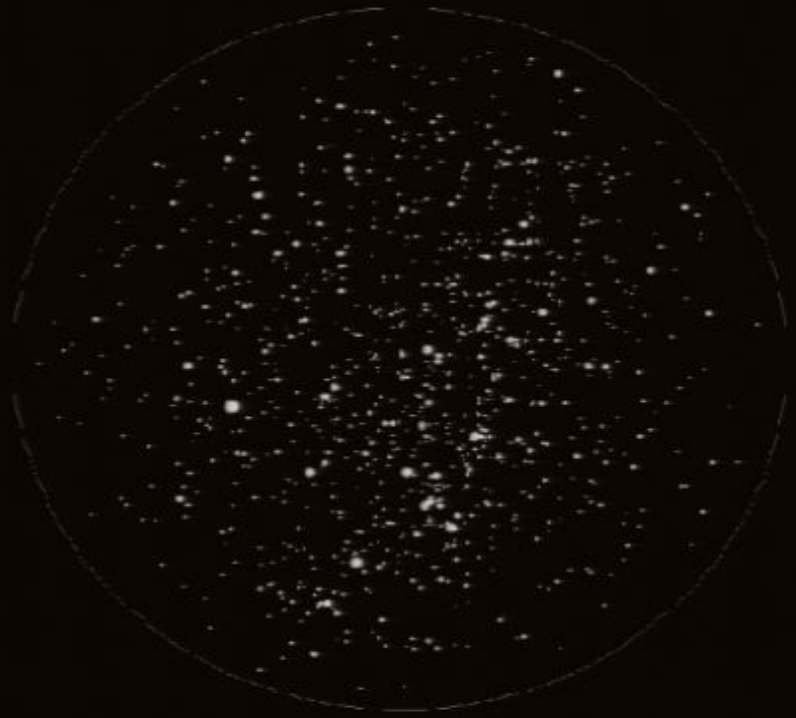
Title: General Relativity 6 - The Star Called a Black Hole

Date: Aug 02, 2006 09:15 AM

URL: http://pirsa.org/06080034

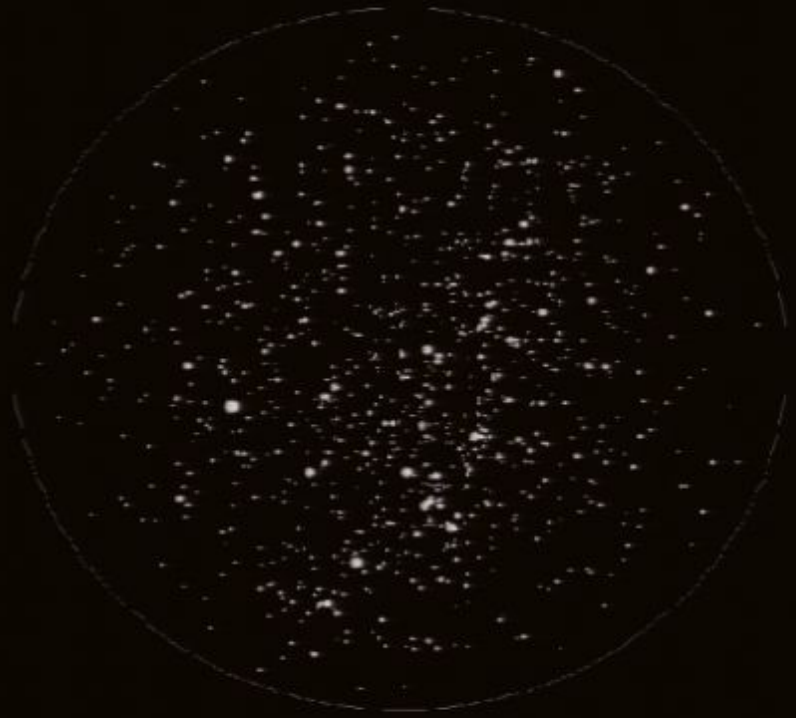
Abstract: The physical attributes of a black hole and what types of physical evidence astronomers use the locate them.
 Learning Outcomes:
 â€¢ What are the physical requirements for a star to become a black hole, and what properties of that star remain after the black hole is formed?
â€¢ The types of black holes, including: the Schwarzschild black hole, the Reissner-NordstrÃ¶m black hole, the Kerr black hole, and the Kerr-Newman black hole.
â€¢ What a traveller would experience if he orbited one of these more general black holes, or fell through to the singularity.

Looking Up



$$r = 12 \tan\left(\frac{5\pi}{6}\sqrt{1-\frac{C_b}{C}}\right)$$

Looking Up



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Looking Up

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Forward Sideways Backwards

Thanks to Ute Kraus,
Max-Planck-Institute

Forward

Sideways

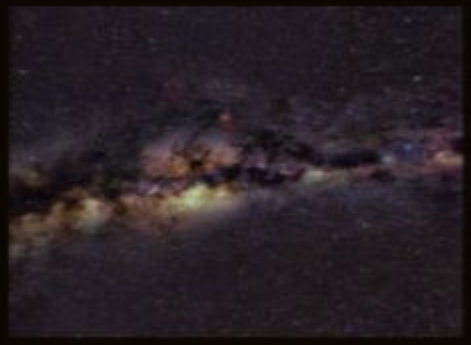
Backwards

r = 100 rs

Thanks to Ute Kraus, Max-Planck-Institute

Forward

Sideways

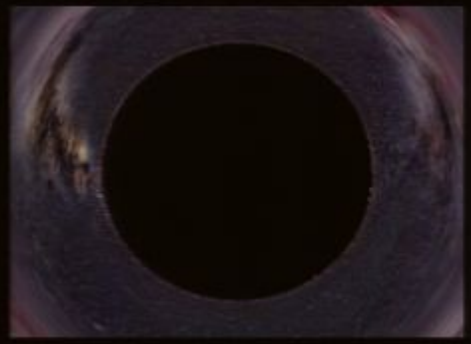


Backwards

r = 20 rs

Thanks to Ute Kraus, Max-Planck-Institute

Forward



Sideways

Backwards

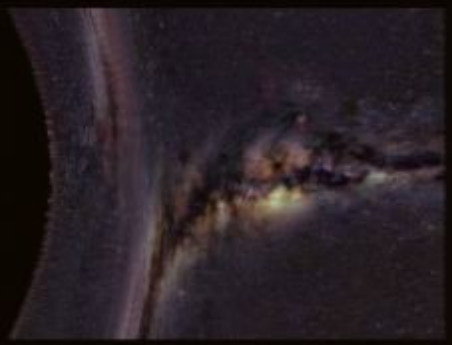
$r = 4.5\ r_s$

Thanks to Ute Kraus, Max-Planck-Institute

Forward

Sideways

Backwards



$r = 2.5\ r_s$

Thanks to Ute Kraus: Max-Planck-Institute

Forward

Sideways

Backwards

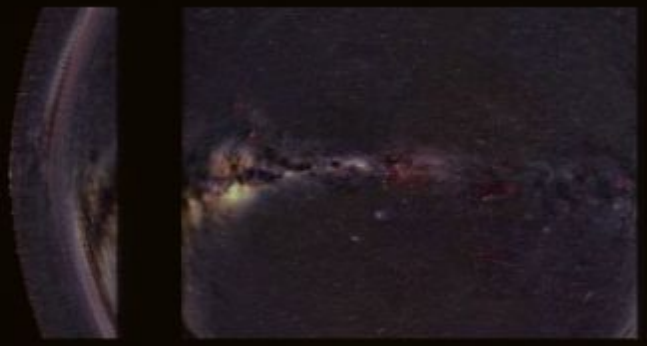
$r = 1.5\ r_s$

Thanks to Ute Kraus, Max-Planck-Institute

Forward

Sideways

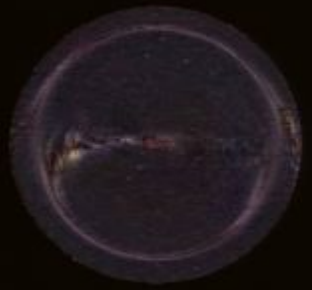
Backwards



r = 1.2 rs

Thanks to Ute Kraus, Max-Planck-Institute

Forward Sideways Backwards



r = 1.05 rs

Thanks to Ute Kraus, Max-Planck-Institute

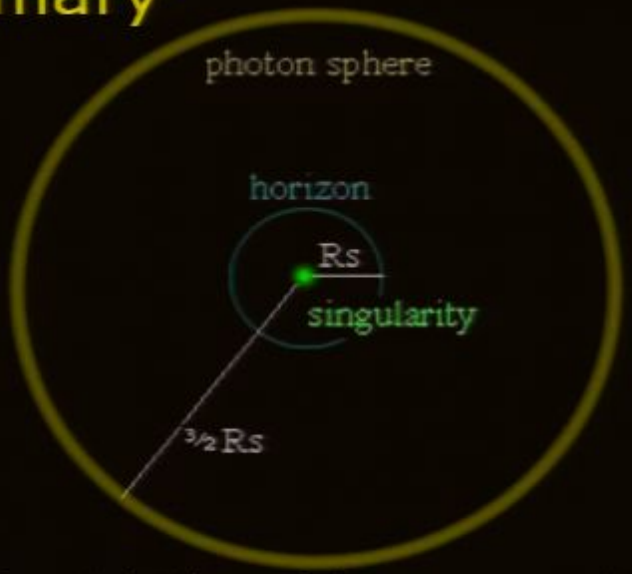
Forward Sideways Backwards

r = 1.005 rs

Thanks to Ute Kraus, Max-Planck-Institute

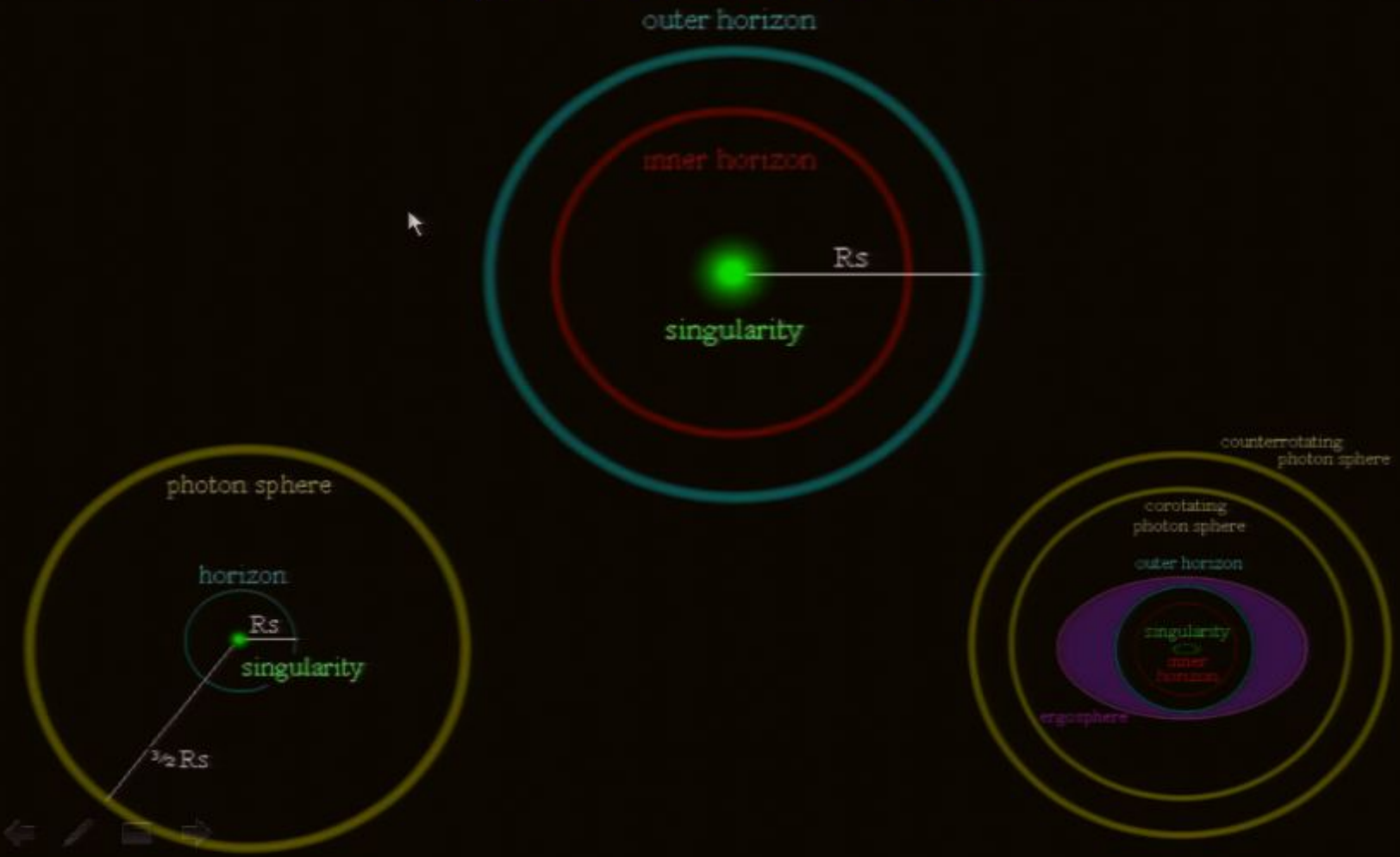
The Anatomy Summary

If you calculate the size of an object whose escape velocity is the speed of light, you get the "Schwarzschild radius", which defines the "event horizon". This is the formal size of a black hole (even though there is nothing at that location). It is given by R_s=3km(M_*/M_{sun}). It is the horizon over which you can see no more events. Outside that at 1.5 R_s photons would orbit the hole (the photon sphere).



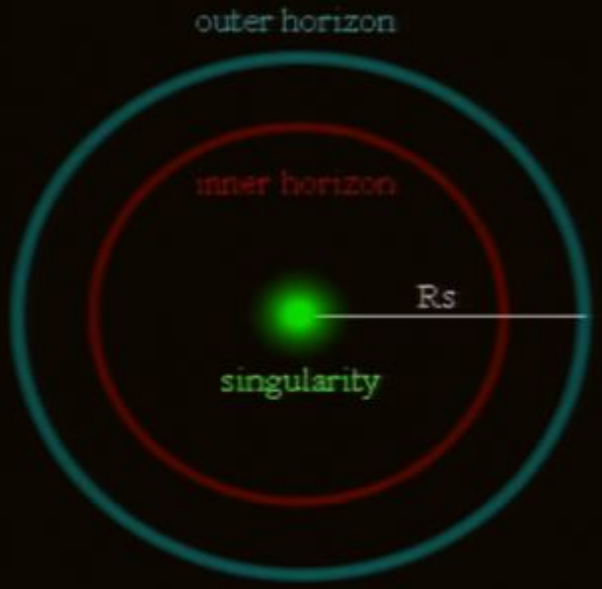
Far from the hole, the gravity is the same as it would be if the star were still there (so no "vacuum cleaner" effect). If the Sun collapsed to a BH, the Earth's orbit would be unaffected.

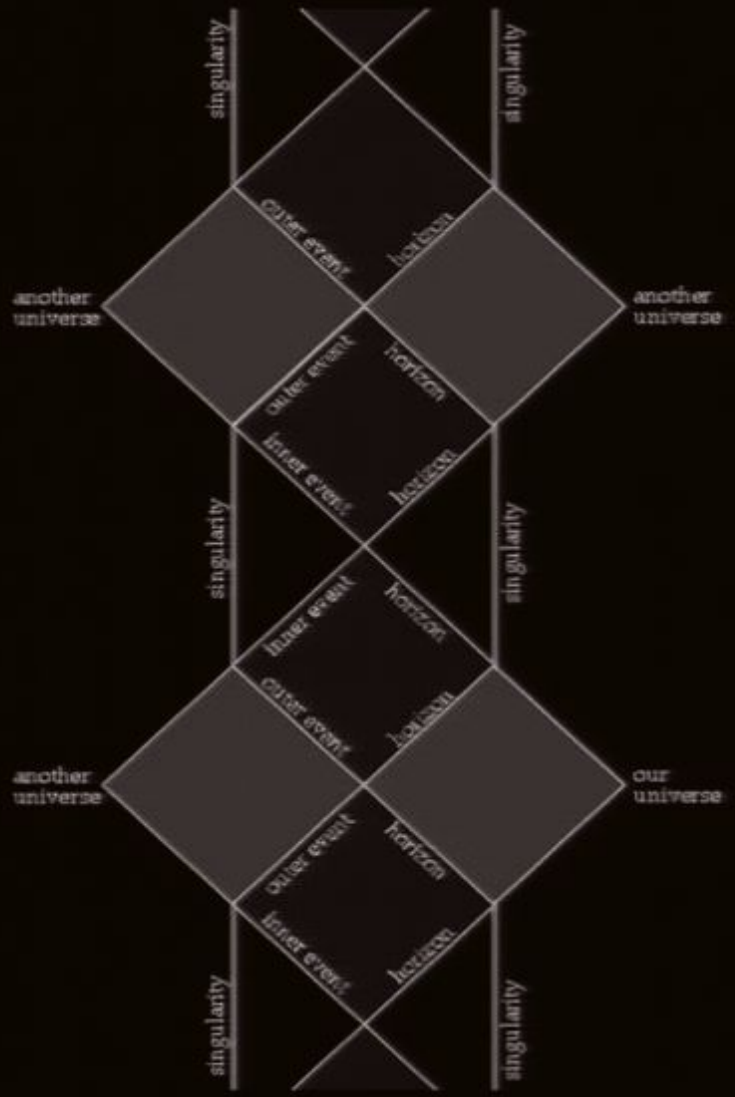
Types of Black Holes

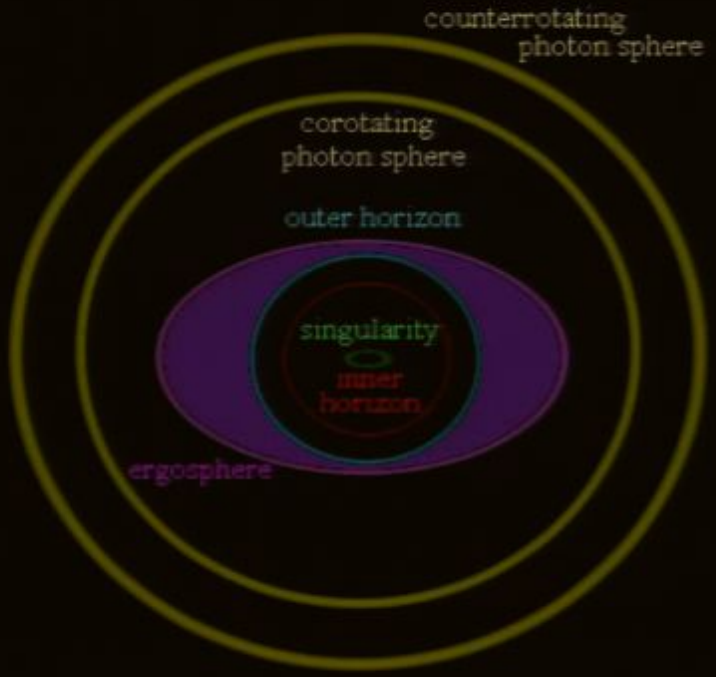


Reissner-Nordström Black Hole

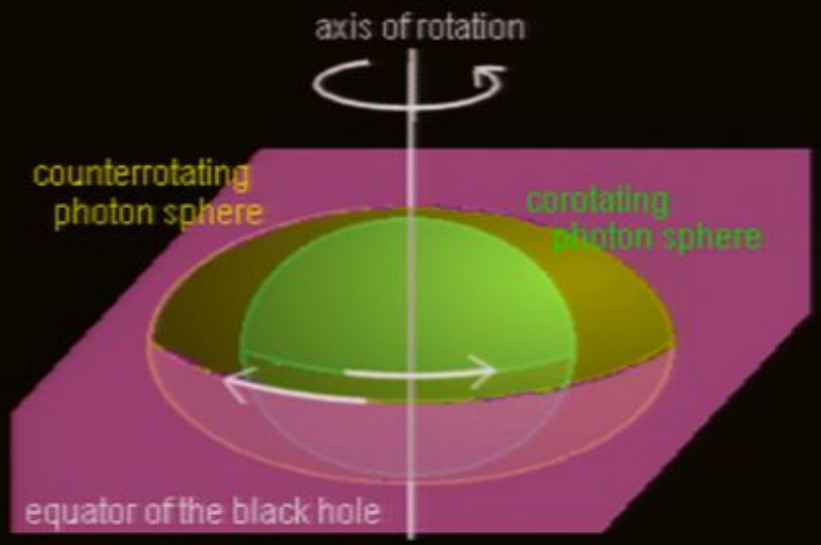
An electrically Charged Black Hole

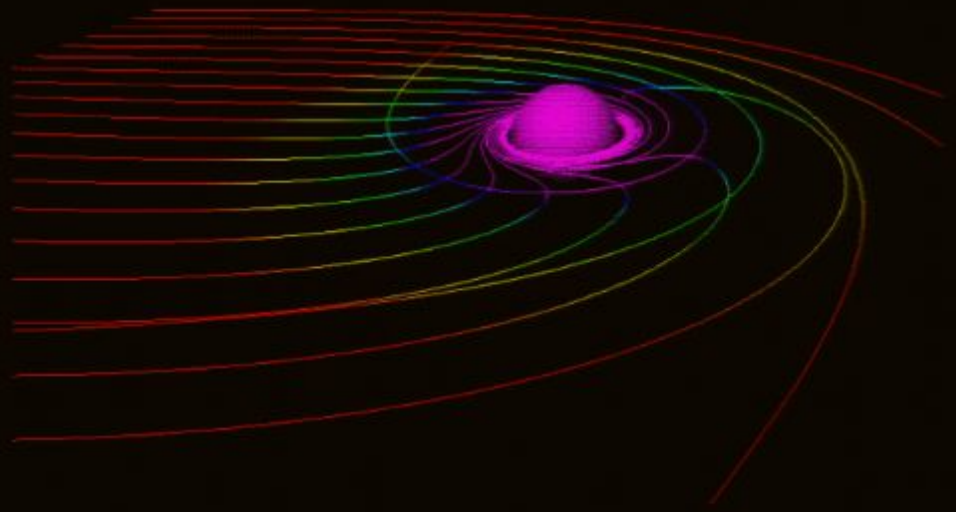






Rotating Black Holes

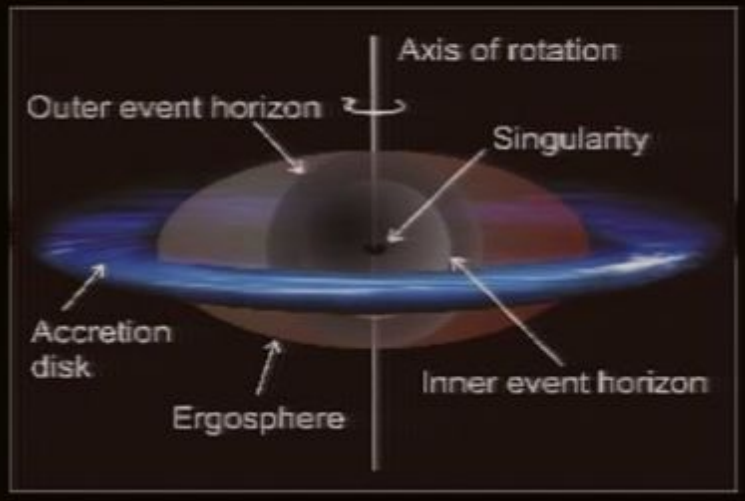


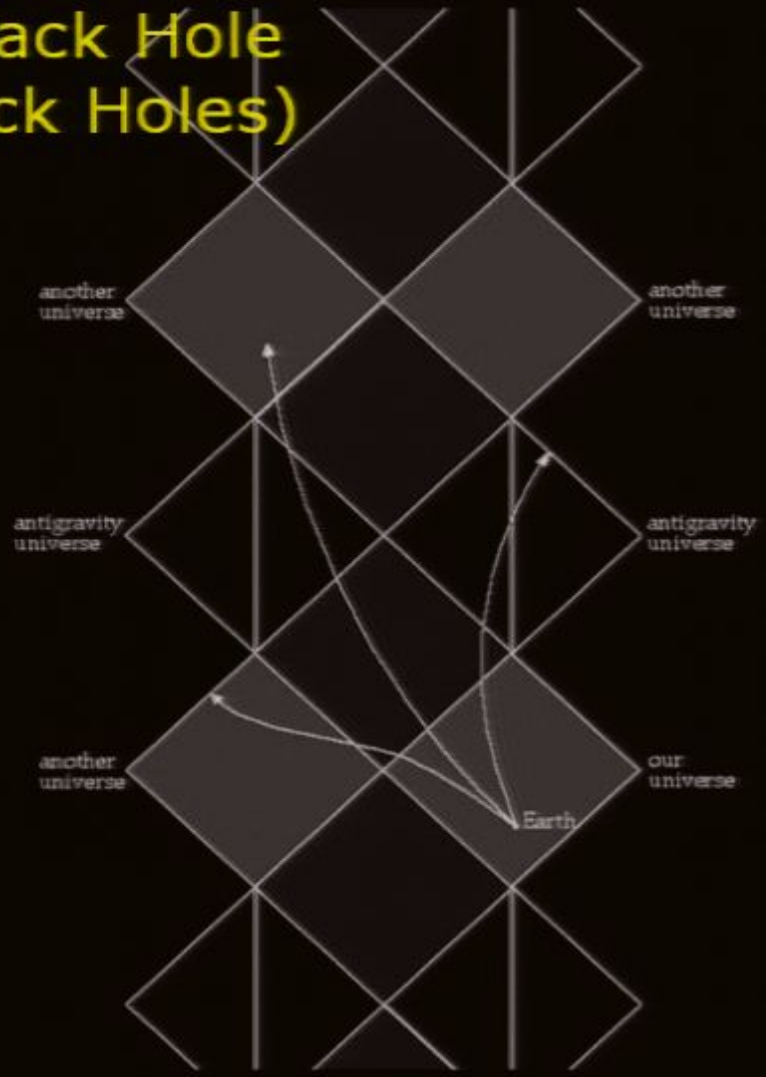


Rotation also leads
to “frame-dragging”

A Rotating Black Hole (The Kerr Black Holes)

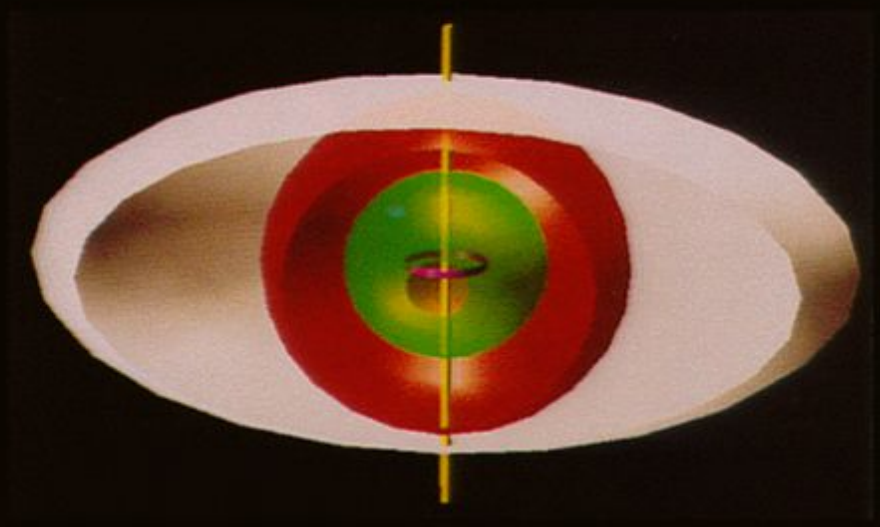
Why is it called a rotating black hole? The event horizon doesn't rotate---it's just a boundary-line

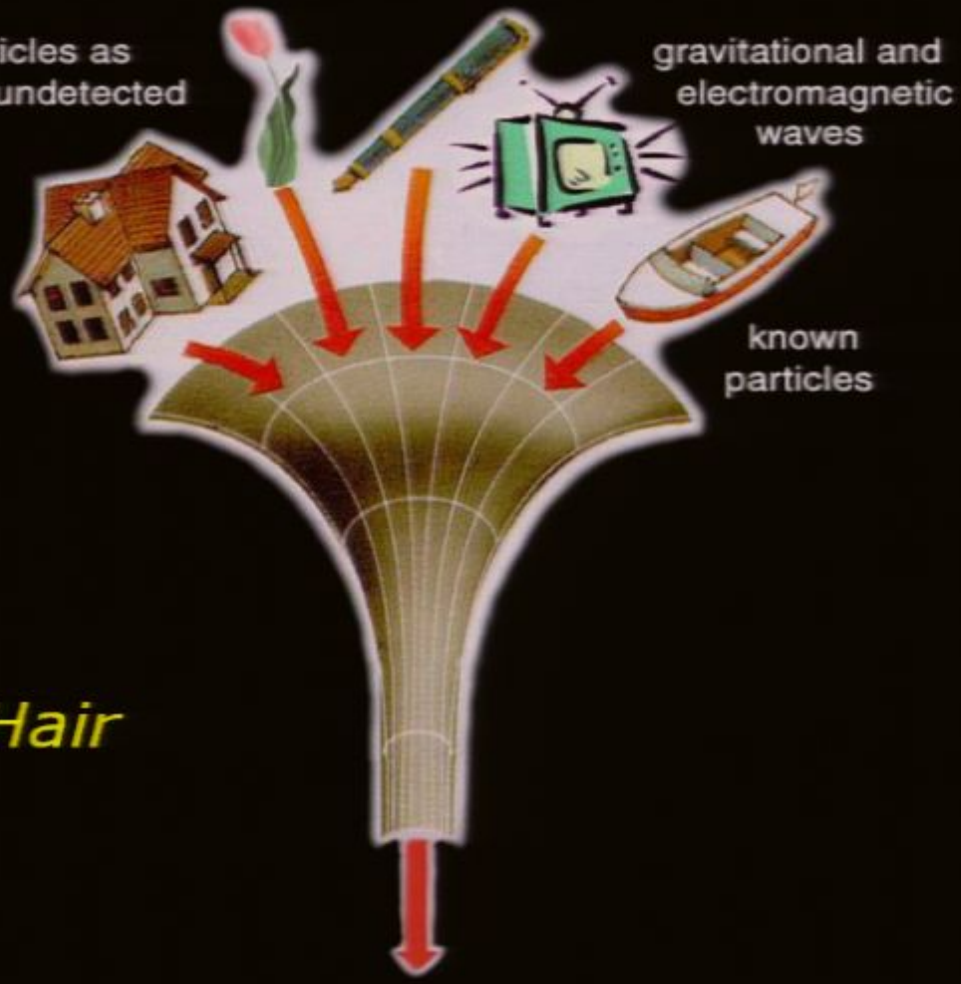




Kerr-Newman Black Hole

Same Structure as Kerr Black Hole.
But now it has a charge as well as a rotation.



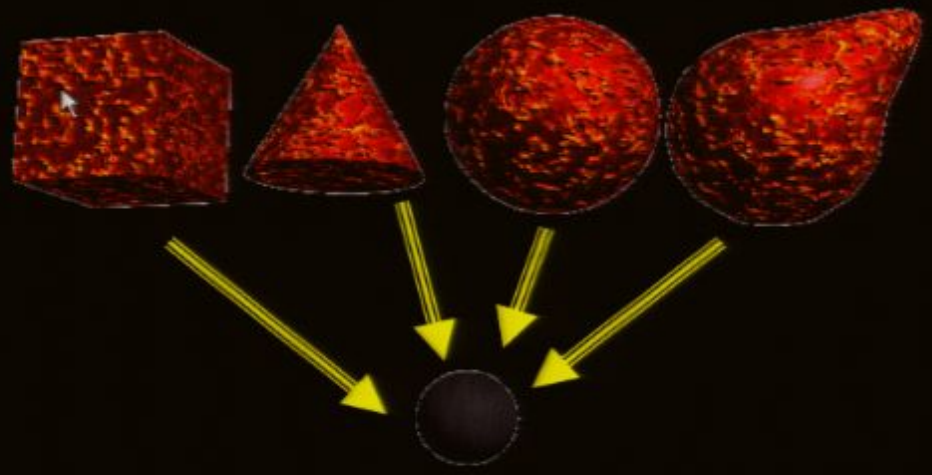

particles as
yet undetected
gravitational and
electromagnetic
waves
known
particles
No Hair
mass
charge
angular momentum

No-hair theorem (well maybe 3 hairs)

- A black hole has no hair;
  its only 'hair' are its
  - mass
  - angular momentum
  - electric charge

John A. Wheeler (b1911)

Stars of all Shapes and Sizes



Types of black holes

- Schwarzschild (1916)
  - mass
- Reissner-Nordström (1916, 1918)
  - mass, electric charge
- Kerr (1963)
  - mass, angular momentum
- Kerr-Newman (1965)
  - mass, angular momentum, electric charge

Entropy of Black Hole

- **Black hole presents us with a problem: What happens to the information when a particle falls inside a Black Hole?**
- **Remember only 3 parameters are required to describe a Black Hole (charge, mass, and angular momentum).**
- **In order to describe a physical system, we need entropy (a measure of disorder).**
- **Hawking had no problem with this "entropy eater"**
- **Hawking (after changing mind) and Bekenstein produced laws of Black Hole mechanics that bore an amazing resemblance to laws of thermodynamics.**
- **The 2nd law of thermodynamics "Entropy (randomness) increases**
- **You replace "Horizon Area" with "Entropy"**

$$S(entropy) = \frac{kAc^3}{4hG}$$

Entropy of Black Hole

New problem: if the Black Hole has an entropy, it must have a temperature too.

Worse Problem: If is has a temperature it must radiate, but in classical definition, nothing can escape a Black Hole.

Crisis:

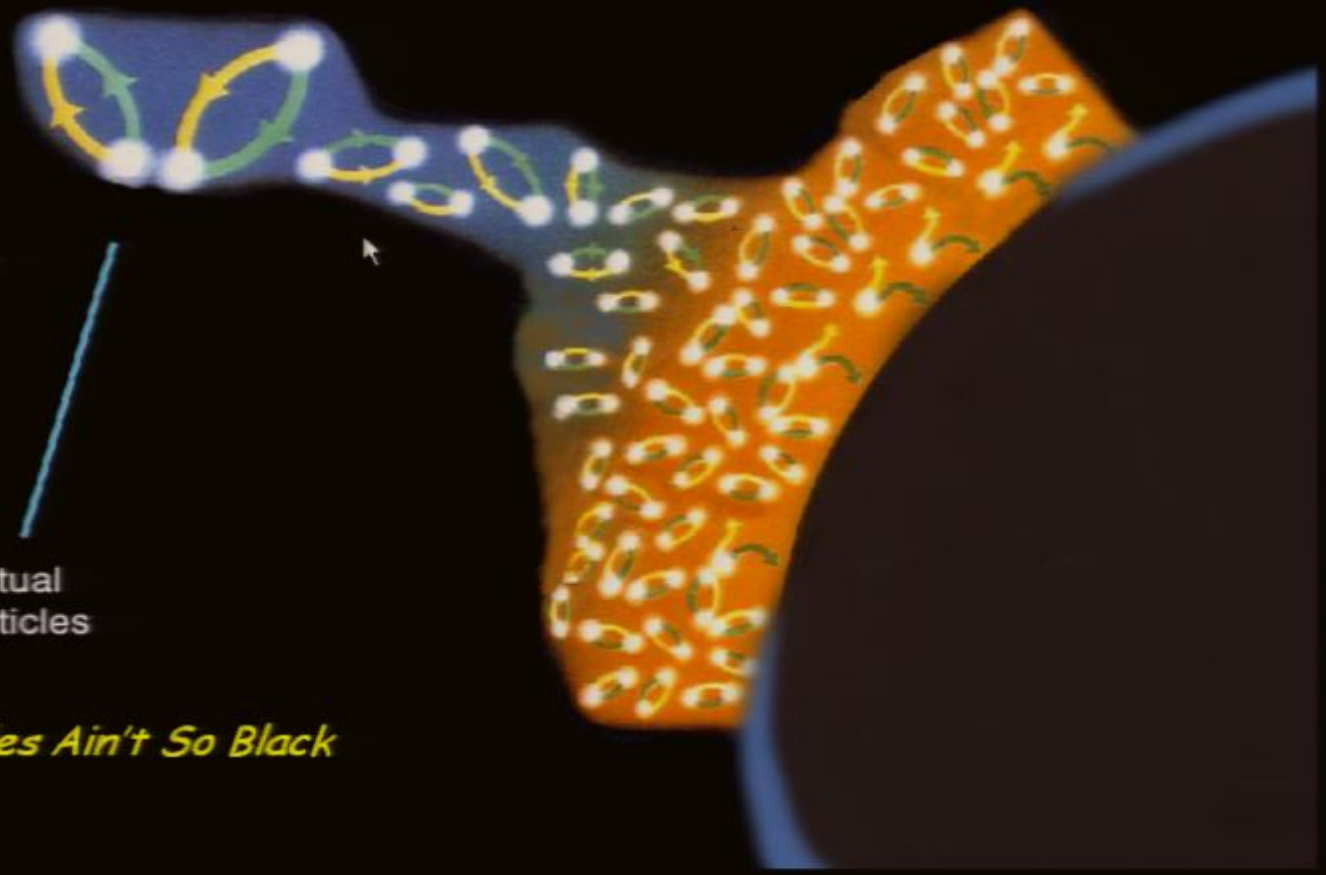
- *Several ways to picture how a black Hole evaporates*
  - *Some ways correspond to different ways of formulating laws of quantum fields.*
  - *Some ways correspond to String Theory*
  - *Some ways correspond to Quantum Gravity*
  - *Some ways make no sense at all.*

Vacuum Fluctuations

- *A vacuum is a place which is anything but empty.*
- *It is a place of continuous creation and destruction. Pairs of virtual particles are born – live a short but happy life – then die.*
- *Possible by Heisenberg's uncertainty principle: The energy of a vacuum, that we suppose to be zero, can be defined with an uncertainty of ΔE during at ΔT.*
- *$\Delta T x\ \Delta E \approx h$*
- *Therefore particles/antiparticles, with $\pm\ \Delta E$ are constantly being created.*
- *One particle has positive energy, one particle has negative energy.*
- *The particles live momentarily on fluctuational energy "borrowed" from neighbouring regions of space.*

Stephen W. Hawking (b1942)

Hawking radiation



Virtual photon is its own antiparticle

virtual particles

Black Holes Ain't So Black

Hawking Radiation

- The Hawking Radiation theory states that virtual particle-antiparticle pairs are sometimes created outside the event horizon of a black hole. Three things can happen to a pair of particles just outside the event horizon:
  - Both particles are pulled into the black hole.
  - Both particles escape from the black hole.
  - One particle escapes while the other is pulled into the black hole.
- For the third possibility, the particle that has escaped becomes real and can therefore be observed from Earth. The energy to separate the two virtual particles (thus making them real particles) is taken from the horizon, thus reducing the energy of the Black Hole.
- The wavelength of the particle/wave that enters the a hole will be of 25% of the hole's circumference.
- For Example: A black hole of 2 Solar Masses with a circumference of about 35K will emit a wavelength of

$$\frac{35}{4} \approx 9 \ km$$

Hawking Radiation

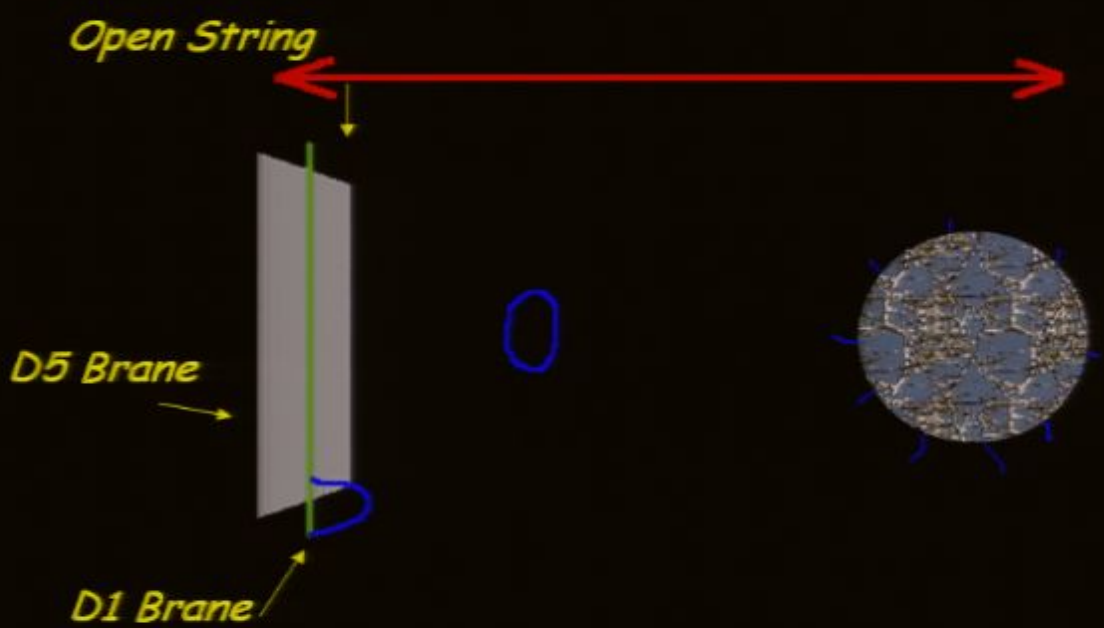
- The larger (more massive) the Black Hole the lower the temperature and the longer it takes to evaporate.

$$Temp_K \approx \frac{6 \times 10^{-8}}{M_\oplus}$$

$$\tau ime \approx 10^{66} \cdot \left[M_\oplus \right]^3$$

- *Remember the age of the Universe is* 10^{10} *years give or take 3 days.*

Superstring Method

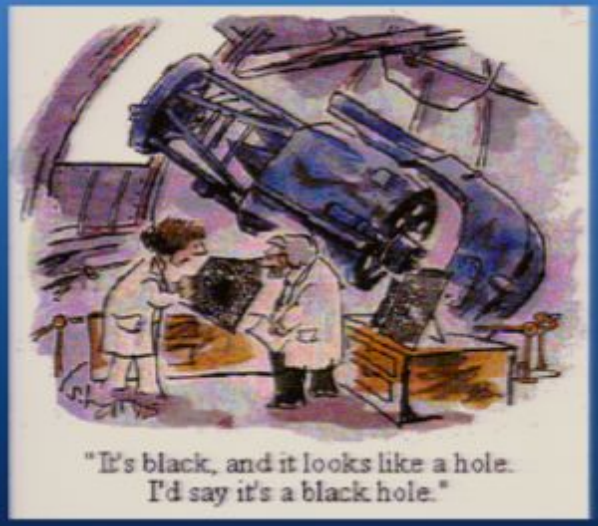


One of the most dramatic recent results in string theory is the derivation of the Bekenstein-Hawking entropy

Are Black Holes Real

What are we going to look for if Black Holes are Real

Observational Evidence for Black Holes

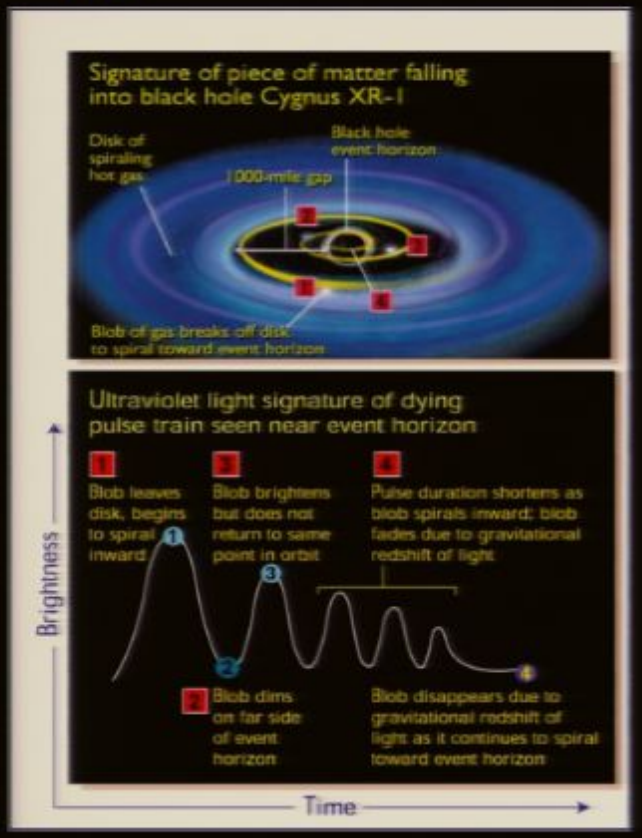


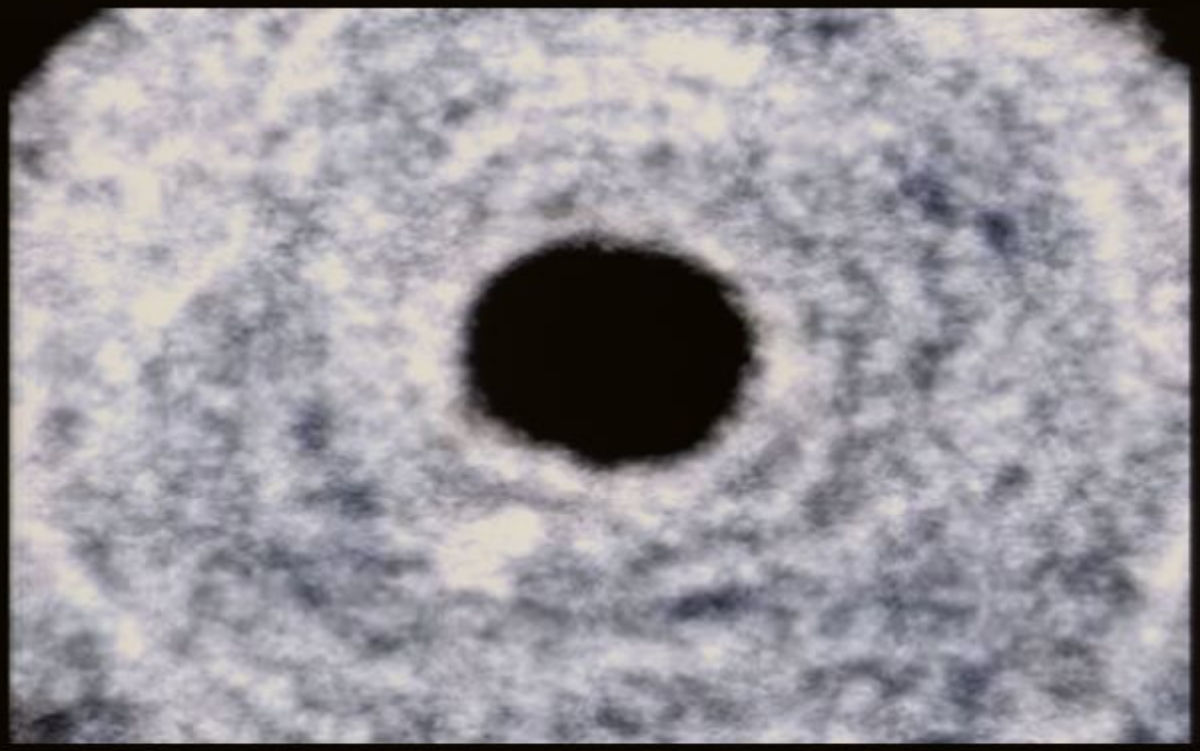
Finding Black Holes
Ultraviolet and X-rays
Seeing Matter Disappear

Hubble observed pulses of UV light emitted by material as it fell into a black hole.

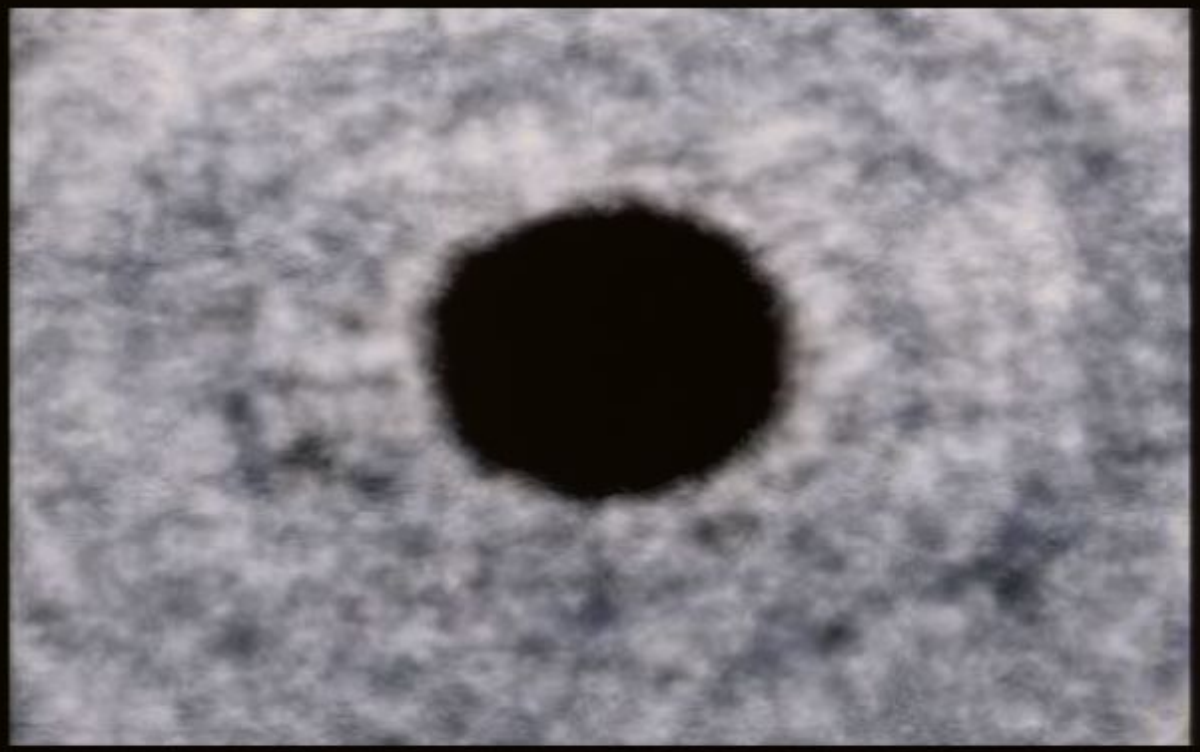
- Pulses arise from material orbiting around intense gravity of the black hole.

- Light pulses, lasting 0.2 s, are red-shifted from X-ray to UV, as they fall into gravity of the black hole.





