Title: Staring into the Abyss

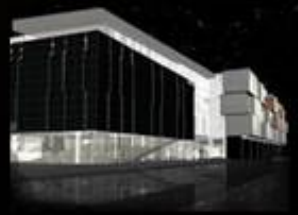
Date: Nov 06, 2013 07:00 PM

URL: http://pirsa.org/13110064

Abstract: Nearly a century after there discovery, black holes remain one of the most striking, and problematic, predictions of general relativity. Even more unsettling is the fact that they actually appear to exist! With only a handful of exceptions, every galaxy contains a supermassive behemoth, millions to billions as massive as the sune, at their center. These supermassive black holes are hardly incidental, they gravitationally power enormous outflows that rule the fates of their hosts. Despite the critical role they play in our understandin gof gravity and impact upon the visible universe, actually testing their nature has remained beyond our reach - until now. Dr. Broderick will describe how astrononomers are currently constructing (and operating) facilities that will image the horizons of black holes, and what we can already say about these enigmatic monsters in the dark.

STARING INTO THE ABYSS

AVERY E BRODERICK

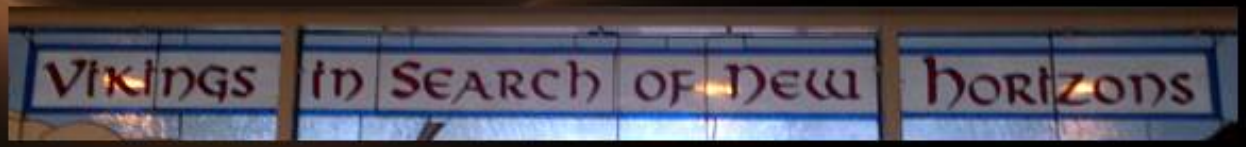


UNIVERSITY OF WATERLOO

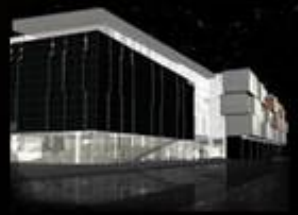
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

STARING INTO THE ABYSS

AVERY E BRODERICK



UNIVERSITY OF WATERLOO



PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

WHAT IS A BLACK HOLE?

Depends on who you ask!

A PHYSICIST'S PERSPECTIVE

A compact object who's influence is felt only gravitationally.

$v_{esc} \sim 11$ km/s

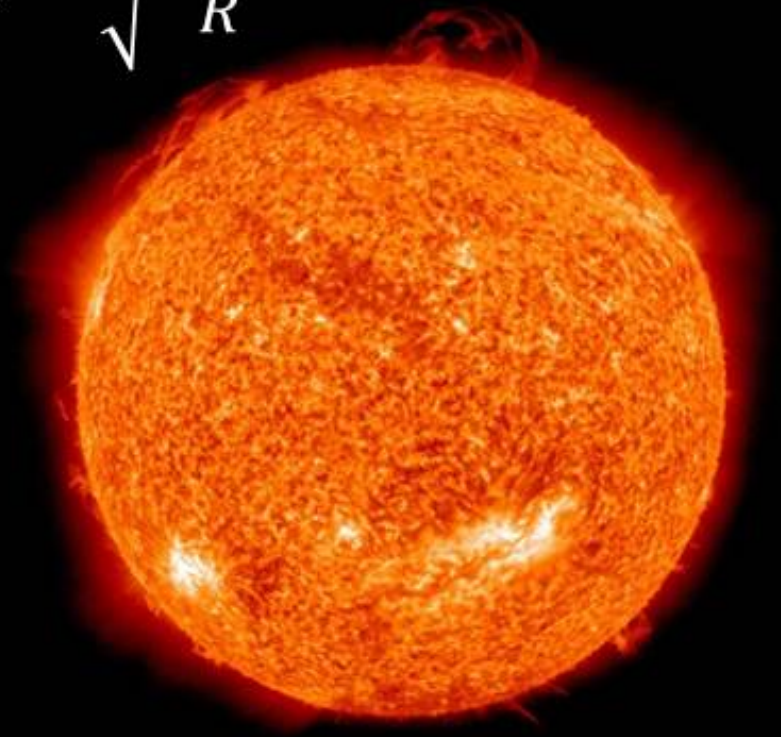
$$R_{max} = \frac{2GM}{2GM/R - v^2}$$

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

BLACK HOLES CIRCA 1784

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

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



$v_{esc} \sim 600$ km/s

$M_\odot = 2 \times 10^{30}$ kg

$R = 7 \times 10^5$ km

$v_{esc} \sim 6{,}000$ km/s

BLACK HOLES CIRCA 1784

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

$v_{esc} \sim 6{,}000$ km/s

$M_\odot = 2 \times 10^{30}$ kg
$R = 7 \times 10^3$ km

BLACK HOLES CIRCA 1784

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

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

$M_\odot = 2 \times 10^{30}$ kg

$R = 3$ km

"Dark Stars"

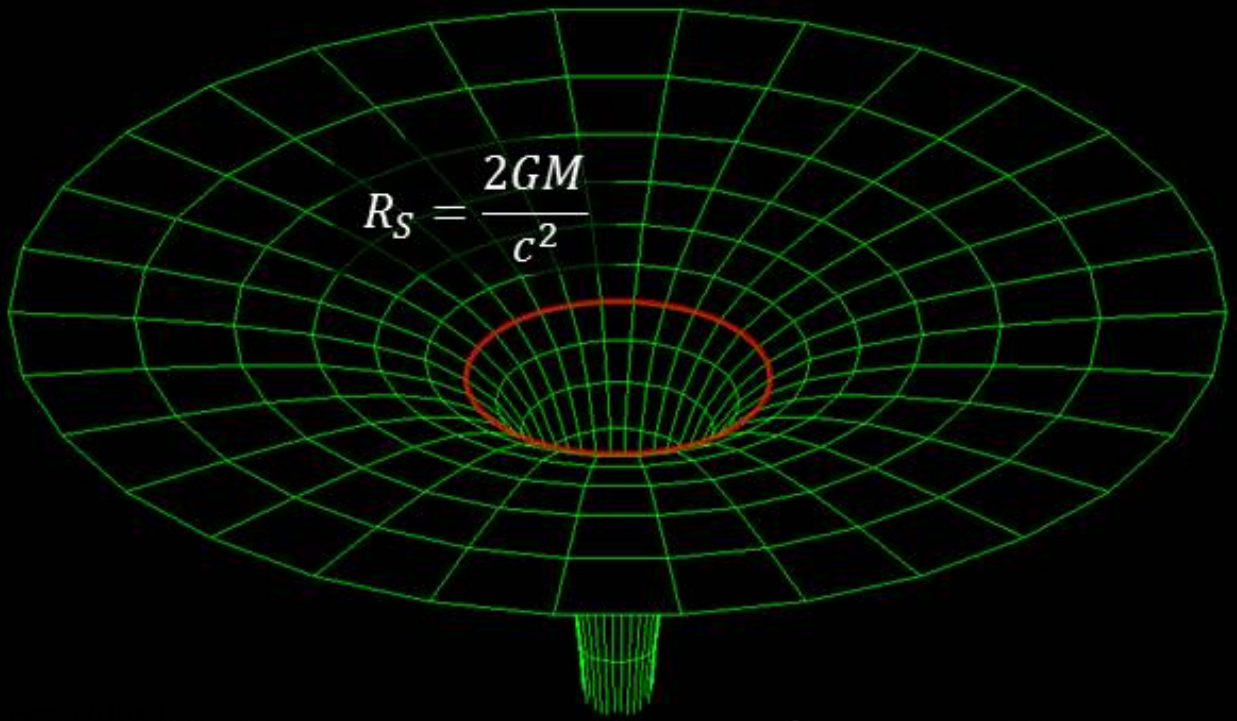
$v_{esc} \sim 300{,}000$ km/s

John Michell

BLACK HOLES CIRCA 1918

~~Action at a distance: "The apple falls because the Earth pulls on it"~~

Spacetime curvature: *"Matter tells spacetime it's shape, spacetime tells matter how to move"*

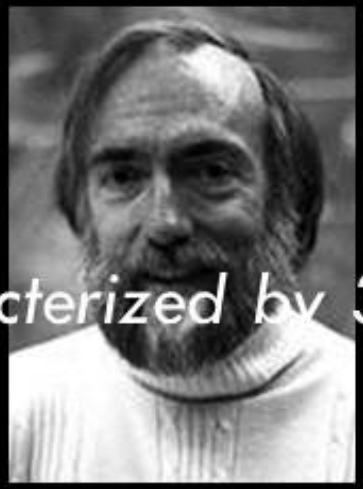


Karl Schwarzschild

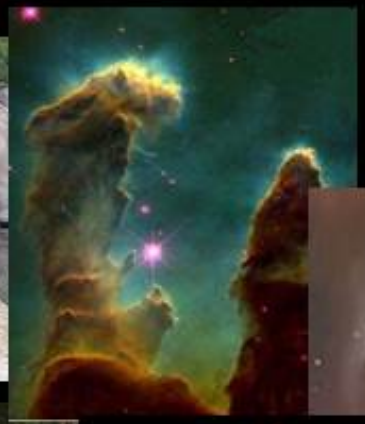
- *Extreme curvature of spacetime*

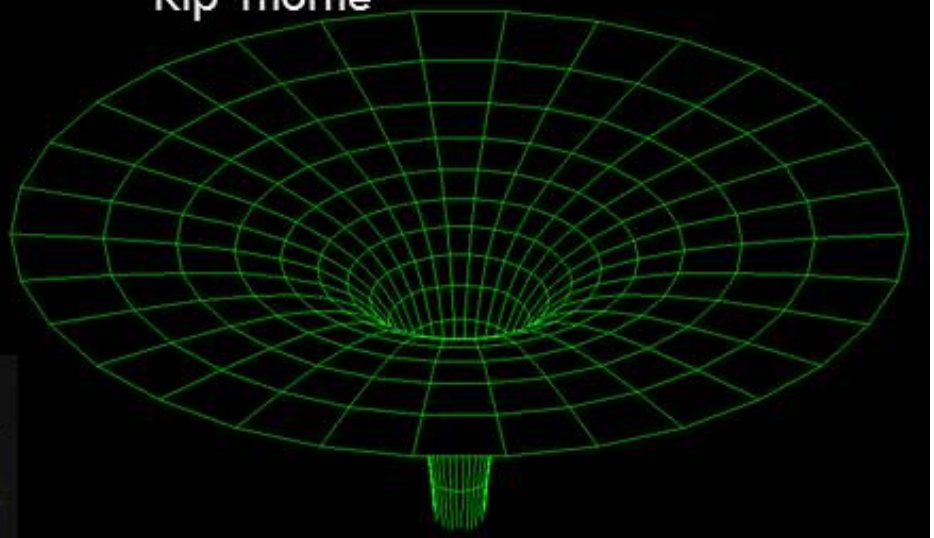
NO HAIR THEOREMS!

Black holes are fully characterized by 3 numbers: M, J, Q



Kip Thorne





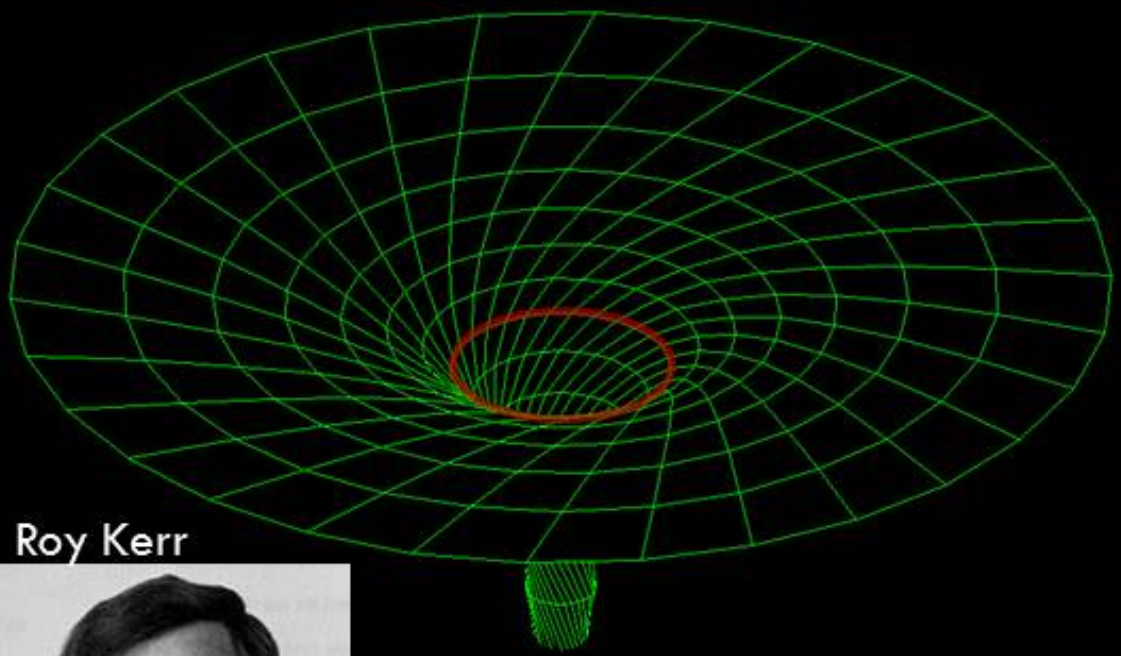
The Universe is Complicated!

Black holes are simple!

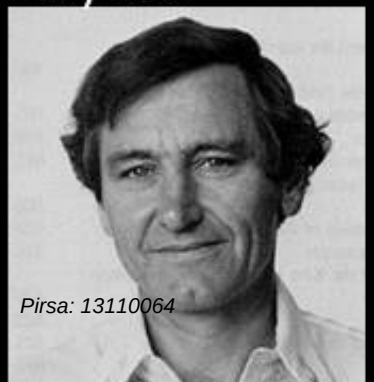
20TH CENTURY BLACK HOLES: A TOUR OF THE KERR SPACETIME (M, J)

- Horizon

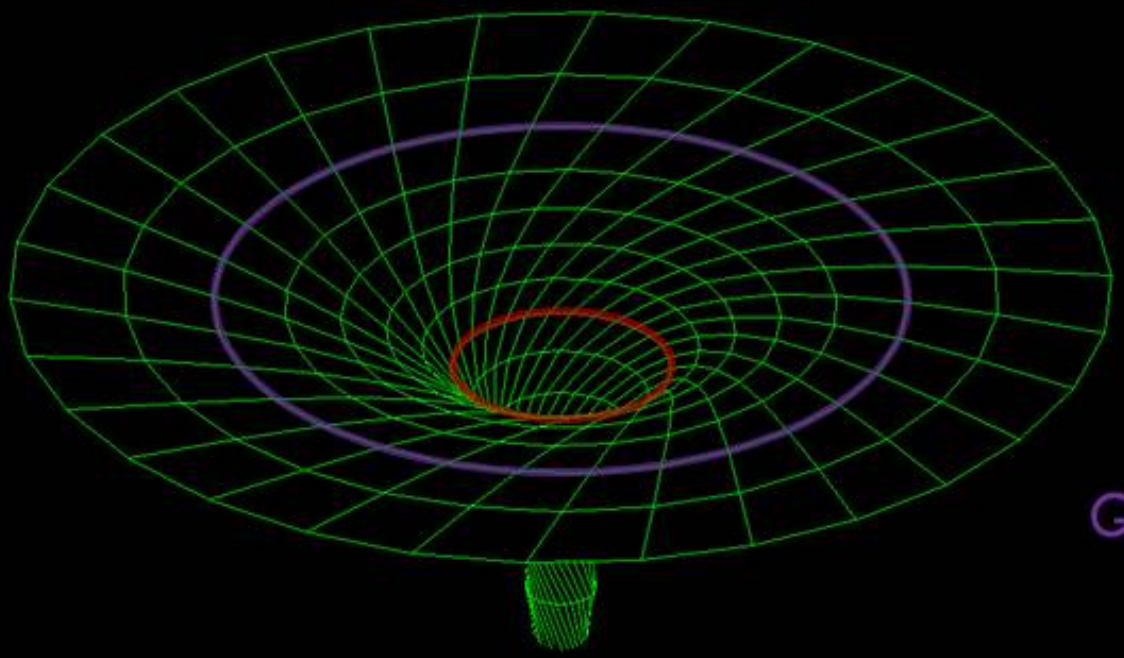
(abandon all hope!)



Roy Kerr



20TH CENTURY BLACK HOLES: A TOUR OF THE KERR SPACETIME (M, J)



- Horizon

  (abandon all hope!)

$$F_{grav} = F_{cent}$$

But in GR energy gravitates

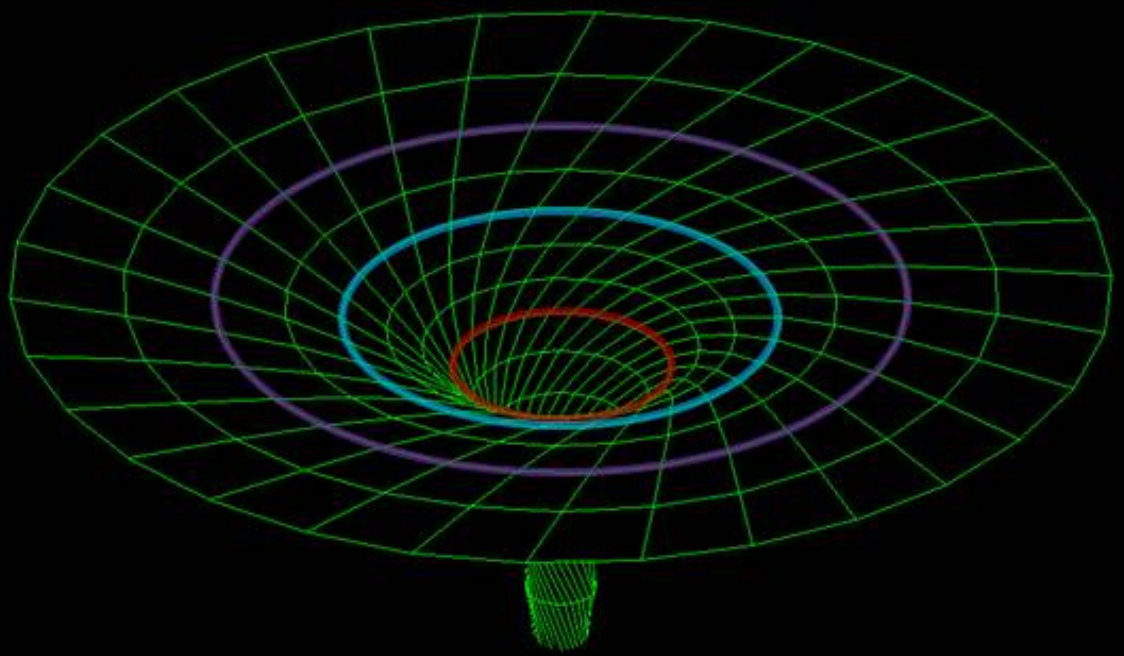
$$F_{grav} = -\frac{GM}{r^2}(mn + E_{orb})$$

Gavity → Fast Orbit → Gravity

- Innermost Stable Circular Orbit

  (last stop for orbiting gas)

20TH CENTURY BLACK HOLES: A TOUR OF THE KERR SPACETIME (M, J)



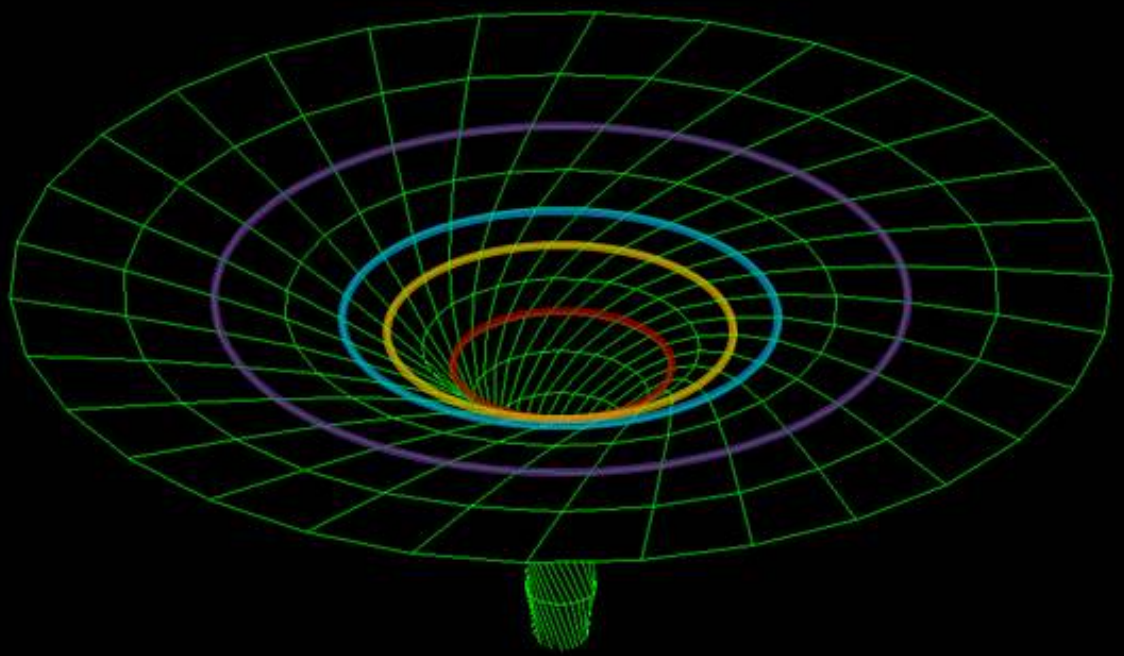
- Horizon
  (abandon all hope!)

$$v_{orb} = c$$

- Photon Orbit
  (marks strong lensing)

- Innermost Stable Circular Orbit
  (last stop for orbiting gas)

20TH CENTURY BLACK HOLES: A TOUR OF THE KERR SPACETIME (M, J)

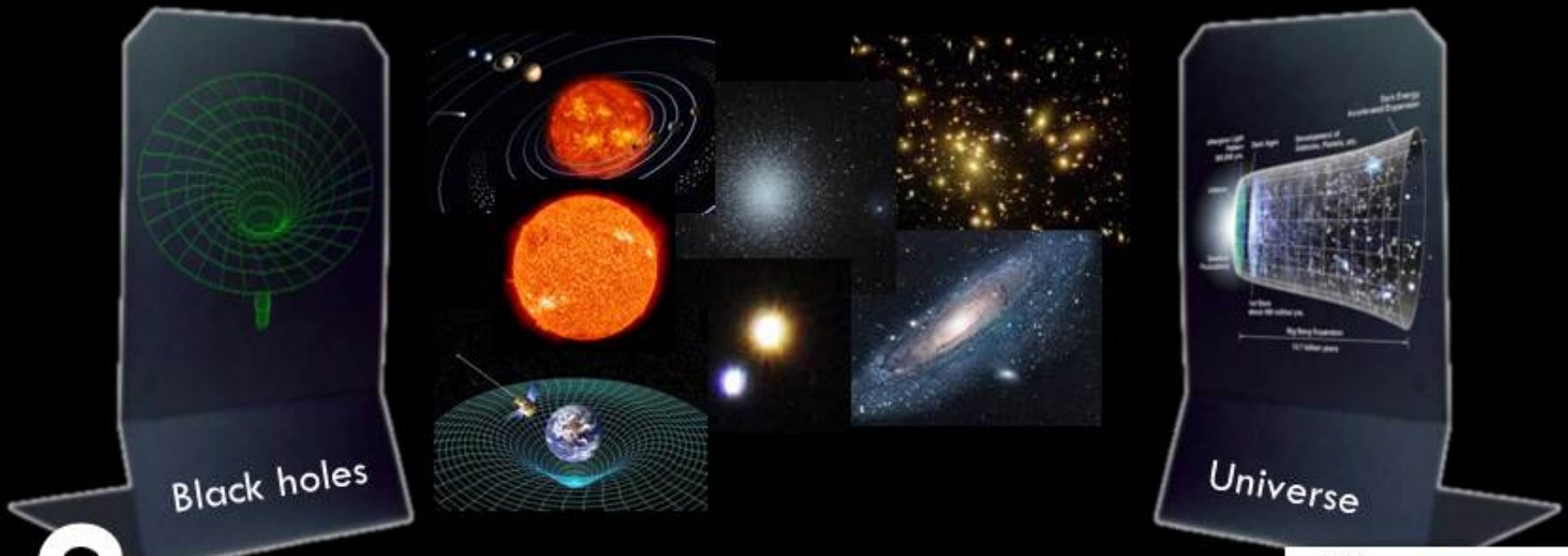


- Horizon
  (abandon all hope!)
- Ergosphere
  (black hole drags spacetime)
- Photon Orbit
  (marks strong lensing)
- Innermost Stable Circular Orbit
  (last stop for orbiting gas)

ISN'T IT THE 21ST CENTURY?

How does strong gravity work? $\frac{GM}{Rc^2} \sim 1$

→ General relativity ~100% different from Newtonian gravity!



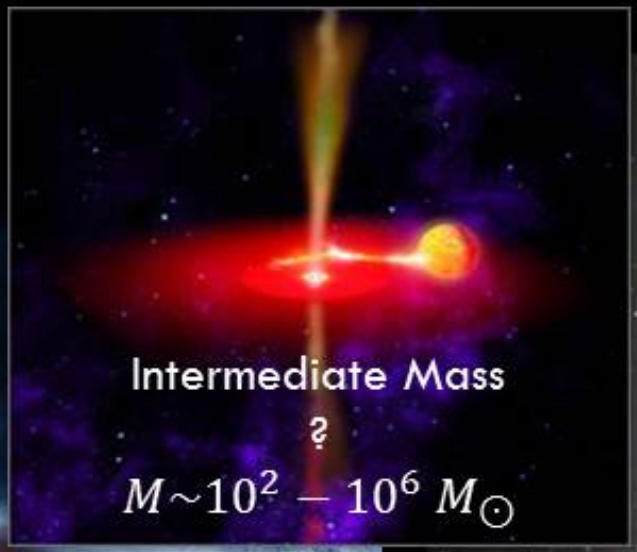
?

