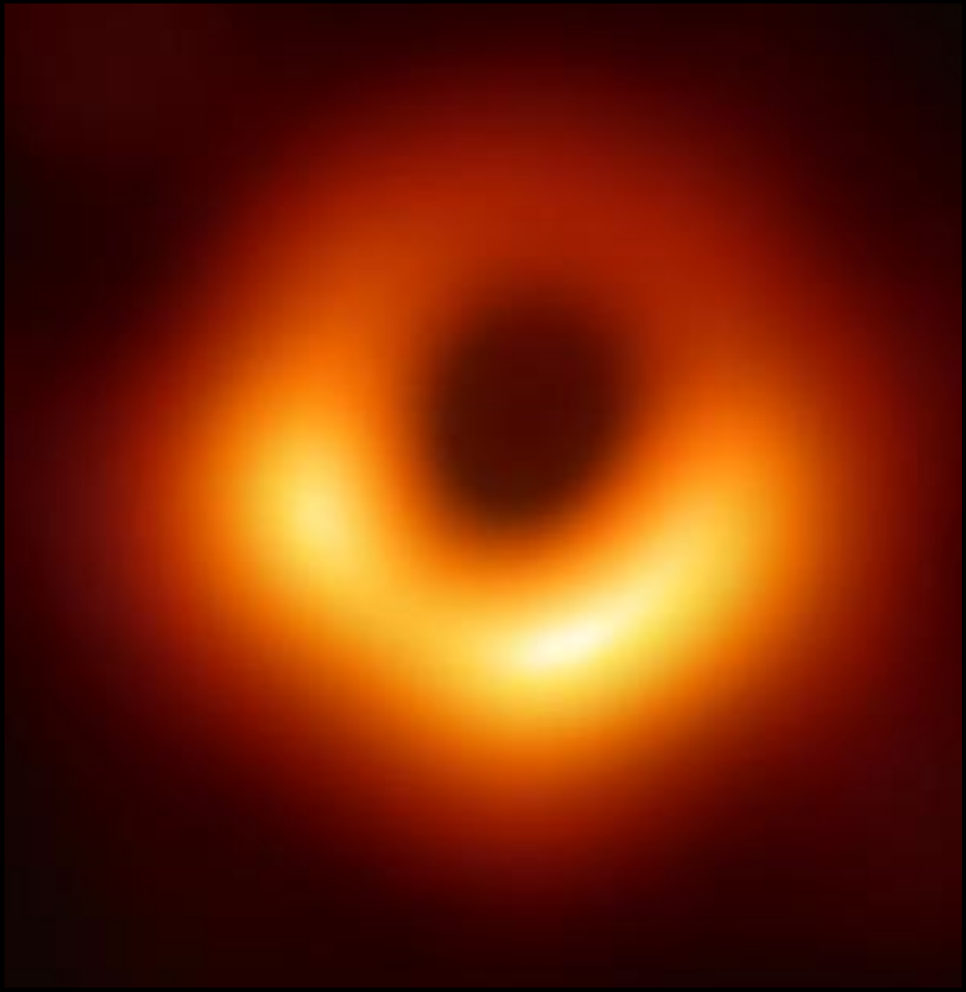
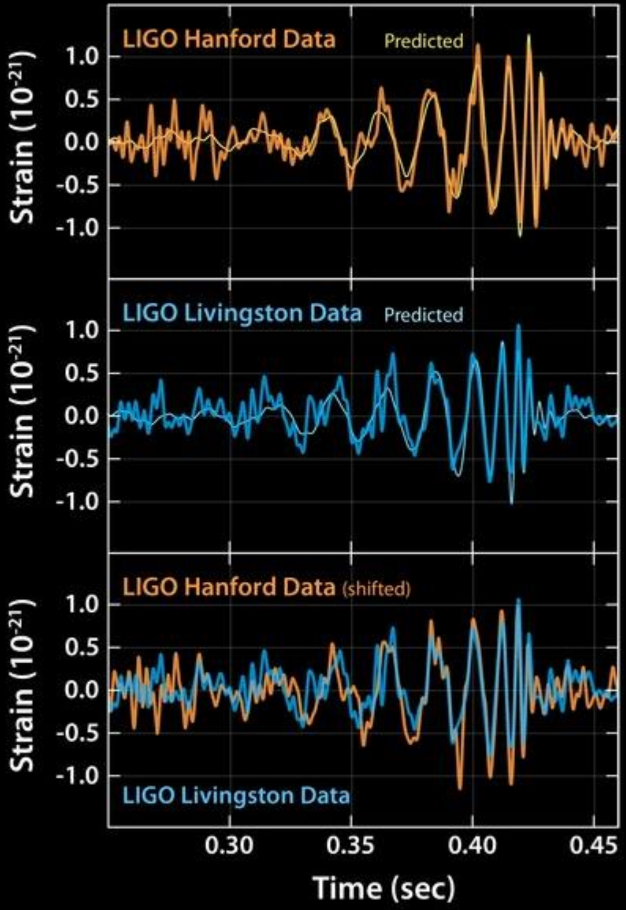
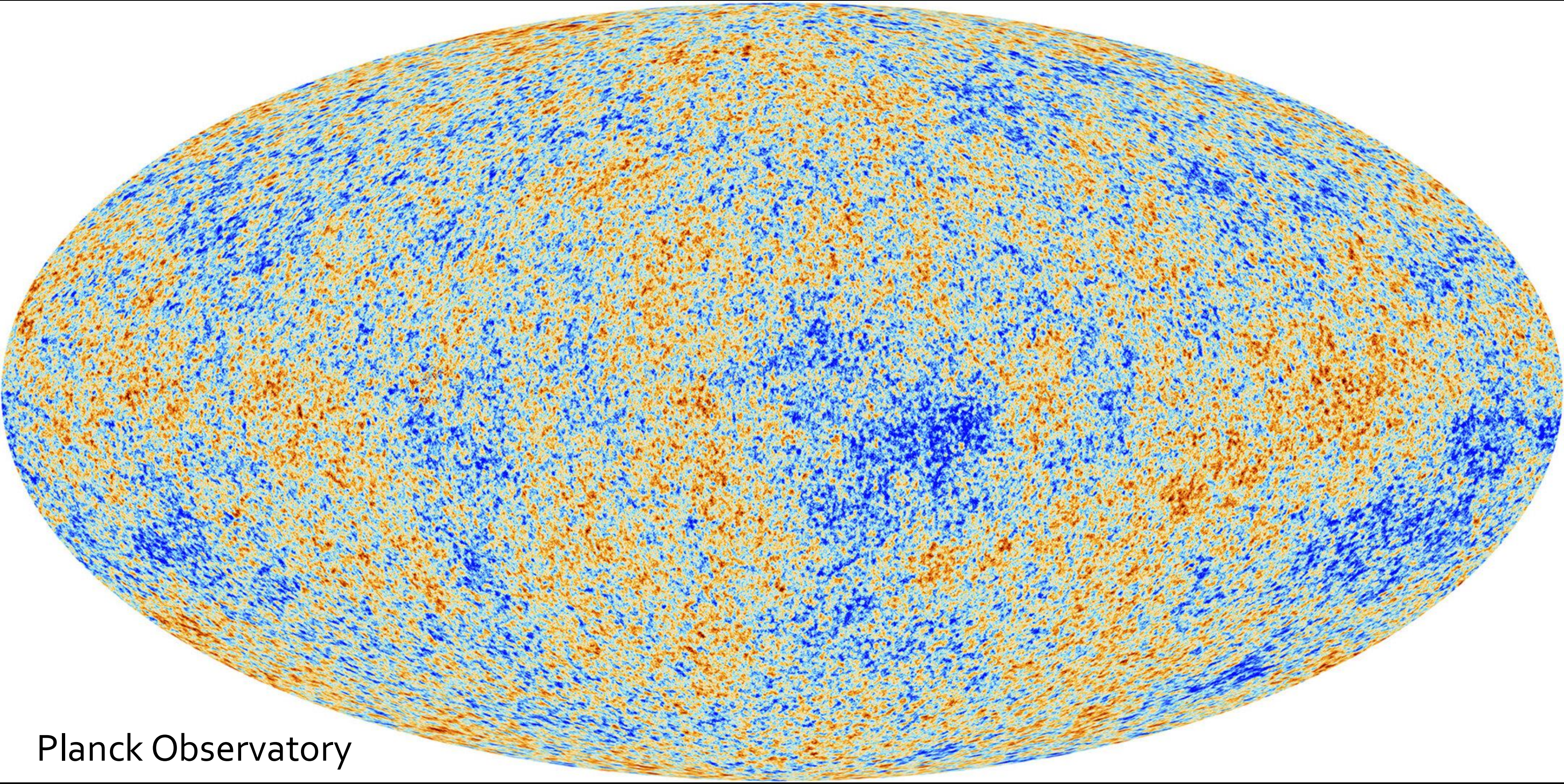
Gravity and black holes





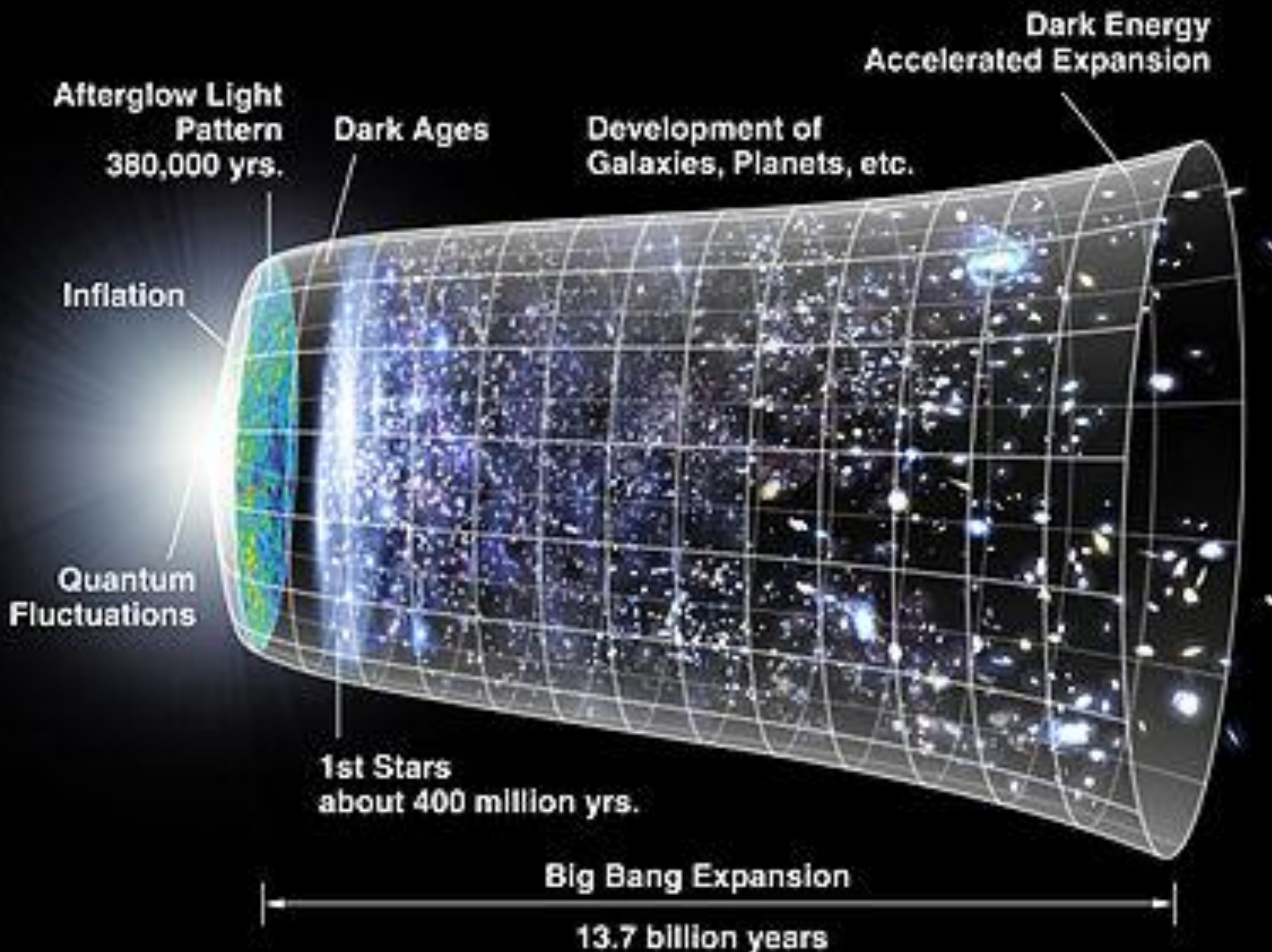
Big Bang: Cosmic Microwave Background



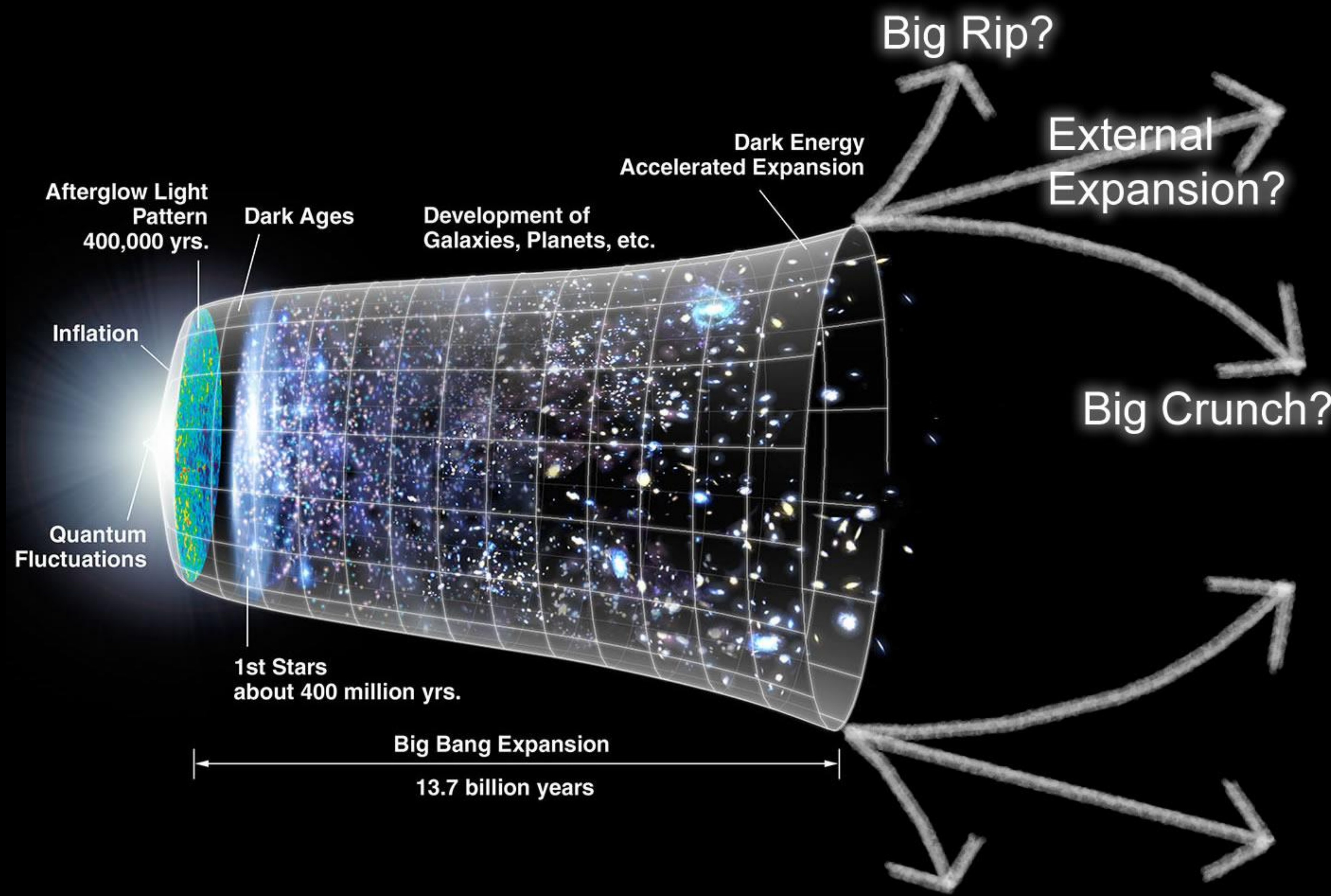
Planck Observatory

Universe was smooth at 1 part in 10,000

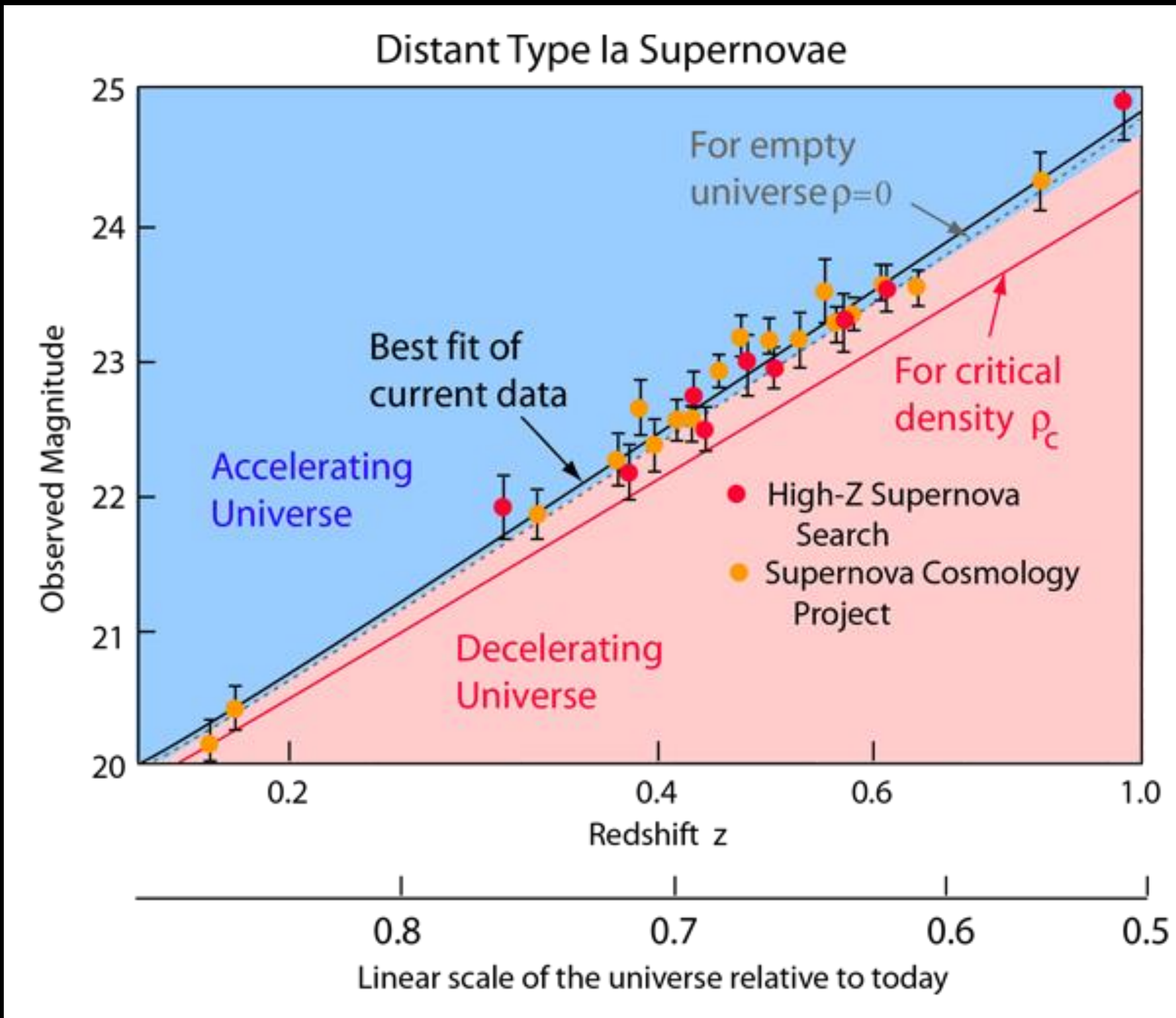
Cosmology in a single plot



Cosmological Future



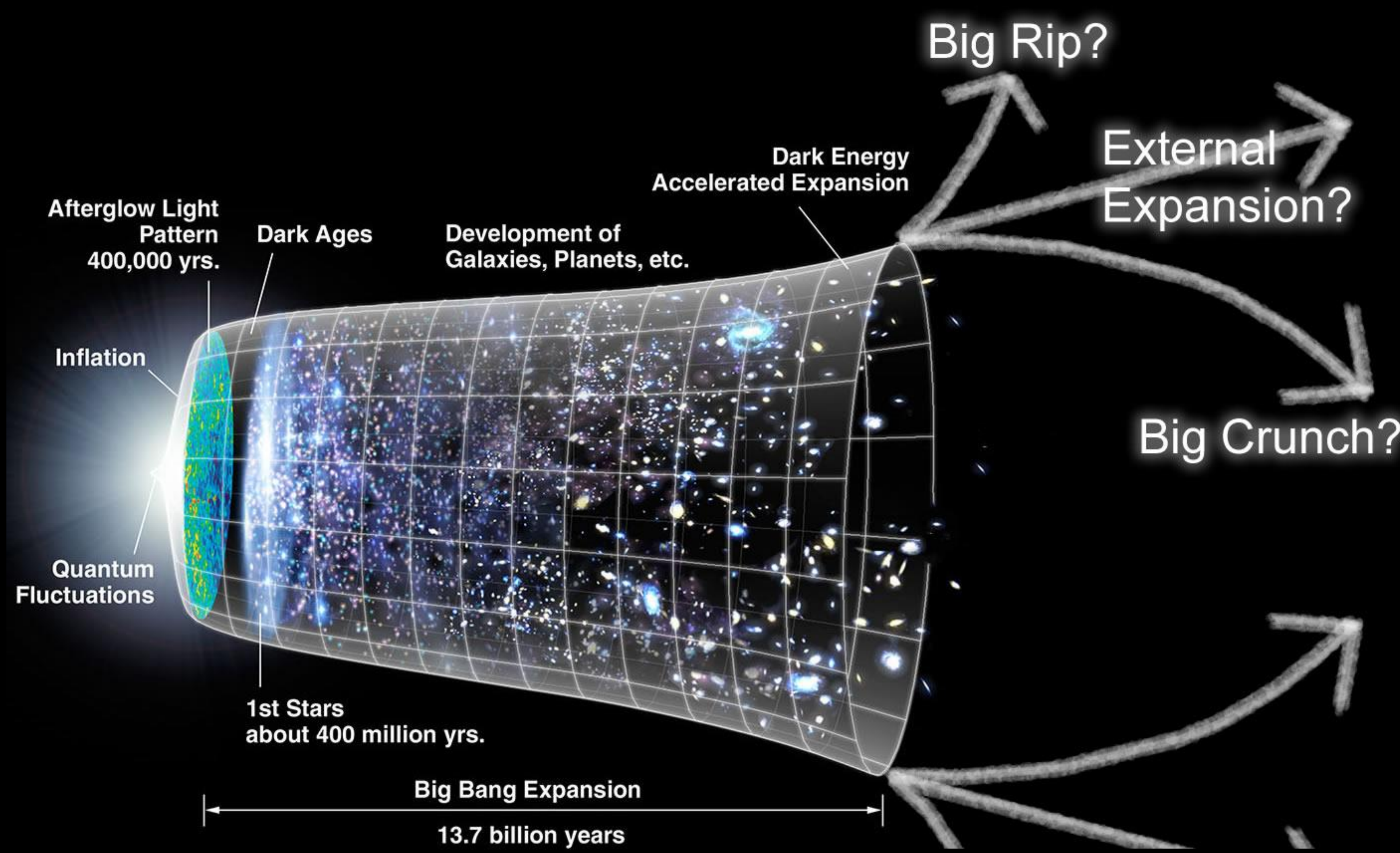
Universe expansion is accelerating



Type 1a supernova: standard candles (always the same brightness)

Distance versus redshift allows us to see that expansion is **accelerating**

Cosmological Future



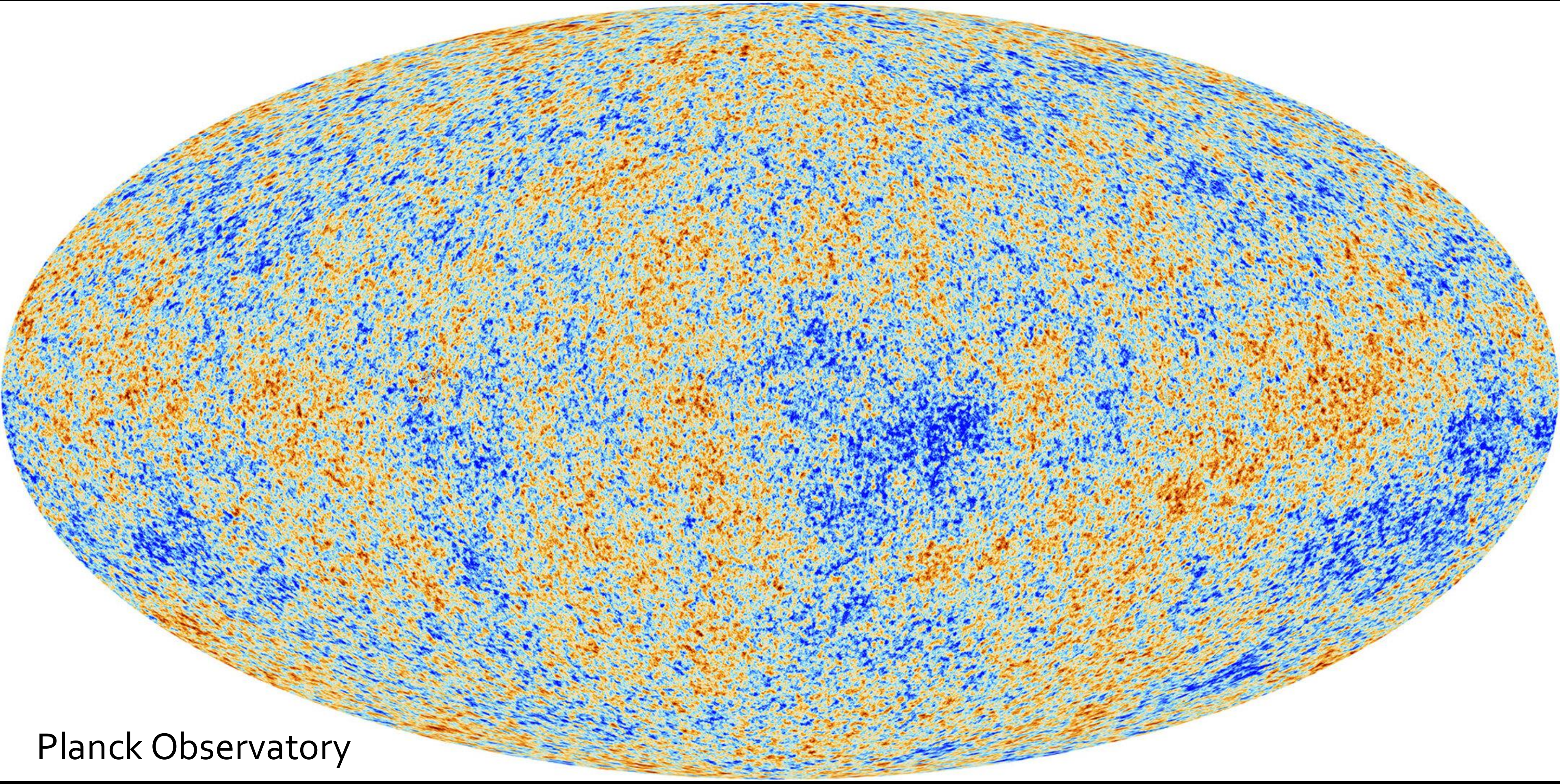
Universe is expanding
Expansion is accelerating

Big Rip (Big Chill/Heat Death): the far-future of the universe

If expansion continues to accelerate

-13.5 billion years: Big Bang
-5 billion years: Sun formed
2 billion years: people better leave Earth
5 billion years: sun evolves off main sequence
4-8 billion years: Andromeda Galaxy, Milky Way merge
100-1,000 billion years: Local Group galaxies merge
150 billion years: galaxies beyond local subcluster will pass beyond cosmological horizon (no causal interactions)
800 billion years: stars burn out, little star formation; luminosities diminish
2 trillion years: galaxies outside local supercluster not detectable
1-100 trillion years: star formation ends
1e20 years: galaxies ripped apart; stars flung out or eaten by black holes
1e50 years: protons decay, normal matter no longer exists
1e70 years: black holes evaporate
1e100 years: supermassive black holes evaporate
1e1000 years to eternity: dark era, heat death

