
Front-row seat on the daily life
of a supermassive black hole
Joss Bland-Hawthorn
University of Sydney
@jossblandhawtho

The original astronomers

Milky Way's centre exploded 3.5 Myr ago

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Science

Milky Way's centre exploded 3.5 million years ago

A cataclysmic energy flare started near the massive black hole in our galaxy, a new research says.

7h | Science & Environment

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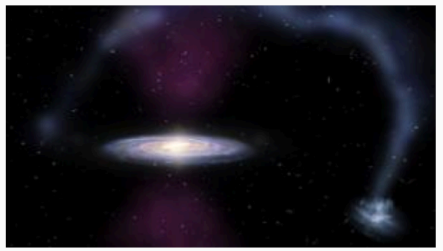
Second whistleblower comes forward

Top stories

US envoy's wife who fled UK after fatal crash was driving on wrong side of road



Milky Way exploded when our ancestors walked the Earth

This is how 'Brexit Day' could play out

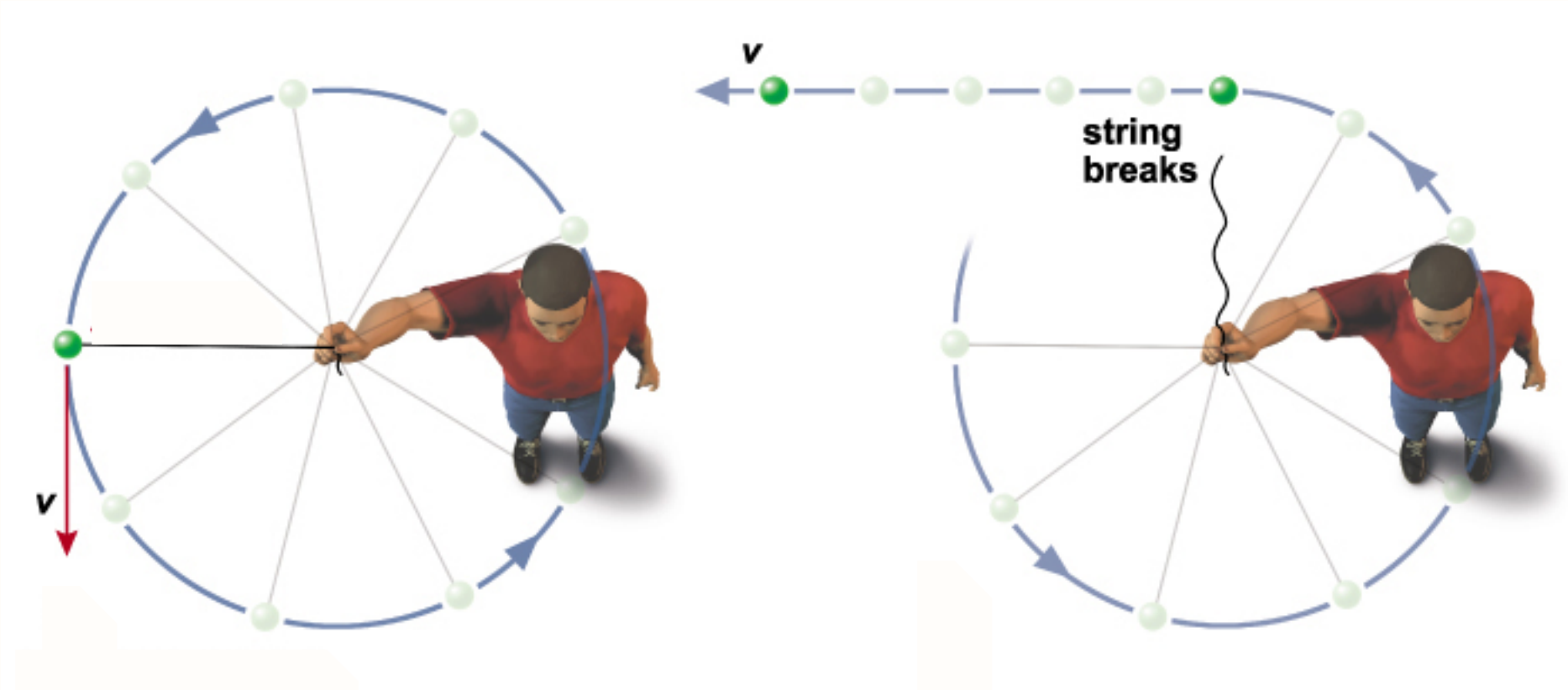
Key witness in ex-cop's murder conviction shot dead days after trial

Pigs seen using tools for the first time

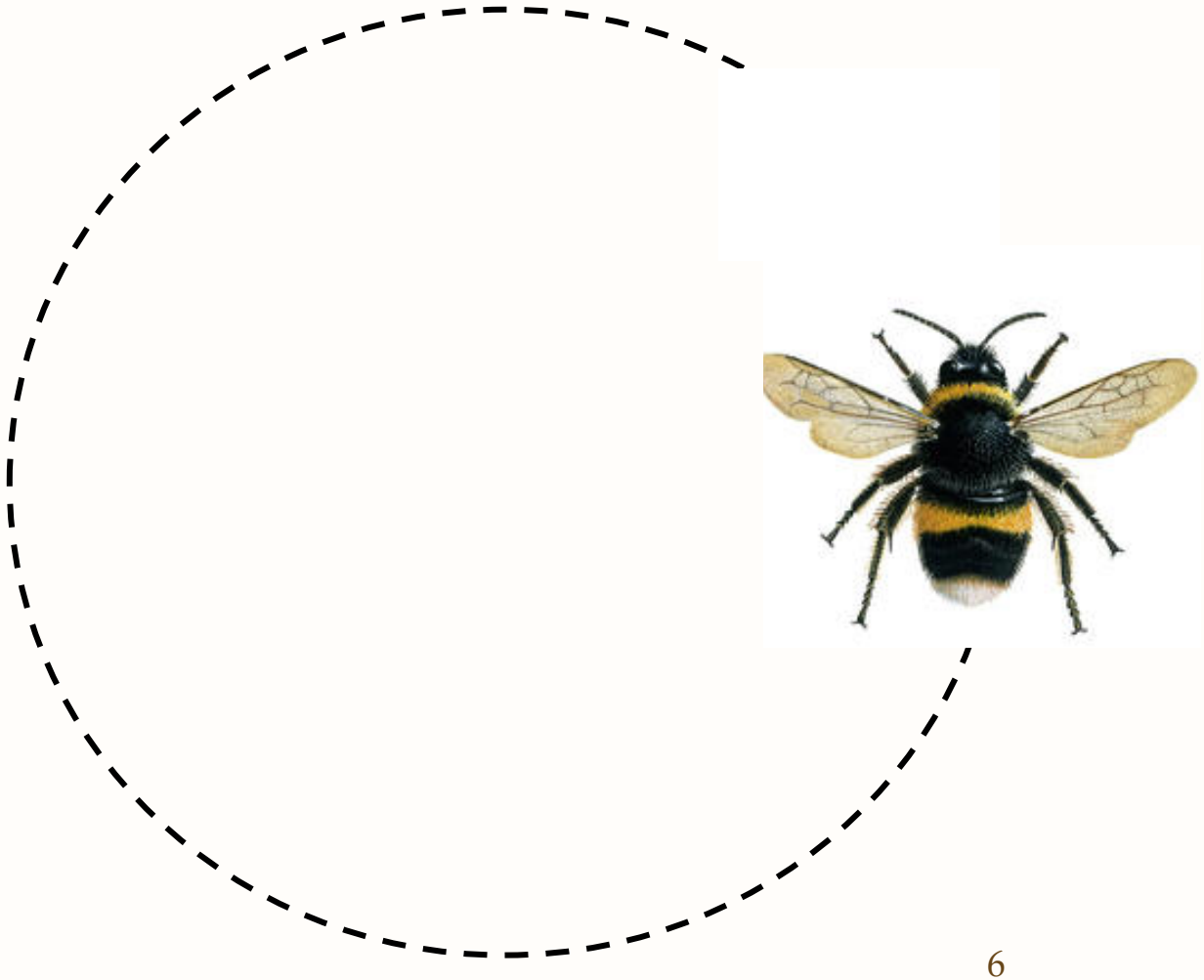
So what holds the moon in orbit?

There’s nothing obvious about gravity.

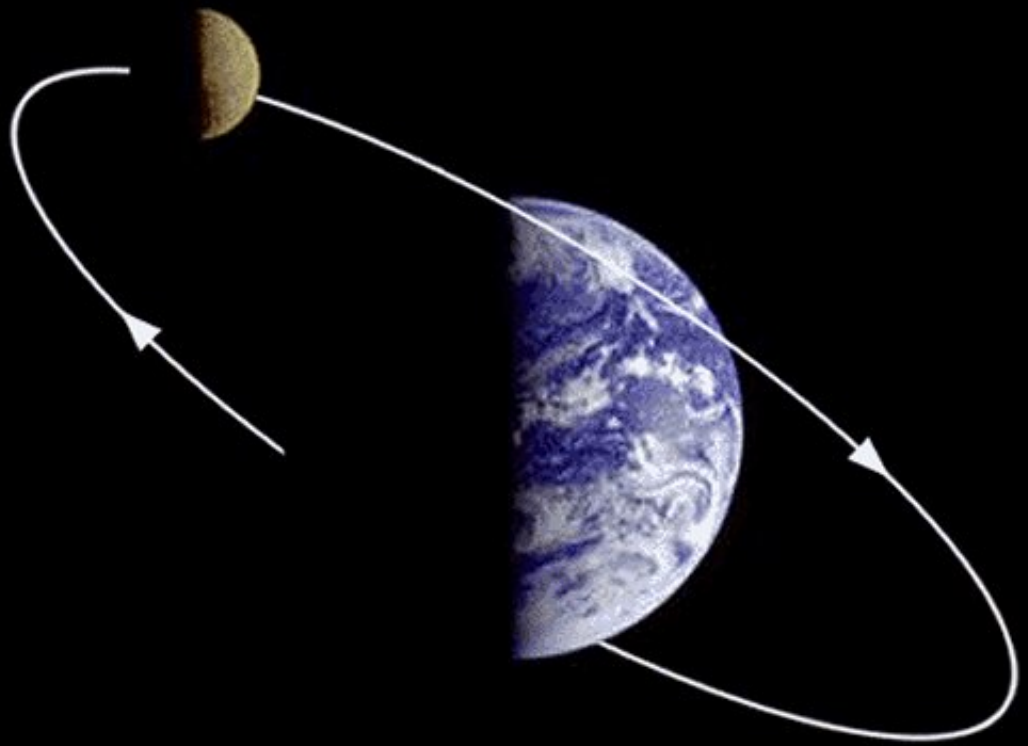
The ball orbits because of the string

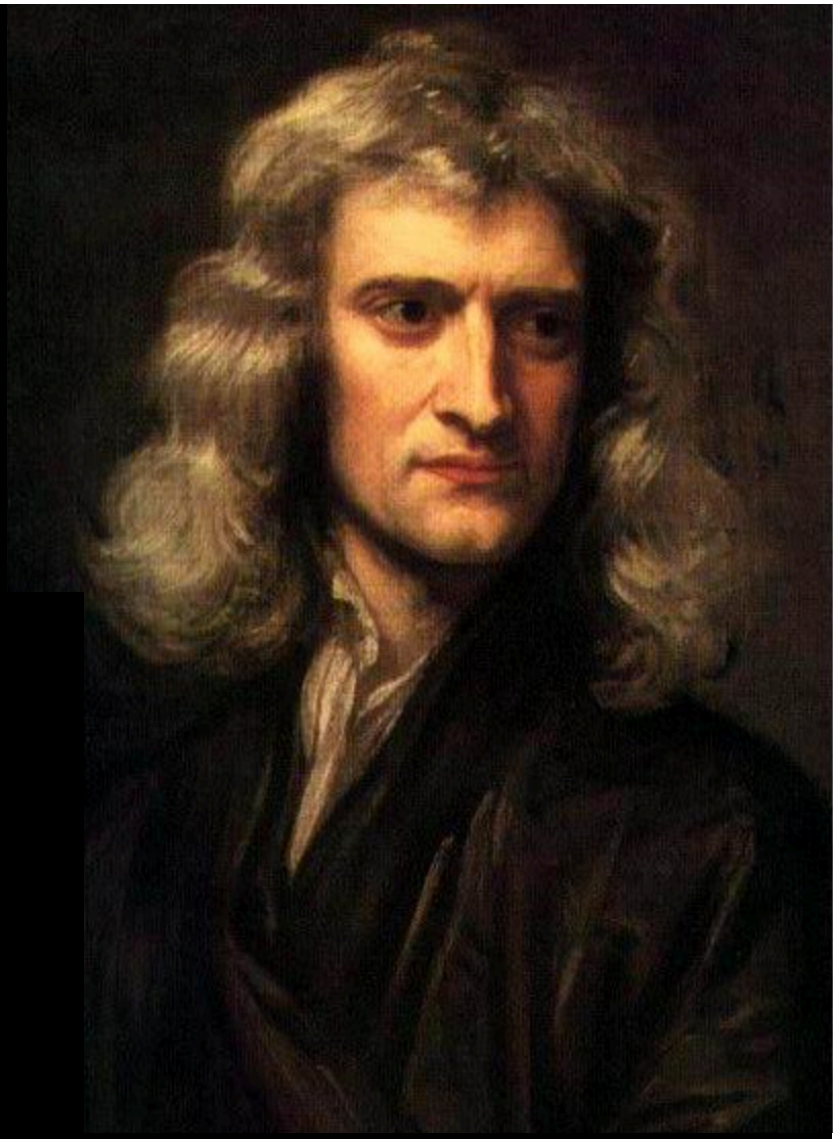


The bee orbits because of its internal energy



Isaac Newton (1642-1727)





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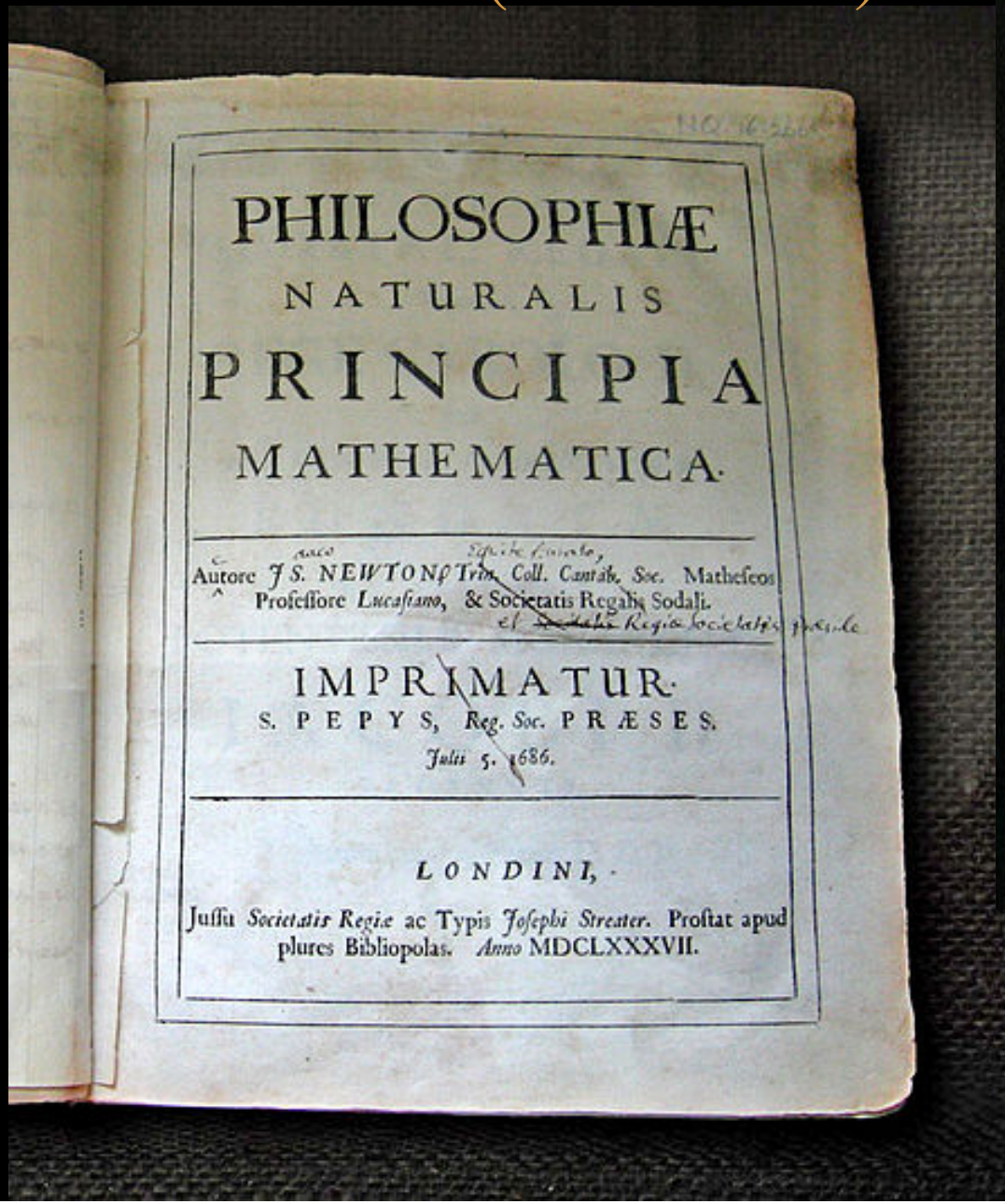
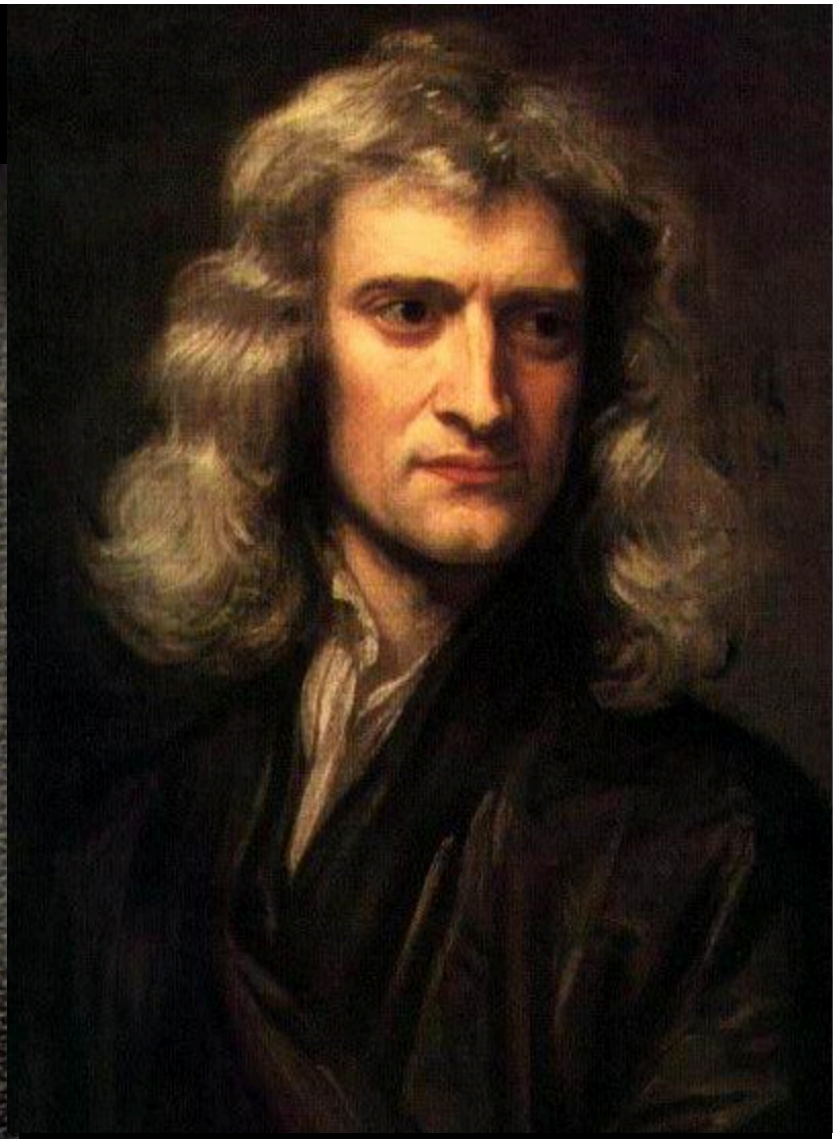


