La prima immagine di un buco nero: i risultati di M87

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Bologna, 30 May 2019

EUROPEAN ARC
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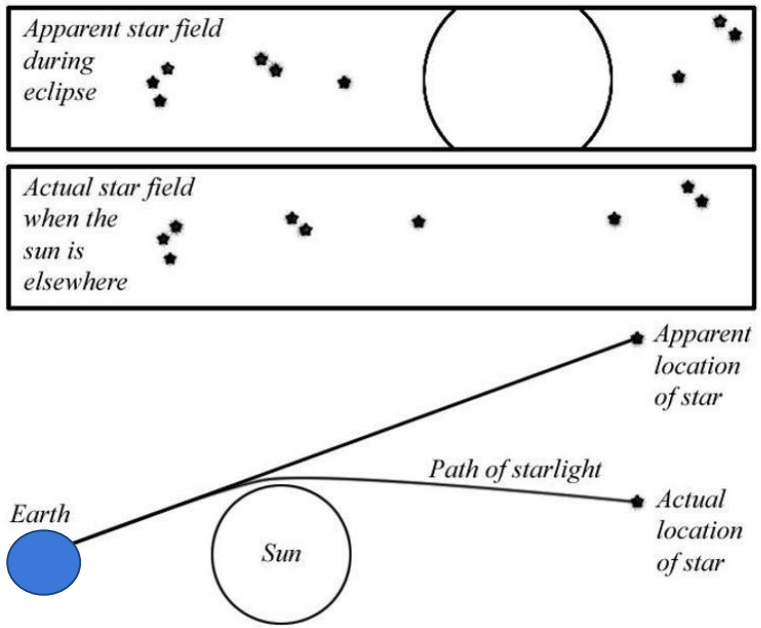
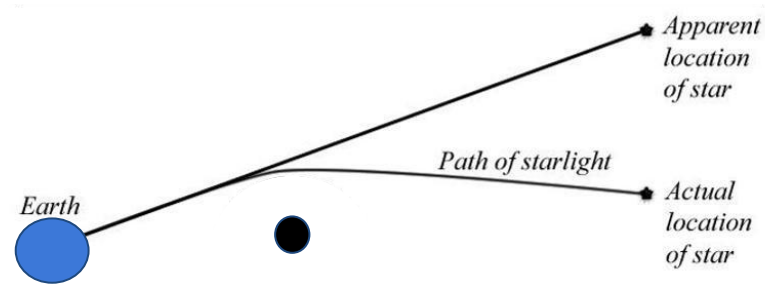
Curvature of space-time



$$\Delta\theta = \frac{4GM}{bc^2}$$



Black hole

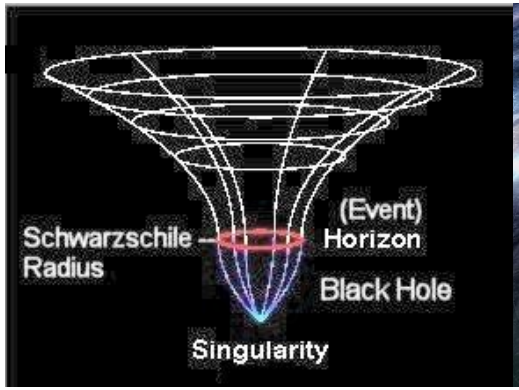
Predicted light bending for grazing incidence at solar radius (70,000km): 1.75 arcsec

Predicted light bending for grazing radius at 3*Schwarzschild radii for a 1Msun BH (9km): 37.7 degree

General Relativity and Black Holes

- **Black holes** (BHs) are one of the most fundamental and extreme predictions of GR characterised by mass, spin ($a_* = Jc/GM^2$) and charge.

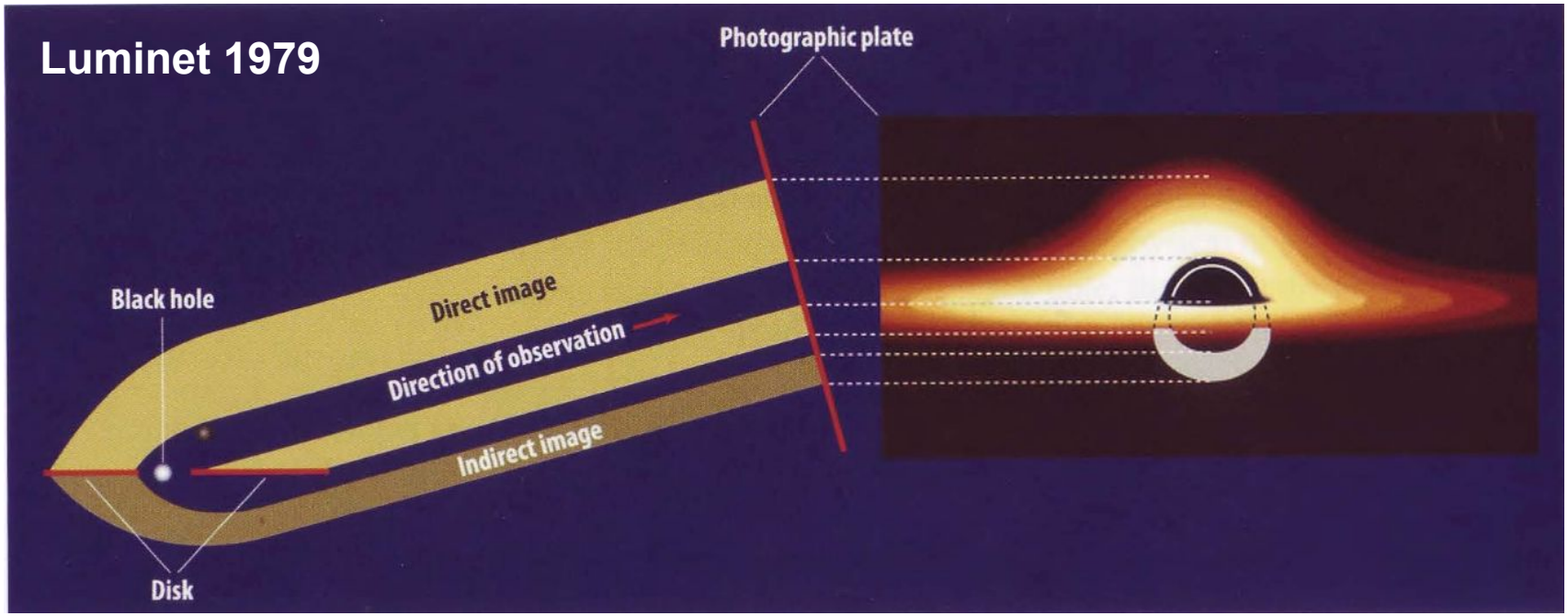
- The **event horizon** is the defining feature of a BH – and yet, we have never seen the event horizon



$$R_{Sch} = \frac{2GM}{c^2}$$

How to directly observe a BH?

Emission ring: gravitational lensing and Doppler beaming



Bardeen 1973,
Luminet 1979
Falcke, Melia & Agol 2000
Broderick & Loeb 2006
Younsi, Bronzwaer, Davelaar 2018

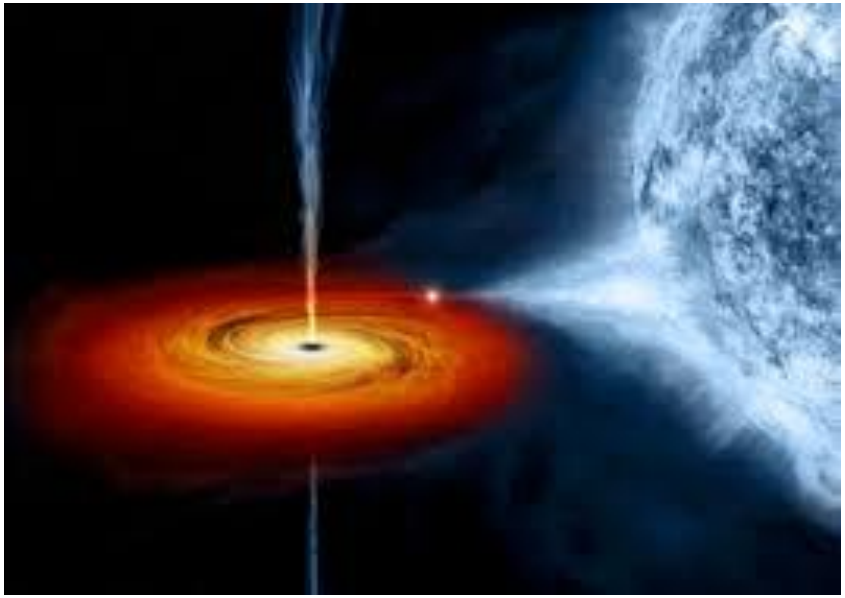
Lensed photon ring radius:

$$R_{ring} = \sqrt{27}\frac{GM}{c^2}$$

Shadow size and shape encodes GR (Psaltis & Johansen 2010).

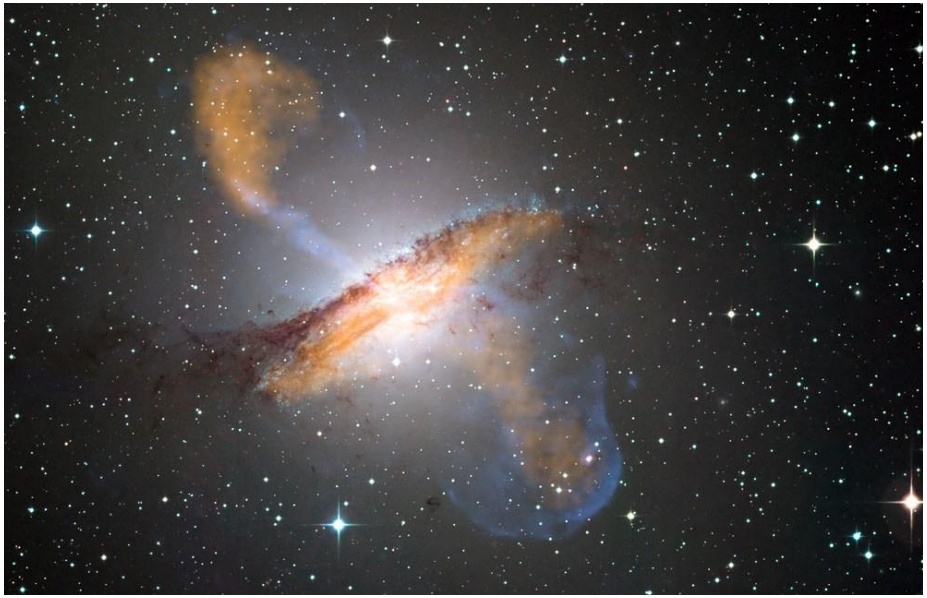
Black holes types

Stellar mass BH (first BH observed indirectly in XRB, Cyg X-1)
masses ~up to tens of Msun