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

BIG QUESTIONS!

- *Do black holes exist?*
- *Does our current picture describe them?*

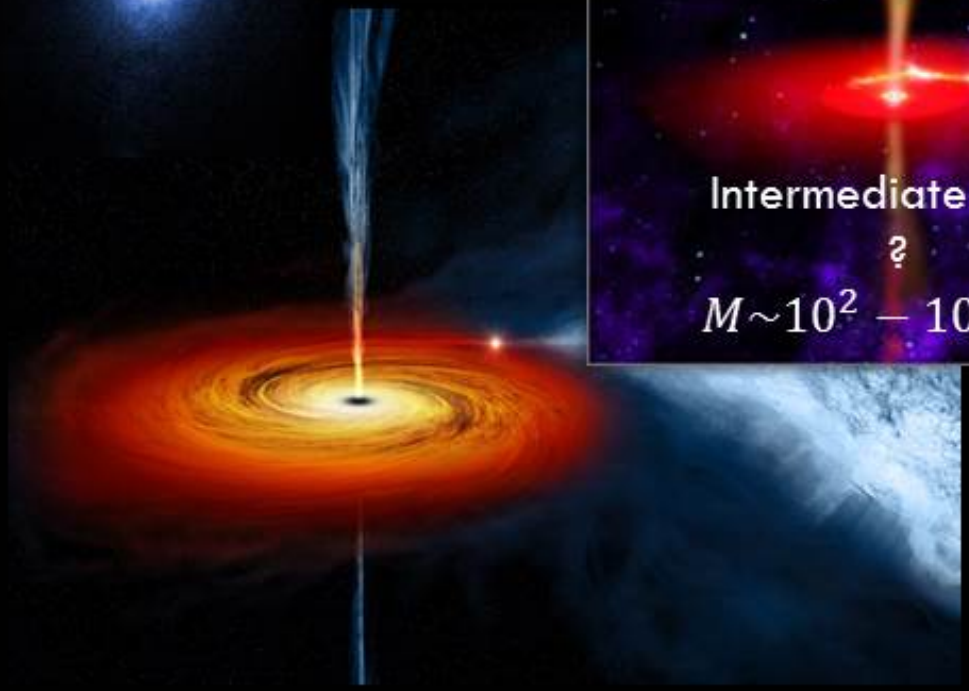
AN ASTRONOMERS PERSPECTIVE



Intermediate Mass

?

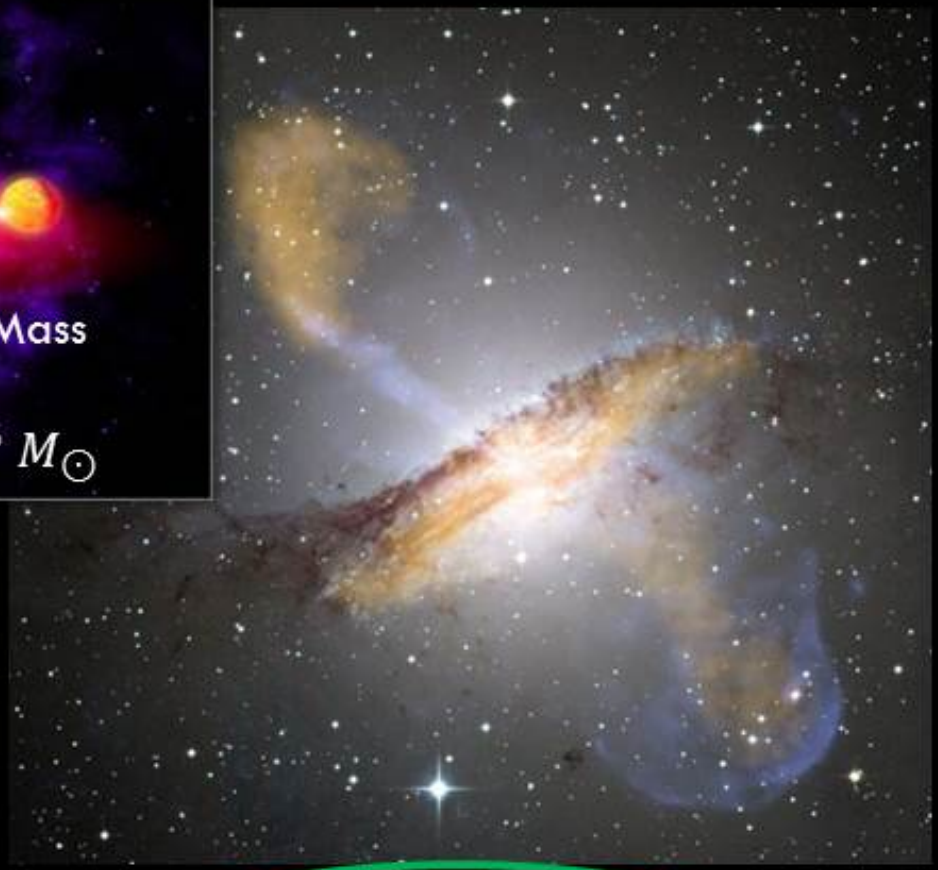
$M \sim 10^2 - 10^6\ M_\odot$



Stellar Mass

Subset of X-ray binaries

$M \sim 3 - 10\ M_\odot$

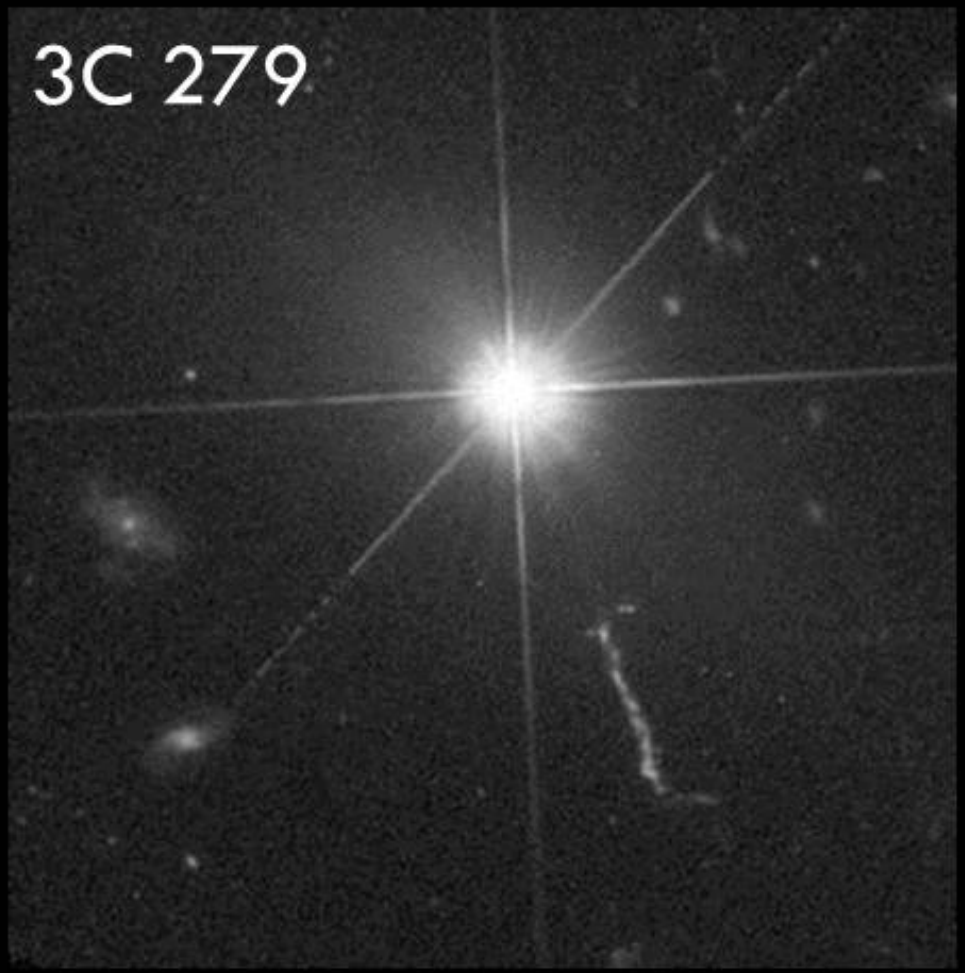


Supermassive

Centers of (almost) all galaxies

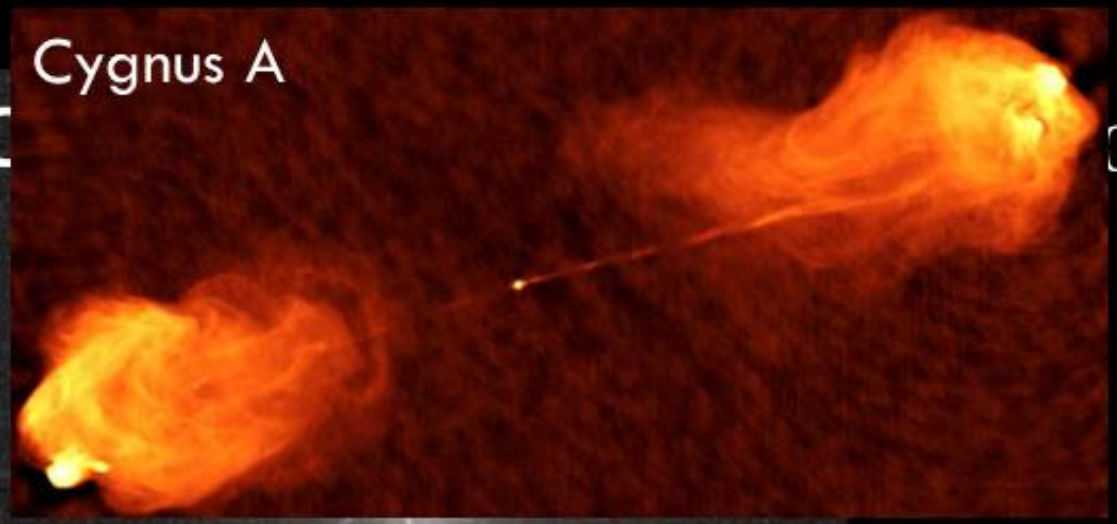
$M \sim 10^6 - 10^{10}\ M_\odot$

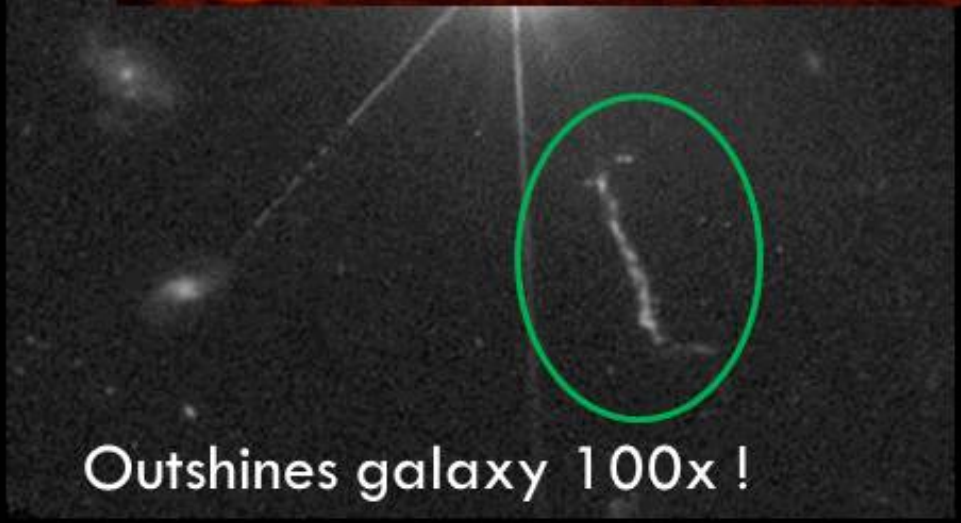
ENGINES OF THE UNIVERSE



$L \sim 10^{47}$ erg/s

ENGINES OF THE UNIVERSE



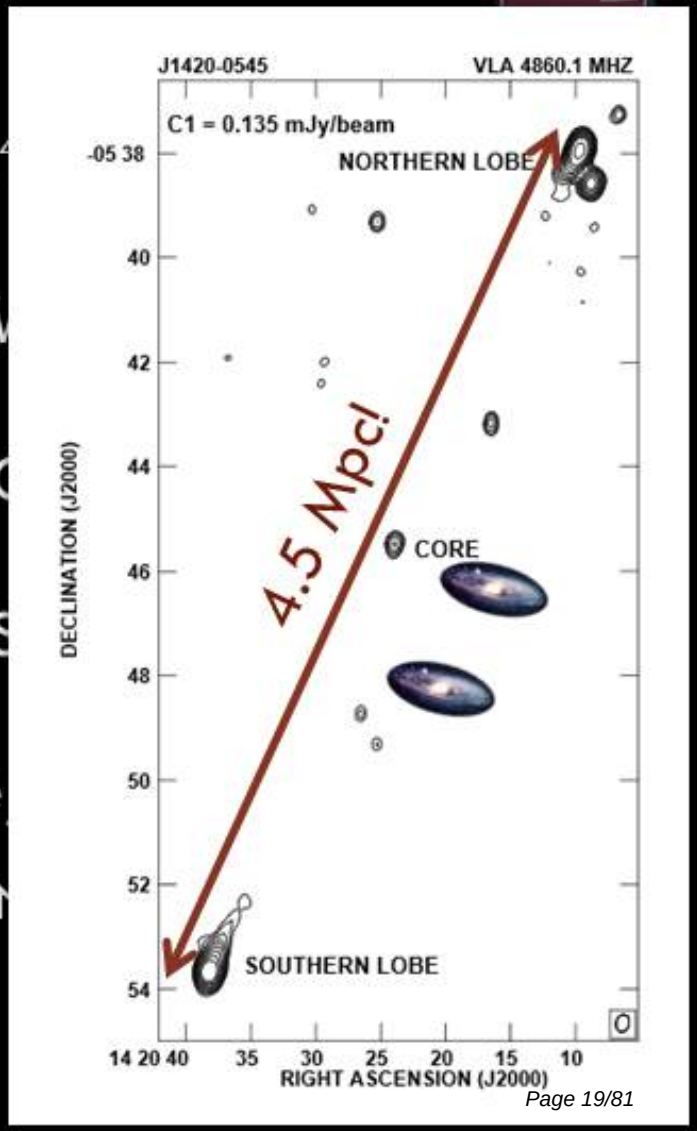


3C

10^{13} S

1 SNe

(cf. 1 SN

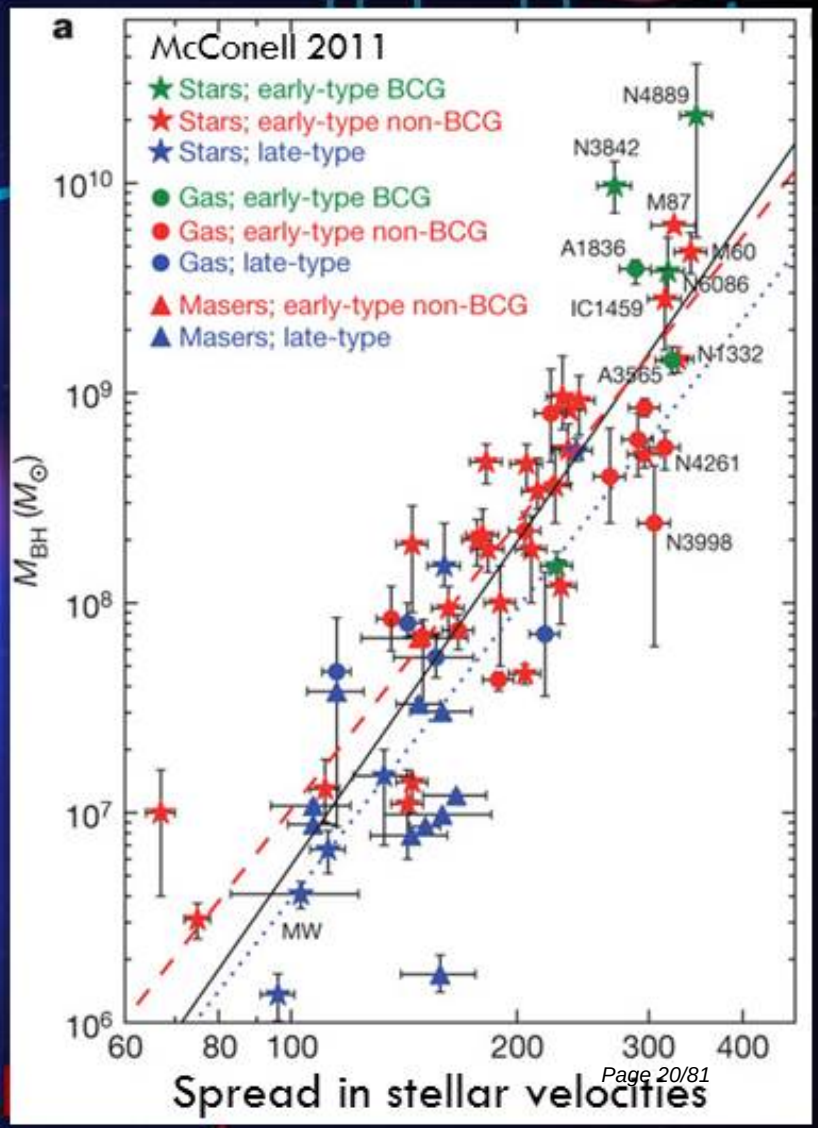


JETS WAGGING THE DOG

MS0735

X-ray-Optical-Radio

Galaxies!



Remnants of blac

BIG QUESTIONS!

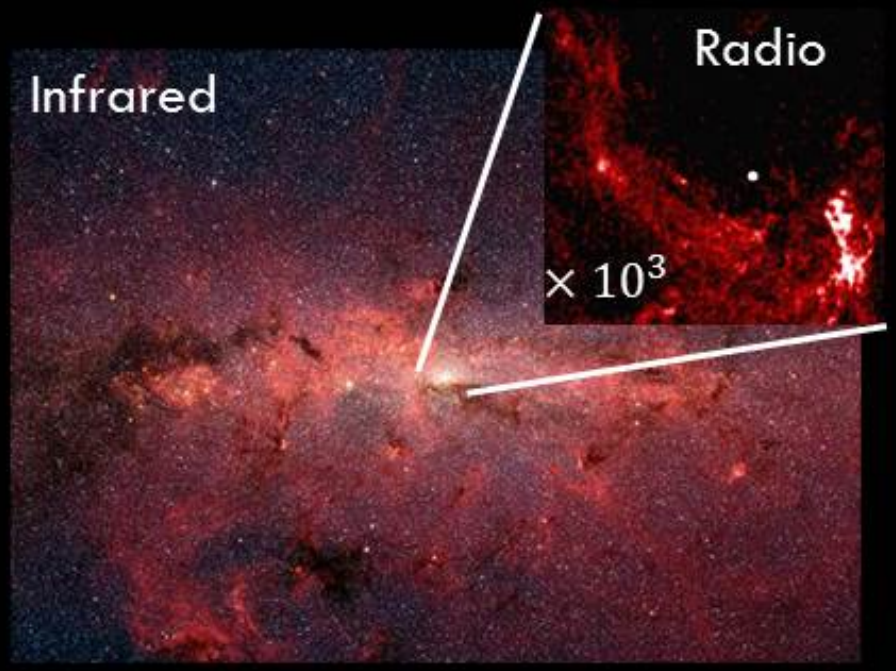
- *Do black holes exist?*
- *Does our current picture describe them?*

- *How are the enormous luminosities produced?*
- *How are the all-important outflows launched?*

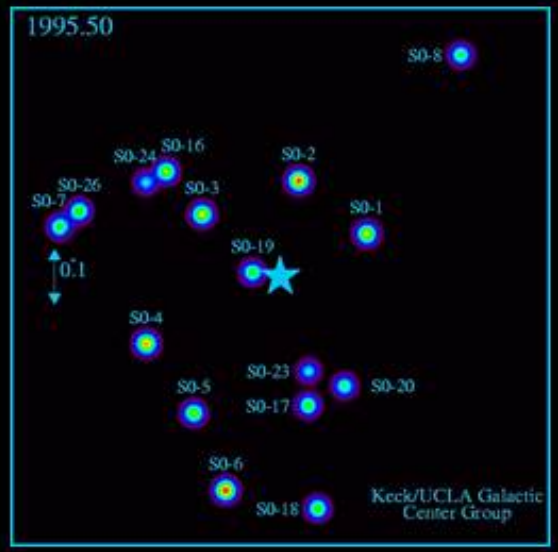
Getting answers from direct imaging!

A TALE OF TWO BLACK HOLES

Sagittarius A*

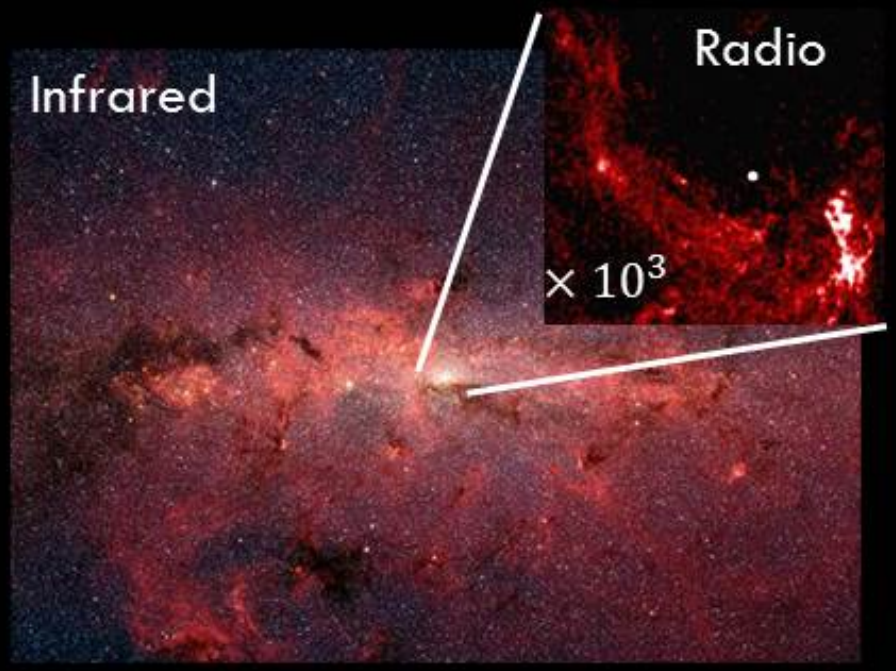


- Center of Milky Way
- 8 kpc ~ 24,000 lyr
- $4.5 \times 10^6\ M_\odot$
- $L \sim 10^{36}$ erg/s



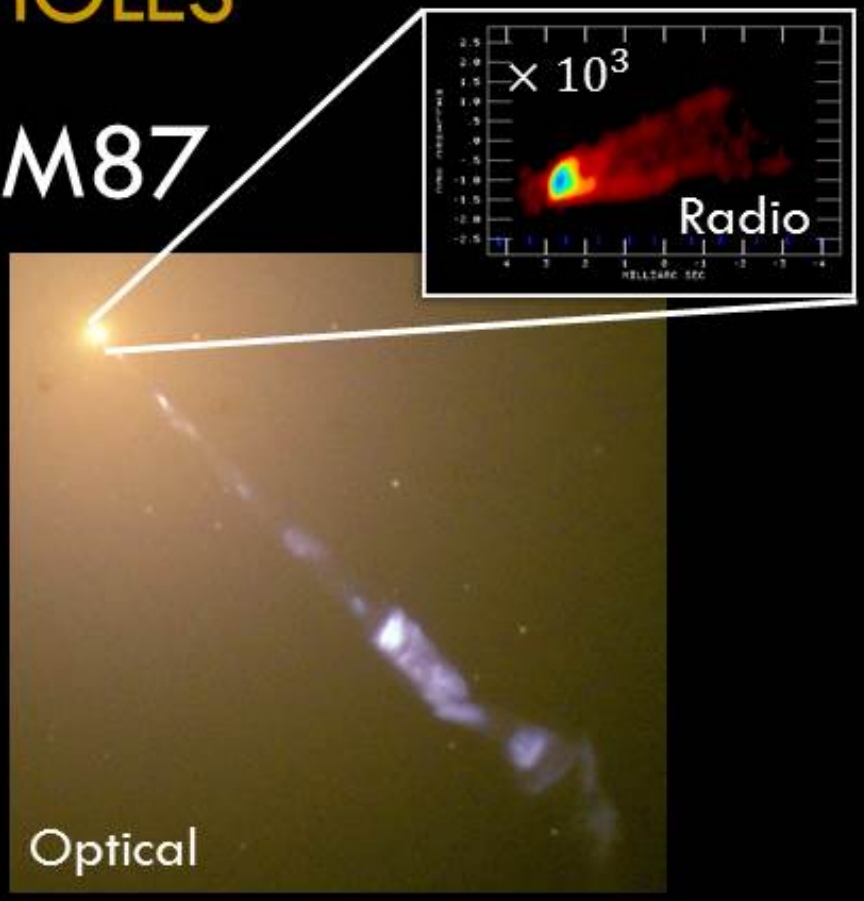
A TALE OF TWO BLACK HOLES

Sagittarius A*



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

M87



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

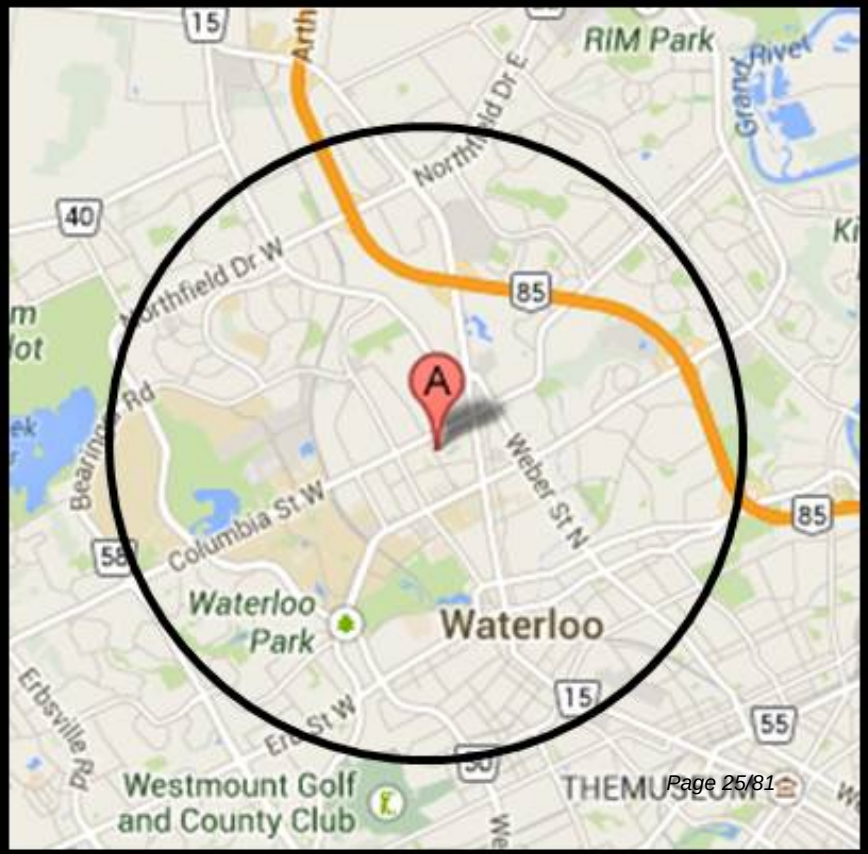
HOW BIG ARE BLACK HOLES?

