



***BLACK HOLES:
The Most Extreme Laboratories of the Universe***

**Maxim TITOV, CEA Saclay,
France**

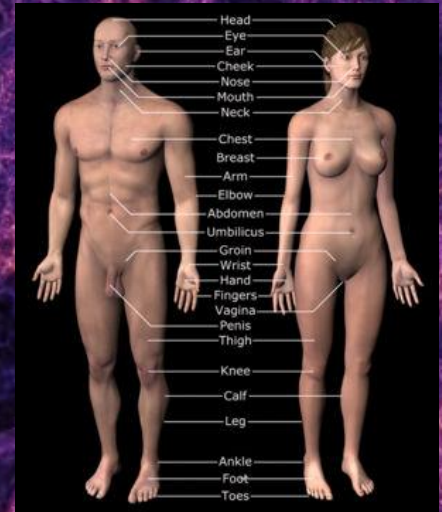
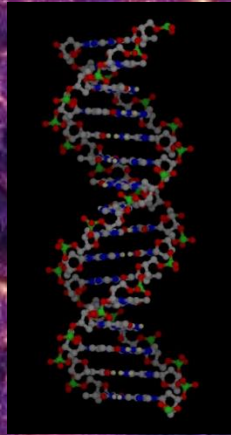
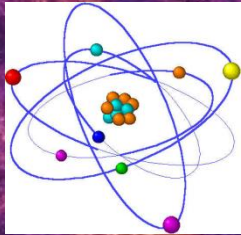
(maxim.titov@cea.fr)

**3rd ONLINE CERN – UKRAINE
Teachers Program
APRIL 24-28, 2023**

Artist's View of Black Hole and Companion Star GRO J1655-40

ESA, NASA and F. Mirabel (CEA) ■ STScI-PRC02-30

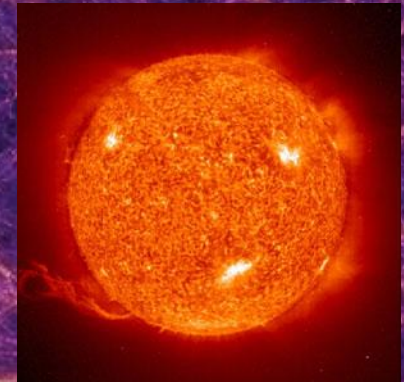
What is everything made of ? What holds it all together ?



125

Where did we come from?

Why do we exist?



Colliding galaxies reveal dark matter

What is Particle Physics ?

**Particle Physics = Study of
Fundamental Laws of Nature
governed by still-mysterious union of
Quantum Mechanics + Spacetime**



We are about to take a journey into the world of Black Holes:

- ✓ **They allow us to probe extreme conditions and fundamental physics**
- ✓ **They are influential for formation and evolution of galaxies**

What is everything made of ? What holds it all together ?

The last stars will die out 120 trillion years from now, followed by 10^{106} years of just black holes.

Condensed, that's like the universe starting with 1 second of stars and then a billion billion billion billion billion years of just black holes.

Stars are basically the immediate after-effects of the Big Bang. A one-second sizzle of brightness before settling into eternal darkness.

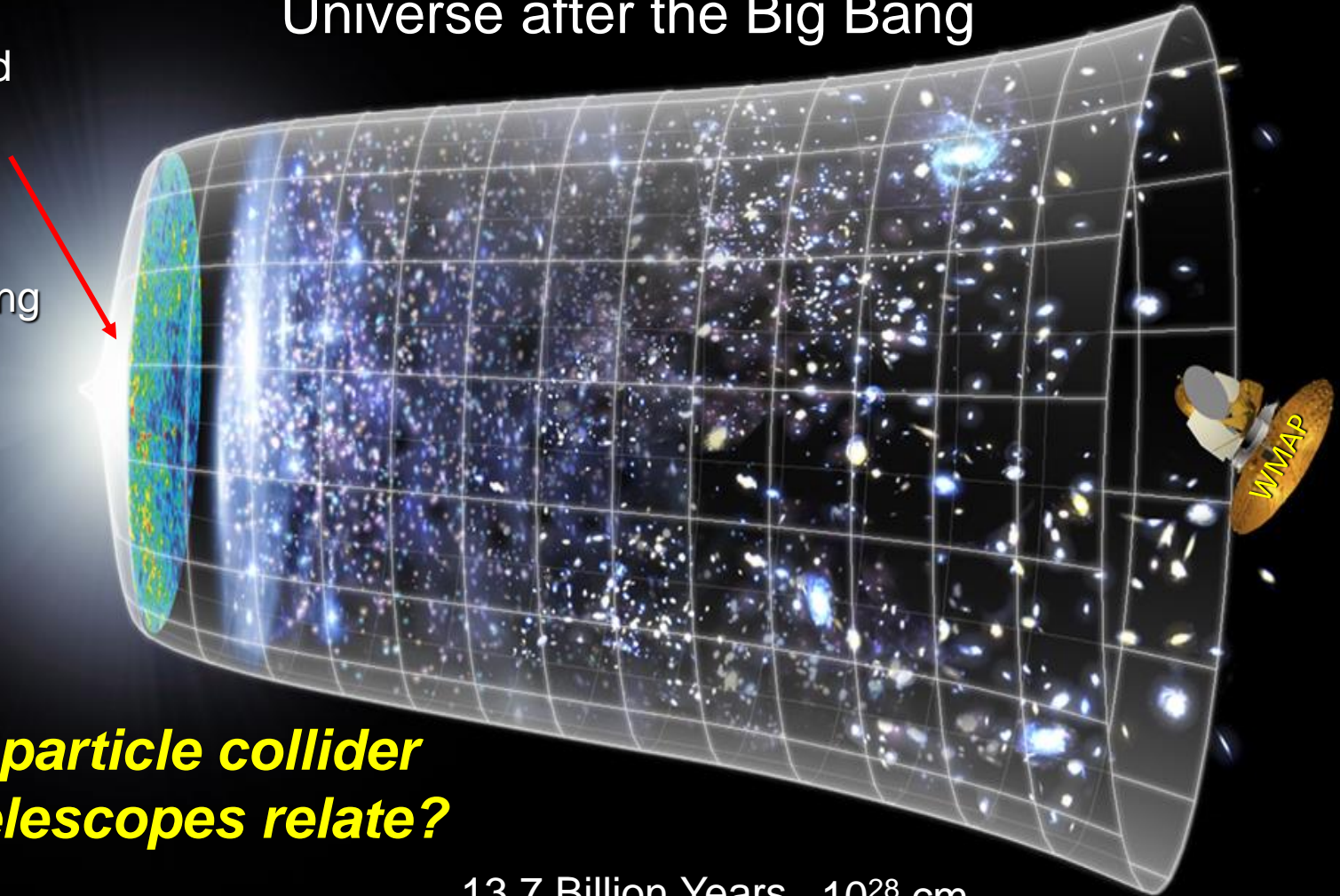
We live in that one bright second.

Today's Scientific Challenge

to understand the very first moments of our
Universe after the Big Bang

What
happened
then ?

Big Bang



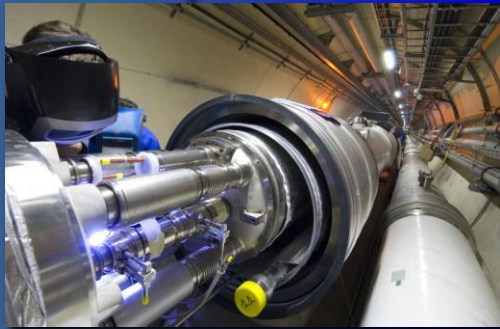
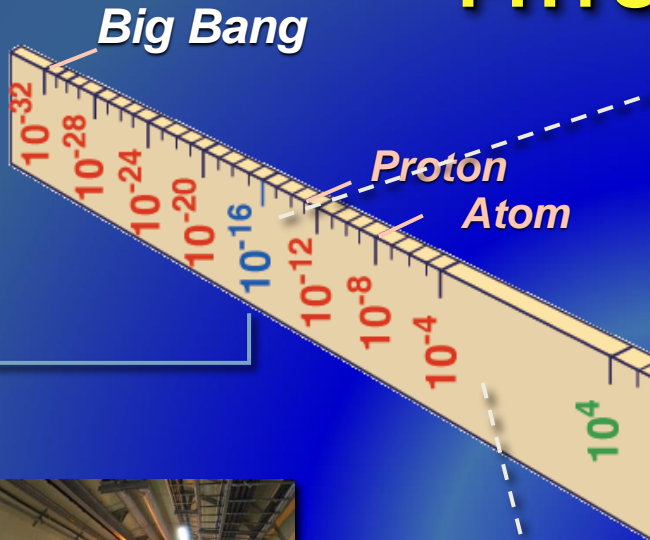
***How particle collider
and telescopes relate?***

13.7 Billion Years, 10^{28} cm

Today

What is Universe made of ?

PHYSICS OF TWO INFINITIES



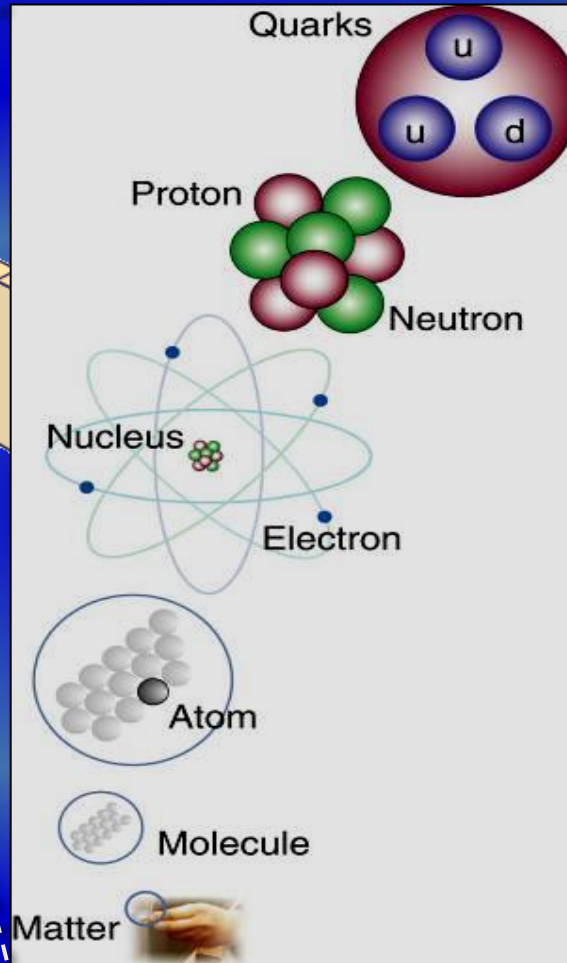
LHC

Super-Microscope

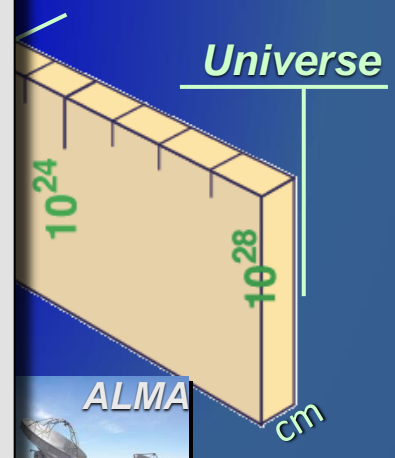


We are entering a golden age of synergy between studies of the very small and the very big.

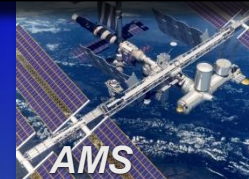
Extra dimensions may solve many known fundamental problems.



