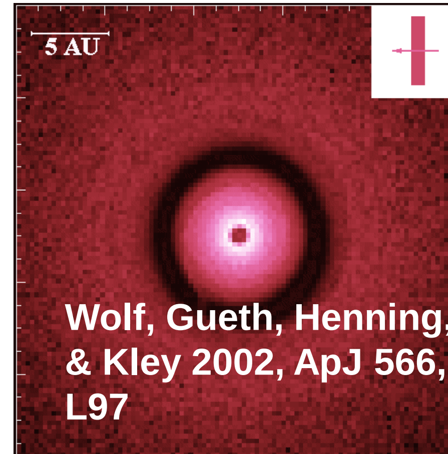
Overview

The ALMA Partnership

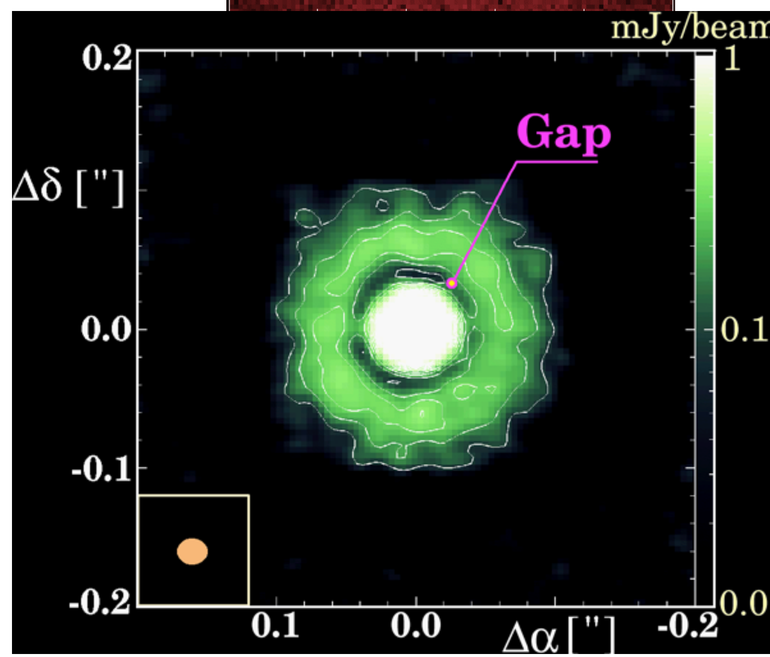
- **ALMA is a <u>global</u> partnership:**
  - North America (US, Canada; Taiwan in process)
  - Europe (via ESO with Spain)
  - Japan (now including Taiwan)
  - 50:50 partnership between NA & Europe + *closely-coordinated but separate effort by Japan (Enhanced ALMA)*
- **Key Science Goals:**
  - Image protoplanetary disks:
    - physical, chemical, magnetic field structure
    - detect tidal gaps created by planets undergoing formation in the disks
  - Image starburst galaxies as early as z = 10
  - Image normal galaxies like the Milky Way out to z = 3
- **Site: Llano de Chajnantor of Altiplano: 16500’ above sea level**
- **Will operate as single Observatory with scientific access via regional centers**

Science Goals:
Imaging Protoplanetary Disks I

- Protoplanetary disk at 140pc:
  - Model of Jupiter mass planet at 5AU



- ALMA simulation
  - 428GHz, bandwidth 8GHz
  - total integration time: 4h
  - max. baseline: 10km



Science Goals:
Imaging Protoplanetary Disks II

$M_{planet} / M_{star} \quad = \quad 1.0 M_{Jup} / 0.5\ M_{sun}$

Orbital radius: 5 AU

Disk mass as in the circumstellar disk as around the Butterfly Star in Taurus

Maximum baseline: 10km,

t_{int}=8h,

30deg phase noise

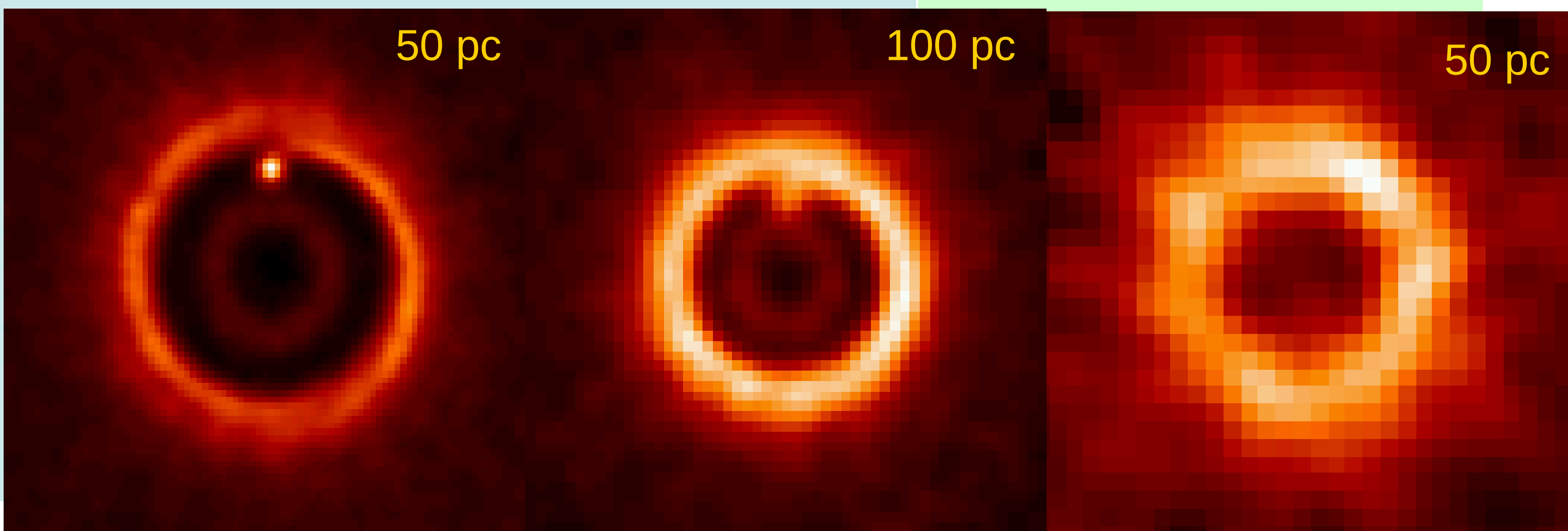
pointing eror 0.6“

Tsys = 1200K (333M) / 220K (870M)

