The Evolution of Black Holes

Nick Warner, Kyoto, November 22, 2015

Original Idea of a Black Hole

PHILOSOPHICAL

TRANSACTIONS,

OF THE

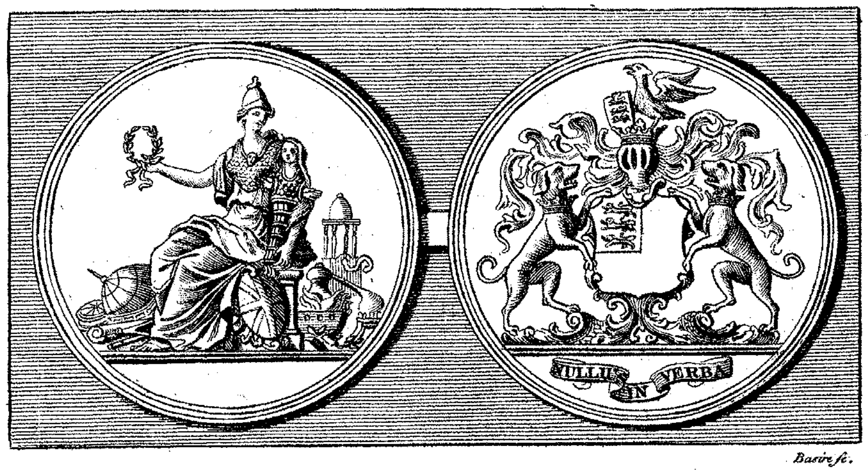
ROYAL SOCIETY

OF

LONDON.

VOL. LXXIV. For the Year 1784.

PART I.



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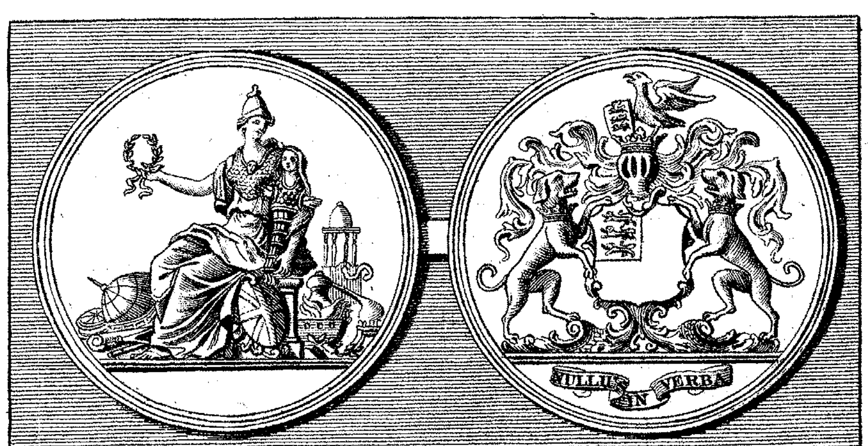

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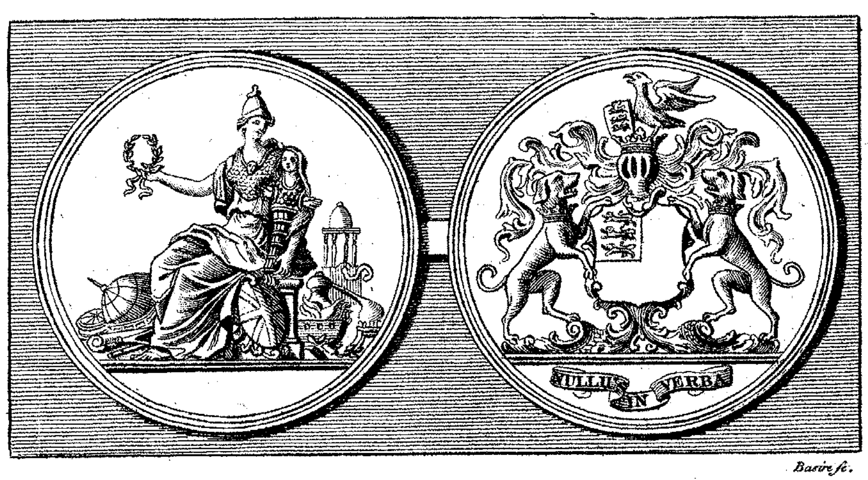

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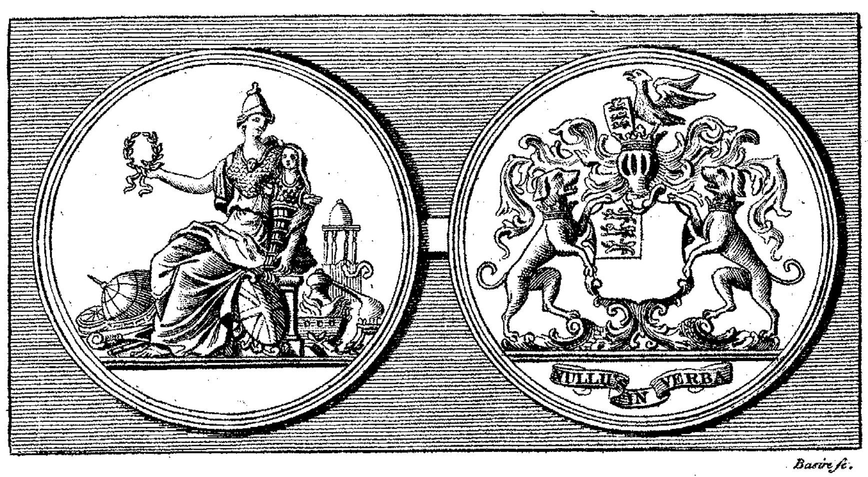

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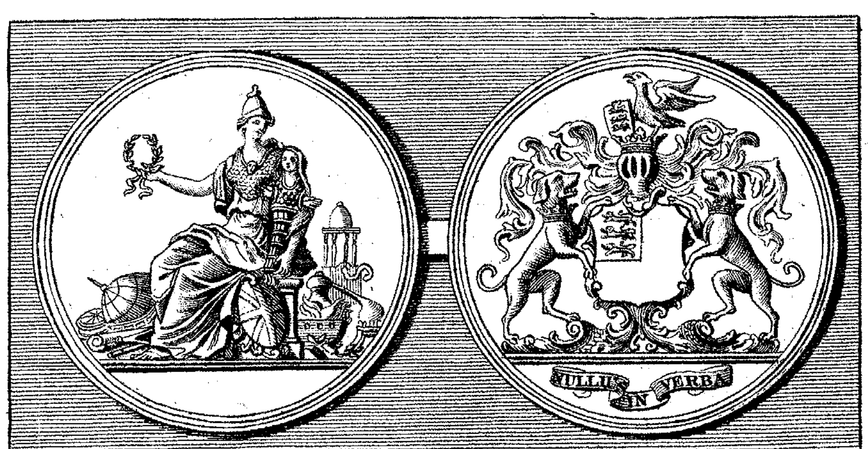

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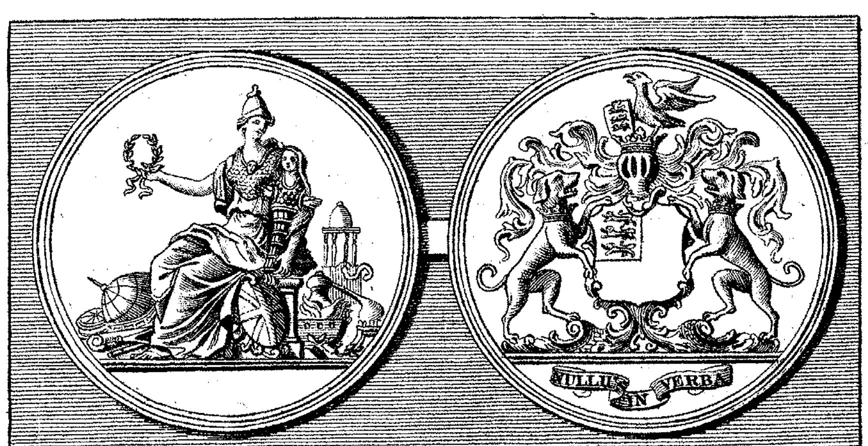

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To understand Michell's *dark stars*, we must understand the physics of 1784 …

Essential Physics in 1784

Ole Rømer

1675: **First measurement of the speed of light**

Done by making careful observations of the orbits of the moons of Jupiter

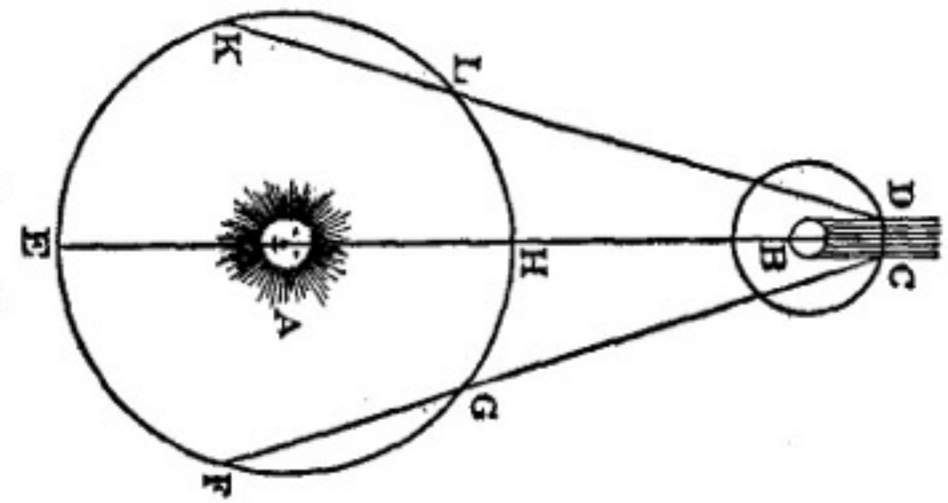

FIG. 70.

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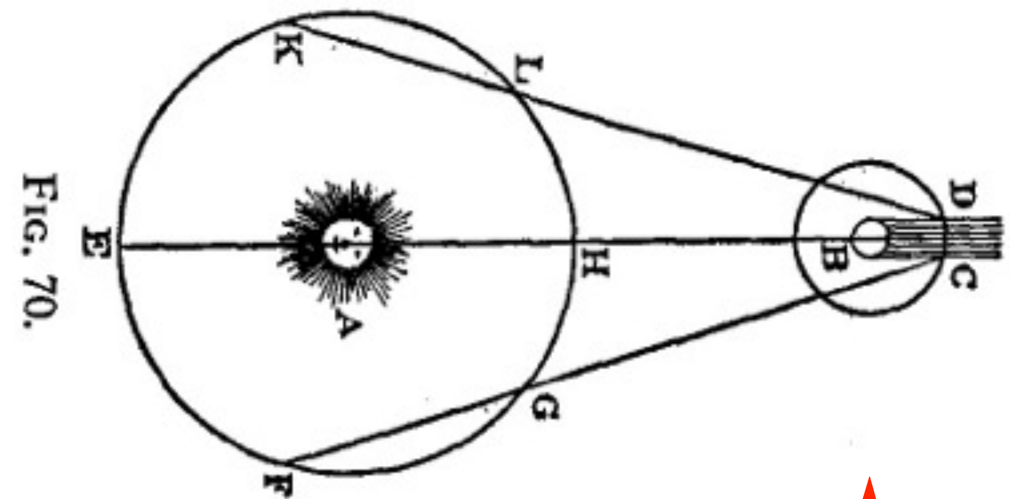
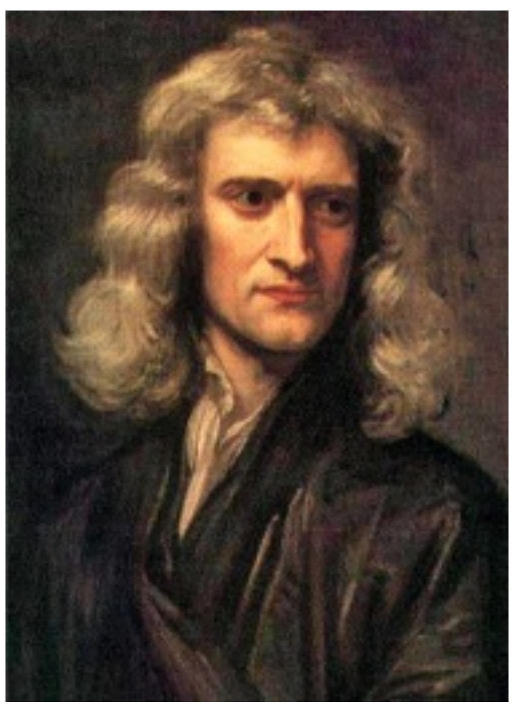


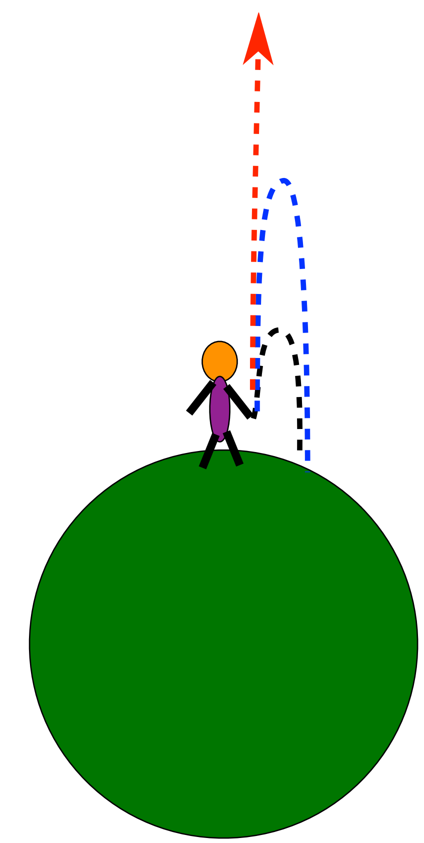


1687: **Newton's Universal Gravitation:**

⇒ Escape speed

How fast must I throw a particle upwards for it to escape the gravity of a planet or star?

Earth: 11.2 km/s, Surface of Sun: 617 km/s



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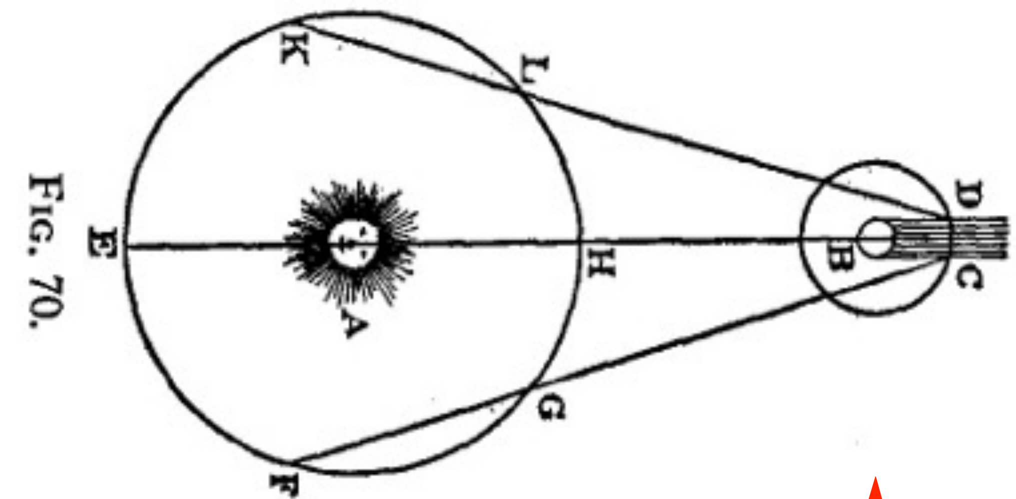

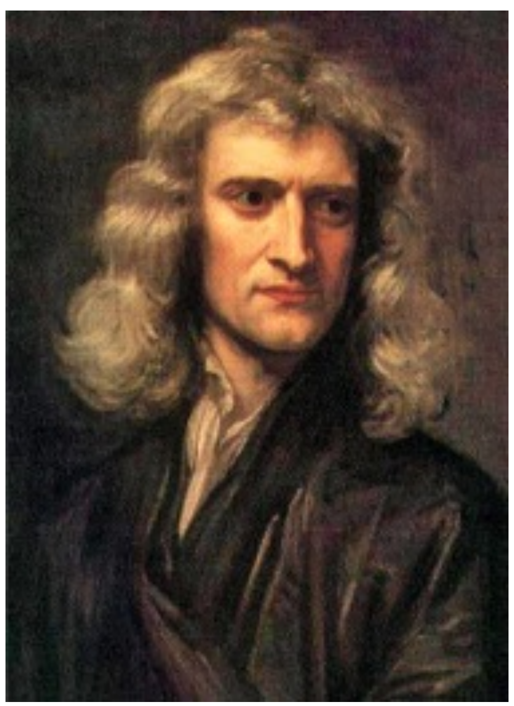

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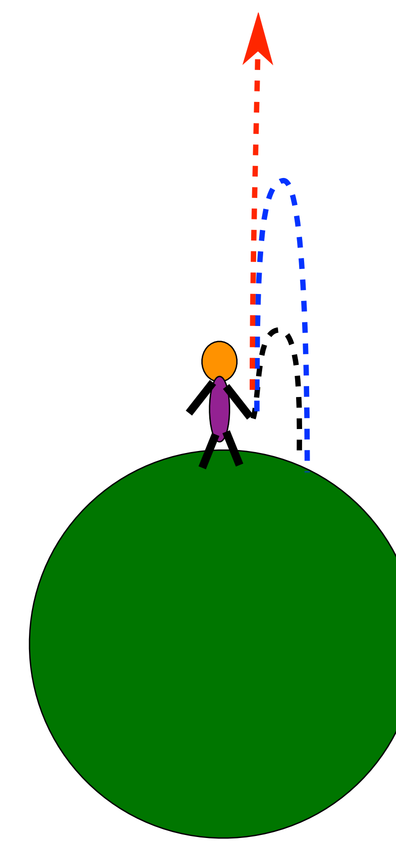

Before 1801: English scientists such as Newton and Michell thought

Light is made of particles

Michell's Dark Star in 1784:

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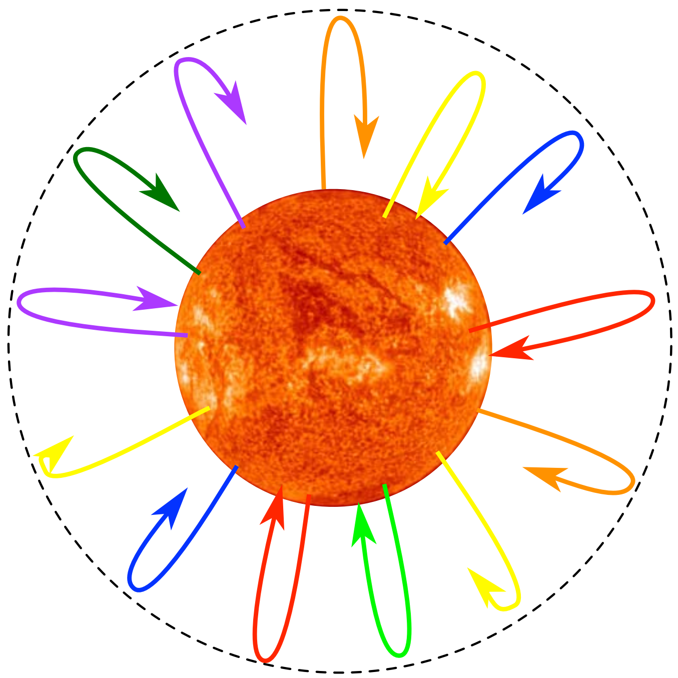

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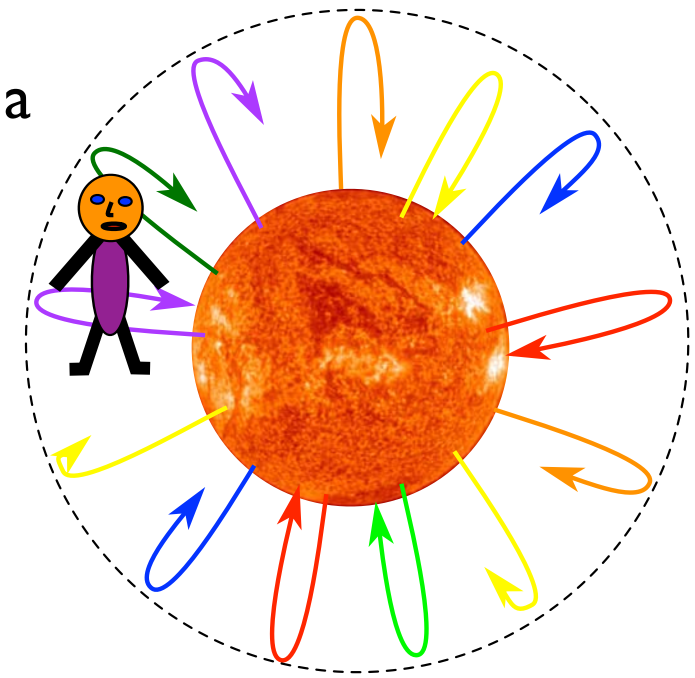
Light from the star reaches a nearby observer

⇒ *The star is visible to the nearby observer*



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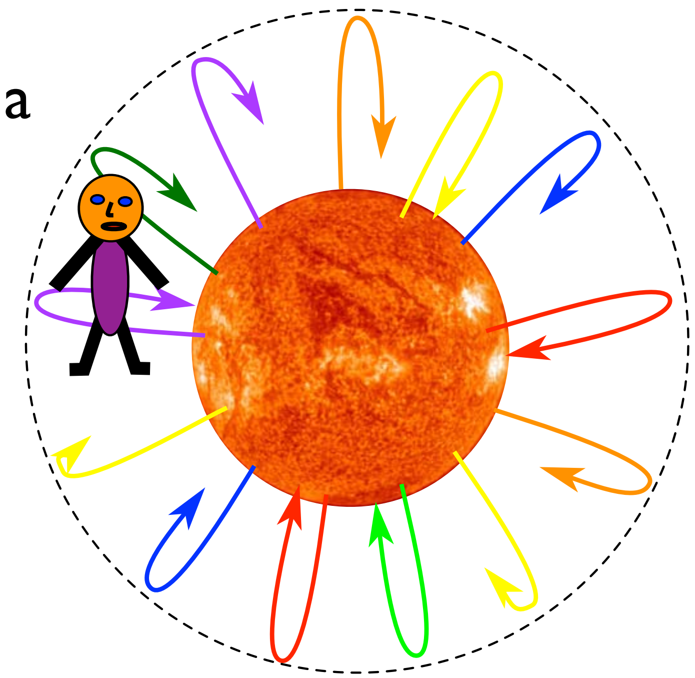

Light from the star ***does not*** reach a more distant observer

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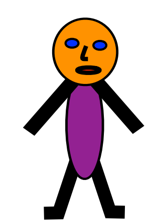

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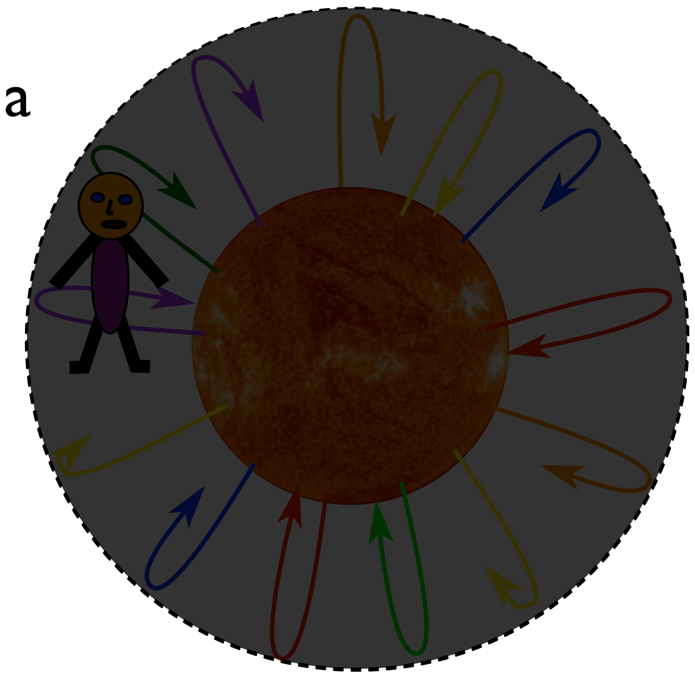

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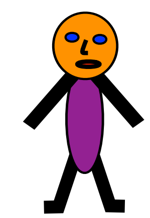

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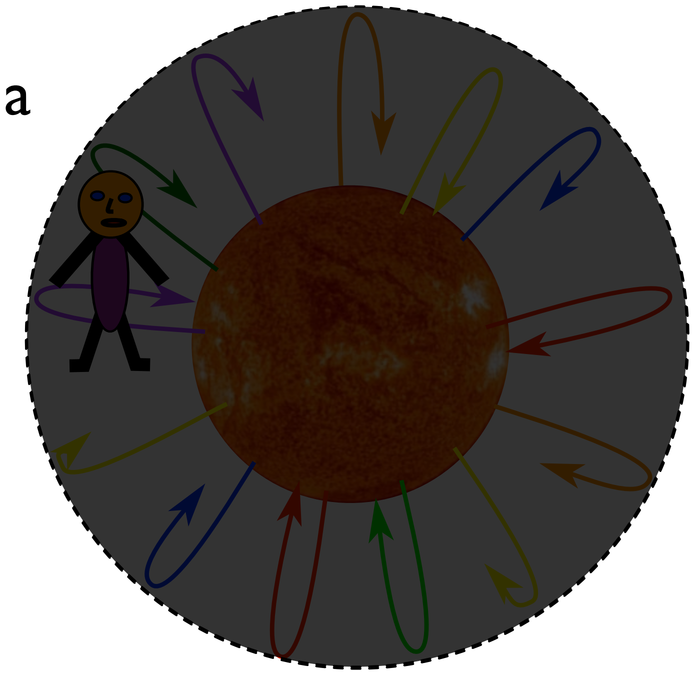

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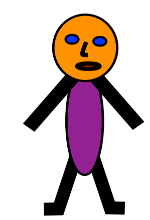

1865-1915: Maxwell and Einstein:

Light never slows down in a vacuum.

The speed of light in a vacuum is an absolute invariant ≈ **300,000** km/s

⇒ Einstein's special and general relativity

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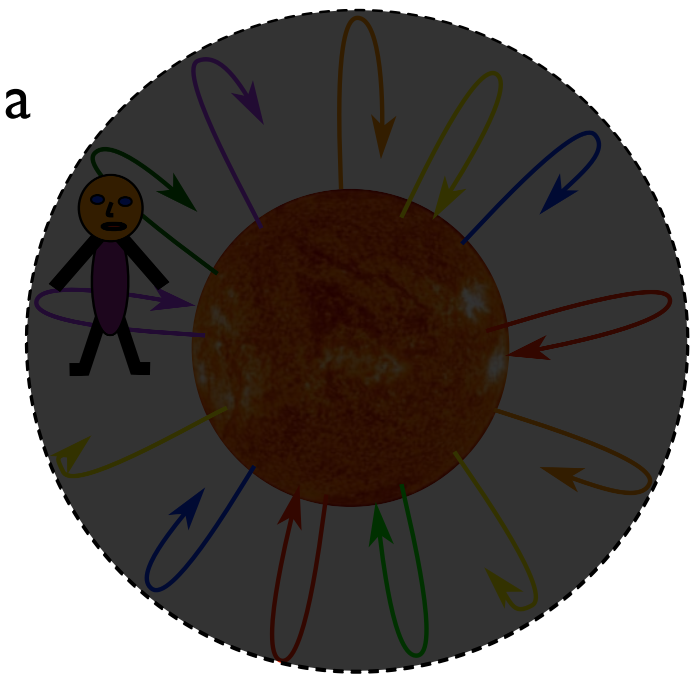

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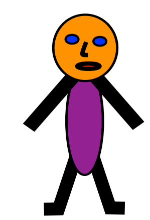

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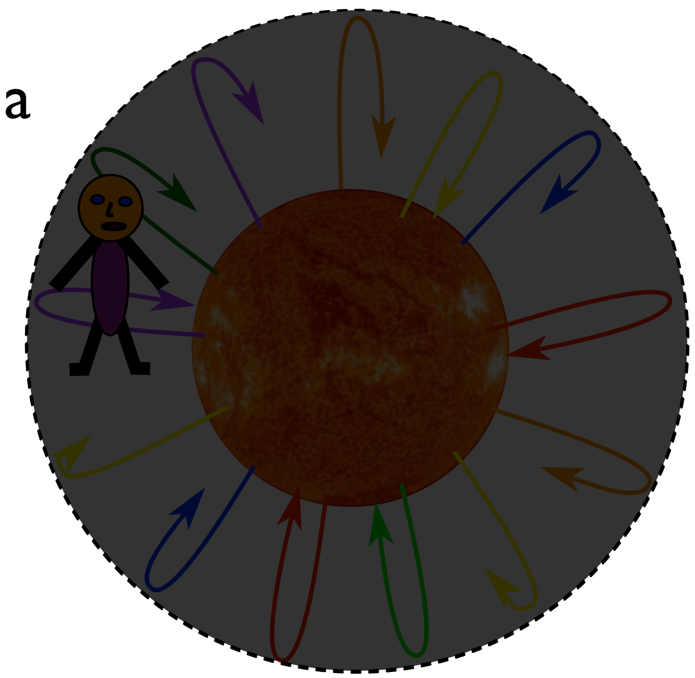

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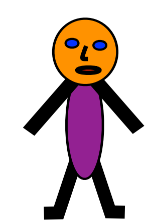

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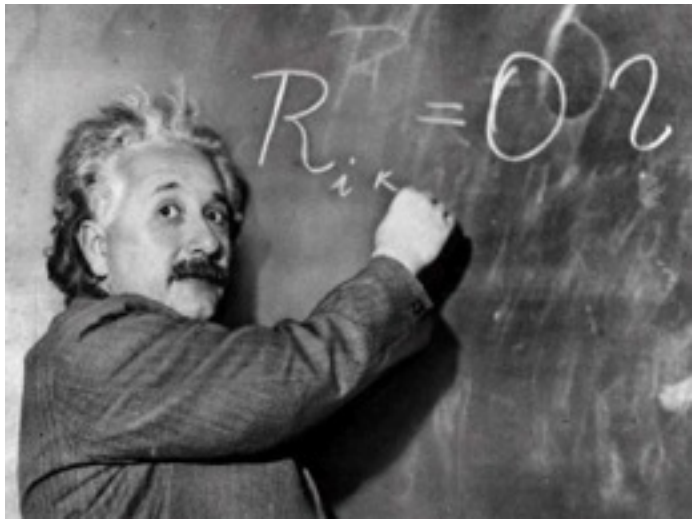
Can there be stars whose gravity is strong enough to trap light?
What does such a dark star look like in general relativity?

