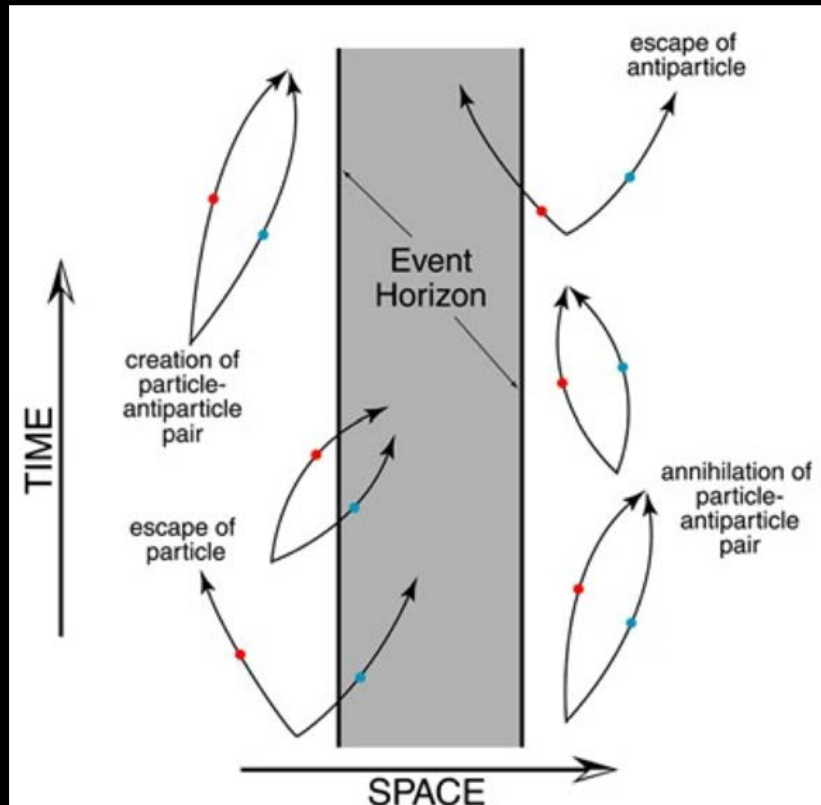
- Details technical

anti-de Sitter space

Entropy, Black Holes & Quantum Gravity

$$\sum_{N=1}^{\text{TONS}} \left(\quad \right)$$

- Entropy in statistical physics
  → Counts number of microstates
  → Specifically, *quantum* states

- Black Hole entropy > 0
  → Black holes have many states
  → Many *quantum* states

- "Quantum Gravity" needed!

Entropy, Black Holes & Quantum Gravity


- Entropy in statistical physics
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Entropy, Black Holes & Quantum Gravity
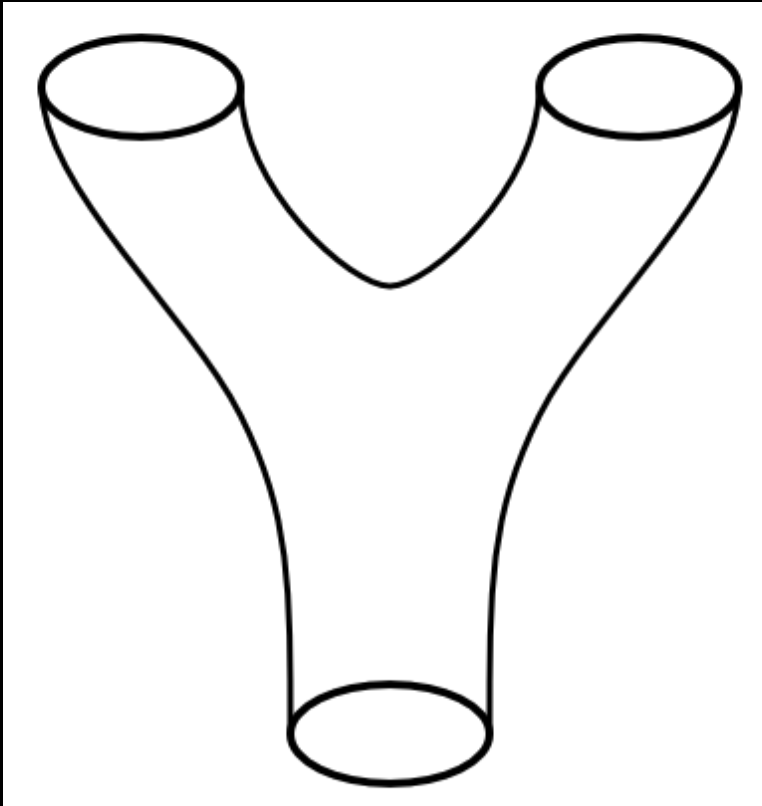
- Quantum Mechanics
  - →Spatial vs Temporal evolution
  - →Asymmetry "x" vs "t"!

