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ALMA Developers Meeting

Göteborg, SE, May 26, 2016

# VLBI WITH ALMA

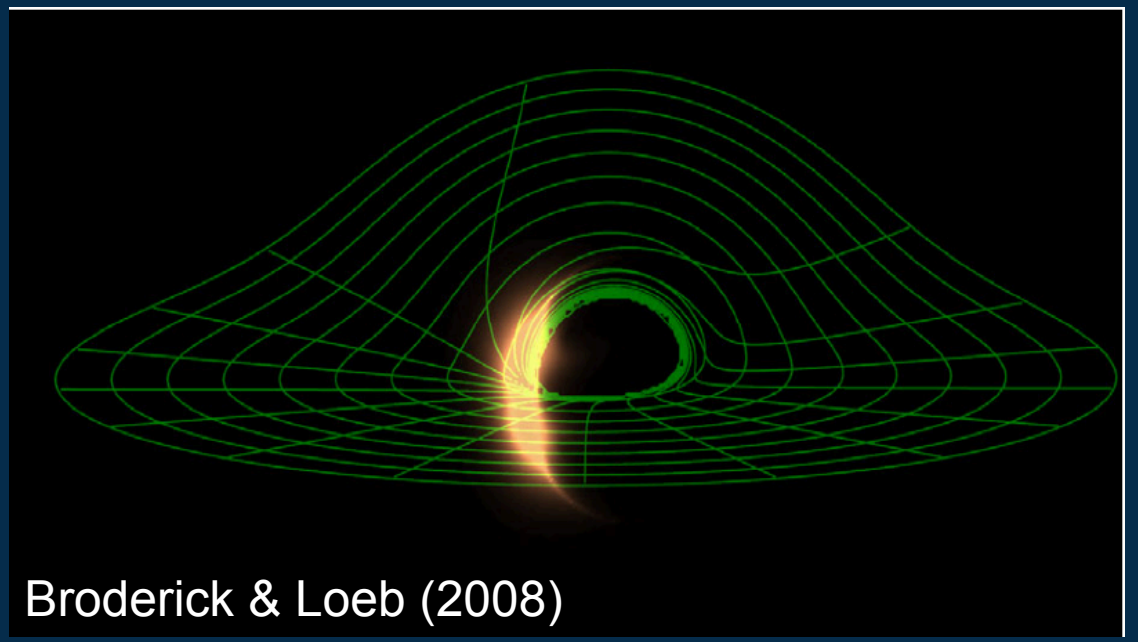

# mm-VLBI science

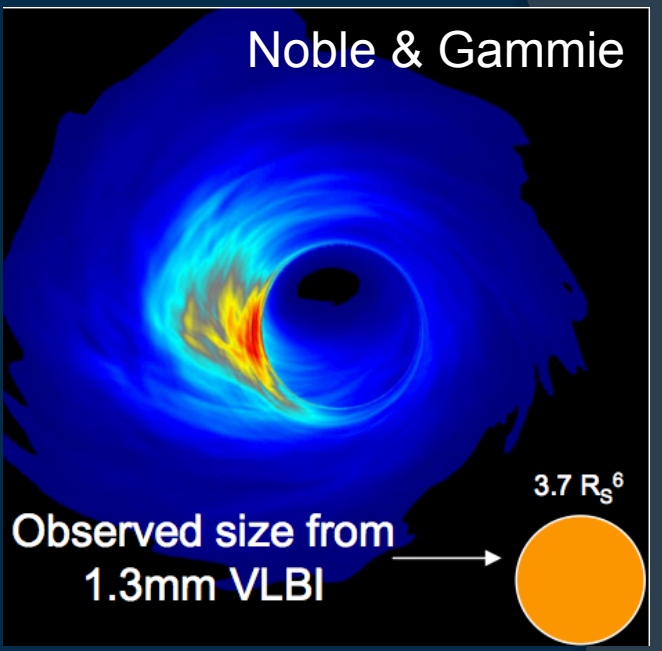
# The science

- Study of the immediate vicinity of the central engine in AGN
  - Schwarzschild-radius size imaging
  - Collimation and acceleration region in jets
- Spectral-line VLBI of absorbing systems for fundamental constant determination
- VLBI of masers in stellar objects and AGN
- Astrometry in the Milky Way and beyond

# Below λ3mm: towards the BH shadow

Doeleman et al. Nature 455, 78-80 (2008)




