The Shadow of the Supermassive Black Hole

Good opportunity
To explain
Active Galactic Nuclei

First M87 Event Horizon Telescope Results

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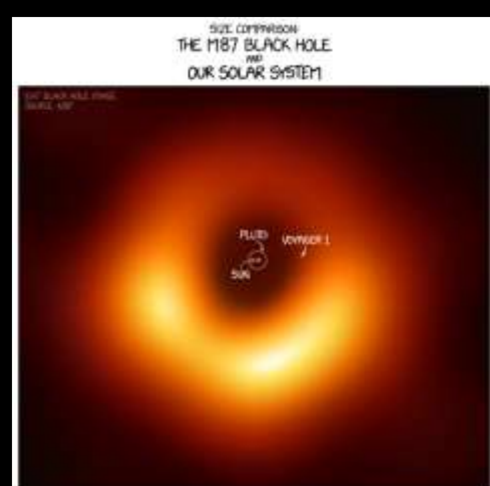
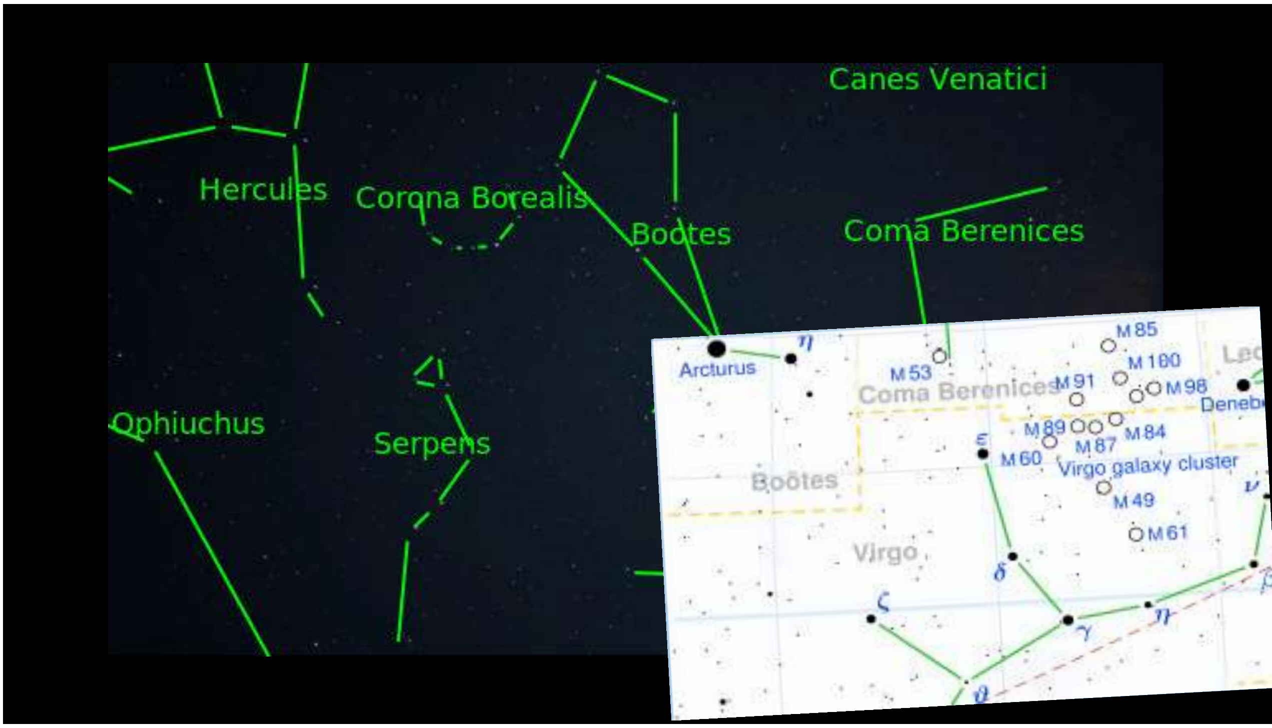
학습목표

- EHT paper 1 – 6 배경/기초 정보 설명
  - 활동성은하핵 (Active Galactic Nuclei)?
  - 전파 간섭계 (Radio Interferometer), VLBI ?





Institutions on the EHT Board

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Large Millimeter Telescope
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Event Horizon Telescope

Event Horizon Telescope

Funding Support

Event Horizon Telescope

Introduction

- Black holes
  - Stellar mass BHs (up to 100 M_{Sun})
    - Keplerian motion + X-ray (Webster & Murdin 1972; Remillard & McClintock 2006)
    - Gravitational-wave measurements (Abbott et al. 2016)
  - Supermassive Black holes (SMBHs; from 10^6 M_{Sun})
    - exist in the centers of nearly all galaxies (Lynden-Bell 1969; Kormendy & Richstone 1995; Miyoshi et al. 1995)
    - Our Galatic center, Sgr A* (Eckart & Genzel 1997; Ghez et al. 1998; (Gravity Collaboration et al. 2018a)
    - M87 (Gebhardt et al. 2011; Walsh et al. 2013)
  - Strong evidence of Micro BHs or Intermediate BHs is yet to be found
    - Hawking radiation afterglow? GW?

Cyg X-1 (Webster & Murdin 1972; Agrawal+ 1971)

- Mass of X-ray 'star' > 2 M_{Sun}
- Spectroscopy, B type supergiant star with Isaac Newton telescope
- Balloon-borne X-ray observation, 22.5 – 154 keV

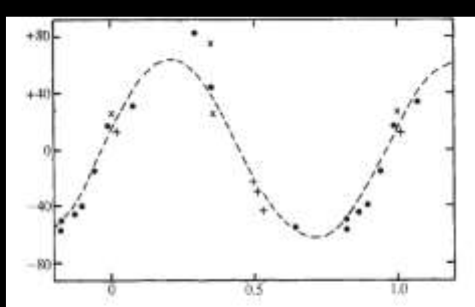


Fig. 1 The radial velocity of HD 226868 plotted against phase in a 5.60 day period. Zero phase is defined to occur at Julian Day 2441163.597. ●, Measurements on photographic spectra at 62 Å/mm; ×, photographic spectra at 184 Å/mm; +, image tube spectra at 75 Å/mm.