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

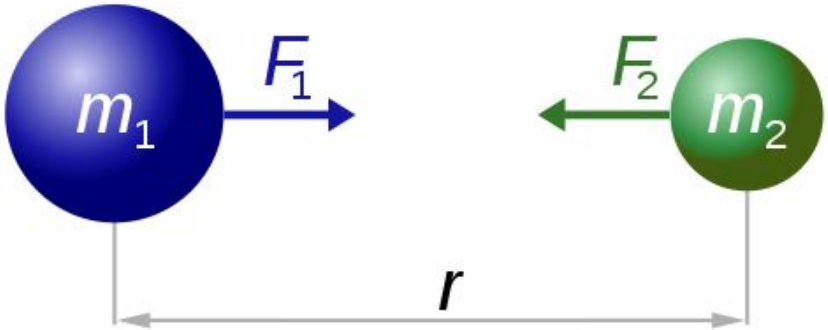
Autore *J. S. NEWTON* Trin. Coll. Cantab. Soc. Matheseos
Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

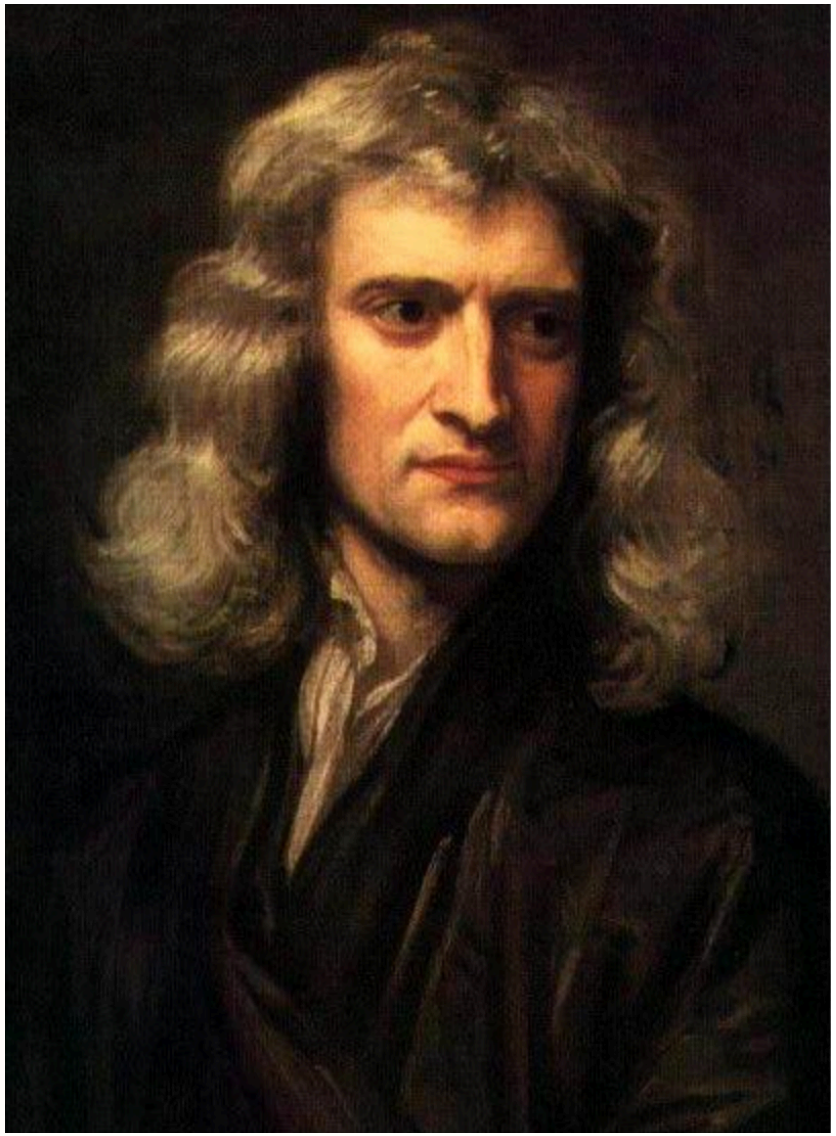
LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.



Isaac Newton (1642-1727)



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$



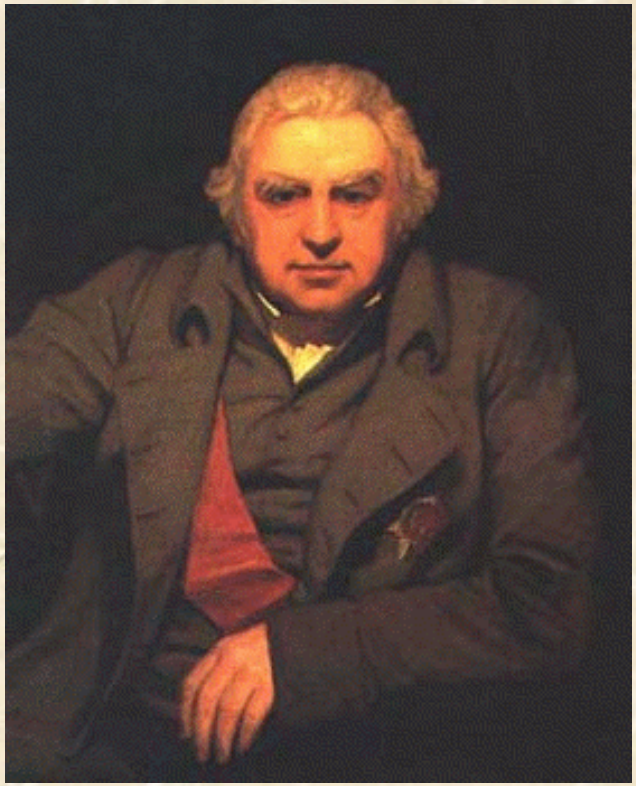
I will limit this talk to a couple of equations

1783: John Mitchell first discussed idea of black holes

VII. *On the Means of diſcovering the Diſtance, Magnitude, &c. of the Fixed Stars, in conſequence of the Diminution of the Velocity of their Light, in caſe ſuch a Diminution ſhould be found to take place in any of them, and ſuch other Data ſhould be procured from Obſervations, as would be farther neceſſary for that Purpoſe. By the Rev.* John Michell, *B. D. F. R. S. In a Letter to* Henry Cavendiſh, *Eſq. F. R. S. and A. S.*

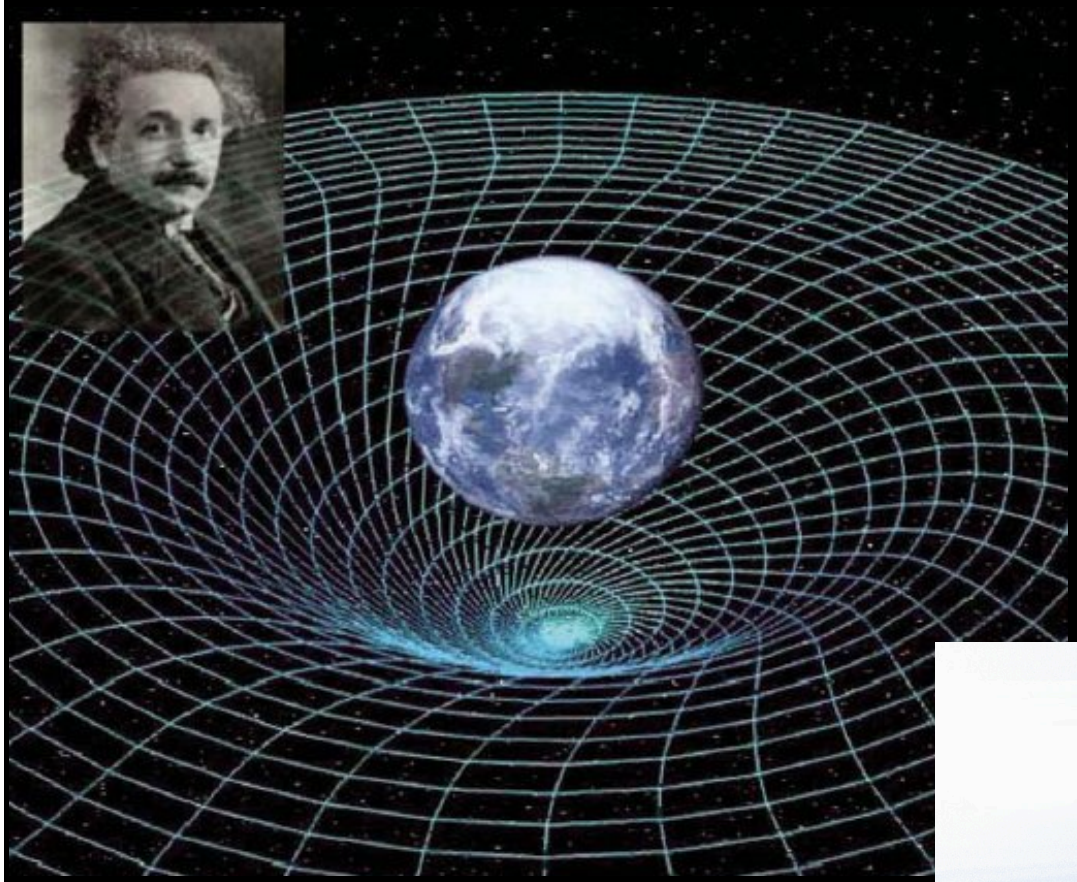
Read November 27, 1783.

29. If there ſhould really exiſt in nature any bodies, whoſe denſity is not leſs than that of the ſun, and whoſe diameters are more than 500 times the diameter of the ſun, ſince their light could not arrive at us; or if there ſhould exiſt any other bodies of a ſomewhat ſmaller ſize, which are not naturally luminous; of the exiſtence of bodies under either of theſe circumſtances, we could have no information from ſight; yet, if any other luminous bodies ſhould happen to revolve about them we might ſtill perhaps from the motions of theſe revolving bodies infer the exiſtence of the central ones with ſome degree of probability, as this might afford a clue to ſome of the apparent irregularities of the revolving bodies, which would not be eaſily explicable on any other hypotheſis; but as the conſequences of ſuch a ſuppoſition are very obvious, and the conſideration of them ſomewhat beſide my preſent purpoſe, I ſhall not proſecute them any farther.



1783: Sir Joseph Banks
"A Proposal for Establishing a Settlement in NSW"

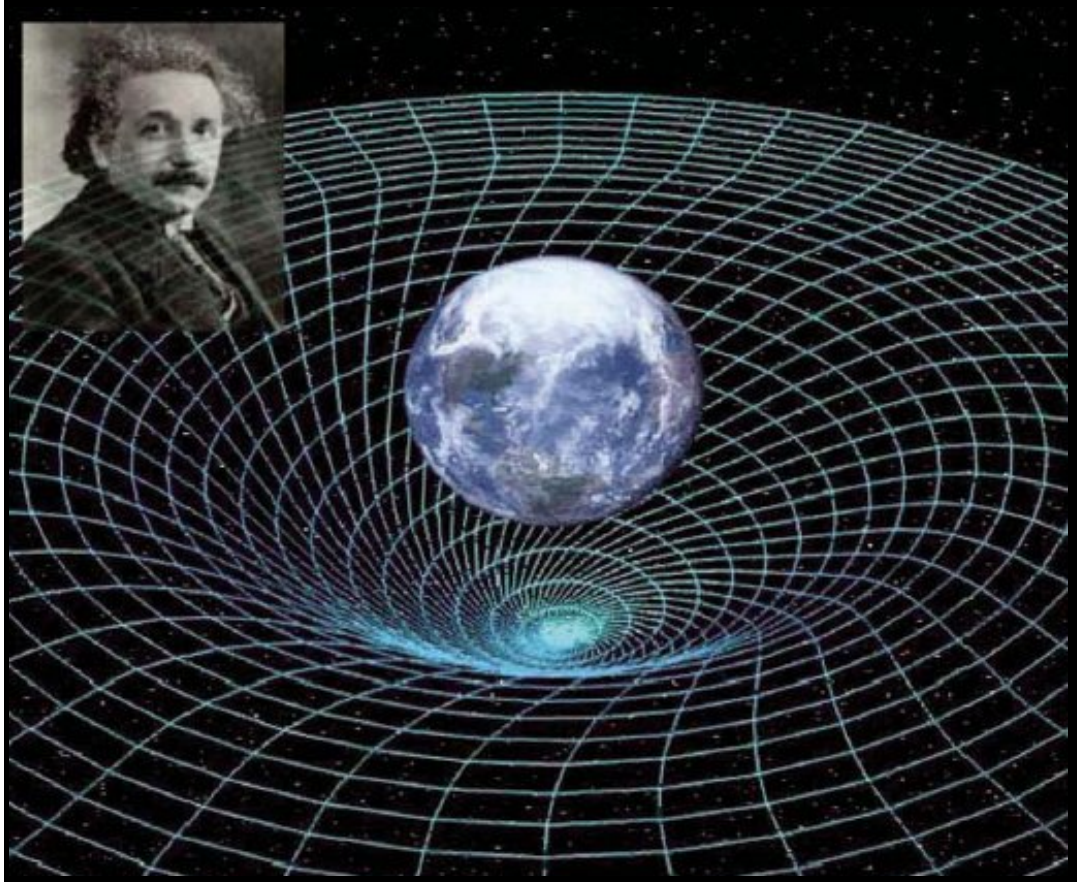
1916: Einstein's General Theory of Relativity



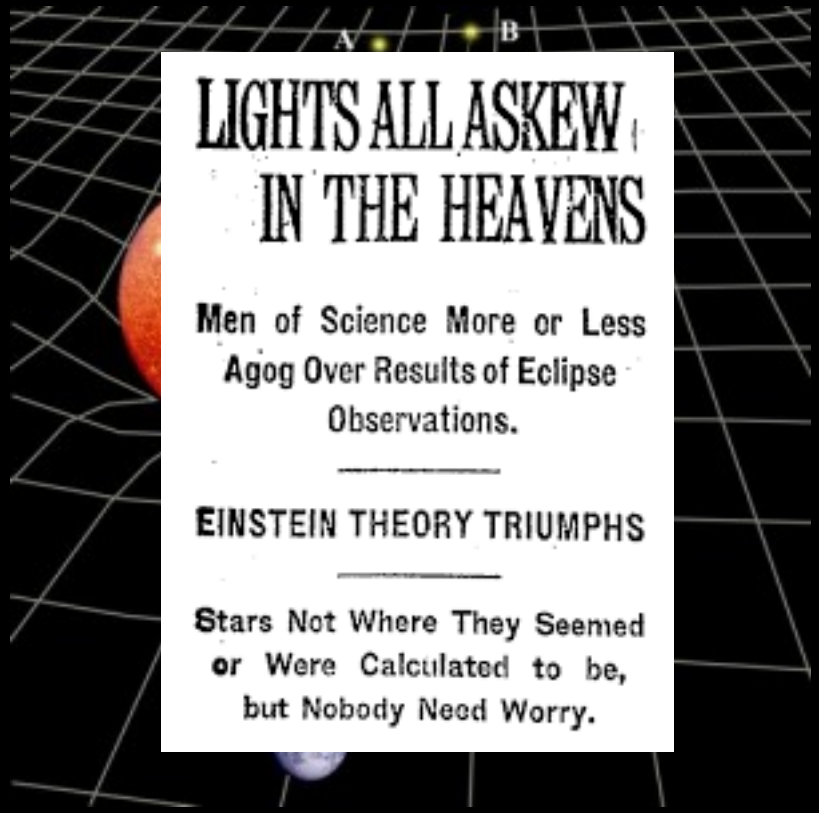
Gravity maintained by waves propagating through space-time

Einstein was unsure about "gravitational waves" but a colleague encouraged him to stick with it.

1916: Einstein's General Theory of Relativity



1919: total eclipse of the Sun



LIGHTS ALL ASKEW IN THE HEAVENS

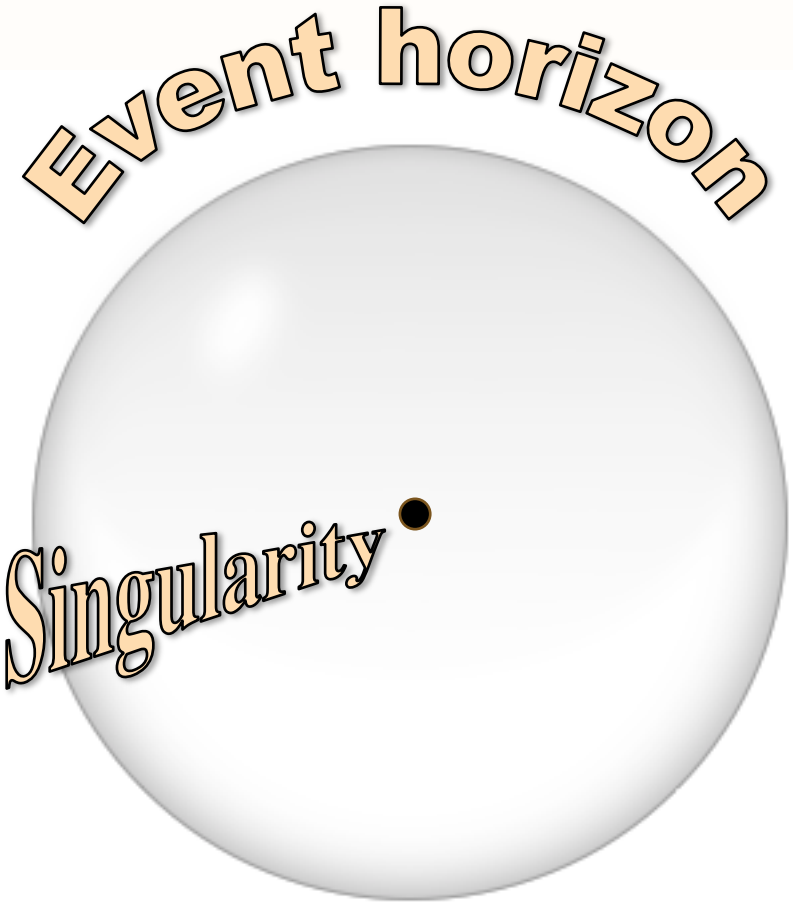
Men of Science More or Less Agog Over Results of Eclipse Observations.

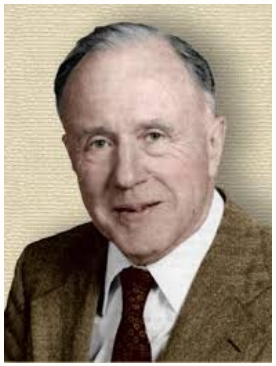
EINSTEIN THEORY TRIUMPHS

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

1939: Einstein claimed black holes may **not** exist; Oppenheimer and Chandrasekhar thought they would.

