

# 高解像度電波望遠鏡で探る 活動銀河ジェット根元の 観測最前線

高エネルギー宇宙物理学研究会2017

2017年9月5-7日 京都

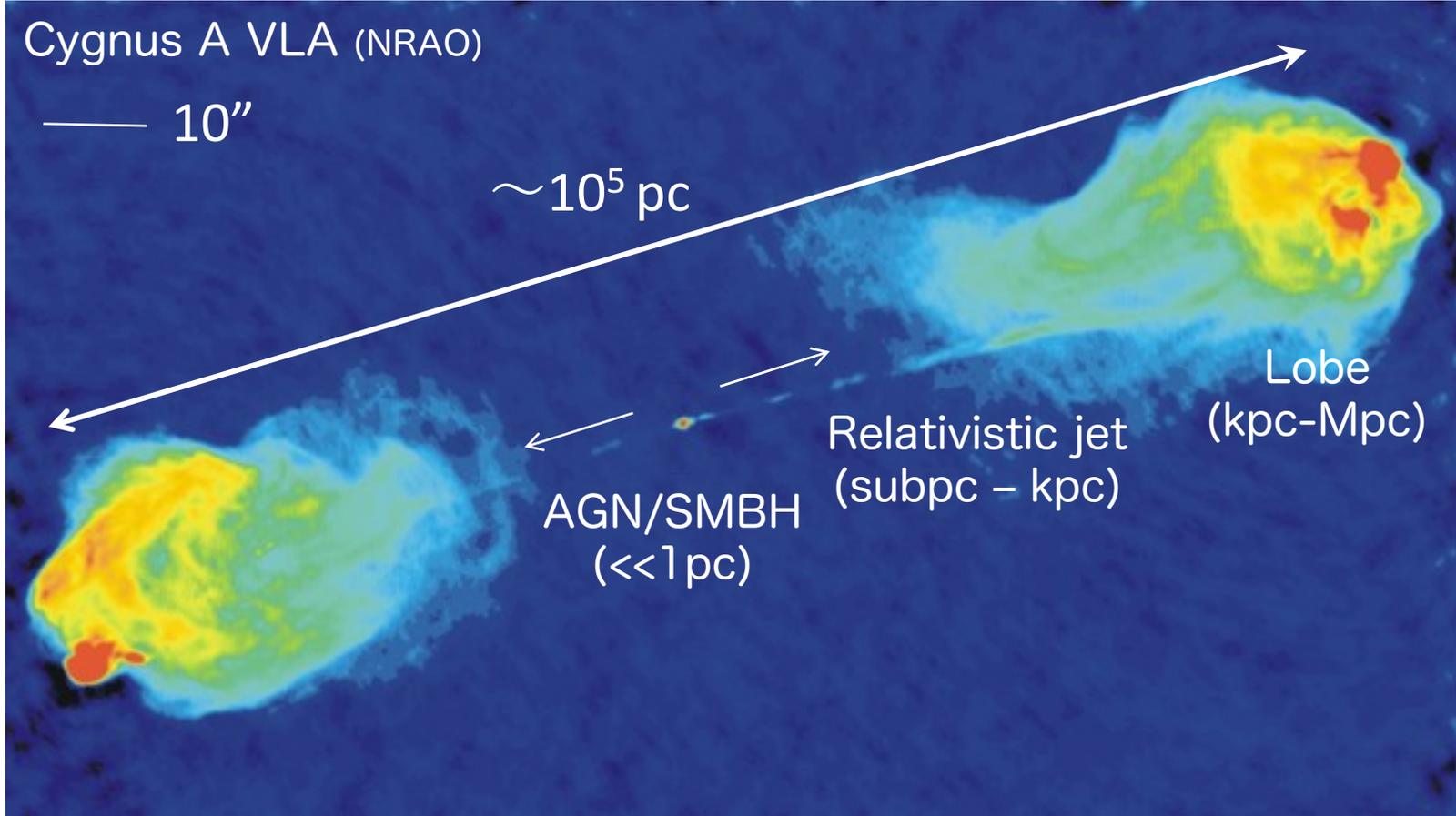
秦 和弘

(国立天文台 水沢VLBI観測所)

# Outline

- **High-resolution radio view of an AGN jet**
  - Recent observational progress on M87
- **Growing international VLBI projects**
  - Event Horizon Telescope (EHT)
  - East Asian VLBI Network (EAVN)

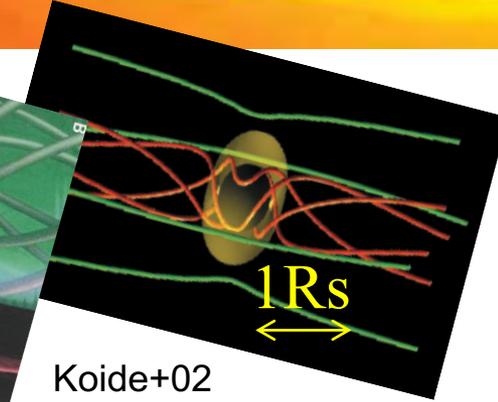
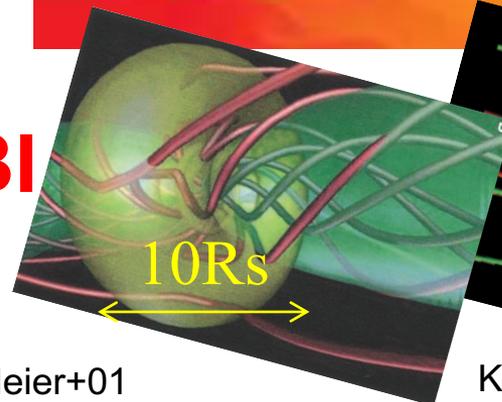
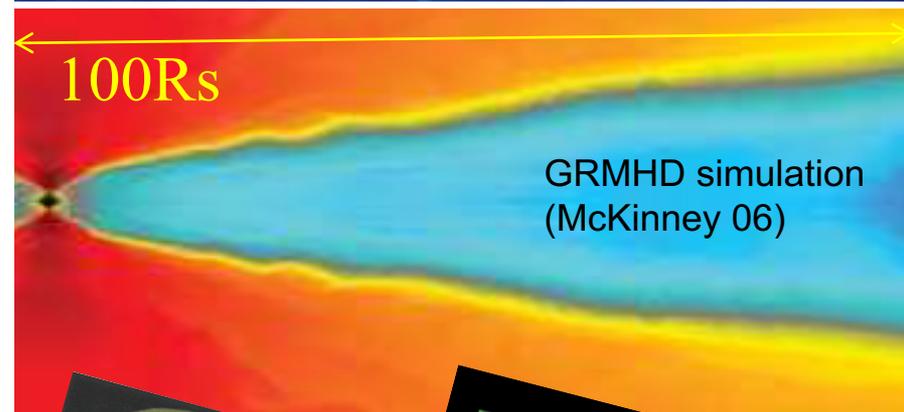
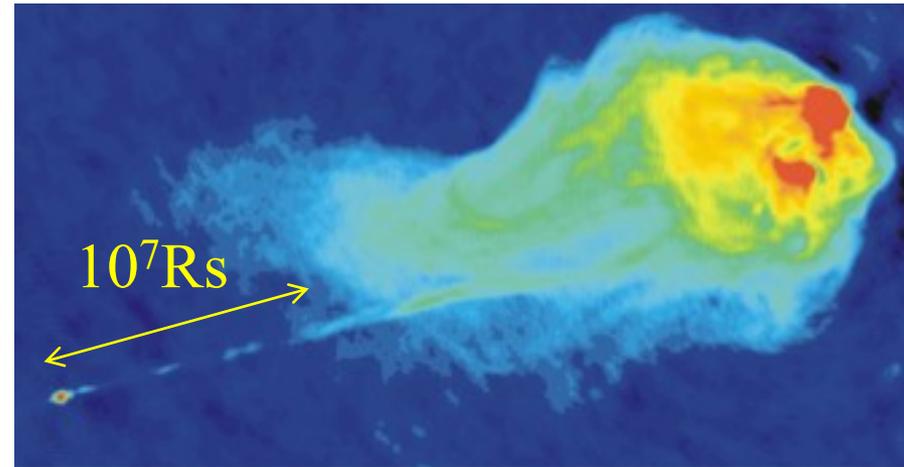
# AGN jets



- Powered by the central engine (SMBH + accretion disk)
- Very fast, collimated, magnetized, nonthermal plasma outflows
- Radio-to-TeV emission (synch. + IC), Doppler beaming

# Longstanding questions

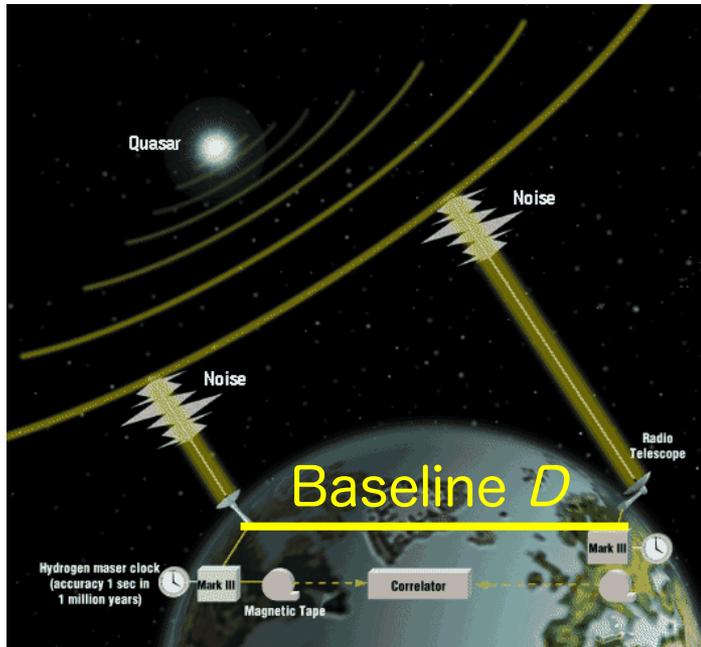
- Collimation ( $\Theta \sim 1^\circ$ )
- Acceleration ( $\Gamma > 10$ )
- Role of B-fields
- Central engine
  - SMBH, accretion flow
- Multi-layered (spine-sheath)
- High-energy emission ( $\sim \text{TeV}$ )
  
- Size  $< 10^3 R_s \sim 1 \text{ pc} \sim 1 \text{ mas}$ 
  - ( $10^8 M_{\text{sun}} @ 1 \text{ Gpc}$ )
  
- => High-resolution VLBI



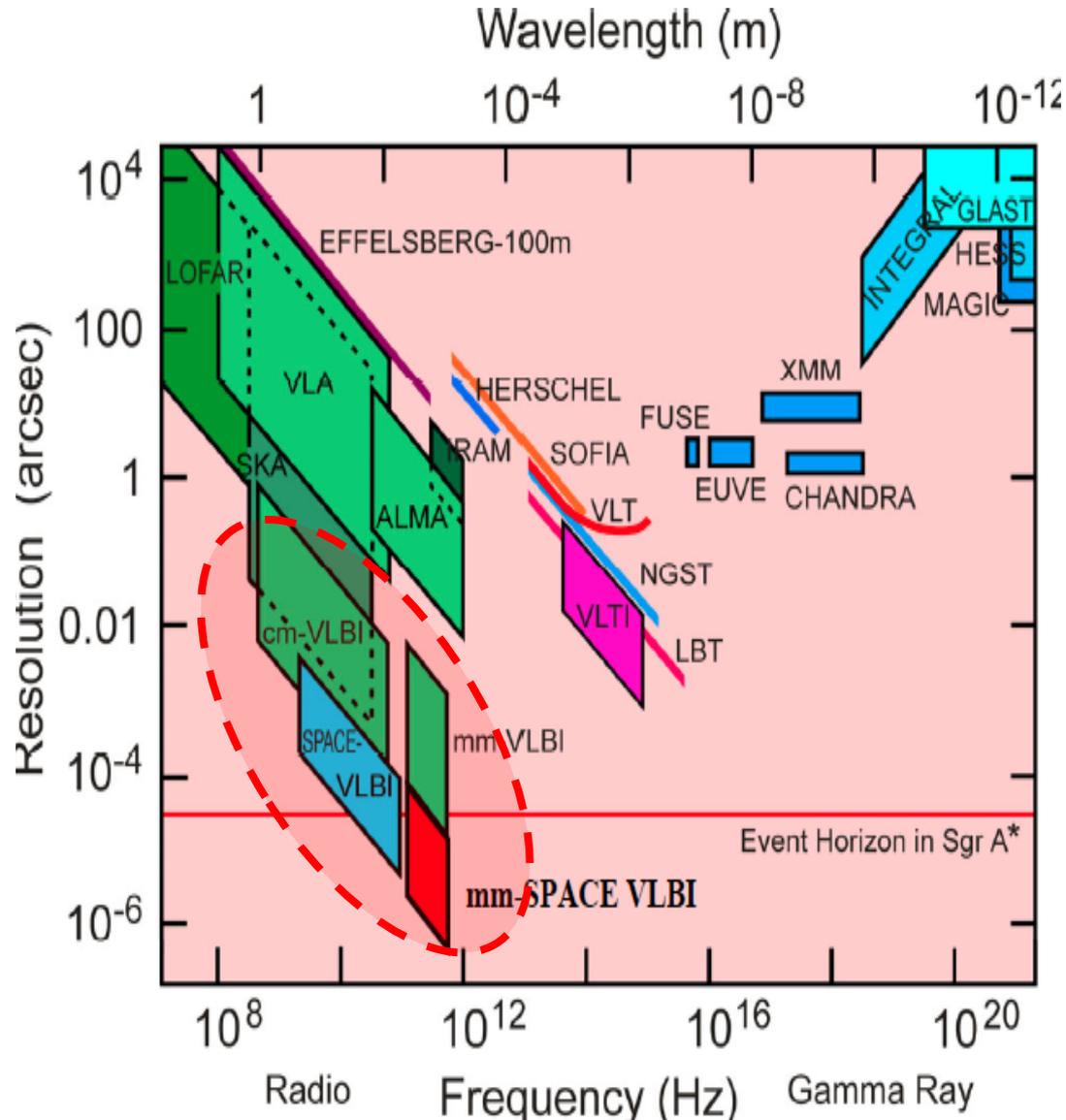
Meier+01

Koide+02

# Very Long Baseline Interferometer



- Angular resolution
- $\theta = \lambda/D$
- $D \sim 5000\text{km}$
- $\lambda \sim 1\text{cm}$  (22GHz)
- $\theta \sim 1\text{mas}$



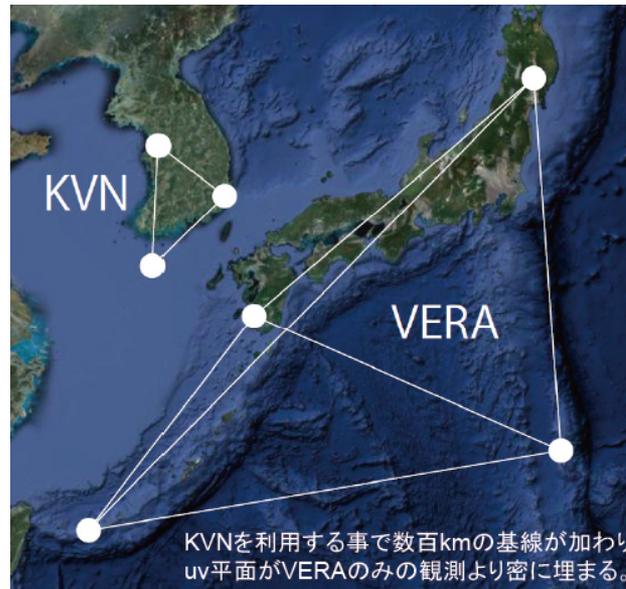
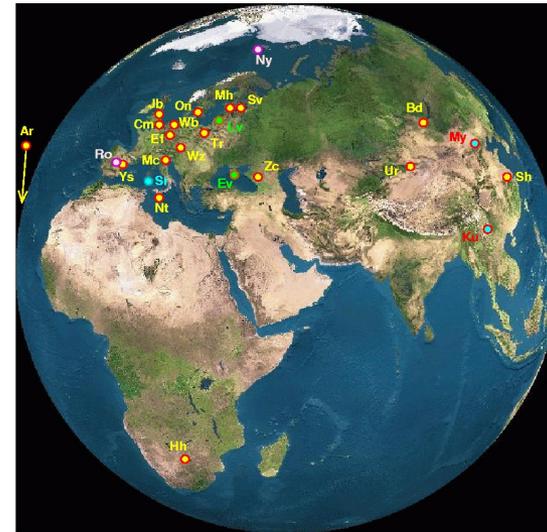
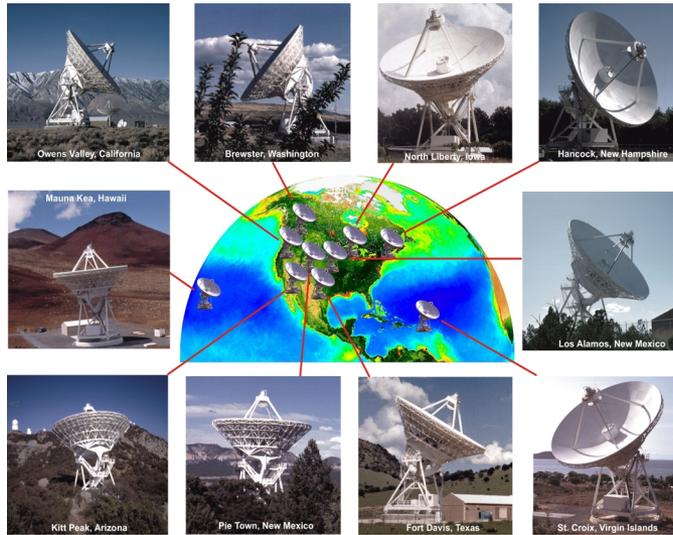
# (Cm-)VLBI network in the world