- Earth ~2 cm

- Sun
- Sgr A*
- M87

HOW BIG ARE BLACK HOLES?

- Earth ~2 cm
- Sun ~3 km
- Sgr A*
- M87

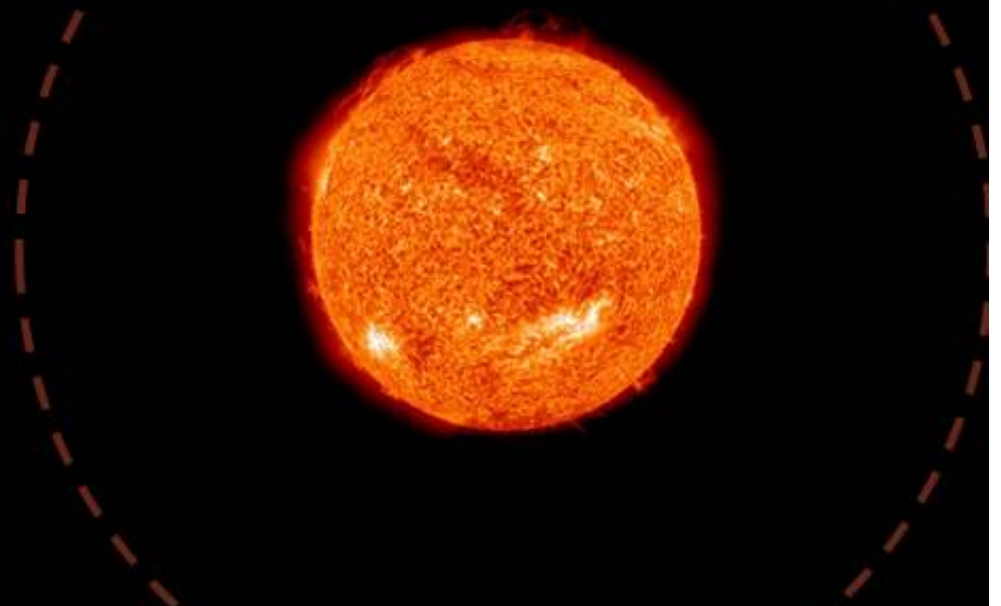


HOW BIG ARE BLACK HOLES?

- Earth ~2 cm

- Sun ~3 km

- Sgr A* ~2 $R_\odot$



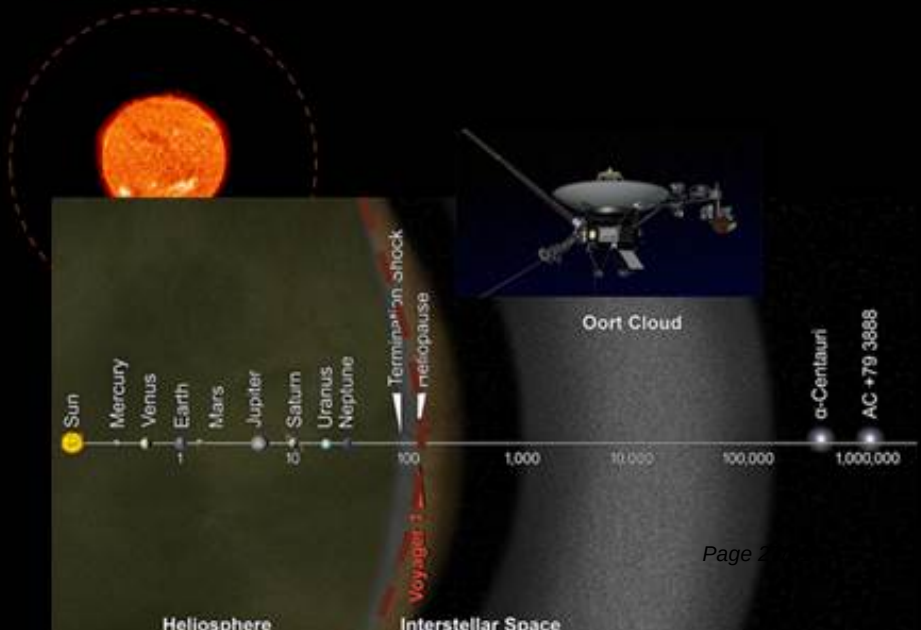
- M87

HOW BIG ARE BLACK HOLES?

- Earth ~2 cm

- Sun ~3 km

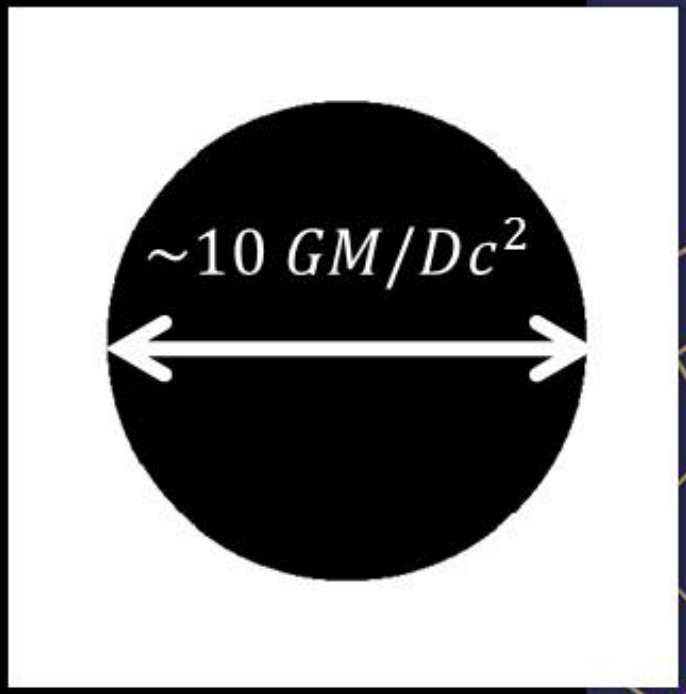
- Sgr A* ~2 $R_\odot$

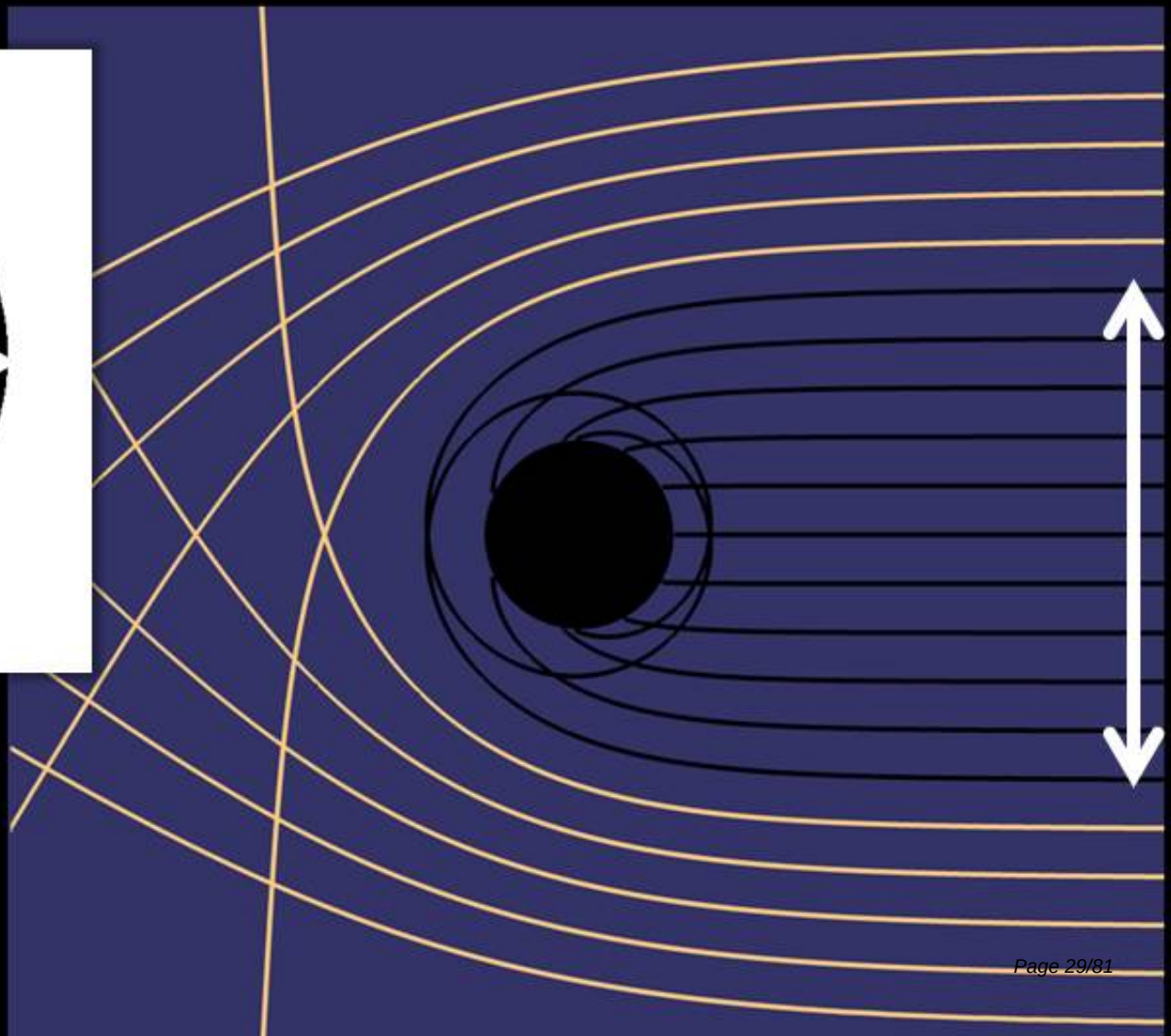


- M87 ~100 AU

WHAT DOES A BLACK HOLE LOOK LIKE?

WHAT DOES A BLACK HOLE LOOK LIKE?



