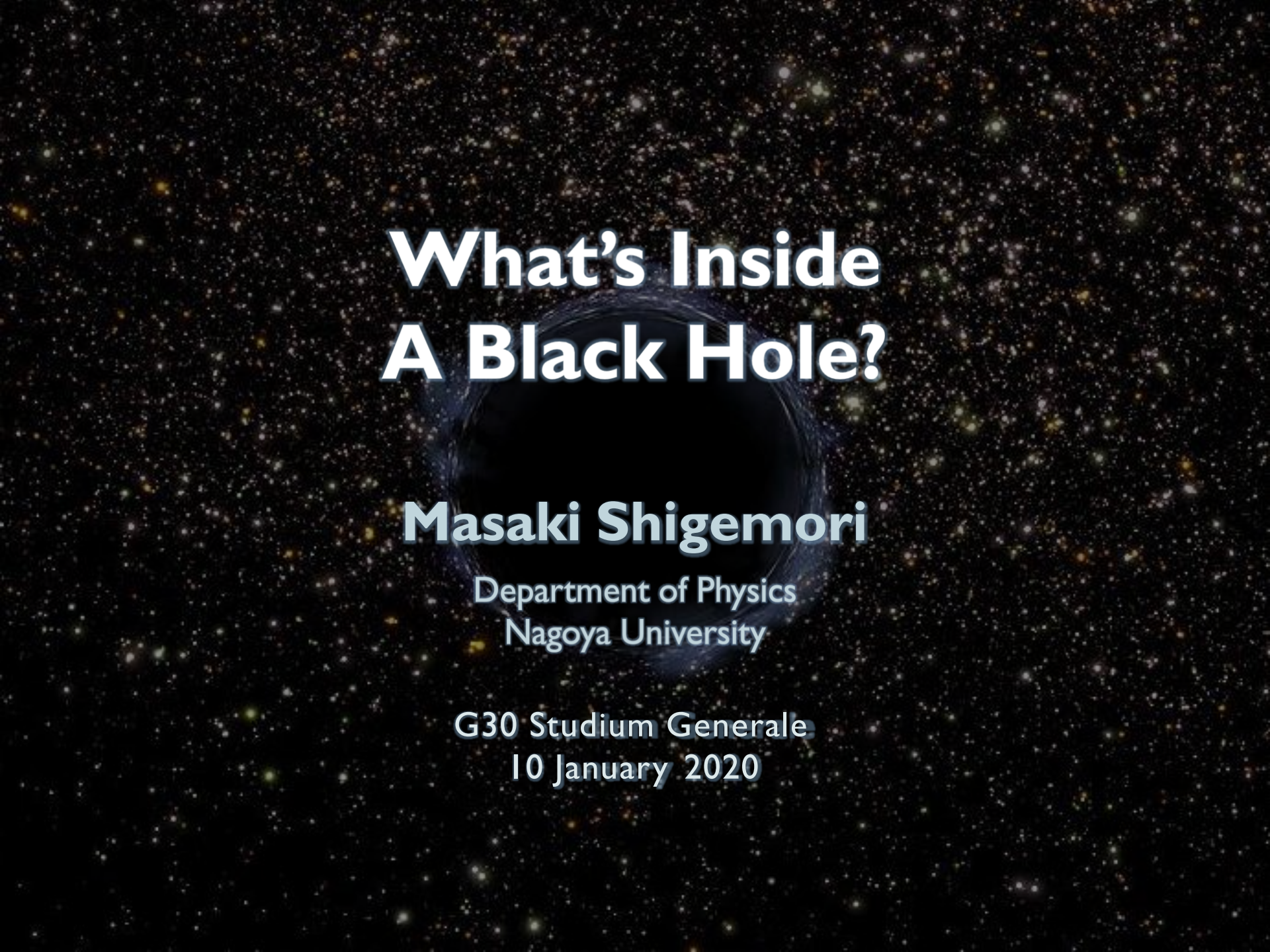


What's Inside A Black Hole?

Masaki Shigemori

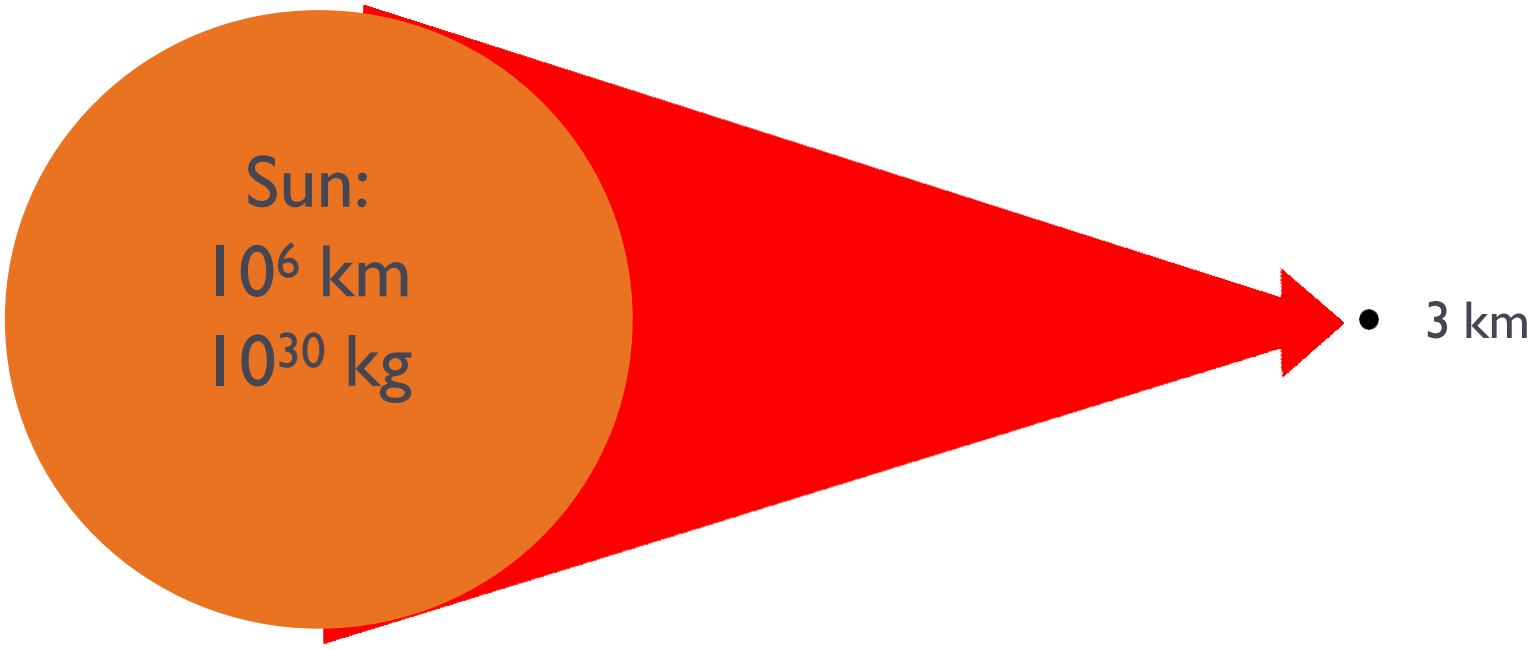
Department of Physics
Nagoya University

G30 Studium Generale
10 January 2020

What Is A Black Hole?

What is a black hole?

What one gets by compressing matter as much as possible



Escape velocity

Minimum velocity for an object to escape a star's gravity

Earth: $v = 11\ \mathrm{km/s}\ (\sim 40{,}000\ \mathrm{km/h})$

Sun: $v = 620\ \mathrm{km/s}\ (\sim 2{,}000{,}000\ \mathrm{km/h})$

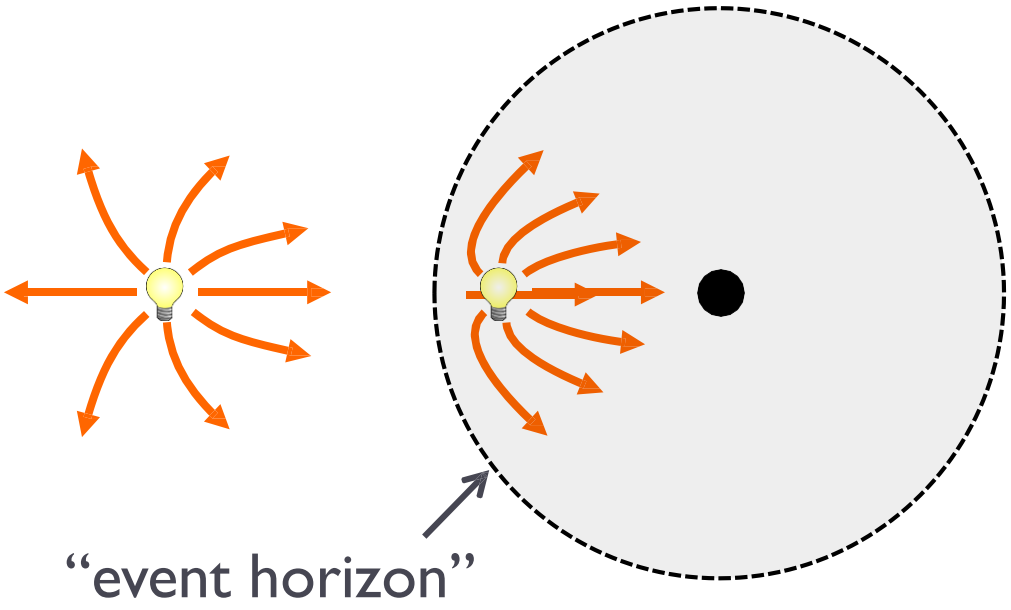
- Heavier star → v: larger
- More compact star → v: larger

Extremely heavy and compact star

→ v is larger than speed of light

→ Nothing can escape

Black hole



What's inside: collapsed star?

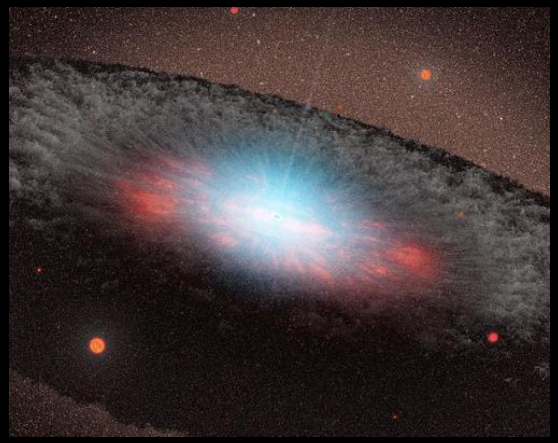
Black holes in the sky

- **Stellar black holes**

Figure removed due to copyright restrictions.

