Impact of LLAMA in current and future mm VLBI arrays: from black holes to stars

Ciriaco Goddi

Universidade de São Paulo (IAG-USP)

FAPESP Jovem Pesquisador

Role of LLAMA in VLBI networks

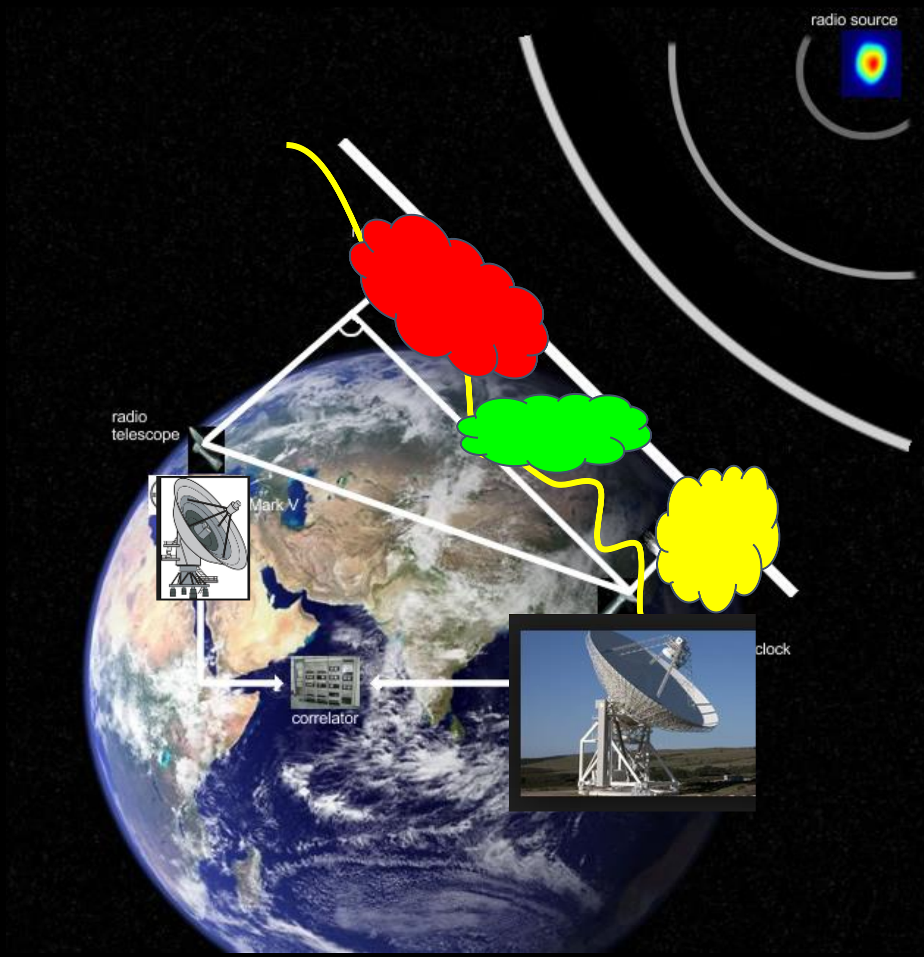
1. LLAMA is 180 km from ALMA, the anchor station in current mm VLBI networks
2. Unique coverage in uv-space with baselines to ALMA/APEX
3. Very sensitive short/intermediate baseline with ALMA to sample “large” (*milliarcsecond*) scale structures
4. LLAMA-ALMA/APEX baselines are important for VLBI data calibration and analysis
5. Stand-in station for ALMA (highly oversubscribed)

1. LLAMA is 180 km from ALMA

Challenges of VLBI at mm-wavelengths

- Distortion effect by the ***troposphere***:
  - Shorter coherence time (atmospheric turbulence)
  - Requires ‘high and dry’ sites with low water-vapor column

  ⇒ new fringe-finding algorithms needed



- Small number of telescopes
  - Surface accuracies of a few μm over sizes of 10s m
  - Difficult to access remote sites and maintain.

  => *poor u-v coverage*

- **Typically *small dishes* (10-15 m)**
  - Surface accuracies of O(10 μm) over sizes of 10s m

  => *poor baseline sensitivity*

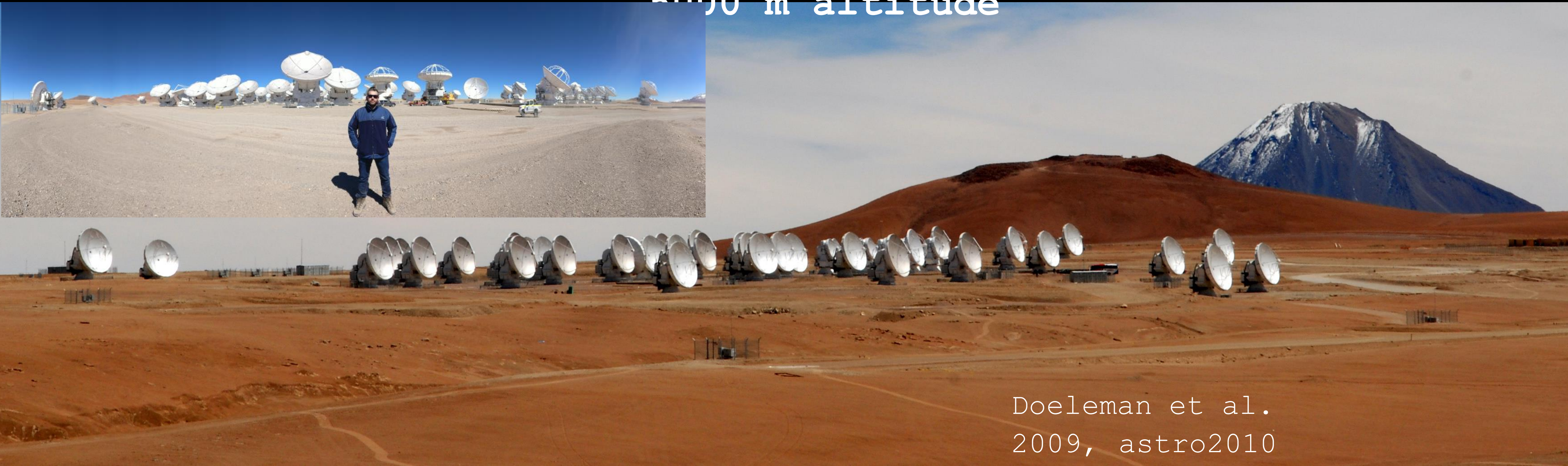
- **Worse receiver performances & high signal losses**

Need for **higher sensitivities**

1. Phased-arrays in VLBI network

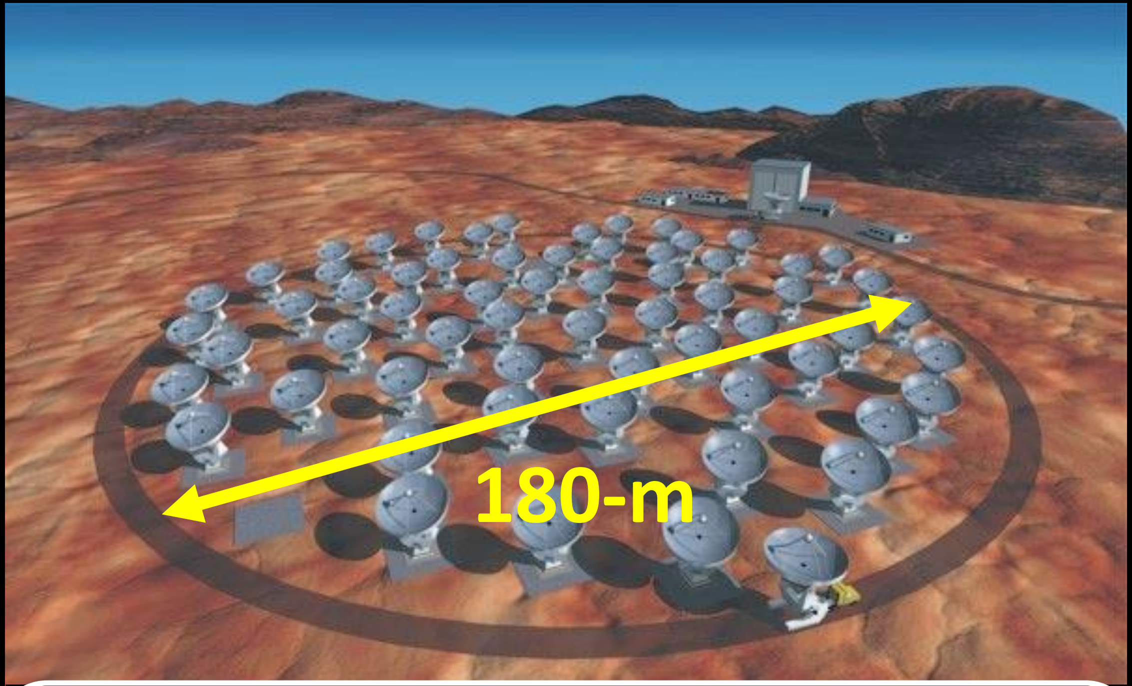
ALMA
(Chile)

66 telescopes (54 12-m, 12 7-m)
5000 m altitude



Doeleman et al. 2009, astro2010

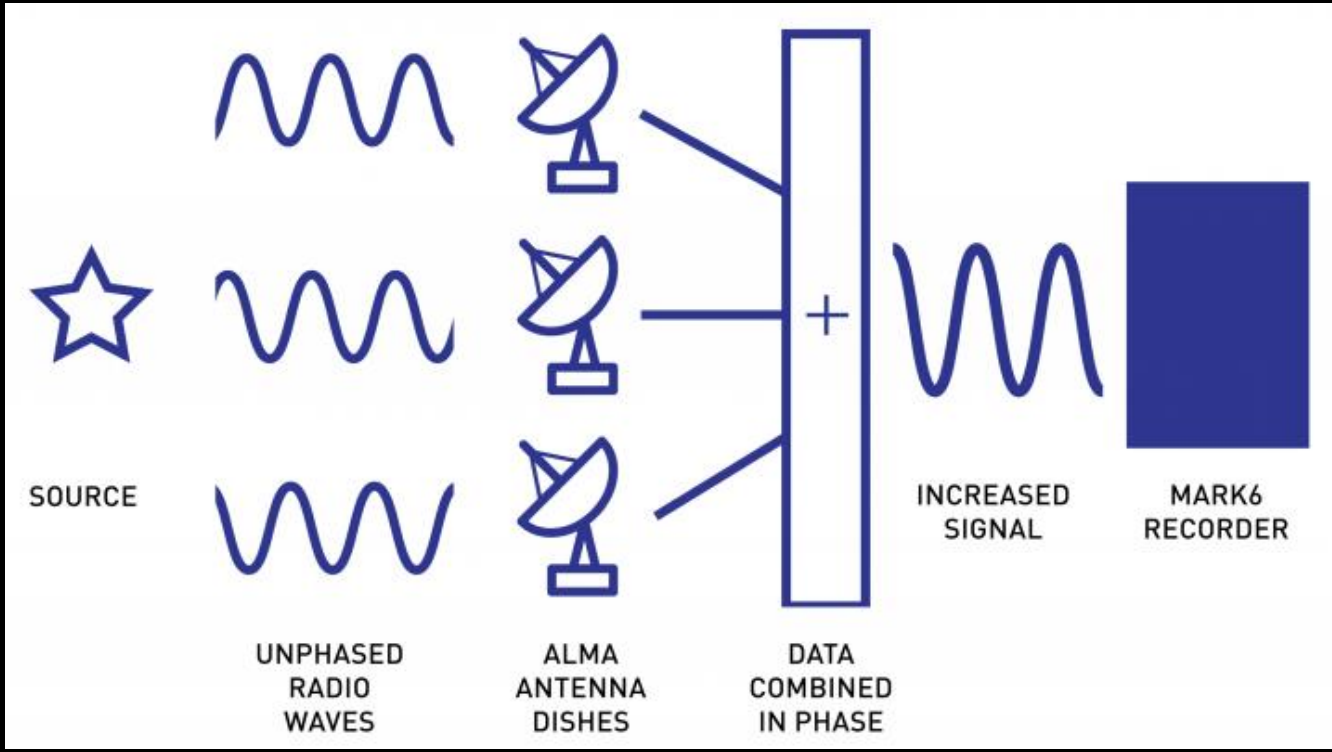
ALMA Phasing Project (APP) for VLBI



- Radius < 180m
- Up to ~41 phased (12-m) antennas
  (≈77-m parabolic dish)