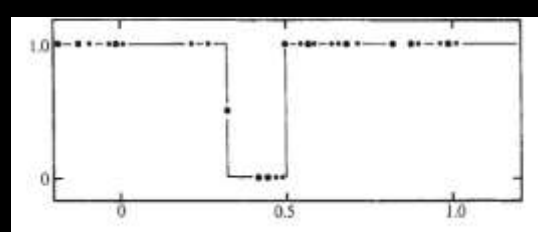


Fig. 2 Intensities of X-rays of energy above 20 keV as a function of phase for the period 5.6075 days. An intensity of 1 represents a maximum as defined by Dolan[7,8] and 0 a minimum. The sudden drop observed by Agrawal *et al.*[9] is the lone point at an intensity of ½. The size of the points plotted represents the subjective opinion of the present authors, on a two-point scale, as to the reliability of the classification of the observed X-ray flux as a maximum or minimum.

Black Hole in Cyg X-1?

- Evidence of BH
  - Radiation from 'very' compact objects
    - Stellar BH - X-ray binary, e. g *[Black body radiation] power of 10^{37} erg/s*, $L = 4\pi R^2 \sigma T_e^4$
    - *[X-ray] Peak* at 1 keV (10^7 K), then r ~ 10 km (Sun ~ 7 x 10^5km, Earth ~ 6 x 10^3 km)
    - If it radiates at optical-UV, then r ~ 10^7 km (a giant star)
  - Mass
    - Cyg X-1 (Webster & Murdin 1972)

(binary) Mass function

- Keplerian 3rd law
  - the centripetal force equal to the gravitational force: $mr\omega^2 = G\frac{mM}{r^2}$
  - $mr(\frac{2\pi}{P})^2 = G\frac{mM}{r^2}$ → $P^2 = \frac{(2\pi)^2}{GM} r^3$ → $\frac{a^3}{P^2}$ = constant (7.5 x 10^{-6} AU^3/day^2)
  - When m is non-negligible, then M→ M_1 & m→ M_2, M = (M_1 + M_2)
  - Then, a = a_1+ a_2, M_1 a_1 = M_2 a_2 (the center of the mass location)
  - $a = a_1 \frac{M}{M_2}$; $K = (\frac{2\pi}{P})\, a_1 \sin i$;
  - $\frac{M_2^3}{M^2} = \frac{P\,K^3}{2\,\pi\,G} \sin^{-3} i$; mass function $f = \frac{M_2^3}{M^2}\sin^3 i = \frac{P\,K^3}{2\,\pi\,G}$;
  - From spectroscopy $v \sin i$
  - For $M_1 << M_2$, f ~ $M_2 \sin^3 i$
  - For $M_1 >> M_2$, f ~ $\frac{M_2^3}{M_1^2}\sin^3 i$

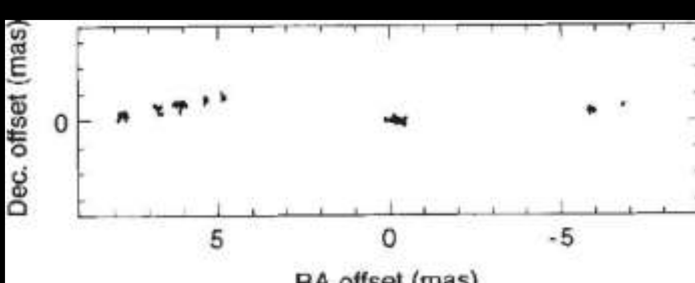

"It's black, and it looks like a hole. I'd say it's a black hole."

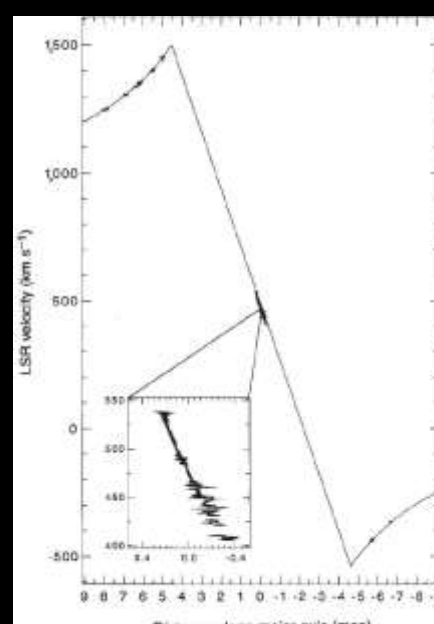
Further evidences from Black Holes

- Keplerian motion around compact objects (mass function)
  - Stars around SMBH (e.g. Sgr A*)
  - Gas disk around SMBH (e.g. NGC4258(M107))
  - Velocity dispersion (e.g. M87)
- Gravitational redshift from center of galaxies
  - Stars, gas
- Optical, IR, Radio (VLBI) , X-ray, ...
- Photometry, spectroscopy, Astrometry, …

NGC4258 (Miyoshi+ 1995)

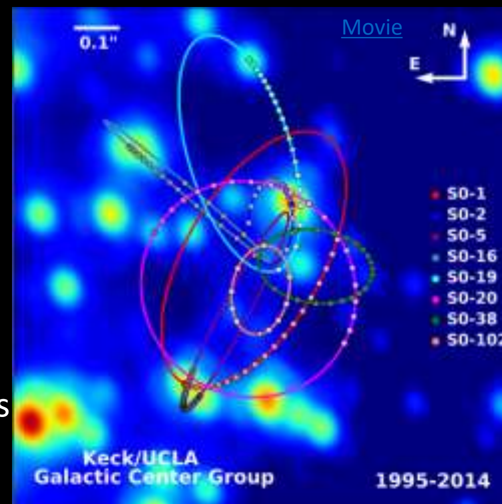
- Water mega-maser disk (outer accretion disk)
  - 6_16 – 5_23 transition; 22,235.08 MHz (1.35 cm)
- VLBI spectroscopy (NRAO VLBA + VLA)
  - 14h on 26 April 1994
- M ~ 3.6 x 10^7 2 M_{sun} (disk mass < 4 x 10^6)
- In a volume with radius of 0.13pc (0.42 ly)
  - Central mass density > 4 x 10^9 M_{sun} pc-3