Sebastian Wolf (2005)

L = 333mm

L = 870mm



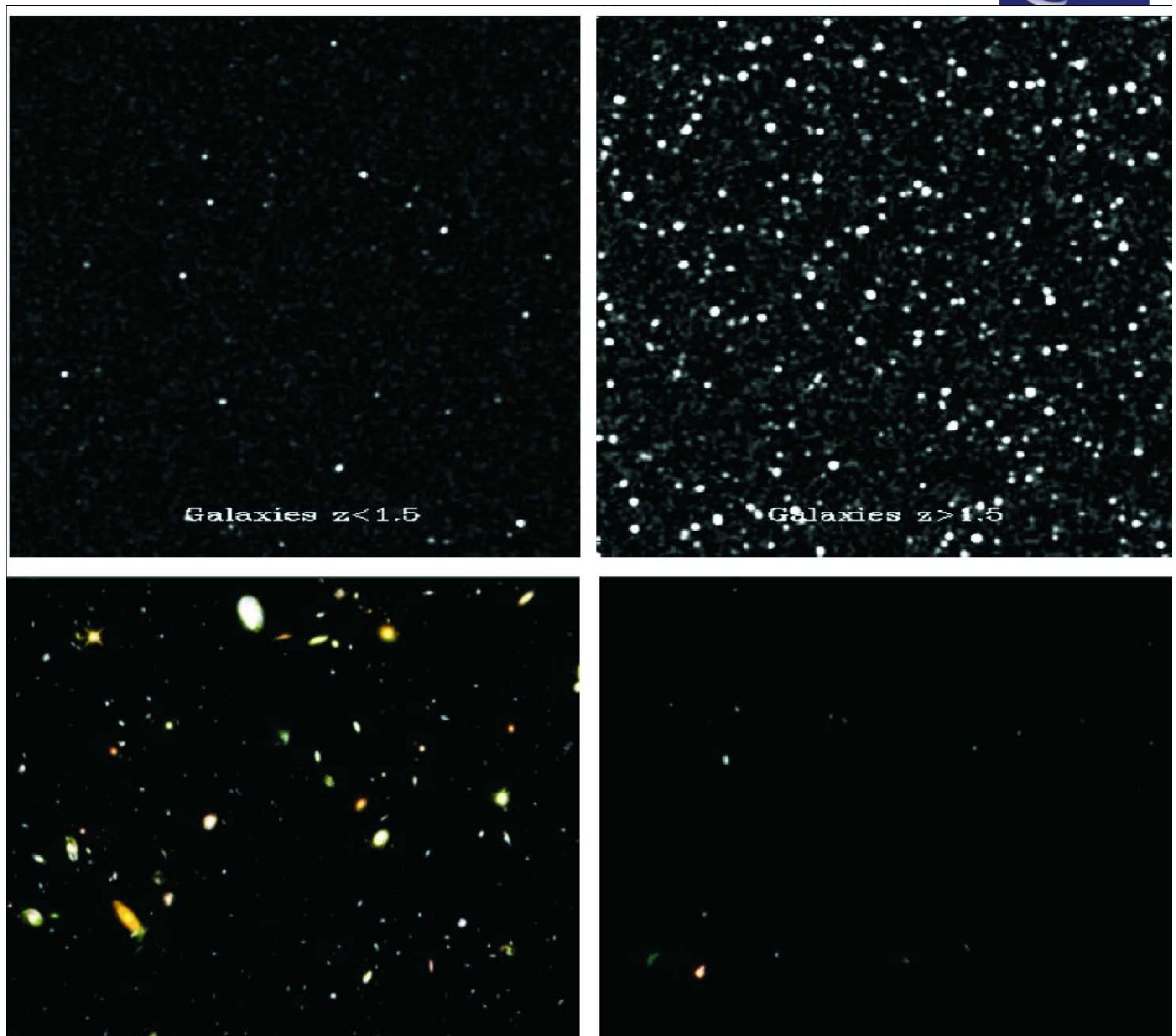
Science Goals: Extragalactic Astronomy

HDF redone:

- Comparable resolution
- Much deeper

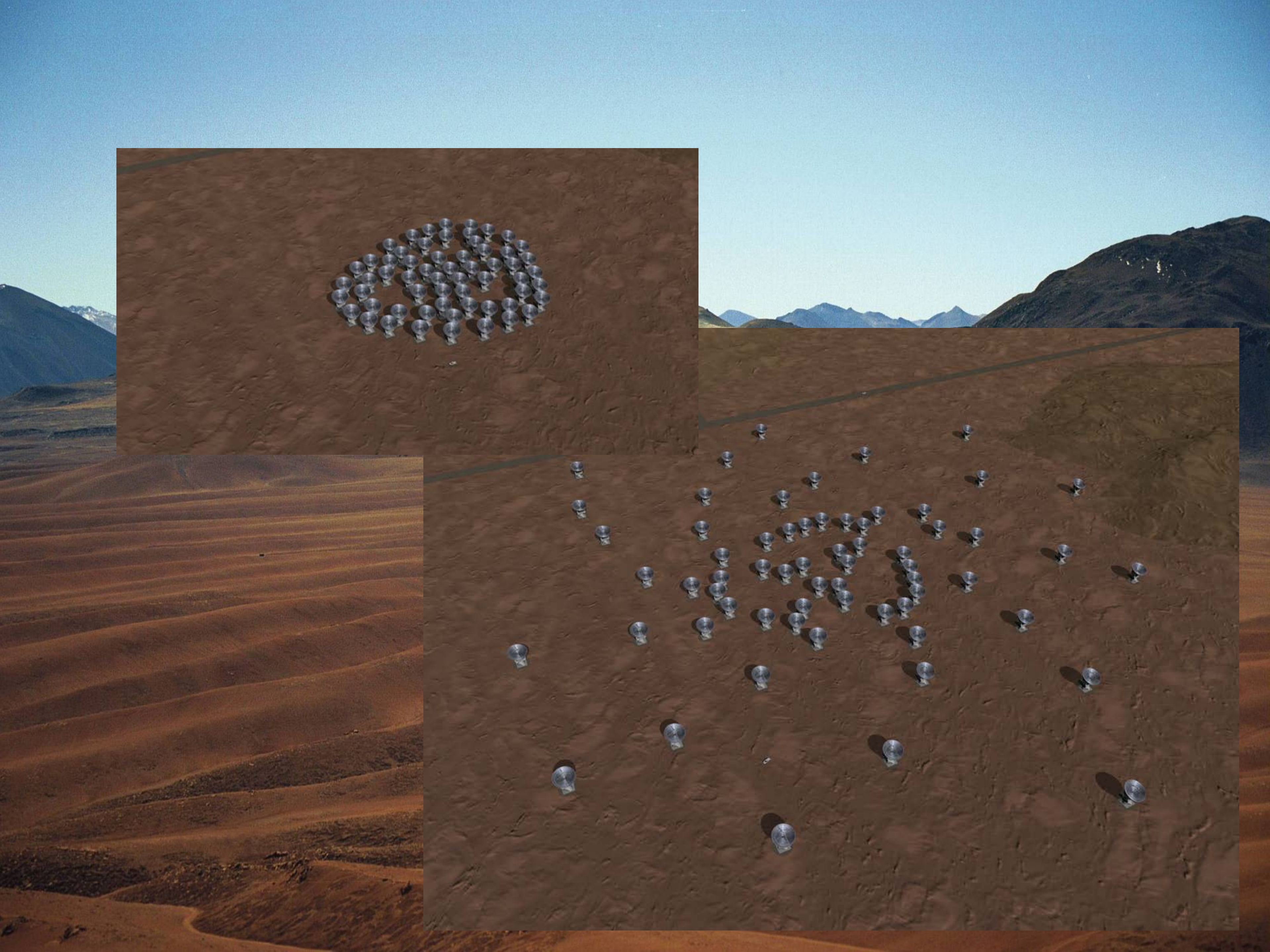
ALMA

HDF



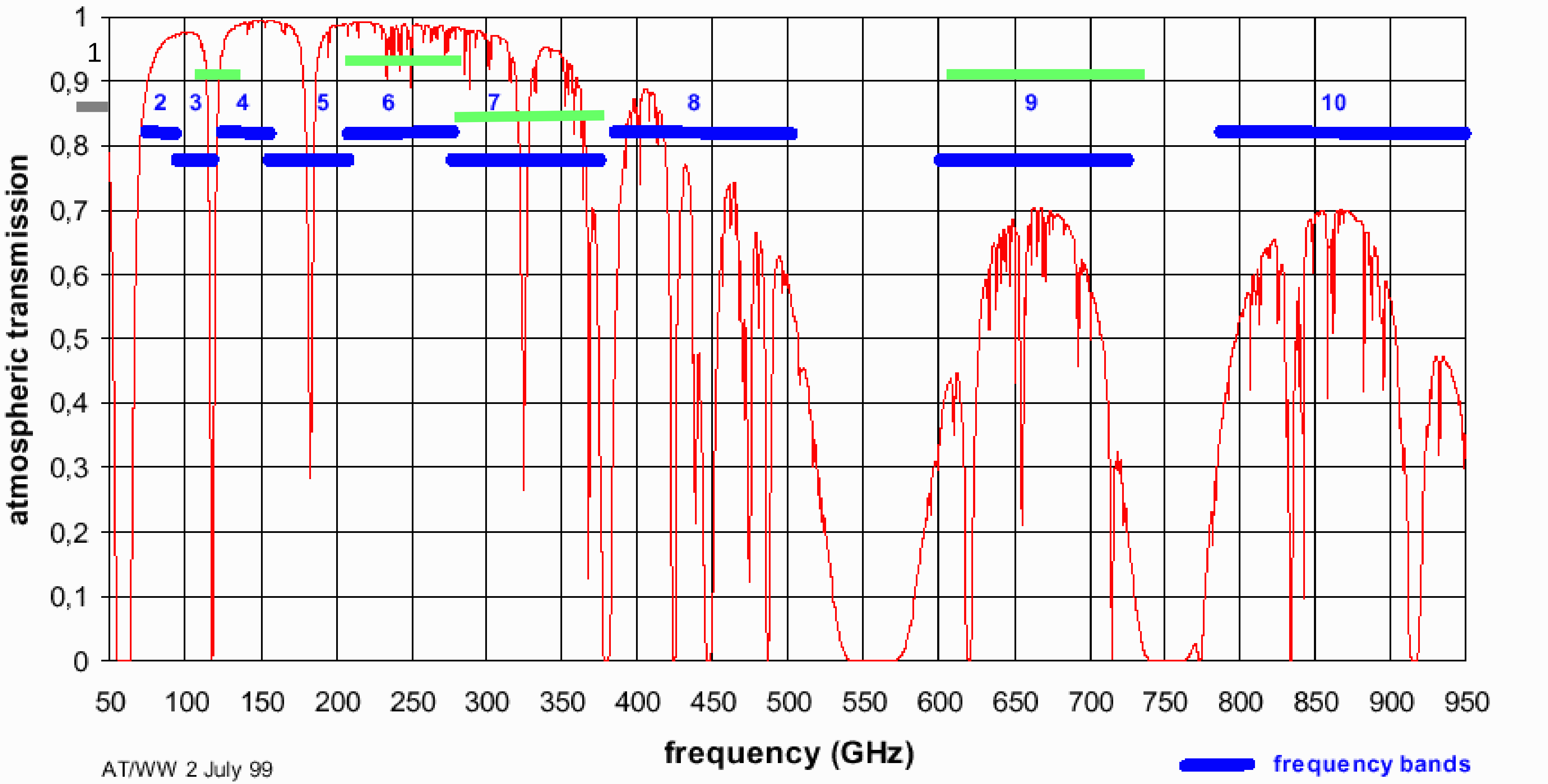
What Is ALMA?

