Introduction to Cosmology

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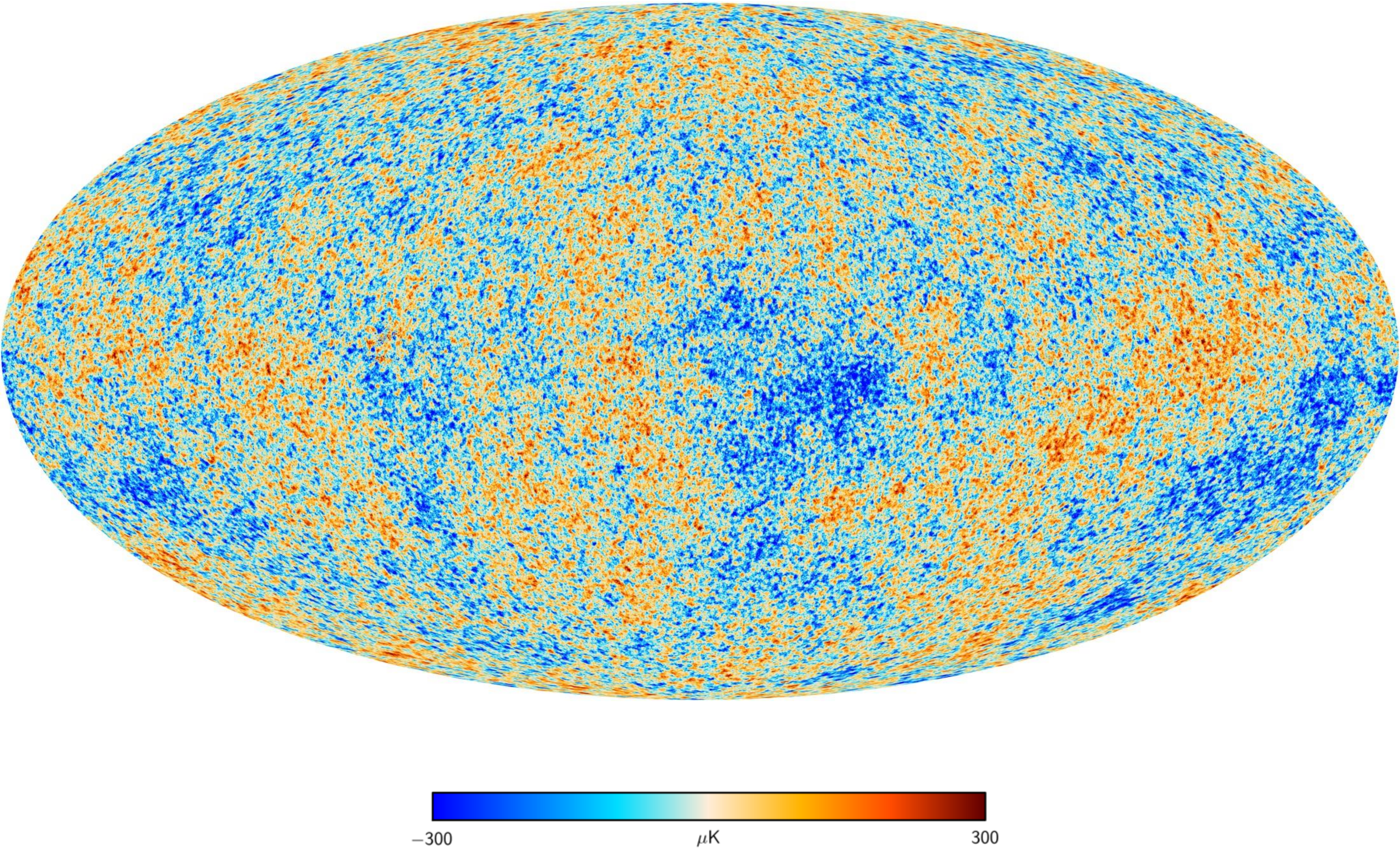
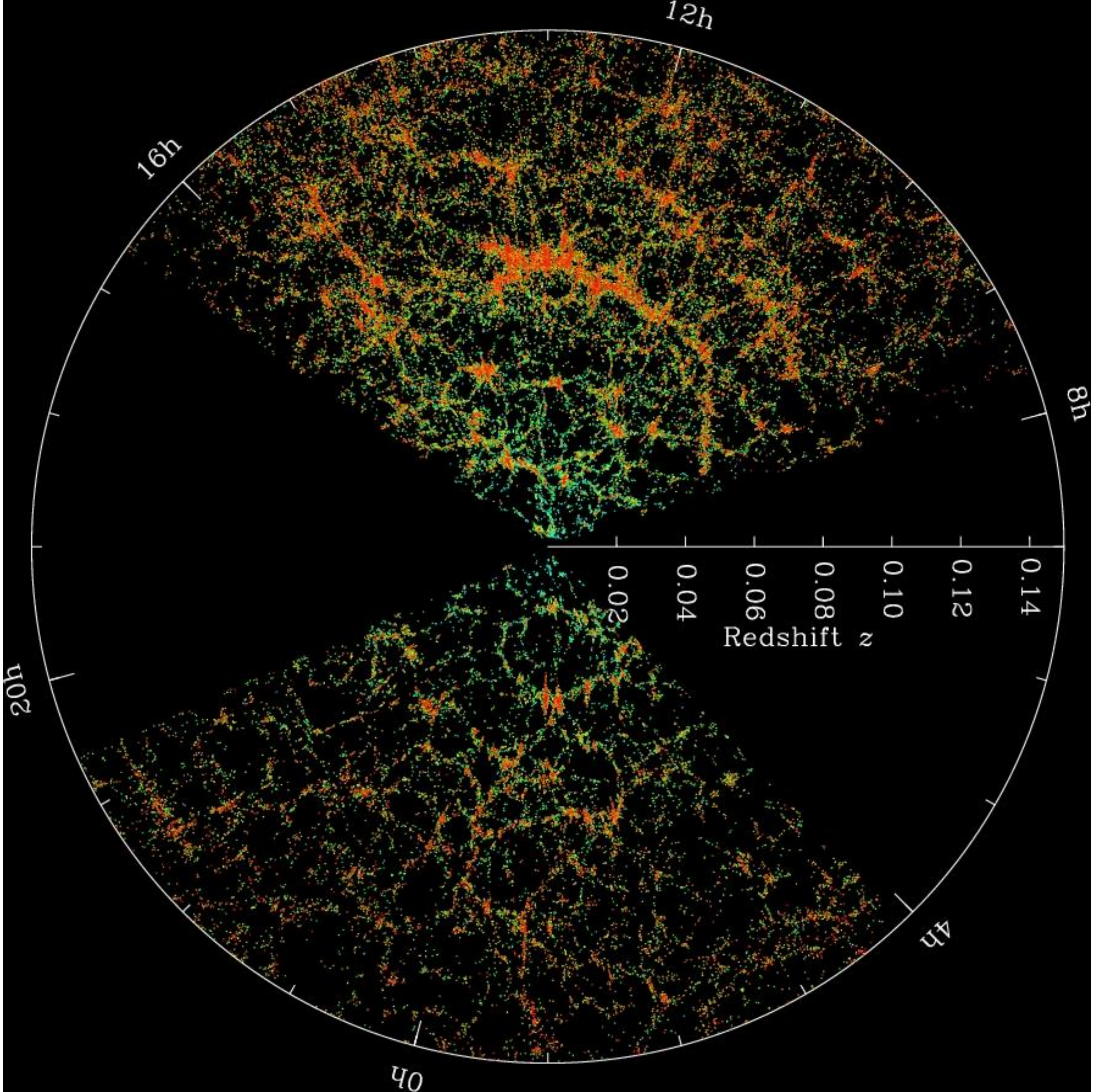
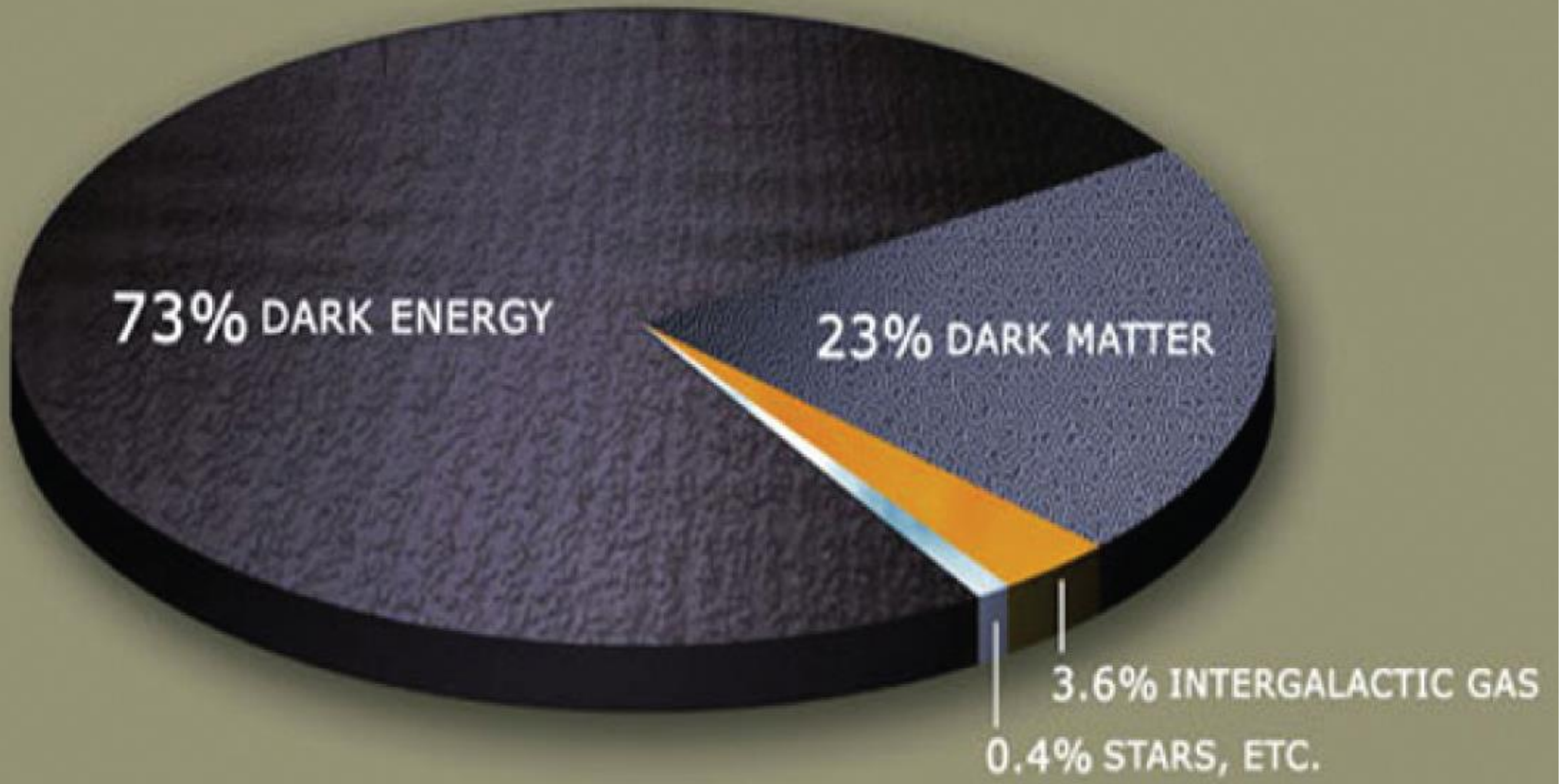
University of Warsaw

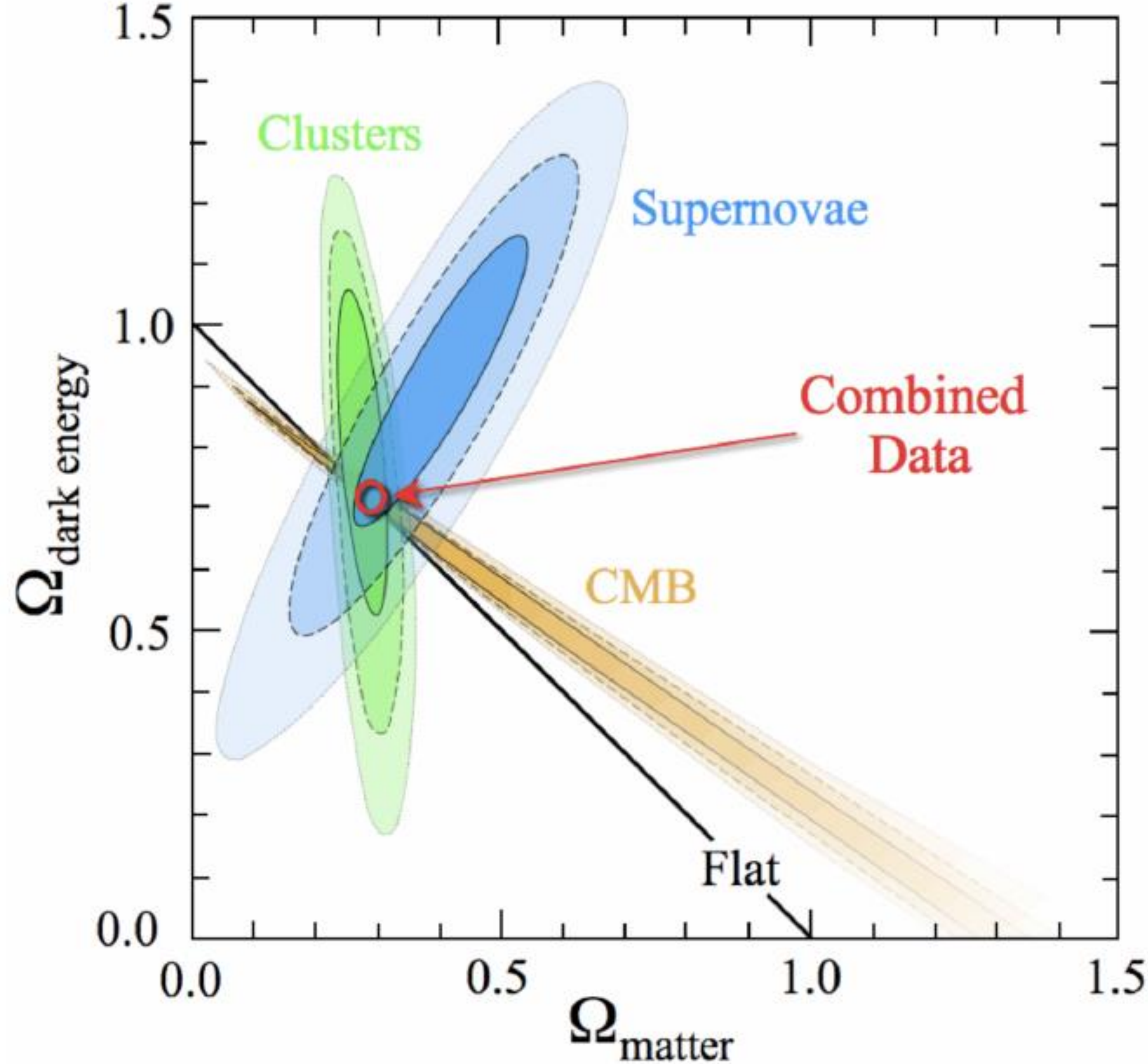


−300
μK
300

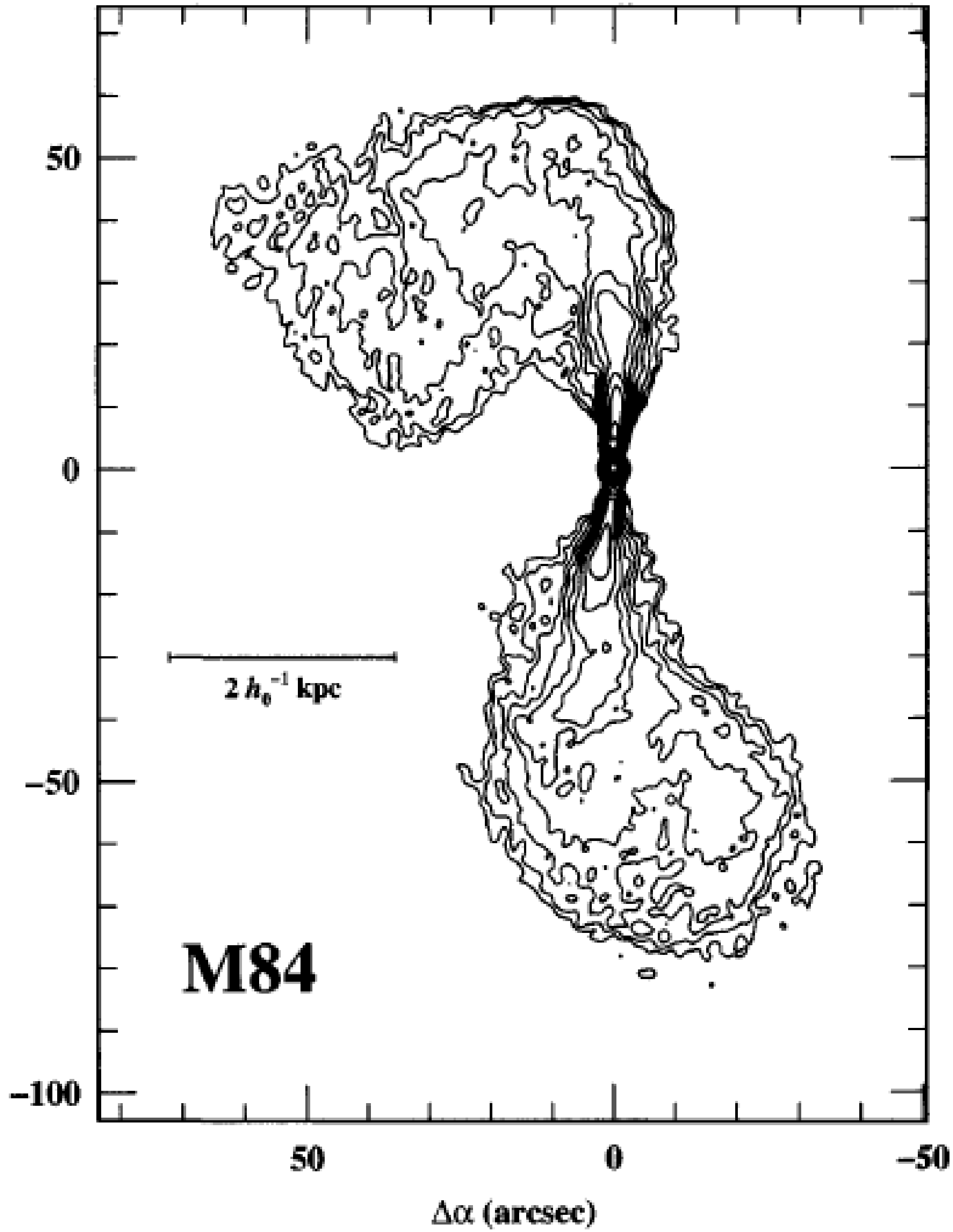

12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z



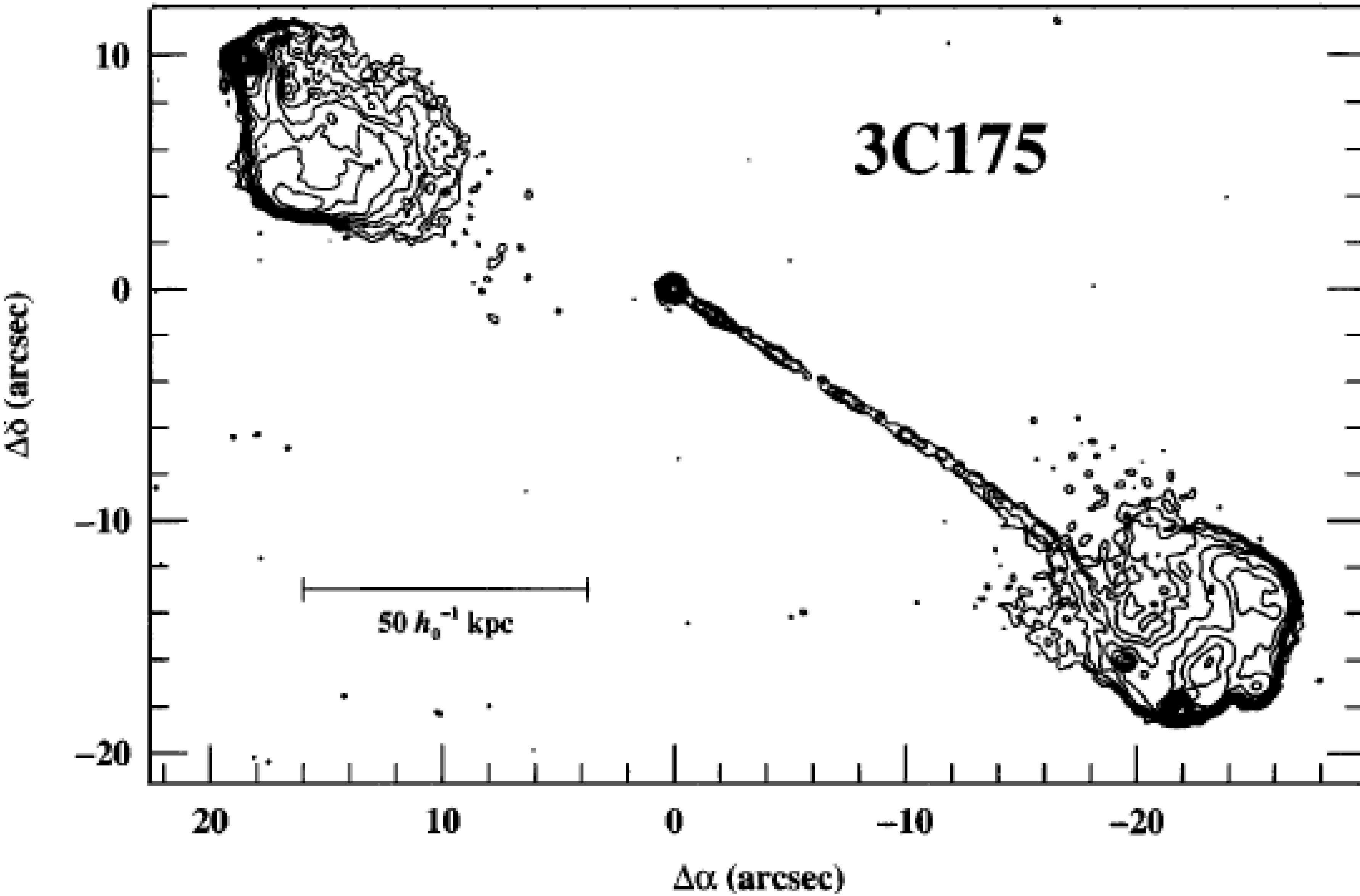
73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.