1958: no evidence yet for **black holes** but Finkelstein found they probably exist and have this structure, i.e. one-way membrane:





Arguably, Dennis Sciama (Oxford, Trieste) had the strongest influence on the development of black hole theory…

Stephen Hawking

George F. R. Ellis

Martin Rees

Brandon Carter

David Deutsch

John D. Barrow

Gary Gibbons

Philip Candelas

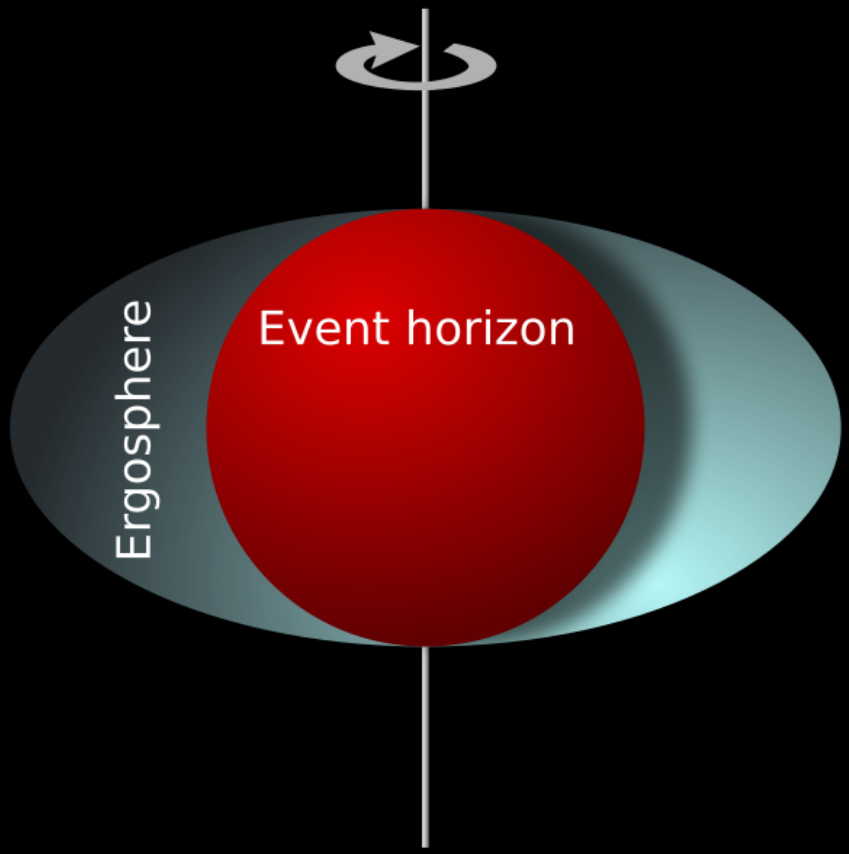
James Binney

Adrian Melott

Tim Palmer

Antony Valentini

1963: black holes rotate !



2009 biography:
Cracking the Einstein code, F. Melia

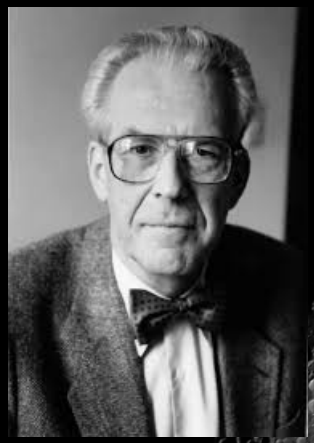
2016 Crafoord Prize:
Roy Kerr & Roger Blandford

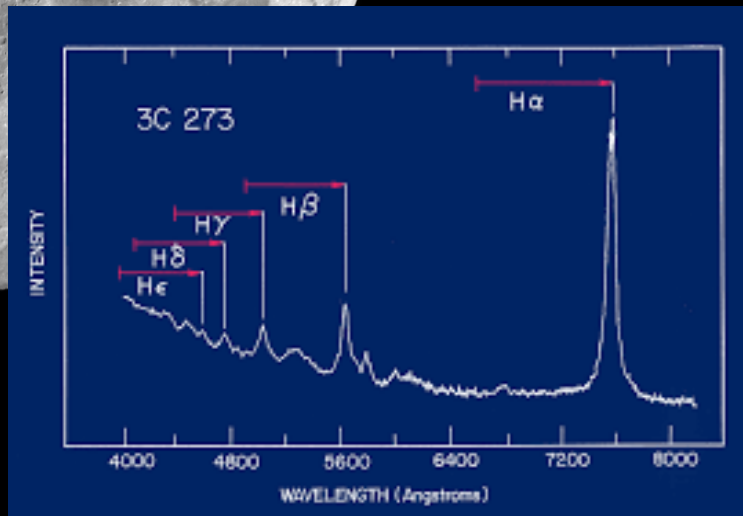
Roy Kerr

1963: a golden year for Australian-US astronomy

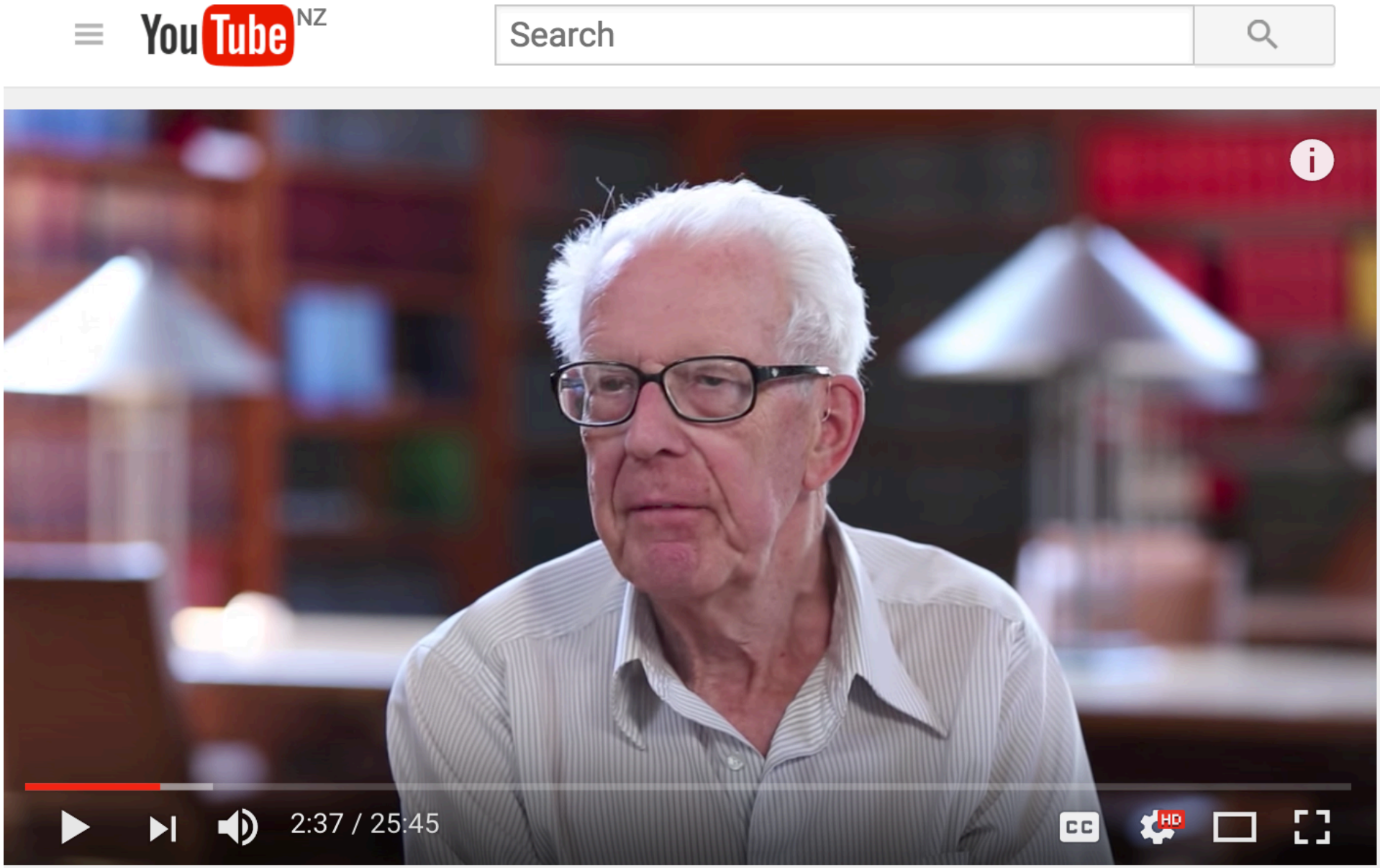
Lunar occultation of
"radio star" 3C273
using Parkes telescope

2008 Kavli Prize





The discovery of quasars:
galaxies in the early universe powered by supermassive black holes at their cores



A Conversation with Maarten Schmidt - The Discovery of Quasars

Who is this ?

1920: born in Wisconsin

1941: graduates in physics & chemistry

1942: joins US navy

1946: gets pilot's license

1972: first woman elected to National Press Club

2010: dies aged 89

Ann Ewing

1920: born in Wisconsin

1941: graduates in physics & chemistry

1942: joins US navy

1946: gets pilot's license

1964: coins term "black hole"

1972: first woman elected to National Press Club

2010: dies aged 89

ASTRONOMY

"Black Holes" in Space

The heavy densely packed dying stars that speckle space may help determine how matter behaves when enclosed in its own gravitational field—By Ann Ewing

➤ SPACE may be peppered with "black holes."

This was suggested at the American Association for the Advancement of Science meeting in Cleveland by astronomers and physicists who are experts on what are called degenerate stars.

Degenerate stars are not Hollywood types with low morals. They are dying stars, or white dwarfs, and make up about 10% of all stars in the sky.

The faint light they emit comes from the little heat left in their last stages of life. It is not known how a star quietly declines to become a white dwarf.

Degenerate stars are made of densely packed electrons and nuclei, or cores of atoms. They are so dense that a thimbleful of their matter weighs a ton.

Some such stars are predicted in theory to have a density of one million tons per thimbleful. When this happens, the star is essentially made of neutrons and strange particles.

Because a degenerate star is so dense, its gravitational field is very strong. According to Einstein's general theory of relativity, as mass is added to a degenerate star a sudden collapse will take place and the intense gravitational field of the star will close in on itself.

Such a star then forms a "black hole" in the universe.

Modern tools, such as telescopes on an orbiting space platform, may be used to detect such black holes and to help determine how matter behaves when it is enclosed by its own gravitational field.

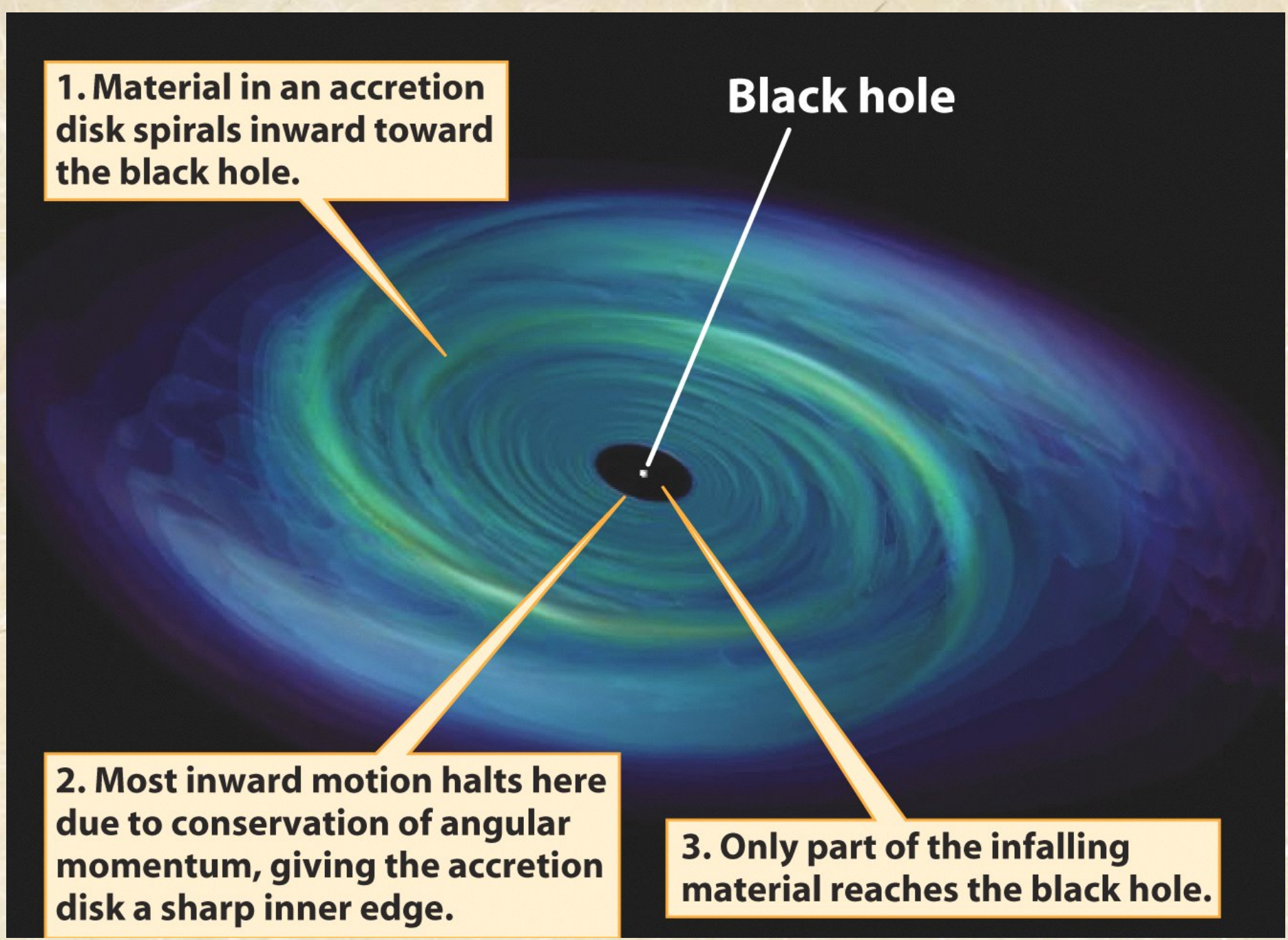
The light from the most famous white dwarf star, Sirius B, a companion to Sirius—which is the brightest star in the heavens visible from earth—has been captured using the 200-inch telescope atop Mt. Palomar. This was done as part of a program to study at least 20 white dwarfs.

Preliminary analysis of the light from Sirius B indicates that it has an effective temperature of 16,800 degrees Kelvin, or 30,000 degrees Fahrenheit. Its radius can be calculated from the temperature, and is only nine-thousandths that of the sun.

The star must therefore consist mainly of helium or heavier elements.

The speakers at the symposium were Drs. A. G. W. Cameron of the National Aeronautics and Space Administration's Goddard Institute for Space Studies, New York; Charles Misner of the University of Maryland; Volker Weidemann, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, and J. B. Oke of California Institute of Technology. The symposium was arranged by Dr. Hong-yee Chiu of the Goddard Institute for Space Studies.

• Science News Letter, 85:39 Jan. 18, 1964


1. Material in an accretion disk spirals inward toward the black hole.
Black hole
2. Most inward motion halts here due to conservation of angular momentum, giving the accretion disk a sharp inner edge.
3. Only part of the infalling material reaches the black hole.

For **non-rotating** black holes:

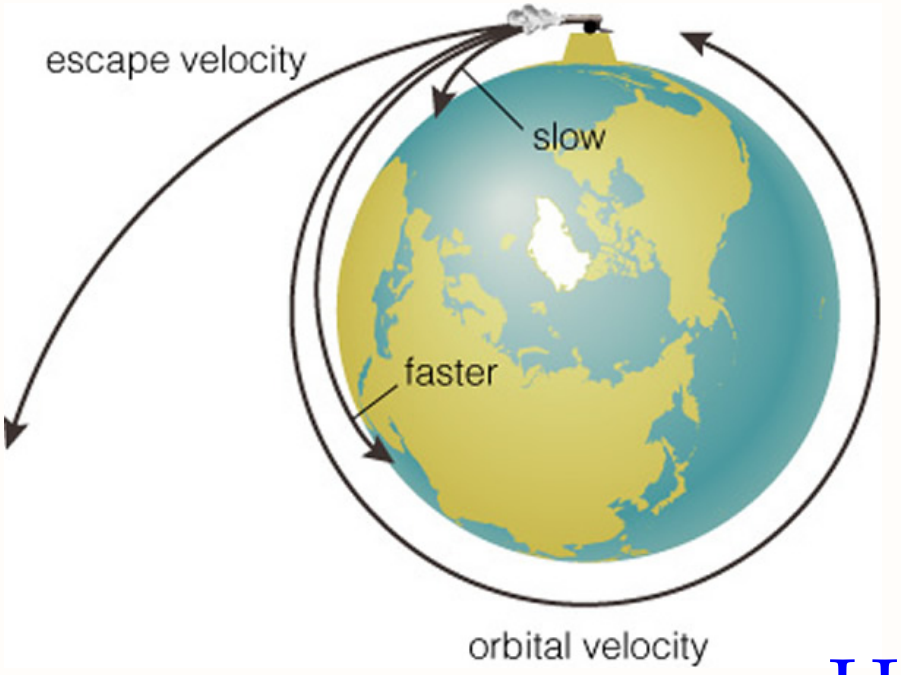
- event horizon is at $R_S = 2GM/c^2$
- inner edge of the disk is at $3\ R_S$

For **maximally rotating** black holes:

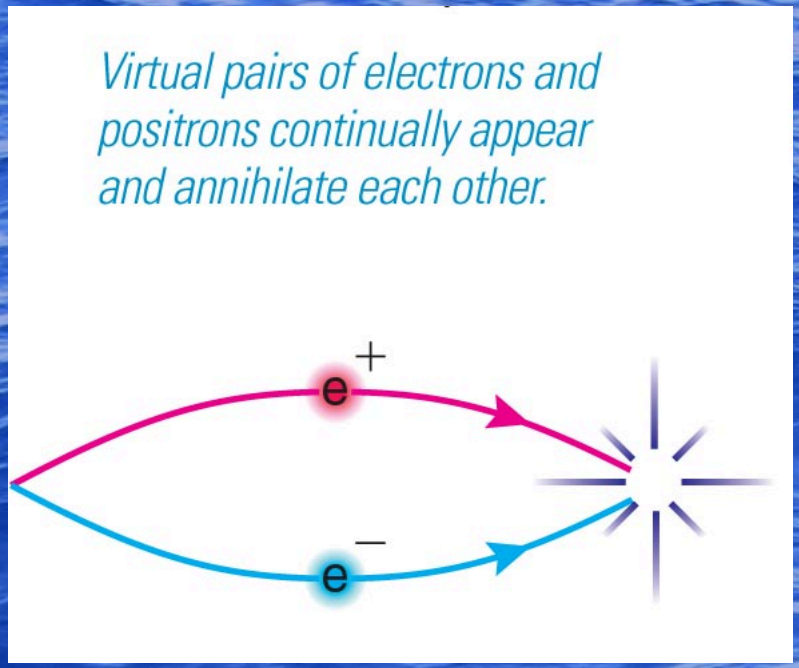
- event horizon is at $\frac{1}{2}\ R_S$
- inner edge of the disk is at $\frac{1}{2}\ R_S$

Our expectation is that black holes **do** rotate

If the Earth collapsed, it could form a **black hole**.