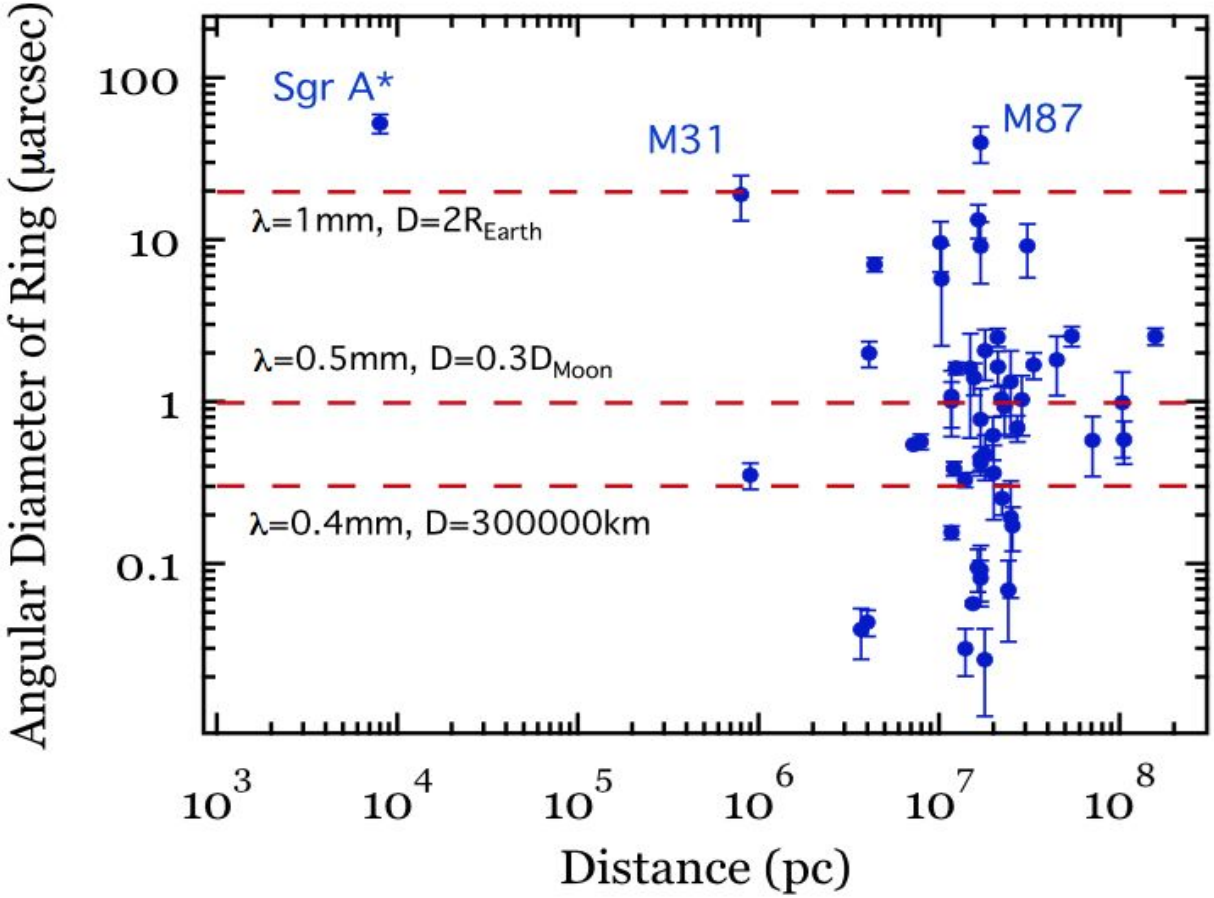
Artist impression of Cygnus X1 feeding off a blue supergiant (NASA/CXC/M.Weiss)

Supermassive BH in the center of Active Galactic Nuclei
masses > 10^6 Msun



Composite image: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray

Observable BH shadows



Johanssen+, arXiv:1201.0758

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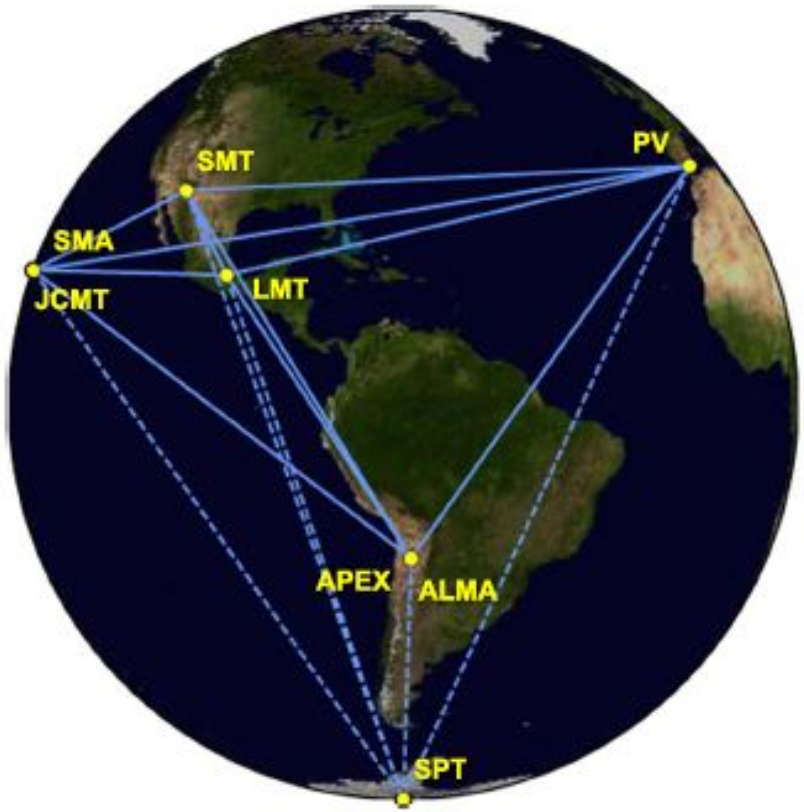
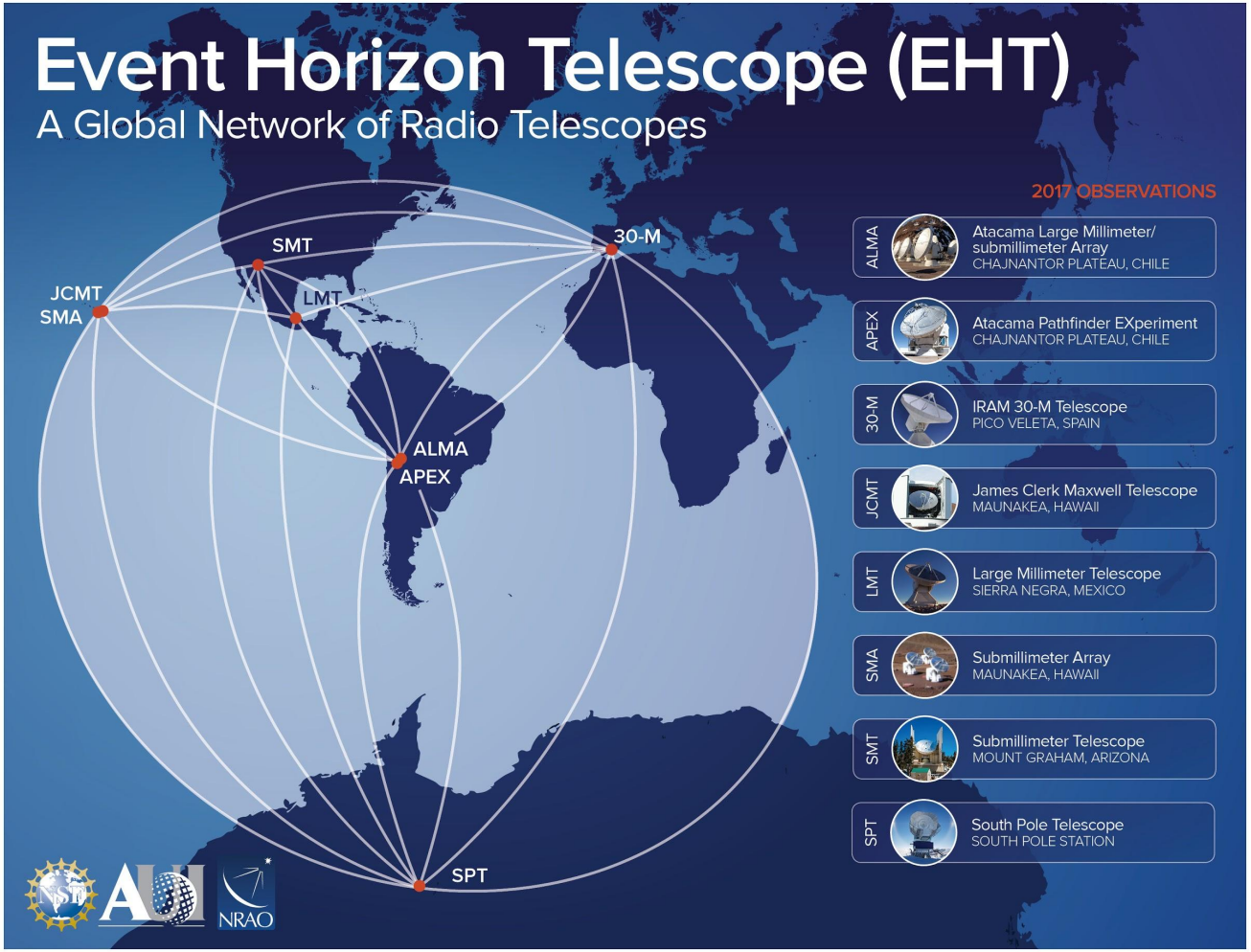
Very Long Baseline Interferometry!



- VLBI angular resolution depending on max the distance between an antenna pair, and observing wavelength
- Each antenna observes at the **same time** the target
- Signal synchronized through atomic clock with precision of 1 s in 100 million years
- **Plasma around BH emits at 1.3 mm!**

$$\theta \simeq \frac{\lambda}{B} = \frac{1.3\,\mathrm{mm}}{10,700\,\mathrm{km}} = 25\mu\mathrm{asec}$$

Event Horizon Telescope



> 200 members

13 stakeholder institutes

> 50 affiliated institutes

In Italy:
INAF-IRA, Bologna
INFN & Uni Napoli

BlackHoleCam Project - ERC Synergy Grant 2014

Pis: H. Falcke (Radboud), M. Kramer (MPIfR), L. Rezzolla (Frankfurt)

Project Scientist:

- Ciriaco Goddi (Radboud/Leiden)
- **Project Manager:**
- Remo Tilanus (Radboud/Leiden)

EU Players & Partners

- Amsterdam: Multi-wavelength observ.
- Bonn VLBI: Data correlation, APEX tel.
- ESO: ALMA telescope
- IRAM: Pico Veleta & NOEMA telescopes
- JIVE: VLBI analysis software
- Rhodes Univ.: VLBI Simulations
- Sweden: Polarisation calibration
- INAF-IRA, IT-ARC: Data calibration

Rhodes Univ. South Africa & U. Namibia

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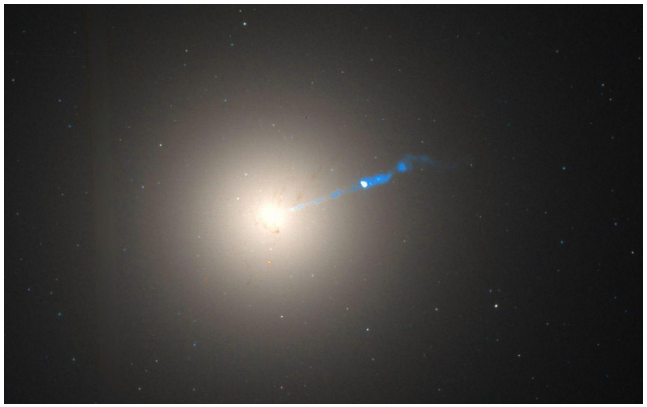
EHT primary targets:

