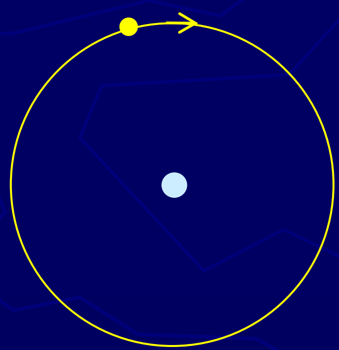
Spacetime *versus* the Quantum

Joseph Polchinski

KITP UCSB

UCSB Faculty Research Lecture, Dec. 12, 2014

“God does not play dice with the world”
(Albert Einstein, 1926)



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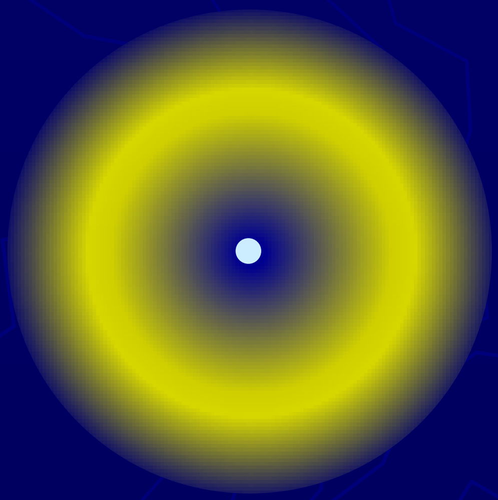

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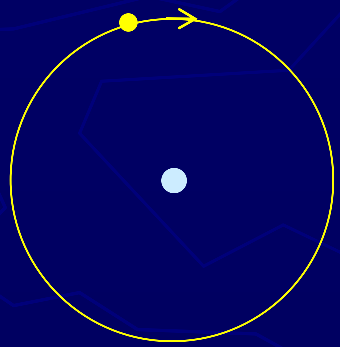

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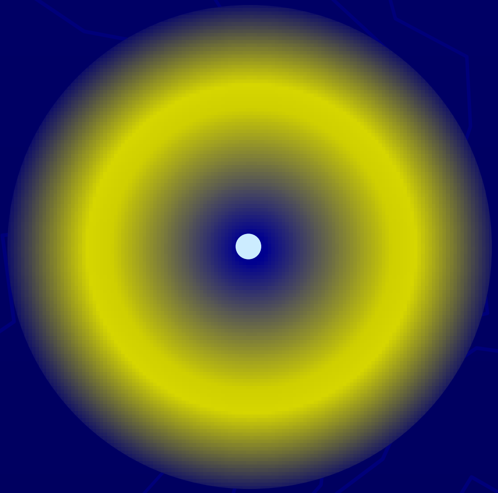

“God not only plays dice, He sometimes throws the dice where they cannot be seen.”

(Stephen Hawking, 1976)

Three great revolution in physics:

Special Relativity (1905)

General Relativity (1915)

Quantum Mechanics (~1925)

The challenge still: to find a theory that unifies quantum mechanics and relativity

Special relativity and quantum mechanics

Special Relativity: very fast

General Relativity: very massive

Quantum Mechanics: very small

Special relativity and quantum mechanics

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General Relativity: very massive

Quantum Mechanics: very small

But what if something is both very fast and very small?

Quantum mechanics + special relativity

Dirac started with Schrodinger's equation:

$$i\hbar\frac{d\psi}{dt} = -\frac{\hbar^2}{2m}D^2\psi + eA_0\psi$$

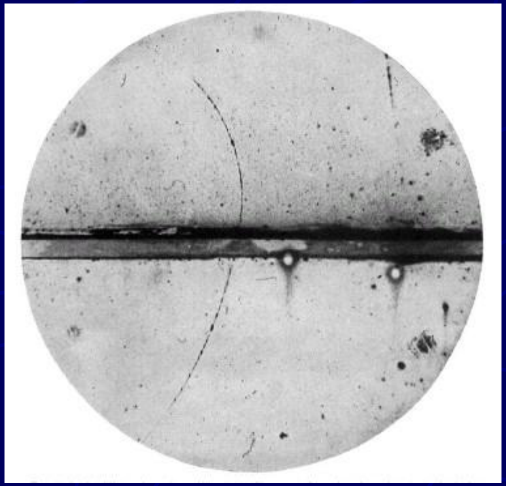
This describes quantum behavior of atoms, molecules, but *fails* for particles moving close to the speed of light. Dirac solved this by finding an improved equation:

$$i\hbar\gamma^\mu D_\mu\psi = m\psi$$

$$i\hbar\gamma^{\mu}D_{\mu}\psi = m\psi$$

Dirac's equation agrees with Schrodinger's equation for `slow' things like atoms and molecules, but it correctly incorporates special relativity.

The surprise: it has twice as many solutions as expected. The extra solutions represent *antimatter*, discovered by Carl Anderson two years later.



The story of special relativity + quantum mechanics went on after Dirac:

Quantum field theory

The Standard Model (~1971). Predicted:

- gluon (discovered 1979)
- W boson (discovered 1983)
- Z boson (discovered 1983)
- top quark (discovered 1995)
- Higgs boson (discovered 2012)

Special relativity + quantum mechanics fit together without conflict. General relativity will be much harder…

General relativity and quantum mechanics

Special Relativity: very fast

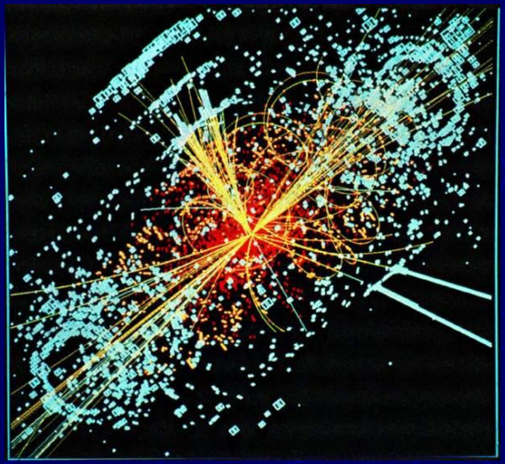
General Relativity: very massive

Quantum Mechanics: very small

Now, what if something is both very massive and very small (and possibly also very fast)?

Very small *and* very massive:

• Particle collisions at *extremely* high energies



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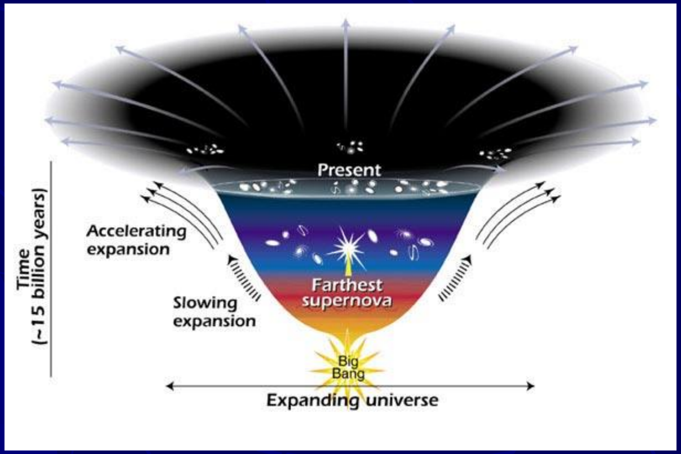
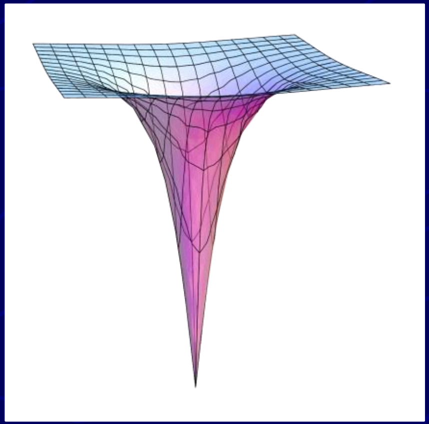
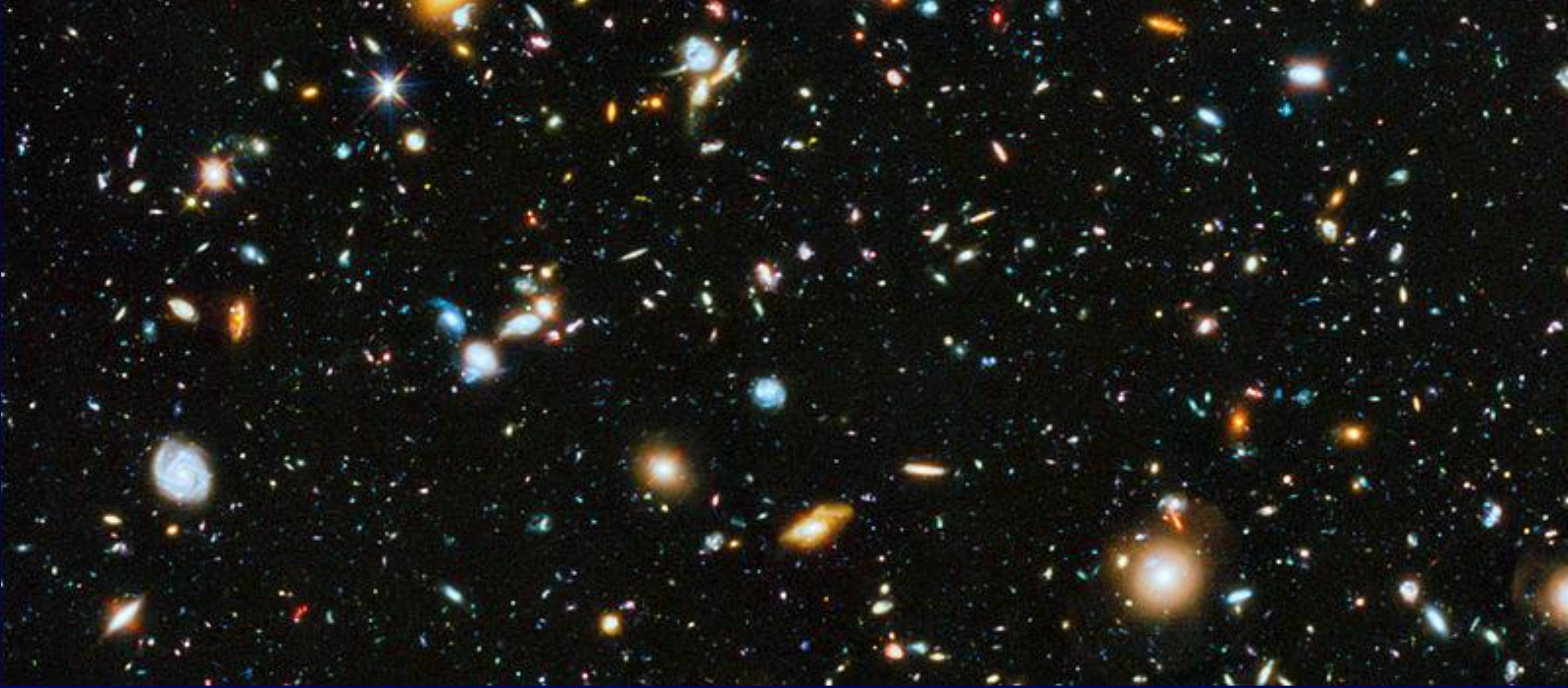