Radius of Galaxies



Universe



AMS

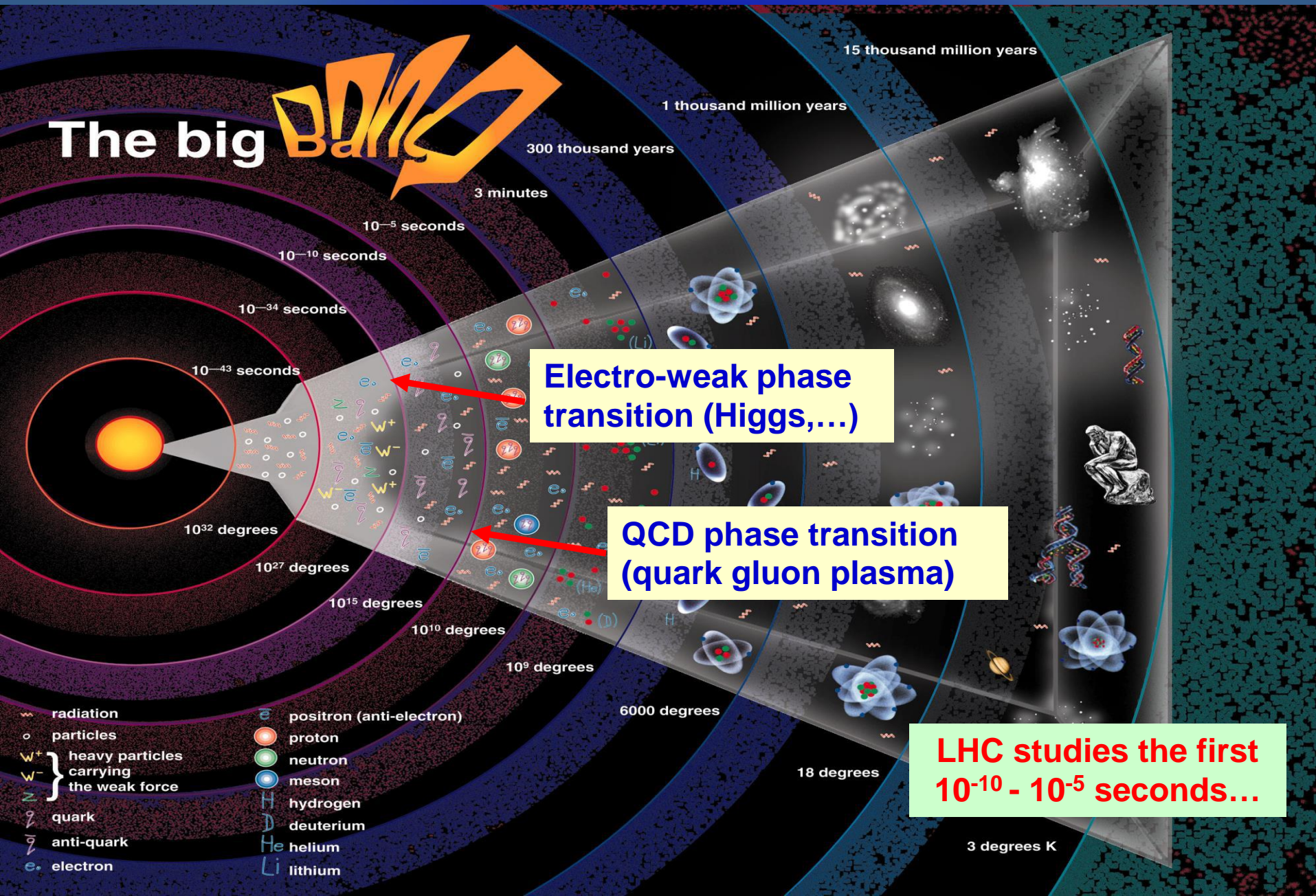


ALMA



VLT

Brief History of Our Universe and Physics at LHC



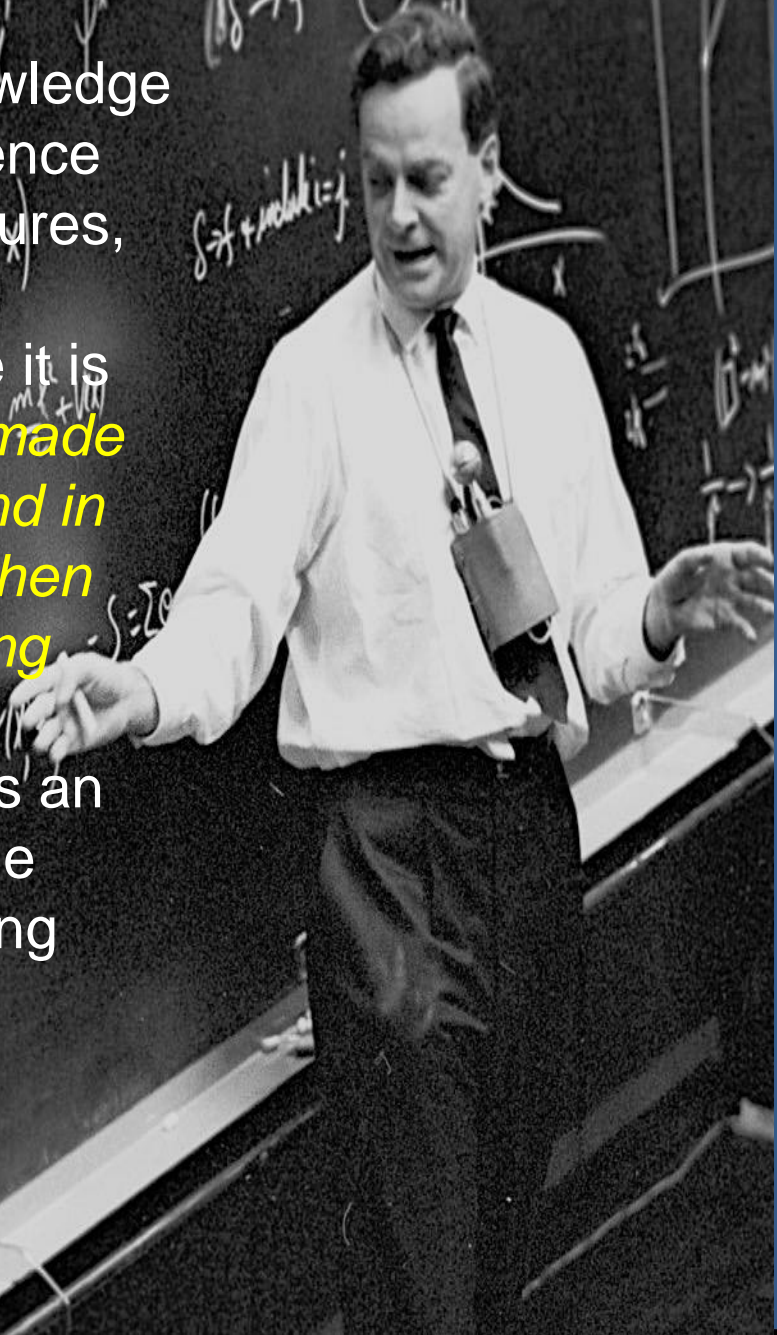
Matter Content of Our Universe

→ *We know only 5% of it ...*

- ✓ **Dark Matter (27%)** → Can be detected only from its gravitational effects
- ✓ **Dark Energy (68%)** → Expansion of Universe is faster than “expected” (Big-Bang + relativity)

If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis that *all things are made of atoms — little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.* In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied.

– Richard Feynman



RICHARD FEYNMAN

There's Plenty of Room at the Bottom (1959)



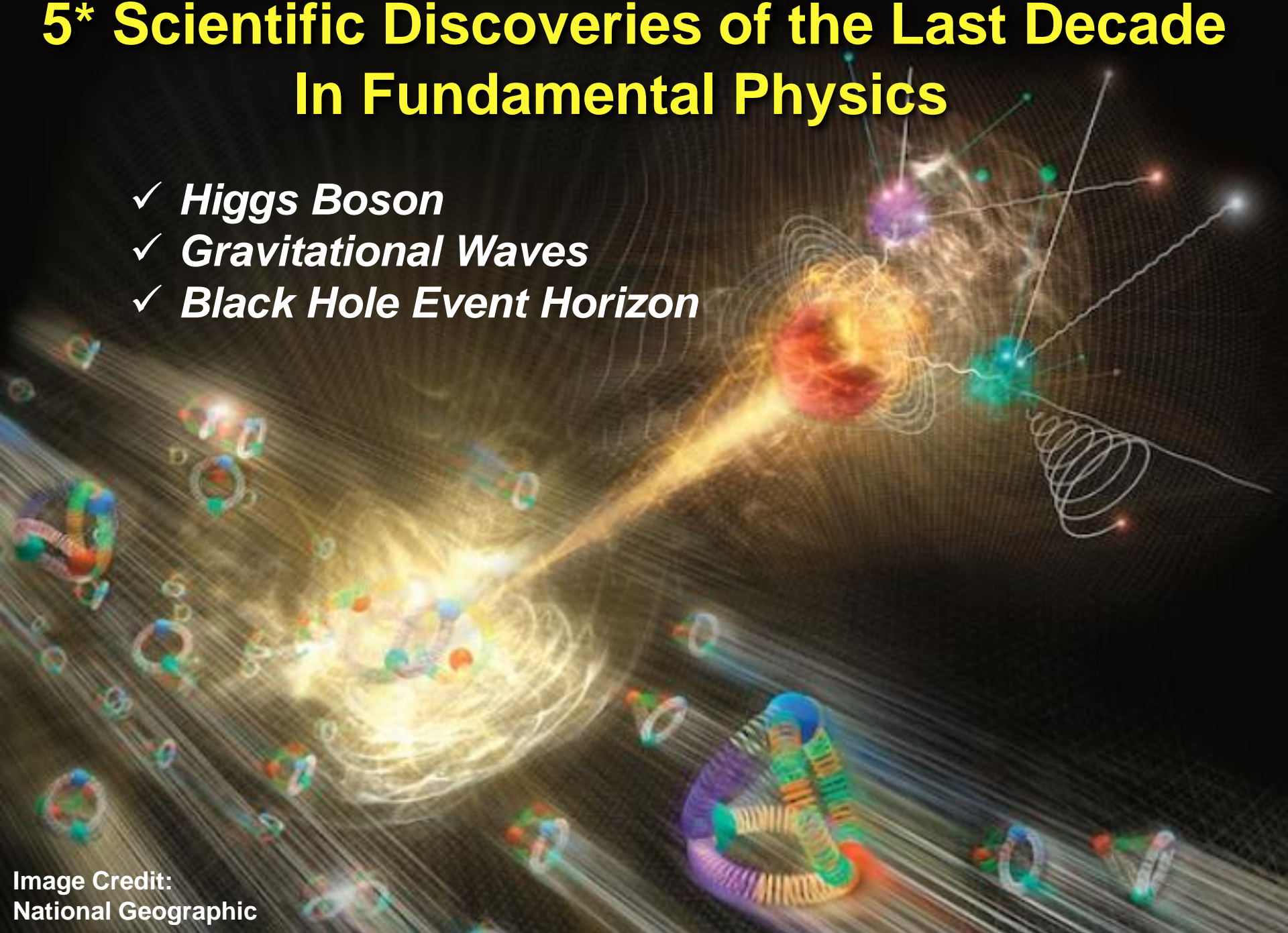
“The principles of physics do not speak against the possibility of maneuvering things atom by atom.”

The Quantum World of Particle Physics

Квантовый мир физики элементарных частиц очень далек от нашего, поэтому его законы часто кажутся нам странными и контр-интуитивными. У человека существует, видимо, глубокая психологическая потребность сводить все явления окружающего мира к простым, понятным образам. Удивительный факт заключается в том, что предсказания квантовой физики подтверждены экспериментально гораздо точнее, чем классической механики и теории относительности Эйнштейна. В 1959 году величайший физик XX века Ричард Фейнман выступил с докладом «Внизу полно места: приглашение в новый мир физики» («There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics»), где была обрисована перспектива прямого манипулирования индивидуальными атомами и фотонами. Однако реальные очертания эти идеи стали приобретать к началу 80-х, прежде всего, в связи с изобретением сканирующего туннельного микроскопа, отмеченного уже в 1986 г. Нобелевской премией. В этом мире атомы ведут себя совсем не так, как объекты макромира, поскольку они подчиняются законам квантовой физики. Наверное, эти идеи тогда и самому Фейнману казались слишком смелыми, но сегодня квантовые сенсоры, универсальные квантовые компьютеры, квантовые коммуникации (криптография) и даже квантовая телепортация (передача квантового состояния частицы из одного места в другое, без использования прямого переноса квантовой частицы в пространстве) постепенно приоткрывают дверь в нашу жизнь. Это должно стать краеугольным камнем для технологий квантовой связи. При этом конфиденциальность информации, передаваемой с помощью квантовых коммуникаций, гарантируется фундаментальными законами физики. Пока это фантастика... Возможно, фантастикой это останется совсем недолго...

5* Scientific Discoveries of the Last Decade In Fundamental Physics

- ✓ *Higgs Boson*
- ✓ *Gravitational Waves*
- ✓ *Black Hole Event Horizon*



I. Higgs Discovery at Large Hadron Collider @ CERN (2012)

“As a layman I would now say... I think we have it – It is a Discovery” (Rolf-Dieter Heuer, CERN DG)



Both ATLAS and CMS Collaborations have reported **observation of a narrow resonance ~ 125 GeV** consistent with long-sought **Higgs boson**

What did we know on that day: it is most probably “**A HIGGS BOSON**”
→ **had to establish** if it is “**THE HIGGS BOSON**” of the Standard Model

About 50 years and Billion(s) of Dollars – The “God Particle” is no Longer a Theory

Physique des particules
La masse est dite

Le Cern a réussi à mettre en évidence le boson de Higgs qui résout un mystère fondamental et ouvre une nouvelle étape scientifique.

The New York Times
Wednesday, July 4, 2012

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WORLD U.S. POLITICS NEW YORK BUSINESS DEALBOOK TECHNOLOGY SPORTS SCIENCE HEALTHY ARTS STYLE OPINION

Rapid H.I.V. Home Test Wins Federal Approval
By DONALD G. MANGEL, Jr.
The OraQuick test, which uses a cheek swab and gives results in 20 to 40 minutes, is the first chance for Americans to learn in the privacy of their own homes whether they are infected.

Auto: Blogs Books Cartoons Classifieds Crosswords Dining & Wine Education Event Guide Fashion & Style Home & Garden Jobs Magazine Movies Music

DEALBOOK As Bank Frames a Defense, Barclays' C.E.O. Resigns
By BEN PROSSER and MARK SCOTT
Ahead of a British parliamentary hearing, senior Barclays executives said they thought they had implicit approval from regulators to manipulate interest rates.

Top Judge Helped

New Particle Could Be Physics' Holy Grail
By DENNIS OVERBYE 4 minutes ago
If confirmed to be the elusive Higgs boson, a newly discovered particle named for the physicist Peter Higgs, above in Geneva could explain the universe's origin.

Fears of Fires Take Fireworks Out of July 4th Celebrations
By DAN FROSCH
Many U.S. cities and towns across the country have decided to scrap their displays.

As Symbols Clash, Fireworks Lose Out to a Hamlet's Bald Eagles
By AARON EDWARDS
The Fire Department in Narrowsburg, N.Y., canceled its annual display after clashes with fireworks were said to be inevitable.

OPINION > EDITORIAL Too Quiet, Again, on Health Care
The Obama campaign has not forcefully countered Republican misinformation on the reform law.

MARKETS > FTSE 100 Germany DAX France CAC 40

Les promesses d'une nouvelle pile tout en un contre le VIH

Higgs within reach
Our understanding of the universe is about to change...

The ATLAS and CMS experiments at CERN The experiments found hints of the new

Le Monde
Le Monde des livres

Science : la matière dévoilée
Le boson de Higgs, particule manquante pour expliquer l'Univers, vient d'être découvert. Les physiciens du CERN de Genève ont prouvé son existence à 99,9999 %.

IMPÔTS CE QUI VA CHANGER
7,2 milliards de plus dès 2012

Réforme fiscale à l'autonomie

ALGÈRE L'INDÉPENDANCE
Une fête sans panache

mais pas de haine

Ces livres qui explorent l'histoire

vkn1
DE NIEUWS OPINIE CULTUUR SPORT ECONOMIE REIZEN

Higgs of niet, het is een spectaculaire ontdekking

VERWANT NIEUWS

MEER OVER

The New York Times
ON THE WEB

Physicists Find Elusive Particle Seen as Key to the Universe
By DENNIS OVERBYE 8:18 PM ET
Researchers said they had discovered what looked for all the world like the Higgs boson, a long-sought particle that

Le Monde: Science: la matière dévoilée

LA REPUBBLICA: La particule de Dieu existe

WELT: L'Univers livre enfin secrets

CORRIERE DELLA SERA: La particule qui fait accélérer notre histoire

HINDU: Le boson de Higgs

UNITA: Le boson de Higgs

THE AUSTRALIAN: The Higgs boson

tribune de Genève: Accélérateur de particules

科技日报: 上海交大首次高效人工合成青蒿素

THE HIGGS BOSON

FINAL PIECE IN THE PUZZLE?

...but there must be a deeper relationship
between Higgs / mass / gravity / dark energy

Determine Higgs properties as precisely as possible to address fundamental questions:

... is it “**THE Higgs Boson**” (of the Standard Model) ? or one of several ?

... its properties could give information on **Dark Matter**

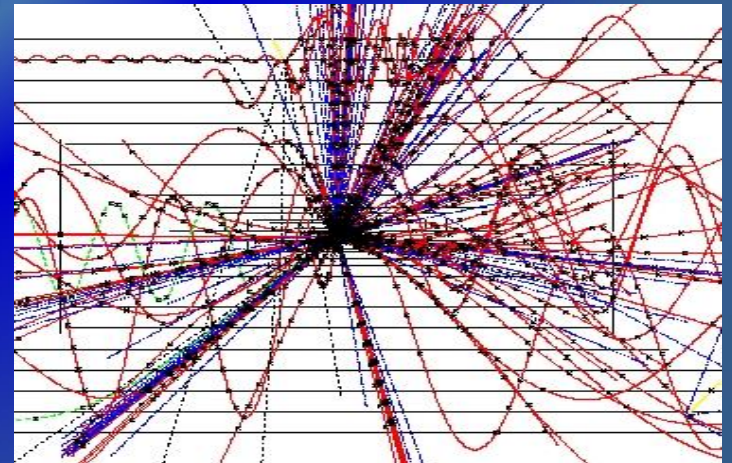
... its properties could give first hints on **Dark Energy**

2000x: Fear and Loathing... Are They Going to End the World?



Has the new CERN project – the **LHC** - the **potential** to create **a black hole** that swallows our planet earth?