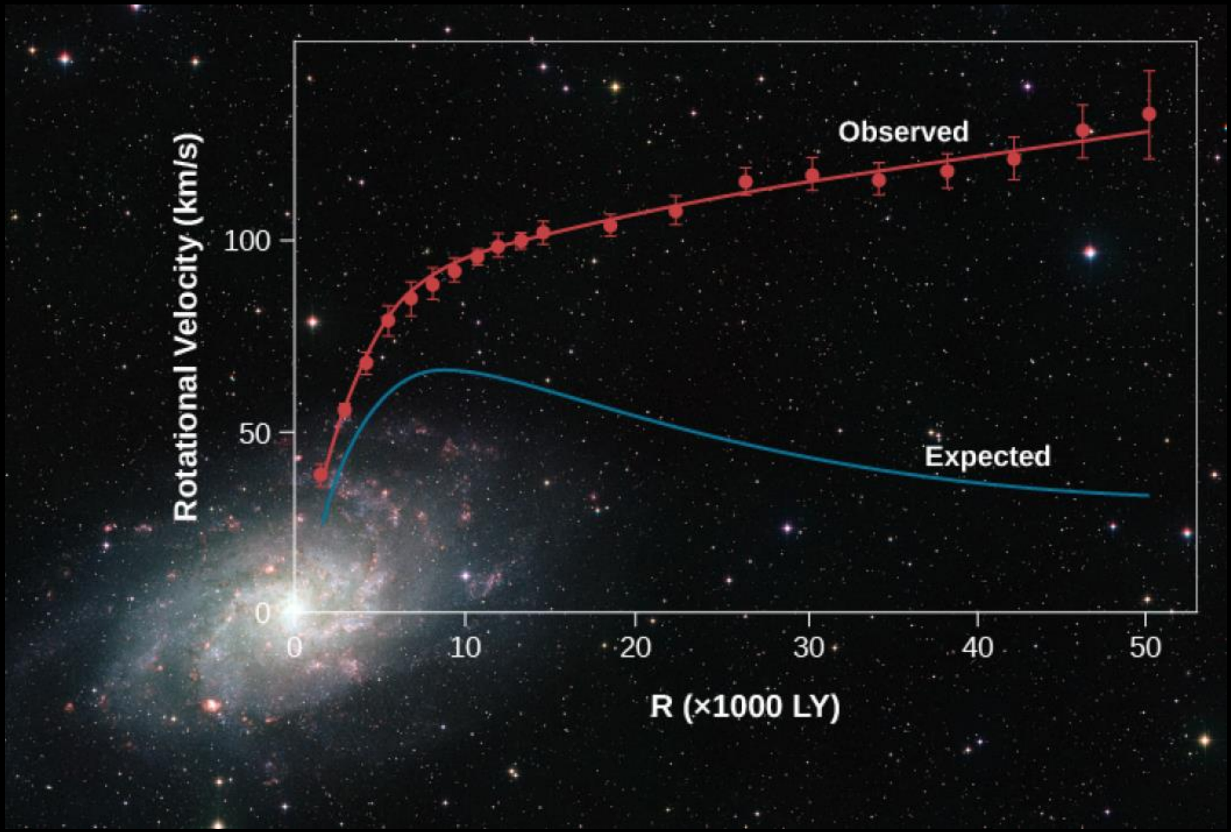
Big Bang: Cosmic Microwave Background



Planck Observatory

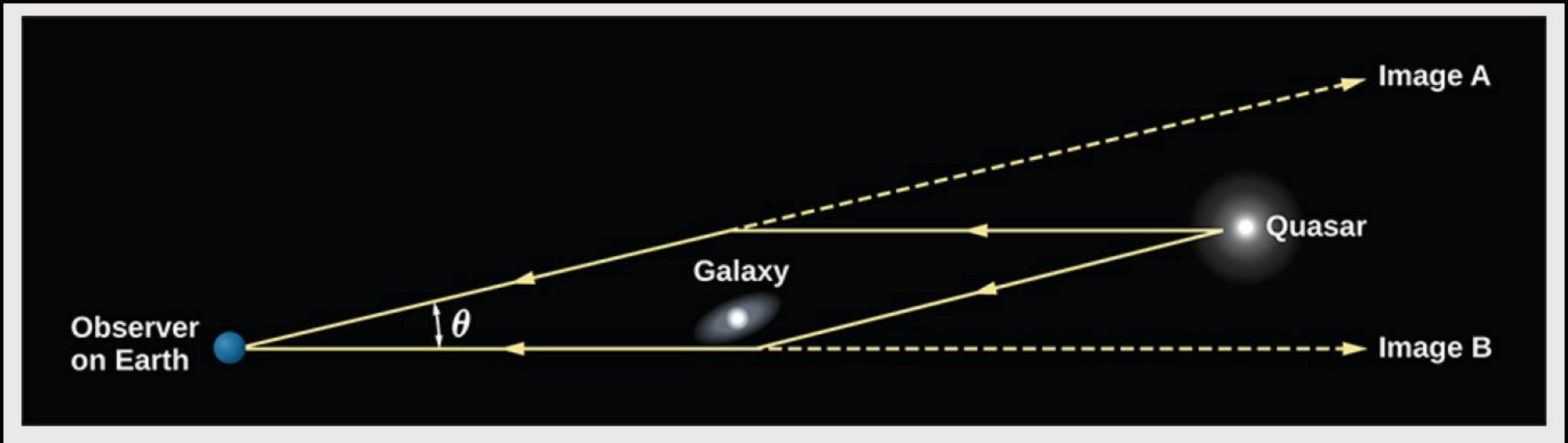
Universe was smooth at 1 part in 10,000

Measuring masses of large structures

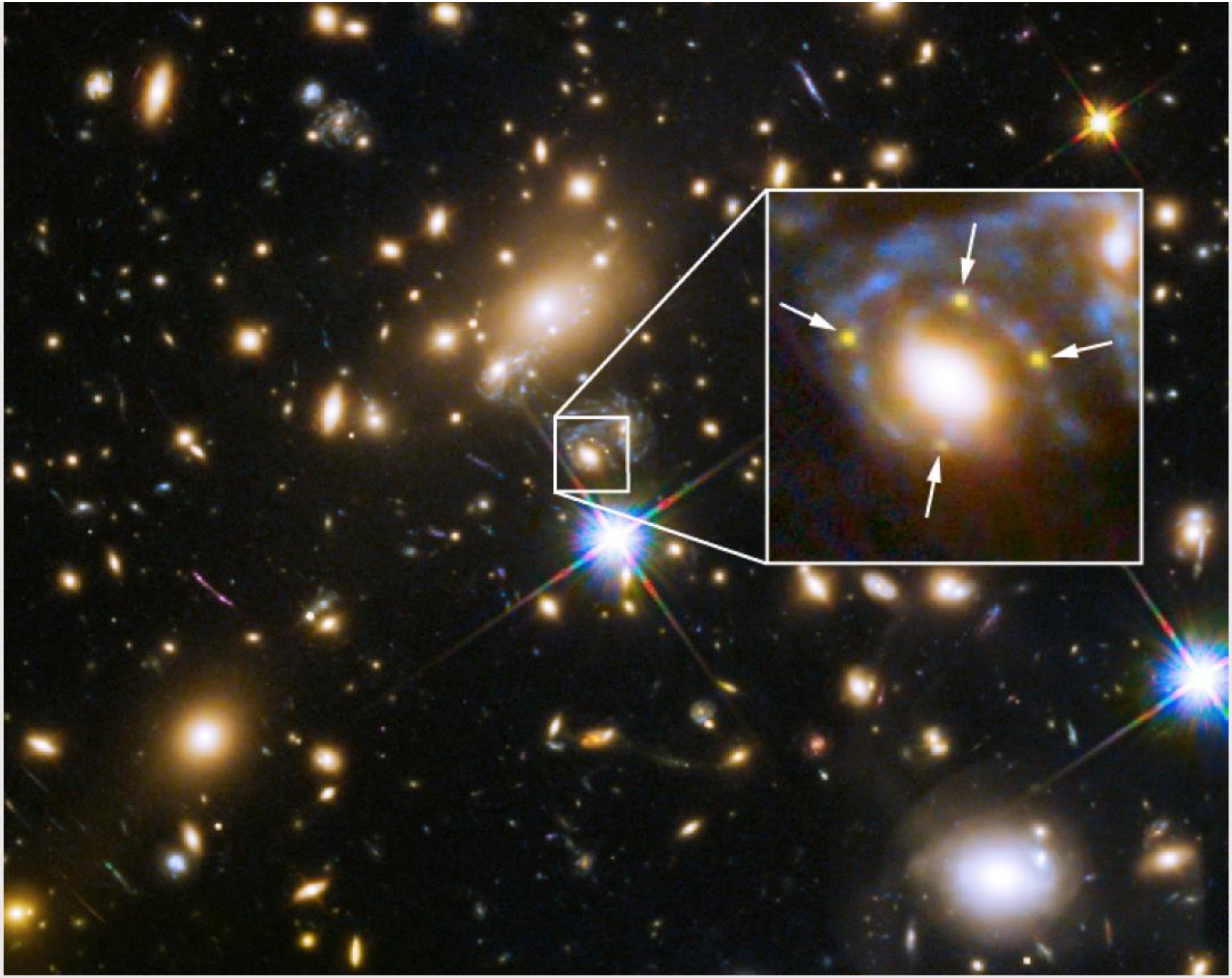


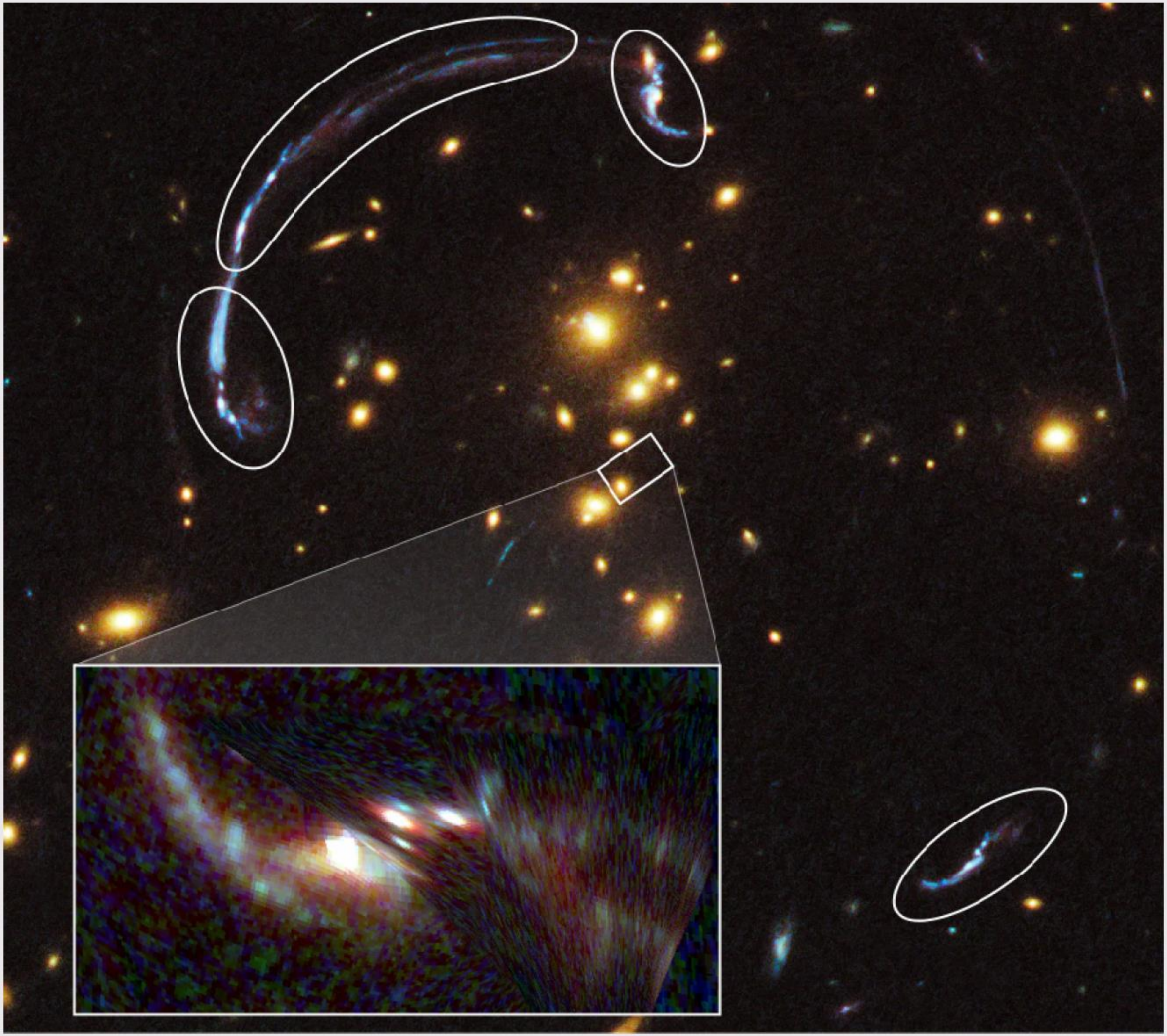
Galaxy rotation curve: evidence for dark matter

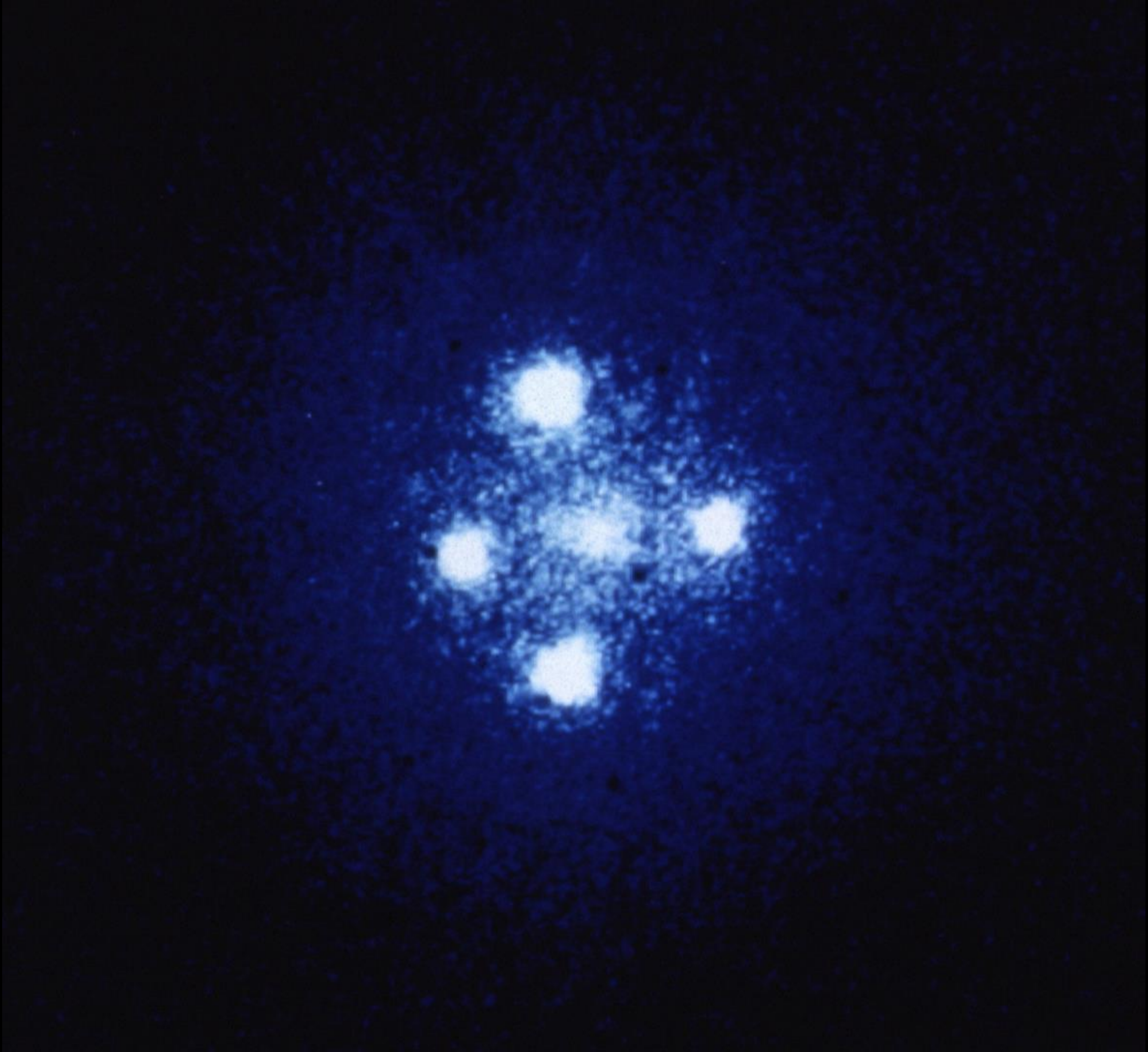
Masses and dark matter: gravitational lensing

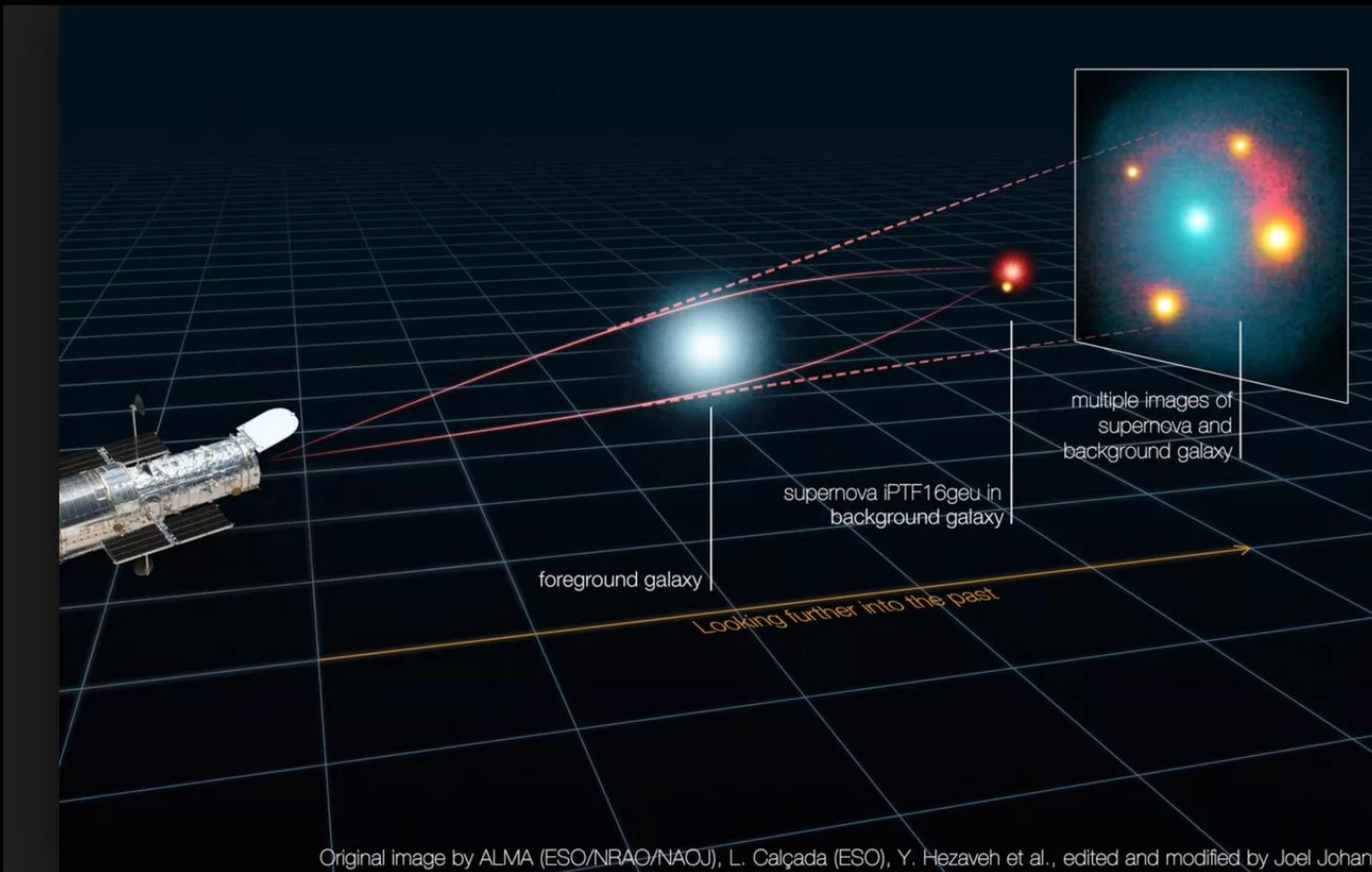


Gravitational lensing

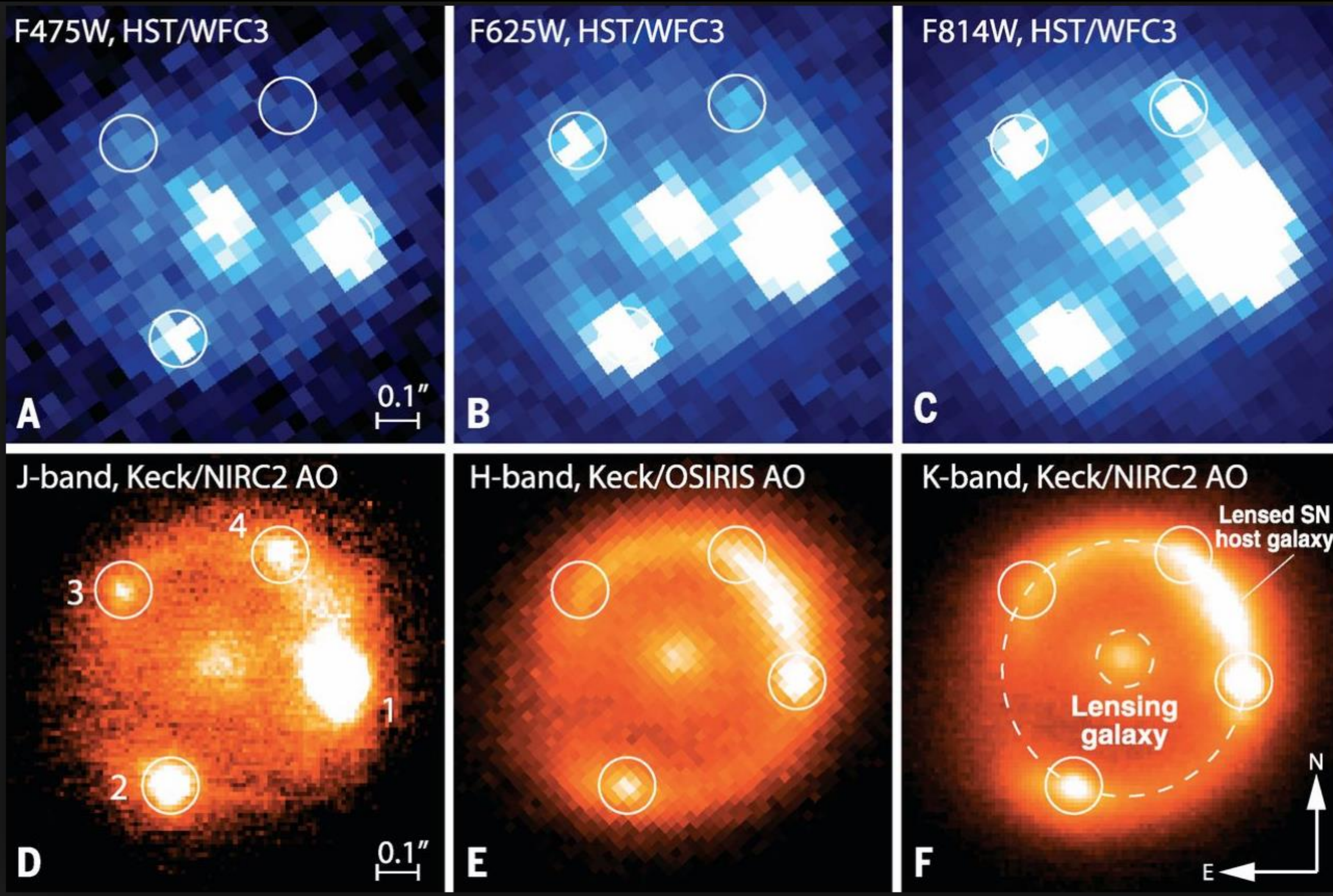


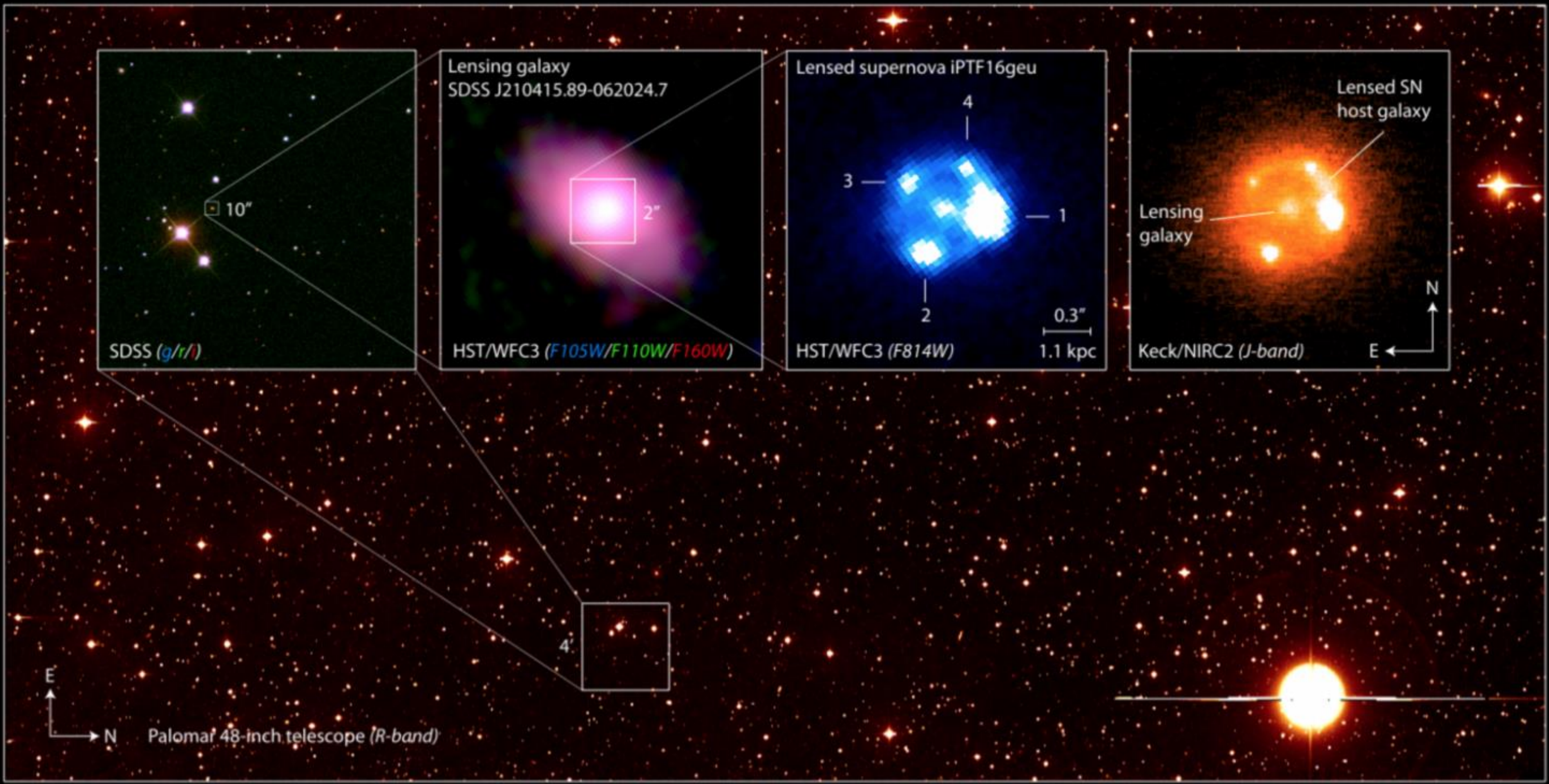




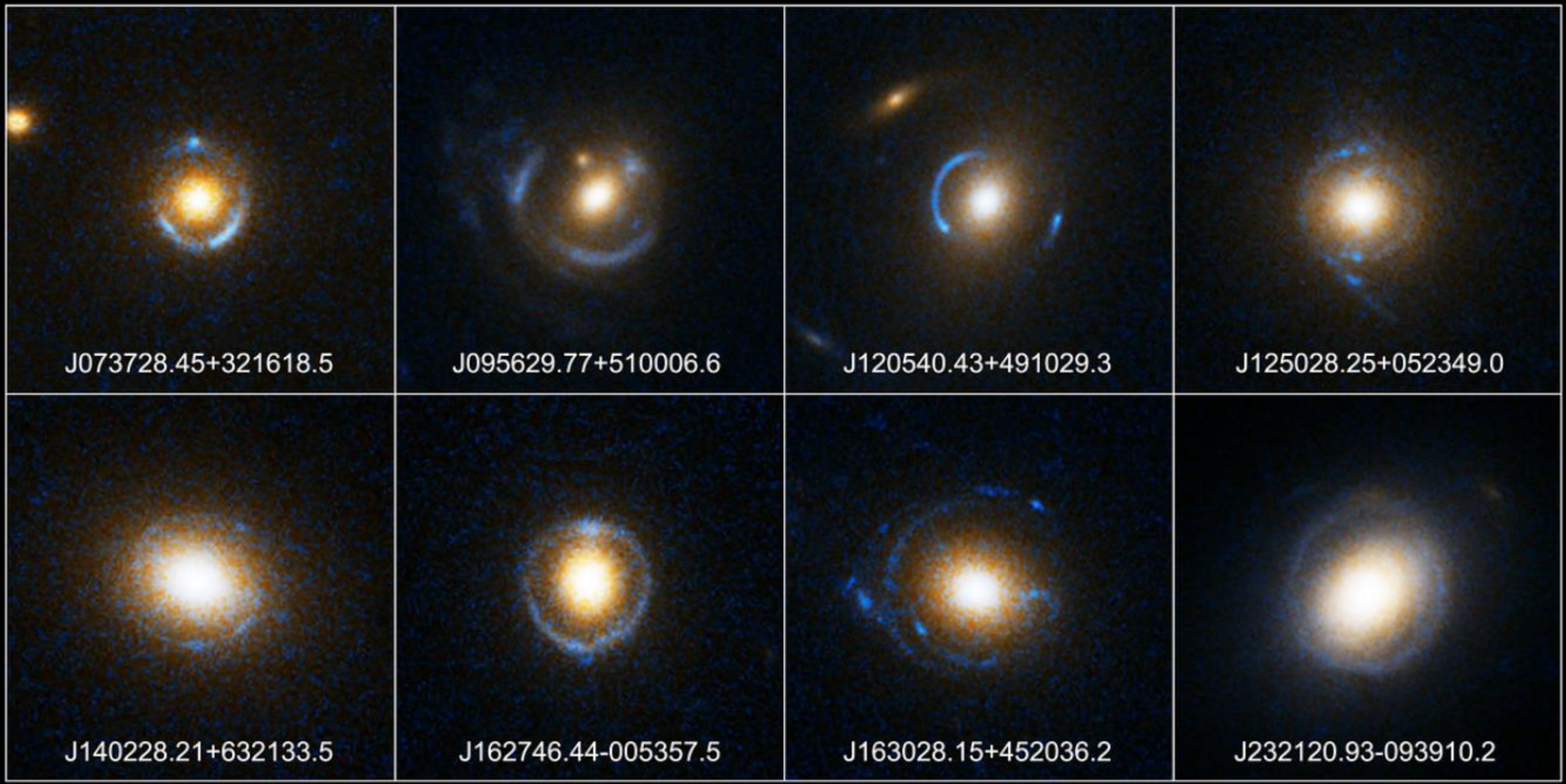


multiple images of
supernova and
background galaxy
supernova iPTF16geu in
background galaxy
foreground galaxy
Looking further into the past
Original image by ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al., edited and modified by Joel Johans


