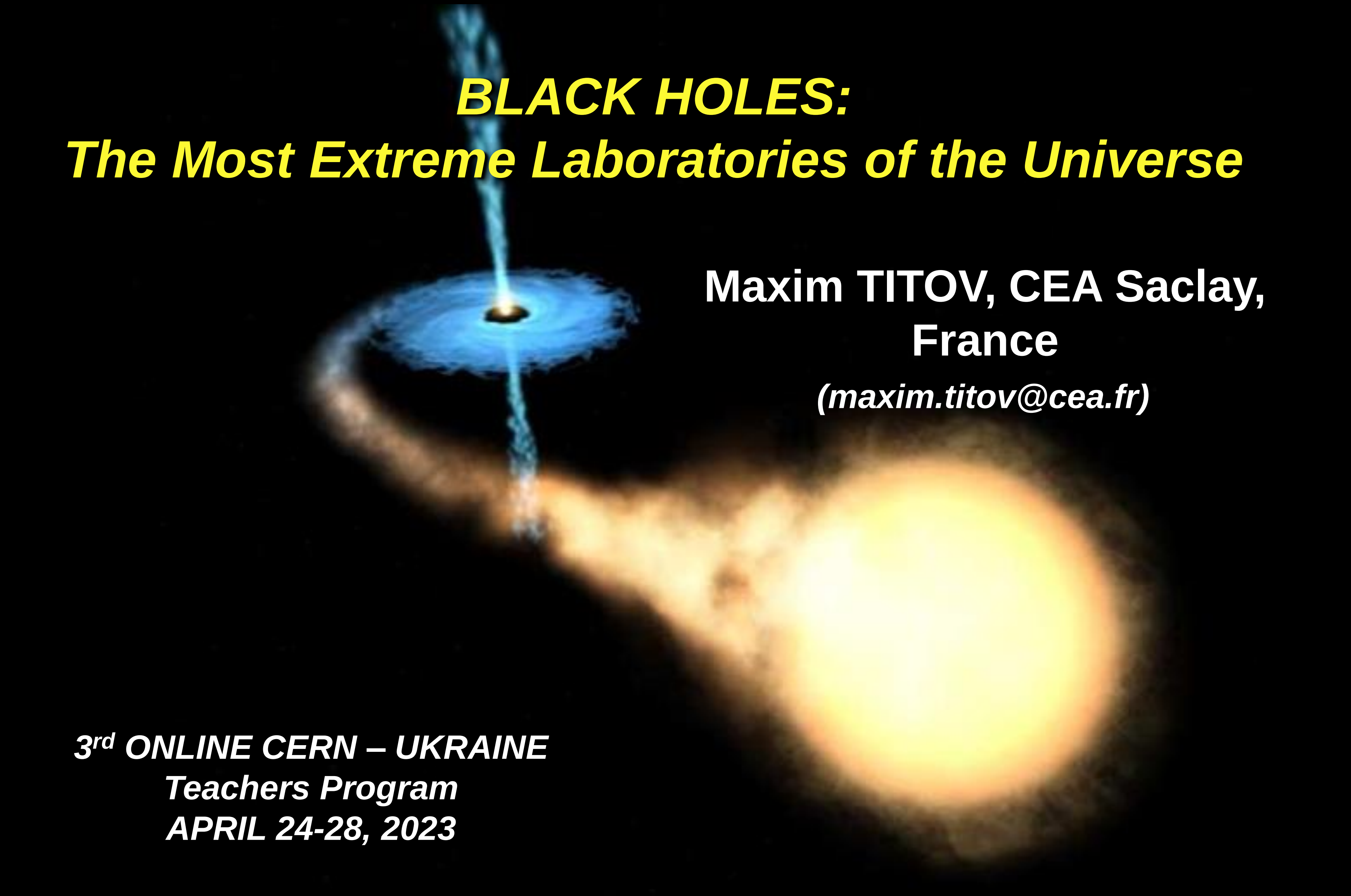
BLACK HOLES:
The Most Extreme Laboratories of the Universe

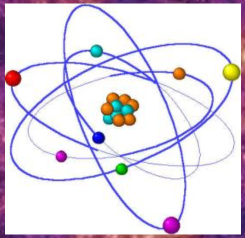
Maxim TITOV, CEA Saclay, France
(maxim.titov@cea.fr)

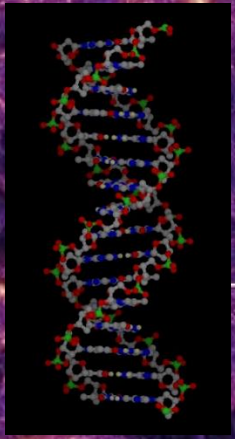
3rd ONLINE CERN – UKRAINE
Teachers Program
APRIL 24-28, 2023

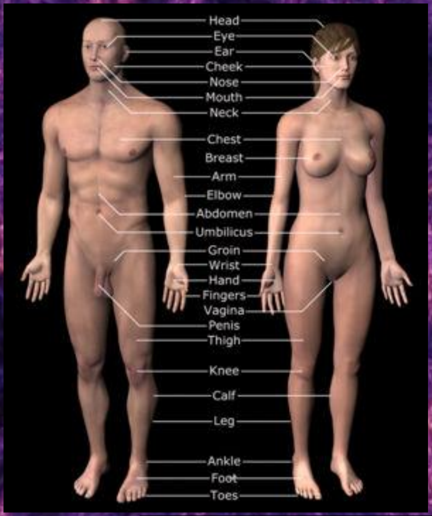


Artist's View of Black Hole and Companion Star GRO J1655-40
ESA, NASA and F. Mirabel (CEA) ▪ STScI-PRC02-30

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



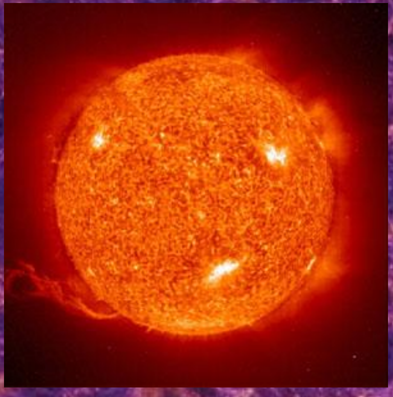




Where did we come from?

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 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.

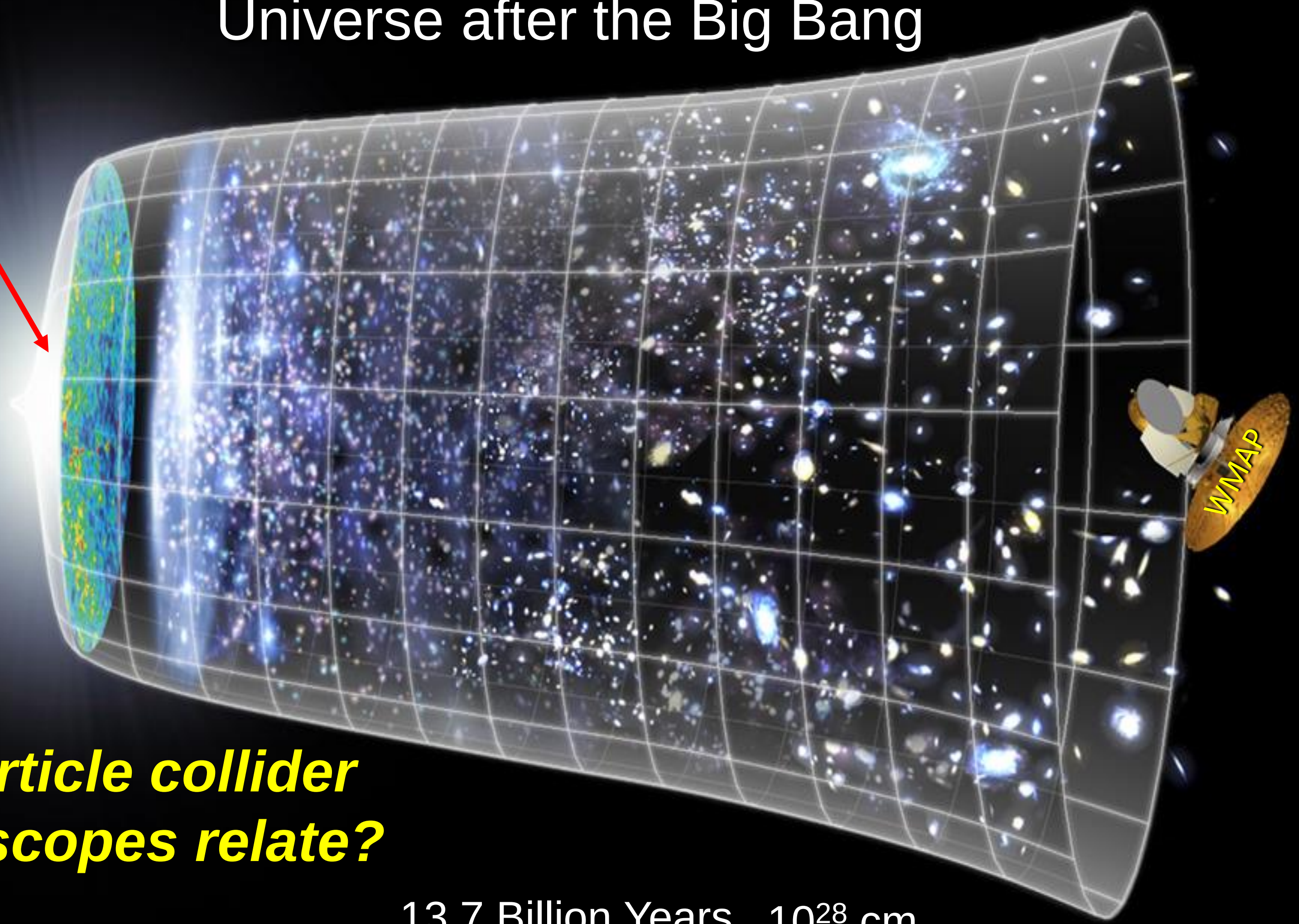
WAITBUTWHY

Today's Scientific Challenge

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

What happened then ?

Big Bang



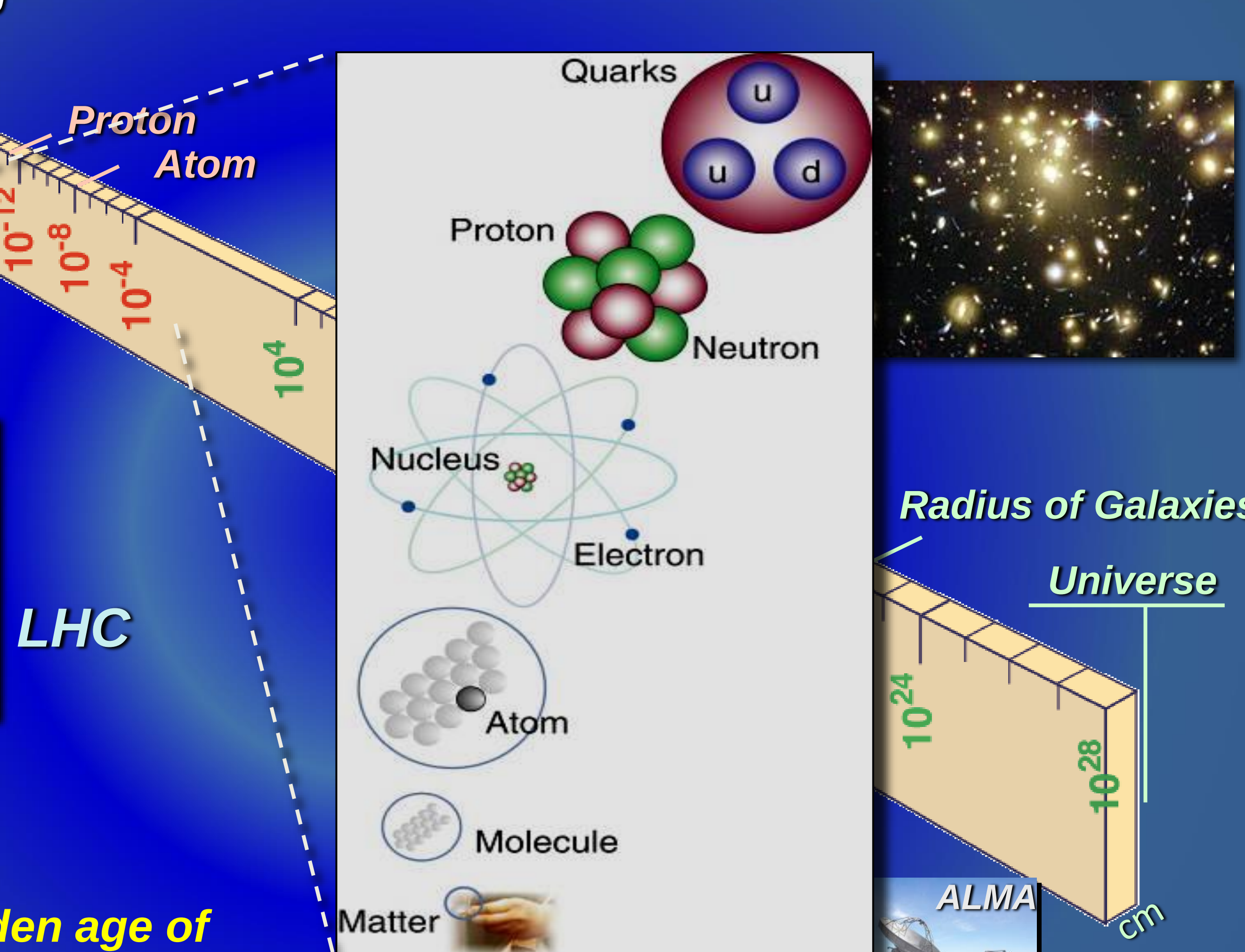
How particle collider and telescopes relate?

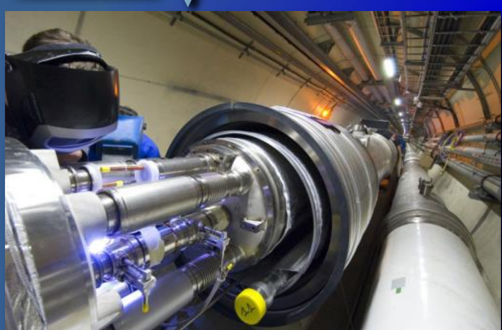
13.7 Billion Years, 10^{28} cm

Today

What is Universe made of ?