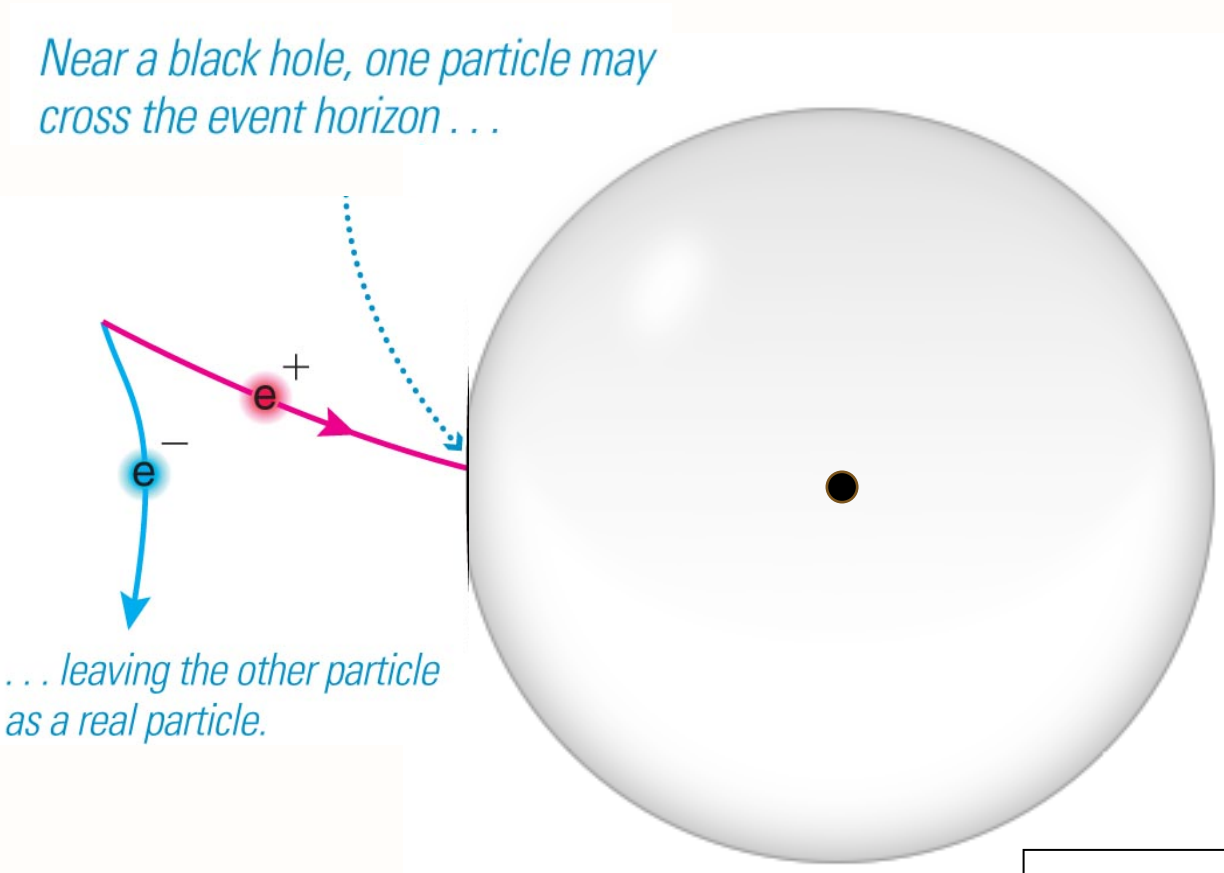


How big would it be?



"Empty space" is full of energy waves

1974: Hawking's bombshell – **black holes evaporate!**



Black hole weighing 200 tons evaporates in 1 second !

2009 Prime Minister's Prize for Science

28 OCTOBER, 2009

in MEDIA RELEASES, PRIME MINISTER'S PRIZES FOR SCIENCE

John O'Sullivan

How astronomy freed the computer from its chains

Nearly a billion people use John O'Sullivan's invention every day. When you use a WiFi network—at home, in the office or at the airport—you are using patented technology born of the work of John and his CSIRO colleagues.

They created a technology that made the wireless LAN fast and robust. And their solution came from John's efforts to hear the faint radio whispers of exploding black holes.

Today John is working on technology that will allow us to look back almost to the beginning of time itself.

For his achievements in astronomy and wireless technologies John O'Sullivan receives the 2009 Prime Minister's Prize for Science.

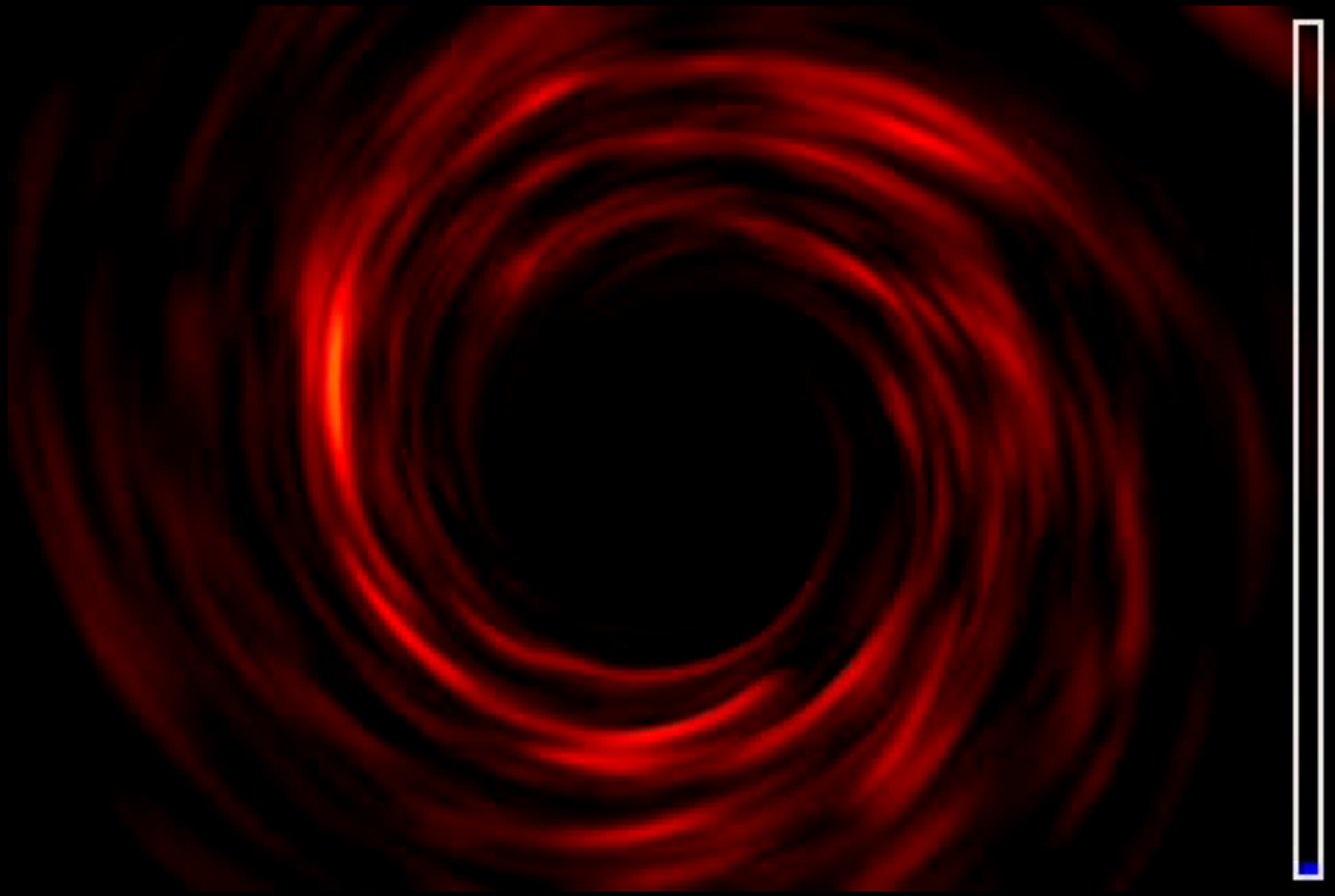
John O'Sullivan video interview: 3'52" in Flash, Quicktime and Windows Media formats

In 1977 John O'Sullivan co-wrote a paper about the use of a set of mathematical equations known as Fourier transforms to sharpen optical telescope images distorted by the atmosphere. The paper is short and, like O'Sullivan, somewhat humble. It builds on first principles of physics, but brings together a broad view joining radio and optics. And the paper is seminal. It explains the techniques known as adaptive optics and proves why they work.

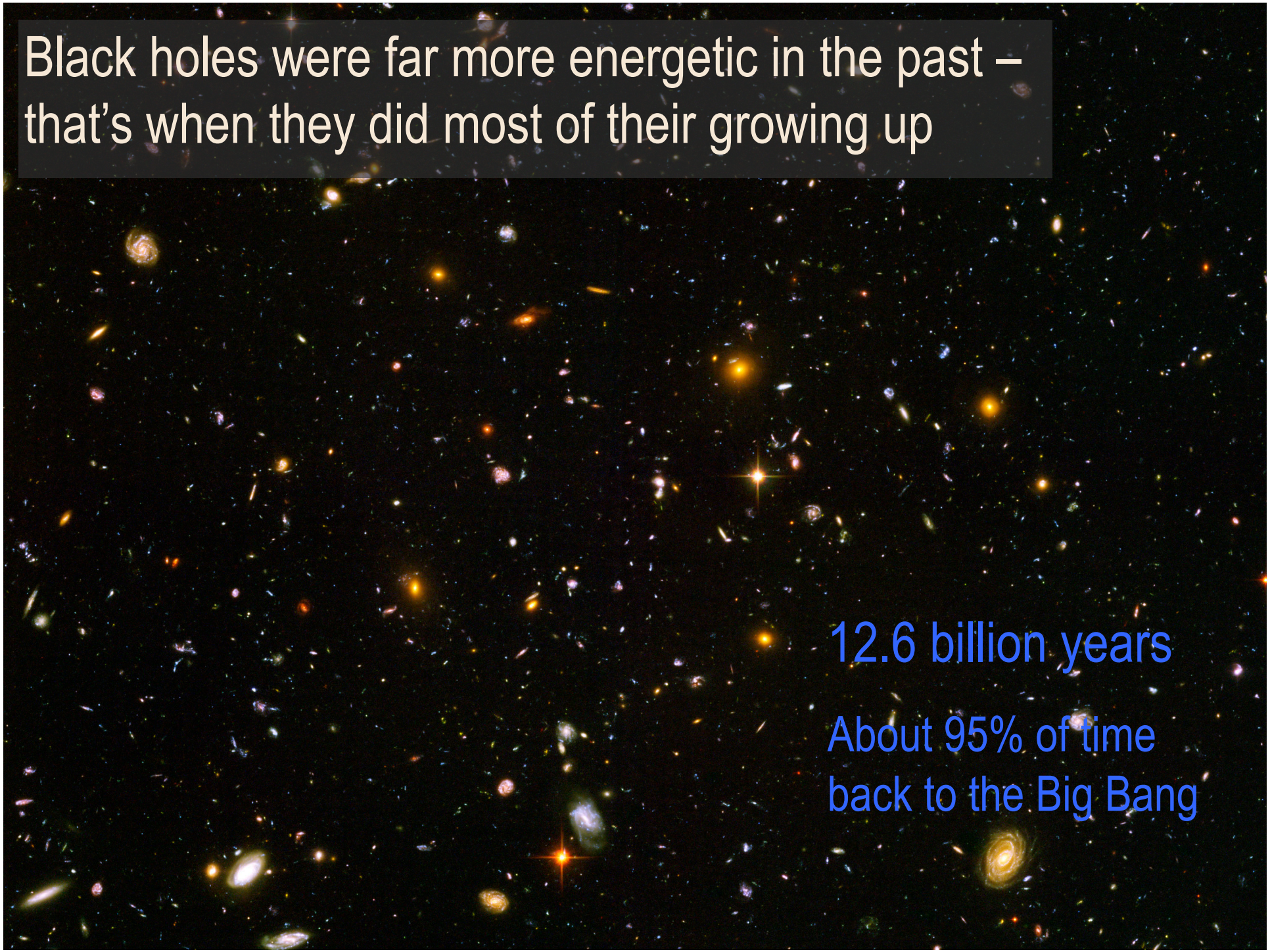
What's truly remarkable is that the consequences of that paper are now at work in millions of homes, airports, cafés, offices, hotels and universities across the world.

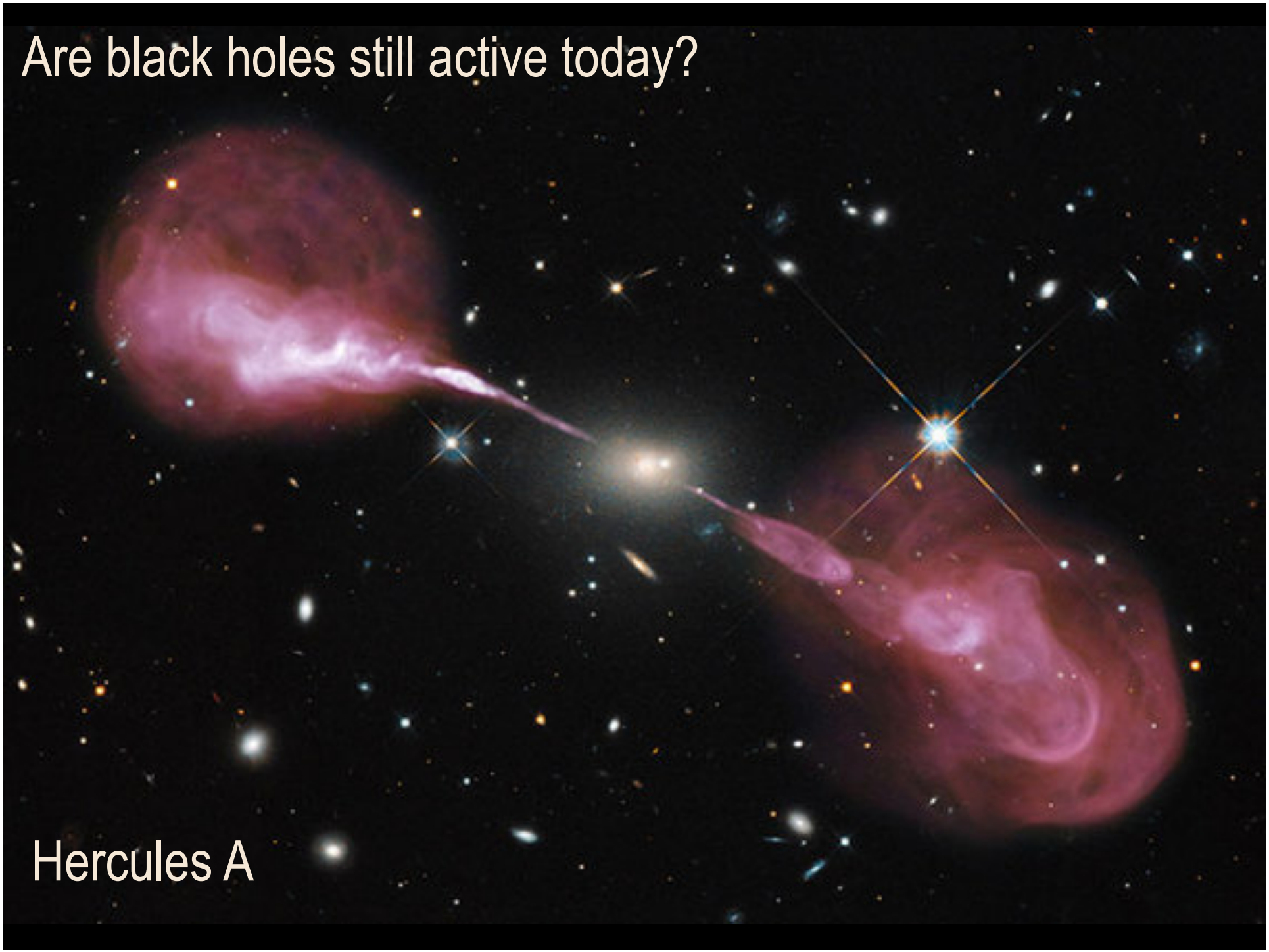
John's search for evaporating black holes led directly to the invention of WiFi

Accretion disk spinning around a black hole



This is how we are able to “see” where black holes are hiding


Black holes were far more energetic in the past –
that's when they did most of their growing up
12.6 billion years
About 95% of time
back to the Big Bang

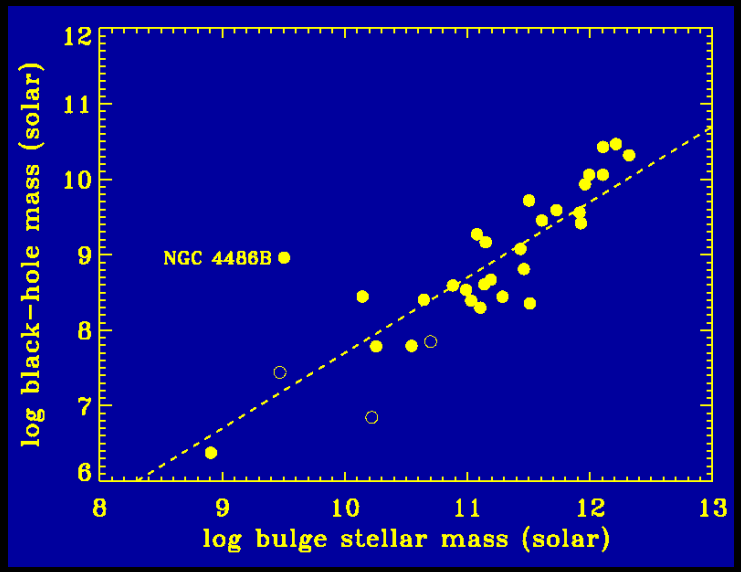

Are black holes still active today?
Hercules A

Are black holes still active today?

Centaurus A

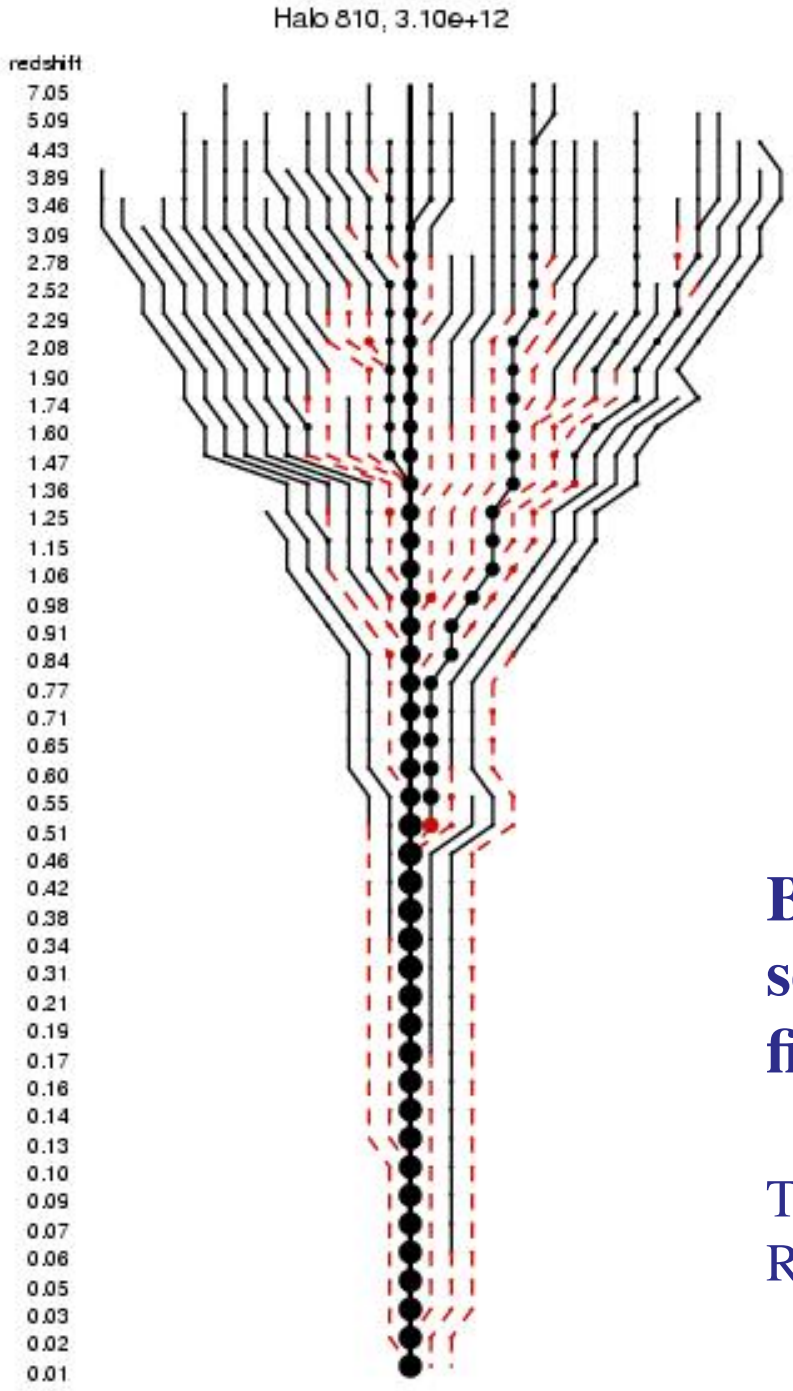
We now believe that all galaxies have black holes at their centres, the most ancient part of the galaxy.

