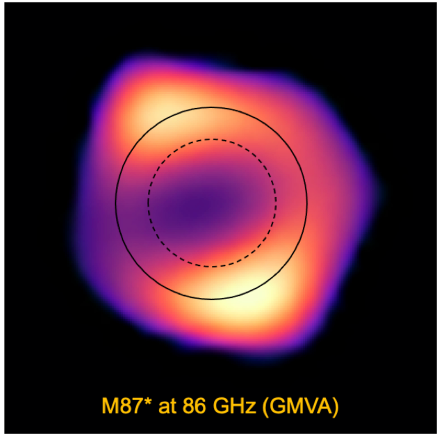
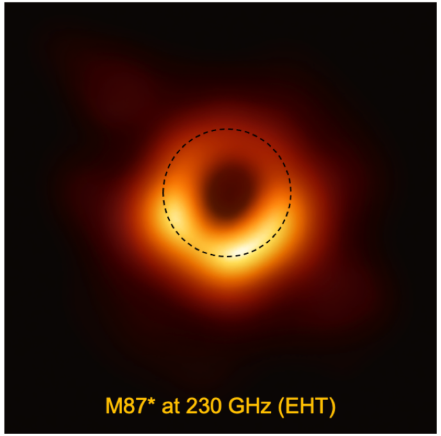
A tale of two black hole images of M87





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A ring-like accretion structure in M87 connecting its black hole and jet

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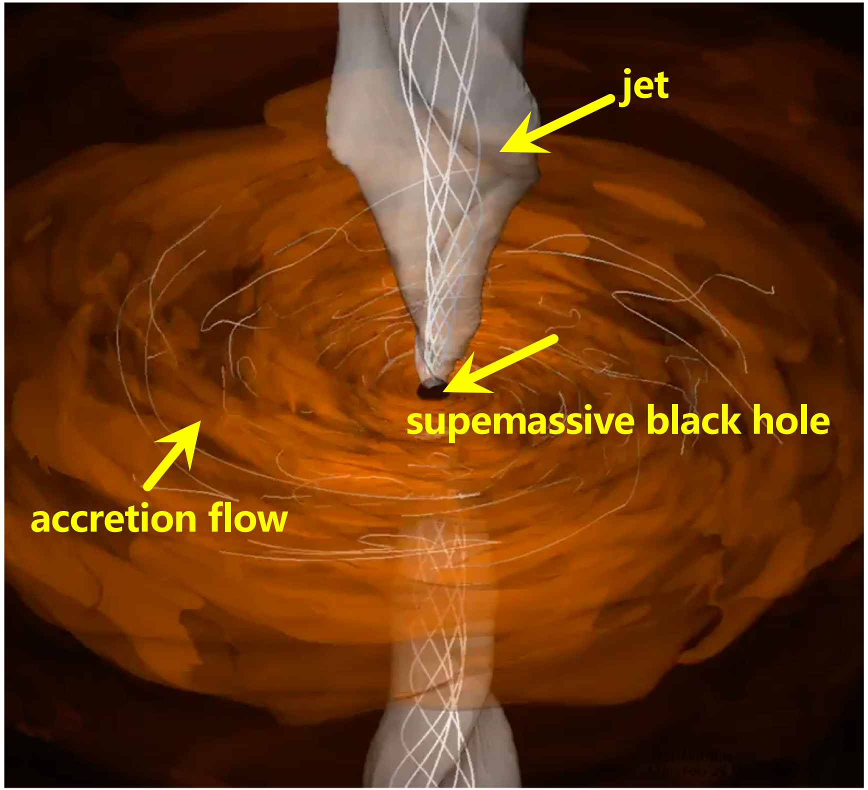
Abstract

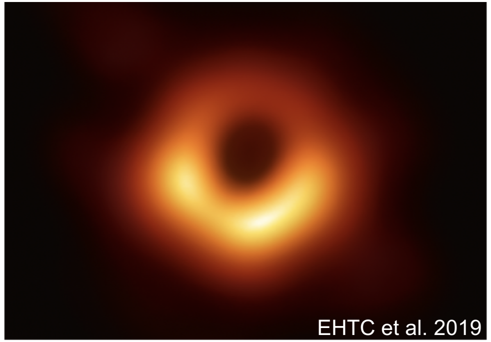
The nearby radio galaxy M87 is a prime target for studying black hole accretion and jet formation[1,2]. Event Horizon Telescope observations of M87 in 2017, at a wavelength of 1.3

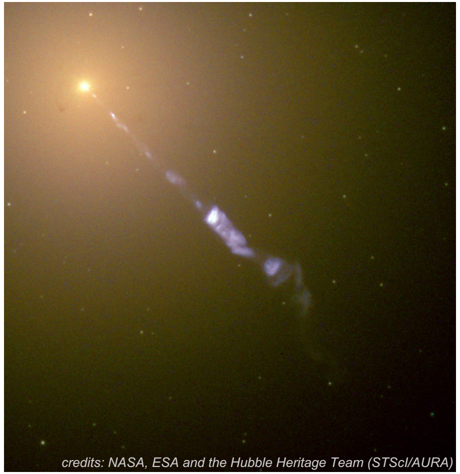
Central engines of AGN



credit: Hotaka Shiokawa

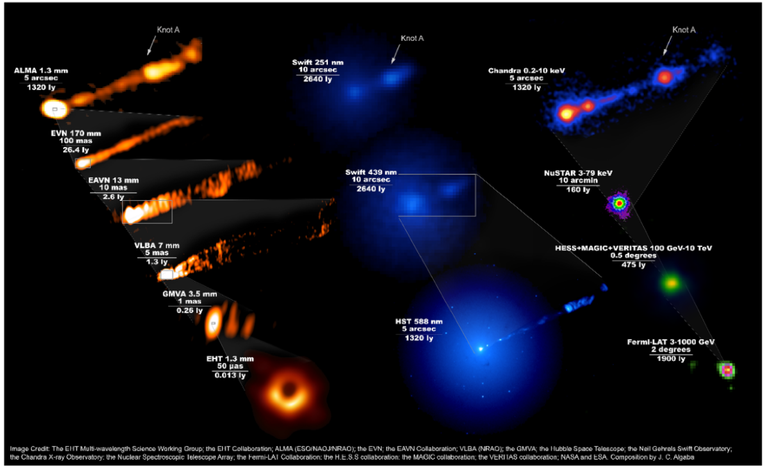
Image of the black hole M87*





M87: the “Rosetta Stone” for studying an AGN central engine

- The first cosmic jet discovered (Curtis 1918)
- 1Rs = 7.6 μas for M=6.5e9 solar mass and D_L=16.8 Mpc
- Edge-brightened structure on VLBI scales, wide initial jet opening angle
- Well studied for jet formation, collimation and acceleration



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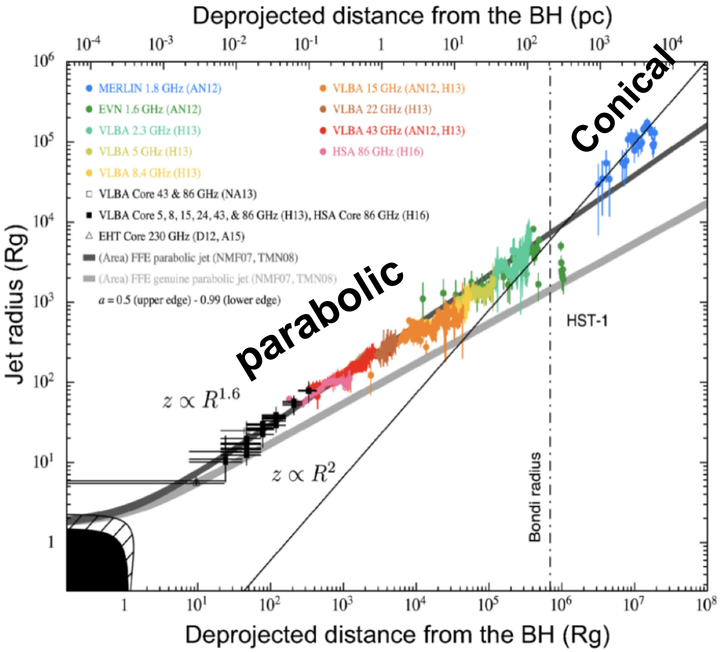

(Asada et al. 2012, Nakamura et al. 2018)