## VLBA

## EVN

D~10000km  
 $\lambda \sim 6-20\text{cm}$

D~ 8000km  
 $\lambda \sim 0.7-20\text{cm}$



D~ 2300km  
 $\lambda \sim 0.7-1\text{cm}$

## KaVA (KVN and VERA Array)

# Why VLBI suitable for jet study?

- **Shape**

- Collimation, transverse structure

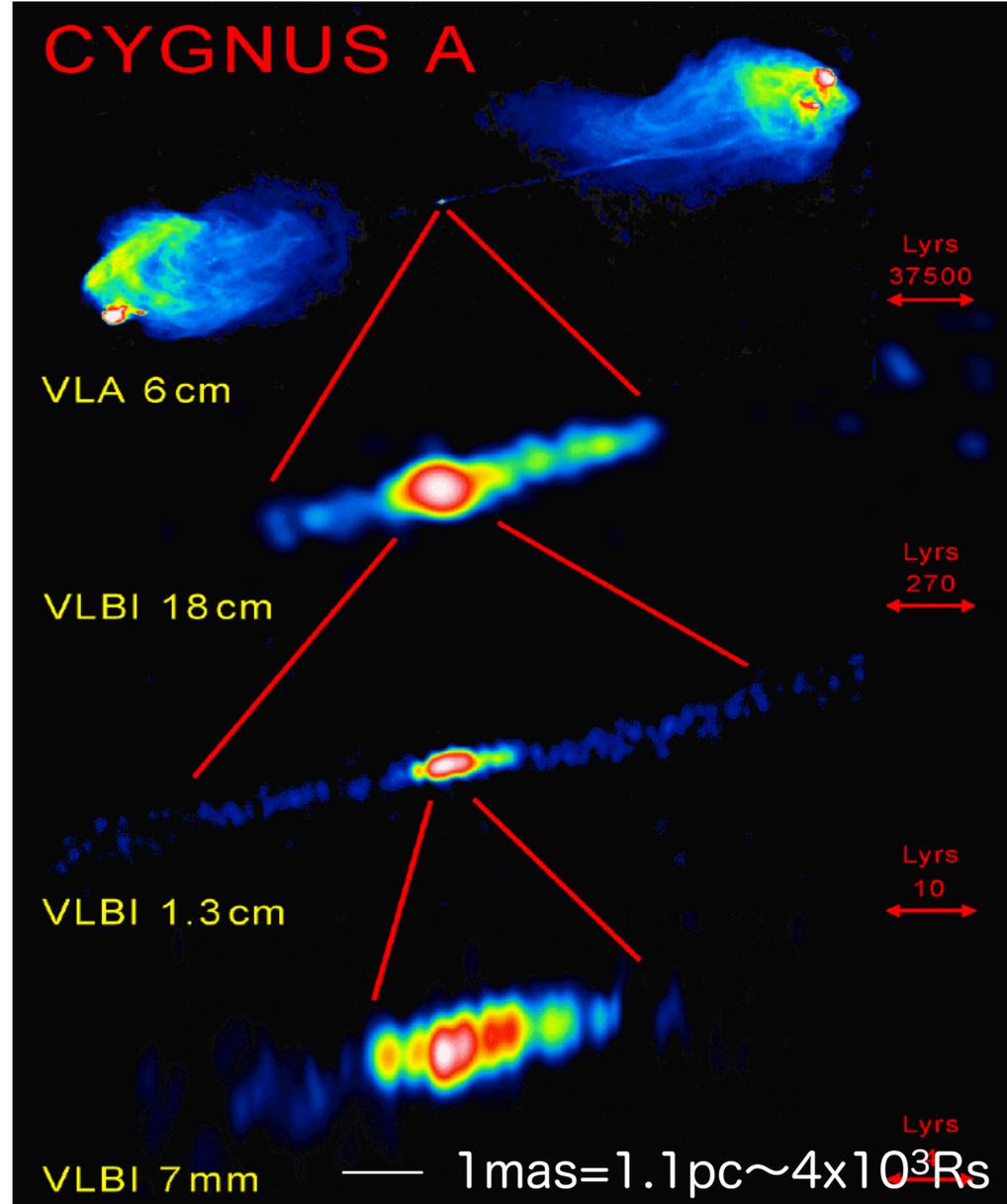
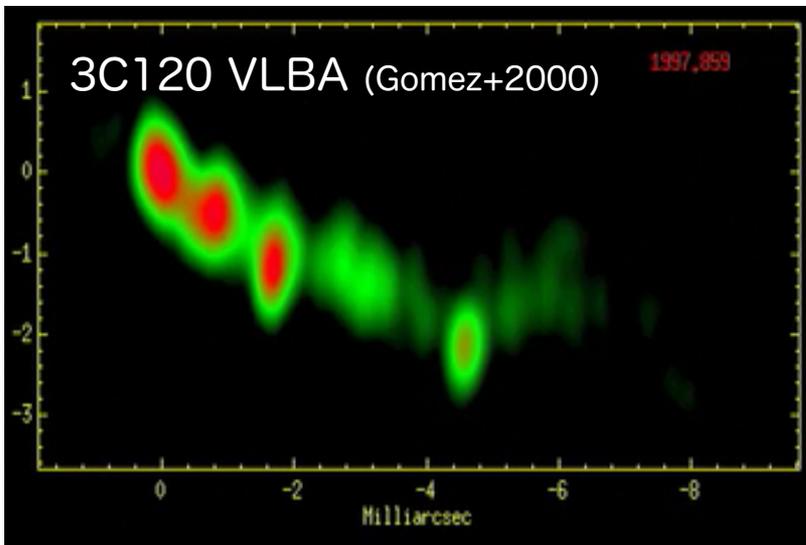
- **Motion**

- Acceleration, velocity fields

- **Polarization**

- B-field structure

- VLBI can directly map these key quantities



# Radio galaxy M87 (Virgo A, 3C274)

Event horizon apparent radius ranking

<i>Object</i>	$M_{BH}$ ( $10^8 M_{sun}$ )	$d$ (Mpc)	$1R_s$ ( $\mu as$ )
<i>SgrA*</i>	0.04	0.008	10
<i>M87</i>	60	16.7	7
<i>Sombrero</i>	10	9.0	2.2
<i>M84</i>	8.5	17	1
<i>Cen A</i>	0.5	3.8	0.3

HST

1 kpc ( $2 \times 10^6 R_s$ )

VLBA 7mm  
(Junor+1999)

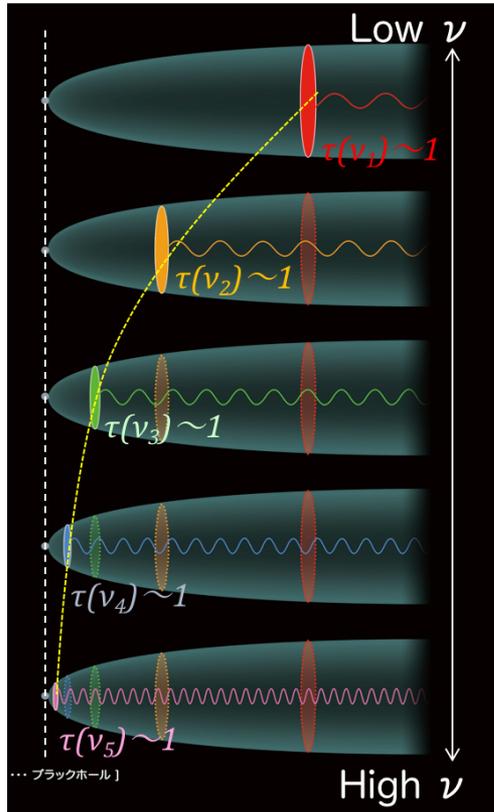
0.06 pc = 100  $R_s$

- 1 mas = 0.08 pc = 140  $R_s$
- “The Rosetta Stone of AGN jets”

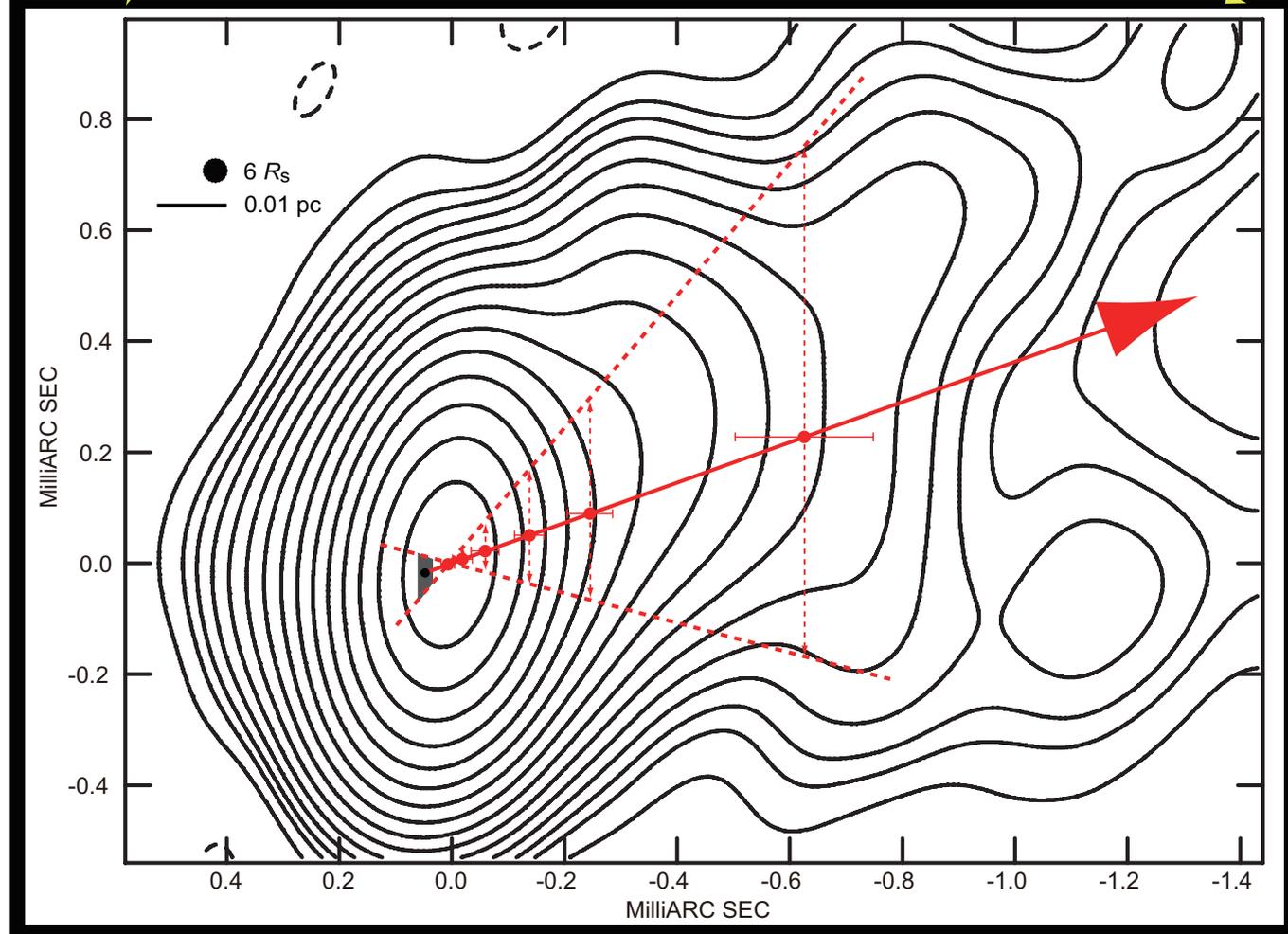
# Where is the central engine?

(Hada et al. 2011)

VLBA 7mm



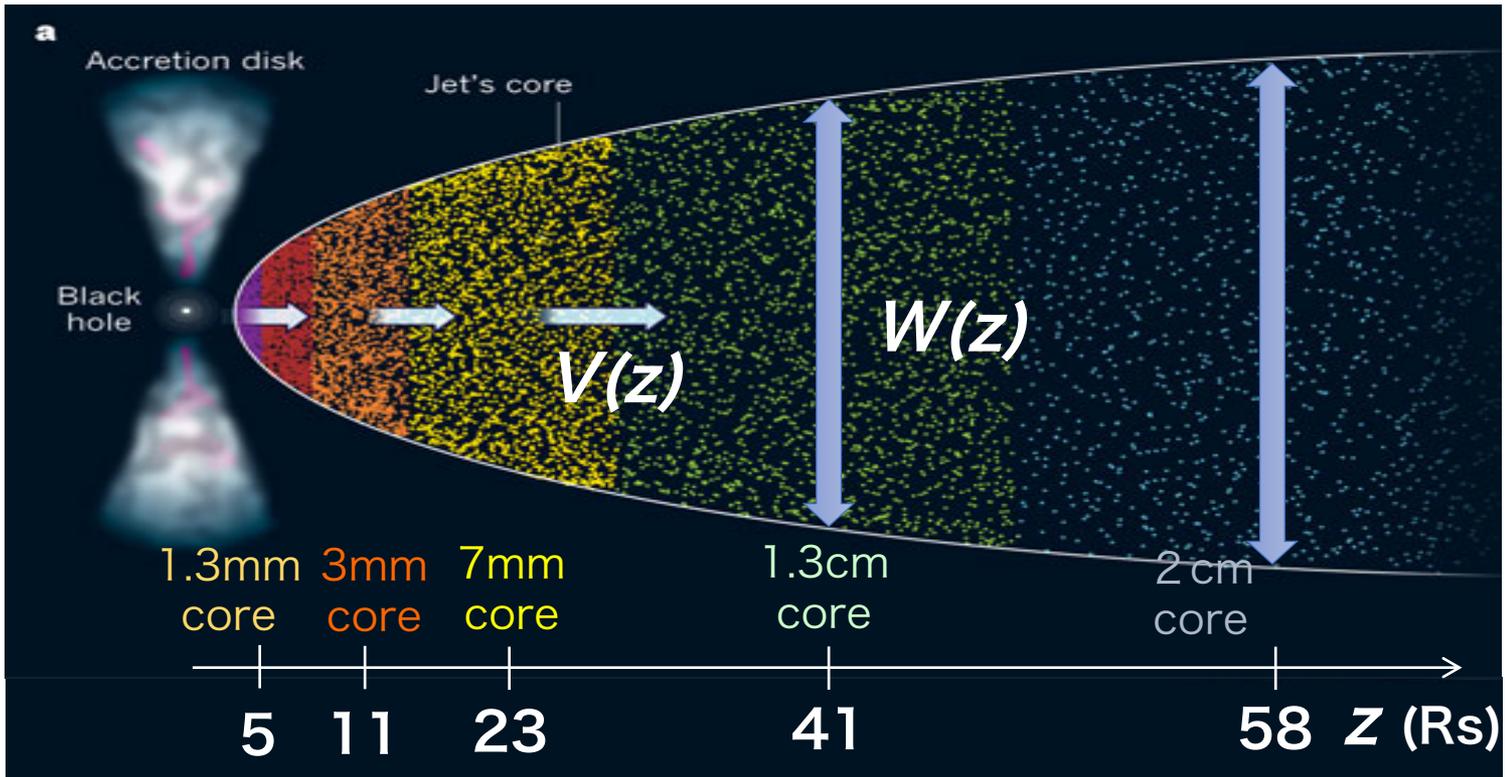
Core-shift  
(Blandford & Konigl 1979)



- High-accuracy core-shift measurement suggests the central engine resides very close to 7mm core

