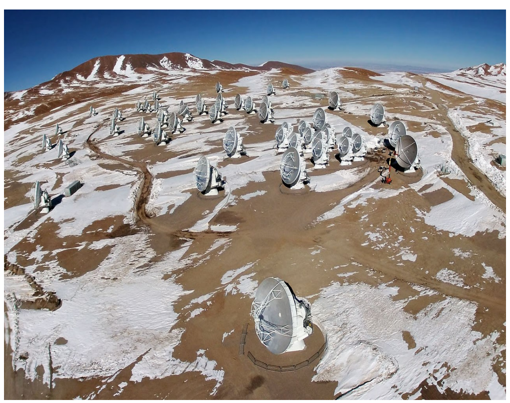
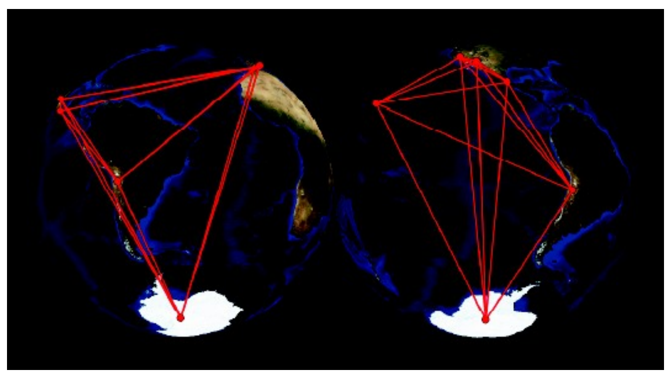
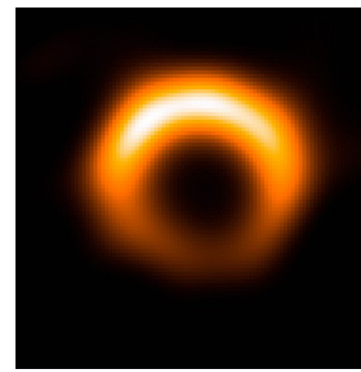
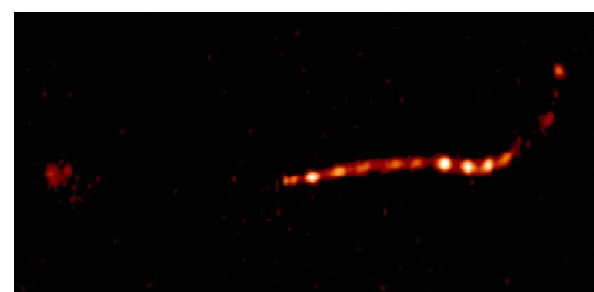
Relativistic Astrophysics with ALMA