- **ALMA is an <u>interferometer:</u>**
  - 50 12m antennas (bilateral project)
  - Japan's Compact Array: 4 x 12m + 12 x 7m antennas
- **Baselines from 15m to 15km**
- **Sensitive, precision imaging between 30 and 950 GHz**
  - Receivers for each atmospheric "window"
  - First light system has 6 bands:
    - 100, 230, 345 and 650GHz
    - Japan 140, 460 and 900GHz
- ***10-100 times more sensitive and 10-100 times better angular resolution compared to current mm/submm telescopes***



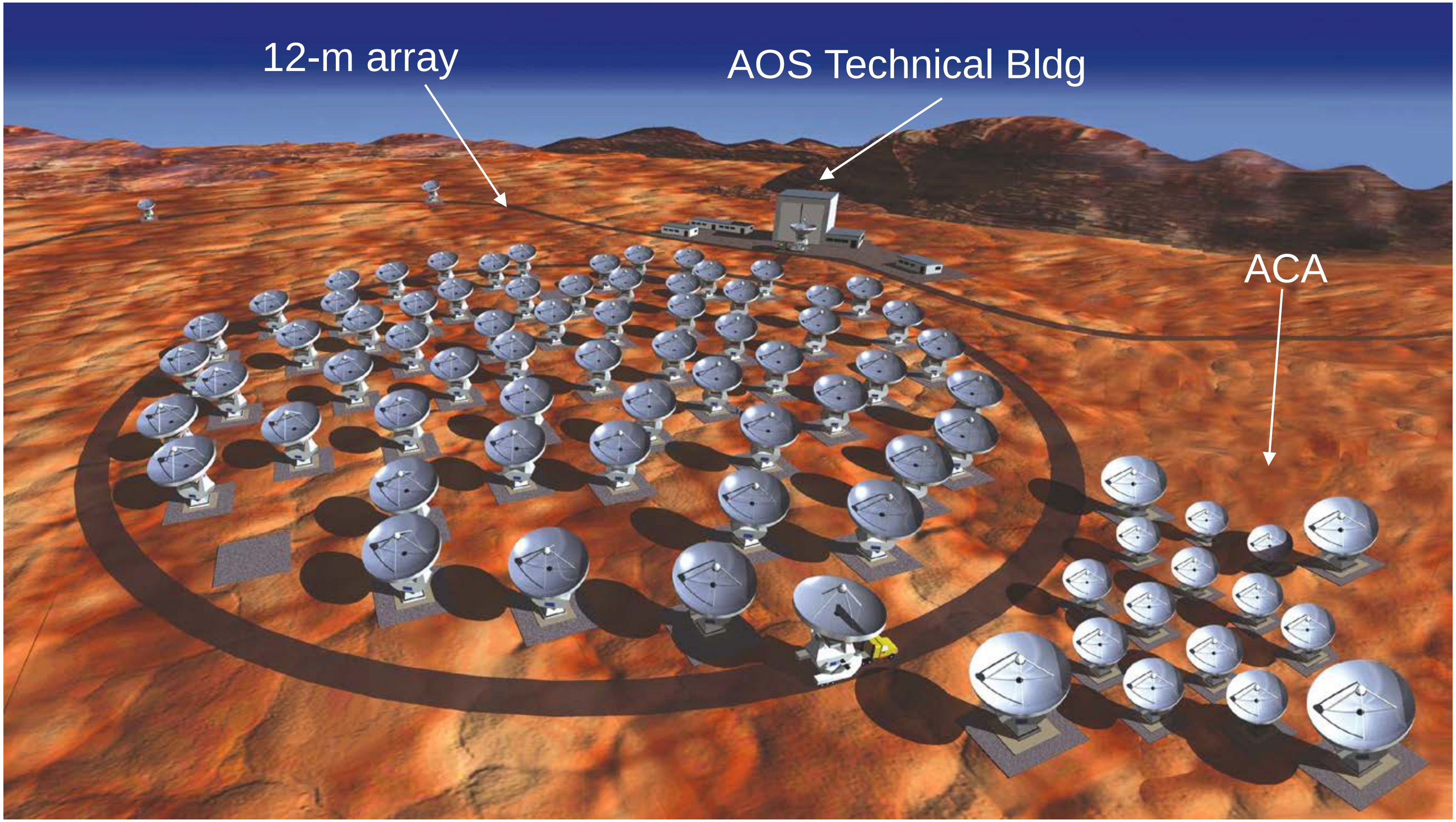
Frequency Coverage

Atmospheric transmission at Chajnantor, pwv = 0.5 mm



Note: Band 1 (31.3-45 GHz) is off-scale to left

Enhanced ALMA



Rebaselined Cost and Schedule: Overview

- **Total Cost**
  - Original: ~ $689M (European contribution very approximate)
  - Rebaselined: ~$1033M (No adjustment for Japan, €)
- **NA Cost**
  - Original: $344.2M
  - Rebaselined: $ 477.68M (+ additional contingency, less Taiwan)
- **Schedule:**
  - Original Completion: 2011
  - Rebaselined Completion: 2012
- **Cost Containment Efforts:**
  - Scope reduction: Decrease N_{ANT} from original 64
  - New Partner: Taiwan

Descopes: Relative Performance –I

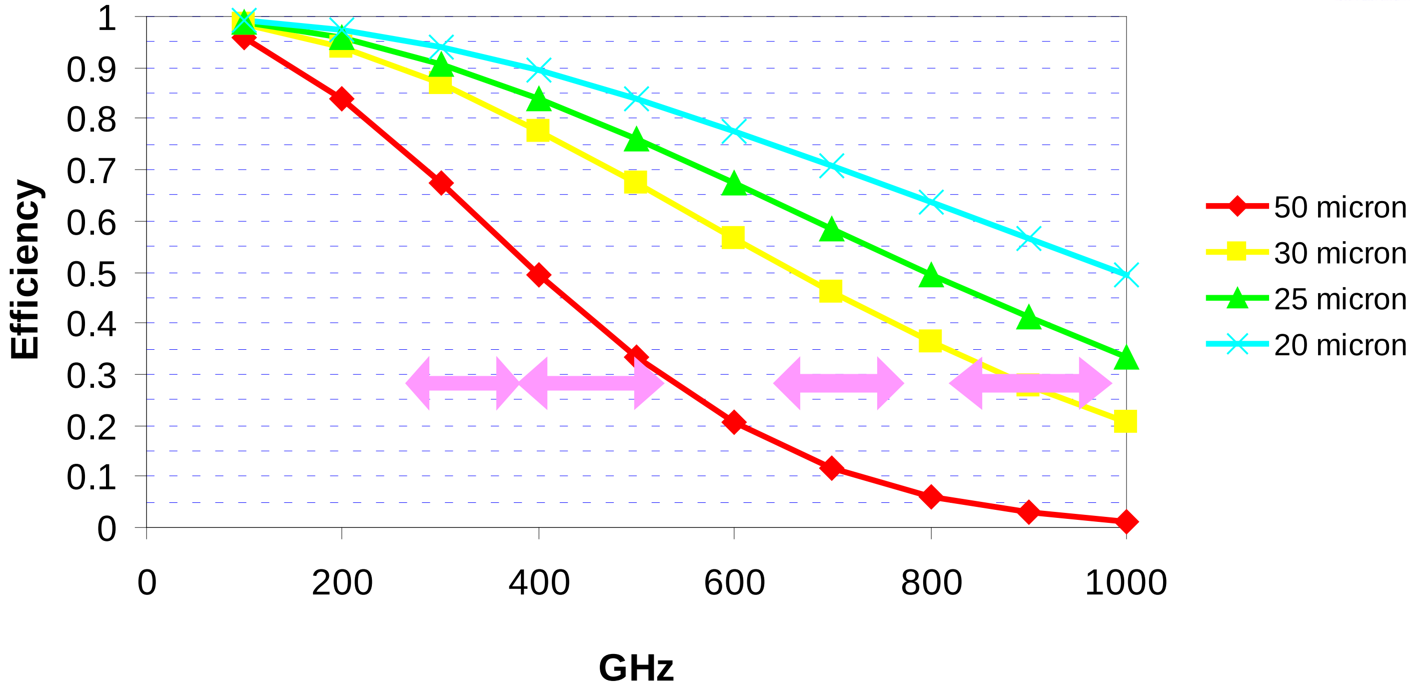
Metrics:

- Point-Source Sensitivity: $N*D^2$ (collecting area)
- Imaging Speed: N*(N-1)/2 (number of baselines)
- Image Fidelity: N*D (mosaics)

Notes:

- Does not account for improved antenna performance relative to surface rms specification
- Does not account for improved receiver performance relative to system temperature specifications
- Impact → ALMA performance relative to existing arrays is better than indicated

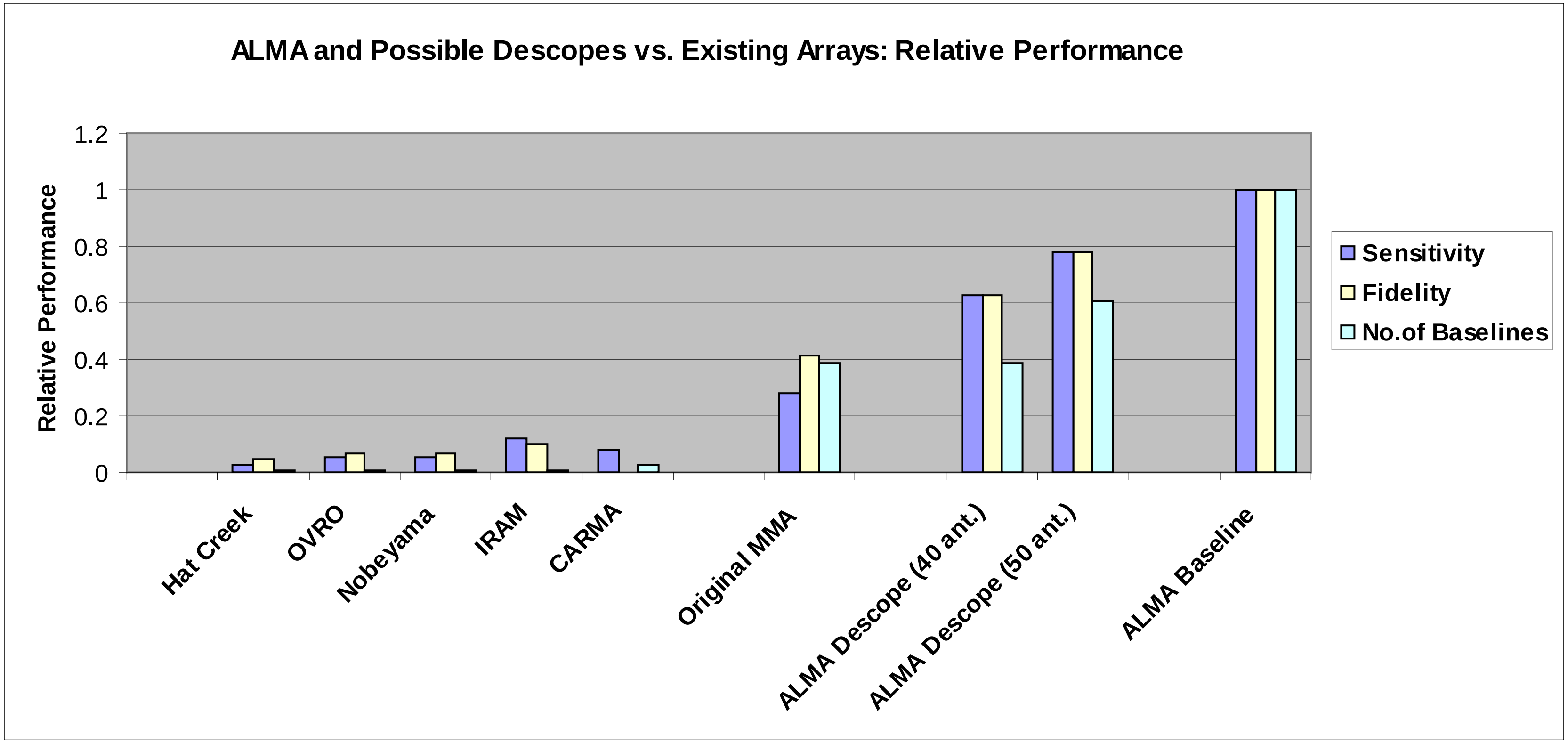
Ruze equation



Importance of trade-offs in efficiency vs number of antennas:

<u>Example:</u> At N ~1 THz, surface improvement of 30→25 Mm is equivalent to having 50% more antennas

Descopes: Relative Performance –II



Timeline

Timeline – I

- **1990**: NRAO/AUI submits proposal to NSF for Millimeter Array
- **1991:** MMA proposal reviewed
- **1994:** NSB approves MMA Project Development Plan (November)
- **1998:** MMA Design and Development funding begins (May)
- **1999**: Phase I international agreement signed (June)
- **1999**: review of US reference design of MMA (July)
- **2000**: ESO Phase I funding begins
- **2000:** US-Canada Letter of Intent to collaborate
- **2002:** US Construction begins (May)
- **2003**: ESO Construction funding begins (January)
- **2003**: ALMA Agreement signed by NSF and ESO (February)
- **2003:** Massimo Tarenghi becomes ALMA Director(April)
- **2003:** US and Canada sign NSF-NRC MoU (June)
- **2003:** ALMA site groundbreaking (November)