PHYSICS OF TWO INFINITIES





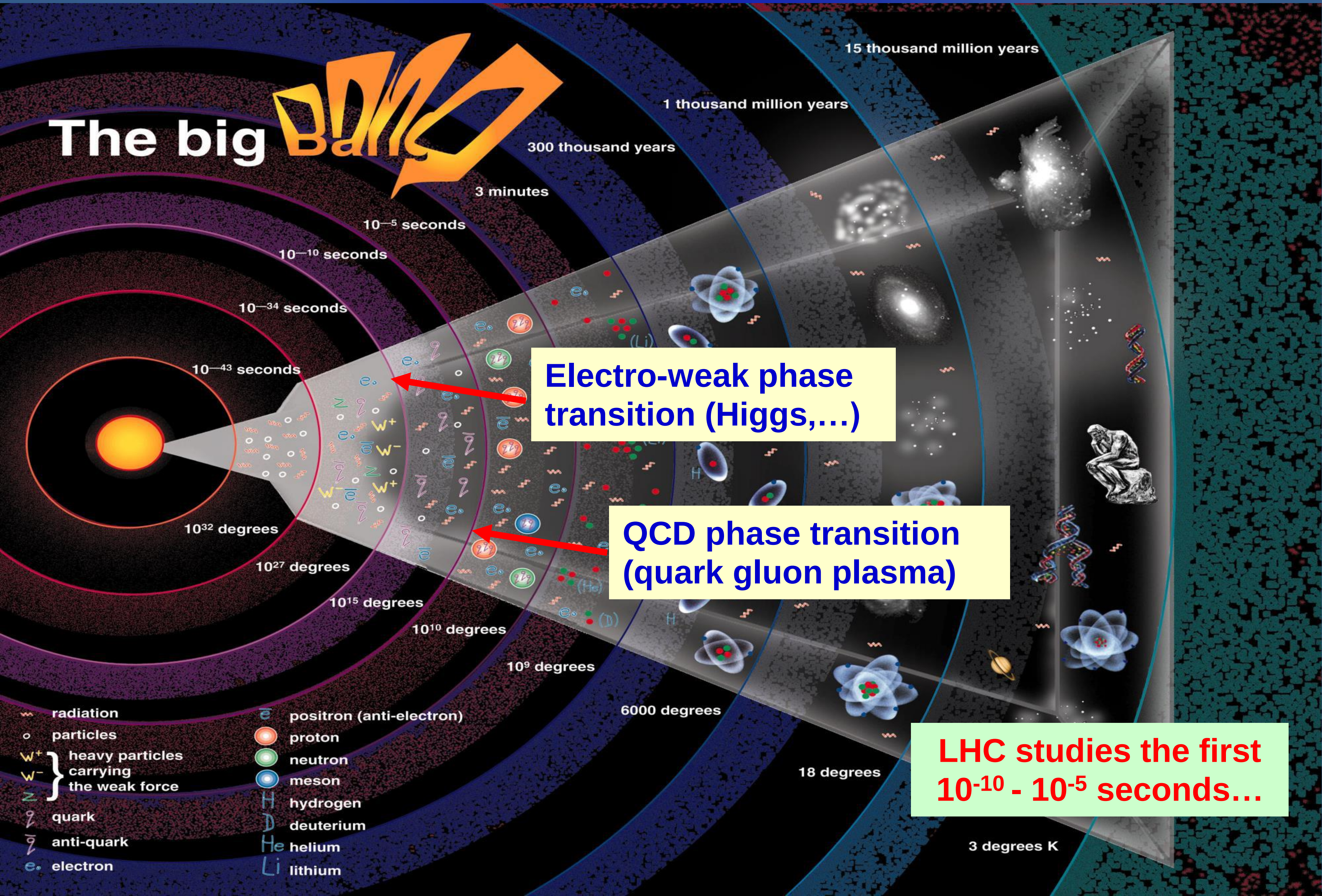
LHC

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.

Brief History of Our Universe and Physics at LHC



Electro-weak phase transition (Higgs,…)

QCD phase transition (quark gluon plasma)

LHC studies the first 10^{-10} - 10^{-5} seconds…

Matter Content of Our Universe

→ We know only 5% of it ...

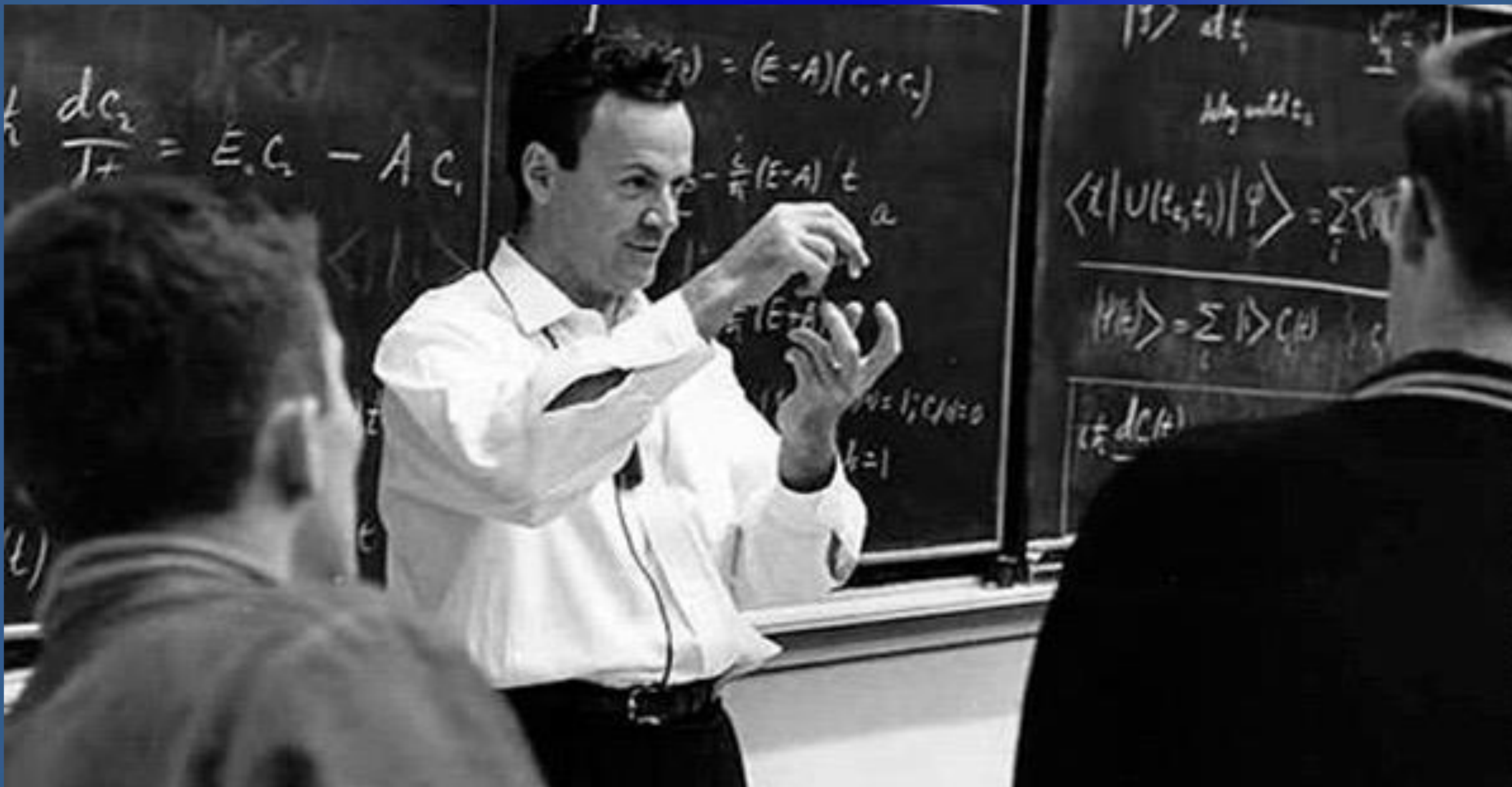
- ✓ **Dark Matter (27%) → Can be detected only from its gravitational effects**
- ✓ **Dark Energy (68%) → Expansion of Universe is faster than “expected” (Big-Bang + relativity)**

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 полным-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*

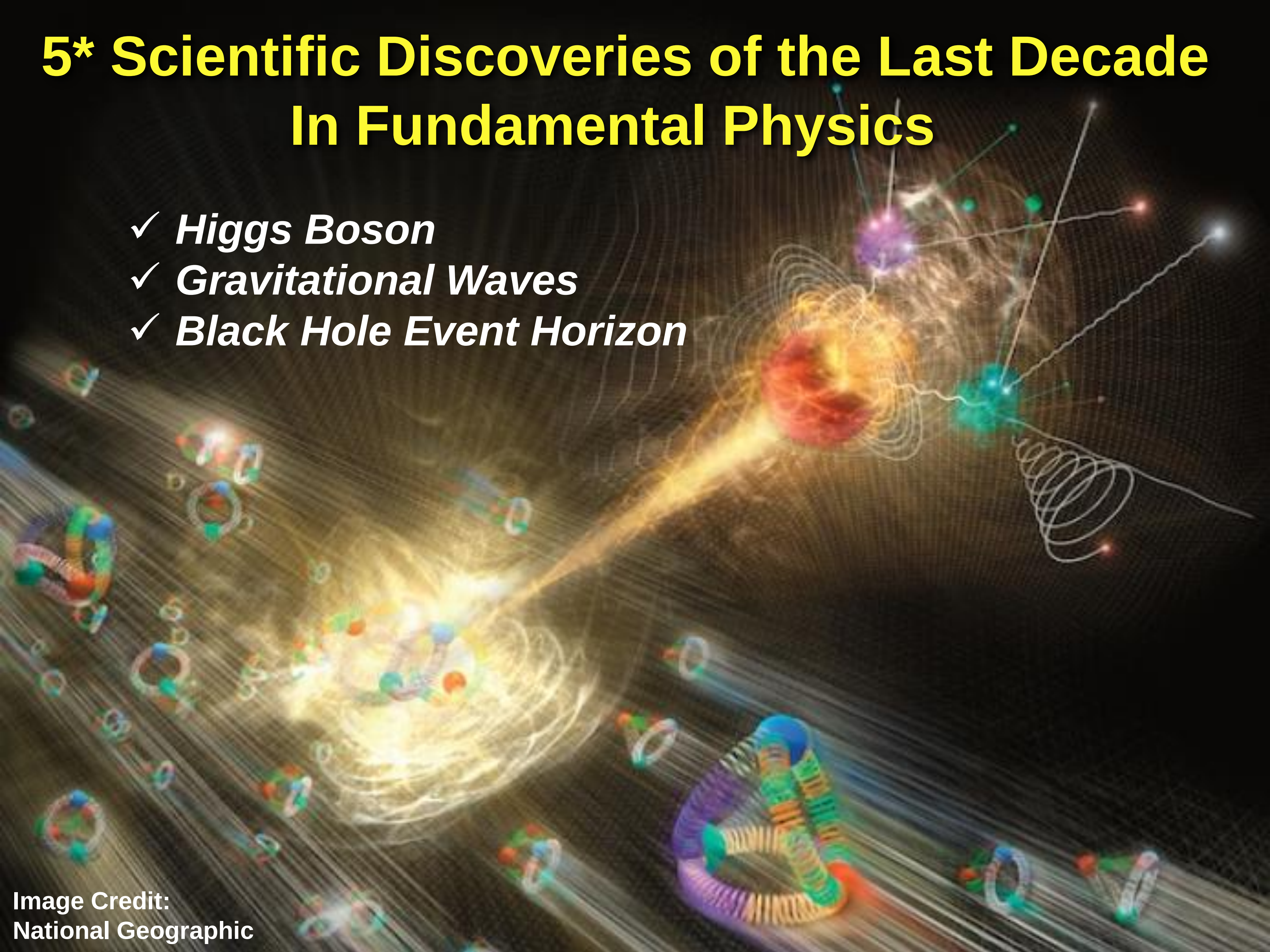


Image Credit:
National Geographic

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

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


Libération
Physique des particules
La masse est dite
Le Cern a réussi à mettre en évidence le boson de Higgs qui résout une énigme fondamentale et ouvre une nouvelle étape scientifique.
Les derniers feux des pharaons
Suicides chez France Télécom : l'ancien patron mis en examen
A nos lecteurs


The New York Times
Wednesday, July 4, 2012
TRY A TIMES DIGITAL SUBSCRIPTION: 4 WEEKS FOR 99¢.
Rapid H.I.V. Home Test Wins Federal Approval
As Bank Frames a Defense, Barclays' C.E.O. Resigns
New Particle Could Be Physics' Holy Grail
By DENNIS OVERBYE
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
As Symbols Clash, Fireworks Lose Out to a Hamlet's Bald Eagles


GENEVA, 4TH JULY 2012
Higgs within reach
Our understanding of the universe is about to change…


Le Cern a mis la main sur le boson de Higgs
Les capteurs de l'Organisation européenne pour la recherche nucléaire ont détecté le nouveau Graal de la physique.


Le Monde
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
ALGÉRIE L'INDÉPENDANCE
M. Ayrault, la fin de la pensée magique


vk.nl
Higgs of niet, het is een spectaculaire ontdekking


Le Monde.fr
Le boson de Higgs découvert avec 99,9999 % de certitude


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

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 fundamentl 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?*

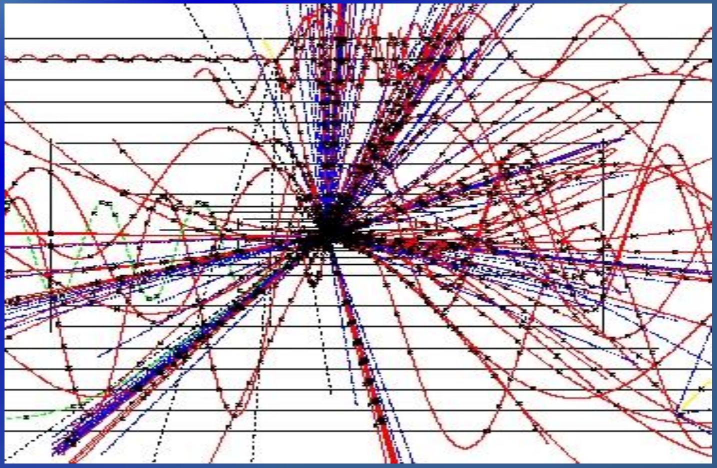
- ***Micro black holes @ LHC:***

  Mass: $M_{BH} \sim 1000\ M_{proton}$

  Size: 10^{-18} m

  Temperature: 10^{16} K

  Lifetime: 10^{-27} s

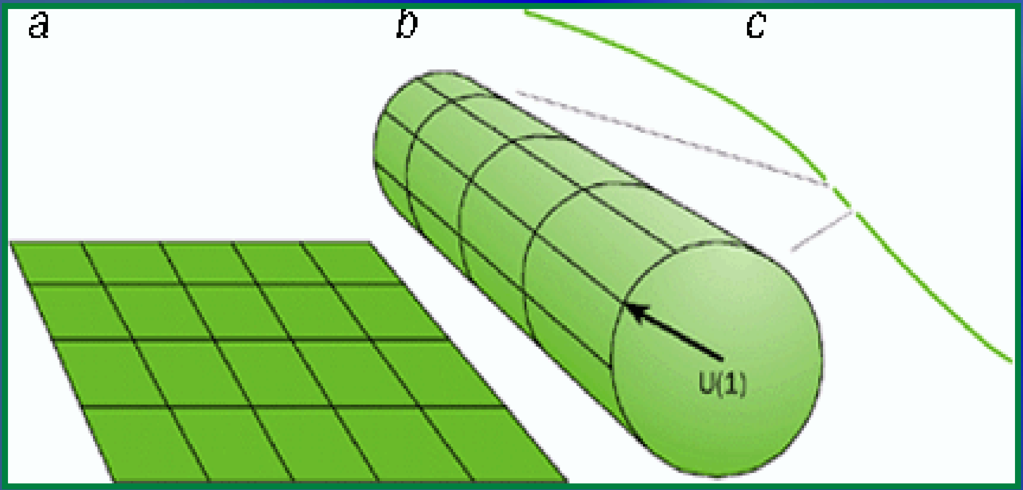


https://www.forbes.com/sites/startswithabang/2016/03/11/could-the-lhc-make-an-earth-killing-black-hole/#2fe64fd02ed5