# Core-shift: What's the benefit?

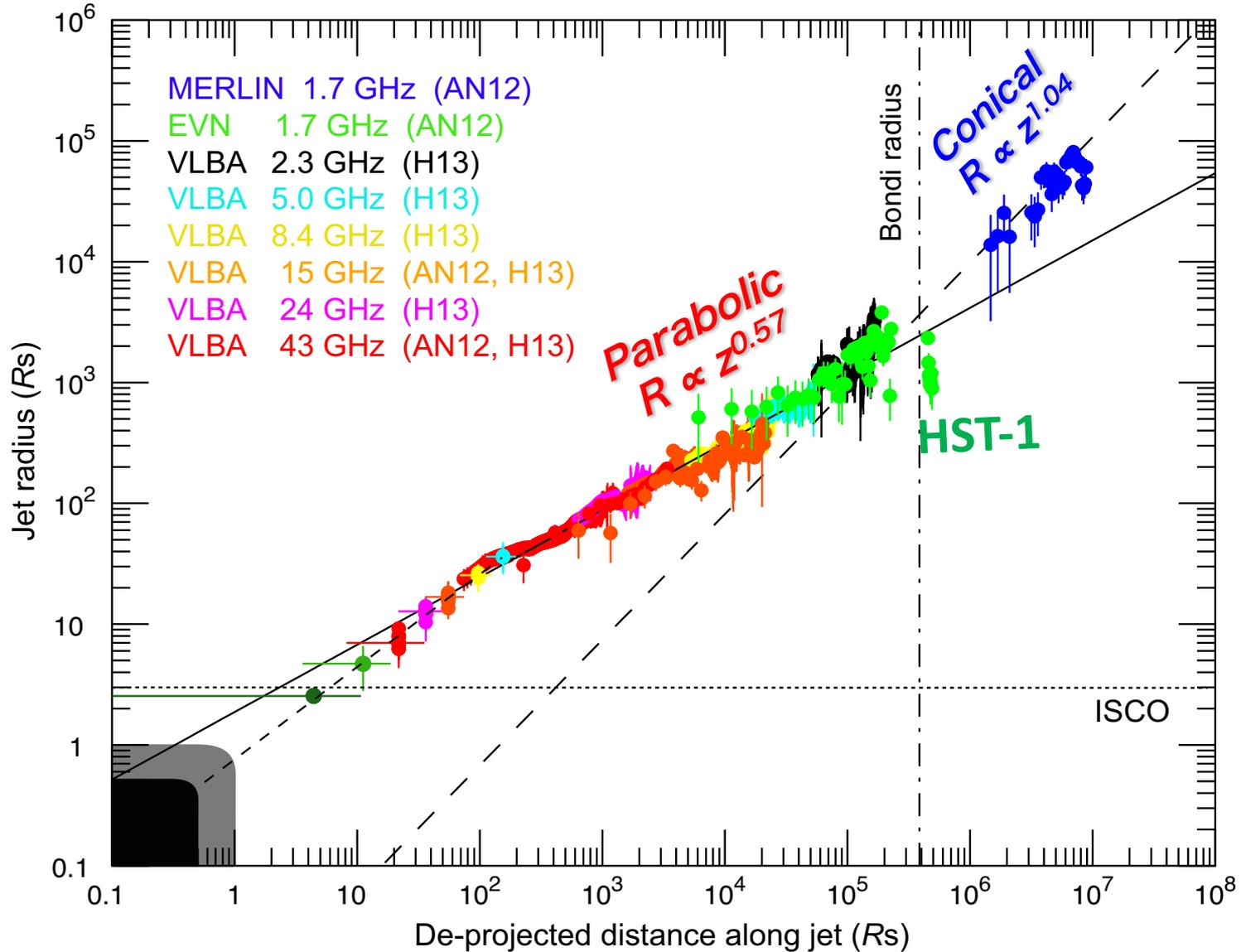
Marscher 2011



- Now various physical quantities can be measured as a function of radial distance “ $z$ ”

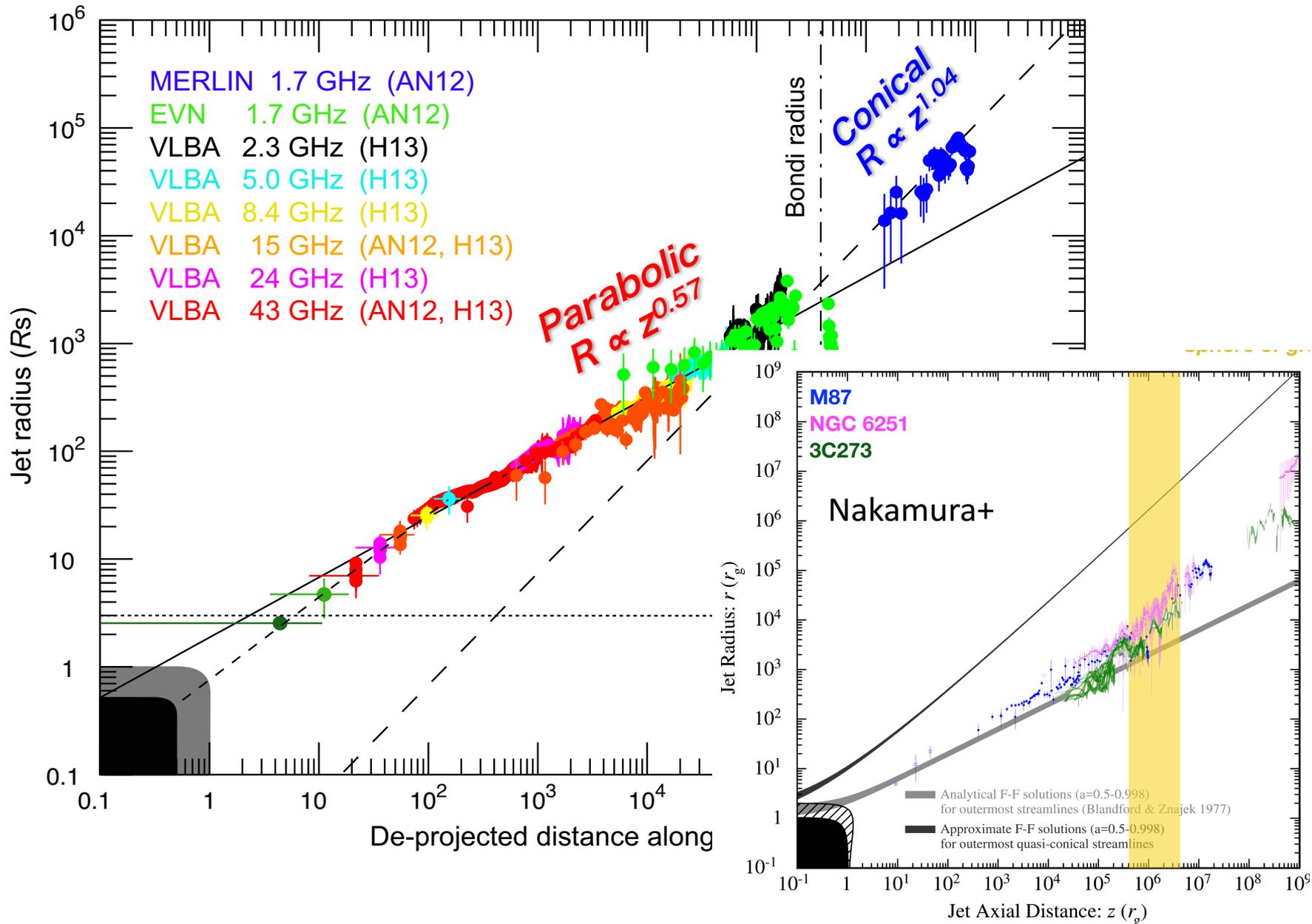
# Determine jet collimation profile $R(z)$

(Asada & Nakamura12; Hada+13)



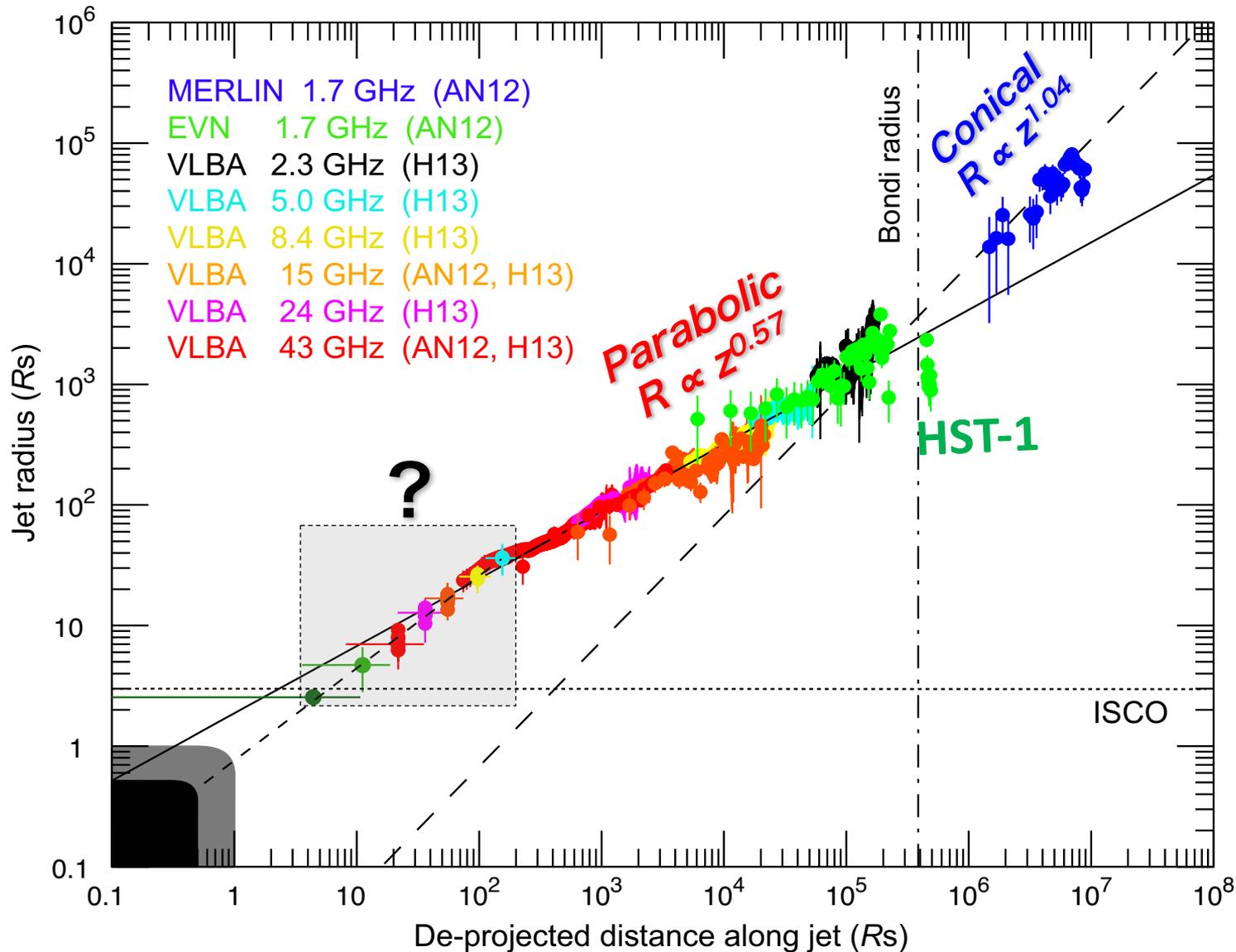
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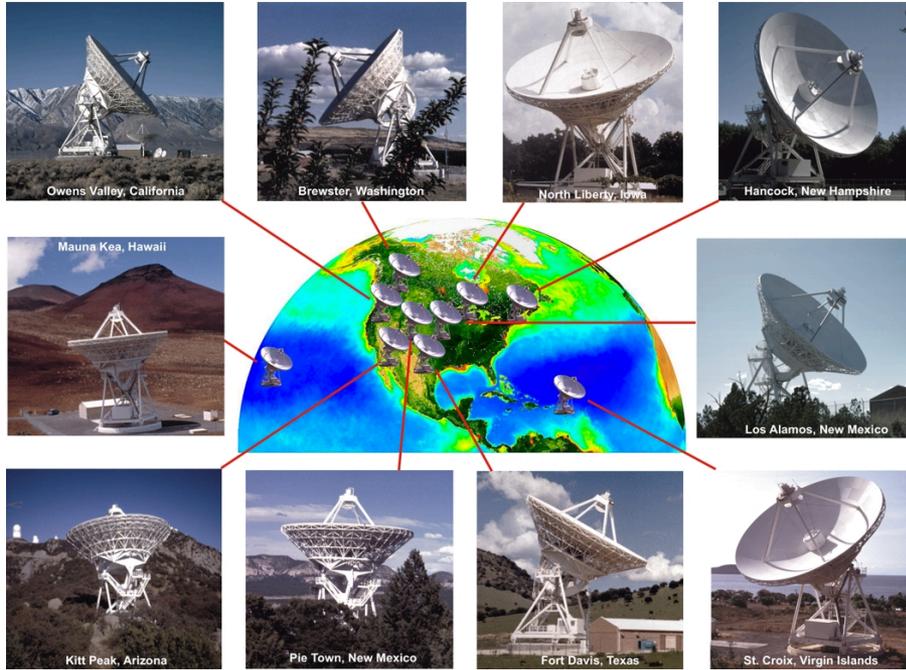
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(Asada & Nakamura12; Hada+13)



# Imaging jet launch structure at highest resolution & transparency (Hada et al. 2016)

VLBA (25m)