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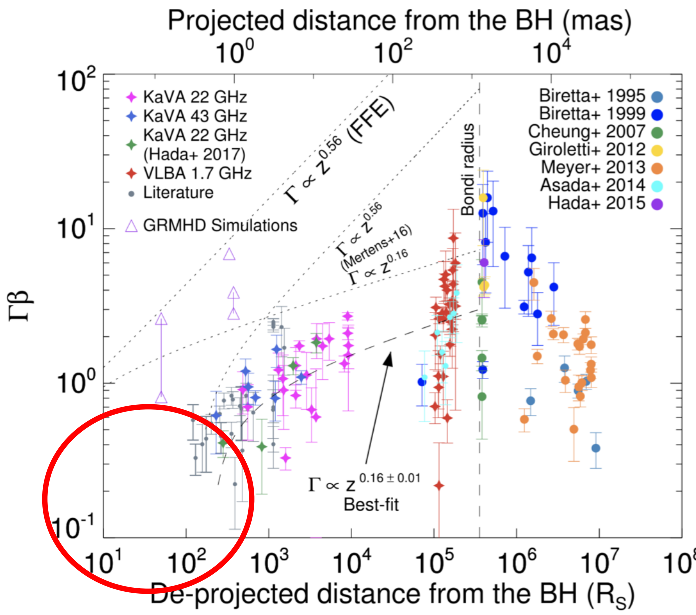
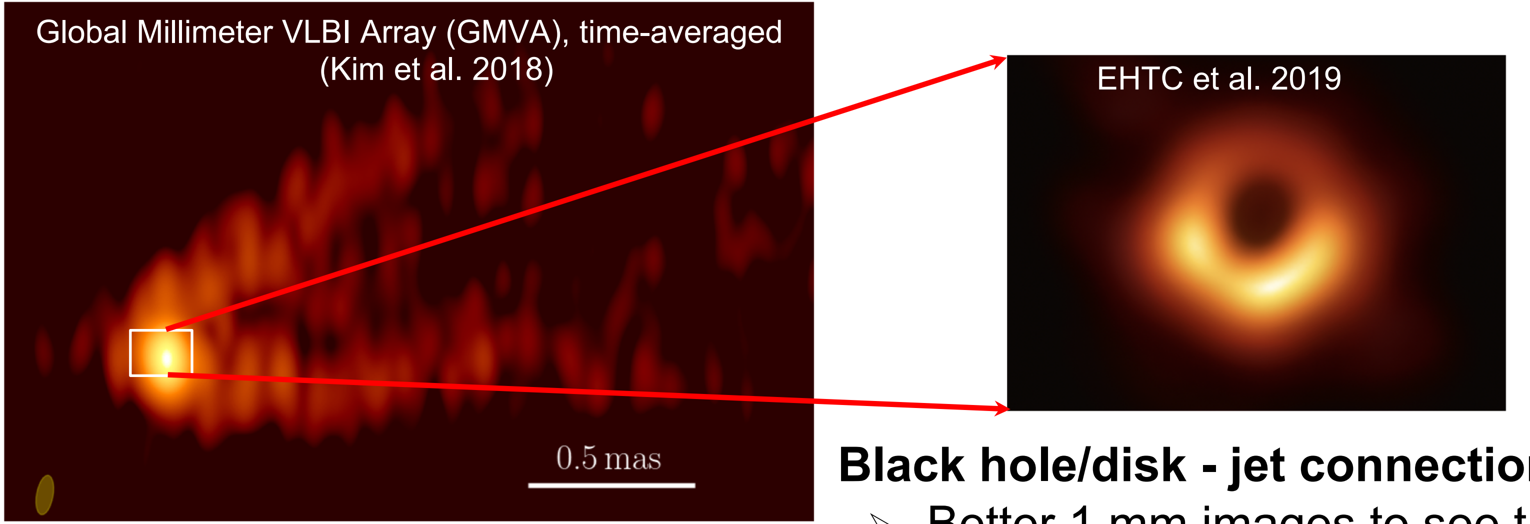
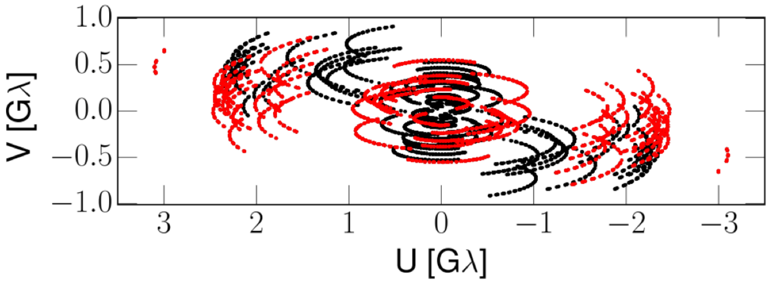


Park et al. 2019

The initial jet forming region has only been imaged with limited sensitivity and resolution

M87: the "Rosetta Stone" for studying an AGN central engine





Black hole/disk - jet connection:

- Better 1 mm images to see the jet?
- Better 3 mm images to resolve the "core"?

  >The jet is brighter at 3 mm

  >More stations available at 3 mm

First GMVA observations of M87 with ALMA +GLT

Main scientific goals:

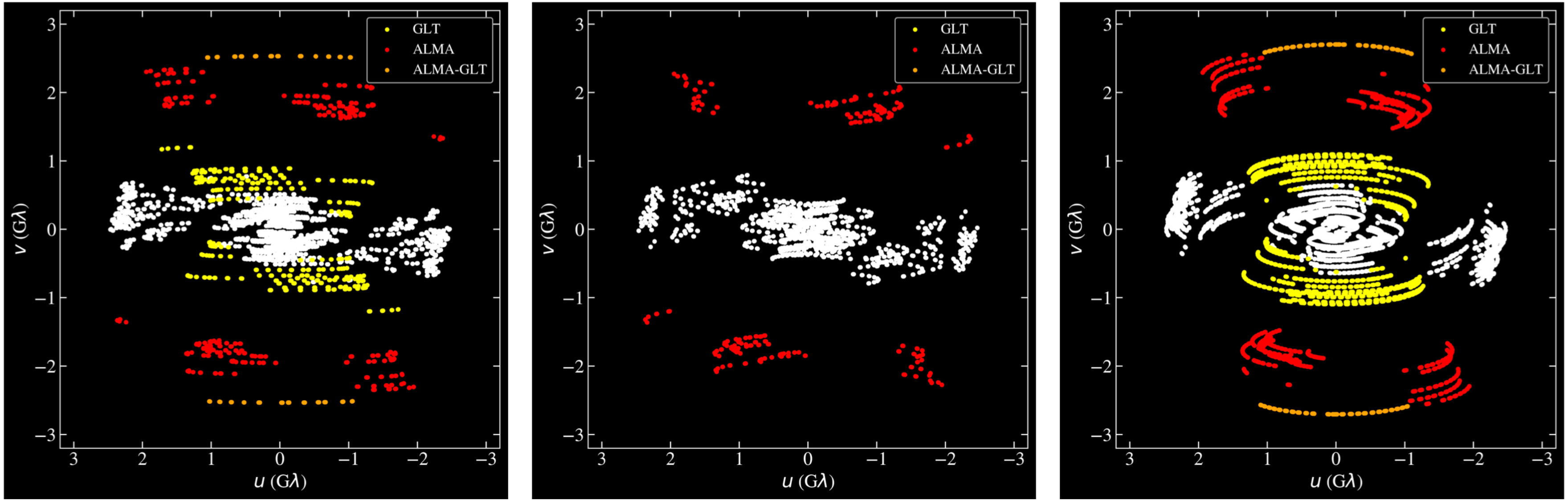
- BH jet formation
- Direct imaging of the BH accretion flow

Observations:

- GMVA+ALMA+GLT, 2018, April 14-15
- 3 sources: M87, 3C273, and 3C279
- 16 stations: Eb, On, Mh, Ys, Pv, GLT, GBT,
  8 x VLBA, phased ALMA
- Recording mode: dual pol., 2Gbps (except Ys)