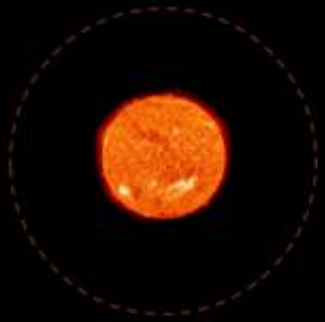


10^{12} pas $= 10^{6}$ μas $= 1^{\text{“}}$

$3600'' = 1^{\circ}$

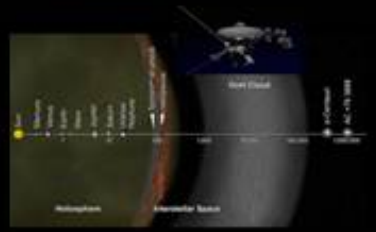
30 pas

- Sgr A* $\sim 2\ R_{\odot}$



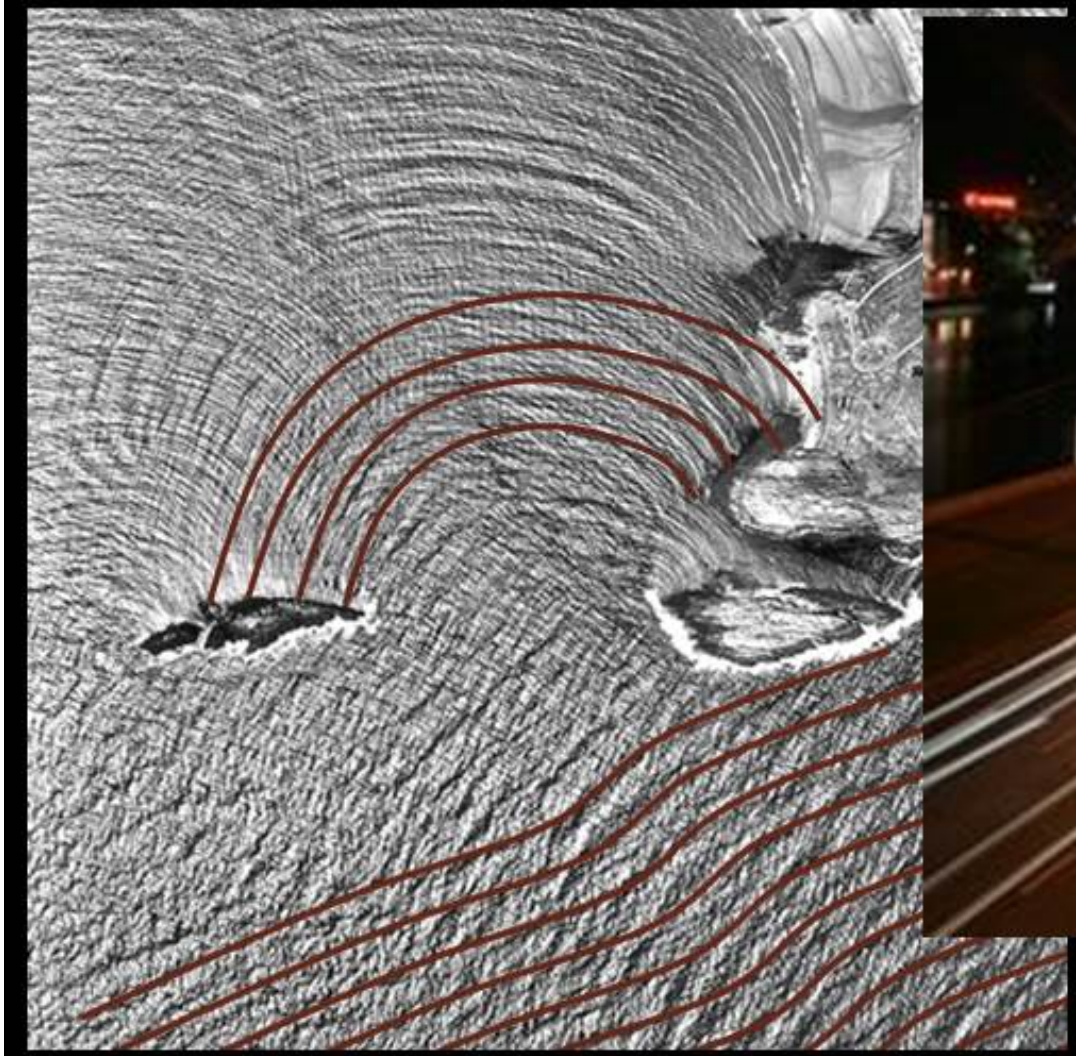
53 μas

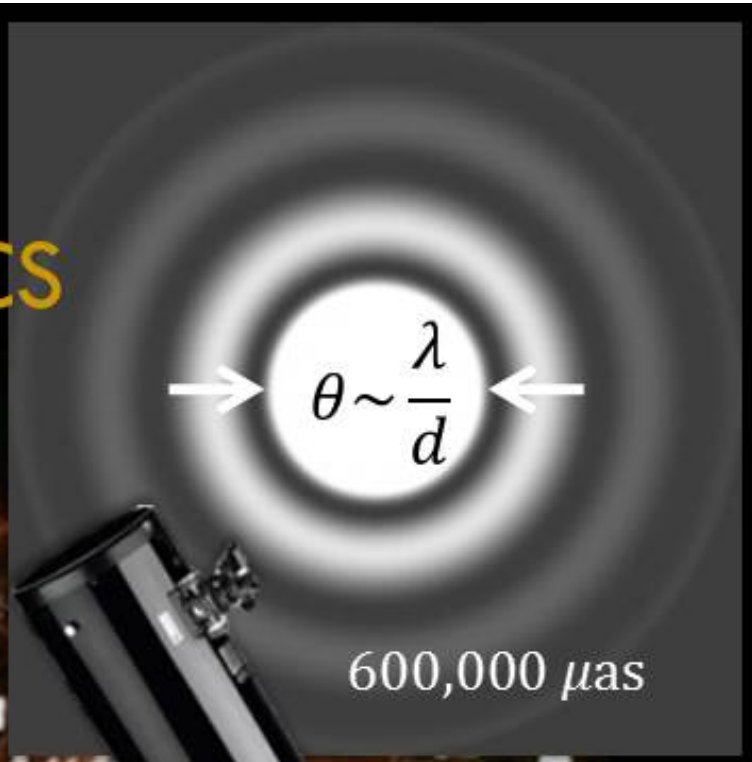
- M87 $\sim$100 AU



40 μas

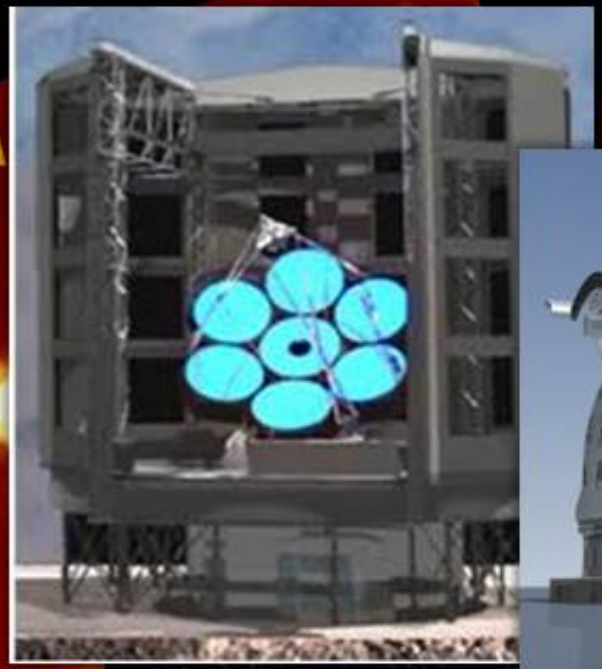
DIFFRACTION LIMITED OPTICS

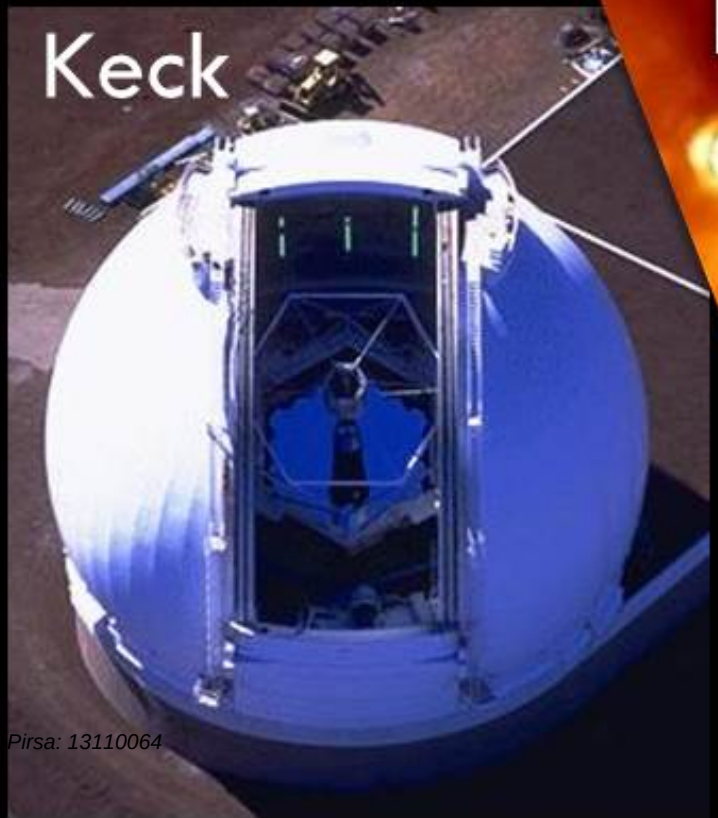


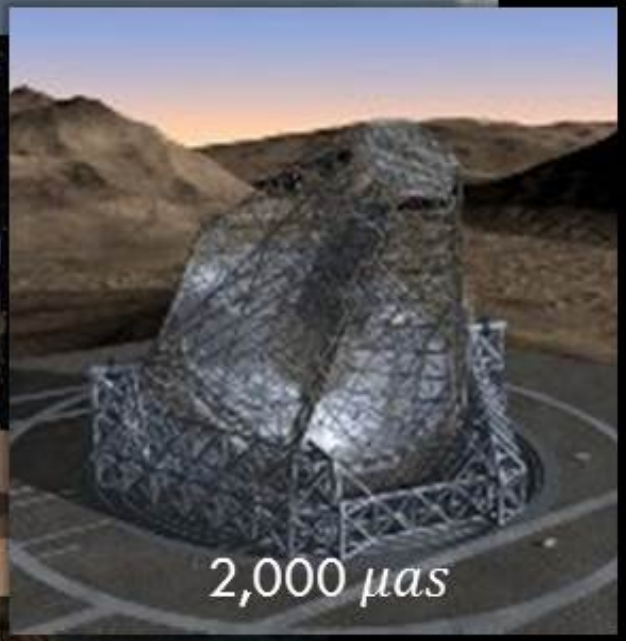


DIFFRACTION LIM ES

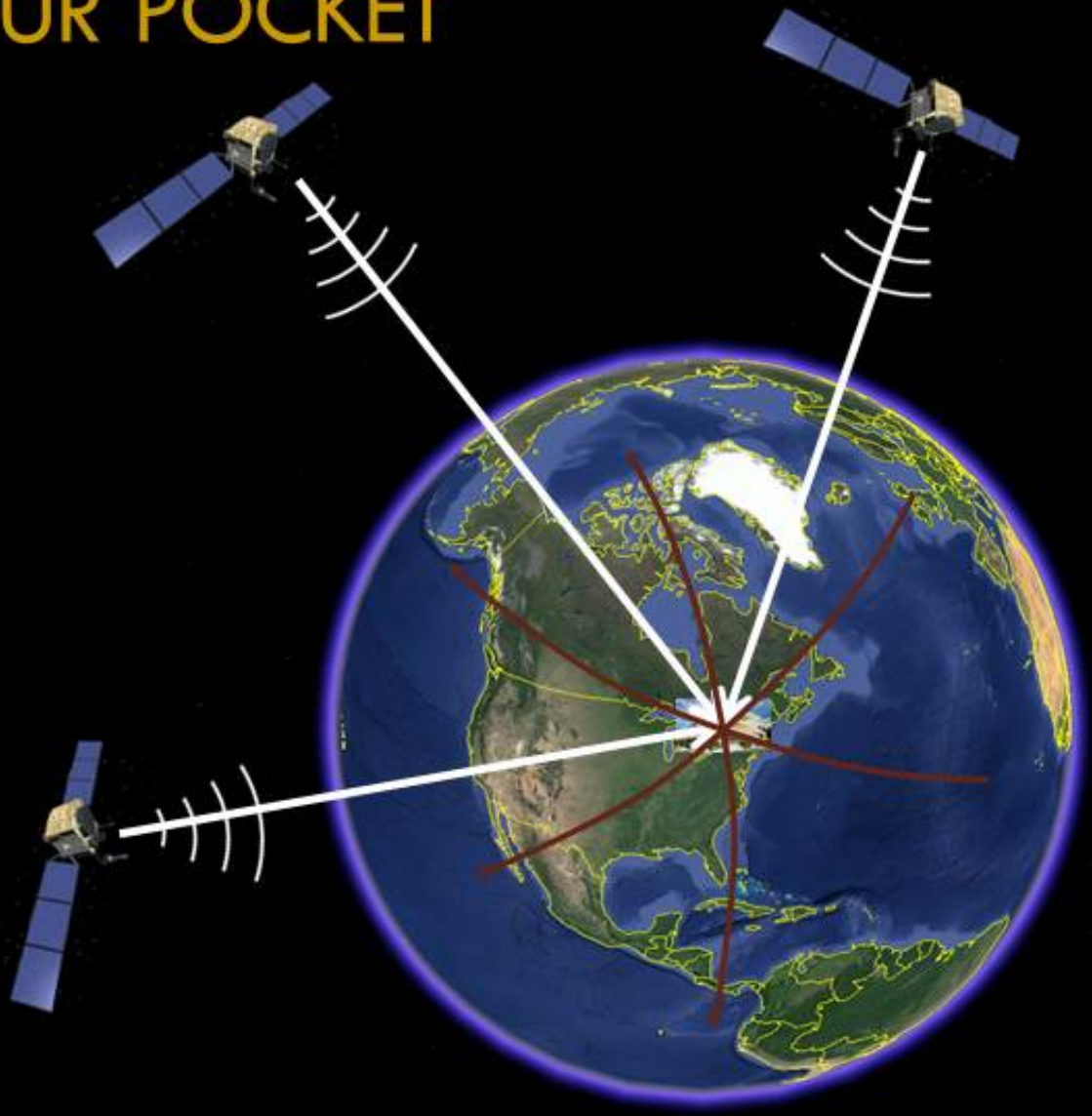
$$\theta \sim \lambda/d$$





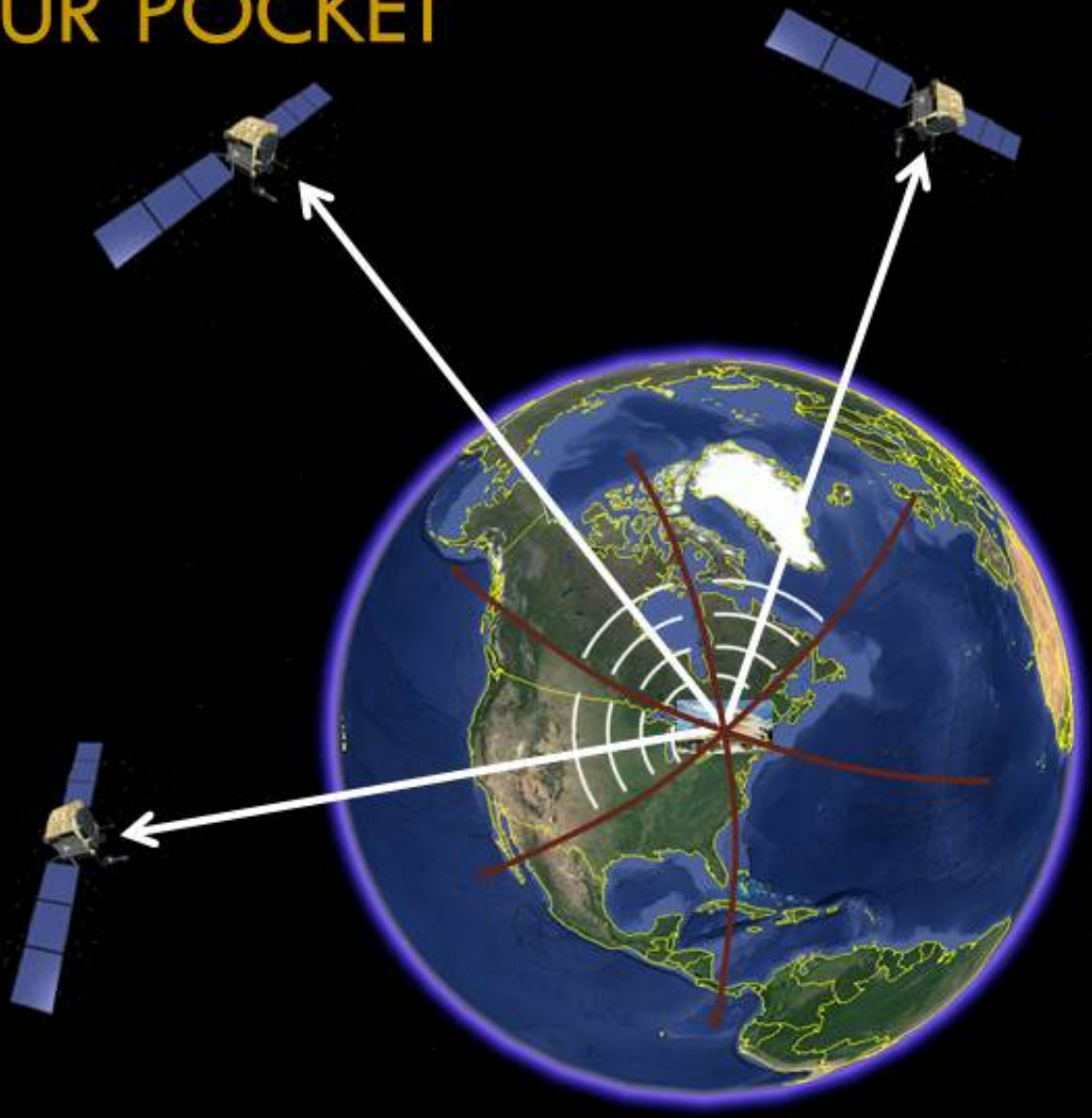


EARTH-SIZED TELESCOPES IN YOUR POCKET



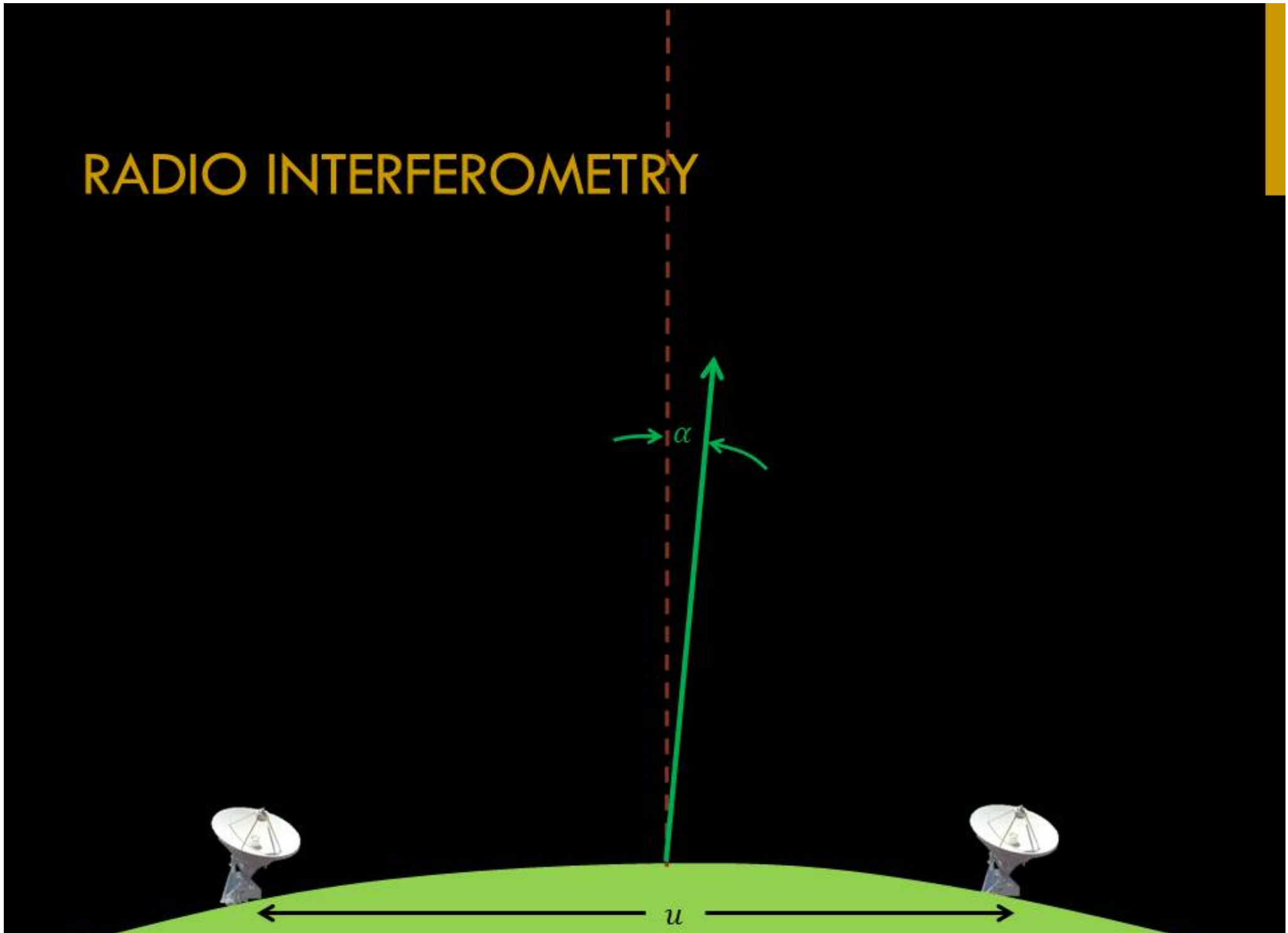
GPS is simply a nanosecond precision timing experiment!

EARTH-SIZED TELESCOPES IN YOUR POCKET



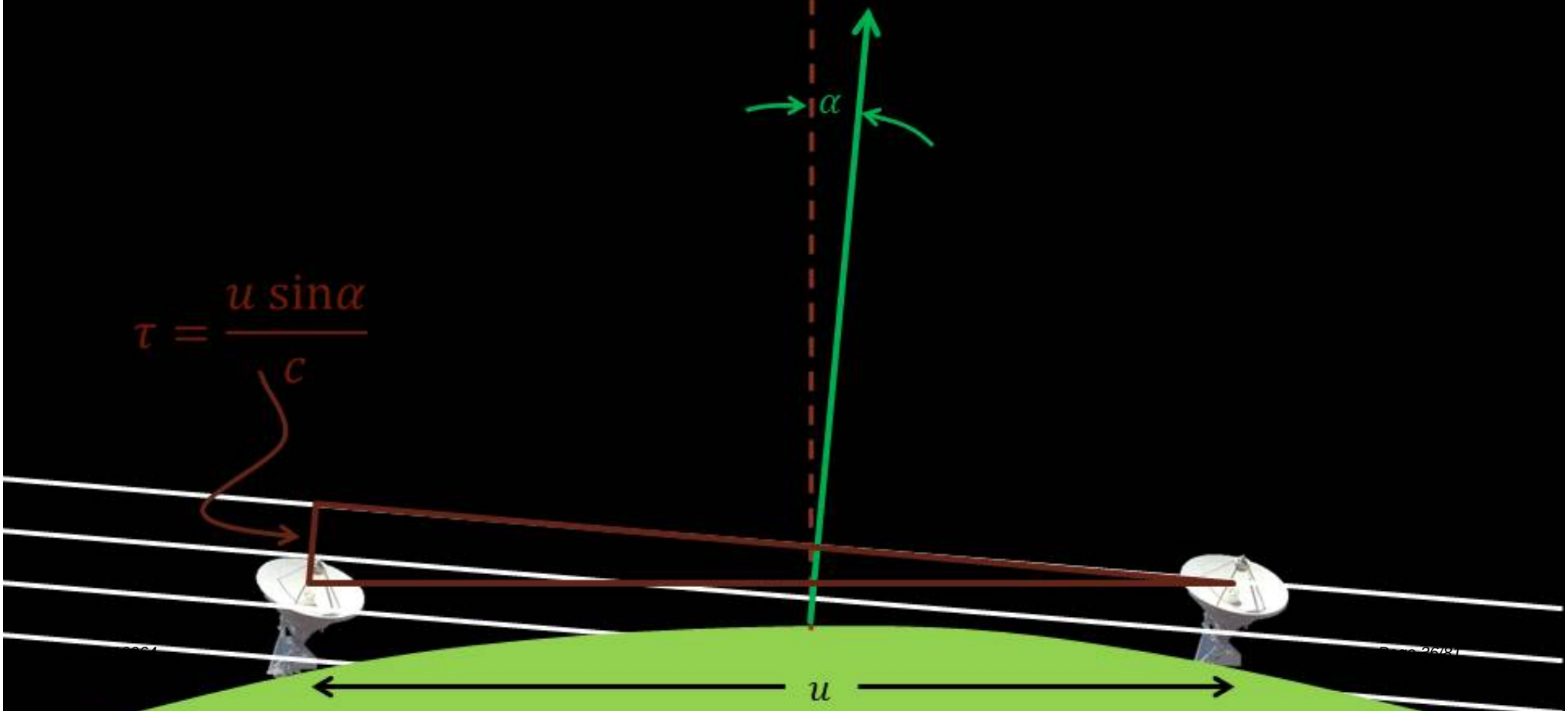
Radio interferometry!

RADIO INTERFEROMETRY



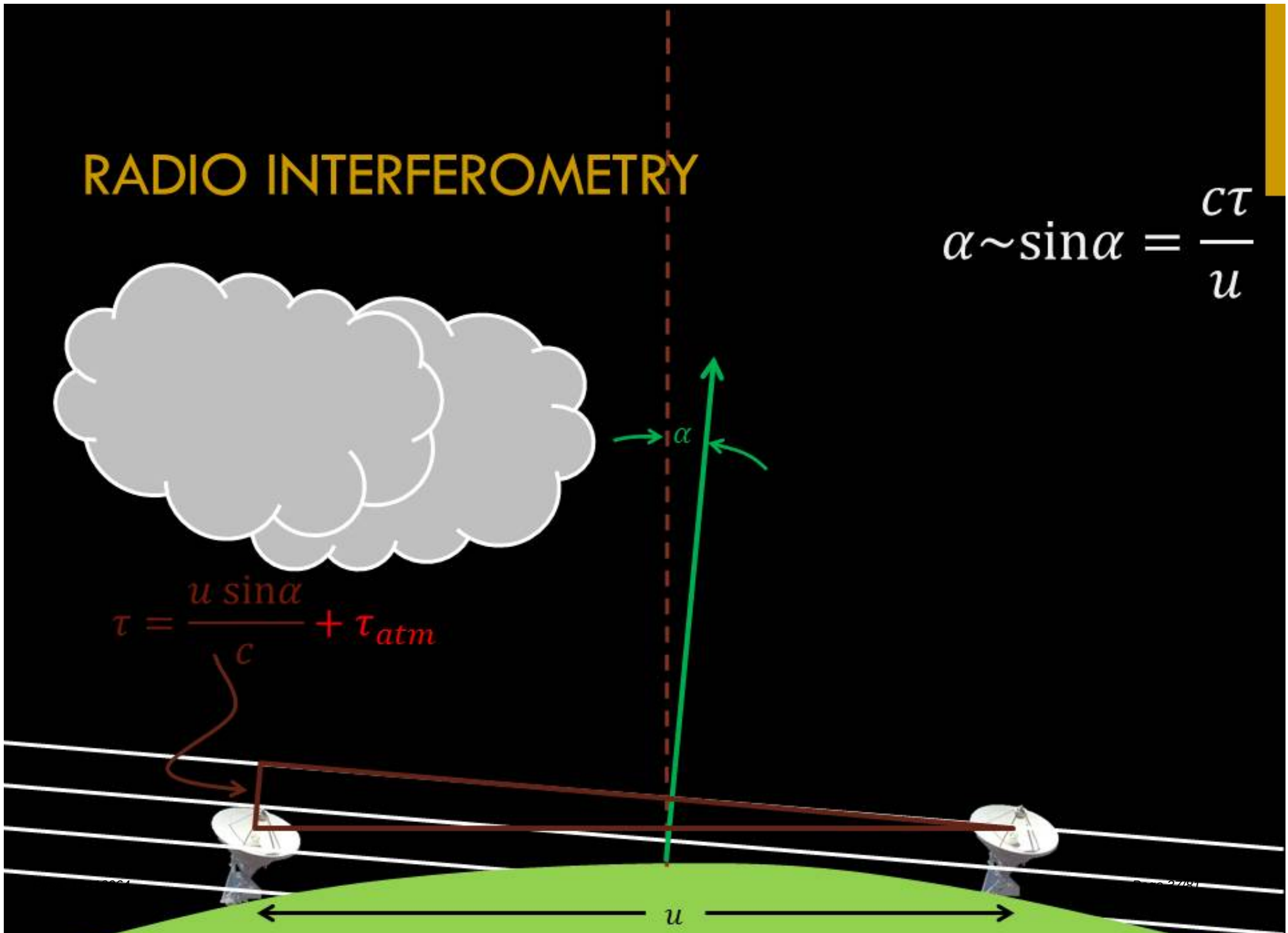
RADIO INTERFEROMETRY

$$\alpha \sim \sin\alpha = \frac{c\tau}{u}$$

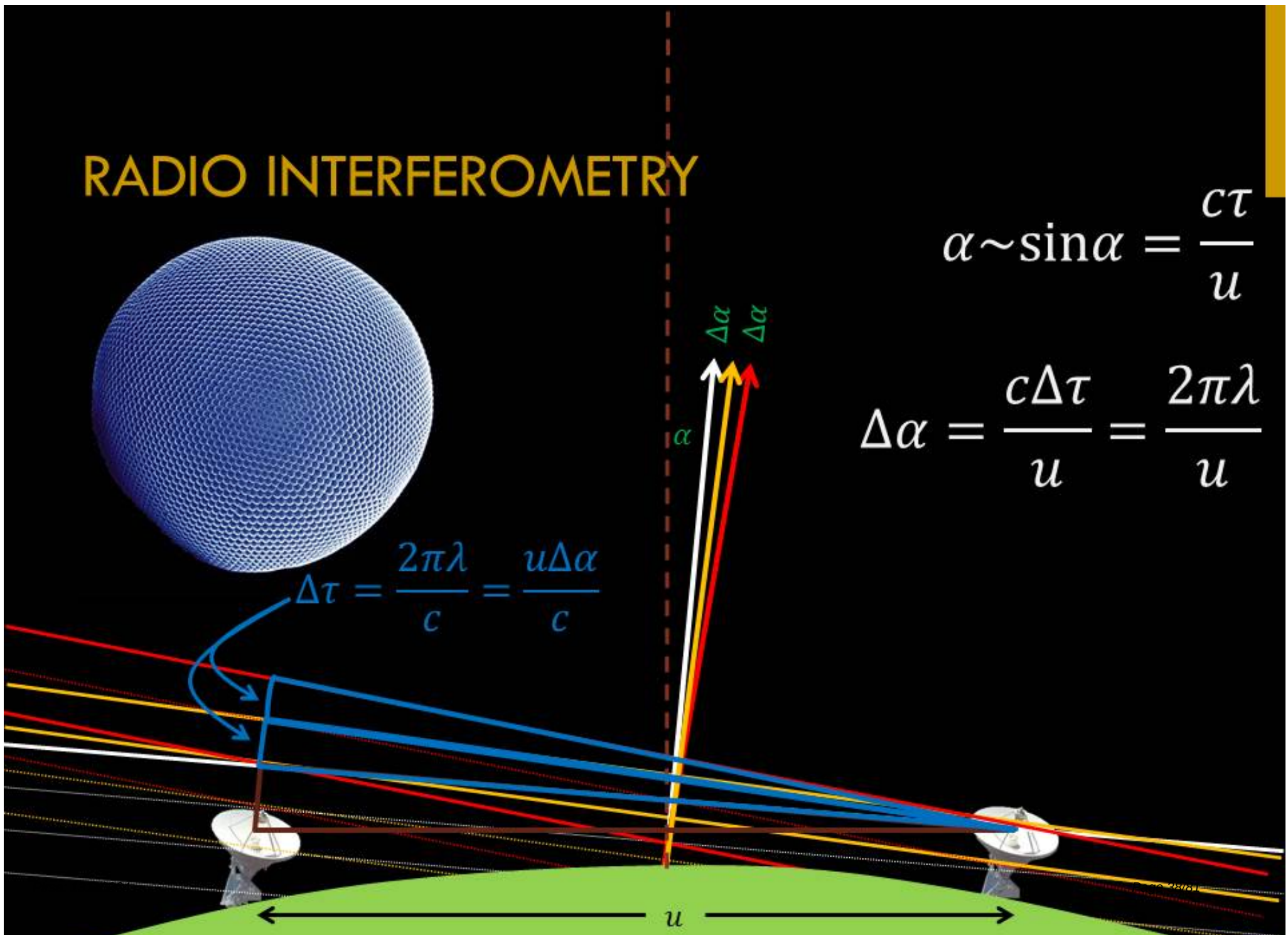


RADIO INTERFEROMETRY

$$\alpha \sim \sin\alpha = \frac{c\tau}{u}$$

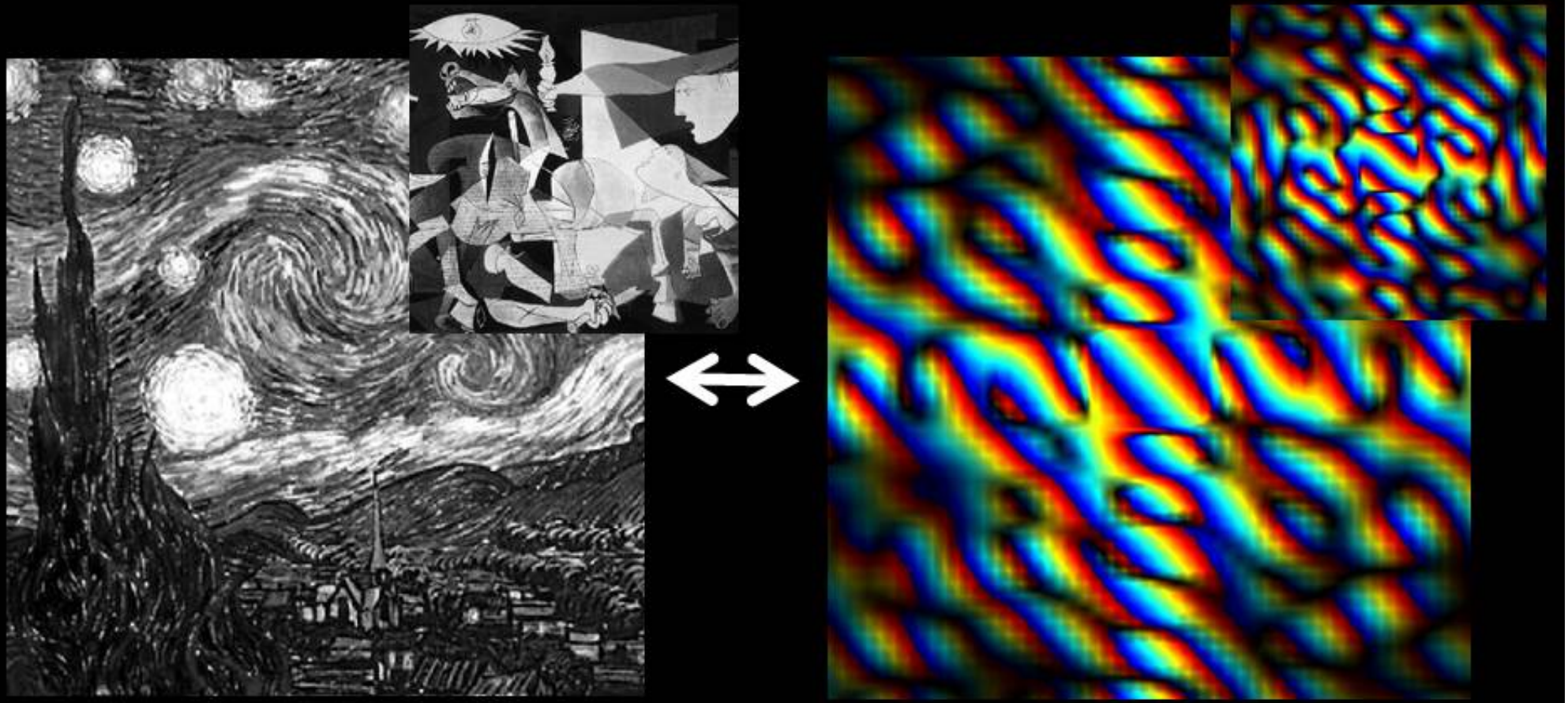


RADIO INTERFEROMETRY



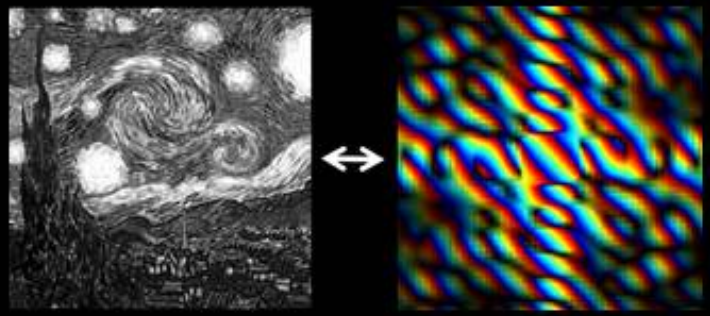
THE PRICE OF LUNCH

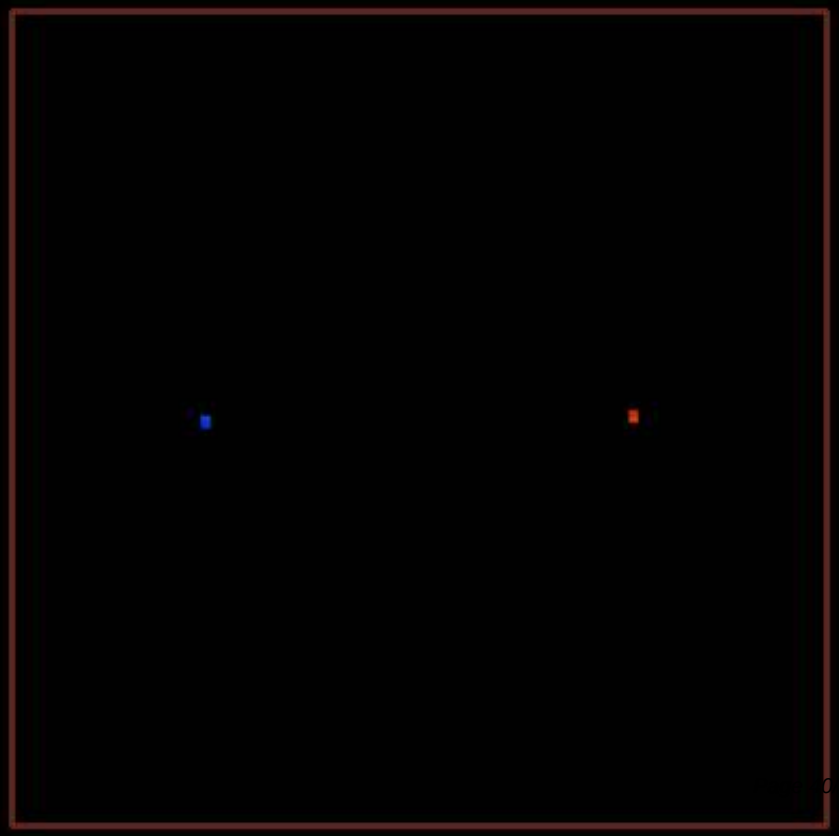
1. **Image space vs. Visibility space**



THE PRICE OF LUNCH

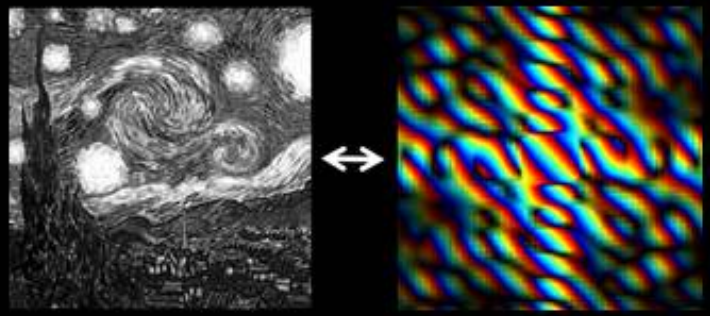
1. Image space vs. Visibility space
2. Sparseness: "1 pixel at a time"

