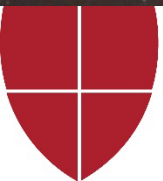


SOAR: Lives of Stars

Supernovae and Black Holes

Aileen A. O'Donoghue
Henry Priest Professor of Physics



ST. LAWRENCE UNIVERSITY

The Lives of Stars

☆ Star Birth: 9/10/26

🌍 Nuclear Explosions Contained by Gravity

☆ Lives & Deaths of Small Stars: 9/17/26

🌍 Planetary Nebulae and White Dwarfs

☆ Deaths of Large Stars: 9/24/26

🌍 Supernovae, Neutron Stars and Black Holes

☆ Black Holes: 10/1/26

🌍 Spaghettification

Outline

★ Review Star Deaths

- 🌍 Small: PN & WD, Large: SN & NS or BH

- 🌍 States of Matter

★ General Relativity, Gravity, & Light

- 🌍 Total Eclipses & Galaxy Clusters

★ Black Holes

- 🌍 Escape Velocity & Spaghettification

- 🌍 Detecting Black Holes

 - › X-Rays, Invisible Companions, Direct Imaging

★ The Adventure Continues

Outline

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Star Deaths

☆ Lifespan, death depend on star's mass

$$t_{\text{Main Sequence}} \approx 10^{10} \times M_{\text{solar masses}}^{-2.5} \text{ years}$$

☆ Small Stars ($0.1 M_{\text{Sol}} < M_{\text{star}} \leq 8M_{\text{Sol}}$)

🌍 Longish lives (10's of billions of years)

› No star smaller than $0.8 M_{\text{sol}}$ has lived out its life!

🌍 Planetary Nebula to White Dwarf

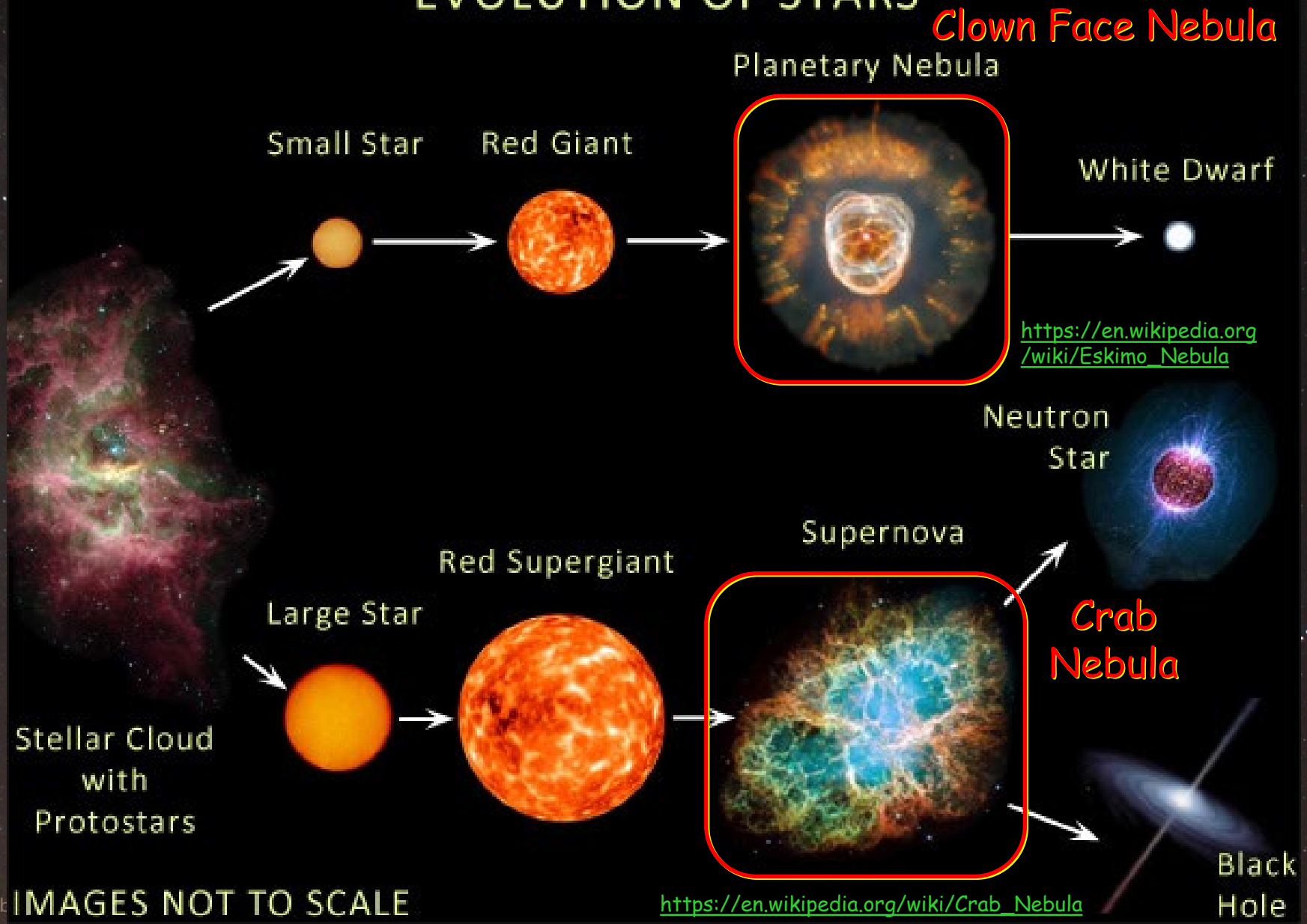
☆ Giant Stars ($M > 8M_{\text{Sol}}$, $M_{\text{max}} \approx 100 M_{\text{Sol}}$)

🌍 Lives can be very short (millions of years)

🌍 Supernova to Neutron Star or Black Hole

Star Death Depends on Mass

EVOLUTION OF STARS

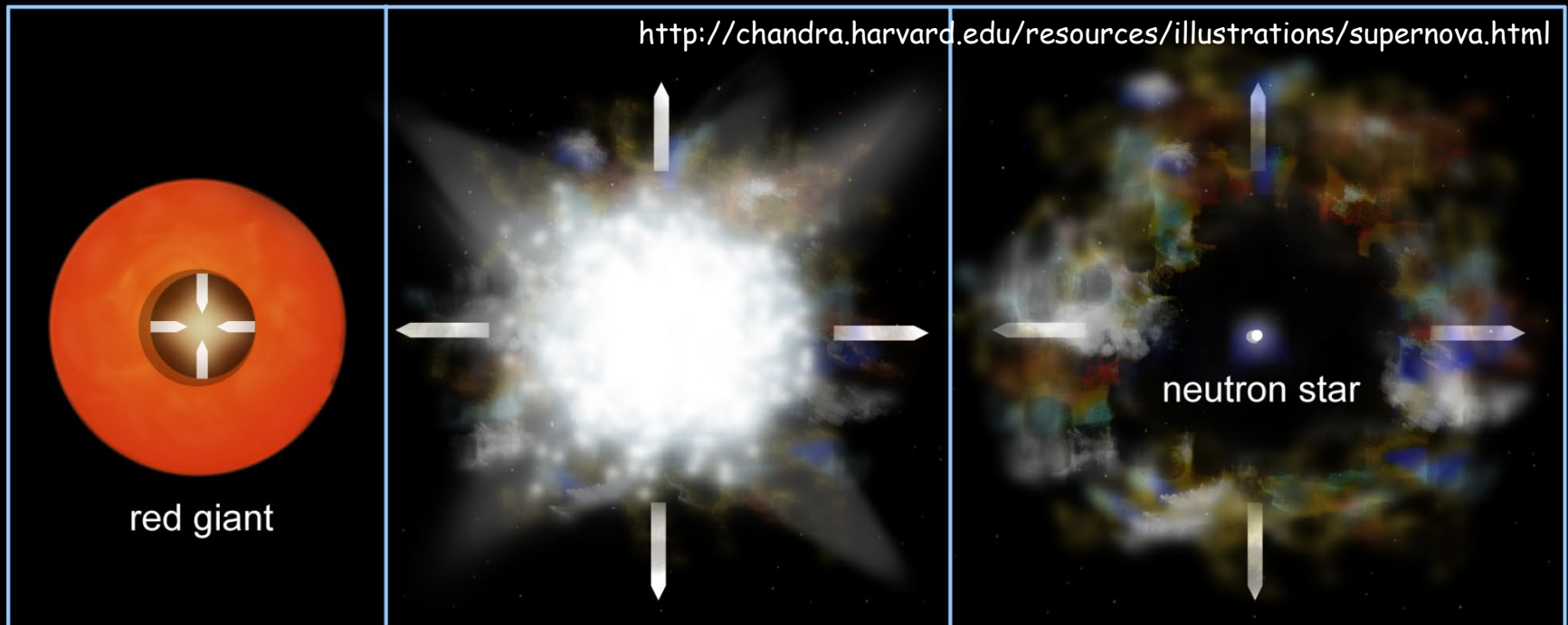


Core Collapse Supernovae

☆ Type II, Ib & Ic

🌐 Core left as neutron star, black hole or nothing

Birth of a Neutron Star and Supernova Remnant (not to scale)



Core Implosion → Supernova Explosion → Supernova Remnant

White Dwarf Supernovae

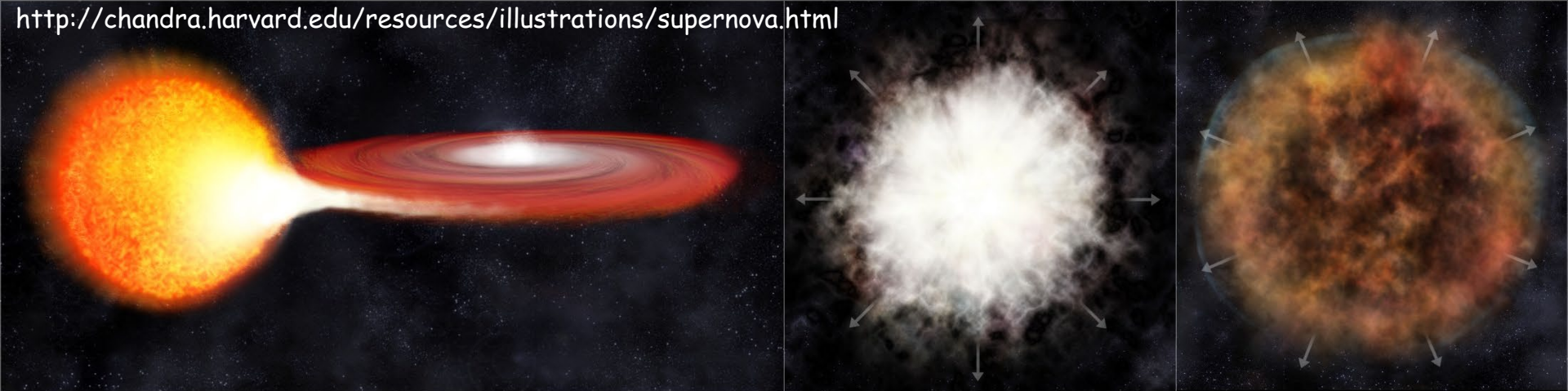
☆ Type Ia

- 🌍 Fusion starting in White Dwarf as it approaches $1.4 M_{\odot}$ (Chandrasekhar Limit)
- 🌍 Merger of two WDs
- 🌍 WD draws matter off companion
- 🌍 Most of Earth's Fe is from these!



TYPE IA (THERMONUCLEAR) SUPERNOVA

[http://chandra.harvard.edu/resources/illustations/supernova.html](http://chandra.harvard.edu/resources/illustrations/supernova.html)



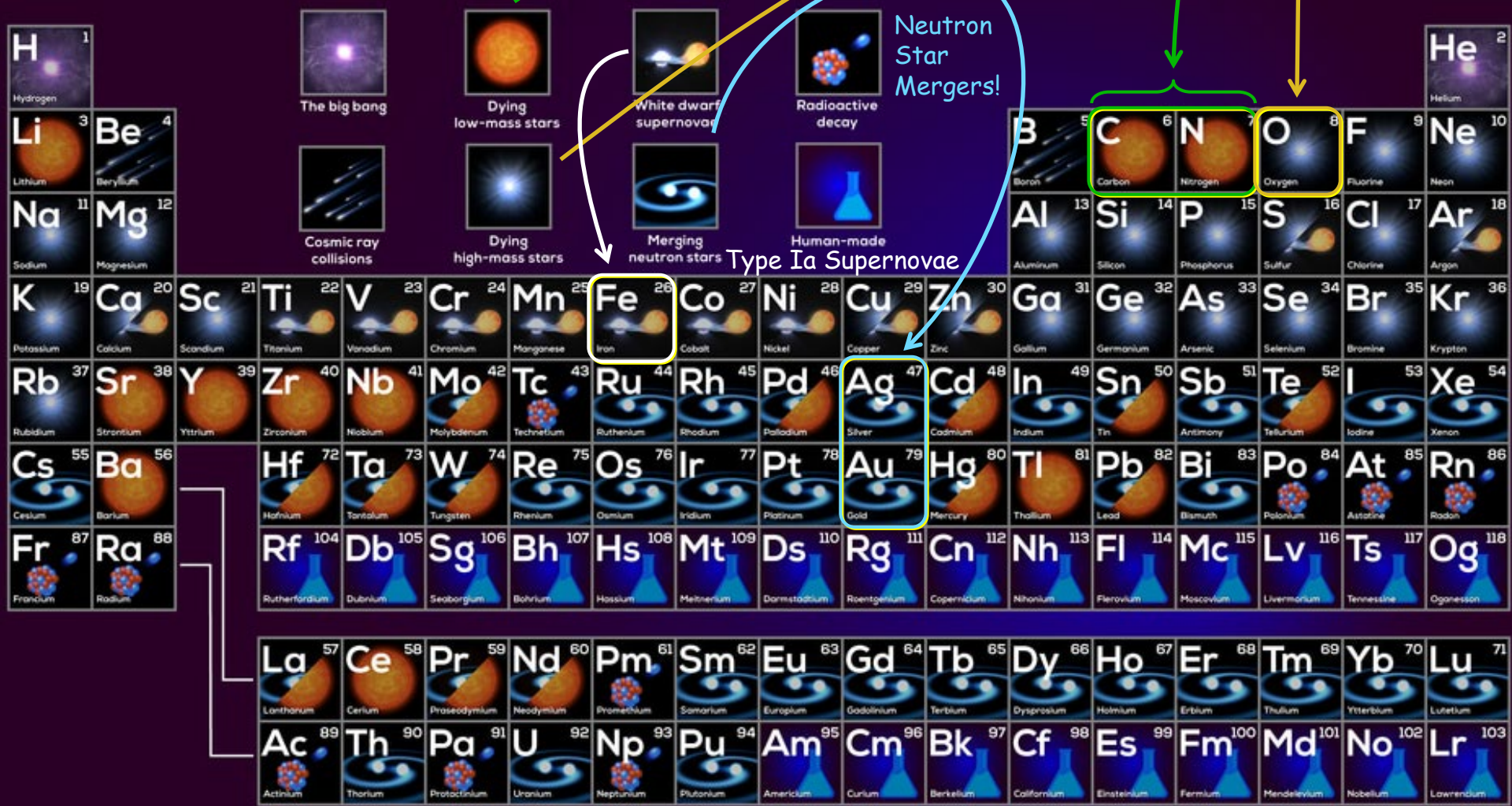
super-critical accretion onto a white dwarf star

thermonuclear supernova explosion

supernova remnant without a neutron star



ORIGINS OF THE ELEMENTS



This periodic table depicts the primary source on Earth for each element. In cases where two sources contribute fairly equally, both appear.

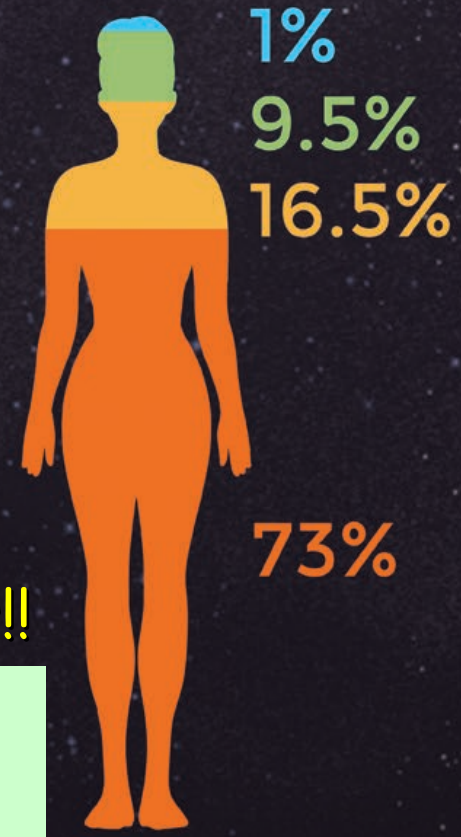
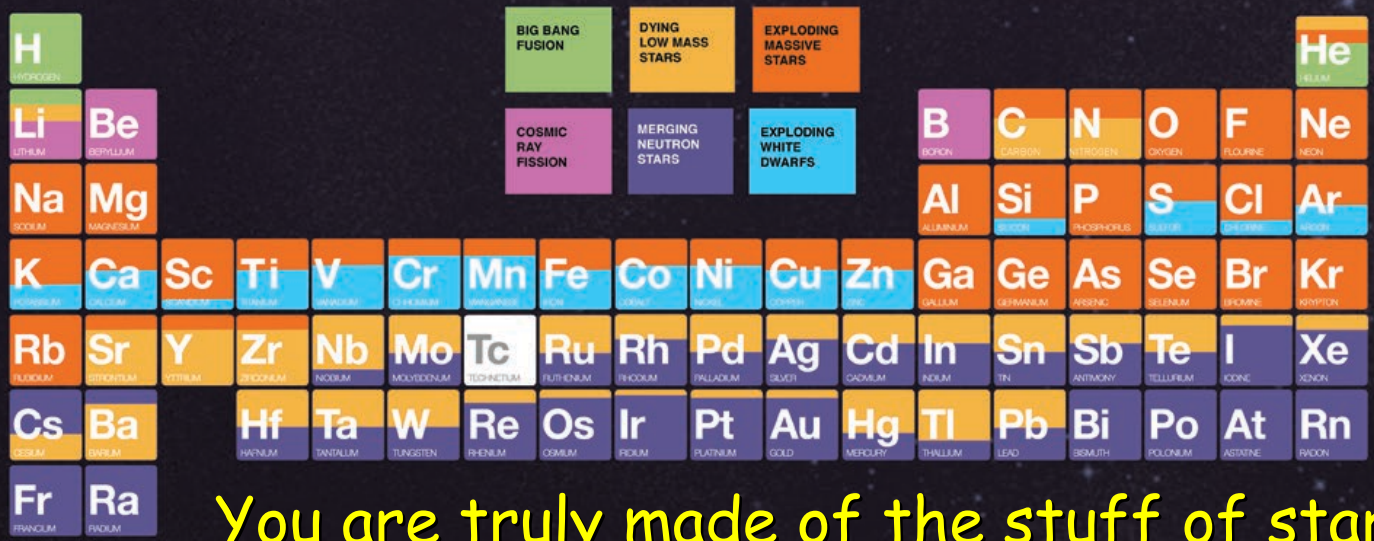


ORIGINS OF THE ELEMENTS

Planetary Nebulae

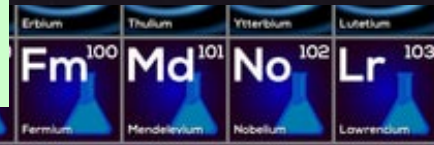
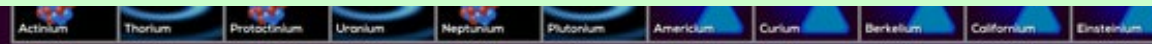
Core collapse SNe

ORIGINS: SOLAR SYSTEM ELEMENTS



You are truly made of the stuff of stars!!

Breathe in ...
 Breathe out ...
 the universe is flowing through you ...

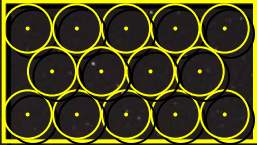


This periodic table depicts the primary source on Earth for each element. In cases where two sources contribute fairly equally, both appear.

