Title: TBA

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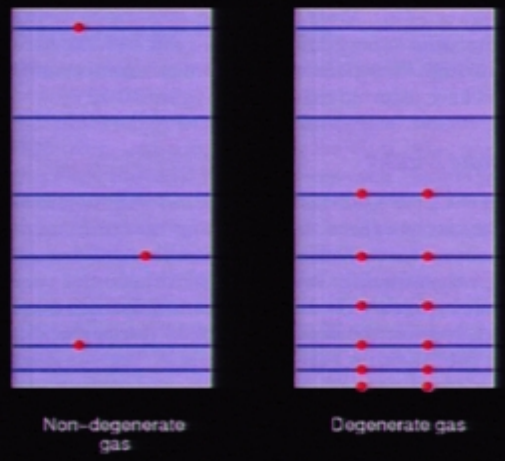
Abstract:

Electron Degeneracy Pressure

- Pauli Exclusion Principle:
  No two electrons can occupy the same position in space at the same time doing the same thing.
- Electrons are packed side by side in a white dwarf
- This prevents it from collapsing any further



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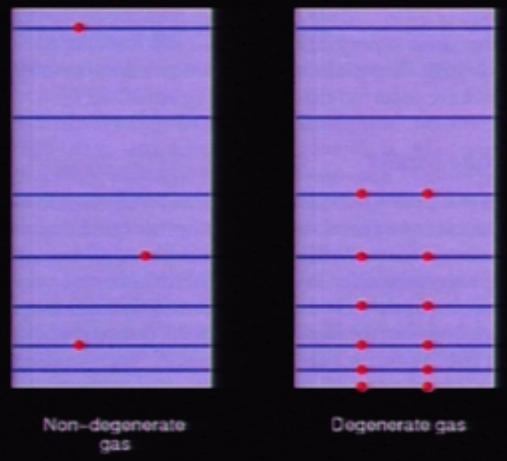
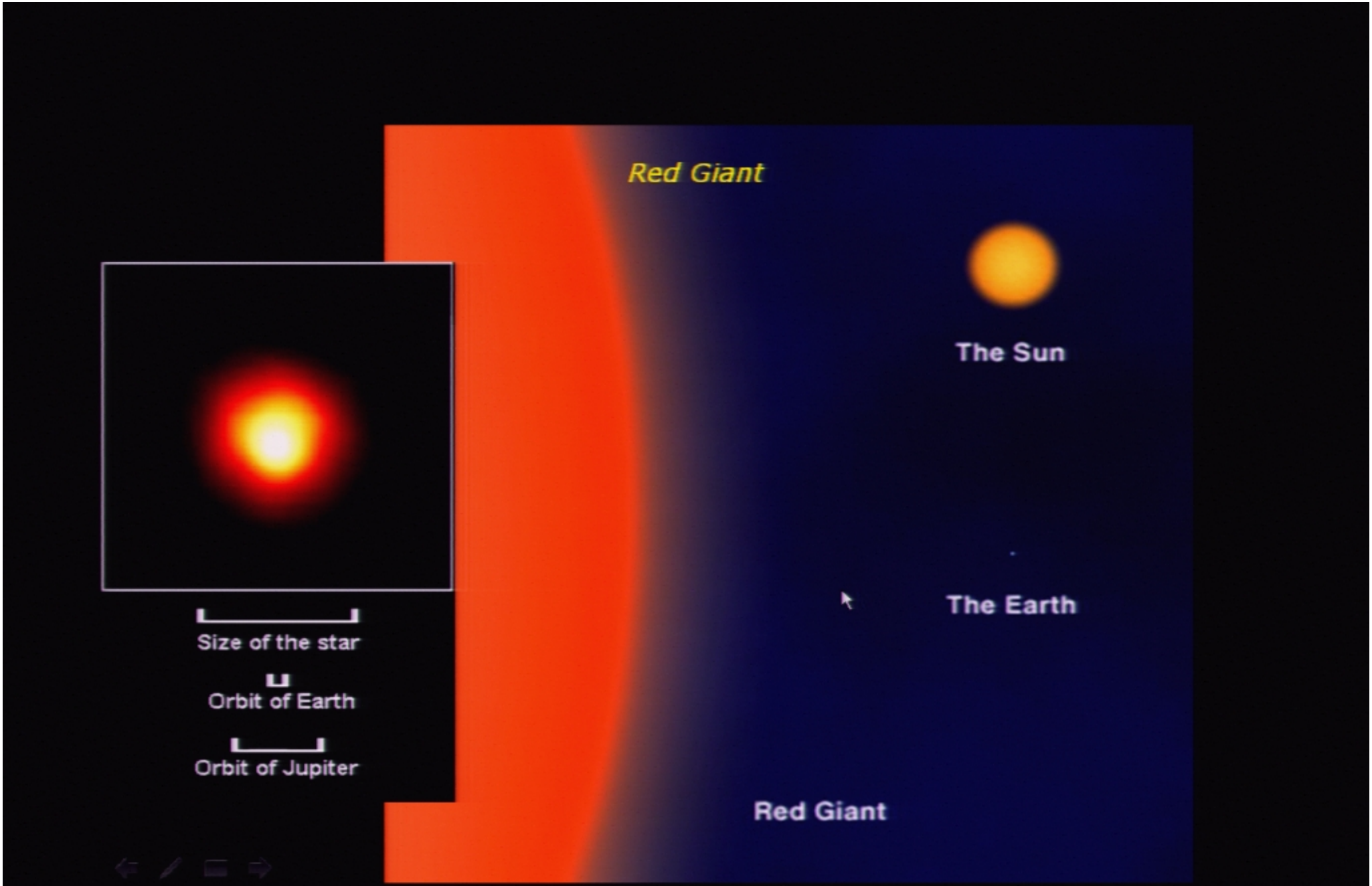
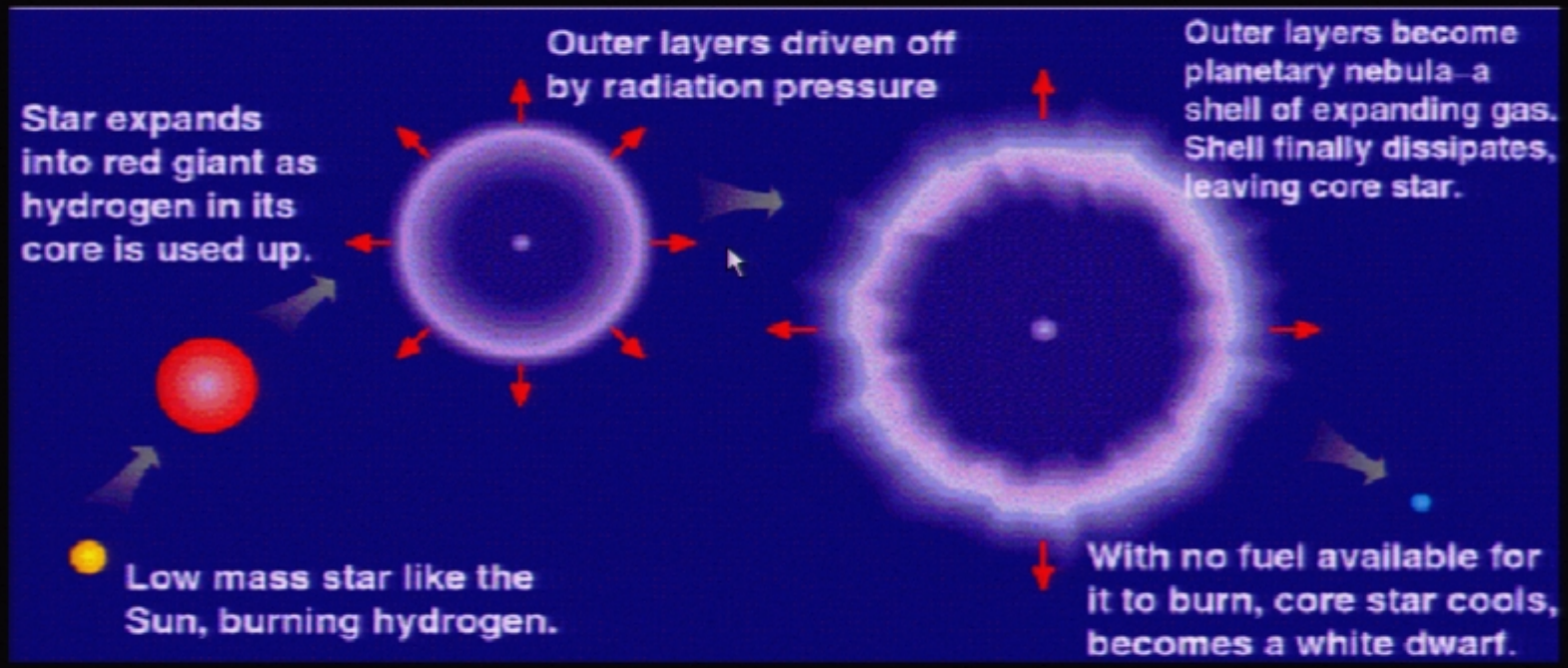



Red Giant
The Sun
The Earth
Size of the star
Orbit of Earth
Orbit of Jupiter
Red Giant

Path to being a White Dwarf



7 solar mass star now reduced to about 20% of its original mass

Properties of White Dwarfs

- Helium exhausted, core collapses until density forces electrons to leave their orbits around the atomic nuclei.

Properties of White Dwarfs

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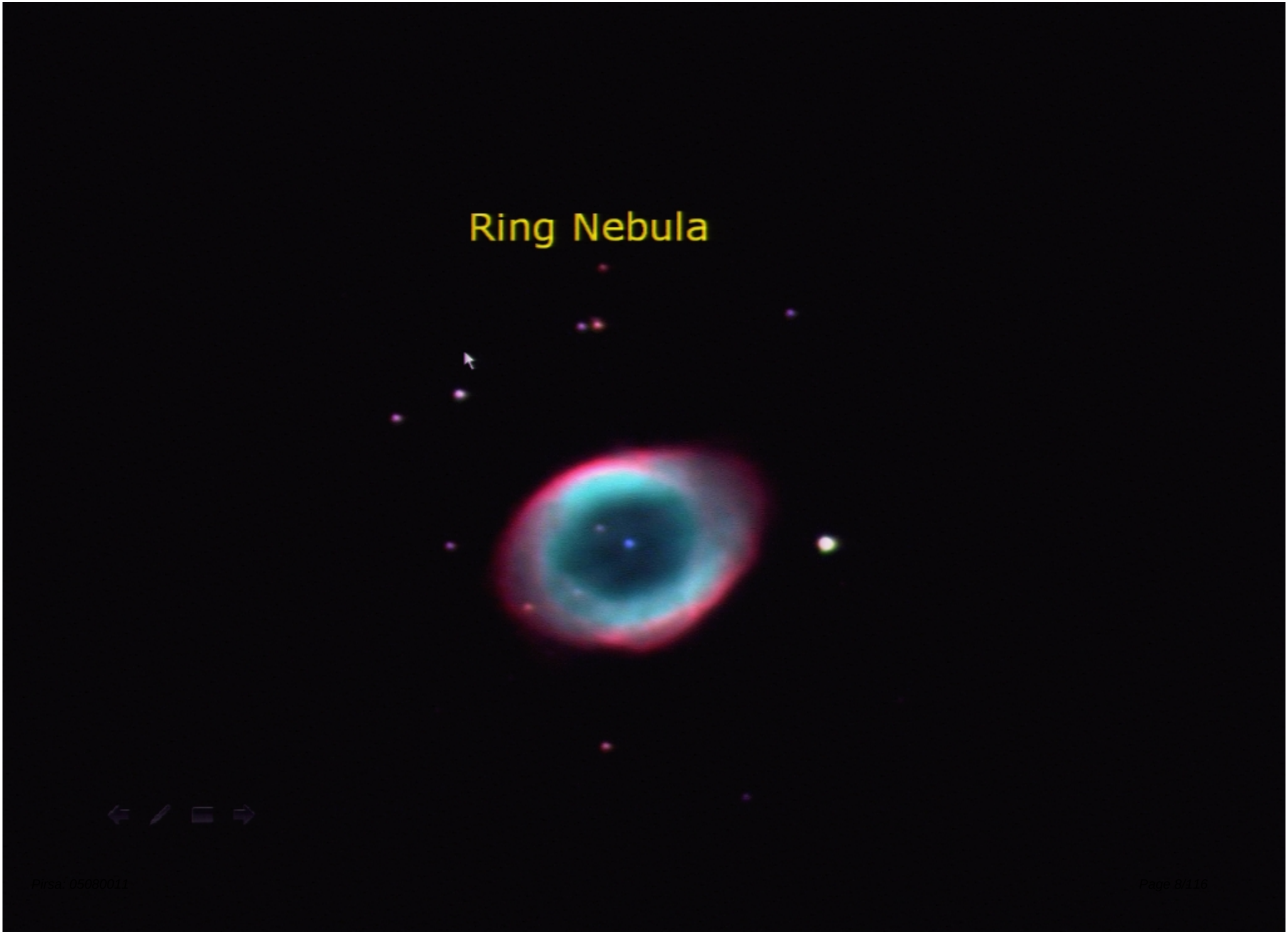
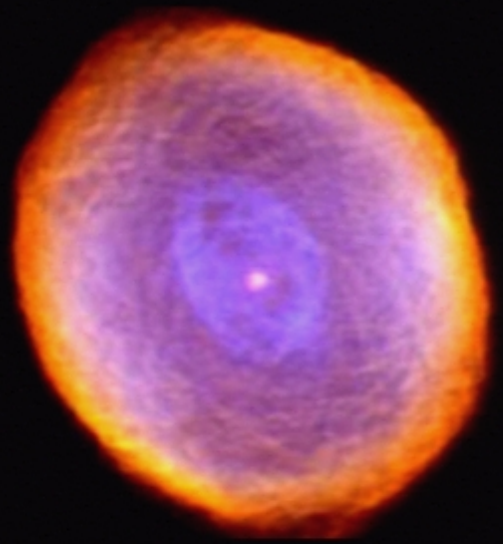
- ...are found in the centers of planetary nebula.
- ...have masses less than the Chandrasekhar n (1.4 Solar Masses).


Ring Nebula

Cat’s eye nebula

Spirograph Nebula



Hourglass nebula

Eskimo Nebula

Chandrasekhar limit

Chandrasekhar limit

- The maximum mass of a white dwarf is 1.4 solar masses
- Above this, even electron degeneracy pressure cannot counterbalance gravity

Supernova Remnant

- In the death of a high-mass star (<40 solar mass), the core is converted to neutrons and collapses catastrophically.
- The collapse and rebound creates a supernova.
- But what happens to the neutrons already at the very center of the core?
- The central core is left behind as a small, dense, sphere of neutrons → a neutron star.

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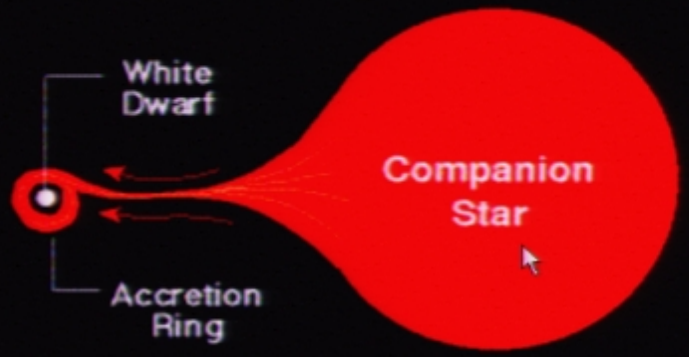
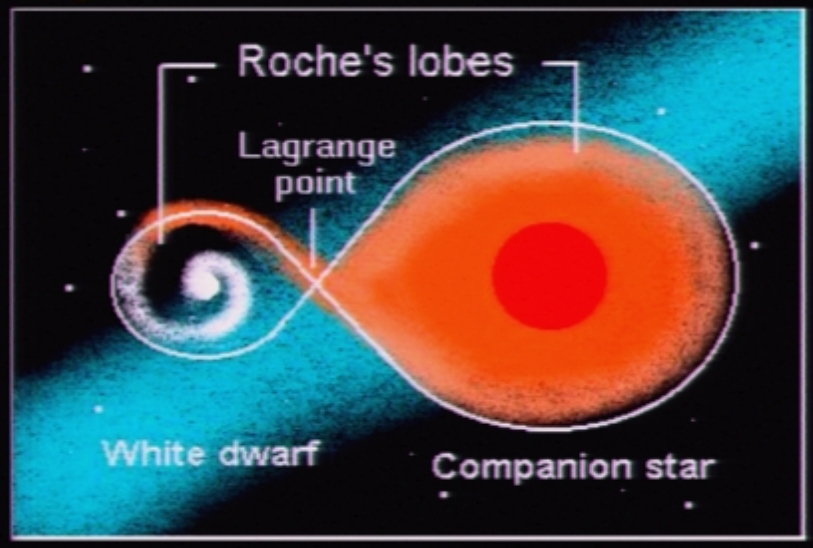
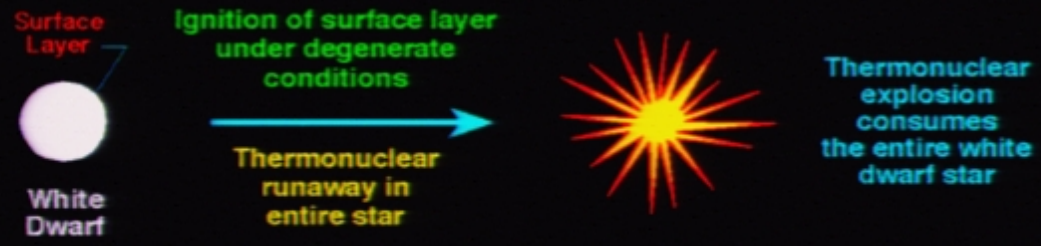
Type 1a Super Nova



Thin hydrogen surface layer accumulated on white dwarf through accretion ring

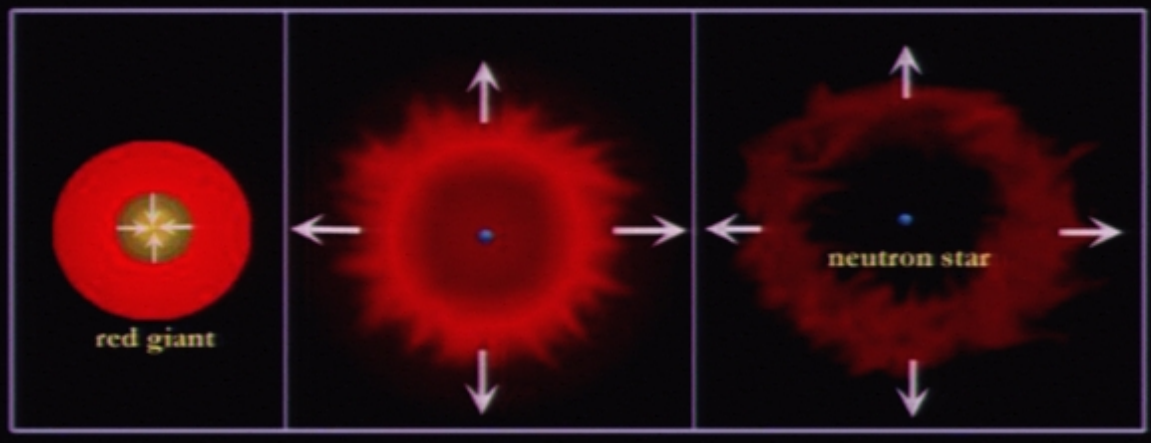




Not of interest to black hole cosmologists, but type 1a's are great yard sticks in determining distances

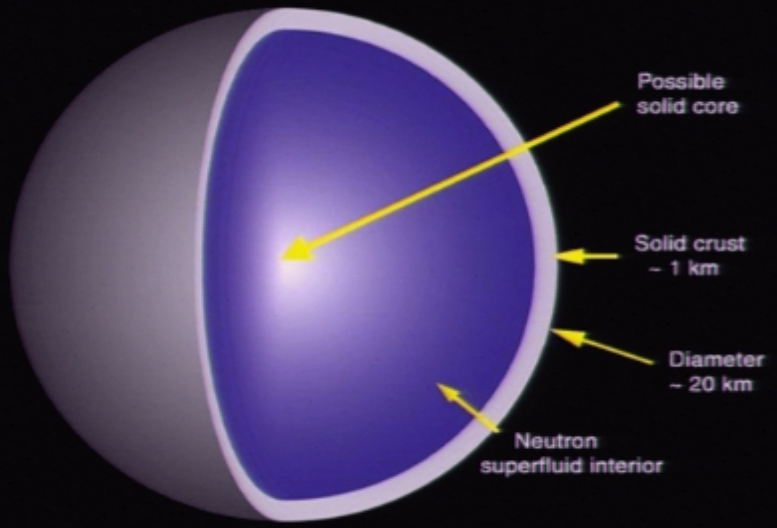
Type II Supernovae: Birth of a neutron star

- *The core survives and is prevented from collapsing any further by neutron degeneracy pressure*
- *These are what we are interested in.*

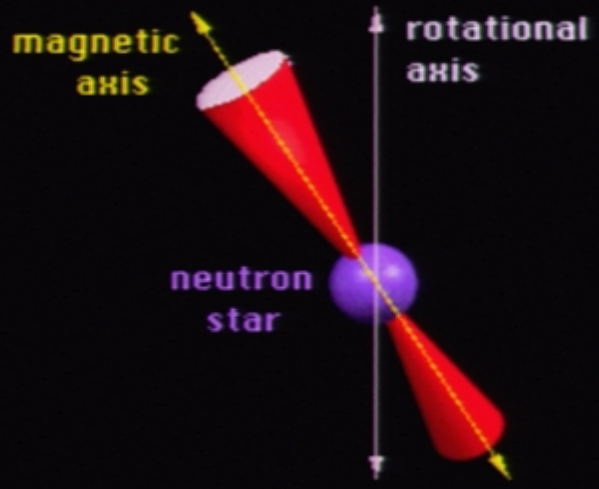


Neutron Star Facts

- A giant ball of neutrons.
- Mass : at least 1.4 x mass of the Sun.
- Temperature 1 million degrees and cooling.
- Diameter: 20 km!
- Density: 10^{18} kg/m^3
  - A sugar cube of this matter weighs 400 billion tons
- Day: 1 – 0.001 seconds!
- Magnetic fields as strong as the Sun, but in the space of a city.