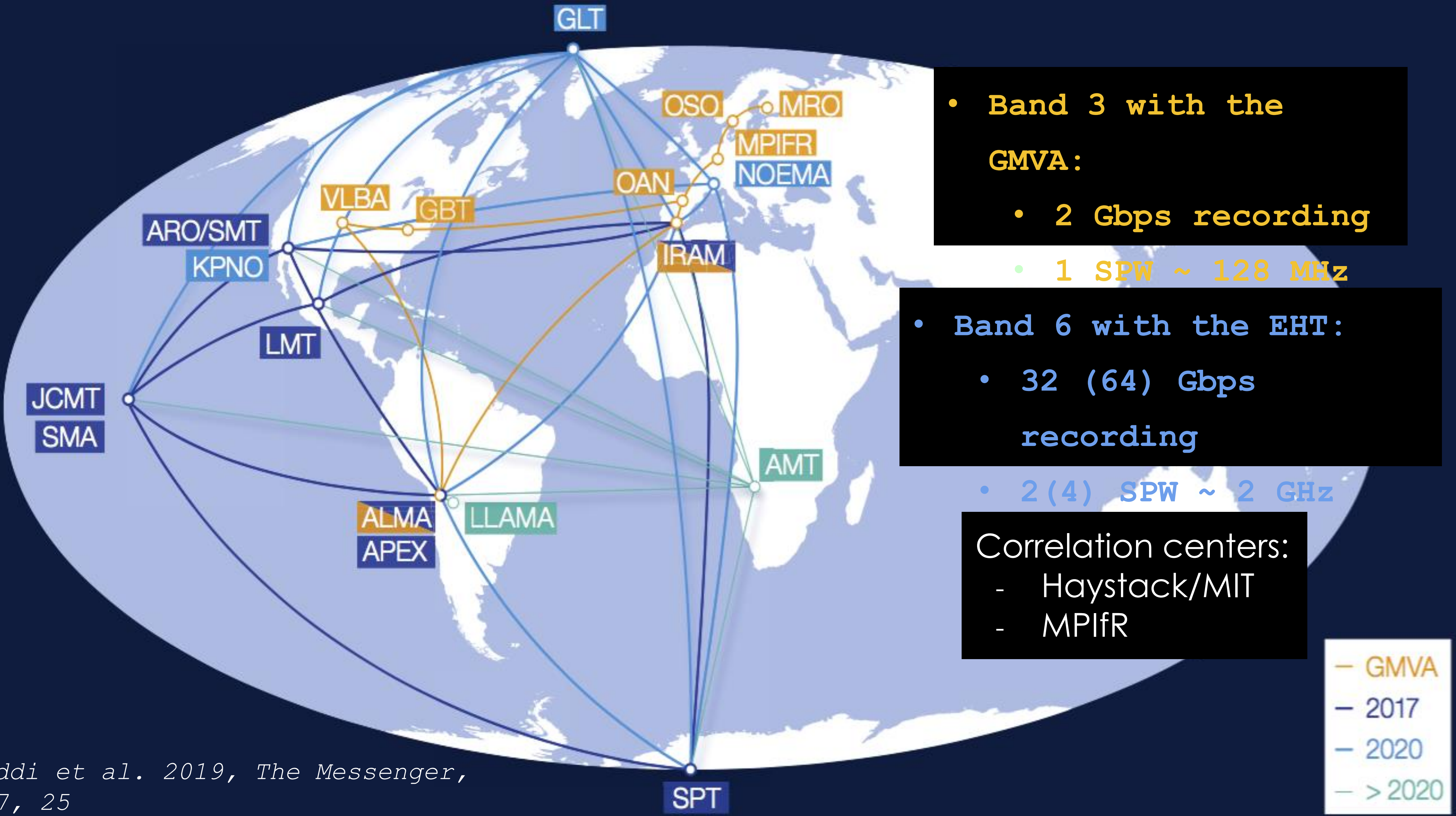
⇒dramatic boost in **sensitivity** (×10)

Phasing of the array



Matthews, Crew, Doeleman, et al. 2018, PASP
Goddi et al. 2019, PASP, 131, 075003
Crew, Goddi, Matthews et al. submitted PASP

Partner VLBI Networks



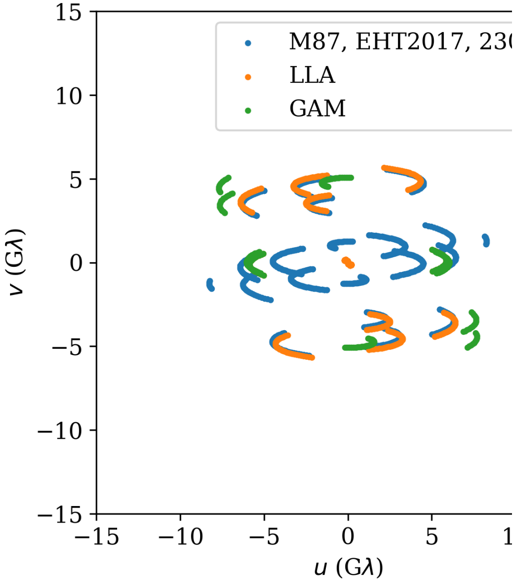
- **Band 3 with the GMVA:**
  - **2 Gbps recording**
  - **1 SPW ~ 128 MHz**
- **Band 6 with the EHT:**
  - **32 (64) Gbps recording**
  - **2(4) SPW ~ 2 GHz**

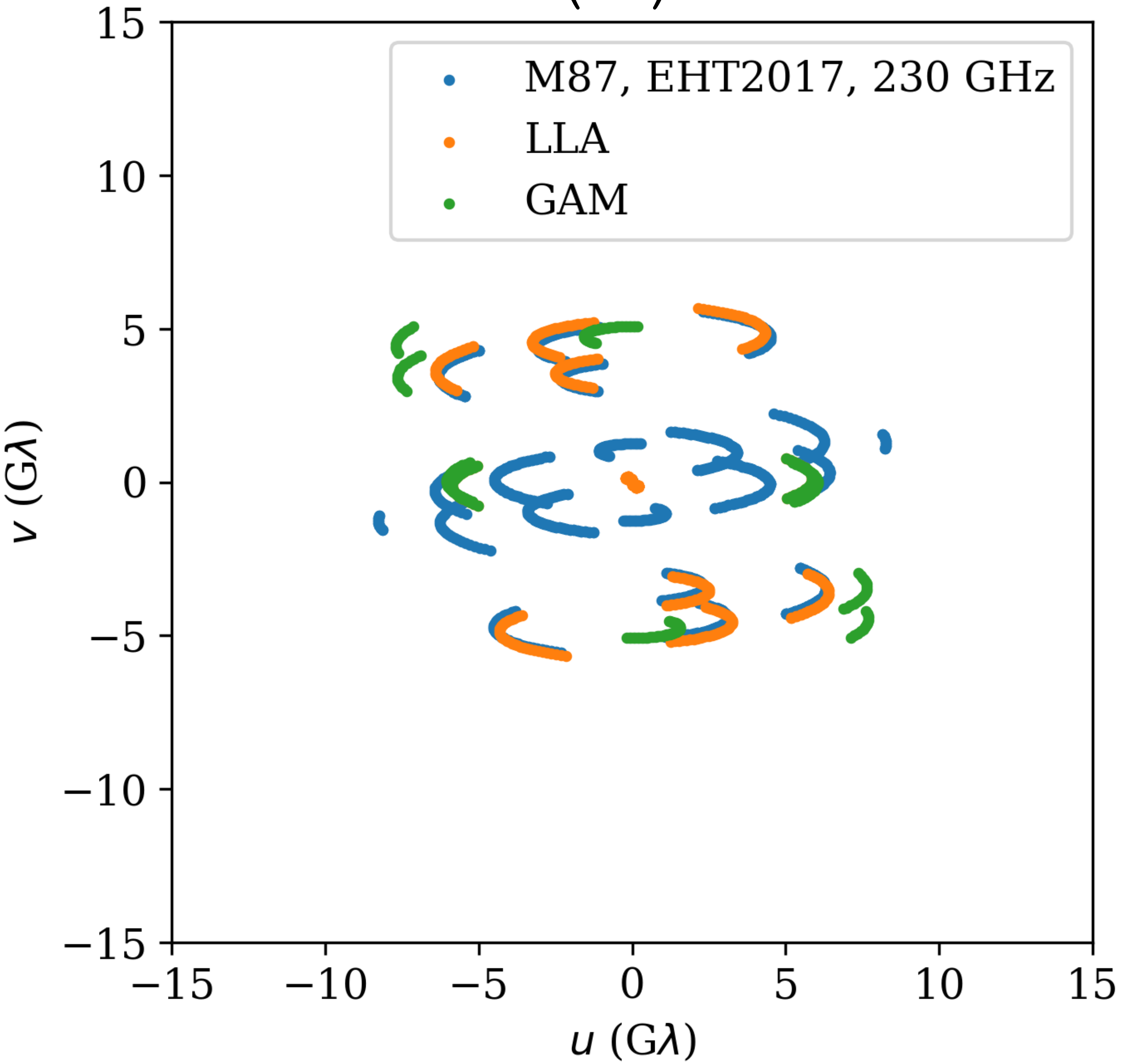
Correlation centers:
- Haystack/MIT
- MPIfR

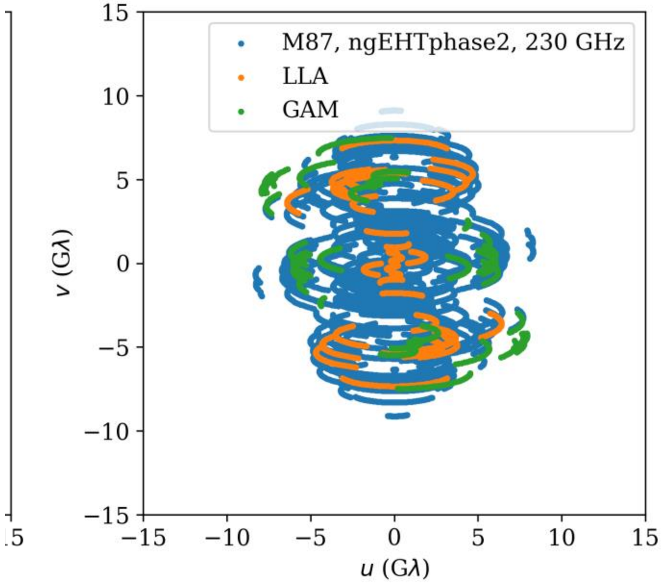
Goddi et al. 2019, The Messenger, 177, 25

2. Baselines to LLAMA provide unique tracks in uv-space

uv-coverage for M87 with the (ng)EHT+LLAMA (I)





