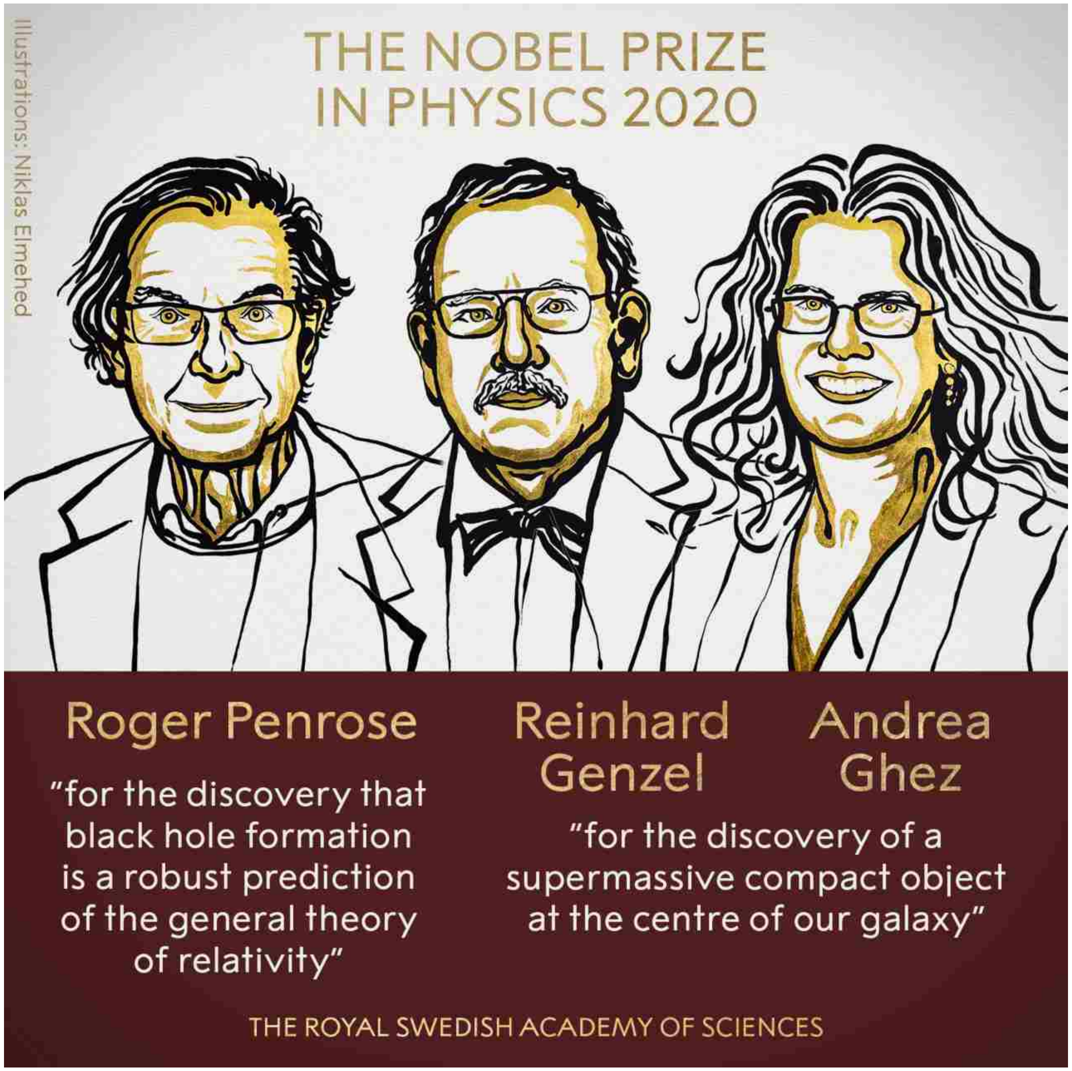
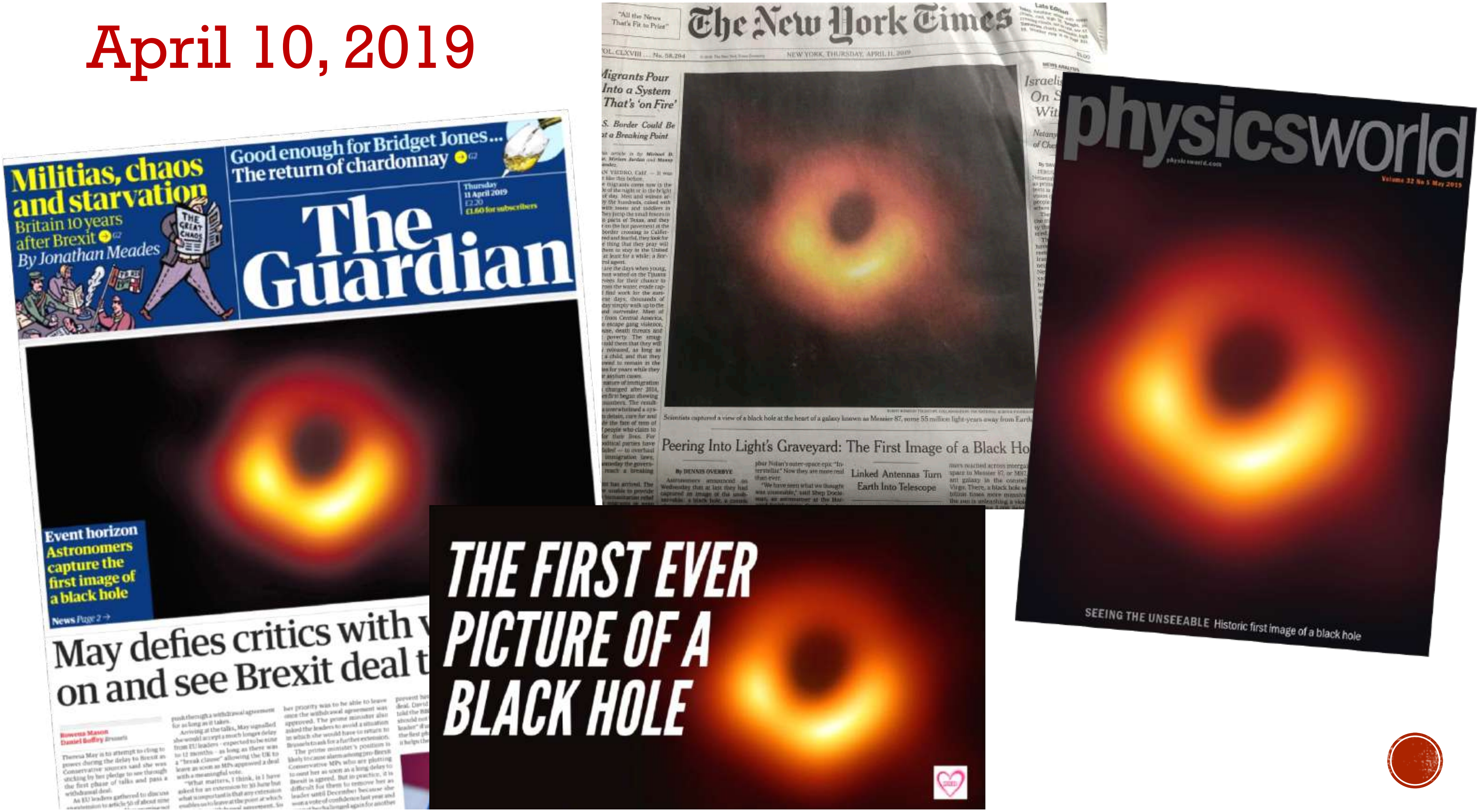
RESEARCH OVERVIEW -- BLACK HOLES

Mini-workshop of NCTS-TCA SSP 2021

Hsiang-Yi Karen Yang, NTHU, 7/5/2021


Illustrations: Niklas Elmehed
THE NOBEL PRIZE
IN PHYSICS 2020
Roger Penrose
"for the discovery that black hole formation is a robust prediction of the general theory of relativity"
Reinhard Genzel
Andrea Ghez
"for the discovery of a supermassive compact object at the centre of our galaxy"
THE ROYAL SWEDISH ACADEMY OF SCIENCES

April 10, 2019




The New York Times

Late Edition

Today, some sunshine giving way to times of clouds, cold, high 26. Tonight, a flurry or heavier squall late, low 15. Tomorrow, windy, frigid, high 21. Weather map, Page A10.

NEW YORK, FRIDAY, FEBRUARY 12, 2016

$2.50

WITH FAINT CHIRP, SCIENTISTS PR… EINSTEIN COR…

A RIPPLE IN SPACE…

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…

Feb 11, 2016


重力波 世界初観測

米大チーム

宇宙成り立ち迫る

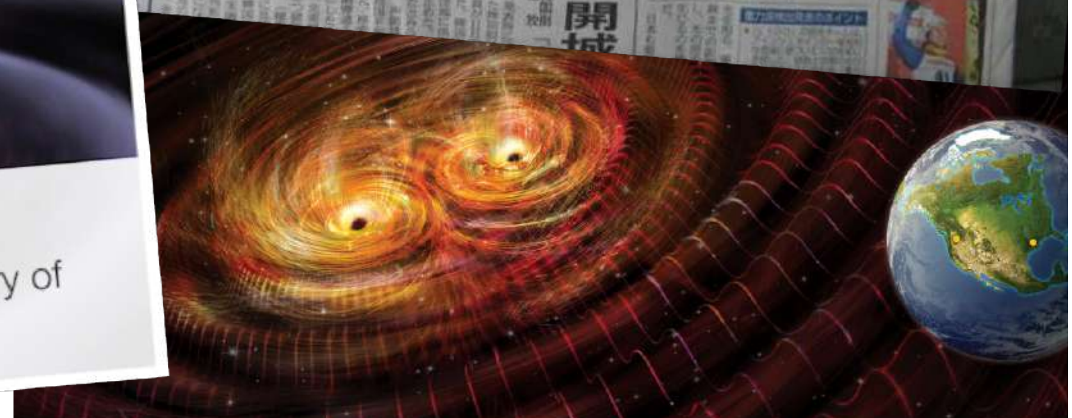
アインシュタイン予言

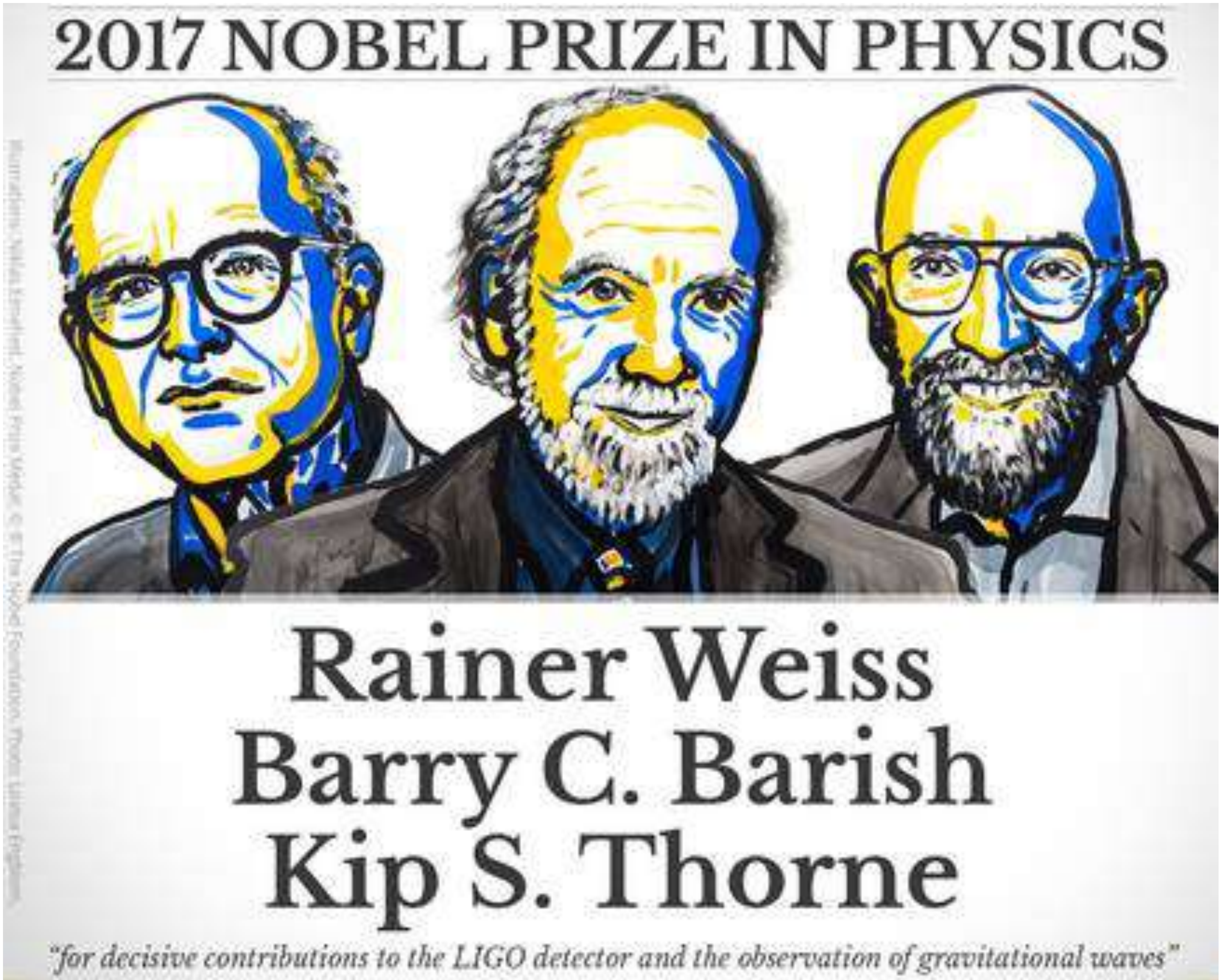
山陰新聞

2月12日

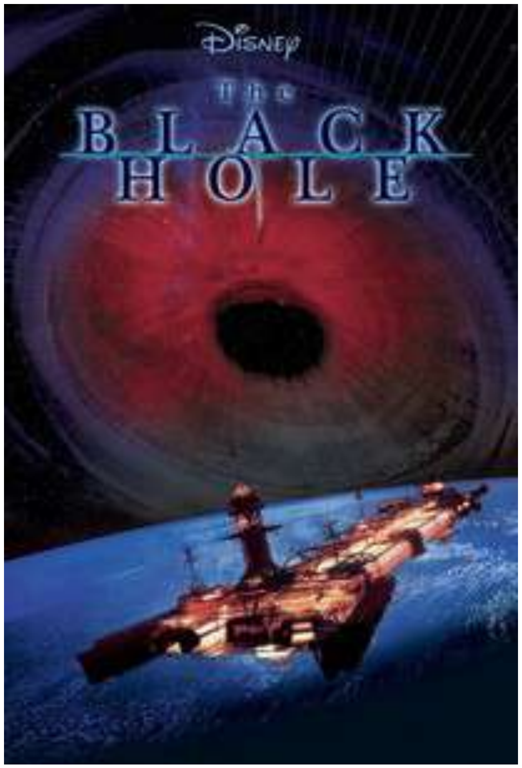
金曜日

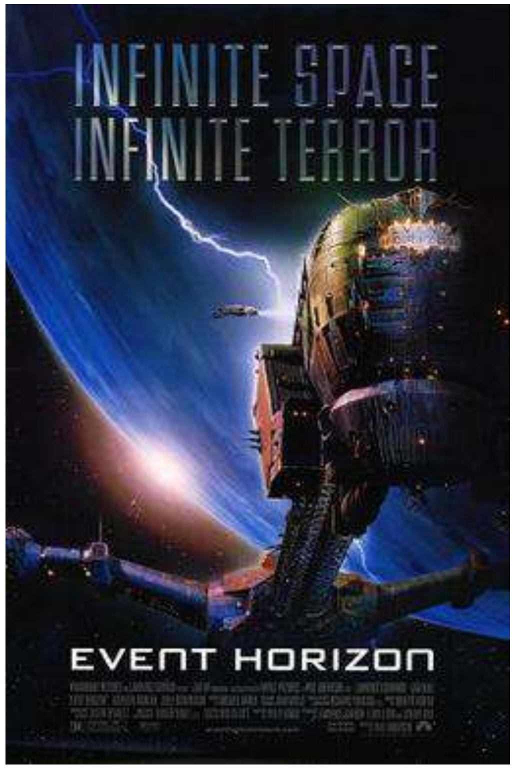
北朝鮮、開城




2017 NOBEL PRIZE IN PHYSICS
Rainer Weiss
Barry C. Barish
Kip S. Thorne
"for decisive contributions to the LIGO detector and the observation of gravitational waves"

The Black Hole (1979) Event Horizon (1997) Interstellar (2014)





EVERYBODY LOVES BLACK HOLES!!!

OUTLINE

- Black hole 101
  - What is a black hole?
  - Do black holes exist?
  - What are active galactic nuclei (AGN)?
- Big questions in black hole astrophysics
  - How do supermassive black holes form?
  - How do AGNs affect the formation and evolution of galaxies?
  - What can we learn from gravitational waves (GWs) and the first black hole image?

WHAT IS A BLACK HOLE?

[redacted]

Dictionary

Search for a word

black hole

noun

ASTRONOMY

a region of space having a gravitational field so intense that no matter or radiation can escape.

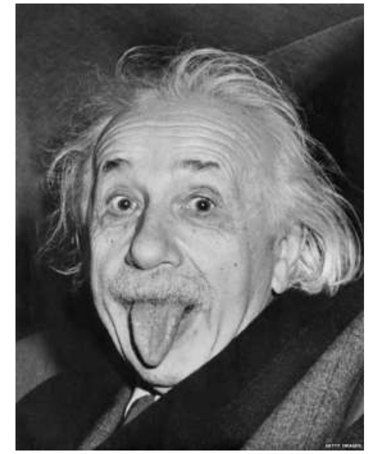
Light : m = 0

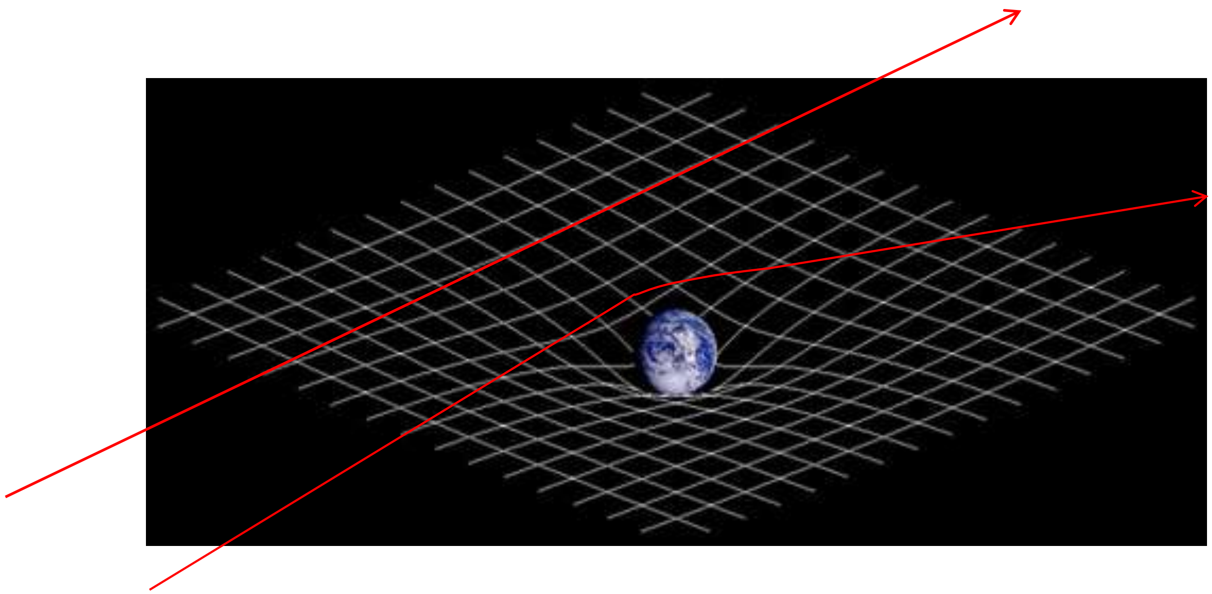
??