The Schwarzschild Black Hole



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***1915*: Einstein's equations in General Relativity**

The basis of modern theories of gravity and cosmology

Describe gravity through the geometry of space-time

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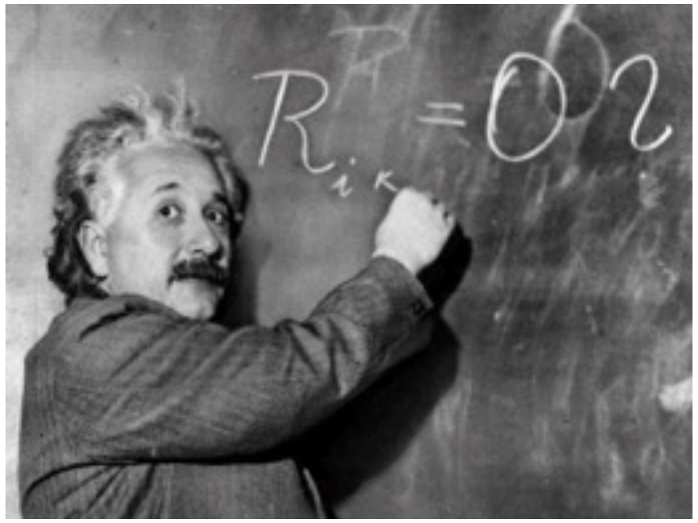

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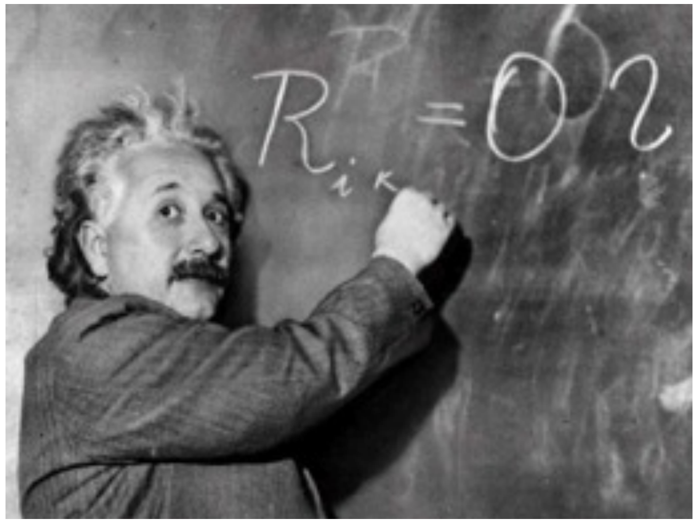

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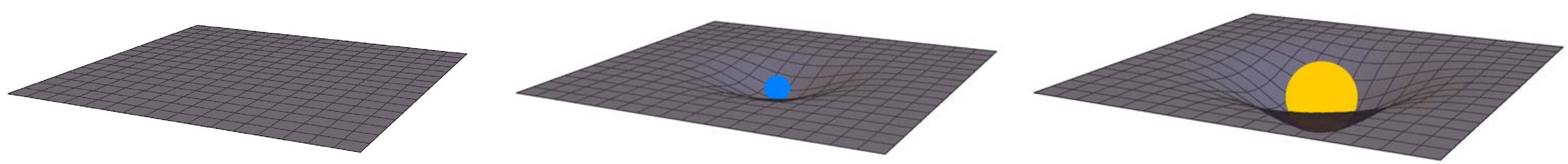

More mass ⇒ More bending of space time

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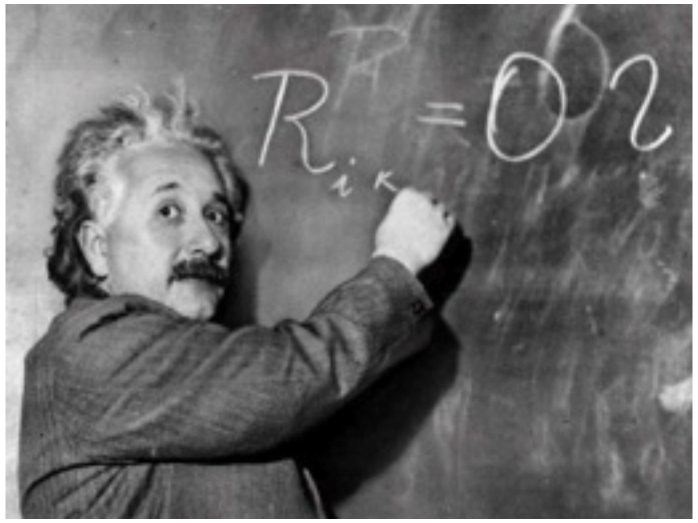

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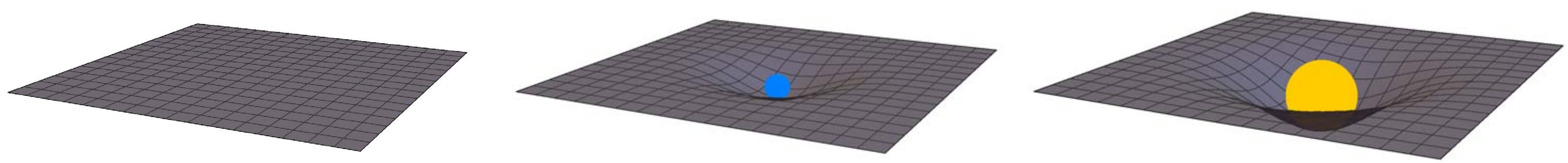

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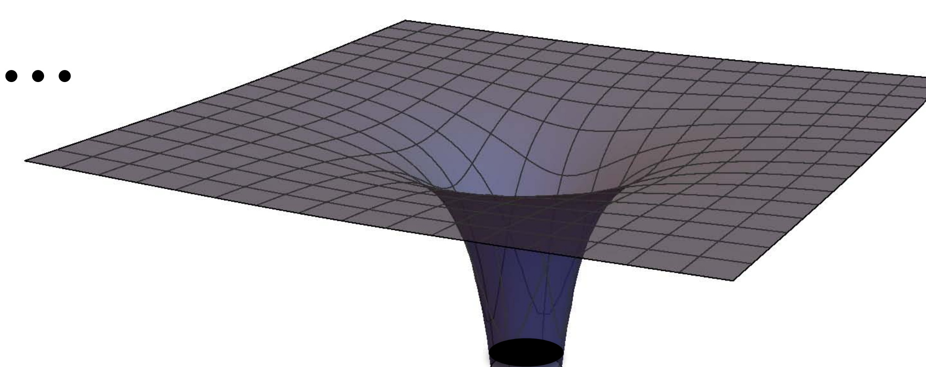
The basis of the standard theory of black holes …

Black Hole ⇒ Extreme (infinite) dimpling



The Black Hole of General Relativity

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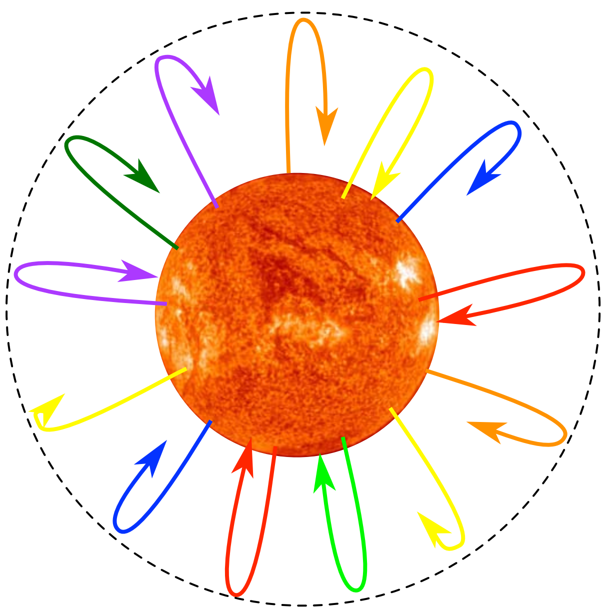

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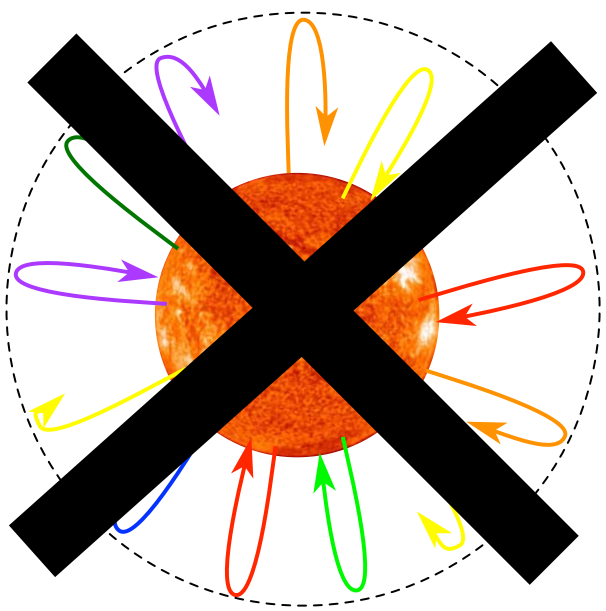

Light does not slow down

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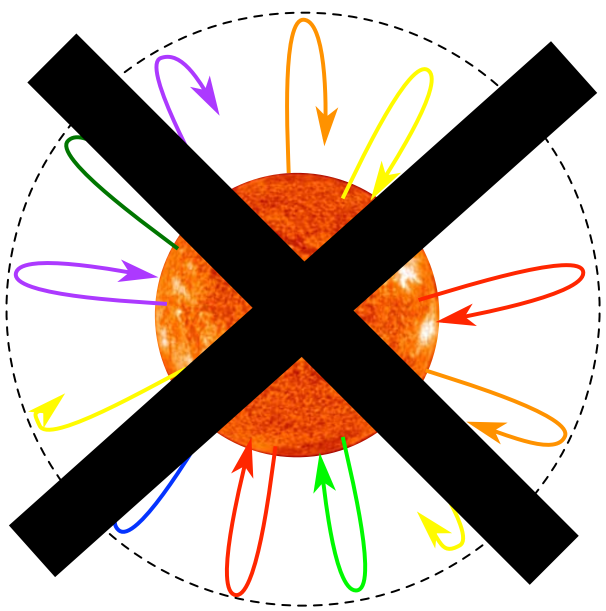

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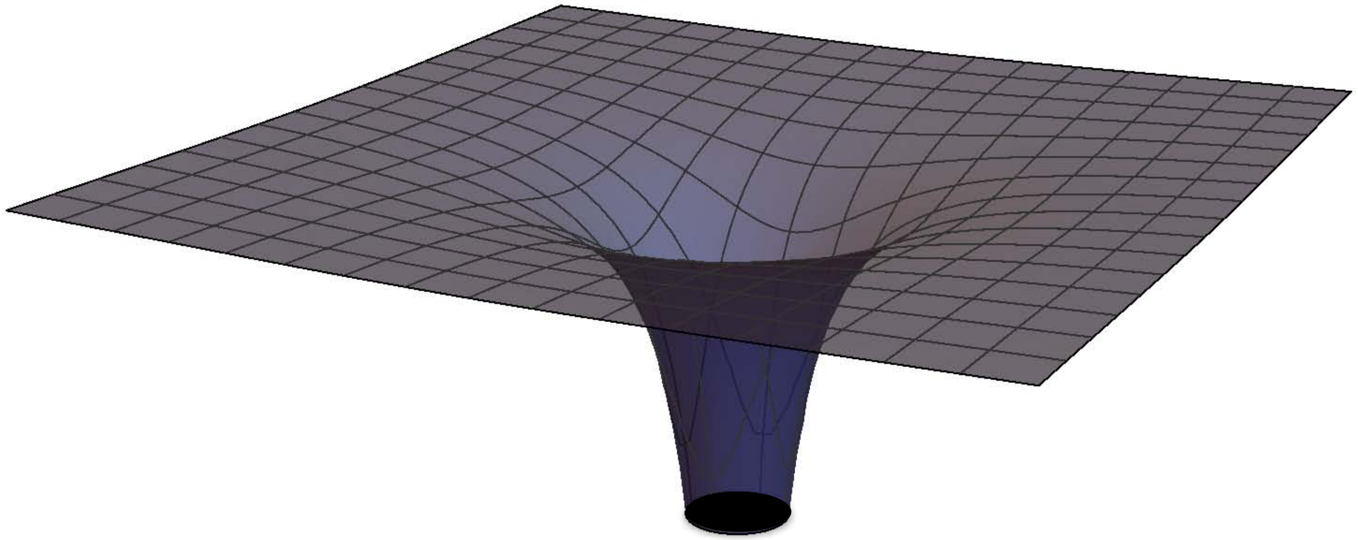
General Relativity: Schwarzschild

Can there be objects that curve space-time strongly enough to trap light?



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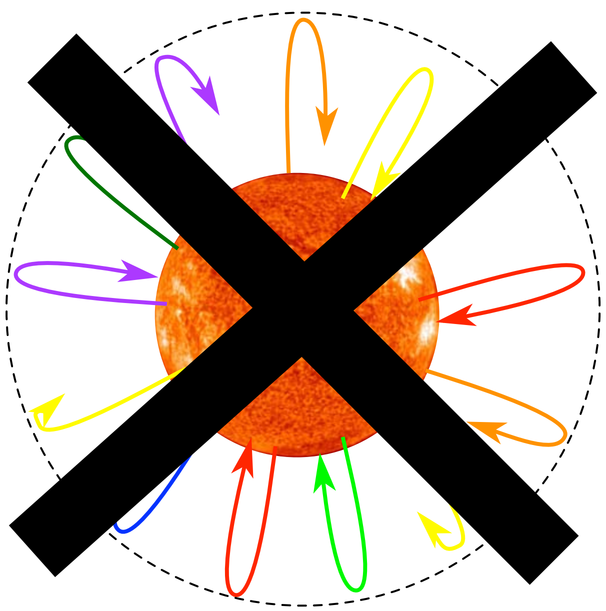

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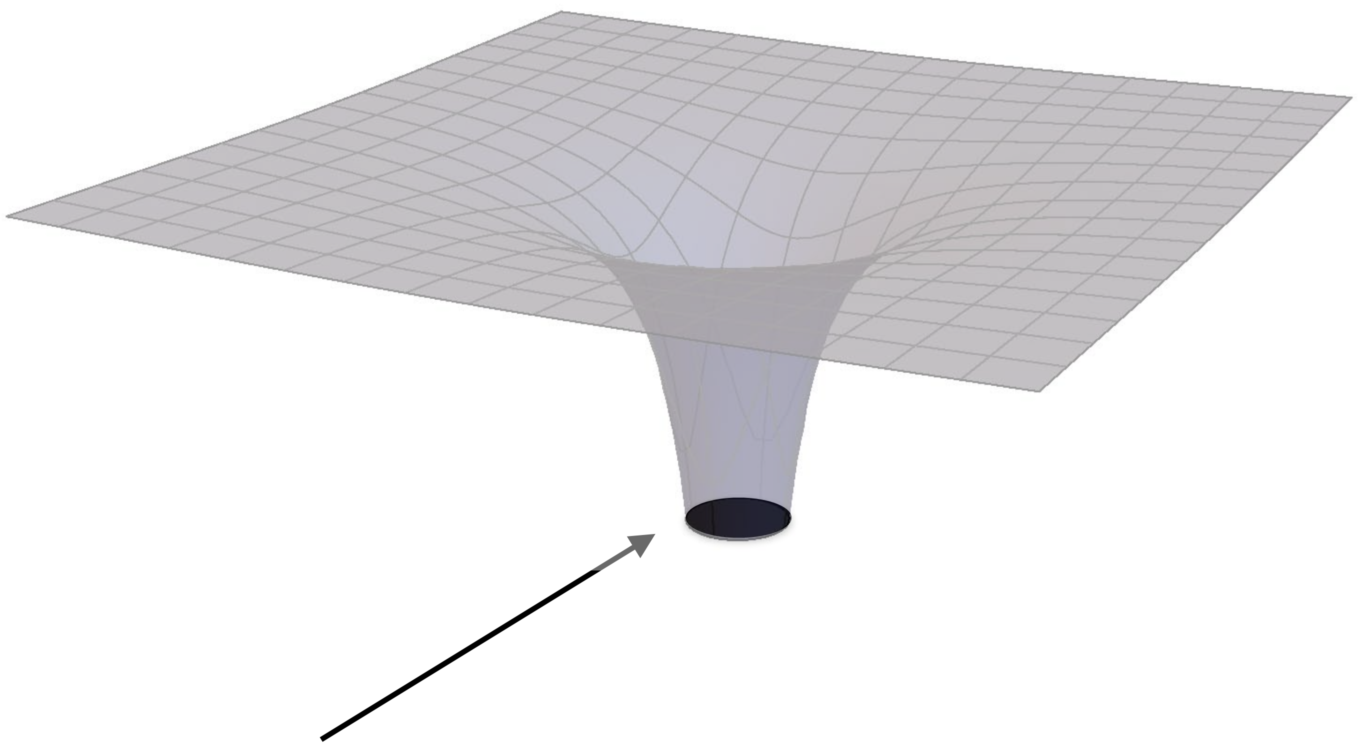

Here the space-time becomes so curved that it traps light …

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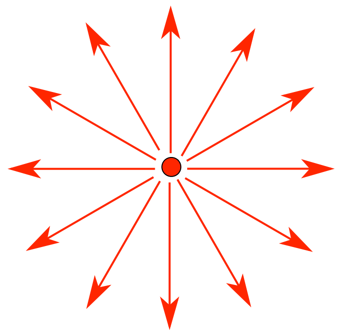
Imagine a light source emitting photons …



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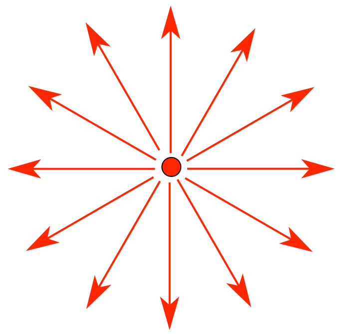
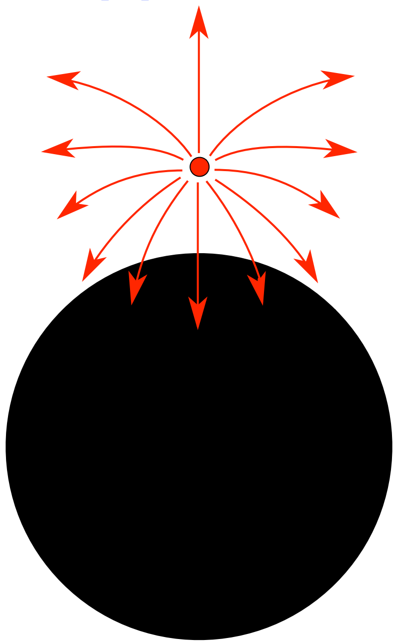


Suppose we drop it into a black hole



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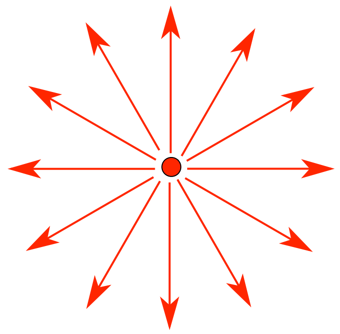

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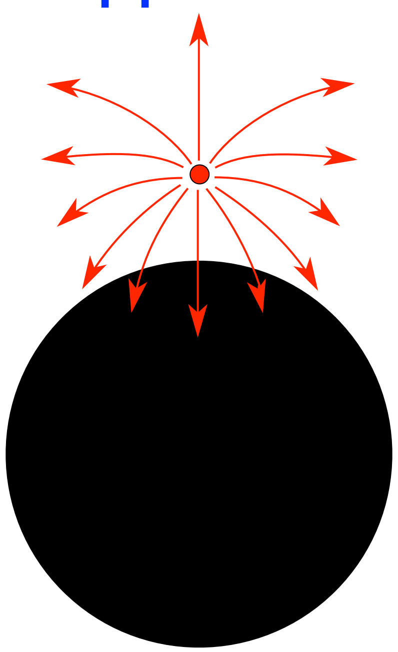

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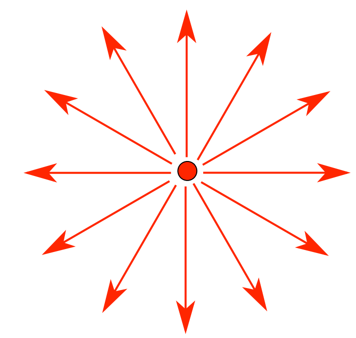

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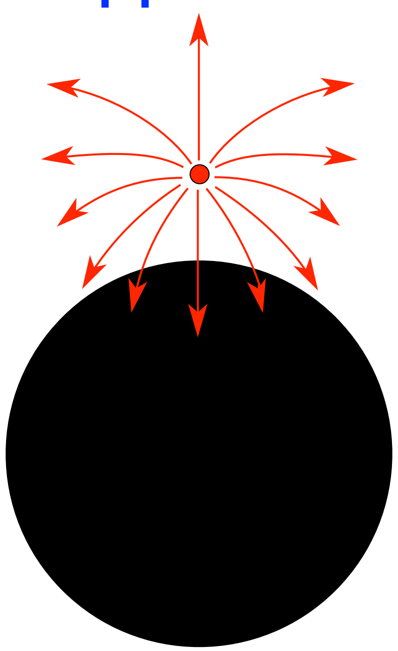

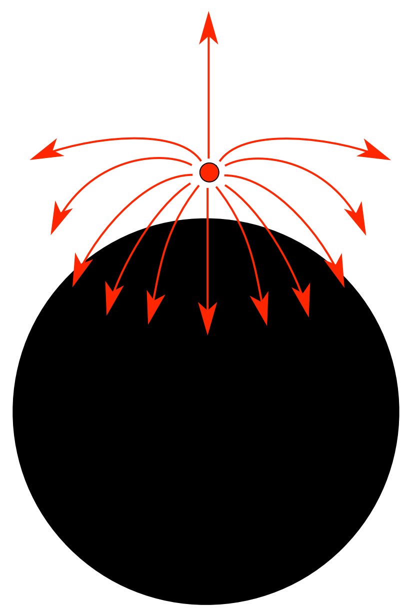

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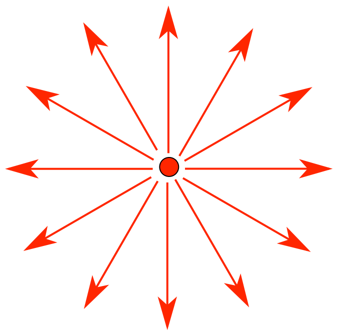

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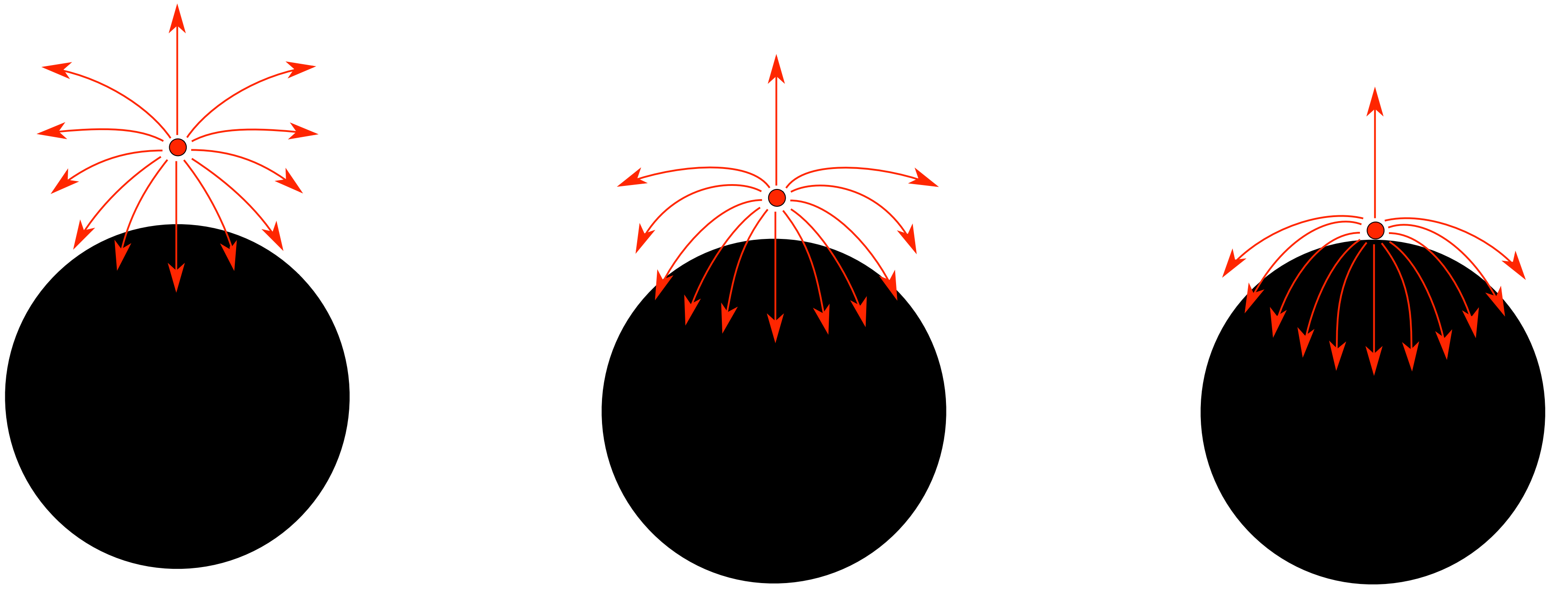


The black hole:

bends the geometry of space and so bends the paths of the photons.

Some photons escape, some fall into the black hole

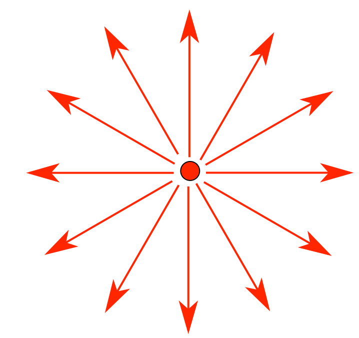
The closer the light source gets, the more photons are captured no matter what direction they are pointed when they leave the source:

More and more photons are bent into the black hole…..

The Black Hole of General Relativity

What does trapping of light "look like?"

Imagine a light source emitting photons …



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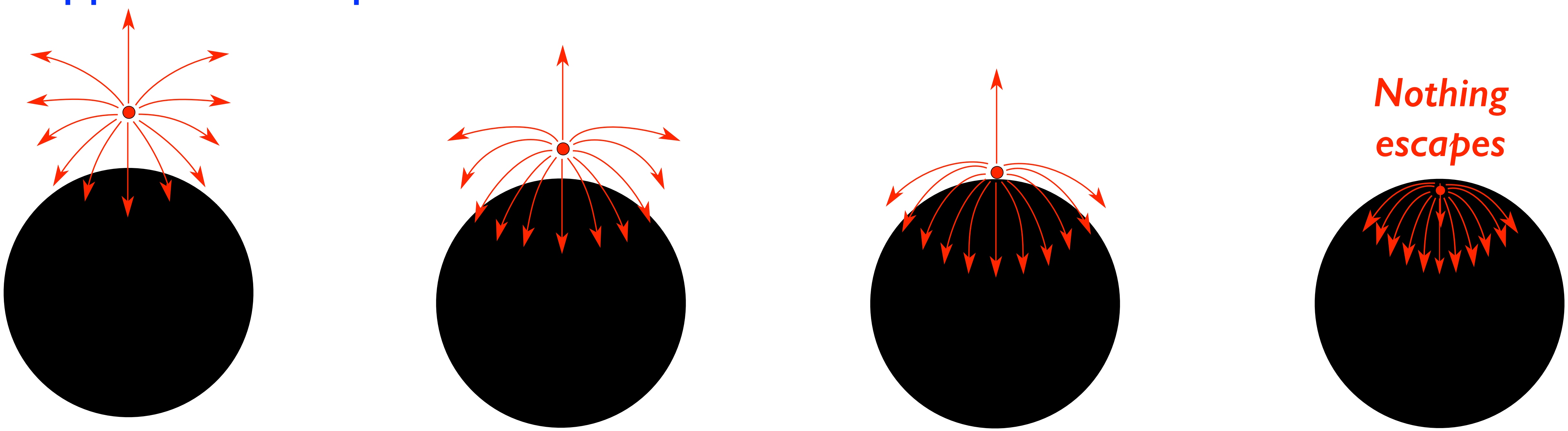

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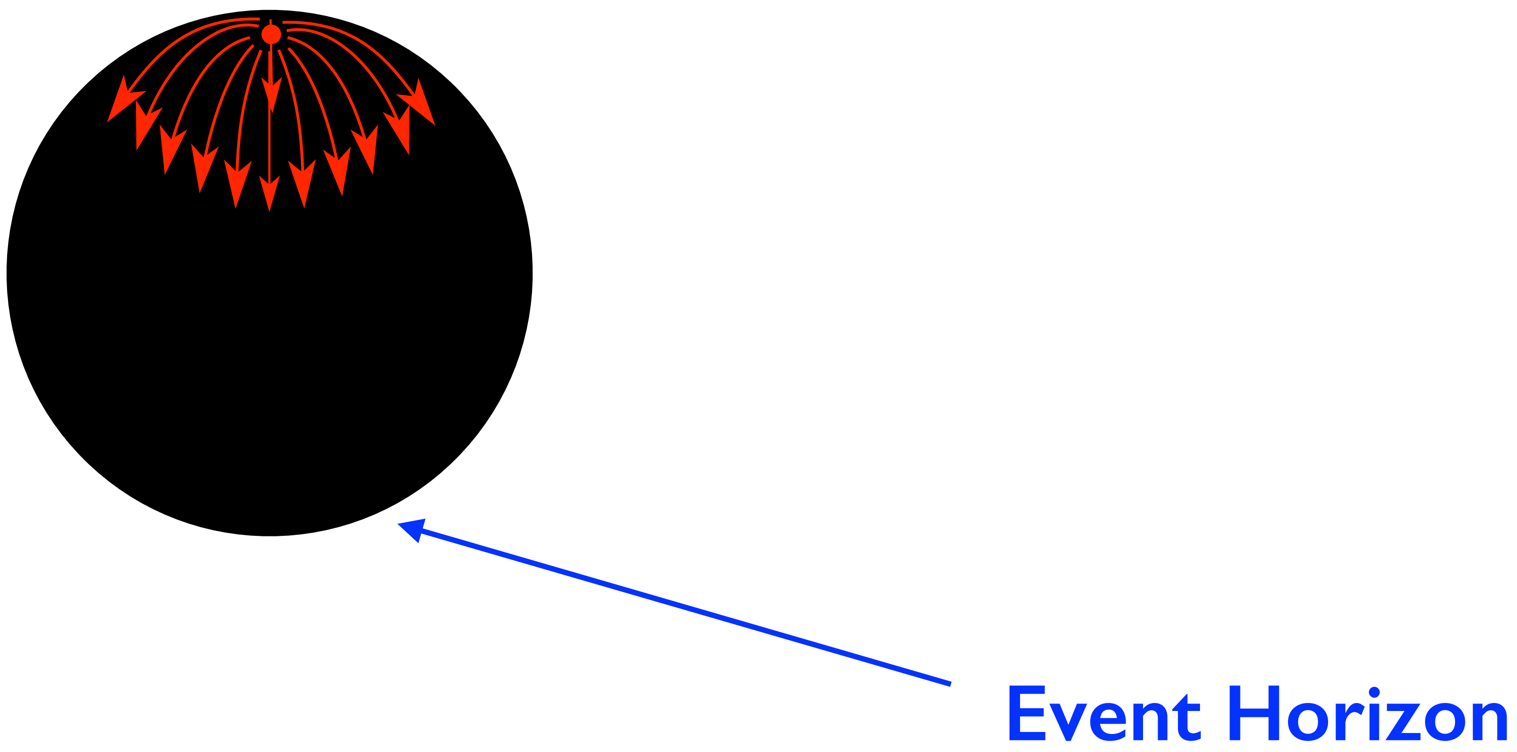
Inside and Outside the Black Hole

Matter and energy falling inside the surface/***event horizon*** of a black hole then falls extremely rapidly into a singularity at the center…



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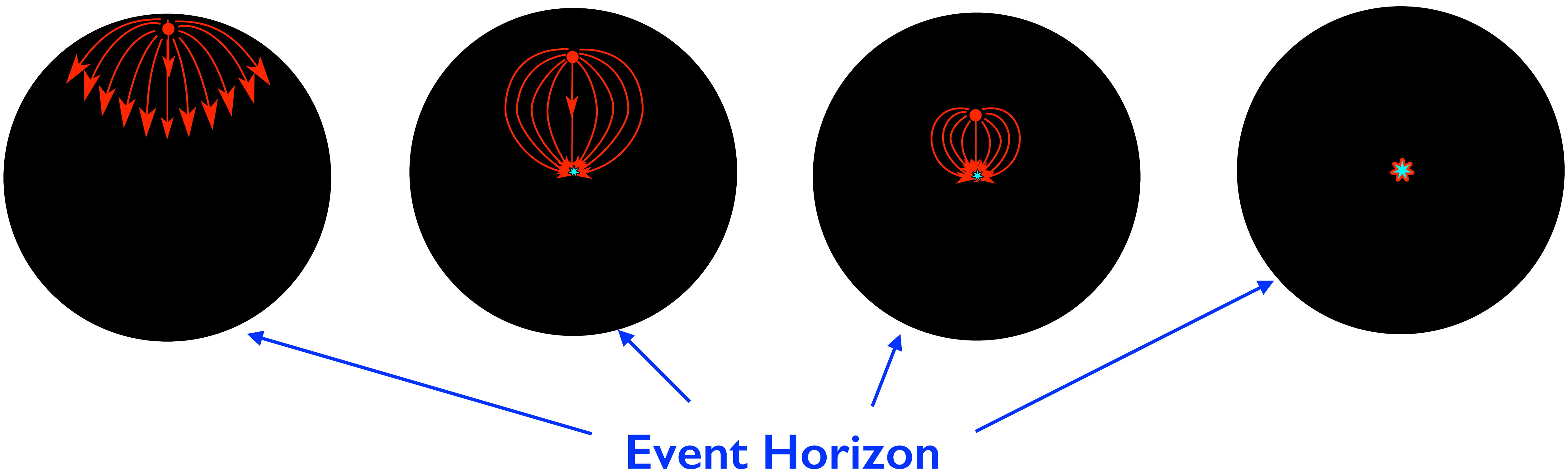

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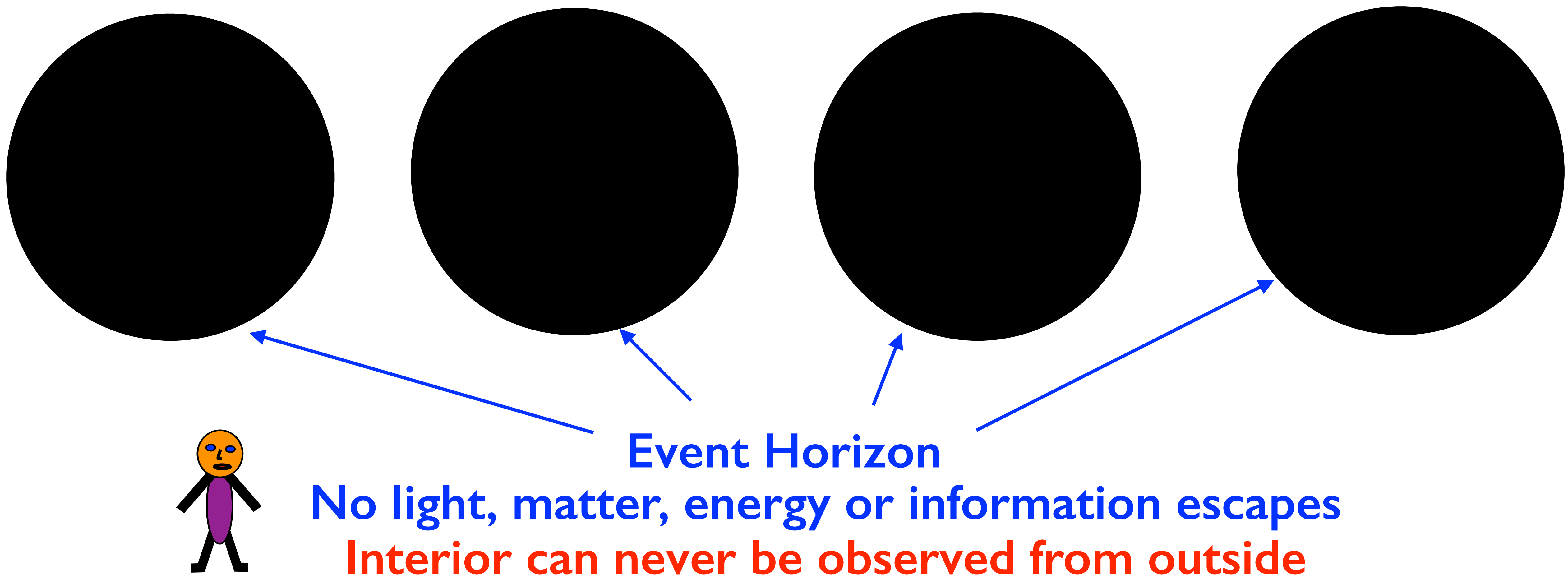

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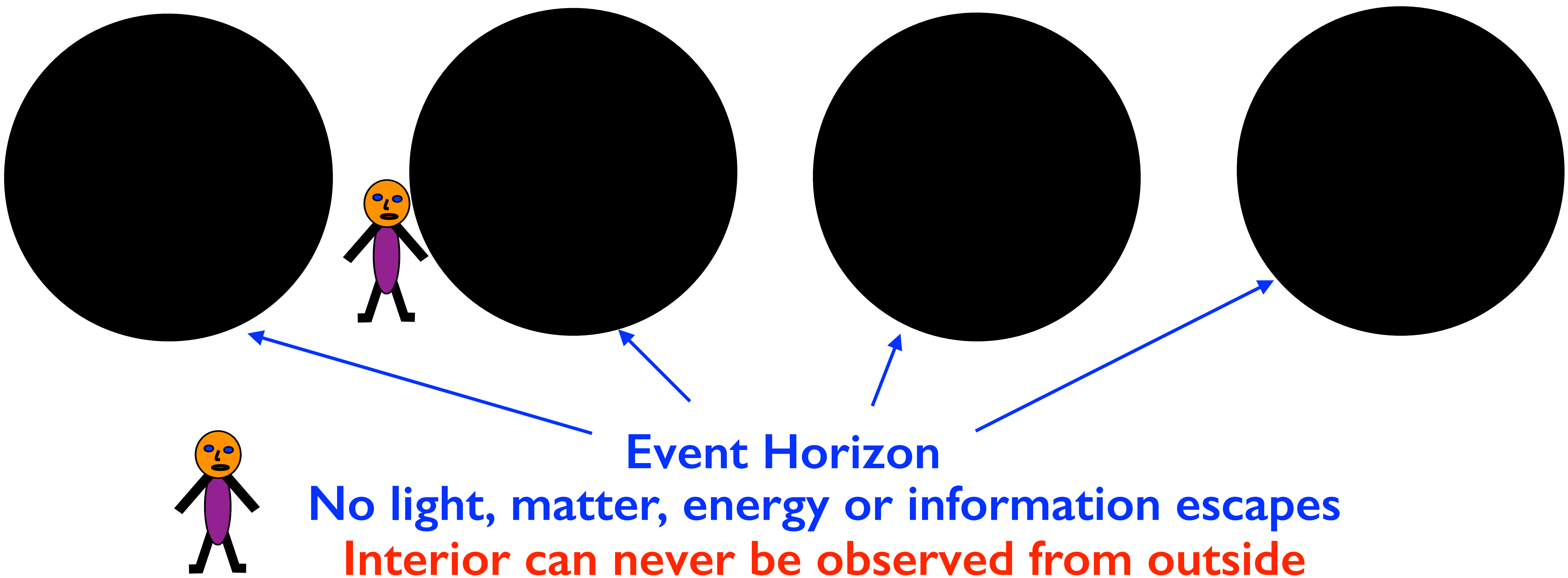