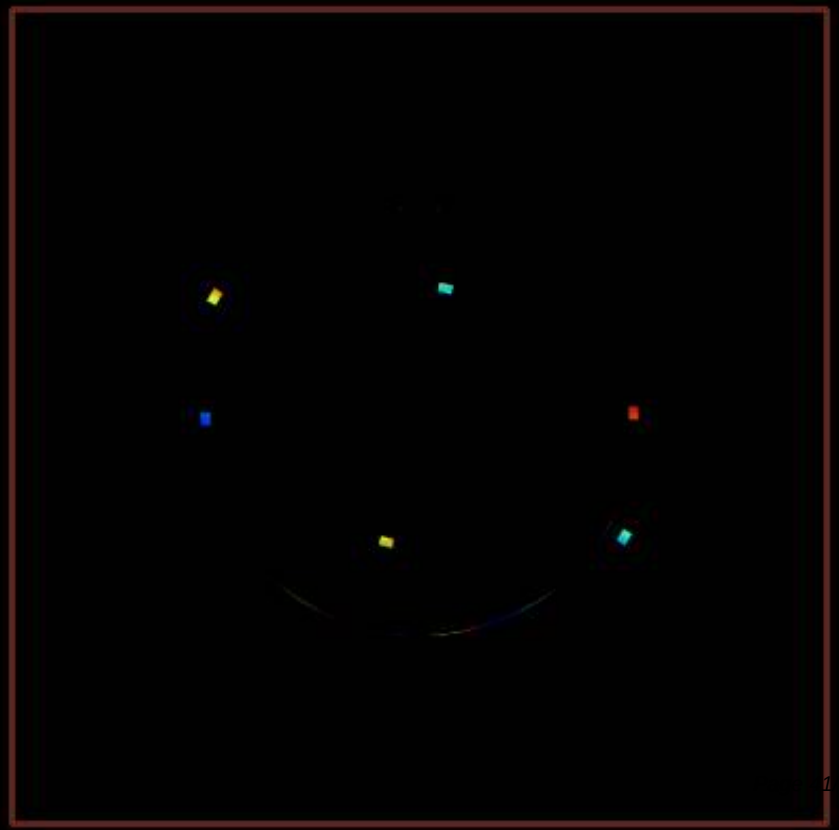




THE PRICE OF LUNCH

1. **Image space vs. Visibility space**
2. **Sparseness: "1 pixel at a time"**
   → *Lots of antennas!*

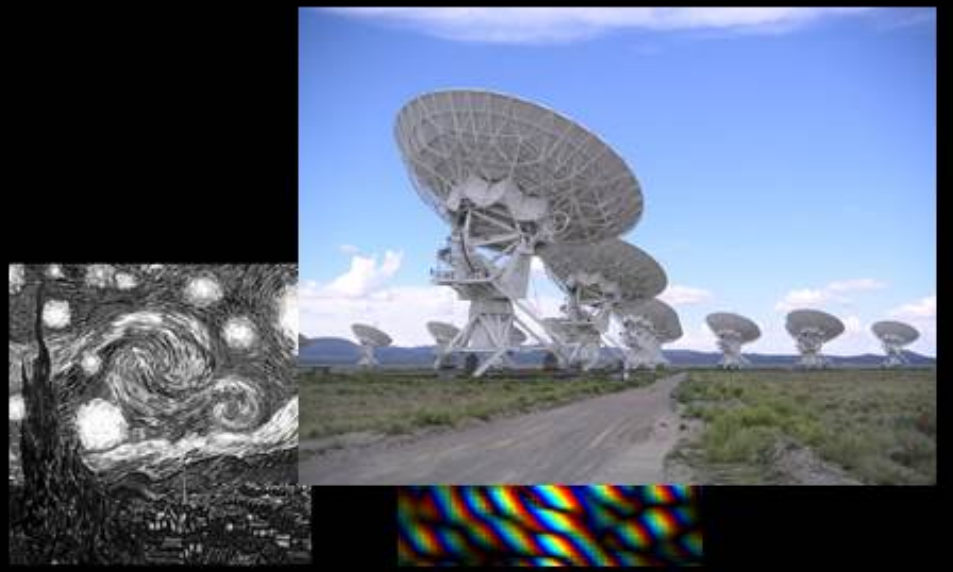




THE PRICE OF LUNCH

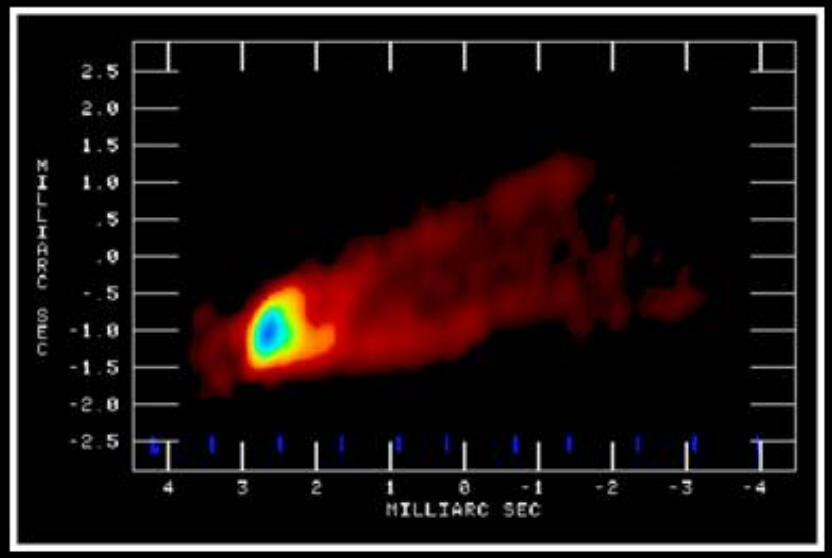
1. **Image space vs. Visibility space**
2. **Sparseness: "1 pixel at a time"**

   → *Lots of antennas and patience!*



A LONG HISTORY NOW

Very Long Baseline Array



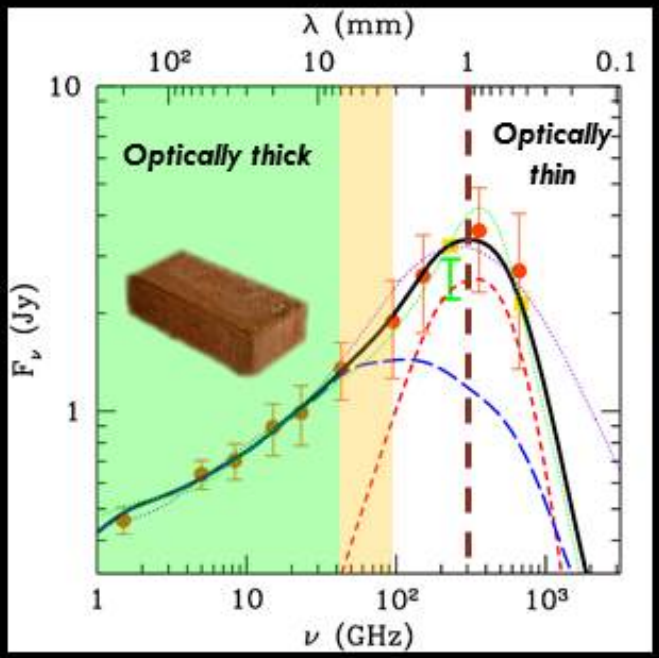
- **Earth-sized baselines**
- **10 or more antennas**
- $\lambda > 3$ mm (7 mm)
- $\lambda/u \sim 0.1$ mas $= 10^2$ μas!
- **Operating for ~20 yrs!**

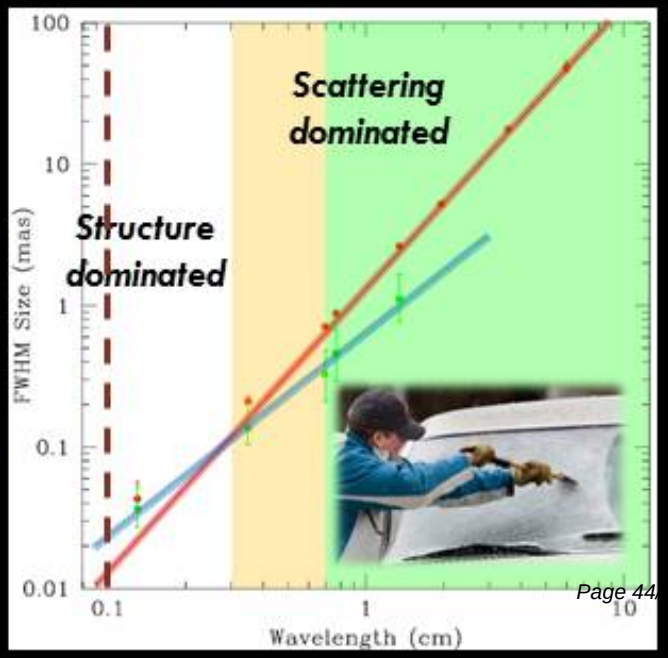
PUSHING HIGHER

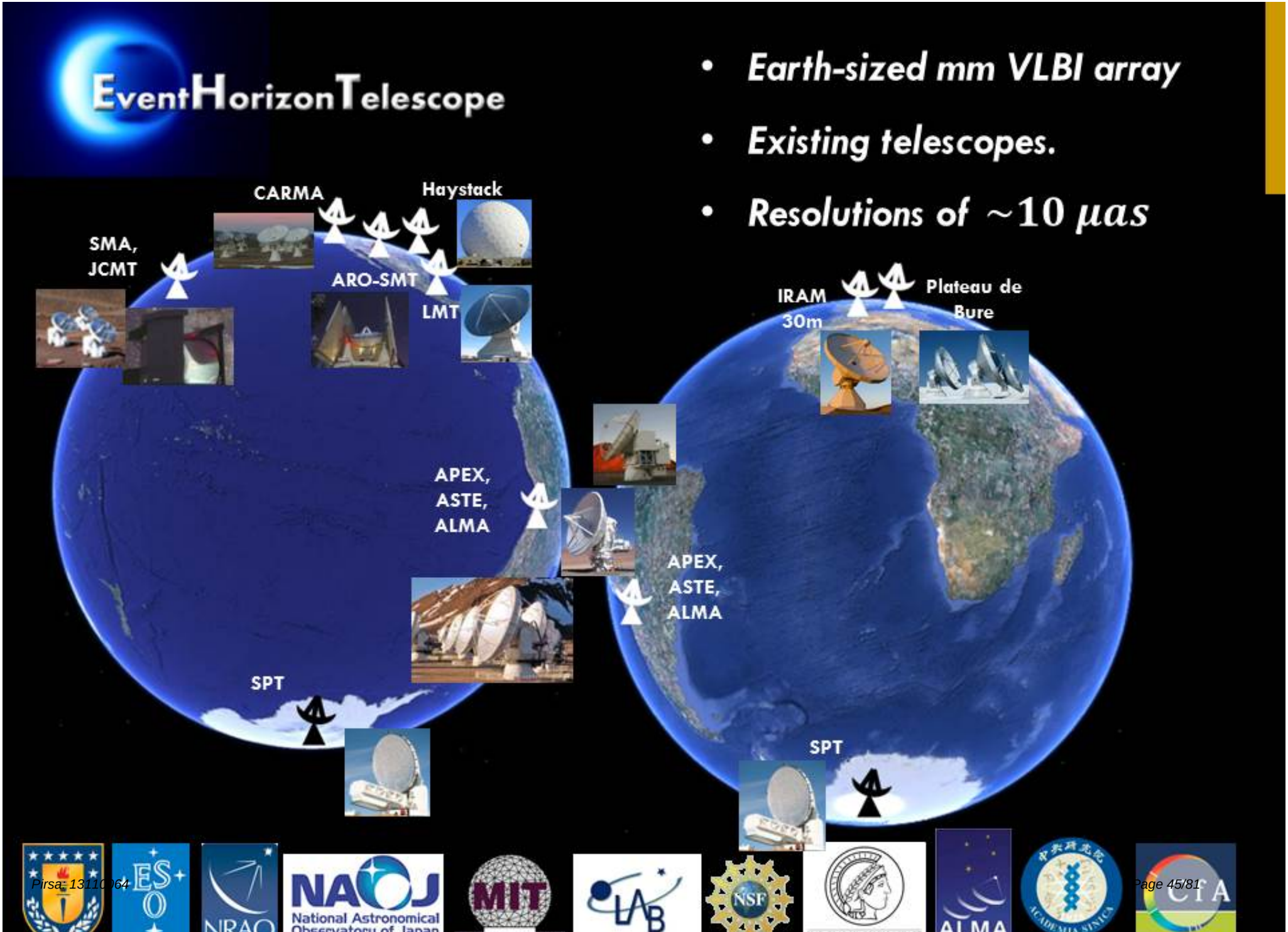
1. **Resolution** $(100 > 50!)$

$$u_{\oplus} \sim 10^4 \text{ km} \rightarrow \lambda \lesssim 1 \text{ mm}$$

2. **Getting a clear view**






EventHorizonTelescope
• Earth-sized mm VLBI array
• Existing telescopes.
• Resolutions of ~10 μas
CARMA
Haystack
SMA,
JCMT
ARO-SMT
LMT
IRAM
30m
Plateau de
Bure
APEX,
ASTE,
ALMA
APEX,
ASTE,
ALMA
SPT
SPT
NAOJ
National Astronomical
Observatory of Japan
MIT
NSF
ALMA
CfA

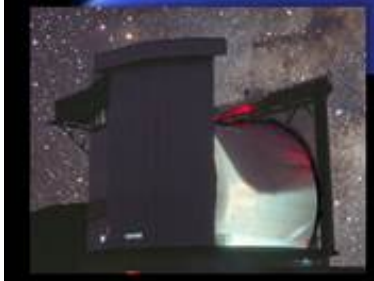
EventHorizonTelescope

"PROTO-EHT" DATA!

CARMA

SMA,
JCMT

ARO-SMT



Sgr A* $37.2 \pm 0.5\ \mu as$

- April 2007
- April 2009
- April 2011
- April 2012
- March 2013

M87 $40.0 \pm 0.6\ \mu as$

- April 2009
- April 2012
- March 2013

Sub-horizon structure already detected!

EventHorizonTelescope

FUTURE OF THE EHT

Increasing Sensitivity:

- Phasing Arrays
  - Hawaii (Done!)
  - CARMA (Done!)
  - ALMA (In progress!)
- Expanding Bandwidth to 8GHz (64 Gb/s!)
- Building New Receivers

Adding Sites:

- ALMA
- LMT
- Plateau de Bure
- Pico Veleta
- SPT
- Haystack
- Greenland Telescope

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

EventHorizonTelescope

BLACK HOLE PORTRAITS

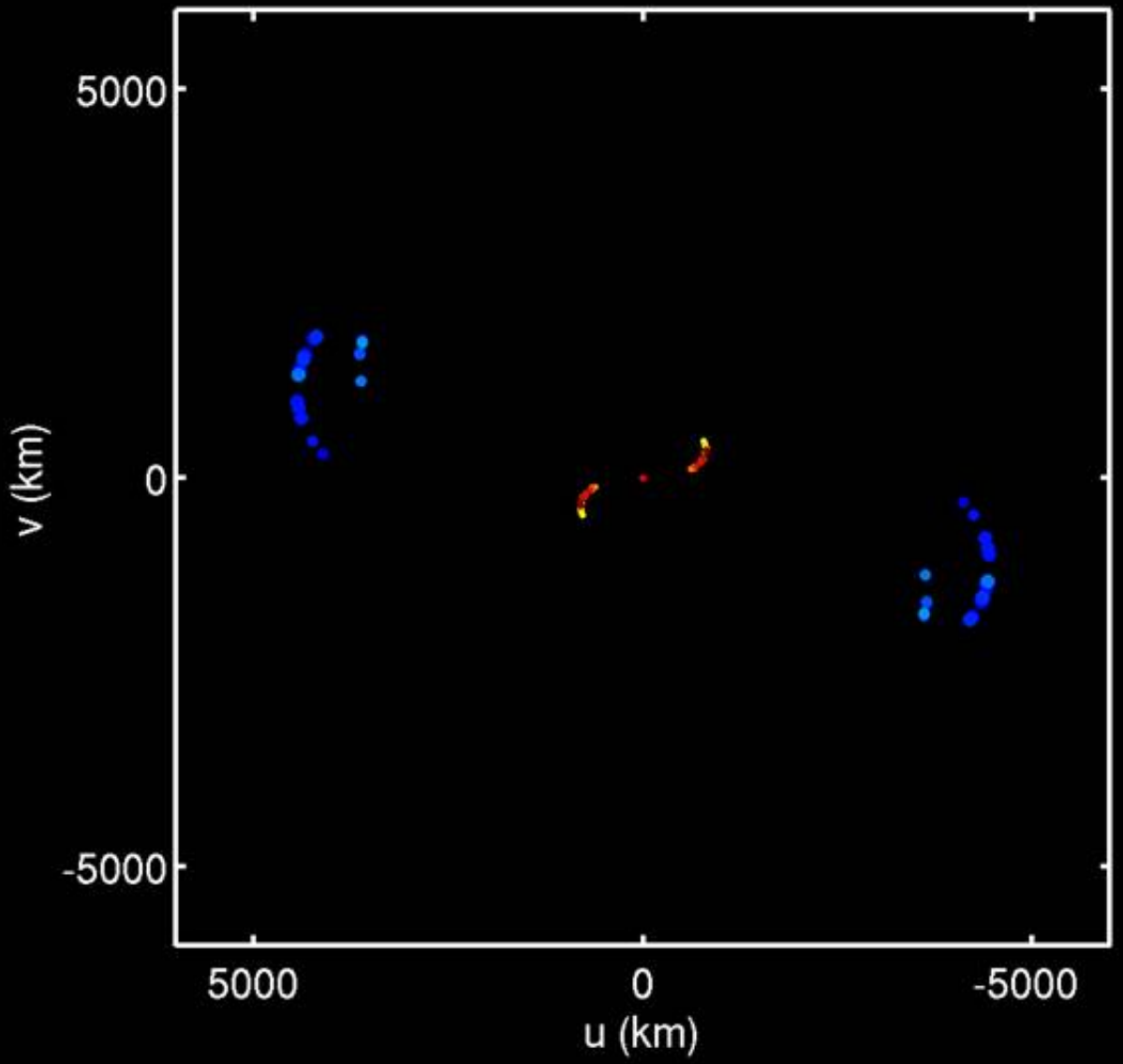
7 stations BSMEM

13

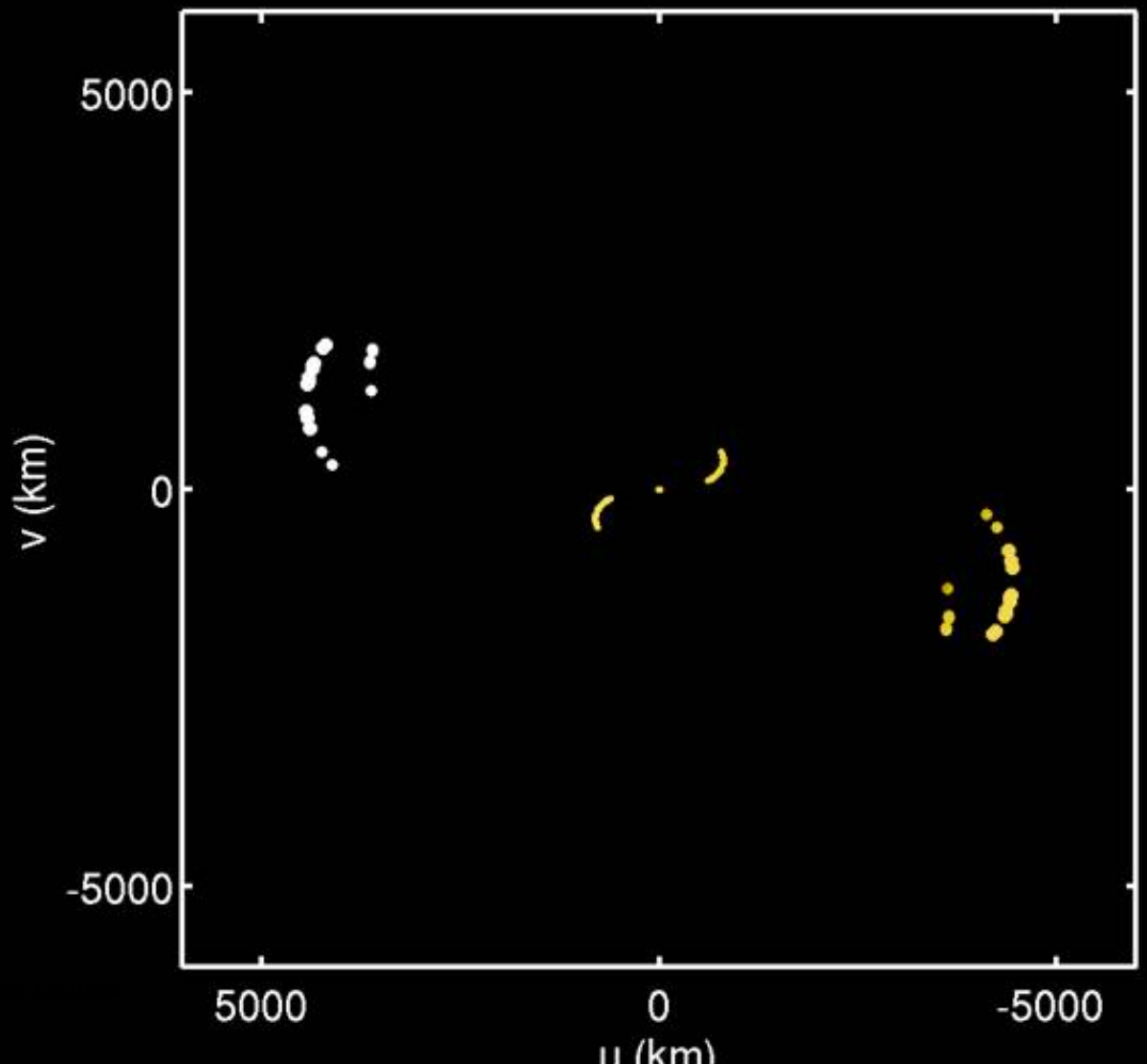
Courtesy of Vincent Fish

EventHorizonTelescope

PRESENT VISIBILITIES



ANNA, BANANA AND CONTEXT



Do event horizons exist?

How do black holes grow?

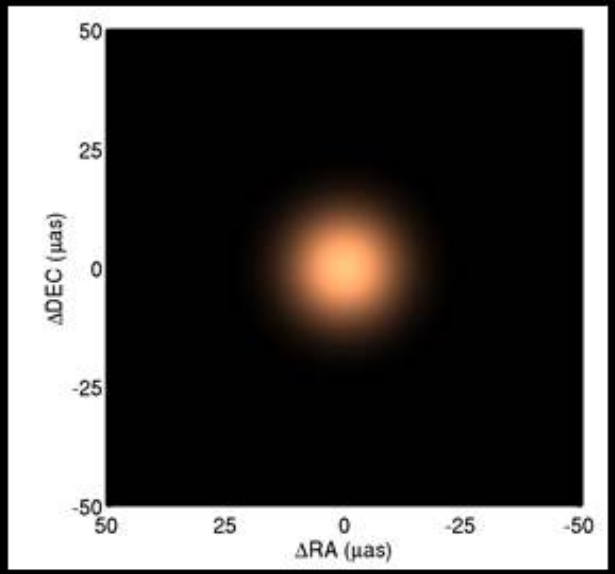
What drives jets?

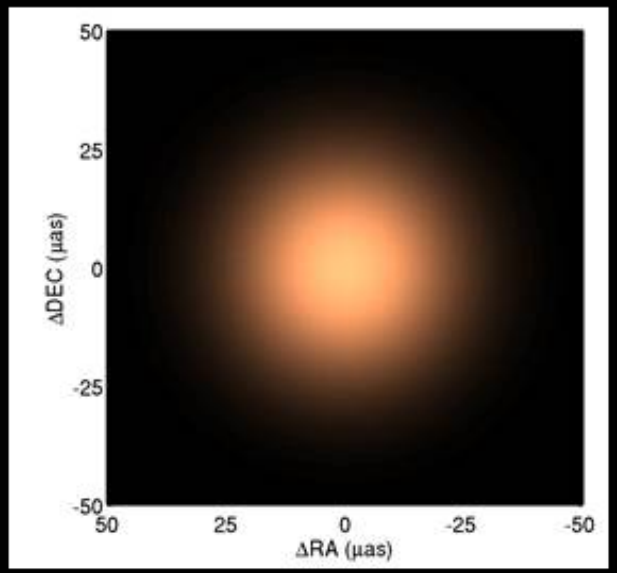
Do event horizons exist?