ALMA +GLT significantly improves the N-S baseline coverage

3C273 (calibrator) **3C279 (calibrator)** **M87 (target)**

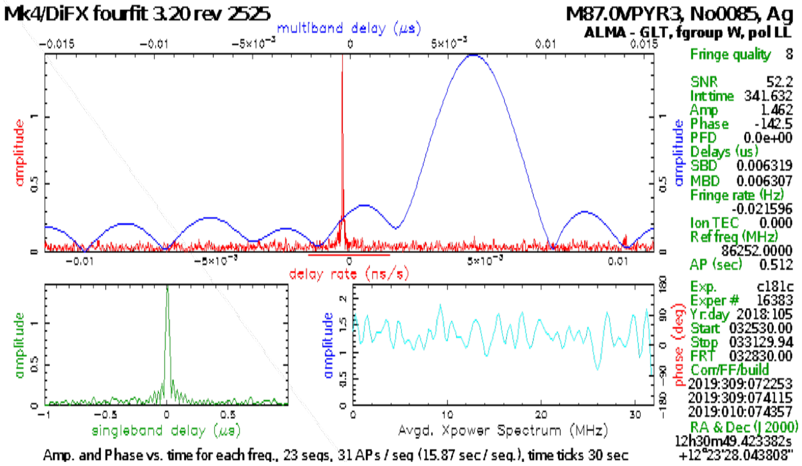


Improved the NS resolution by a factor of 4 for M87

Typical resolution for M87: 40*70 μas (**5-9 Rs**)

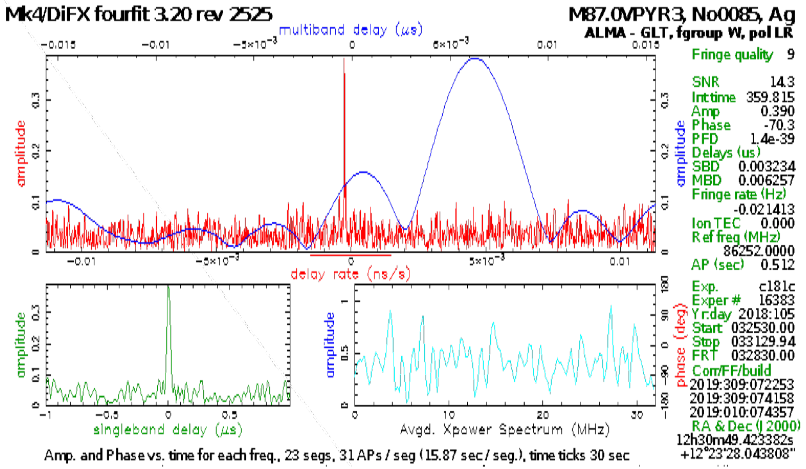
M87 was detected with high SNR

SNR=52



ALMA-GLT (LL)

SNR=14

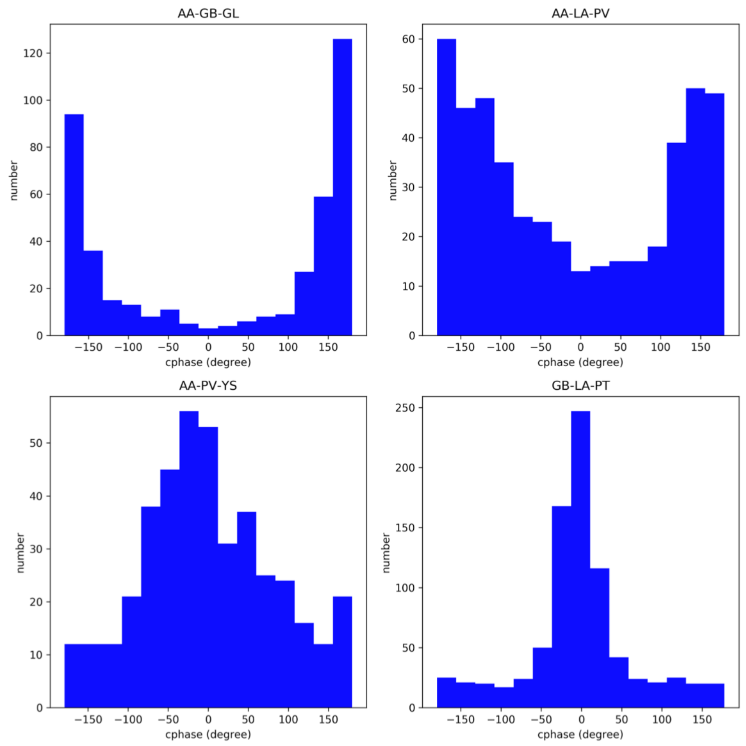


ALMA-GLT (LR)

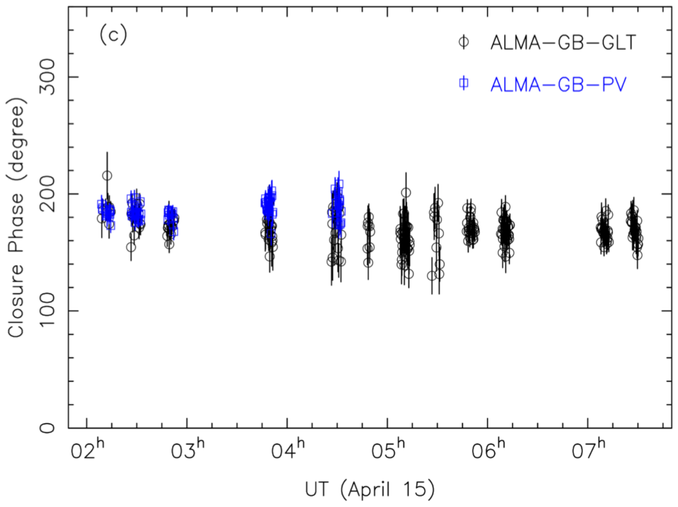
longest baseline length (ALMA-GLT): 10366 km

(longer than the longest baseline of the EHT2017 array that captured the first black hole image!)

Robust closure phase measurements of M87



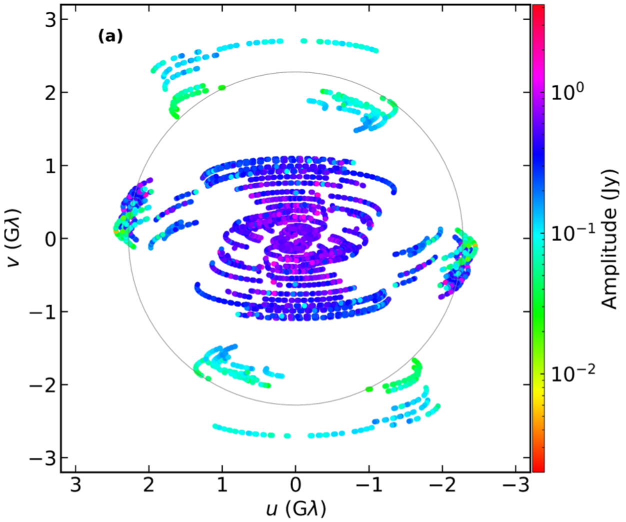
(time-collapsed) closure phase histograms for four triangles



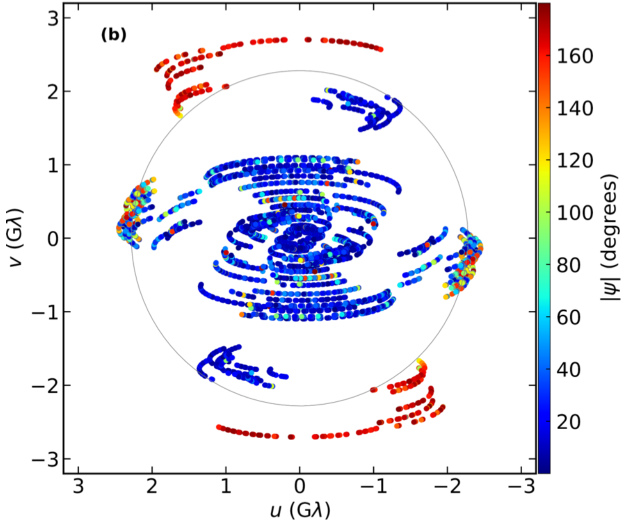
Cross-software (HOPS/AIPS) confirmed closure phases