No matter how close you go, you cannot see inside the Event Horizon

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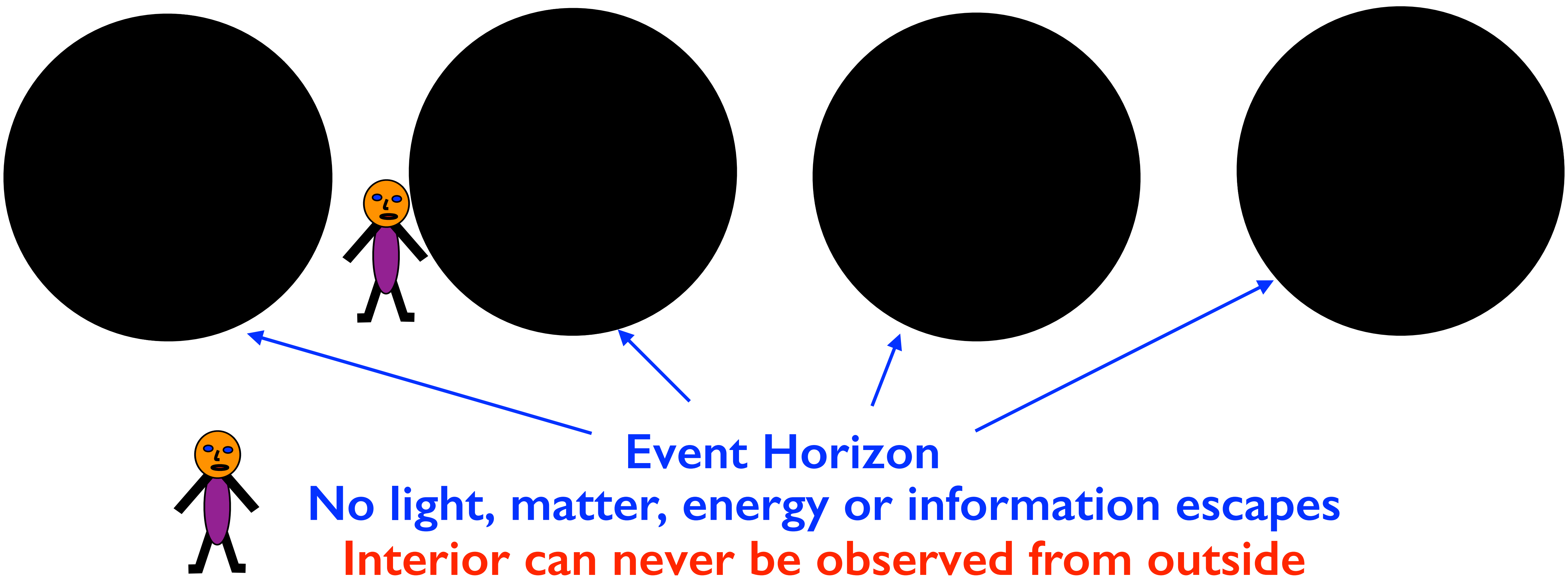


No light, matter, energy or information escapes

Interior can never be observed from outside

No matter how close you go, you cannot see inside the Event Horizon

The event horizon is *almost* featureless

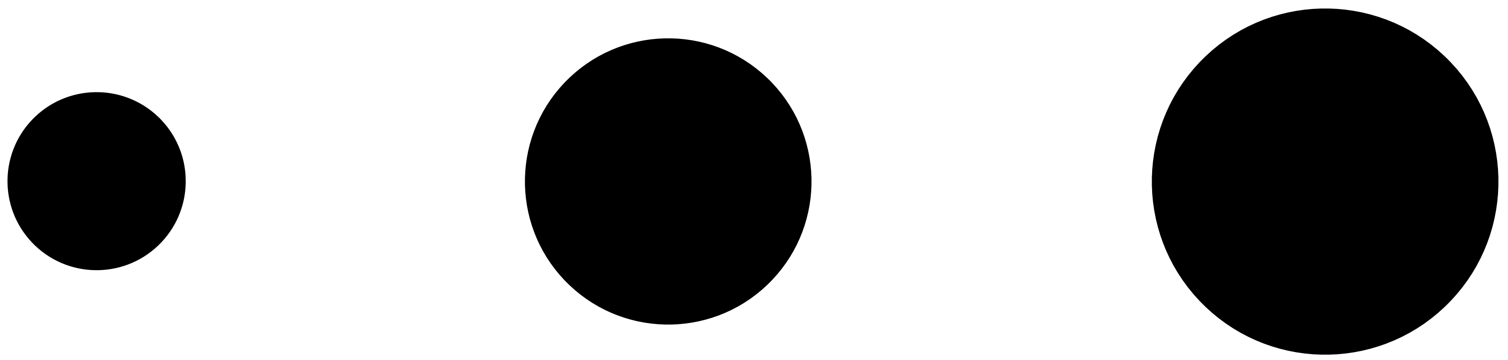
All you can see from outside: **Mass**, **Charge** and **Rotation** of the black hole

Black Hole Uniqueness

Once a black hole forms, all you can measure from outside is

Mass ~ Size

Radius ~ Mass



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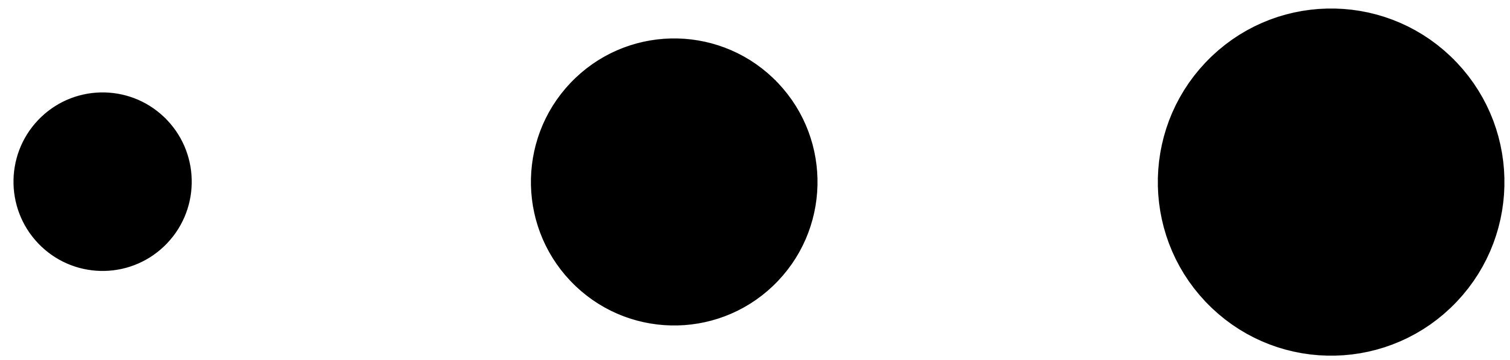
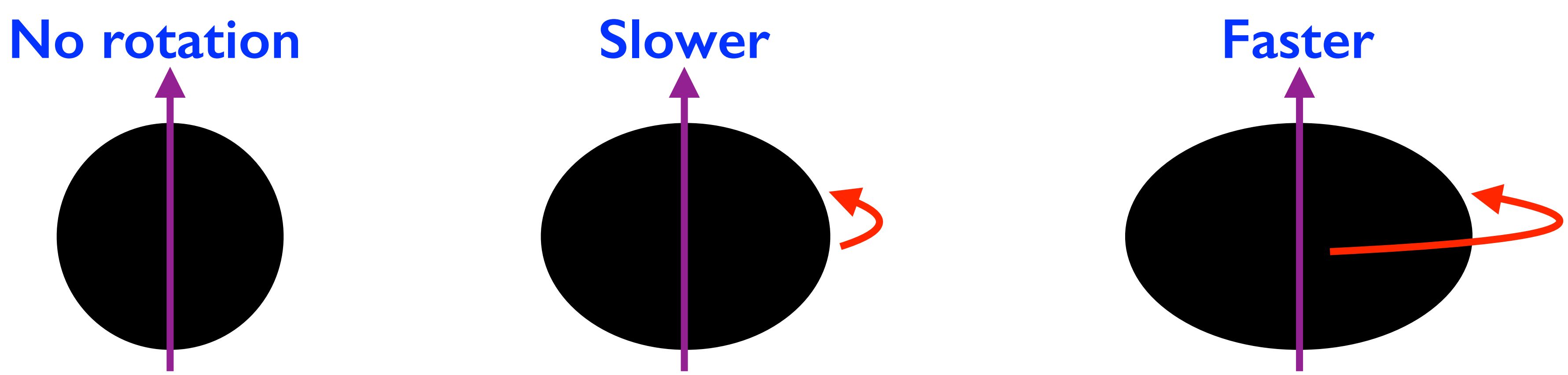


Rotation or Angular Momentum ~ *Elliptical bulge* at equator



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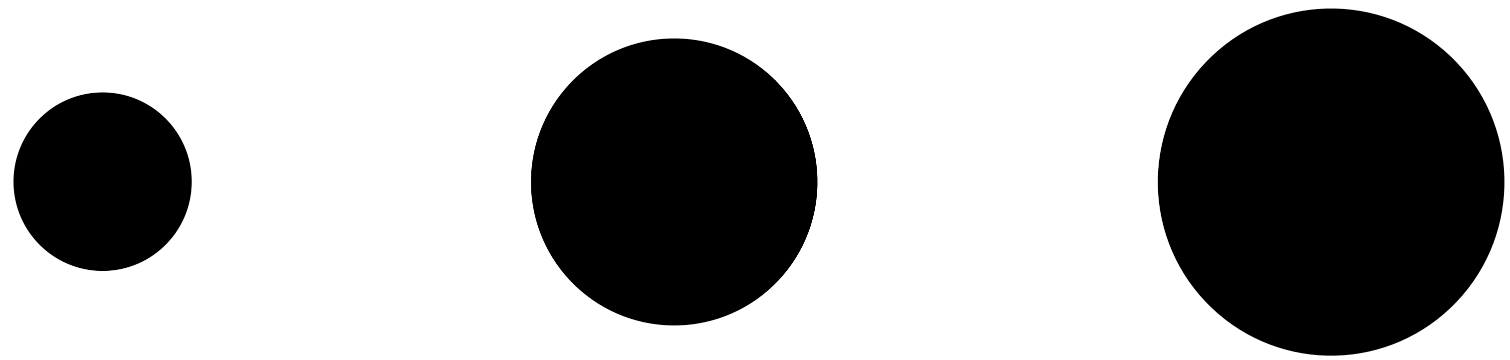

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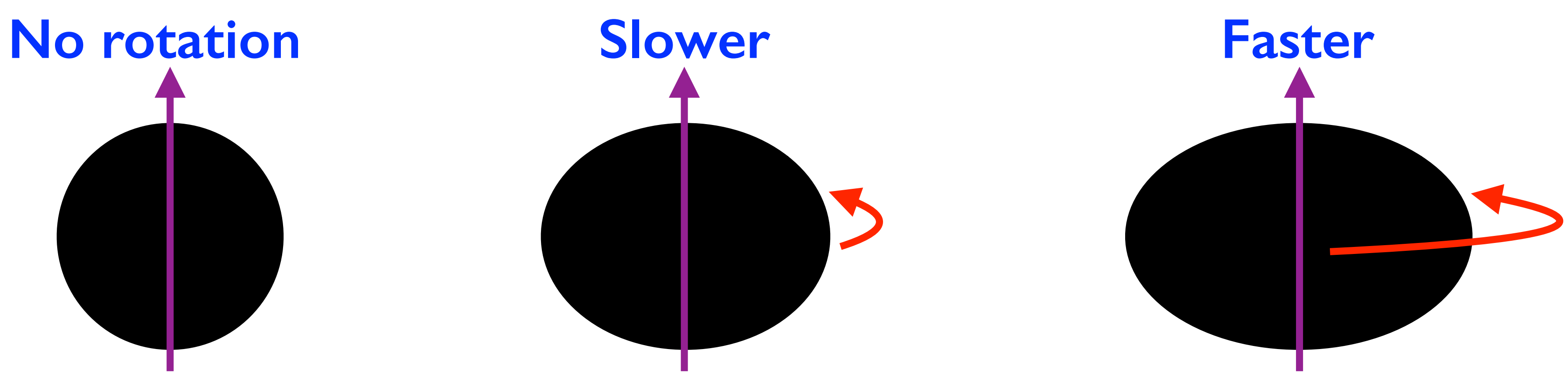
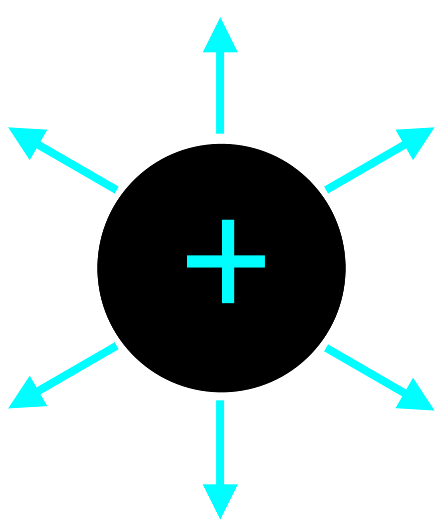


Electric Charge



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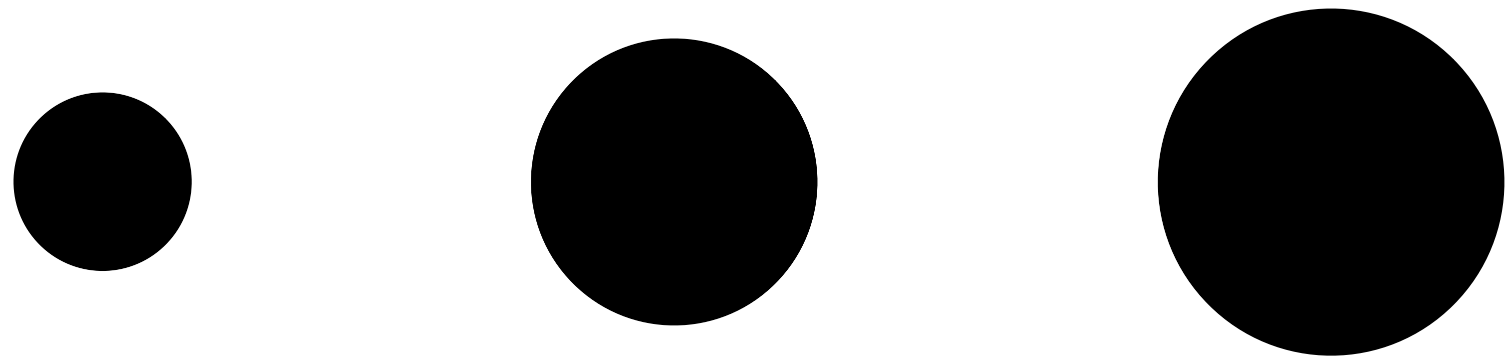
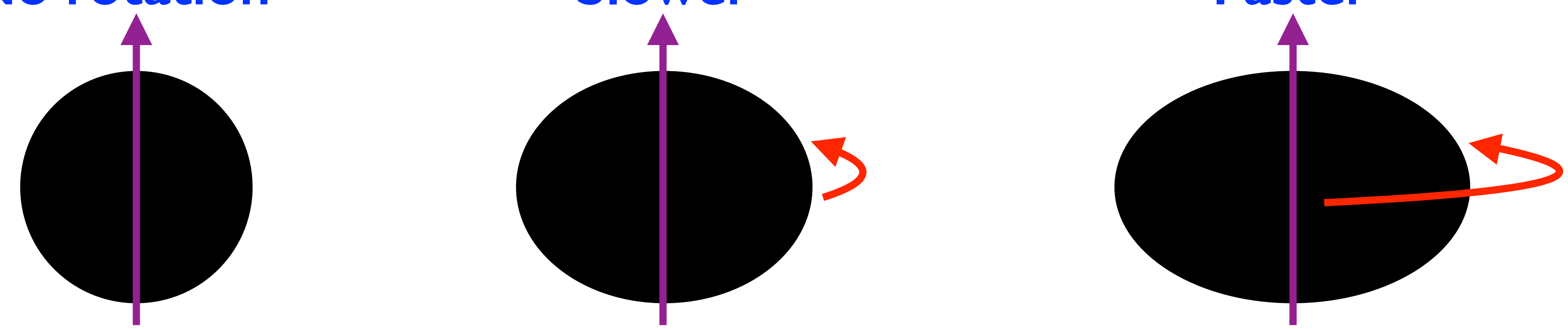


Rotation or Angular Momentum ~ *Elliptical bulge* at equator

No rotation   Slower   Faster



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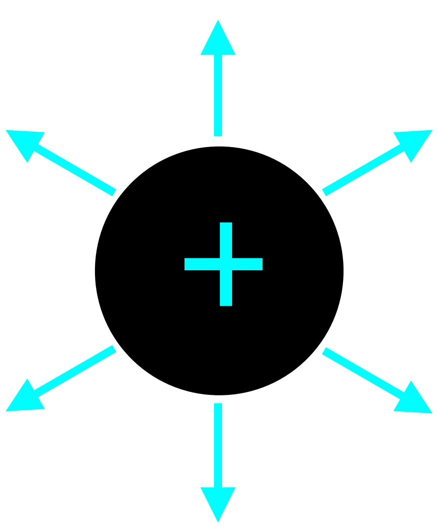

No matter what goes into the black hole, the horizon has a simple bulging, elliptical shape with no other features whatsoever.

Black holes are made by compressing matter/energy to extreme densities …

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Whatever the ingredients, the resulting black holes are indistinguishable:

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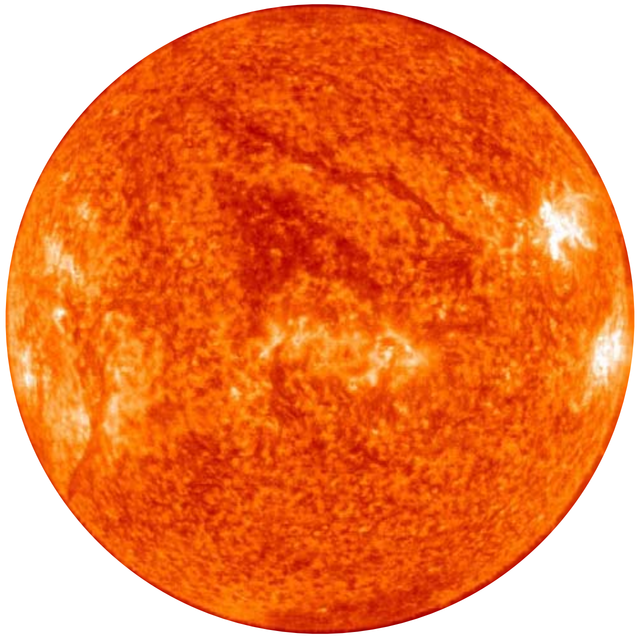
A star



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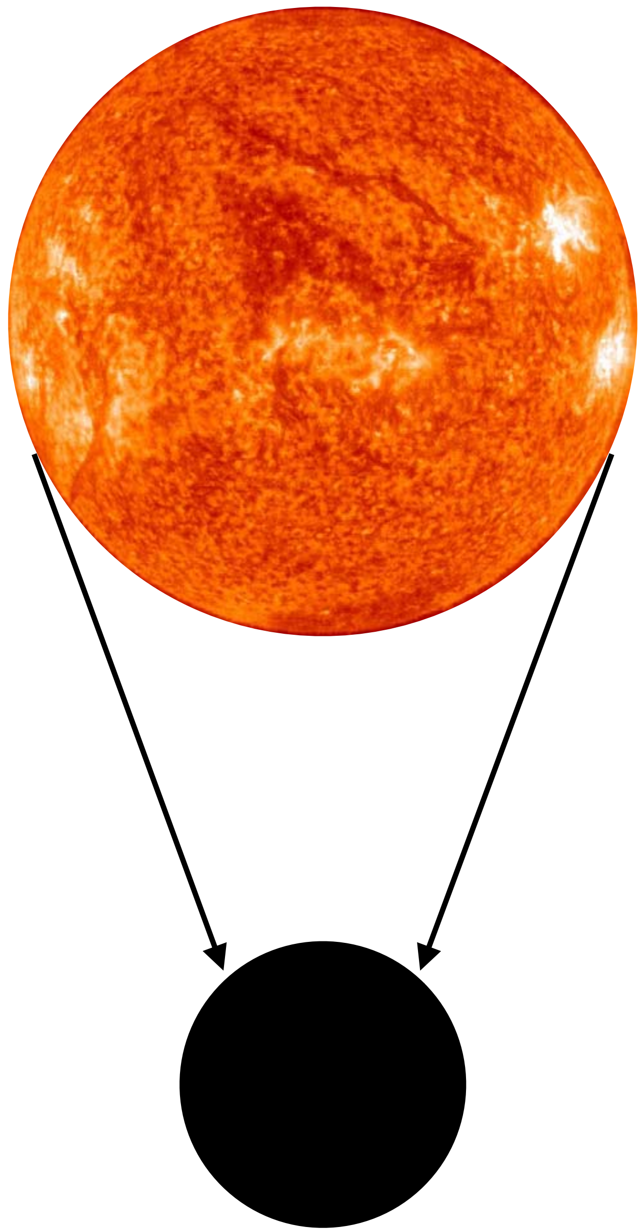

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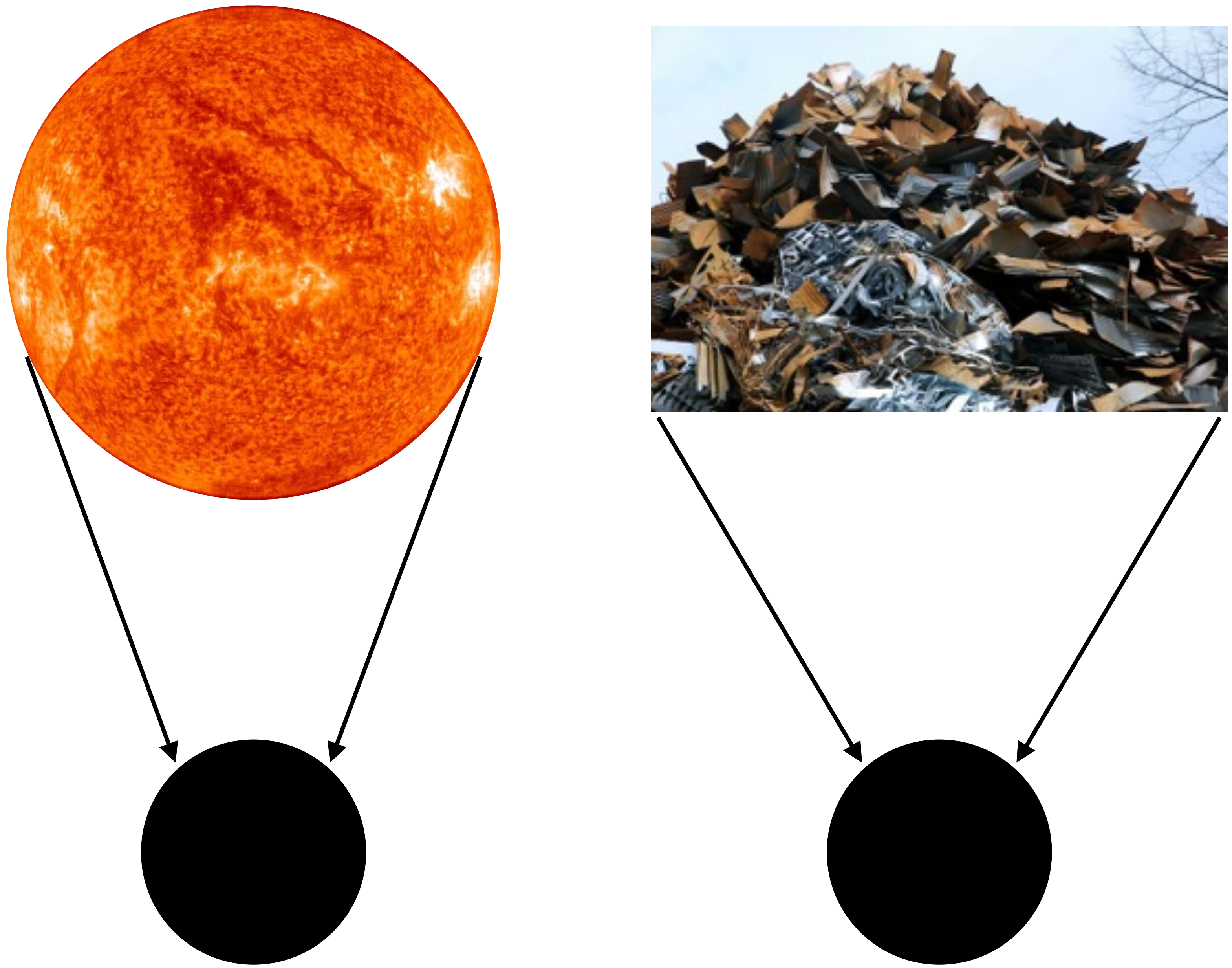

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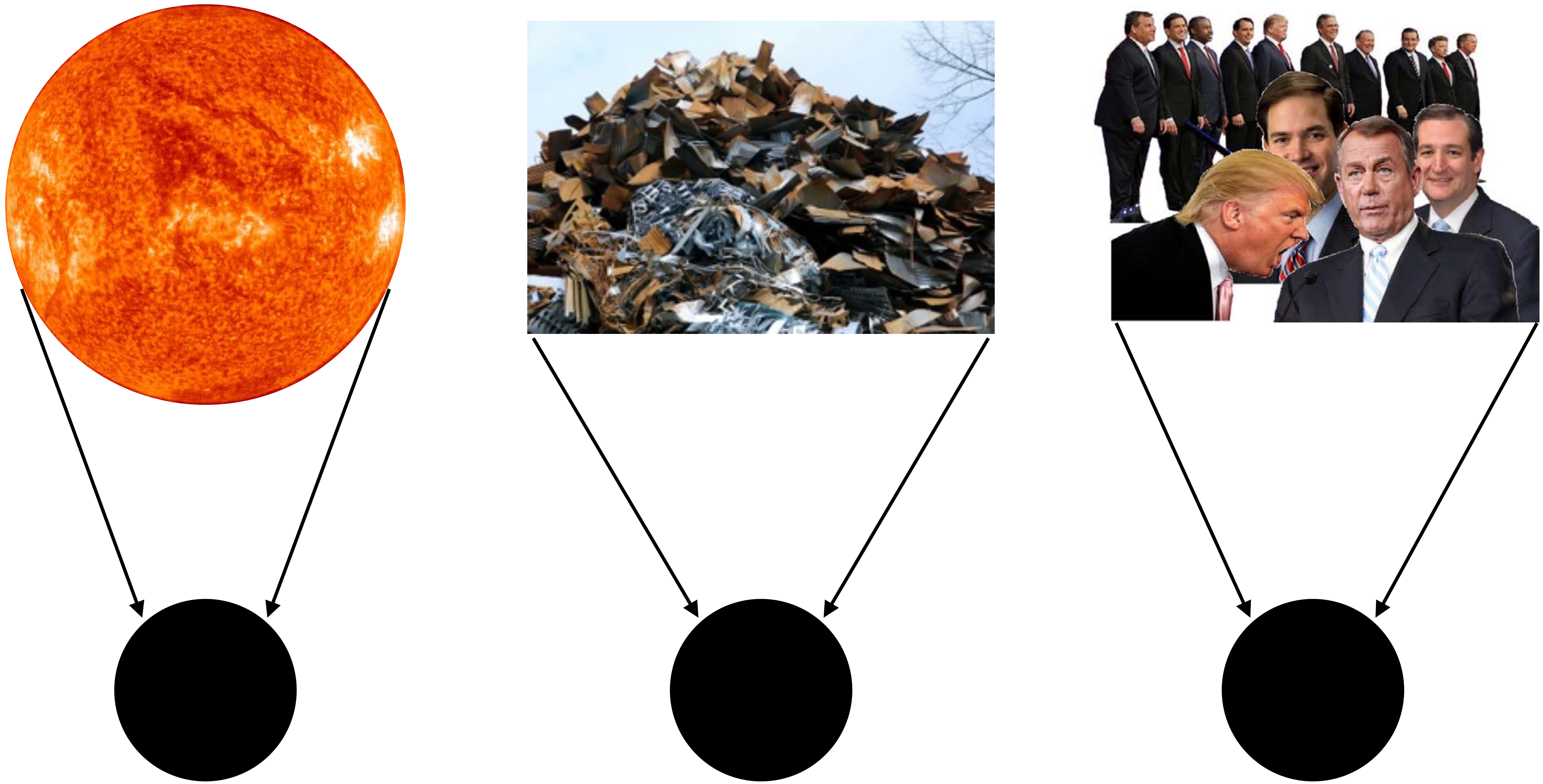
A star | Trash | Politicians



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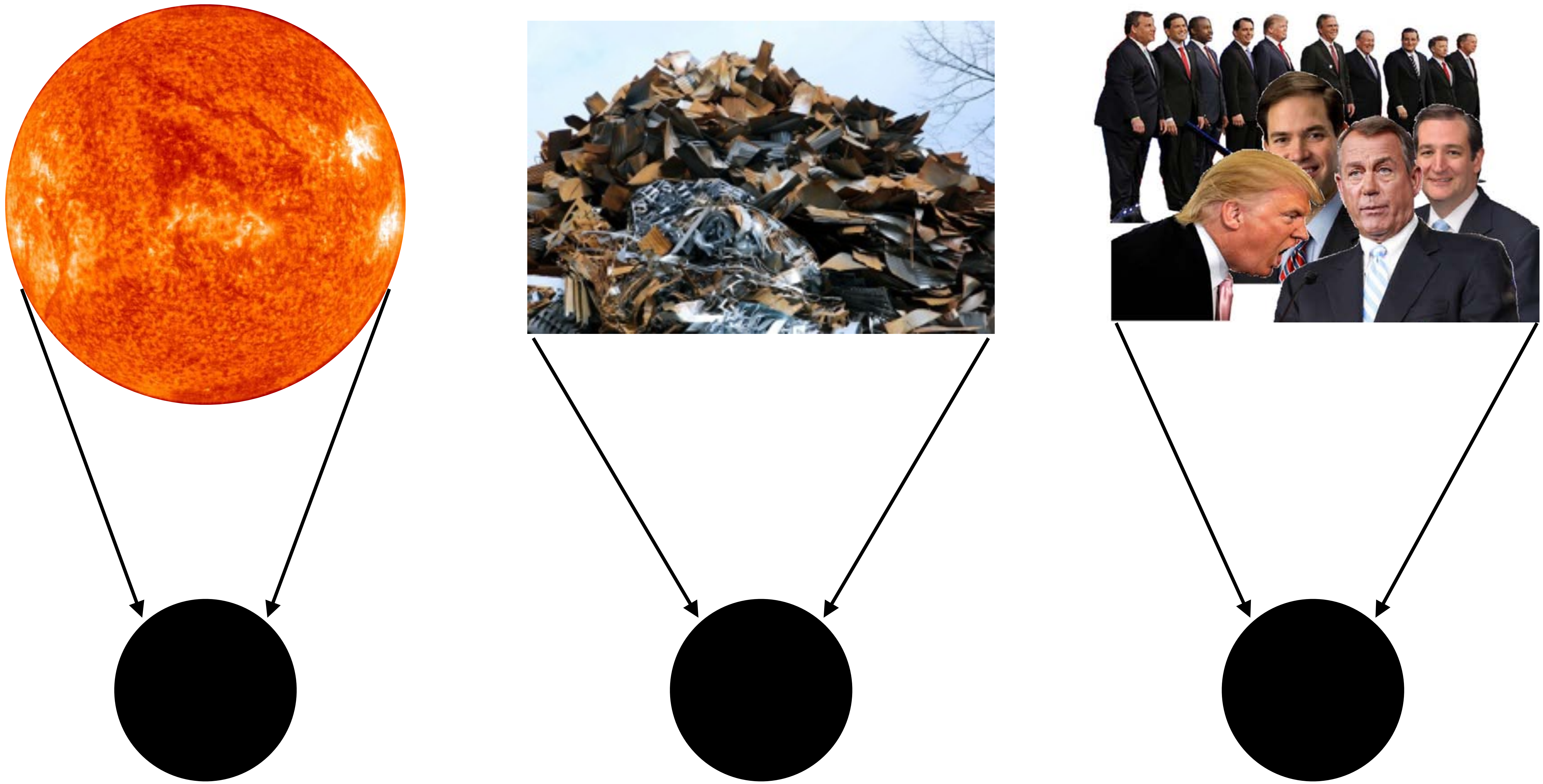

If the star, trash and politicians have the same mass, charge and rotation then *the black holes are utterly indistinguishable from outside*

How do we see/detect black holes?

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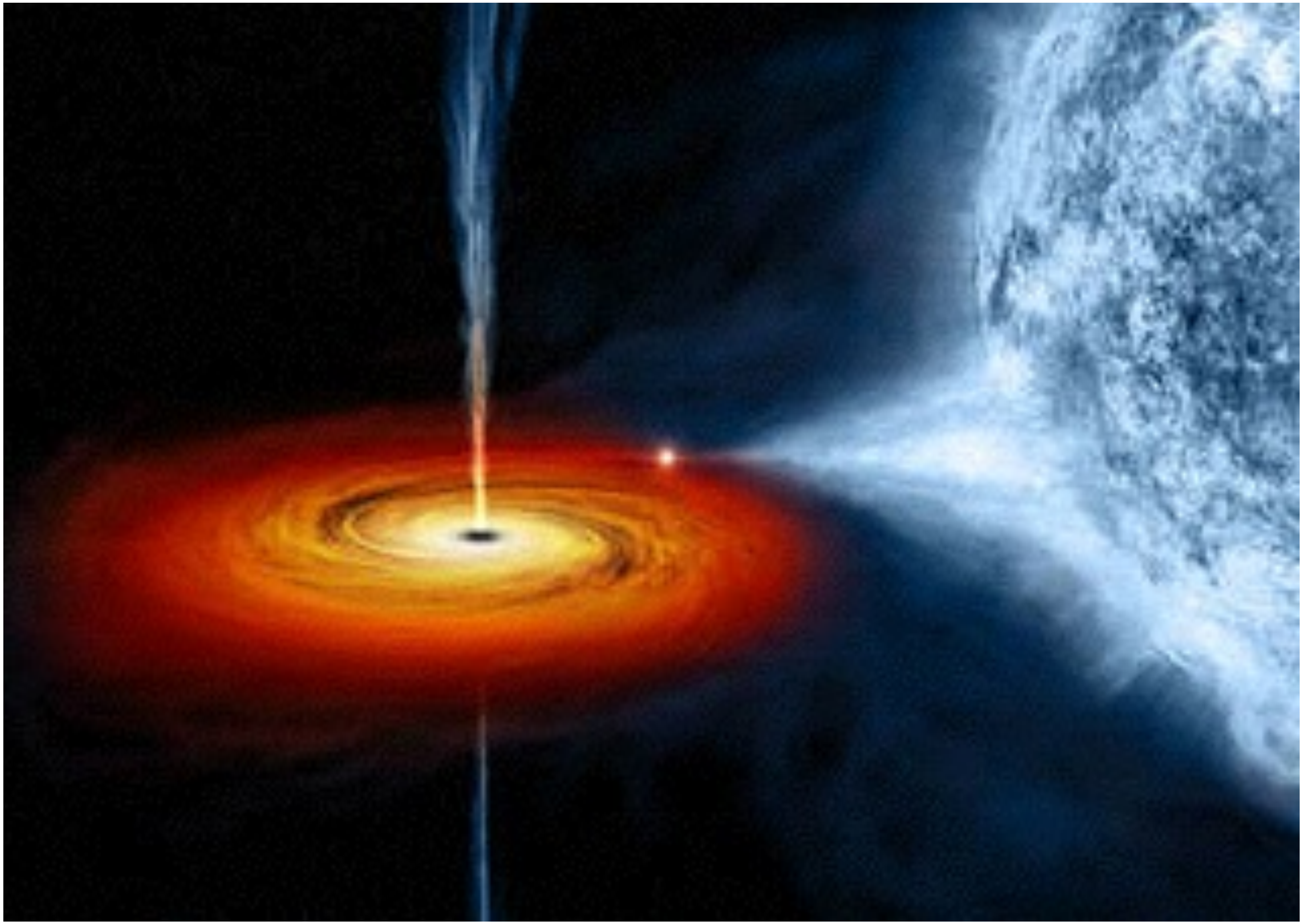
Black and featureless suggests this is impossible …

“Seeing” Black Holes in Nature

We detect black holes through their effects on surrounding matter.