Large Extra Dimensions – A Little Bit of History …

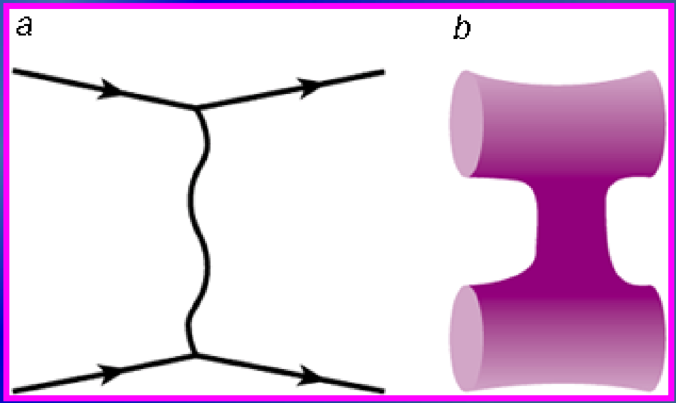
- *Once upon a time (1921), Theodor Kaluza in the hope of unifying gravitation and electromagnetism extended general relativity by including the U(1) symmetry of electromagnetism by adding a 4th spatial dimension.*

- *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.*



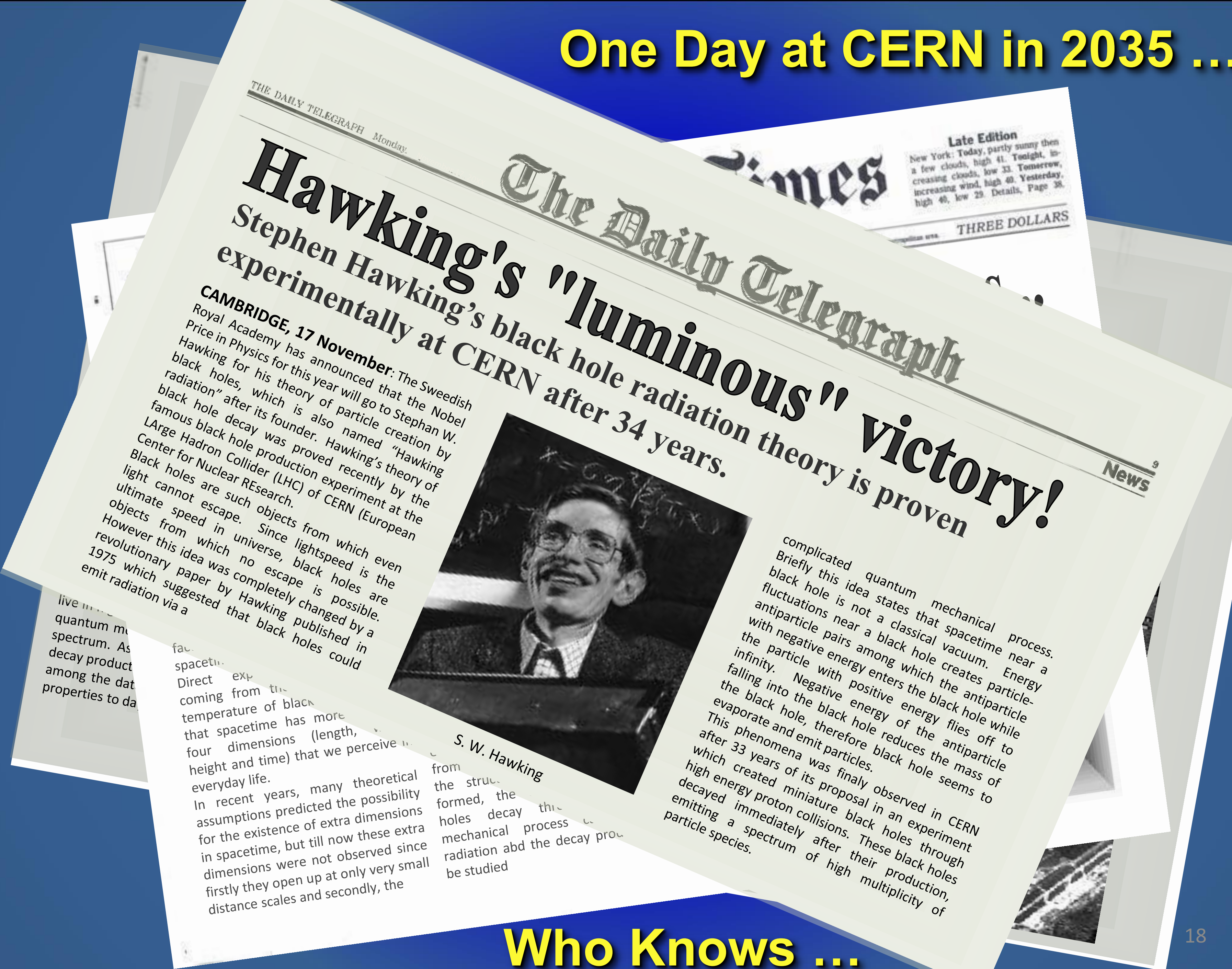
- *In the 1970's and 1980's there's been renewed interest in (multiple) extra dimensions: SUSY and string theory.*

- *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 …

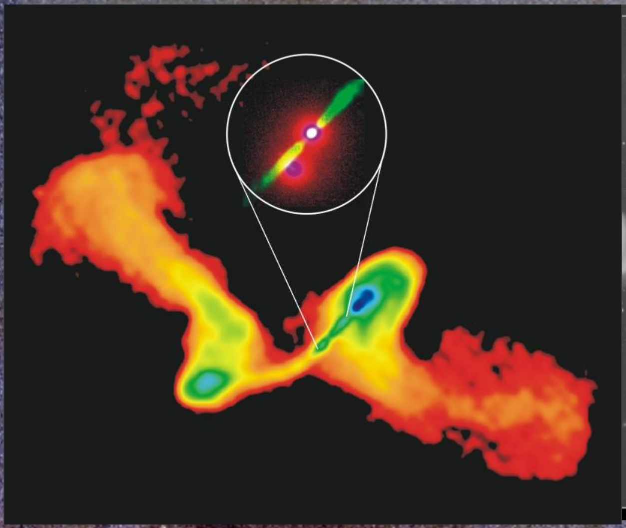


Who Knows …

II. Gravitational Waves – LIGO Observatory (2016)

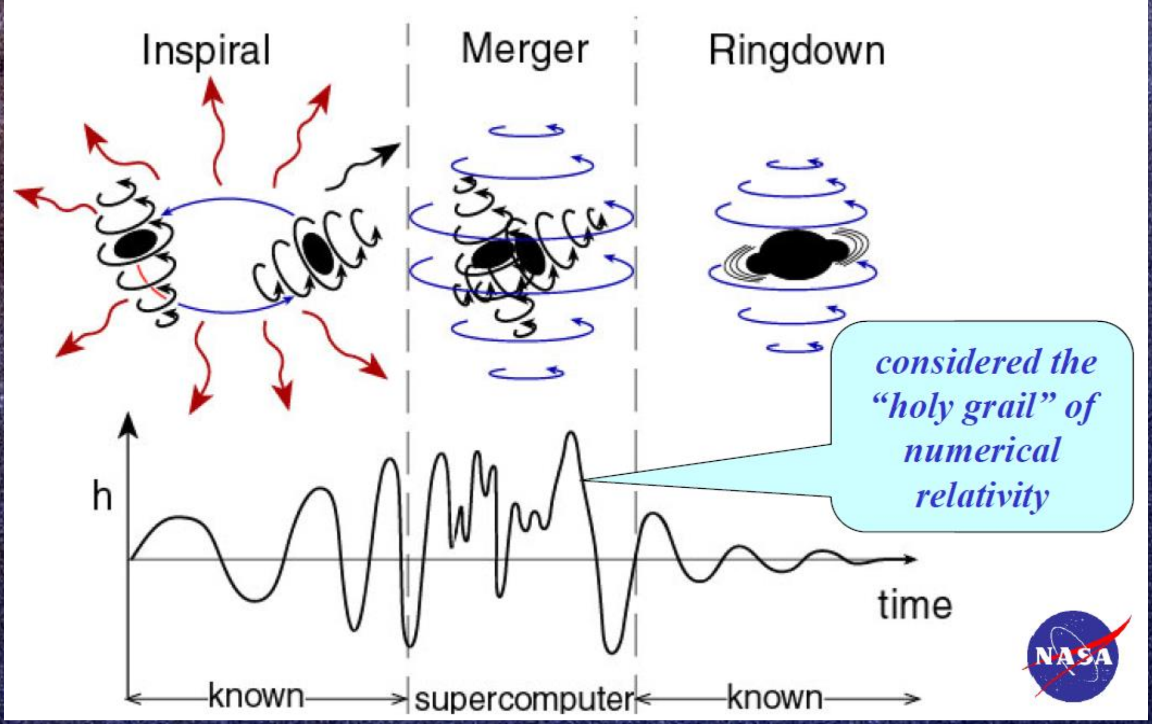
Gravitational Waves Encode Dynamics of Massive Objects

- *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:*

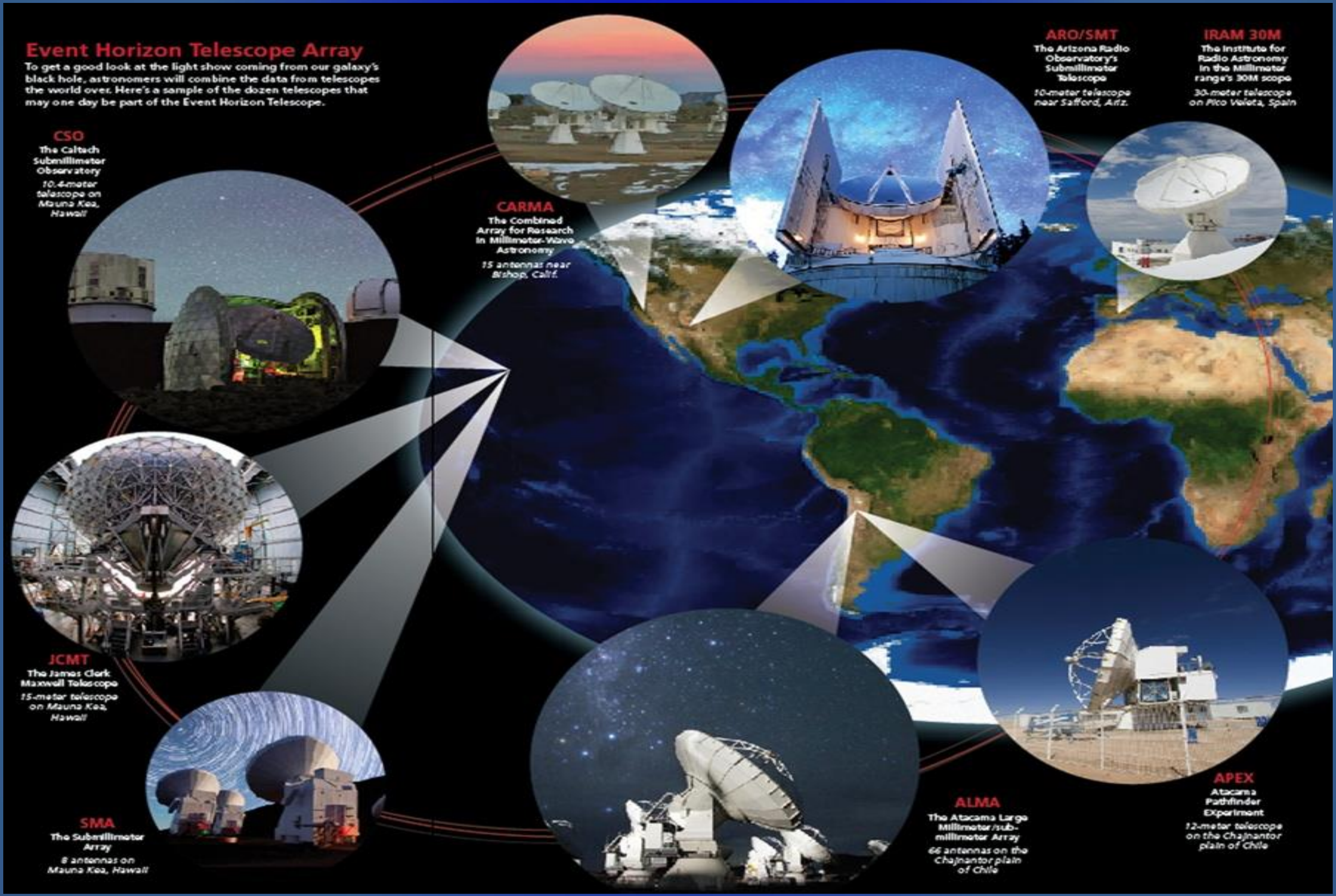
  → Requires numerical relativity to calculate dynamics & waveforms
  → Waveforms scale w/ masses, spins → apply to ground-based & LISA



III. M87 Black Hole – Event Horizon Telescope (2019)

Event Horizon Telescope (EHT)

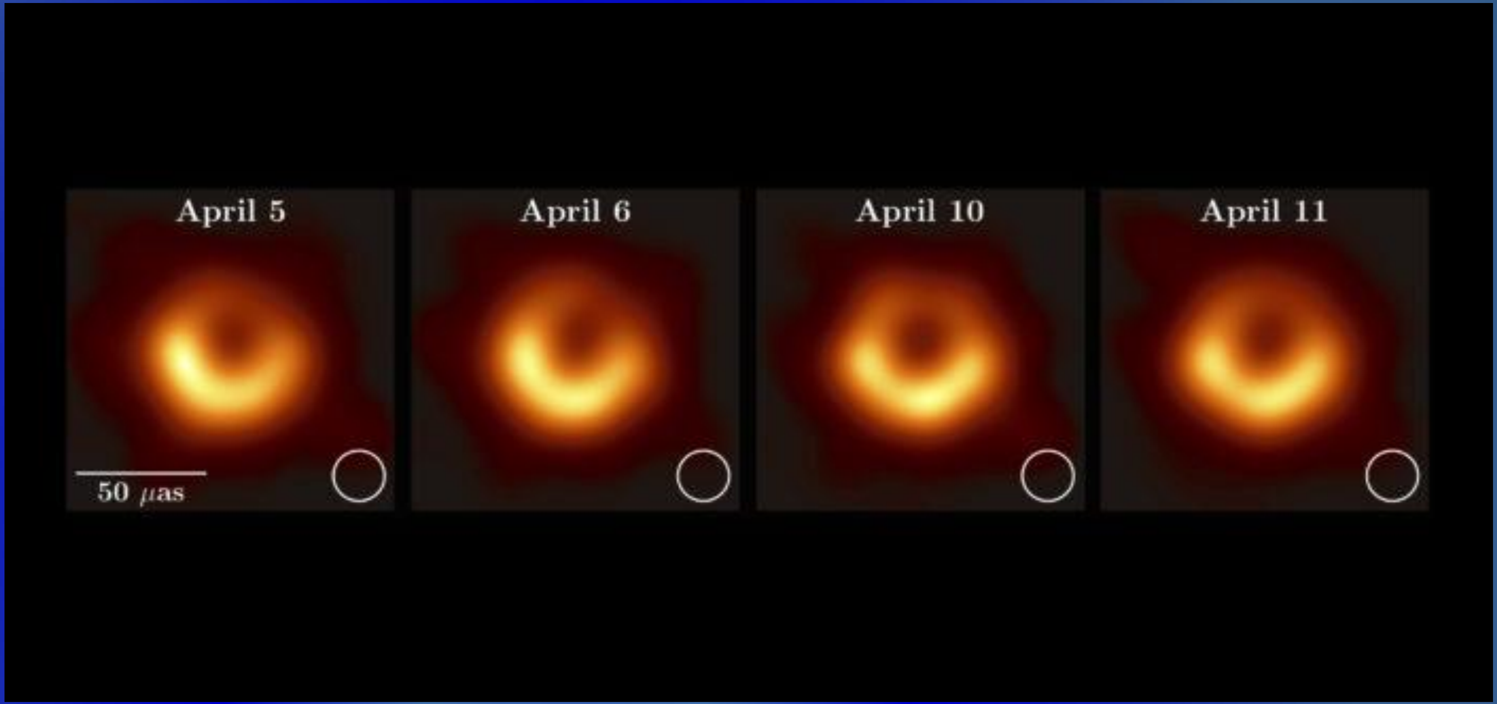
8 telescope array at radio frequency around the Earth



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.