Newton's law of gravitation:

$$F = \frac{GMm}{r^2}$$

EINSTEIN'S GENERAL THEORY OF RELATIVITY(1915) :
"MATTER TELLS SPACETIME HOW TO CURVE; SPACETIME TELLS MATTER HOW TO MOVE"





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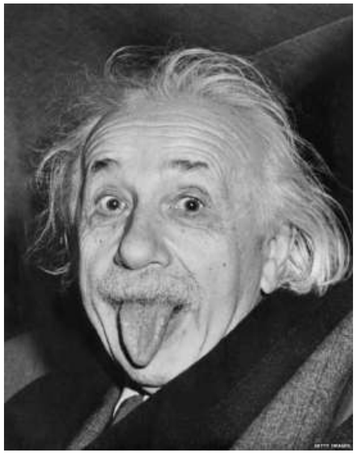
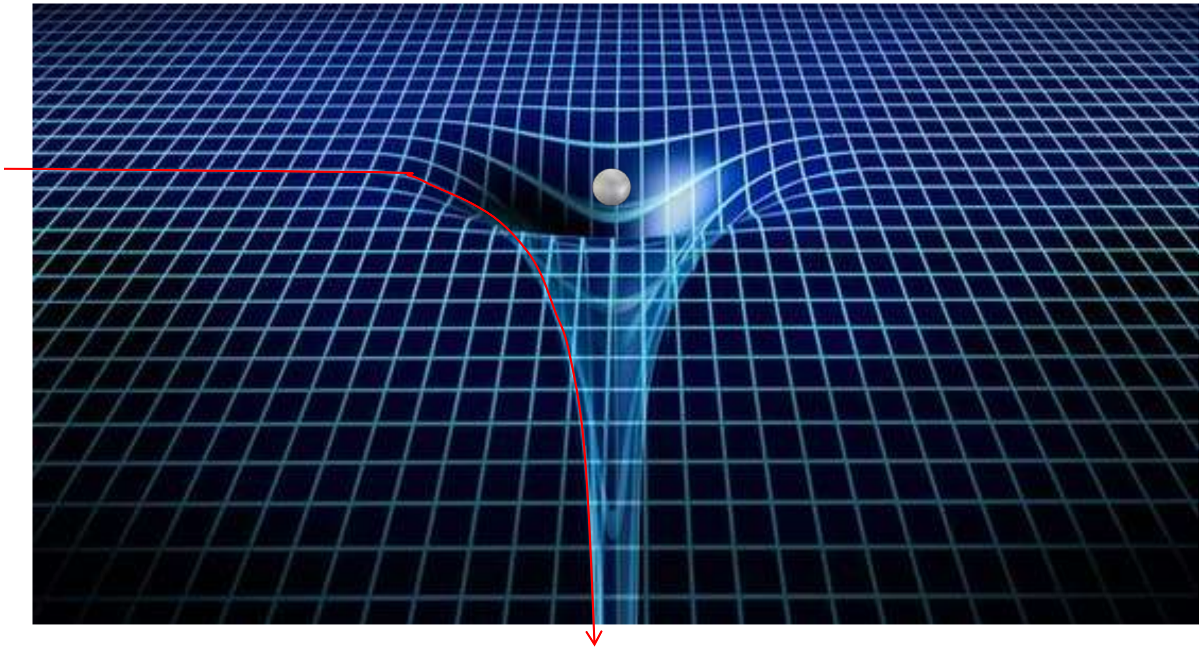
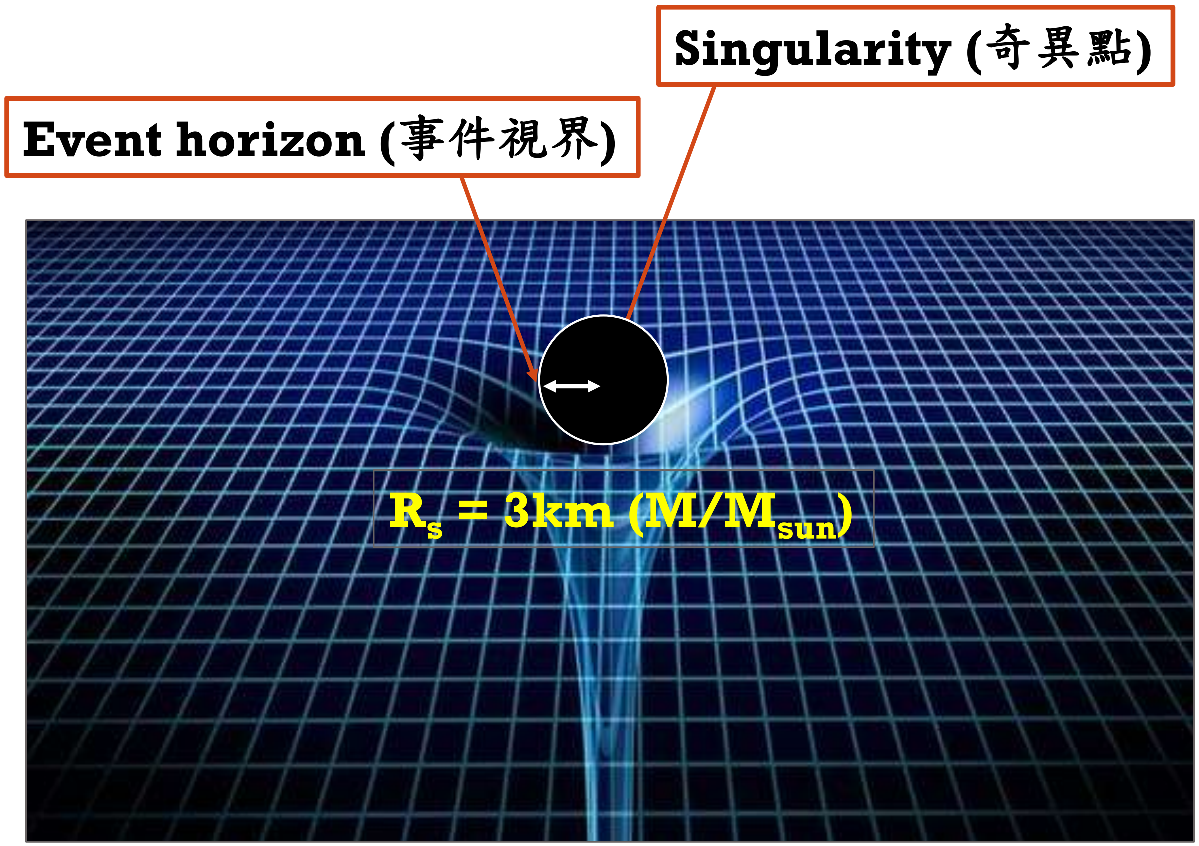


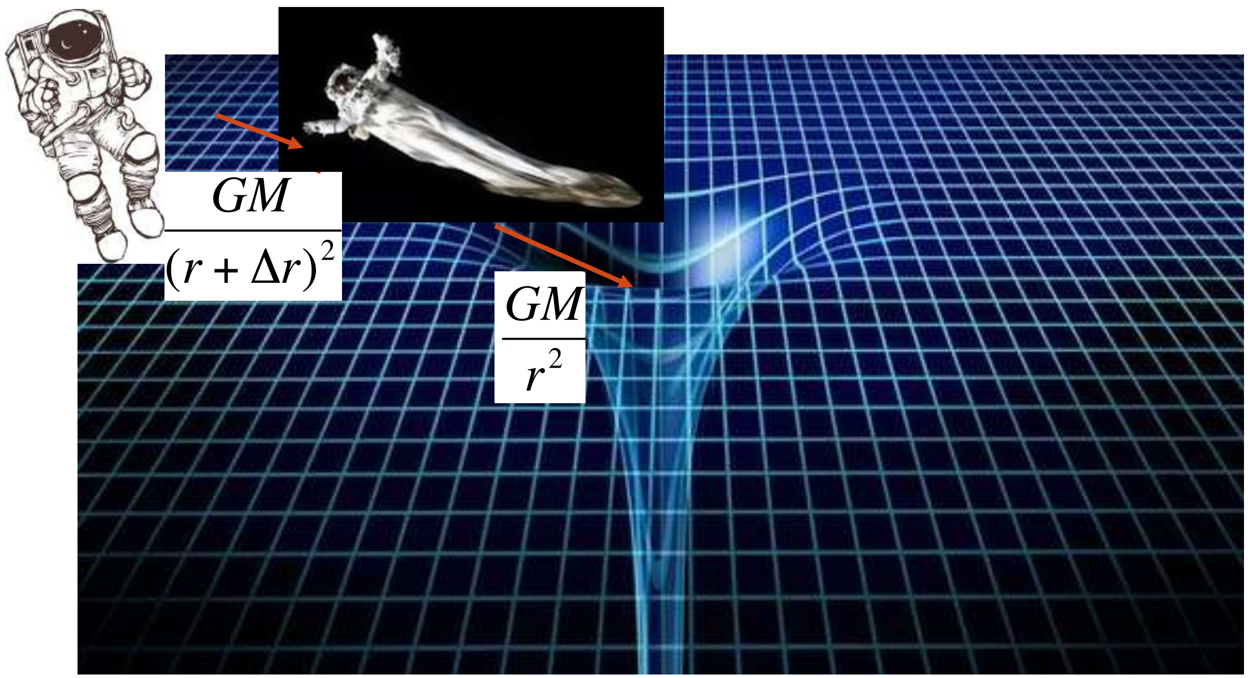


SCHWARZSCHILD BLACK HOLE



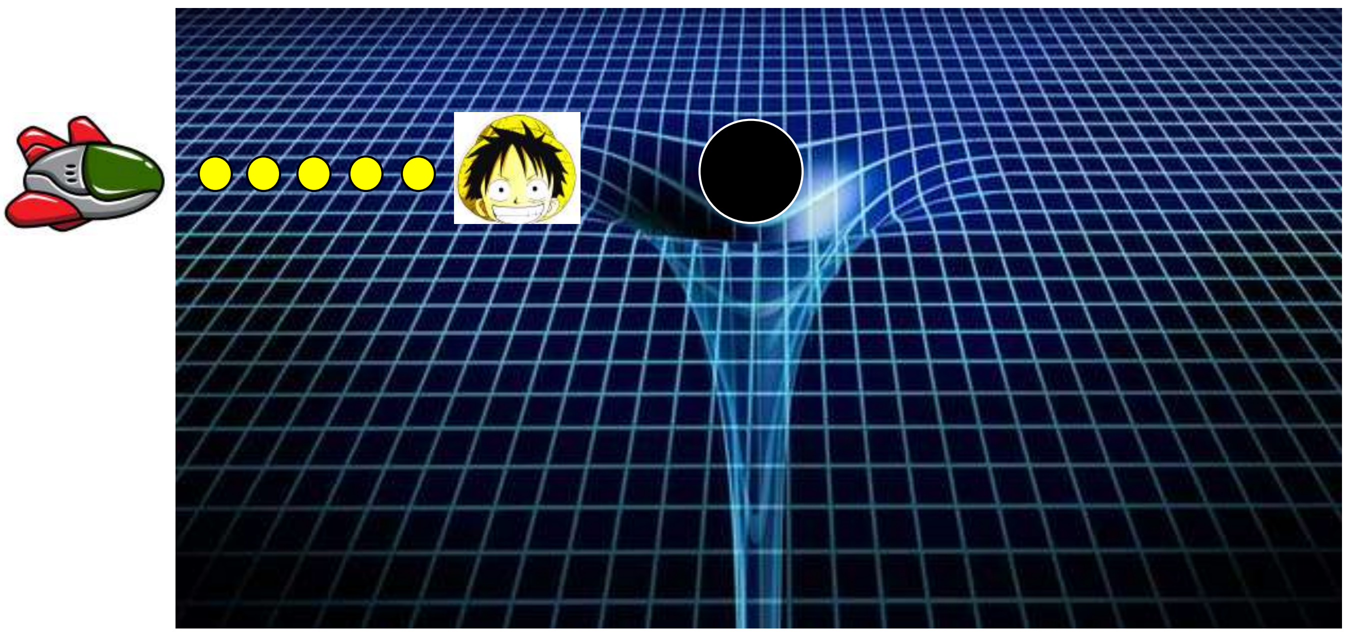
Karl Schwarzschild
(1873-1916)

SPAGHETTIFICATION

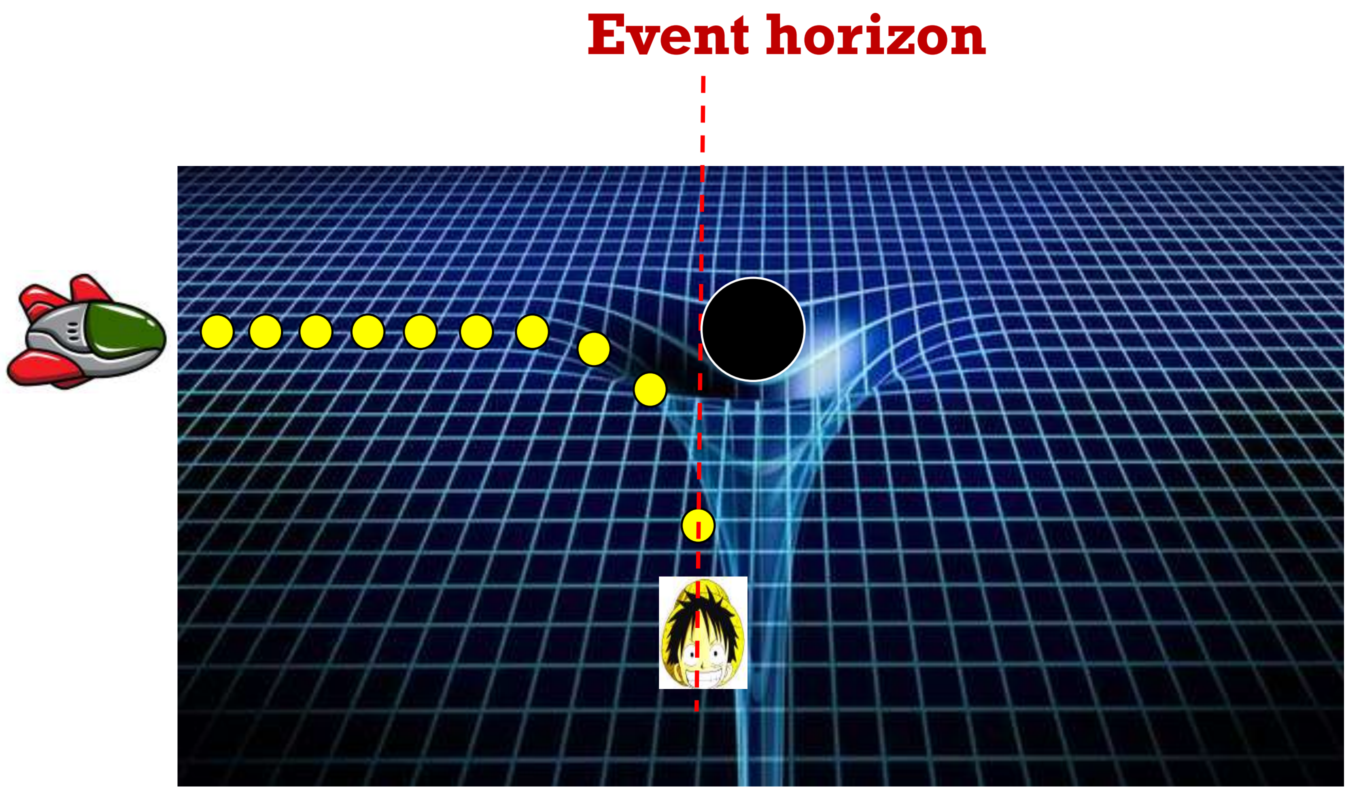


- We would never make it to the center intact because the tidal force (F_{tidal}~M/r^3) would tear us apart

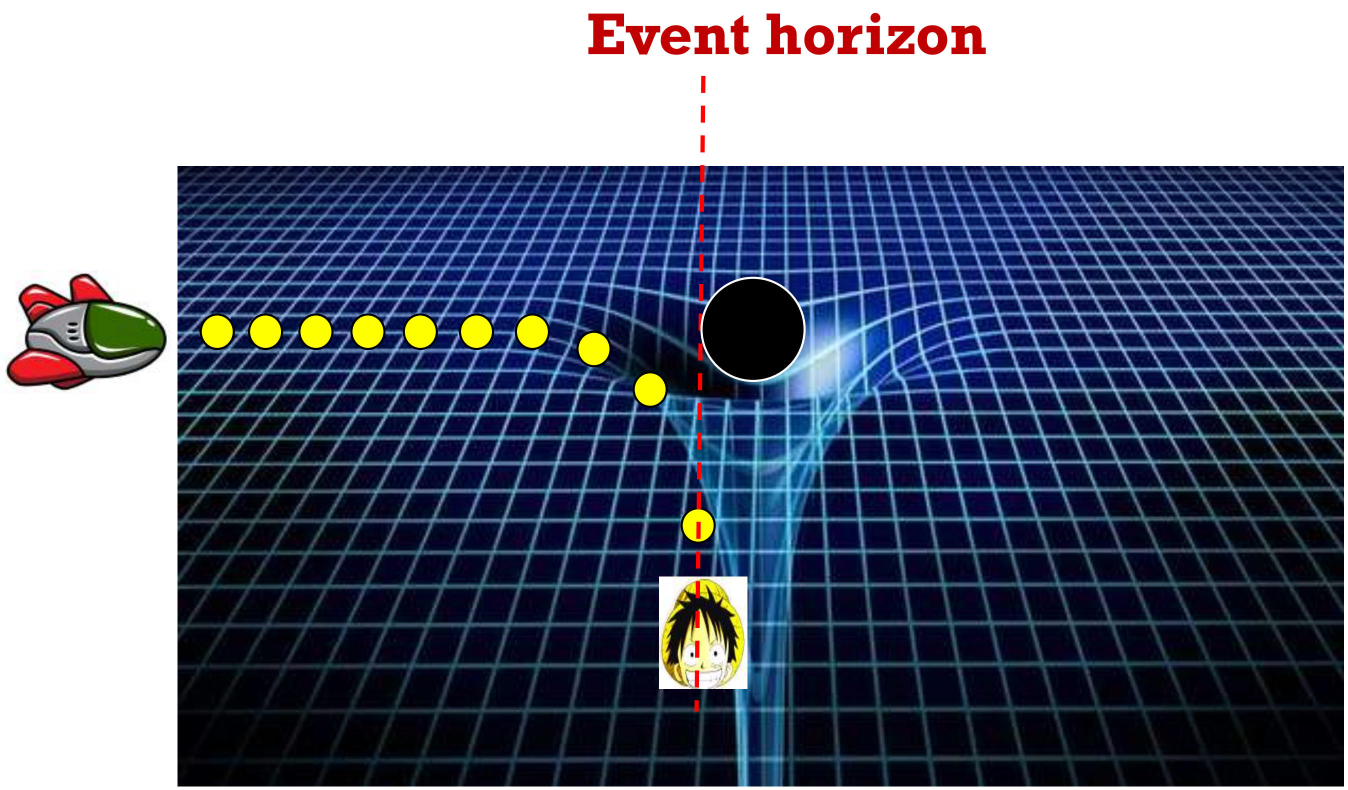
WHAT WOULD WE SEE IF LUFFY FALLS INTO THE BLACK HOLE……?



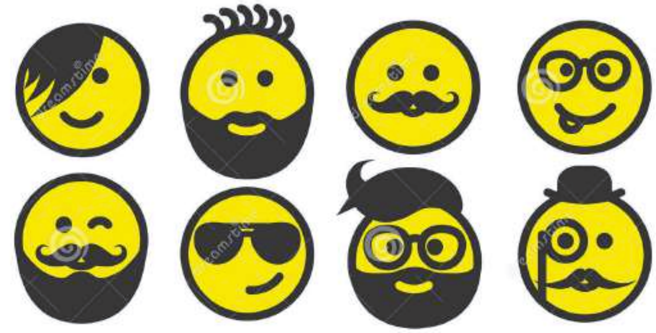
WHAT WOULD WE SEE IF LUFFY FALLS INTO THE BLACK HOLE......?



