

Title: Avery Broderick: Perimeter Institute and University of Waterloo

Date: Oct 03, 2018 07:00 PM

URL: <http://pirsa.org/18100065>

Abstract: <p>Dr. Avery Broderick will provide a highly accessible and interesting lecture on the Event Horizon Telescope (EHT) and international efforts to interpret horizon-resolving images of numerous supermassive black holes. Black holes are among the most powerful and mysterious phenomena in the universe. Almost every galaxy has at its core a supermassive black hole, millions or even billions of times more massive than our sun. Despite composing a small fraction of the galactic mass budgets, they set the stage for astrophysical dramas that dictate the fates of their hosts. Though black holes are in theory the ultimate manifestation of strong gravityâ€™s impact on the visible universe, placing these exotic phenomena on concrete empirical footing has been impossible - until now.</p>

IMAGES FROM THE EDGE OF SPACETIME: RESOLVING BLACK HOLES

AVERY E BRODERICK



BLACK HOLES AND CULTURE



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WHAT GOES UP MUST COME DOWN: BLACK HOLES CIRCA 1784

Body	v_{esc}
Earth	11 km/s
Jupiter	60 km/s
Sun	620 km/s

$$R = \frac{2GM}{c^2}$$

c

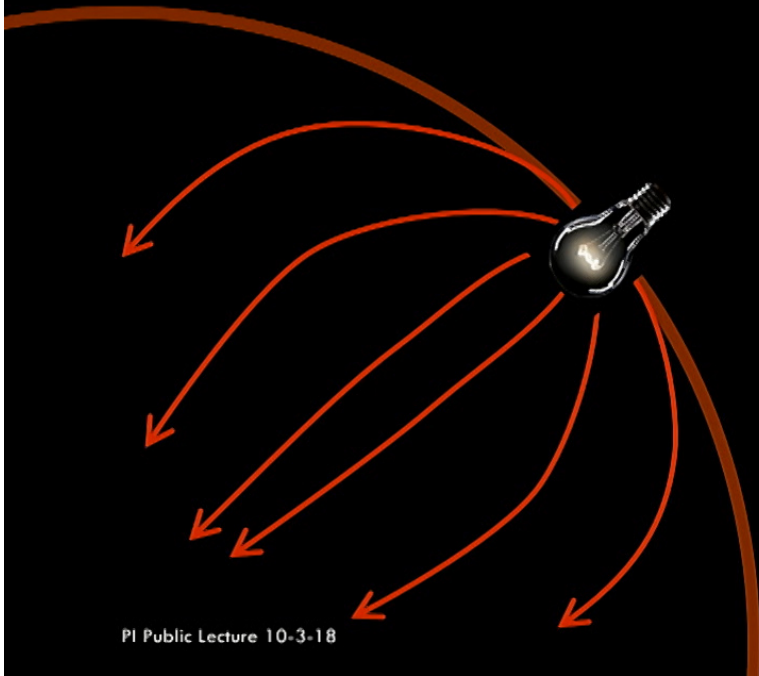
$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

“... 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 ...”

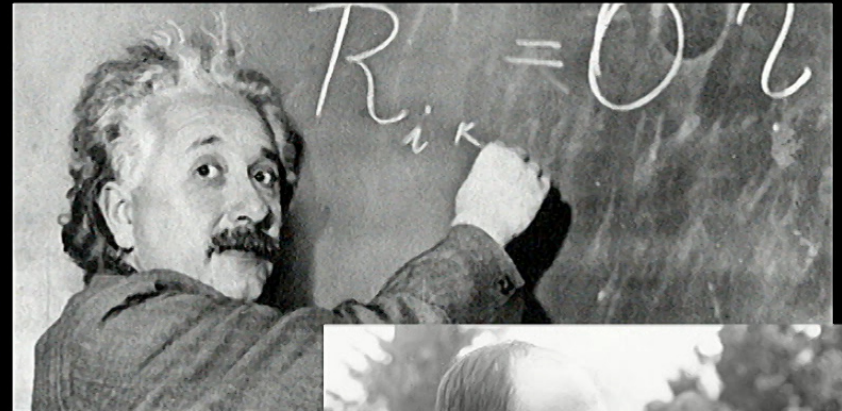
— John Michell, 1784

POCKETS OF SPACE: BLACK HOLES CIRCA 1918

The “Event Horizon”

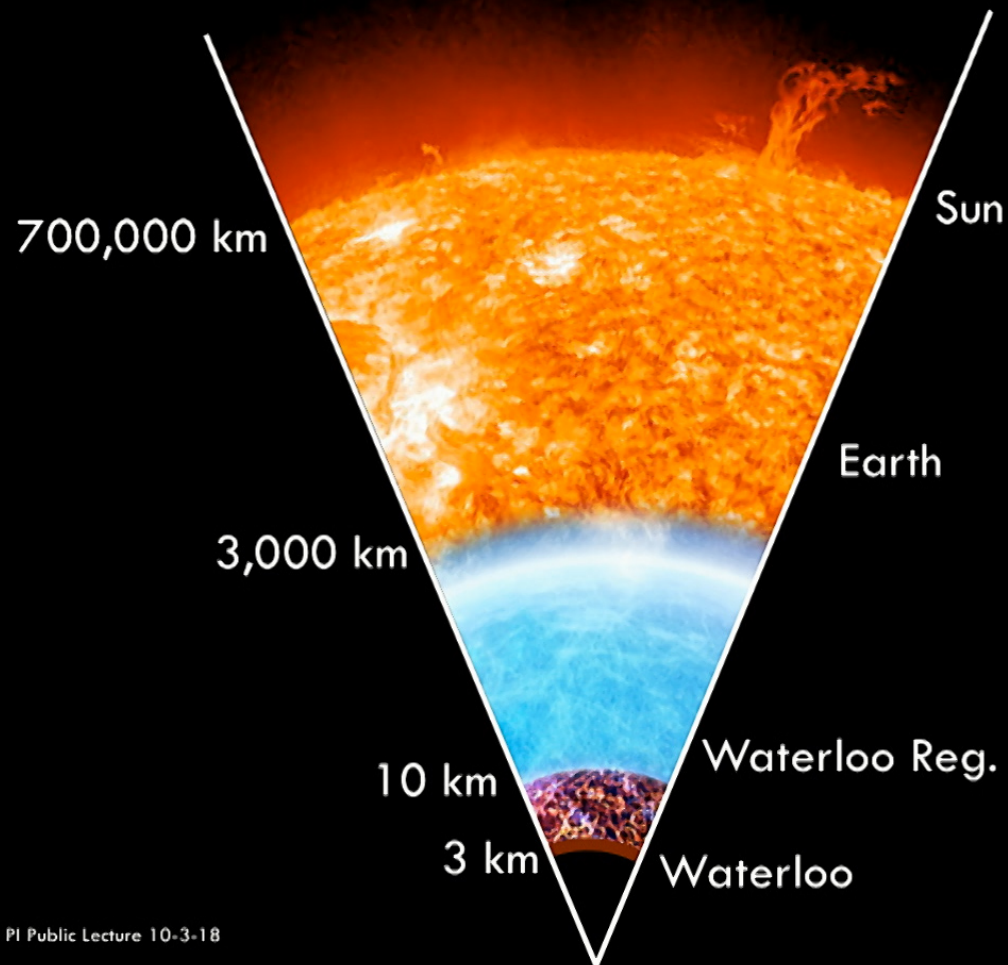


$$R_S = \frac{2GM}{c^2}$$



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HOW TO MAKE A BLACK HOLE

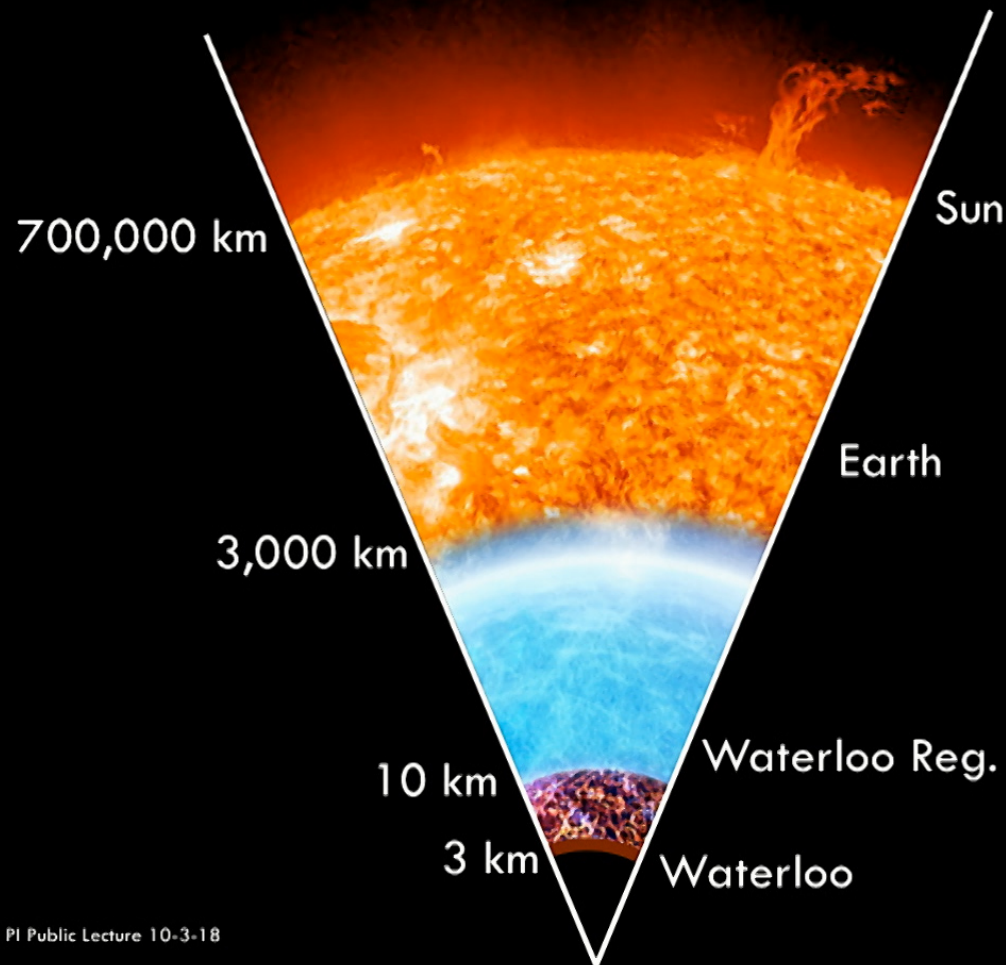


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A matter of size!

$$R_S = 3 \left(\frac{M}{M_{Sun}} \right) \text{ km}$$

HOW TO MAKE A BLACK HOLE



A matter of size!

$$R_S = 3 \left(\frac{M}{M_{Sun}} \right) \text{ km}$$

Body	R_S
Sun	3 km
Earth	1 cm
Professor	10^{-15} fm
Universe	10 Gpc

WHAT CAN MAKE A BLACK HOLE? (WITH ENOUGH EFFORT!)

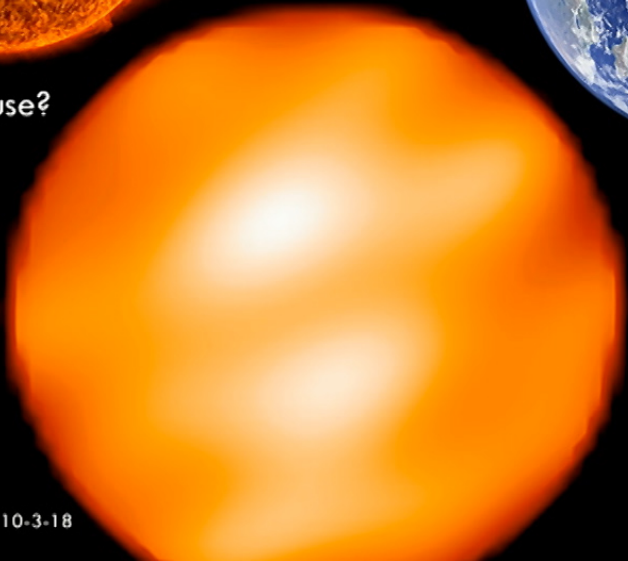


The Sun?
YES!



Earth?
YES!

Betelgeuse?
YES!



Me?
YES!

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WHAT CAN MAKE A BLACK HOLE? (WITH ENOUGH EFFORT!)

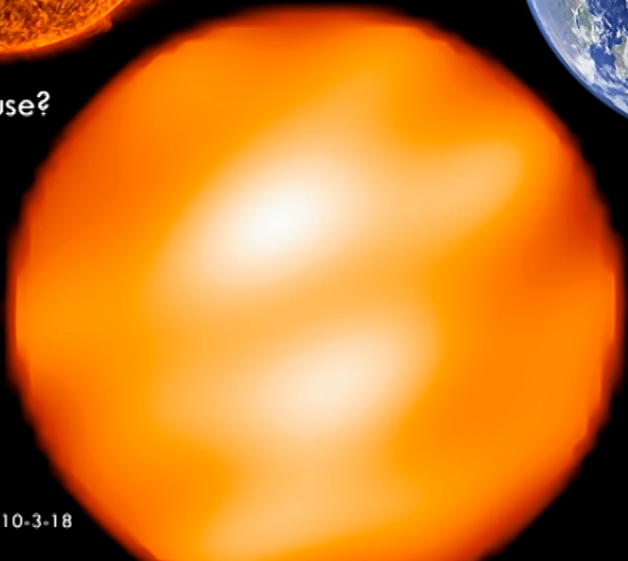


The Sun?
YES!

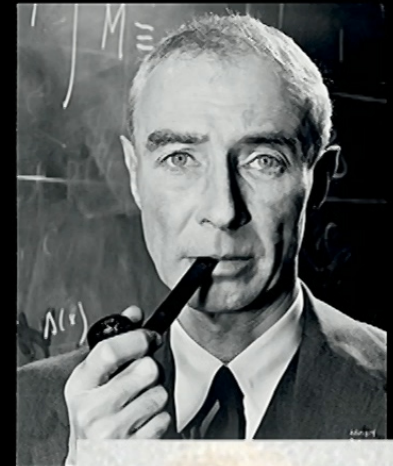


Earth?
YES!

Betelgeuse?
YES!

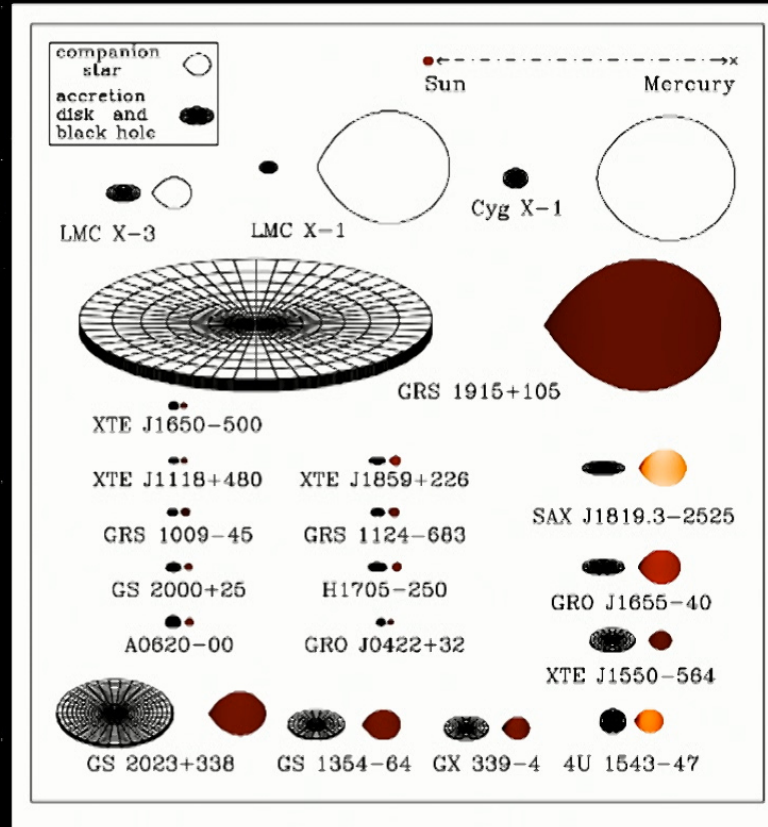
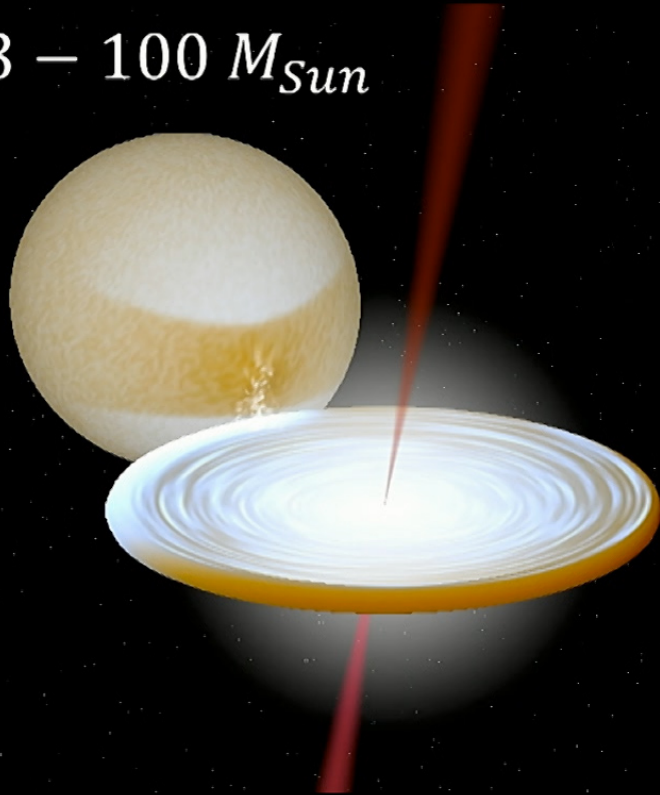


Me?
YES!



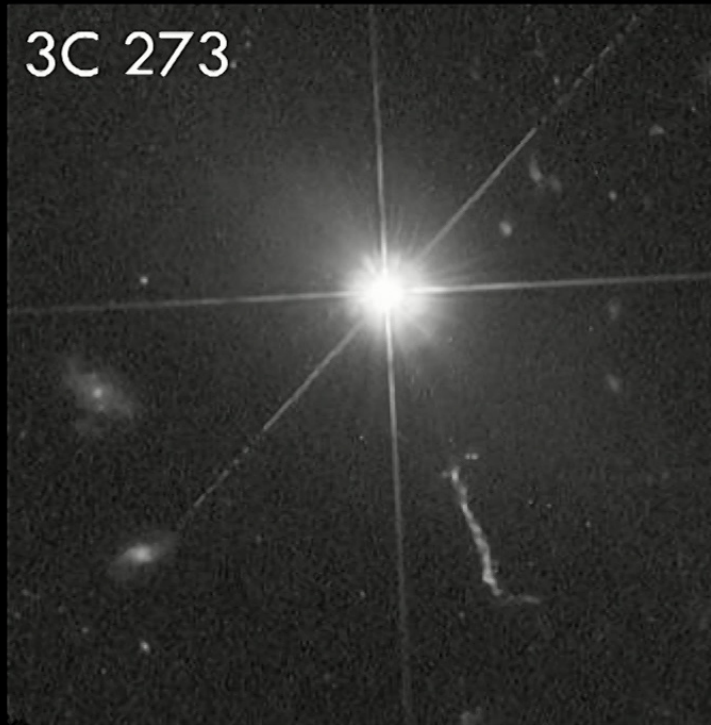
BLACK HOLES – AN ASTRONOMICAL PERSPECTIVE

$3 - 100 M_{\text{Sun}}$



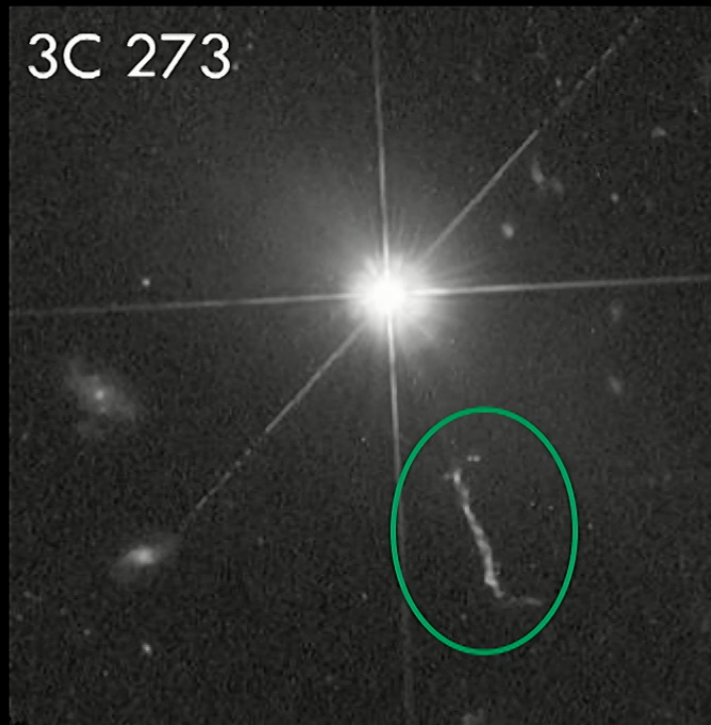
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BLACK HOLES – AN ASTRONOMICAL PERSPECTIVE



$10^6 - 10^9 M_{\text{Sun}}$

BLACK HOLES – AN ASTRONOMICAL PERSPECTIVE



$$10^6 - 10^9 M_{\text{Sun}}$$

$$L \sim 10^{48} \text{ erg/s}$$

$$10^{13} \text{ Suns}$$

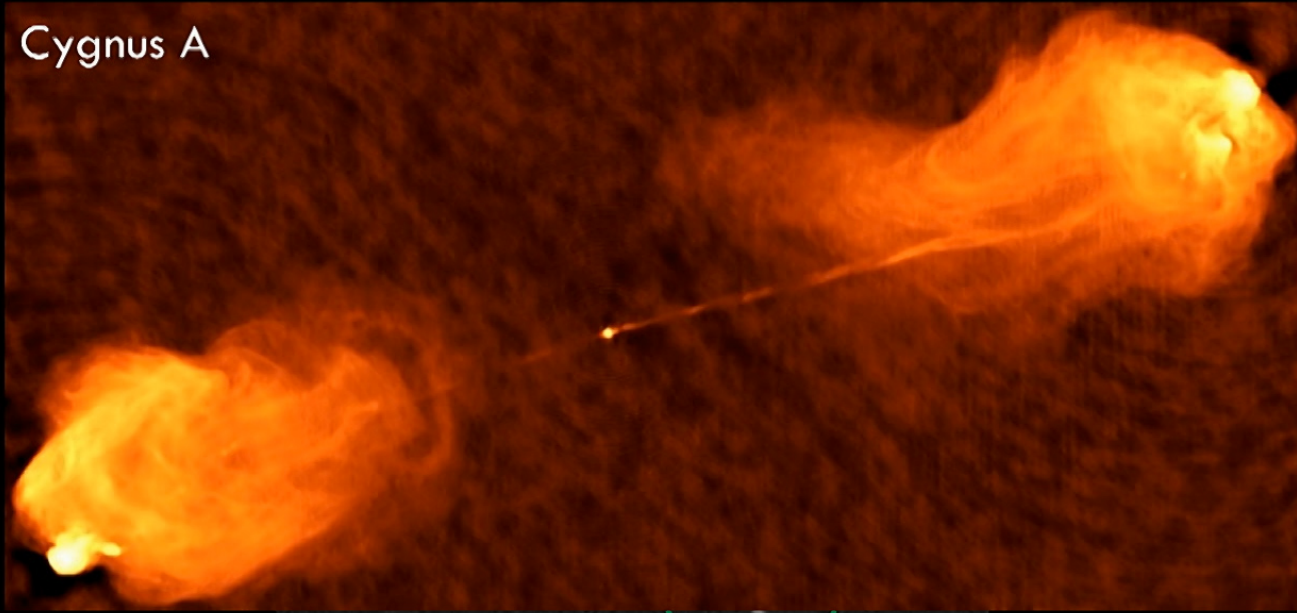
$$1 \text{ SNe}/15 \text{ min}$$

(cf. 1 SNe/Century in MW!)