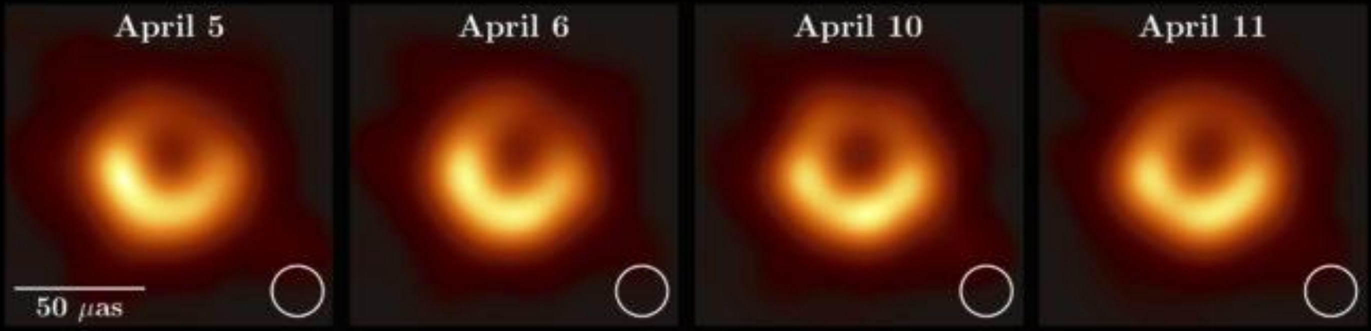


- ***It was found in a galaxy called M87 and is larger than the size of our entire Solar System.***
- ***The black hole is 500 million trillion km away and it was captured by the Event Horizon Telescope (EHT), a network of eight linked telescopes around the world.***
- ***"It has a mass 6.5 billion times 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.



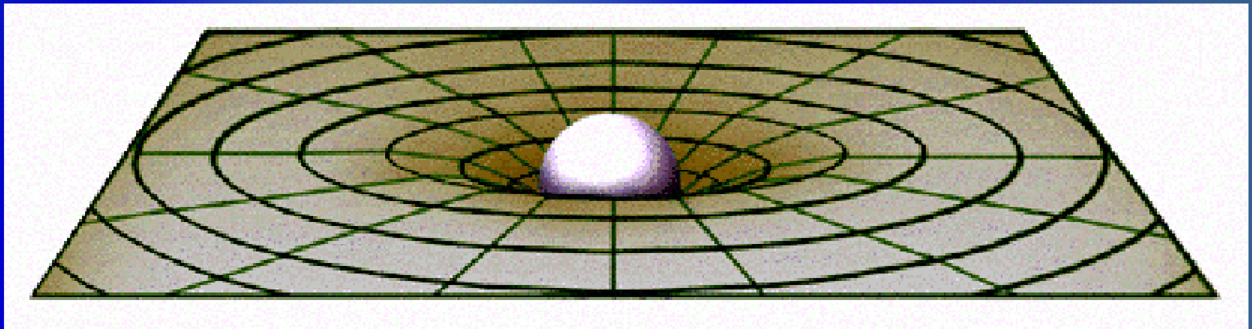
- *It was found in a gala...*
- ...n
- *...of the Sun. And it is one of the heaviest black holes ...ists. It is an absolute monster, the heavy weight champion of black holes in the Universe”*

What Are We Seeing in This image ?

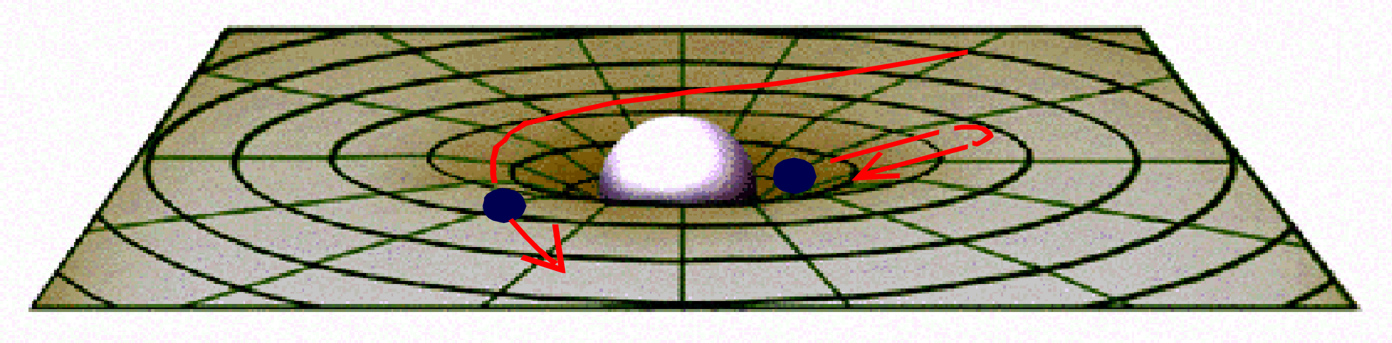
- **The first DIRECT evidence for black holes!!**
- **Black holes are REALLY BLACK, consistent with GR predictions**
- **The bright ring comes from emission of the accreting materials**

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).



"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.*

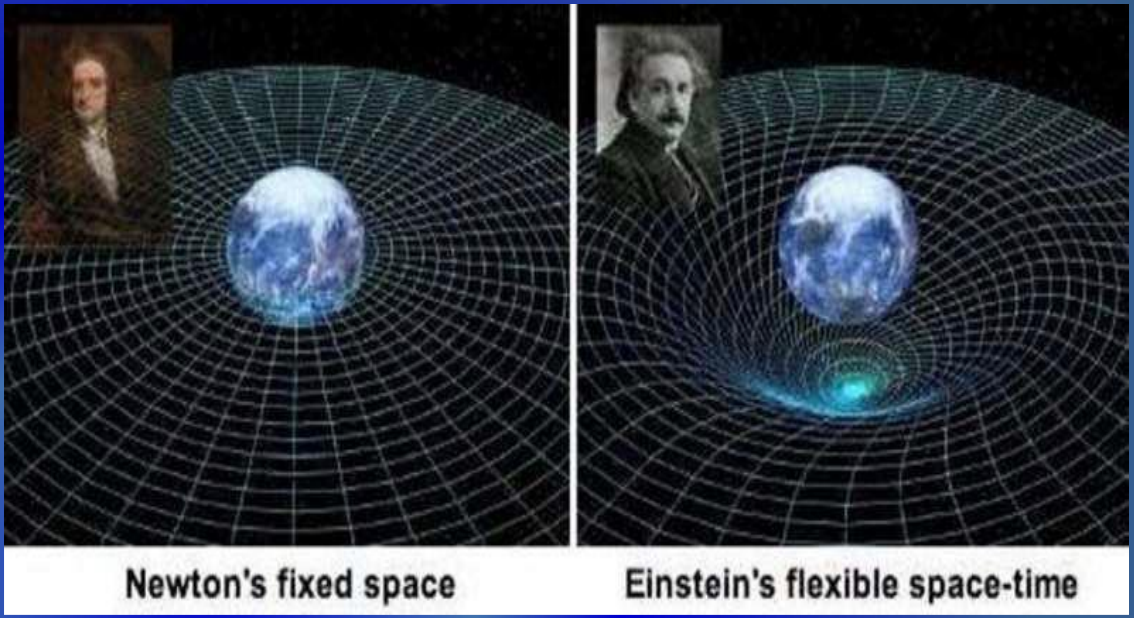
$$\mathbf{G} = 8\pi\mathbf{T}$$

Describes curvature of space-time (G) — ***Mass-energy density of matter*** (T)

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.

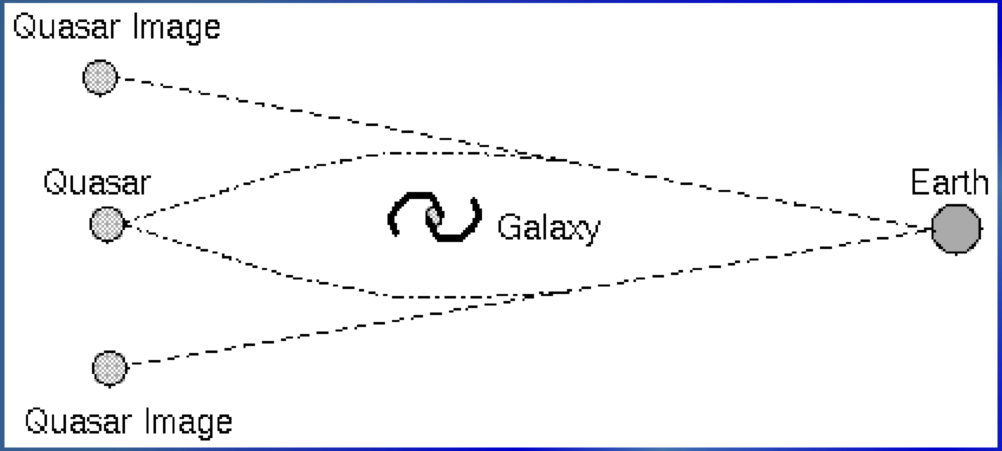
- Einstein's theory says
that the presence of matter warps space and time. Gravity is replaced by warping of space-time.

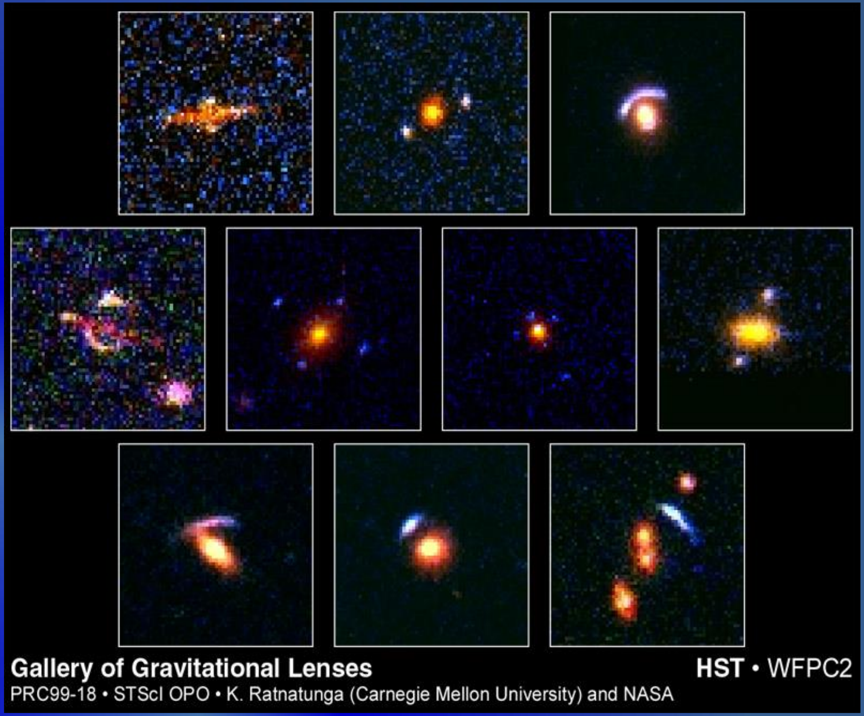


- ***GR remains one of the most accurate theories in physics:***
  - Precession of the perihelion of Mercury
  - Light will be bent when passing near large objects
  - Time will slow down near a large mass
  - Gravitational redshift of light
  - Gravitational Waves
  - ***Massive objects will collapse 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)*



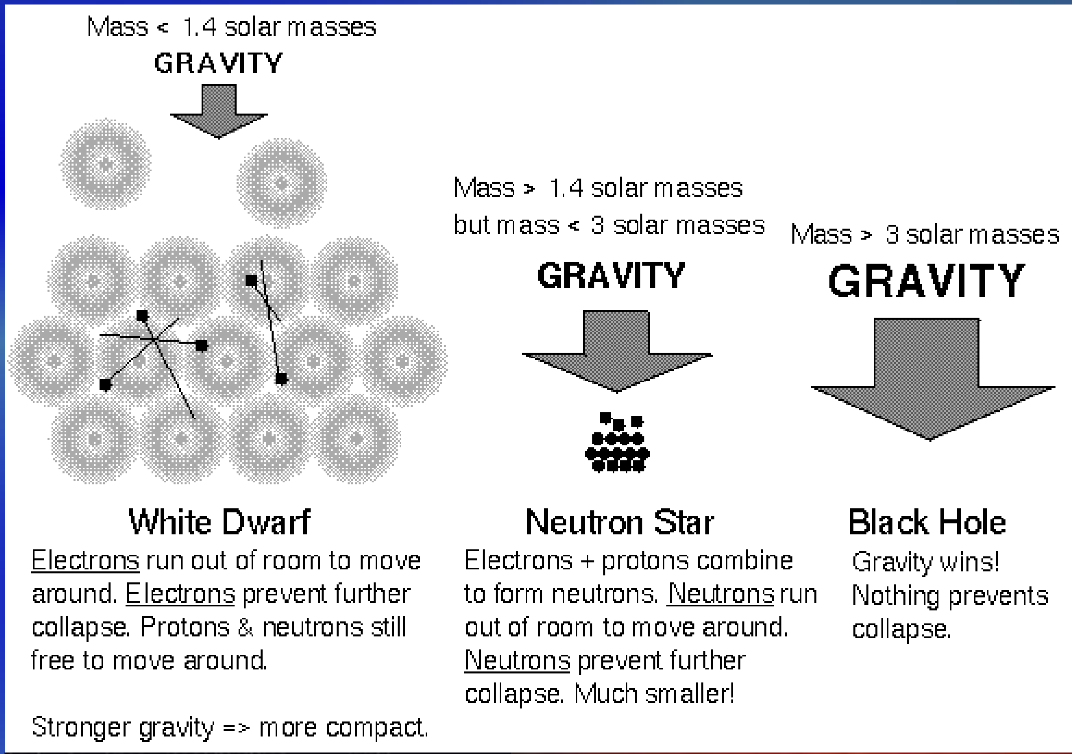


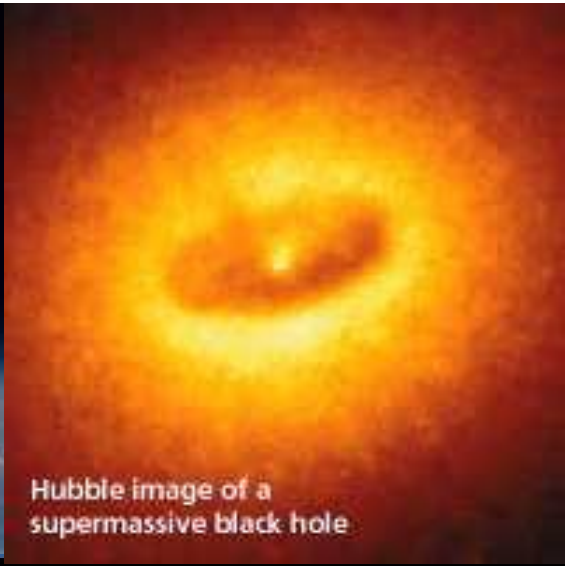
Can be used to estimate the mass of intermediate galaxy