- ***Gravitational time dilation*** – time measured by a distant observer would increase as the emitting object moves closer to the event horizon
- ***Gravitational redshift*** – light emitted near the event horizon would appear redder and dimmer as viewed by a distant observer



NO HAIR THEOREM



- It says that ***"Stationary BHs after formation can be uniquely described given mass (M), angular momentum (J), and charge (Q)."***
- Once (M, J, Q) are given, the spacetime is determined
- It means that BHs are in fact very simple objects!
- In the universe, EM force >> gravity, so it is easy for the black hole to attract an opposite charge -> Q = 0
- Important properties of a black hole: M and J

Maximum set of parameters:

$\{M, J, Q\}$

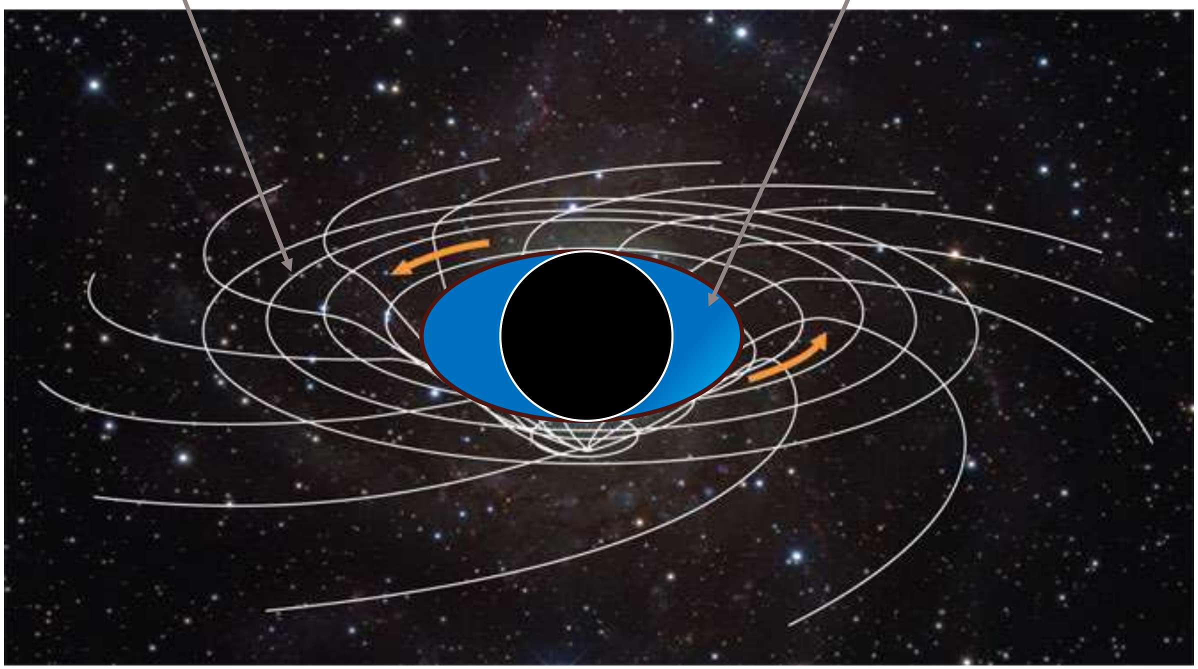
SPINNING BLACK HOLES

参考系拖曳

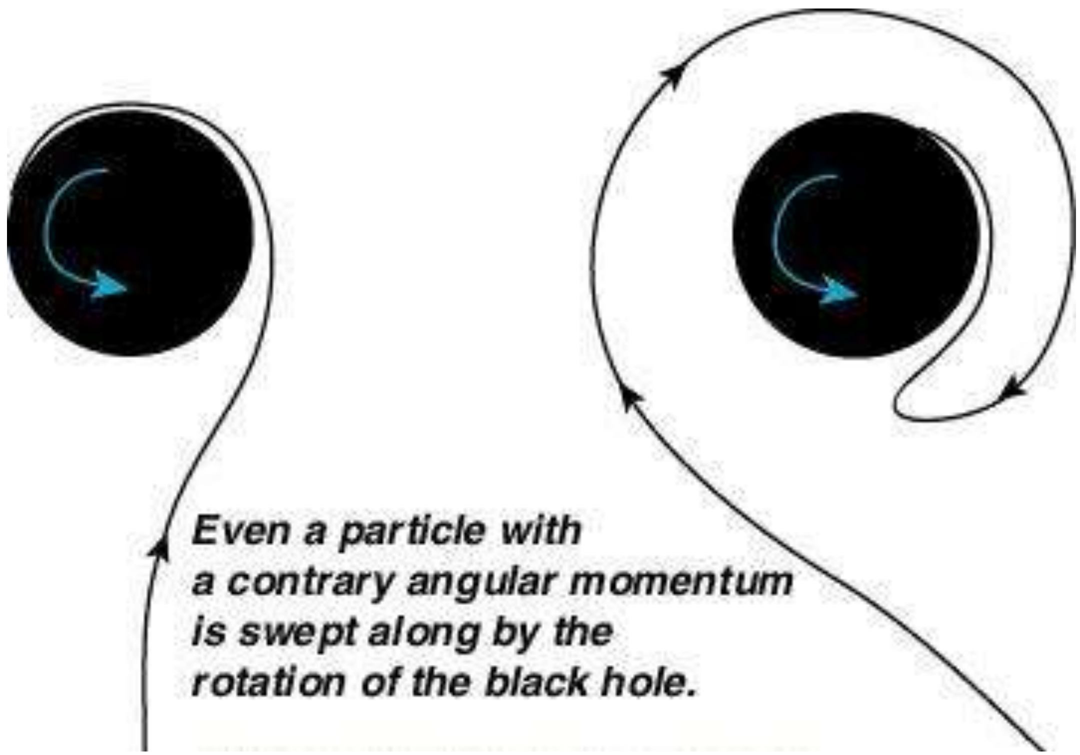
(Frame dragging)

動圈

(ergosphere)

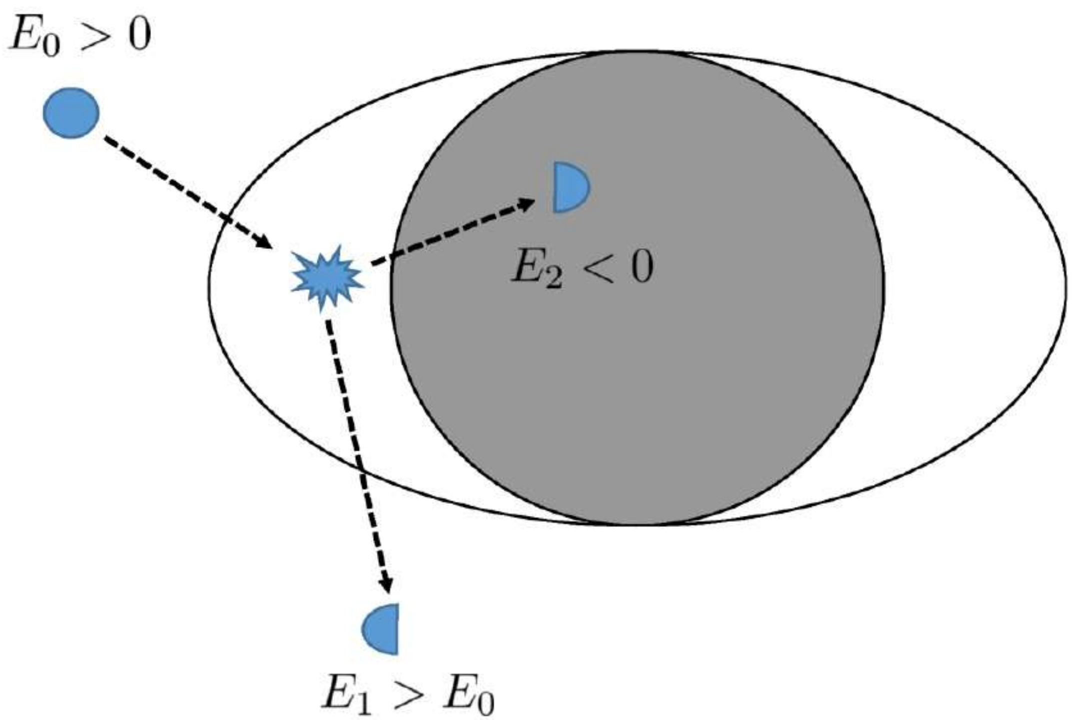


SPINNING BLACK HOLES



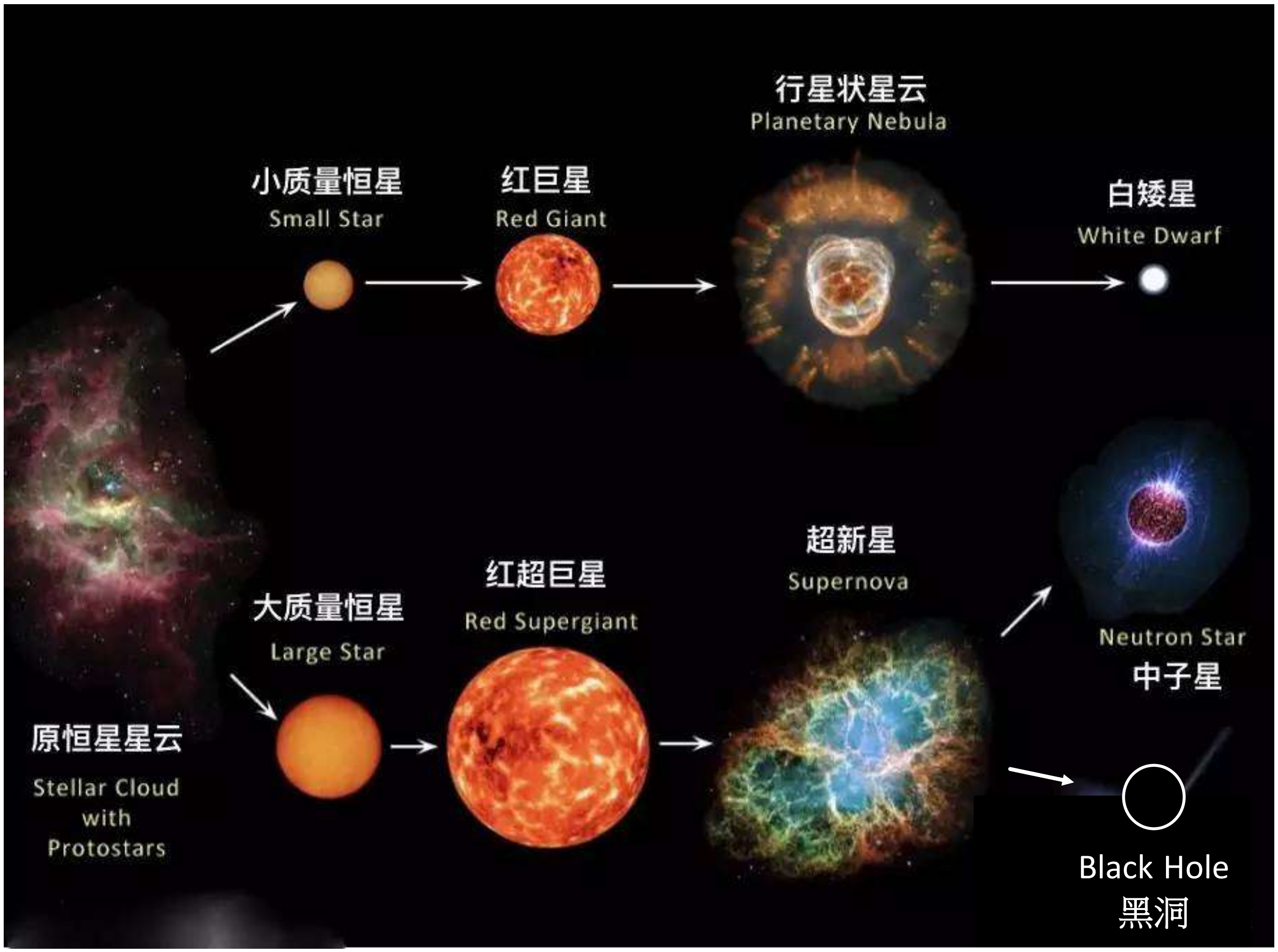
PENROSE PROCESS (1971)

It's possible to extract the rotational energy of a black hole this way!!

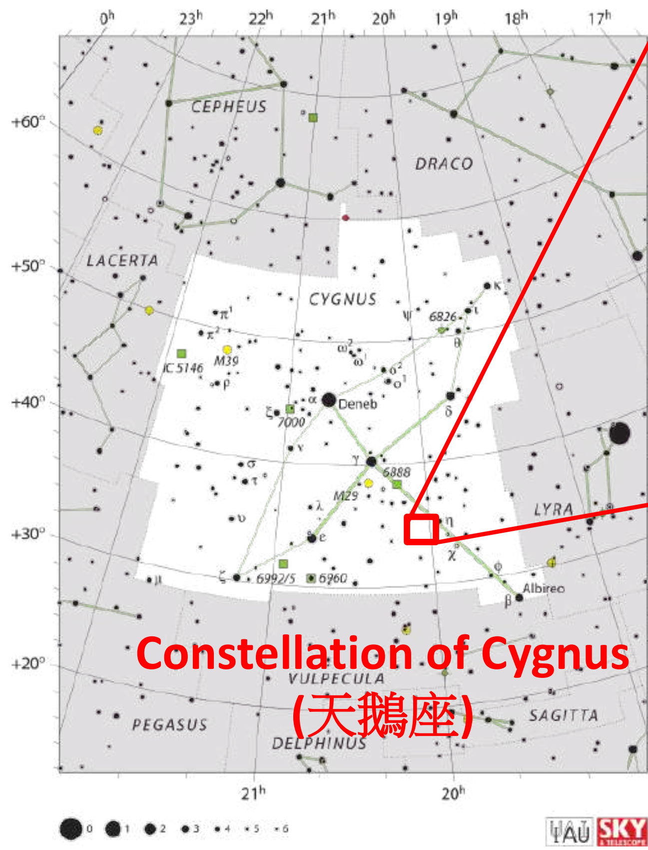


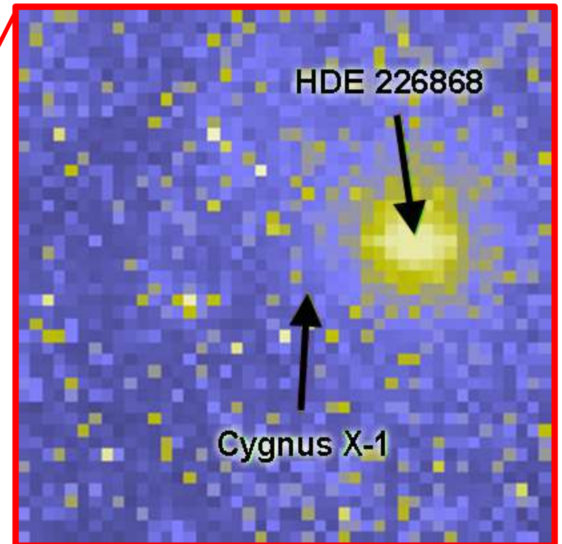
DO BLACK HOLES EXIST?

EVOLUTION OF STARS



AN INVISIBLE STAR??



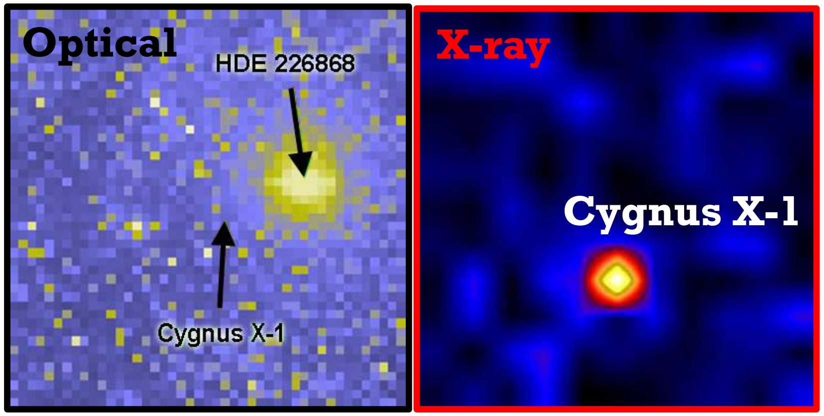


Period：5.6 days

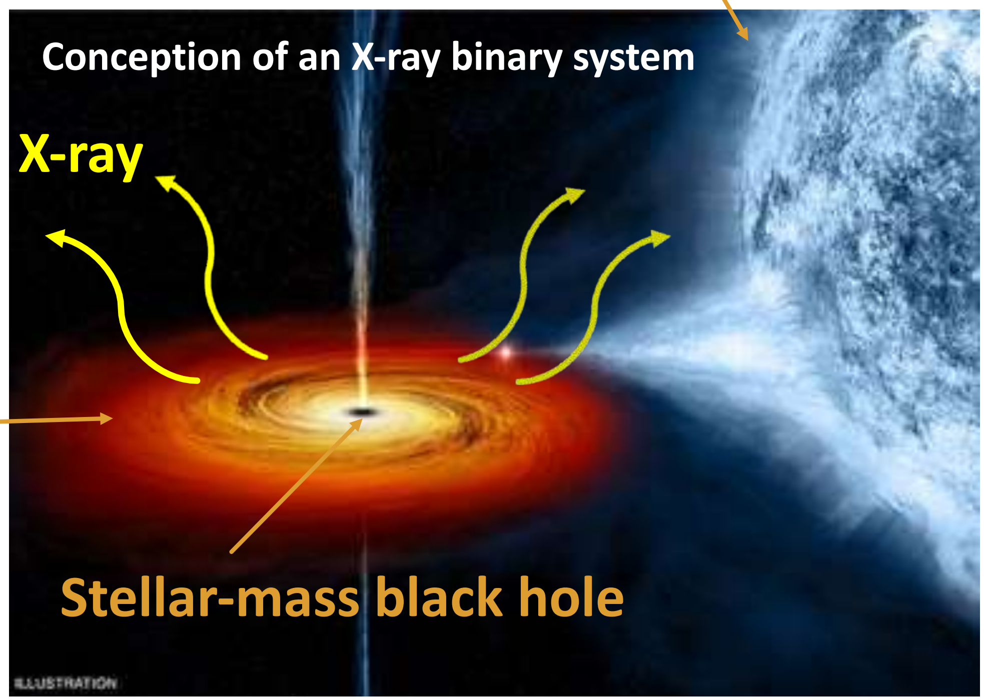
Radius：~1/5 AU

Inferred mass：14.8 M_{sun}!!

WAIT...DO BLACK HOLES SHINE??

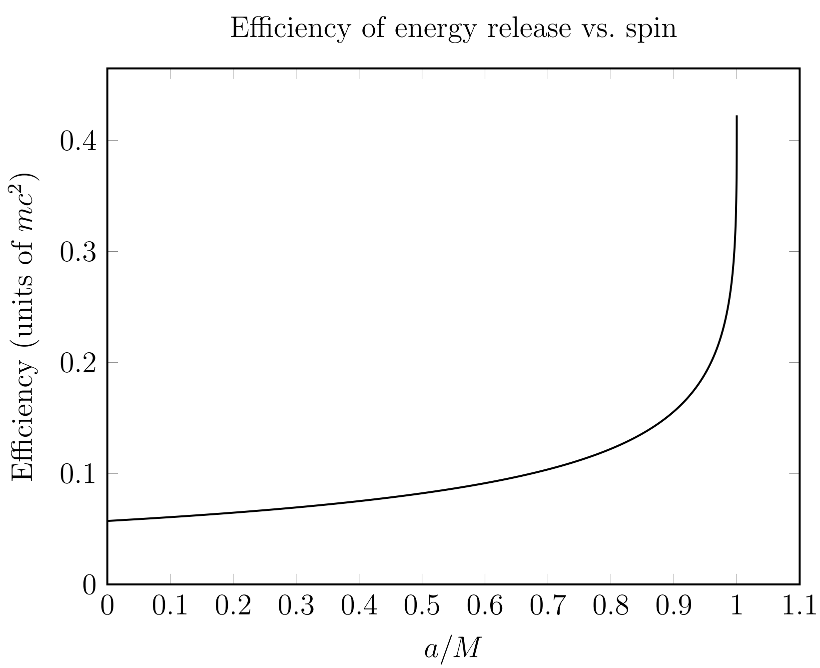


BLACK HOLES SHINE BY ACCRETING MATTER



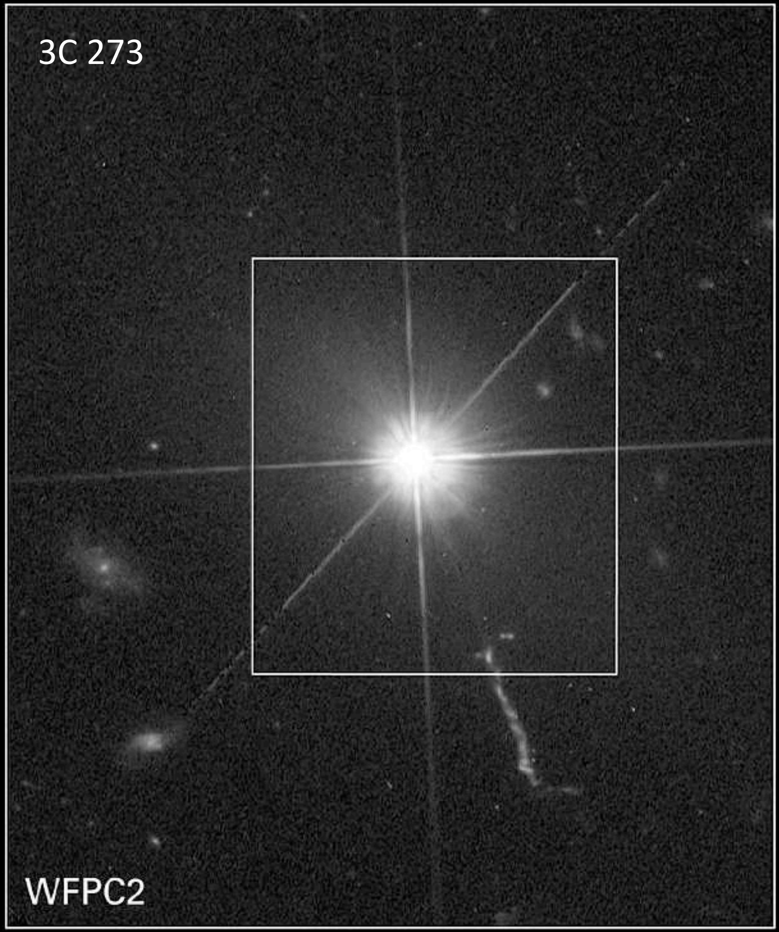
ACCRETING BLACK HOLES ARE THE MOST EFFICIENT POWER FACTORIES!