• The early moments of the Big Bang

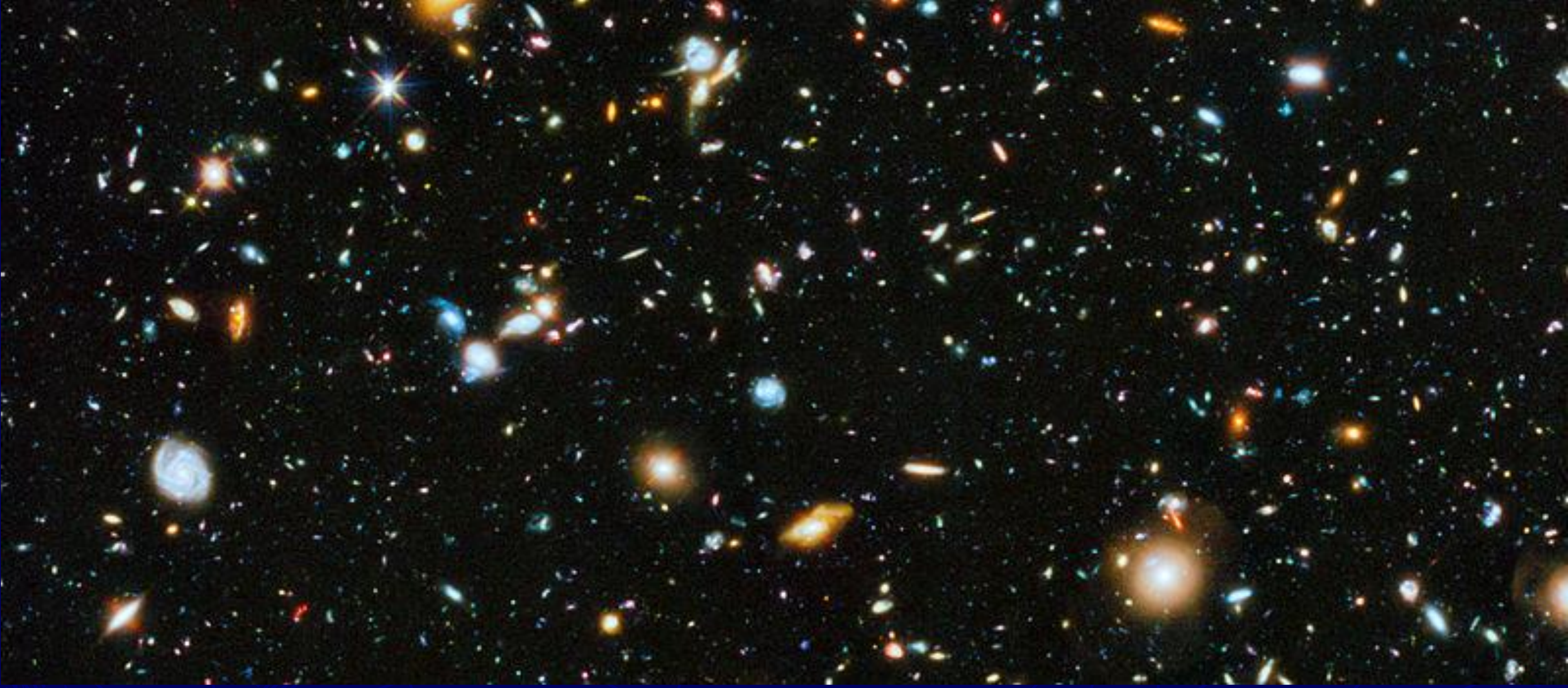
• The singularities of black holes





Why are there galaxies, instead of a uniform gas?

What determines the *pattern:* the sizes and numbers of galaxies, and their distribution?



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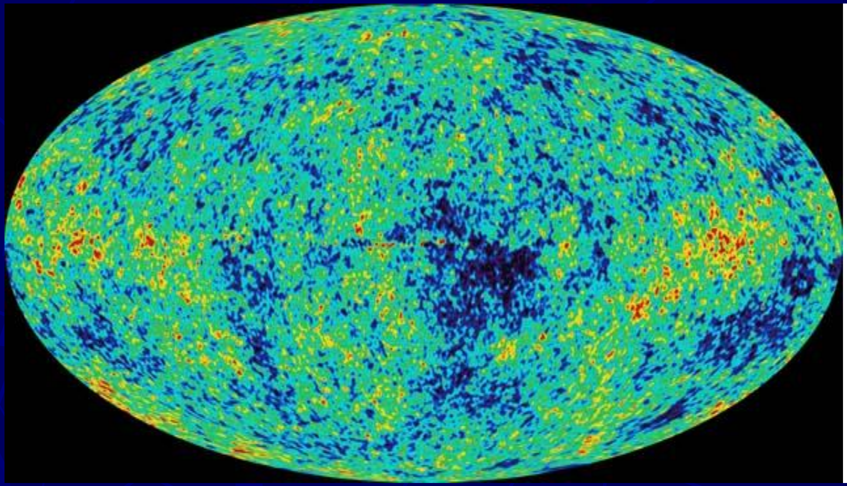
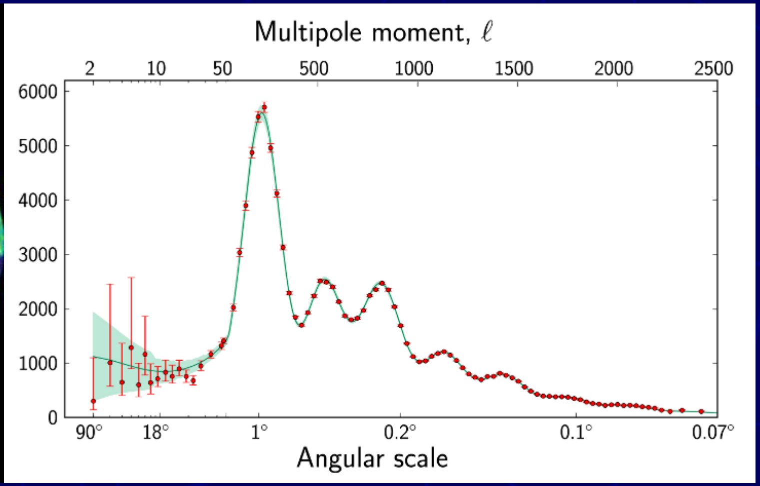
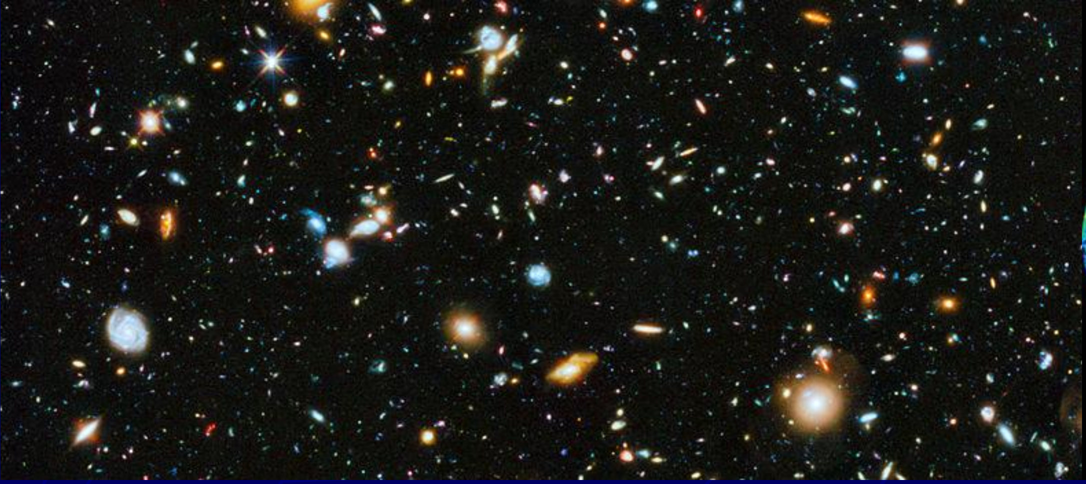
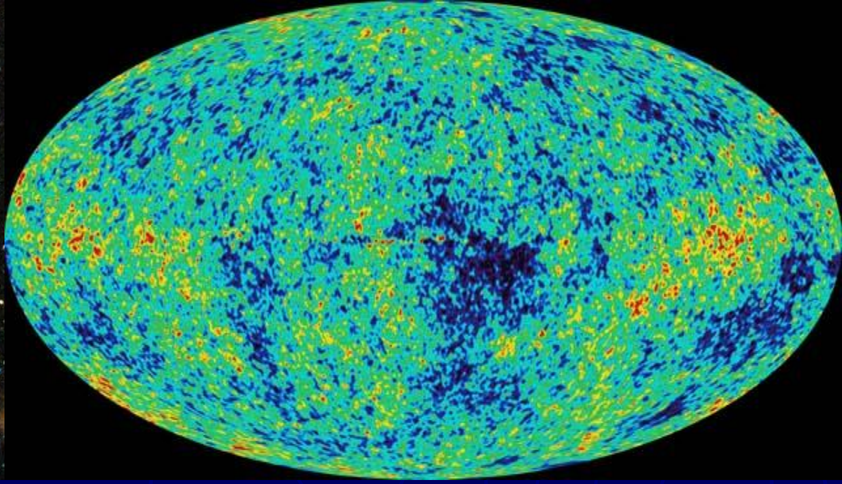
Quantum mechanics!

This quantum pattern is also seen in the Cosmic Microwave Background (CMB), radiation left from the early moments of the Big Bang.