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_{sun} leaves behind a core larger than 3 M_{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.*

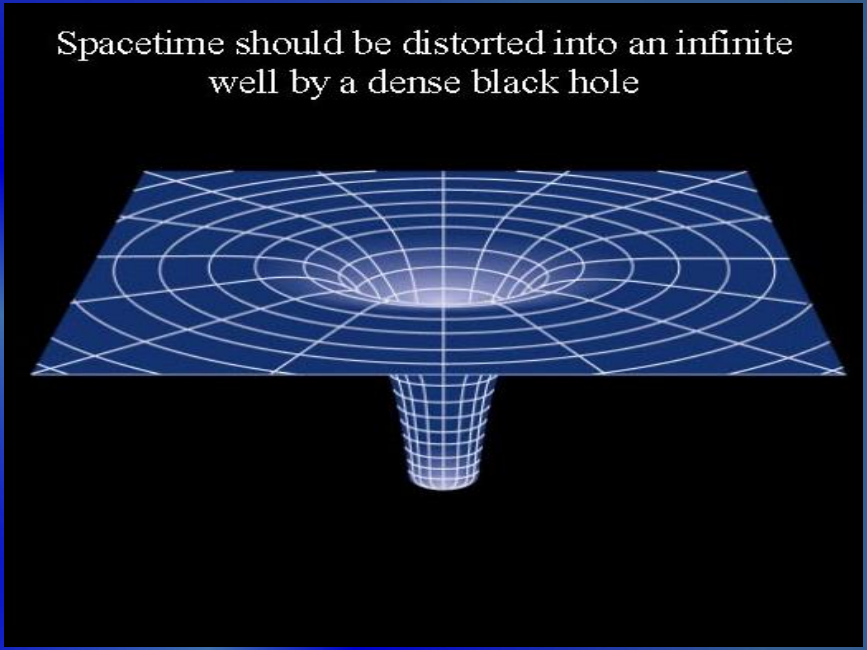


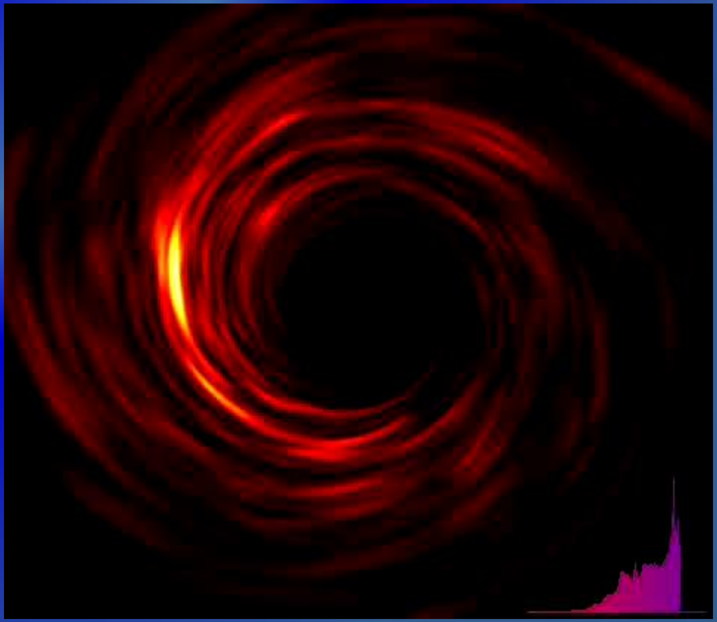


Black Hole: A Theoretical Definition (I)

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

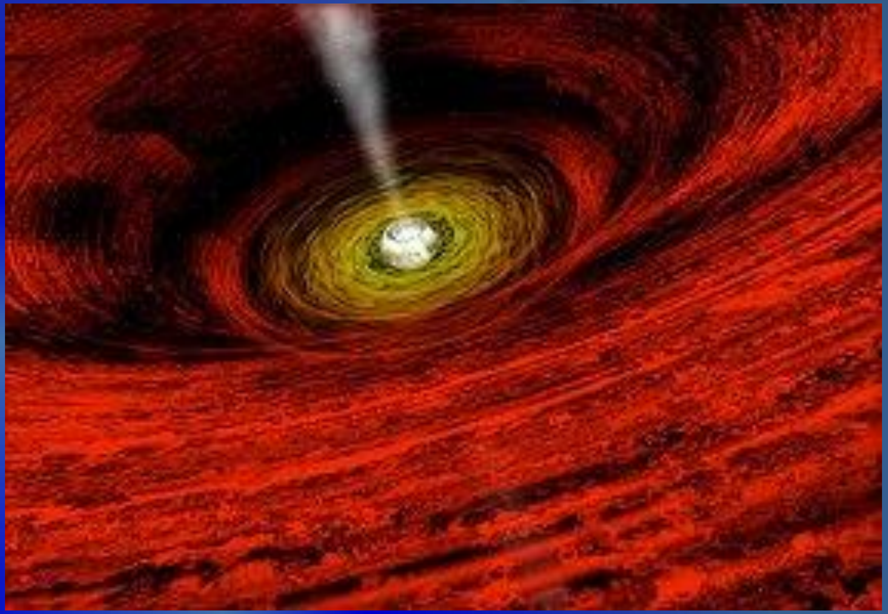
- ✓ ***A black hole is a true "hole" in space: Anything that crosses the edge of the hole - called the "event horizon" - is swallowed forever***
- ✓ ***As you get closer to a black hole, the flow of time slows down, compared to flow of time far from the hole.***
- ✓ ***At the event horizon, time actually 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.***

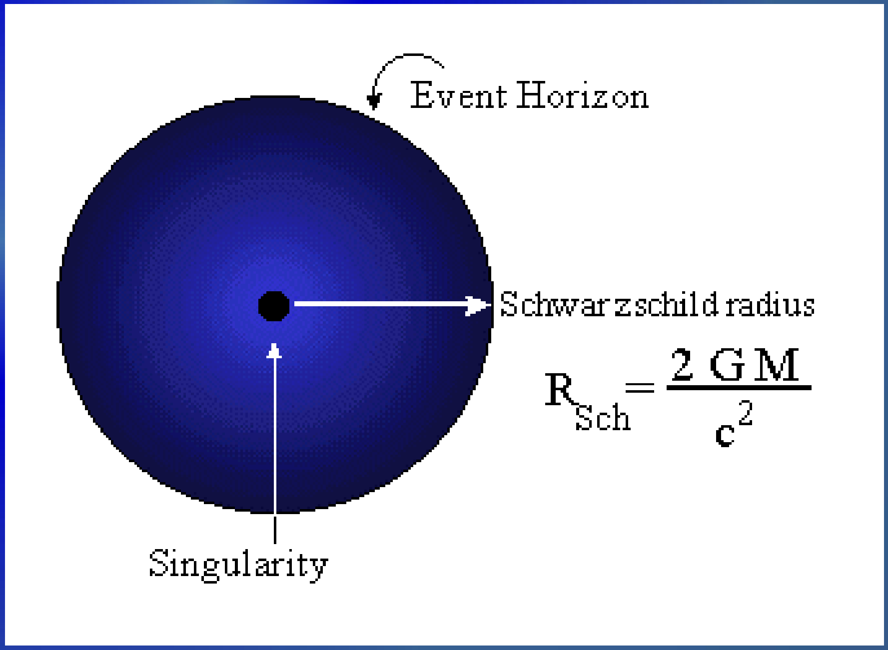




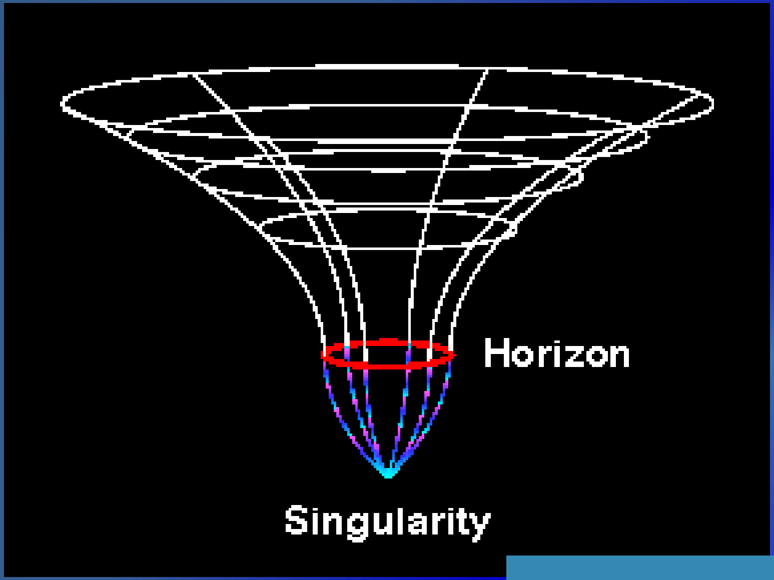
Black Hole: A Theoretical Definition (II)

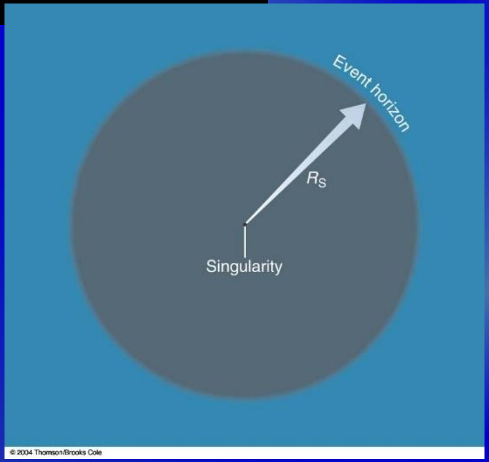
- ✓ The **black hole** is surrounded by an "event horizon" which is the sphere from which light cannot escape;
- ✓ The distance between the black hole and its event horizon is the Schwarzschild radius ($R_{Sch} = 2GM/c^2$);
- ✓ The center of the black hole is a point of infinite density and zero volume, 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





General relativity breaks down at Planck scale:

$$l_p = \sqrt{\frac{G\hbar}{c^3}} \sim 1.6\times10^{-35}\ \mathrm{m}$$

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.*

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

Schwazschild radius

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

GRAVITATIONAL COLLAPSE AND SPACE-TIME SINGULARITIES

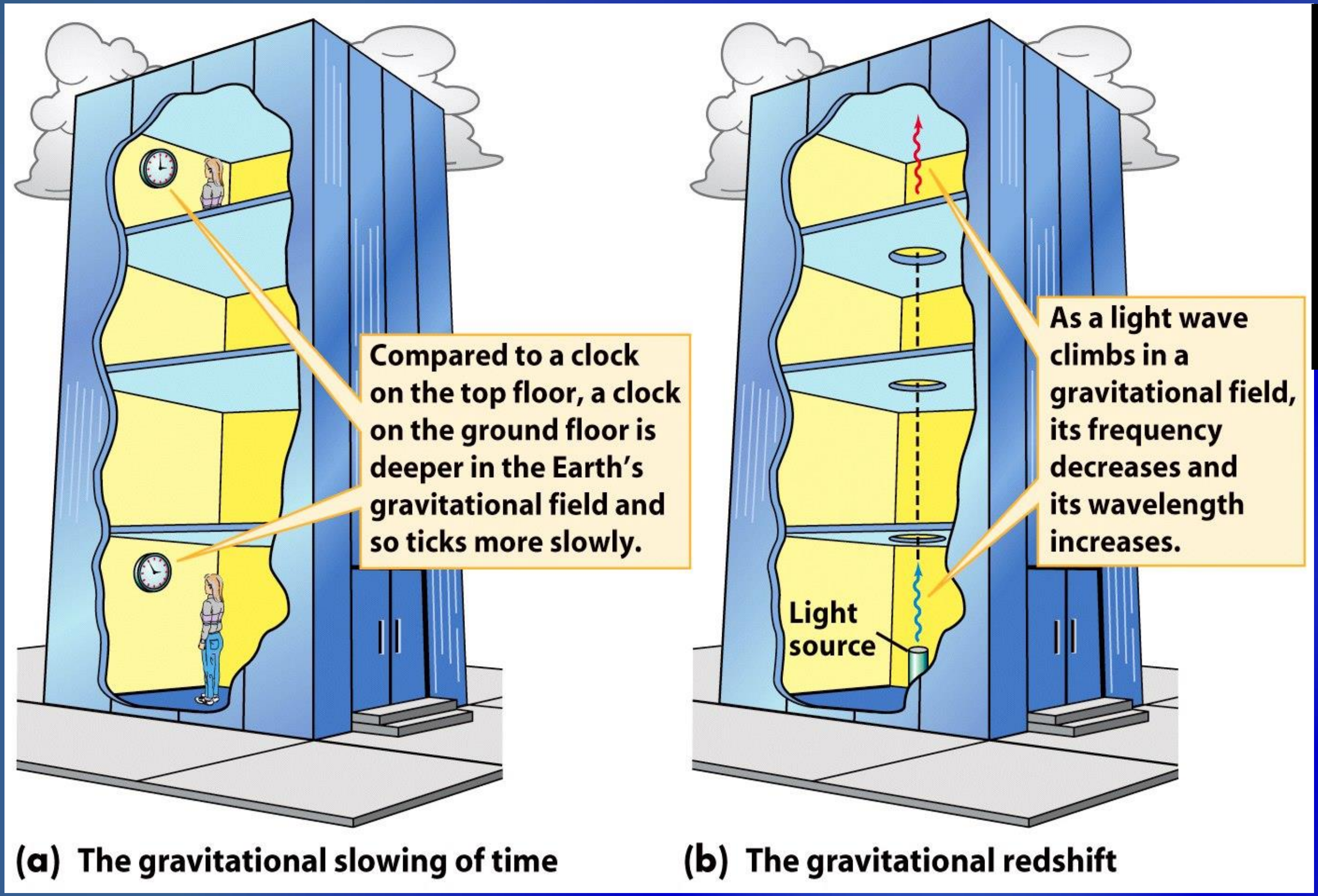
Roger Penrose
Department of Mathematics, Birkbeck College, London, England
(Received 18 December 1964)

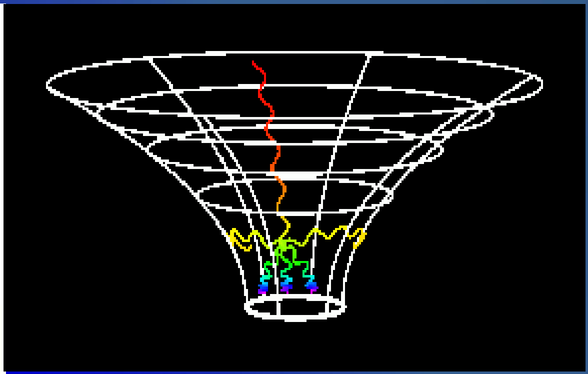
(This paper is only 2.5 pages long!!)