Smaller black holes can attract and heat up matter from nearby stars



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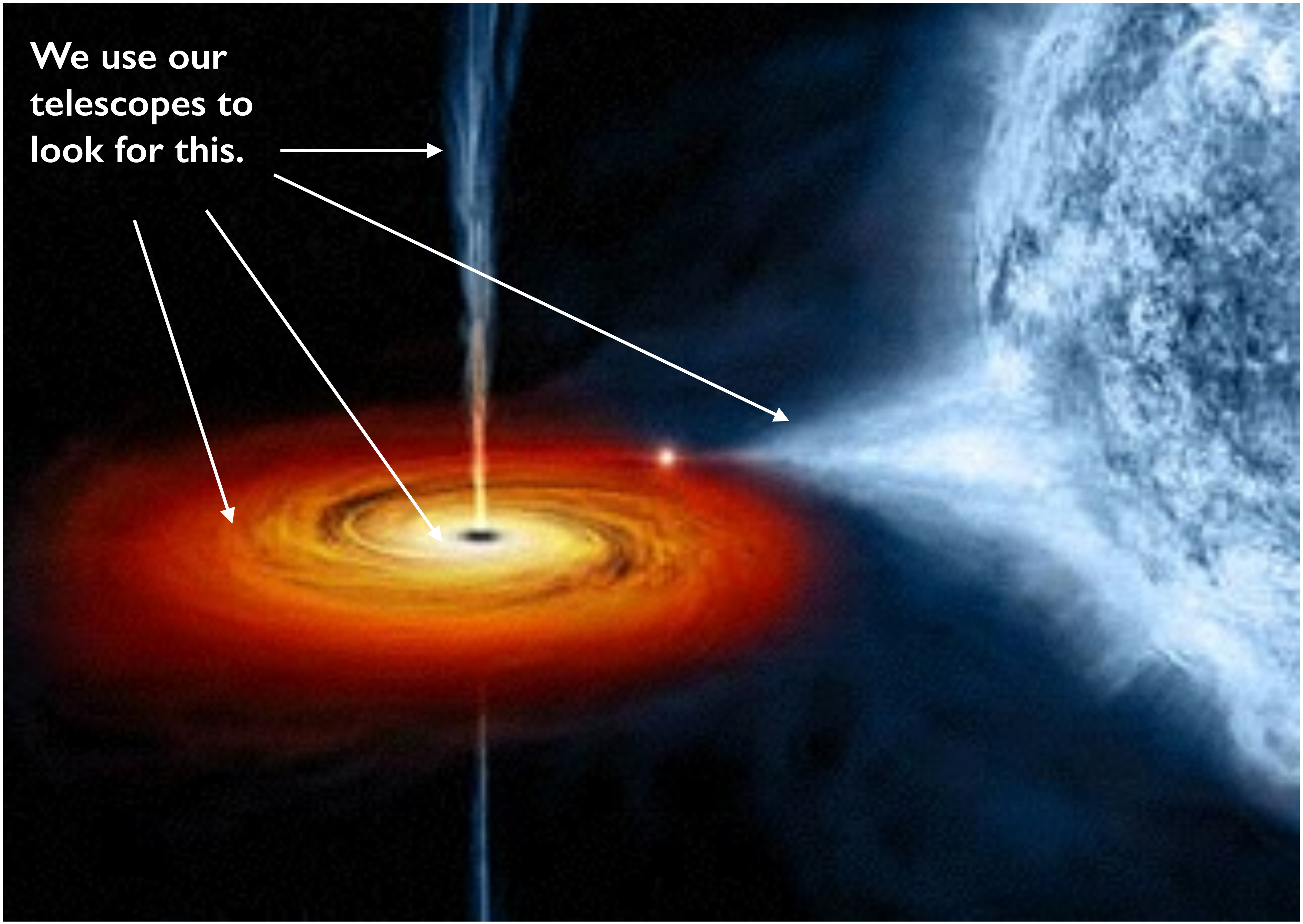
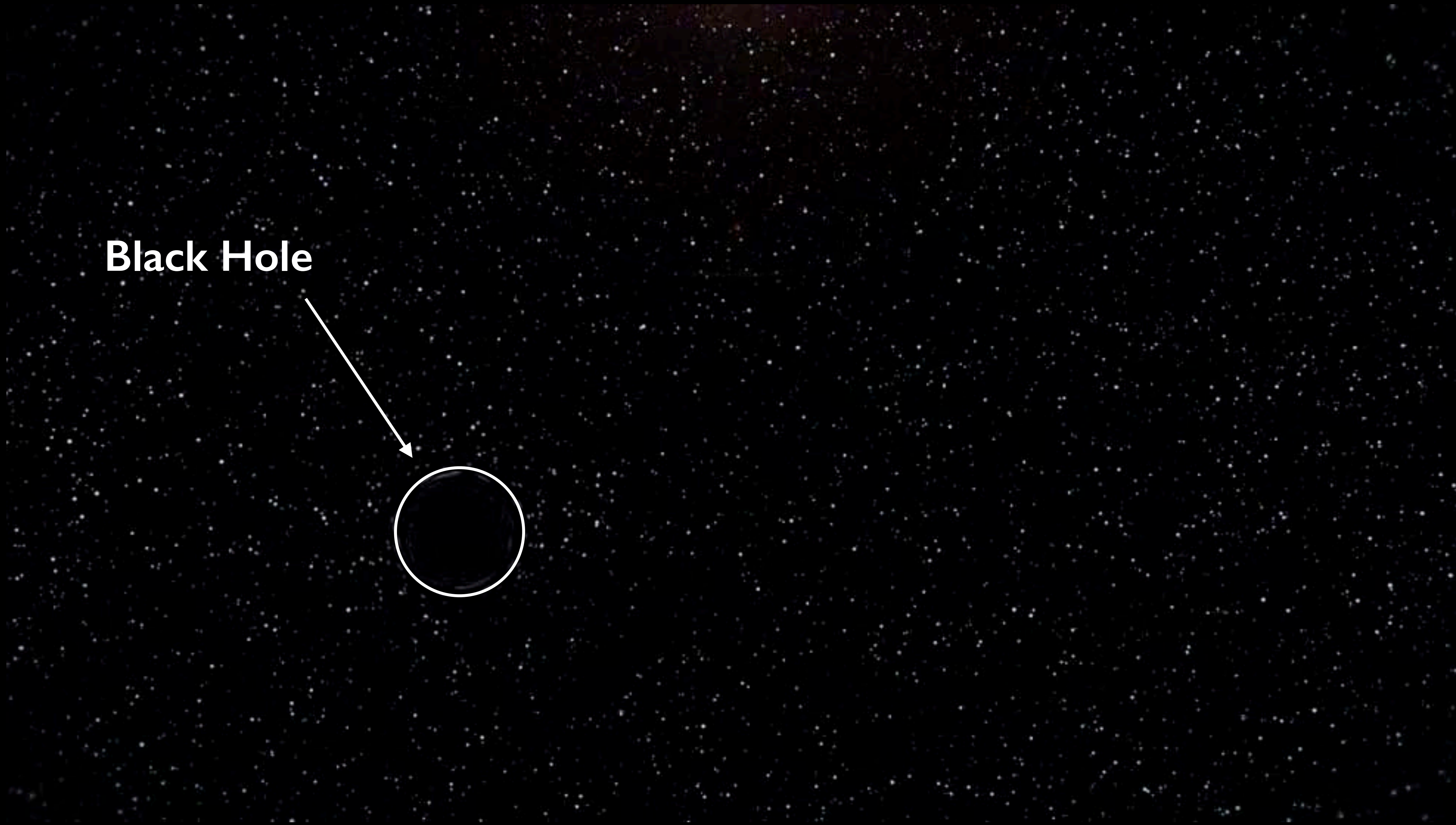


Larger black holes in the cores of galaxies disrupt and swallow whole stars



Credits: NASA's Goddard Space Flight Center

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Simulations and visualizations of black holes based on General Relativity

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The real universe

NGC 5128/Centaurus A

Jet from M87

There is now overwhelming evidence that there are black holes in Nature…

1974: Hawking Radiation. A new incarnation of black holes

How does quantum mechanics change our picture of black holes?

Stephen Hawking

PHOTO BY PHILIP WATERSON, LBIPP, LRPS

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Hawking: quantum mechanics implies that black holes actually emit radiation…

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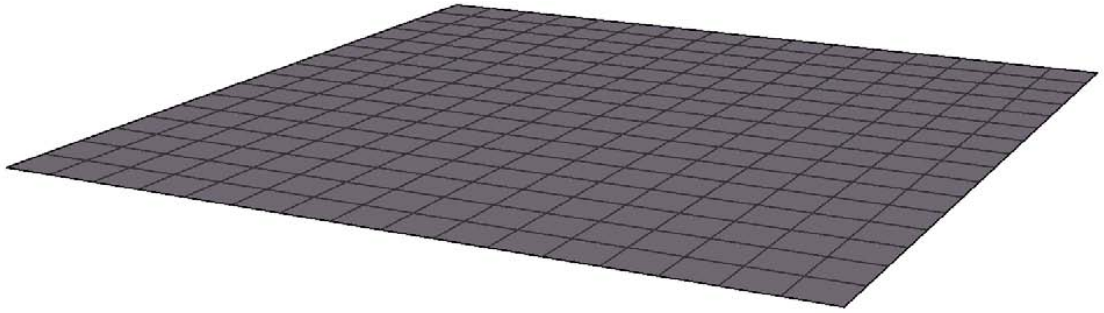
Hawking: quantum mechanics implies that black holes actually emit radiation…

To understand how such *Hawking radiation* is generated, one must understand that quantum mechanics completely changes the idea of the vacuum of empty space …

The vacuum of empty space

The vacuum of empty space

General Relativity



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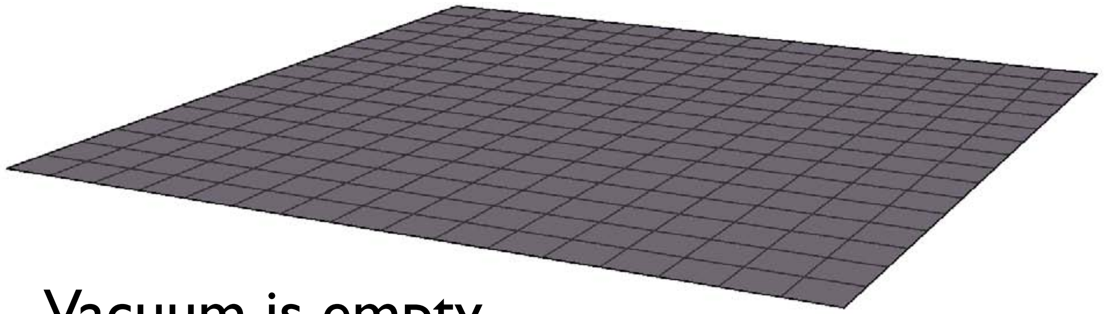
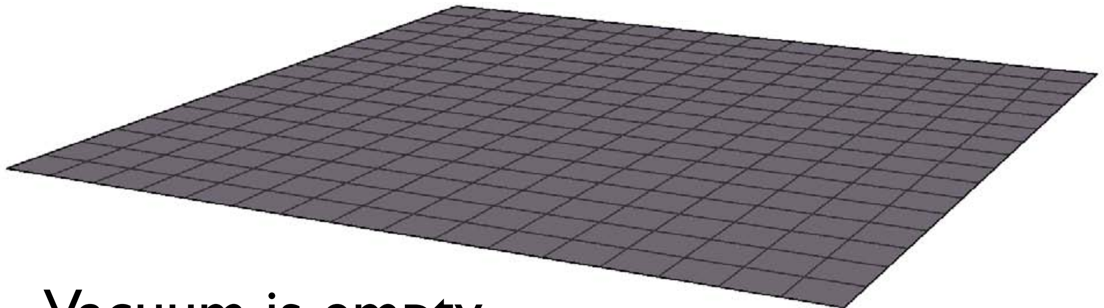


Vacuum is empty.

Vacuum has zero energy

The vacuum of empty space

General Relativity



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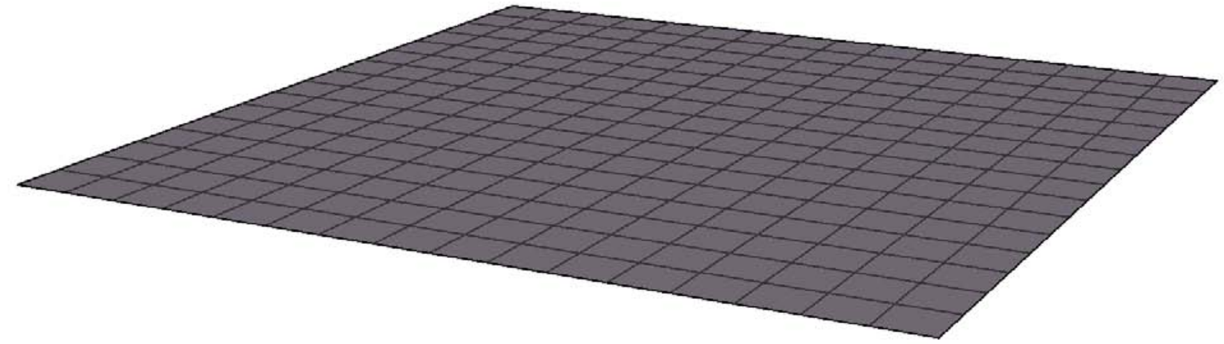

Quantum fluctuations: The ***Vacuum*** involves particle and anti-particles momentarily appearing and disappearing borrowing energy for a duration that is consistent with the Heisenberg uncertainty principle

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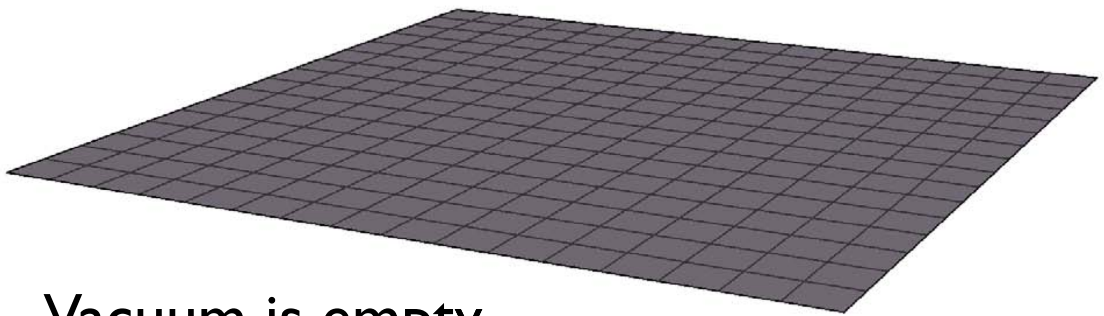

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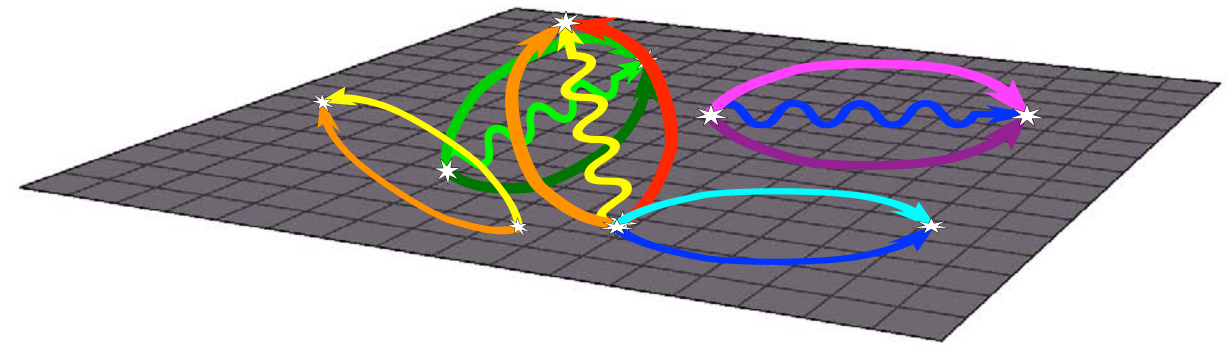

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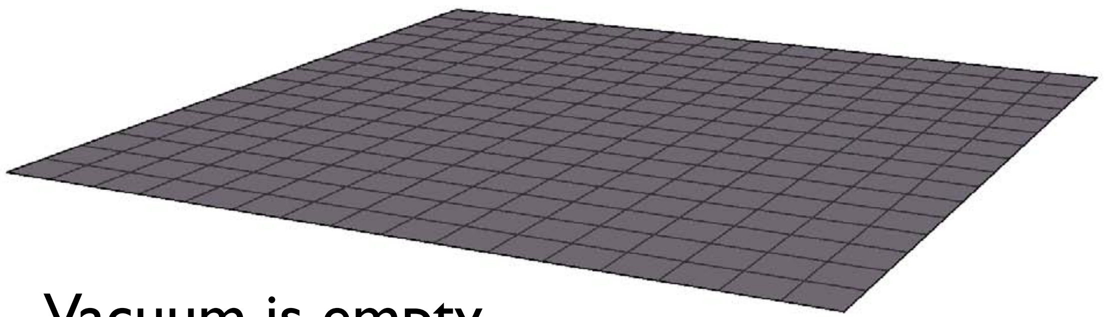

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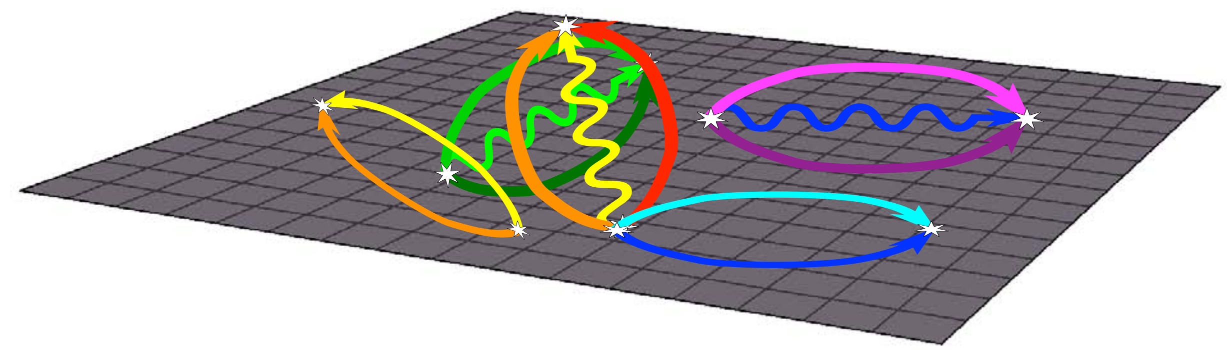

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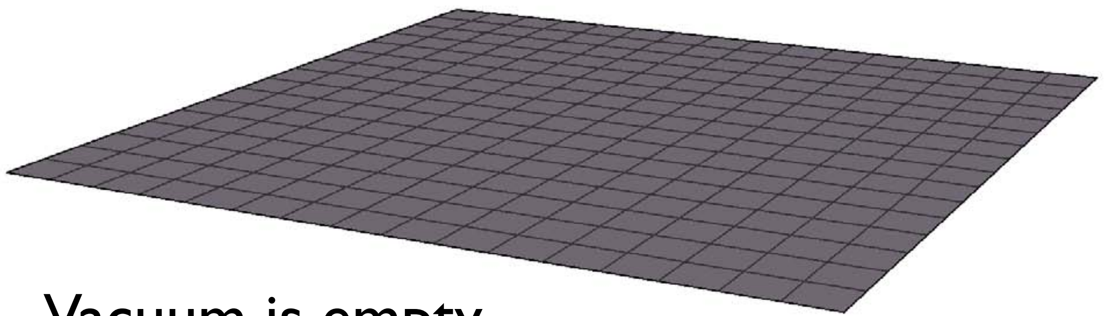

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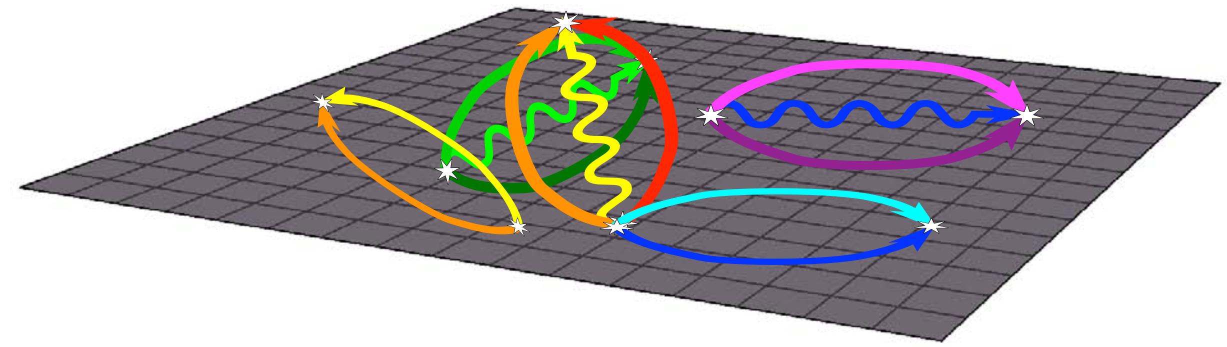

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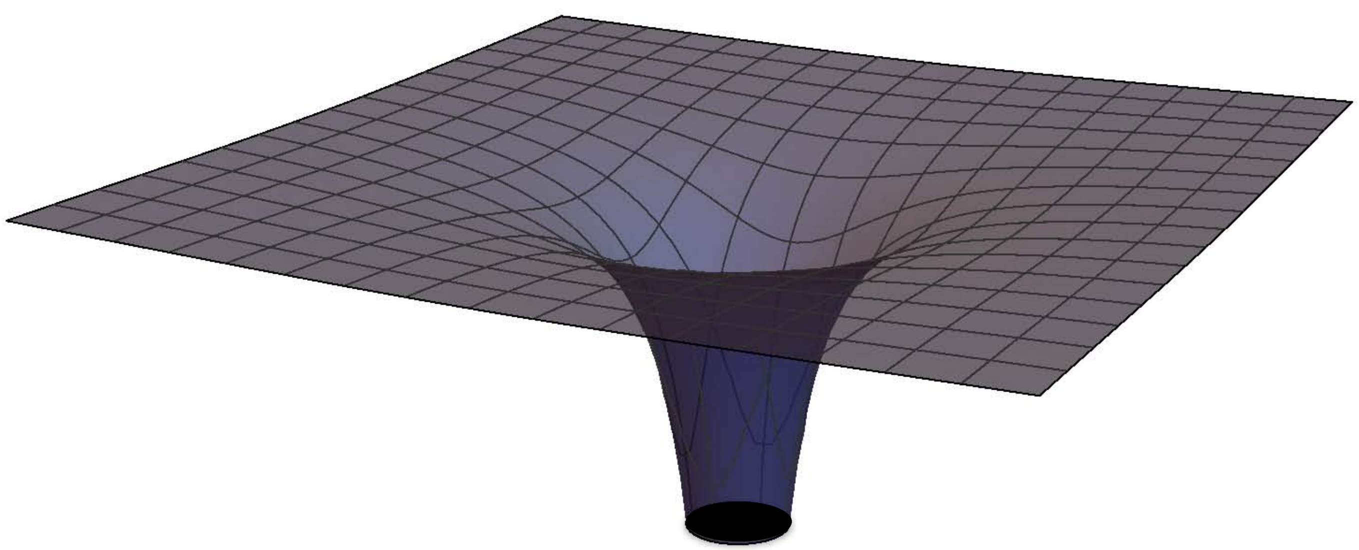

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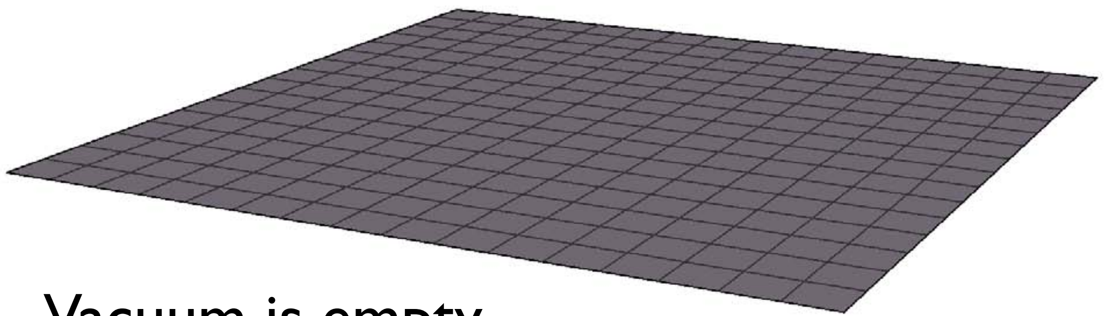

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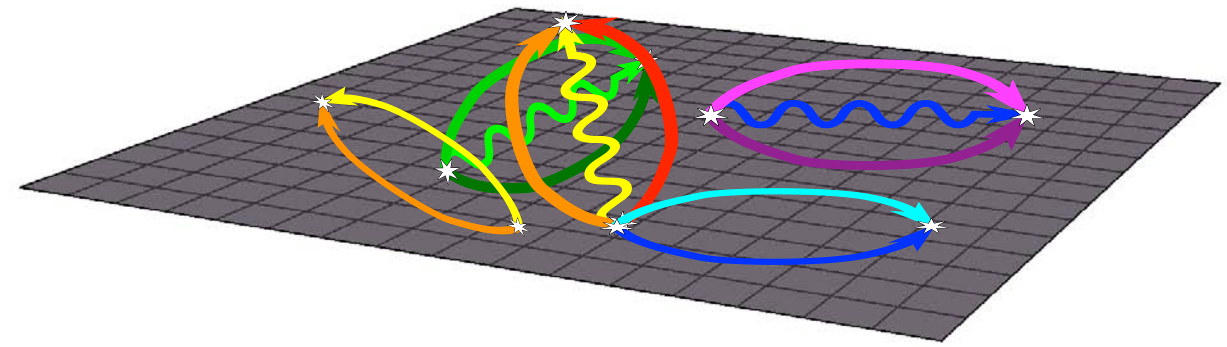

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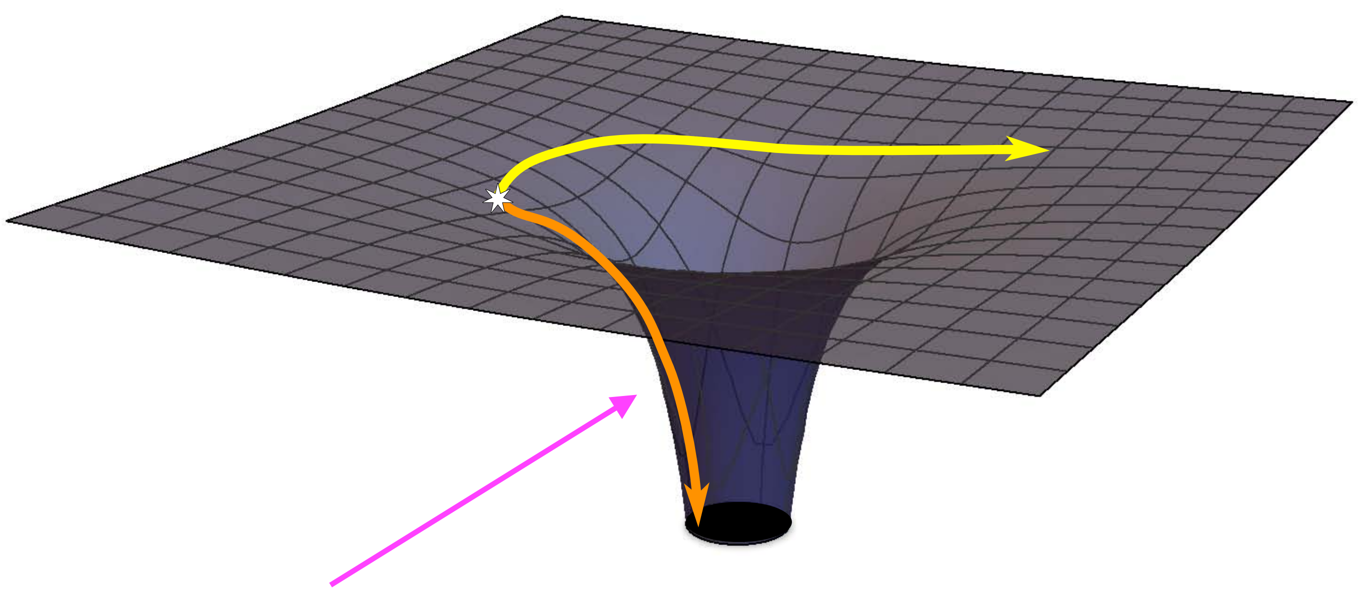
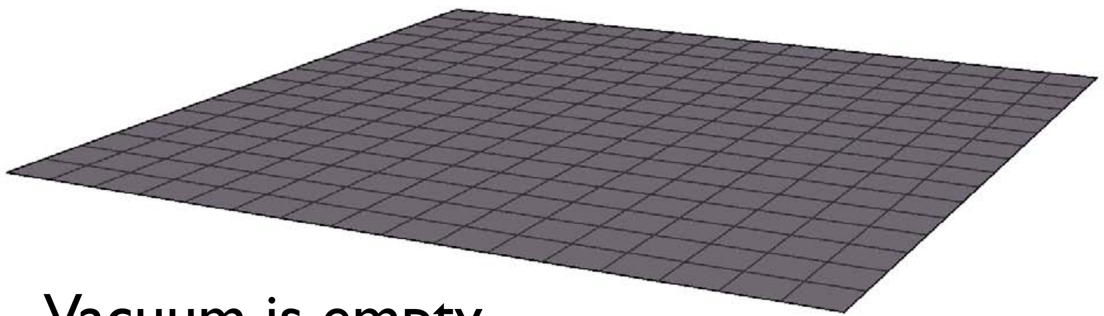


Suppose one of these evanescent particle partners falls into a black hole …

never to return!

The vacuum of empty space

General Relativity



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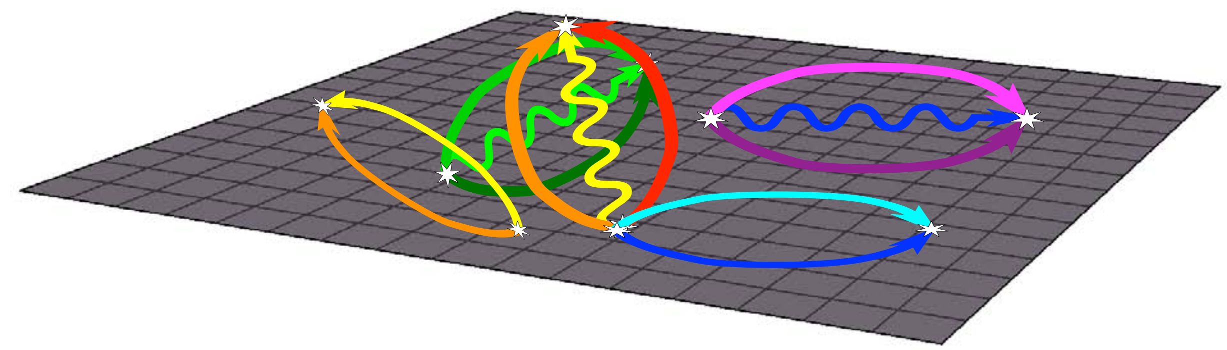

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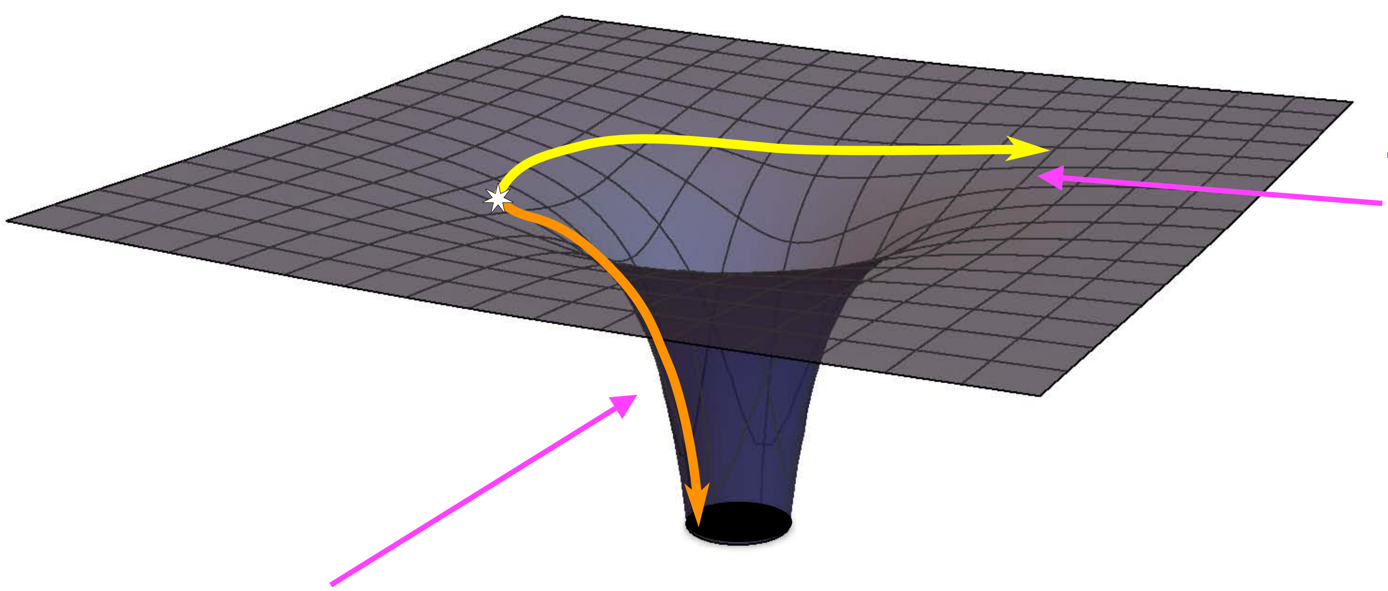

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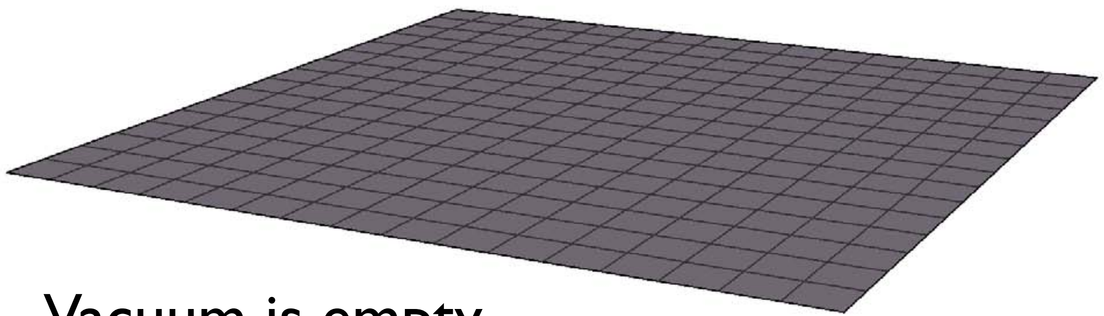

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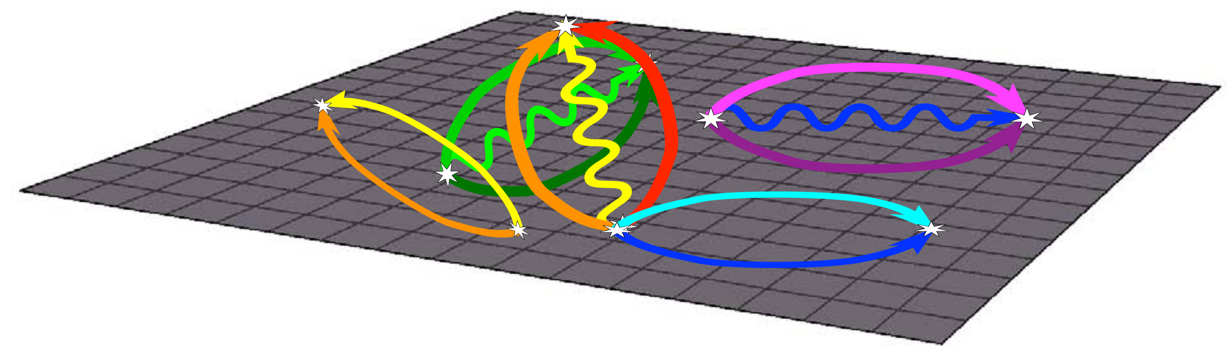

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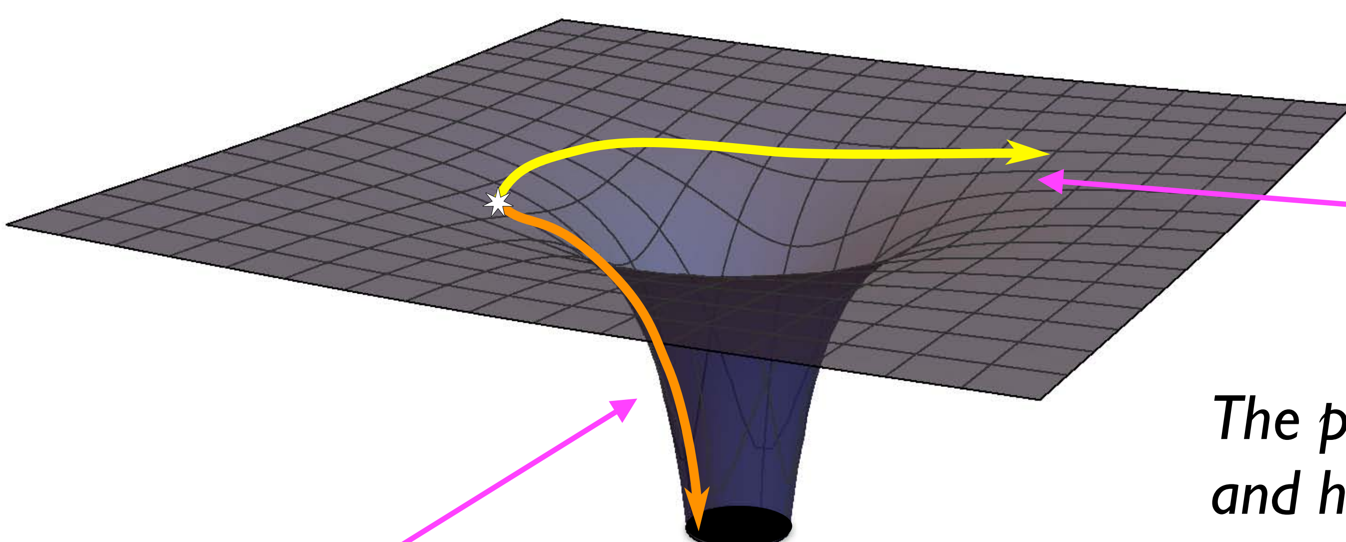

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The particle escaping to infinity is real and measurable and has positive energy ….