Observed size: $43^{+14}_{-8}$ μas
Deconvolved: 37 μas
Intrinsic: 3.7 $R_s$

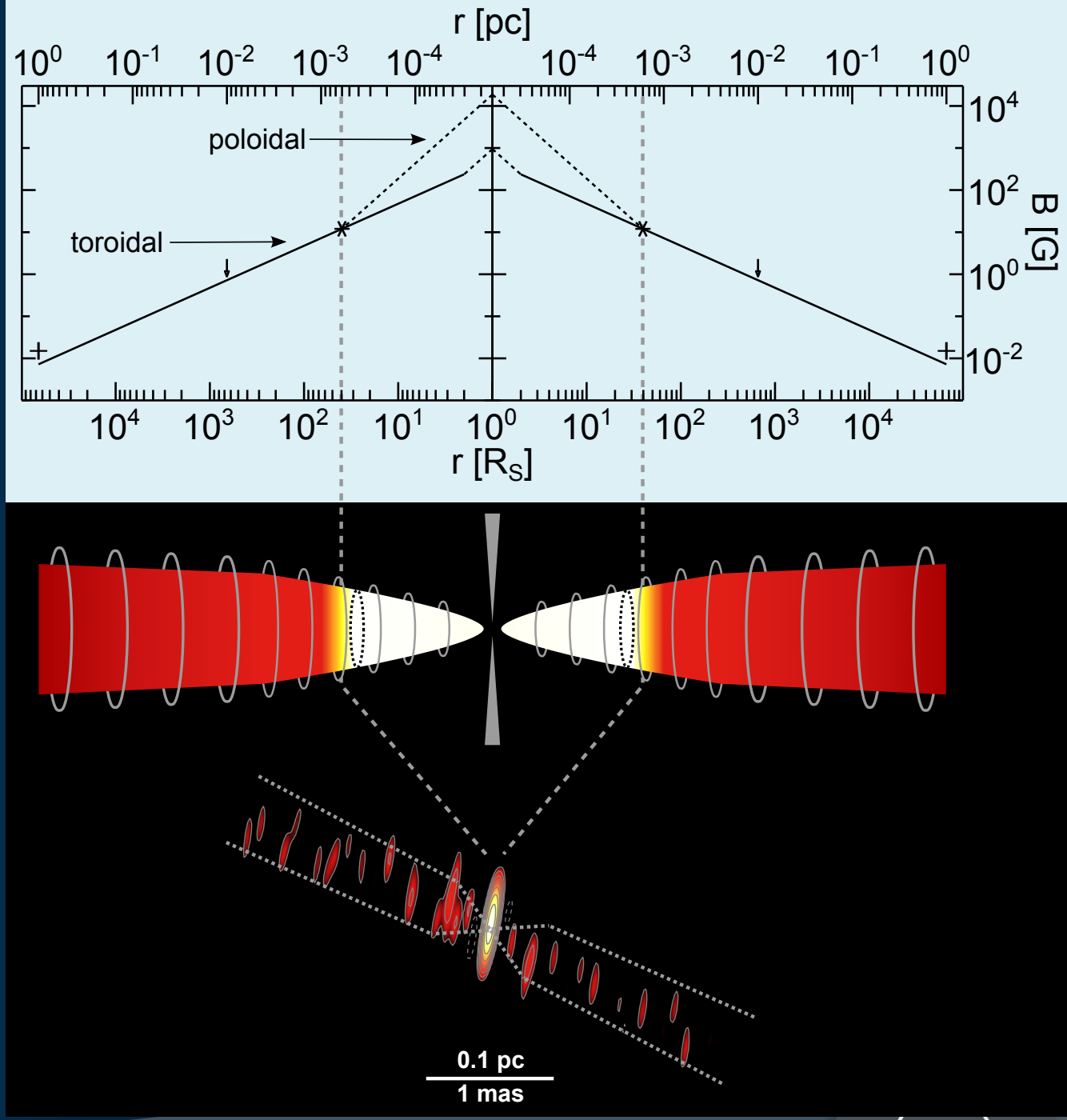
$$M_6 = \frac{0.1}{\alpha}\,\theta_{\mu\mathrm{as}}\,D_{\mathrm{Kpc}}$$

Observed size smaller than expected size of ISCO or photon ring:
Emission from hot spot or width of crescent shaped larger photon ring?

