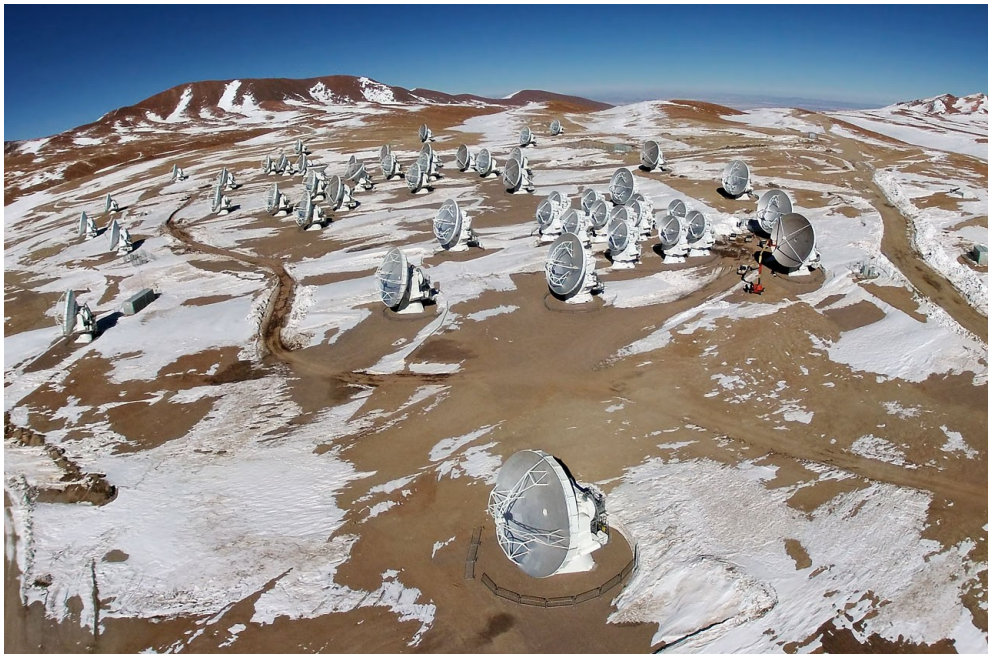
ALMA for VLBI

Robert Laing, ESO



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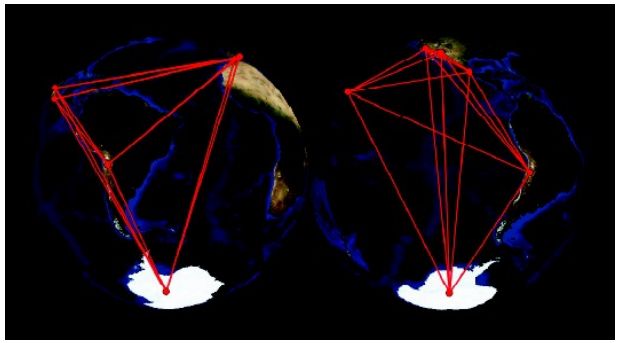

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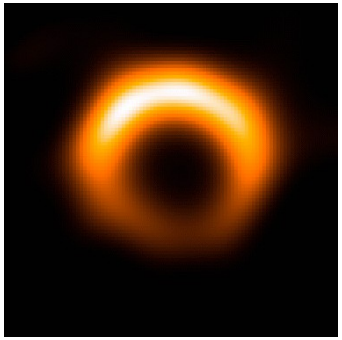