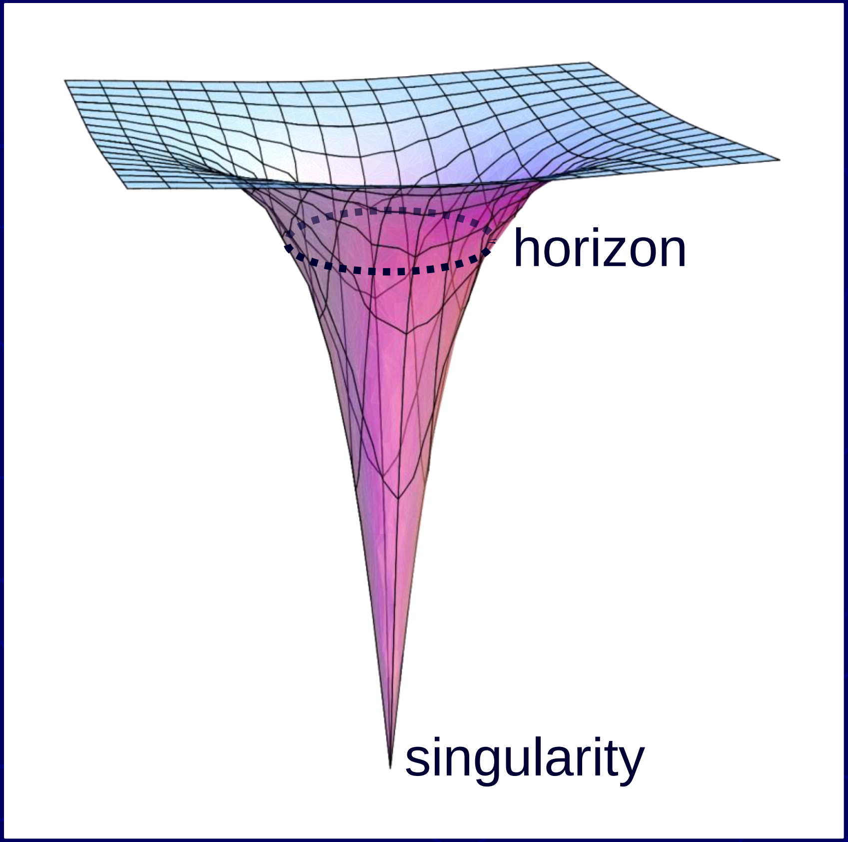




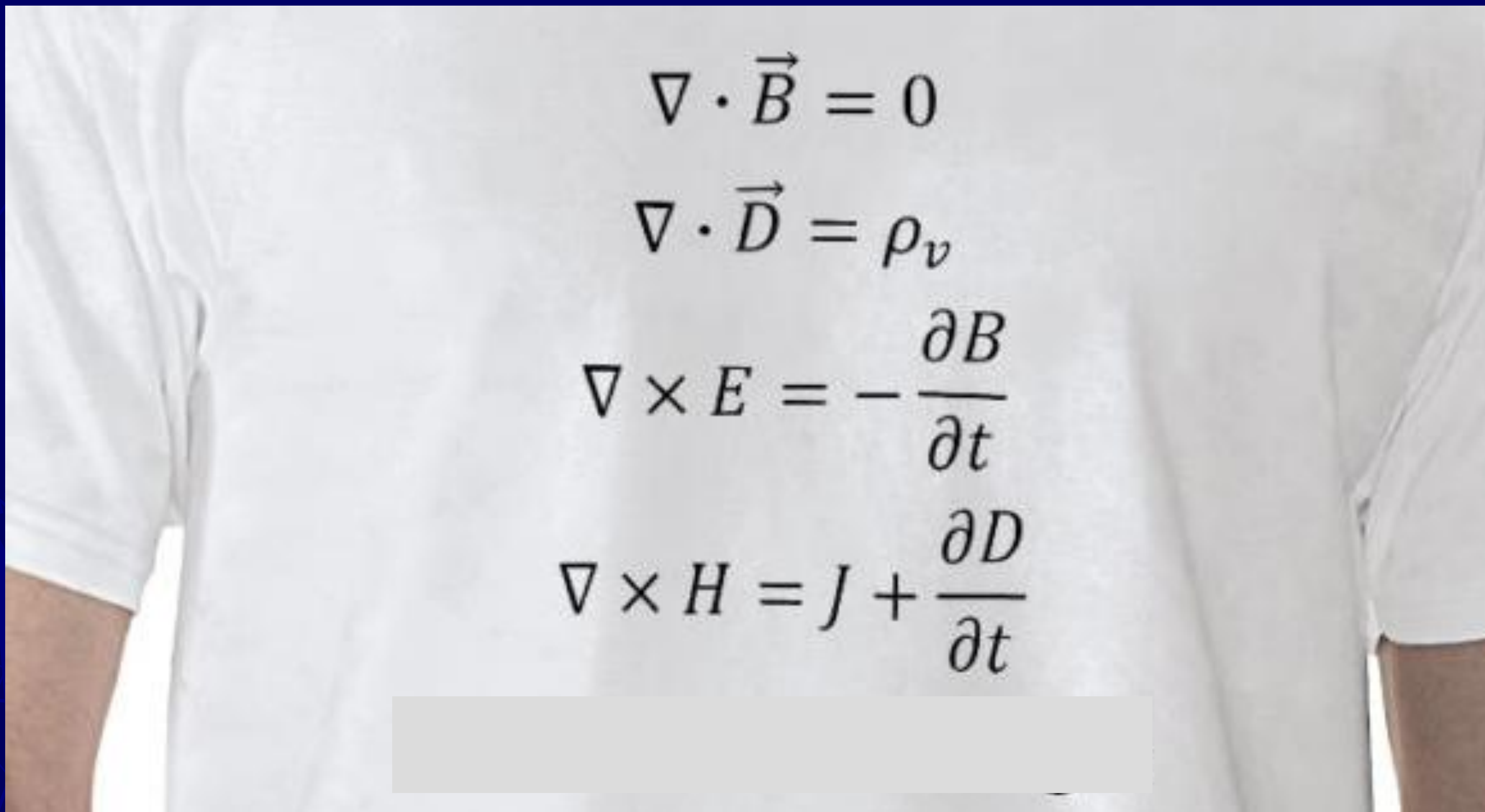
 

The pattern in the galaxies, and in the CMB, formed in the first second after the Big Bang. But we want to push back even further in time, and our theories break down.

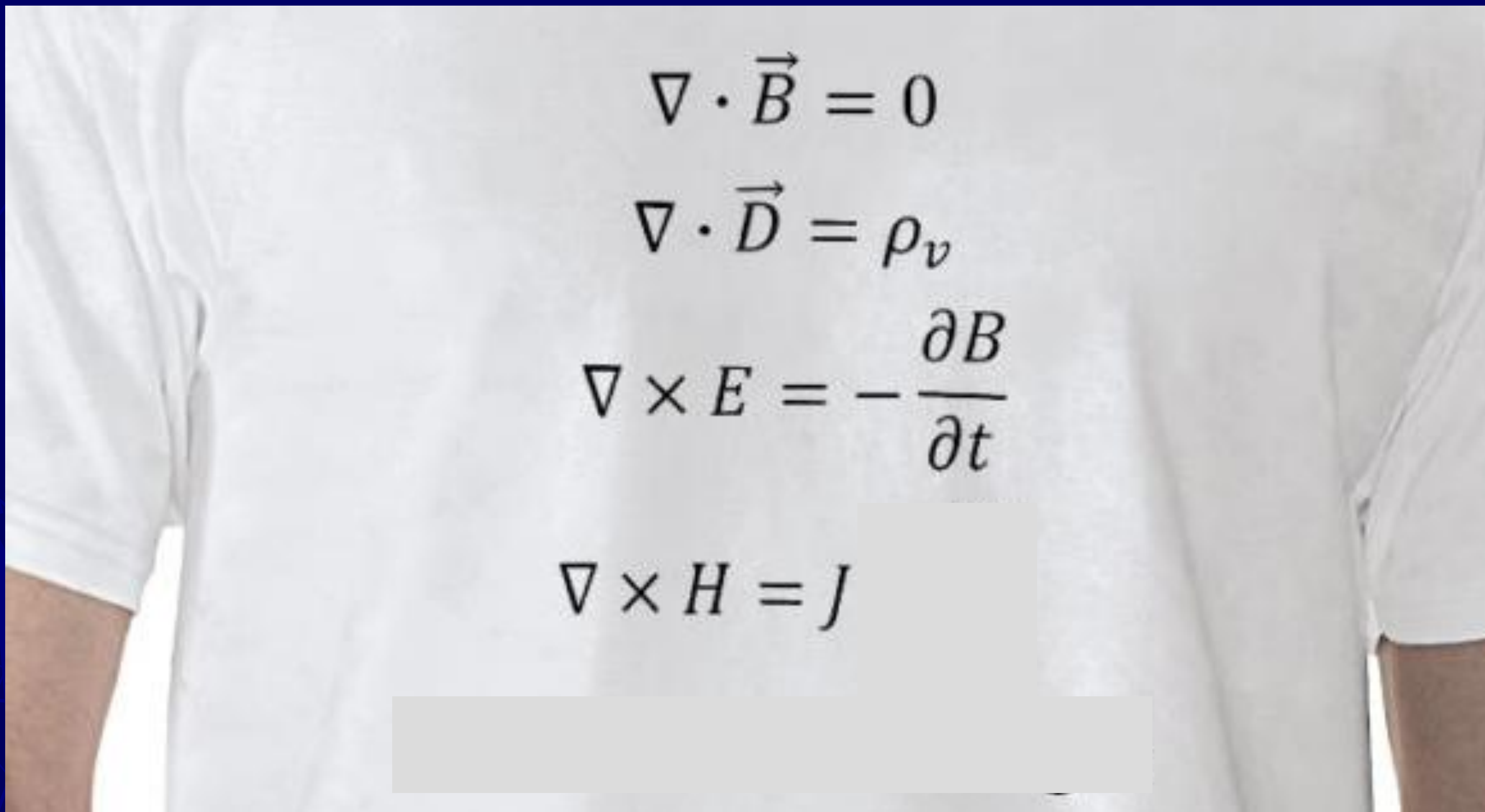
Black holes:



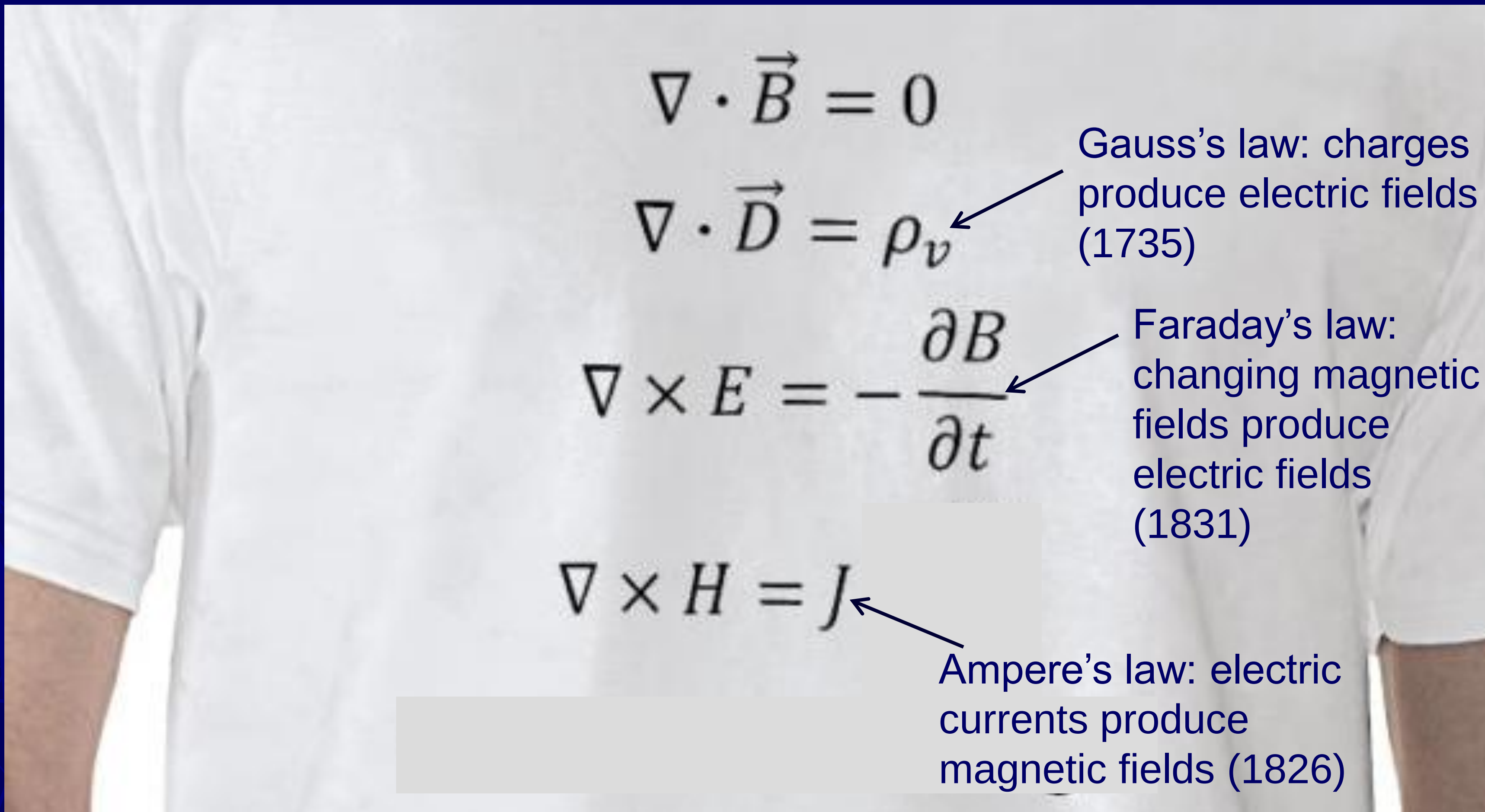
James Clerk Maxwell’s thought experiment