M87 :

LLAGN
55 milions light years
~7 billions Msun

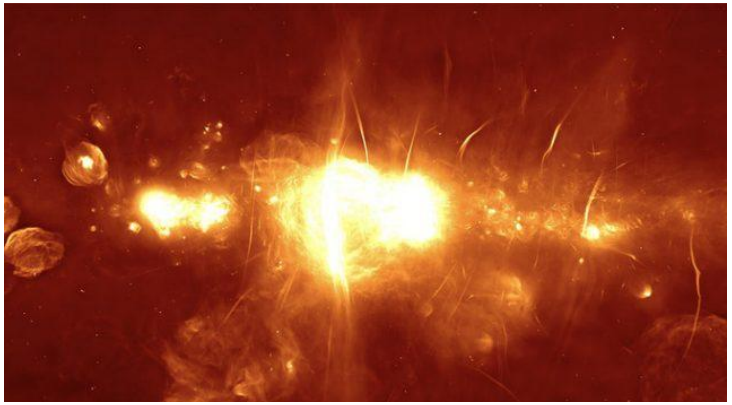


M87 : D~17 Mpc, M_{BH} ~6.5×10^9 $M_\odot$

=> $\boldsymbol{\theta_{ring,\ diameter}}$ ~ 40 micro-arcseconds

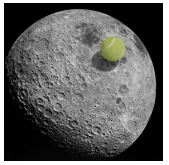
Sgr A* :

LLAGN
25000 light years
~4 milions Msun



D~8 kpc, M_{BH} ~4.3×10^6 $M_\odot$

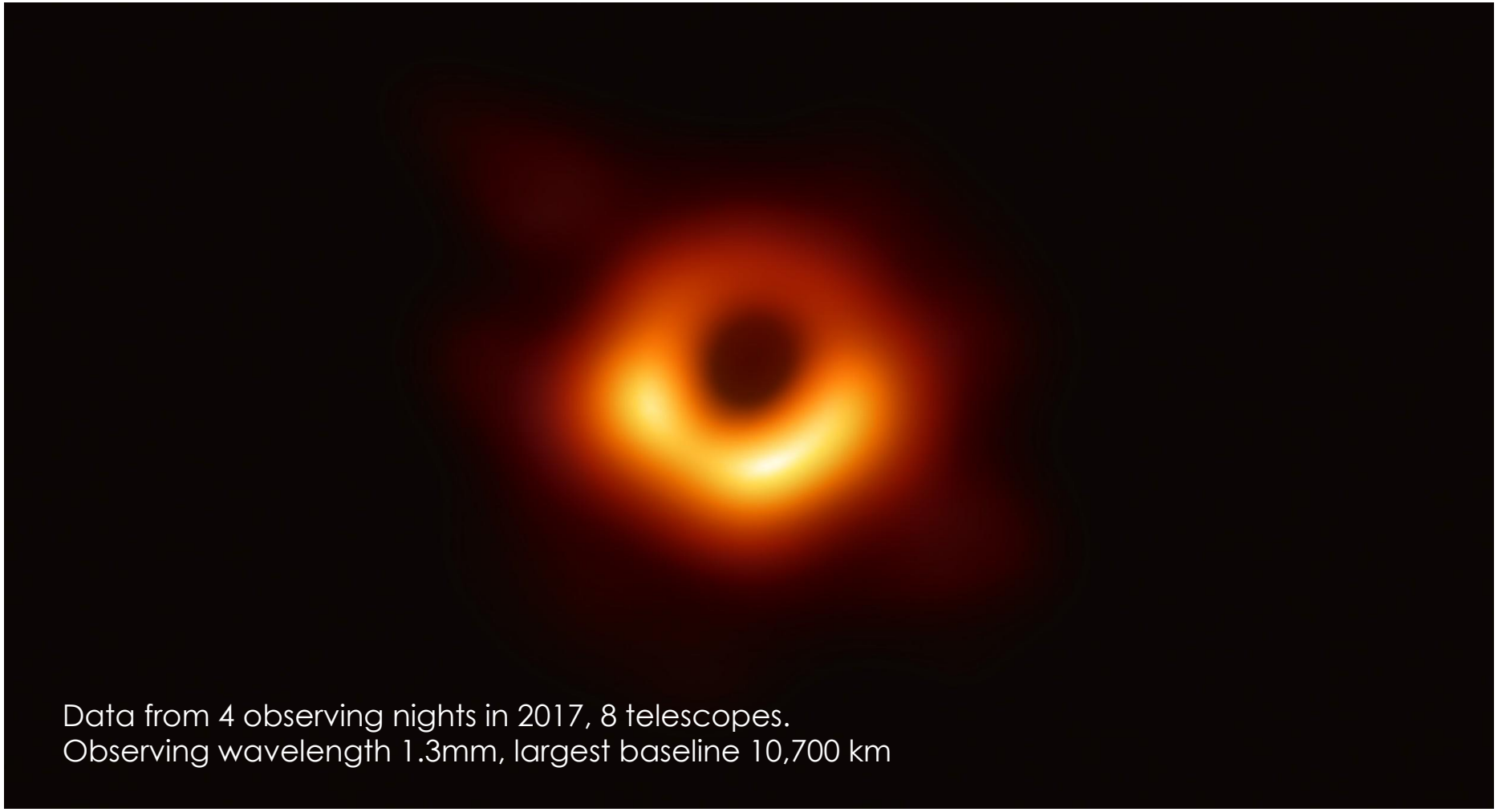
=> $\boldsymbol{\theta_{ring,diameter}}$ ~ 50 micro-arcseconds



M87 is ~2000 times more distant but almost 2000 more massive!

=> Gravitationally-lensed size ~40-50 micro-arcseconds

M87: first image of a black hole shadow



EHT Coll. 2019

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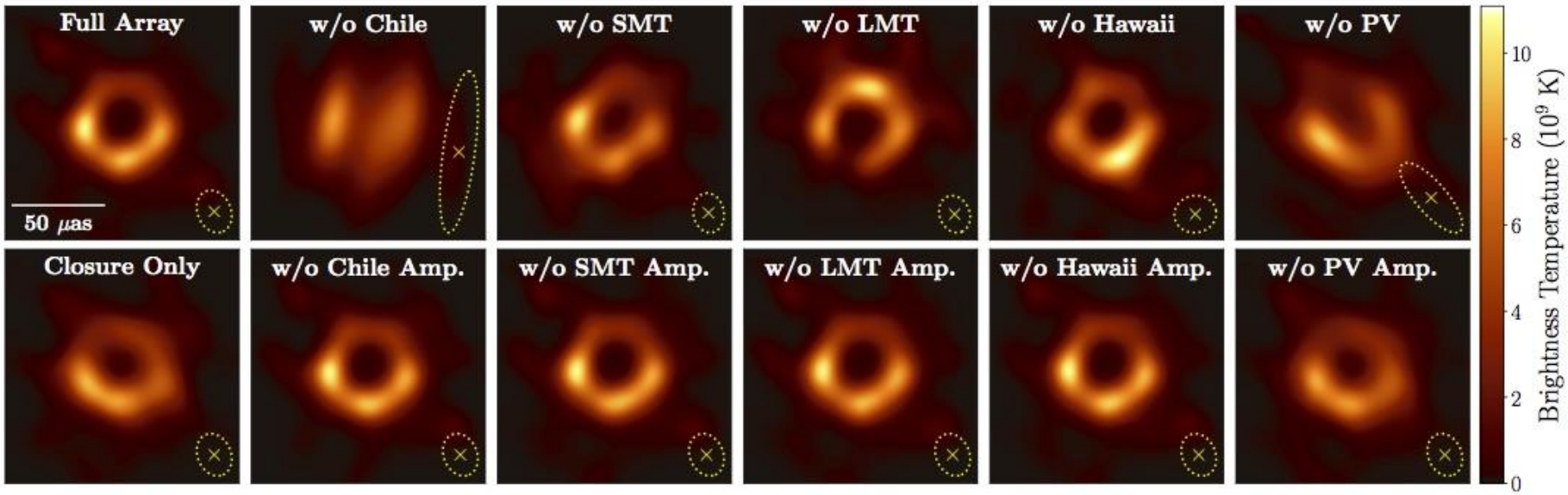
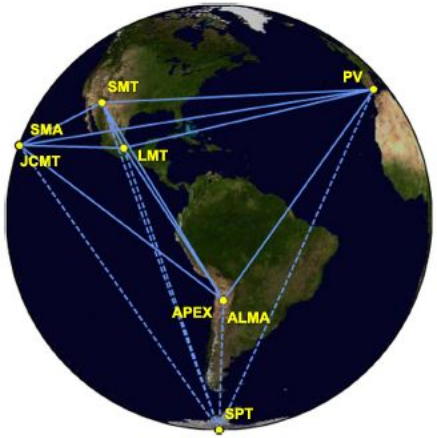
The ALMA/APEX component is crucial

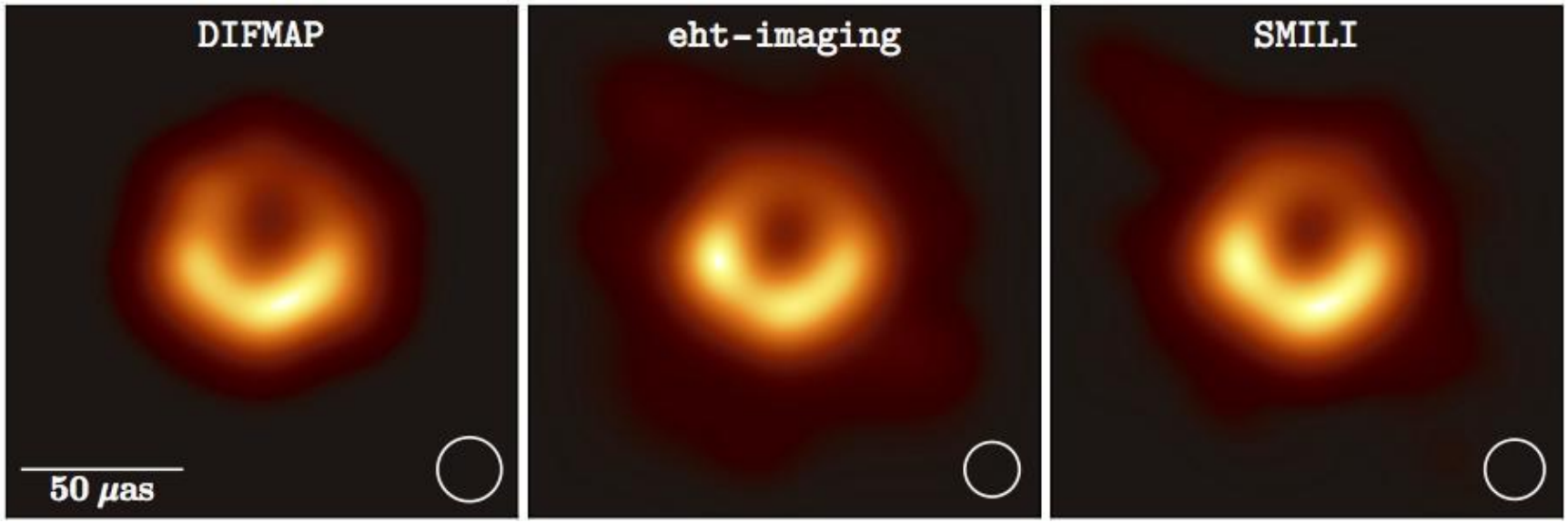




Credit: EHT collaboration, Paper IV, 2019

Fidelity of calibration and imaging

3 different calibration softwares
3 different imaging softwares
Result: consistent structure for M87* black hole shadow