Outline

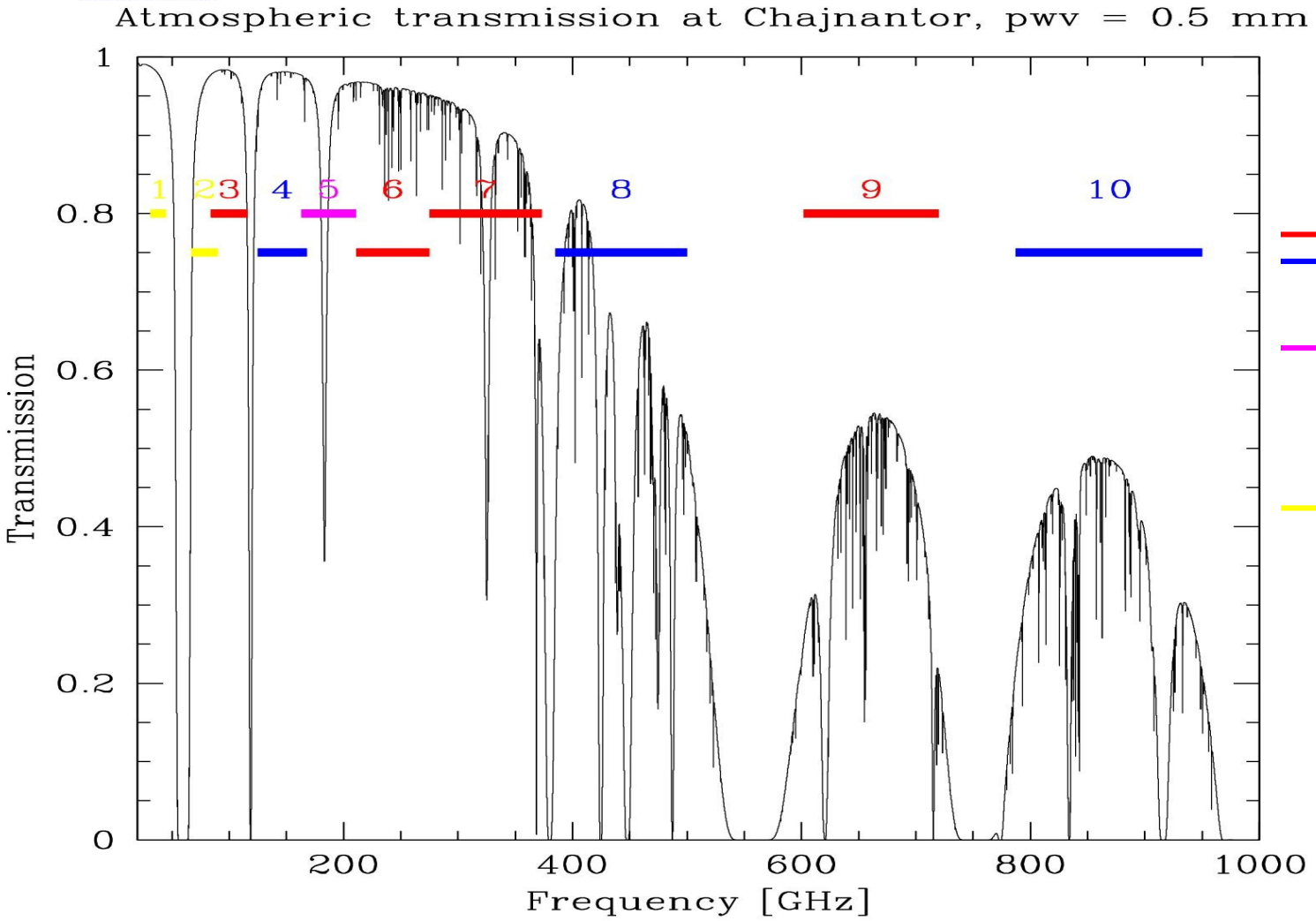
- ALMA numbers and update
- Multifrequency observing with ALMA
- ALMA and VLBI
- ALMA Development Strategy

ALMA Numbers

- Aperture synthesis array optimised for wavelengths of 1cm – 0.3mm (35 – 950 GHz)
- **High, dry site**, Chajnantor Plateau, Chile (5000m)
- 54 12m + 12 7m antennas
- Baselines from ~15m to 16km.
- **Resolution**/ arcsec $\approx$ 0.2(λ/mm)/(max baseline/km)

  5 mas for highest frequency/longest baseline
- Field of view / arcsec $\approx$ 17 (λ/mm) [12m dish]
- **Sensitive**, wide-band (currently 8 GHz) receivers; full polarization
- **Flexible** digital correlator giving wide range of spectral resolutions.
- **Software**

ALMA Bands



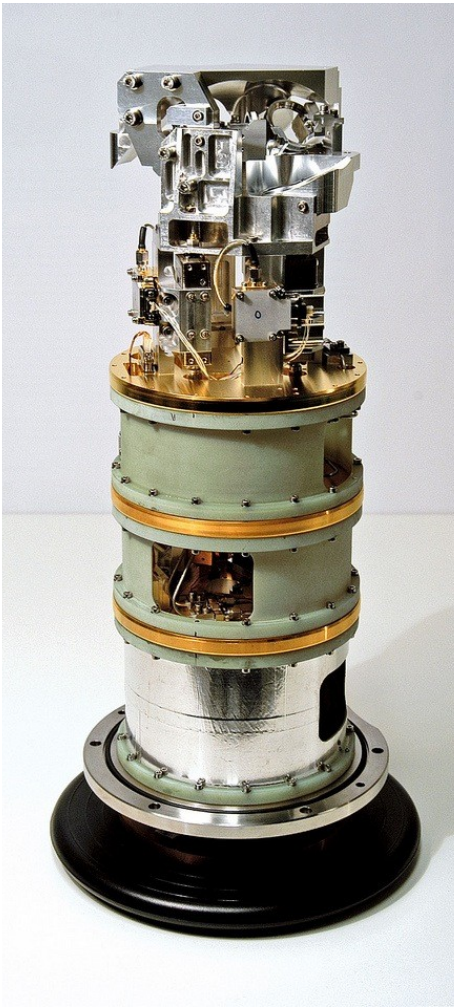
Complete

Being integrated

Not yet built

Keys to sub-mm observing

- Site
- Antennas
- LO distribution
- Sensitive SIS receivers
- Phase correction
  - Water-vapour radiometers
  - Fast phase calibration cycle
  - Band-to-band phase transfer
  - Self-calibration

