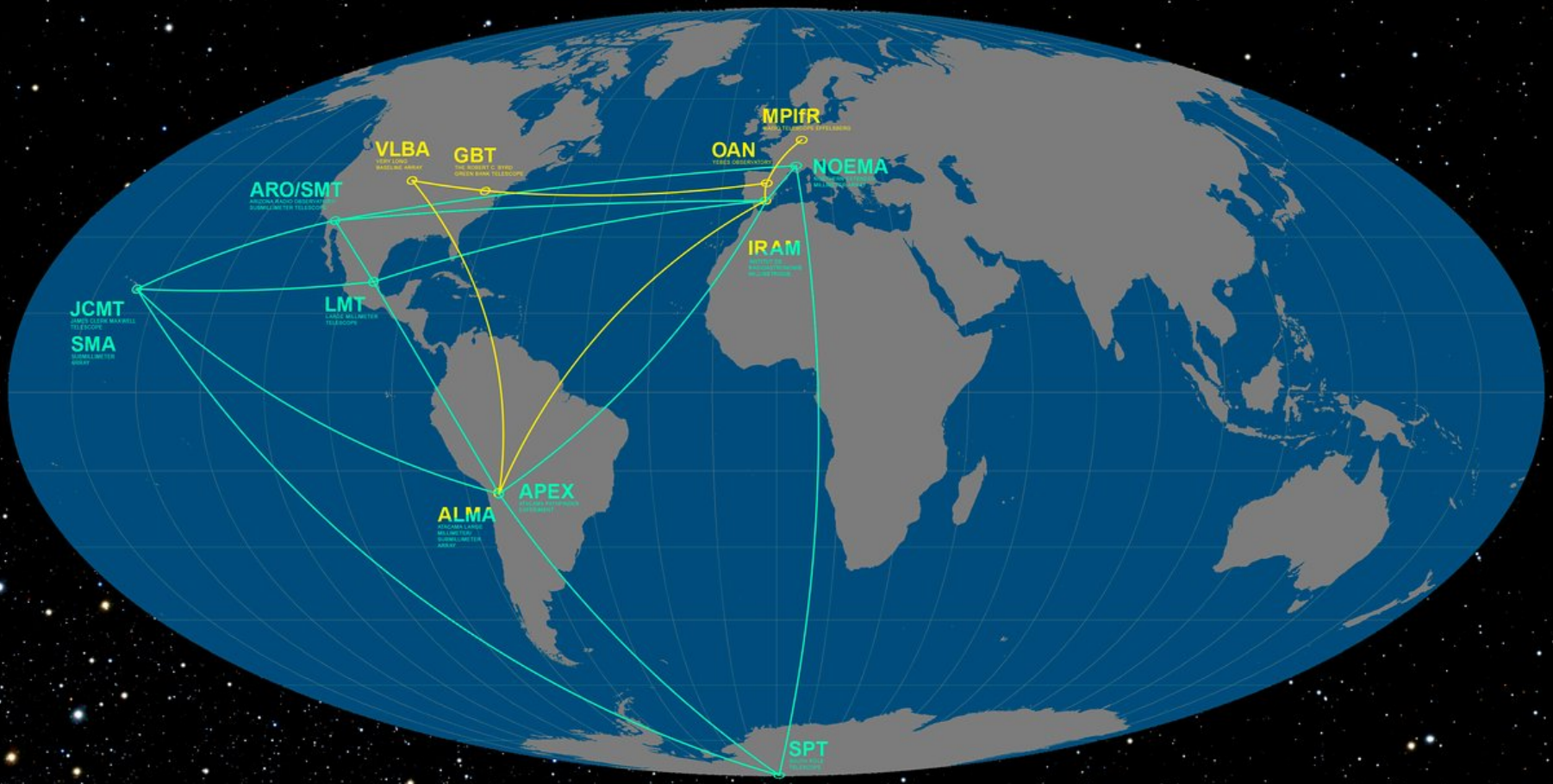
Introduction to VLBI (with ALMA)



CIRIACO GODDI

ALLEGRO, Leiden Observatory / Nijmegen University, the Netherlands

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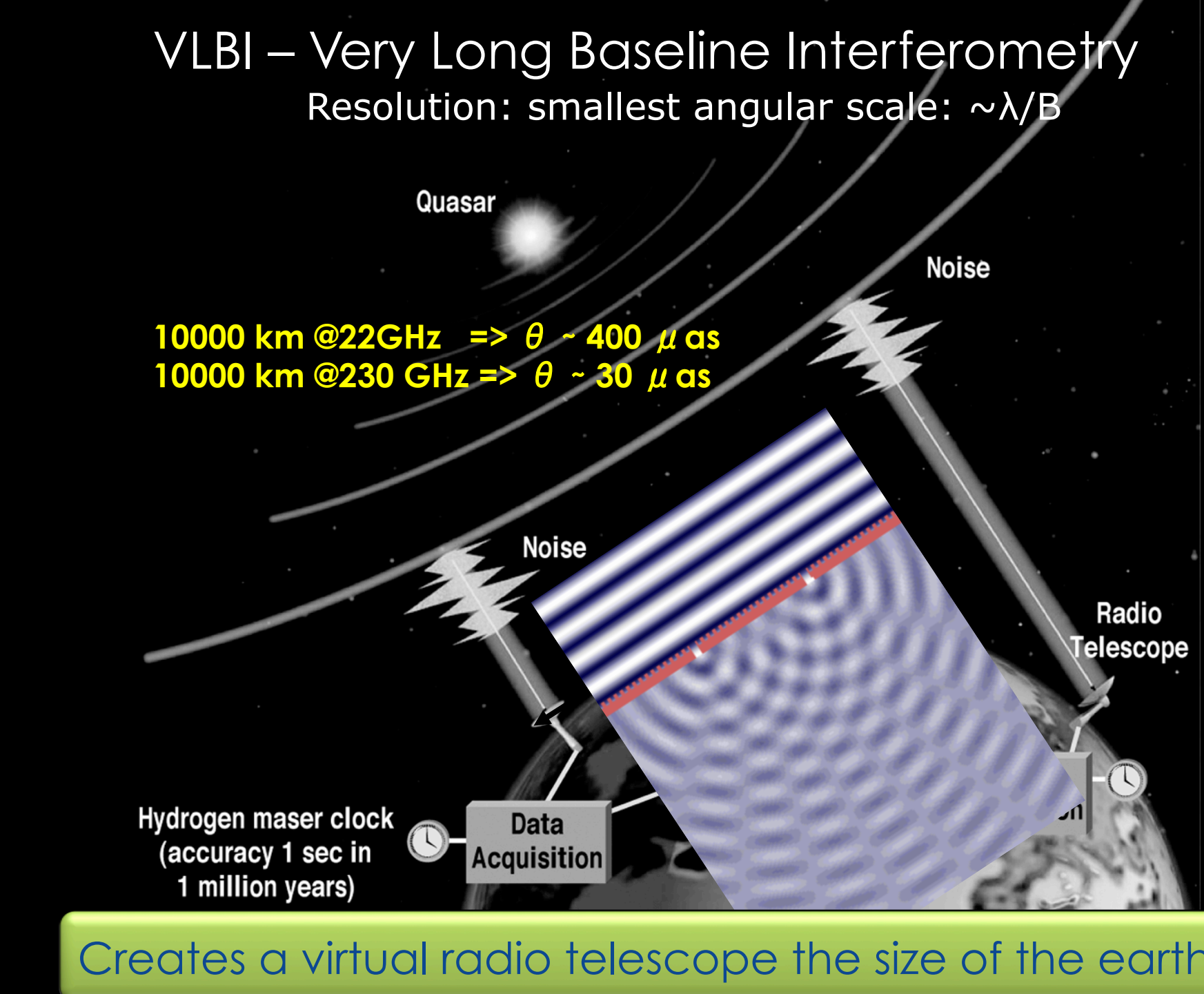
Outline