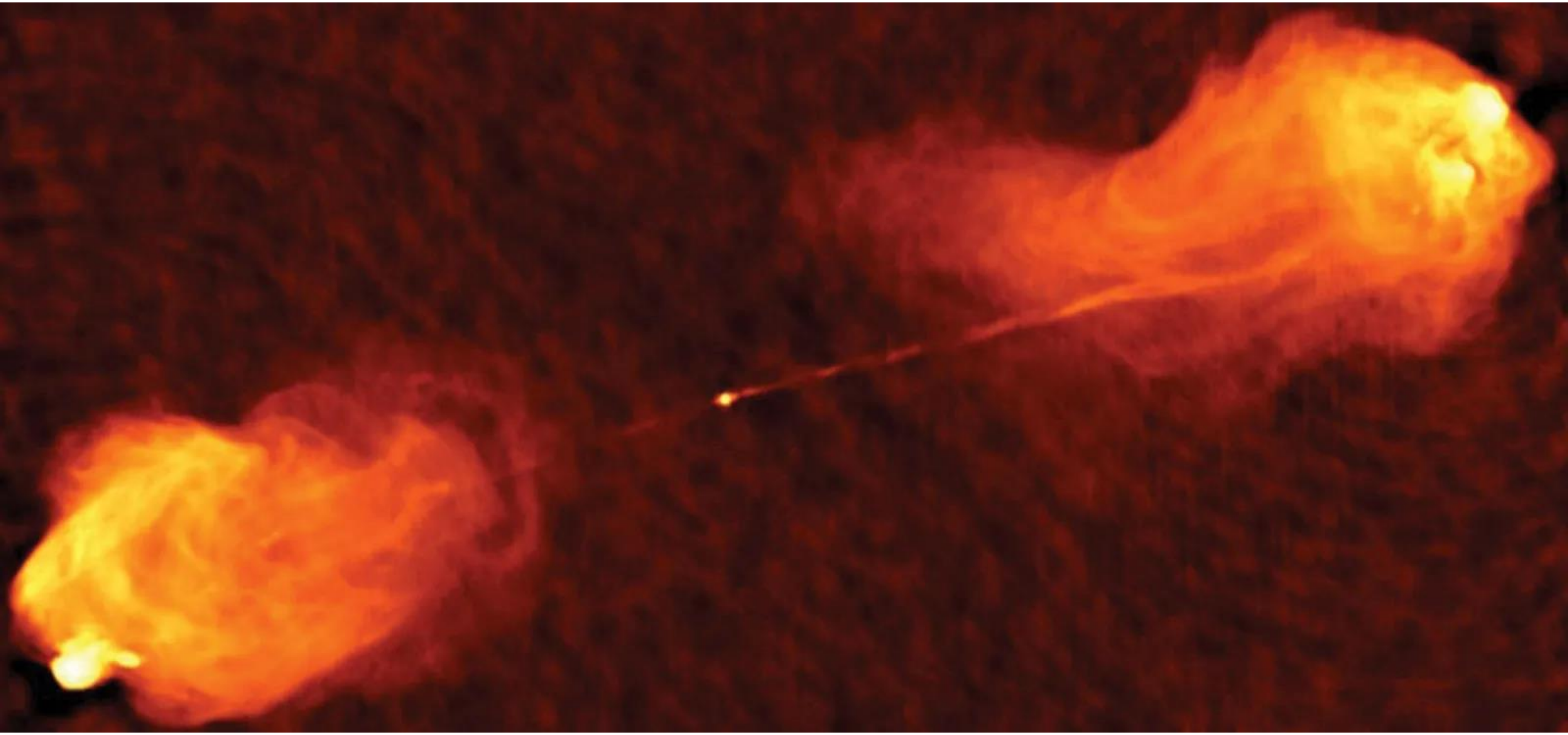
1.5
1.0
0.5
0.0
Clusters
Supernovae
Combined
Data
CMB
Flat
0.0
0.5
1.0
1.5
$\Omega_{dark\ energy}$
Ω_{matter}

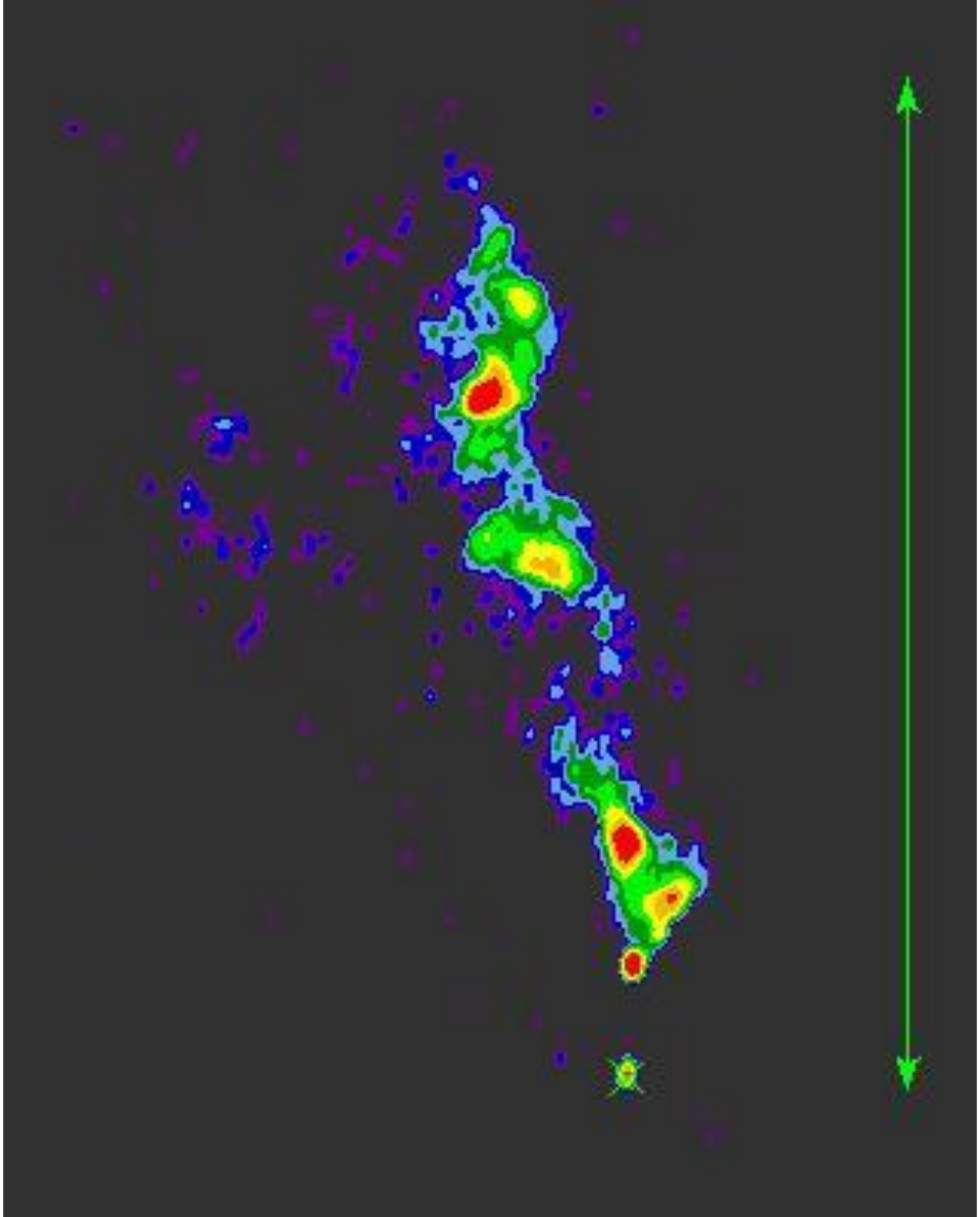


50
0
−50
−100
Δδ (arcsec)
2 h_0^{-1} kpc
M84
50
0
−50
Δα (arcsec)

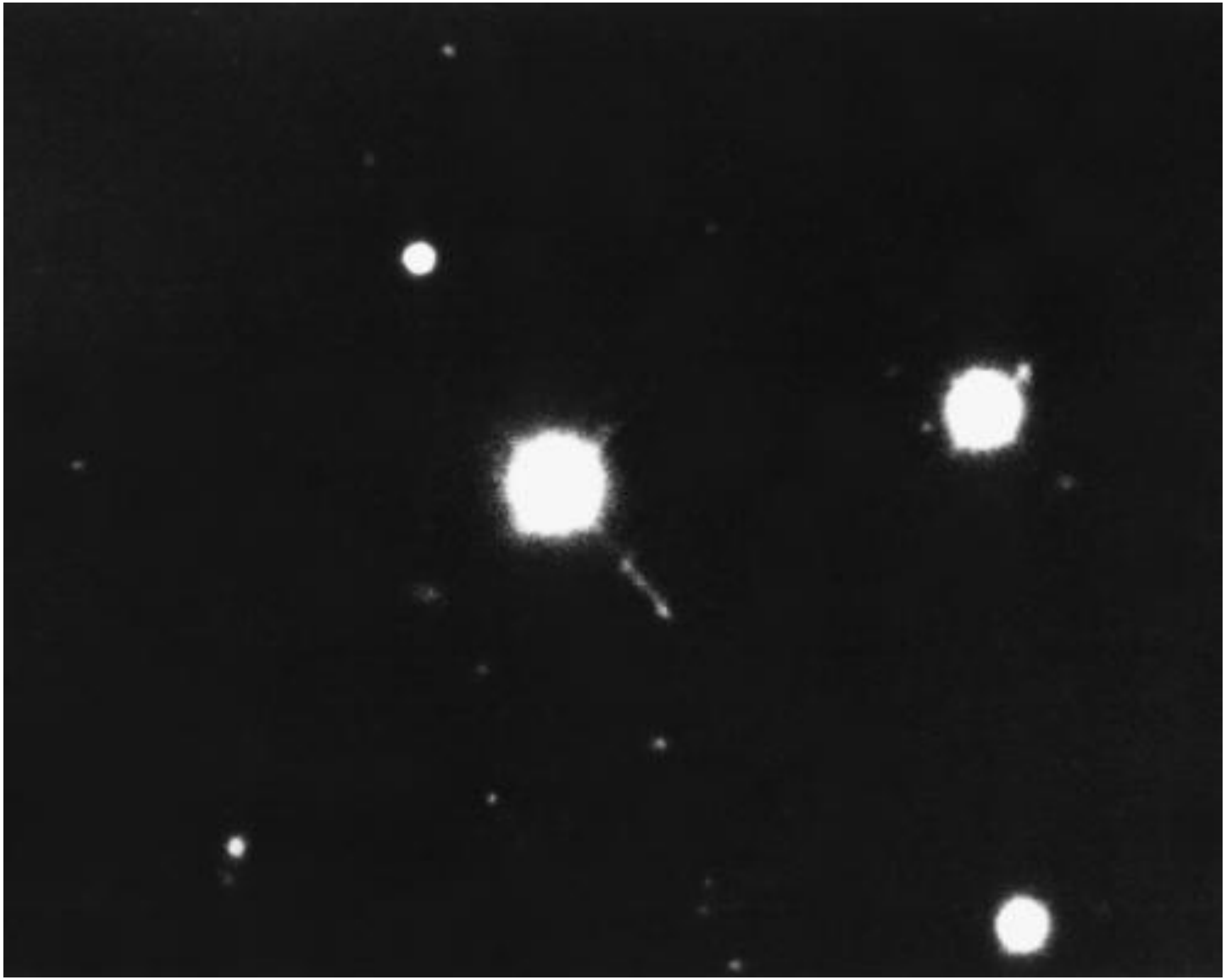


3C175
50 h_0^{-1} kpc
Δδ (arcsec)
Δα (arcsec)
10
0
−10
−20
20
10
0
−10
−20



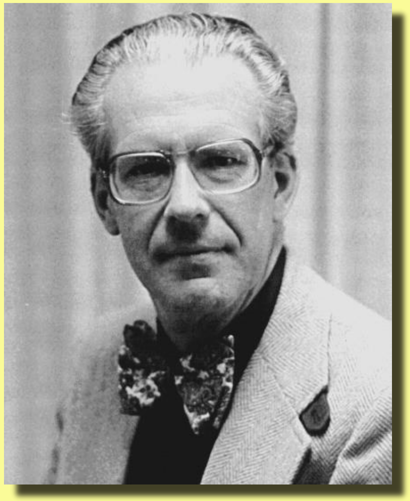


3C 48
radio

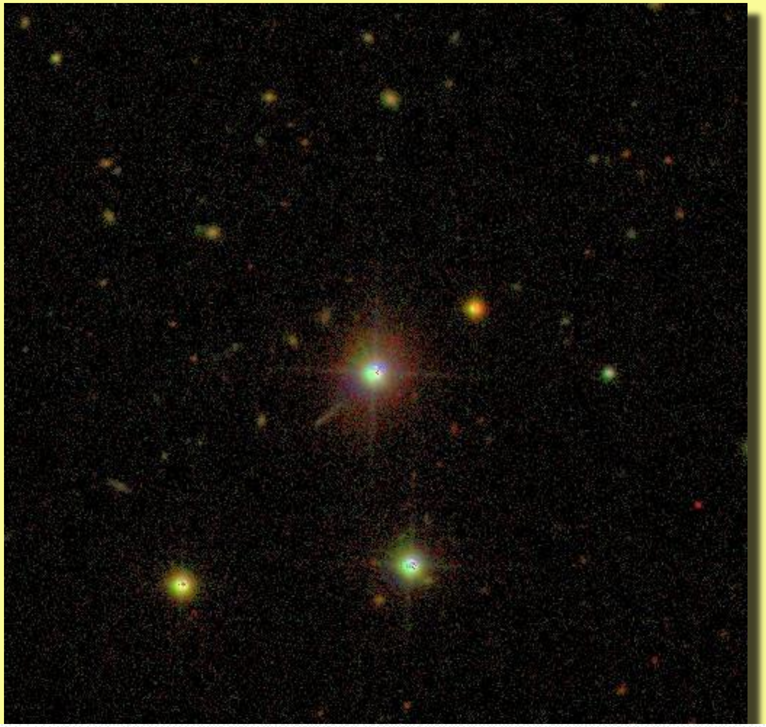


3C 273 Optical

Mysterious quasars

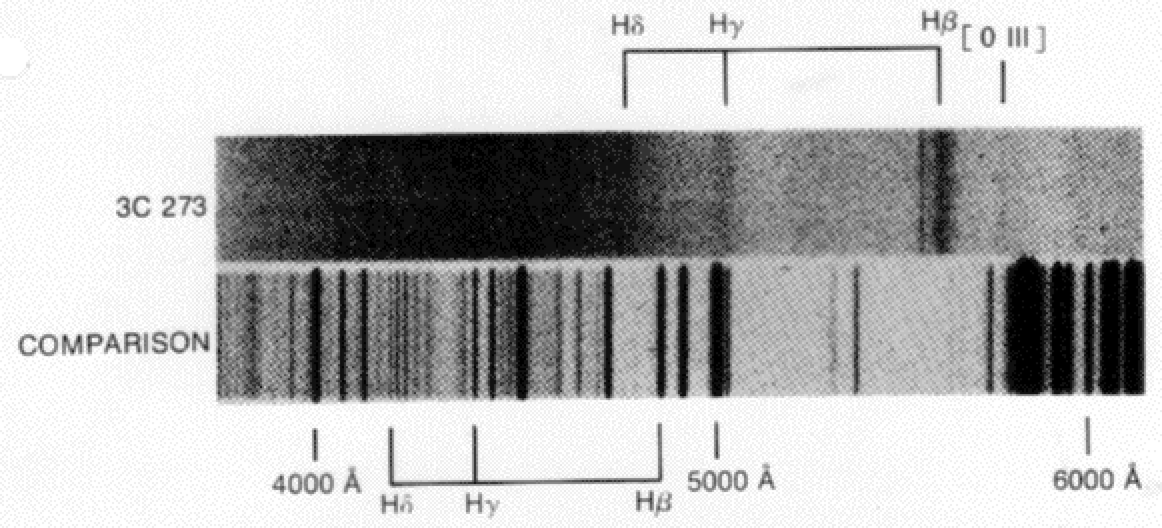


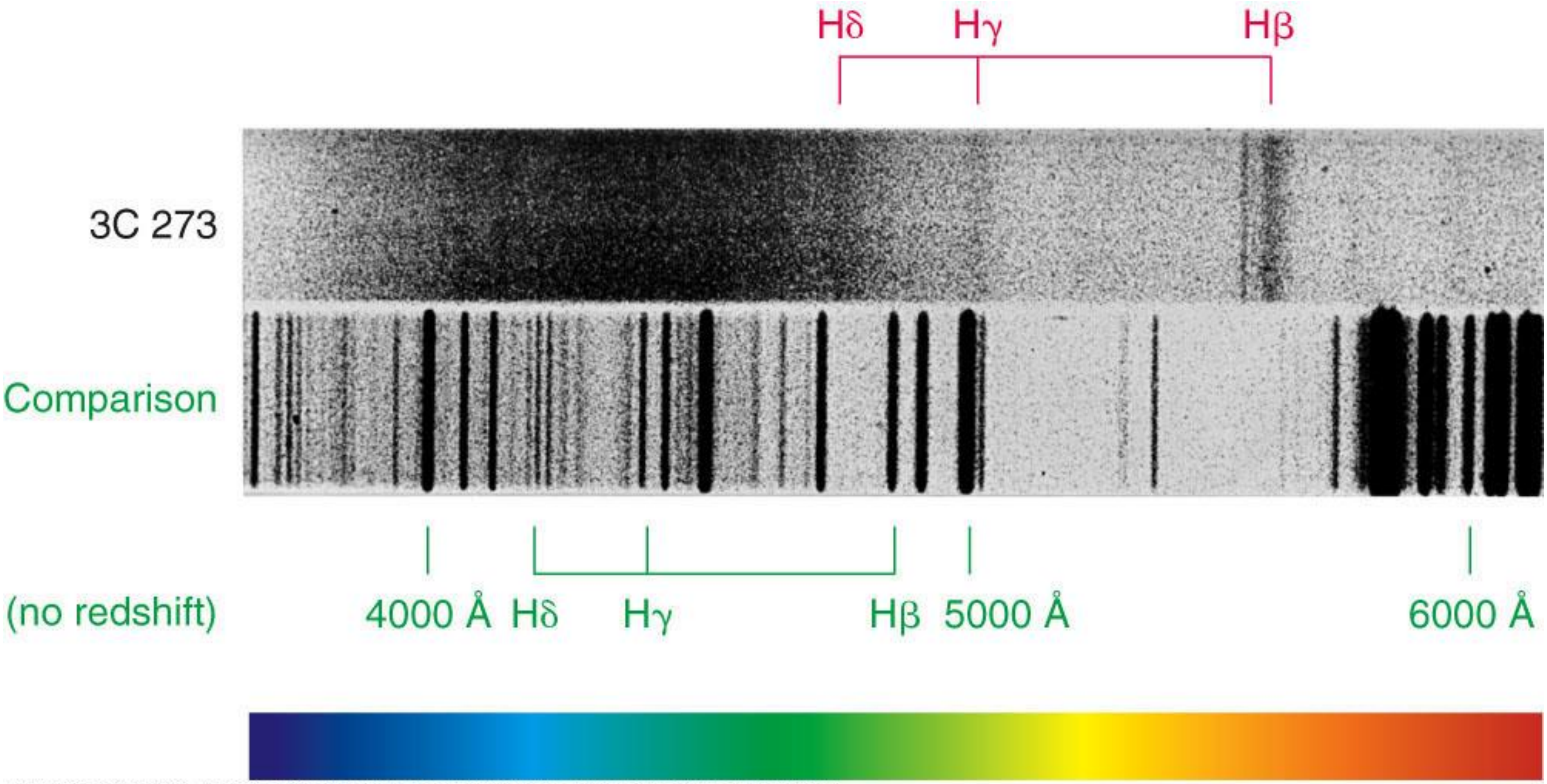
Marteen Schmidt



”3C 273: a starlike object with a large redshift”

Nature **197**, 1040 (1963)