Galactic Center

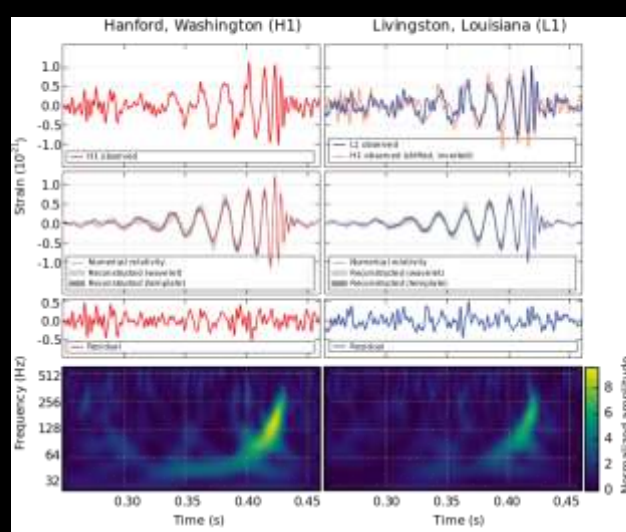
(Eckart & Genzel 1997; Ghez+ 1998; UCLA GC group)



- Long-term monitoring of star's positons
- In a volume with radius of 60 AU
  - ~ 0.3 mPC ~ 0.00095 ly ~ 8.3 lhr
- M ~ 4.1 ± 0.6 x 10^6 M_{Sun}
  - 0.1 arcsec ~ 850 AU at 8.5 kpc
  - Then, R_{sch} ~ 0.08 AU (0.39 μpc)
- Full phase coverage measured for two stars
  - S0-2 with an orbital period of 15.56 years
  - S0-102 with 11.5 years
  - At the closest approach, S0-2 is only 17 light hours

And Gravitational Wave! (LIGO & VIRGO collaboration 2016)

- On 11 February 2016, the LIGO collaboration announced the first observation of gravitational waves, from a signal detected at 09:50:45 GMT on 14 September 2015[85] of two black holes with masses of 29 and 36 solar masses merging about 1.3 billion light-years away. During the final fraction of a second of the merger, it released more than 50 times the power of all the stars in the observable universe combined.[86] The signal increased in frequency from 35 to 250 Hz over 10 cycles (5 orbits) as it rose in strength for a period of 0.2 second.[9] The mass of the new merged black hole was 62 solar masses.



Active Galactic Nuclei

or Active SMBH

Active Galactic Nuclei (AGNs)

- Central bright regions that can outshine the entire stellar population of their host galaxy
- NGC1068 first discovered by Fath in 1908
- Mass-accreting SMBH and surrounding regions
- Simplified classification
  - High accretion rate Quasars
    - Optically thick, geometrically thin accretion disk (Shakura & Sunyaev 1973; Sun & Malkan 1989)
  - Low accretion rate LLAGN
    - fed by hot, tenuous accretion flows with much lower accretion rates (Ichimaru 1977; Narayan & Yi 1995; Blandford & Begelman 1999; Yuan & Narayan 2014)
  - All together maybe ~10% of whole SMBHs

First found 'Active Galaxy' NGC1068 (M77, Cetus A)

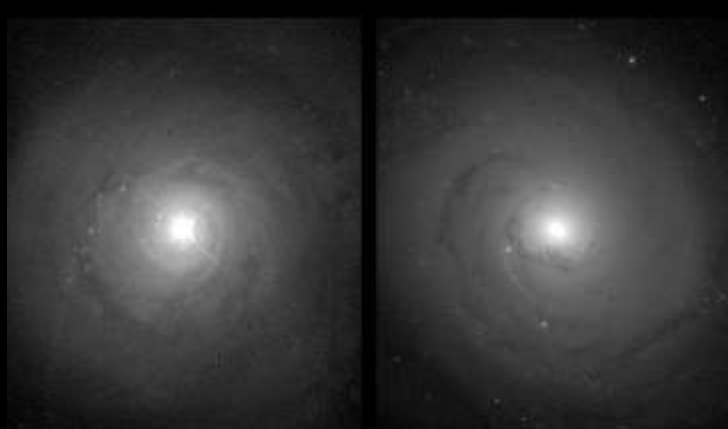
X-ray red
Optical green
Radio blue

Distance ~ 14.4Mpc

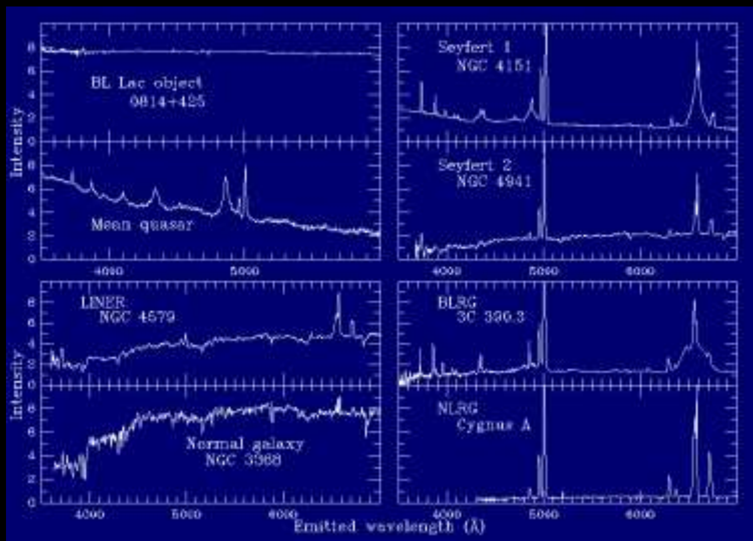
Is the core (or nucleus) of this galaxy unusually bright?

X-ray (NASA/CXC/ MIT/C.Canizares, D.Evans et al), Optical (NASA/STScI), Radio (NSF/ NRAO/VLA)

Seyfert Galaxy NGC 5548 (AGN in Spiral Galaxy) versus normal galaxy NGC 3277



Optical spectra of various AGNs

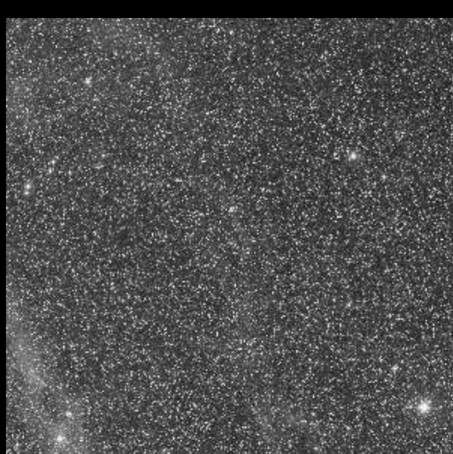


NGC 4579 & NGC 4941 Keel (1983); Cygnus A Owen et al. (1990);
0814+425 & 3C 390.3 Lawrence et al.(1996);
"mean quasar" Francis et al.(1991); NGC 3368 Kennicutt