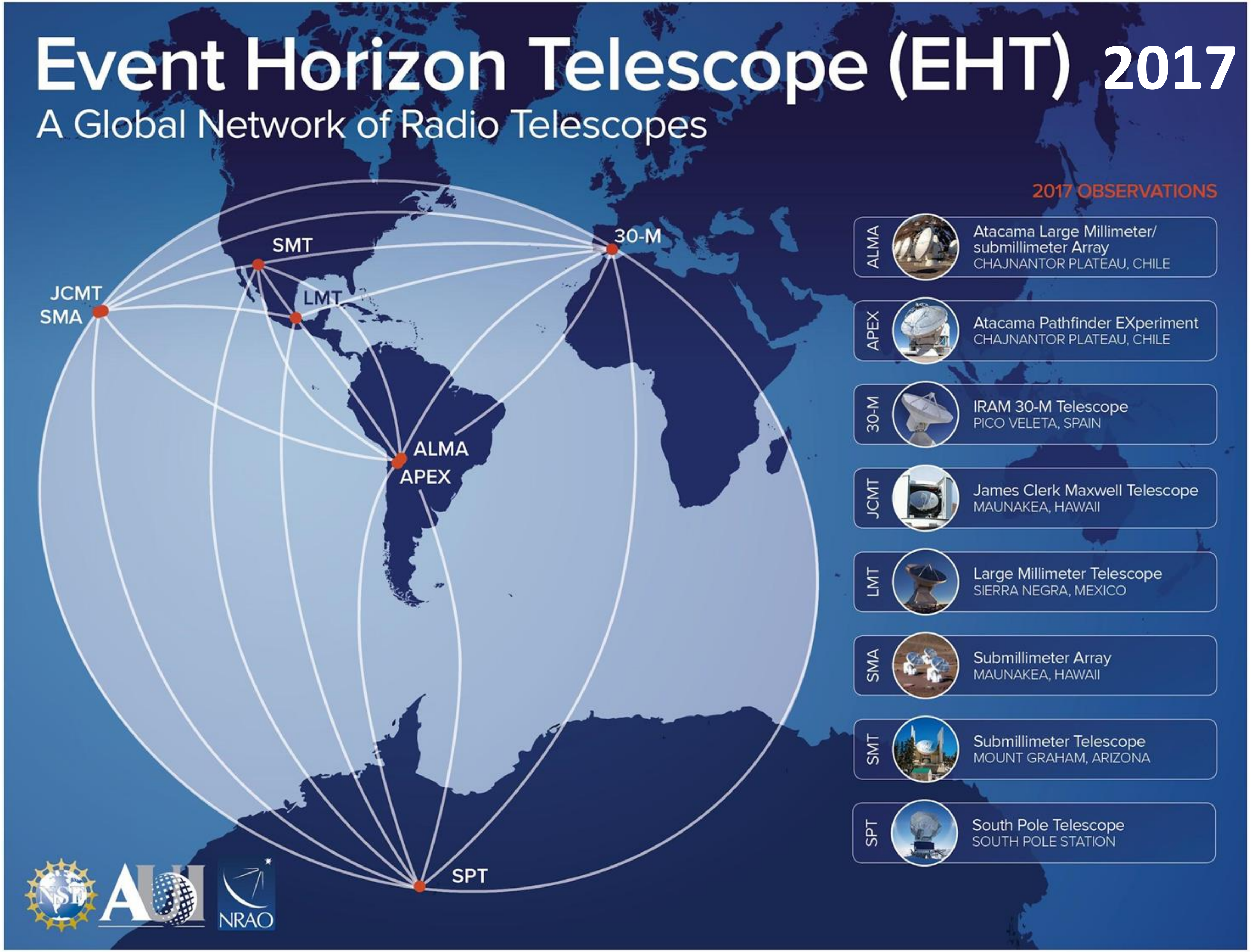


(almost) cros A/APEX and LLAMA

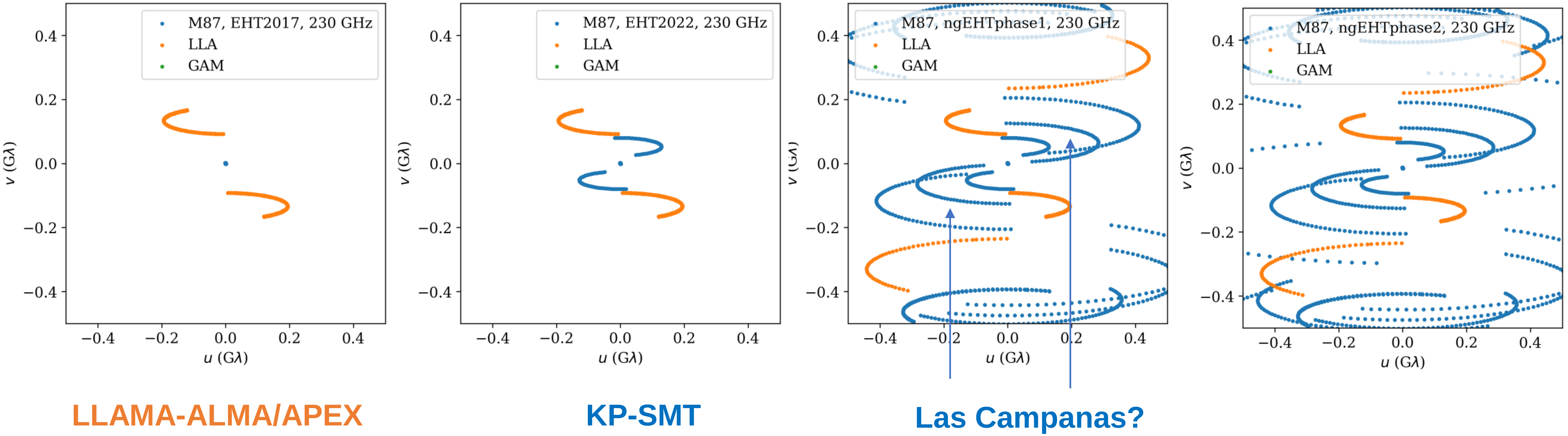
⇒No new uv-s

⇒Still usefu tly constrain

larger-scal

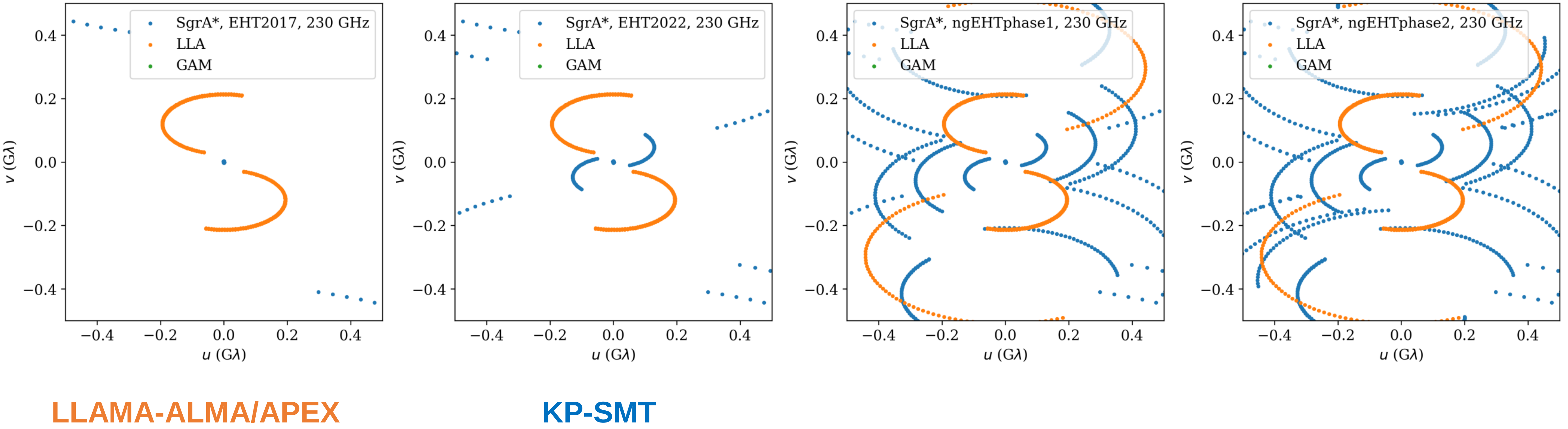

Event Horizon Telescope (EHT) 2017
A Global Network of Radio Telescopes
SMT
30-M
JCMT
SMA
LMT
ALMA
APEX
SPT
2017 OBSERVATIONS
ALMA
Atacama Large Millimeter/ submillimeter Array
CHAJNANTOR PLATEAU, CHILE
APEX
Atacama Pathfinder EXperiment
CHAJNANTOR PLATEAU, CHILE
30-M
IRAM 30-M Telescope
PICO VELETA, SPAIN
JCMT
James Clerk Maxwell Telescope
MAUNAKEA, HAWAII
LMT
Large Millimeter Telescope
SIERRA NEGRA, MEXICO
SMA
Submillimeter Array
MAUNAKEA, HAWAII
SMT
Submillimeter Telescope
MOUNT GRAHAM, ARIZONA
SPT
South Pole Telescope
SOUTH POLE STATION
NSF
AUI
NRAO

uv-coverage for M87 with the (ng)EHT+LLAMA (II)



The LLAMA-ALMA/APEX baselines trace a unique region in u

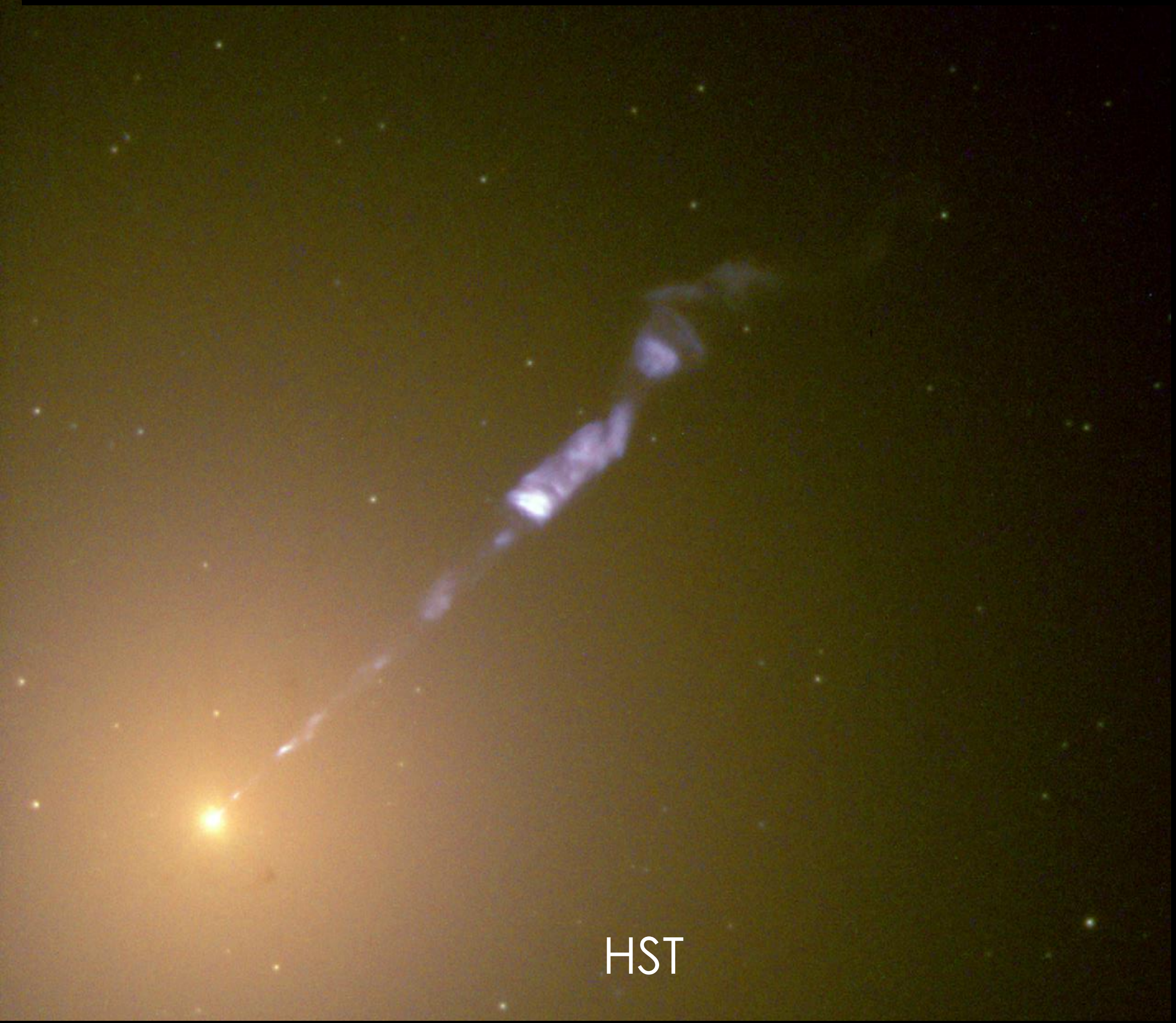
uv-coverage for Sgr A* with the (ng)EHT+LLAMA

