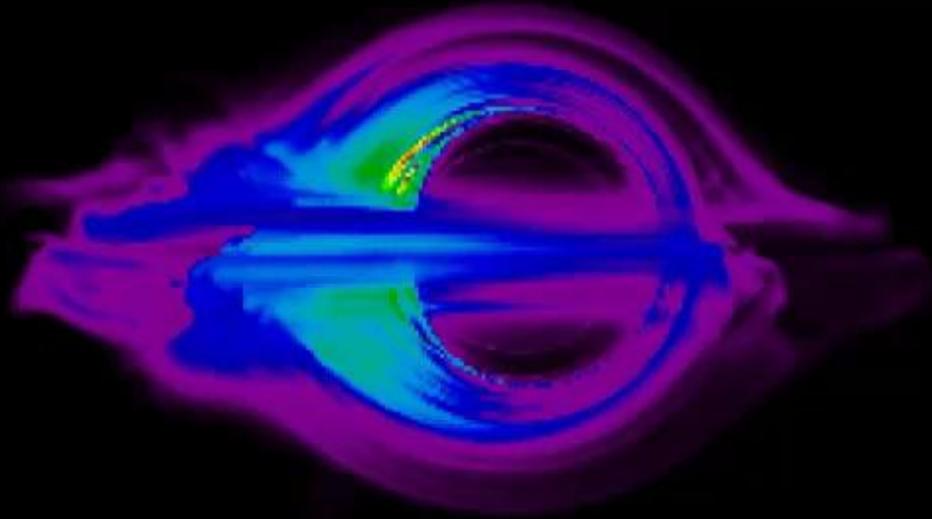


*Prospects on mm/submm VLBI,  
EHT/GLT and SMA role*



Movie: GRRT+GRMHD simulation by H. Y. Pu

*Keiichi Asada (ASIAA)*

# Do we want to have wSMA, while there is ALMA?



For mm/submm VLBI prospect, the answer is easy.

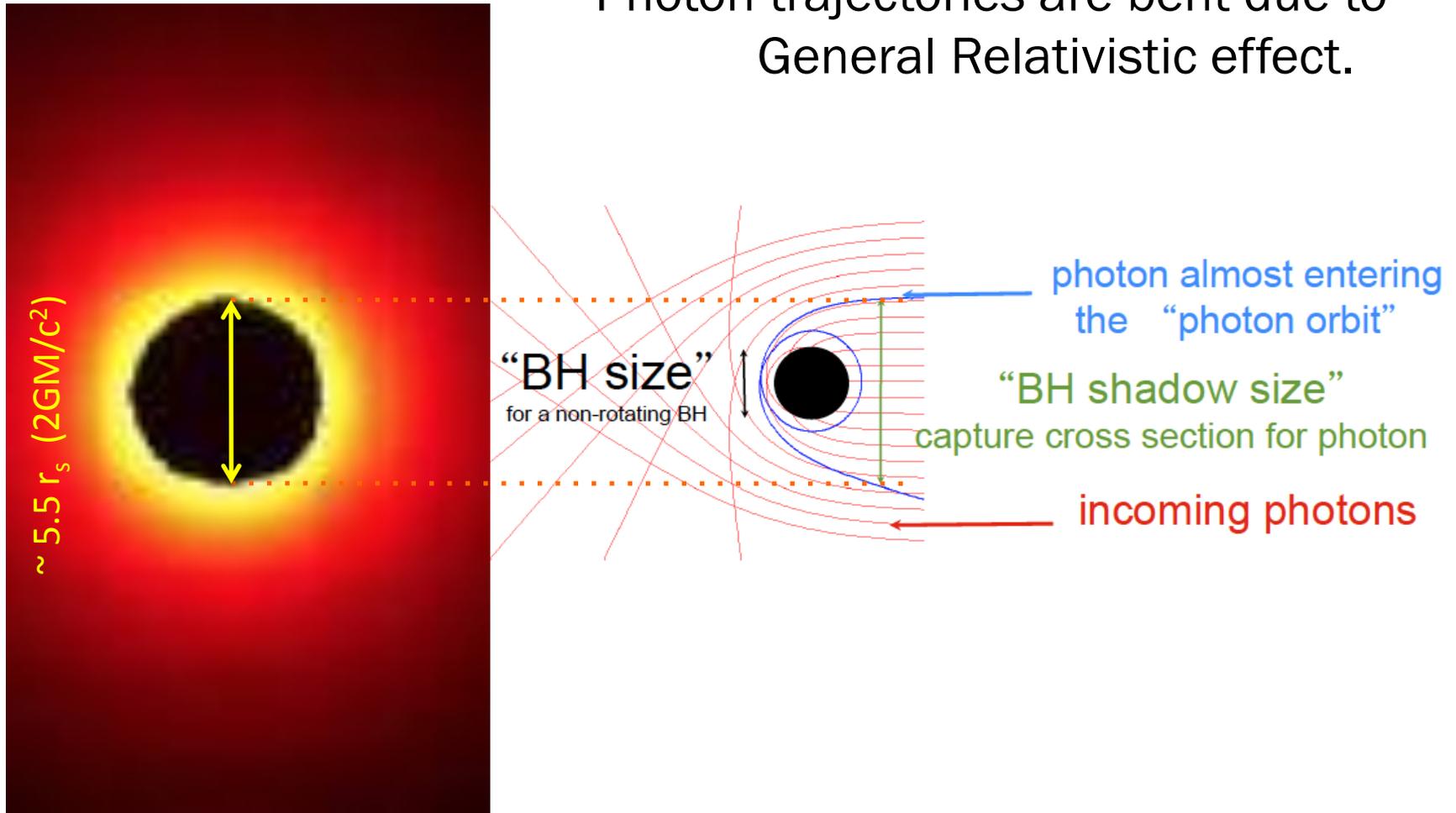
Of cause “YES”

ALMA can not be the substitute of wSMA.

1. Geographically different !!
2. Combination of SMA-JCMT is beneficial for calibration

# Image the shadow of the black hole

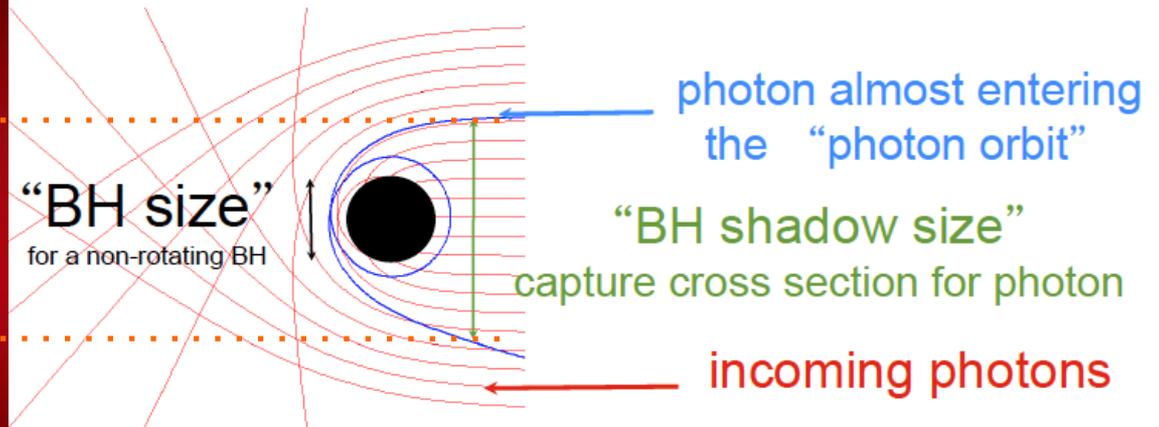
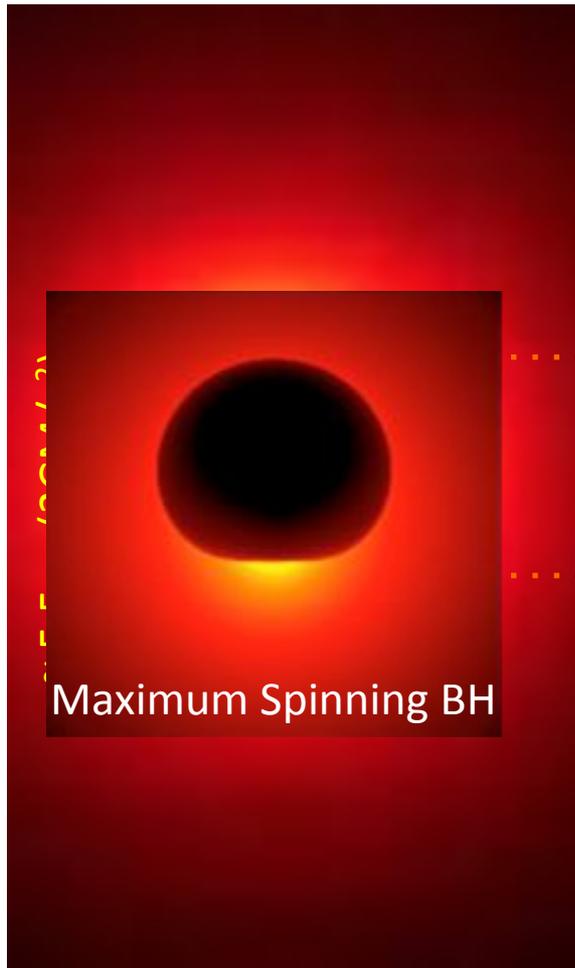
Photon trajectories are bent due to General Relativistic effect.



Images by Hung-Yi Pu

# Image the shadow of the black hole

Photon trajectories are bent due to General Relativistic effect.



Images by Hung-Yi Pu

# Apparent Size of BH

Source	Sgr A*	M 87	Cen A
BH Mass	$0.045 \times 10^8 M_{\odot}$	$66 (35) \times 10^8 M_{\odot}$	$0.45 \times 10^8 M_{\odot}$
Distance	0.008 Mpc	16.7 Mpc	3.4 Mpc
$r_s$	11 $\mu\text{as}$	8 (4) $\mu\text{as}$	0.3 $\mu\text{as}$
Size of Shadow	52 $\mu\text{as}$	40 (20) $\mu\text{as}$	1.5 $\mu\text{as}$

Resolution  $\propto \lambda / D$

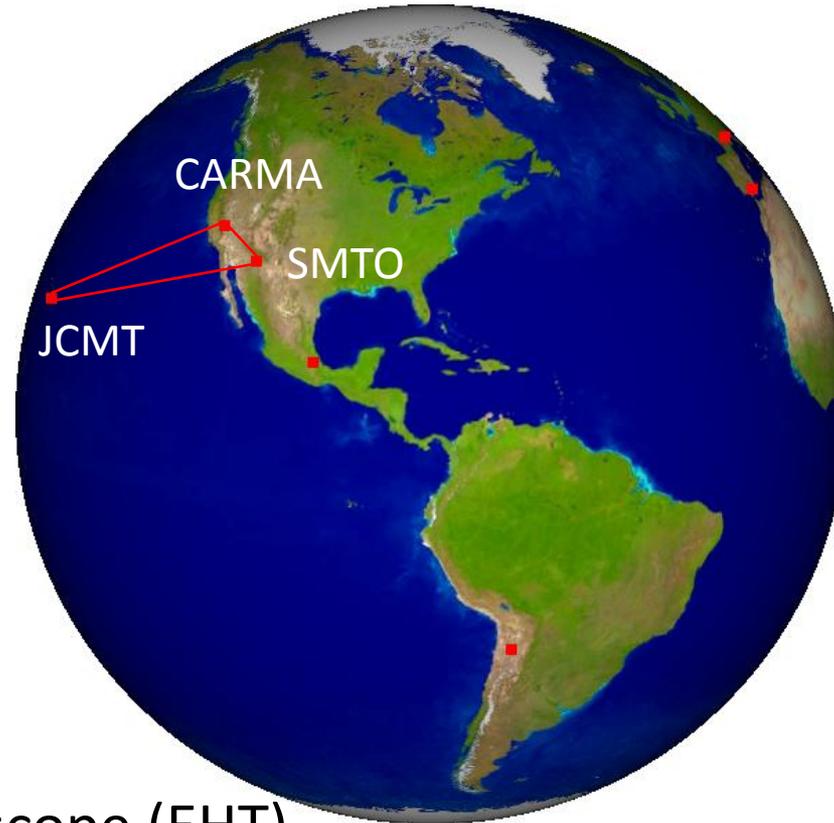
$\lambda$ : wavelength  
D: baseline



c.f. If  $\lambda$  is 1 mm (300 GHz) and D is 4000 km, resolution is 50  $\mu\text{as}$ .

Submm VLBI is the only way to achieve this angular resolution in near future !!

# EHT observation in 2007



Event Horizon Telescope (EHT)

Array coordinated based on experimental collaboration

Led by Shep Doeleman (CfA)

# Submm VLBI as a tool to study BH

Doeleman et al. 2008

nature

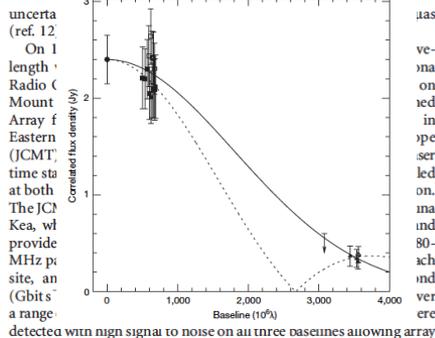
Vol 455 | 4 September 2008 | doi:10.1038/nature07245

LETTERS

## Event-horizon-scale structure in the supermassive black hole candidate at the Galactic Centre

Sheperd S. Doeleman<sup>1</sup>, Jonathan Weintraub<sup>2</sup>, Alan E. E. Rogers<sup>1</sup>, Richard Plambeck<sup>3</sup>, Robert Freund<sup>4</sup>, Remo P. J. Tilanus<sup>5,6</sup>, Per Friberg<sup>7</sup>, Lucy M. Ziurys<sup>4</sup>, James M. Moran<sup>2</sup>, Brian Corey<sup>1</sup>, Ken H. Young<sup>7</sup>, Daniel L. Smythe<sup>1</sup>, Michael Titus<sup>1</sup>, Daniel P. Marrone<sup>7,8</sup>, Roger J. Cappallo<sup>1</sup>, Douglas C.-J. Bock<sup>9</sup>, Geoffrey C. Bower<sup>3</sup>, Richard Chamberlin<sup>10</sup>, Gary R. Davis<sup>5</sup>, Thomas P. Krichbaum<sup>11</sup>, James Lamb<sup>12</sup>, Holly Maness<sup>3</sup>, Arthur E. Niell<sup>4</sup>, Alan Roy<sup>11</sup>, Peter Strittmatter<sup>4</sup>, Daniel Werthimer<sup>13</sup>, Alan R. Whitney<sup>1</sup> & David Woody<sup>12</sup>

The cores of most galaxies are thought to harbour supermassive black holes, which power galactic nuclei by converting the gravitational energy of accreting matter into radiation<sup>1</sup>. Sagittarius A\* (Sgr A\*), the compact source of radio, infrared and X-ray emission at the centre of the Milky Way, is the closest example of this phenomenon, with an estimated black hole mass that is 4,000,000 times that of the Sun<sup>2,3</sup>. A long-standing astronomical goal is to resolve structures in the innermost accretion flow surrounding Sgr A\*, where strong gravitational fields will distort the appearance of radiation emitted near the black hole. Radio observations at wavelengths of 3.5 mm and 7 mm have detected intrinsic structure in Sgr A\*, but the spatial resolution of observations at these wavelengths is limited by interstellar scattering<sup>4-7</sup>. Here we report observations at a wavelength of 1.3 mm that set a size of  $37_{-10}^{+16}$  microarcseconds on the intrinsic diameter of Sgr A\*. This is less than the expected apparent size of the event horizon of the presumed black hole, suggesting that the bulk of Sgr A\* emission may not be centred on the black hole, but arises in the surrounding accretion flow.



Size  $\sim 40 \mu\text{as} \sim 4 r_s$  !!

Sgr A\*

Doeleman et al. 2012

Scienceexpress

Reports

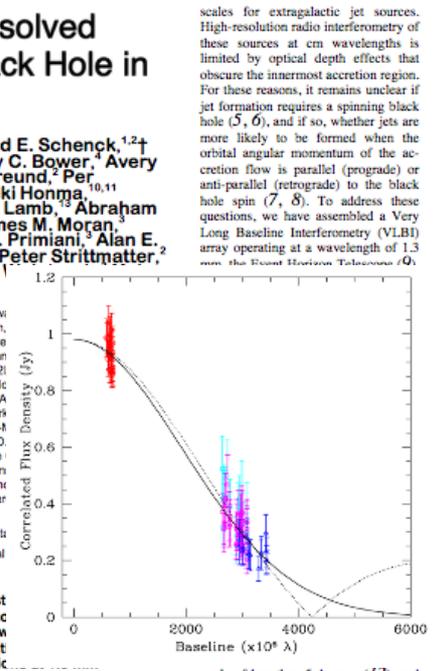
## Jet Launching Structure Resolved Near the Supermassive Black Hole in M87

Sheperd S. Doeleman<sup>1,3\*</sup>, Vincent L. Fish<sup>1</sup>, David E. Schenck<sup>1,2†</sup>, Christopher Beaudoin<sup>1</sup>, Ray Blundell<sup>3</sup>, Geoffrey C. Bower<sup>4</sup>, Avery E. Broderick<sup>5,6</sup>, Richard Chamberlin<sup>7</sup>, Robert Freund<sup>2</sup>, Per Friberg<sup>8</sup>, Mark A. Gurwell<sup>9</sup>, Paul T. P. Ho<sup>10</sup>, Mareki Honma<sup>10,11</sup>, Makoto Inoue<sup>12</sup>, Thomas P. Krichbaum<sup>12</sup>, James Lamb<sup>13</sup>, Abraham Loeb<sup>14</sup>, Colin Longdale<sup>15</sup>, Daniel P. Marrone<sup>16</sup>, James M. Moran<sup>17</sup>, Tomoaki Oyama<sup>18</sup>, Richard Plambeck<sup>19</sup>, Rurik A. Primiani<sup>3</sup>, Alan E. Rogers<sup>1</sup>, Daniel L. Smythe<sup>1</sup>, Jason SooHoo<sup>1</sup>, Peter Strittmatter<sup>2</sup>, Remo P. J. Tilanus<sup>2,14</sup>, Michael Titus<sup>1</sup>, Jonathan Wright<sup>4</sup>, Ken H. Young<sup>3</sup>, Lucy Ziurys<sup>20</sup>

<sup>1</sup>MIT Haystack Observatory, Off Route 40, Westford, MA 01886, USA. <sup>2</sup>Steward Radio Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, <sup>3</sup>Harvard Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge Department of Astronomy, University of California Berkeley, Hearsh Field Ann <sup>4</sup>Perimeter Institute, 31 Caroline Street, North Waterloo, Ontario, Canada N2L and Astronomy, University of Waterloo, 200 University Avenue West, Waterloo <sup>5</sup>Catech Submillimeter Observatory, 111 Nowele Street, Hilo, HI 96720, USA <sup>6</sup>Telescope, Joint Astronomy Centre, 660 North A'ohoku Place University Park <sup>7</sup>Academia Sinica Institute for Astronomy and Astrophysics, 11F Astronomy-III <sup>8</sup>Taiwan University, No. 1, Roosevelt Rd., Sec. 4 Taipei 10617, Taiwan, R.O. <sup>9</sup>Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588 Japan. <sup>10</sup>The <sup>11</sup>Advanced Studies, Osawa, Mitaka, Tokyo 181-8588, Japan. <sup>12</sup>Max-Planck-In <sup>13</sup>dem Hugel 69, 53121 Bonn, Germany. <sup>14</sup>OVRO, California Institute of Techn <sup>15</sup>Pine, CA 93513-0968, USA. <sup>16</sup>Netherlands Organization for Scientific Resear <sup>17</sup>300, NL-2509 AC The Hague, Netherlands.

\*To whom correspondence should be addressed. E-mail: sdoeleman@hayst <sup>†</sup>Present address: University of Colorado at Boulder, Dept. of Astrophysical <sup>‡</sup>UCB, Boulder, CO, 80309 USA.

Approximately 10% of active galactic nuclei exhibit relativist powered by accretion of matter onto super massive black hc measured width profiles of such jets on large scales agree w collimation, predicted structure on accretion disk scales at t not been detected. We report radio interferometry observati

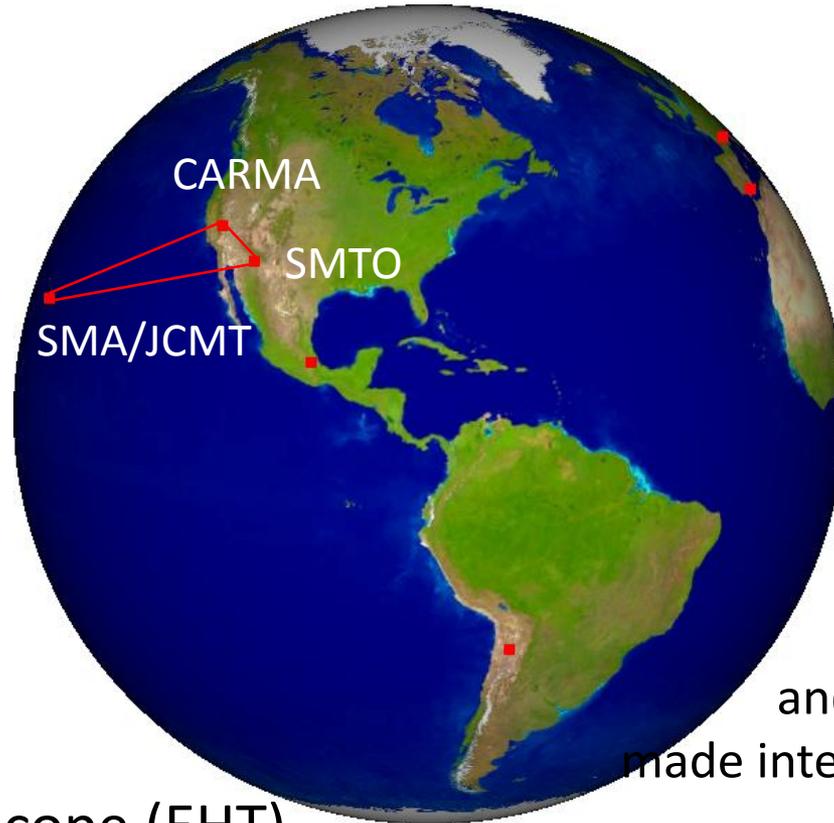


Size  $\sim 40 \mu\text{as} \sim 5 r_s$  !!

M 87

Submm VLBI is feasible and promising to image the shadow of BH !!

# EHT observation in 2009



First participation of SMA



Jonathan Weintroub and his group continuously made intensive efforts to realize it

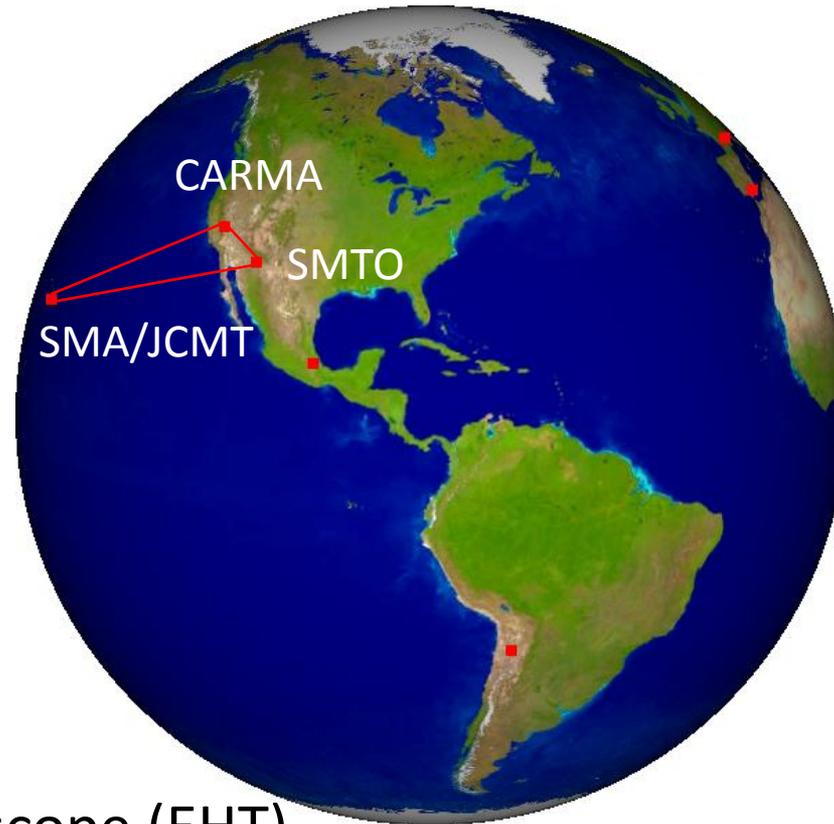
## Event Horizon Telescope (EHT)

Array coordinated based on experimental collaboration

Each session: ~ a few - 5 days within 10 days slots

Host institutes for EHT collaboration: MPIfR – Bonn, ASIAA, SAO/CfA, MIT Haystack, CARMA, NAOJ, NRAO, UC Berkeley, IRAM, APEX, JCMT, U. Concepcion, UNAM, Perimeter Inst.