Timeline – II

- **2003**: production antenna RfP/CfT issued (December)
- **2004:** initial report on technical evaluation of ALMA prototype antennas (June)
- **2004:** production antenna bids opened by AUI and ESO (June)
- **2004:** Vertex carries out uncontrolled adjustments and tests of prototype (summer)
- **2004:** production antenna bid review and reconciliation between AUI & ESO begin (July)
- **2004:** AUI presents draft bid package to purchase Vertex antenna to NSF (August)
- **2004:** ALMA Project Engineer and Project Manager join JAO (late summer)
- **2004:** ALMA-NINS MoU with Japan signed (September)
- **2004:** potential problem with ALMA prototype antennas brought to Board, NSF(October)

Timeline – III

- **2004:** NSF suspends AUI antenna procurement approval process (October)
- **2004:** additional prototype testing program mandated, assigned to ALMA PM (November)
- **2004:** Chile agreements finalized (December)
- **2004:** ALMA rebaselining begins (December)
- **2005:** Follow-up testing of prototypes complete, antennas found compliant (April)
- **2005:** AUI finalizes bid package (April)
- **2005:** ESO Finance Committee declines to recommend purchase of Vertex antennas (May)
- **2005:** ESO Council declines to approve purchase of antennas w/o review of new construction budget (June)
- **2005:** ESO Council encourages NSF to allow AUI to purchase antennas first (June)

Timeline – IV

- **2005:** ALMA Board approves proposed AUI Vertex contract (June)
- **2005:** AUI antenna contract signed (July)
- **2005:** Project rebaselining completed and distributed to ALMA Board by JAO (September)
- **2005:** ESO receives drastically lowered antenna bid from AEM; moves toward purchase (September)
- **2005:** Garmisch review of new baseline by Beckwith Committee (October)
- **2005**: ALMA Board begins reform process (November)
- **2005:** ALMA Board approves proposed ESO antenna contract (December)
- **2005:** ESO Council and Finance Committee approve AEM antenna contract (December)
- **2005:** ESO signs antenna contract (December)
- **2005:** ESO signs antenna transporter contract (December)
- **2006:** Review of "delta" costs associated with two antenna decision (January)
- **2006:** Review of new NA baseline by Hartill committee (February)
- **2006:** Director's Review (March)

Interferometry

Angular Resolution

- $\alpha \sim (\lambda / D)$ (smaller is better)
- Hubble Space Telescope:

  $\alpha \sim 0.1$ arcseconds at 5000Å
- Green Bank Telescope:

  100m antenna at $\lambda = 21$ cm, $\alpha \sim 0.1$ <u>degrees</u>

  <u>Single dish sizes limited by materials</u>
- → Interferometers (Arrays): $\alpha \sim (\lambda /$ <u>separation)</u>

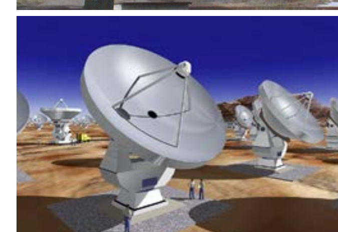
  Antennas needed for collecting area

  Computers essential

  Complex optimization

  35 km separation at $\lambda = 21$ cm, $\alpha \sim 1$ <u>arcsecond</u>
- ALMA

  At 15 km separation, $\lambda = 0.35$mm, $\alpha \sim 0.01$ <u>arcsecond</u>

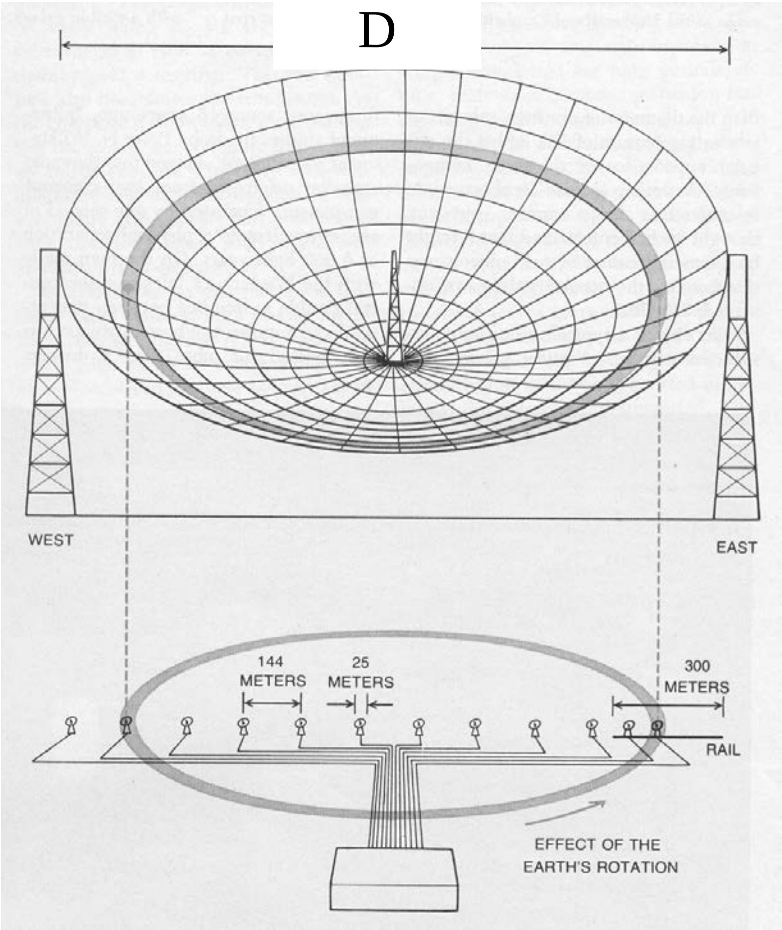


Optical and Radio Telescopes

- Angular resolution: $\alpha \sim (\lambda / D)$ (smaller is better)
- Optical Telescopes:
  - Geometric optics
  - Focal plane large
  - Angular resolution ("detail") limited by atmospheric distortion, not diffraction (except for HST and AO systems)
  - Field diameter/Resolution ~ 5000
- Radio Telescopes:
  - Physical optics
  - Small focal plane (single on-axis pixel spot is typical)
  - Angular resolution determined by physical size of antenna
  - Field diameter/Resolution < a few
  - Resolution limited by physical limitations of structures…**BUT**