- Zel'dovich speculated that if a black hole was surround by gas and this gas was orbiting the black hole in an accretion disk, it Would give off x-rays
- The U.S. then used WW2 V-2 rockets with a simple x-ray machine in the 40's to see if it could detect x-rays



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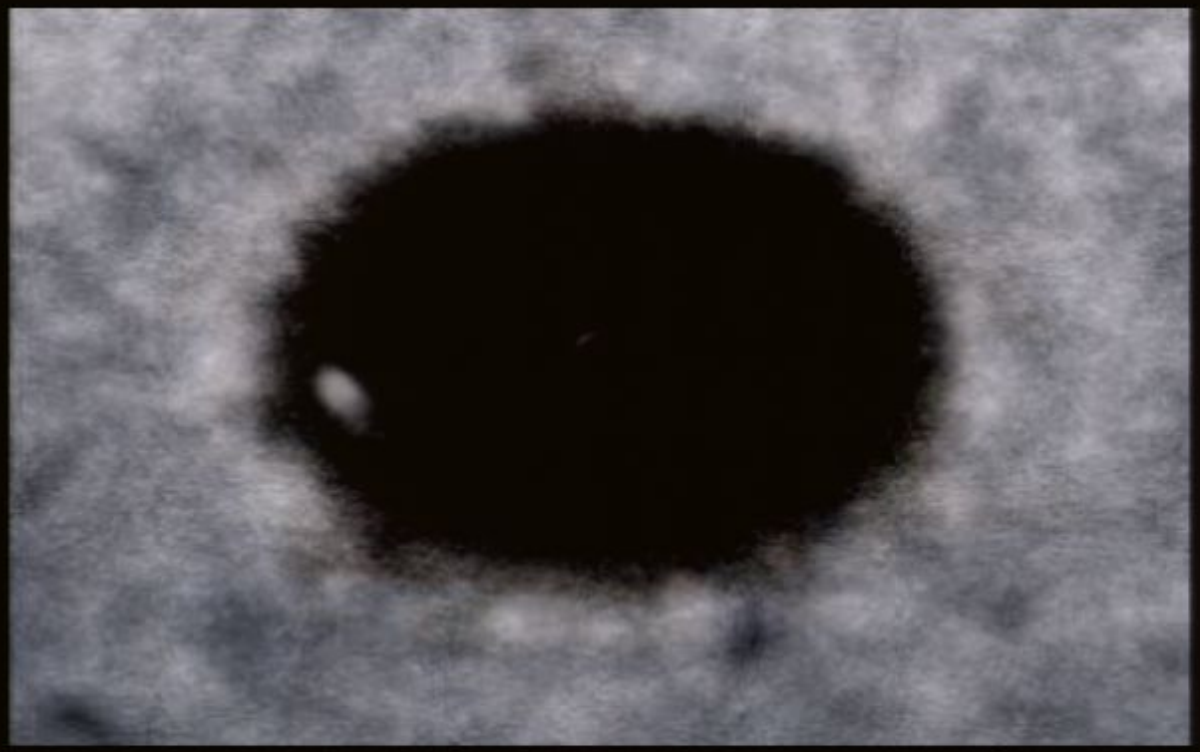

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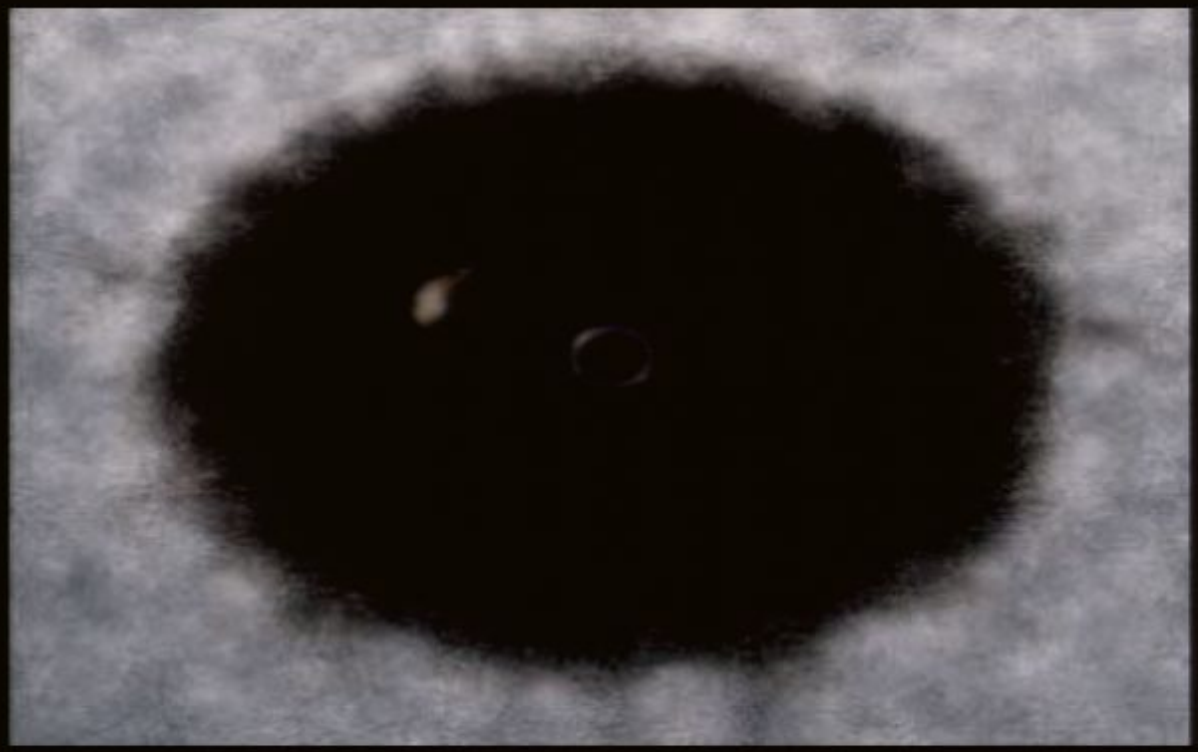

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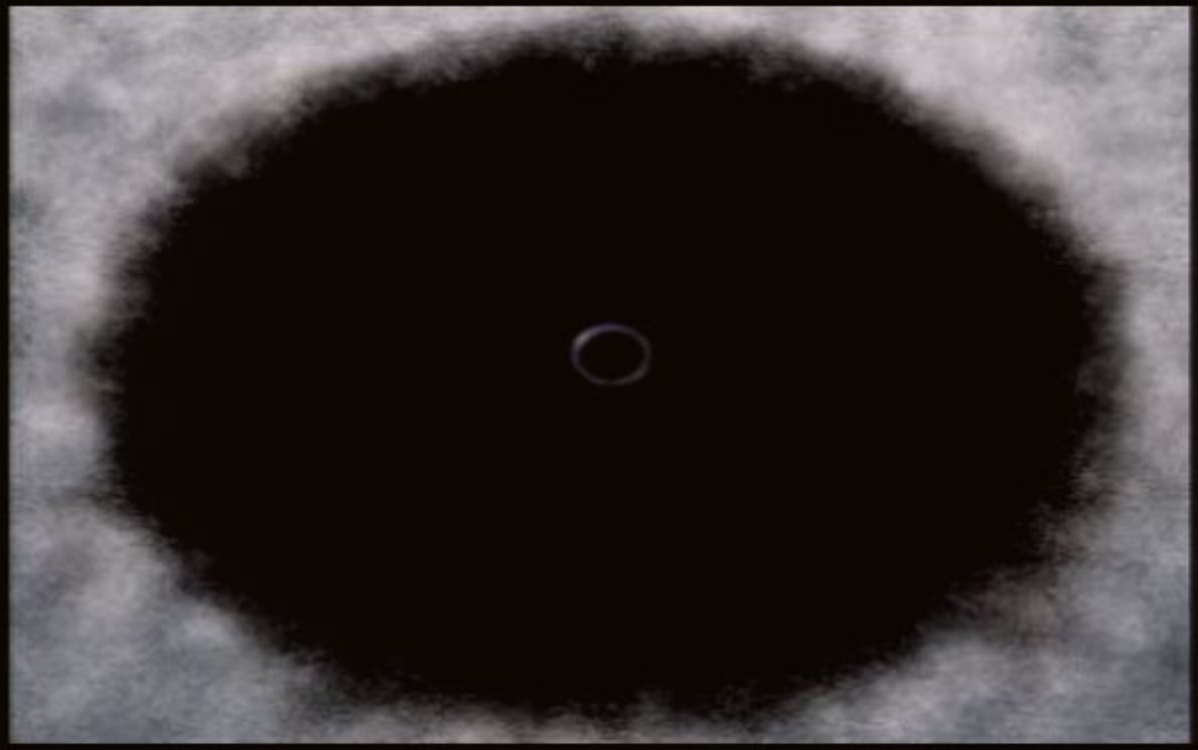

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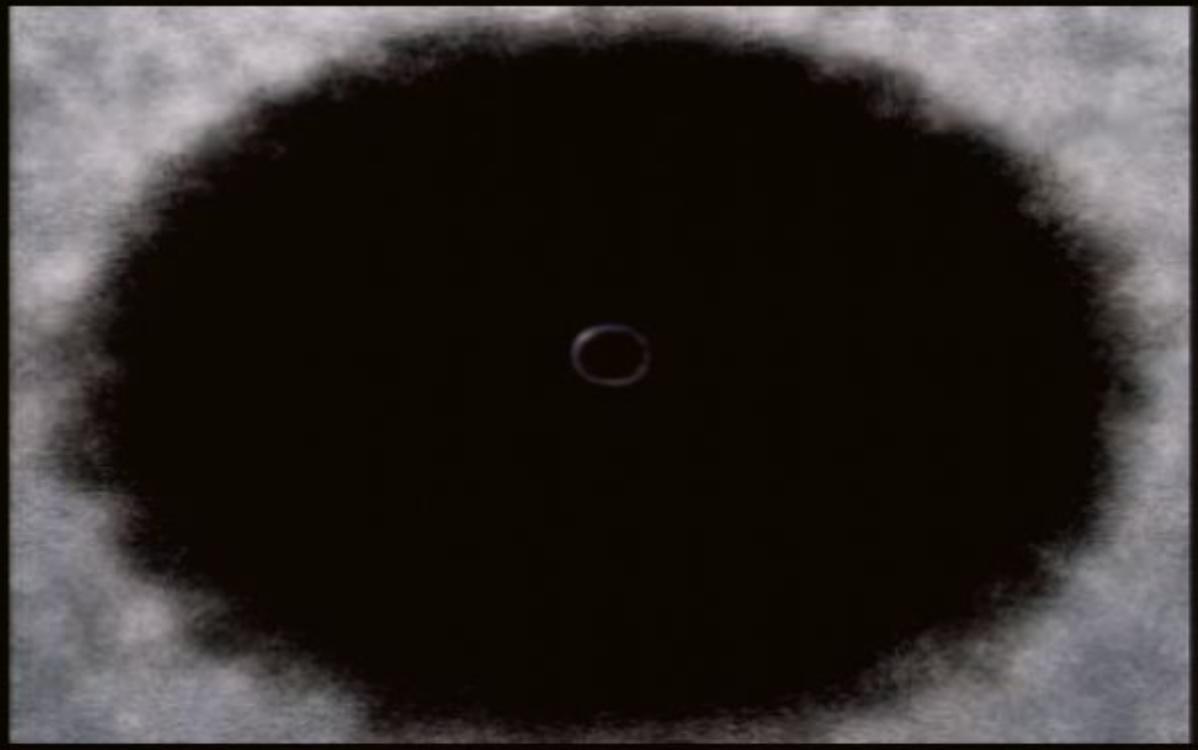

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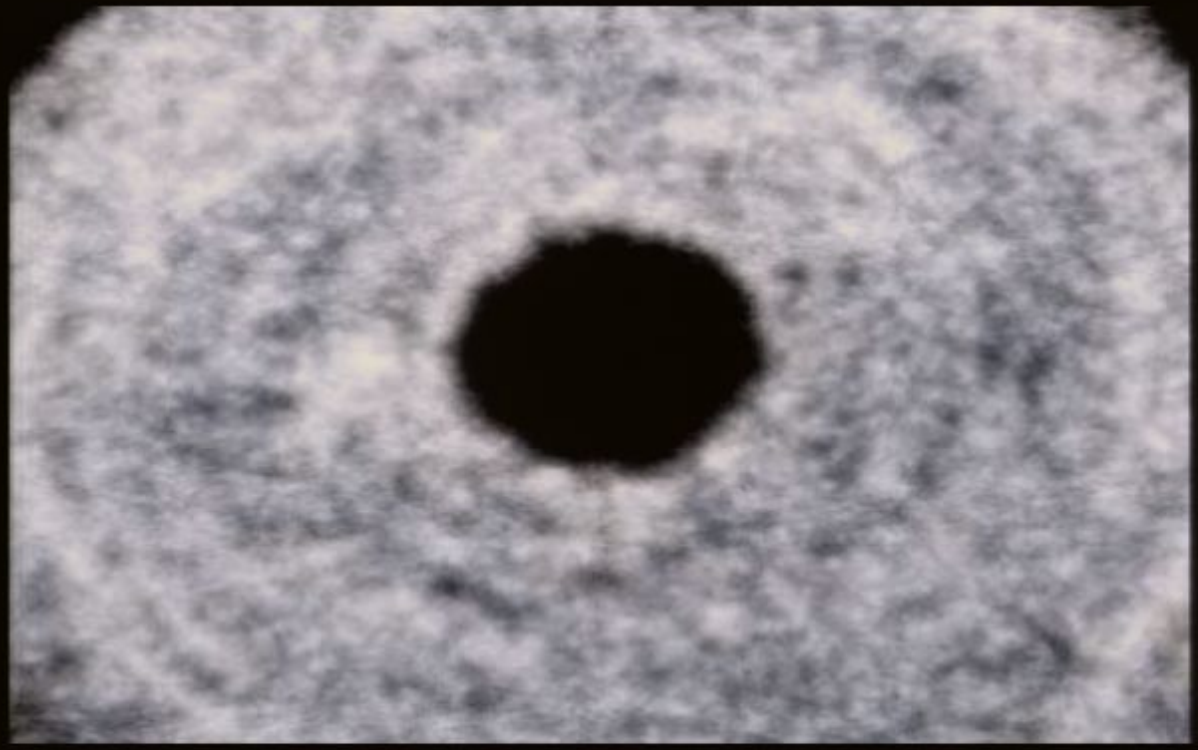

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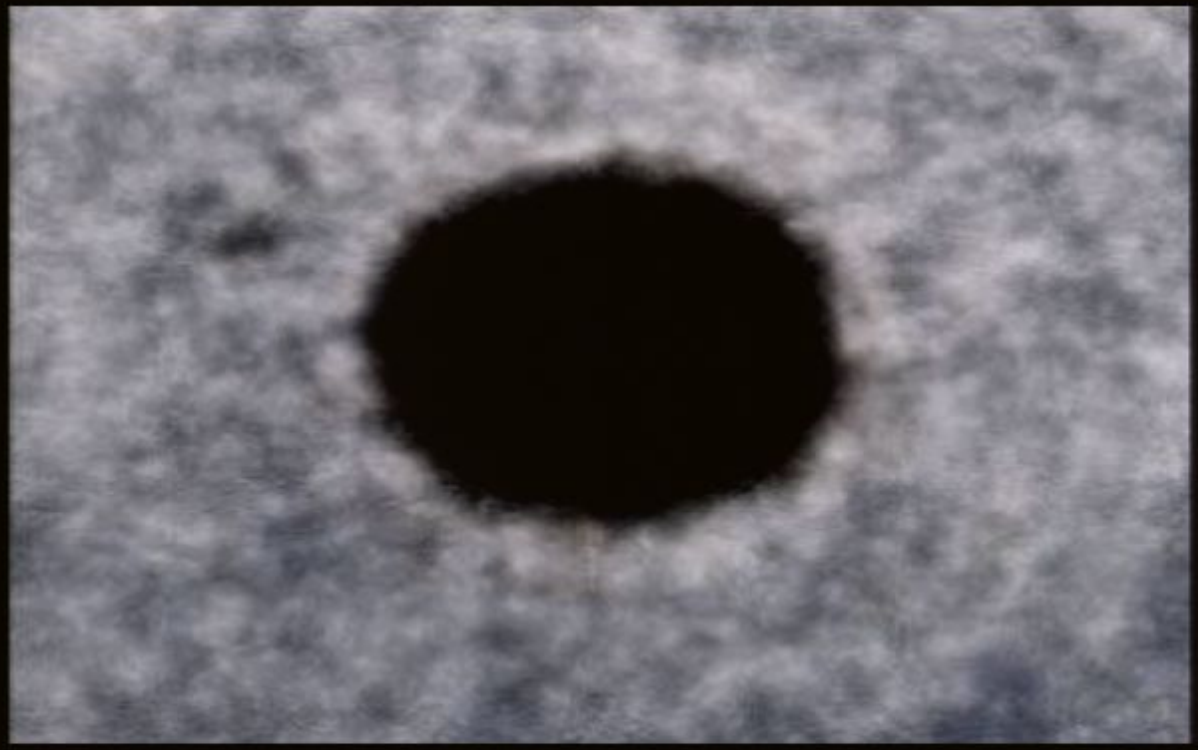

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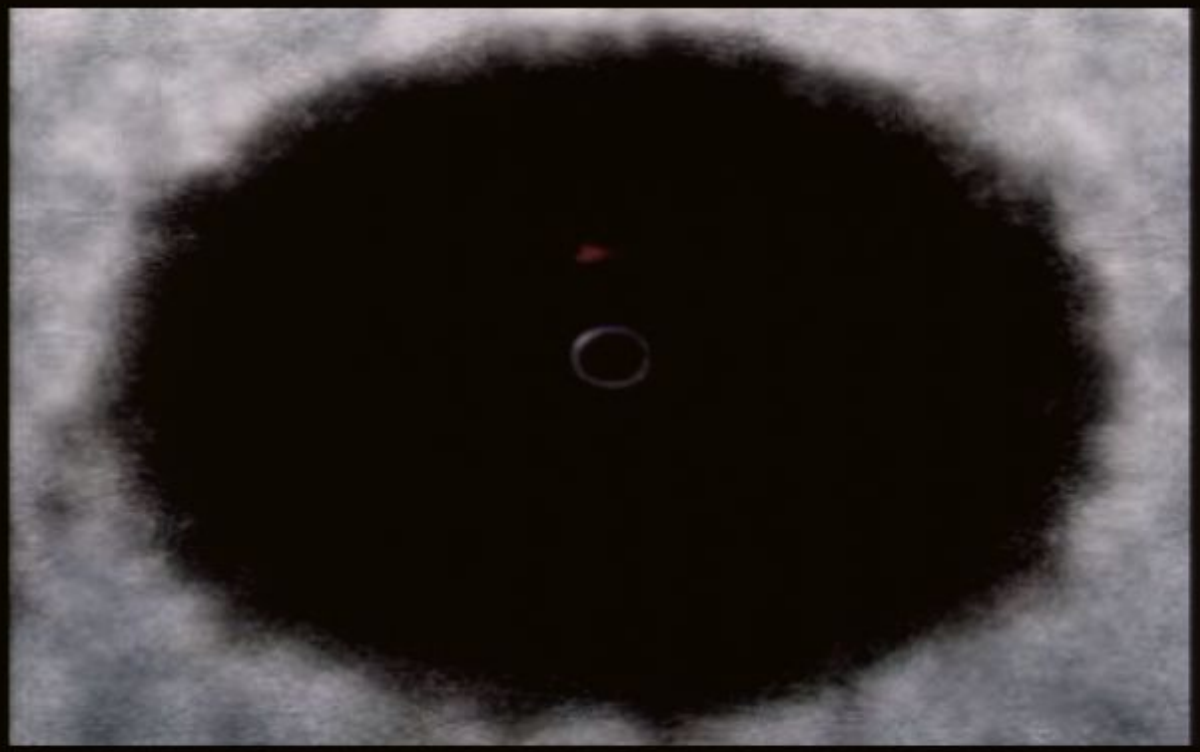

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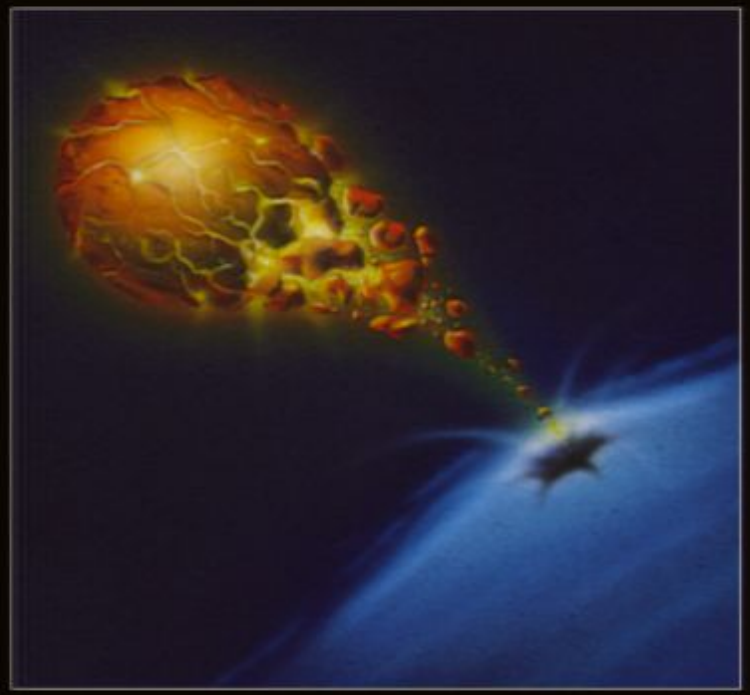
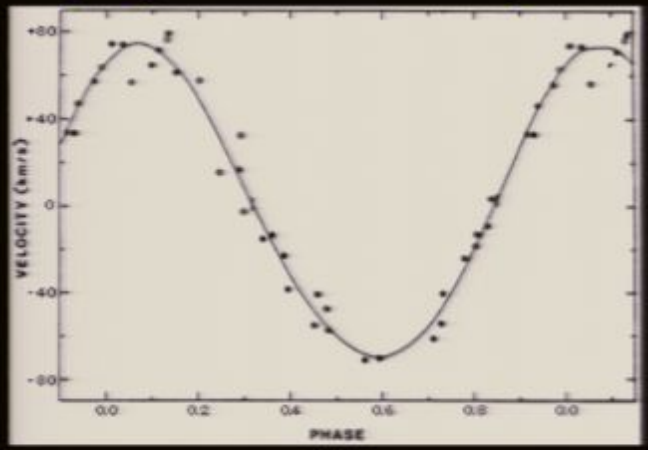
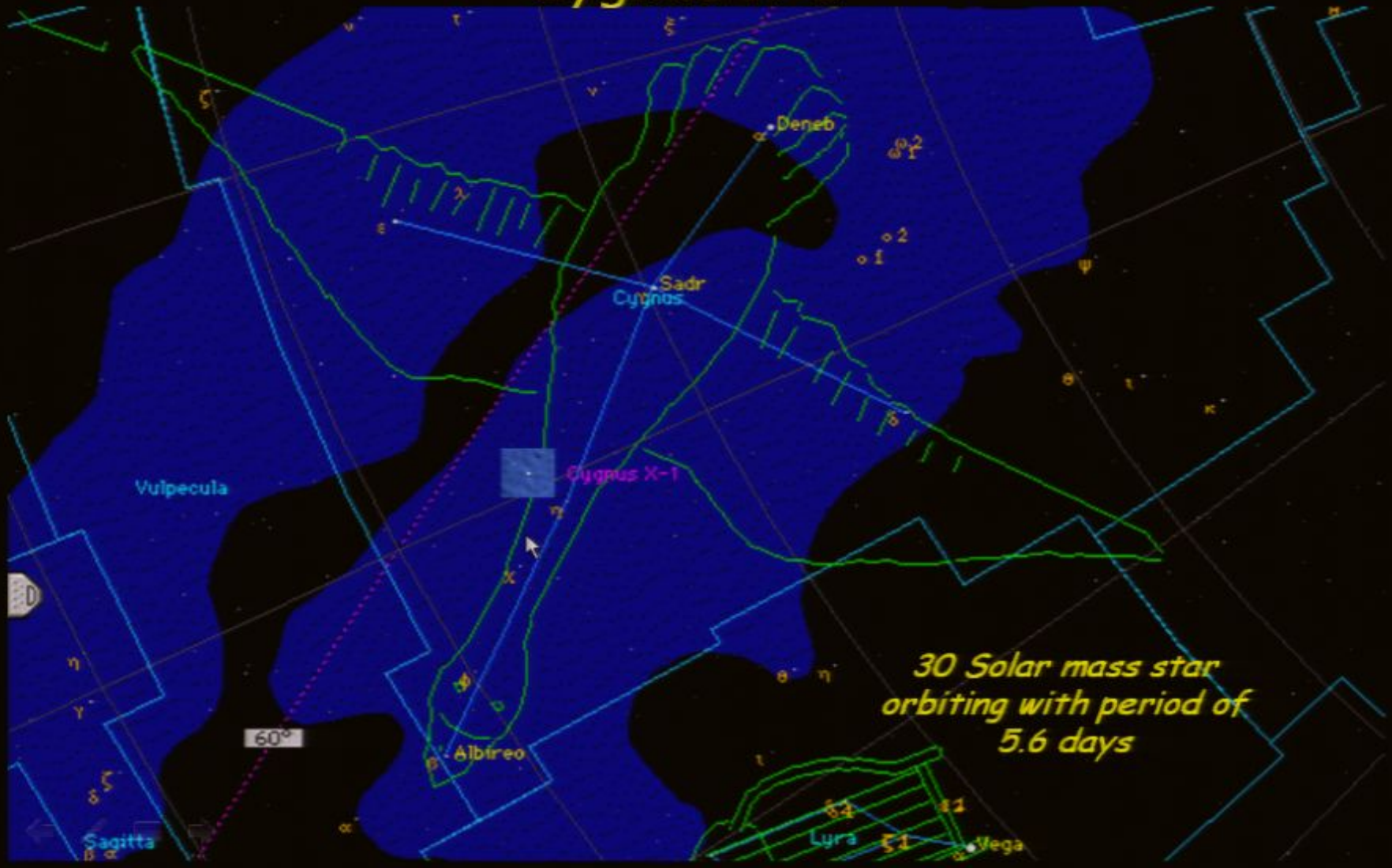
Seeing Holes



- Can't see black hole itself, but can see matter falling into a hole.
- Gravitational forces stretch and rip matter: heats up.
- Very hot objects emit in X-rays (interior of Sun)



Cygnus X-1


Deneb
Sadr
Cygnus
Cygnus X-1
Vulpecula
60°
Albireo
Sagitta
Lyra
Vega
30 Solar mass star
orbiting with period of
5.6 days

NGC 6240 Chandra XRay Images

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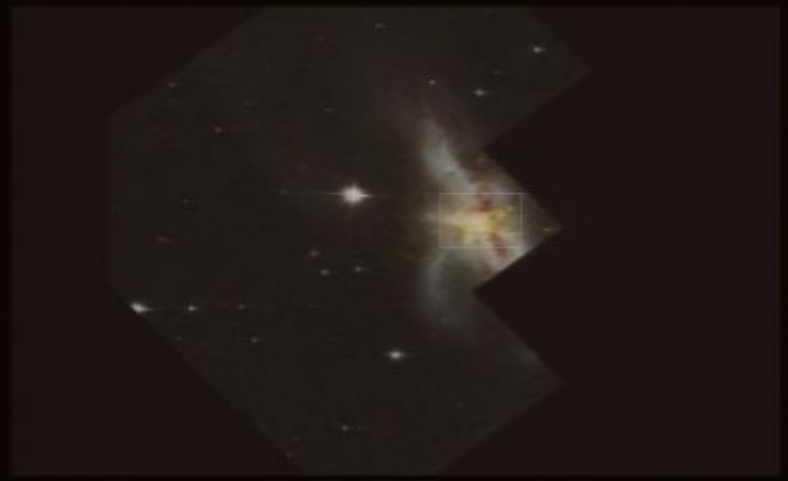
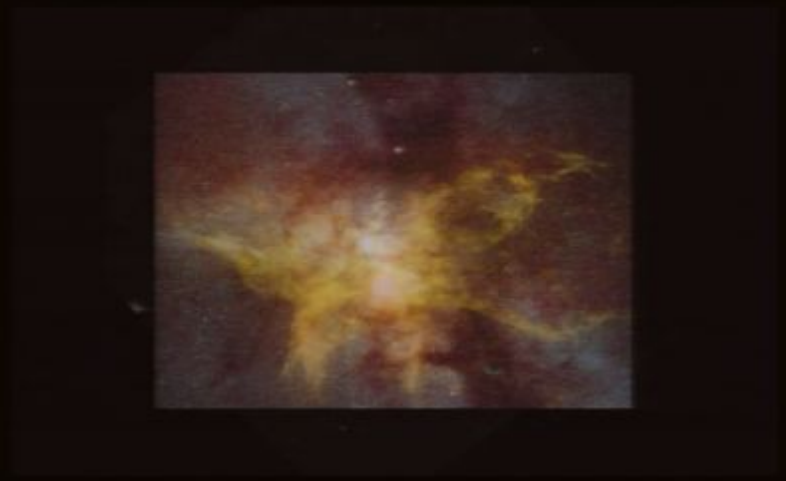
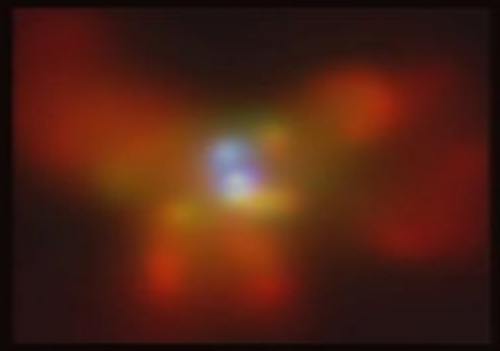


NGC 6240 Chandra XRay Images



NGC 6240 Chandra XRay Images

NGC 6240 Chandra XRay Images

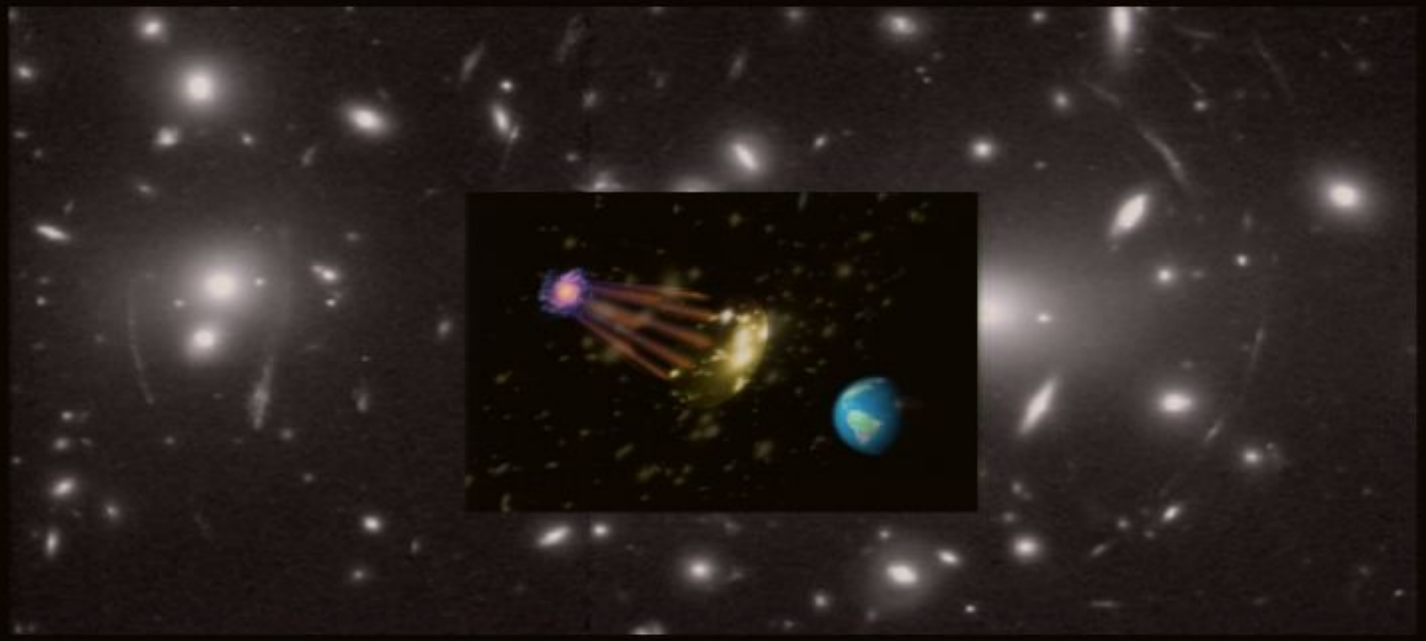


NGC 6240 Chandra XRay Images

Lens

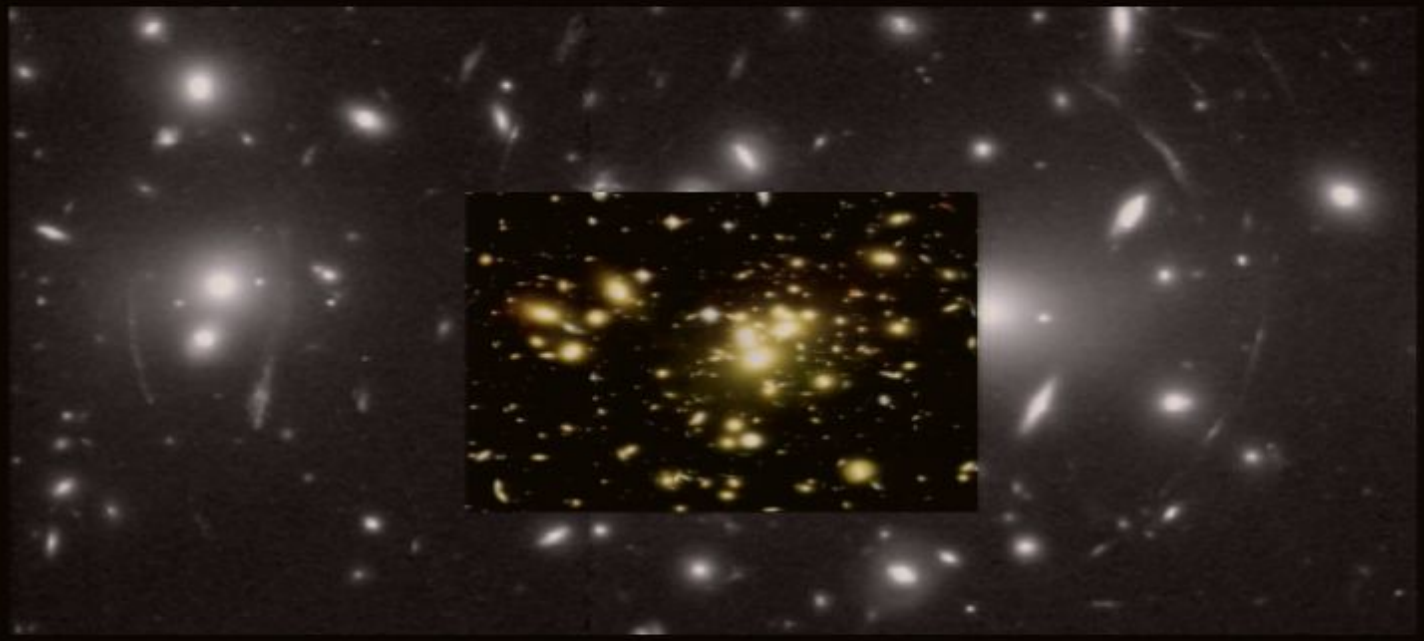
Black Holes can act like a lens. Almost all of the bright objects in this image are galaxies in the cluster known as Abell 2218..

Lens



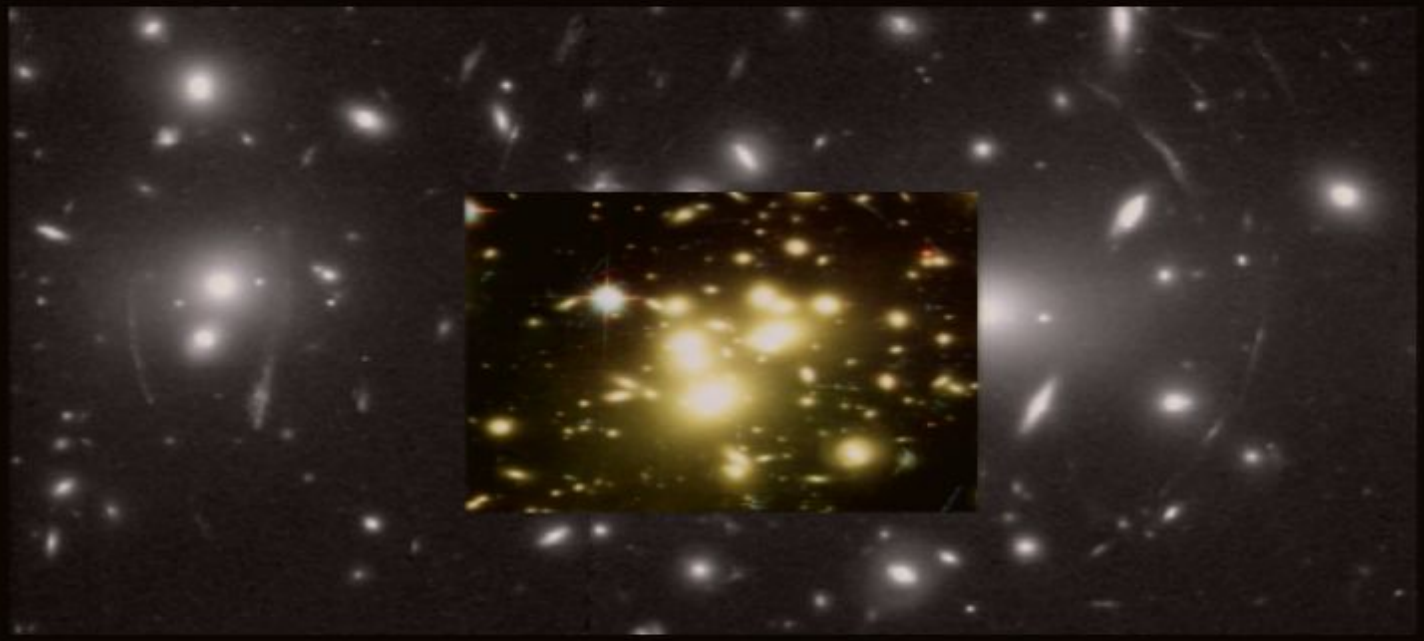
Black Holes can act like a lens. Almost all of the bright objects in this image are galaxies in the cluster known as Abell 2218..

Lens



Black Holes can act like a lens. Almost all of the bright objects in this image are galaxies in the cluster known as Abell 2218..

Lens



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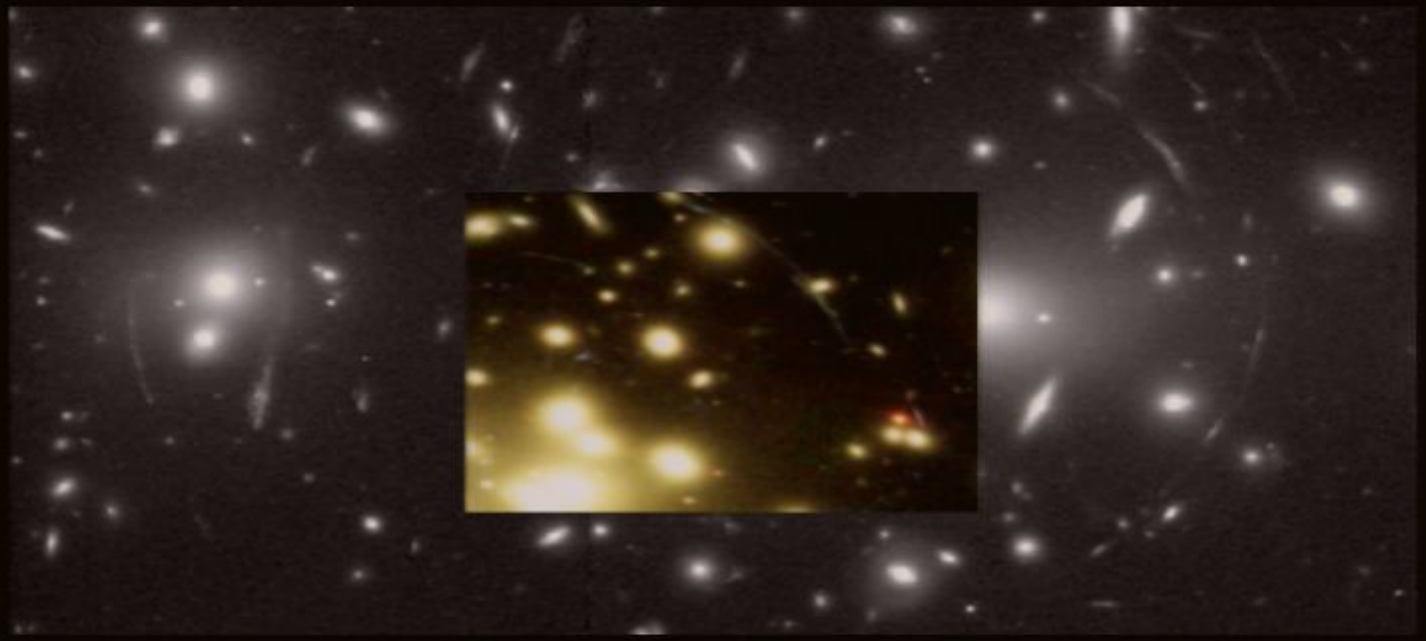
Lens



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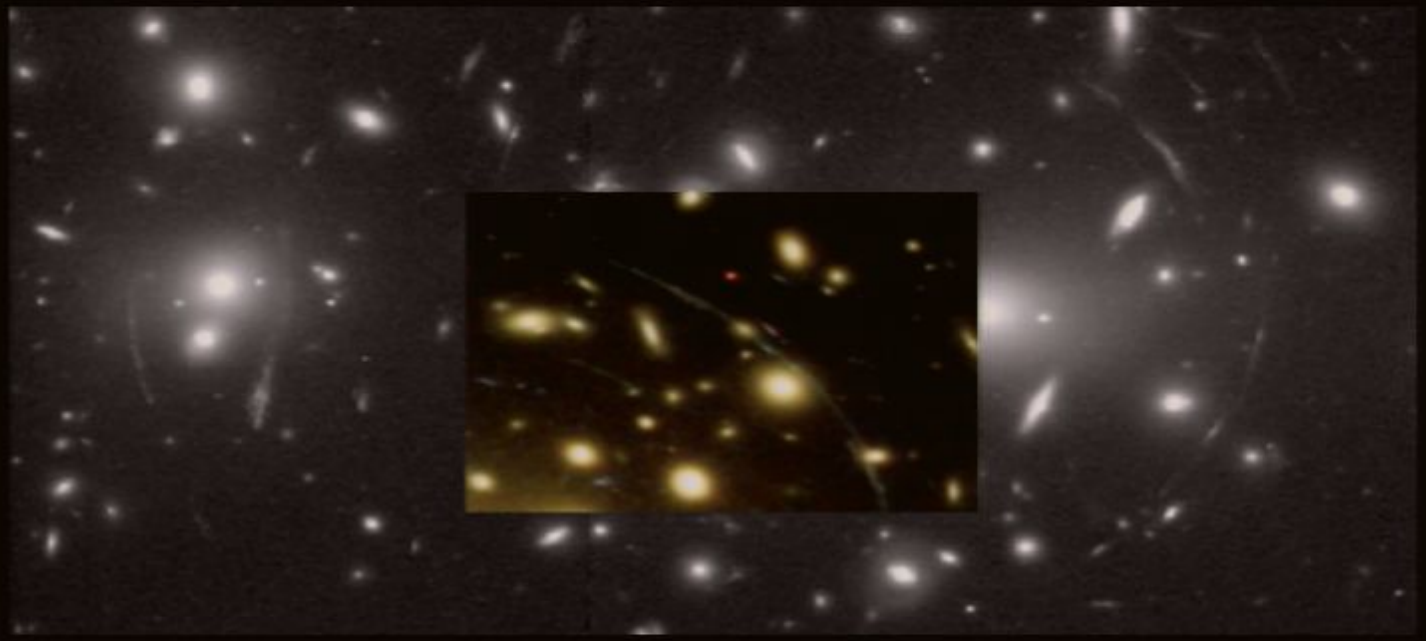
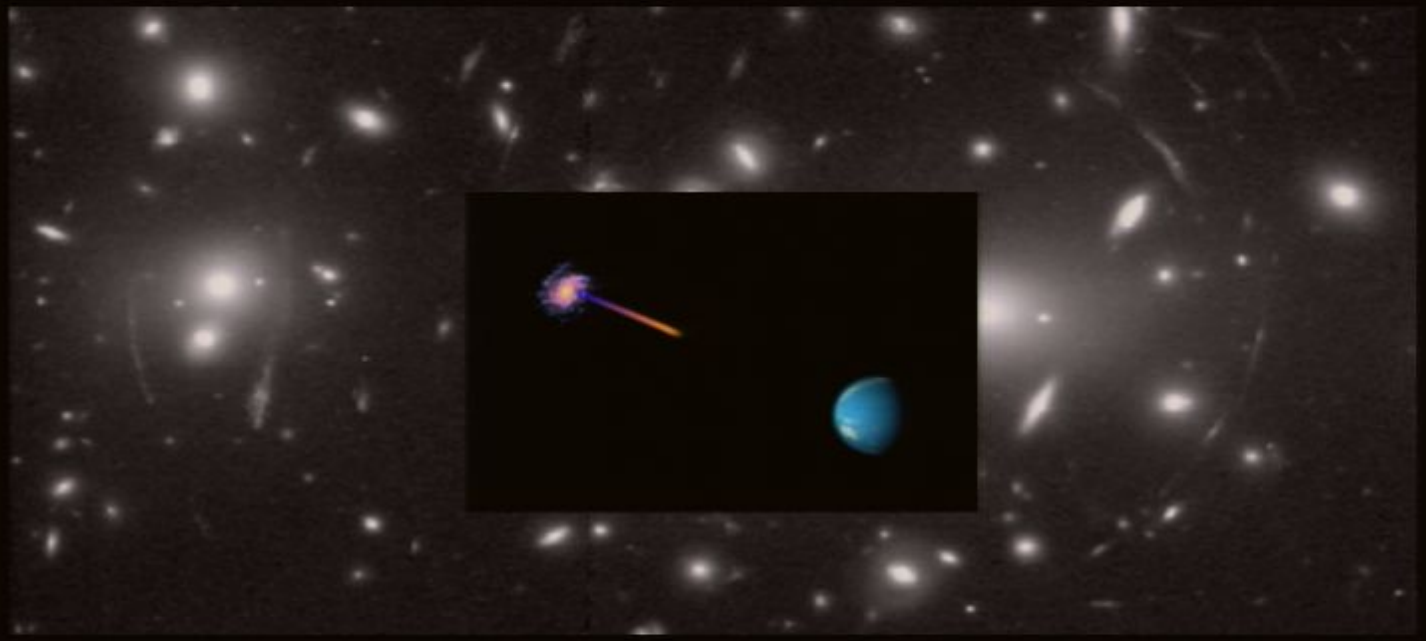
Lens



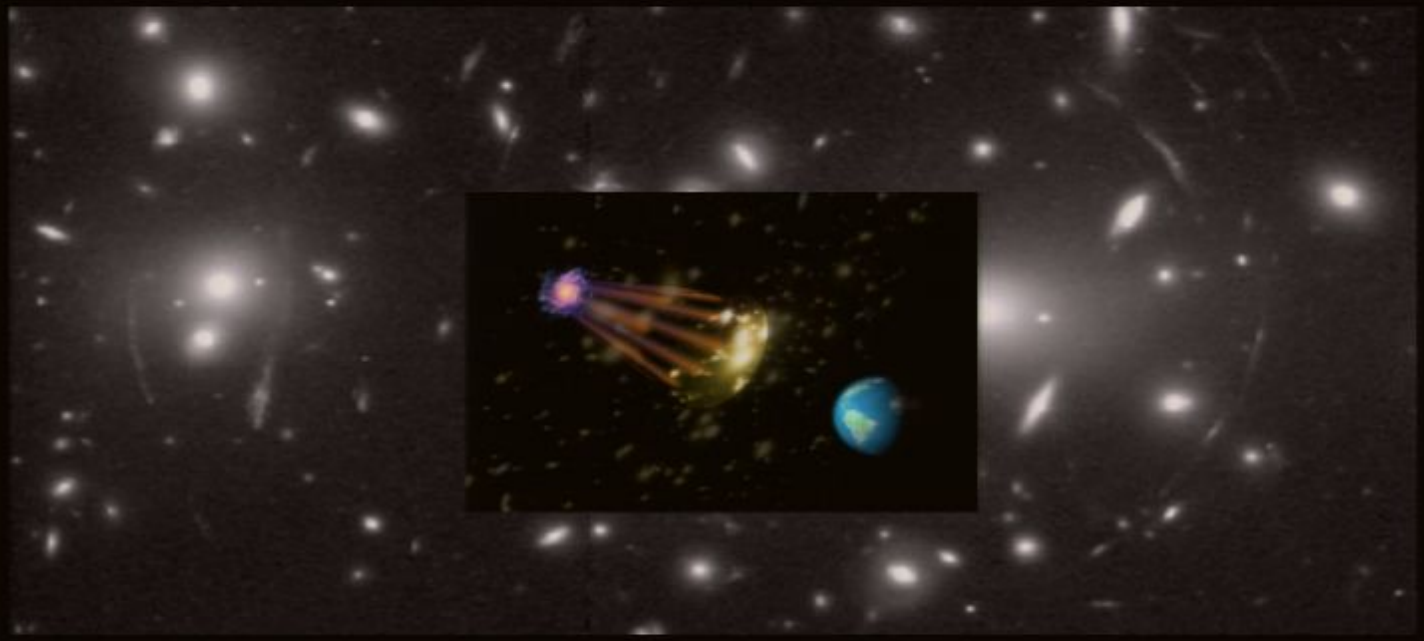
Black Holes can act like a lens. Almost all of the bright objects in this image are galaxies in the cluster known as Abell 2218..

Lens



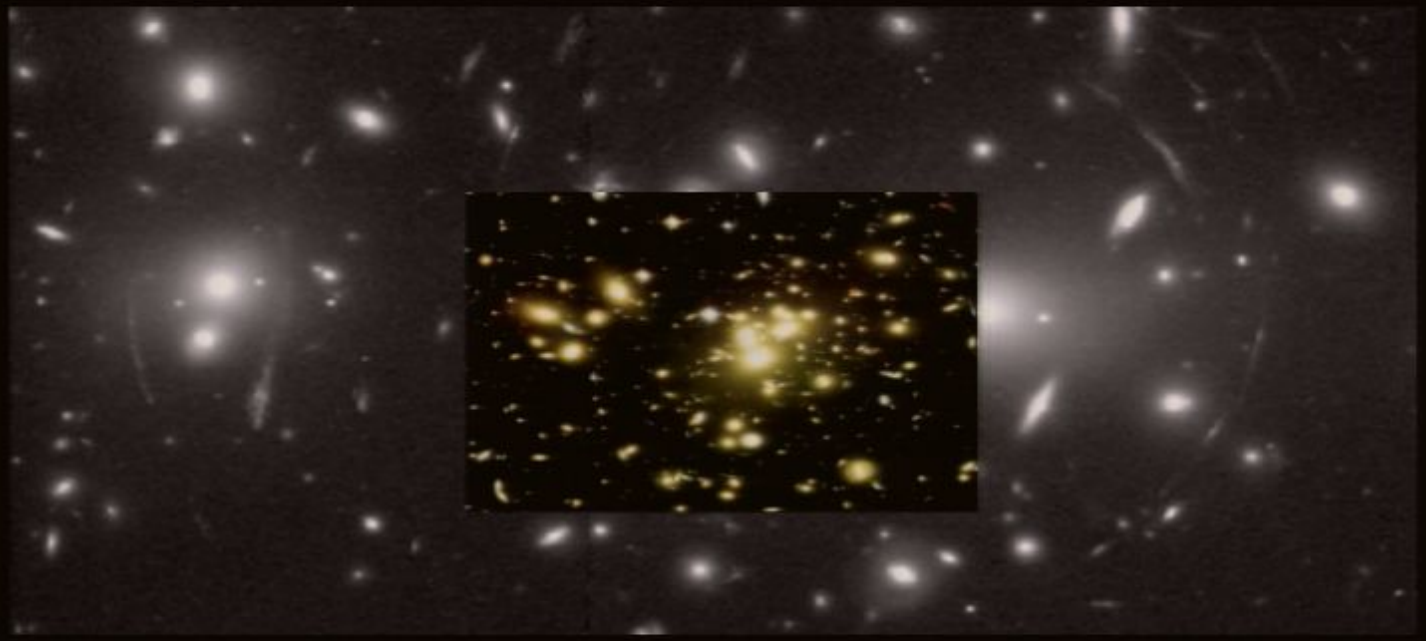
Black Holes can act like a lens. Almost all of the bright objects in this image are galaxies in the cluster known as Abell 2218..