The tee-shirt before Maxwell:



Before Maxwell:



$$\nabla \cdot \vec{B} = 0$$

$$\nabla \cdot \vec{D} = \rho_v$$

Gauss's law: charges produce electric fields (1735)

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

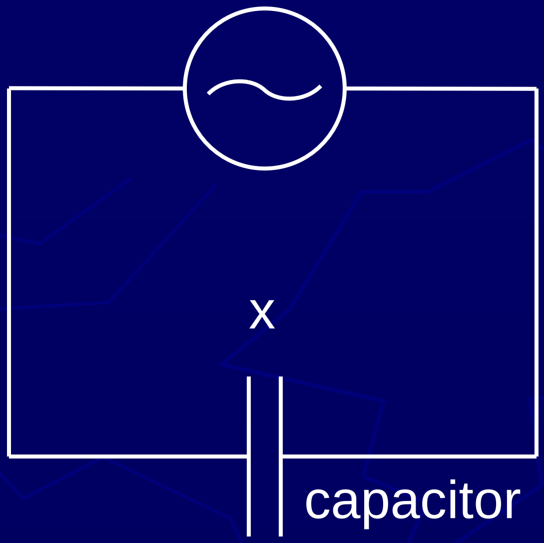
Faraday's law: changing magnetic fields produce electric fields (1831)

$$\nabla \times H = J$$

Ampere's law: electric currents produce magnetic fields (1826)

Earlier terms discovered experimentally

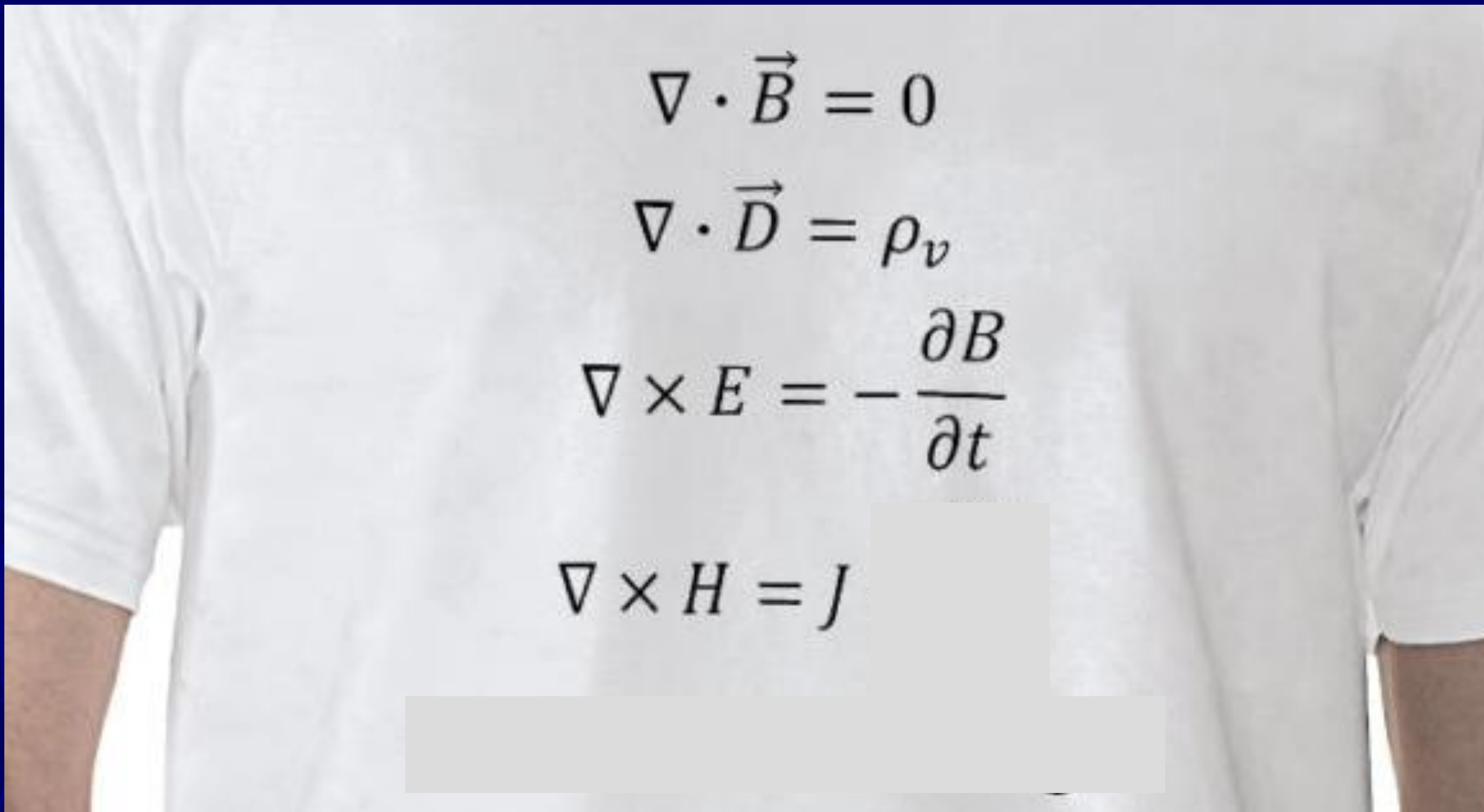
Maxwell's simple thought experiment:



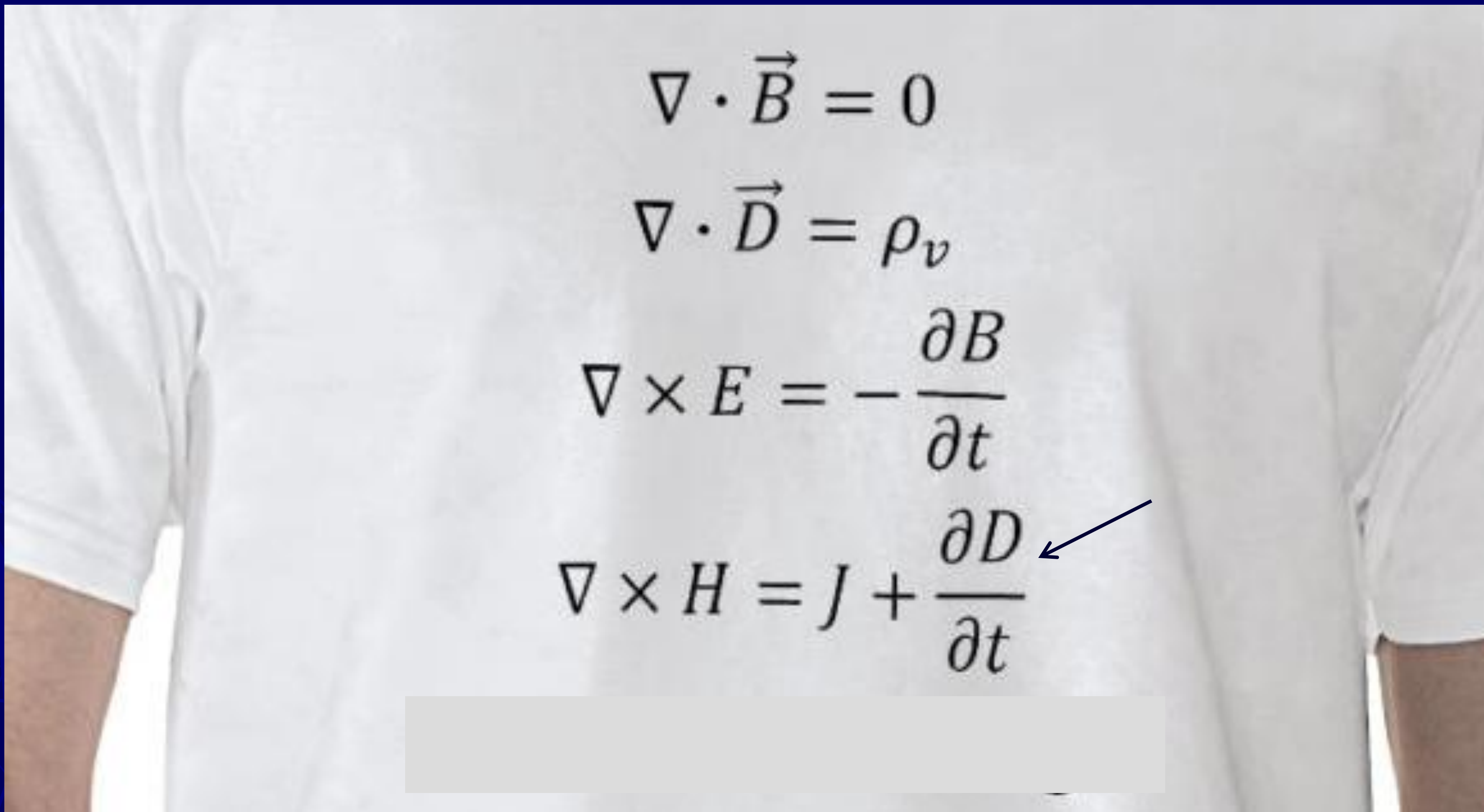
Experiment: put a capacitor in an alternating current. Measure the magnetic field at x.

The incomplete set of equations gives two different answers. This can be fixed by adding one more term.