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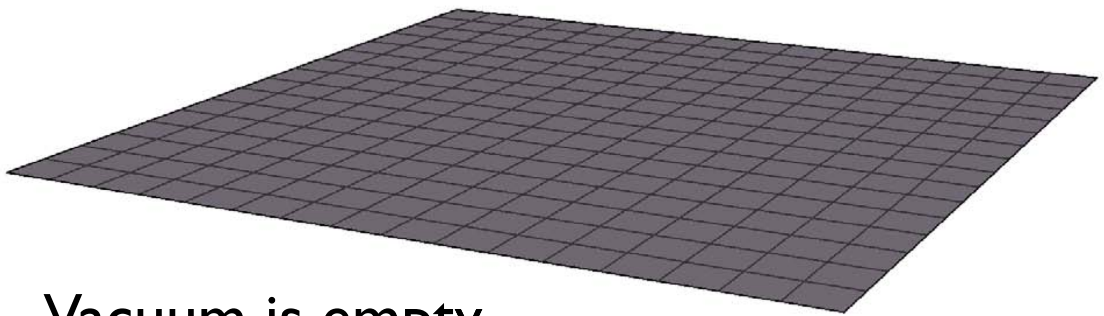

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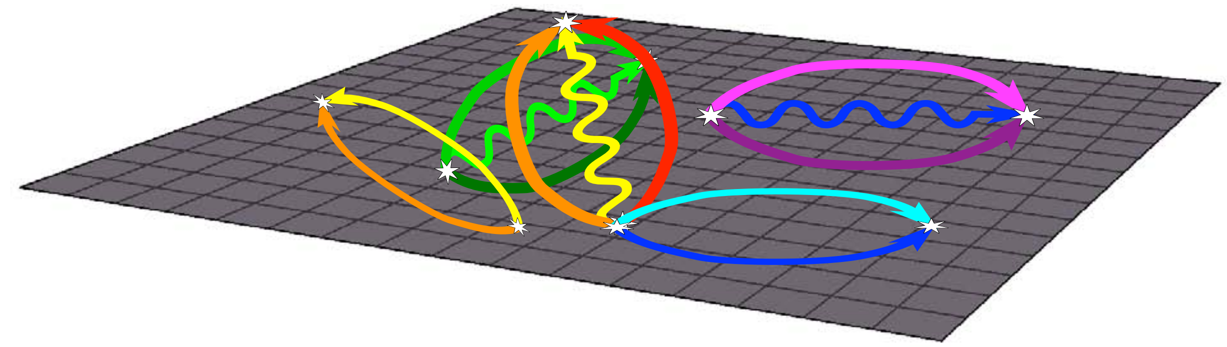

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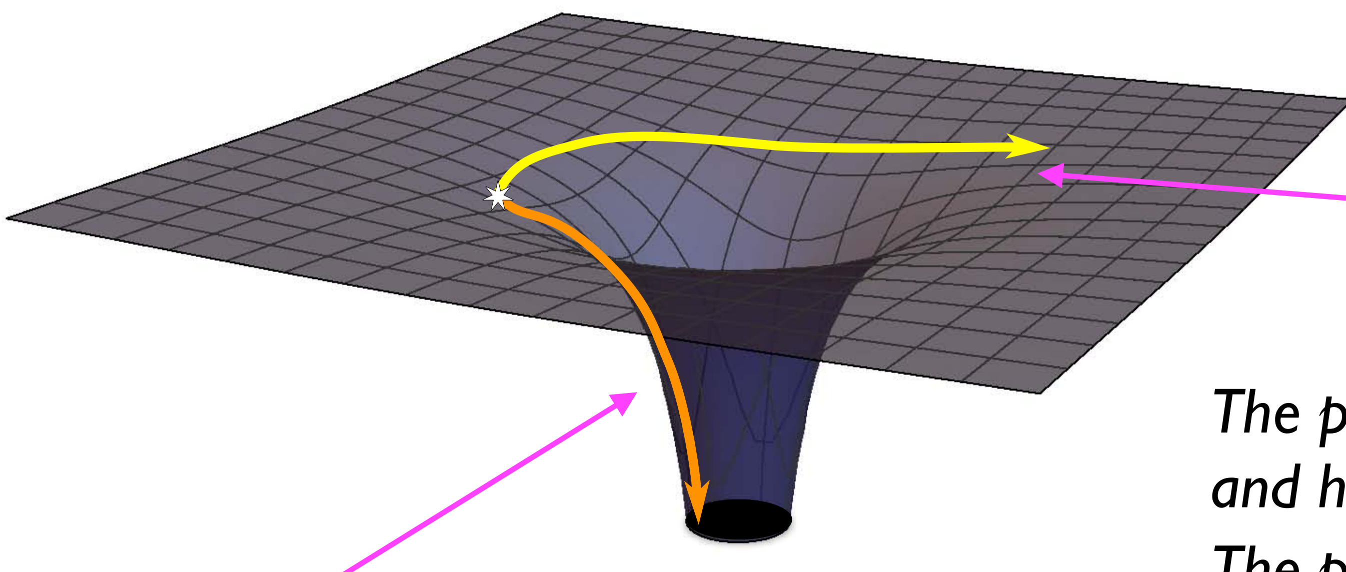

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The particle escaping to infinity is real and measurable and has positive energy ….

*The particle falling into the black hole has **negative energy(!)** and decreases the mass of the black hole.*

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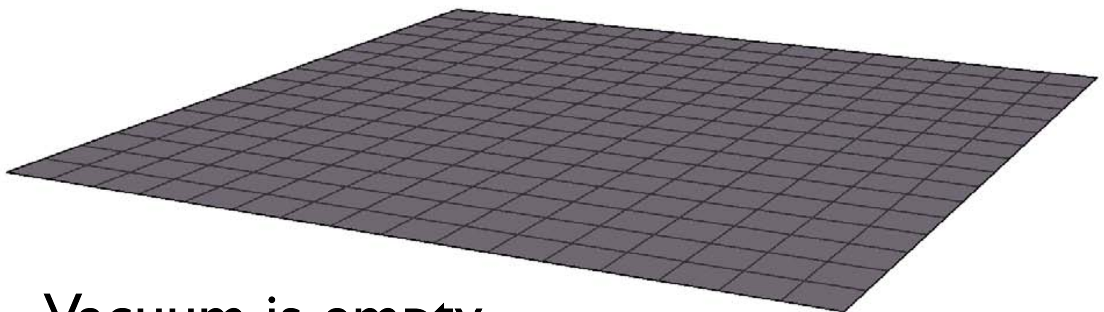
General Relativity



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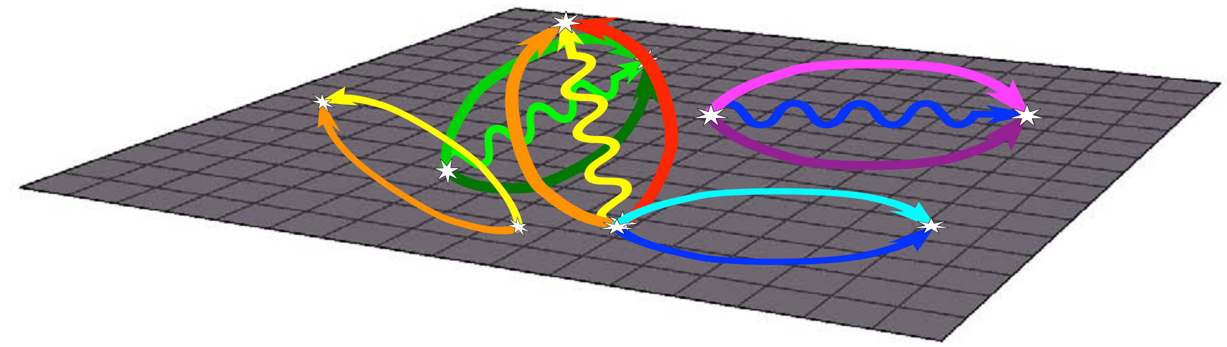

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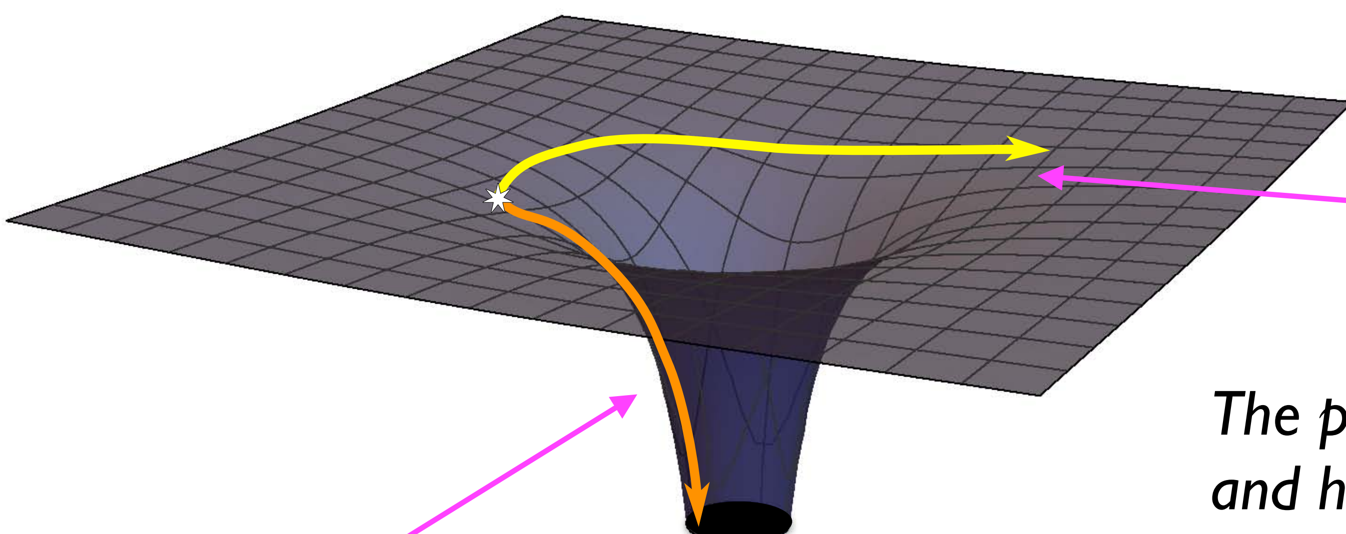

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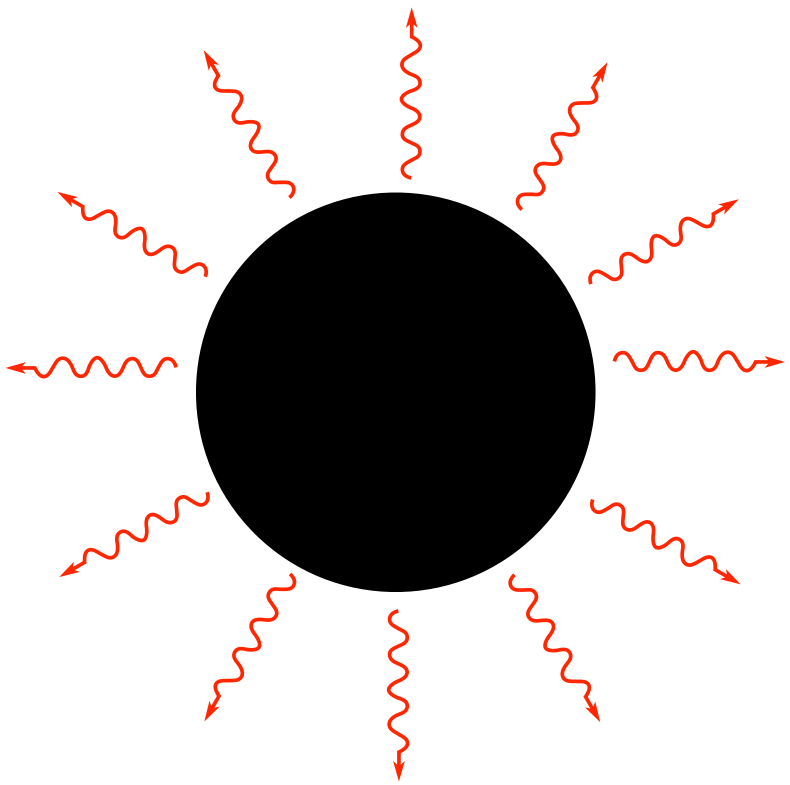
Hawking radiation emerges from quantum fluctuations near the black hole and draws energy from the black hole

Hawking Radiation from a black hole

Hawking Radiation from a black hole

Hawking radiation from a black hole is exactly like radiation from a normal "hot" body $\Rightarrow$ black holes have a Hawking temperature

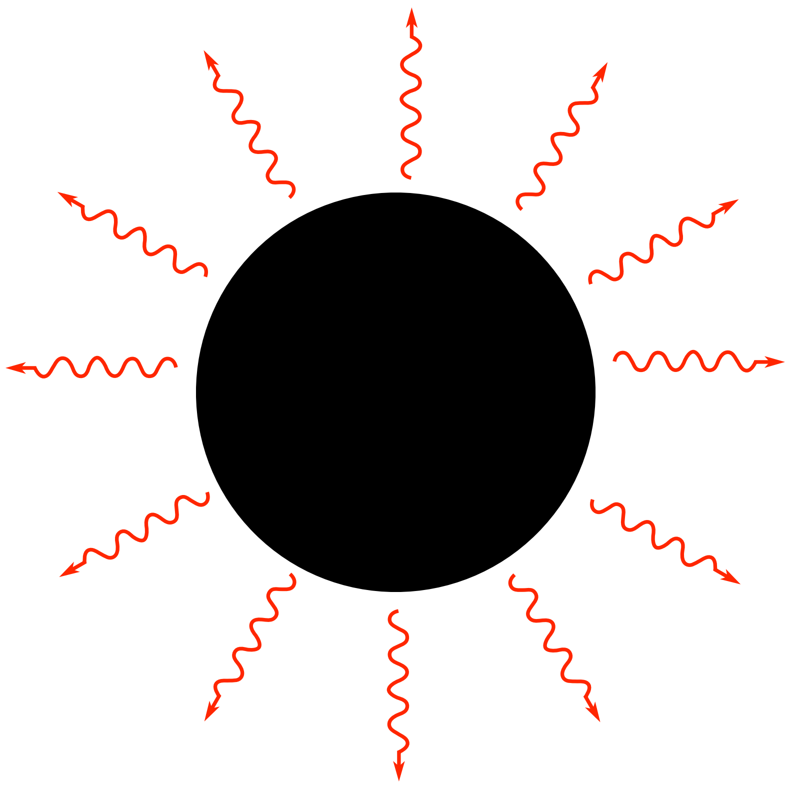


Hawking Radiation from a black hole

Hawking radiation from a black hole is exactly like radiation from a normal "hot" body ⇒ black holes have a Hawking temperature

Hawking radiation takes energy from the black hole

⇒ the black hole slowly loses mass/energy



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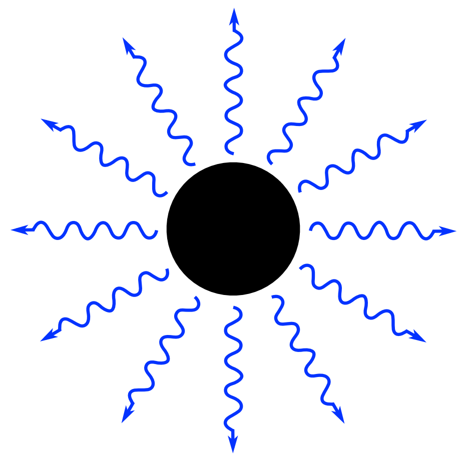

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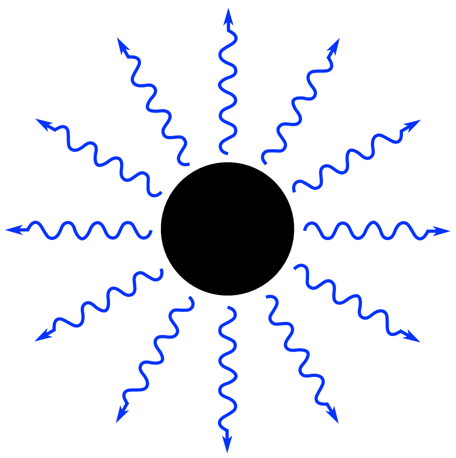

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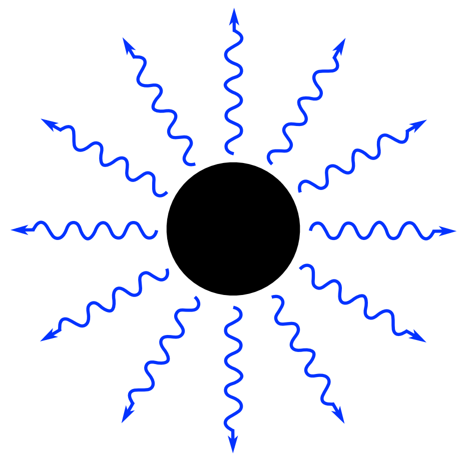

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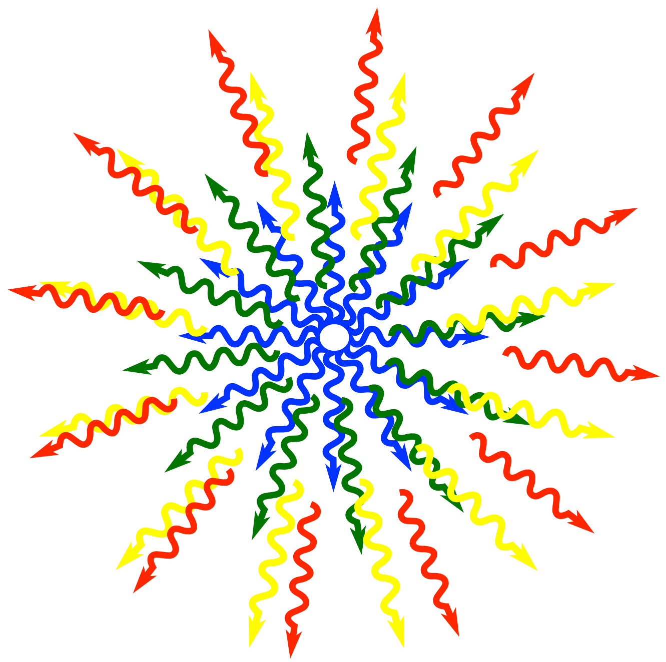

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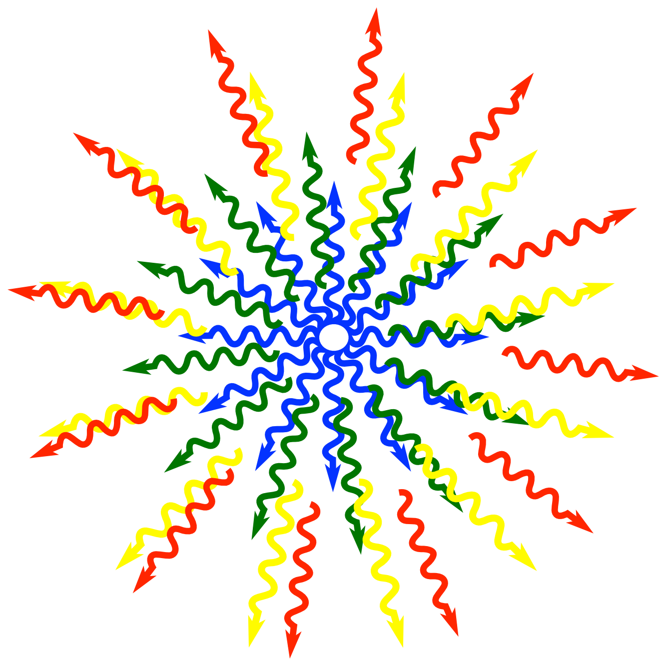
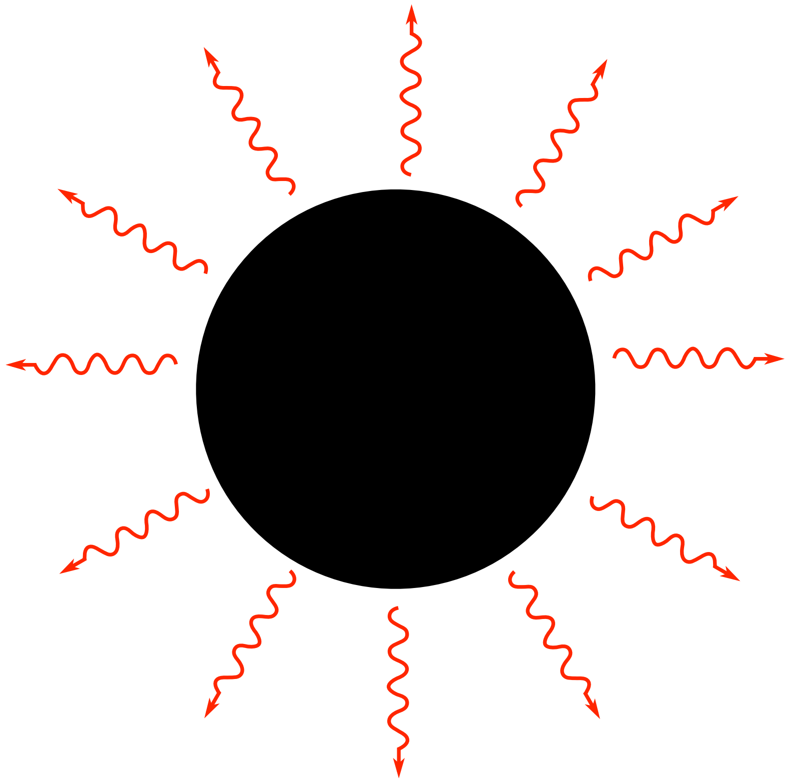
Leaving behind lots of Hawking radiation



The Hawking Temperature of a black hole with the same mass as our Sun is extremely low



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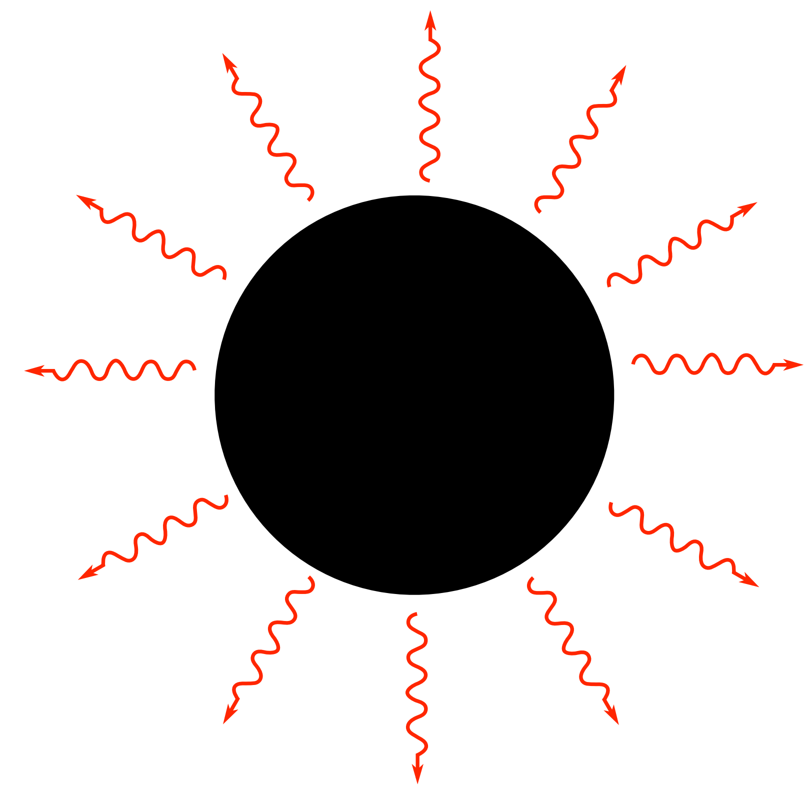

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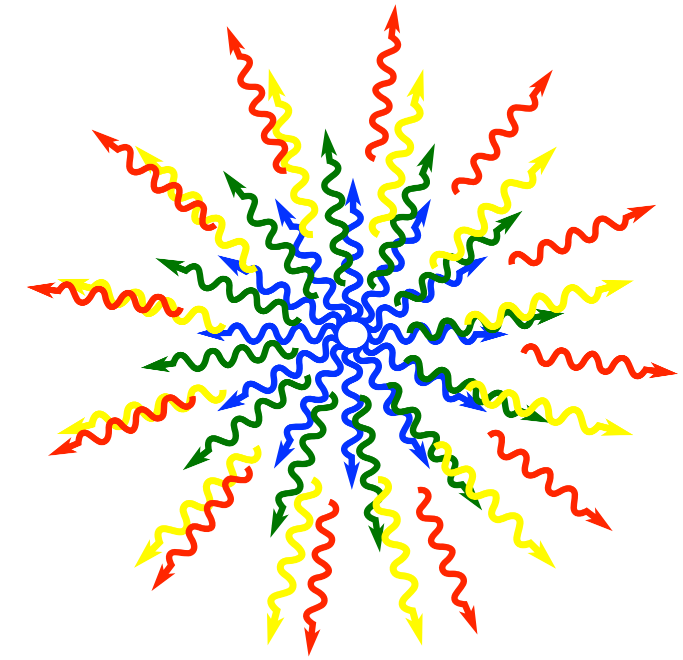

The evaporation of a black hole with the same mass as our Sun takes about:

10,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000 years

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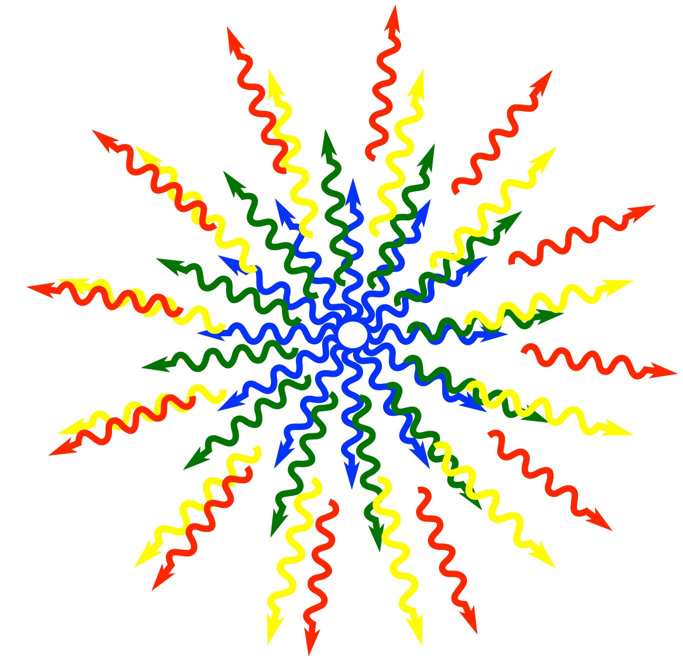

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000,000,000,000,000,000,000,000,
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= 10^{67} years

But no matter how slow the process of Hawking evaporation is, *it presents a fundamental conflict with the principles of quantum mechanics.*

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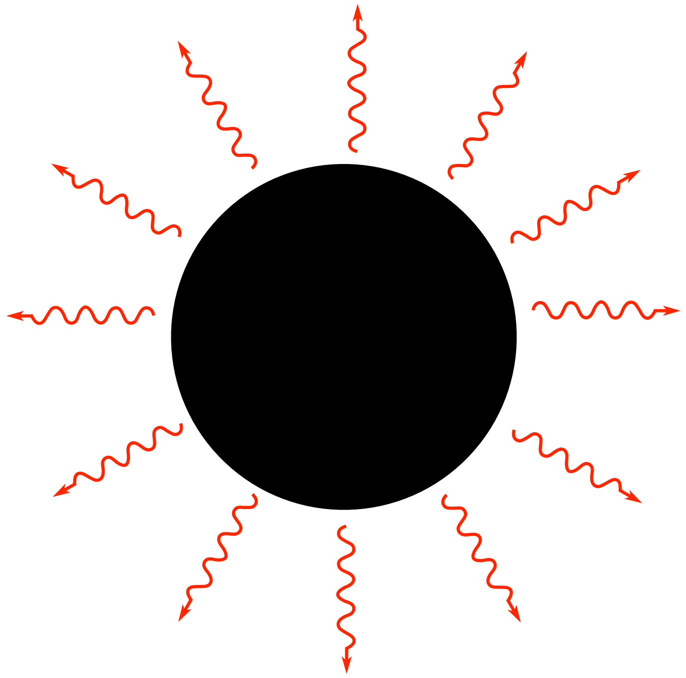
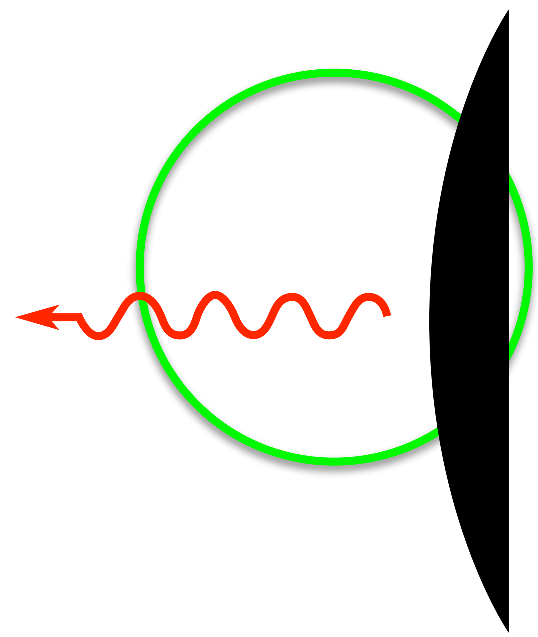
There are two crucial features of Hawking Radiation that reveal this conflict …

Two very important points



Two very important points

1) **Hawking Radiation** originates from quantum fluctuations in a region just outside the ***event horizon***



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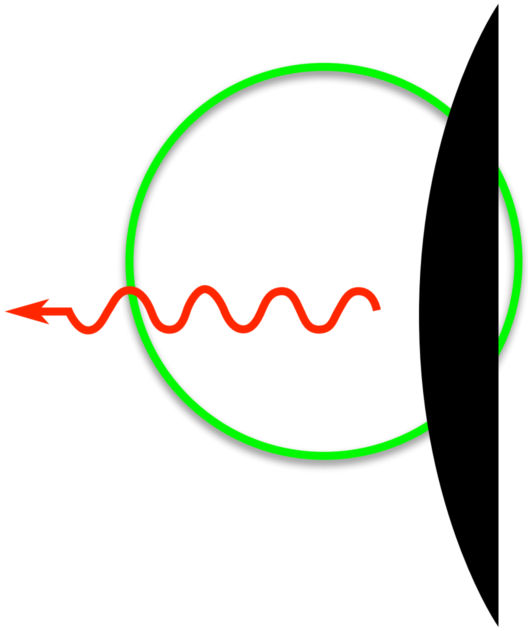

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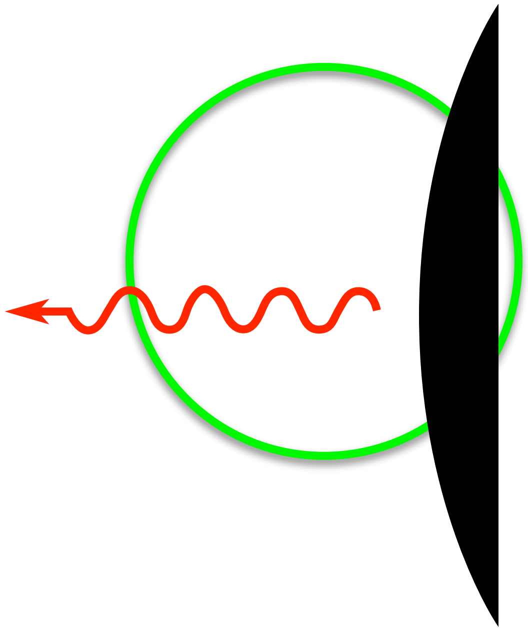

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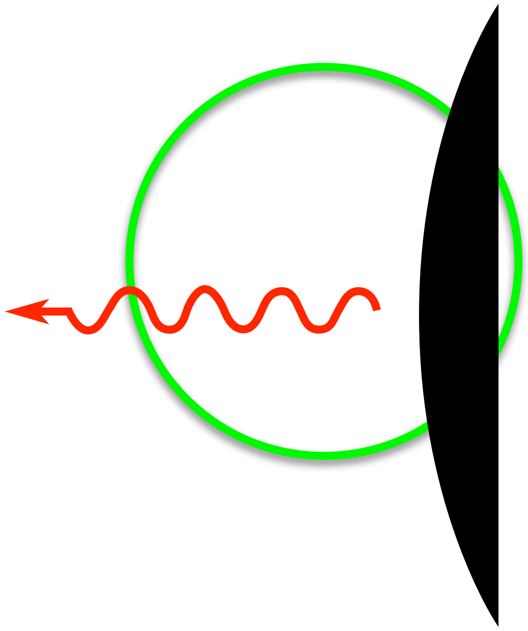