- BH accretion disks can efficiently convert gravitational energy into radiation
- Radiative efficiency depends on BH spin parameter "a"
  - a = 0: Schwarzschild BHs
  - a /= 0: spinning BHs
- ***Radiative efficiency ε ~ 10%*** for most BHs
- This is much greater than ε ~ 0.7% for nuclear fusion!



ALL MYSTERIES SOLVED?

類星體（QSO/QUASAR）



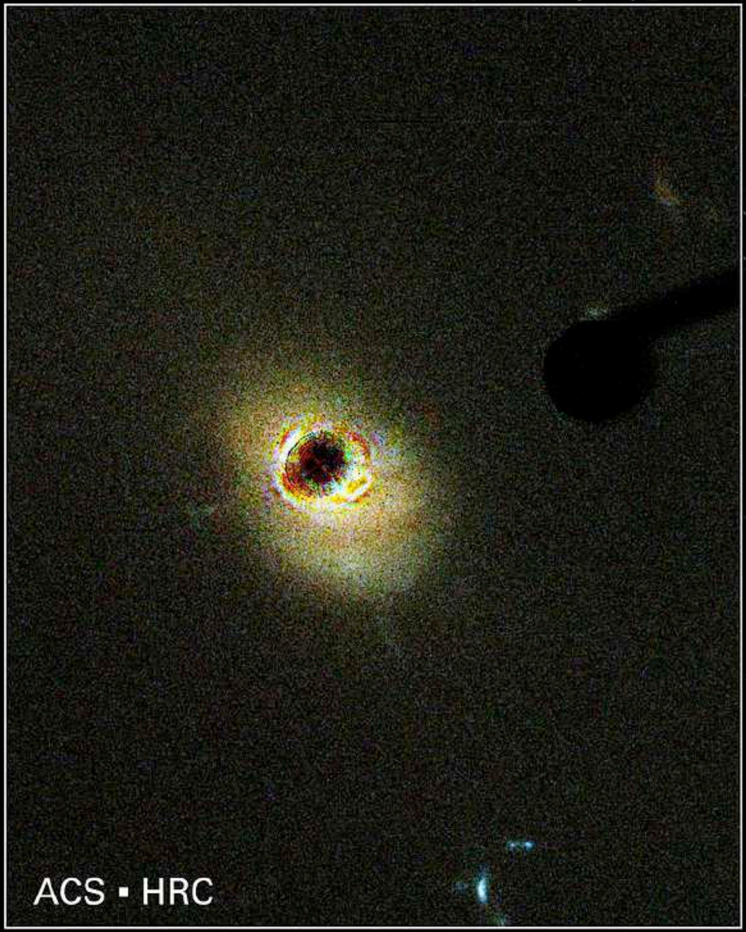
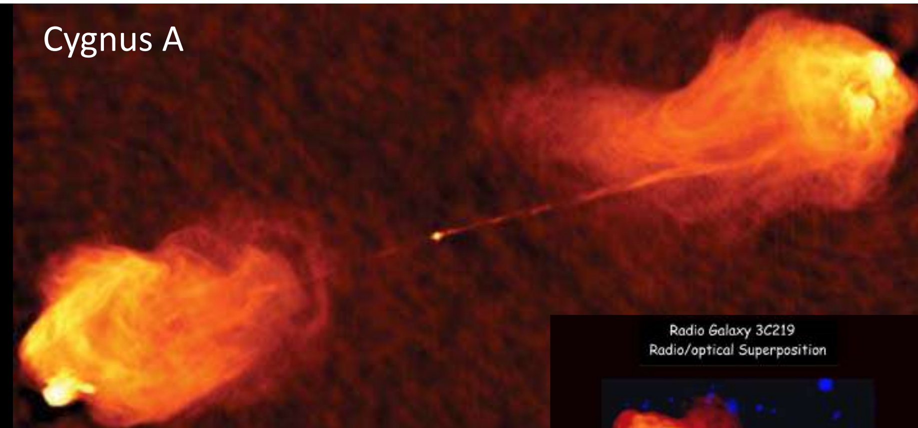
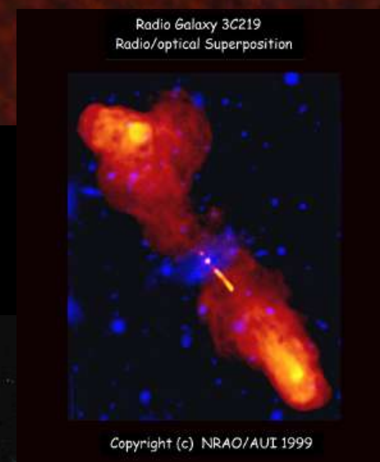


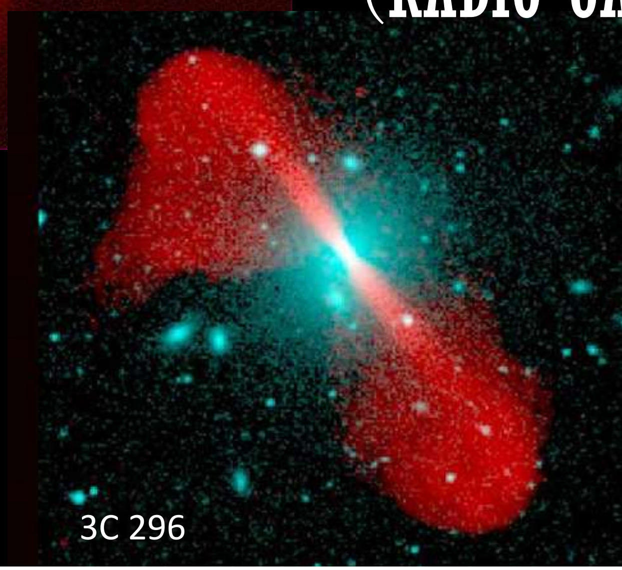
Image credit: NASA, J. Bahcall, A. Martel, H. Ford, M. Clampin, G. Hartig, G. Illingworth, the ACS Science Team and ESA

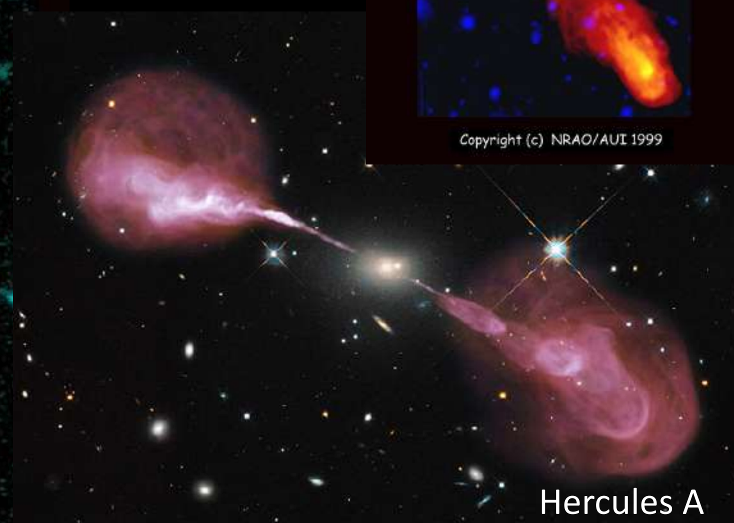

NGC6814
NGC1097
賽弗特星系
(SEYFERT GALAXIES)
M88
NGC3081

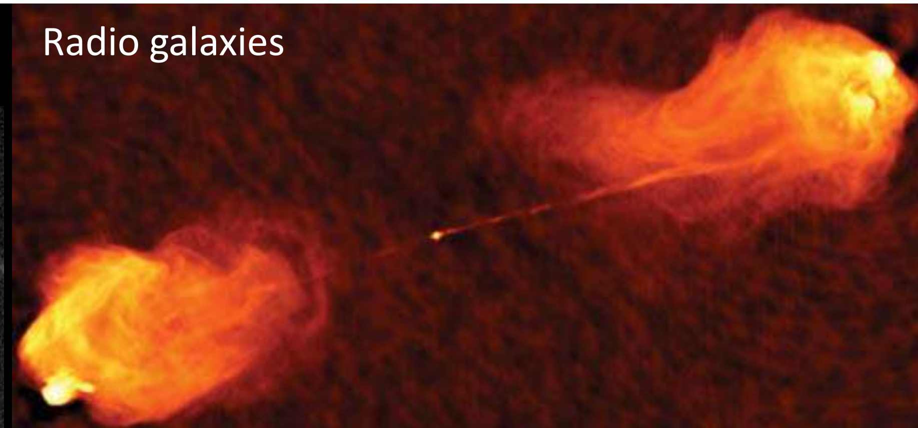


無線電星系
(RADIO GALAXIES)