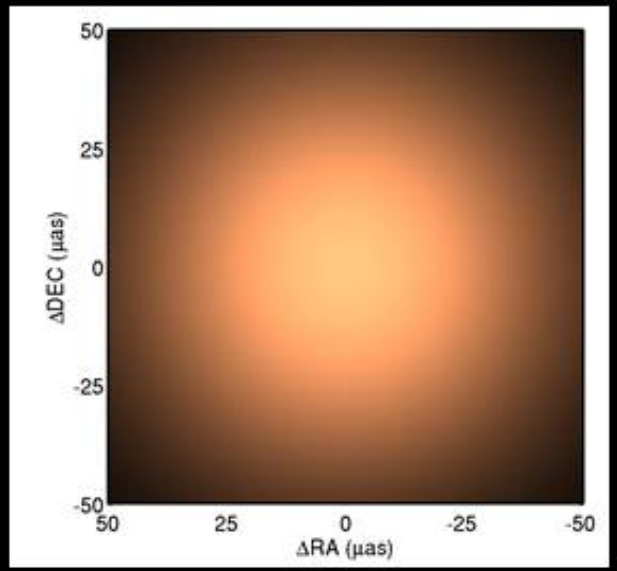
Horizons

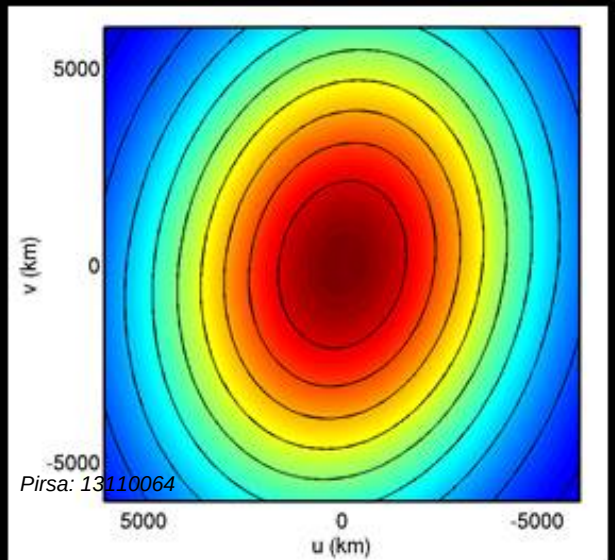
SIZES FROM BLOBS

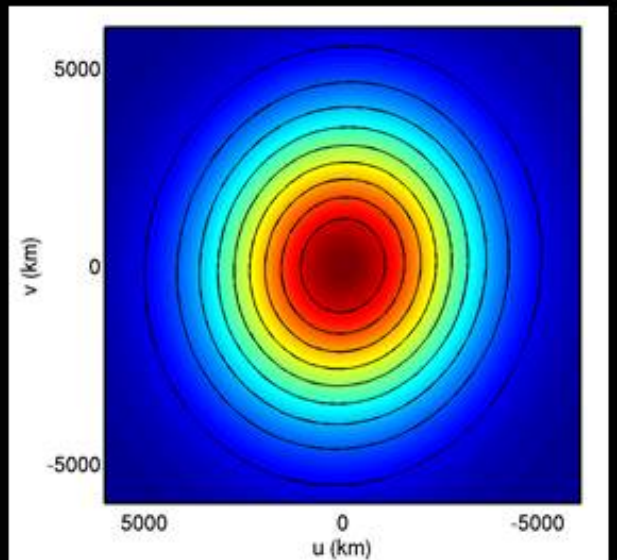
$\rightarrow 37.2 \pm 0.5\ \mu as$

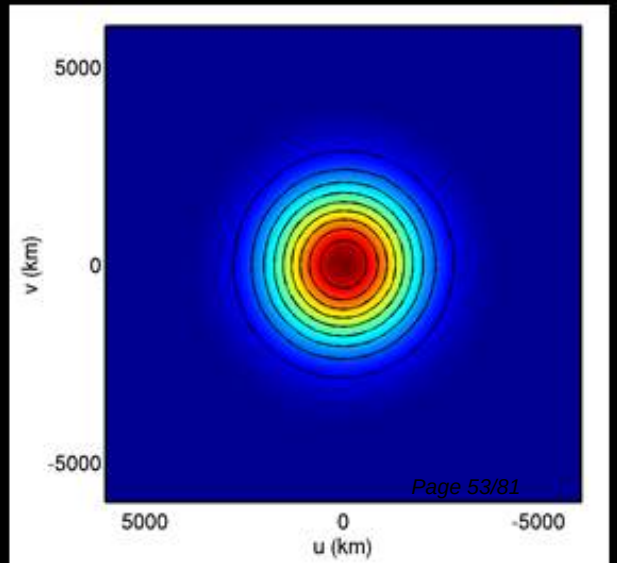








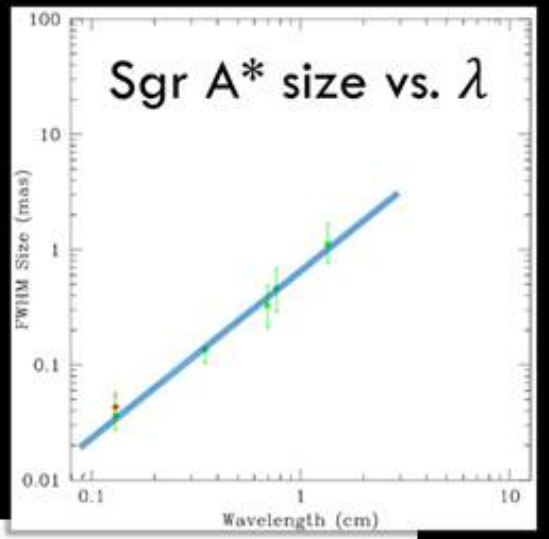


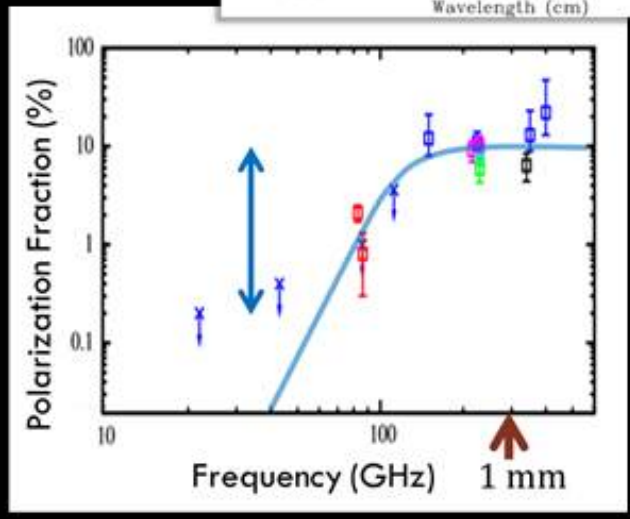


Horizons

WHY DOES SGR A* SHINE?

Nested structure

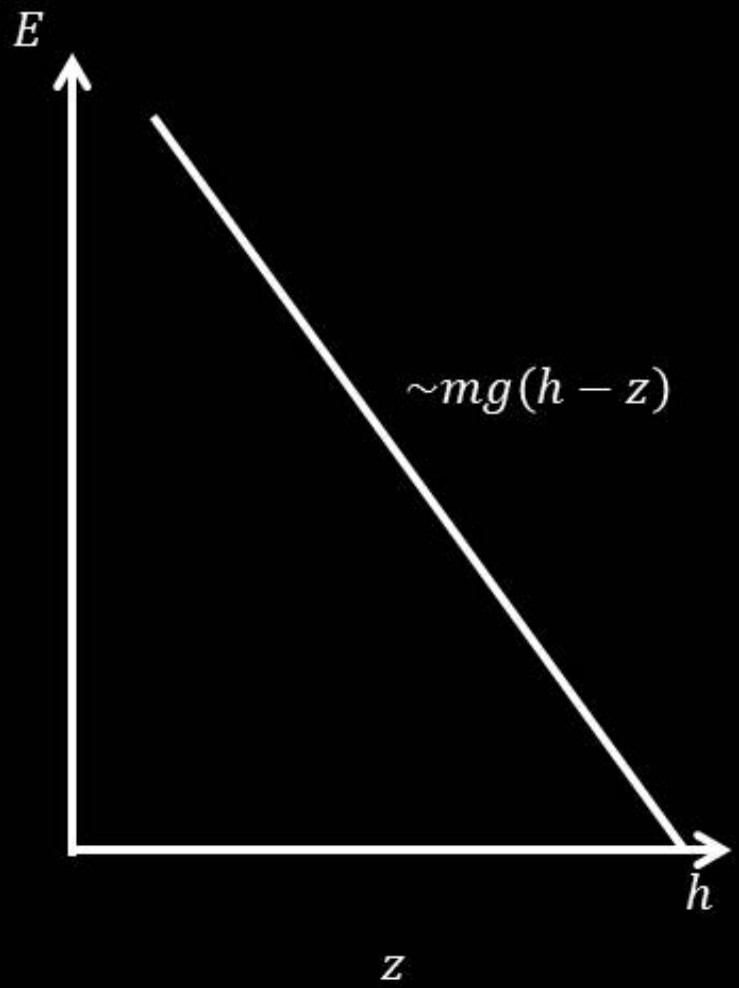




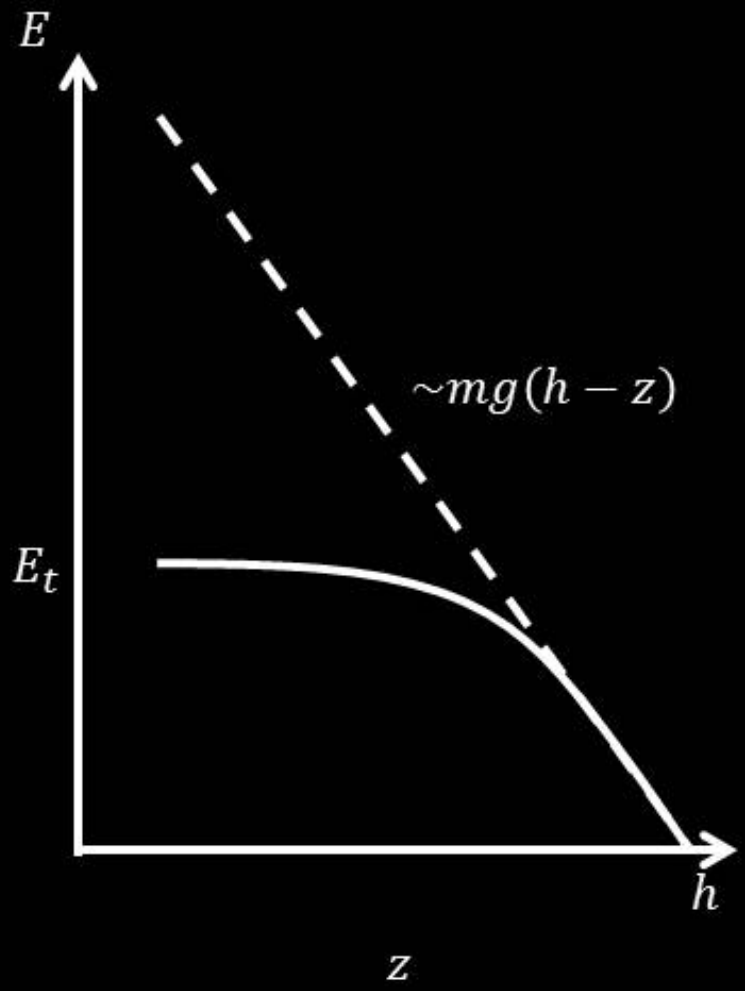
Lots of gas near black hole

Sgr A is accretion powered with* $\dot{M} \sim 10^{-8}\ M_\odot/yr$

ACCRETION IN BRIEF

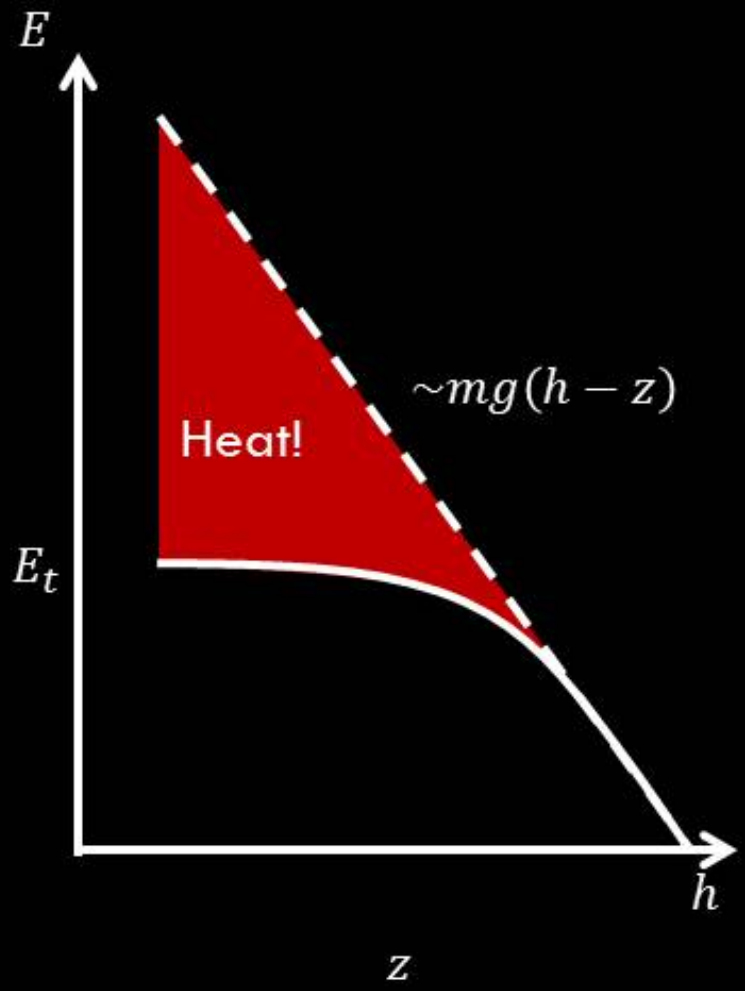


ACCRETION IN BRIEF



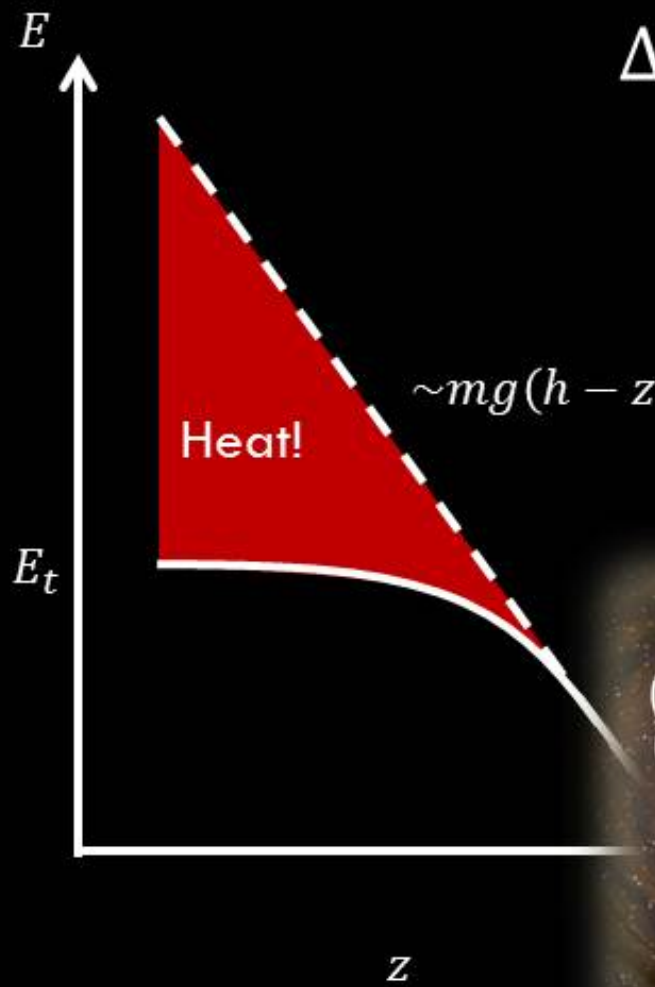
ACCRETION IN BRIEF

$$\Delta E \sim \frac{GM_{\oplus}m}{R_{\oplus}} \sim 10^{-9}mc^2$$



ACCRETION IN BRIEF

$$\Delta E \sim \frac{GMm}{R_S} \sim \frac{GMm}{(2GM/c^2)} \sim 0.5\, mc^2$$



$$\rightarrow L = \eta \dot{M} c^2$$

($\eta \sim 10\%$ for quasars)
($\eta \sim 0.1\%$ for Sgr A*/M87)

ACCRETION AT THE HORIZON

← Accretion Lumino

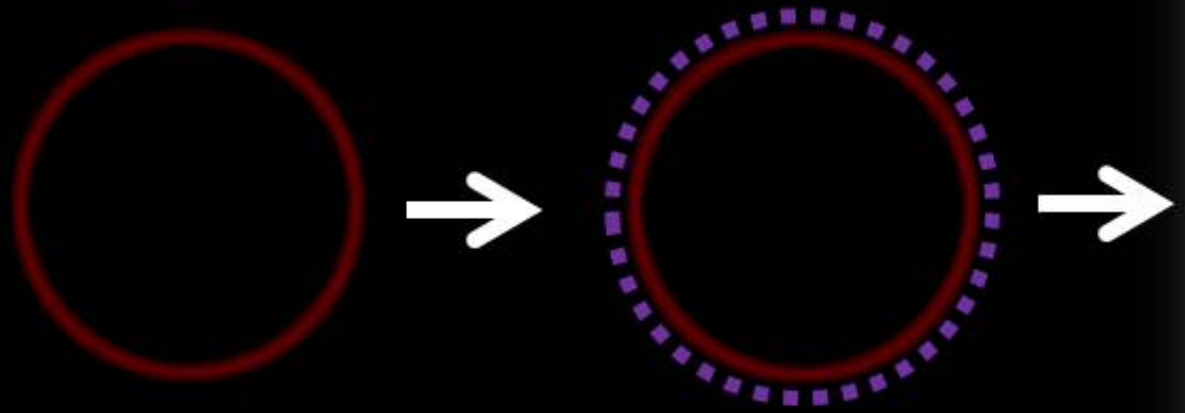
Heat!

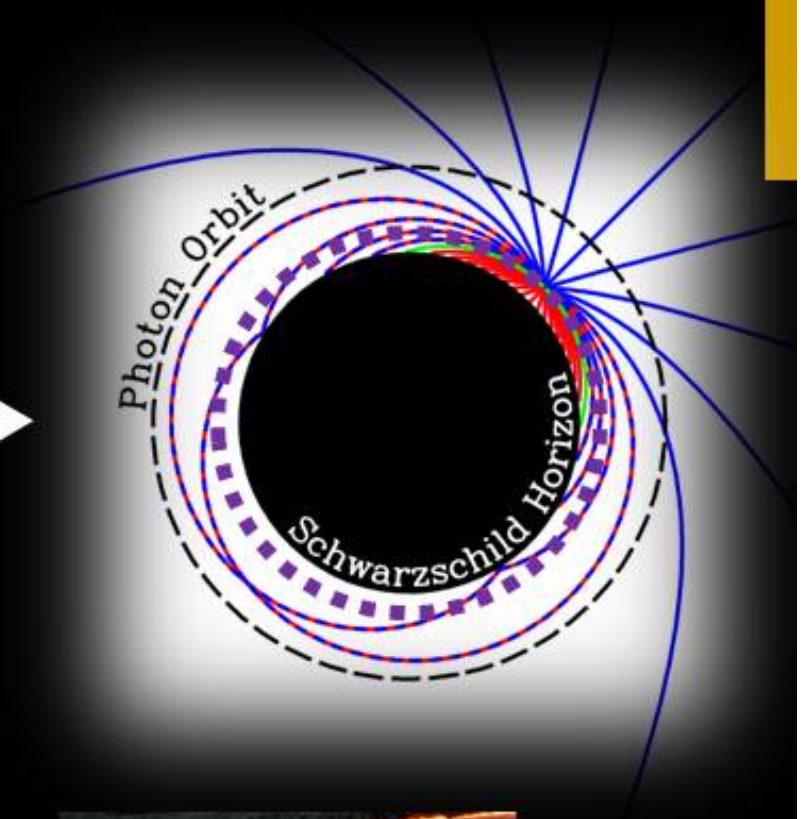
Surface Luminosity →

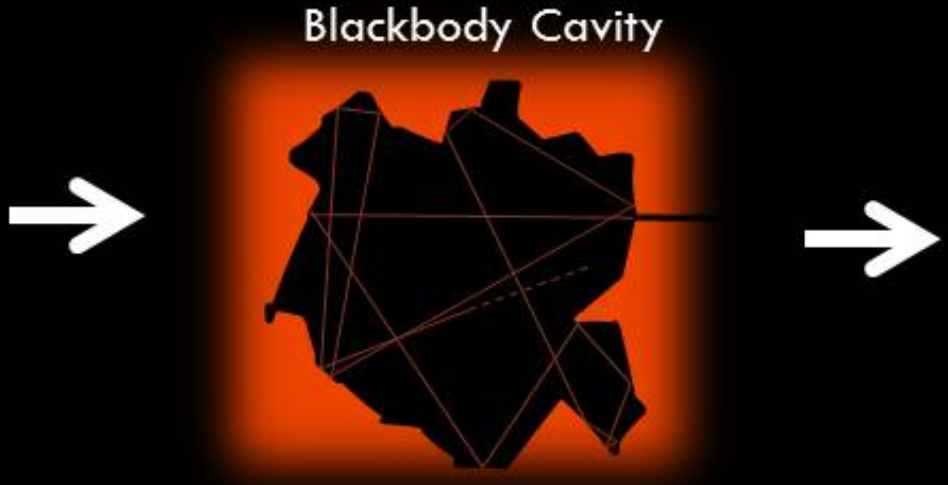
Passes right through

Horizons

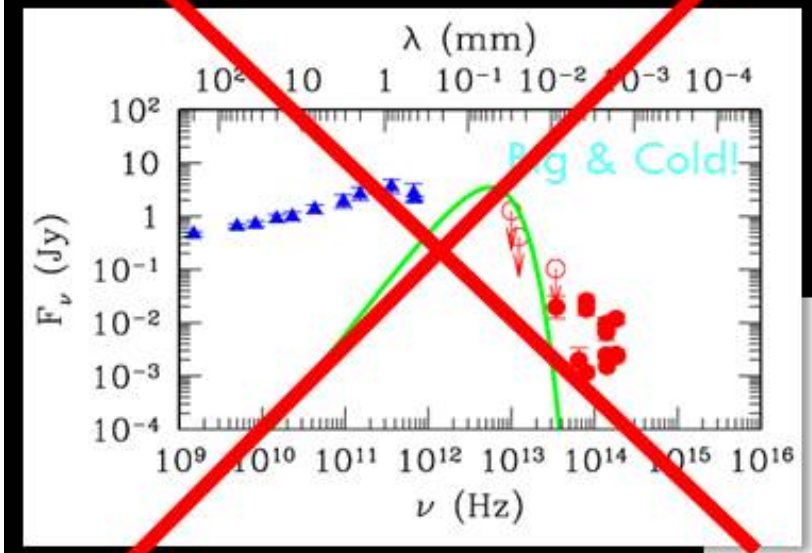
$37 < 53!$



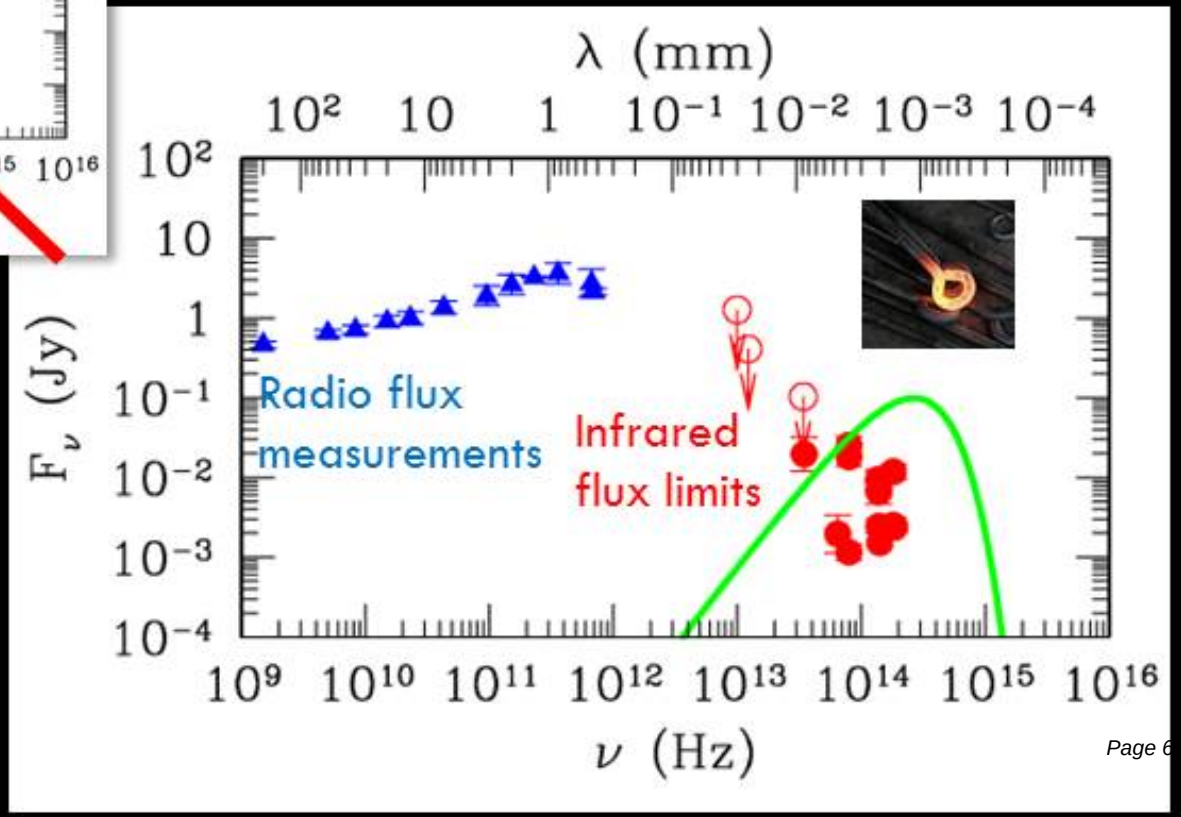




DOES SGR A* HAVE A TEMP? NO!



→ The kinetic energy of infalling material is disappearing, i.e., *there is an event horizon!*



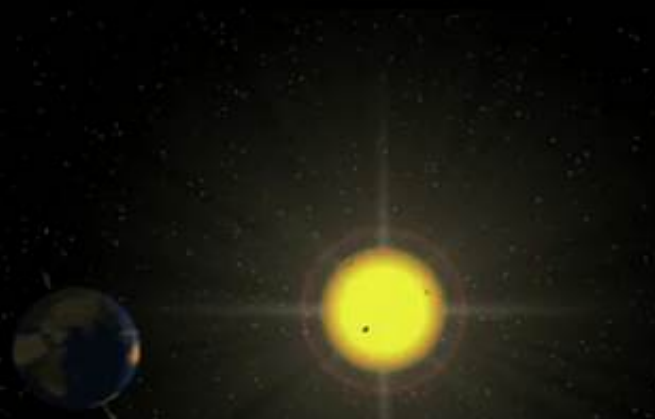
Do event horizons exist?

