# **MWL observations of M87**

Original plan...

Results from MWL campaign during EHT-2017



# Kazuhiro Hada

(NAOJ/Mizusawa VLBI Observatory)

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Original plan...

Results from MWL campaign during EHT-2017



Not ready for public yet...

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- 0. Introduction
- 1. Linking BH to jet
  - Synergistic study by mm-VLBI (EHT) and cm-VLBI
- 2. Radio-TeV connection at jet base
  - Synergistic study by VLBI and VHE instruments
- 3. High-resolution view of HST-1
  - Long-term radio monitoring and recent status

#### M87

D = 16.8 Mpc $M_{BH} = 6.5 \times 10^9 M_{sun}$ 

Was everything answered about SMBH of M87? Of course no! Opening new era of SMBH astrophysics

#### Post-BH shadow era: Questions to be addressed

- What's the exact spacetime geometry near SMBH?
- What drives accretion onto SMBH?
- How SMBH generates powerful relativistic jets?
- What's the key parameters controlling accretion & jet?
  BH spin? B-fields? Accretion rate?
- How particles are highly accelerated near SMBH?
- What makes the diversity of AGN/SMBH?

#### **MWL study together with EHT is essential**

## M87 is bright across whole EM spectrum



#### M87 MWL campaign during EHT-2017 (EHT-MWL Working GP et al.)



First-ever MWL dataset allowing us to establish simultaneous broadband SED together with a BH shadow image!

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# Formation of AGN jet

Marscher+2008



## Quest for uncovering ACZ of M87 jet



*Kim+2018; Nakamura+2018* 

Park+2019

# **Quest for uncovering**



Intensive (~biweekly) monitoring with EAVN/KaVA (Hada+2017, Park+2019)



# Quest for uncovering ACZ of M87 jet



- Beautiful coexistence of collimation and acceleration zone
- MHD-driven jet of M87 is now strongly supported by both EHT and cm-VLBI

For more details about jet kinematics, see Jongho Park's talk at AGNjetWS2020

# Year-scale "wobbling" of BH shadow

Wielgus+2020



- Year-scale PA change of bright part of EHT ring
- What causes such wobbling? Still highly uncertain
- Any possible hint/correlation in large-scale jet?

# Accumulation of 43GHz VLBI data reveals year-scale wobbling of jet base at ~100Rs





#### Periodic oscillation of jet PA and North-South brightness ratio?



#### Periodic oscillation of jet PA and North-South brightness ratio?



# First global VLBI with ALMA at 86GHz



- 86GHz: a "sweet spot" to connect BH shadow and jet
- First 86GHz global VLBI with ALMA done in 2018
- EastAsia M87 team is leading this, stay tuned!

43GHz

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# M87 as a TeV emitter

- One of few radio galaxies detected in GeV/TeV
- Several TeV episodes in the past
- 2005: HST-1?
- 2008 (+2010, 2012): Nucleus
- Some γ-ray photons must be produced near SMBH where EHT/VLBI is directly resolving



# Large discrepancy in $U_e/U_B$ ratio



Why large discrepancy despite observing similar spatial scales?

#### (Moderate) TeV event in 2012



#### Triple-ridge jet structure revealed by high-sensitivity VLBI imaging



 $\theta = 18^{\circ}$ 

 $Log \nu$  [Hz]

20

25

15

10

Strong evidence that M87 jet is stratified Different layers may be associated with high/low-energy components

#### **Growing EHT-MWL campaigns on M87**

#### M 87 Multi-Wavelength Campaigns

Telescopes	2017	2018	2019	2021
EVN 180mm	Joined	Joined		Planned
VLA 15-75mm		Joined	0- <u></u> -1	Planned
<i>EAVN</i> 7-13mm	Joined	Joined	Joined	Submitted
<i>R.A.</i> 13mm		Joined		
VLBA 7mm	Joined	Joined		Planned
HSA 3mm	Joined	Joined		Planned
GMVA 3mm	Joined <sup>a</sup>	Joined	Joined <sup>a</sup>	Submitted
EHT 1mm	Joined	Joined	Rejected	This proposal
Kanata		Joined		Planned
TESS	—		—	Submitted
Chandra	Joined	Joined	Joined	Submitted
NUSTAR	Joined	Joined	Joined	Submitted
Swift-XRT	Joined	Joined	Joined	Submitted
AstroSAT		Joined	Joined	Submitted
Fermi-LAT	Joined	Joined	Joined	Planned
HESS	Joined	Joined	Joined	Planned
MAGIC	Joined	Joined	Joined	Planned
VERITAS	Joined	Joined	Joined	Planned