Credit: EHT collaboration, Paper IV, 2019

M87 measured quantities

Important derived quantities:

- Ring diameter: 42 ± 3 μas

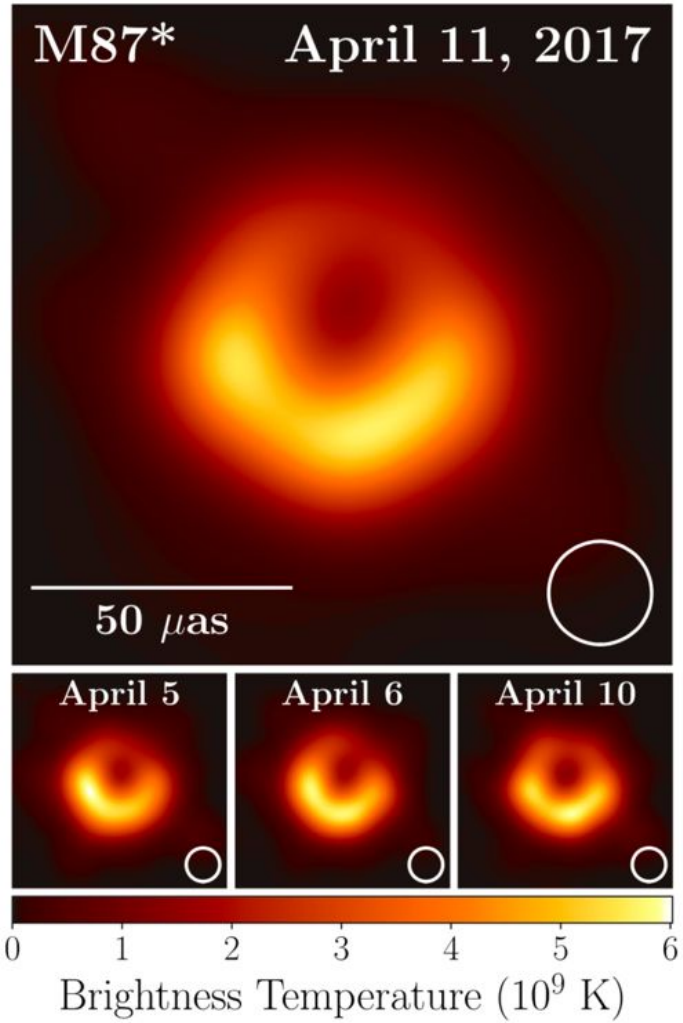
  → **confirms GR**

- Axial ratio: < 4:3

  → indication of **rotating (Kerr) BH**

- PA brightest peak: 150-200 degree (EoN)

  → **doppler boosting** effect

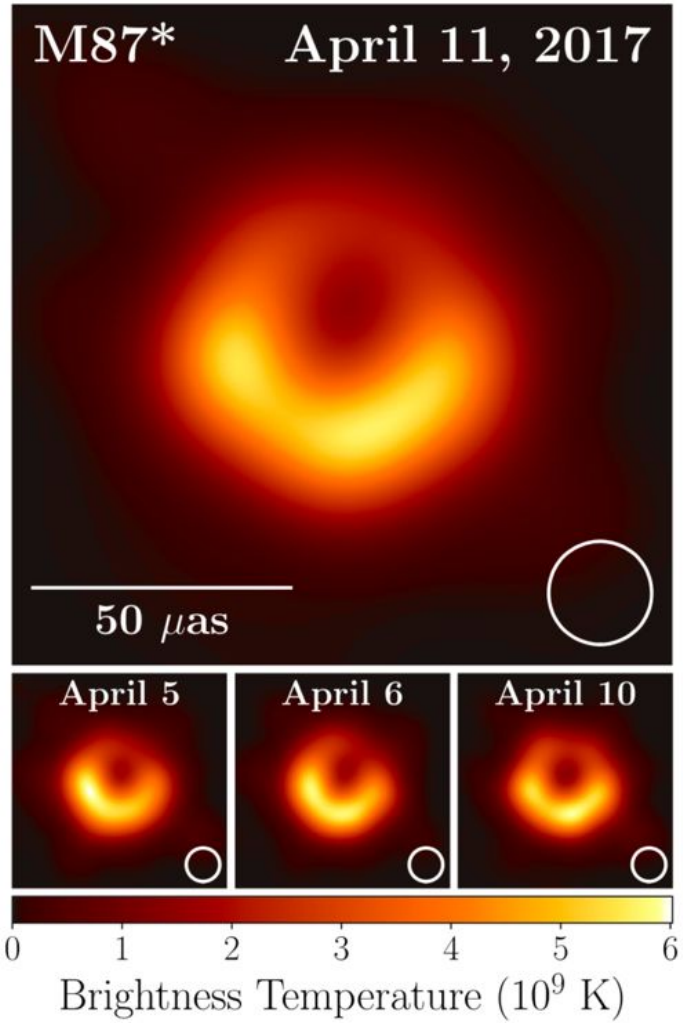


EHT collaboration: Paper I, 2019

M87 measured quantities

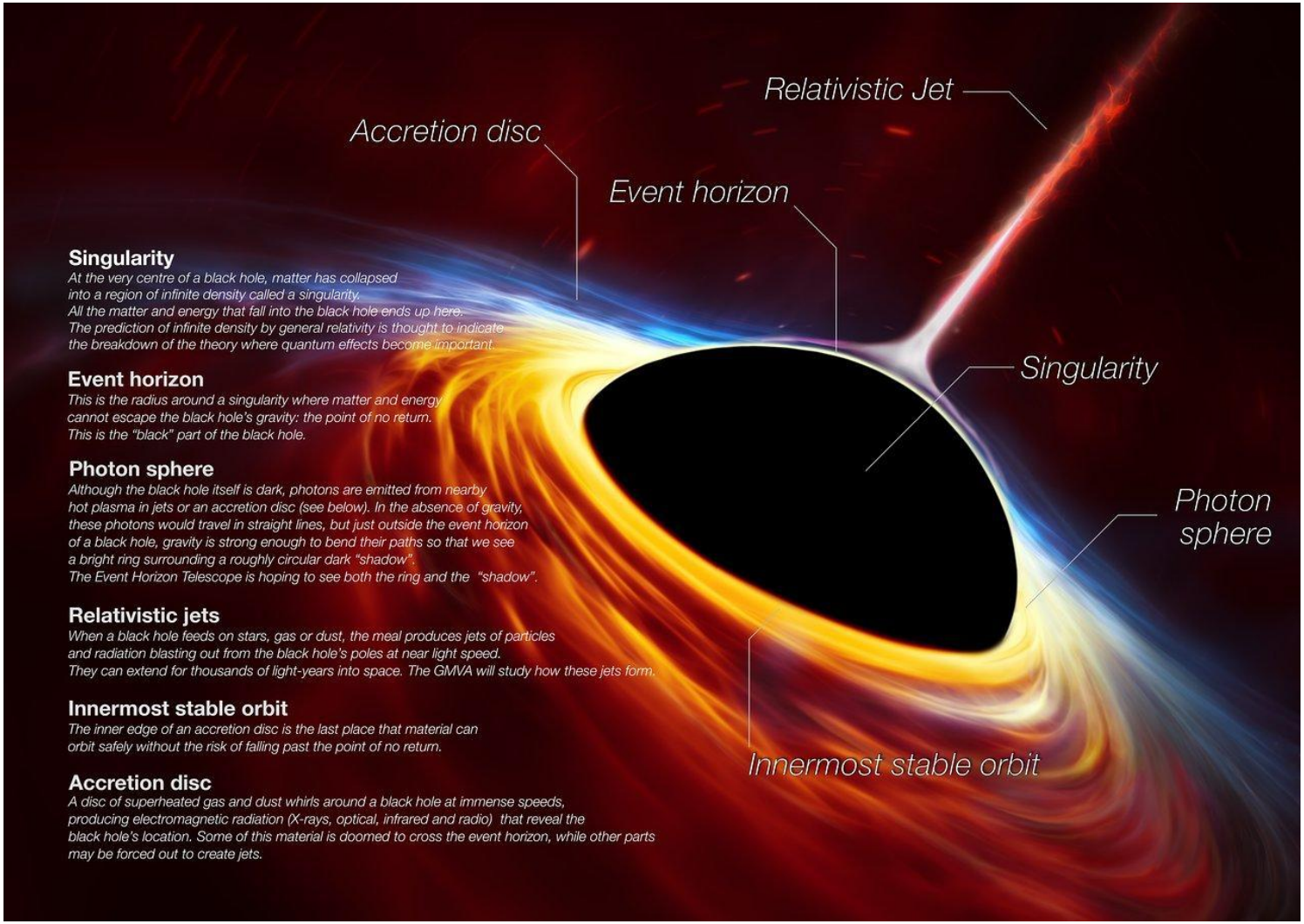
Other image quantities for model comparison :

- Ring width: < 20 μas
- Flux ratio (peak/central depression): > 10:1
- Total flux density: 0.5Jy
- Peak brightness temperature: 6×10^9 K
- Variable on small scales (<25 μas)