States of Matter

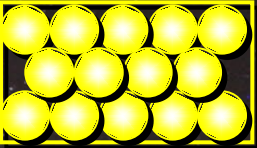
☆ Normal Gas  $R_{\text{Sol}} = 100R_{\text{Earth}}$

🌍 Lots of space between atoms

☆ Degenerate e^- gas 

$$\rho_{\text{WD}} = \frac{M_{\text{Sol}}}{V_{\text{Earth}}} = 1800 \frac{\text{kg}}{\text{cm}^3}$$

🌍 Space squeezed out from between atoms

☆ Degenerate n^0 gas 

$$\rho_{\text{NS}} = \frac{M_{\text{Sol}}}{V_{10\text{mi}}} = 100 \text{ billion } \frac{\text{kg}}{\text{cm}^3}$$

🌍 Space squeezed out from within atoms

☆ Black Hole $R_{\text{Sol}} \approx 0$

$$\rho_{\text{BH}} = \frac{M_{\text{Sol}}}{\text{zero}} \Rightarrow \infty \dots \text{OOPS!}$$

🌍 Atoms squeezed out of space

🌍 Quantum Foam

» spacetime & matterenergy recombined

Outline

☆ Review Star Deaths

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☆ The Adventure Continues

General Relativity

☆ Acceleration bends light

Light beam
appears to
bend

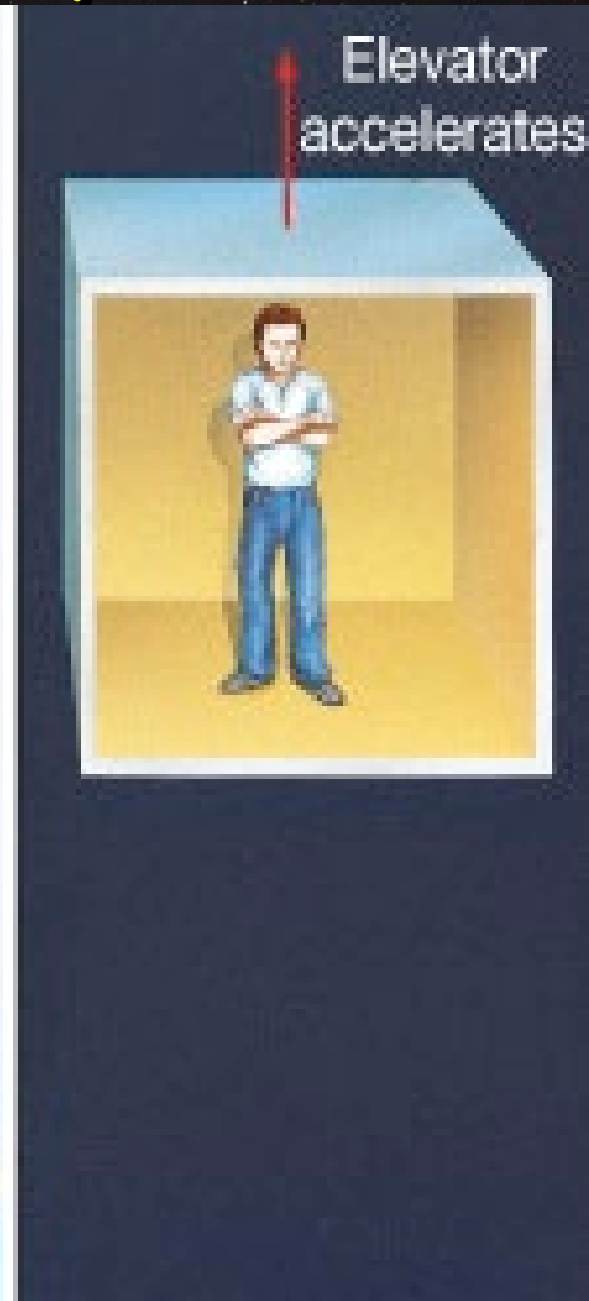
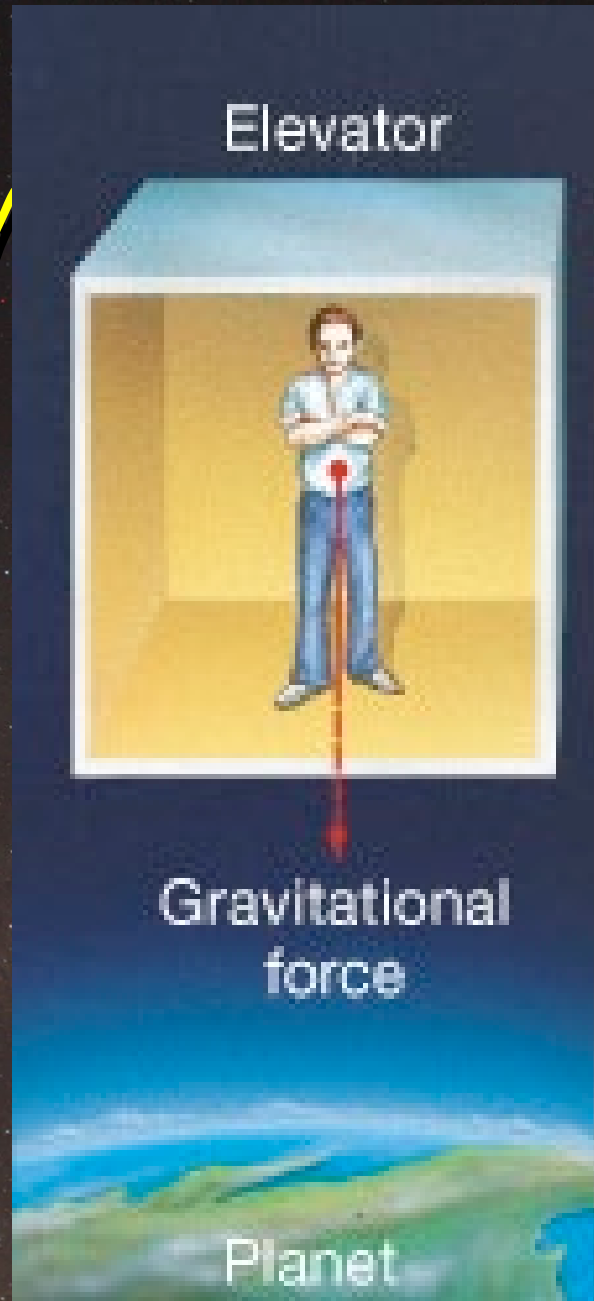
Ship
accelerates
upward while
beam is
crossing

Observer sees
beam crossing
ship



General Relativity

- ☆ Observations can't tell gravity from acceleration
- ☆ Acceleration bends light so
→ Gravity must bend light!

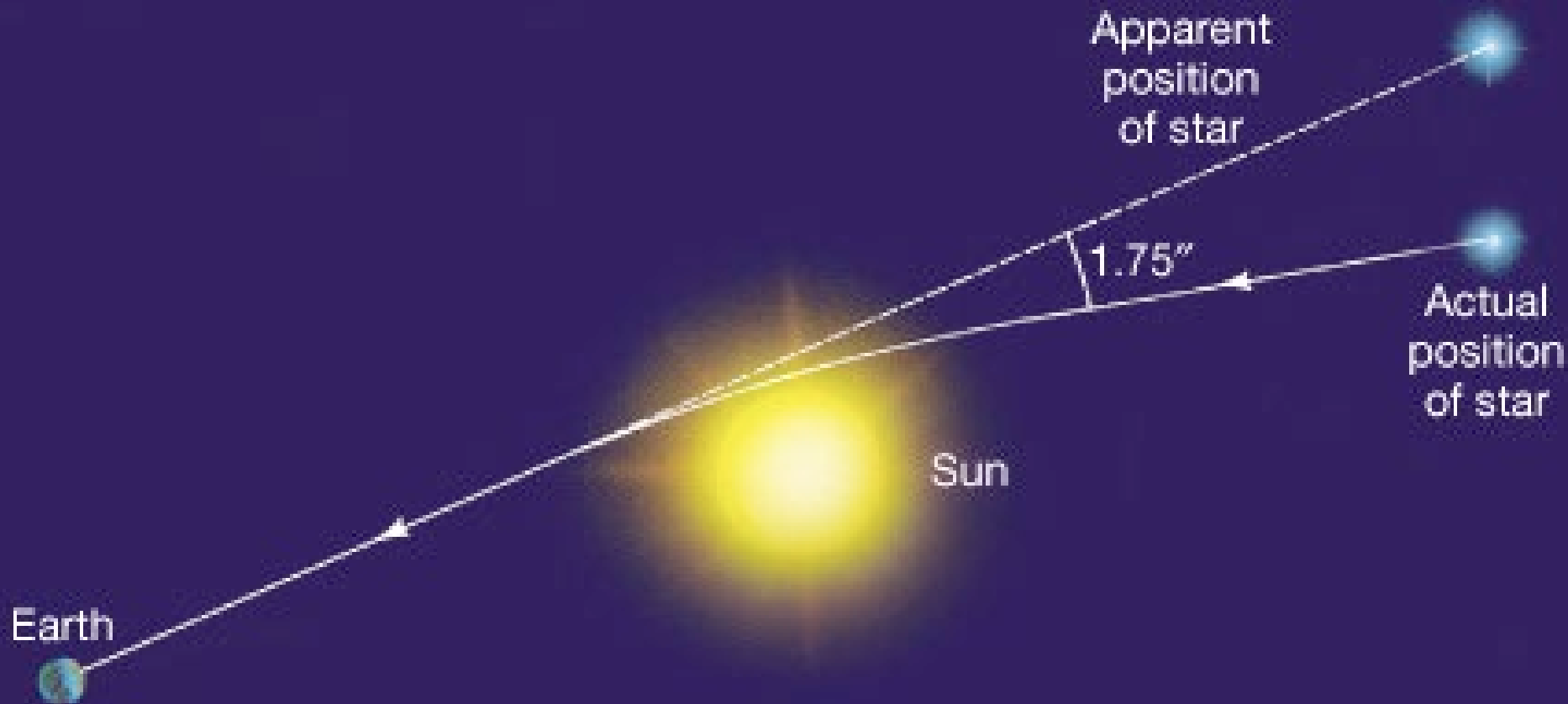


Gravity Bends Path of Light

☆ Star positions change when near Sun!

🌍 Seen during total eclipse

🌍 A confirmation of General Relativity

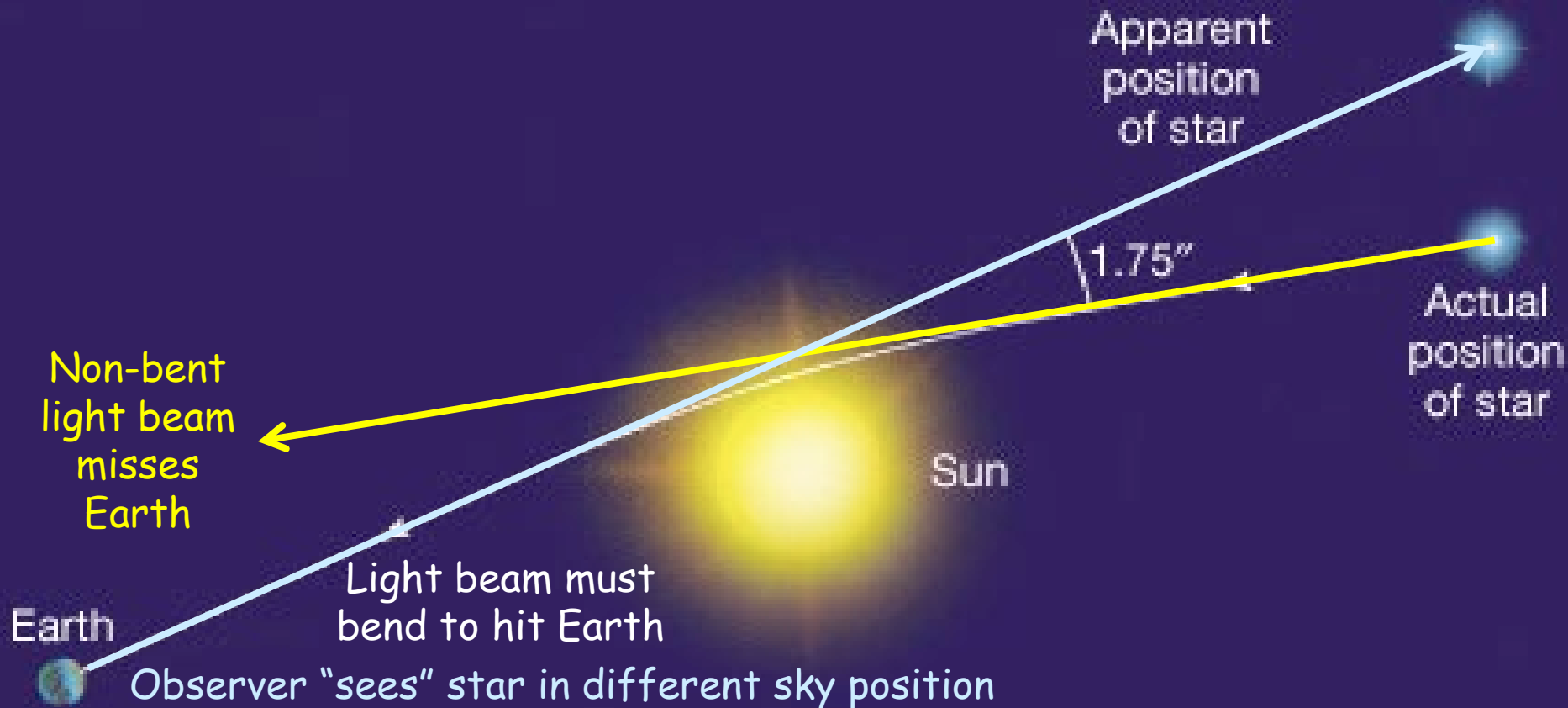


Gravity Bends Path of Light

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🌍 Seen during total eclipse

🌍 A confirmation of General Relativity



G

☆ Star



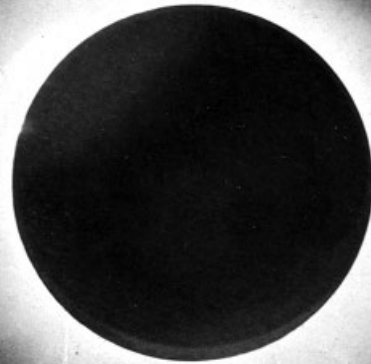
Stars with positions
deflected by the
presence of the Sun.

Light
r Sun!

ity

Non-ben
light bear
misses
Earth

Earth
Obs



Orbits

☆ Gravity bends the path of matter into orbits

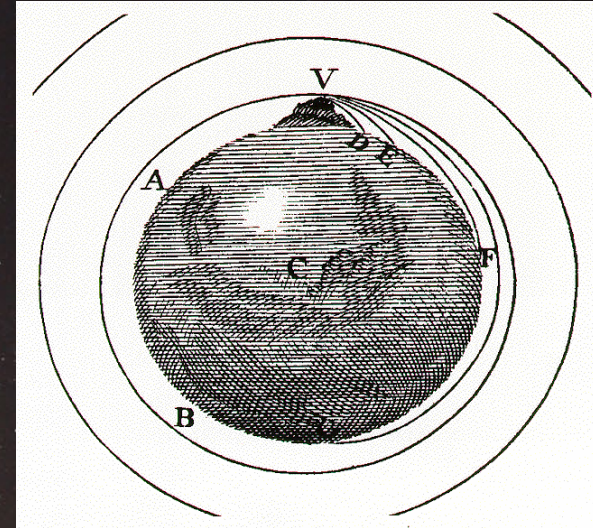
Newton's Mountain

☆ Orbit is falling without hitting surface

🌍 Orbital speed

$$v_{\text{orbit}} = \sqrt{\frac{GM}{r}}$$

$$v_{\text{low Earth orbit}} = 7,900 \text{ m/s} = 17,700 \text{ mph}$$



🌍 Light sphere = Orbit where speed is c

Gravity Bends Path of Light

☆ Light can "orbit" black holes

$$r_{\text{Light Sphere}} = \frac{3GM}{c^2}$$

For a 1 Solar Mass Black Hole

$$r_{\text{Light Sphere}} = 4500 \text{ m}$$

Star



Star light

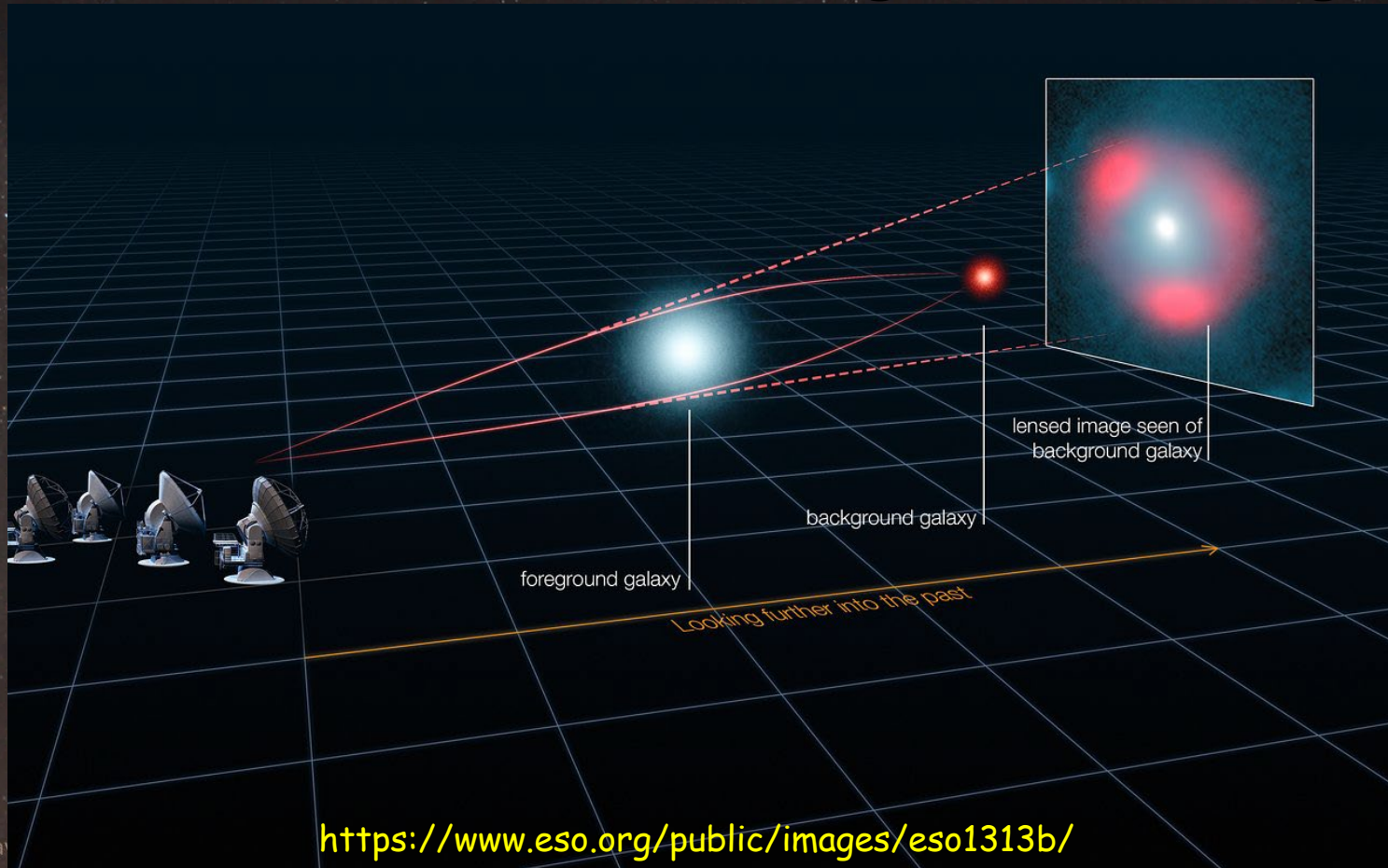
Star's
image



Gravitational Lensing

☆ Galaxy Lensing

🌐 Light rays bend around nearby galaxy
focus to create image of distant galaxy

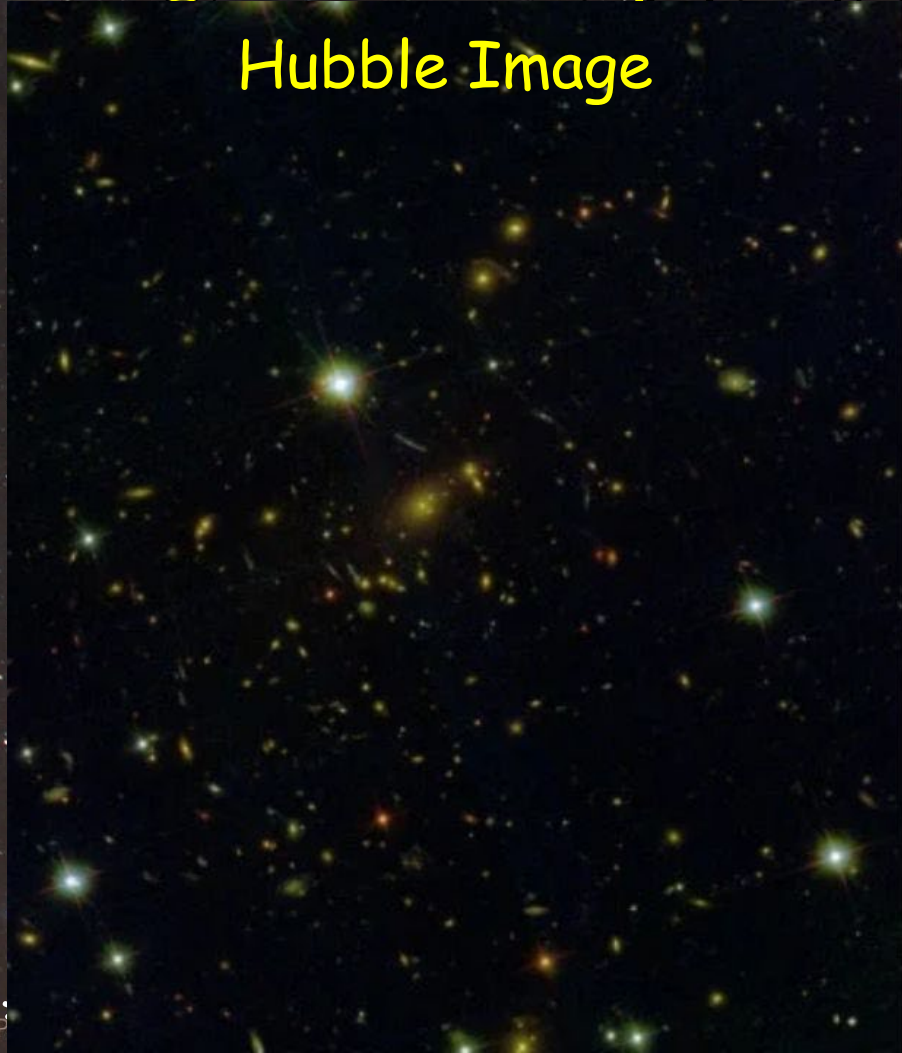


JWST Galaxy Images

☆ Galaxy Cluster SMACS* 0723

🌐 ~ 4 billion ly from Earth

Hubble Image



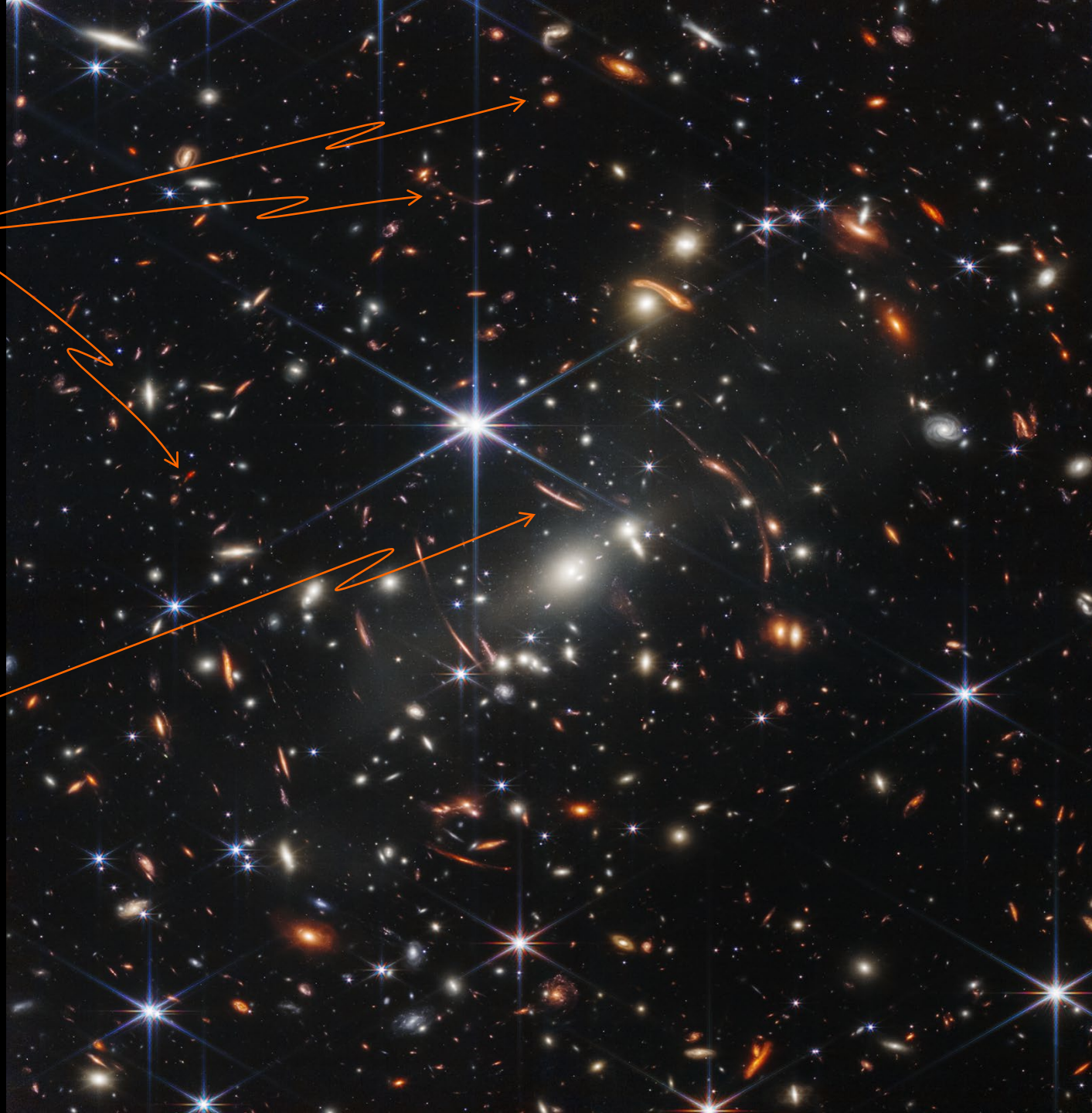
JWST Image



Every
spike-less
smudge
is a galaxy!