# EHT observation in 2011



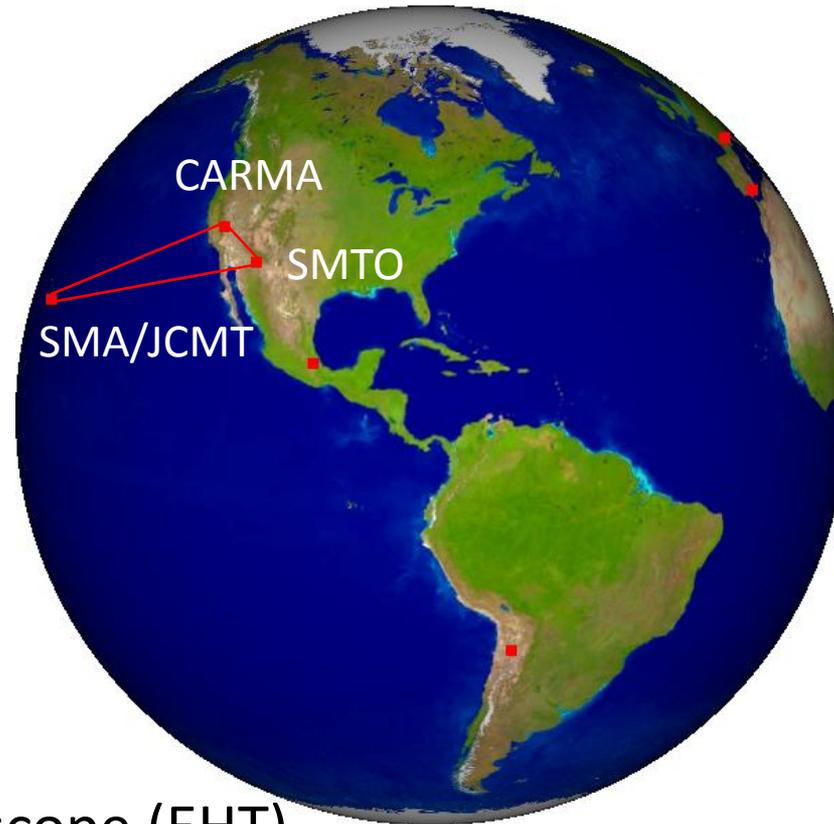
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# EHT observation in 2012



First dual Pol.  
observation

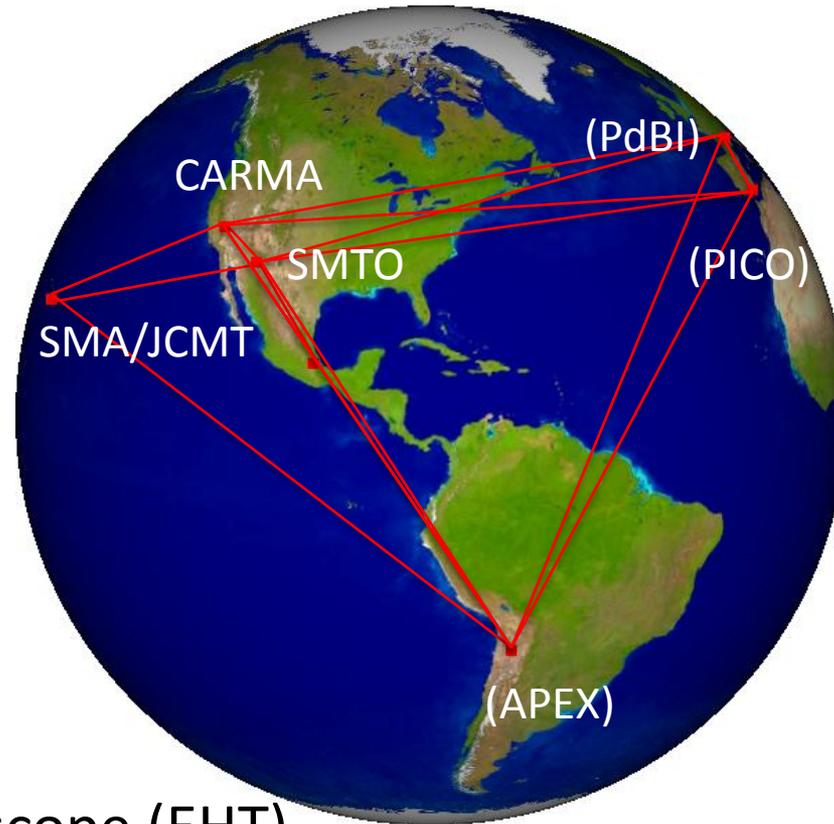
## Event Horizon Telescope (EHT)

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# EHT observation in 2013



First global  
observation

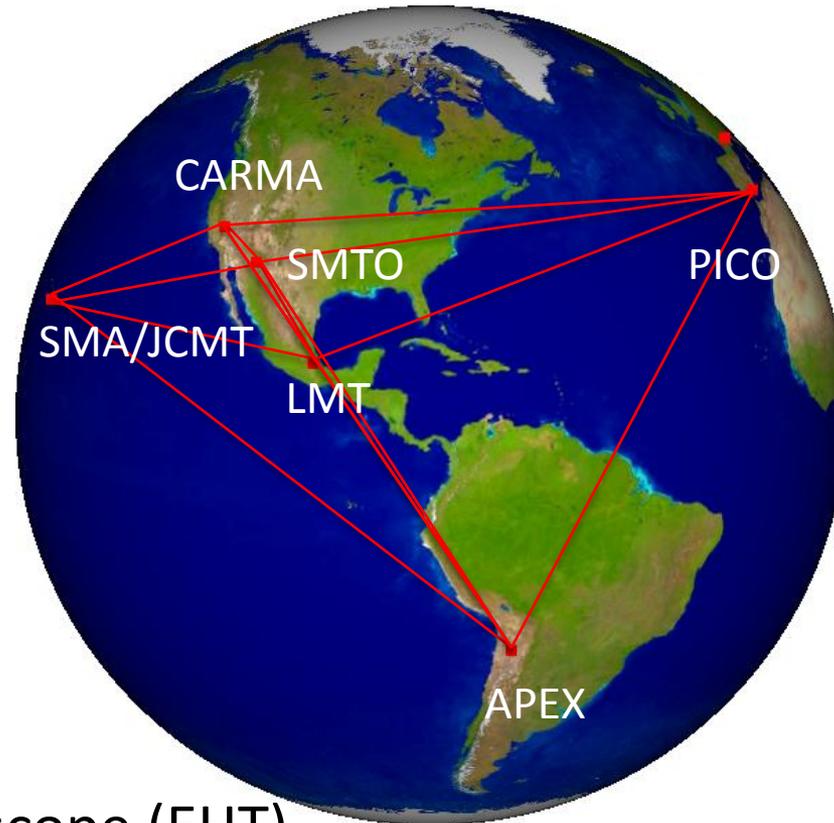
## Event Horizon Telescope (EHT)

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# EHT observation in 2015



First 16 Gbps  
observation

## Event Horizon Telescope (EHT)

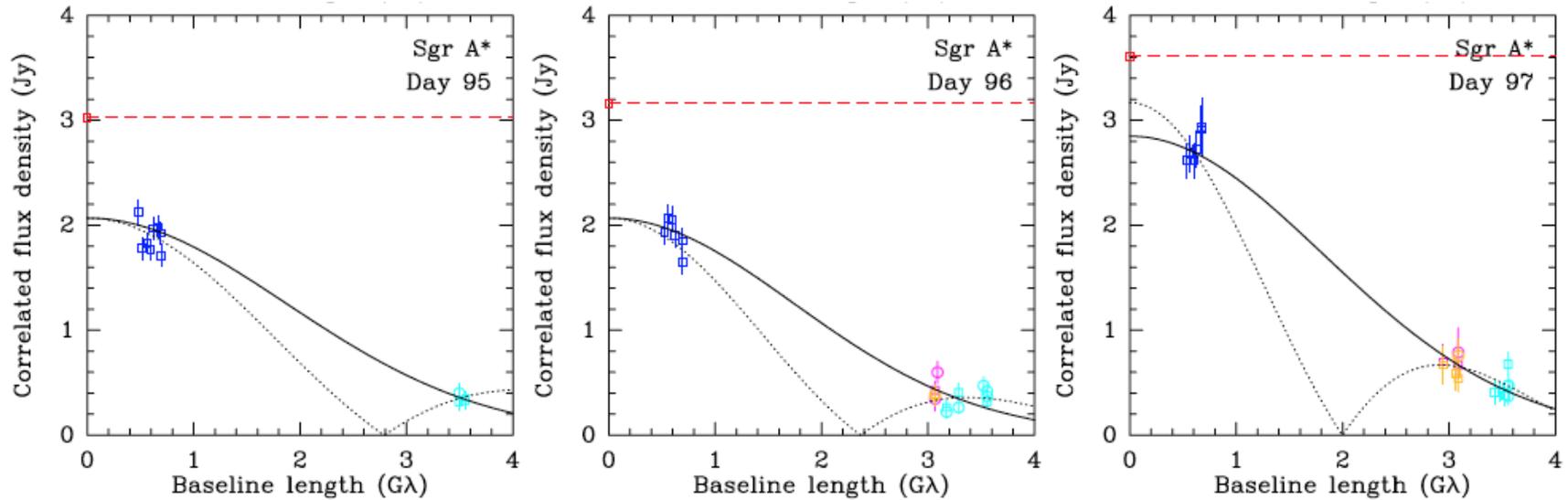
Array coordinated based on experimental collaboration

Each session: ~ a few - 5 days within 10 days slots

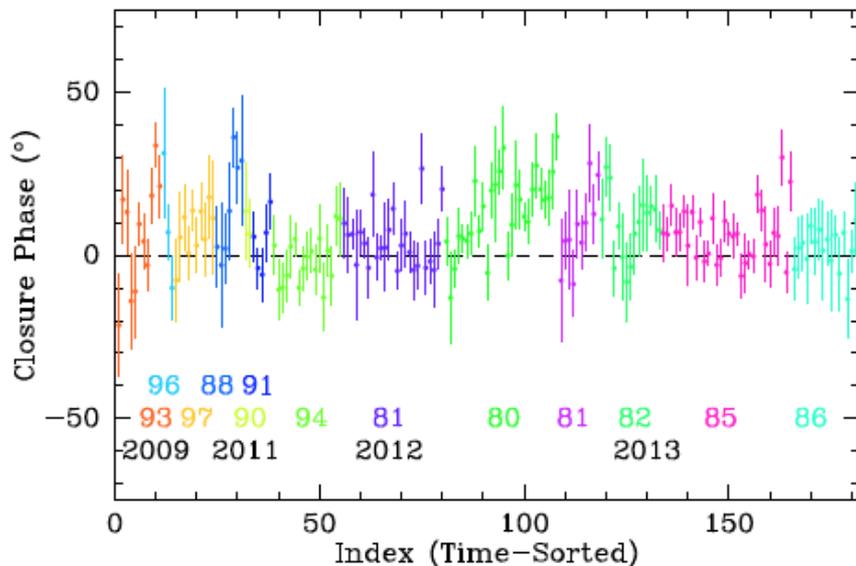
Host institutes for EHT collaboration: MPIfR – Bonn, ASIAA, SAO/CfA, MIT Haystack, CARMA, NAOJ, NRAO, UC Berkeley, IRAM, APEX, JCMT, U. Concepcion, UNAM, Perimeter Inst.

# Series of Sgr A\* observations

Fish et al. (2011)



Fish et al. (2016)



- Rapid time variation of the structure at EH scale

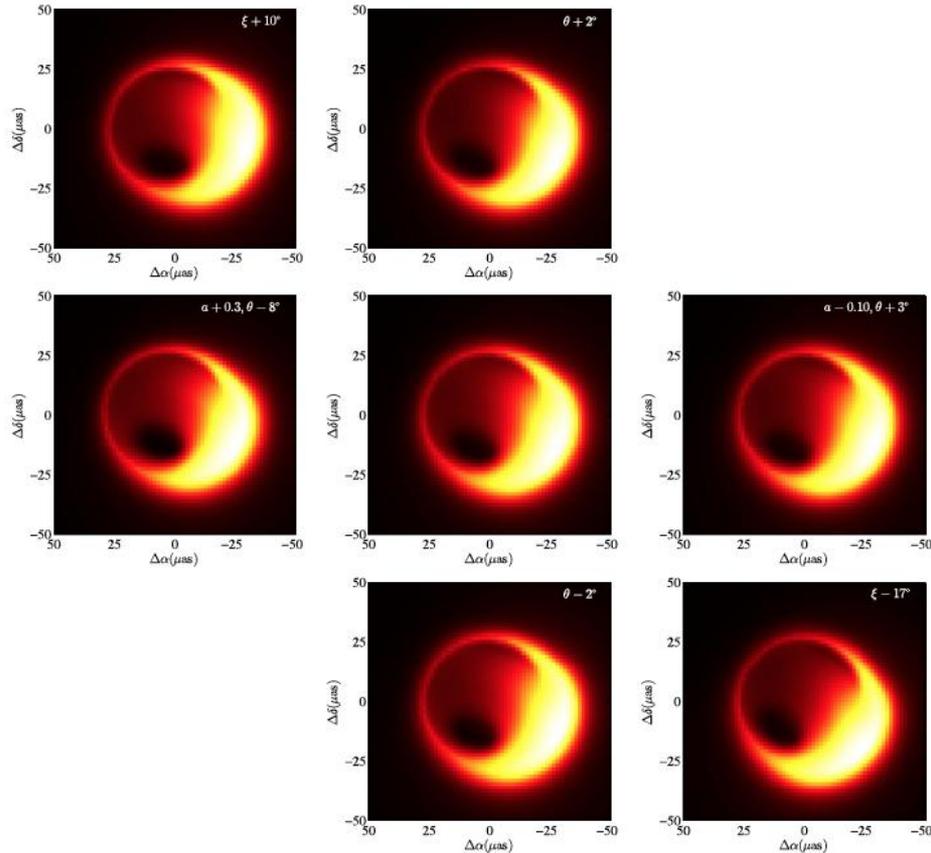
- Non Zero Closure phase

$$\mathbf{g}_1 \mathbf{g}_2^* \mathbf{g}_2 \mathbf{g}_3^* \mathbf{g}_3 \mathbf{g}_1^* \mathbf{V}_{12} \mathbf{V}_{23} \mathbf{V}_{31}$$

-> persist asymmetric structure at EH scale

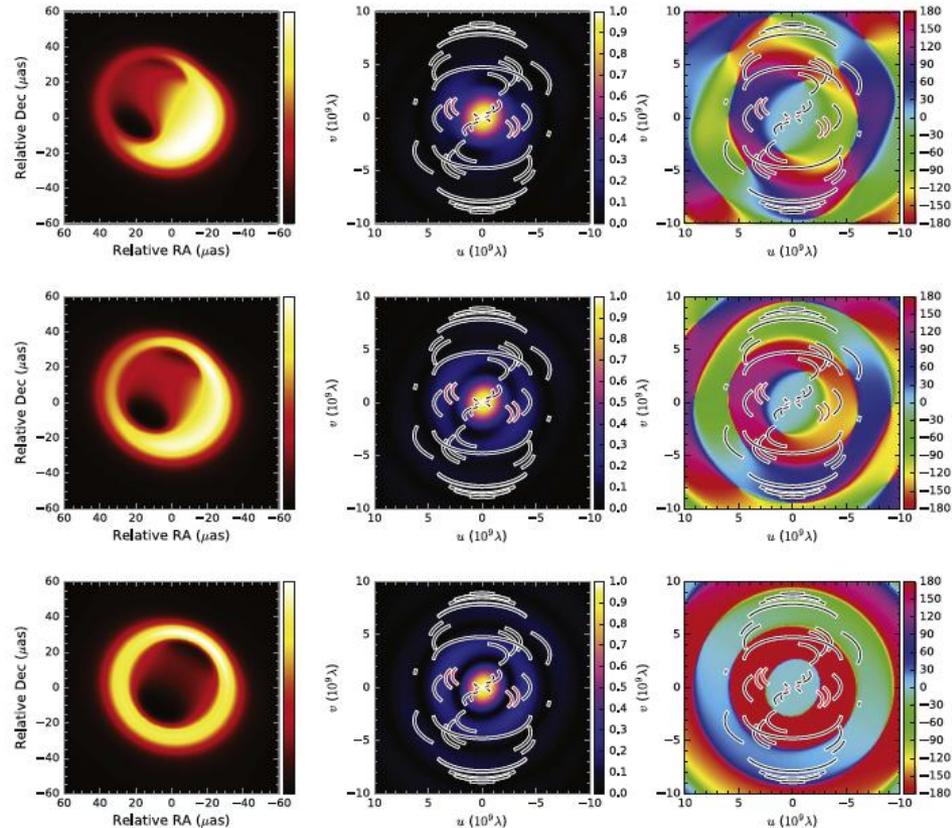
# Series of Sgr A\* observations

Broderick et al. 2016



Constrain on the spin of BH.

Pu et al. 2016

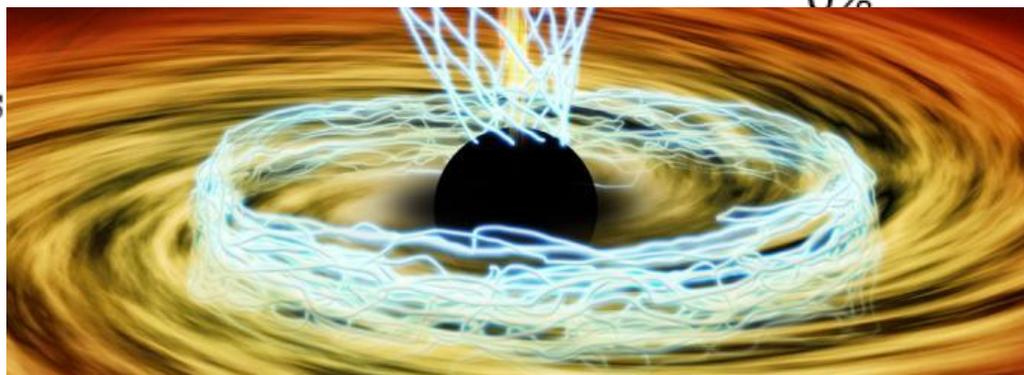
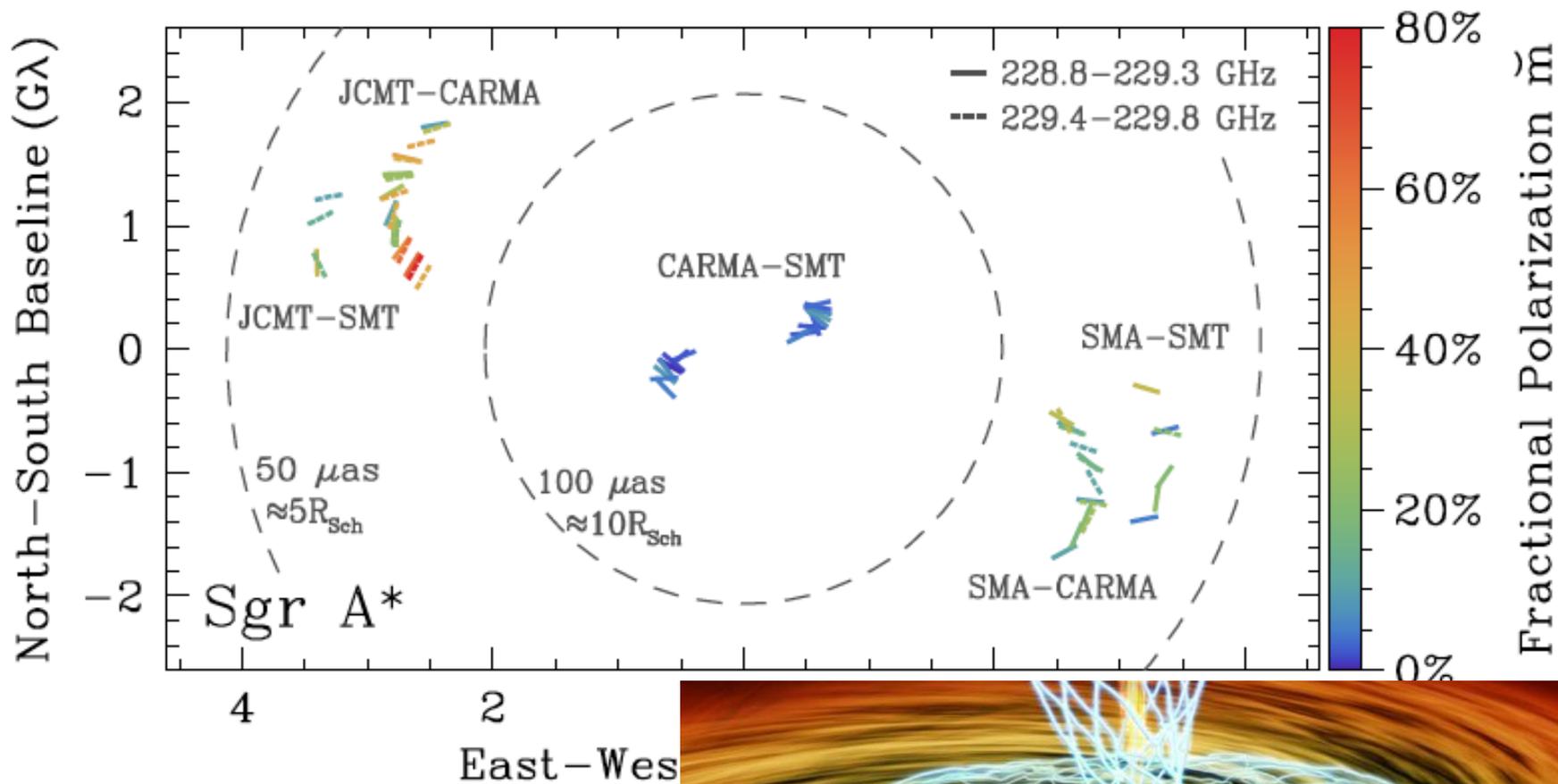


Constrain on the accretion flow dynamics

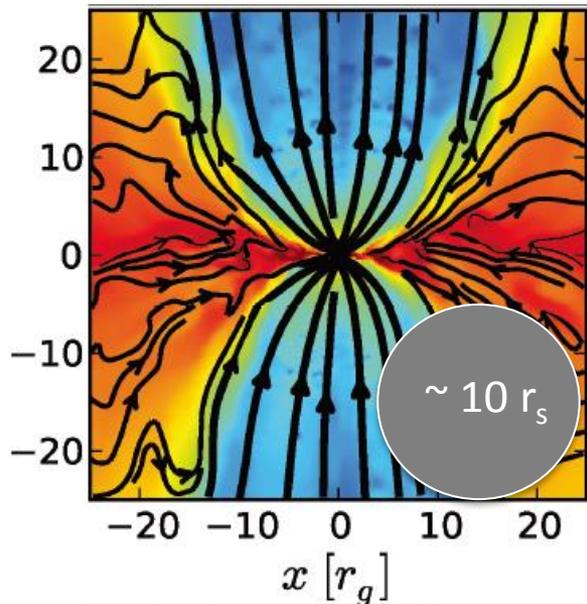
More astrophysics on accretion flow (jet base) is needed,  
while more data will easily solve this degeneracy.