1998: An amazing discovery is that the black hole knows about the galaxy around it.



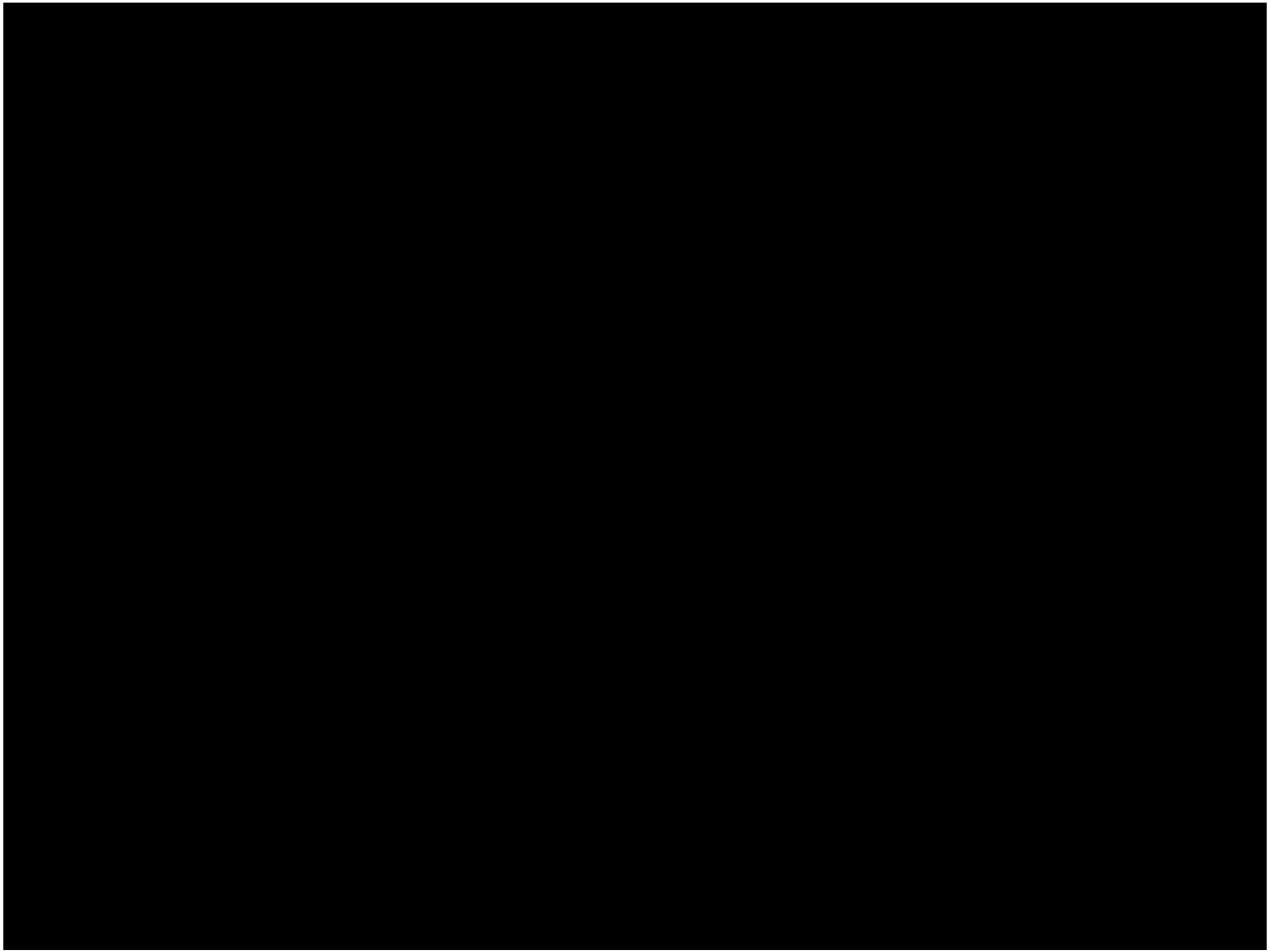
CDM paradigm:

The growth of a supermassive black hole over cosmic time



Black holes are seeded by the first stars

TK, VB, JBH
Rev Mod Phys 2013



Centre of the Galaxy – Sixtieth anniversary of an Australian discovery

Peter Robertson

School of Physics, University of Melbourne, Vic. 3010
and
School of Agricultural, Computational and Environmental Sciences,
University of Southern Queensland, Toowoomba, Qld 4350
prob@unimelb.edu.au

Joss Bland-Hawthorn

Sydney Institute for Astronomy, University of Sydney, NSW 2006
jbh@physics.usyd.edu.au

In 1954 two young radio astronomers at the Radiophysics Laboratory in Sydney proposed that the strong radio source known as Sagittarius A is the Galactic nucleus – the centre of the Milky Way. Dick McGee and John Bolton had just completed a survey of the Galactic plane using the 'hole-in-the-ground' radio telescope at the Dover Heights field station, near the entrance to Sydney Harbour. Their identification of the Galactic nucleus was accepted almost immediately. In 1958 the International Astronomical Union officially adopted Sagittarius A as the true centre of the Galaxy, making its position the zero of latitude and longitude in a new system of Galactic coordinates.

Dover Heights

COMMONWEALTH OF AUSTRALIA
COMMONWEALTH SCIENTIFIC AND INDUSTRIAL
RESEARCH ORGANIZATION

(*Reprinted from Nature, Vol.* 173, *p.* 985, *May* 22, 1954)

PROBABLE OBSERVATION OF THE GALACTIC NUCLEUS AT 400 Mc./s.

By R. X. McGEE and J. G. BOLTON
Division of Radiophysics, Commonwealth Scientific and Industrial Research Organization, Sydney, N.S.W.

WE have recently made a survey of the central section of the Milky Way using a pencil-beam aerial at a frequency of 400 Mc./s. The survey covered the zone of the celestial sphere from − 17° to − 49° in declination and approximately 15 hr. to 20 hr. in right ascension. The aerial reflector, a paraboloid of revolution of aperture diameter 80 ft. and focal length 40 ft., is hollowed out of the earth; its surface is consolidated with concrete and covered with half-inch mesh wire-netting. The feed consists

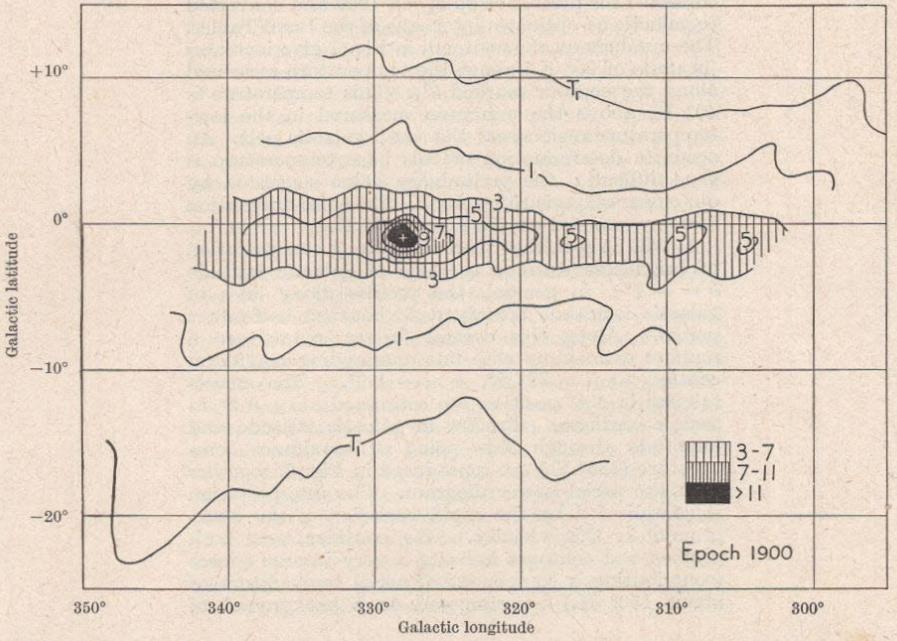
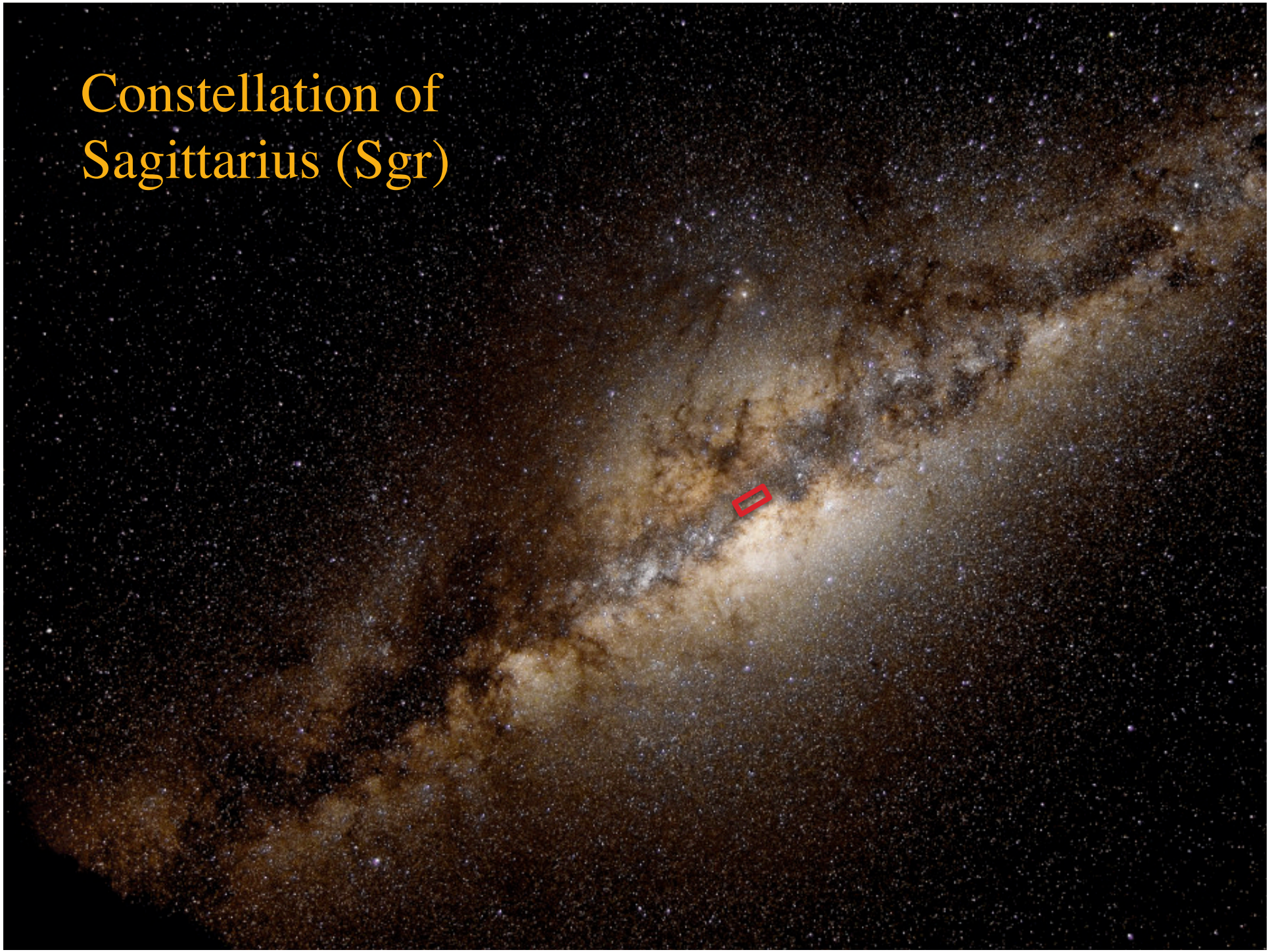
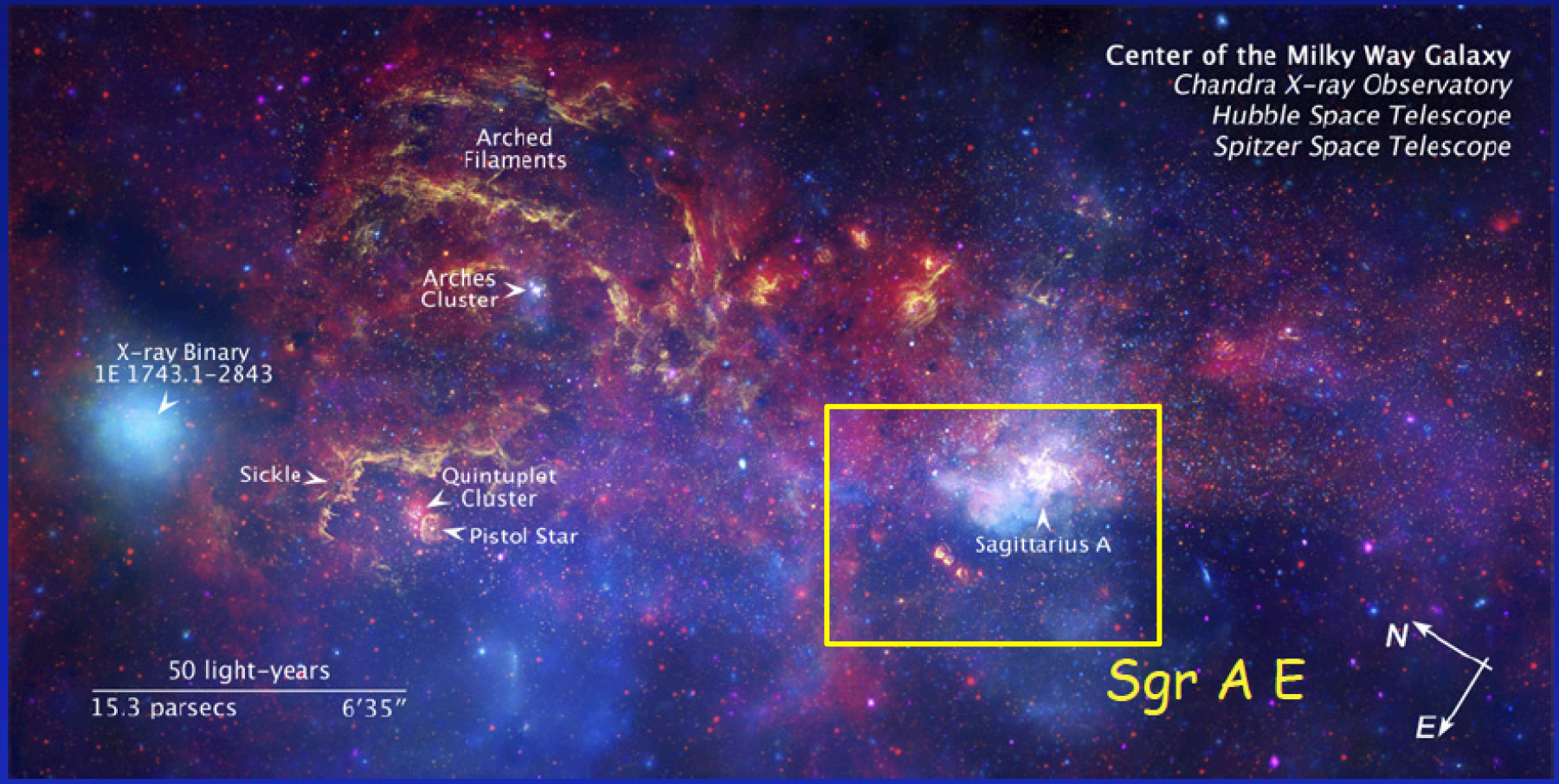
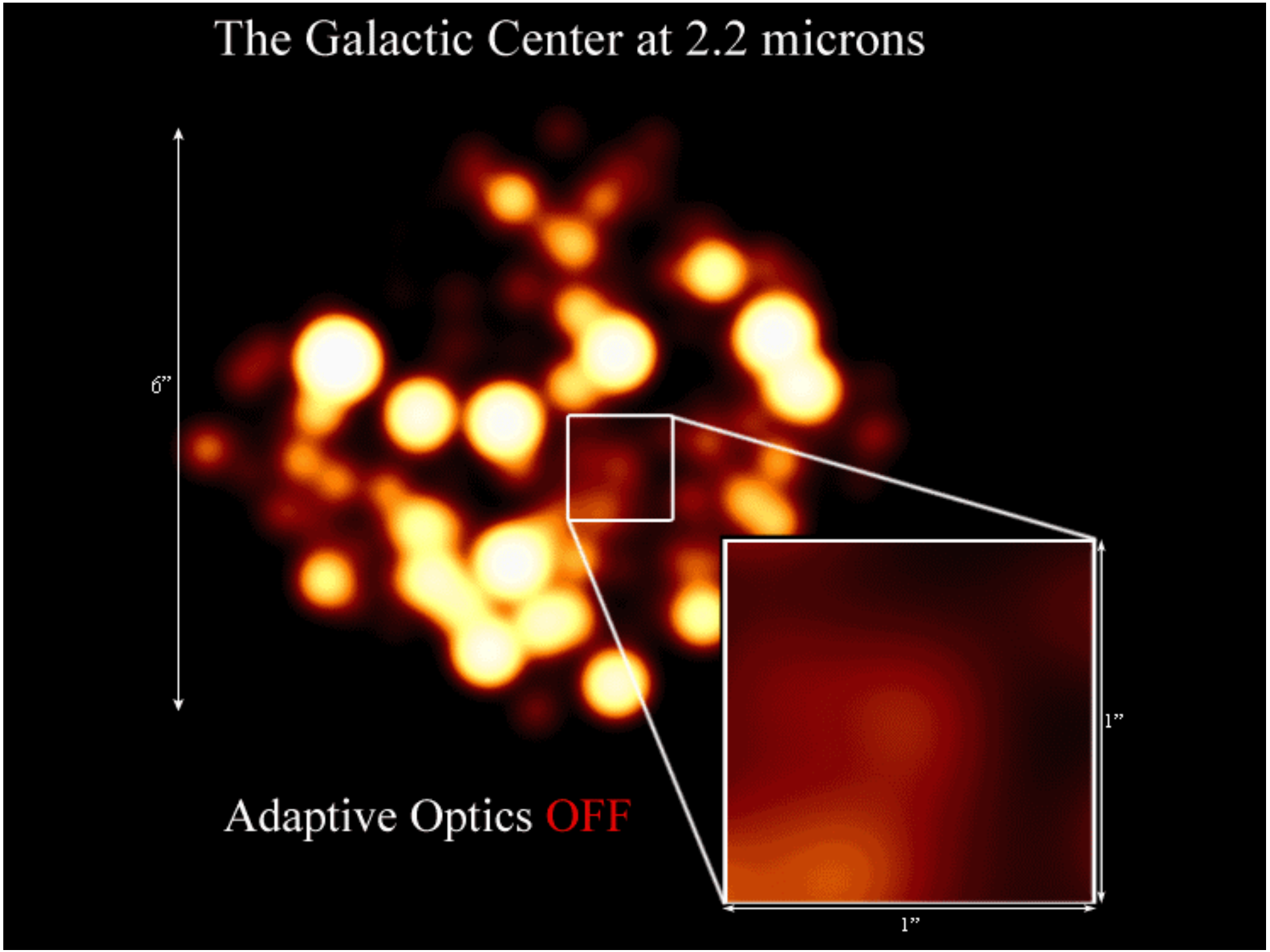


Fig. 1. Contours of equivalent aerial temperature at 400 Mc./s. plotted in galactic co-ordinates. The numbers on the contours give the increase (in units of 30° K.) above the temperature measured along the contour T_1. This temperature is approximately 55° K.