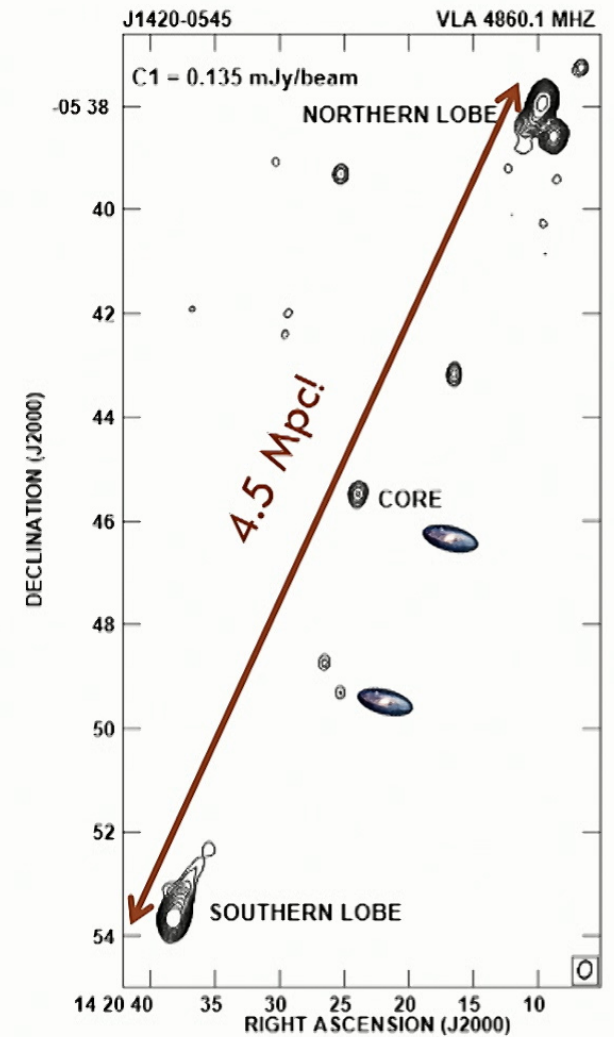
Outshines galaxy 100x !

BLACK HOLES – AN ASTRONOMICAL PER

Cygnus A

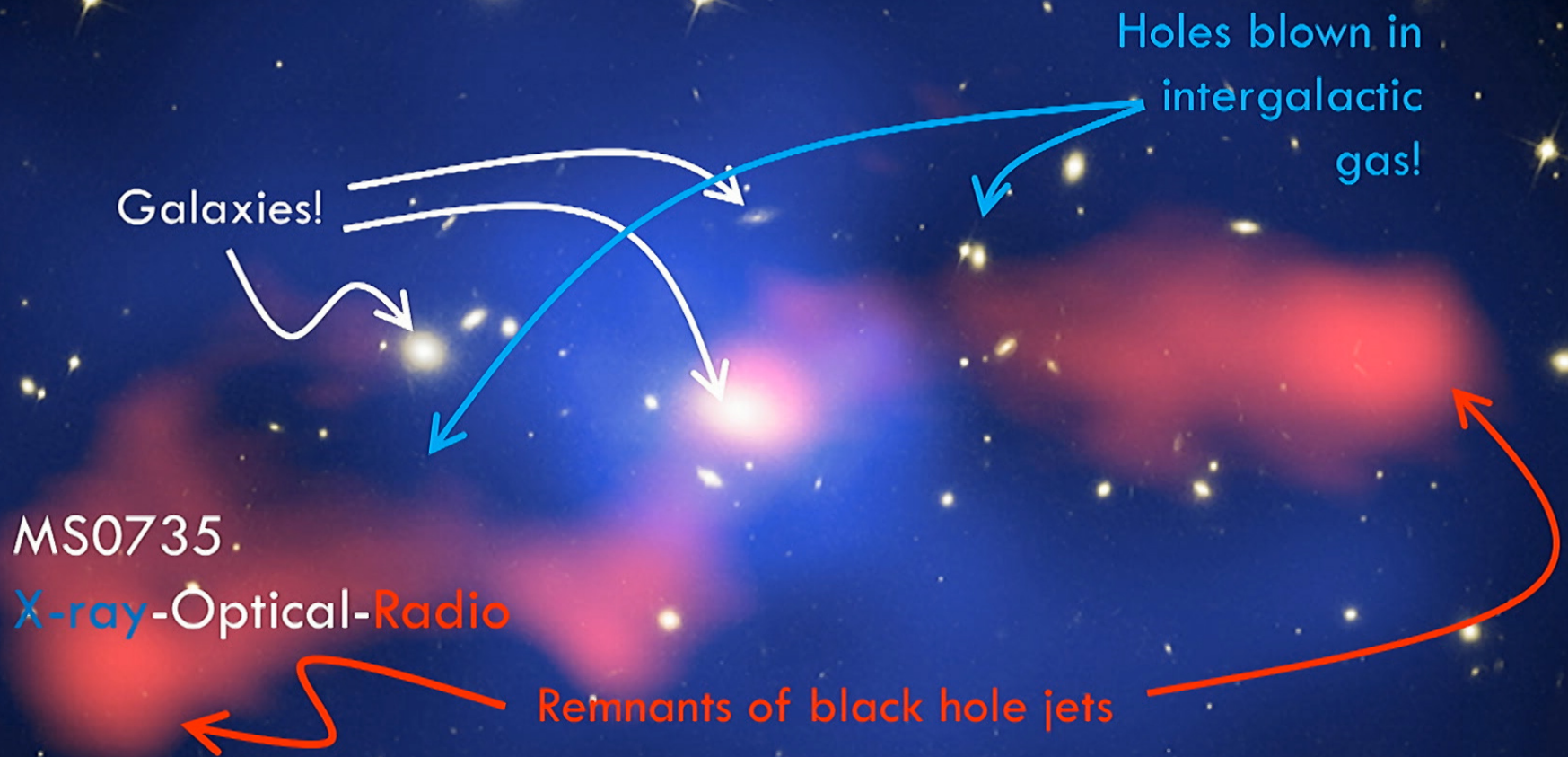


Outshine



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BLACK HOLES – AN ASTRONOMICAL PERSPECTIVE

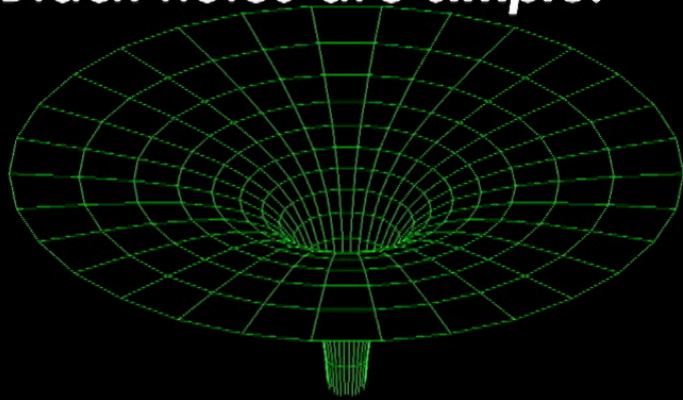


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(Composite Image – Hubble and Chandra Image Credit: NASA, ESA, CXO, STScI and B. McNamara (University of Waterloo) / Very Large Array Telescope Image Credit: NRAO, and L. Birzan and team (Ohio University))

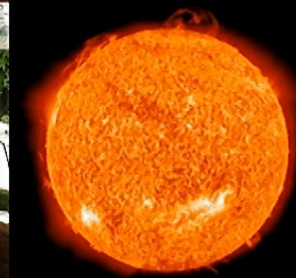
BLACK HOLES AT THE NEXUS OF MODERN PHYSICS

Black holes are *simple*.



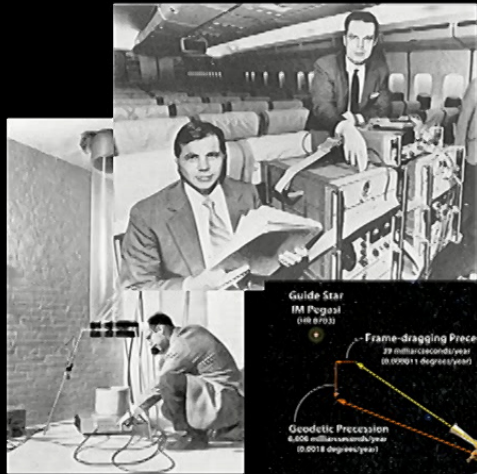
Gravitational impacts of BHs all predicted by ~~3~~ 2 parameters:

- Mass 2
- Angular Momentum
- ~~Electric Charge~~

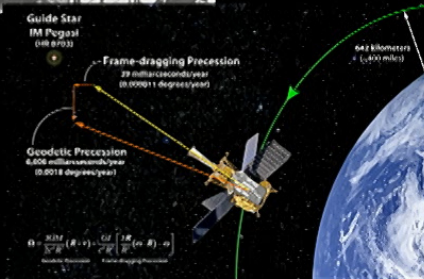


HIGH-PRECISION WEAK GRAVITY

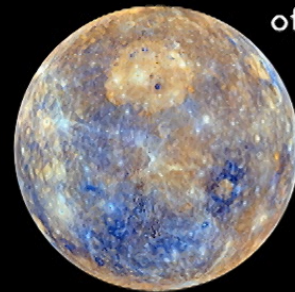
Hafele-Keating Exp.
(Grav. redshift)



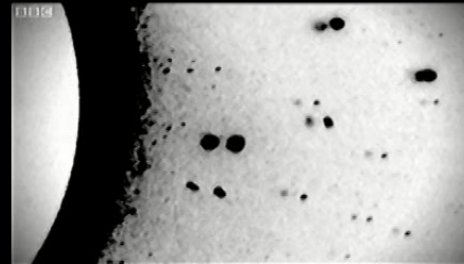
Pound-Rebka Exp.
(Grav. redshift)



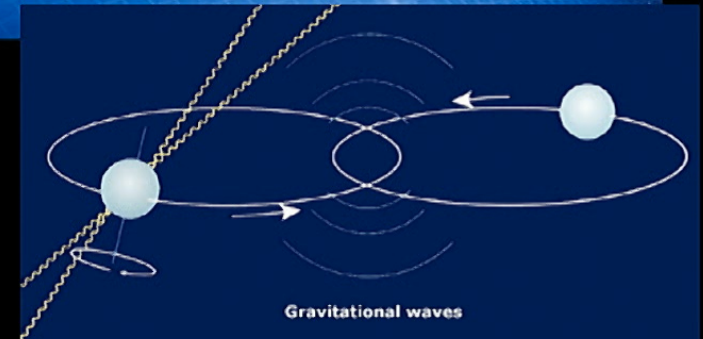
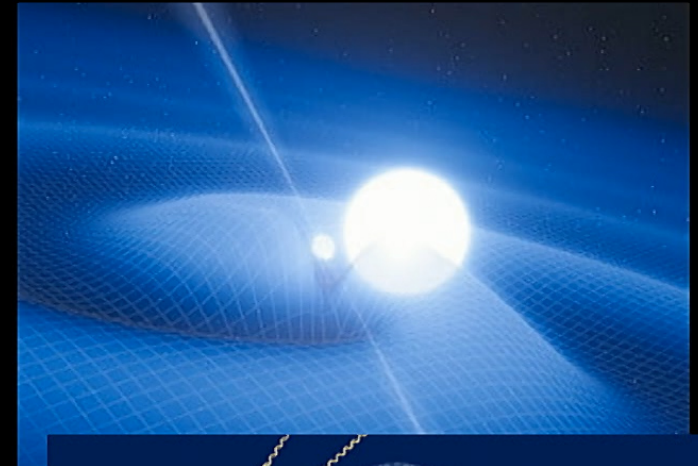
Gravity Probe B



Perihelion advance
of Mercury
(Einstein)



Solar grav. lensing (Eddington)



Terrestrial Experiments
1/100 Million

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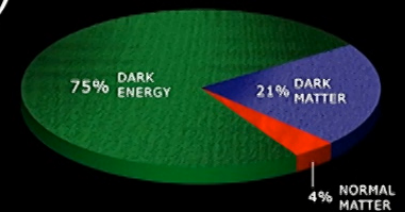
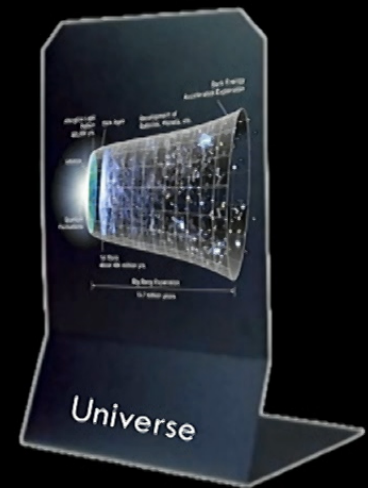
Solar System Experiments
1/100 Million

Rel. Binary Experiments
1/Million

A WINDOW ON STRONG GRAVITY

$$\frac{GM}{Rc^2} \sim 1$$

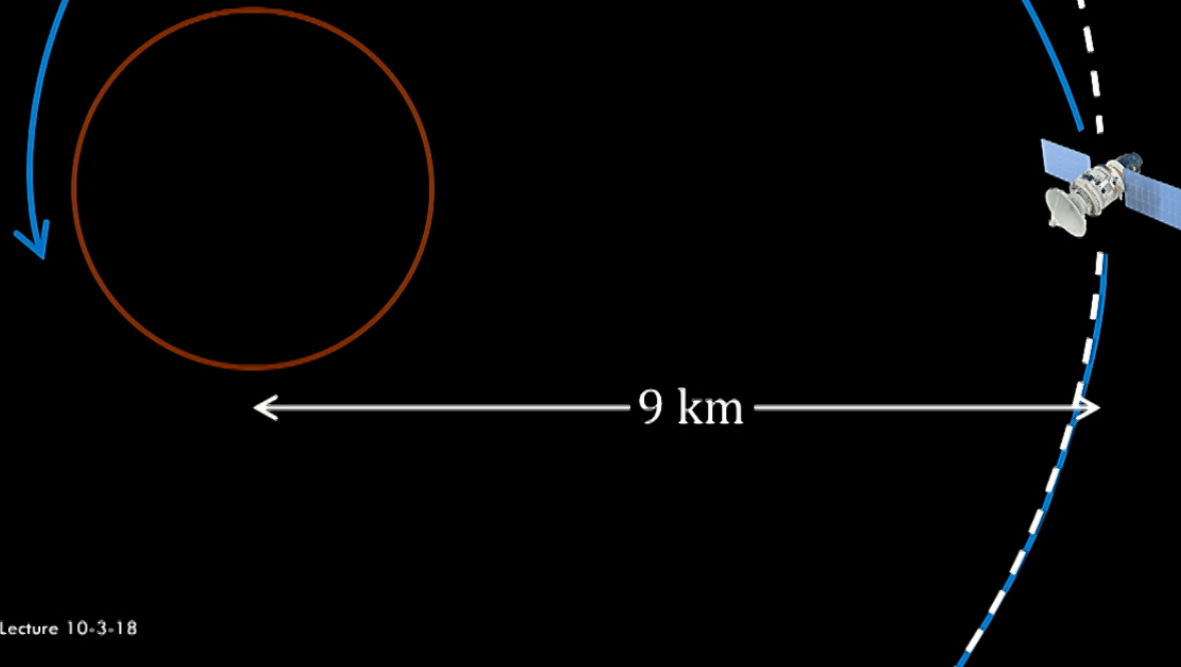
$$\frac{GM}{Rc^2} \sim \frac{G}{Rc^2} \left(\frac{4\pi}{3} \rho R^3 \right) \sim 1 \left(\frac{\rho}{1 \text{ H atom/m}^3} \right) \left(\frac{R}{10 \text{ Gpc}} \right)^2$$



A WINDOW ON STRONG GRAVITY



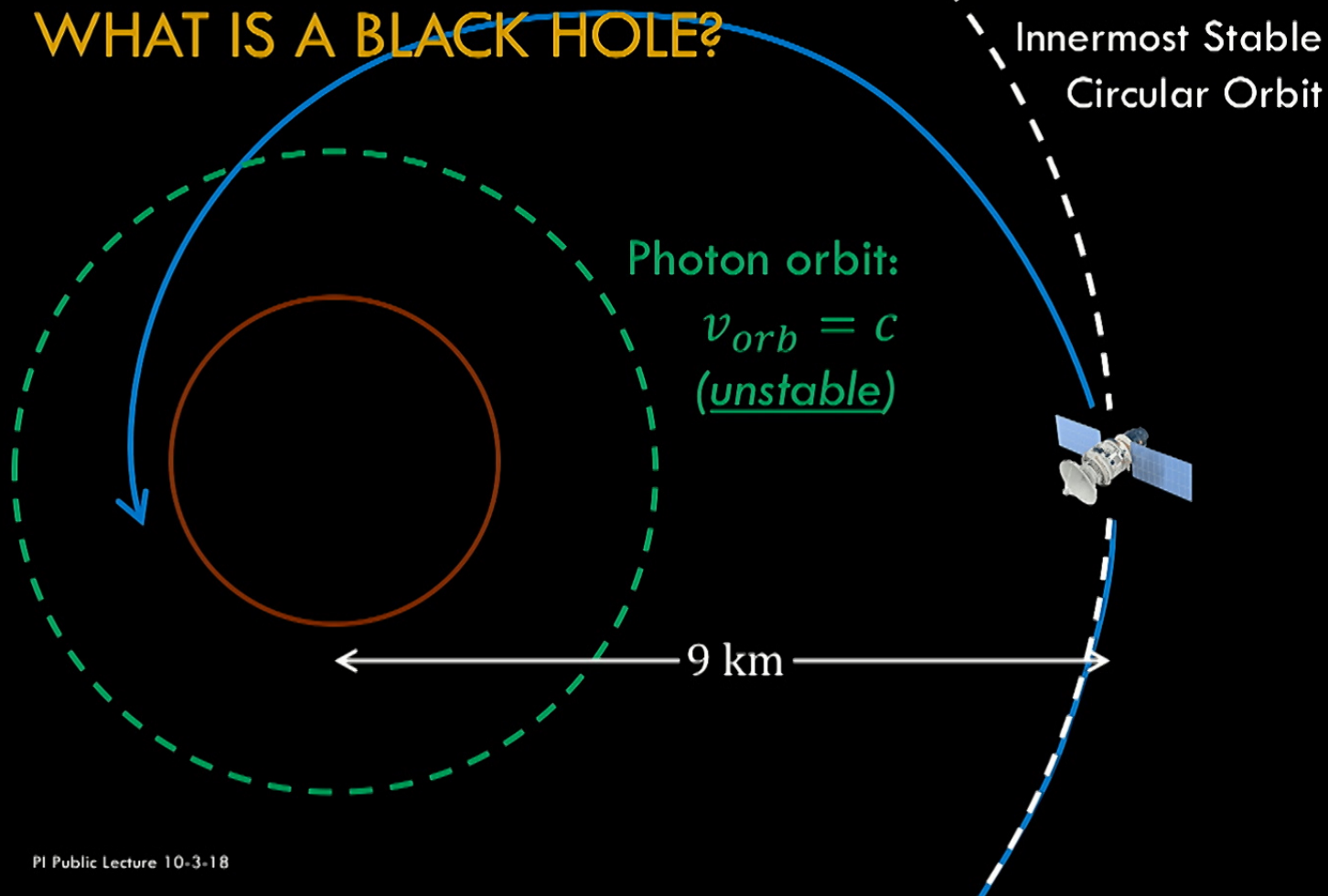
BEYOND THE HORIZON: WHAT IS A BLACK HOLE?