F475W, HST/WFC3
F625W, HST/WFC3
F814W, HST/WFC3
0.1"
A
B
C
J-band, Keck/NIRC2 AO
H-band, Keck/OSIRIS AO
K-band, Keck/NIRC2 AO
4
3
1
2
0.1"
D
E
F
Lensed SN
host galaxy
Lensing
galaxy
N
E



SDSS (g/r/i)
10″
Lensing galaxy
SDSS J210415.89-062024.7
2″
HST/WFC3 (F105W/F110W/F160W)
Lensed supernova iPTF16geu
4
3
1
2
0.3″
1.1 kpc
HST/WFC3 (F814W)
Lensed SN
host galaxy
Lensing
galaxy
N
E
Keck/NIRC2 (J-band)
4′
E
N
Palomar 48-inch telescope (R-band)

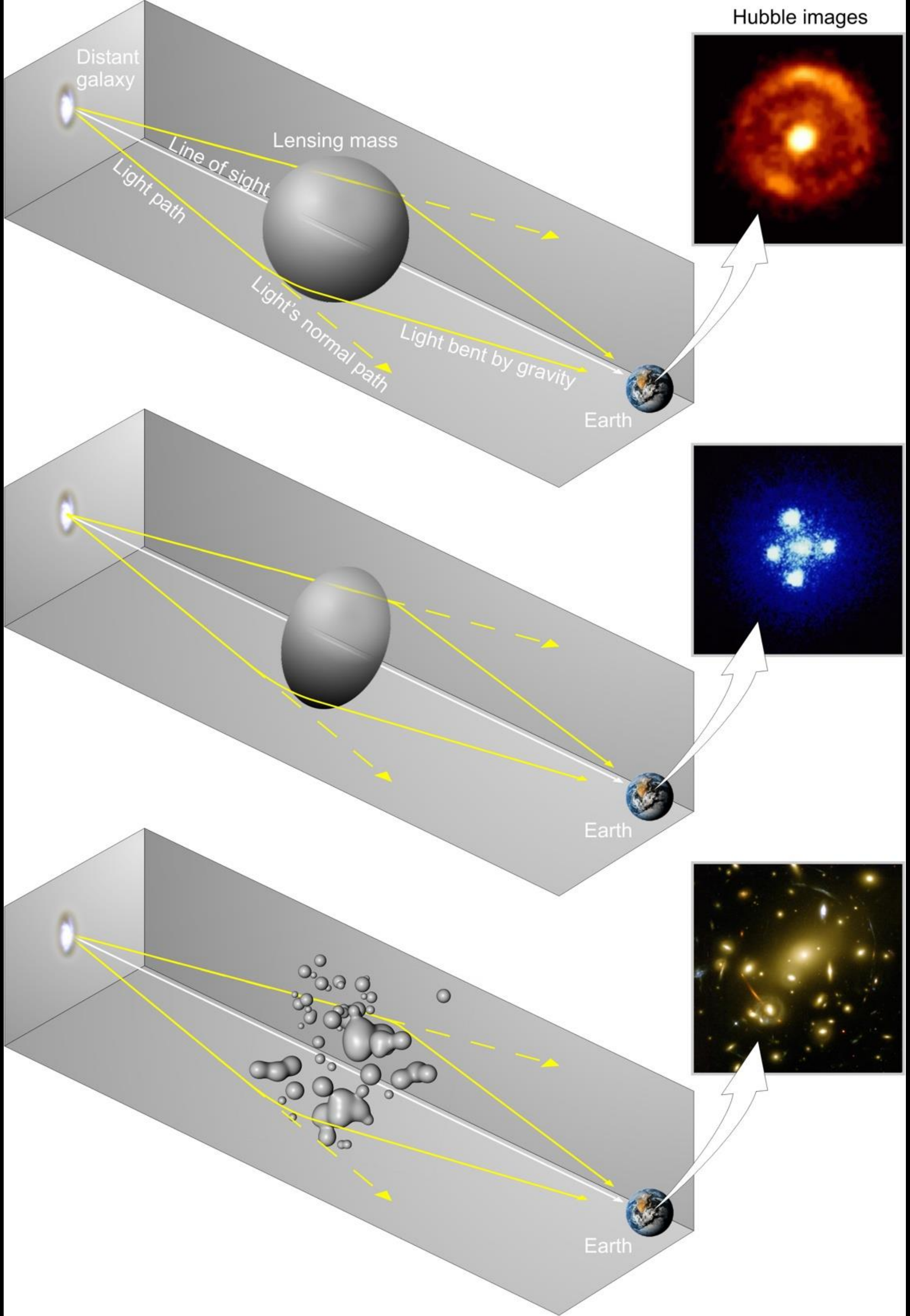


Einstein Ring Gravitational Lenses

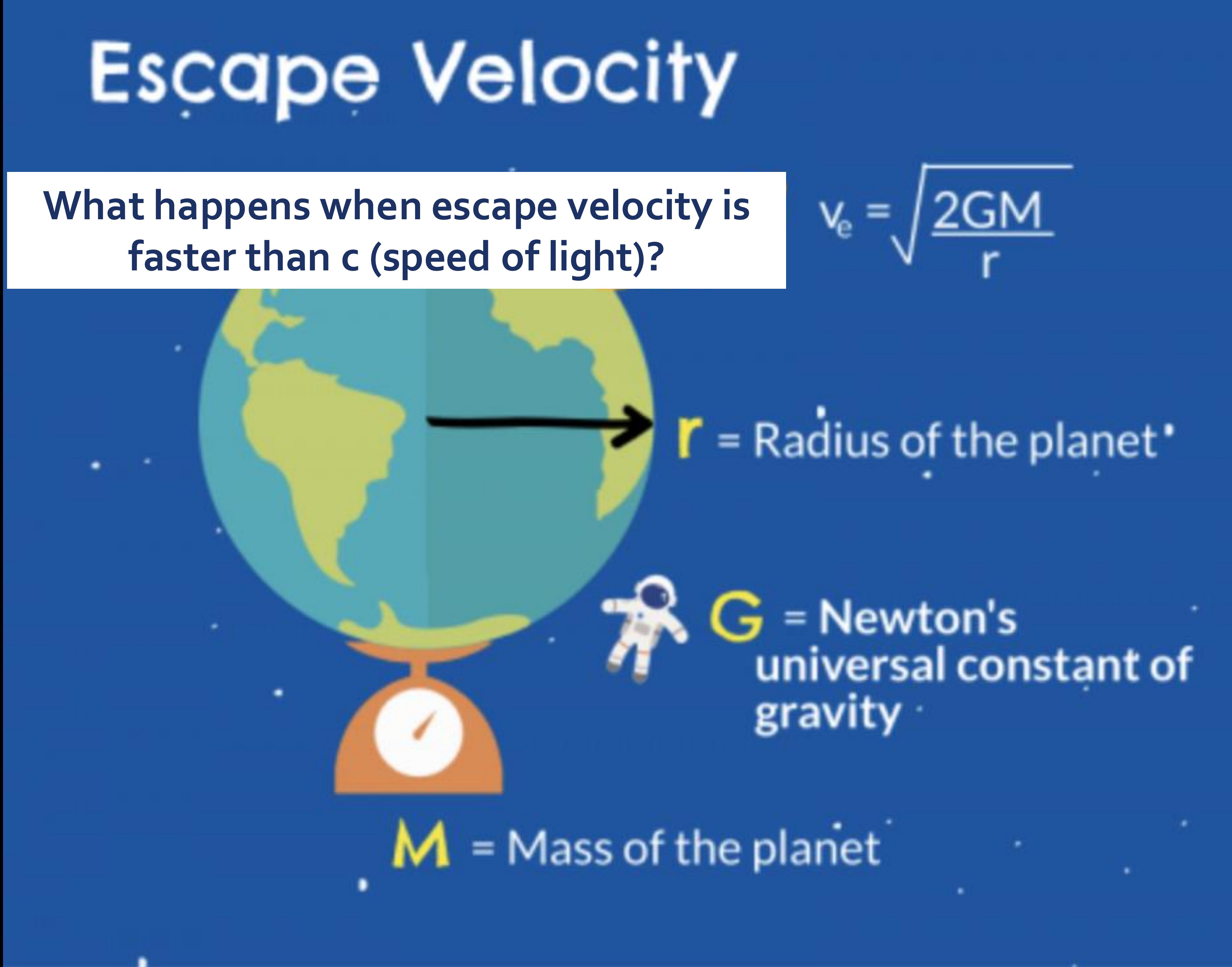
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

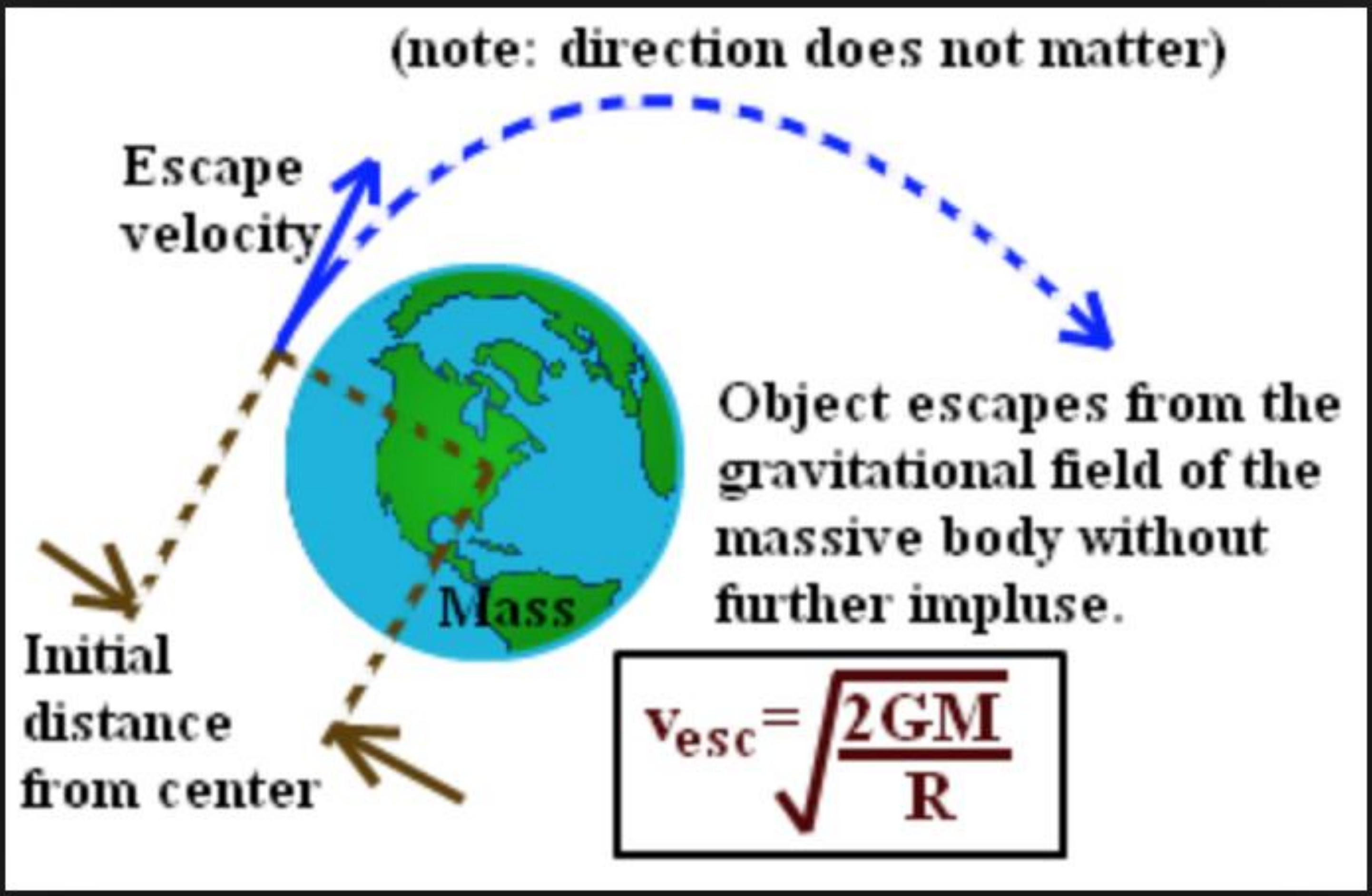
STScI-PRC05-32


Hubble images
Distant galaxy
Lensing mass
Line of sight
Light path
Light's normal path
Light bent by gravity
Earth
Earth
Earth

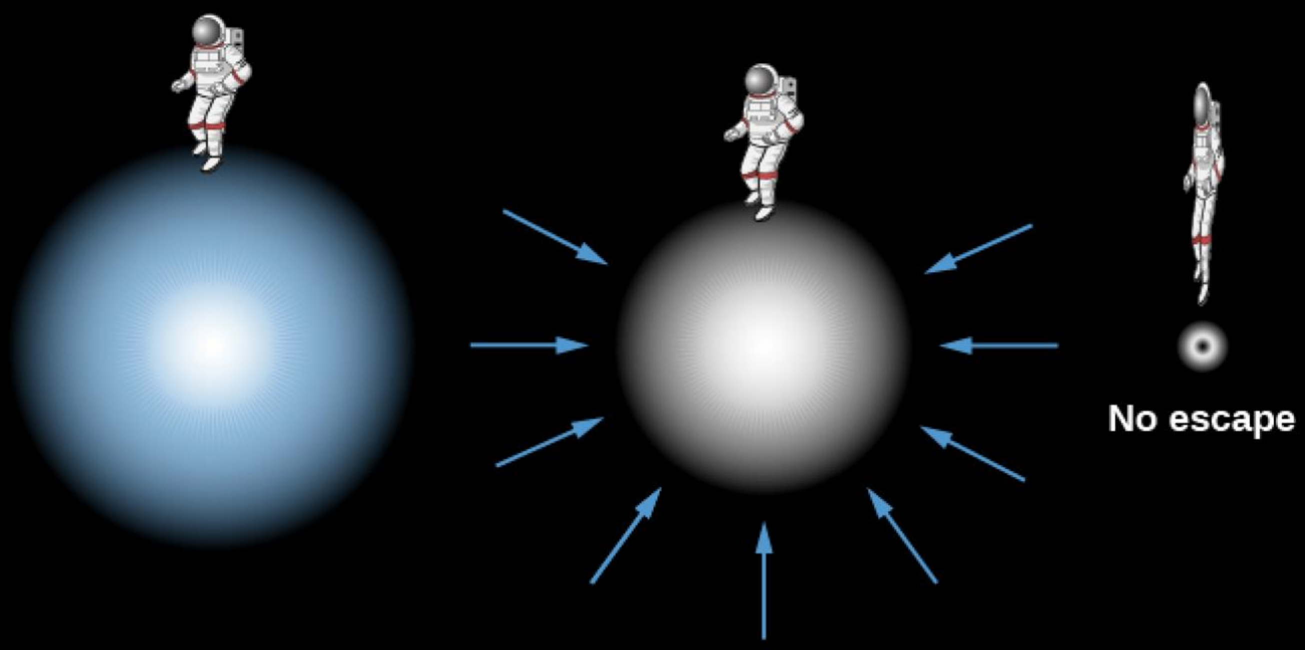
What happens when escape velocity is faster than c (speed of light)?



Black holes: gravity high enough (large mass, small volume) that light cannot escape



Black holes: gravity high enough (large mass, small volume) that light cannot escape



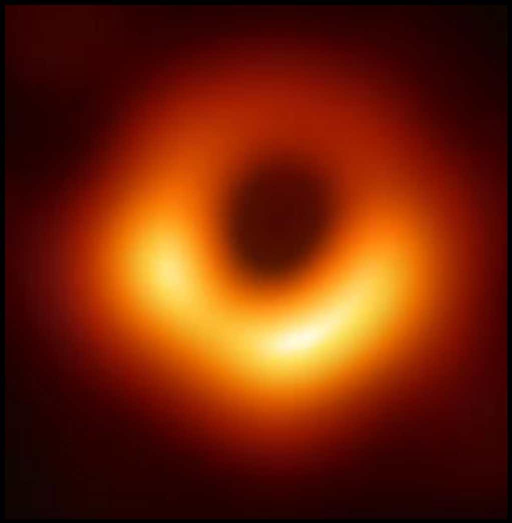
Black holes: event horizon defines radius where light can no longer escape


(a) (b)

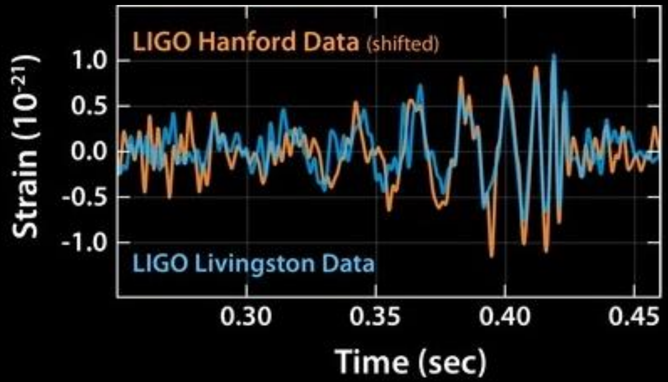
Figure 24.14 Light Paths near a Massive Object. Suppose a person could stand on the surface of a normal star with a flashlight. The light leaving the flashlight travels in a straight line no matter where the flashlight is pointed. Now consider what happens if the star collapses so that it is just a little larger than a black hole. All the light paths, except the one straight up, curve back to the surface. When the star shrinks inside the event horizon and becomes a black hole, even a beam directed straight up returns.

Types of black holes

- Supermassive black holes
  - Centers of galaxies

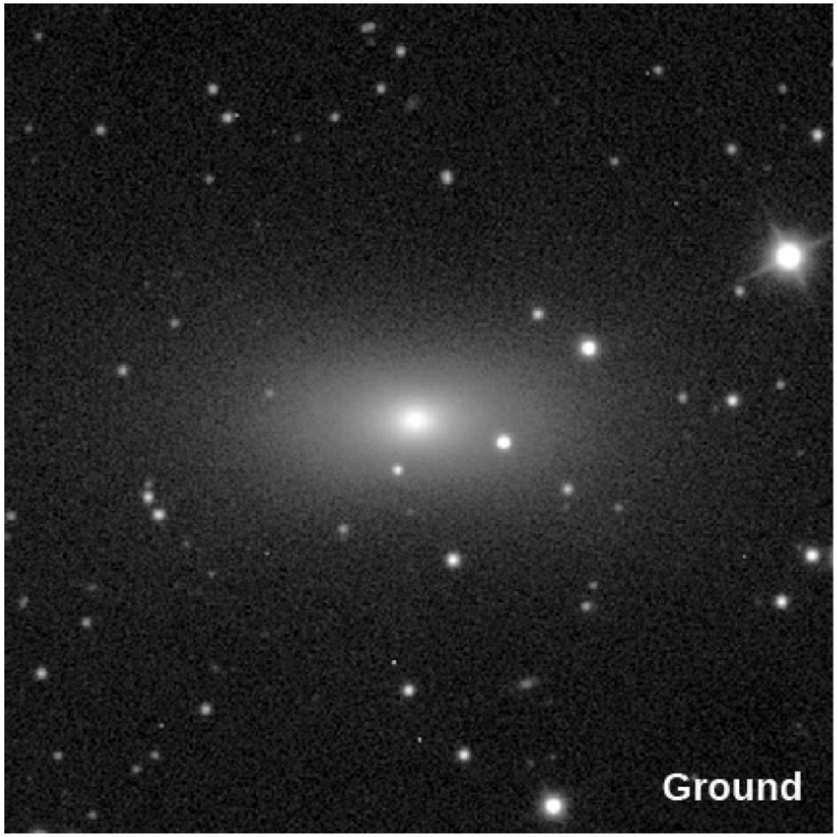


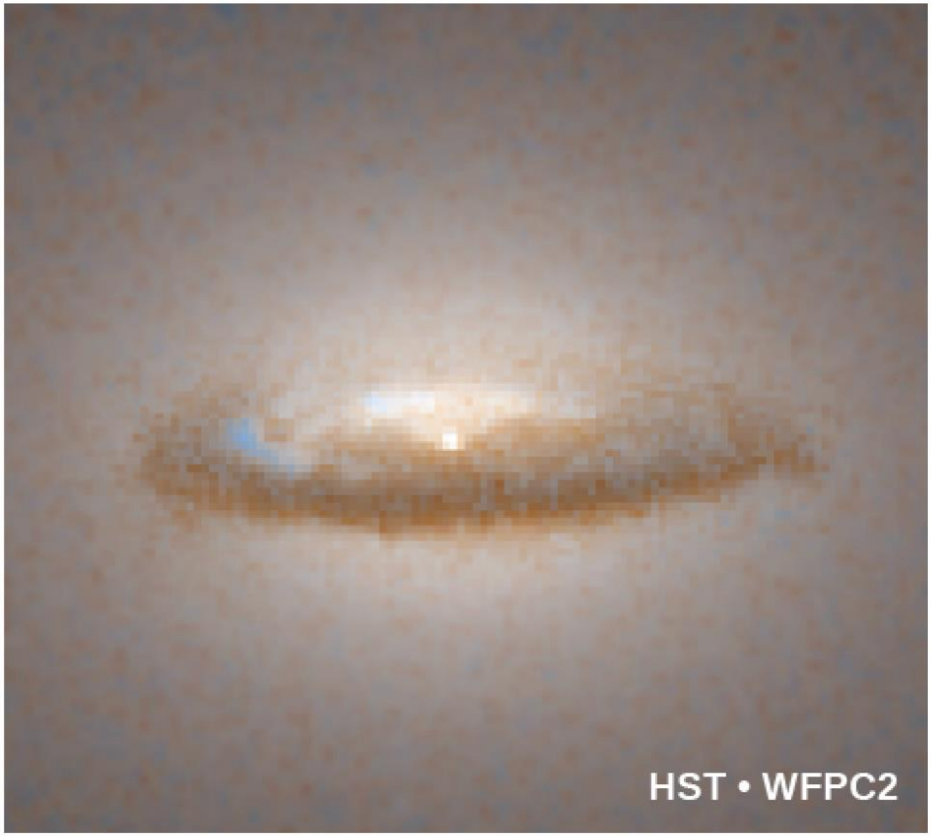
- Stellar mass black holes
  - Remnant of a dead stars



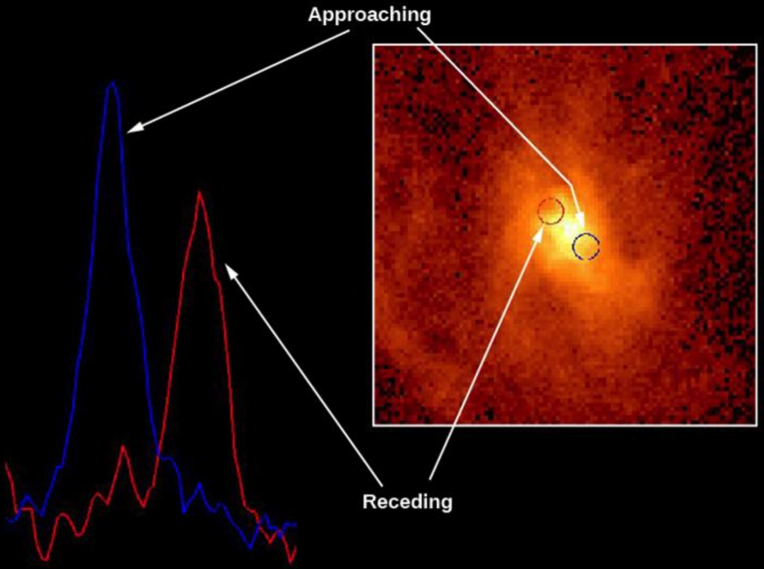
- Primordial black holes?
  - Speculative, no idea whether they exist
  - They would be tiny

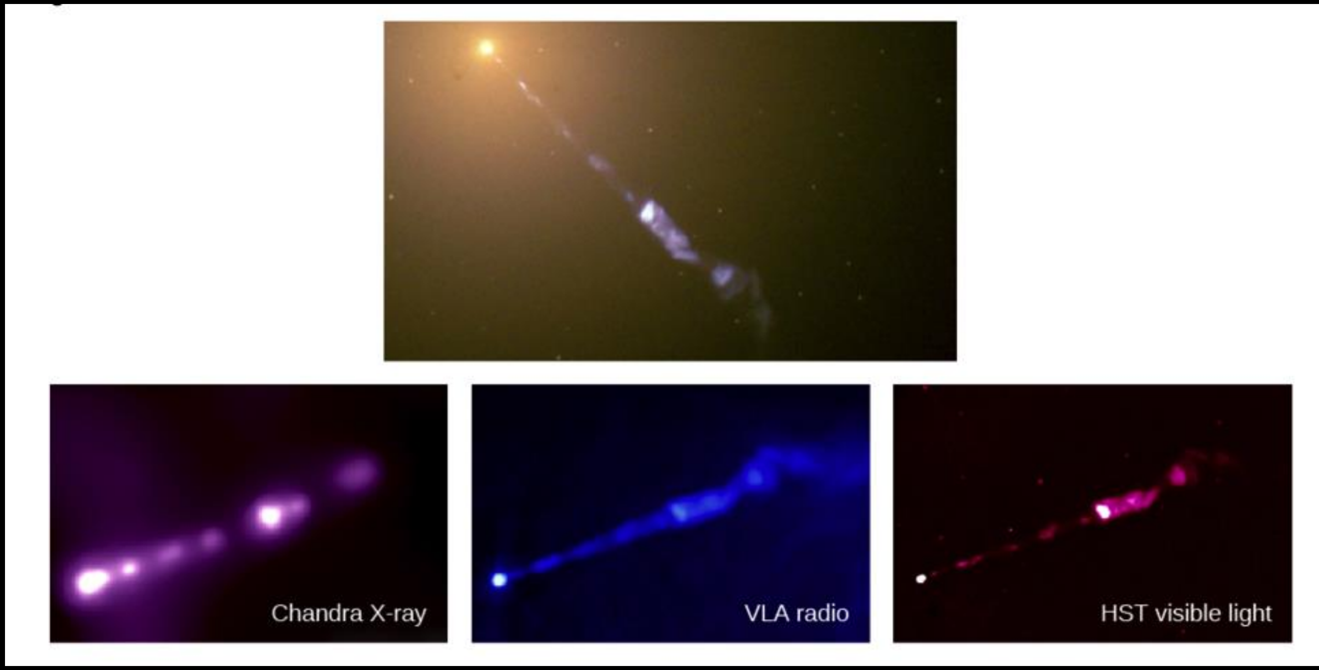
Imaging: usually can't resolve the black hole