GBT 100m

+

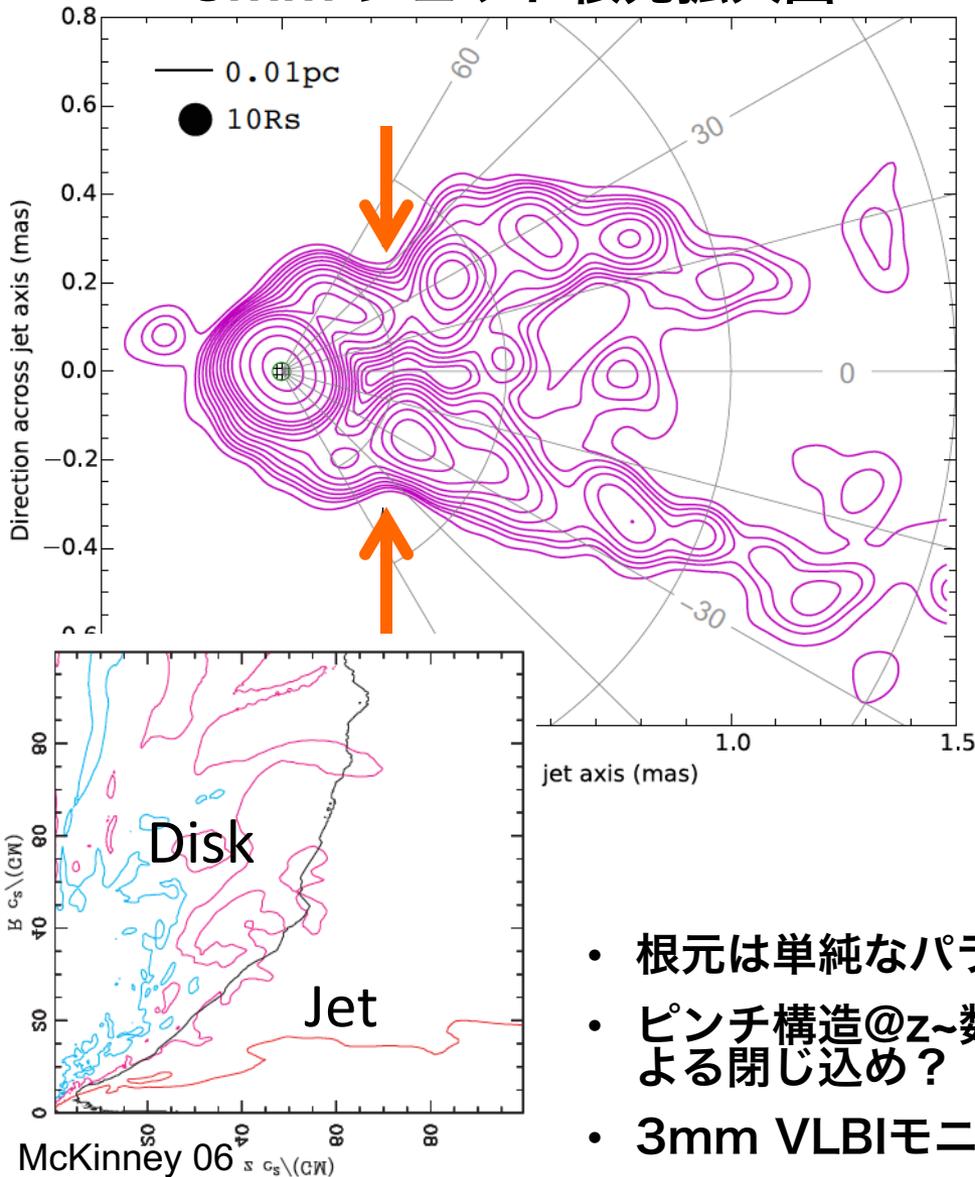


**3mm observations with VLBA+GBT100m**

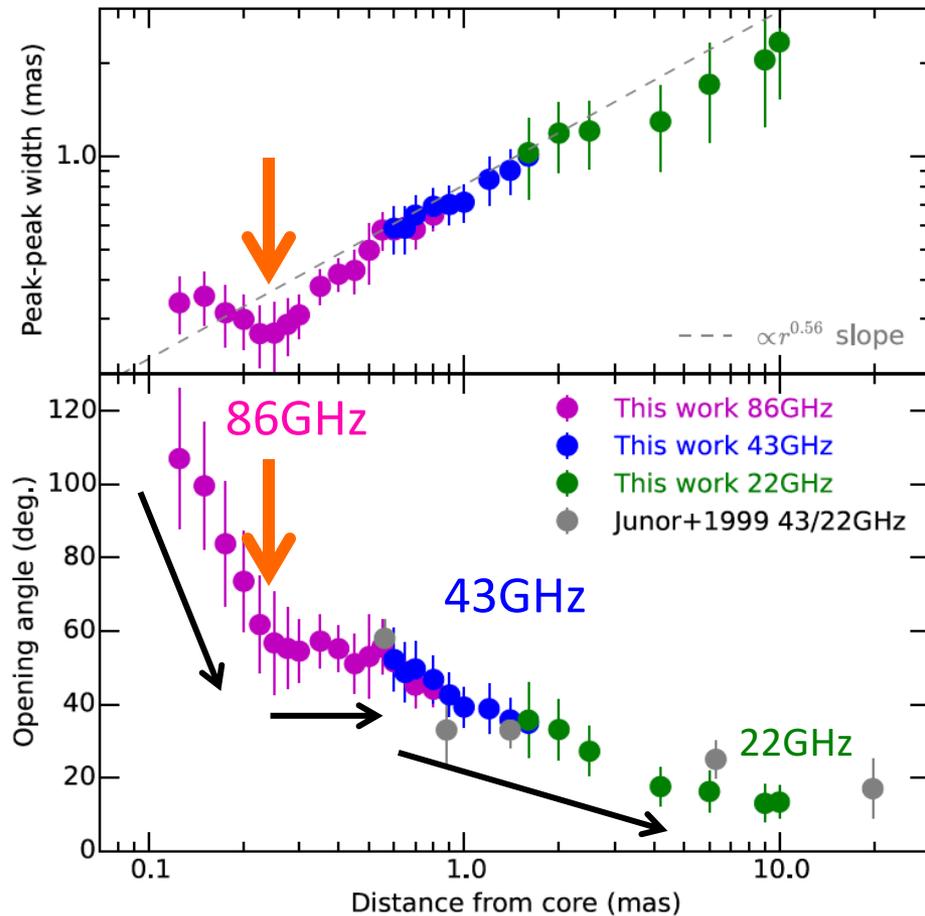


# z~10-100Rs structure

3mm ジェット根元拡大図



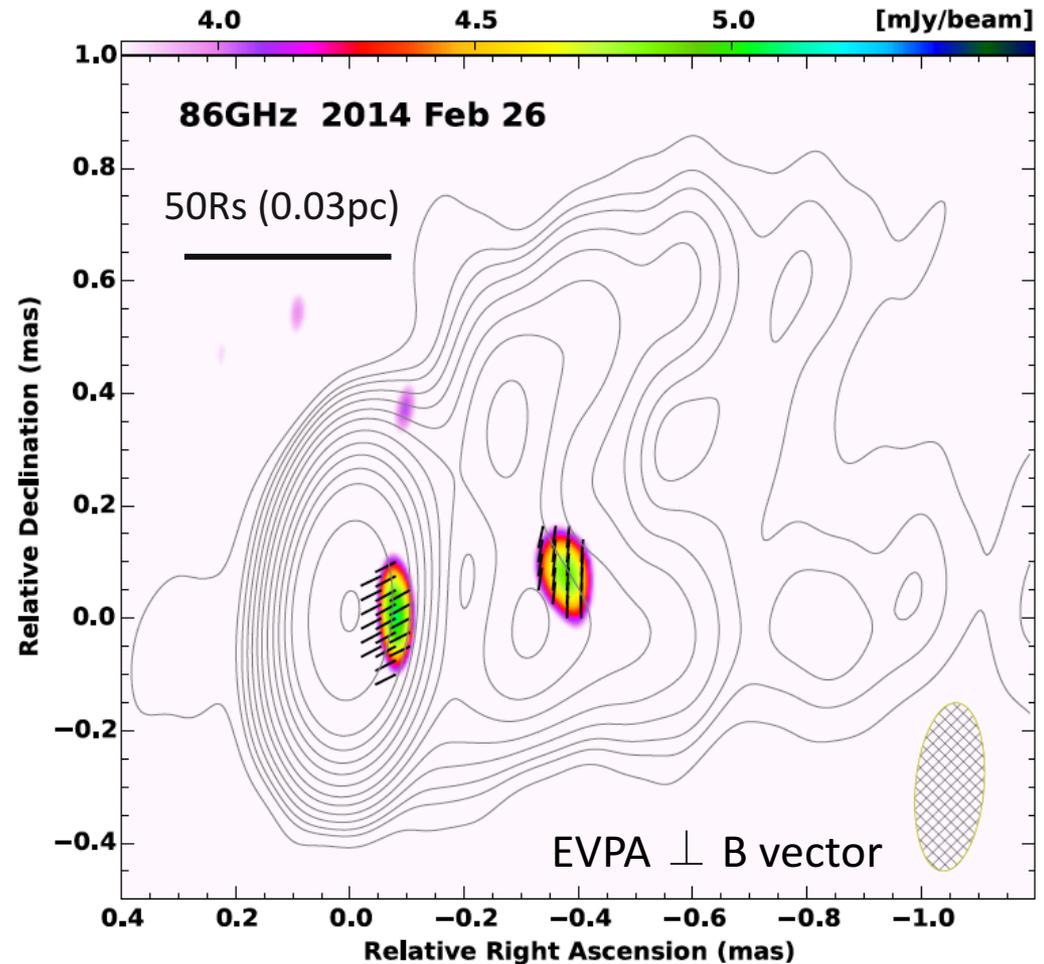
ジェット幅(上図) / 開口角(下図)

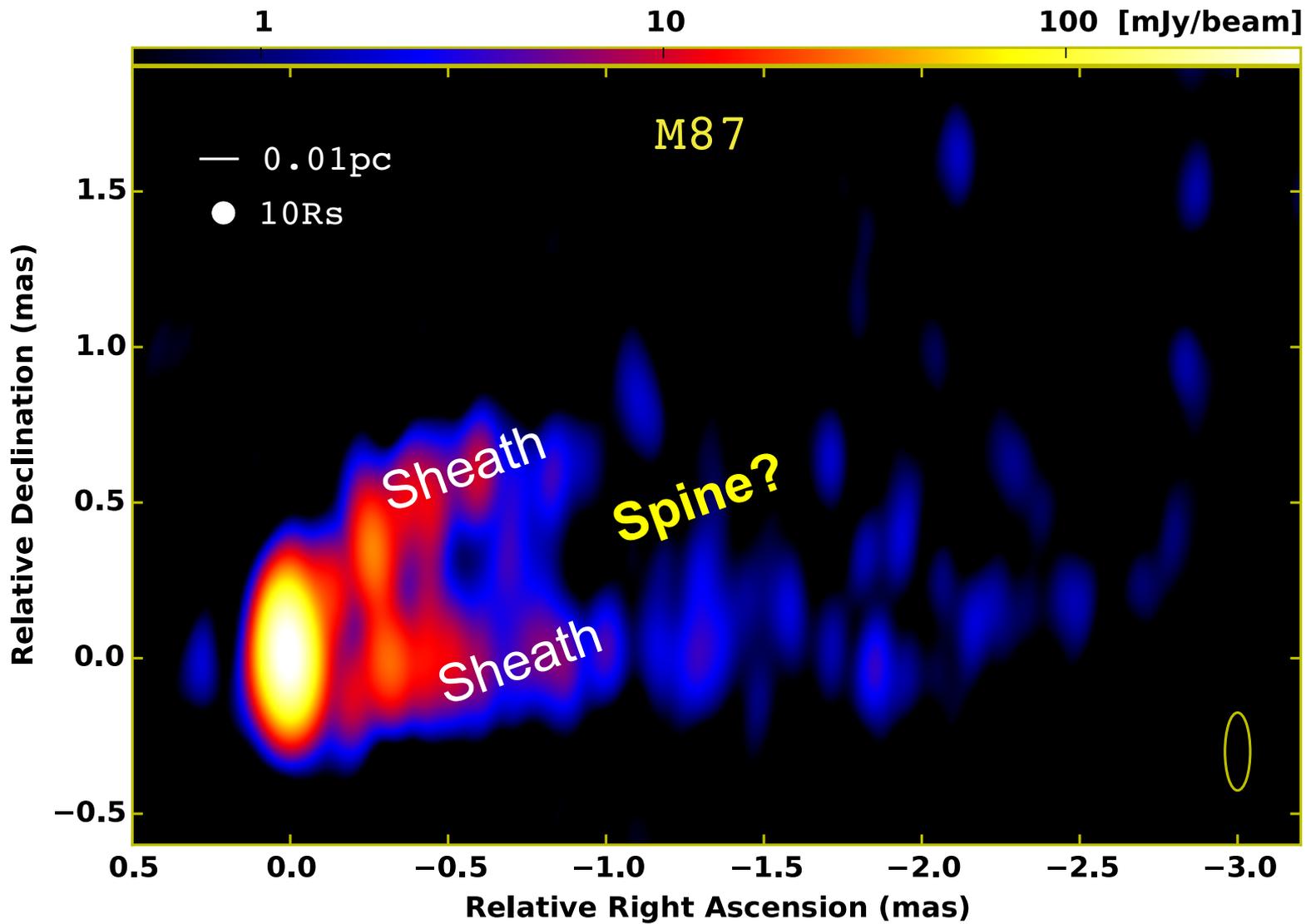


- 根元は単純なパラボラ形状ではないらしい
- ピンチ構造@z~数10Rs: 幾何学的に厚い降着流(ADAF)による閉じ込め?
- 3mm VLBIモニター or 1.3mm VLBI撮像が今後のカギ

# First detection of polarization near BH

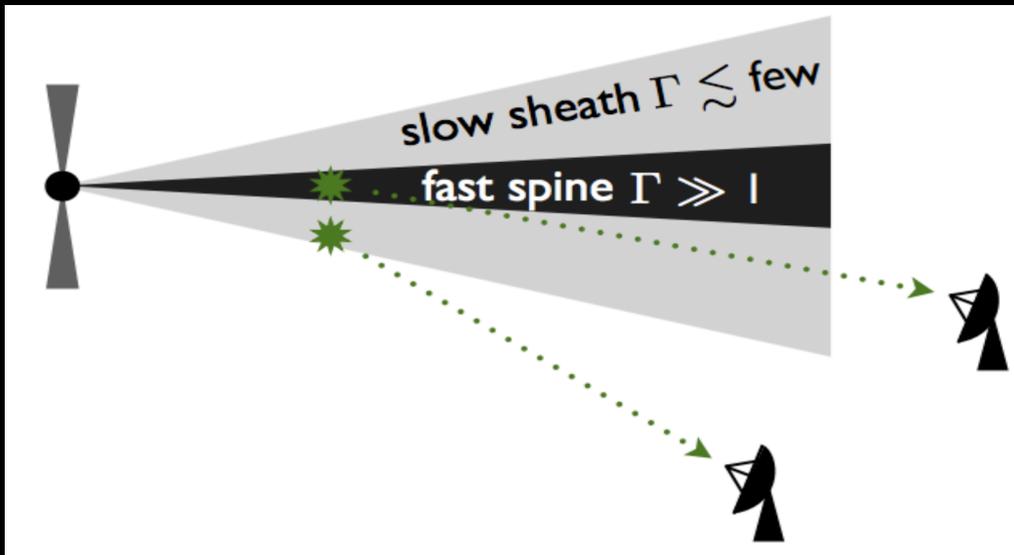
- M87 inner jet: severe Faraday depolarization at long wavelengths ( $>7\text{mm}$ )
- 3mm VLBI just began to detect polarized fluxes
  - Toroidal-dominated B-field at jet base?
- 1mm VLBI (with ALMA) more promising



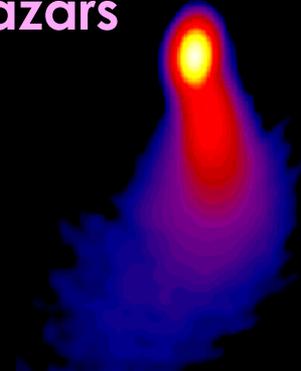


# Multi-layered (“spine-sheath”) unification paradigm of AGN jets

Clausen-Brown+ 2013



Blazars

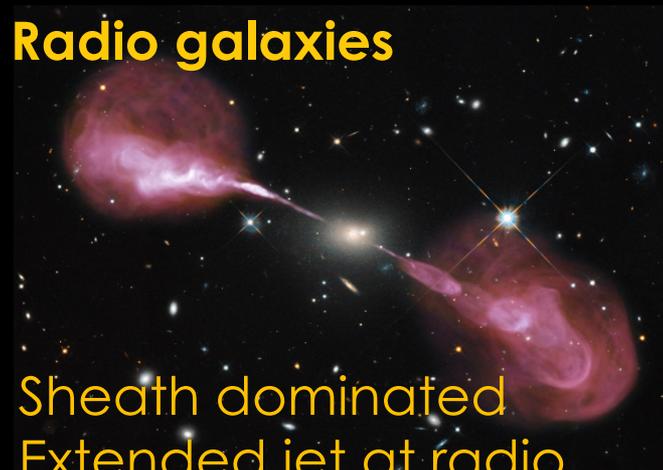


Spine dominated  
GeV/TeV

A lot of “indirect” evidence in favor of this scenario, but no “direct” evidence so far

No jet is known in which both the spine/sheath are imaged at the same time

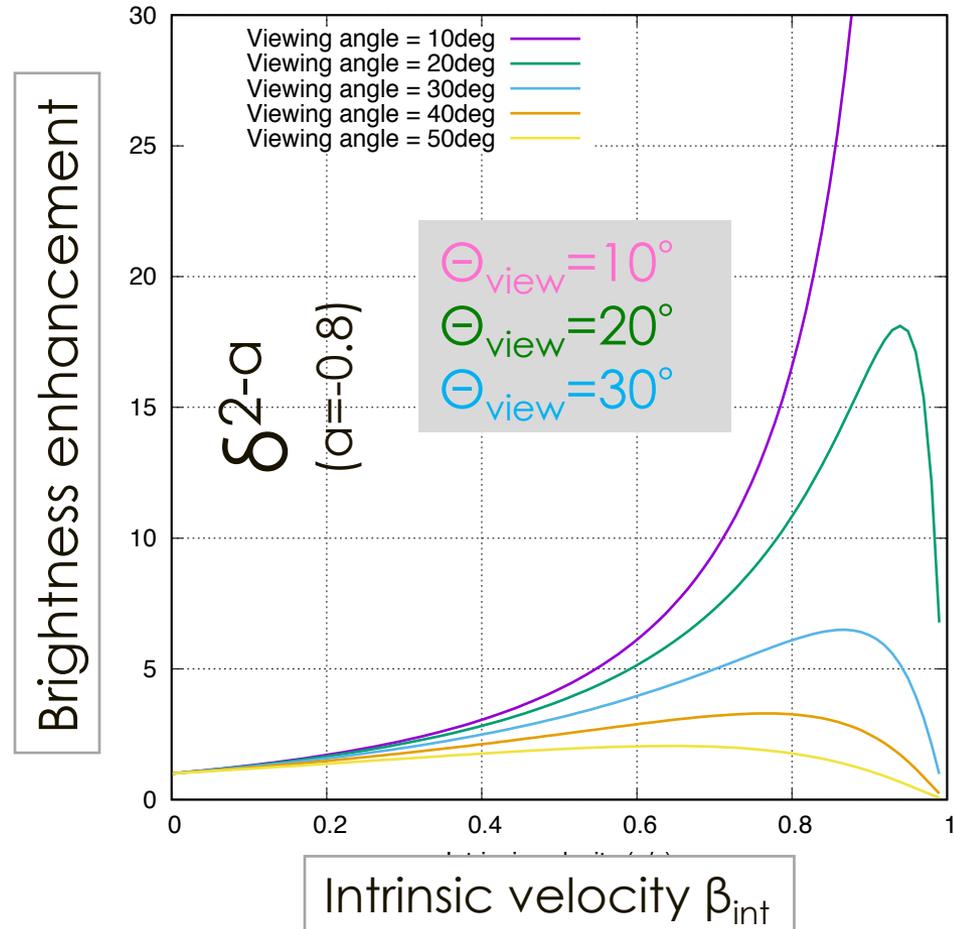
Radio galaxies



Sheath dominated  
Extended jet at radio

# Can we detect a spine at radio?

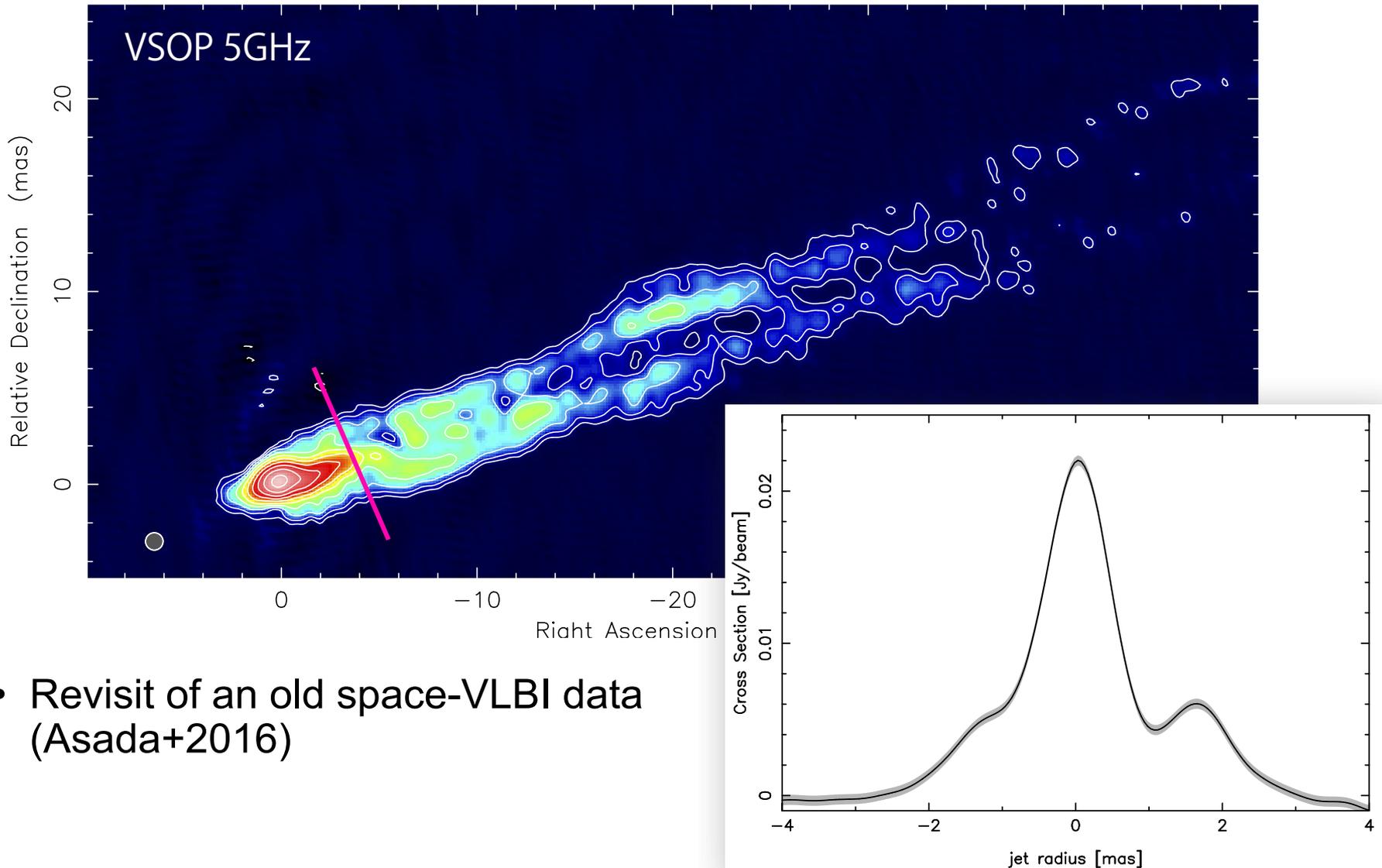
- 6c motion of HST-1
  - $\Theta_{\text{view}} < 19^\circ$  (Biretta+1999)
- Faster flow may be more Doppler boosted
  - $\delta(\text{spine}) > \delta(\text{sheath})$