Innermost Stable
Circular Orbit

$E = mc^2$
Kinetic energy
gravitates!

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Circular Orbit

$E = mc^2$
Kinetic energy
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Photon orbit:
 $v_{orb} = c$
(unstable)

1.5 – 9 km

Ergosphere
Dragging
spacetime!



Gravity
from mass

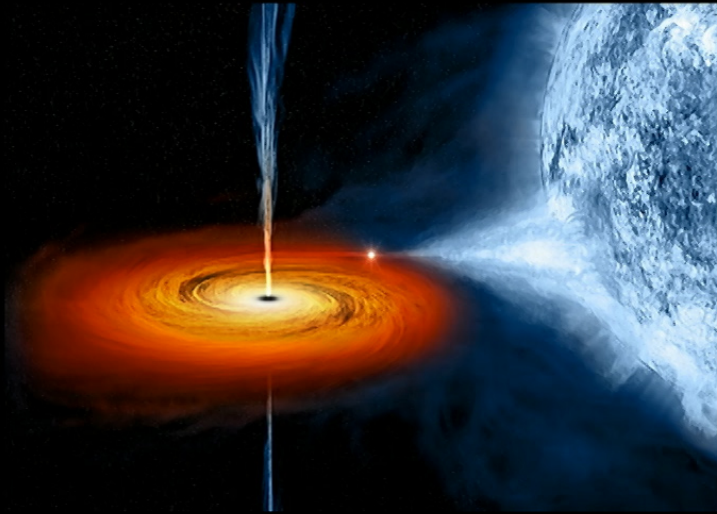


Gravity
from mass
currents

MYSTERIES ABOUND

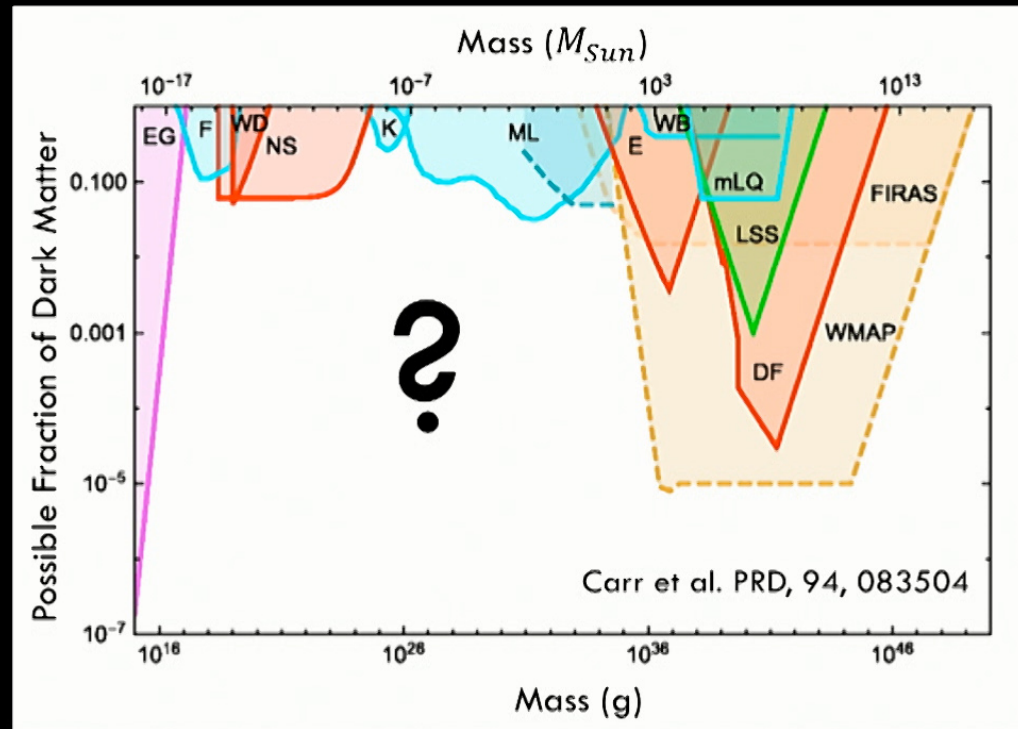
Mini-monsters – From stars and ?

$$M < 100M_{\text{Sun}}$$



- ~20 BH X-ray binaries.
- 100 million dark BHs roaming the Milky Way!
- Up to 10% of dark matter?

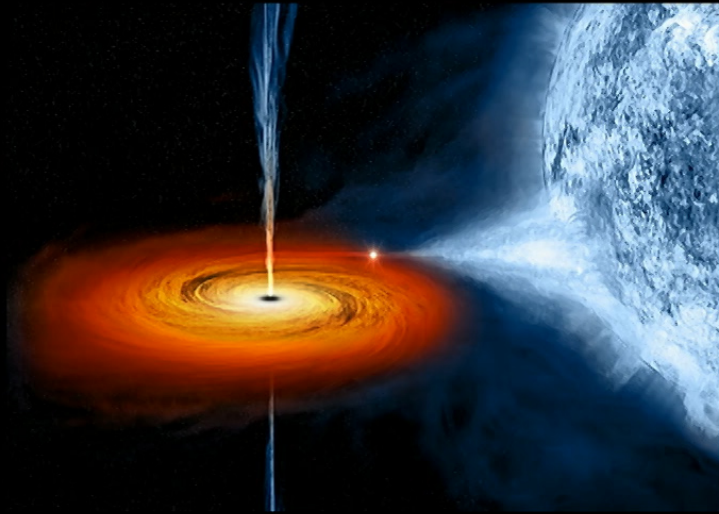
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Monsters at the centers of Galaxies

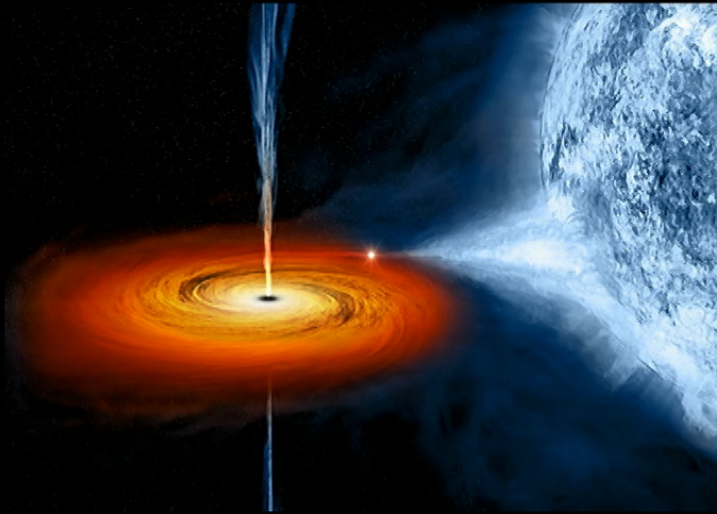
$$1 \text{ Million } M_{\text{Sun}} \lesssim M \lesssim 10 \text{ billion } M_{\text{Sun}}$$



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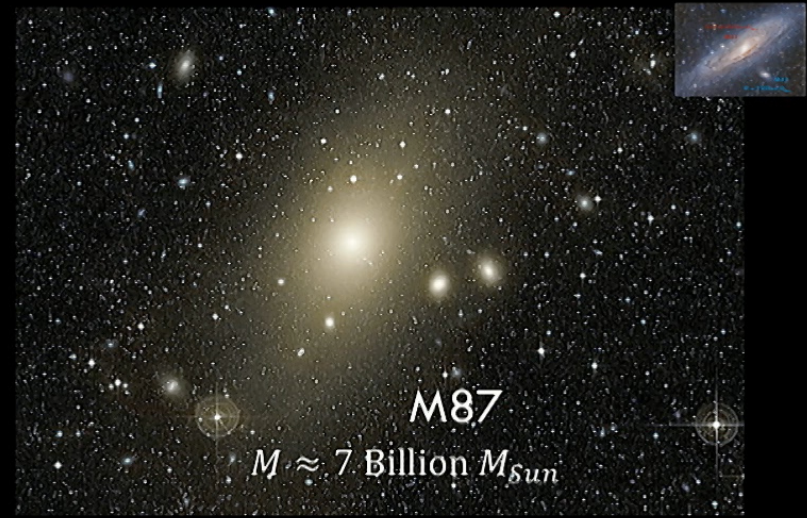


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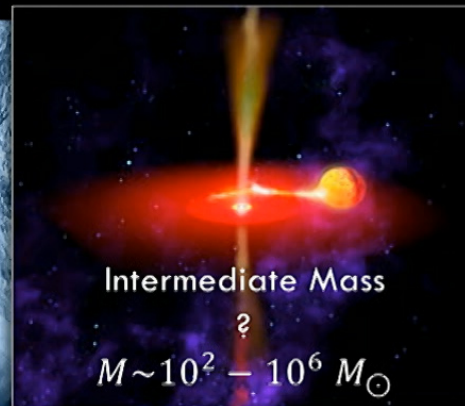
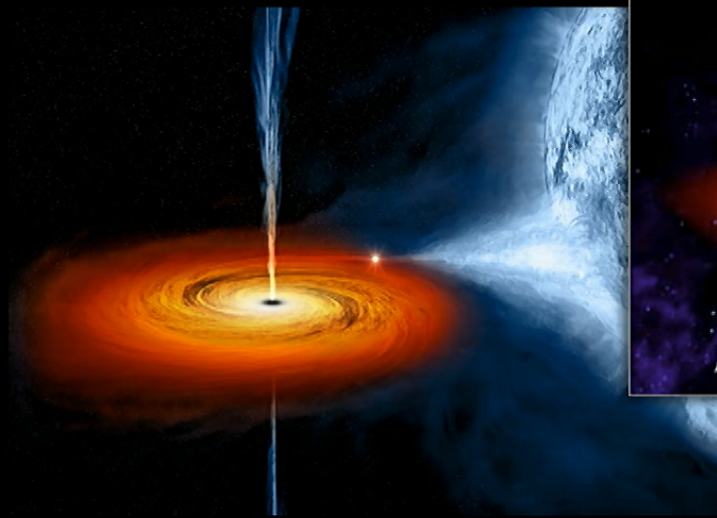


- Bigger BHs at the centers of bigger galaxies, even though tiny fraction of mass
- How do they grow and launch jets?
- Are these black holes?

MYSTERIES ABOUND

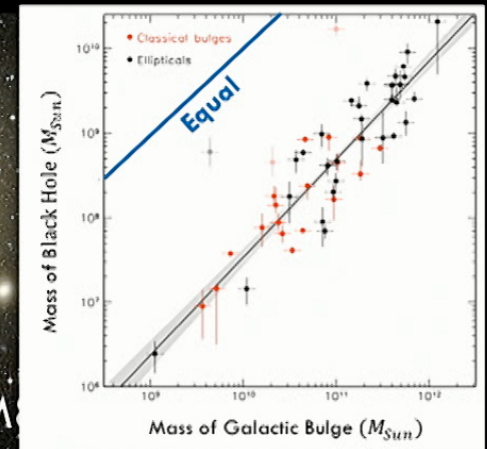
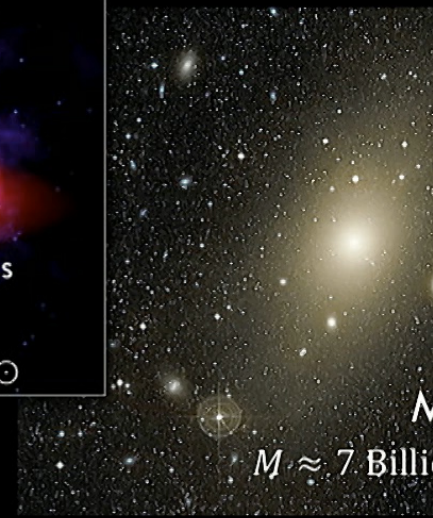
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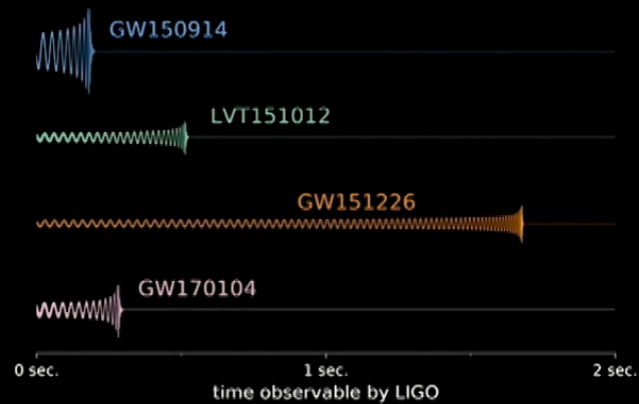
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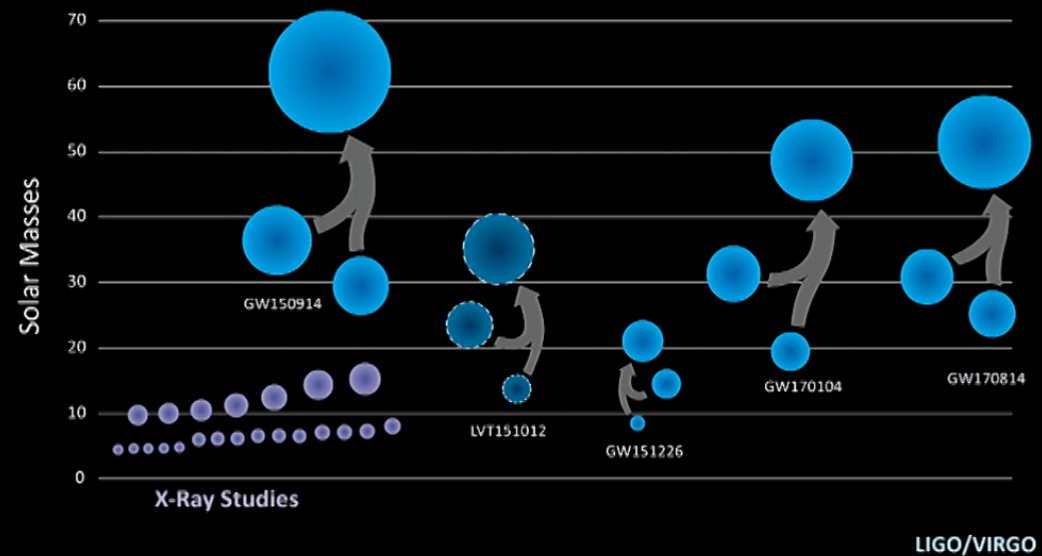
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A GOLDEN AGE OF BLACK HOLE ASTRONOMY

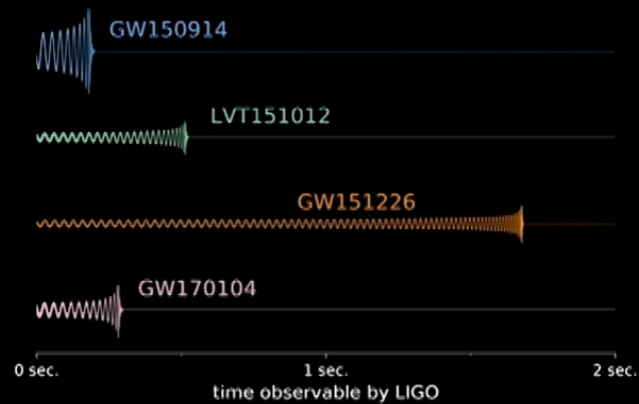


Gravitational Waves:
“Hearing” ripples in spacetime!

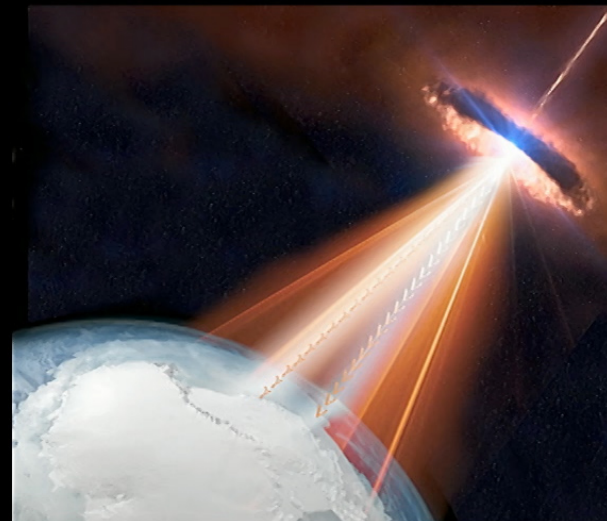
Black Holes of Known Mass



A GOLDEN AGE OF BLACK HOLE ASTRONOMY



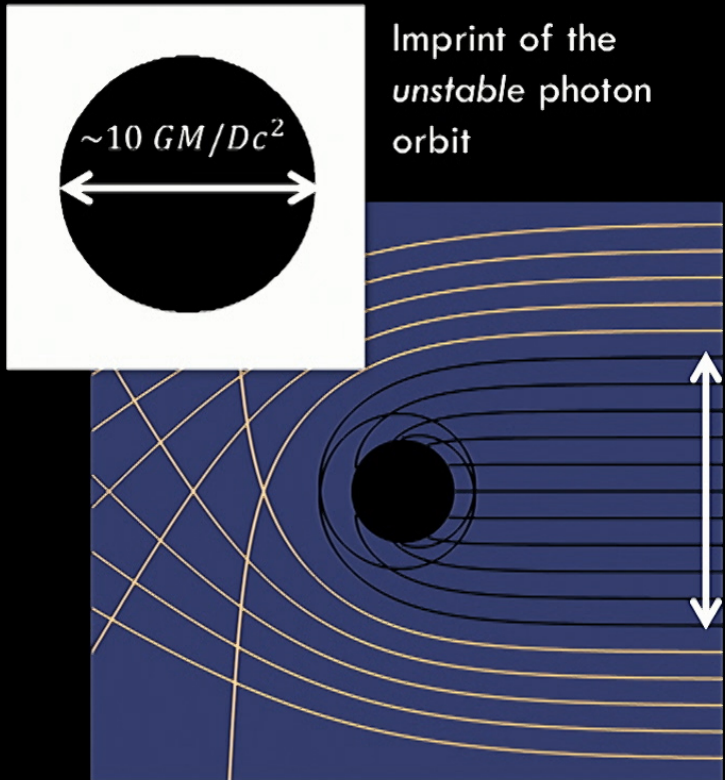
Gravitational Waves:
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Multi-messenger:
Neutrino astronomy
and others ...

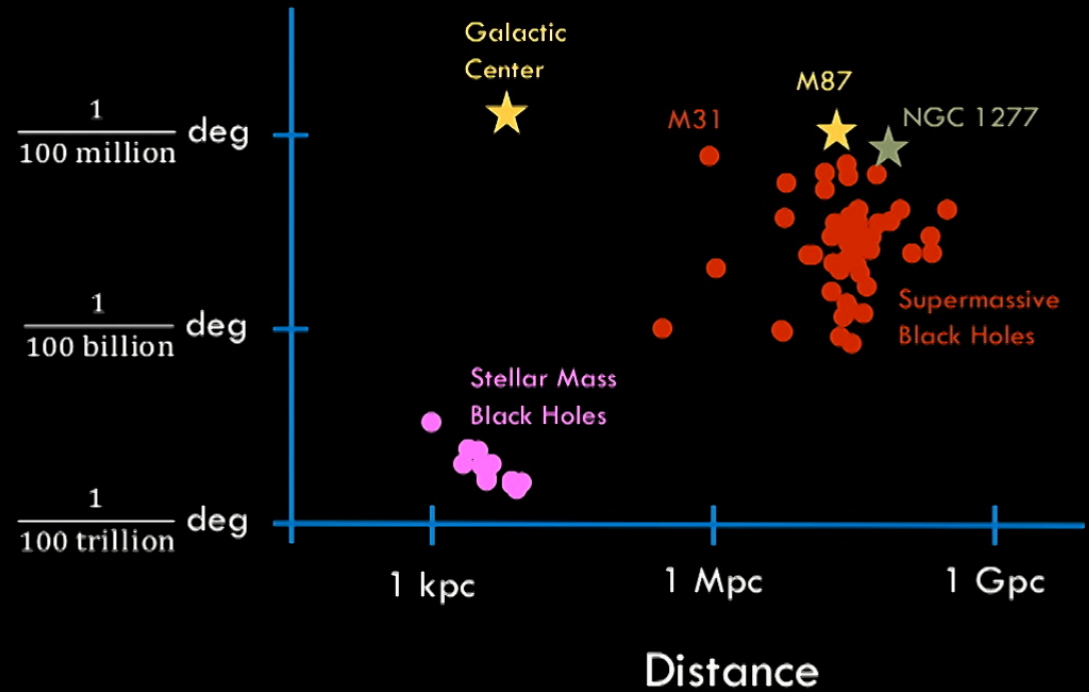
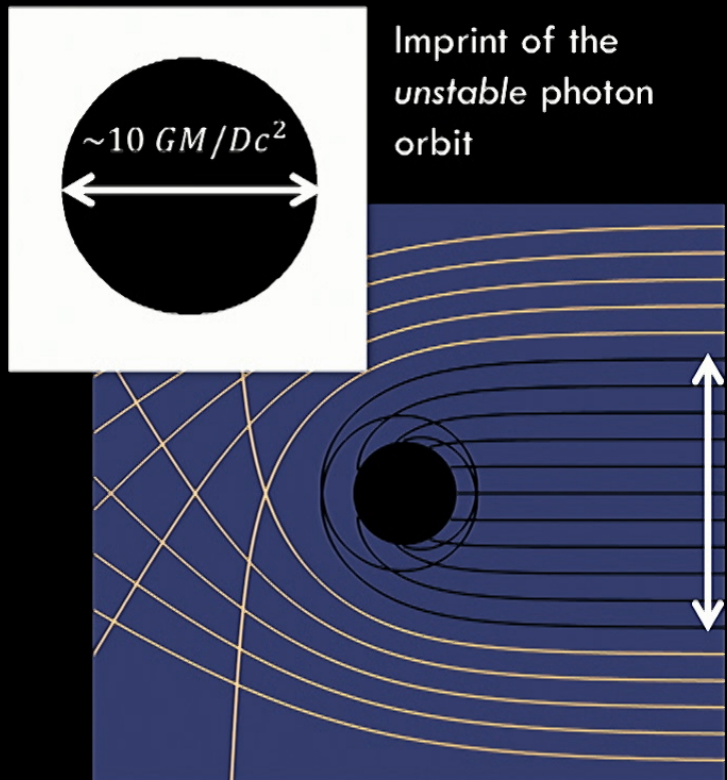


PRACTICAL DIFFICULTIES: BLACK HOLES ARE SMALL ...