- Einstein Relativity
  - →Space and time interwoven
  - →Democracy and symmetry

- String Theory fuses these two

Entropy, Black Holes & Quantum Gravity
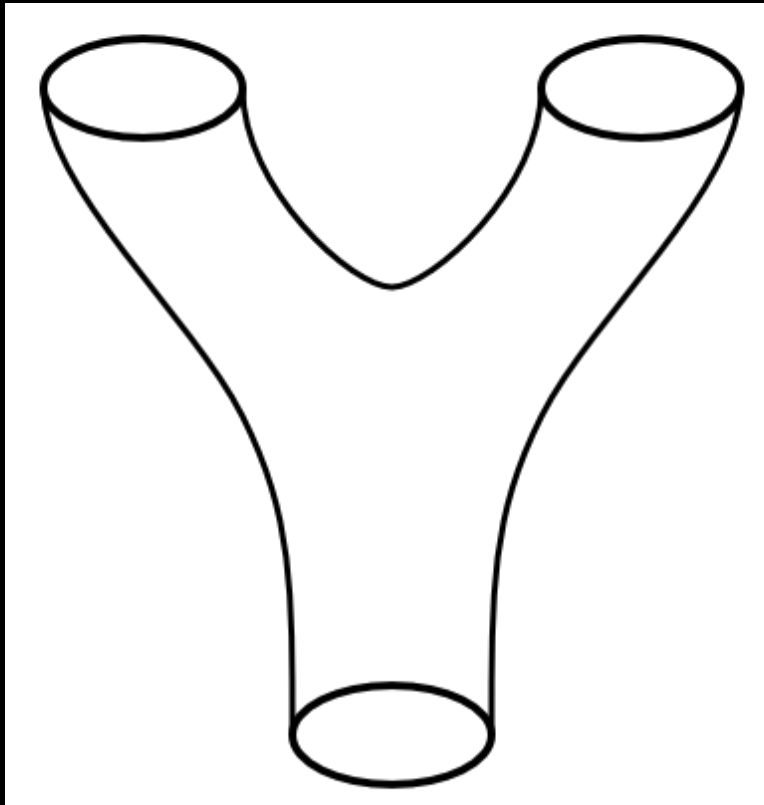
- Note: several ways to fuse QM and GR.

- Strings have led to two main victories for QM+Black Holes:
  - →Precise entropy formula!
  - →Precise holographic example!

- But String Theory ain't a cure-all! (Smoke and fire...)