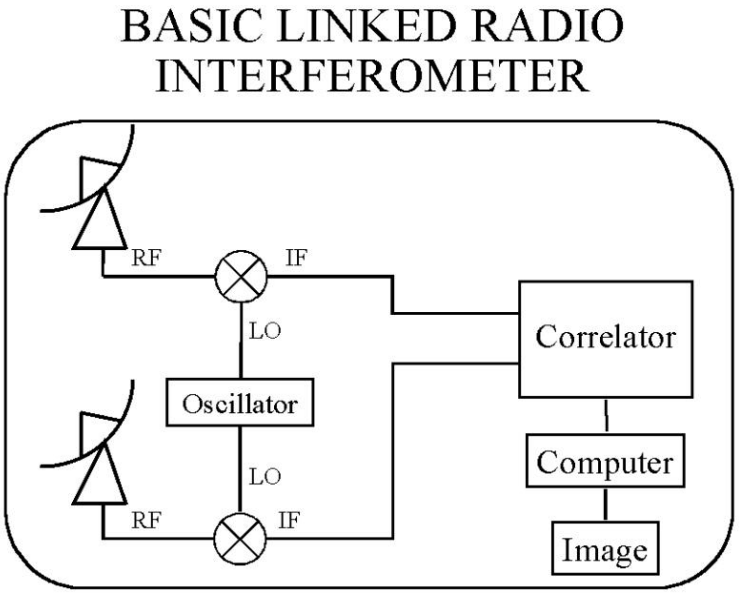
Interferometry - I

- Resolution $\propto \lambda/D$
  - 5 cm/100m = 2 arc-minutes (GBT)
- Use an array of smaller telescopes to make much larger 'virtual' telescope
- **Maximum distance between antennas determines resolution**
- *e.g.,* VLA = 22-mile diameter radio telescope
  - 5 cm/22 miles = 0.3 arc-second



Interferometry – II

- Each pair of outputs of the antennas in an interferometric array must be multiplied in strict phase
- This is done with a specialized computer ("correlator")
- <u>Example:</u> In the 2-antenna interferometer, one measures $<E_1E_2>$, the 2-point correlation of the full (amplitude <u>and</u> phase) signal across the wave-front of the radiation from the source



$<E_1E_2>$

Interferometry – III
Caveats

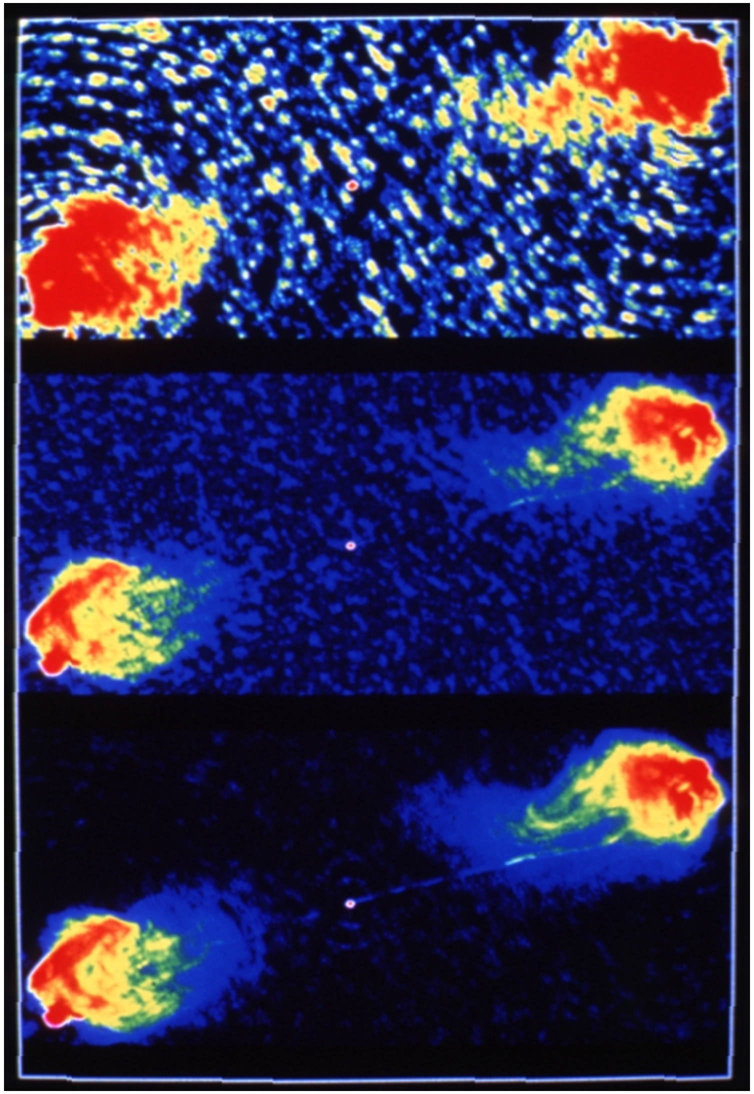
- *All* interferometric images are reconstructed estimates of the image one would have seen had one mapped the field with a filled-aperture telescope
- Because the aperture of an interferometer is not filled:
  - the edges of the individual antennas produce diffraction artefacts in the images which must be corrected for (next slide)
  - the total intensity level of any reconstructed image is totally unknown unless it is separately measured, i.e., uniform or slowly varying brightness components across the field are "resolved out"
  - for regions of the sky larger than λ / D, special mosaic techniques must be used to estimate and restore the resolved-out intensities
  - this will be the case for most Galactic sources and some extragalactic ones
  - the ALMA Compact Array is designed specially to assist with this