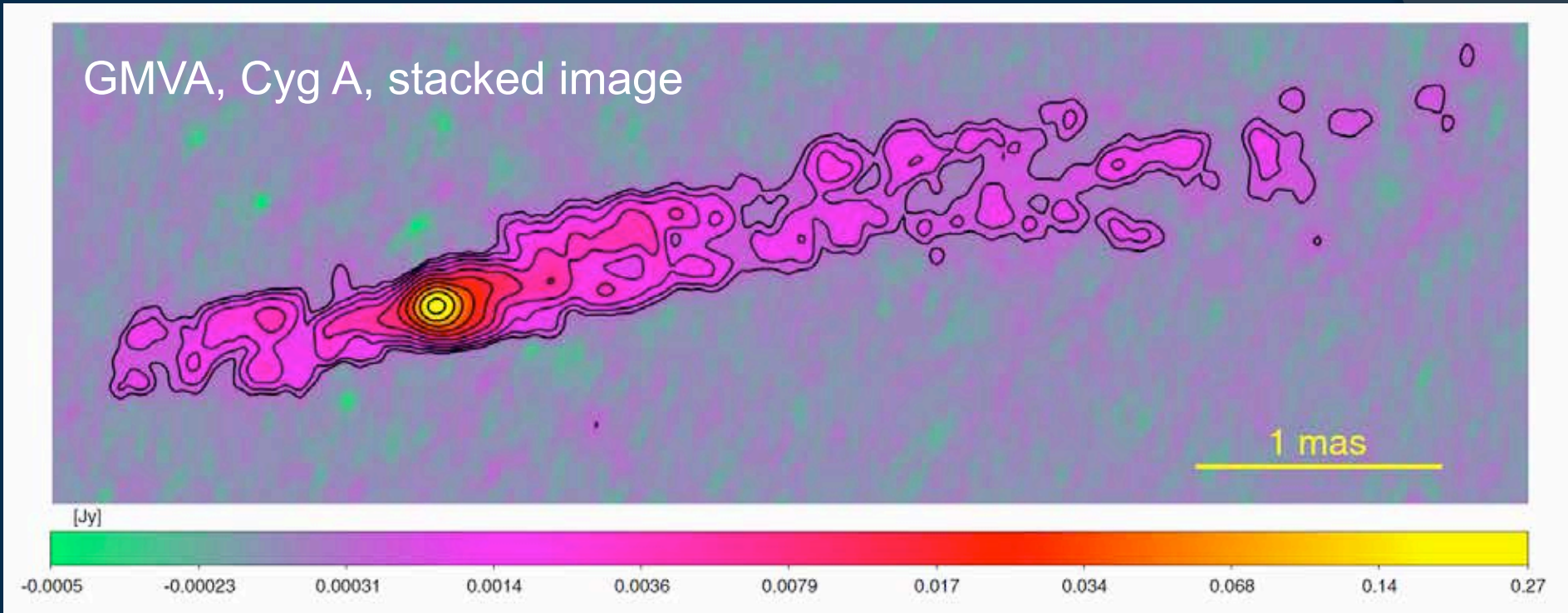
# NGC1052 at 3mm: High magnetic fields

$B_{Sc,1Rs}$ = 200-80000 G

Baczko et al. (in press, arXiv:1605.07100)



# Jet ejection from accretion disk




Boccardi et al. A&A **588**, L9 (2016)
Highlighted in Nature **532**, 150 (2016)

Jet base 100× wider than event horizon region.
The disk is responsible for the jet ejection


# Technique: present status

# ALMA and VLBI

- ALMA did not include VLBI options to start, hooks for phasing included in the correlator
- Additions to make VLBI possible:
  - H-Maser
  - Phasing system & software
  - VLBI formatting, data transport & recorders
  - Briefing ALMA staff

# Background

1. ALMA upgraded by implementing a beamformer for phasing up ALMA for VLBI and PSR (feasibility under investigation) observations
2. Event Horizon Telescope assembles
3. Preparing operation of ALMA in a VLBI network: GMVA proposed upgrade to ALMA
   - Procedures established, suggesting operational modus
4. Goal: joint observations ALMA with VLBI networks – approved by board at bands 3&6

# Activities

- ALMA Phasing Program
- Science case for ALMA beamformer (Fish et al. 2013, arXiv:1309.3519)
- White paper on implementation (Tilanus et al. 2014, arXiv:1406.4650)
- ERC granted a Synergy Proposal (BlackHoleCam) to several European partners to achieve scientific goals
- Definition of operations by upgrade study, board approved
- ALMA VLBI Coordination Committee grounded:
  - ALMA Cycle 4 call included VLBI option
  - Observations planned for April 2017 in Bands 3&6

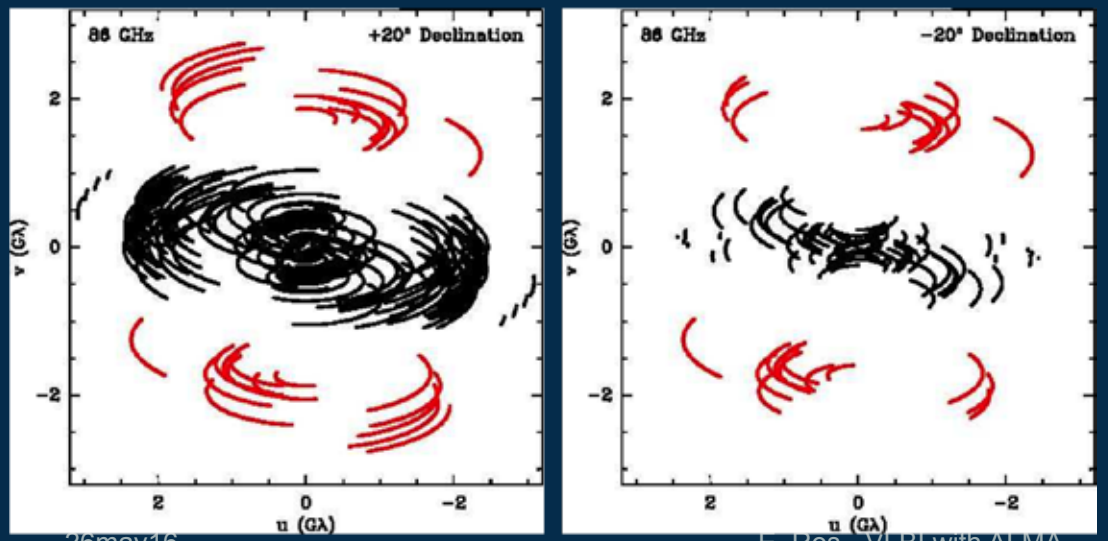
# Technical development: DBBC3, correlator