Visibility amplitudes and (absolute) phases of M87

Visibility amplitude



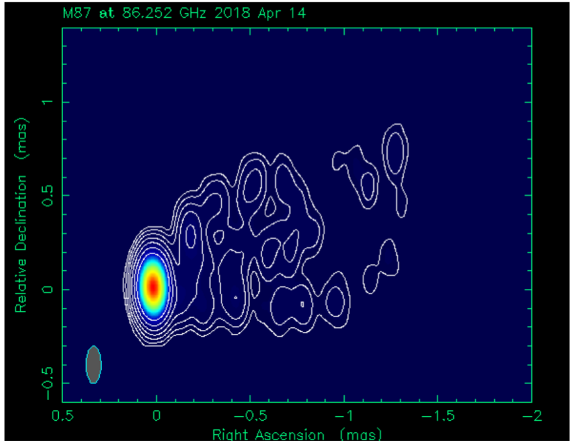
(absolute)Visibility phases

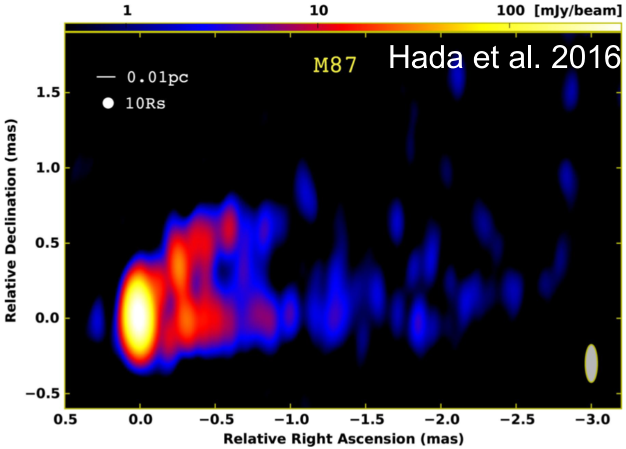


A visibility minimum and a clear phase jump from 0° to 180° across the minimum are seen around ~2.3 Gλ

(the location of this minimum does not depend on amplitude calibration)

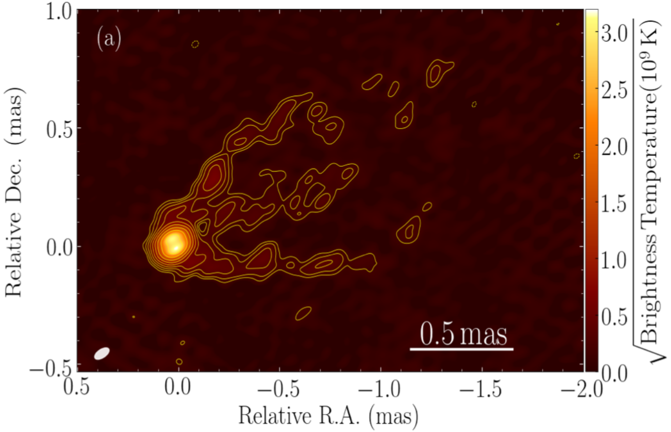
Imaging: an edge-brightened jet

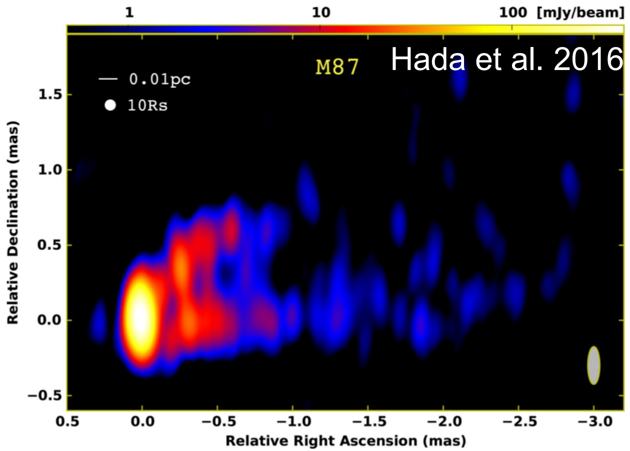




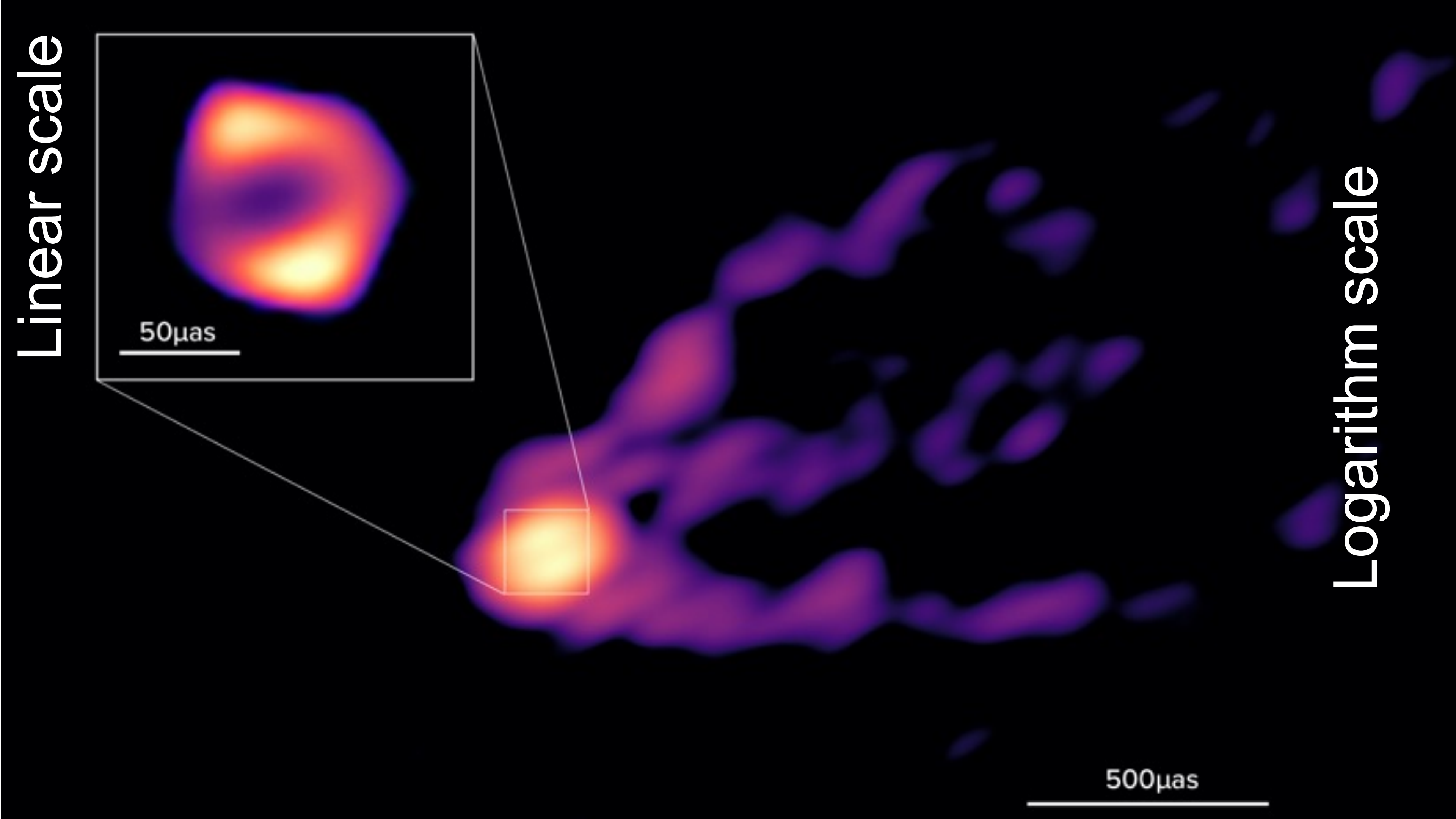
- Limb-brightened jet structure is clearly seen, consistent with previous results
- No strong indication of a counter-jet

Imaging: an edge-brightened jet with a spatially resolved core



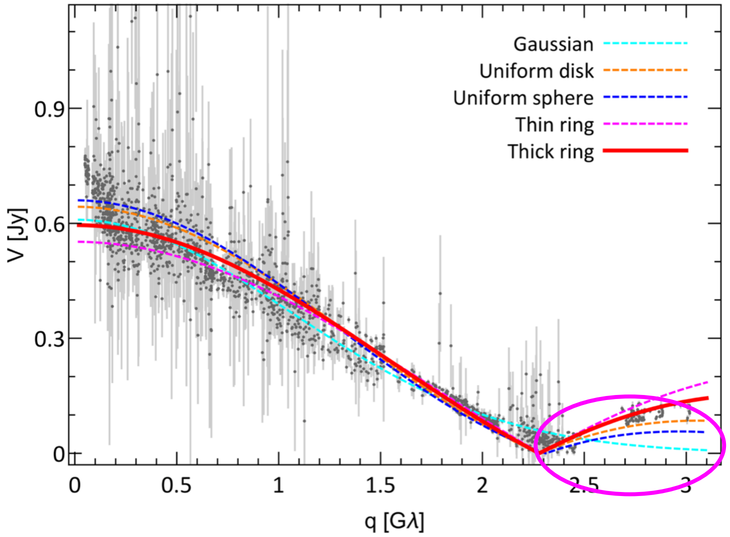


- Limb-brightened jet structure is clearly seen, consistent with previous results
- No strong indication of a counter-jet
- A relatively weak central jet spine
- Core region is clearly resolved at 3mm for the first time, showing a ring-like structure