1. What is VLBI?
2. Why VLBI at mm-waves (mmVLBI)?
3. How does VLBI with ALMA work?

VLBI – Very Long Baseline Interferometry

Resolution: smallest angular scale: ~λ/B



Creates a virtual radio telescope the size of the earth

VLBI: Key Features

- (sub-) milliarcsecond resolution imaging
  - AU-scale in MW, pc-scale extragalactic
- Astrometry of microarcsecond precision

....but.....

- Requires high surface brightness: $T_b > 10^7$ K
  - No *thermal* emission observable
  - Ideal to probe synchrotron (continuum), maser (line) emission

VLBI vs. shorter-BI

Additional difficulties

- More stringent requirements on correlator model to avoid de-correlating during coherent averaging
- Each antenna has its own "clock" (H-maser) and own equipment (IF-chain, BBCs, etc.)
- Sparser u-v coverage
- No truly point-like (primary flux) calibrators in sky

VLBI vs. shorter-BI
Delay/Rate Calibration

- Each antenna has its own "clock" (H-maser) and own equipment (IF-chain, BBCs, etc.)
- Differing delays & rates per station/subband/pol
- Delay → $\partial\phi/\partial\nu$ (phase-slope across band)
- Rate → $\partial\phi/\partial t$ (phase-slope vs.time)
- Regular variations: clocks, source-structure, etc.
- Irregular variations: propagation, instrumental noise
- Solving for these variations is the essence of the so-called *fringe-fitting*

VLBI Arrays

The EVN (European VLBI Network)

Composed of existing antennas

- generally larger (32m – 100m)
  - sensitive baselines
- heterogeneous,
  - generally slower slewing

Frequency coverage [GHz]:

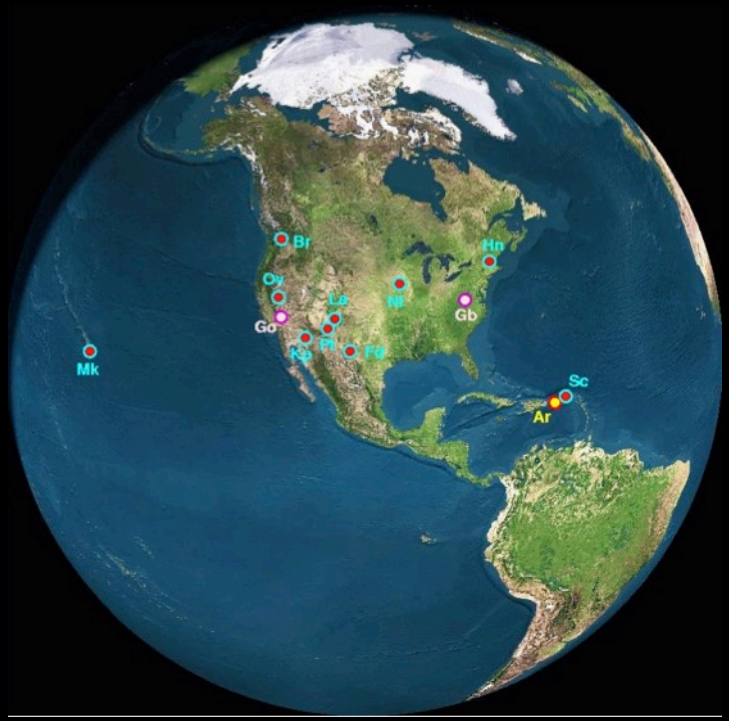
- 1.4/1.6, 5, 6.0/6.7, 2.3/8.4, 22

Real-time e-VLBI experiments

- Target of Opportunity
- ~10 scheduled e-VLBI days per year

VLBI Arrays

The VLBA (Very Long Baseline Array)



Homogeneous array (10x 25m)

- planned locations, dedicated array
- Baselines~8600–250 km (~50 km w/ JVLA)
- Faster slewing
- HSA (+ Ef + Ar + GBT + JVLA)