A few solar masses. Radius ~10 km

- **Supermassive black holes**



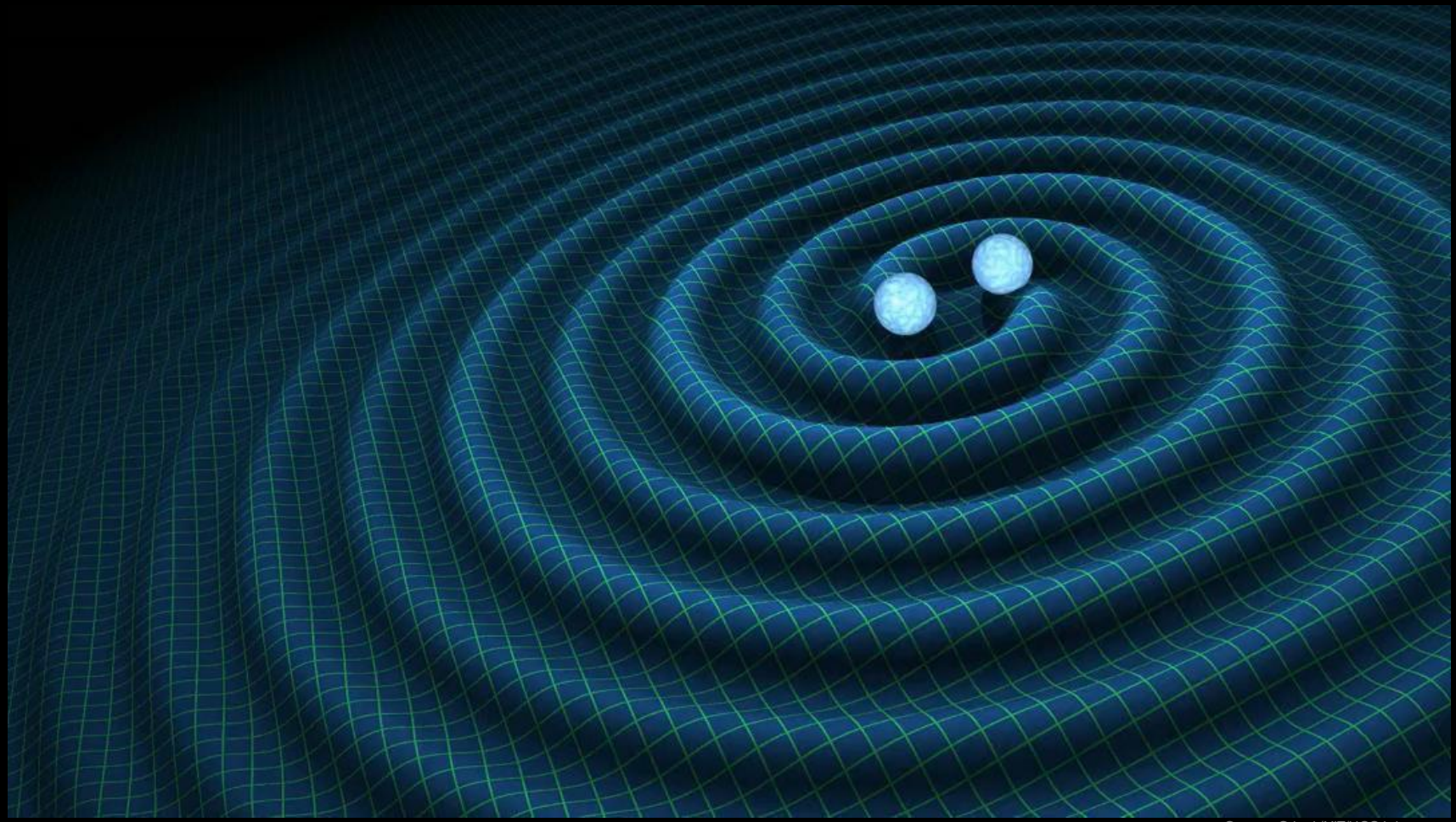
Millions of solar masses.

Radius:
can be larger than Pluto's orbit

https://ja.wikipedia.org/wiki/%E3%83%95%E3%82%A1%E3%82%A4%E3%83%AB:Supermassiveblackhole_nasajpl.jpg 2020/02/13

How do we observe a black hole?

Gravitational waves



Courtesy Caltech/MIT/LIGO Laboratory

Gravitational wave detectors

LIGO Hanford, USA

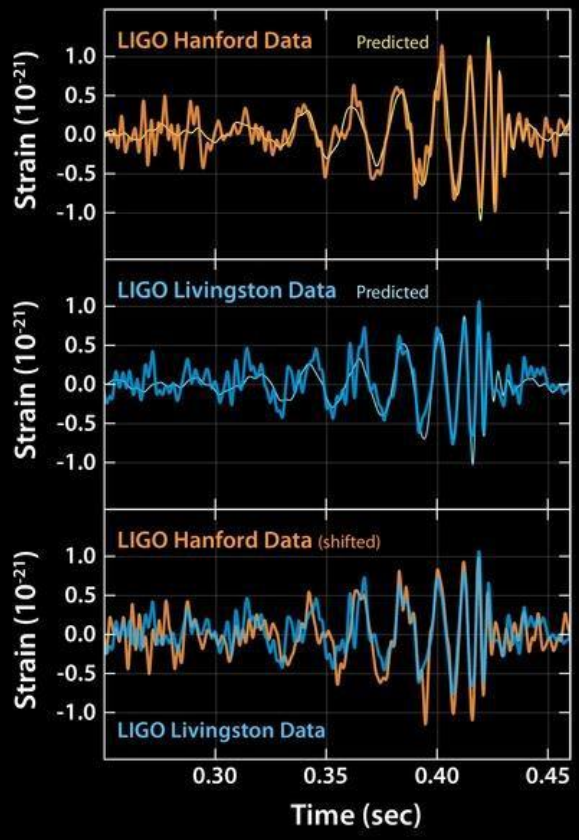
VIRGO, Italy

- Detects tiny distortion of spacetime (1/1000 of proton radius) when gravitational waves reach the earth.

First detection of grav. waves

September 14, 2015

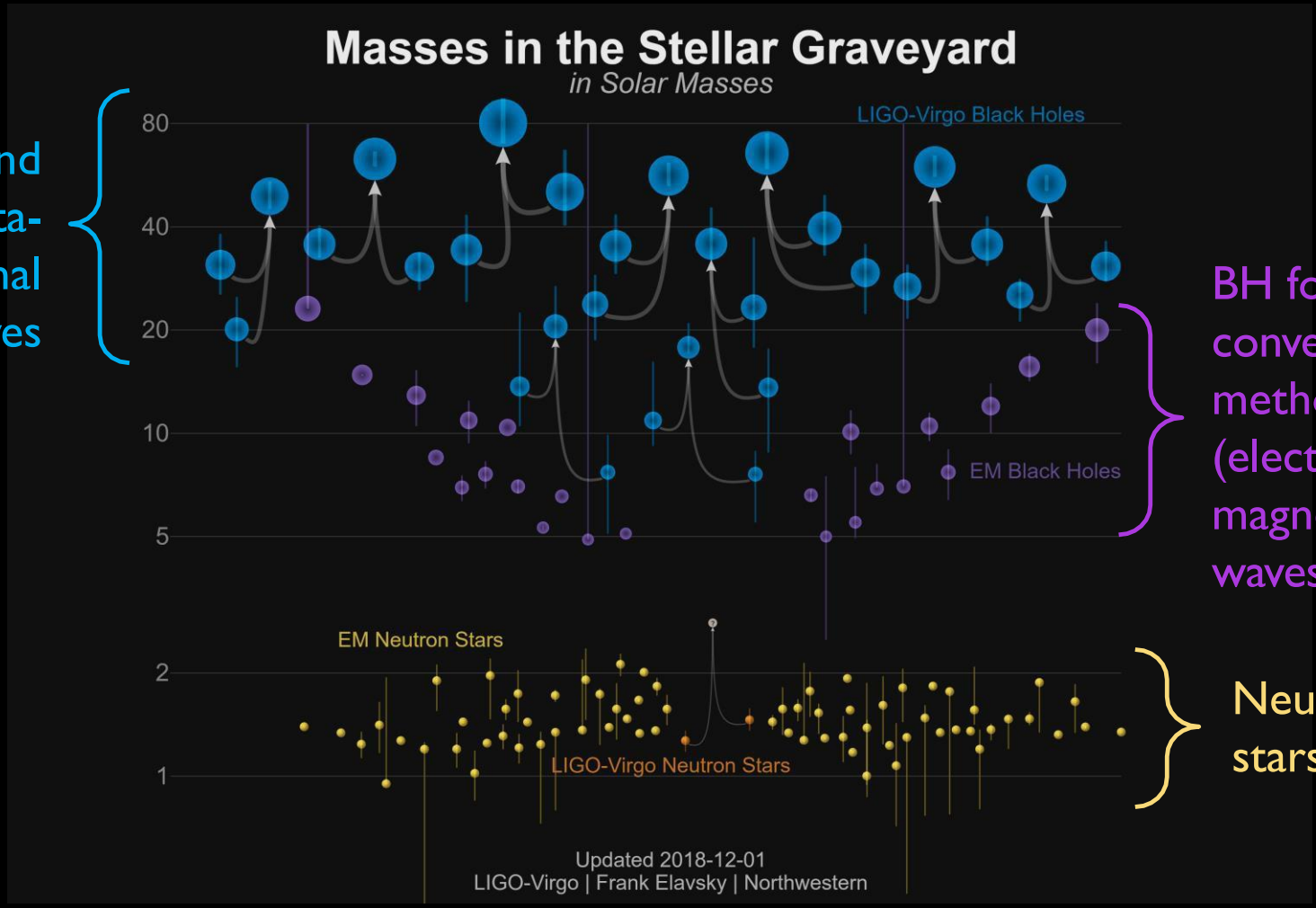
- Merger of binary black holes
- 2017 Nobel prize



LIGO

Current status of GW observation

BHs found by gravita-tional waves



BH found by conventional method (electro-magnetic waves)