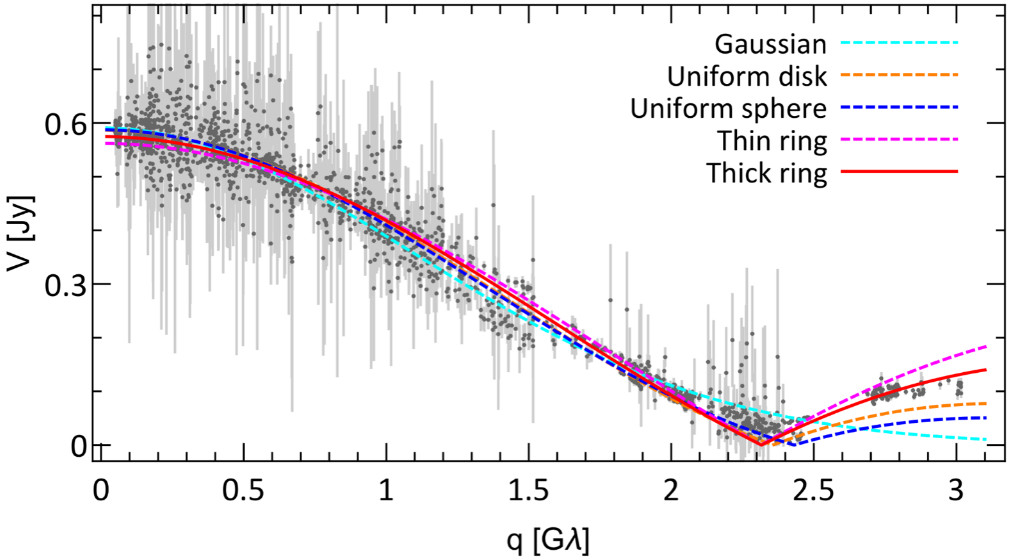


Linear scale
50μas
Logarithm scale
500μas

Modeling of visibility amplitudes



(full data, scan-averaged)



(jet-subtracted data, scan averaged)

- A significant visibility minimum is seen at ~2.3 Gλ
- Data at q >2.5 Gλ belong to ALMA; calibration of these data is very robust

Modeling of visibility amplitudes

- EHT first null is at ~3.4 Gλ
- GMVA null is at ~2.3 Gλ

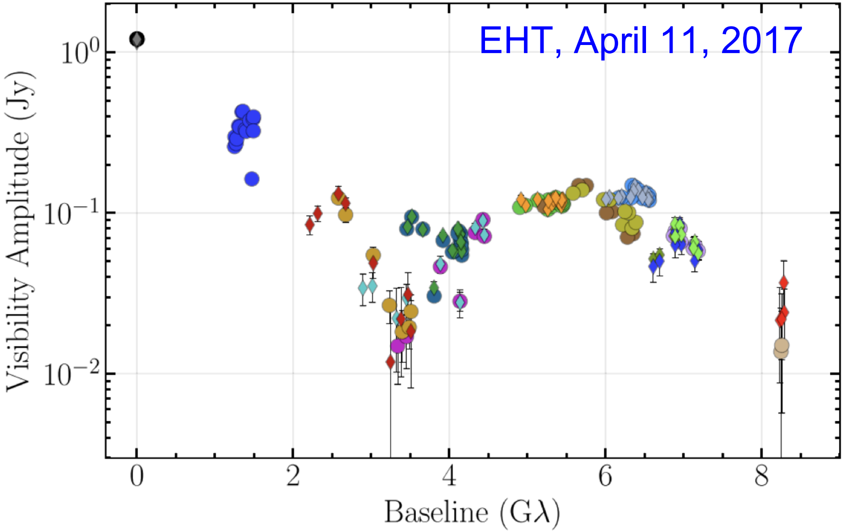
For a thin ring model (EHT M87 paper VI):

$$d_0 \simeq 45 \left(\frac{b_1}{3.5\ \mathrm{G}\lambda} \right)^{-1} \mu\mathrm{as}.$$

=> 46 μas (1 mm)

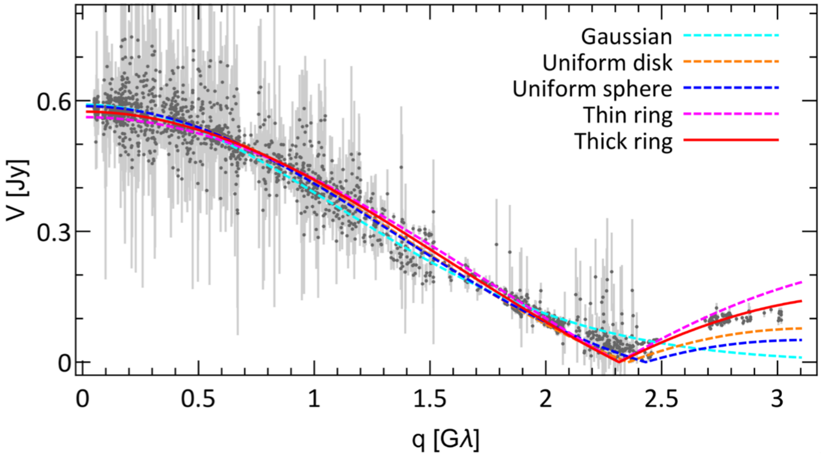
=> 68 μas (3 mm)