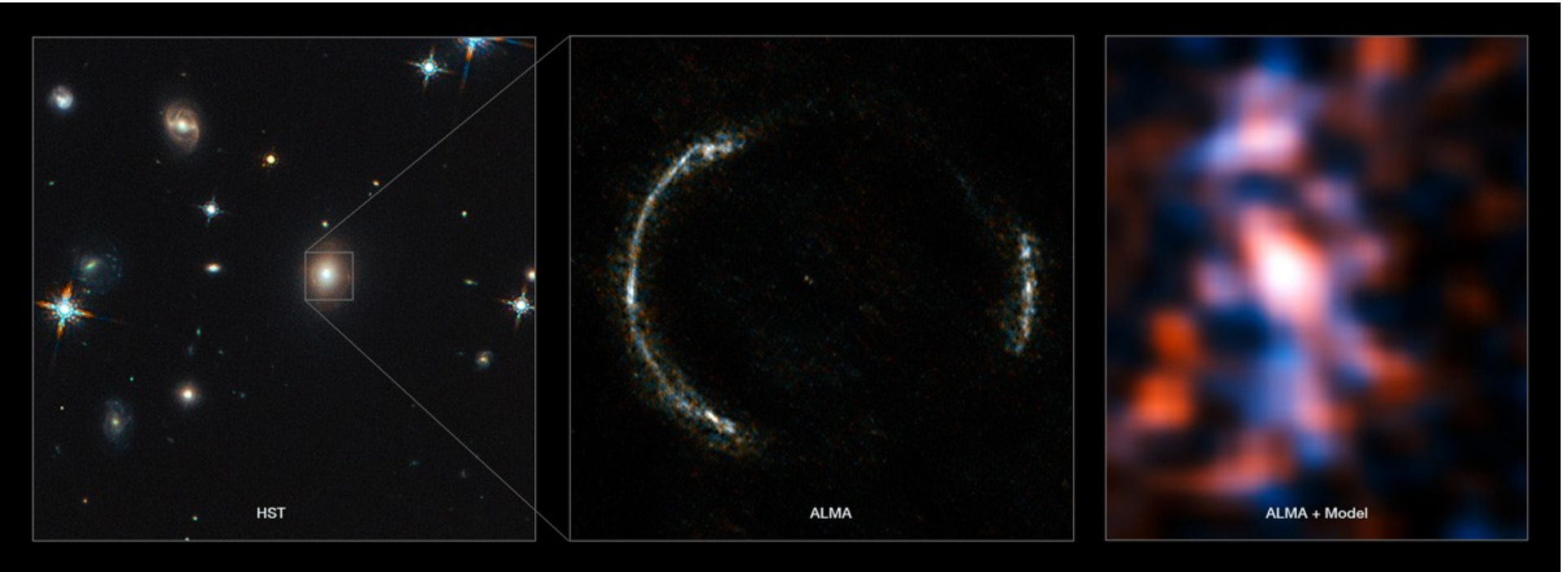


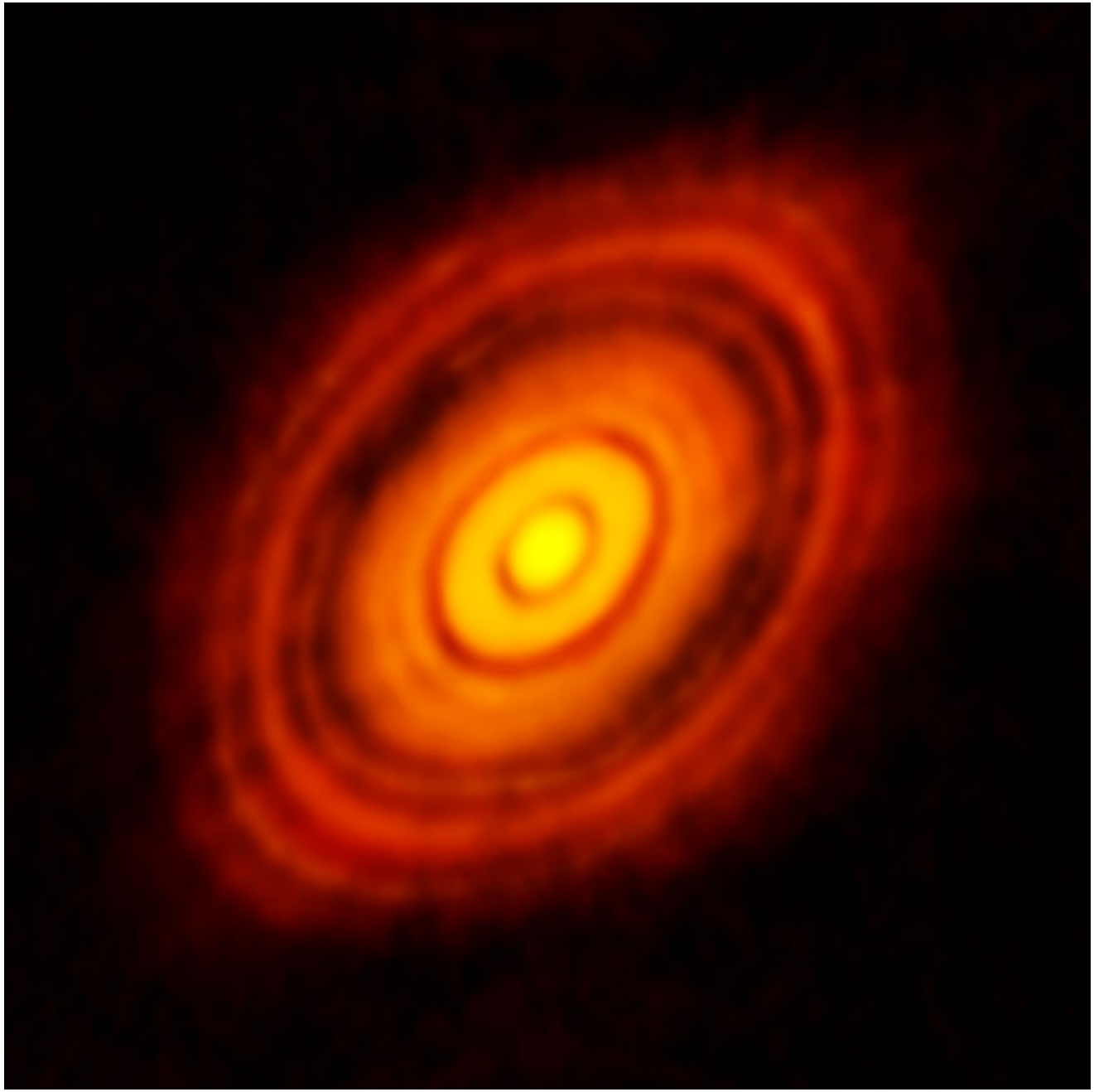
ALMA Early Science

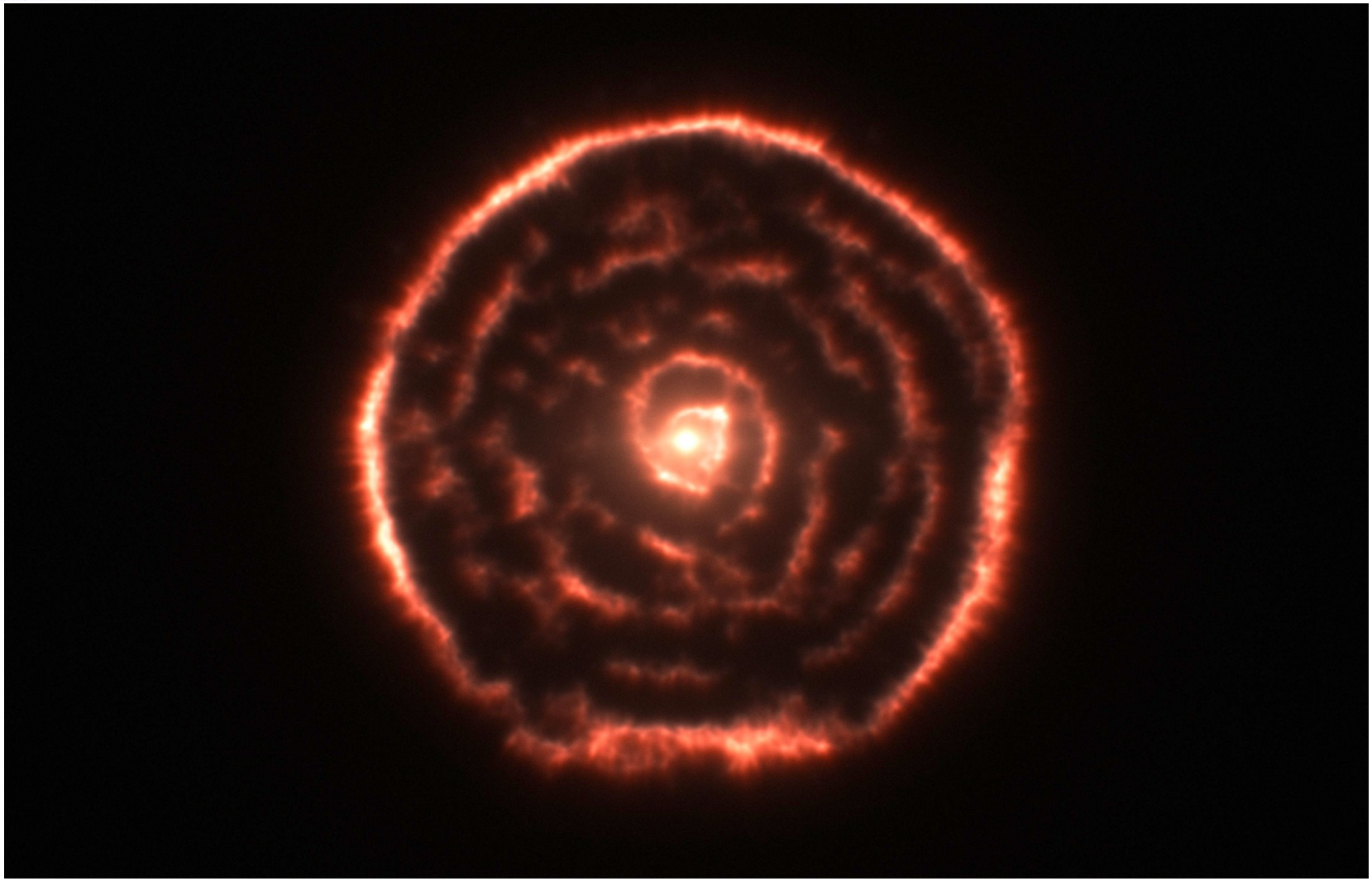
- Cycles 0, 1 and 2 complete
- 30-70% of total number of antennas available; baselines up to 3 km
- Already the most powerful sub-mm observatory
- Enormous user pressure: oversubscribed 9x in time
- Cycle 3: 1582 proposals (41% from EU)
- 60% sub-mm (Bands 7-9)