Neutron stars

https://media.ligo.northwestern.edu/

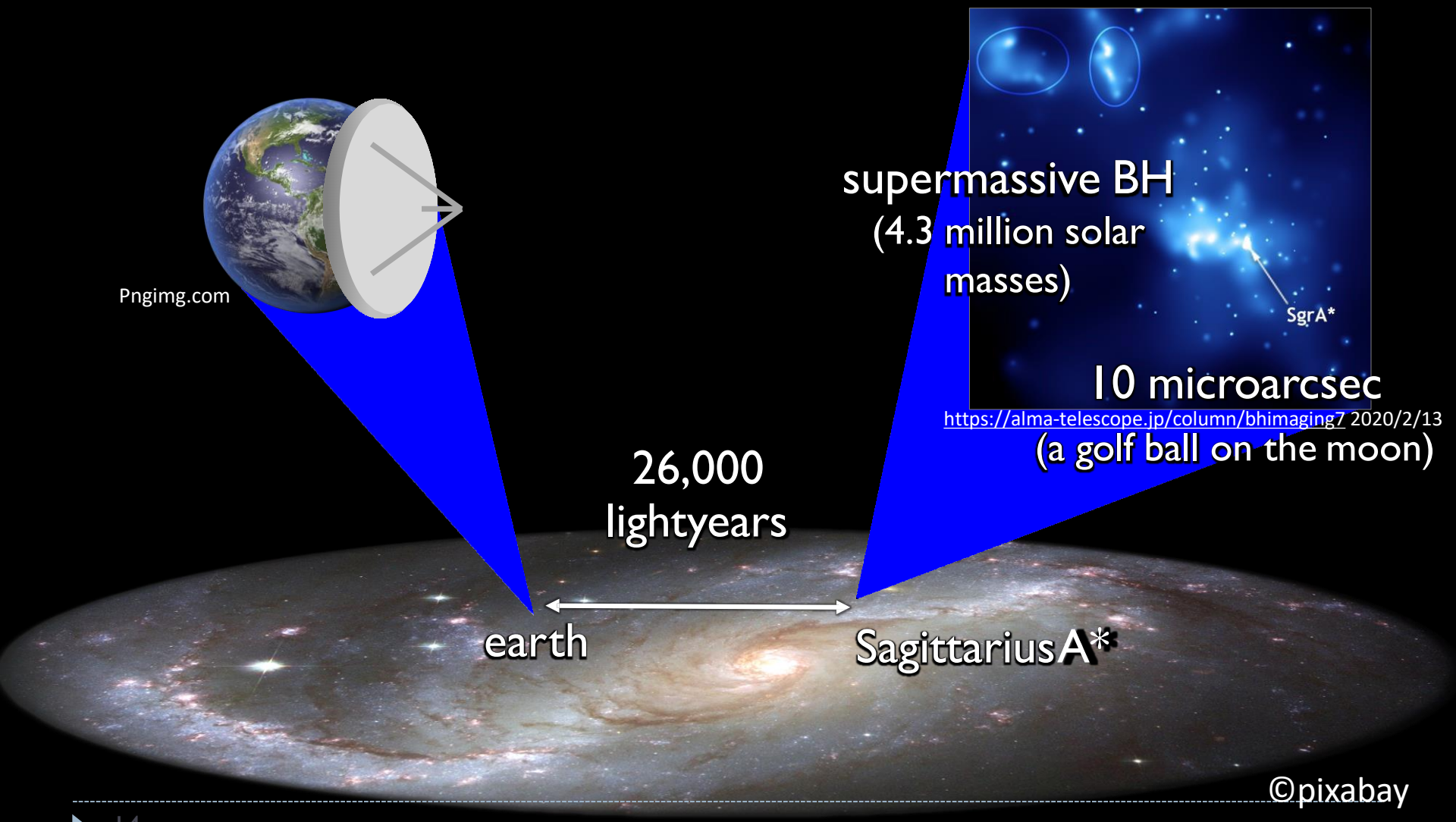
“Event Horizon Telescope”

- Observe BHs with an earth-sized radio telescope

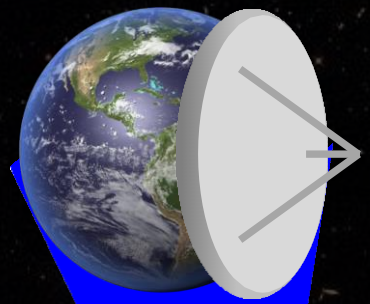
EHT network

https://twitter.com/thenrao/status/940237297697677312

BH at the center of Milky Way Galaxy



BH at the center of M87



supermassive BH
(6.5 billion solar masses)

earth

55 million
lightyears

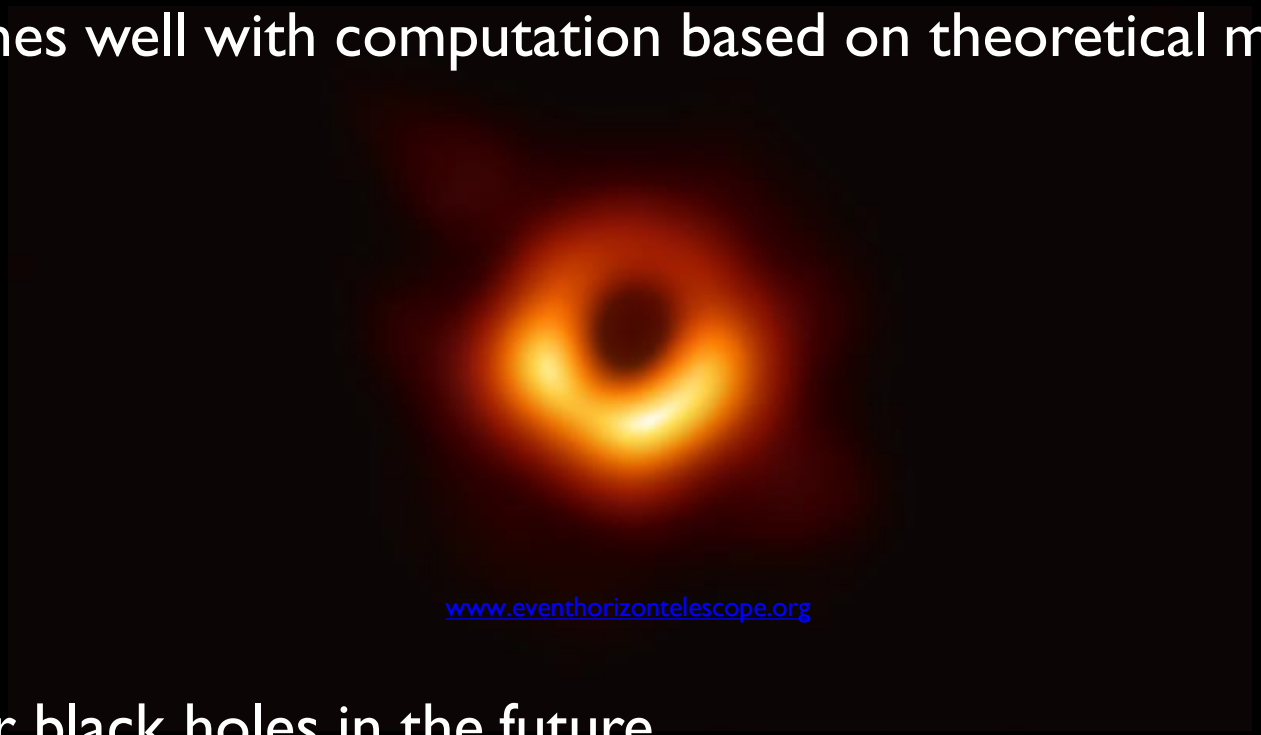
Figure removed due to copyright restrictions

Supergiant elliptic
galaxy M87

Image of the BH in M87

April 10, 2019

- The first direct image of a BH
- Matches well with computation based on theoretical model

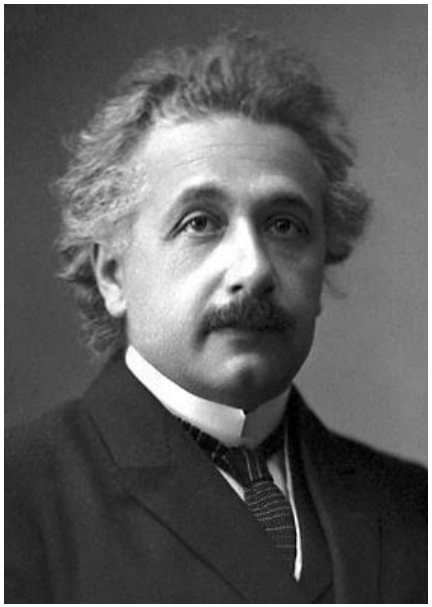


www.eventhorizontelescope.org

- Other black holes in the future

Spacetime and Black Holes

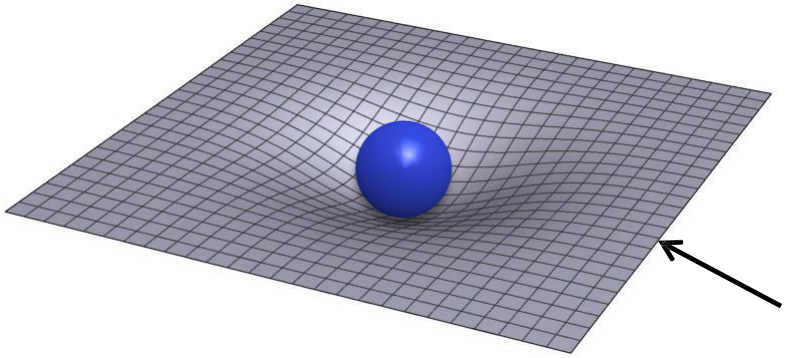
Einstein's "general relativity"



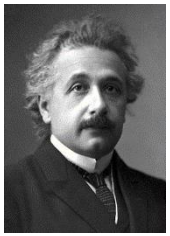
Albert Einstein

https://listas.20minutos.es/lista/personajes-famosos-de-la-astronomia-95863/2020/2/13

Not only matter but its container – *spacetime* – is also a physical object. It does stuff like move, bend,etc.