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

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Gravitational Redshift of Light





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).

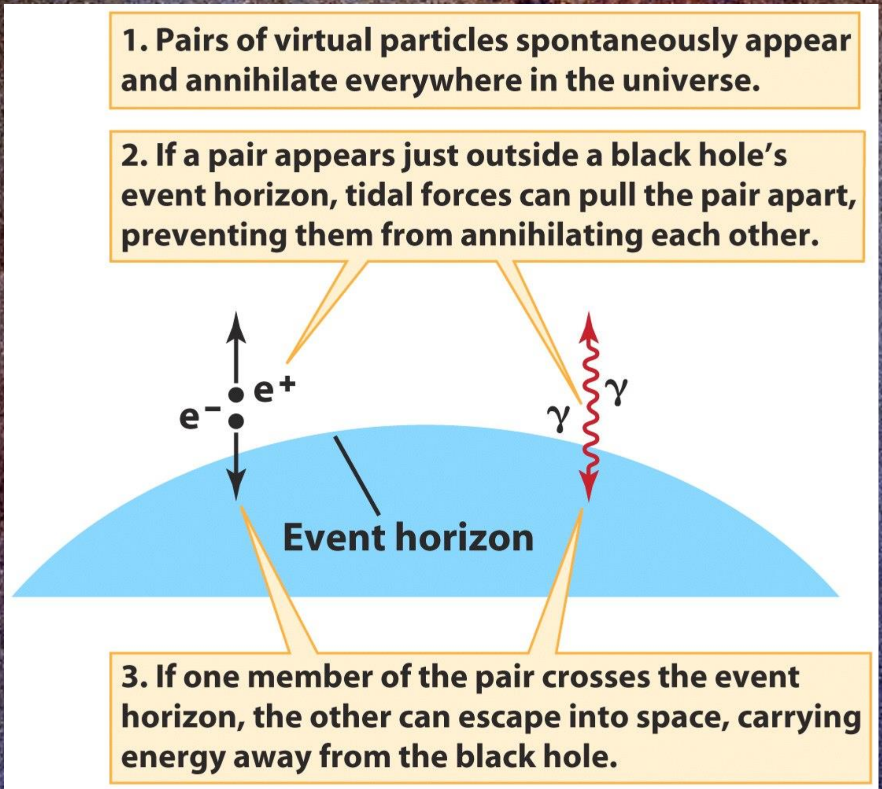
- ✓ Black holes have entropy (a measure of disorder) that is proportional to the size of the event horizon.

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

Evaporating Black Holes

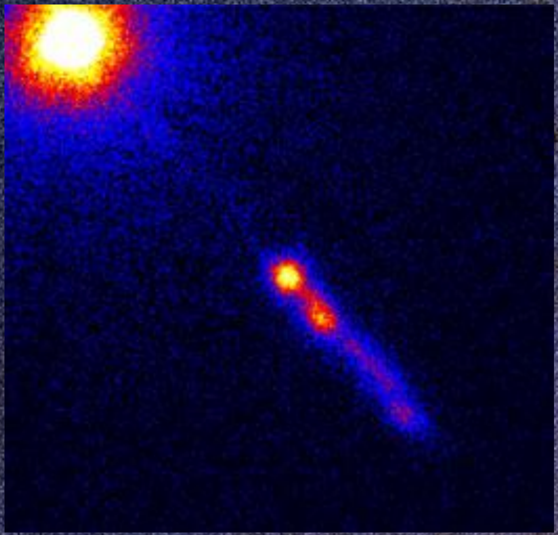
BHs can decay via a quantum mechanical process near event horizon of a BH

- ✓ Black Holes evaporate slowly by emitting "Hawking radiation" → particles falling into the BH have negative energy, BH looses 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



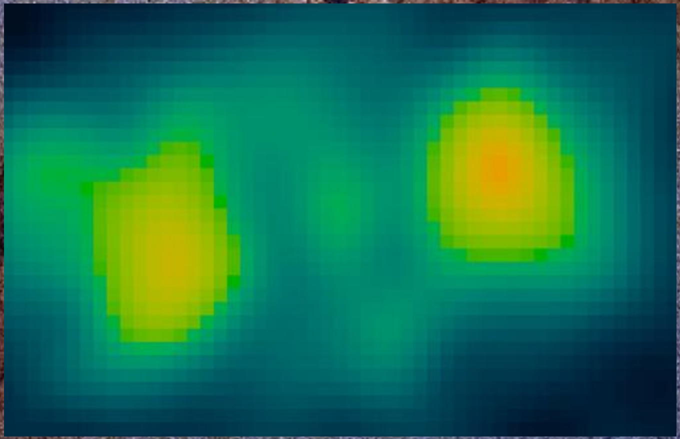
- ***Questions Remain about Black Holes:***
  - ***Is the information that falls into a Black Hole lost forever?*** → this contradicts the laws of quantum mechanics, and scientists have been trying to deal with this paradox for decades)
  - **What is inside a black hole?**
  - Can wormholes be produced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

Black Hole Galore

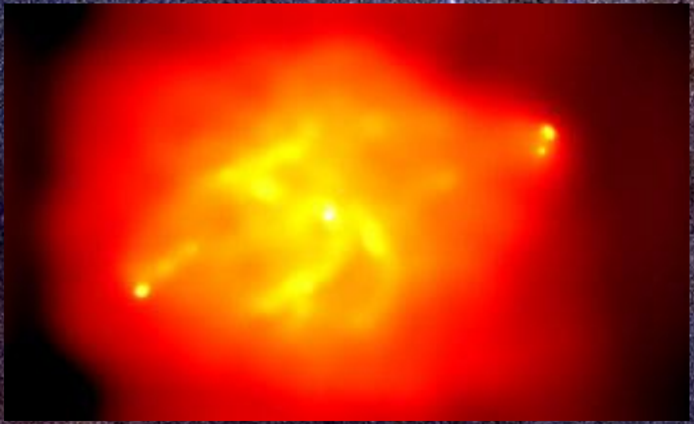


NASA/CXC/SAO/H.Marshall et al.

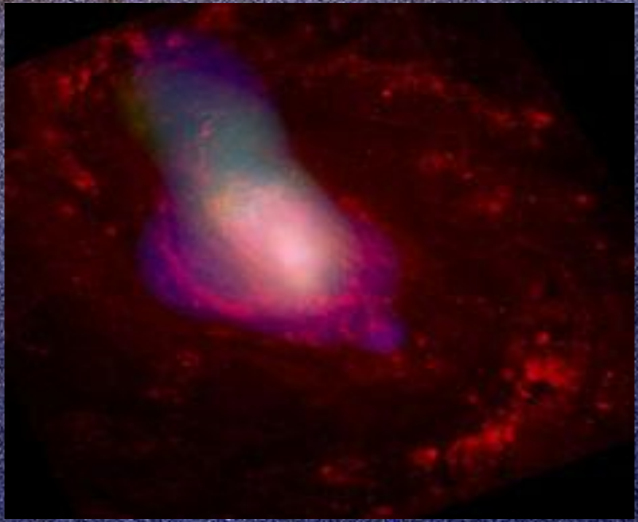
NASA/CXC/MIT/F.K.Baganoff et al.



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

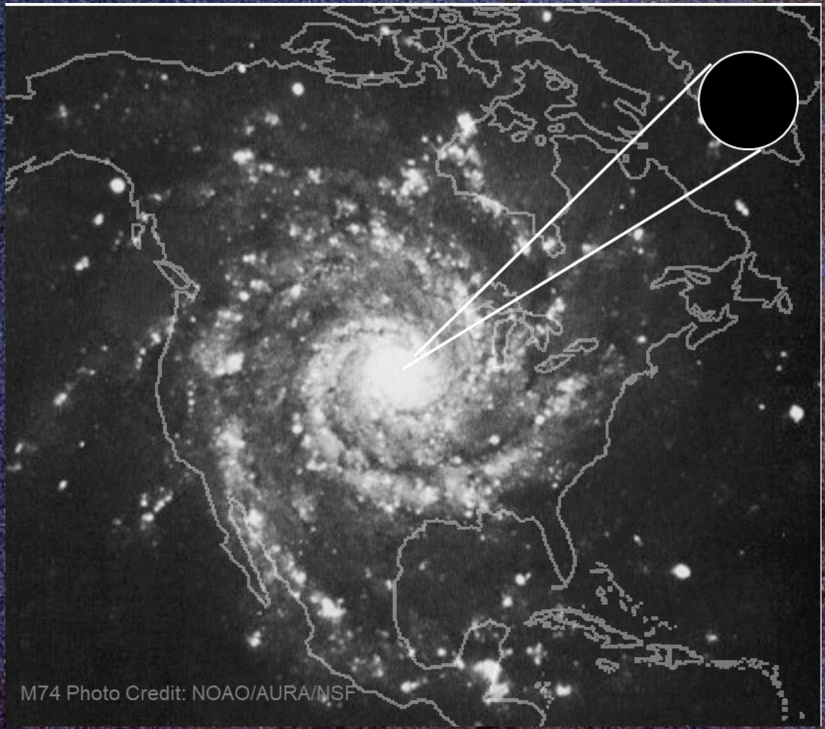
There are also millions of black holes

Including one giant black hole at the very center.

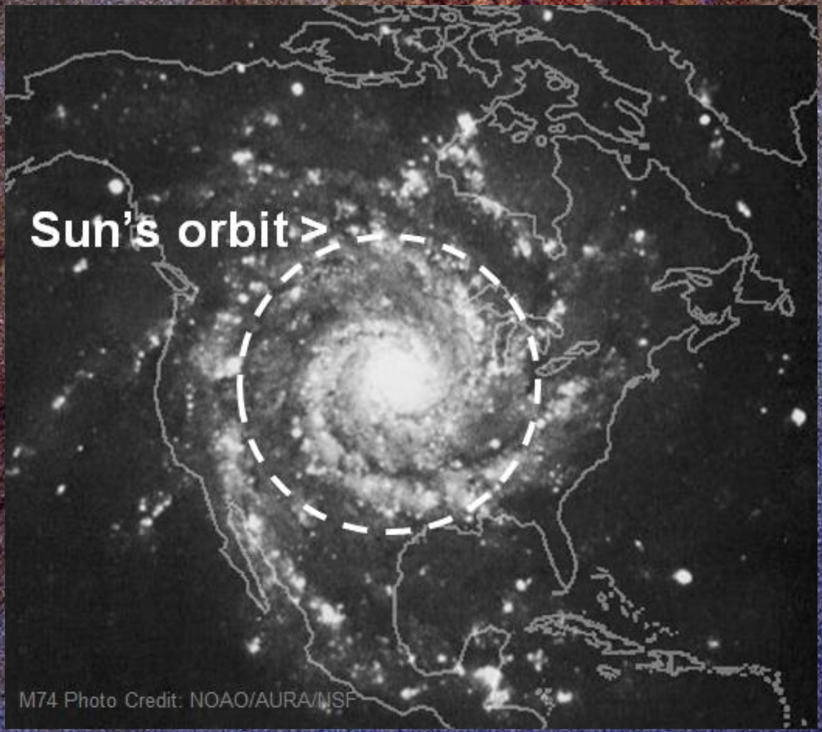
How have we survived?

So How Do we Survive amid All These Black Holes ?

Great distances between the stars



Everything is orbiting fast enough!

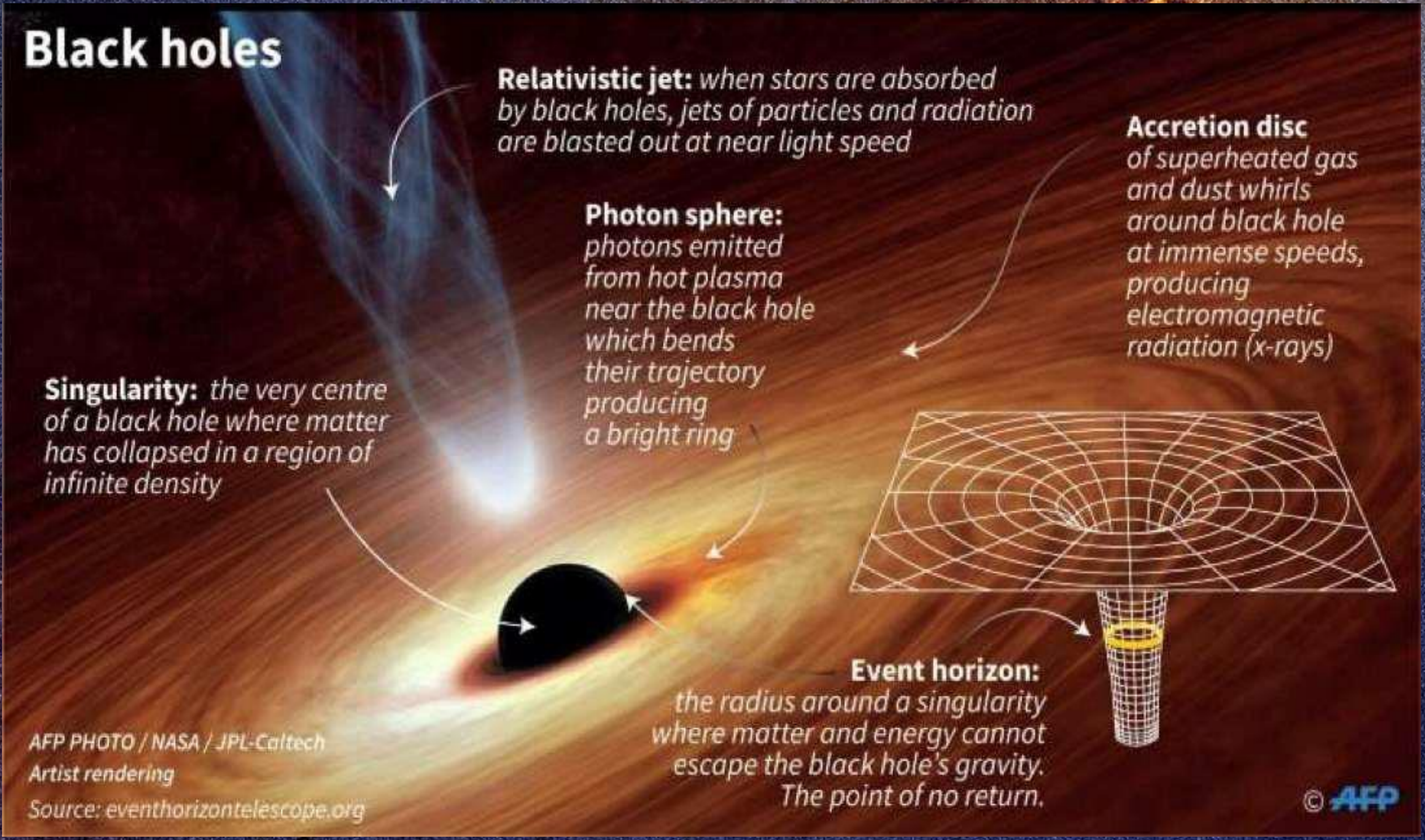


- ***Far away from a black hole:***
  - *Gravity is the same as for a star of the same mass.*
  - *If the Sun became a Black Hole, all the planets would continue in the same orbits.*
  - *It would however be darker and MUCH colder*