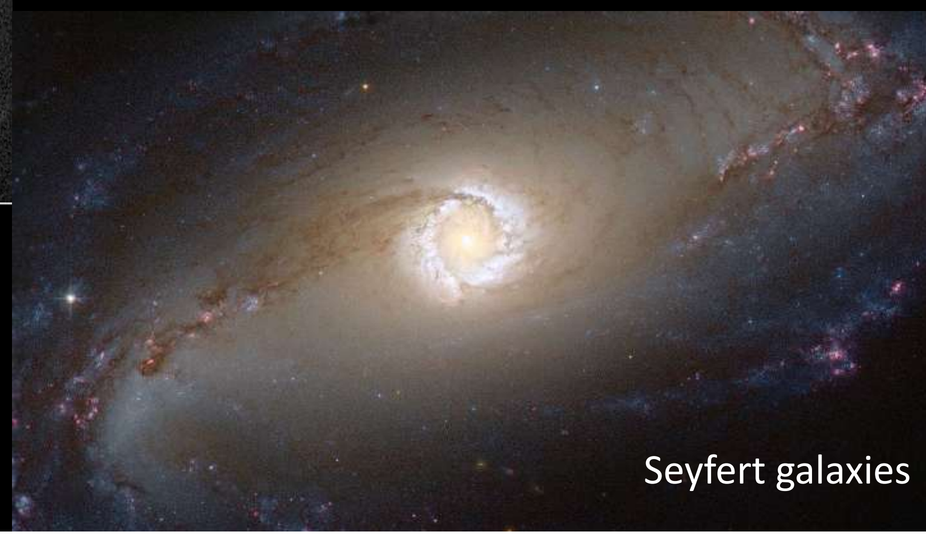




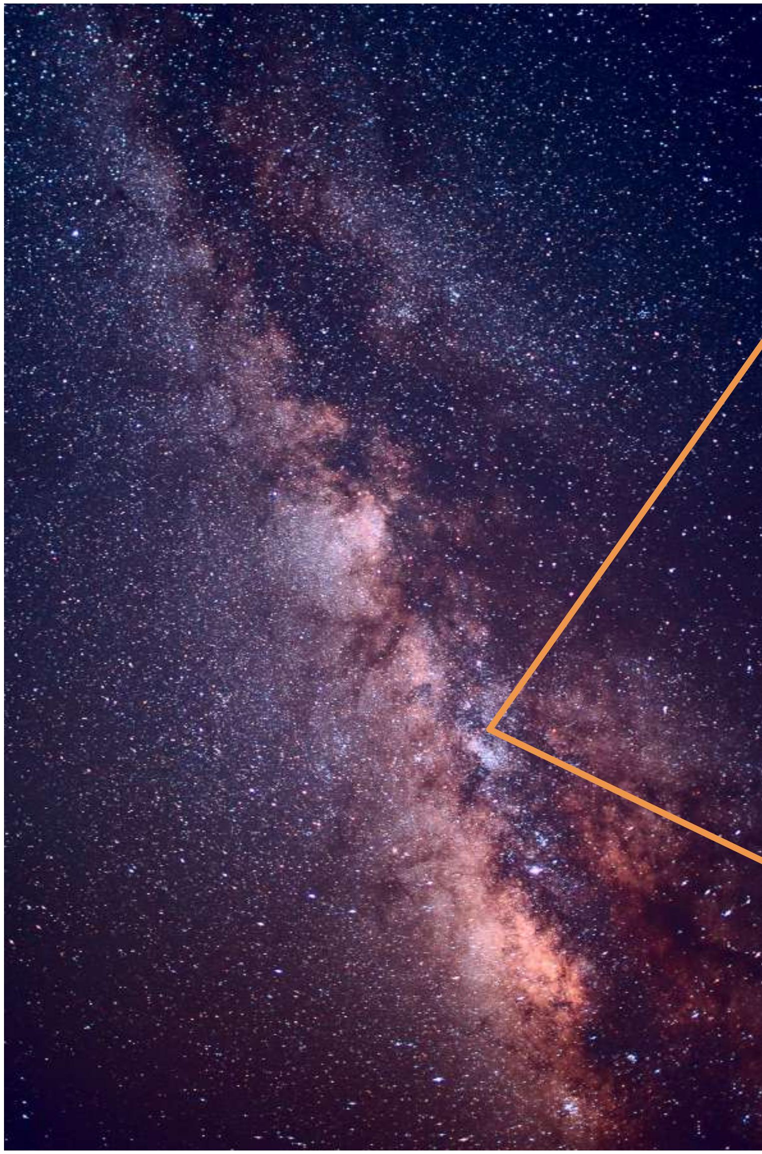




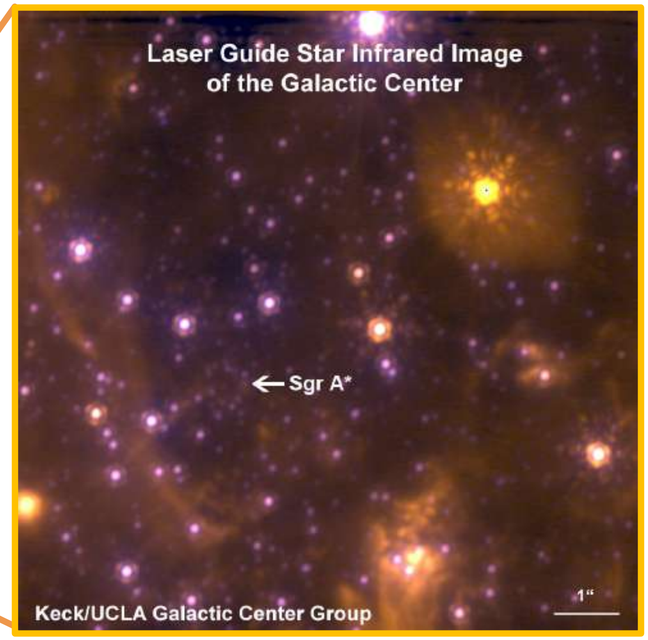
活躍星系核
（ACTIVE GALACTIC NUCLEI）



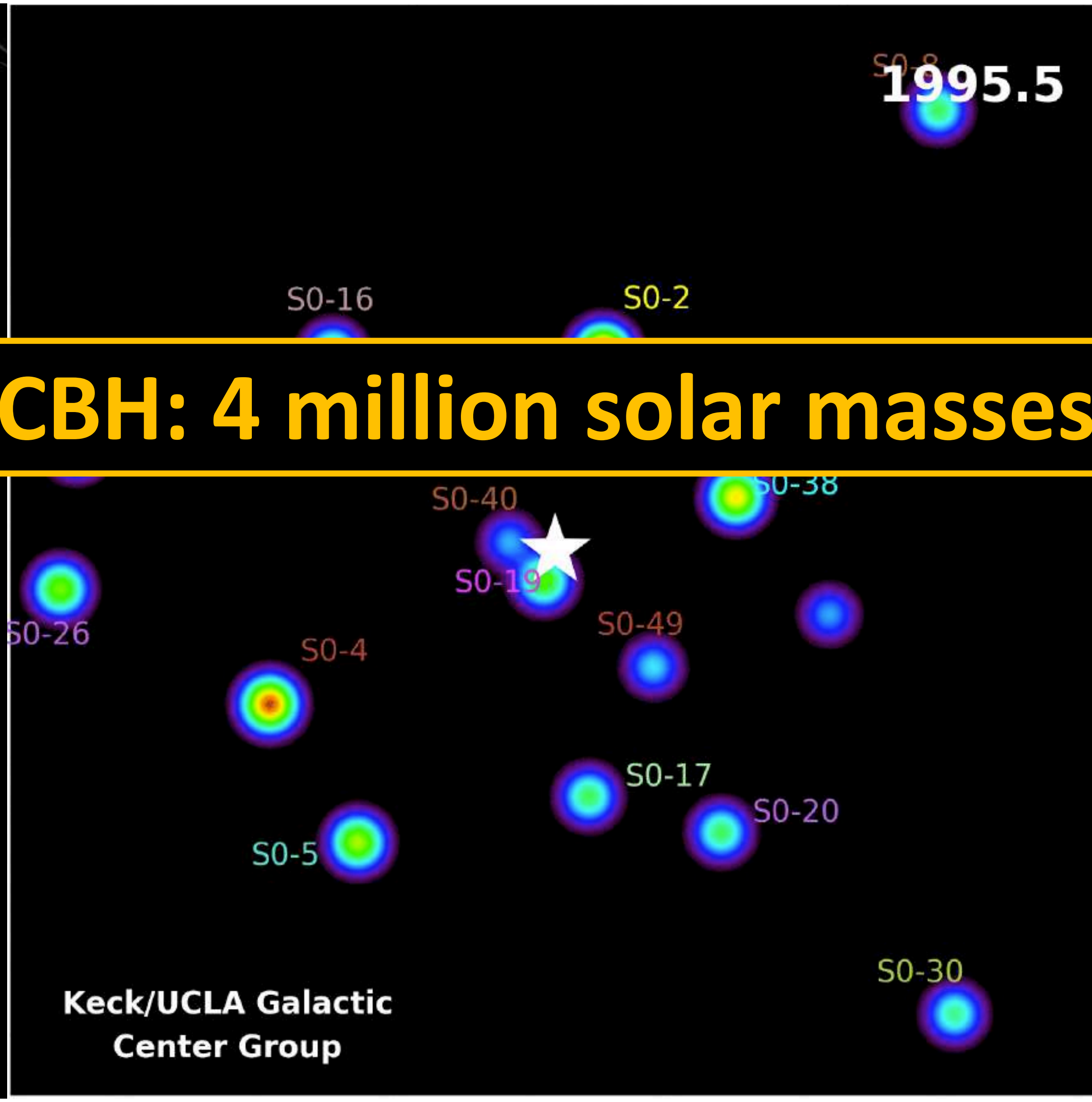
MILKY WAY GALAXY



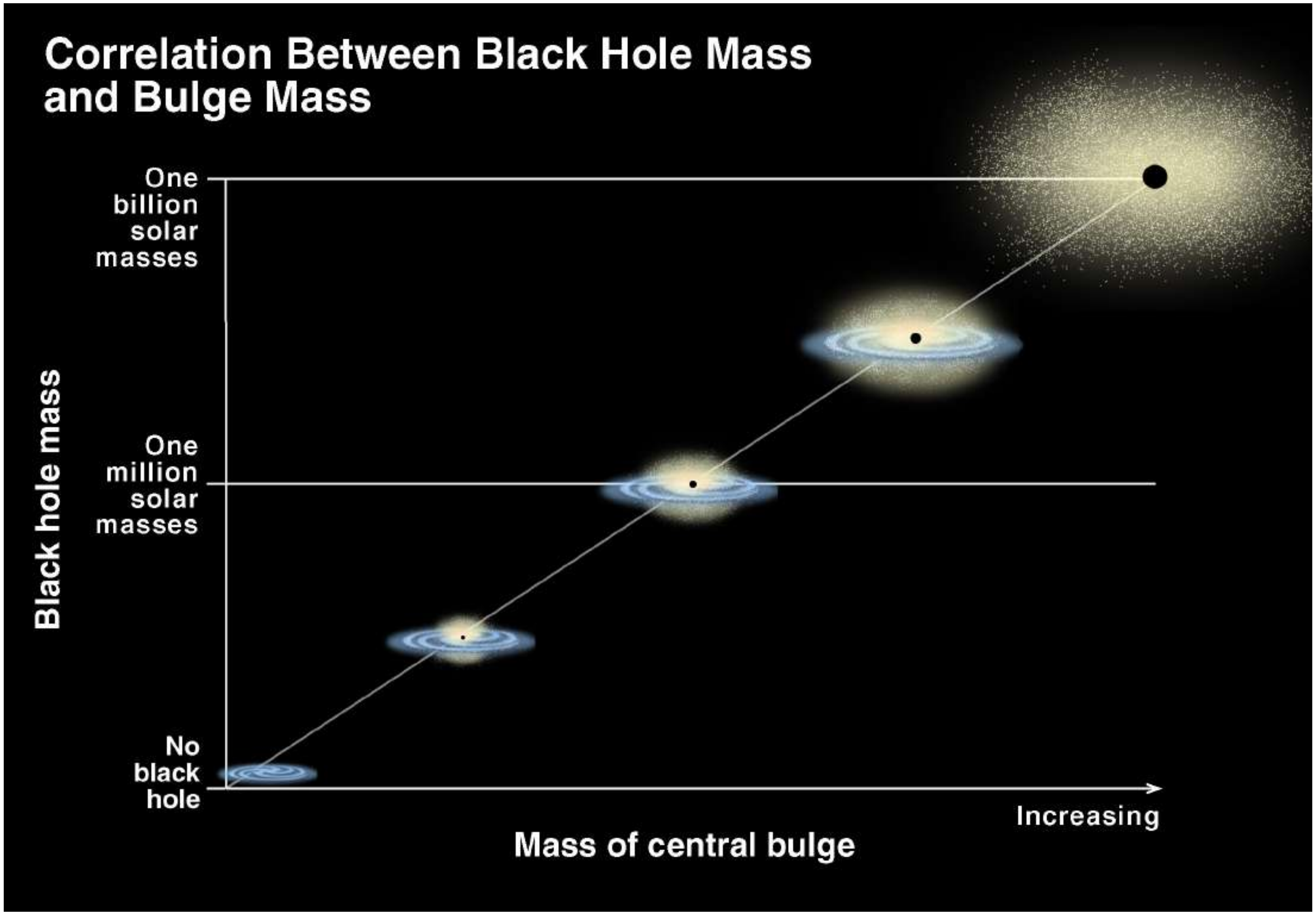
Infrared image of the Galactic center



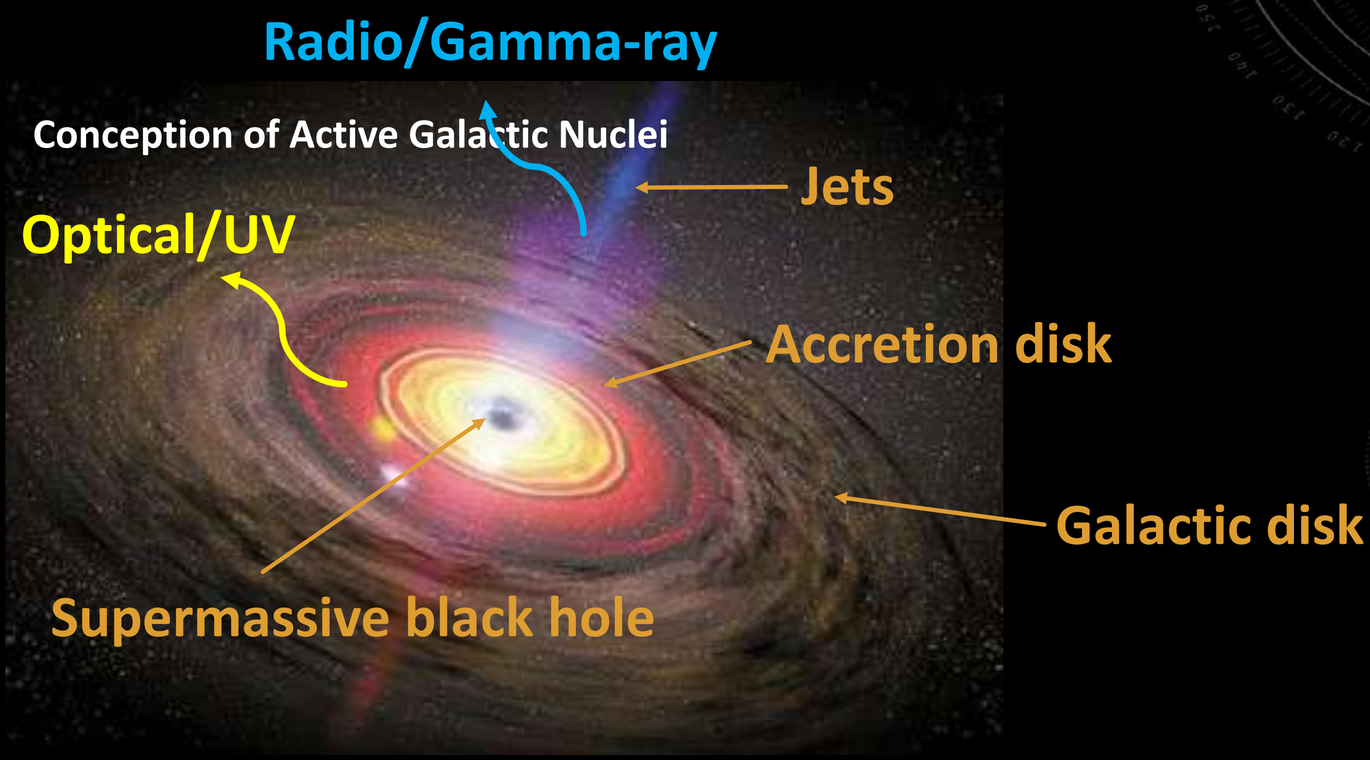
GCBH: 4 million solar masses!!!



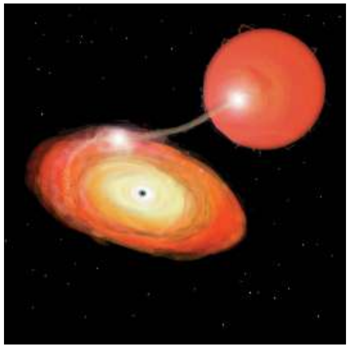
EVERY GALAXY HOSTS A SMBH AT THE CENTER!!



ACTIVE GALACTIC NUCLEI (AGN) = ACTIVELY ACCRETING SUPERMASSIVE BLACK HOLES

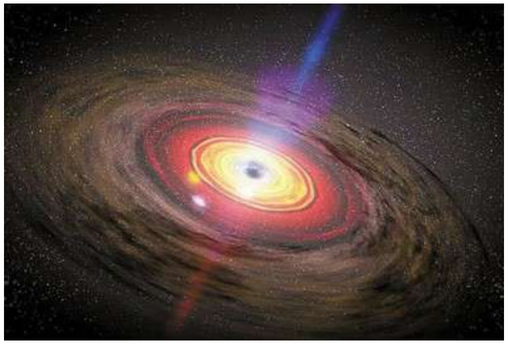


BLACK HOLES COME IN TWO FLAVORS



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

HOW DO SUPERMASSIVE BLACK HOLES FORM?

SUPERMASSIVE BLACK HOLES GROW BY MERGERS AND ACCRETION

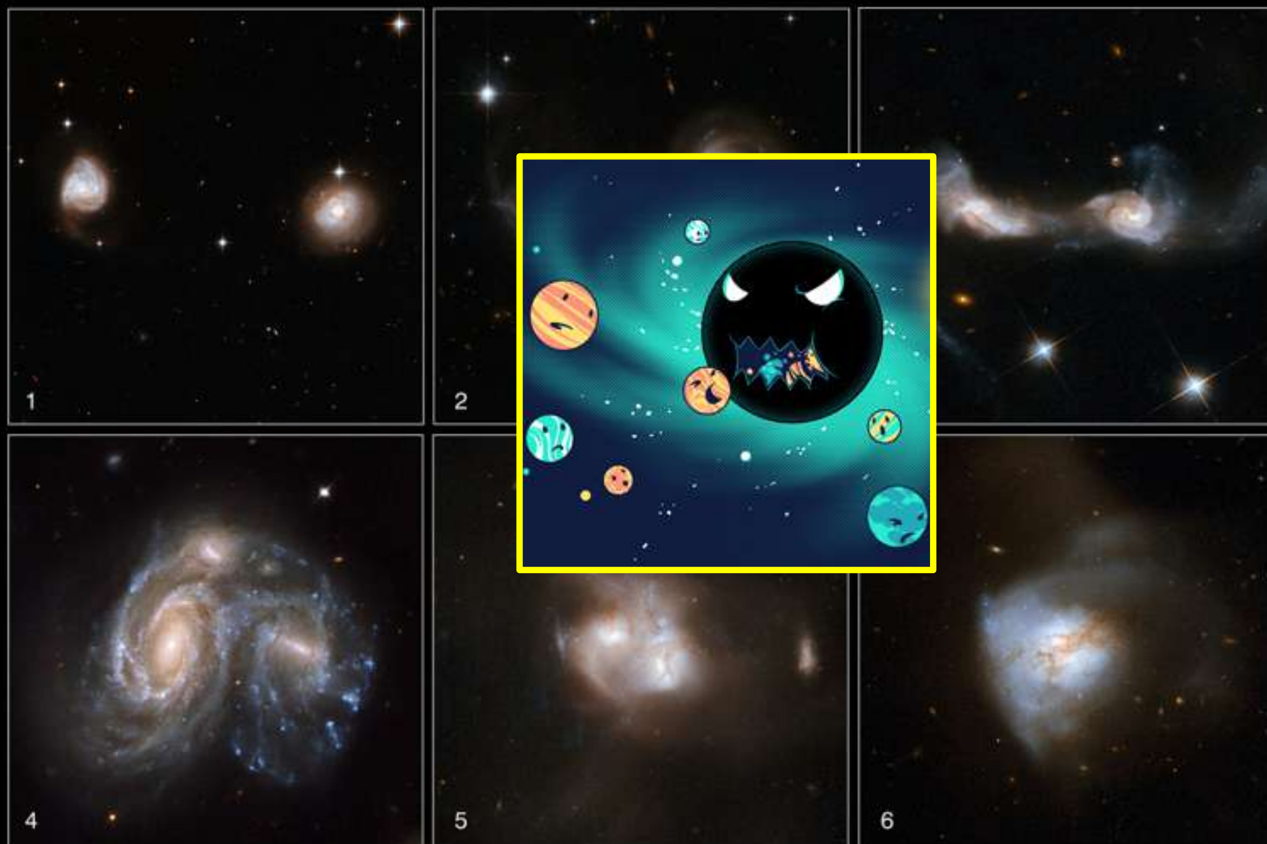
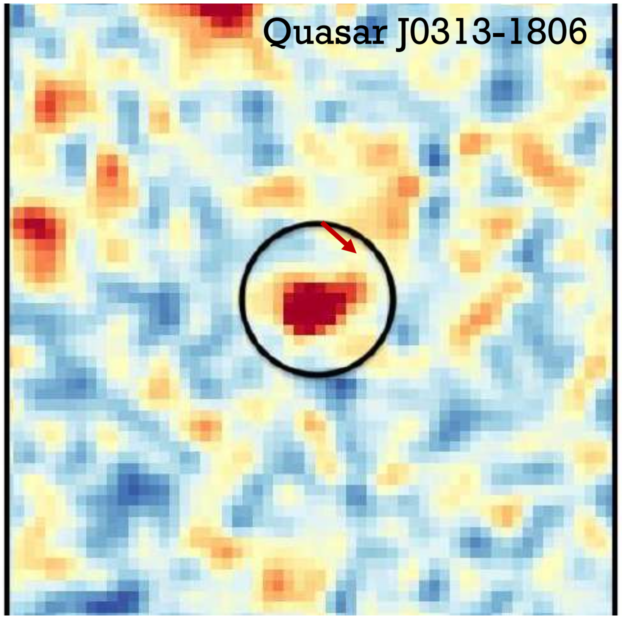


Image credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration

THE POWERFUL QUASARS IN THE EARLY UNIVERSE



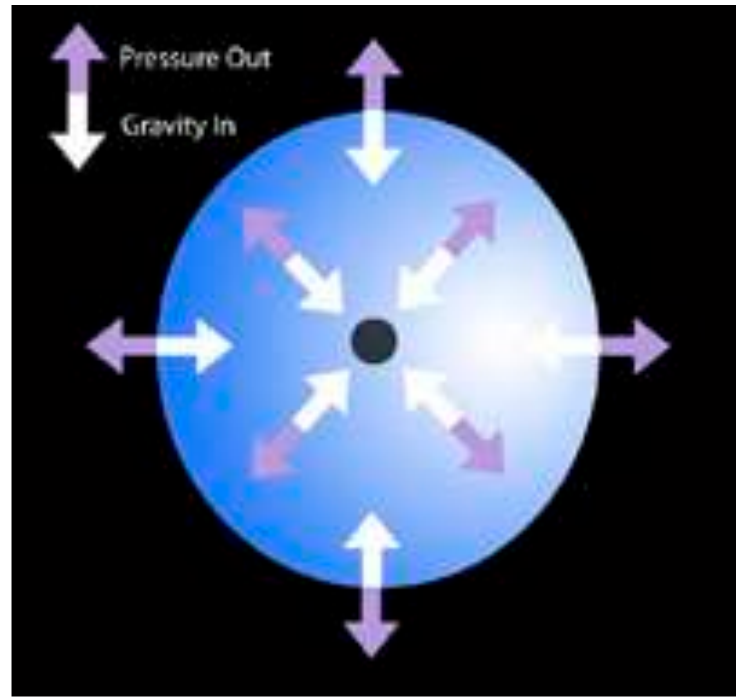
- Quasars with billions of M_{sun} at $z > 7$ were discovered
- Current record holder: J0313-1806 found in 2021
  - Redshift $z = 7.642$ (***690 Myr*** after Big Bang)
  - ***$M \sim 1.6 \times 10^9 M_{sun}$***
- These objects are relatively rare; most quasars are found at z~2-3
- But their existence is surprising!!

THE GROWTH OF SMBHS

- Accretion of black holes are limited by the Eddington accretion rate
  - The ***Eddington limit*** refers to the balance between ***gravity*** and ***radiation pressure force***
  - This is the maximum rate black holes can accrete
- The Eddington accretion rate is proportional to black hole mass, i.e.,

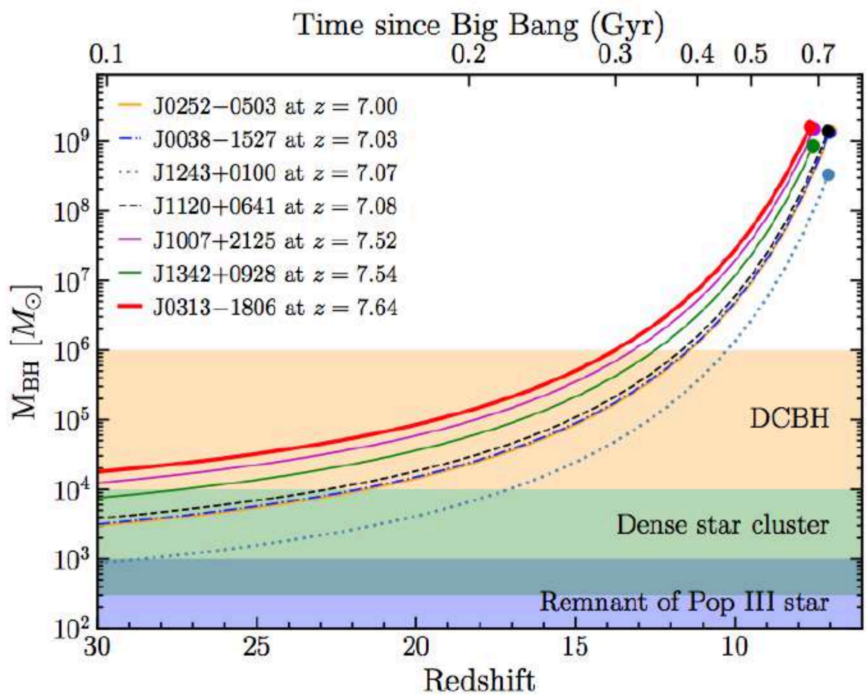
$$\boxed{\dot{M}_{BH} = \frac{dM_{BH}}{dt} = AM_{BH}}$$

- Therefore, for BHs accreting at the Eddington rate, their masses grow ***exponentially***



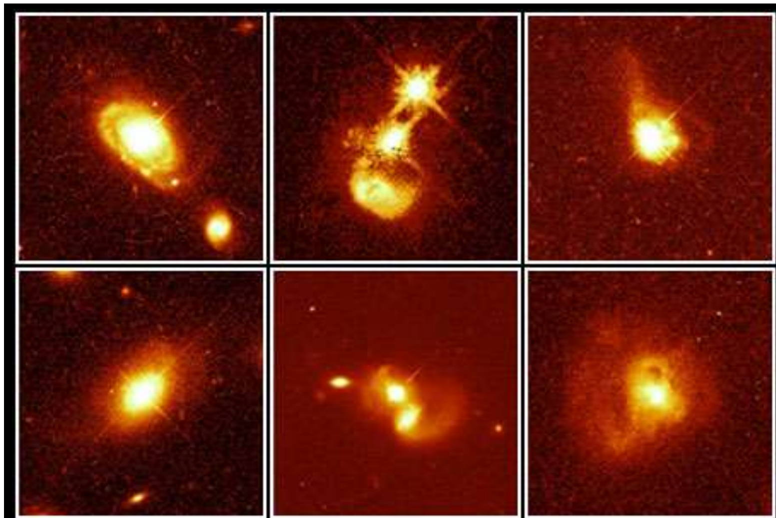
CAN EARLY QUASARS GROW FROM STELLAR-MASS BLACK HOLES?

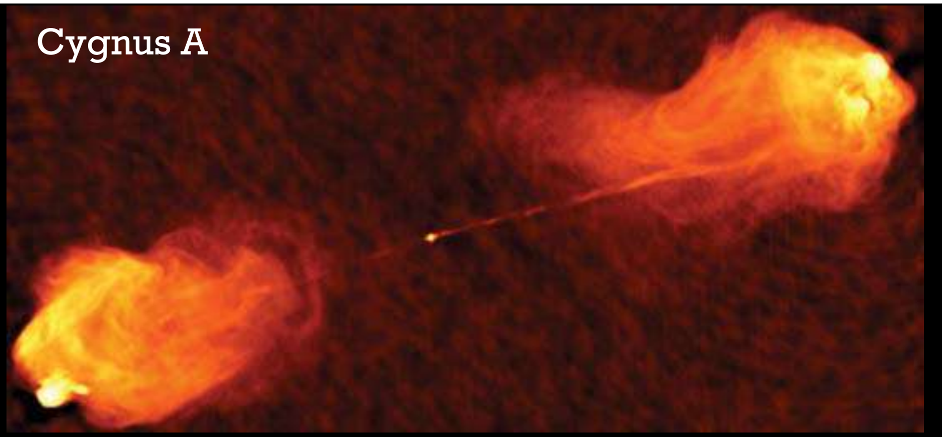
- No – there is not enough time!
- To explain the existence of massive SMBHs in the early universe, they must form from black hole "***seeds***" of ***~10^2 – 10^5 M_{sun}***
- Three proposed BH seed formation mechanisms:
  - ***Pop III stars***: $M_{BH} \sim 10^2 \sim 10^3$ M_{sun} (light seeds)
  - ***Collapse of star clusters***: $M_{BH} \sim 10^2 \sim 10^4$ M_{sun} (intermediate seeds)
  - ***Direct collapse of gas clouds***: $M_{BH} \sim 10^4 \sim 10^6$ M_{sun} (heavy seeds)



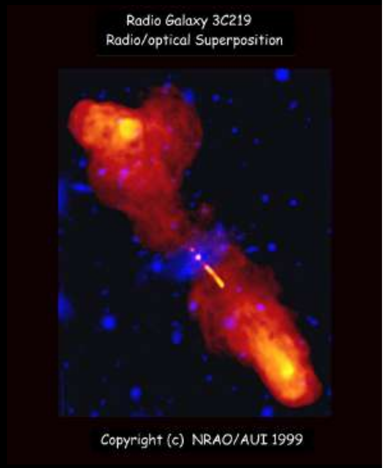
Wang et al. (2021)

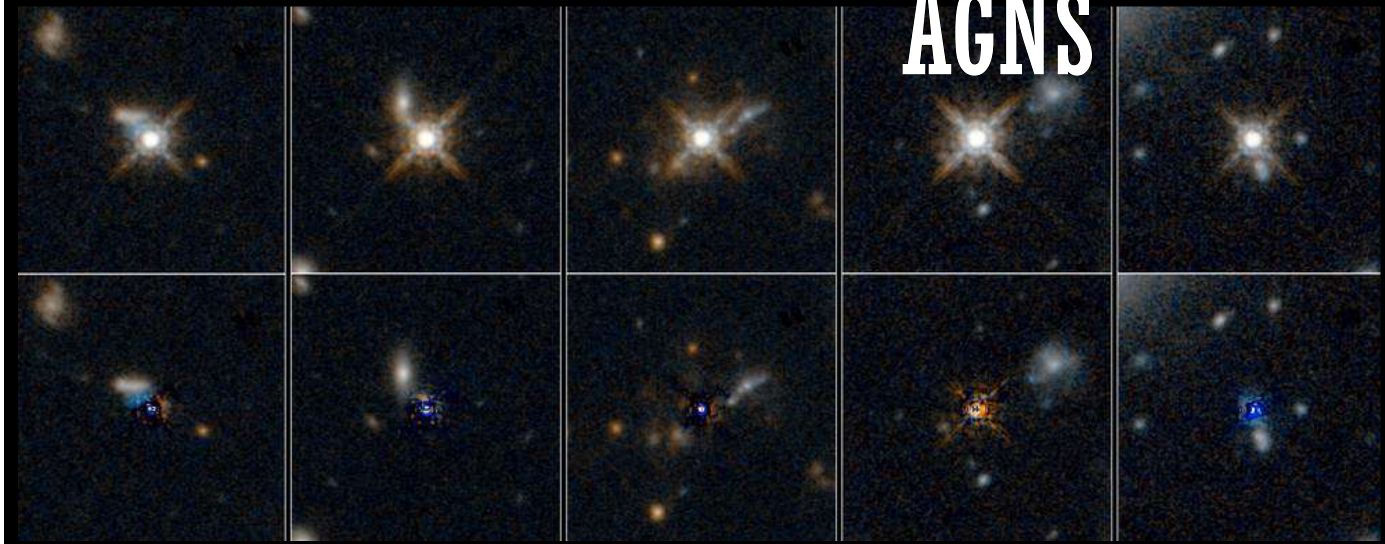
HOW DO AGNS AFFECT GALAXY EVOLUTION?