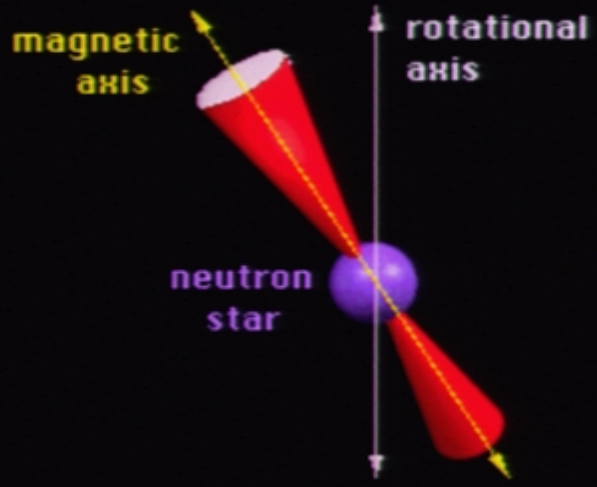


Pulsars



Pulsars

- Discovered by Bell and Hewish in 196
- Stands for pulsating stars, since they emit regular pulses



Crab Nebula Pulsar

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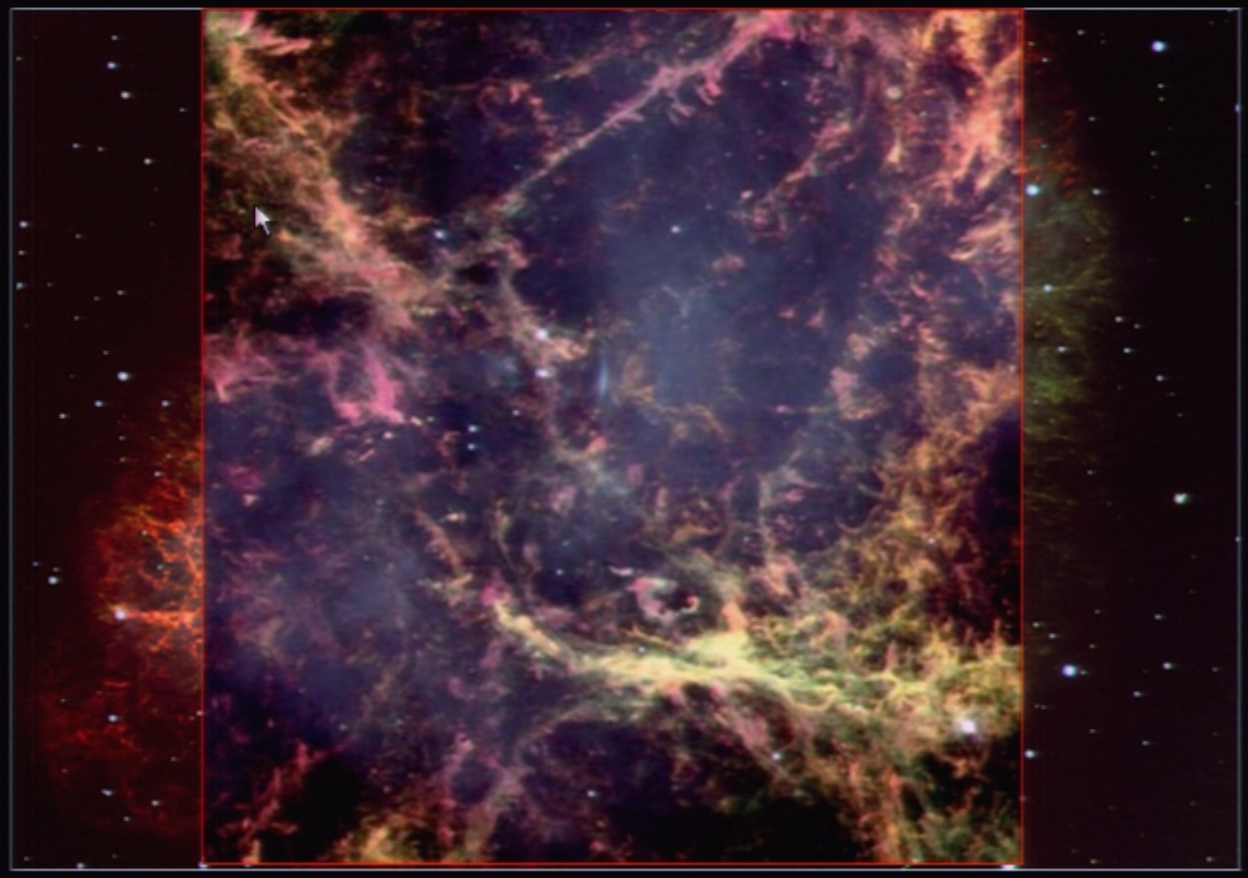

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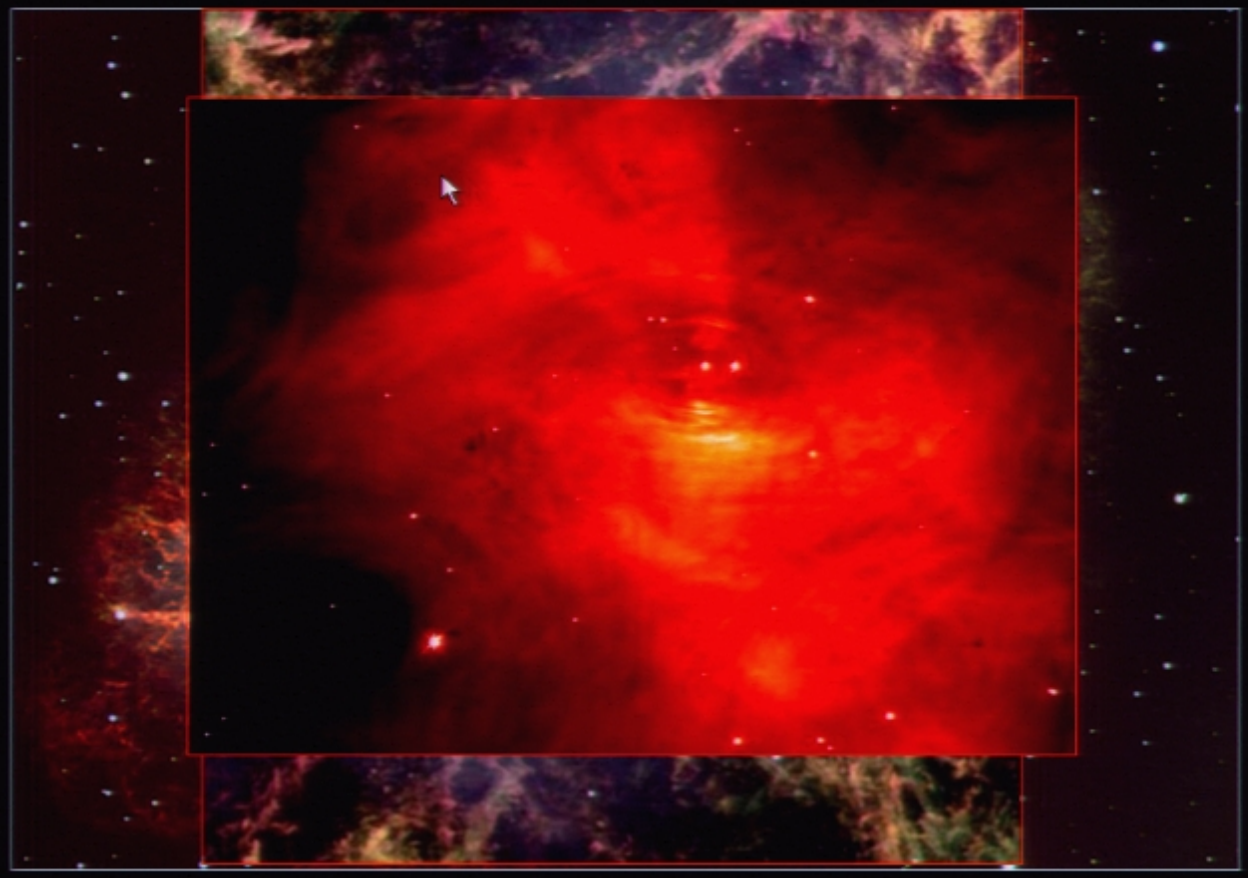

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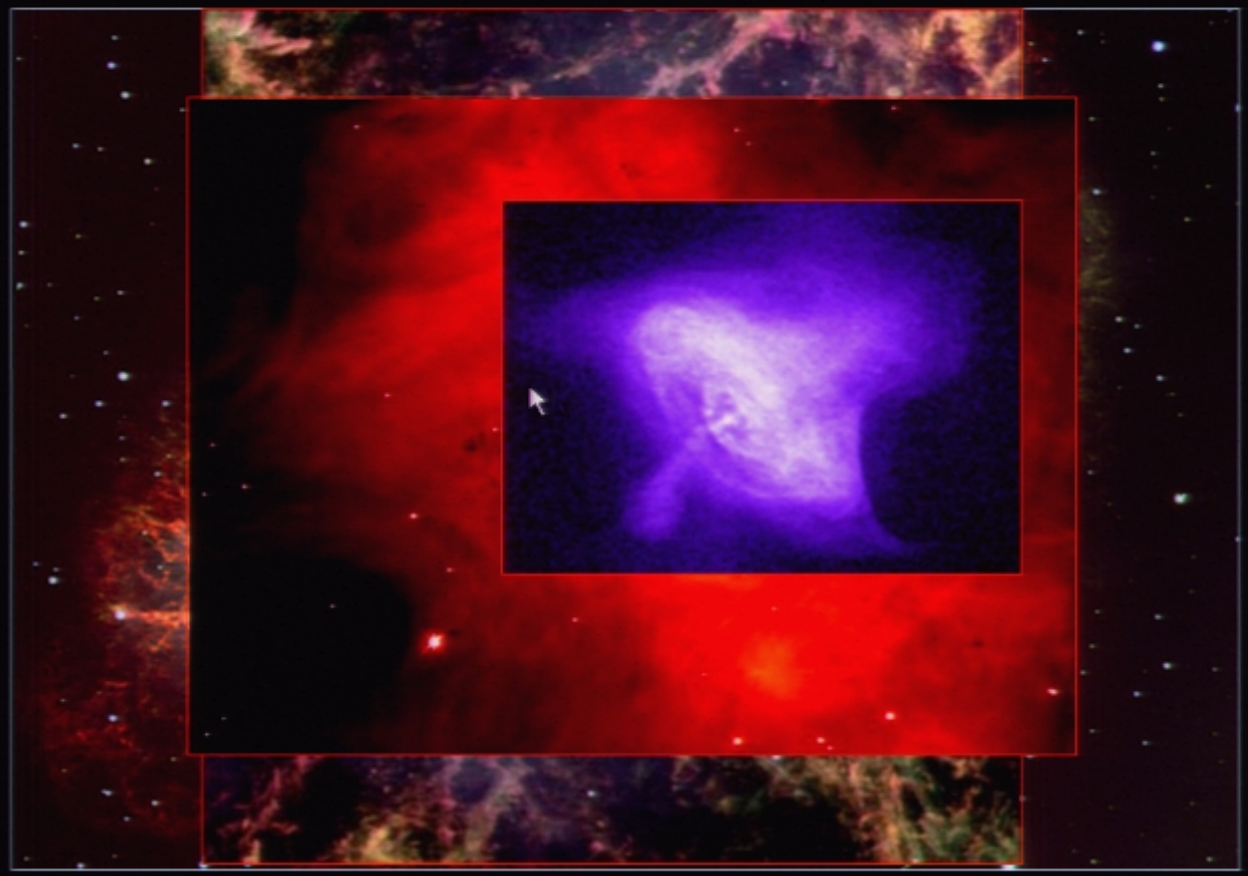

Mass

- Low mass stars
  - Less than 8 $M_\odot$ on Main Sequence
  - Become White Dwarf (< 1.4 $M_\odot$)
    - Electron Degeneracy Pressure
- High Mass Stars
  - Less than 40 $M_\odot$ on Main Sequence
  - Become Neutron Stars (3 $M_\odot$ < M <1.4 $M_\odot$)
    - Neutron Degeneracy

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- Neutron stars are held up by neutron degeneracy pressure.
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- How dense can something get?
- How strong can the force of gravity be?

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- How dense can something get?
- How strong can the force of gravity be?
- What if the escape velocity is faster than light?

Black Hole

- The star collapses to form a Black Hole.

Watching a Star Collapse from a Safe Distance

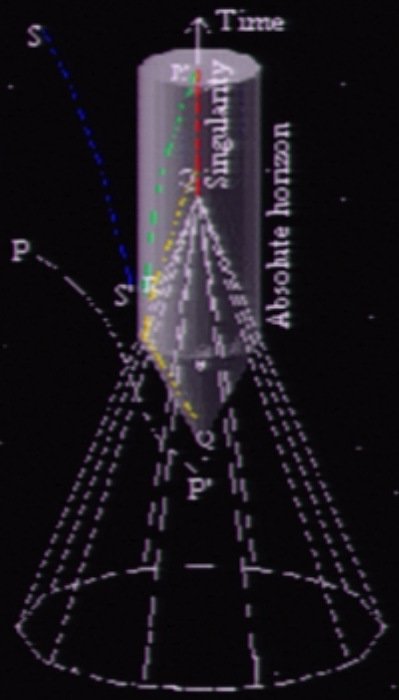
If you watched a star collapsing into a Black Hole, the light emitted from the star would be red-shifted and as a result would get dimmer by a factor of 2 every 20 micro-seconds per solar mass. At the same time the surface would appear to slow down and become frozen

$$L \propto e^{-\frac{t}{3\sqrt{3}M}}$$

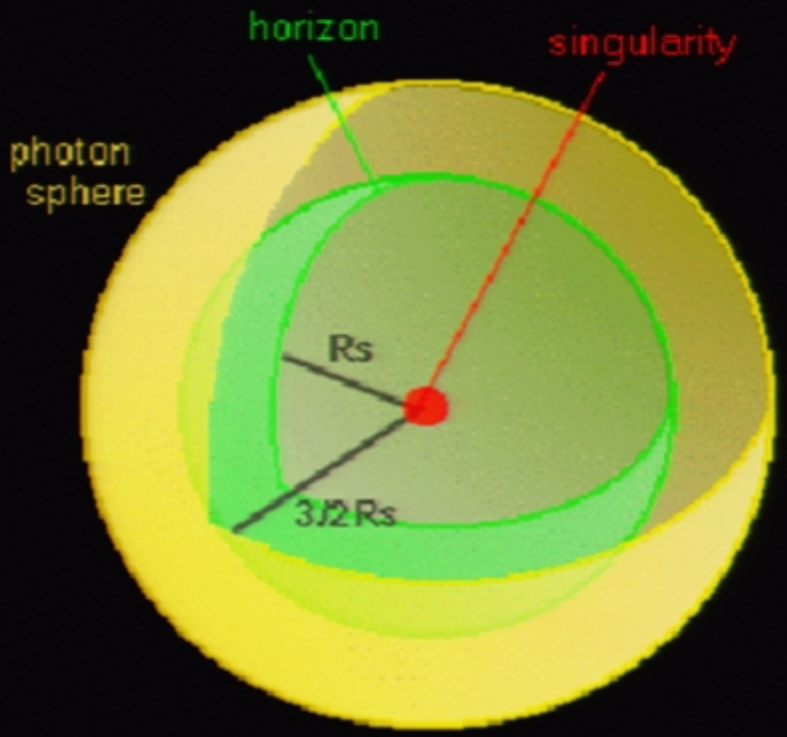
$$t = 10^{-3}\left(\frac{M_{star}}{M_{\odot}}\right)$$

Riding the Surface Down

- When the star passes the critical circumference creating an apparent horizon around itself, the star continues to implode to infinite density and zero volume, where upon it creates and merges into a space time singularity.
- The location where photons trying to escape get "bent" back in is the "apparent horizon"
- The "absolute horizon" is the boundery between where events can send signals to the outside world and where events cannot.



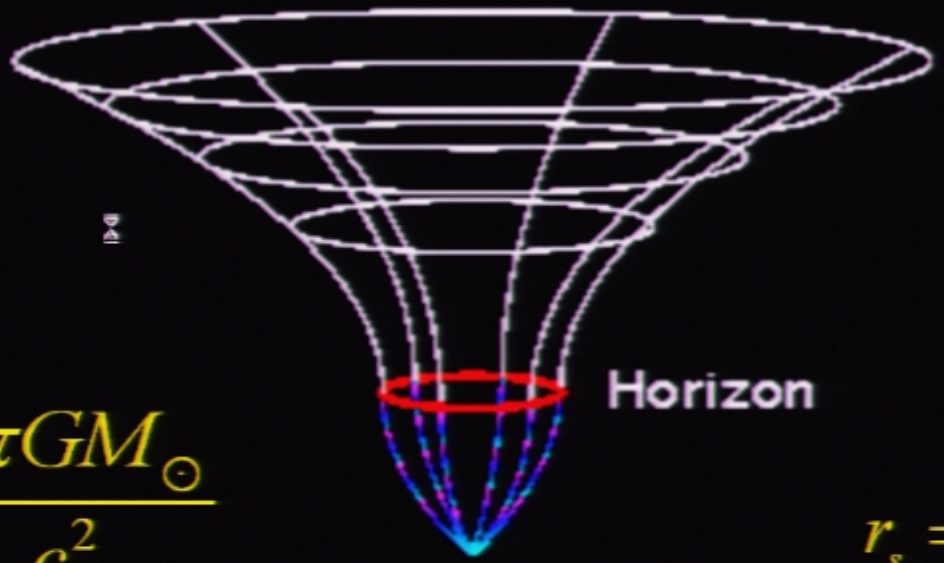
Structure of a black hole



Singularity

- *Within the singularity, matter is infinitely compressed into a region of infinite density. At the singularity, gravity is infinite. Space-time has become infinitely curved. At the present time, science has no tools to describe conditions within the singularity. All laws of physics lose meaning in such a region.*
- *At a singularity, space and time cease to exist as we know them. The laws of physics as we know them break down at a singularity, so it's not really possible to envision something with infinite density and zero volume.*

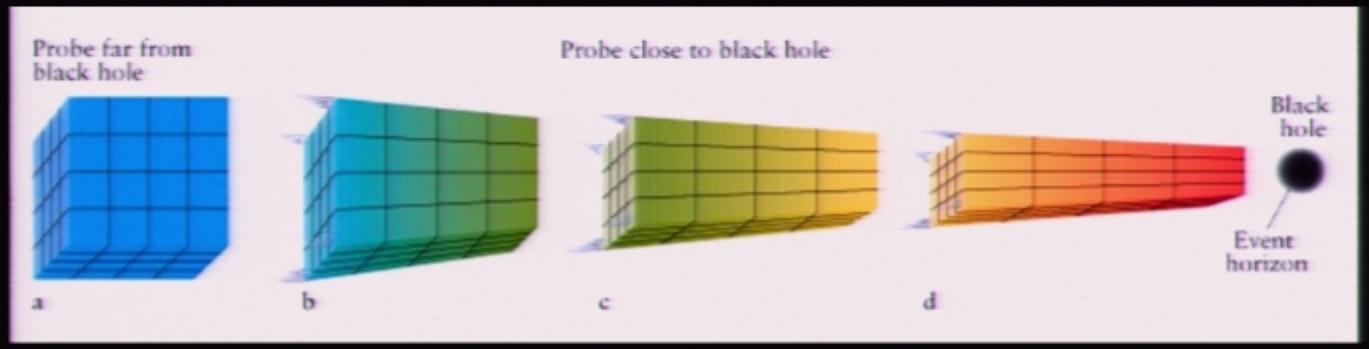
Embedding Structure



$$C_b = \frac{4\pi G M_\odot}{c^2}$$

$$r_s = \frac{2GM_\odot}{c^2}$$

Traveling into a Black Hole



- As the ship approaches the black hole, the ship is elongated by the variation in gravity
- The ship is also gravitationally red shifted at the end closer to the black hole
- The ship will appear to hover forever at the edge of the hole to us - an effect of the time dilation
- In the ship though, you do go into the black hole.
- Nothing can leave a singularity (cosmic censorship).

Time Dilation and Blueshift

$$t_2 = \frac{t_1}{\sqrt{1 - \frac{C_b}{C}}}$$

If you hovered at 1.00 0001 times the event horizon circumference, one day for you would mean 1024 days for the rest of the universe.

$$\lambda_r = \lambda_e \sqrt{1 - \frac{C_b}{C}}$$

If you hovered at 1.000008 times the event horizon circumference, visible light from the stars would appear to be in the x-rays

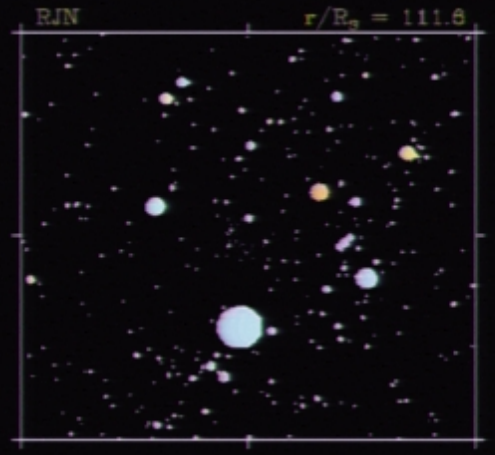
Visiting a Black Hole

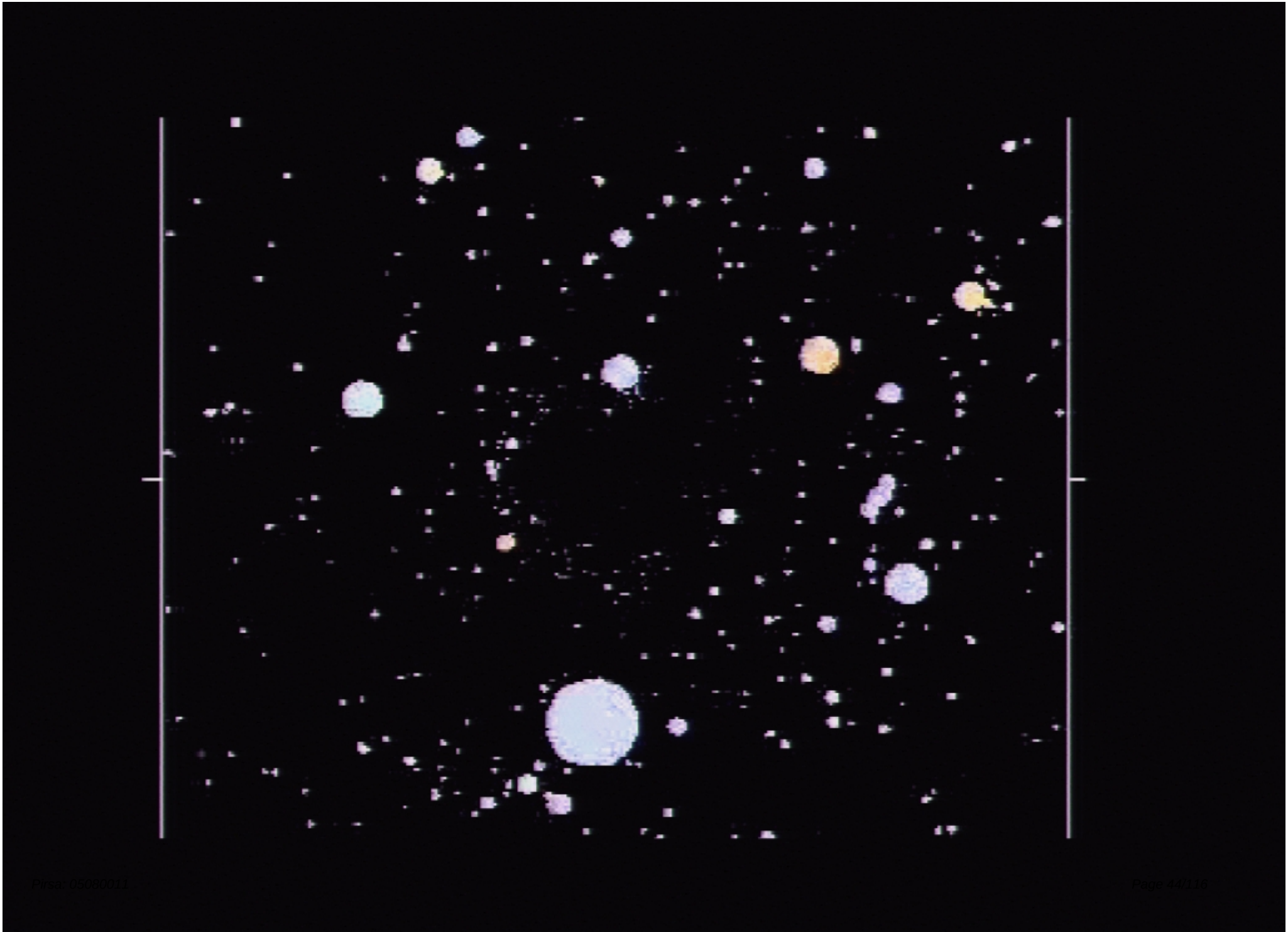
Spaghettification!

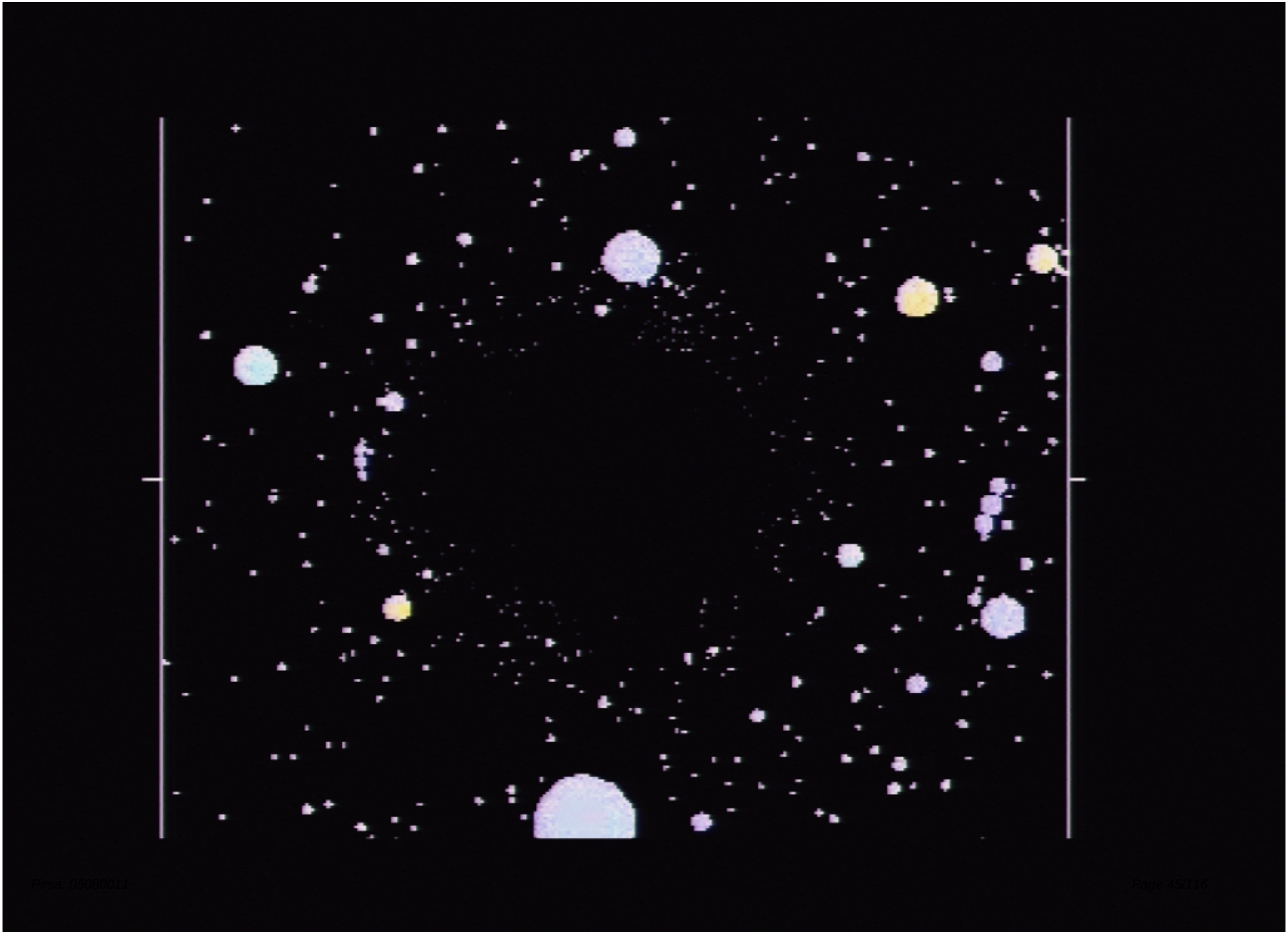
$$\Delta a = \frac{16\pi^3 GLM_b}{C^3}$$