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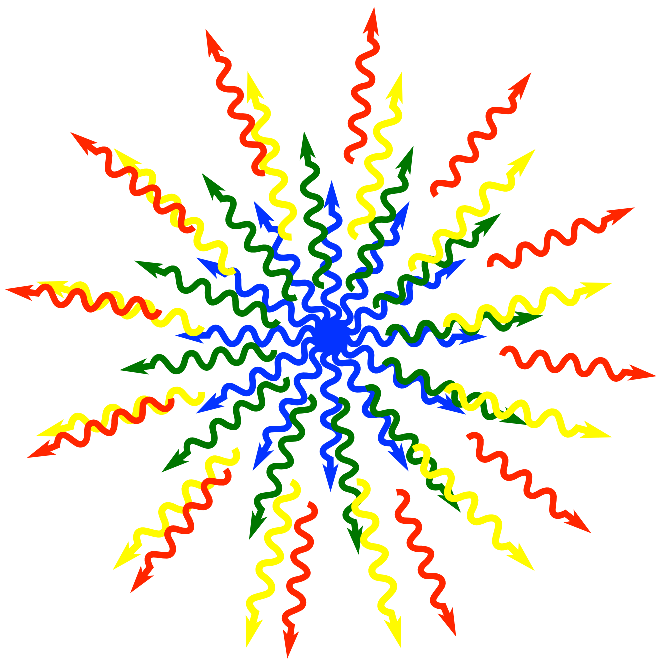

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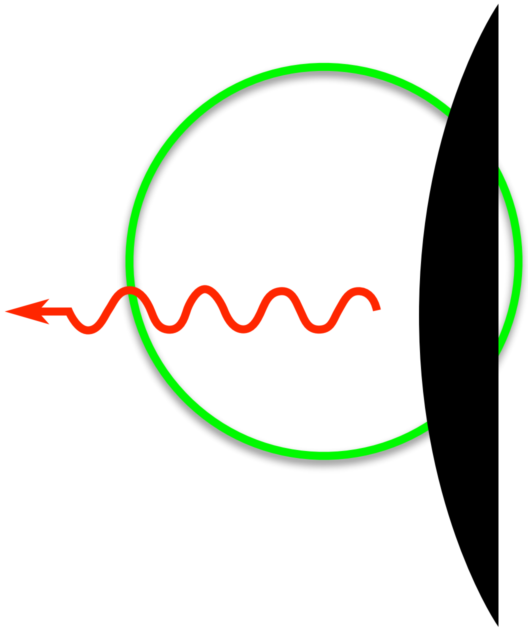

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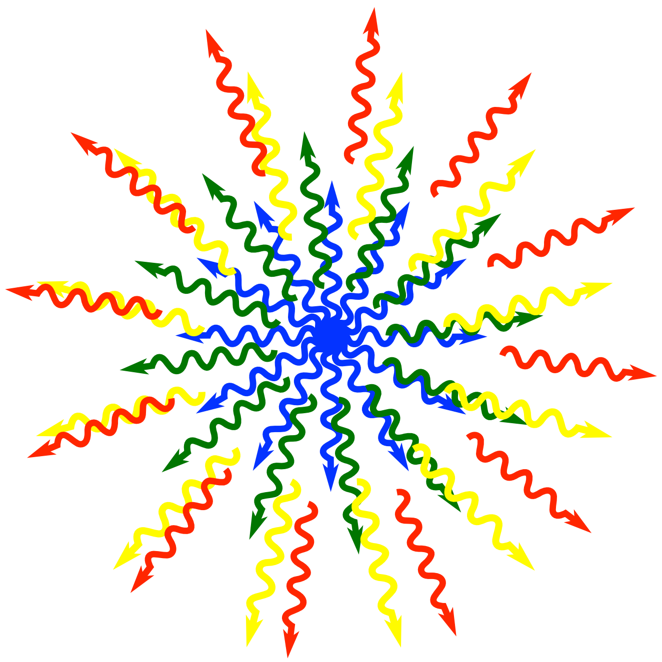
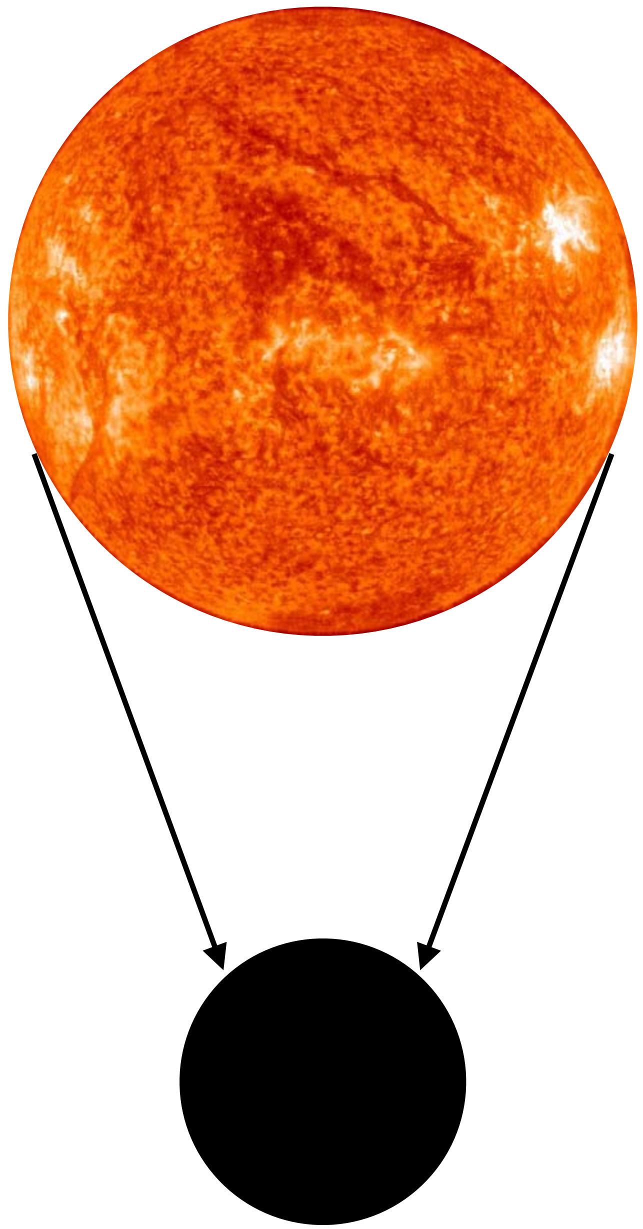


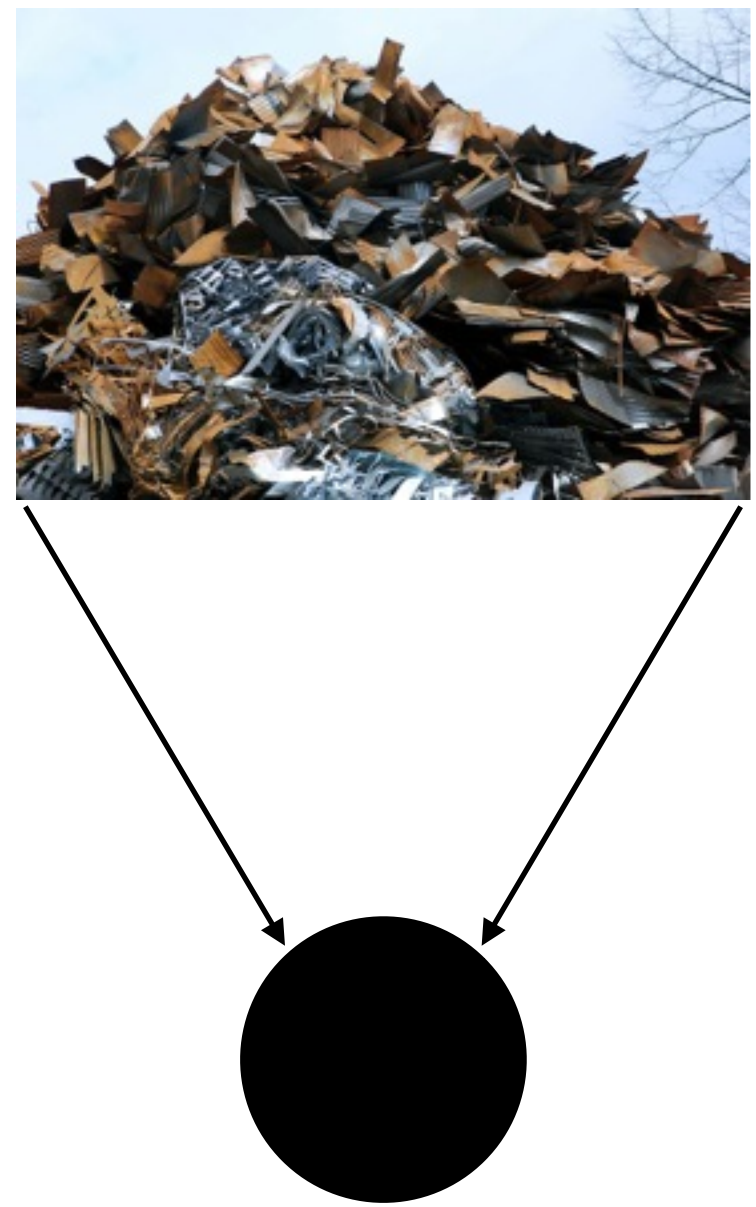
Black-hole uniqueness ⇒ Hawking radiation is (almost) featureless

No matter how you make a black hole,
the resulting *Hawking radiation* is the same

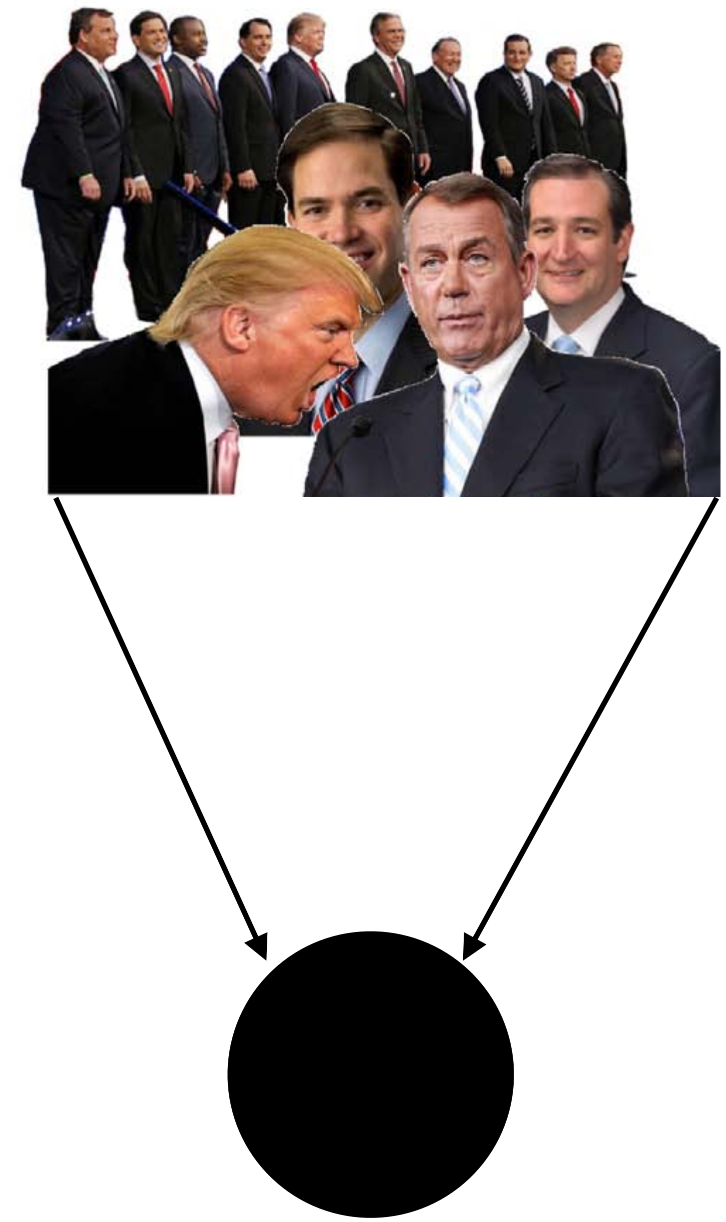
A star



Trash



Politicians



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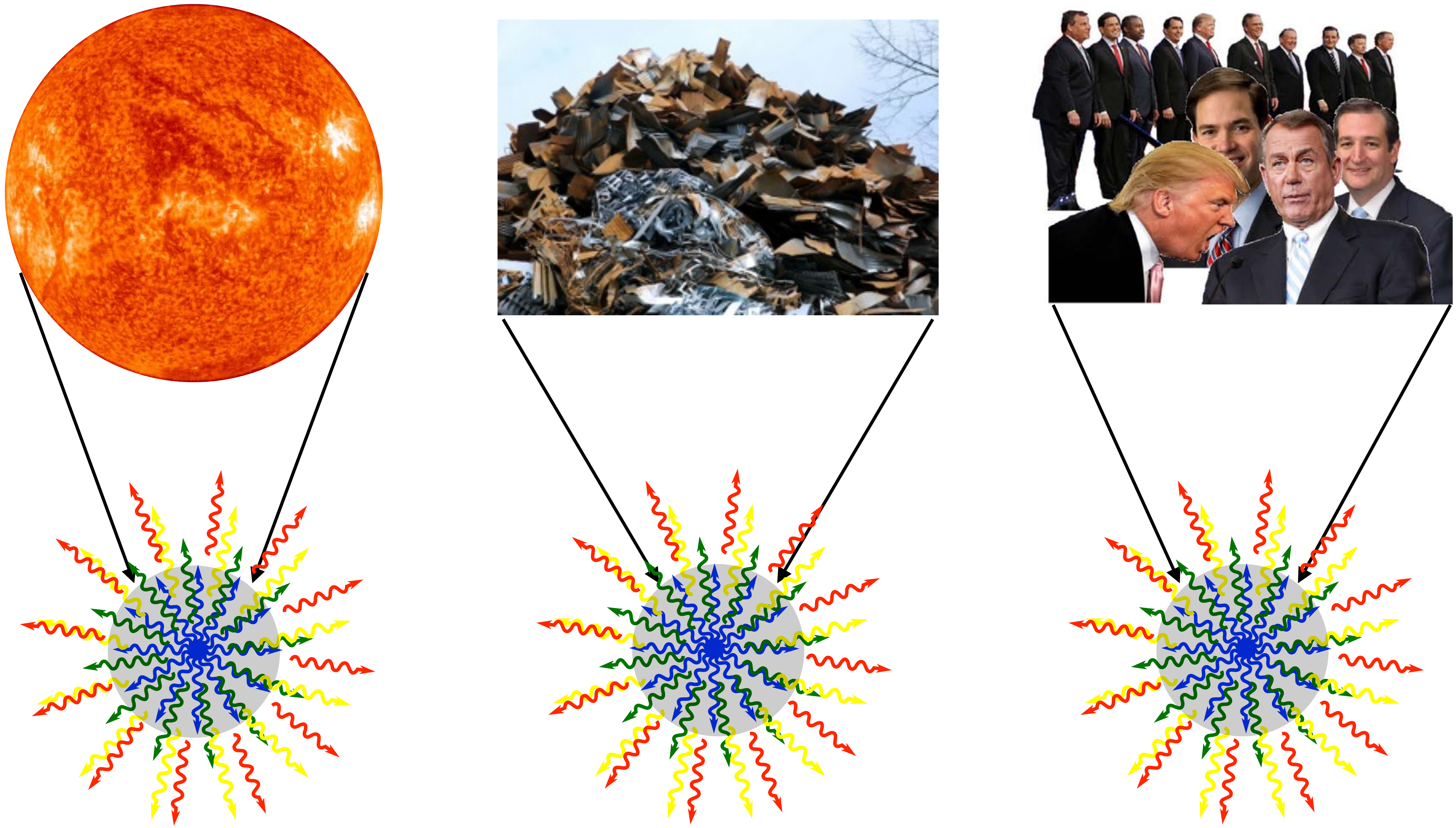

If the star, trash and politicians have the same mass, charge and rotation and form a black hole, then *the Hawking radiation is universally the same*

A Foundation of Quantum Mechanics: *"Unitary Evolution"*

Information on paper

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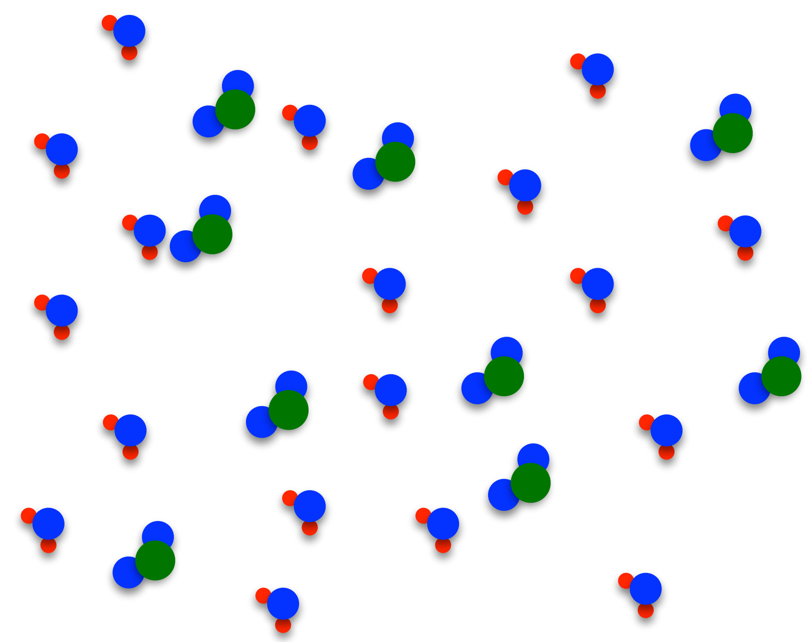
Information on paper

Molecules fly off



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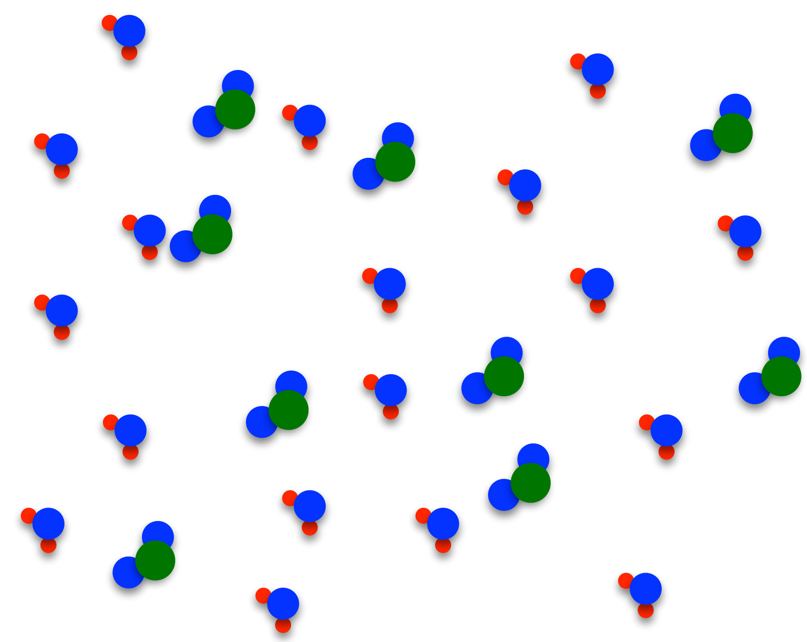

Unitary Evolution means that with a lot of effort we ***can reconstruct the original paper*** and information by measuring positions and speeds of all the molecules of the burnt paper

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Like a jigsaw puzzle, one can scatter the pieces…

Unitary evolution means that the evolution can be run backwards or forwards.

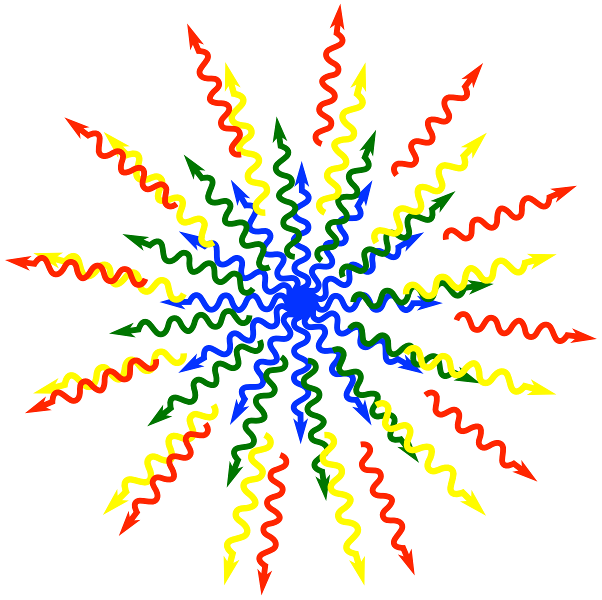
With a lot of effort one can figure out where everything came from and *reconstruct the original state*

Just like the the burnt paper…

Just like the the burnt paper…

What happens when you try the same thing with black holes?

Hawking Radiation



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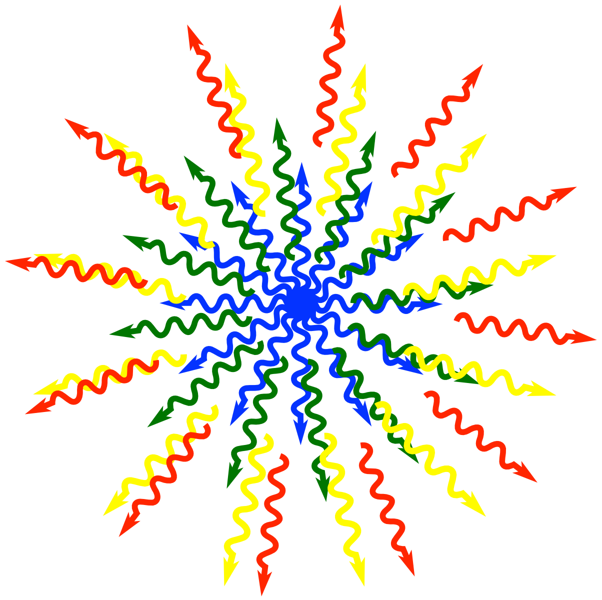
(almost) featureless



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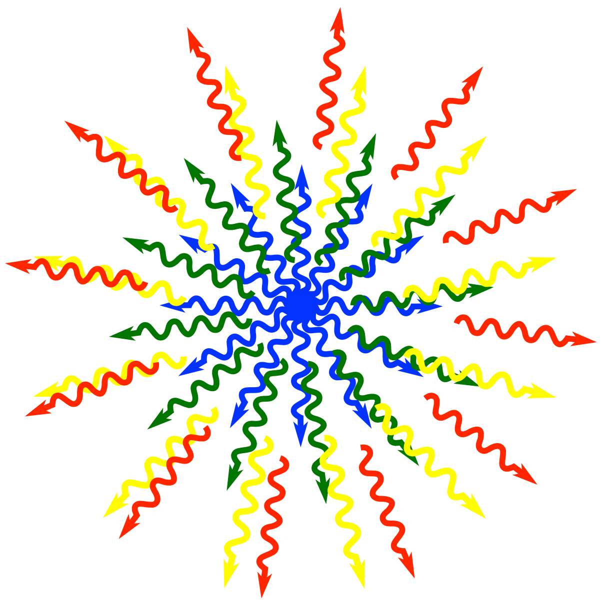
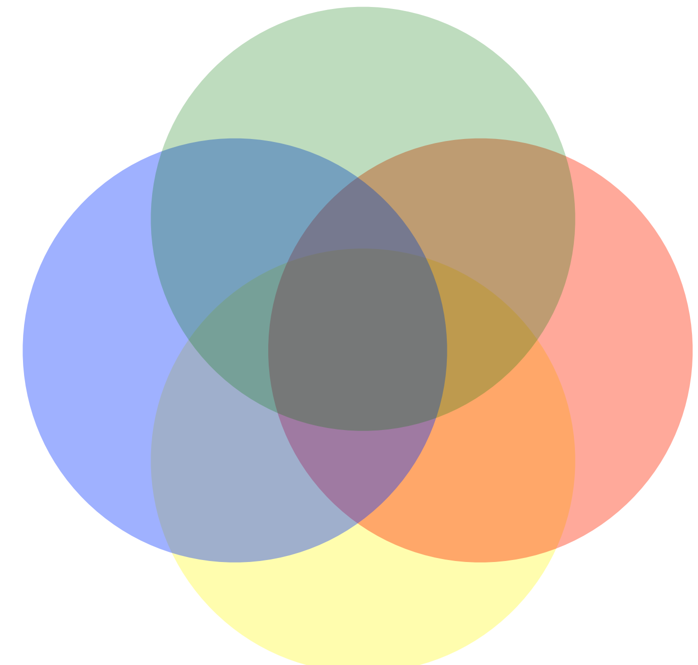


Rebuild black hole



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Hawking Radiation
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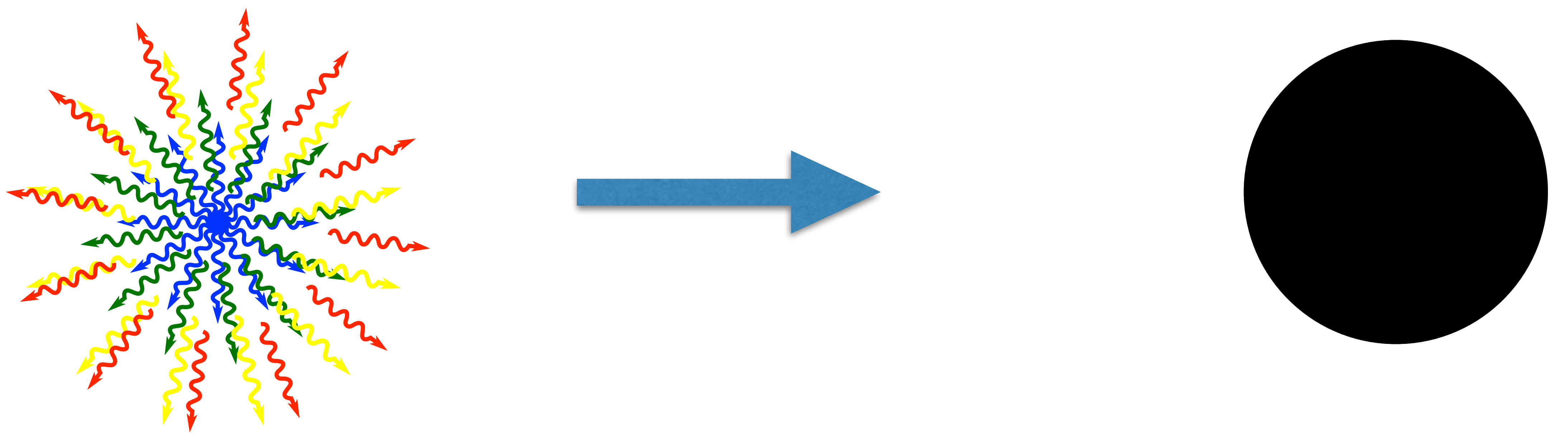
Rebuild black hole
(almost) featureless



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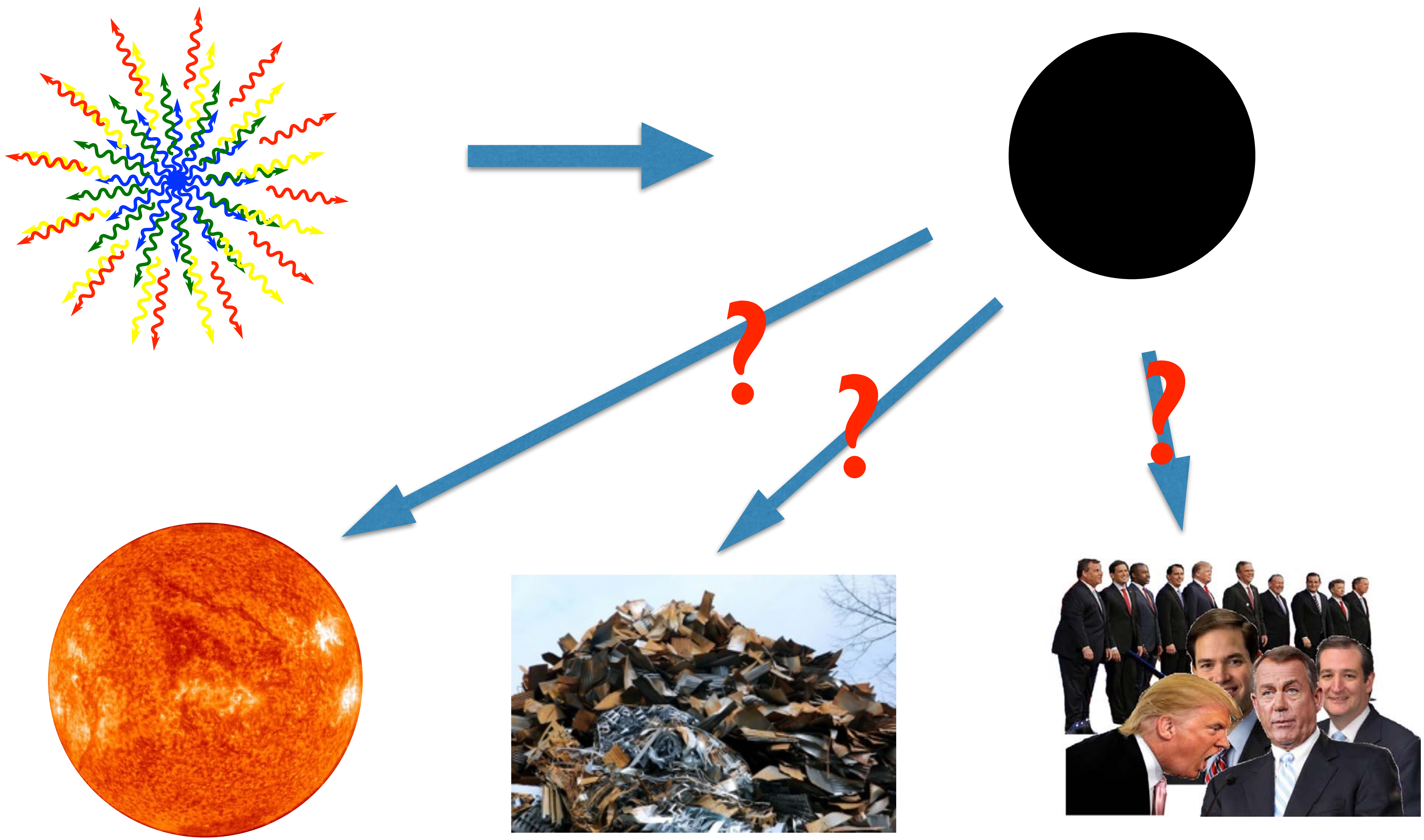

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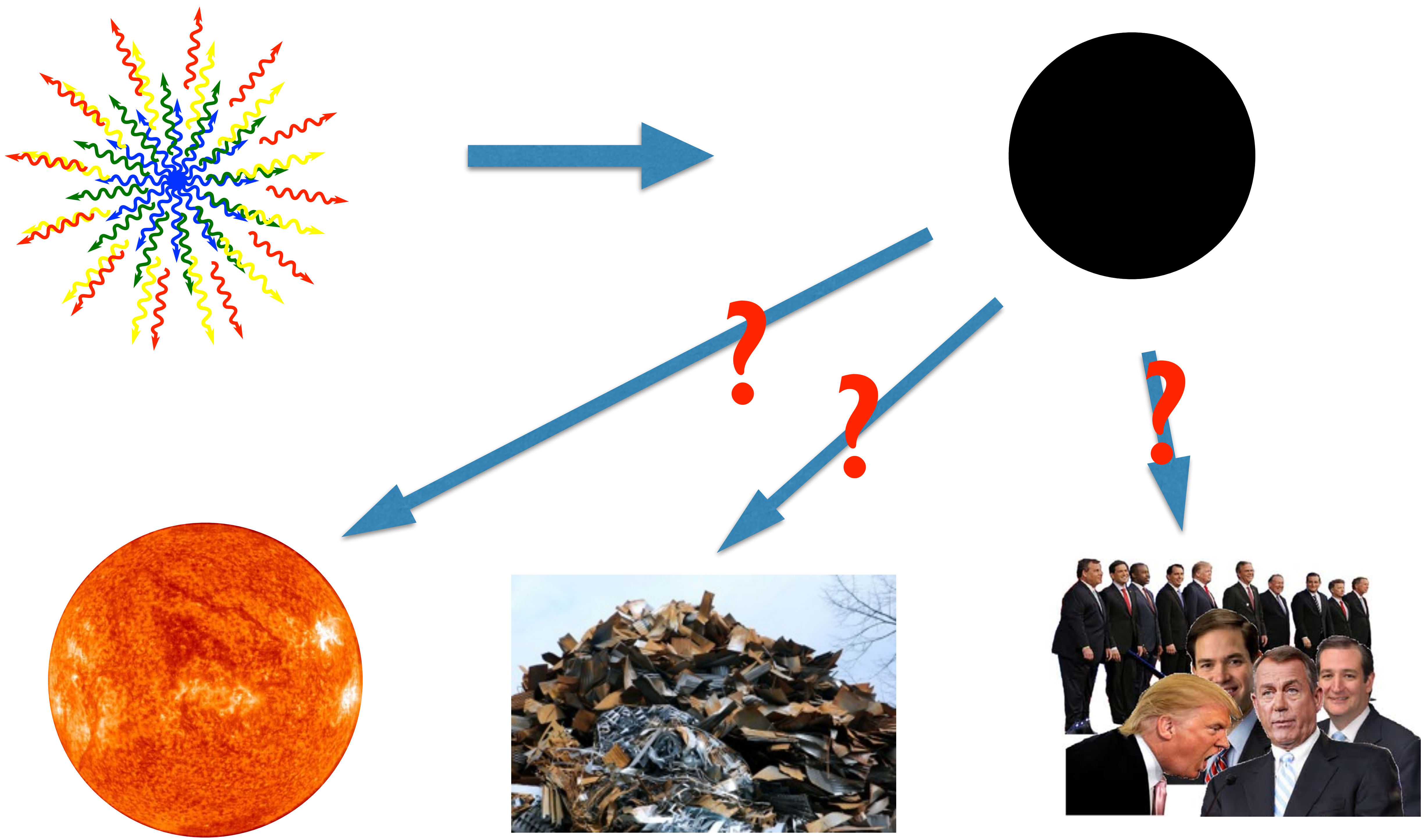
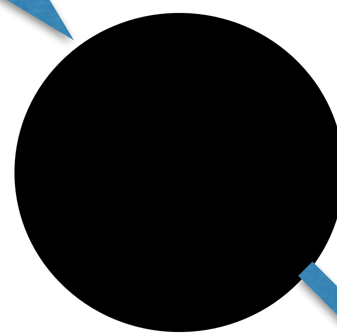


It is impossible to determine the original state!

Ordinarily one can break up a puzzle and then reconstruct the initial state: *Unitary evolution of quantum mechanics*

If it goes through a black hole intermediate then all pieces are wiped of their information ..