Arcs &
smears are
images of
more distant
galaxies!

Stars have
spikes due to
telescope
structure





Individual star clusters
can be studied in lensed
galaxies!

Outline

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Escape Velocity

☆ Speed for an object to escape to infinity

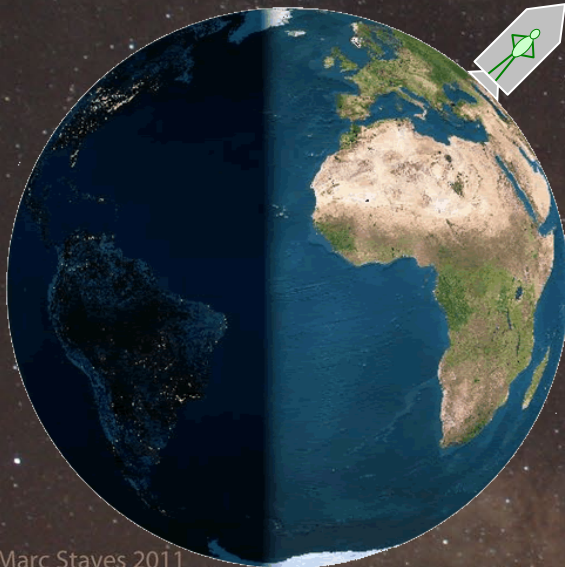
🌐 Event horizon $\Rightarrow$ escape speed = c

$$v_{\text{escape}} = \sqrt{\frac{2GM}{R}}$$

G = Gravitational Constant

M = Mass of world

R = Radius of world



$$v_{e,\text{Earth}} = 11.2 \text{ km/s} = 25,000 \text{ mph}$$

$$v_{e,\text{Jupiter}} = 59.5 \text{ km/s} = 133,000 \text{ mph}$$

$$v_{e,\text{Sol}} = 617.5 \text{ km/s} = 1,381,000 \text{ mph}$$

$$v_{e,\text{BH}} = c = 300,000 \text{ km/s} \\ = 671,000,000 \text{ mph}$$

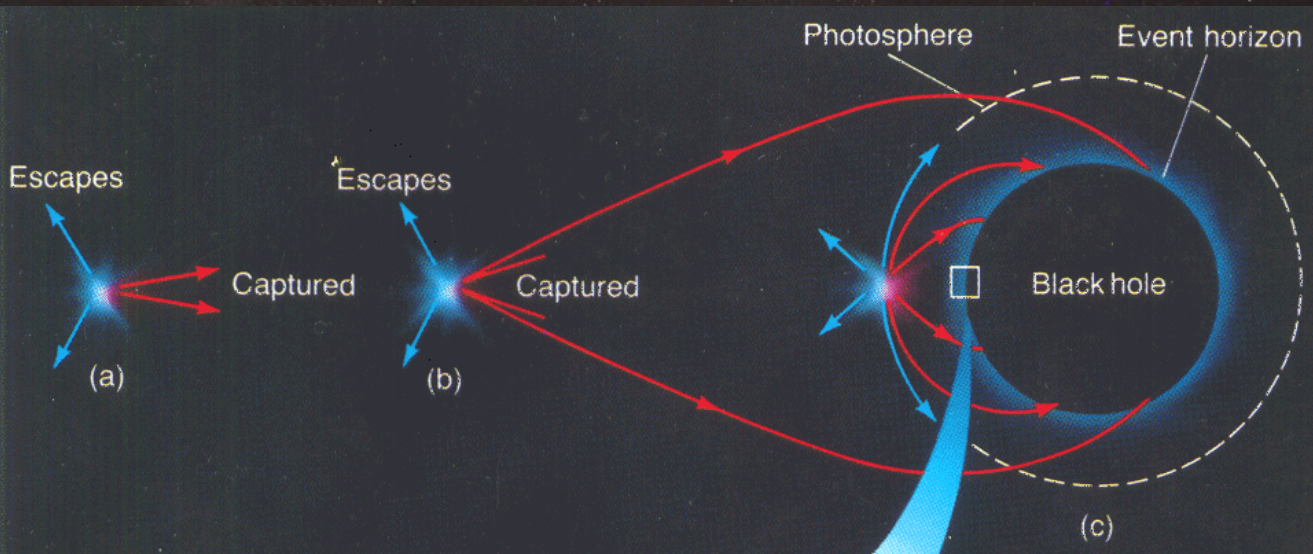
Gravity Bends Path of Light

★ Light can't escape black holes

$$R_{\text{Event Horizon}} = \frac{2GM}{c^2}$$

For a 1 Solar Mass Black Hole

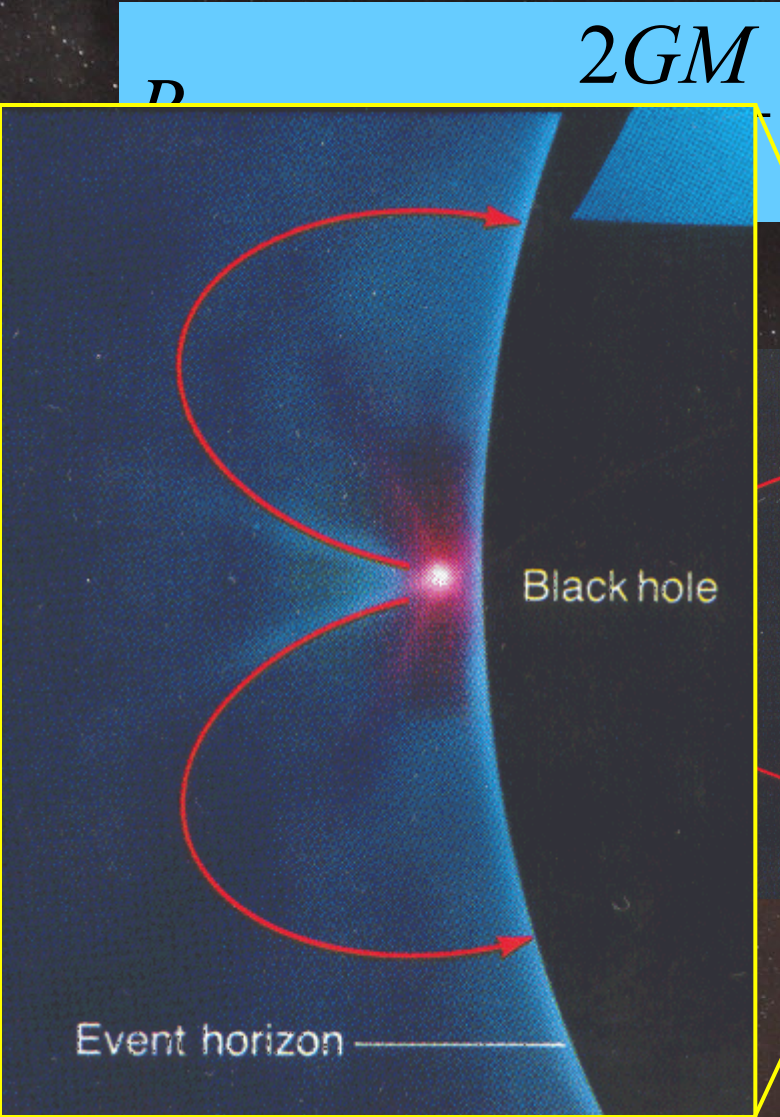
$$R_{\text{Event Horizon}} = 2952 \text{ m}$$



Light leaving
black hole
escapes
outside EH

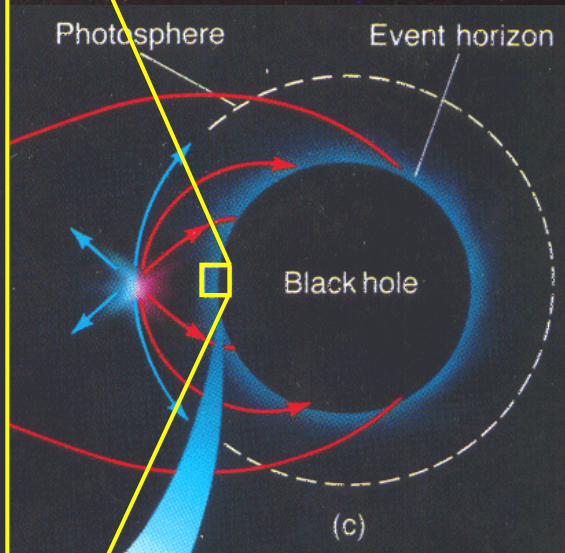
Gravity Bends Path of Light

★ Light can't escape black holes



For a 1 Solar Mass Black Hole

$$R_{\text{Event Horizon}} = 2952 \text{ m}$$

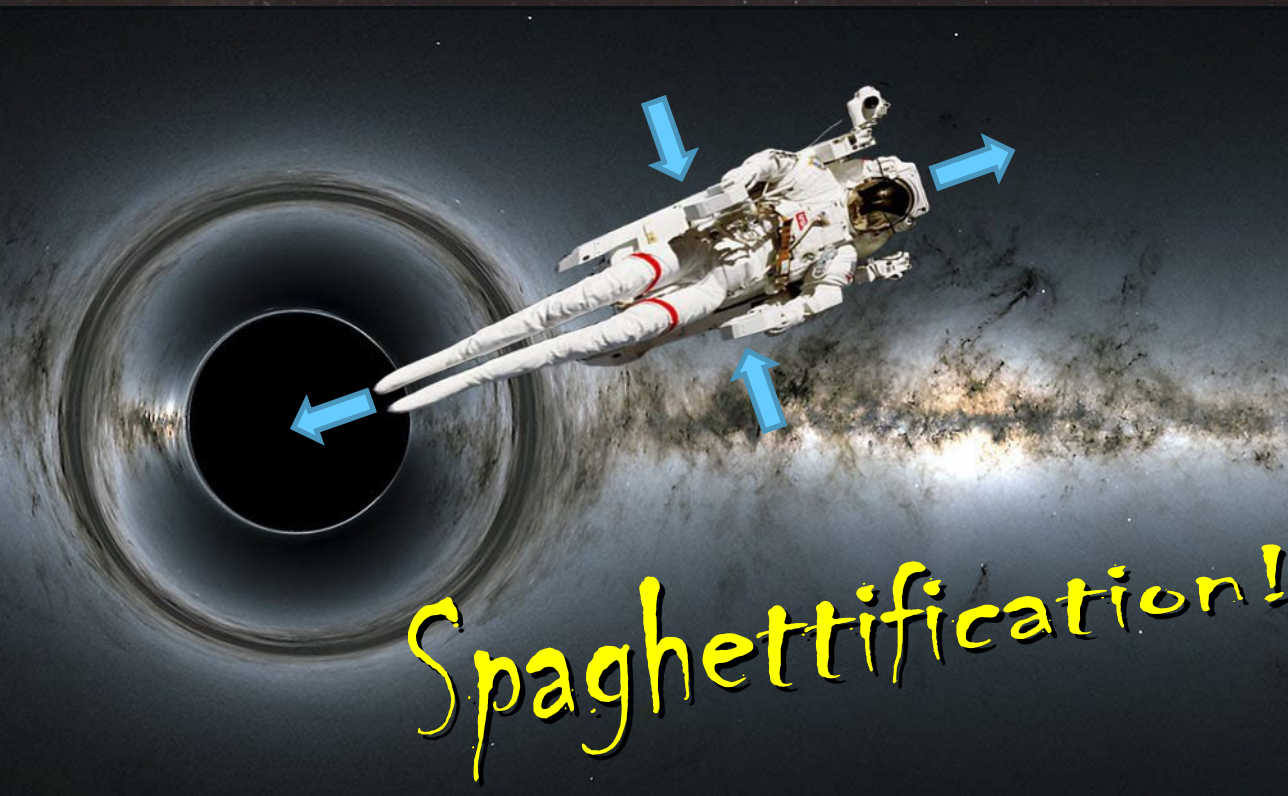


Light leaving
black hole
escapes
outside EH

Light at EH
can't escape

Escape Velocity & Event Horizon

- ☆ Event Horizon is where escape speed = c
 - 🌐 Light inside EH can not escape BH
- ☆ Objects falling into BH feel tidal forces
 - 🌐 Can get to EH and fall in!!



Tidal
Forces
squeeze and
lengthen
astronaut
falling in ...

Spaghettification!

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Black Holes

☆ Detecting Black Holes

🌍 Bright X-Ray sources orbiting stars

- » Cygnus X-1 ... no star at X-ray source
- » X-Rays from accretion
- » particles accelerate as they spiral in
 - ∩ Emit at higher and higher frequencies (energies)
 - ∩ X-Rays = "death scream" of infalling matter

🌍 Direct imaging by Event Horizon Telescope

- » M87 and SgrA*

🌍 Bipolar Jets

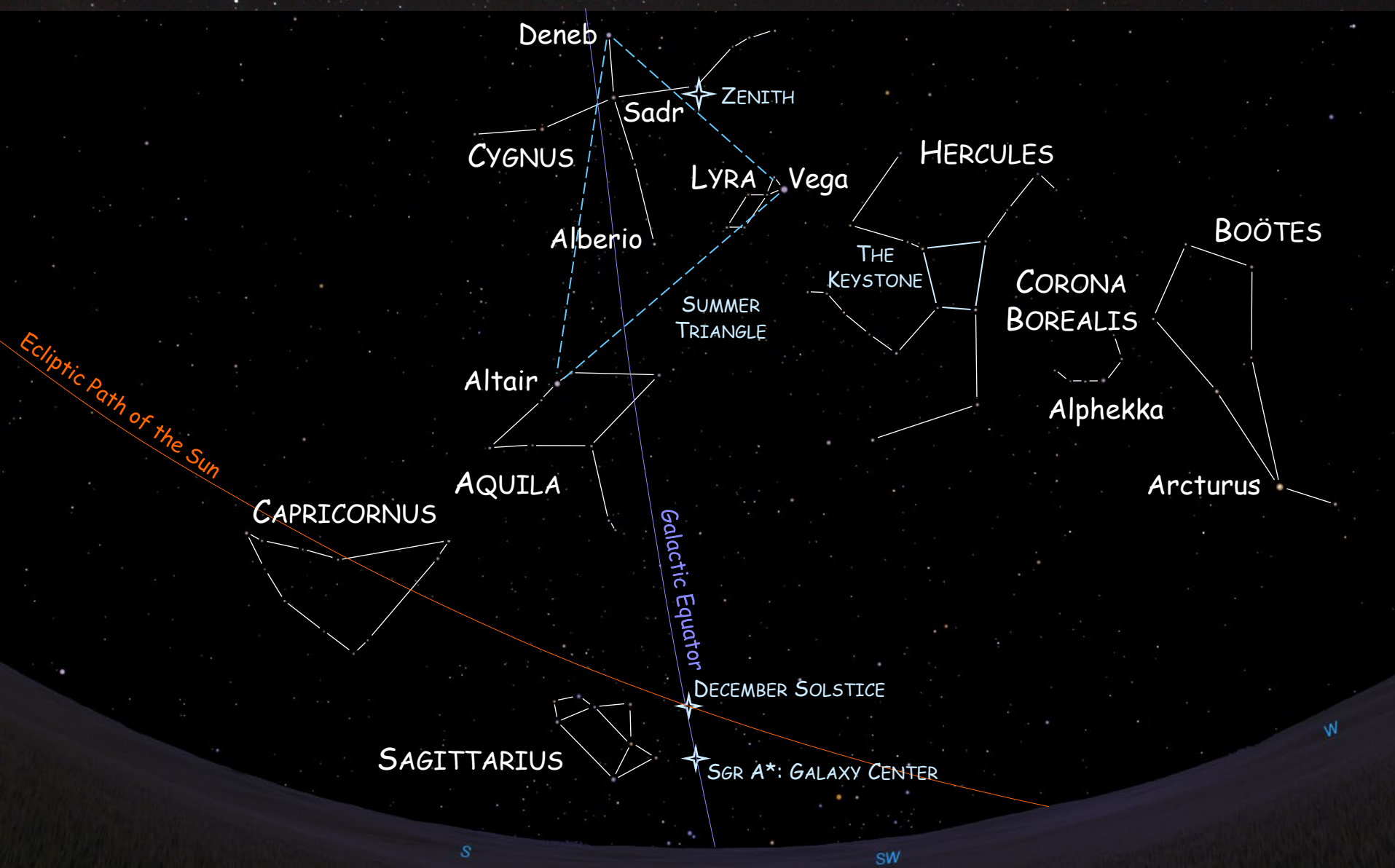
- » Supermassive Black Holes in Galaxies
 - ∩ Jets of material create radio "plumes"
 - ∩ AOD's PhD. Thesis project

Black Holes

☆ Detecting Black Holes

- 🌐 Bright X-Ray sources orbiting stars
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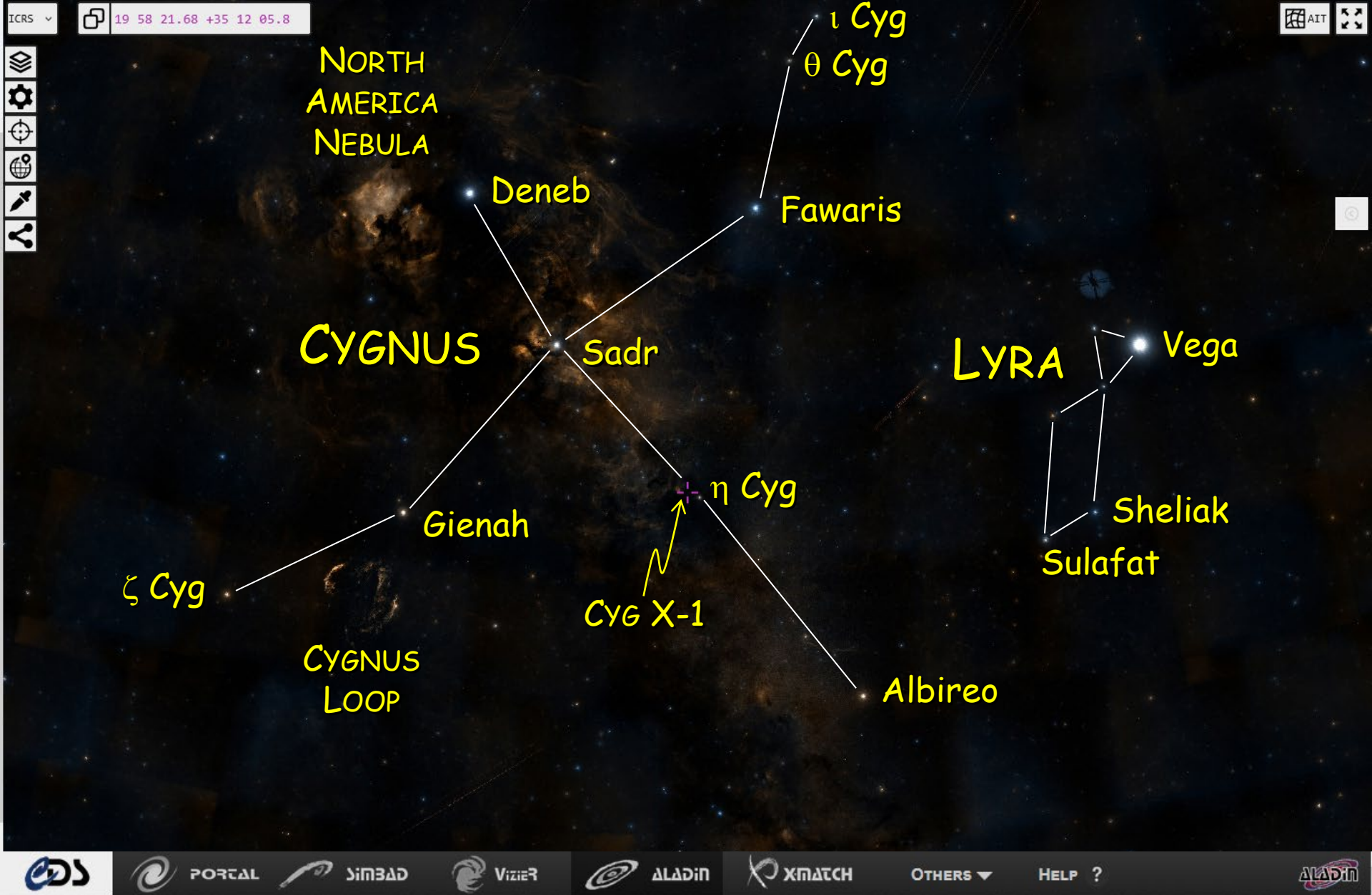
The Sky Tonight



Black Holes Stellar Remnants

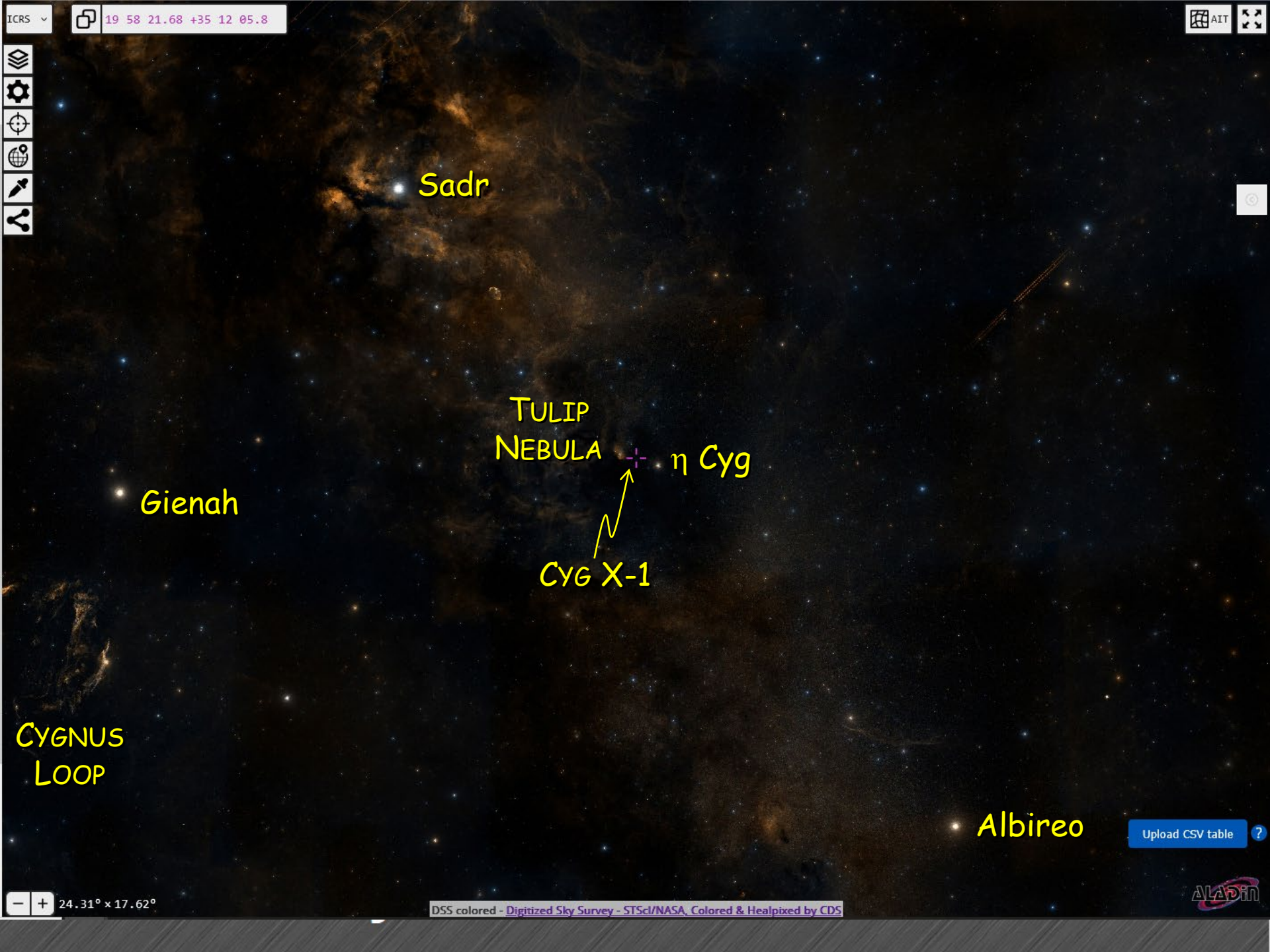


Black Hole in Cyg is
bright in X-rays



Aladin Sky Atlas

<https://aladin.cds.unistra.fr/AladinLite/>



Sadr

Gienah

TULIP
NEBULA

η Cyg

CYG X-1

CYGNUS
LOOP

Albireo

Upload CSV table ?