Before Maxwell:



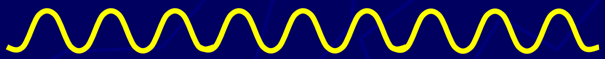
After Maxwell (1861):



Adding Maxwell’s term fixed everything, and gave an unexpected bonus:

Faraday   Maxwell

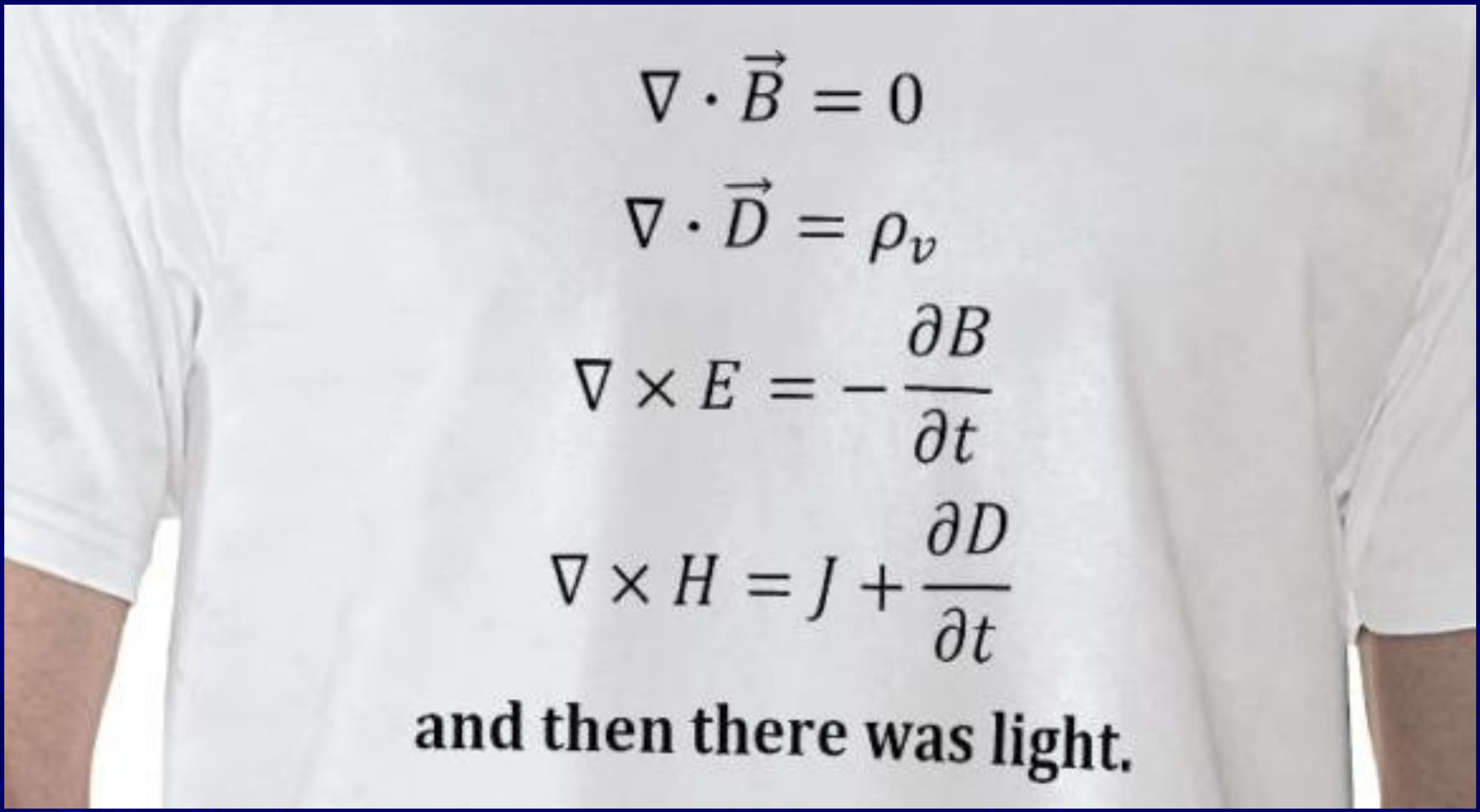
magnetic → electric → magnetic → electric →

magnetic → electric → ... 

= electromagnetic wave

speed = $1/\mu_0\varepsilon_0$ = speed of light (to few % accuracy)

After Maxwell:



Unification often leads to unexpected discoveries:

QM + special relativity $\rightarrow$ antimatter

electricity + magnetism $\rightarrow$ light

For quantum mechanics + general relativity:

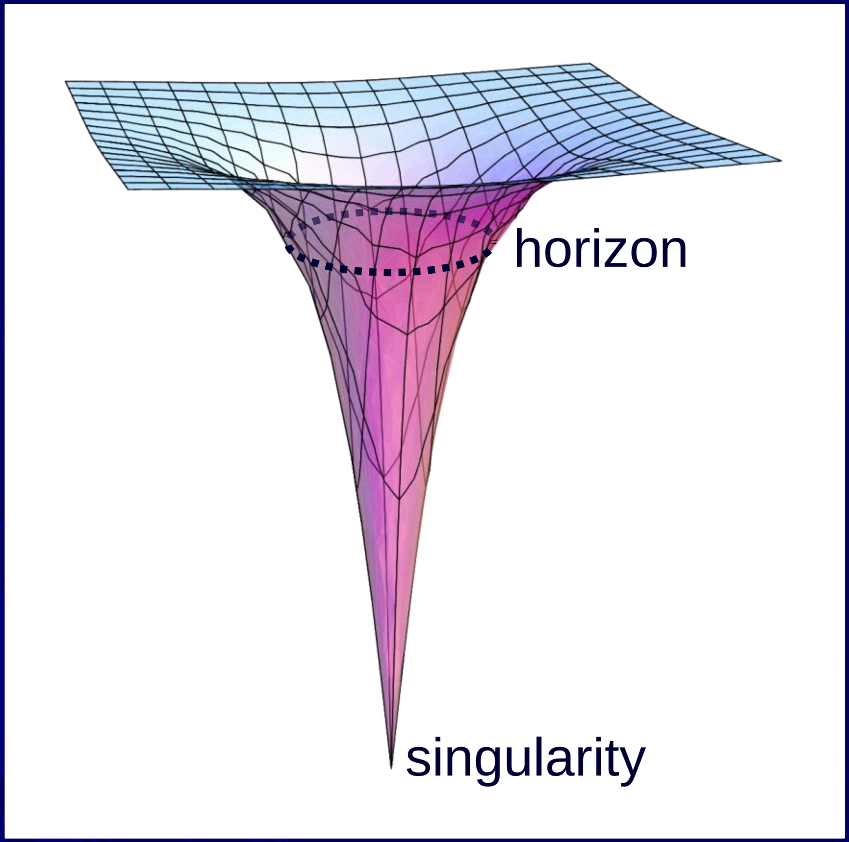
Consider various black hole thought experiments.

See what quantum mechanics predicts.

See what general relativity predicts.

If they disagree, we get an important clue.

Thought experiments with black holes

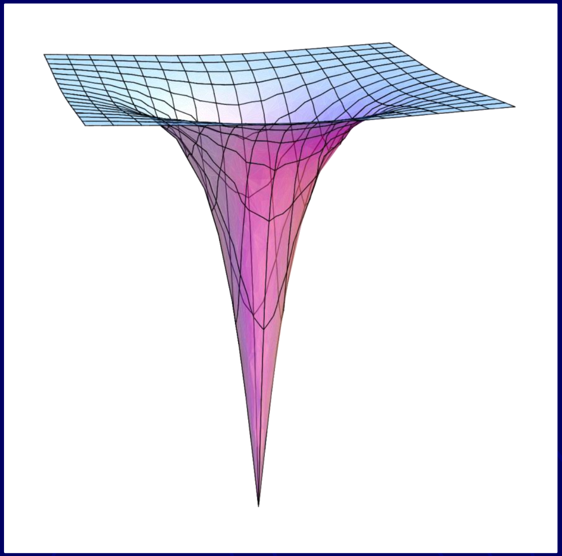


- The fate of very massive objects.
- An extreme bending of spacetime.
- `Infinite' density at the singularity
- The horizon: the point of no return.

Confronting quantum mechanics with general relativity in a black hole leads to two conflicts:

- The entropy puzzle (Bekenstein, Hawking, 1972-4)
- The information paradox (Hawking, 1976). Latest incarnation: the *firewall.*

Entropy puzzle: general relativity describes black holes as smooth geometries, without `hair.' Quantum mechanics points to an atomic or bit substructure.



Evidence for the latter:

- Information storage limit (Bekenstein)
- The black hole temperature (Hawking, 1974).

A further lesson: the *holographic principle*.

Bekenstein: calculate number of bits of information that a black hole can contain, as a function of its radius R.

- Minimum energy to add one bit: $\hbar c/R$
- Total energy of a black hole of radius R: c^4R/G.
- # of bits = energy/(energy per bit) = $c^3R^2/\hbar G$.

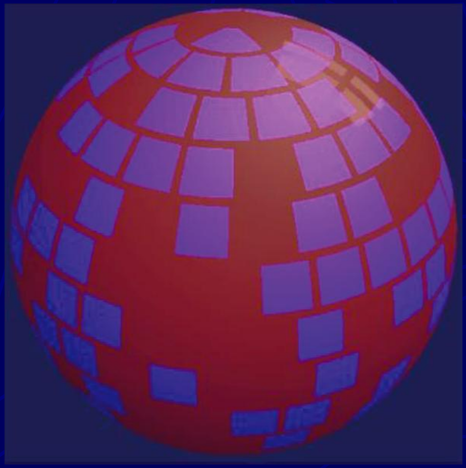
Hawking: black holes radiate with a temperature $kT = hc/R$.
Total number of bits = energy/kT = $c^3R^2/\hbar G$.

What are these bits?

The *holographic principle*: the Bekenstein-Hawking result for the number of bits in a black hole is interesting:

$$c^3 R^2/\hbar G$$

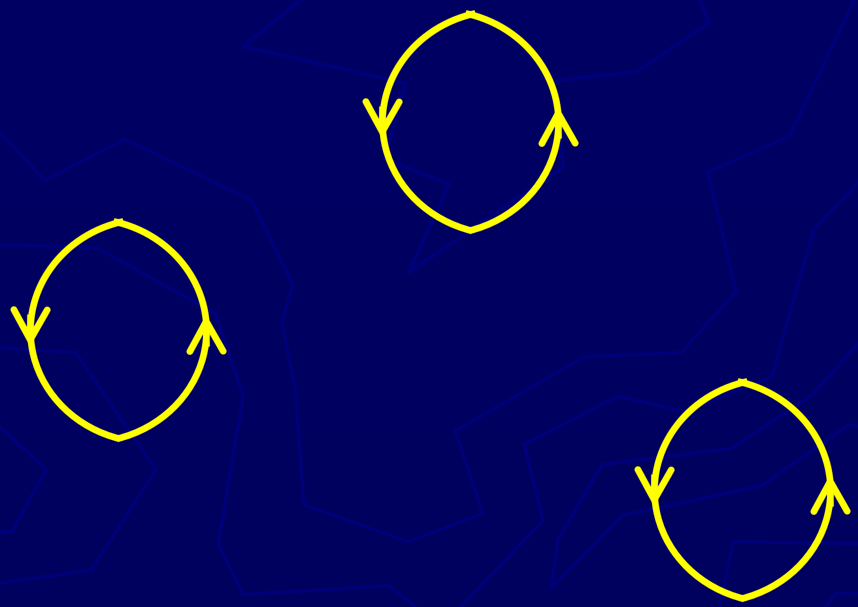
For most systems the number of bits is proportional to the volume, R^3. This suggests that the fundamental degrees of freedom of a gravitating system live on its surface:



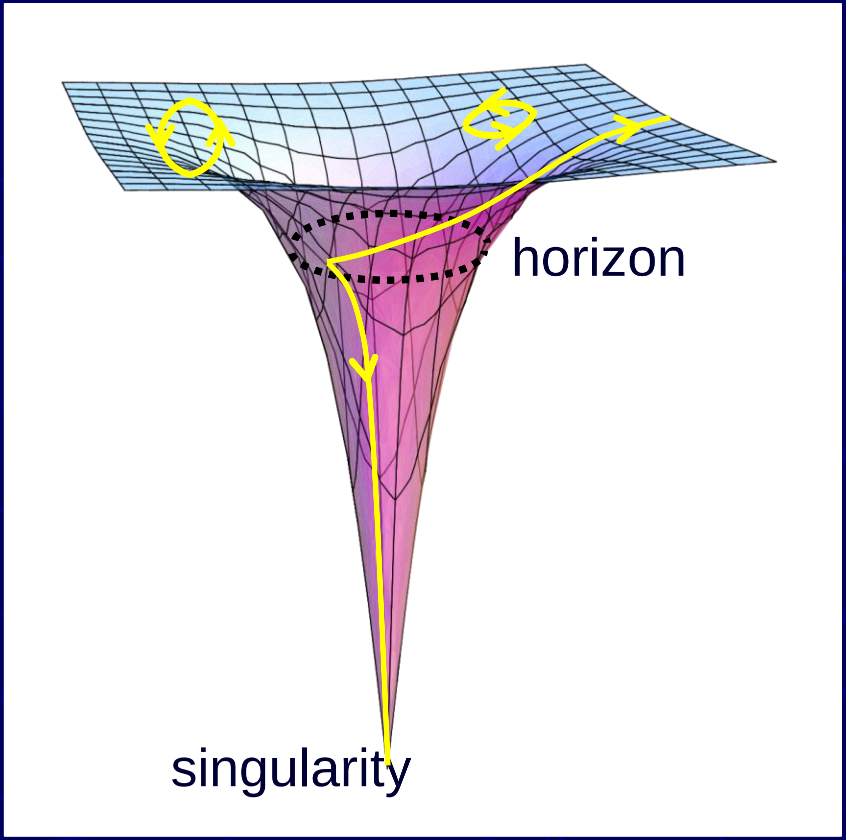
If so, this would be fundamentally different from any system that we are familiar with, a radical change in the nature of space.

Hawking radiation and black hole evaporation

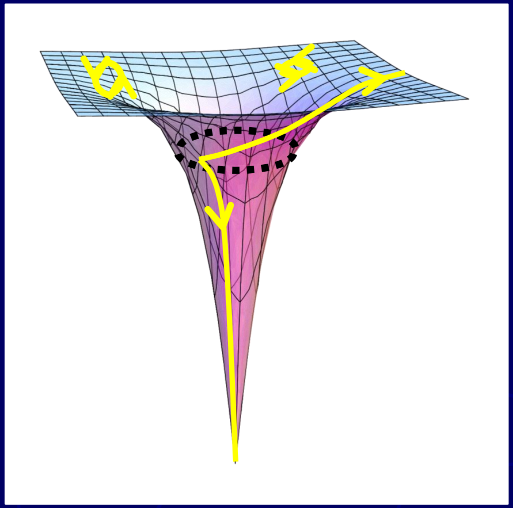
Quantum mechanics says that empty space is full of particle-antiparticle pairs that pop into and out of existence:



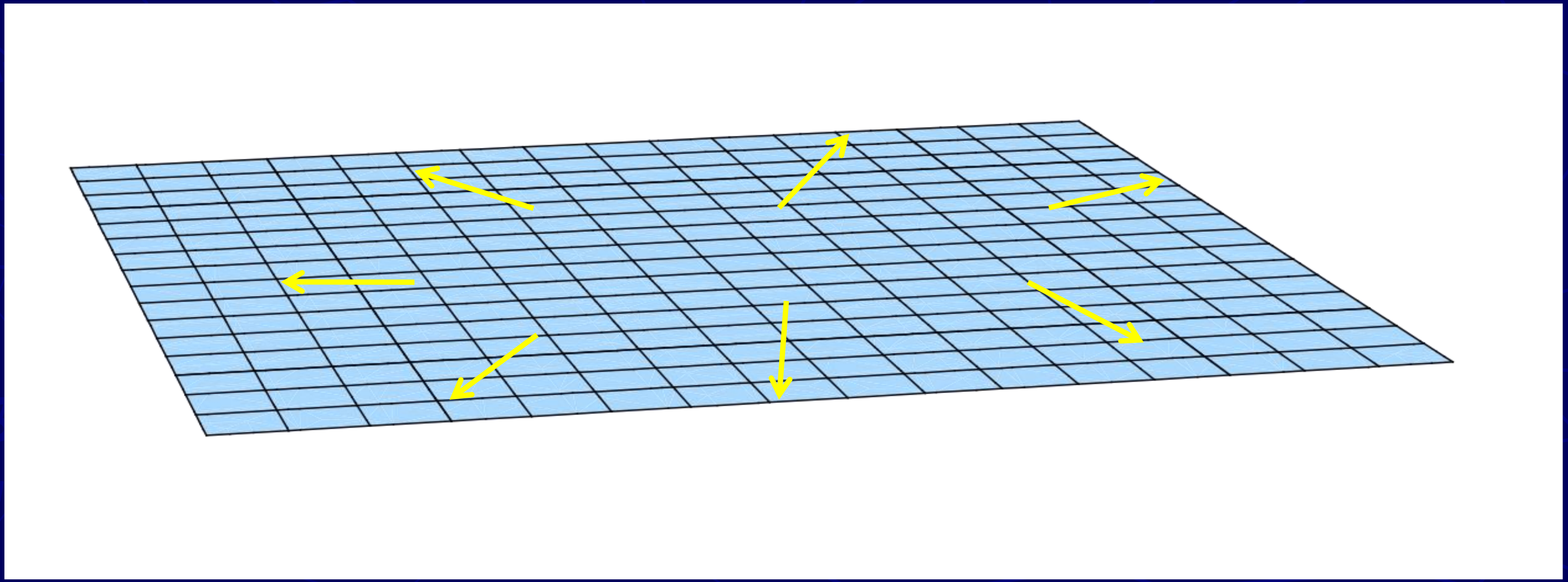
When this happens near the horizon, sometimes one particle falls into the singularity and one escapes:



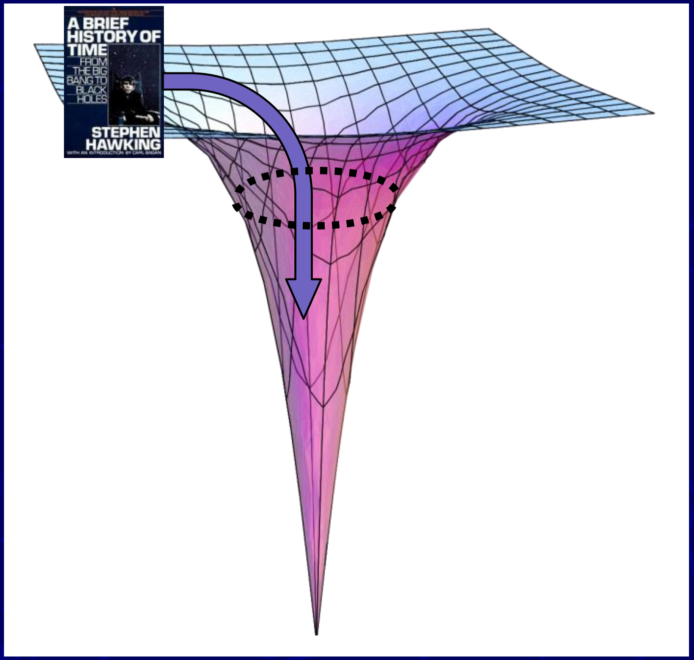
This carries energy away, and the black hole loses mass.

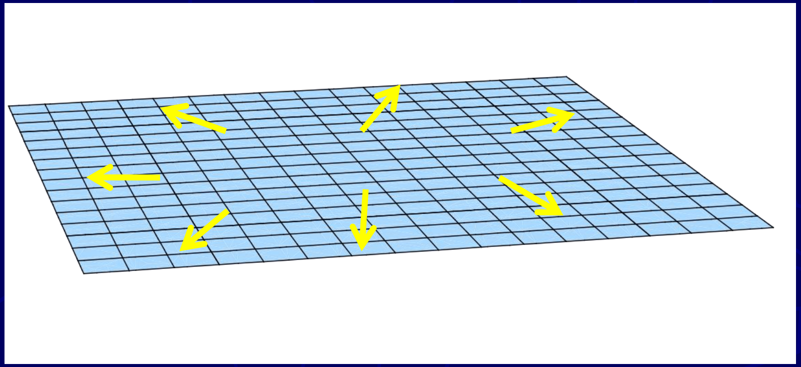


Without quantum mechanics, black holes always grow, but due to Hawking radiation they can `evaporate’ and eventually disappear:



Black hole evaporation is not controversial, but it leads to the *information paradox,* which is: evaporation destroys information about what falls into black holes.





Quantum mechanics does not allow information to be destroyed. But for the information to get out, it would have to travel faster than light!

Quantum mechanics versus relativity!

Hawking: “God not only plays dice, He sometimes throws the dice where they cannot be seen.”

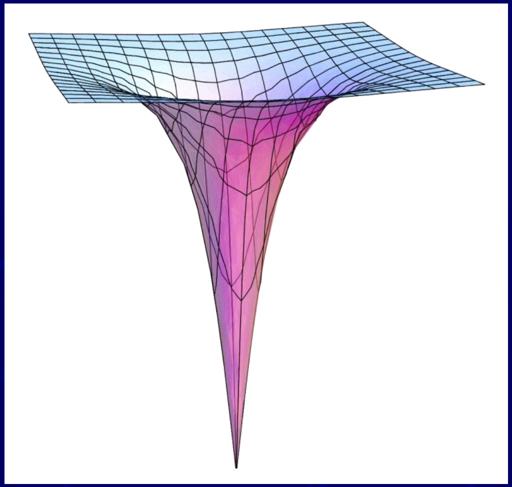
- Information lost: violates quantum mechanics
- Information escapes: violates relativity

How this was resolved:

Duality: two seemingly different systems that are actually the same (like waves and particles). When one description becomes highly quantum, the second becomes classical and simple.