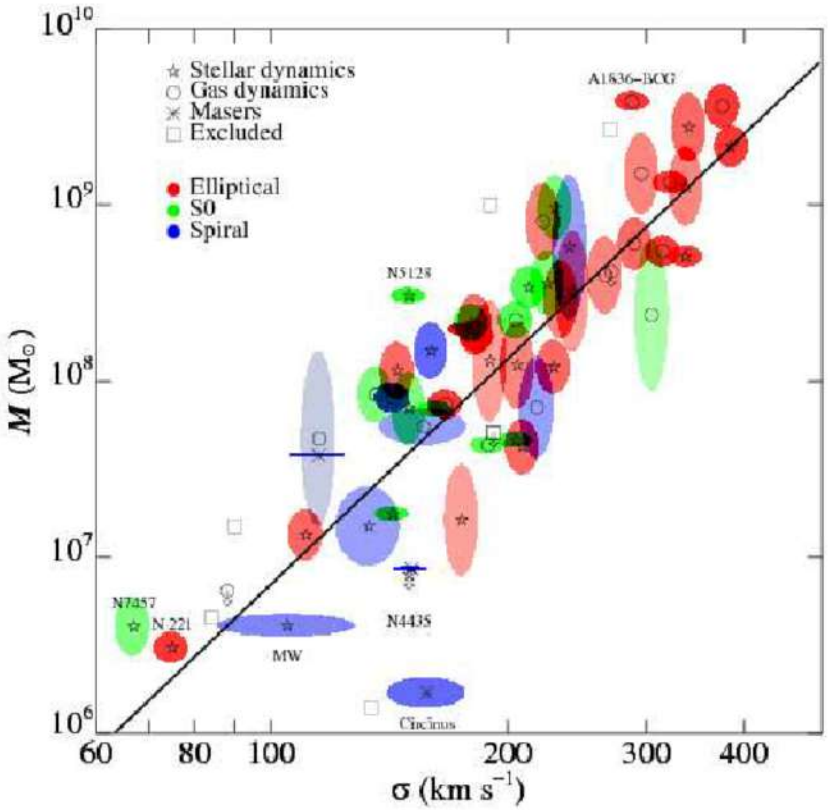


POWERFUL AGNS





ORIGIN OF THE M-SIGMA RELATION?

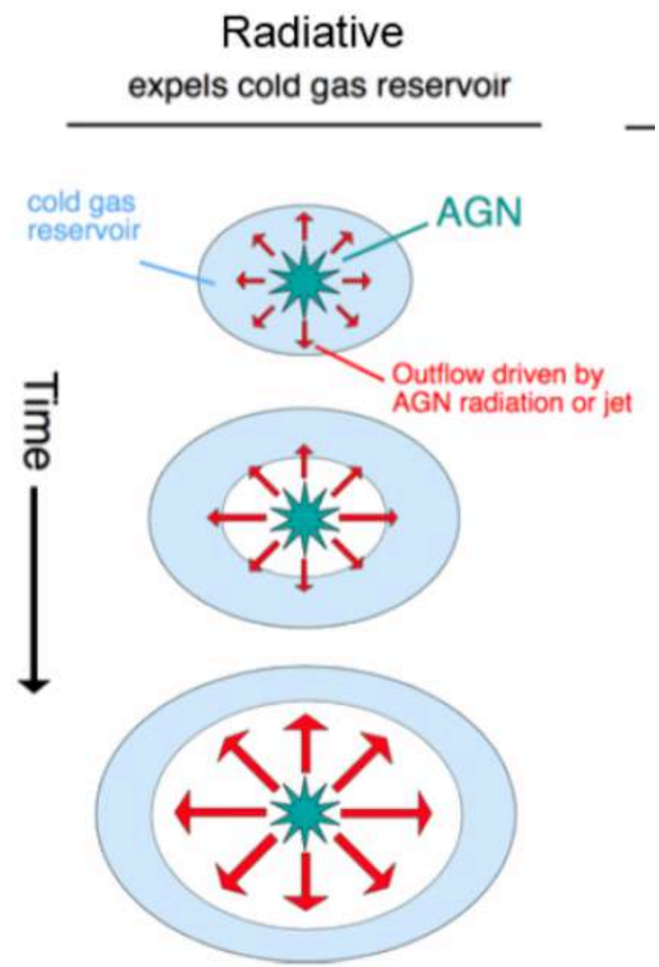


Stellar velocity dispersion

- Most discussed hypothesis: ***AGN feedback***
- BHs and galaxies ***co-evolve***: both grow from accretion of gas
- Eventually the BH is so big and powerful that it blasts the gas from the galaxy and stops them from growing

THE "QUASAR-MODE" FEEDBACK

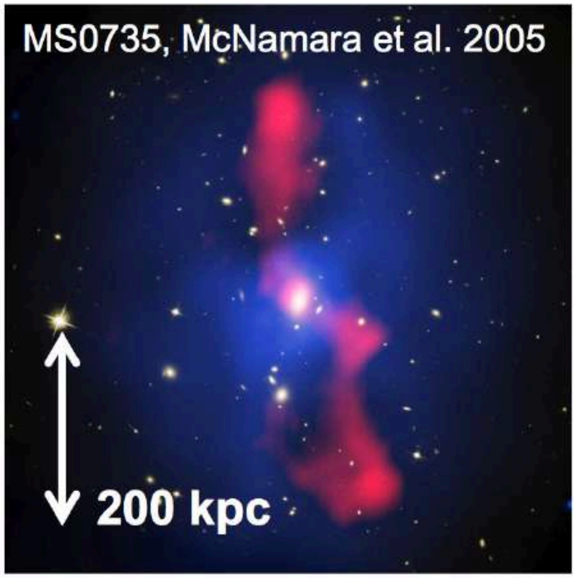
- ***Quasar/radiative mode feedback***
- More important at ***higher redshifts***
- Operates mainly by ***expelling gas***
- A plausible mechanism for the M-sigma relation
- Could quench star formation and regulate SMBH growth

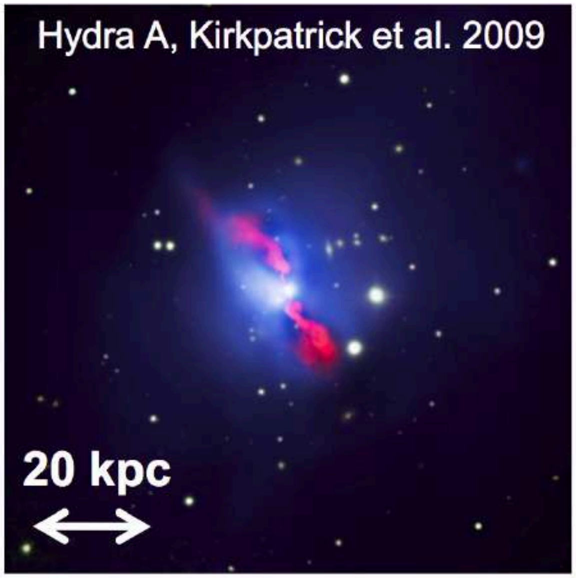


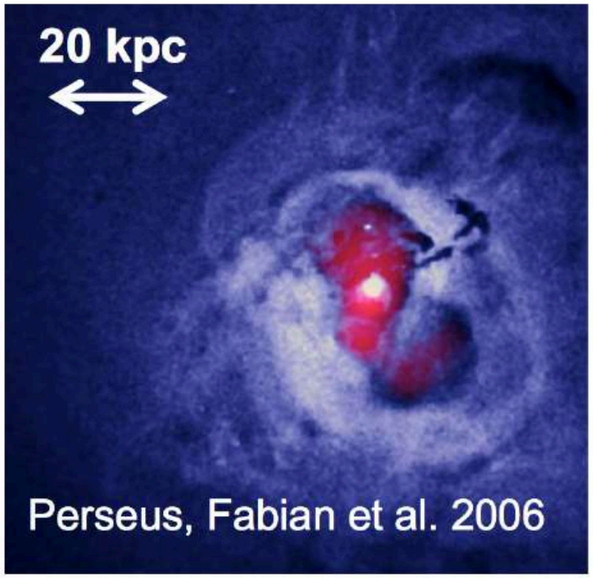
THE "JET-MODE" FEEDBACK

- In massive ***galaxy clusters***, the cluster gas is hot ($T \sim 10^7 K$) and emits in X-ray
- This allows us to clearly see interactions between the jets and the gas
- The jets can provide lots of energy to heat the gas, otherwise the galaxy at cluster centers would produce too many stars and be too massive

Blue: X-ray gas
Red: radio jets

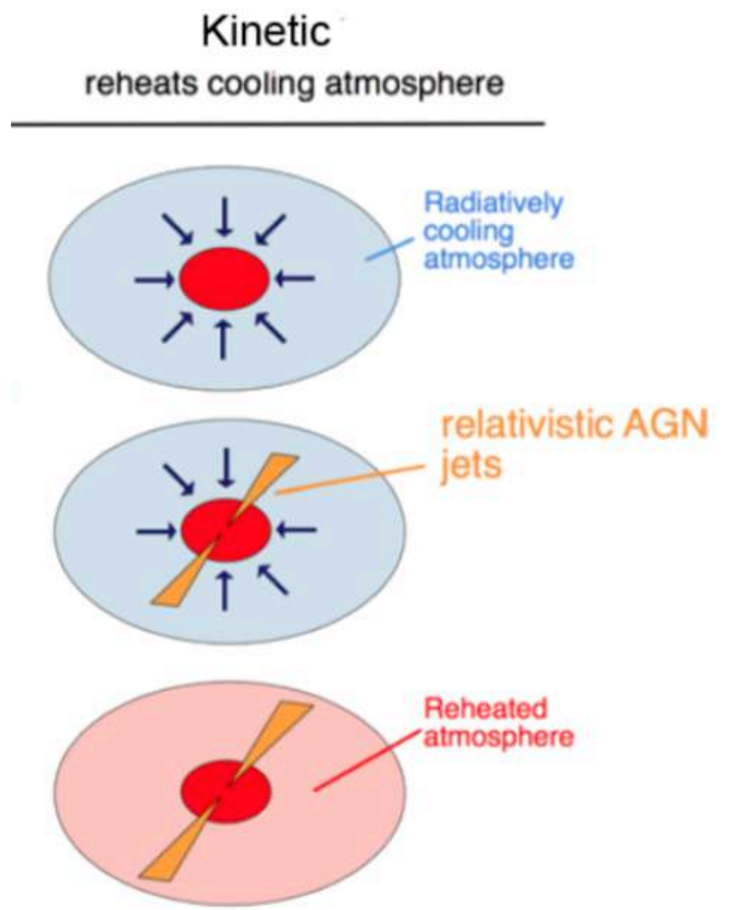




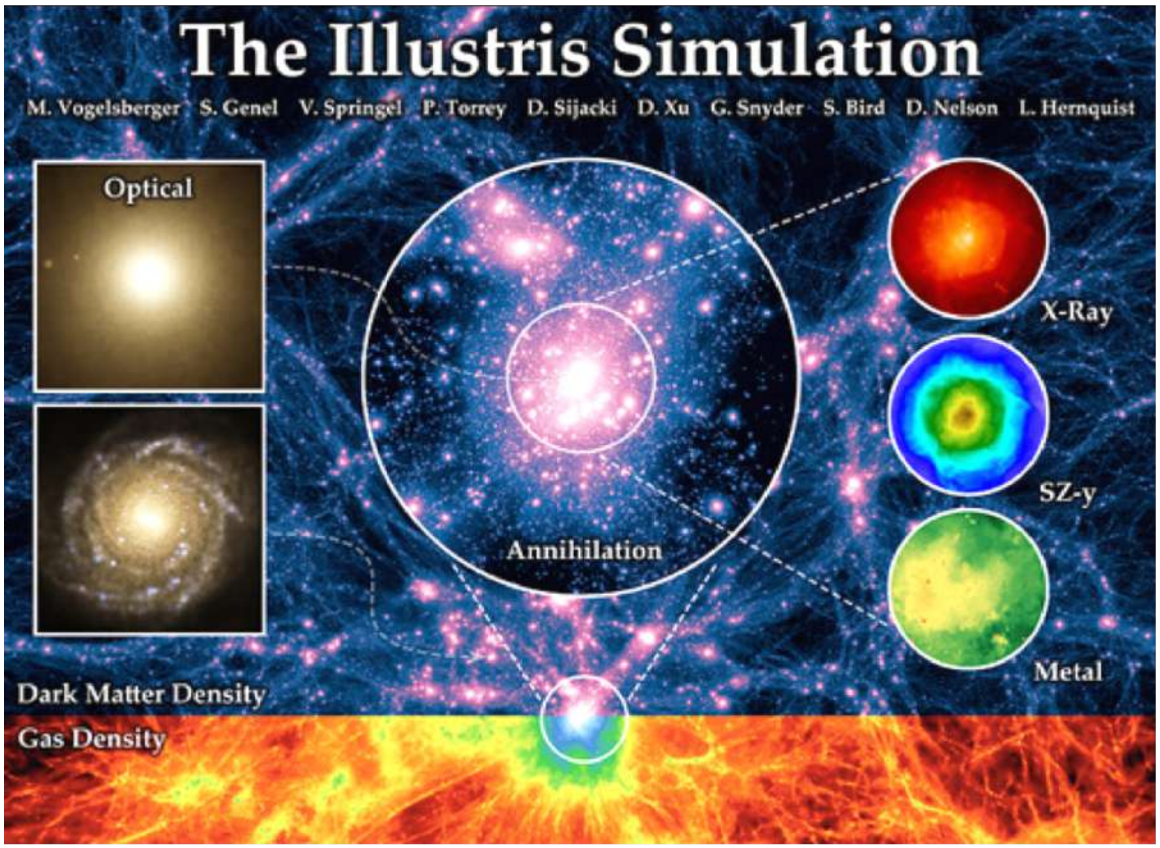


THE JET-MODE FEEDBACK

- ***Jet/kinetic mode feedback***
- More important at ***lower redshifts***
- Operates mainly by ***heating gas*** via jets
- Can reduce star formation at cluster centers and limit the growth of massive galaxies

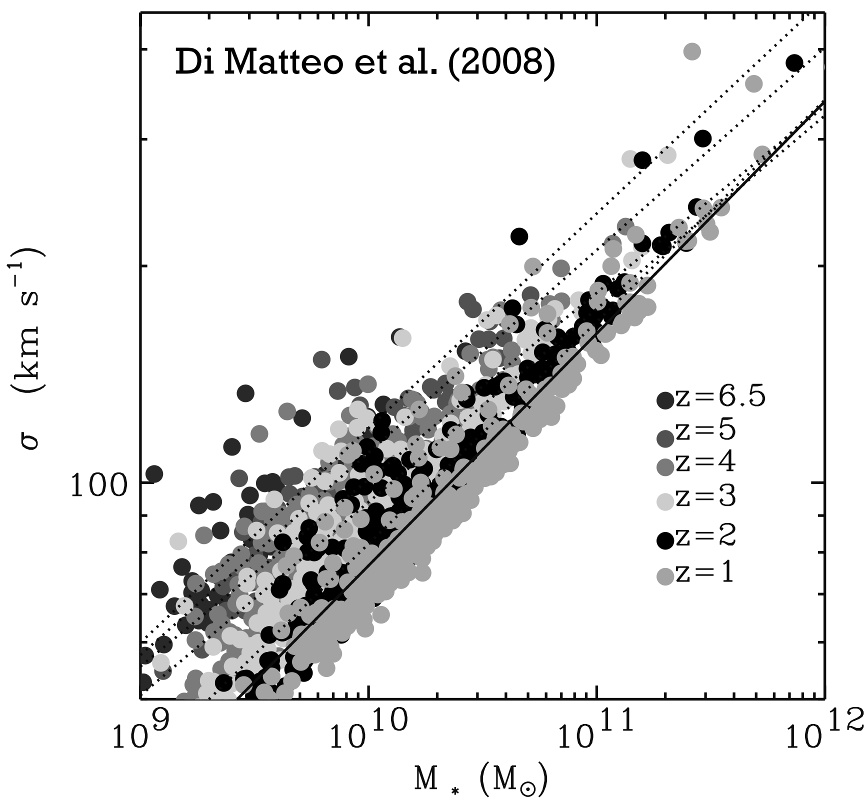


SUCCESSES OF COSMOLOGICAL SIMULATIONS



- ***Cosmological simulations*** of galaxy formation
- Ingredients:
  - Baryons, dark matter, dark energy
  - Gravity
  - Gas dynamics
  - Star formation and supernova feedback
  - SMBH seeds and growth
  - Quasar- and jet-mode AGN feedback