log scale

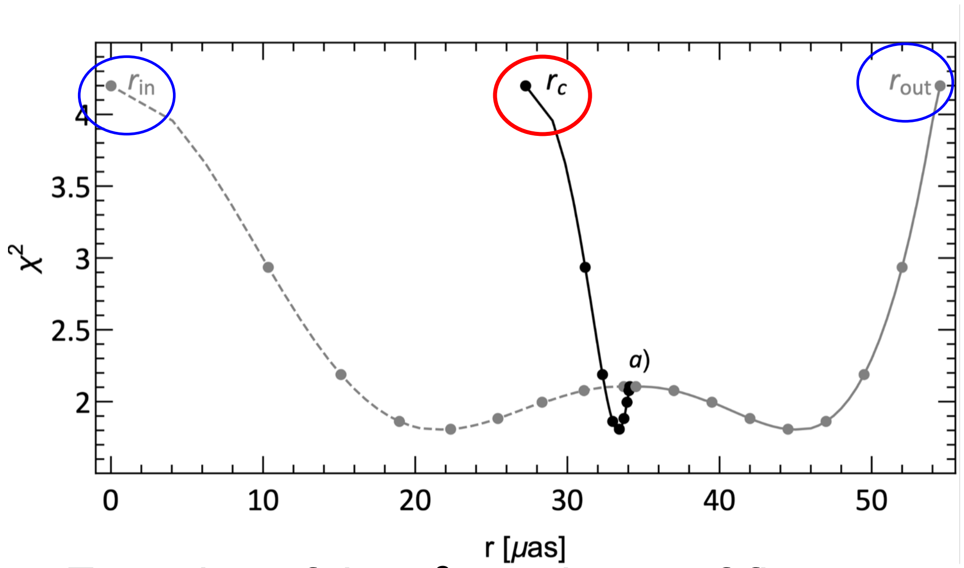


GMVA+ALMA+GLT, April 14/15, 2018

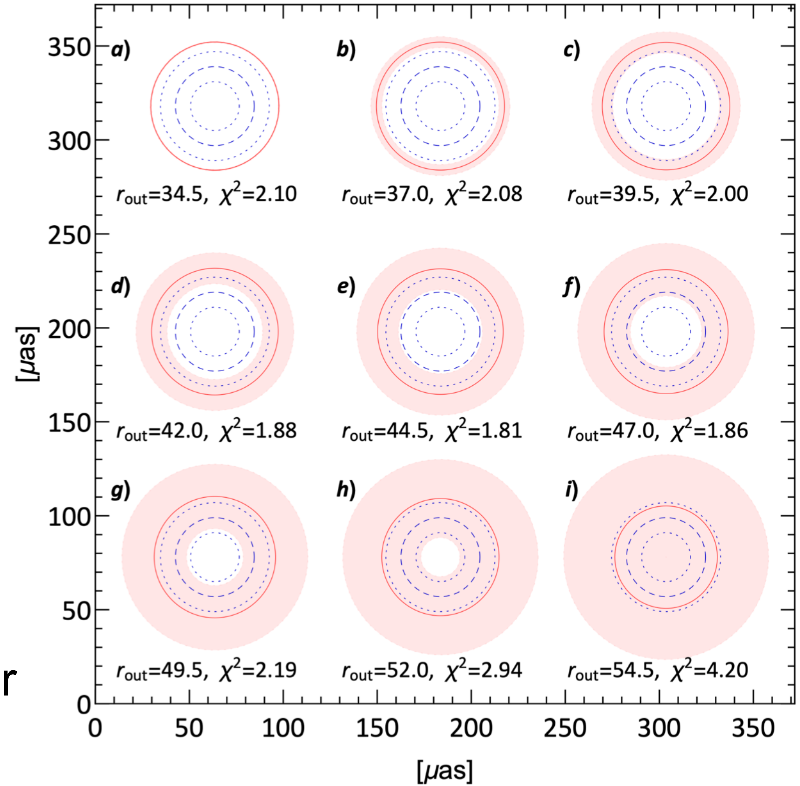
linear scale



Modeling of visibility amplitudes

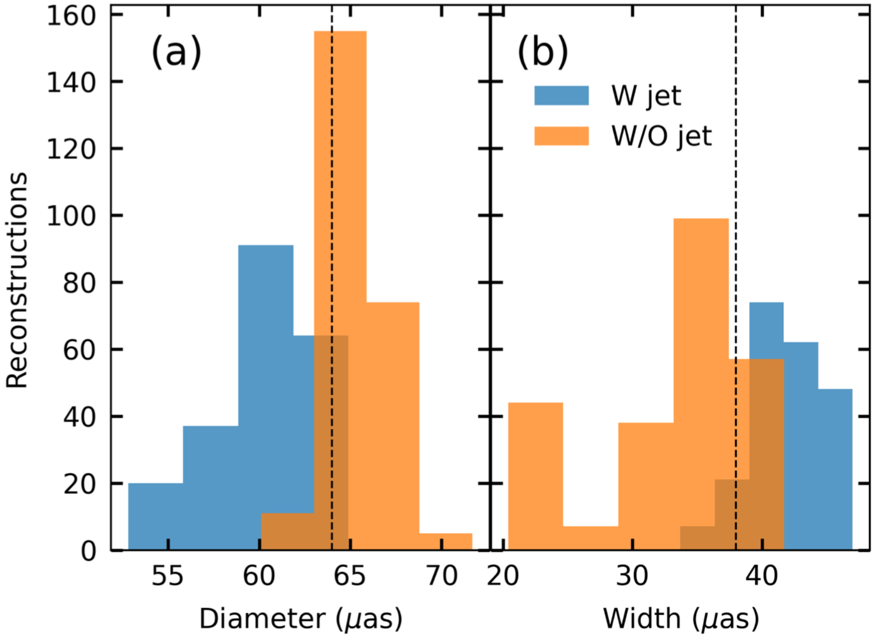


Evolution of the χ^2 goodness-of-fit parameter



A ring with a width of ~20 μas (thick ring) is favored by the data

Properties of the ring-like structure

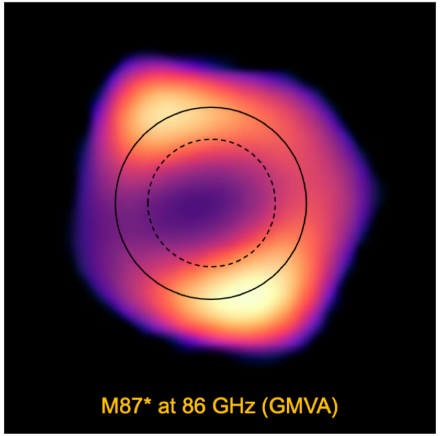


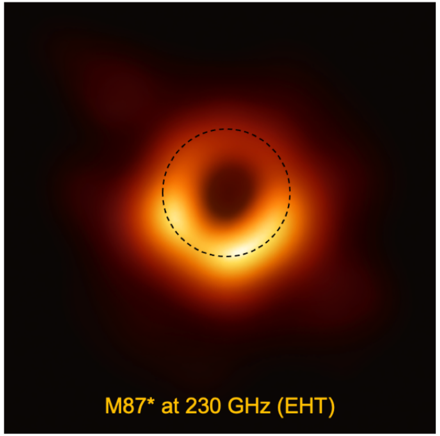
- Ring diameter: 64^{+4}_{-8} μas (~50% larger than the 1 mm ring)

  (results from image domain analysis and model fitting are consistent)

- Ring width is less well constrained (≳20 μas)

Properties of the ring-like structure





- Ring diameter: 64^{+4}_{-8} μas (~50% larger than the 1 mm ring)

  (results from image domain analysis and model fitting are consistent)

- Ring width is less well constrained ($\gtrsim$20 μas)

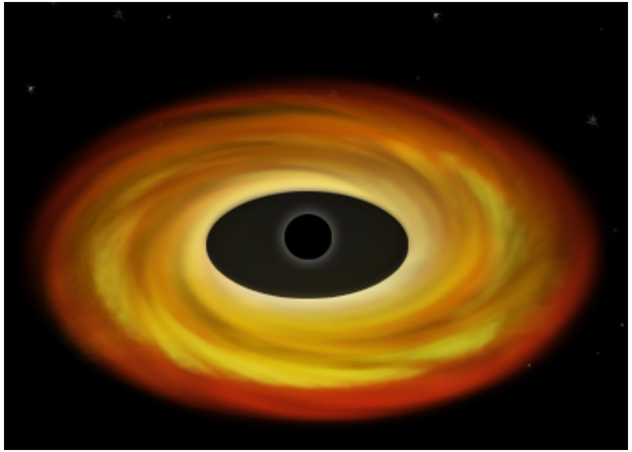
Modeling of Black hole Accretion Flow and Jet

— innermost regions

Thin disk

(Radiatively efficient)

$T_i = T_e$



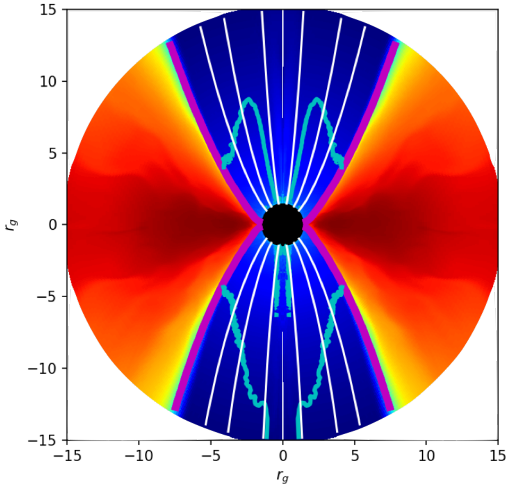
RIAF

Radiatively inefficient accretion flow

(e.g., M87, Sgr A*)

$T_i \gg T_e$

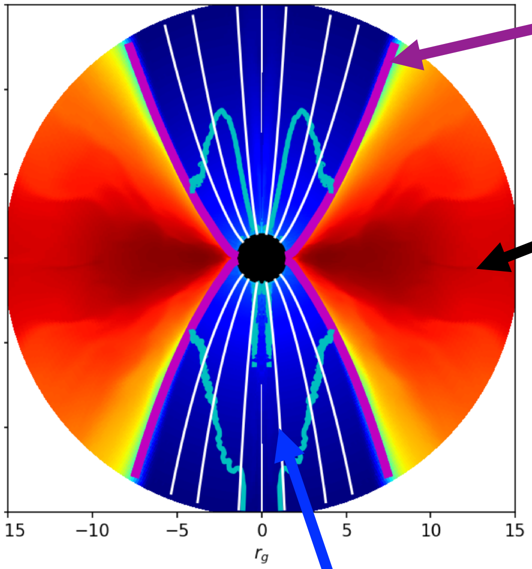
($\sim 10^{12}$K) ($\sim 10^{10}$K)



Accretion rate

Pu et al. 2022

Radiative Modeling



σ=1

(*Ratio between magnetic energy and rest mass energy)

Accretion model σ<1

Synchrotron emission from thermally distributed electrons

$n_e=n_i$

T_i/T_e=constant

(the coefficients are determined by spectrum)

(Moscibrodzka+ 09, Dexter+ 10)