(b: A. Filippenko and R. J. Foley, UC Berkeley) Maarten Schmidt/Palomar Observatory/Caltech photograph

negative of spectra of 3C 273

Big surprise – starlike object

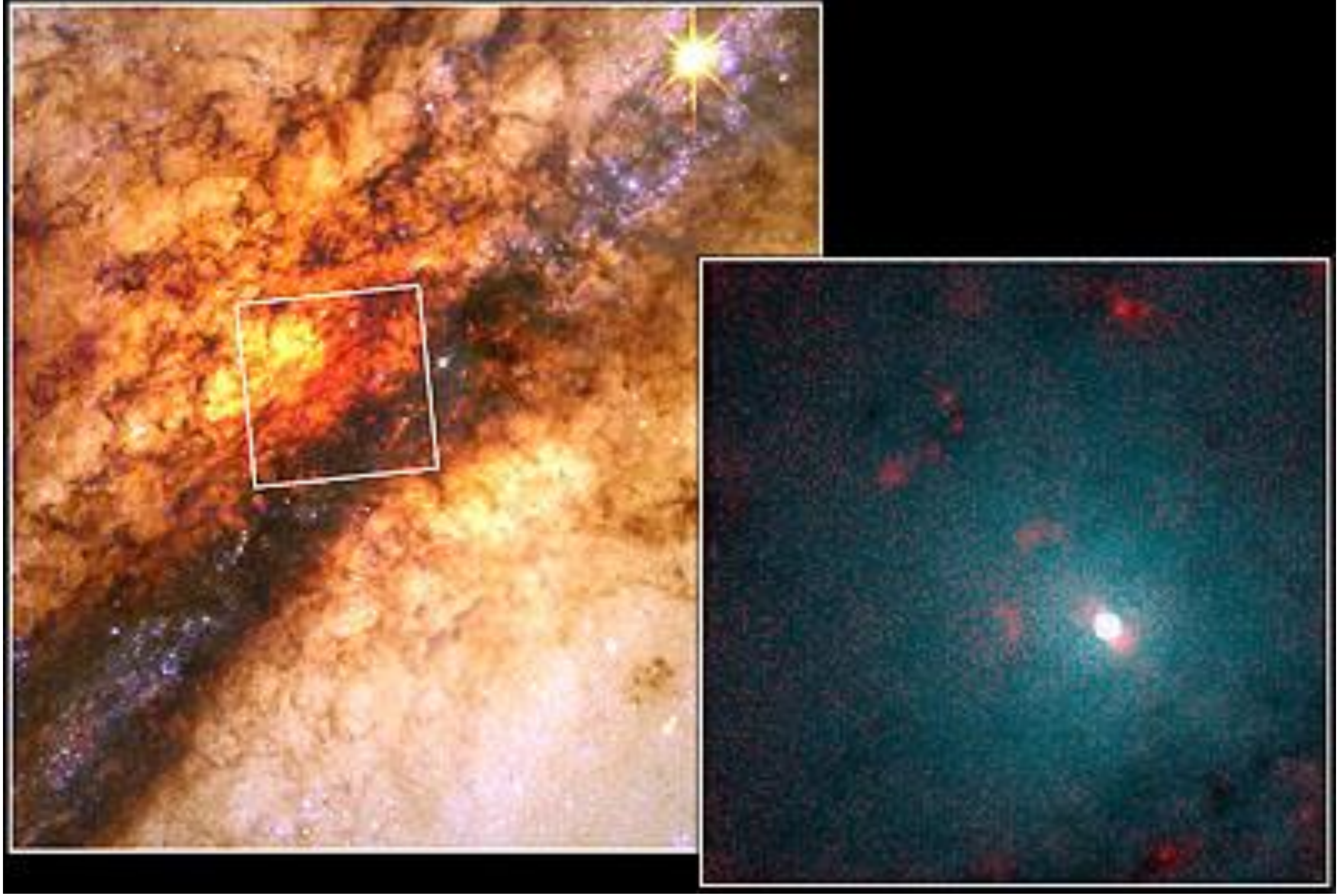
at z = 0.158 !!!

L ~ $10^{14} L_{\odot}$!!!

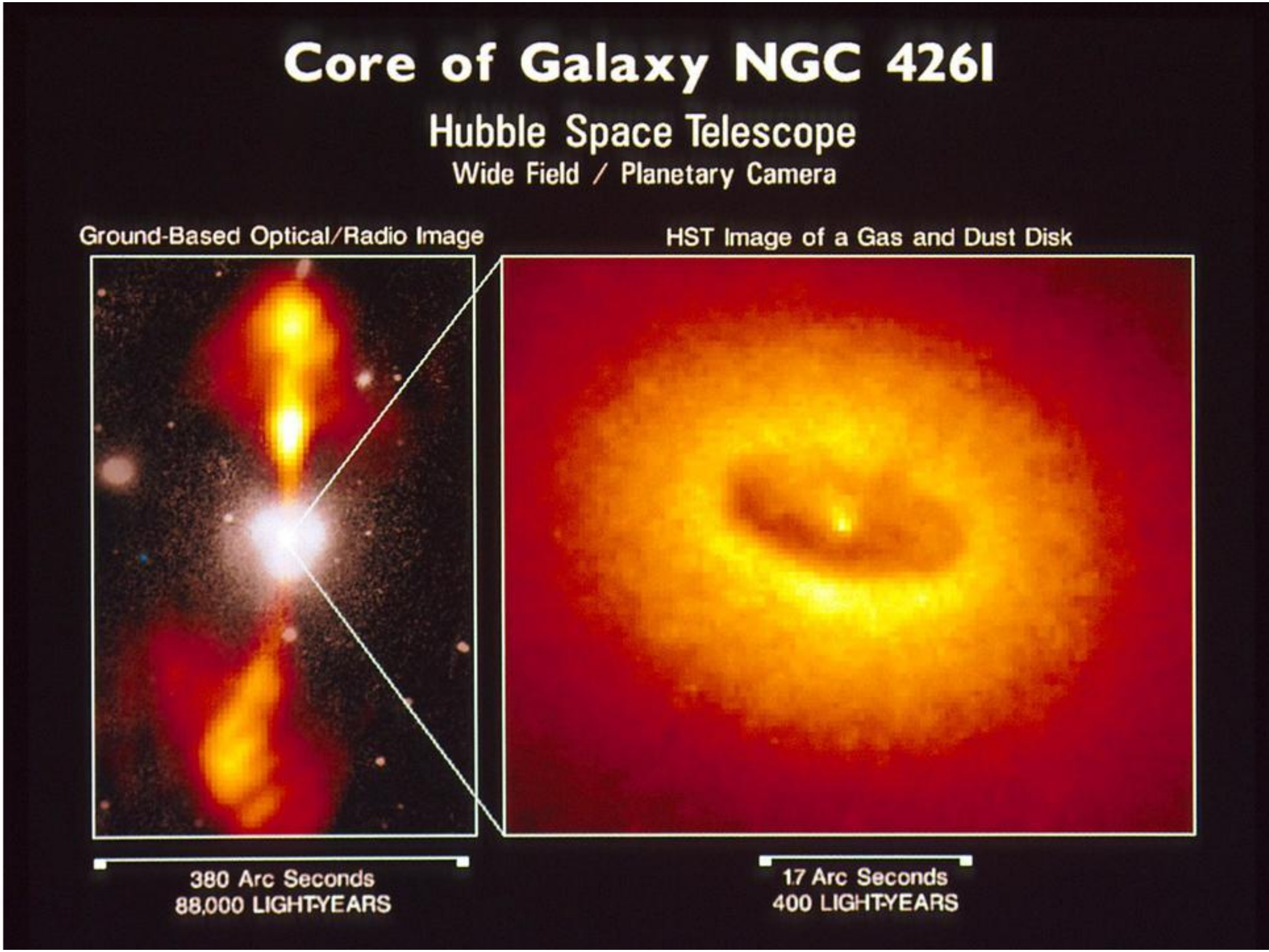
A

Centaurus A

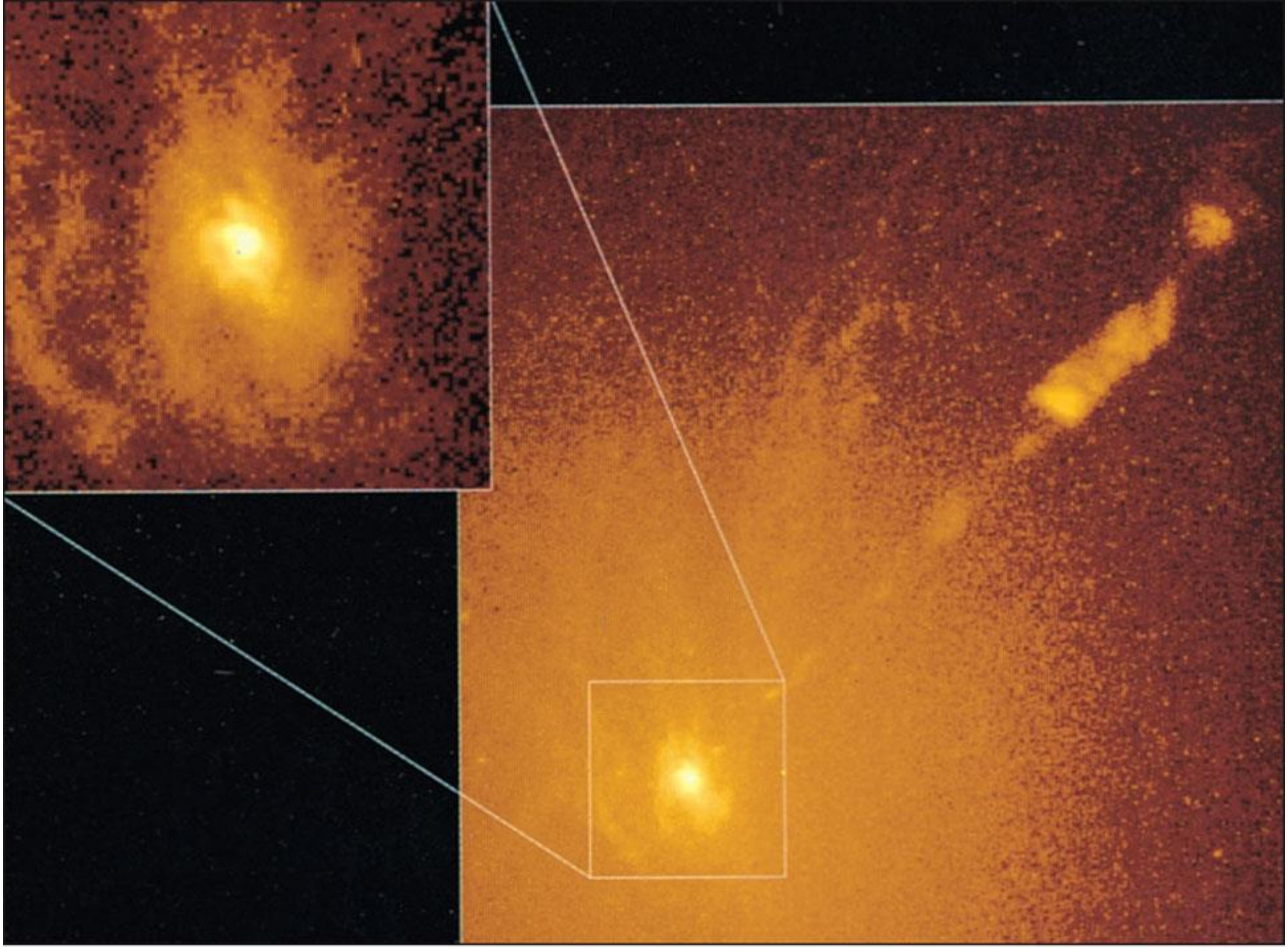
Centaurus A



Centaurus A HST + infrared

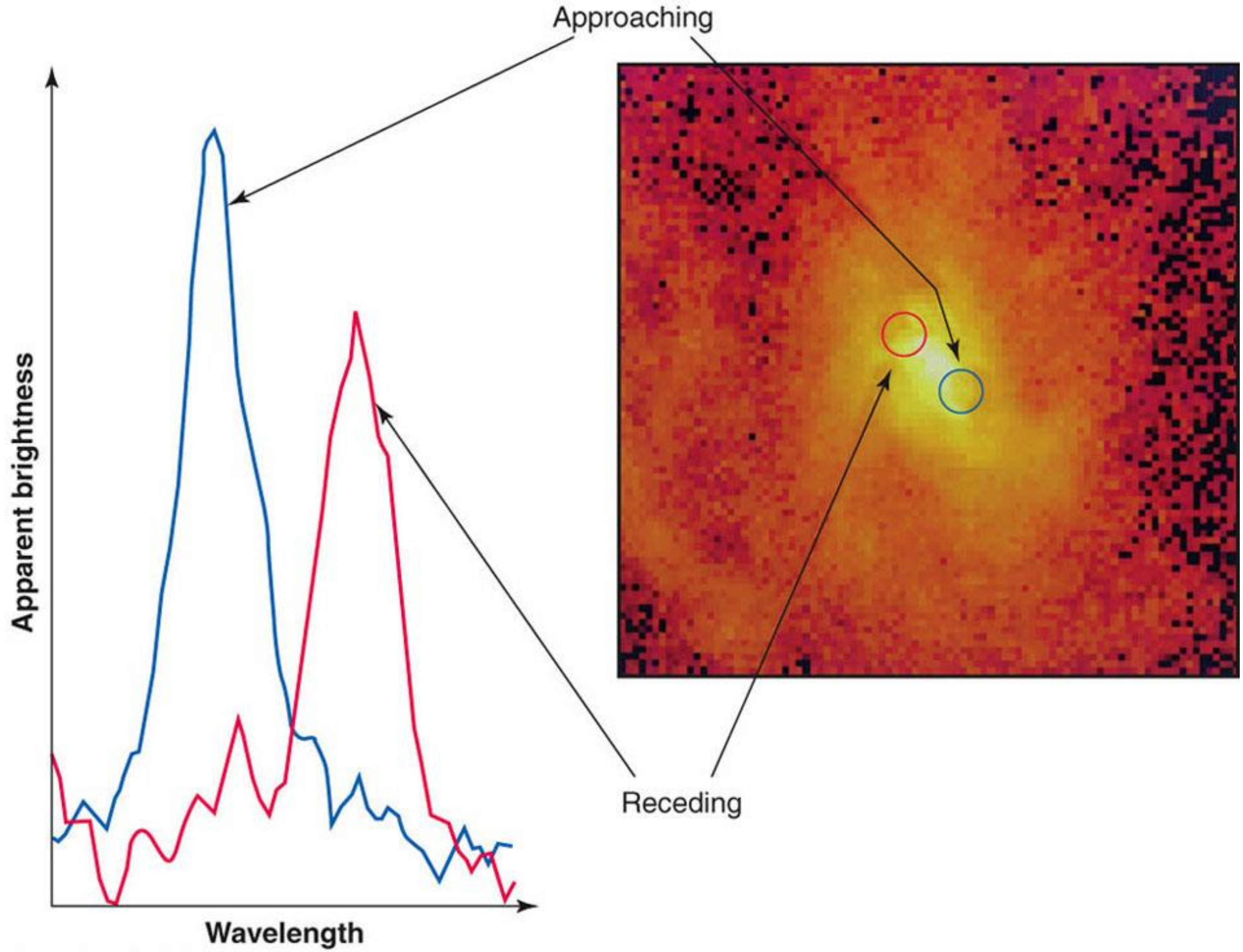

Core of Galaxy NGC 4261
Hubble Space Telescope
Wide Field / Planetary Camera
Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk
380 Arc Seconds
88,000 LIGHT-YEARS
17 Arc Seconds
400 LIGHT-YEARS

M87



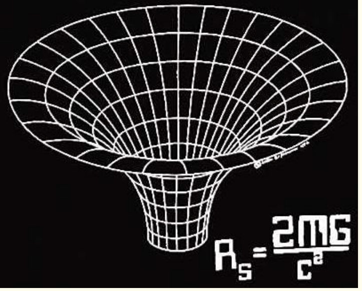
B This later Hubble image of M87's nucleus and jet also shows (enlarged) an unusual spiral disk in the galaxy's center.

Holland Ford, STScI/Johns Hopkins U.; Richard Harms, Applied Research Corp.; Zlatan Tsvetanov, Arthur Davidsen, and Gerard Kriss, Johns Hopkins U.; Ralph Bohlin and George Hartig, STScI; Linda Dressel and Ajay K. Kochar, Applied Research Corp.; and Bruce Margon, STScI; NASA/ESA/STScI



Holland Ford, STScI/Johns Hopkins U.; Richard Harms, Applied Research Corp.; Zlatan Tsvetanov, Arthur Davidsen, and Gerard Kriss, Johns Hopkins U.; Ralph Bohlin and George Hartig, STScI; Linda Dressel and Ajay K. Kochar, applied Research Corp.; and Bruce Margon, STScI; NASA/ESA/STScI

Spectra of the regions shown on the image of the center of M87, taken with the Faint Object Spectrograph aboard the Hubble Space Telescope, reveal Doppler shifts of the gas. (The single emission line appears at different wavelengths.) The orbital speed of 550 km/sec at this distance of 60 light-years from the nucleus allows astronomers to calculate how much mass must be inside those locations to keep the gas in orbit. The result is about 3 billion solar masses !!!, after various effects like the inclination of the disk are taken into account.



Accretion onto a BH

Recall: $R_{BH} = 2GM / c^2$

$$L = \frac{GM\dot{M}}{R} \sim \frac{GM\dot{M}}{2GM/c^2} = 0.5 \times \dot{M}c^2$$

This gives ***radiation efficiency*** (fraction of rest mass E converted to radiation):

$$e = \frac{L}{\dot{M}c^2} \sim 0.5$$

cf: p-p fusion: 0.007

→ Gas accretion is extremely efficient, producing high L

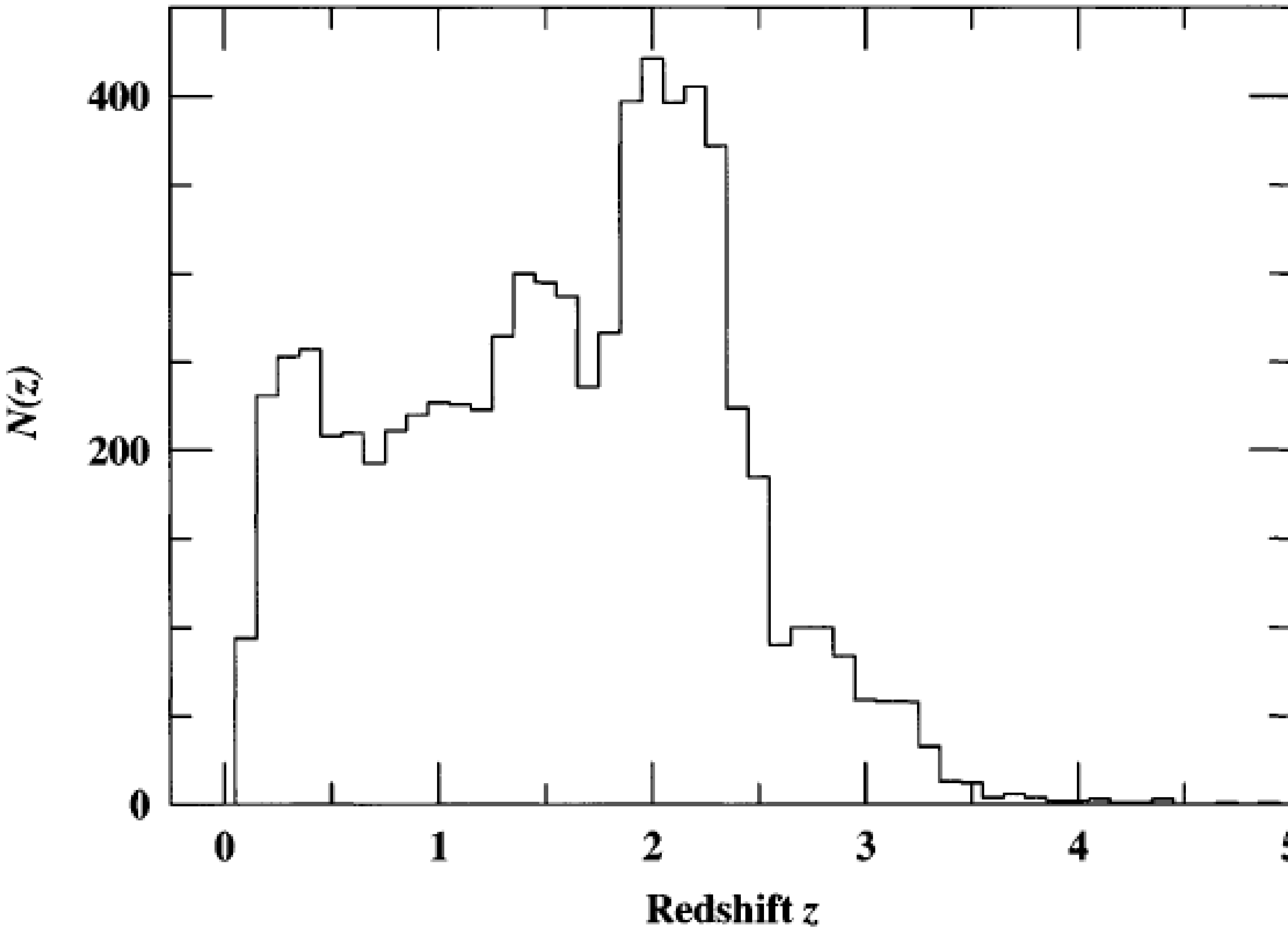
The Eddington luminosity

$$\frac{G m_p M}{r^2} \approx \frac{\sigma_T L}{4\pi r^2 c}$$

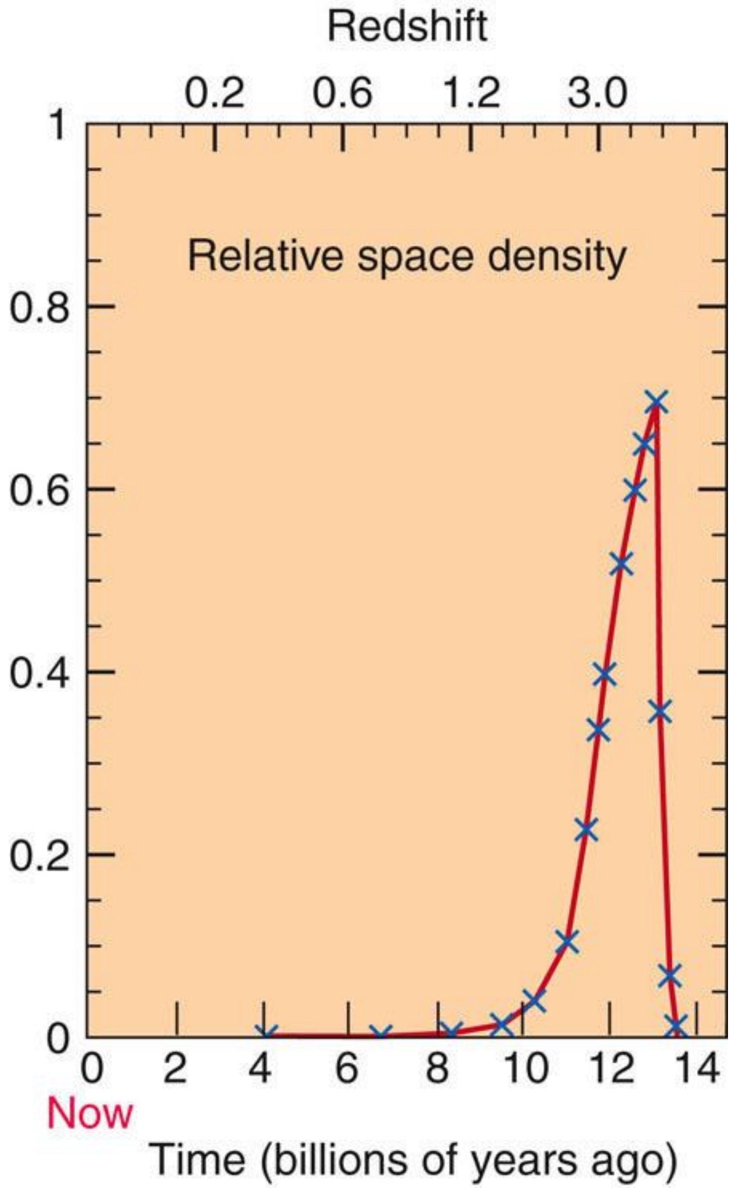
where σ_T - Thomson cross section

$$\sigma_T = (\frac{8\pi}{3})(\frac{e^2}{m_e c^2})^2$$

$$L_{Edd} = \frac{4\pi c m_p G M}{\sigma_T} = 3.2 \cdot 10^4 \frac{M}{M_\odot} L_\odot \, .$$