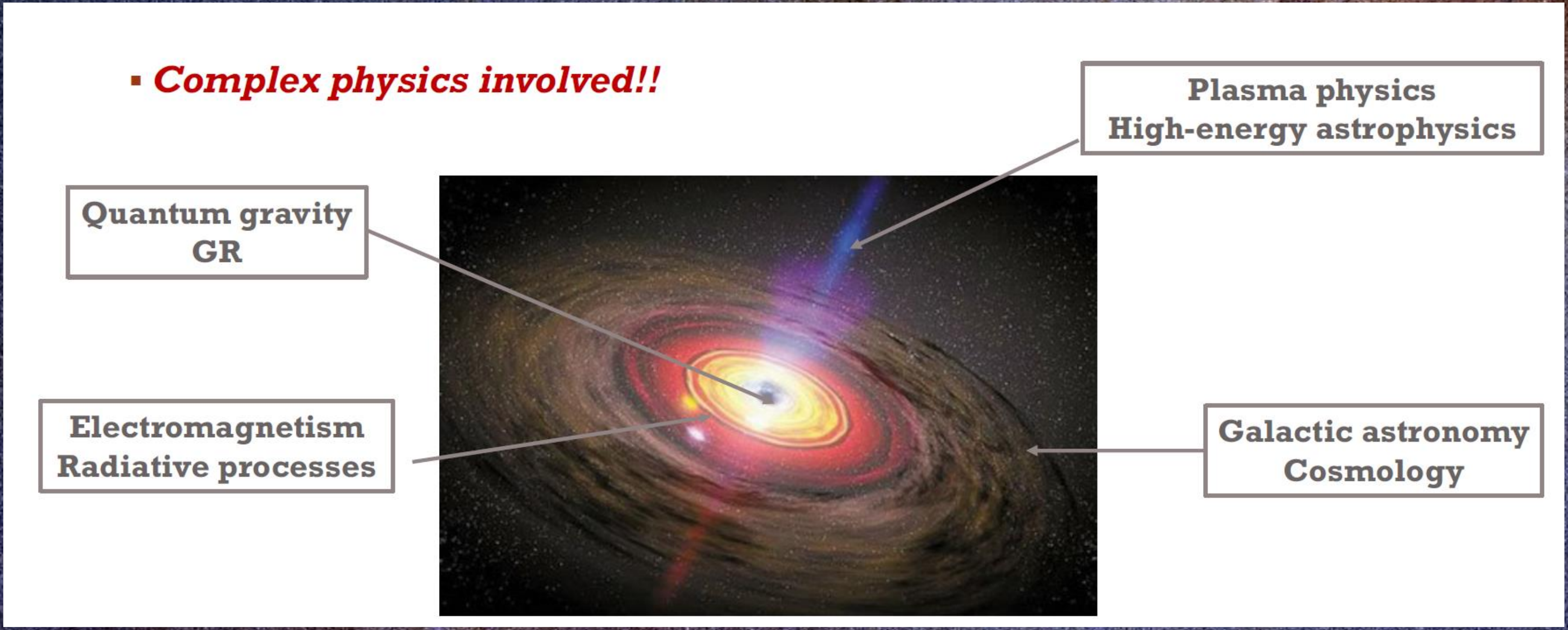
- ***Close to a black hole:***
  - *$R < 3 R_S$, there are no stable orbits - all matter eventually gets sucked in.*

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.



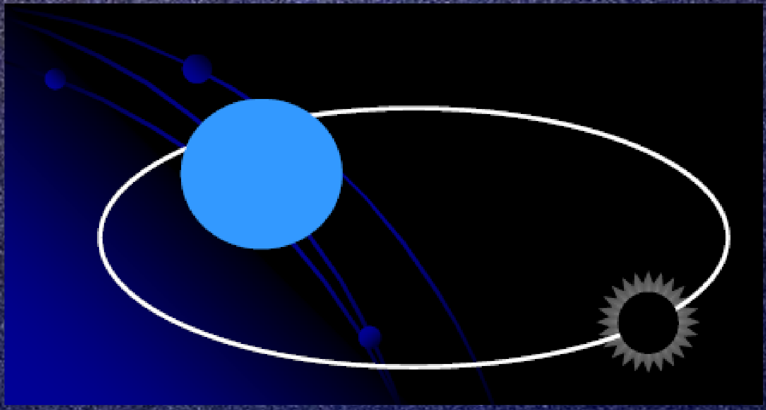
Black Holes as Laboratories of Fundamental Physics



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

- ✓ *Motion of visible companion betrays black hole:*
  - *→ Kepler's 3rd law ⇒ 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!*

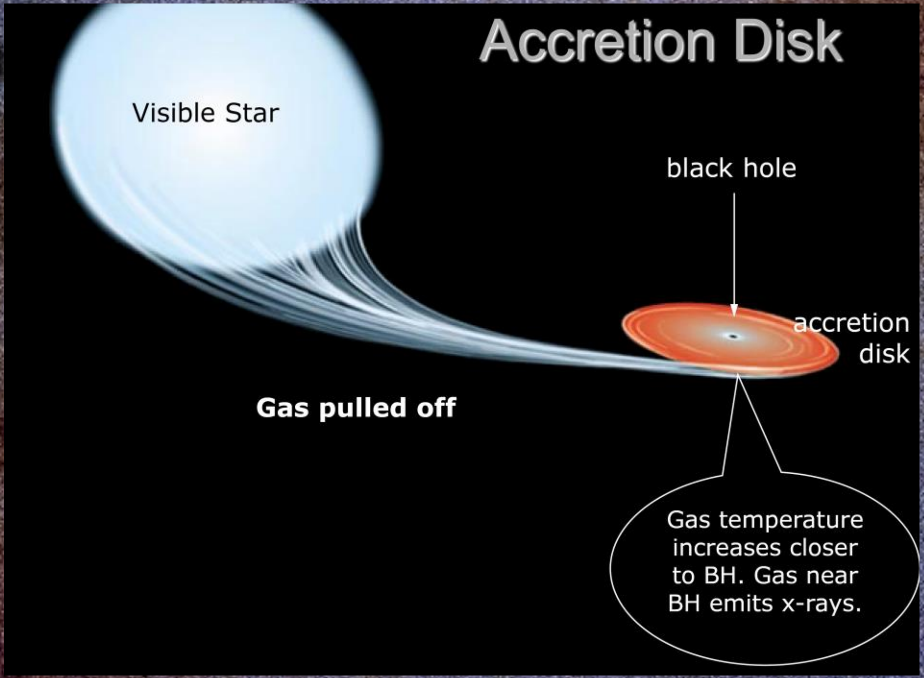
Orbits depend on masses of two obejects:

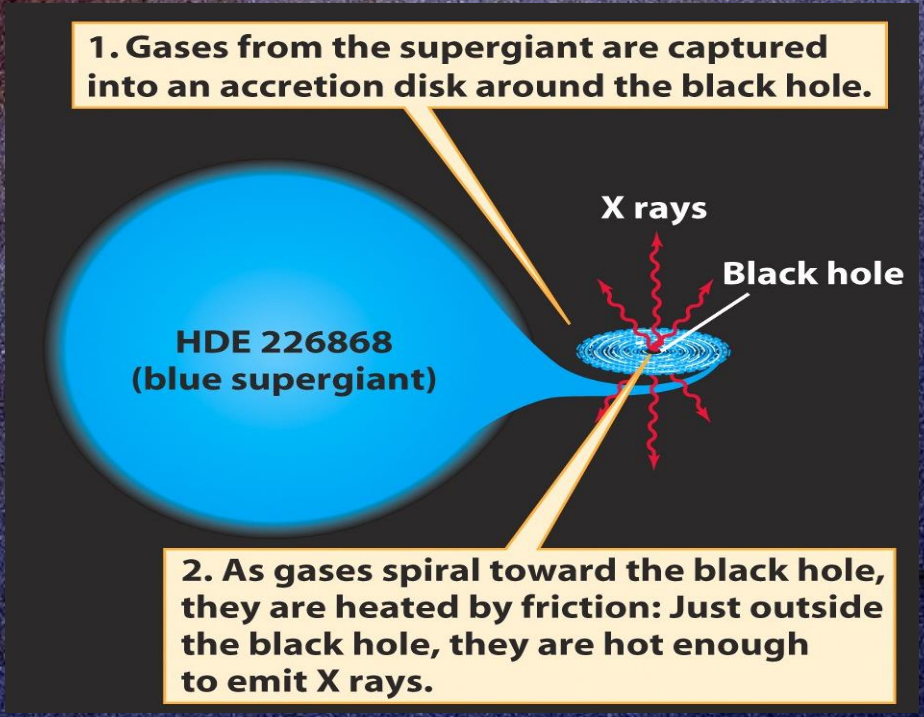


Black Holes: X-Ray Emission

- *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!



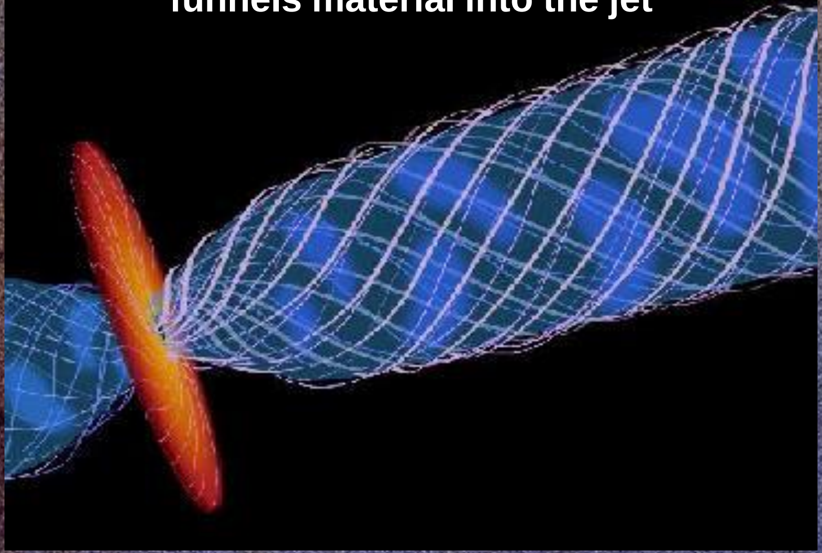


Radio Jets from Black Holes

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)***



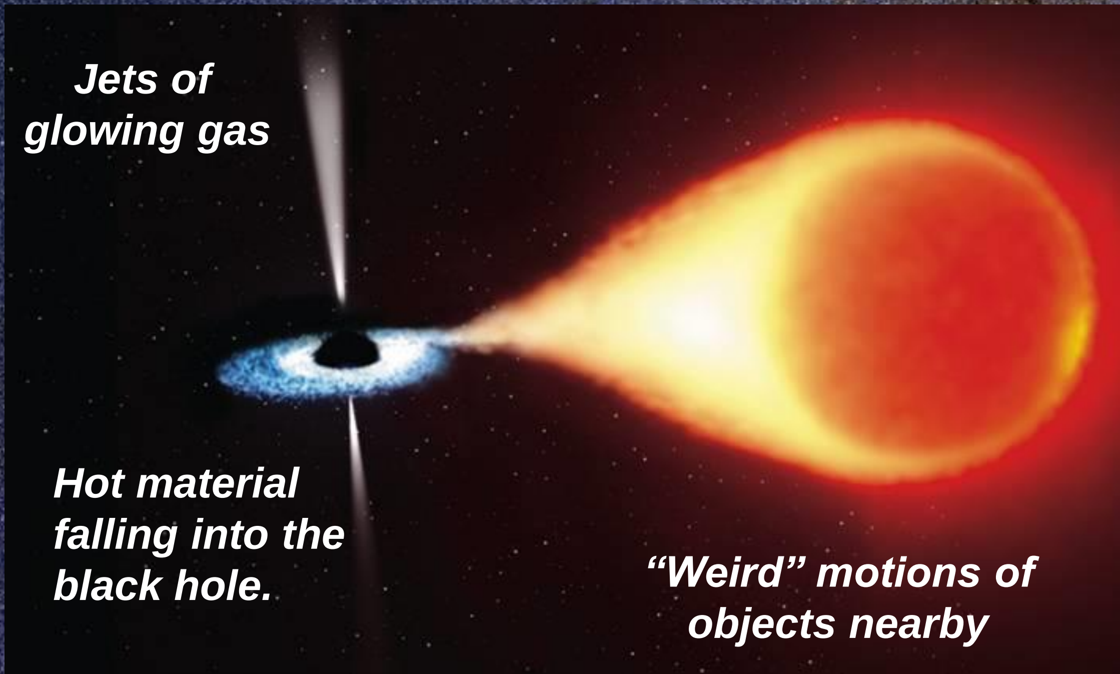
Magnetic field from surrounding disk funnels material into the jet

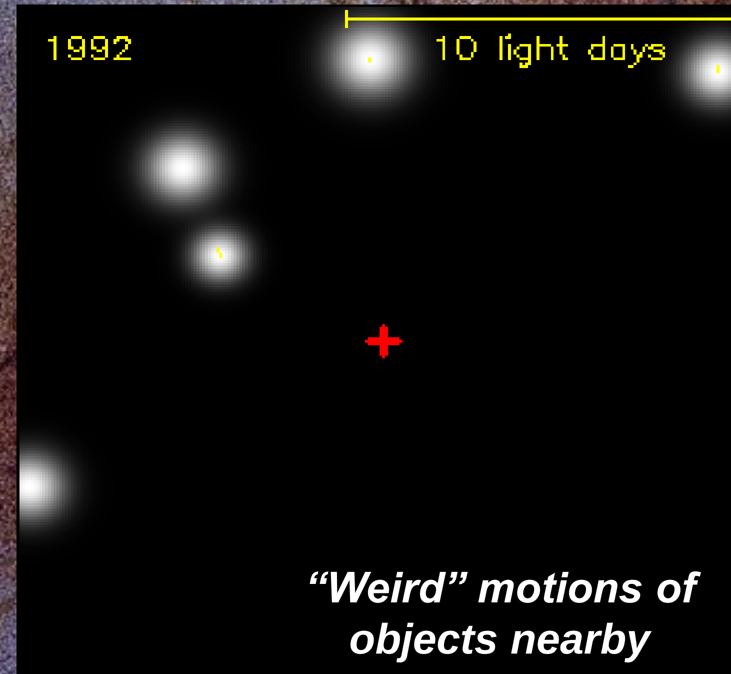
✓ ***Material in jet moving at 0.9c.***

✓ ***Jet likely composed of electrons and positrons.***

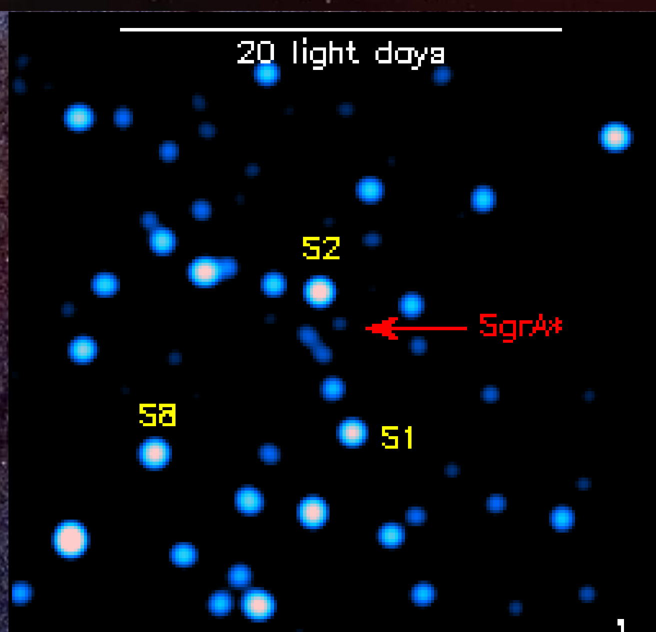
✓ ***Interaction of jet material with magnetic field gives rise to Radio emission.***

How Do We Know Black Hole is There ?