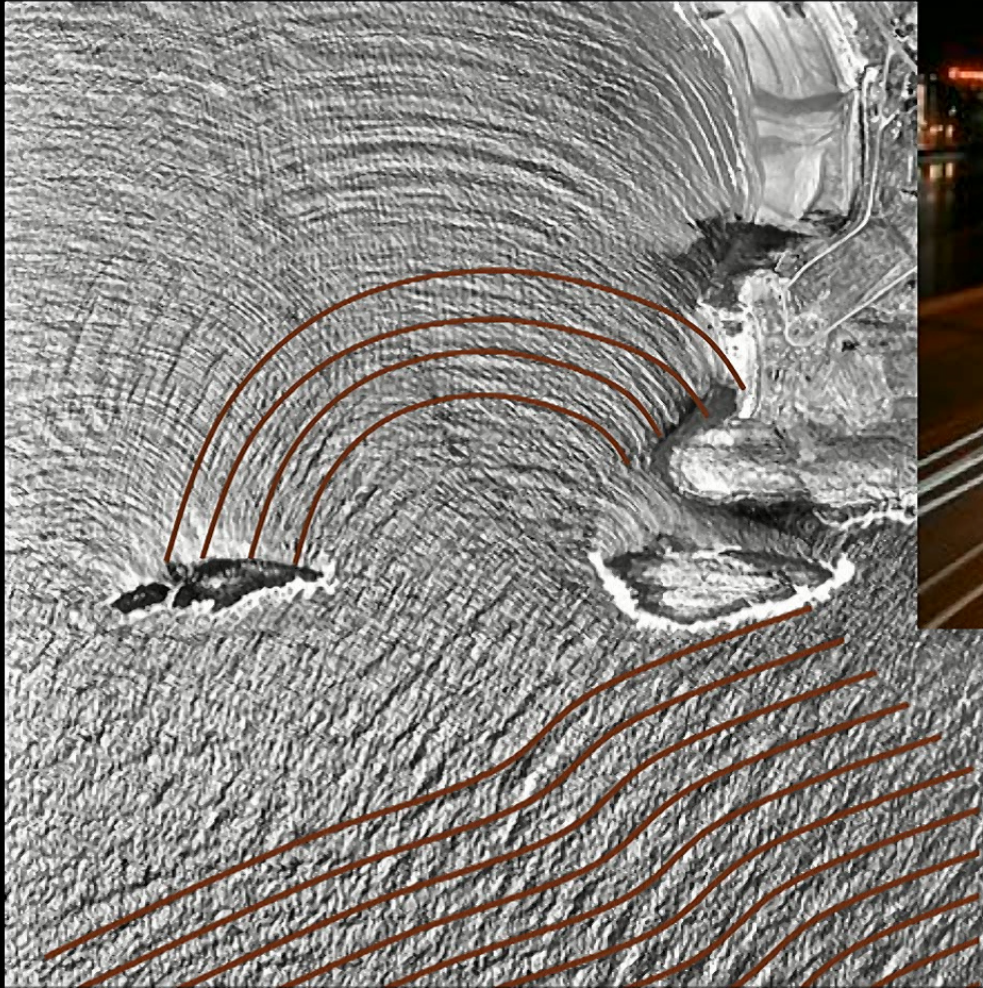
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PRACTICAL DIFFICULTIES: BLACK HOLES ARE SMALL ...





THE DIFFRACTION LIMIT

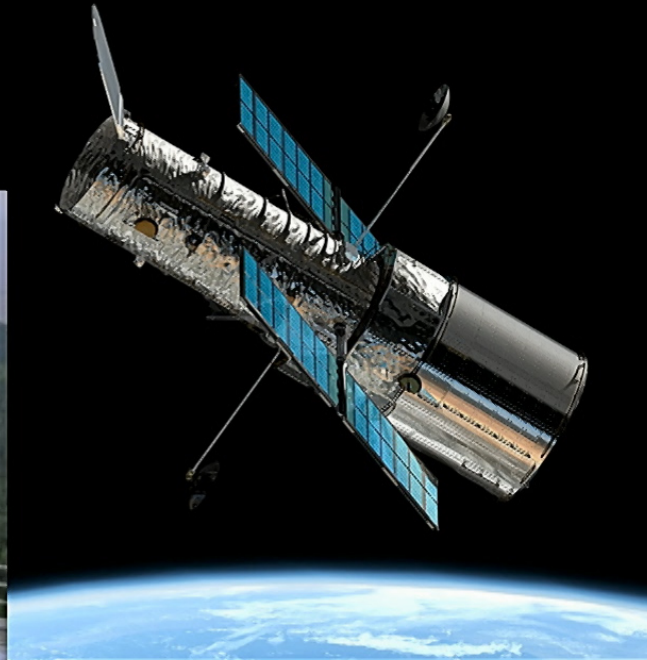


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DIFFRACTION LIMITS ACROSS ASTRONOMY



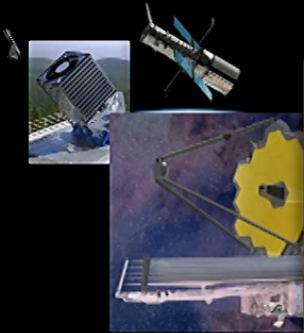
Sloan Digital Spectroscopic Survey



Hubble Space Telescope

×2000

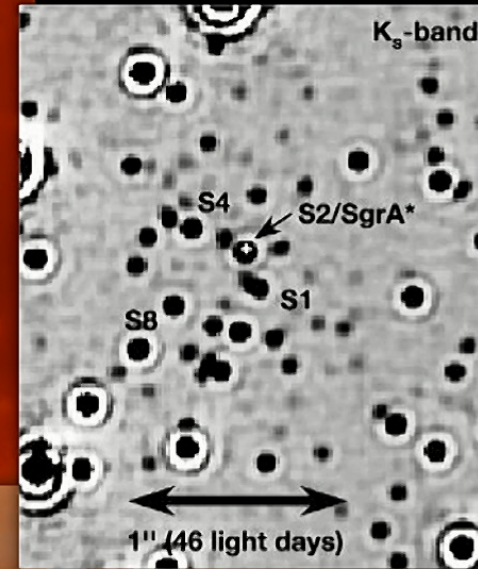
DIFFRACTION LIMITS ACROSS ASTRONOMY



Keck

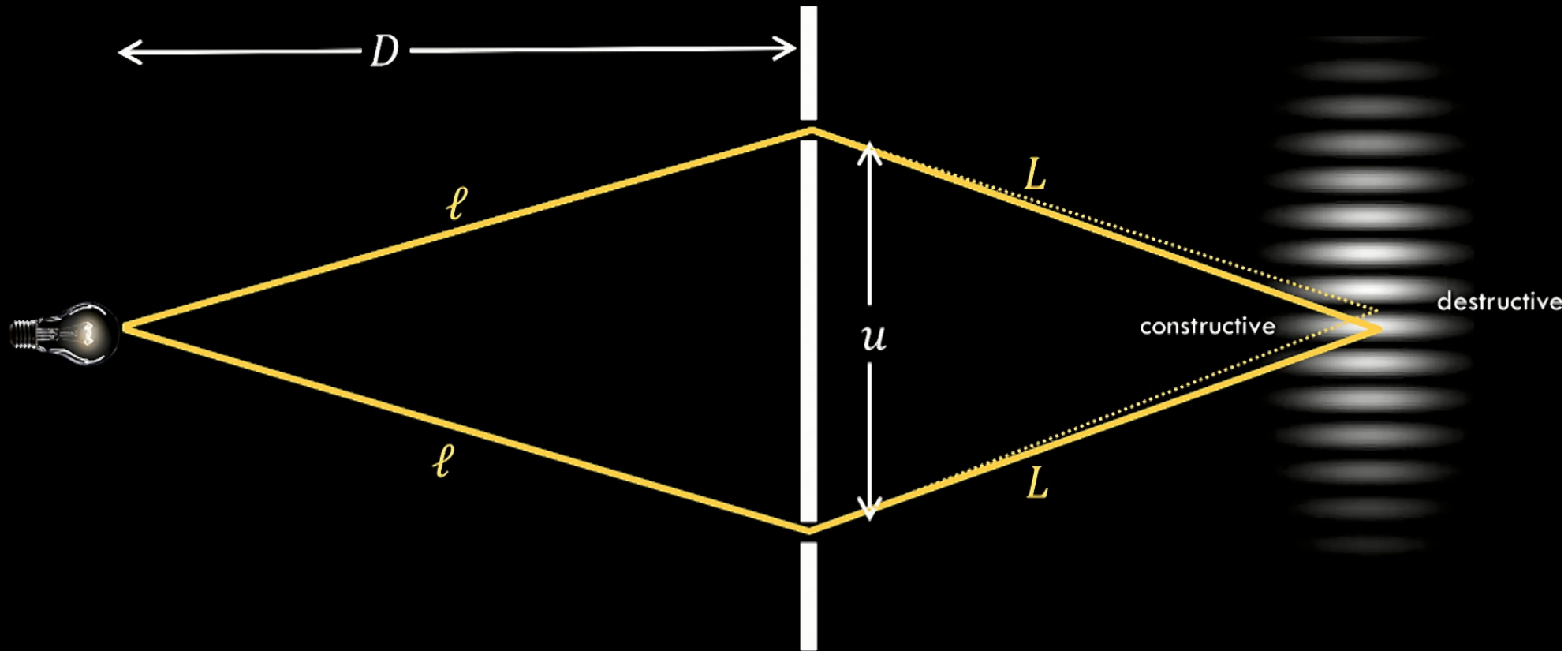


VLT



×500

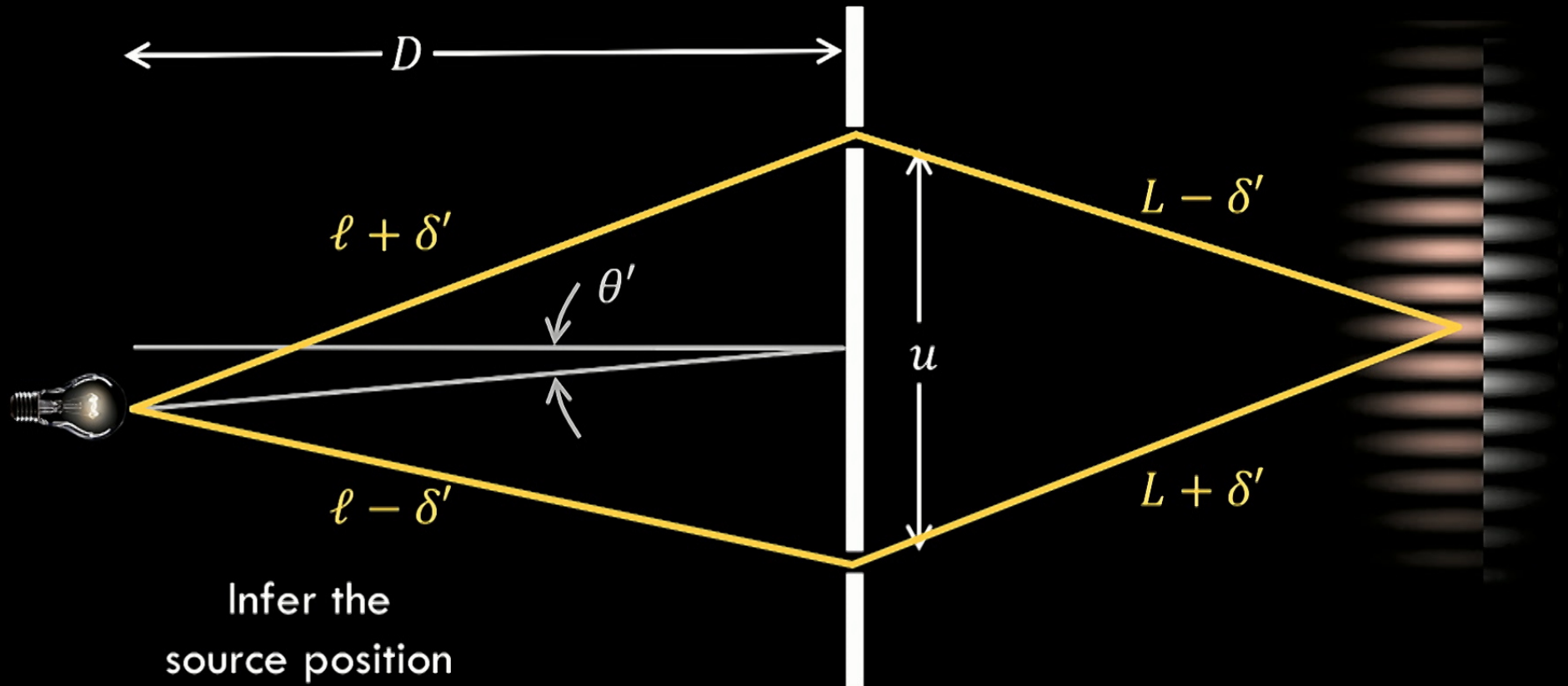
INTERFEROMETRY



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INTERFEROMETRY

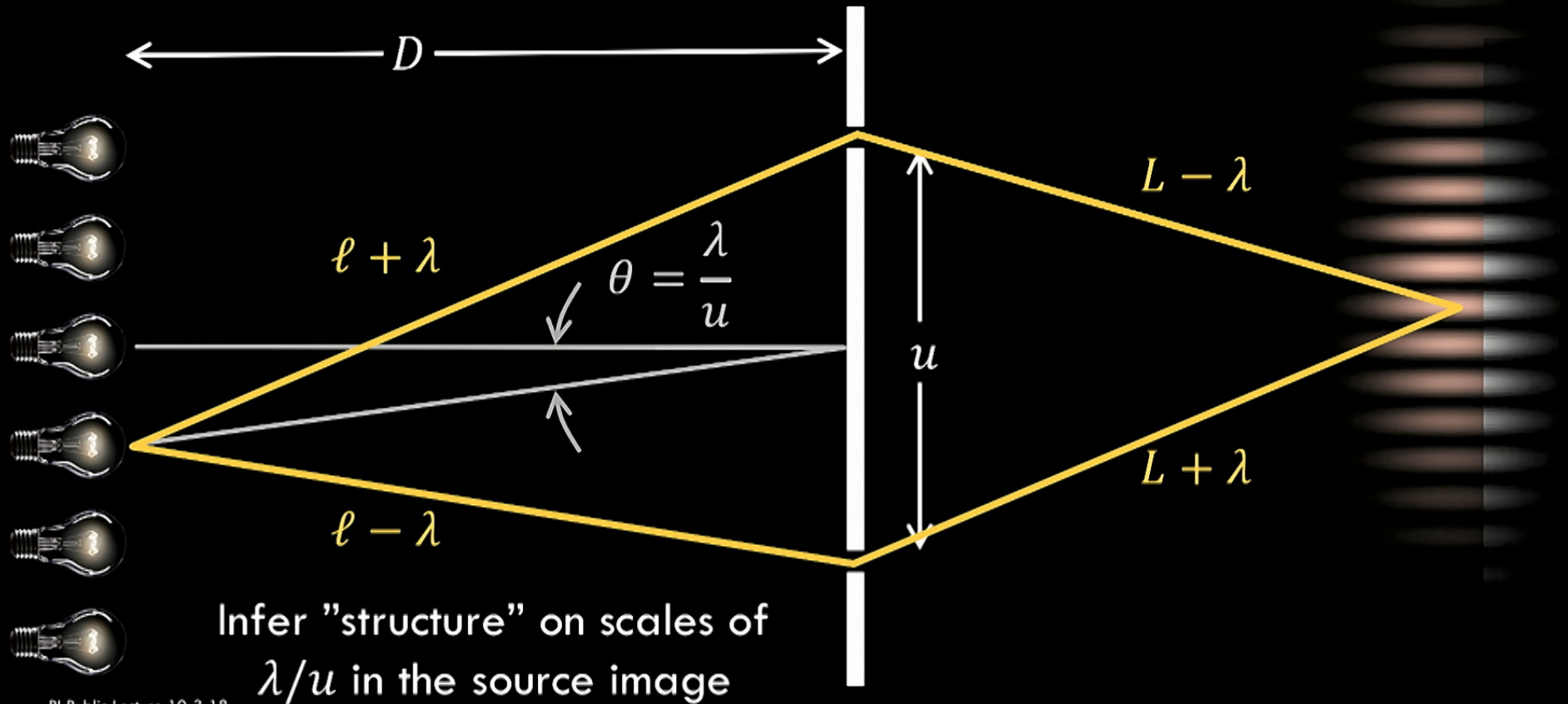
Measure the
fringe pattern



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INTERFEROMETRY

Measure the
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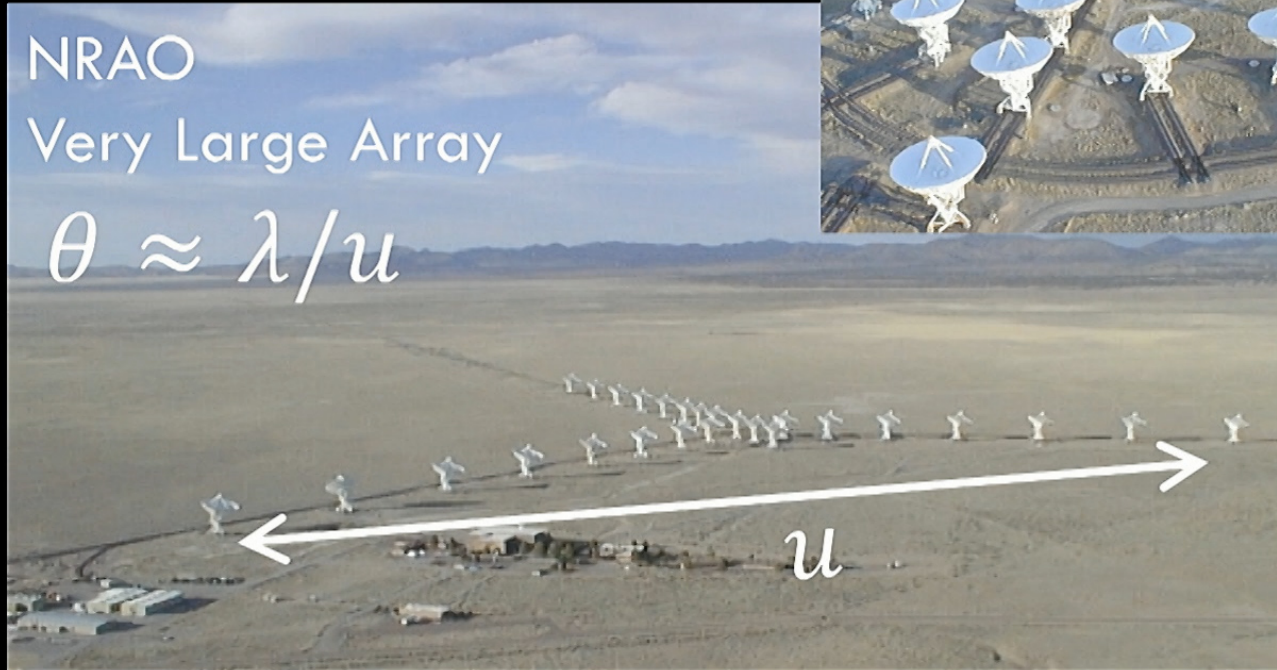
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RADIO INTERFEROMETRY

NRAO

Very Large Array

$$\theta \approx \lambda/u$$



- Measure waves!
- Combine to make interference patterns (“correlation”)
- Repeat for each pair of antennas.

RADIO INTERFEROMETRY

NRAO

Very Large Array

$$\theta \approx \lambda/u$$



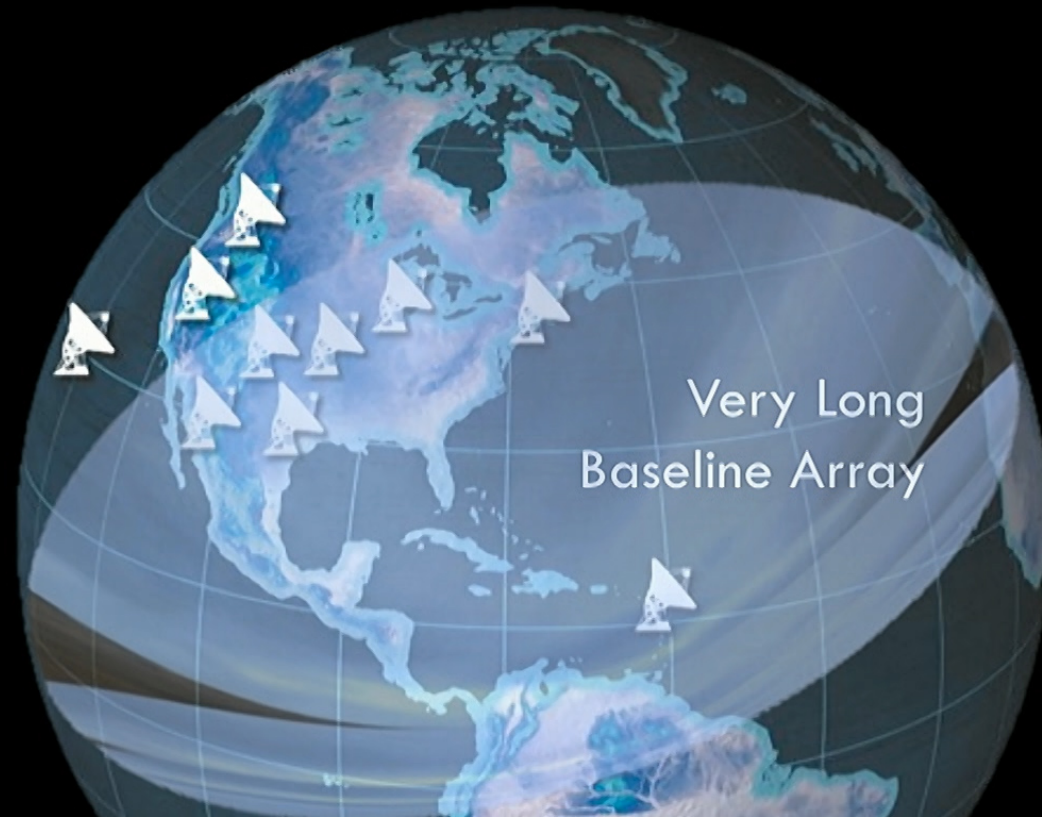
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- Repeat for each pair of antennas.