- State-of-the-art technology enabling cutting-edge science
- DBBC3:
  - Development by INAF-Noto, MPIfR & OSO
  - Production Hat-Lab
  - Flexible data rate up to 128 Gbps, EHT target 64 Gbps
  - Supported by RadioNet
- DiFX correlator:
  - New cluster Q1/2015 1000-1500 computer cores
  - 6×Mark6 units


See http://www.hat-lab.com

# ALMA Phasing Project (2011-15)

- Goal: Coherently add the signals from individual antennas to form a very sensitive single-dish mm/sub-mm instrument (PSR & VLBI)
- Resources: 25 FTE-yr, over 4 M$ (NSF/ MRI + other partners)




uv-coverage including ALMA (3mm left, 1mm right)

# ALMA Phasing Project

Oct 2009: International team assembled

Jan 2011: ALMA board endorses NSF proposal

Sep 2011: NSF Awards MRI grant and international funding secured

Dec 2011: Project kickoff meeting

Nov 2012: PDR passed

May 2013: CDR passed with minor issues to be solved.

Jul 2015: ALMA Acceptance Review passed

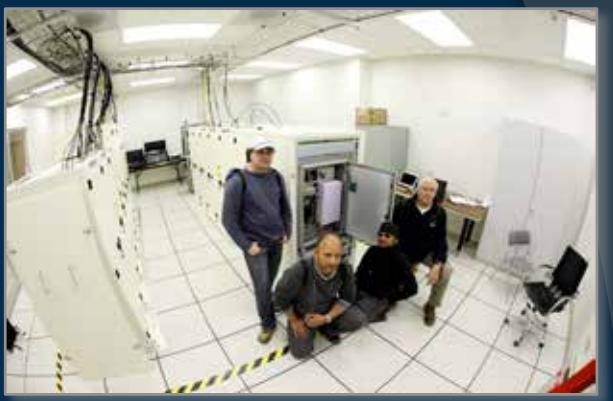
Aug 2015: ALMA Phasing Project ends; NSF grants prolongation

# VLBI recent tests

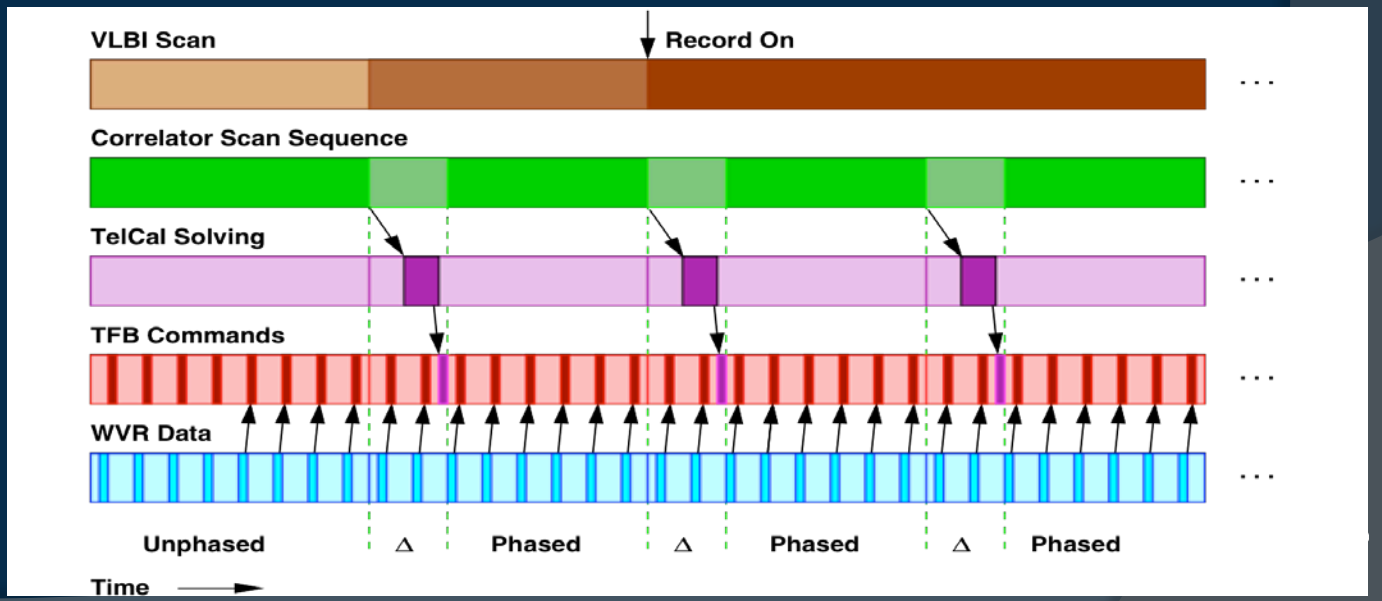
| Date | λ | Antennas | Purpose | Fringes? | Comments |
|---|---|---|---|---|---|
| 2015/01 | 1.3 | **ALMA**-APEX | Comm. | ✔ | 1st ALMA fringes |
| 2015/01 | 1.3 | SPT-APEX | Comm. | ✔ | 1st SPT fringes |
| 2015/03 | 1.3 | **ALMA**-PV | Test | ✔ | 1st ALMA intercont. frg. |
| 2015/08 | 3.5 | **ALMA**-VLBA-EB | Comm. | ✔ | 1st ALMA 3mm fringes, DBBC2 mode failed |
| 2015/10 | 3.5 | Local | Test | × | DBBC mode improvements |
| 2016/05 | 3.5 | Local | Test | ✔ | DBBC2 ALMA mode works |
| 2016/05 | 3.5 | GMVA | Test | search | ALMA mode & 4 Gbps |