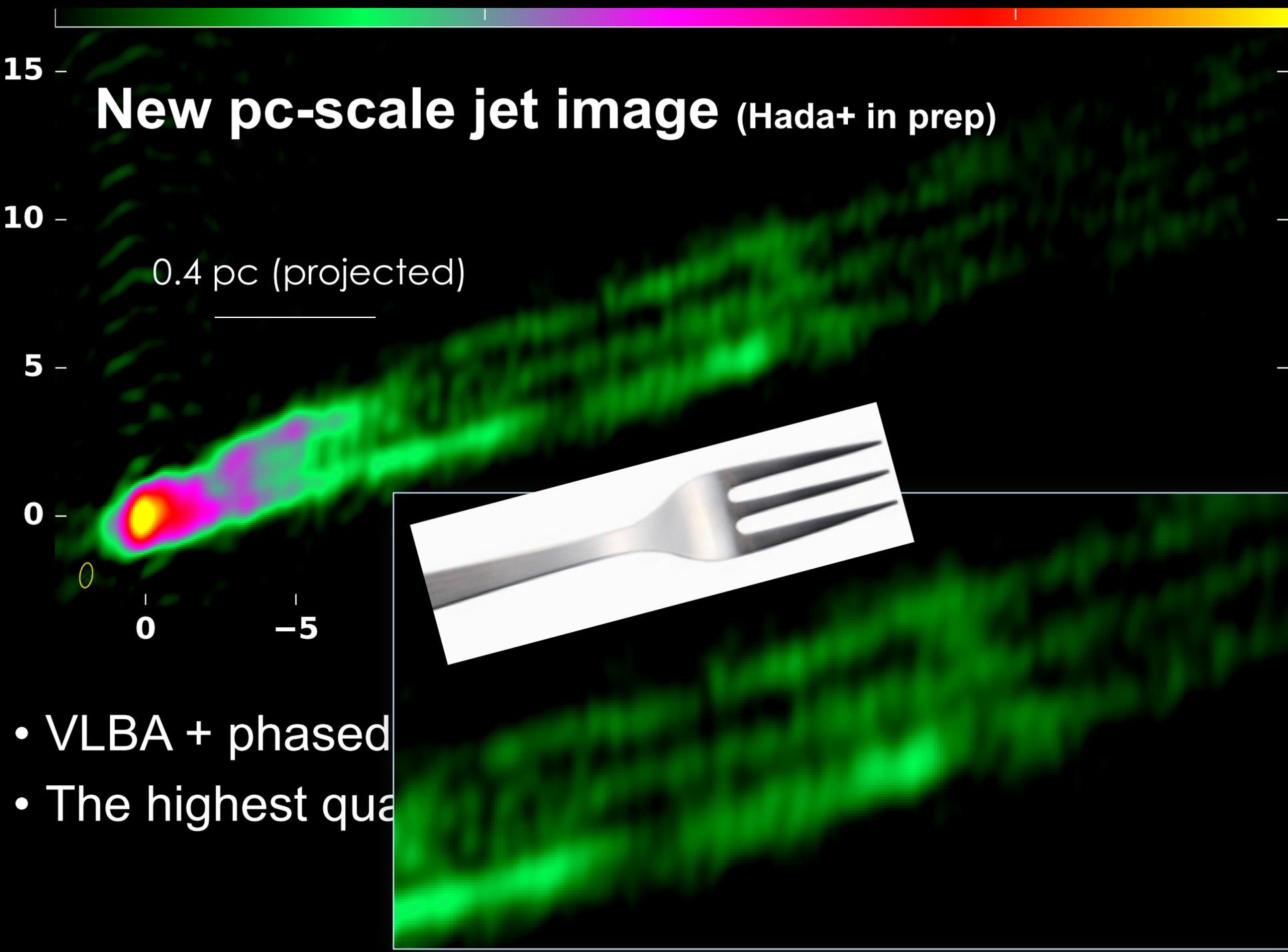
**In M87 we might see a spine as well as the known sheath**

# The first hint of a spine ridge !!?

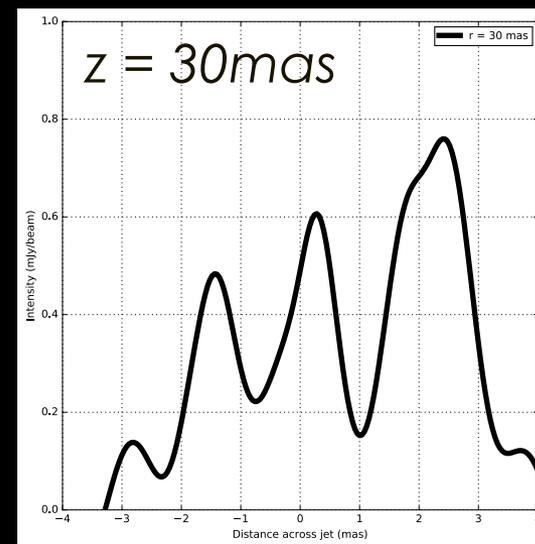
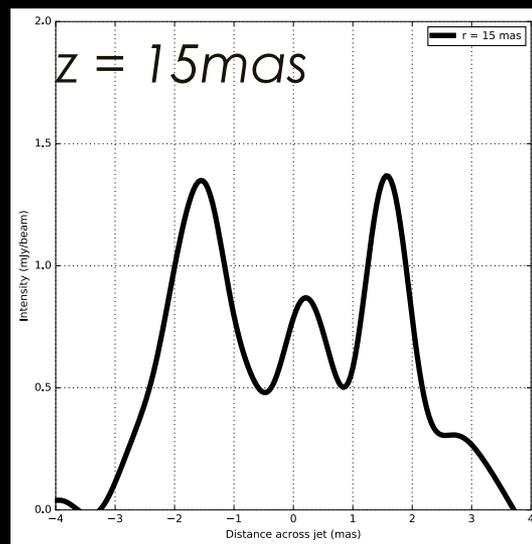
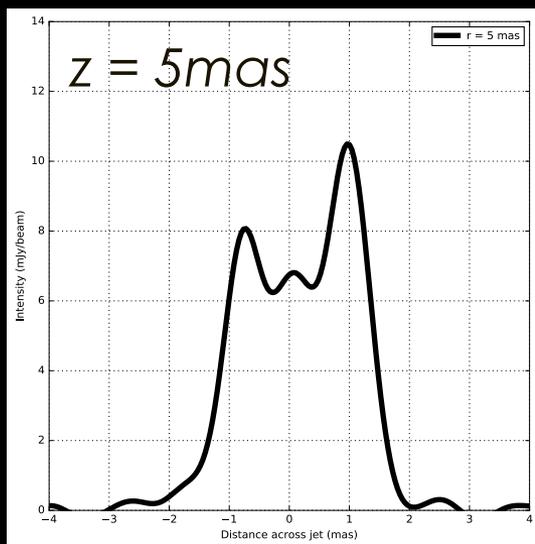
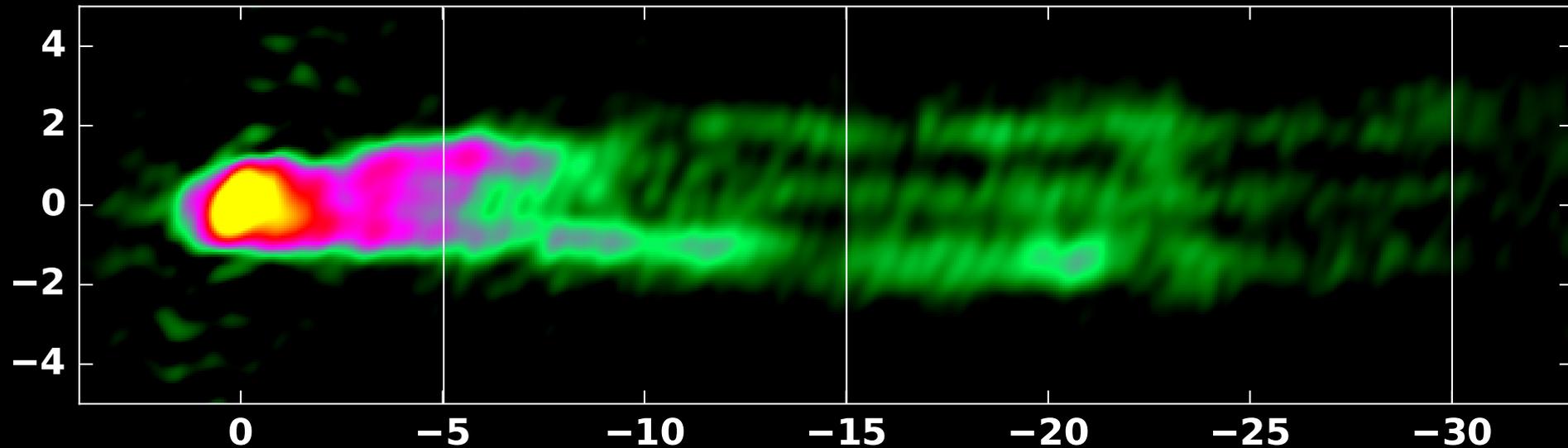
Asada, Nakamura & Pu 2016



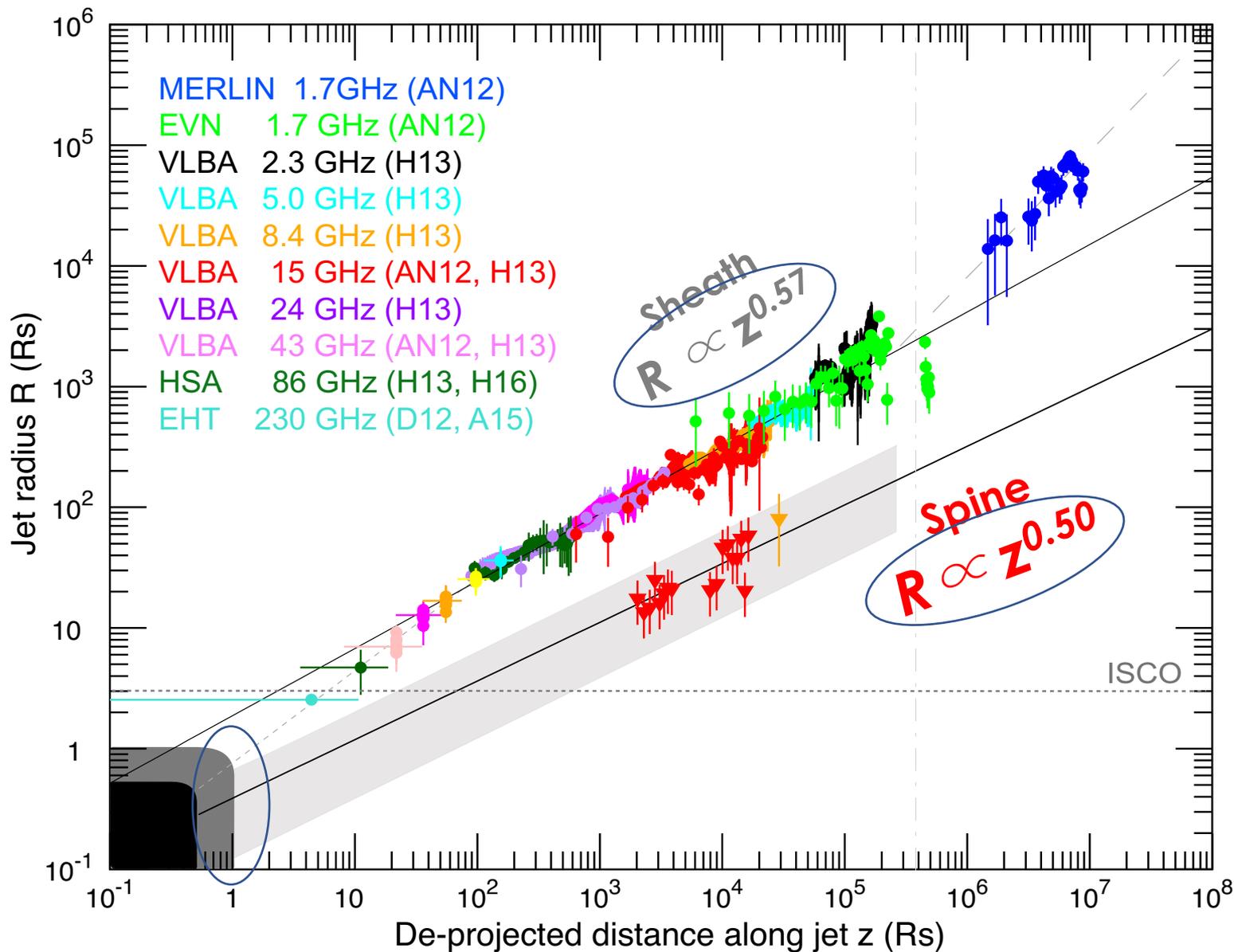
- Revisit of an old space-VLBI data (Asada+2016)



# Continuing triple-ridge structure



# “Spine-sheath” collimation profile



# Work in progress...



## Observing Application

Date: Aug 01, 2016  
Proposal ID: VLBA/17A-318  
Legacy ID: BH221  
PI: Kazuhiro Hada  
Type: Regular  
Category: Active Galactic Nuclei  
Total time: 36.0

### Ultra-deep imaging of the spine-sheath structure of the M87 jet

#### Abstract:

Detailed imaging of the transverse structure of relativistic jets in active galactic nuclei (AGN) is essential to understand the multi-layered ("spine-sheath") jet paradigm and their launching mechanisms. The radio galaxy M87 contains one of the nearest AGN jets, offering a rare opportunity to resolve and image the detailed transverse jet structure at unprecedented linear scales. Here we propose full-track VLBA+Y27+EB observations of M87 at 8, 15 and 24GHz, in order to obtain ultra-deep images of the pc-to-subpc-scale transverse structure of this jet. Our primary objectives are summarized as follows: (1) obtain conclusive evidence of a persistent "triple-ridge" structure which

- Is the observed central ridge really a spine?
- We obtained new VLBA + phasedVLA data
  - Collimation efficiency (differential collimation)
  - Velocity gradient between sheath-spine
  - Spectral properties
- Stay tuned!