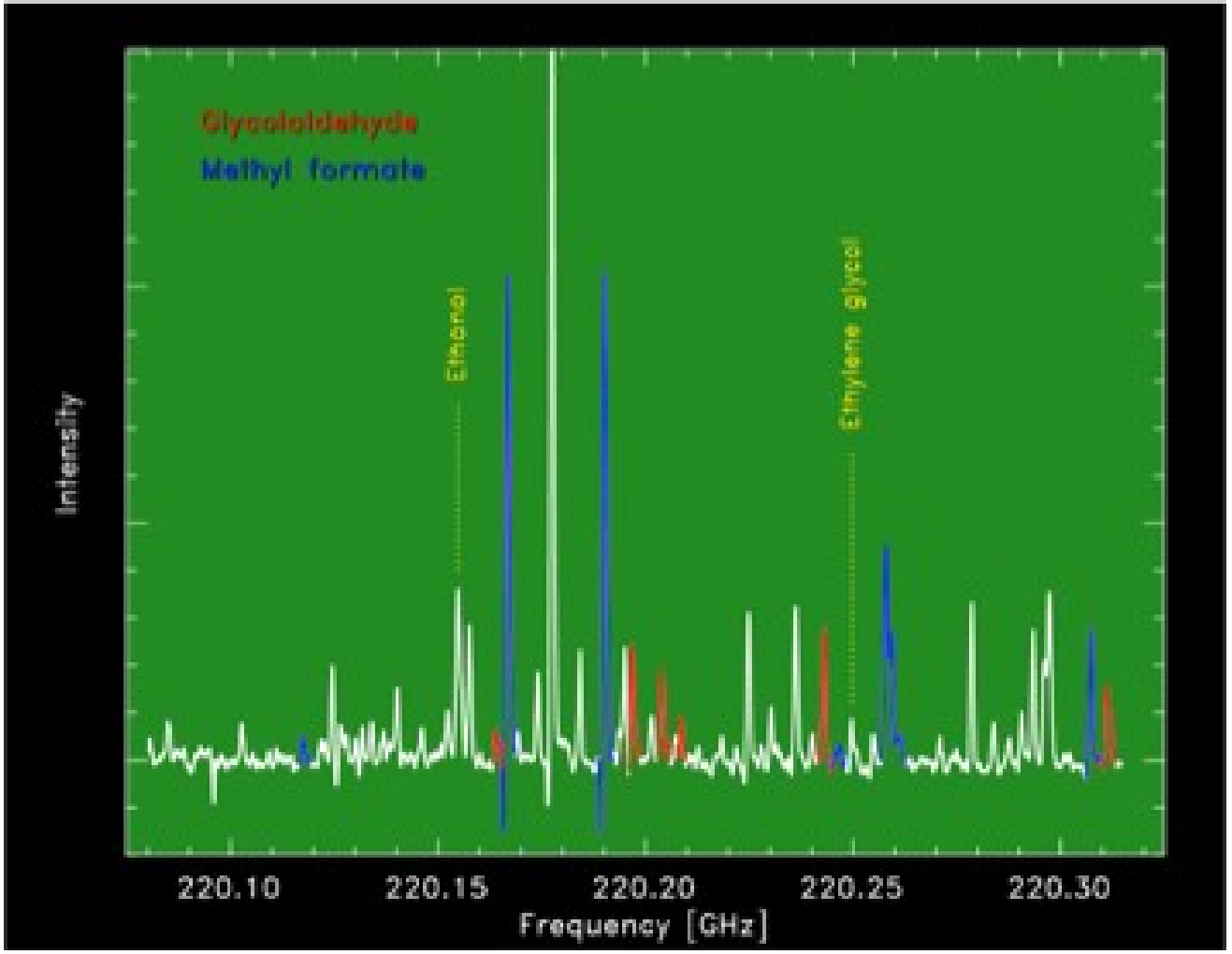
ALMA Science Output
(September 21)

- 275 refereed publications as of September 21
- 72% of Cycle 0 projects resulted in at least 1 publication
- ~6% Nature/Science
- Wide range of science








Glycolaldehyde
Methyl formate
Ethanol
Ethylene glycol
Intensity
220.10
220.15
220.20
220.25
220.30
Frequency [GHz]

Coming shortly: Cycle 4 Goals

- Improved spectral scans
- Line IQUV
- mmVLBI at 1 and 3mm
- Solar modes at 1 and 3mm
- On-the-fly interferometry
- Technical improvements
  - ACA correlator linearity
  - 90 deg Walsh switching
  - Sideband separation Bands 9 and 10 (DSB)
  - Full baseline range
  - Subarrays
  - Improved polarization capabilities

Multifrequency observations with ALMA: frequency switching

- Frequency switching either within a band or to another band on standby is specified to happen in <1.5s
  - Currently 3-4s in practice
  - Restrictions set by the need to pre-tune laser synthesizers
  - One band operational and up to two in standby (may increase)
- Use in practice: band-to-band transfer (related to frequency phase referencing)
  - Used for complex gain calibration when there is no nearby calibrator at the (usually high) observing frequency
  - Requires a measurement of the relative complex gains in 2 bands on a bright calibrator
  - Various options, dependent on conditions, locations and flux densities of calibrators, e.g. for a Band 9 observation:
    - calibrate and observe target in B9 (best in very good conditions)
    - calibrate in B6; observe target in B9 (moderate extrapolation; fewer calibrators than B3)
    - calibrate in B3; observe target in B9 (large extrapolation; many more calibrators available)
    - more calibrators than we thought; close calibrator better than faster switching
- Troposphere is essentially non-dispersive
  - but there are deviations, e.g. around the 183 and 327 GHz water lines
  - atmospheric models (ATM)

Multifrequency observations with ALMA: Subarrays

- 4 independently-tunable subarrays
  - Main array + ACA
  - Software currently being tested
  - In principle up to 6 subarrays (= number of laser synthesizers)
  - One phased sum
- Strictly simultaneous observations
  - Possible using different subarrays
  - In principle, can use paired antennas observing at different frequencies to correct phase (CARMA C-PACS; Perez et al. 2010).