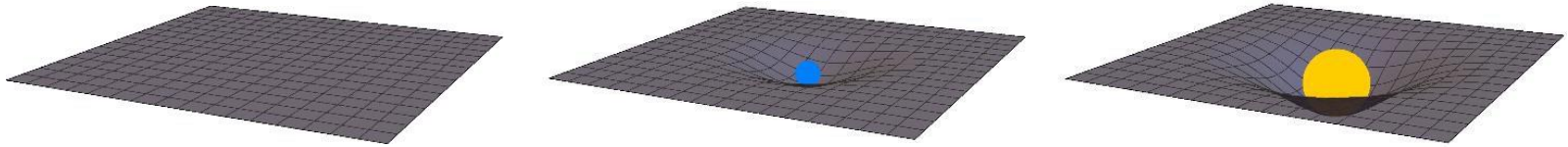


"spacetime"

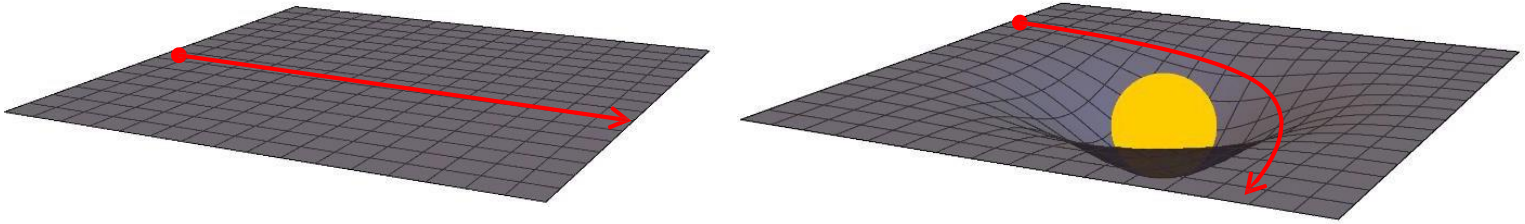


Matter bends spacetime. Conversely, bent spacetime affects the motion of matter inside it.

https://listas.20minutos.es/lista/personajes-famosos-de-la-astronomia-95863/2019/2/13



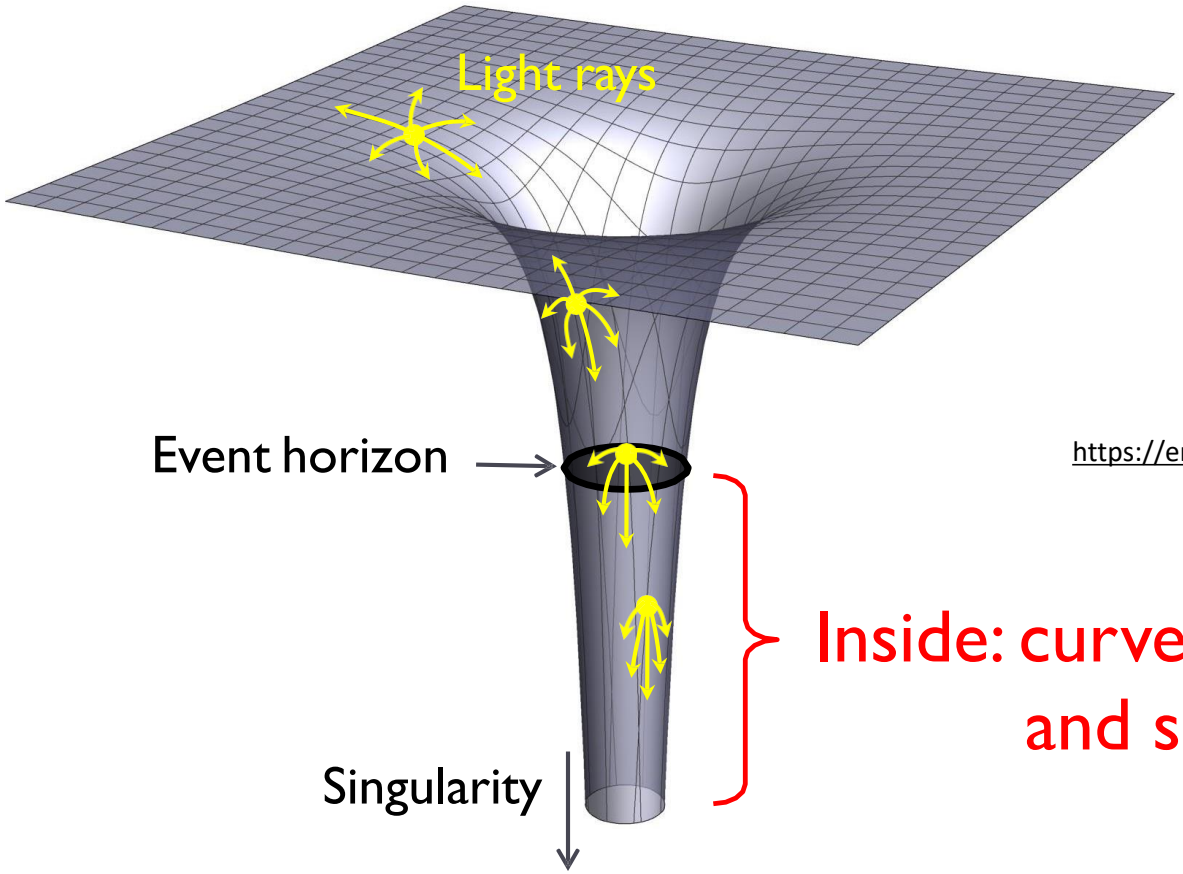
A heavy object bends spacetime around it



Bent spacetime affects motion of matter in it

Black holes in general relativity

Extremely curved spacetime



Inside: curved spacetime and singularity

Karl Schwarzschild

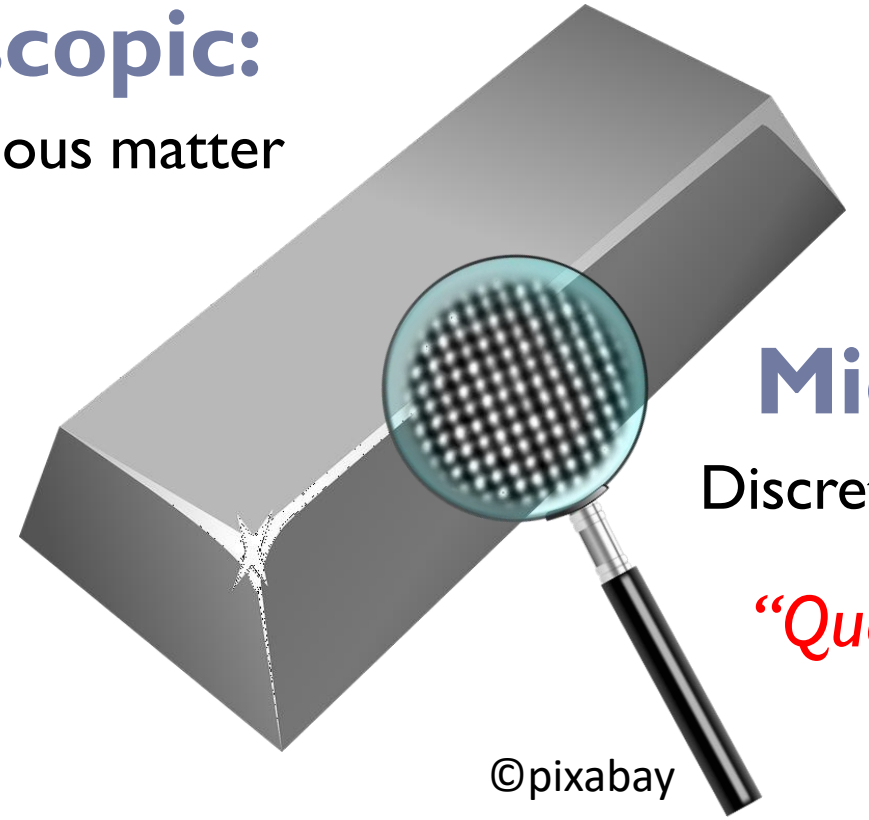
https://en.wikipedia.org/wiki/Karl_Schwarzschild 2020/2/13

Microphysics of Black Holes

Macroscopic vs microscopic

Macroscopic:

Continuous matter



©pixabay

Microscopic:

Discrete structure (atoms)

"Quantum mechanics"

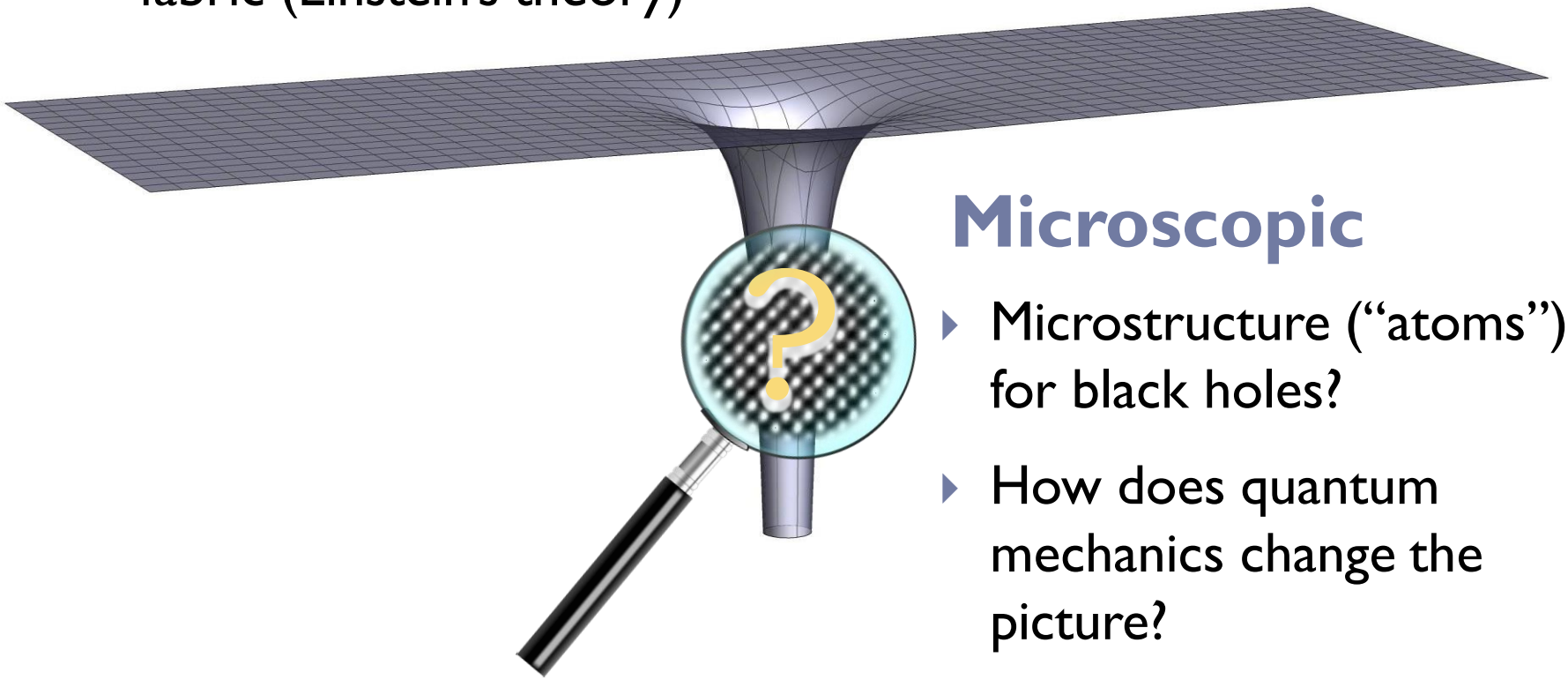
Niels Bohr

https://ja.wikipedia.org/wiki/%E3%83%8B%E3%83%BC%E3%83%AB%E3%82%B9%E3%83%BB%E3%83%9C%E3%83%BC%E3%82%A2 2020/2/13