Lens



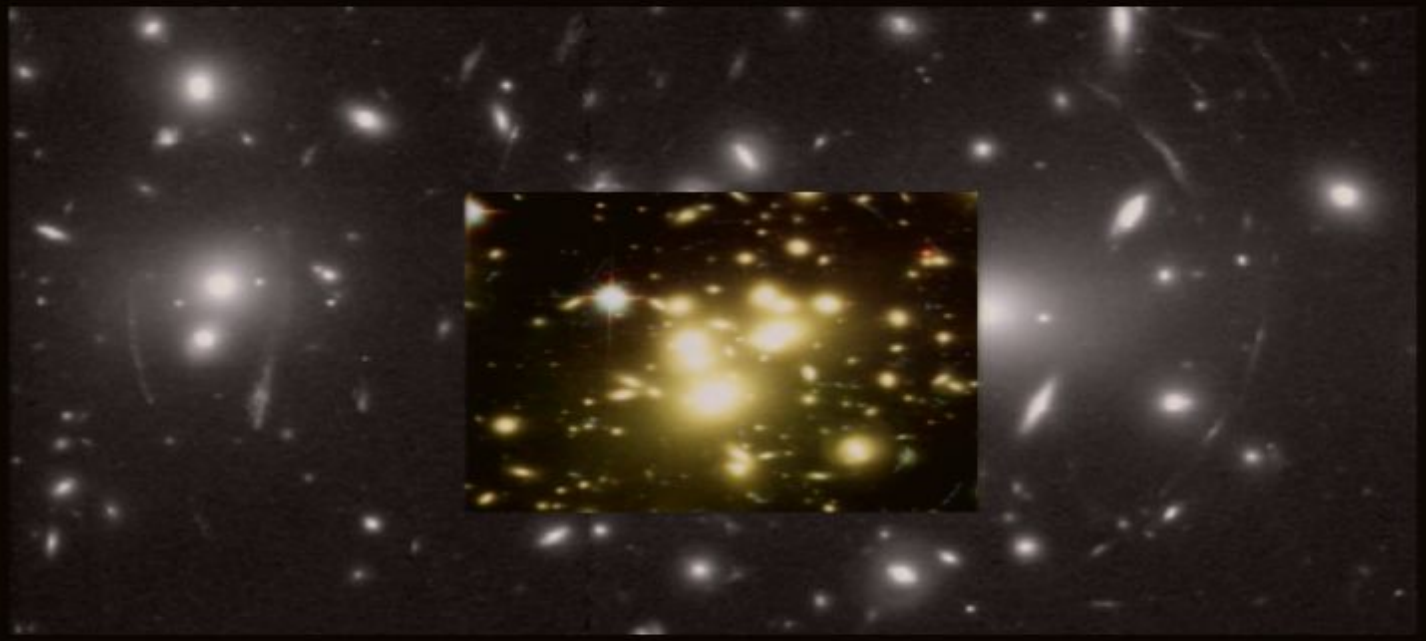
Black Holes can act like a lens. Almost all of the bright objects in this image are galaxies in the cluster known as Abell 2218..

Lens



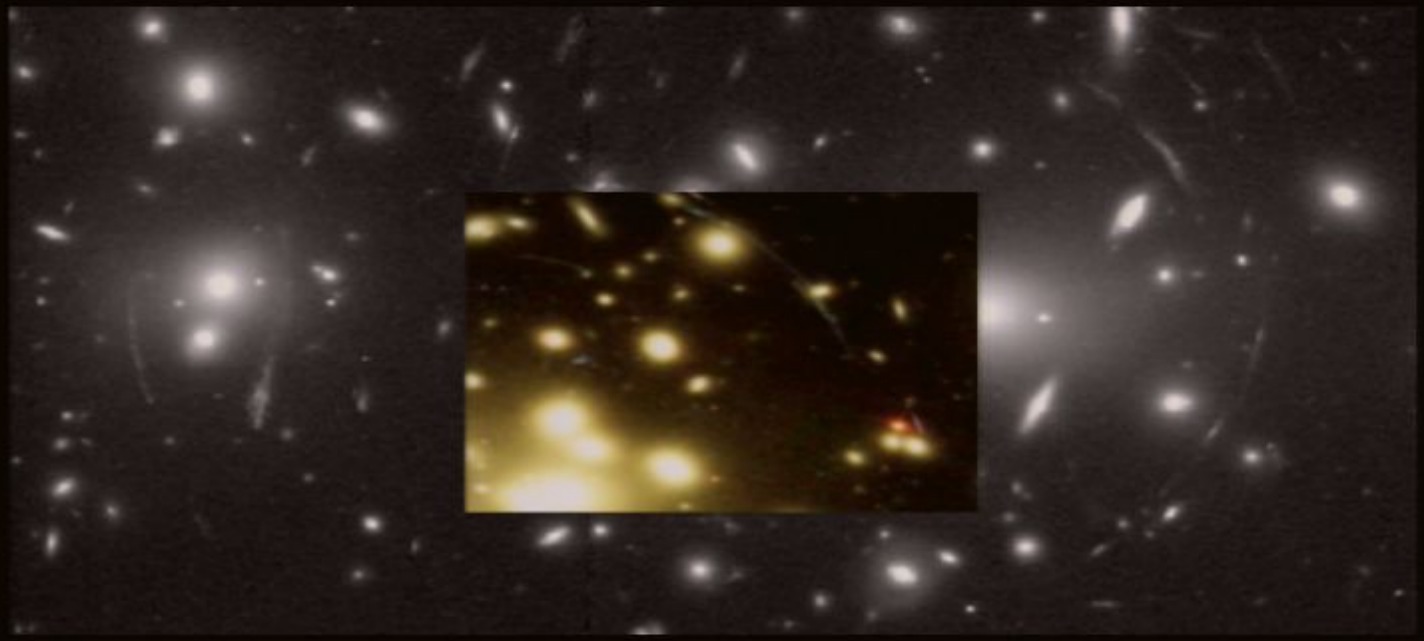
Black Holes can act like a lens. Almost all of the bright objects in this image are galaxies in the cluster known as Abell 2218..

Lens



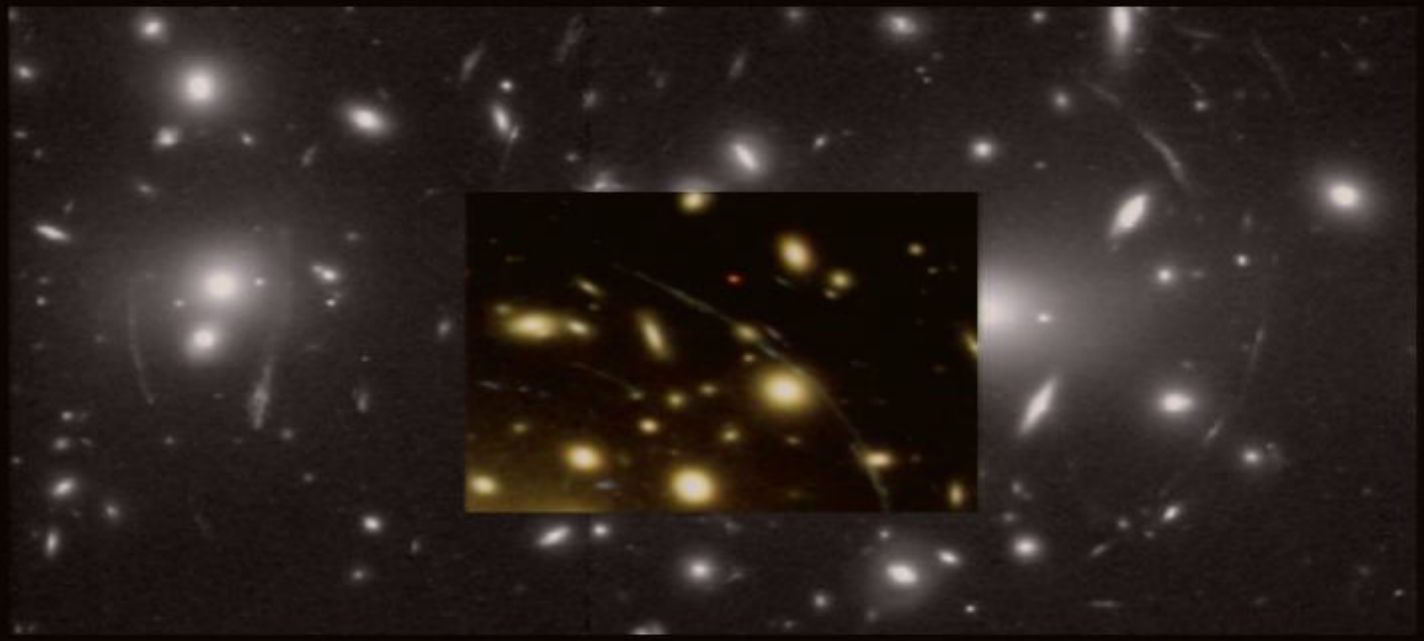
Black Holes can act like a lens. Almost all of the bright objects in this image are galaxies in the cluster known as Abell 2218..

Lens



Black Holes can act like a lens. Almost all of the bright objects in this image are galaxies in the cluster known as Abell 2218..

Lens



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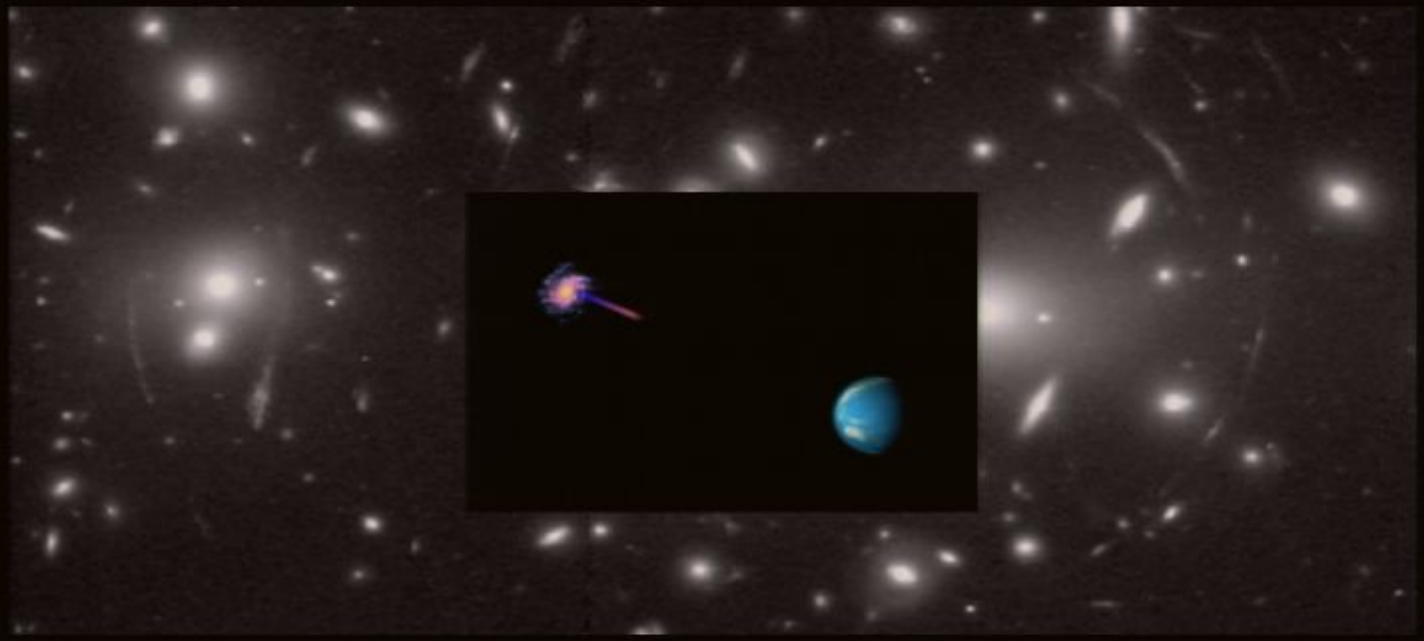
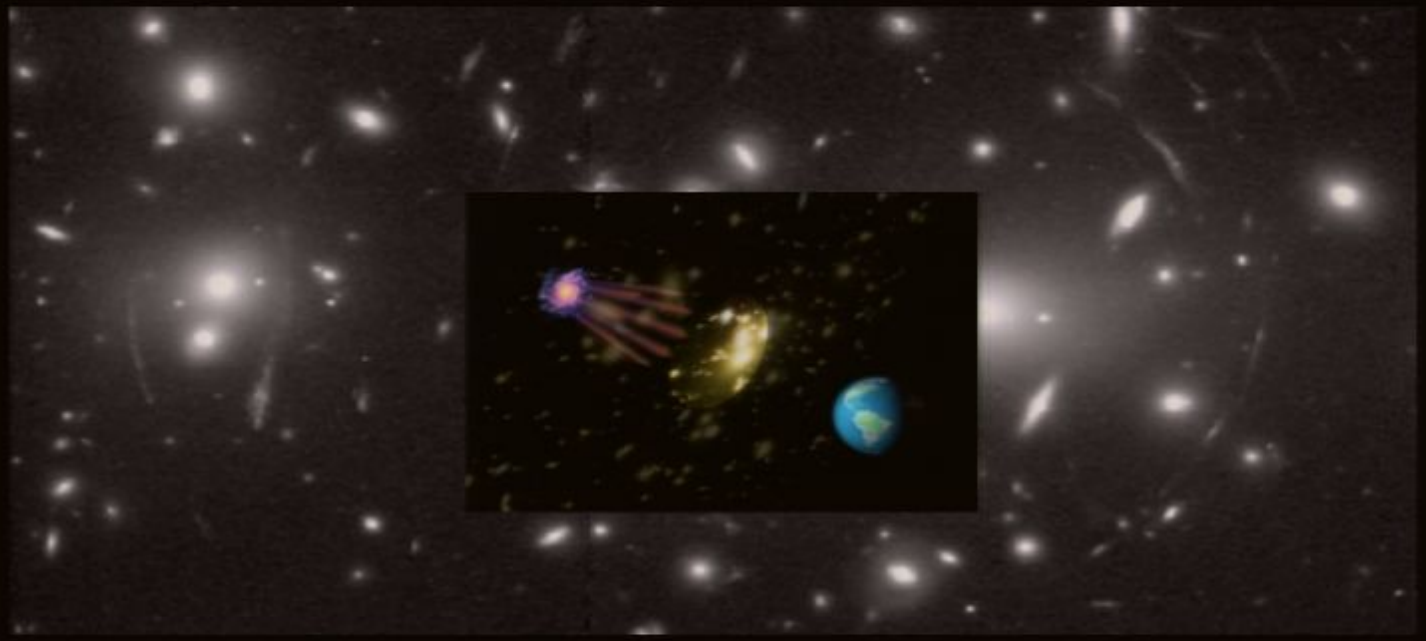
Lens



Black Holes can act like a lens. Almost all of the bright objects in this image are galaxies in the cluster known as Abell 2218..

Lens



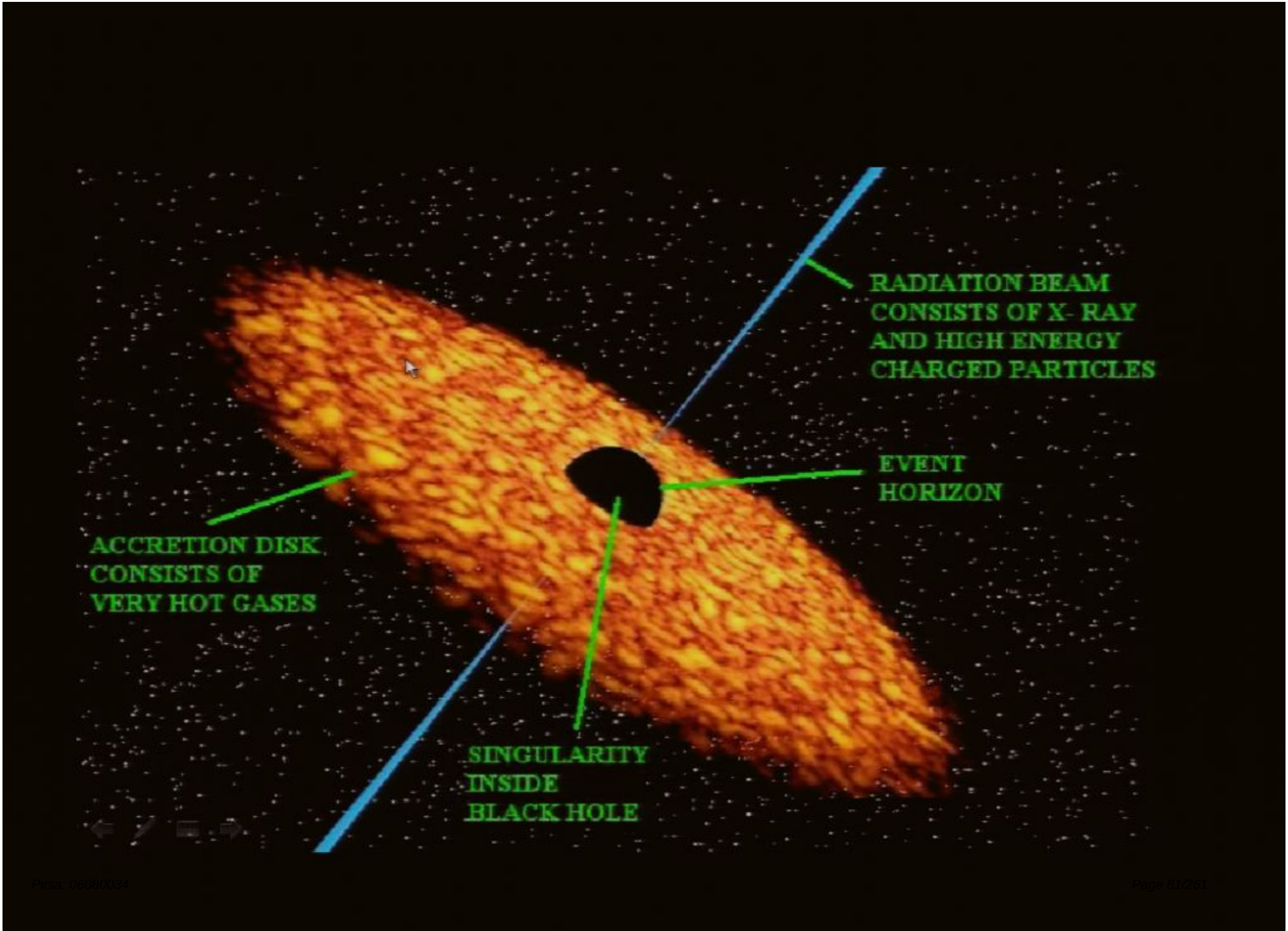
Black Holes can act like a lens. Almost all of the bright objects in this image are galaxies in the cluster known as Abell 2218..

What else should we look for?

Jets

What else should we look for?

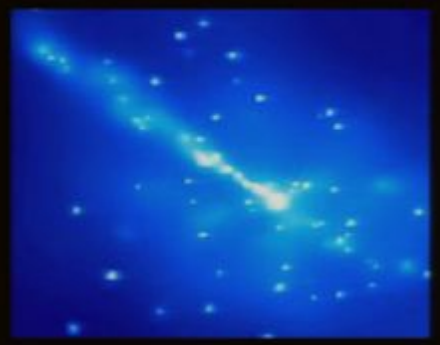
Jets

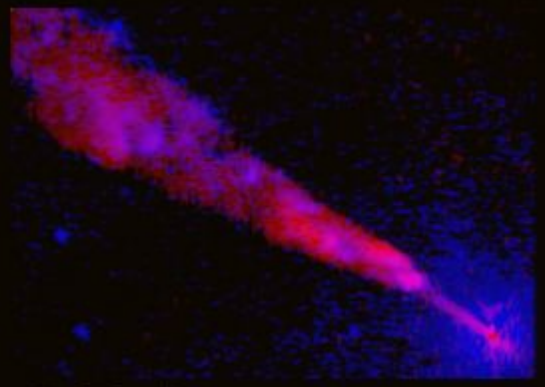

RADIATION BEAM
CONSISTS OF X- RAY
AND HIGH ENERGY
CHARGED PARTICLES
EVENT
HORIZON
ACCRETION DISK
CONSISTS OF
VERY HOT GASES
SINGULARITY
INSIDE
BLACK HOLE

Radio Jets from Black Holes

- Many black holes emit jets.
  - Material in jet moving at 0.9c.
  - Jet likely composed of electrons and positrons.
- Magnetic fields surrounding black hole expel material and form the jet.
  - Interaction of jet material with magnetic field gives rise to Radio emission.

Jets

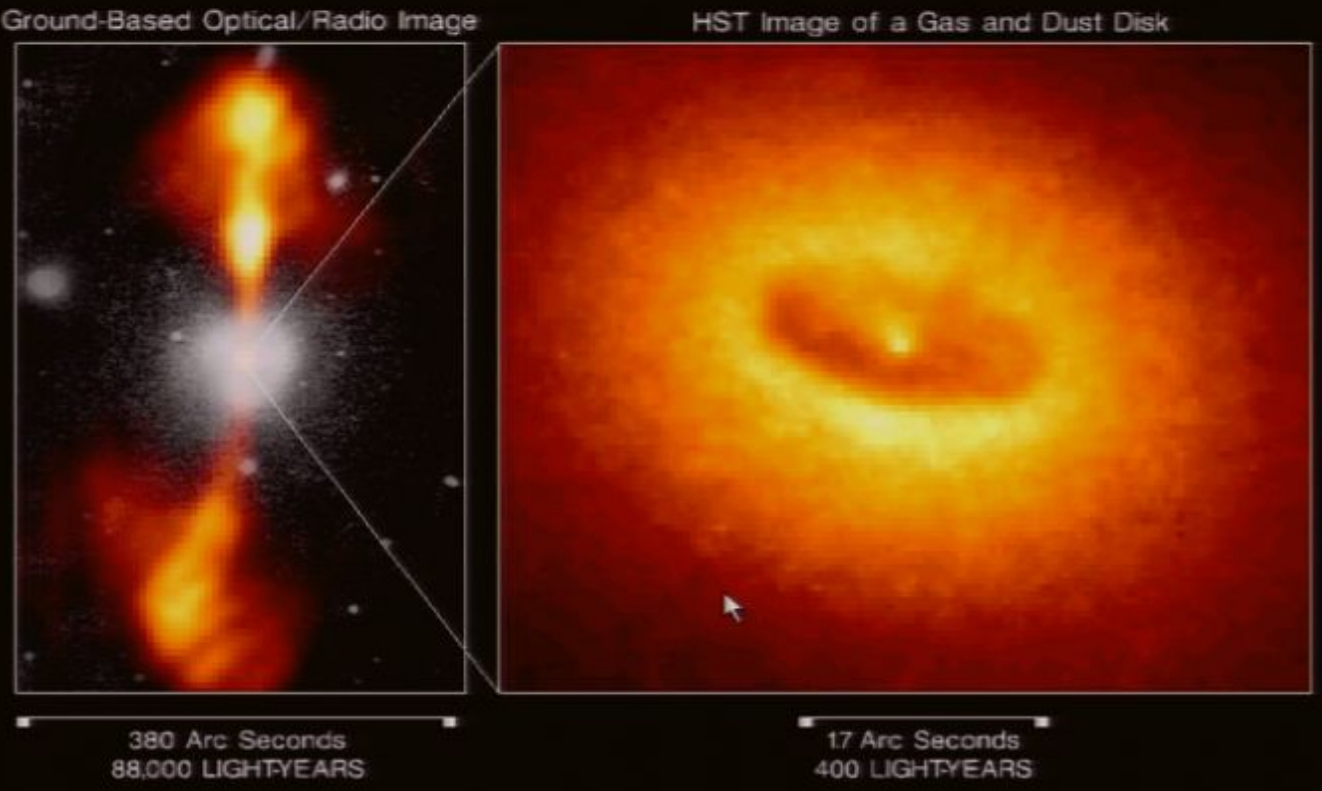




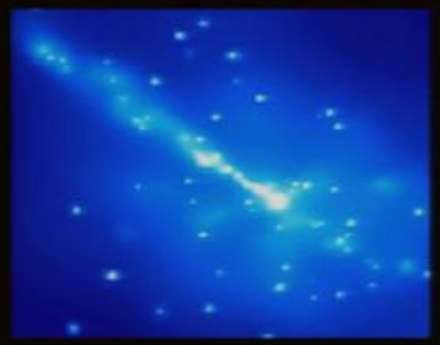
Core of Galaxy NGC 4261

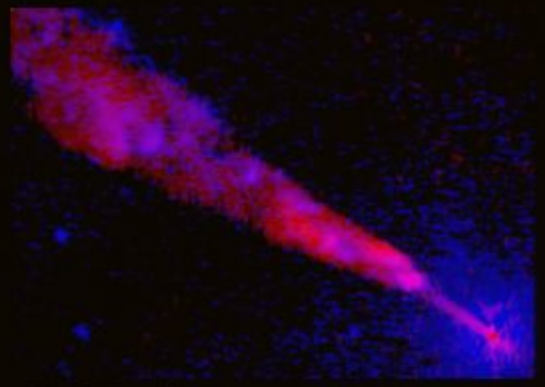
Hubble Space Telescope

Wide Field / Planetary Camera



Jets

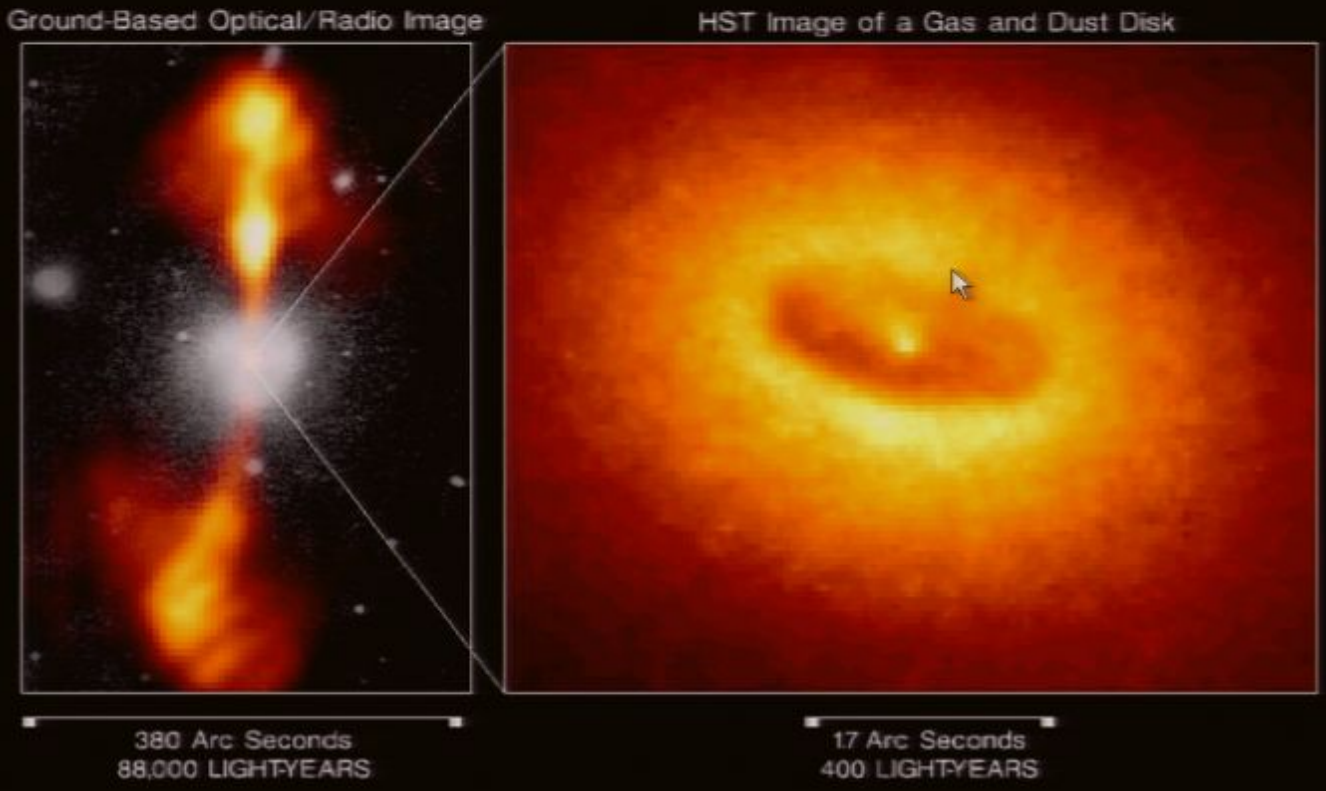




Core of Galaxy NGC 4261

Hubble Space Telescope

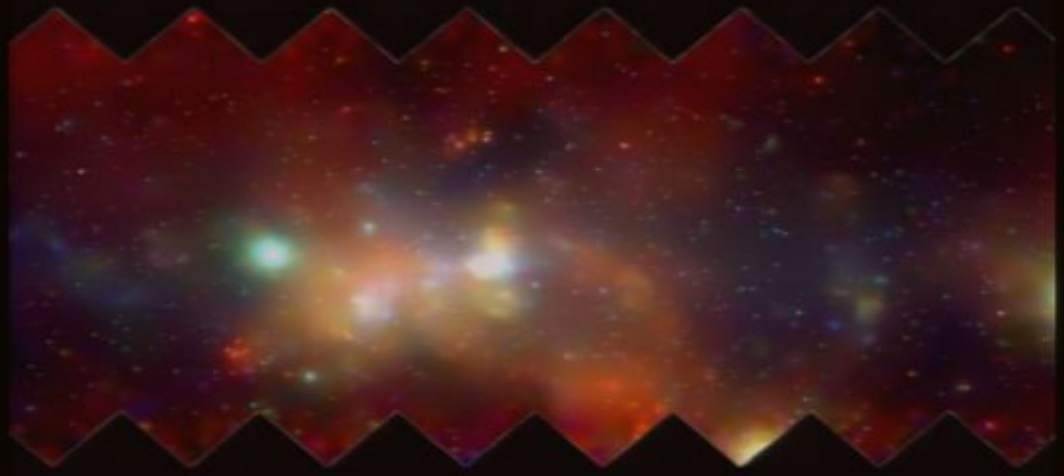
Wide Field / Planetary Camera



More Evidence

Thanks to Chandra Team at Nasa

More Evidence



What about inside our own Galaxy?

More Evidence

What about inside our own Galaxy?

More Evidence

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More Evidence

What about inside our own Galaxy?

More Evidence

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More Evidence

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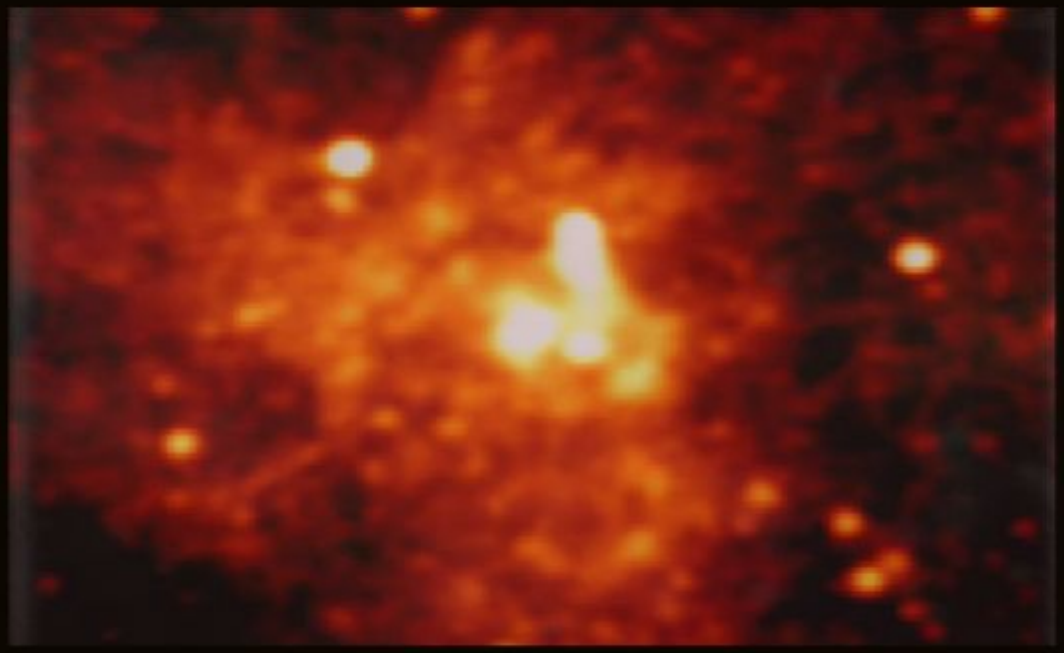
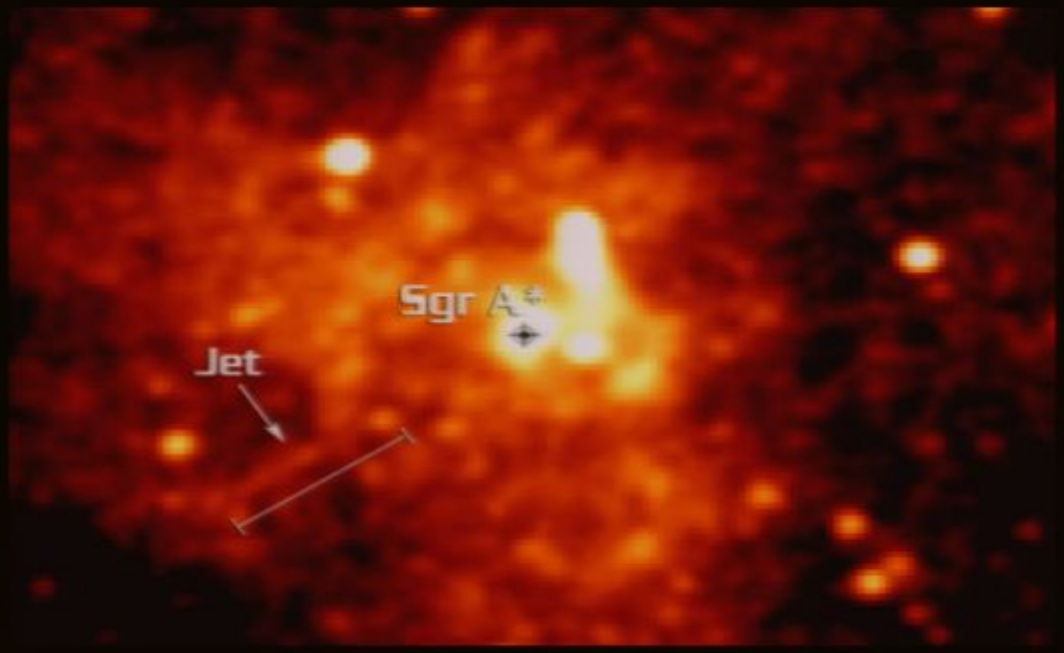


What about inside our own Galaxy?

More Evidence



What about inside our own Galaxy?

More Evidence

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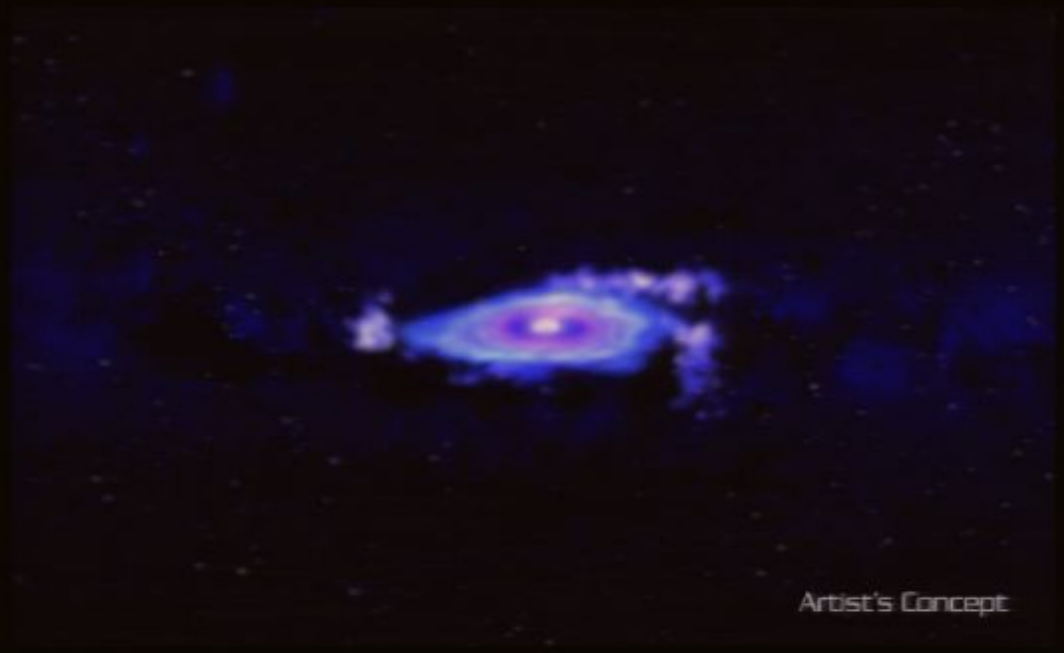
More Evidence



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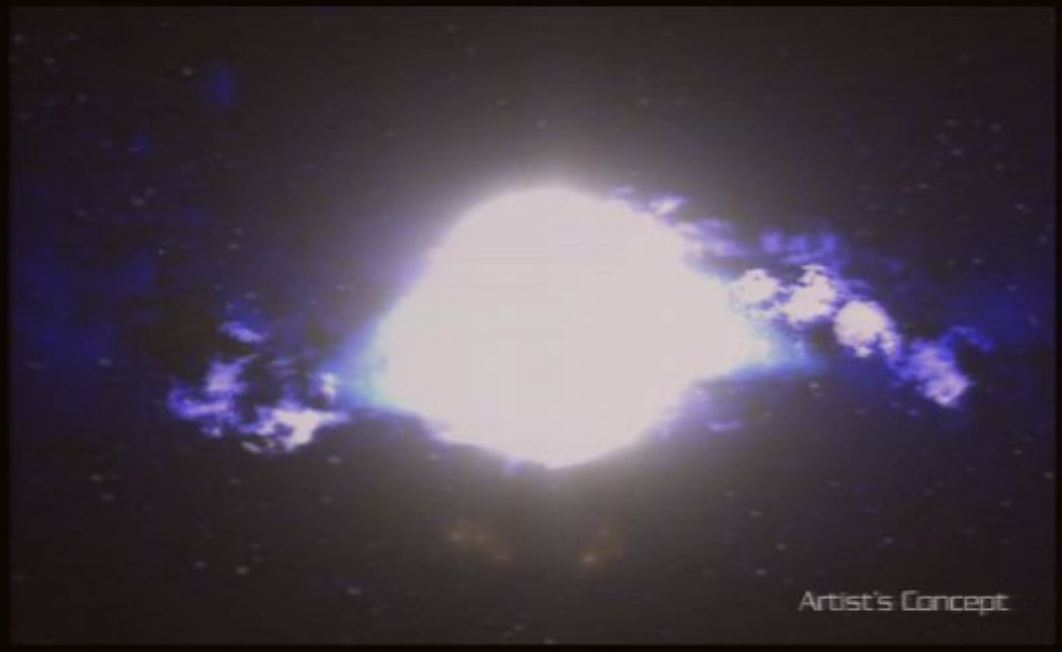
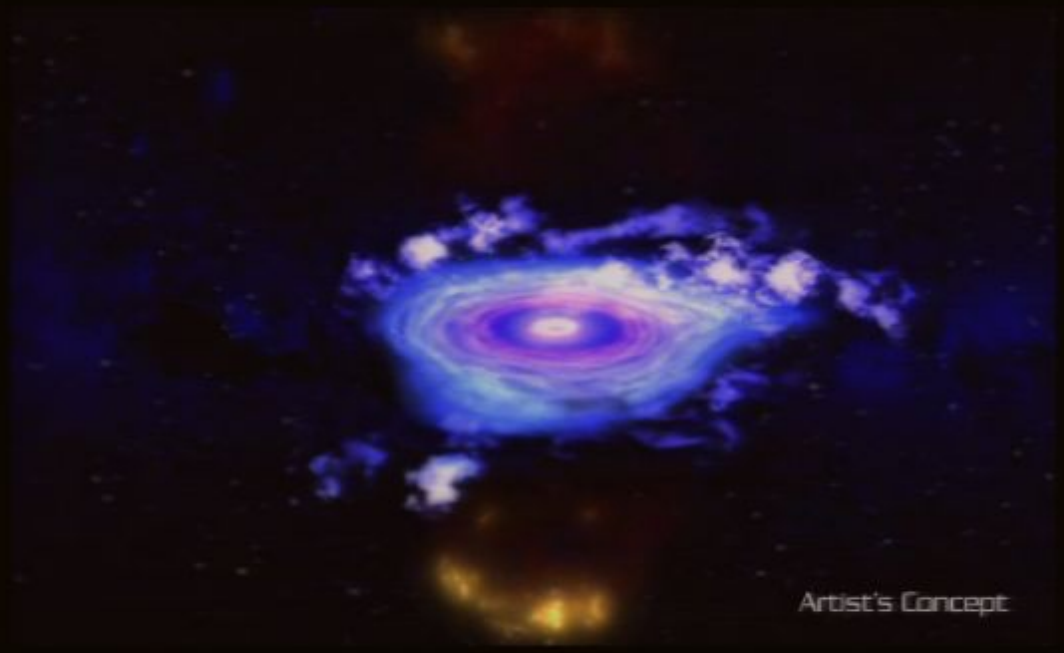
More Evidence



What about inside our own Galaxy?

More Evidence



What about inside our own Galaxy?

More Evidence

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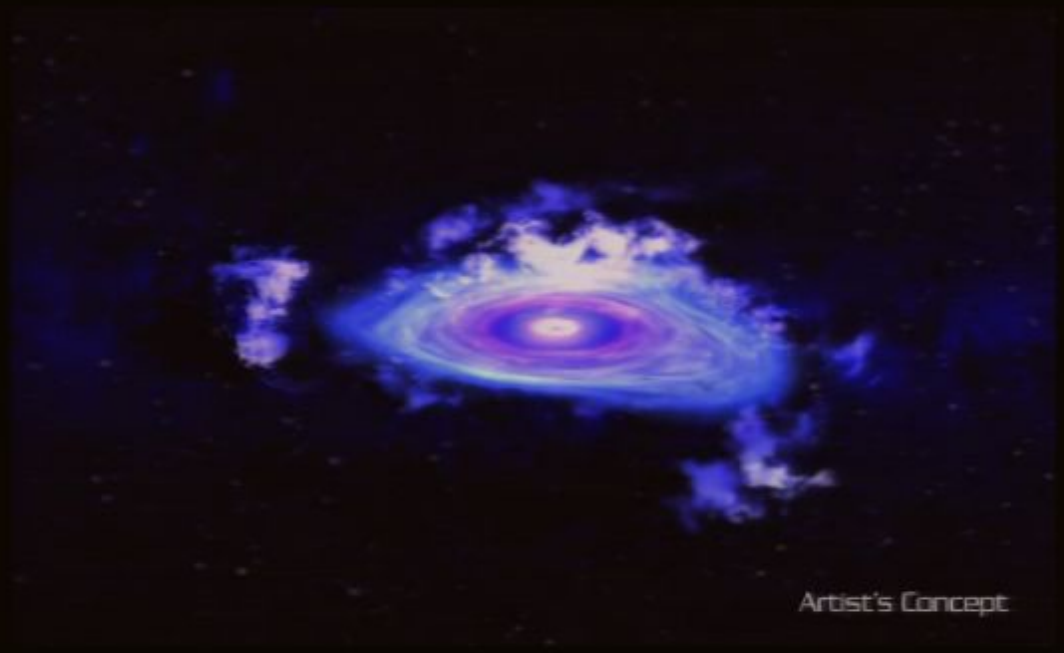
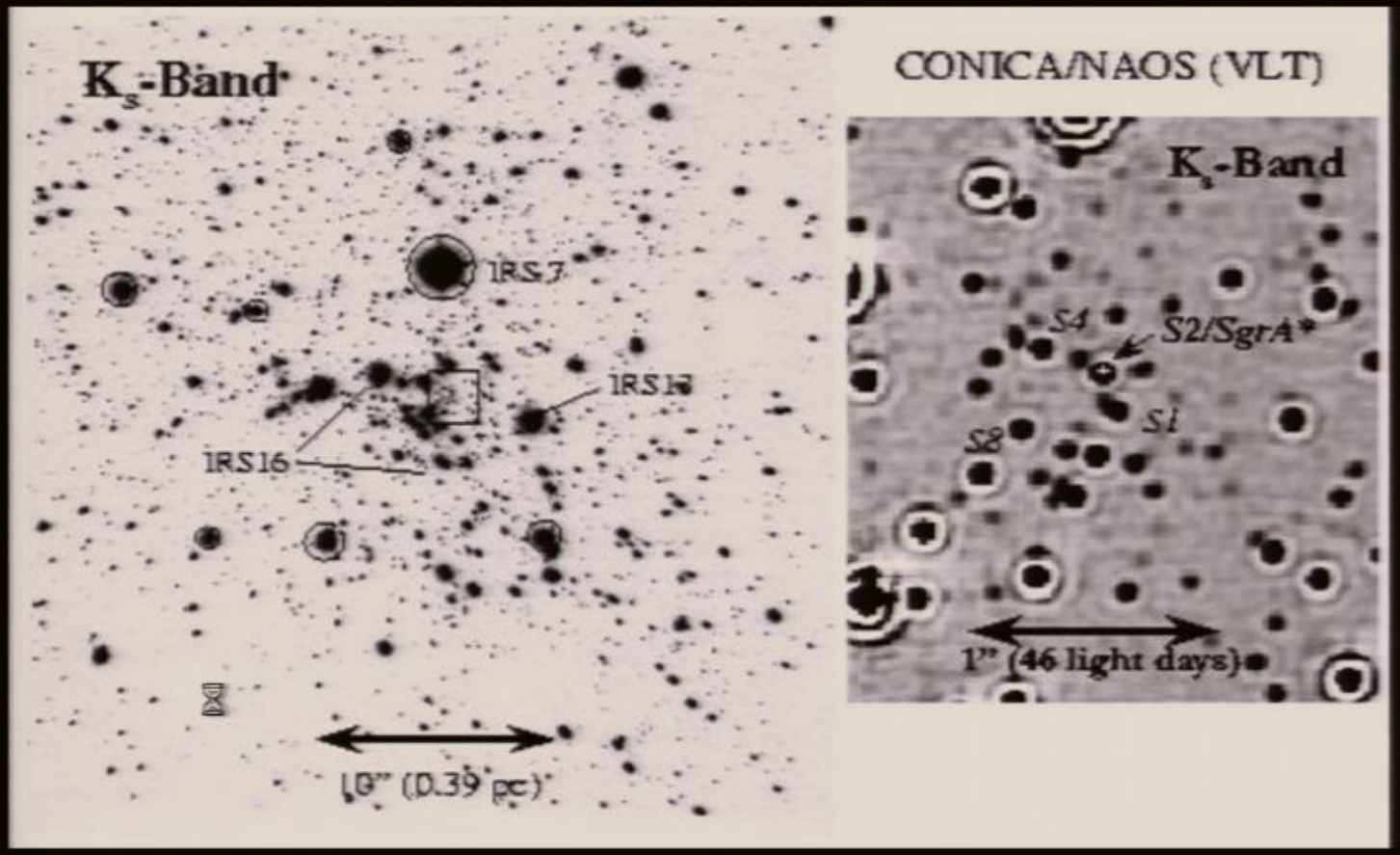
More Evidence

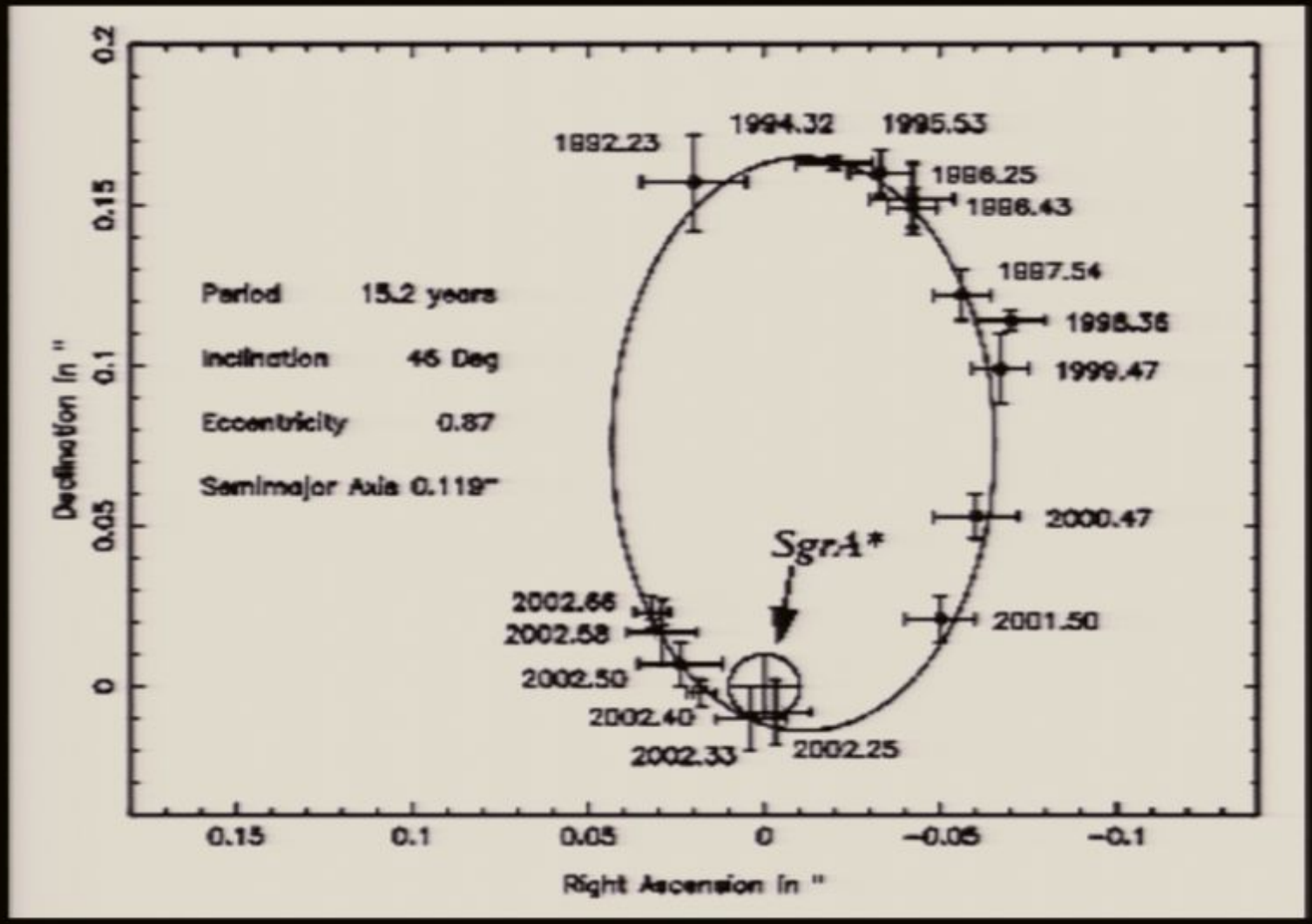


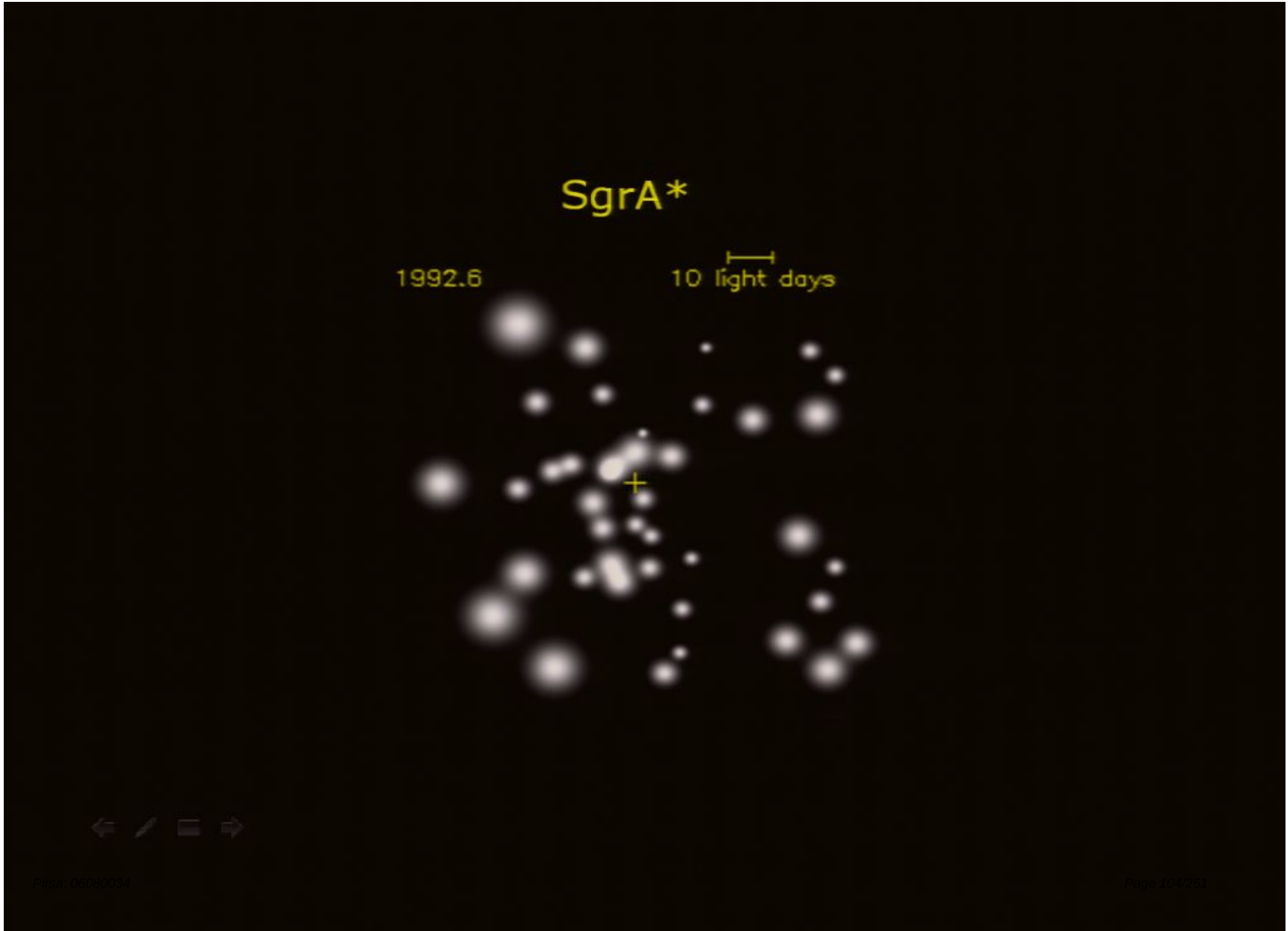
What about inside our own Galaxy?