# Polarization with EHT

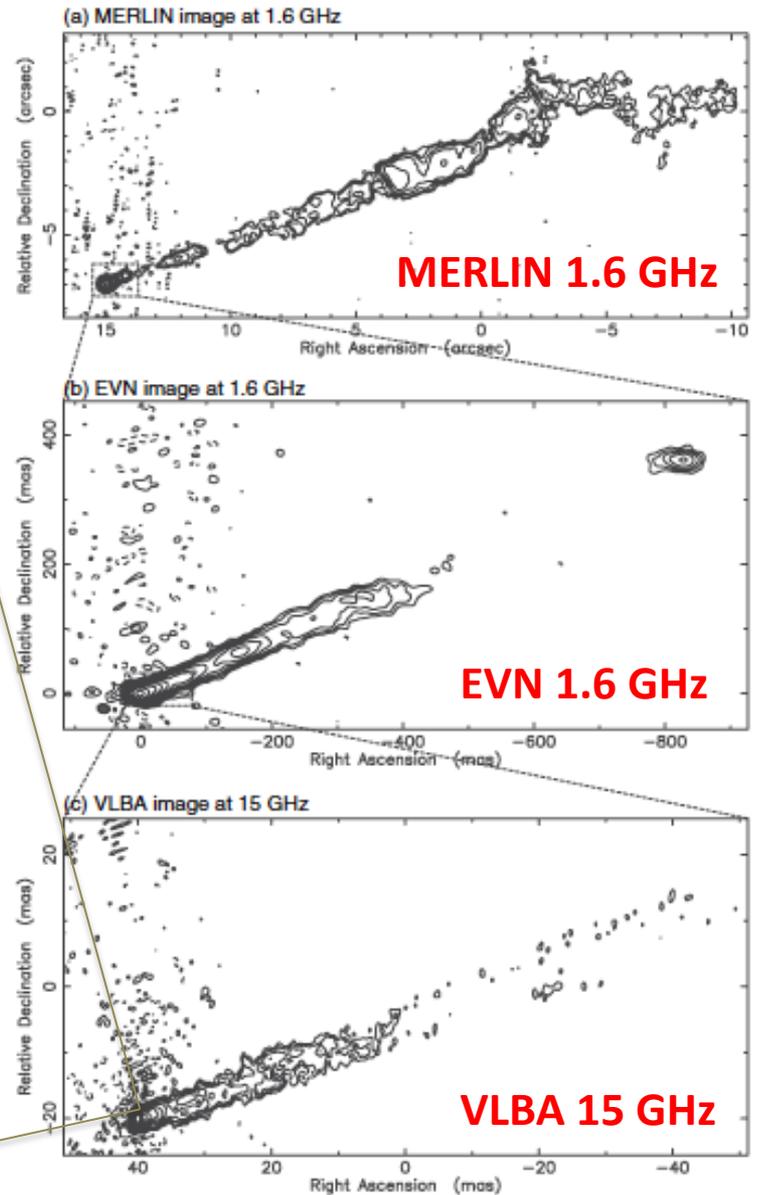
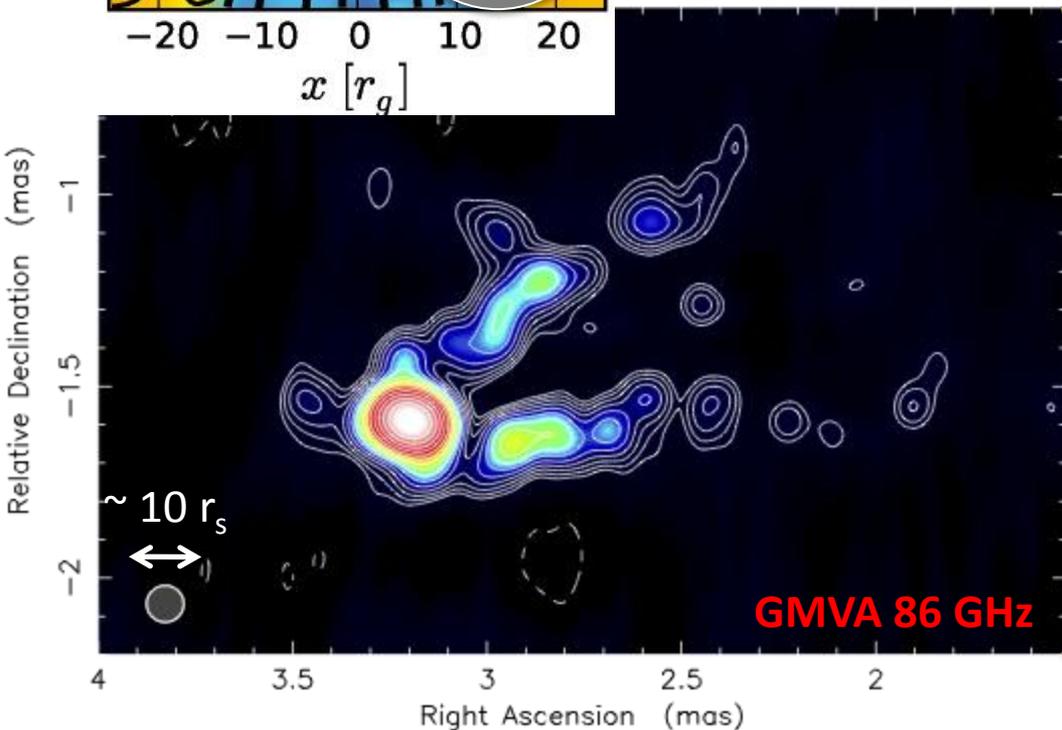
Johnson et al. 2015, Science



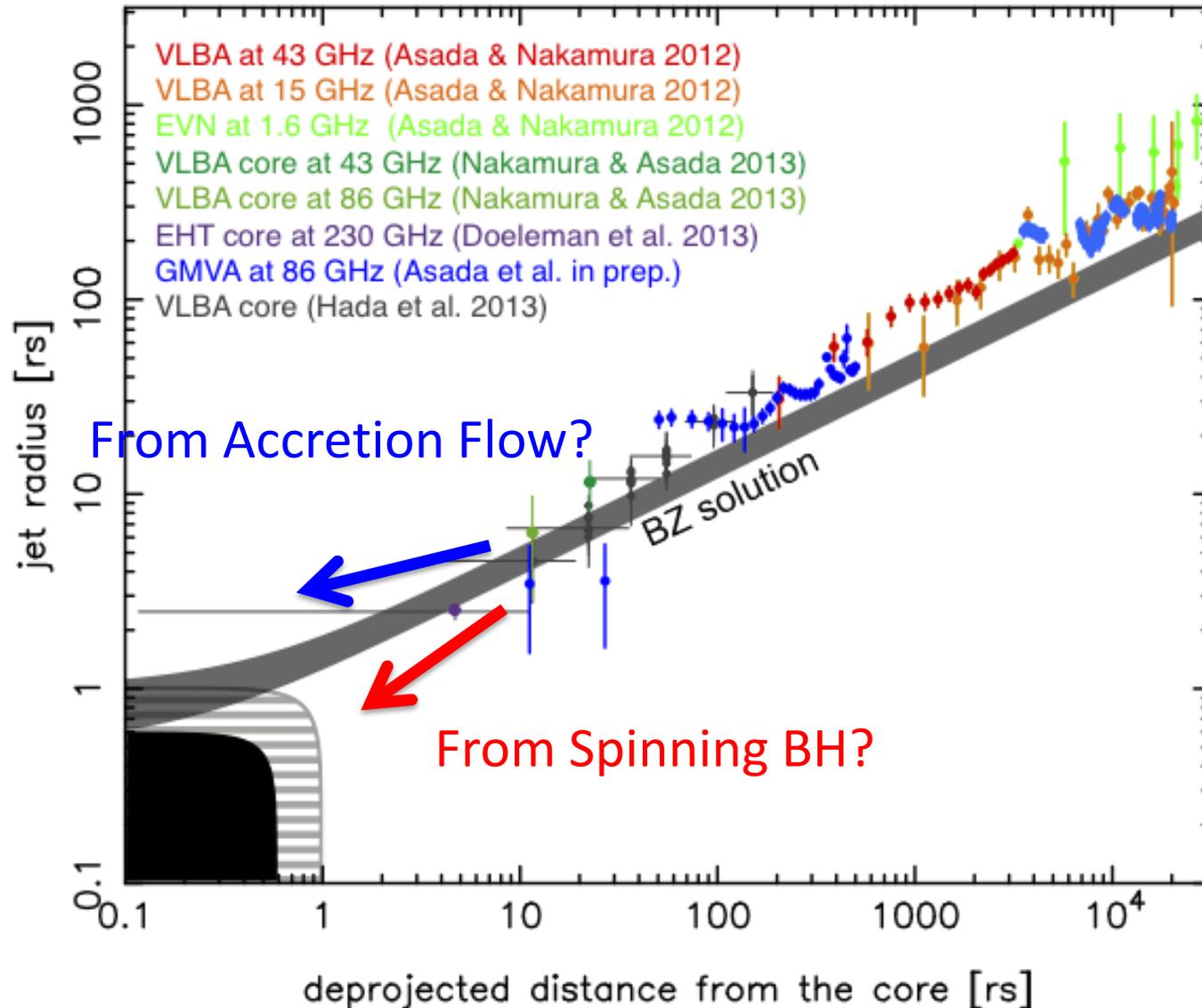
# M87 with mm/submm VLBI



GRMHD simulation by Tchekhovskoy et al. 2011



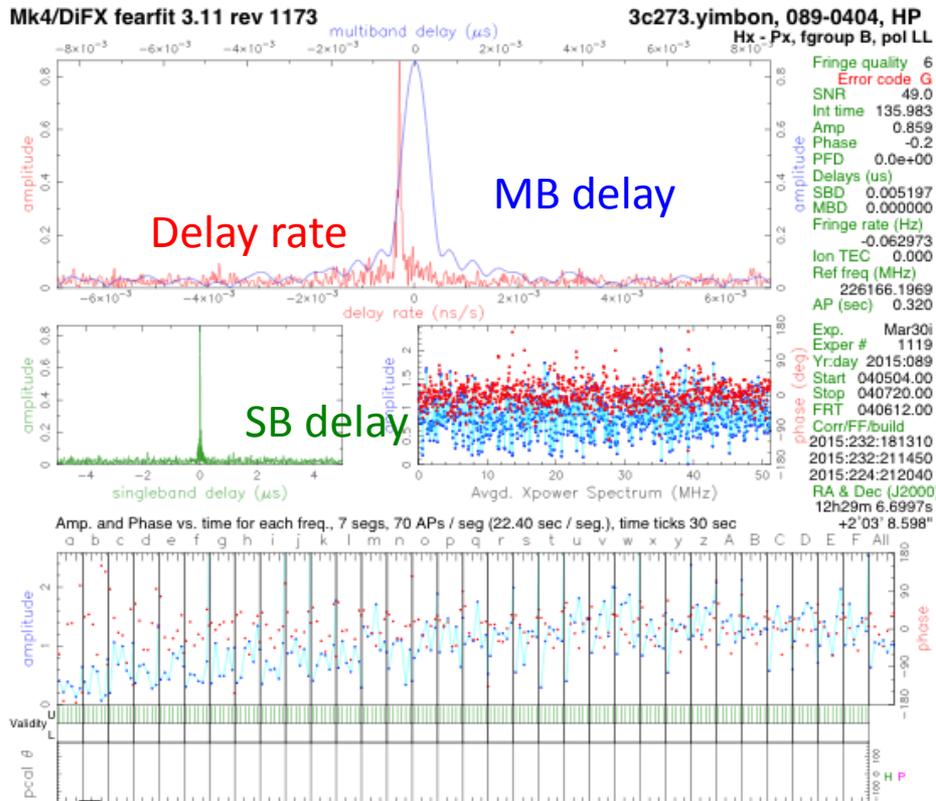
# M87 with mm/submm VLBI



# ALMA Phase-up Project

International Collaboration led by MIT Haystack:

- P.I. Shep Doeleman
- Beam former: 50 x 12 m dishes -> 85 m single dish



Test observation at 2015, Jul.

- IRAM 30 m – ALMA
- Towards 3C 273
- LHCP – Linear (H?)



# ALMA CY4 proposal

1mm VLBI Call for Proposals: Introduction — Science Website

https://science.nrao.edu/observing/call-for-proposals/1mm-vlbi-cycle4

Apple astro search eat-out shop travel ニュース etc blogs N-food tmp taiwan receipt

Institute of Astronomy & Astroph... M87 Workshop: Towards the 100... 1mm VLBI Call for Proposals: Intr... https://arxiv.org/pdf/1512.0141... The Astrophysical Journal - IOP...

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HelpDesk **Call For Proposals** Prop Prep Prop Eval & Time Alloc Obs Prep Scheduling Data Proc Pub Support

Observing > Call For Proposals > 1mm VLBI Call For Proposals: Cycle 4

**1mm VLBI Call for Proposals: Introduction**

by [Davis Murphy](#) — last modified Mar 22, 2016 by [Claire Chandler](#)



The National Radio Astronomy Observatory (NRAO) invites proposals for 1mm Very Long Baseline Interferometry (VLBI) using the phased output of the Atacama Large Millimeter/submillimeter Array ([ALMA](#)) and the Event Horizon Telescope ([EHT](#)) during ALMA Cycle 4. Up to 5% of ALMA Cycle 4 observing time is available for VLBI, shared between 1mm and 3mm. *Note that the EHT without phased ALMA is not being offered as part of this Call.*

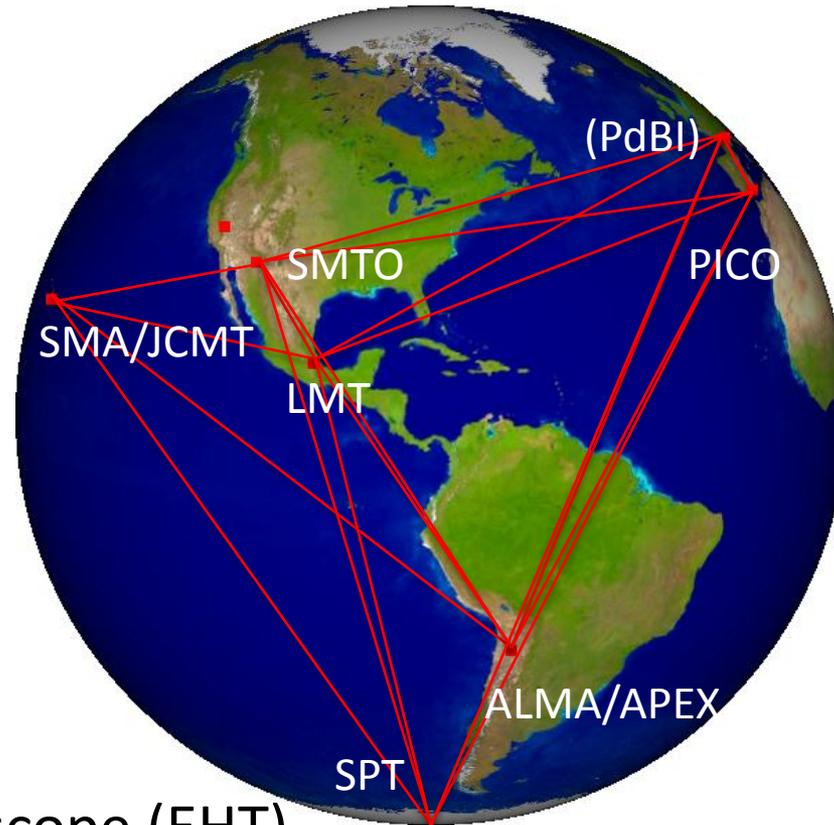
**The submission deadline for 1mm VLBI proposals is Thursday, 28 April 2016, at 23:59 UT.**

An overview of phased ALMA and the EHT is provided below, and further technical information to support proposal preparation is available at the [Proposal Preparation](#) link above, and at the EHT web page for [1mm VLBI with ALMA and the EHT](#).

The same proposal (including scientific and technical justification) must be submitted in response to this Call for Proposals as that submitted to the [ALMA Cycle 4 Call](#) to request phased ALMA. Proposal preparation is therefore through the ALMA Observing Tool ([OT](#)), which requires registration through the ALMA Science Portal beforehand. The [ALMA OT Quickstart Guide](#) provides more information on how to use OT. Proposers will then submit a PDF copy of their full ALMA Cycle 4 proposal through the [1mm VLBI Proposal Submission](#) website by the above deadline. Additional information on proposing to ALMA may be found in the [ALMA Cycle 4 Proposer's Guide](#).

Proposers who need assistance with proposal preparation or have questions regarding the Call should

# EHT observation in 2017



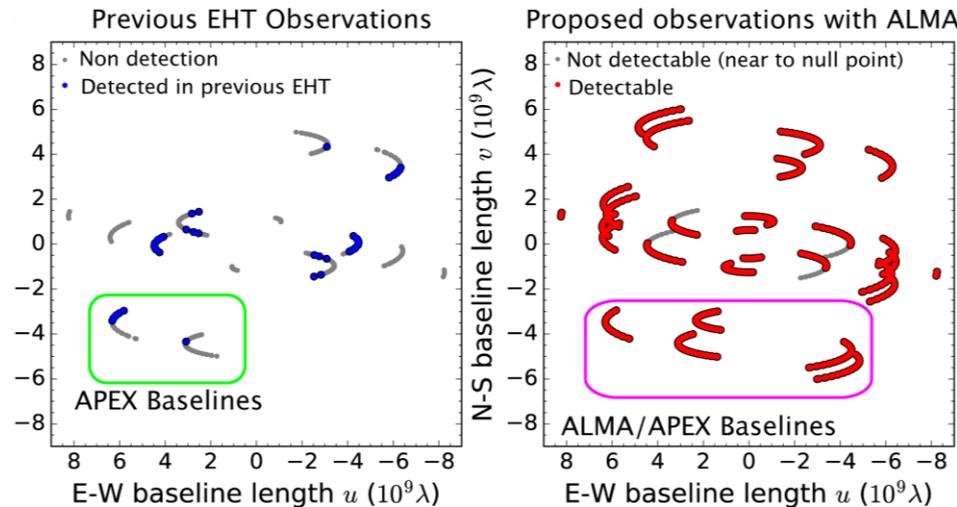
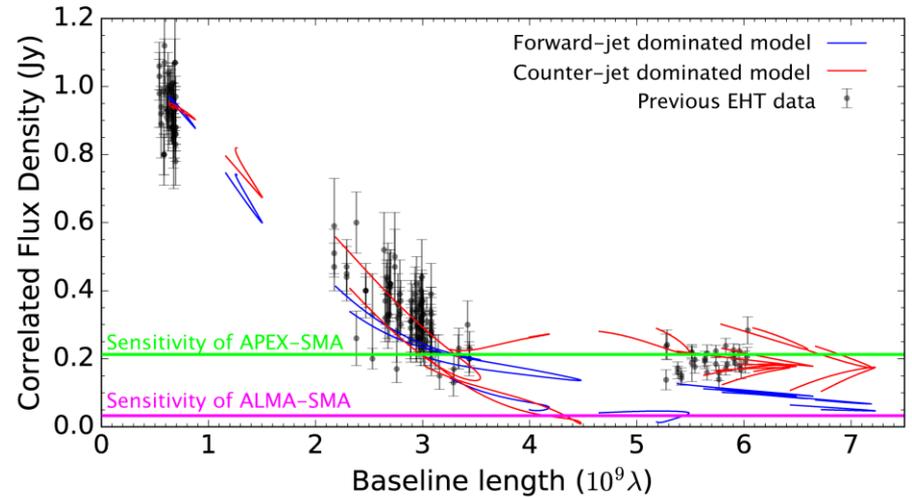
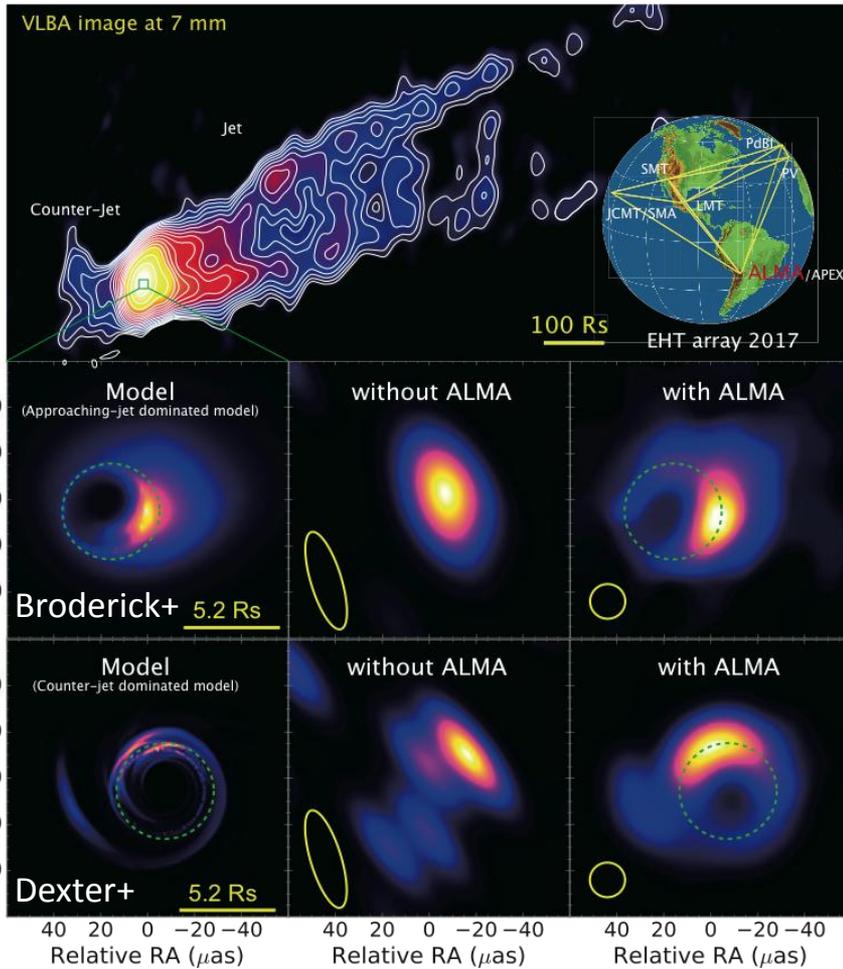
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# Towards 2017



EHT+ALMA proposal in CY4 was approved for Sgr A\*, M87 and some QSO jets.  
 We are expecting to image the first signature of BH shadow of Sgr A\*/M87 in 2017

# Role of SMA



ALMA can not be the substitute of wSMA.

1. Geographically different !!

SMA provides highest angular resolution in East-West Direction

2. SMA-JCMT combination is very unique!!

No standard flux calibrators!! No point source !!

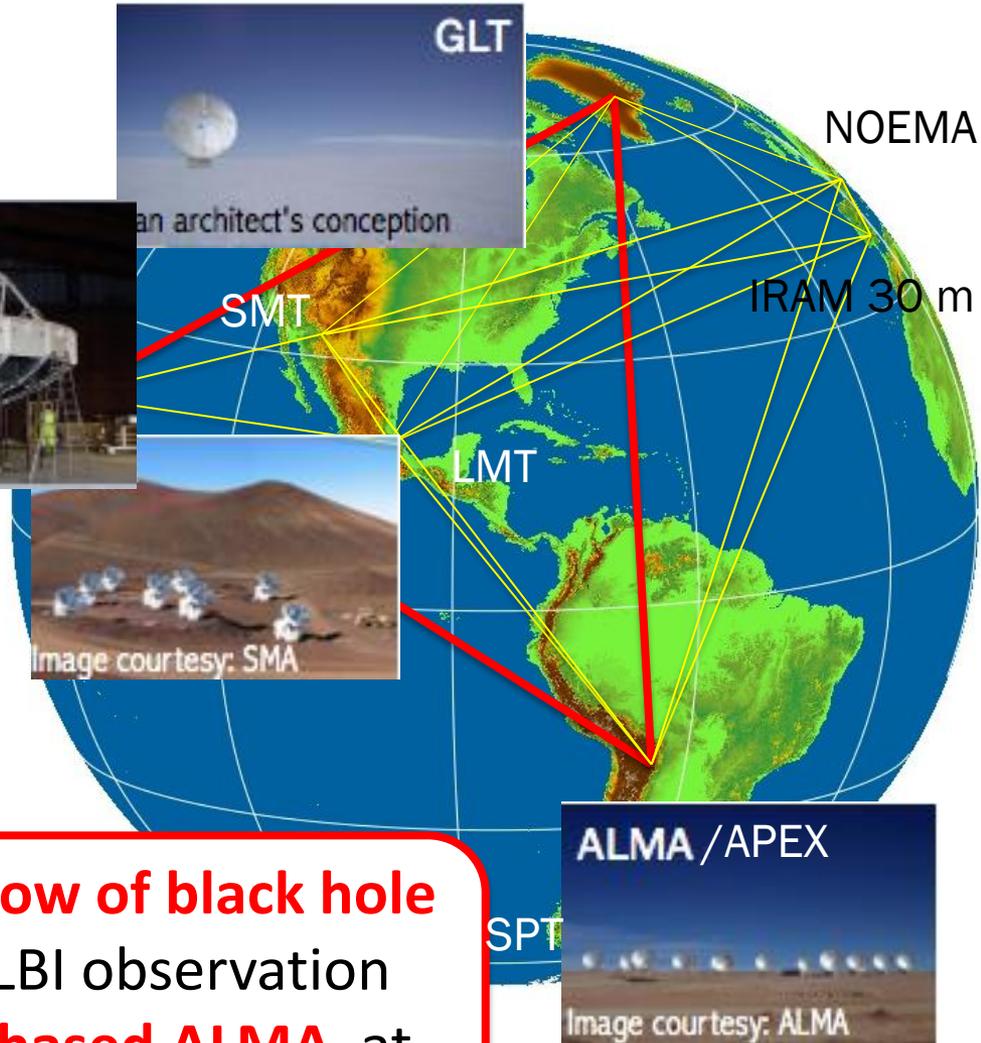
- SMA-JCMT provides flux scaling.
- SMA, JCMT – “station A” provides redundant baselines

# Beyond 2017

More Stations will come:  
GLT, LLAMA, KP, NOEMA, etc...