*Red/black text: programs led by members of the EHT Consortium or external collaborators.* <sup>a</sup>: No *ALMA in 2017.* 

- Growing MWL coverage
- Low state in 2017
- High state in 2018
- Hopefully resume 2021

#### Future synergy between EHT and next-gen high-energy instruments Chael, Akiyama+



- Expansion of EHT in coming years will allow us to image shadow + extended jet up to ~1000Rs at 3Rs resolution, covering a full range of scales expected by various VHE models
- Joint observations with ngEHT and CTA!



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#### Biretta+1998

Superluminal Motion in the M87 Jet



### HST-1

- Peculiar complex knot at 100pc (~1")
- Fastest feature in M87 jet
  - ~6c@optical (also in X-rays: Snios+2020)
  - ~4c@radio
- Quasi-stationary feature in upstream edge
- Possible recollimation shock at the end of ACZ



Cheung+2007

### **Radio-to-TeV flares in 2005**



What's the subsequent evolution of HST-1? Recent status?

#### **16-year-long VLBI monitoring of HST-1** (VLBA or EVN at 1.7/5GHz)

KH, Giroletti+

in prep



### **Light curves**

HST-1 at optical VLBI 1-2GHz total flux of HST-1 01-01-2012 31-12-20 01-01-2016 F(>300 GeV) [10<sup>12</sup> cm<sup>2</sup> s<sup>1</sup>] minimum + MAGIC HST-1 1.4/1.7GHz (EVN or VLBA) ф ₩, 1.4 200 ..... <sup>2</sup>(0.3-500 GeV) [10<sup>-0</sup> cm<sup>2</sup> s<sup>-1</sup>] minn Fermi-LAT 0.3-500 GeV 175 Ô Flux density at L-band (mJy) 150 - Chandra core . keV) . . ---- Chandra HST-1 2005 flare (0.5-7 125 + HST core + HST HST-1 F, (NUV 100 þ RING/02 .9.0 - RINGO3 red 75 Polariza [%] mmm RINGO3 gree 2. 8 200 O - RINGO3 blue 1. þ - RINGO2 50 - RINGO3 red EVPA ['] RINGO3 gre 0.0 + RINGO3 blu 1. 9.300 25 ¢-----\$ °¢¢ (Rad ф Ċ 0 2012 2004 2006 2008 2010 2014 2016 2018 56000 56500 57000 57500 58000 MJD Epoch (year)

MAGIC Collaboration+2019

#### Repeated ejections of superluminal components from upstream edge of HST-1



- Long-term VLBI monitoring continues to witness active evolution of HST-1
- Detection up to ~6c motion discovered also at radio (comp4)

#### **3D helical motion in HST-1?**

30 20

10

-10

-20

-30





 Significant change in apparent speed when changing moving direction

# Present and future on HST-1 study

- Despite being quiescent after 2005, HST-1 continues to exhibit interesting activities on mas-scales
- Fastest flows in M87 jet, likely traveling in helical paths
- Many other peculiar observational characteristics
- HST-1 will continue to be the "suspect" of gamma-ray production. Worth while keeping our MWL eyes
- HST-1 will be a very interesting target of future MWL study with SKA, ngVLA and CTA



# Summary

- EHT obtained the first BH shadow image of M87, but still many key questions remain to be solved
- MWL study together with EHT is essential
- Future MWL collaboration with next-gen MWL instruments (ngEHT, global VLBI, SKA, ngVLA, XRISM, CTA etc), as well as state-ofthe-art theory/simulations, will be promising to fully understand the nature of SMBH in M87 and other AGNs



Let's enjoy the workshop!