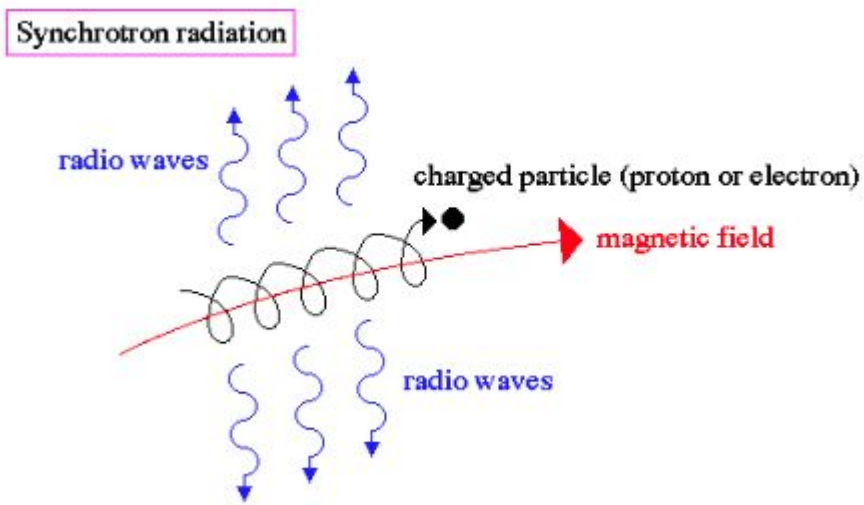
EHT collaboration: Paper I, 2019

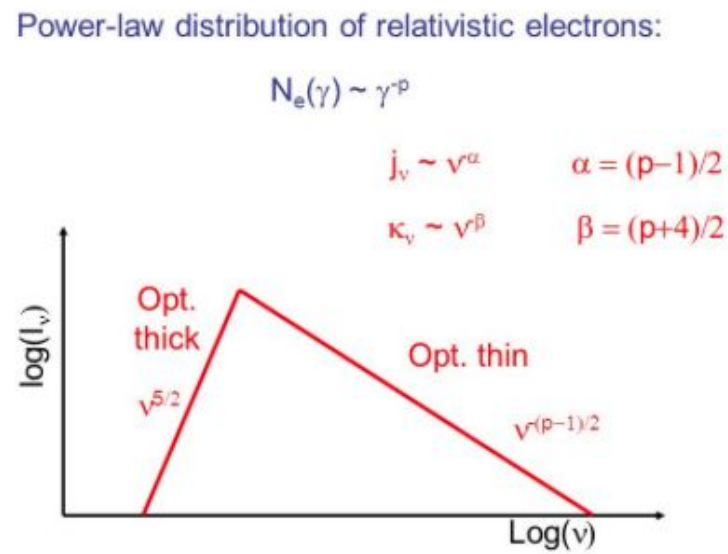
Black Hole anatomy



M87 emission mechanism

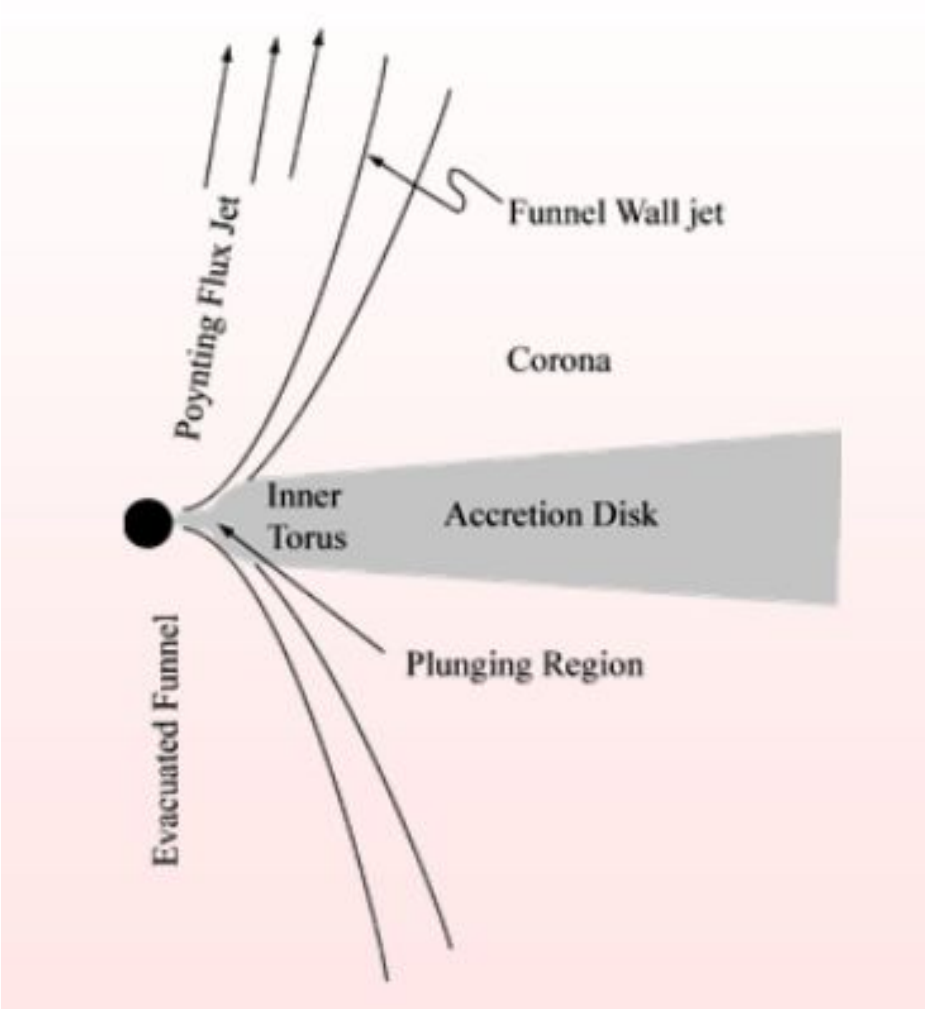
Optically thin **synchrotron emission** (already at 7mm, Hada+ 2011)





← wavelength

Plasma composition



Prescription:

non relativistic ions + relativistic electrons with

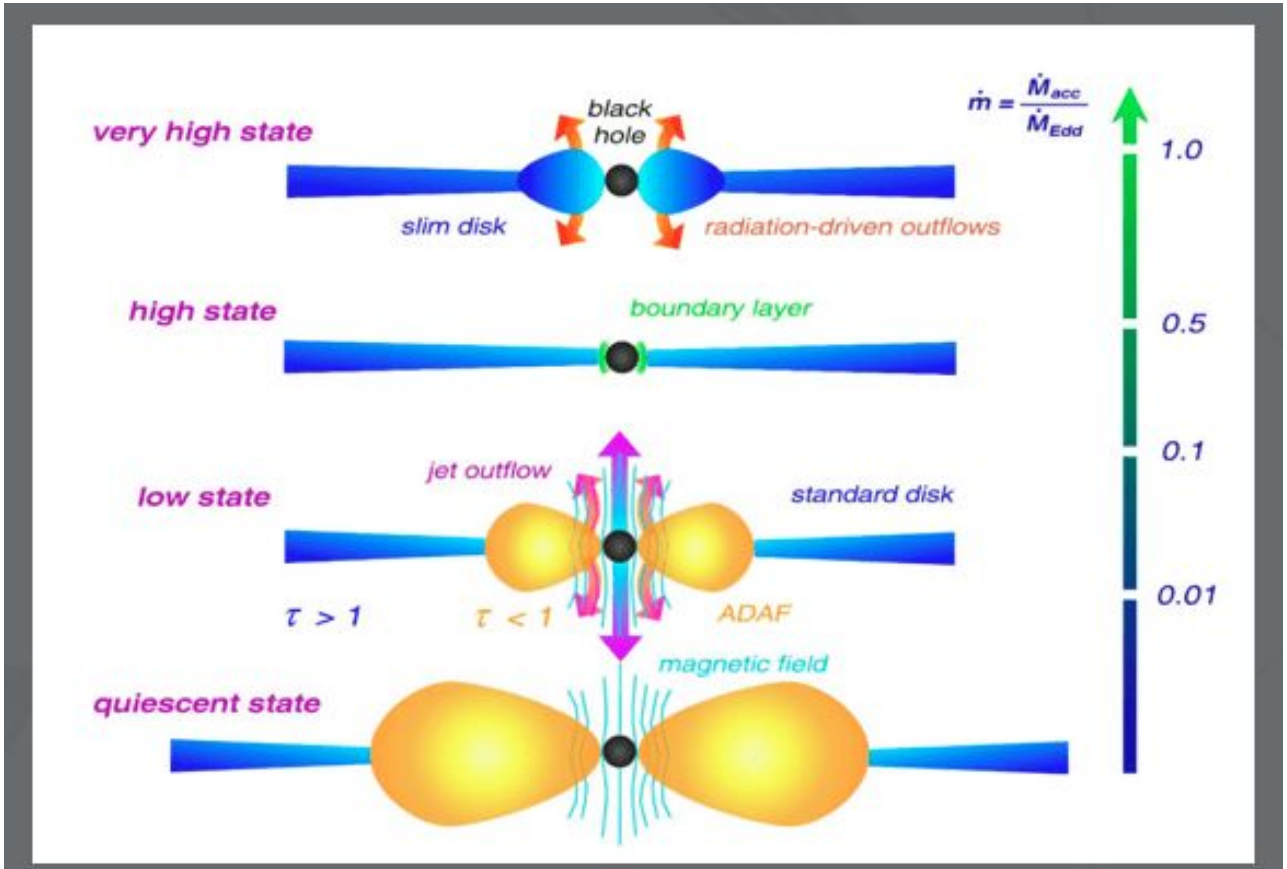
- $T_i = T_e$ in the funnel
- $T_e < T_i$ in the disk midplane

Accretion mechanism

Radiatively inefficient accretion flow models

For LLAGN M87
(from EHT data)

$$\frac{\dot{M}}{\dot{M}_{\rm Edd}} = 2 \times 10^{-5}$$



The schematic figure of the state of a black hole accretion disk (Müller 2004). The label on the left of each model indicates the X-ray state.

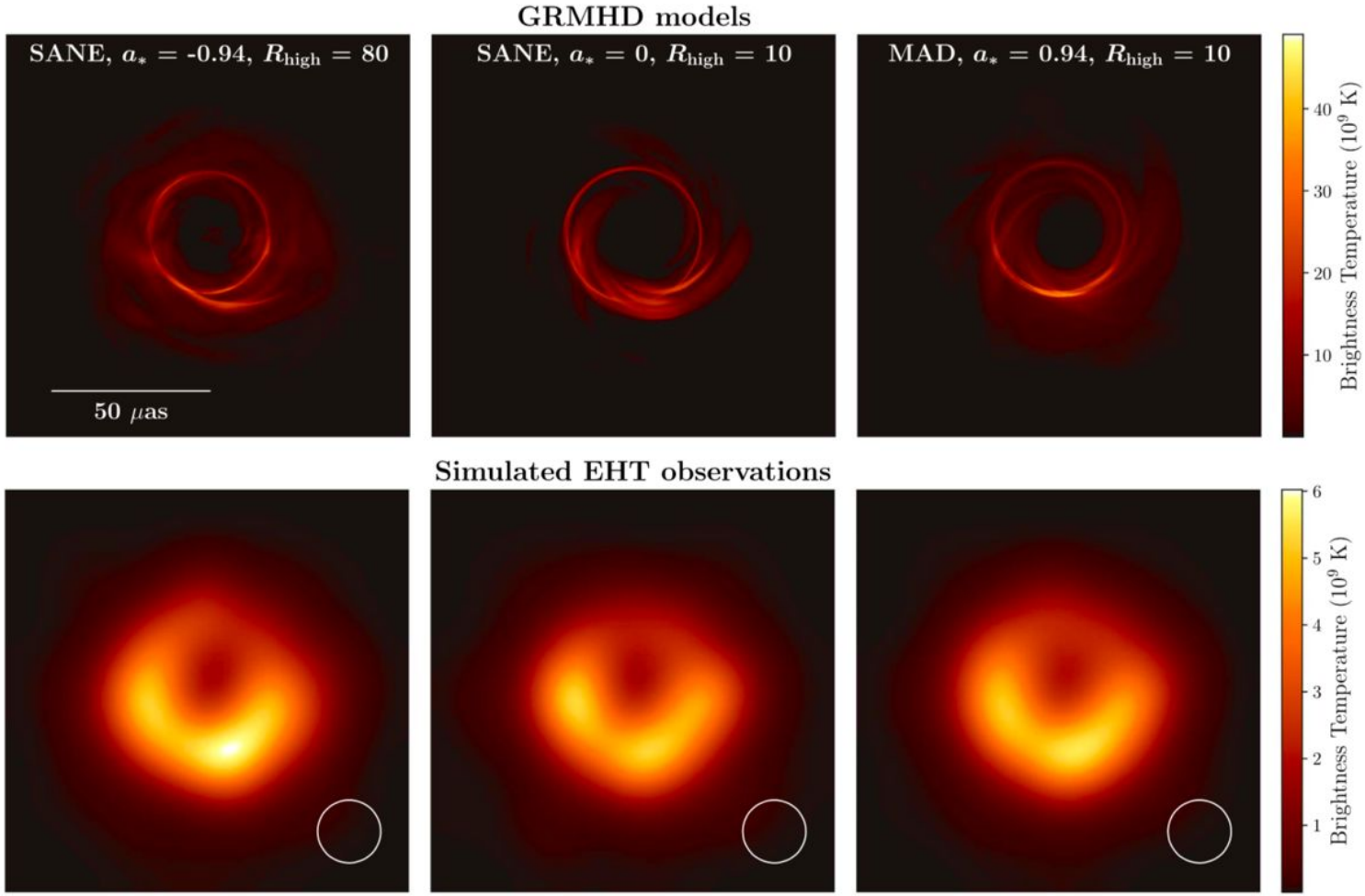
M87 simulations: 43 GRMHD, > 60, 000 images