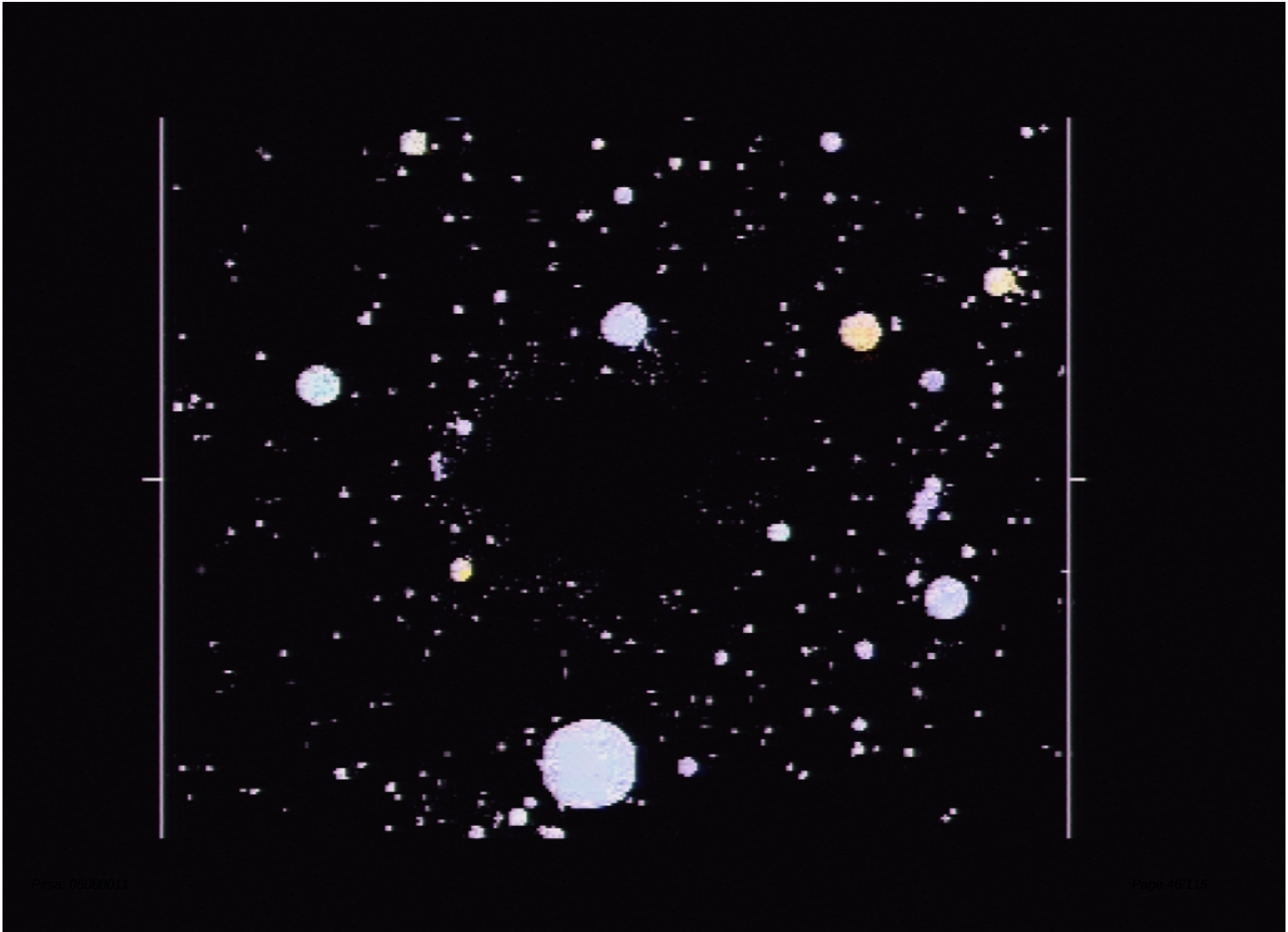
$$\Delta a \propto \frac{1}{M_b{}^2}$$

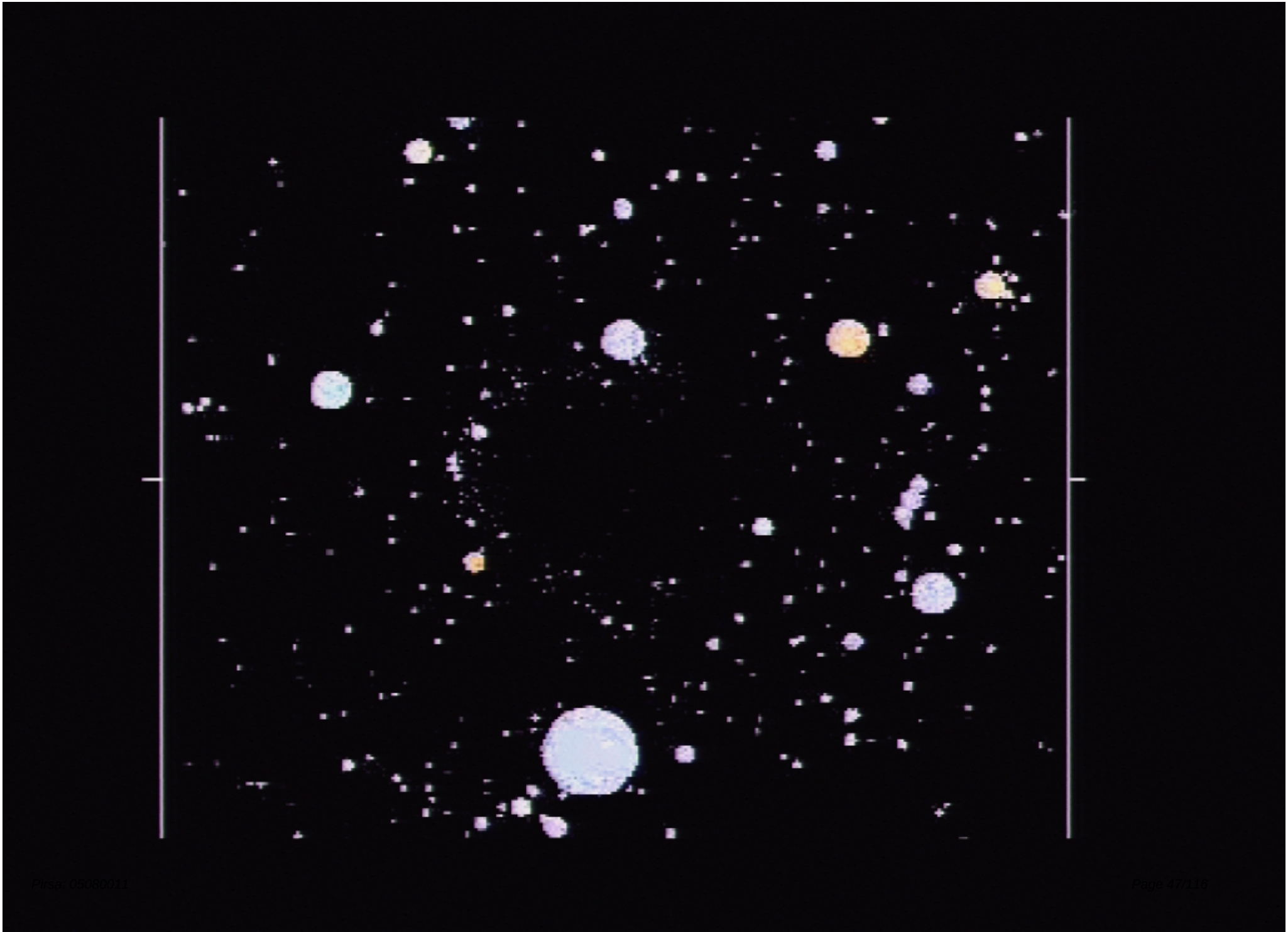
Approaching

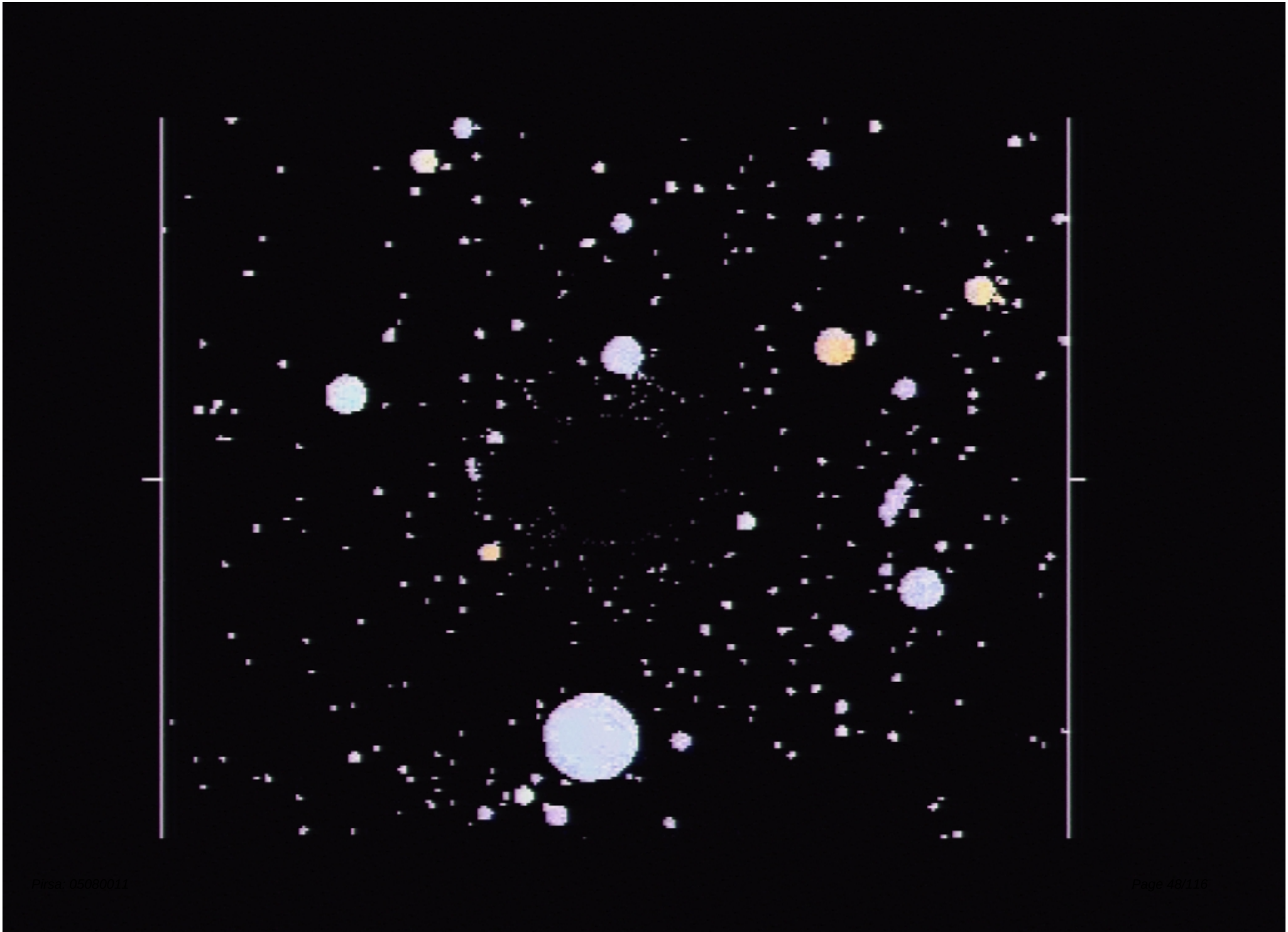




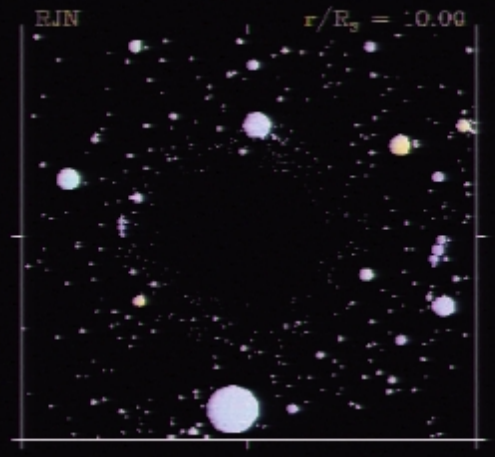




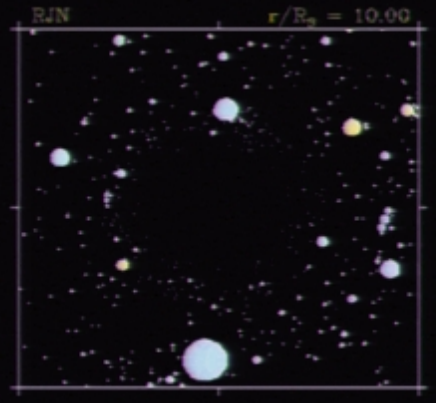




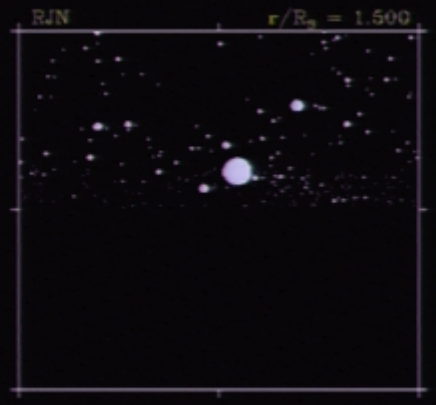
Approaching



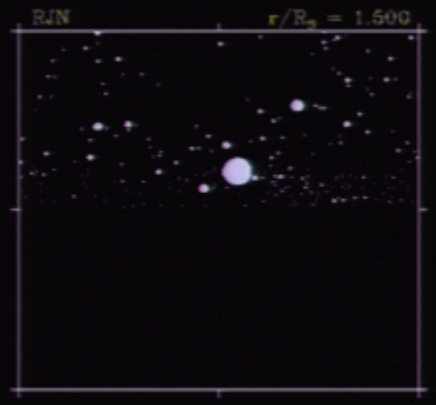
Orbiting Black Hole Looking Down



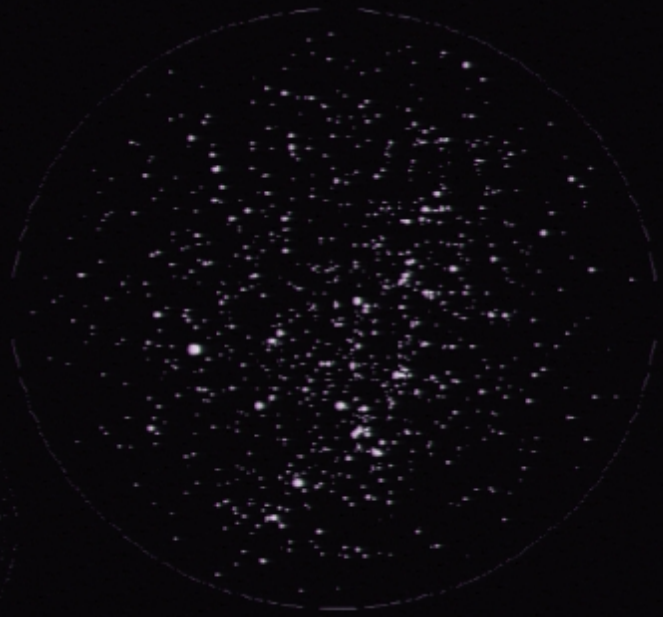
Orbiting Looking Horizontal



Orbiting Looking Horizontally

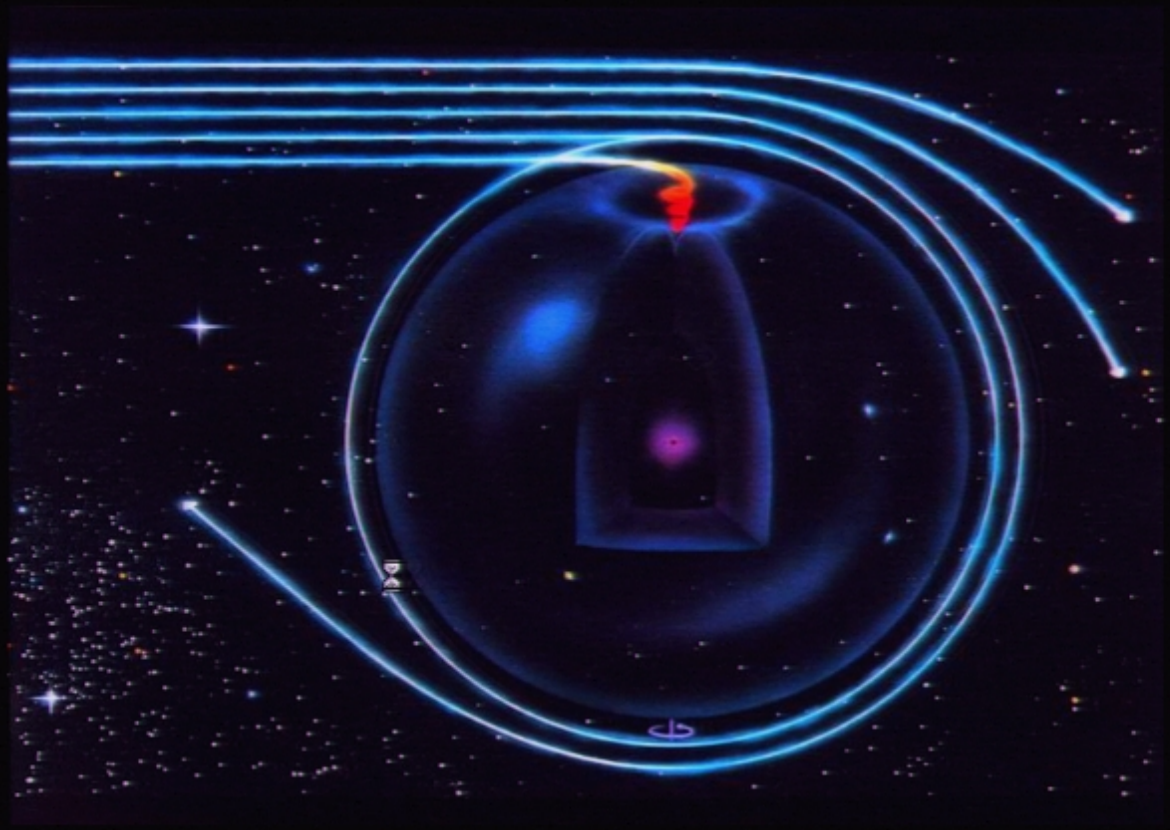


Looking Up



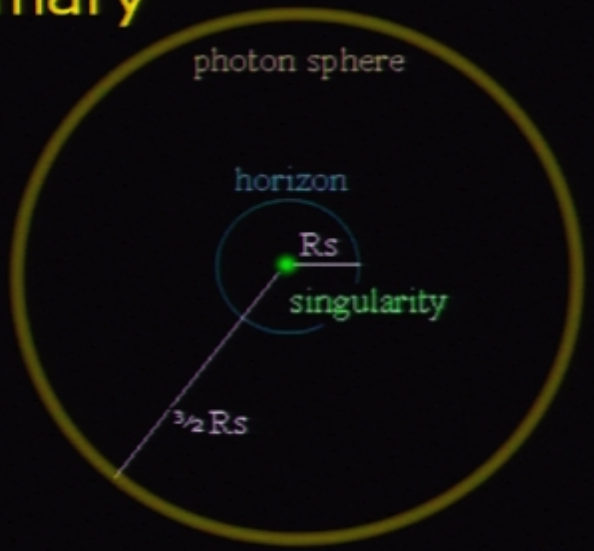
$$r = 12 \tan\left(\frac{5\pi}{6}\sqrt{1-\frac{C_b}{C}}\right)$$

Photon orbits around a black hole

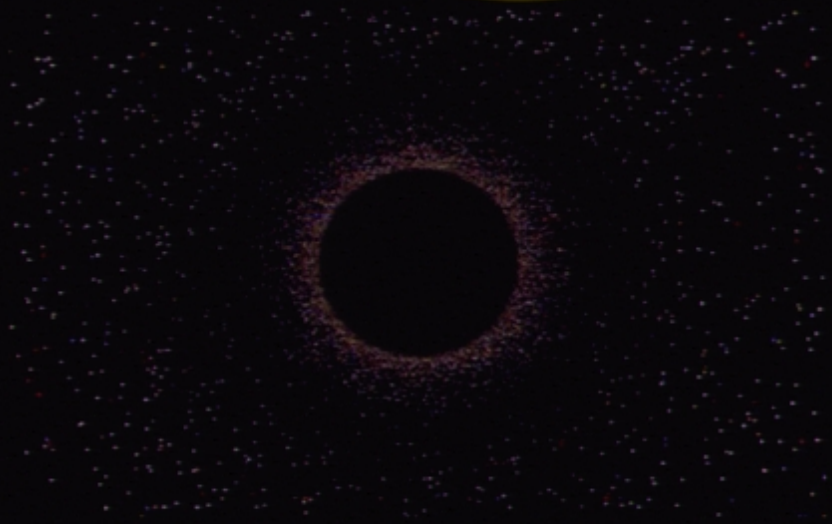


The Anatomy Summary

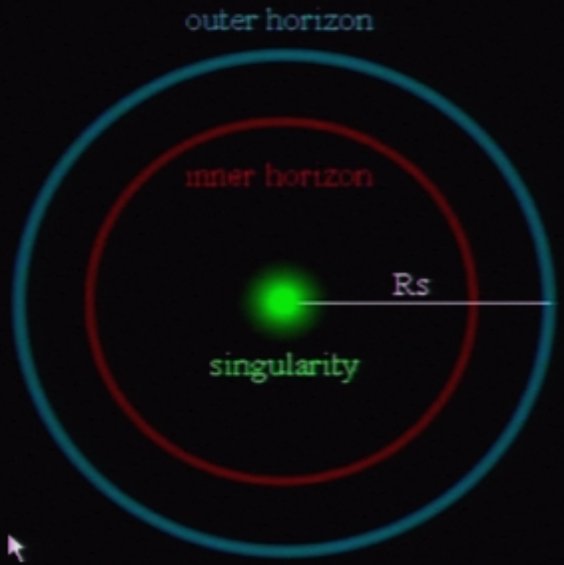
If you calculate the size of an object whose escape velocity is the speed of light, you get the "Schwarzschild radius", which defines the "event horizon". This is the formal size of a black hole (even though there is nothing at that location). It is given by R_s=3km(M_*/M_{sun}). It is the horizon over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

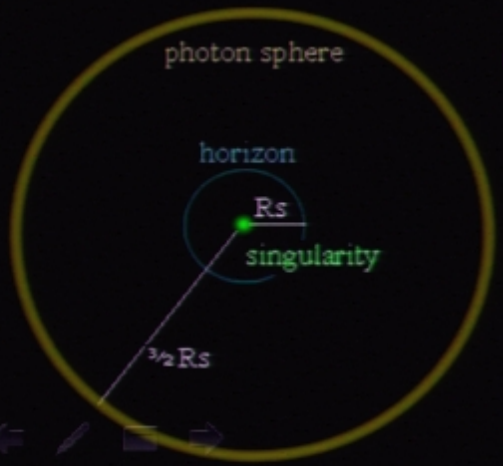


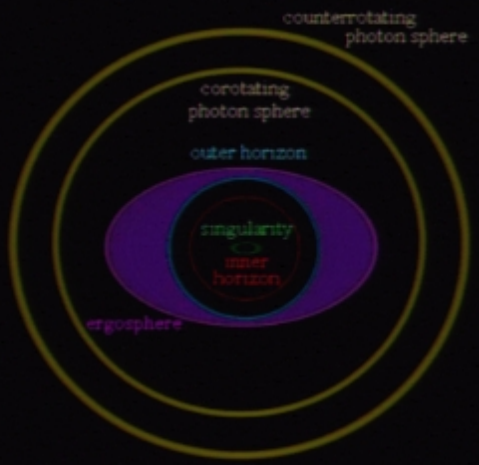
Far from the hole, the gravity is the same as it would be if the star were still there (so no "vacuum cleaner" effect). If the Sun collapsed to a BH, the Earth's orbit would be unaffected.