Robert Laing, ESO









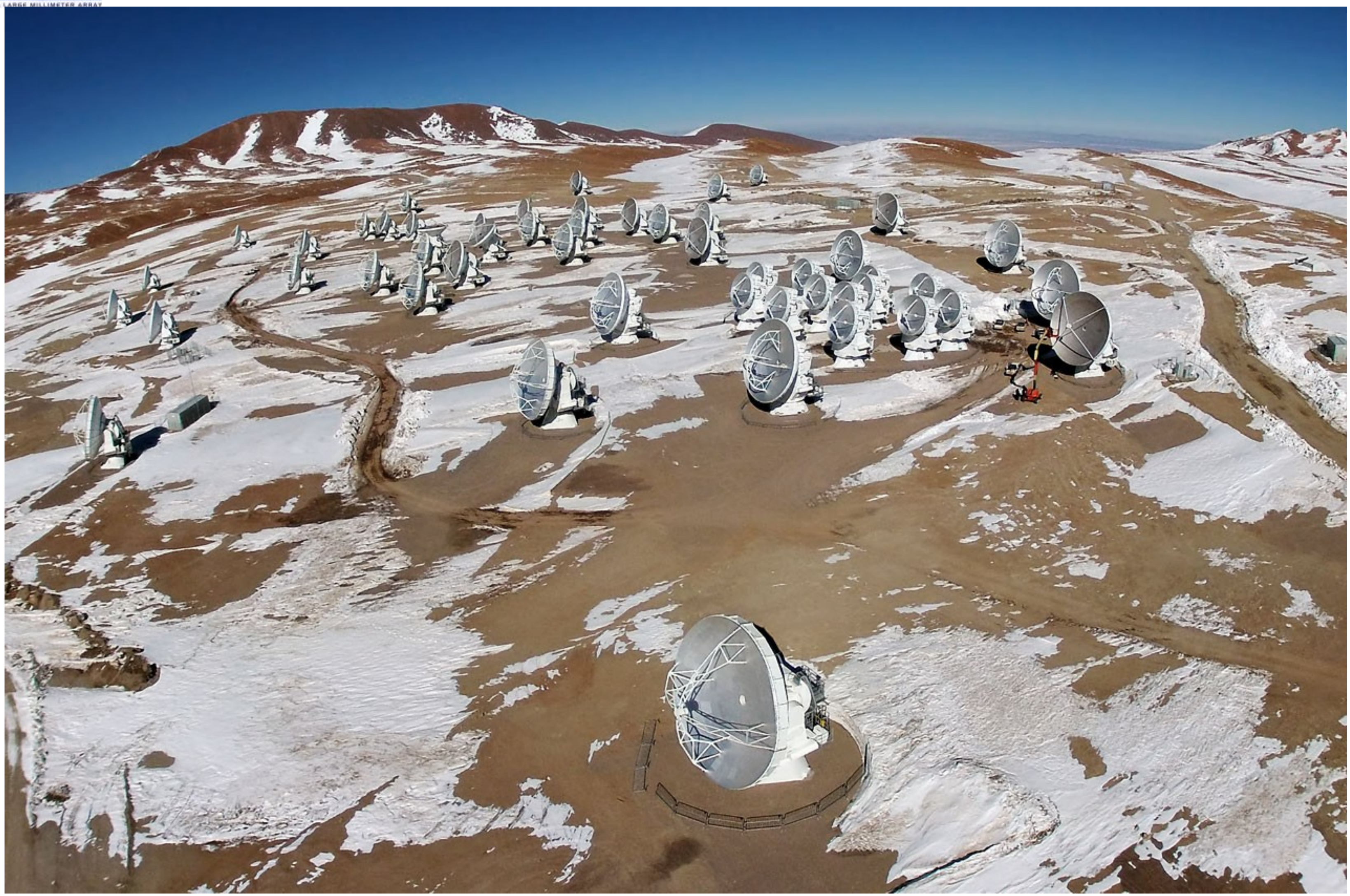
Outline

- What is ALMA?
- ALMA Science Highlights: the Cool Universe
- Relativistic Astrophysics with ALMA
  - Non-thermal emission and jets
  - Gravitational lensing
- ALMA as a phased array: testing General Relativity and more
  - VLBI at (sub-)mm wavelengths
  - Event Horizon shadows
  - Jet launching

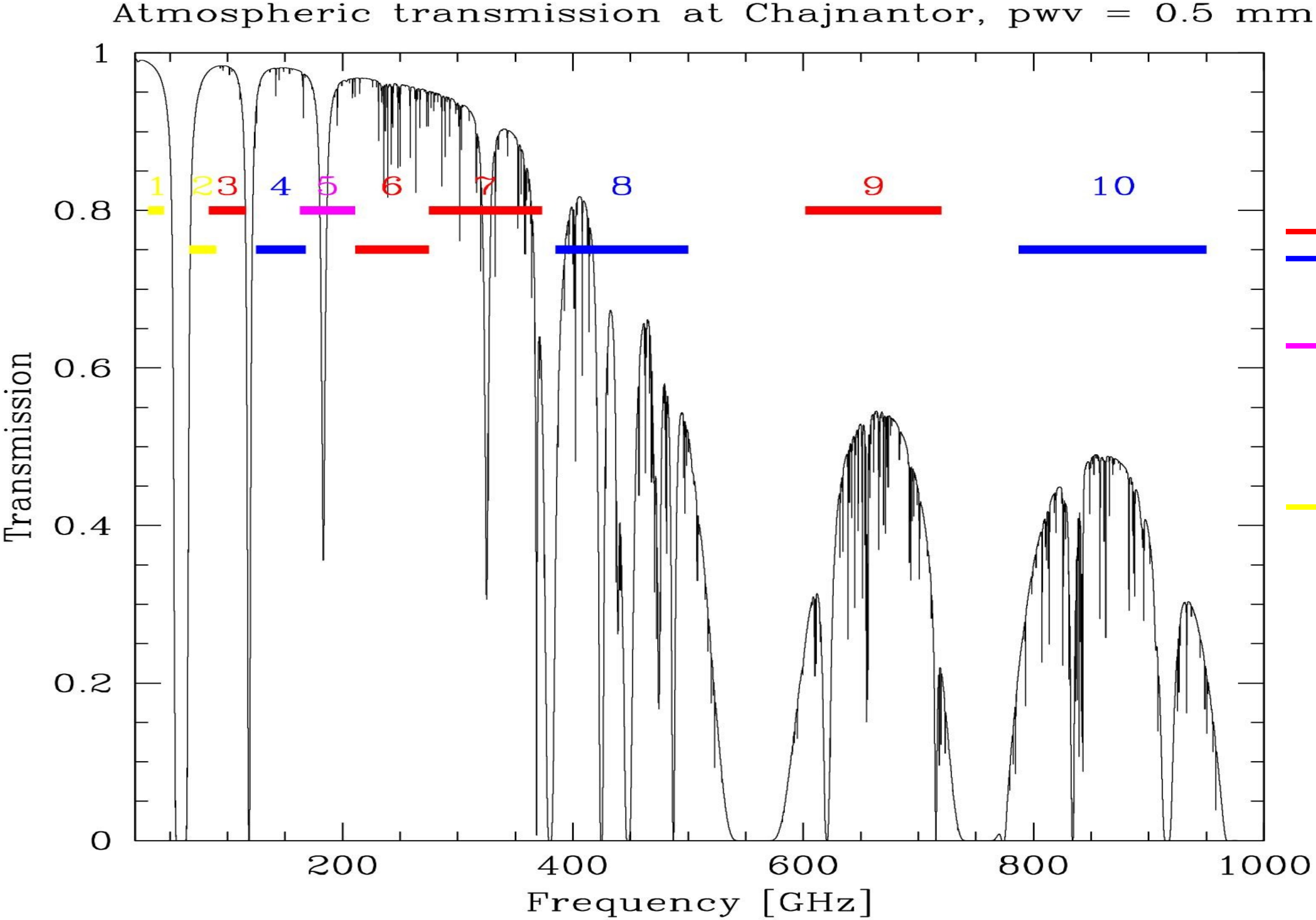
What is ALMA?