SANE: Φ low
MAD: Φ high
where Φ is magnetic flux

$\mathbf{a_*}$ = BH spin

$\mathbf{R_{high}} \sim T_{Ion}/T_{e-}$
(if >> jet is dominant)

Simulation convolved with 20 μas PSF



EHT collaboration: Paper V, 2019

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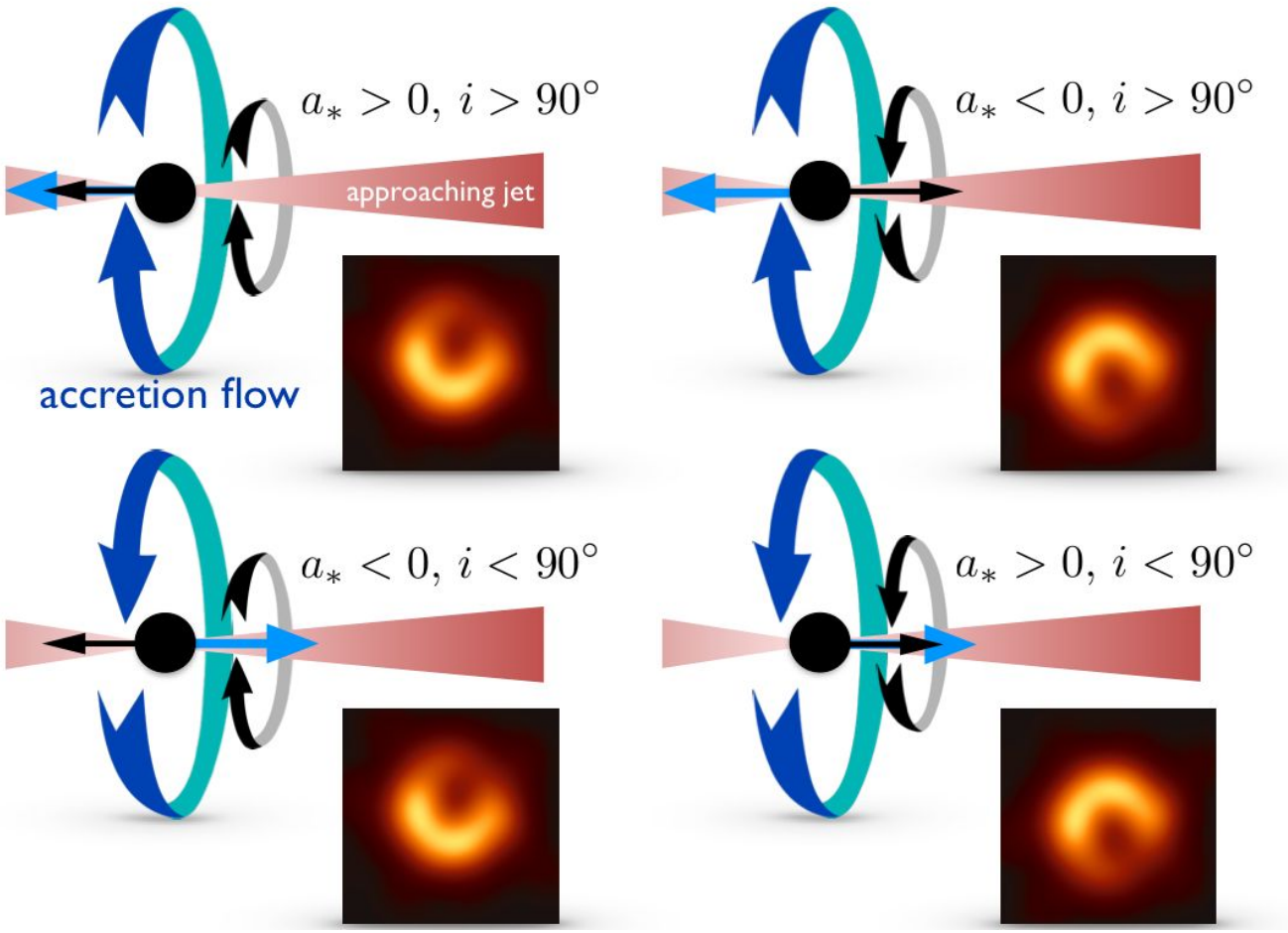
M87 ring asymmetry

Due to Doppler boosting

BH spin orientation dependent



a_* BH spin w.r.t. accretion flow, *i* angle between disk angular momentum vector and line of sight

EHT collaboration: Paper V 2019

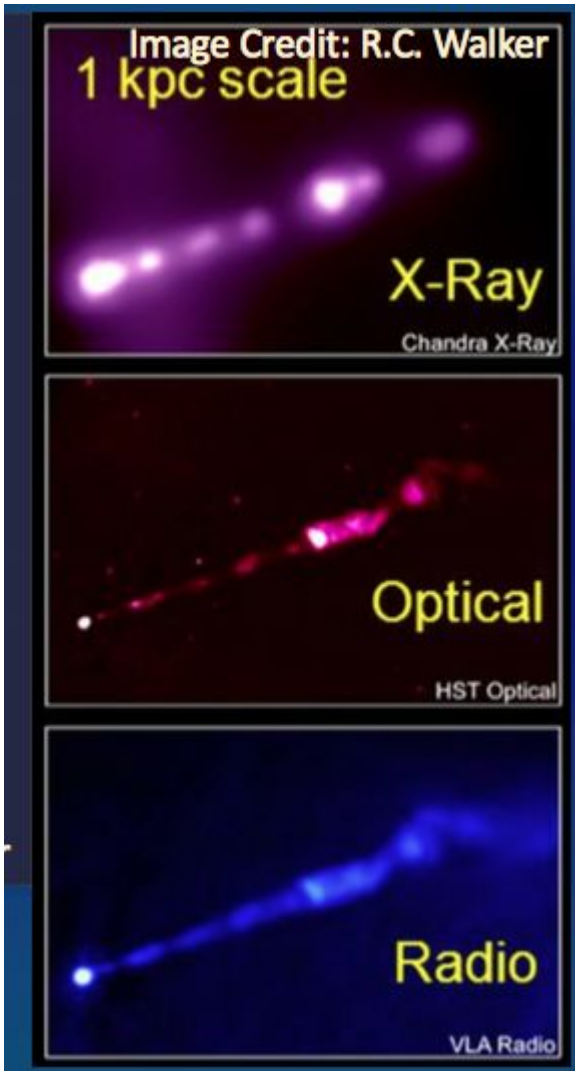
M87 Black hole characterization

Other constraints:

- Must not overproduce X-rays
- Must produce jet power
- Close to radiative equilibrium

The zero rotation models are excluded!

M87 hosts a Kerr BH of M~6.5 10^9 M⊙
confirming the estimation based on stellar dynamics (Gebhardt+ 2011)



Constraint Summary

Most **SANE models fail**, except a_* =-0.94 and a_* =0.94 models with large R_{high}