Frequency agile

- down to 0.329, up to 86 GHz

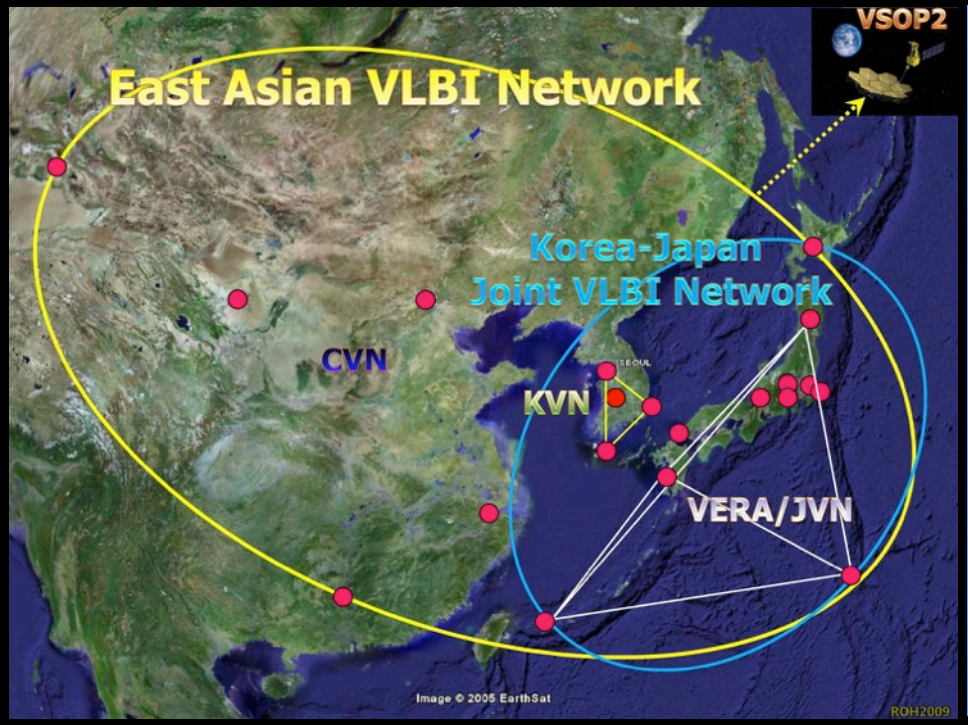
Extremely large proposals

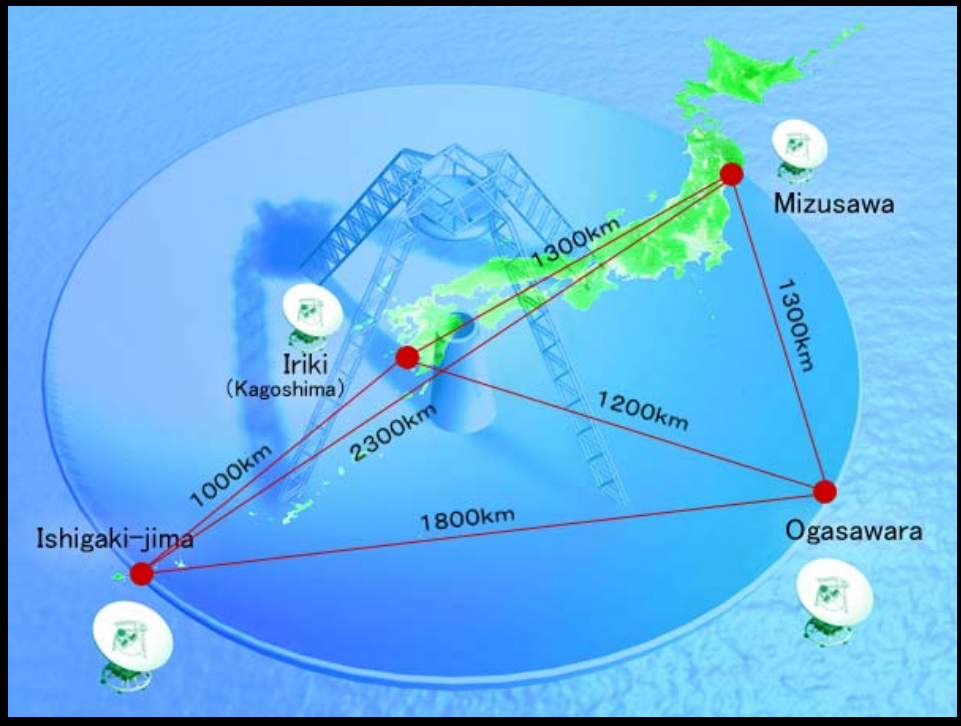
- Up towards 1000 hr per year

- Globals: EVN + VLBA (+ GBT + JVLA)
  - proposed at EVN proposal deadlines (1Feb, 1Jun, 1Oct)
  - VLBA-only proposals: 1Feb, 1Aug

VLBI Arrays
East Asian VLBI Networks

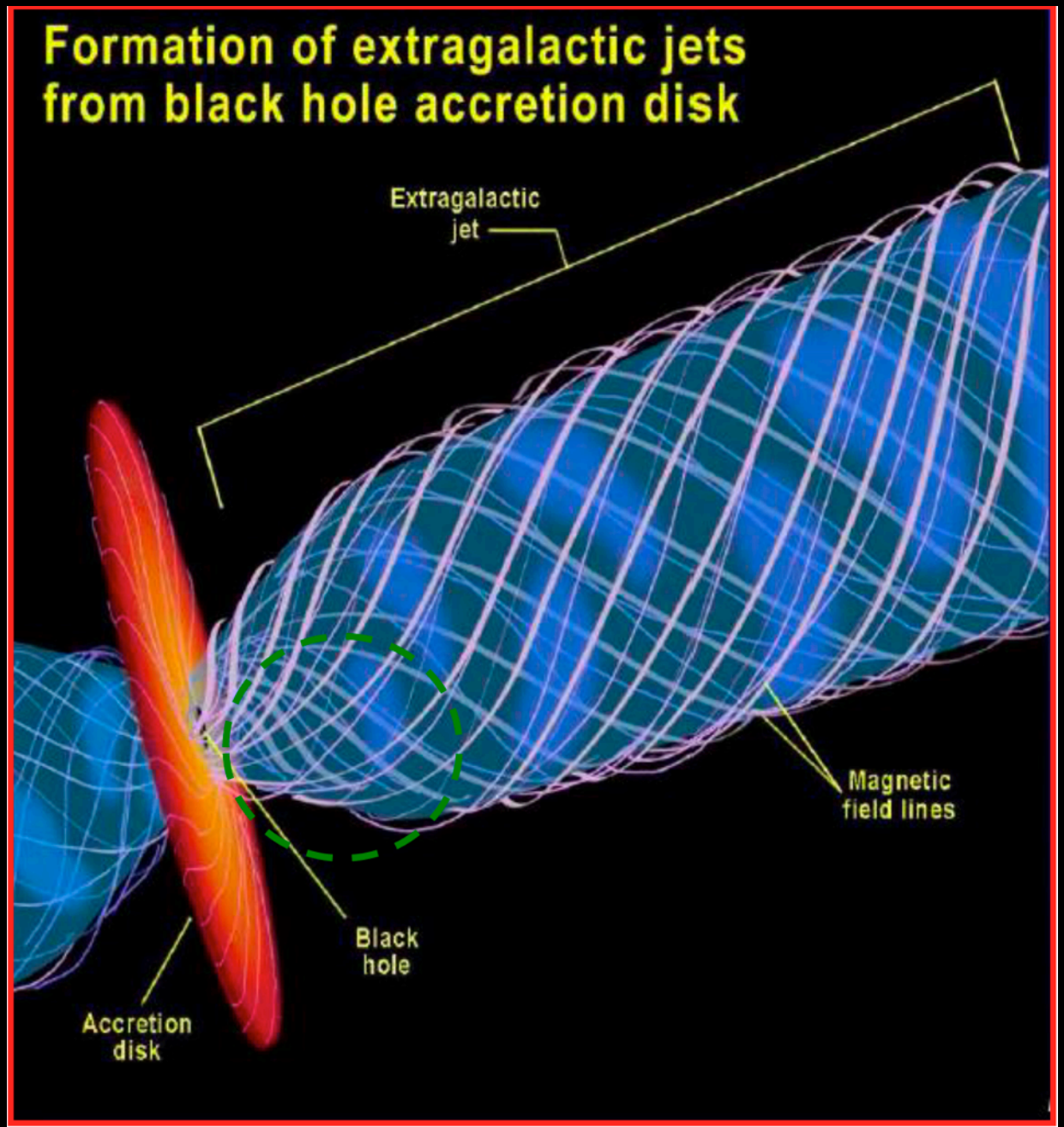
- Chinese (CVN): 4 ants., primarily satellite tracking
- Korean (KVN): 3 ants., simultaneous 22, 43, 86, 129 GHz
- VERA: 4 dual-beam ants., maser astrometry 22-49 GHz
  - KaVA == KVN + VERA (issues separate KaVA calls for proposals)
- Japanese: various astronomical & geodetic stations