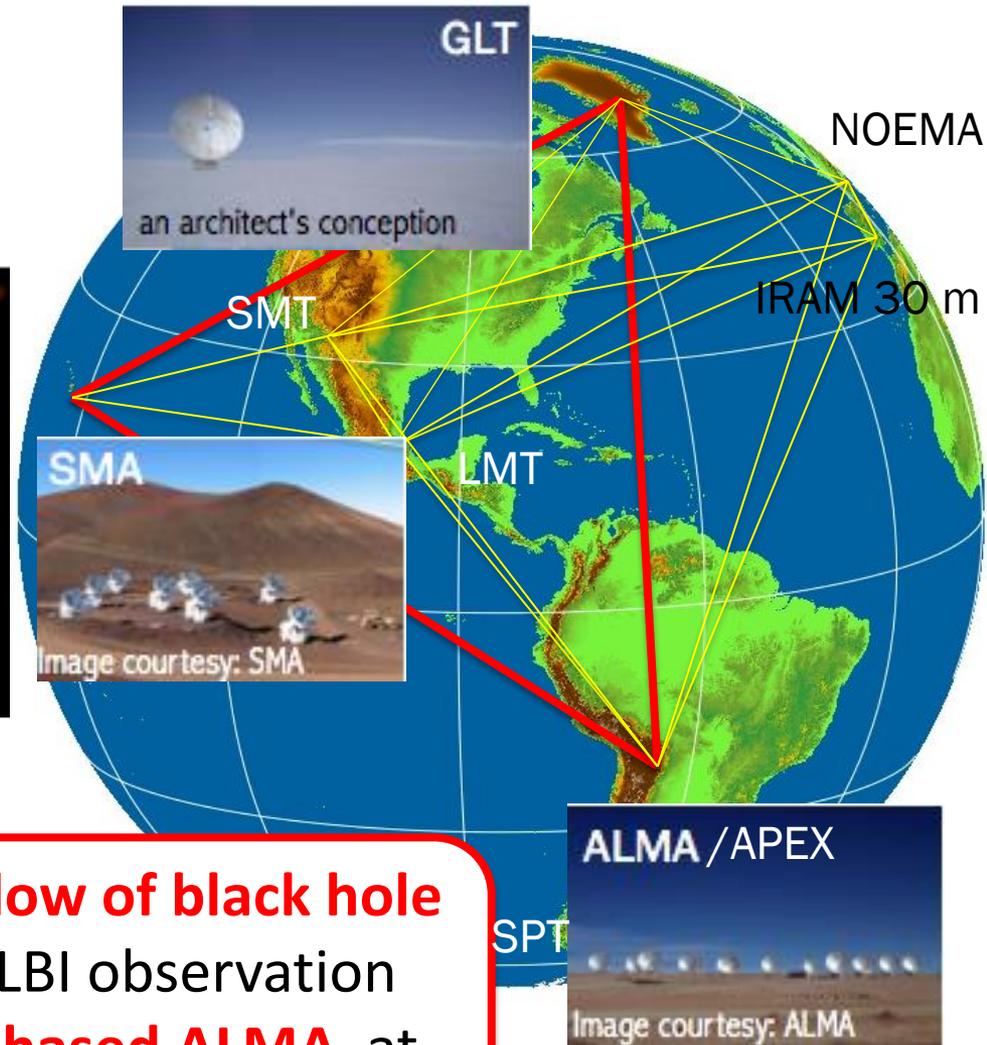
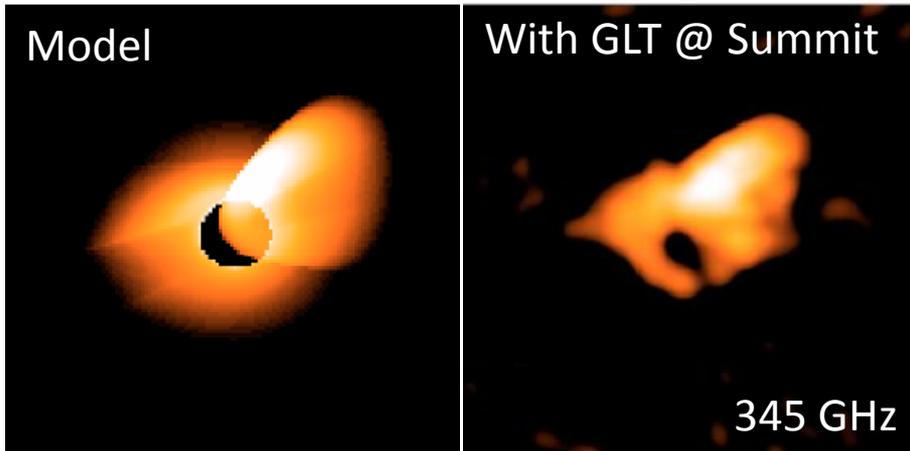
See Poster by Satoki Matsushita



Primary objective: Image **a shadow of black hole** of **M 87** with sub-millimeter VLBI observation includes **GLT, SMA/JCMT and phased ALMA** at 230, **345** GHz and higher frequency.

# Beyond 2017

More Stations will come:  
GLT, LLAMA, KP, NOEMA, etc...

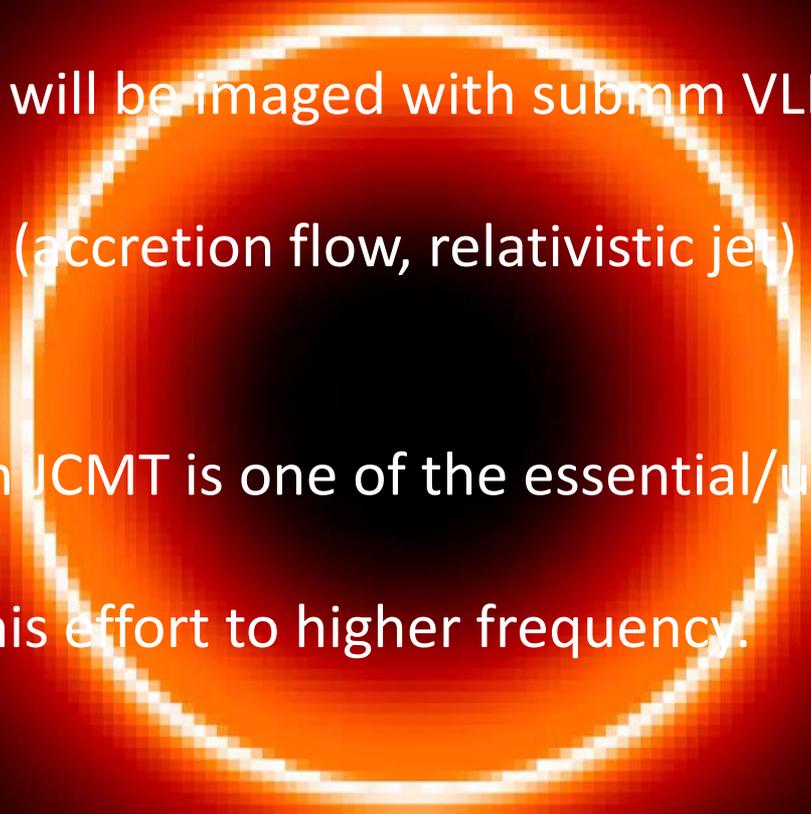


Primary objective: Image **a shadow of black hole** of **M 87** with sub-millimeter VLBI observation includes **GLT, SMA/JCMT and phased ALMA** at 230, **345** GHz and higher frequency.

# Summary



# Summary



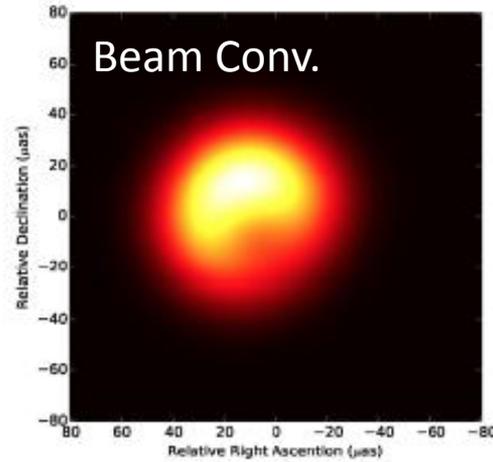
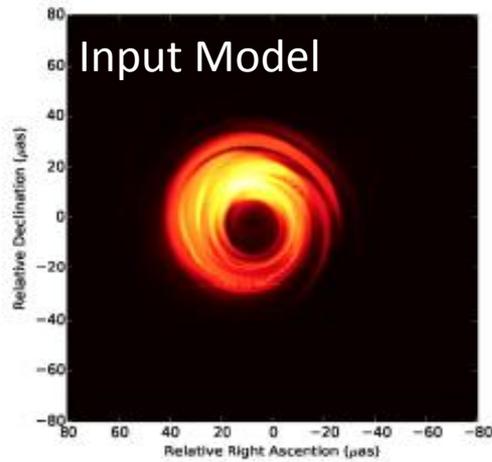
The shadow of BH will be imaged with submm VLBI in a few years!!

More astrophysics (accretion flow, relativistic jet) will be there.

SMA together with JCMT is one of the essential/unique station.

We should push this effort to higher frequency.

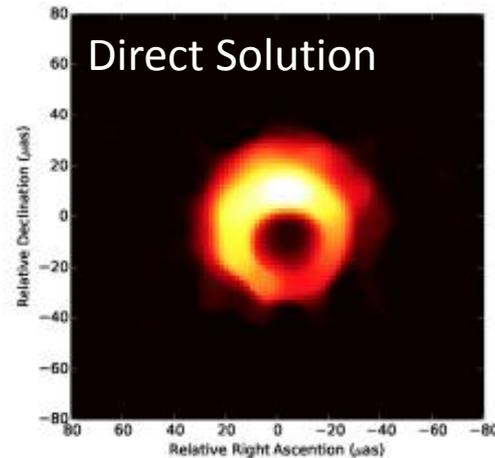
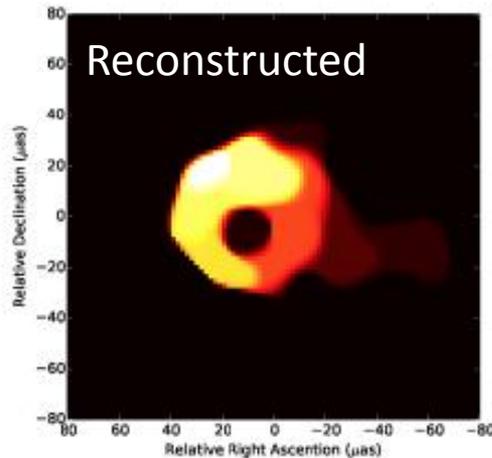
# New imaging techniques



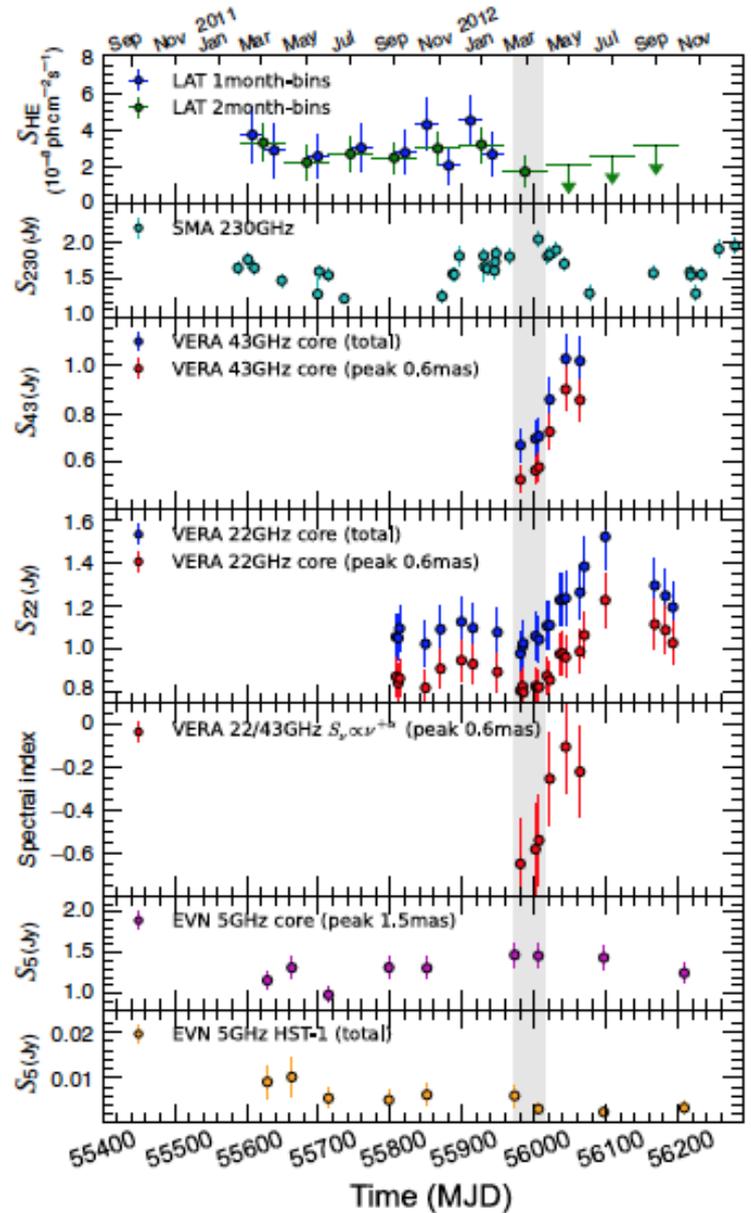
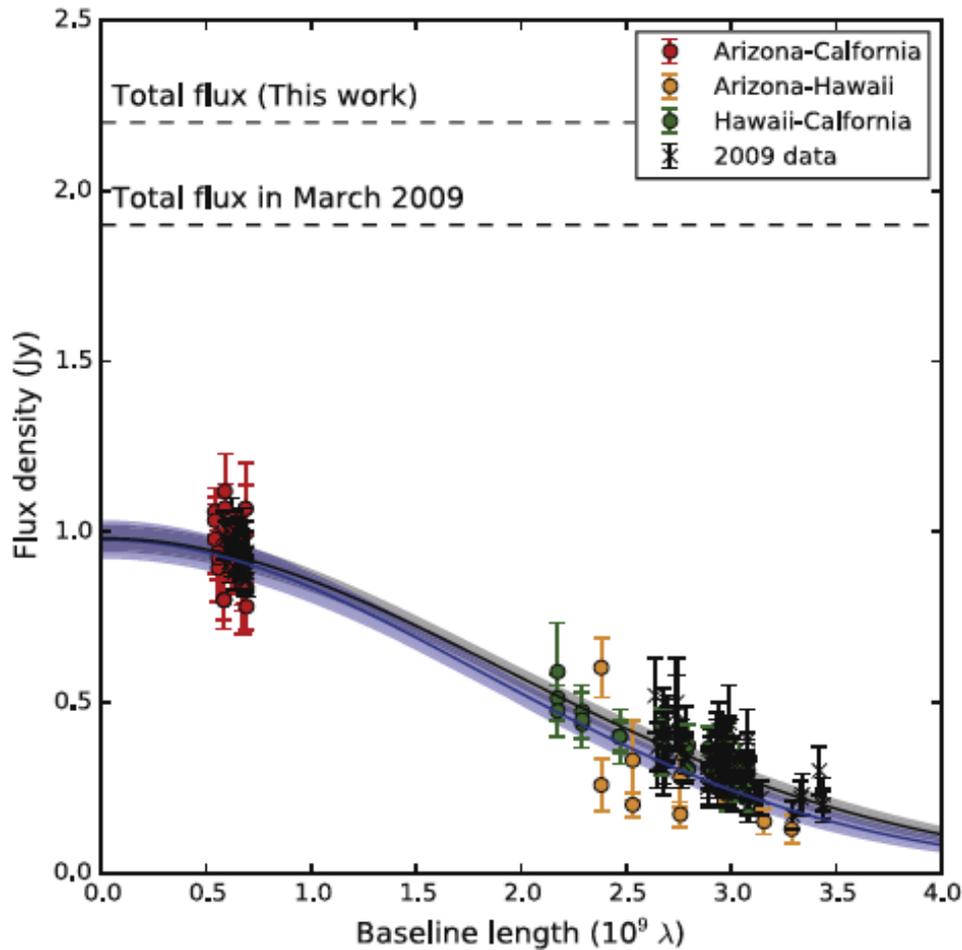
PRECL (Ikeda et al. 2016)

See more

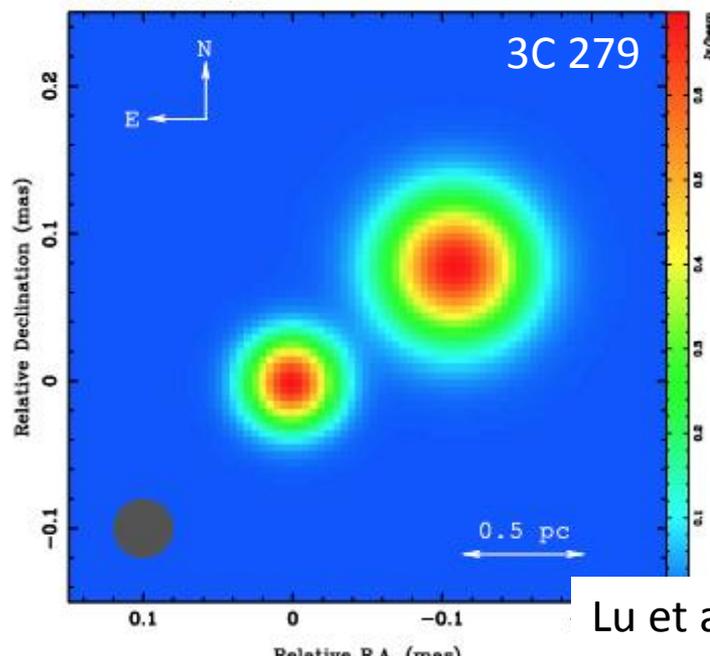
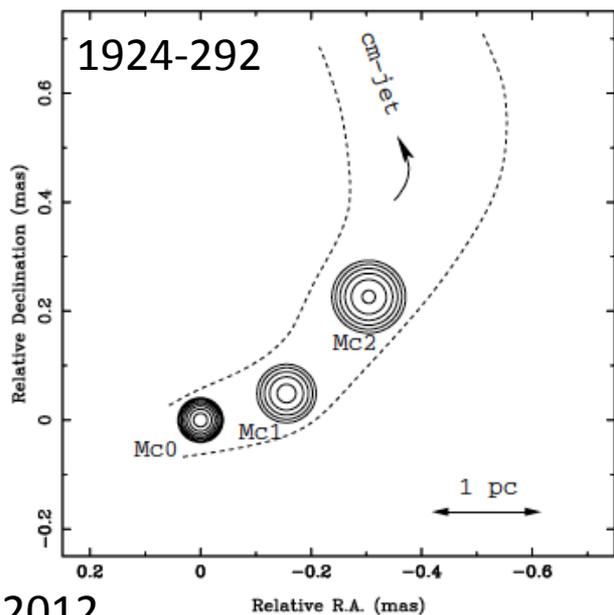
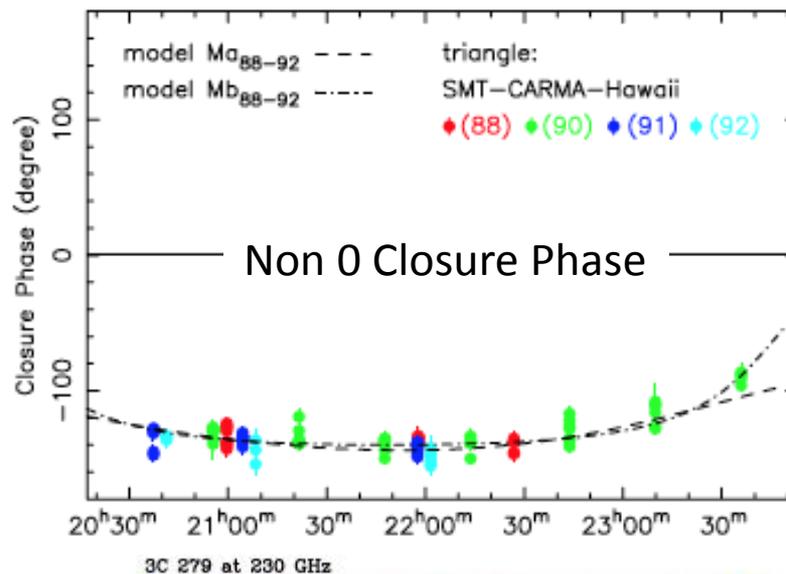
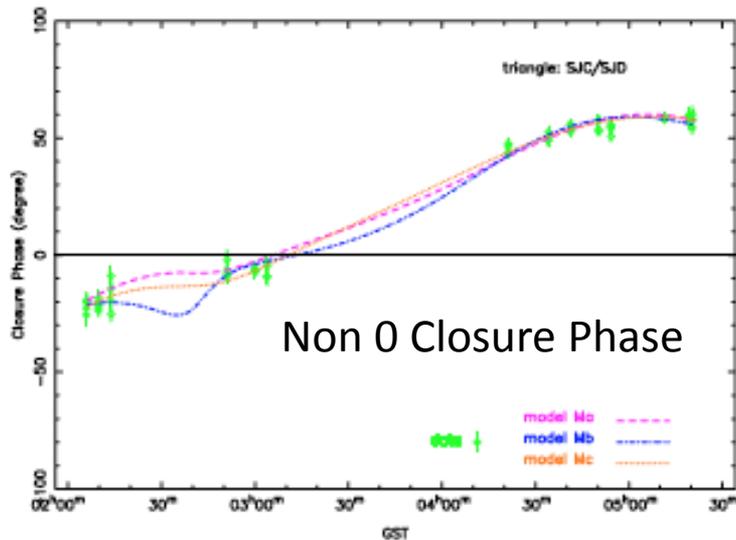
- Sparse Modeling (Honma et al. 2014)
- Adopting BSMEM etc. (Lu et al. 2014)
- Polarimetric MEM (Chael et al. 2016)
- Bayesian approach (Bouman et al. 2015)



# M87 with EHT



# Modeling for Quasar jets



# Beyond 2017



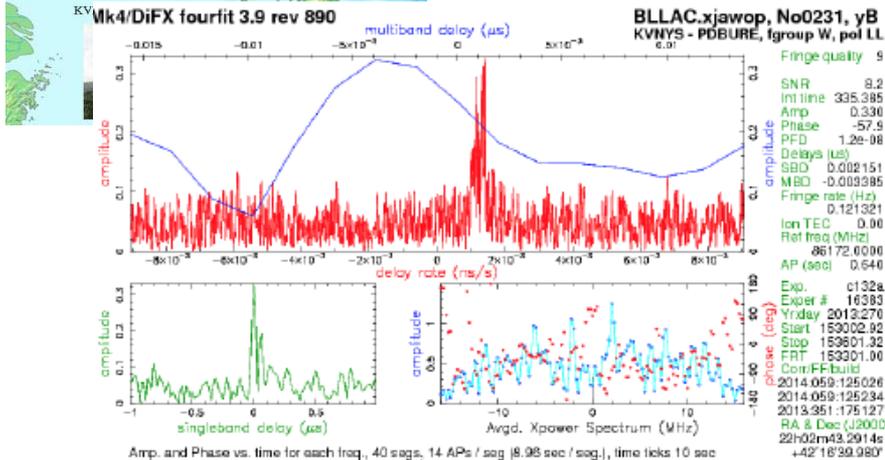
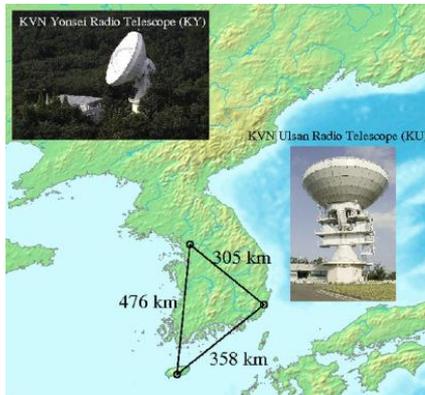
謝謝 very much



# EA contributions

## KVN start to join GMVA

From Thomas Krichbaum's presentation

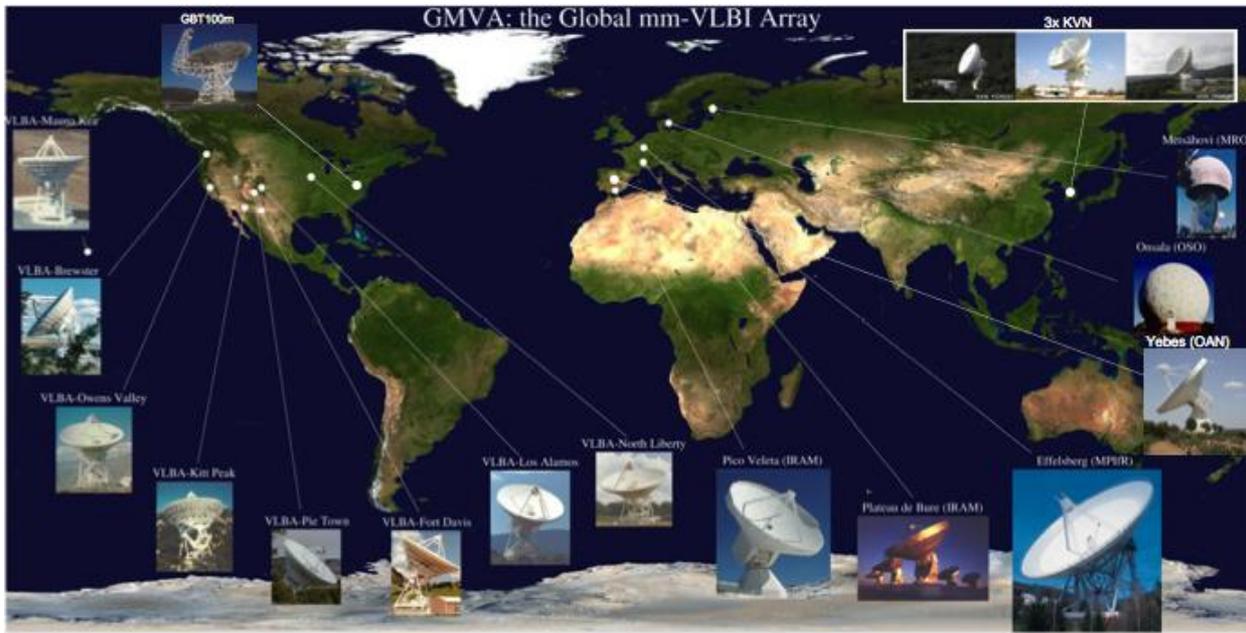


3 mm Fringe between  
Yonsei (KVN) - PdBI

## JCMT joins EHT observations



# Current VLBI @ 3 mm (Band 3)



Global mm-VLBI Array (2003- ):

Two sessions/yr: May and September (irregular session can be arranged)

Each session: ~ one week coordinated and fixed (no dynamic scheduling)