Types of Black Holes

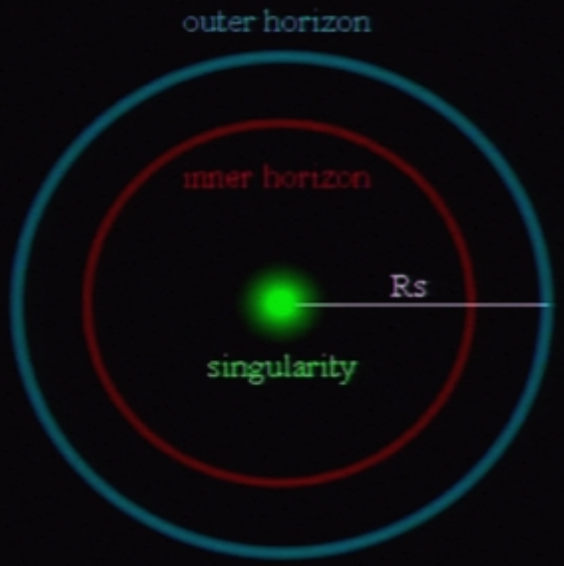


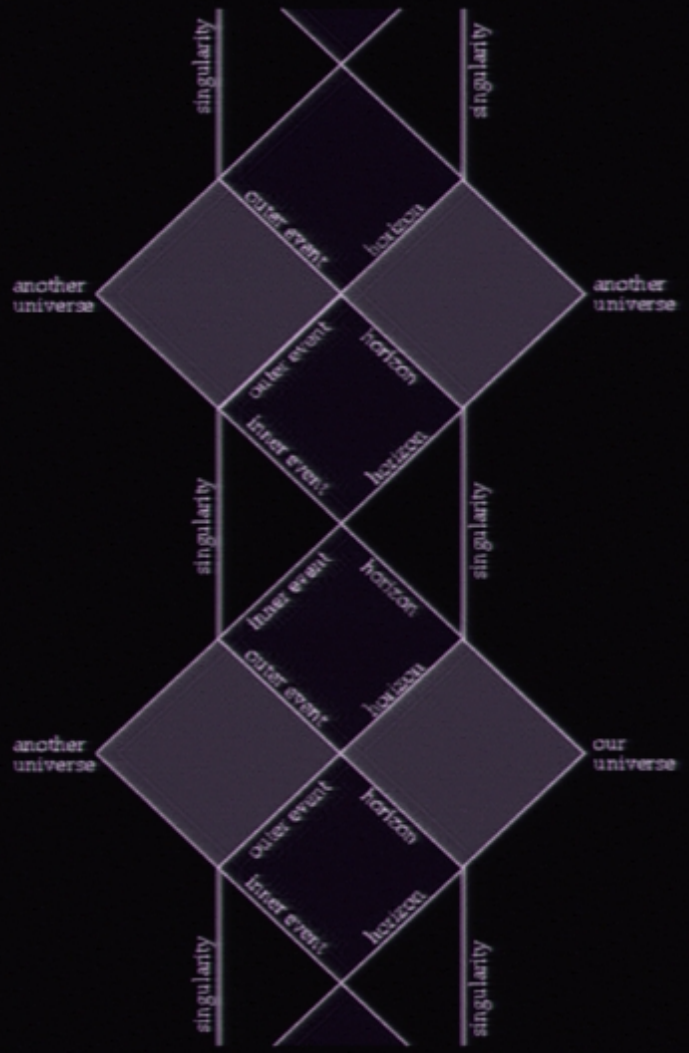


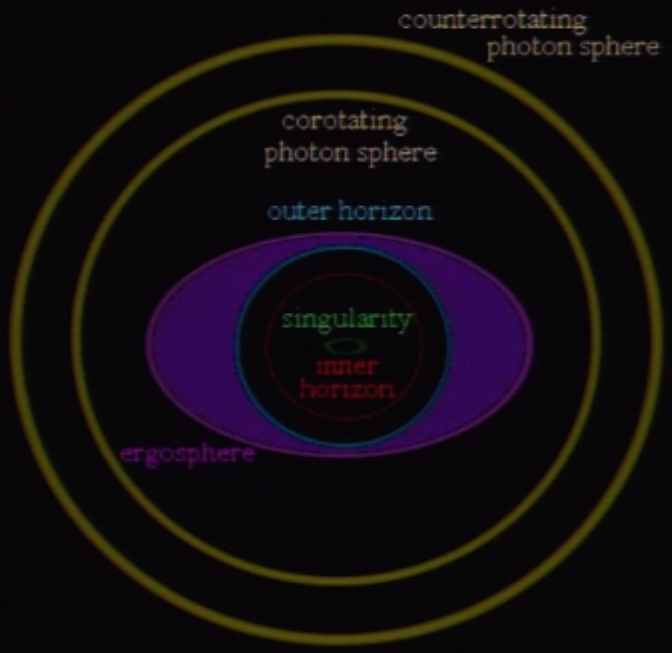


Reissner-Nordström Black Hole

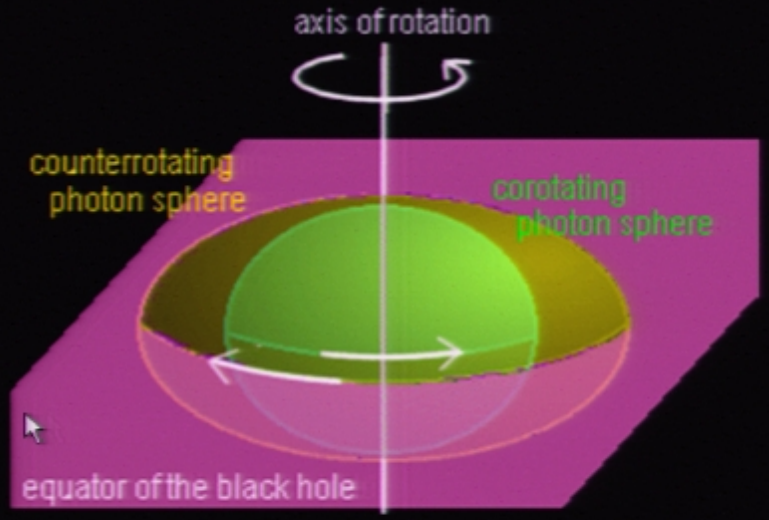
An electrically Charged Black Hole

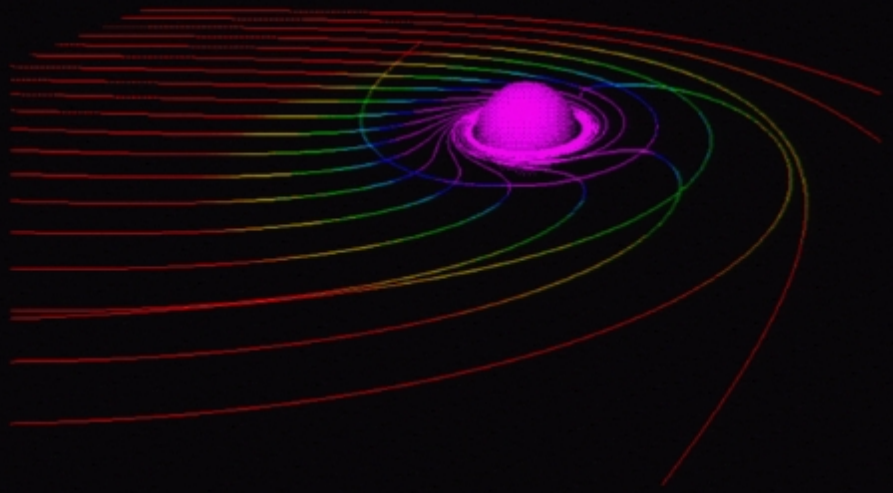






Rotating Black Holes

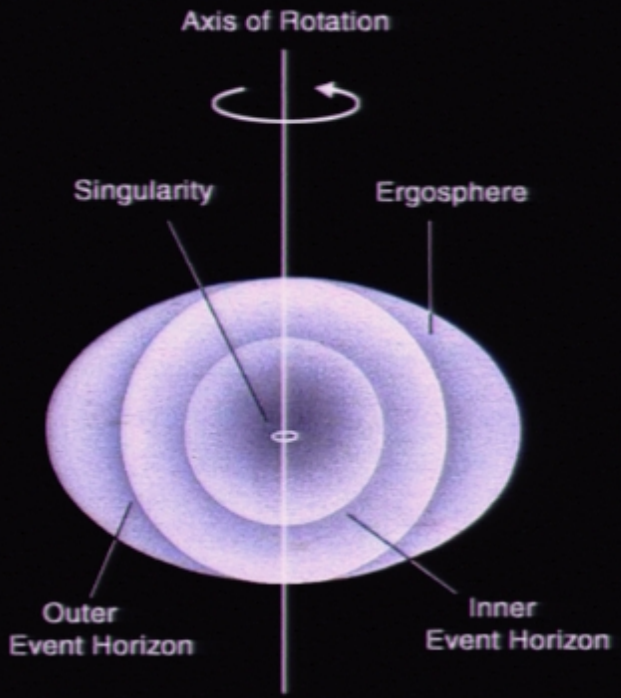


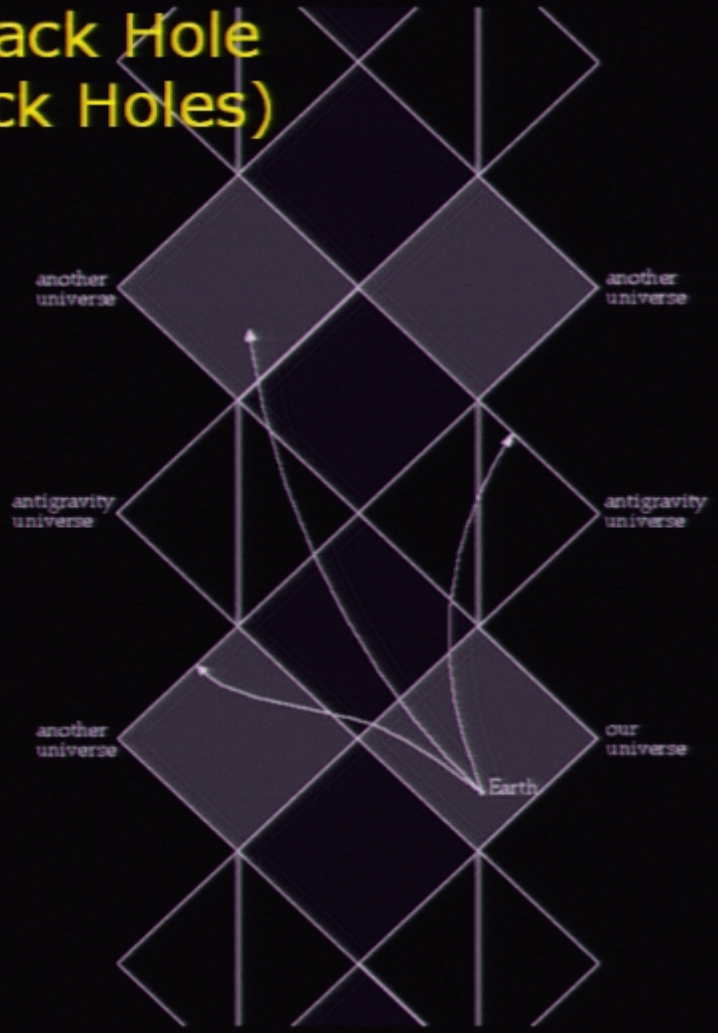


Rotation also leads
to “frame-dragging”

A Rotating Black Hole (The Kerr Black Holes)

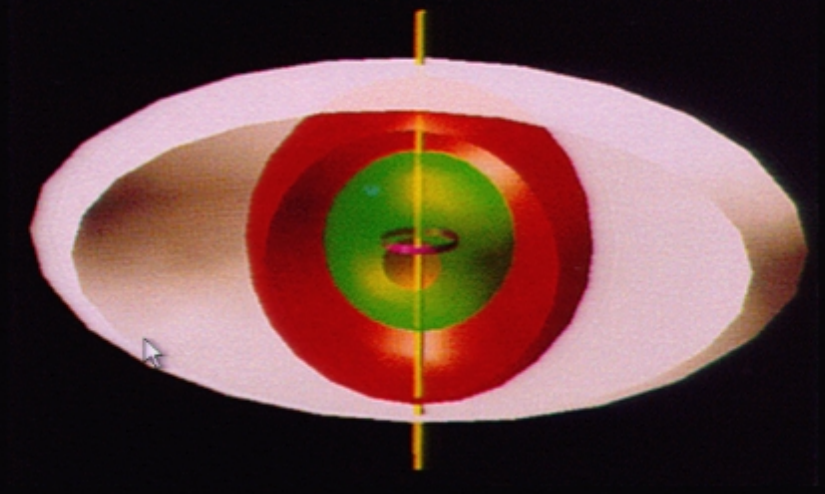
Why is it called a rotating black hole? The event horizon doesn't rotate---it's just a boundary-line

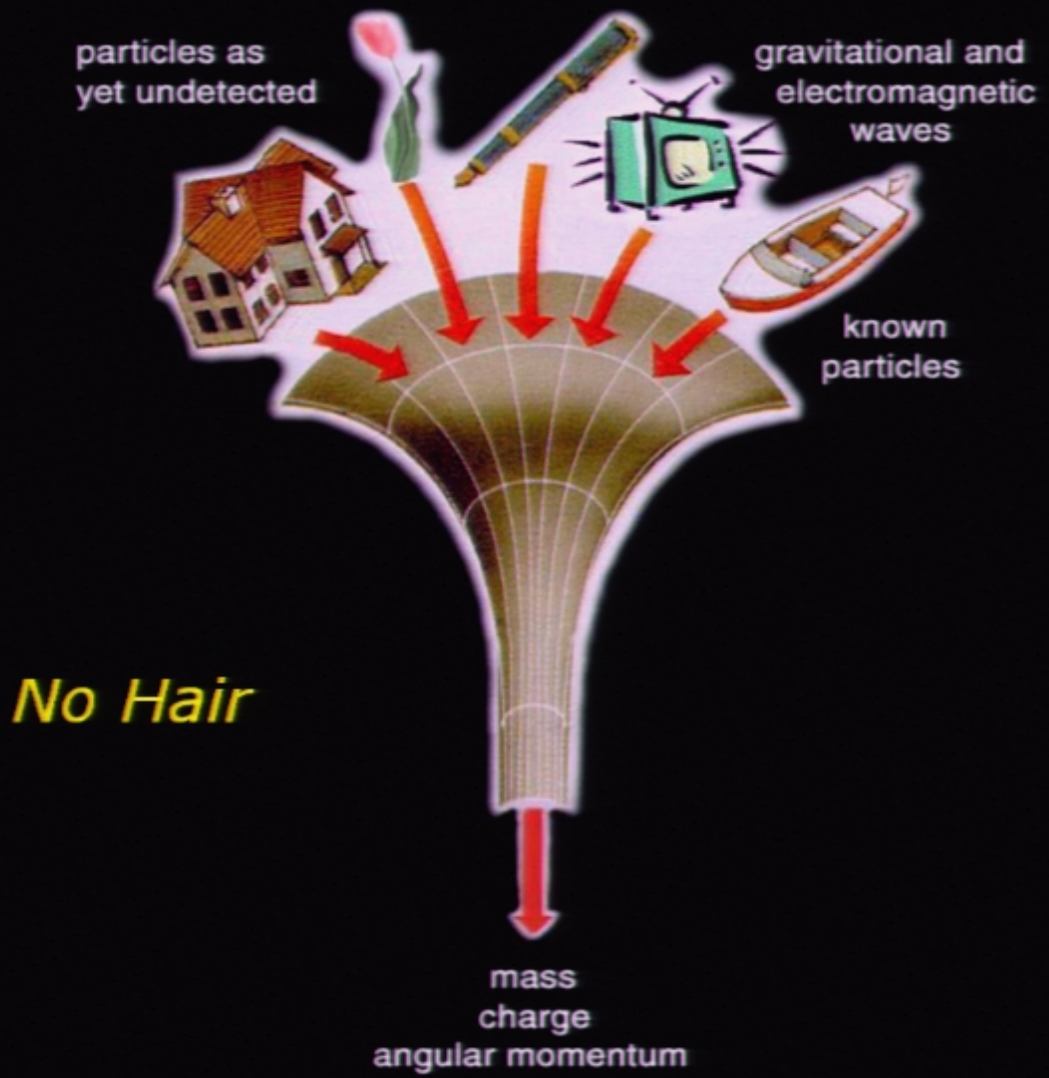




Kerr-Newman Black Hole

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



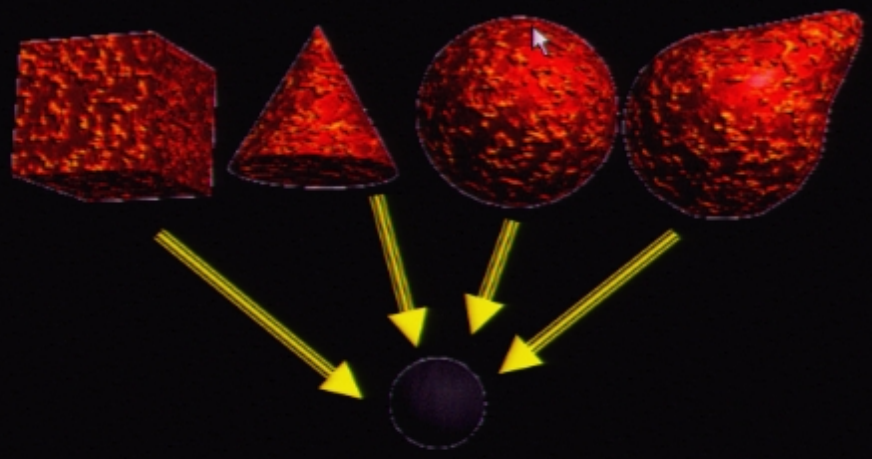

particles as
yet undetected
gravitational and
electromagnetic
waves
known
particles
No Hair
mass
charge
angular momentum

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 h

- 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 resent 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"
- You replace "Horizon Surface Gravity" with "Temperature"

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

Entropy of Black Hole

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

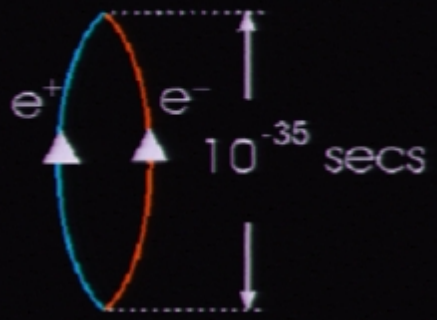
Worse Problem: If is has a temperature it must radiate, but in classical definition, nothing can escape a Black Hole.

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 make no sense at all.*

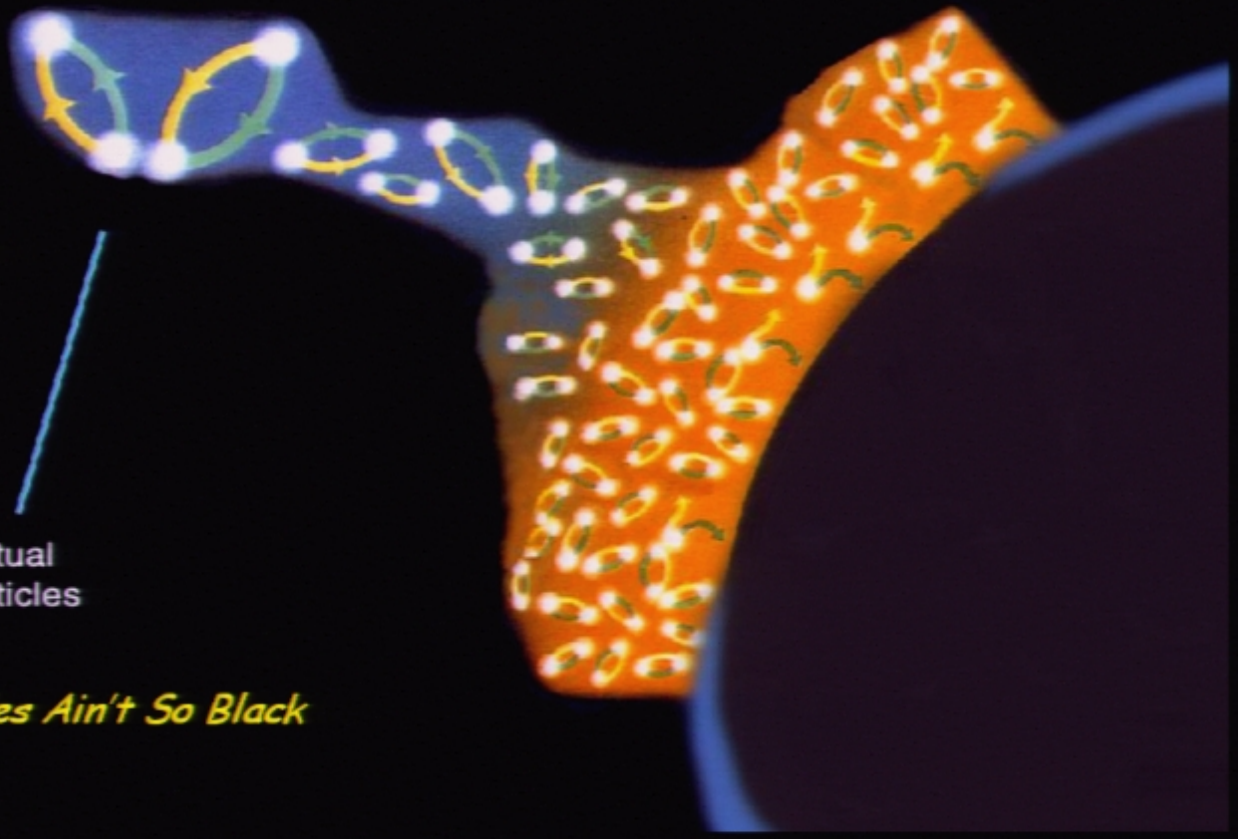
Vacuum Fluctuations

- *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

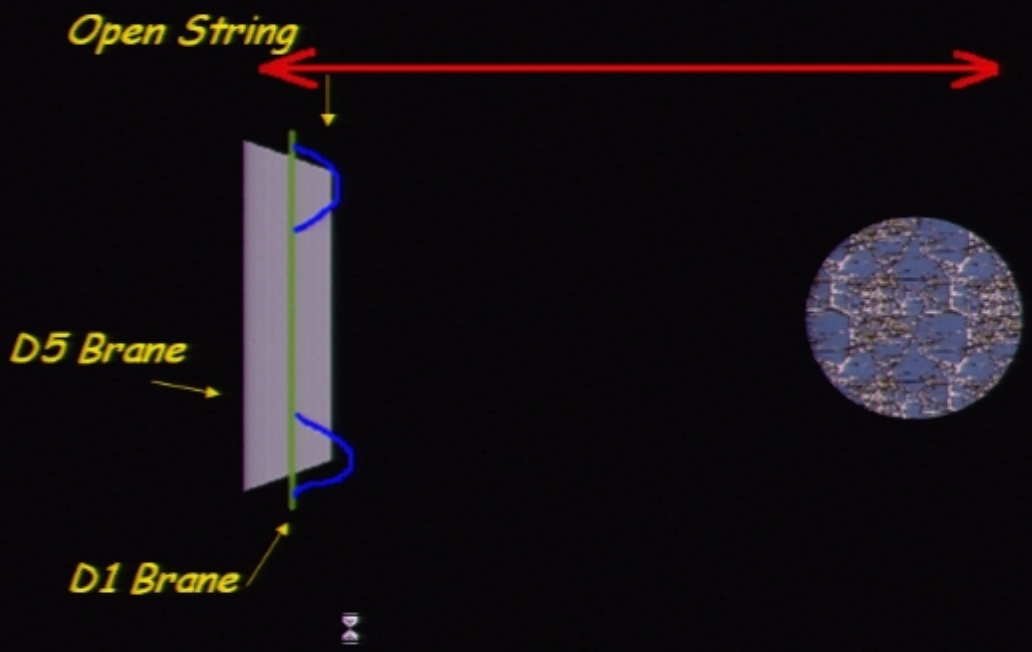
- The larger (more massive) the Black Hole the lower the temperature and the longer it takes to evaporate.

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

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

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

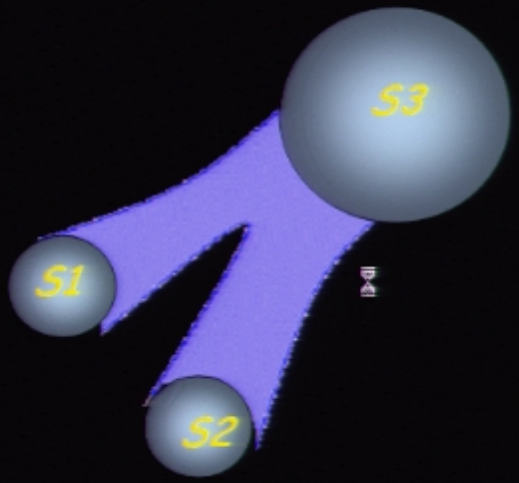
Superstring Method



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

Merging Black Holes

$$S3 \geq S1 + S2$$

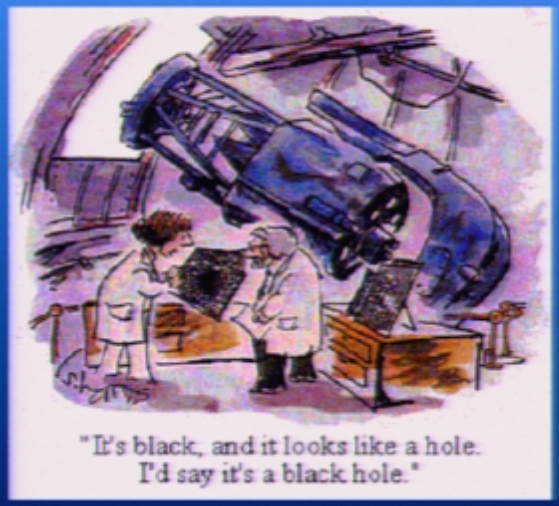


The area of the final horizon is greater than the sum of the areas of initial horizons

Are Black Holes Real

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

Observational Evidence for Black Holes



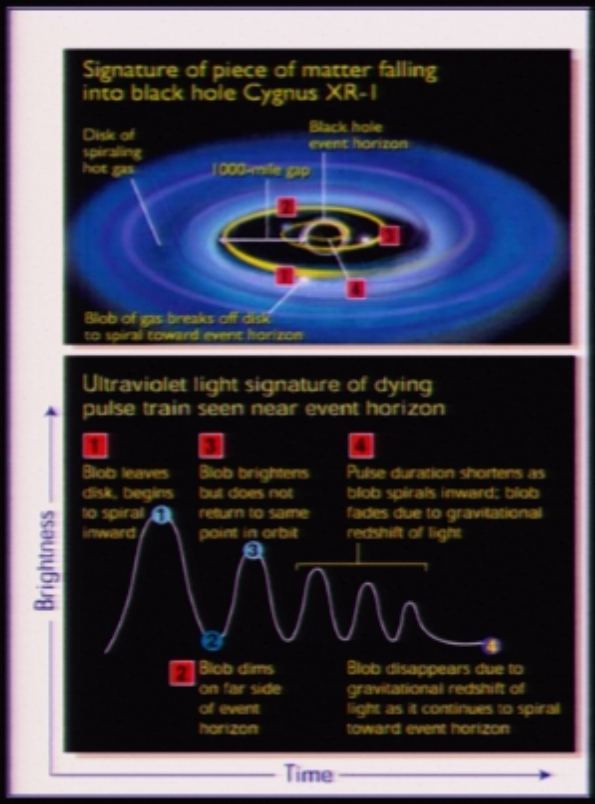
"It's black, and it looks like a hole. I'd say it's a black hole."