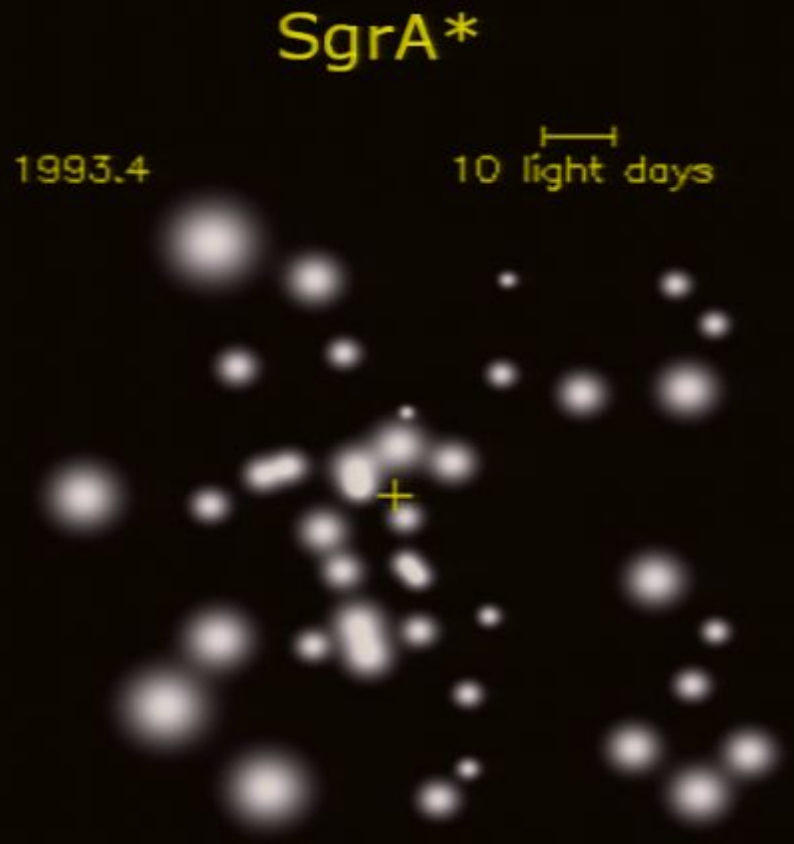
SgrA*

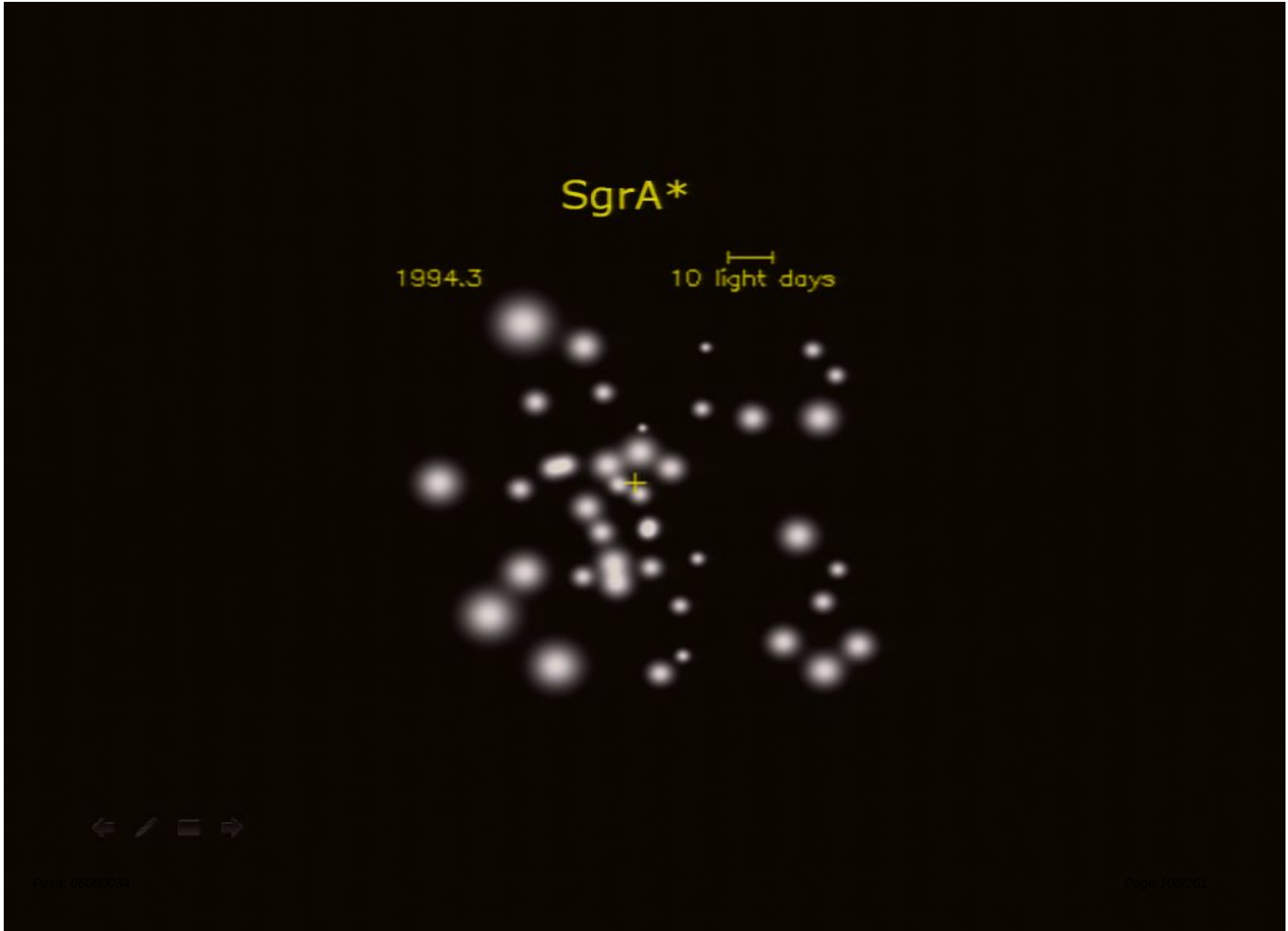


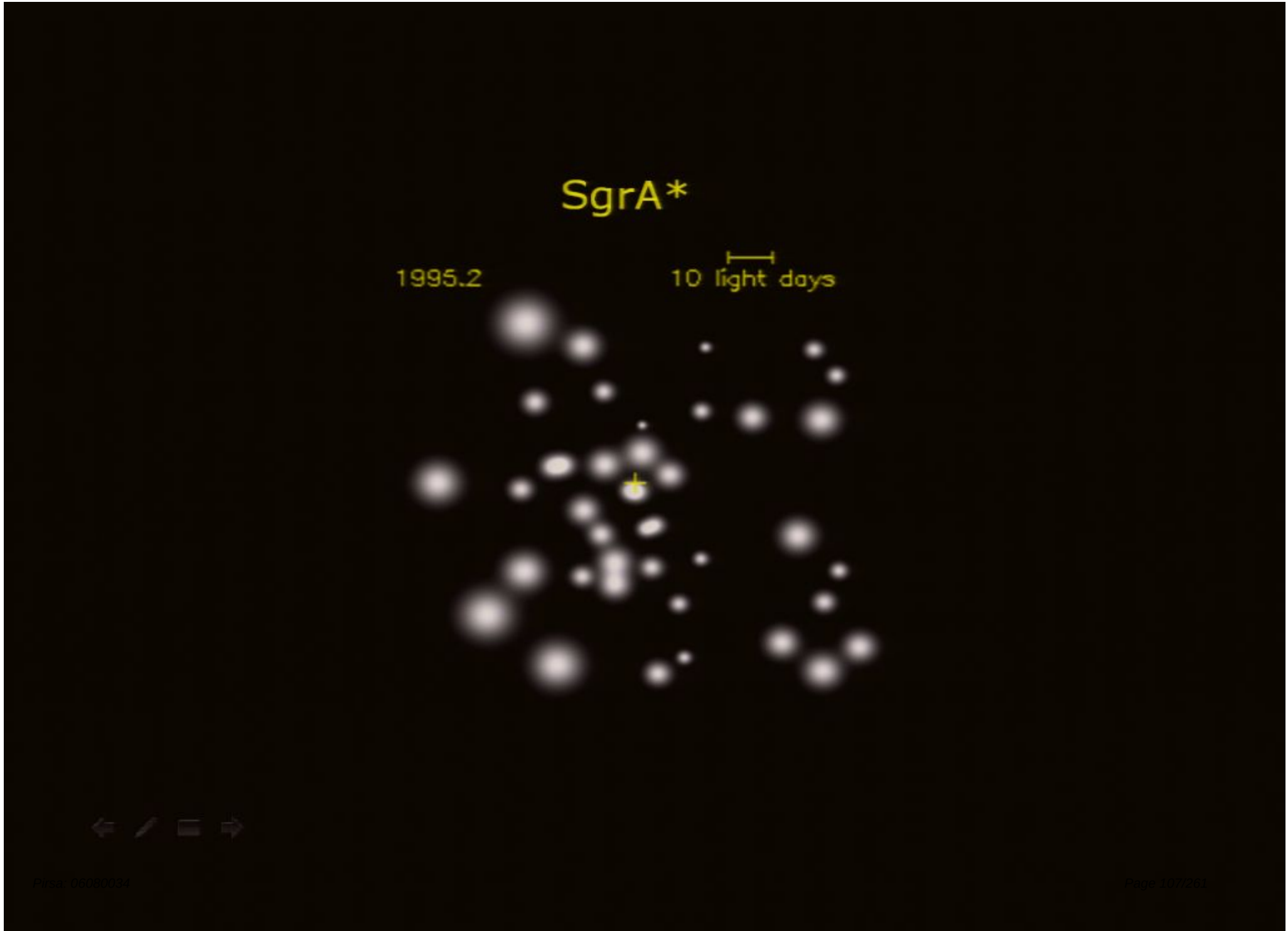
3,700,000 solar masses

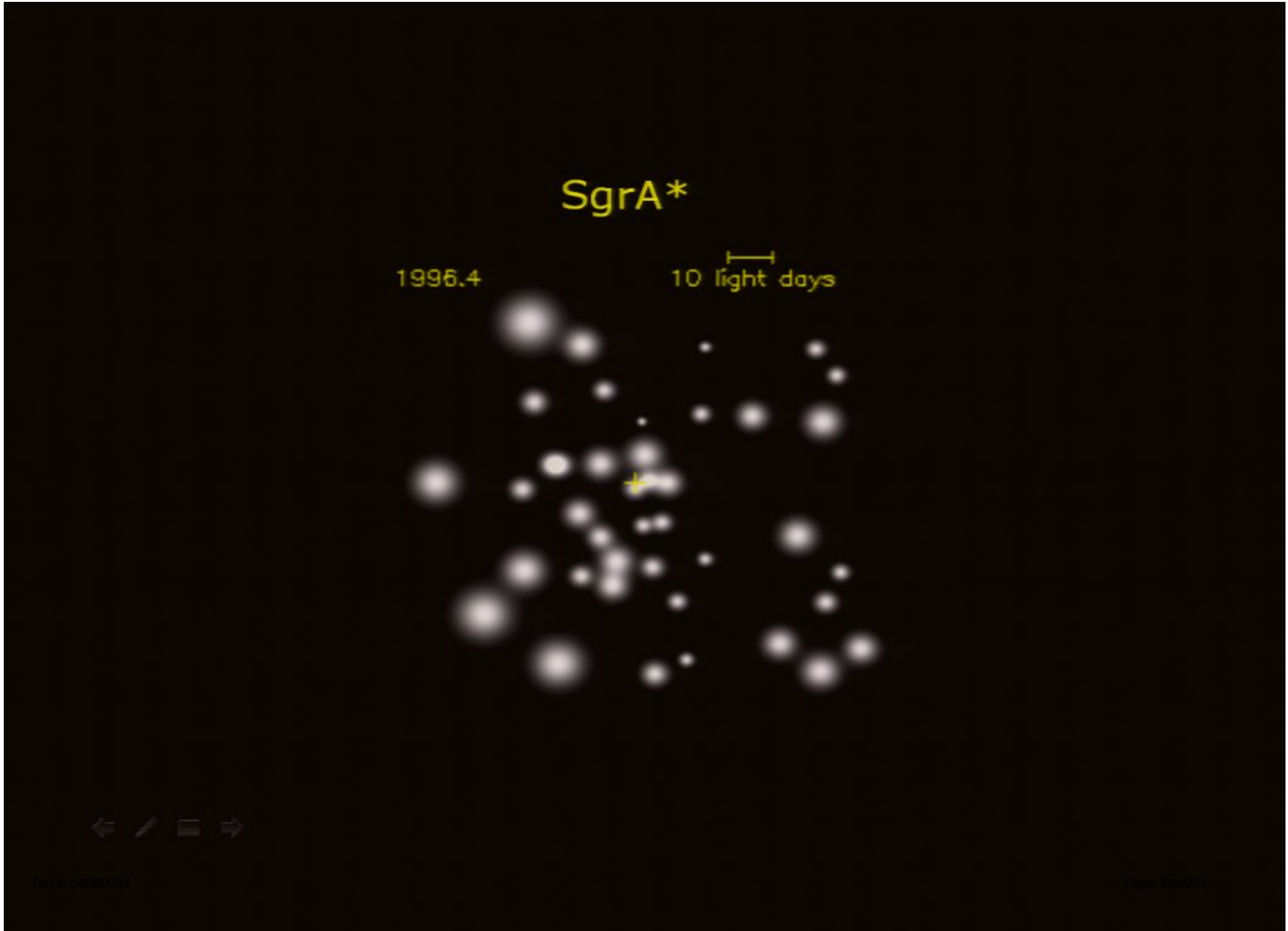

Period 15.2 years
Inclination 46 Deg
Eccentricity 0.87
Semimajor Axis 0.119"
SgrA*
1992.23
1994.32
1995.53
1996.25
1996.43
1997.54
1998.36
1999.47
2000.47
2001.50
2002.25
2002.33
2002.40
2002.50
2002.58
2002.66
0.2
0.15
0.1
0.05
0
0.15
0.1
0.05
0
−0.05
−0.1
Declination (in ")
Right Ascension (in ")