# 前半のまとめ

- M87のセンチ波~長ミリ波帯VLBI観測に基づくジェット根元観測の進展
- コアシフト測定を皮切りに、収束形状の精密探査が急速に進展
- アレイの高感度化・高分解能化による画質の大幅改善により、これまで見えなかった(見落としてきた)成分が見え始めてきた
  - 長ミリ波(3mm): 降着流10Rsスケールの撮像. 根元磁場の検出
  - センチ波(2cm): transverse structure, spine-sheath構造

# **Event Horizon Telescope**

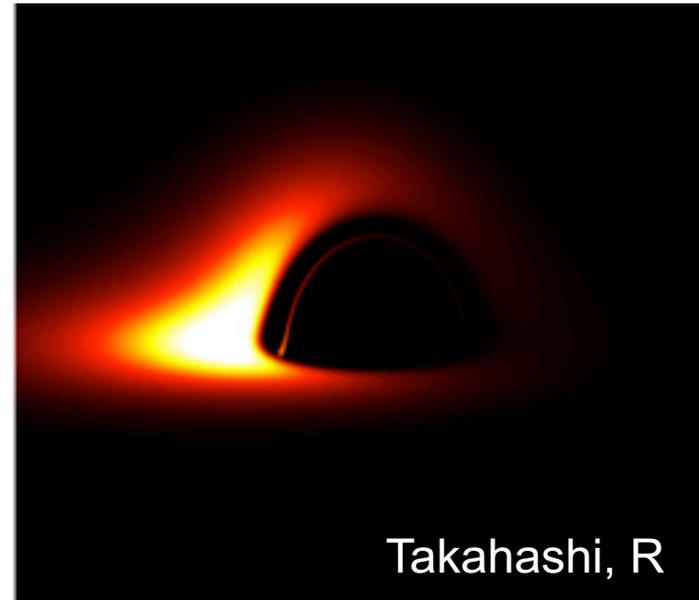
# Millimeter VLBI

The higher angular resolution & transparency toward AGN cores

$$\theta = 34 \left( \frac{\lambda}{1\text{mm}} \right) \left( \frac{D}{6000\text{km}} \right)^{-1} (\mu\text{as})$$

$$\alpha_{\nu}^{\text{syn}} \propto n_e B^{(p+2)/2} \nu^{-(p+4)/2}$$

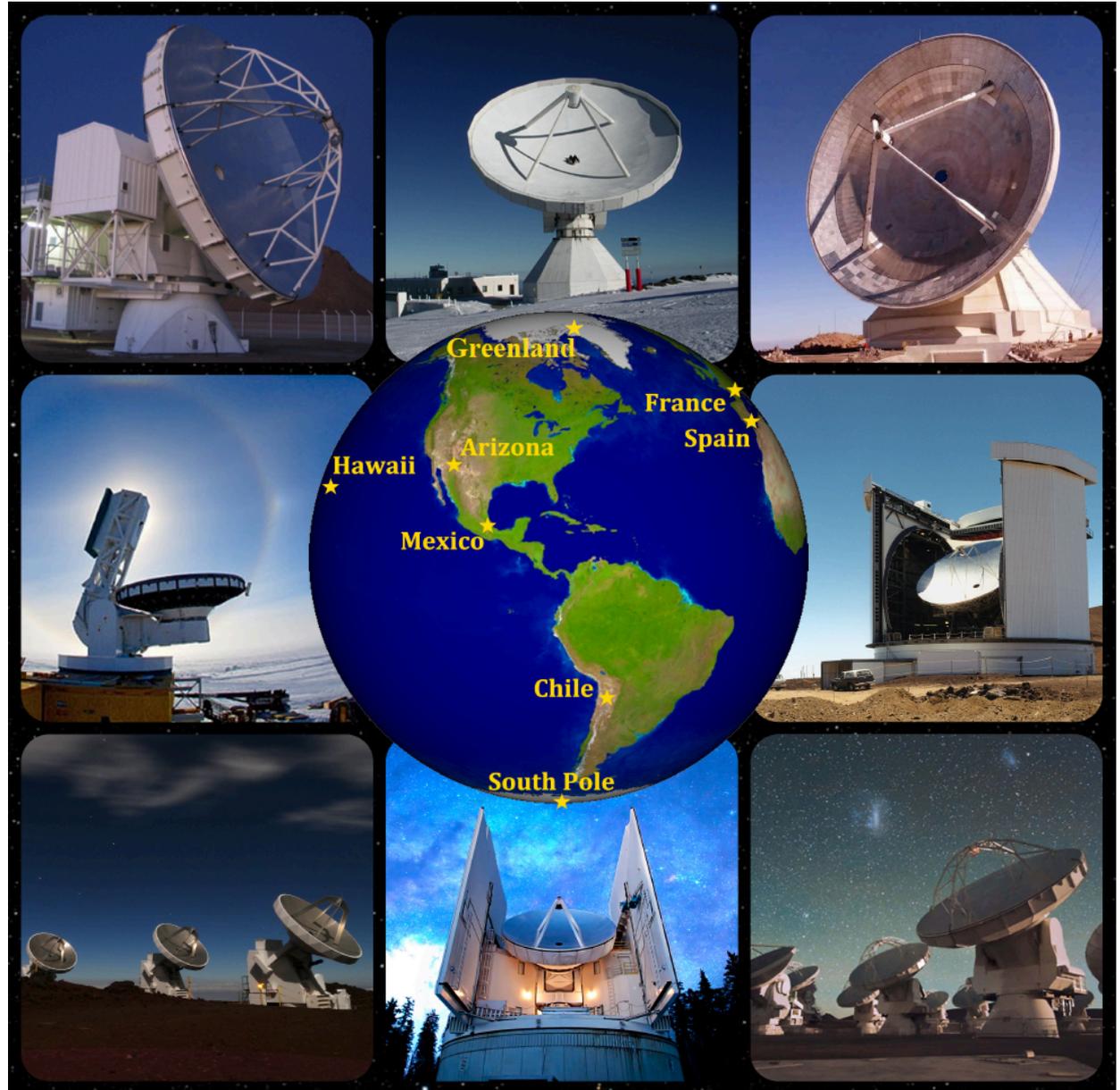
- BH shadow
- Inner accretion flow
- Jet launching
- Gamma-ray site



Takahashi, R

# Event Horizon Telescope (EHT)

- Global VLBI array at 1.3mm/230GHz
- US, EU, EA joint project
  - More than 100 members
- EA
  - Mizusawa VLBI Observatory (JP)
  - ASIAA (TW)



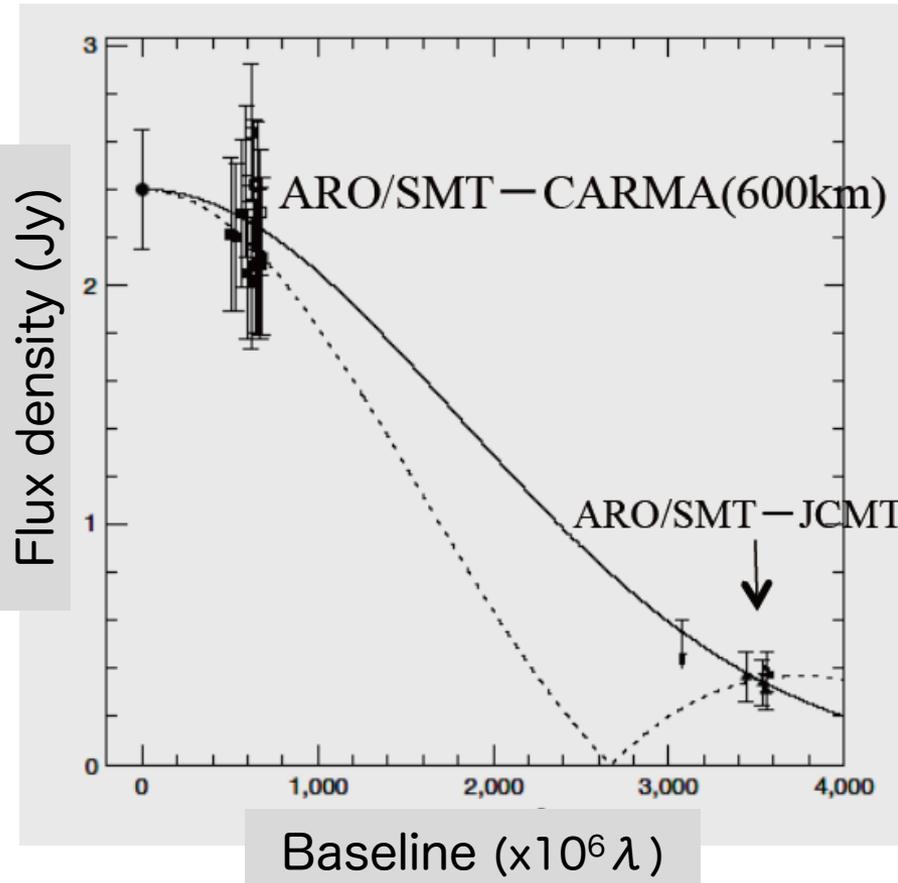
# Early EHT results

(Doeleman+08, 12)

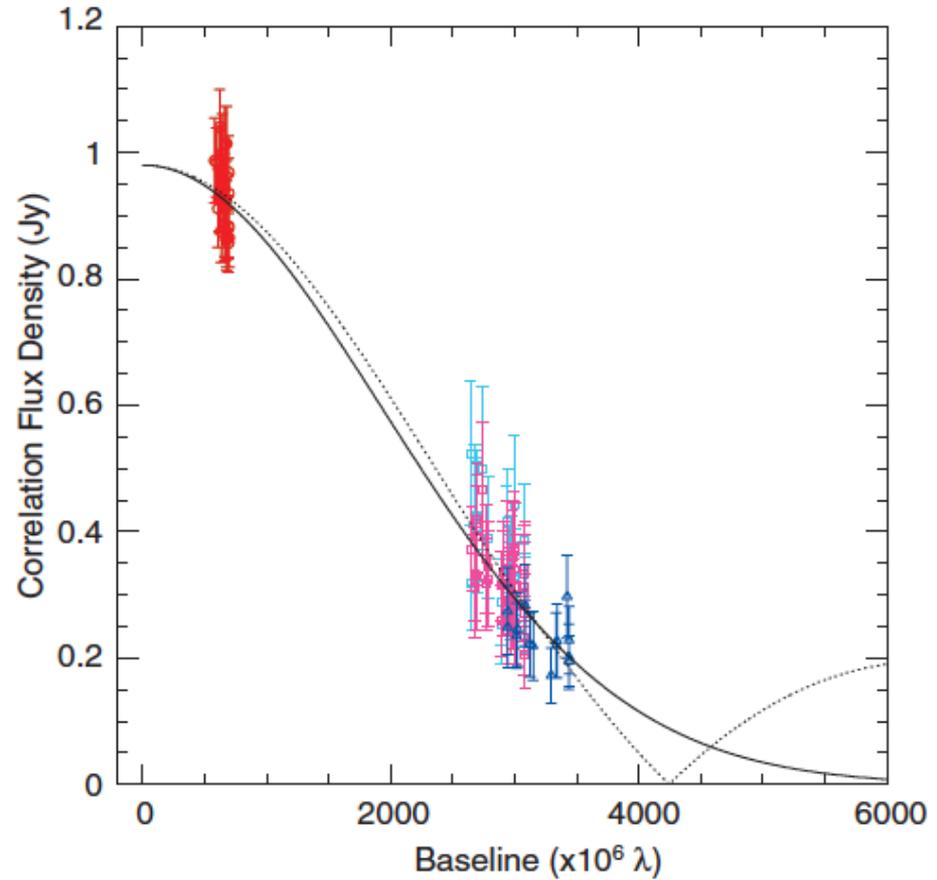


SgrA\*

M87



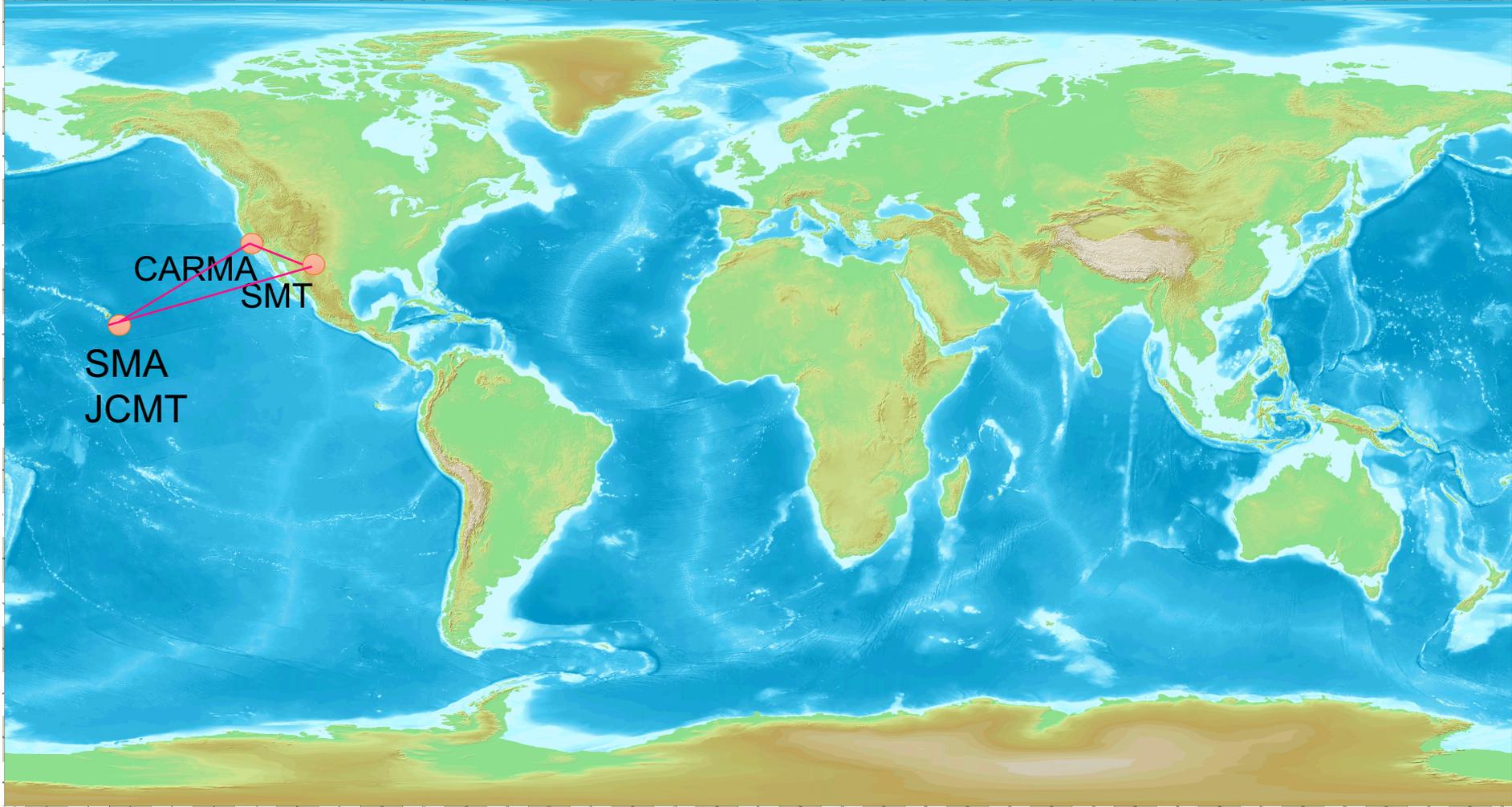
Core size =  $37 \mu\text{as} = 3.7 R_s$



Core size =  $40 \mu\text{as} = 5.5 R_s$

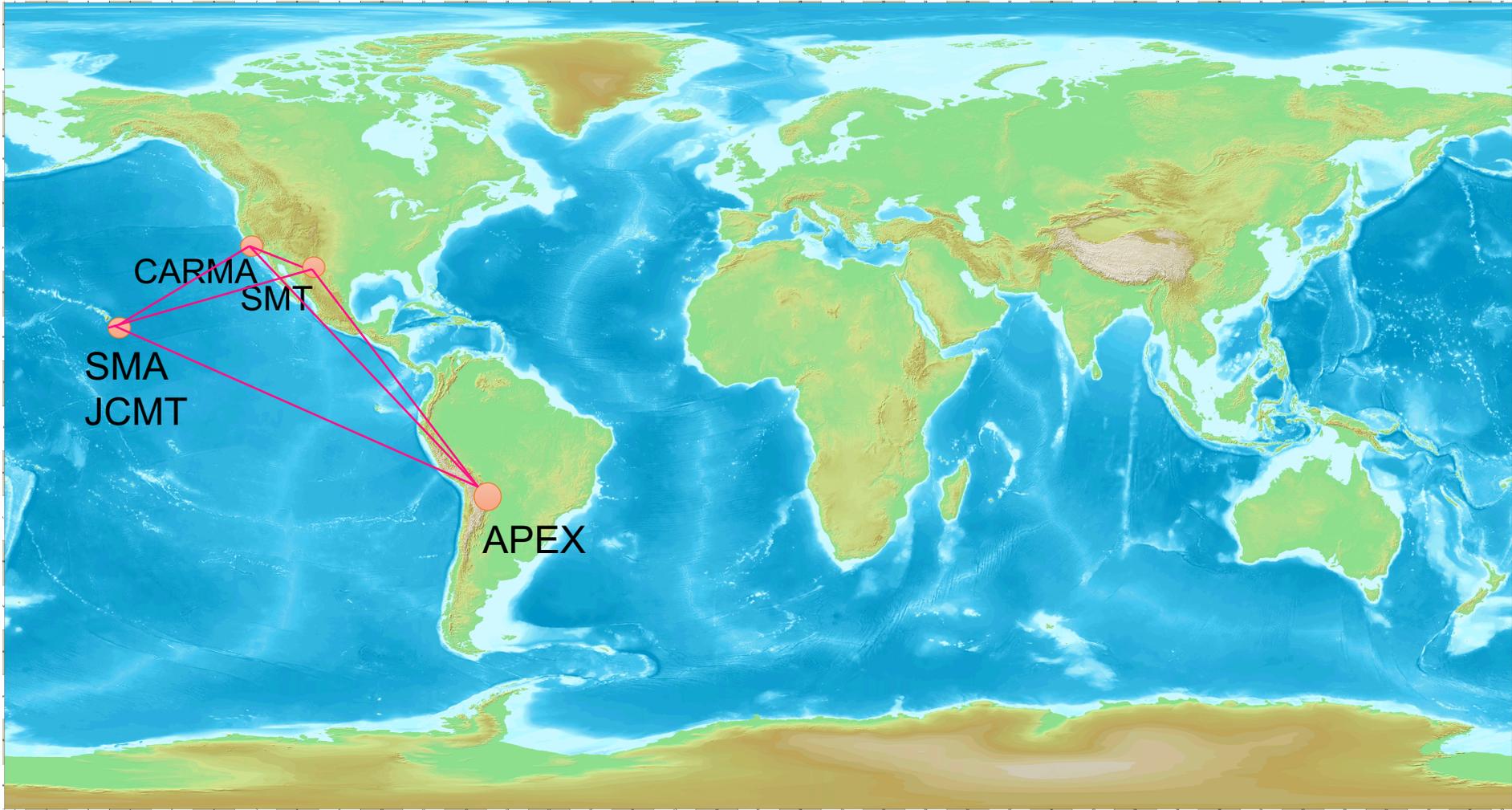
# Rapid expansion of EHT network

~2012 2013 2015 2017 2018?