HOW BIG CAN u GET?

VERY LONG BASELINE INTERFEROMETRY

$$\theta \approx \frac{1 \text{ cm}}{10,000 \text{ km}} = 200 \mu\text{as}$$

1. Bigger? Very expensive!
2. Shorter wavelength?



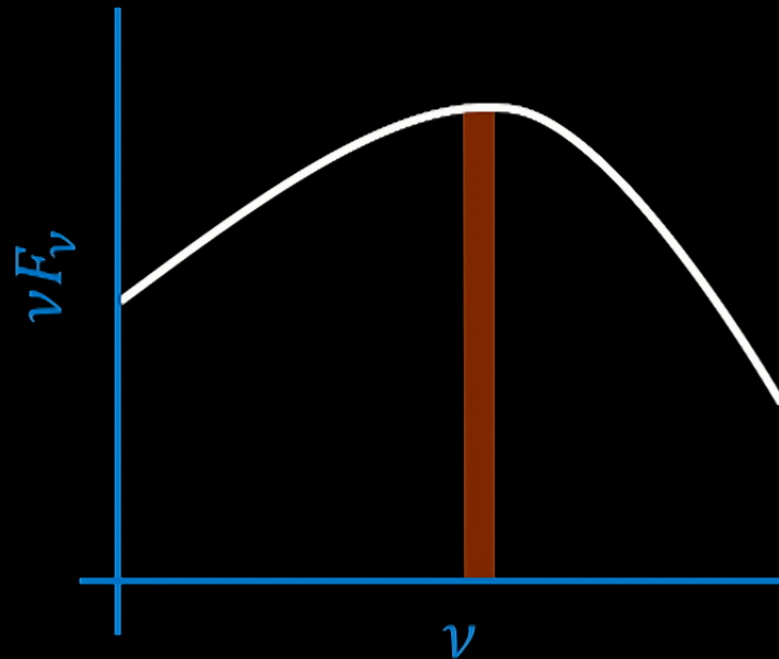
WHY NOW? THE COST OF SENSITIVITY

EHT targets are bright astronomical sources.

- Microwave: ~ 1000 W
- You: ~ 80 W
- Galactic Center: $\sim 10^{-15} \left(\overbrace{\left(\frac{A}{100 \text{ m}^2} \right)}^{\text{Dish size}} \right) \left(\overbrace{\left(\frac{B}{1 \text{ GHz}} \right)}^{\text{Bandwidth}} \right) \text{ W}$

Adding insult to injury: atmospheric coherence $\rightarrow 10$ s!

1. Keep the microwaves off! (Perytons)
2. Sensitivity is critical:
 - A. Bigger dishes (hard)
 - B. Larger bandwidth (easier)



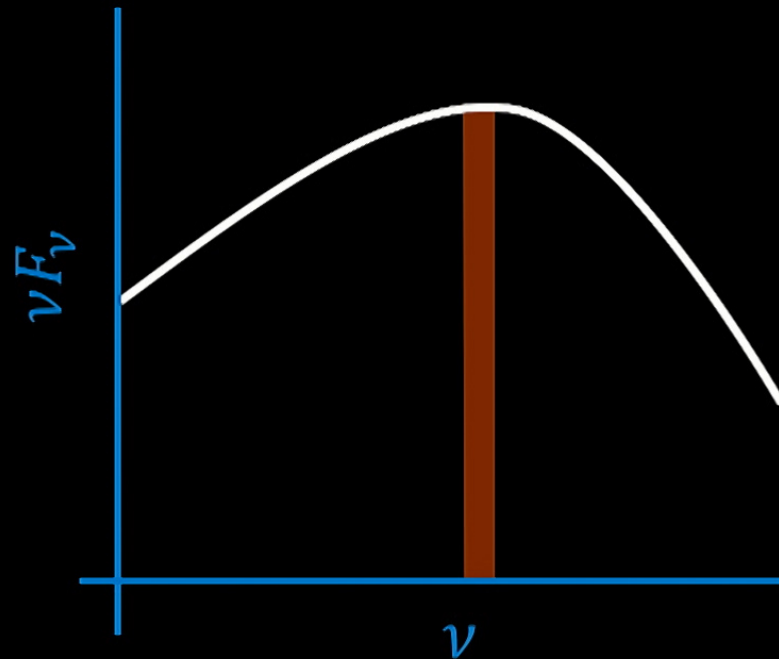
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WHY NOW? THE COST OF SENSITIVITY

Recording full waves, not simply power

→ Think audio, not film, 230 billion times a second!



Not quite so bad – need only resolve the bandwidth.

EHT records 8 GB per second at each station!

64 GB per second across the full array.

225 TB per hour for the full array.

For a 1 week observing run, 27 PB.

BIG data science!

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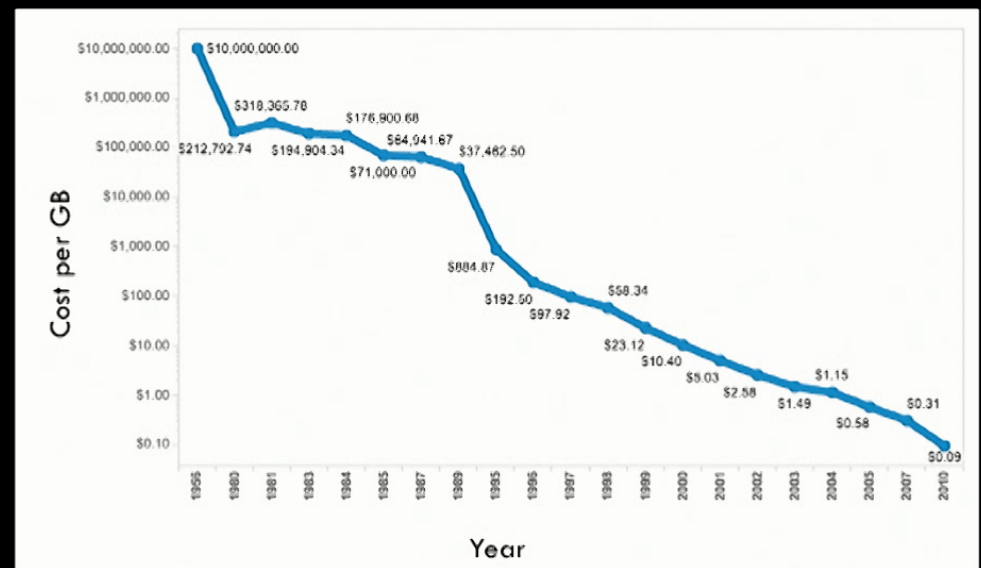
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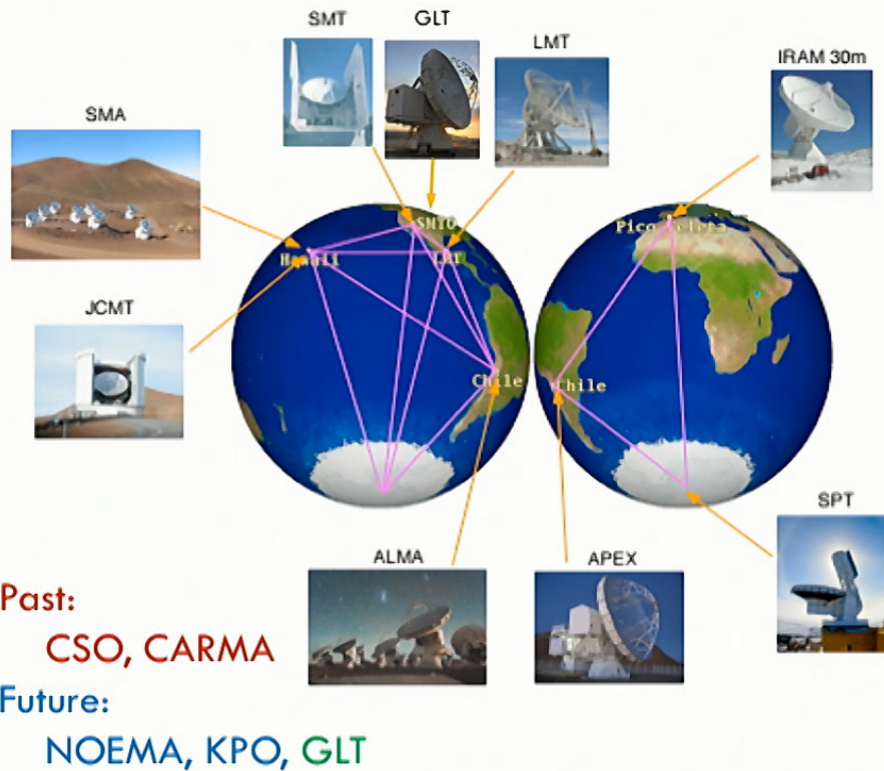
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Only now has the EHT become feasible!



THE EVENT HORIZON TELESCOPE

CIRCA APRIL, 2017 & 2018



AIP, 23.08.2018

- **Synthesis of global collection of millimeter/sub-millimeter telescopes**
- **“Smart” science – Leveraging decades of investment for something fundamentally new**
- **Many stations:**
 - 8 currently
 - 2 previously
 - 2 coming in 2019
- **Operates at:**
 - 230 GHz (1.3 mm)
 - 345 GHz (0.87 mm)
- **Obtains full set of polarization information**
- **Robust detections of EHT targets in ~ 1 s**



Event Horizon Telescope “PROTO-EHT” SINCE 2007

Doeleman et al. 2008, *Nature*, 455, 78

Broderick et al. 2009, *ApJ*, 697, 45

Fish et al. 2011, *ApJ*, 727, 36

Broderick et al. 2011, *ApJ*, 735, 110

Doeleman et al. 2012, *Science*, 338, 355

Broderick et al. 2014, *ApJ*, 784, 7

Akiyama et al. 2015, *ApJ*, 807, 150

Johnson et al. 2015, *Science*, 350, 1242

Broderick et al. 2016, *ApJ*, 820, 137

First 1.3mm VLBI observation of Sgr A*

First physics-based modeling of EHT data

First detection of horizon-scale variability

First demonstration that physics-based models
are preferred by EHT data

First 1.3mm VLBI observations of M87

First constraints on BH hair from EHT data

First measurement of horizon-scale structure in
M87 coincident with TeV flares

First detection of ordered, horizon scale
polarization around a BH

First physics-based modeling of EHT data that
included closure phases



SMA,
JCMT



CARMA



ARO-SMT



A Decade of Horizon-scale Science in the Galactic Center!

Global Team at the EHT2016 Conference



11/2016; Cambridge, MA



>200 People
5 Continents
13 Partners
36 Affiliates



Event Horizon Telescope

Affiliated Institutions

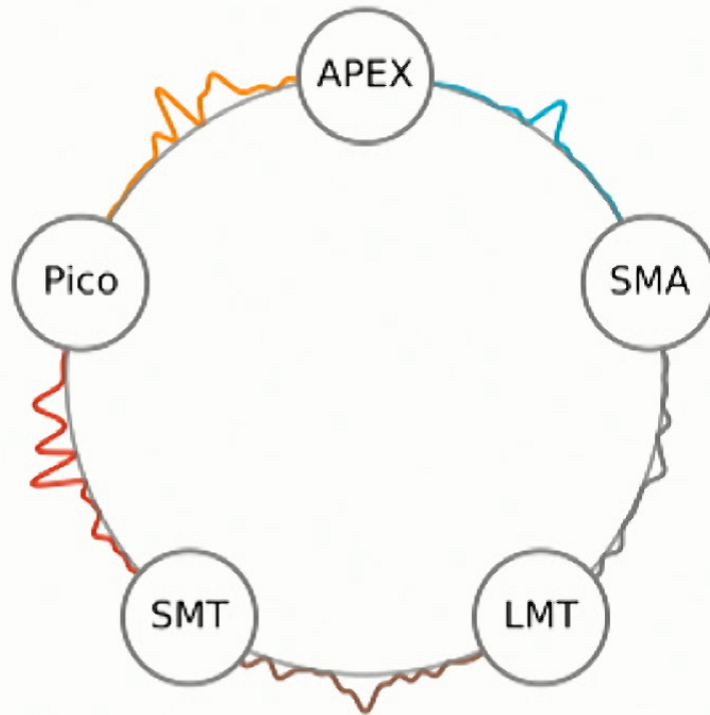
Aalto University
Universiteit van Amsterdam
Arizona Radio Observatory
Instituto de Astrofísica de Andalucía
Instituto Nacional de Astrofísica, Óptica y Electrónica
Institute for Astrophysical Research
Boston University
Brandeis University
University of California, Berkeley
California Institute of Technology
Chinese Academy of Sciences
Cologne University
Universidad de Concepción
Cornell University
Institute of High Energy Physics
Huazhong University of Science & Technology
University of Illinois
Joint Institute for VLBI ERIC

Kavli Institute for Astronomy and Astrophysics
Korea Astronomy and Space Science Institute
Leiden University
University of Maryland
University of Massachusetts Amherst
Max Planck Institute for Extraterrestrial Physics
Nanjing University
National Astronomical Observatories of China
Onsala Space Observatory
Peking University
Purple Mountain Observatory
University of Science and Technology
University of Science and Technology of China
Seoul National University
Shanghai Astronomical Observatory
Institute of Statistical Mathematics
University of Waterloo
Yunnan Observatory