2. VLBI at mm-waves (mmVLBI)

mmVLBI: Why?



Resolve jet collimation region within tens of Schwarzschild Radii R_s along jet

$$R_{Sch} = 2\,GM_{BH}/c^2$$
$$\theta_{Sch} = R_{Sch}/D$$
$$\approx 0.02 \text{ nas}$$
$$(M_{BH}/M_\odot)/(\text{kpc}/D)$$

Two promising targets:

Sgr A* :

D~8 kpc, M_{BH} ~4×10^6 $M_\odot$

=> θ_{Sch} ~ 10 μas

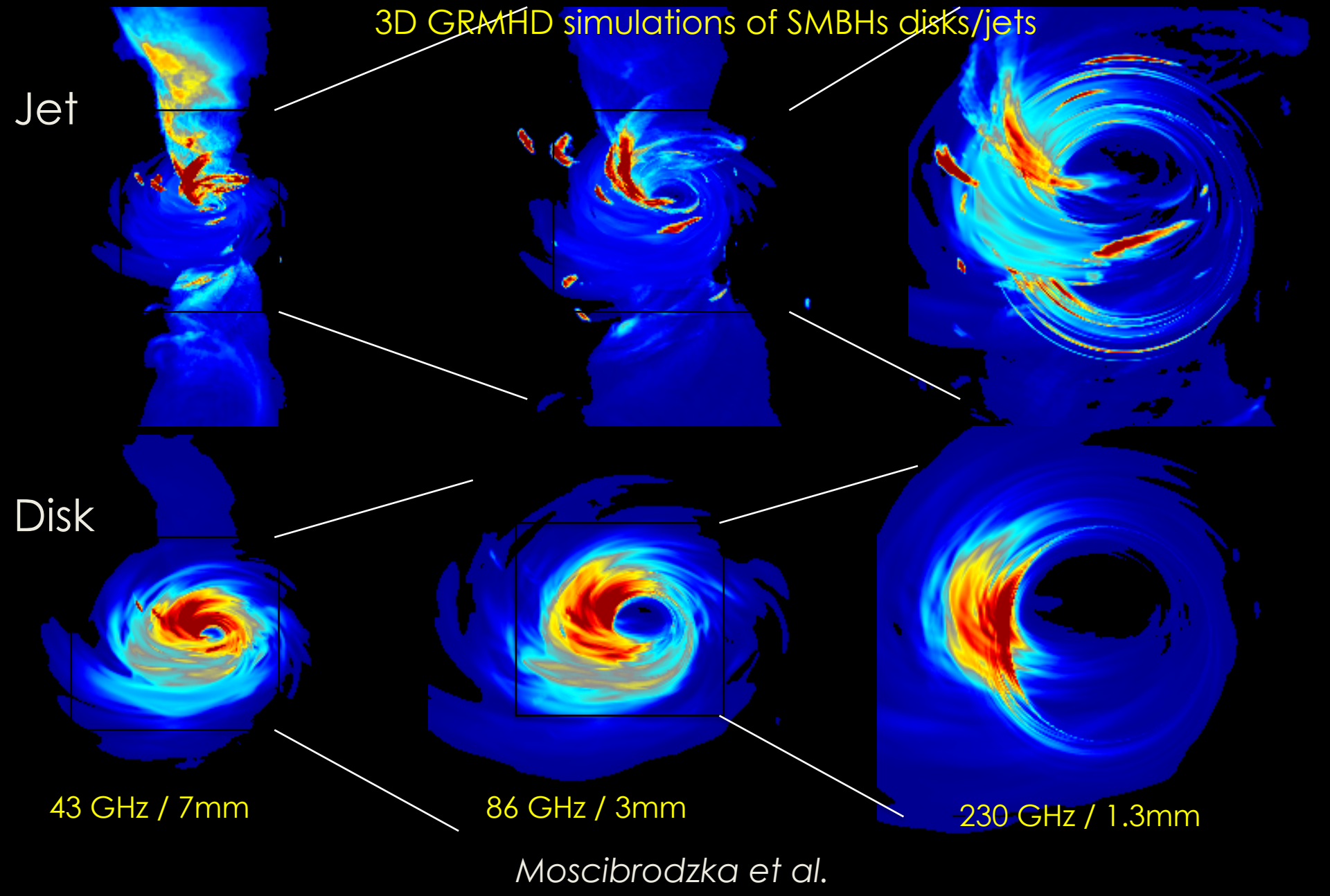
M87 :

D~17 Mpc, M_{BH} ~7×10^9 $M_\odot$

=> θ_{Sch} ~ 8μas

mmVLBI: Why?