- **Atacama Large Millimetre/sub-millimetre Array**
- 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; reconfigurable
- **Resolution**/ arcsec ≈ 0.2(λ/mm)/(max baseline/km)
- Field of view / arcsec ≈ 17 (λ/mm) [12m dish]
- **Phase-stable**: fast switching, water-vapour radiometers, LO distribution
- **Sensitive**, wide-band (currently 8 GHz) SIS receivers; full polarization
- **Flexible** digital correlator giving wide range of spectral resolutions.

ALMA



ALMA Bands



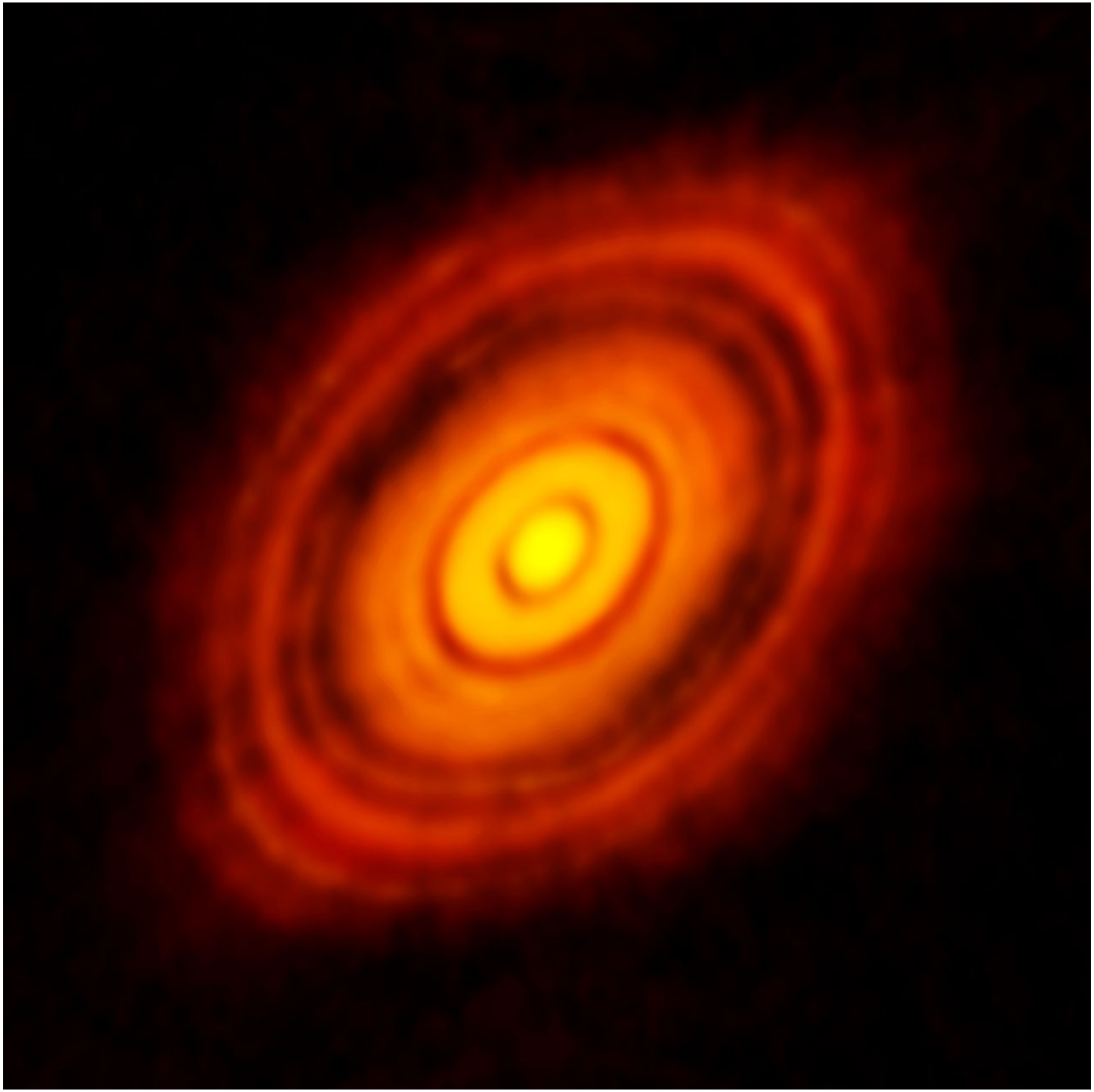
Complete

Being integrated

Not yet built

ALMA Status