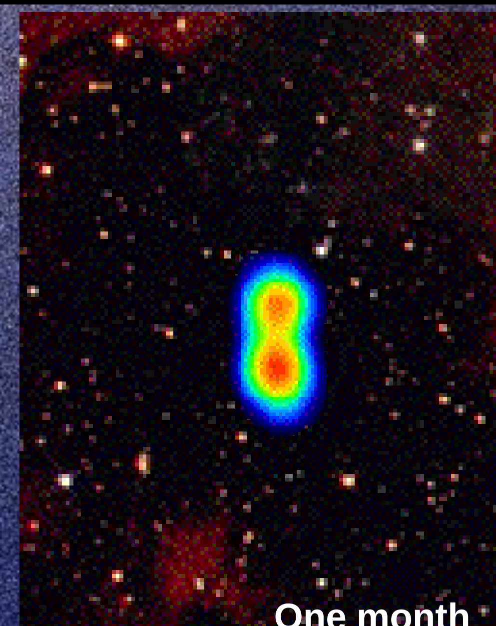




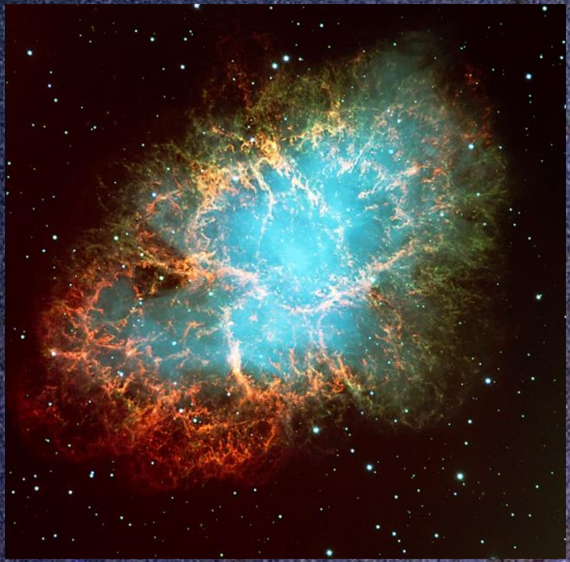
Hot material falling into the black hole.

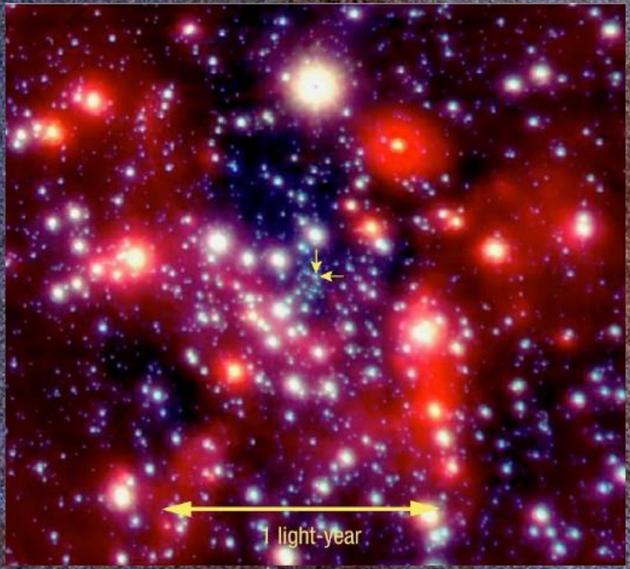


Jets of glowing gas



Where do Black Holes Come From ?

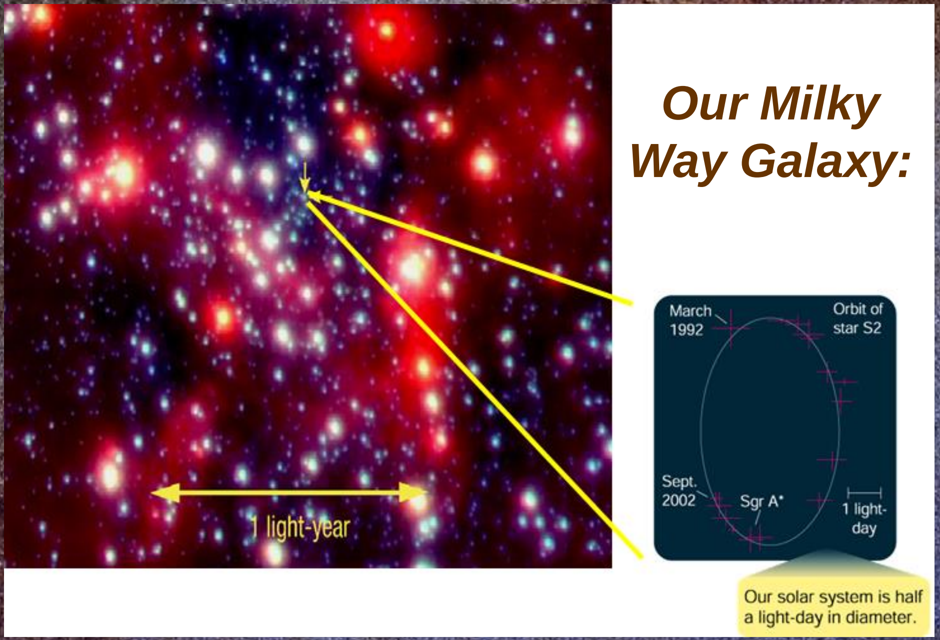




- **Primordial –** *can be any size, including very small (If <1014 g, they would still exist) → cannot be described only with GR,because they emit Hawking radiation and evaporate*
- **"Stellar-mass" black holes** *– must be at least 3 Mo to 20 Mo (~1034 g) – many examples are known*
- **Mid-mass black holes** *– range from 100 to 1000 Mo - located in normal galaxies – many seen*
- **Massive black holes –** *about 106 Mo – such as in the center of the Milky Way – many seen*
- **Supermassive black holes –** *about 109-10 Mo - 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*

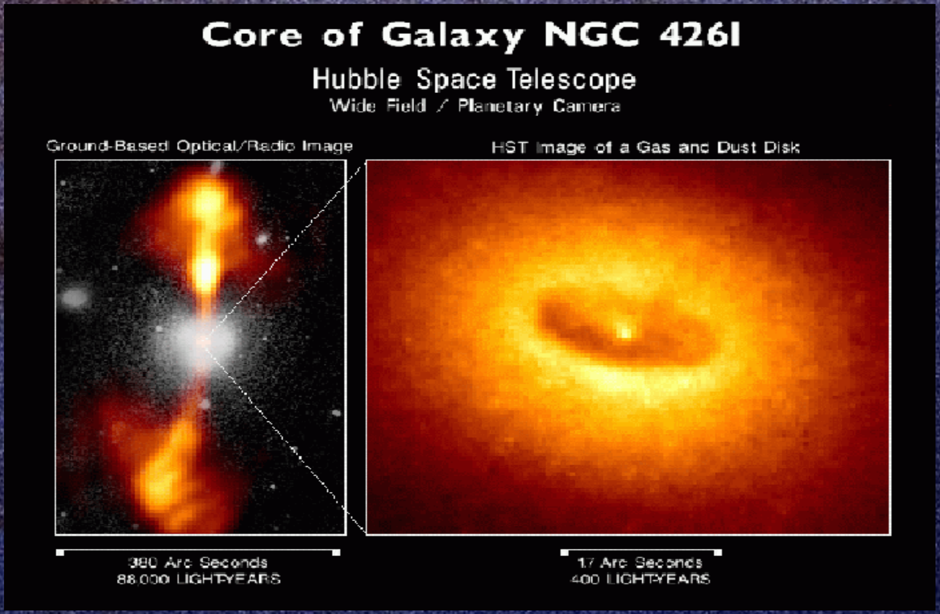


Super-Massive Black Hole Theories:

- ***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)*

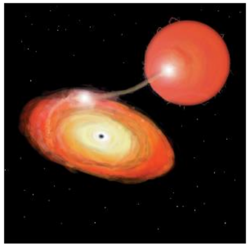
- ***Collapse of a whole star cluster*** *(stars from a tight cluster in early Universe could form a few Black Holes, causing smaller stars to be absorbed, and black holes to combine)*



Where do ***Stellar-mass Black Holes*** Come From ?

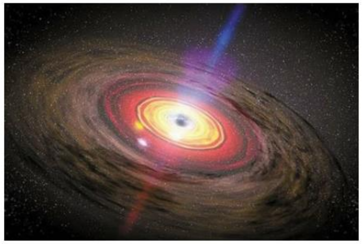
- ***Stellar-mass black holes are made when a massive star, manty (3 – 20) times the mass of our Sun, dies***
- ***Most of the star's atmosphere is blown into space as a supernova explosion.***
- ***The star's spent core collapses under its own weight.***
- ***If the remaining mass is more than the mass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


Credit: European Southern Observatory



Stellar-mass BHs

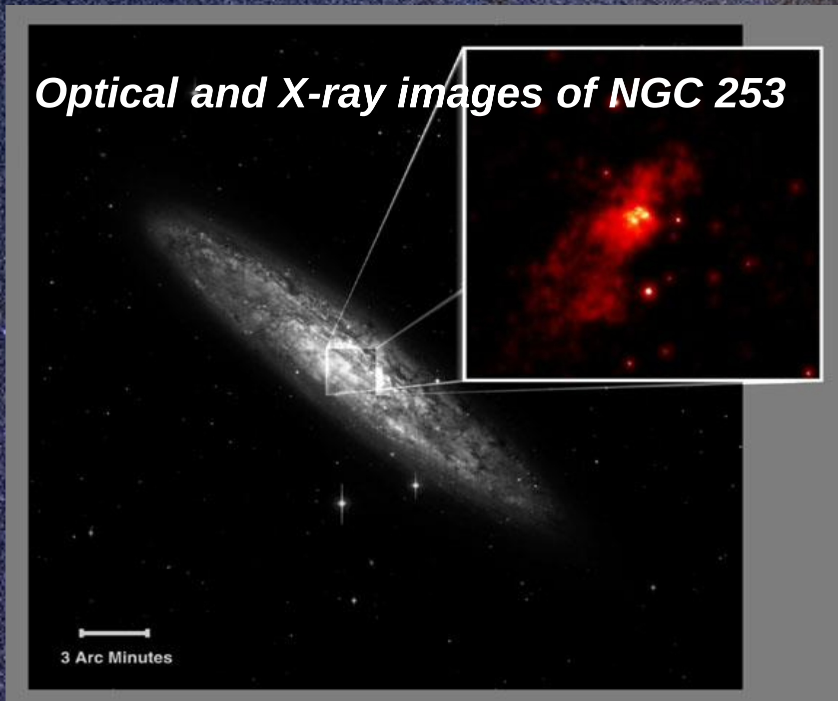
- Masses: ~3-100 M_{sun}
- Originated from collapses of massive stars
- Distributed within galaxies
- Shine in X-ray when accreting from a companion star – X-ray binary



SMBHs

- Masses: ~10^6-10^{10} M_{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 ?

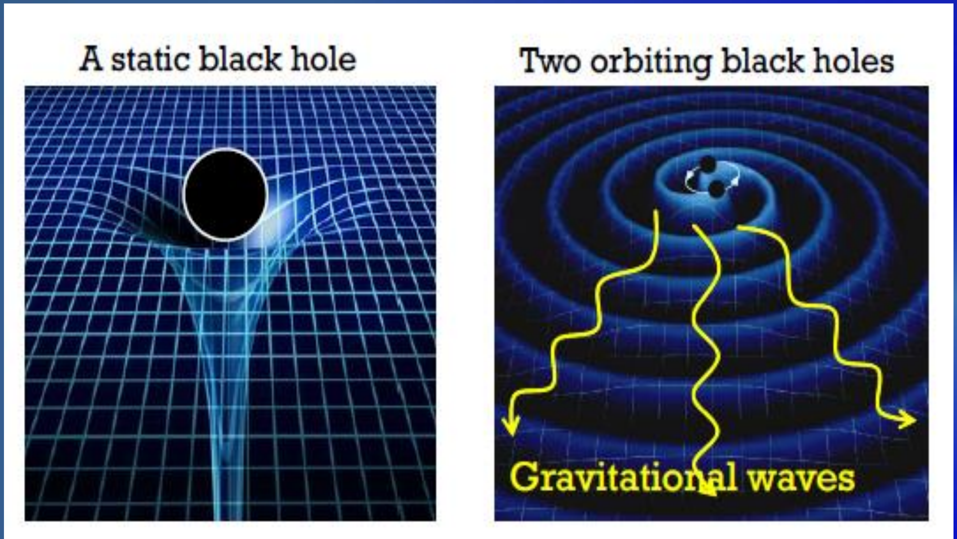


Star cluster, called M15, in our Galaxy:

- ✓ *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*

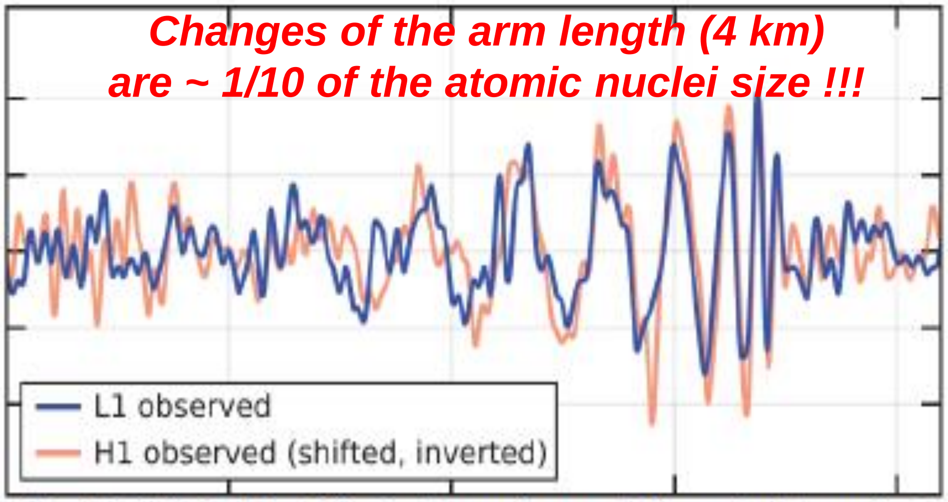
Image Credit: NASA and The Hubble Heritage Team (STScI/AURA)

A New Golden Age for Gravitation



- 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):



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

Credit: Event Horizon Telescope collaboration