# Hardware & software in place

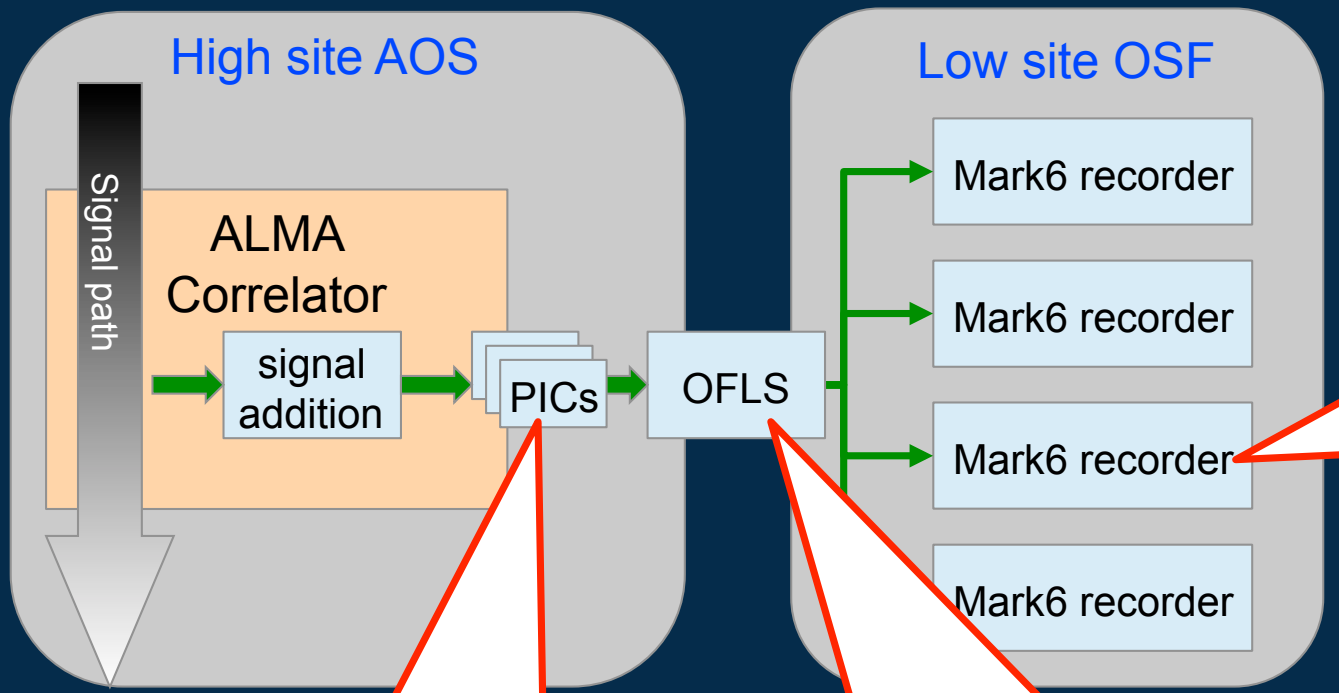
ALMA rubidium clock replaced by H-maser
Installed and tested in 2014



**Phasing loop timing**
Phase variations due to troposphere, WVR corrections applied



# Signal transport, formatting & recording




**Mark6 recorders**

Recording rate/unit= 16 Gbps

Total rate = 64 Gbps

**PIC = Phasing Interface Card**

Delivers formatted data
- VDIF format
-10GbE packetization
- synchronization
- channelization (32 x 62.5MHz)
- 2bit sampling