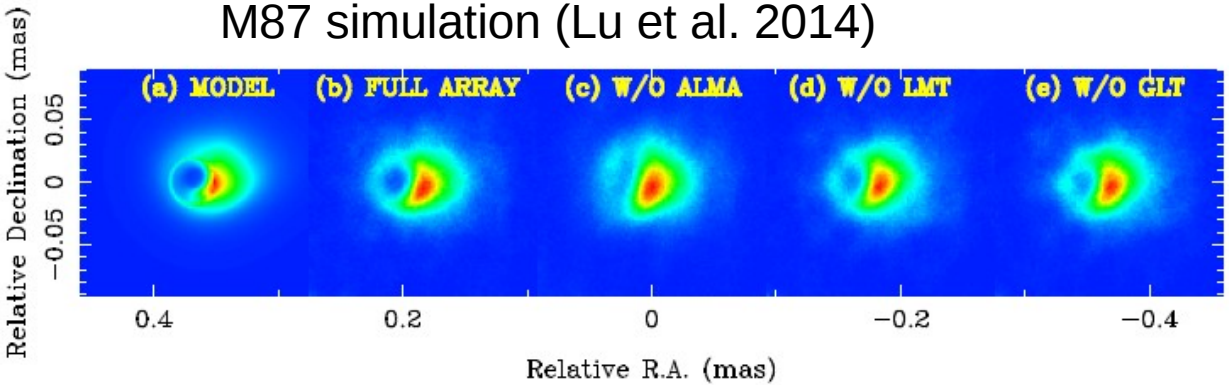
ALMA for VLBI: Science Drivers

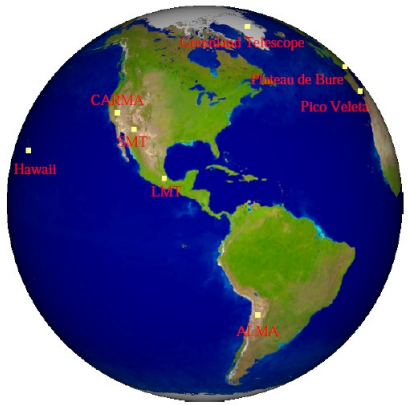
- Imaging a black hole event horizon
- Testing GR
- Jet formation
- Masers (SiO, water, ...)
  - astrometry, distance measurement
  - black hole dynamics,
  - AGB stars
- Pulsars near the Galactic Centre
- Extragalactic absorption lines
  - Change of fundamental constants with time

Fish et al. (2013)
Tilanus et al. (2014)

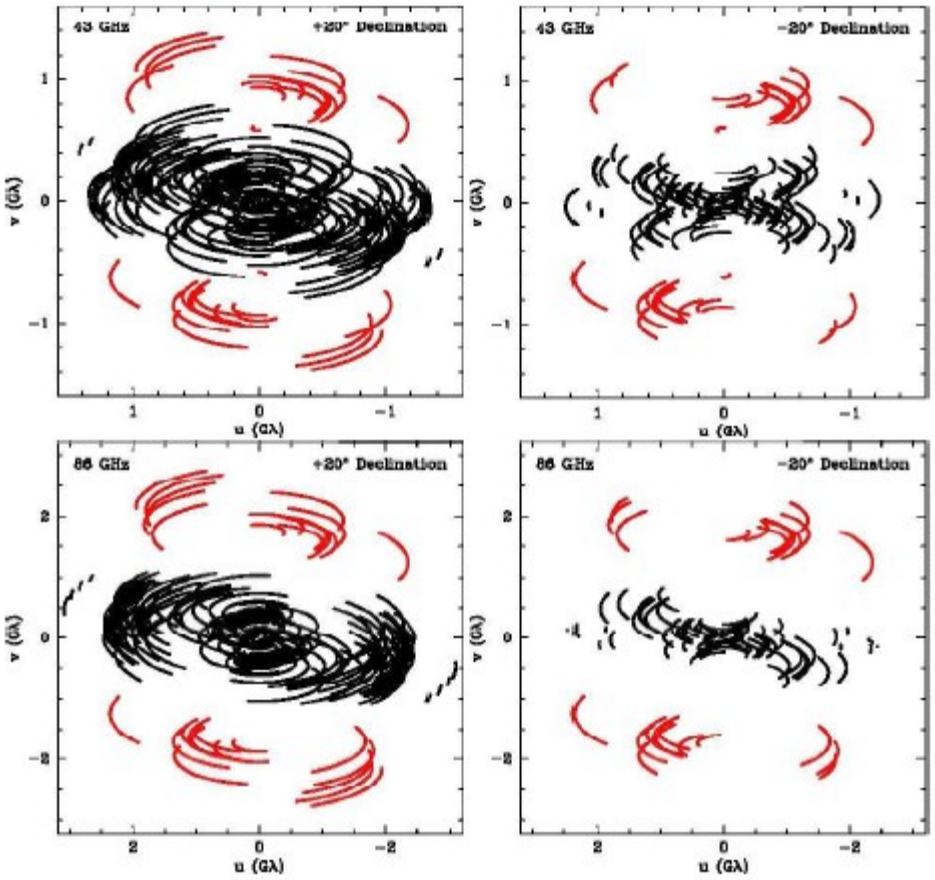
Phased ALMA with 50 antennas is the equivalent of an 85 m single dish on an excellent site