An Aside on String Theory

- QM and Relativity merge well in at least three frameworks:
  - →Quantum Field Theory
  - →String Theory
  - →Worldline Formalism

- Physics is the same

- Given in different languages
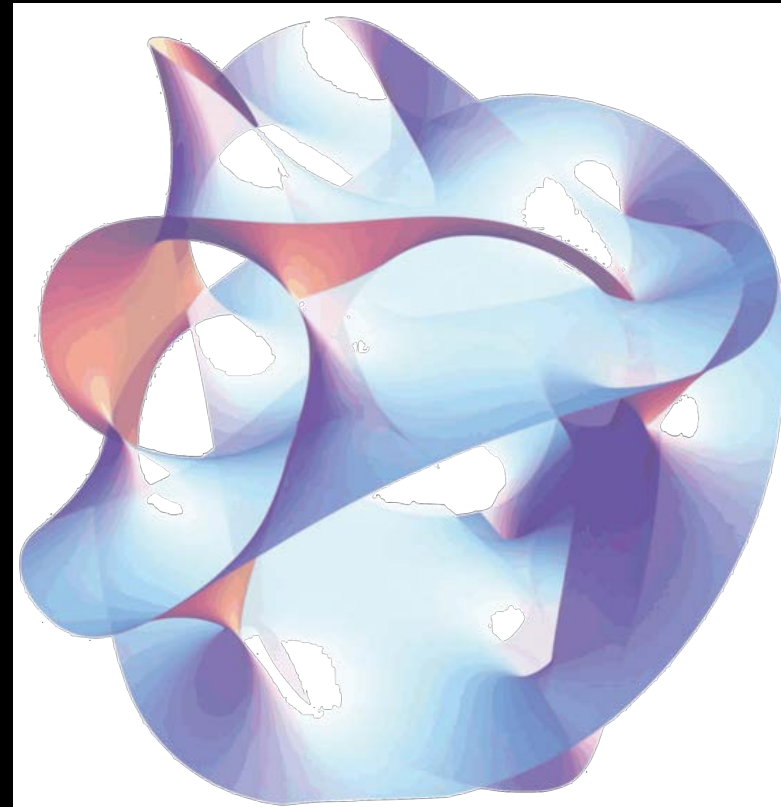
An Aside on String Theory

- String Theory can give useful ideas on hard problems...

- ...by giving a new point of view on the problem.

- Strings *may* be fundamental.

- They *ARE* useful: Black Holes!
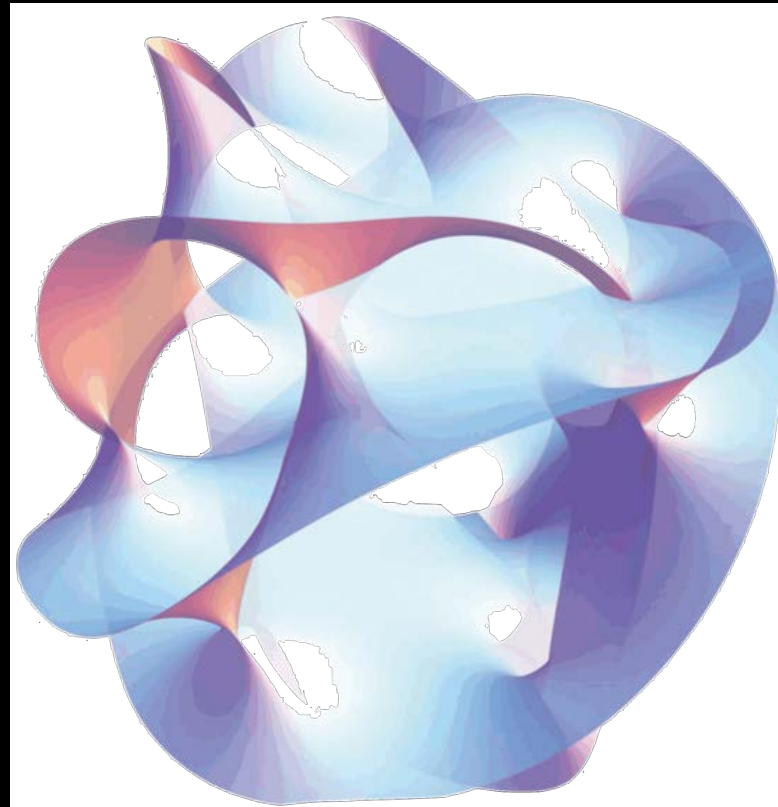
Entropy, Black Holes & Quantum Gravity

- For a lot of Quantum Gravity, String Theory reigns supreme

- Big part of why: Black Holes
  → Black Hole state counting
  → *Works* for very special BHs!
  → Big test of Quantum Gravity

- Exactly matches Hawking!