Maldacena (1997) found a duality between a quantum mechanical black hole and a much more ordinary system, a gas of particles similar to the quarks and gluons of nuclear physics.

gauge/gravity duality:



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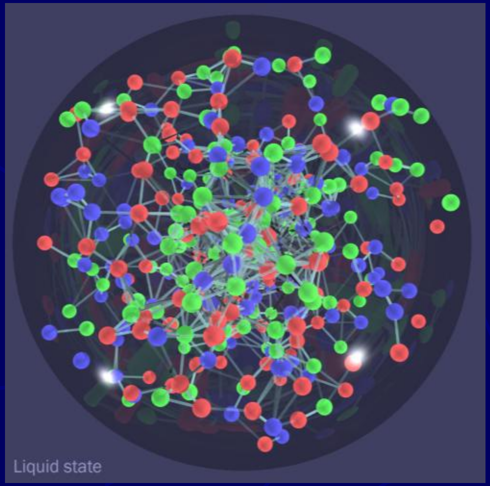
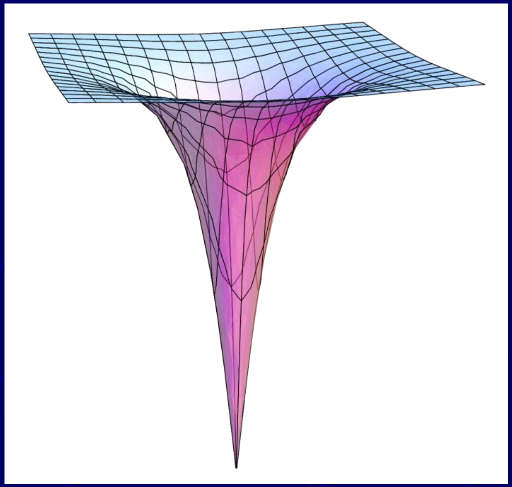


Like Maxwell, an unexpected connection between widely different areas of physics.

The most complete construction of quantum gravity to date.

gauge/gravity duality:



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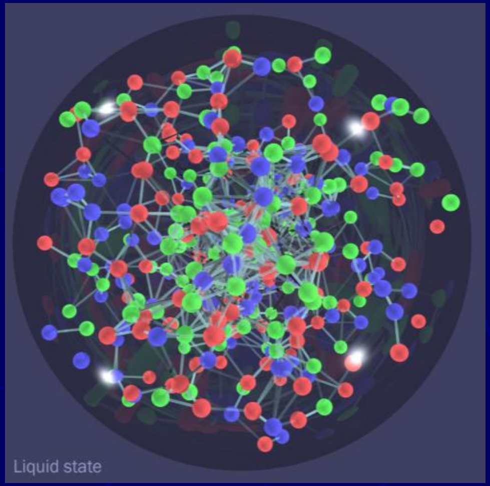

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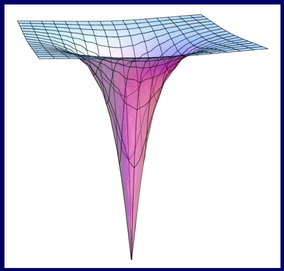

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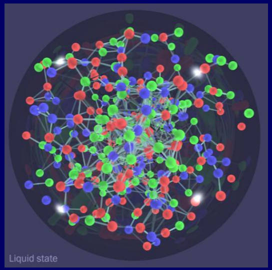

Consequences:

- Quarks + gluons obey ordinary QM: info can’t be lost.
- Provides the bits predicted by Bekenstein and Hawking.
- Holographic: the bits live on the surface.

But we're not done:

• Where exactly did Hawking go wrong – exactly how does the information get out?

• How does this holographic principle work, and how do we generalize it from black holes to the Big Bang?

Good news: a new paradox

Things that were widely believed:

- Information is not lost.
- An observer who stays outside the black hole sees nothing unusual.
- An observer who falls through the horizon sees nothing unusual.

Black hole complementarity: information doesn't actually travel faster than light. The outside observer sees it come out, the infalling observer sees it inside, and they can't compare notes – a new relativity principle ('t Hooft Susskind).

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Actually these seem to be inconsistent! They imply an impossible quantum state for the Hawking radiation.

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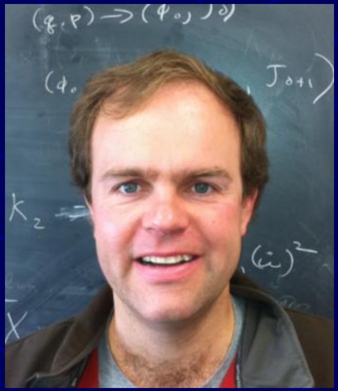
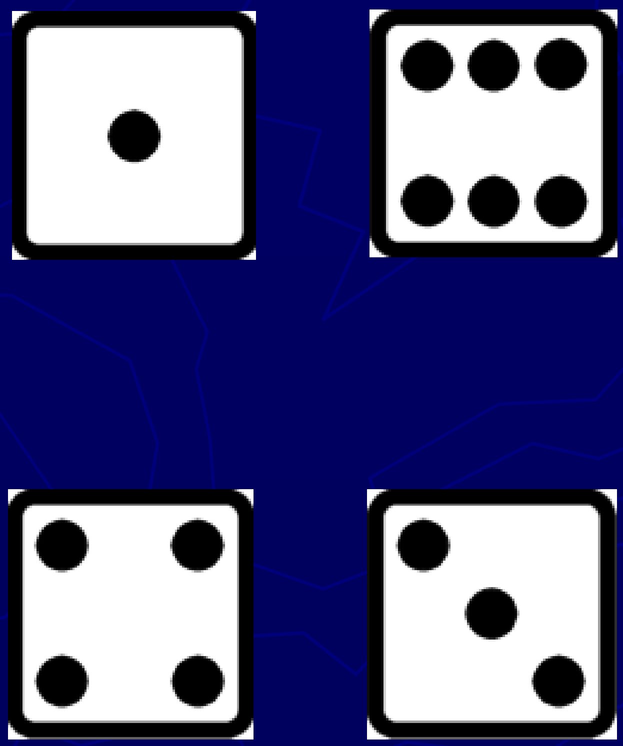
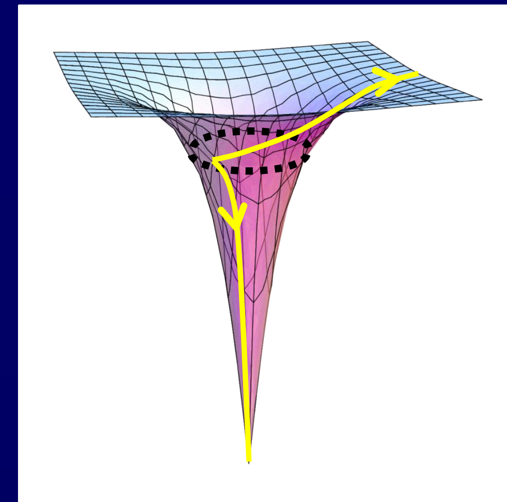
Actually these seem to be inconsistent! They imply an impossible quantum state for the Hawking radiation.
My partners in crime:



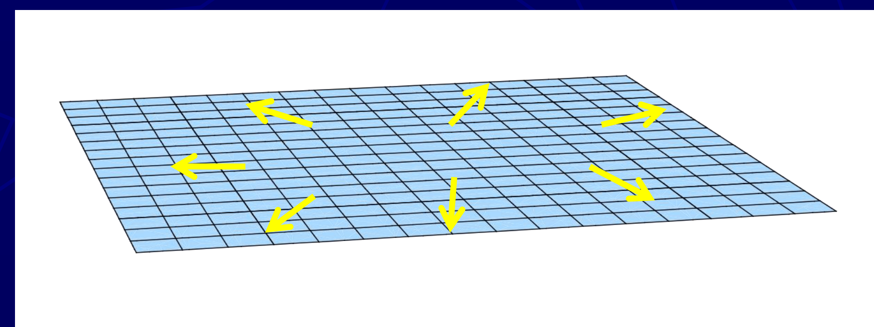
The argument is based on another mysterious property of quantum mechanics: *entanglement*.



The Hawking pair is produced in an *entangled state,* $|0\rangle|0\rangle + |1\rangle|1\rangle$



Conservation of information requires that the Hawking photons be entangled with each other (a pure state).

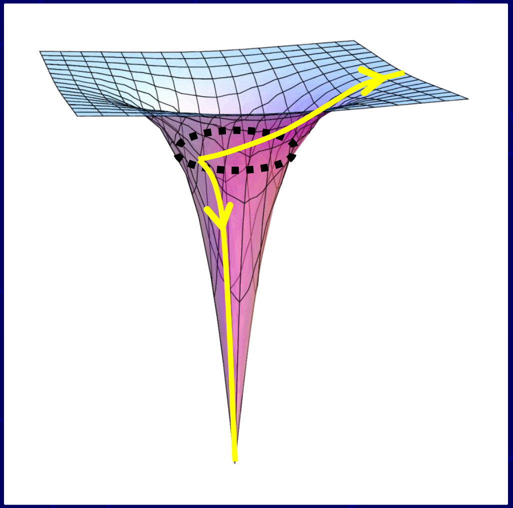


QM does not allow this, entanglement is monogamous!

$$(|0\rangle|0\rangle + |1\rangle|1\rangle)|0\rangle \text{ vs. } |0\rangle(|0\rangle|0\rangle + |1\rangle|1\rangle)$$

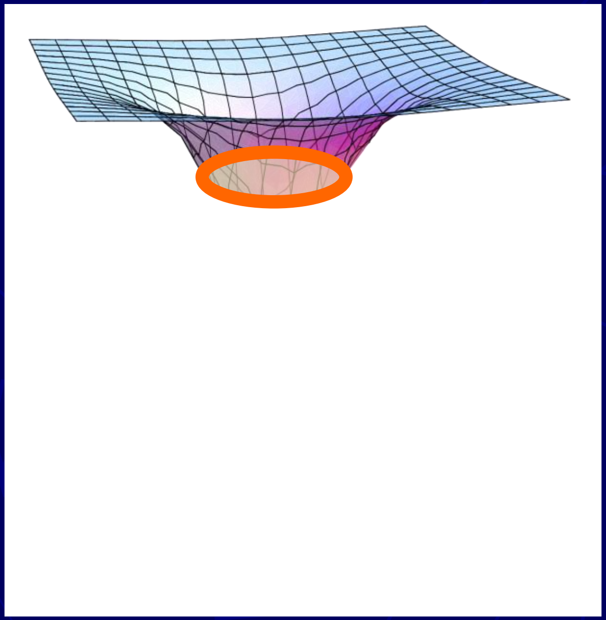
$$(|0\rangle|0\rangle + |1\rangle|1\rangle)|0\rangle \quad \text{vs.} \quad |0\rangle(|0\rangle|0\rangle + |1\rangle|1\rangle)$$

information loss   firewall!

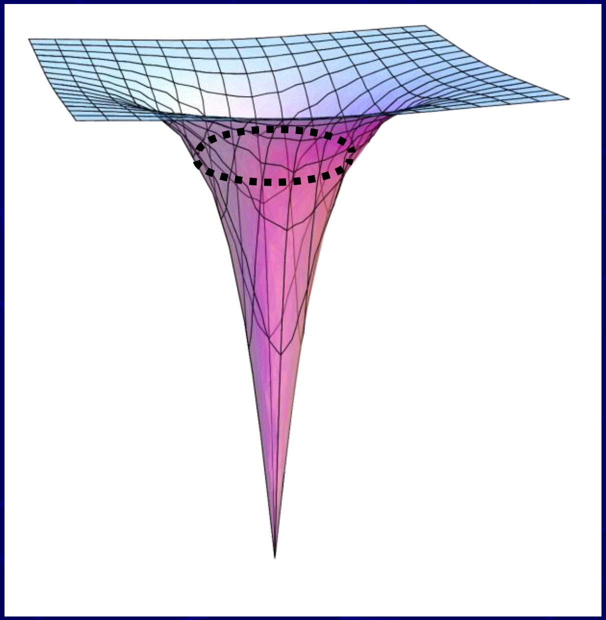


Sort of like breaking a chemical bond, losing the entanglement across the horizon implies a higher energy state.