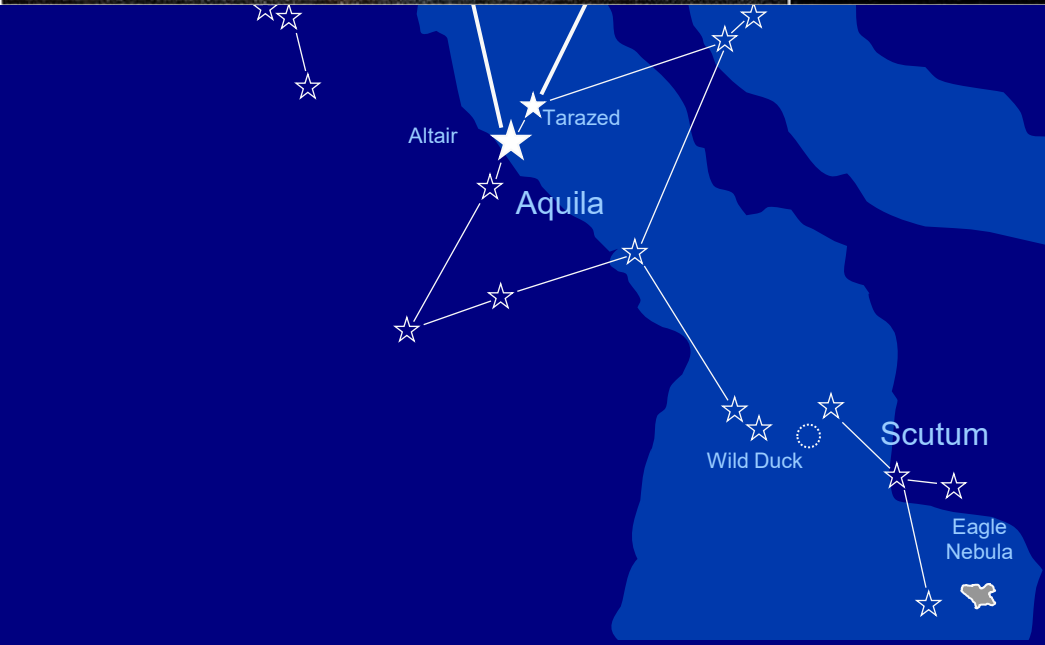
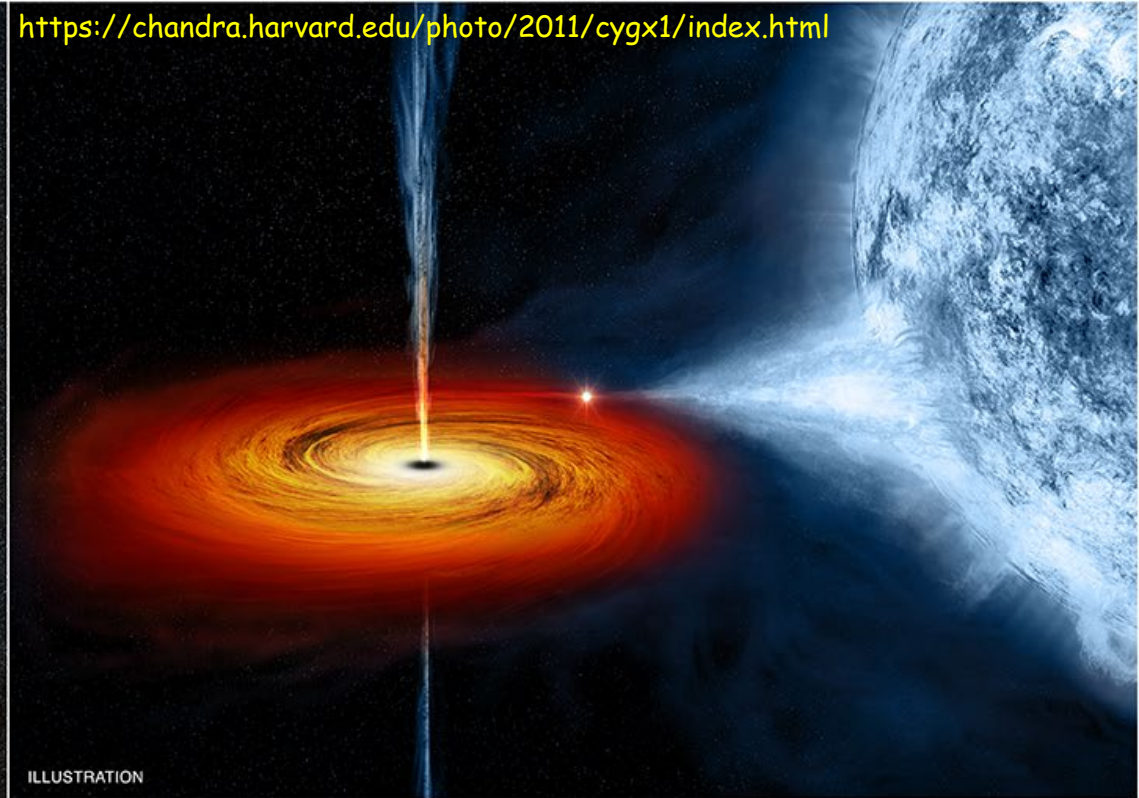
TULIP
NEBULA

CYG X-1

η Cyg

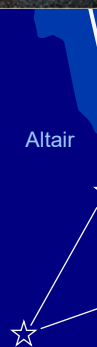
Upload CSV table







OPTICAL



Altair

Wild Duck

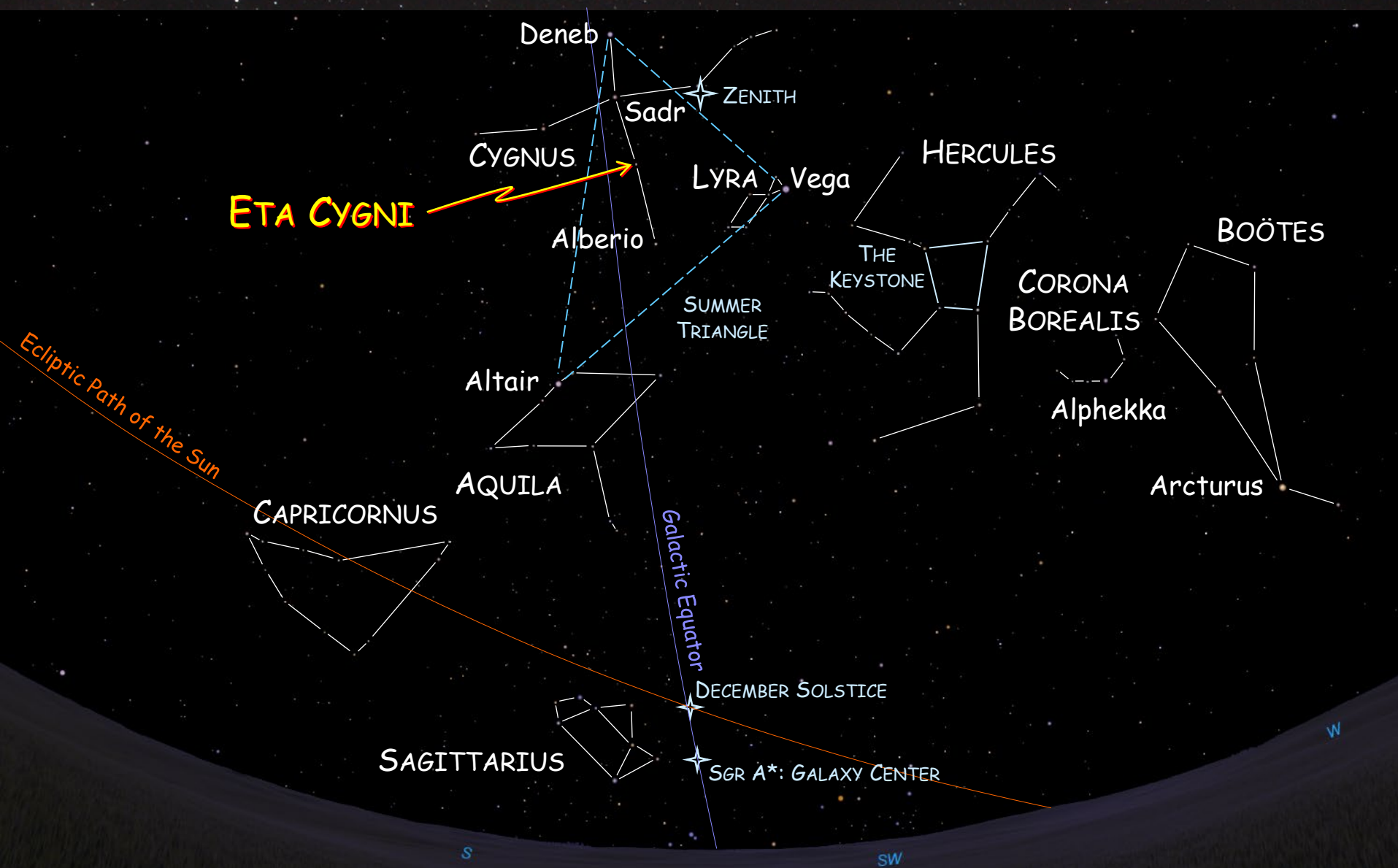
Scutum

Eagle
Nebula

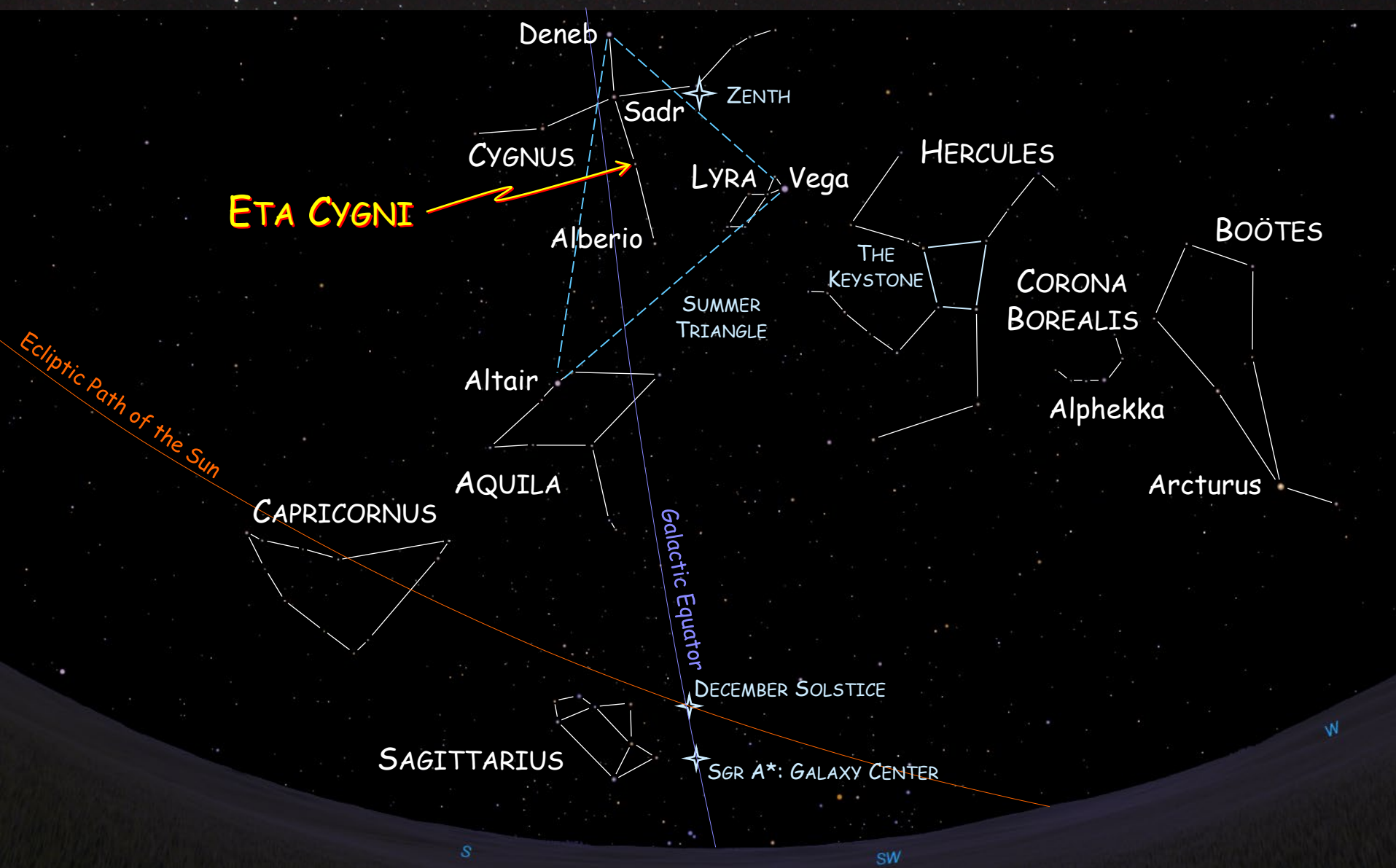
Black Hole in Cyg is
bright in X-rays



The Sky Tonight



The Sky Tonight



Black Holes

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 - ∩ Jets of material create radio "plumes"
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M87, Virgo A, Virgo X-1

☆ Supergiant elliptical galaxy

- 🌐 53.5 Million light years (ly) away
- 🌐 6 trillion times the mass of the Sun ($M_{\odot}$)
 - › Milky Way has about 1.4 trillion $M_{\odot}$
- 🌐 Stellar envelope 490,000 ly in diameter
 - › Milky Way's is 330,000 ly in diameter

☆ Observations

- 🌐 Optical: M87, NGC 4486
- 🌐 Radio: Virgo A
- 🌐 X-ray: Virgo X-1

Radio Galaxies

☆ Radiate in radio frequencies

- ① Like waves from cell tower to your phone
 - › e.g. AT&T 4G/LTE 710-716 MHz & 740-746 MHz
 - › e.g. Verizon 746-757 MHz & 776-787 MHz

☆ Detected by receivers

- ① Images created from data in computers
 - › NOT like images viewed on your phone!!

http://www.aroundtheworldineightyyears.com/wp-content/uploads/2012/01/DSC_0132-1-2.jpg



© Jim O'Donnell

Photo by Ma

Radio Galaxies

☆ Electrons “glow” in radio

🌐 electrons spiral along magnetic field lines



Radiate due to acceleration
(centripetal acceleration)
“beamed” in forward direction
(relativistic motion)

synchrotron radiation

M87

- ☆ Virgo A radio emissions detected 1947
 - 🌐 Stanley & Slee 1950 Australia
- ☆ Confirmed to be from M87 1953
 - 🌐 Thought to originate in jet
- ☆ Virgo X-1 X-ray emissions detected in 1967
 - 🌐 Million-degree gas glowing

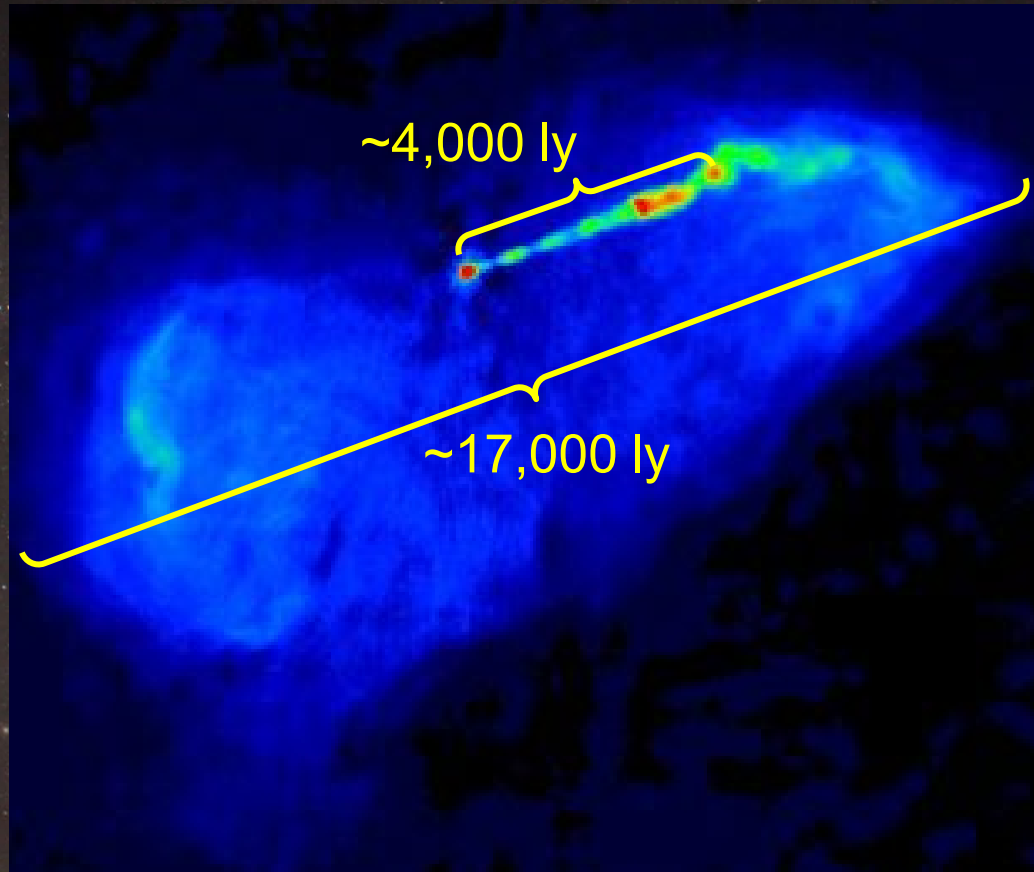
X-ray emission



M87: Virgo A

☆ VLA Radio images

🌐 The 20 cm image of M87 I knew in the 1980's



Angle of the jet changes due to orientation of telescope. Jet is same one seen in optical.

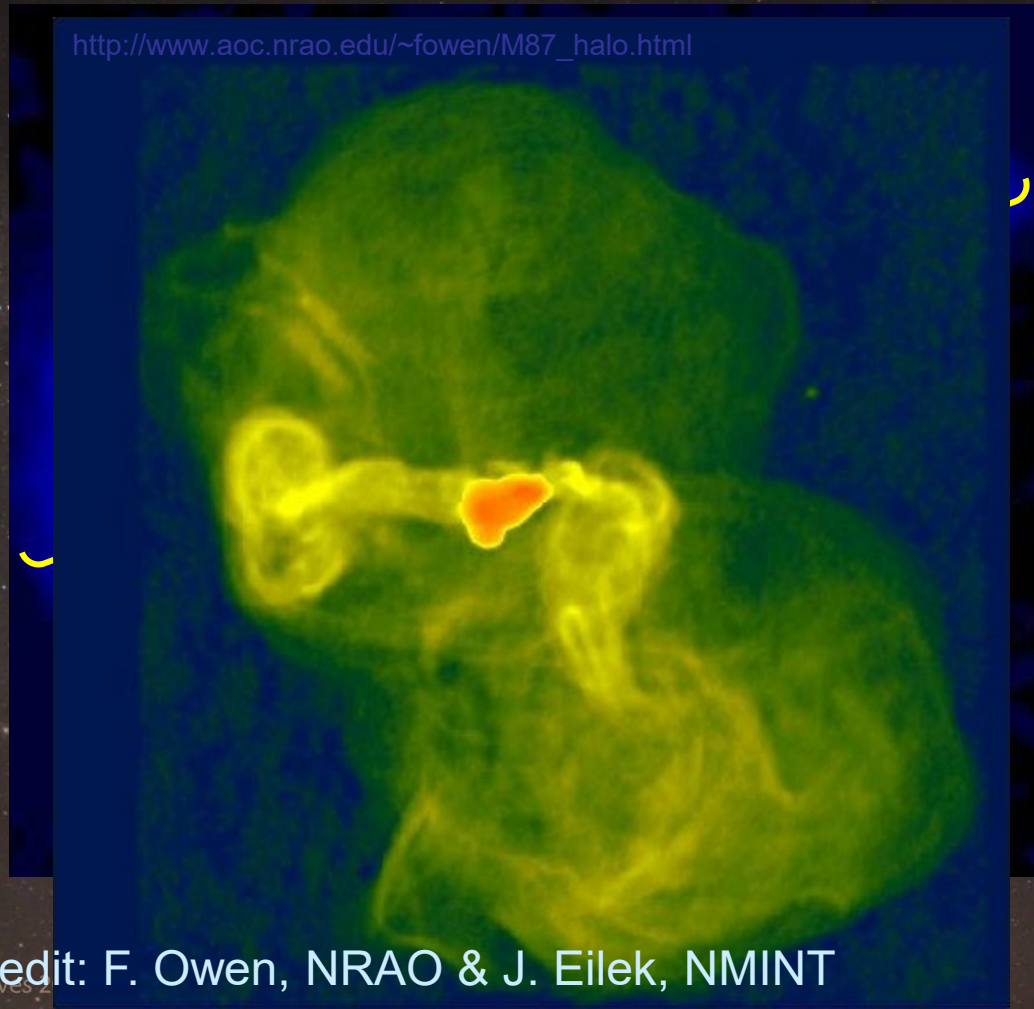
<http://www.aoc.nrao.edu/~jeilek/research/M87Virgo.html>