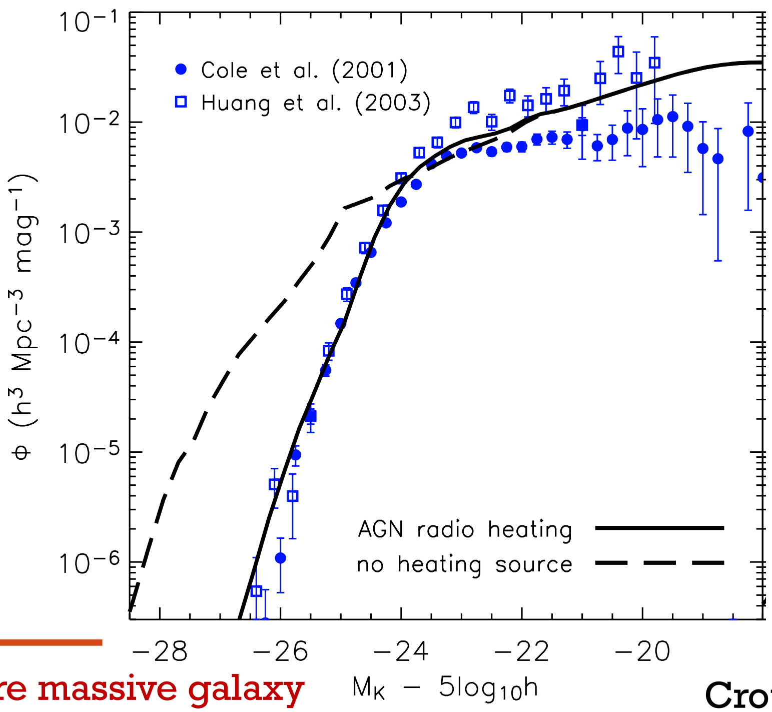
M-SIGMA RELATION REPRODUCED



- Critical ingredient -- "***quasar-mode***" feedback

DISTRIBUTION OF GALAXIES REPRODUCED

Galaxy number density vs. galaxy mass

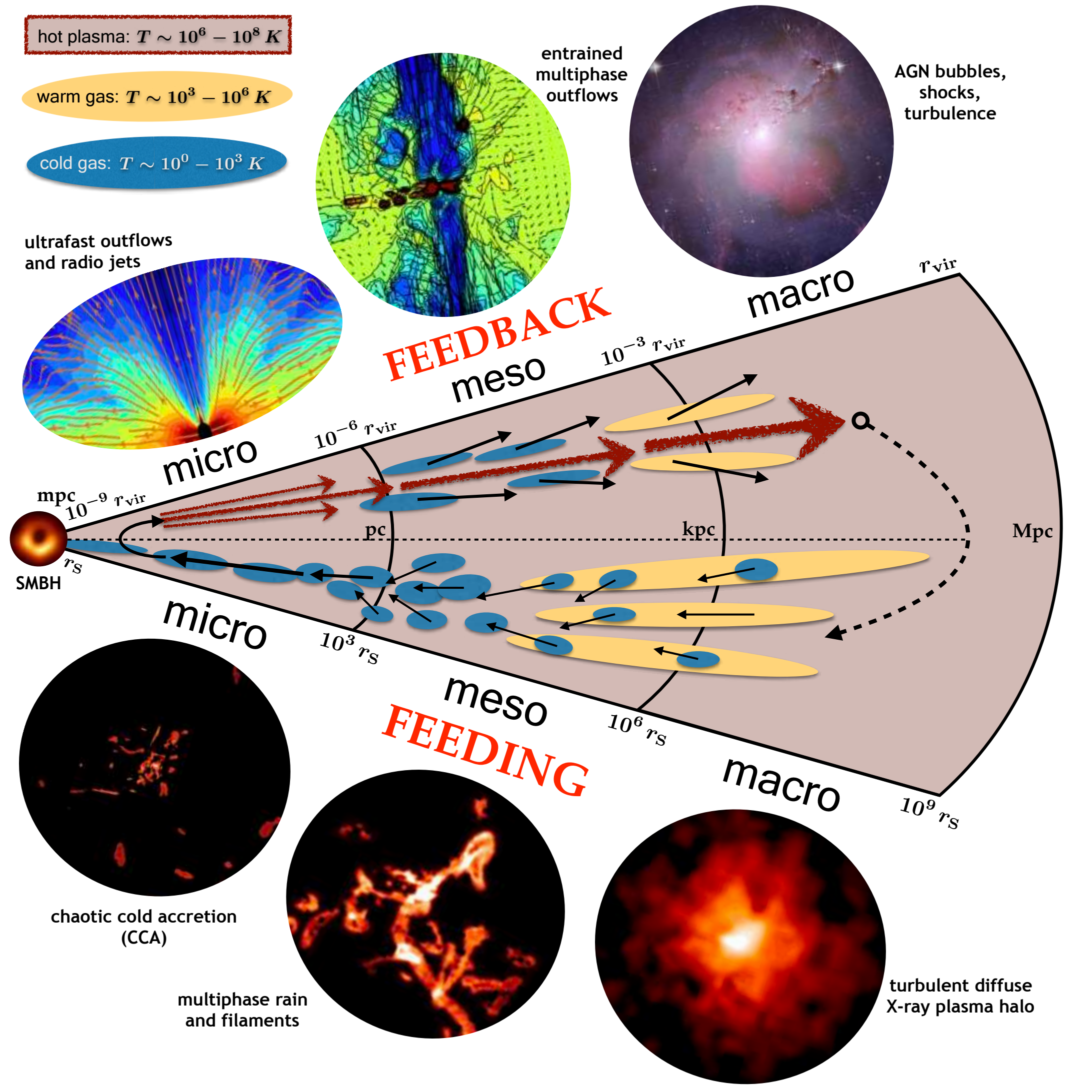


More massive galaxy

Croton et al. (2006)

- Critical ingredient: "***jet-mode***" feedback

Devils lie in the details!



Gaspari (2020)

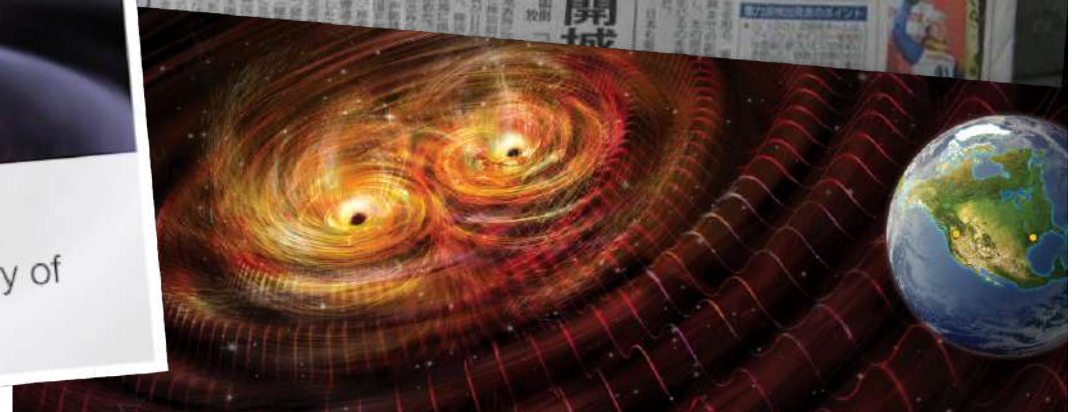
WHAT CAN WE LEARN FROM GRAVITATIONAL WAVES?


The New York Times
Late Edition
NEW YORK, FRIDAY, FEBRUARY 12, 2016
$2.50
WITH FAINT CHIRP, SCIENTISTS PR
EINSTEIN COR
A RIPPLE IN SPACE
An Echo of Black Holes Colliding a Billion Light-Years Away
By DENNIS OVERBYE

Feb 11, 2016

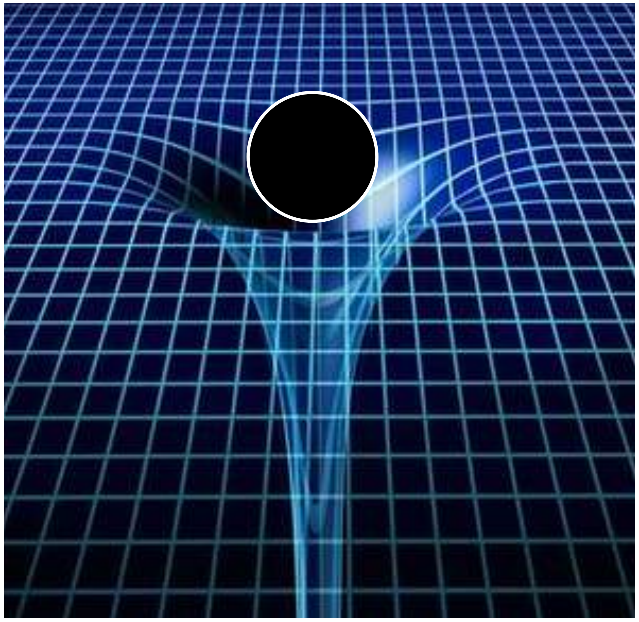

重力波 世界初観測
山陰新聞
2月12日
米大チーム
宇宙成り立ち迫る
アインシュタイン予言
北朝鮮、開城


Gravitational waves are real
Astounding discovery was predicted by Einstein's theory of relativity
Einstein's theory: It's relative to YOU | His dark mistake foretells the end of the universe

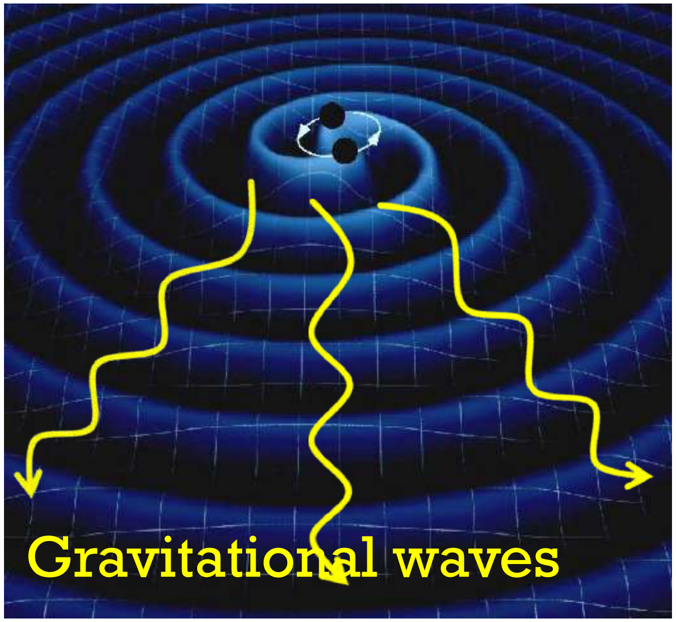


GENERAL RELATIVITY PREDICTS CURVED SPACETIME AROUND MASSES

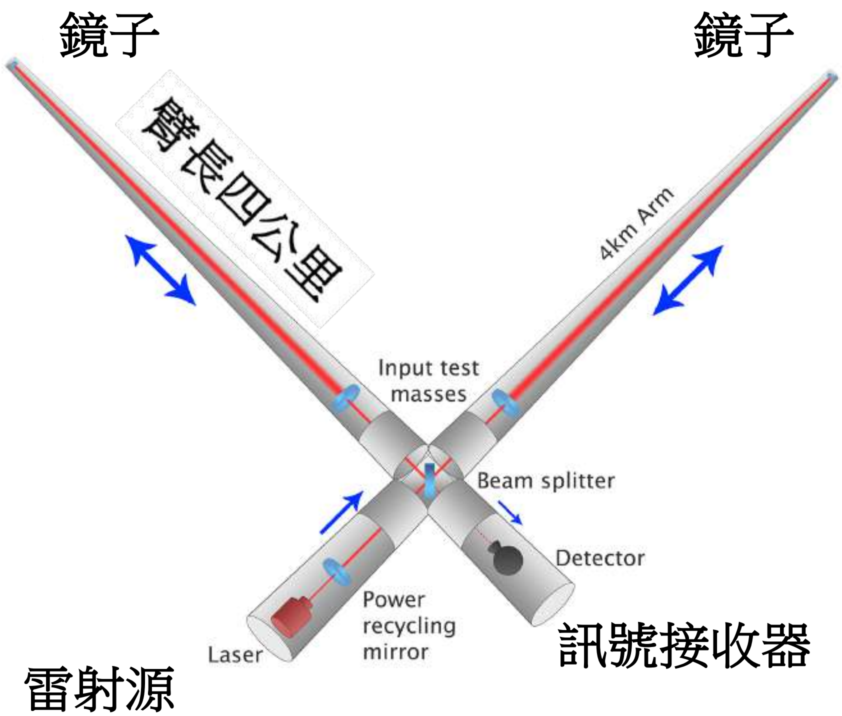
A static black hole



Two orbiting black holes

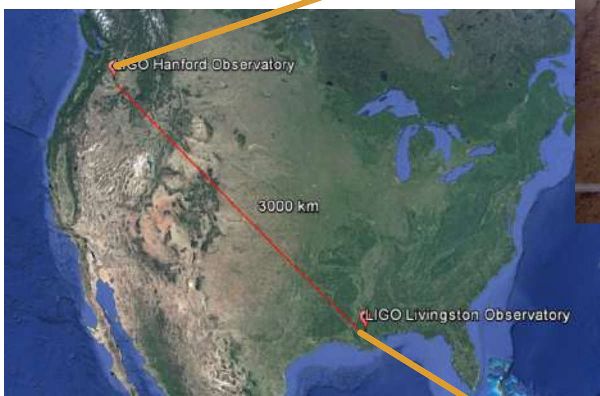


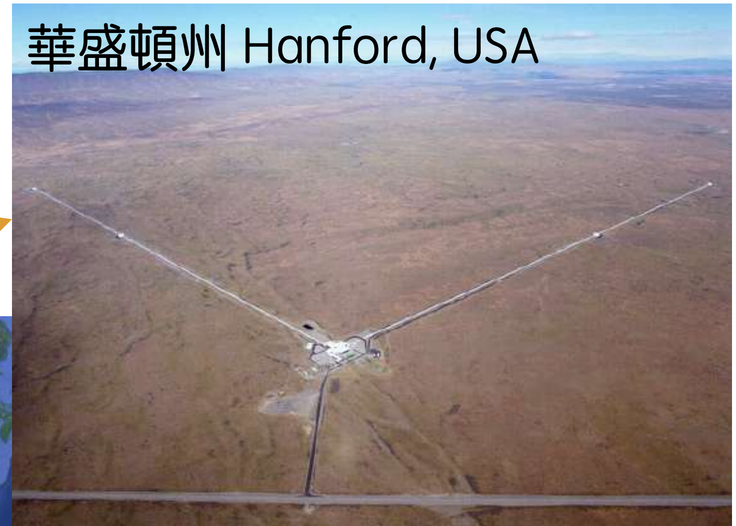
LIGO (雷射干涉重力波天文台)



Changes of the arm length are ~1/10 of the atomic nuclei!!!

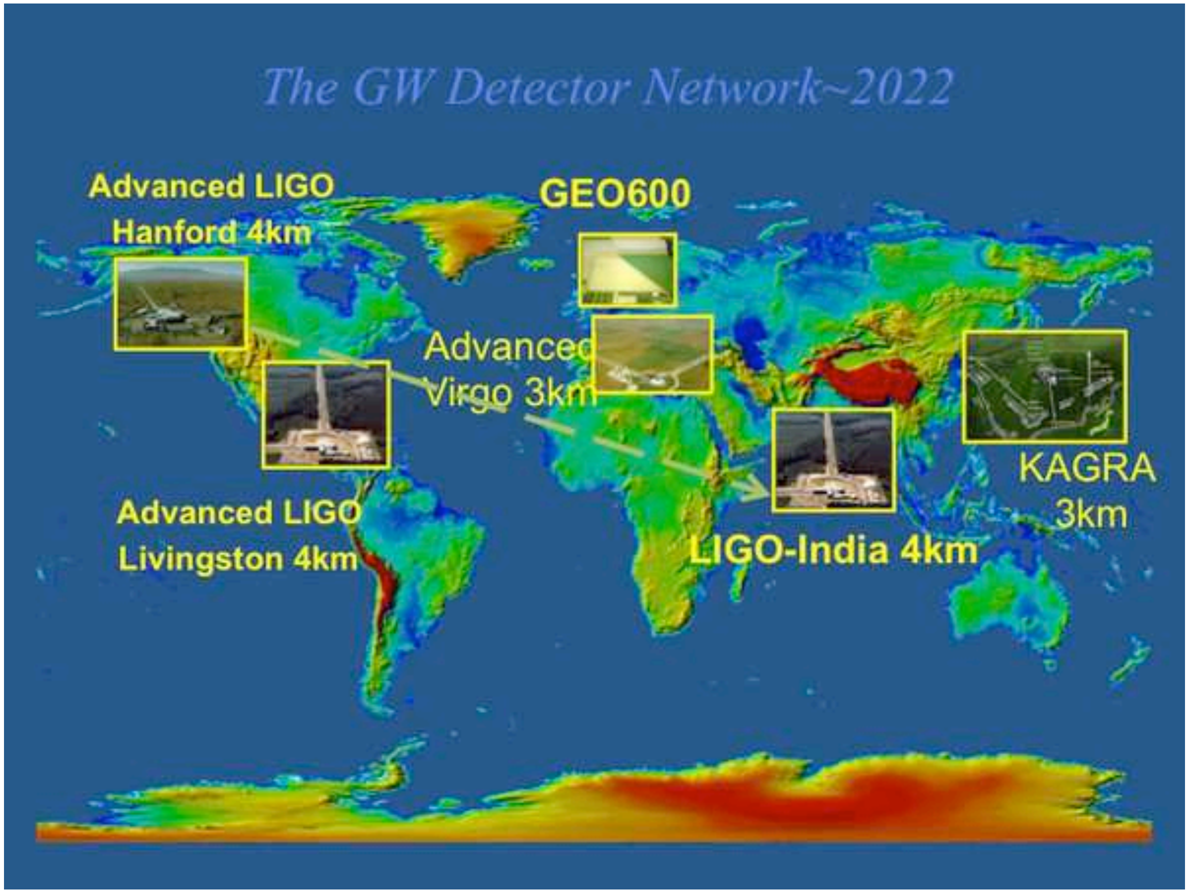
LIGO


Hanford Observatory
3000 km
LIGO Livingston Observatory

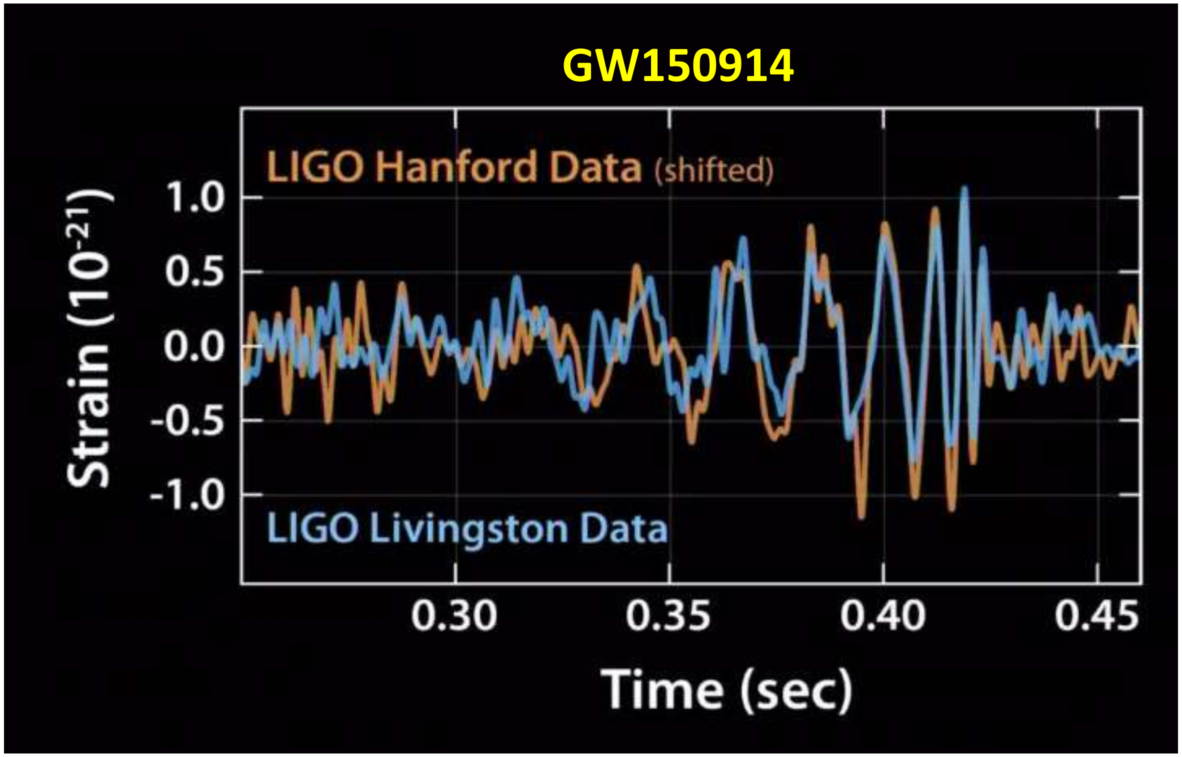

華盛頓州 Hanford, USA


路易斯安那州 Livingston, USA

GRAVITATIONAL WAVE NETWORK



FIRST DETECTION OF GW IN HISTORY!!!