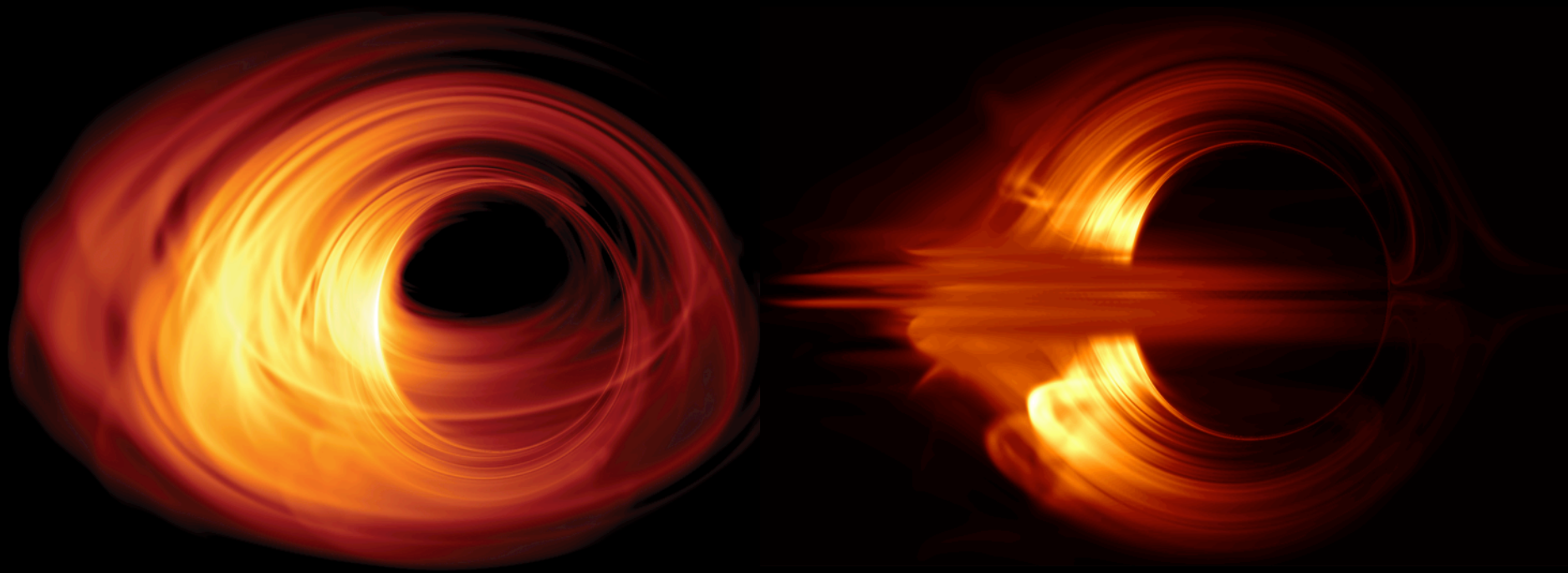
3D GRMHD simulations of SMBHs disks/jets



Moscibrodzka et al.

mmVLBI: Why?

The Shadow of a Black Hole



More face-on

More edge-on

Bardeen 1973, Luminet 1979

Falcke, Melia, Agol (2000)

Bronzwaer et al. Davelaar, et al.

mmVLBI: Why?

General science case

- Imaging the event horizon of the black hole at the center of the Galaxy
- Testing General Relativity (GR) and/or searching for alternative theories
- Studying the origin of AGN jets and jet formation
- Cosmological evolution of galaxies and Black Holes (BHs), AGN feedback
- Masers in the Milky Way (in evolved stars and star-forming regions)
- Extragalactic emission lines and astro-chemistry
- Redshifted absorption lines in distant galaxies and study of their ISM
- Pulsars, neutron stars, and X-ray binaries
- Testing cosmology and fundamental physical constants

For a full review, see Fish et al. 2013 arXiv1309.3519

3. VLBI with ALMA:
How does it work?

VLBI with ALMA I

- The ALMA Phasing Project (APP) has developed a beamformer for ALMA that can aggregate the entire collecting area of the array into a single, very large aperture (equivalent to an 84m diameter telescope). In such a phased-array all antennas are combined to act jointly as a single "giant" dish.

- Phased-ALMA as an "element" in a VLBI array offered from **Cycle 4**
  - B3 with the GMVA (128 MHz BW, dual pol., 2 Gbps recording)
  - B6 with the EHT (~4 GHz BW, dual pol., 32 Gbps recording)
  - Up to ~41 phased (12-m) antennas (≈73-m parabolic dish)

- Cycle 4/5/6 proposals deadlines on **April 2016/7/8**
  - VLBI proposals assessed rigorously against other ALMA proposals