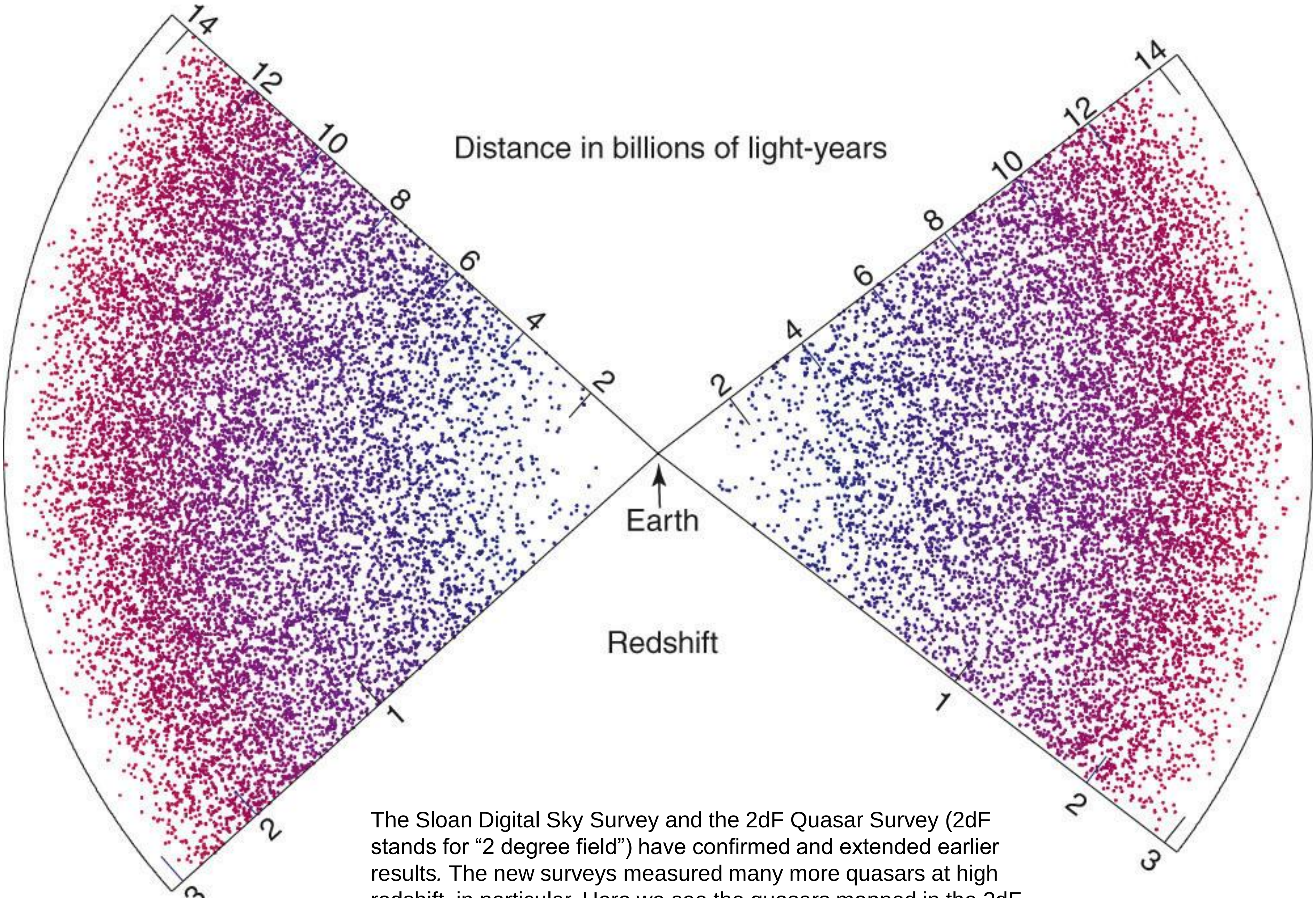


400
200
0
N(z)
0
1
2
3
4
5
Redshift z



(S. Warren, P. Hewett, and P. Osmer, 1994 Astrophys. J.)

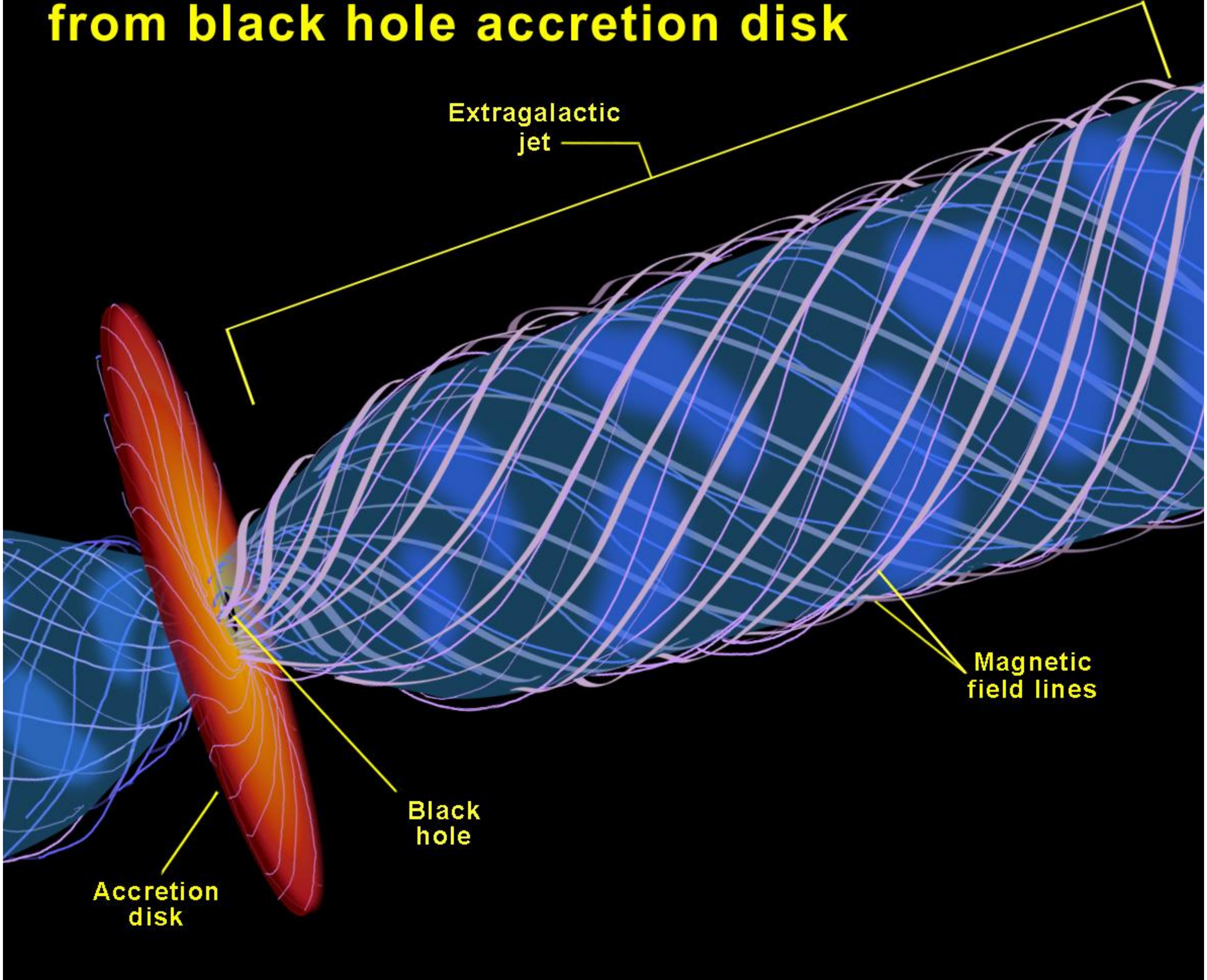
The number density of quasars (number per billion cubic parsecs) is plotted versus cosmic time, for an assumed Universe age of 14 billion years. There was a bright, spectacular era of quasars billions of years ago, and essentially none now remain.

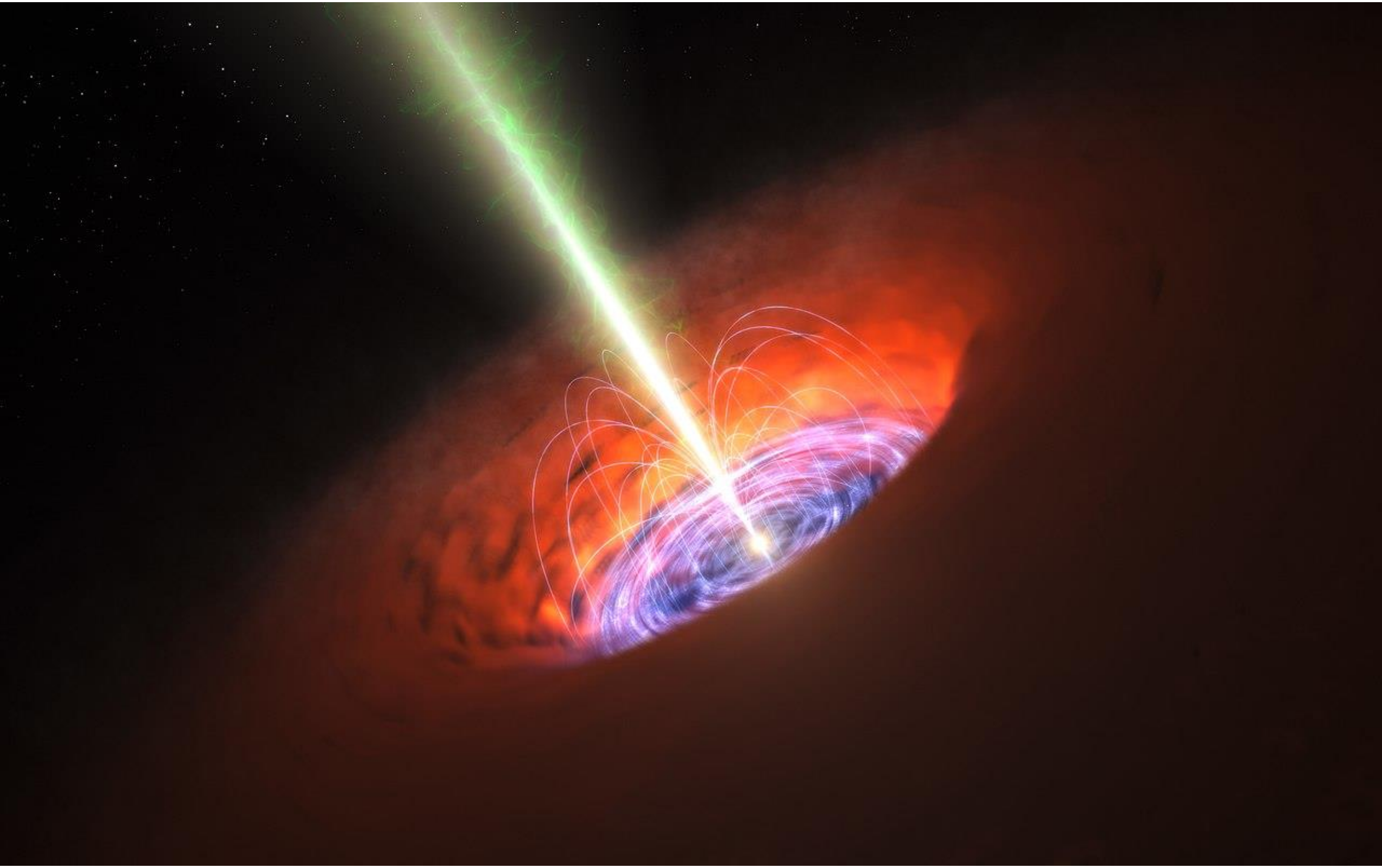


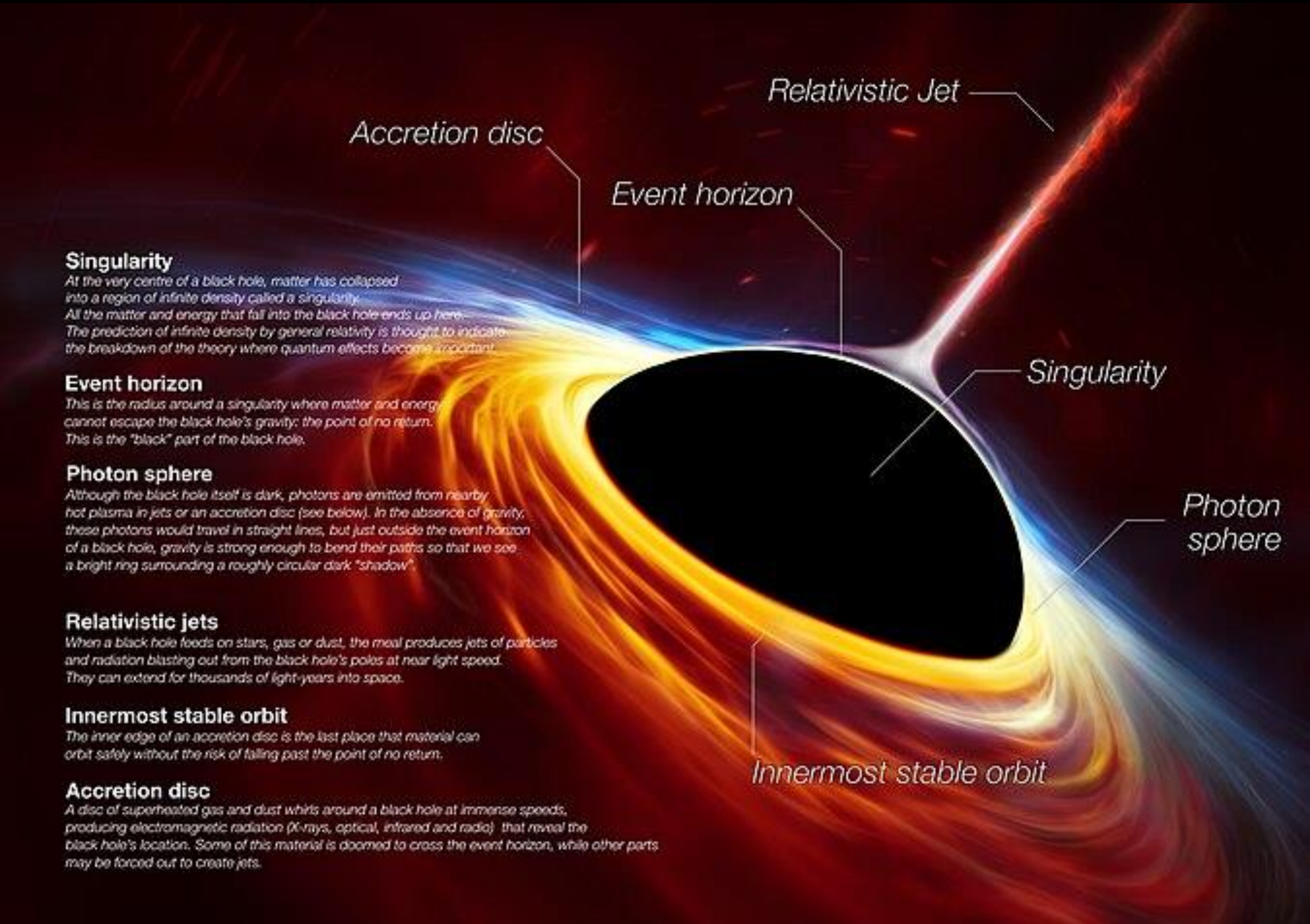
The Sloan Digital Sky Survey and the 2dF Quasar Survey (2dF stands for “2 degree field”) have confirmed and extended earlier results. The new surveys measured many more quasars at high redshift, in particular. Here we see the quasars mapped in the 2dF Quasar Survey.

2dFQSO Redshift Survey (2Qz) Collaboration

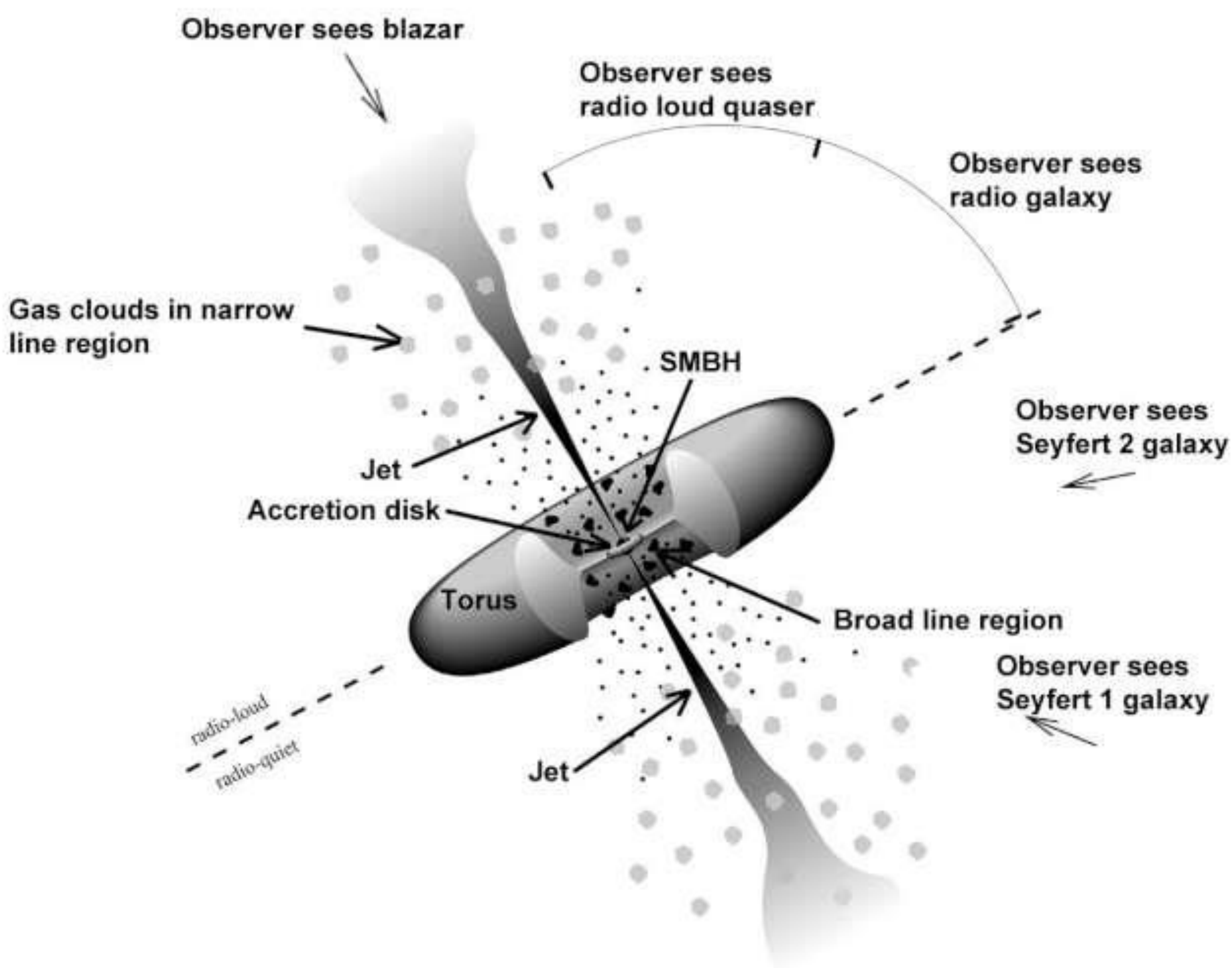
Formation of extragalactic jets from black hole accretion disk