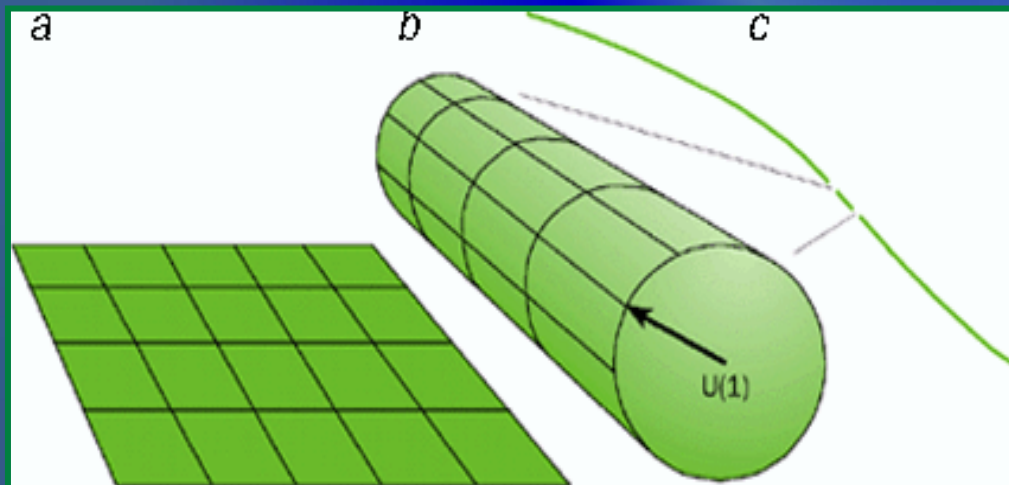
- **Micro black holes @ LHC:**
Mass: $M_{BH} \sim 1000 M_{proton}$
Size: $10^{-18} m$
Temperature: $10^{16} K$
Lifetime: $10^{-27} s$



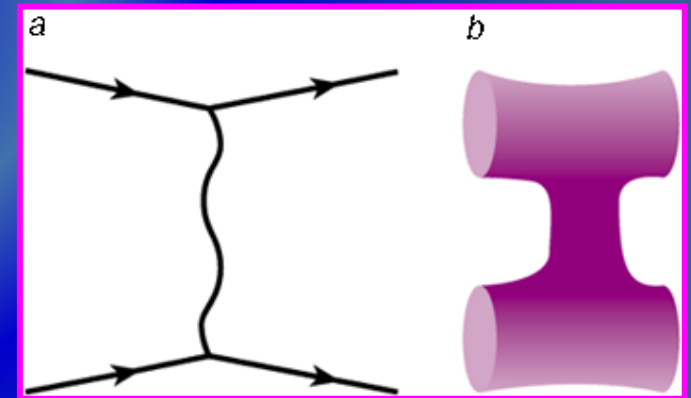
<https://www.forbes.com/sites/startswithabang/2016/03/11/could-the-lhc-make-an-earth-killing-black-hole/#2fe64fd02ed5>

Large Extra Dimensions – A Little Bit of History ...

- ⊖ Once upon a time (1921), Theodor Kaluza in the **hope of unifying gravitation and electromagnetism** extended general relativity by including the $U(1)$ symmetry of electromagnetism by adding a 4th spatial dimension.
- ⊖ In 1926, Oskar Klein proposed that **the fourth spatial dimension is curled up (compactified)** in a circle of very small radius “ R ”, therefore a particle moving a short distance along that axis would return where it began.



- ⊖ In the 1970's and 1980's there's been **renewed interest in (multiple) extra dimensions**: SUSY and string theory.
- ⊖ From 1998 onwards, **new models** have surfaced (ADD, RS, etc.) which **address the hierarchy problem** by exploiting the geometry of spacetime.



Gravity is automatically included in string theory; there is a vibration mode with the properties of the graviton.

One Day at CERN in 2035 ...

THE DAILY TELEGRAPH Monday

The Daily Telegraph

Hawking's "luminous" victory!

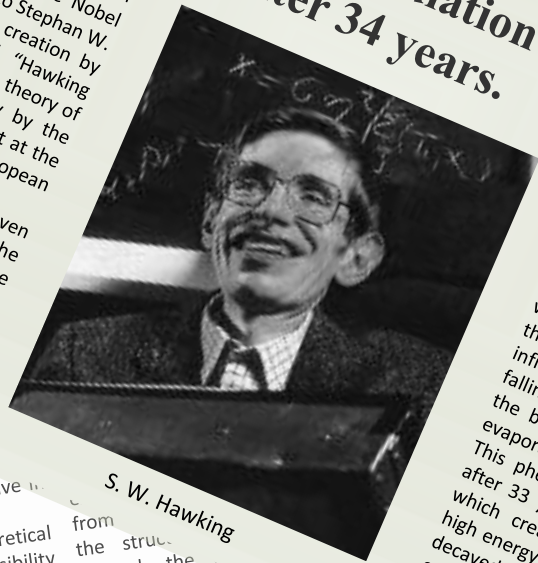
Stephen Hawking's black hole radiation theory is proven experimentally at CERN after 34 years.

Late Edition
New York: Today, partly sunny then a few clouds, high 41. Tonight, increasing clouds, low 33. Tomorrow, increasing wind, high 40. Yesterday, high 40, low 29. Details, Page 38.

THREE DOLLARS

News

CAMBRIDGE, 17 November: The Swedish Royal Academy has announced that the Nobel Prize in Physics for this year will go to Stephen W. Hawking for his theory of particle creation by black holes, which is also named "Hawking radiation" after its founder. Hawking's theory of black hole decay was proved recently by the Large Hadron Collider (LHC) of CERN (European Center for Nuclear REsearch).



S. W. Hawking

black holes are such objects from which even light cannot escape. Since lightspeed is the ultimate speed in universe, black holes are objects from which no escape is possible. However this idea was completely changed by a revolutionary paper by Hawking published in 1975 which suggested that black holes could emit radiation via a

complicated quantum mechanical process. Briefly this idea states that spacetime near a black hole is not a classical vacuum. Energy fluctuations near a black hole creates particle-antiparticle pairs among which the antiparticle with negative energy enters the black hole while the particle with positive energy flies off to infinity. Negative energy of the antiparticle falling into the black hole reduces the mass of the black hole, therefore black hole seems to evaporate and emit particles. This phenomena was finally observed in CERN after 33 years of its proposal in an experiment which created miniature black holes through high energy proton collisions. These black holes decayed immediately after their production, emitting a spectrum of high multiplicity of particle species.

In recent years, many theoretical assumptions predicted the possibility for the existence of extra dimensions in spacetime, but till now these extra dimensions were not observed since firstly they open up at only very small distance scales and secondly, the

from the structure formed, the holes decay through mechanical process. radiation and the decay process be studied

Who Knows ...

II. Gravitational Waves – LIGO Observatory (2016)

the guardian



Scientists work on the LIGO gravitational wave detector, part of the scientific consortium that made the breakthrough. Photograph: Cyril Feiler/Getty

So it turns out Einstein was right all along ...

The Riddle
Physicists have confirmed the discovery of gravitational waves – ripples in the fabric of space – that were first predicted by Albert Einstein a century ago. The announcement is the first century of speculation, in part of 1915 and more, and 70 years predicting a set of instruments as sensitive they could identify a disturbance in space over a thousandth of the diameter of an atom and a millionth of a second.

Philadelphia Inquirer

Deal would halt Syria fighting

World powers asked to allow humanitarian aid into besieged areas.

POST STAR

'Einstein Would Be Beaming'

Clinton, Sanders cordial but firm

Tri-City Herald

Leap pipe a W in W

Spot grad aided in breakthrough

BUNE-REVIEW

Gravitational waves detected at LIGO

Discovery opens ears to cosmos

Tri-City Herald

Gravitational waves detected at LIGO

Frankfurter Allgemeine

ZEITUNG FÜR DEUTSCHLAND

Einstein hat wieder mal recht

Die Wissenschaftler haben bestätigt, was Albert Einstein im Jahr 1915 voraussagte: Gravitationswellen existieren. Sie sind die Verzerrungen der Raumzeit, die durch die Beschleunigung von Massen entstehen.

THE ADVOCATE

'WE CAN HEAR THE UNIVERSE'

Scientists confirm gravitational waves finding

BRainerd Dispatch

'HOLY GRAIL OF SCIENCE'

Scientists confirm gravitational waves finding

The Boston Globe

Rivals debate their support for Obama

A whisper from across the universe

The New York Times

Deal set for truce, aid drops in Syria

White House bans guns – finally

The New York Times

Democrats politic but pointed

White House bans guns – finally

The New York Times

NEW YORK, FRIDAY, FEBRUARY 12, 2016 \$2.50



A worker installed a baffle in 2010 to shield light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

MONITOR

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a finding that fulfilled the last prediction of Einstein's general theory of relativity.

USA TODAY WEEKEND

'A WHOLE NEW WINDOW ON THE UNIVERSE'

LANL crew had faith discovery was matter of time

USA TODAY WEEKEND

'AT THE CENTER' OF CONFIRMING EINSTEIN'S THEORY OF RELATIVITY

The Washington Post

U.S., Russia agree to a halt in Syrian war

Fault line spotlighted in Wis. debate

The Washington Post

U.S., Russia agree to a halt in Syrian war

Gravitational waves: Einstein foresees are detected

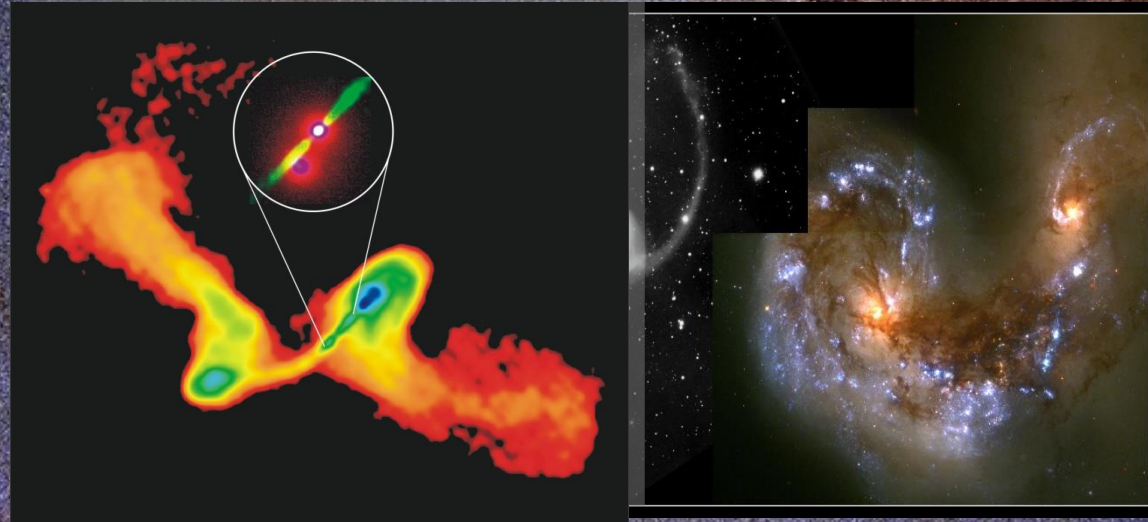
Archbishop Flores grateful to join Pope in

CLAMPTON, MISSOURI (AP) — A BUREAU OF CHURCHES WOULD BE ASKING DEAR, VALER

Lawmakers hold key to building mega prisons

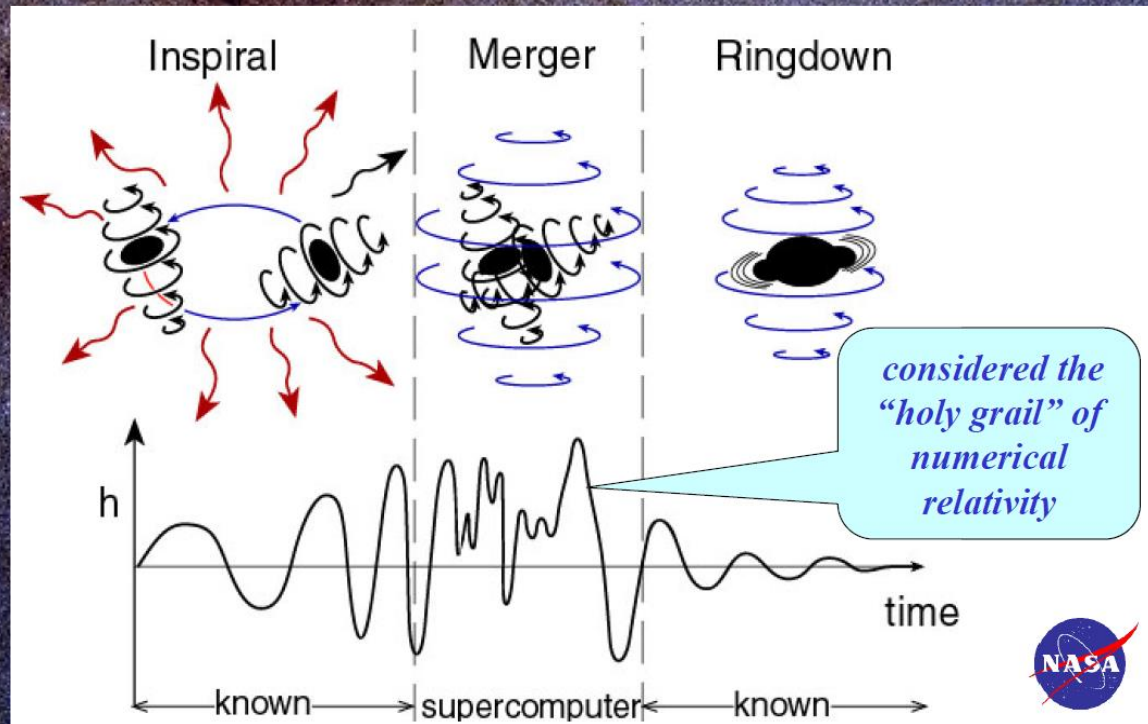
Gravitational Waves Encode Dynamics of Massive Objects

- MBHs are found at the centers of most galaxies
- Most galaxies merge one or more times → **Massive Black Hole (MBH) binaries***
- Final merger of MBHs occurs in the arena of very strong gravity (**strong GW sources**)



- **Observing gravitational waves allows direct tests of GR and probe early stages of structure formation:**

- Requires numerical relativity to calculate dynamics & waveforms
- Waveforms scale w/ masses, spins → apply to ground-based & LISA



Event Horizon Telescope (EHT)

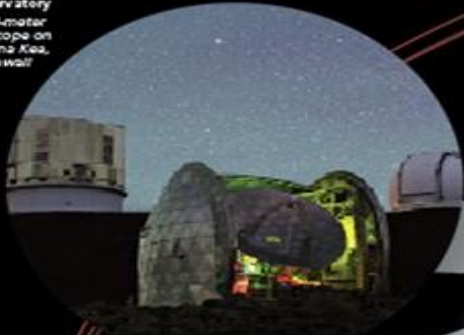
8 telescope array at radio frequency around the Earth

Event Horizon Telescope Array

To get a good look at the light show coming from our galaxy's black hole, astronomers will combine the data from telescopes the world over. Here's a sample of the dozen telescopes that may one day be part of the Event Horizon Telescope.

CSO

The Caltech Submillimeter Observatory
10.4-meter telescope on Mauna Kea, Hawaii



CARMA

The Combined Array for Research in Millimeter-Wave Astronomy
15 antennas near Bishop, Calif.



ARO/SMT

The Arizona Radio Observatory's Submillimeter Telescope
10-meter telescope near Safford, Ariz.