Finding Black Holes
Ultraviolet and X-rays
Seeing Matter Disappear

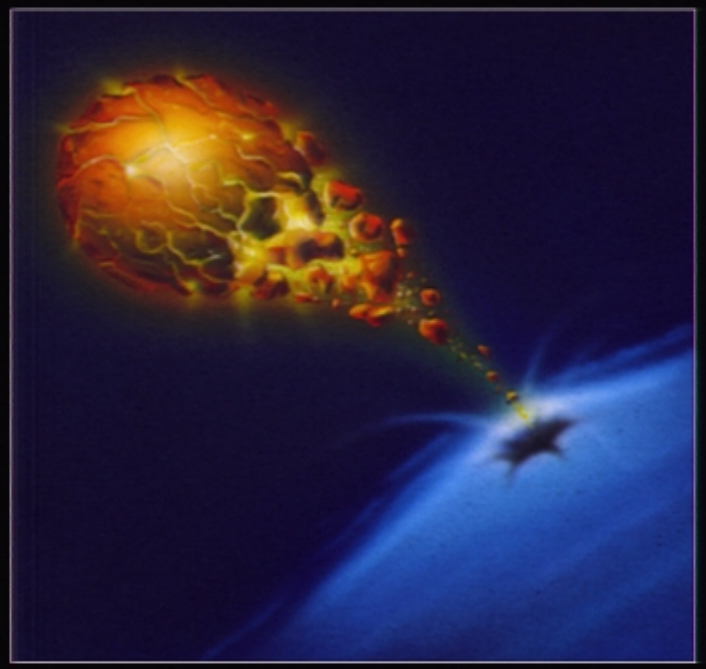
Hubble observed pulses of UV light emitted by material as it fell into a black hole.

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

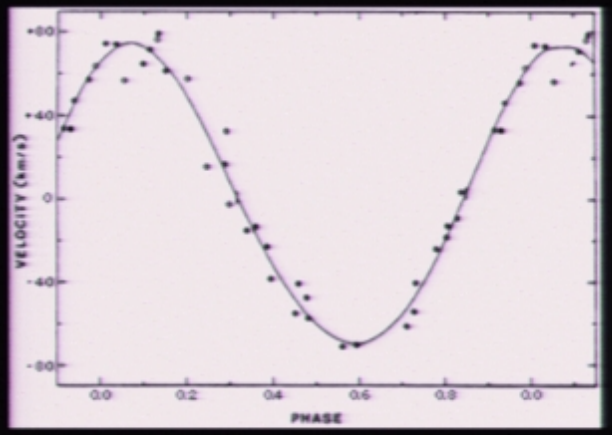
- Light pulses, lasting 0.2 s, are red-shifted from X-ray to UV, as they fall into gravity of the black hole.



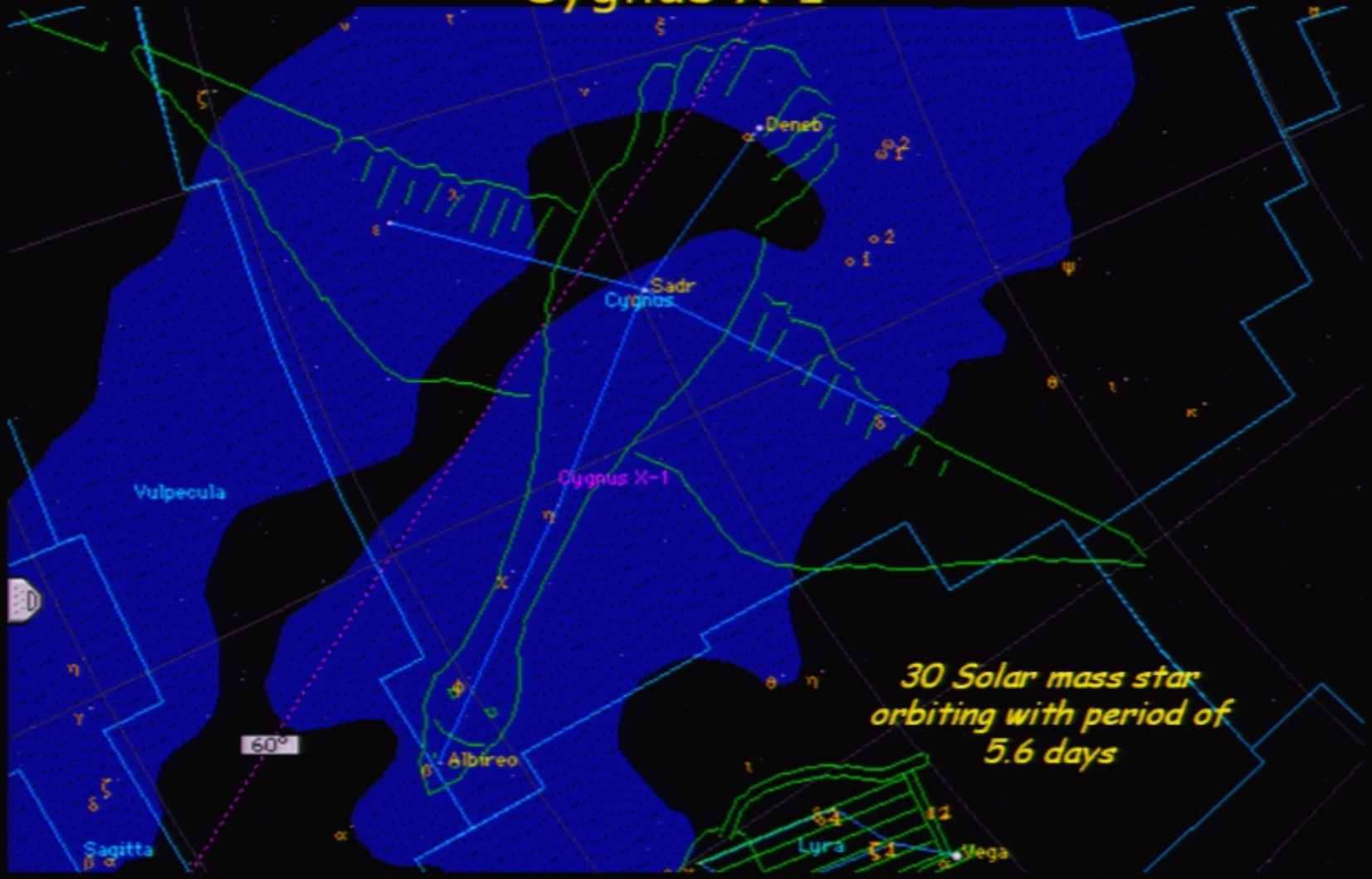
Seeing Holes

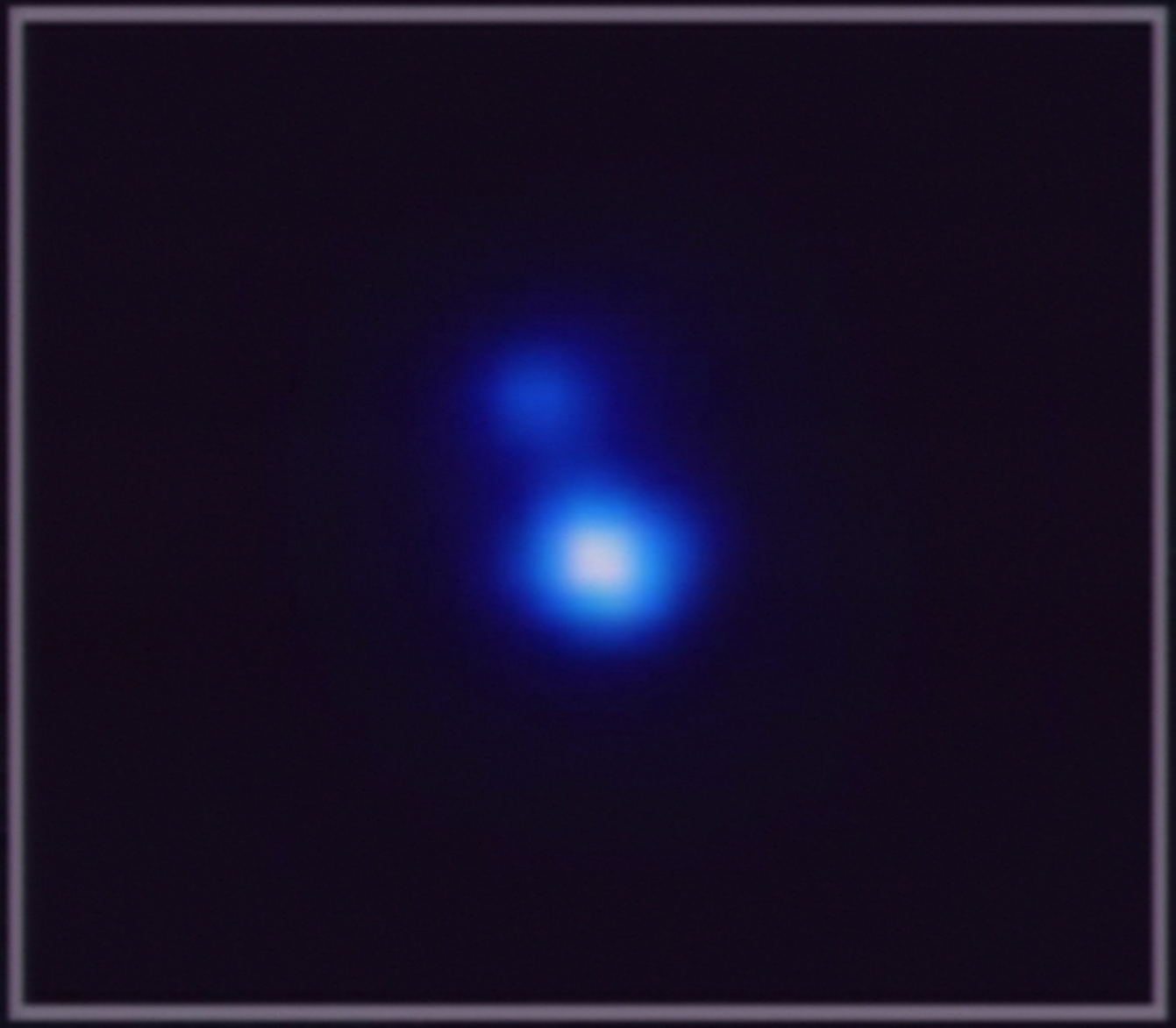


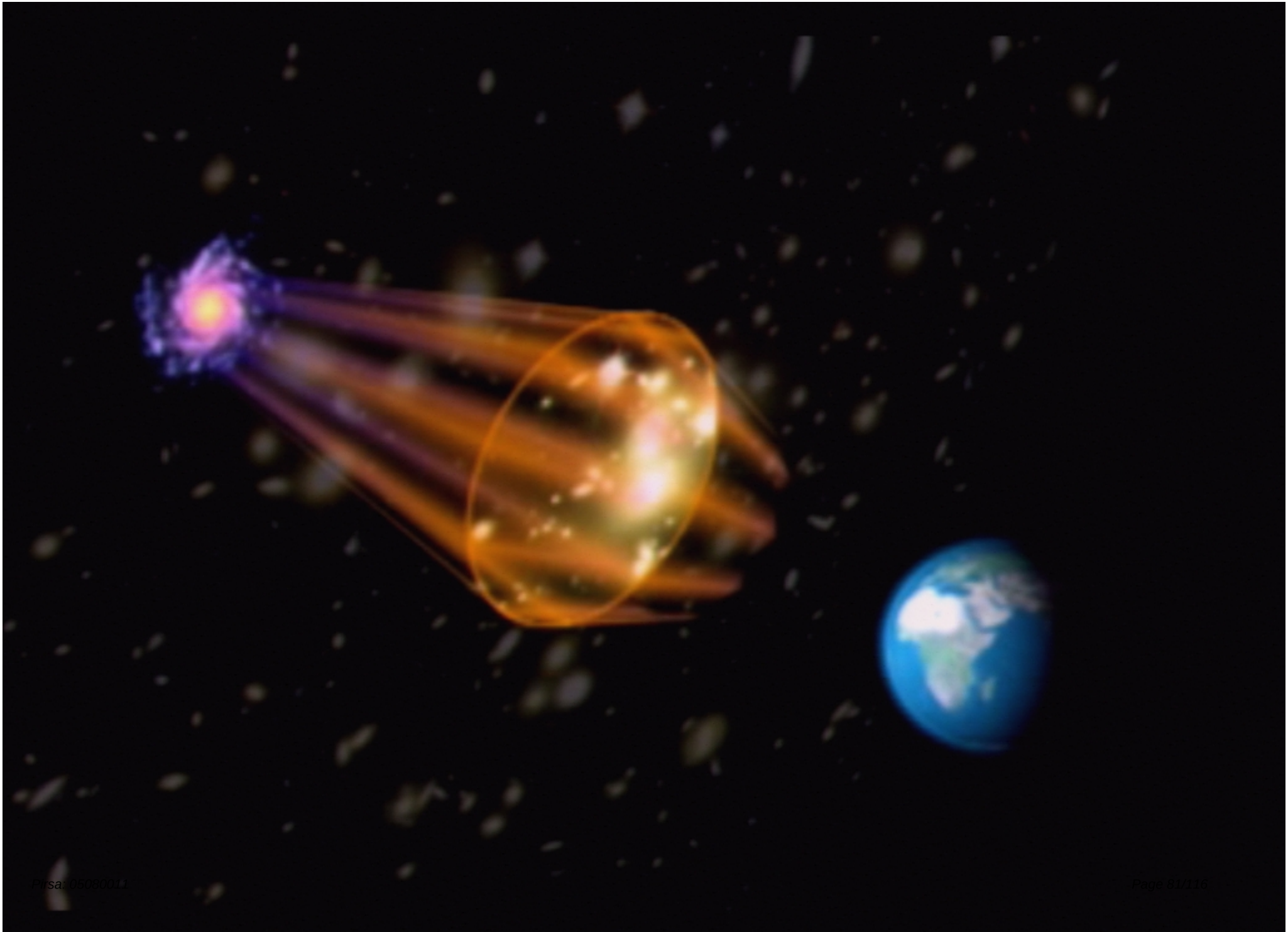
- Can't see black hole itself, but can see matter falling into a hole.
- Gravitational forces stretch and rip matter: heats up.
- Very hot objects emit in X-rays (interior of Sun)

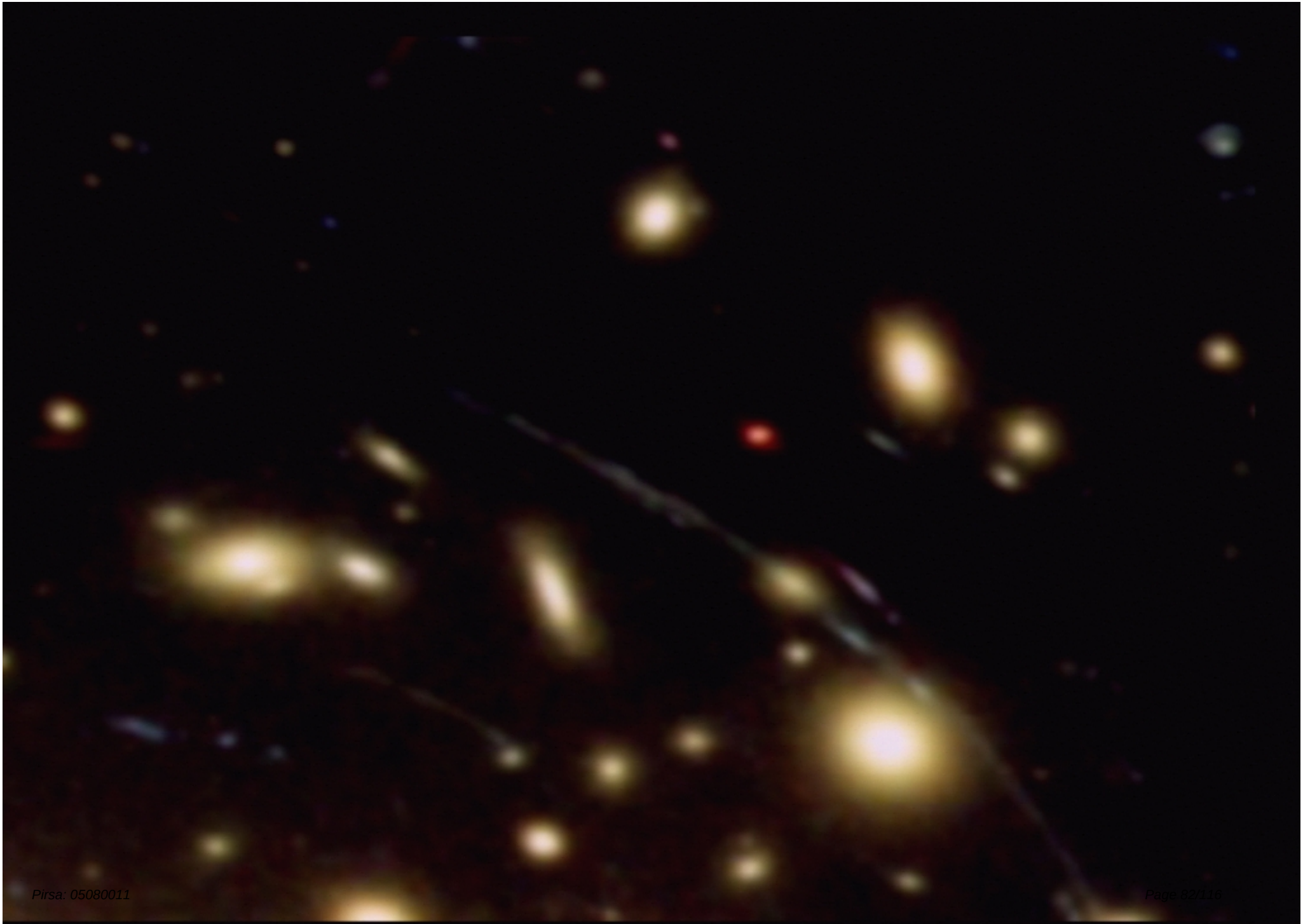


Cygnus X-1

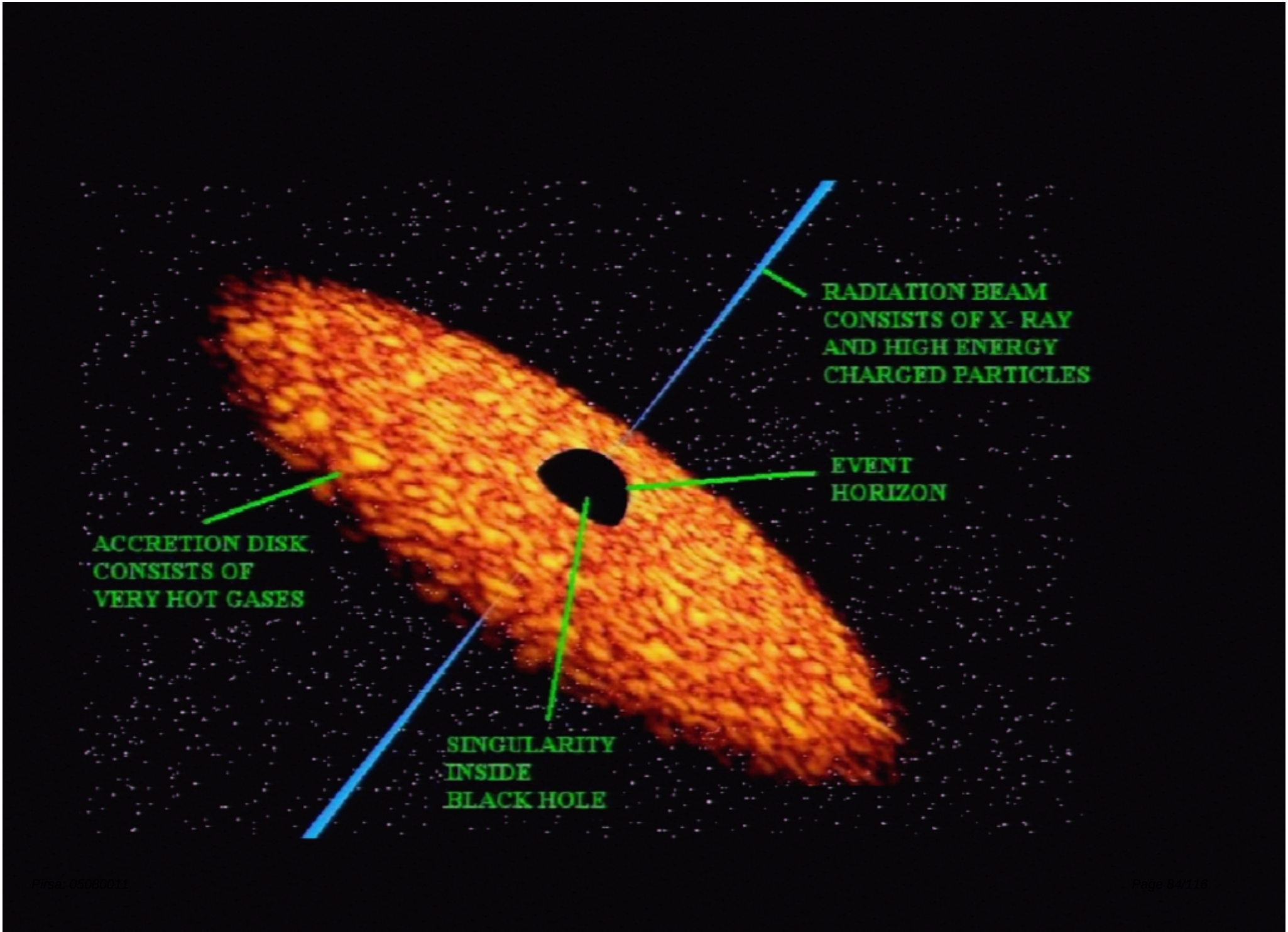

Deneb
Sadr
Cygnus
Cygnus X-1
Vulpecula
Albireo
60°
Sagitta
Lyra
Vega
30 Solar mass star
orbiting with period of
5.6 days





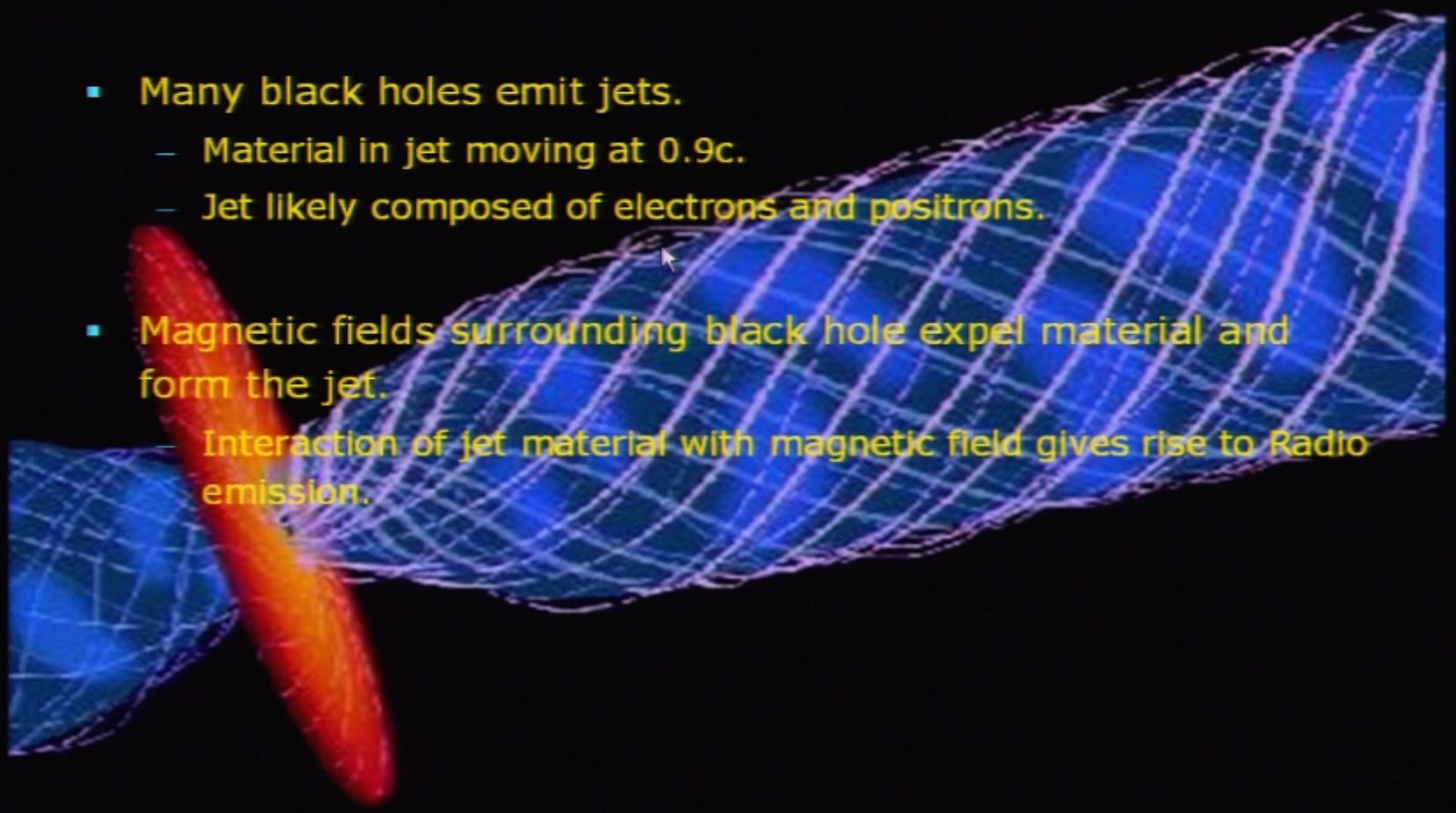


What else should we look for?