Constellation of
Sagittarius (Sgr)

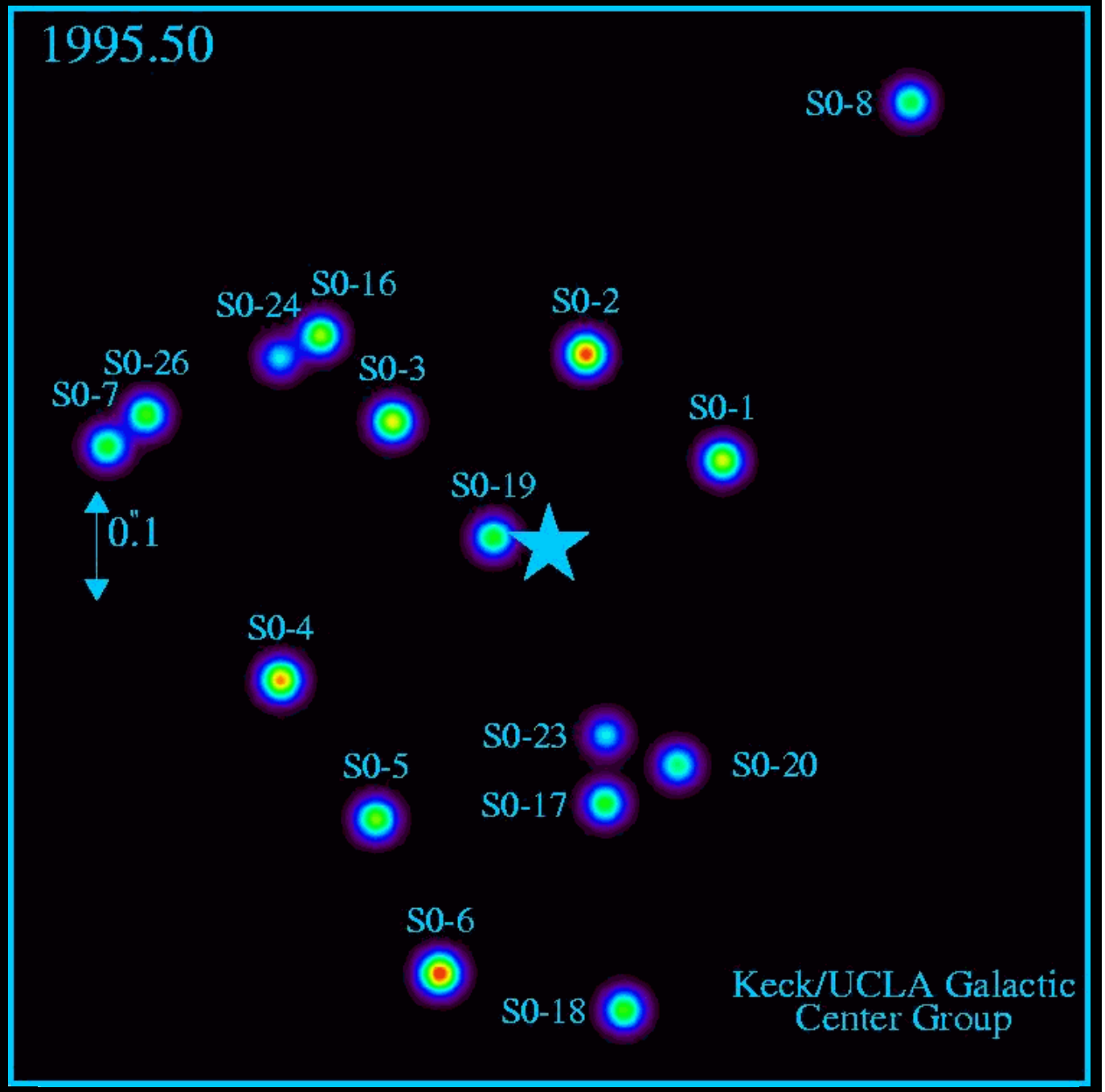
Chandra, Hubble & Spitzer Views of the Galactic Center




The Galactic Center at 2.2 microns
6”
1”
1”
Adaptive Optics OFF

Sgr A*

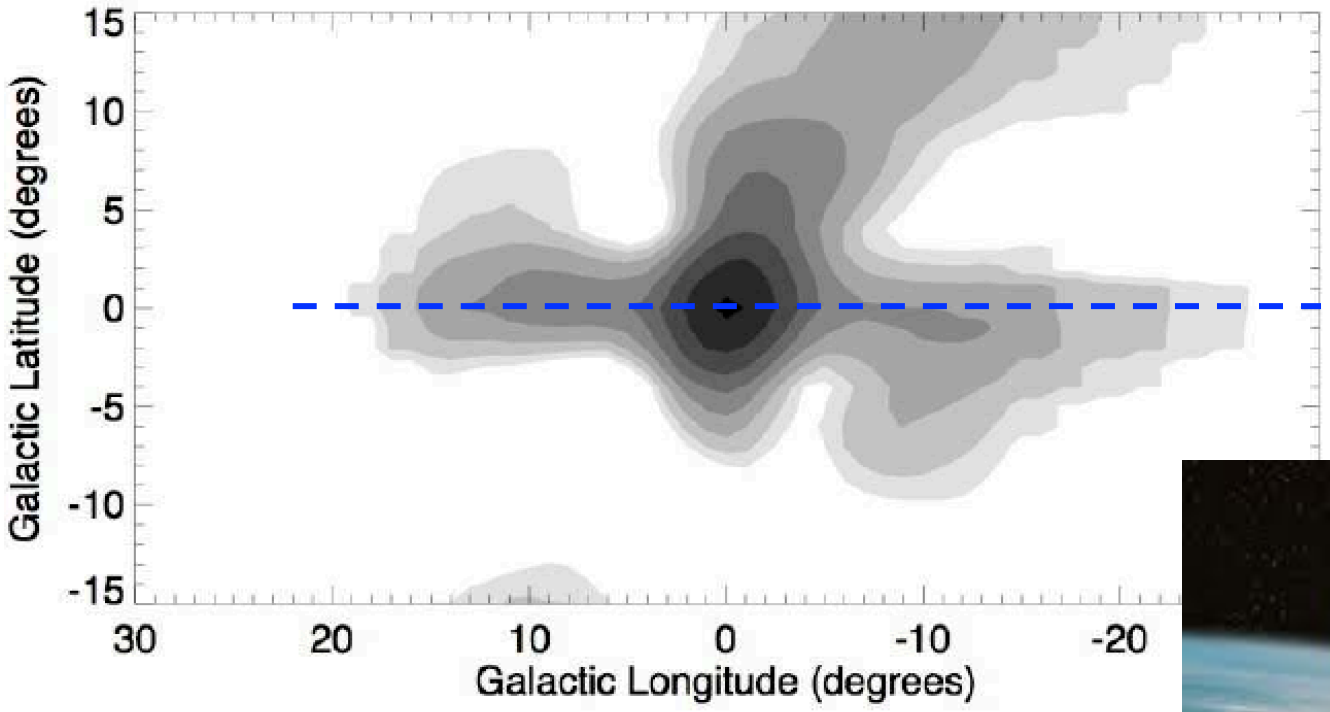
Star motions show the black hole is 4 million times the mass of the Sun



Now we move to degree scales

1974: Our first clue of something weird in Sgr A* –

a plume of **antimatter** streaming out of the region



Milky Way disk

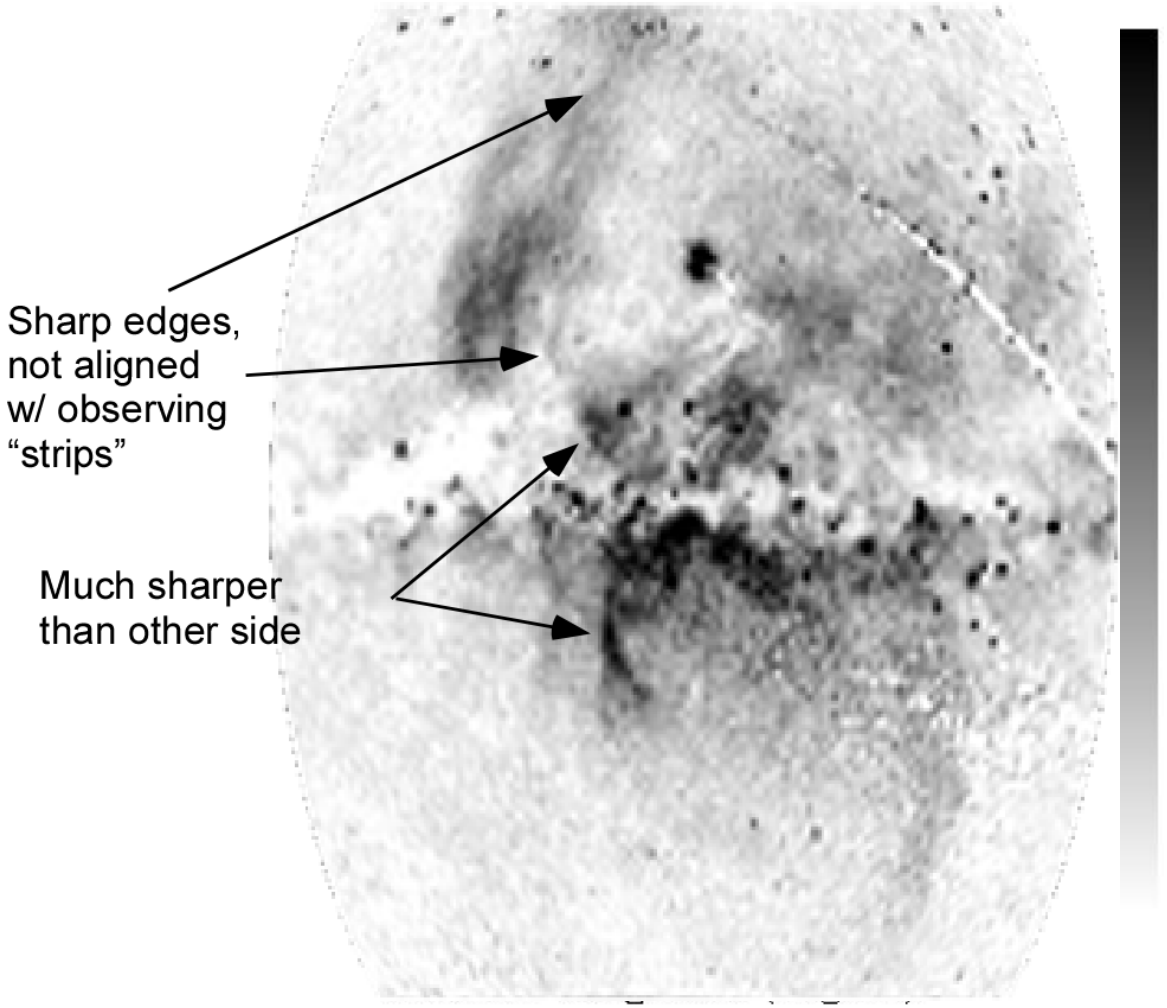
2005: INTEGRAL satellite

The Galaxy's bipolar wind seen on 10 kpc scales…

What powers it ?

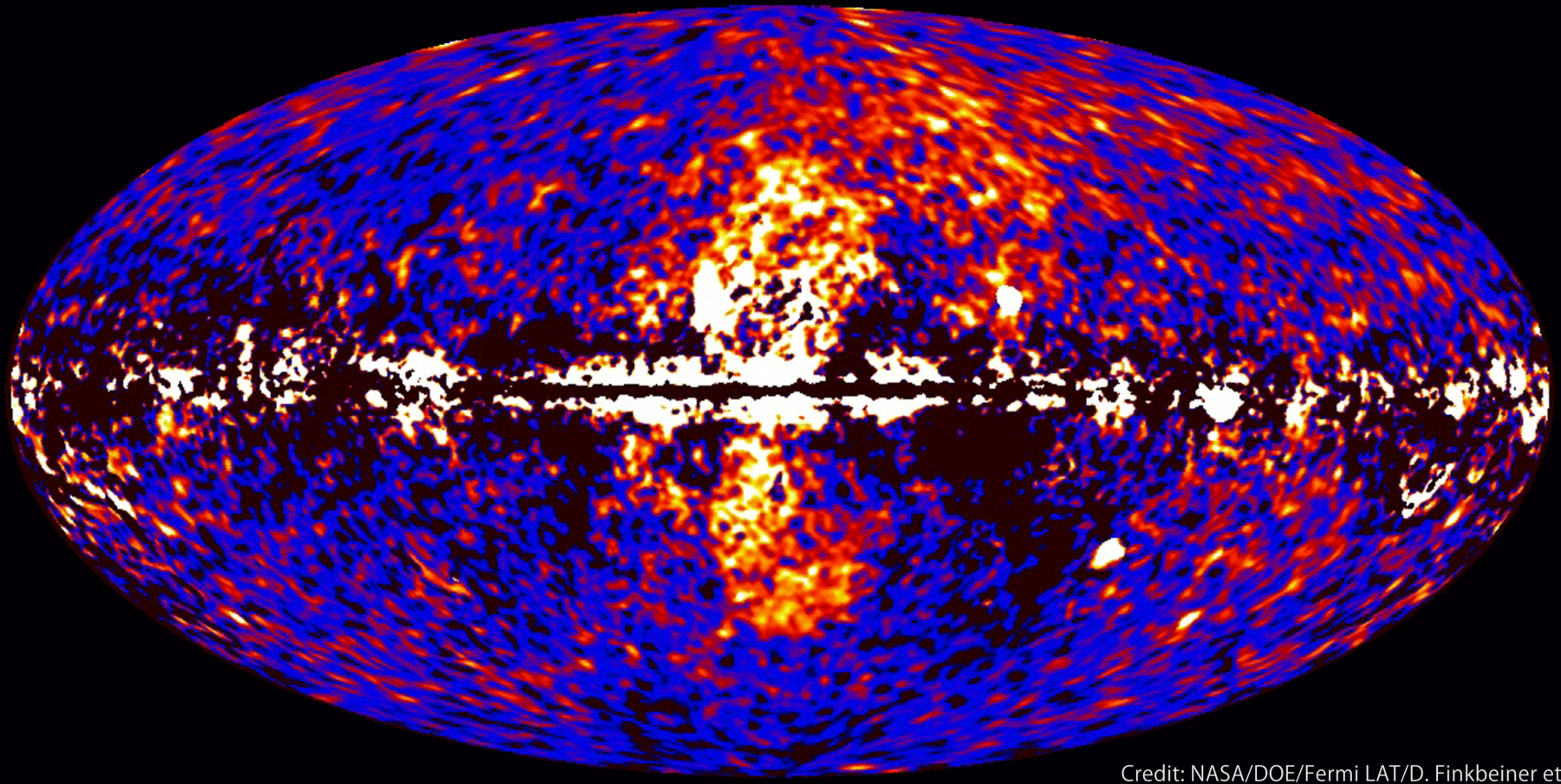
Estimated energy ~ 10^{55} erg

JBH & Cohen (2003)



2010: big NASA discovery

Fermi data reveal giant gamma-ray bubbles

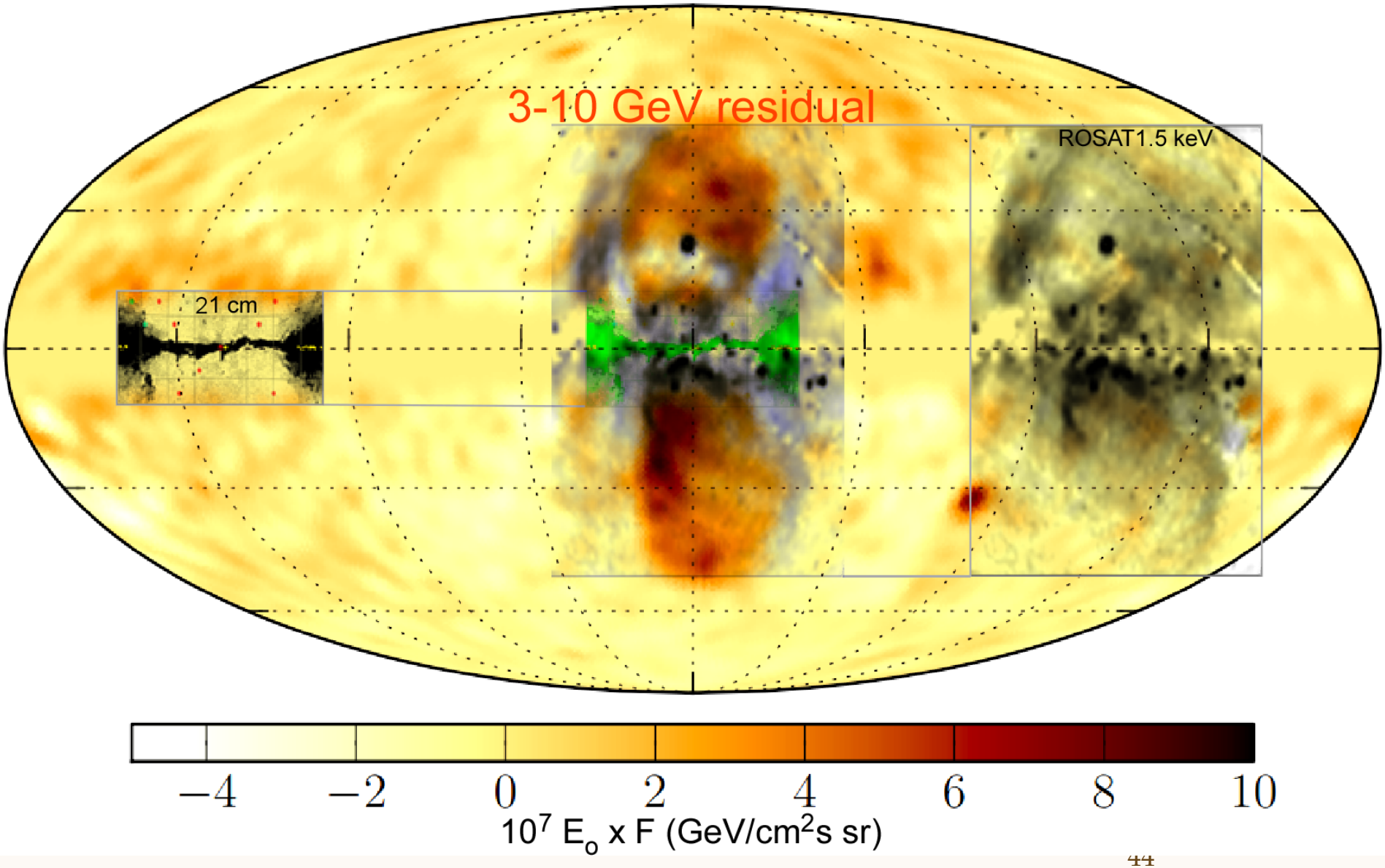


Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

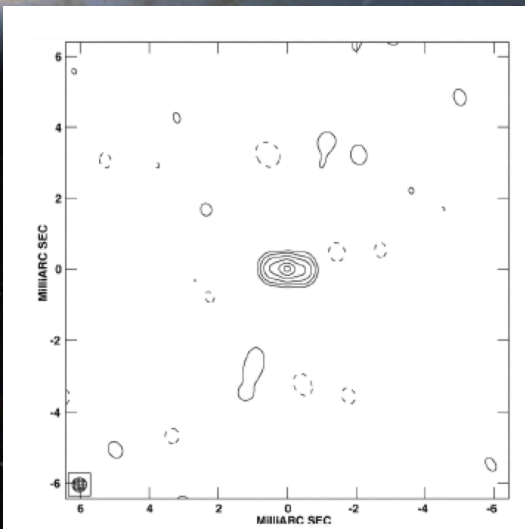
2014 Rossi Prize

Estimated energy > 10^{56} erg

You're the first audience to see this composite…



Claims for a jet not convincing



7mm VLBA of the Sgr A*
(Bower & Backer 1998)