Macro vs. micro for black holes

Macroscopic

- Smooth configuration of spacetime fabric (Einstein's theory)

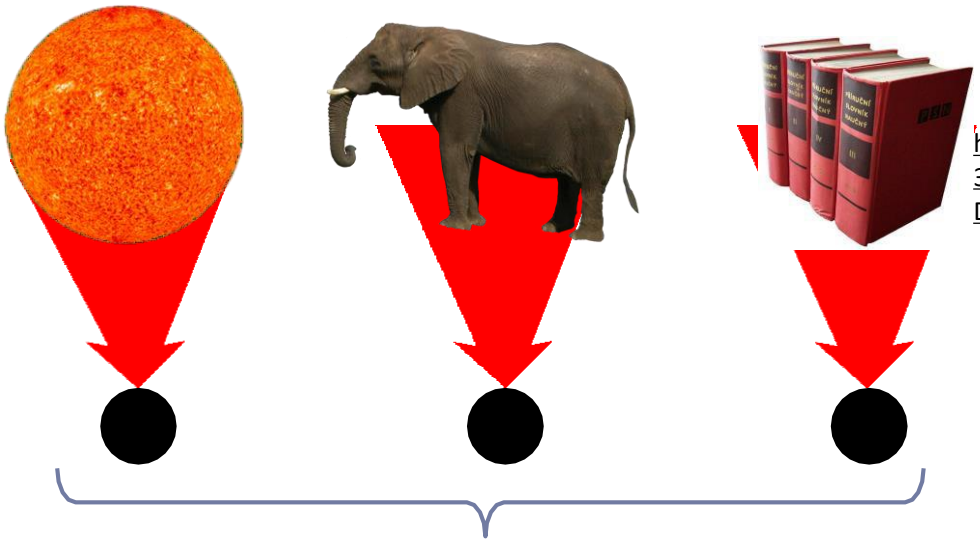


Microscopic

- Microstructure ("atoms") for black holes?
- How does quantum mechanics change the picture?

What does Einstein's theory miss?

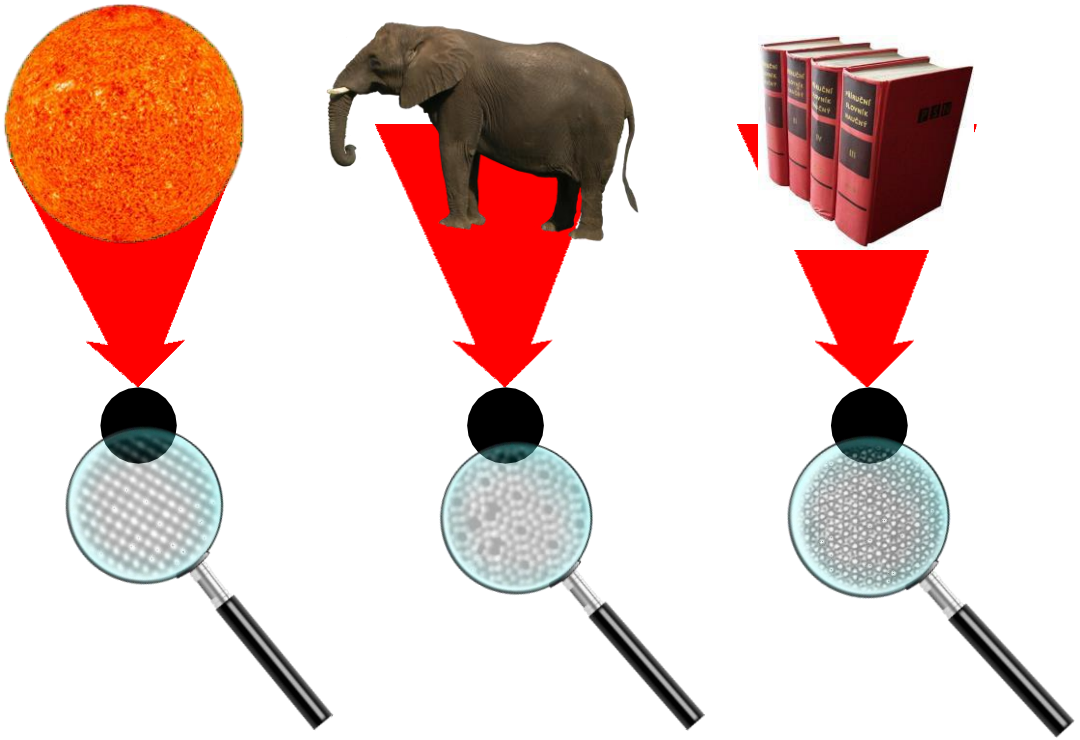
No matter what you make a black hole from…



http://en.wikibedia.ru/wiki/P%C5%99%C3%ADru%C4%8Dn%C3%AD_slovn%C3%ADk_nau%C4%8Dn%C3%BD 2020/2/13

All look identical… Information lost?

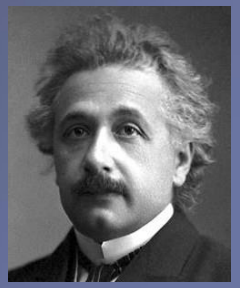
But according to quantum mechanics, information can *never* be lost



- Information must be stored in black holes in some microscopic structure
- Need to go beyond Einstein's theory

To understand the microscopic physics of black holes,
we need to unify:

Quantum gravity



General Relativity

Quantum Mechanics

Most promising candidate:
superstring theory

Superstring theory

What is superstring theory?

What if the fundamental element of Nature is not a point particle but a tiny vibrating“string”?

$\sim 0.000000000000000000000000000000001\,\text{m}$

$(10^{-35}\ \text{m})$

Too small to be observed with our current technology

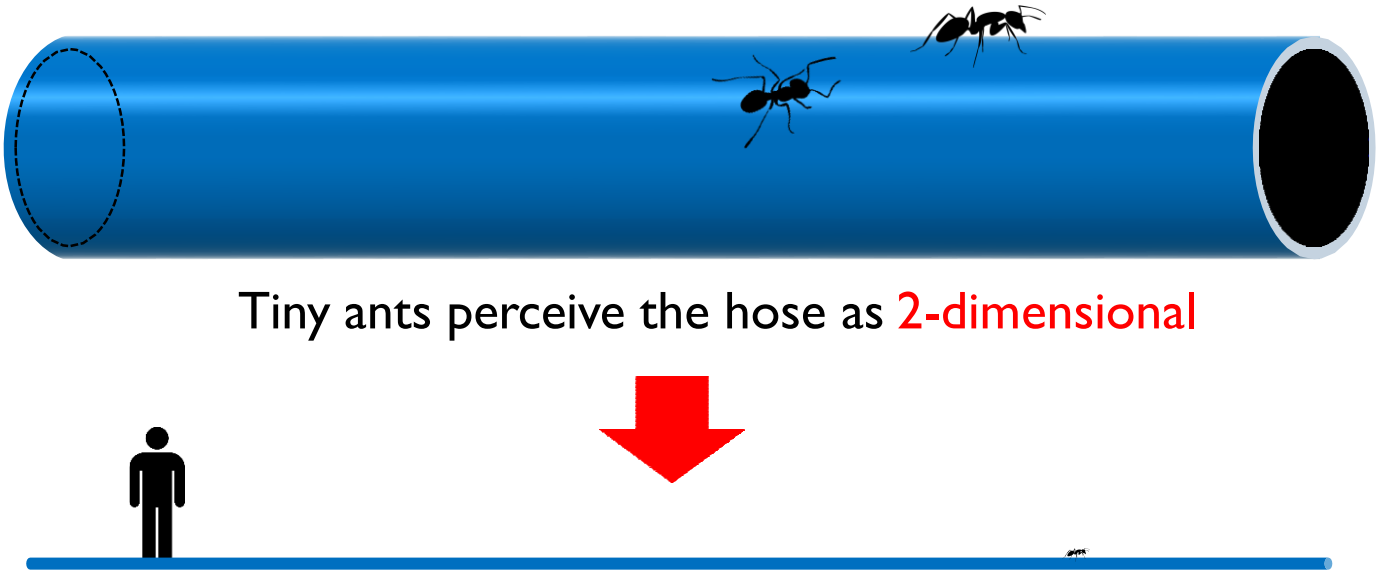
Superstring theory

- First developed in late 1960's
- Found to be a theory of quantum gravity in 1980's
- Studied very actively even now as the most promising candidate for a theory to unify all forces in Nature
- Surprising predictions

Prediction 1: extra dimensions

- Spacetime is not 4-dimensional but 10-dimensional. Extra 6 are "compactified" and invisible.

What is compactification?



Tiny ants perceive the hose as 2-dimensional

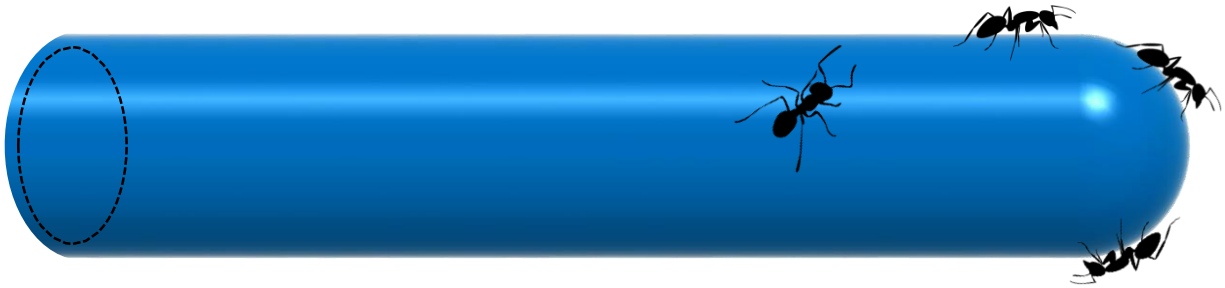
At large scale, it looks like 1-dimensional

Likewise, in our universe, 6 among 10 dimensions are very small and compactified

Extra 6 dimensions. Too small to be observed.

4 dimensions we can perceive

What are extra dimensions good for?