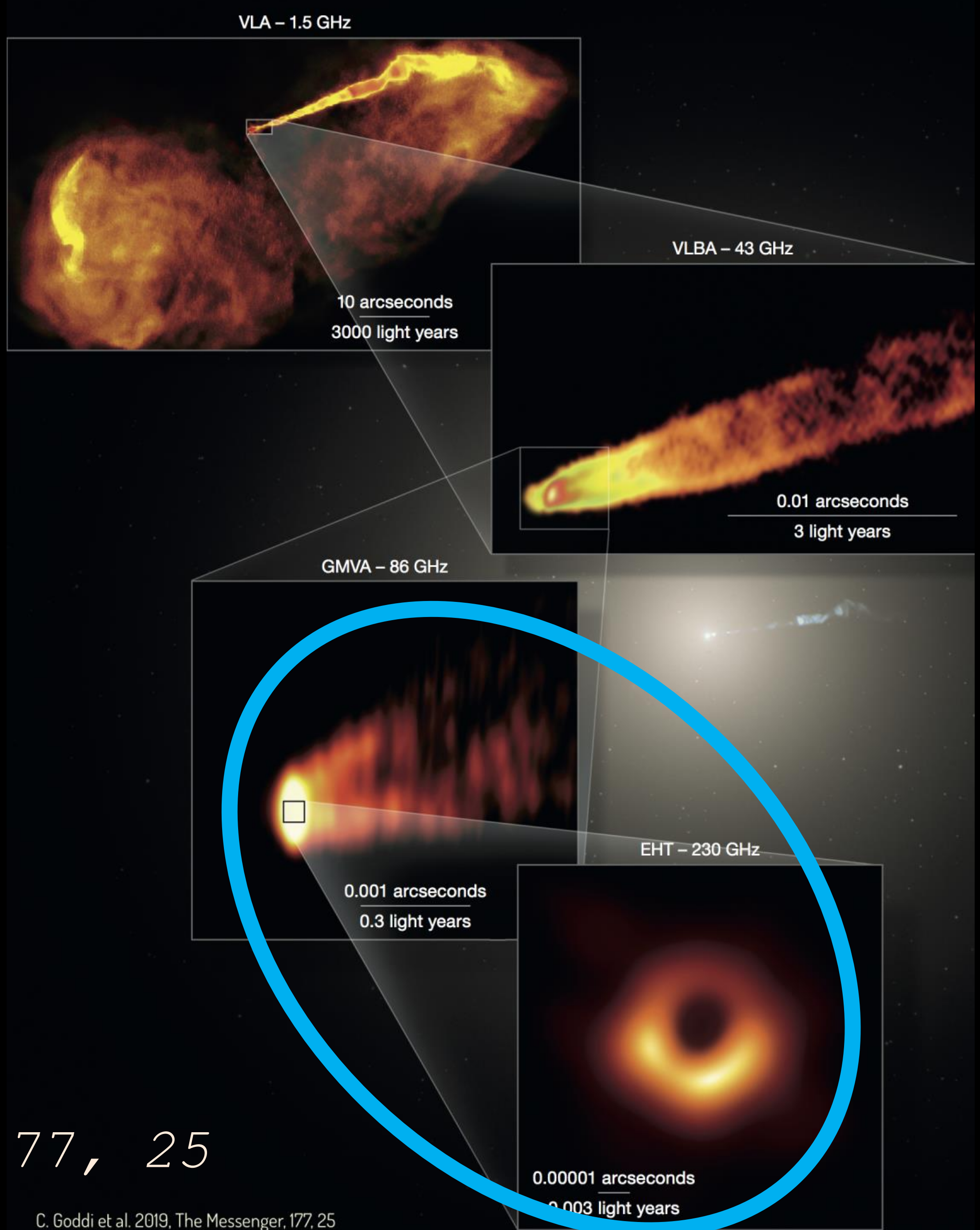


The LLAMA-ALMA/APEX baselines trace a unique region in u

3. Very sensitive short/intermediate baseline with ALMA to sample large-scale structures

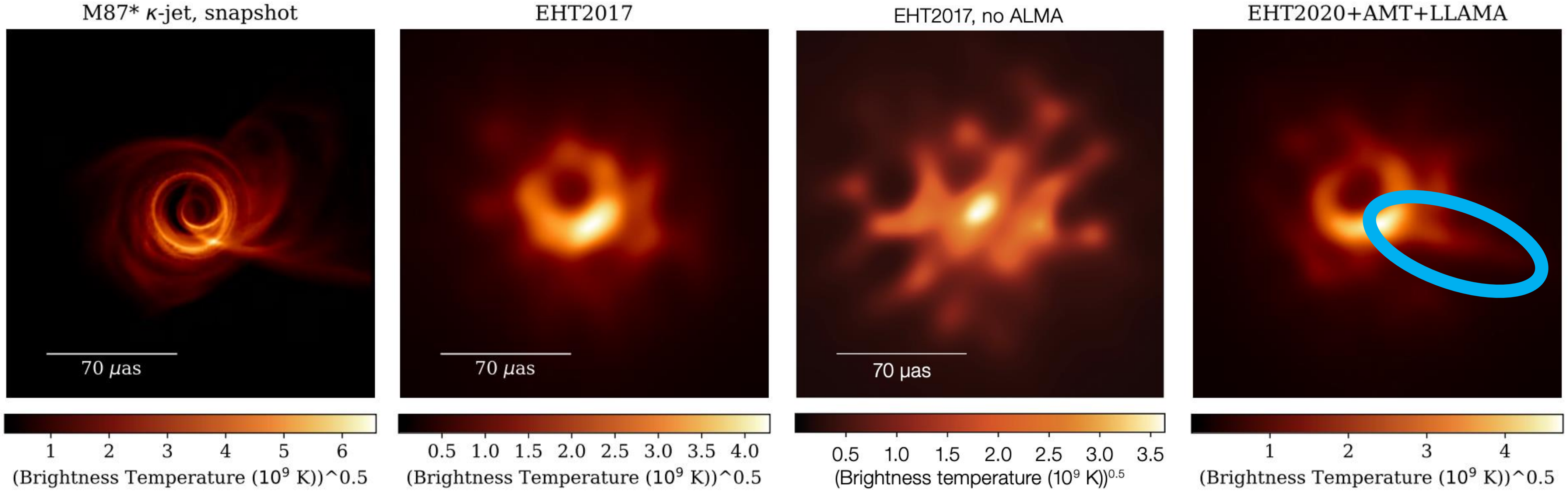
The relativistic jet in **M87**





Goddi et al. 2019, The Messenger, 177, 25

Impact of (new) stations from simulated images

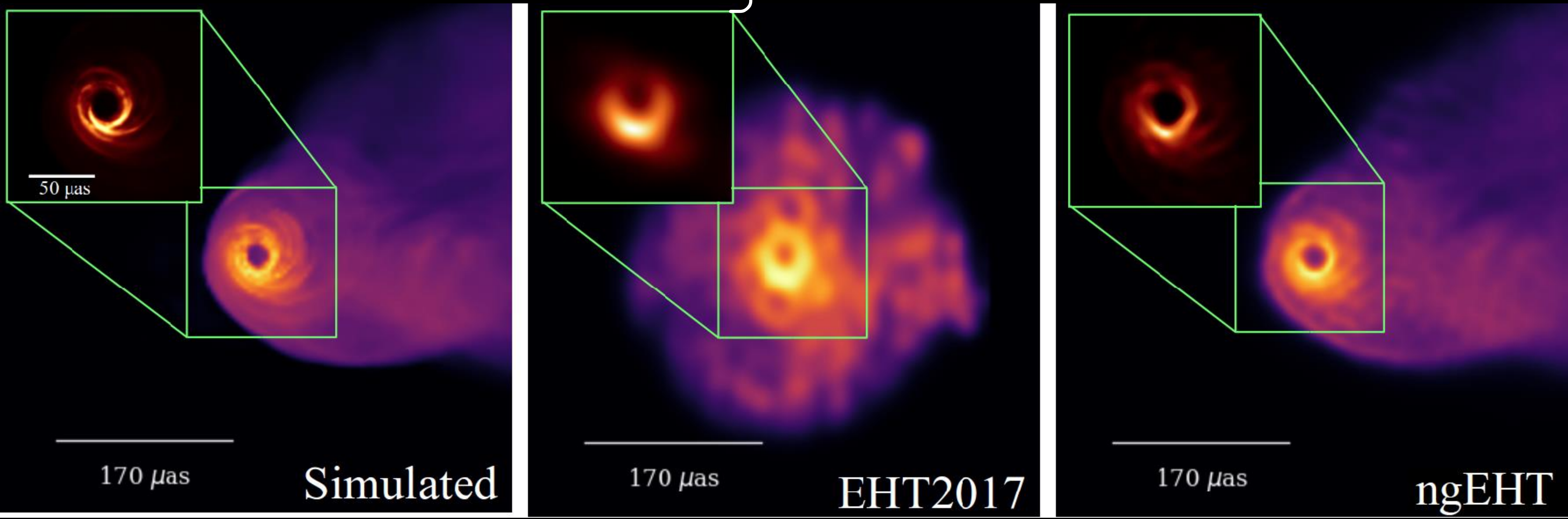


GRMHD model + GRRT image of the jet base in M87 (Davelaar et al. 2019)

Synthetic images produced with the synthetic data generation pipeline SYMBA (Roelofs, Janssen, et al. 2020)

Goddi et al. 2019, The Messenger, 177

M87 jet simulated images with the ngEHT

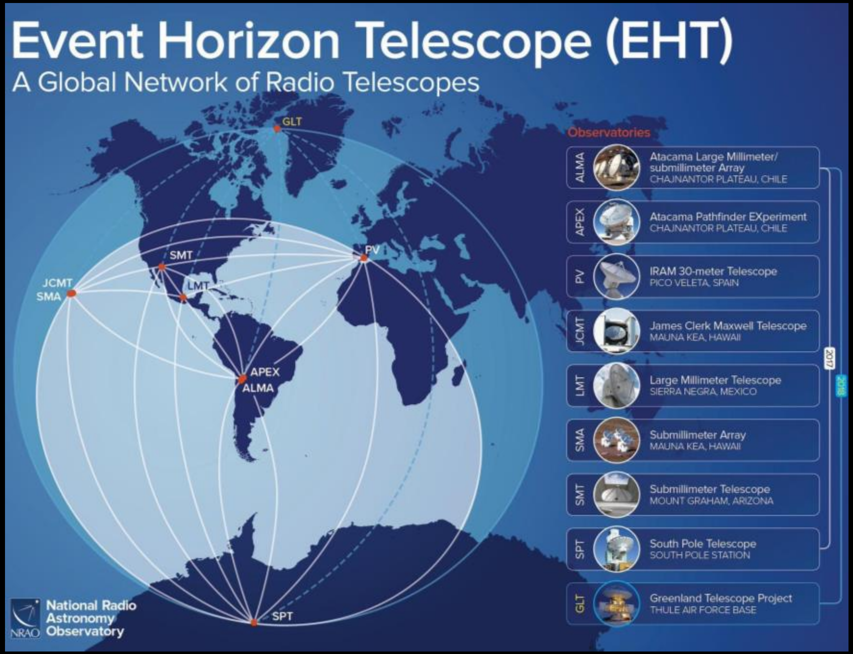


Doeleman et al. 2019

The very sensitive LLAMA-ALMA baseline can sample mas-scale structures that will allow to:

1. Link the horizon scales to the jet launching region in the M87 jet
2. Look for a jet in Sgr A*
3. Probe pc to kpc scales in AGN jets