Jet model σ>1

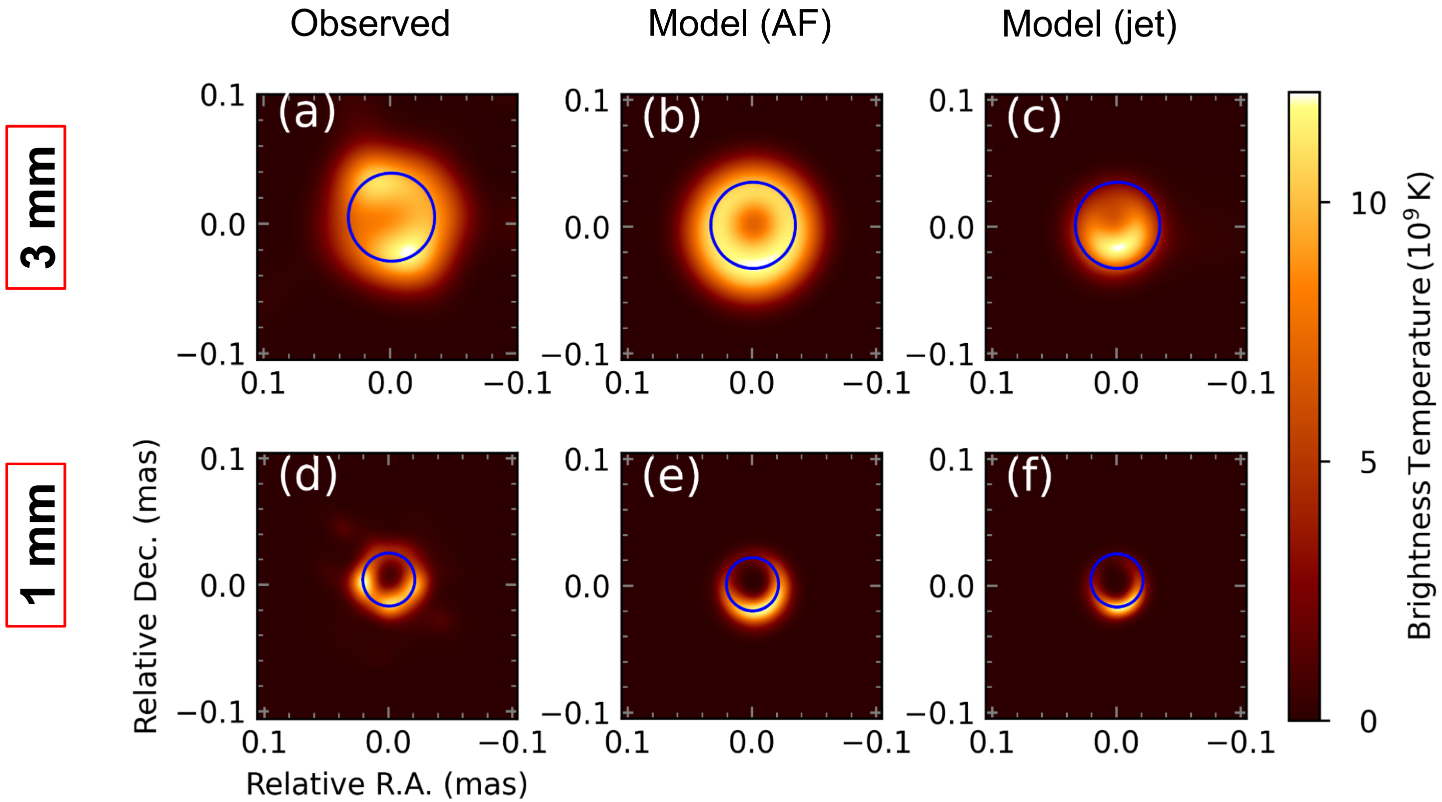
Synchrotron emission from non-thermal (power-law) distributed electrons

$n_e \propto B^2$ (Dexter 12)

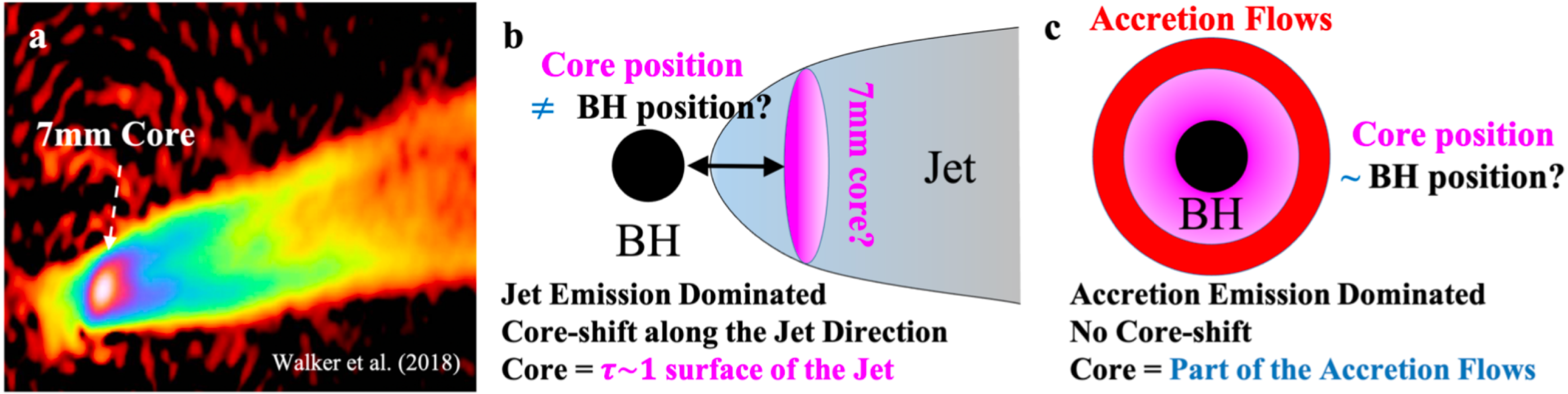
Given power-law index, energy cut-offs

(the coefficients are determined by spectrum)