Open sky policy

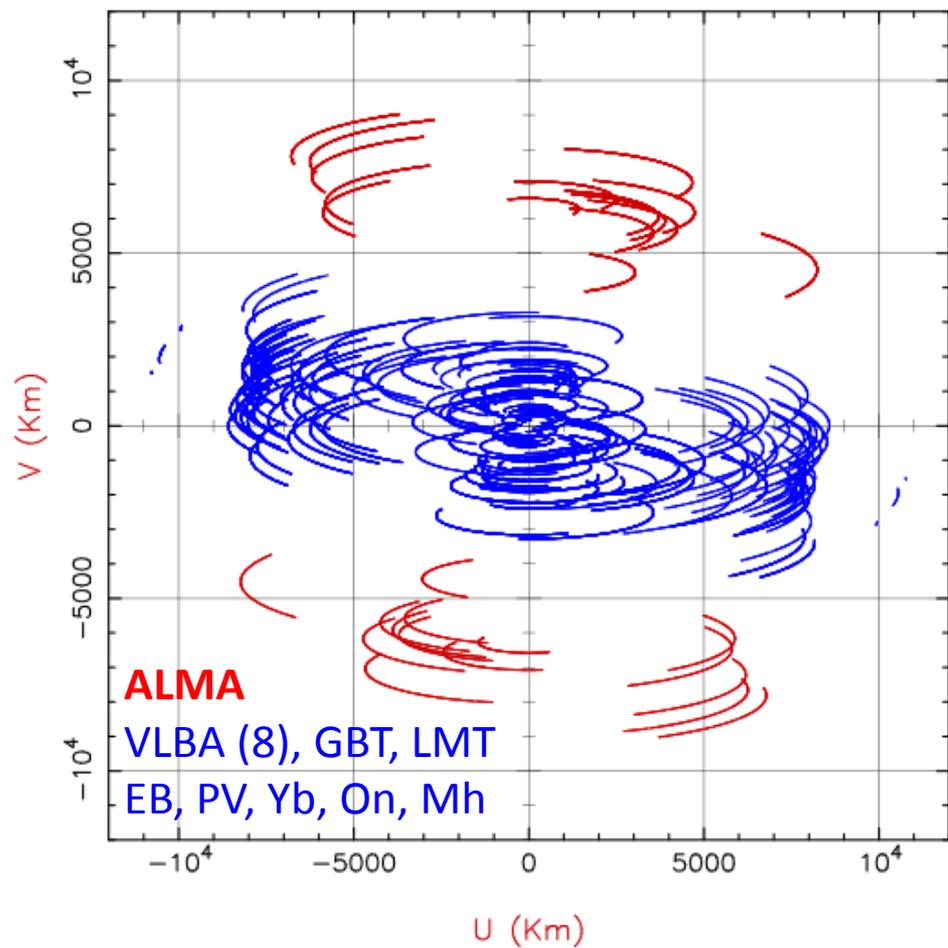
Host institute: MPIfR, Bonn, Germany

Due for the proposal: February 1<sup>st</sup> and August 1<sup>st</sup>

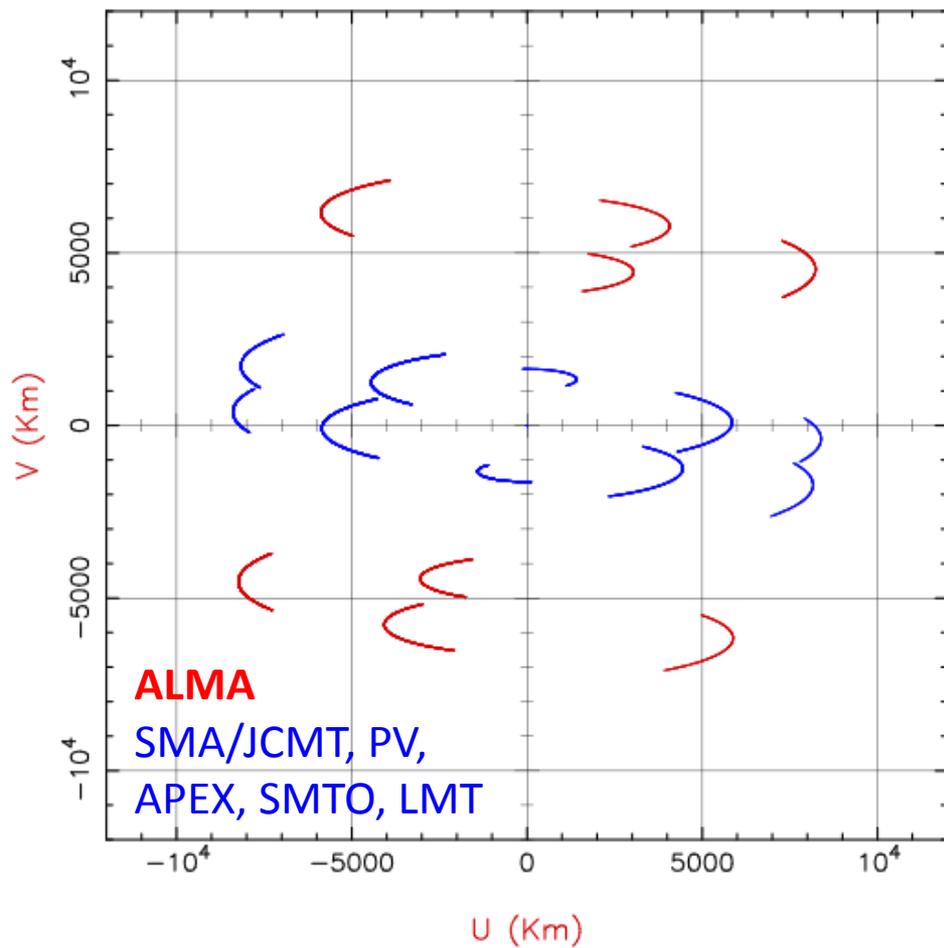
# Impact to have ALMA in the array

- Angular Resolution -

M87 (Dec = 18)



**3 mm array**

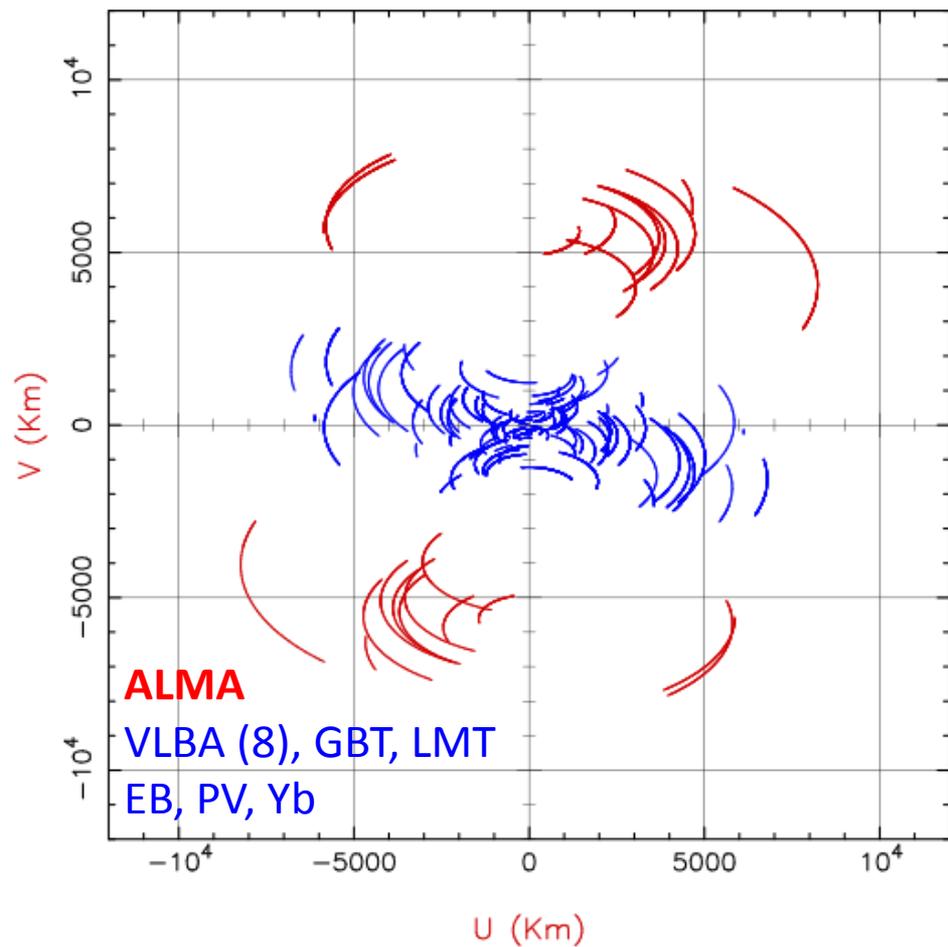


**1.3 mm array**

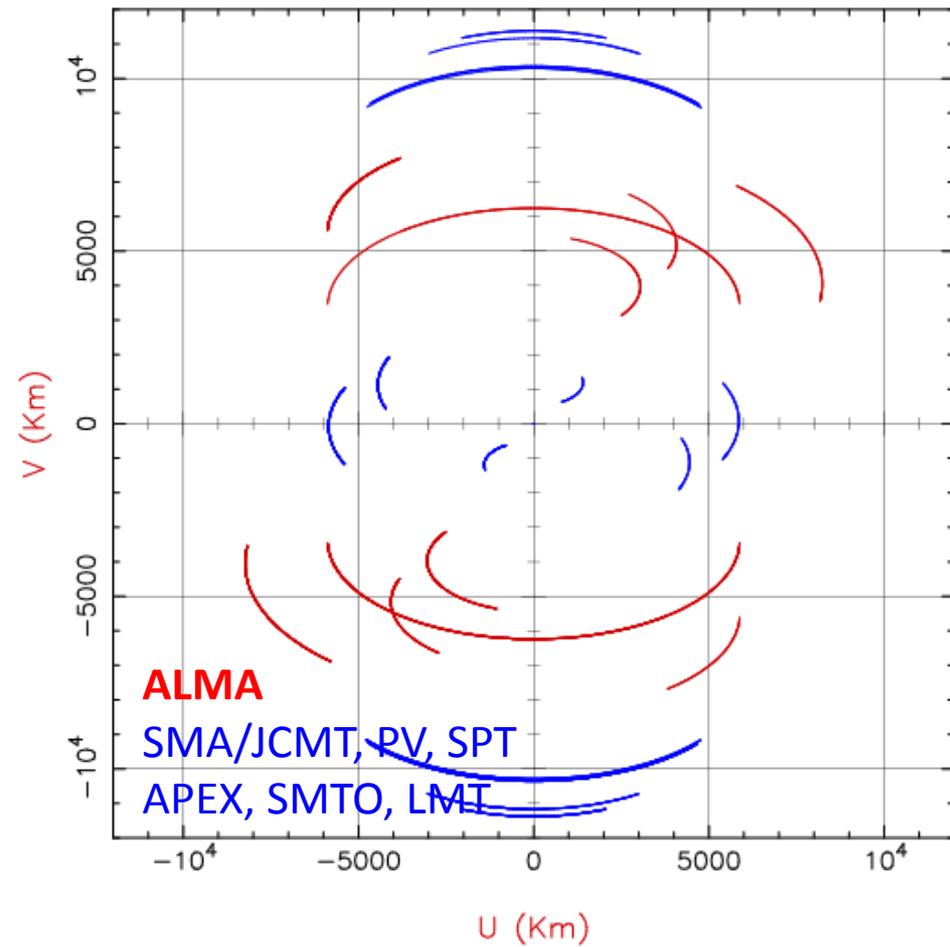
# Impact to have ALMA in the array

- Angular Resolution -

Sgr A\* (Dec = -28)



**3 mm array**



**1.3 mm array**

# Impact to have ALMA in the array

## - Sensitivity -

Without ALMA

	3 mm	1 mm
Resolution [uas]	~ <b>50</b> (bad for N-S for low dec. sources)	~ <b>20</b>
Baseline sensitivity [mJy]	With VLBA 25 m <b>70 -100</b> (7 $\sigma$ )	With 10m dish <b>190</b> (7 $\sigma$ )
Image sensitivity [mJy/beam]	0.5 /hr	4 /hr

With ALMA

	3 mm	1 mm
Resolution [uas]	~ <b>50</b>	~ <b>20</b>
Baseline sensitivity [mJy]	With VLBA 25 m <b>20 -30</b> (7 $\sigma$ )	With 10m dish <b>40</b> (7 $\sigma$ )
Image sensitivity [mJy/beam]	0.2 /hr	1 /hr

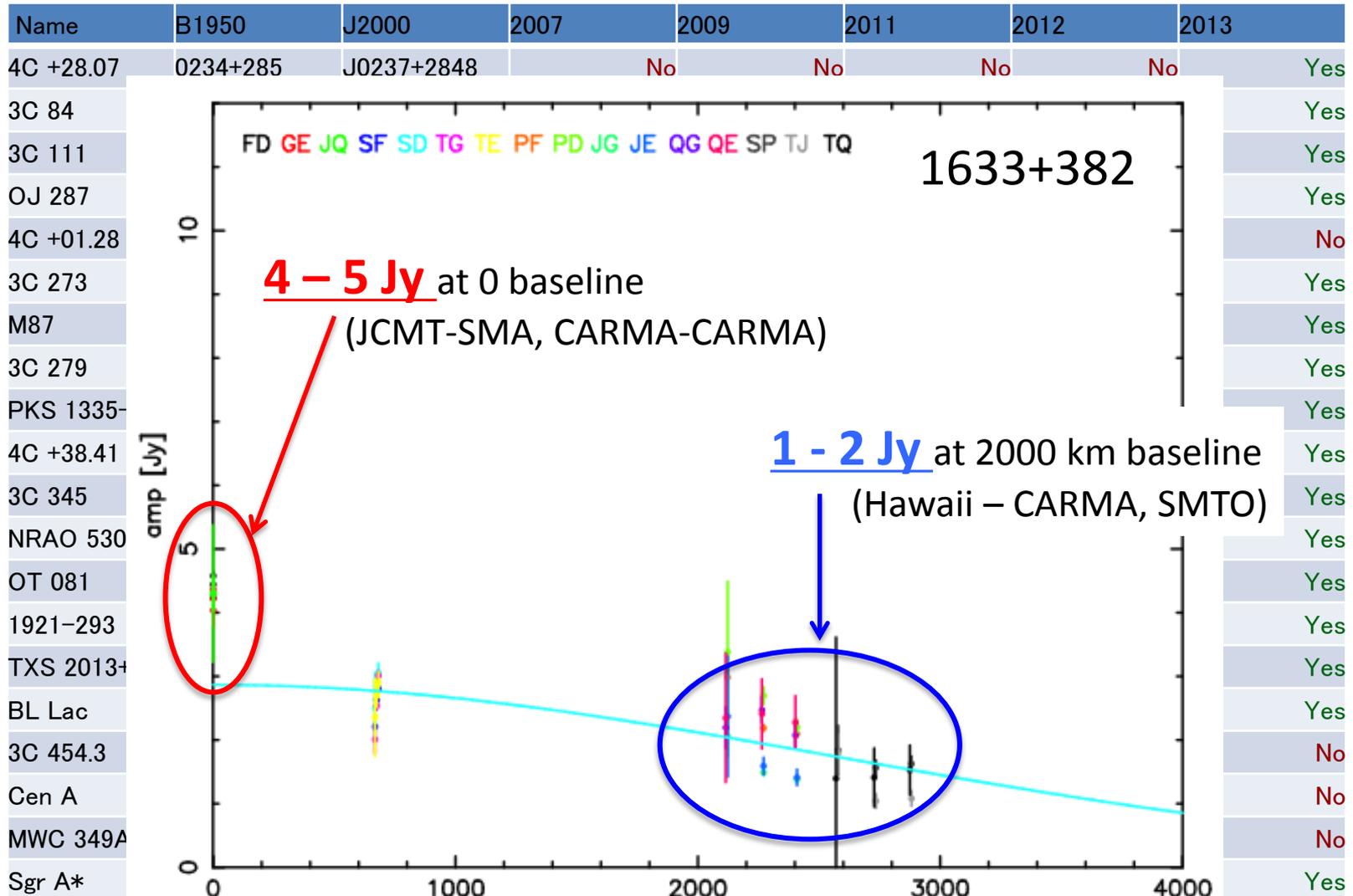
2 bit, 512 MHz BW, 20 sec integration for band 3, 8 GHz BW, 12 sec integration for band 6

# APEX vs ALMA at 1 mm

Name	B1950	J2000	2007	2009	2011	2012	2013
4C +28.07	0234+285	J0237+2848	No	No	No	No	Yes
3C 84	0316+413	J0319+4130	No	No	No	No	Yes
3C 111	0415+379	J0418+3801	No	No	No	No	Yes
OJ 287	0851+202	J0854+2006	No	Yes	No	Yes	Yes
4C +01.28	1055+018	J1058+0133	Yes	No	No	No	No
3C 273	1226+023	J1229+0203	Yes	Yes	Yes	Yes	Yes
M87	1228+126	J1230+1223	No	Yes	Yes	Yes	Yes
3C 279	1253-055	J1256-0547	Yes	Yes	Yes	Yes	Yes
PKS 1335-127	1334-127	J1337-1257	Yes	No	No	No	Yes
4C +38.41	1633+382	J1635+3808	No	No	Yes	No	Yes
3C 345	1641+399	J1642+3948	No	Yes	Yes	Yes	Yes
NRAO 530	1730-130	J1733-1304	No	Yes	Yes	Yes	Yes
OT 081	1749+096	J1751+0939	Yes	No	Yes	No	Yes
1921-293	1921-293	J1924-2914	Yes	Yes	Yes	Yes	Yes
TXS 2013+370	2013+370	J2015+3710	No	No	No	No	Yes
BL Lac	2200+420	J2202+4216	Yes	Yes	No	Yes	Yes
3C 454.3	2251+158	J2253+1608	No	No	No	No	No
Cen A	1322-427	J1325-4301	No	No	No	No	No
MWC 349A			No	No	No	No	No
Sgr A*			Yes	Yes	Yes	Yes	Yes

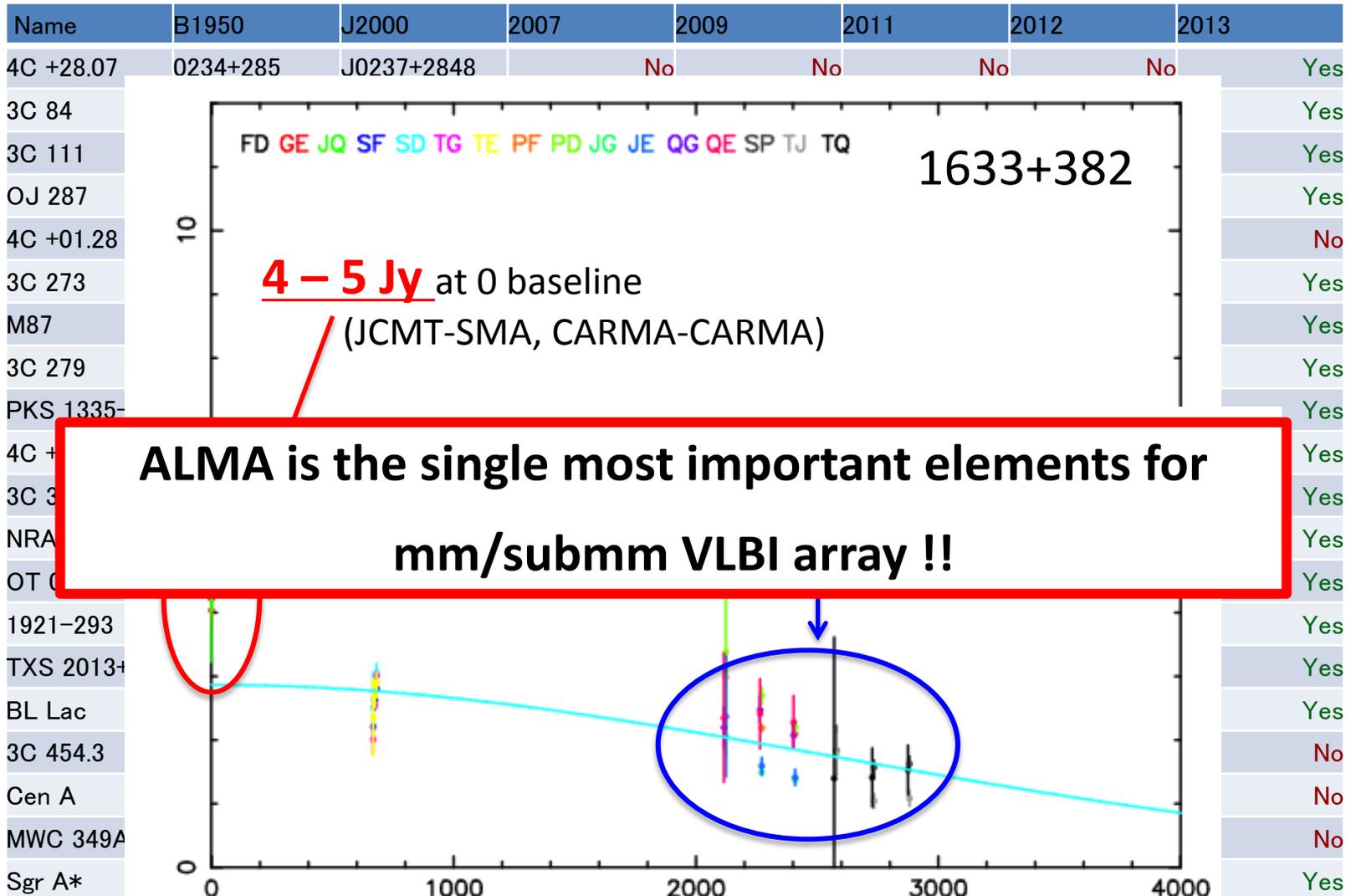
Compiled by Kazu Akiyama (MIT Haystack)

# APEX vs ALMA at 1 mm



(MIT Haystack)

# APEX vs ALMA at 1 mm



# ALMA Phase-up Project

International Collaboration led by MIT Haystack:

- P.I. Shep Doeleman
- Beam former: 50 x 12 m dishes -> 85 m single dish

Contributions from EA

ASIAA:

- software automatically adjust miss-match of sampling rate  
(125 Mbps for ALMA and 128 Mbps for VLBI)
- Data simulator (E-noise, bbsim)
- buy recorder for ALMA

NAOJ:

- optical fiber link (AOS-OSF)

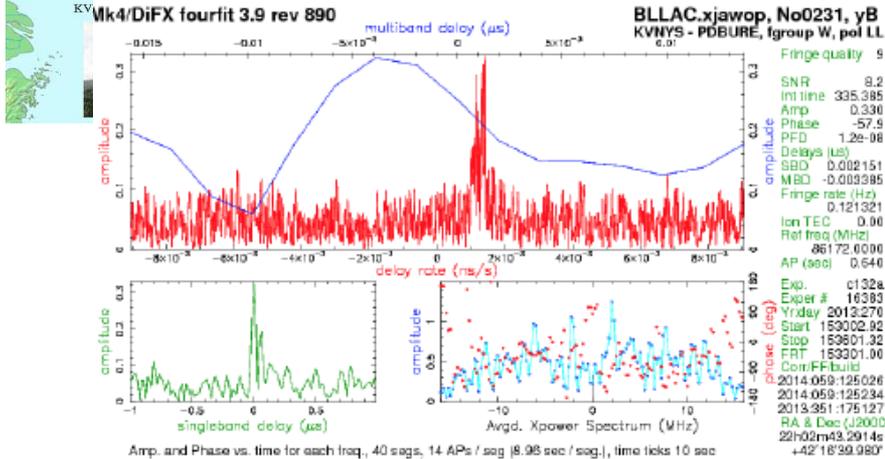




# EA contributions

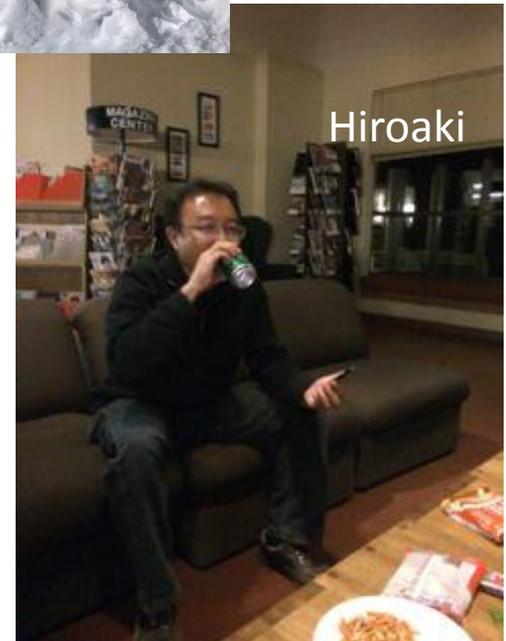
## KVN start to join GMVA

From Thomas Krichbaum's presentation



3 mm Fringe between  
 Yonsei (KVN) - PdBI

## JCMT joins EHT observations



# mm/submm VLBI at 2017 and beyond



## 3 mm array

### More Stations:

- Greenland Telescope
- Sardinia Telescope
- NRO 45m?
- VERA ?