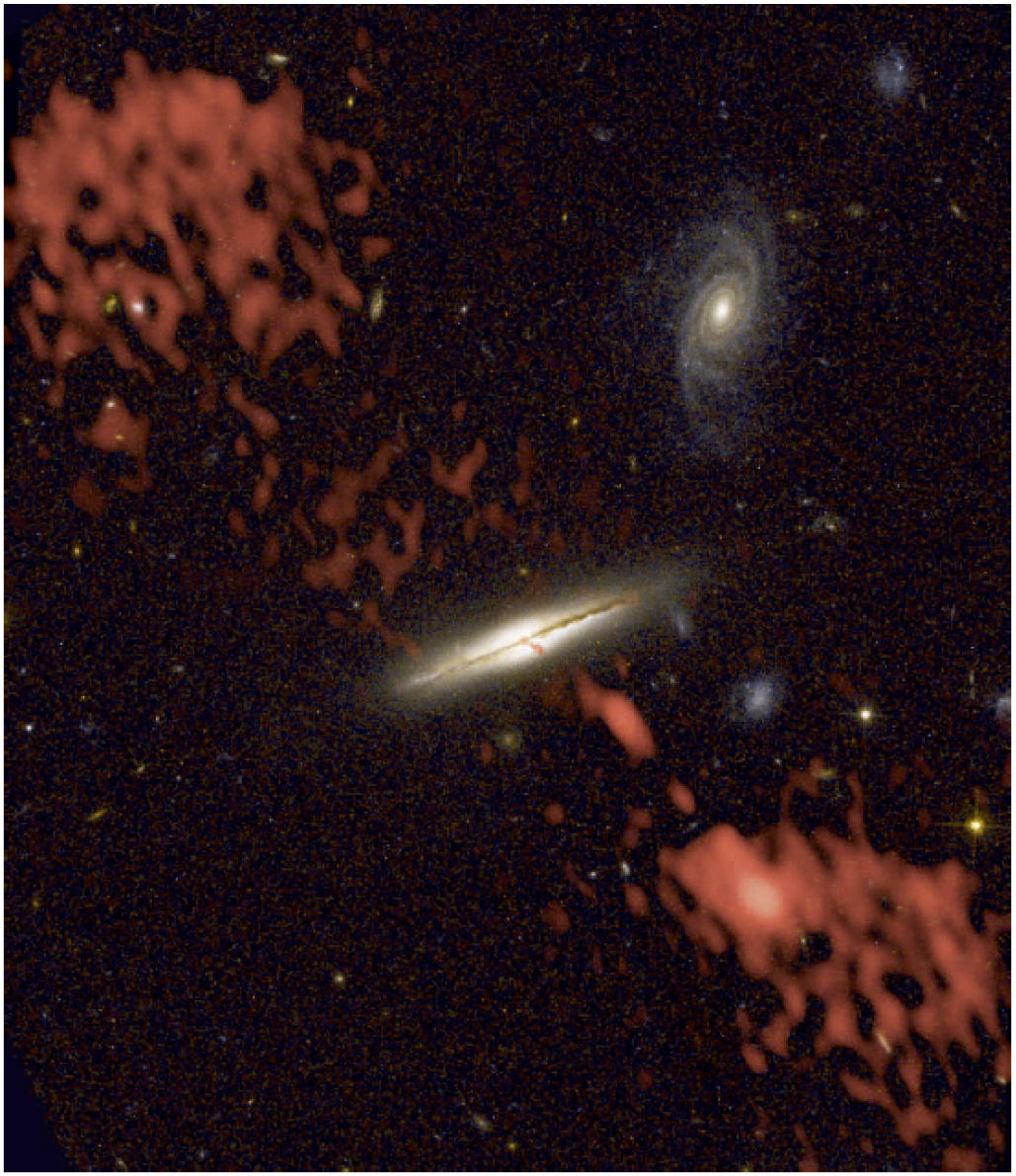


FIG. 1.—Radio galaxy 0313−192 and its environment in a color composite produced from the ACS images in F555W and F814W. The red overlay shows the VLA 20 cm structure, encompassing a wide field of 82″ × 96″ to show most of the radio source. Multiple arrays have been combined to retain higher resolution in the kiloparsec-scale jet. This image is available as STScI-PRC03-04. North is about 20° counterclockwise from the top. The less inclined spiral has a substantially different redshift and, while likely part of Abell 428, does not form a bound interacting system with 0313−192.

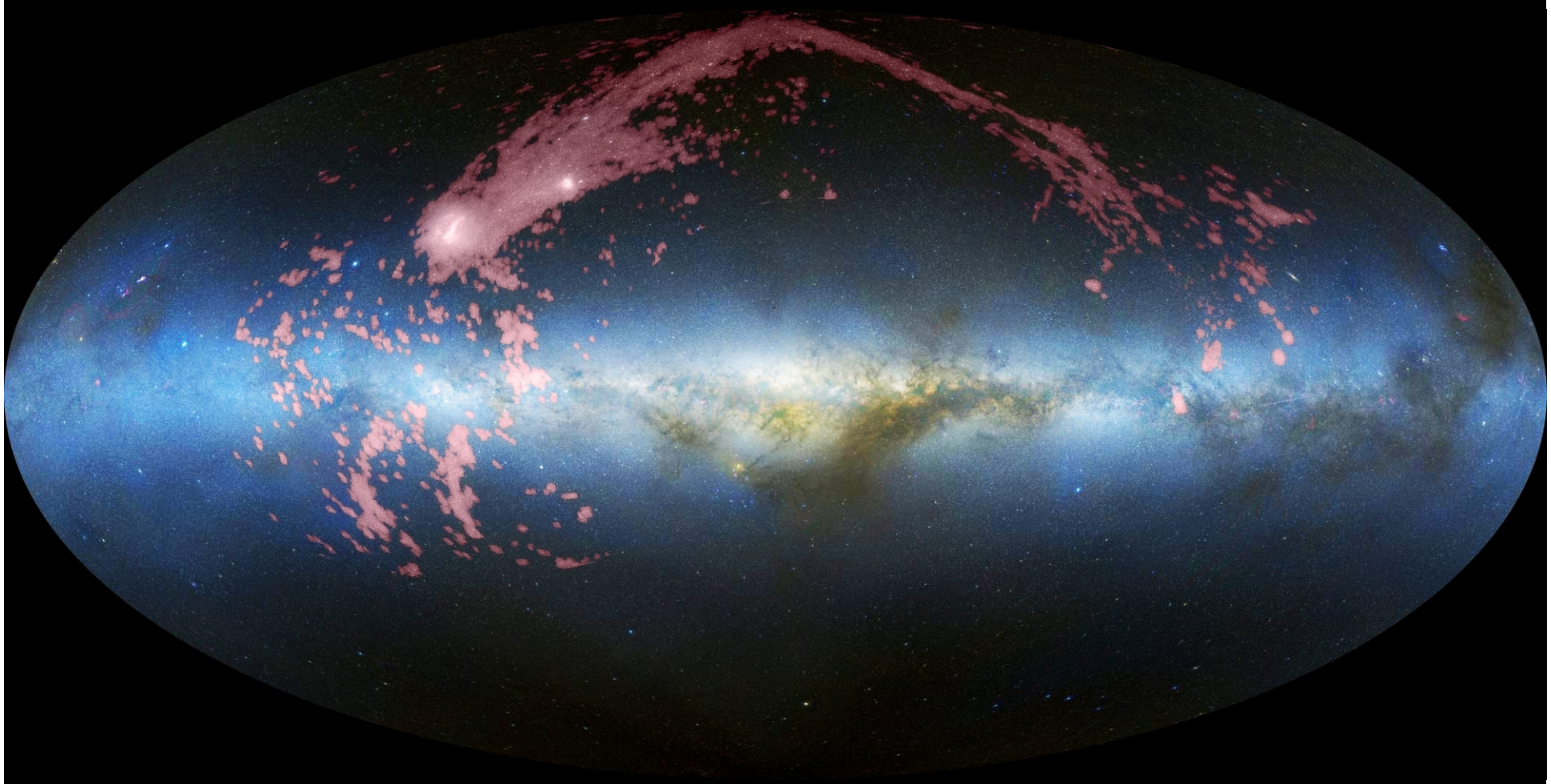
30 or more nearby Seyfert examples:

0313-192
NGC 1068
NGC 2992
NGC 3079
NGC 3801
NGC 5506
NGC 6764
Circinus
Markarian 6
M51
…

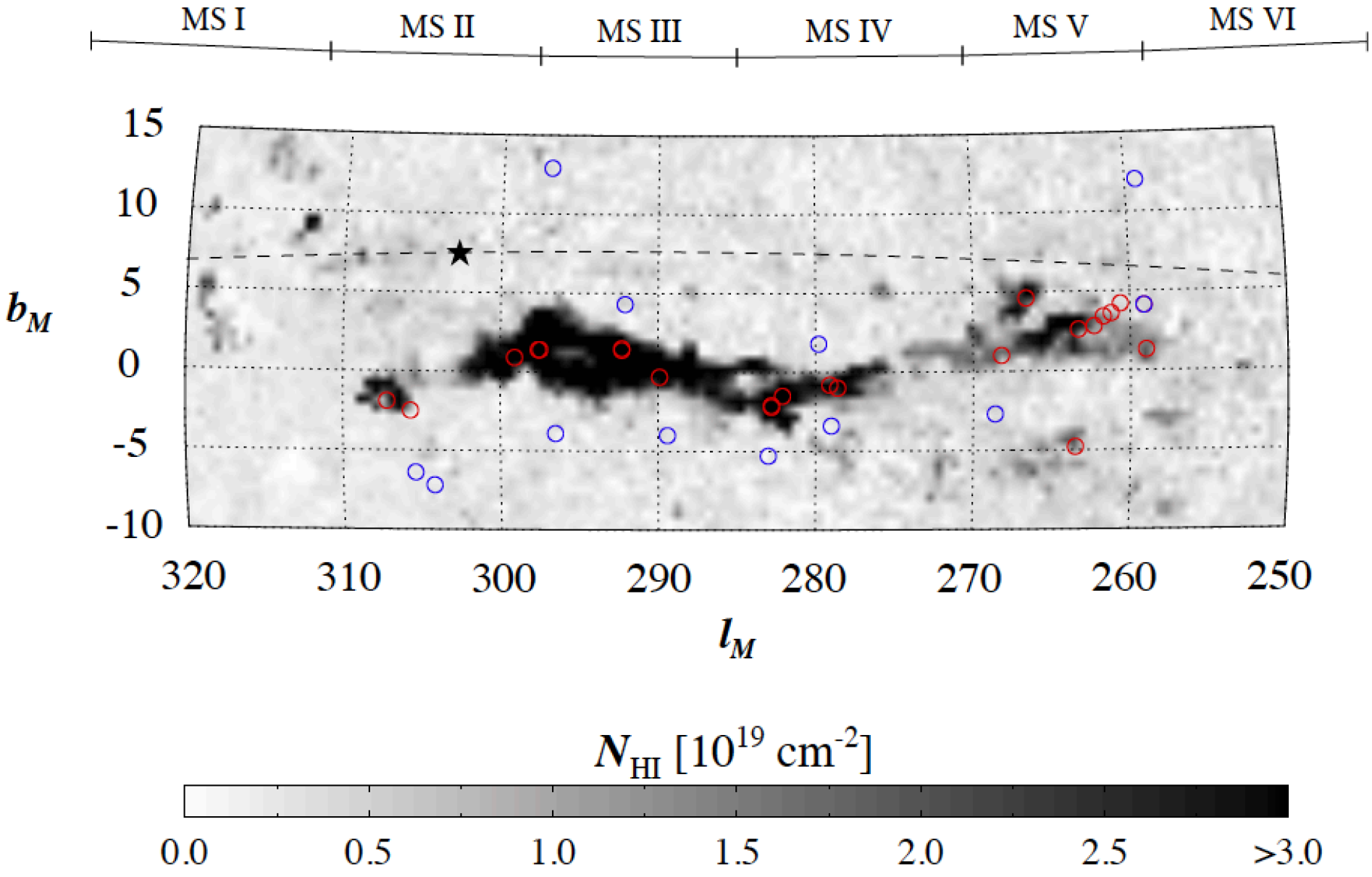
So when did all this happen?

Until recently, there was no corroborating evidence for when the Galactic nucleus exploded.

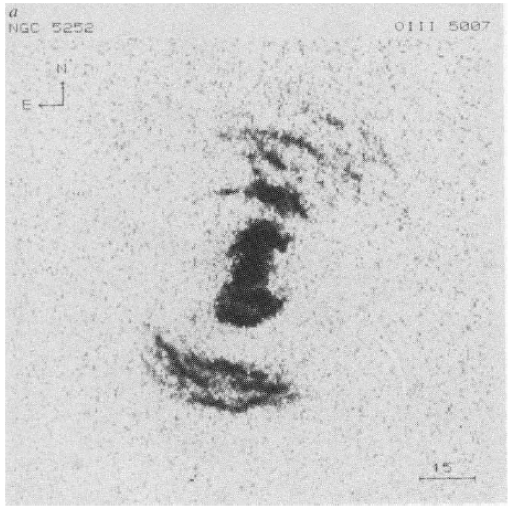
The mystery of the Magellanic Stream's ionization

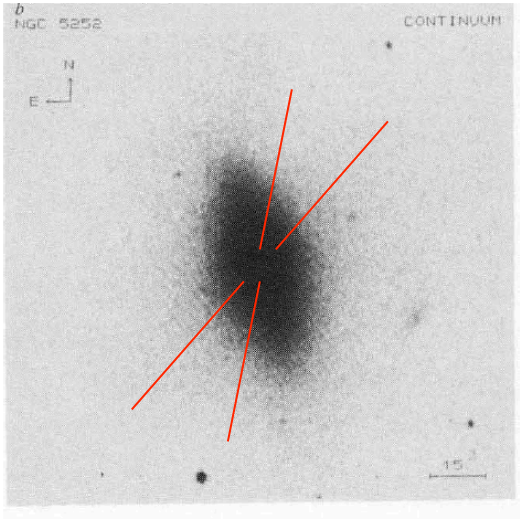


The Magellanic HI Stream

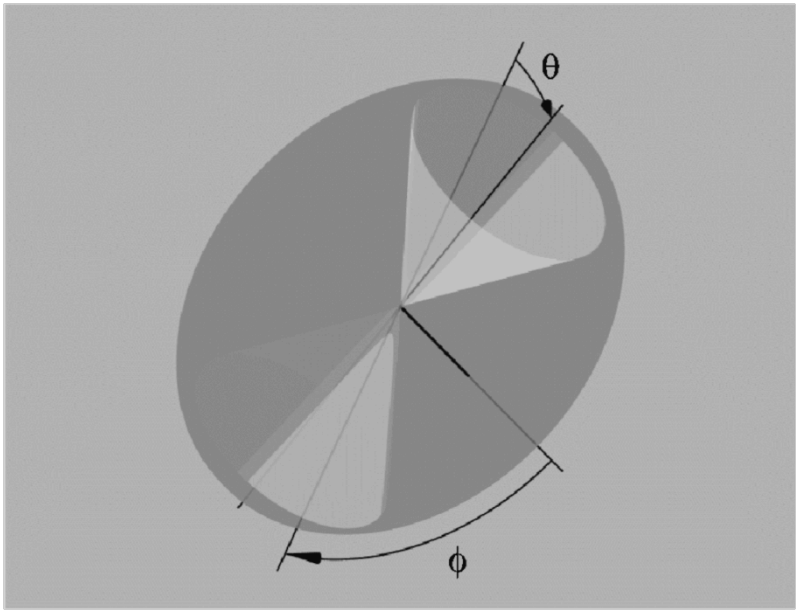


Radiation field restricted by the surrounding galaxy is often seen from low power AGNs (Seyferts)





Seyfert ionizes gas streams at up to ~ 35 kpc



LETTERS TO NATURE

Anisotropic ionizing radiation in NGC5252

Clive Tadhunter* & Zlatan Tsvetanov†

* Royal Greenwich Observatory, Madingley Road, Cambridge CB3 0EZ, UK
† European Southern Observatory, Karl-Schwarzschild-Strasse-2, D-8046, Garching bei München, FRG

The Magellanic Stream was lit up by Sgr A*
only a few million years ago

Sgr A* was ten million times more powerful than today

D. Mukherjee, ANU

What was the “event” ?

2016: simulation of a star being stretched by a factor 300 as it falls into a massive black hole

The “event” was not an infalling star, too rare, too little mass.

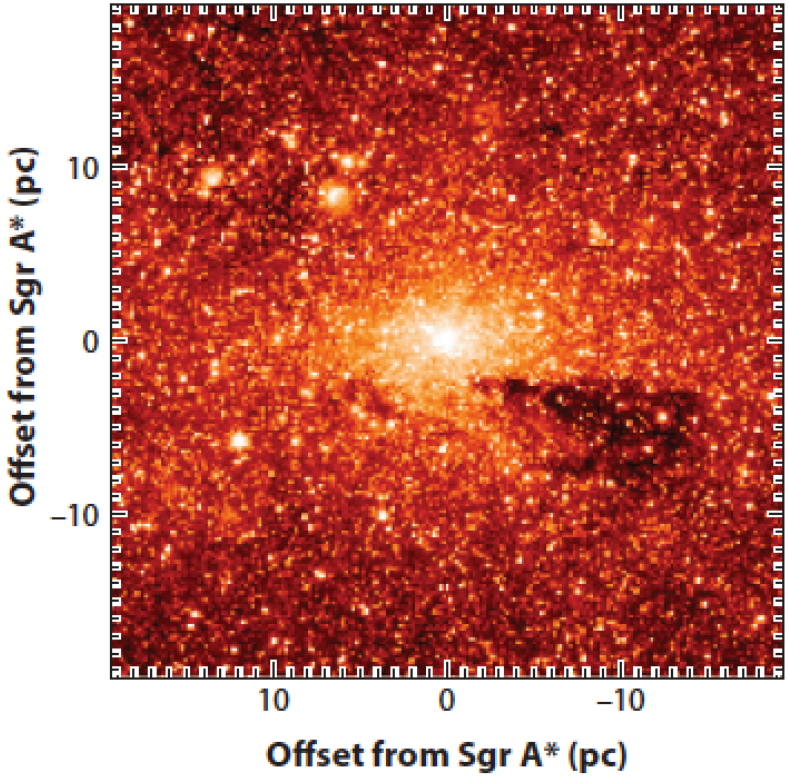
The "event" was likely due to a gas cloud ~ 10,000 solar masses.