AGN observed with EHT+ALMA



<u>Key Targets:</u> **Sgr A*, M87**

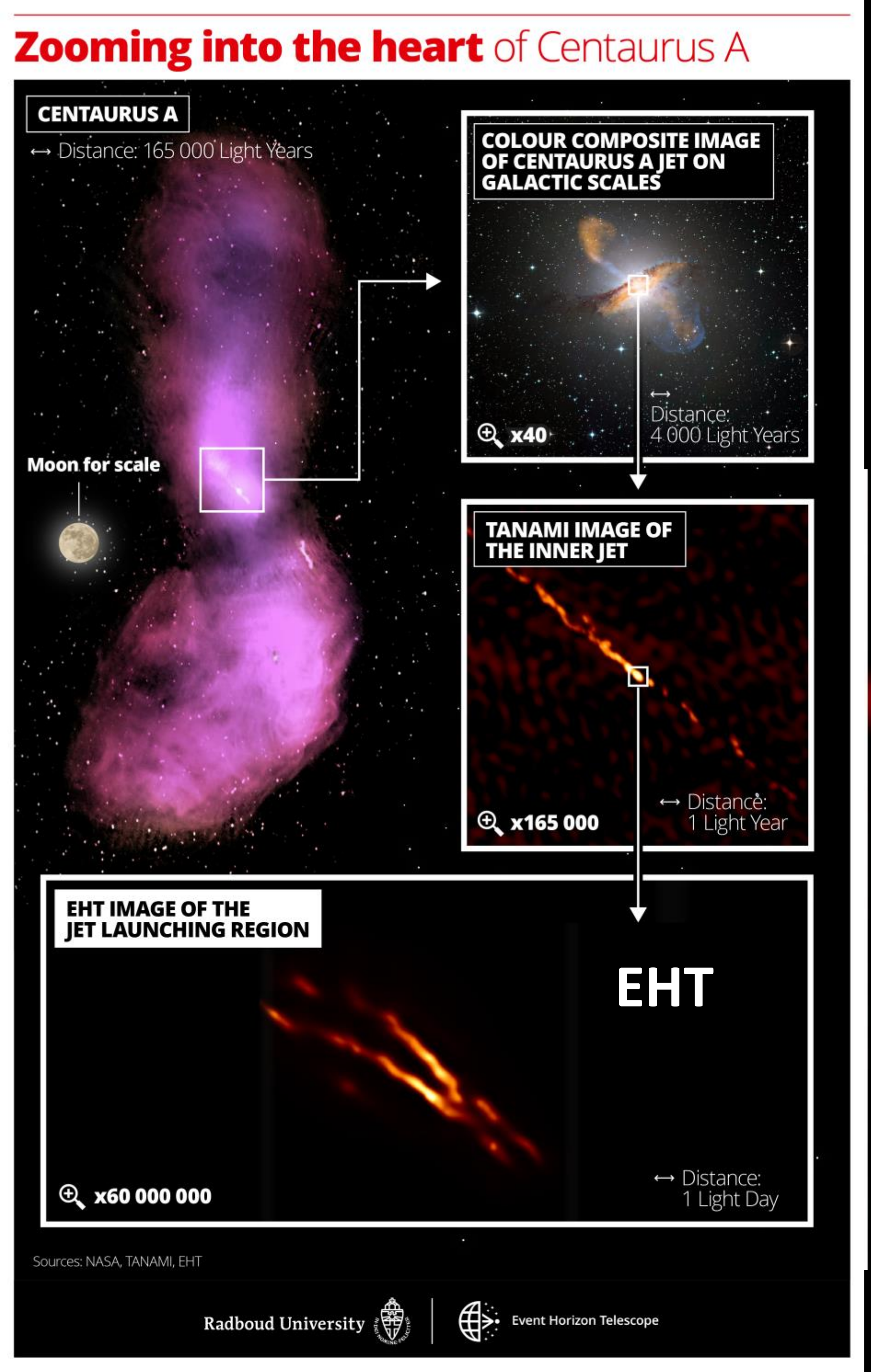
<u>AGN targets:</u>

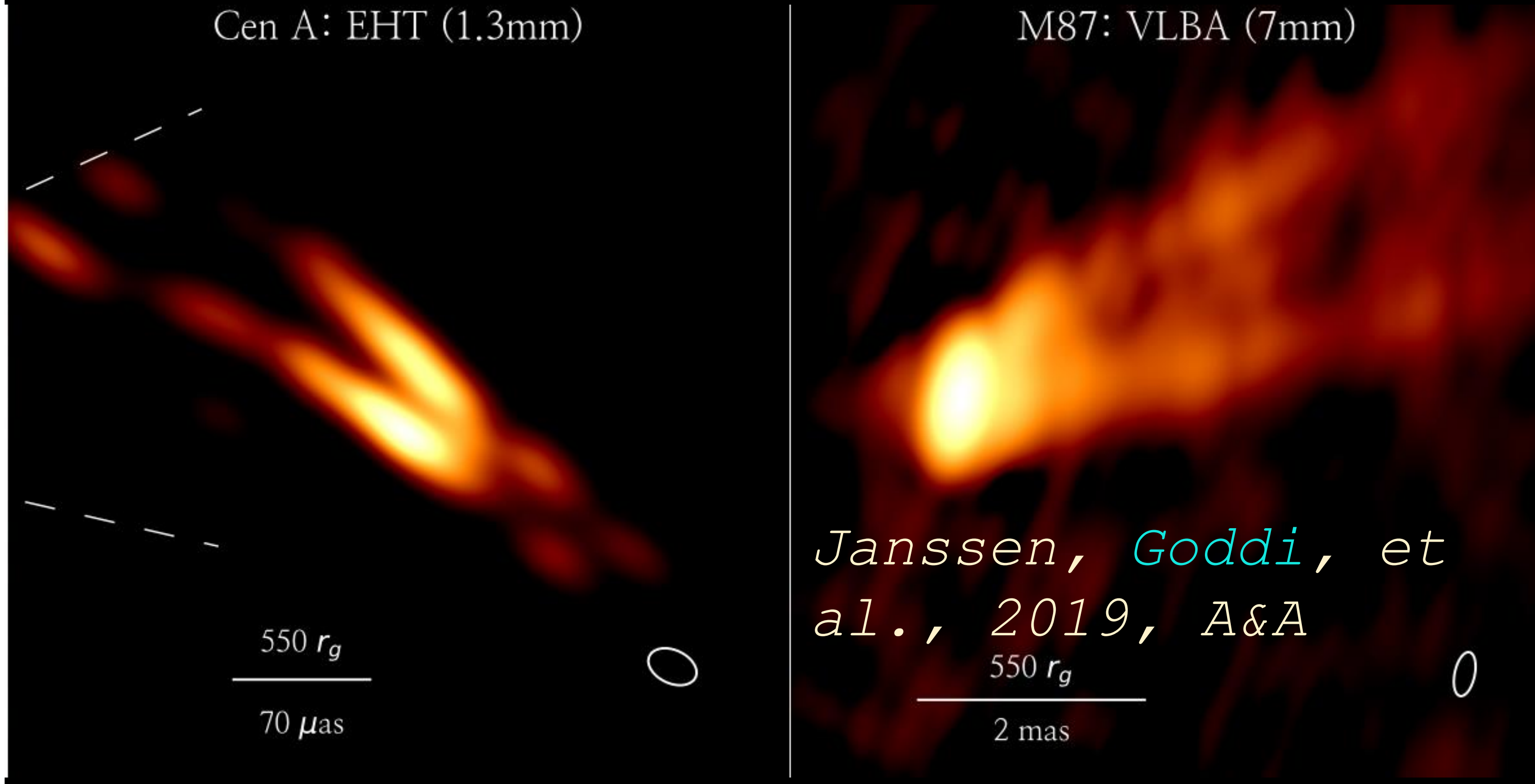
- **Radio galaxies** : NGC1052, Cen A
- **Blazars:** 3C279, OJ287, 4C 01.28, J1924-2914, J0006-0623, 4C 09.57, J0510+1800
- **other QSOs:** 3C273, NRAO 530, J0132-1654

Centaurus A

D ~ 3.8 Mpc

$M_{BH} \sim 5.5 \times 10^7 M_\odot$





Janssen, Goddi, et al., 2019, A&A

Janssen+EHTC, 2021, Nature Astronomy

4. LLAMA-ALMA/APEX baselines are important for VLBI data calibration

- **Phase calibration** (*fringe-fitting*)
  - a global least-squares solver uses **all** baselines (the sensitive ALMA-LLAMA baseline would be very beneficial)
  - Trivial closure phases on ALMA- APEX -any and ALMA-LLAMA-any (=0) can be a robust diagnostics to assess data quality after fringe-fitting and baseline-dependent systematics.

- **Absolute amplitude calibration** (*Network ca*
  - Correct amplitudes at sites with short-baselines
    total intensity V_0 measured by ALMA:
  - Adding ALMA-LLAMA, APEX-LLAMA to the least-square
    minimization improves the gain calibration (g_i)
  - Assess baseline-dependent systematics comparing ALMA-APEX vs. ALMA-LLAMA

$$\mathcal{V}_{\mathrm{SMA-JCMT}} = \mathcal{V}_{\mathrm{ALMA-APEX}} = V_0$$

$$\chi^2 = \sum_{i<j} \frac{|g_i g_j^* \mathcal{V}_{ij} - V_{ij}|^2}{\sigma_{ij}^2}$$

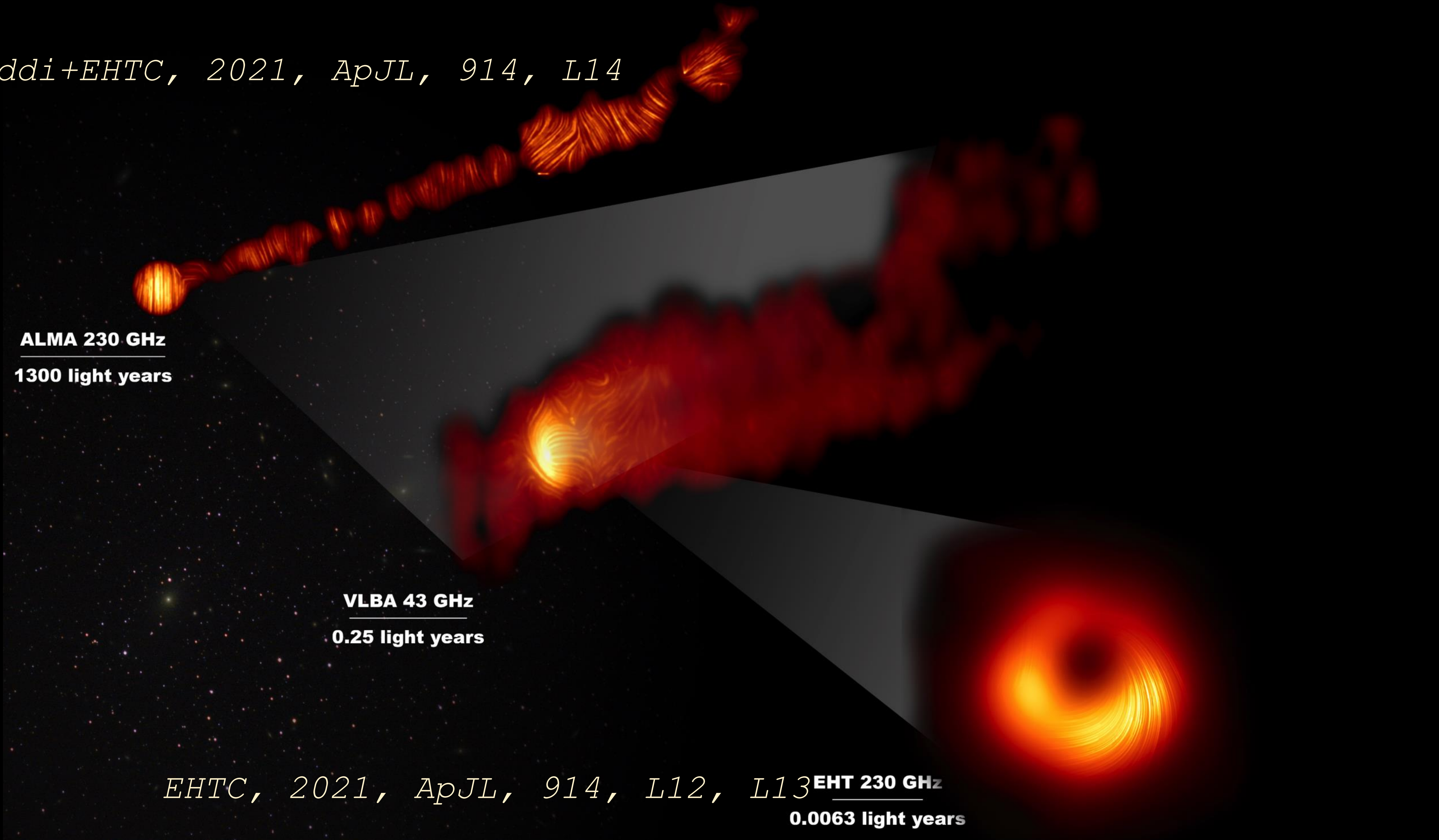
- **Polarization** (*D-term calibration*)