VLBI with ALMA II

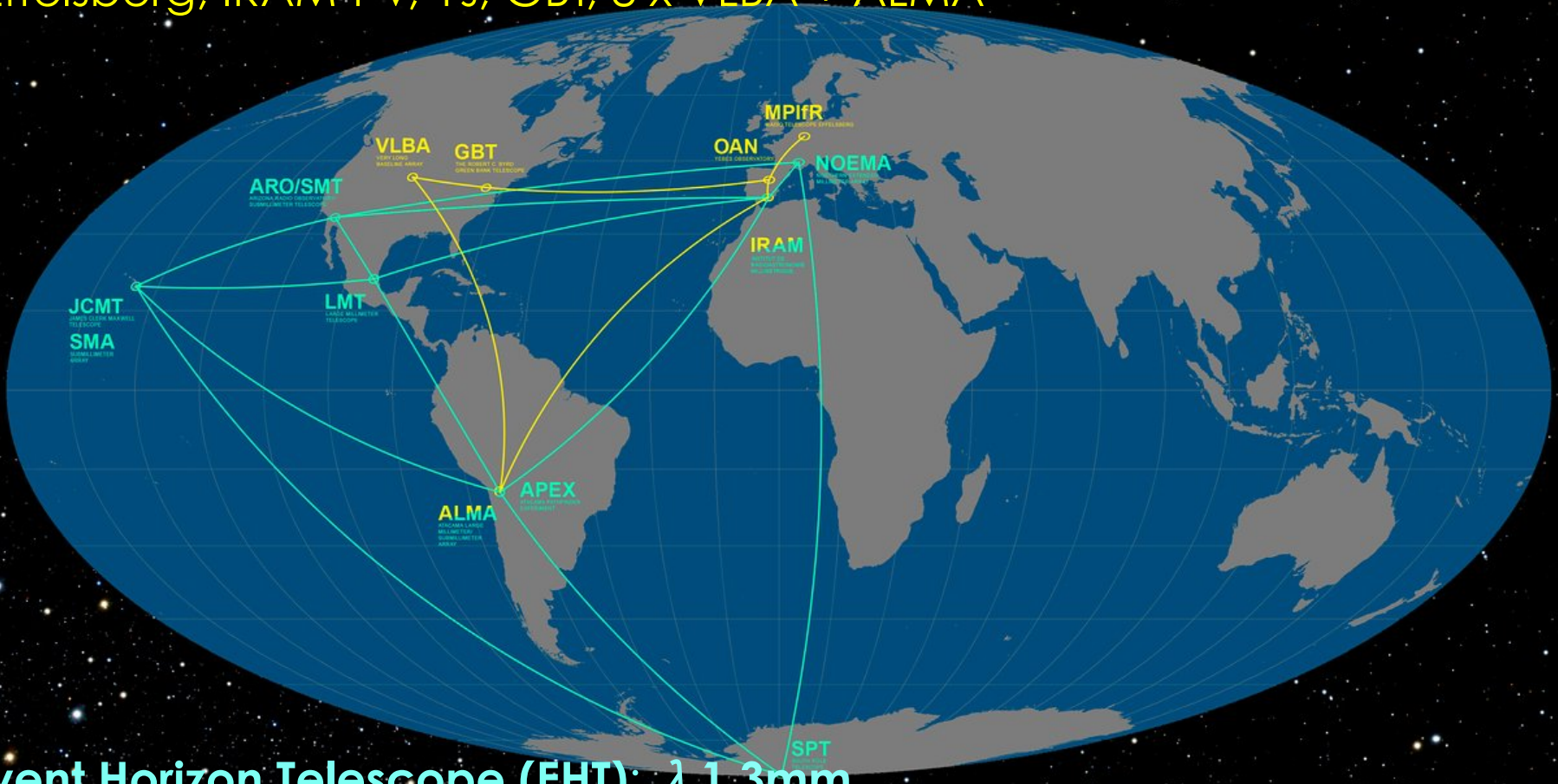
- Past Observations: 1 session on **April 2-15 2017**
  - Apr 2-4 GMVA (3mm) and Apr 5-11 EHT (1.3mm)

- Next Observations: 1 session on **April 15-27 2018**

- VLBI data correlation :
  - Haystack/MIT (EHT Low-band)
  - MPIfR/Bonn (EHT High-band and GMVA).

mmVLBI Networks with ALMA

Global mm VLBI Network (GMVA): λ 3mm
Effelsberg, IRAM-PV, Ys, GBT, 8 x VLBA + ALMA



Event Horizon Telescope (EHT): **λ 1.3mm**
SPT, APEX, LMT, SMT, SMA/JCMT, PV + ALMA

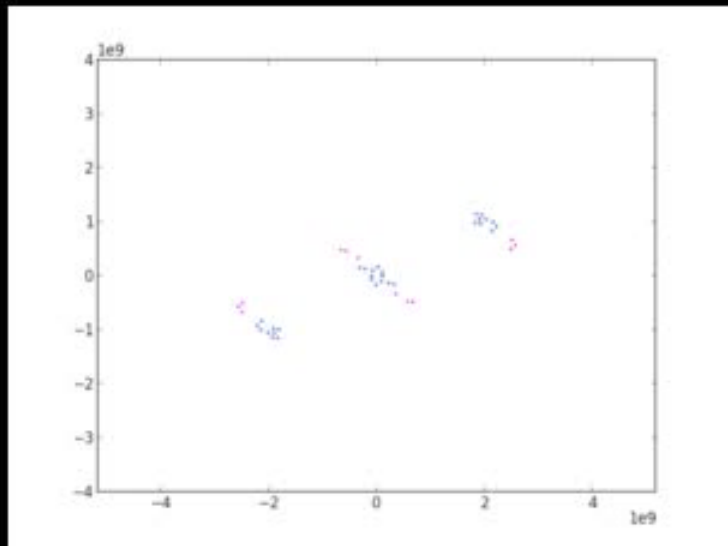
- GMVA @3mm (128 MHz BW, dual pol., 2 Gbps recording)
- EHT @1.3mm (~4 GHz BW, dual pol., 32 Gbps recording)

Arrays: 3 mm

Global mm VLBI Network (GMVA)

ALMA, Effelsberg, IRAM-PV, Ys, GBT, 8 x VLBA (+LMT, Onsala, Metsahövi, NOEMA, KVN, LLMA, AMT,…)

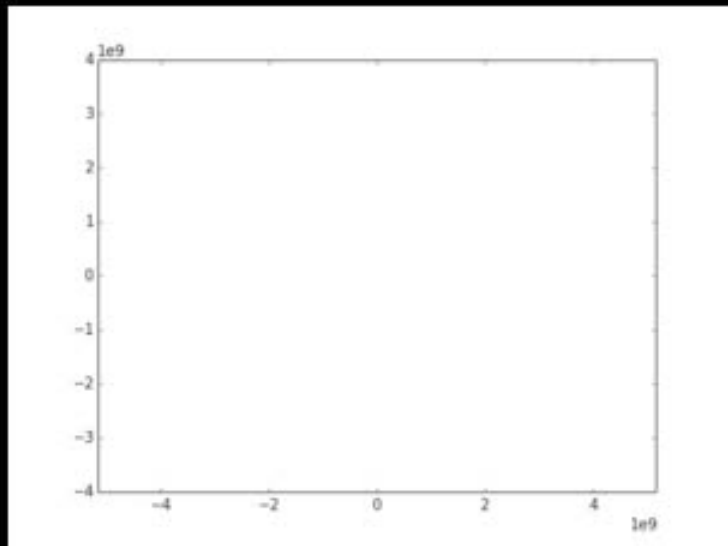
- ~2 weeks per year
- Coordinated from MPIfR Bonn



Arrays: 1 mm
The Event Horizon Telescope (EHT)

ALMA, IRAM-PV, LMT, SPT, APEX, SMT, SMA/JCMT (+Greenland, NOEMA, LLAMA, AMT,…)

- Coordinated from Haystack/MIT



EHT 2017 Campaign

- April 5 -11 2017
- 8 telescopes, 6 sites (Largest 1mm VLBI experiment ever tried)
- 3 new stations, one dropped
- 5 observing nights in 10 day period (used all allocated time at ALMA: 62 hours)
- ~4 PB raw data
- Overall excellent weather!
- Only minor technical hiccups (fraction of lost data small)