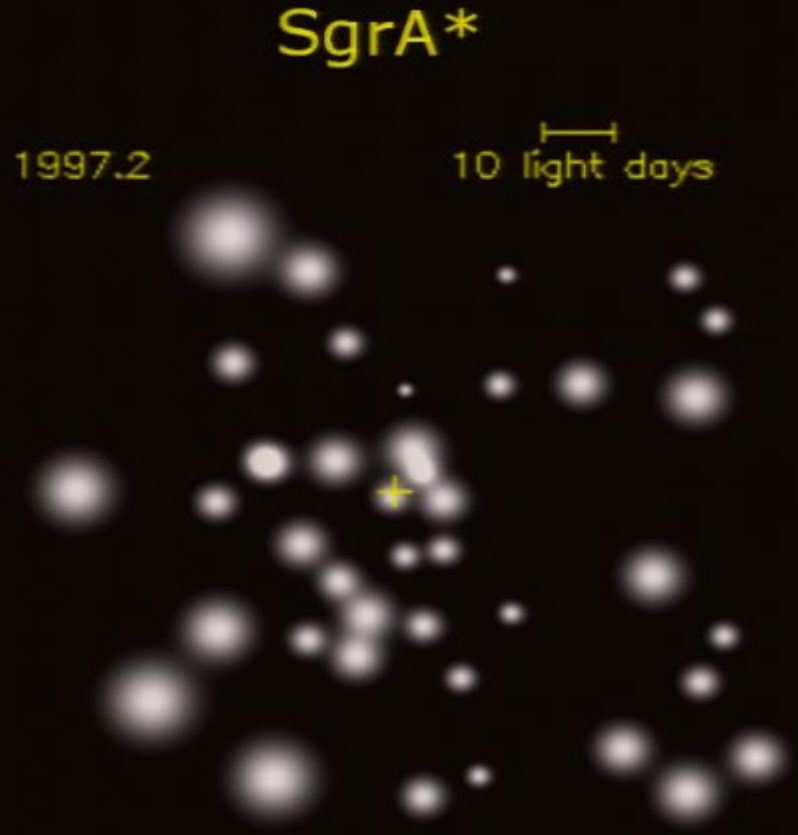

SgrA*
1992.6
10 light days


SgrA*
1993.4
10 light days

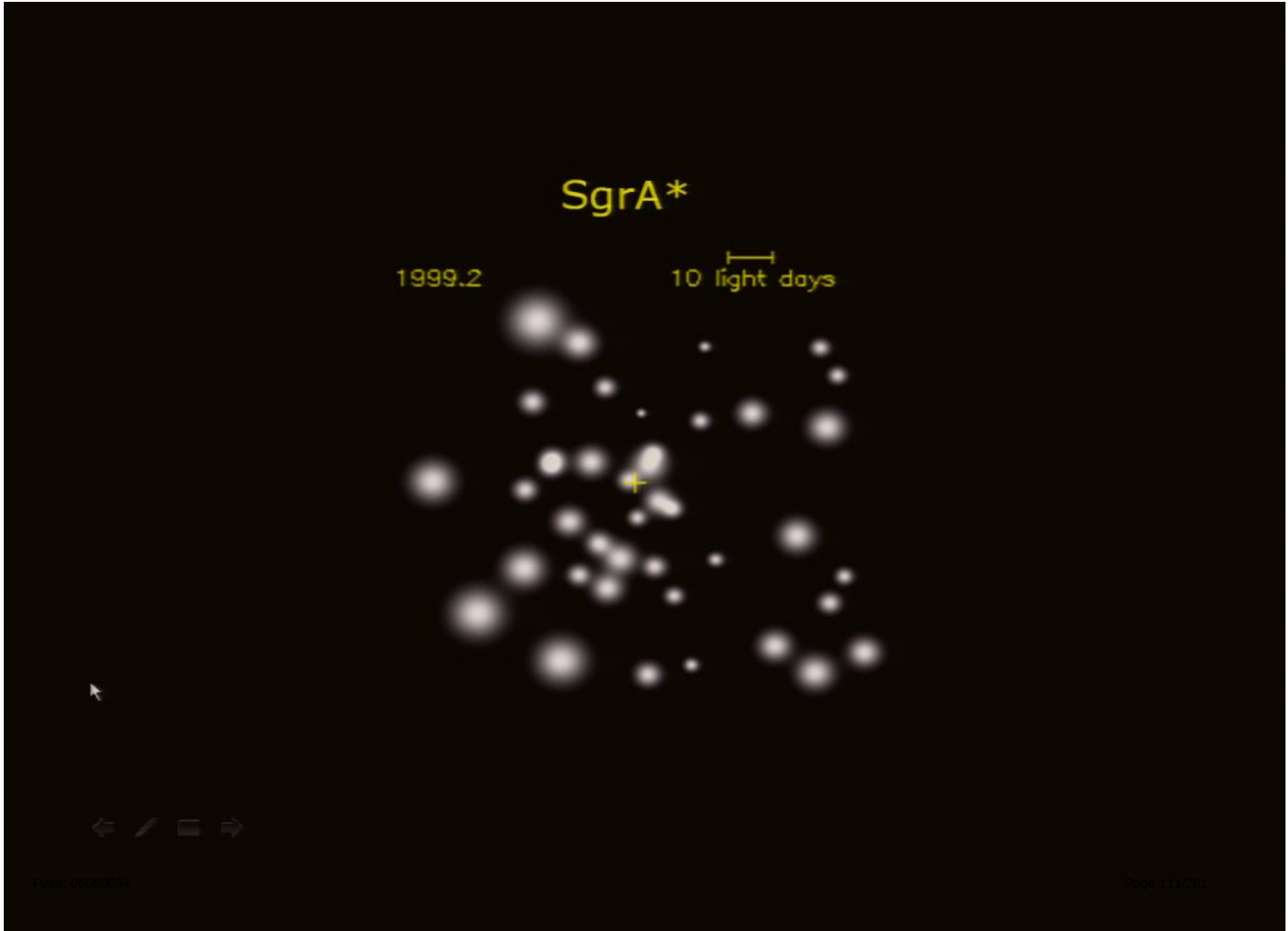

SgrA*
1994.3
10 light days

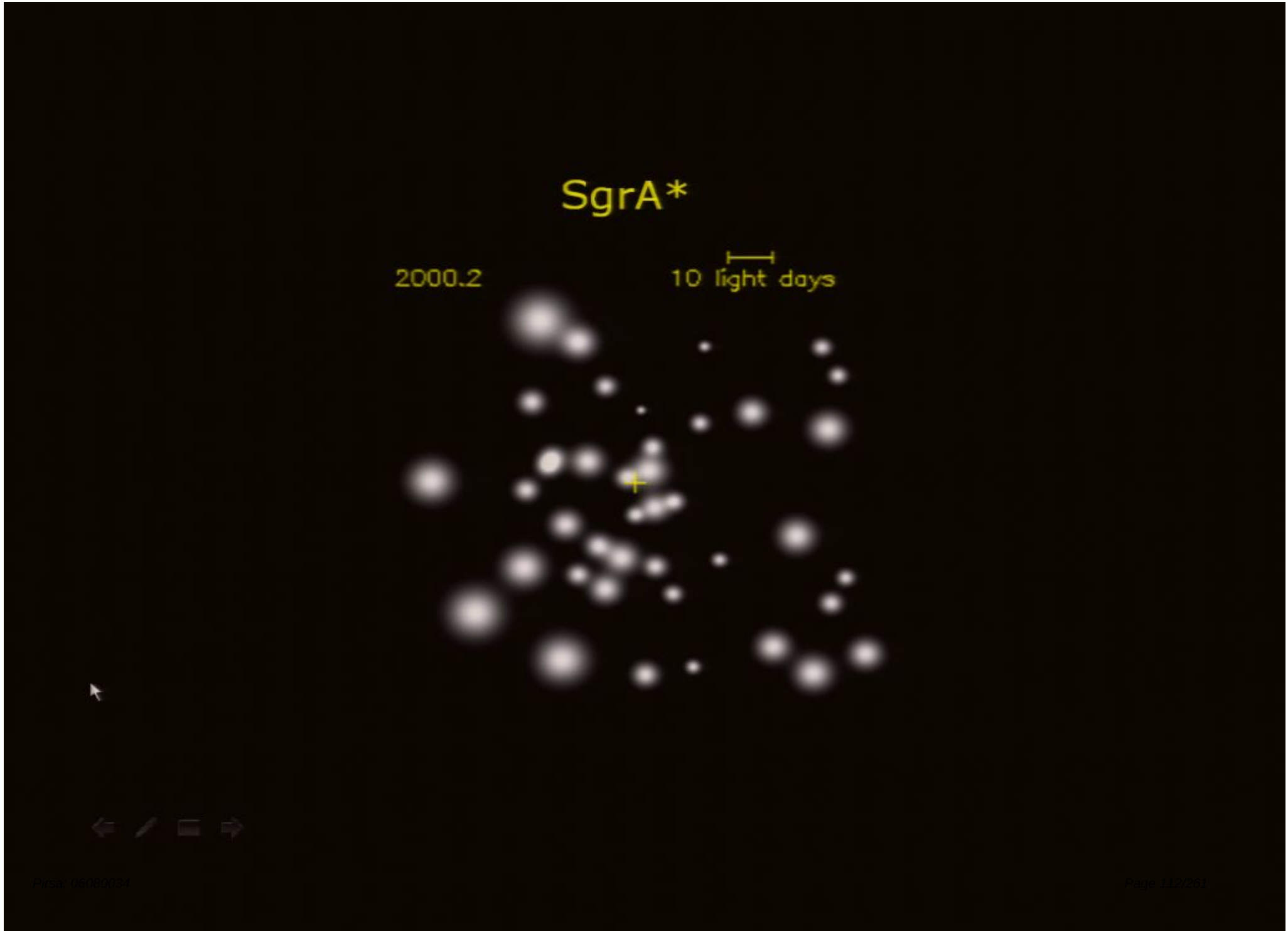

SgrA*
1995.2
10 light days

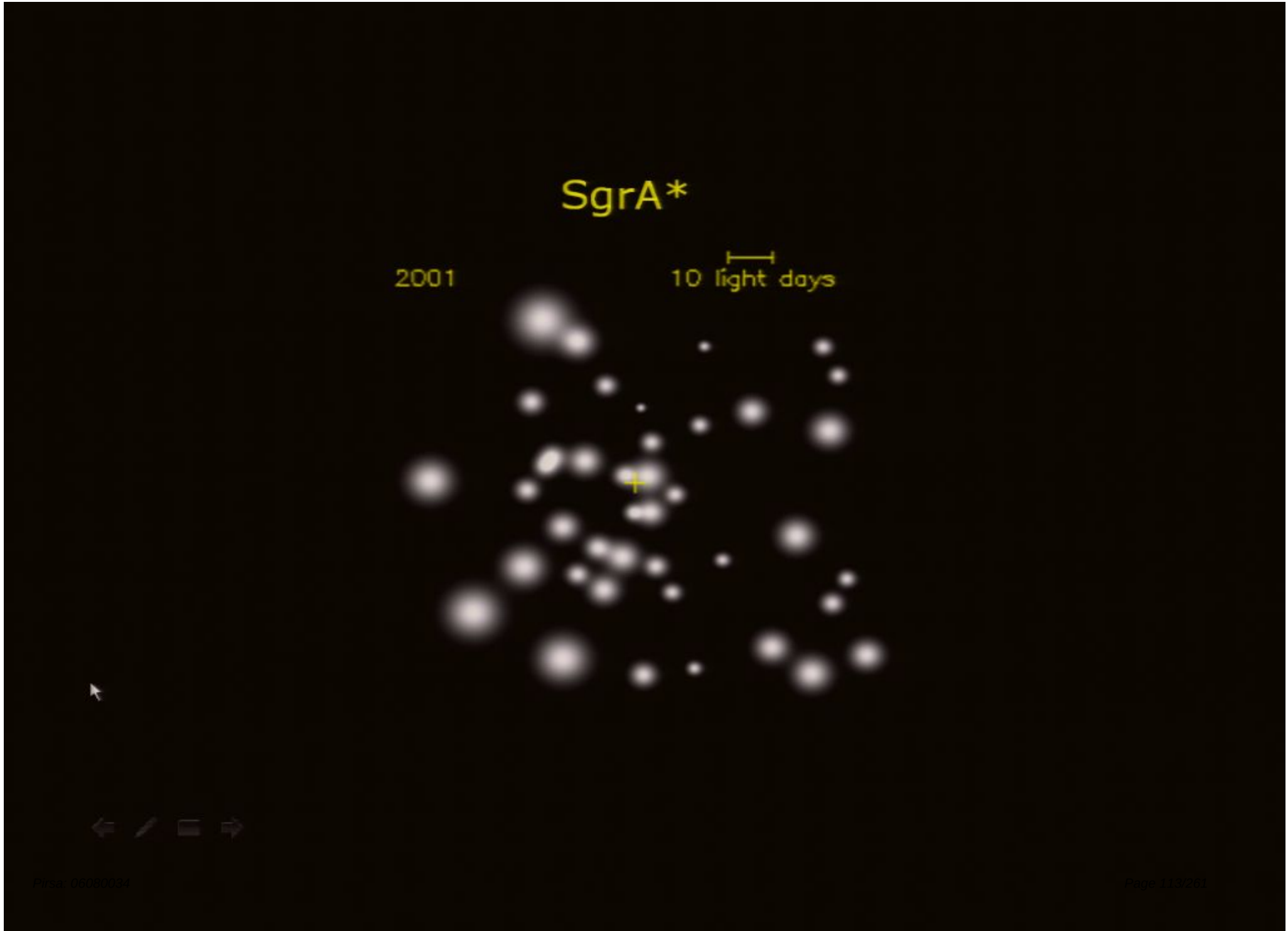

SgrA*
1996.4
10 light days

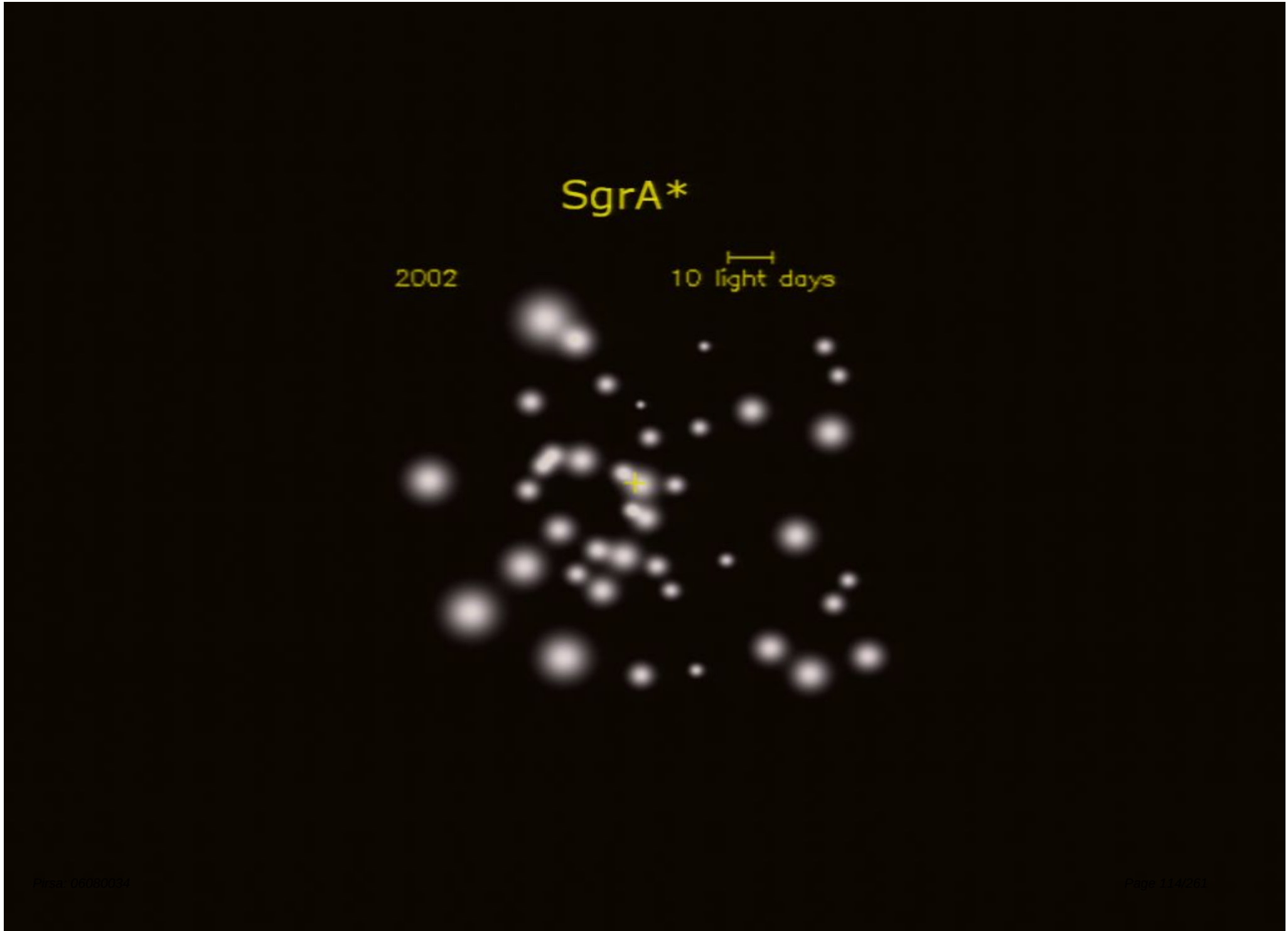

SgrA*
1997.2
10 light days

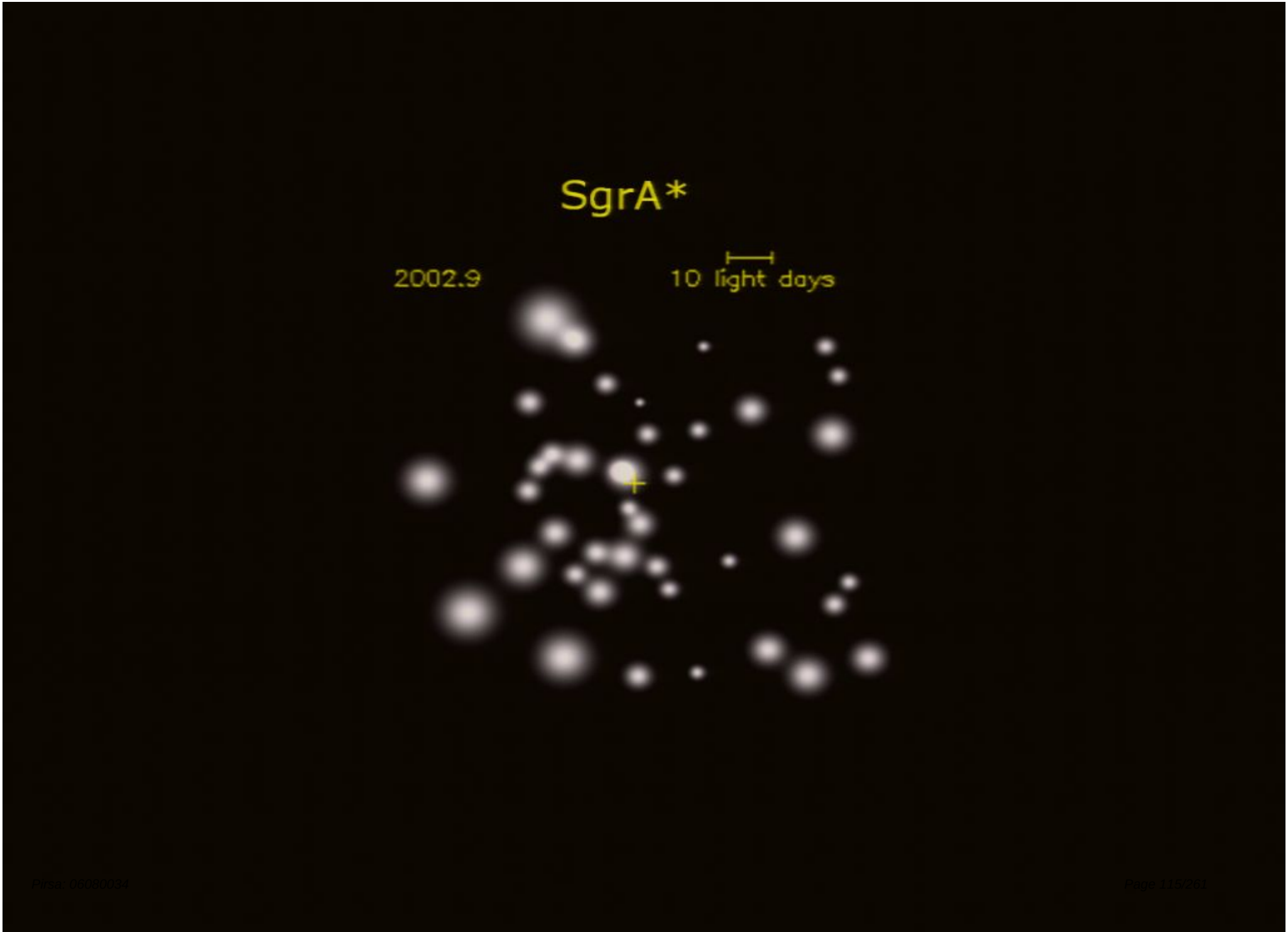

SgrA*
1998.2
10 light days

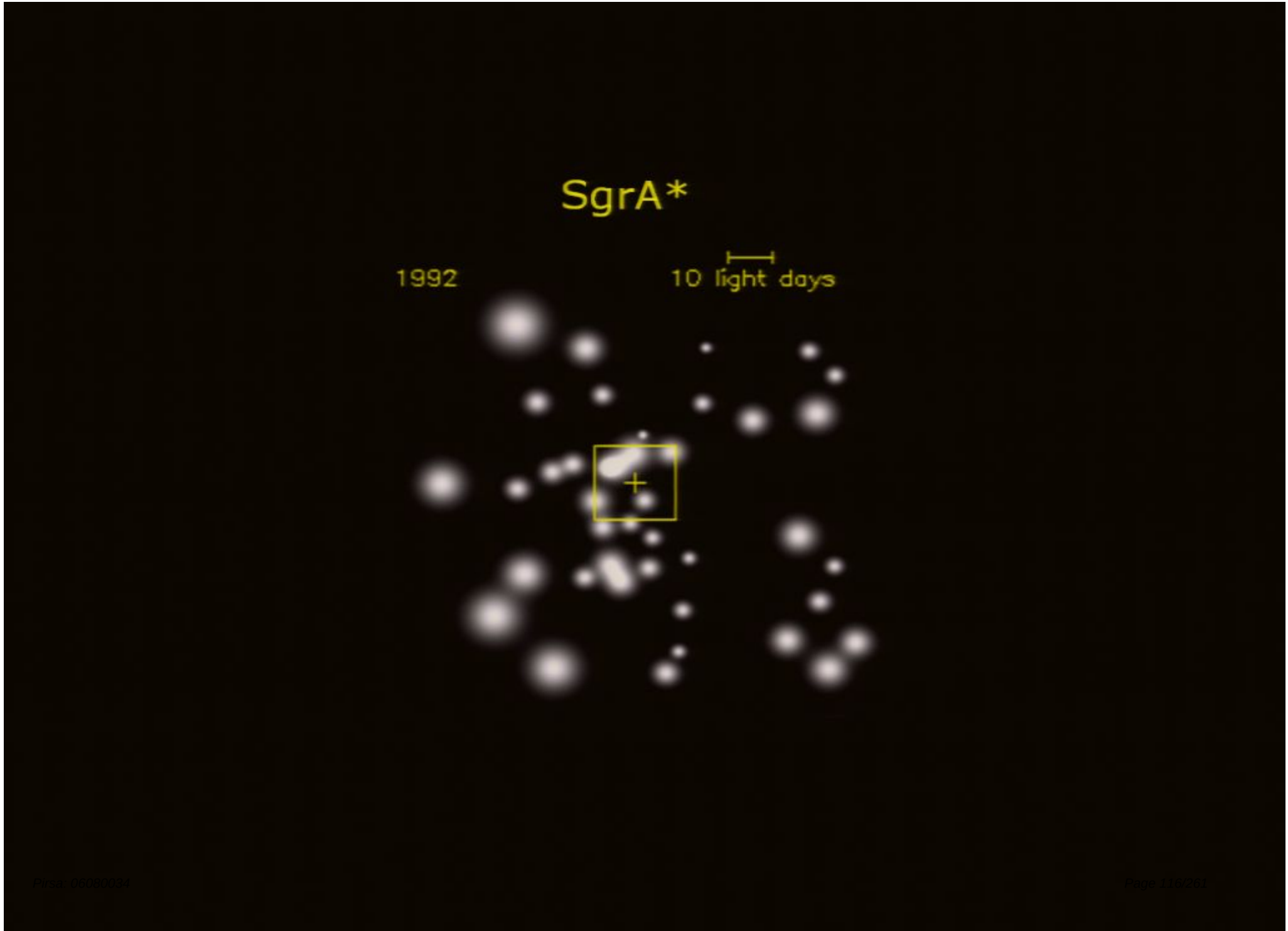

SgrA*
1999.2
10 light days

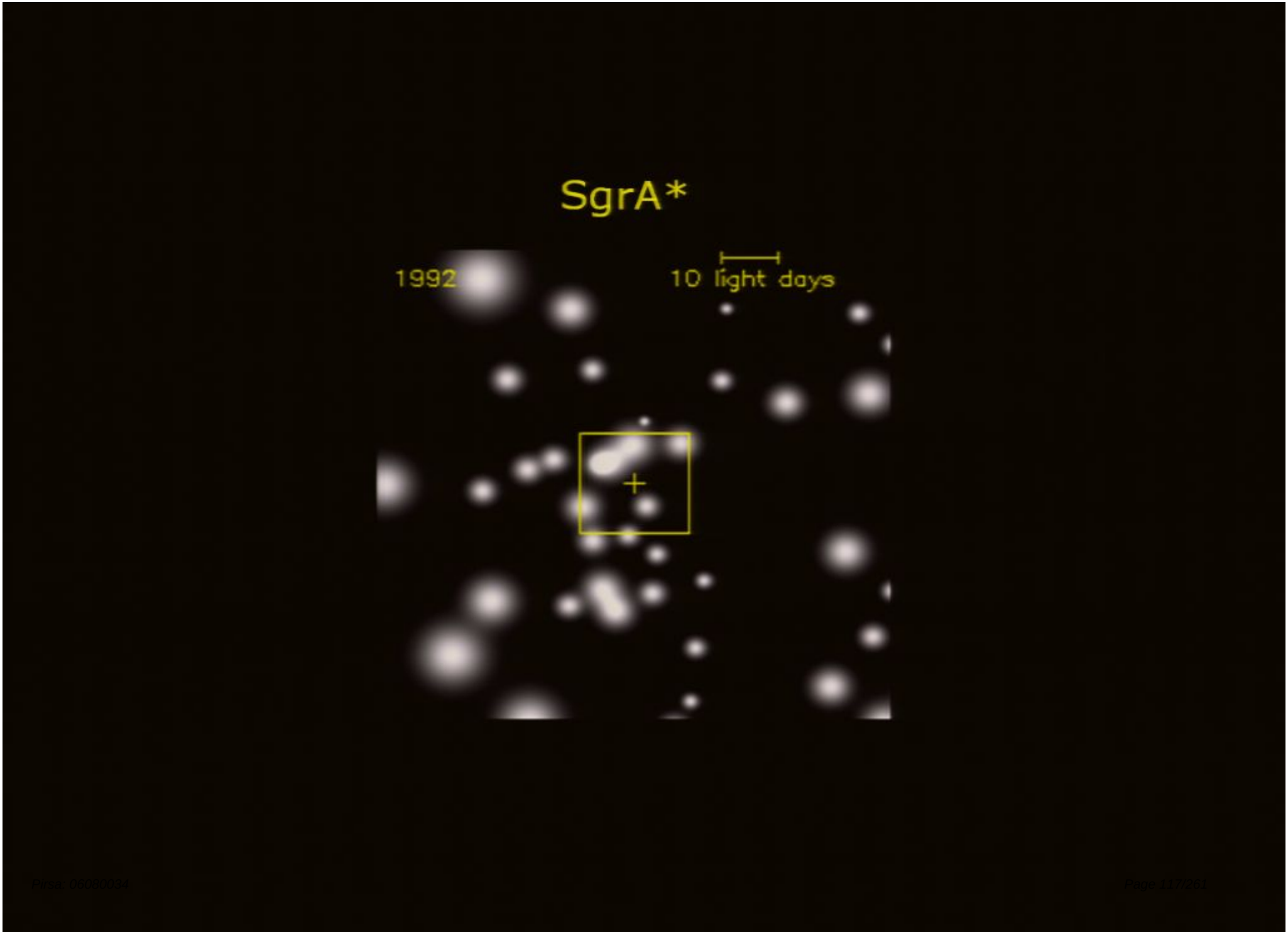

SgrA*
2000.2
10 light days

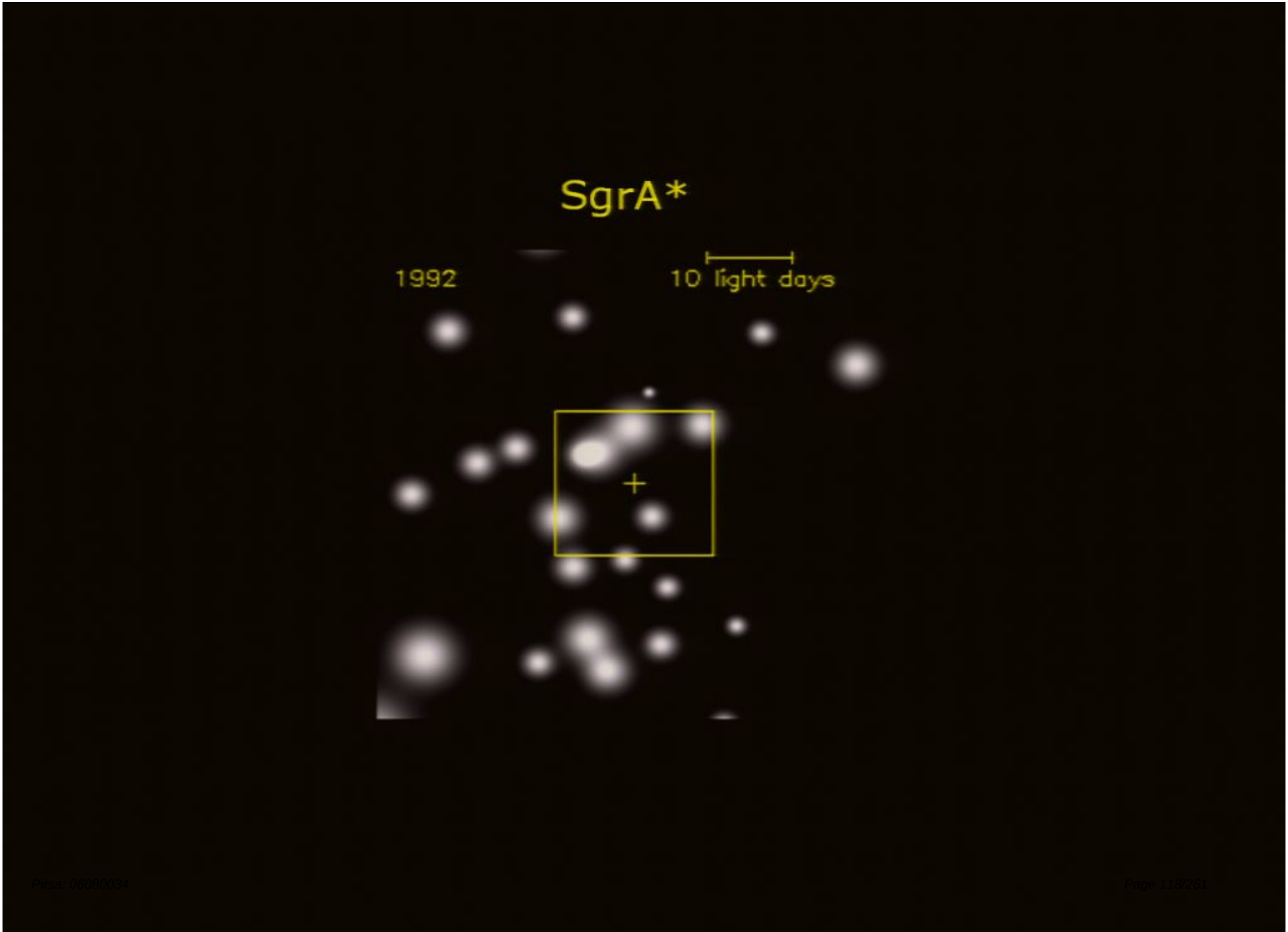

SgrA*
2001
10 light days

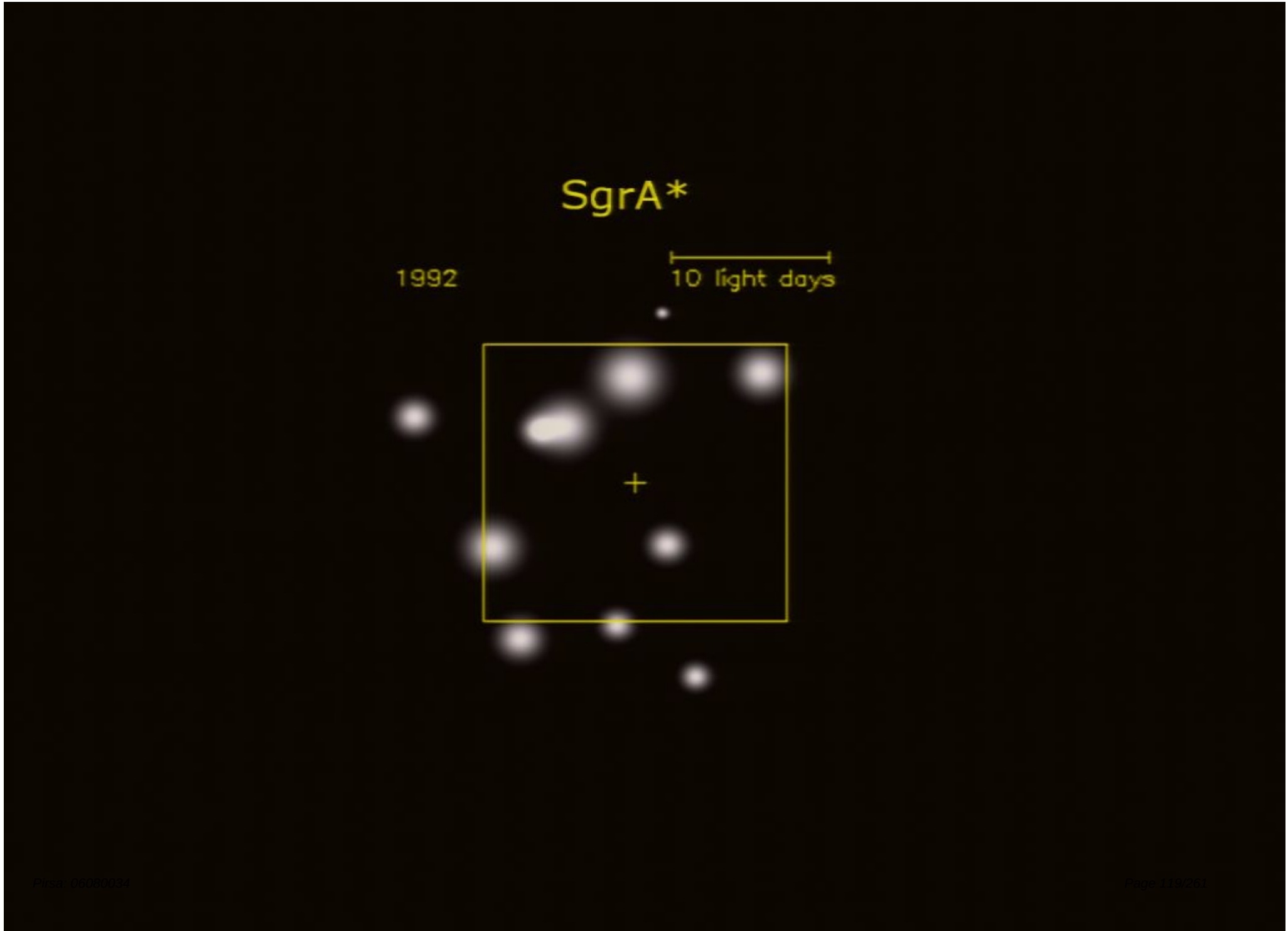

SgrA*
2002
10 light days

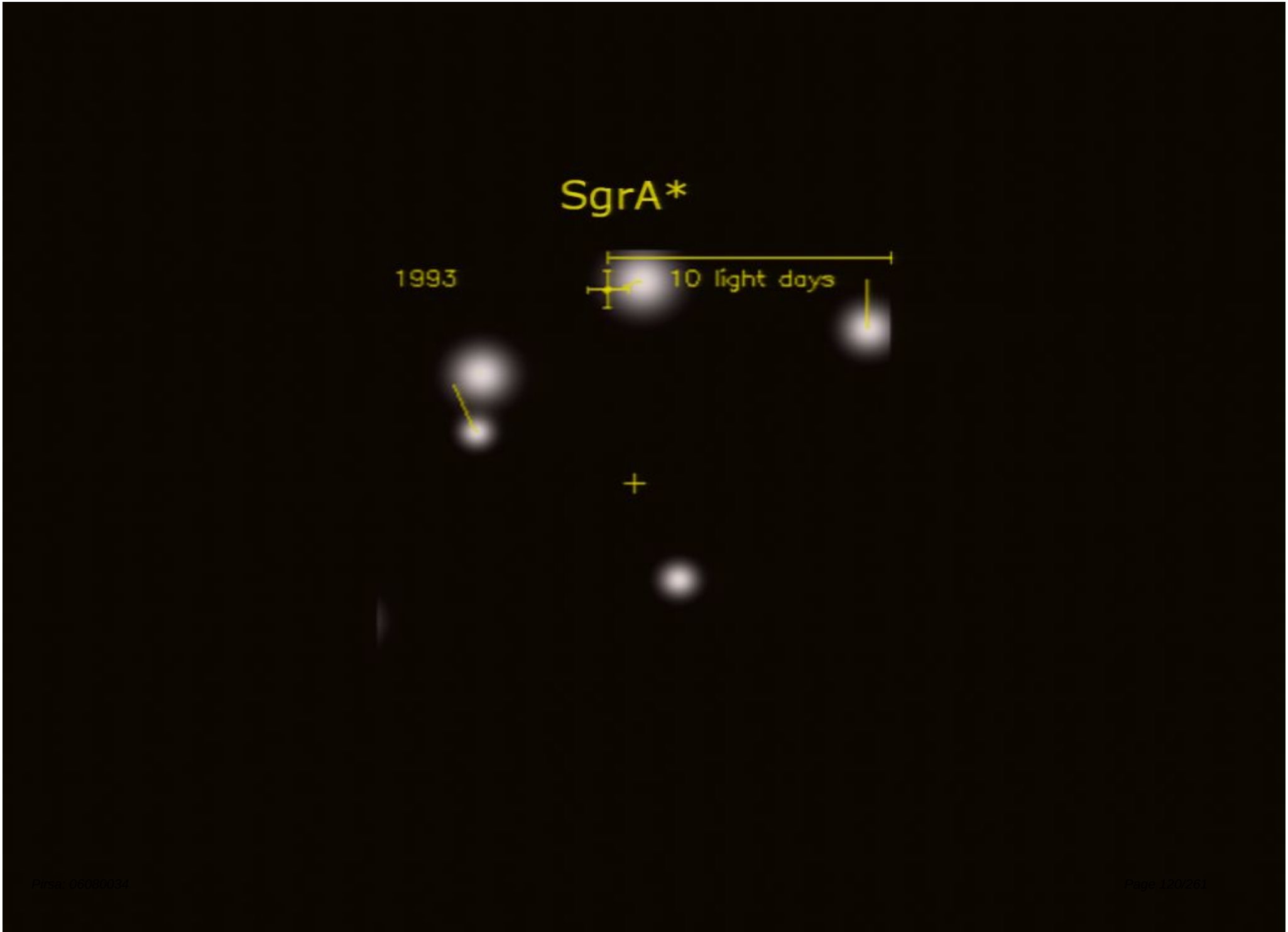

SgrA*
2002.9
10 light days


SgrA*
1992
10 light days

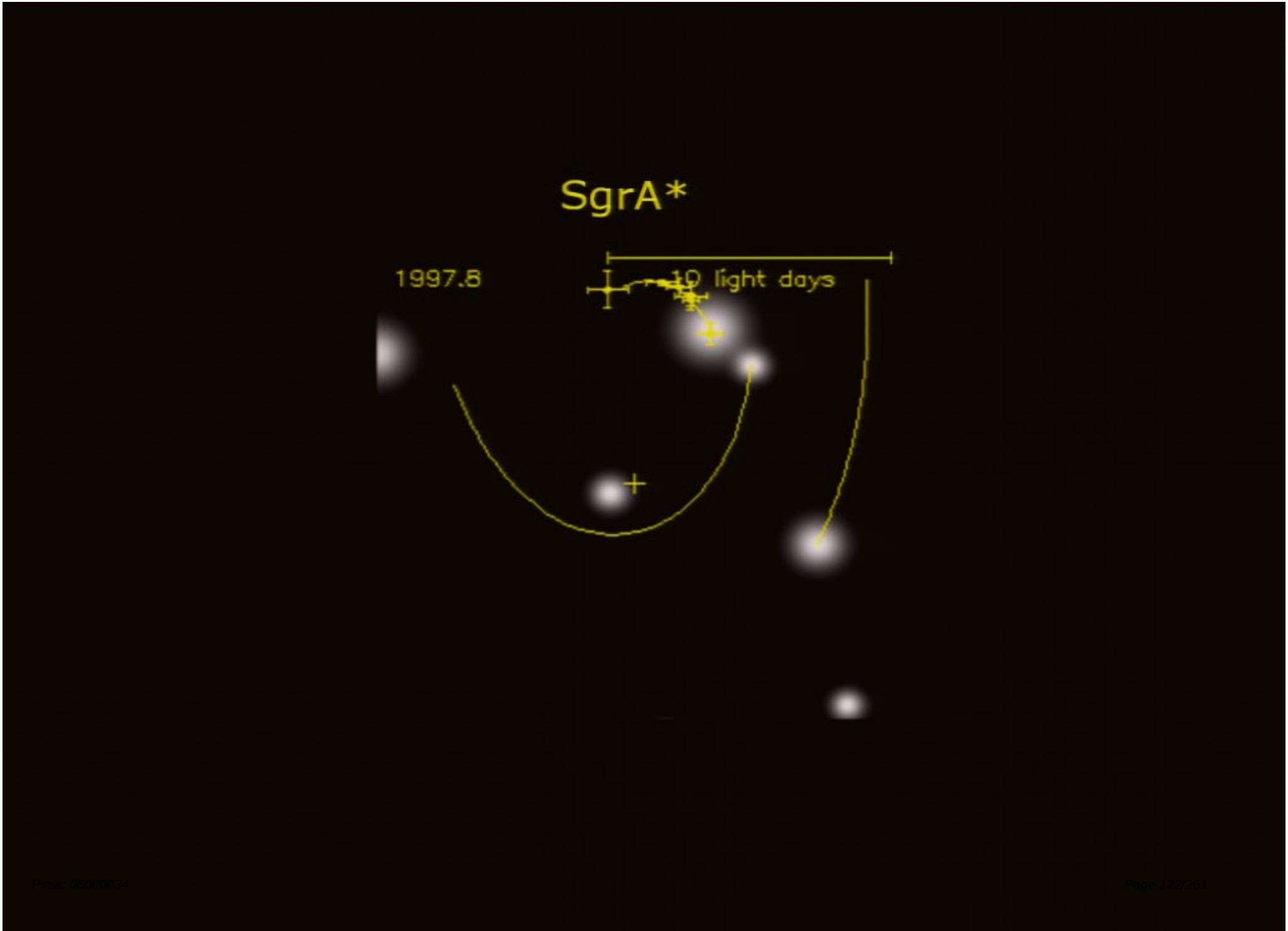

SgrA*
1992
10 light days

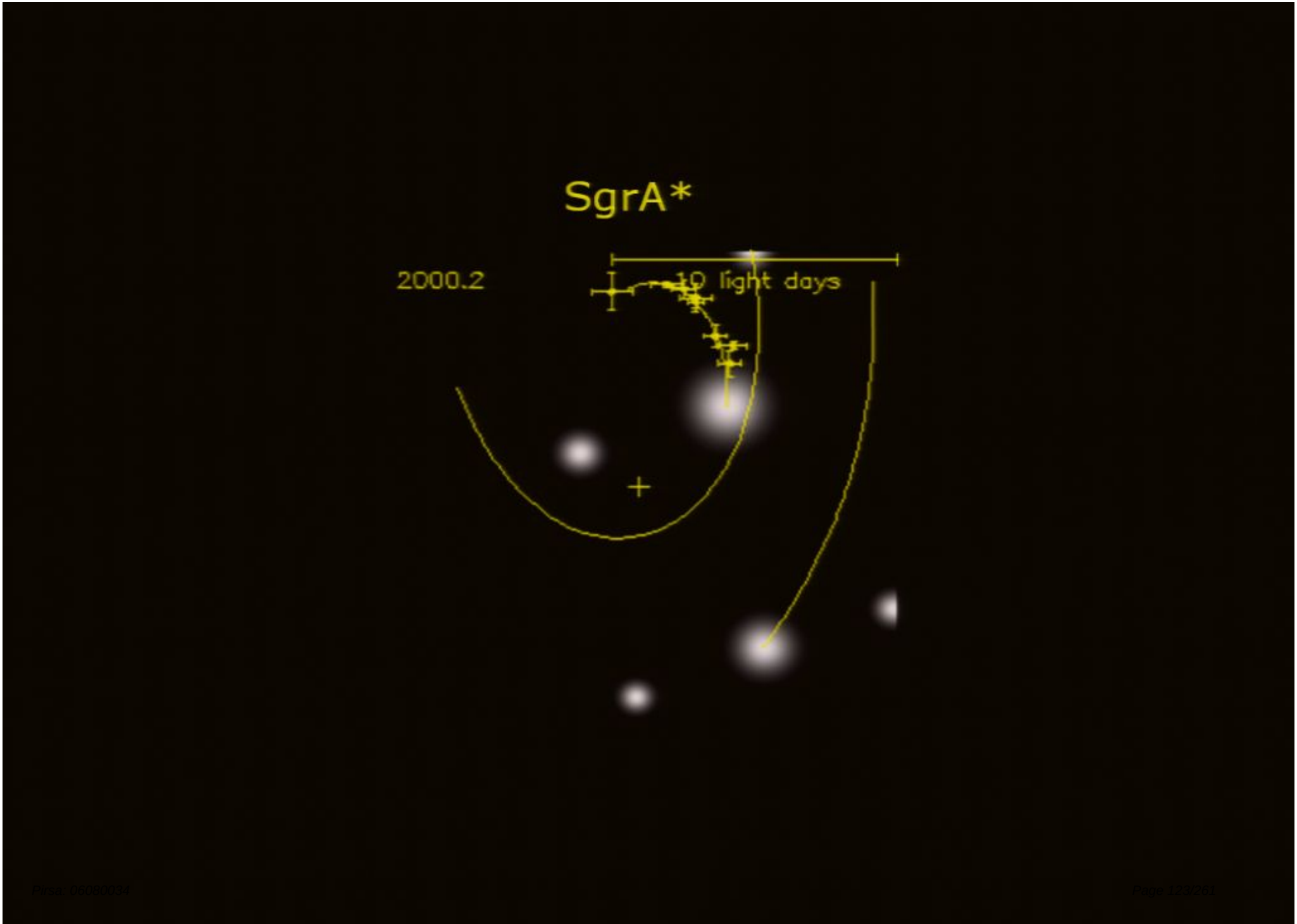

SgrA*
1992
10 light days

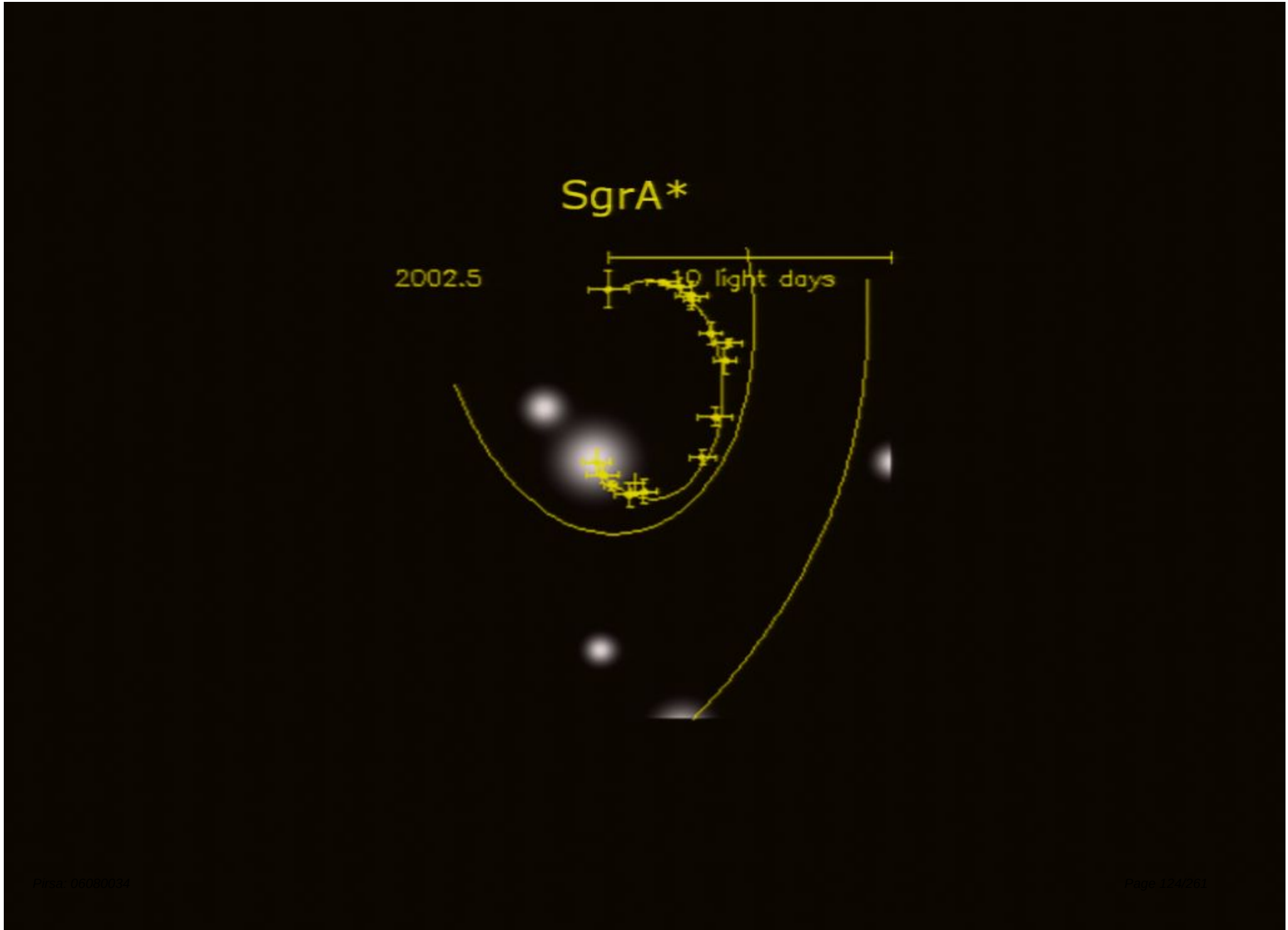

SgrA*
1992
10 light days

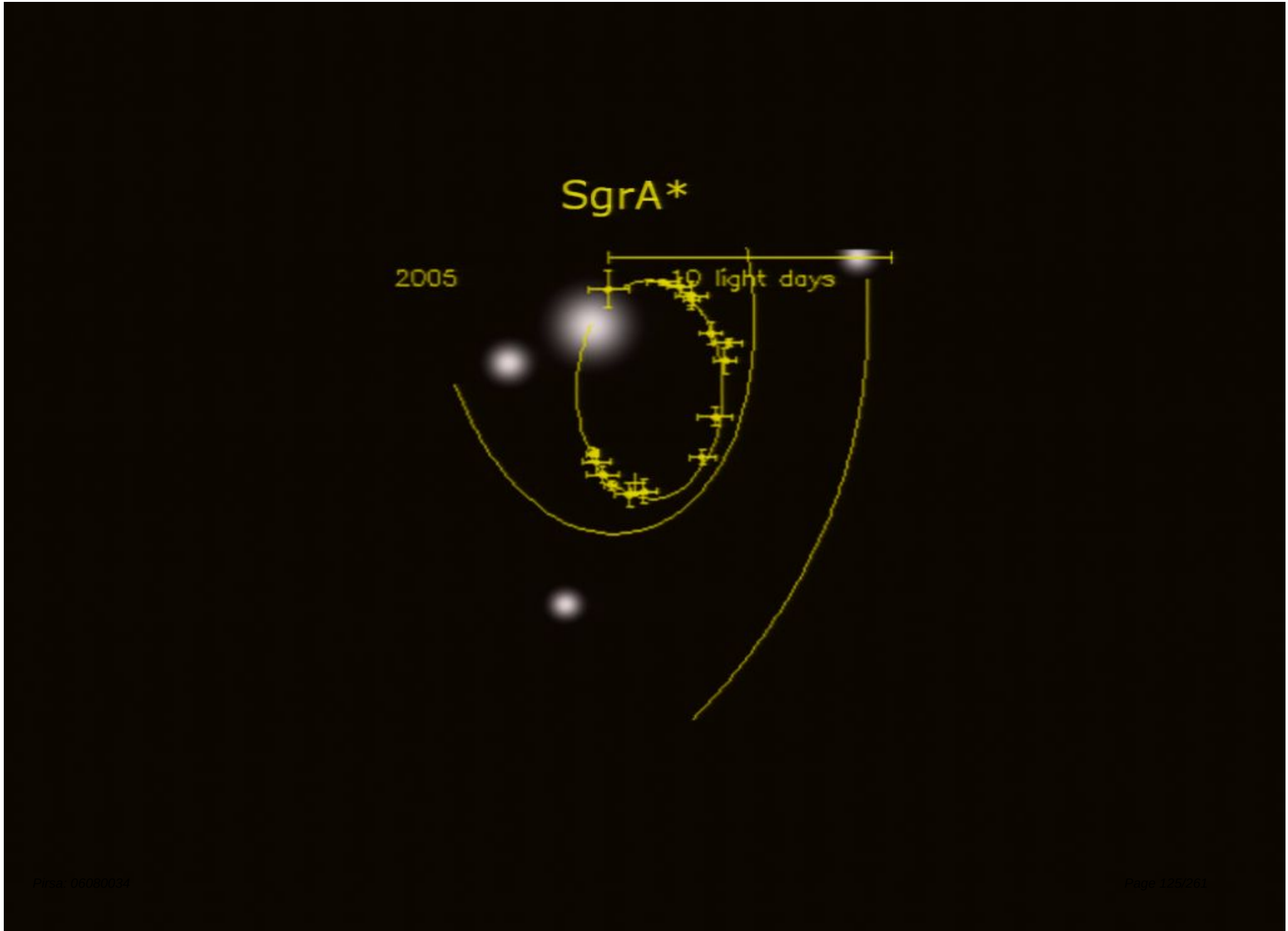

SgrA*
1993
10 light days

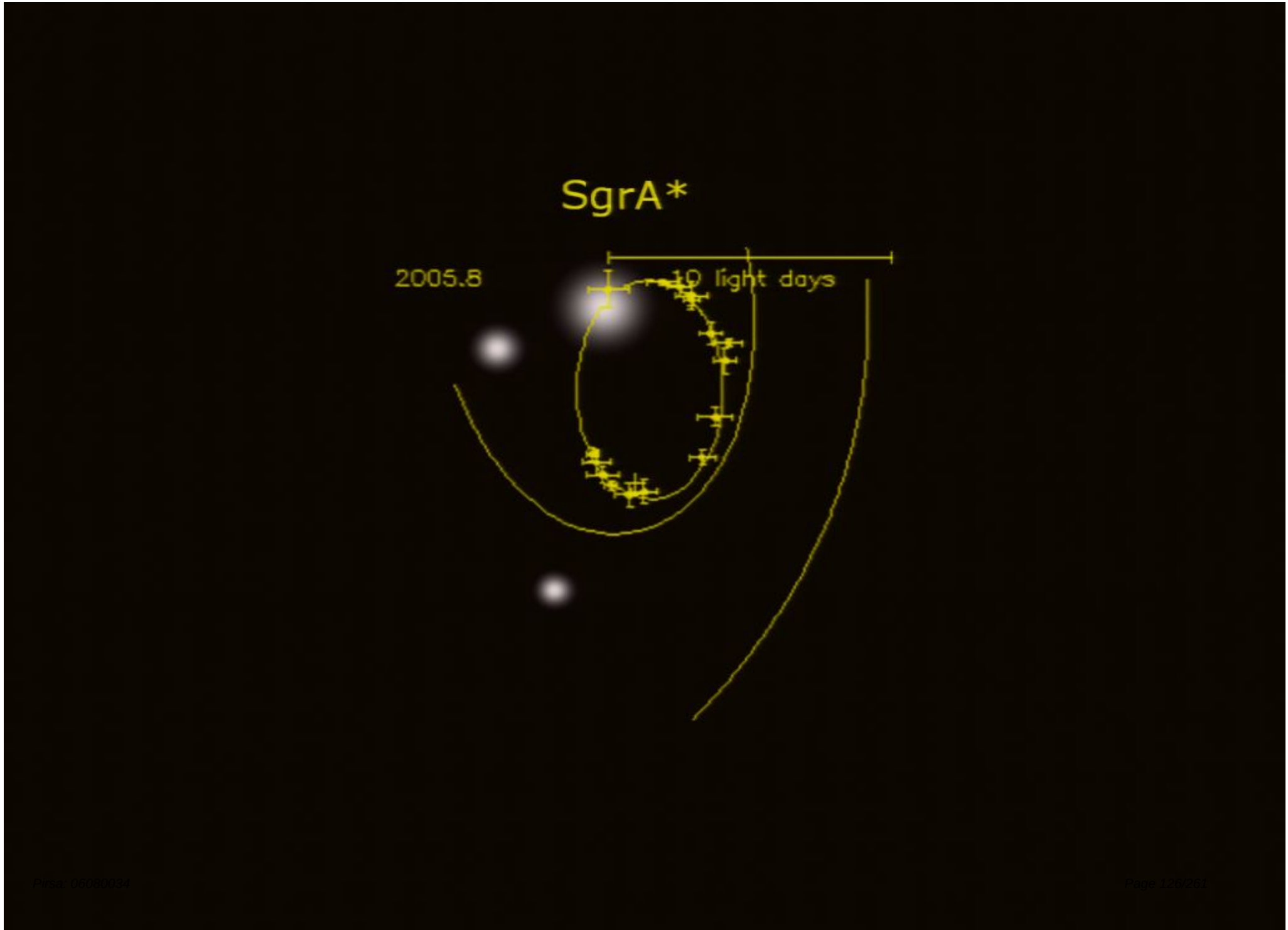

SgrA*
1995.4
10 light days

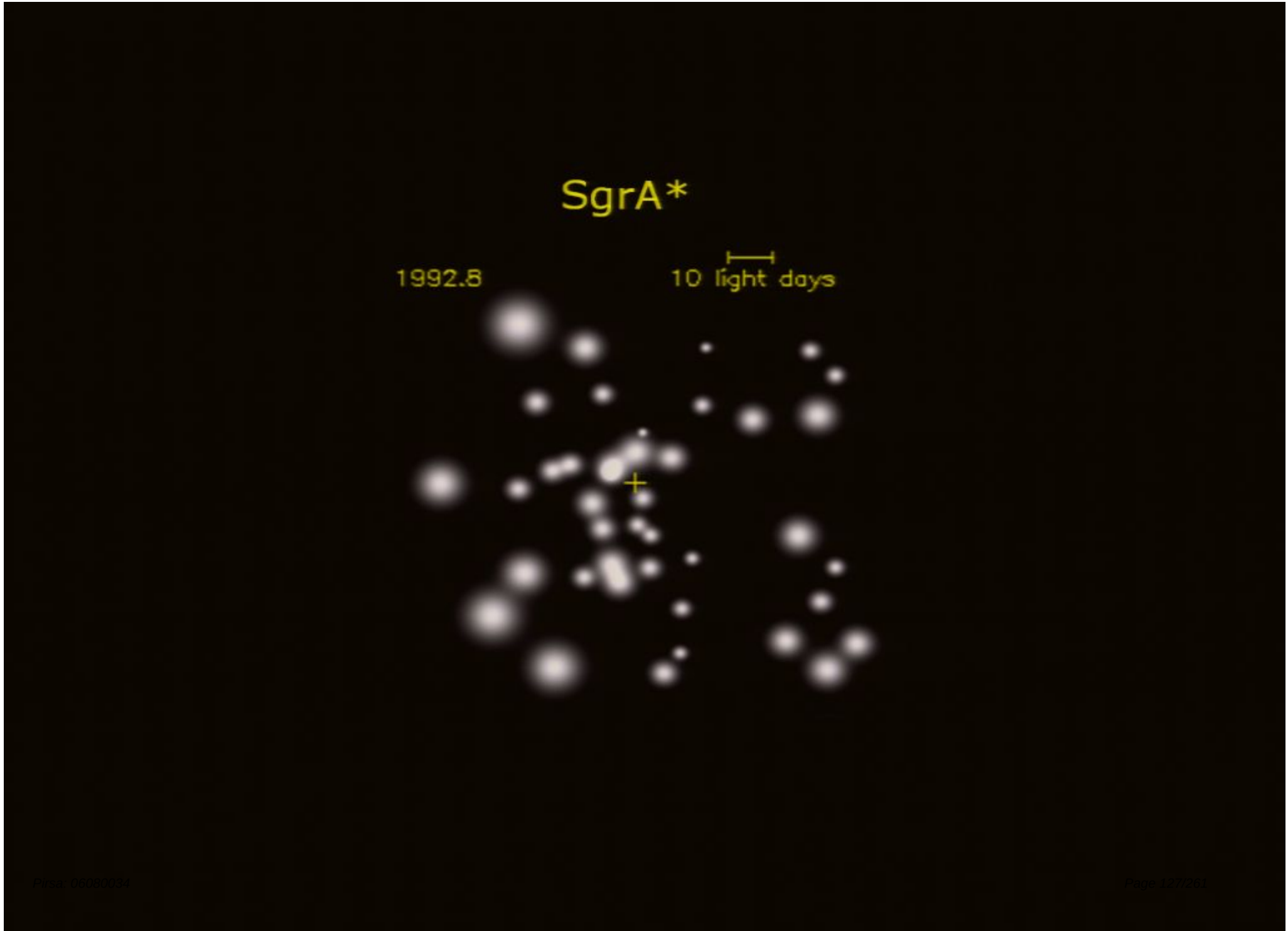

SgrA*
1997.8
10 light days

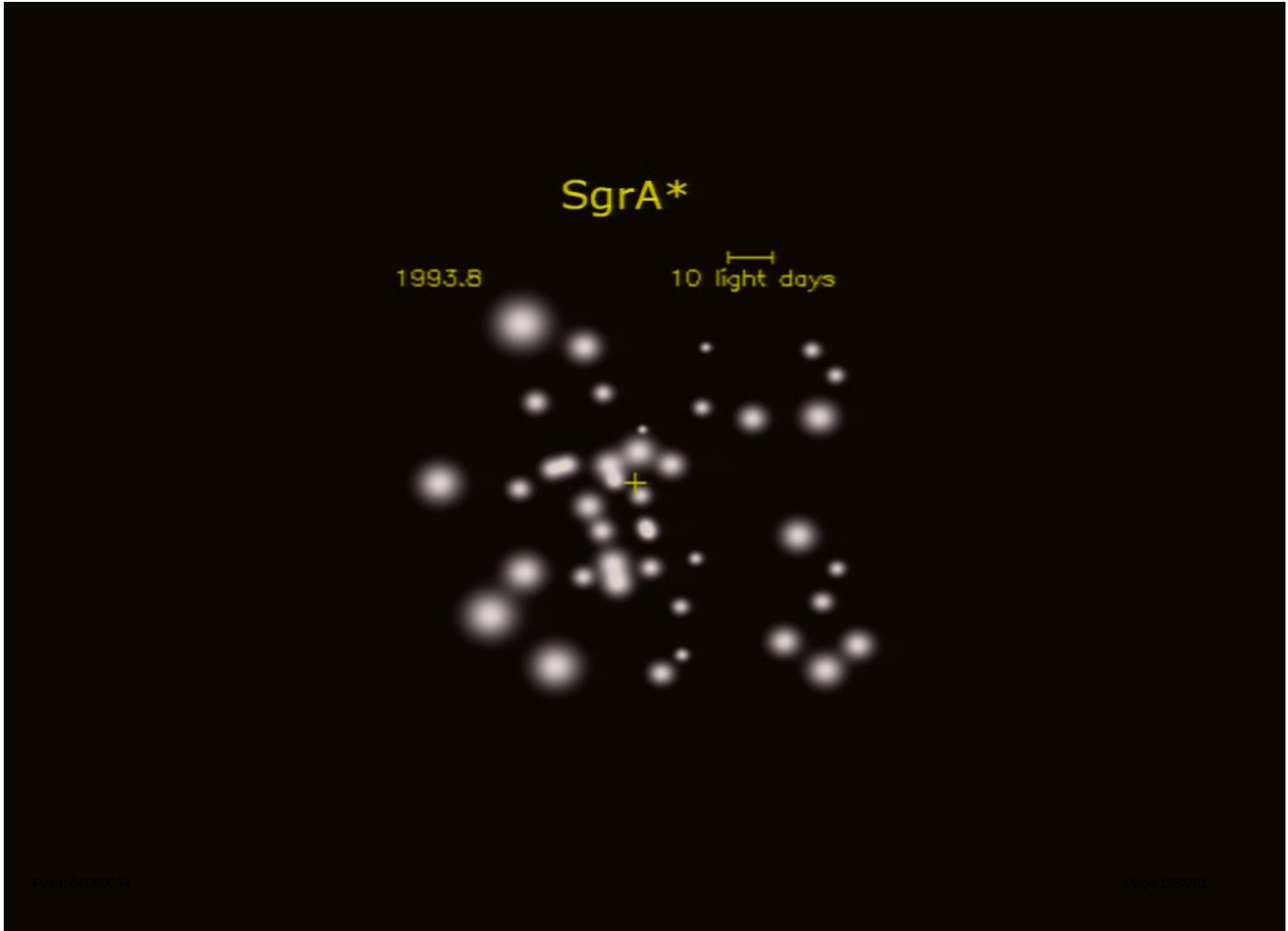

SgrA*
2000.2
10 light days

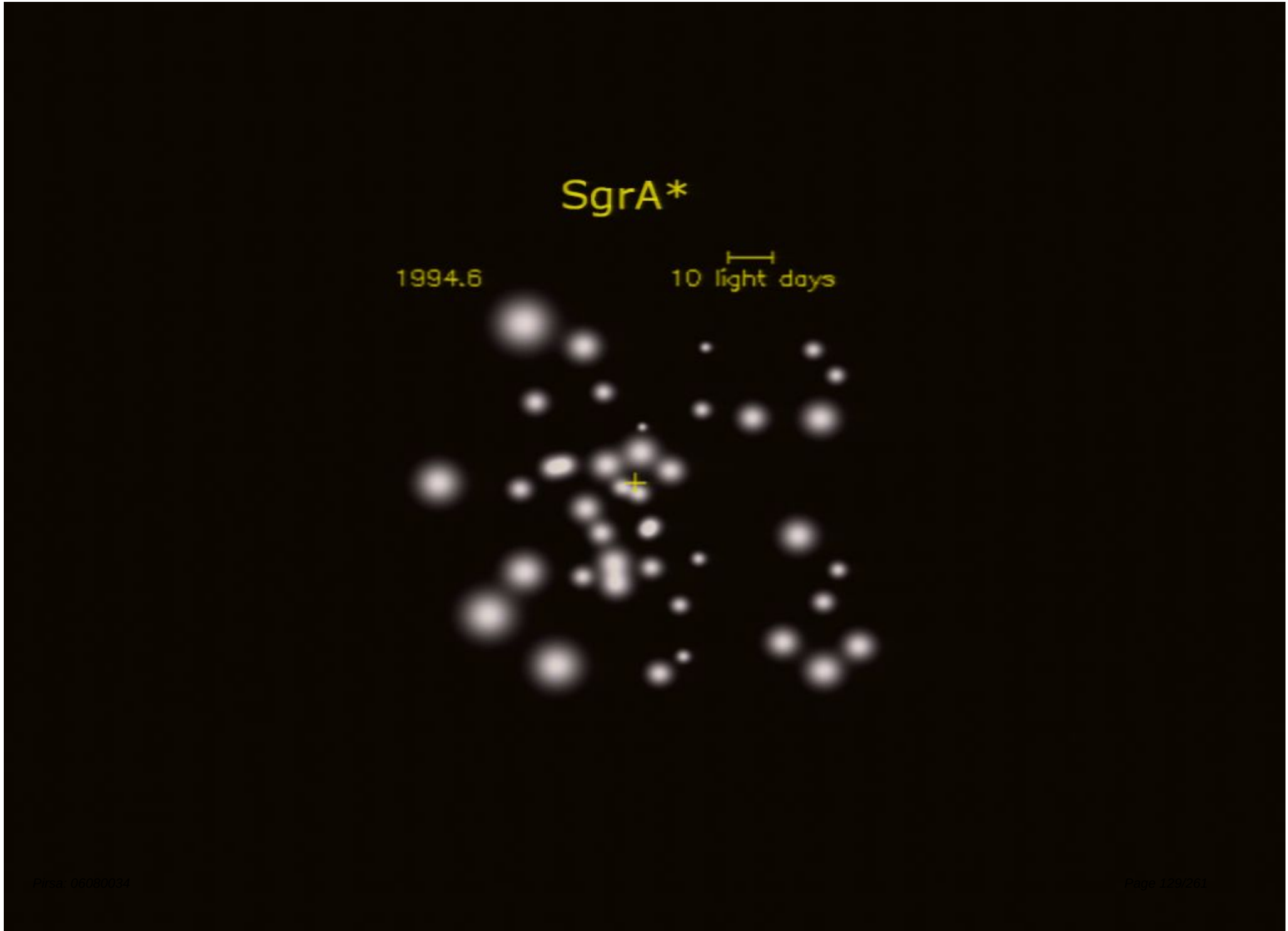

SgrA*
2002.5
10 light days

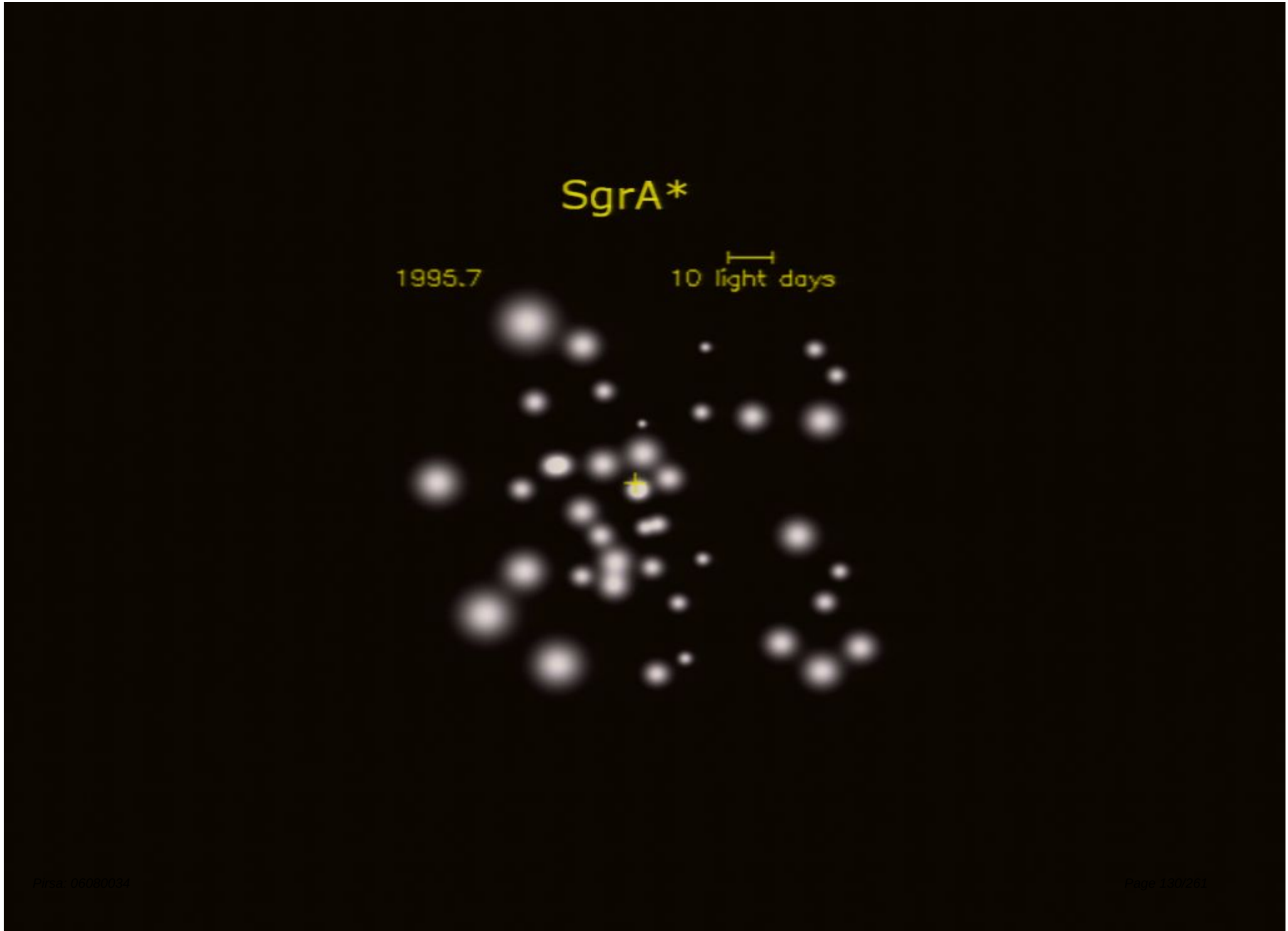

SgrA*
2005
10 light days

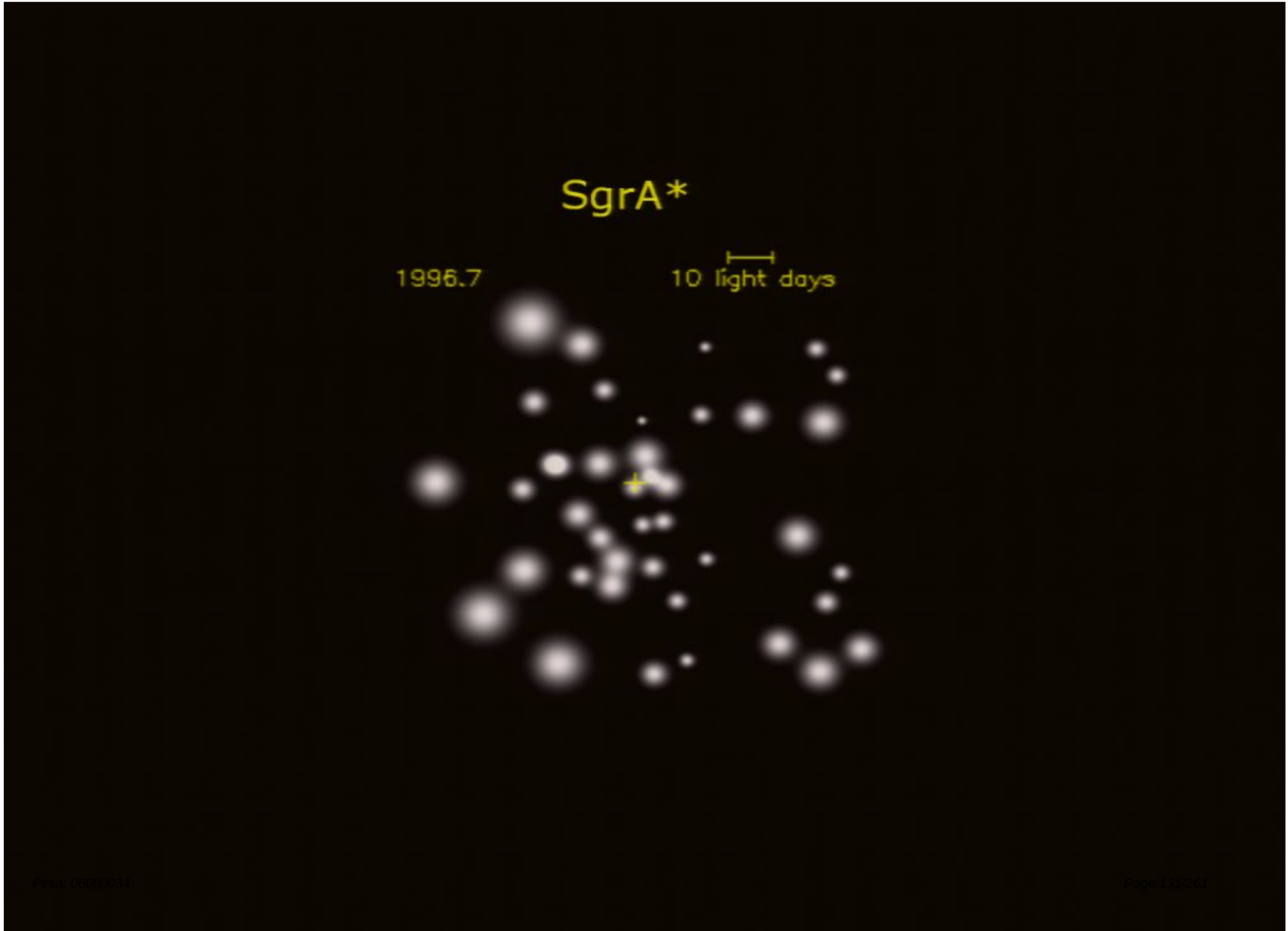

SgrA*
2005.8
10 light days


SgrA*
1992.8
10 light days


SgrA*
1993.8
10 light days


SgrA*
1994.6
10 light days


SgrA*
1995.7
10 light days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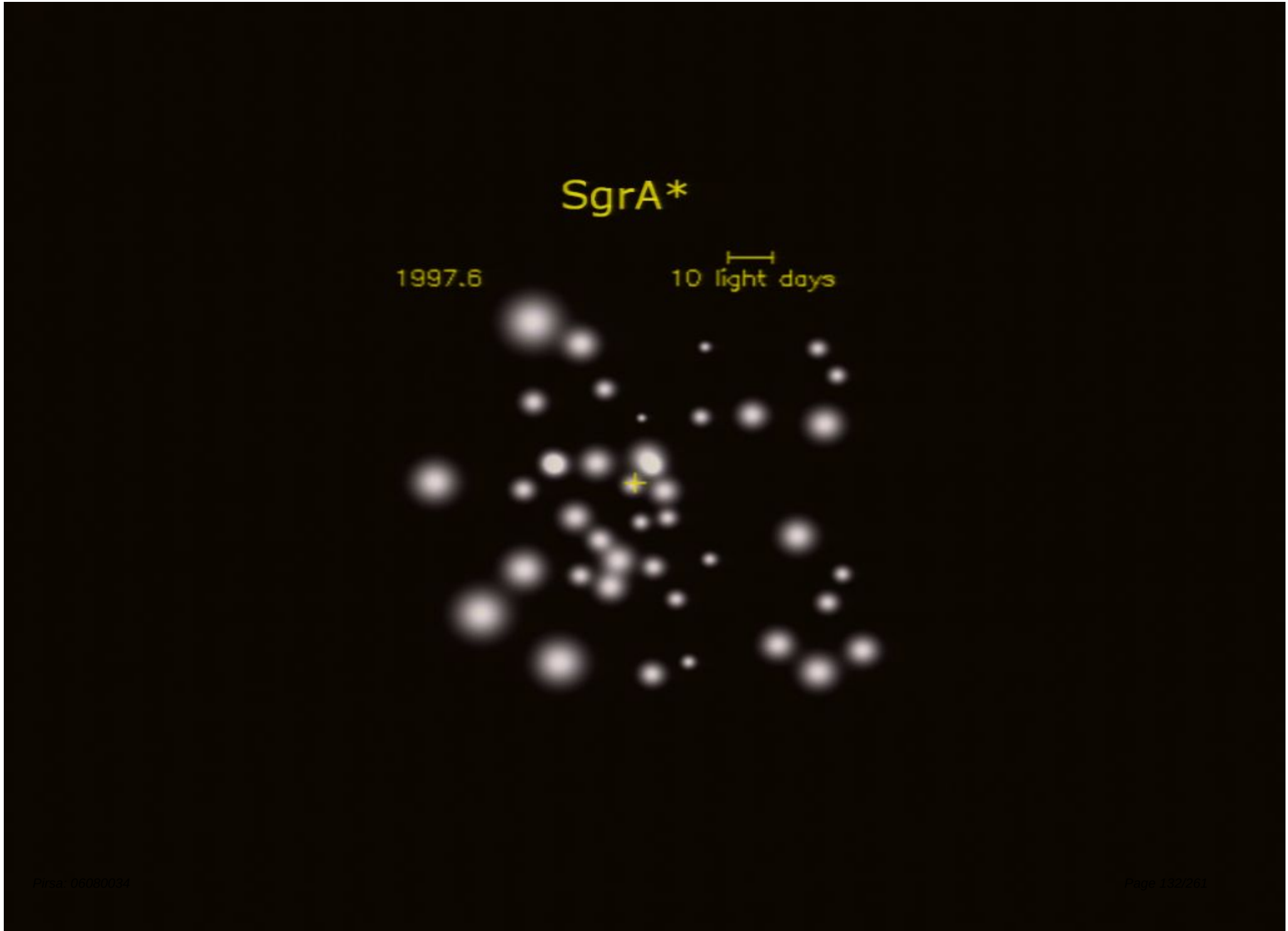
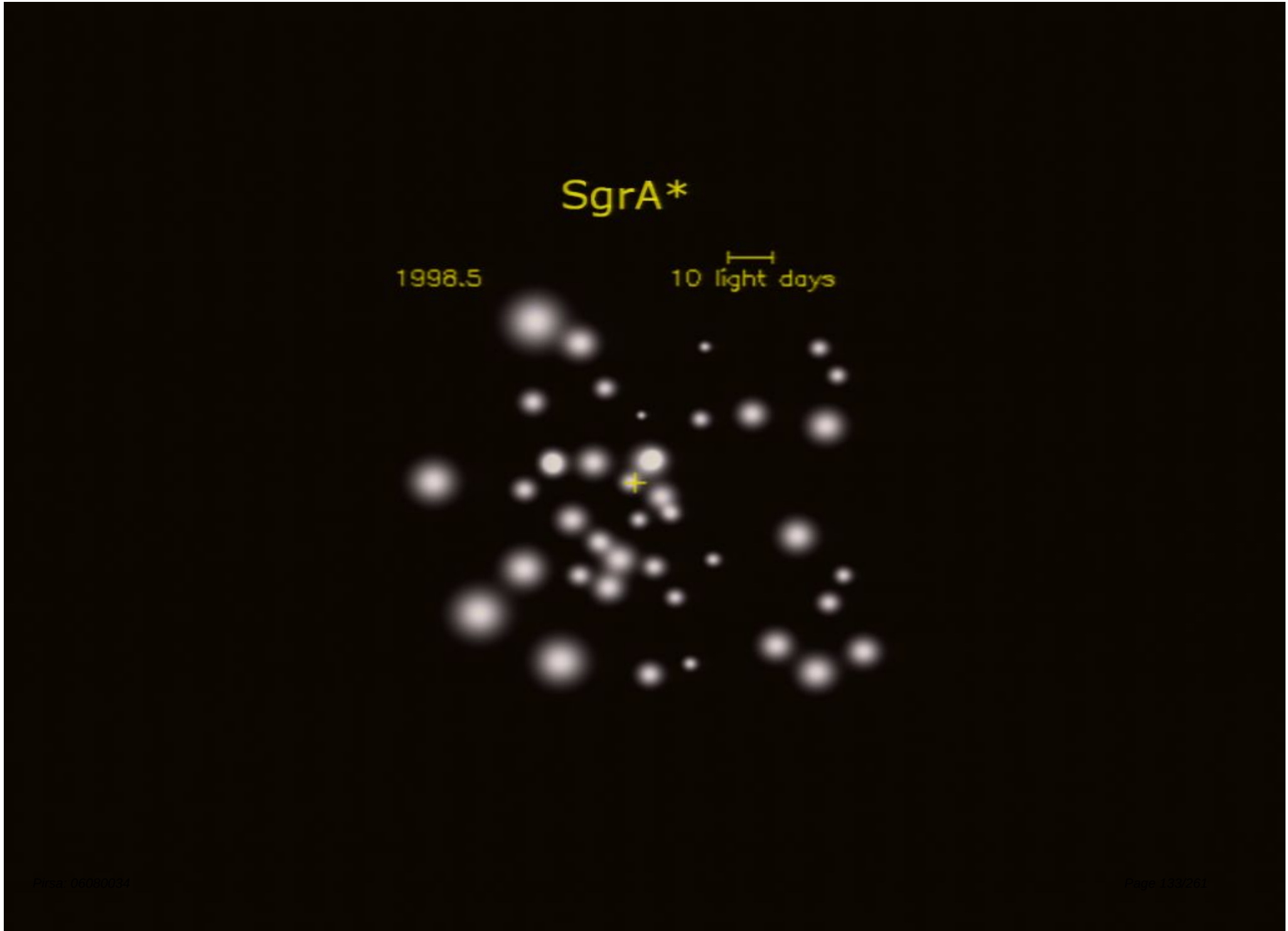
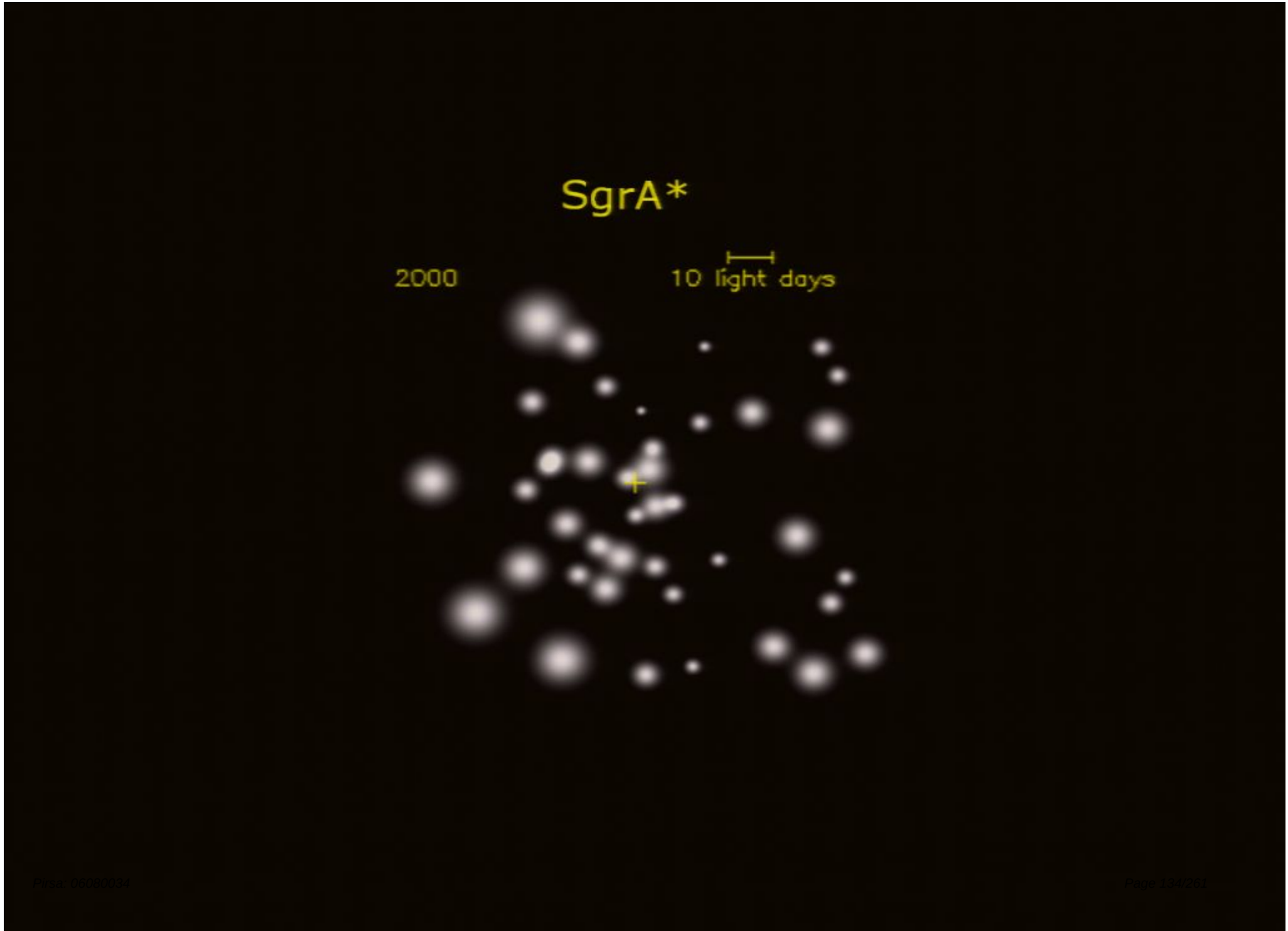
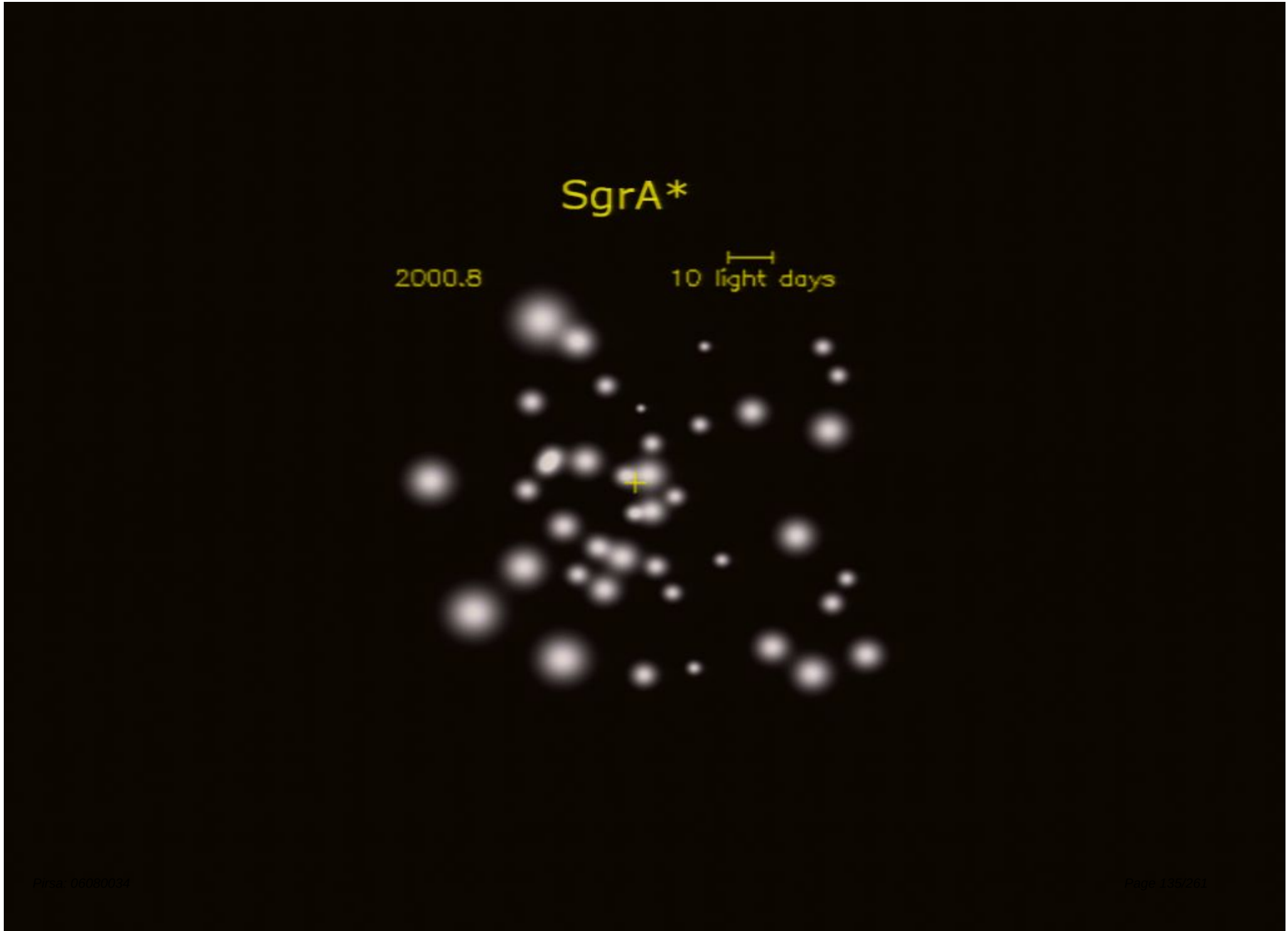
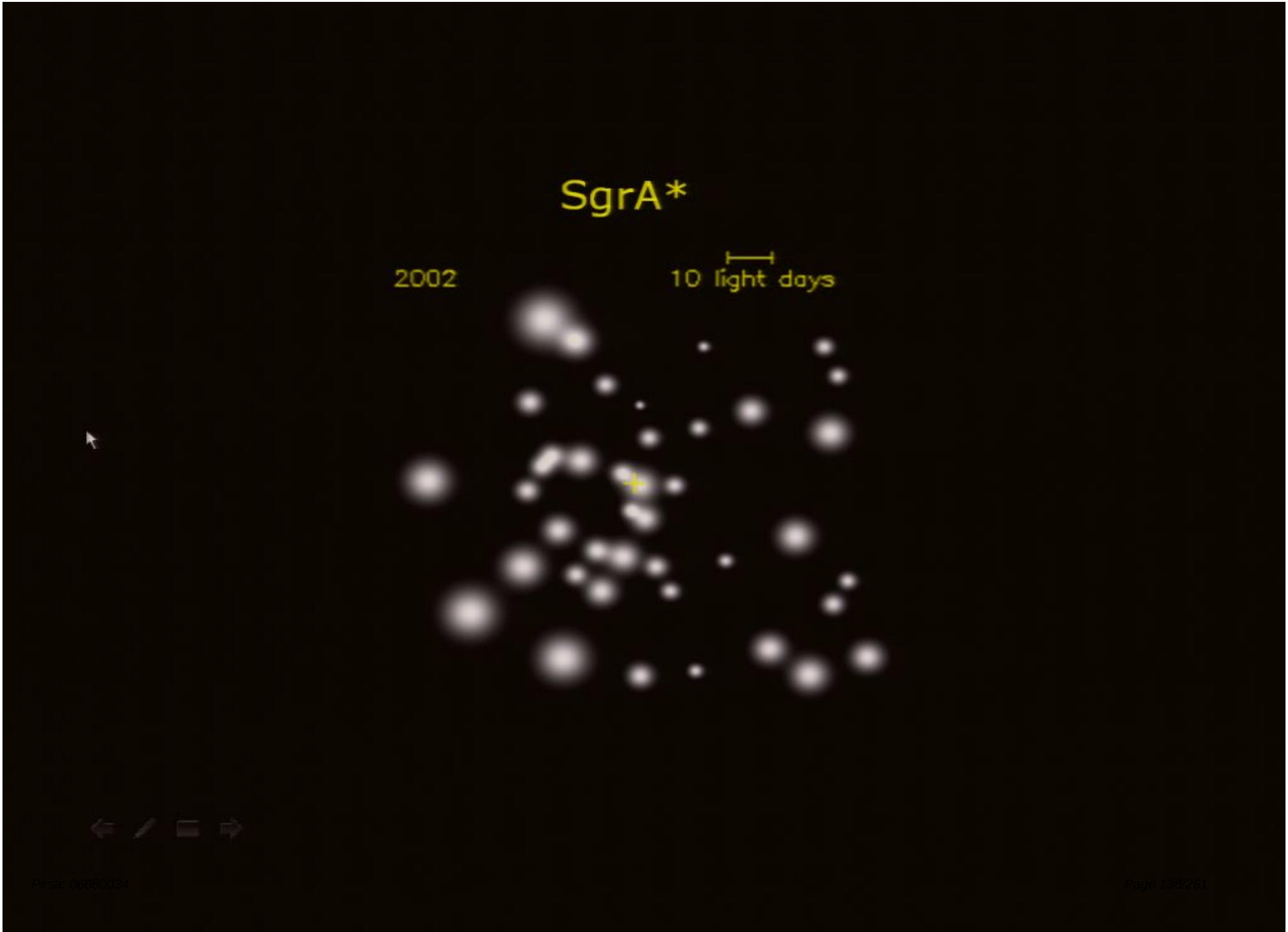
1996.7
10 light days