- **Time variability** (*crossing tracks*)

Magnetic Field Structure Near The Event Horizon

EHTC, 2021, ApJL, L12, L

Goddi+EHTC, 2021, ApJL, 914, L14



EHTC, 2021, ApJL, 914, L12, L13

VLBI polarization calibration in a nutshell

This is what we measure:

R^a, L^a, R^b, L^b

Visibility matrix

This is what we want:

I, Q, U, V

Brightness matrix

$$\mathbf{V}^{ab} = \begin{bmatrix} V^{ab}_{rr} & V^{ab}_{rl} \\ V^{ab}_{lr} & V^{ab}_{ll} \end{bmatrix} \xleftrightarrow{\text{FT}} \mathbf{B}^{ab} = \begin{bmatrix} \tilde{\mathcal{I}} + \tilde{\mathcal{V}} & \tilde{\mathcal{Q}} + j\tilde{\mathcal{U}} \\ \tilde{\mathcal{Q}} - j\tilde{\mathcal{U}} & \tilde{\mathcal{I}} - \tilde{\mathcal{V}} \end{bmatrix}$$

$$\boxed{(\mathbf{J}^a)^{-1}\mathbf{V}^{ab}((\mathbf{J}^b)^H)^{-1} \xleftrightarrow{\text{FT}} \mathbf{B}^{ab}}$$

$$\mathbf{J}^a = \mathbf{G}^a\mathbf{D}^a\mathbf{P}^a = \begin{bmatrix} G^a_r & 0 \\ 0 & G^a_l \end{bmatrix} \boxed{\begin{bmatrix} 1 & D^a_r \\ D^a_l & 1 \end{bmatrix}} \begin{bmatrix} e^{j\phi_a} & 0 \\ 0 & e^{-j\phi_a} \end{bmatrix}$$

The worst is ***D*** - the “leakage” term

Jones matrices ***J*** include the instrumental effects

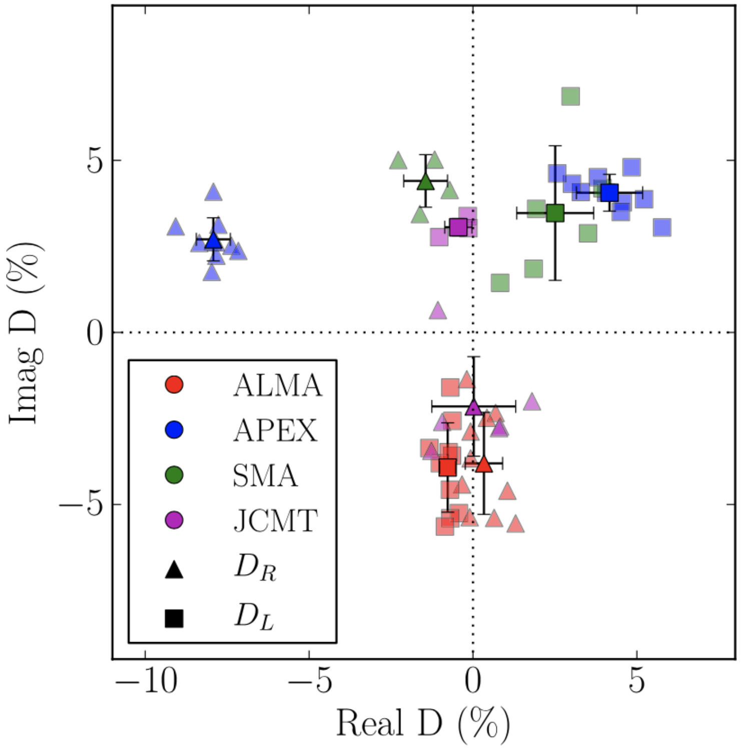
Issues:

- need to solve for the ***D*** and ***B*** matrices at the same time (using ***V***)
- most (all?) polarization calibrators have resolved structure in VLBI, so we need a good model for ***B***.

EHT polarization calibration

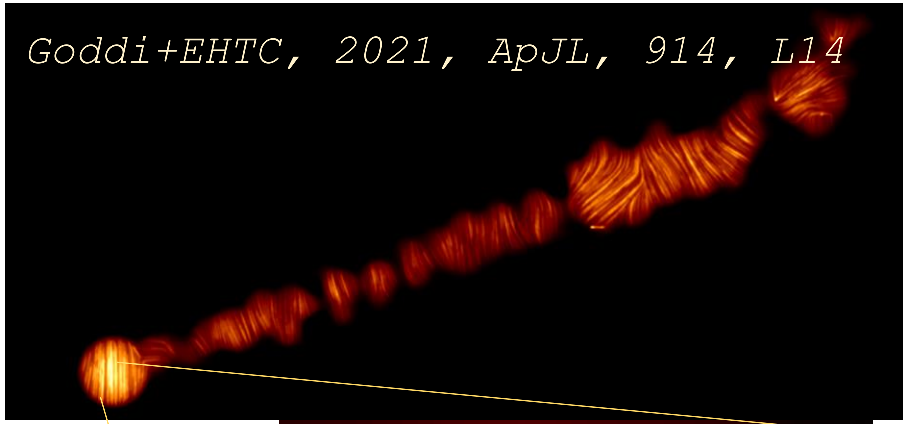
Assume a point source model for ***B*** on short baselines to

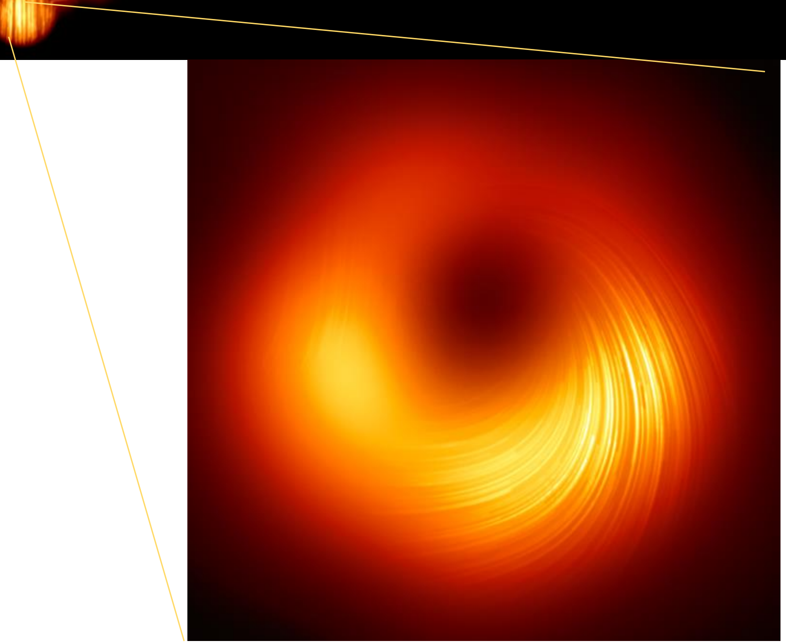
$$\chi^2_{\mathrm{RIME}} = \sum_{k,m} w_k \left(\left| \left[(\mathbf{J}^a)^{-1} \mathbf{V}^{ab} ((\mathbf{J}^\mathbf{b})^{-1})^H \right]_m - \mathbf{B}_m \right|^2 \right)$$



<u>model-independent</u> D-term calibration for ALMA, APEX, SMA, and JCMT

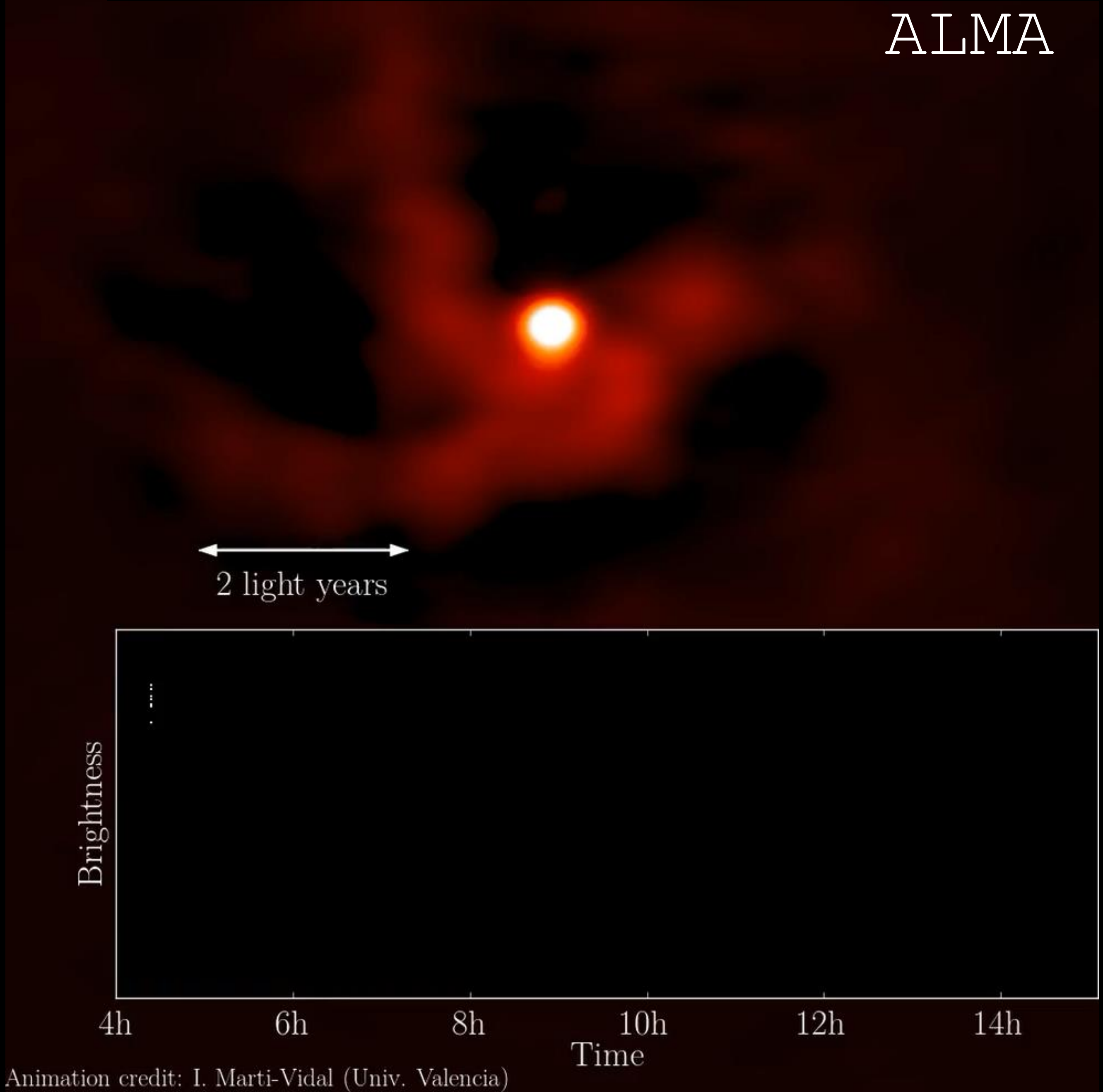
Assuming our AGN sources are compact on 200 km baselines, having LLAMA will improve the D-terms estimates of EHT antennas