Entropy, Black Holes & Quantum Gravity

- For a lot of Quantum Gravity, String Theory reigns supreme

- Big part of why: Black Holes
  - →Black Hole state counting
  - →*Works* for very special BHs!
  - →Big test of Quantum Gravity

- Exact match for large Q_F!
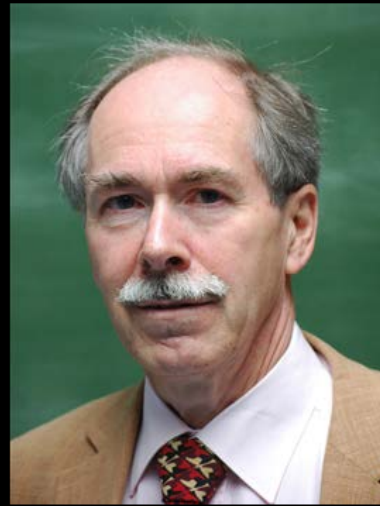
Beckenstein − Hawking prediction:

$$S_{\mathrm{BH}} = 2\pi\sqrt{Q_H Q_F^2/2}$$

Strominger − Vafa calculation:

$$S_{\mathrm{BH}} = 2\pi\sqrt{Q_H(Q_F^2/2 + 1)} + \cdots$$

Entropy, Black Holes & Quantum Gravity

- For most Quantum Gravity,
  String Theory reigns supreme

- Moreover: Holography!

- Maldacena's Holendy:
  → Purely "stringy" origin
  → QM on edge understood
  → Gravity in middle has BHs!

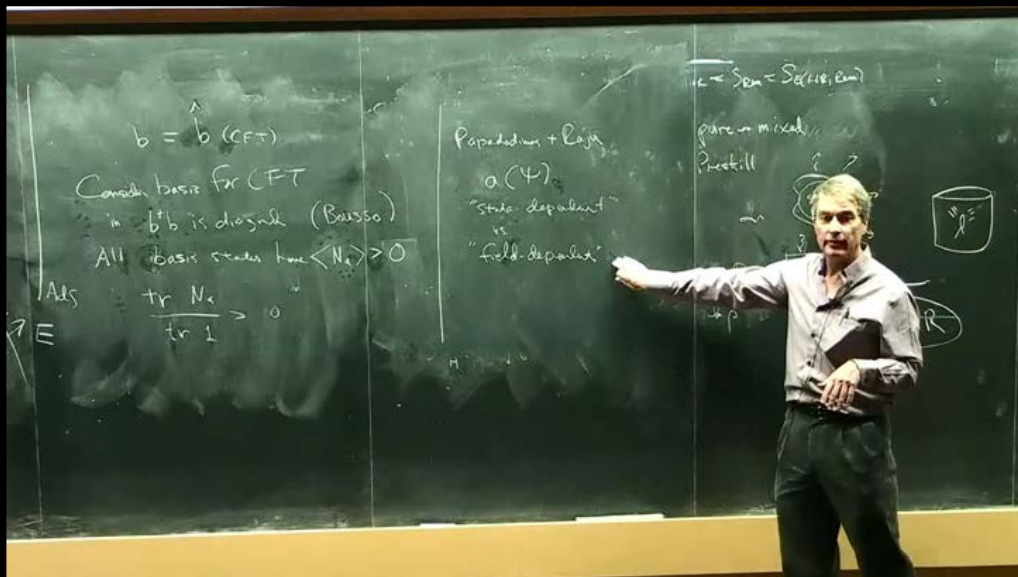# Entropy, Black Holes & Quantum Gravity

- For most Quantum Gravity, String Theory reigns supreme

- "AdS/CFT" = real Holography!