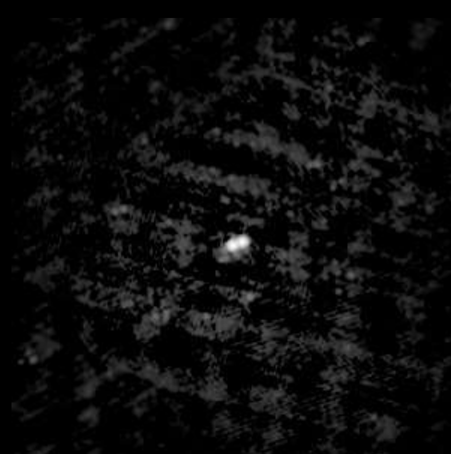
Some AGNs are powerful radio sources

Cygnus A area (DSS & NVSS) from 'SkyView'

1 deg x 1 deg

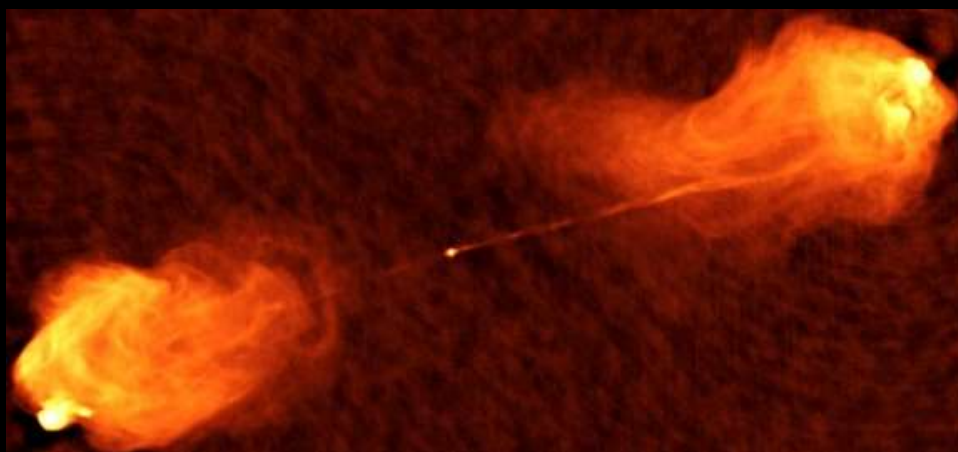


Optical Digital Sky Survey (optical)



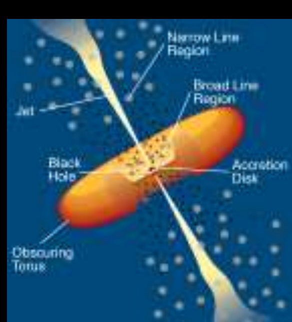
NRAO VLA Sky Survey (20cm;1.4GHz radio)

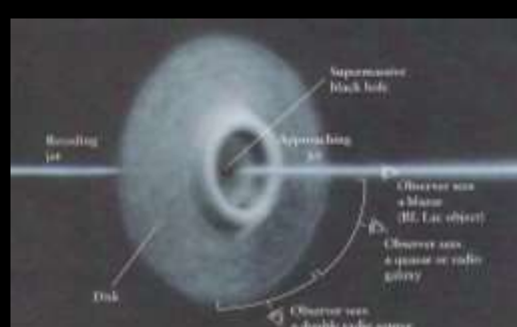
Cygnus A



AGN – unification scheme

- SMBH – Accretion Disk – Emission Line Clouds – Jet (relativistic)
- Different inclination angle, different power



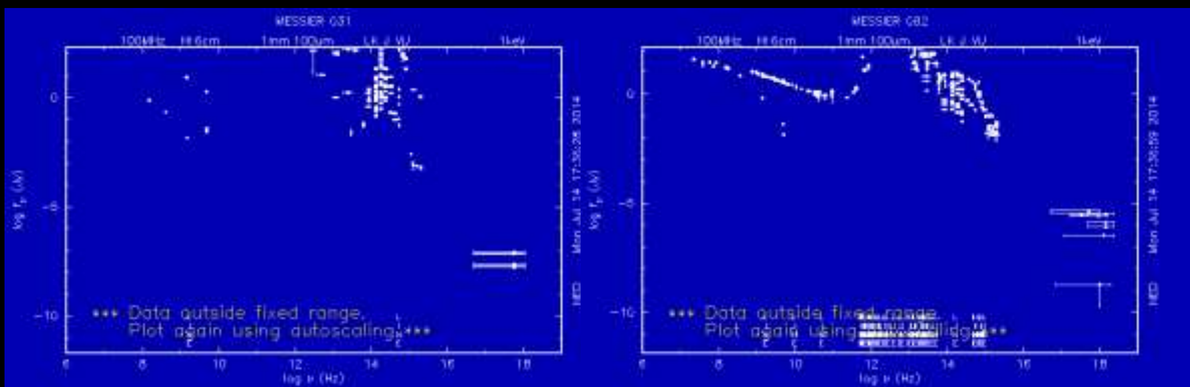


AGN emission close to Event Horizon

- Collimated relativistic plasma jets in many AGNs (Bridle & Perley 1984; Zensus 1997)
  - Powered magnetic fields threading the event horizon, extracting the rotational energy (Blandford & Znajek 1977)
  - Or from accretion flow (Blandford & Payne 1982)
- The near-horizon emission from LLAGNs (Ho 1999) is produced by synchrotron radiation that peaks from the radio through the far-infrared
  - accretion flow (Narayan et al. 1995)
  - jet (Falcke et al. 1993)
  - or both accretion flow and jet (Yuan et al. 2002).