IRAM 30M

The Institute for Radio Astronomy in the millimeter range's 30M scope
30-meter telescope on Pico Veleta, Spain



JCMT

The James Clerk Maxwell Telescope
15-meter telescope on Mauna Kea, Hawaii



SMA

The Submillimeter Array
8 antennas on Mauna Kea, Hawaii



ALMA

The Atacama Large Millimeter/submillimeter Array
66 antennas on the Chajnantor plain of Chile



APEX

Atacama Pathfinder Experiment
12-meter telescope on the Chajnantor plain of Chile

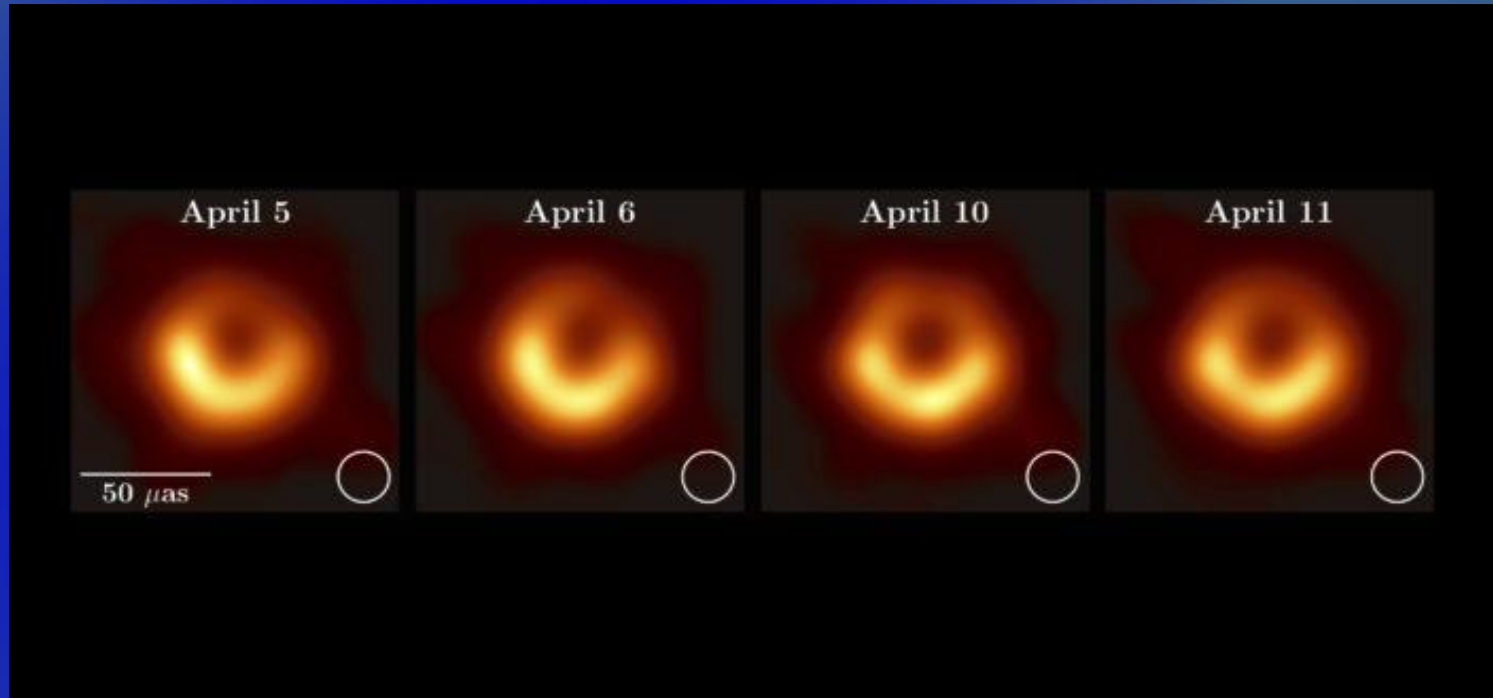


EHT: What the Real Image of Black Hole is (M87) ?

Watch the history and the importance of the M87 black hole picture:

<https://www.youtube.com/watch?v=omz77qrDjsU>

Image of the supermassive black hole at the center of the elliptical galaxy M87, for four different days.

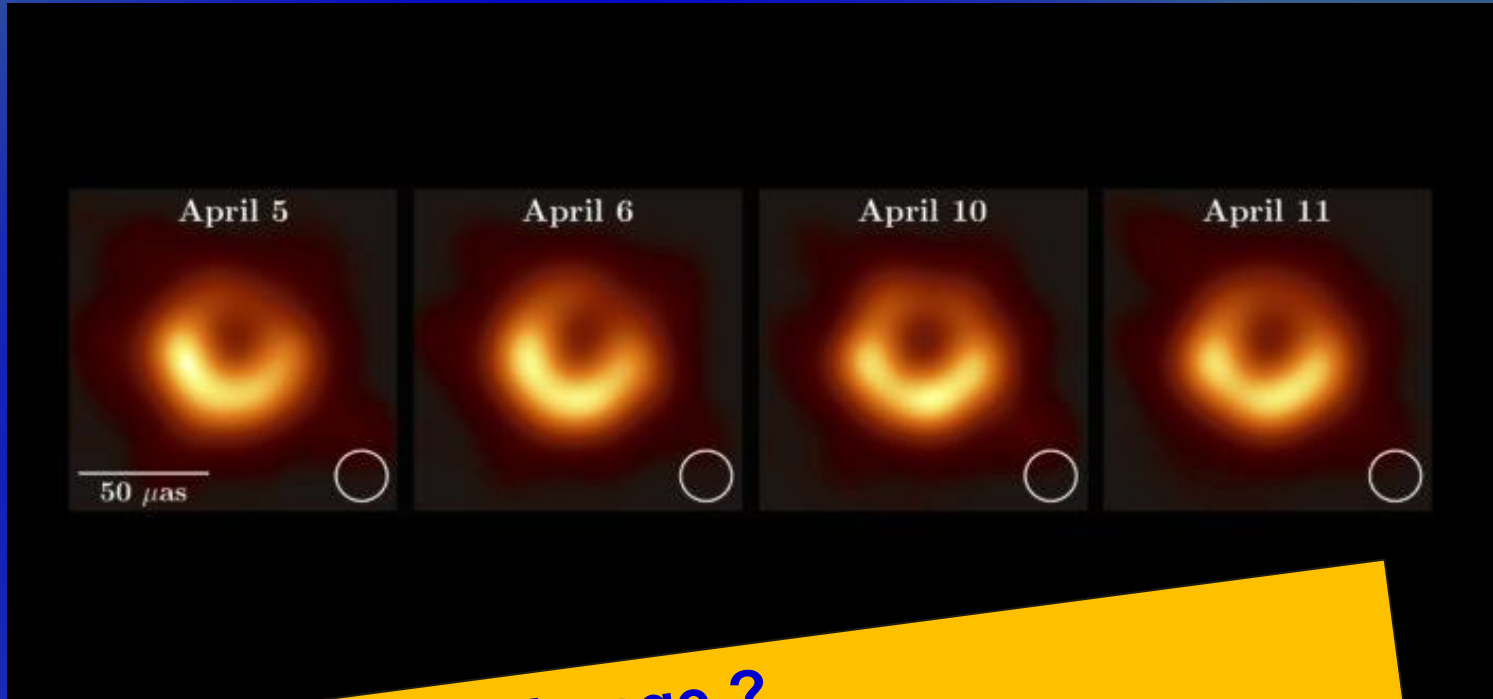


- It was found in a **galaxy** called **M87** and is **larger than** the size of our entire **Solar System**.
- The black hole is **500 million trillion km** away and it was captured by the Event Horizon Telescope (EHT), a network of eight linked telescopes around the world.
- "It has a **mass 6.5 billion times that of the Sun**. And it is one of the heaviest black holes that we think exists. It is an **absolute monster**, the heavy weight champion of black holes in the Universe"

EHT: What the Real Image of Black Hole is (M87) ?

Watch the history and the importance of the M87 black hole picture:
<https://www.youtube.com/watch?v=omz77qrDjsU>

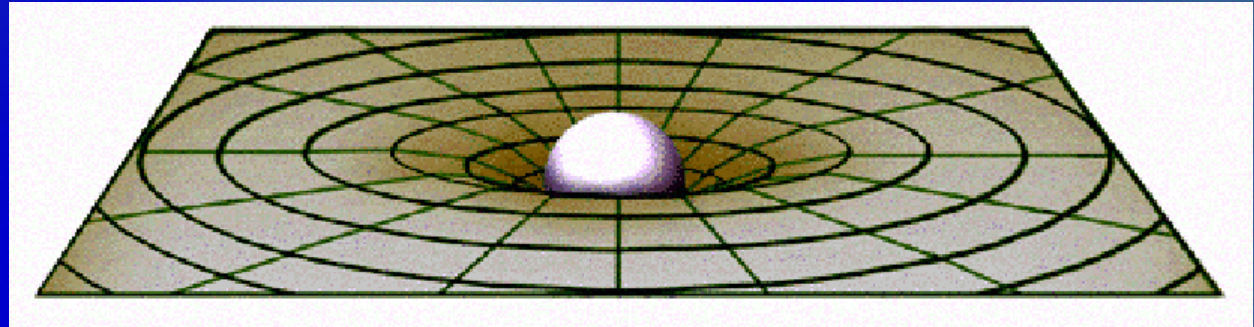
Image of the supermassive black hole at the center of the elliptical galaxy M87, for four different days.



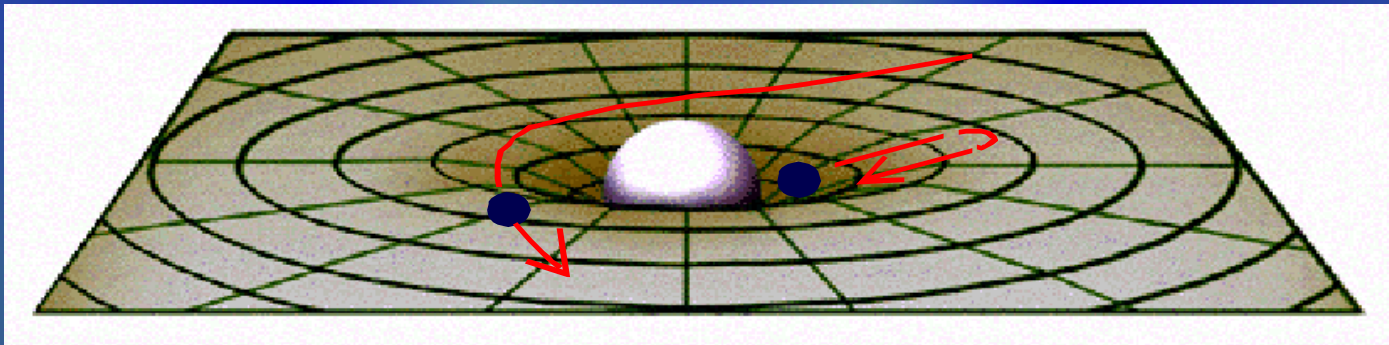
- It was found in a galaxy...
- **What Are We Seeing in This image ?**
- The first **DIRECT** evidence for black holes!!
- Black holes are **REALLY BLACK**, consistent with GR predictions
- The bright ring comes from emission of the accreting materials
- ... it is an **absolute monster**, the heavy weight champion of black holes in the Universe”

Einstein's General Theory of Relativity Warping of Spacetime Produces the Effects of Gravitational Force

- ✓ *Space-time gets curved by masses (mass distorts space). Objects traveling in curved space-time have their paths deflected, as if a force has acted on them.*
- ✓ *"Curvature" of time means that the time flows with a different rate in different points in space*



Objects and light moving near the massive object are forced to take a curved path around the object. (Just like the Moon orbiting Earth).



25

"Matter tells spacetime how to bend and spacetime returns the compliment by telling matter how to move."

A. Einstein (1915): Spacetime is an active player: curves, expands, shrinks, ...

- ✓ **Aristotle:** there are absolute space and absolute time. There is absolute rest different from motion for all observers.
- ✓ **Galileo-Newton:** there are absolute space and absolute time. Motion and rest are relative to an observer. Laws of physics are the same for all uniformly moving observers. Acceleration is absolute.
- ✓ **Einstein (Special relativity):** space and time are relative to an observer. Laws of physics are the same for all uniformly moving observers. Space-time is a fixed flat background.
- ✓ **Einstein (General relativity):**
 - ALL kinds of motion are unified, including accelerated motion
 - Gravity and acceleration are unified and depend on the observer
 - Space-time is not a fixed background anymore. Space-time and matter interact with each other and affect each other.

$$\mathbf{G} = 8\pi\mathbf{T}$$

Describes curvature of space-time

Mass-energy density of matter

Thinking in Terms of Einstein's Theory of General Relativity

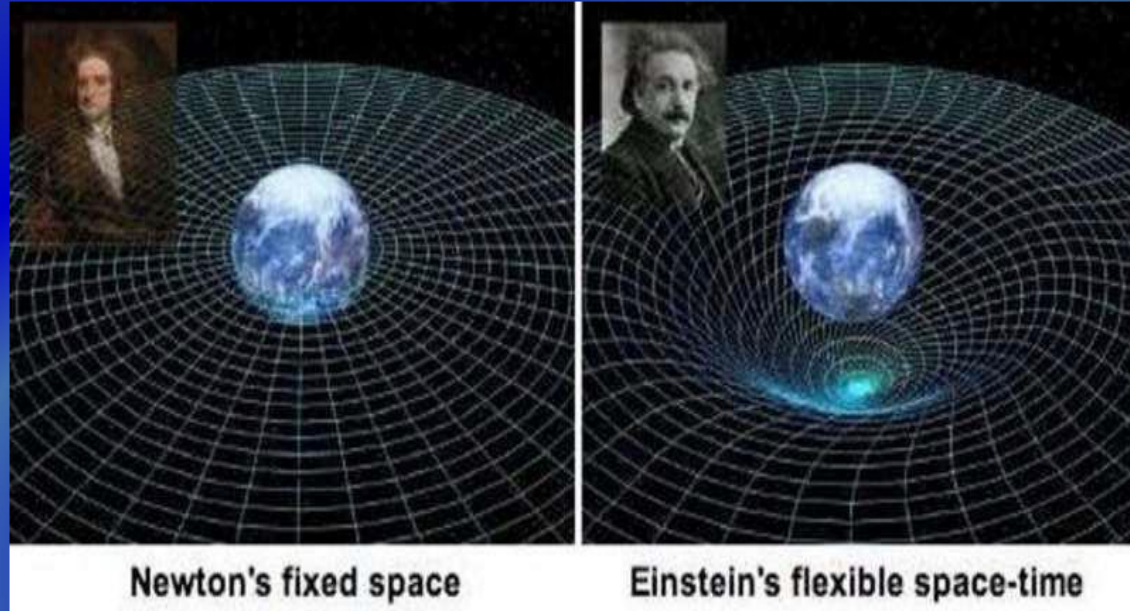
- **Newton's gravity works well**

in most situations (planetary orbits, binary stars) but fails when:

- Gravity becomes extremely intense
- Large masses move rapidly.
- Light is effected by a large mass.

- **Einstein's theory says**

that the presence of matter warps space and time. Gravity is replaced by warping of space-time.

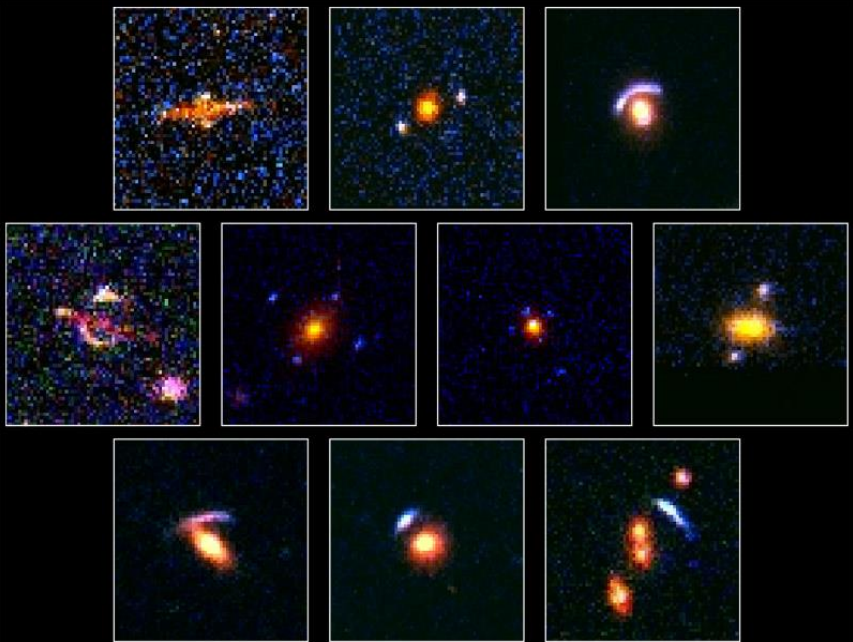
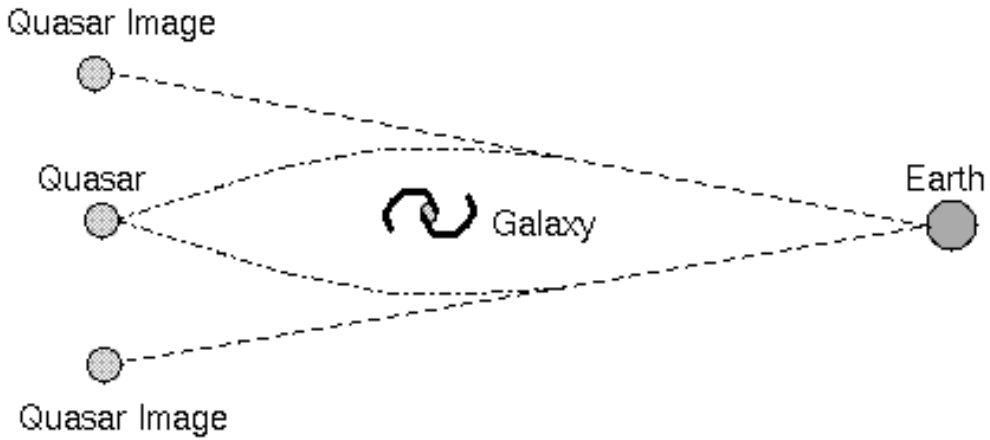


• **GR remains one of the most accurate theories in physics:**

- Precession of the perihelion of Mercury
- Light will be bent when passing near large objects
- Time will slow down near a large mass
- Gravitational redshift of light
- Gravitational Waves
- **Massive objects will collapse to a singularity (black hole)**
 - existence of Black Hole Event Horizon (no one believed in 1915)

Gravitational Lensing is Now a Tool

Gravitational lens - gravity can bend light around a very heavy obstacle (triumph of GR)



Gallery of Gravitational Lenses
PRC99-18 • STScI OPO • K. Ratnatunga (Carnegie Mellon University) and NASA HST • WFPC2

Lensing Galaxy



Can be used to estimate the mass of intermediate galaxy



Gravity's Final Victory

Black holes are the evolutionary endpoints of stars at least 10 to 15 times as massive as the Sun.