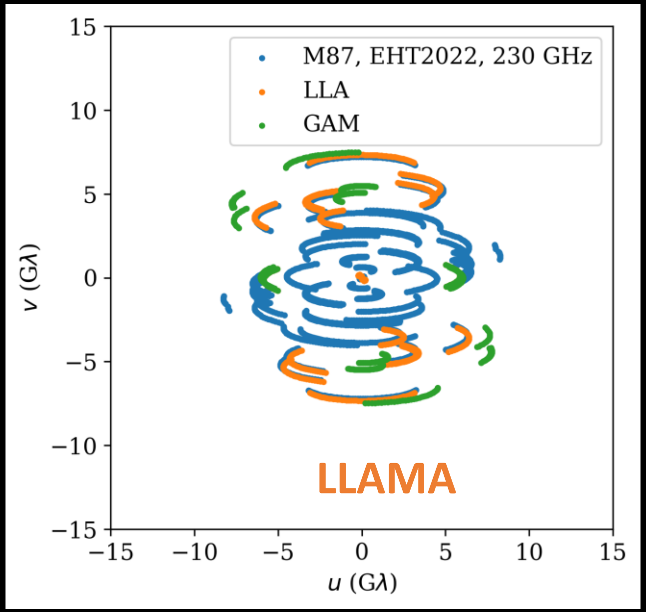


EHTC, 2021, ApJL, 914, L12 (Paper VII)

Light-curve of Sgr A* at 1.3mm with ALMA



Using the ALMA light-curve information as a prior, one can derive a time-dependent absolute flux-scale / network calibration for all EHT stations with short baselines

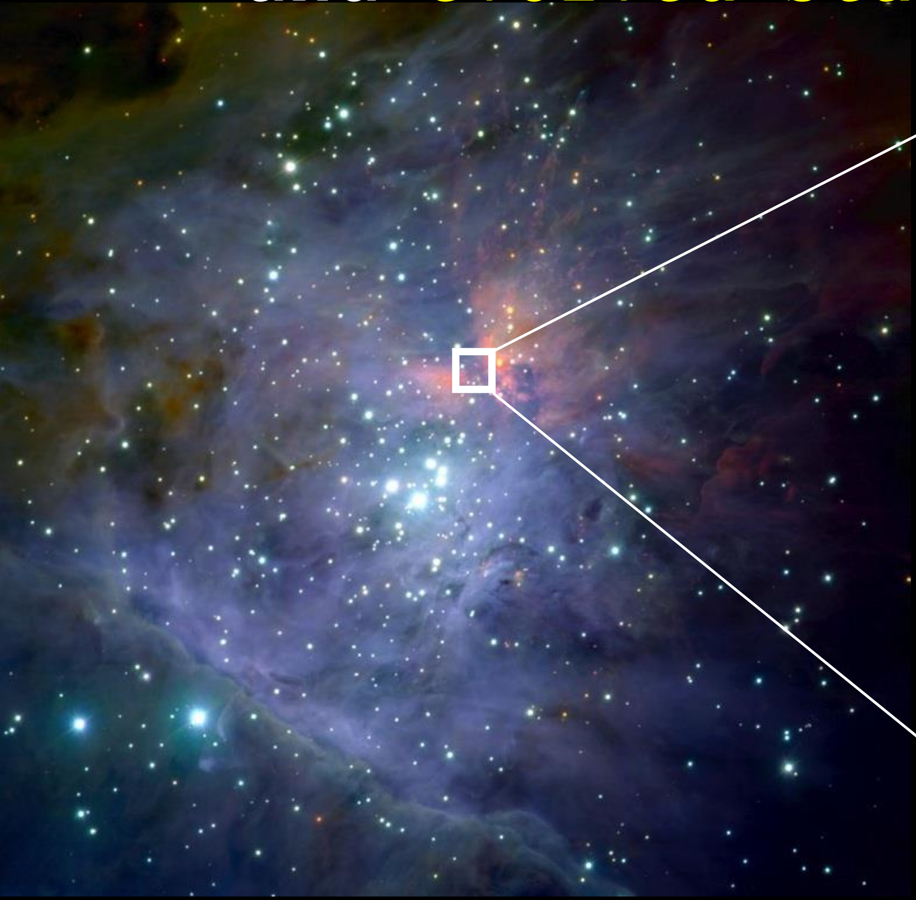


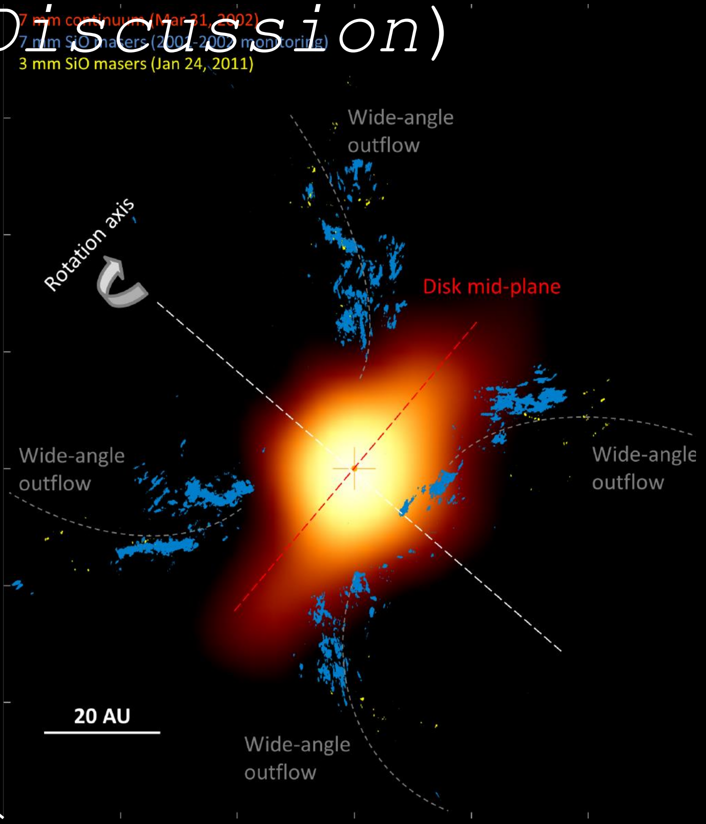
Goddi+EHTC, 2021, ApJL, 914, L14
Wielgus+EHTC 2022, ApJL, 930, L19

Not only Black Holes!

- Short baselines important also to image maser spectral lines in Galactic star-forming regions and evolved stars

(Discussion)





Summary

Short VLBI baselines to ALMA/APEX will:

- provide unique tracks in uv-space
- probe large-scale structures linking the horizon scales to the relativistic jet (k)pc scales and resolving the jet-launching region in M87 and other AGN
  - Also important for galactic studies of masers! [*Discussion*]
- Provide crucial information for VLBI data calibration and analysis (e.g. polarization)
- All the above even if ALMA does not observe (with the less-sensitive LLAMA-APEX baseline)

Points for discussion

1. VLBI Capabilities offered at ALMA

2. LLAMA as stand-in for ALMA

3. Receivers (*Priority*?)
   - **Band 6 / 230 GHz (EHT+ALMA)**
   - **Band 7 / 350 GHz (EHT+ALMA)**
   - Band 3 / 86 GHZ (GMVA/VLBA +ALMA)
   - Band 1 / 43 GHz (VLBA+ALMA) (future)
   - Band 9 / 690 GHz (ALMA+SMA+GLT+LLAMA) (future)

   Multi-band capability for LLAMA?

4. Science case (e.g., Fish+2013, Tilanus+2014)
   - AGN jet imaging
   - Polarization and magnetic fields (Sgr A*, M87, AGN)
   - Time variability (Sgr A*, AGN)
   - Spectral lines in galactic masers
   - Other

What's offered at ALMA for VLBI

- Continuum in Band 3 (3 mm) and Band 6 (1 mm) [**Cycle 4-**]
  - Fixed tunings
  - Targets must be bright (≥500 mJy on baselines <1 km)
- Passive Phasing in Band 3 & 6 [**Cycle 8-**]
  - Allows array phase-up using a nearby calibrator instead of the science target
  - Enables VLBI on arbitrarily faint targets (…*and pulsar studies*)
- Continuum in Band 7 (0.8 mm) [**Cycle 9-**]
- Spectral line mode in Band 3 [**Cycle 9-**]
  - Fixed tuning (suitable for Galactic 3mm SiO masers)

LLAMA as stand-in for ALMA: motivations

A variety of factors will make continuing to do VLBI with ALMA challenging:

- **High oversubscription rate**
- **Array not always in a compact configuration**
- Annual array shutdown during February
- Limited staff with VLBI expertise
- **VLBI currently allowed only in fixed campaigns**
- Need to 'PolConvert' demands long (>3 hr) observing blocks for parallactic angle coverage
- Project approval may be required from multiple review panels
- Distributed/dual anonymous review may disfavor nonstandard observing modes
- **No subarraying likely until ~2030**
  - **Impossible to conduct simultaneous observations with multiple frequency bands**
- Bandwidths > 8 GHz not available until 2030+

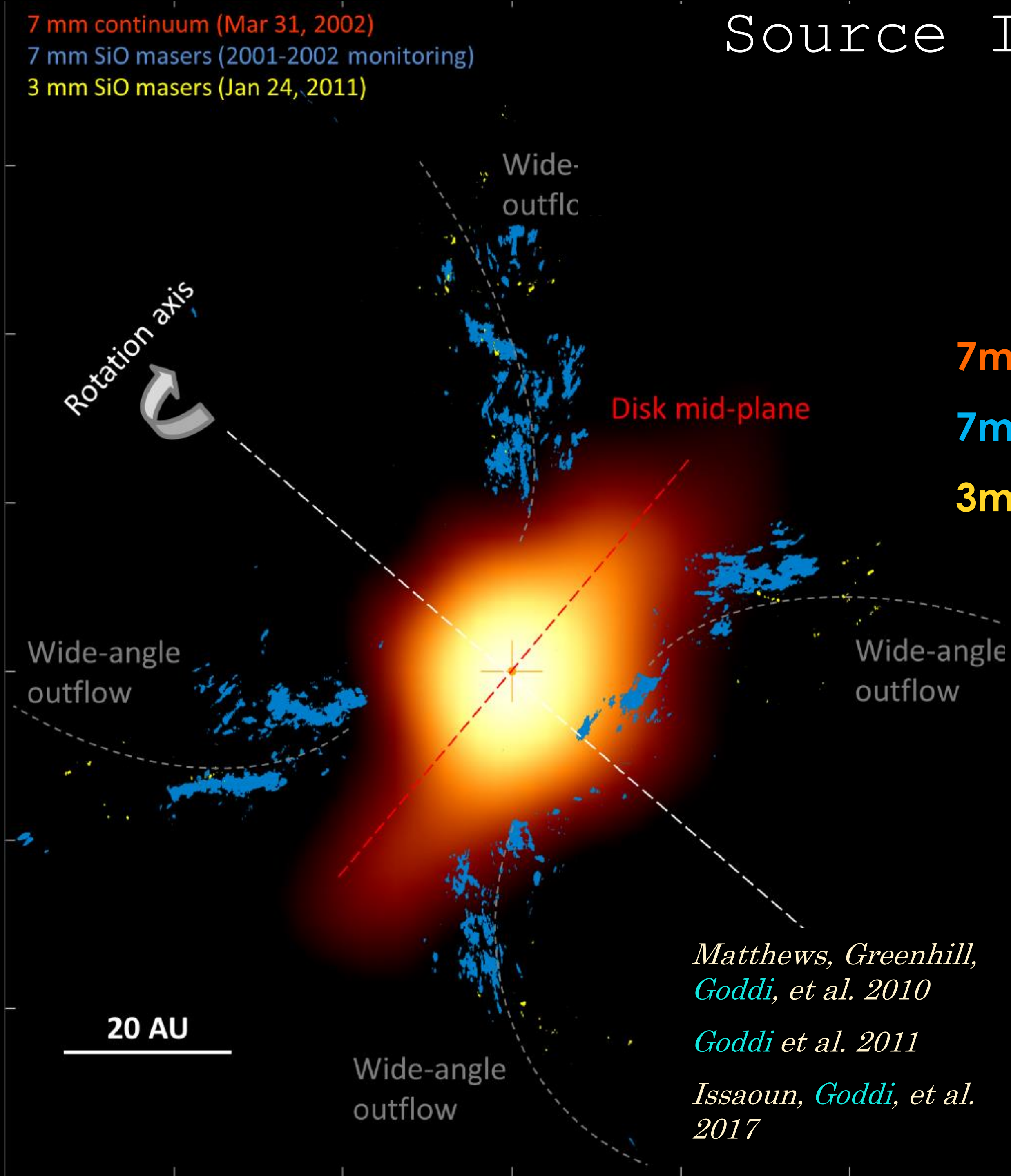
L. Matthews

New ALMA VLBI Capabilities Under Development
Cycle 10- (pending approval)