YES! Probably… Like Sgr A*

How do black holes grow?

THANKFULLY, THE END IS NOT NIGH!

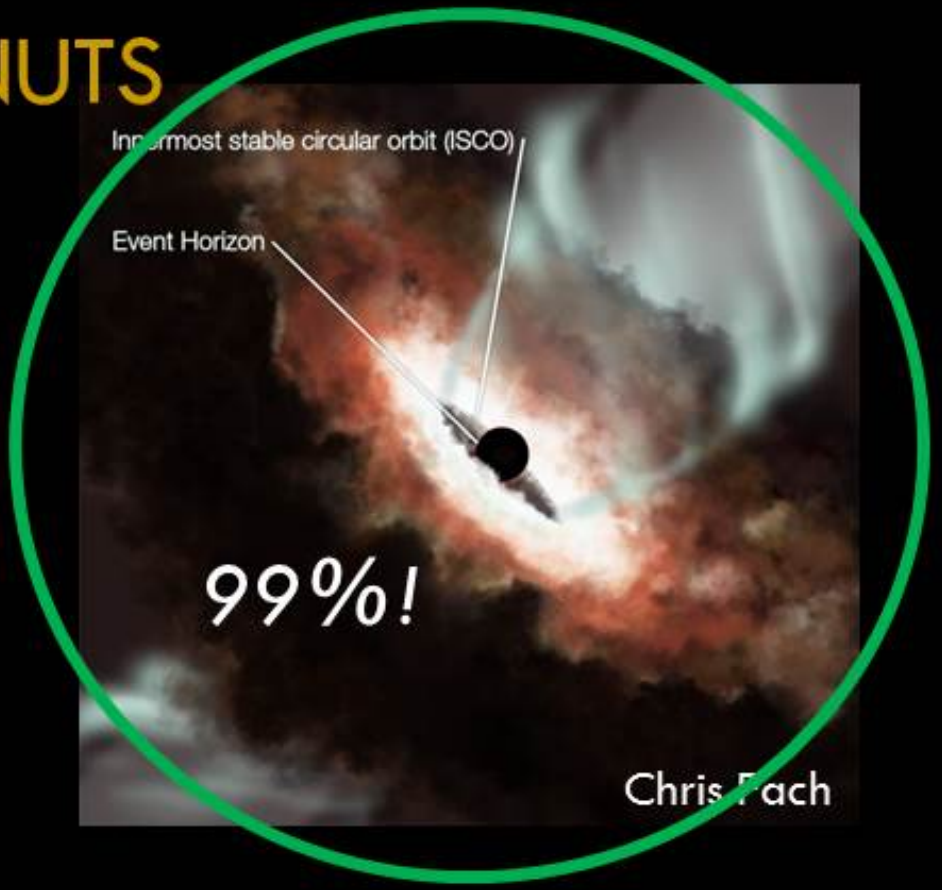
The Earth is not presently falling into the Sun.



Accretion is really the story of angular momentum transport!

Accretion in Sgr A*

PANCAKES & DOUGHNUTS



High Accretion Rate
- Thin, cool disk
- Efficiently cools
- Slow transport of ang. mom.

Low Accretion Rate
- Thick, hot disk
- Cannot efficiently cool
- Rapid transport of ang. mom.

Accretion in Sgr A*

POETRY NOT PROSE

Theoretical Unknowns:

- Details of angular momentum transport (magnetic turbulence)
- Relationship between emitting electrons and the gravitating ions

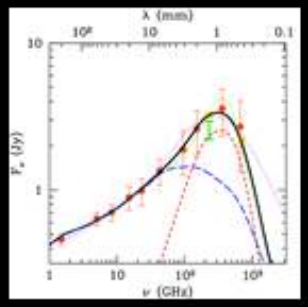
→*Detailed structure of the accretion flow uncertain*

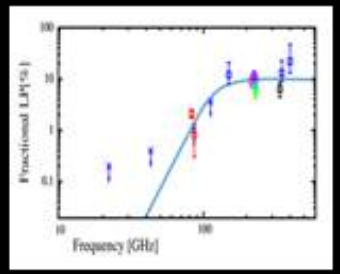
Theoretical Leverage

- Hydrodynamics/Magnetohydrodynamics
- Synchrotron emission theory
- General relativity & photon propagation around black holes

Observational Confines

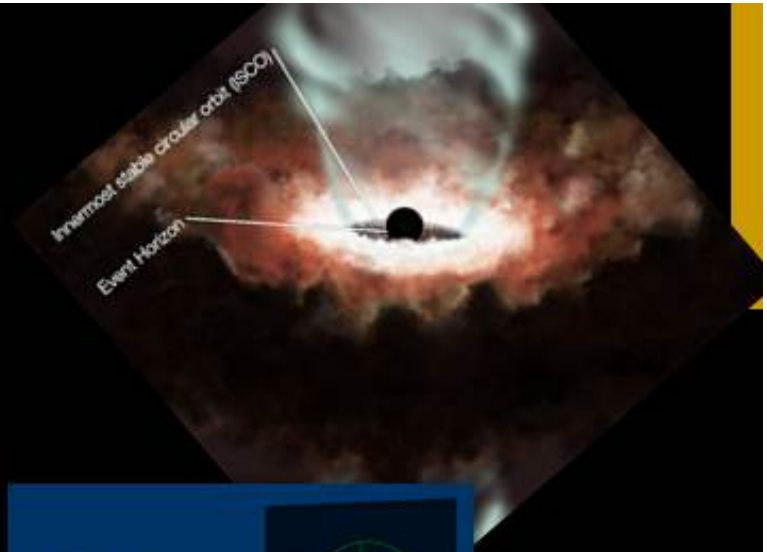
- Radiative efficiency (0.1-0.01%)
- Spectral energy distribution
- Polarization properties
- …

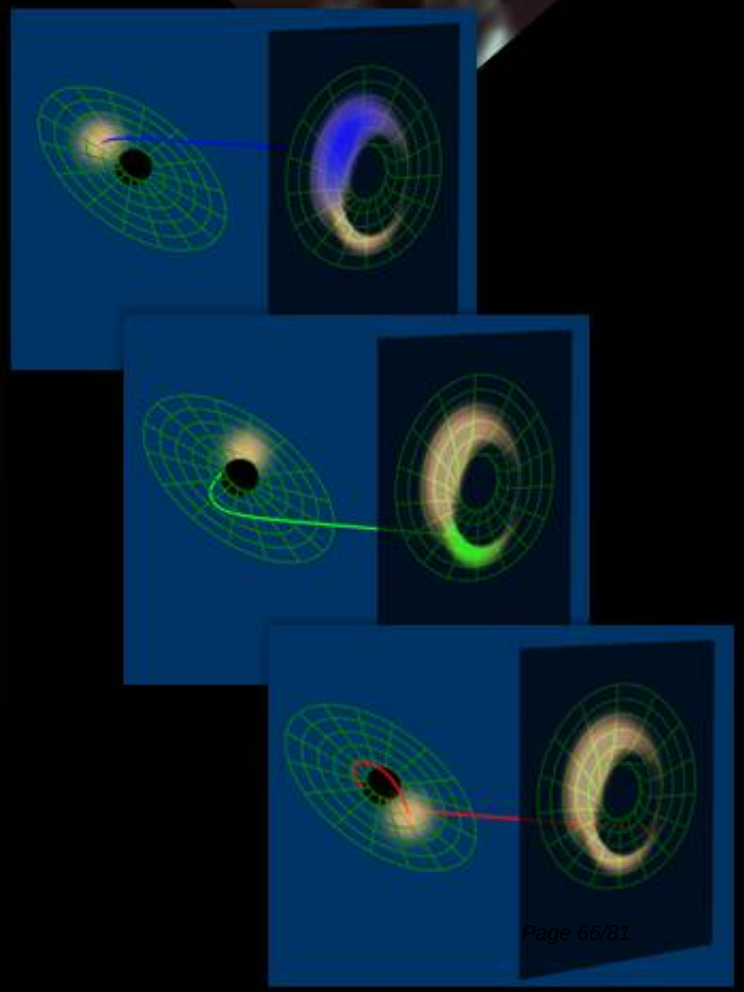




Accretion in Sgr A*

ANATOMY OF AN IMAGE





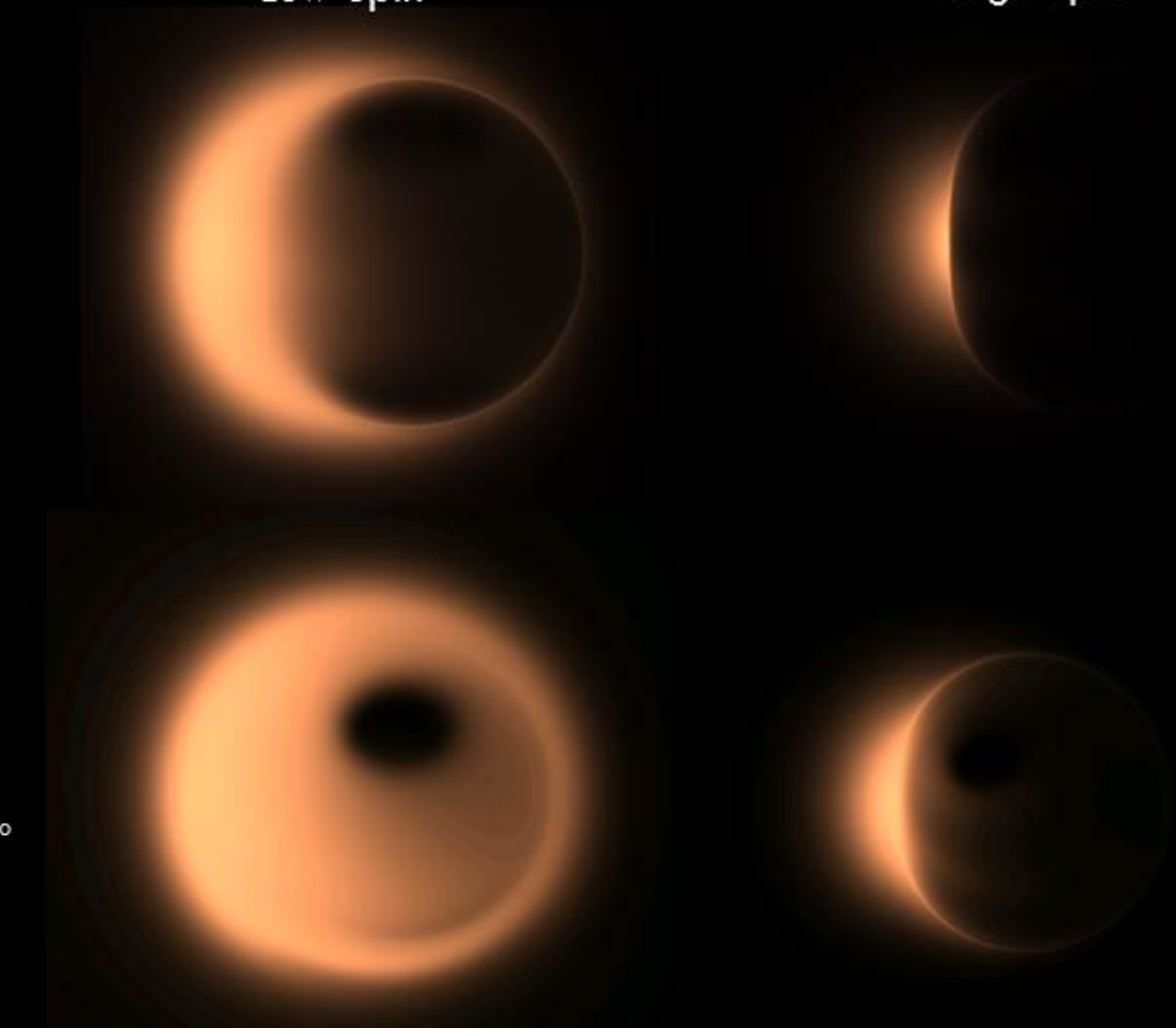
$\sim 53\ \mu as$

Towards

Away

Accretion in Sgr A*

ANATOMY OF AN IMAGE



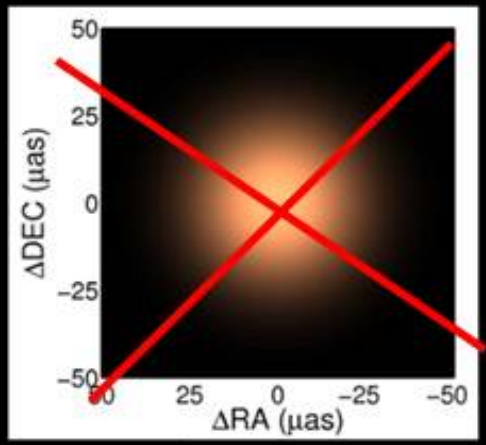
Accretion in Sgr A*

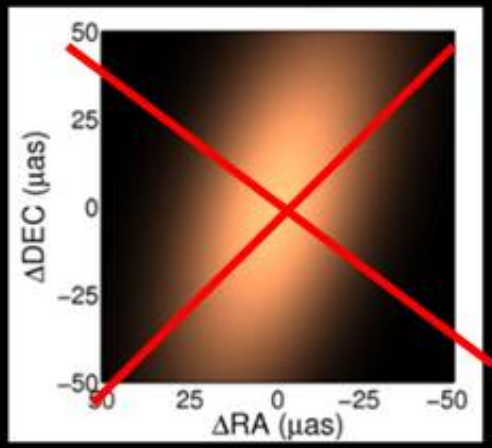
BLACK HOLE FAMILY PHOTOS: SGR A*!

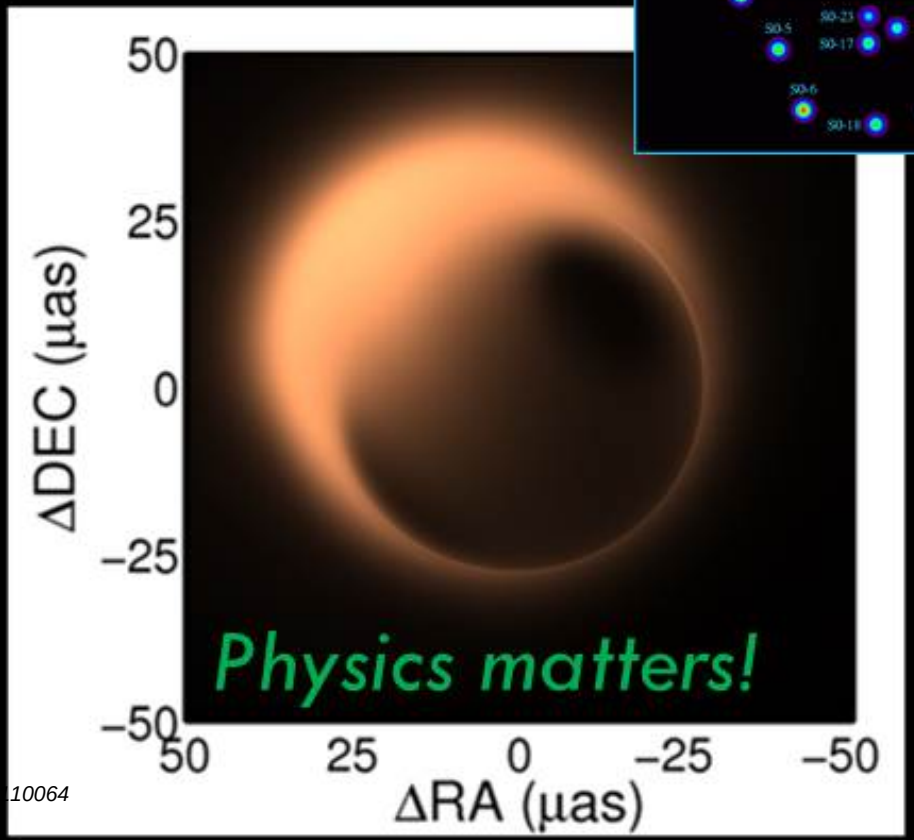
$a \sim 0^{+0.64+0.86}$

$\theta = 68^{+5+8}_{-20-28}$ deg.

$\xi = -52^{+17+33}_{-15-24}$ deg.





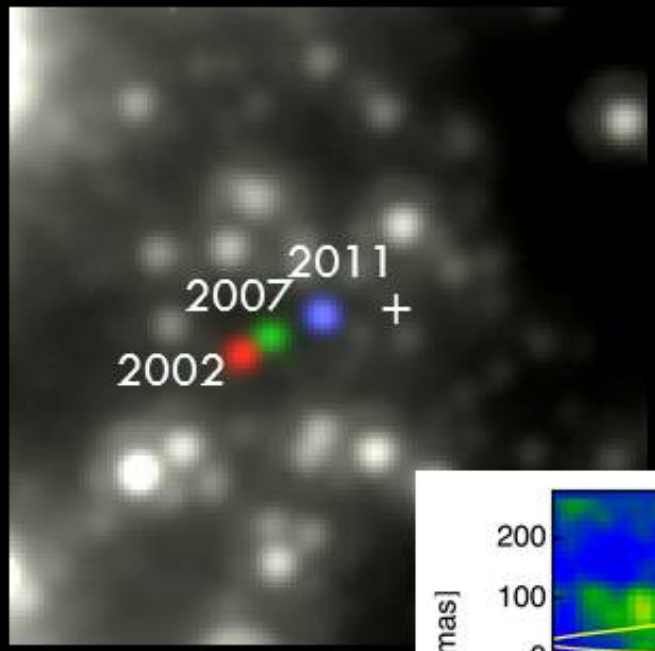


Excluded at ~3σ level

10064

Accretion in Sgr A*

EXCITING TIMES: G2

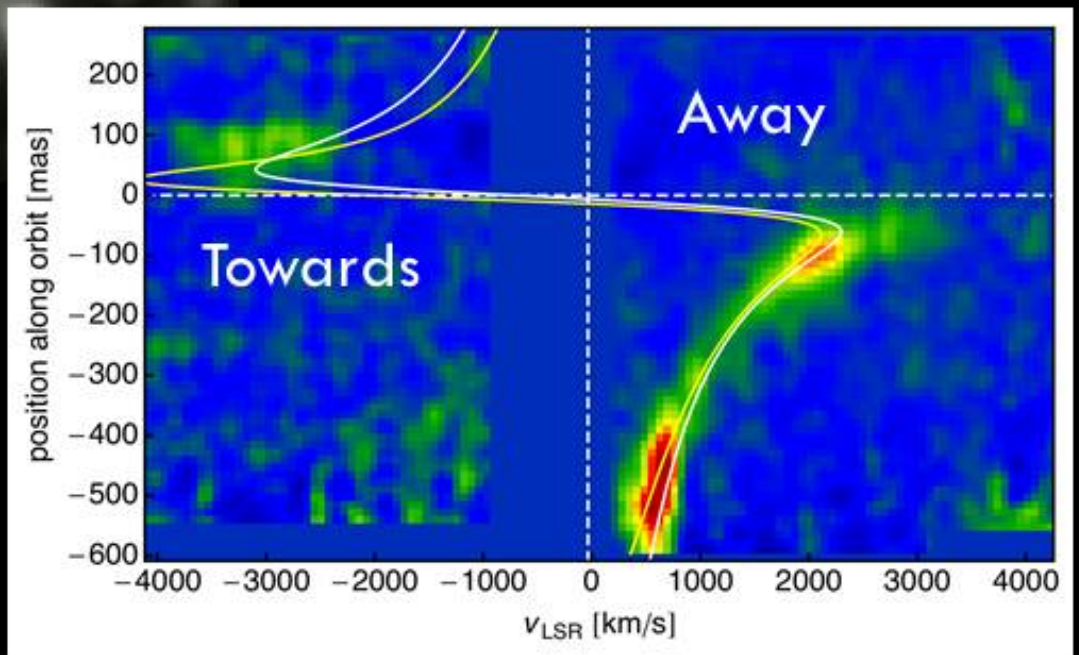


A gas cloud on its way into the super-massive black hole in the Galactic Centre

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

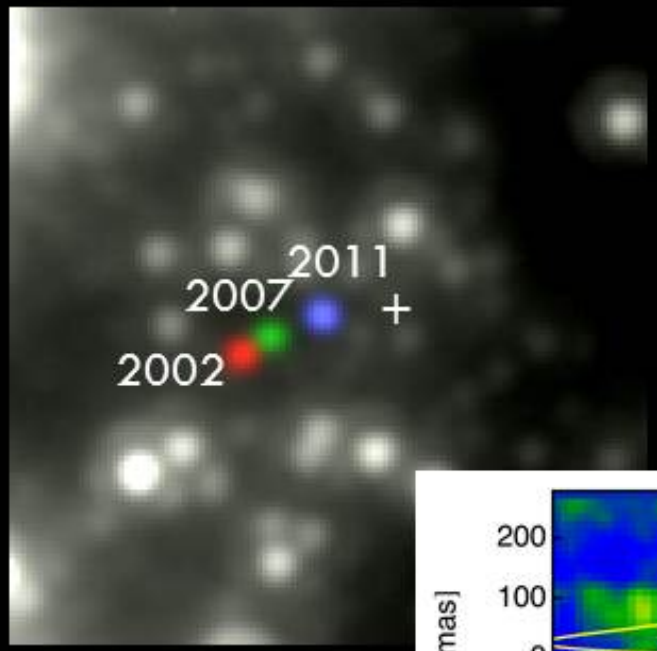
MPE

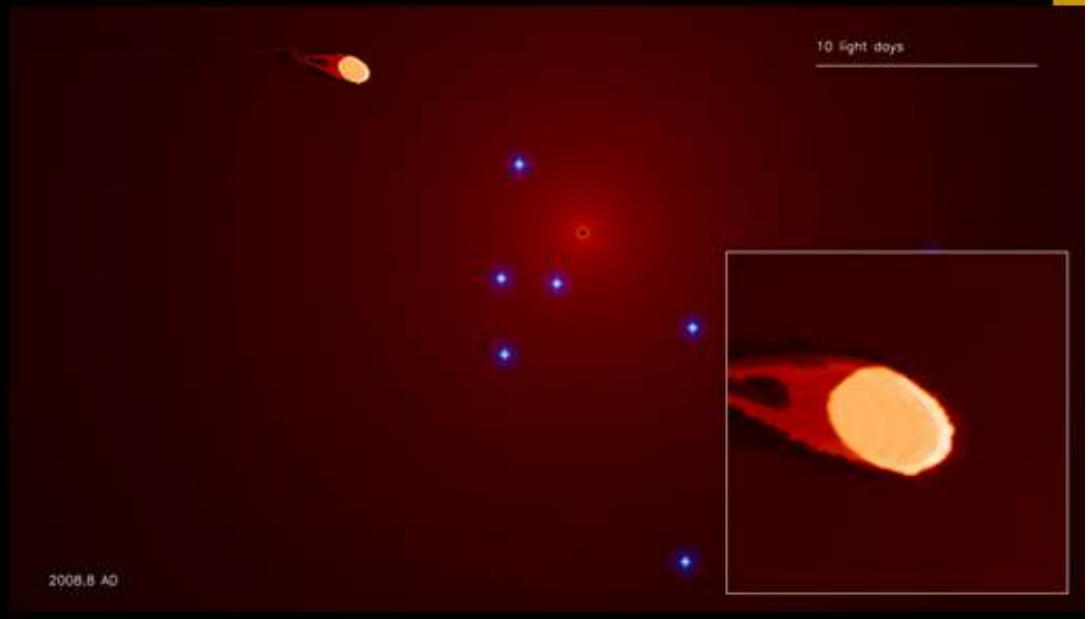
Simulation by: M. Schartmann, A. Burkert, C. Alig, S. Gillessen, R. Genzel using PLUTO 3.1.1 (Mignone et al. 2007)

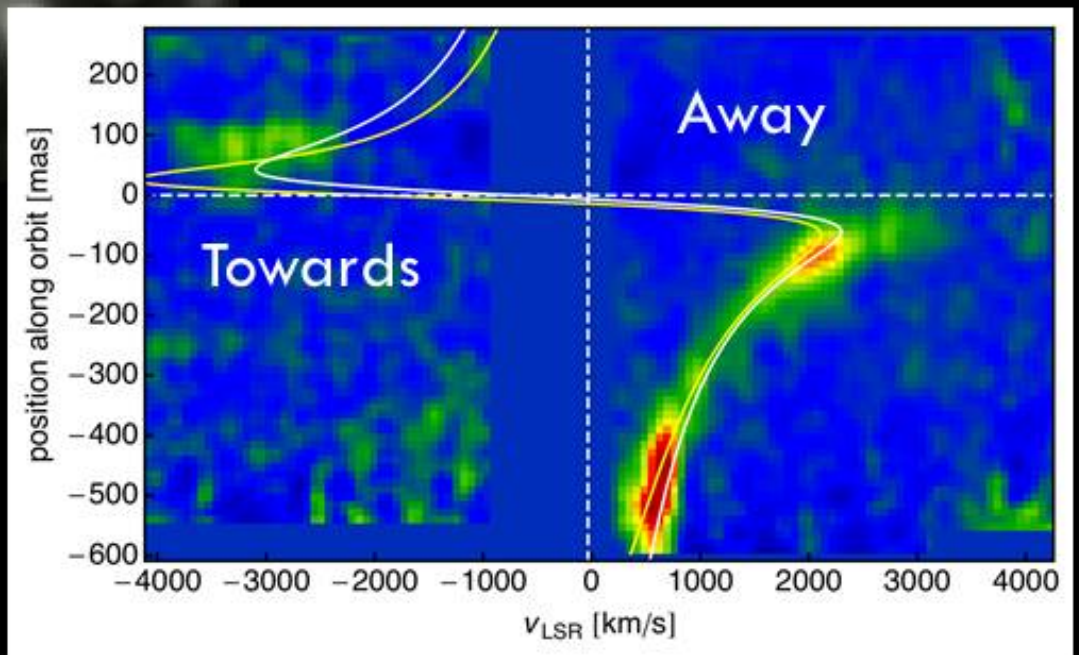


Accretion in Sgr A*

EXCITING TIMES: G2







Accretion in Sgr A*

EXCITING TIMES: G2

$0.5\dot{M}$ $\dot{M}$ $2\dot{M}$

$\Delta t \sim 0.1 - 100$ yr, depending on angular momentum transport.