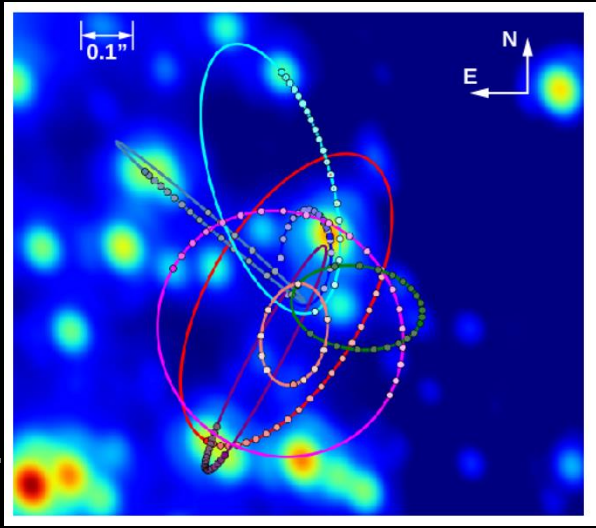
Indirect evidence: accretion disks, jets

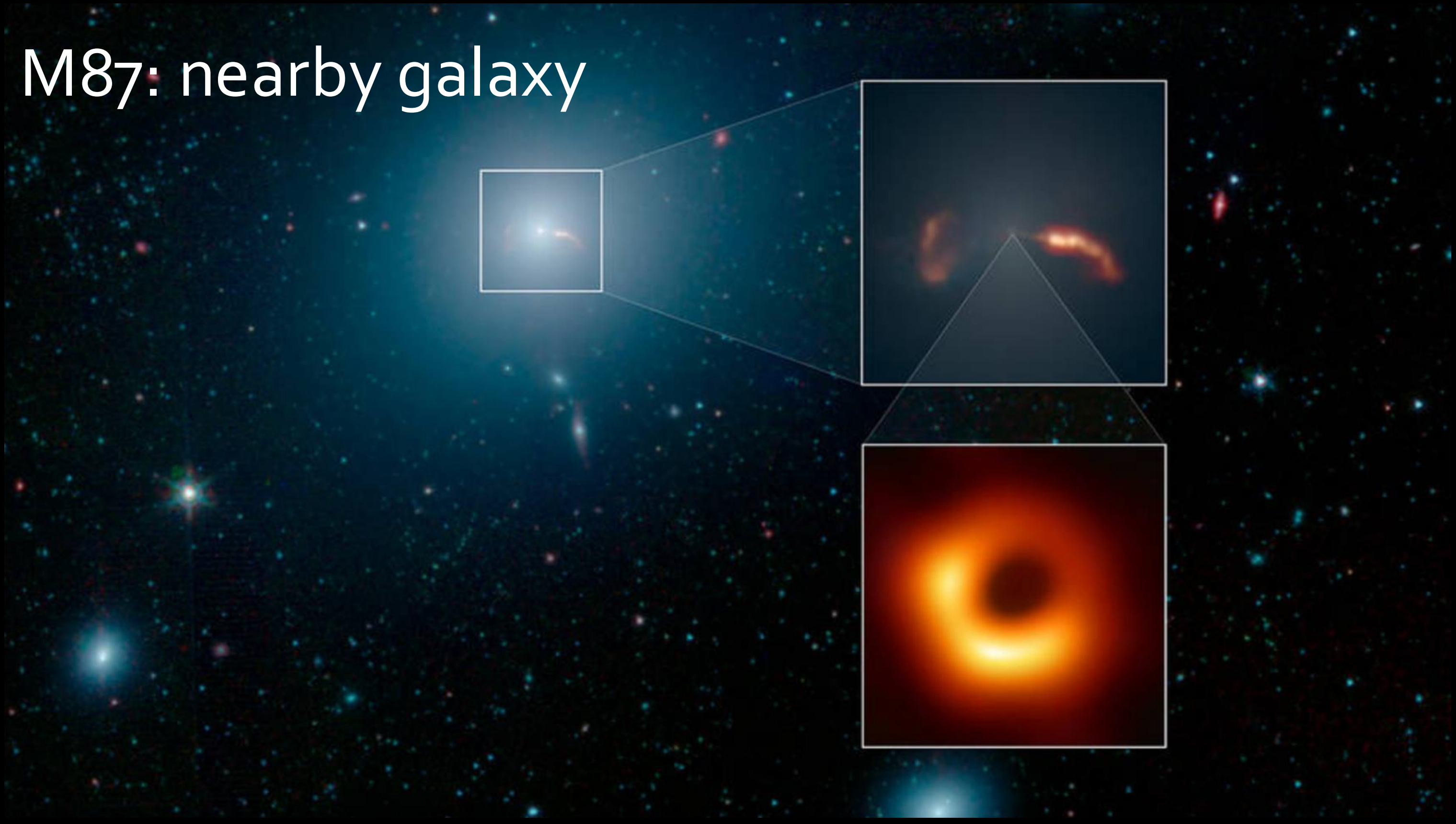




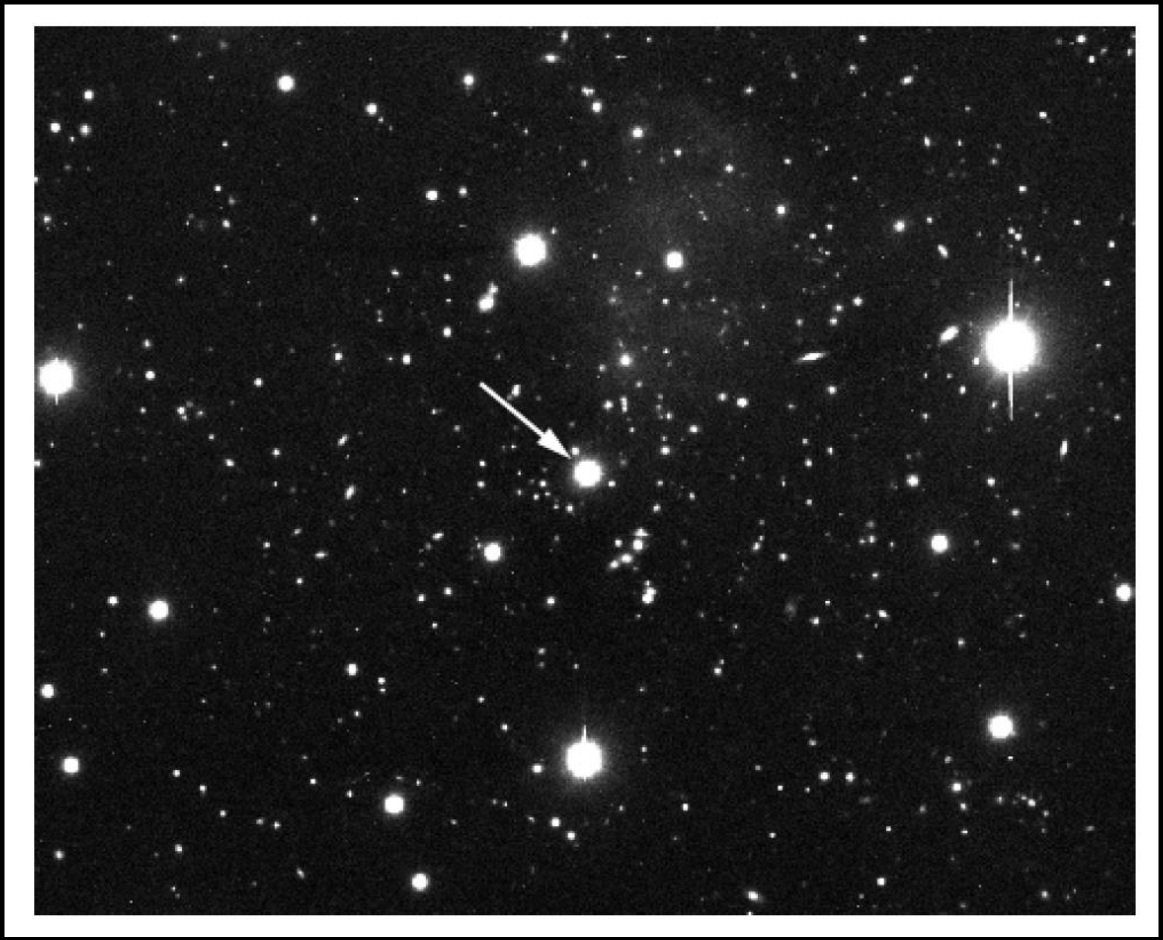
Supermassive black holes
Direct evidence

Milky Way:
galactic center

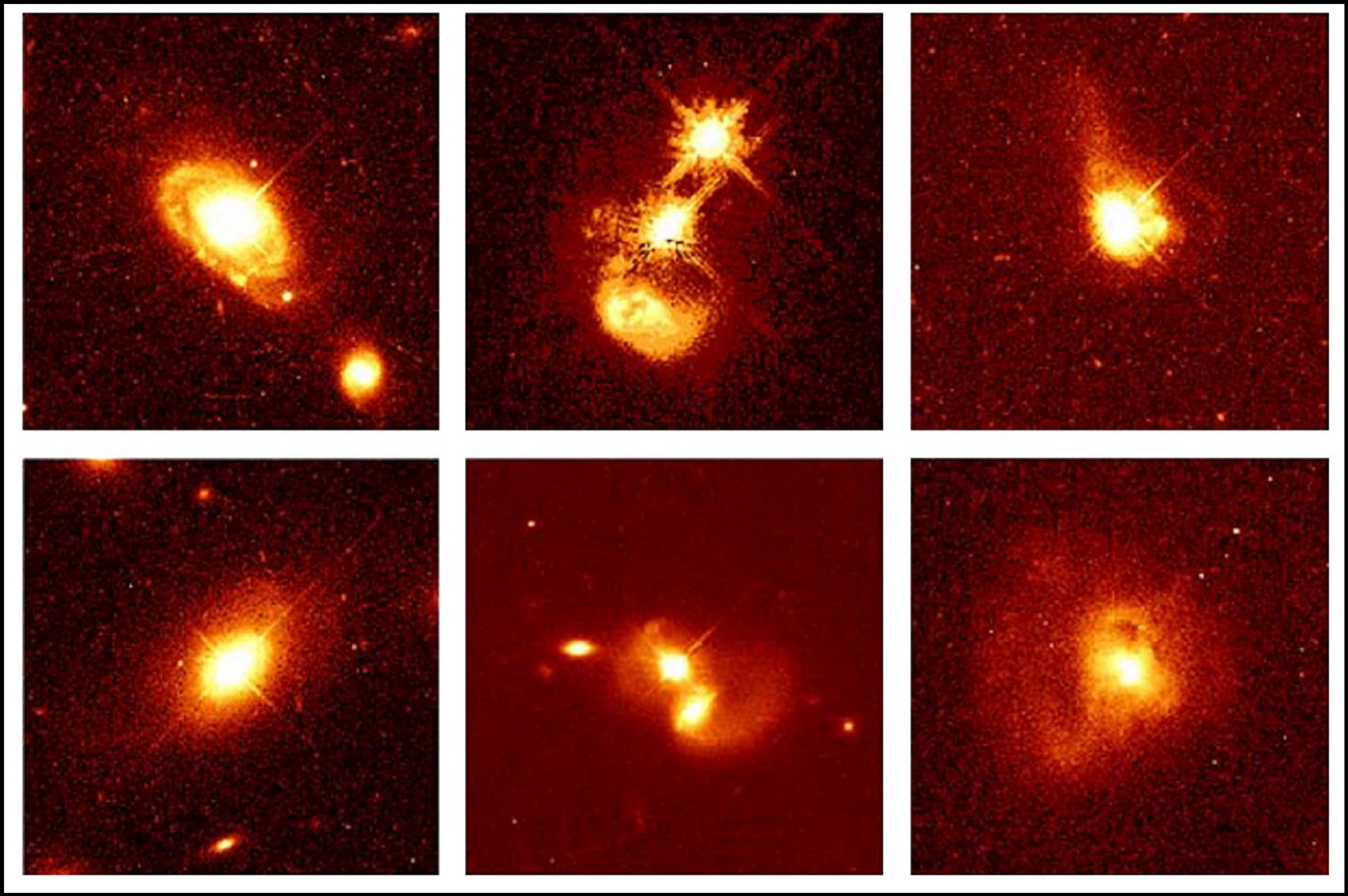




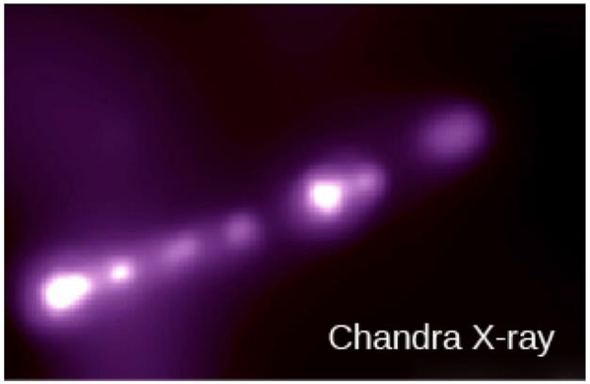
Supermassive black holes!
Quasars: quasi-stellar objects

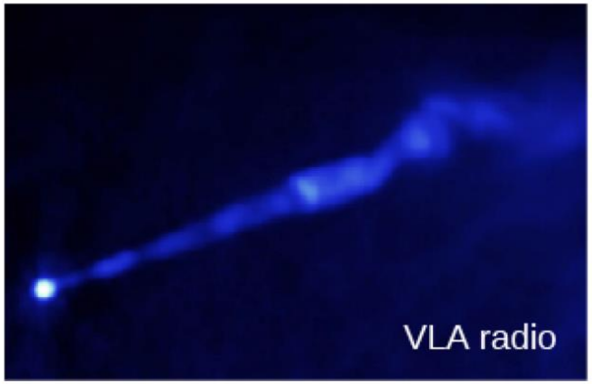


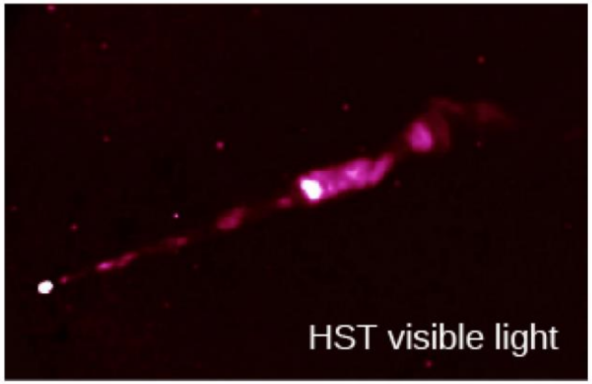
Quasars: accreting gas, outshines their host galaxies (but they do have host galaxies)

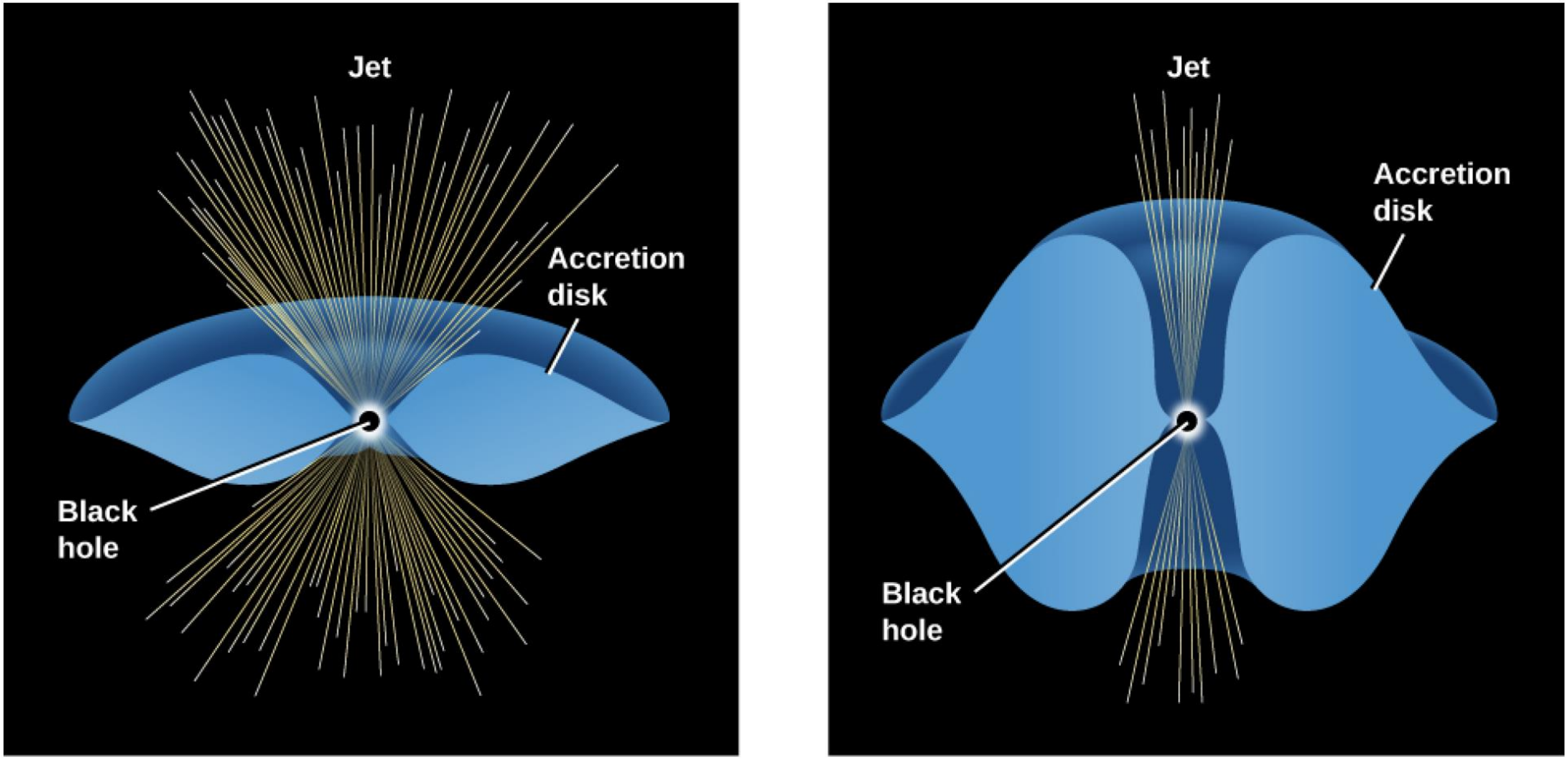


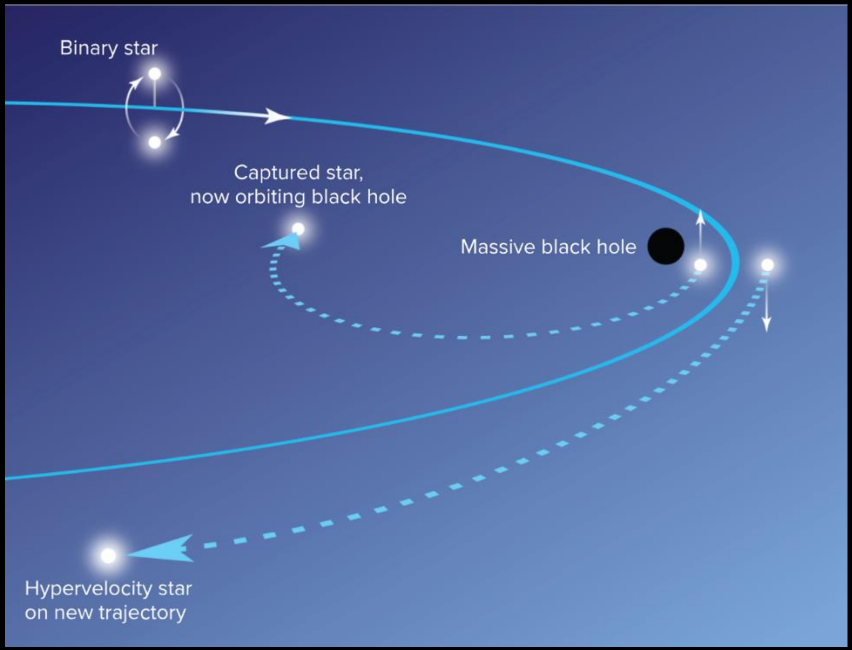
Jets from the central black hole





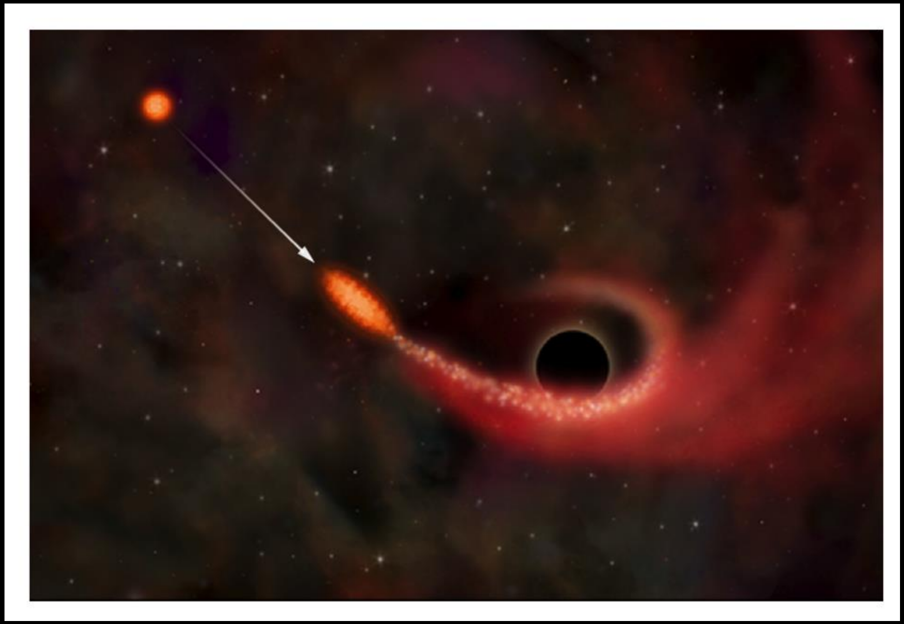



Jet
Accretion disk
Black hole
Jet
Accretion disk
Black hole



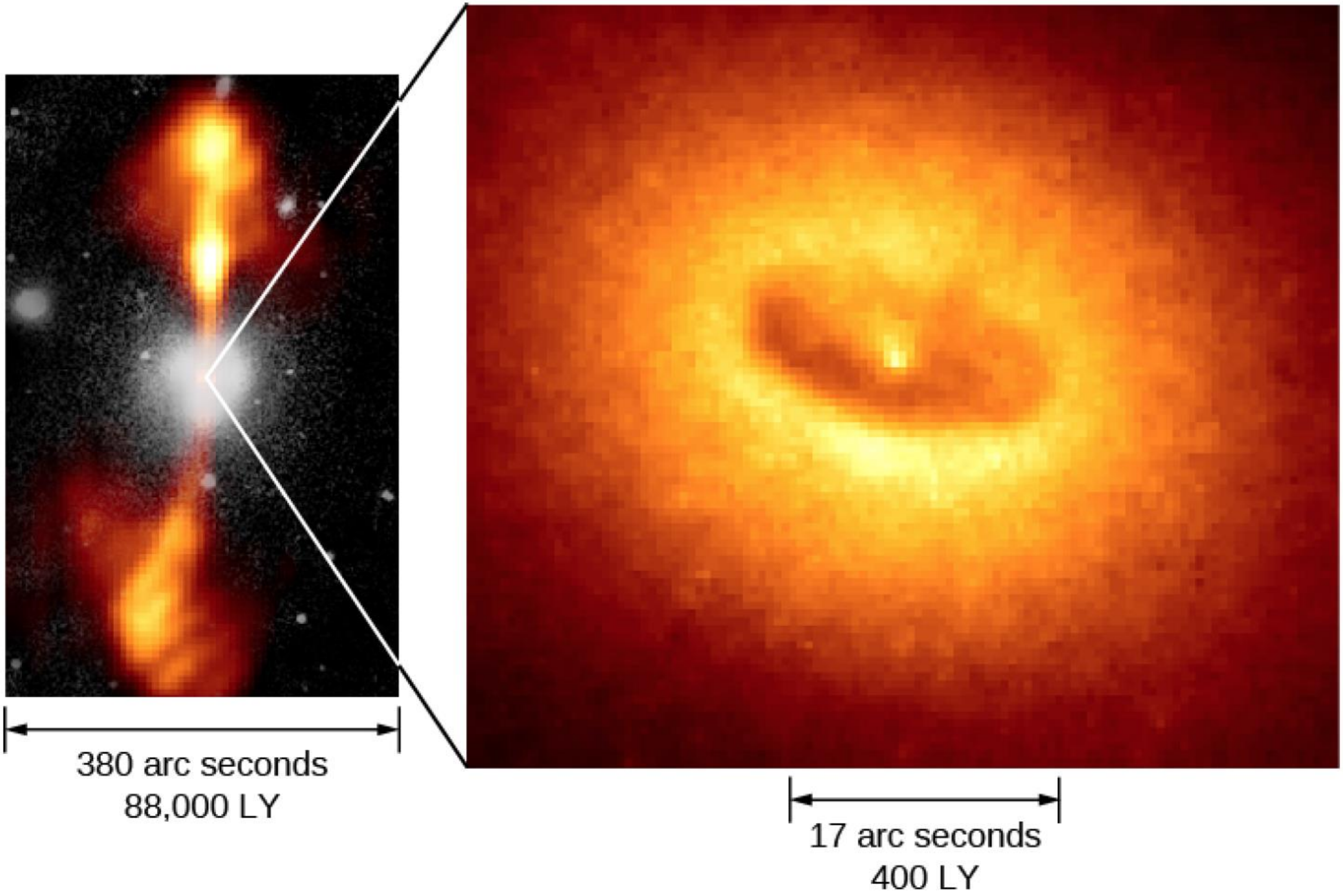
Hypervelocity stars:

Thrown out of galaxy by close encounter with supermassive black hole



Tidal disruption events:

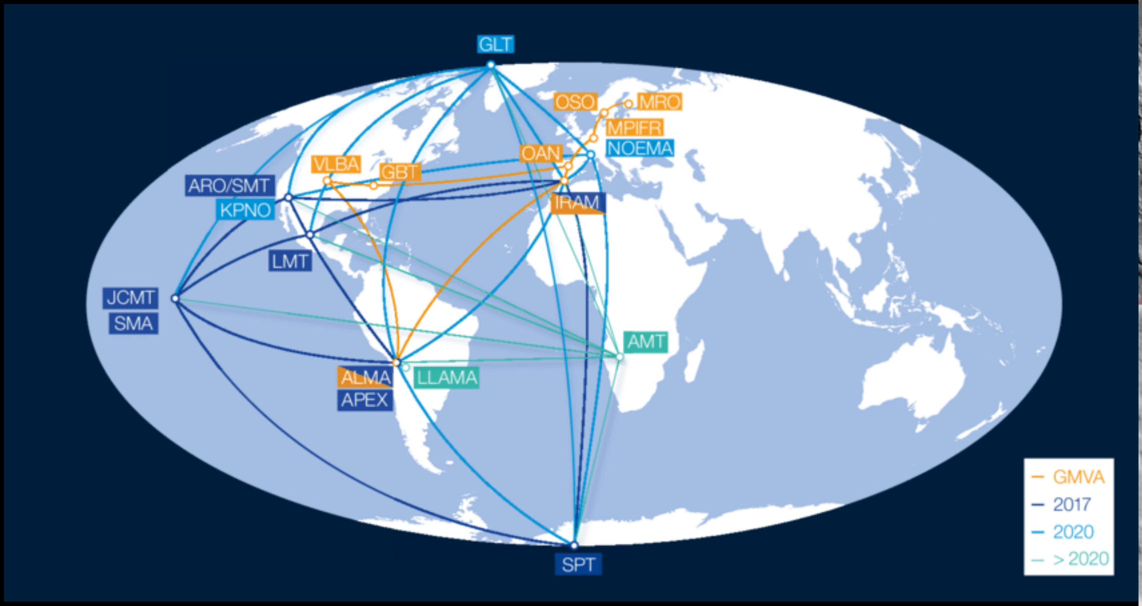
sometimes black hole eats a star!