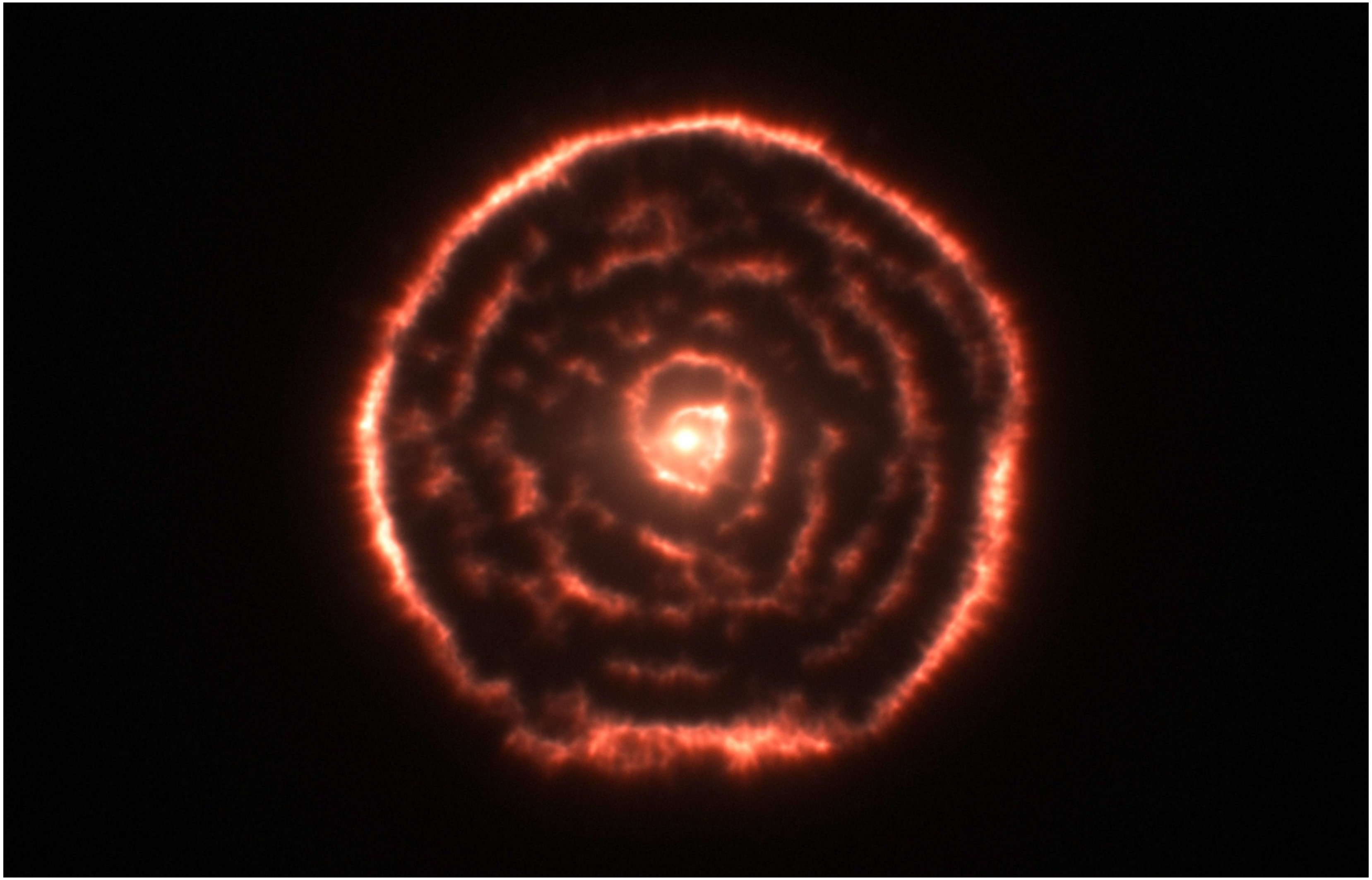
- Construction (essentially) complete
- Early Science began in 2011
- Cycles 0, 1 and 2 complete
  - 30-70% of total number of antennas available; baselines up to 3 km
- ~300 refereed papers
- Already the most powerful sub-mm observatory
- Enormous user pressure: oversubscribed 9x in time
- Cycle 3: 1582 proposals (41% from EU); started Oct 2015
- Cycle 4 deadline April 2016
  - Many new capabilities
- 60% sub-mm (Bands 7-9)



HL Tau protoplanetary disk

(ALMA Collaboration 2015)

CO2-1 emission from R Sculptoris
(Maercker et al. 2012)