Total number of PICs: 8

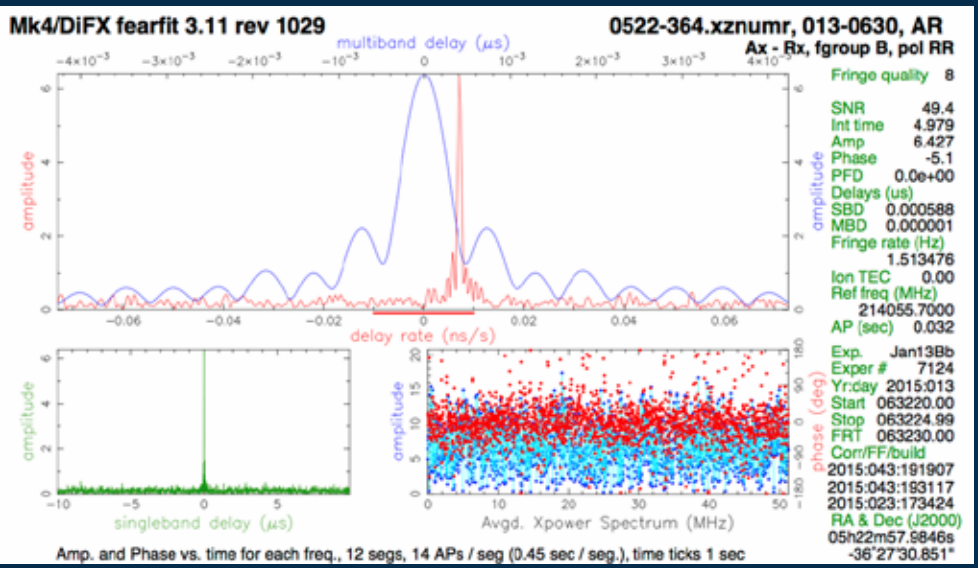
**OFLS = Optical Fibre Line System**

Transports the formatted signal
from correlator (AOS high site)
to recorder (OSF low site)

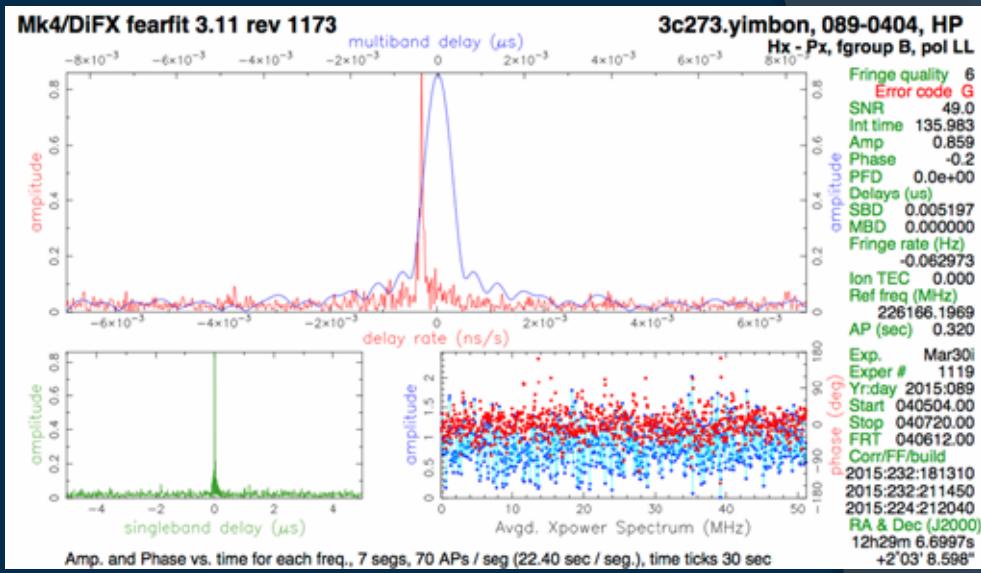
MUX/DEMUX over optical fibre

VLBI recorders cannot be operated at
very high altitudes (hard disks)