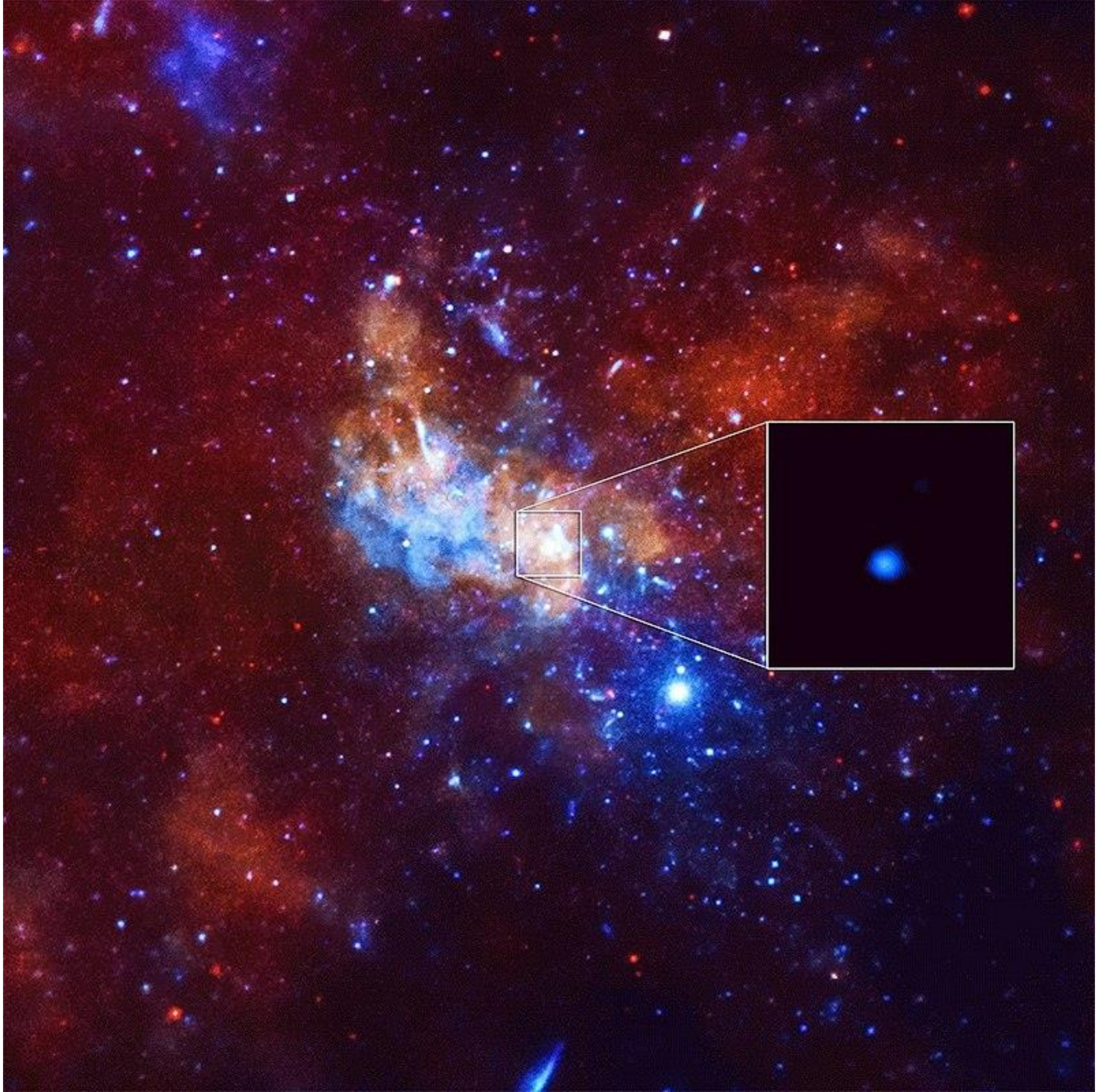






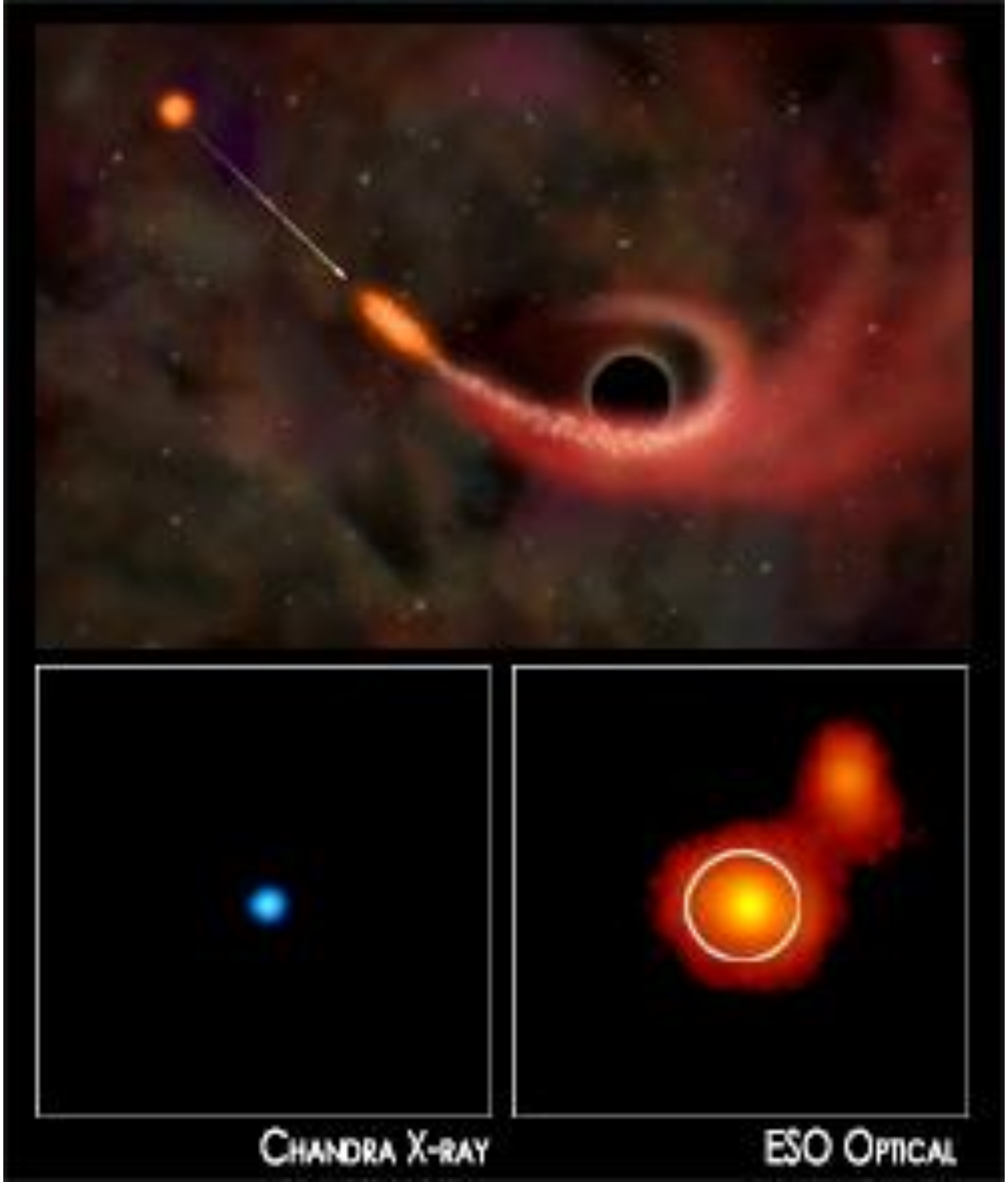
Relativistic Jet
Accretion disc
Event horizon
Singularity
Photon sphere
Innermost stable orbit
Singularity
At the very centre of a black hole, matter has collapsed into a region of infinite density called a singularity. All the matter and energy that fall into the black hole ends up here. The prediction of infinite density by general relativity is thought to indicate the breakdown of the theory where quantum effects become important.
Event horizon
This is the radius around a singularity where matter and energy cannot escape the black hole's gravity: the point of no return. This is the "black" part of the black hole.
Photon sphere
Although the black hole itself is dark, photons are emitted from nearby hot plasma in jets or an accretion disc (see below). In the absence of gravity, these photons would travel in straight lines, but just outside the event horizon of a black hole, gravity is strong enough to bend their paths so that we see a bright ring surrounding a roughly circular dark "shadow".
Relativistic jets
When a black hole feeds on stars, gas or dust, the meal produces jets of particles and radiation blasting out from the black hole's poles at near light speed. They can extend for thousands of light-years into space.
Innermost stable orbit
The inner edge of an accretion disc is the last place that material can orbit safely without the risk of falling past the point of no return.
Accretion disc
A disc of superheated gas and dust whirls around a black hole at immense speeds, producing electromagnetic radiation (X-rays, optical, infrared and radio) that reveal the black hole's location. Some of this material is doomed to cross the event horizon, while other parts may be forced out to create jets.


Observer sees blazar
Observer sees
radio loud quaser
Observer sees
radio galaxy
Gas clouds in narrow
line region
SMBH
Observer sees
Seyfert 2 galaxy
Jet
Accretion disk
Torus
Broad line region
Observer sees
Seyfert 1 galaxy
radio-loud
radio-quiet
Jet