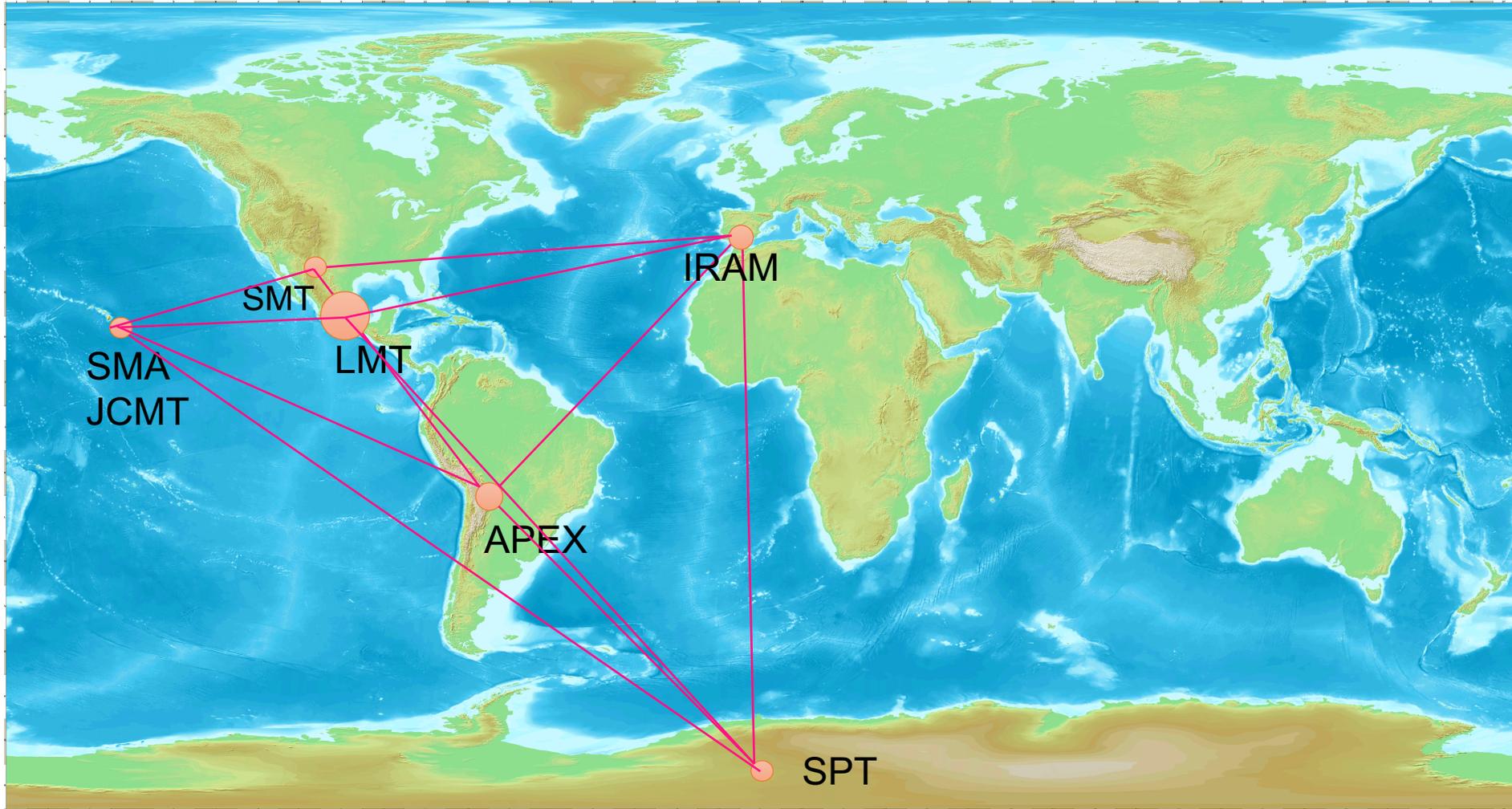
# Rapid expansion of EHT network

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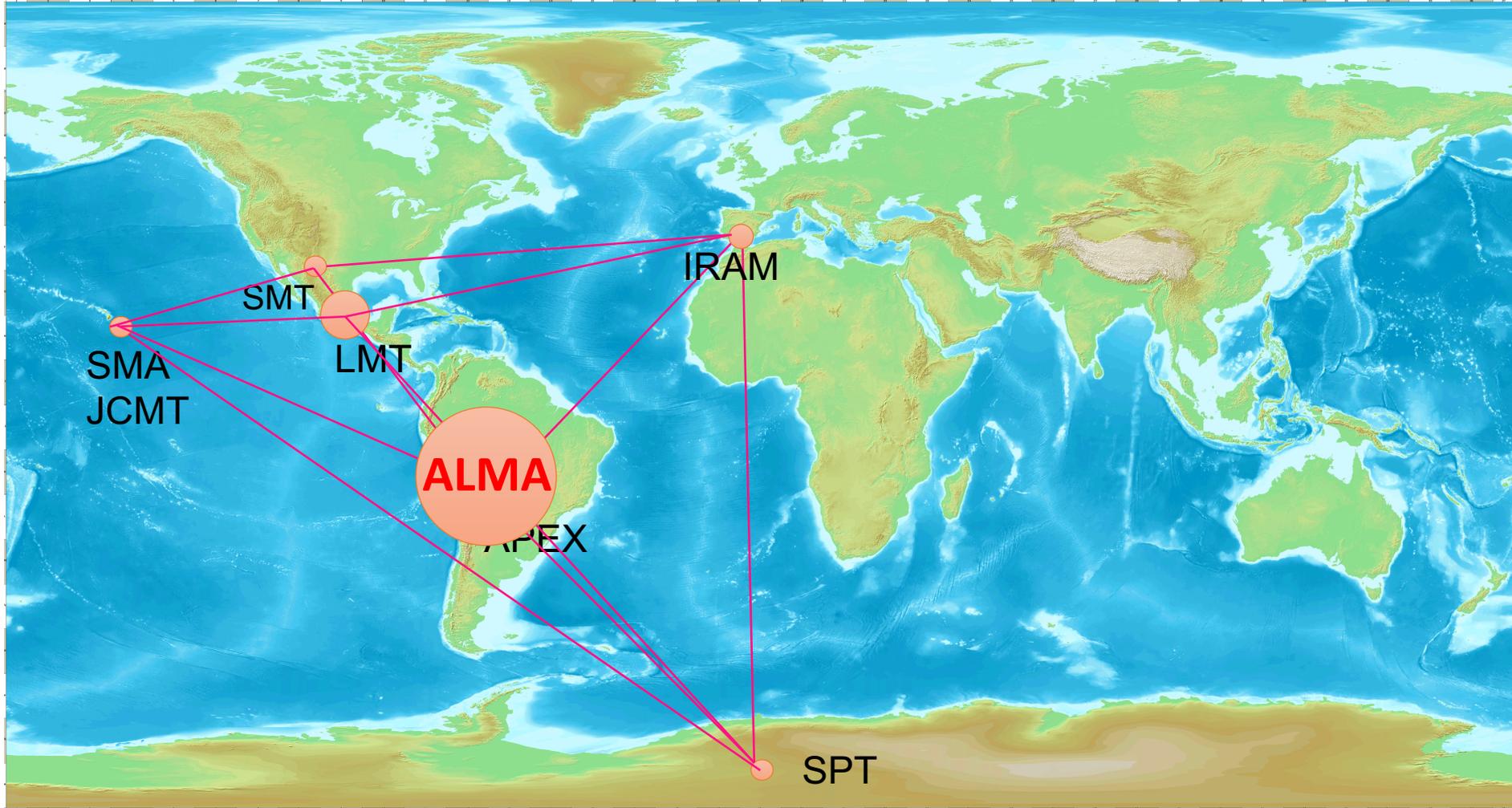
# Rapid expansion of EHT network

~2012 2013 2015 2017 2018?



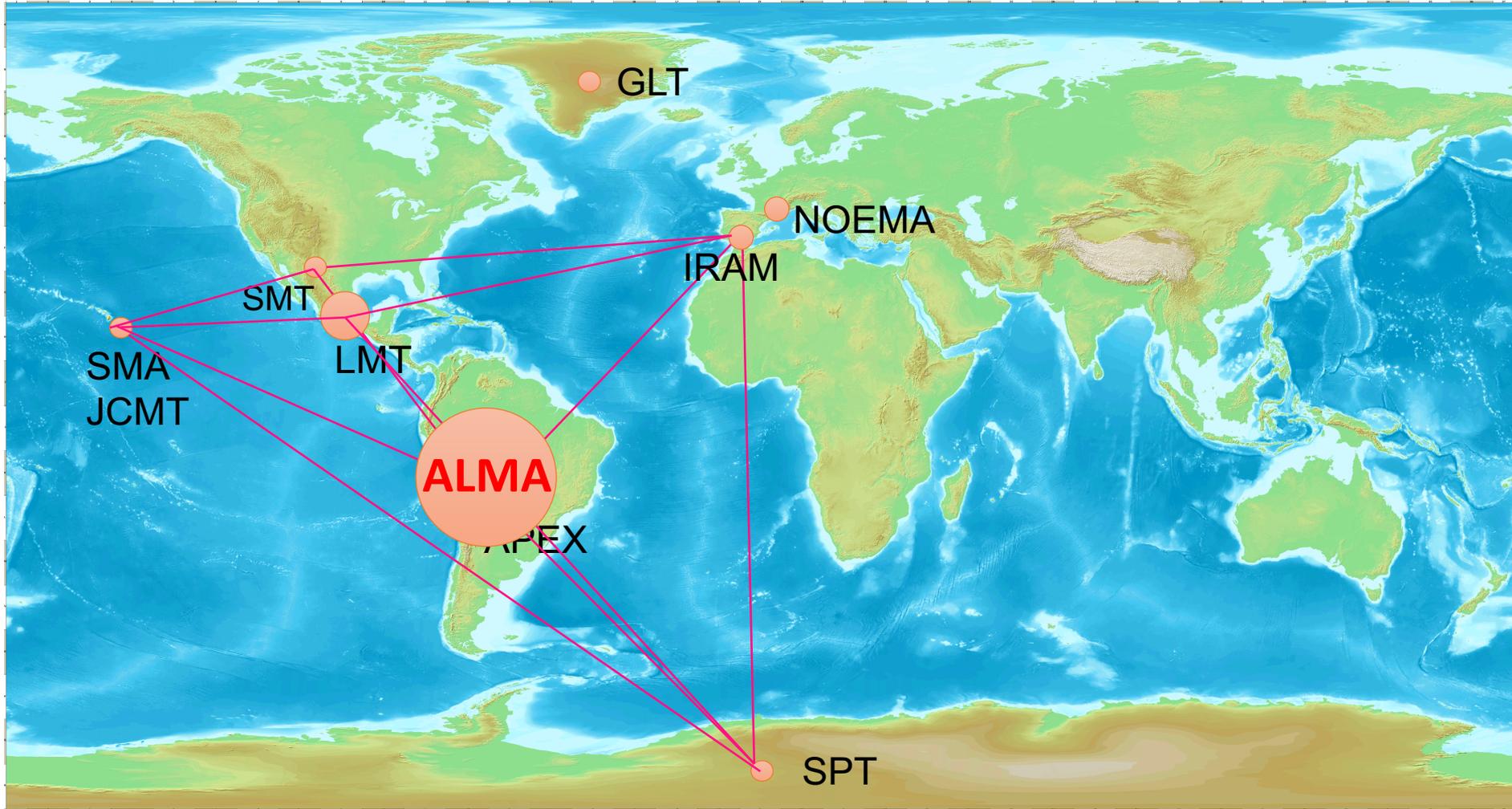
# Rapid expansion of EHT network

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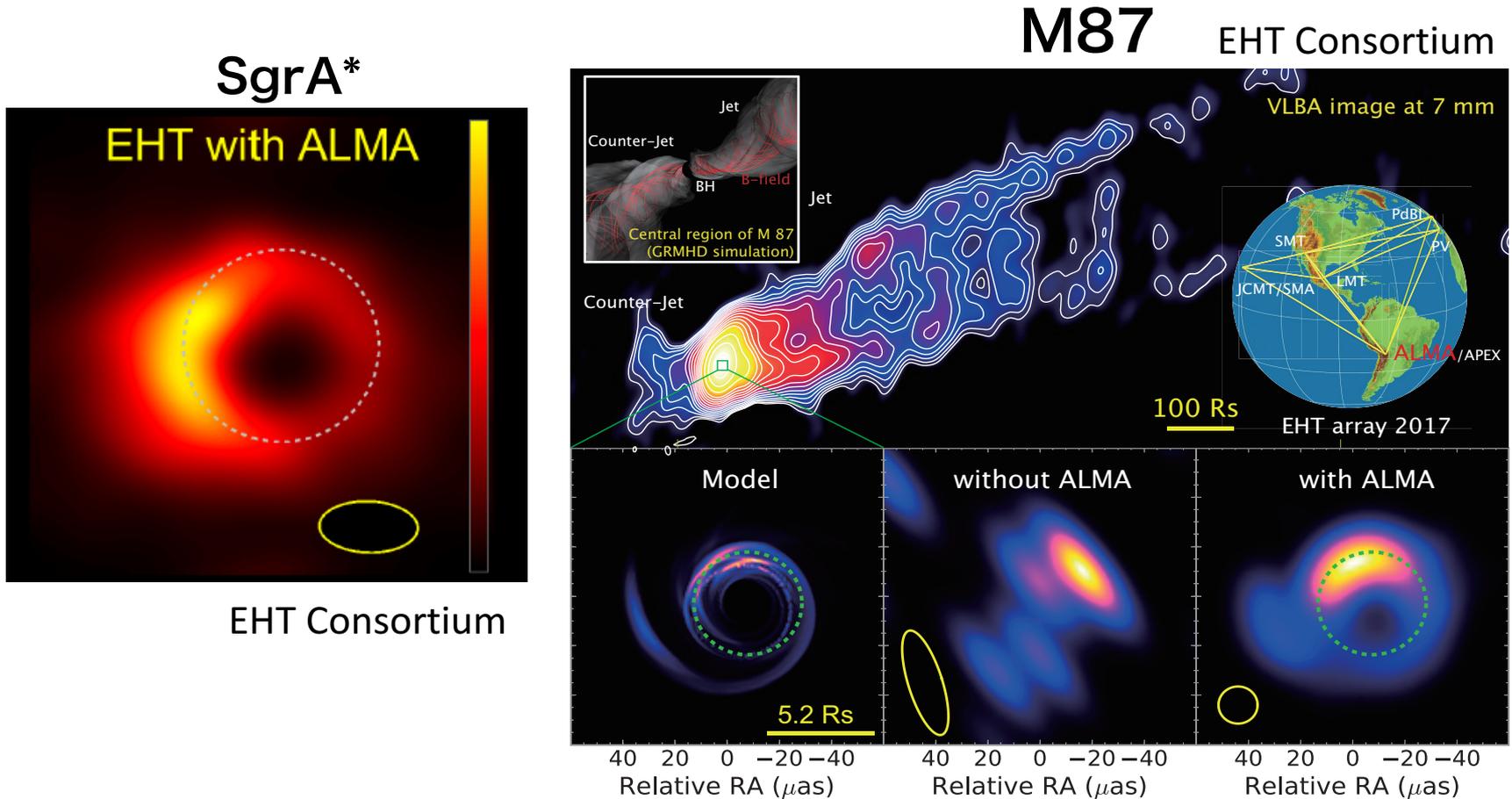


# Rapid expansion of EHT network

~2012 2013 2015 2017 2018?