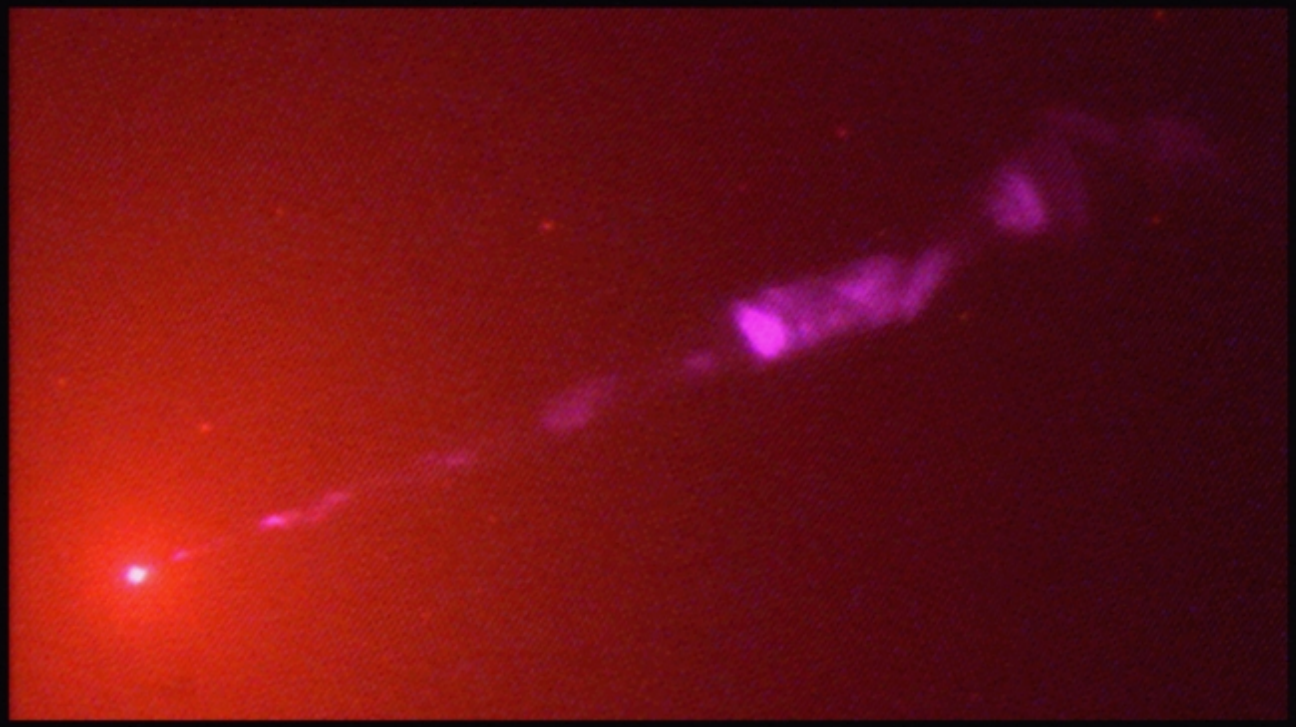

RADIATION BEAM
CONSISTS OF X- RAY
AND HIGH ENERGY
CHARGED PARTICLES
EVENT
HORIZON
ACCRETION DISK
CONSISTS OF
VERY HOT GASES
SINGULARITY
INSIDE
BLACK HOLE

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.

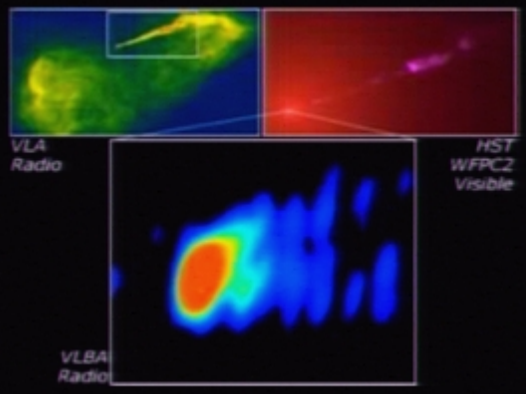


Jets



More Pictures of Black Hole Jets

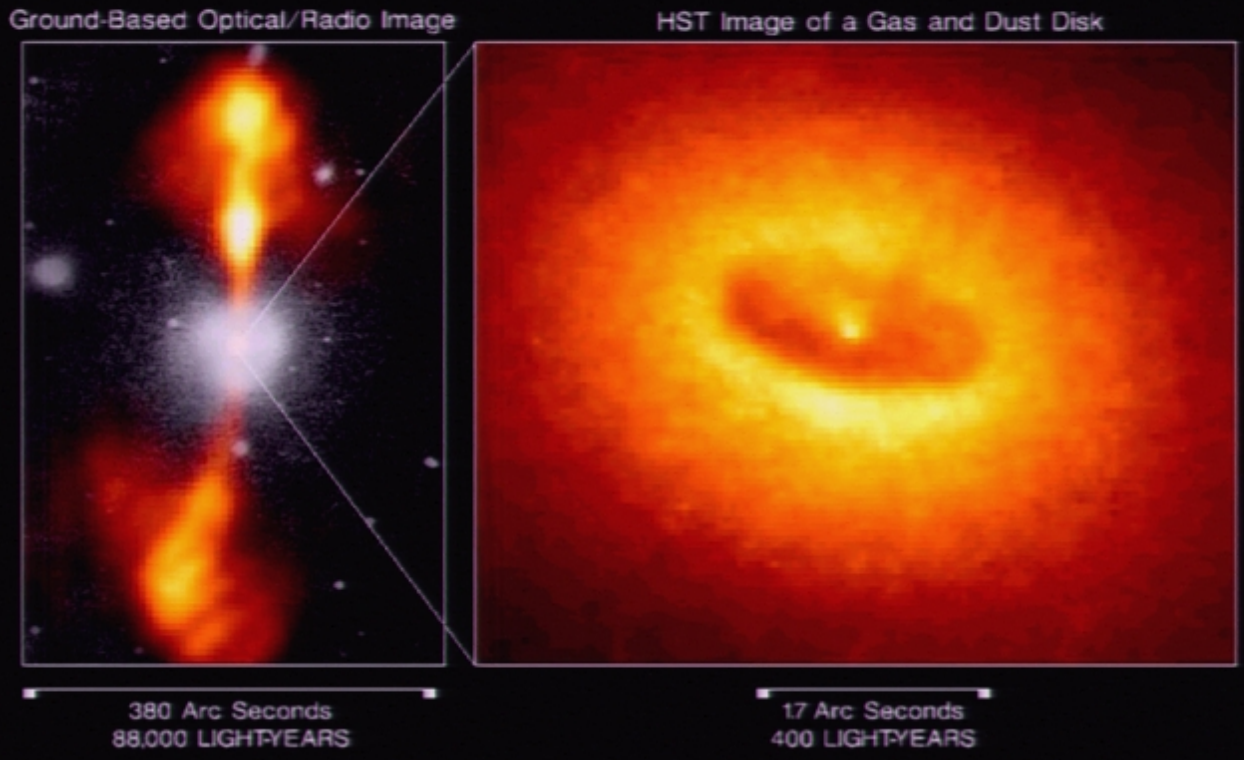
The orangish picture focuses on the very center of the active galaxy Markarian 573. The image, which combines readings taken in visible and near-infrared light, traces a spiral of galactic dust with what scientists believe is a supermassive black hole at its center

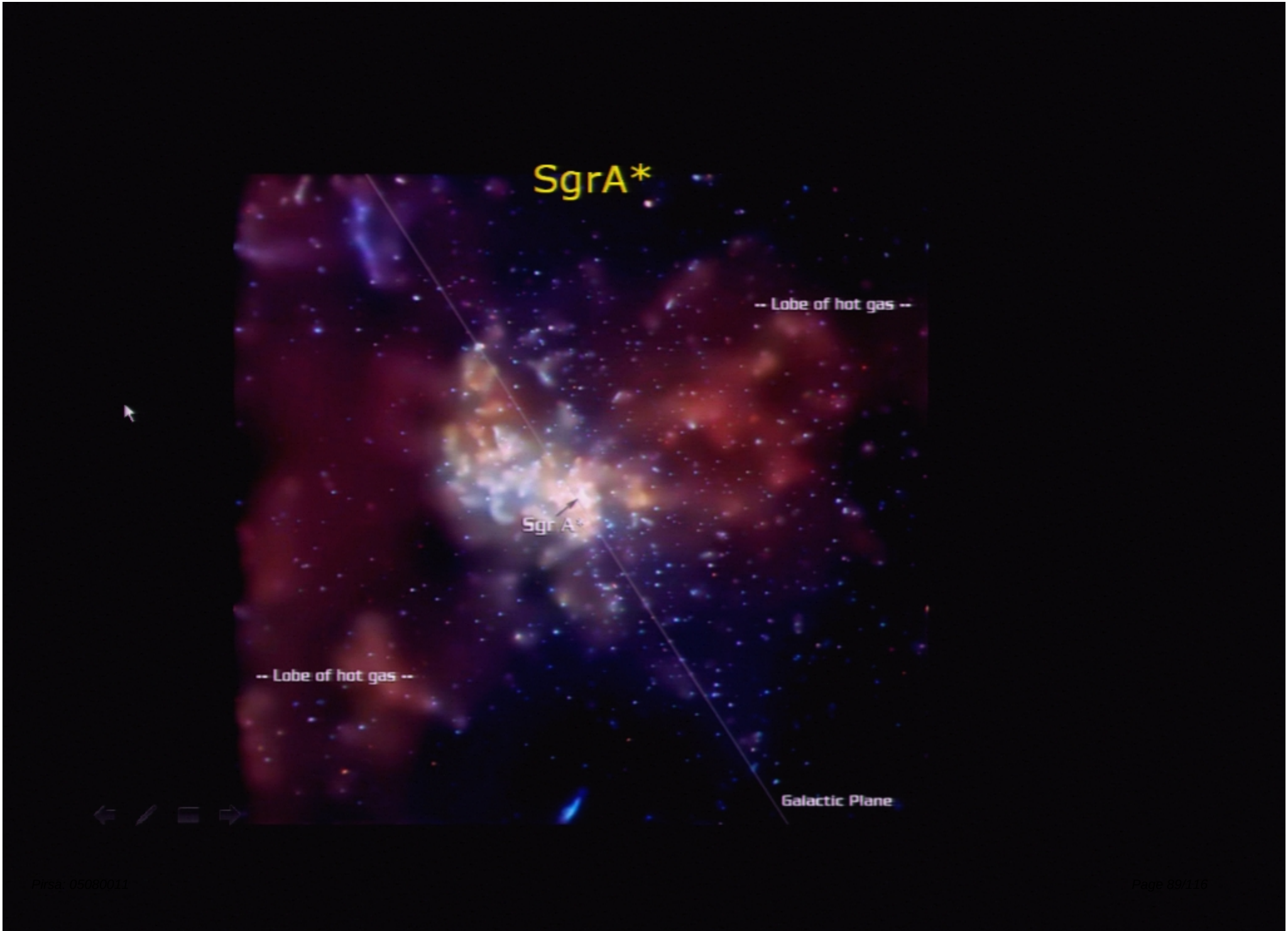


Core of Galaxy NGC 4261

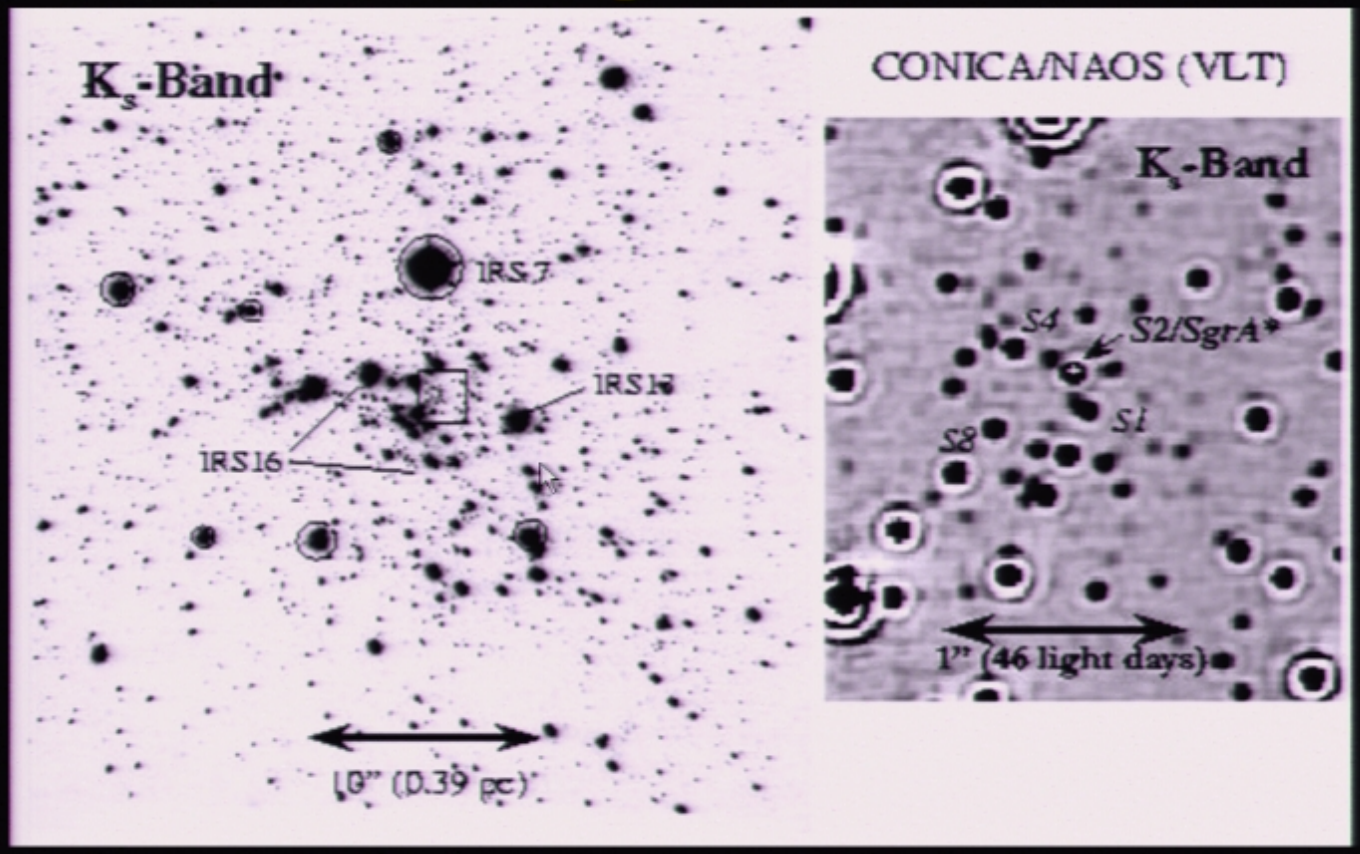
Hubble Space Telescope

Wide Field / Planetary Camera

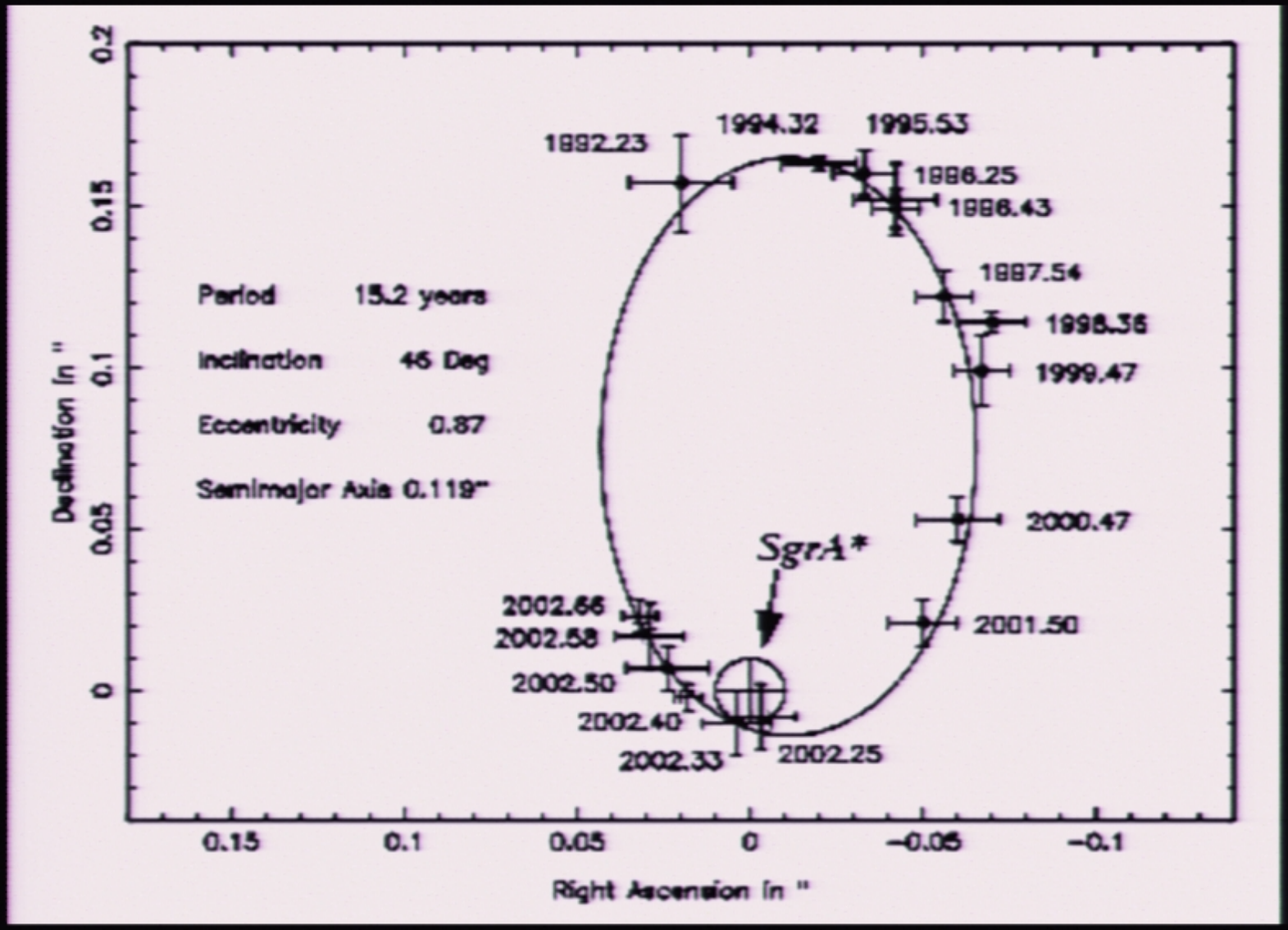



SgrA*
-- Lobe of hot gas --
Sgr A*
-- Lobe of hot gas --
Galactic Plane

SgrA*

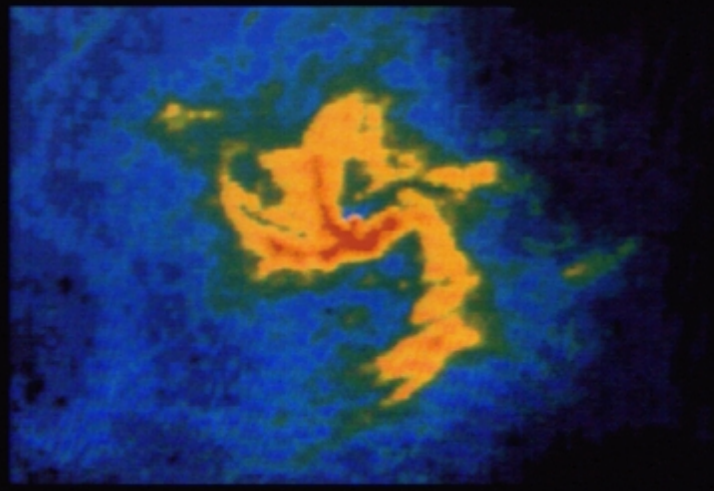


3,700,000 solar masses

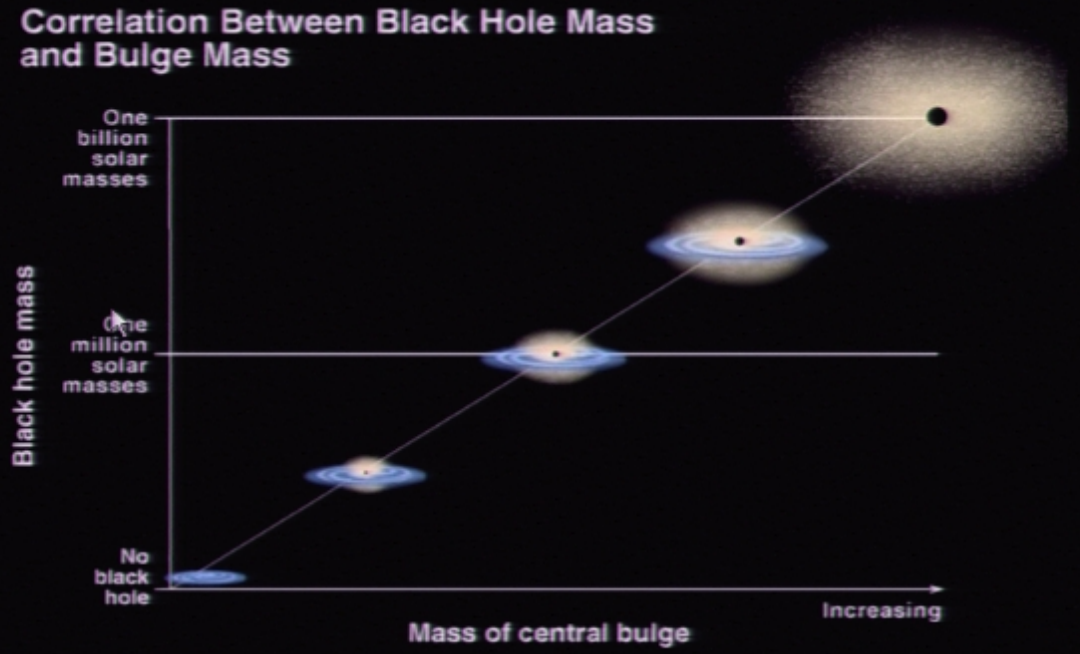

Declination in "
0.2
0.15
0.1
0.05
0
Period 15.2 years
Inclination 46 Deg
Eccentricity 0.87
Semimajor Axis 0.119"
1992.23
1994.32
1995.53
1996.25
1996.43
1997.54
1998.36
1999.47
2000.47
2001.50
SgrA*
2002.66
2002.58
2002.50
2002.40
2002.33
2002.25
0.15
0.1
0.05
0
−0.05
−0.1
Right Ascension in "

More Black Hole Evidence

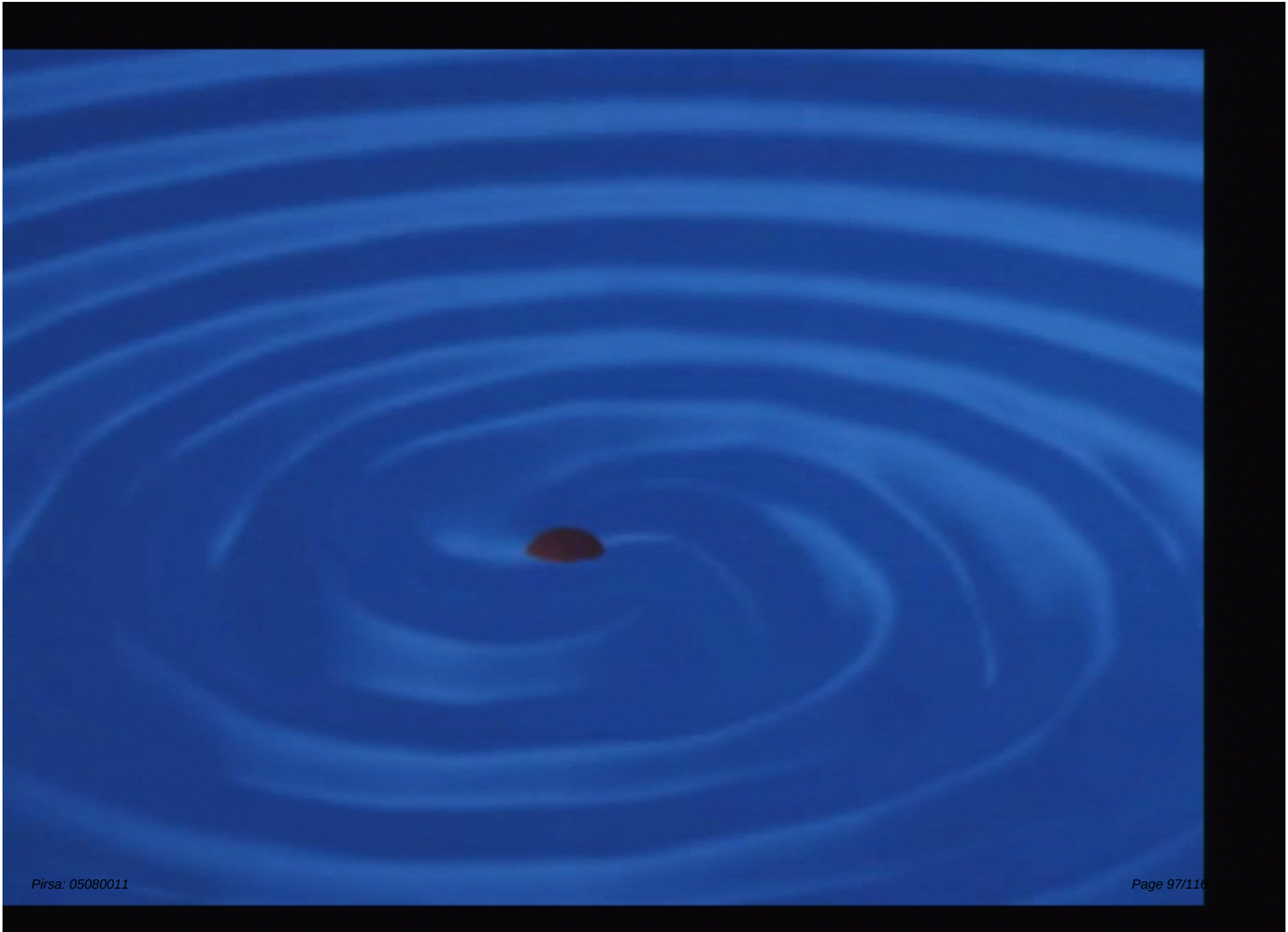
The radio image below shows the central area of the Milky Way. It has been suggested that a massive Black Hole at the center of the Milky Way could be responsible for the central bulge and mini spiral.