## 1.3 mm array

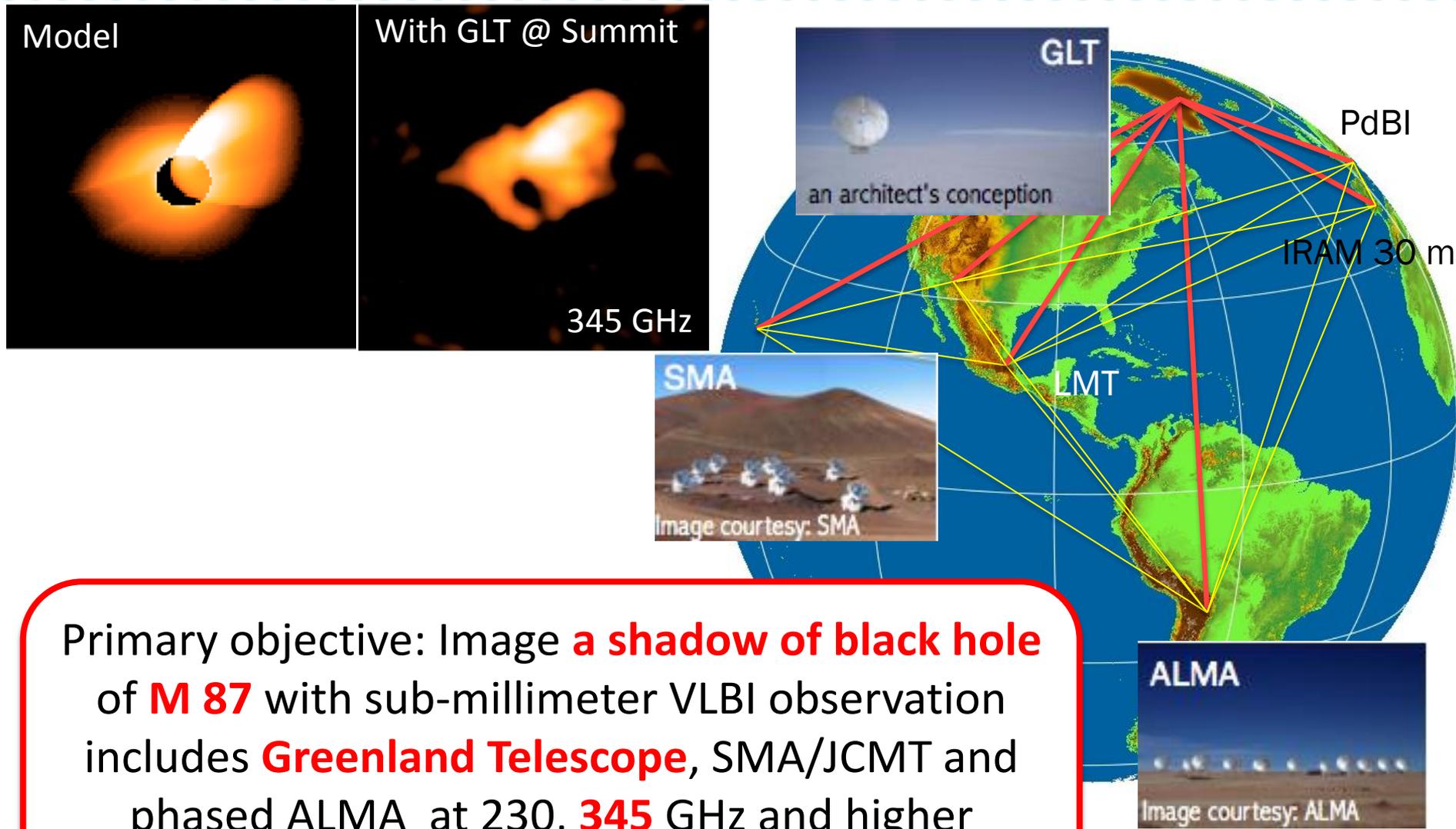
### More Stations:

- Greenland Telescope
- Haystack
- Kitt Peak
- Owens Valley 1
- LLAMA
- SPART?
- ....

### Band Width:

- 16 Gbps (2015)
- 32 Gbps (2016)
- 64 Gbps (2017)

# Goal of the Greenland Telescope Project



Primary objective: Image **a shadow of black hole** of **M 87** with sub-millimeter VLBI observation includes **Greenland Telescope**, SMA/JCMT and phased ALMA at 230, **345** GHz and higher frequency.

# Plan of GLT project for 2016 and beyond

- Antenna shipping to Thule (2016).
- Antenna re-assemble and test at Thule, including VLBI test (2016-2019).
- Single-dish & VLBI first light at Thule at 86 and 230 GHz (2017-2018).
- Transport antenna across ice sheet (2019).
- First light at the Summit Station (2019/20).



Thule, GL



# Correlation and Post Processing

## ■ Correlation:

- 3 mm experiments: DiFX correlator at MPIfR, Bonn
- 1.3 mm experiments: DiFX correlator at MIT Haystack and MPIfR

## ■ Post Processing:

- 3 mm experiments:
  - Fringe fit and a priori amplitude calibration: AIPS
  - Imaging and self-calibration: AIPS and/or Difmap
- 1.3 mm experiments:
  - Fringe fit: HOPS (developed by MIT Haystack)
  - a priori amplitude calibration: Hand-writing code
  - modeling: hand-writing code

JIVE (Joint Institute for VLBI in Europe, Netherland)

developing(ed?) 'Fringe Fitting' in CASA.

# Need Proposal to GMVA or EHT?

## ■ GMVA (3 mm array)

- MPIfR announced we need to submit proposal at next due.
- Next due is Feb. 1<sup>st</sup> 2016 !!
- All proposal should be submitted through Proposal Submission Tool (PST), NRAO.

## ■ EHT (1 mm array)

- I do not know....,

NRAO host proposals, and due for the NRAO is usually Feb 1<sup>st</sup>.



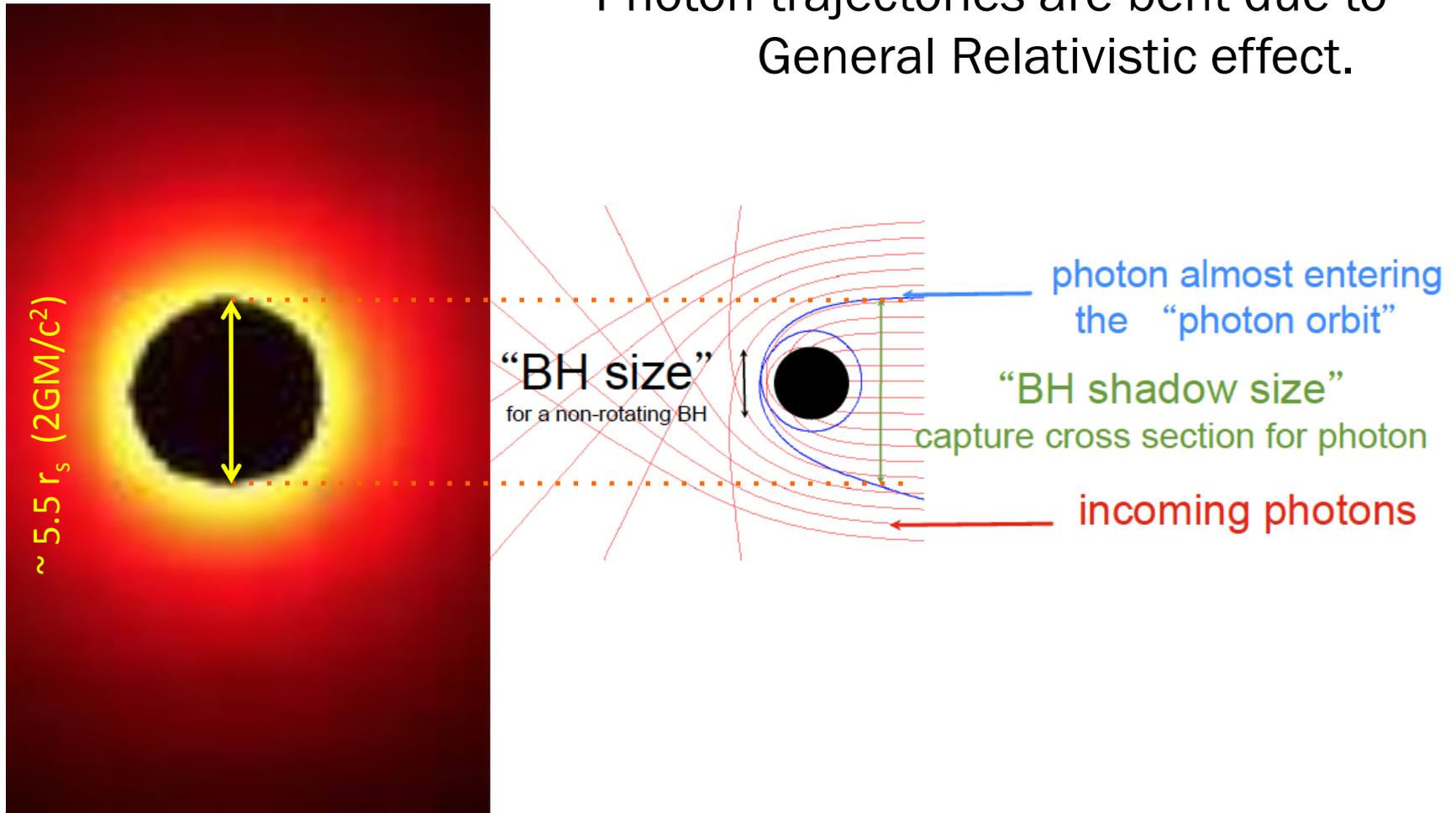
A screenshot of the NRAO website dashboard. The page title is "National Radio Astronomy Observatory". The navigation menu includes "Dashboard", "Proposals", "Data Processing", "Obs Prep", "Helpdesk", and "Profile". The user is logged in as "Hi, Keichi" and the date is "Thursday 10 December 2015". The dashboard content includes sections for "Options", "Web Browser" (with a warning about file uploads), "User Accounts", and "Telescope News" (with information about proposal deadlines and tools).

Possible (my?) science cases

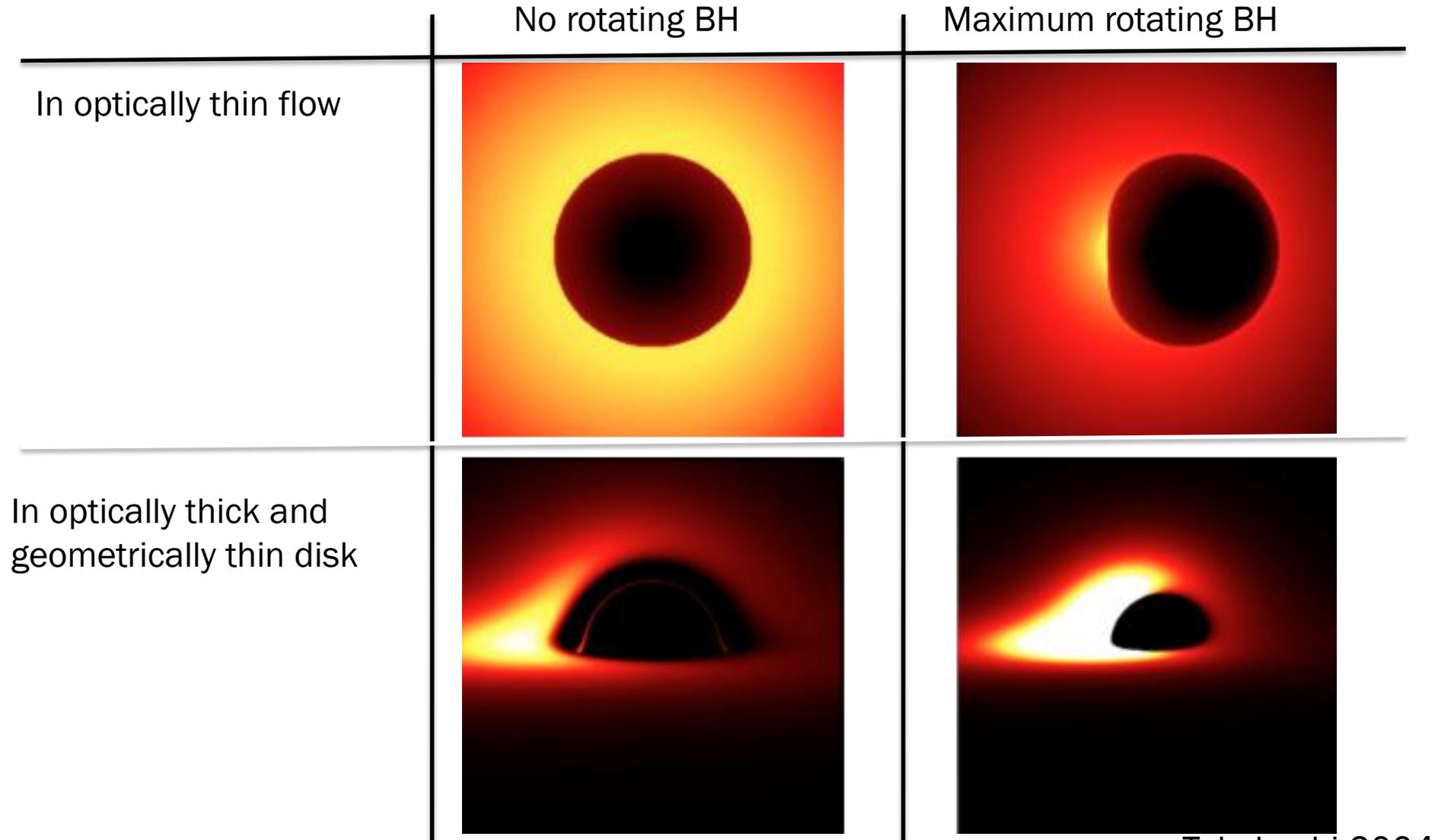
A horizontal line of small blue dots spans the width of the slide, positioned below the text.

# Image the shadow of the black hole

Photon trajectories are bent due to General Relativistic effect.



# Image the shadow of the black hole



# Apparent Size of BH

Source	Sgr A*	M 87	Cen A
BH Mass	$0.045 \times 10^8 M_{\text{sun}}$	$66 (32) \times 10^8 M_{\text{sun}}$	$0.45 \times 10^8 M_{\text{sun}}$
Distance	$0.026 \times 10^6 \text{ light yr}$	$54 \times 10^6 \text{ light yr}$	$11 \times 10^6 \text{ light yr}$
$r_s$	$11 \mu\text{as}$	$8 \mu\text{as}$	$0.3 \mu\text{as}$
Size of Shadow	$52 \mu\text{as}$	$40 (20) \mu\text{as}$	$1.5 \mu\text{as}$

Resolution  $\propto \lambda / D$

$\lambda$ : wavelength  
D: baseline



c.f. If  $\lambda$  is 1.3 mm (230 GHz) and D is 9000 km, resolution is 30  $\mu\text{as}$ .

Submm VLBI is the only way to achieve this angular resolution in near future !!

# Submm VLBI as a tool to study BH

Doeleman et al. 2008

nature

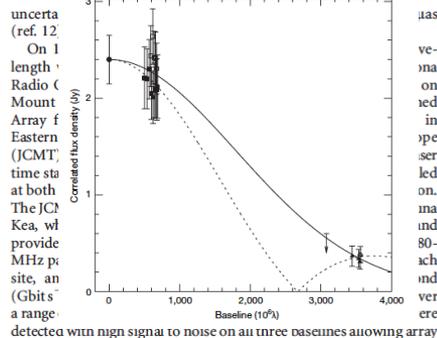
Vol 455 | 4 September 2008 | doi:10.1038/nature07245

LETTERS

## Event-horizon-scale structure in the supermassive black hole candidate at the Galactic Centre

Sheperd S. Doeleman<sup>1</sup>, Jonathan Weintraub<sup>2</sup>, Alan E. E. Rogers<sup>1</sup>, Richard Plambeck<sup>3</sup>, Robert Freund<sup>4</sup>, Remo P. J. Tilanus<sup>5,6</sup>, Per Friberg<sup>5</sup>, Lucy M. Ziurys<sup>4</sup>, James M. Moran<sup>2</sup>, Brian Corey<sup>1</sup>, Ken H. Young<sup>7</sup>, Daniel L. Smythe<sup>1</sup>, Michael Titus<sup>1</sup>, Daniel P. Marrone<sup>7,8</sup>, Roger J. Cappallo<sup>1</sup>, Douglas C.-J. Bock<sup>9</sup>, Geoffrey C. Bower<sup>3</sup>, Richard Chamberlain<sup>10</sup>, Gary R. Davis<sup>5</sup>, Thomas P. Krichbaum<sup>11</sup>, James Lamb<sup>12</sup>, Holly Maness<sup>3</sup>, Arthur E. Niell<sup>1</sup>, Alan Roy<sup>11</sup>, Peter Strittmatter<sup>4</sup>, Daniel Werthimer<sup>13</sup>, Alan R. Whitney<sup>1</sup> & David Woody<sup>12</sup>

The cores of most galaxies are thought to harbour supermassive black holes, which power galactic nuclei by converting the gravitational energy of accreting matter into radiation<sup>1</sup>. Sagittarius A\* (Sgr A\*), the compact source of radio, infrared and X-ray emission at the centre of the Milky Way, is the closest example of this phenomenon, with an estimated black hole mass that is 4,000,000 times that of the Sun<sup>2,3</sup>. A long-standing astronomical goal is to resolve structures in the innermost accretion flow surrounding Sgr A\*, where strong gravitational fields will distort the appearance of radiation emitted near the black hole. Radio observations at wavelengths of 3.5 mm and 7 mm have detected intrinsic structure in Sgr A\*, but the spatial resolution of observations at these wavelengths is limited by interstellar scattering<sup>4-7</sup>. Here we report observations at a wavelength of 1.3 mm that set a size of 37<sup>+16</sup><sub>-10</sub> microarcseconds on the intrinsic diameter of Sgr A\*. This is less than the expected apparent size of the event horizon of the presumed black hole, suggesting that the bulk of Sgr A\* emission may not be centred on the black hole, but arises in the surrounding accretion flow.



Sgr A\*

Doeleman et al. 2012

Science **exp**

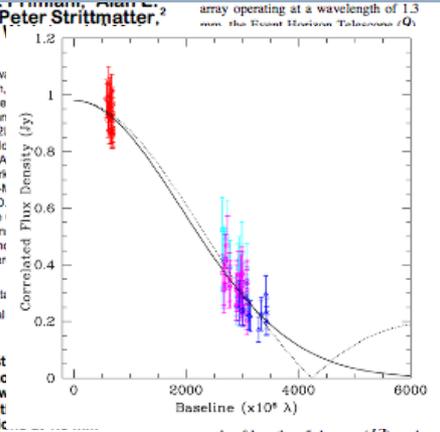
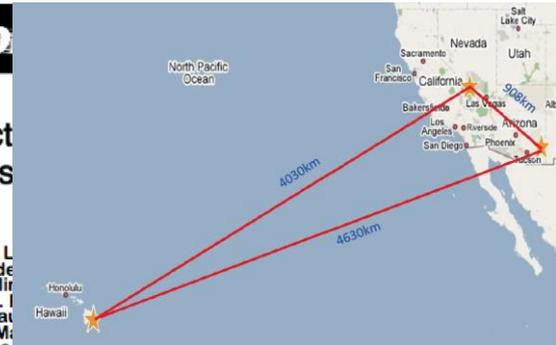
## Jet Launching Structure Near the Supermassive M87

Sheperd S. Doeleman<sup>1,3\*</sup>, Vincent L. Christopher<sup>4</sup>, Beaudoin<sup>1</sup>, Ray Blundell<sup>5</sup>, E. Broderick<sup>6,8</sup>, Richard Chamberlain<sup>9</sup>, Friberg<sup>8</sup>, Mark A. Gurwell<sup>7</sup>, Paul T. I. Makoto Inoue<sup>9</sup>, Thomas P. Krichbaum<sup>10</sup>, Loeb<sup>11</sup>, Colin Longsdale<sup>12</sup>, Daniel P. Marrone<sup>13</sup>, Tomoaki Oyama<sup>14</sup>, Richard Plambeck<sup>15</sup>, Alan E. Rogers<sup>1</sup>, Daniel L. Smythe<sup>1</sup>, Jason SooHoo<sup>1</sup>, Peter Strittmatter<sup>2</sup>, Remo P. J. Tilanus<sup>3,14</sup>, Michael Titus<sup>1</sup>, Jonathan I. Wright<sup>4</sup>, Ken H. Young<sup>3</sup>, Lucy Ziurys<sup>16</sup>

<sup>1</sup>MIT Haystack Observatory, Off Route 40, Westford, MA 01886, USA. <sup>2</sup>Steward Radio Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, <sup>3</sup>Harvard Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge <sup>4</sup>Department of Astronomy, University of California Berkeley, Hearsh Field Ann <sup>5</sup>Perimeter Institute, 31 Caroline Street, North Waterloo, Ontario, Canada N2L <sup>6</sup>and Astronomy, University of Waterloo, 200 University Avenue West, Waterloo <sup>7</sup>Catech Submillimeter Observatory, 111 Nowelo Street, Hilo, HI 96720, USA <sup>8</sup>Telescope, Joint Astronomy Centre, 660 North A'ohoku Place University Park <sup>9</sup>Academia Sinica Institute for Astronomy and Astrophysics, 11F Astronomy-I <sup>10</sup>Taiwan University, No. 1, Roosevelt Rd., Sec. 4 Taipei 10617, Taiwan, R.O. <sup>11</sup>Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588 Japan. <sup>12</sup>The <sup>13</sup>Advanced Studies, Osawa, Mitaka, Tokyo 181-8588, Japan. <sup>14</sup>Max-Planck-In <sup>15</sup>dem Hugel 69, 53121 Bonn, Germany. <sup>16</sup>OVRO, California Institute of Techn <sup>17</sup>Pine, CA 93513-0968, USA. <sup>18</sup>Netherlands Organization for Scientific Resear <sup>19</sup>300, NL2509 AC The Hague, Netherlands.

\*To whom correspondence should be addressed. E-mail: sdoeleman@hayst  
†Present address: University of Colorado at Boulder, Dept. of Astrophysical <sup>20</sup>UCB, Boulder, CO, 80309 USA.

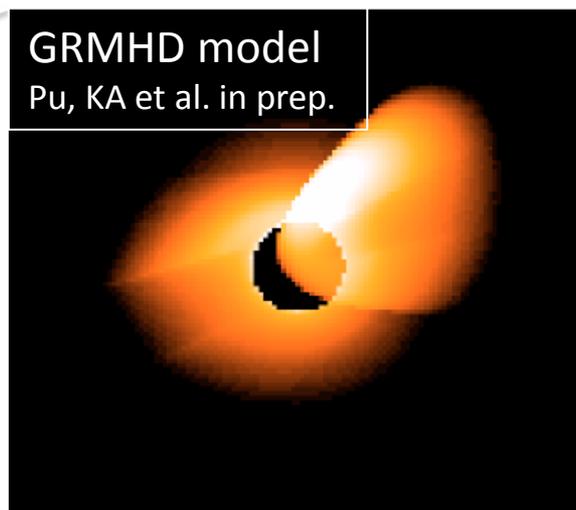
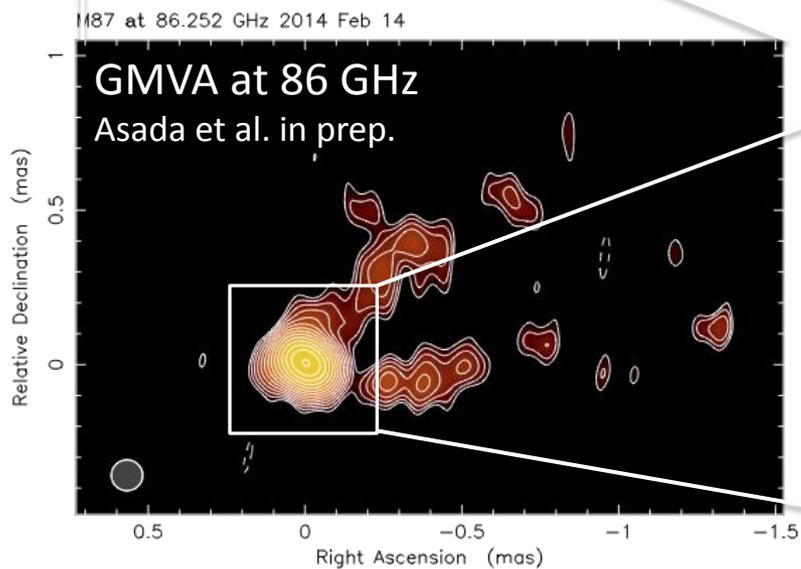
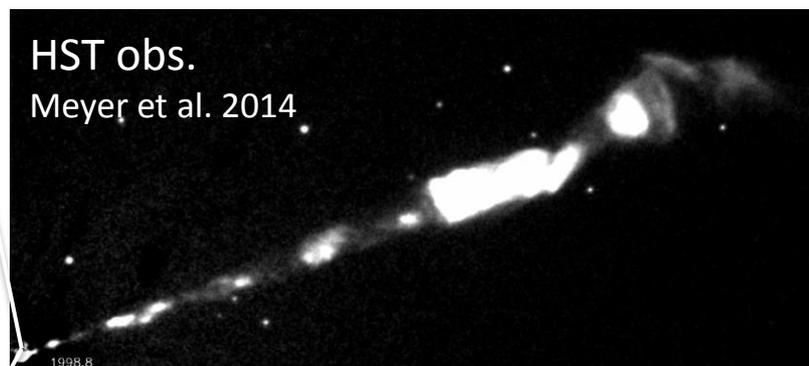
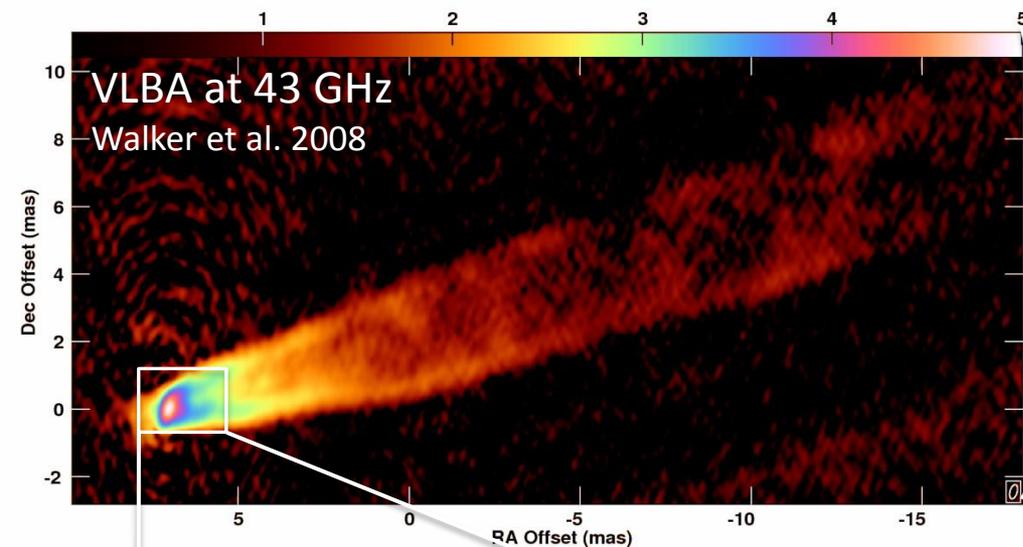
Approximately 10% of active galactic nuclei exhibit relativist powered by accretion of matter onto super massive black hc measured width profiles of such jets on large scales agree w collimation, predicted structure on accretion disk scales at t not been detected. We report radio interferometry observati