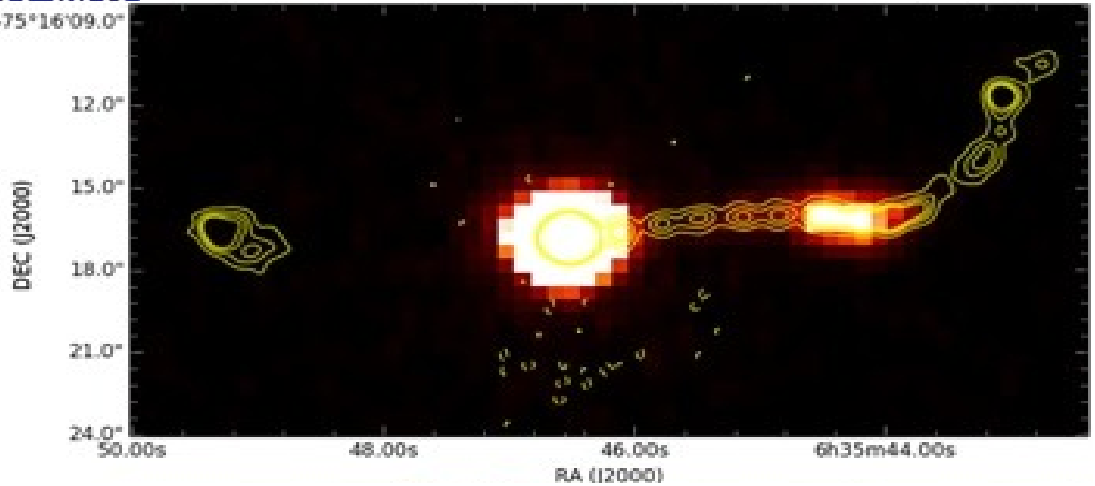
ALMA and Relativistic Astrophysics

- Science drivers are planet, star and galaxy formation
  - Thermal emission from dust; rest-frame molecular and redshifted atomic transitions

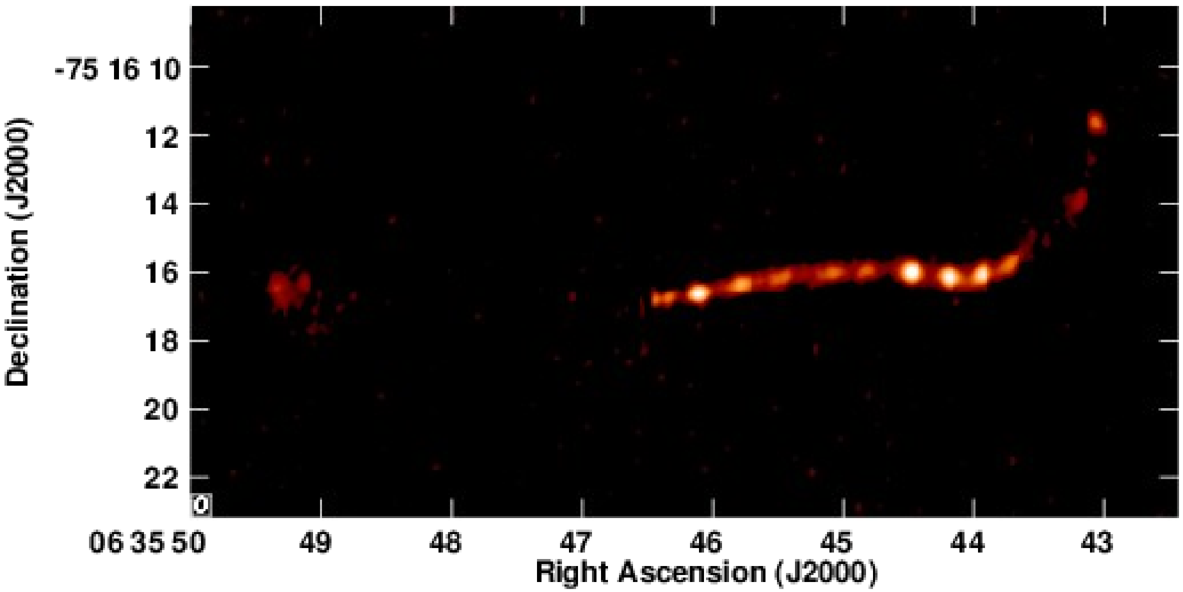
So why am I giving a talk at a conference on relativistic astrophysics?

- Relativistic electrons (usually non-thermal distribution)
  - Synchrotron emission in mm/sub-mm
- Extremely high spatial resolution (VLBI)
- Extreme Faraday rotation (e.g. in accretion flows)
- Strong gravitational lensing
- Compton scattering
  - SZ Effect