Image Credit: F. Owen, NRAO & J. Eilek, NMINT
Photo by Marc Staves 2011

M87: Virgo A

☆ VLA Radio images

🌐 The 90 cm image of M87



Wider field image
of lower energy
plasma shows
bubbles &
turbulence

Image Credit: F. Owen, NRAO & J. Eilek, NMINT

★ VL

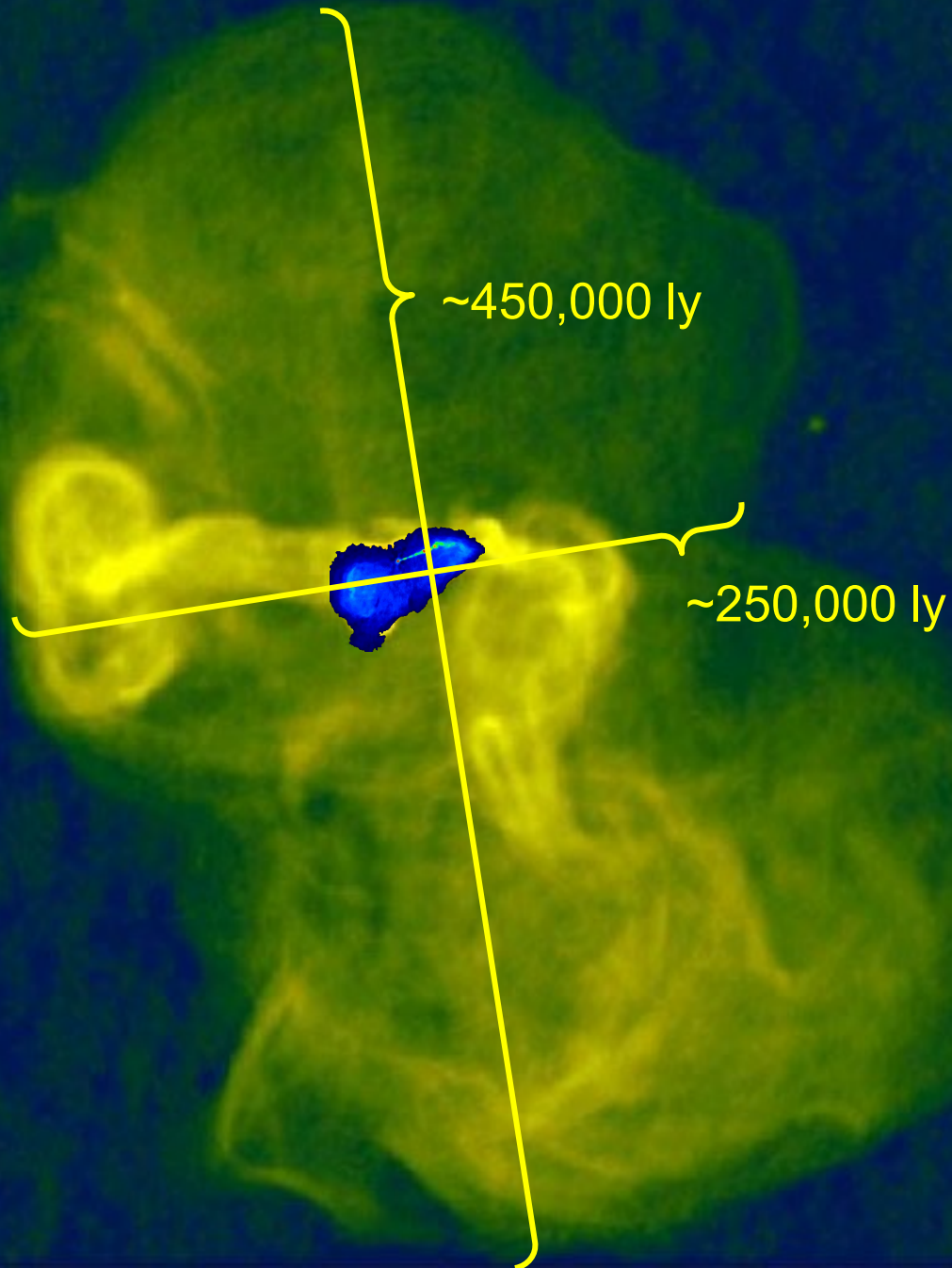
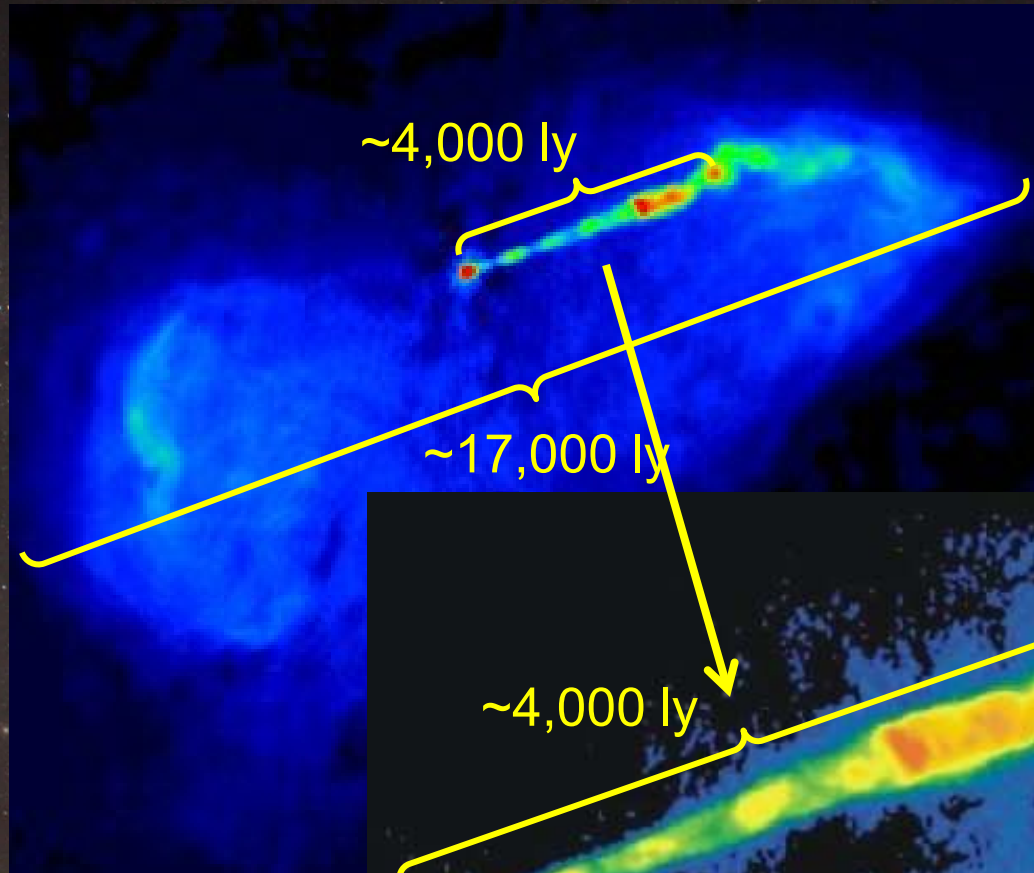


image
energy
flows
&
nce

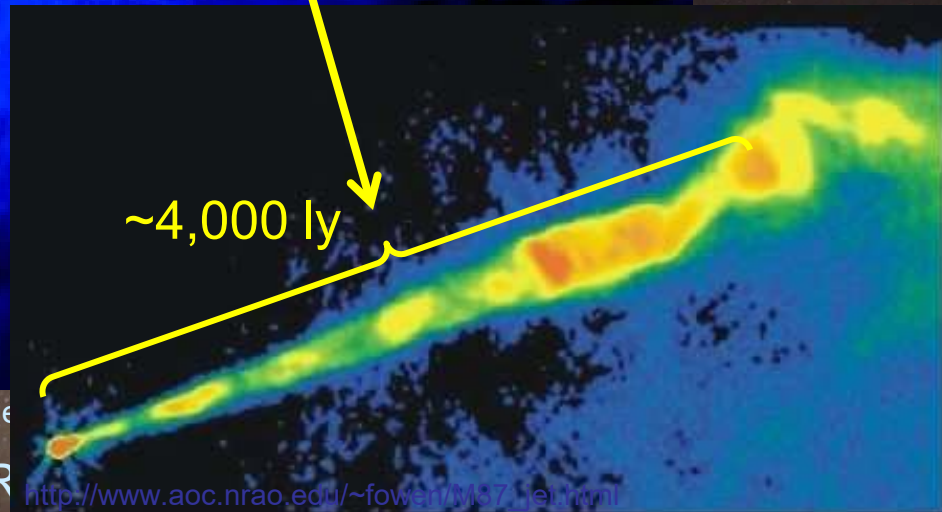
M87: Virgo A

☆ VLA Radio images

🌐 The 2 cm image of M87



Higher resolution image of higher energy plasma shows jet emerging from nucleus



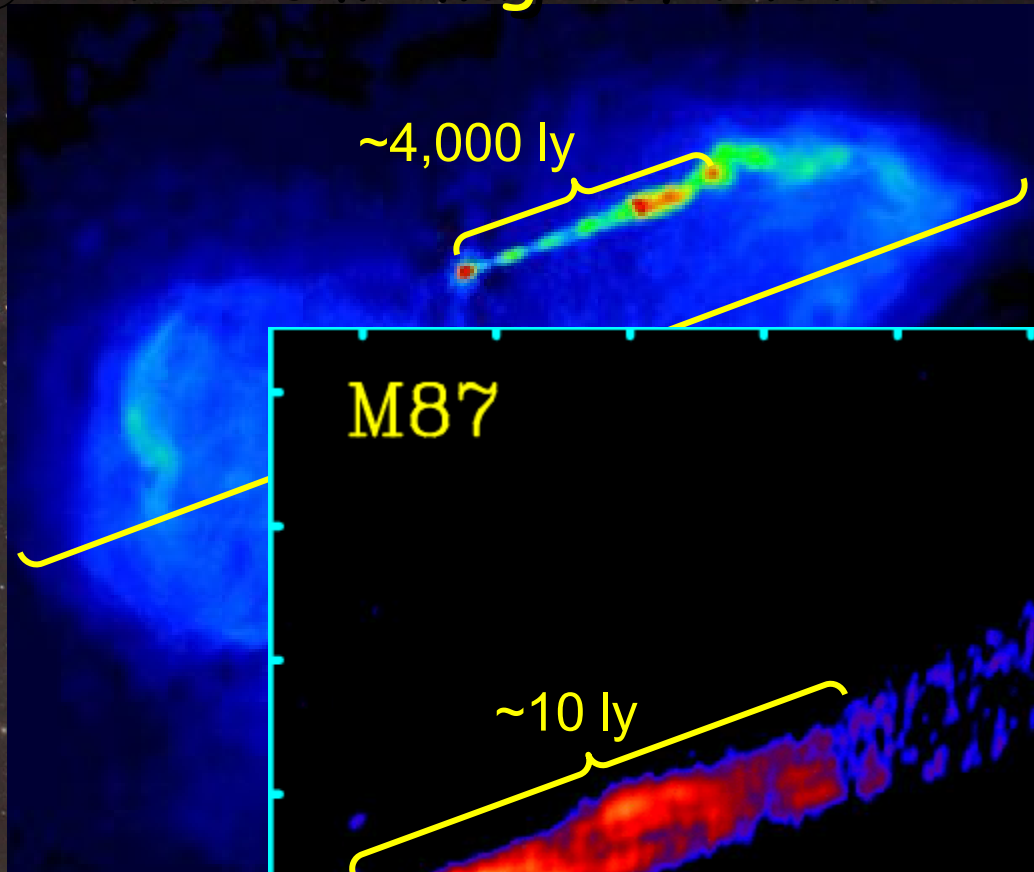
<http://www.aoc.nrao.edu>

http://www.aoc.nrao.edu/~fowen/M87_jet.html

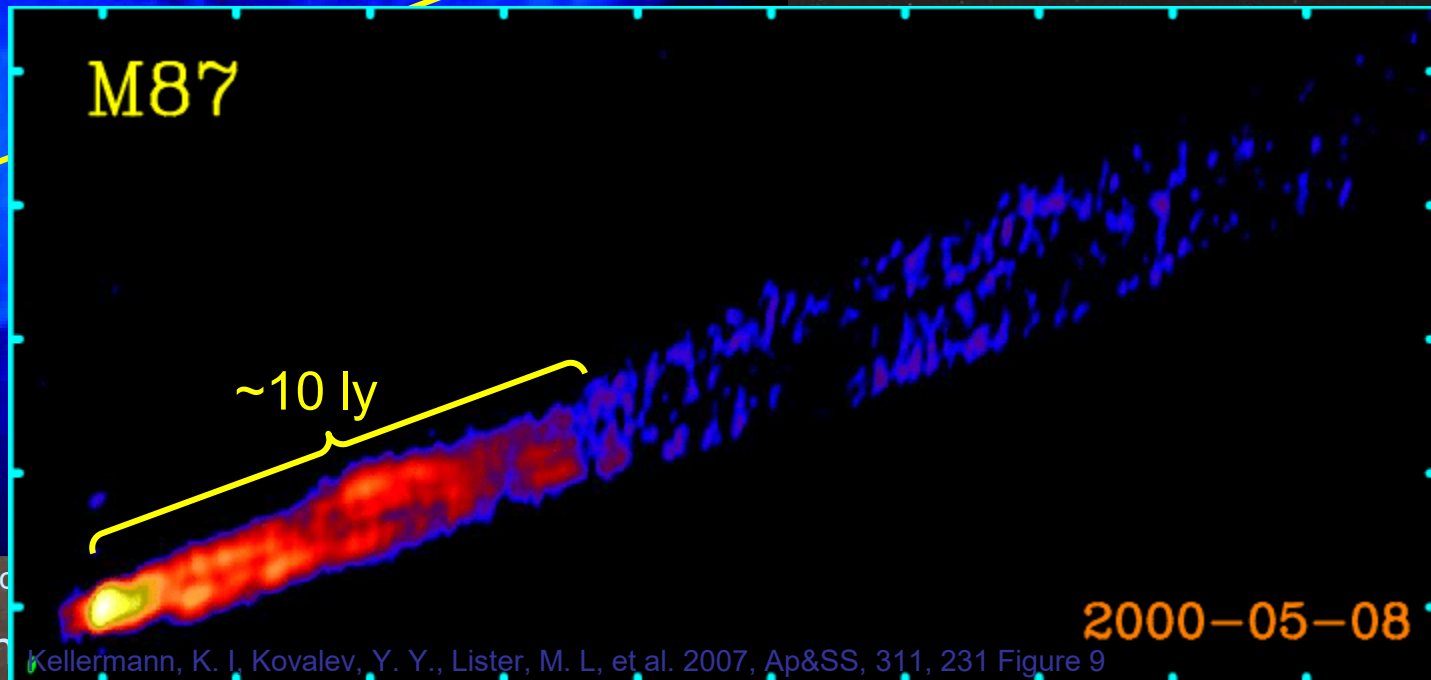
M87: Virgo A

☆ VLBA Radio images: higher resolution

🌐 The 2 cm image of M87



Even higher resolution image shows jet emerging from nucleus



<http://www.aoc>

2000-05-08

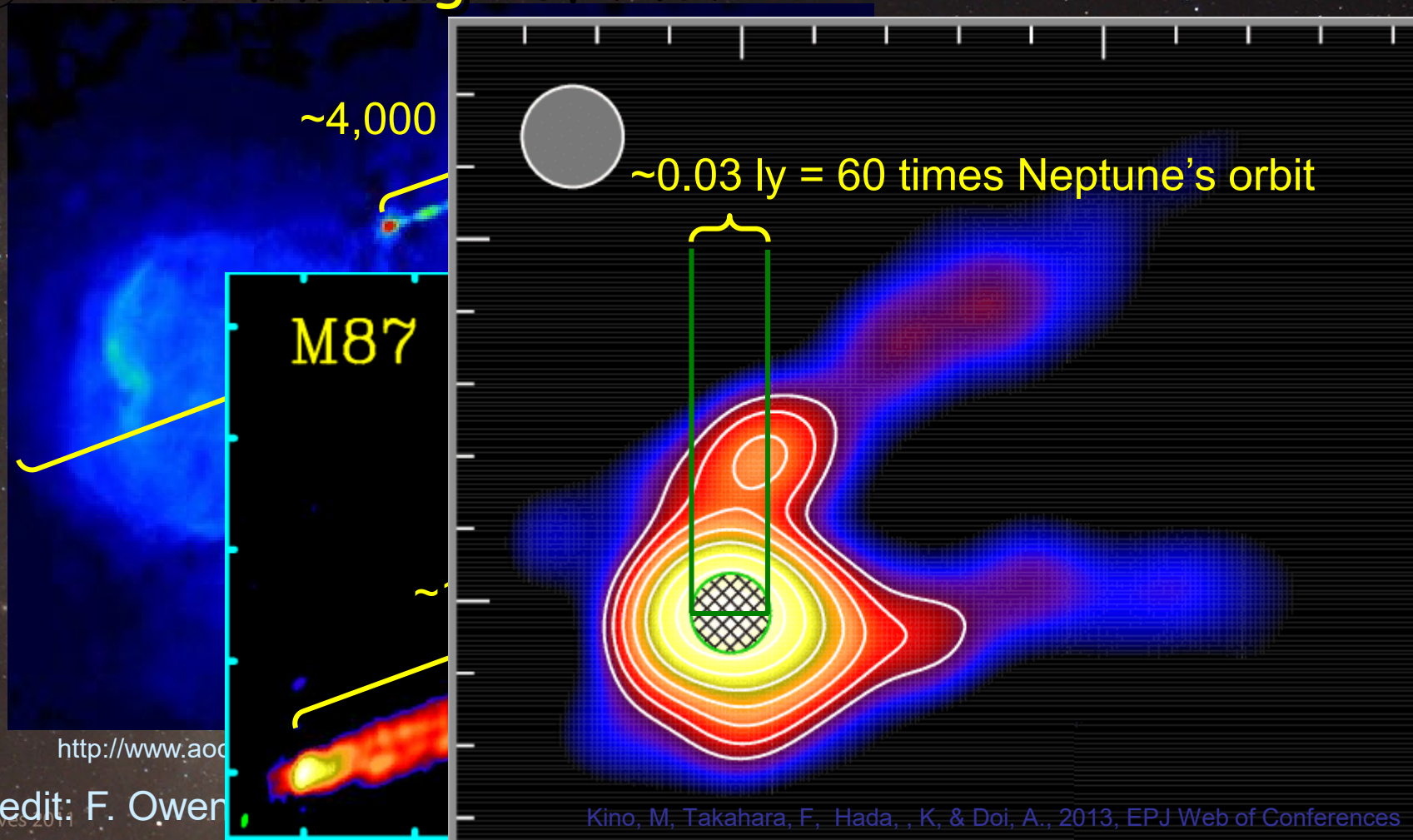
Kellermann, K. I., Kovalev, Y. Y., Lister, M. L., et al. 2007, Ap&SS, 311, 231 Figure 9

Image Credit: F. Owen

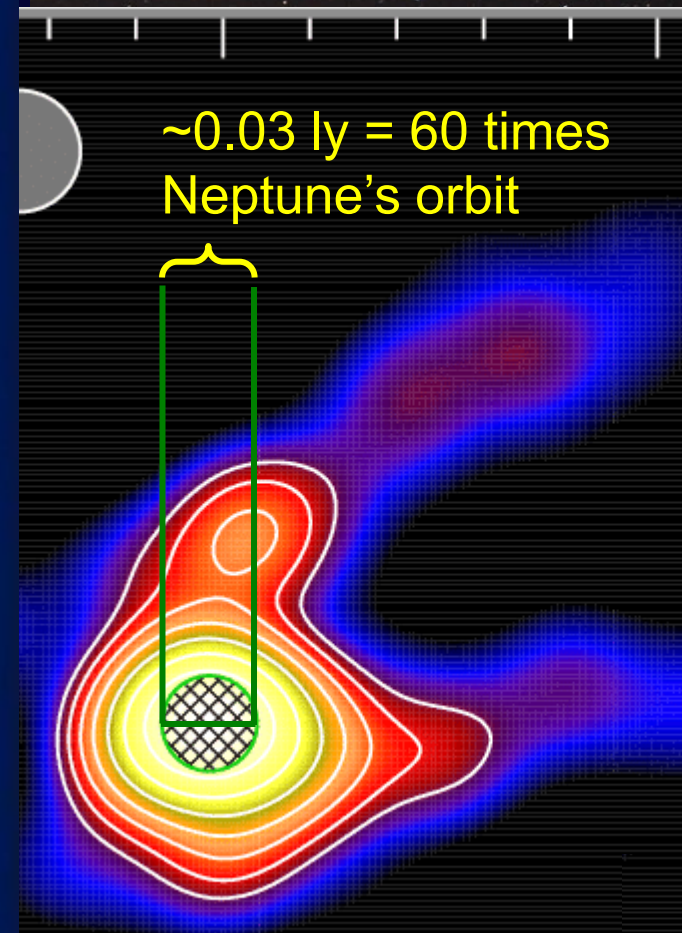
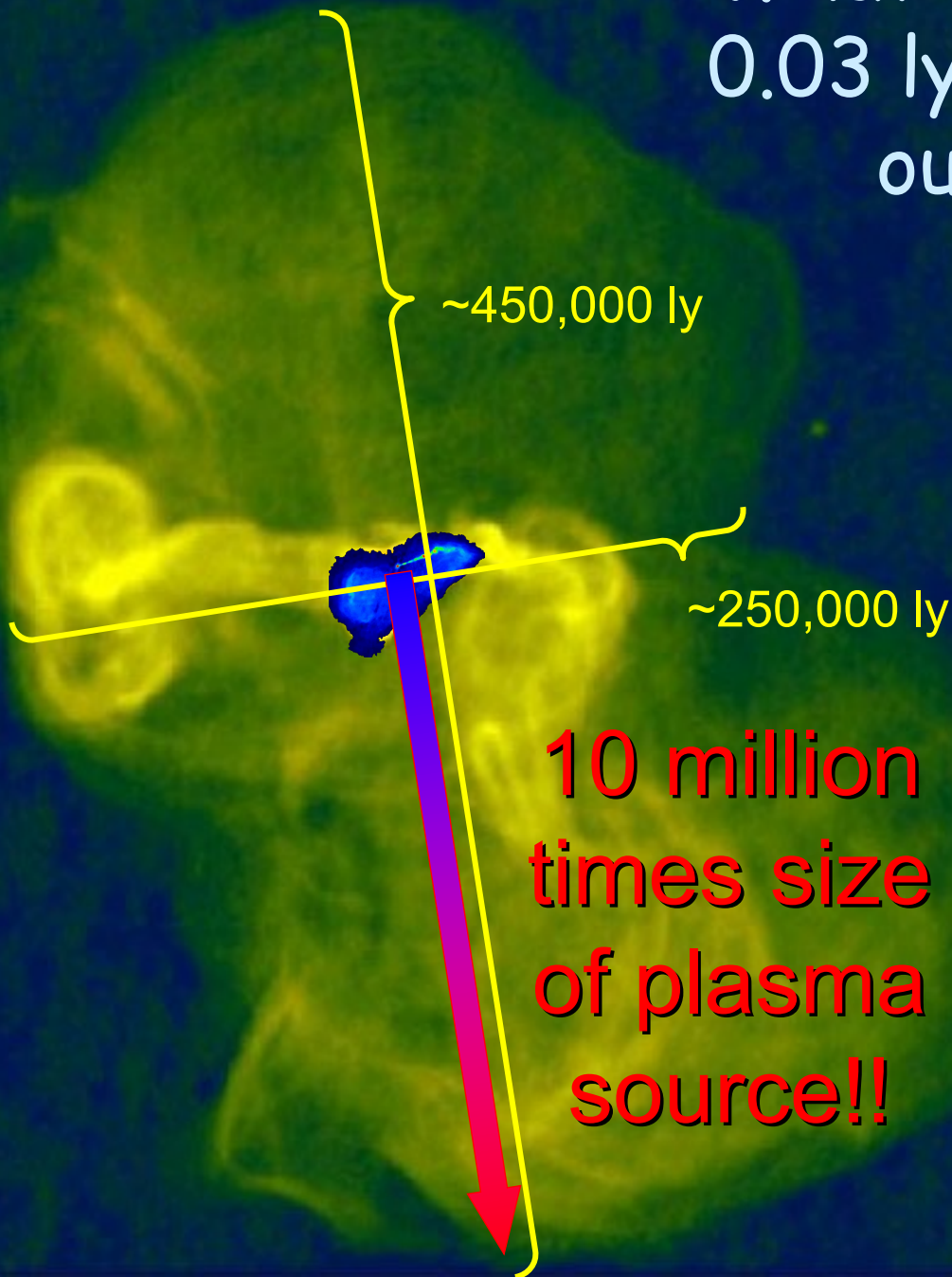
M87: Virgo A

☆ VLBA Radio images: higher resolution

🌐 The 7 mm image of M87



What object smaller than
0.03 ly can shoot material
out 300,000 ly??