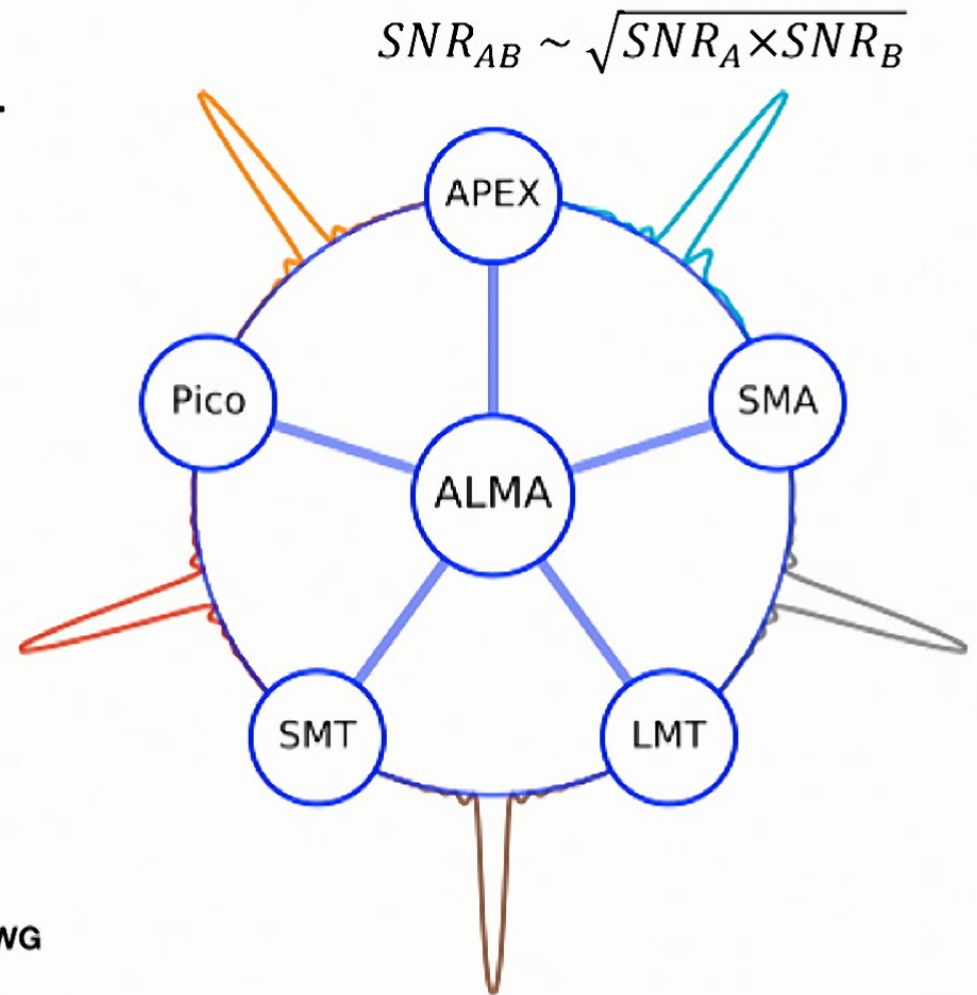


Event Horizon Telescope

Phase Referencing



EHT Calibration & Error WG

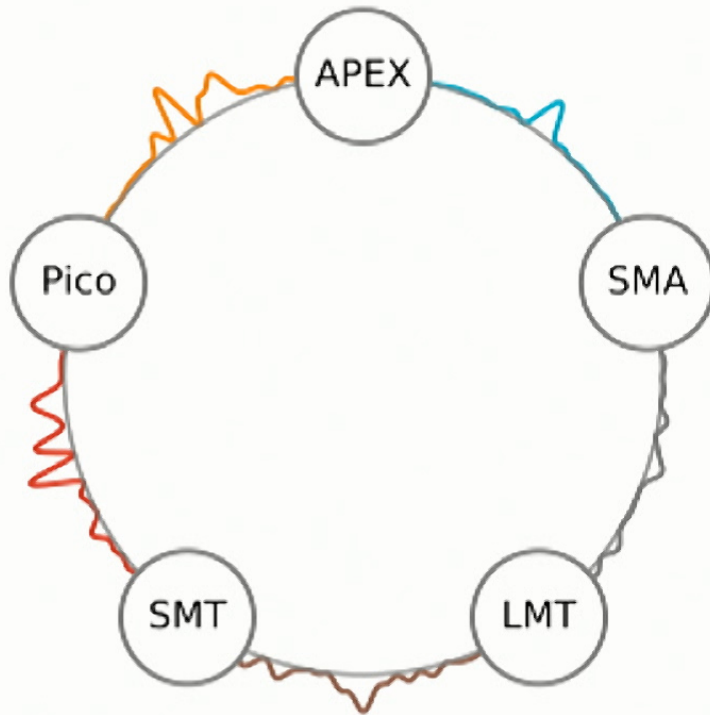


$$SNR_{AB} \sim \sqrt{SNR_A \times SNR_B}$$

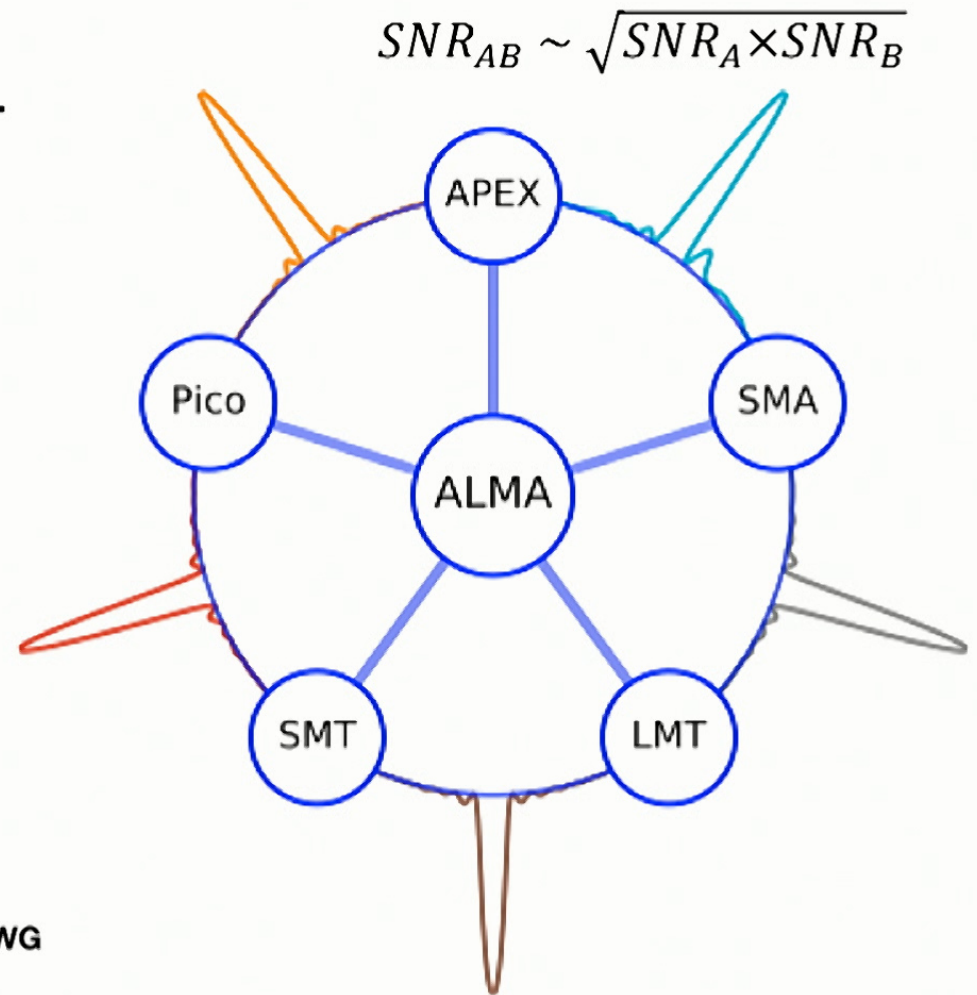


Event Horizon Telescope

Phase Referencing



EHT Calibration & Error WG



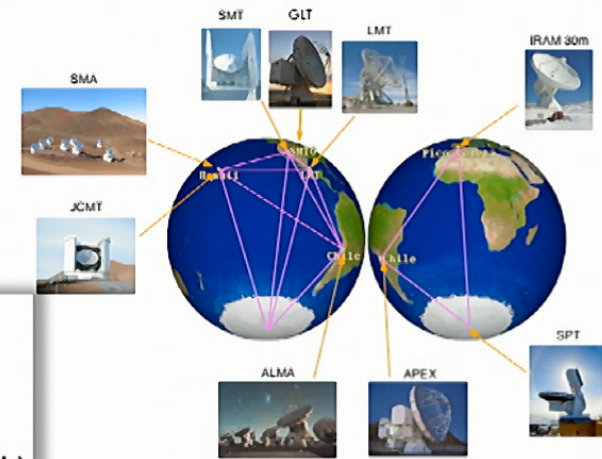
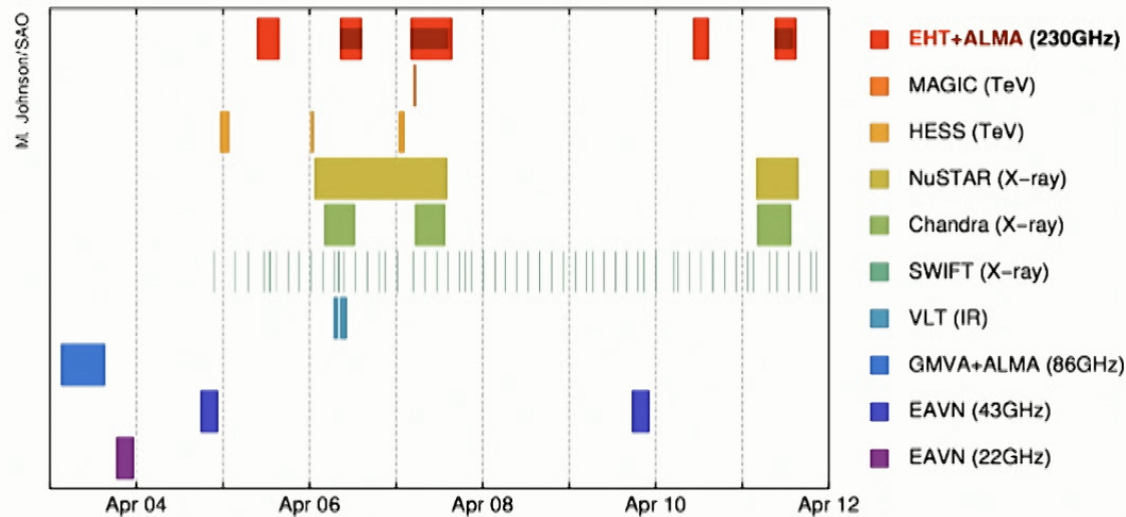
$$SNR_{AB} \sim \sqrt{SNR_A \times SNR_B}$$



Event Horizon Telescope

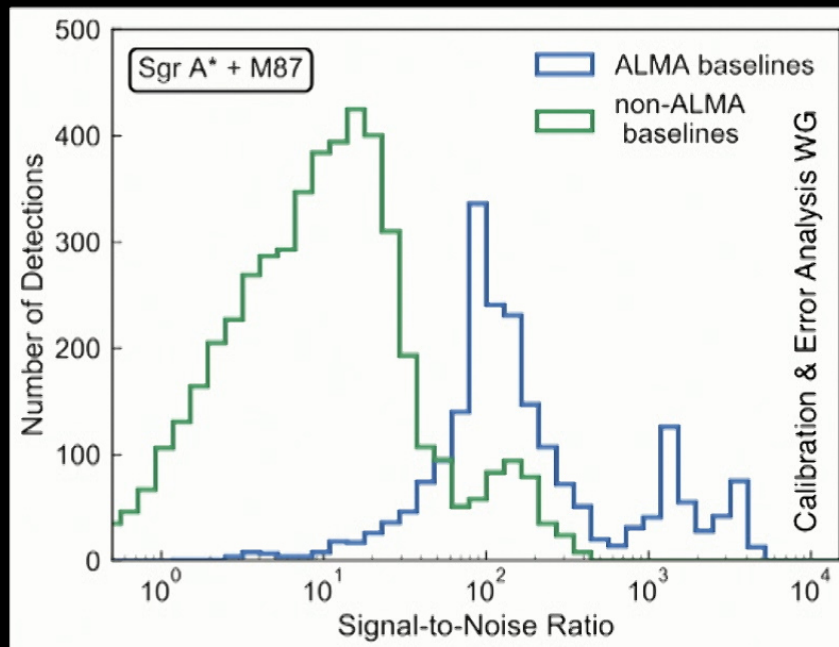
THE EVENT HORIZON TELESCOPE CIRCA APRIL, 2017 & 2018

Multi-Wavelength Coverage: Sgr A* in April 2017



EHT2017 CAMPAIGN

Amplitude of Central Fringe



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Analysis takes time!



- Hard drives *physically* collected
- Brought to correlation facilities



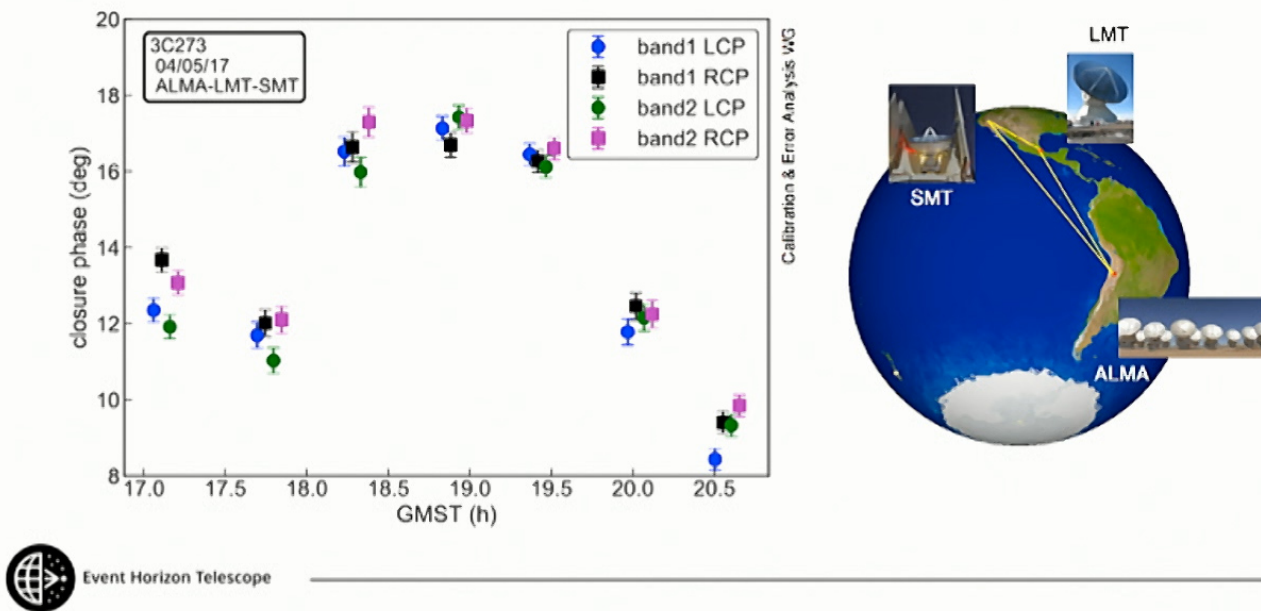
- Ancillary telescope data is used to generate and test calibration models
- **Success!**



Event Horizon Telescope

EHT2017 CAMPAIGN DATA!

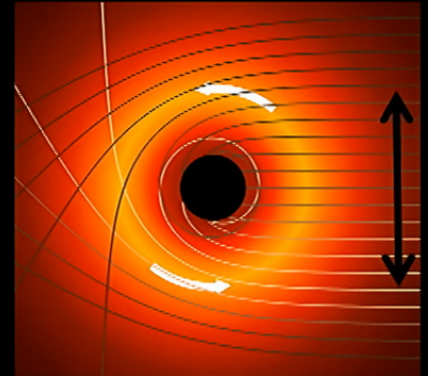
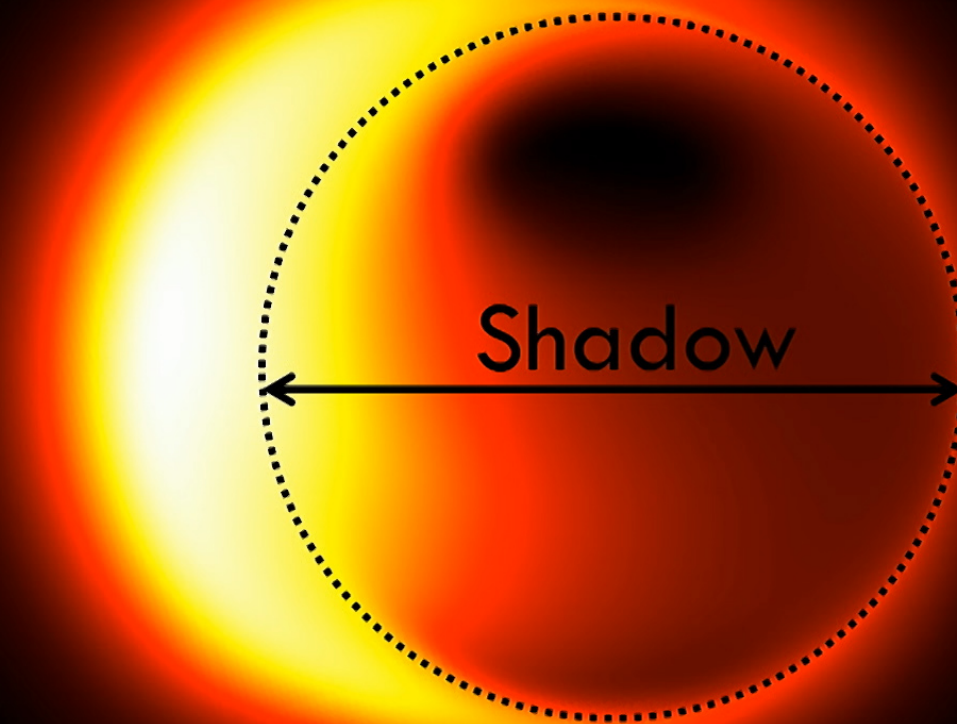
EHT2017: 3C273



ANATOMY OF AN IMAGE

PI Public Lecture 10-3-18

ANATOMY OF AN IMAGE



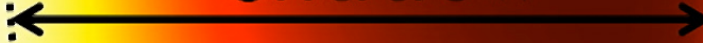
ANATOMY OF AN IMAGE

Approaching

- More opaque
- Much brighter

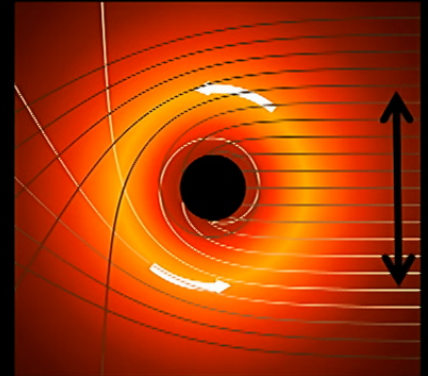


Shadow



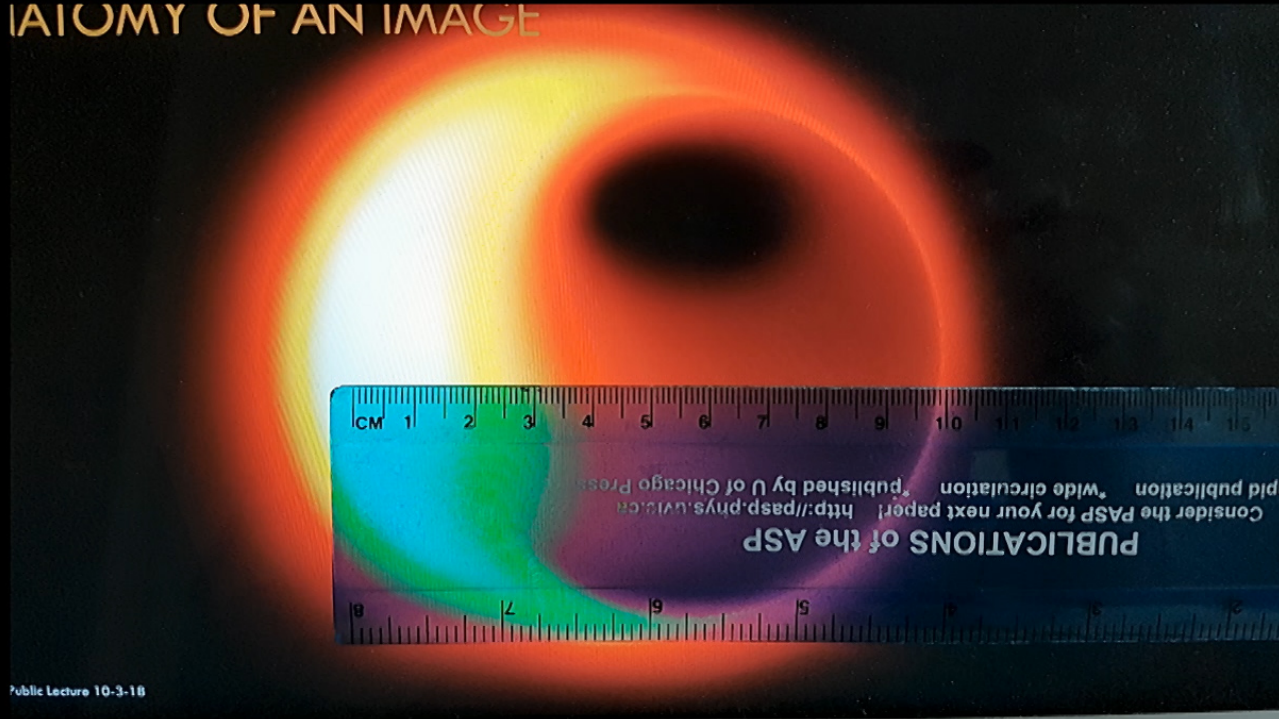
Receding

- More transparent
- Much dimmer



WHAT'S IN A SIZE?

ATOMY OF AN IMAGE

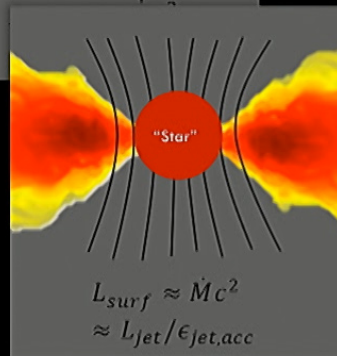
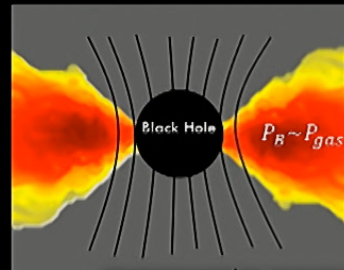


Public Lecture 10-3-18

PI Public Lecture 10-3-18

WHAT'S IN A SIZE – HORIZONS EXIST!

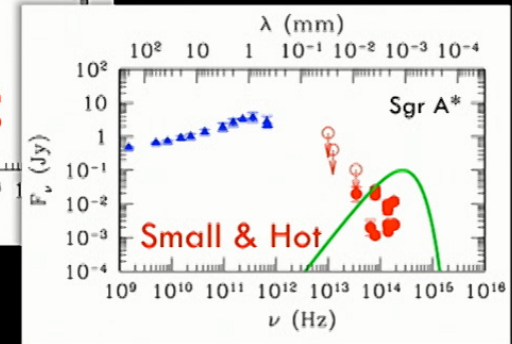
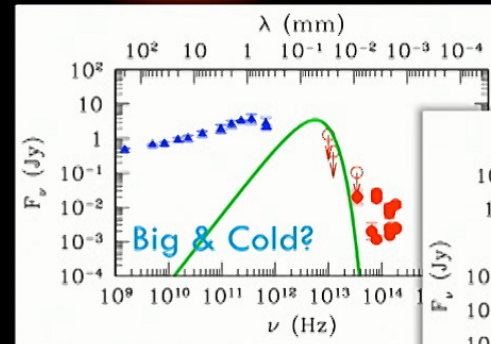
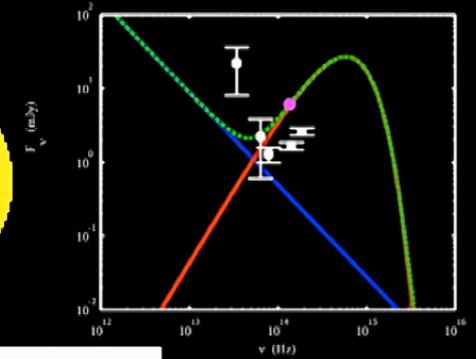
Gravitational potential energy release



$T_\infty = 10000.0 \text{ K}$
 $2.2 \mu\text{m}$

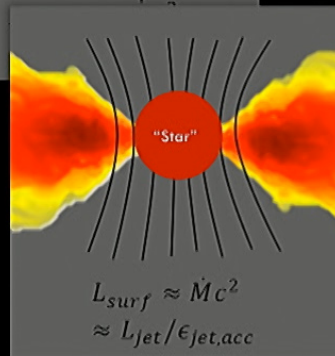
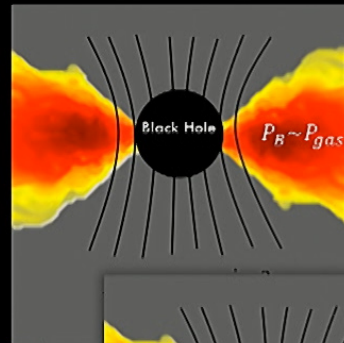


Galactic Center



WHAT'S IN A SIZE – HORIZONS EXIST!

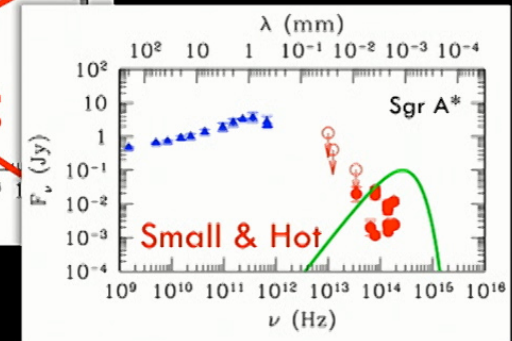
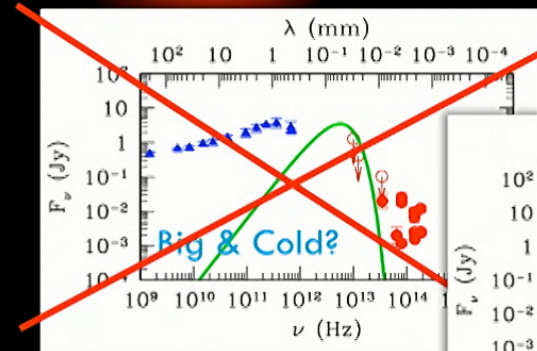
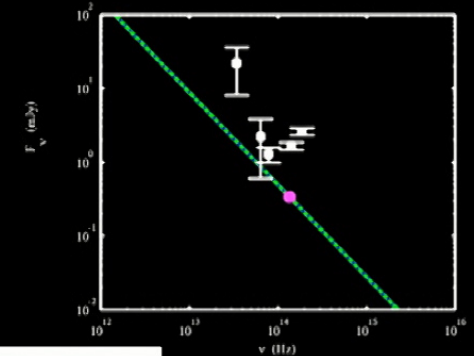
Gravitational potential energy release



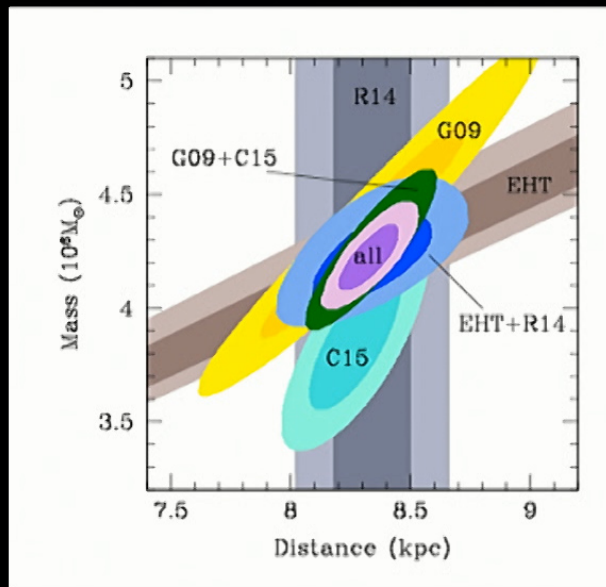
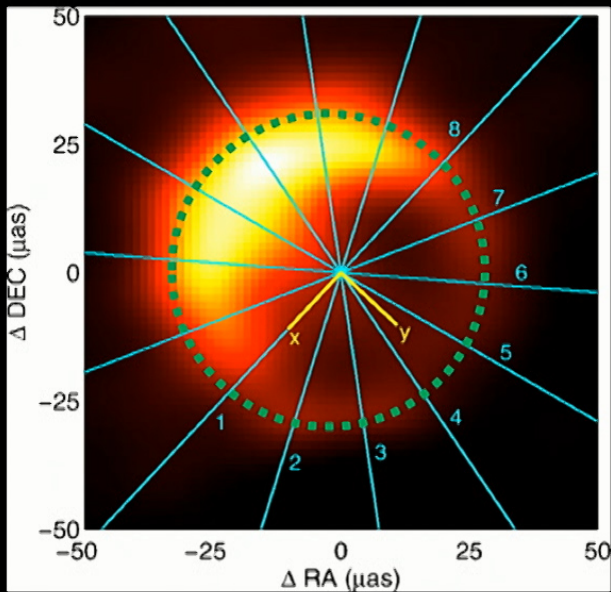
$T_\infty = 371.8 \text{ K}$
 $2.2 \mu\text{m}$