# April 2017: First EHT run with ALMA



- Imaging BH shadow and accretion flow
- Imaging jet-launch structure (BZ vs BP)
- Imaging B-field topology (poloidal vs toroidal)
- Other jet sources: 3C273, 3C279, OJ287, CenA

# Multi-wavelength collaboration

SgrA\*

- EHT+ALMA (230GHz)
- MAGIC (TeV)
- HESS (TeV)
- NuSTAR (X-ray)
- Chandra (X-ray)
- SWIFT (X-ray)
- VLT (IR)
- GMVA+ALMA (86GHz)
- EAVN (43GHz)
- EAVN (22GHz)

2

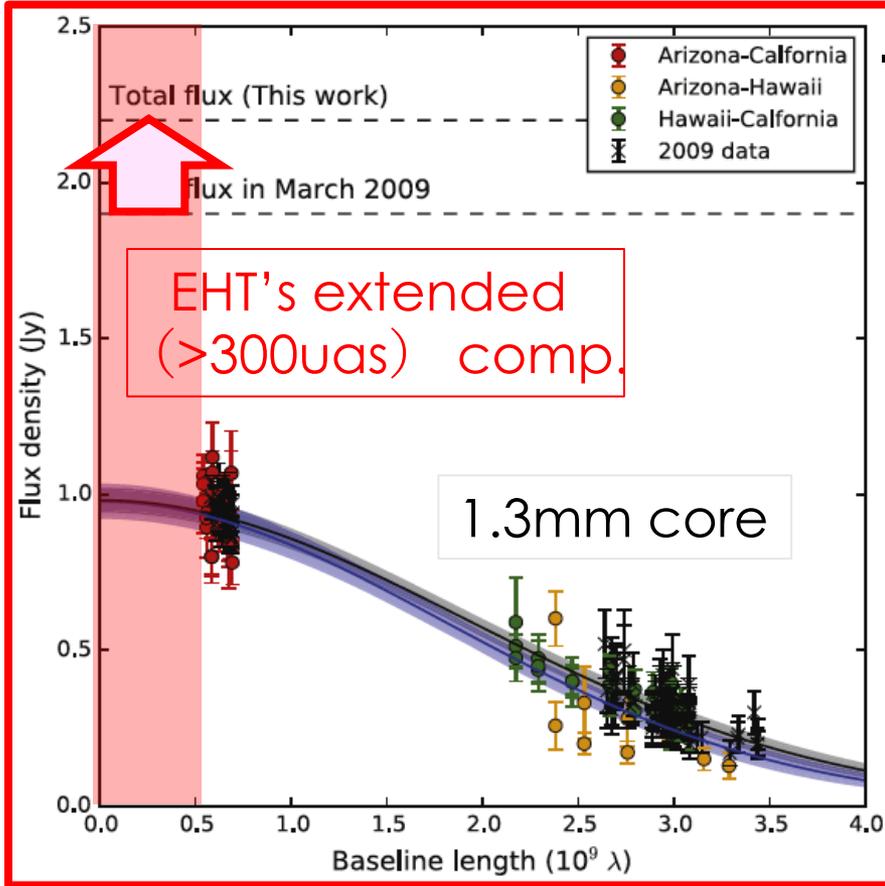
M87

- EHT+ALMA (230GHz)
- VERITAS (TeV)
- MAGIC (TeV)
- Fermi (GeV)
- NuSTAR (X-ray)
- Chandra (X-ray)
- SWIFT (X-ray)
- HSA (8,15,22GHz)
- EAVN (43GHz)
- EAVN (22GHz)

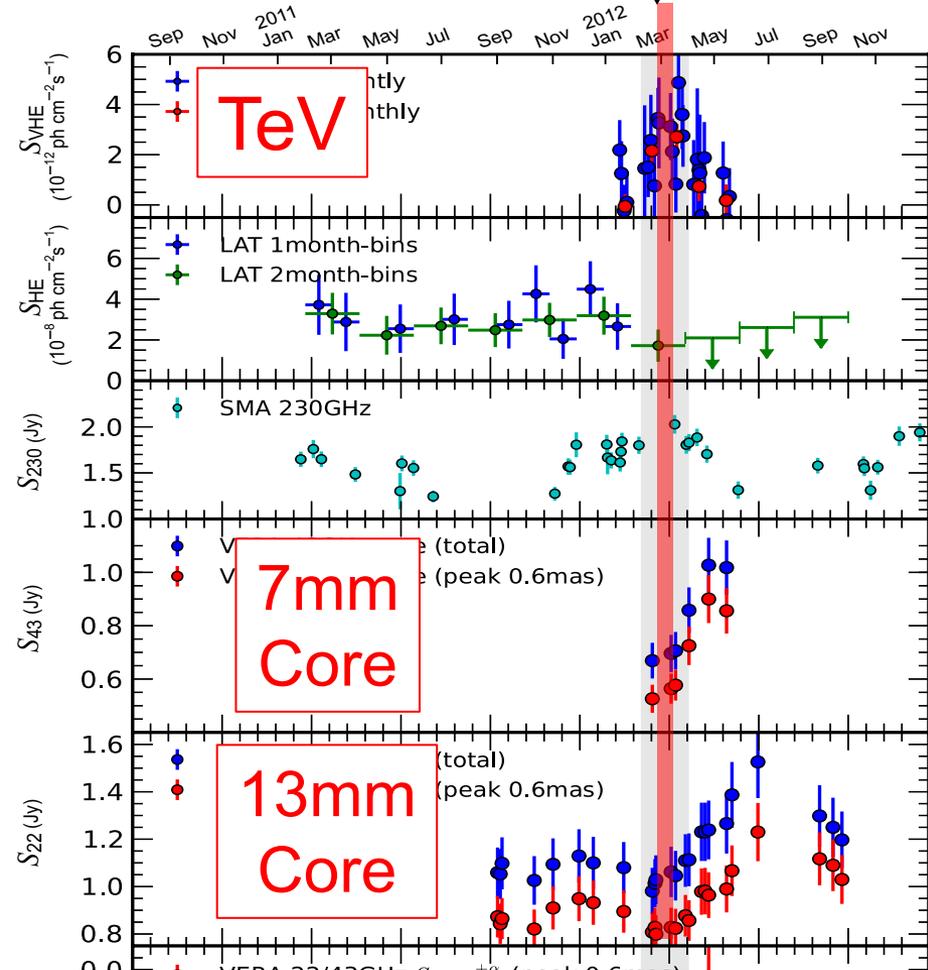
- Horizon-scale MWL science
  - Radio-to-TeV SED
  - Origin of flares
  - Particle energetics
  - Blazar zone
- EHT welcomes “External collaborators” who join/lead MWL science with EHT data/results
  - Observational/Theoretical
- Hada: contact person

# Probing TeV site with VLBI

EHT 1.3mm (Akiyama+2015)



VERA  
 7mm/13mm  
 (Hada+2014)



- TeV site could be located between 1.3mm core and 7mm core
- TeV site could be extended (size  $\sim 20\text{-}60R_s$ )

# EA white paper (astro-ph 1705.04776)

## White Paper on East Asian Vision for mm/submm VLBI: Toward Black Hole Astrophysics down to Angular Resolution of $1 R_S$

### Editors

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# **East Asia VLBI Network**



# The East-Asian VLBI Network

(Image Credit: Reto Stöckli, NASA Earth Observatory)

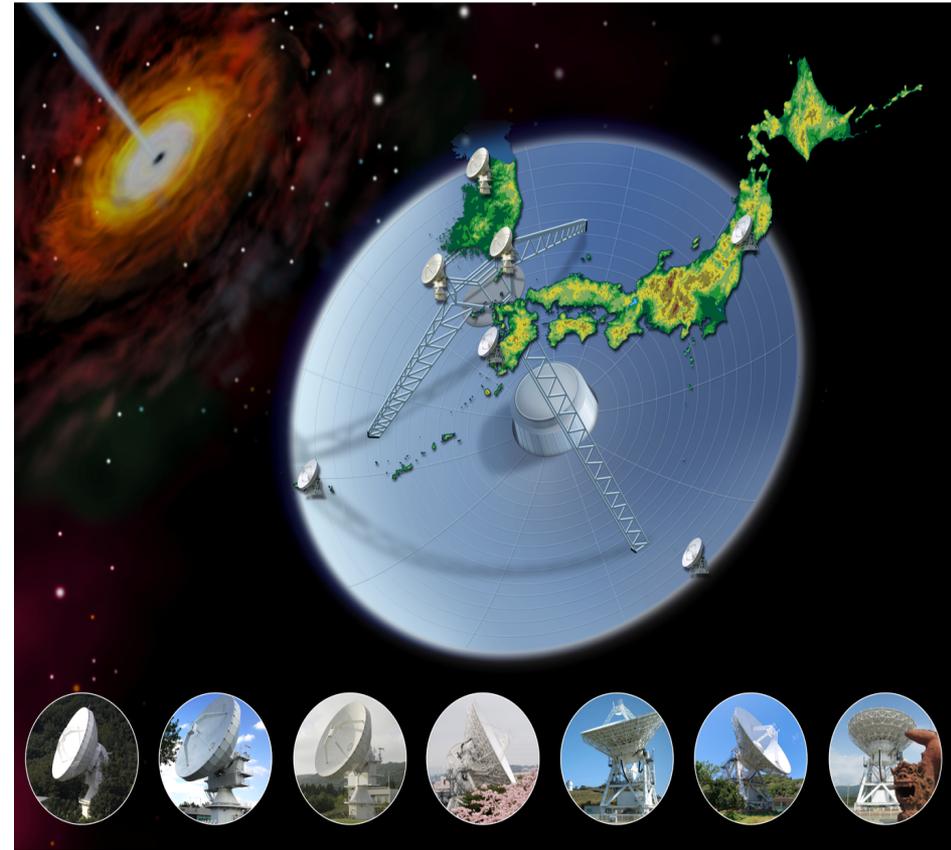
- 6.7 GHz
- 8 GHz
- 22 GHz
- 43 GHz

# KaVA: a core array of EAVN

- First international VLBI array in EA
- Operation started from 2014
- $D = 2300\text{km}$
- $\lambda = 1.3\text{cm}(22\text{GHz}), 7\text{mm}(43\text{GHz})$
- Resolution:  $1.2\text{mas}, 0.6\text{mas}$

- Good imaging performance
- Dense monitoring capability
- My telescope!

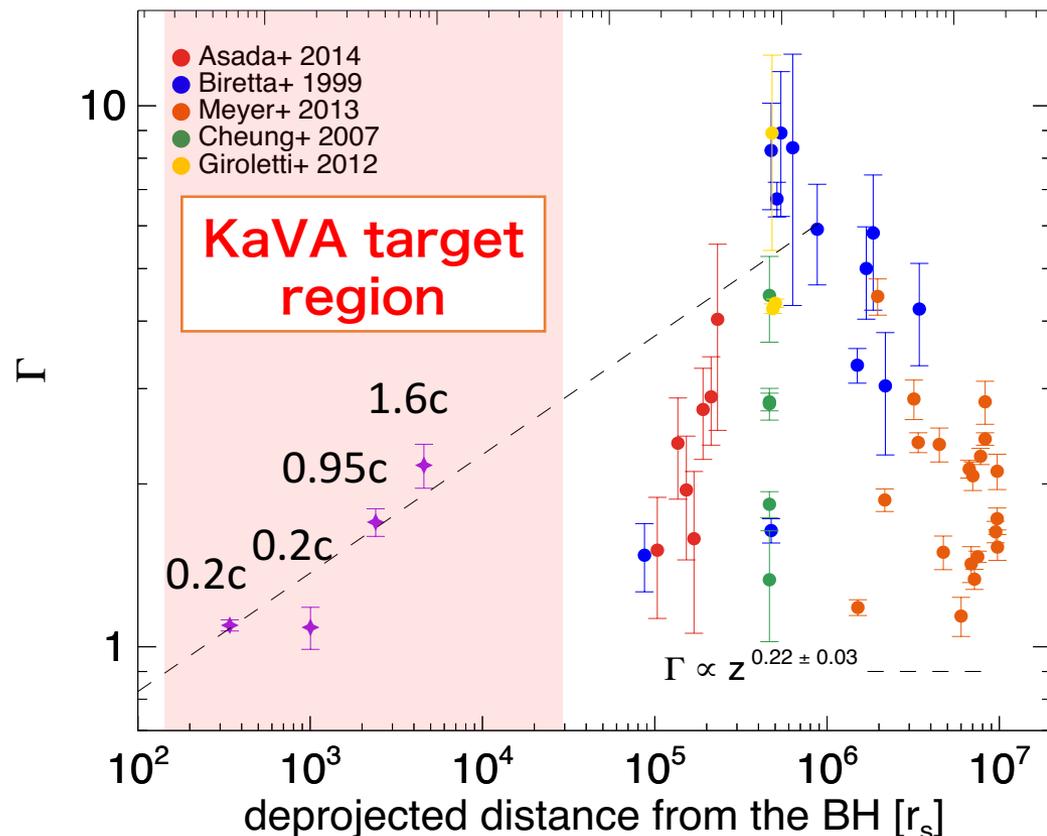
- 海外の望遠鏡に頼っていたネタを自前で占有的に
- 海外の望遠鏡でやらせてくれないネタを自前で占有的に



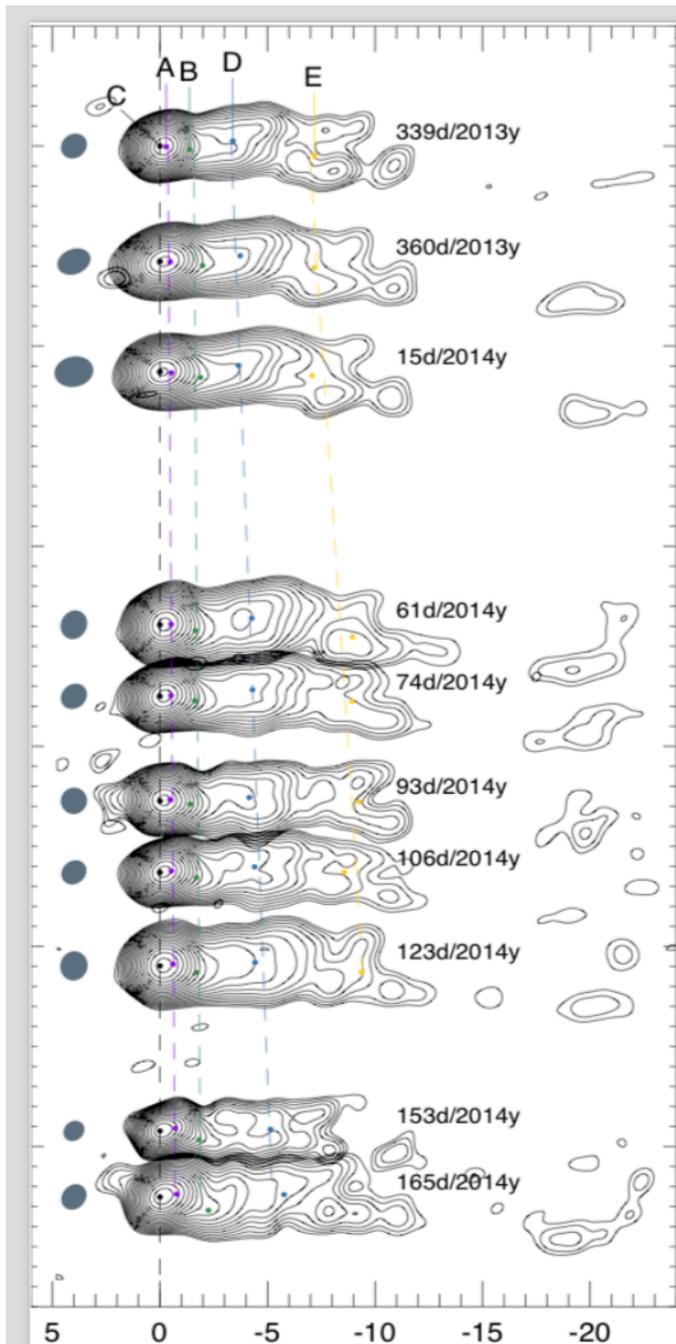
# Search for jet

## acceleration zone (Hada+2017)

M87 jet velocity-distance profile



M87 KaVA 1.3cm monitoring



- KaVA discovered a transition of subluminal to superluminal motions between  $z= 100-10000R_s$
- Acceleration and collimation co-spatial

# EAVN-EHT tie-up campaign (Spring 2017)



• Complement EHT

• EAで一致団結してVLBI観測しようという機運が過去最大級の盛り上がり

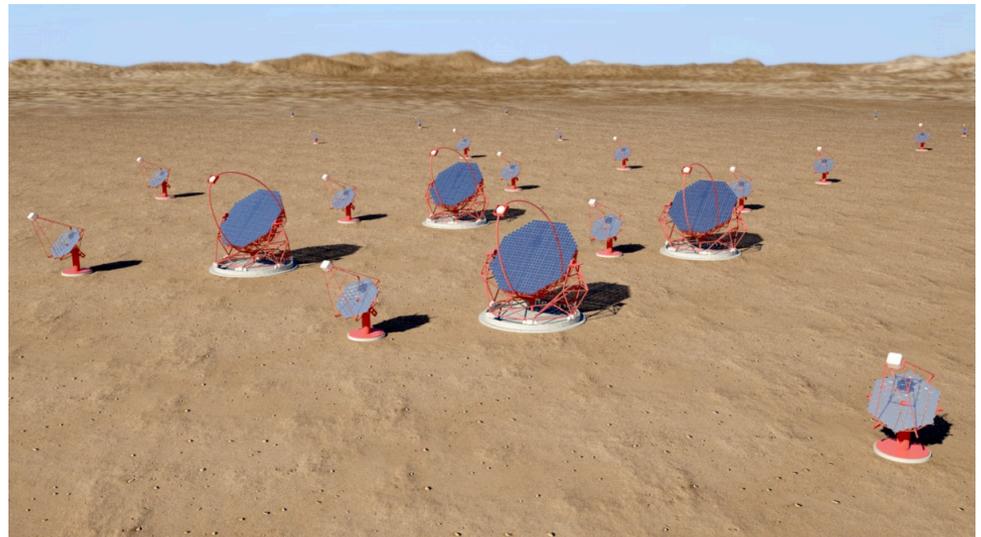
# More to come in East Asia

- EAVN will rapidly expand in the next few years
  - $\Leftrightarrow$  VLBA
- Broader range of science targets
- Synergy with CTA
  
- EAVN is a telescope for EA community!

FAST 500m (China)



TVN (Thai)



CTA

# 後半のまとめ

- 急速に拡張中の2つの国際VLBI観測網について紹介
- EHT (ミリ波VLBI)
  - 初めてshadowを解像した上でジェット根元を撮影 (できるかも)
- EAVN (センチ波VLBI)
  - センチ波帯で世界最高性能のVLBIアレイを「マイテレスコープ」として整備中
  - AGN以外にも様々な高エネルギーサイエンスに展開したい。ぜひ幅広いコミュニティー、多波長コラボに活用して頂きたい!
- どちらも日本・EAが中心的役割
- AGNジェット観測はEHT(1-100Rs)及びEAVN(>100Rs)を中心として今後数年も飛躍的に前進