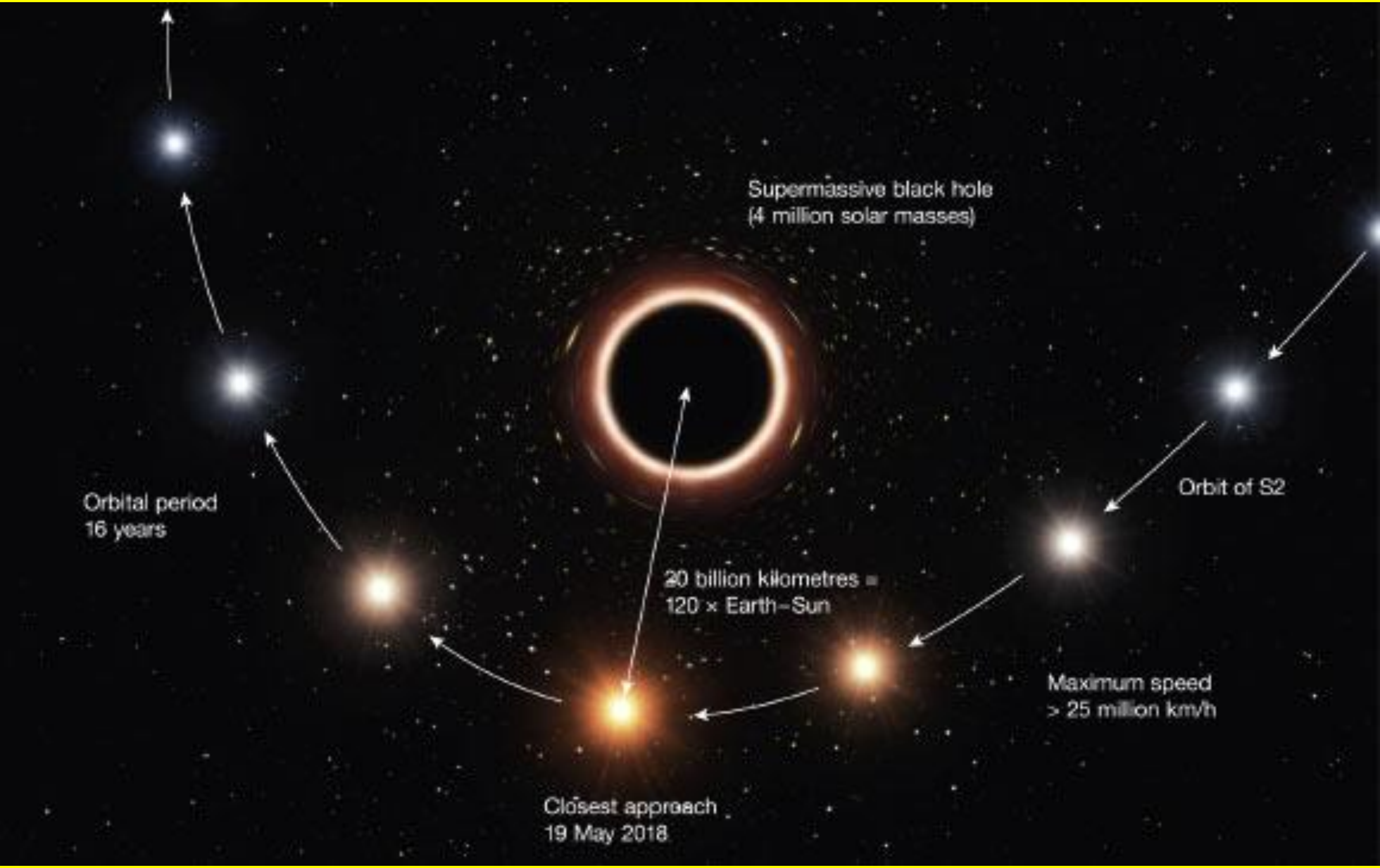


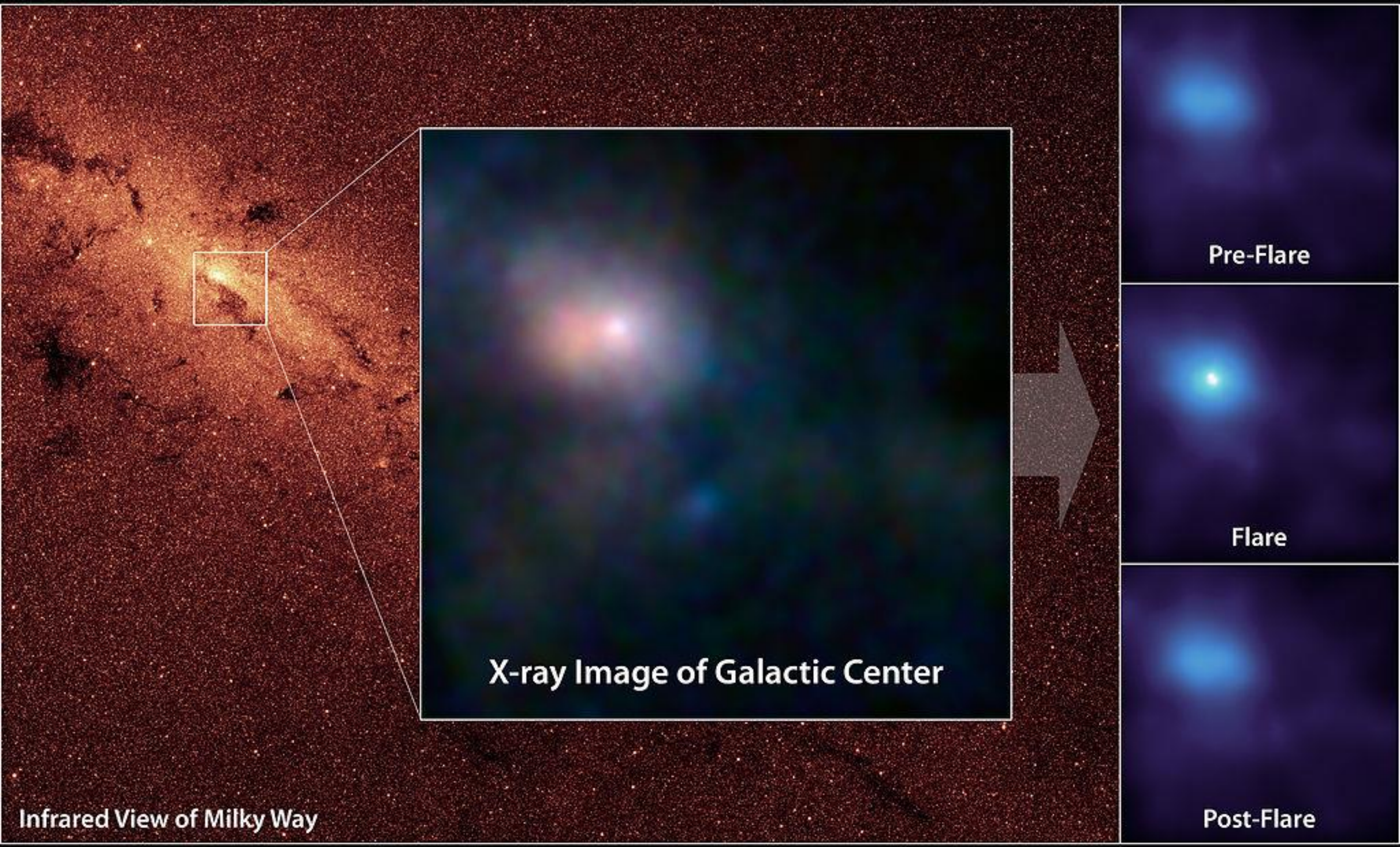
Cygnus A

X-ray Chandra telescope

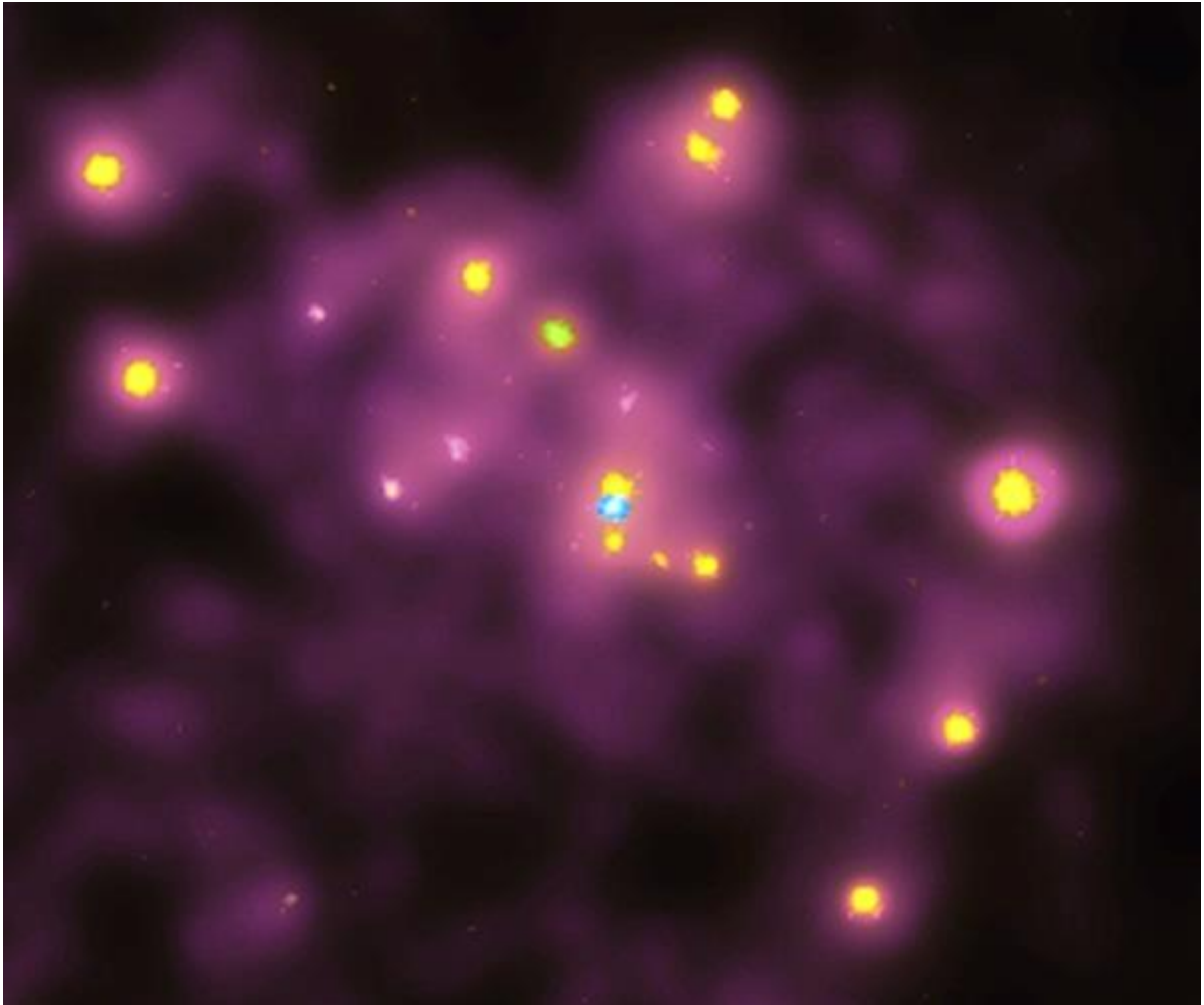


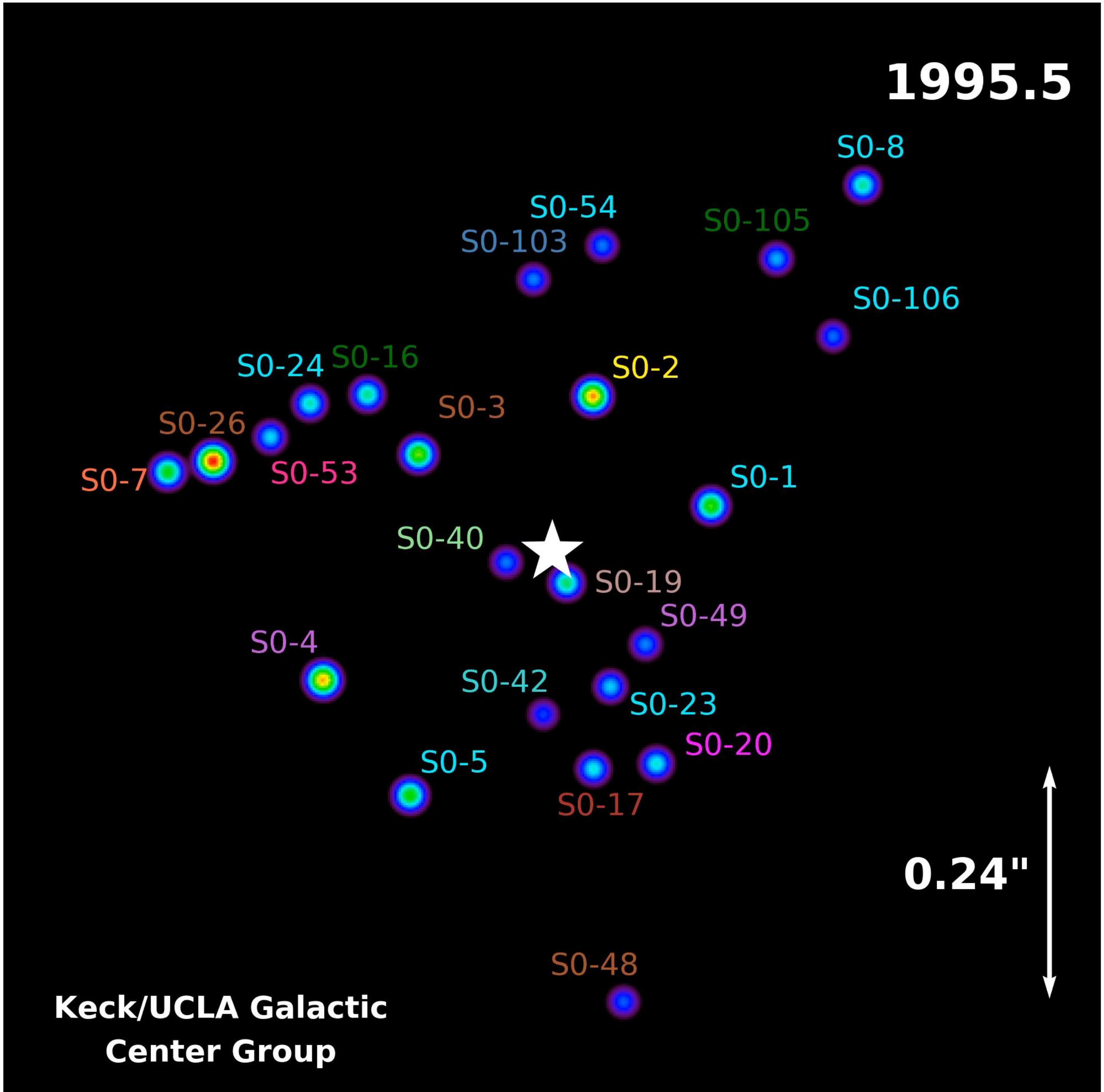
Sgr A

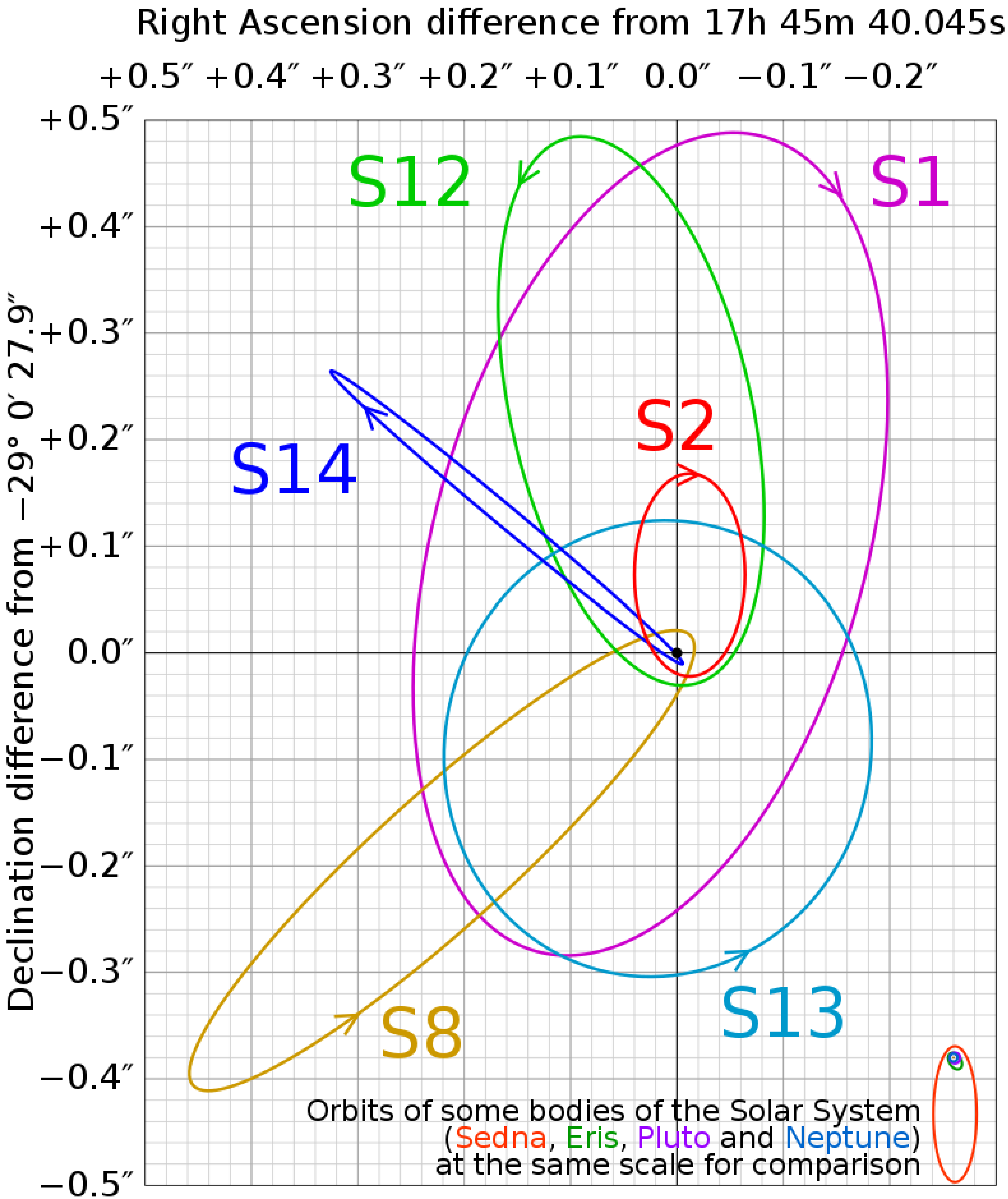

Supermassive black hole
(4 million solar masses)
Orbital period
16 years
Orbit of S2
20 billion kilometres =
120 × Earth–Sun
Maximum speed
> 25 million km/h
Closest approach
19 May 2018



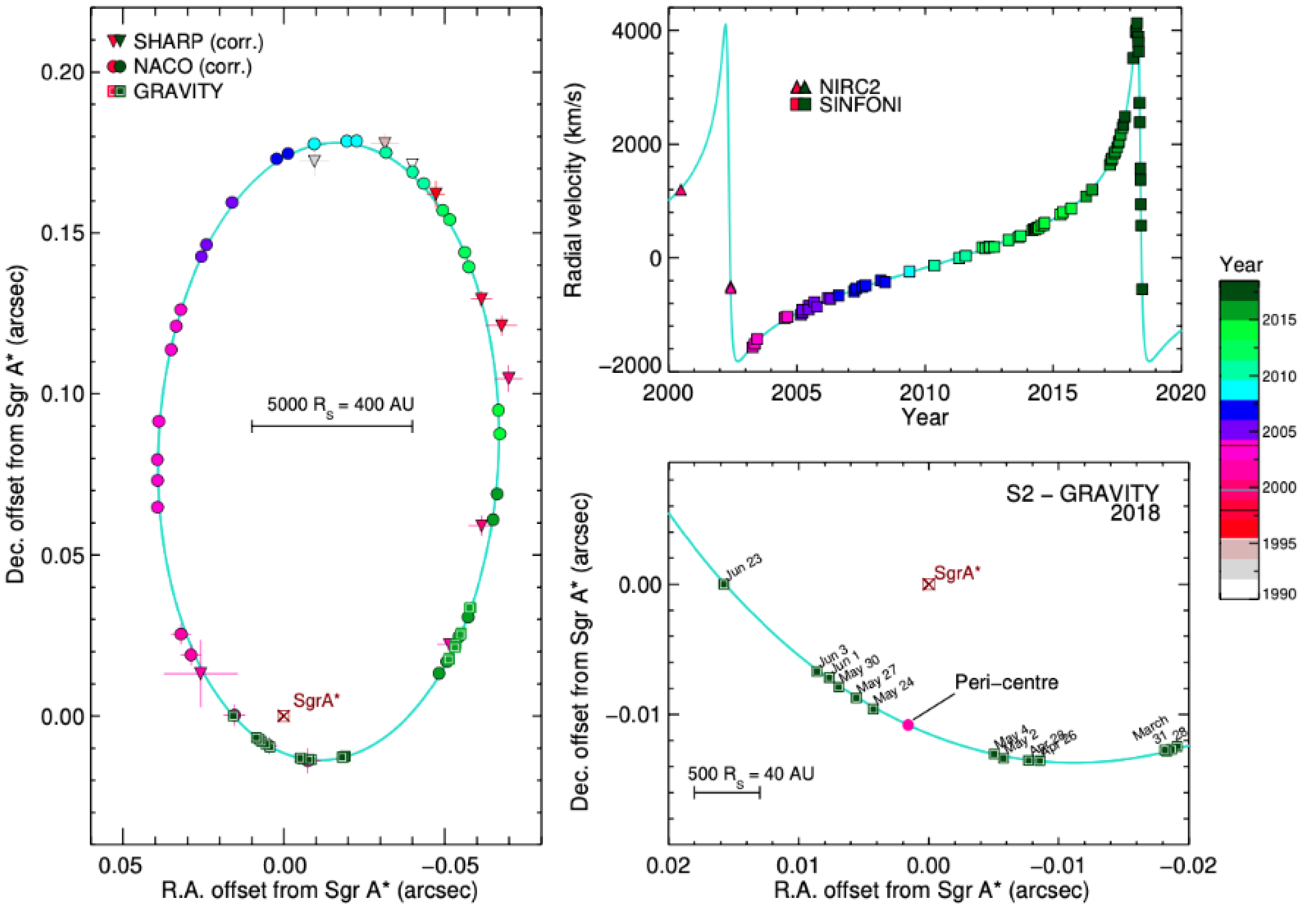
Infrared View of Milky Way
X-ray Image of Galactic Center
Pre-Flare
Flare
Post-Flare




1995.5
S0-8
S0-54
S0-105
S0-103
S0-106
S0-24
S0-16
S0-2
S0-3
S0-26
S0-53
S0-7
S0-1
S0-40
S0-19
S0-49
S0-4
S0-42
S0-23
S0-20
S0-5
S0-17
0.24"
S0-48
Keck/UCLA Galactic
Center Group

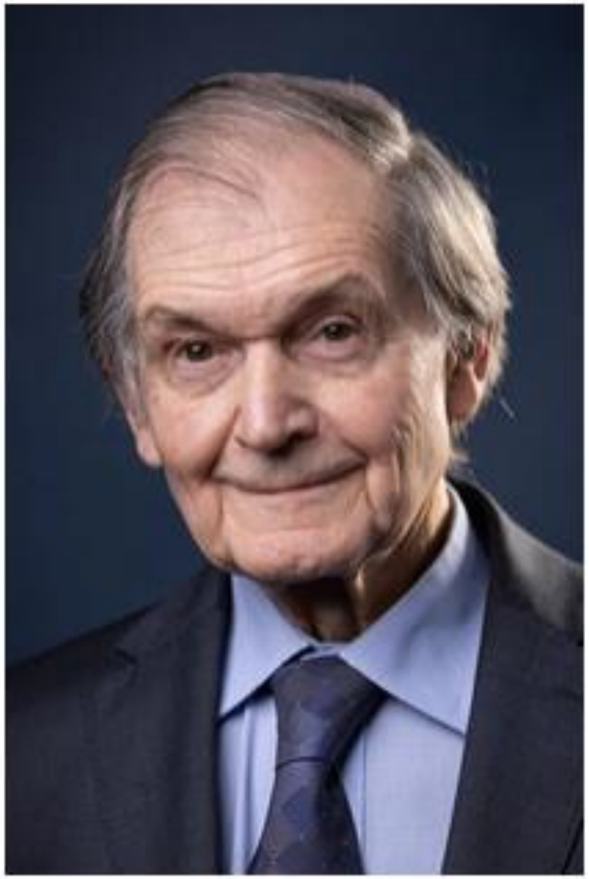


Right Ascension difference from 17h 45m 40.045s
+0.5″ +0.4″ +0.3″ +0.2″ +0.1″ 0.0″ −0.1″ −0.2″
Declination difference from −29° 0′ 27.9″
+0.5″
+0.4″
+0.3″
+0.2″
+0.1″
0.0″
−0.1″
−0.2″
−0.3″
−0.4″
−0.5″
S12
S1
S2
S14
S13
S8
Orbits of some bodies of the Solar System
(Sedna, Eris, Pluto and Neptune)
at the same scale for comparison