# 1-mm VLBI with ALMA: successful tests




ALMA-APEX fringes, 230 GHz, Mar 2015

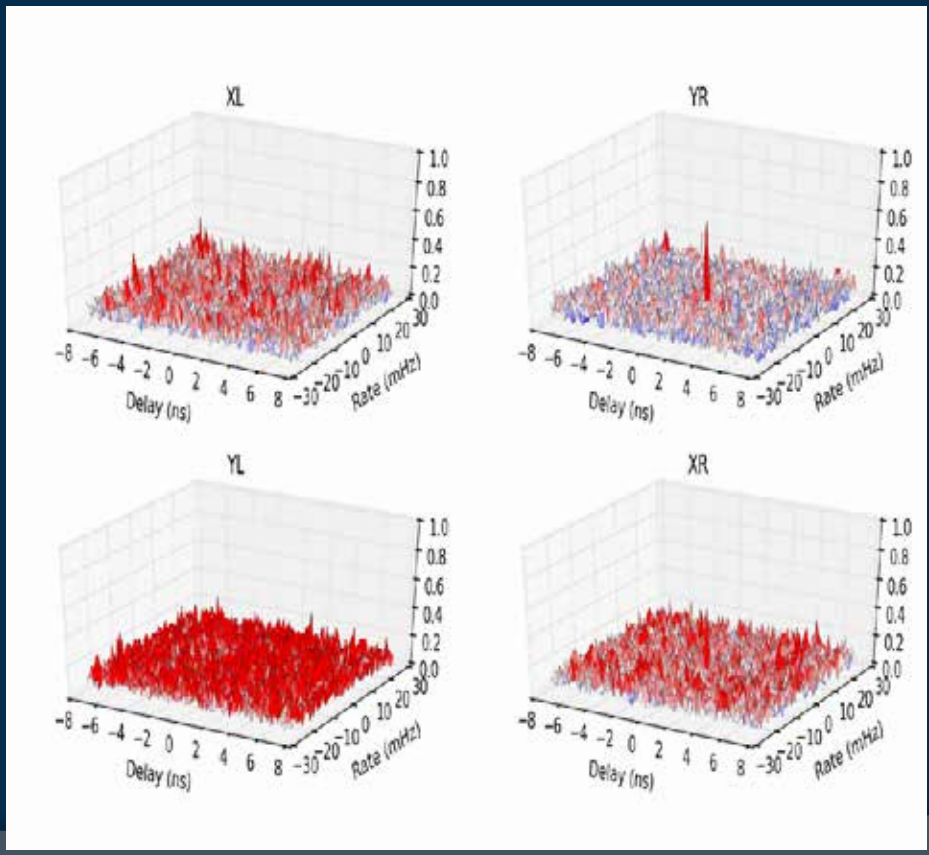


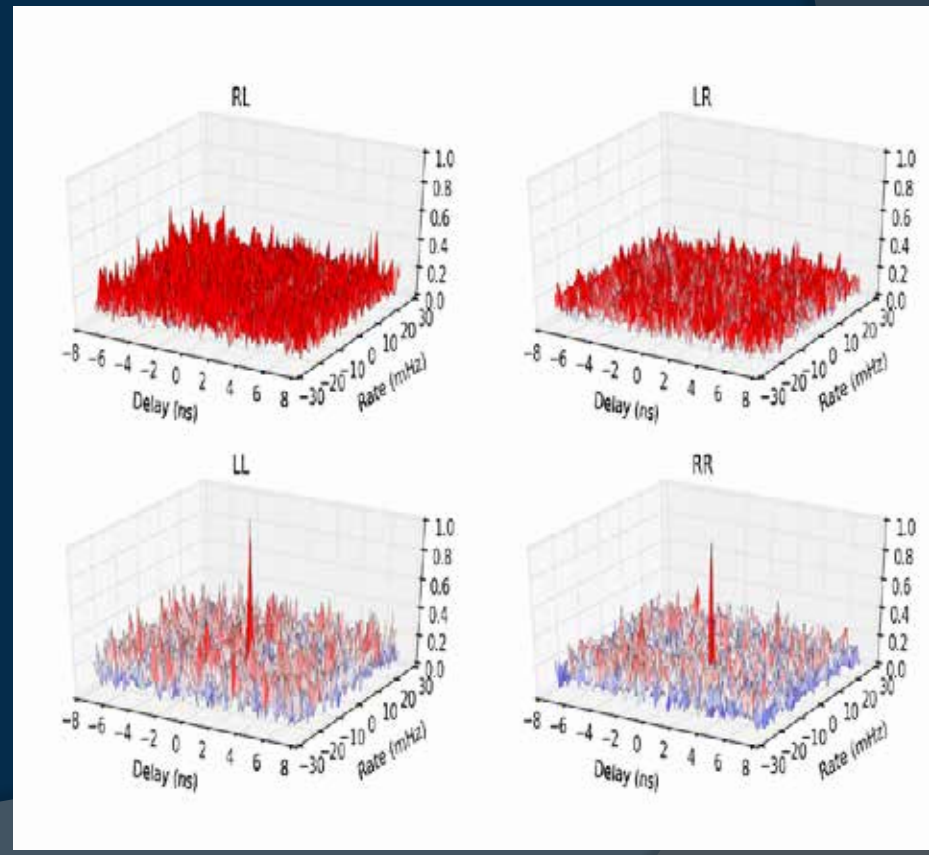

ALMA-PV fringes, 240 GHz, Aug 2015

# ALMA polarisation

See Martí-Vidal's talk

- Eb-On test at 86 GHz (On XY, Ef RCP/LCP) – DiFX correlation – PolConvert software



# ALMA network providers

- 3mm: GMVA
  - GMVA submission: February 1st
    - Forwarded to TACs of network partners
  - ALMA submission: April 21st
- 1.3mm: EHT
  - ALMA submission: April 21st
  - NRAO submission: April 28th
    - Technical and scientific review in progress

# The GMVA

http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm


- Complementary to EVN and VLBA, matching resolution with RadioAstron
- Open-sky policy
- Requires expertise for the common user
- At present:
  - 2 sessions per year (spring & fall), off-session observations possible
  - 3.5 mm (also 7 mm)