kpc-scale jets

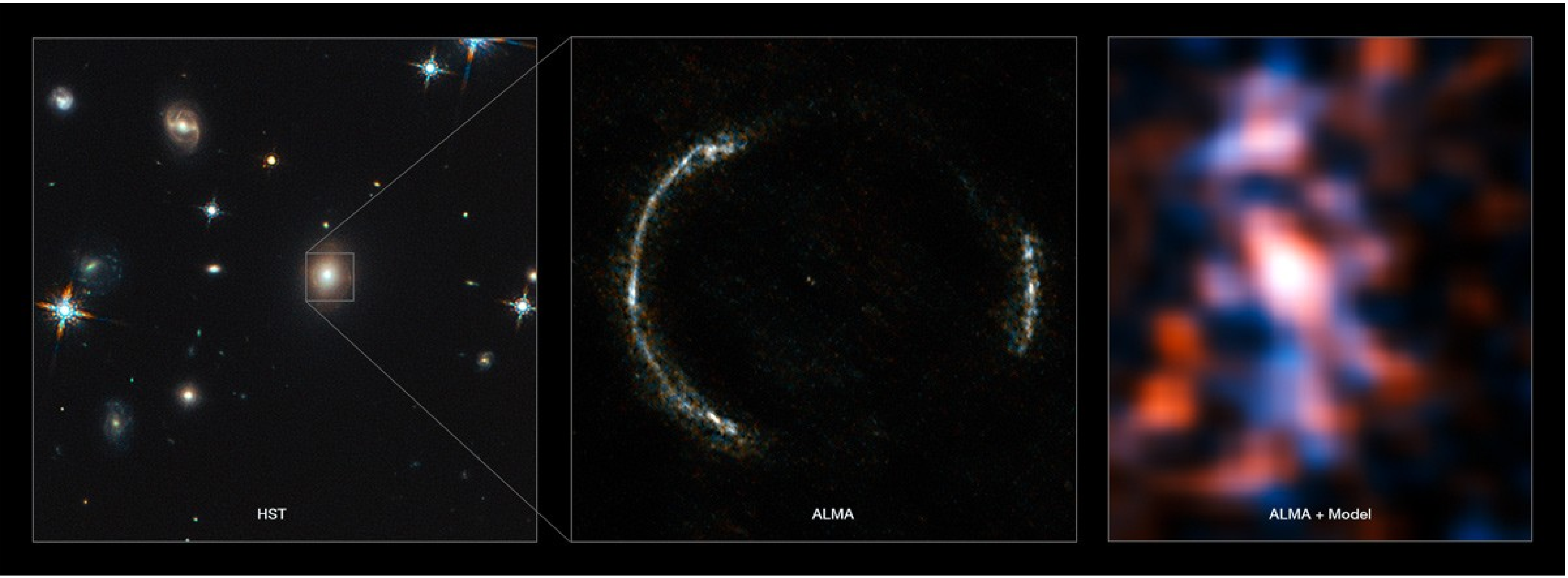


ATCA 18 GHz contours
Chandra false colour
Meyer et al. (2015)



ALMA 230 GHz
Calibration source
Core subtracted

Gravitational Lensing



Lensing galaxy at z=0.3 (HST)

Lensed image (ALMA, 1mm, 30mas)

Background source, z=3.04 <100pc clumps in 2kpc disk

ALMA Collaboration (2015) + Tamura et al. (2015) and others

ALMA in VLBI
Science Drivers

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

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

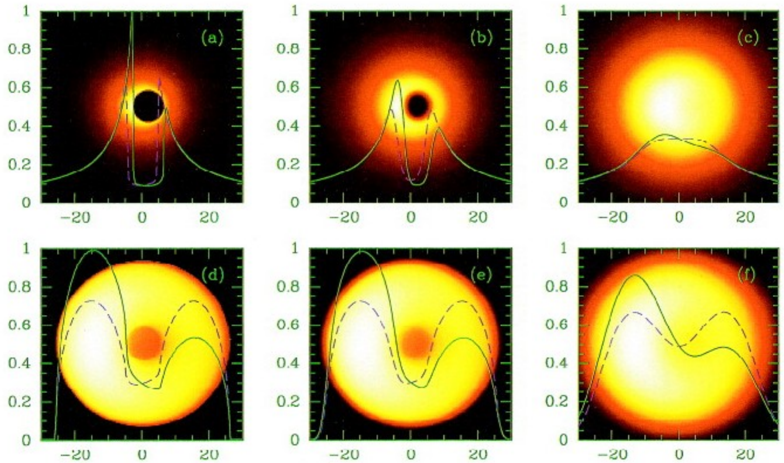
Phased ALMA with 50 antennas is the equivalent of an 85 m single dish on an excellent site

Stand-alone phased array observations: find (ms) pulsars near the Galactic Centre

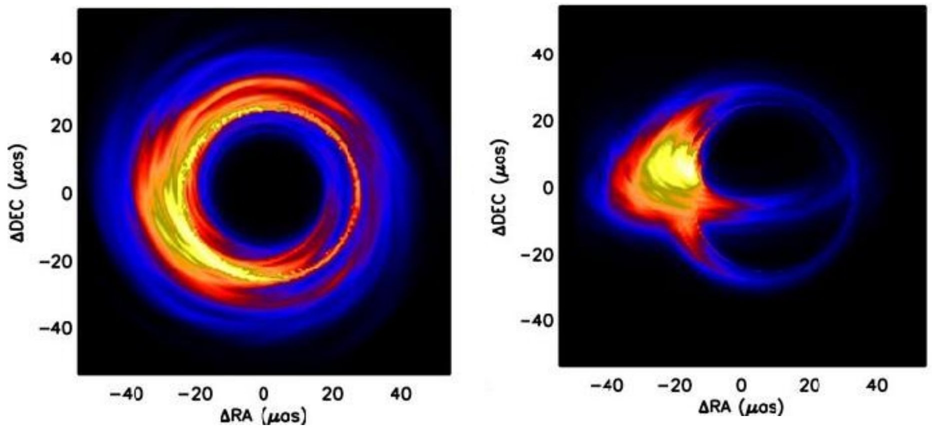
Imaging the Event Horizon Shadow

- Prediction
  - Shadow, surrounded by bright ring; embedded in complex image (accretion or jet)
  - GR: precisely circular for Schwarzschild black hole; nearly circular for Kerr; angular radius ≈ $5r_g/D$
  - If no-hair theorem is violated, radius and shape may change (e.g. Johanssen et al. 2015)
- Galactic centre (Sgr A*)
  - Accurately known mass (4.2×10^6 $M_\odot$) and distance (8.3 kpc)
  - Largest angular size of event horizon
  - Scatter-broadened at frequencies <200 GHz
  - Emission from accretion flow and/or jet
- M87
  - Mass estimates from gas and stellar dynamics differ by a factor of 2 ($3.5 – 6.6 \times 10^9$ $M_\odot$; Walsh et al. 2013; Gebhardt et al. 2011)
  - No significant interstellar scattering
  - Emission dominated by jet