Speed of Gas and Black Holes

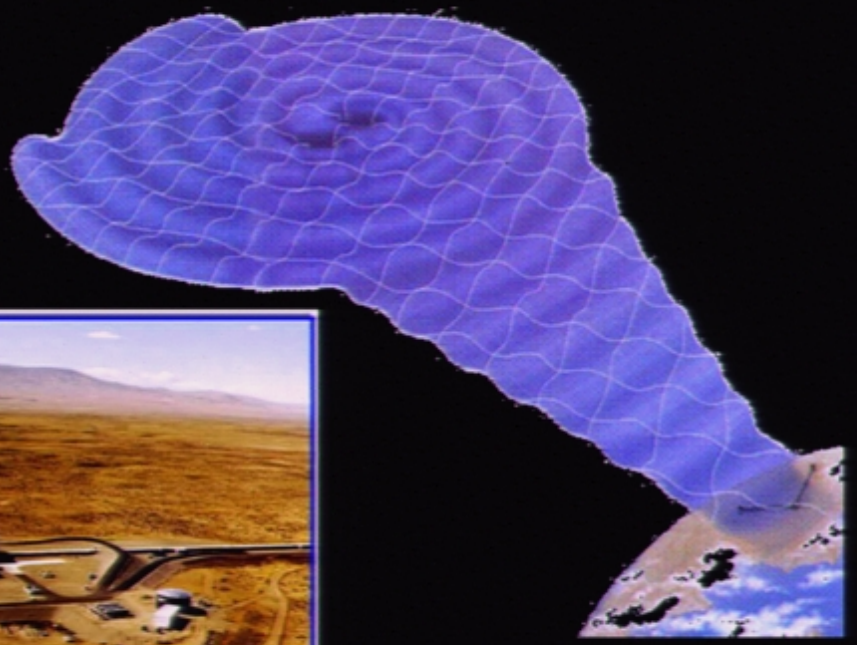


- It discovered a correlation between a Black Hole's mass and the average speed of the stars in the galaxy's central bulge.
- The faster the stars are moving, the larger the black hole.
- The central Black Hole comprises 0.5% of mass of stars in the spheroid of the galaxy. (Magorrian Relation)



Wave Detectection

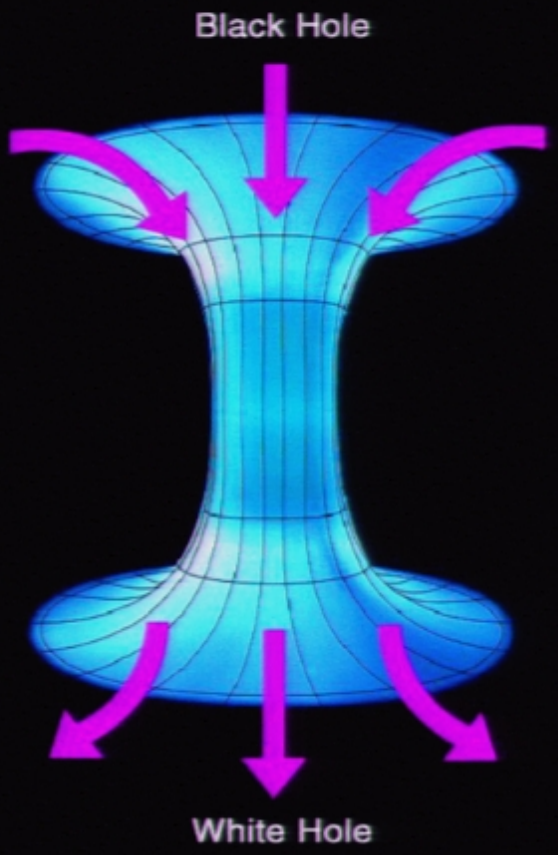
LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA

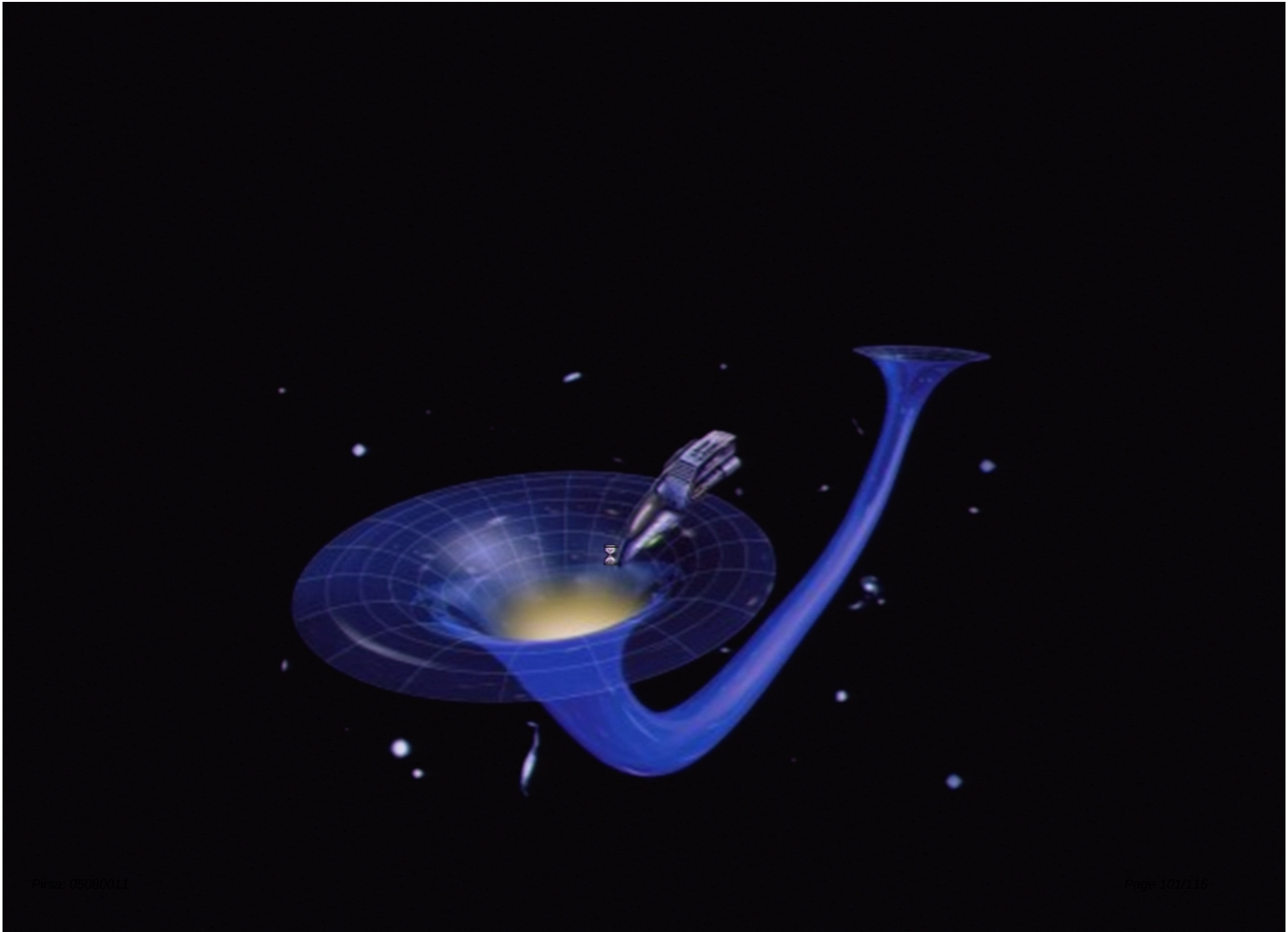


Laser Interferometer Gravitational Wave Observatory (LIGO)

Strange Predictions

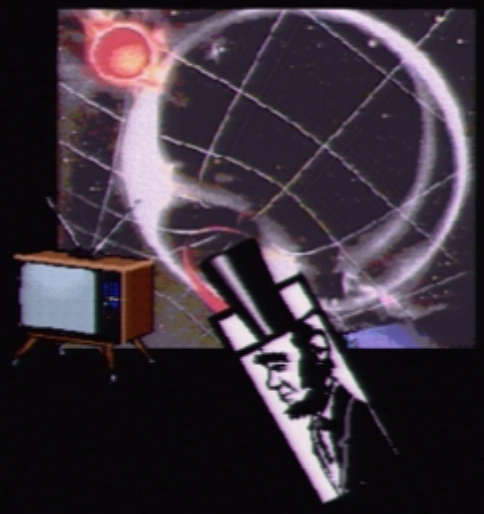
Wormhole



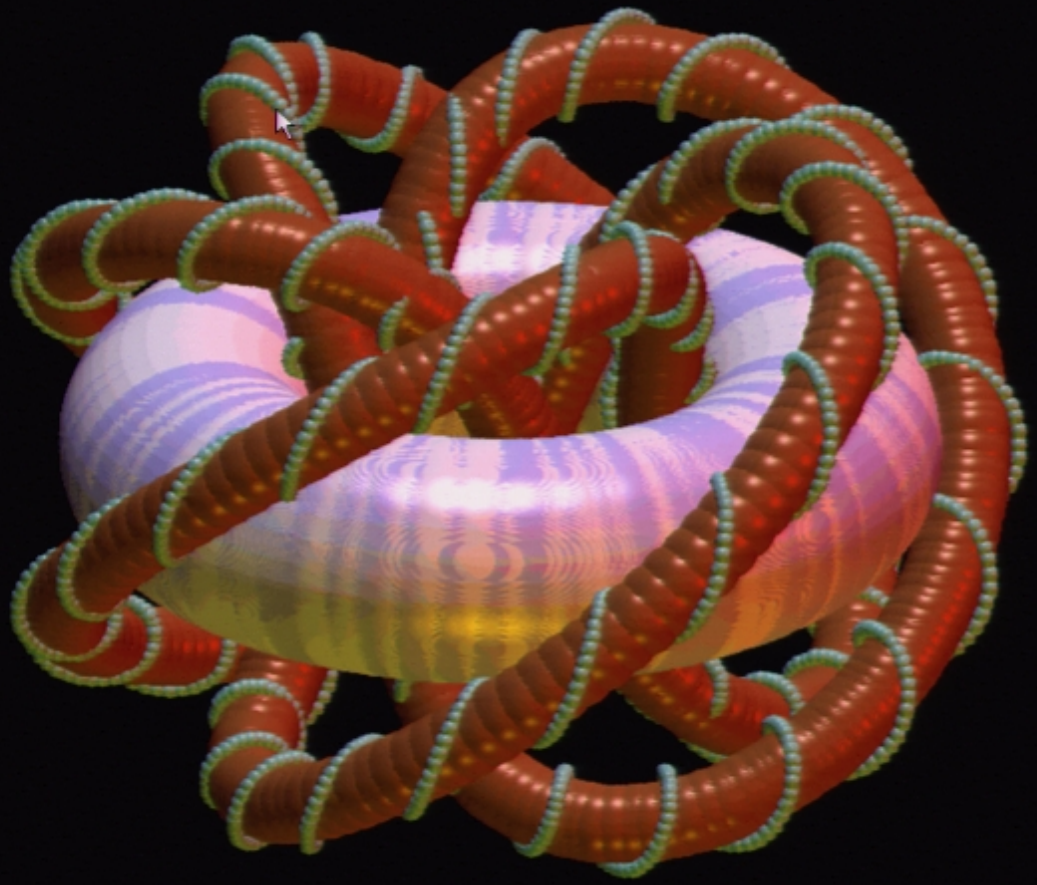


Naked Singularity

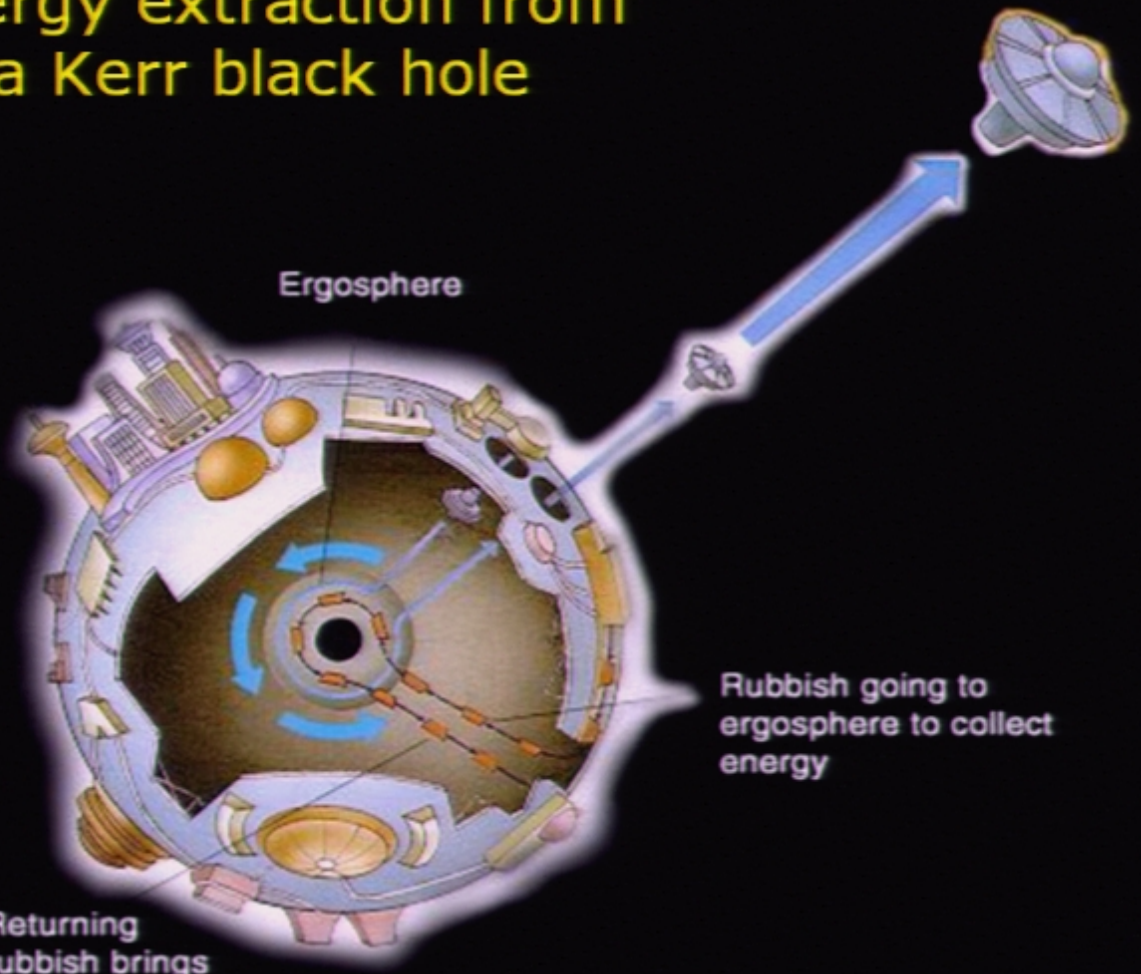
Such a naked singularity would be a breakdown in the laws of physics. After that, you could no longer guess what would come out of the black hole--it could be anything (to quote William H. Press) "from television sets to busts of Abraham Lincoln."



Time Travel

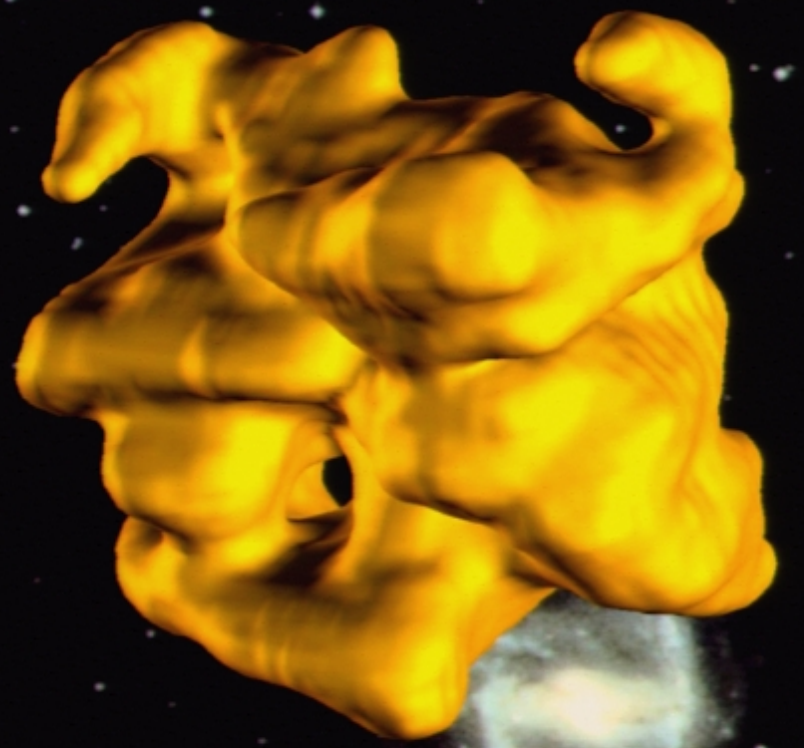


Energy extraction from a Kerr black hole



Naked singularity

Roger Penrose (b1931)

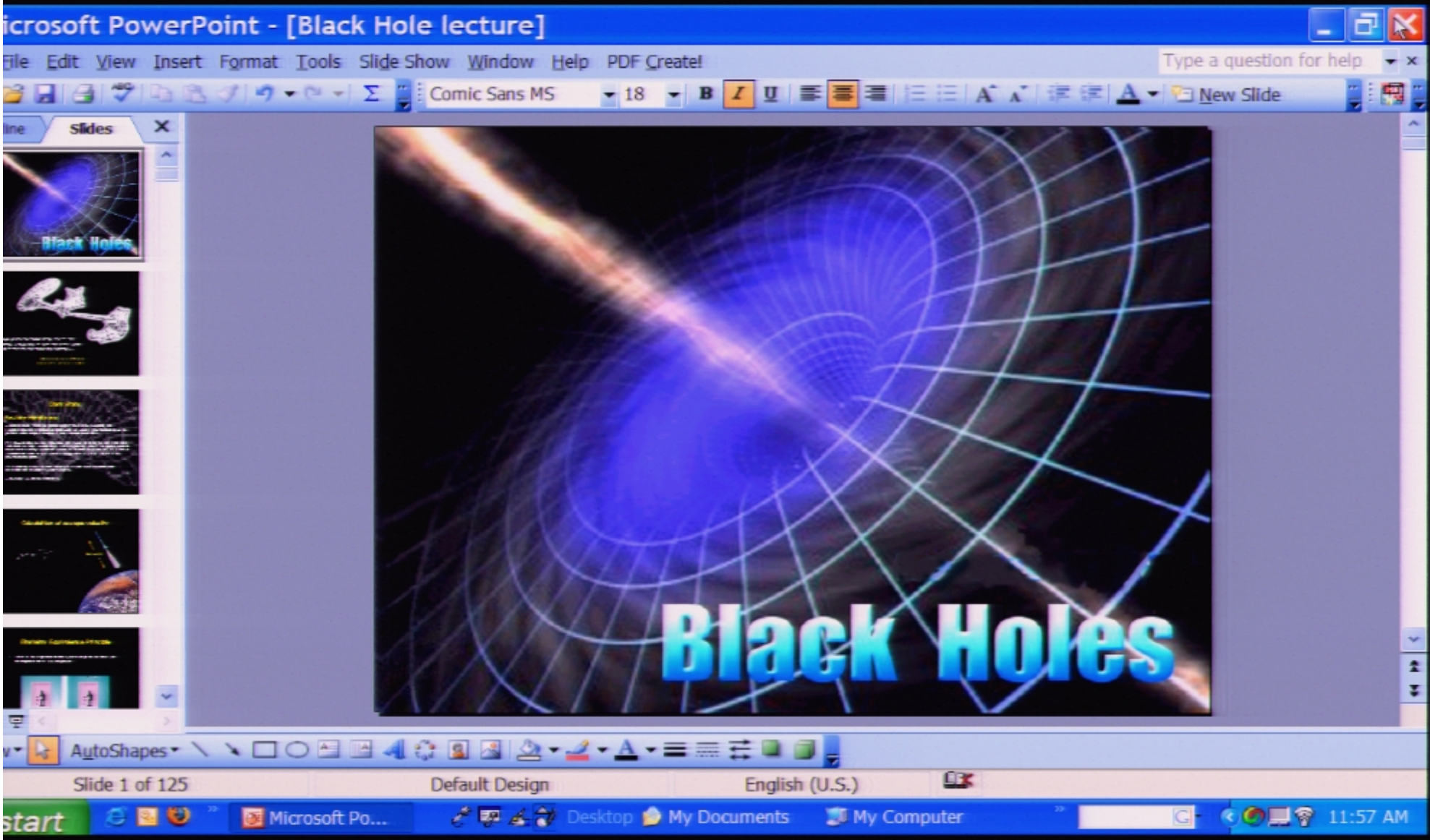


A singularity that is not inside a black hole (not surrounded by an event horizon), and therefore can be seen by someone outside it.

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.