$$M_{BH} = 4.29 \cdot 10^6 M_\odot$$

The Nobel Prize in Physics 2020



Roger Penrose

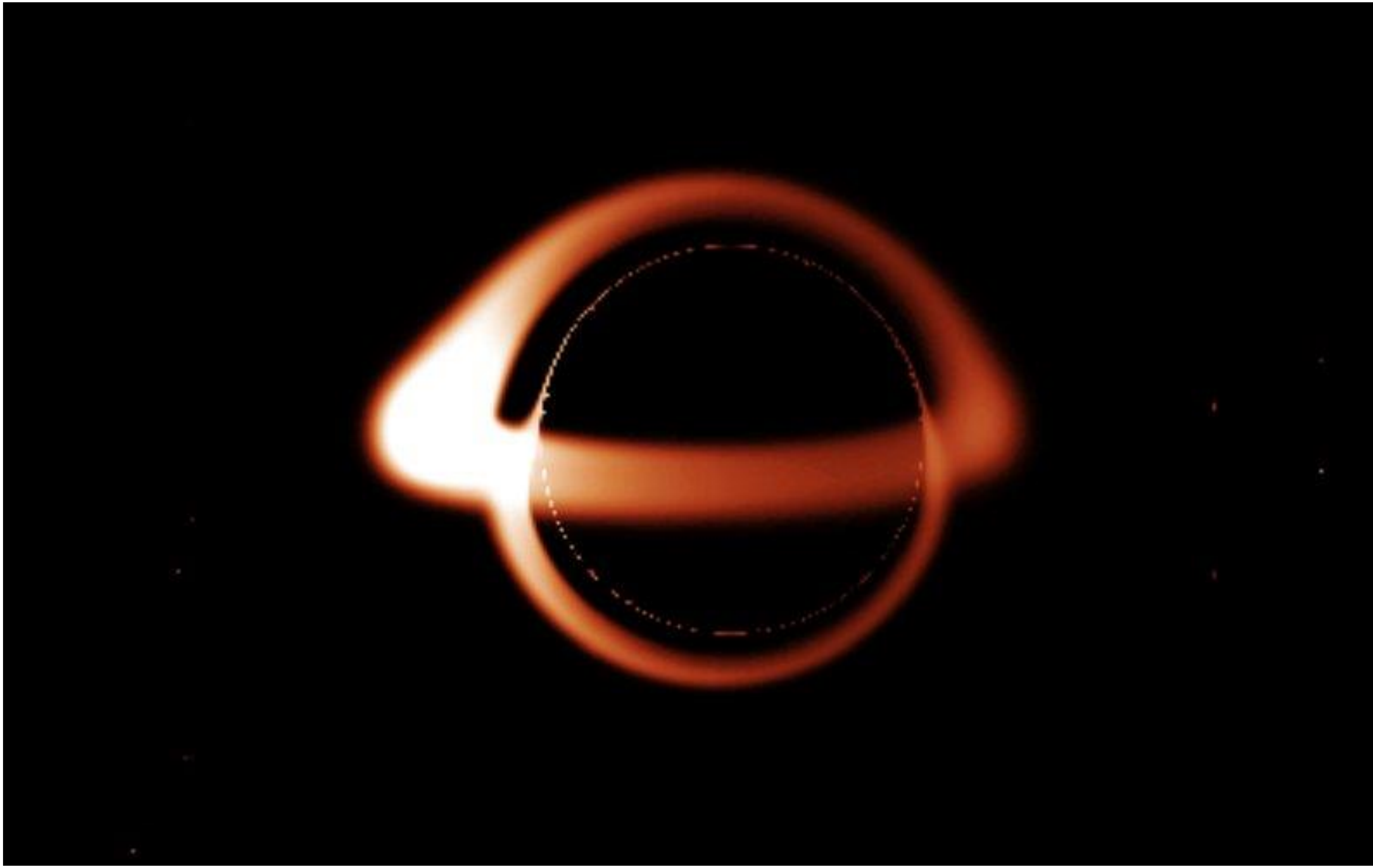
Prize share: 1/2

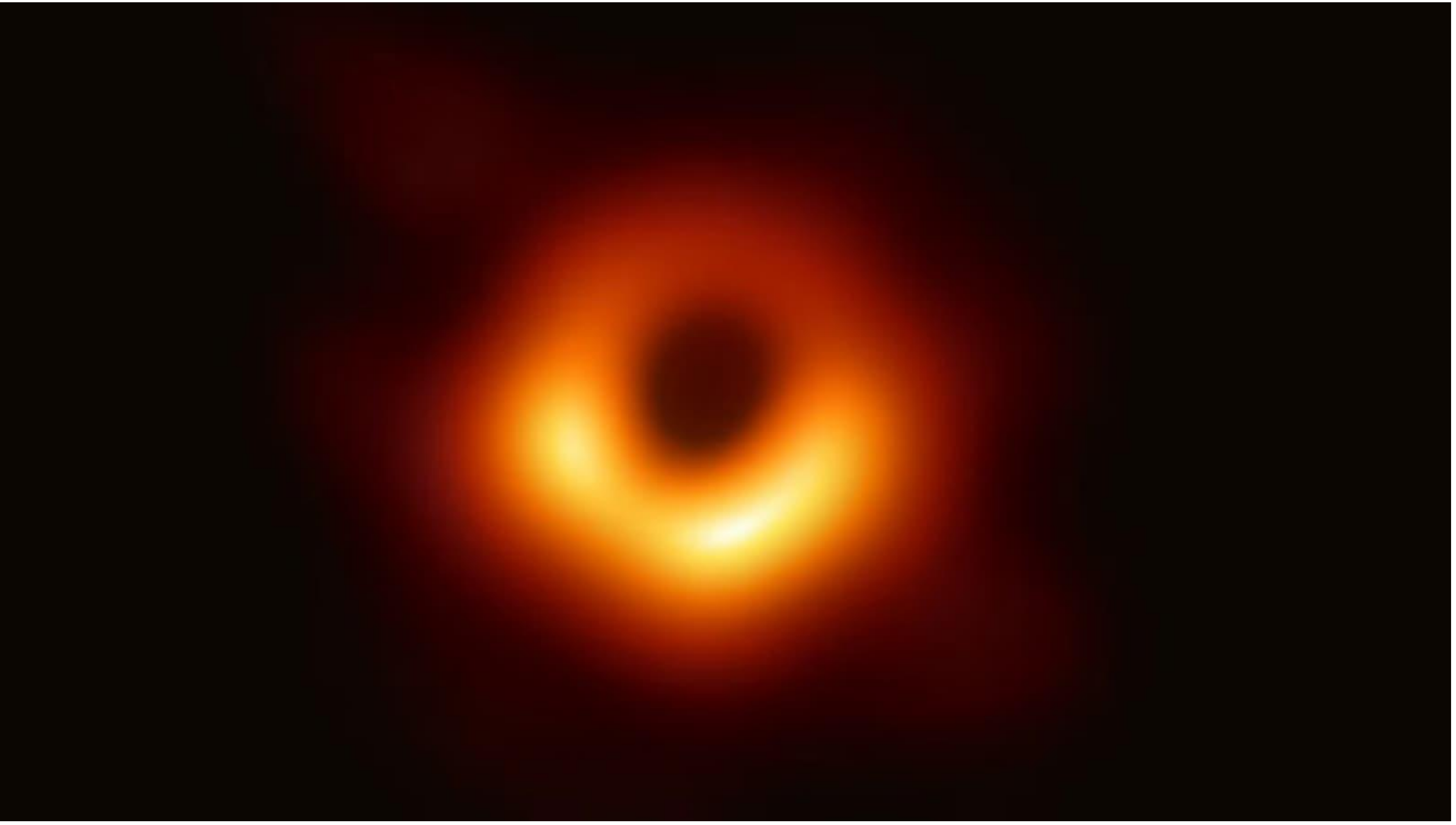
Reinhard Genzel

Prize share: 1/4

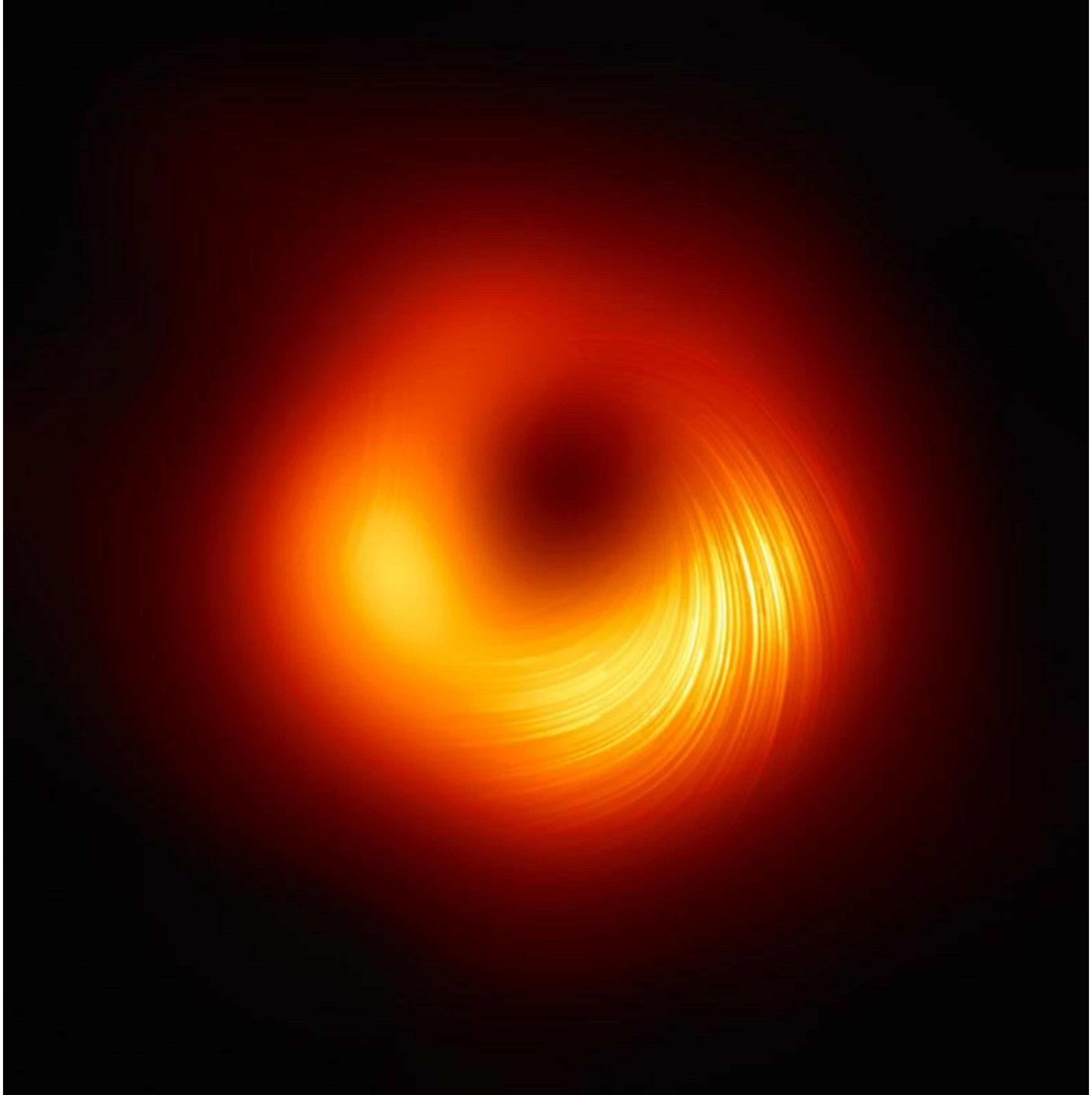
Andrea Ghez

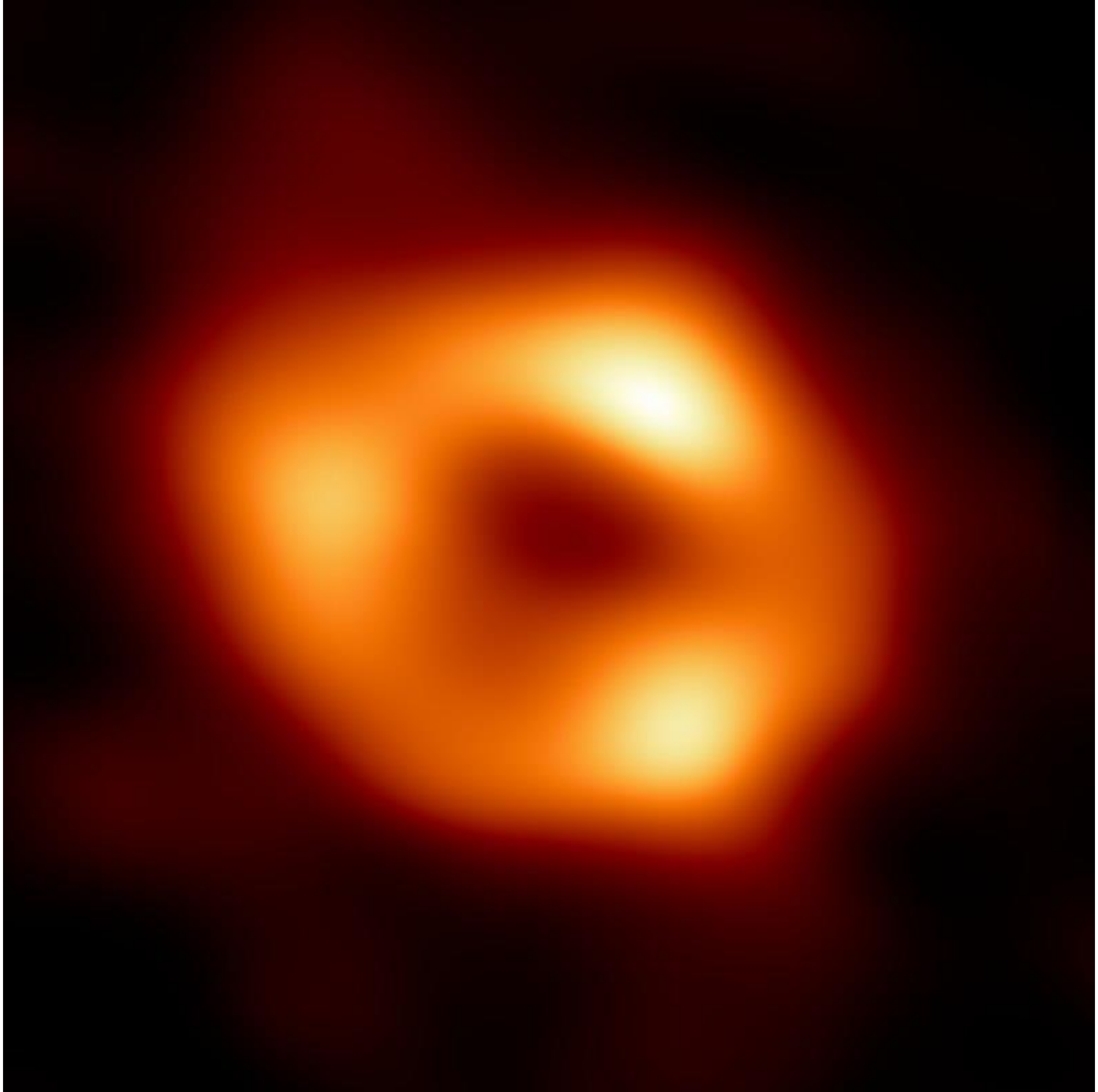
Prize share: 1/4



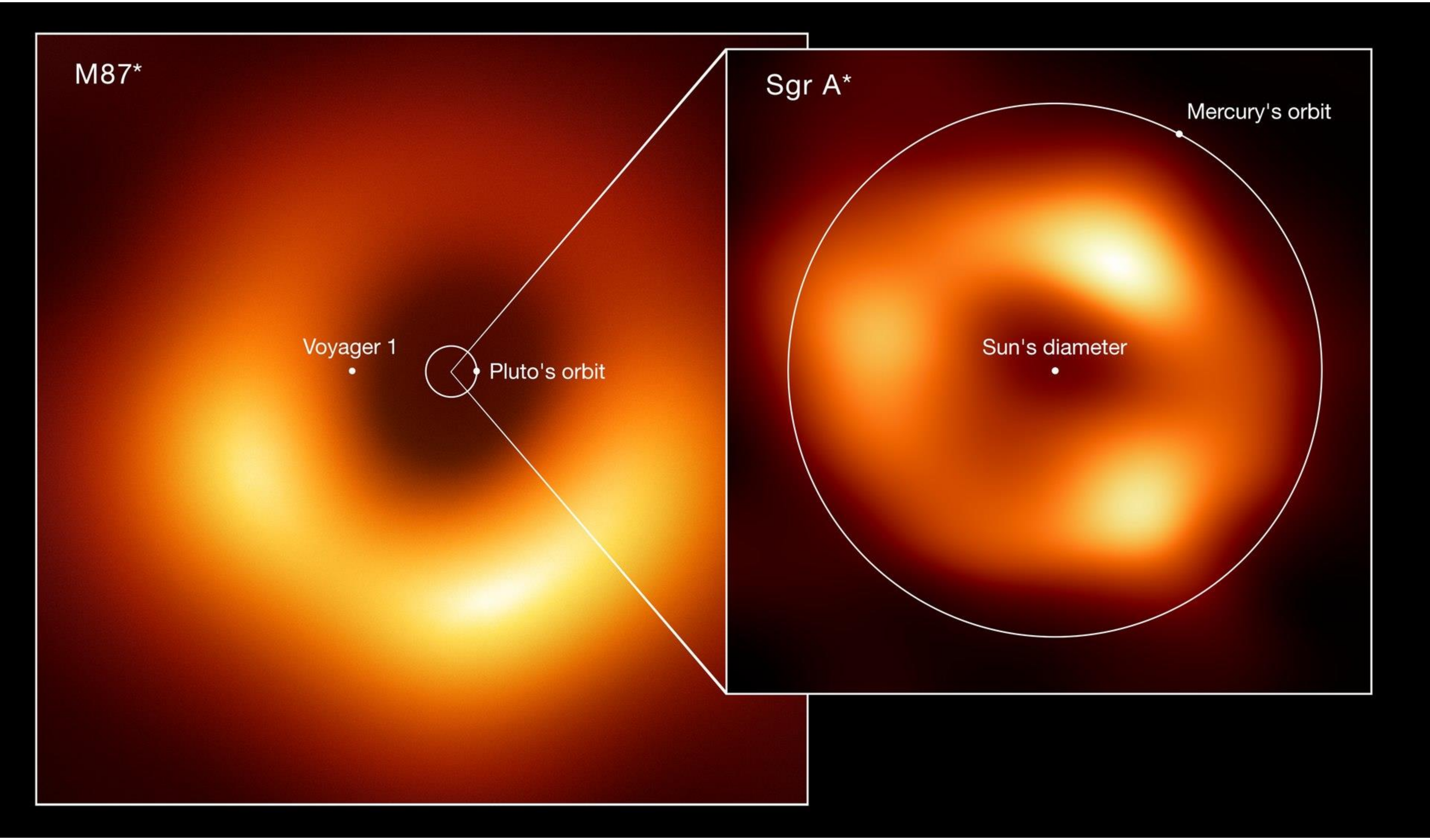


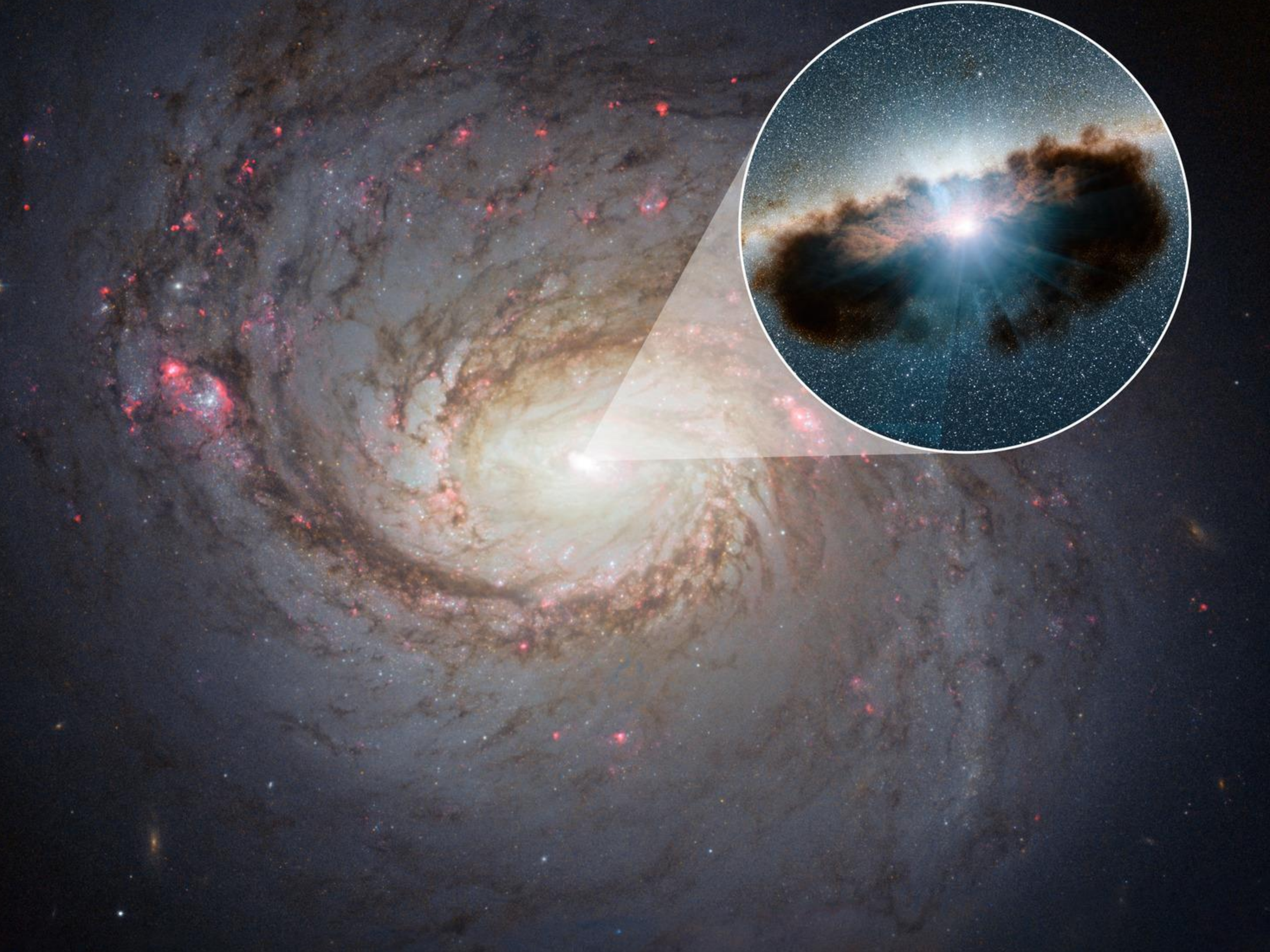
M 87 black hole of mass = $6.5 \cdot 10^9 \, L_\odot$



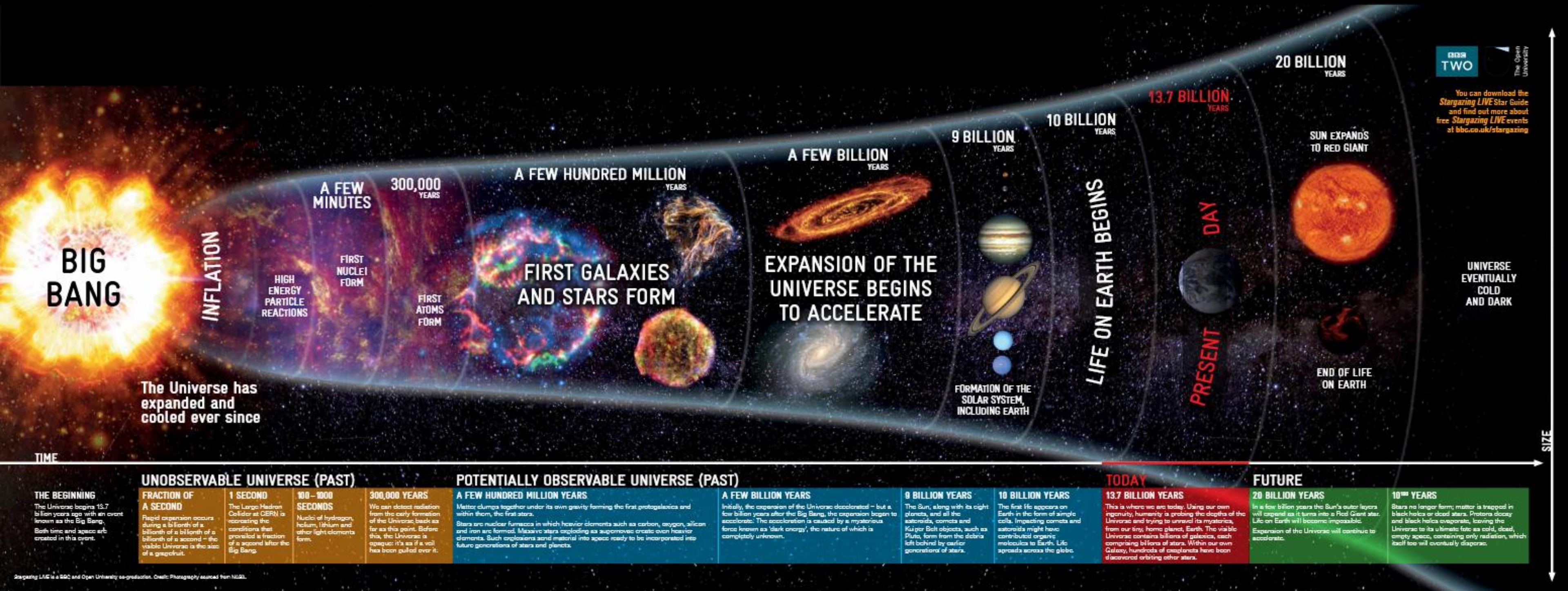


Sgr A^*

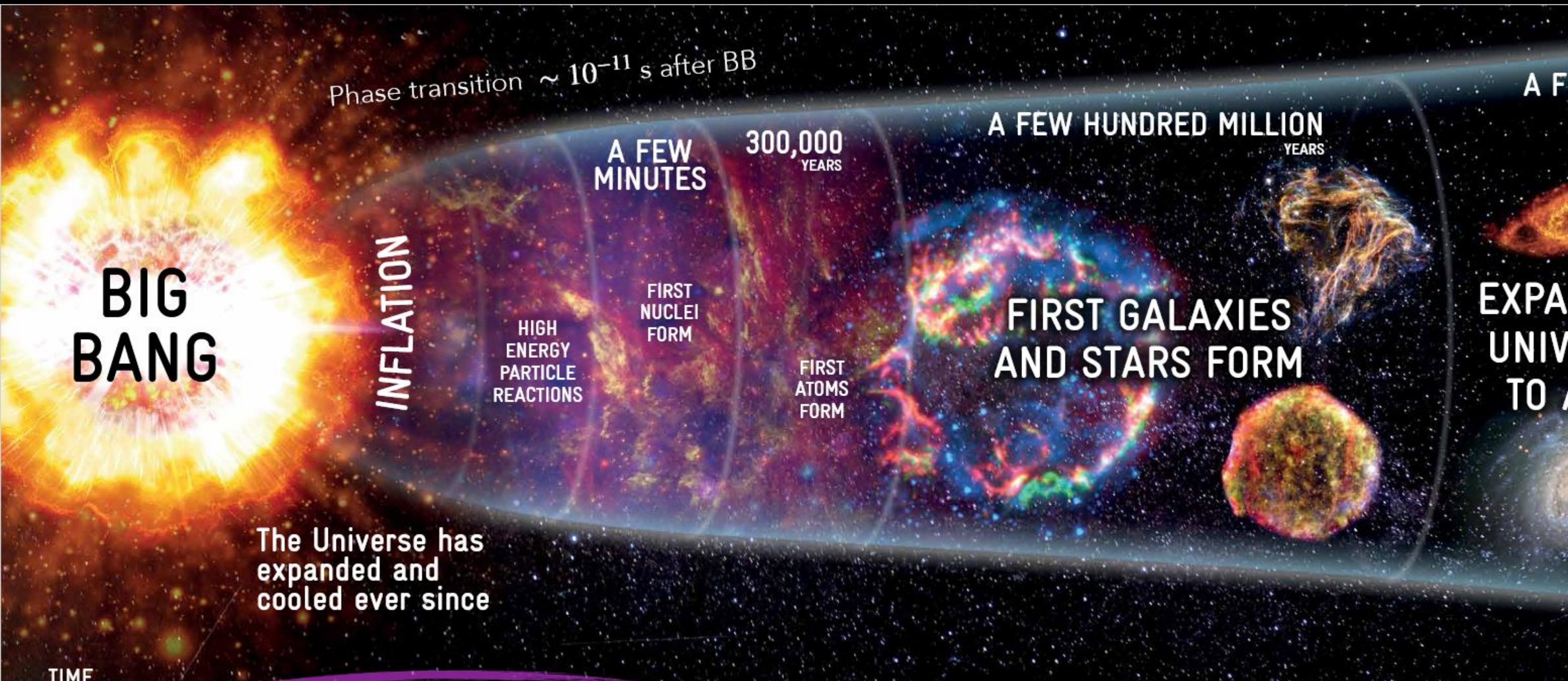

M87*
Voyager 1
Pluto's orbit
Sgr A*
Mercury's orbit
Sun's diameter



LOOKING BACK IN TIME



[Image source: BBC.CO.UK]



UNOBSERVABLE UNIVERSE (PAST)

POTENTIALLY OBSERVABLE UNIVERSE (PAST)

THE BEGINNING
The Universe begins 13.7 billion years ago with an event known as the Big Bang.
Both time and space are created in this event.

FRACTION OF A SECOND
Rapid expansion occurs during a billionth of a billionth of a billionth of a billionth of a second – the visible Universe is the size of a grapefruit.