VLBI with ALMA

Scheduling

- VLBI projects are different from normal ALMA projects in that the targets need to be observed at (the same) specified times at all sites in the VLBI array
- The schedule is captured in a VLBI EXperiment (**VEX**) file (includes info about VLBI sites, scan timing, and other ancillary information)

```
scan No0015;
* intent = "ALMA:AUTOPHASE_DETERMINE"
     start=2017y100d01h59m00s; mode=1mmlcp; source=3C279;
     station=Aa:    0 sec:  300 sec: 4984.603 GB:   :       : 1;
     station=Ap:    0 sec:  300 sec: 4984.603 GB:   :       : 1;
     station=Lm:    0 sec:  300 sec: 4984.603 GB:   :       : 1;
     station=PV:    0 sec:  300 sec: 4984.603 GB:   :       : 1;
endscan;
scan No0016;
* intent = "ALMA:AUTOPHASE_DETERMINE"
     start=2017y100d02h09m00s; mode=1mmlcp; source=M87;
     station=Aa:    0 sec:  240 sec: 5292.294 GB:   :       : 1;
     station=Ap:    0 sec:  240 sec: 5292.294 GB:   :       : 1;
     station=Lm:    0 sec:  240 sec: 5292.294 GB:   :       : 1;
     station=PV:    0 sec:  240 sec: 5292.294 GB:   :       : 1;
     station=Az:    0 sec:  240 sec: 4246.143 GB:   :       : 1;
endscan;
```

VLBI with ALMA

Scheduling

- Expert Parameters:
  - ArrayRadius is 180 (m)
  - VLBIExpName is mg002 (vex)
  - DropRecorder is BB_2,BB_3,BB_4
  - ReferenceAntenna is DA61
  - EfficiencyArray is DA60,PM04
  - SessionControl Enabled (1)
- First VLBI Scan is 2017y092d21h00m00s No0081
  - Run-#0 from 2017y092d21h00m00s to 2017
    - Exec UID: uid://A002/Xbeae14/X10a
    - Sum Antenna: DV03
    - Reference Antenna: DA61
    - Other Phased Antennas: DA41,DA42,DA44,DA46,DA47,DA48
    - Total # Phased: 41
    - Comparison Antennas: DA60,PM04

The VEX2VOM software translates information from the VEX file into OT expert parameters so that the observing script can successfully execute the VLBI Observing Mode (**VOM**)

VLBI with ALMA
Observation Setup

- Sufficient 12-m antennas (30-40) with working band 3 and/or 6 receivers in a relatively compact configuration
- use the shadowing calculation to determine which *reference antenna* to use (in case of compact configuration)
- make sure you have *an interactive* or *dynamic* array (for SB execution)
- make sure that the *sum antenna* is out of the array (DV03 in Cycle 4)

VLBI with ALMA
Archiving

- ALMA
  - archives its own interferometric data products
  - Looks like a normal ALMA dataset with ALMA- and APP-mode scans
  - Delivered to PIs after QA2
  - Publicly available after normal proprietary period.

- VLBI data
  - The VLBI Correlators archive the **correlated** data
  - the raw data will eventually be discarded (same disk packs are re-used in the following campaign)

VLBI with ALMA
Data Structure

- In VLBI, ALMA observes in two modes: VLBI mode and ALMA mode
- ALMA data are divided in two subsets:
  - ALMA-mode scans (phasing system OFF)
  - APP-mode scans (phasing system ON)
- *TelCal* (the ALMA online data reduction software) applies phasing corrections in phase and delay at the correlation stage which are different from normal ALMA observations

=> the ALMA-mode and APP-mode scans are not compatible calibration-wise, so separate calibrations are needed

VLBI with ALMA

Data Structure

BAND	Central Freq. (GHz)				Chan. Width	Integ. time
	spw 0	spw 1	spw 2	spw 3	kHz	(s)
1 mm	213.1	215.1	227.1	229.1	7812.5	4.03
3 mm	86.268	88.268	98.328	100.268	7812.5	4.03

Table 1: **ALMA correlator setups.**

GMVA records only the lowest BB_1 (VLBIRecorder1): SPW=0 (**86.268 GHz)** is the critical one

EHT records only the two highest BB_3 & BB_4(VLBIRecorders3 & 4): spw=2,3 (226 & 228 GHz)

Scans

```
Observed from   03-Apr-2017/06:55:08.2   to   03-Apr-2017/15:19:42.7 (UTC)

 ObservationID = 0         ArrayID = 0
Date        Timerange (UTC)          Scan  FldId FieldName             nRows     SpwIds   Average Interval(s)     ScanIntent
03-Apr-2017/06:55:08.2 - 07:00:10.6     3      0 4C 09.57             297000  [0,1,2,3]  [4.03, 4.03, 4.03, 4.03] [CALIBRATE_BANDPASS#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
            07:01:18.4 - 07:03:51.6     5      1 Callisto             150480  [0,1,2,3]  [4.03, 4.03, 4.03, 4.03] [CALIBRATE_FLUX#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
            07:04:58.1 - 07:06:59.1     7      0 4C 09.57             118800  [0,1,2,3]  [4.03, 4.03, 4.03, 4.03] [CALIBRATE_POLARIZATION#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
            07:07:27.9 - 07:08:00.1     8      2 J1744-3116            31680  [0,1,2,3]  [4.03, 4.03, 4.03, 4.03] [CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
            07:19:27.9 - 07:19:44.1    10      0 4C 09.57              15840  [0,1,2,3]  [4.03, 4.03, 4.03, 4.03] [CALIBRATE_APPPHASE_ACTIVE#ON_SOURCE]
            07:19:46.1 - 07:20:02.3    11      0 4C 09.57              15840  [0,1,2,3]  [4.03, 4.03, 4.03, 4.03] [CALIBRATE_APPPHASE_ACTIVE#ON_SOURCE]
            07:20:04.3 - 07:20:20.4    12      0 4C 09.57              15840  [0,1,2,3]  [4.03, 4.03, 4.03, 4.03] [CALIBRATE_APPPHASE_ACTIVE#ON_SOURCE]
            07:20:22.5 - 07:20:38.6    13      0 4C 09.57              15840  [0,1,2,3]  [4.03, 4.03, 4.03, 4.03] [CALIBRATE_APPPHASE_ACTIVE#ON_SOURCE]
            07:20:40.7 - 07:20:56.8    14      0 4C 09.57              15840  [0,1,2,3]  [4.03, 4.03, 4.03, 4.03] [CALIBRATE_APPPHASE_ACTIVE#ON_SOURCE]
            07:20:58.9 - 07:21:15.0    15      0 4C 09.57              15840  [0,1,2,3]  [4.03, 4.03, 4.03, 4.03] [CALIBRATE_APPPHASE_ACTIVE#ON_SOURCE]
```