Galactic Center



WHAT'S IN A SIZE – MASSES



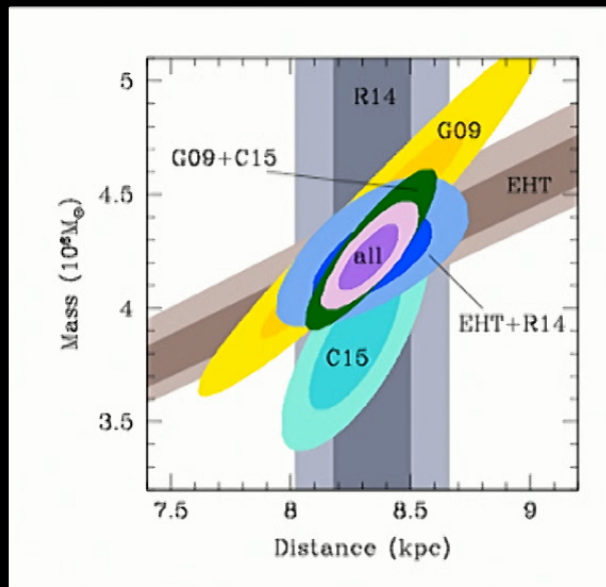
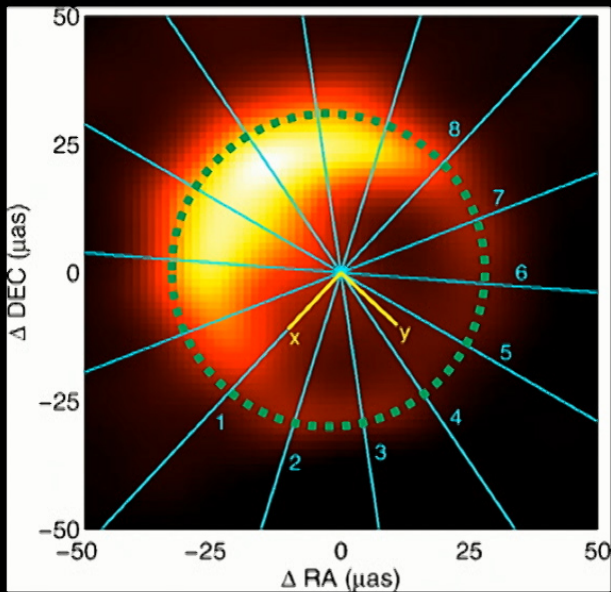
Sgr A* – Incremental improvement
M87 – Revolutionary improvement!

$$v_K \approx \sqrt{\frac{GM}{R}} \quad \text{Keplerian velocities}$$

Observing stars: $6.6 \pm 0.4 \times 10^9 M_{\text{Sun}}$

Observing gas: $3.5 \pm 0.8 \times 10^9 M_{\text{Sun}}$

WHAT'S IN A SIZE – MASSES



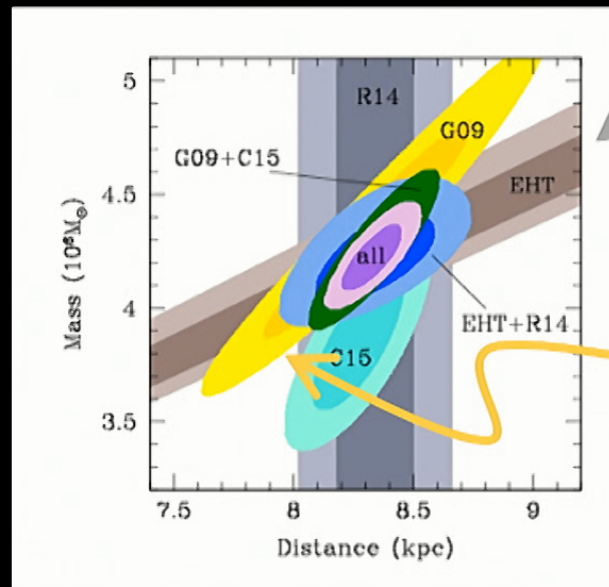
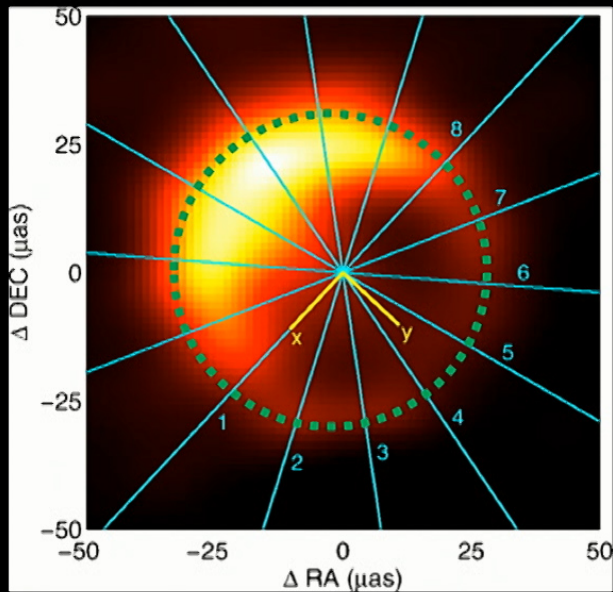
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WHAT'S IN A SIZE – MASSES NEAR AND FAR



Gravity on
horizon scales
from size

GR

Gravity on
thousands of R_S
from stars

A TALE OF TWO BLACK HOLES: SGR A* & M87

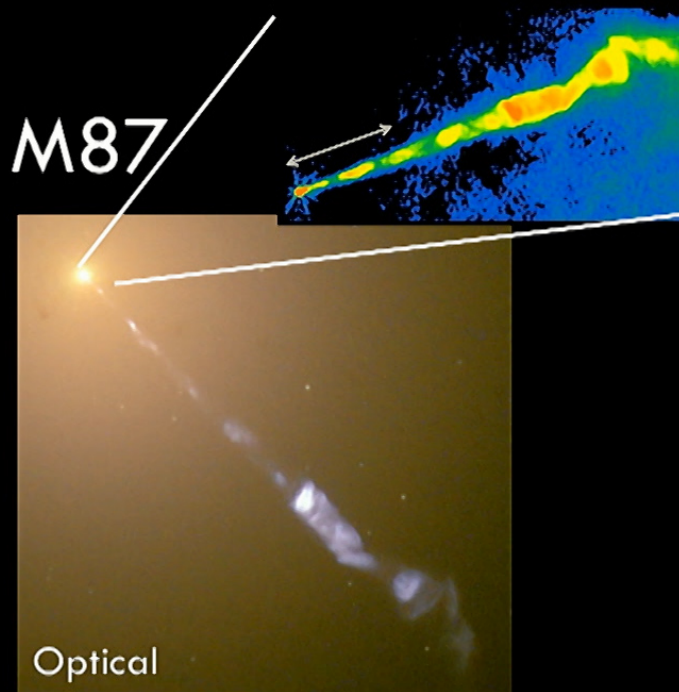
Sagittarius A*



- Center of Milky Way
- 8 kpc $\sim$ 24,000 lyr
- $4.5 \times 10^6 M_{\odot}$
- $L \sim 10^{36}$ erg/s

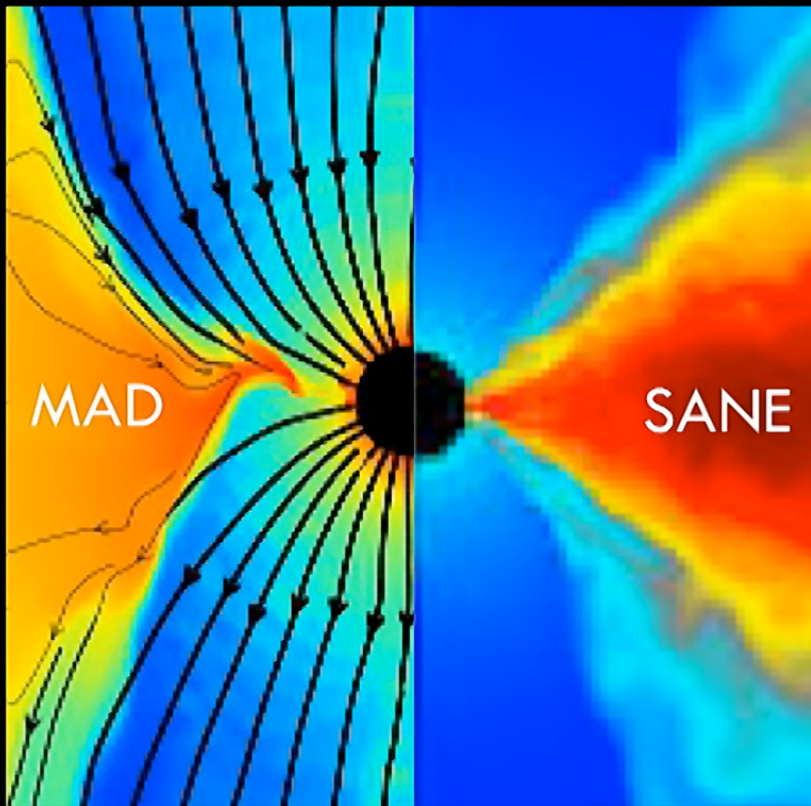
Penn State 17.10.2013

M87



- Center of M87
- 18 Mpc $\sim$ 54,000,000 lyr
- $6.6 \times 10^9 M_{\odot}$
- $L \sim 10^{42}$ erg/s

PHYSICAL/ASTROPHYSICAL HAIR?

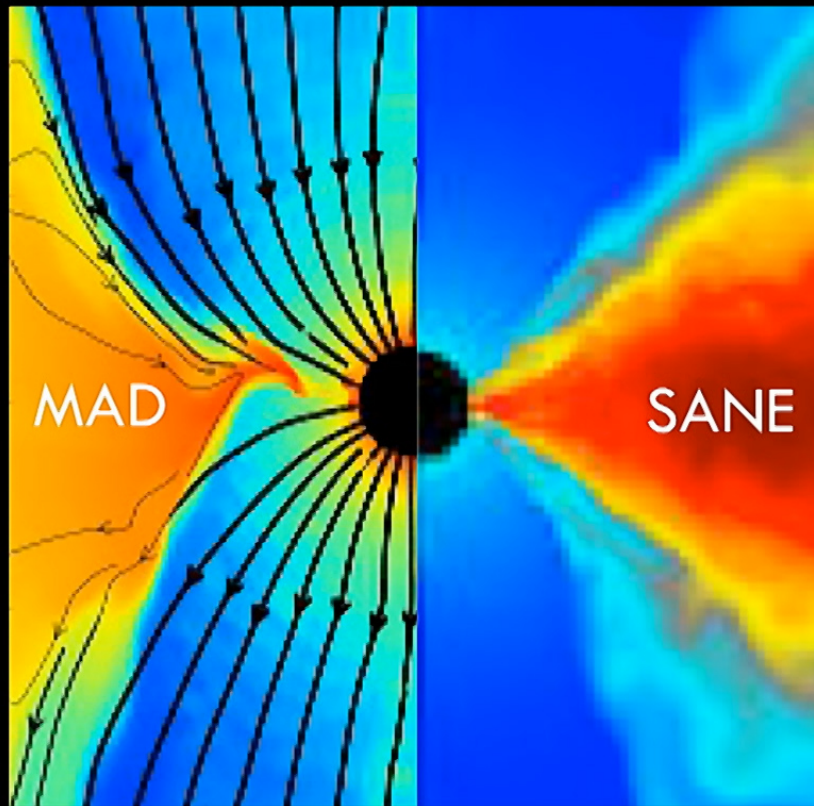


J. McKinney, A. Tchkhovskoy, et al.

Typical model for Sgr A* & M87:

- Very low density – better than the best vacuums on Earth.
- Can't effectively cool
→ Stays hot and thick

PHYSICAL/ASTROPHYSICAL HAIR?



J. McKinney, A. Tchkhovskoy, et al.

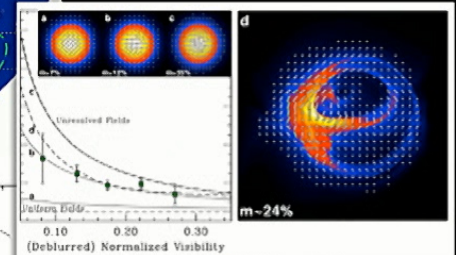
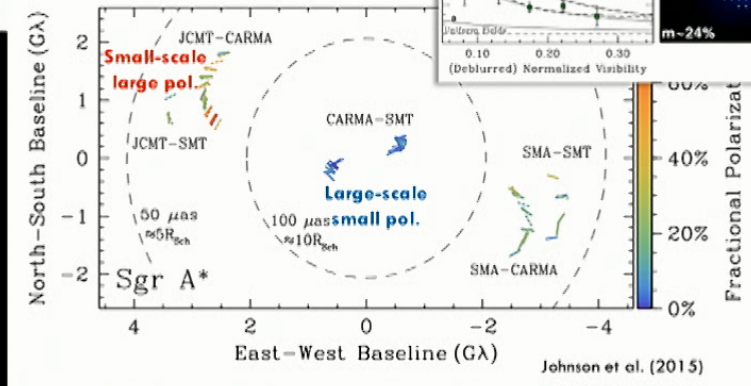
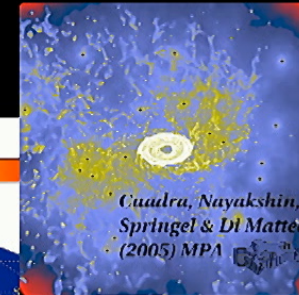
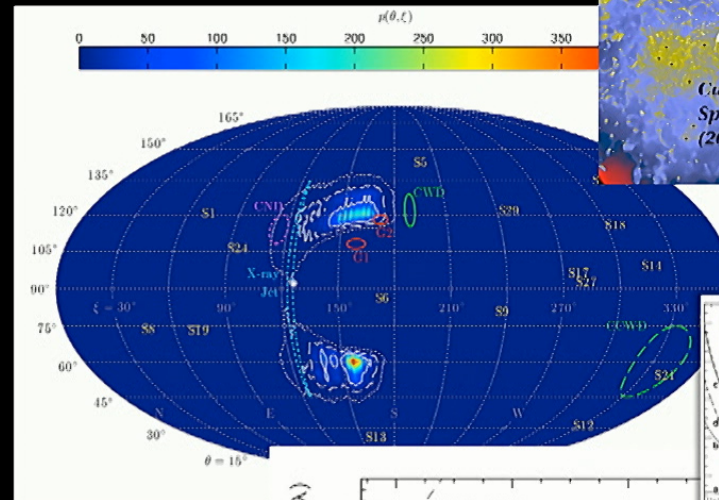
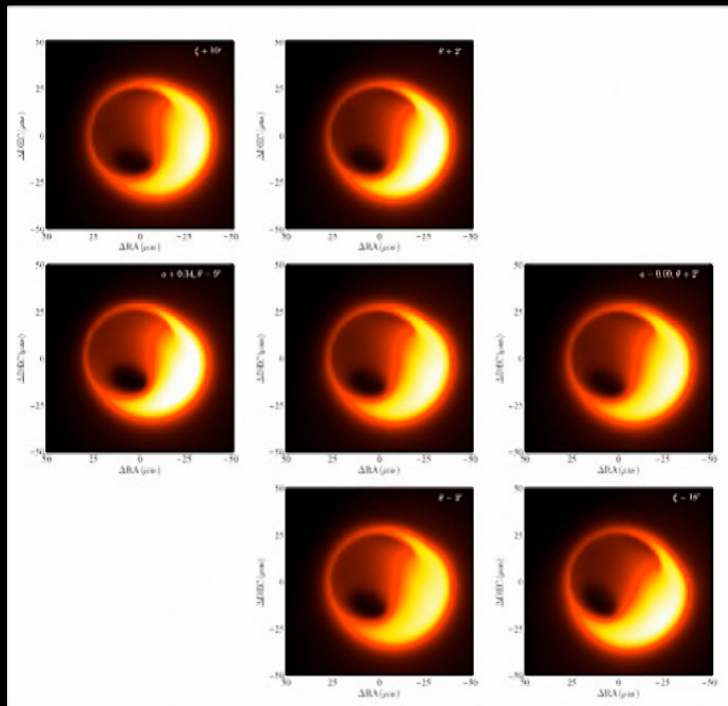
Typical model for Sgr A* & M87:

- Very low density – better than the best vacuums on Earth.
- Can't effectively cool
→ Stays hot and thick

Knobs:

- Mass accretion rate
- Black hole angular momentum
- Accreted magnetic flux

FITTING 7 YEARS OF PROTO-EHT DATA



1000000

Deformed Black Hole

$$Q(M, J) \times (1 + \epsilon)$$

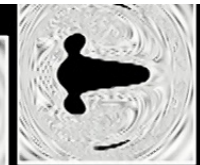
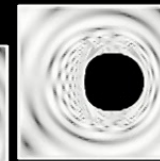
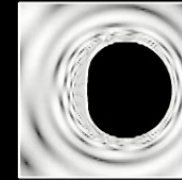

Breaking GR!

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MAKING THE SIMPLE COMPLEX

Schwarzschild Black Hole

Deformed Black Hole



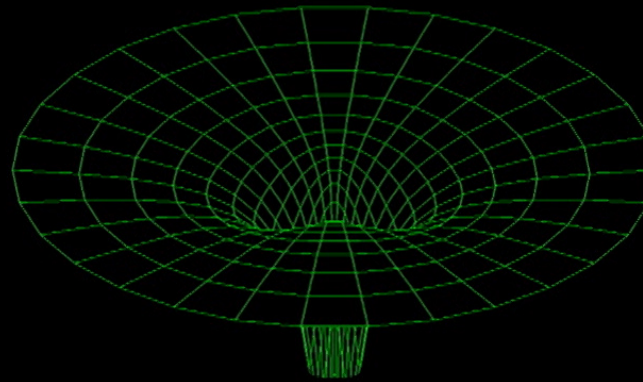
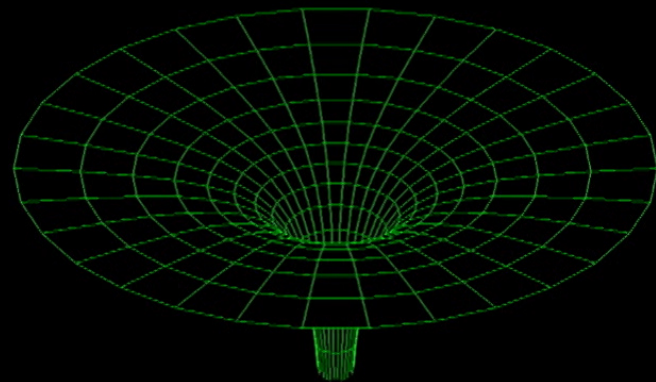
New light particles?
Cuhna et al. (2016)
 $\epsilon = 0.8$



$\epsilon = 0$



$\epsilon = -0.8$



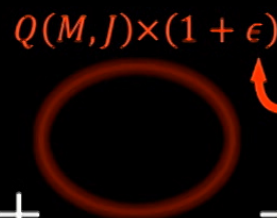
Mass Moments



+



+



+



+ ...