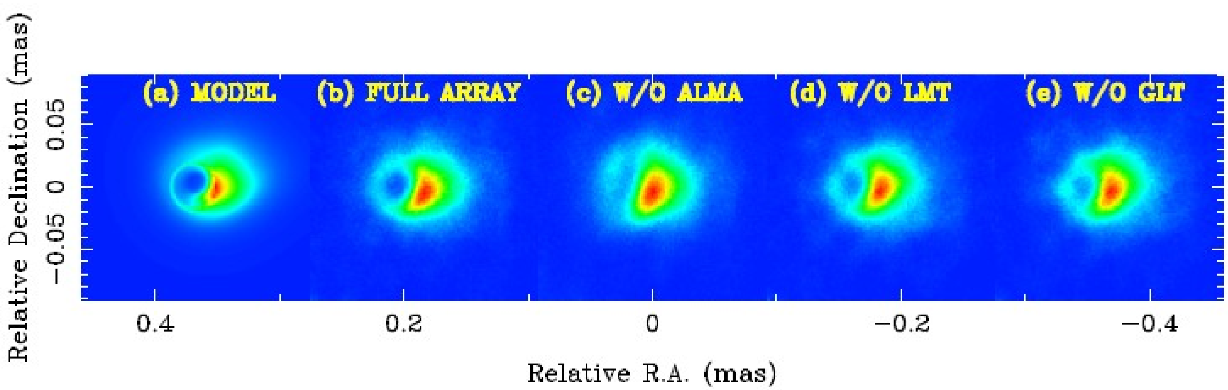
Imaging the Event Horizon Shadow: Simulations



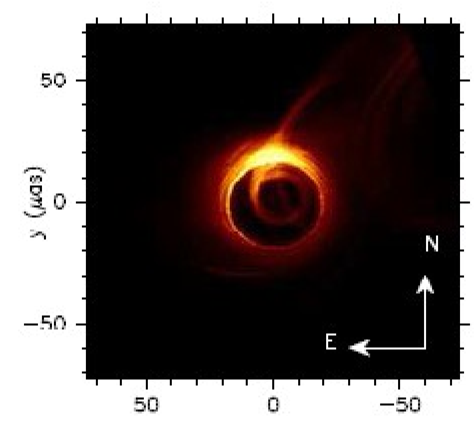
Sgr A* Falcke et al. (2000)



Sgr A* Dexter et al. (2009)