icrosoft PowerPoint - [Black Hole lecture]
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Type a question for help
Comic Sans MS
18
New Slide
Slides
Black Holes
AutoShapes
Slide 1 of 125
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Microsoft Po...
Desktop
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My Computer
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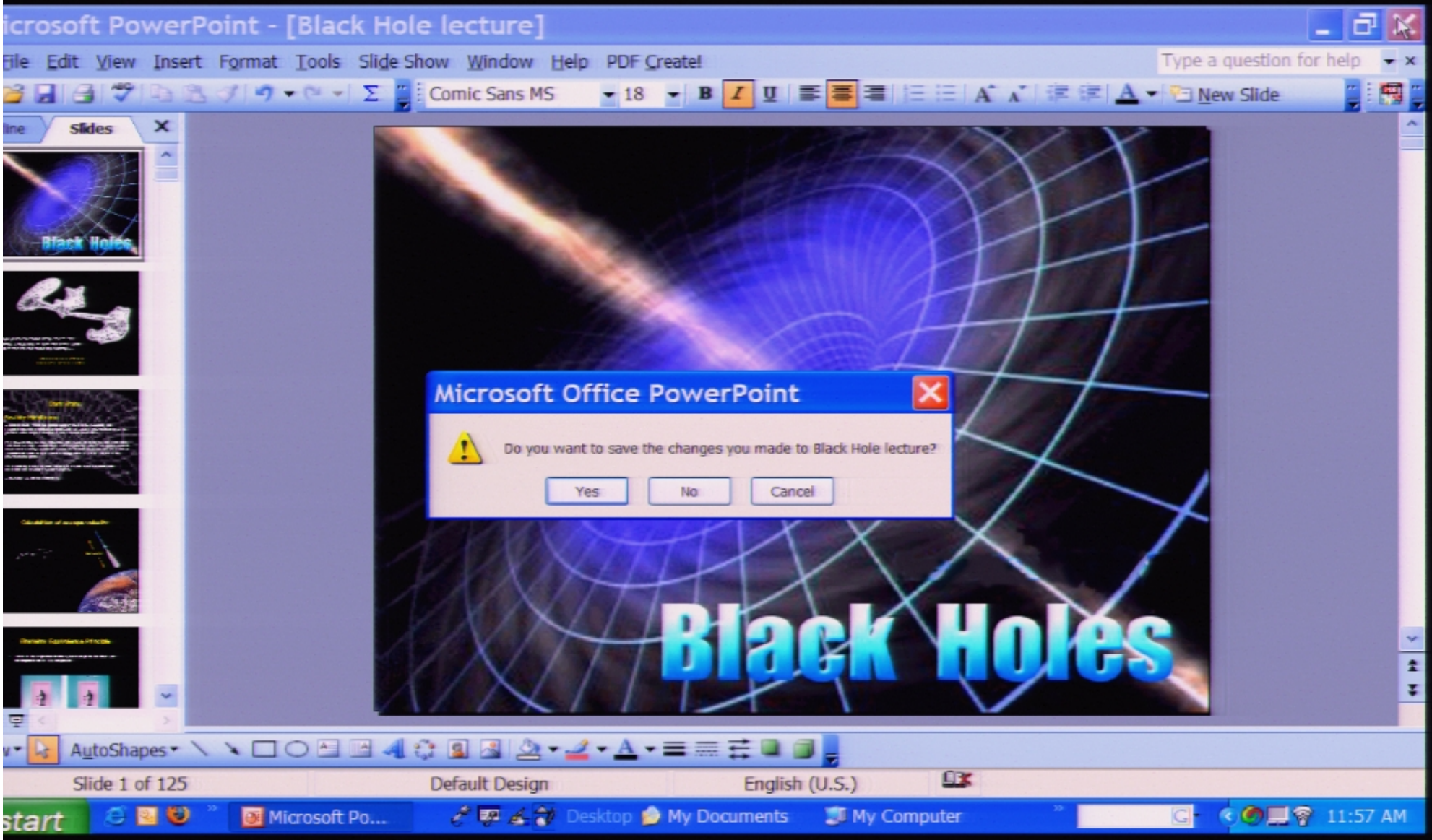
icrosoft PowerPoint - [Black Hole lecture]
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Type a question for help
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Yes
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Cancel
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Slide 1 of 125
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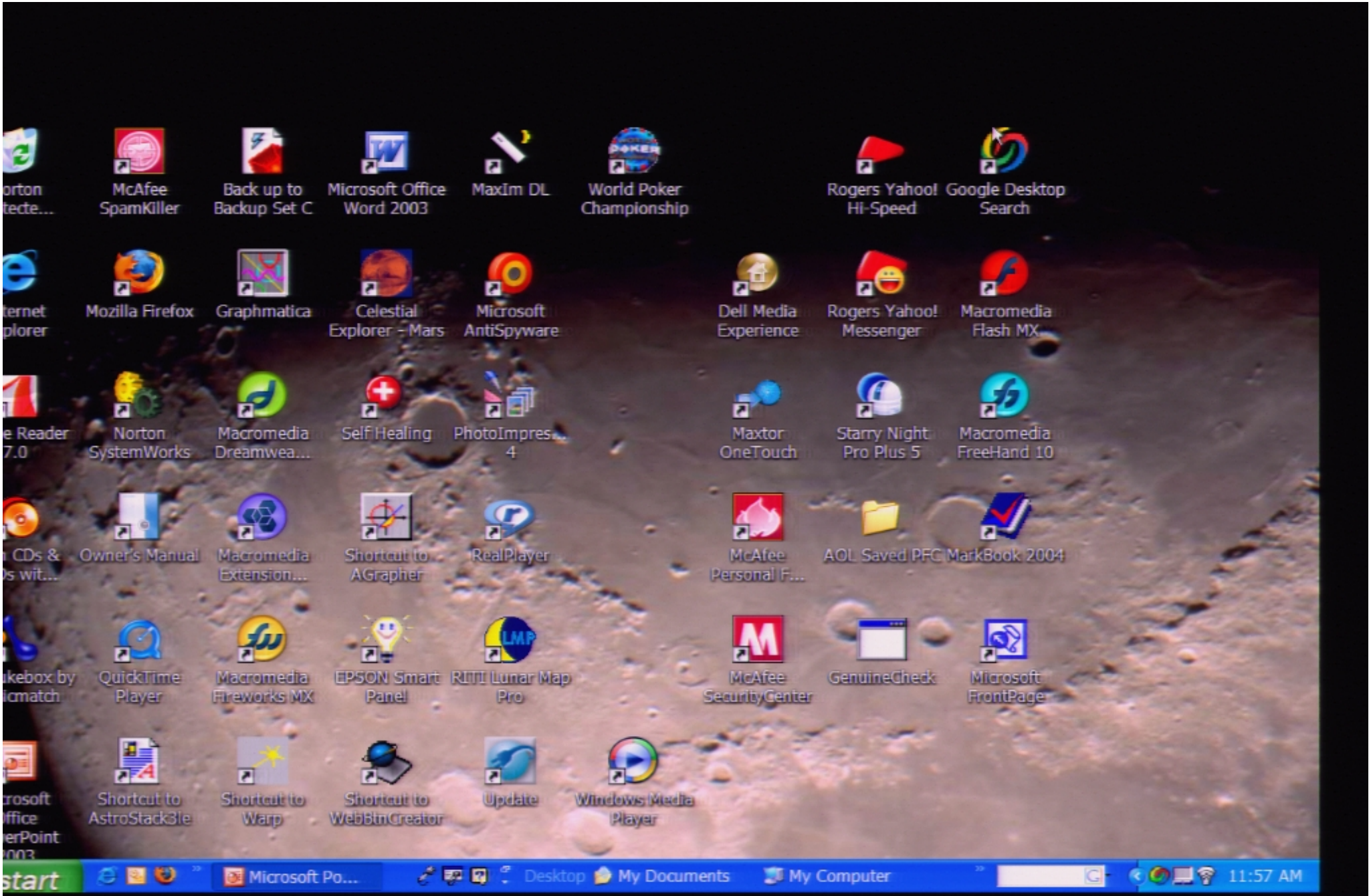
McAfee SpamKiller
Back up to Backup Set C
Microsoft Office Word 2003
MaxIm DL
World Poker Championship
Rogers Yahoo! Hi-Speed
Google Desktop Search
Mozilla Firefox
Graphmatica
Celestial Explorer - Mars
Microsoft AntiSpyware
Dell Media Experience
Rogers Yahoo! Messenger
Macromedia Flash MX
Norton SystemWorks
Macromedia Dreamwea...
Self Healing
PhotoImpres... 4
Maxtor OneTouch
Starry Night Pro Plus 5
Macromedia FreeHand 10
Owner's Manual
Macromedia Extension...
Shortcut to AGrapher
RealPlayer
McAfee Personal F...
AOL Saved PFC
MarkBook 2004
QuickTime Player
Macromedia Fireworks MX
EPSON Smart Panel
RITI Lunar Map Pro
McAfee SecurityCenter
GenuineCheck
Microsoft FrontPage
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start
Microsoft Po...
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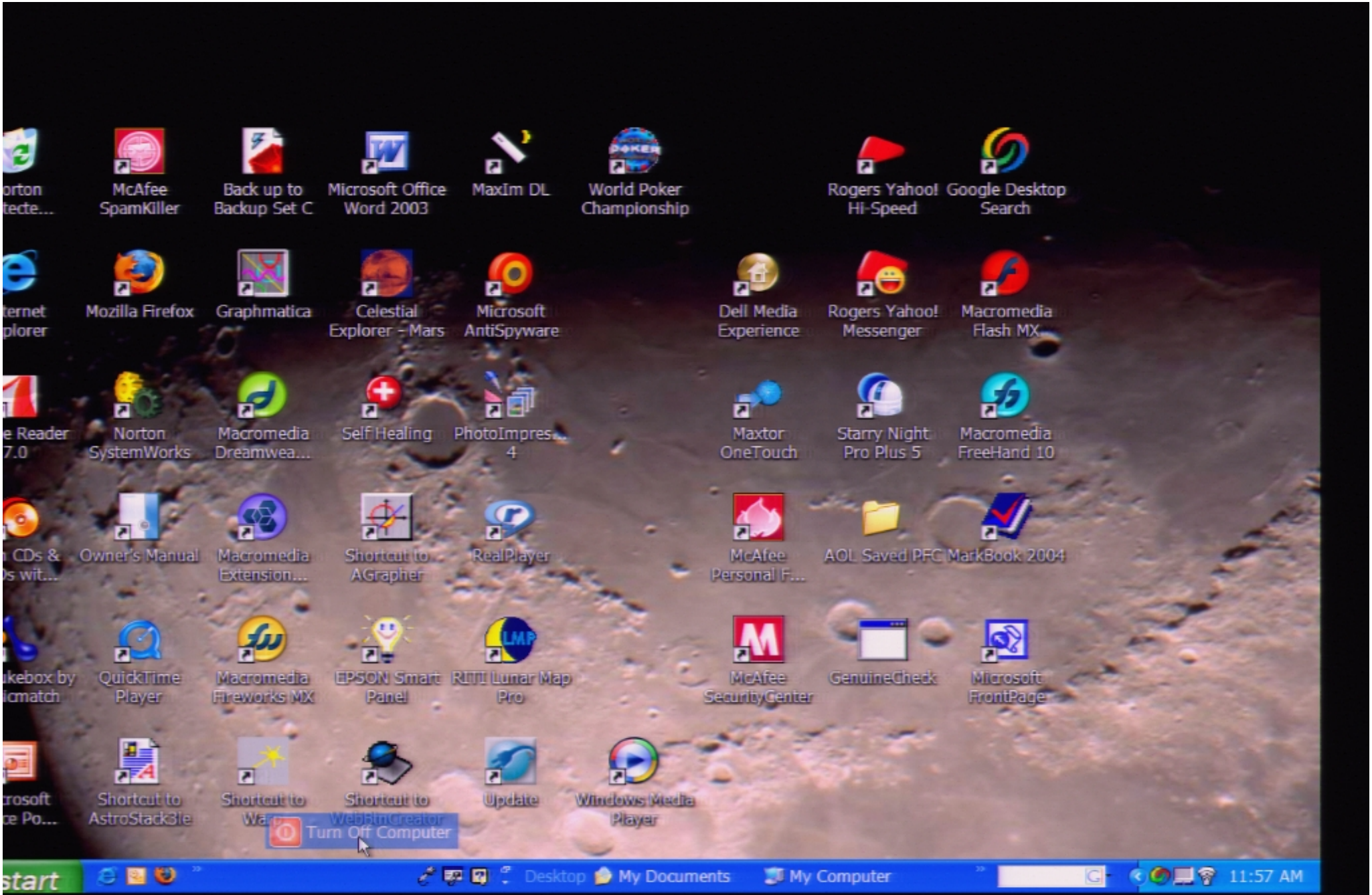
McAfee SpamKiller
Back up to Backup Set C
Microsoft Office Word 2003
MaxIm DL
World Poker Championship
Rogers Yahoo! Hi-Speed
Google Desktop Search
Mozilla Firefox
Graphmatica
Celestial Explorer - Mars
Microsoft AntiSpyware
Dell Media Experience
Rogers Yahoo! Messenger
Macromedia Flash MX
Norton SystemWorks
Macromedia Dreamwea...
Self Healing
PhotoImpres... 4
Maxtor OneTouch
Starry Night Pro Plus 5
Macromedia FreeHand 10
Owner's Manual
Macromedia Extension...
Shortcut to AGrapher
RealPlayer
McAfee Personal F...
AOL Saved PFC
MarkBook 2004
QuickTime Player
Macromedia Fireworks MX
EPSON Smart Panel
RITI Lunar Map Pro
McAfee SecurityCenter
GenuineCheck
Microsoft FrontPage
Shortcut to AstroStack3le
Update
Windows Media Player
Turn Off Computer
start
Desktop
My Documents
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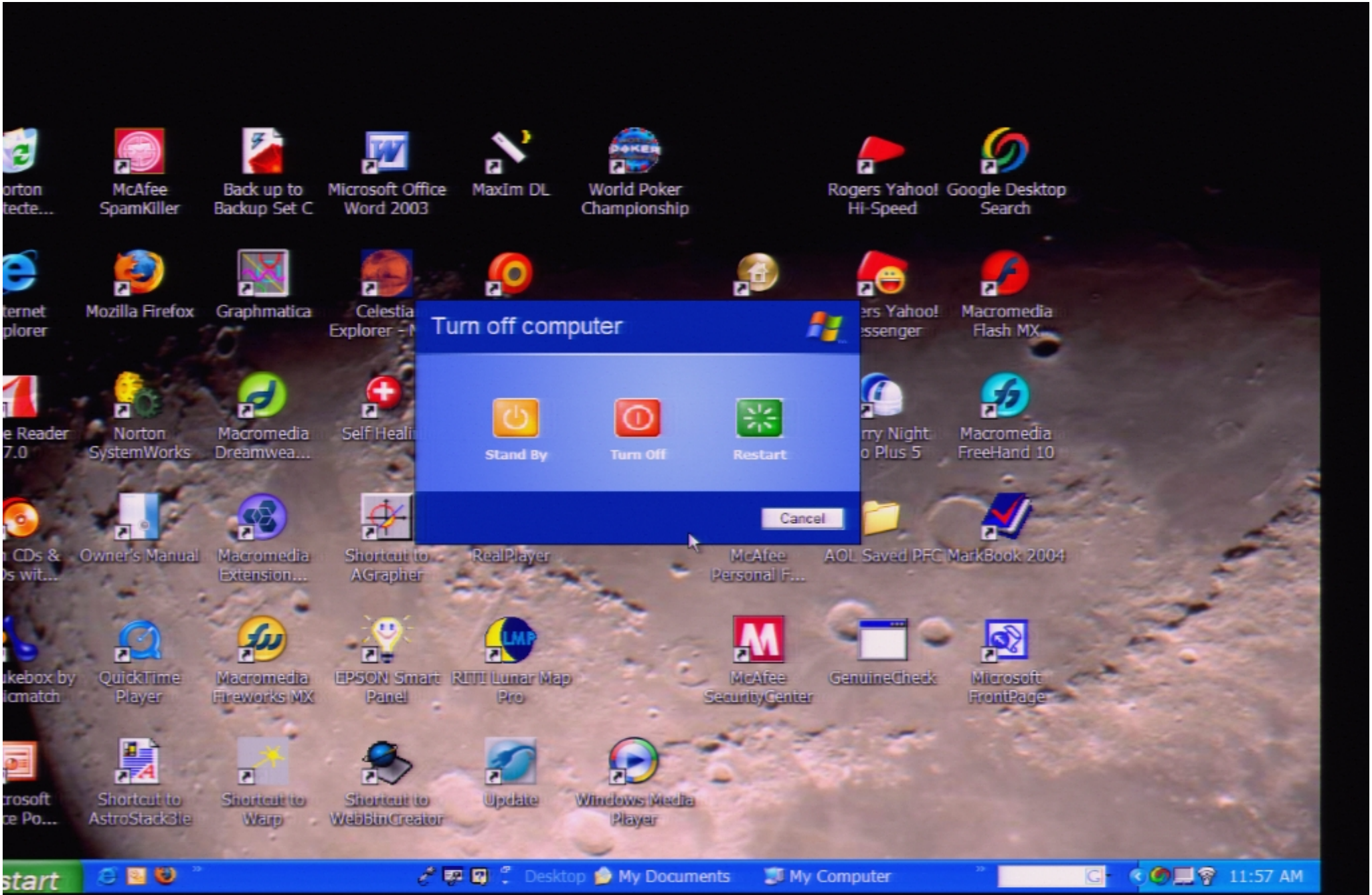
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World Poker Championship
Rogers Yahoo! Hi-Speed
Google Desktop Search
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Owner's Manual
Macromedia Extension...
Shortcut to AGrapher
RealPlayer
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Macromedia Fireworks MX
EPSON Smart Panel
RITI Lunar Map Pro
McAfee SecurityCenter
GenuineCheck
Microsoft FrontPage
Shortcut to AstroStack3le
Shortcut to Warp
Shortcut to WebBtnCreator
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Turn off computer
Stand By
Turn Off
Restart
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Desktop
My Documents
My Computer
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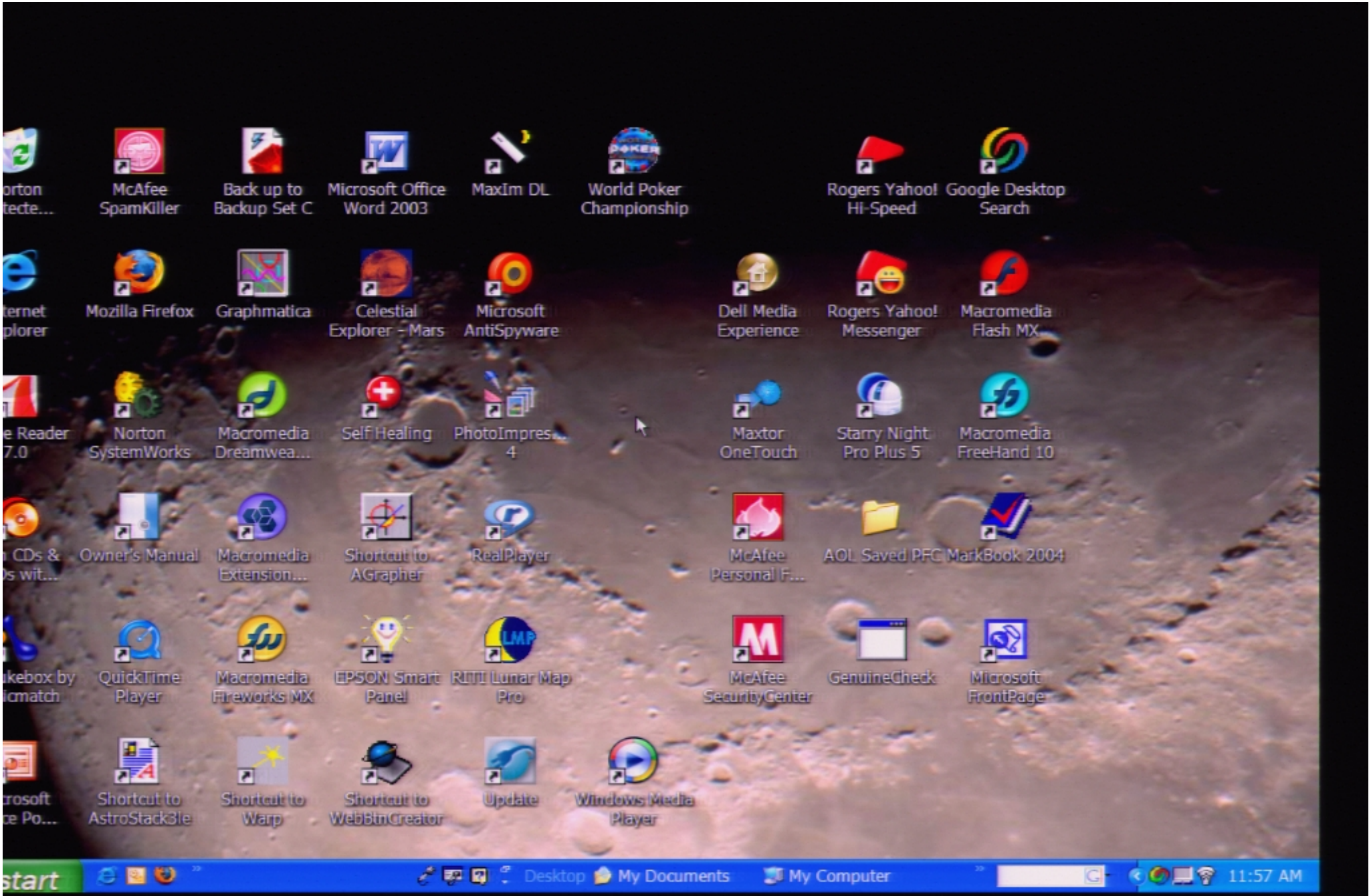
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Microsoft AntiSpyware
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Rogers Yahoo! Messenger
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Maxtor OneTouch
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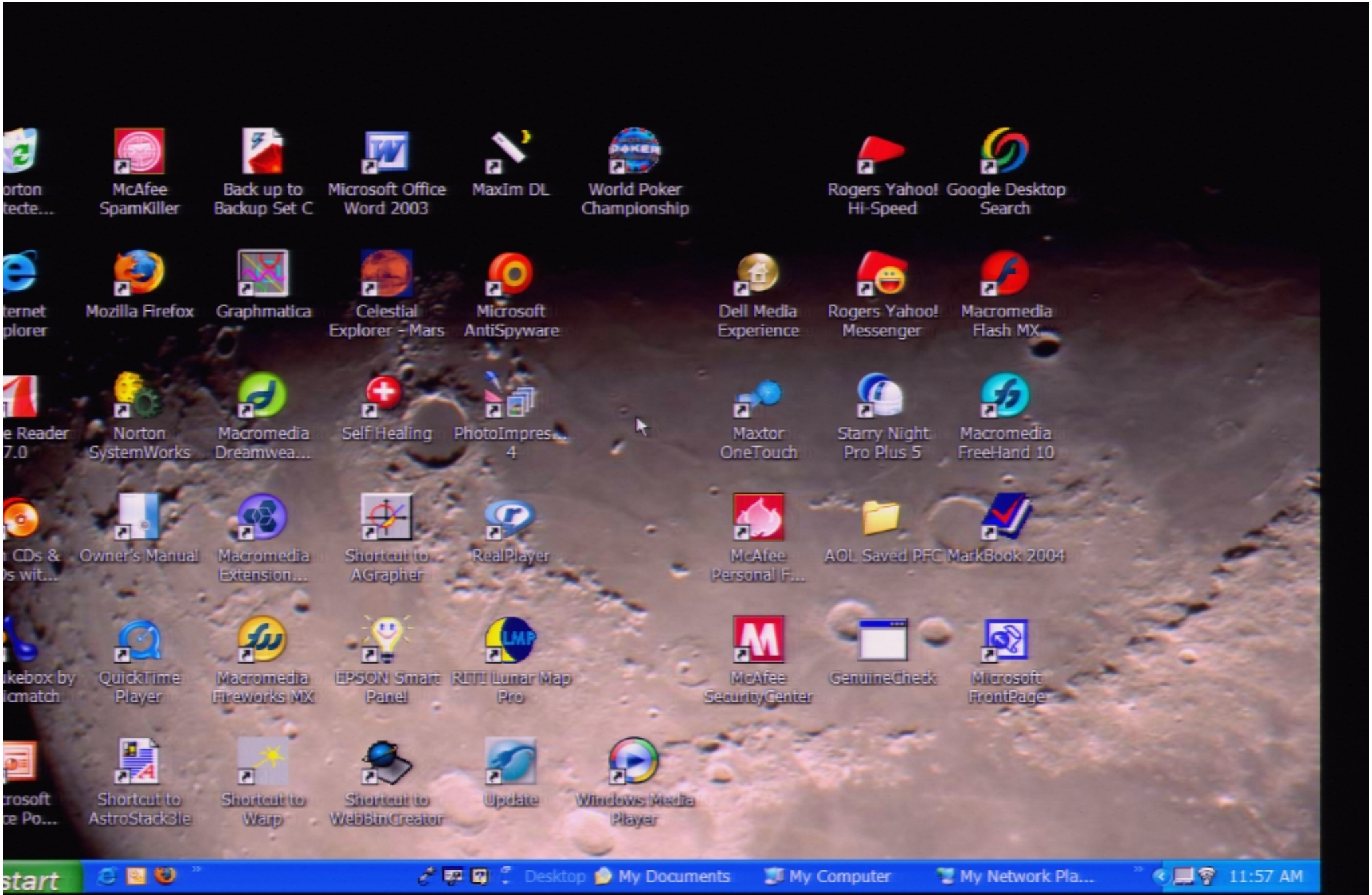
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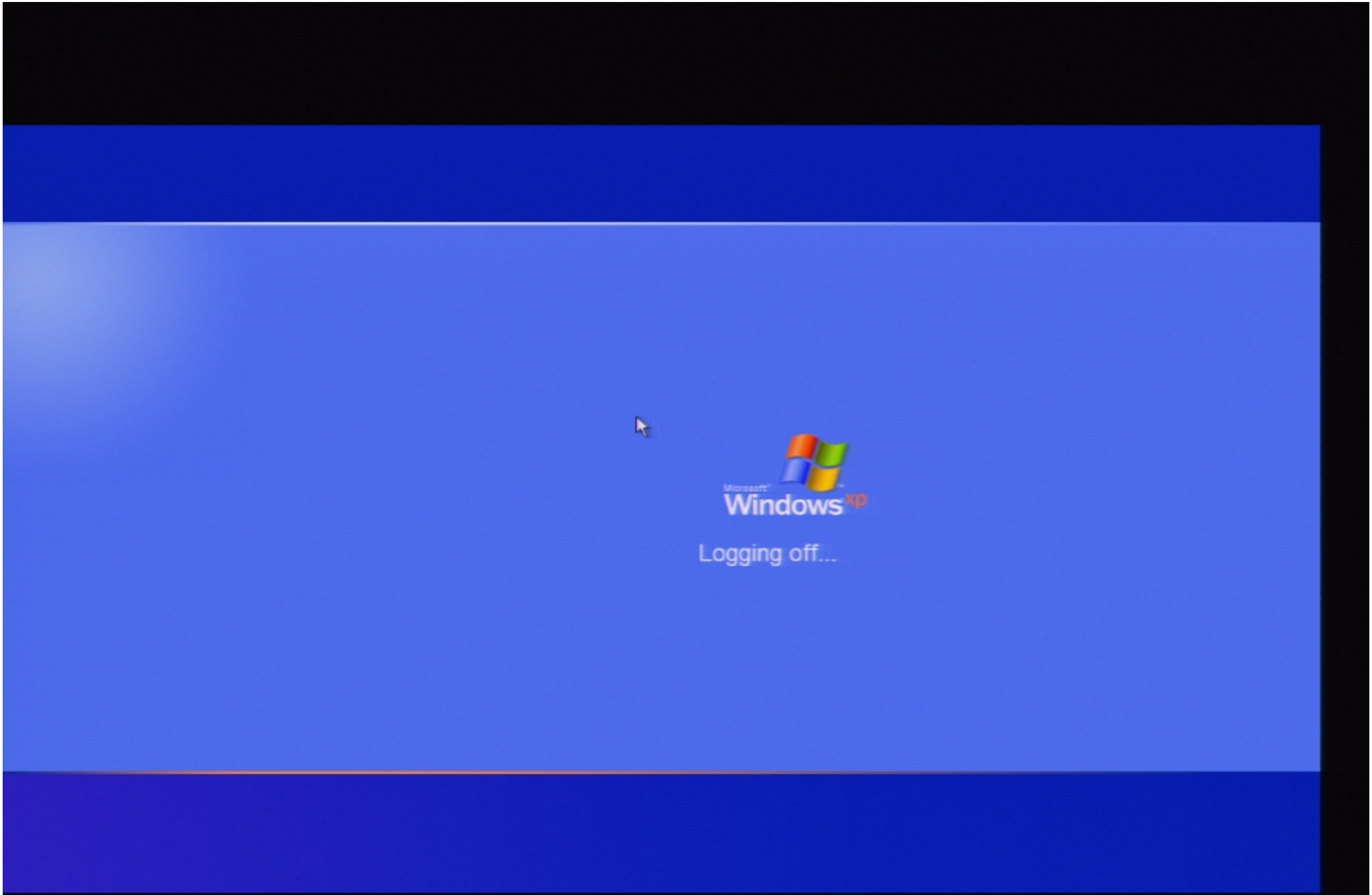
Microsoft
Windows xp
Logging off...