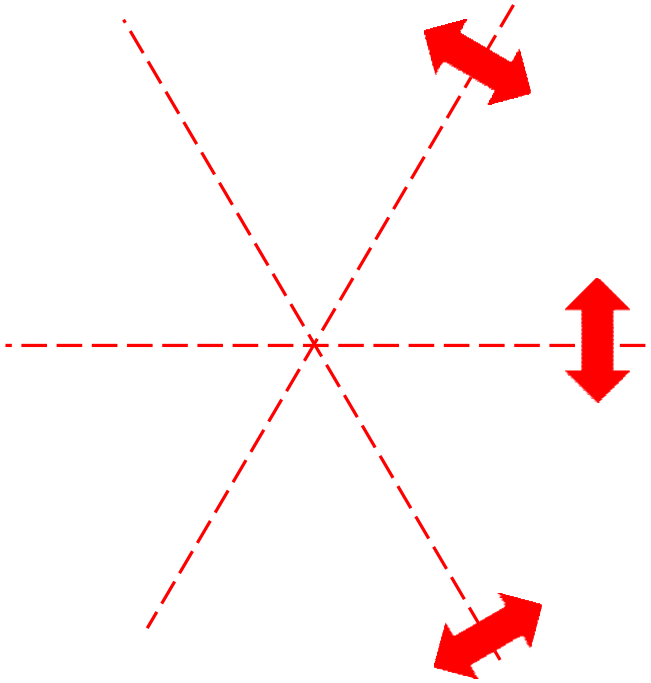
Smooth in higher dimensions

Appears singular in lower dimensions

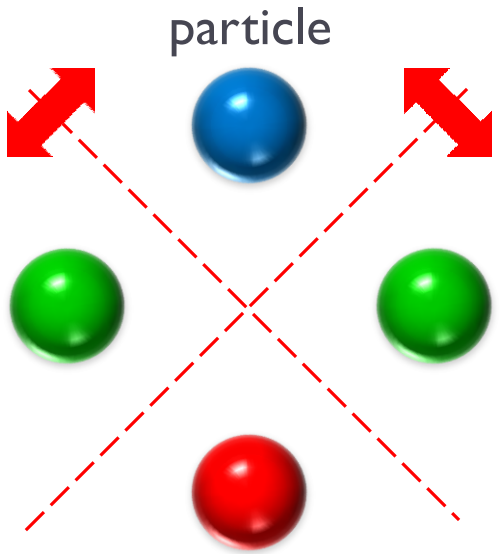
- Conversely, singular spacetimes not allowed in lower dimensions are allowed in higher dimensions.
- Room to store "what the black hole is made from" in higher dimensions.

Prediction 2: supersymmetry

Symmetry of snow flake



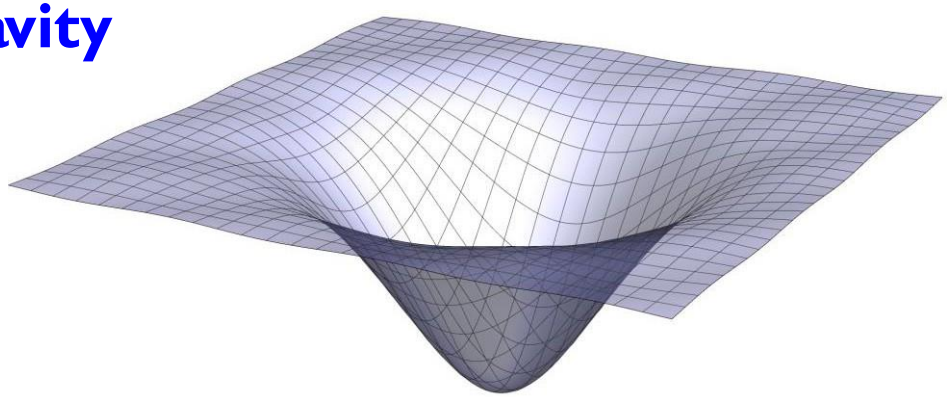
Supersymmetry



To each particle, there exist superpartners.

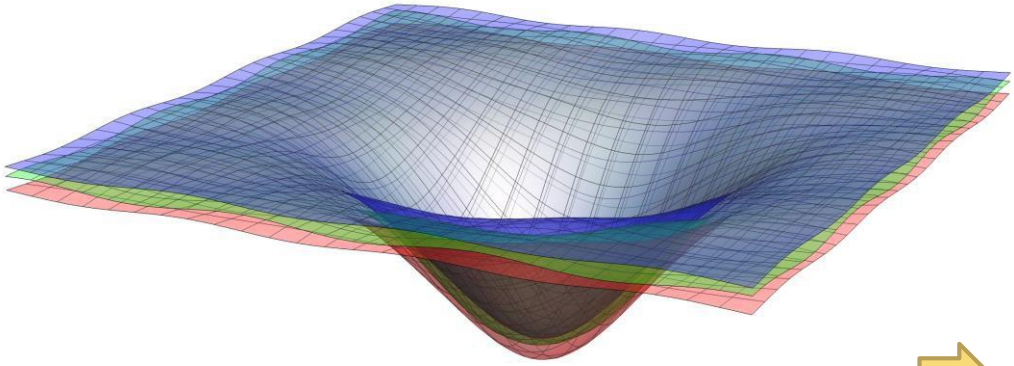
Gravity is extended to supergravity

Gravity



graviton

Supergravity



graviton

super partners

Richer physics, more room to store information

Superstring theory

Extra dimensions + supersymmetry

Rich structure to store more information

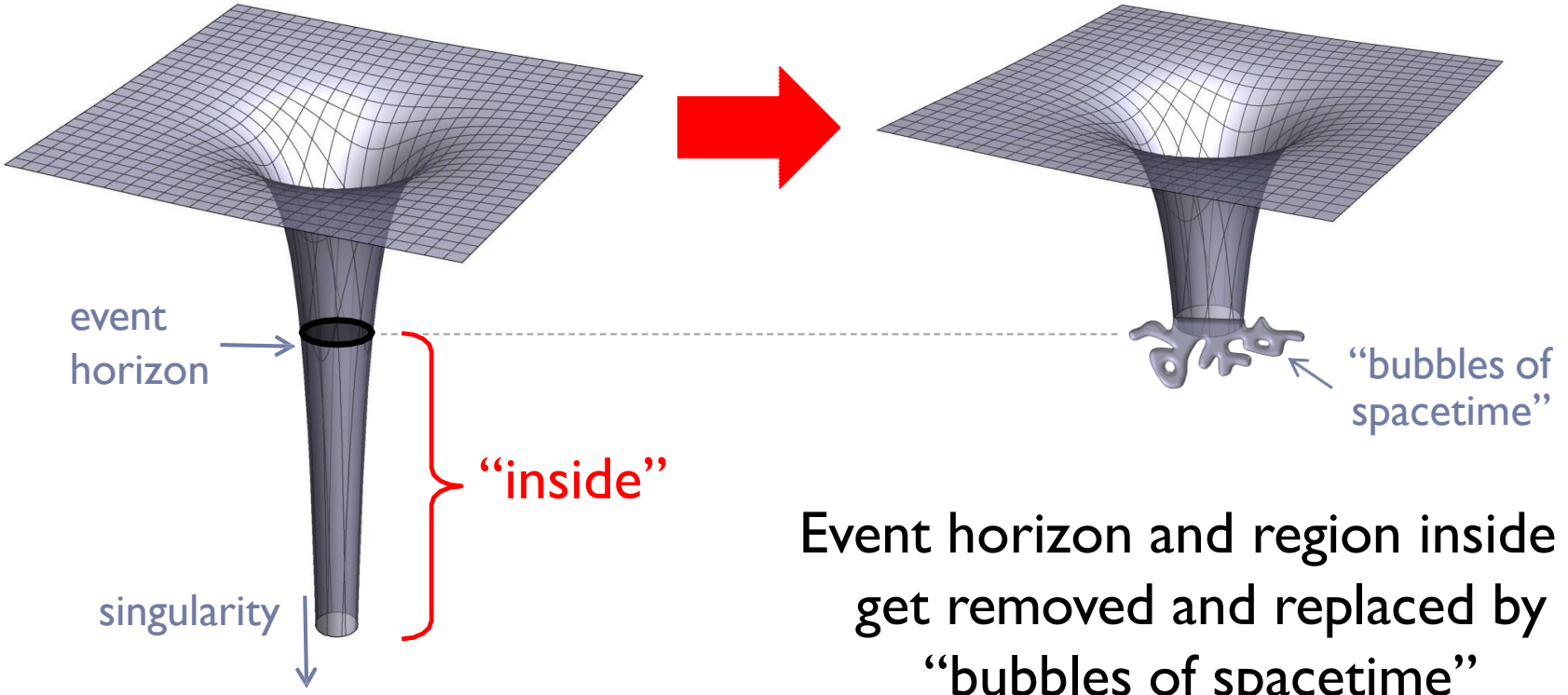
Suggests a novel picture of black holes totally different from the conventional one.

A new picture of black holes

New picture of black holes

Conventional picture

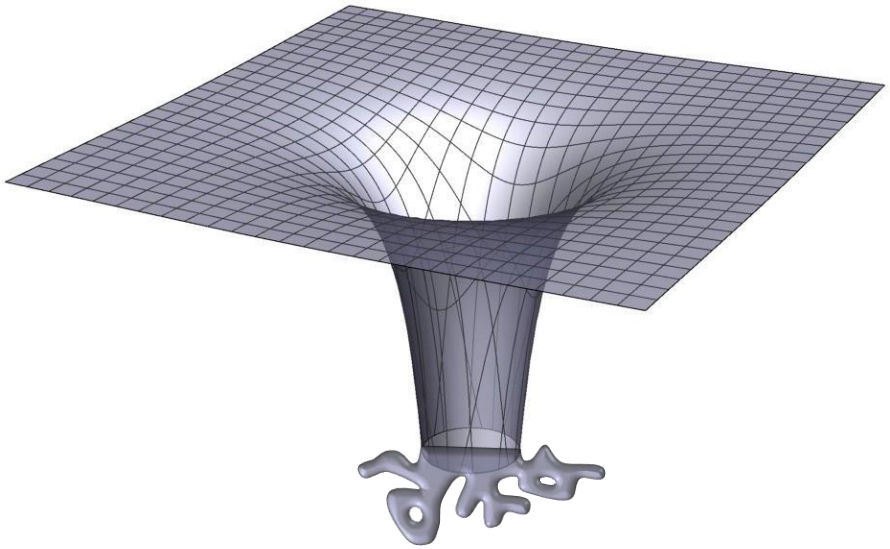
New picture



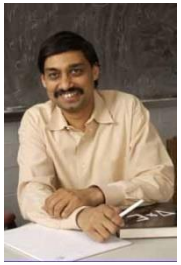
Event horizon and region inside it get removed and replaced by "bubbles of spacetime"

No "inside" in naïve sense

“Bubbles of spacetime”



- Smooth microstructure
- Possible in higher dimensions
- Stabilized by various excitations in supergravity
- Called “fuzzballs”