- ✓ A star more massive than about $18 M_{\text{sun}}$ leaves behind a core larger than $3 M_{\text{sun}}$
- ✓ Neutron degeneracy pressure fails
- ✓ Nothing can stop its gravitational collapse.
- ✓ Core collapses to a **singularity**:
 - **zero radius**
 - **infinite density**
- ✓ Near the singularity gravity is so strong that not even light can escape.

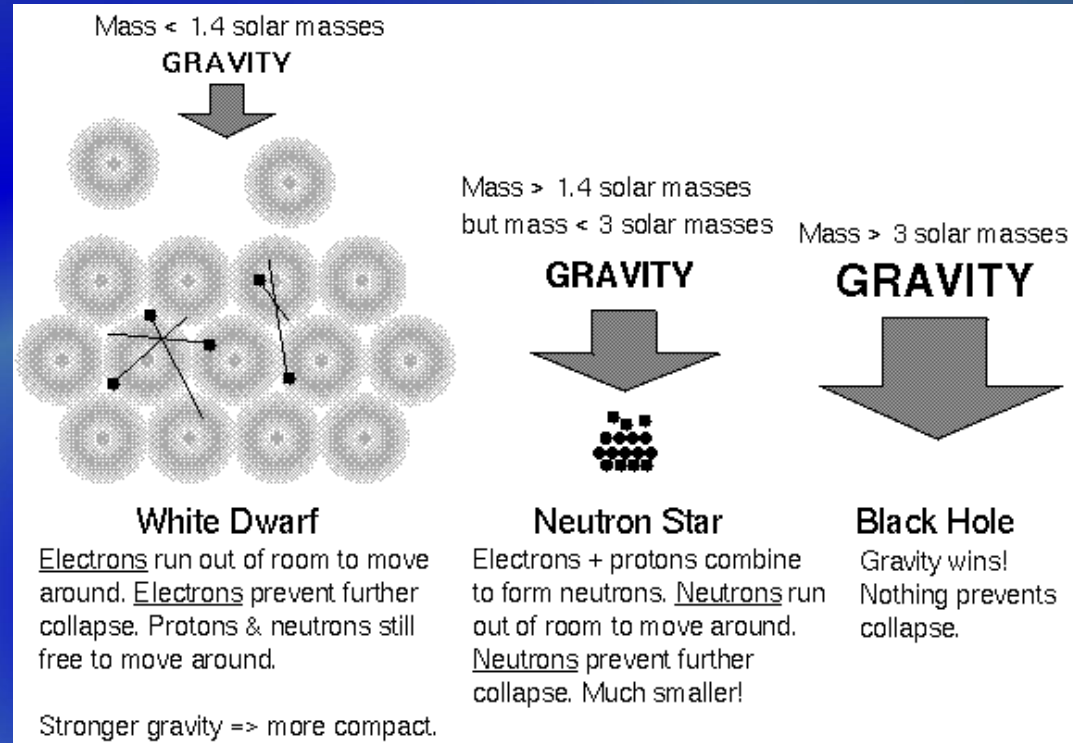
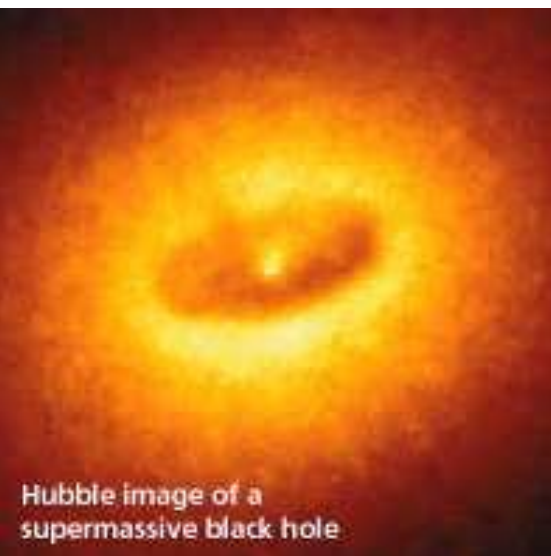


Photo of the Hubble Space Telescope



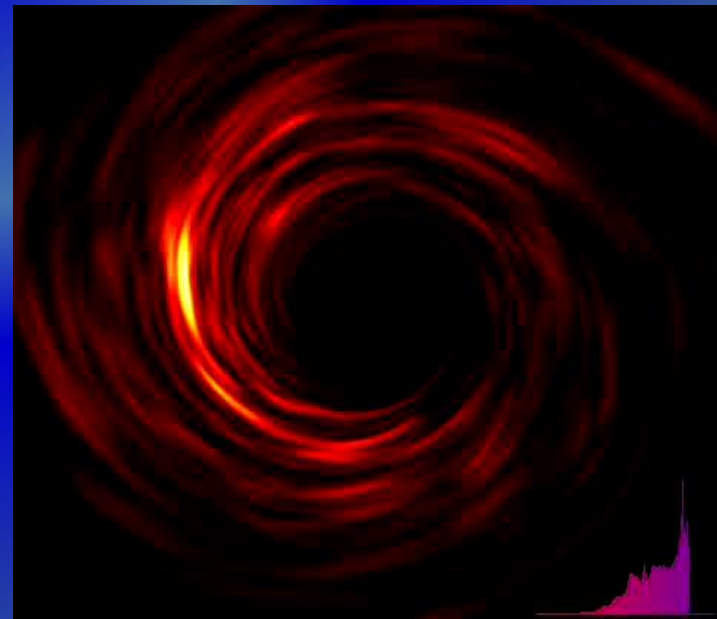
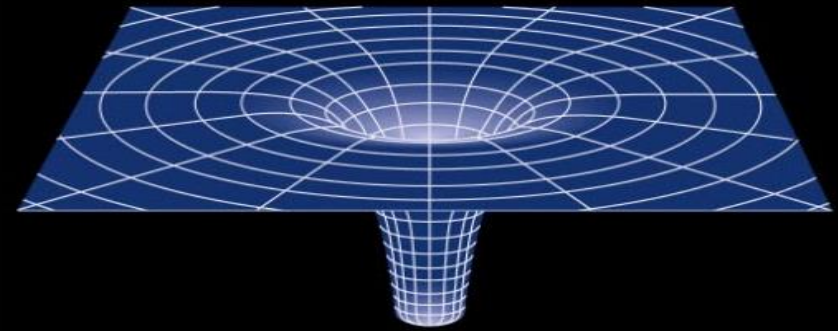
Hubble image of a supermassive black hole

Black Hole: A Theoretical Definition (I)

A black hole is a region of space-time from which nothing can escape, even light:

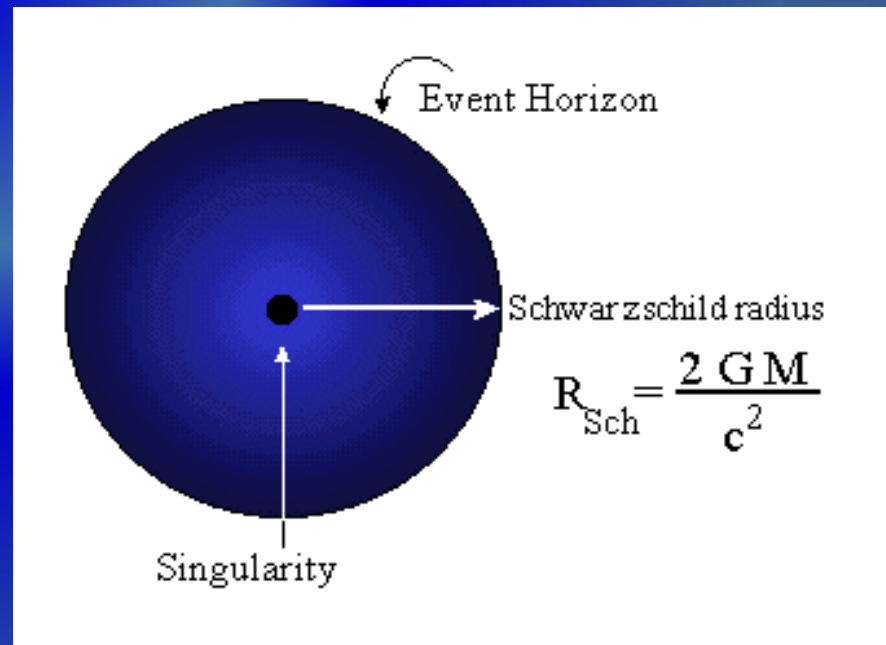
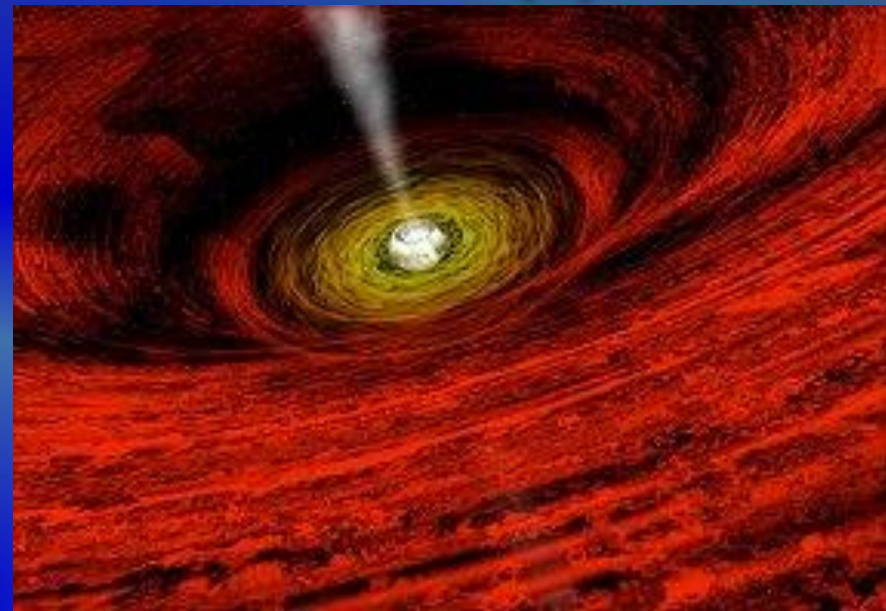
- ✓ *A black hole is a true "hole" in space: Anything that crosses the edge of the hole - called the "event horizon" - is swallowed forever*
- ✓ *As you get closer to a black hole, the flow of time slows down, compared to flow of time far from the hole.*
- ✓ *At the event horizon, time actually appears to stop. An object falling into the hole would appear frozen in time at the edge of the black hole!*
- ✓ *Our laws of physics break down at the very center of the black hole . Time itself seems to come to an abrupt end there. For this reason, a black hole is sometimes described as the "reverse of creation."*
- ✓ *Einstein's theory of gravity allows the possibility of a black hole forming a link - or wormhole - to another universe, or another part of our universe.*

Spacetime should be distorted into an infinite well by a dense black hole

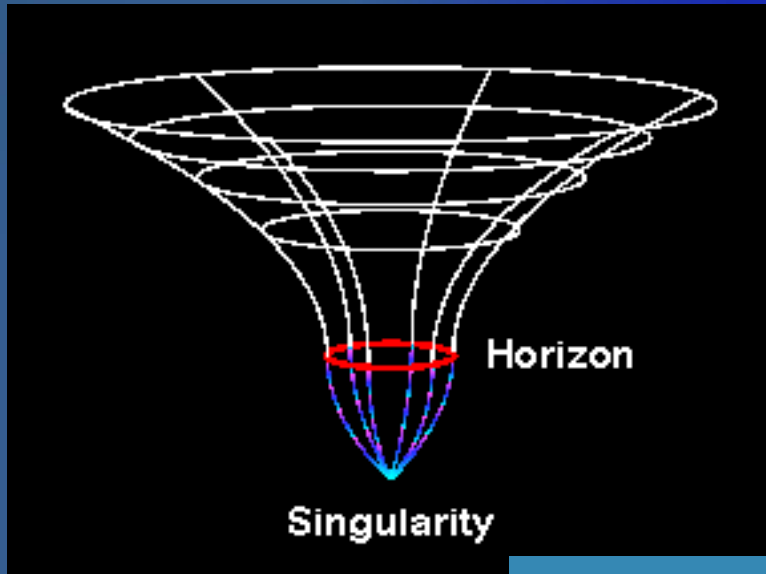


Black Hole: A Theoretical Definition (II)

- ✓ The **black hole** is surrounded by an **“event horizon”** which is the sphere from which light cannot escape;
- ✓ The distance between the black hole and its event horizon is the **Schwarzschild radius** ($R_{\text{Sch}} = 2GM/c^2$);
- ✓ The center of the black hole is a point of infinite density and zero volume, called a **singularity**;
- ✓ The **“event horizon”** hides the **singularity** from the outside universe:
 - Events occurring inside are invisible to the outside universe.
 - Anything closer to the singularity can never leave the black hole
 - The important thing is this area can be of any size;

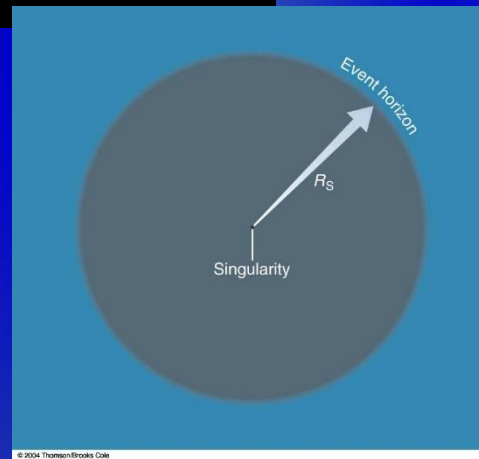


Some Unresolved Problems: What is the Singularity



Singularities Clothed and Naked

The singularity is the point of infinite density thought to exist at the center of a black hole. We have *no way of understanding* what would happen in the *vicinity of a singularity*, since in essence nature divides our equations by zero at such a point. There is an hypothesis, called the "Law of Cosmic Censorship" that *all singularities in the Universe are contained inside event horizons and therefore are in principle not observable* (because no information about the singularity can make it past the event horizon to the outside world). However, this is an hypothesis, not proven, so it is conceivable that so-called "*Naked Singularities*" might exist, *not clothed by an event horizon*.