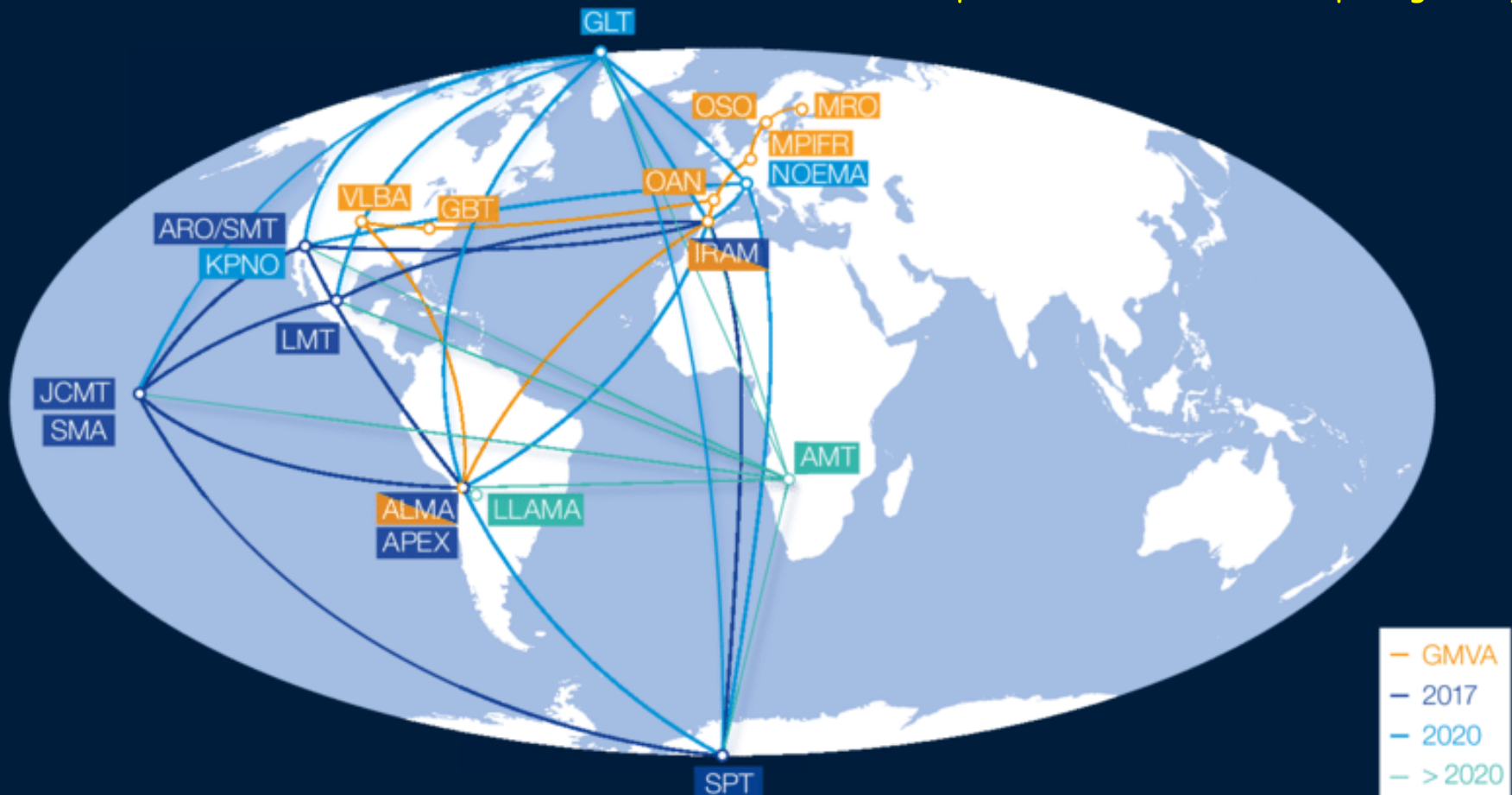


Event Horizons Telescope

☆ A telescope the size of Earth

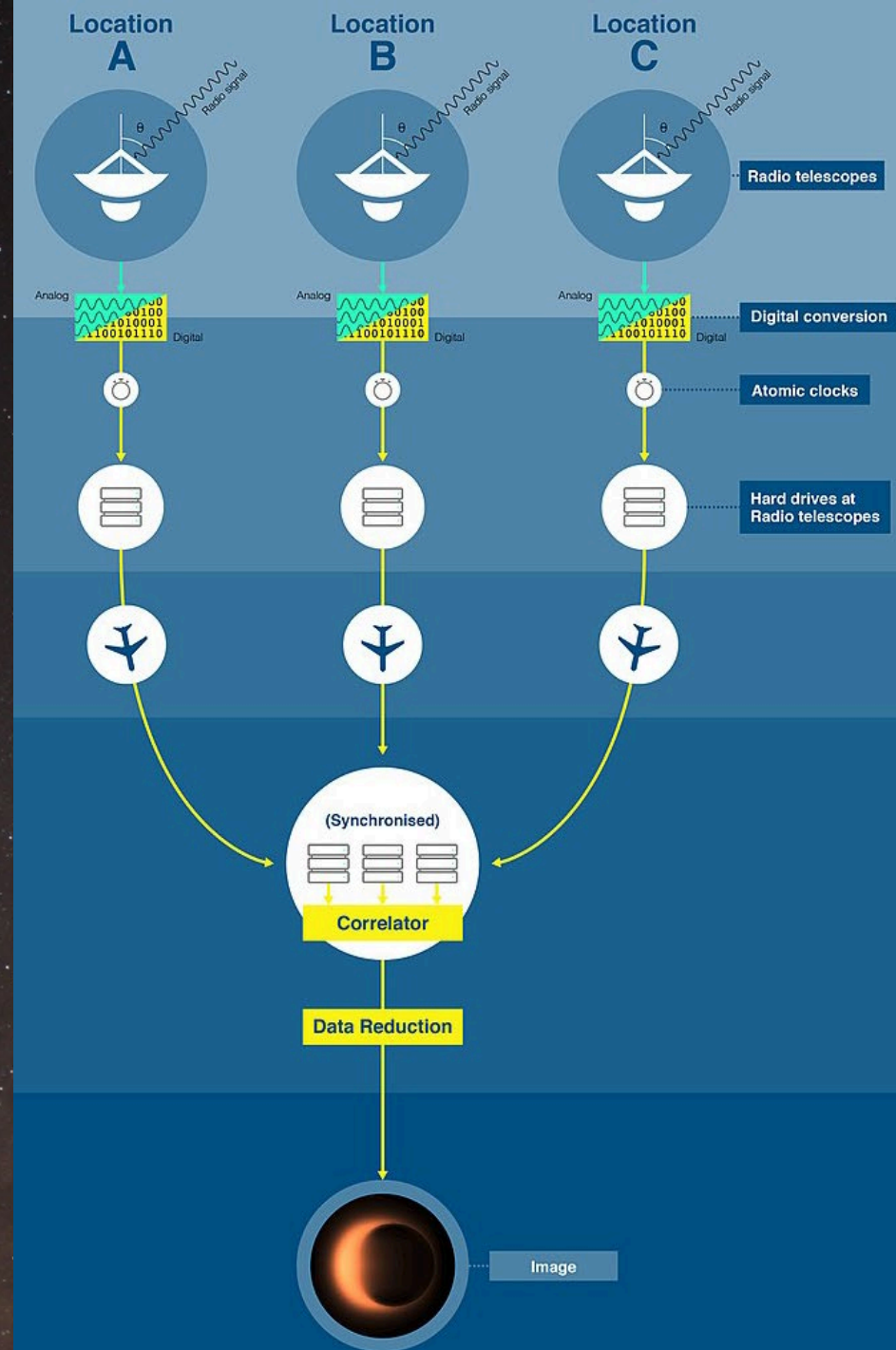
🌐 Radio observations synchronized & combined!

<https://eventhorizontelescope.org/array>

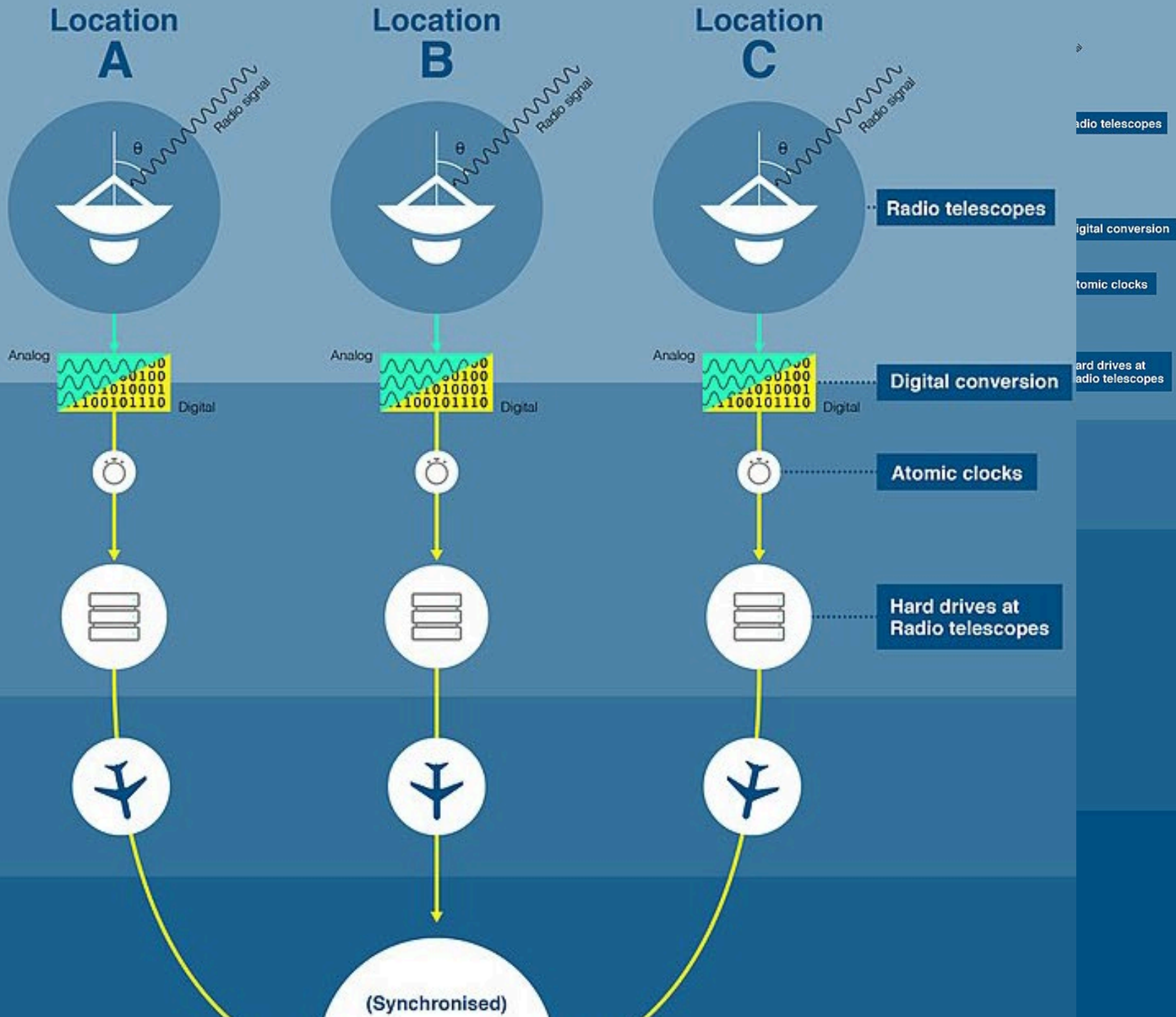


Event Horizon Telescope (EHT)

- ☆ Observations at same times
 - 🌐 Atomic clock timers
- ☆ Data recorded on hard drives at sites
- ☆ Hard drives flown by commercial aircraft to MIT and Max Planck for analysis



Even
Teles
★ O
sal
★ D
ha
★ H
by
air
Mo
and



Radio telescopes

Digital conversion

Atomic clocks

Hard drives at
radio telescopes

Accretion Disks

☆ Material spirals into black hole

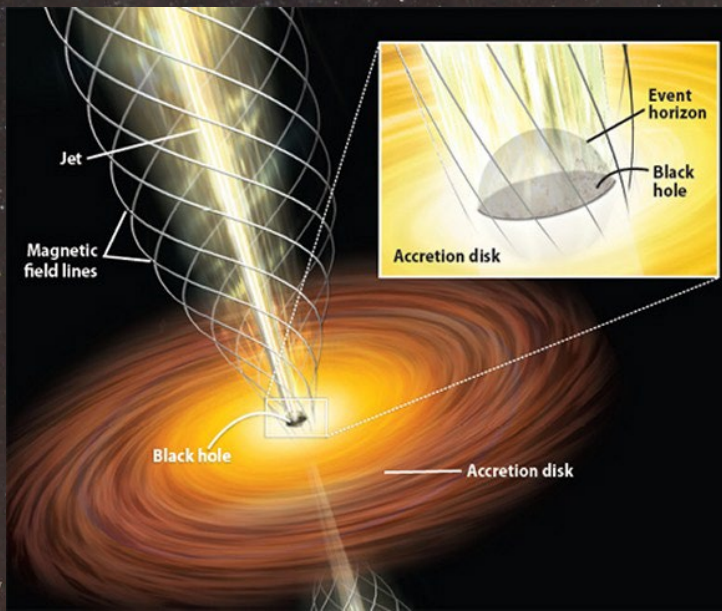
🌐 accelerates as it gets closer

› Particles fly off in all directions

🌐 charged particles create magnetic field

› Very strong, spiraling out from black hole

› Constrains particles to create jets



DAVID DARLING

<http://www.daviddarling.info/index.html>

https://www.physicsoftheuniverse.com/topics_blackholes_event.html

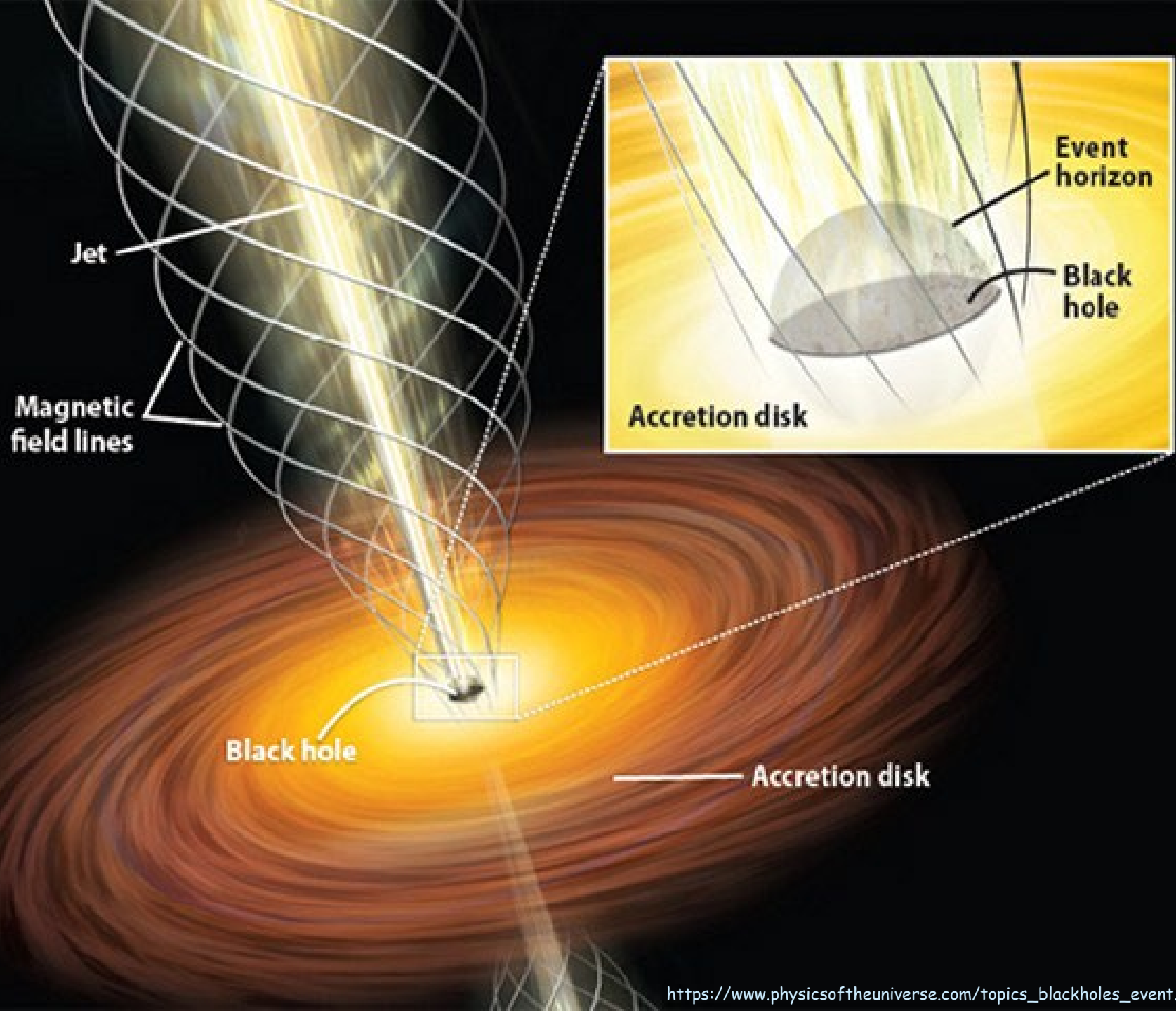


Image of a Black Hole

☆ M87 Giant Galaxy in Virgo

🌐 Radiation from material orbiting black hole
imaged by Event Horizons Telescope in 2019

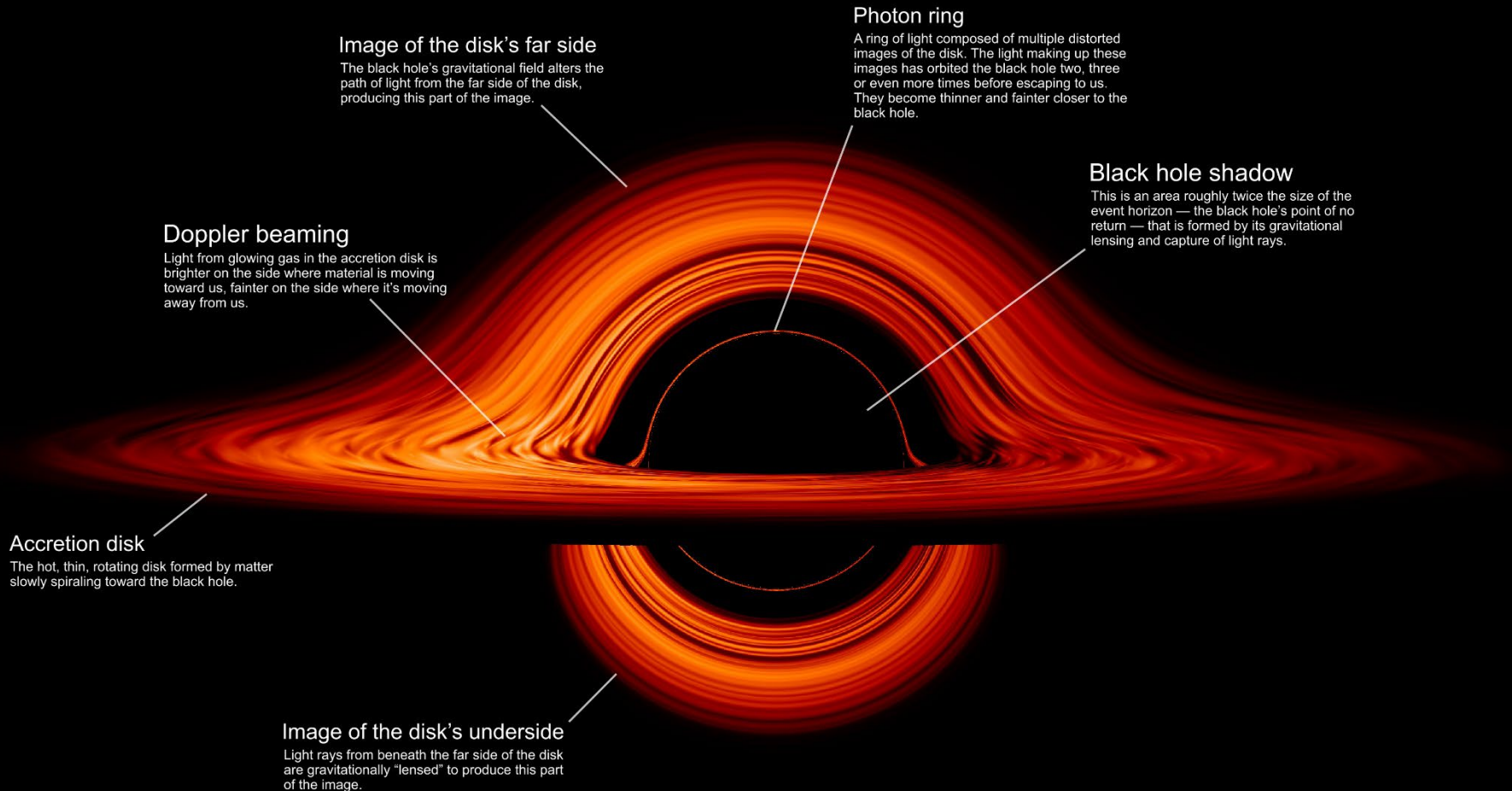


Event Horizon Telescope

<https://eventhorizontelescope.org/>

Black Hole Images

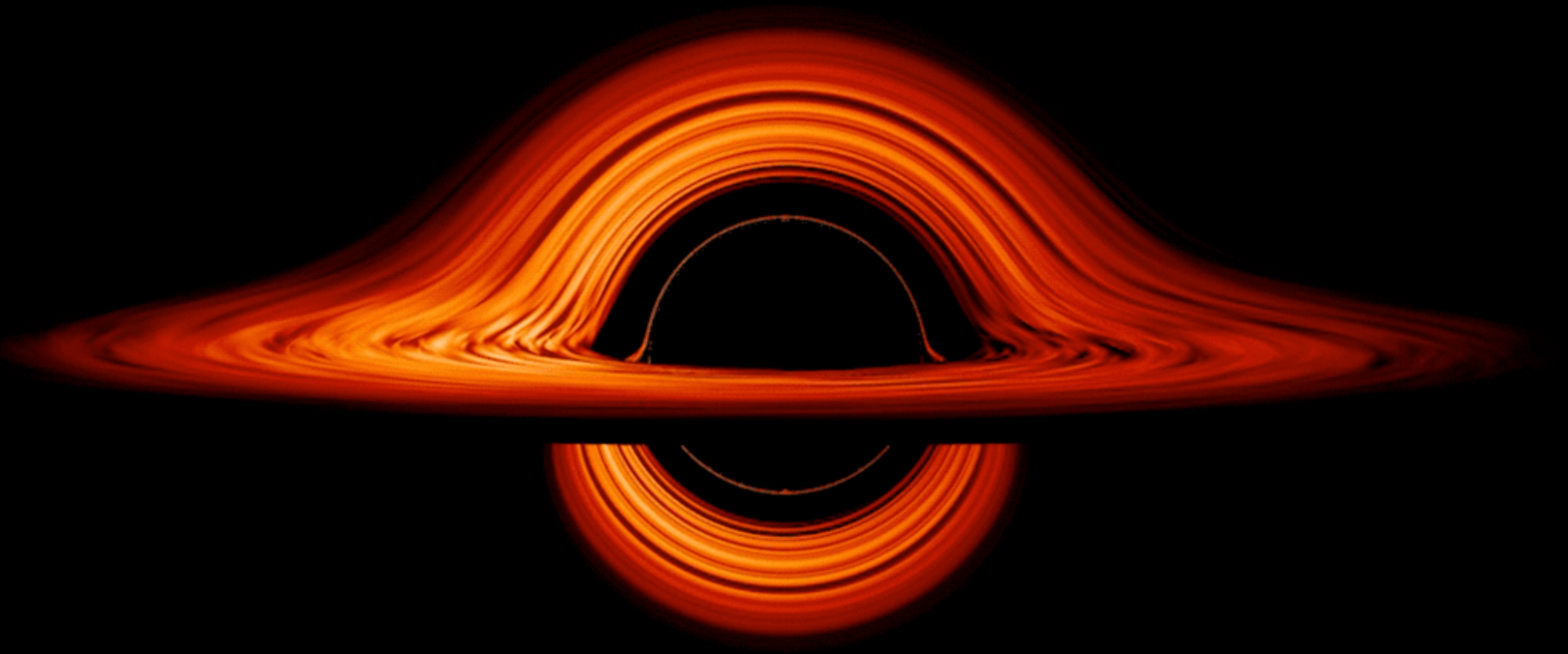
☆NASA: Black Hole's Warped World



<https://www.nasa.gov/feature/goddard/2019/nasa-visualization-shows-a-black-hole-s-warped-world>