- Maldacena's AdS/CFT:
  - →Purely "stringy" origin
  - →QM on edge understood
  - →Gravity in middle has BHs!

Maldacena and Witten et al:

$$Z_{\text{Quantum}}(\text{edge}) = Z_{\text{Black Hole}}(\text{middle})$$

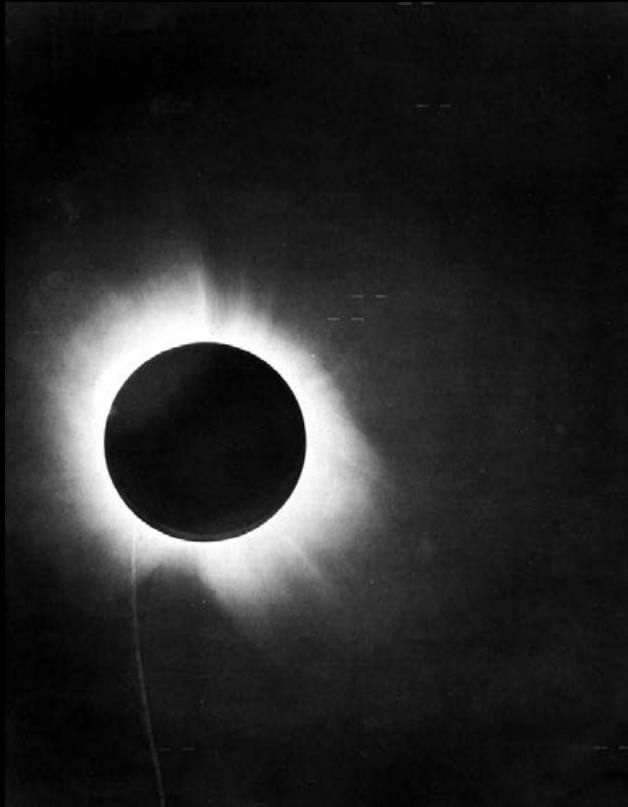# NEW Problems for Black Holes: Firewalls?

Almheiri, Marolf, **Polchinski** & Sully

"AMPS" Firewall & arXiv:1207.3123

- String Theory ain't a cure-all: works well in SPECIAL cases

- But big questions loom...

- Hawking: BH info from outside? Old info paradox...

- AMPS: BH info for person falling into BH?! New version!

NEW Problems for Black Holes: Firewalls?

- QM and GR: Tension AGAIN

- You hit the firewall on way in

- AMPS Firewall torches all

- Qualitative shift in our view of Black Holes needed?

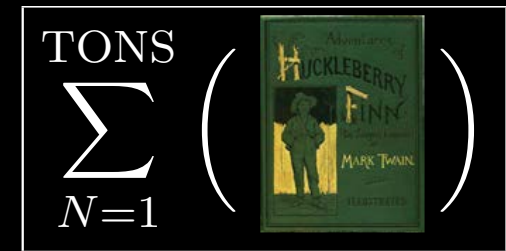# Black Holes from GR with Quantum & Thermo

- Black Holes exist! Amazing!