Physical origin of the 3mm ring-like structure

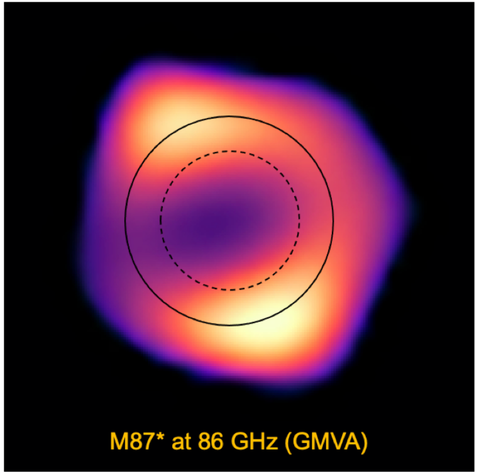


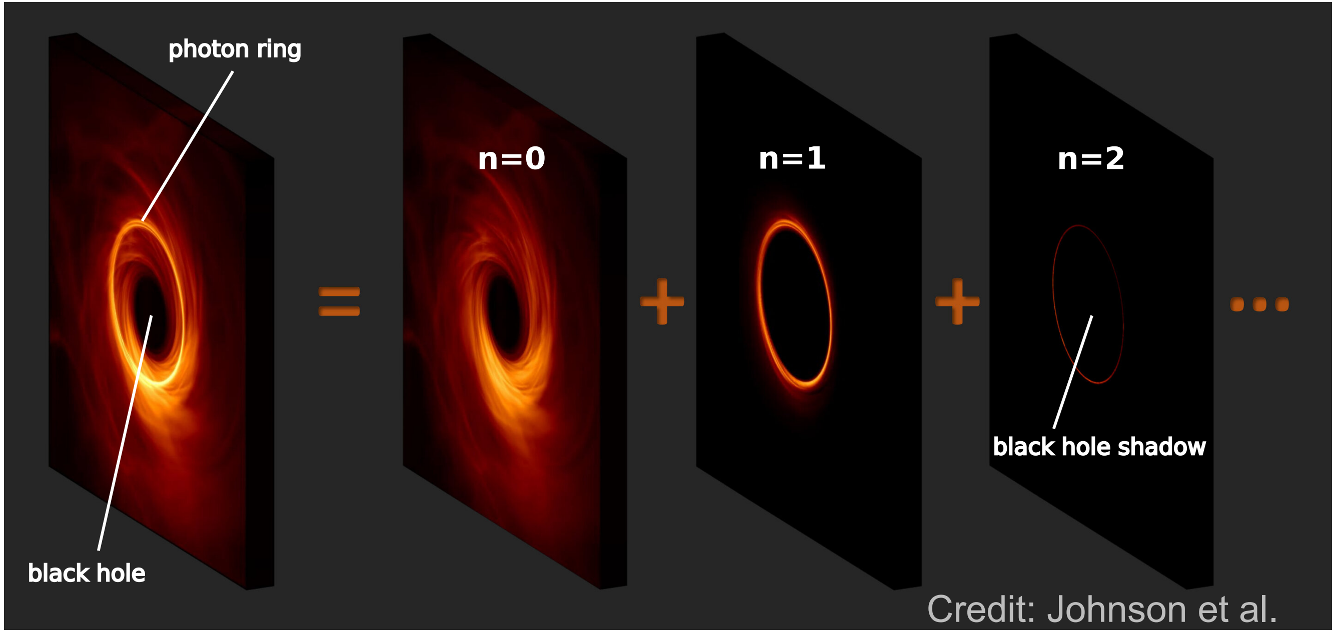
Challenges/opportunities



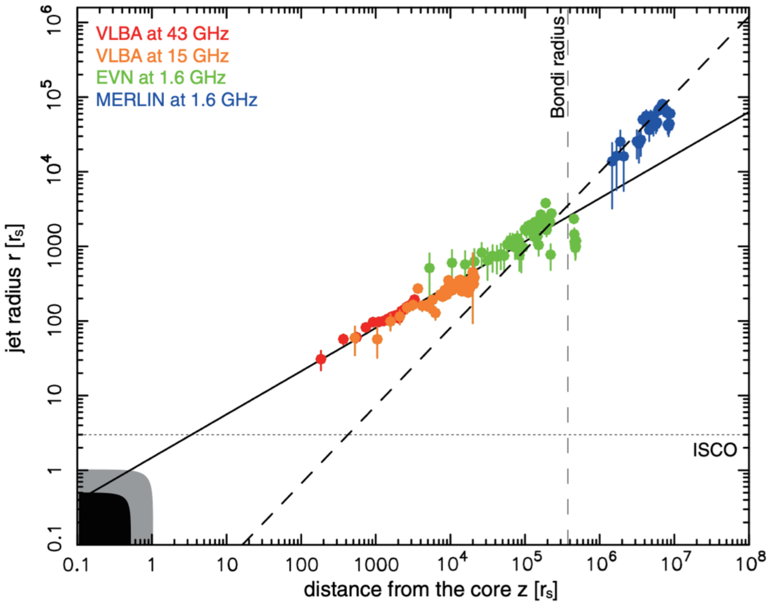
(credit: J. Park et al.)

Challenges/opportunities



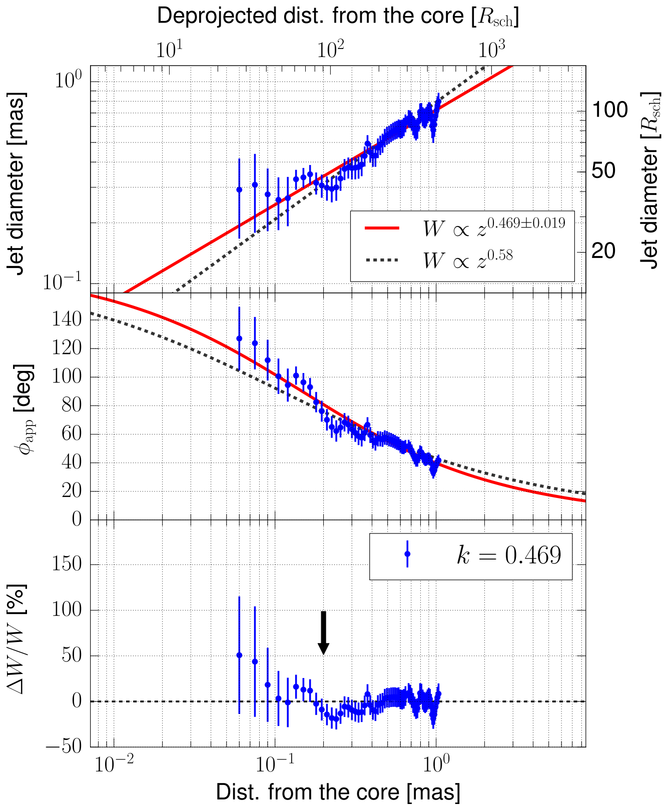


Jet collimation within ~100 Rs



k ~0.56

(Asada & Nakamura (2012); Hada et al. (2013,2016))

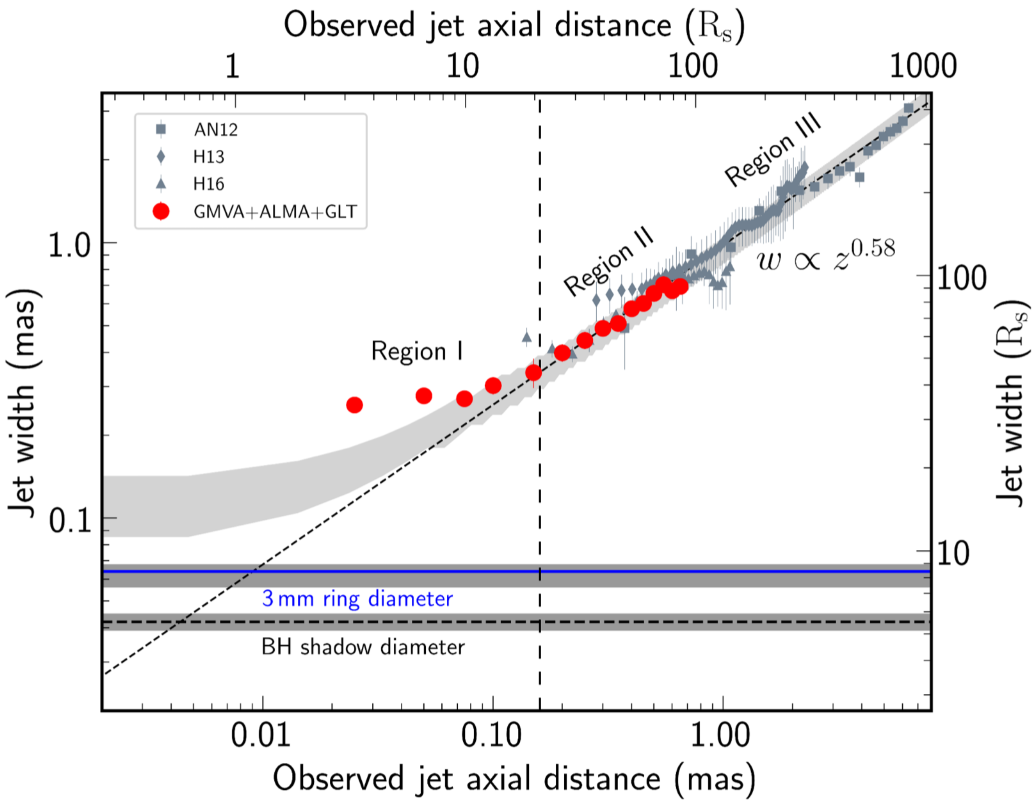


k=0.47–0.51

(Kim et al. 2018)

some flatterning trend toward the black hole?

Jet collimation within ~100 Rs



- study jet collimation within 0.8 mas (~100 Rs) in more detail
- The width profile in region II is consistent with previous measurements (region III)
- Within 0.2mas, the profile flattens toward the BH; the jet is wider than the theoretically expected width of a BZ jet (grey area) , suggesting an additional emission component (wind)

Summary: a “panoramic” picture of the central engine in M87

- The 3 mm core is resolved and the edge-brightened jet is connecting to a ring-like structure
- The 3 mm ring is ~50% larger and thicker than that seen at 1 mm. This indicates a significant contribution of the accretion flow, which adds to the gravitationally lensed ring-like emission around the black hole
- Near the BH, emission profile is wider than the expected profile of a black hole driven jet, suggesting possible presence of a wind associated with the accretion flow
- Future observations with better baseline coverage (e.g., KVN, NOEMA, LMT, JCMT, ATCA, etc.) and larger bandwidth (≧ 4 Gbps) will allow a more detailed study of the ring/jet in M87
- Synergy between 0.8/1 mm and 3 mm would allow us to study the spectral/polarization properties of the jet and the spatially-resolved “core”

Thank you for your attention