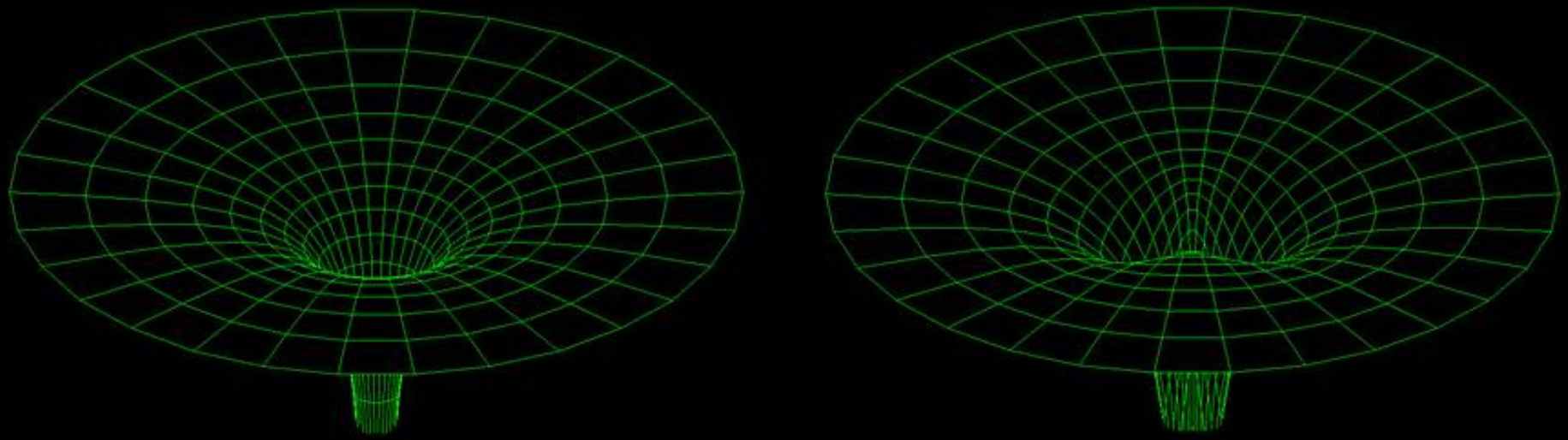
$\Delta\dot{M} \sim 1\% - 100\%$, depending on wind loss

Accretion in Sgr A*

EXCITING TIMES: BEYOND GENERAL RELATIVITY

Schwarzschild Black Hole

Deformed Black Hole



M

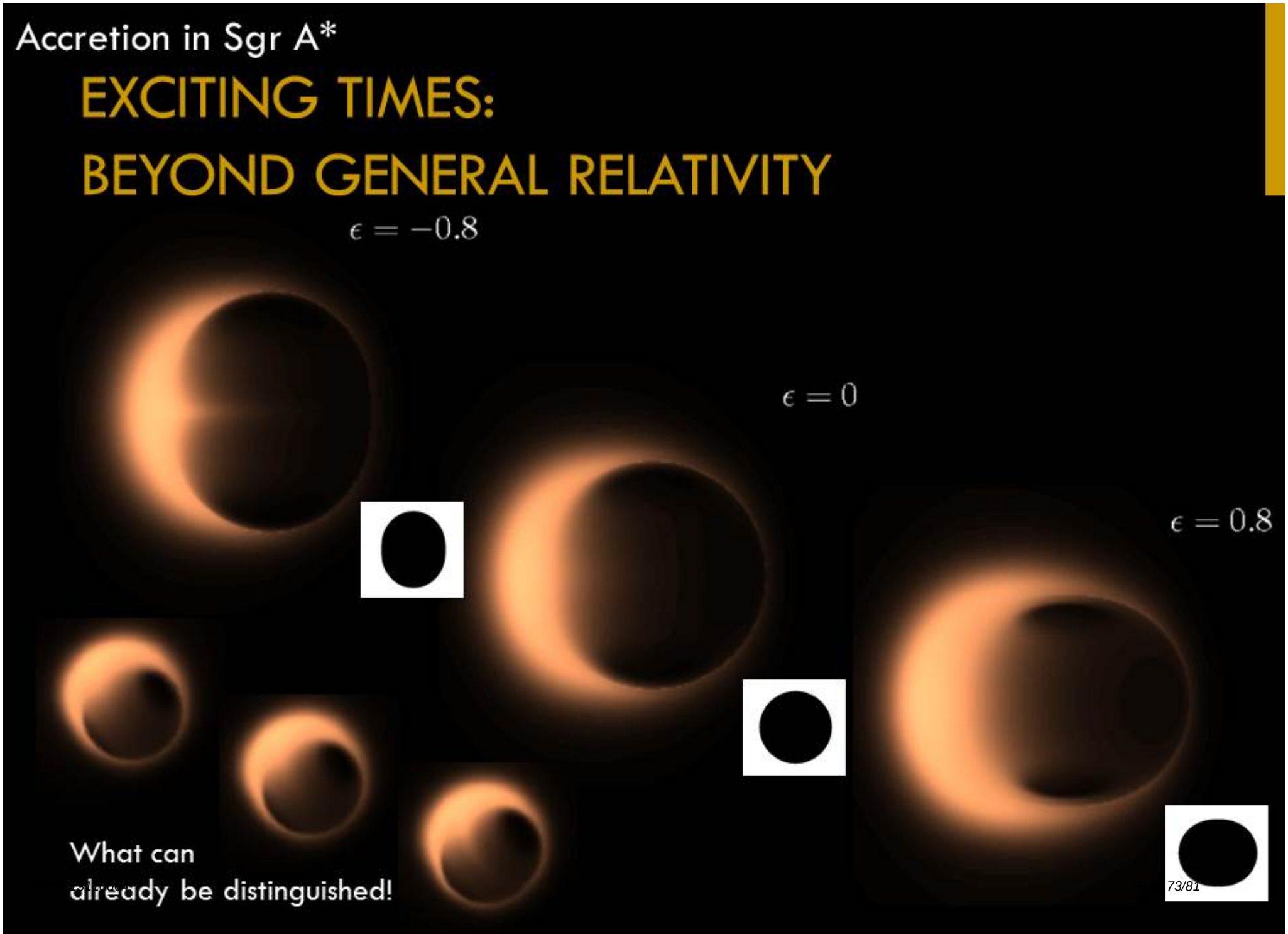
$Q(M,J) \times (1+\epsilon)$

Mass Moments

Mass Current Moments

Accretion in Sgr A*

EXCITING TIMES: BEYOND GENERAL RELATIVITY



Do event horizons exist?

YES! Probably... Like Sgr A*

How do black holes grow?

For 99% in hot, dim, thick disks

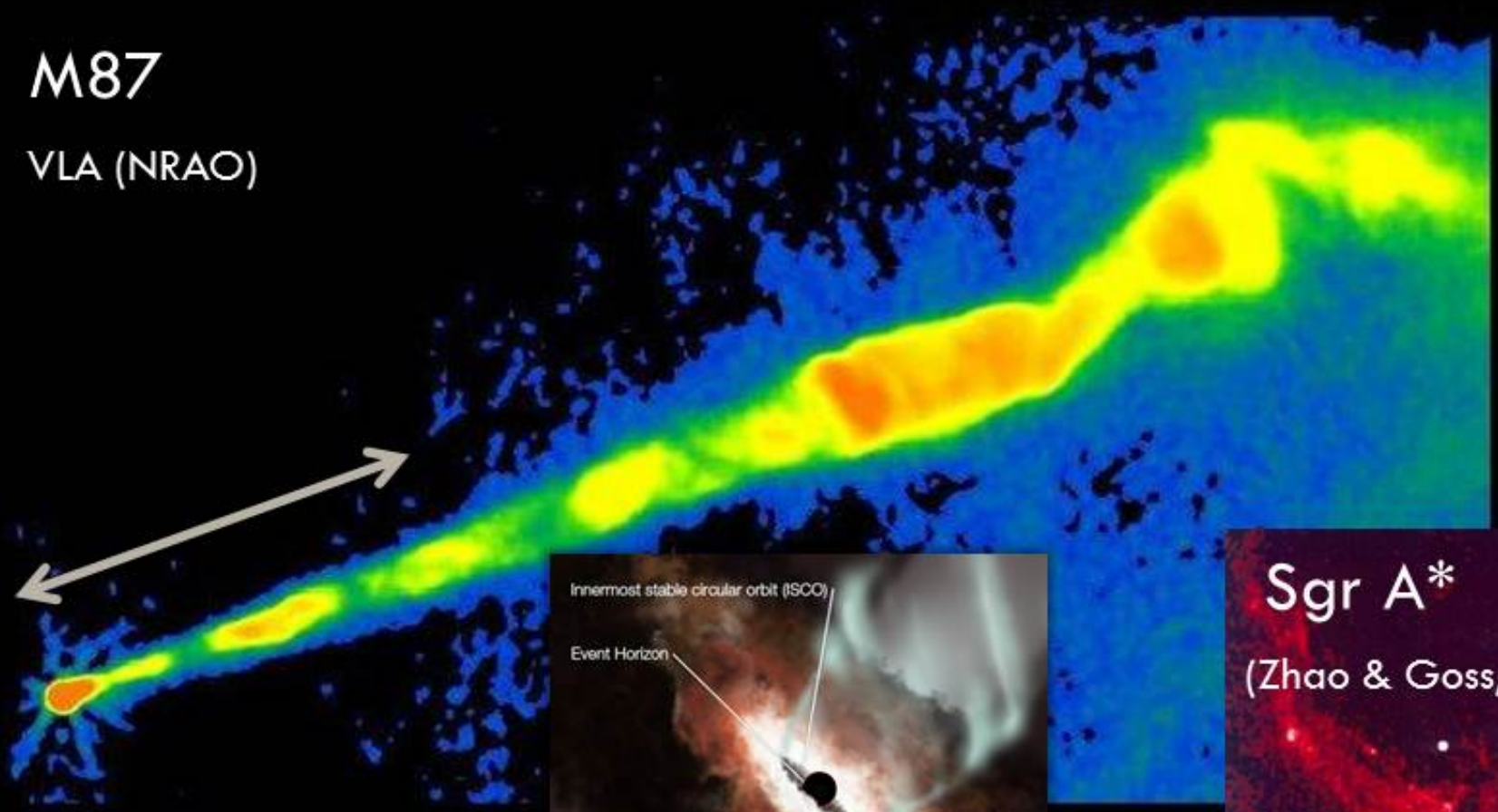
What drives jets?

Jets in M87

ZACK & CODY

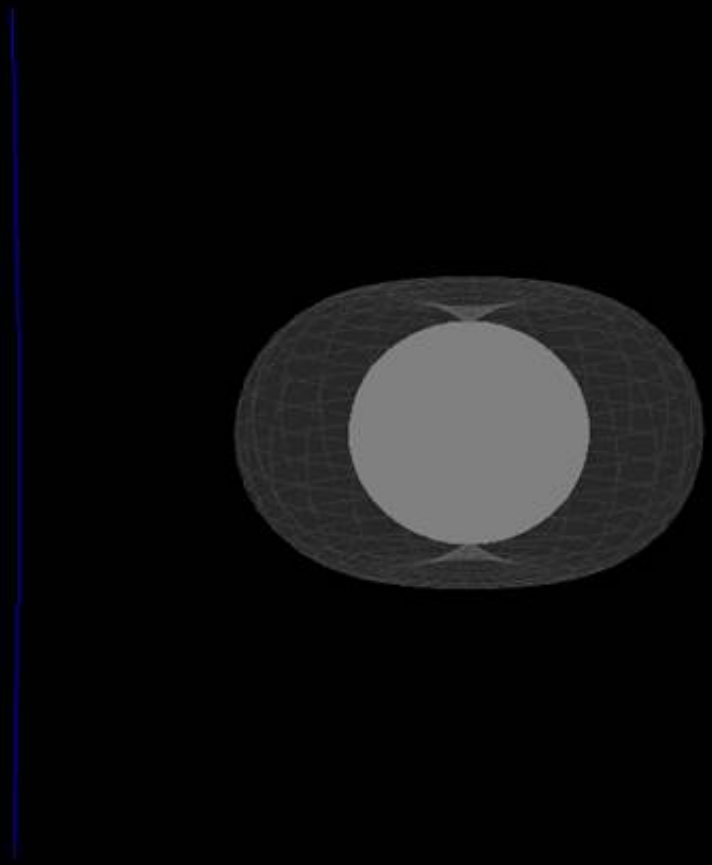
M87

VLA (NRAO)



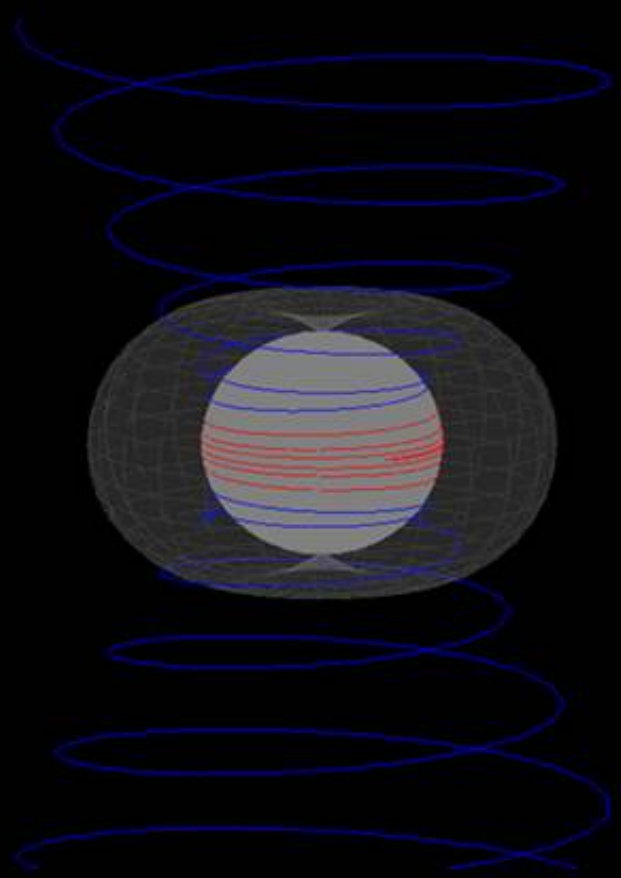
Jets in M87

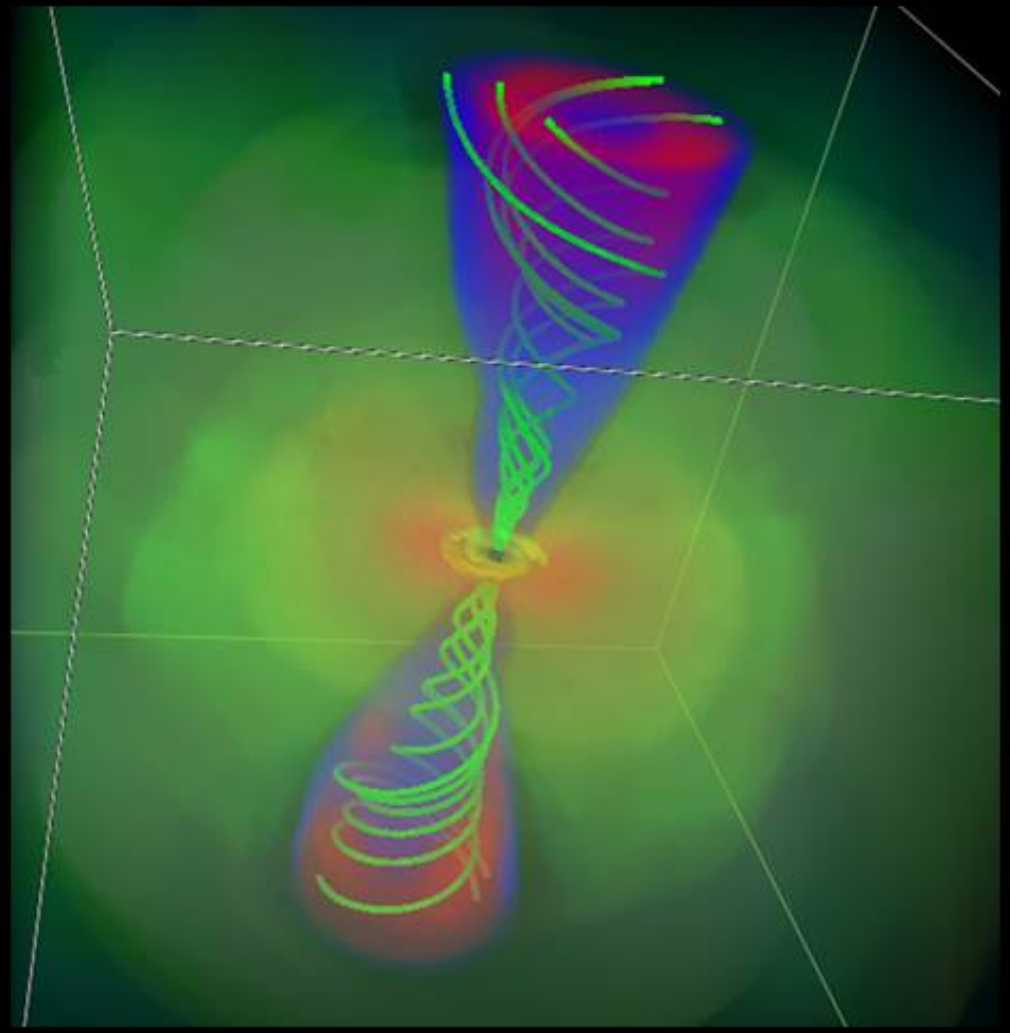
DO THE BLACK HOLE TWIST!



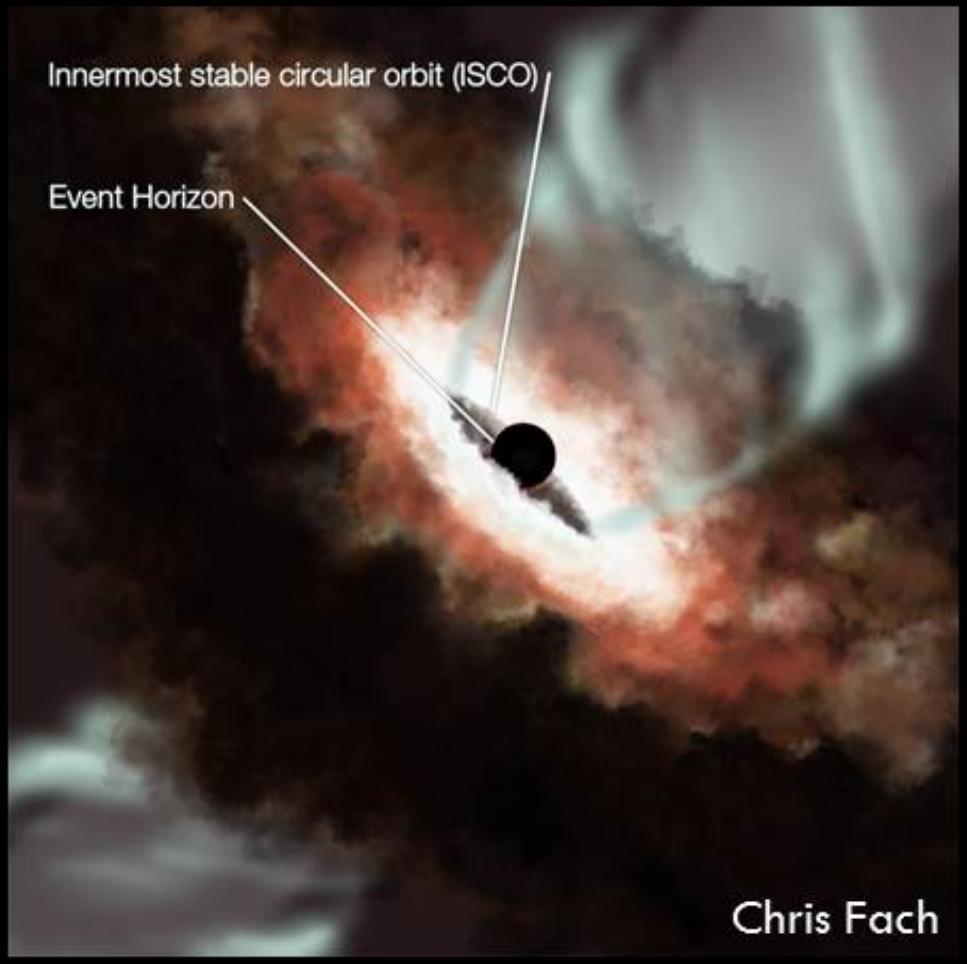
Jets in M87

DO THE BLACK HOLE TWIST!



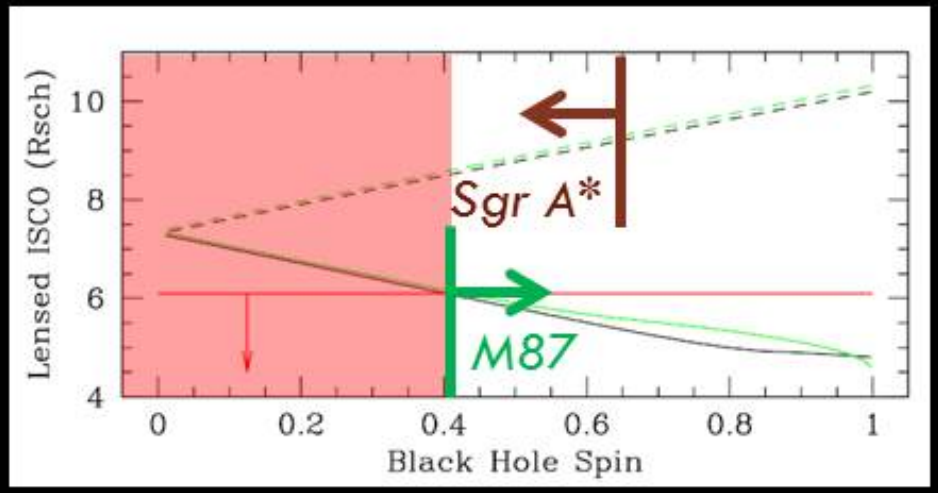


LIMITING THE LAUNCH FOOTPRINT IN M87



$$40.0 \pm 0.6\ \mu\text{as}$$

$$\rightarrow R_{jet}^{app} < 5.5 R_S^{app}$$

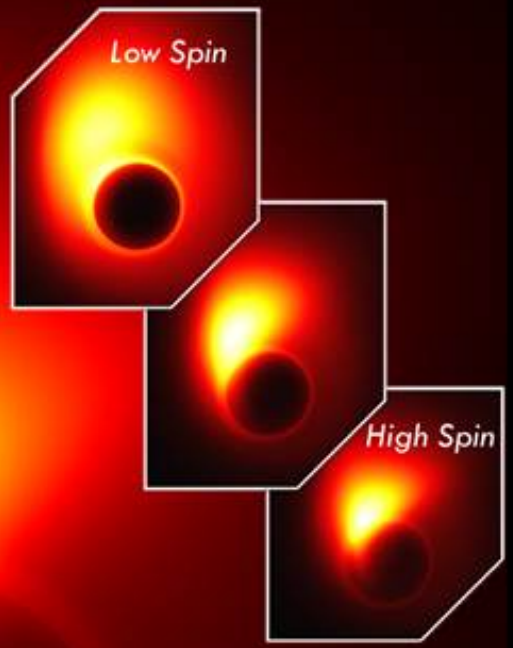


Not rotating

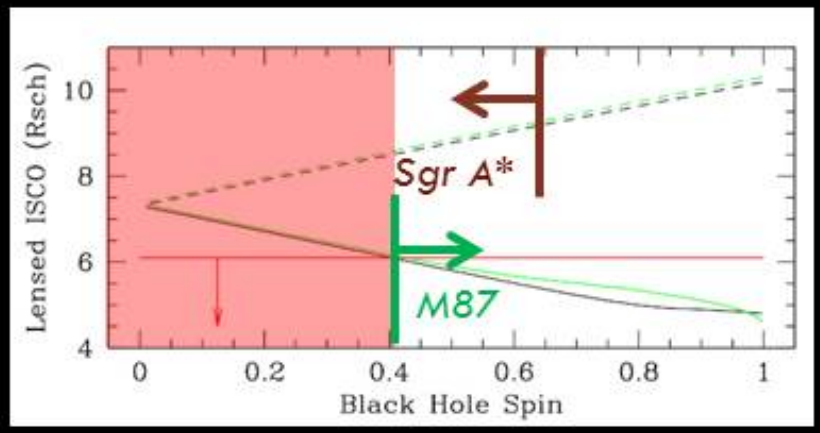
Rotating at speed of light on horizon

Jets in M87

DETAILED PHYSICAL MODELLING



$a > 0.95$!



- *Very high spin!*
- *Jets are launched from very near black hole*
- *Jets get filled with energetic electrons (& positrons?) very near black hole!*

arXiv:1311.0064

Do event horizons exist?

YES! Probably... Like Sgr A*

How do black holes grow?

For 99% in hot, dim, thick disks

What drives jets?

Black hole spin!

WHAT A BLACK HOLES IS!

- *The era of direct access to black holes is upon us!*
- *The* **EventHorizonTelescope** *is observing!*
- *Already we have fundamental insights:*
  - *Horizons exist!*
  - *GR is probably not 2000% wrong on horizon scales*
  - *99% of black holes really do prefer doughnuts to pancakes*
  - *Black hole spin may be a critical component for powerful jets*
- *On the horizon:*
  - *G2 and accretion in progress*
  - *Searching for black hole hair*
  - *…*