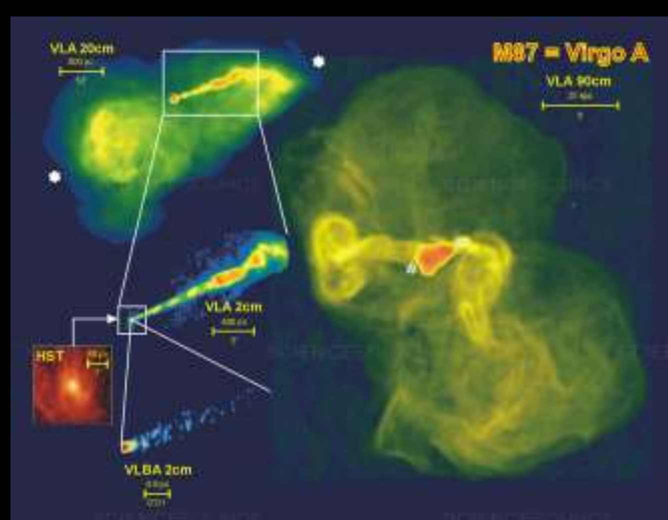
Cygnus A(FR II) and M87(FR I)

M31 and M82



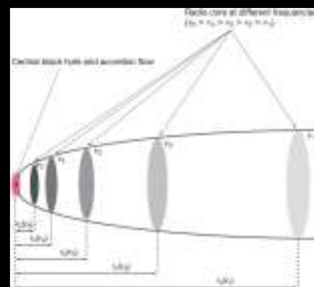
Radio structure of M87

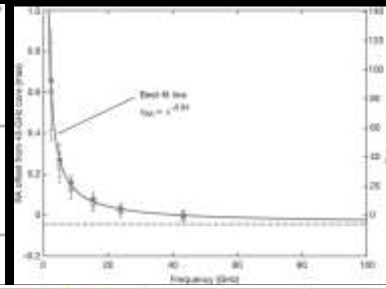
- Linear feature found in M87 by Curtis in 1918
  - Called “jet” by Baade and Minkowski (1954)
  - 65kpc; 40 Myr
    - Power close to 10^45 erg/s (de Gasperin+, 2012)
  - Compact (unresolved) source at the upstream end of the jet – LLAGN

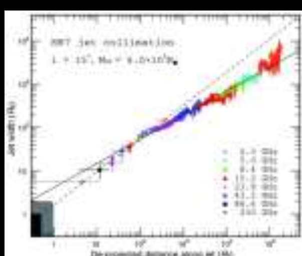


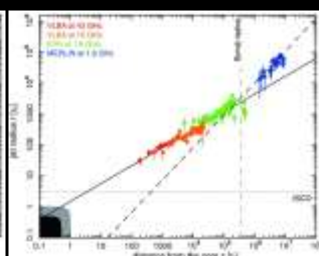
Radio core in M87

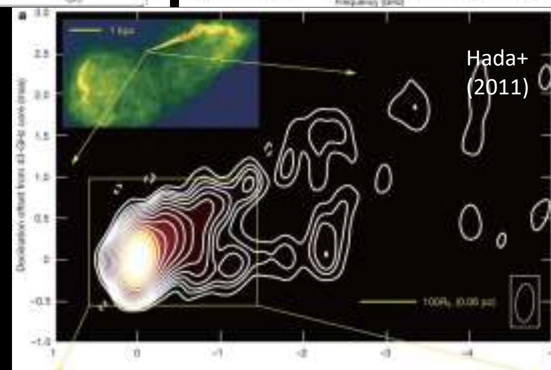
- Blandford-Koenigl (1979) jet
  - Synchrotron self-absorption
  - Confirmed (Hada+ 2011)
  - Quasi-parabolic limb shape
    - From 10^5 r_g to 20 r_g (Hada+ 2013)
    - Further to 10^7 r_g (Asada+ 2012)











Hada+ (2011)

Looking for Best objects to see Black Hole Shadow

Black Hole Photon Capture

Find movie at EHT homepage

Event Horizon Telescope

Event Horizon Telescope

- A global millimeter VLBI experiment
  - Baseline 160 m to 10,700 km
  - 230GHz; 1.3mm → resolution ~25 µas
  - 6 locations, 8 stations (2017)
  - Sensitivity increase by a factor of ~30 increased over last ten years (ALMA and high performance recorders)

Radio interferometer

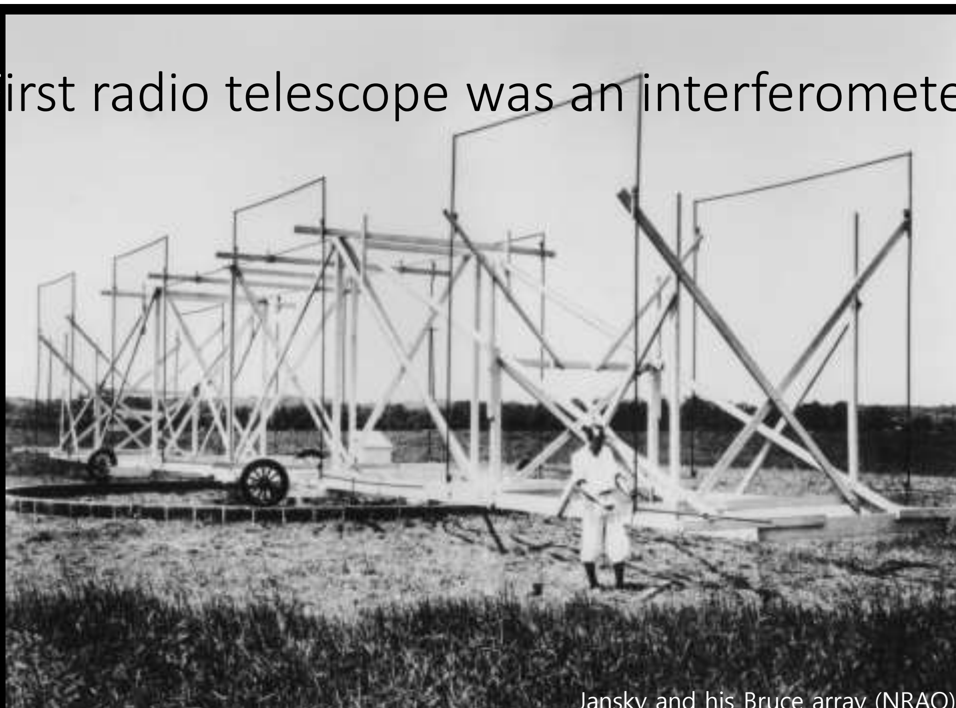
- Interferometer sees ‘visibility’ (e.g. fringes of Young’s experiment)
- Visibility (ν_x, ν_y) FT Image (x, y); FT ‘Fourier Transformation’
- In imaging, transformation between Spatial Frequency and position

$$\bar{E}(\xi) = \int_{-\infty}^{\infty} E(x_\lambda)\, e^{-i2\pi x_\lambda \xi}\, dx_\lambda$$