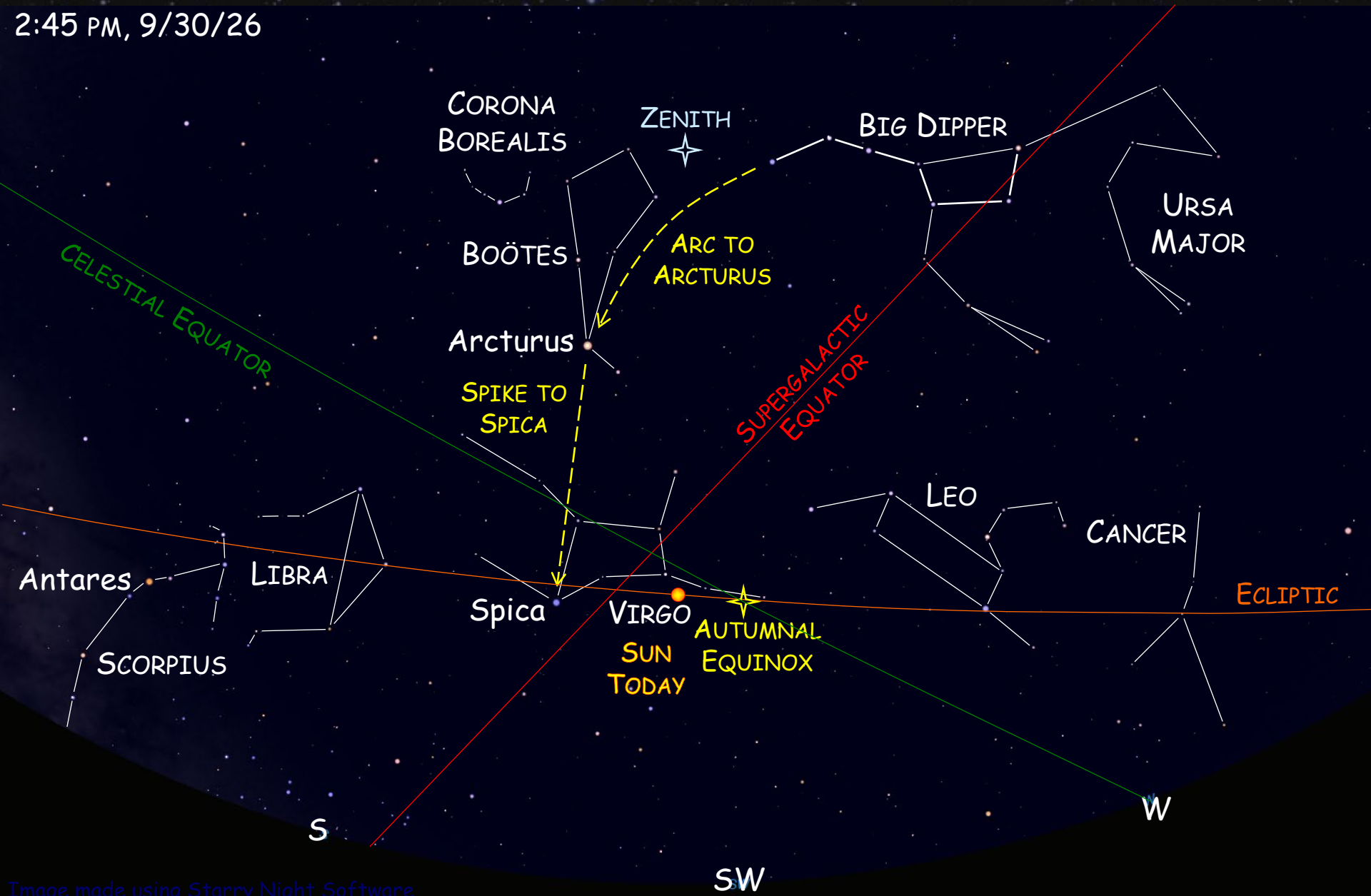
Black Hole Images

☆ NASA: Black Hole's Warped World

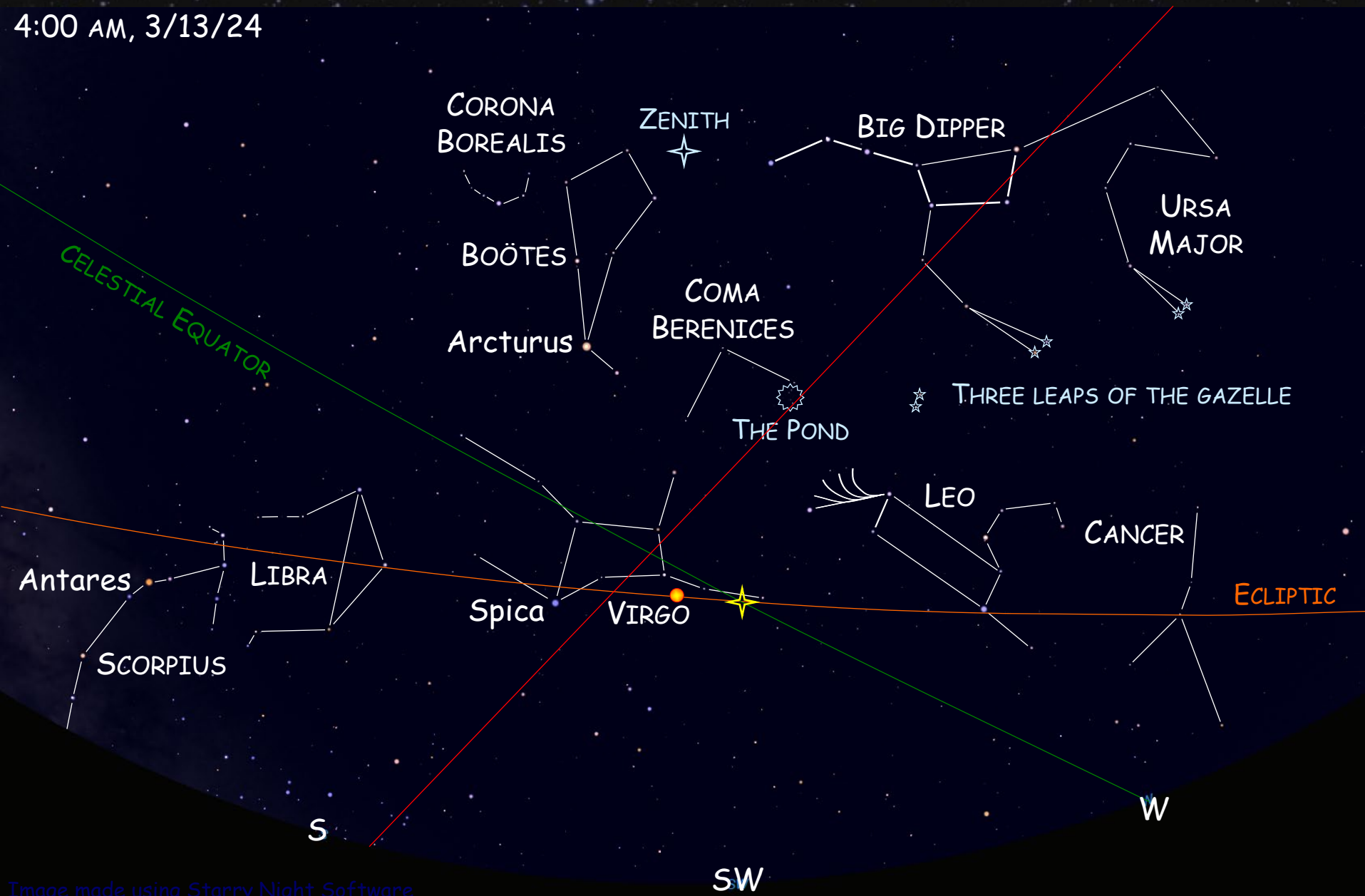


Where is M87? ... the Sky Today

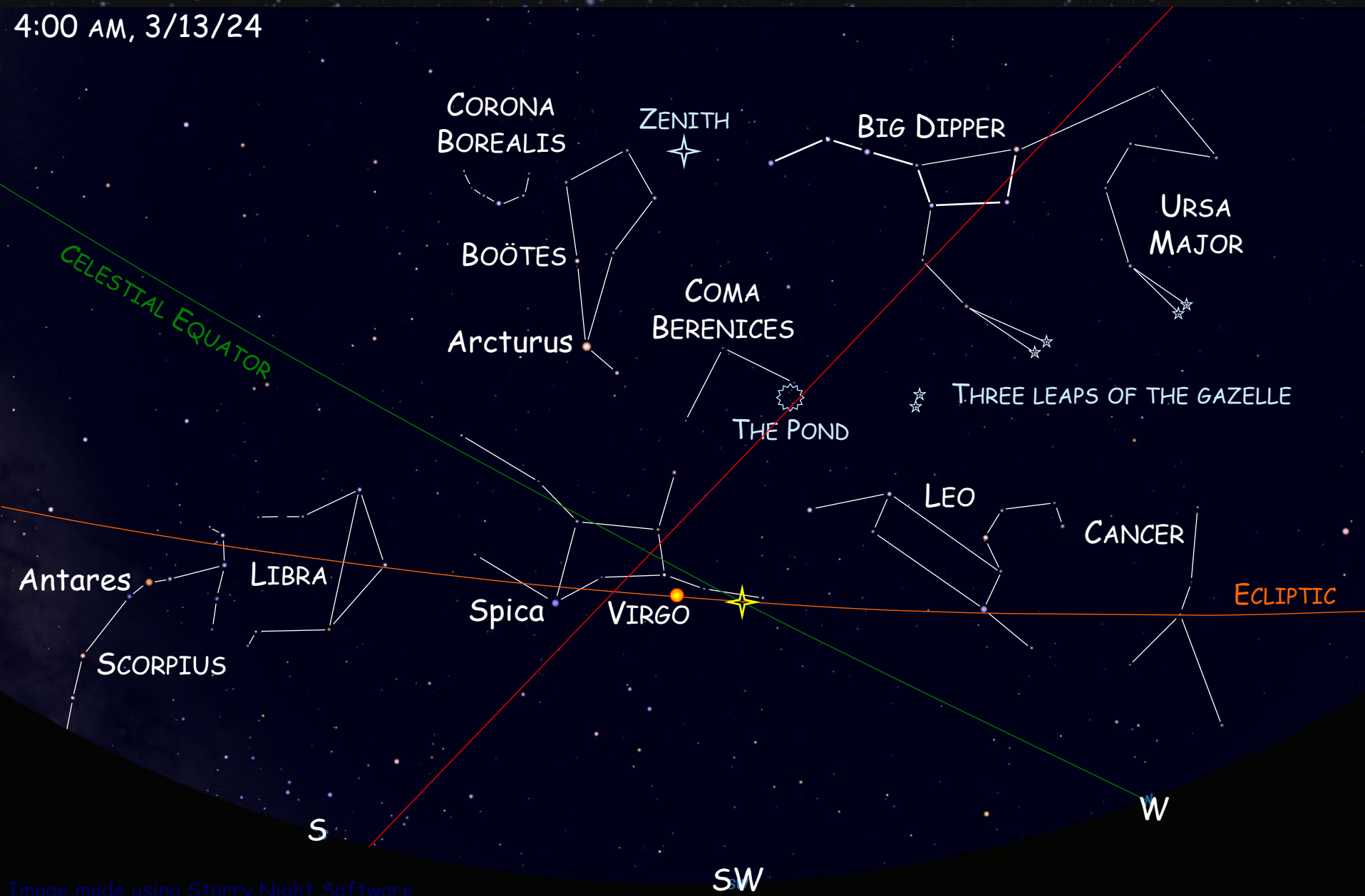
2:45 PM, 9/30/26



4:00 AM, 3/13/24



4:00 AM, 3/13/24



Where is M87? ... the Sky Tonight

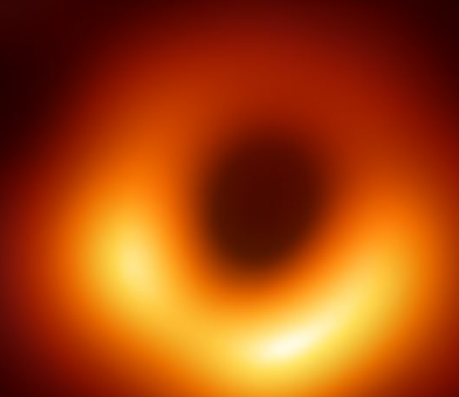
4:00 AM, 3/13/24



Black Hole in M87

☆ M87 Giant Galaxy in Virgo

🌐 Radiation from material orbiting black hole
imaged by Event Horizons Telescope in 2019



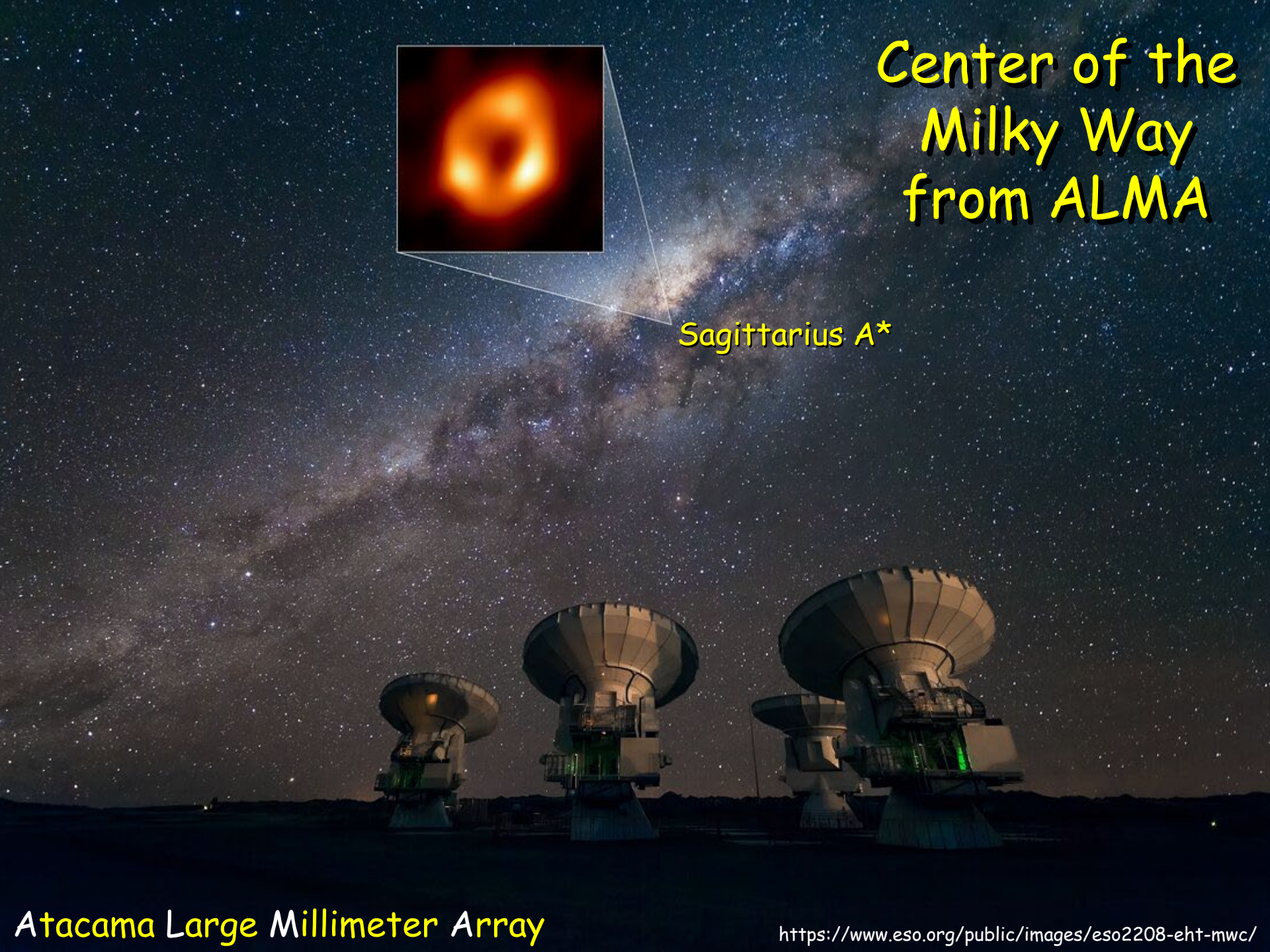
Event Horizon Telescope

<https://eventhorizontelescope.org/>

Center of the Milky Way from ALMA



Sagittarius A*



Atacama Large Millimeter Array

<https://www.eso.org/public/images/eso2208-eh-t-mwc/>

Center of the Milky Way from ALMA



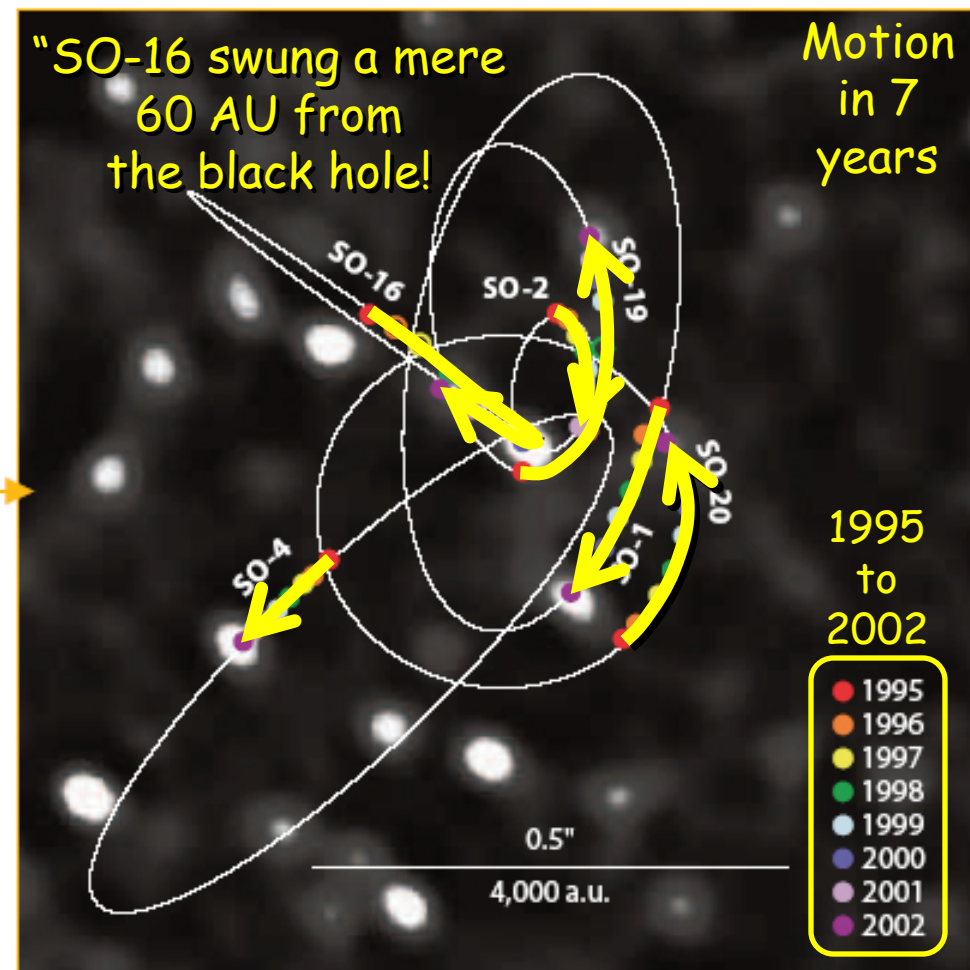
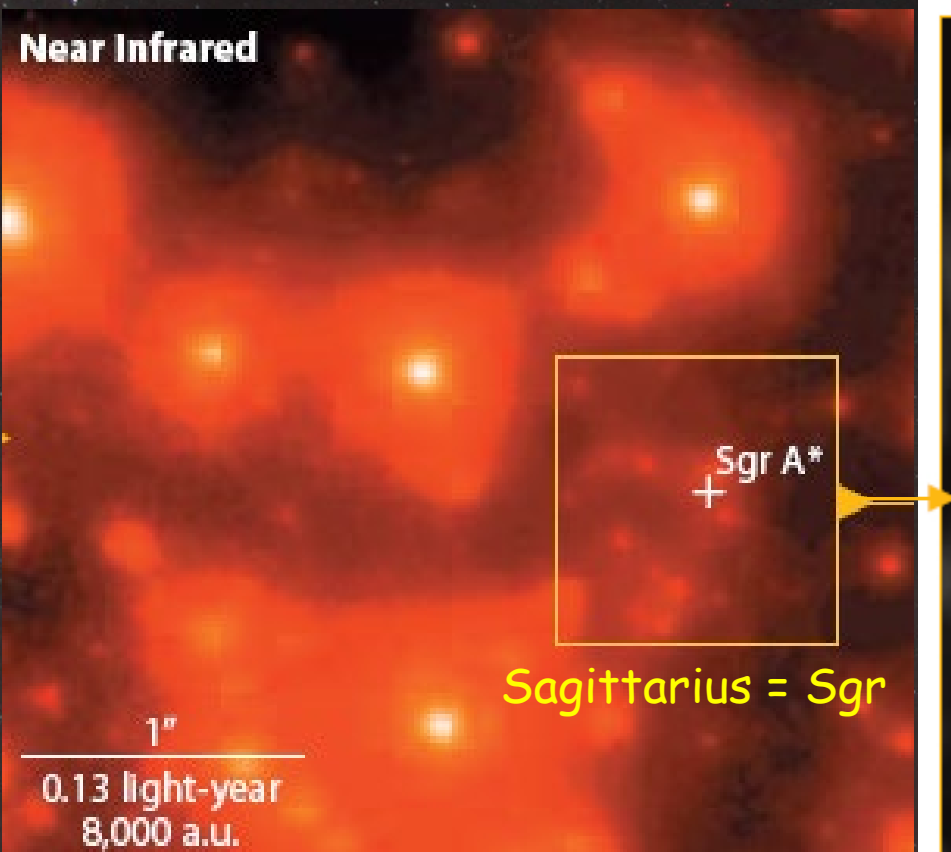
Sagittarius A*