If nothing unusual happens outside the horizon, and information is not lost, and infalling observer will hit a firewall of high energy particles:



instead of



Once again, a sharp conflict between quantum mechanics and spacetime…

A simple argument $\rightarrow$ lots of controversy. After two years and >250 papers, there is no consensus.

Most* attempts to evade the firewall require loosening the rules of quantum mechanics:

- Strong complementarity (no global Hilbert space)
- Limits on quantum computation (Harlow & Hayden)
- Final state boundary condition at the black hole singularity (Horowitz & Maldacena; Preskill & Lloyd).
- EPR = ER (Spacetime from entanglement, Maldacena & Susskind).
- Nonlinear observables (Papadodimas & Raju, Verlinde^2).

All of these are preliminary frameworks, not theories.

- Are there any observational effects for black holes?

Some ideas would lead to this, but the argument is consistent with the exterior being exactly as in the usual picture, except perhaps for very subtle quantum effects.

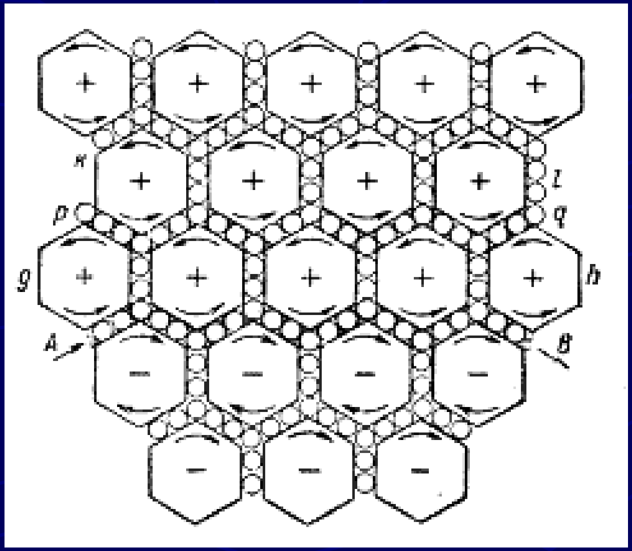
- Are there any consequences for the early universe?

Too early to say. Are cosmological horizons like black hole horizons? Is there a version of the information problem? Most important, this may give us a new lever on applying holography to cosmology.

Conclusion:

Thought experiments with black holes have led to some surprising discoveries: black hole bits, the holographic principle, Maldacena’s duality.

The latest thought experiment presents new challenges, and we can hope that it will lead us to a more complete theory of quantum gravity.



extra slides

Planck units (1899):

Planck time $\sqrt{\hbar G/c^5} = 5.4 \text{ x } 10^{-44}$ sec.

Planck length $\sqrt{\hbar G/c^3} = 1.6 \text{ x } 10^{-33}$ cm.

Each of Planck's chosen constants was about to lead to a great revolution in physics:

c: Special Relativity (1905)

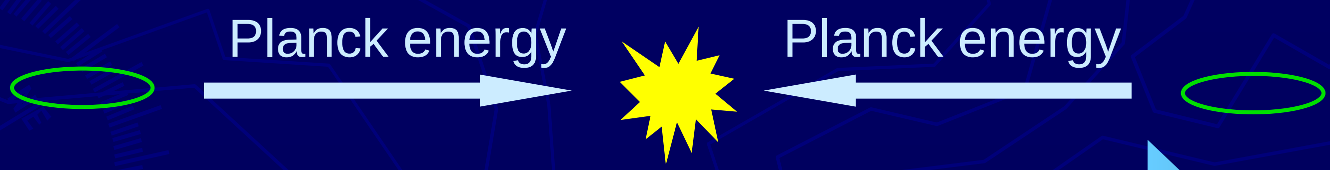
G: General Relativity (1915)

$\hbar$: Quantum Mechanics (~1925)

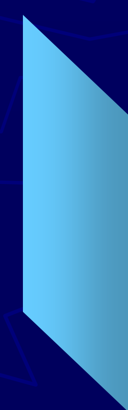
Scattering at the giga^5 scale:

Applying the existing theories of QM + GR gives a nonsense answer, an infinite rate of scattering.

A difficult problem, but it turns out that one can fix it if particles are not *points* but *strings*,



A strange idea, but it seems to work. Further thought experiments show that theory also need *branes*:



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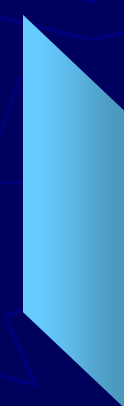
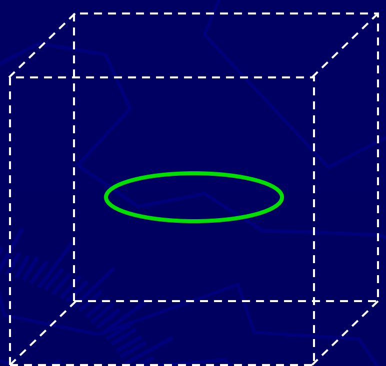
A difficult problem, but it turns out that one can fix it if particles are not *points* but *strings*,

A strange idea, but it seems to work. Further thought experiments show that theory also need *branes*:

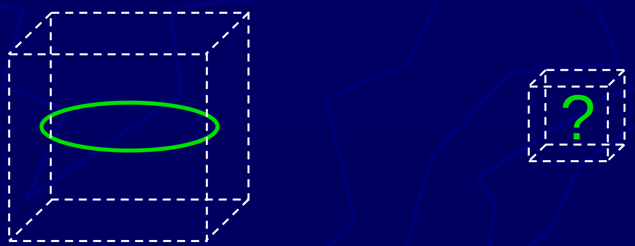


The string-in-a-box thought experiment

Strings were an unfamiliar idea, and many thought experiments have been useful in understanding their physics. Here is an important one:

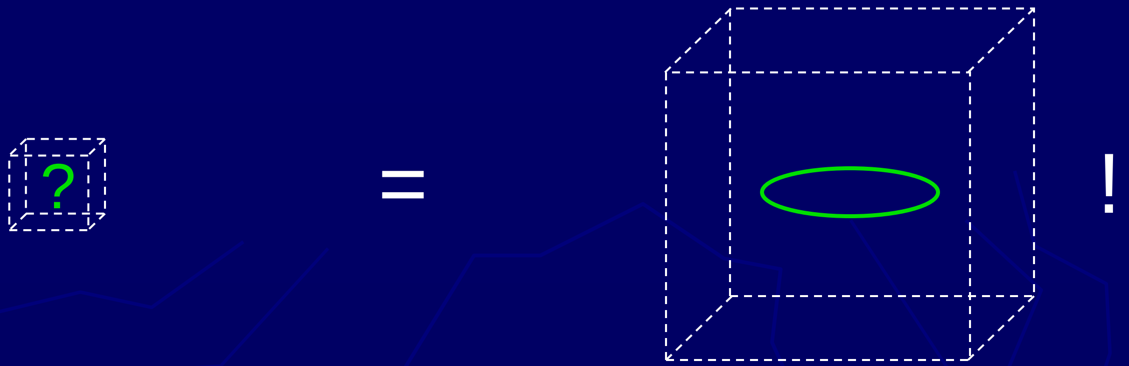


Put a string in a finite space



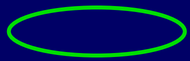
Make the space smaller…and smaller

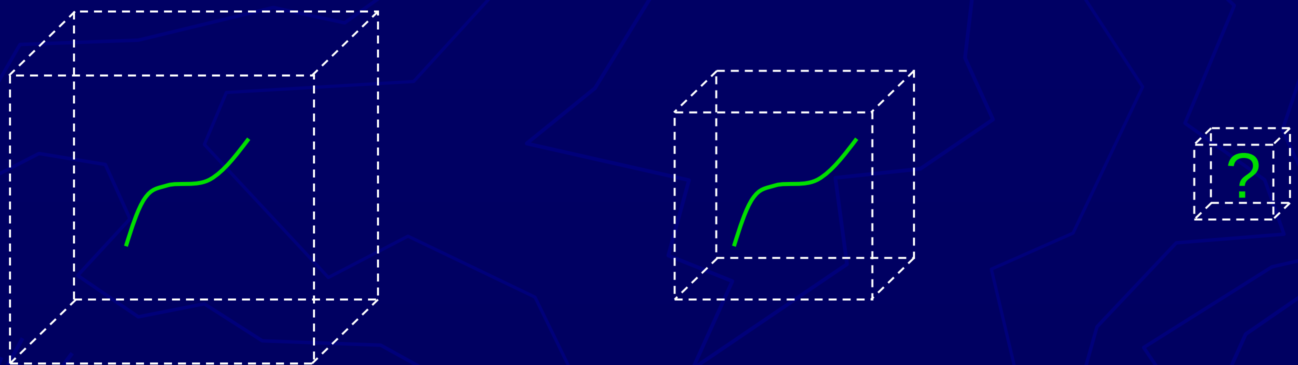
The mathematics gets interesting, and leads to a surprising picture:



When the original space goes away, a new large space emerges (`T-duality'). Lessons:

- Space is emergent, not fundamental.
- There is a minimum distance.

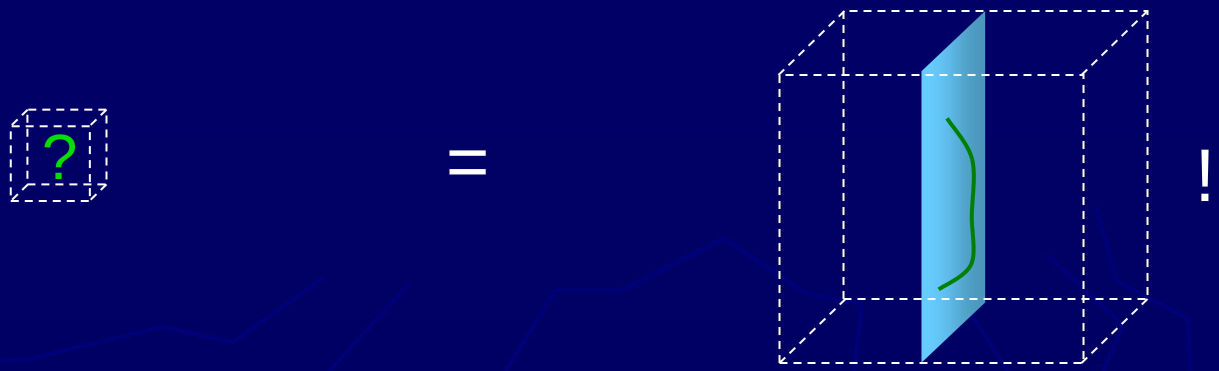
That was for a closed string . Now try it for an open string:



Put a string in a finite space

Make the space smaller…and smaller

Again, the trick is to figure out what is the physical picture that emerges from the math, and the answer is unexpected:



The emergent space also contains a new object, a `Dirichlet membrane,' or `D-brane' for short.

We do not know the full and final formulation of `string theory,' it is a work in progress. The strings were just a step toward the final answer, and the D-branes seem a little closer.