SgrA*
1997.6
10 light days

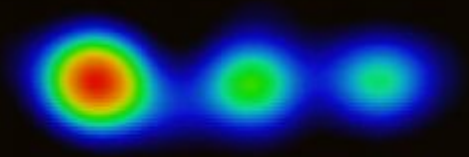

SgrA*
1998.5
10 light days


SgrA*
2000
10 light days


SgrA*
2000.8
10 light days

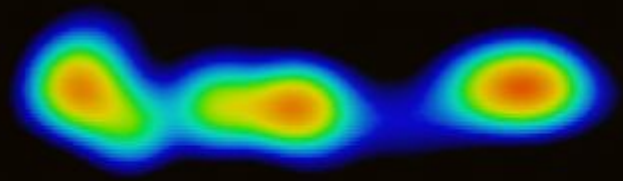

SgrA*
2002
10 light days

Black Hole Evidence



The object is known as GRS1915, a ``micro-quasar'' in the constellation of Aquila the Eagle at a distance of 40000 light years on the other side of the Milky Way. Scientists believe this object contains a black hole and a normal star and that theses images show energetic explosions at the center of the system.

Black Hole Evidence



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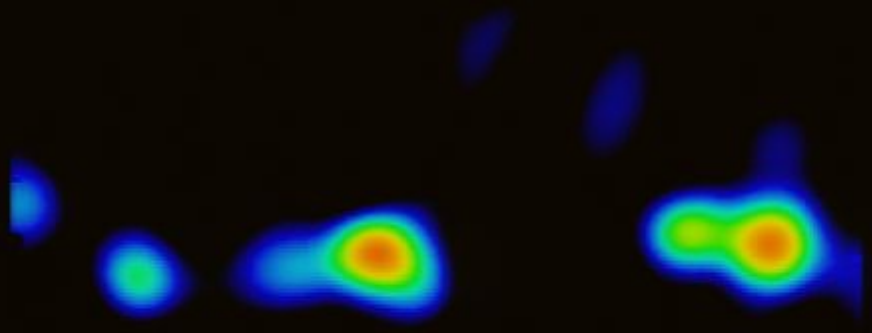

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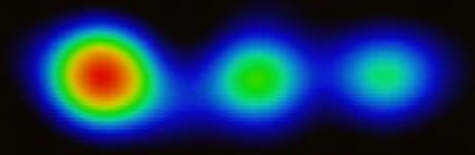

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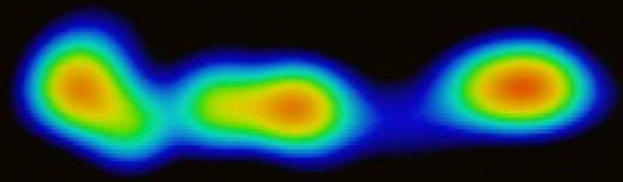

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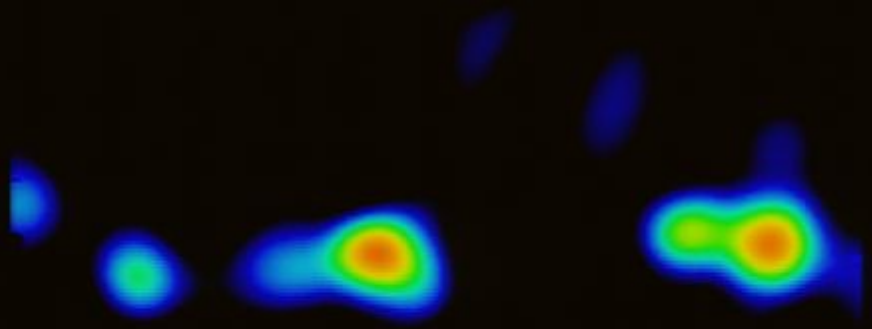

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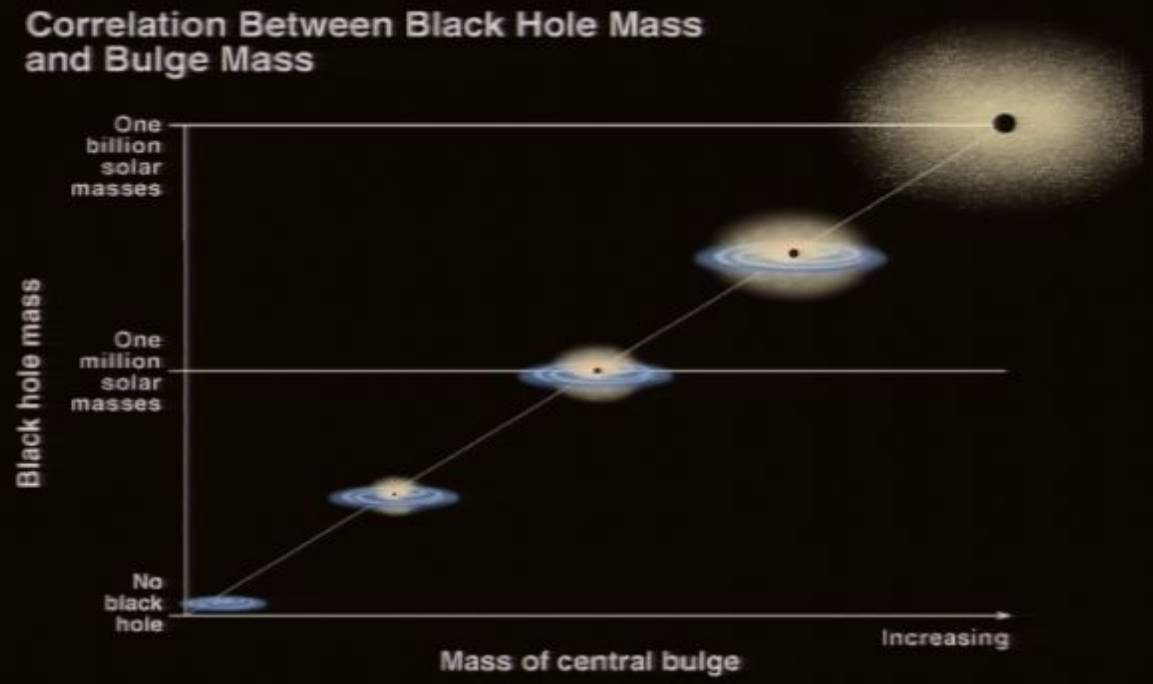
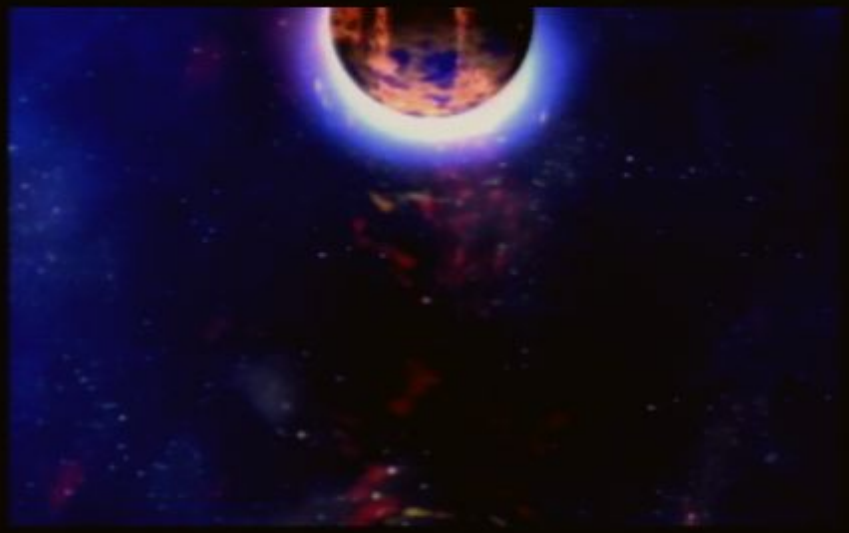
Speed of Gas and Black Holes



- It discovered a correlation between a Black Hole's mass and the average speed of the stars in the galaxy's central bulge.
- The faster the stars are moving, the larger the black hole.
- The central Black Hole comprises 0.5% of mass of stars in the spheroid of the galaxy. (Magorrian Relation)
- Previously, black holes were seen as the endpoints of evolution, the final resting state of most or all of the matter in the universe. Now we believe black holes also play a critical role in the birth of galaxies."

When Black Holes Collide



When Black Holes Collide

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Frame Dragging and Gravitational Waves

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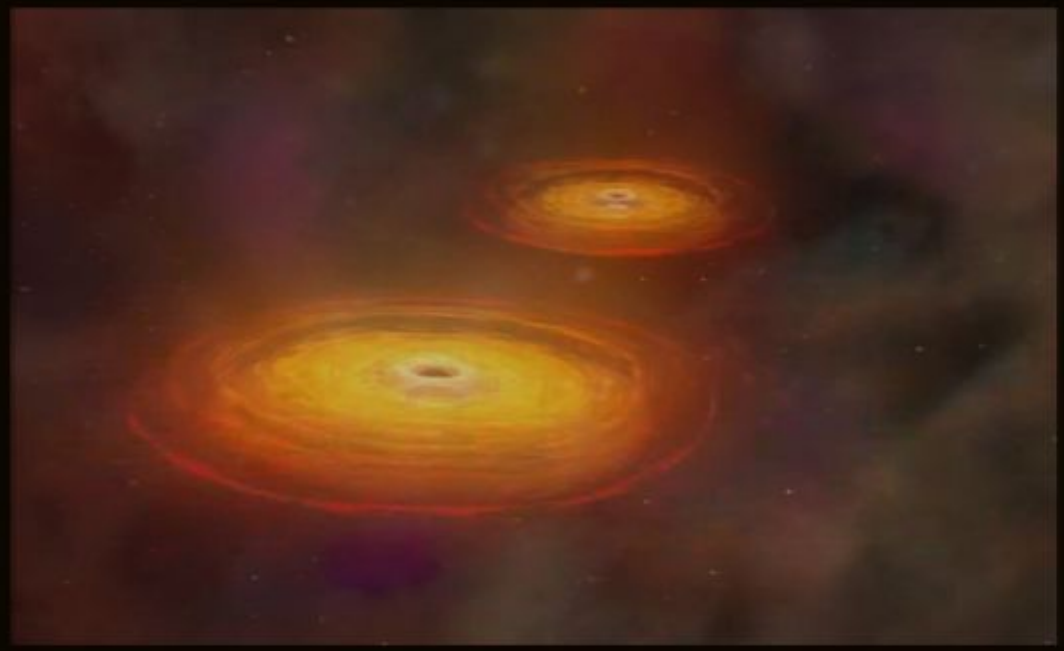
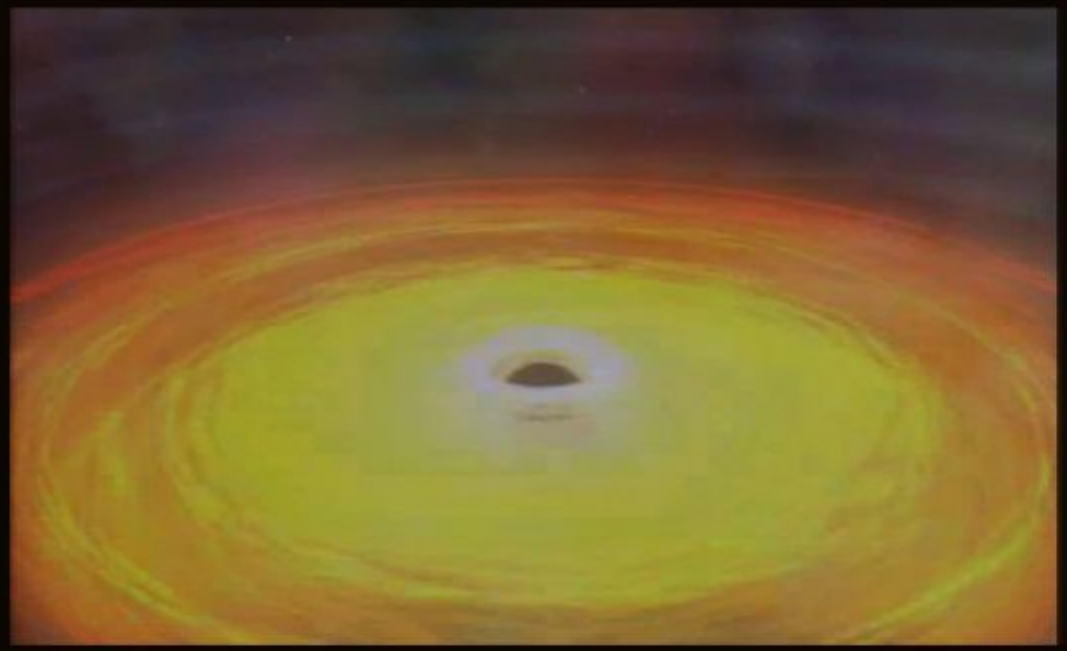


Frame Dragging and Gravitational Waves



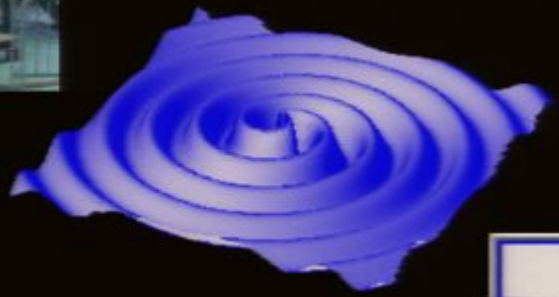
Frame Dragging and Gravitational Waves

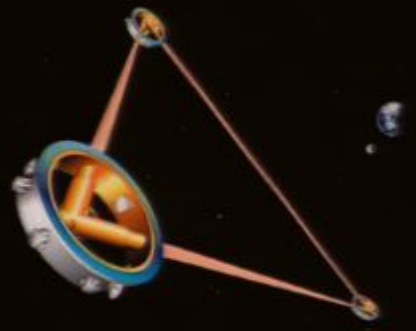
Frame Dragging and Gravitational Waves

Wave Detection

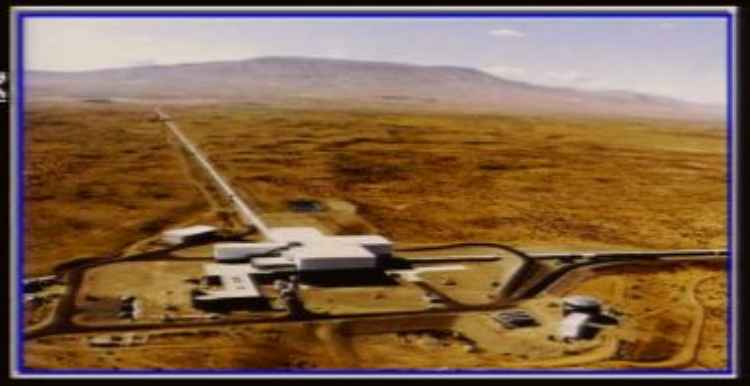
Nautilus

Auriga





Laser Interferometer Space Antenna

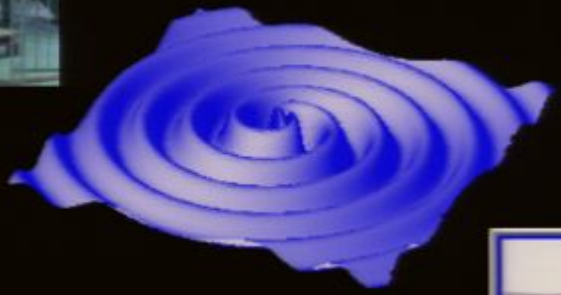


Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga



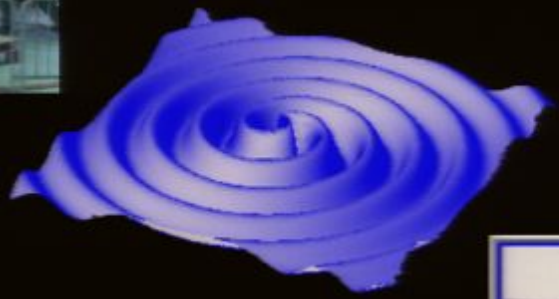
Laser Interferometer Space Antenna

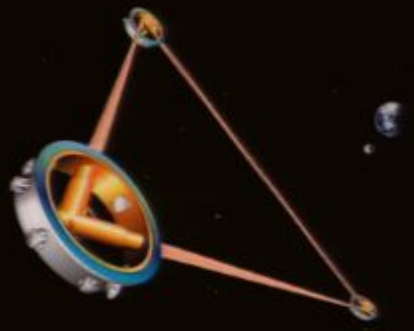
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga





Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

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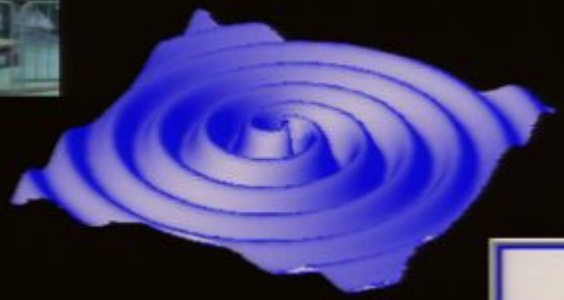
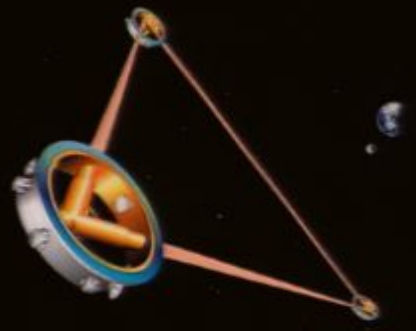
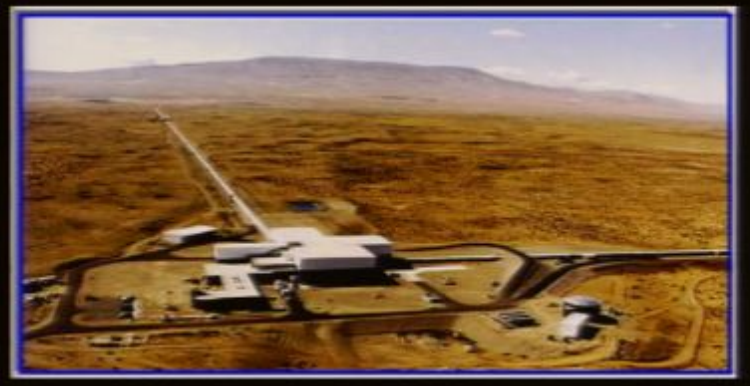




Laser Interferometer Space Antenna

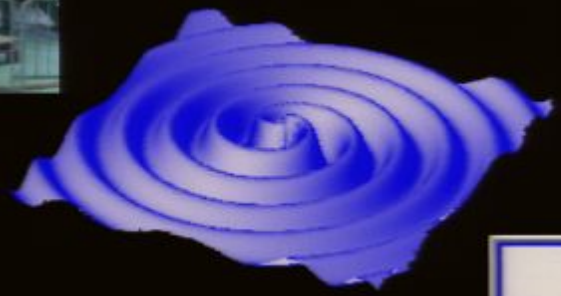


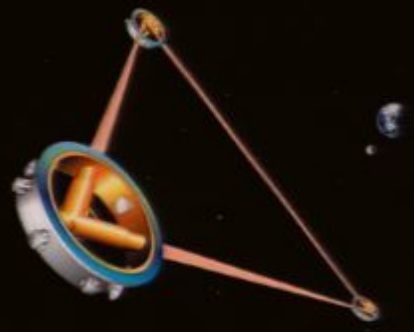
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

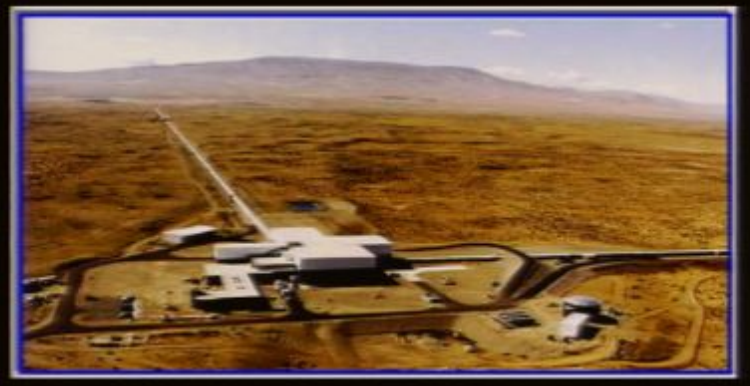
Nautilus

Auriga





Laser Interferometer Space Antenna

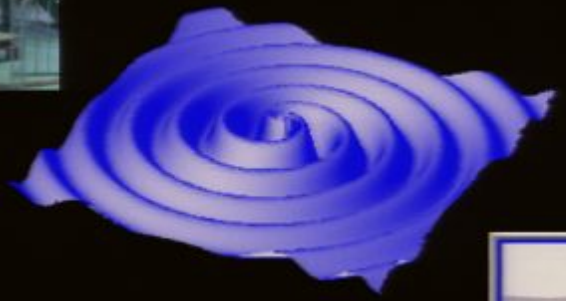


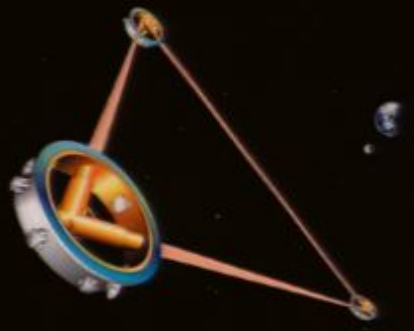
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga





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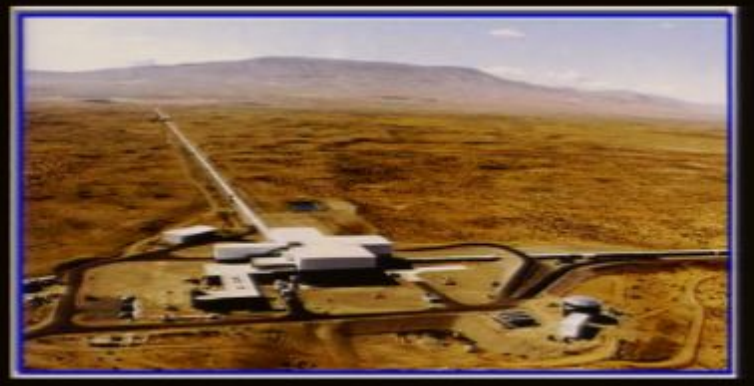
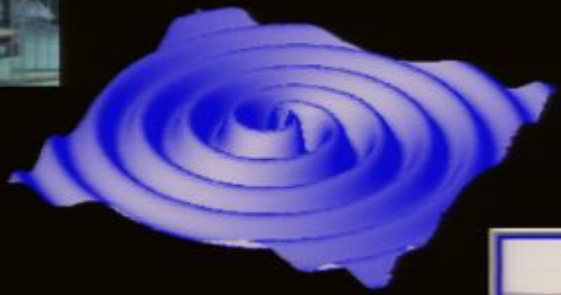


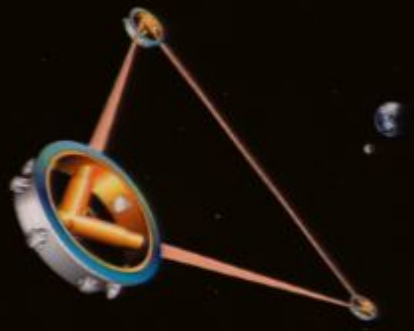
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga





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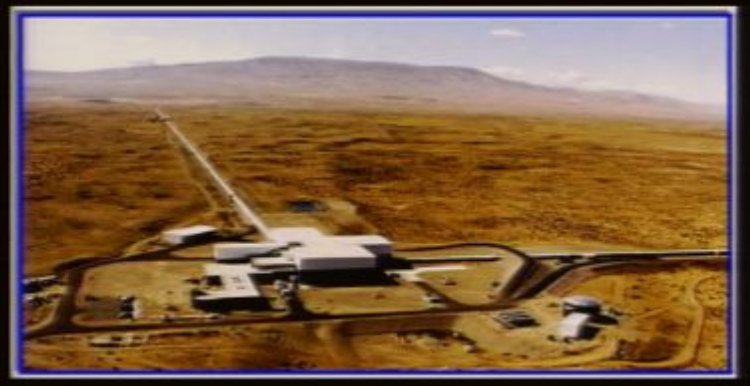
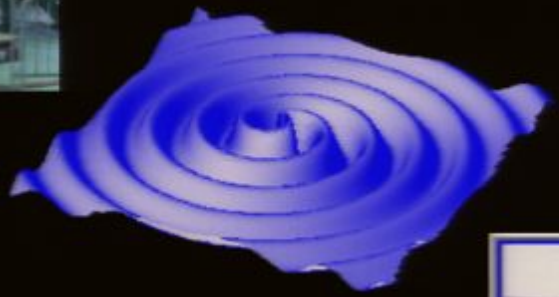


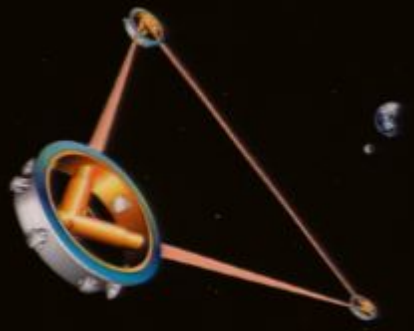
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga





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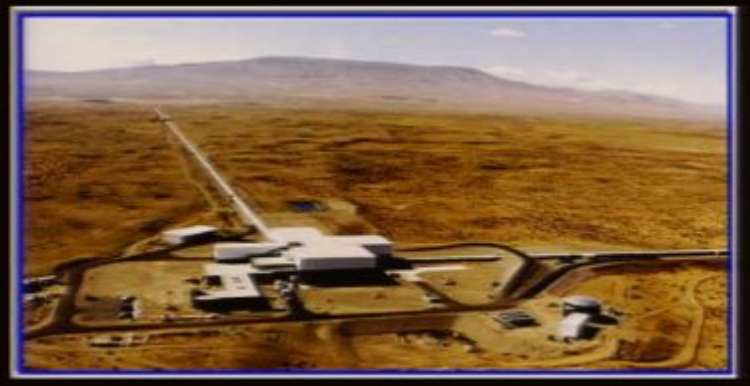

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

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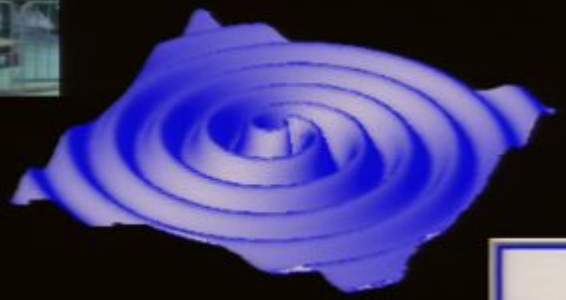

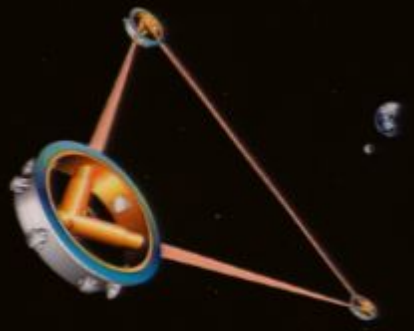

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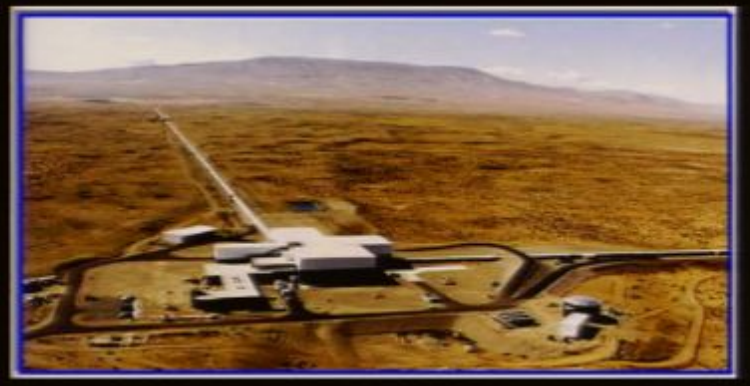
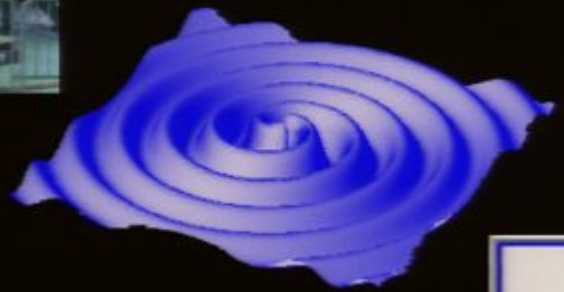


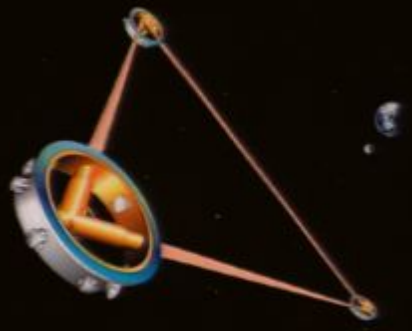
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga





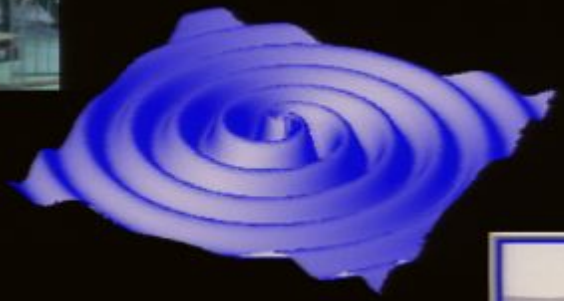
Laser Interferometer Space Antenna

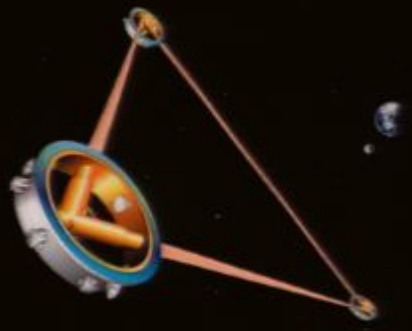
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

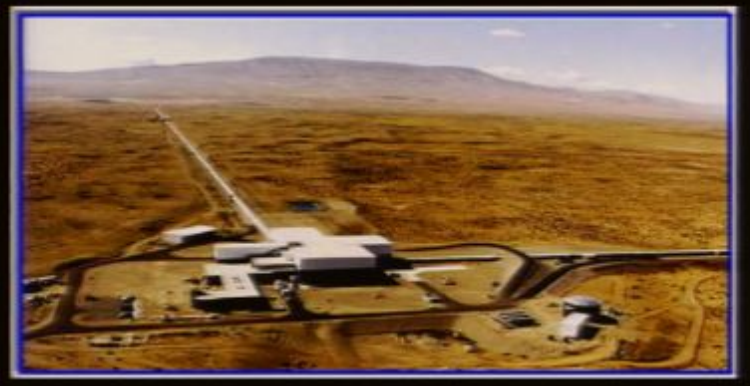
Nautilus

Auriga





Laser Interferometer Space Antenna

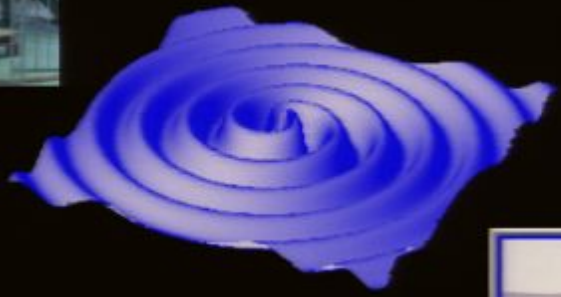


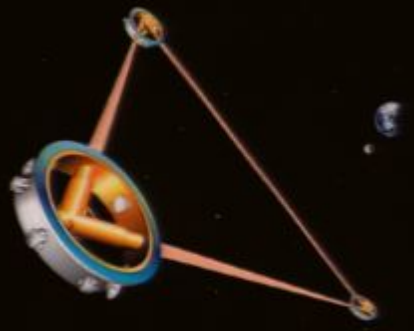
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga





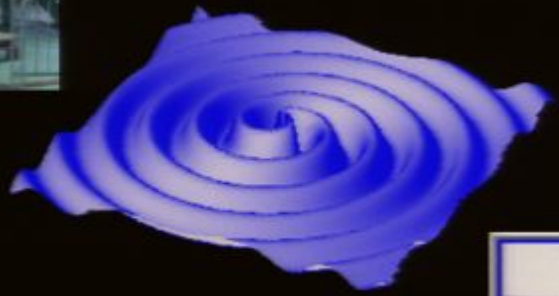
Laser Interferometer Space Antenna

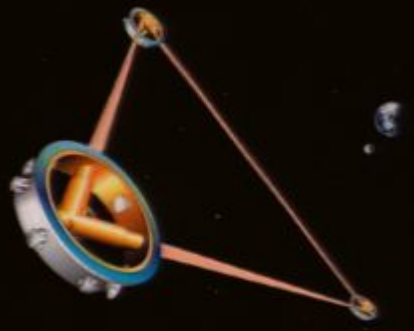
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga





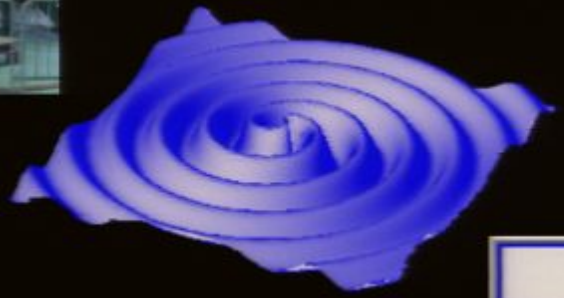
Laser Interferometer Space Antenna

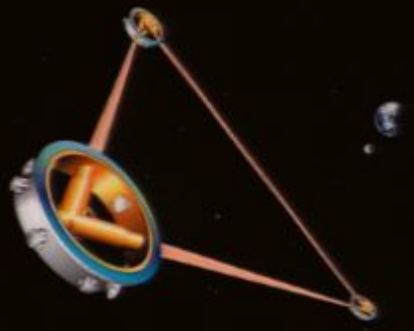
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

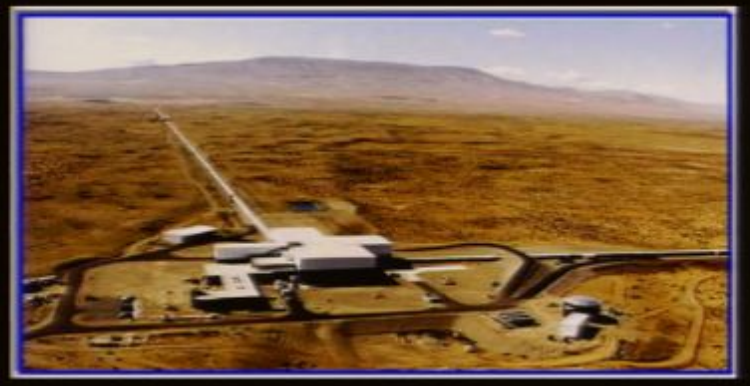
Nautilus

Auriga





Laser Interferometer Space Antenna

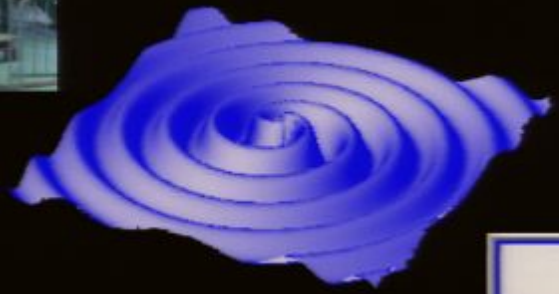


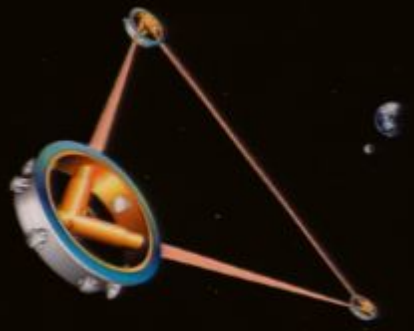
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga





Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

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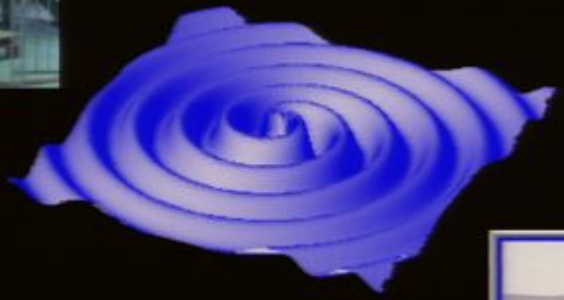
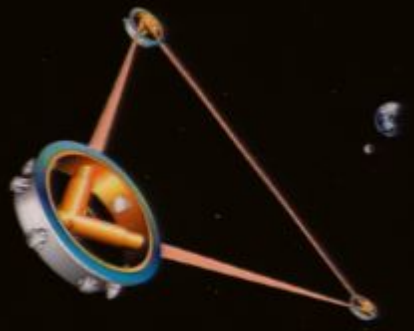
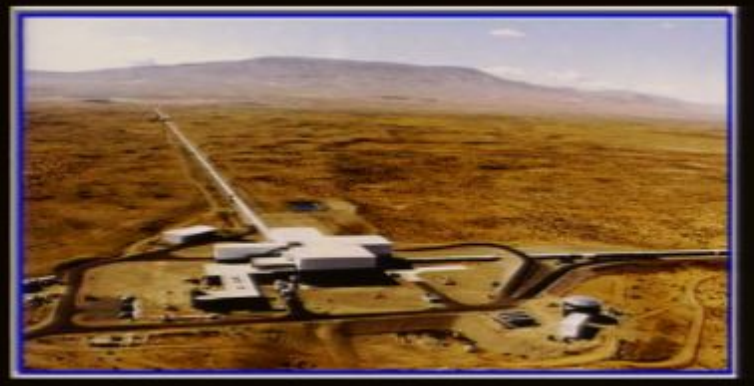




Laser Interferometer Space Antenna



Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

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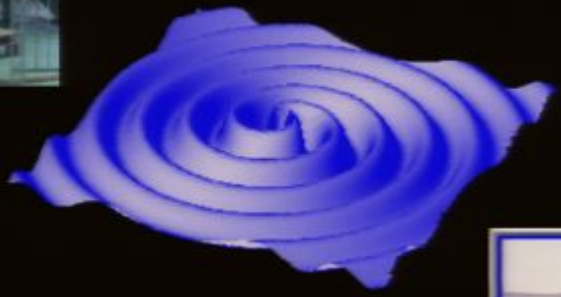

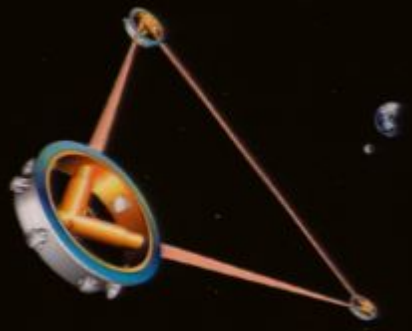

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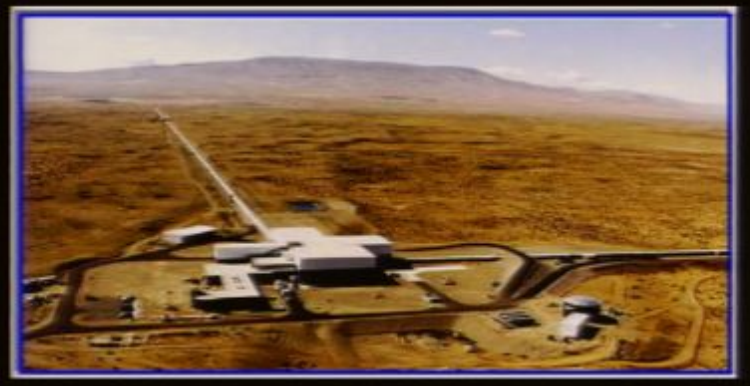

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

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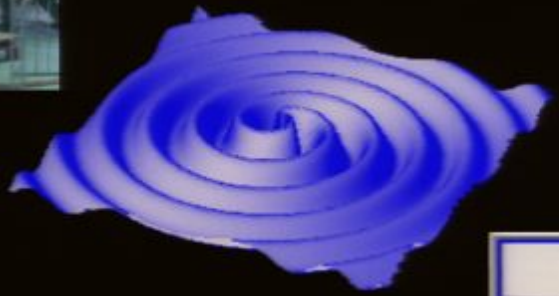
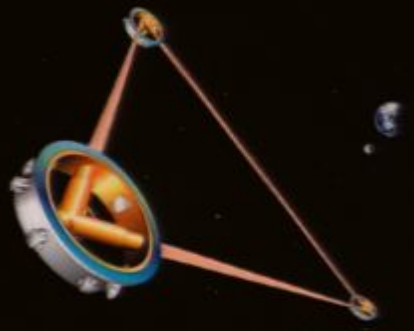
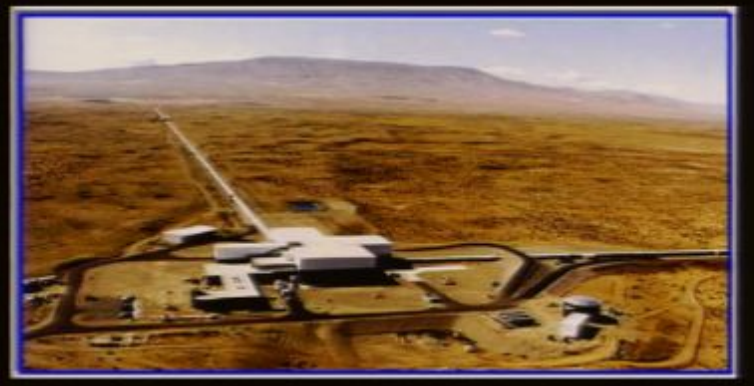




Laser Interferometer Space Antenna



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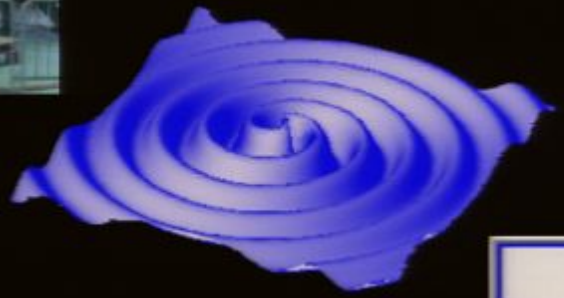

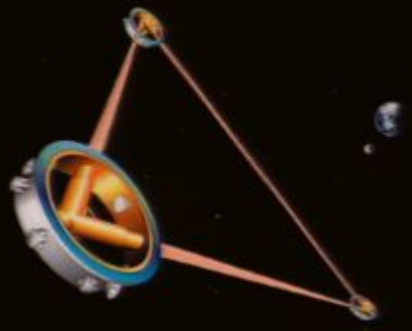

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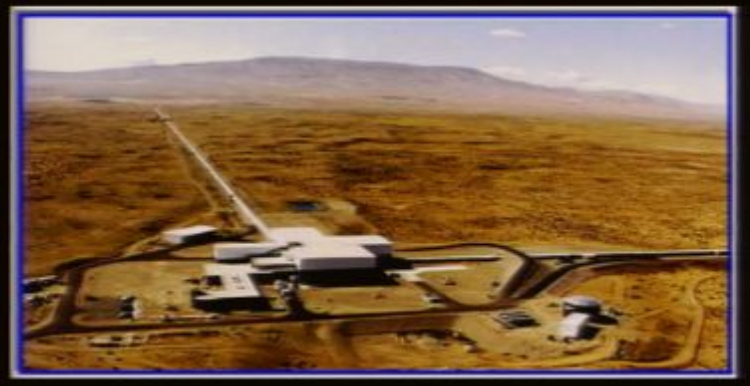

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

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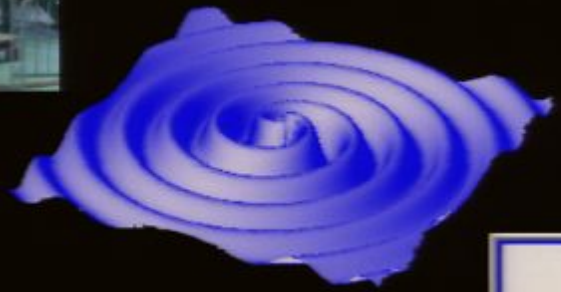
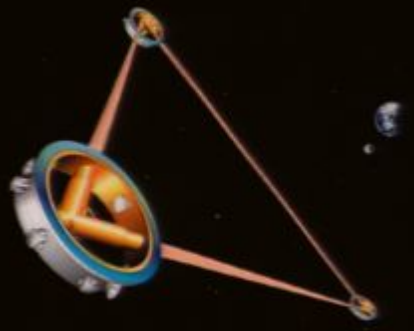
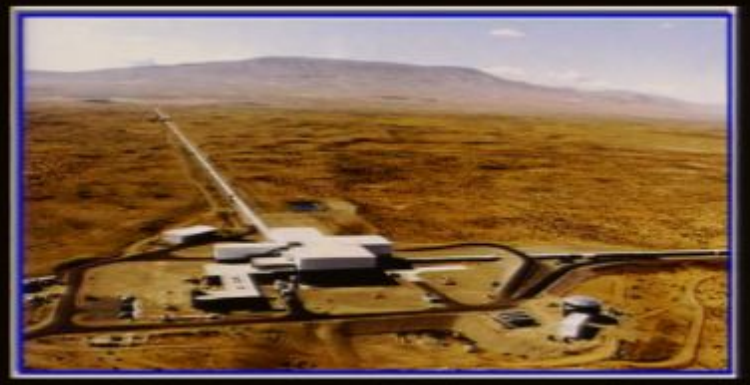