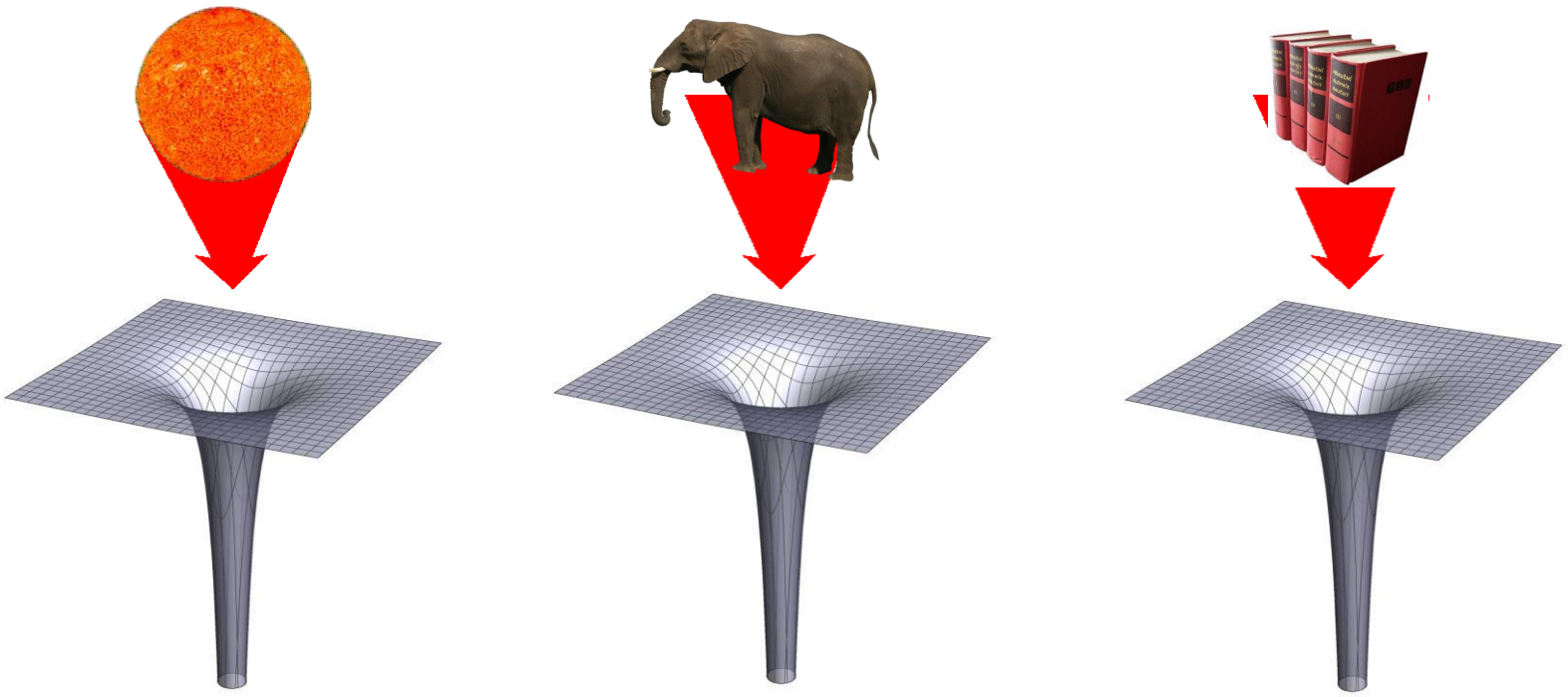


www.physics.ohio-state.edu

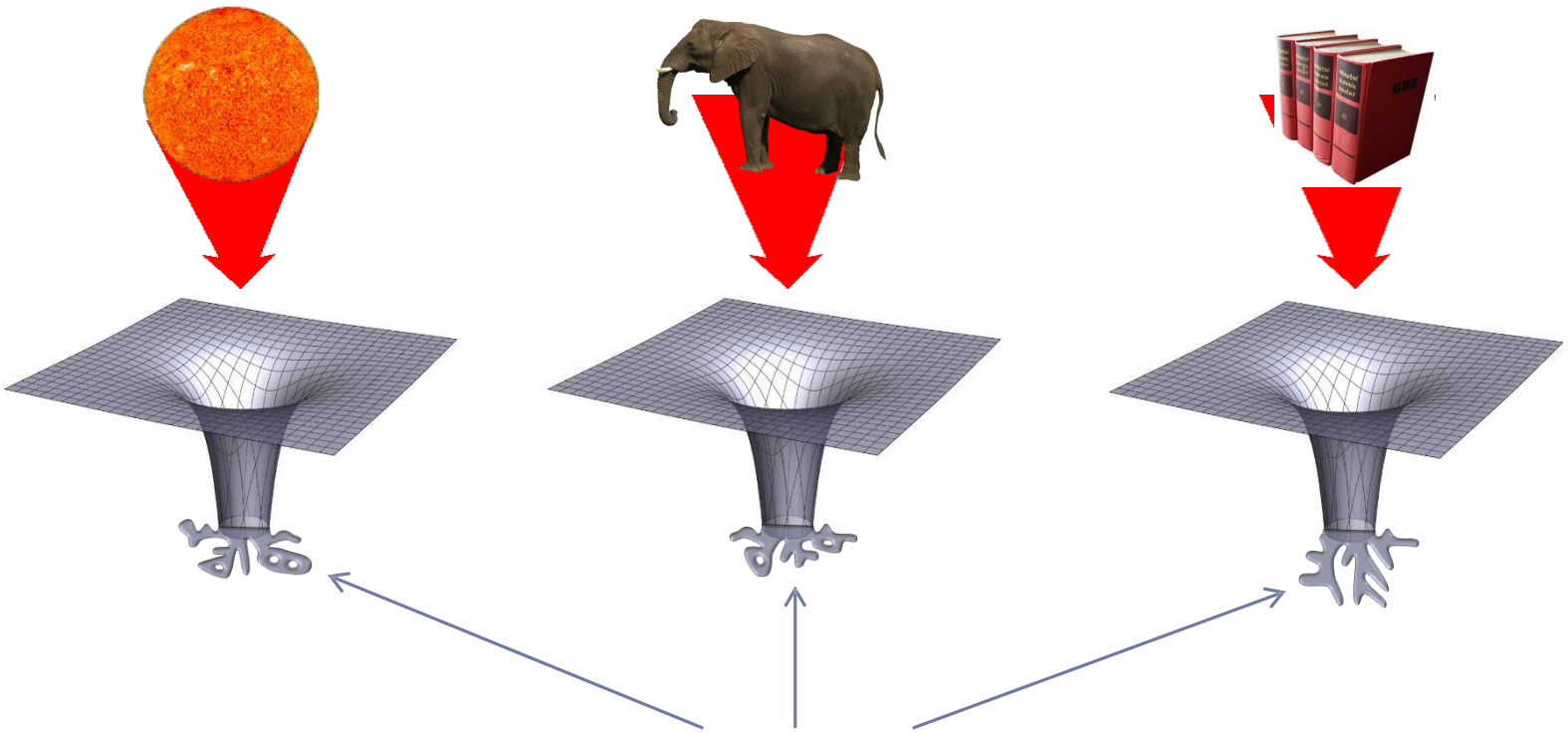
Samir D. Mathur

- Increasing evidence, but still conjectural

Information loss problem?



Information loss problem?

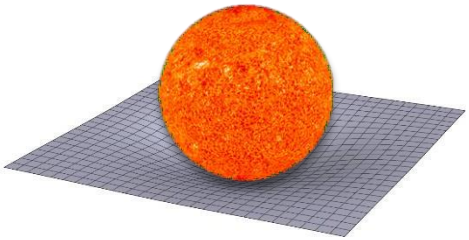


Different microstructure depending on what BH was made from

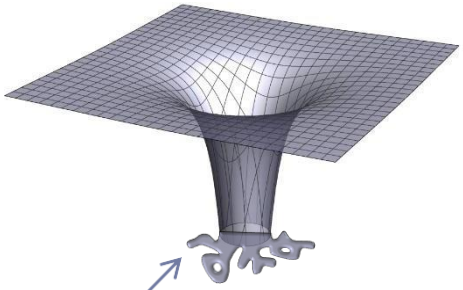
Information about what BH was made from is stored in fuzzballs and never lost

Life of a black hole (conjecture)

Star collapses

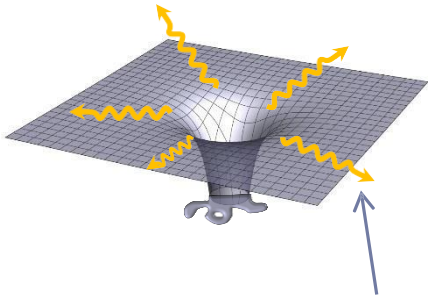


BH produced



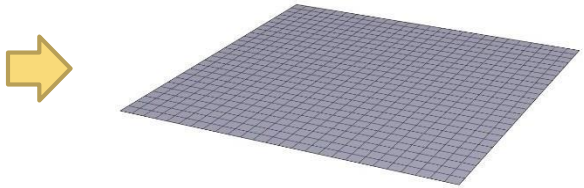
Information about original star stored in fuzzballs

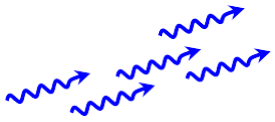
Becomes smaller by radiation



Radiation comes out of fuzzballs and thus contains information about original star

Evaporate & disappear





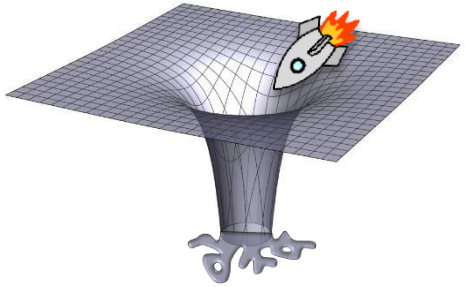
All information carried away in radiation

Can reconstruct the original star from the information in radiation.

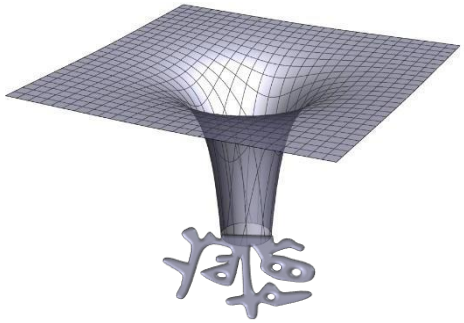
Just like burning a dictionary.

What happens if you fall into a BH?