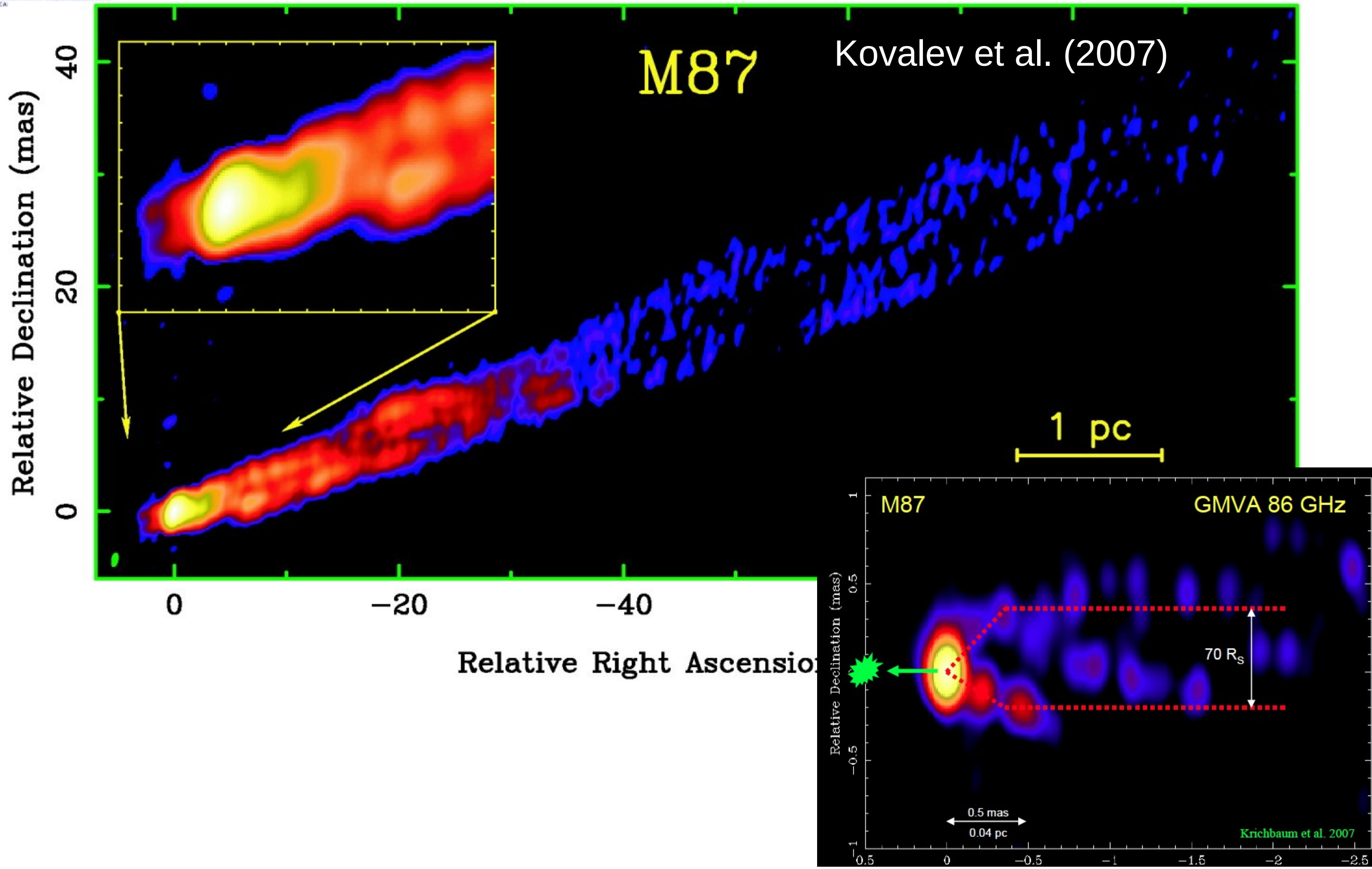


M87: Lu et al. (2014)



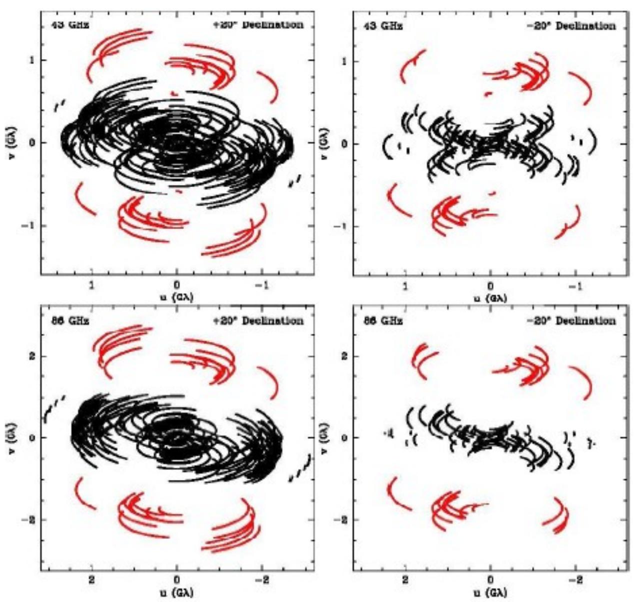
M87: Moscibrodzka et a; (2015)

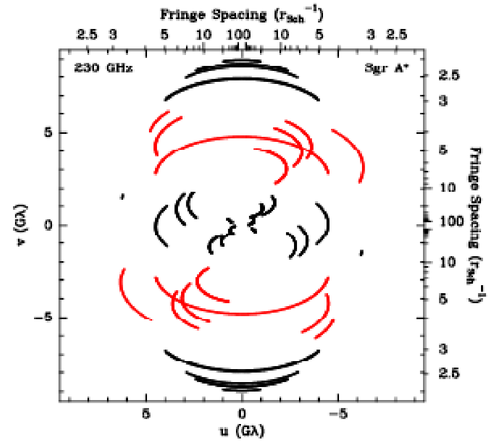
Jet Formation



Arrays

- 230 GHz (1.3mm)
  - ALMA, LMT, SMT, JCMT+SMA, IRAM 30m, PdB, SPT
- 86 GHz (3mm)
  - ALMA, VLBA (8 antennas), GBT, Yebes, Effelsberg, Onsala, IRAM 30m, PdB, (LMT)





Shadow radius for Sgr A* = 28 μas

Resolution $\lambda/D_{max} \approx 20$ μas

Dictionary

- ALMA Phasing Project
  - Hardware and software to use ALMA as a phased array
  - Led by MIT/Haystack (PI S Doeleman), with NRAO; MPIfR and OSO in Europe; ASIAA, NAOJ
  - Majority funding from NSF + in-kind contributions
- Event Horizon Telescope Collaboration
  - Global collaboration for VLBI at 230 (and 345) GHz
  - Prime targets are Sgr A* event horizon and the M87 jet
  - Structure at $8r_g$ scales in Sgr A* with 3-station array (Doeleman et al. 2008)
- 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

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
- **Fringes on baseline ALMA – IRAM Pico Veleta at 1mm; March 2015**
- **Fringes on baselines ALMA – six VLBA antennas; Aug 2015**

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
- 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 – EHTC + NRAO

ALMA Board approval Nov 18 2015
ALMA Observatory technical approval Nov 30 2015
Proposal deadlines Feb – April 2016