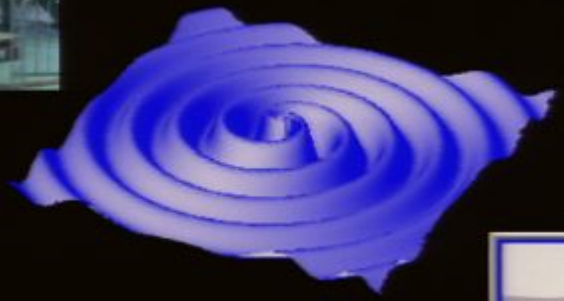
Laser Interferometer Space Antenna



Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus



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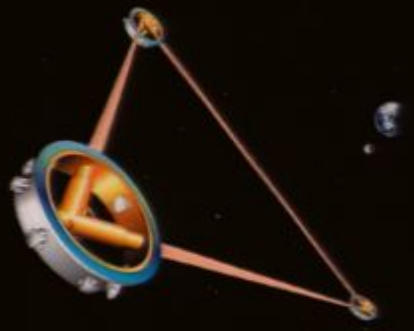

Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

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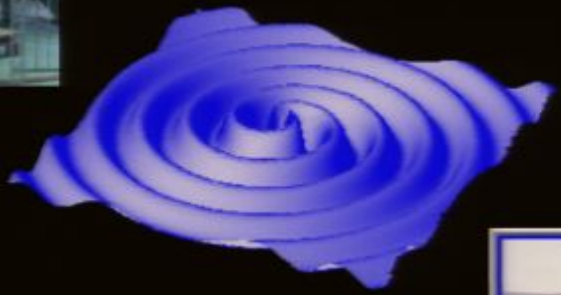

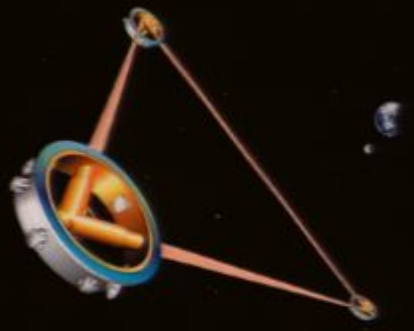

Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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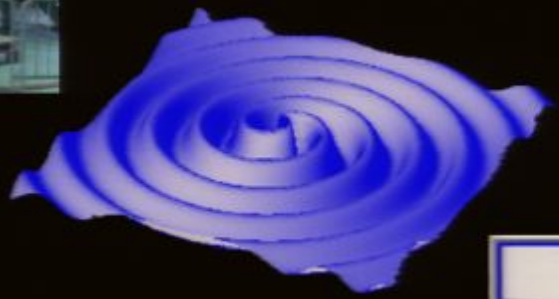

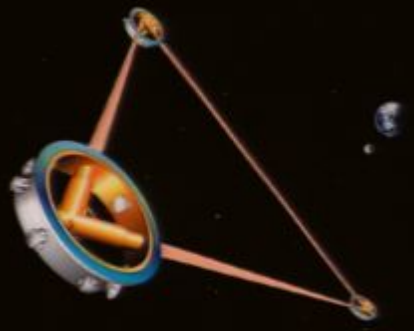

Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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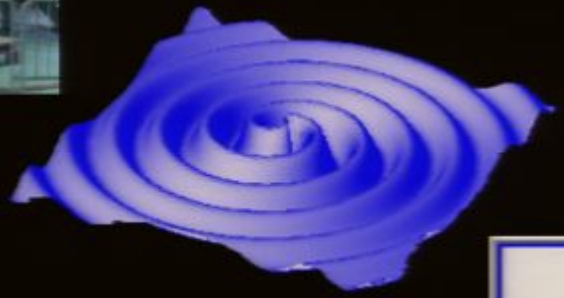

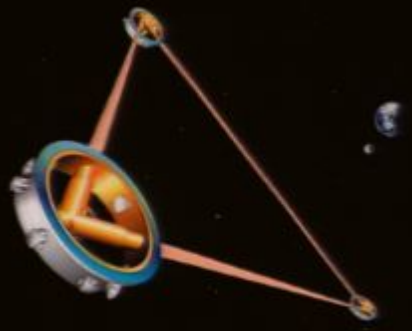

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Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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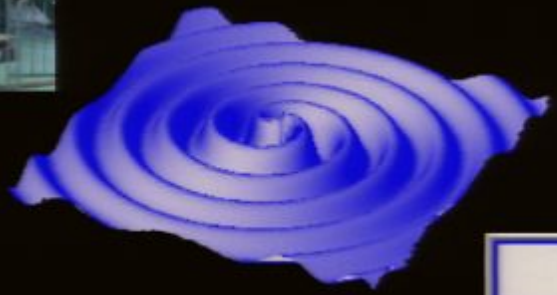

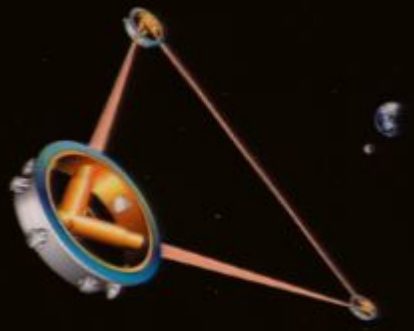

Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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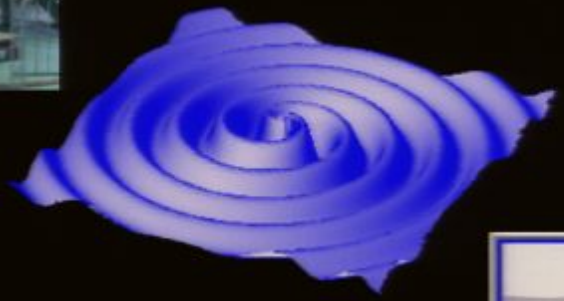

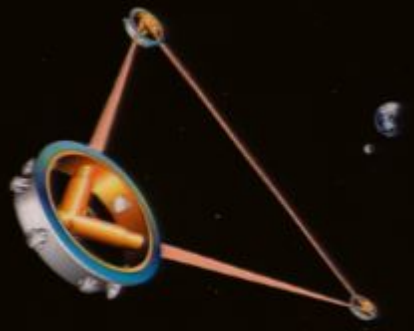

Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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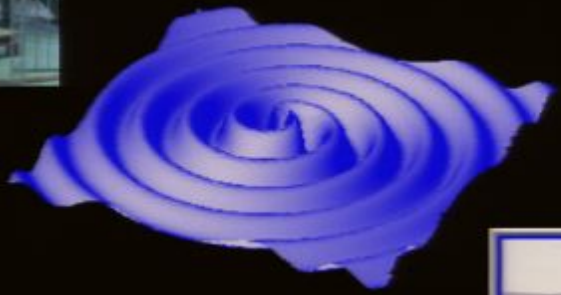
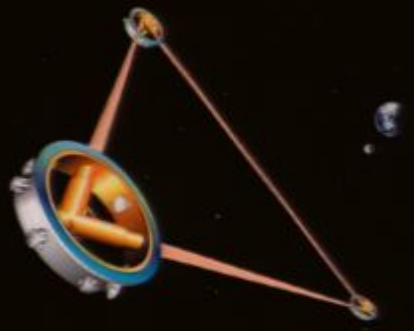
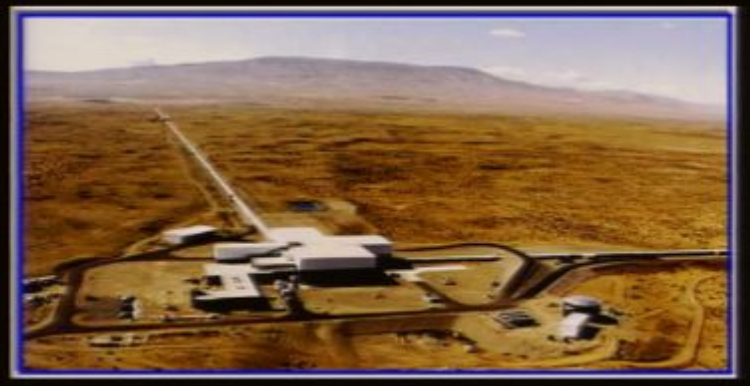




Laser Interferometer Space Antenna



Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

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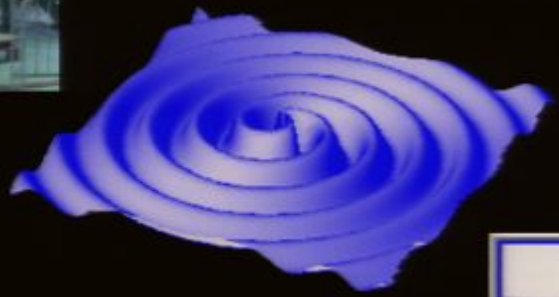

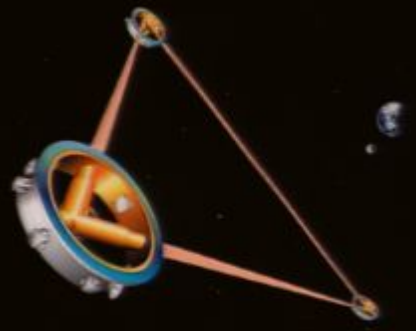

Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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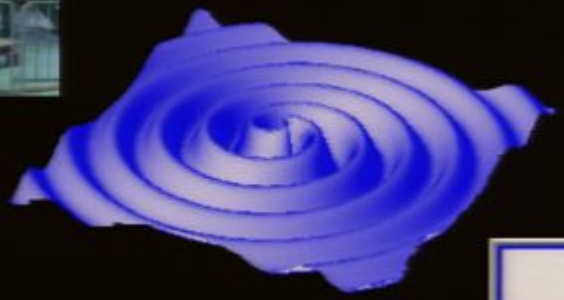
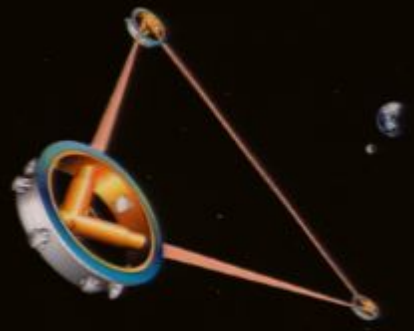


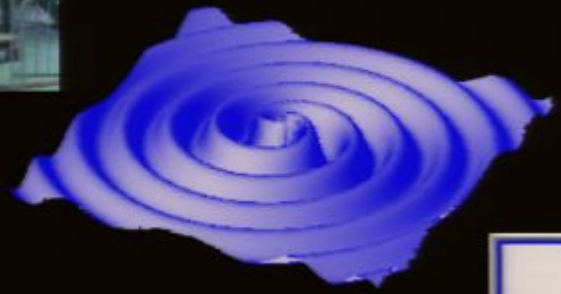


Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus



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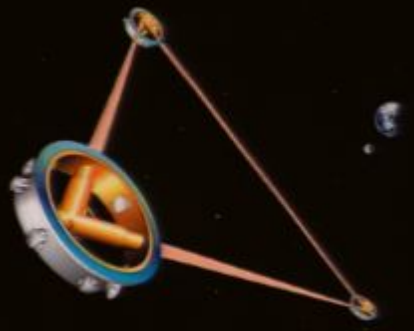
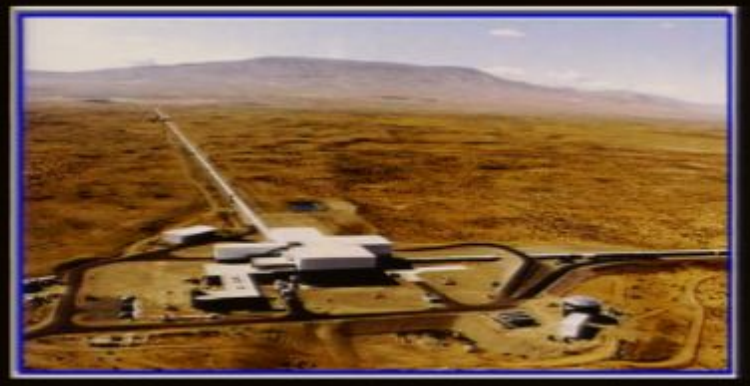


Laser Interferometer Space Antenna



Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

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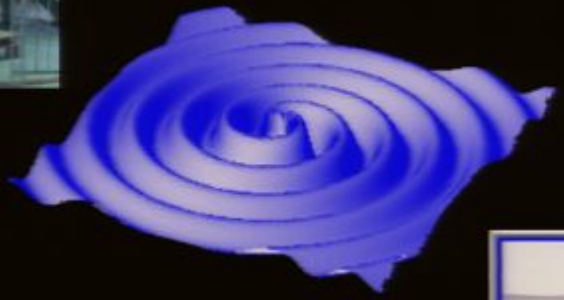

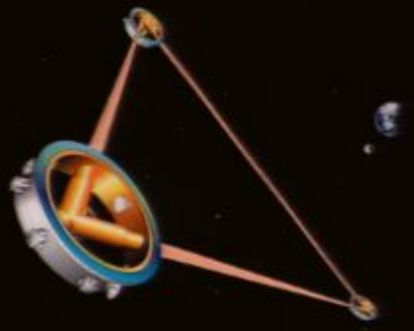

Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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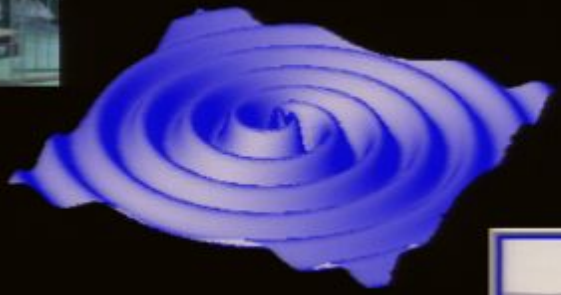
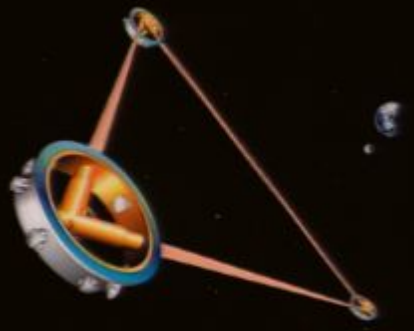
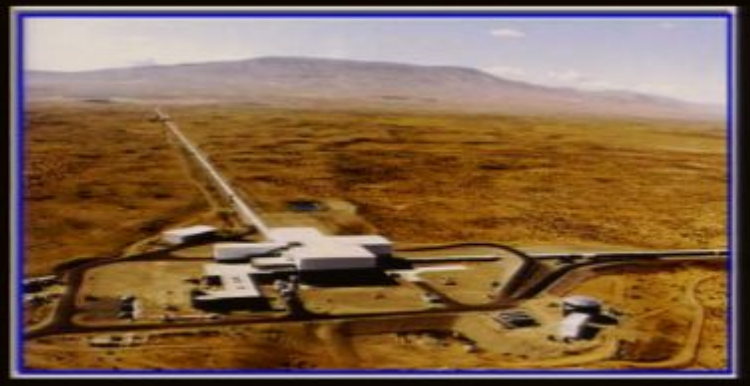




Laser Interferometer Space Antenna



Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

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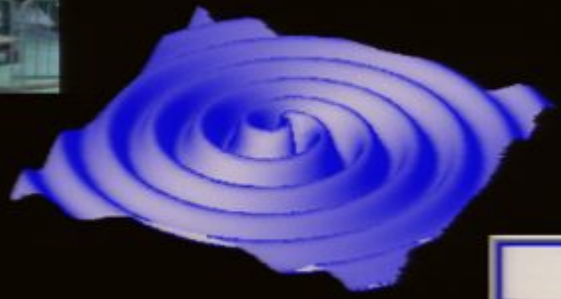
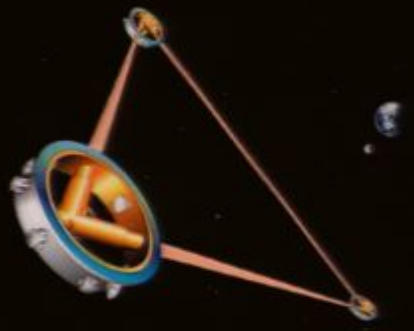
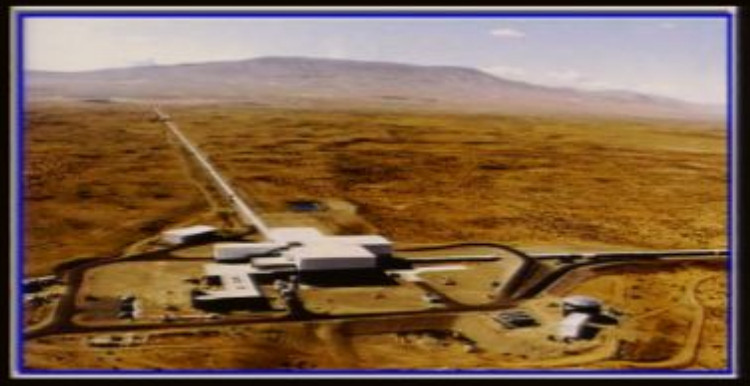




Laser Interferometer Space Antenna



Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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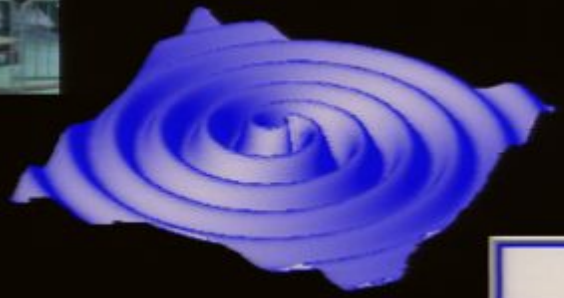

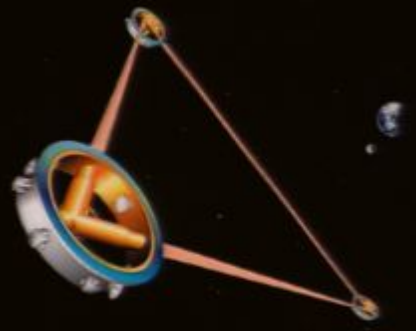

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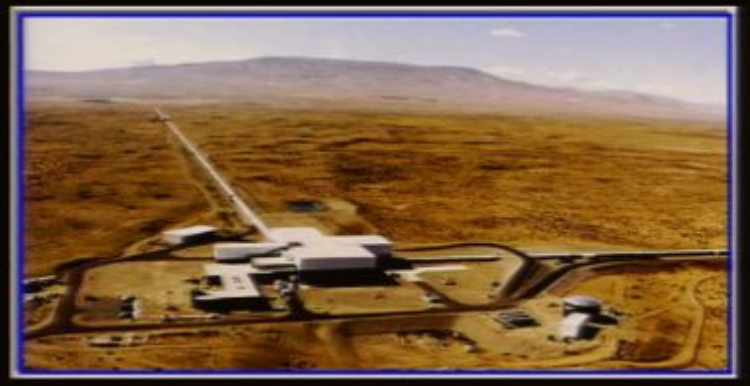

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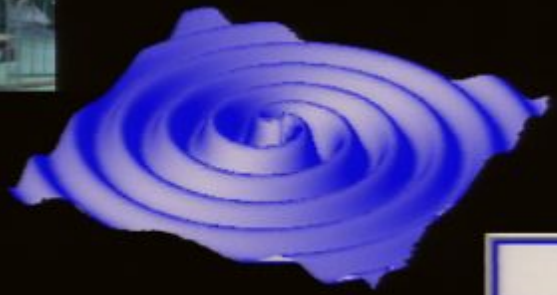
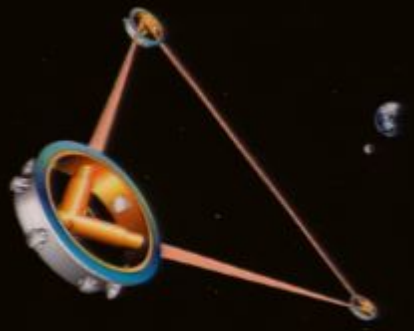
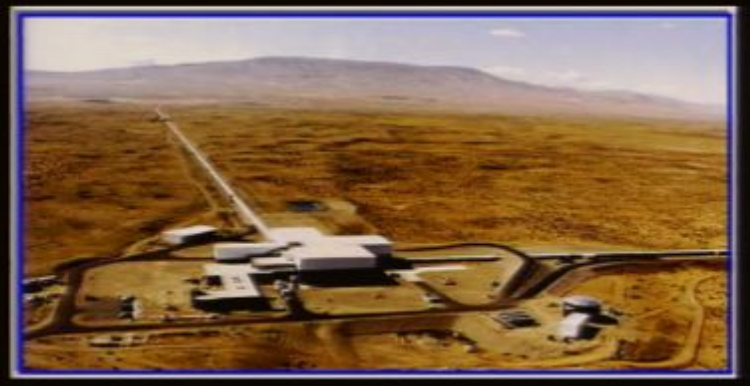




Laser Interferometer Space Antenna

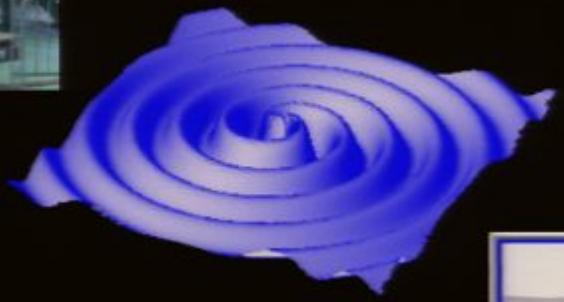


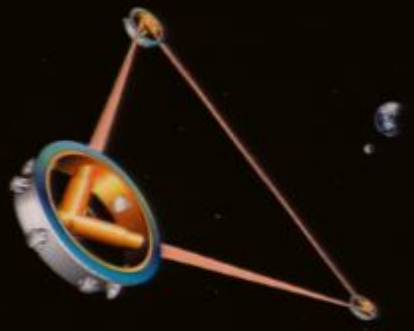
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

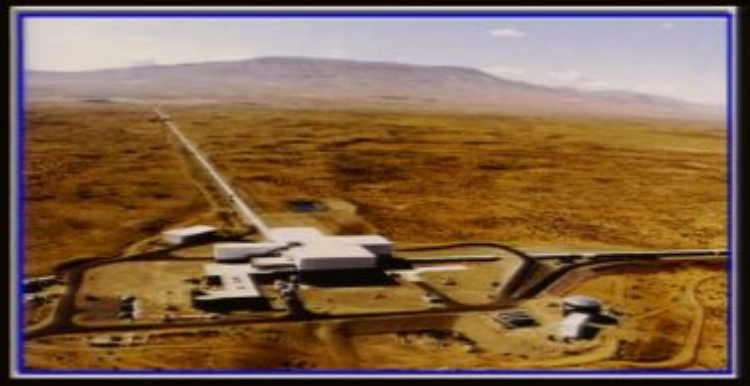
Nautilus

Auriga





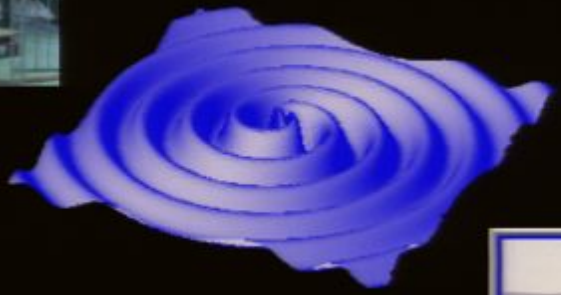
Laser Interferometer Space Antenna



Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus



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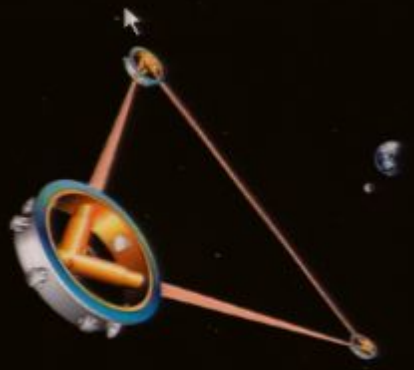
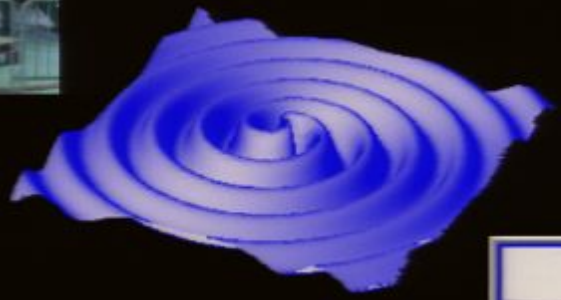


Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus



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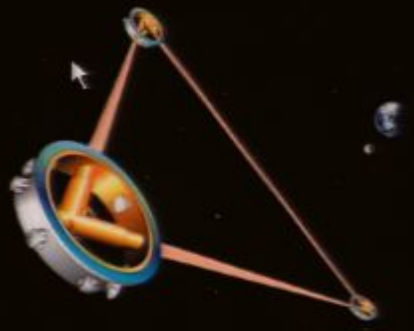
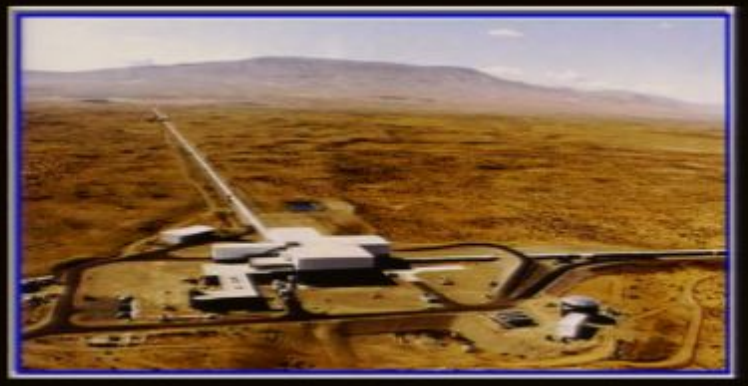


Laser Interferometer Space Antenna

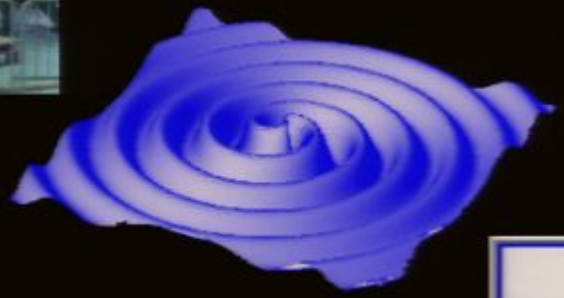


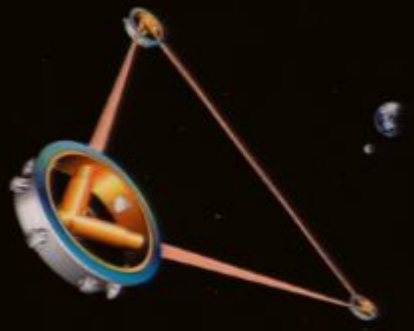
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga





Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

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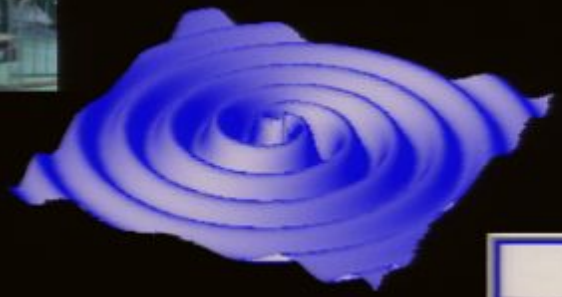

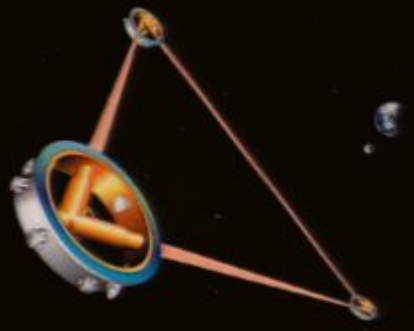

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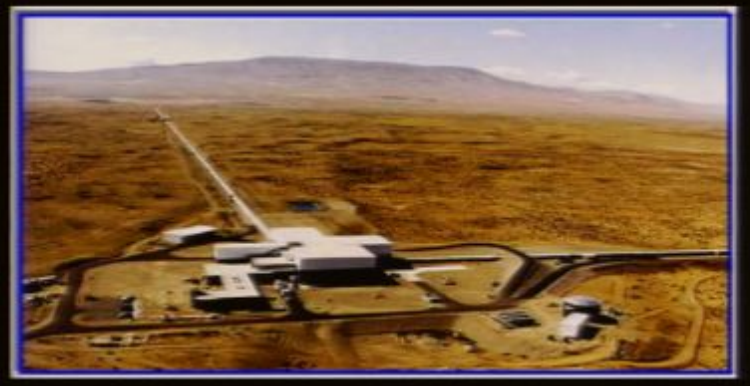
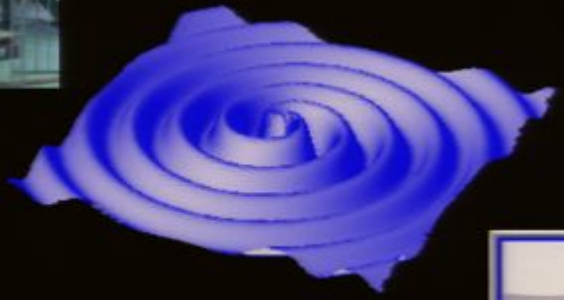


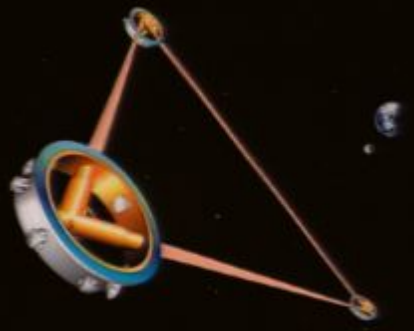
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

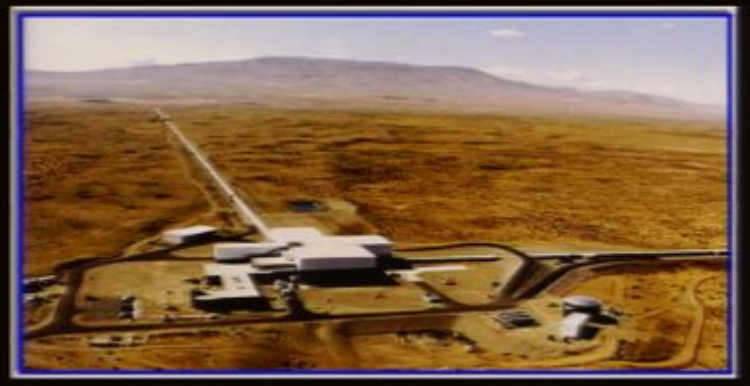
Nautilus

Auriga





Laser Interferometer Space Antenna



Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

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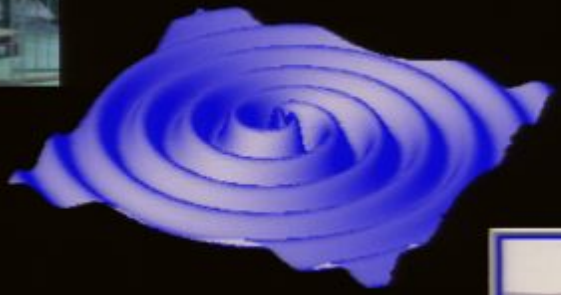
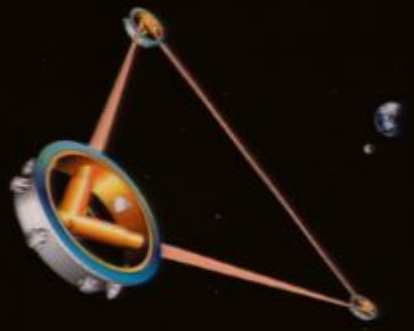
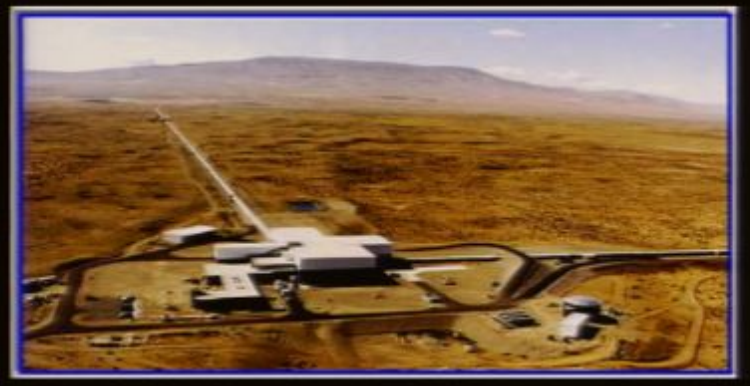




Laser Interferometer Space Antenna

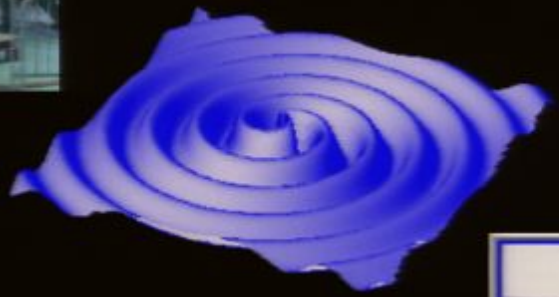


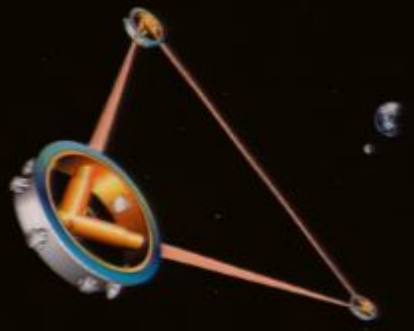
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga





Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

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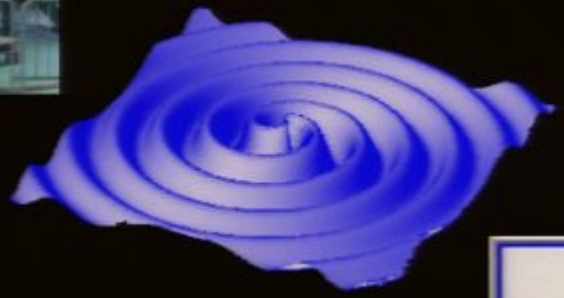
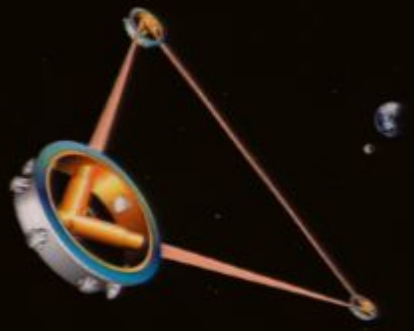
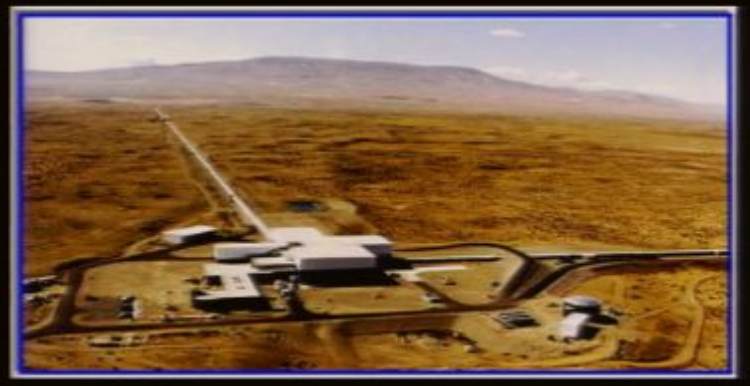




Laser Interferometer Space Antenna

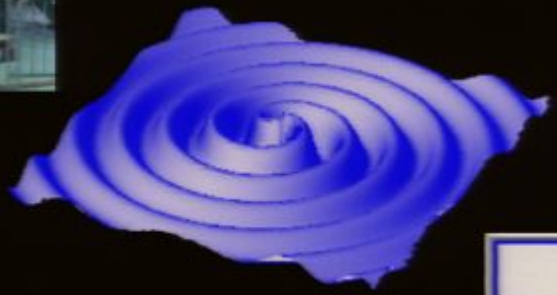


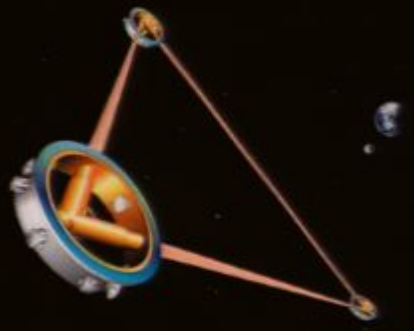
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

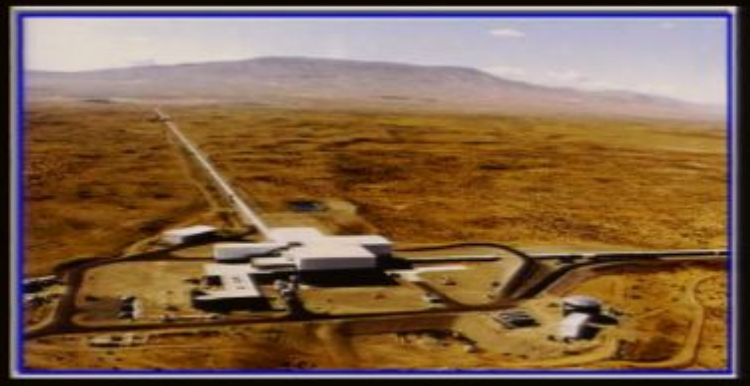
Nautilus

Auriga





Laser Interferometer Space Antenna

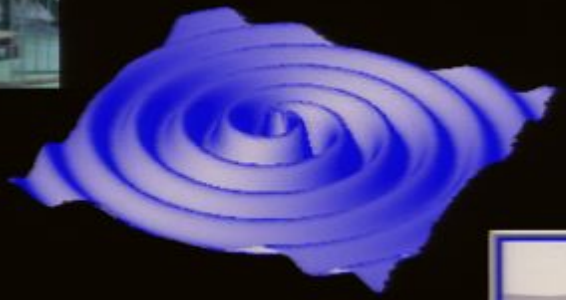


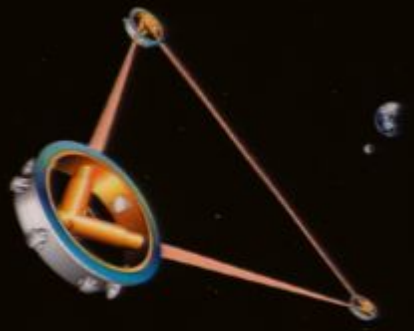
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga



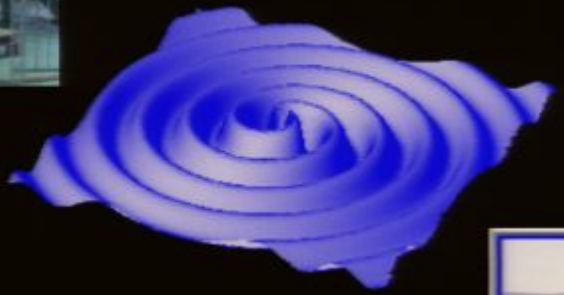


Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus



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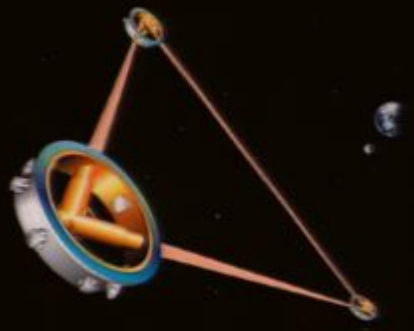
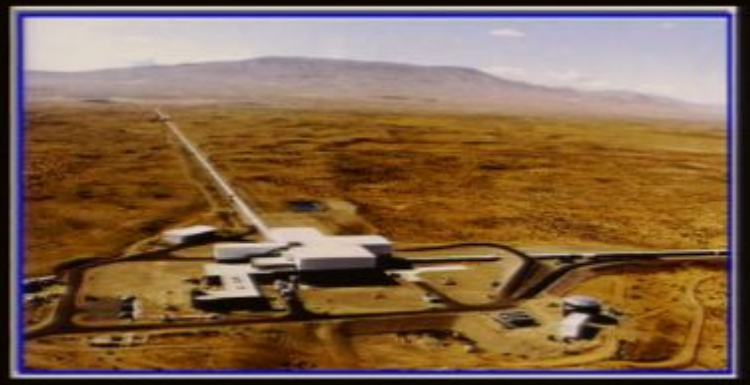


Laser Interferometer Space Antenna

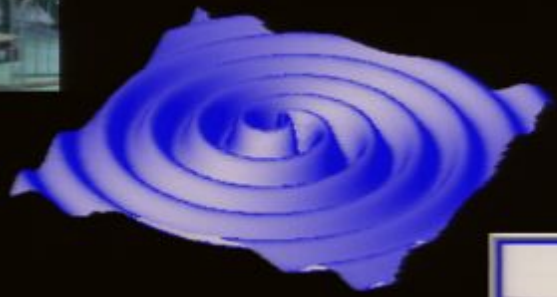


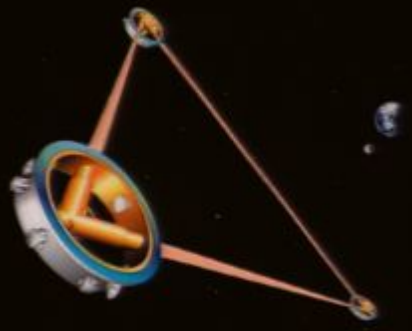
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

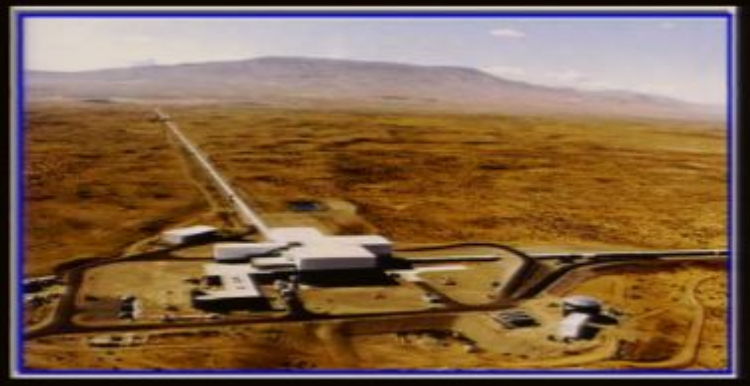
Nautilus

Auriga





Laser Interferometer Space Antenna

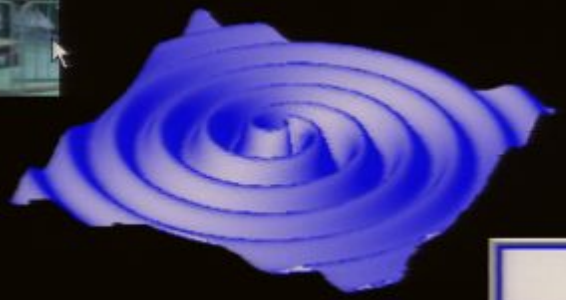


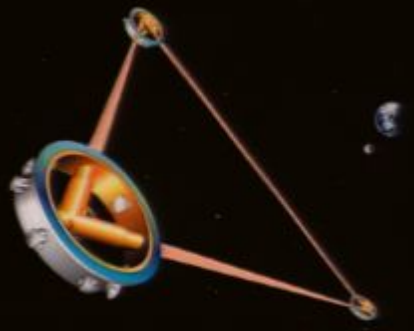
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

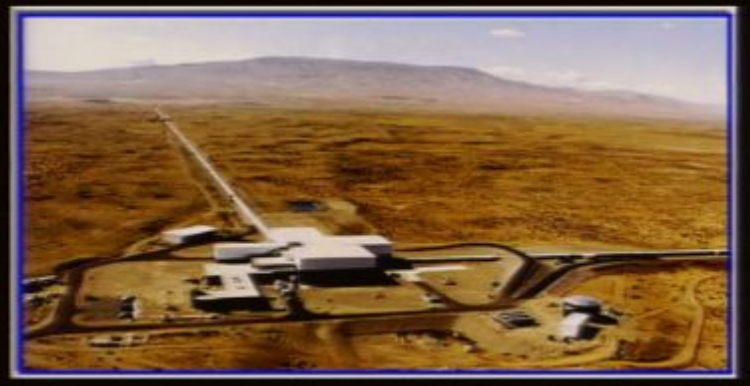
Nautilus

Auriga





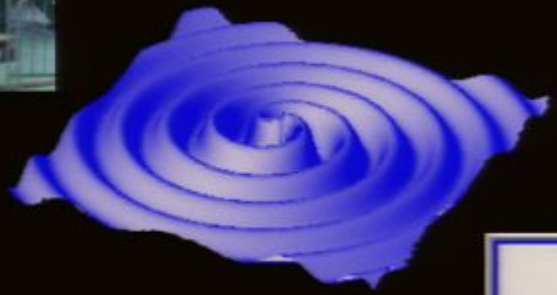
Laser Interferometer Space Antenna



Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus



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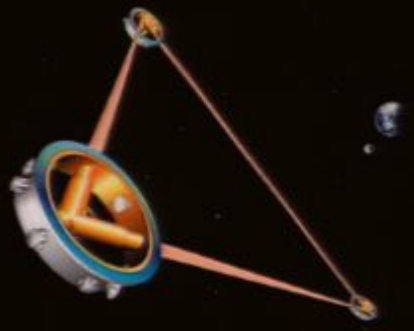
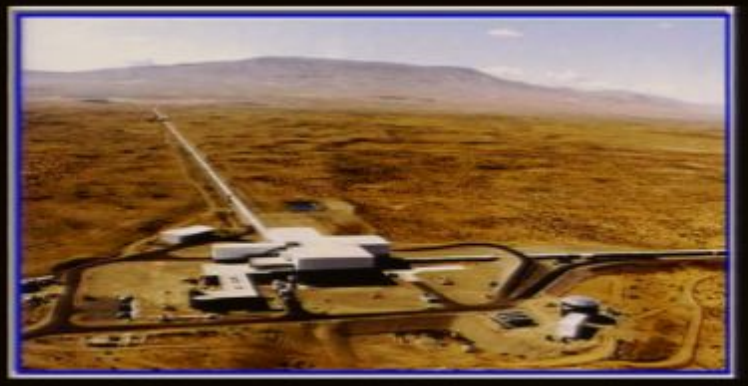


Laser Interferometer Space Antenna

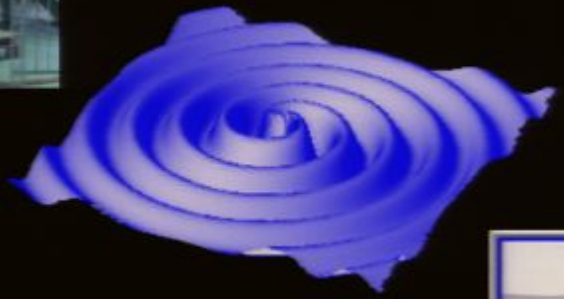


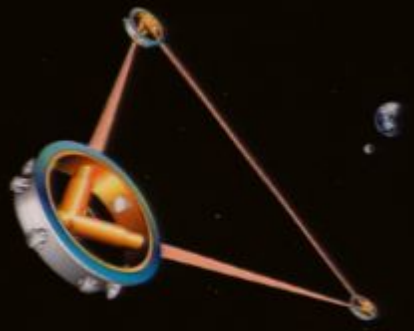
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

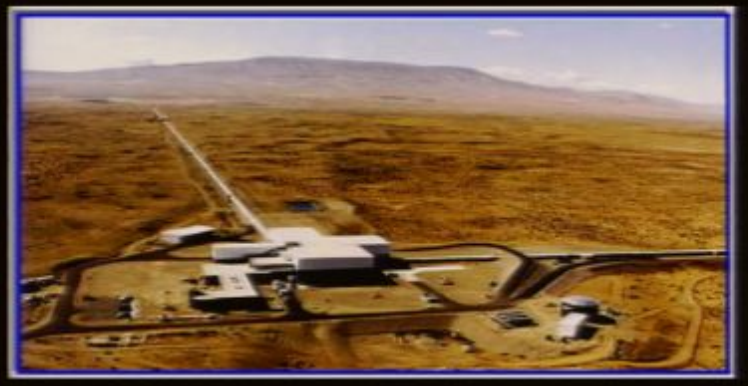
Nautilus

Auriga





Laser Interferometer Space Antenna

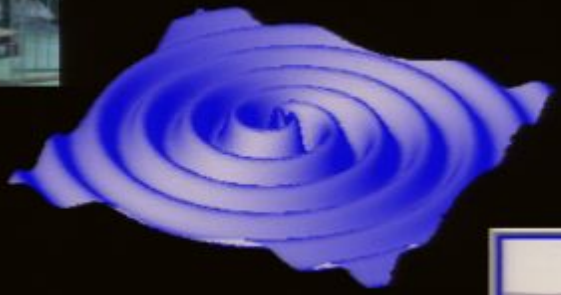


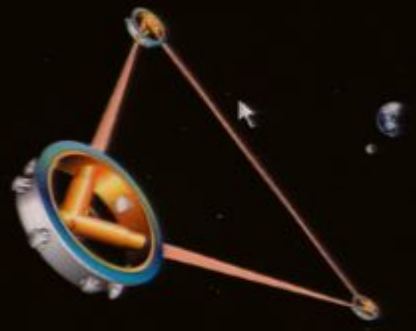
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga





Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

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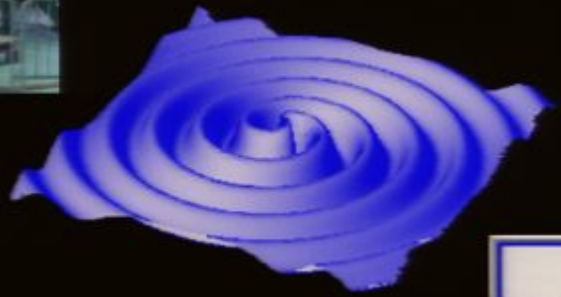
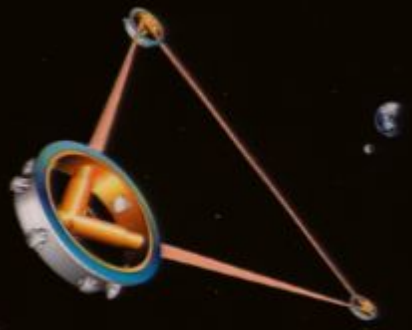


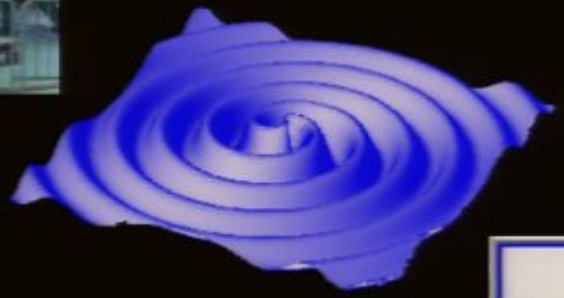


Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus



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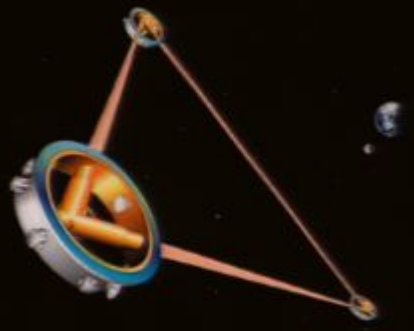

Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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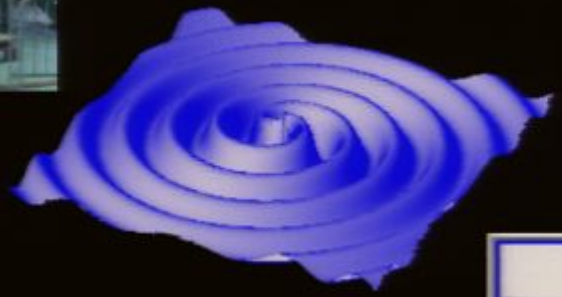