M87 simulation (Lu et al. 2014)



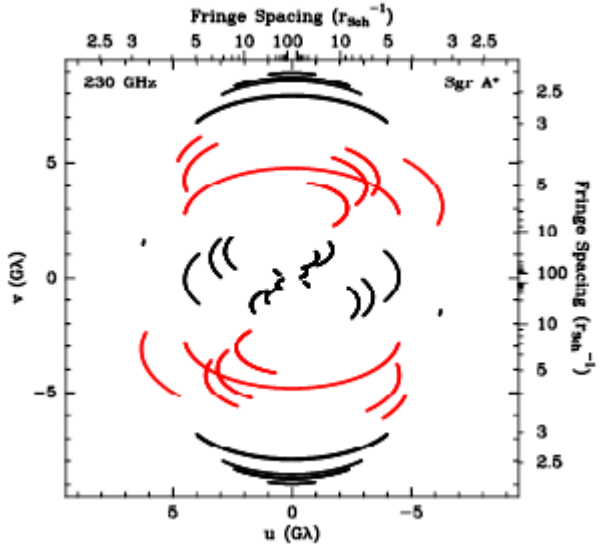


(u,v) coverage



43 GHz

86 GHz

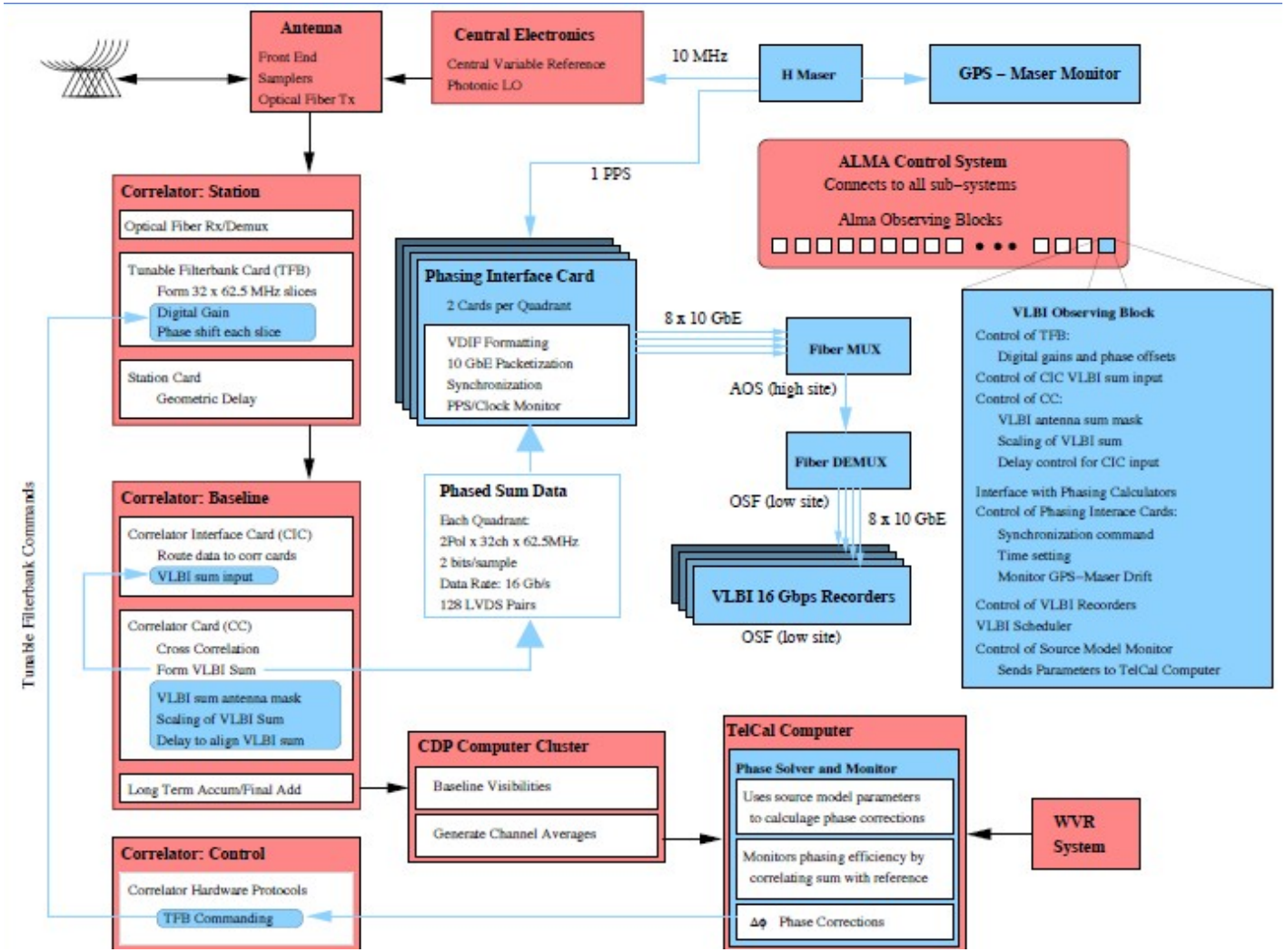


230 GHz
Sgr A*

Dictionary

- ALMA Phasing Project
  - Hardware and software to use ALMA as a phased array
  - Led by MIT/Haystack, with NRAO; MPIfR and OSO in Europe; ASIAA, NAOJ
  - Majority funding from NSF + in-kind contributions
- Event Horizon Telescope Collaboration
  - Collaboration for VLBI at 230 (and 345?) GHz
  - Prime targets are Sgr A* event horizon and the M87 jet
  - New receivers for existing telescopes (NSF+)
- BlackHoleCam
  - ERC synergy grant
  - Black hole imaging + pulsars + theory
- Infrastructure for VLBI at (sub-)mm wavelengths
  - Open facility for VLBI at wavelengths of 7mm or below.
  - GMVA
  - HSA

APP Block Diagram



APP: Technical Detail

- H maser frequency standard
- Mark 6 recorder
  - Located at 2900m site; optical fibre link from AOS
  - Up to 16 Gbit/s (4 GHz bandwidth; 2 polarizations; 2-bit sampling) – upgrade to 32 Gbit/s possible in principle.
  - 512 MHz/2 Gbit/s for compatibility with VLBA
- Correlator upgrade
  - Phased sum
  - Phasing interface cards
- Software
  - Control
  - Phase solver
  - Polarization conversion (ALMA uses linearly polarized feeds; others circular)
- Frequencies
  - In principle, any ALMA band, but
  - Concentrate initially on Bands 3 and 6 (84-116 and 211-275 GHz)

ALMA Phasing Project - status

- H maser installed and in operation as ALMA frequency standard
- APP hardware accepted
- Most software delivered
- Baseline correlator phased with high efficiency (40 antennas, Band 3, >99%)
- Fringes obtained in “local VLBI” (phased ALMA – APEX); Jan 2015
- On-line water vapour radiometer corrections demonstrated
- **Tests on intercontinental baselines at 3 and 1mm: ongoing**
- Extensive ongoing work to provide “ALMA standard” equipment at other telescopes (e.g. SPT, LMT)
- Plan is to be ready for VLBI science observing by Dec 2015: the technical go/no-go decision date for ALMA Cycle 4

ALMA in VLBI Networks

- Principles of ALMA participation in VLBI
  - ALMA will only participate in open-access VLBI networks
  - VLBI proposals will be assessed in competition with other ALMA proposals