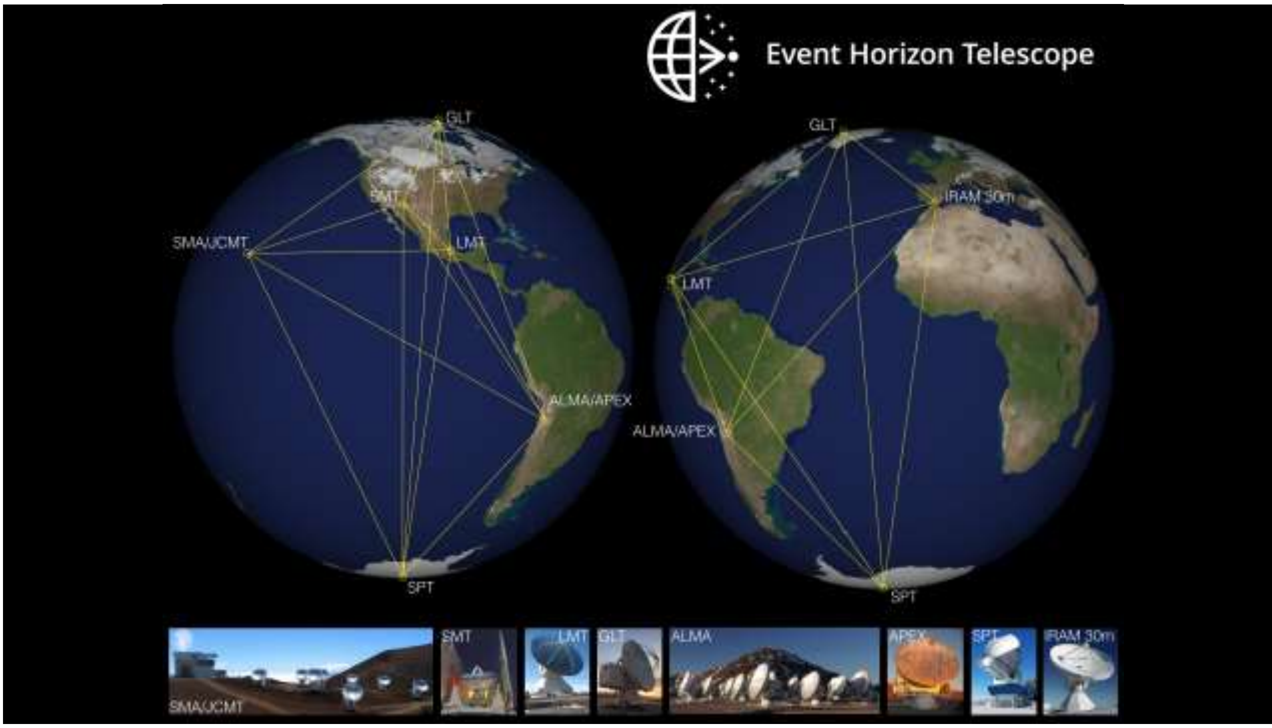
$$E(x_\lambda) = \int_{-\infty}^{\infty} \bar{E}(\xi)\, e^{i2\pi \xi x_\lambda}\, d\xi$$

- Radio interferometer with very long baseline
  - ‘Very long’ means separate freq. time standard and incoherent atmosphere

First radio telescope was an interferometer



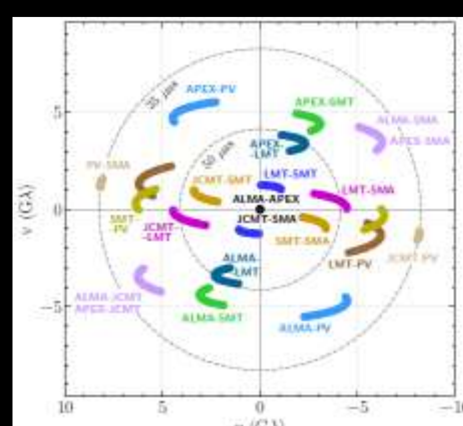
Jansky and his Bruce array (NRAO)



Event Horizon Telescope

Observation, Correlation and Calibration

- M87* observed on 2017 April 5, 6, 10 and 11
- τ (opacity) 0.03 ~ 0.28 at 230 GHz
- M87* scans (alias 3C274) interleaved with 3C279
  - A scan 3 to 7 minutes duration
  - Seven scans on April 10, twenty-five scans on April 6
  - Dual circular polarization observation
  - 2GHz BW, centered at 227.1 and 229.1 GHz, digitized and recorded at 32Gbps
  - Typical coherence time ~ 10 s
    - mainly due to water vapor
- Corraleted at MIT Haystack and at MPIfR Bonn
- ALMA as reference station
  - Amplitude accuracies 5 to 10 %



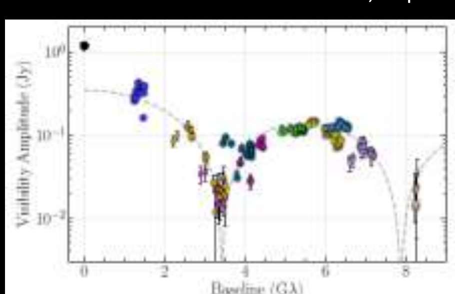
Observation Demo

Find Demo at EHT homepage

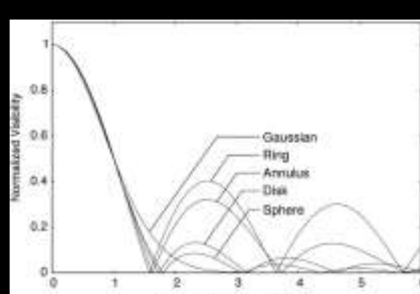
Event Horizon Telescope

Observation, Correlation and Calibration

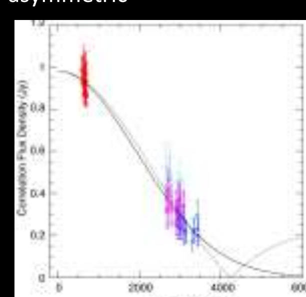
- ALMA baseline SNR > 100, non-ALMA baseline > 10
- 2 bands & 2 polarization, three independent pipelines
  - 1deg phase and 2% amplitude systematic errors
- Visibility distribution (left) resembles a thin ring (middle)
  - Huge improve of UV coverage since 2012 (right)
  - 46 µas diameter, a first null at 3.4 Gλ, but not a simple plain ring
  - 50% flux resolved out, depth of first minima as a function of orientation ➔ asymmetric