ALMA scans on bandpass, flux, polarization, phase : OK

VLBI with ALMA
Calibration / QA2

- In VLBI mode, ALMA still produces ordinary ASDMs (ALMA Science Data Model), but include also:
  - CalAPPPhase ASDM table (i.e., list of phased antennas vs. time)
  - APP- and ALMA-mode scans
- Calibration / QA2 is needed for 2 reasons:
  - Deliver calibration products to the PIs (as any standard ALMA project)
  - Deliver calibration products to the VLBI correlators to run the *PolConvert* program to convert VLBI visibilities from linear basis into a circular polarization basis

VLBI with ALMA
Calibration / QA2

- Necessarily the observations need to be executed as polarization observations
  - requires continuous monitoring of polarized calibrator(s)

- Calibration is divided in two parts:
  - Ordinary calibration, based on XX and YY alone (bandpass, phase, amplitude). The bandpass and phase are solved twice.
  - Polarization calibration: X/Y phase offset (solved twice), calibrator's QU, and D-terms

- Calibrations need to be transferred between ALMA and APP scans.
  - calibrator(s) need to appear in both scans modes

VLBI with ALMA
Calibration / QA2

```
# Calibration

thesteps = []
step_title = {0: ' Import of the ASDMs',
 1: ' Fix of SYSCAL table times',
 2: ' Listobs, get Tsys, and split ALMA-calibration scans (for ordinary QA2)',
 3: ' A priori flagging (autocorrs and phased-signal antenna)',
 4: ' Apply Tsys, split out science SPWs, concatenate, listobs, and build CALAPP table',
 5: ' Save original flags',
 6: ' Initial flagging',
 7: ' Putting a model for the flux calibrator(s)',
 8: ' Save flags before bandpass cal',
 9: ' Bandpass calibration',
 10: ' Save flags before gain cal',
 11: ' Gain calibration',
 12: ' Apply ordinary calibration',
 13: ' Split calibrated data',
 14: ' Save flags before polarization calibration',
 15: ' Polarization calibration',
 16: ' Save flags before applycal',
 17: ' Apply calibration and split corrected column',
 18: ' Save flags after applycal',
 19: ' Run the imaging script on ALL sources',
 20: ' Tar up APP deliverables and make QA2 package'}
```

Data Import

Ordinary Calibration (XX,YY)
Separated for ALMA and APP scans

Polarization Calibration (XX,YY, XY, YX)
Separated for ALMA and APP scans

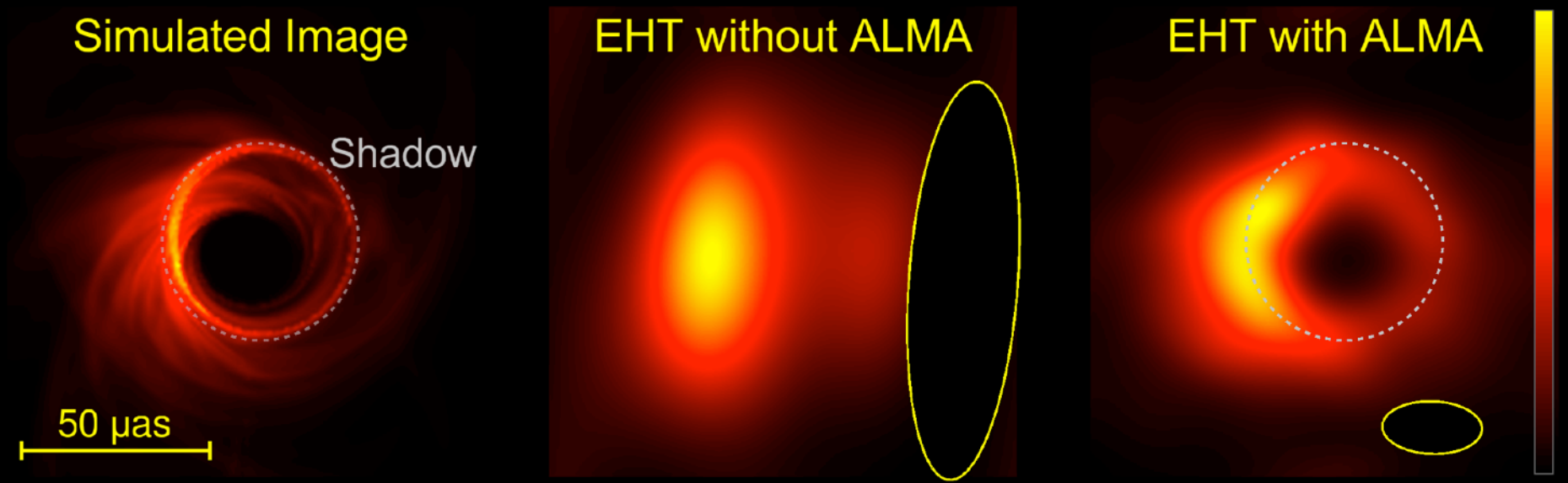
Imaging and Packaging of Products

What's Next for the VLBI with ALMA?

- Cycle 4 included only a subset of fully envisioned capabilities of the APP. Limitations include:
  - Phasing in Band 3 (3 mm) or Band 6 (1 mm) only :
    - Extension of Phasing Capabilities to Band 7?
  - Continuum only (no spectral line mode)
  - Fixed tunings
  - Targets must be bright (≥500 mJy on baselines <1 km)
- Cycle 5 ALMA VLBI capabilities (and likely Cycle 6) will be nearly identical to Cycle 4
- Developments from current ALMA N.A. Study Projects will not be available until Cycle 7
  - ALMA NA has approved the Implementation, so study project work is now contingent on ALMA Board Approval

VLBI with ALMA

Why is it so important?



GRMHD

mm-VLBI data simulator

Summary

- ALMA in VLBI mode *works*!
- First EHT/GMVA campaign with ALMA conducted in April 2017
- We have developed a general script for the calibration and QA2 of ALMA observations in VLBI mode, automatic PI-script generation and packaging
- Successful QA2 for all projects (all 2017 data delivered to PIs)

Next deadline for VLBI: ALMA cycle 6 proposal call!