**General relativity
breaks down
at Planck scale:**

$$l_p = \sqrt{\frac{G\hbar}{c^3}} \sim 1.6 \times 10^{-35} \text{ m}$$

Black Holes: “Where God Divided by Zero”

Recipe for a black hole:

Just squeeze a body of mass M below its Schwarzschild's radius

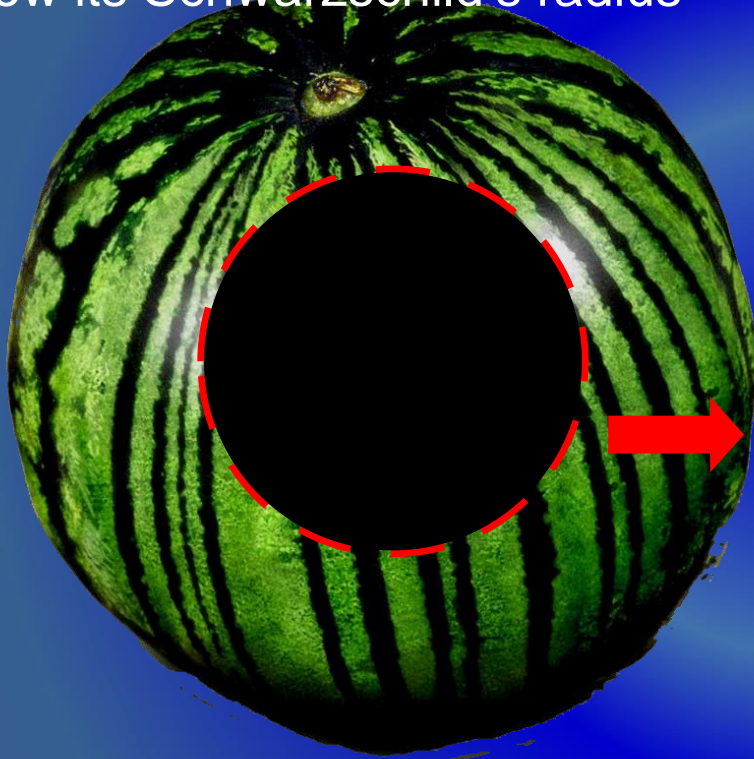


TABLE 11-1

The Schwarzschild Radius

	Mass (M_{\odot})	R_s
Star	10	30 km
Star	3	9 km
Star	2	6 km
Sun	1	3 km
Earth	0.000003	0.9 cm

© 2004 Thomson/Brooks Cole

Schwarzschild radius

$$r_s = 2GM_{\text{WM/BH}} / c^3$$

GRAVITATIONAL COLLAPSE AND SPACE-TIME SINGULARITIES

Roger Penrose

Department of Mathematics, Birkbeck College, London, England

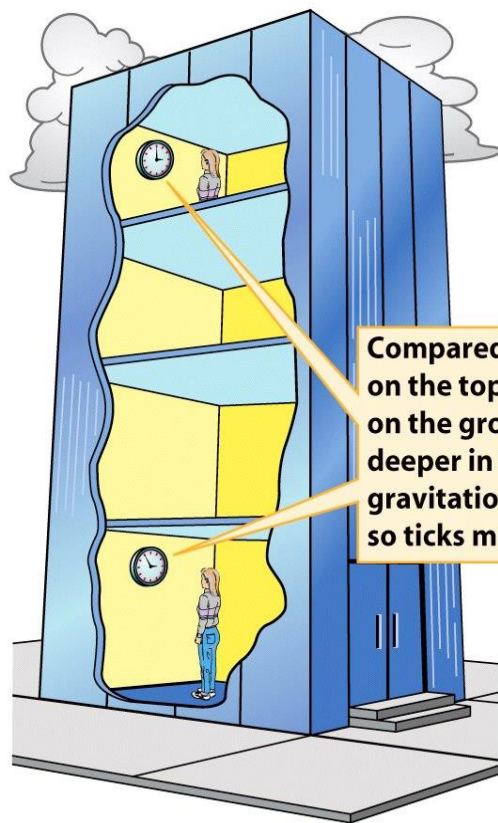
(Received 18 December 1964)

(This paper is only 2.5 pages long!!)

Geometry of the spacetime near a BH can be found by solving Einstein's equations for different conditions (spin, charge):

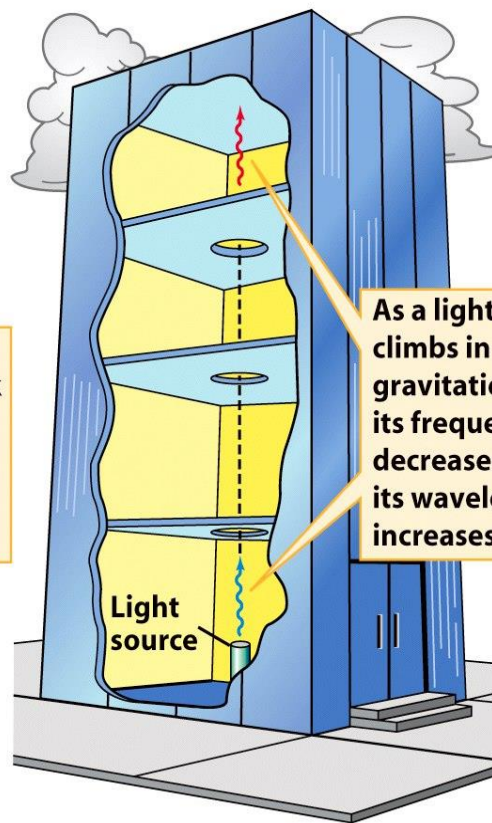
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi GT_{\mu\nu}$$

Gravitational Redshift of Light



Compared to a clock on the top floor, a clock on the ground floor is deeper in the Earth's gravitational field and so ticks more slowly.

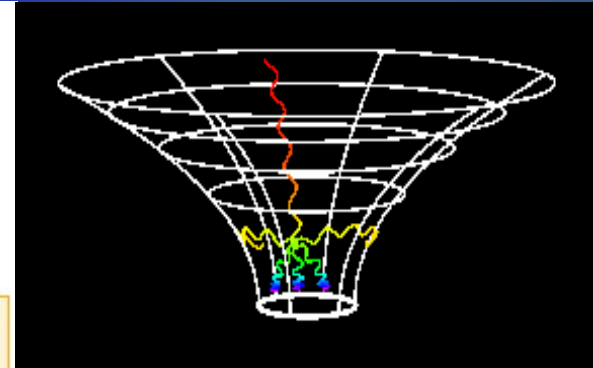
(a) The gravitational slowing of time



As a light wave climbs in a gravitational field, its frequency decreases and its wavelength increases.

Light source

(b) The gravitational redshift



Frequency of light is shifted in the accelerated frame.

→ It should be also shifted in the gravitational field!

$$f = f_0 \sqrt{1 - \frac{R_s}{r}}$$

Photons always travel at the speed of light, but they lose energy when traveling out of a gravitational field and appear to be **redder** to an external observer. The stronger the gravitational field, the more energy the photons lose because of this **gravitational redshift**. The extreme case is for photons emitted at event horizon of black hole, **gravitational redshift is infinite**. The observed frequency is zero, i.e. the **photons loose all their energy are never observed**.

A Plunge into a Black Hole

- ✓ Modern physics has two basic sets of laws for the universe:
 - **General relativity** -- macro-scale
 - **Quantum field theory** -- micro-scale
- ✓ The two are not compatible!
- ✓ Most problems fall into one category only.

- ✓ **Black holes need both:**
 - **micro-size and macro-mass**
 - the study of black holes helps understand how to combine the two theories.

- ✓ Black holes are “**simple**” objects – their structure is defined by three parameters:
 - **Mass** (as measured by the black hole’s effect on orbiting bodies, such as another star)
 - **Total electric charge** (as measured by the strength of the electric force)
 - **Spin** = angular momentum (how fast the black hole is spinning)

- ✓ Black holes have no hair → All event horizons are spherical, no matter what the mass looked like before collapse

- ✓ Black holes have no magnetic field (internal).

- ✓ Black holes have entropy (a measure of disorder) that is proportional to the size of the event horizon.

- ✓ Black holes have a temperature → black body (The heavier a BH, the cooler it is!)

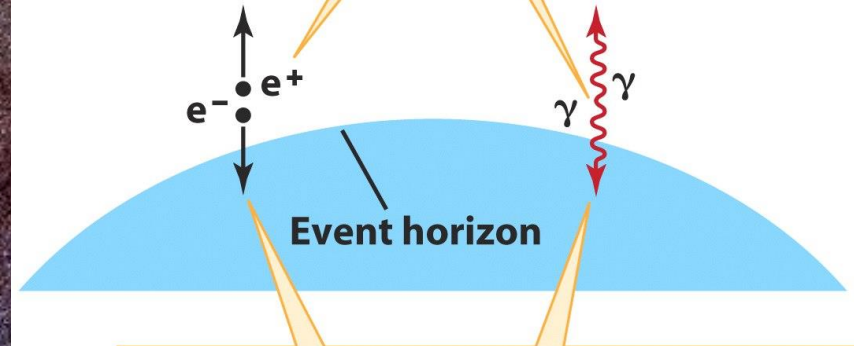
Evaporating Black Holes

BHs can decay via a quantum mechanical process near event horizon of a BH

- ✓ **Black Holes evaporate** slowly by emitting “Hawking radiation” → particles falling into the BH have negative energy, BH loses mass and energy is conserved.
- ✓ The **smaller** the mass, the **faster** the evaporation
- ✓ Hawking radiation is equivalent to black body radiation → Each particle carries off a little of the black hole's mass
- ✓ **Most properties of matter vanish** when matter **enters a black hole**, such as chemical composition, texture, color, shape, size, distinctions between protons and electrons, etc

1. Pairs of virtual particles spontaneously appear and annihilate everywhere in the universe.

2. If a pair appears just outside a black hole's event horizon, tidal forces can pull the pair apart, preventing them from annihilating each other.

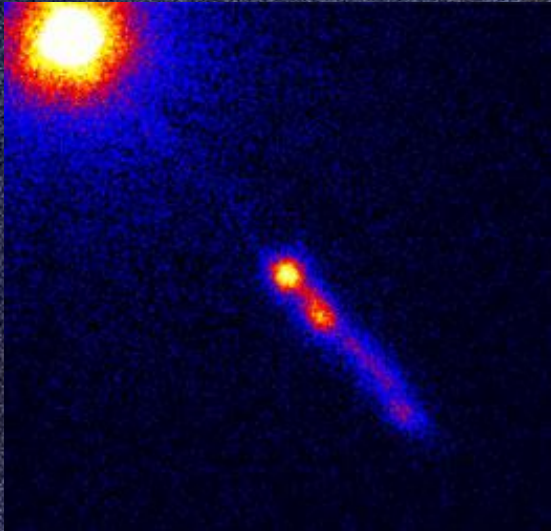


3. If one member of the pair crosses the event horizon, the other can escape into space, carrying energy away from the black hole.

- **Questions Remain about Black Holes:**

- **Is the information that falls into a Black Hole lost forever?** → this contradicts the laws of quantum mechanics, and scientists have been trying to deal with this paradox for decades)
- **What is inside a black hole?**
- Can **wormholes** be produced to travel in time and/or space?

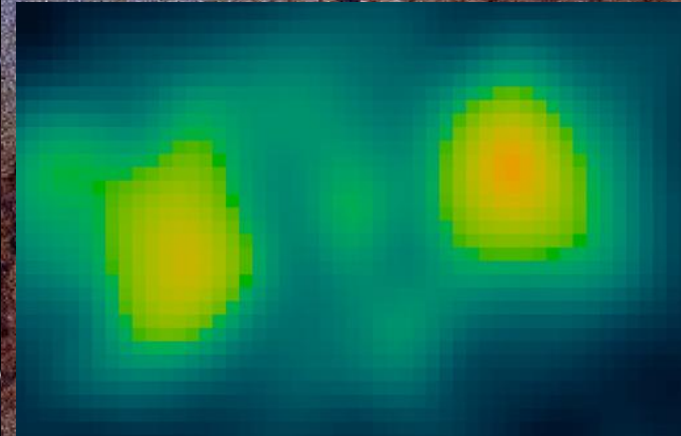
Black Hole Galore



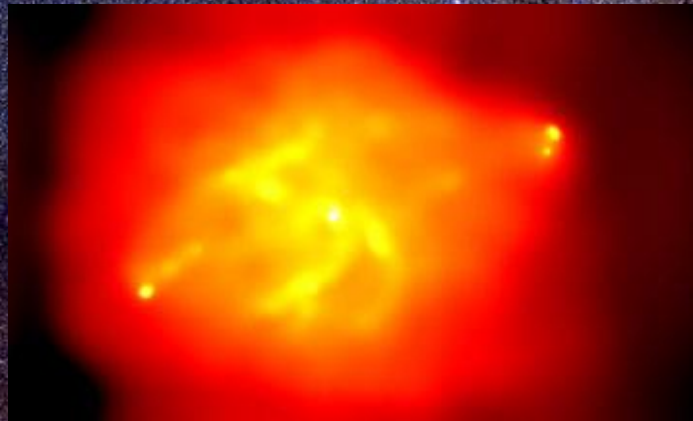
NASA/CXC/SAO/H.Marshall et al.



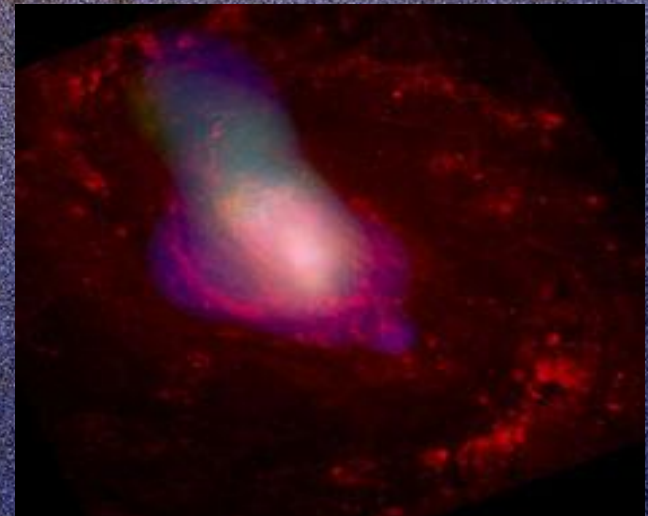
NASA/CXC/MIT/F.K.Baganoff et al.



NASA/CXC/U.Amsterdam/S.Migliari et al.



NASA/UMD/A.Wilson et al.



X-ray: NASA/CXC/MIT/UCSB/P. Ogle et al. Optical: NASA/STScI/A.Capetti et al.

From the formation of galaxies to the deaths of stars, black holes are an integral part of our universe's history.