Atacama Large Millimeter Array

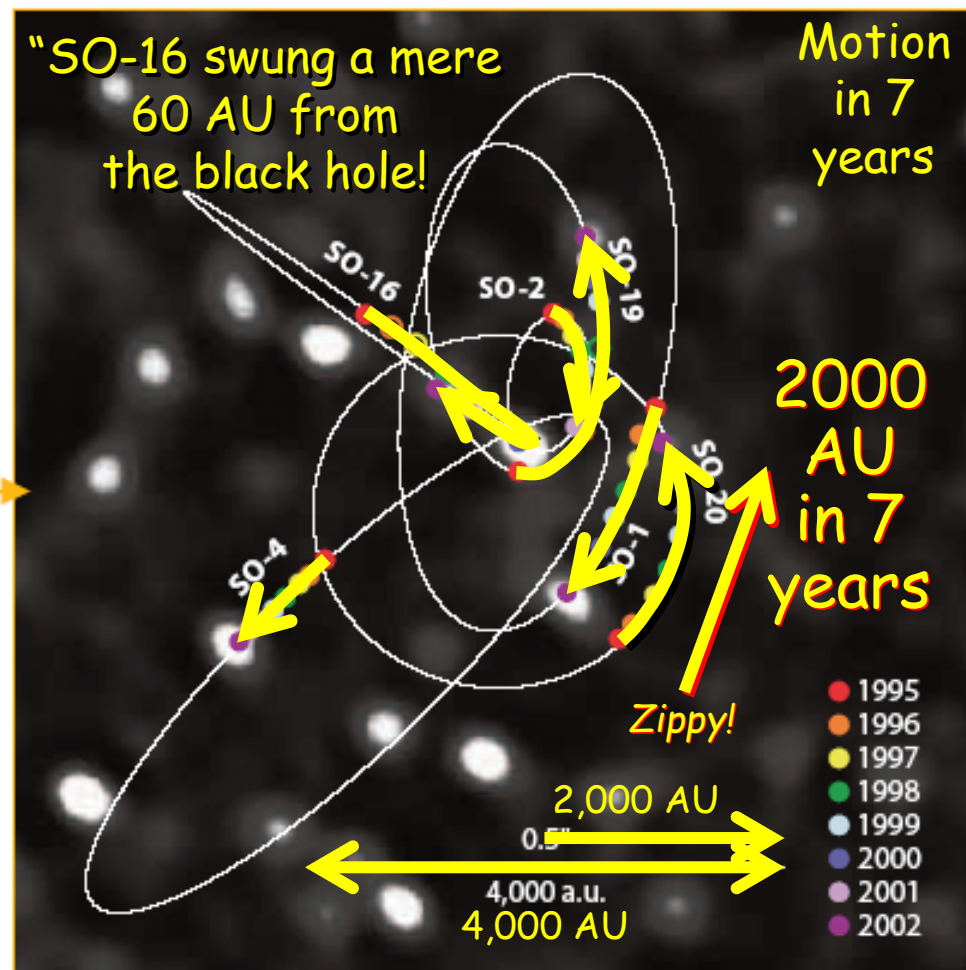
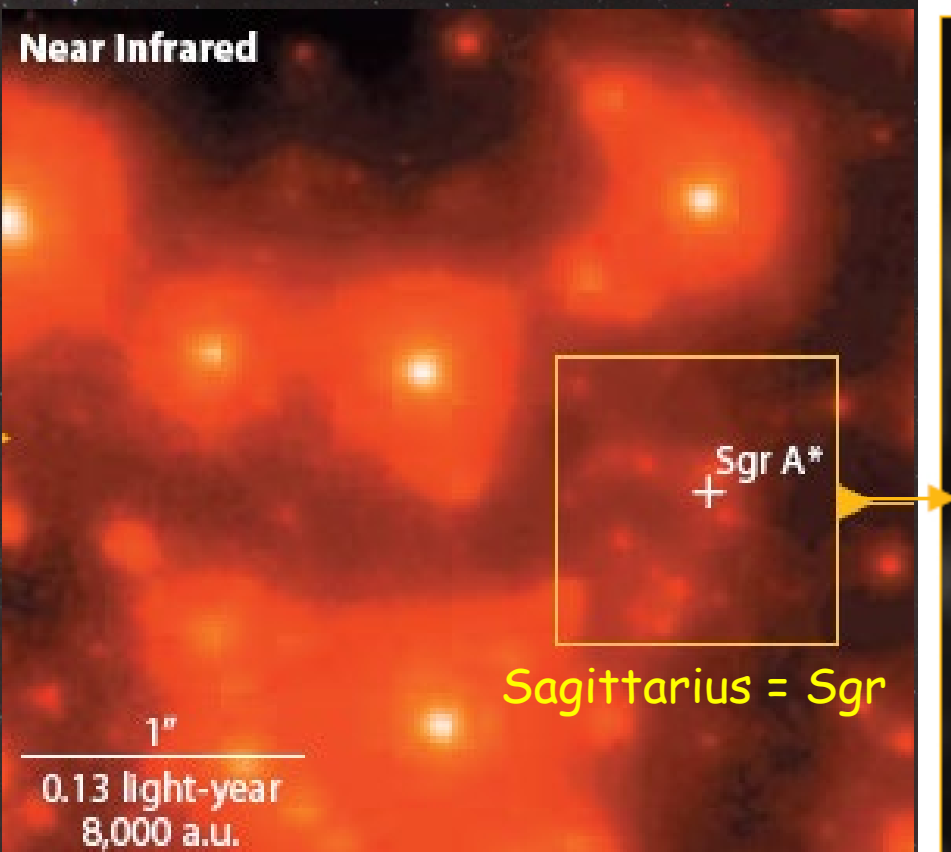
Stars Orbiting Galactic Center

Orbits of six stars around Sagittarius A*. This 2.2-micron adaptive-optics image, a mere 1 arcsecond square, was taken in 2002; symbols show the positions of the six stars for each of the previous 7 years as well. The white orbits are best fits to these positions. Four of the orbits have only short arcs of data and thus are very tentative, but the stars S0-2 and S0-16 have swung through half or more of their ellipses, allowing their orbits to be specified well. **S0-16 swung a mere 60 astronomical units from the black hole.** Courtesy A. Tanner, S. Hornstein, A. Ghez, and Keck Observatory.



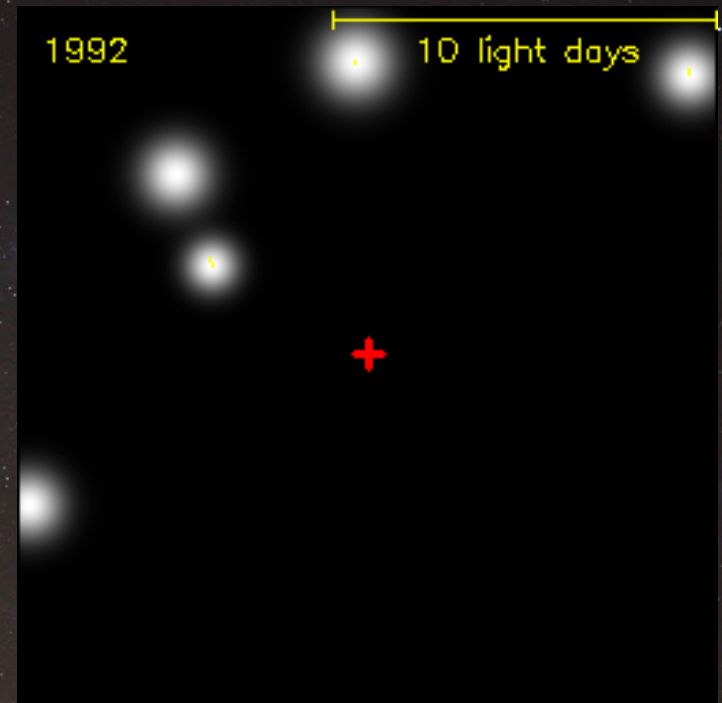
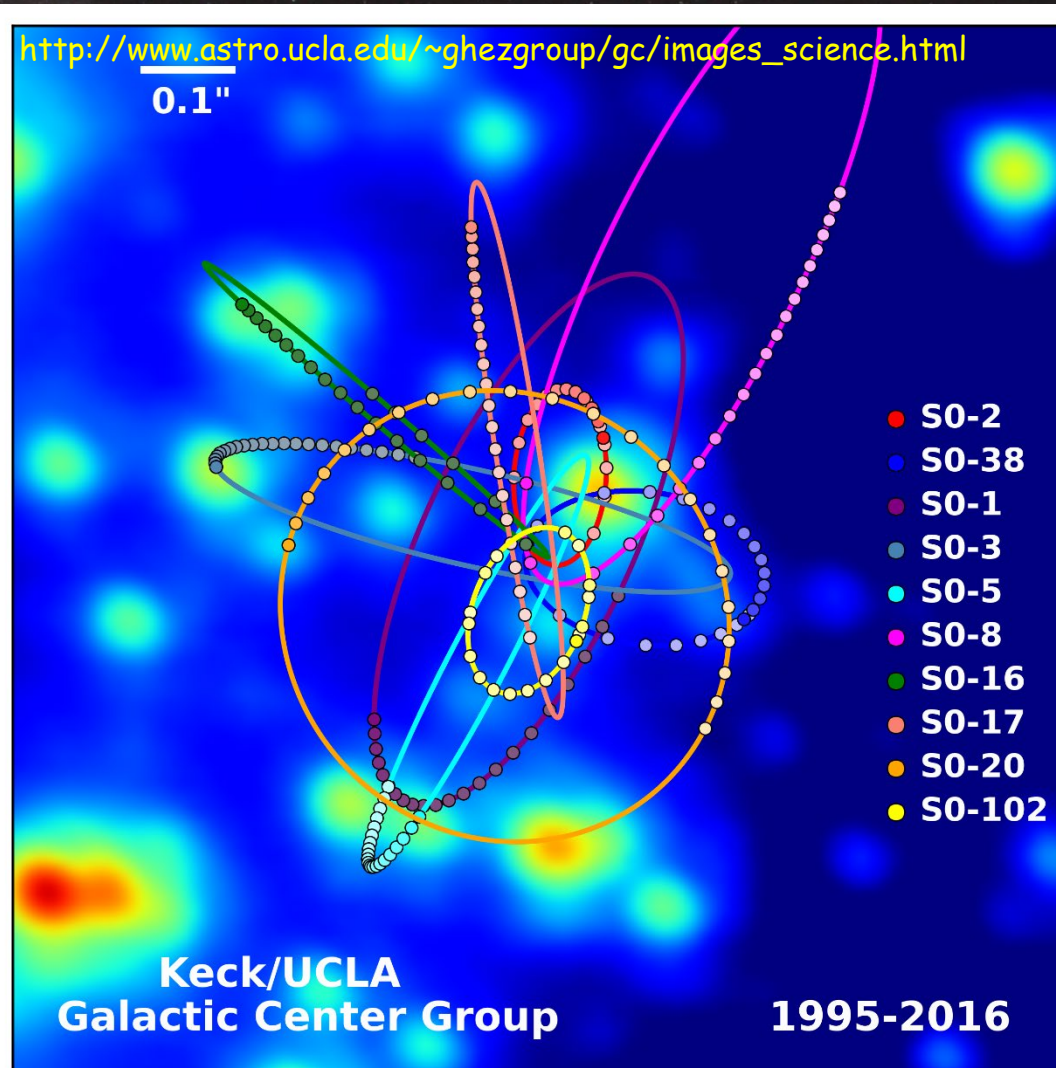
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Stars Orbiting Galactic Center

Mass needed in center of orbits =
4.1 million times the mass of Sol!

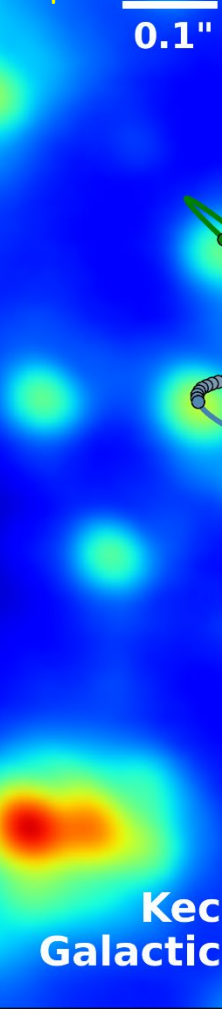


St

er

<http://www.asi>

0.1"



Kec
Galactic



days

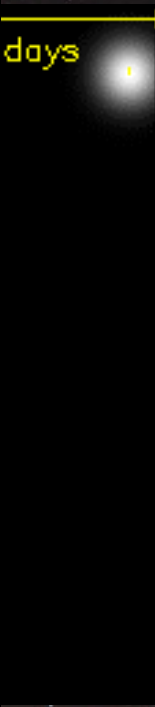


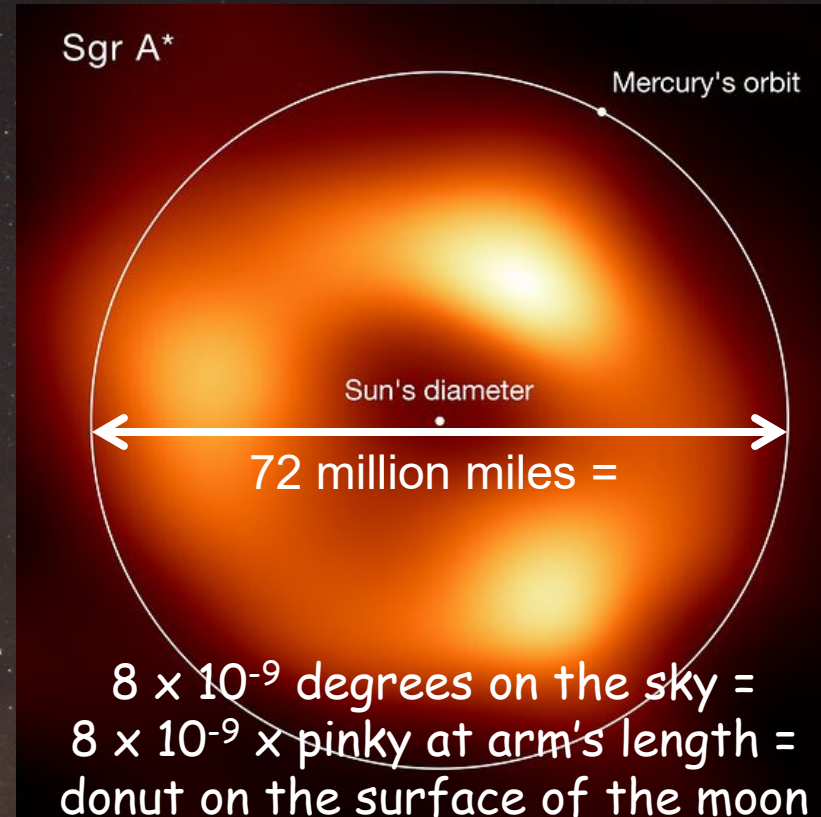
Image of a Black Hole

☆ Sagittarius A* Center of the Milky Way

- 🌐 Stars orbit center at high speeds!
 - › Observed from 1995 until 2019
 - › Orbital speeds give mass of object in center

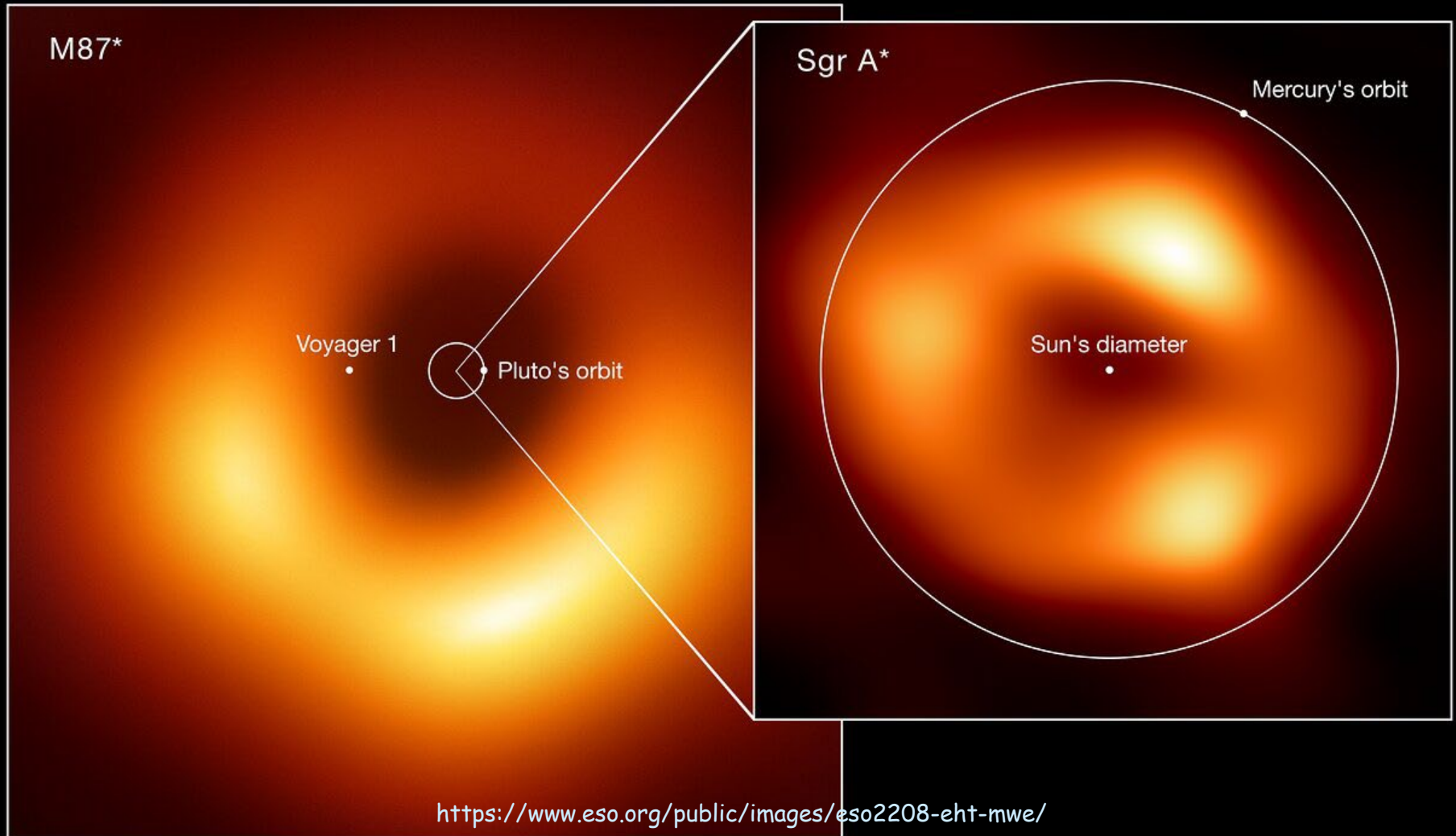
$$M_{\text{MW Black Hole}} = 4.3 \text{ million } M_{\text{Sun}}$$

Milky Way's black hole is 4.3 million times the Sun's mass in a volume much smaller than the Sun ... $r_{\text{BH}} = 0$



Black Hole Images

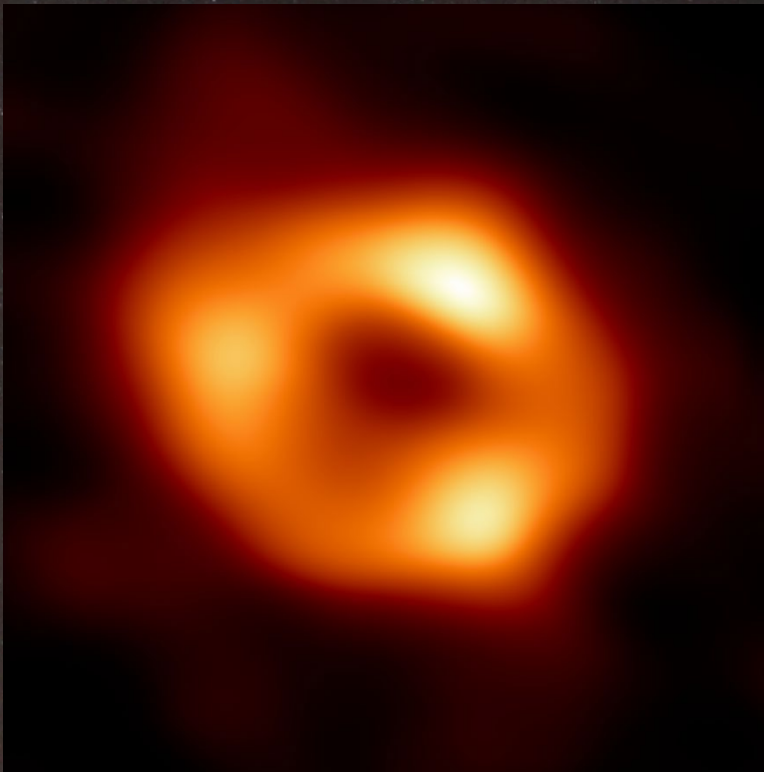
☆ M 87 vs. Sgr A*: Pluto orbit $\sim 100 \times$ Mercury's



Black Hole Images

☆ Why orange?

- ① Human eye can see more levels
 - » Black → orange → yellow → white
 - » Standard for images in low frequencies (JWST)



Outline

★ Review Star Deaths

- 🌍 Small: PN & WD, Large: SN & NS or BH

- 🌍 States of Matter

★ General Relativity, Gravity, & Light

- 🌍 Total Eclipses & Galaxy Clusters

★ Black Holes

- 🌍 Escape Velocity & Spaghettification

- 🌍 Detecting Black Holes

 - › X-Rays, Invisible Companions, Direct Imaging

★ The Adventure Continues



We are the Legacy of the Stars

We are alive!

We are made of stars ...

... And we KNOW that we are!

We are the Legacy of the Stars

We are alive!

We are made of stars ...

... And we KNOW that we are!

Every "ordinary" thing around us ...

the Earth

the mountains and rusty nails!

the rivers and oceans and puddles!

all the other Earthlings ... Puppies and Bugs!

... Are made of STARS and we know it!

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Breathe in, Breathe out ...

... the Cosmos lives within you

We are the Legacy of the Stars!

THE ADVENTURE CONTINUES