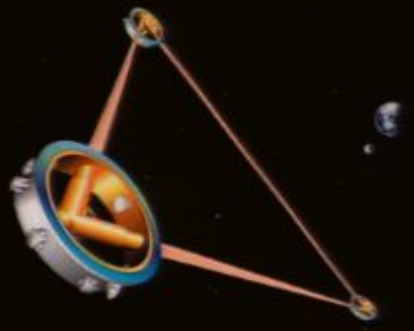

Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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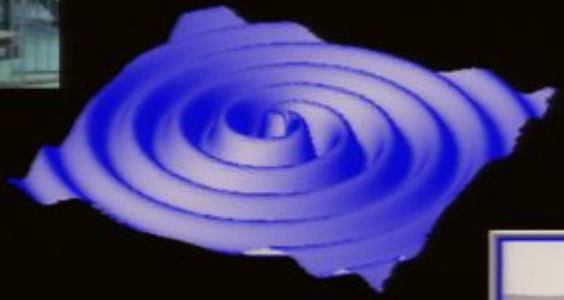

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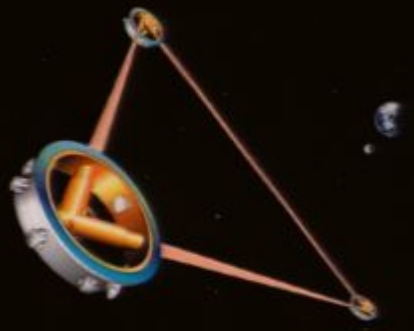

Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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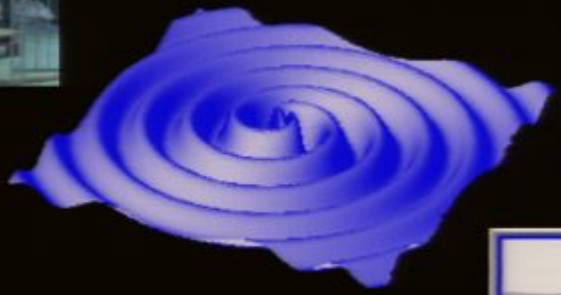
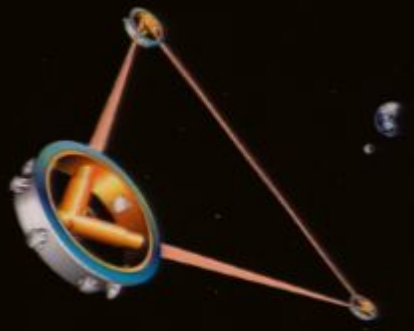
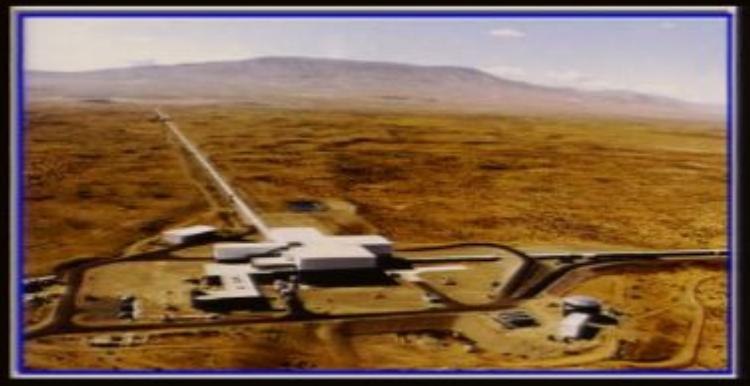
Auriga





Laser Interferometer Space Antenna

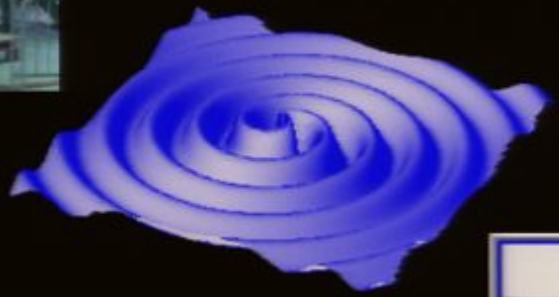


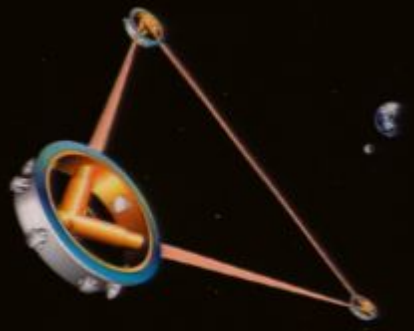
Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

Nautilus

Auriga





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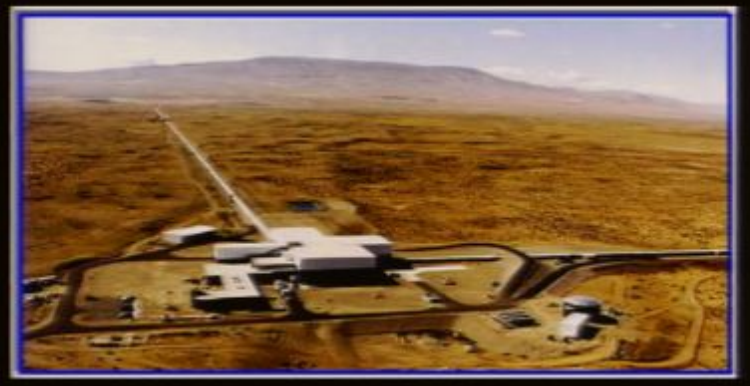

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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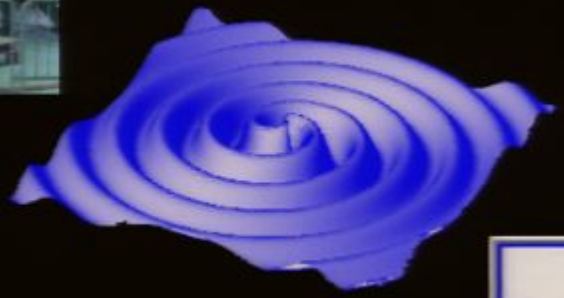

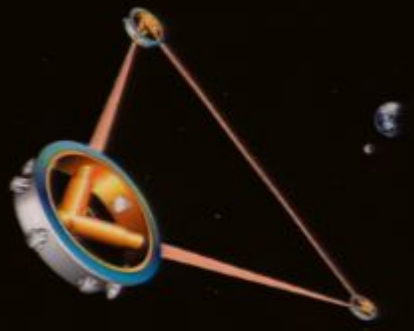

Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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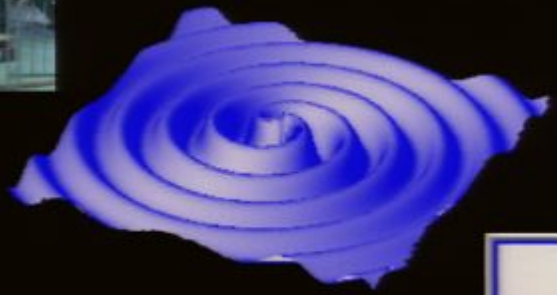

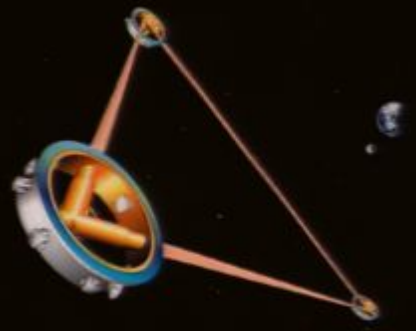

Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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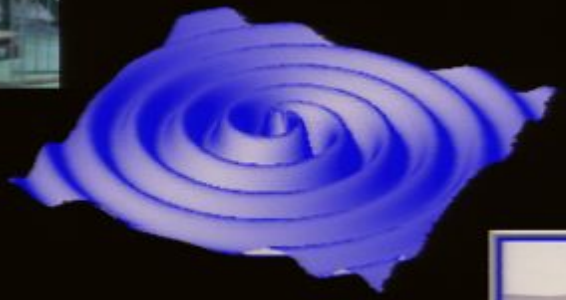
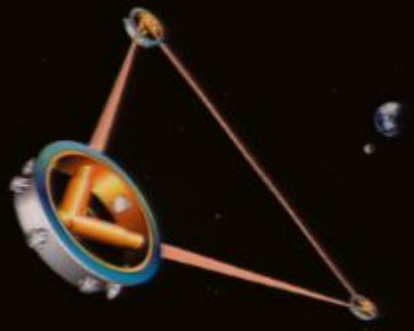
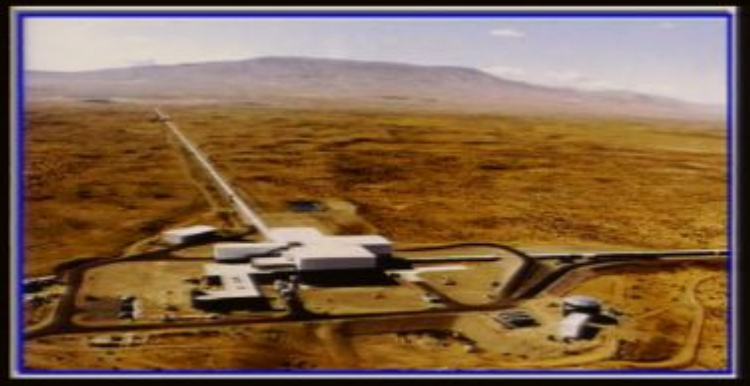




Laser Interferometer Space Antenna



Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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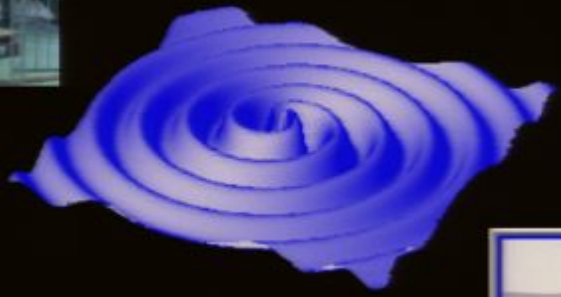

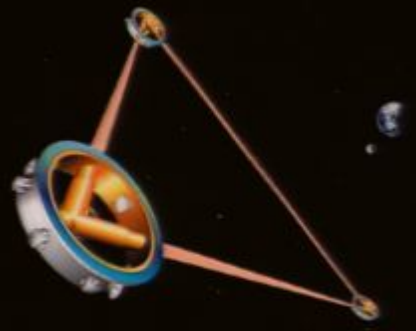

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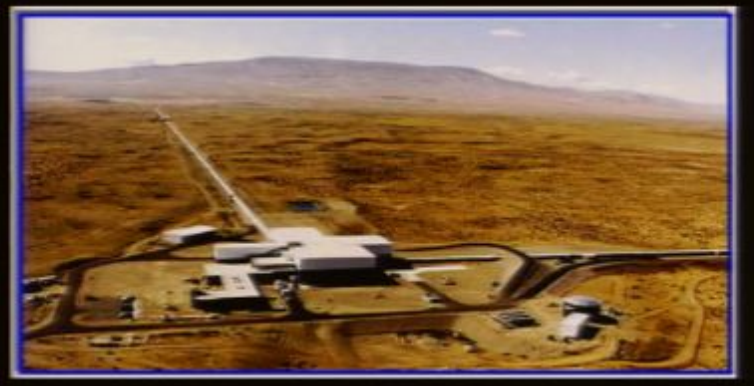

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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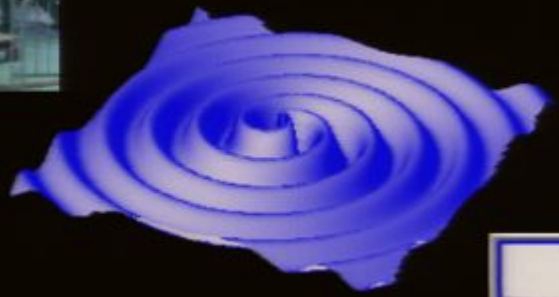

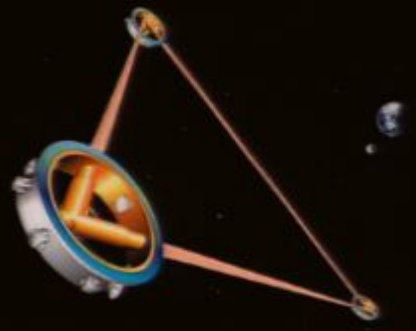

Laser Interferometer Space Antenna

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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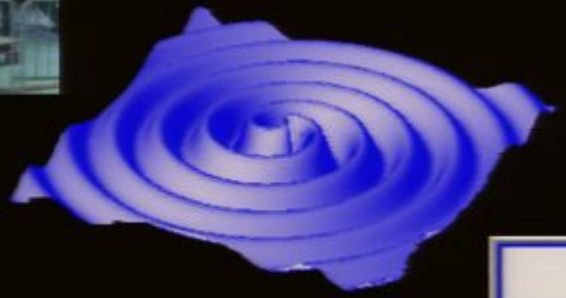

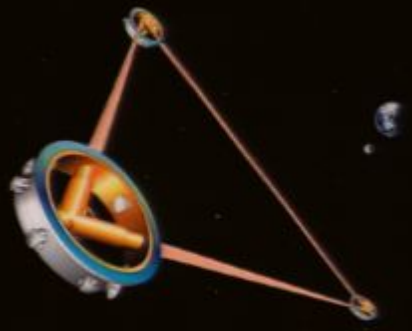

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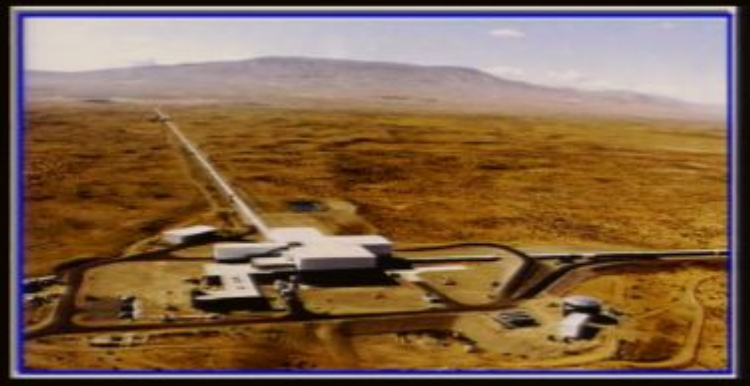

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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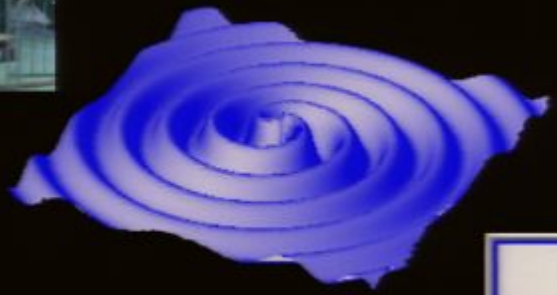
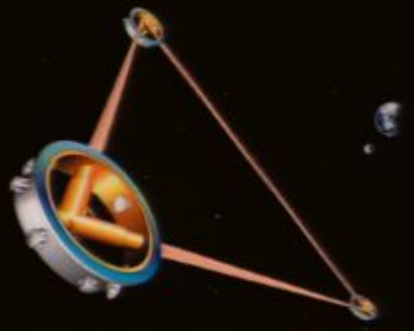
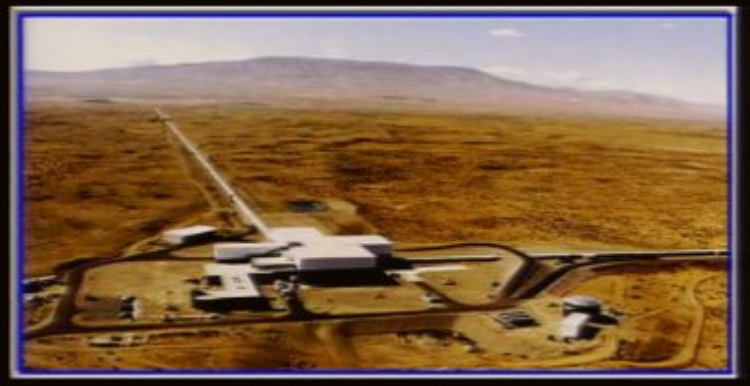




Laser Interferometer Space Antenna



Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

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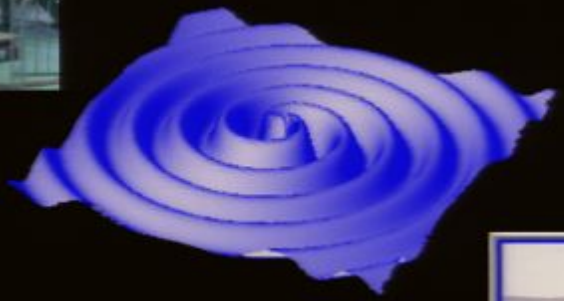

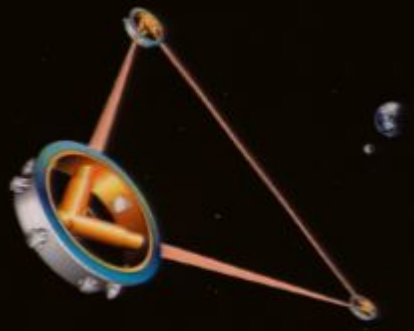

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Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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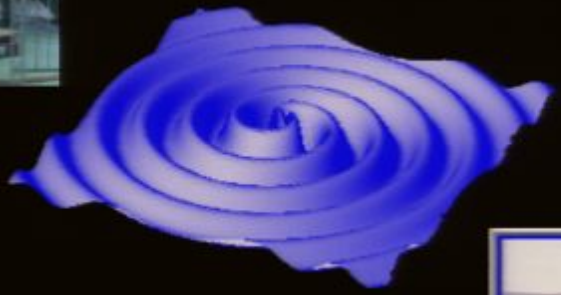

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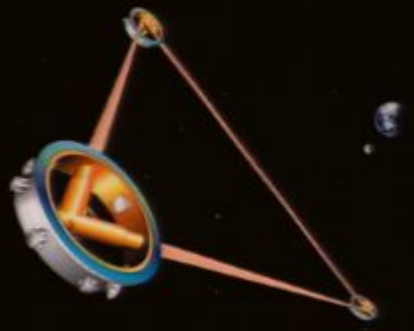

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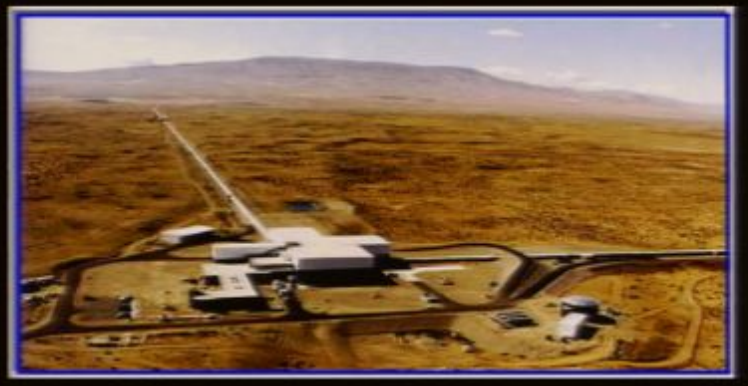

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Wave Detection

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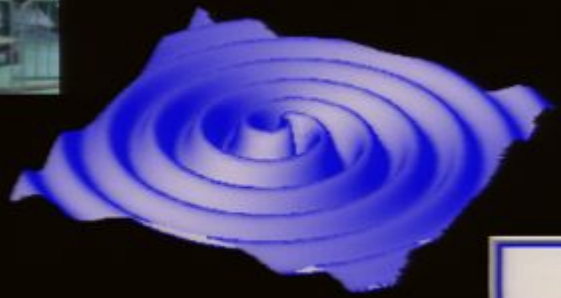

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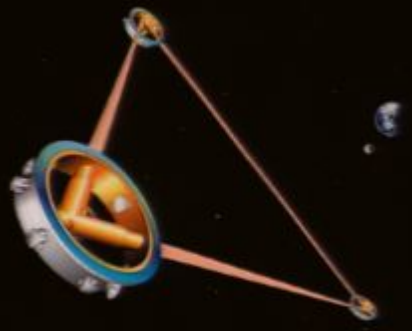

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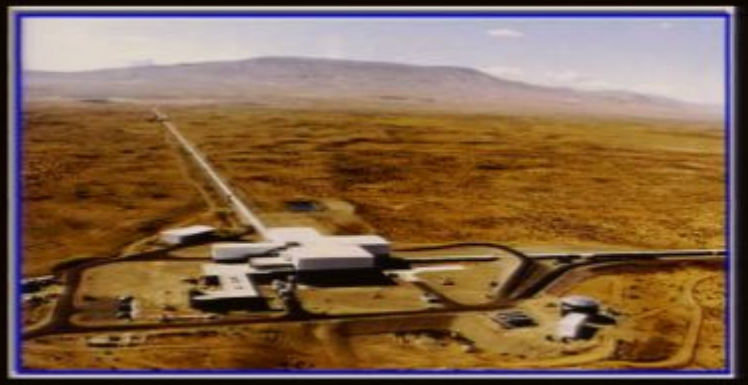

Laser Interferometer Gravitational Wave Observatory (LIGO), Richland

Strange Predictions

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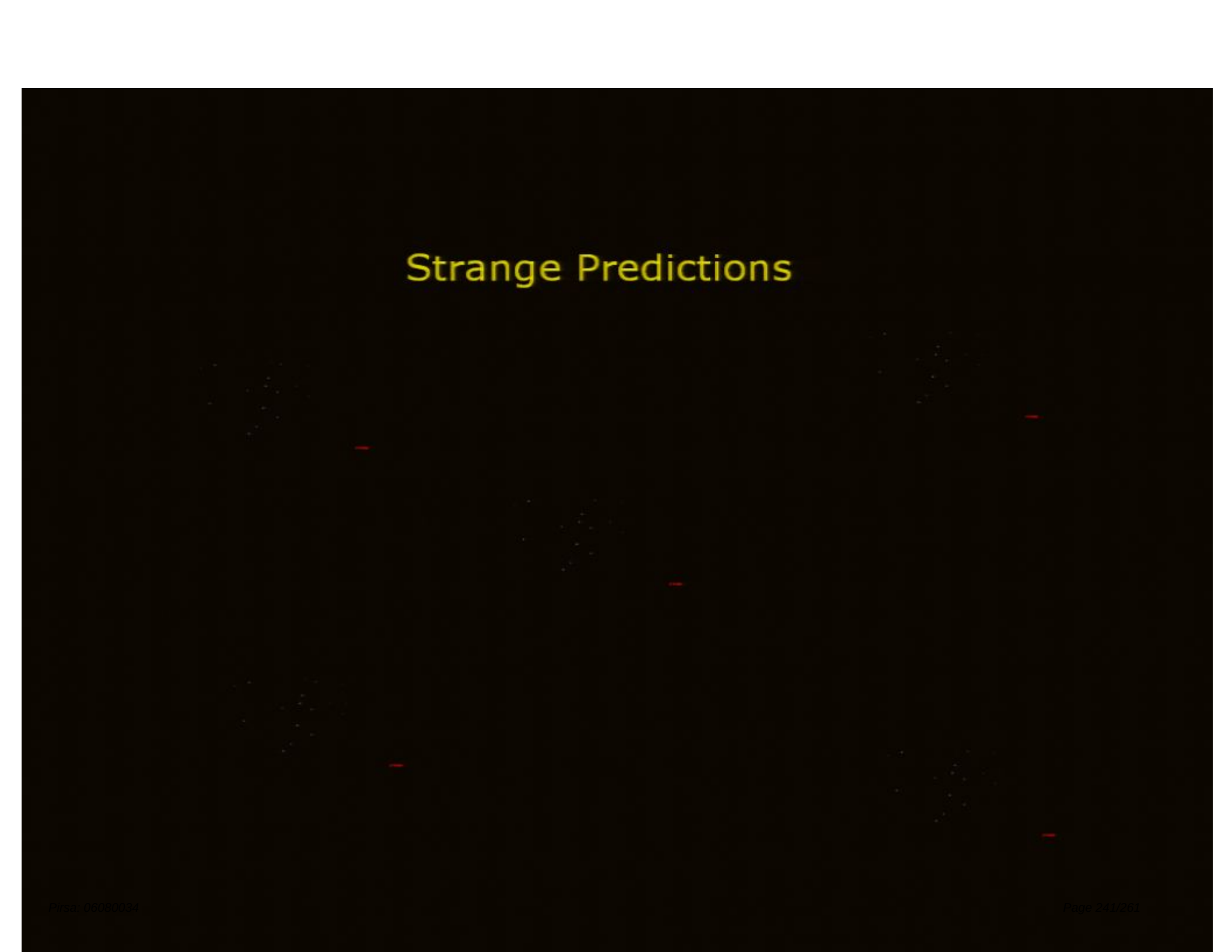

Strange Predictions

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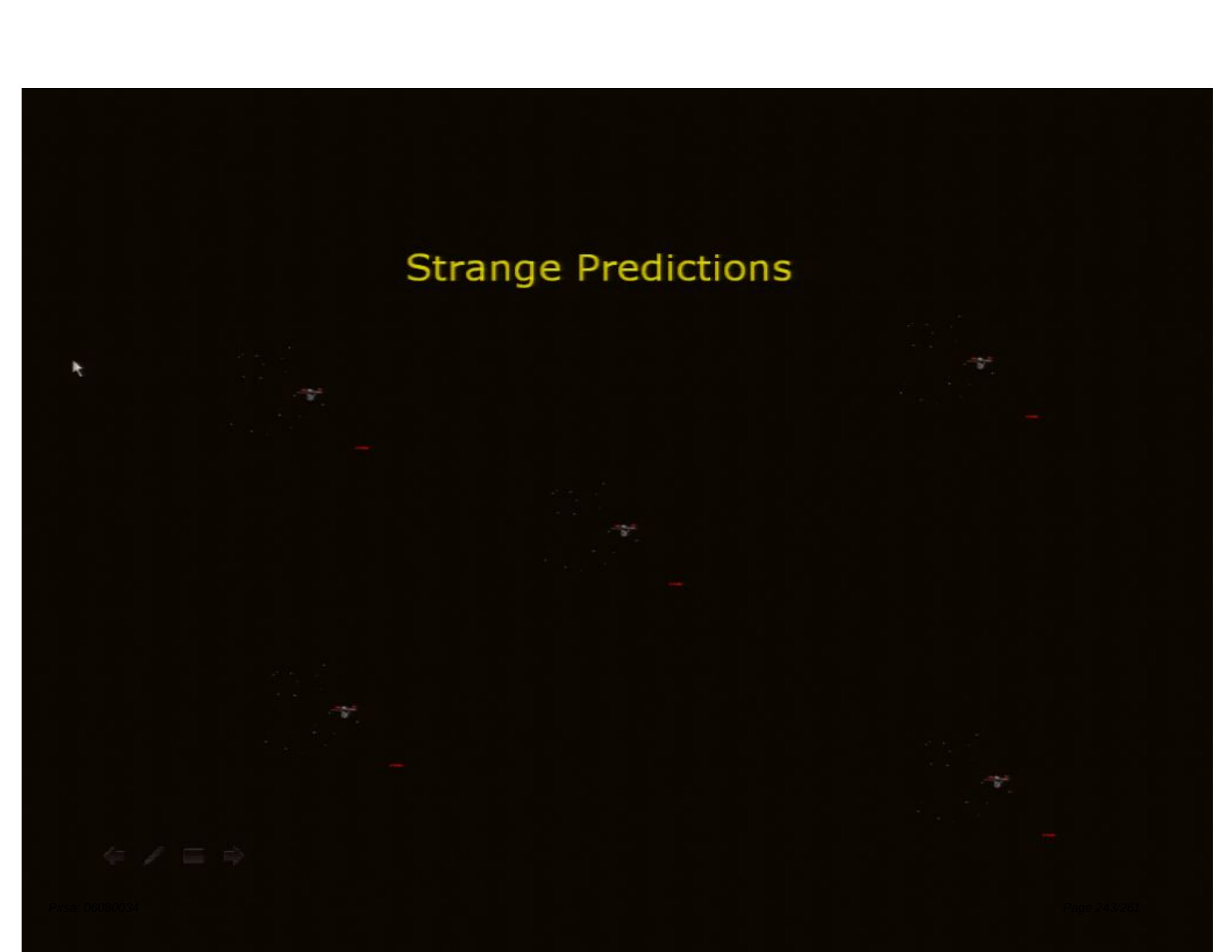

Strange Predictions

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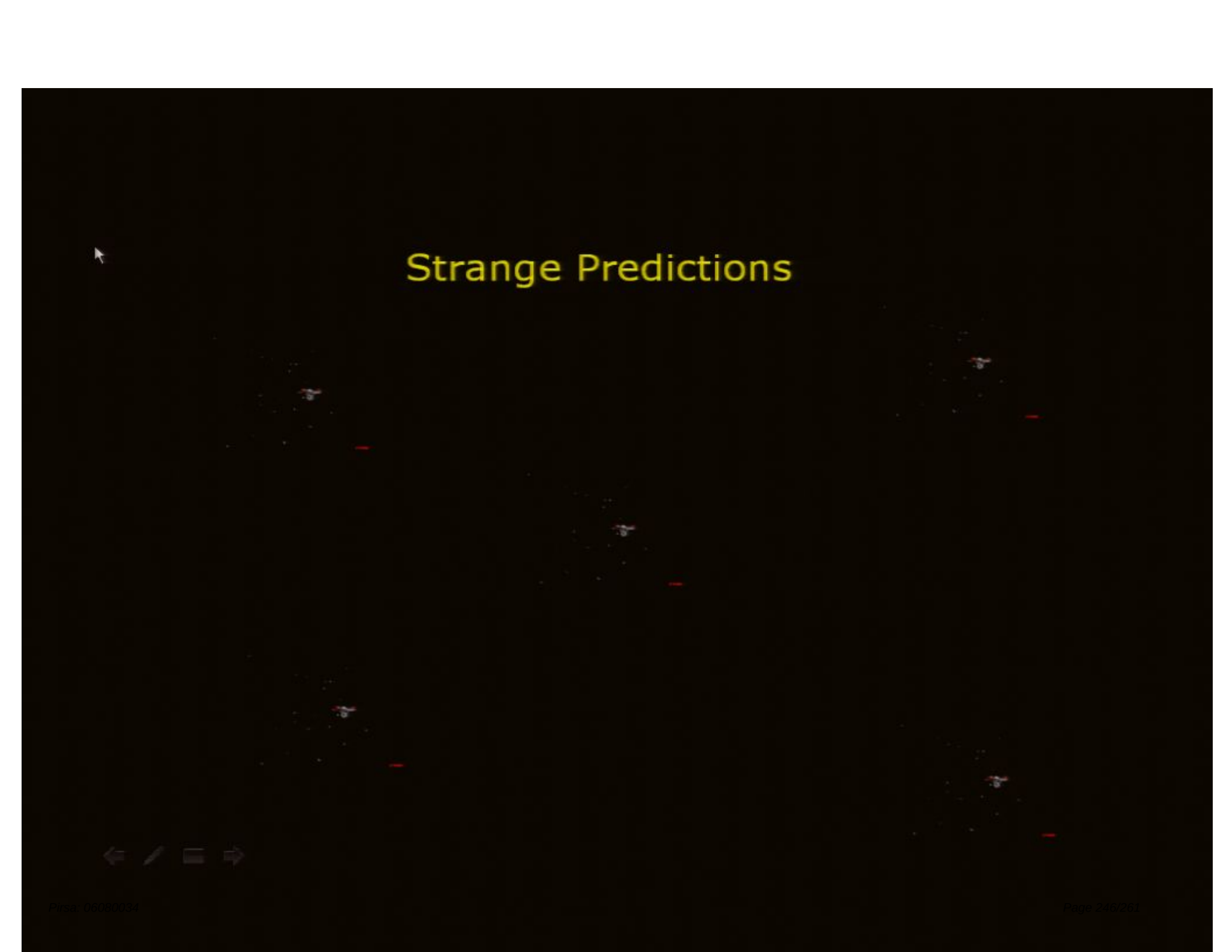

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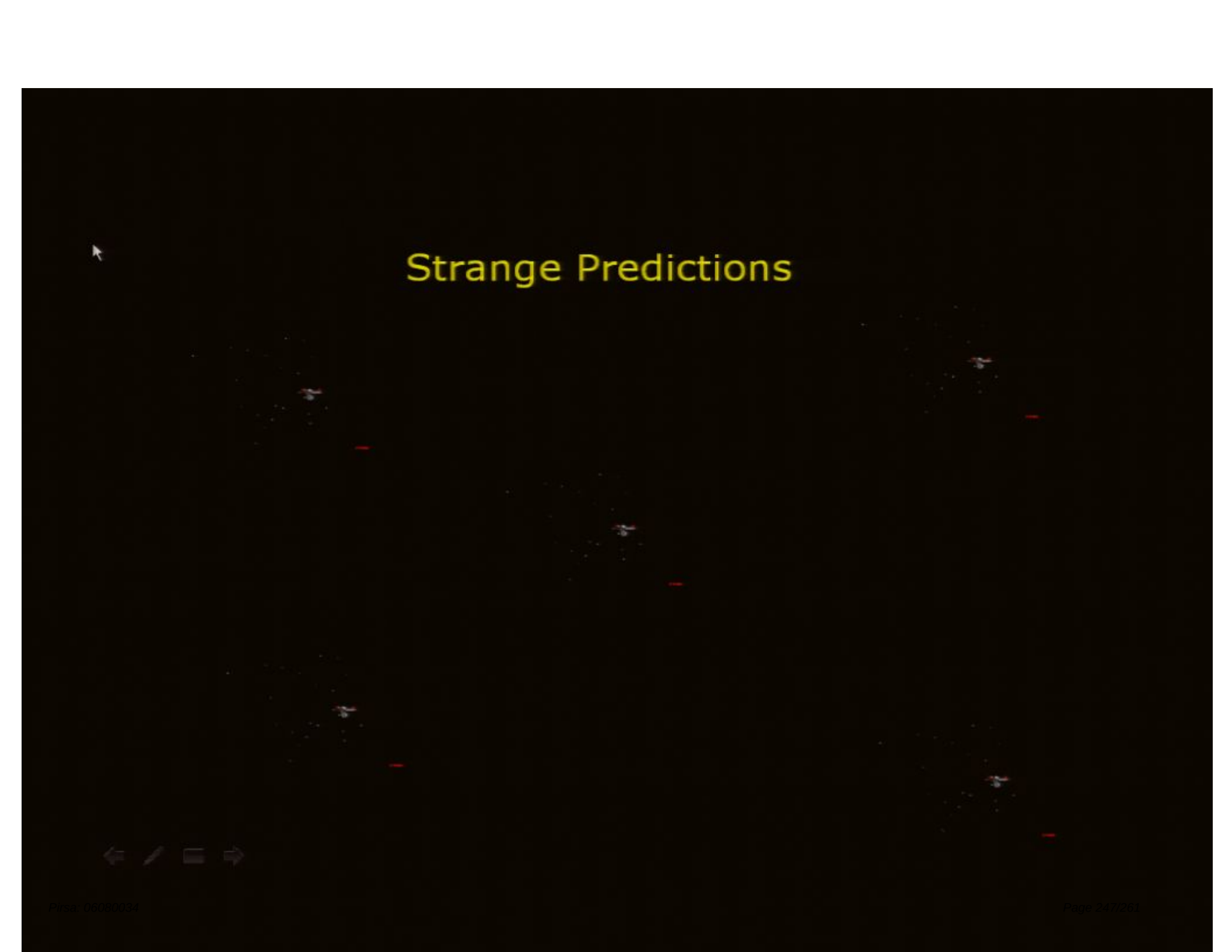


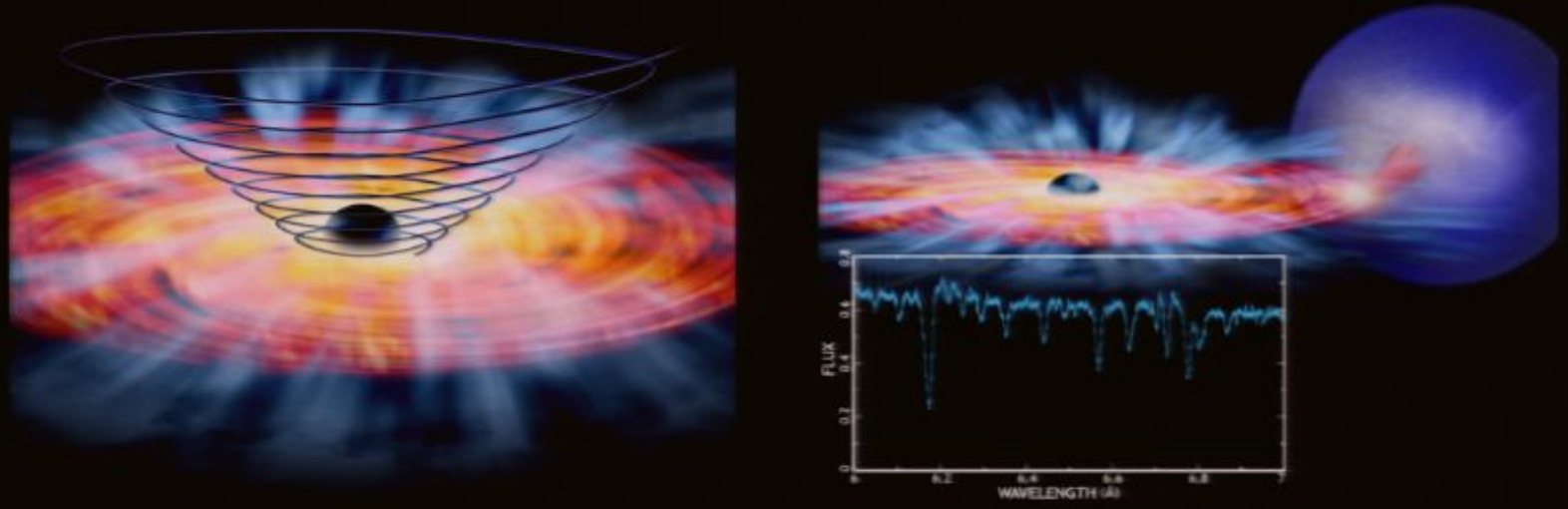
Strange Predictions

Strange Predictions

Strange Predictions

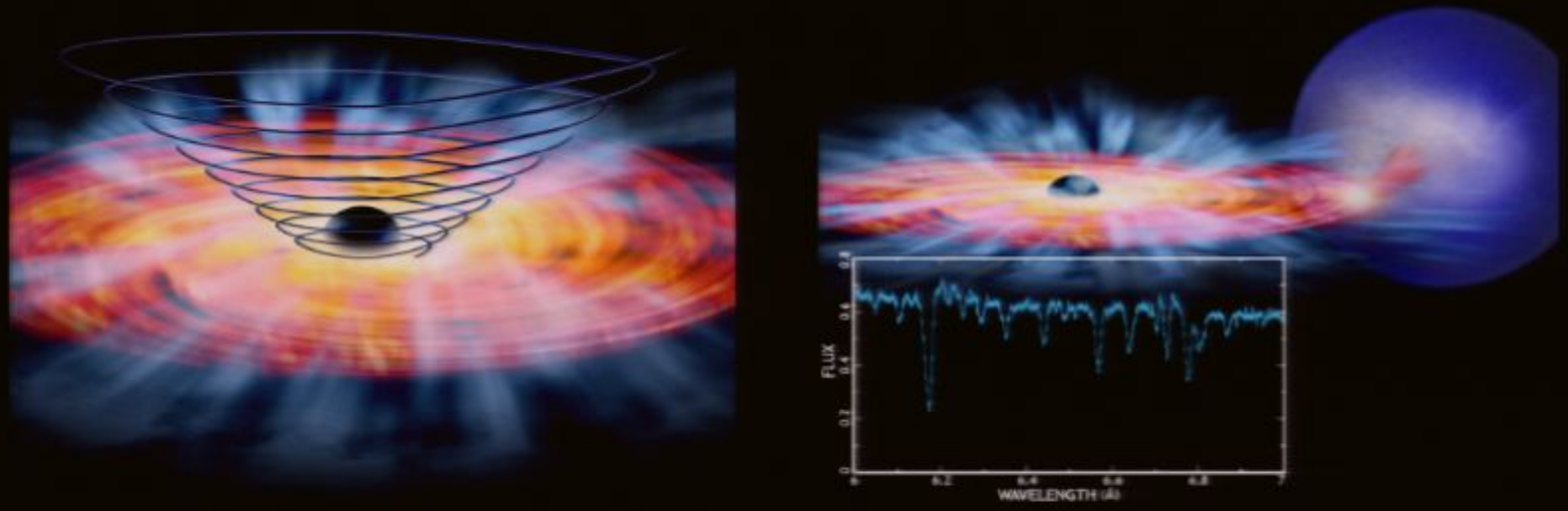
Strange Predictions

Strange Energy Out-Bursts



1655 is a binary system that harbors a black hole with a mass seven times that of the sun, which is pulling matter from a normal star about twice as massive as the sun. The Chandra observation revealed a bright X-ray source whose spectrum showed dips produced by absorption from a wide variety of atoms ranging from oxygen to nickel. A detailed study of these absorption features shows that the atoms are highly ionized and are moving away from the black hole in a high-speed wind.

Strange Energy Out-Bursts



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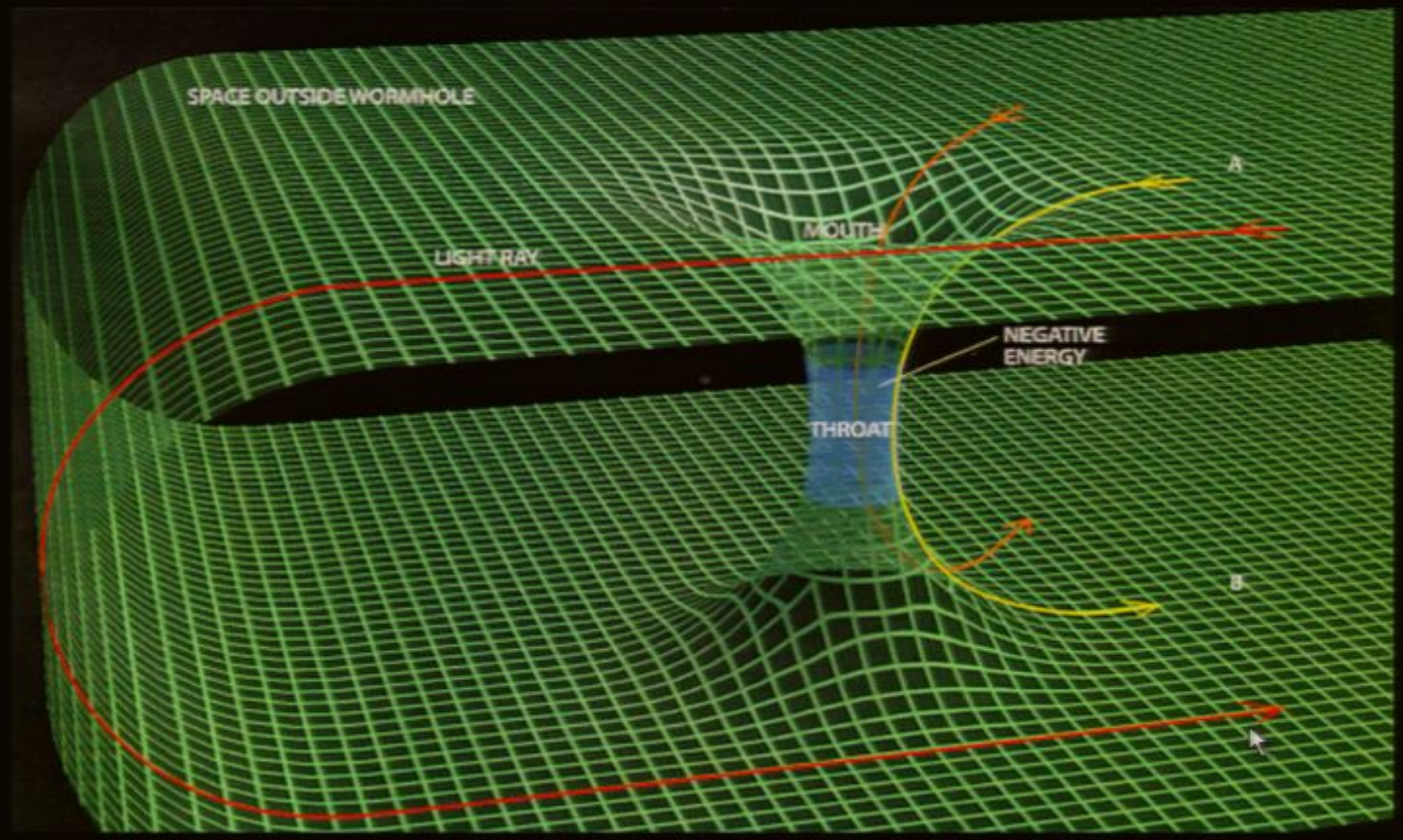
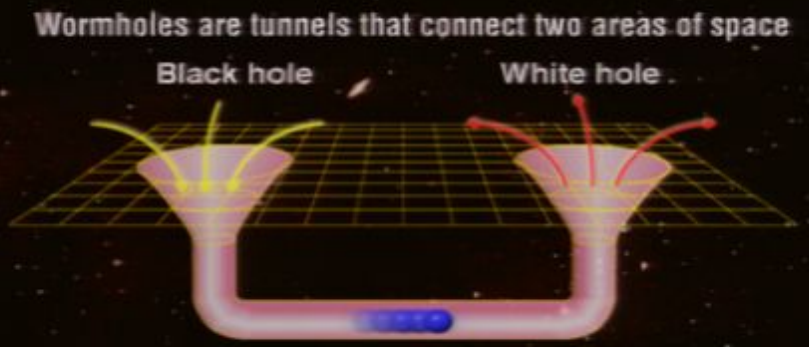
Wormhole


SPACE OUTSIDE WORMHOLE
A
MOUTH
LIGHT RAY
NEGATIVE ENERGY
THROAT
B


Wormholes are tunnels that connect two areas of space
Black hole
White hole
Can wormholes lead to time travel?

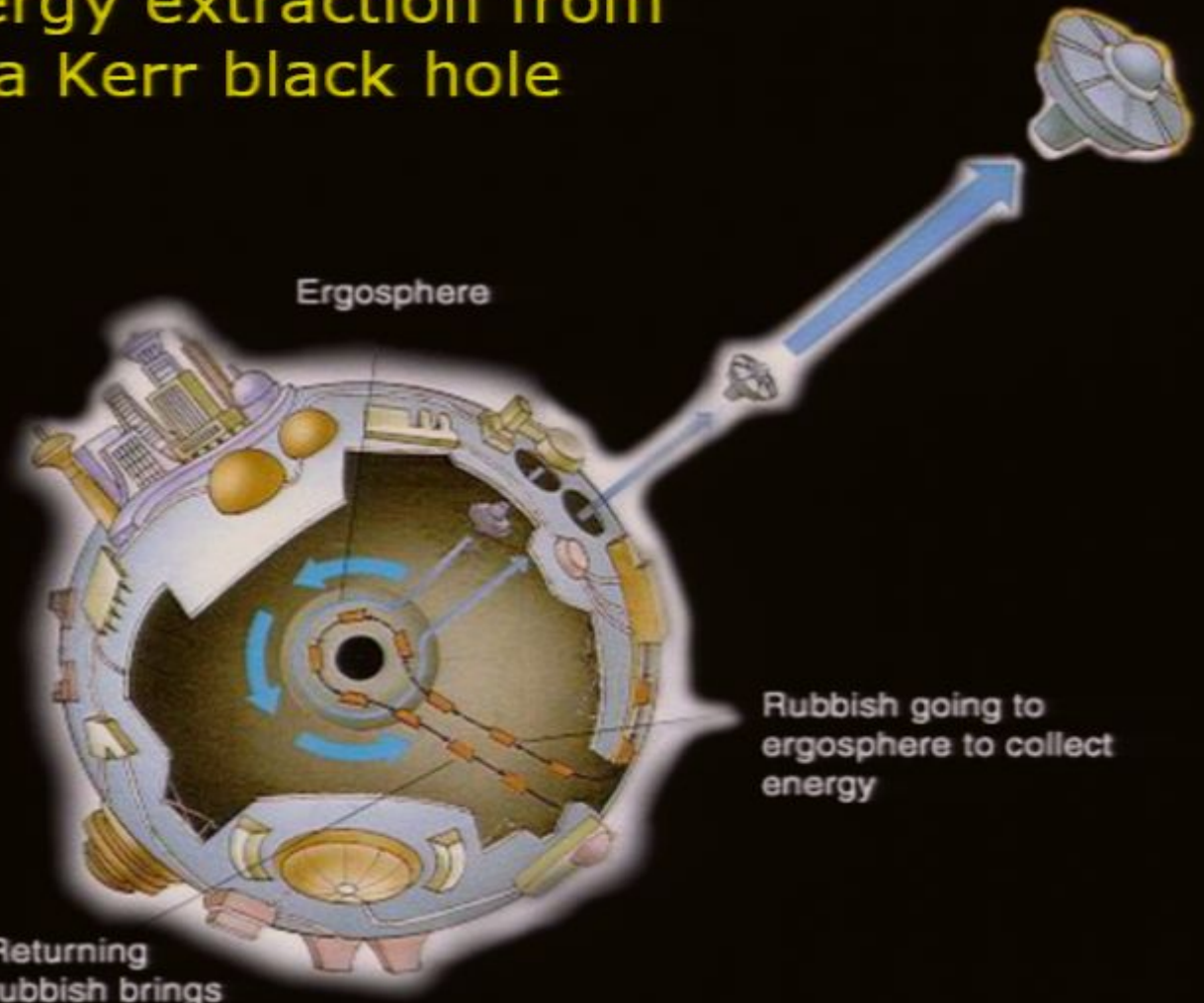
Naked Singularity

Such a naked singularity would be a breakdown in the laws of physics. After that, you could no longer guess what would come out of the black hole--it could be anything (to quote William H. Press) "from television sets to busts of Abraham Lincoln."

A singularity that is not inside a black hole (not surrounded by an event horizon), and therefore can be seen by someone outside it.

Time Travel

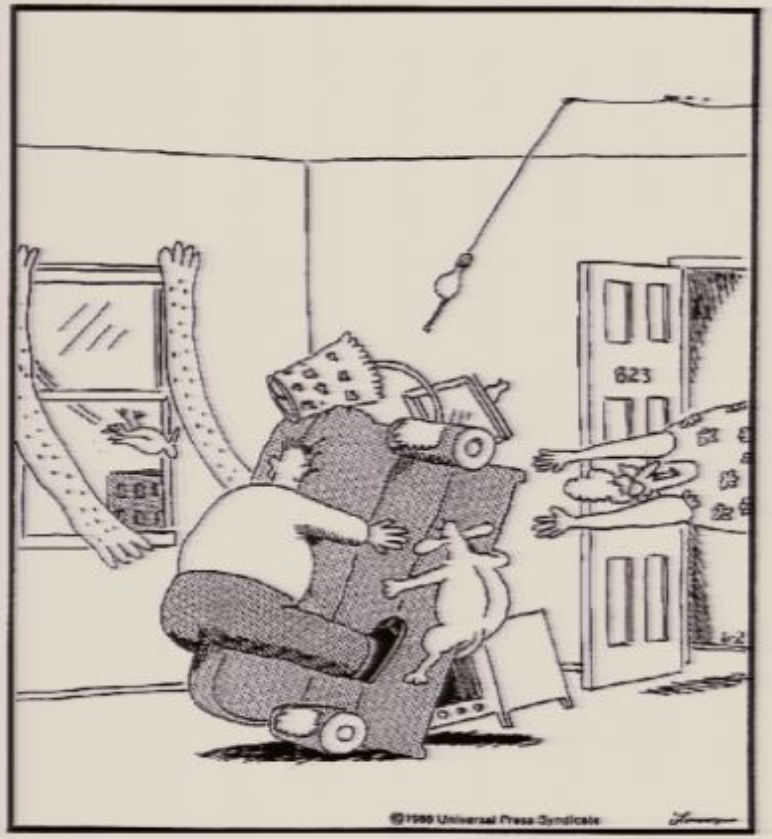
Energy extraction from a Kerr black hole



Roger Penrose (*b* 1931)

Quantum Foam

THE FAR SIDE By GARY LARSON



Suddenly, through forces not yet fully understood, Darren Belsky's apartment became the center of a new black hole.

End of slide show, click to exit.