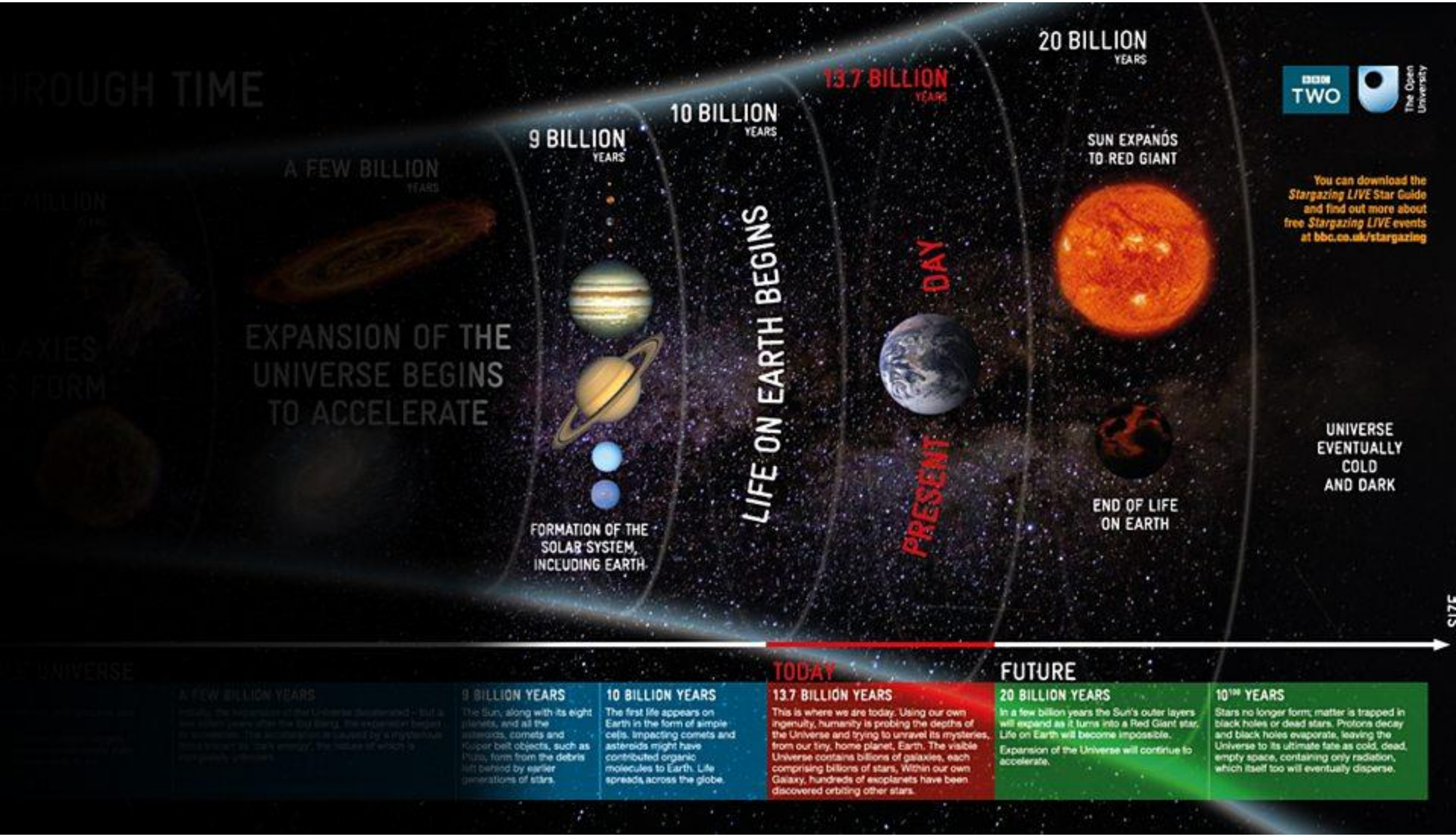
1 SECOND
The Large Hadron Collider at CERN is recreating the conditions that prevailed a fraction of a second after the Big Bang.

100 – 1000 SECONDS
Nuclei of hydrogen, helium, lithium and other light elements form.

300,000 YEARS
We can detect radiation from the early formation of the Universe back as far as this point. Before this, the Universe is opaque: it's as if a veil has been pulled over it.

A FEW HUNDRED MILLION YEARS
Matter clumps together under its own gravity forming the first protogalaxies and within them, the first stars.
Stars are nuclear furnaces in which heavier elements such as carbon, oxygen, silicon and iron are formed. Massive stars exploding as supernovae create even heavier elements. Such explosions send material into space ready to be incorporated into future generations of stars and planets.

A FEW BILLION YEARS
Initially, the expansion of the U
few billion years after the Big B
accelerate. The acceleration is
force known as 'dark energy',
completely unknown.



HROUGH TIME
A FEW BILLION
YEARS
EXPANSION OF THE
UNIVERSE BEGINS
TO ACCELERATE
9 BILLION
YEARS
FORMATION OF THE
SOLAR SYSTEM,
INCLUDING EARTH
10 BILLION
YEARS
LIFE ON EARTH BEGINS
13.7 BILLION
YEARS
PRESENT DAY
20 BILLION
YEARS
SUN EXPANDS
TO RED GIANT
END OF LIFE
ON EARTH
UNIVERSE
EVENTUALLY
COLD
AND DARK
BBC TWO
The Open University
You can download the
Stargazing LIVE Star Guide
and find out more about
free Stargazing LIVE events
at bbc.co.uk/stargazing
SIZE
TODAY
FUTURE
A FEW BILLION YEARS
9 BILLION YEARS
The Sun, along with its eight planets, and all the asteroids, comets and Kuiper belt objects, such as Pluto, form from the debris left behind by earlier generations of stars.
10 BILLION YEARS
The first life appears on Earth in the form of simple cells. Impacting comets and asteroids might have contributed organic molecules to Earth. Life spreads across the globe.
13.7 BILLION YEARS
This is where we are today. Using our own ingenuity, humanity is probing the depths of the Universe and trying to unravel its mysteries, from our tiny, home planet, Earth. The visible Universe contains billions of galaxies, each comprising billions of stars, Within our own Galaxy, hundreds of exoplanets have been discovered orbiting other stars.
20 BILLION YEARS
In a few billion years the Sun's outer layers will expand as it turns into a Red Giant star. Life on Earth will become impossible.
Expansion of the Universe will continue to accelerate.
10^100 YEARS
Stars no longer form; matter is trapped in black holes or dead stars. Protons decay and black holes evaporate, leaving the Universe to its ultimate fate as cold, dead, empty space, containing only radiation, which itself too will eventually disperse.

Article

Particle exchange statistics beyond fermions and bosons

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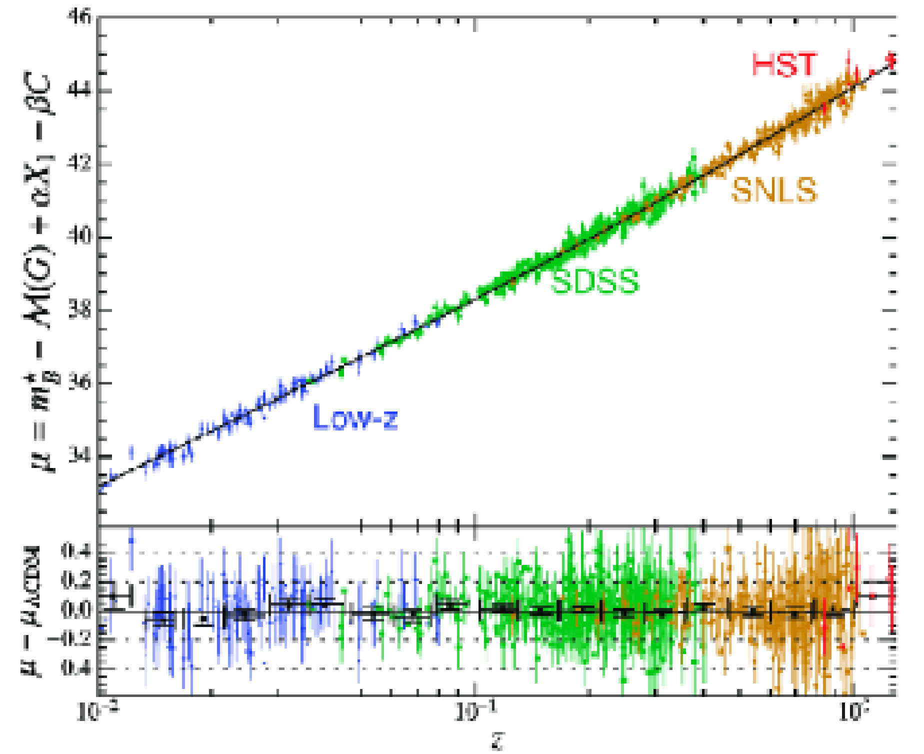
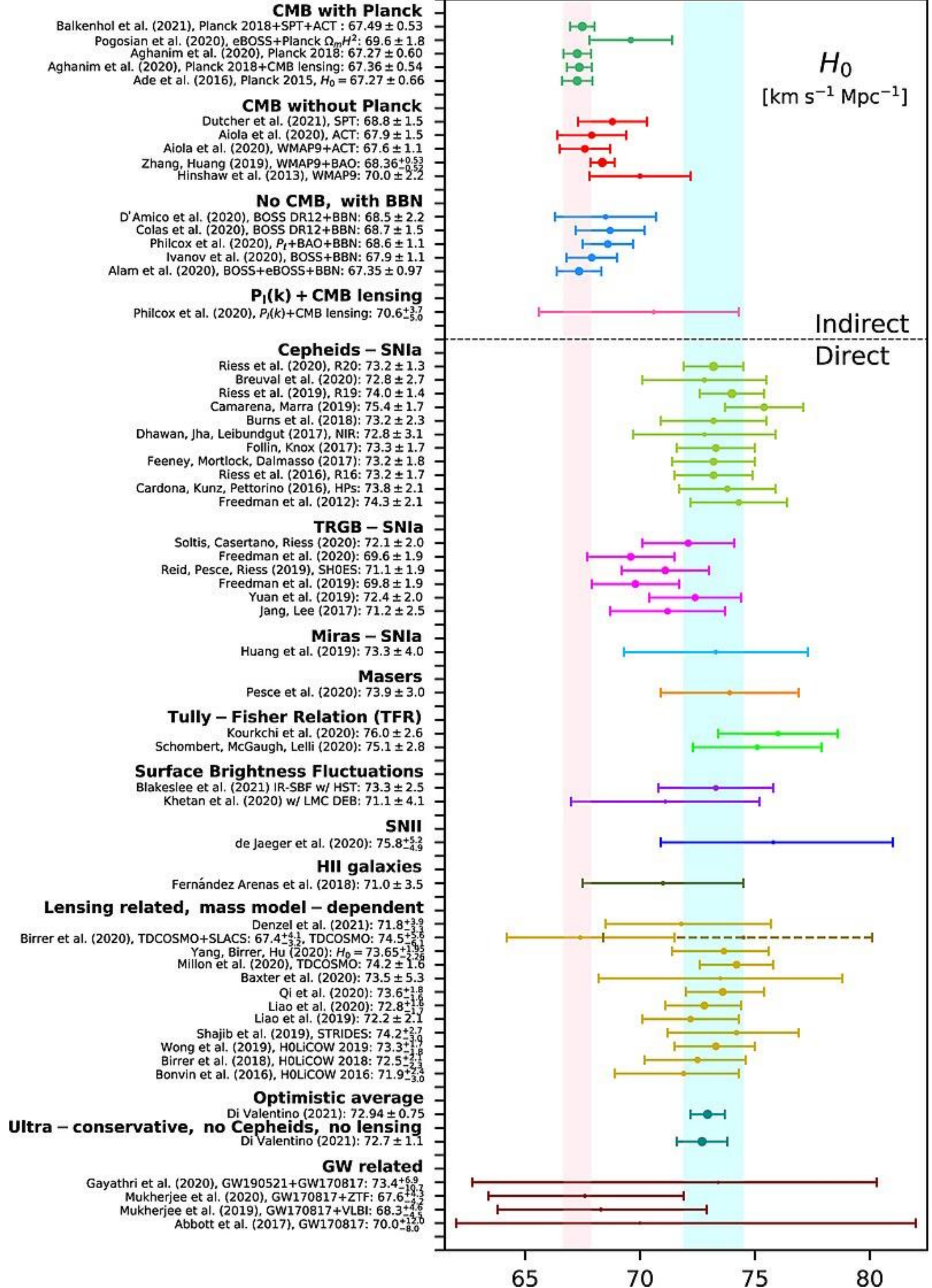
It is commonly believed that there are only two types of particle exchange statistics in quantum mechanics, fermions and bosons, with the exception of anyons in two dimensions[1–5]. In principle, a second exception known as parastatistics, which extends outside two dimensions, has been considered[6] but was believed to be physically equivalent to fermions and bosons[7–9]. Here we show that non-trivial parastatistics inequivalent to either fermions or bosons can exist in physical systems. These new types of identical particle obey generalized exclusion principles, leading to exotic free-particle thermodynamics distinct from any system of free fermions and bosons. We formulate our theory by developing a second quantization of paraparticles that naturally includes exactly solvable non-interacting theories and incorporates physical constraints such as locality. We then construct a family of exactly solvable quantum spin models in one and two dimensions, in which free paraparticles emerge as quasiparticle excitations, and their exchange statistics can be physically observed and are notably distinct from fermions and bosons. This demonstrates the possibility of a new type of quasiparticle in condensed matter systems and—more speculatively—the potential for previously unconsidered types of elementary particle.

The modern Hubble diagram

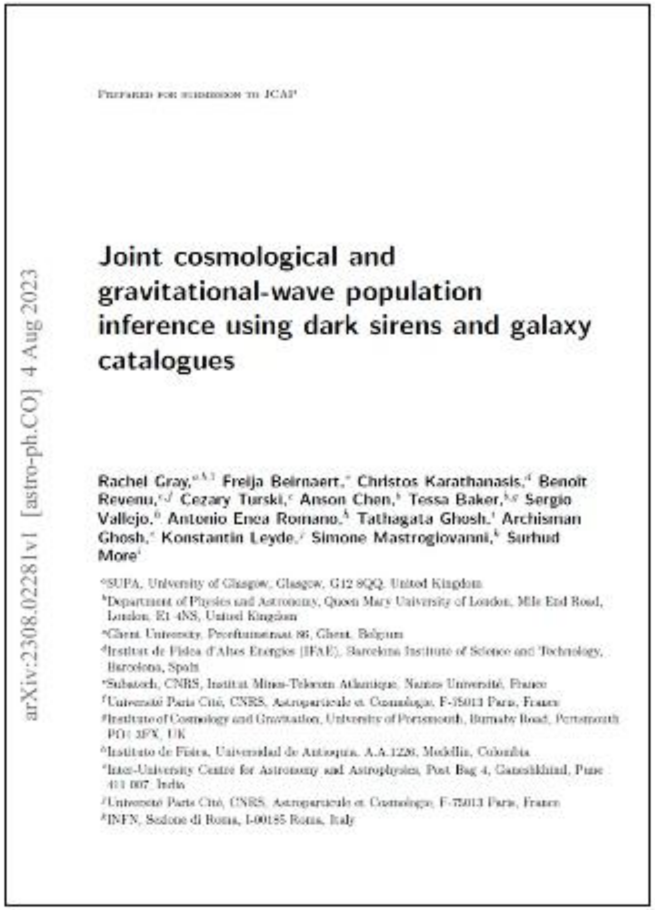
- In the past 100 years we have measured the distance and velocity of many more objects, not just Cepheid stars but also exploding stars called Supernovae.



- Now the Hubble diagram, i.e. a diagram of velocity over distance is much more precise and we will see later led to a second revolution in cosmology in 1998



Hubble constant tension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Joint cosmological and gravitational-wave population inference using dark sirens and galaxy catalogues

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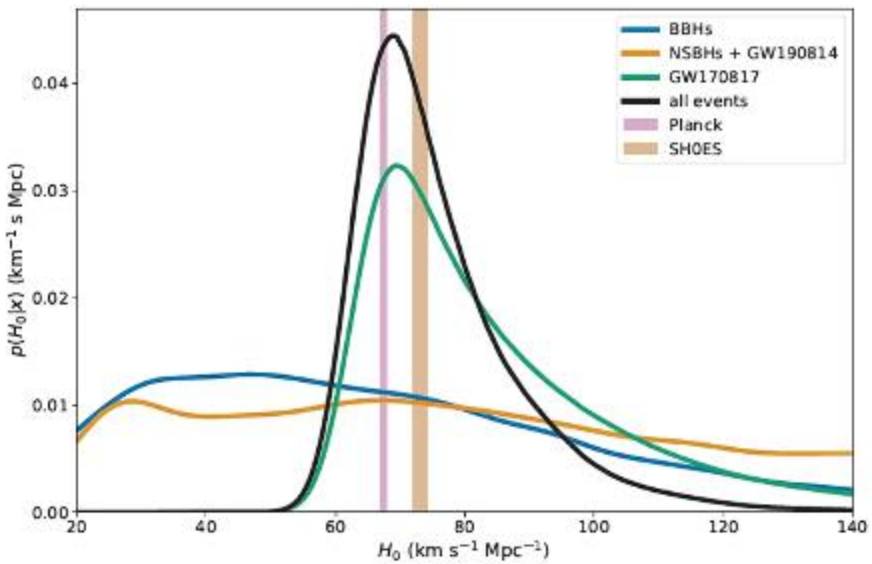
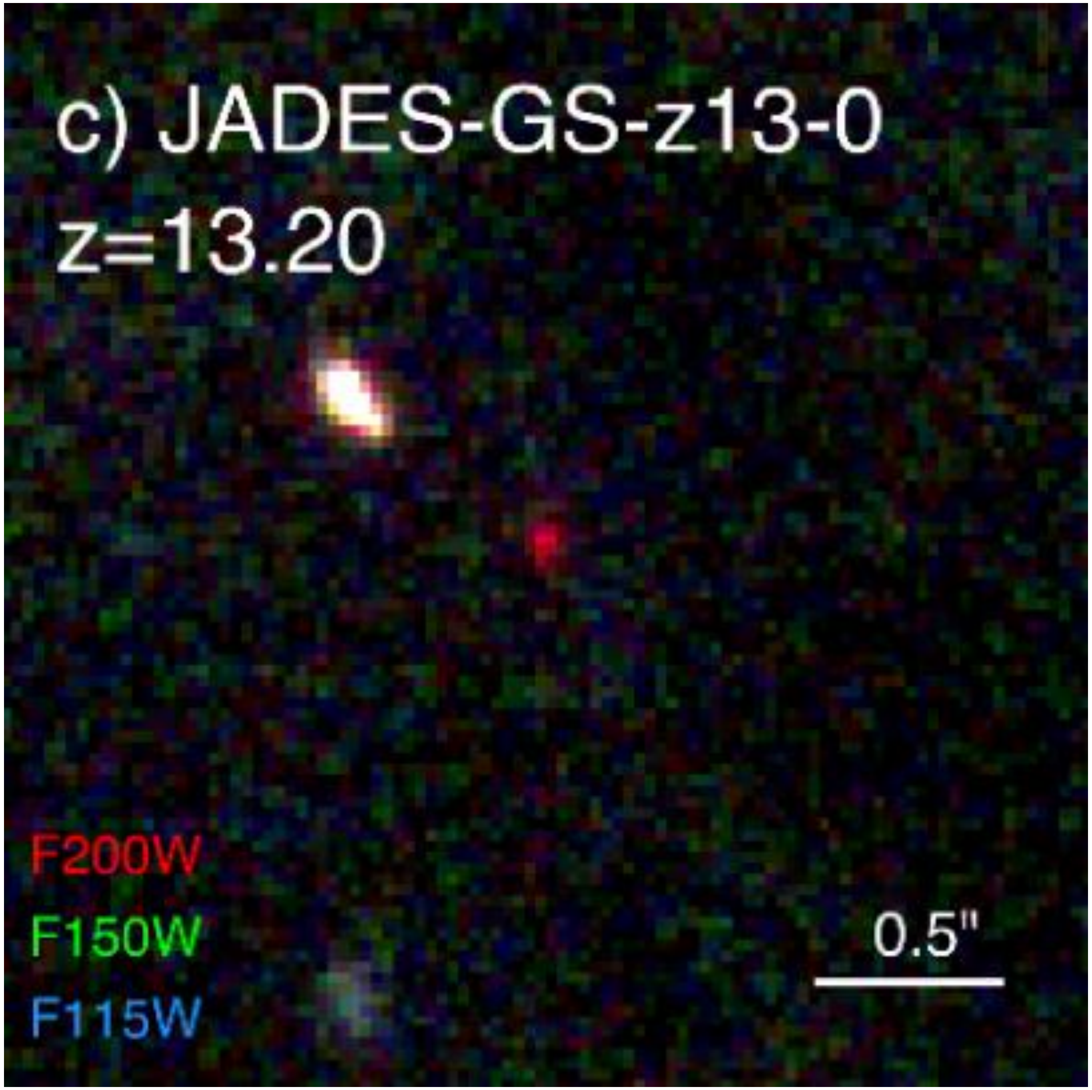


$$H_0 = 69^{+12}_{-7}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

Less informative but more **robust** than the GWTC-3 result with GWCOSMO: $H_0 = 68^{+8}_{-6}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$


c) JADES-GS-z13-0
z=13.20
F200W
F150W
F115W
0.5"

Z = 14.32

z ~ 14.32 (+0.08/-0.20)
born ~ 300 million years after the big bang
distance ~ 13.4 billion lightyears

[Credits: NASA, ESA, CSA, STScI, Brant Robertson (UC Santa Cruz), Ben Johnson (CfA), Sandro Tacchella (Cambridge), Phill Cargile (CfA)]

Big unsolved problems:

Nature of Dark Matter particles

Nature of Dark Energy

The value of the Hubble constant