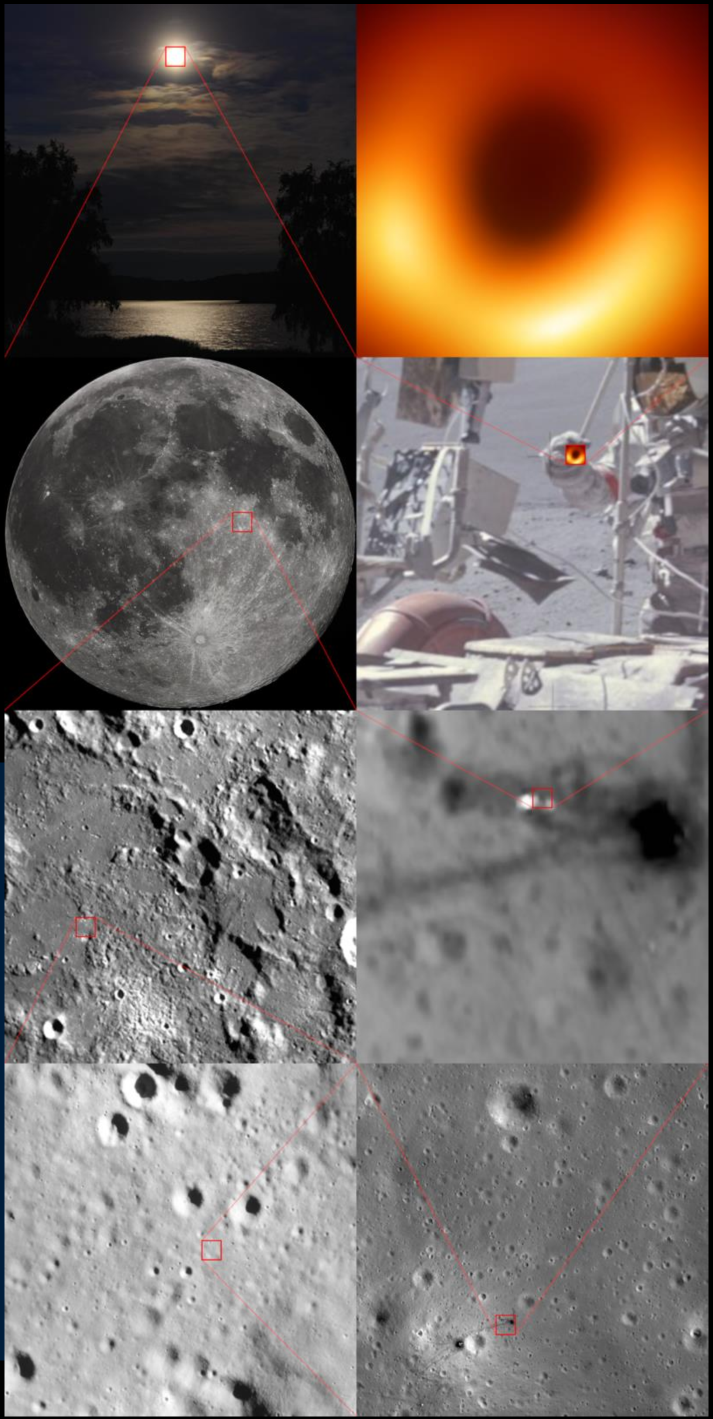

380 arc seconds
88,000 LY
17 arc seconds
400 LY

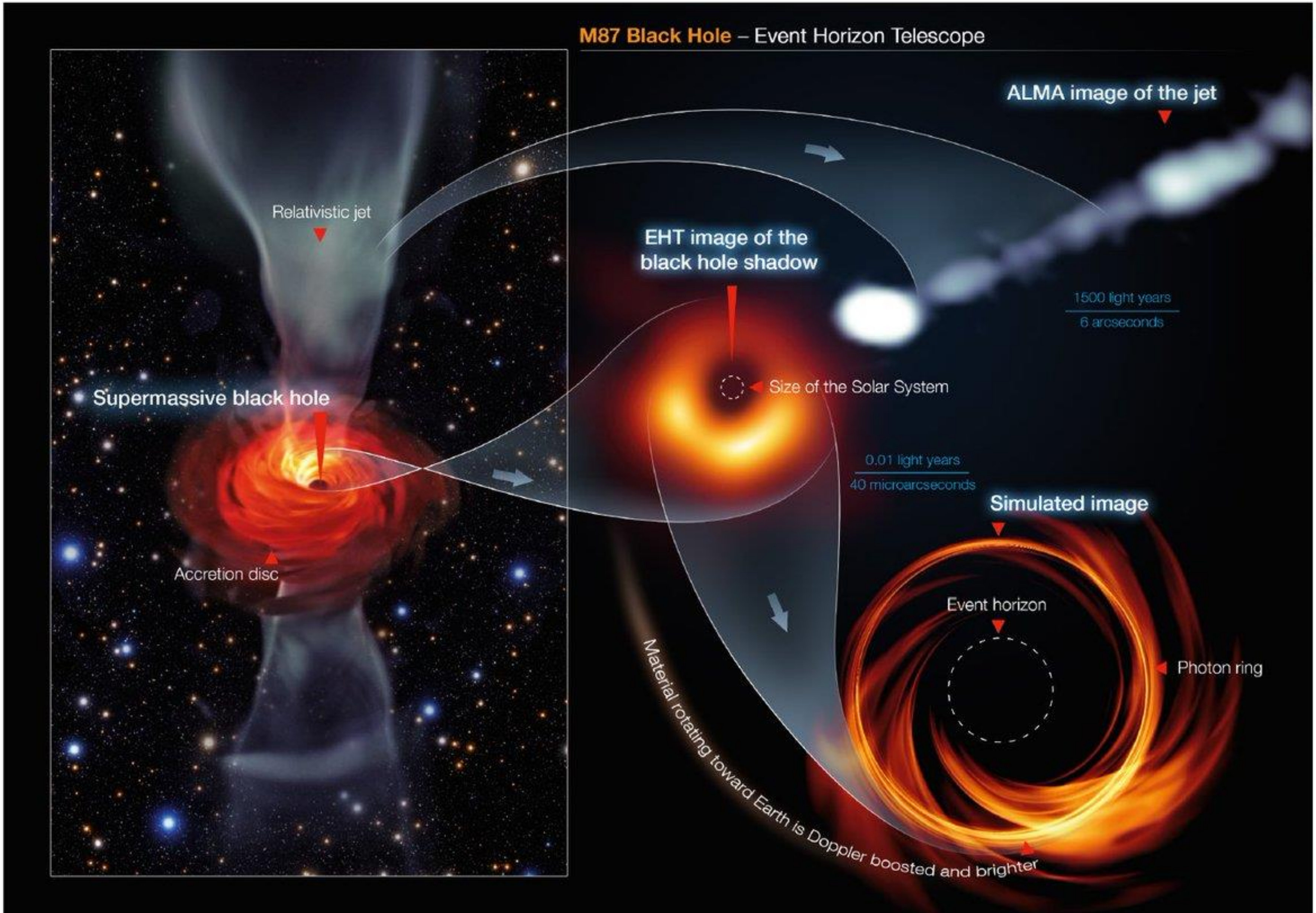
Event Horizon Telescope:

Uses radius of earth

spatial resolution = wavelength/diameter

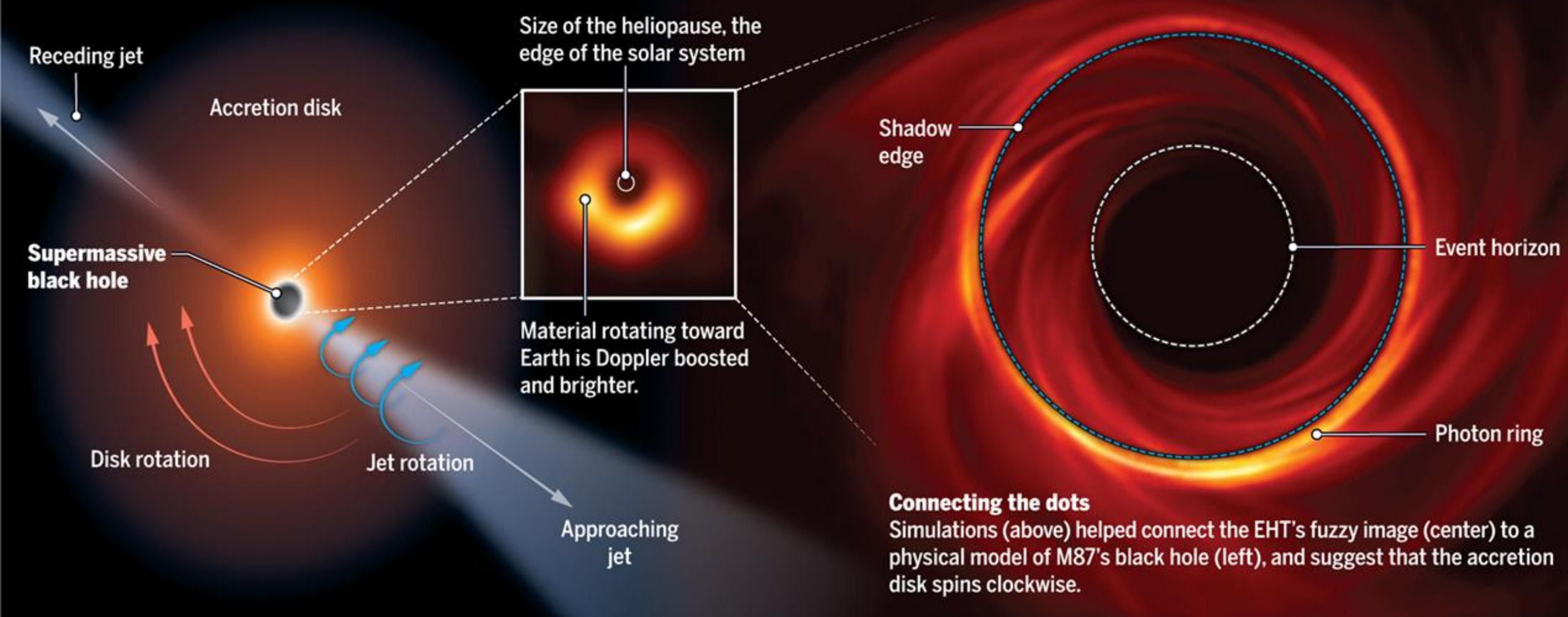




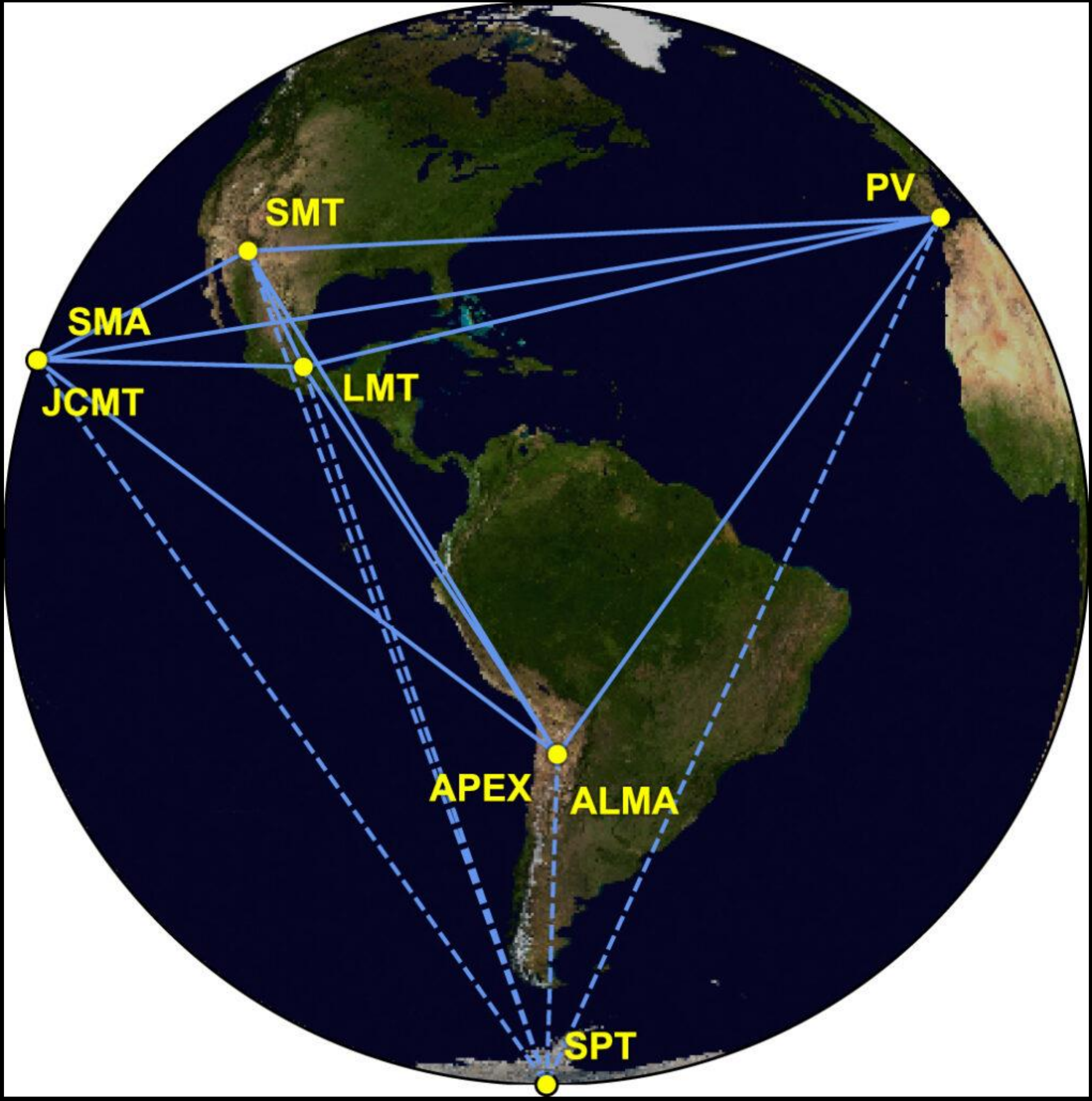

M87 Black Hole – Event Horizon Telescope
ALMA image of the jet
Relativistic jet
EHT image of the black hole shadow
1500 light years
6 arcseconds
Size of the Solar System
Supermassive black hole
0.01 light years
40 microarcseconds
Simulated image
Accretion disc
Event horizon
Photon ring
Material rotating toward Earth is Doppler boosted and brighter
C. Goddi, Z. Younsi, J. Davelaar/M.Kornmesser/ESO

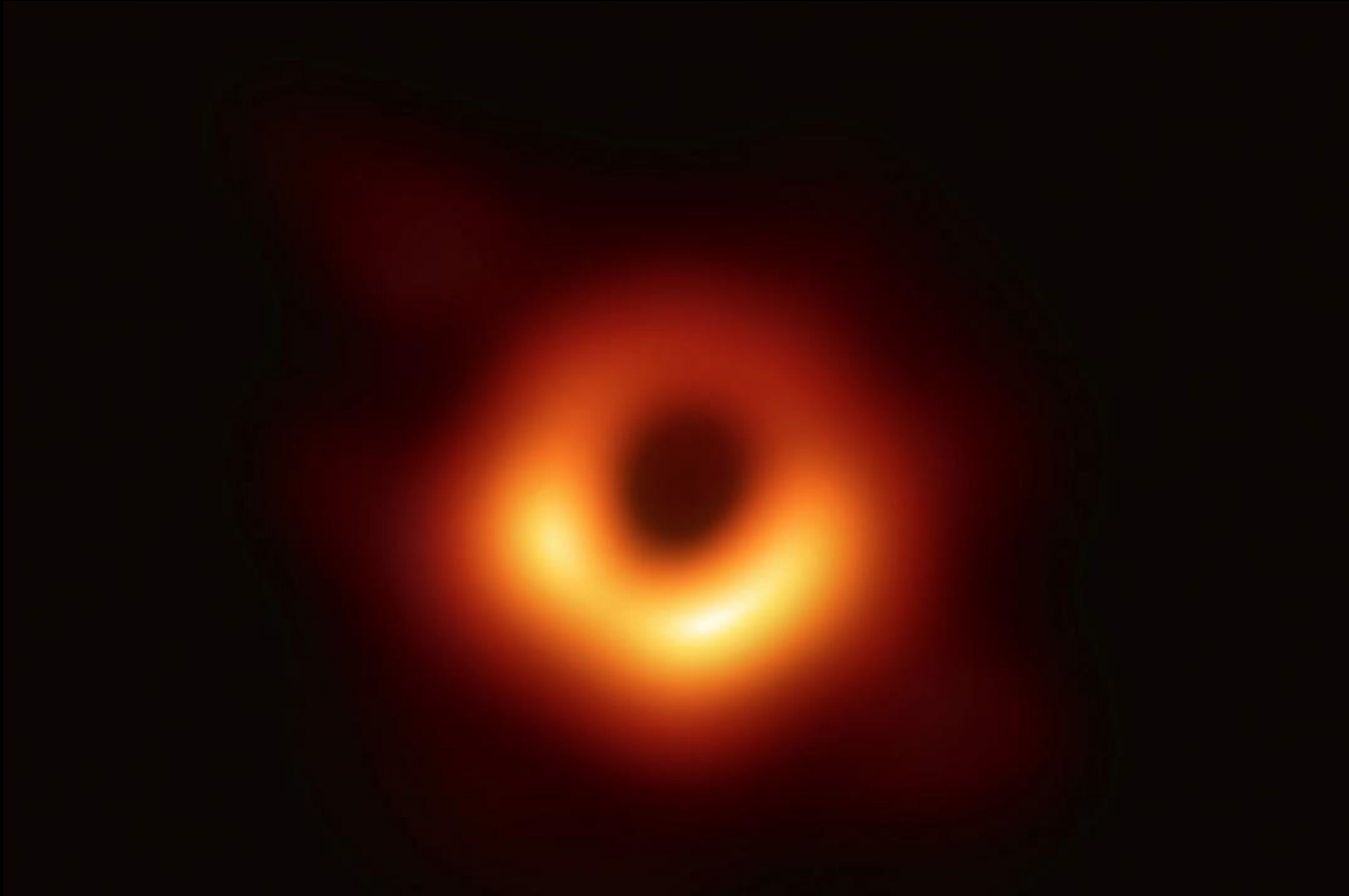
Strange beast

The Event Horizon Telescope (EHT) team took 2 years to produce an image of the black hole at the center of nearby galaxy Messier 87 (M87), which feeds on a swirling disk of bright matter. Its gravity is so strong that photons orbit it, creating a bright ring. Gravitational lensing magnifies the black hole's event horizon into a larger dark shadow, which may be partially filled by material in front of the hole.

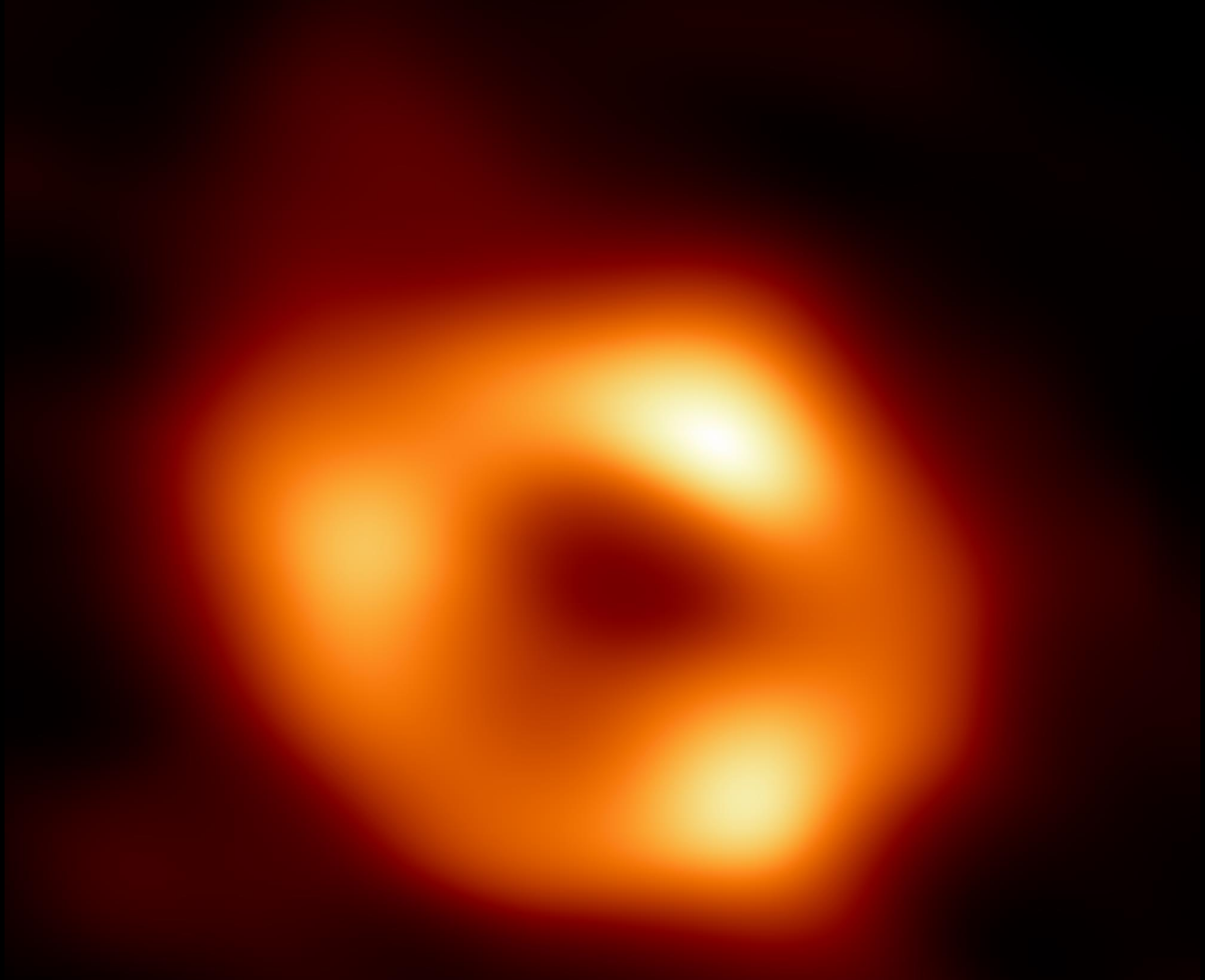


Connecting the dots
Simulations (above) helped connect the EHT's fuzzy image (center) to a physical model of M87's black hole (left), and suggest that the accretion disk spins clockwise.

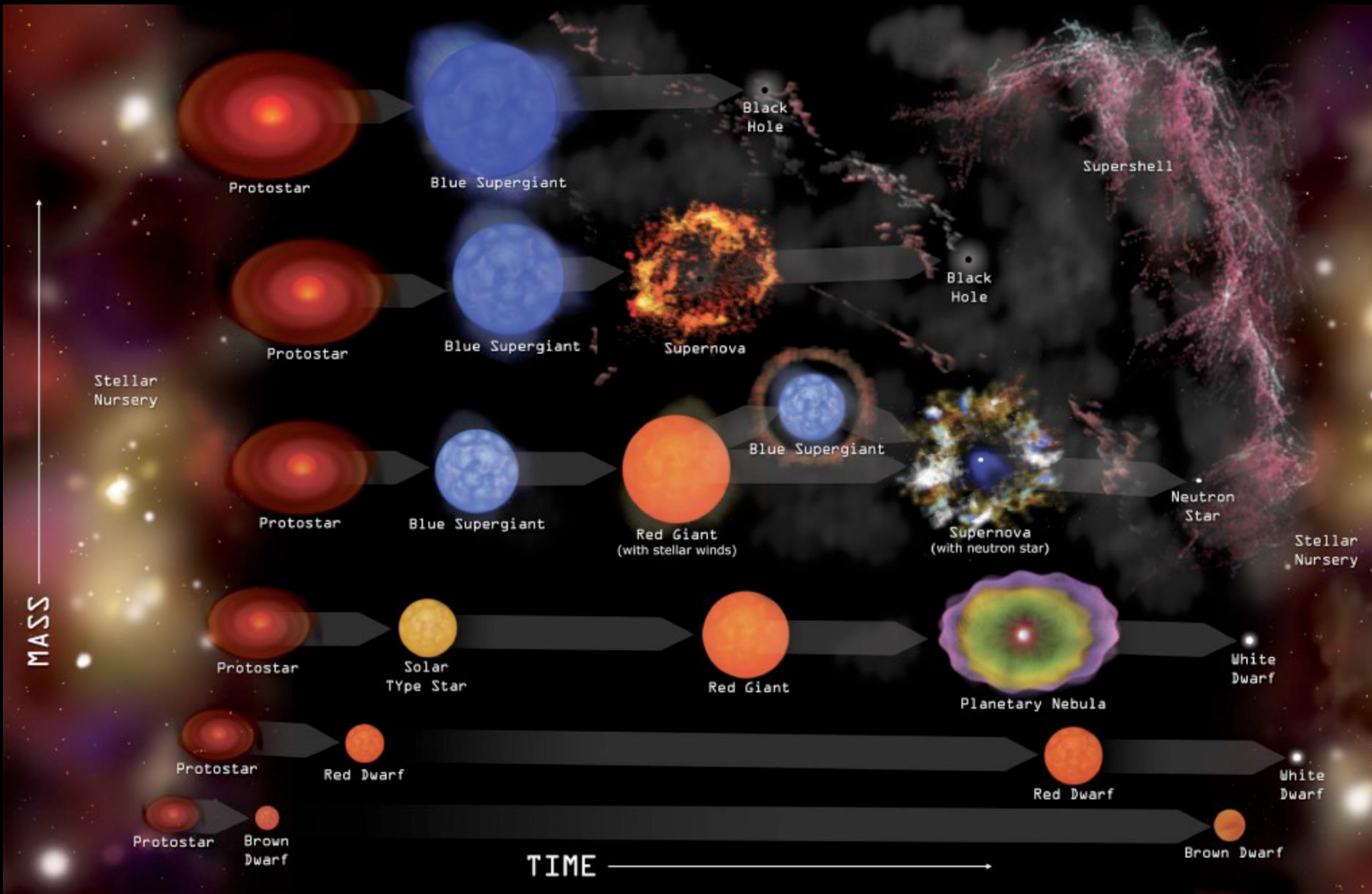

PV
SMT
SMA
JCMT
LMT
APEX
ALMA
SPT



Event Horizon Telescope:
image of M87 black hole



Event Horizon Telescope:
image of Milky Way black hole



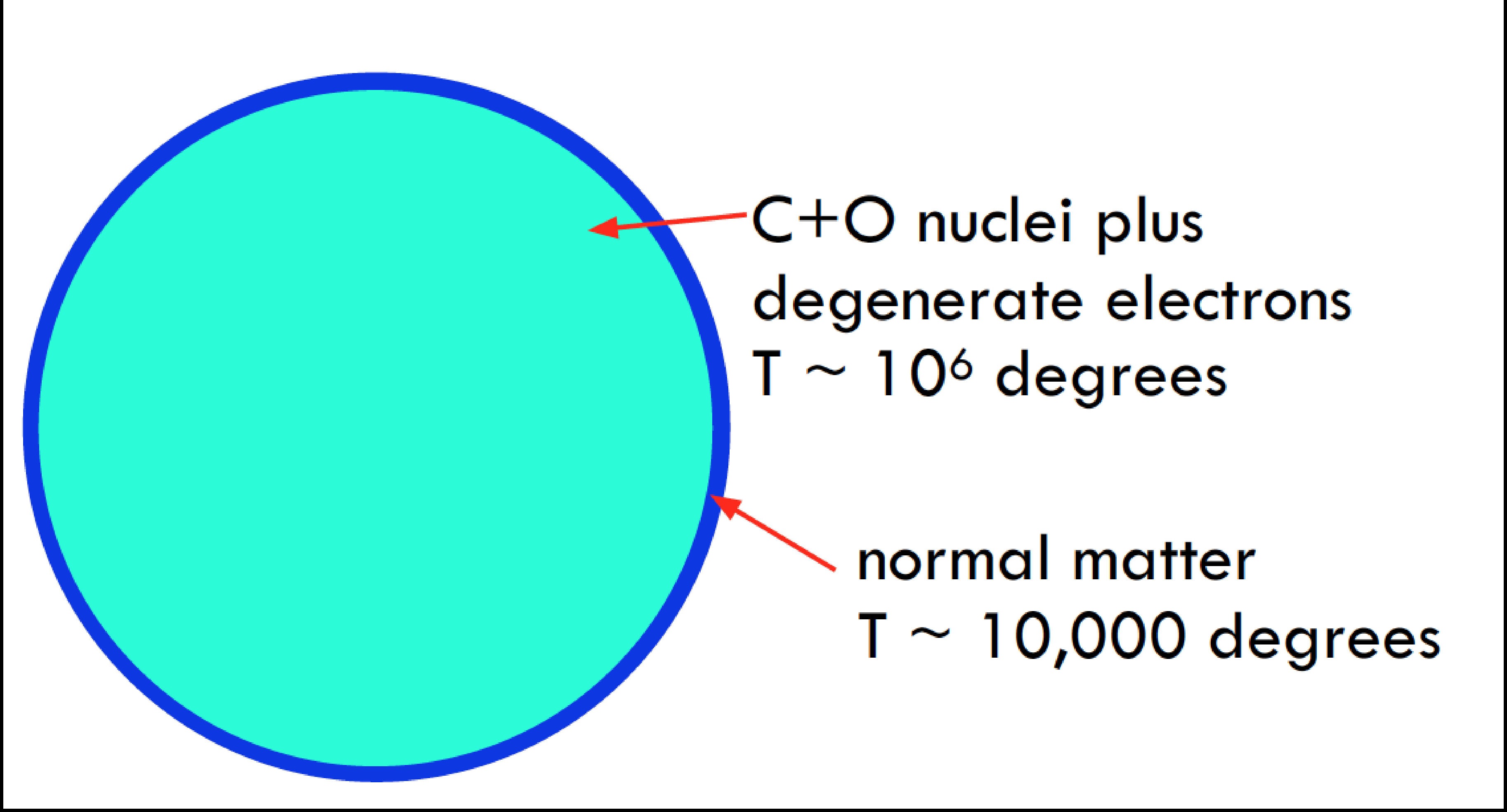
Protostar
Blue Supergiant
Black Hole
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Protostar
Blue Supergiant
Red Giant
(with stellar winds)
Blue Supergiant
Supernova
(with neutron star)
Neutron Star
Stellar Nursery
Protostar
Solar Type Star
Red Giant
Planetary Nebula
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
Brown Dwarf
MASS
TIME