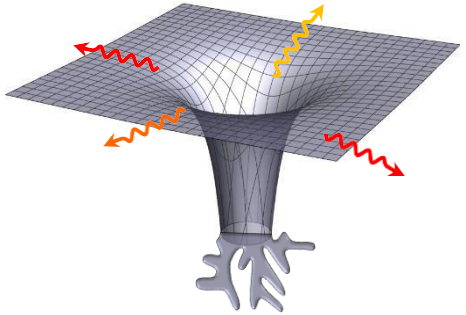
Spaceship falls into BH



Spaceship melts and becomes part of fuzzball

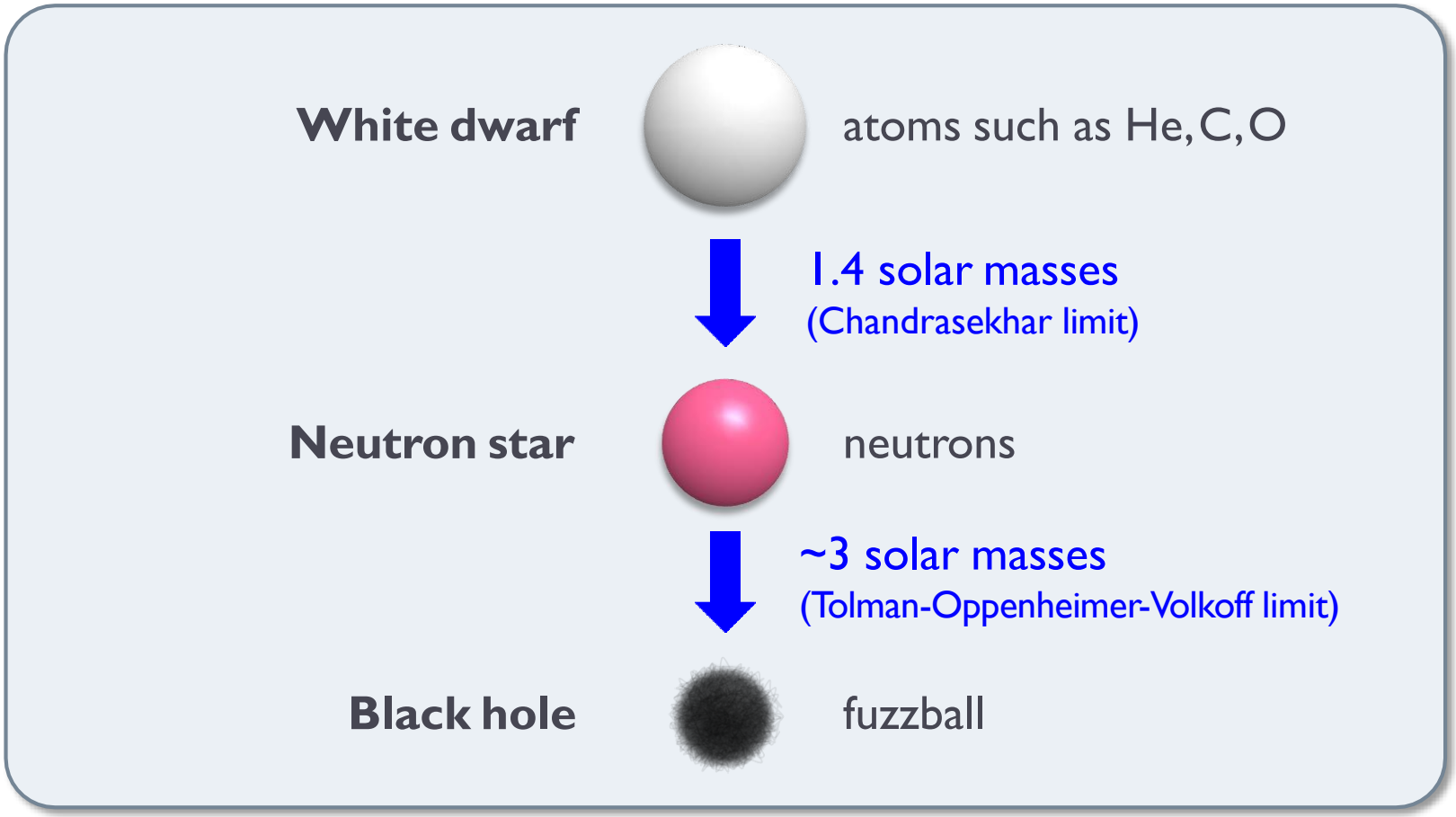


Comes back out as radiation



Can reconstruct information about spaceship from the radiation.

Matter takes various forms depending on mass

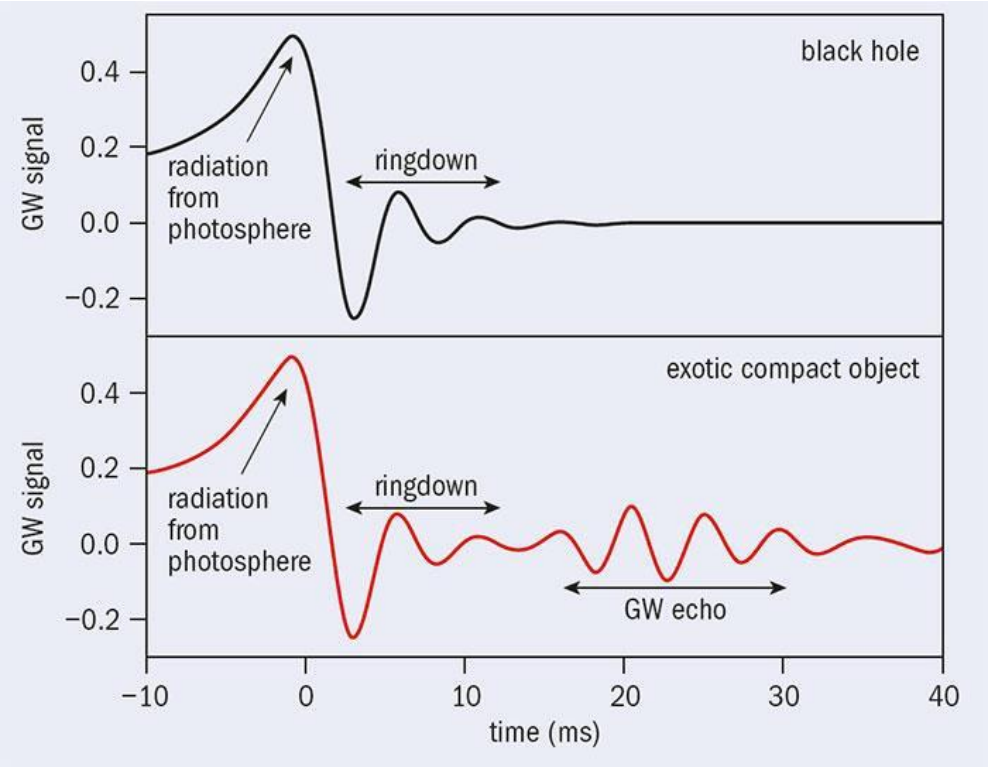


Above critical value, ordinary matter cannot support mass.
Spacetime "melts" into a new form of existence (fuzzball) to support it.

Can we observe fuzzballs?

Can we observe fuzzballs?

Gravitational wave echoes

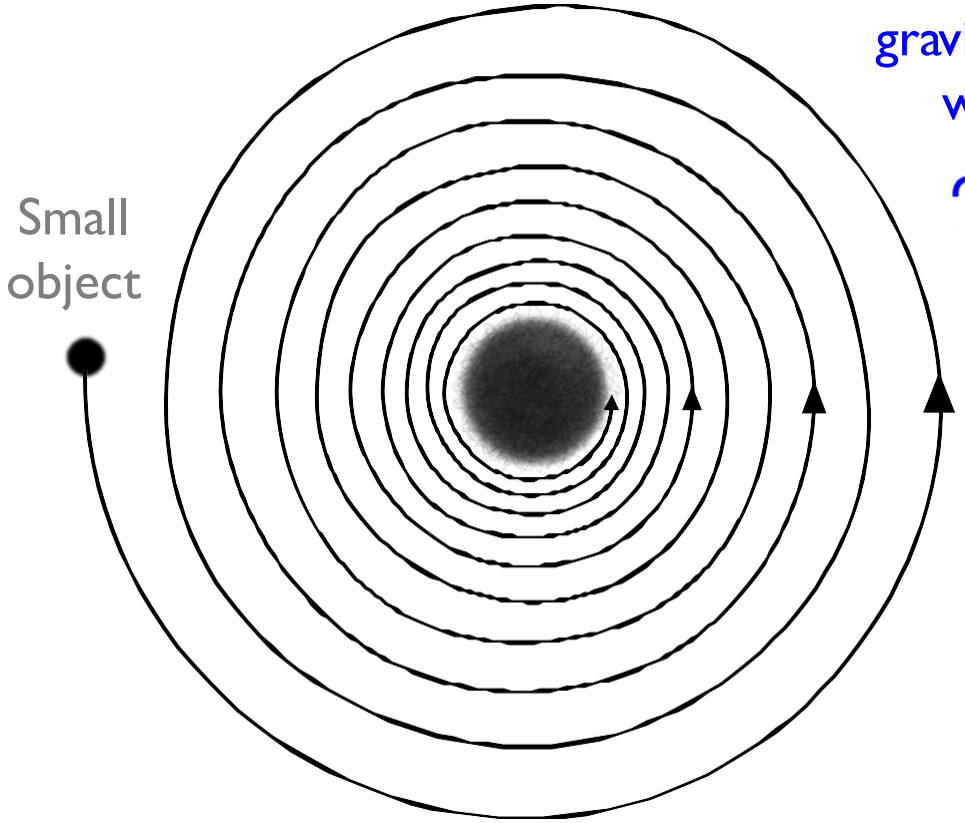


http://cerncourier.com/cws/article/cern/67457

- Allow us to probe near-horizon structure
- Bubbles of spacetime observable?

Can we observe fuzzballs?

"Extreme Mass Ratio Inspiral" (EMRI)



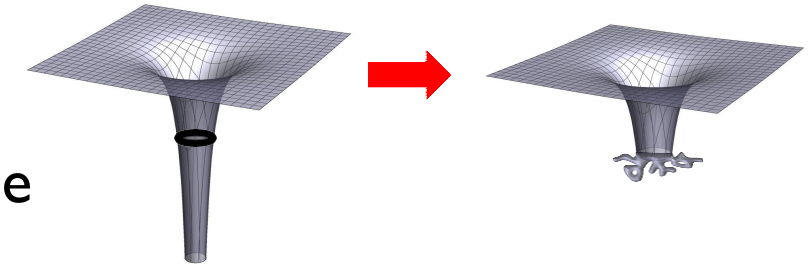
Gravitational waves contain detailed information about spacetime near BH

May be able to observe deviation from conventional theory

Conclusions

Conclusions (1)

- Black holes are ubiquitous in our universe.
  They are now objects of direct observation
- The conventional picture of BHs is macroscopic and approximate
- According to string theory, BHs have microscopic structure called "fuzzballs"
- In future, microstructure of
  BHs may also become observable



Conclusions (2)

Q. What's inside a black hole?
(What is behind the event horizon?)

A. There is no "inside" in naïve sense.

Spacetime has "melted" into bubbles of spacetime ("fuzzball") just before the event horizon.