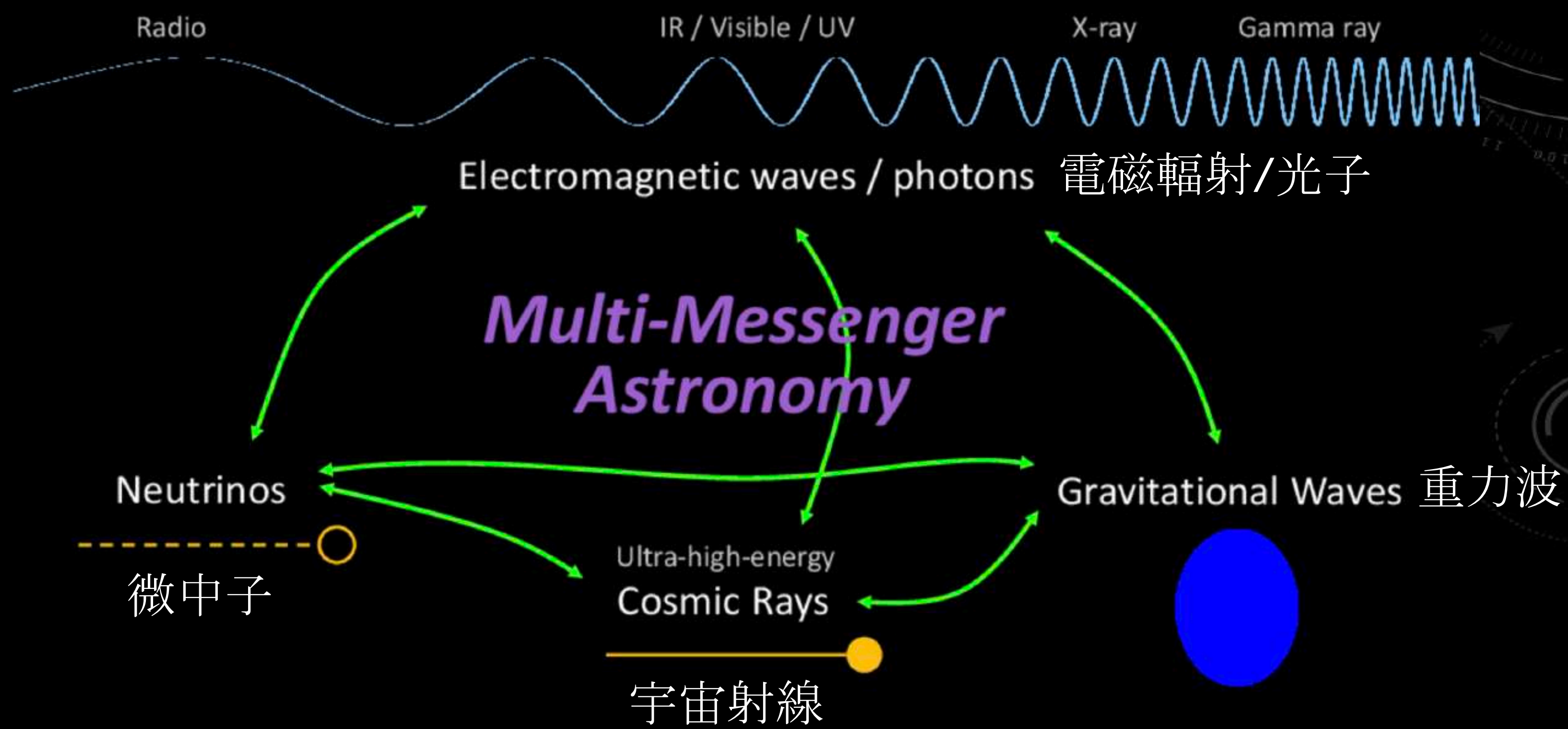
- On Sep. 14th, 2015, human detected GWs for the first time
- GWs resulted from merger of two stellar-mass black holes

FIRST DETECTION OF GW FROM A NS-NS MERGER

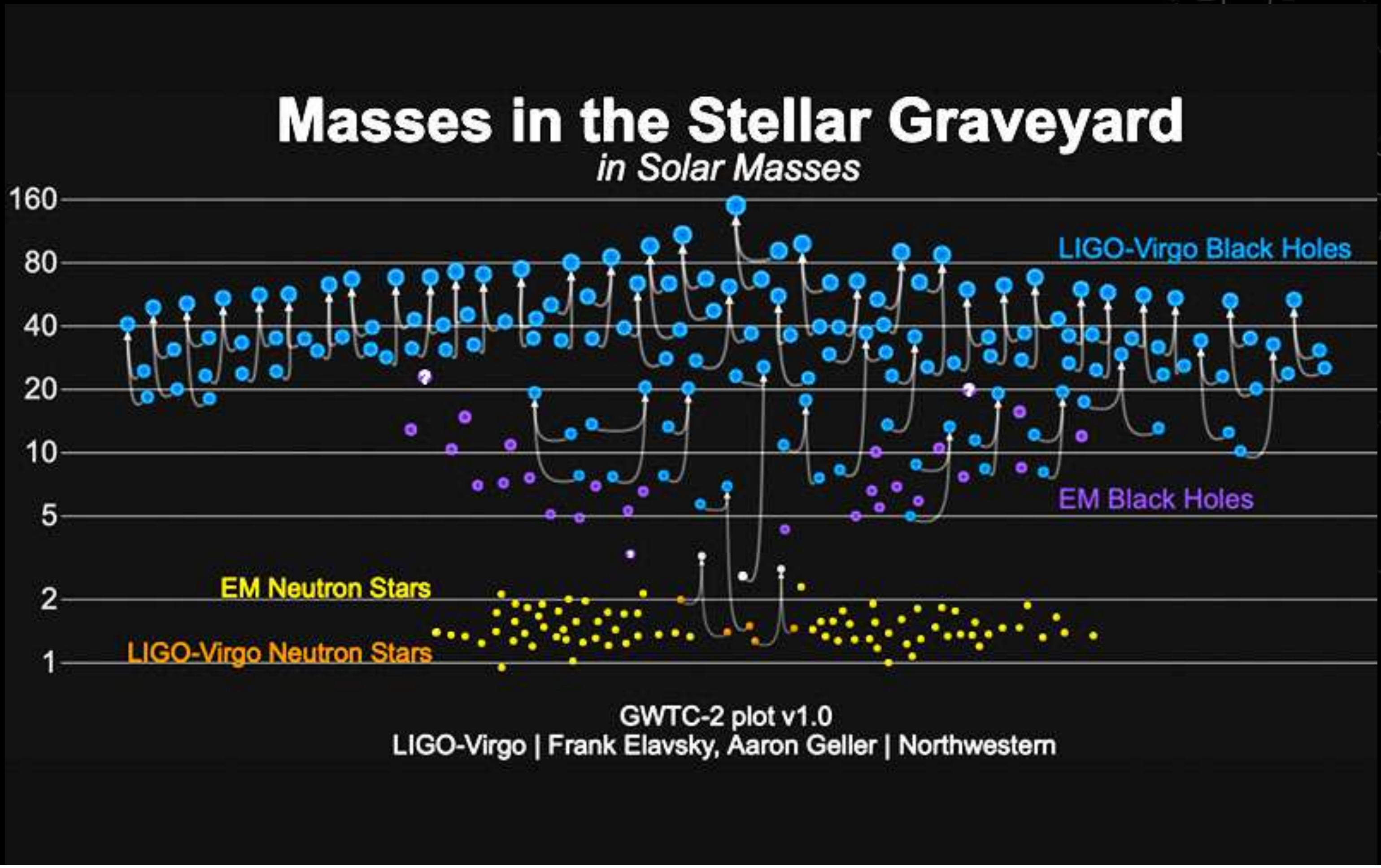
Conception of a NS–NS merger

- On Aug. 17, 2017, LIGO detected the first NS-NS merger event
- 70 observatories around the globe were watching the show
- Also detected in gamma-ray, optical, and infrared wavelengths
- This opened up the brand new field of "***multi-messenger astrophysics***"

MULTI-MESSENGER ASTRONOMY 多信使天文領域



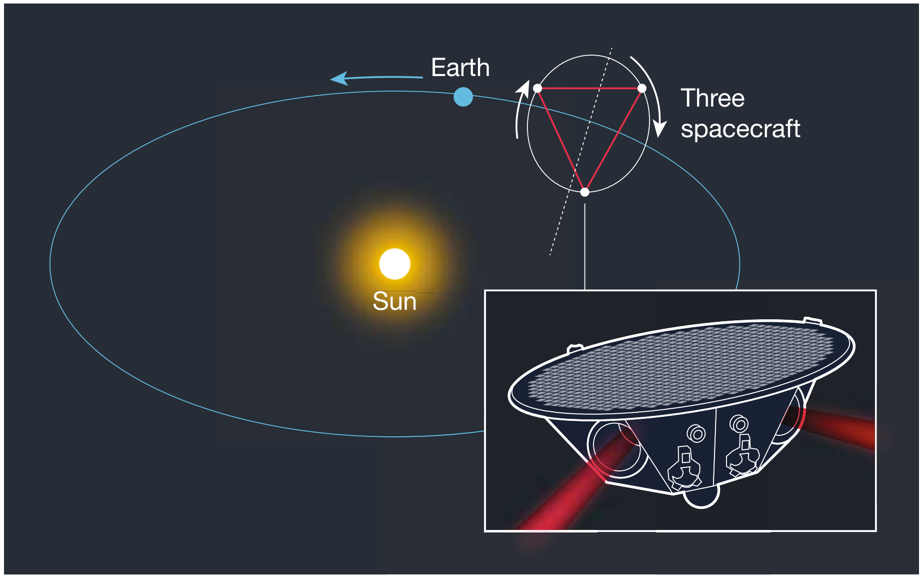
LIGO DETECTIONS TO DATE: 50 EVENTS



FUTURE PROSPECTS

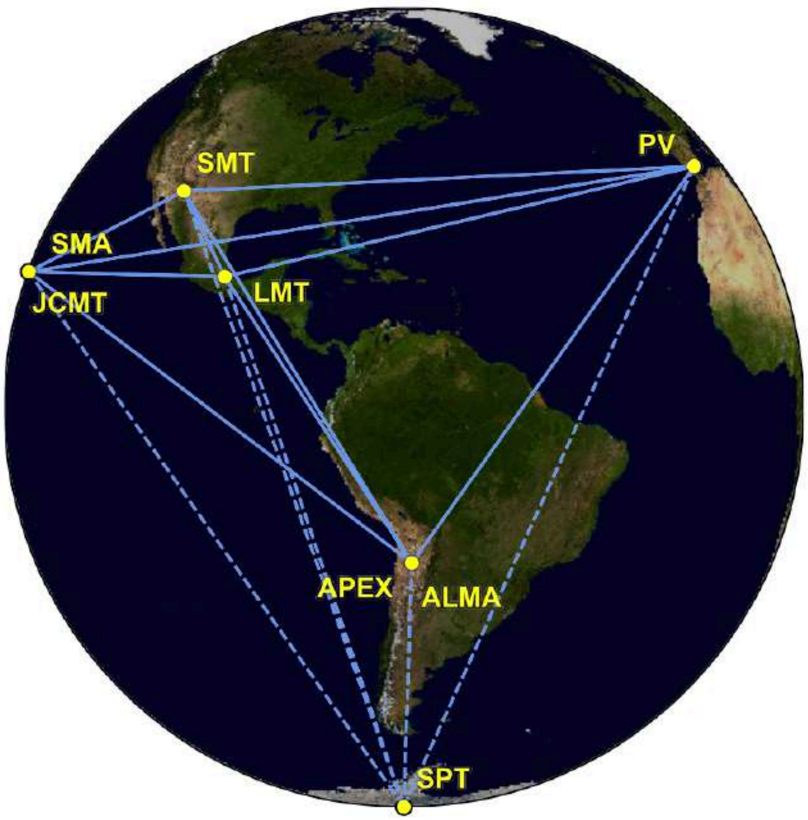
- ***LISA*** (Laser Interferometer Space Antenna)
  - Three test masses forming a triangle with 5 million km arms in space!
  - Frequency range ***~0.001-0.1 Hz***
  - Can detect mergers of SMBHs with $10^4 - 10^7$ M_{sun}
- Will probe the poorly understood distribution of intermediate black holes (IMBHs) with masses of $10^2 - 10^6$ M_{sun}!
  - Crucial for understanding SMBH formation

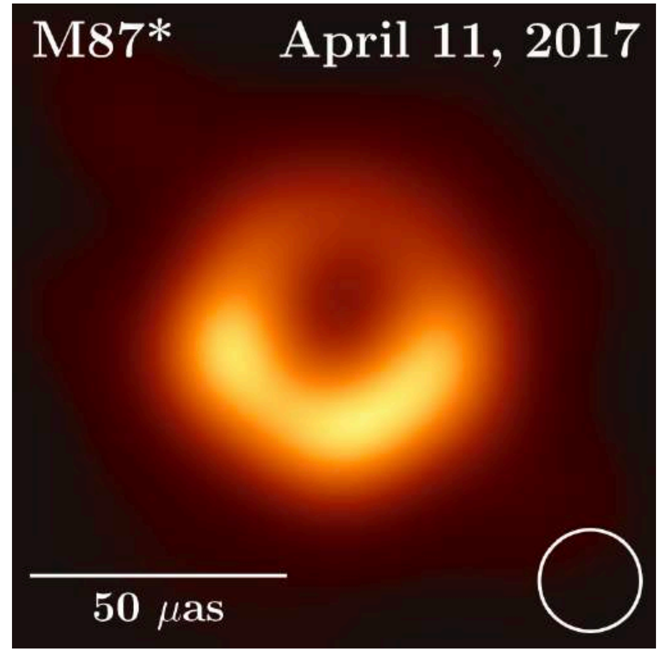
Design of LISA gravitational wave detector



THE FIRST IMAGE OF BLACK HOLE

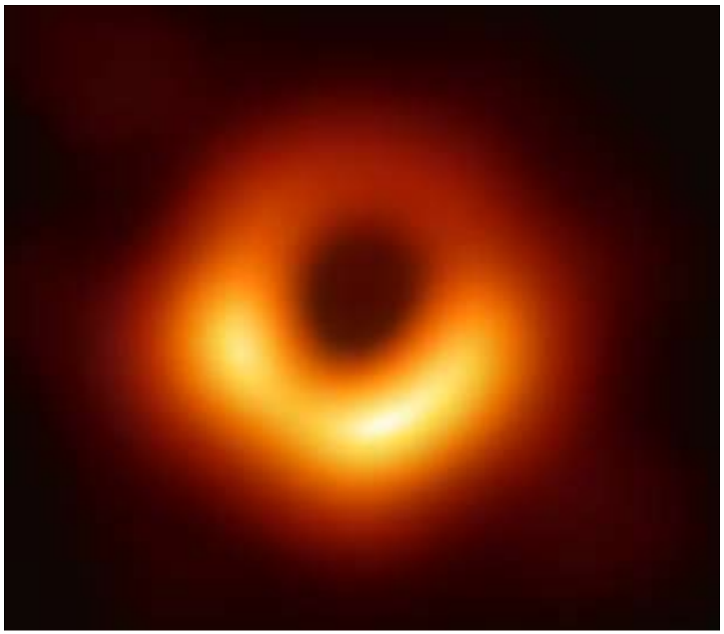
FIRST IMAGE OF BLACK HOLES – M87



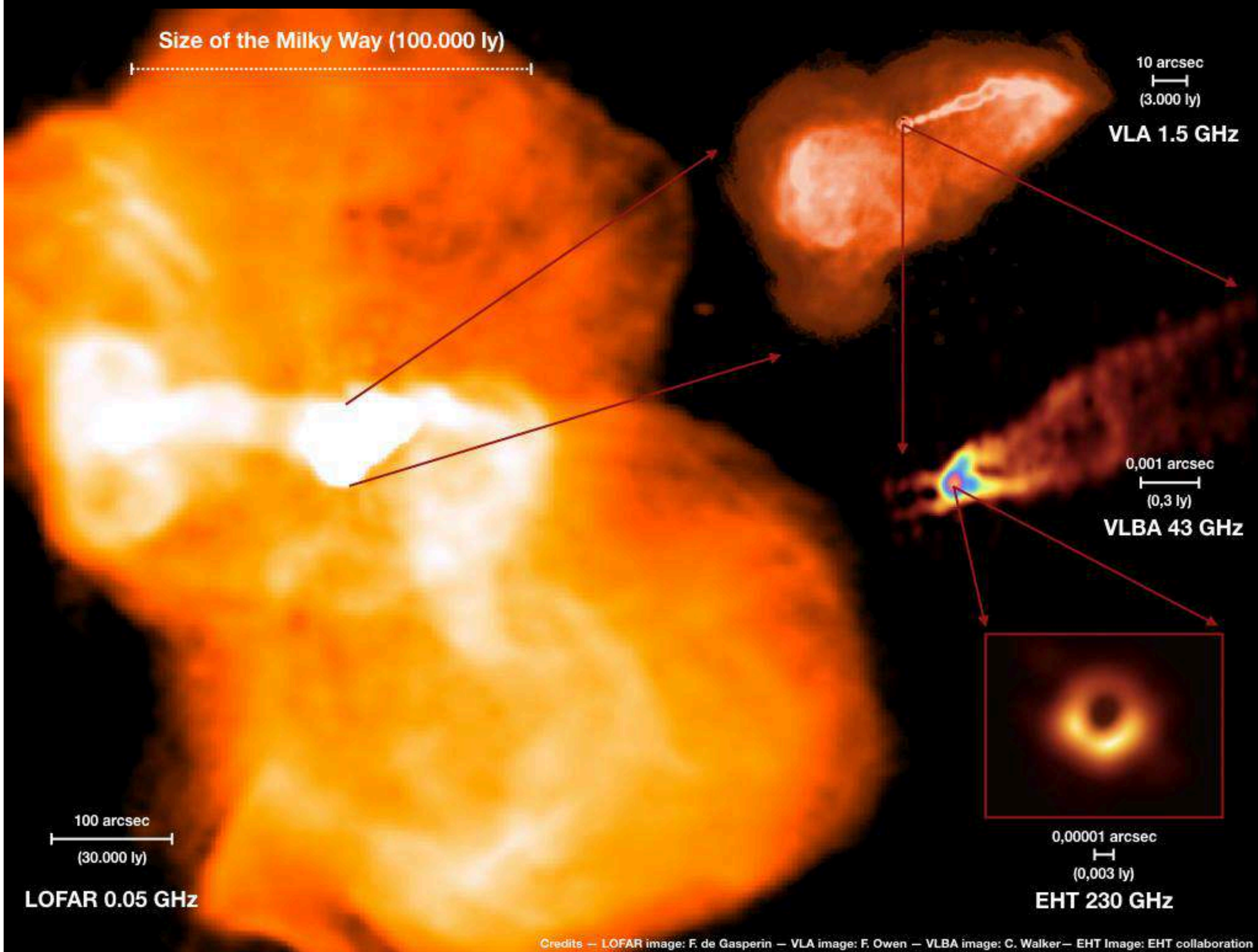


- Taken by the ***Event Horizon Telescope (EHT),*** which is a network of 8 radio telescopes across 4 continents in the world
- Angular resolution: $\theta \propto \lambda/D$
- Extraordinary resolution ~ 25 microarcsec!

WHAT ARE WE SEEING IN THIS IMAGE?



- The first ***DIRECT*** evidence for black holes!!
- Black holes are black, consistent with GR predictions
- Dark region is called "***BH shadow***"
- The bright ring comes from emission of materials near the BH (e.g., accretion flow/jets)

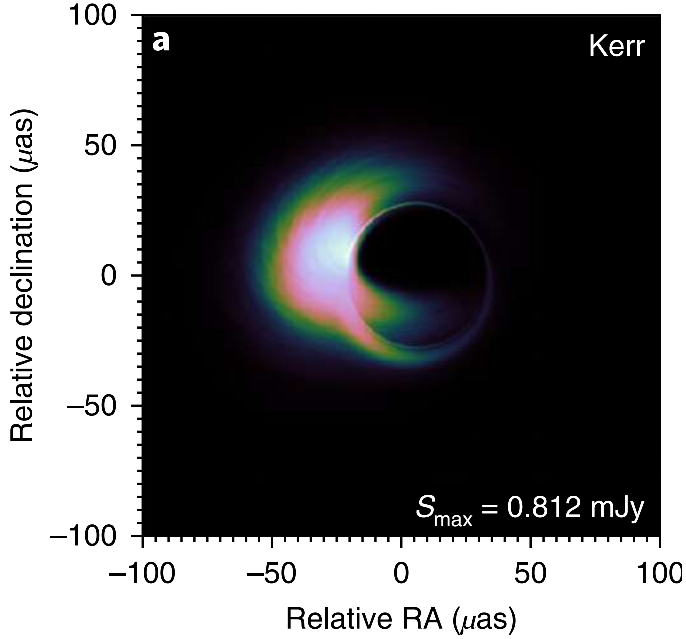


THE M87 SMBH

- M_{BH}~$6.5x10^9$ M_{sun} within M87 galaxy in Virgo cluster
- Relativistic jets and lobes extending to 10^5 light years
- Crucial to monitor changes to understand jet formation mechanisms

COMING SOON – IMAGE OF THE GCBH

Simulated image of Sgr A*



- The Sgr A* is ~1500x smaller than M87, but also closer, so shadow sizes are comparable
- Given the current resolution of EHT, these are the ***ONLY*** two BHs in the universe that we could resolve!!
- Things around Sgr A* vary on shorter timescales (~hours) so more difficult to analyze

SUMMARY

- Black holes are predicted by Einstein's theory of general relativity, and are confirmed to exist in the real universe
- There are two types of black holes
  - Stellar-mass black holes (smbhs): ~3-100 M_{sun}
  - Supermassive black holes (SMBHs): ~10^6 – 10^{10} M_{sun}
- Black holes are important in astrophysics because
  - They allow us to probe extreme conditions and fundamental physics
  - Energetic feedback from AGNs are influential for formation and evolution of galaxies
- Now is a golden age for studying black holes
  - First image of black holes is a direct evidence and allows us to probe physics near the event horizon
  - Detection of gravitational waves open up a brand new way for studying the universe – multi-messenger astronomy