Properties of a Typical White Dwarf and a Neutron Star

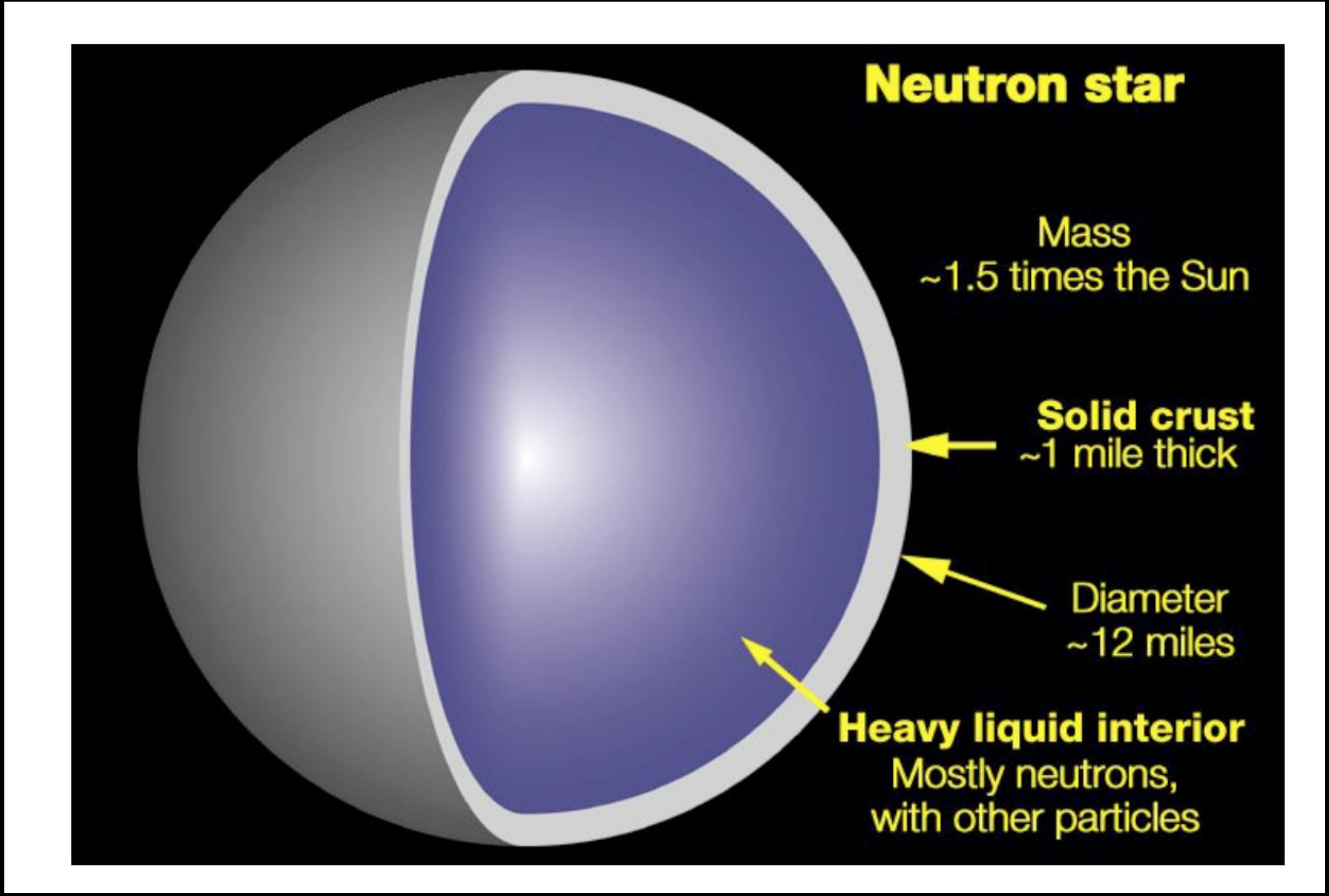
Property	White Dwarf	Neutron Star
Mass (Sun = 1)	0.6 (always <1.4)	Always >1.4 and <3
Radius	7000 km	10 km
Density	8×10^5 g/cm^3	10^{14} g/cm^3

X-ray image of accreting neutron star

White dwarf


C+O nuclei plus
degenerate electrons
T ~ 10^6 degrees
normal matter
T ~ 10,000 degrees

Neutron star: density of nucleus!



- **white dwarf:** electrons run out of room and halt the collapse of the star

maximum mass
1.4 solar masses

- **neutron star:** neutrons run out of room and halt the collapse of the star

maximum mass
~3 solar masses

- **black hole:** gravity wins: collapse continues

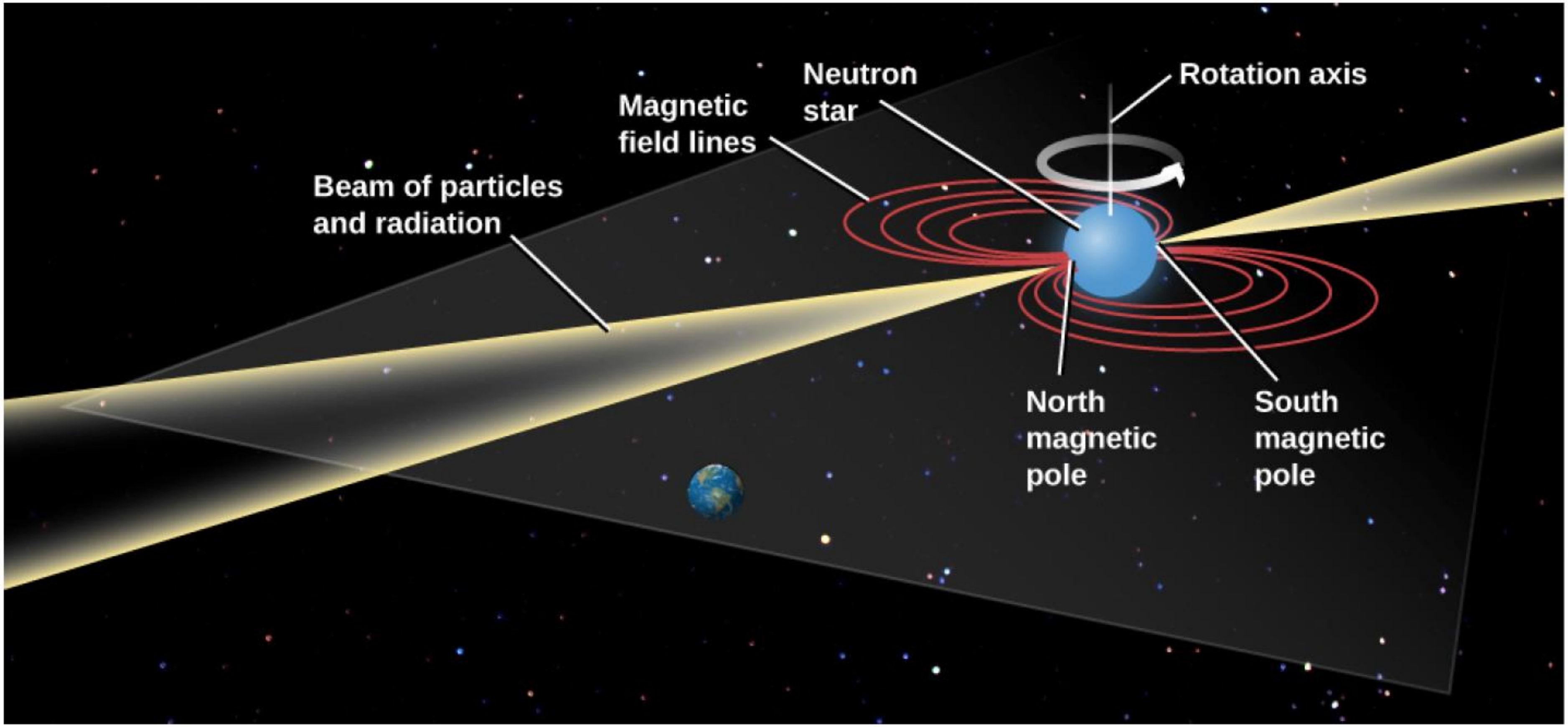
Sun: size 1.4×10^6 km

rotation period 27 days = 2.3×10^6 s

Neutron star: size 14 km = 1 million times smaller

☞ rotation period 1 million times shorter = 2.3 s

Pulsar: neutron star with beamed light pulses from electrons



Jocelyn Bell: Found pulsars

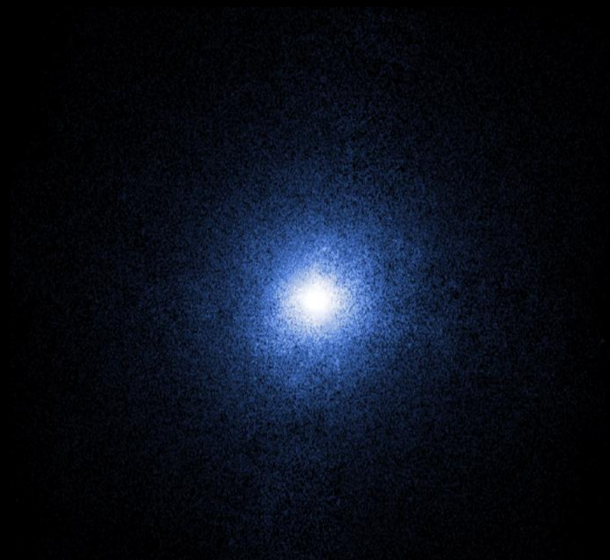
(discovery won Nobel Prize, but she did not)

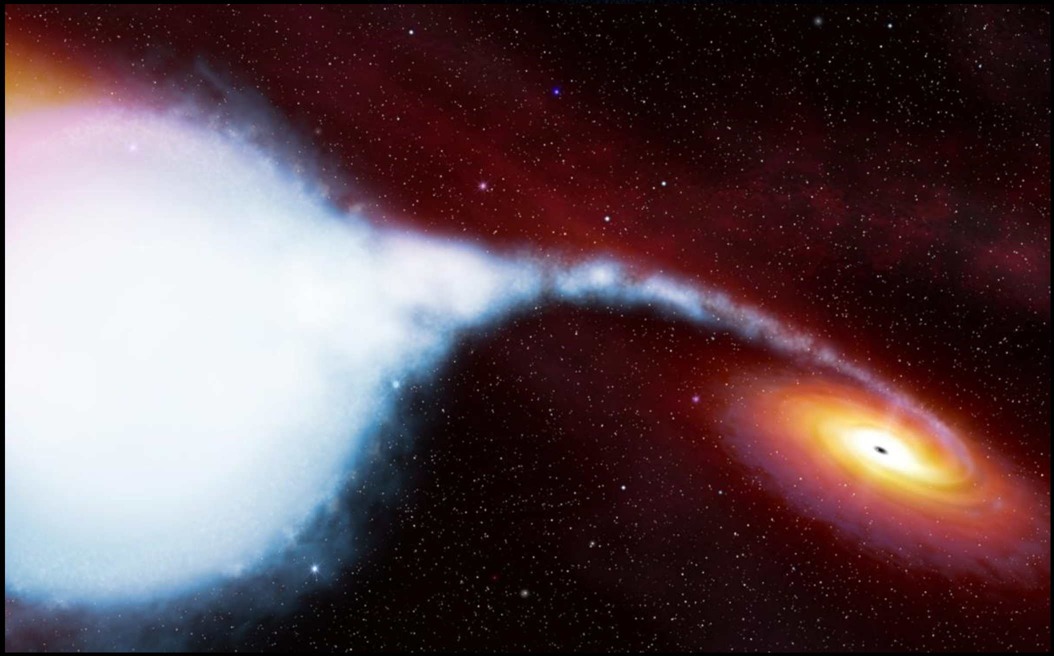
Cygnus X-1: first accepted black hole

- Black holes in binary systems can "steal" mass from the companion

- Accretion disk: very hot
  - Strong X-rays

- Some X-ray binaries identified as stellar mass black holes





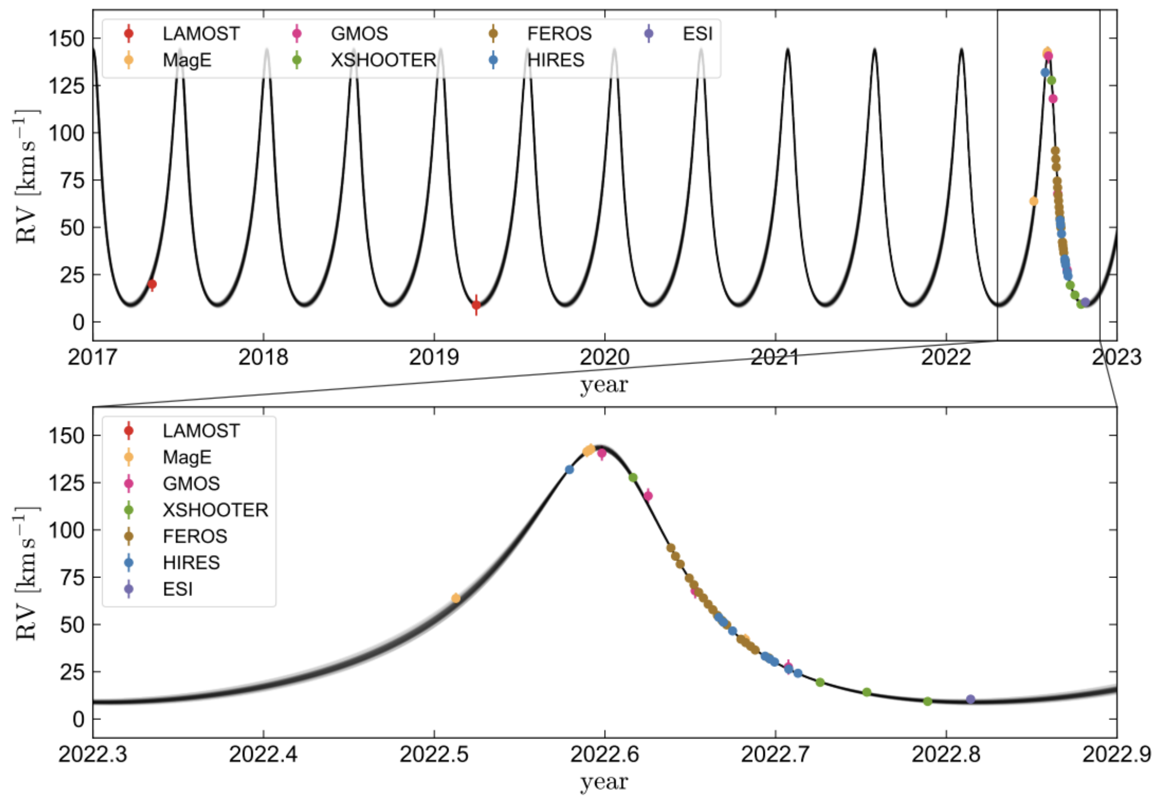
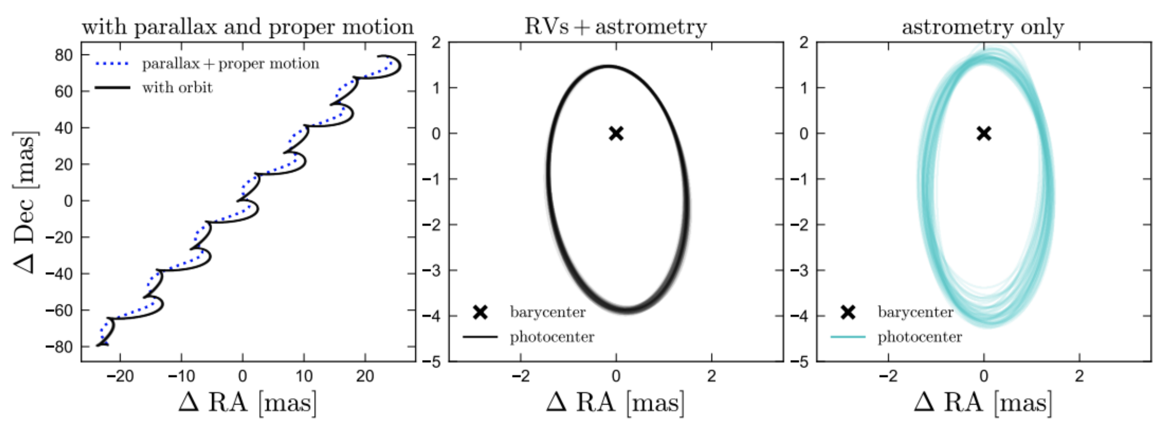


Figure 2. Radial velocities. Points with error bars are measurements; gray lines are draws from the posterior when jointly fitting these RVs and the *Gaia* astrometric constraints. Top panel shows all available RVs, including observations by the LAMOST survey in 2017 and 2019; bottom panel highlights our follow-up in 2022. The best-fit solution has a period of 186 days, eccentricity 0.45, and RV semi-amplitude of 67 km s^{-1}. Together with the inclination constraint from astrometry, this implies a companion mass of $9.62 \pm 0.18\, M_{\odot}$.