Large fraction of **MAD model pass**, except a_* =0 and small R_{high}

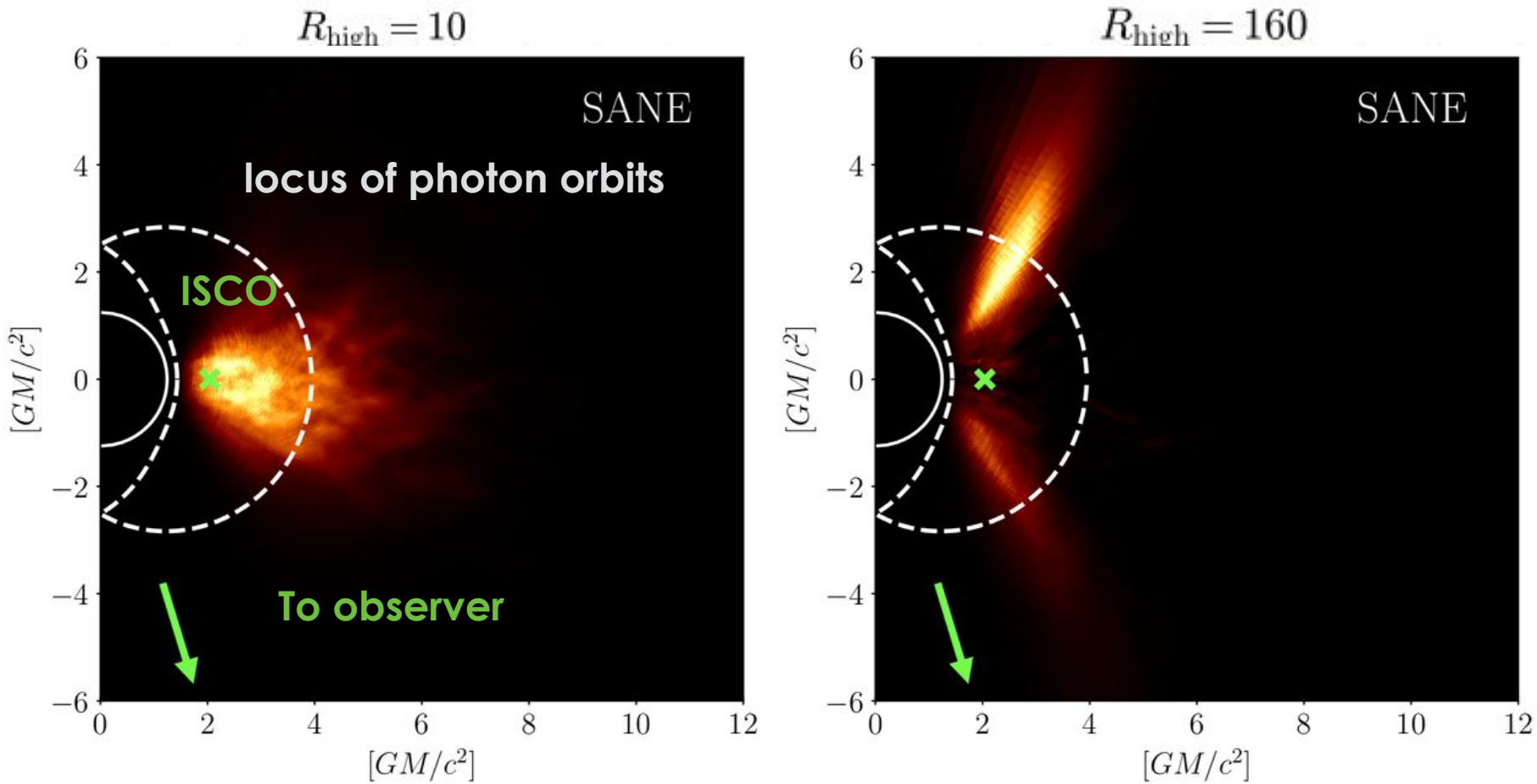
SANE

flux[1]	a_*[2]	R_{high}[3]	AIS[4]	ϵ[5]	L_X[6]	P_{jet}[7]	
SANE	-0.94	1	Fail	Pass	Pass	Pass	Fail
SANE	-0.94	10	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	20	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	40	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	80	Pass	Pass	Pass	Pass	**Pass**
SANE	-0.94	160	Fail	Pass	Pass	Pass	Fail
SANE	-0.5	1	Pass	Pass	Fail	Fail	Fail
SANE	-0.5	10	Pass	Pass	Fail	Fail	Fail
SANE	-0.5	20	Pass	Pass	Pass	Fail	Fail
SANE	-0.5	40	Pass	Pass	Pass	Fail	Fail
SANE	-0.5	80	Fail	Pass	Pass	Fail	Fail
SANE	-0.5	160	Pass	Pass	Pass	Fail	Fail
SANE	0	1	Pass	Pass	Pass	Fail	Fail
SANE	0	10	Pass	Pass	Pass	Fail	Fail
SANE	0	20	Pass	Pass	Fail	Fail	Fail
SANE	0	40	Pass	Pass	Pass	Fail	Fail
SANE	0	80	Pass	Pass	Pass	Fail	Fail
SANE	0	160	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	1	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	10	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	20	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	40	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	80	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	160	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	1	Pass	Fail	Pass	Fail	Fail
SANE	+0.94	10	Pass	Fail	Pass	Fail	Fail
SANE	+0.94	20	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	40	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	80	Pass	Pass	Pass	Pass	**Pass**
SANE	+0.94	160	Pass	Pass	Pass	Pass	**Pass**

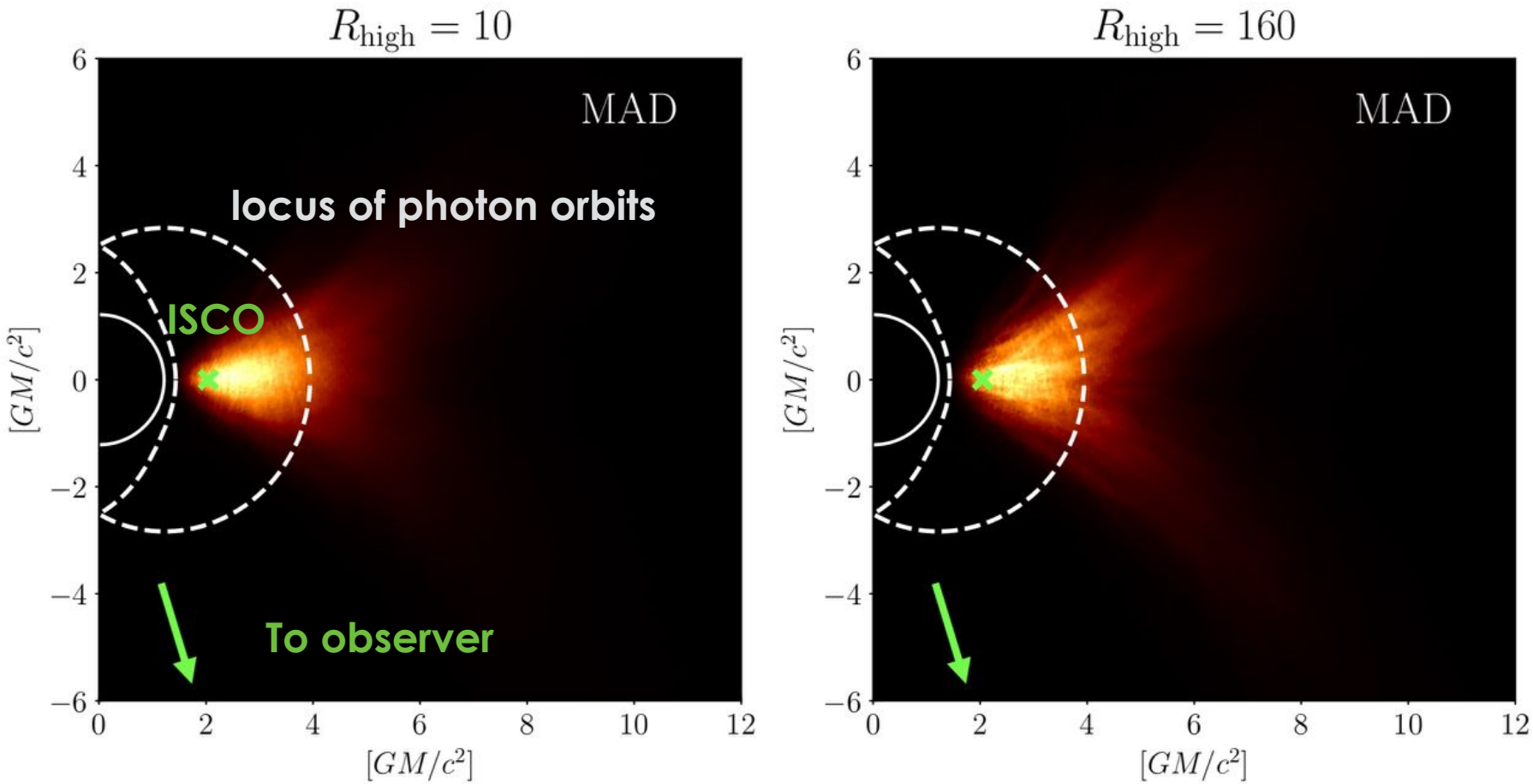
MAD

flux[1]	a_*[2]	R_{high}[3]	AIS[4]	ϵ[5]	L_X[6]	P_{jet}[7]	
MAD	-0.94	1	Fail	Fail	Pass	Pass	Fail
MAD	-0.94	10	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	20	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	40	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	80	Fail	Pass	Pass	Pass	Fail
MAD	-0.94	160	Fail	Pass	Pass	Pass	Fail
MAD	-0.5	1	Pass	Fail	Pass	Fail	Fail
MAD	-0.5	10	Pass	Pass	Pass	Fail	Fail
MAD	-0.5	20	Pass	Pass	Pass	Pass	**Pass**
MAD	-0.5	40	Pass	Pass	Pass	Pass	**Pass**
MAD	-0.5	80	Pass	Pass	Pass	Pass	**Pass**
MAD	-0.5	160	Pass	Pass	Pass	Pass	**Pass**
MAD	0	1	Pass	Fail	Pass	Fail	Fail
MAD	0	10	Pass	Pass	Pass	Fail	Fail
MAD	0	20	Pass	Pass	Pass	Fail	Fail
MAD	0	40	Pass	Pass	Pass	Fail	Fail
MAD	0	80	Pass	Pass	Pass	Fail	Fail
MAD	0	160	Pass	Pass	Pass	Fail	Fail
MAD	+0.5	1	Pass	Fail	Pass	Fail	Fail
MAD	+0.5	10	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	20	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	40	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	80	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.5	160	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.94	1	Pass	Fail	Fail	Pass	Fail
MAD	+0.94	10	Pass	Fail	Pass	Pass	Fail
MAD	+0.94	20	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.94	40	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.94	80	Pass	Pass	Pass	Pass	**Pass**
MAD	+0.94	160	Pass	Pass	Pass	Pass	**Pass**

Where do mm photons originate? SANE ($a_* = 0.96$)



Where do mm photons originate? MAD ($a_* = 0.96$)



AGN jet regions

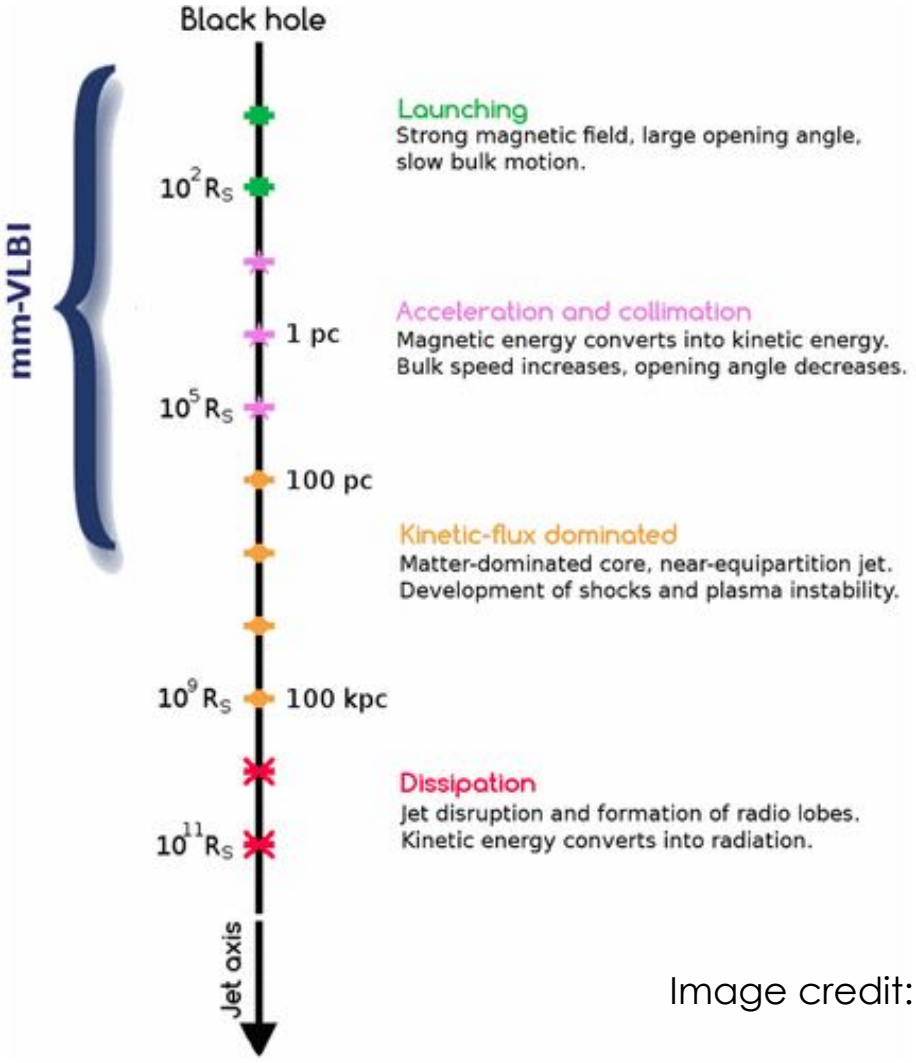


Image credit: Boccardi+ 2017

Jet launching mechanism

- **BH launched jet:** Blandford & Znajek (1977)
- **Disk launched jet**: Blandford & Payne (1982)
- **Combination**