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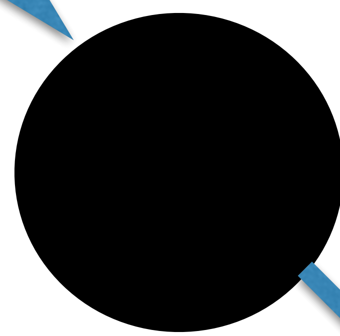
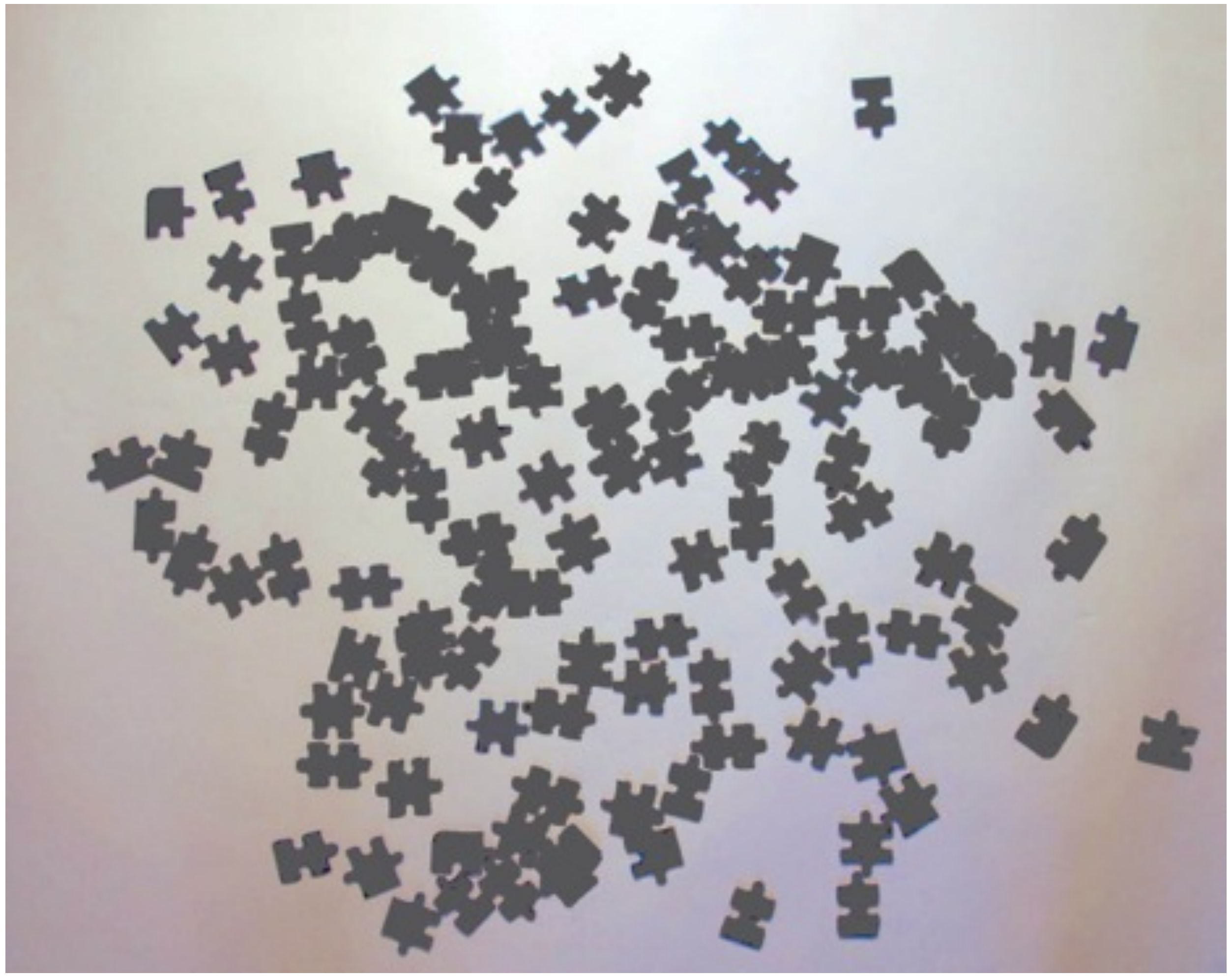


Almost all information is lost

(almost) featureless pieces



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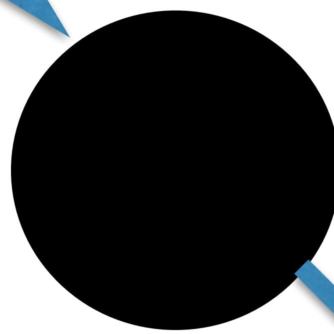
Any attempt at reconstruction results in a featureless picture



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(almost) featureless reconstruction

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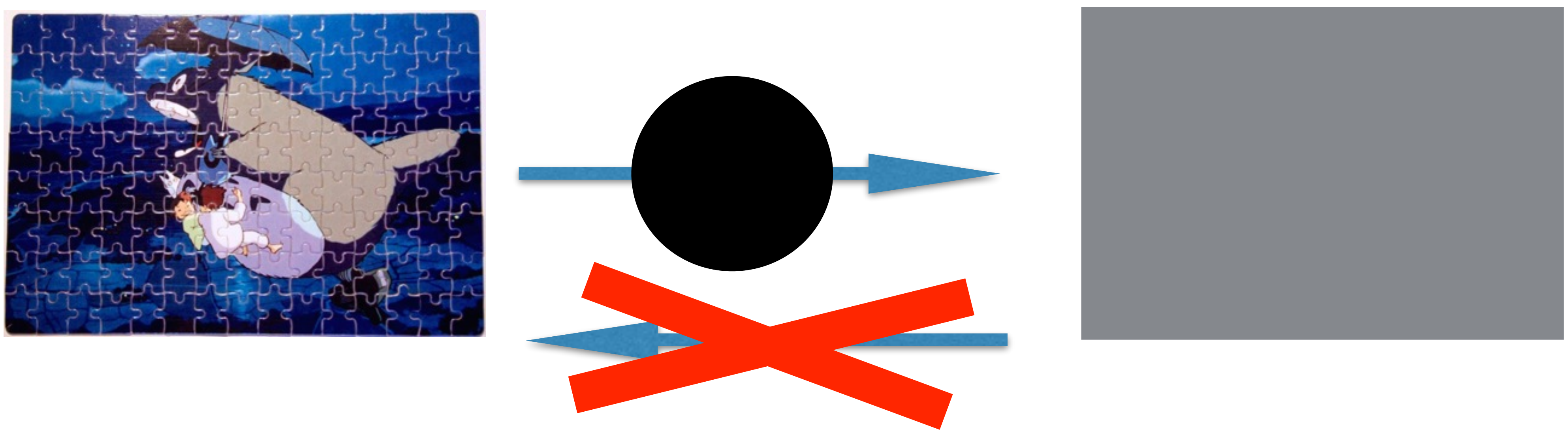

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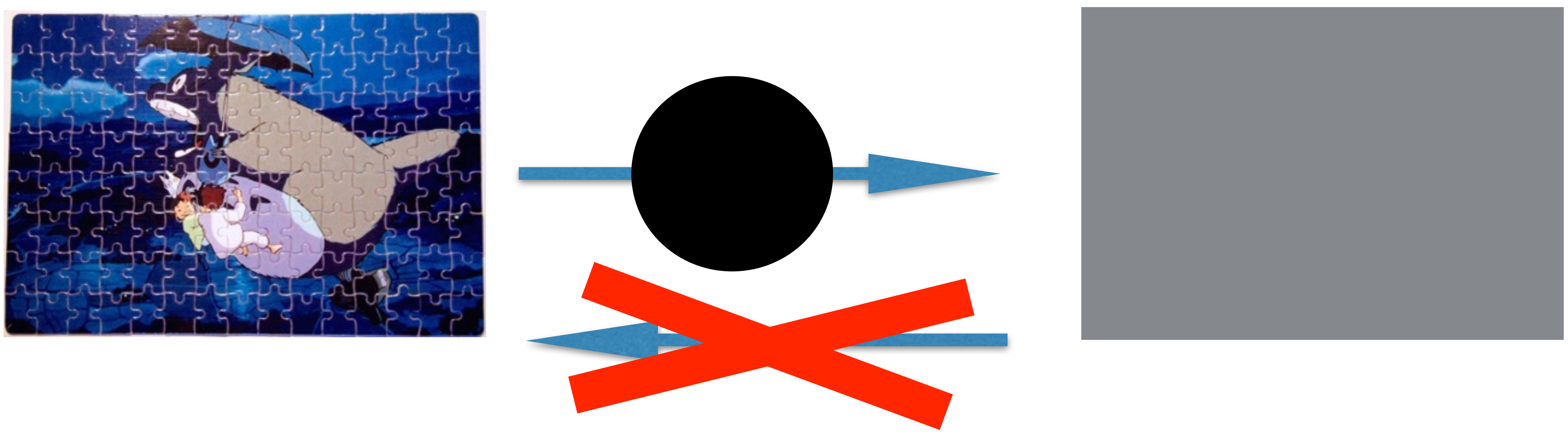

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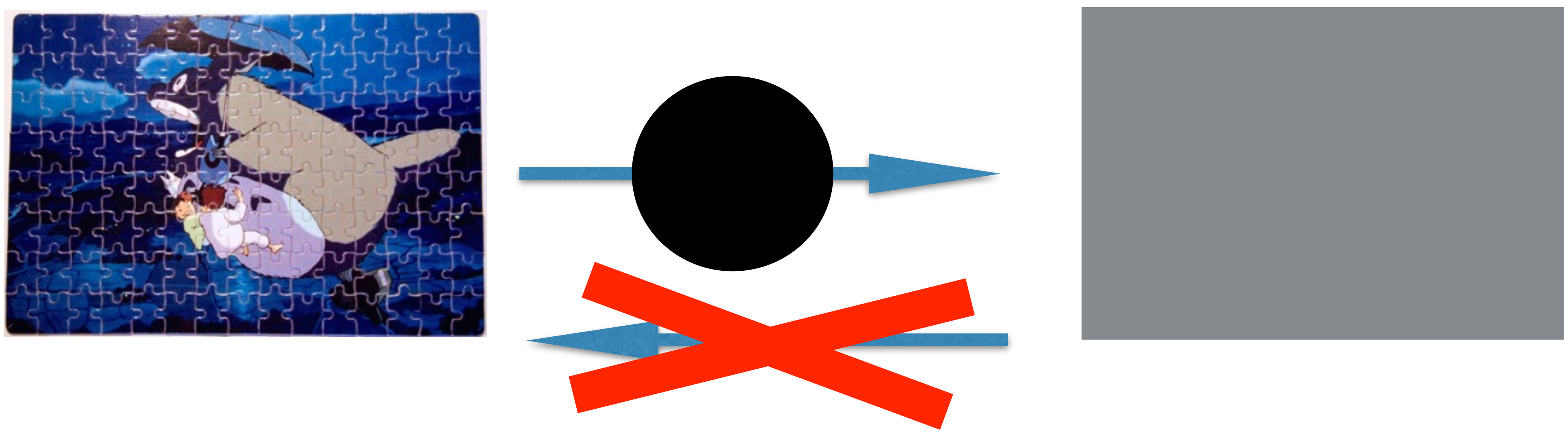

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BUT…

General Relativity and Quantum Mechanics are foundational theories upon which we have based much of technological society and upon which we bet lives every day …. and yet these theories do not agree!

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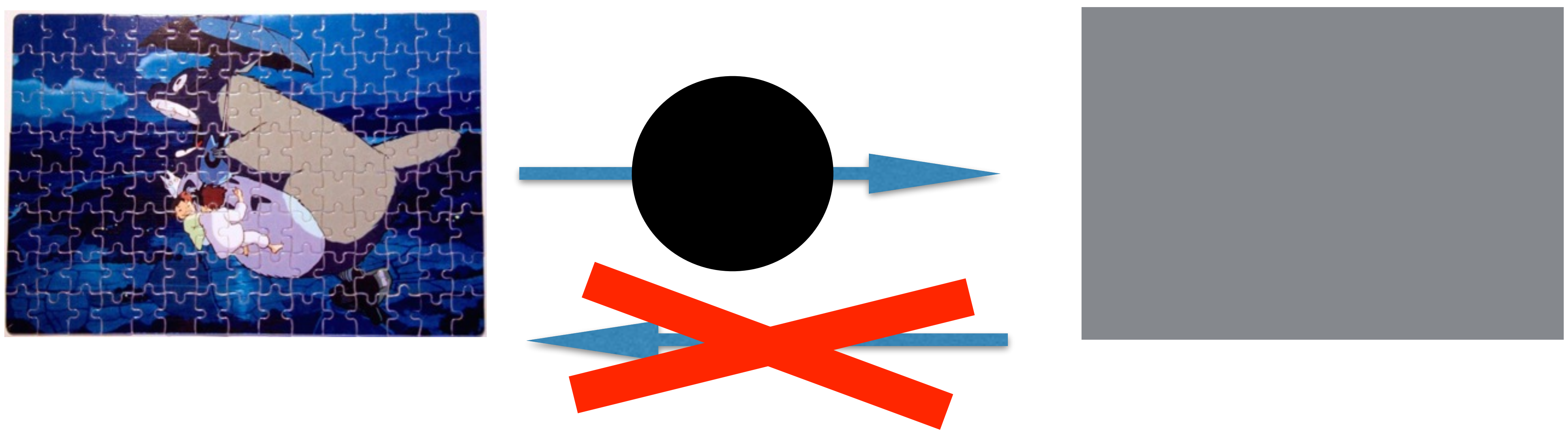

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How can we fix this problem?

We need a consistent, combined theory of quantum mechanics and gravity

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Most promising candidate: String Theory

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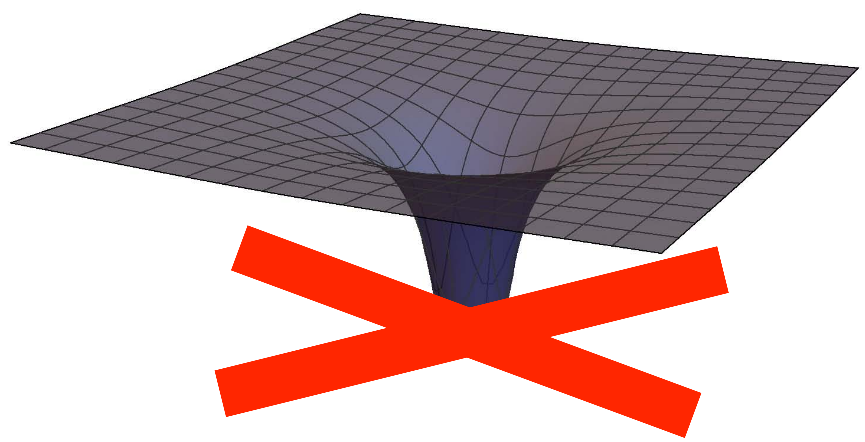
<u>General Relativity: Schwarzschild</u>



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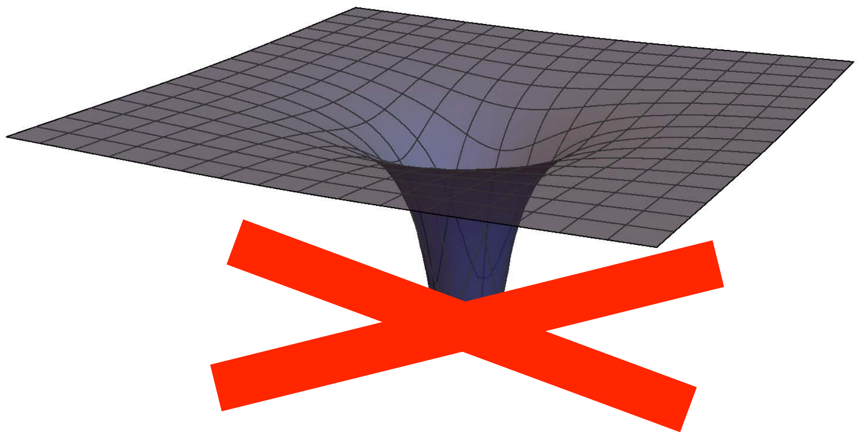

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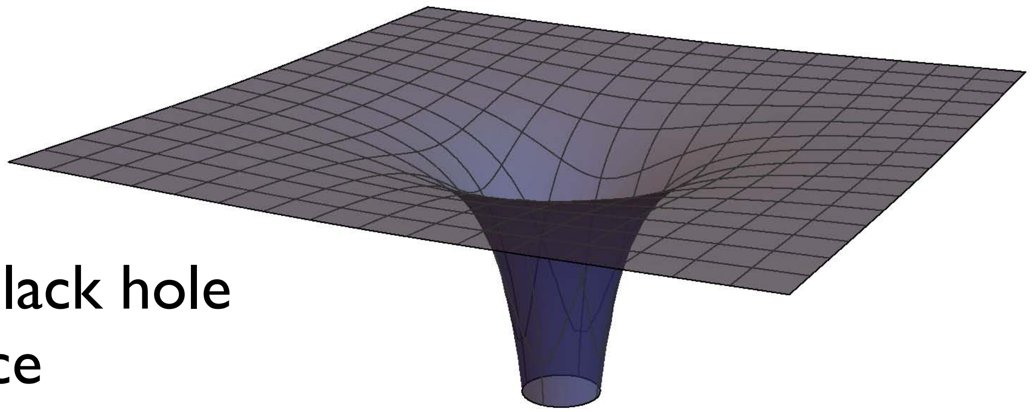
Stringy Black Hole:



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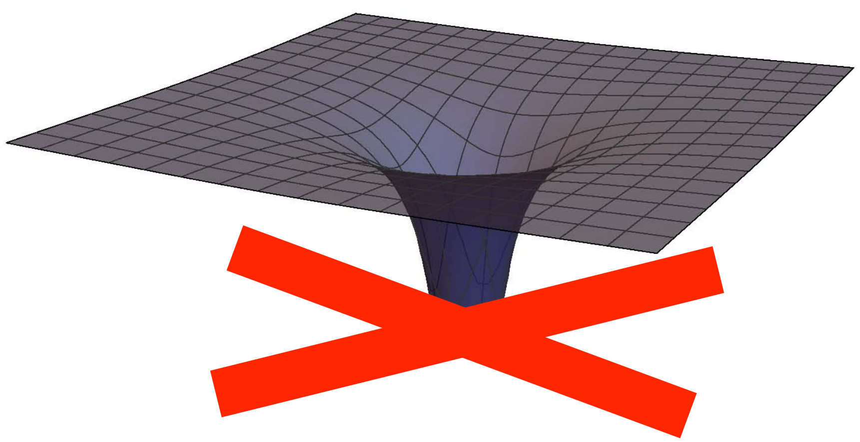

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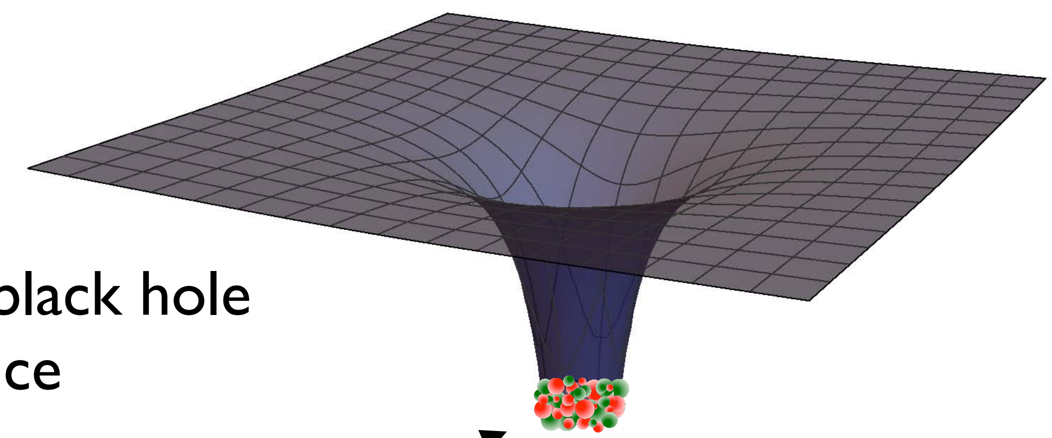


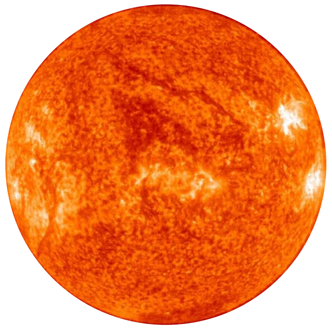
Looks like a black hole from a distance

New states and phases of matter and even *extra dimensions of space* emerge from string theory in a way that can encode everything about what made the black hole …

⇒ Professor Shigemori's talk

Making *stringy* black holes

A star



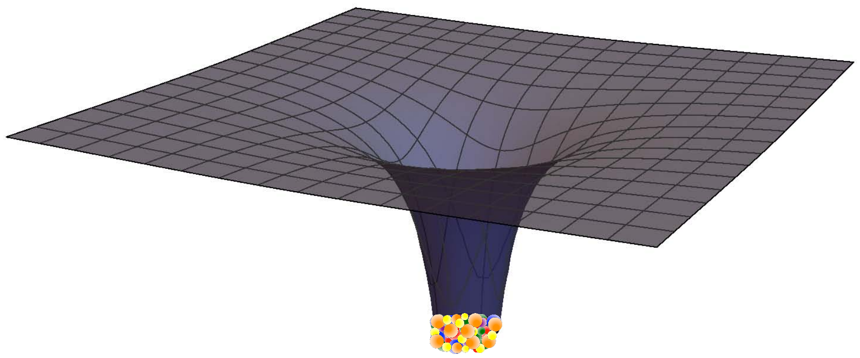
Trash

Politicians

Making *stringy* black holes

The details of what formed the black hole are stored in the new string theory structures at the bottom of the black-hole geometry …

A star



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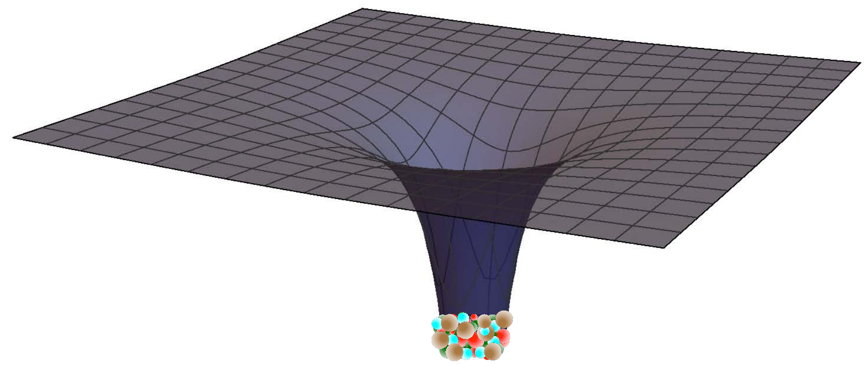
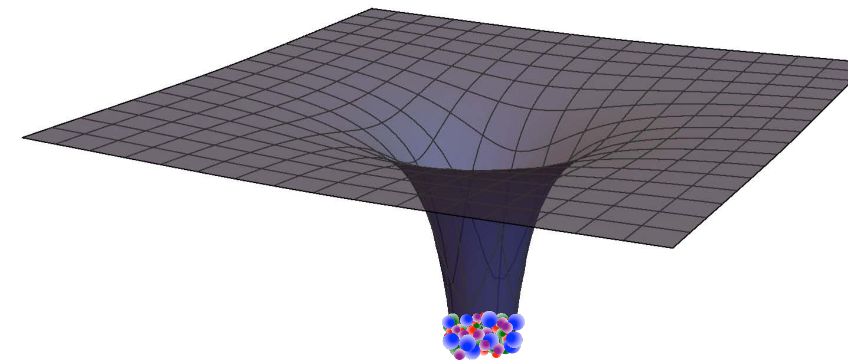


Politicians



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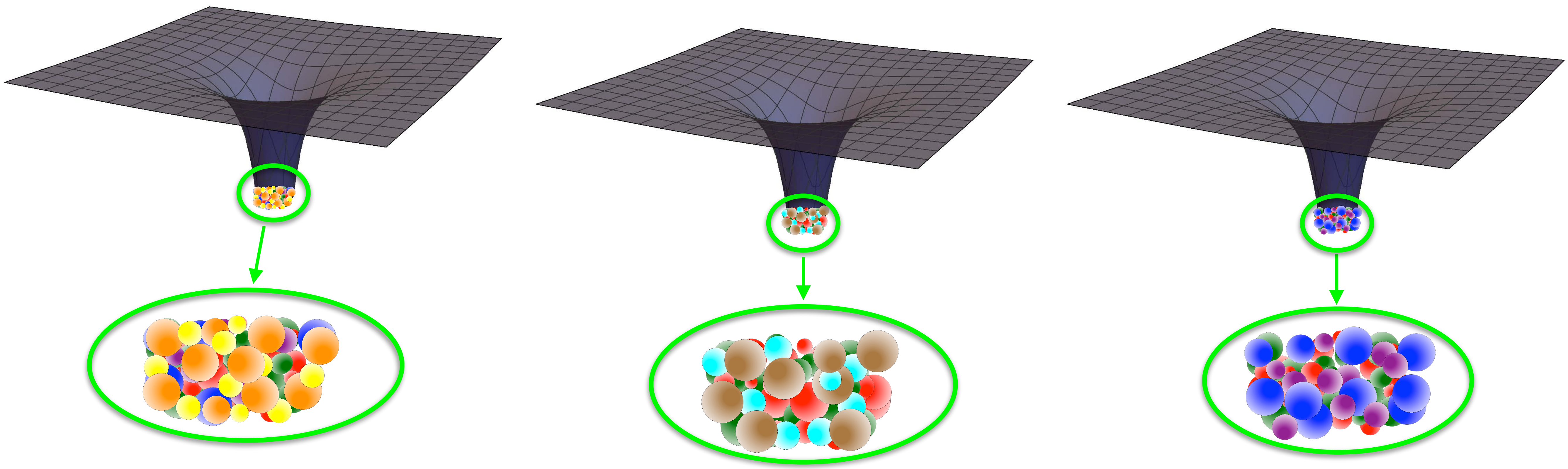

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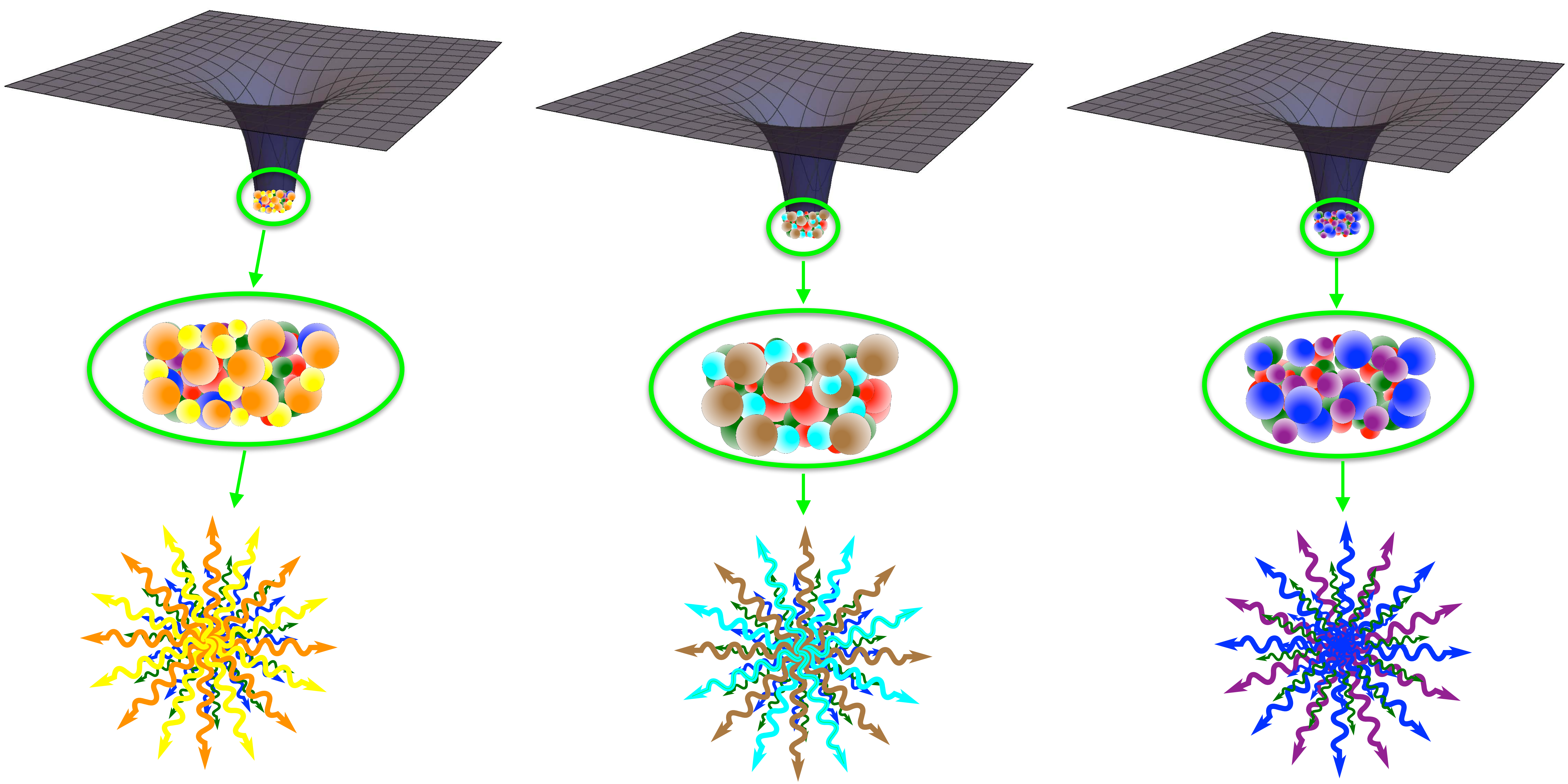
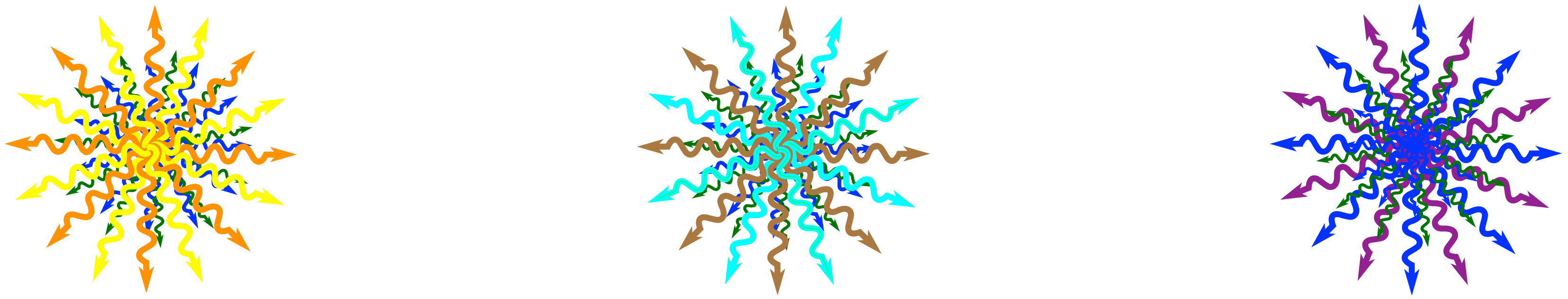
A star | Trash | Politicians



The details are recycled as differences in the Hawking Radiation …

The Goal: Show that stringy black holes have "Unitary Evolution"

From the differences in the Hawking radiation …



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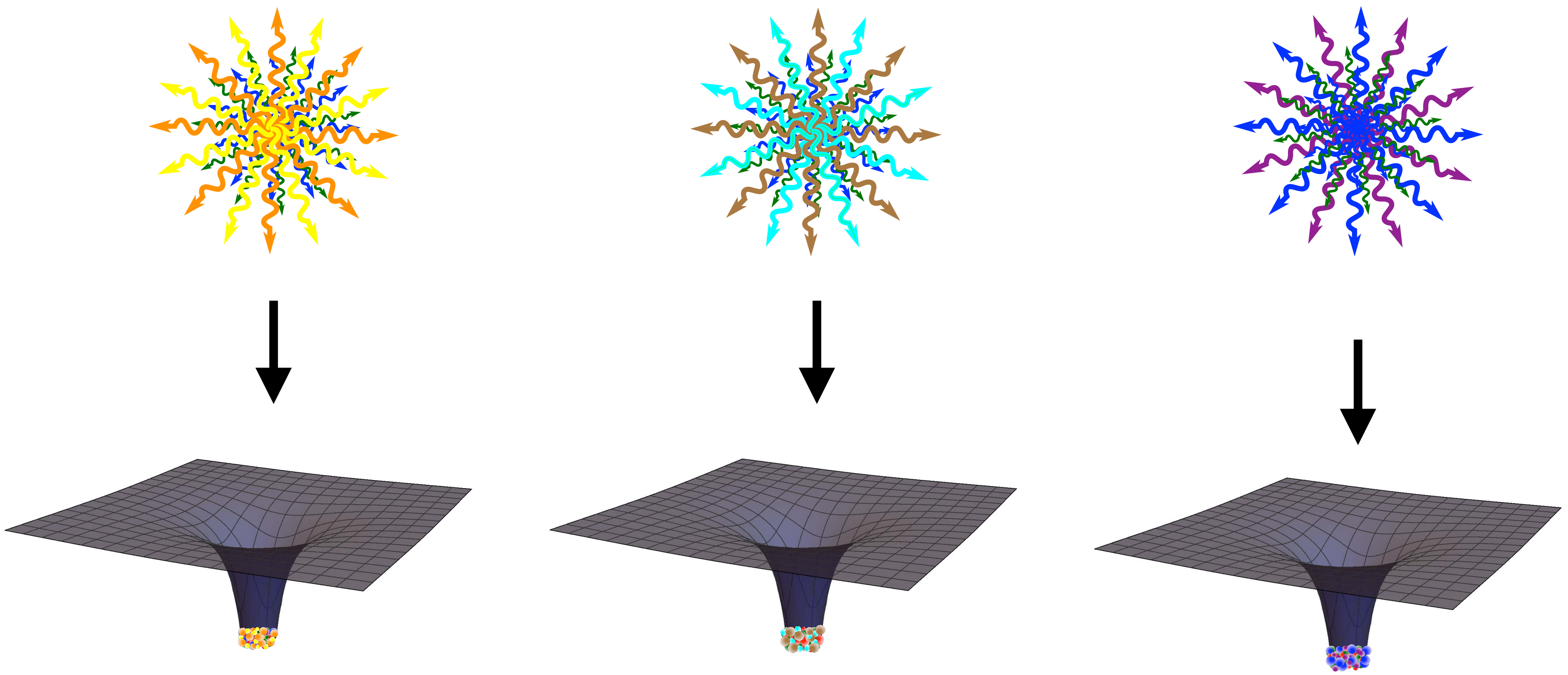
One can reconstruct the *stringy* black holes



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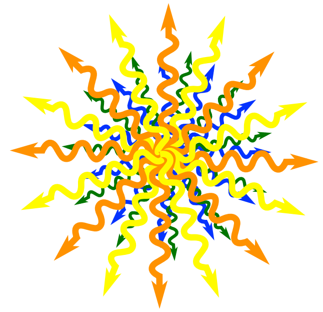

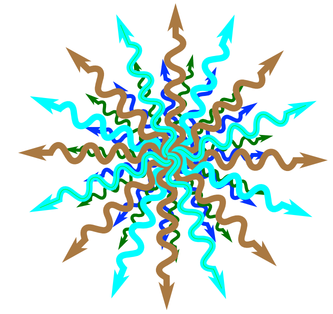

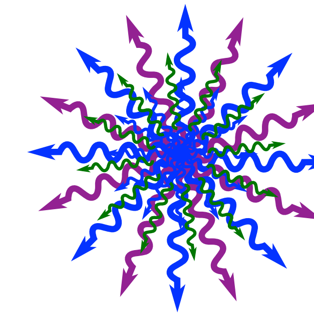

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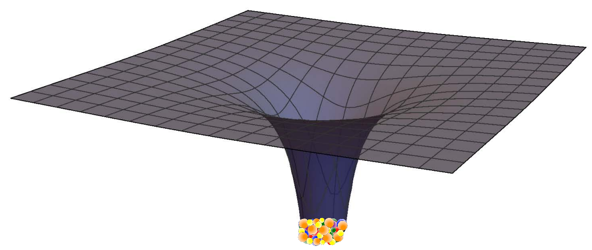
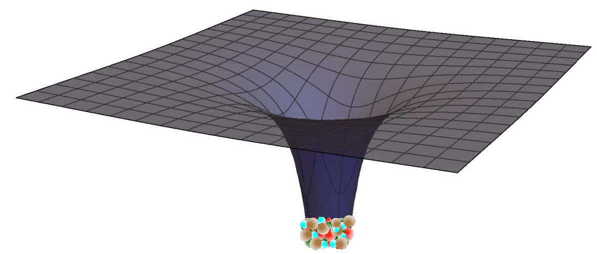
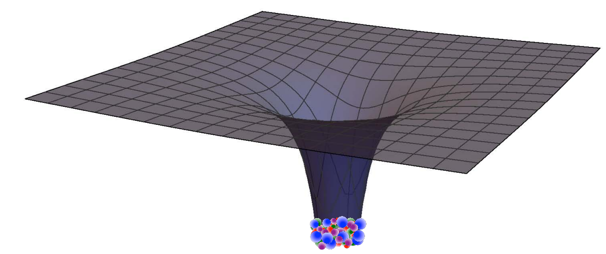
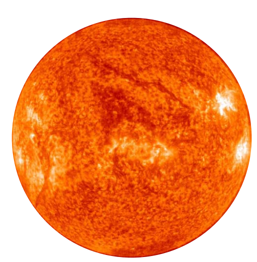