- Quantum: Hawking Radiation

- Thermodynamics: Entropy

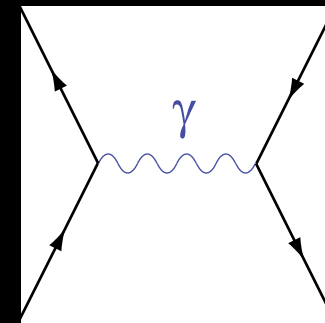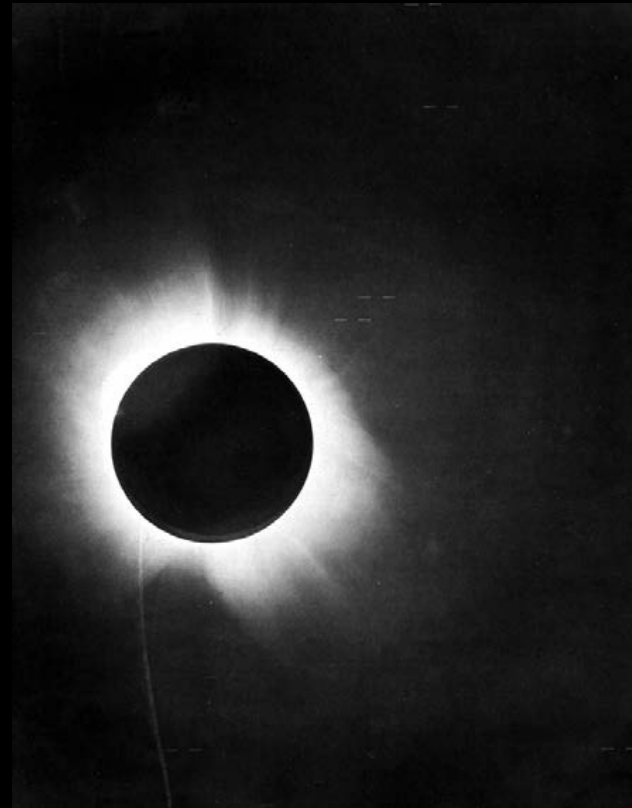- Robust: Quantum Mechanics and Theromdynamics require the same things for BHs!
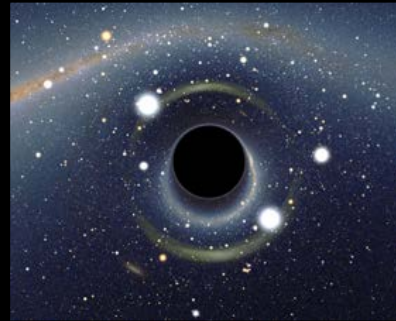
Black Holes from GR with Quantum & Thermo

- BH = Relativity's *1st* solution!

- BH information paradox...

- ...and String Theory success
    - →Holography: Edge = Middle!
    - →Precise BH entropy!

- Firewall paradox: unresolved!

Black Holes from GR with Quantum & Thermo

- Black Holes: First "real" solutions to GR (from 1916)!!

- Super exciting! Hitting them "just a little bit" starts whole avalanches of new physics!!

- 102 years old & going strong!
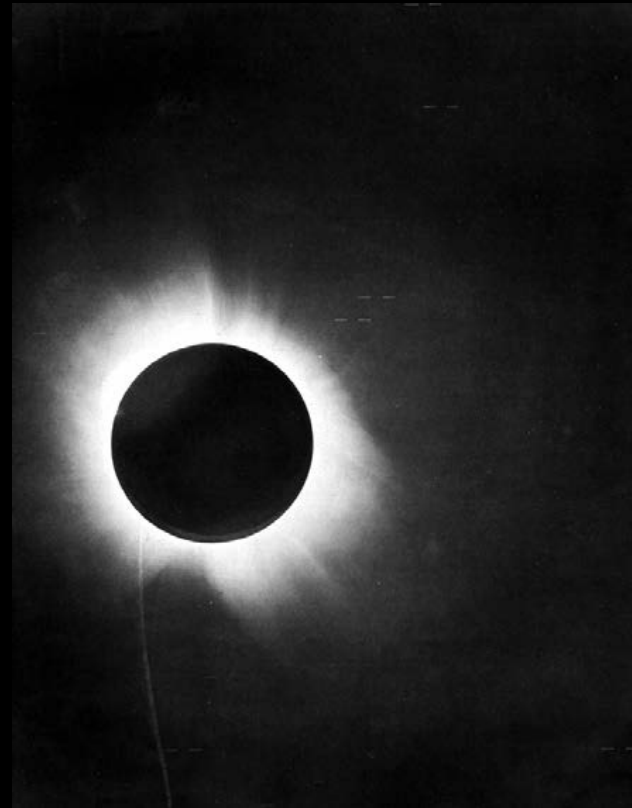
Structure of talk: 20th and 21st century physics