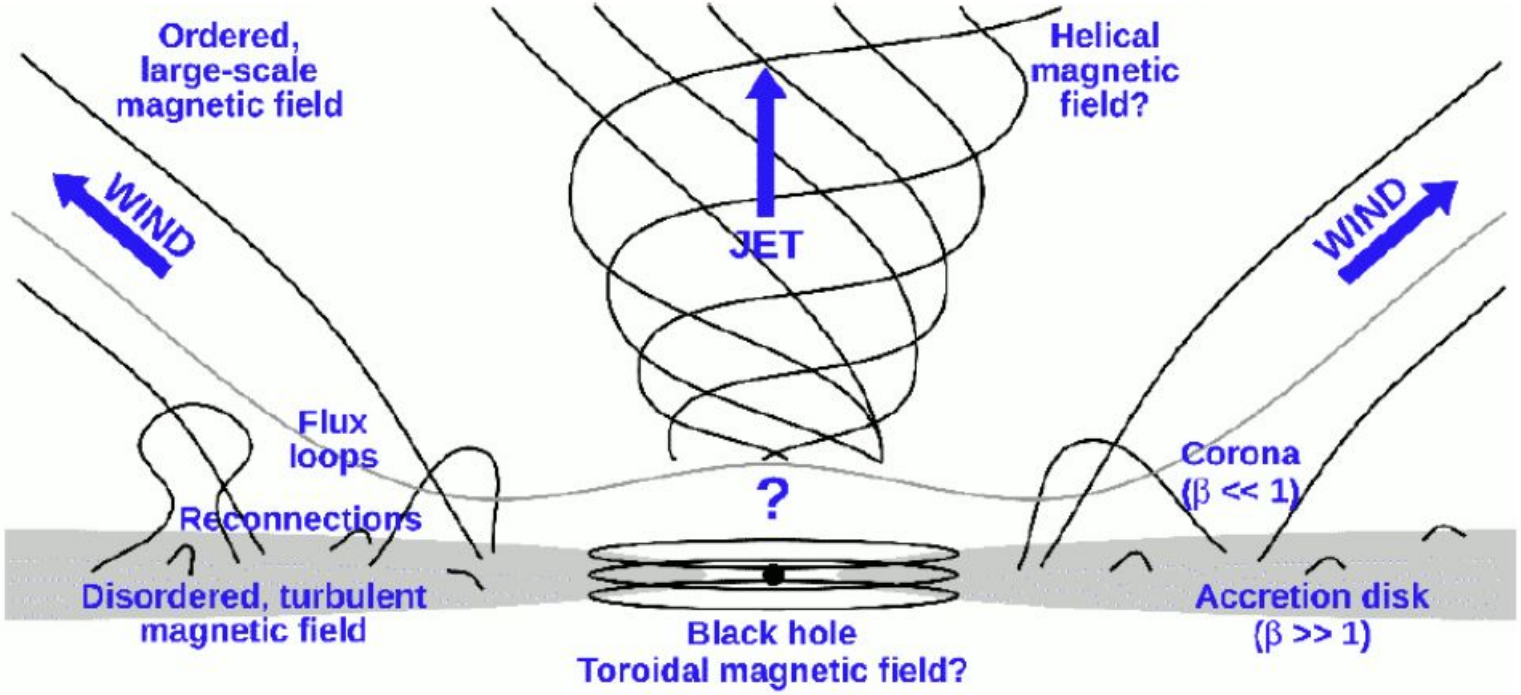


Image credit: Dobbie+ 2009

M87 data in agreement with BZ jet

M87 future EHT study

- Jet acceleration mechanism through **Magnetic field study:** Data are there!

- **Multi-wavelength data analysis** to connect with EHT results: Multi-band campaign are ongoing

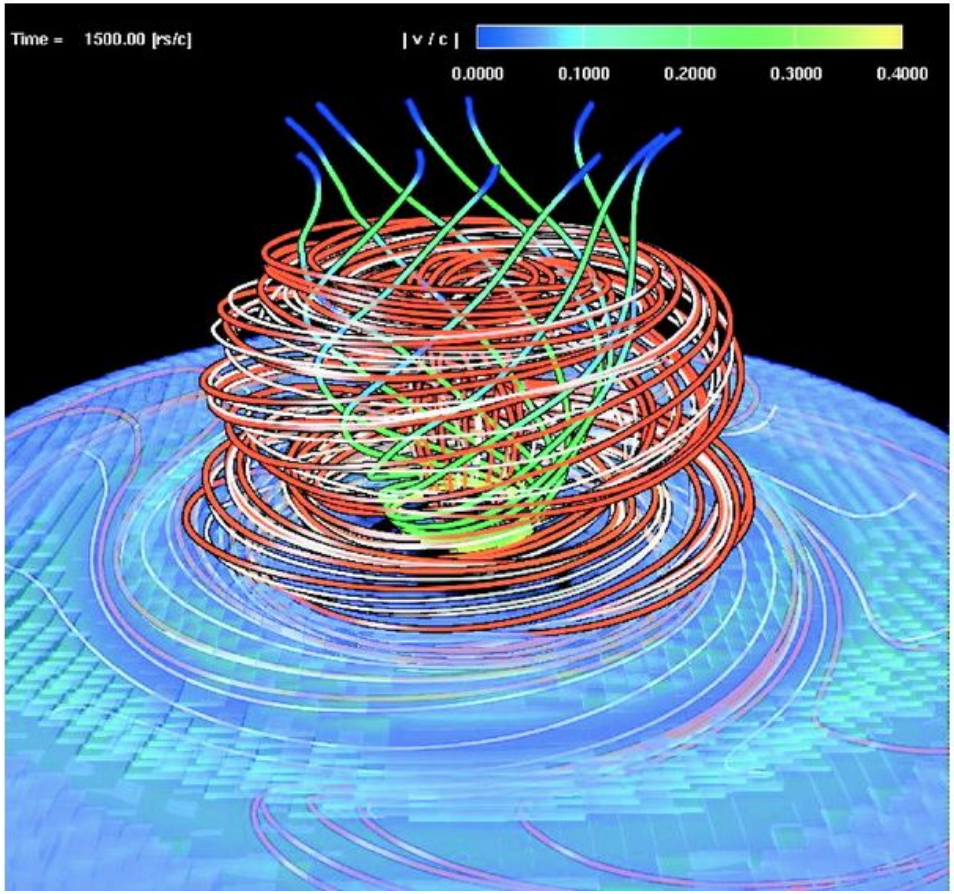
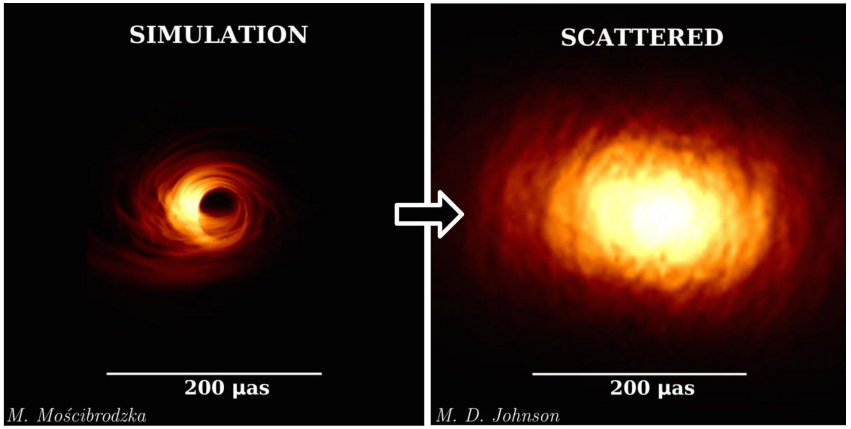


Image credit: Kato+ 2004

Sagittarius A* in the center of the Milky Way



Difficulties:

- Intra-Hour Variability
- Scattering

Data already taken → working in progress

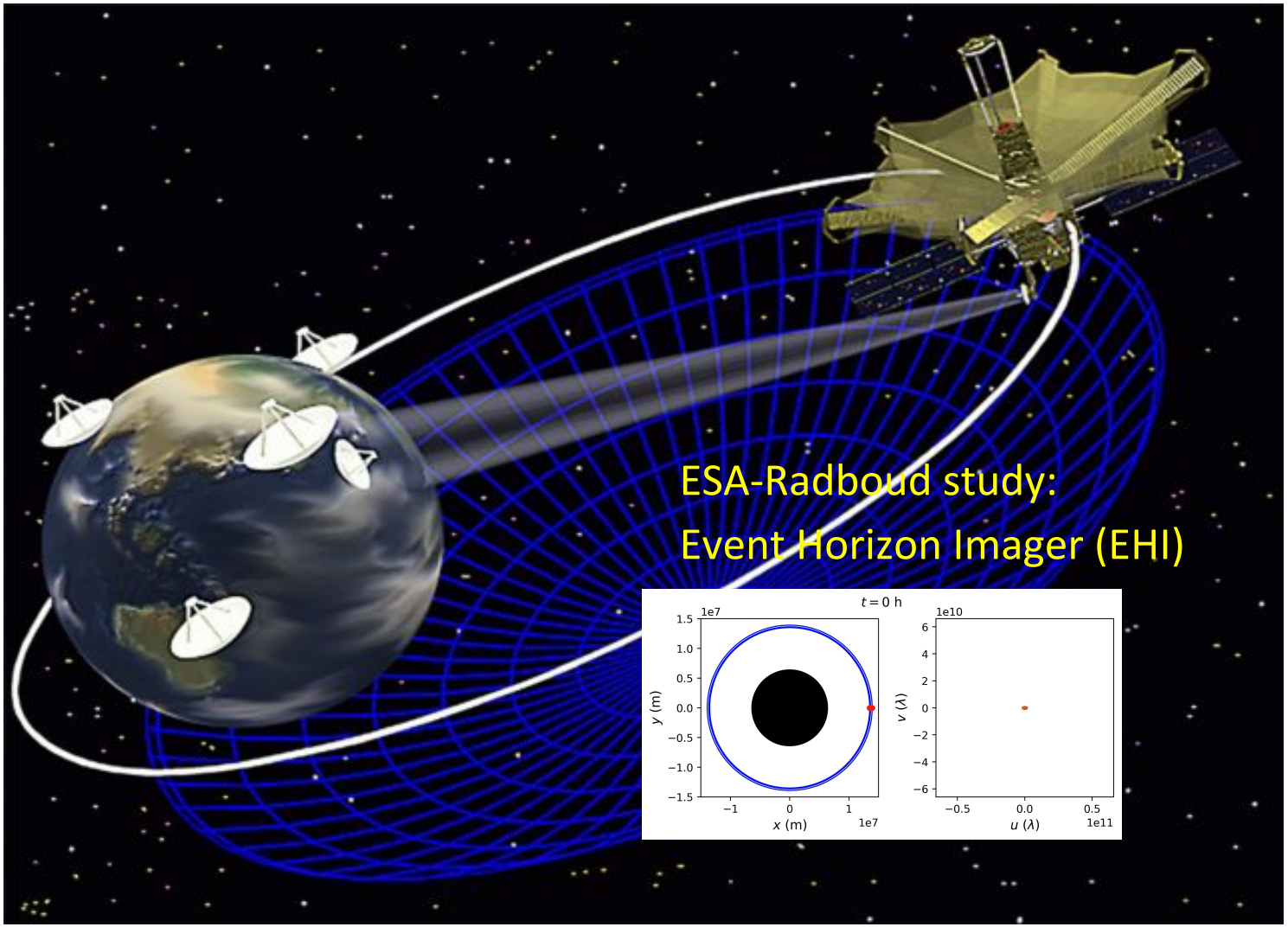
Credit: Moscibrodzka et al. 2016, Johnson et al. 2018

More telescopes, higher observing frequency

Upgrade planned:

- **2020** :
  - Kit Peak (Arizona)
  - phased-NOEMA
- **2021** :
  - LLAMA (Brazil/Argentina)
- **After 2021**:
  - African mm Telescope

Future of VLBI: space



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