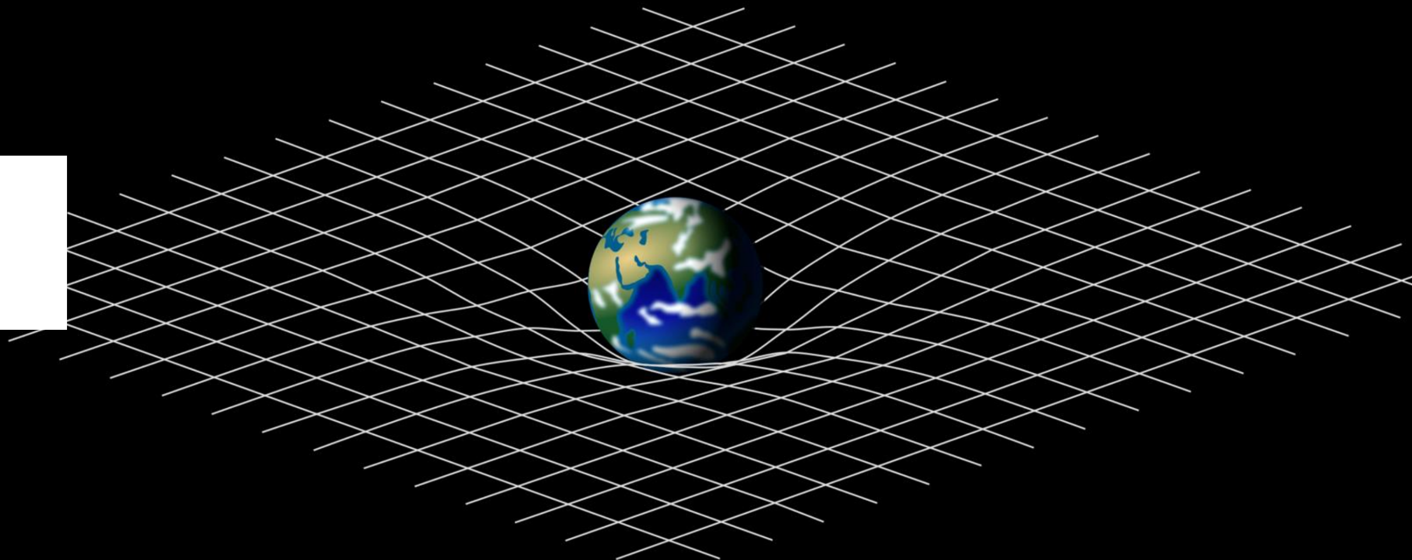


Gaia BH1

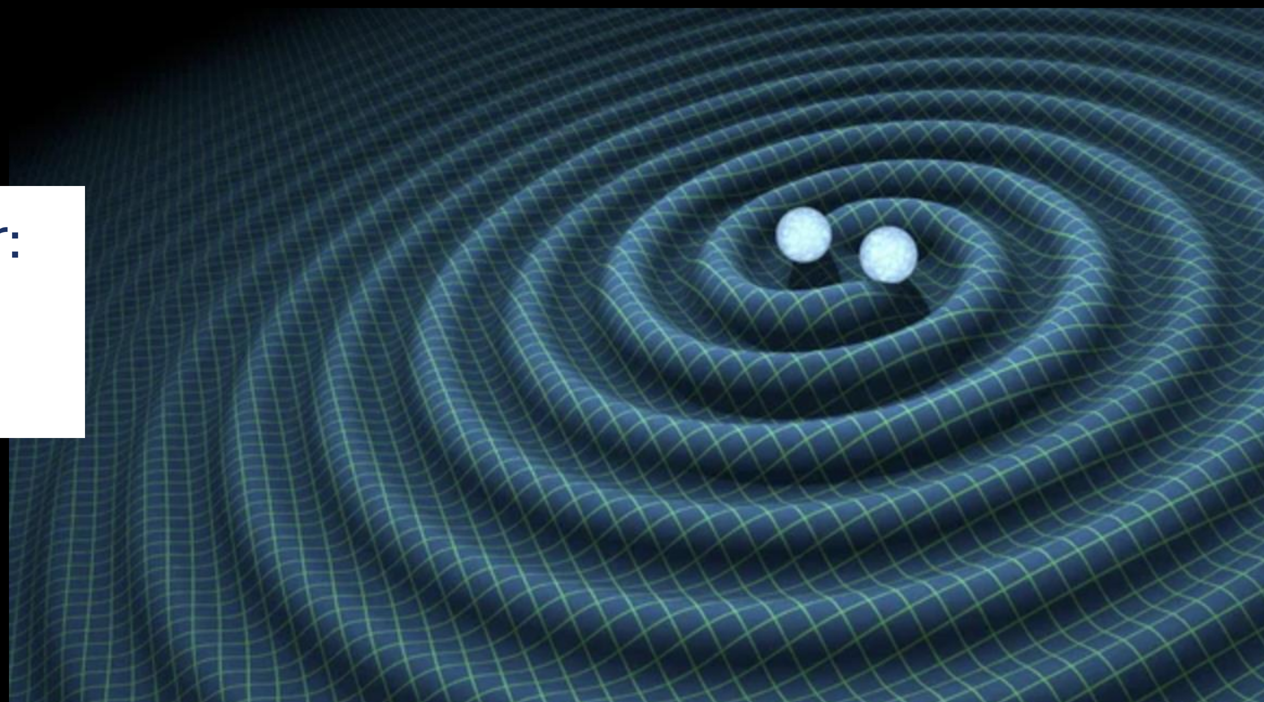
First “quiet” stellar-mass black hole

Found by orbit of a star

Mass: curves space-time

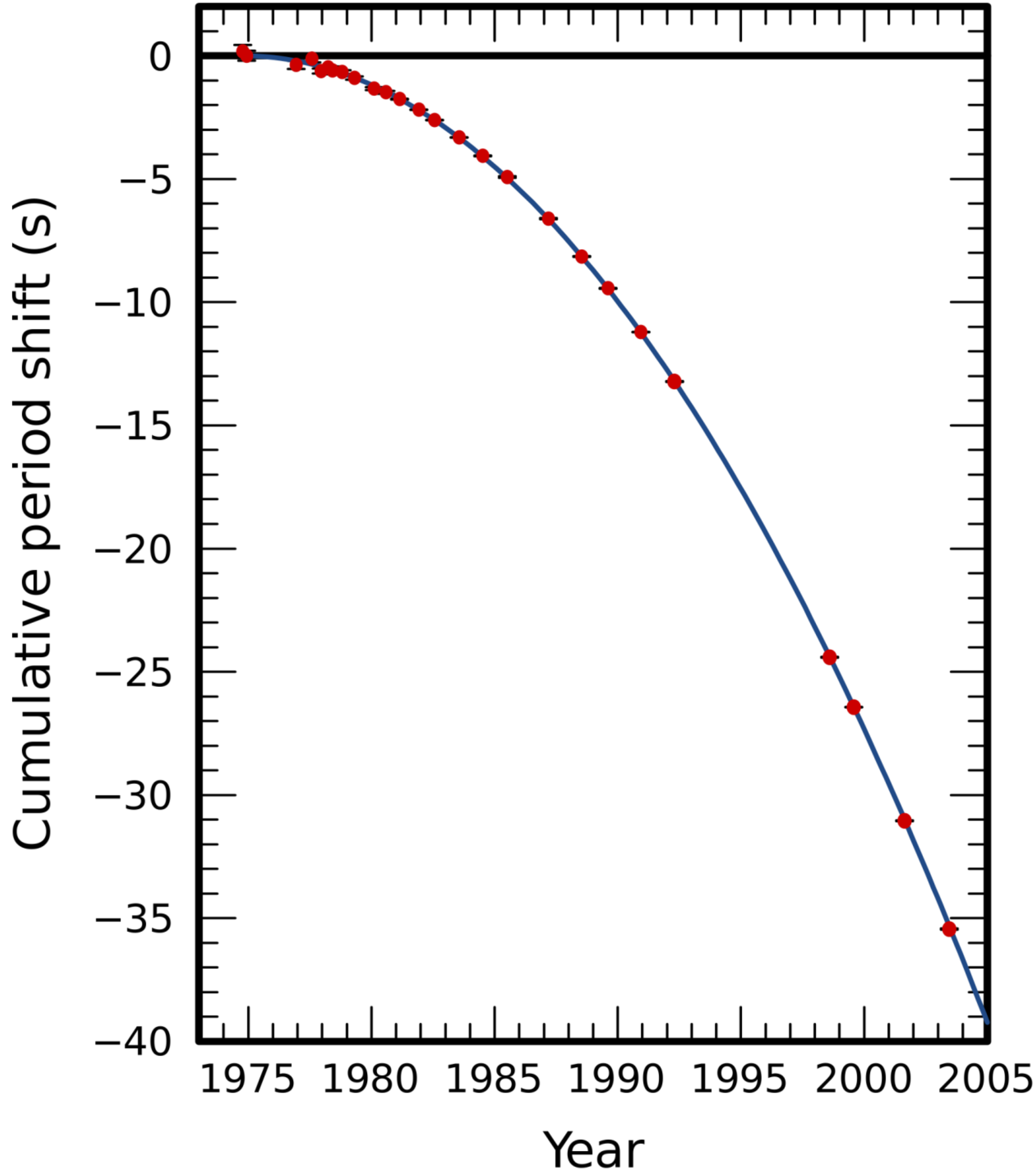


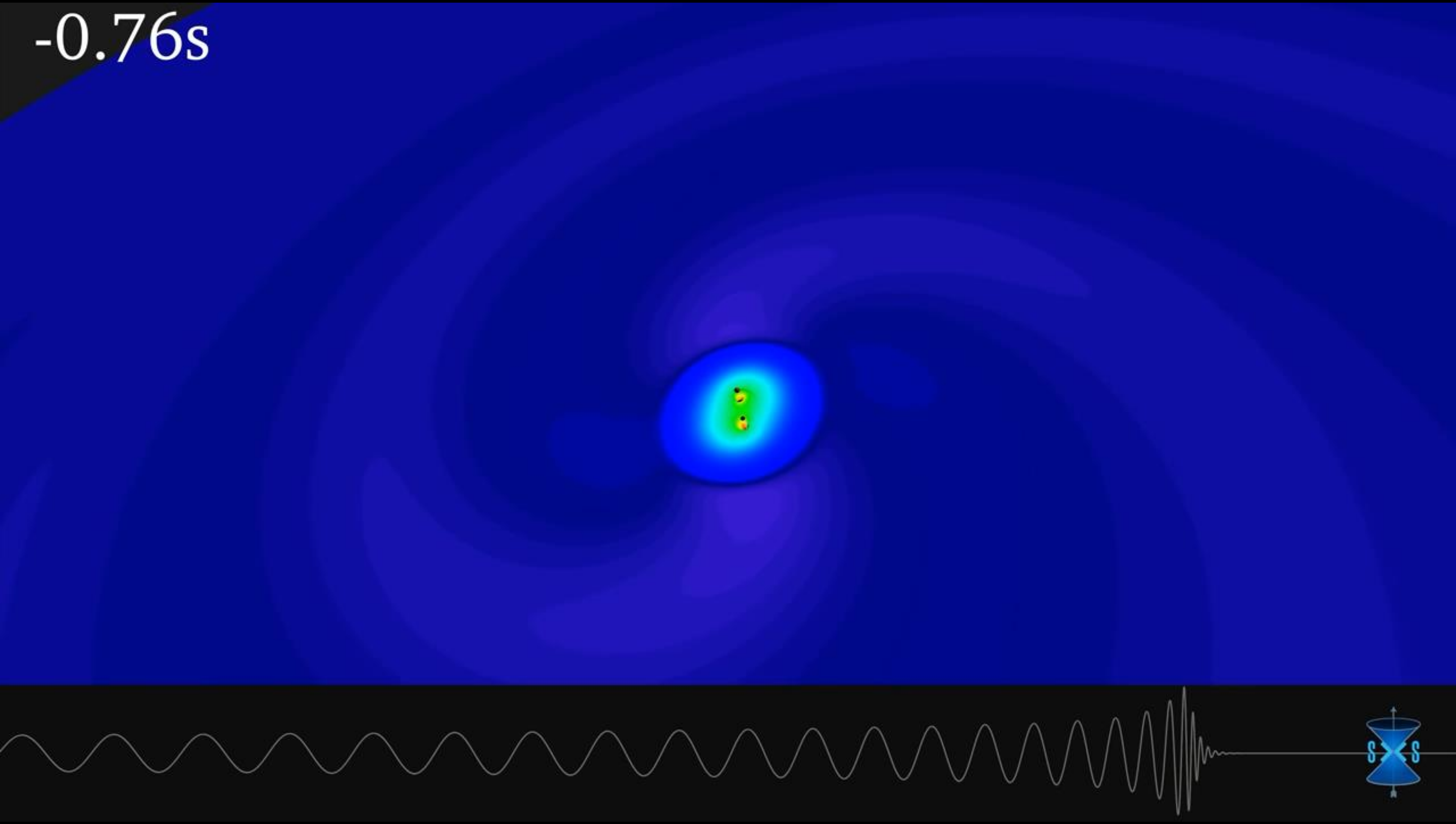
Binary merger: gravitational waves

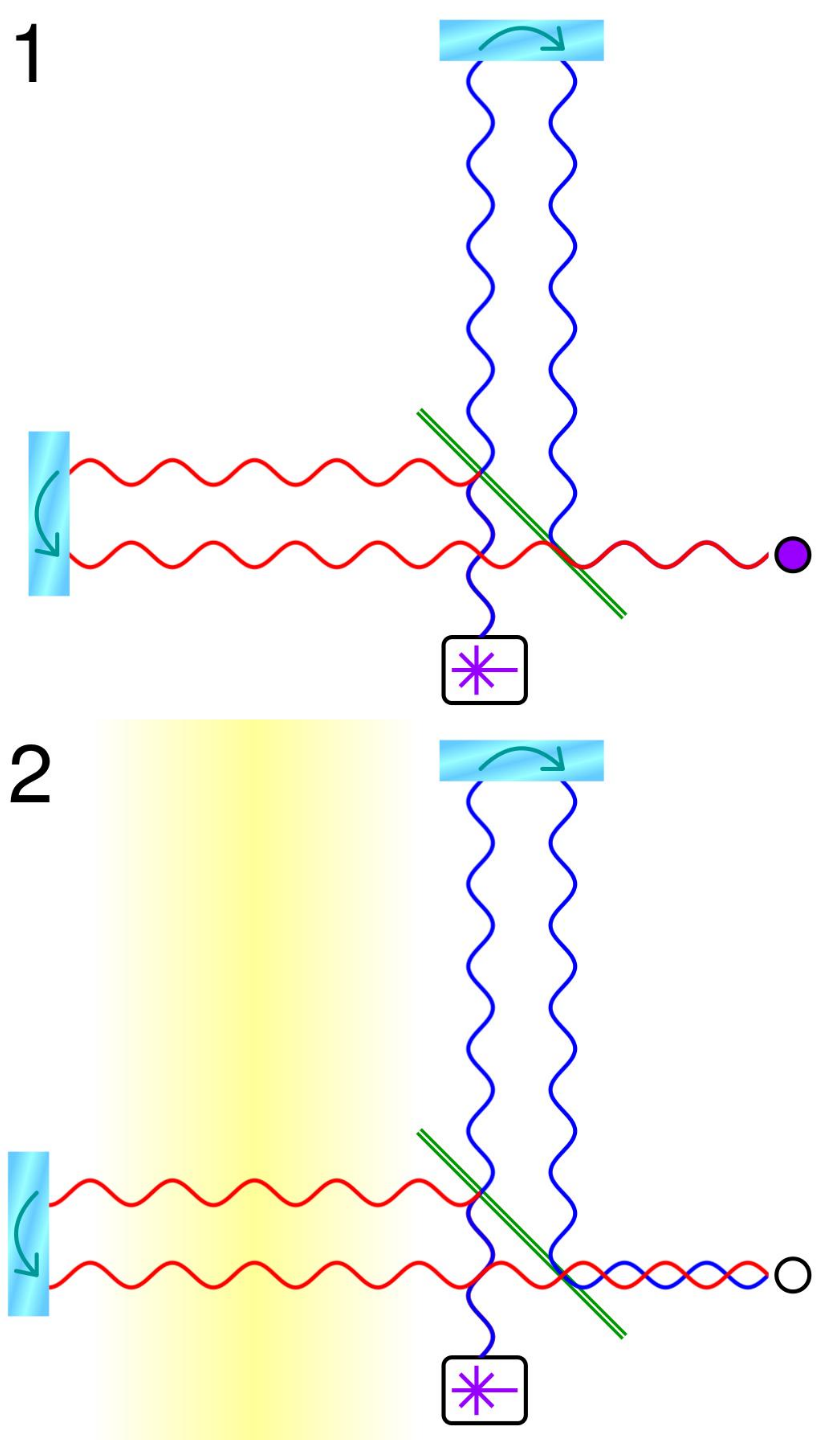


Hulse-Taylor binary pulsar

Orbital decay requires gravitational waves

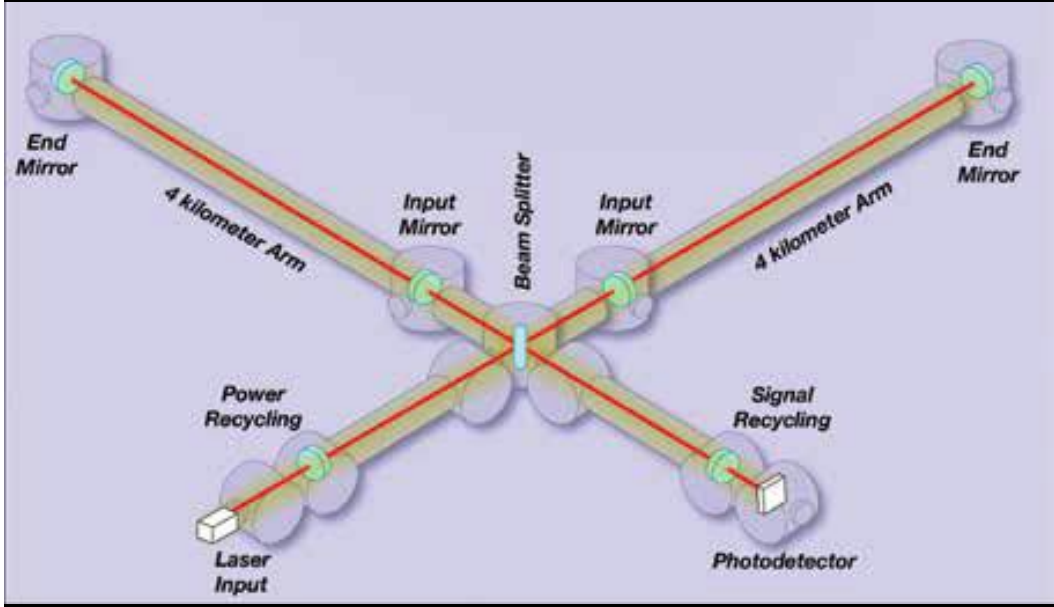



-0.76s

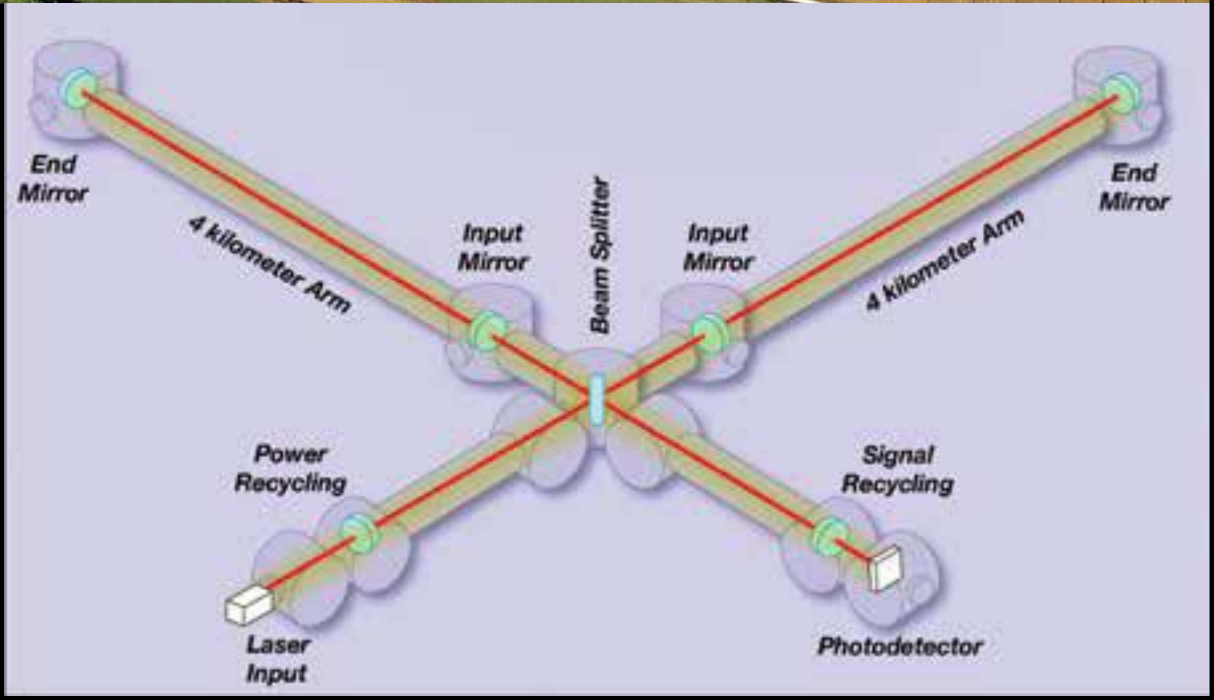


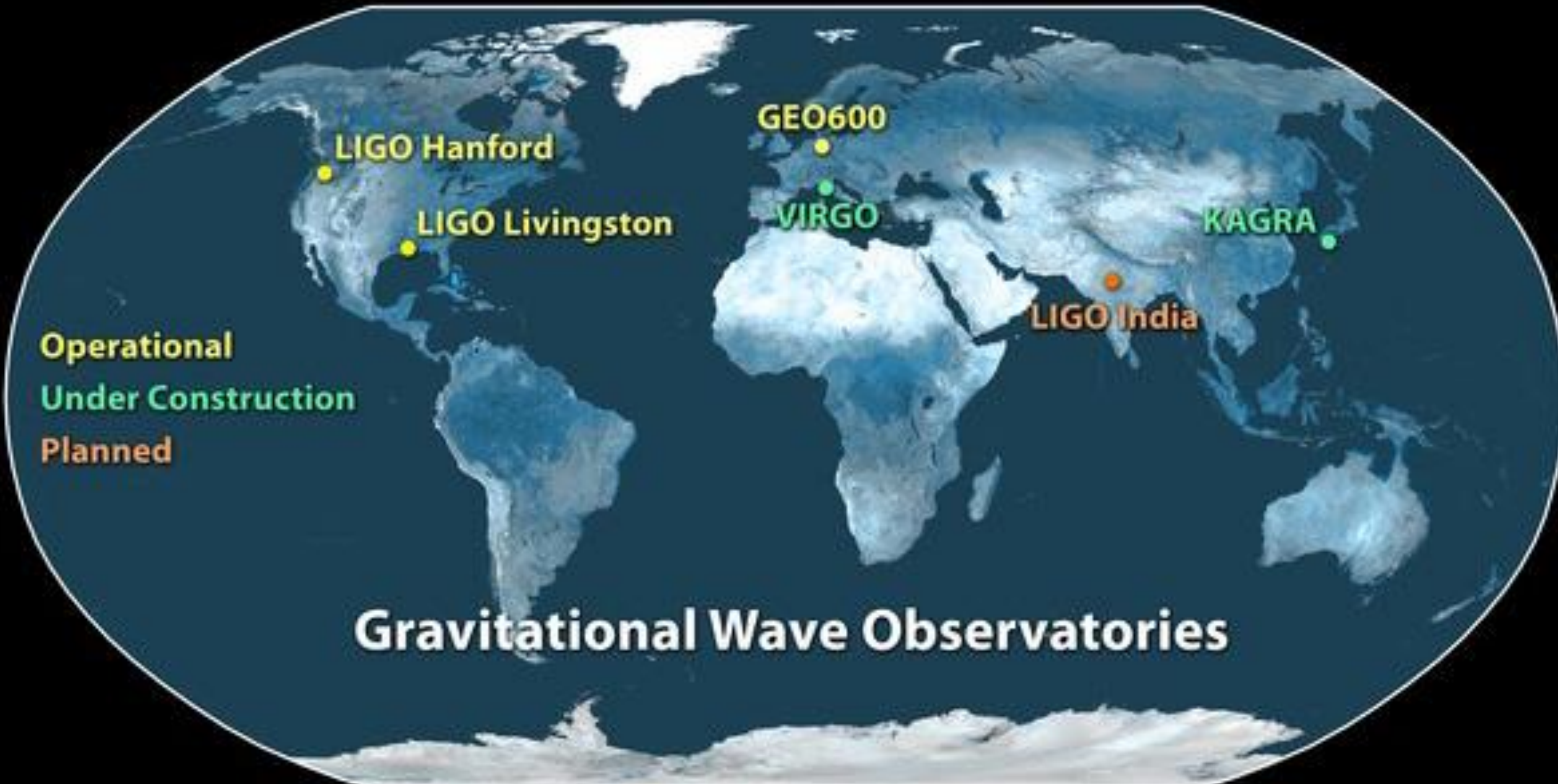
How to detect gravitational waves: ripples in space time?

Gravitational wave detectors



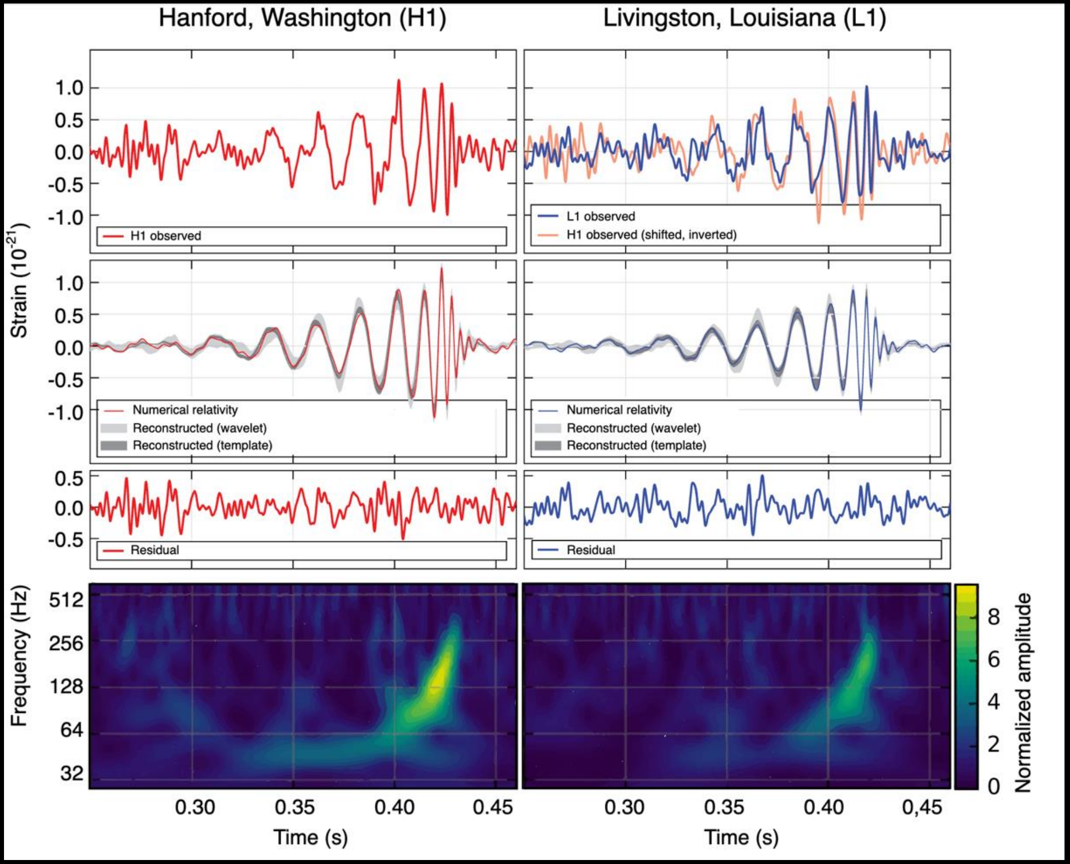
Gravitational waves: distort space by 10^-19 m (smaller than proton)


End Mirror
4 kilometer Arm
Input Mirror
Beam Splitter
Input Mirror
4 kilometer Arm
End Mirror
Power Recycling
Signal Recycling
Laser Input
Photodetector


LIGO Hanford
LIGO Livingston
GEO600
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

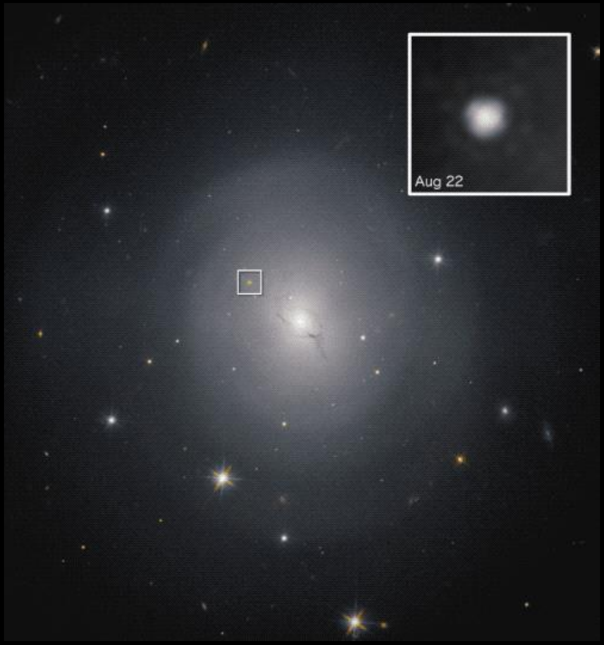
First direct gravitational wave detection

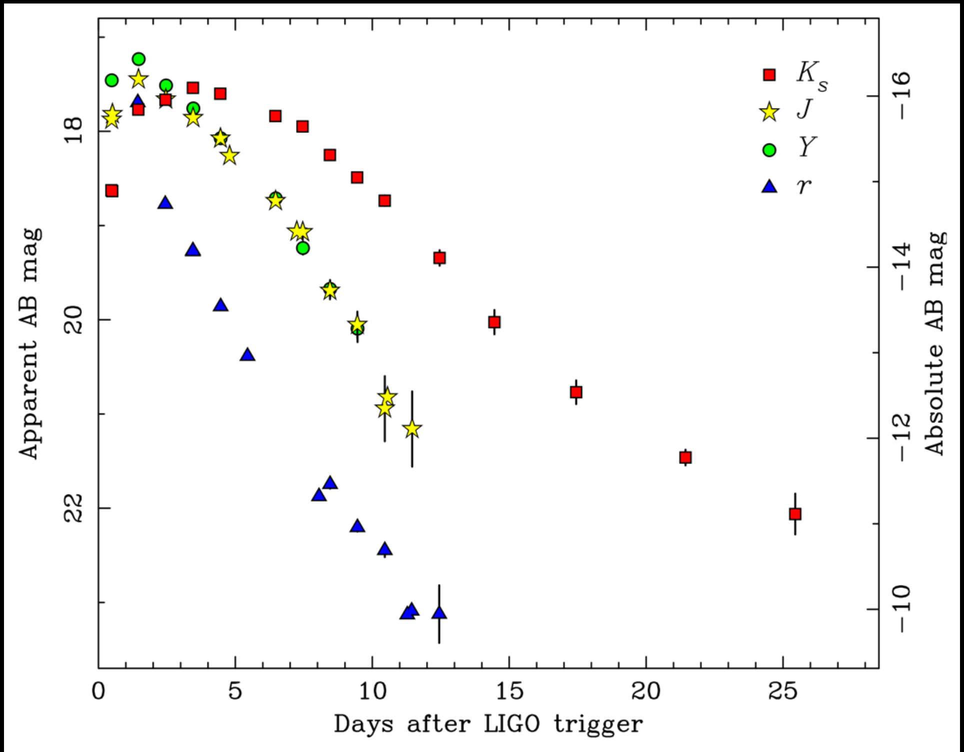
- LIGO in 2015
- Merger of two 30 solar mass black holes
  - Surprising: did not know that black holes of that mass existed
  - Stellar remnant: failed supernova?



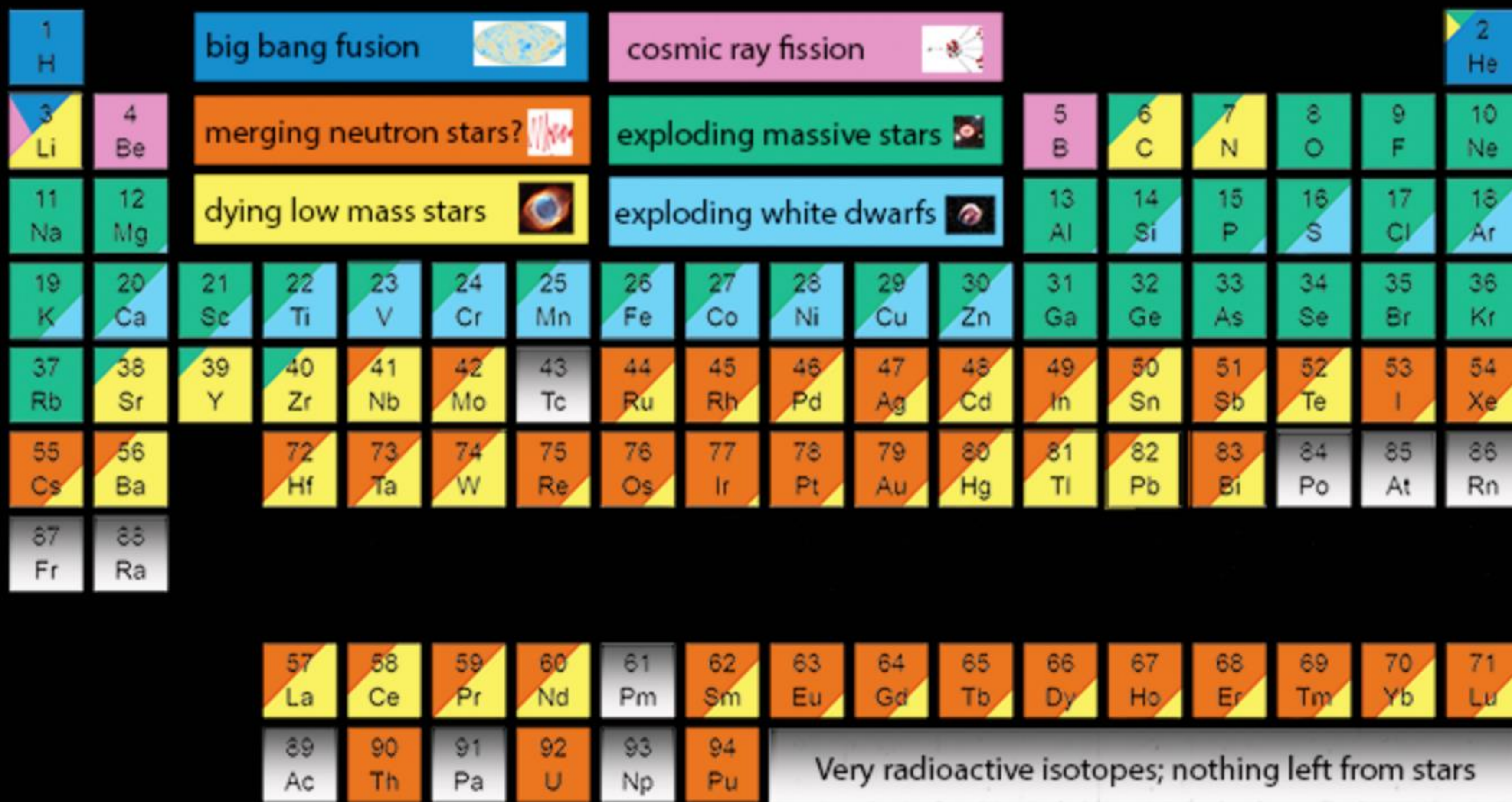
Gravitational wave detection

- About 90 events to date!
- Neutron star-neutron star merger:
  - optical and gamma ray counterparts help to understand the explosion, production of heavy elements