1. Gravity and Black Holes(BHs)
   - Newton
   - Einstein & Democracy
   - Schwarzschild & Black Holes
   - Hawking

2. Quantum mechanics & Info
   - Bohr & Heisenberg
   - Dirac & Feynman
   - Vacuum fluctuations
   - Hawking & Radiation

3. Thermodynamics & Hawking
   - Boltzmann & Entropy
   - Entropy & Temperature
   - Thermo & Quantum for BHs
   - (Quantum = Thermodynamics)

4. String Theory & Firewalls?
   - Maldacena & Holography
   - Quantum Gravity & Strings
   - Success: Strings & Black Holes
   - Firewalls & (exciting) future!

Black Holes, Information, and String Theory

Thanks for your time!!

Supplementary: Verifying Pluto's Library = BH!

2018I031-0AM ①

ORIGIN OF THE "SUN TO PLUTO" SIZED LIBRARY
= A BLACK HOLE:

① For any mass, M, there is the associated Schwarzschild radius, which is given by $R_s = \frac{2G_N M}{c^2}$.

Here, • G_N = Newton's constant,
• M = Mass of the star, and
• c = the speed of light.

② To find that "radius" I did three things:

Ⓐ Assumed that the "library" of books was NOT gravitationally interacting — or, rather, that the books could not be compressed. Thus, the mass density of the books was not changed.

Ⓑ This gives the mass of the library as a function of "radius":

$M(R) = \frac{4}{3}\pi R^3 \rho$, where

$\begin{cases} M = \text{Mass of library,} \\ R = \text{Radius of library, and} \\ \rho = \text{mass-density of the library.} \end{cases}$

②Ⓒ I then solved for $R_s = \frac{2G_N}{c^2} M$ for $R = R_s$: ②

$R_s = R = \frac{2G_N}{c^2} M(R) = \frac{2G_N}{c^2}\left(\frac{4\pi}{3} R^3 \rho\right)$ 2018I031-0AM

$= \frac{8\pi}{3}\frac{G_N}{c^2}\rho \cdot R^3$

$\Rightarrow R^{-2} = \frac{8\pi}{3}\frac{G_N}{c^2}\rho$

$\Rightarrow R = \frac{1}{\sqrt{\frac{8\pi}{3}\frac{G_N}{c^2}\rho}}$

③ To get actual numbers to ACTUALLY find the radius, you

Ⓐ Look-up G_N and C. Via Wikipedia, you get an answer like

$\begin{cases} G_N = 7\times 10^{-11}\frac{m^3}{kg\cdot s^2} \\ c \approx 3\times 10^8 \frac{m}{s}, \text{ and} \end{cases}$

Ⓑ Recall that books ALMOST float in water. Thus we have $\rho \simeq \frac{1 g}{cm^3} = \frac{10^3 kg}{m^3}$

(Yeah, water is SUPER HEAVY! ONE CUBIC METER OF WATER = ONE TON OF WATER!!)

[Page 3]

③ ... Plugging these number in, you get something like ③

$\sim 1.2\times 10^{13}$ meters $\approx \frac{1}{\sqrt{\frac{8\pi}{3}\frac{G_N}{c^2}\rho}}$ 2018I031-0AM

④ Now, to convert this into something LESS ABSTRACT, we can ask how long it takes light to get from the CENTER of this BALL of RADIUS 10^{13} meters to the EDGE. To do this, we simply do the following:

$t = \frac{distance}{speed} \Rightarrow \frac{1.2\times 10^{13} m}{3\times 10^8 m/s} \simeq 4\times 10^4$ seconds

⑤ Now, recall it takes $\sim 5\times 10^2$ seconds for light from the SUN to reach EARTH! so $4\times 10^4 \simeq 80\times R_{Earth-sun}$!

⑥ Now, the average distance between sun and Pluto is $\sim 40\times R_{sun-EARTH}$. So this library would be TONS BIGGER ($\sim 8\times$) than even the solar system.

Supplementary: Verifying Pluto's Library = BH!