  - ALMA will potentially be available to observe in VLBI mode during 2-3 sessions of a few days each per cycle – times agreed in advance
  - ALMA and VLBI data products will become public after some proprietary period
- Proposed model for ALMA in Cycle 4 (Oct 2016 – Sept 2017)
  - ALMA joins the GMVA for (a subset of) observations at 3mm
  - Ad hoc network for 1mm observations – negotiations in progress
  - Decision on Cycle 4 model at November ALMA Board Meeting

Near/mid-term Development Strategy

- Top priority: complete commissioning of rebaselined ALMA trilateral programme
  - Full polarization, single dish, observing efficiency, solar modes
- Restore capability lost in descopes before 2005
  - mmVLBI; Bands 1, 2, 5; subarrays; data rate
  - whenever possible, tighten specifications, use new technology
- Studies aimed at a major upgrade of ALMA by 2030
  - Increase bandwidth to at least 16 GHz/polarization
  - Receivers, digital electronics, correlator, sotfware
  - Longer baselines?
  - Focal plane arrays?

True multifrequency receivers could form part of this plan. Probably most effective to combine low+high frequency for calibration, but easiest to have two very high frequencies.

Ongoing development (1)

- Band 5
  - 163-211 GHz
  - Production in progress (NOVA/GARD/NRAO)
  - 8 cartridges integrated and tested; completion expected 2017
  - Performance well within specification
- Band 1
  - Lowest frequency band for ALMA: 35 – 50(52) GHz
  - 8 GHz IF bandwidth
  - LNA technology, SSB
  - T_{SSB} < 25K (80%), <32K (full band)
  - Prototype under construction by ASIAA
  - Full production proposal after successful CDR
- Band 2
  - 67-90 GHz
  - Prototype being built at NRAO
  - European Development Study – Band 2+3 (67-116 GHz) INAF Arcetri/Bologna; Manchester, RAL, ESO

Ongoing development (2)

- Phased signal for pulsar observations
  - Search for millisecond pulsars near Galactic Centre
  - Optimum frequency?
  - Commensal with VLBI or not?
  - Cycle 5?
- European Development Studies
  - Next call will be in 2016 (deadline ~September)

Summary

- ALMA is already providing transformational (sub-)mm science
- Lots still to do, especially to improve efficiency, but also to add new functionality
- Good prospects for VLBI including ALMA from Cycle 4
- Think about multifrequency enhancements.