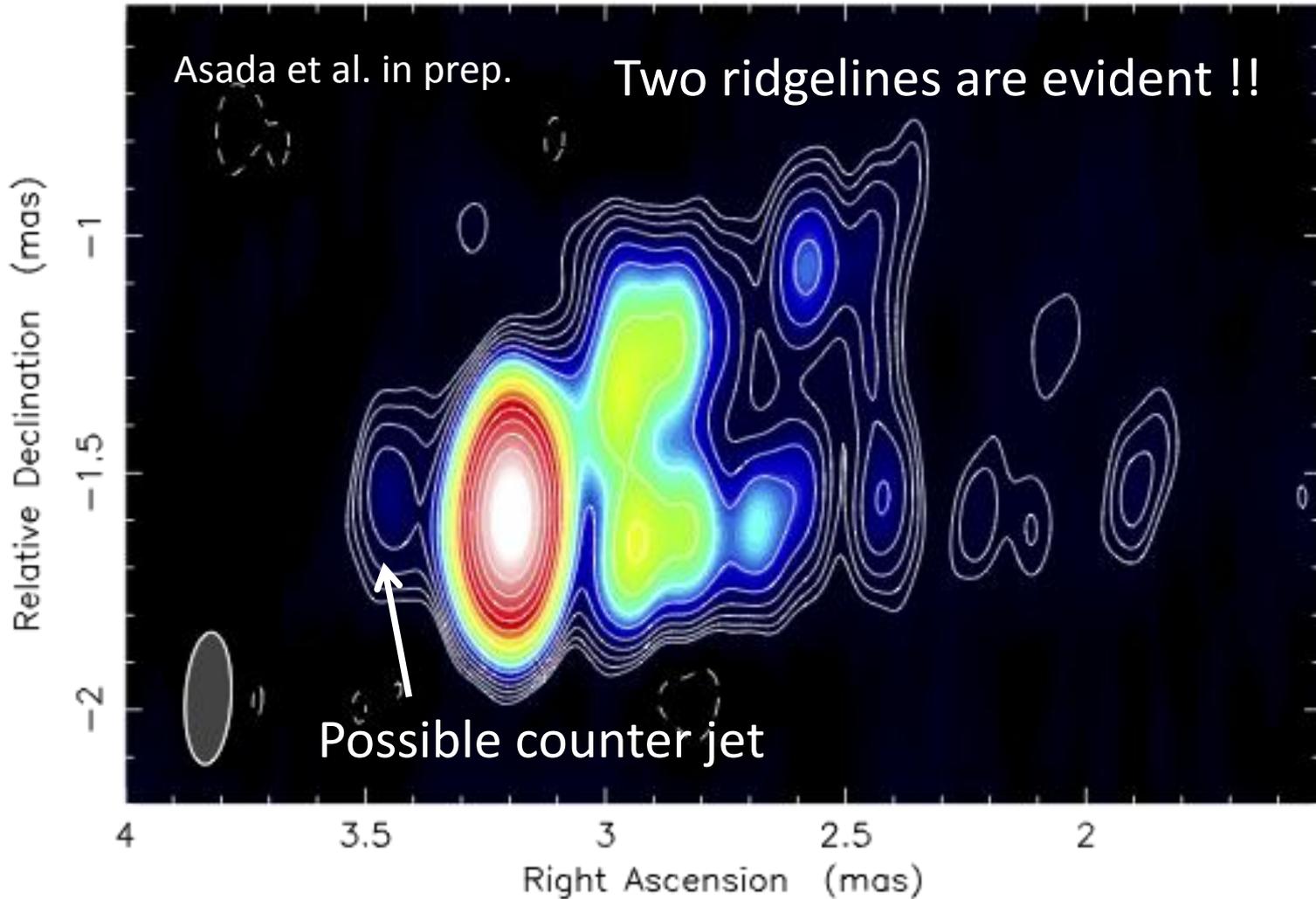
M 87

Submm VLBI is feasible and promising to image the shadow of BH !!

# M 87 with powers of 10

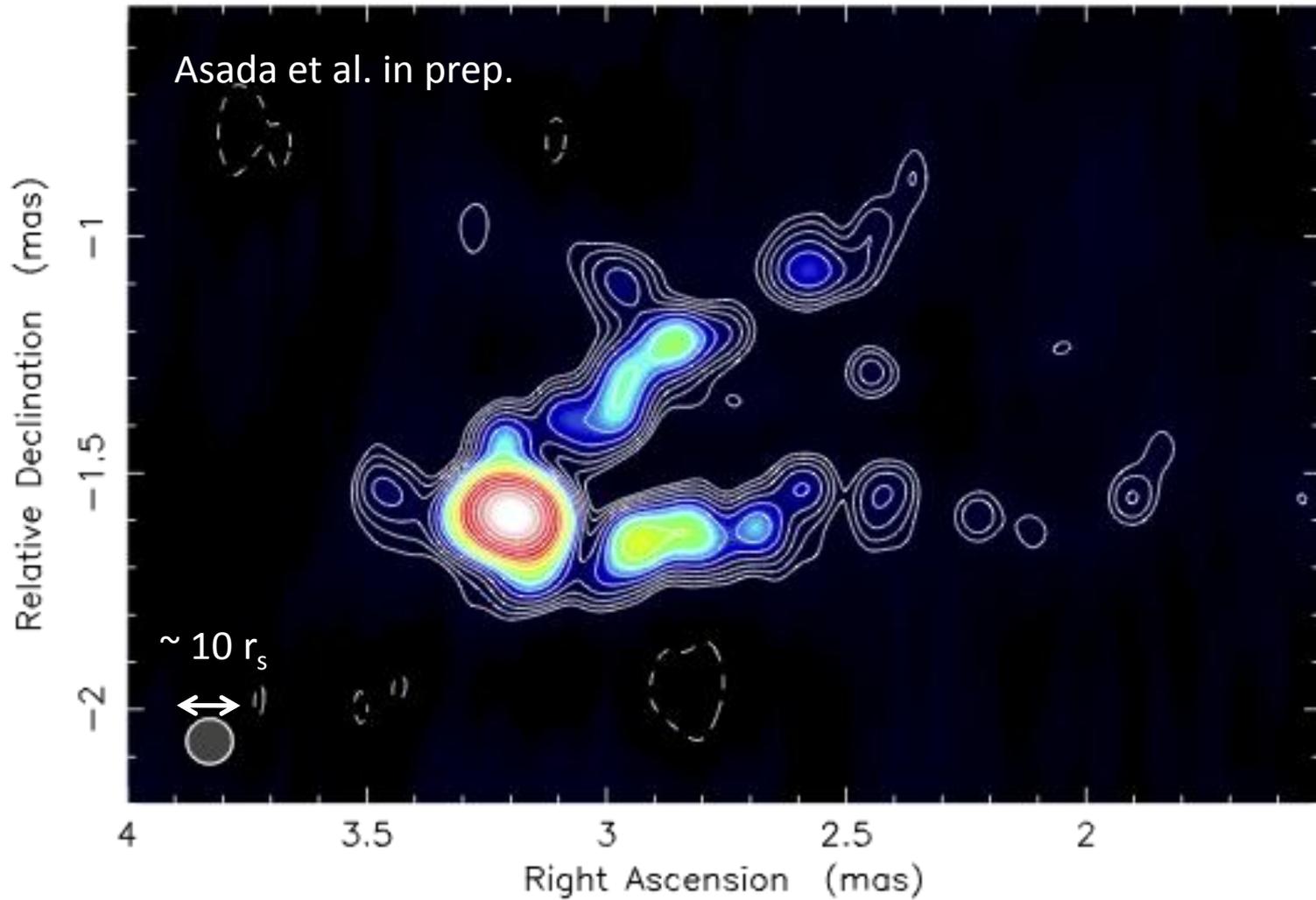


# GMVA image at 2014



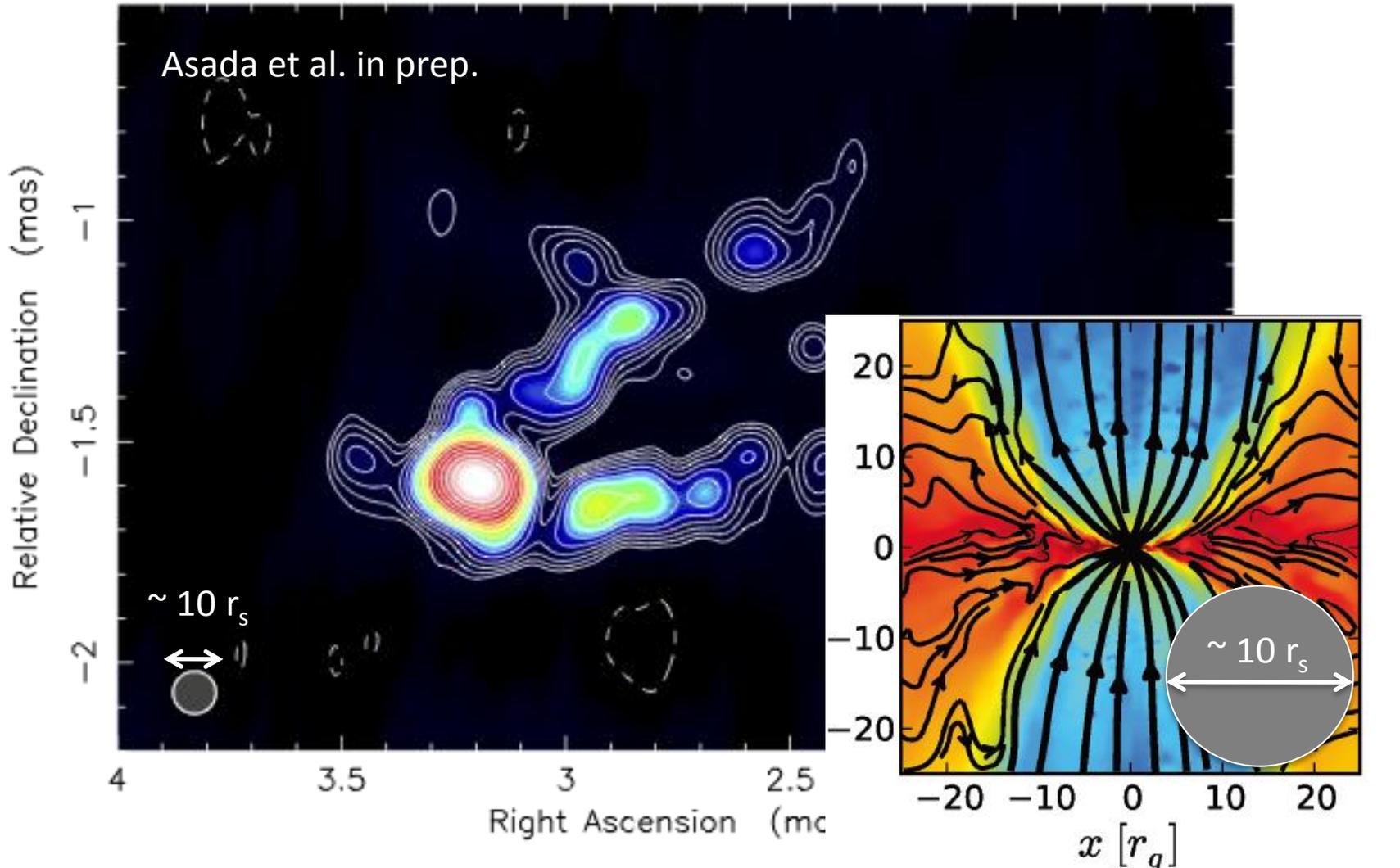
See also Hada et al. 2015

# GMVA image at 2014



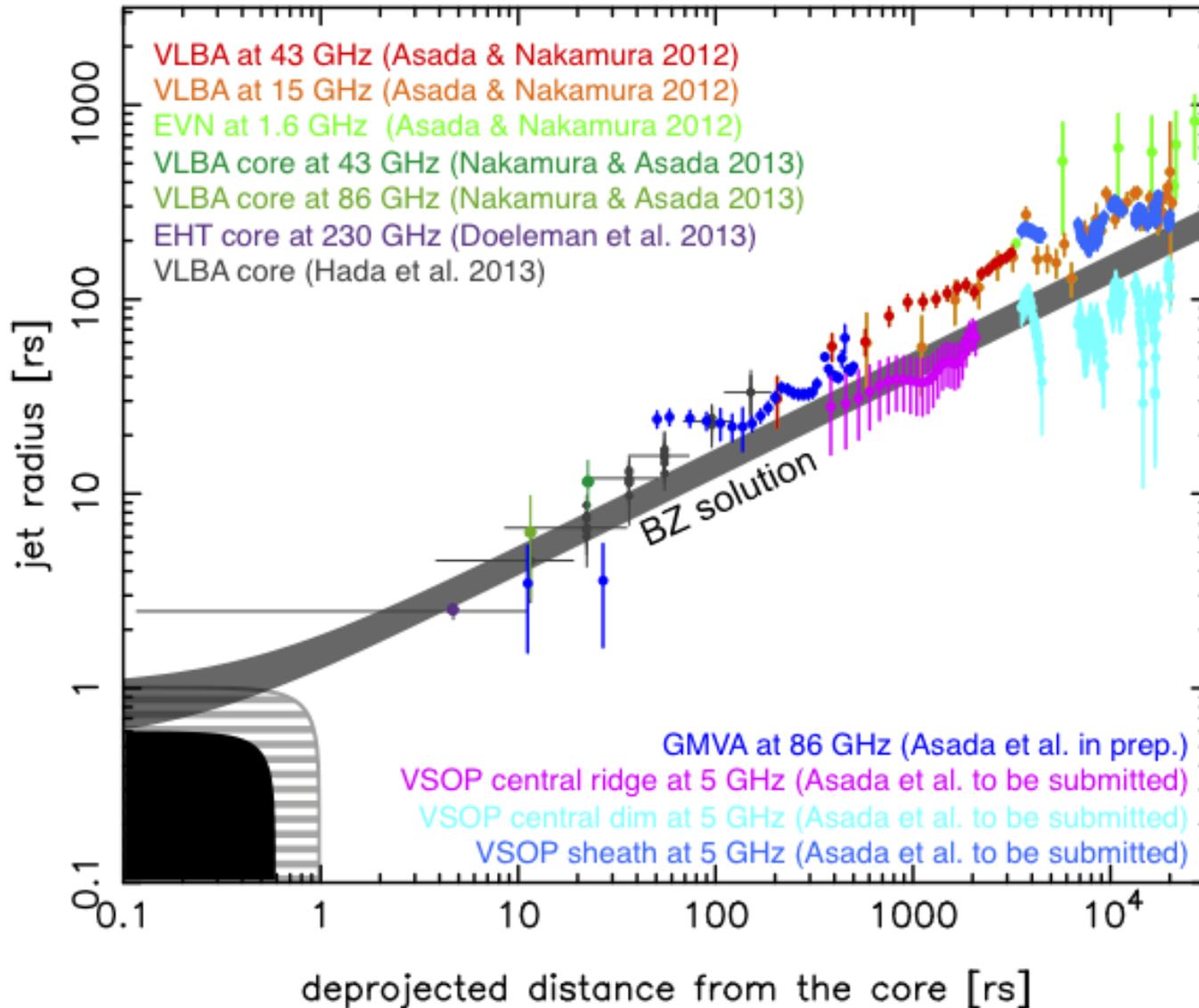
See also Hada et al. 2015

# GMVA image at 2014



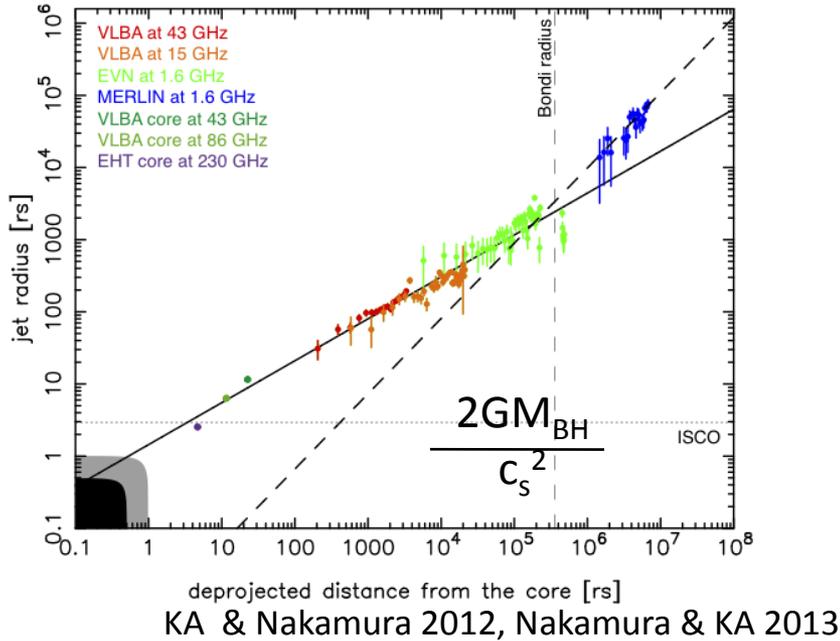
GRMHD simulation by  
Tchekhovskoy et al. 2011

# Streamline of M 87 jet

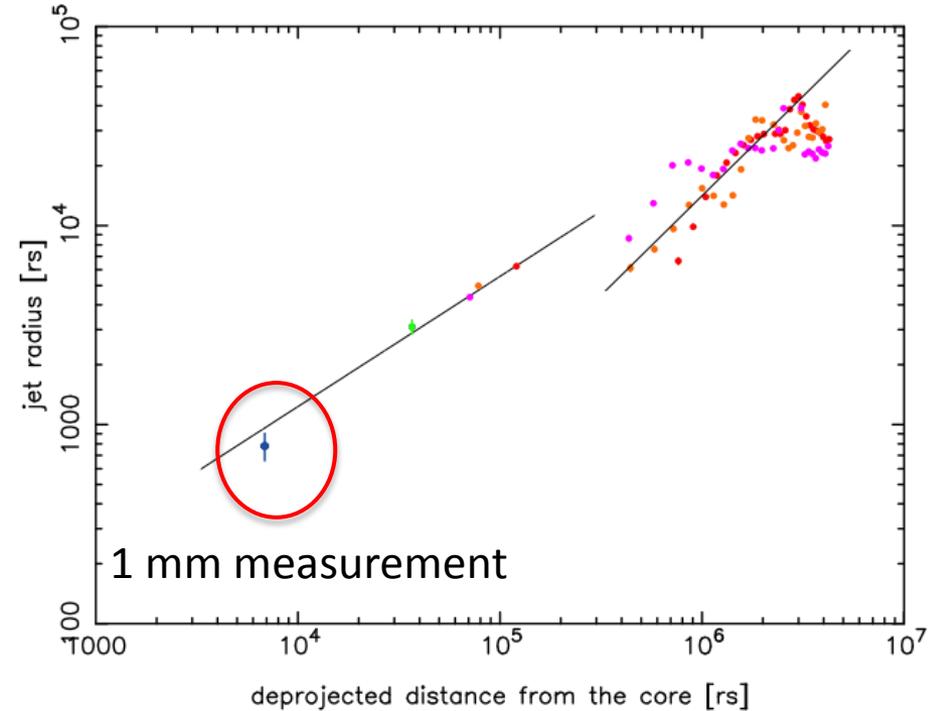


# Even with just size measurements

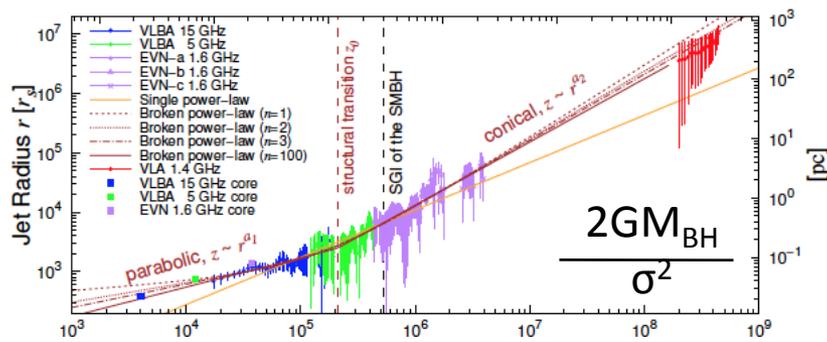
## Streamline of M 87



## Streamline of 1633+382



## Streamline of NGC 6251



There is a transition around  $10^5 r_s$ .  
First case for QSO!!

# Regional Activities



# EA white paper

Please also see:

- Fish et al. 2013, astro-ph/1309.3519
- Tilanus et al. 2014, astro-ph/1406.4650

## Draft: Towards an Angular Resolution of $1 R_S$ (TBD)

A White paper on mm/submm VLBI from East Asia Vision

### Editors

Asada, K.<sup>1</sup>, Kino, M.<sup>2</sup>, Honma, M.<sup>3</sup>, Hirota, T.<sup>3</sup>, Lu, R.-S.<sup>4</sup>,  
Inoue, M.<sup>1</sup>, Sohn, B.-W.<sup>2</sup>, Shen, Z.-Q.<sup>4</sup>, and Ho, P.T.P.<sup>1,5</sup>

### Authors

Author1, Author2, Author3, Author4 ...

<sup>1</sup>Institute of Astronomy and Astrophysics, Academia Sinica, Taipei, Taiwan, R.O.C. <sup>4</sup>Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, China

<sup>2</sup>Korea Astronomy and Space Science Institute, Daejeon, Republic of Korea <sup>5</sup>East Asian Observatory

<sup>3</sup>National Astronomical Observatory of Japan, Mitaka, Tokyo, Japan

# ALMA Workshop in next Jan.



**ALMA workshop "Ultra-High Resolution Observation with Phased-ALMA"**

**Date: January 13-14, 2016**

**Venue: "Cosmos-Kaikan" meeting room, Mitaka campus of NAOJ.**

S/LOC Chair: Hiroshi Nagai (ALMA/NAOJ)

Deadline for contributed talks:

November 20, 2015 (if financial support is needed)

November 30, 2015 (no financial support)

Language: Talks and slides shall be given in English.

Scope: ALMA phase-up capability will be offered in ALMA Cycle 4. This capability will enable us to do VLBI observations with the spatial resolution better than 100 micro-arcsec and unprecedented sensitivity at millimeter wavelengths. Potential scientific targets are imaging of black hole shadow, accretion disk, and jet base of active galactic nuclei. The main aim of this workshop is to review the recent progress of these scientific topics and discuss the prospects for Cycle 4 and beyond. All researchers from multi-wavelength and theoretical communities are welcomed to join this workshop.

Towards the 100<sup>th</sup> Anniversary of the Discovery of Cosmic Jets

# M87 Workshop

May 23-27 2016, ASIAA, Taipei



Web.: <http://events.asiaa.sinica.edu.tw/workshop/20160523/index.php>

Contact: [m87ws2016@asiaa.sinica.edu.tw](mailto:m87ws2016@asiaa.sinica.edu.tw)

Image courtesy (left: Francisco Diez, middle: J.-C. Algaba, right: Greenland telescope)

## TOPICS

**Registration & abstract submission (- 2016/02/15)**

- SMBHs; mass, spin, and imaging of BH silhouettes
- BH accretion flows; from Bondi radius to the horizon
- BH Jets; from the horizon to galactic scale
- Co-evolution of galaxy and black hole: AGN feedback
- High energy emissions in LLAGNs; their sites and mechanisms



**SOC:** P. Ho (ASIAA, Chair)

L. Ho (KIAA, Vice-chair, keynote speaker)

R. Blandford (Stanford, keynote speaker)

A. Fabian (IoA, Keynote speaker)

R. Narayan (CfA, Keynote speaker)

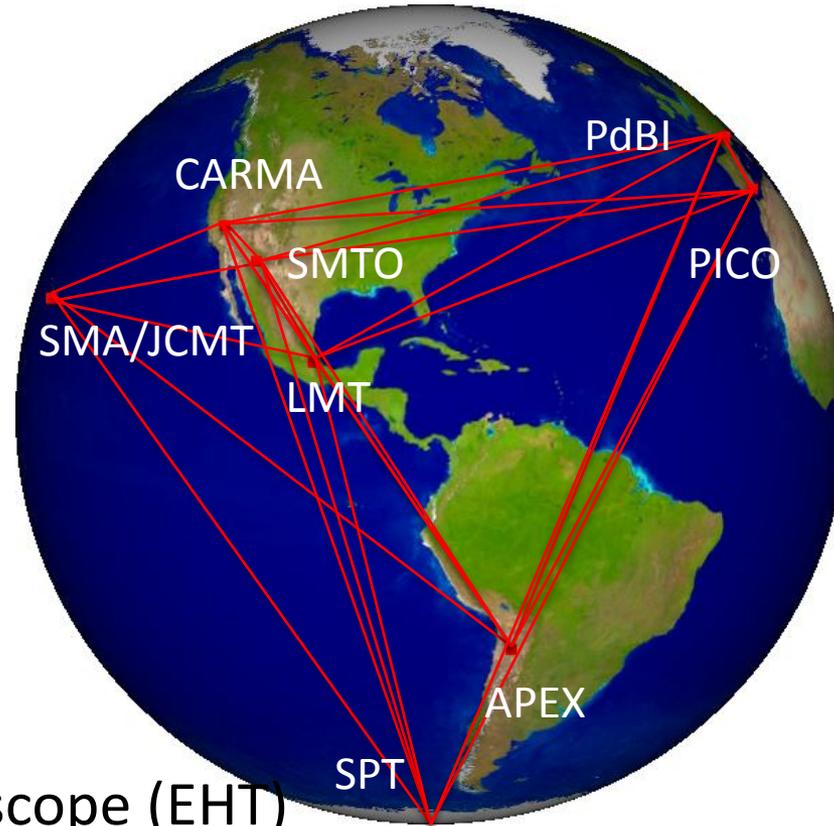
K. Asada (ASIAA, Secretary)

M. Nakamura (ASIAA, Secretary)

**Invited Speakers (\*TBD):**

K. Asada (ASIAA), J. Biretta (STScI), G. Bower (ASIAA), A. Broderick (U. Waterloo), E. Churazov (MPA), S. Doeleman (MIT Haystack), \*A. Doi (JAXA), J. Hawley (U. Virginia), A. Levinson (Tel Aviv U.), B. McNamara (U. Waterloo), H. Li (LANL), \*D. Meier (Caltech), S. Mineshige (Kyoto U.), M. Mościbrodzka (Radboud U.), M. Nakamura (ASIAA), E. Perlman (FIT), W. Potter (U. Oxford), Ł. Stawarz (Jagiellonian U.), A. Tchekhovskoy (UCB), \*C. Walker (NRAO), J. Walsh (Texas A&M U.)