EHT collaboration 2019



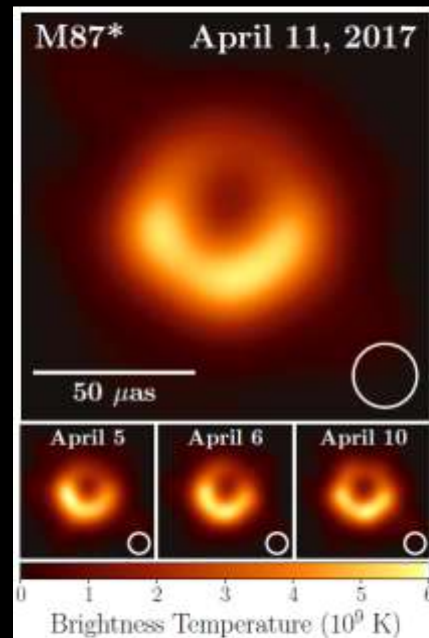
Thompson+ 2017



Doeleman+ 2012

Images and Features

- EHT baselines sample a (very) limited range of spatial frequencies
  - 25 to 160 μas
- Two algorithms
  - Inverse-modelling – CLEAN & self-calibration
    - Deconvolve PSF from Visibilities
  - Forward-modelling – RML
    - Searching for images
- Four teams independently imaging
  - Common ring feature 38-44 μas diameter
  - With common enhanced brightness to the South
- Position angle 20deg between 5/6 and 10/11



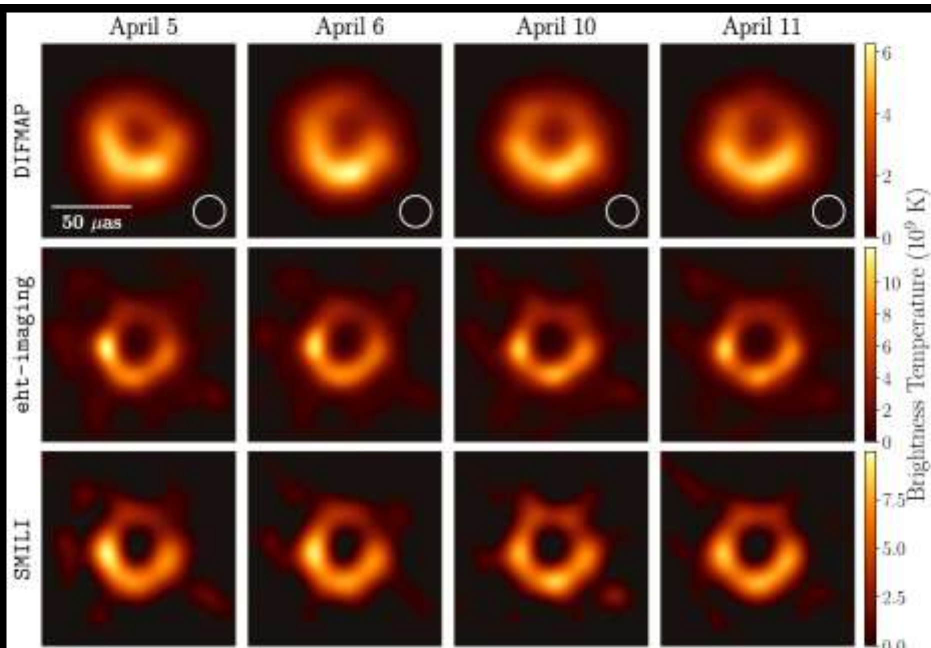


Figure 11. Fiducial images of M87 on all four observed days from each of the three imaging pipelines. CLEAN images (from DIFMAP) are shown after convolution with a 20 μas beam; eht-imaging and SMILI results have no restoring beam applied. Different selected fiducial imaging parameters (e.g., compact flux) result in different peak brightness temperatures for each method, as indicated by the unique color bars for each row.

Paper4

After beam-convolution of forward modelling data

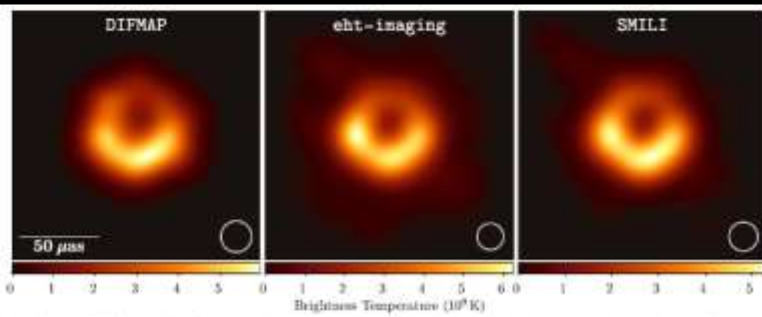
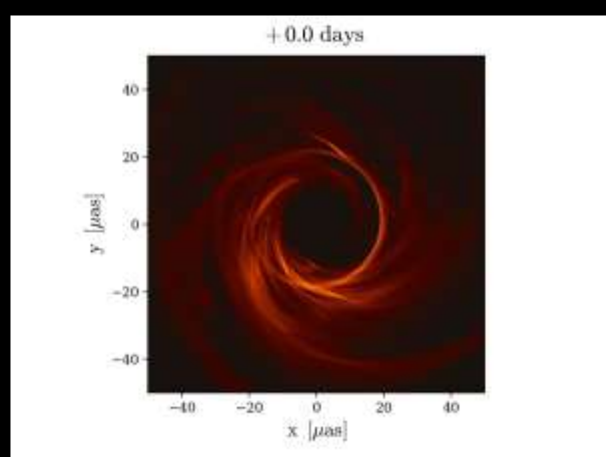


Figure 14. Fiducial images of M87 on April 11 from our three separate imaging pipelines after restoring each to an equivalent resolution. The eht-imaging and SMILI images have been restored with 17.1 and 18.6 μas FWHM Gaussian beams, respectively, to match the resolution of the DIFMAP reconstruction restored with a 20 μas beam.