From which one can reconstruct the matter from which the black holes formed …



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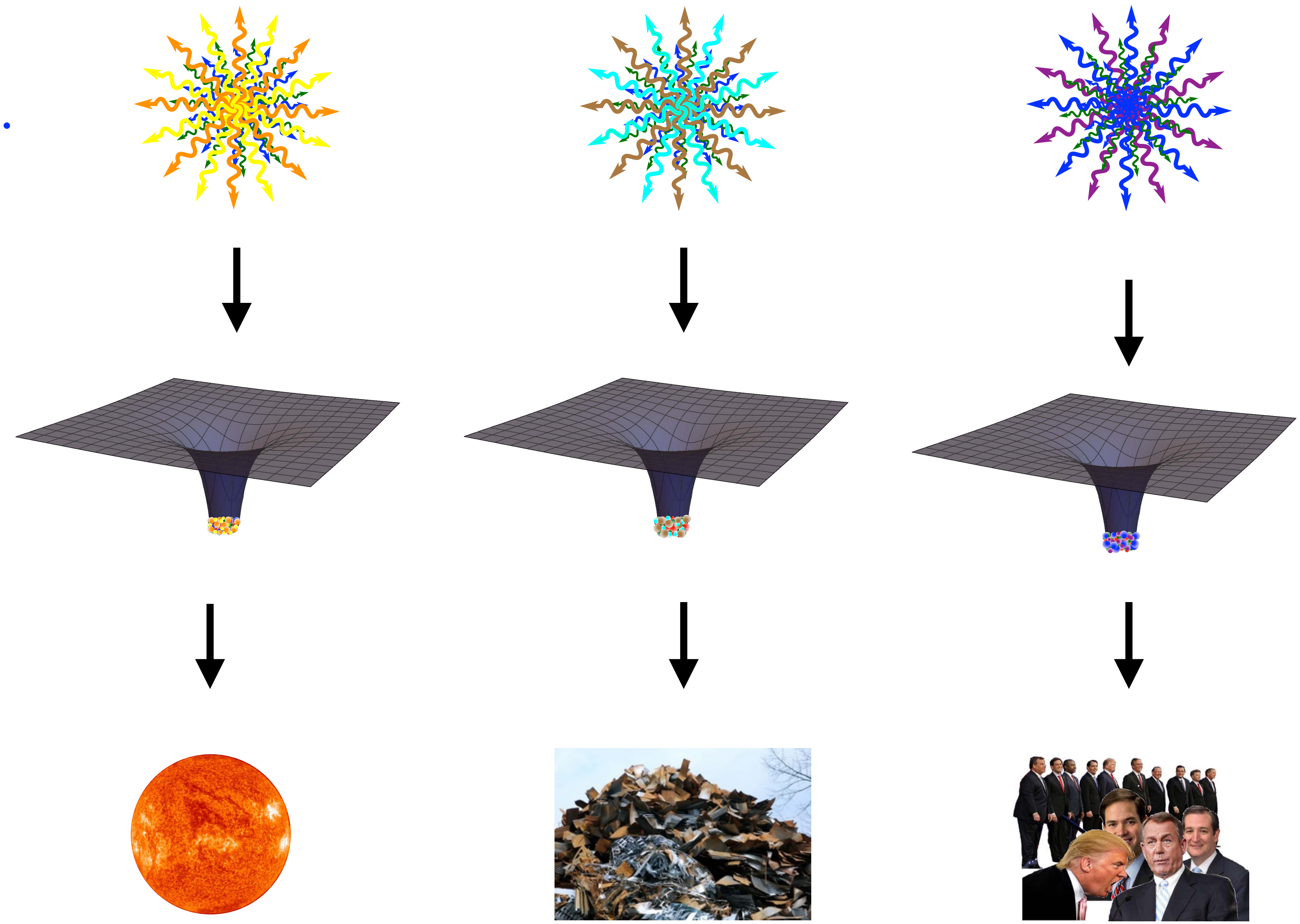

If this idea can be made to work in string theory, then it would finally reconcile Einstein's theory of gravity with the principles of quantum mechanics …

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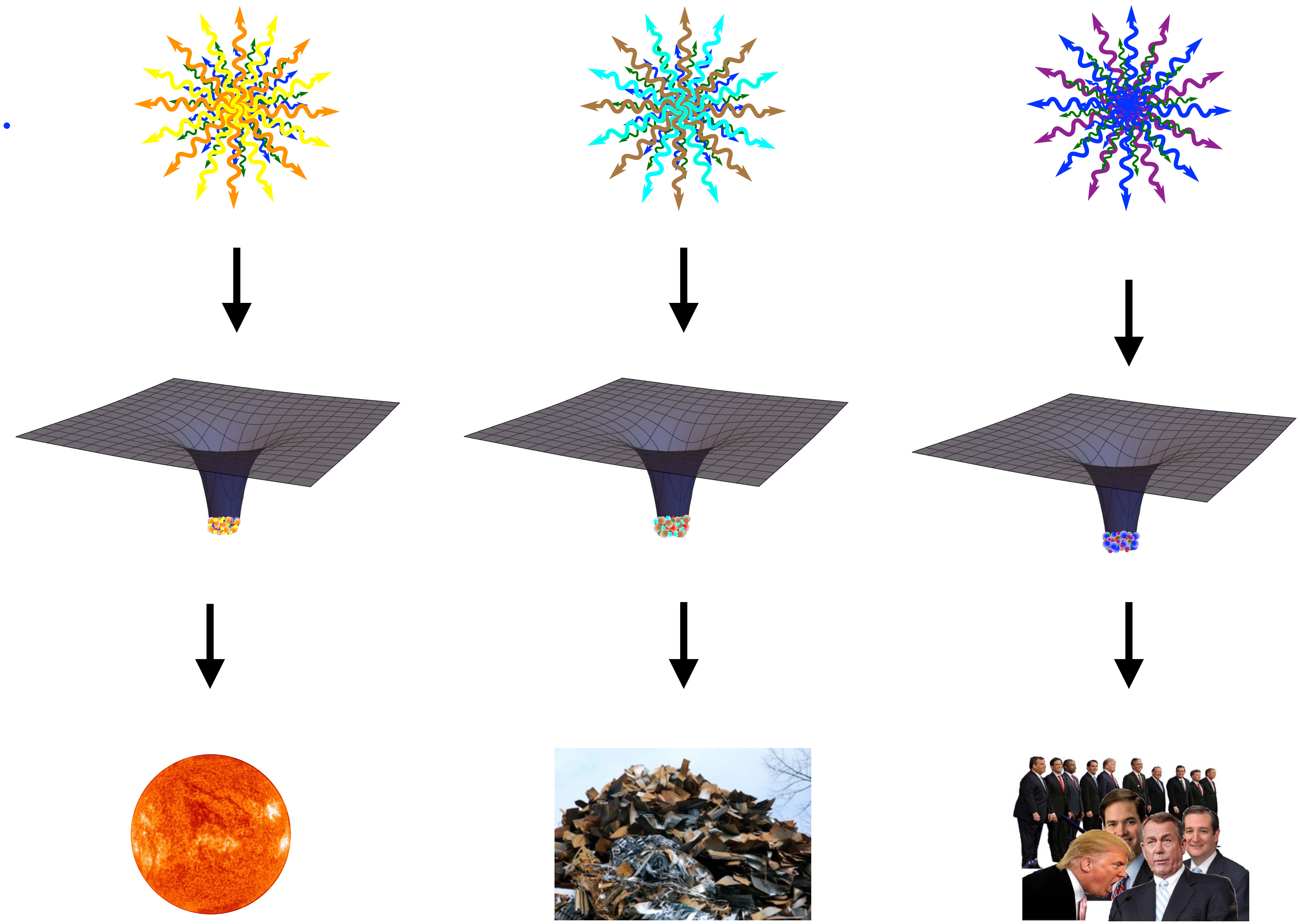

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A very hard problem: but we are making progress towards the solution….

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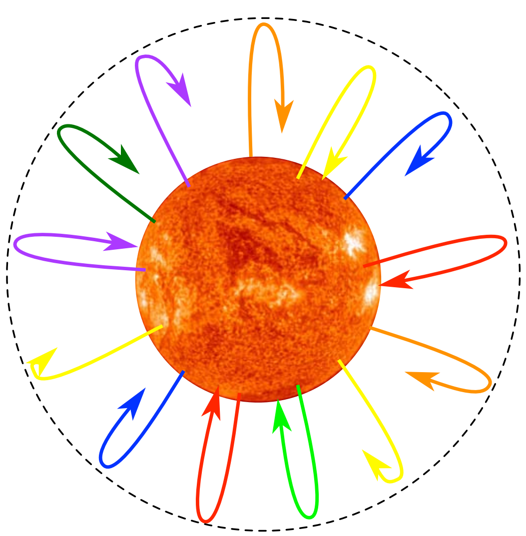
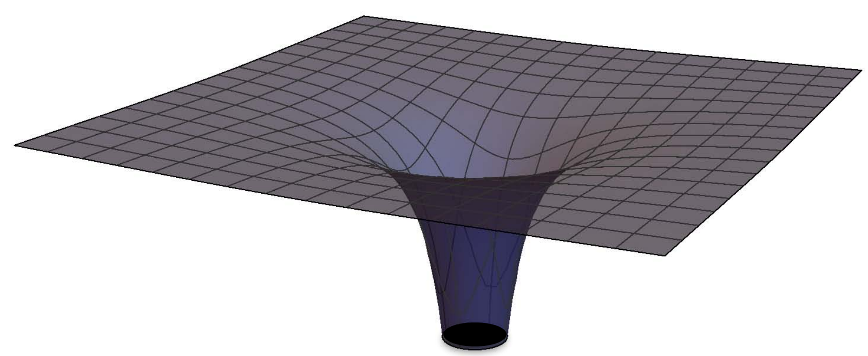


<u>Schwarzschild</u>



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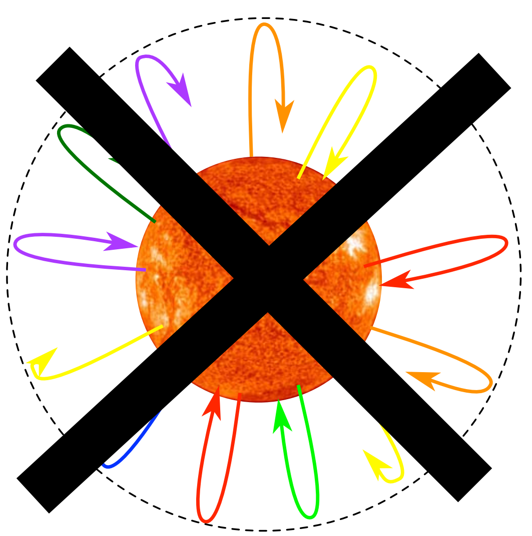

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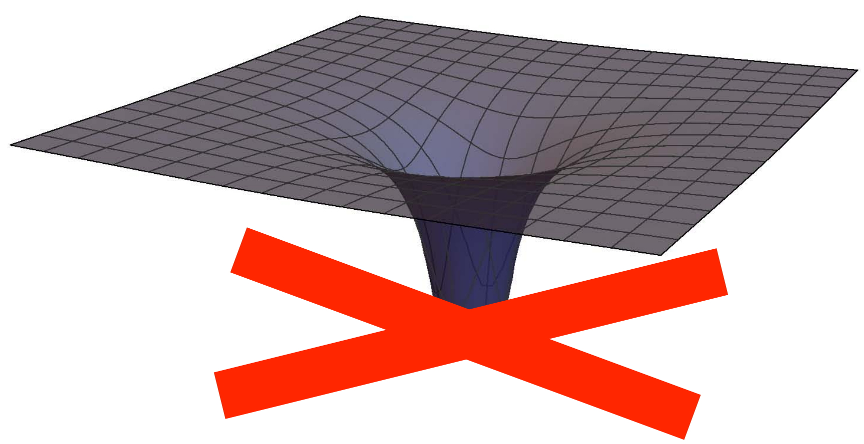

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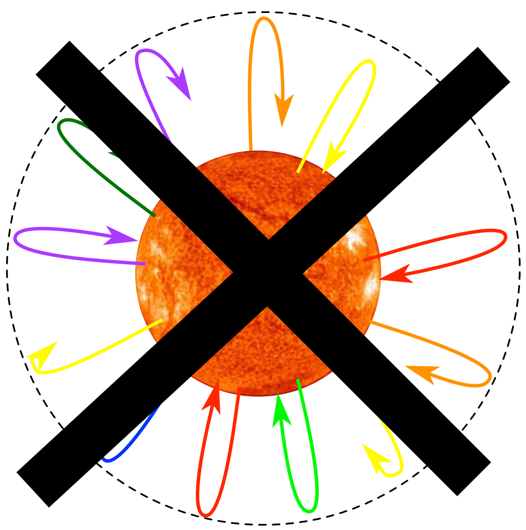

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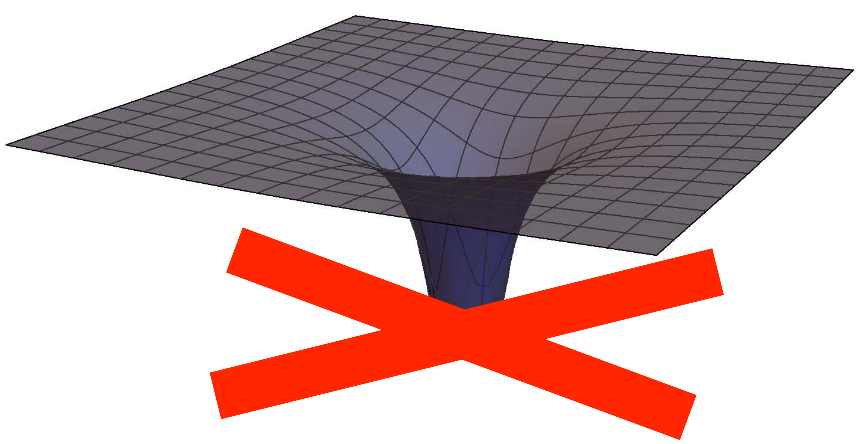
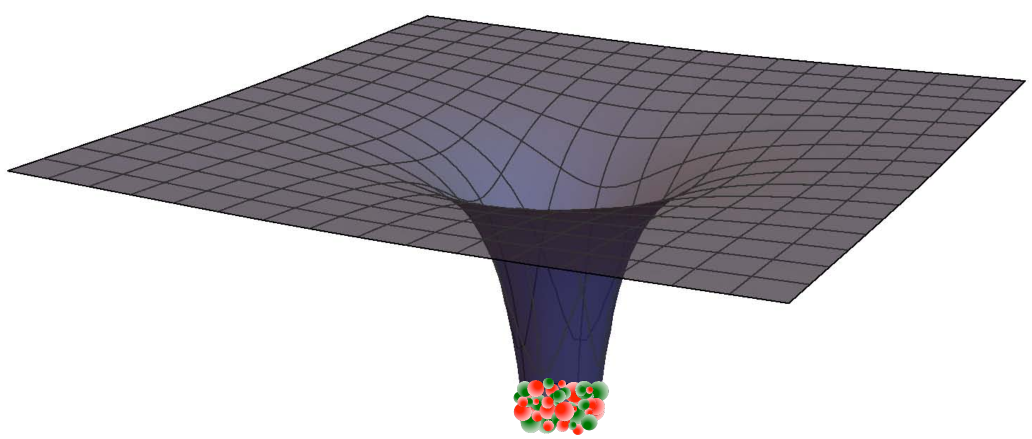


Black holes in string theory



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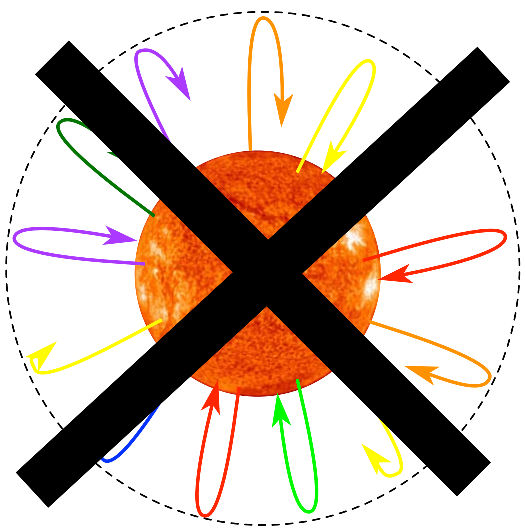

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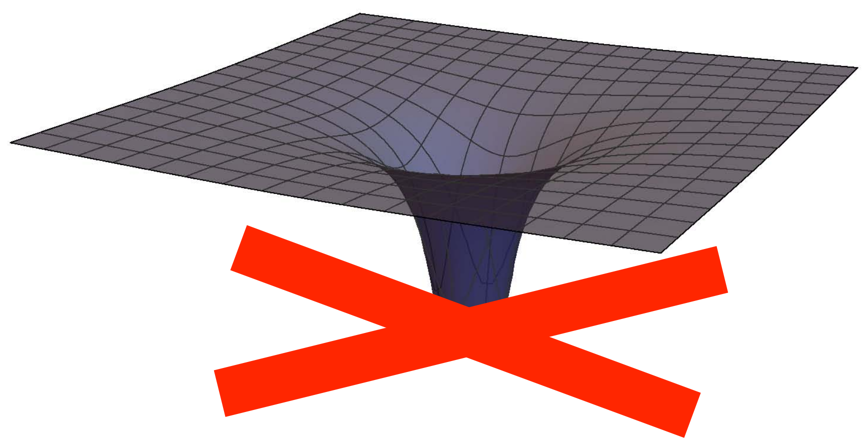

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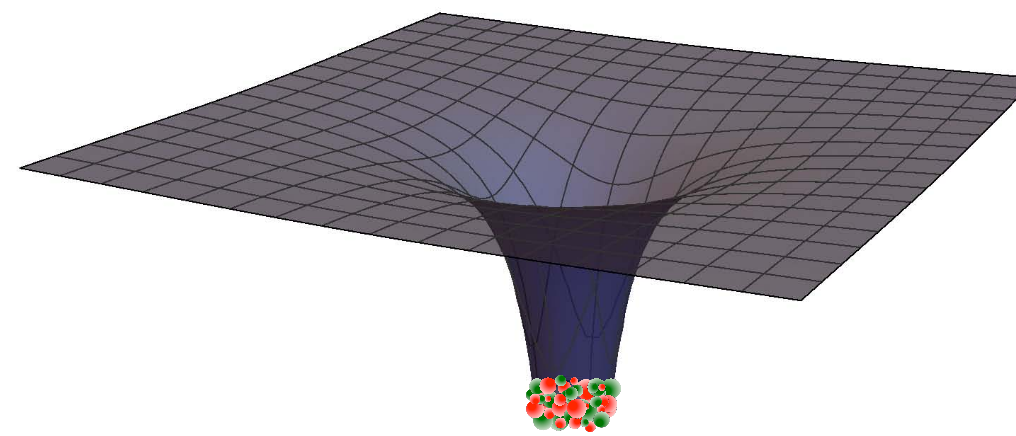

The issue for the present and new generations of theoretical physicists: Can string theory ultimately reconcile gravity and quantum mechanics?

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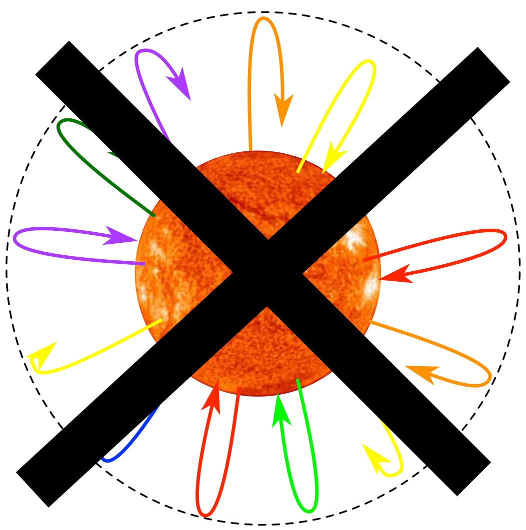

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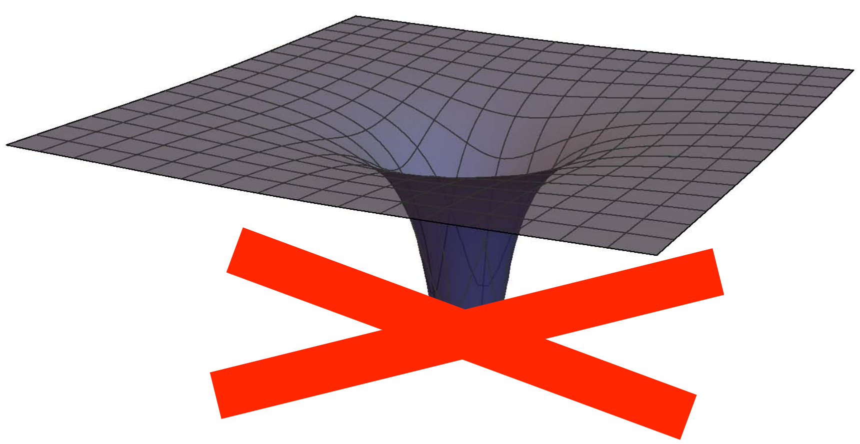

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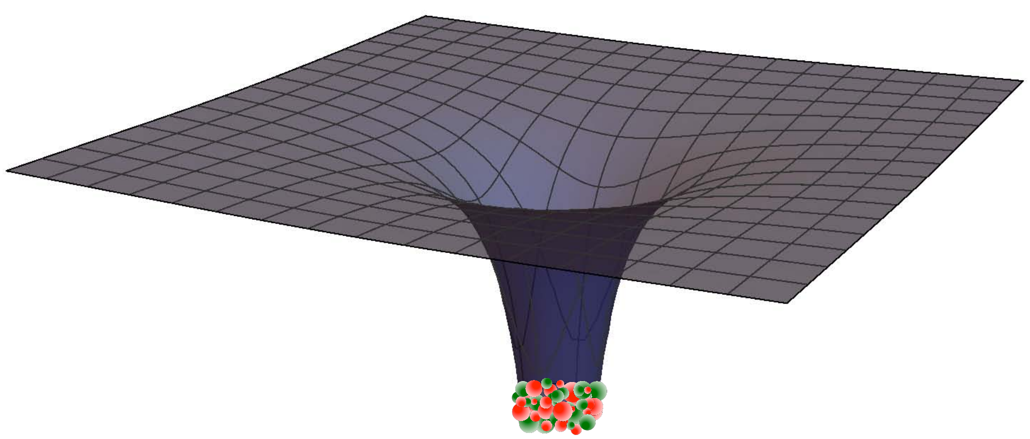

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(or something else)

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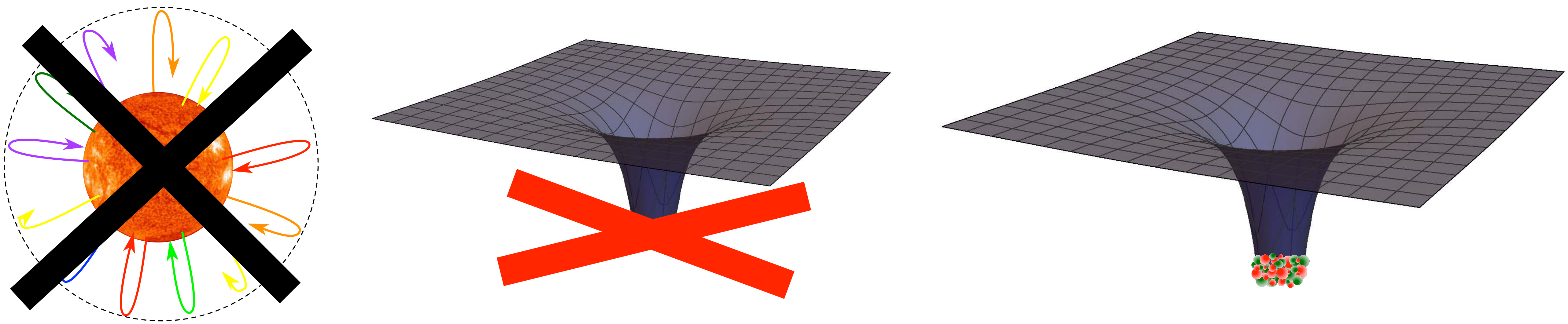
Michell | Schwarzschild | Black holes in string theory



The issue for the present and new generations of theoretical physicists: Can string theory ultimately reconcile gravity and quantum mechanics?
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But we must always remember something a crucial fact about Nature:

The universe has many objects that, on very large scales, behave like the black holes of General Relativity…

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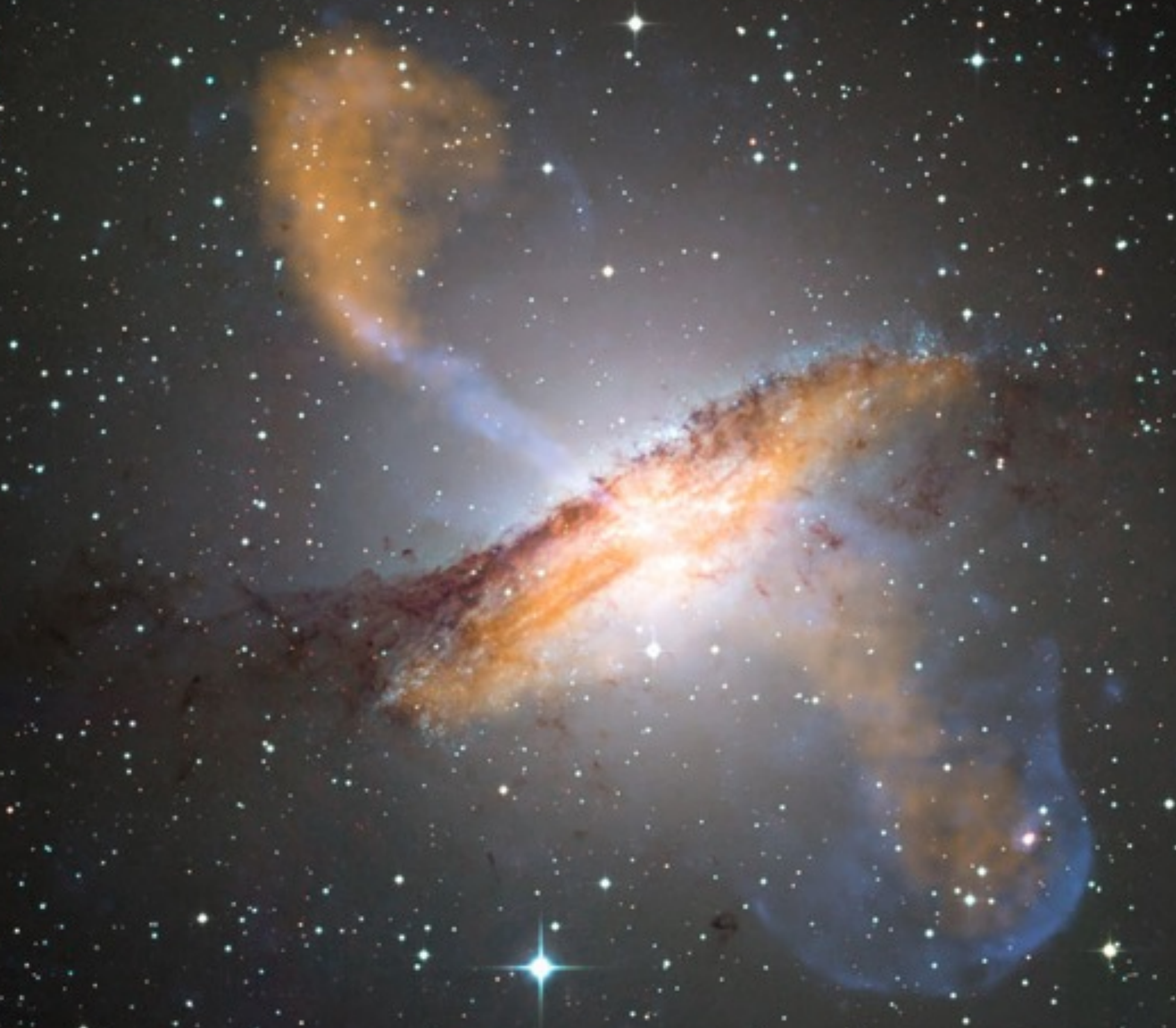

Through the study of black holes, we have begun to find ways in which we might resolve the conflicts between quantum mechanics and general relativity …

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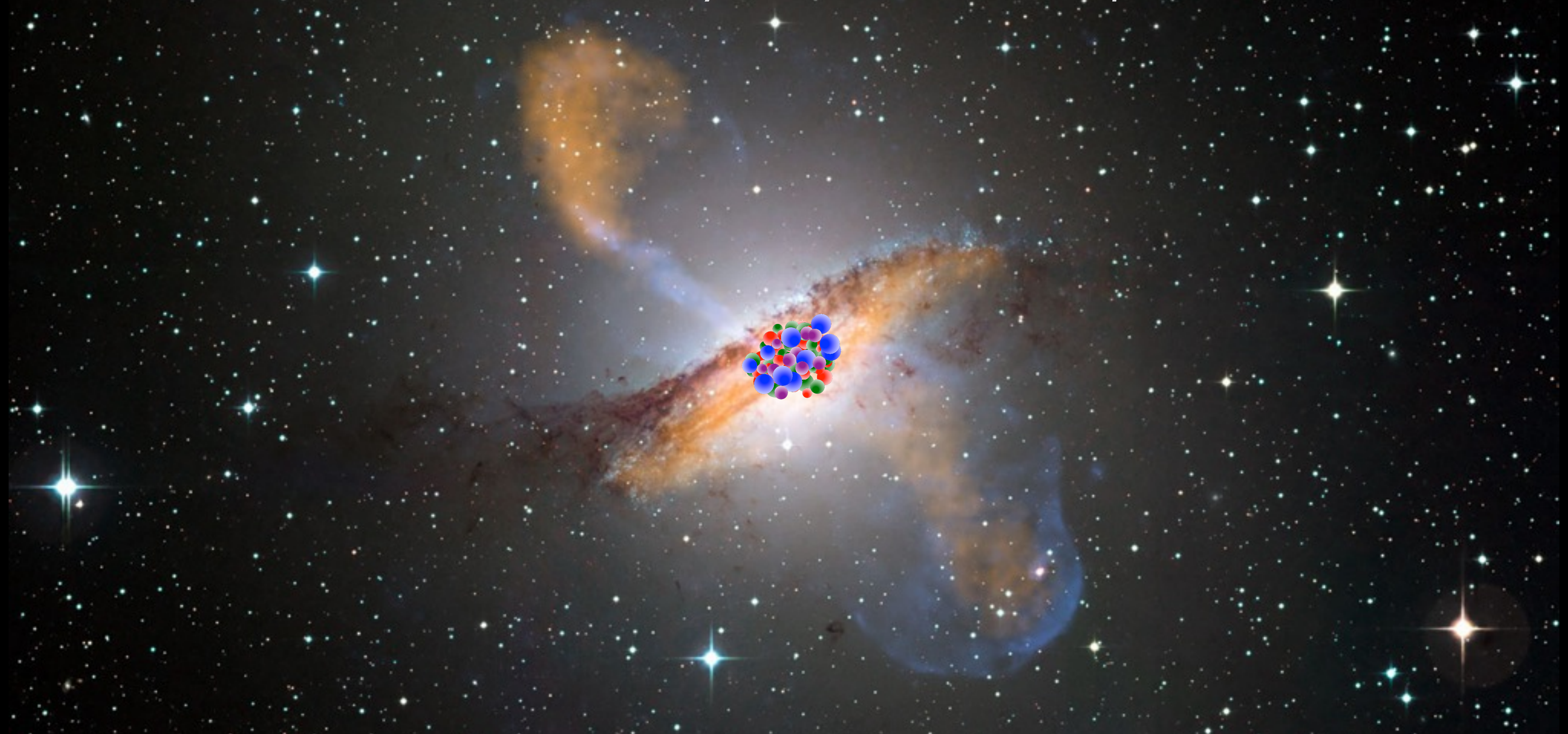

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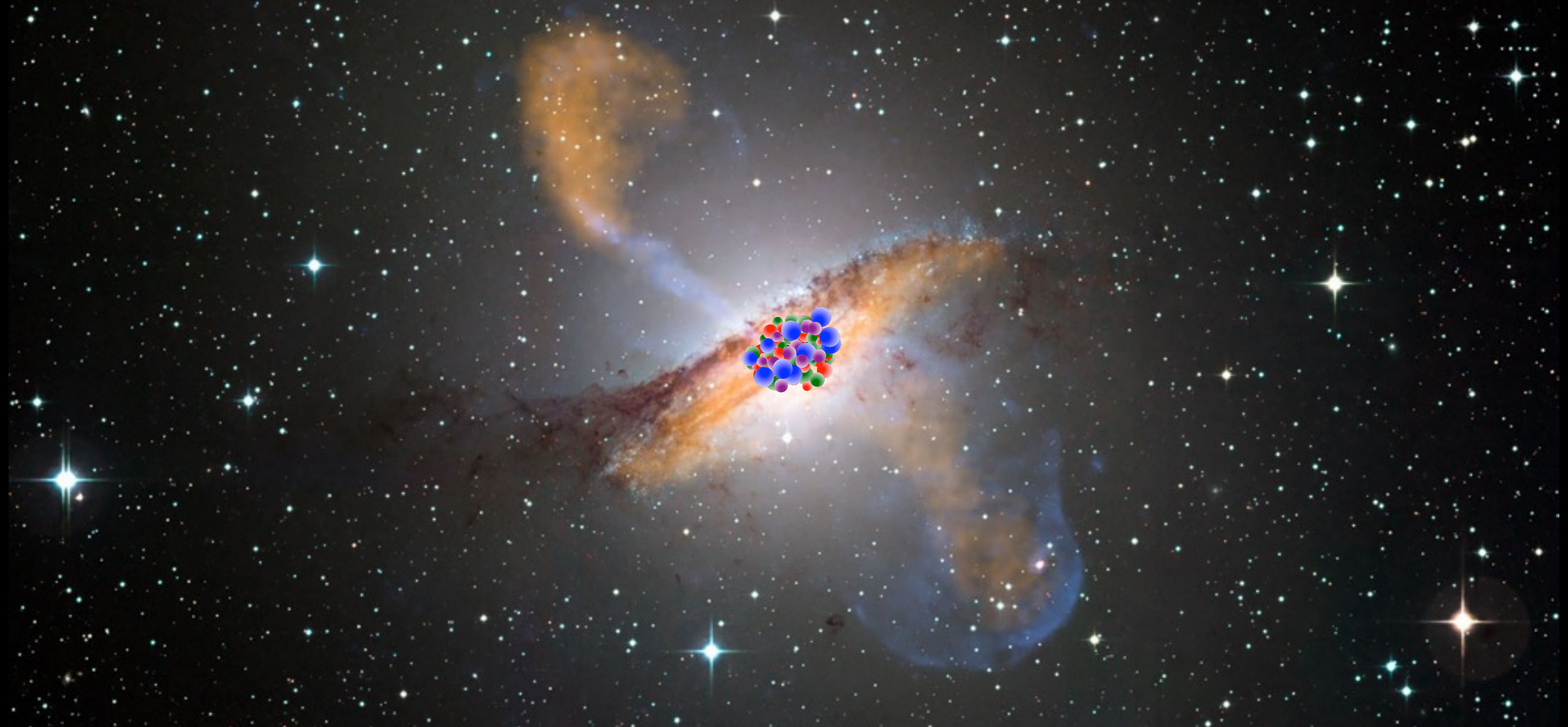

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….. Professor Shigemori's talk