A gas cloud on its way into the super-massive black hole in the Galactic Centre

S. Gillessen, R. Genzel, T. Fritz, E. Quataert, C. Alig, A. Burkert, J. Cuadra, F. Eisenhauer, O. Pfuhl, K. Dodds-Eden, C. Gammie, T. Ott
Nature, Dec. 2011

Simulation by: M. Schartmann, A. Burkert, C. Alig, S. Gillessen, R. Genzel
using PLUTO 3.1.1 (Mignone et al. 2007)

Singular event – formation of young inner disk



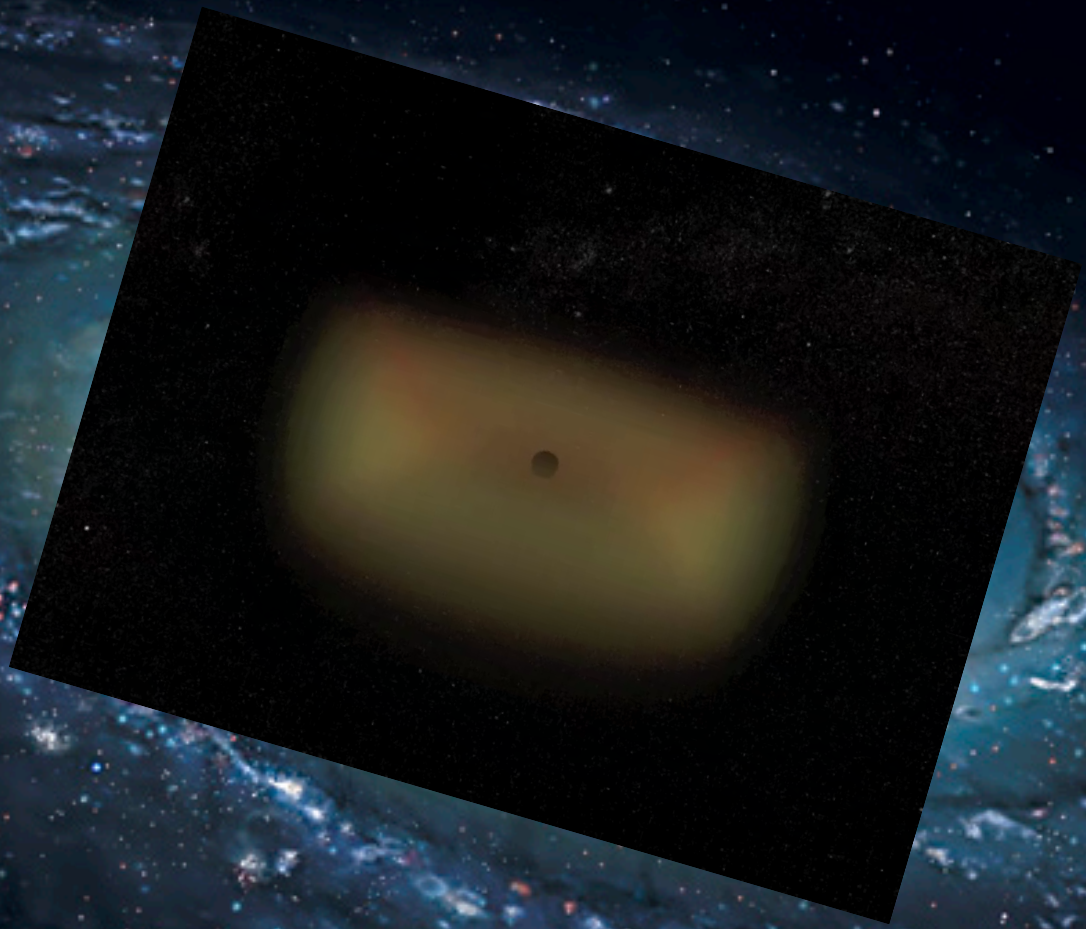
T = 4-6 Myr

R = 0.04 – 4 pc

Fermi bubbles are AGN jet-driven, arguing for event at T_0 ~ 2-5 Myr and burst time T_B ~ 0.5-1 Myr (e.g. Guo & Mathews 2012).

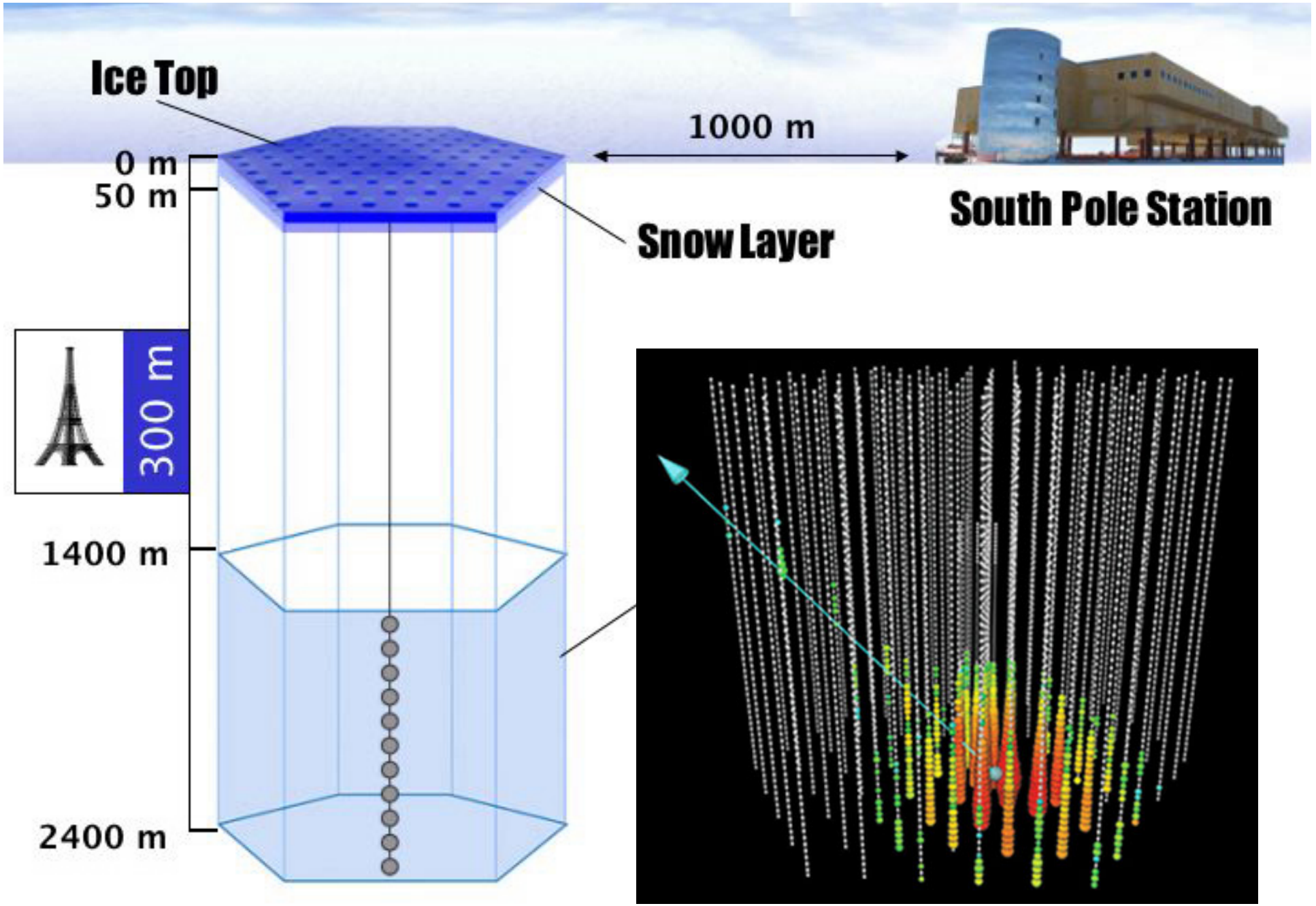
Associated with central hole of young disk ?

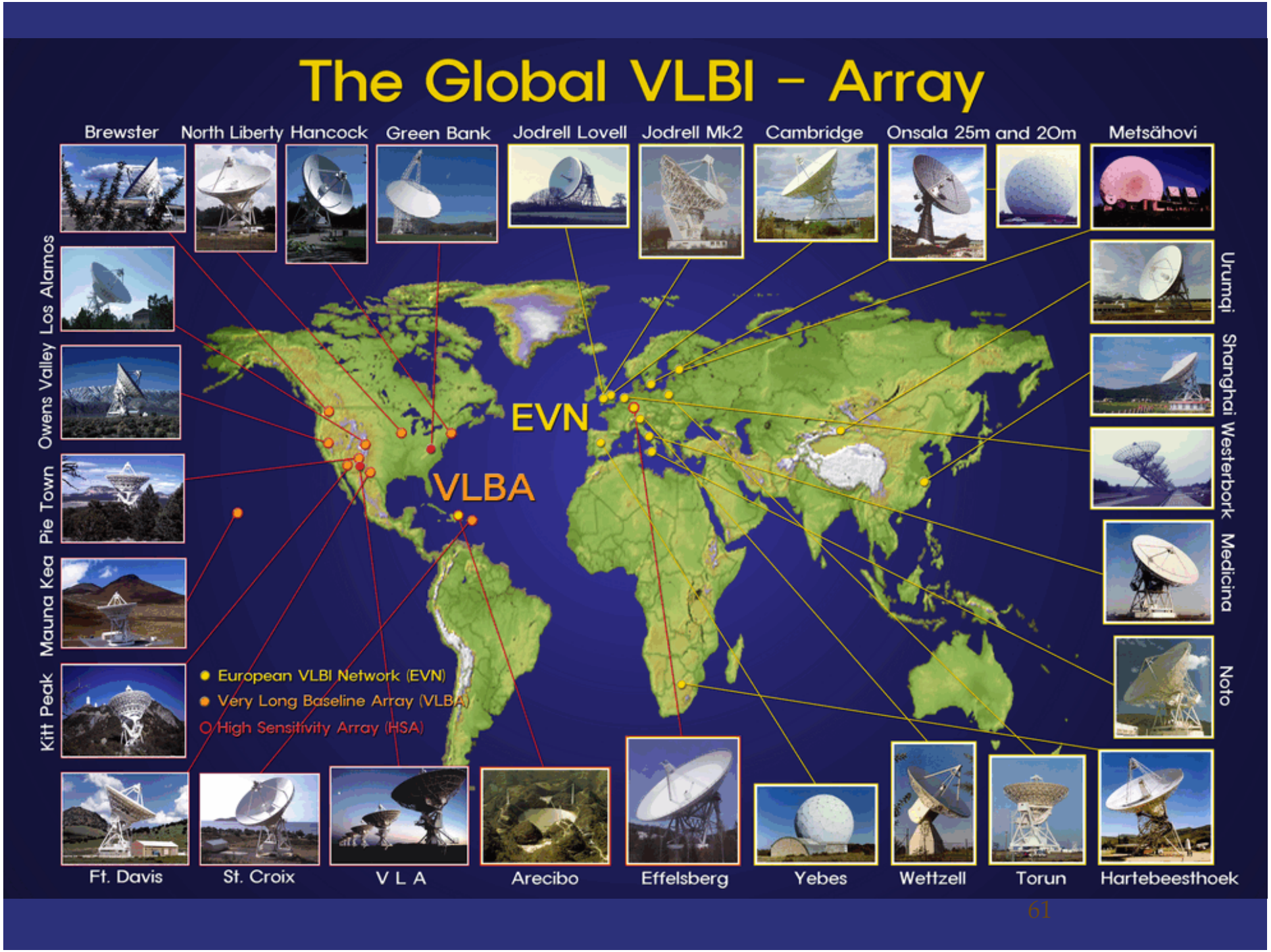
Are we in any danger?



- O Gravity instrument says accretion disk is pointing at Earth now.

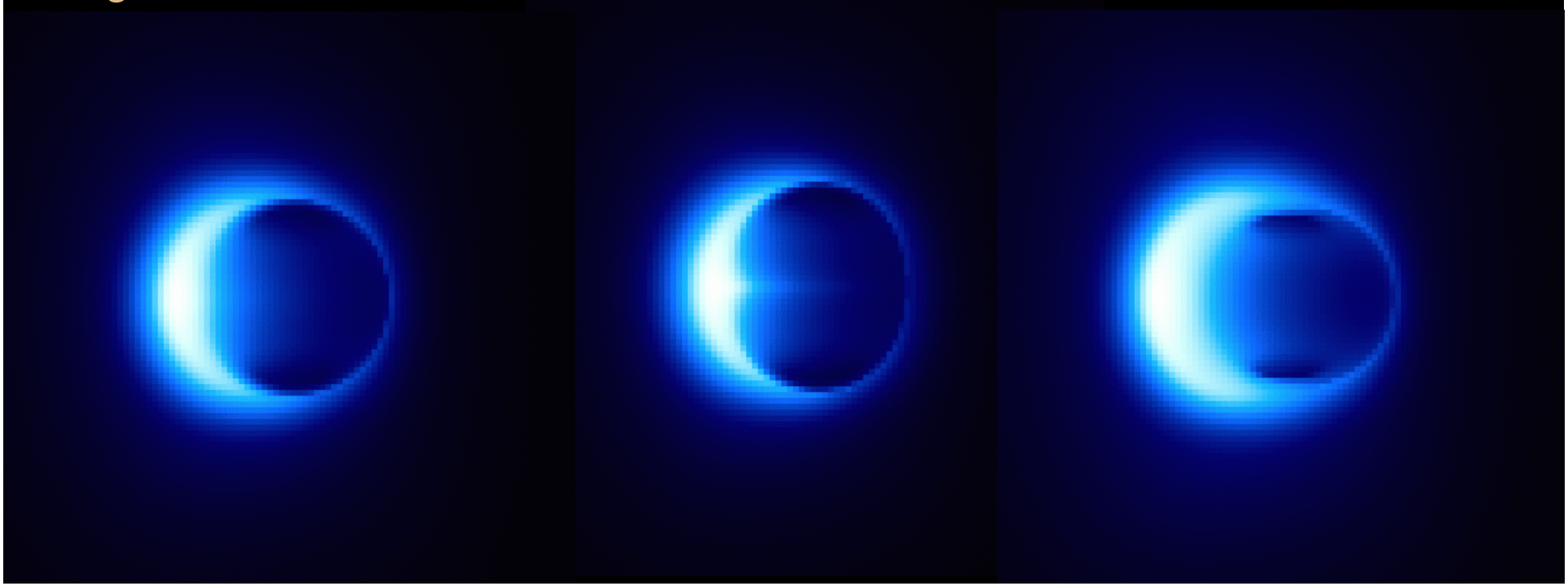
Looking to the future


Ice Top
1000 m
South Pole Station
0 m
50 m
Snow Layer
300 m
1400 m
2400 m


The Global VLBI – Array
Brewster
North Liberty
Hancock
Green Bank
Jodrell Lovell
Jodrell Mk2
Cambridge
Onsala 25m and 20m
Metsähovi
Los Alamos
Owens Valley
Pie Town
Mauna Kea
Kitt Peak
Urumqi
Shanghai
Westerbork
Medicina
Noto
EVN
VLBA
European VLBI Network (EVN)
Very Long Baseline Array (VLBA)
High Sensitivity Array (HSA)
Ft. Davis
St. Croix
V L A
Arecibo
Effelsberg
Yebes
Wettzell
Torun
Hartebeesthoek

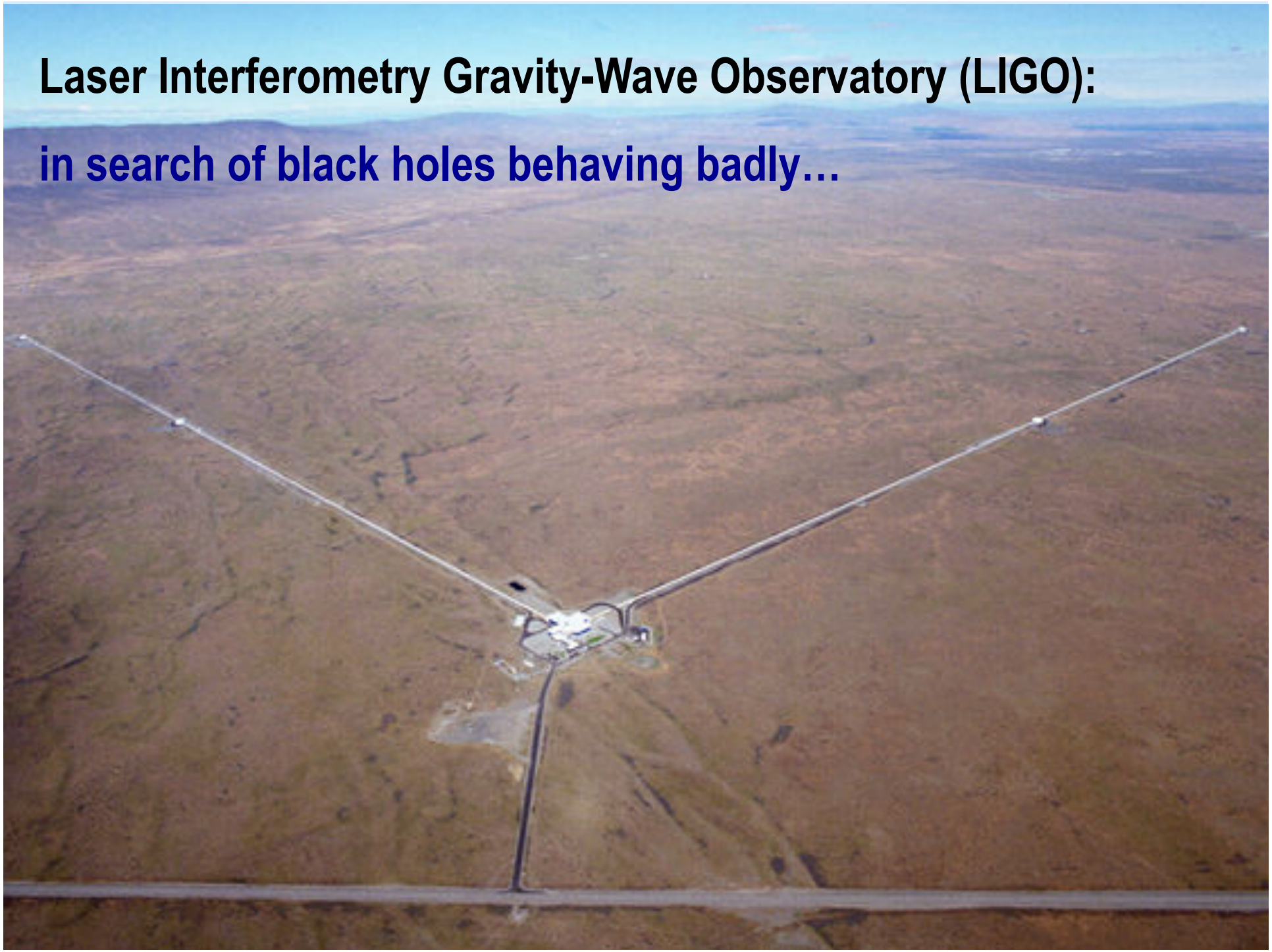
Event Horizon Telescope

Einstein's General Relativity predicts mysterious shadows and rings around an event horizon



Laser Interferometry Gravity-Wave Observatory (LIGO):

in search of black holes behaving badly…




Expect great advances in the decades ahead –
Sgr A* research guarantees longevity for astrophysics
I predict that Galactic Centre research will become a distinct field of physics