Paper 4

Theoretical Modeling

- General-relativistic magneto-hydrodynamics (GRMHD) simulations
  - A turbulent, hot, magnetized disk orbiting a Kerr black hole
  - Powerful jet and the broad-band SED observed in LLAGN
  - a shadow and an asymmetric emission ring predicted
  - Ring – lensed photon ring rather than ISCO
- Synthetic image library built
  - Magnetized accretion flows onto black holes in GR
  - Coupled to three diffrent general-relativistic ray-tracing and radiative-transfer codes



MAD: a=0.94, R_high = 160

Paper 5

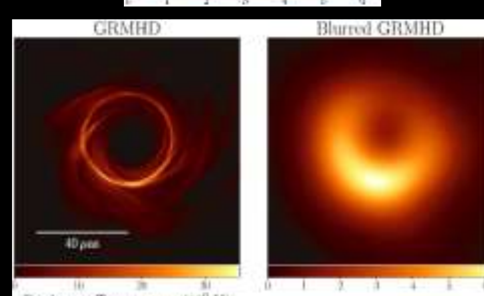
Model Comparison and Parameter Estimation

Parameters of M87*

Parameter	Estimate
Ring diameter [a] d	42 ± 3 μas
Ring width [a]	<20 μas
Crescent contrast [b]	$>10:1$
Axial ratio [a]	$<4:3$
Orientation PA	150°–200° east of north
$\theta_g = GM/Dc^2$ [c]	3.8 ± 0.4 μas
$\alpha = d/\theta_g$ [d]	$11^{+0.5}_{-0.3}$
M [c]	$(6.5 \pm 0.7) \times 10^9\ M_\odot$
Parameter	**Prior Estimate**
D [e]	(16.8 ± 0.8) Mpc
M(stars) [e]	$6.2^{+1.1}_{-0.6} \times 10^9\ M_\odot$
M(gas) [e]	$3.5^{+0.9}_{-0.3} \times 10^9\ M_\odot$

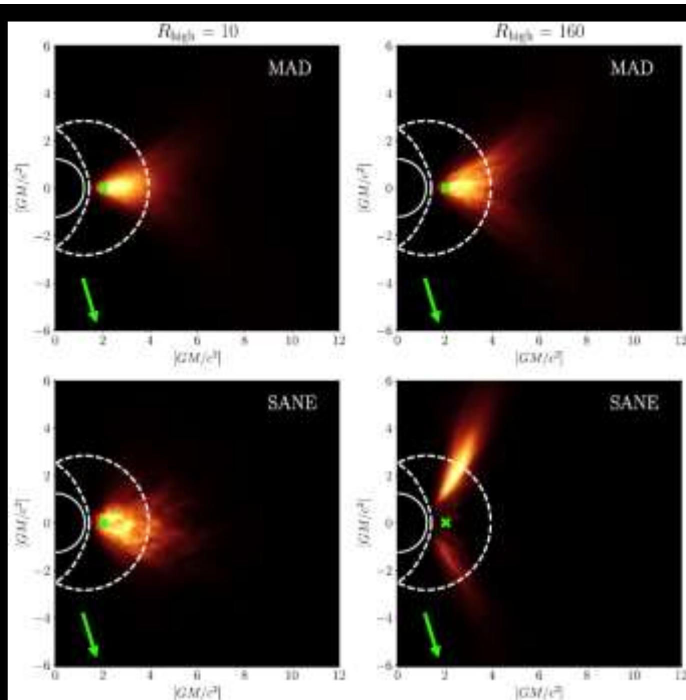
Theoretical Modeling

- Kerr Black hole with accretion flow
  - Initial: Thermal ion, relativistic electron and weakly magnetized torus, axis aligned
  - Outcome: All Corona with β_p ~ 1 & strongly magnetized poles (B^2 / ρc^2)
  - Schwarzschild BH disfavored : Accretion rate << Jet power
    - Blandford-Payne (1982, accretion disk) not enough
    - Blandford-Znajek (1977, BH spin + B) – Kerr BH
- MAD Highly magnetized
  - Magnetic flux / accretion rate ~ 15
  - ➢ All strongly magnetized
  - ➢ Emission mostly from disk midplane
- SANE Mildly magnetized
  - Magnetic flux / accretion rate ~ 1
  - ➢ Jet (disk) strongly (weakly) magnetized
  - ➢ High (low) R_high, emission mostly from jet (disk)



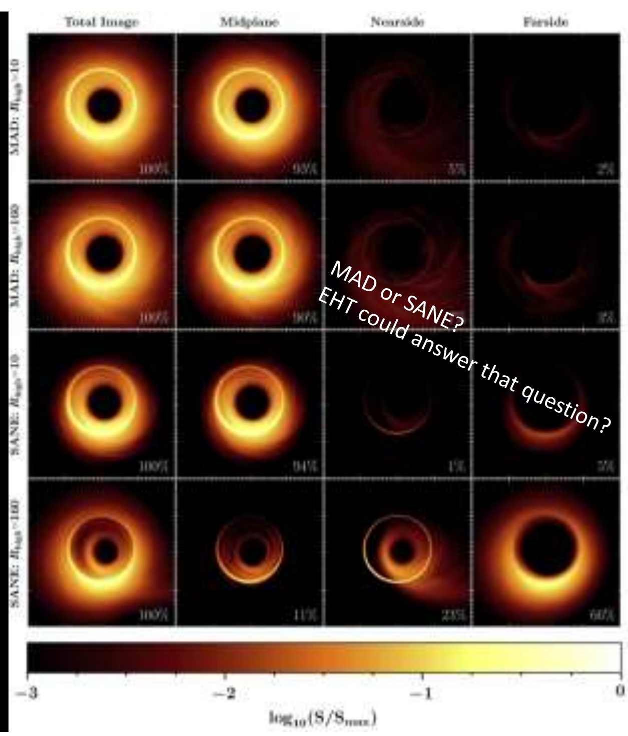
Paper 5

Where the lights come from?



Paper 5

Where the lights come from?



Paper 5

Conclusion and Outlook

- EHT, VLBI at a wavelength of 1.3 mm imaged horizon-scale structures around SMBH candidate in M87
- The image to be dominated by a ring structure of 42±3 μas diameter brighter in the south
- central brightness depression with a contrast of >10:1, which we identify with the black hole shadow
- Extensive library of synthetic images obtained from GRMHD simulations
  - basic features of our image are relatively independent of the detailed astrophysical model
  - black hole mass of 6.5±0.7×10^9M
- rotation of the black hole in the clockwise direction
  - The brightness excess in the south explained as relativistic beaming of material rotating in the clockwise
- To come: Polarization (RM → accretion rate), … Sgr A*! And other jetted AGNs
- And more stations (a KVN?) and higher frequency