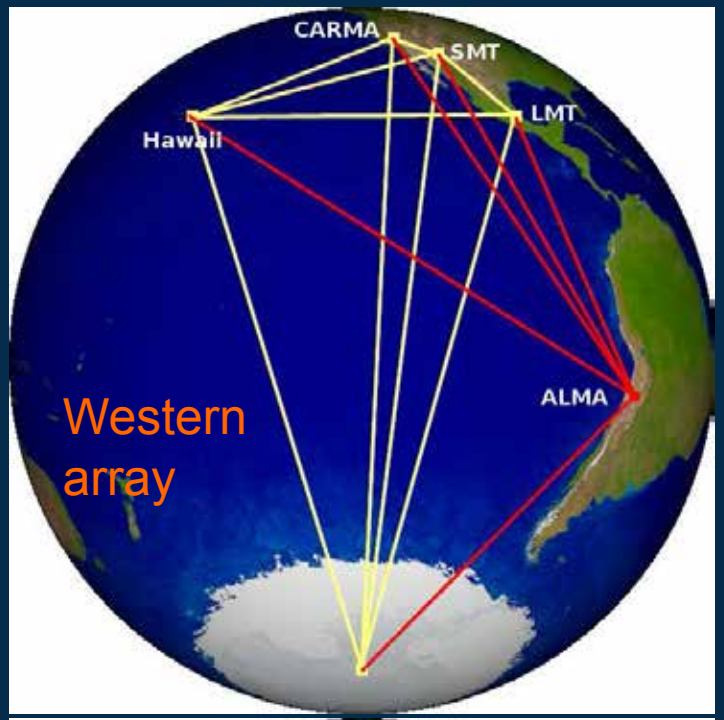
Image credit: T.P. Krichbaum (MPIfR)

# GMVA sensitivities

| Array | Stations | Base-line [mJy] | Array [mJy/hr] | SNR 12-hr map [ × $10^3$] | Comment |
|---|---|---|---|---|---|
| VLBA 2 Gb/s | VLBA(8) | > 164 | 2.33 | 1.0 | no HN, SC |
| GMVA 2 Gb/s | VLBA+Eb+Pb +Pv+On+Mh | > 33 | 0.86 | 2.8 | 68 mJy VLBA-IRAM |
| +Yb | GMVA+Yb | > 27 | 0.67 | 3.7 | 68 mJy VLBA-Yb |
| +Lm+Gb | GMVA+Yb+Lm +Gb | > 10 | 0.30 | 8.2 | 31 mJy VLBA-Gb |
| +ALMA37 | GMVA+Yb +LMT+Gb +ALMA37 | > 5 | 0.19 | 12.9 | 5 mJy ALMA-Gb |

Δv=512 MHz (2 Gb/s), t=20s, 7σ fringe detection, 2-bit

# Event Horizon Telescope





From Fish et al. (arXiv:1309.3519)

- Mauna Kea, Hawaii:
  - SMA, JCMT ($D_{eff}$: 23m)
- Mount Graham, Arizona:
  - SMT (10-m)
- Inyo Mountains, California:
  - CARMA ($D_{eff}$: 27m)
- Sierra Negra, Mexico:
  - LMT (50-m)
- Atacama desert:
  - ALMA, ($D_{eff}$: 85-m)
  - APEX, (12-m)
- Pico Veleta (Sierra Nevada, Spain, 30-m)
- Plateau de Bure/NOEMA (France, $D_{eff}$: 37-m)
- South Pole Telescope (10-m)
- Greenland Telescope (12-m)

# Enhancement at λ1.3mm

| | PdB | SMTO | APEX | ALMA |
|---|---|---|---|---|
| Pico Veleta | 0.063 | 0.201 | 0.169 | **0.024** |
| Plateau de Bure | | 0.153 | 0.129 | **0.019** |
| SMTO | | | 0.413 | **0.059** |
| APEX | | | | **0.050** |

Baseline sensitivity (Jy) at 1.3mm for 10s integration time

Sensitivity increase > 3

# Developments external to ALMA

- Continuous upgrades: e.g., APEX RX 1mm
- GLT being installed in Thule in Summer 2016, commissioning, observations
- Simultaneous multi-wavelength receivers (e.g. KVN)
- New antennas to enhance image fidelity (uv-coverage & sensitivity)
  - Europe: SRT at 3mm
  - Latin America & Africa: LLAMA project, studies
  - Asia & Australia: new dishes, Nobeyama/ATCA/ Mopra option
- Technical developments: data bit rate, correlator output

# Summary: VLBI at ALMA

- Equipment in place (H-maser, recorders)
- Phasing completed
- Polarisation conversion completed
- APP lifetime extended to 2016 for completing features
- Cycle 4 call closed

- Present limitations
  - 3-hr on source for calibration
  - S > 0.5 Jy (phasing on program source)
- Pending:
  - Model source (extended structure) for phasing
  - Commissioning of weak sources for additional targets – phasing on calibrator (high-sensitivity science)


# Thanks!