A Galaxy Full of Black Holes

There are 200 billion stars in our galaxy, the Milky Way

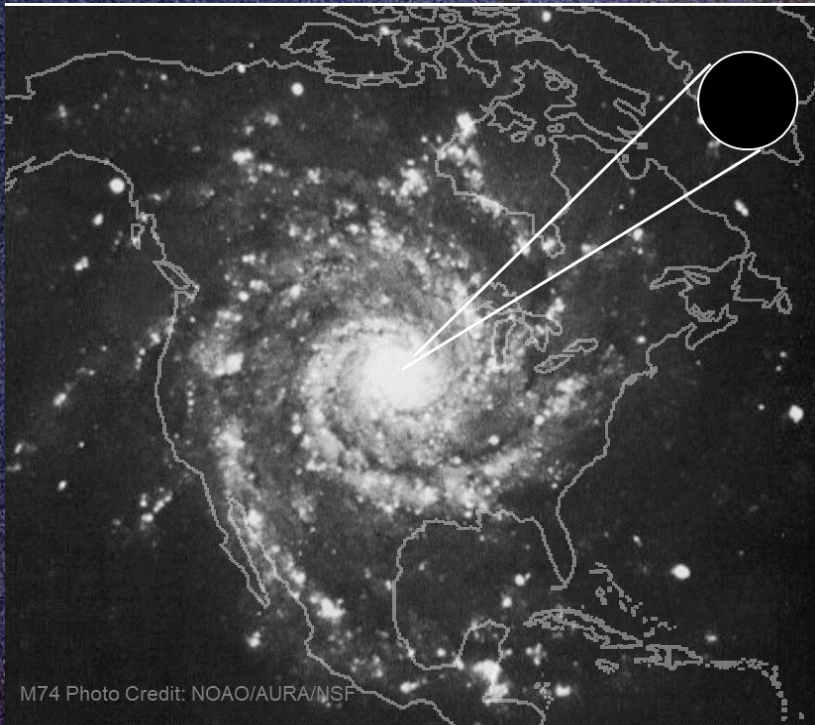
There are also millions of black holes

Including one giant black hole at the very center.

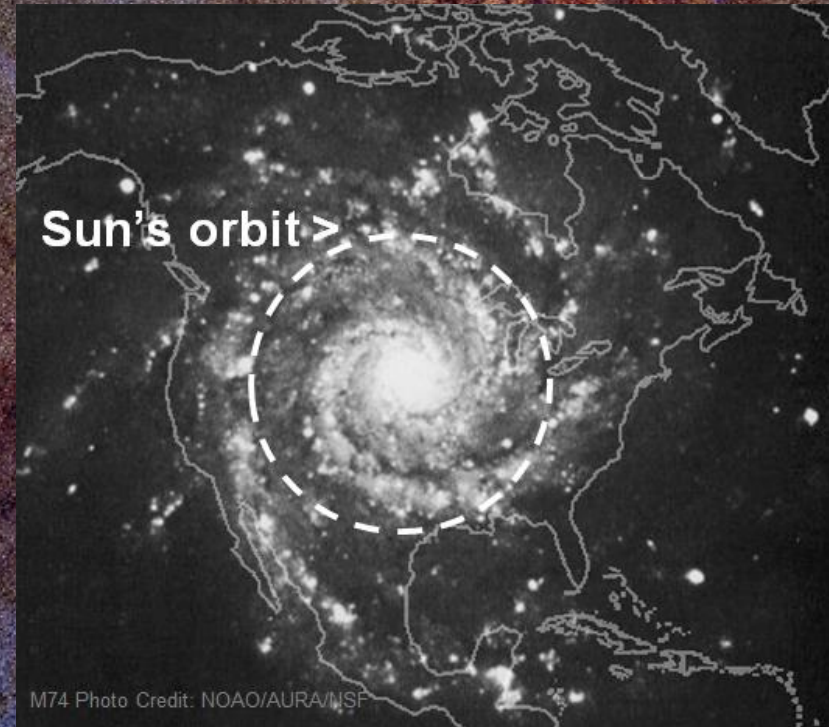
How have we survived?

So How Do we Survive amid All These Black Holes ?

Great distances between the stars



Everything is orbiting fast enough!



- **Far away from a black hole:**

- Gravity is the same as for a star of the same mass.
- If the Sun became a Black Hole, all the planets would continue in the same orbits.
- It would however be darker and MUCH colder

- **Close to a black hole:**

- $R < 3 R_S$, there are no stable orbits - all matter eventually gets sucked in.

What a Strange Object a Black Hole is ?

We cannot see black holes directly, but their influence on the matter around them reveals their presence.

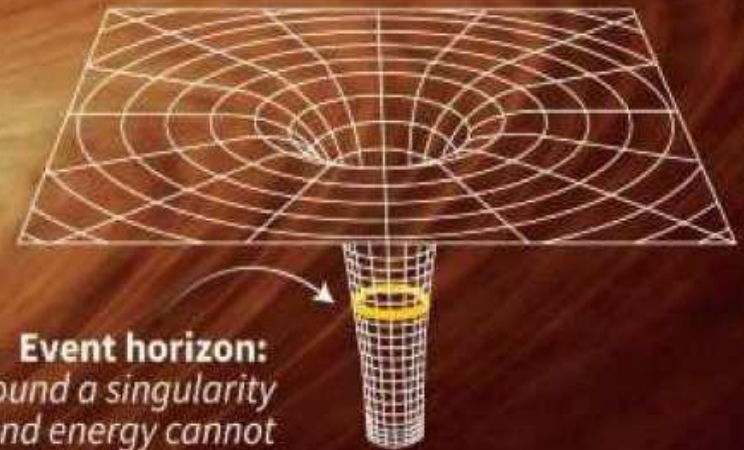
Black holes

Relativistic jet: when stars are absorbed by black holes, jets of particles and radiation are blasted out at near light speed

Accretion disc of superheated gas and dust whirls around black hole at immense speeds, producing electromagnetic radiation (x-rays)

Singularity: the very centre of a black hole where matter has collapsed in a region of infinite density

Photon sphere: photons emitted from hot plasma near the black hole which bends their trajectory producing a bright ring



Event horizon: the radius around a singularity where matter and energy cannot escape the black hole's gravity. The point of no return.

AFP PHOTO / NASA / JPL-Caltech

Artist rendering

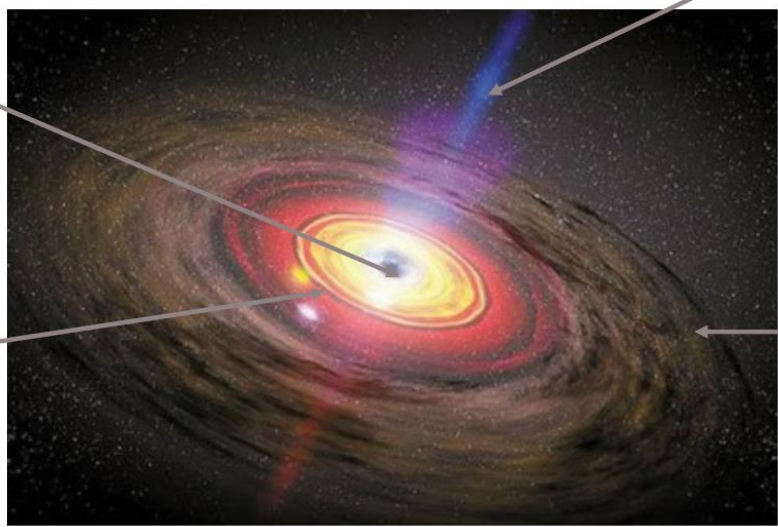
Source: eventhorizontelescope.org

Black Holes as Laboratories of Fundamental Physics

▪ *Complex physics involved!!*

Quantum gravity
GR

Electromagnetism
Radiative processes



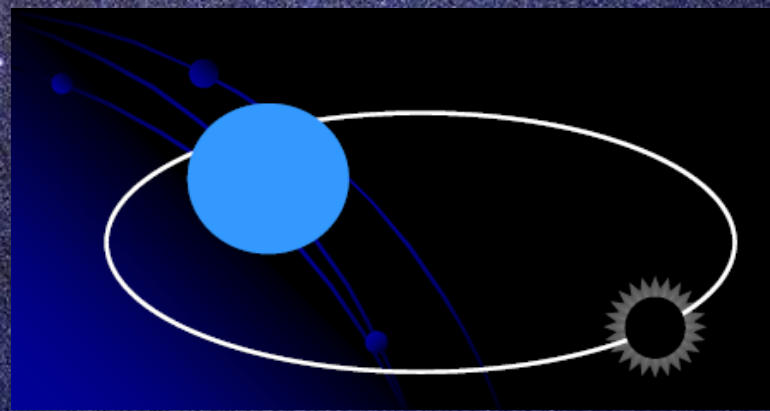
Plasma physics
High-energy astrophysics

Galactic astronomy
Cosmology

Binary Systems with one Black hole and visible giant star orbit around a center of mass :

Orbits depend on masses of two objects:

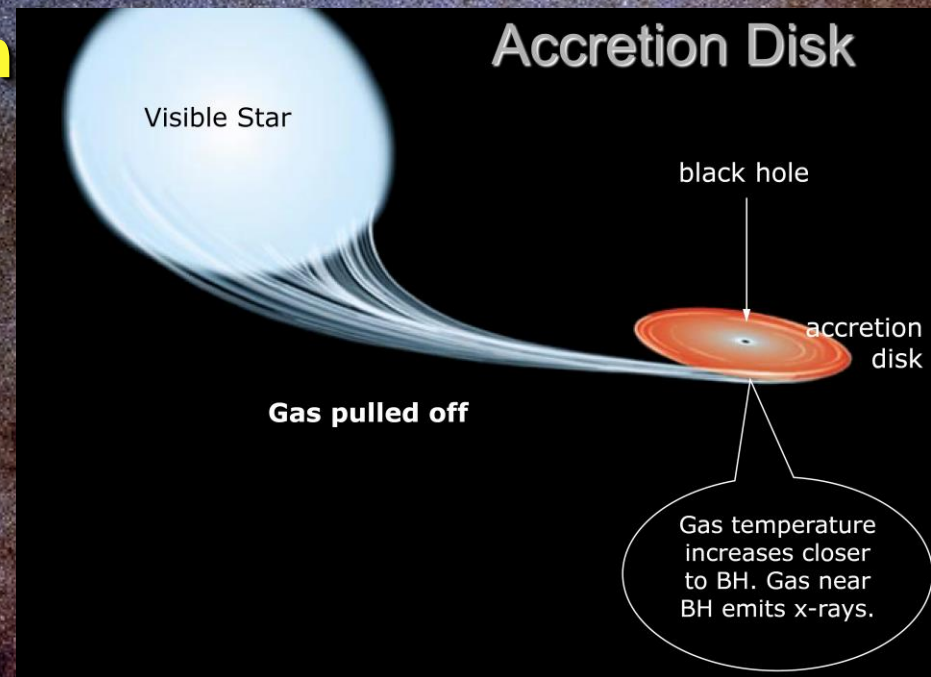
- ✓ *Motion of visible companion betrays black hole:*
 - *Kepler's 3rd law \Rightarrow total mass of the system;*
 - *If the mass of the unseen object is too big for a neutron star or a white dwarf, then it is very likely a black hole!*



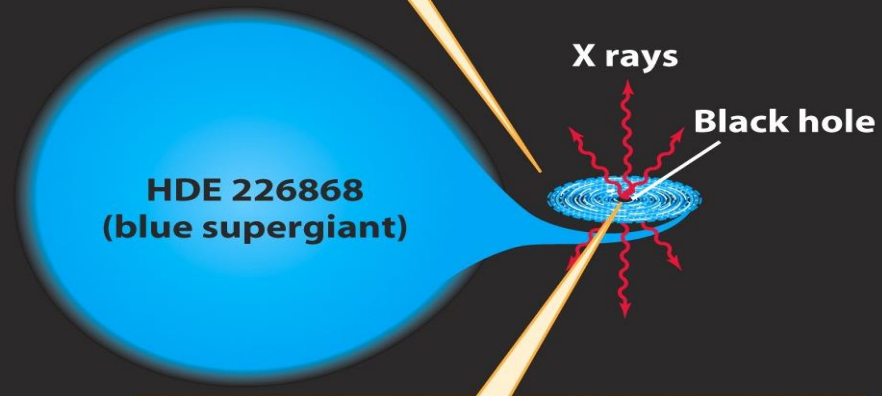
Black Holes: X-Ray Emission

- *Visible star in a binary system loses some of its gas to the black hole*
- *Gas material forms an **accretion disk** as it spirals onto the black hole*
- *Material in Disk gains energy as it falls into black hole:*
- *Gravitational energy is converted into kinetic energy (up to 40% of the mass of infalling material is converted into energy)*
- *Gas particles in the disk rub against each and heat up from friction (up to 10^7 K)*
- *Near event horizon, emitting thermal radiation peaking in X-Ray*

Black Hole are efficient « Power Factories » when they accrete!



1. Gases from the supergiant are captured into an accretion disk around the black hole.



2. As gases spiral toward the black hole, they are heated by friction: Just outside the black hole, they are hot enough to emit X rays.

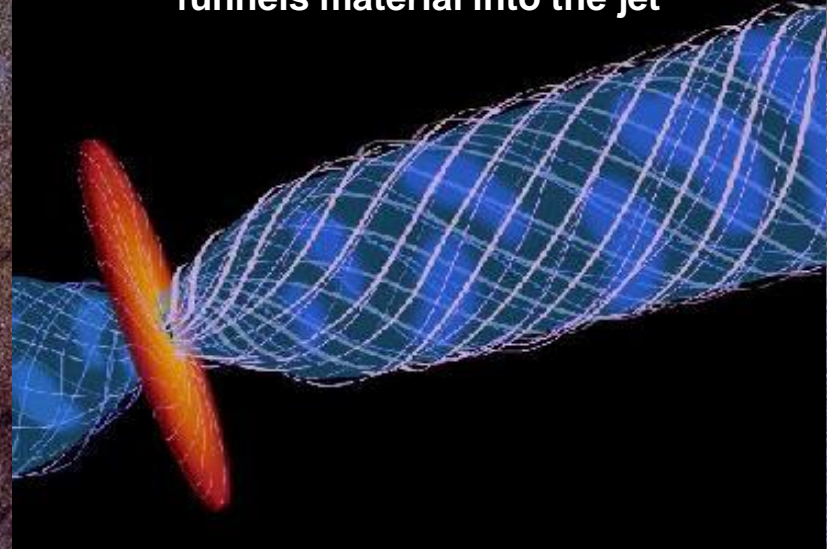
Radio Jets from Black Holes

Radio tells us about motions of particles in magnetic fields:

MANY BLACK HOLES EMIT JETS:

- *Magnetic fields surrounding the black hole produce spectacular jets of high-energy particles (B-field comes from the disk of hot gas around the BH, and not BH itself)*
- ✓ *Material in jet moving at 0.9c.*
- ✓ *Jet likely composed of electrons and positrons.*
- ✓ *Interaction of jet material with magnetic field gives rise to Radio emission.*

Magnetic field from surrounding disk funnels material into the jet



Optical image of Cen A

Cen A is known to be a peculiar galaxy with strong radio emission.



But it is also a strong X-ray emitter, and has an X-ray jet.

Chandra image of Cen A

How Do We Know Black Hole is There ?

Jets of glowing gas

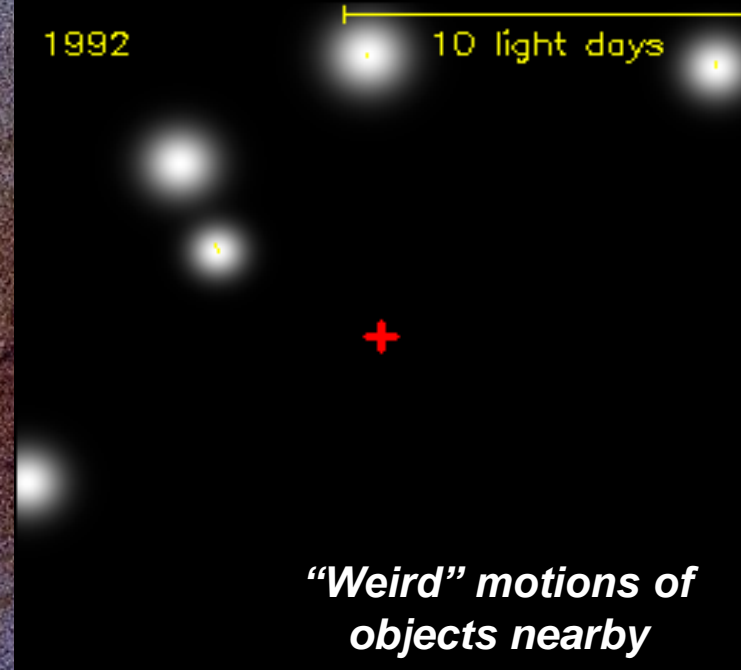


Hot material falling into the black hole.