The Origin of the Solar System Elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
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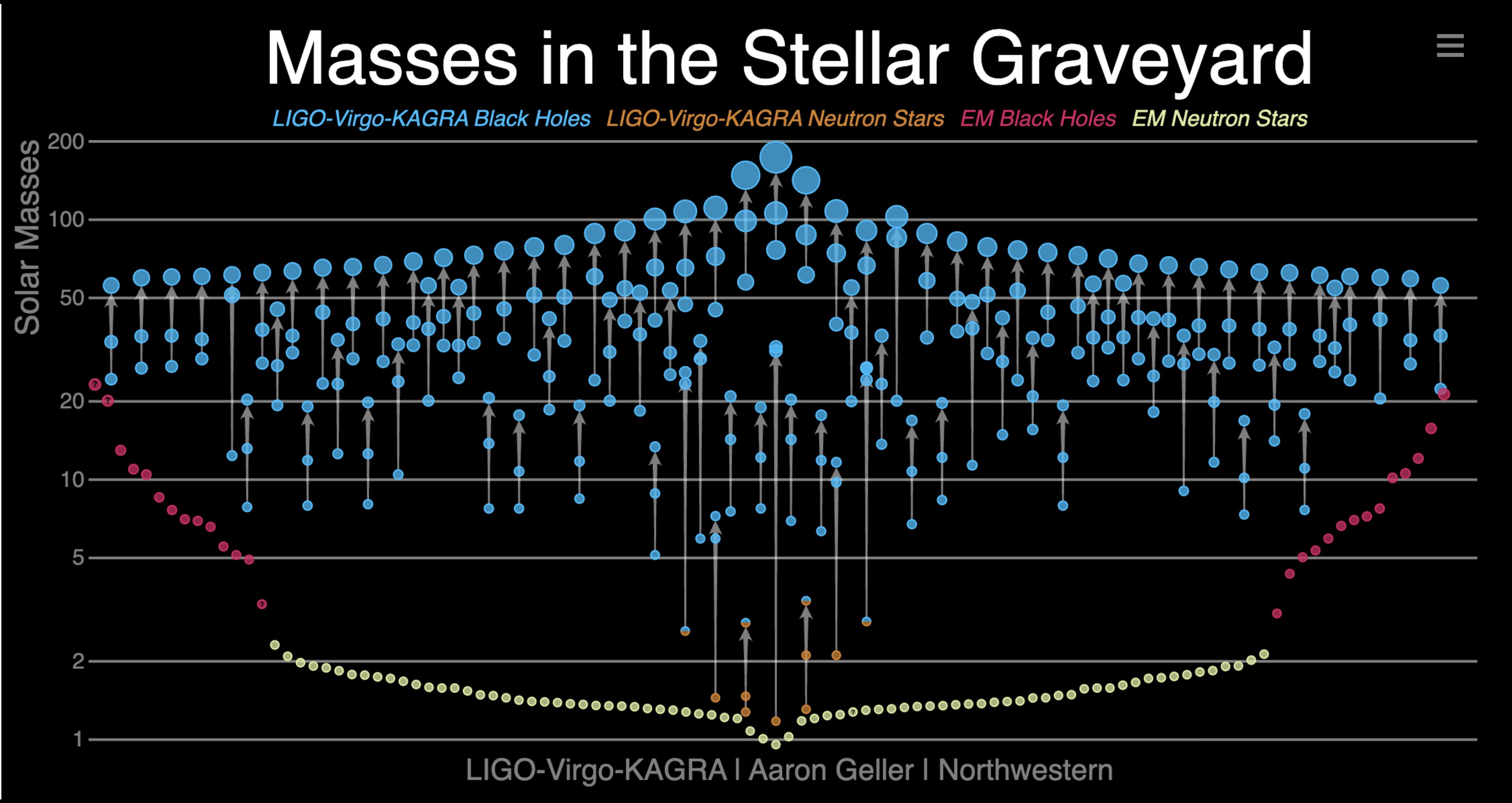
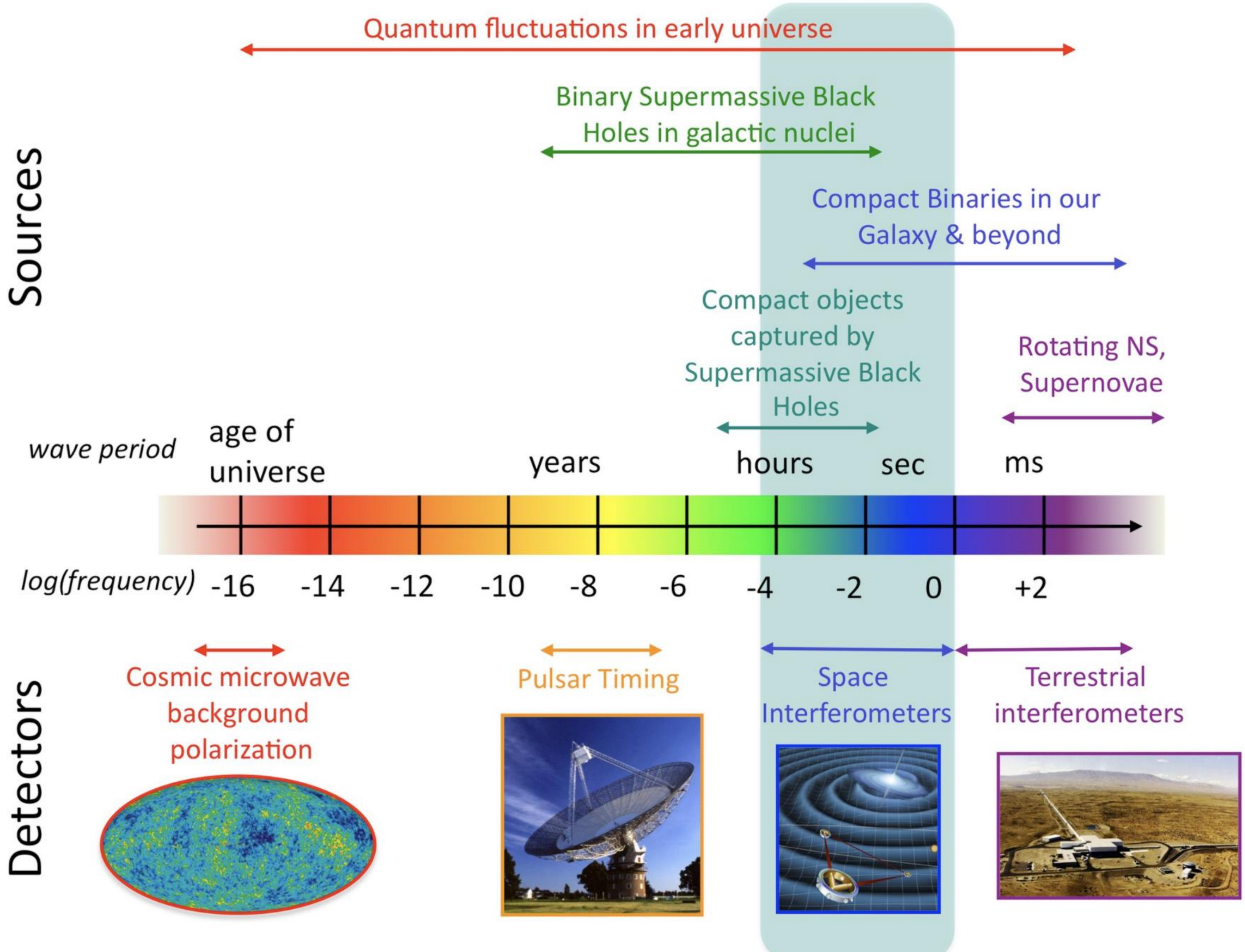


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

The Gravitational Wave Spectrum

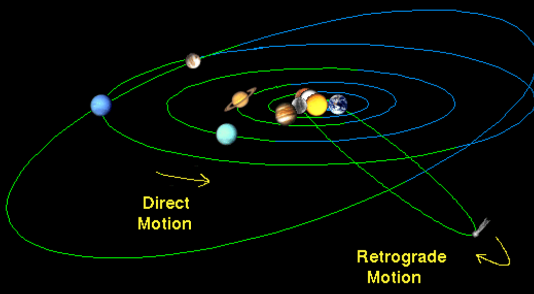


Primordial black holes

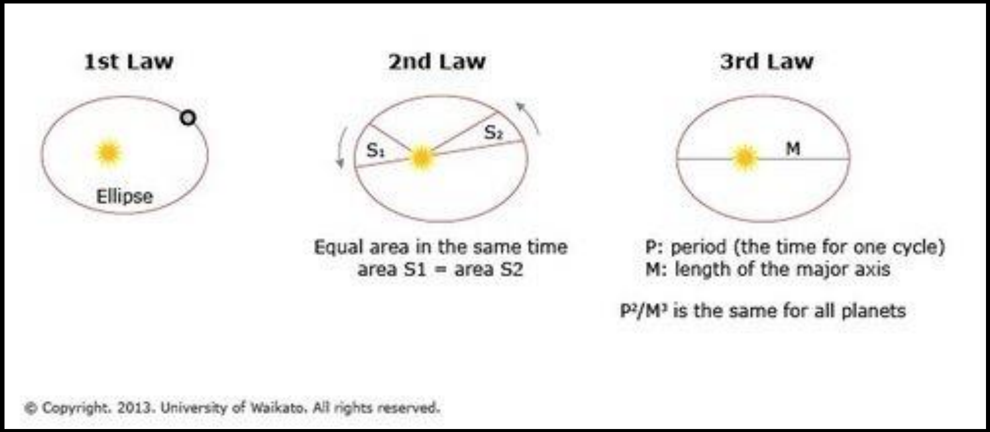
- Quantum fluctuations soon after big bang
- Initial mass as low as 1e-8 kg
- Anything below 1e11 kg would have evaporated away
  - Hawking radiation: black holes evaporate
  - Relativistic+quantum effects: radiation released outside black hole
- Any measurements will help constrain cosmology

History of gravitational theories

- Copernicus: Earth orbits the sun



- Kepler's laws
  - 1^{st} law: planetary orbits are ellipses
  - 2^{nd} law: orbit sweeps out equal areas from sun in equal time
  - 3^{rd} law: P^2 = a^3 (period^2 = orbital distance^3)



- Newton: connected planetary motion to gravity on Earth

$$F = G\frac{m_1 m_2}{r^2}$$

Special Relativity

- Laws of physics are invariant in all inertial frames of reference

- Speed of light in a vacuum is the same for all observers

Time Dilation and length contraction

- To an observer at rest, the time of something moving quickly will appear much longer than in the faster reference frame

$$\Delta t' = \frac{\Delta t}{\sqrt{1 - \frac{v^2}{c^2}}}$$

- An object would be measured to be shorter in the inertial frame

$$L = L_0\sqrt{1 - v^2/c^2}$$

- As an object's speed approaches the speed of light, the relativistic mass increases towards infinity

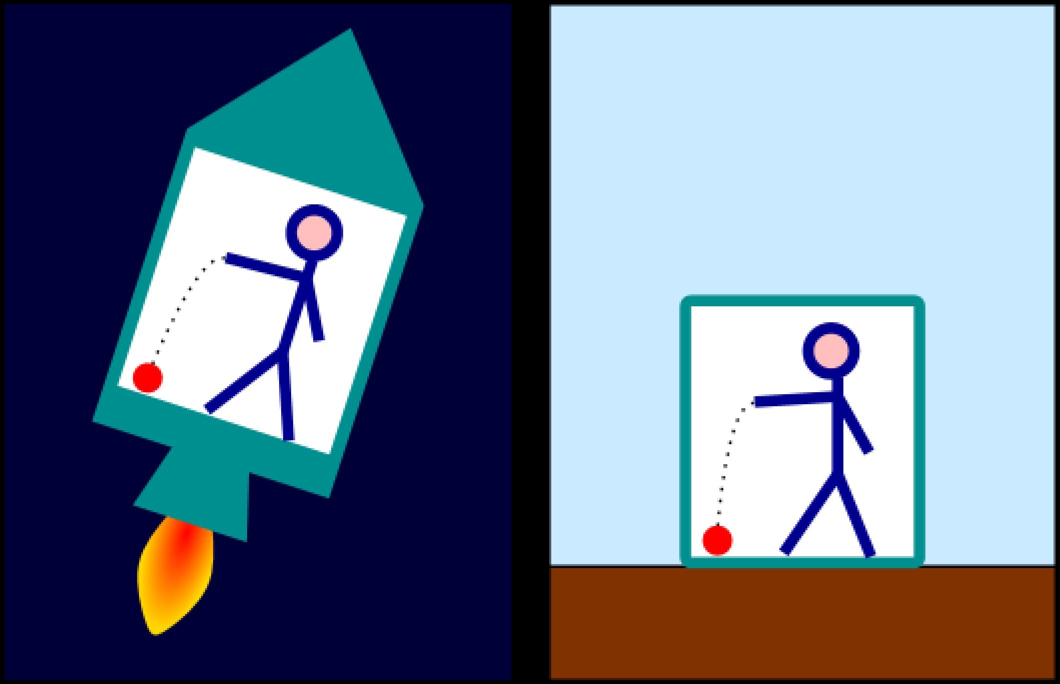
$$m_{\text{rel}} = \frac{m}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Implications of special relativity

- Information cannot travel faster than the speed of light
  - It would take infinite energy to accelerate any mass to the speed of light
- Mass-energy equivalence ($E=mc^2$)
- No absolute reference frame
  - Previous idea: aether in space is absolute state of rest

General relativity: geometric theory of gravity

- Curvature of spacetime is directly related to energy and momentum
- Specified by Einstein field equations



Elevator thought experiment:

No way to tell whether the ball is

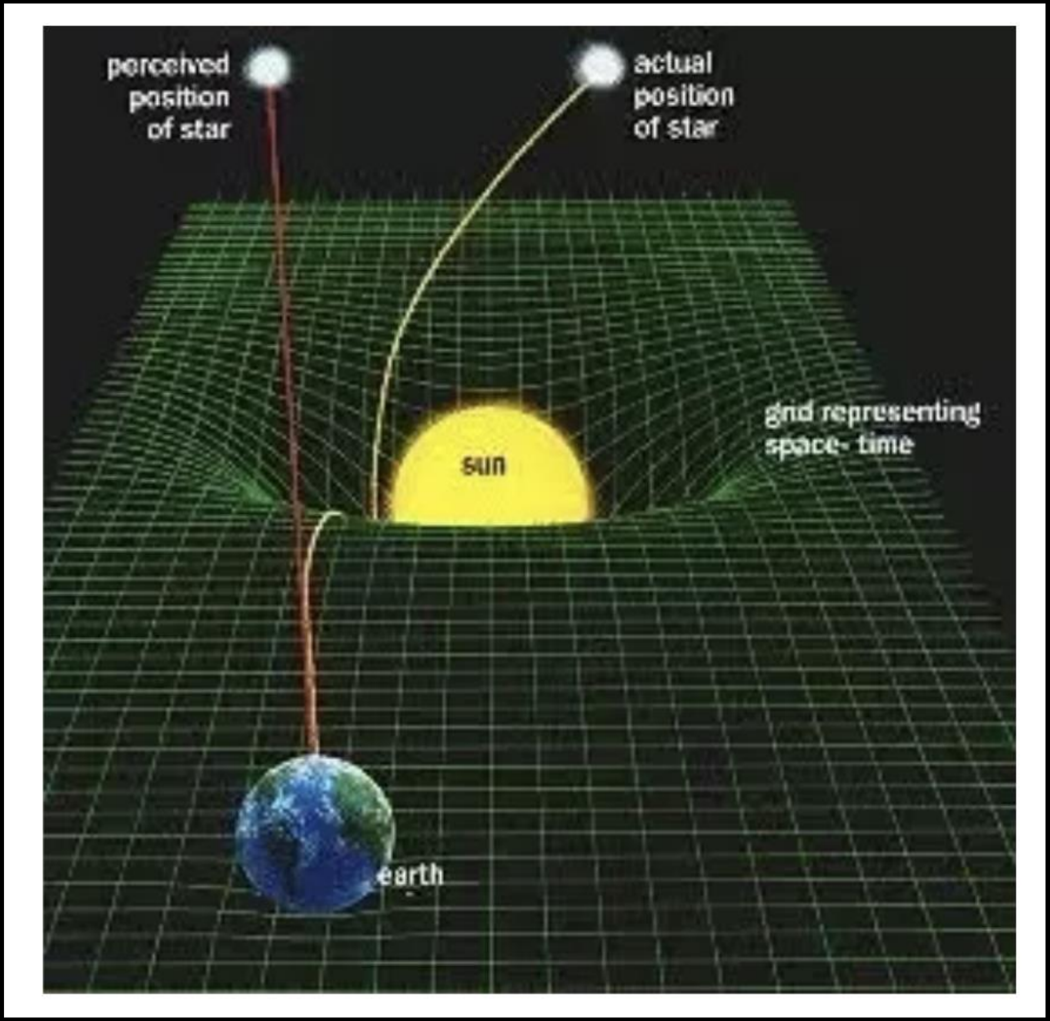
(a) falling to a gravitational well

(b) Falling because the elevator is accelerating

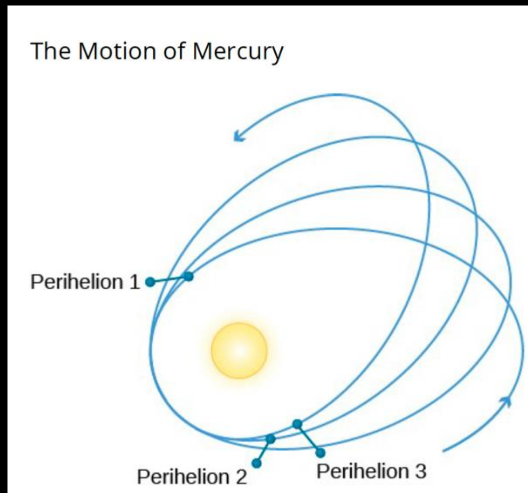
Implications of general relativity

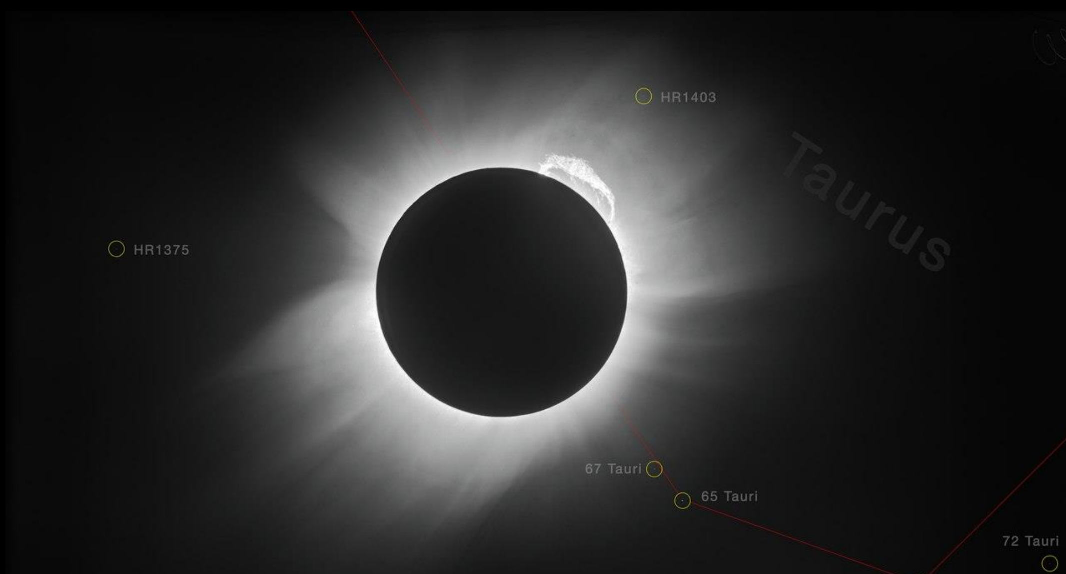
- Gravitational lensing
- Gravitational waves
- Black holes
- Everything!

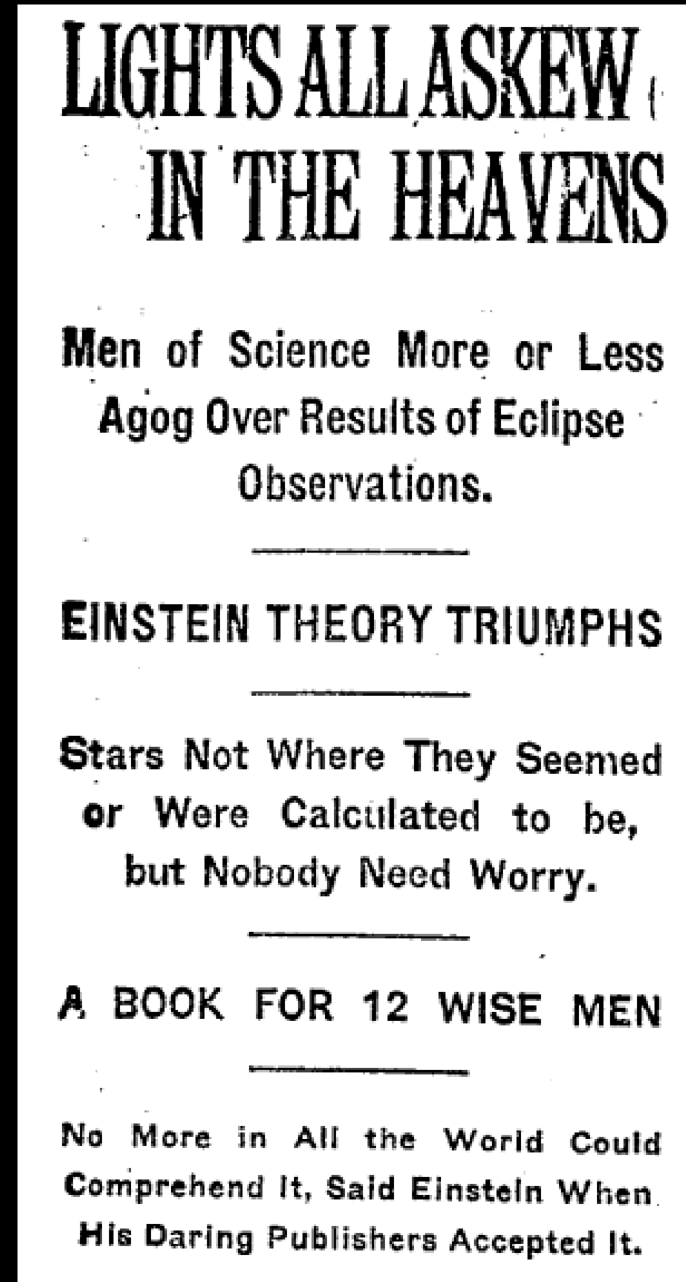
- Newton's laws are limiting (non-relativistic) case of general relativity



Test of General Relativity







LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

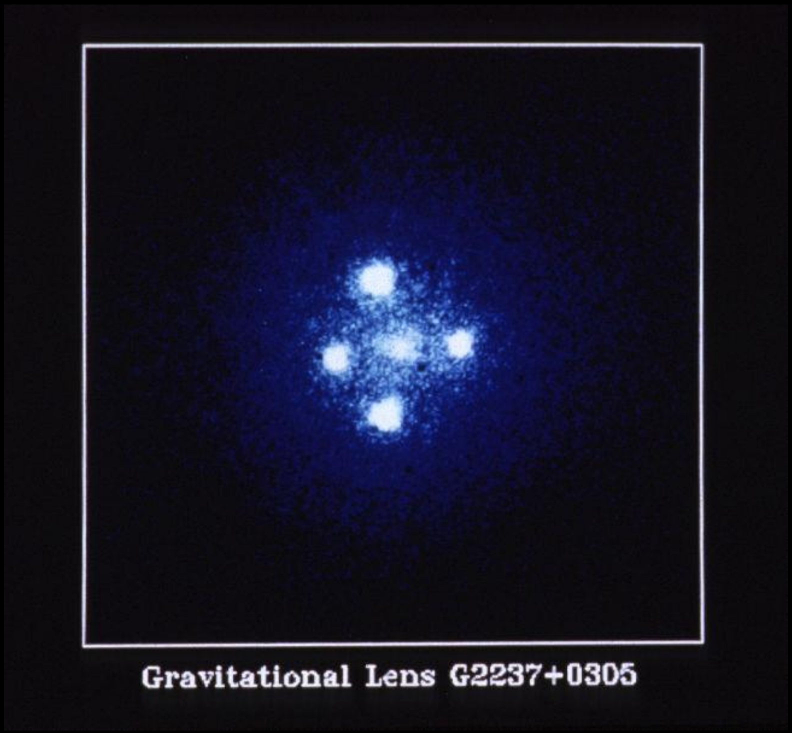
EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

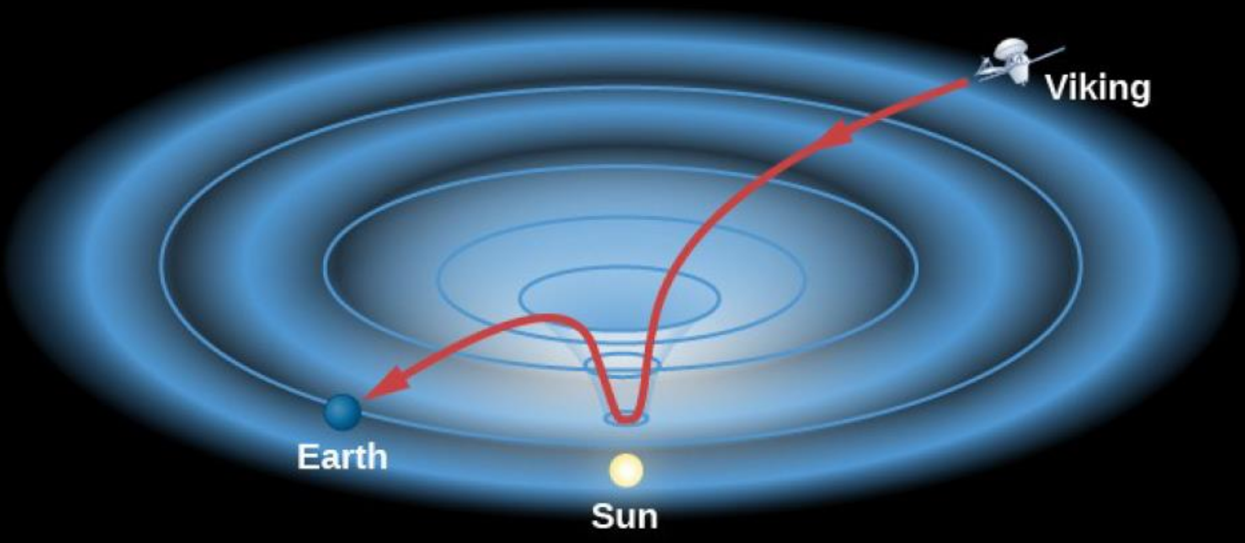
Test in 1919 eclipse: precise measurement of Mercury's position



Tests of general relativity

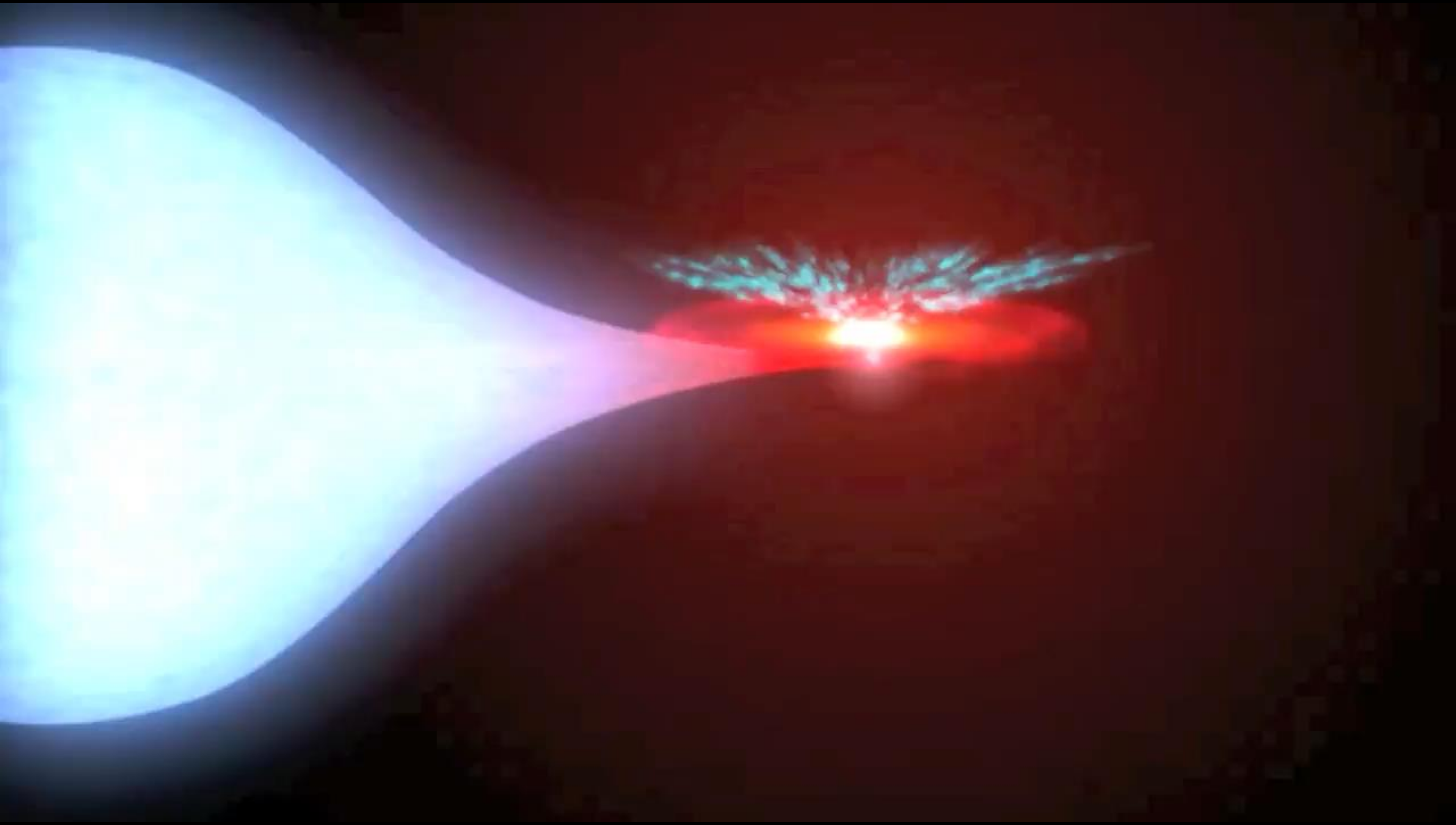
Gravitational lens

Bending of signal from Viking Mission



ScienceClic

Alessandro Roussel



Gravity and black holes

- General relativity governs our universe
  - Every experiment has confirmed general relativity
- Gravity: best tested in extreme environments: black holes
- Black holes are common
  - Stellar mass black holes: stellar remnants
  - Centers of galaxies (primordial? Early formation from massive stars?)
  - Primordial black holes

Next week: our solar system!