1. **Band 1 (7mm) VLBI**
   - currently ~12 ALMA antennas equipped with Band 1 receivers
   - deployment ongoing
2. **Flexible Tuning in all VLBI bands**
   - Removes fixed VLBI tuning restrictions in all bands
3. **Expanded Spectral Line VLBI**
   - Flexible tuning
   - Allowed in bands 1, 3, 6, 7
   - Active or passive phasing options

L. Matthews
APP2/3 PI

Source I protostar in the Orion nebula (D~420 pc)



7mm cont (JVLA)

7mm SiO v=1,2 (**VLBA+Y**)

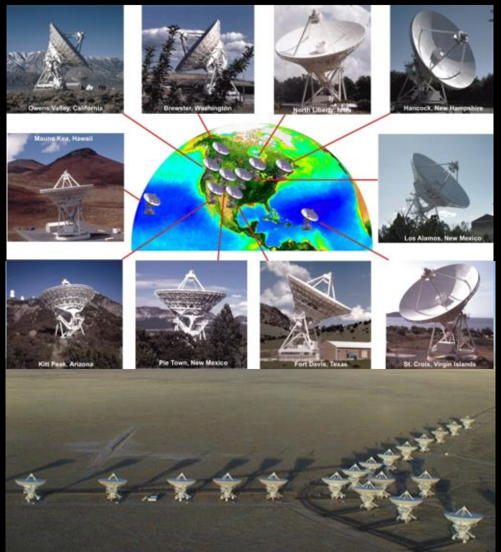
3mm SiO v=1 (VLBA)

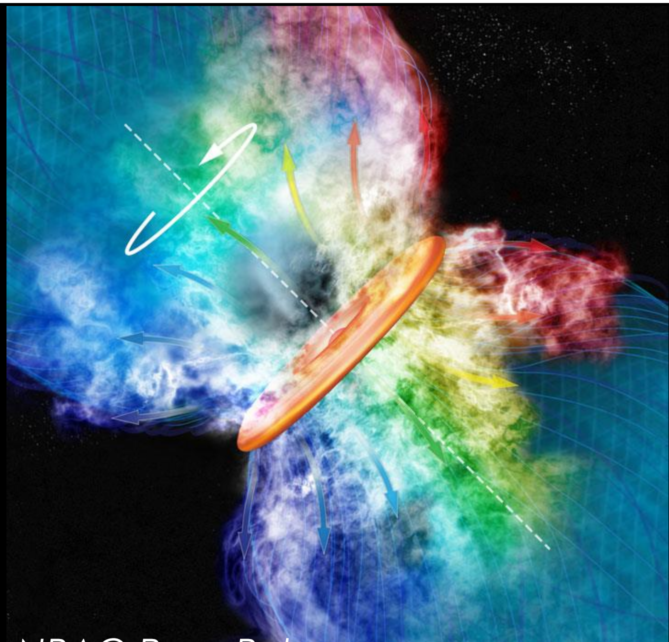
VLBI imaging of SiO masers resolves outflow in the launch and collimation region from a compact disk

Matthews, Greenhill, Goddi, et al. 2010

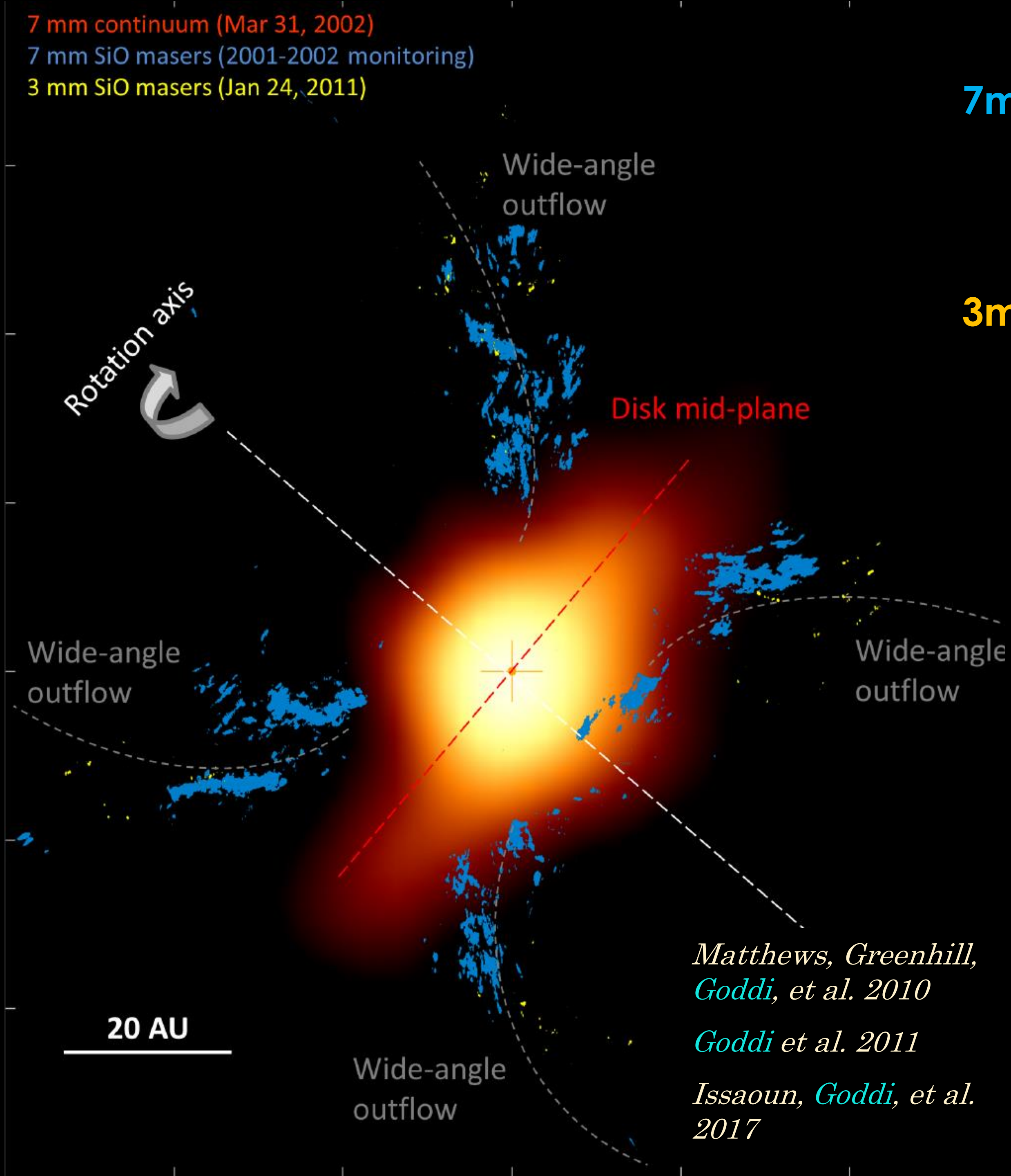
Goddi et al. 2011

Issaoun, Goddi, et al. 2017





NRAO Press Release



Matthews, Greenhill, Goddi, et al. 2010

Goddi et al. 2011

Issaoun, Goddi, et al. 2017

7mm SiO J=1-0 v=1,2

(10 **VLBA+Y1**)

3mm SiO J=2-1 v=1

(8 VLBA)

- 7mm: Short baseline to a VLA station allows us to recover extended SiO maser emission sampling more completely the disk-wind region.
- 3mm: Only compact spot emission was recovered at 3mm with no short baselines

Spectral-line is now offered at in VLBI @ ALMA and ALMA-LLAMA could permit to recover extended SiO J=2-1 line emission at 3mm

More masers at 3 mm

Observing Application

Date:	Feb 01, 2018
Proposal ID:	VLBA/18B-114
Legacy ID:	BG256
PI:	Ciriaco Goddi
Type:	Regular
Category:	Star Formation
Total time:	9.0

3mm methanol masers in high-mass star forming regions: a pilot VLBA program

Abstract:

Methanol masers are excellent probes of the 3D gas kinematics and mass-accretion in massive star formation, but their use to constrain gas physical conditions has been difficult. This in fact requires a radiative transfer analysis which includes pumping models, but more than one transition is usually required to reliably constrain these models. Luckily, methanol emits maser transitions in a wide range of wavelengths, from the cm to the mm. With new sensitive antennas coming online at mm-waves, VLBI studies of mm masers are now becoming possible, and potentially have the power to open up new frontiers in star-formation studies at the highest achievable resolutions. The present proposal is a pilot for a VLBA program to observe two class II methanol maser lines at 86 GHz in a selected sample of high-mass star forming regions. Here, we ask for only one target, W51, the closest most luminous massive star formation complex and a remarkably rich maser source, where methanol masers may reveal for the first time accretion disks around young O-type stars.

ALMA Extended Array

"Thermal universe with VLBI resolution"

- Plan: add 5 additional 12-m antennas (or pads) < 300 km from the central cluster of ALMA
  - Correlated as normal ALMA antennas with next generation correlator
  - Pads connected through fiber-link
  - …or VLBI-type recording?
- Why? it will realize angular resolution of < 1mas and with sensitivity to detect T_b < 1000K (i.e. the **thermal** universe).

  ⇒ fills the gap between VLBI and the connected array
- Science case: BH formation in SMGs, mass accretion processes onto AGN engines, imaging stellar photospheres, distance measurements to stars and exoplanet characterization through astrometric measurements of host star motion

LLAMA is essentially a step in this direction!

Kameno et al., 2013, ASPC

ASAC *ALMA2030, 2018 white paper*

1. LLAMA is 180 km from ALMA

A fiber between LLAMA and ALMA very feasible

ALMA Extended Array (ALMA2030)

- Conventional VLBI measurements so far are limited to compact, non-thermal high-brightness sources such as synchrotron radiation from AGN jets or maser from star forming regions, evolved stars, and circumnuclear regions of AGNs.
- The intermediate-length baselines up to 300 km will allow us to study the lower surface brightness emission, namely emission that are thermal origin; for example accretion of matter onto the super-massive black holes (SMBHs) of AGNs, or photospheres of nearby giants/supergiant stars.
- The high-z universe can be studied at 10-pc scale, allowing us to search for SMBHs in forming galaxies, which is ultimately linked to the galaxy-BH co-evolution scenario.
- The 1 hour continuum sensitivity is 20 uJy, which corresponds to a detection limit of Tb ~ 3,000 K (5 sigma) with an angular resolution of 0.6 mas at Band 7.
  - This will result in a factor of ~20 improvement in resolution compared to the 16 km baseline array