“Weird” motions of objects nearby

1992

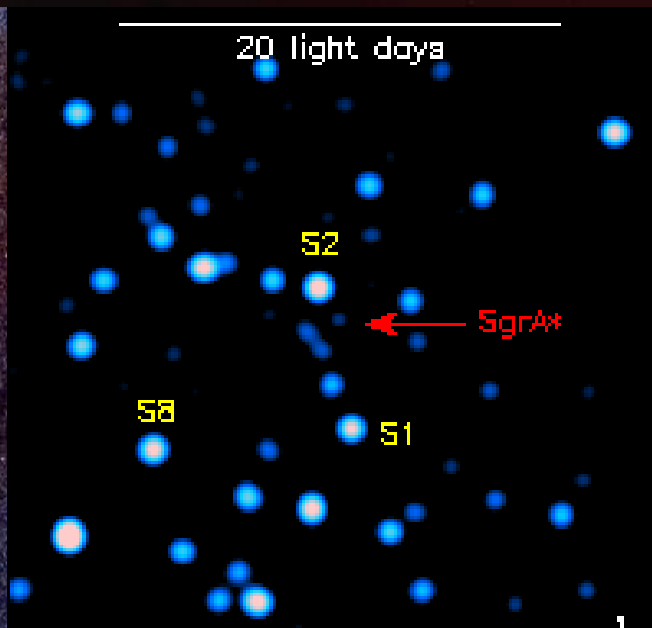
10 light days



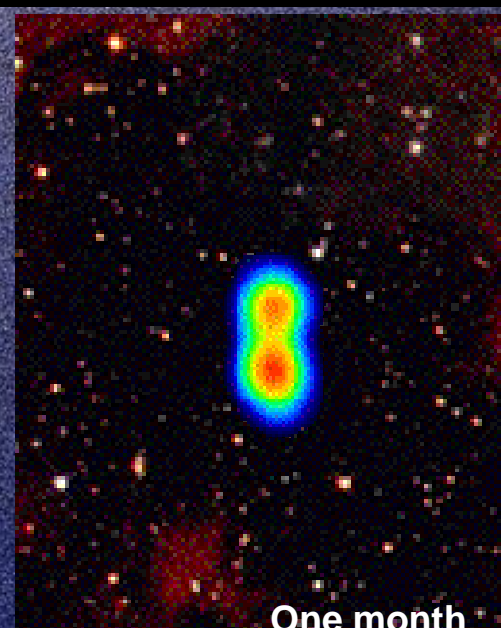
“Weird” motions of objects nearby

20 light days

Hot material falling into the black hole.

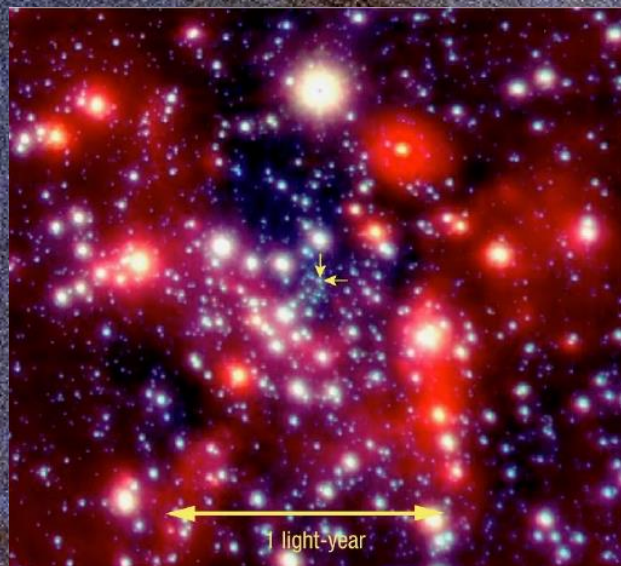


Jets of glowing gas



One month

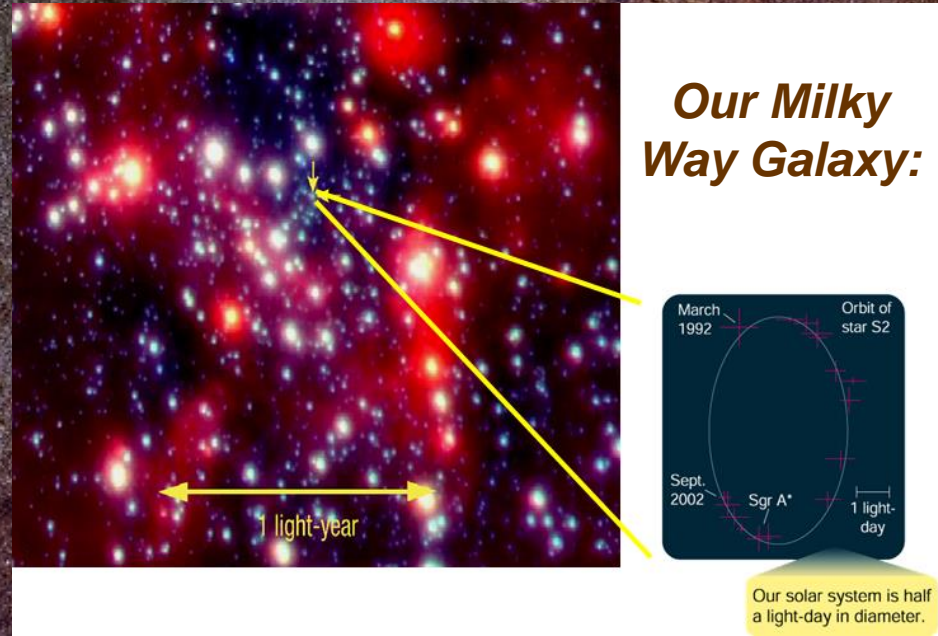
Where do Black Holes Come From ?



- ❖ **Primordial** – can be any size, including very small (If $<10^{14}$ g, they would still exist) → cannot be described only with GR, because they emit Hawking radiation and evaporate
- ❖ **“Stellar-mass” black holes** – must be at least 3 M_{\odot} to 20 M_{\odot} ($\sim 10^{34}$ g) – many examples are known
- ❖ **Mid-mass black holes** – range from 100 to 1000 M_{\odot} - located in normal galaxies – many seen
- ❖ **Massive black holes** – about $10^6 M_{\odot}$ – such as in the center of the Milky Way – many seen
- ❖ **Supermassive black holes** – about 10^9 - $10^{10} M_{\odot}$ - located in Active Galactic Nuclei, often accompanied by jets – many seen

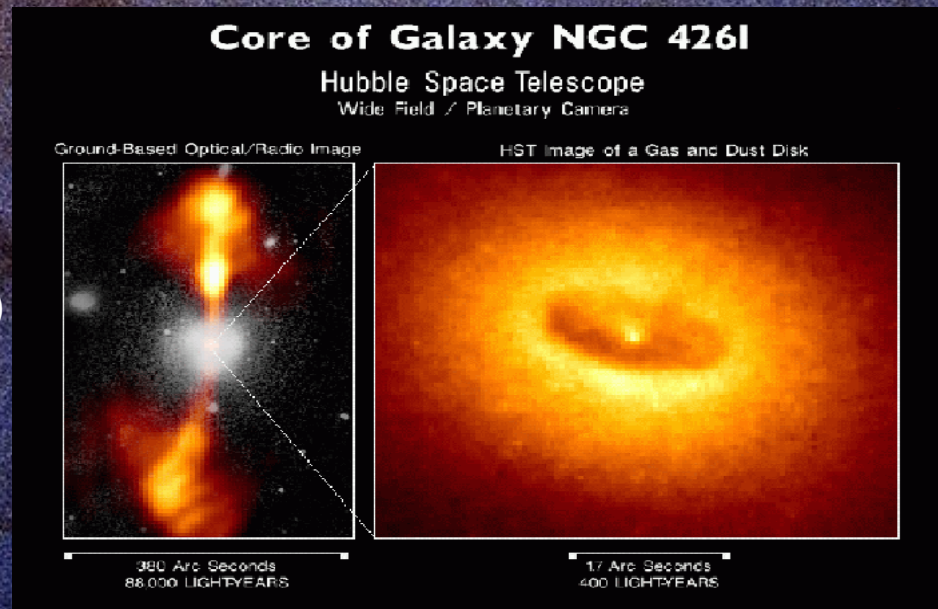
Where do Supermassive Black Holes Come From ?

- ✓ Cores of many other galaxies show compact objects in the centers and accretion disks with possible black holes ;
- ✓ Following the orbits of individual stars near the center of the Milky Way, the mass of the central BH is ~ 2.6 million solar masses;
- ✓ *We don't know which comes first, the galaxy or the black hole*



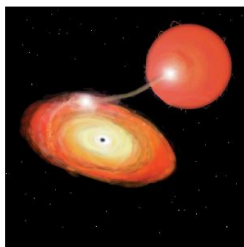
Super-Massive Black Hole Theories:

- **From “Lumps” in the early universe** (lumps in early Universe could have formed and of matter dense enough that a black hole formed)
- **The “Stellar Seed” Model** (giant black hole could result in an initial “stellar seed” of 10 mass of sun produced during a supernova)
- **Collapse of a whole star cluster** (stars from a tight cluster in early Universe could form a few Black Holes, causing smaller stars to be absorbed, and black holes to combine)



Where do Stellar-mass Black Holes Come From ?

- *Stellar-mass black holes are made when a massive star, many (3 – 20) times the mass of our Sun, dies*
- *Most of the star's atmosphere is blown into space as a supernova explosion.*
- *The star's spent core collapses under its own weight.*
- *If the remaining mass is more than the mass of 3 Suns, it will collapse into a black hole.*



**Stellar-mass
BHs**

- Masses: $\sim 3-100 M_{\text{sun}}$
- Originated from collapses of massive stars
- Distributed within galaxies
- Shine in X-ray when accreting from a companion star – X-ray binary

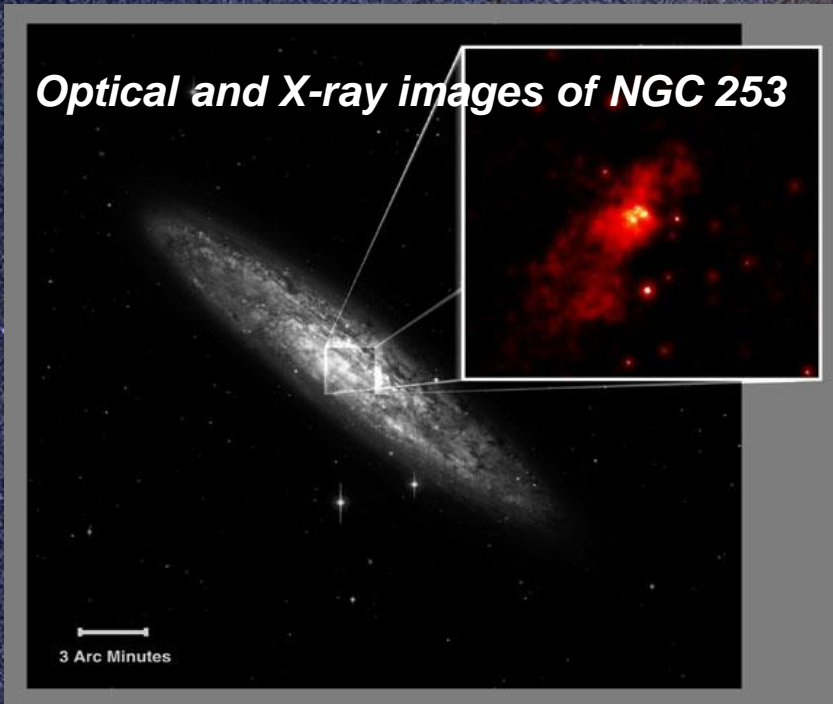


SMBHs

- Masses: $\sim 10^6-10^{10} M_{\text{sun}}$
- Origin???
- Located at the center of galaxies
- Shine in optical/UV when accreting materials near the galactic centers -- AGN

Where do Mid-Mass Black Holes Come From ?

Optical and X-ray images of NGC 253



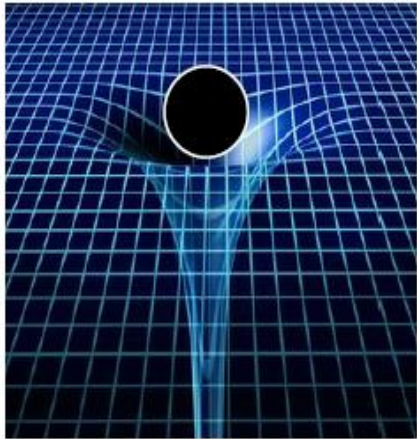
Star cluster, called M15, in our Galaxy:



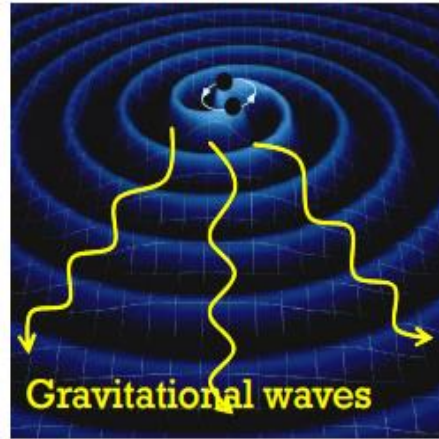
- ✓ **Black Holes with masses a few hundred to a few thousand times the mass of the sun have been found outside the central regions of a number of galaxies**
- ✓ **Often found in Starburst galaxies (in centers of large, dense star clusters)**
- ✓ **May be precursors to Active Galaxies**

A New Golden Age for Gravitation

A static black hole



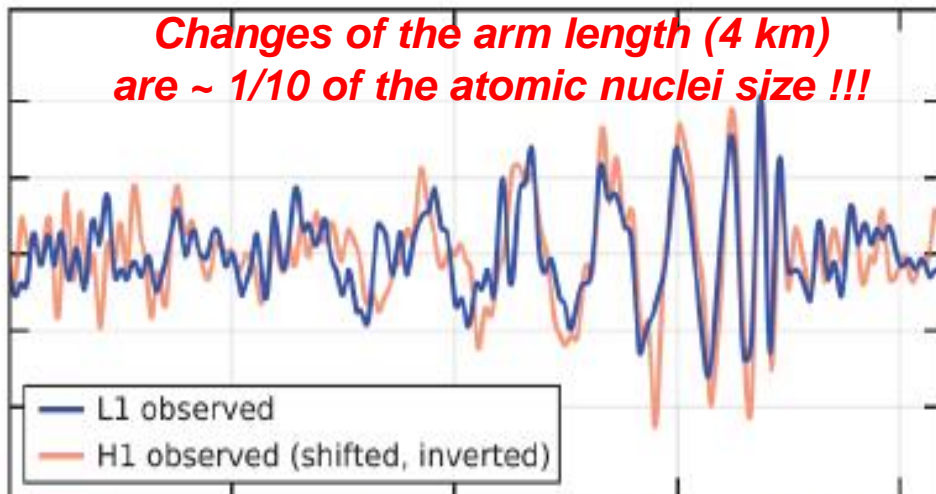
Two orbiting black holes



- ❖ Gravitational physics is entering a **new golden age**
- ❖ A wealth of data, from **gravitational waves to EHT observations**, is opening new doors for potential discoveries.
- ❖ In the coming years, especially with **LISA** and **3G** detectors, we will be doing “**precision** gravitational-wave physics”.
- ❖ Plenty of room for **unexpected** discoveries

Gravitational wave detection (interferometer):

Changes of the arm length (4 km) are ~ 1/10 of the atomic nuclei size !!!



Credit: (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. 116, 061102

**Event Horizon Telescope -
First real image of Black Hole:**



Credit: Event Horizon Telescope collaboration