# EHT observations in 2015



## Event Horizon Telescope (EHT)

Array coordinated based on experimental collaboration

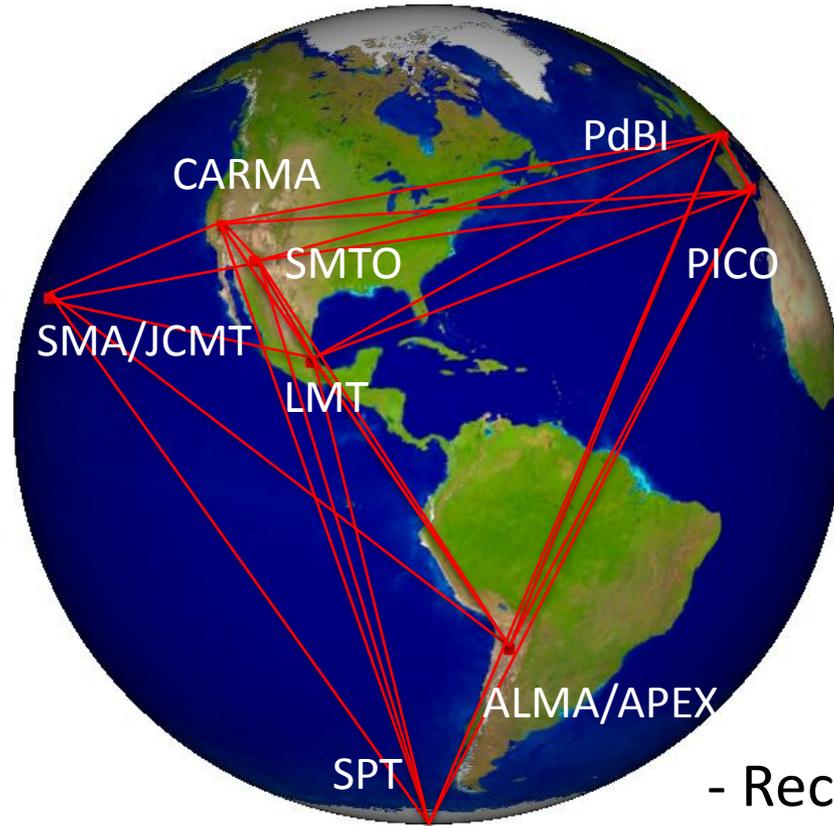
One sessions / yr:

Each session: ~ 5 day within 10 days slots

Host institute: EHT collaboration

Call for Proposal: you can (could) submit proposal

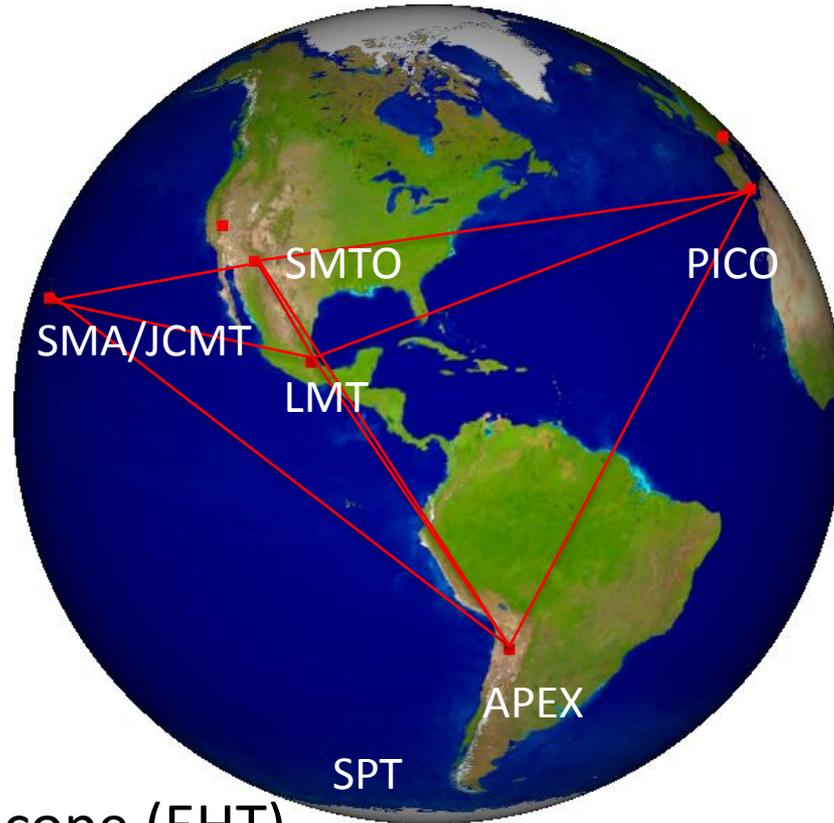
# EHT observations in 2017



- Recording Rate: 64 Gbps

- ALMA • APEX • ASIAA • Arizona Radio Observatory (U. of Arizona) • Caltech Submillimeter Observatory • CARMA • ESO
- Georgia State University • Goethe-Universität Frankfurt am Main • GLT • Harvard Smithsonian Center for Astrophysics
- Submillimeter Array • University of Massachusetts – Amherst • Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)
- IRAM • JCMT (East Asian Observatory (operators)) • LMT • MIT Computer Science and Artificial Intelligence Lab (CSAIL)
- MIT Haystack Observatory • Max-Planck-Institut für extraterrestrische Physik • MPIfR • NAOJ • NRAO
- NSF - The EHT project gratefully acknowledges support from the National Science Foundation • Onsala Space Observatory
- Perimeter Institute • Radboud University • Shanghai Astronomical Observatory (SHAO) • Universidad de Concepción
- Universidad Nacional Autónoma de México (UNAM) • University of California - Berkeley (RAL) • University of Chicago (South Pole Telescope)
- University of Illinois Urbana-Champaign • University of Michigan

# EHT observations in 2017



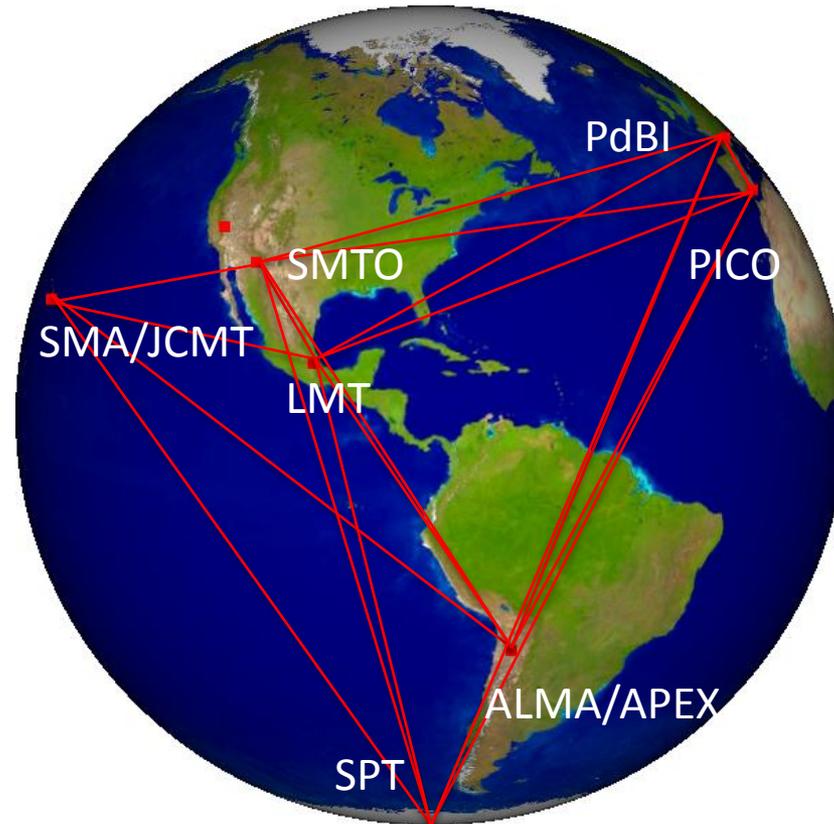
## Event Horizon Telescope (EHT)

Array coordinated based on experimental collaboration

Each session: ~ a few - 5 days within 10 days slots

Host institutes for EHT collaboration: MPIfR – Bonn, ASIAA, SAO/CfA, MIT Haystack, CARMA, NAOJ, NRAO, UC Berkeley, IRAM, APEX, JCMT, U. Concepcion, UNAM, Perimeter Inst.

# EHT observations in 2015

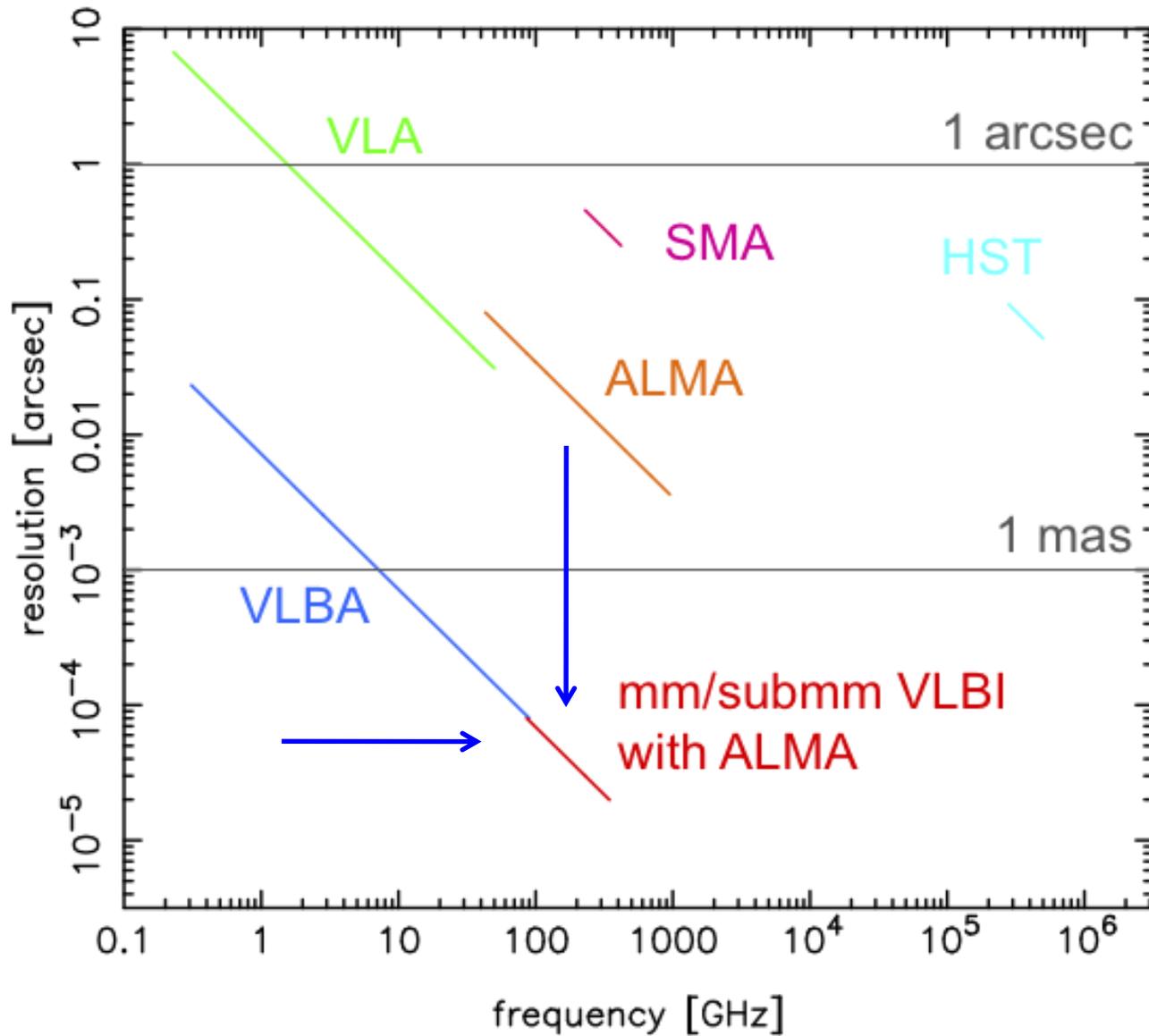


- Recording Rate:

4 Gbps (2007) -> 16 Gbps (2013) -> 32 Gbps (2015) -> 64 Gbps (2017)

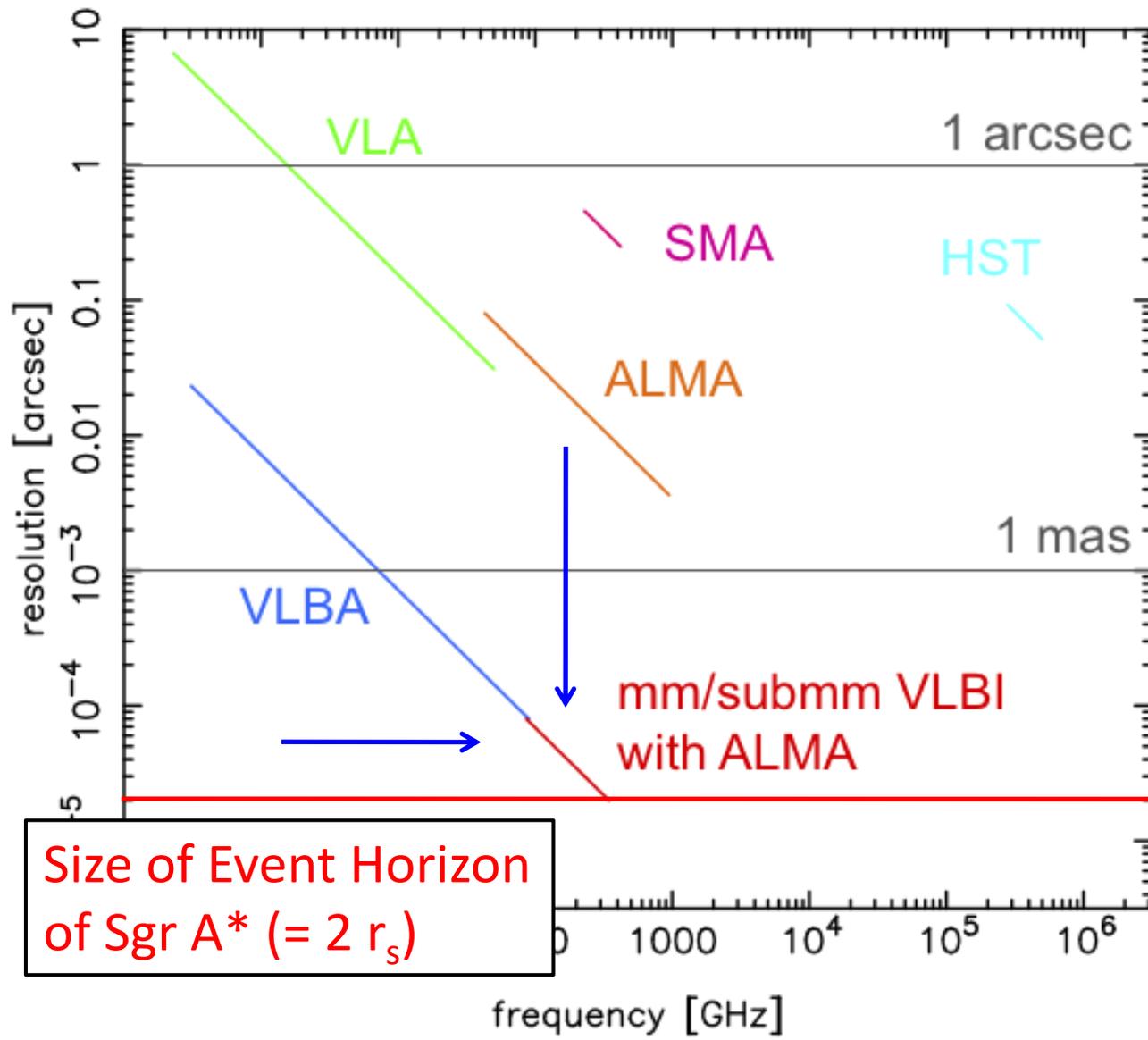
MPIfR – Bonn, ASIAA, SAO/CfA, MIT Haystack, CARMA, NAOJ,  
NRAO, UC Berkeley, IRAM, APEX, JCMT, U. Concepcion,  
UNAM, Perimeter Inst.

# Mm/submm VLBI



$$\Theta \sim \lambda/D$$

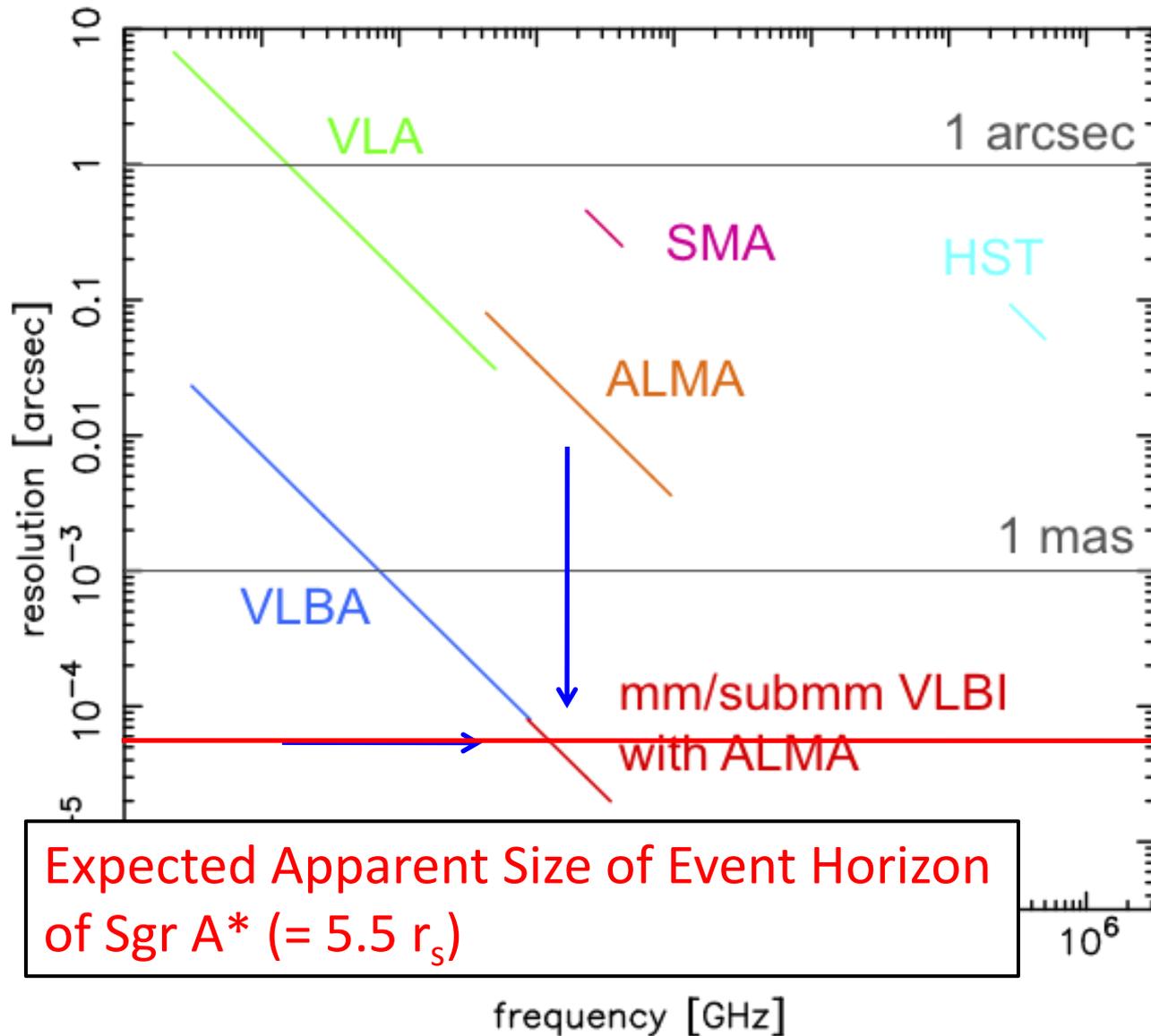
# Mm/submm VLBI



$$\Theta \sim \lambda/D$$

Size of Event Horizon of Sgr A\* (= 2 r<sub>s</sub>)

# Mm/submm VLBI

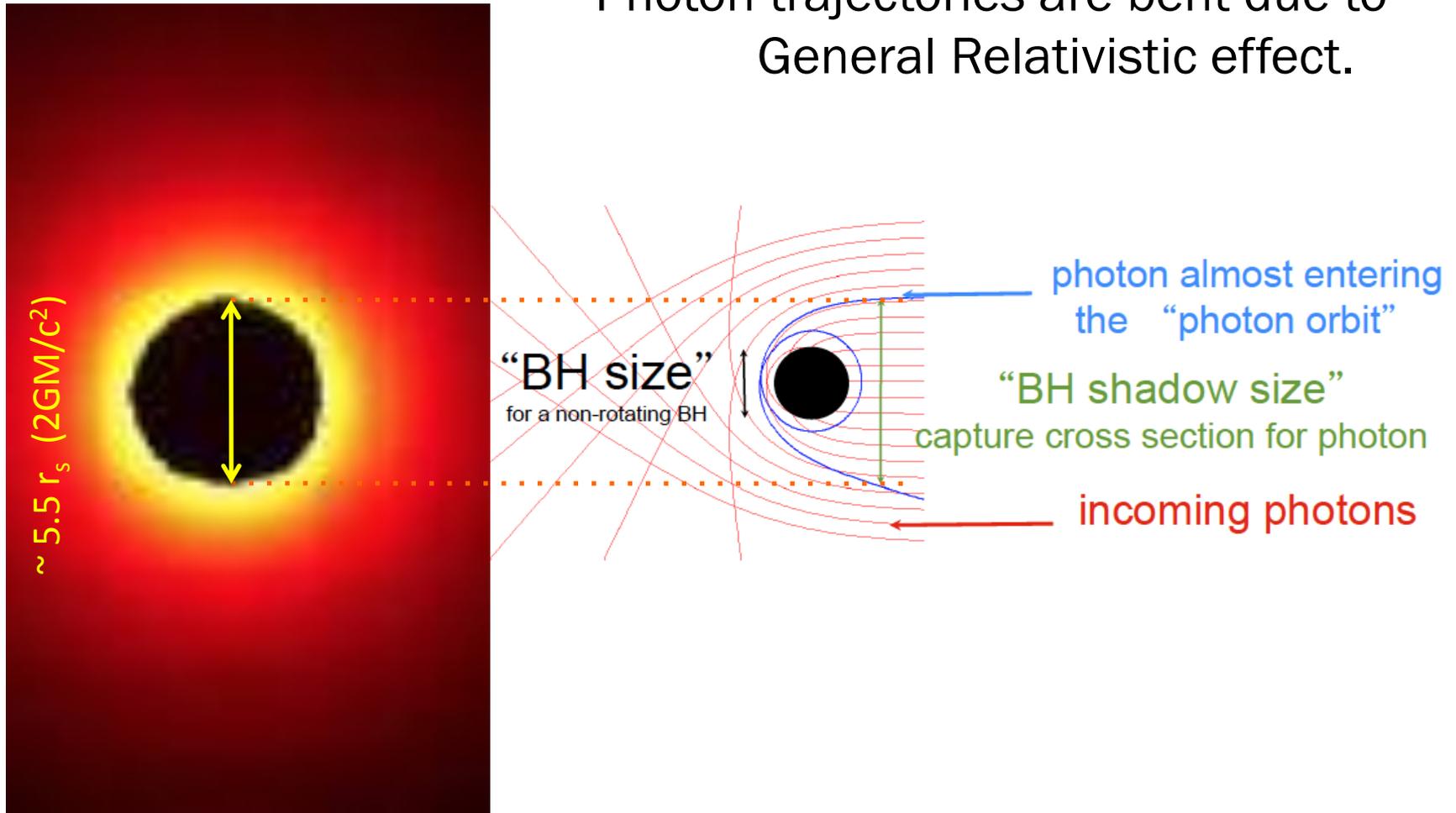


$$\Theta \sim \lambda/D$$

Expected Apparent Size of Event Horizon of Sgr A\* (= 5.5 r<sub>s</sub>)

# Image the shadow of the black hole

Photon trajectories are bent due to General Relativistic effect.



Images by Hung-Yi Pu

# Image the shadow of the black hole