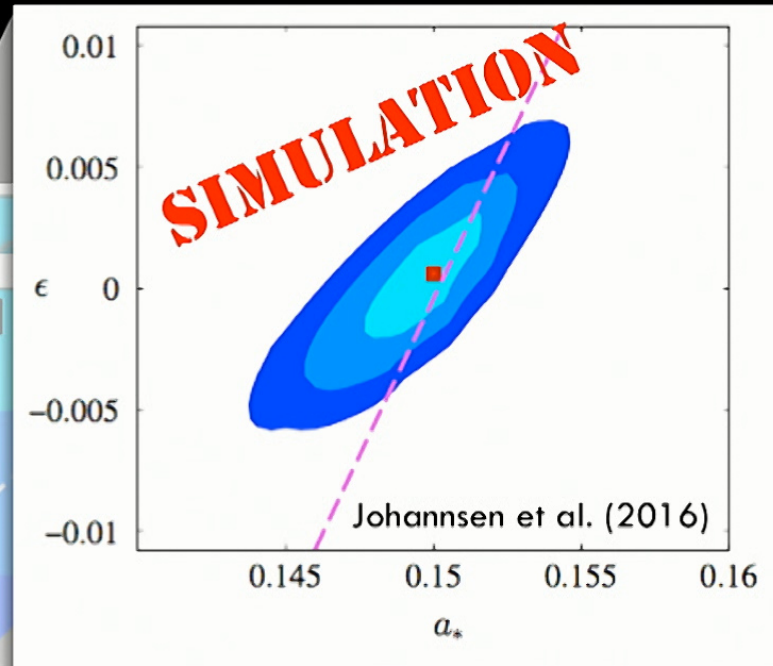
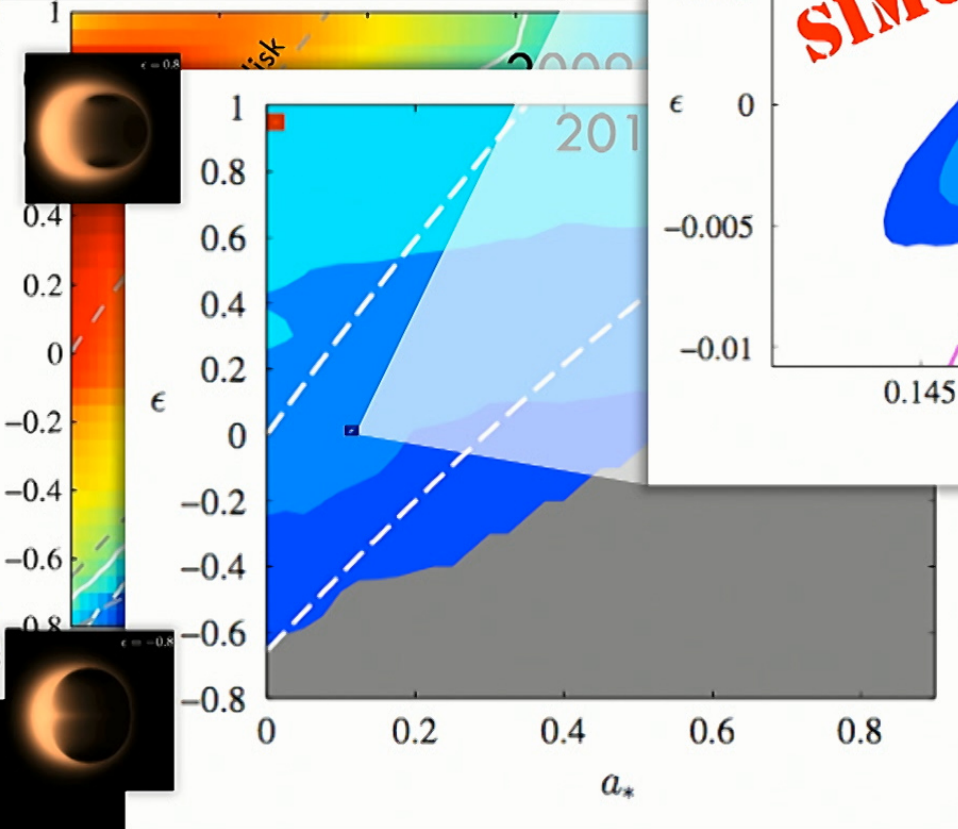
$Q(M, J) \times (1 + \epsilon)$

Breaking GR!

Mass Current
Moments

VALIDATING EINSTEIN

How much GR is broken



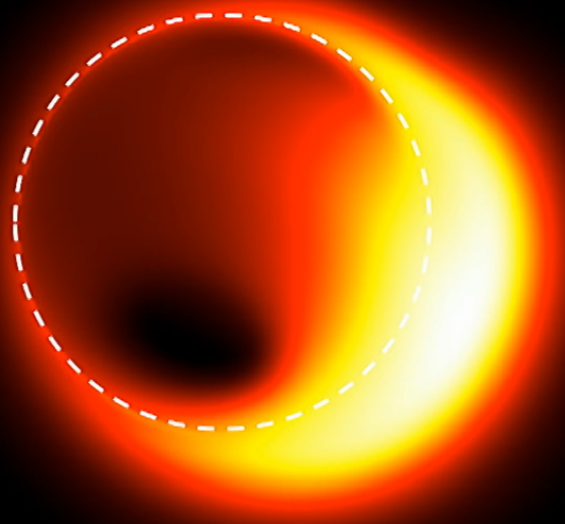
BLACK HOLE CINEMA: MOVING FROM IMAGES TO MOVIES

The *first* image is great, but ...

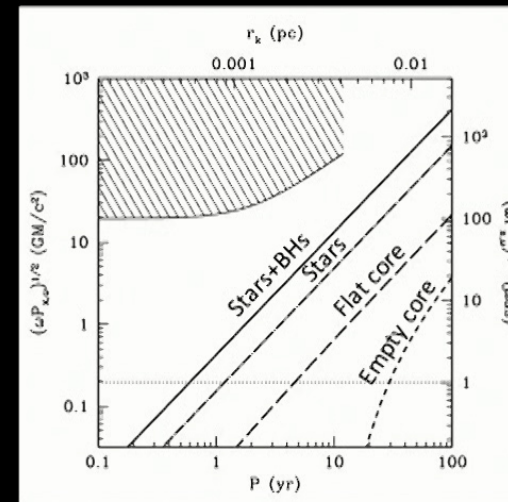
EHT targets should exhibit *structural* variability over many time scales, each telling a story about the physics of black holes and their environments,
... so, the next 1000 images are even better!



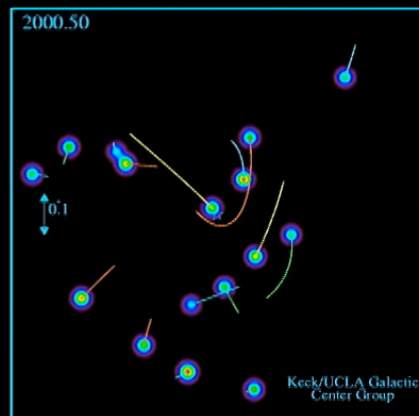
NUCLEAR CLUSTER: $10^4 - 10^6 R_S$ BLACK HOLE JITTER



$$\langle x^2 \rangle \propto m^2 n$$

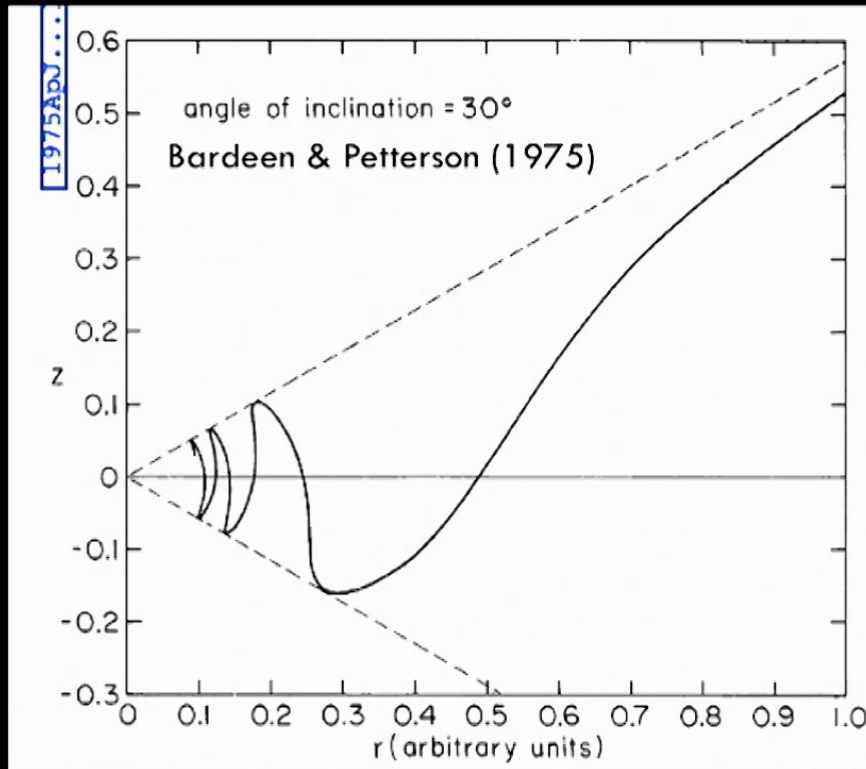


NUCLEAR CLUSTER: $10^4 - 10^6 R_S$ A COMPANION?



FEEDING SGR A*: 100-10,000 R_S , YEARS

BLACK HOLE SPIN, FRAME DRAGGING & DISK WARPS

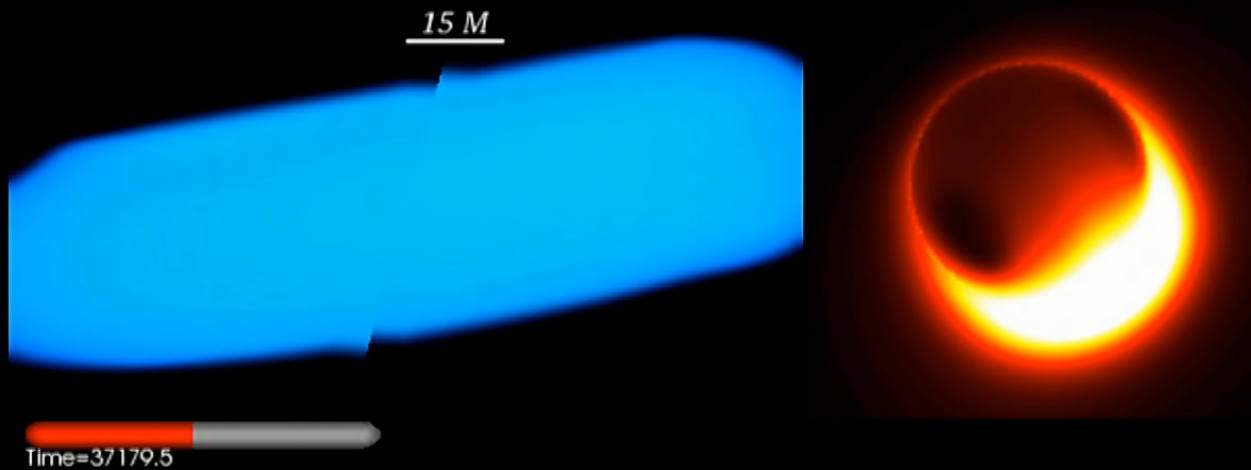


Nealon, Price & Nixon (2015)

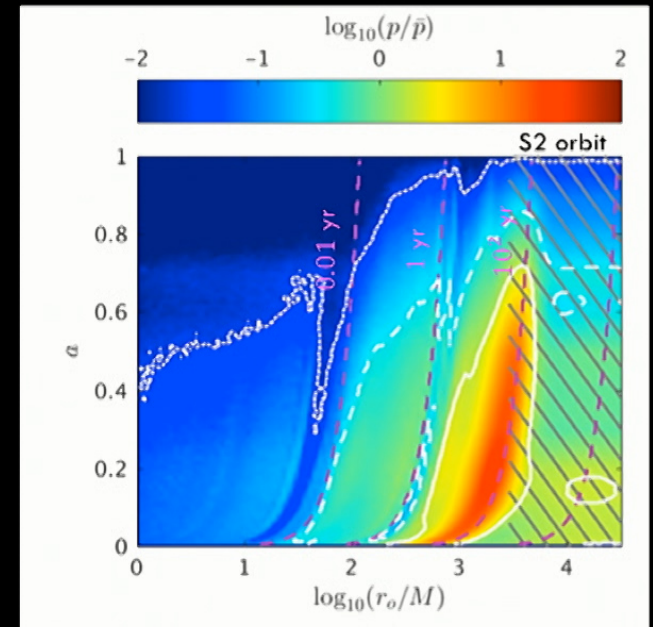


FEEDING SGR A*: 100-10,000 R_S , YEARS LENSE-THIRRING AND THE EHT

Courtesy of Chris Fragile



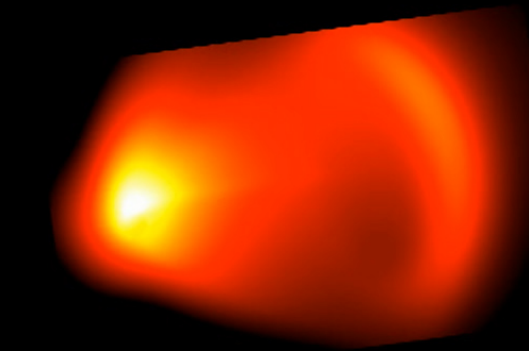
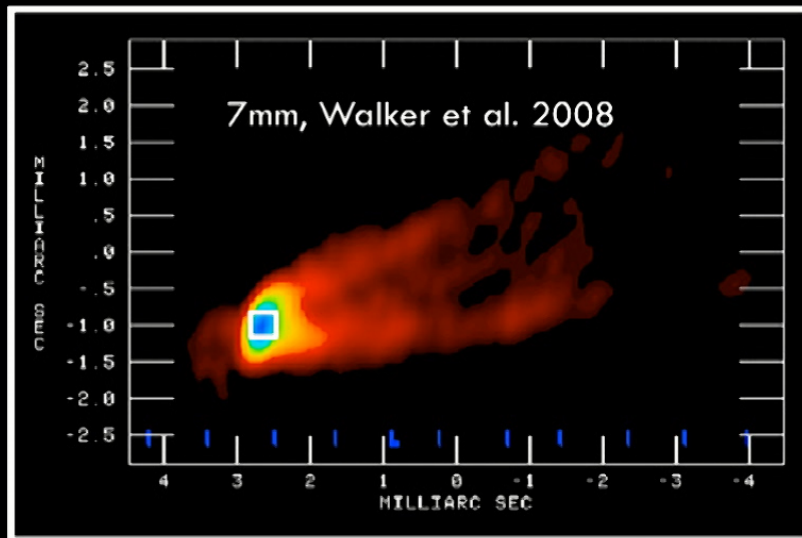
$$T_{prec} \sim \frac{L_{disk}}{\tau_{LT}} \sim \frac{2}{a \sin \Theta} \left(\frac{r_o}{10^3} \right)^{5/2} \text{ yr}$$



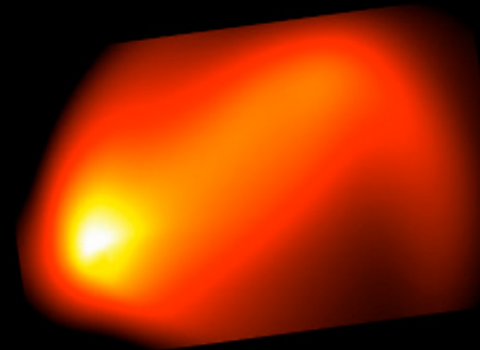
BHI 8.5.2017

LAUNCHING JETS: $10 - 1,000 R_S$, WEEKS

FLARES IN M87



Driven by the BH
(flare inside the jet)



Driven by the disk
(flare outside the jet)

ON THE HORIZON: 1 – 10 R_S , MINUTES FLARES IN SGR A*



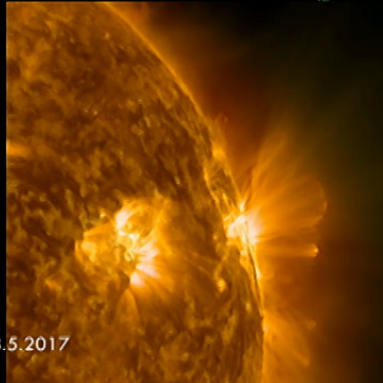
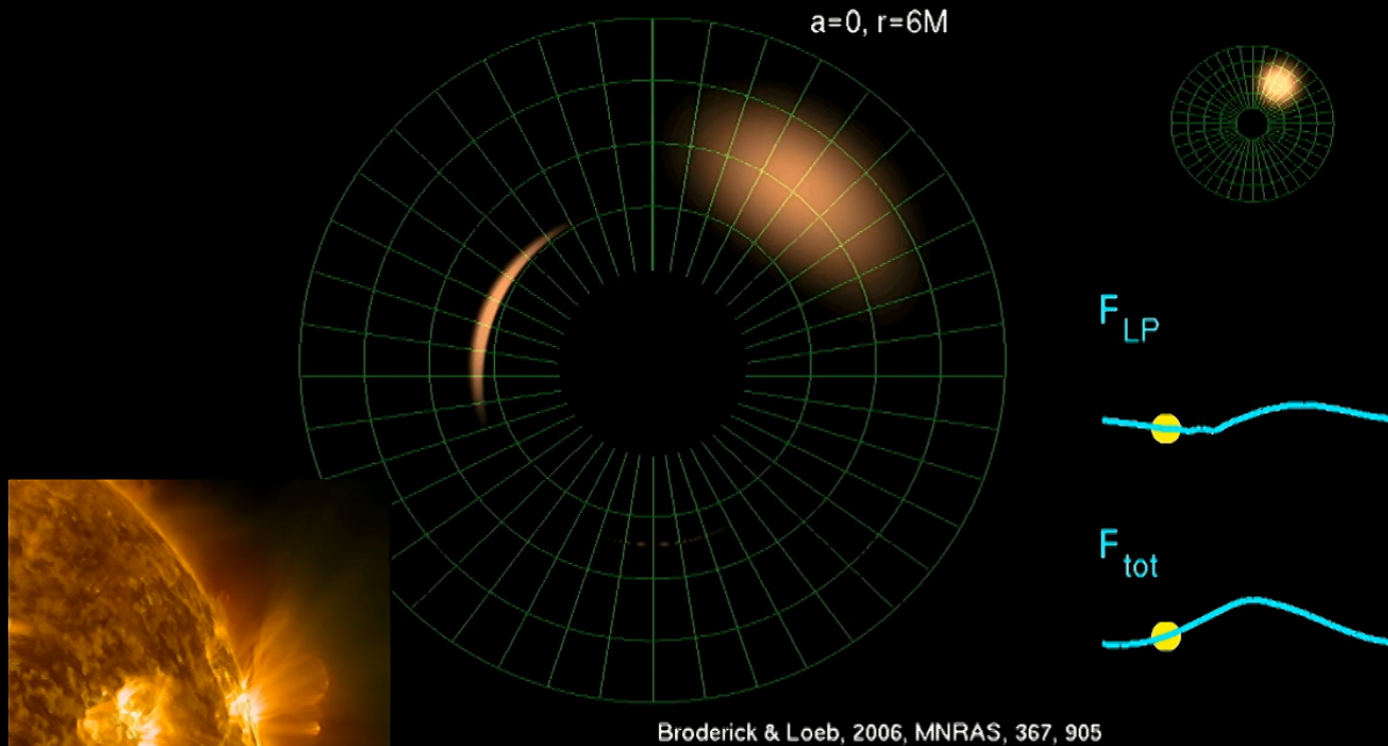
Courtesy of Hotaka Shiokawa

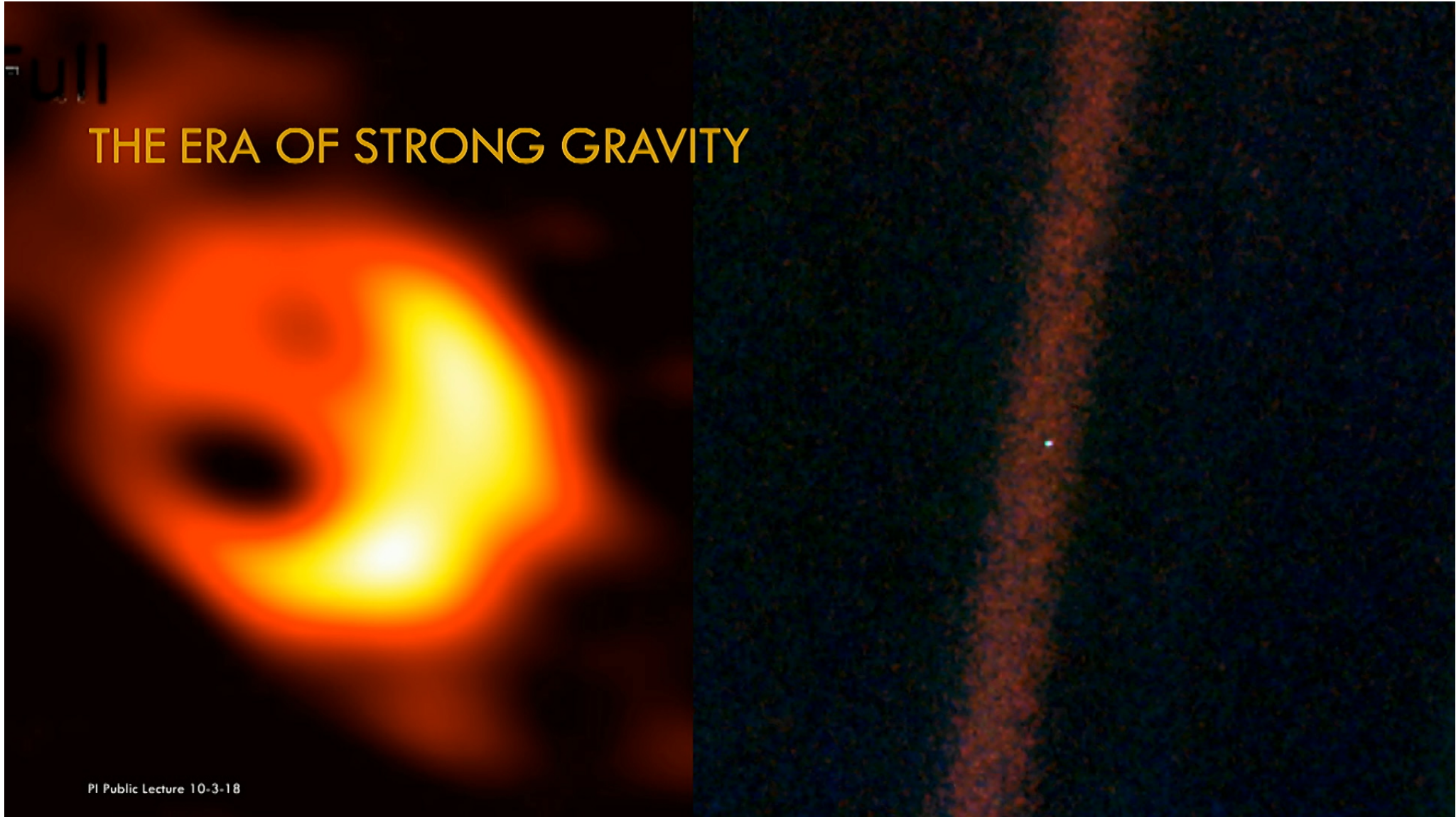


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ON THE HORIZON: 1 – 10 R_S , MINUTES

NONTHERMAL CATASTROPHES





Full

THE ERA OF STRONG GRAVITY

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