Image Processing

Raw “dirty” map

Χλεαν μαπ

Σελφ–χαλιβρατεδ



Discards

ALMA - II

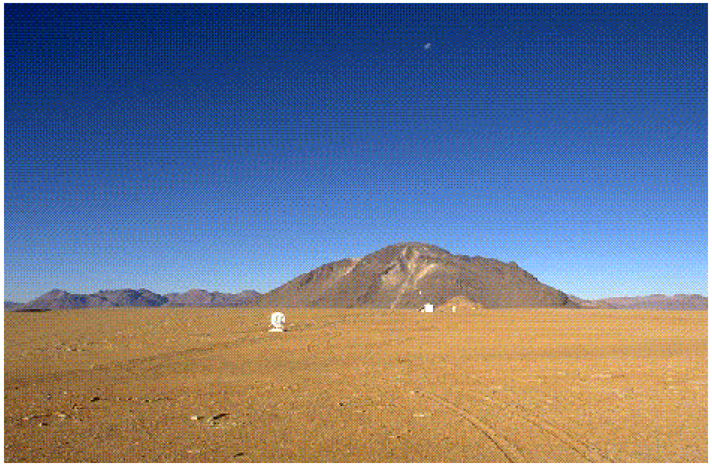
- ALMA began in the U.S. as the Millimeter Array
  - Proposed by AUI/NRAO in 1990
  - Design and Development (D&D) funding began in FY 1998
  - Original scope 40 8m antennas, no submillimeter
  - International partnership required before Construction would be approved by NSB
  - FY 2002 initially proposed as 5th year of D&D, but Congress mandated start of construction in early 2002
- D&D partnership with Europe
  - Parallel, closely coordinated R&D programs
  - Collaboration with Japan active (though not a formal partner)
  - Scope began to evolve: scientific advances (protogalaxies at high redshift), accomodation to slightly different regional scientific interests: More flexible and capable instrument.
  - Bilateral scope: 64 12m antennas, 4 receiver bands into submillimeter

ALMA - III

- ALMA Construction and Operations Partnership
  - ALMA Agreement (binding international agreement)
  - NSF (with Canada) + ESO (with Spain)
  - Signed February 2003, beginning construction project
  - Cost $552.4M (Y2k)
  - Deliverables not expended cash define parity in partnership
- Japan
  -

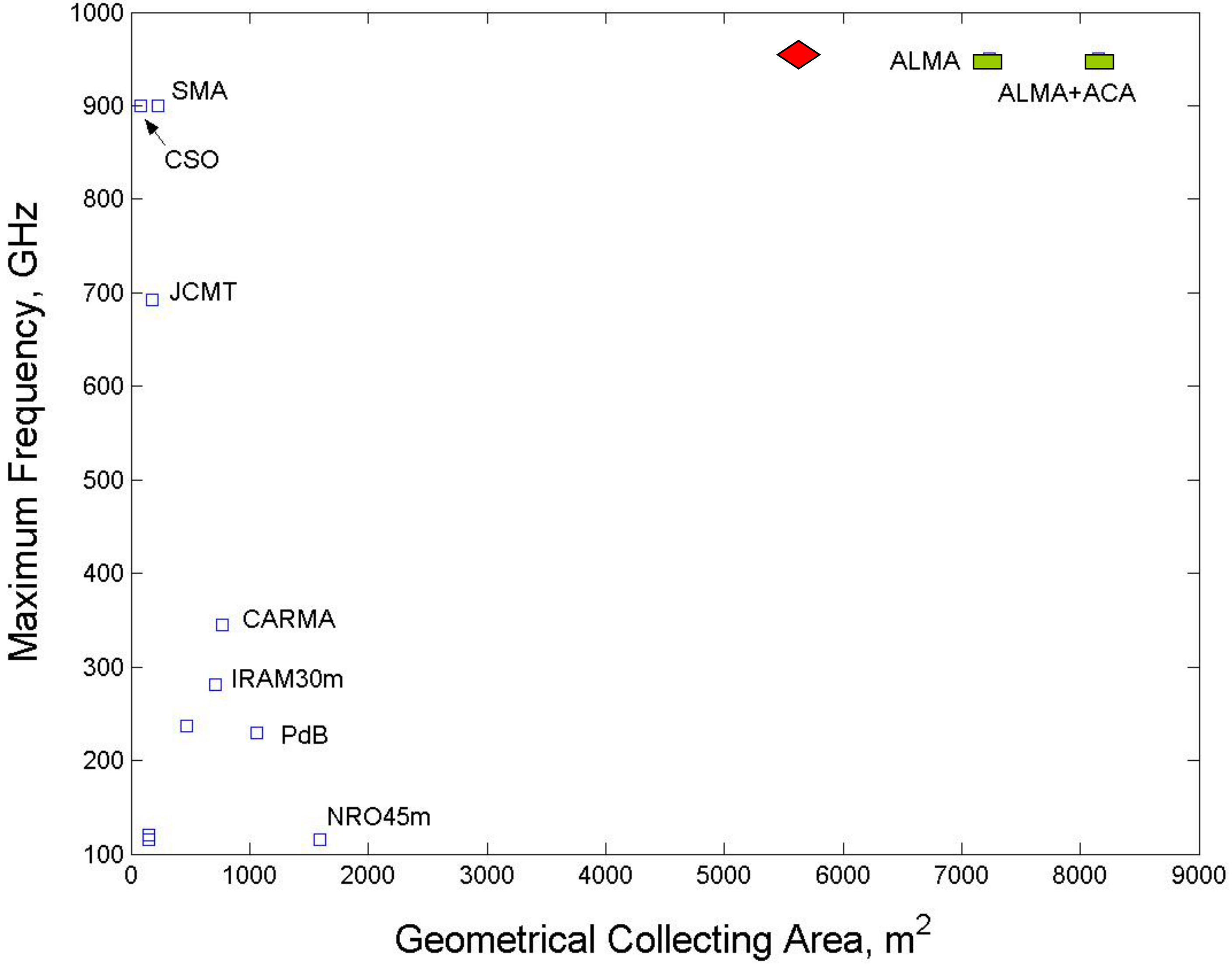
ALMA - IV

- Chile is ALMA Host Country
  - 10% of observing time
  - No capital contributions
- Site near San Pedro de Atacama
  - Altiplano of Andes:
  - Sub-millimeter capability requires arid and high (5050 m, ~16,500 ft.) site for atmospheric transparency
  - Long-baseline interferometry requires flat site 15-20km across
  - Llano de Chajnantor -- near international highway
- Site work is challenging:
  - Altitude
  - Chilean economy is booming
  - Other $\Rightarrow$

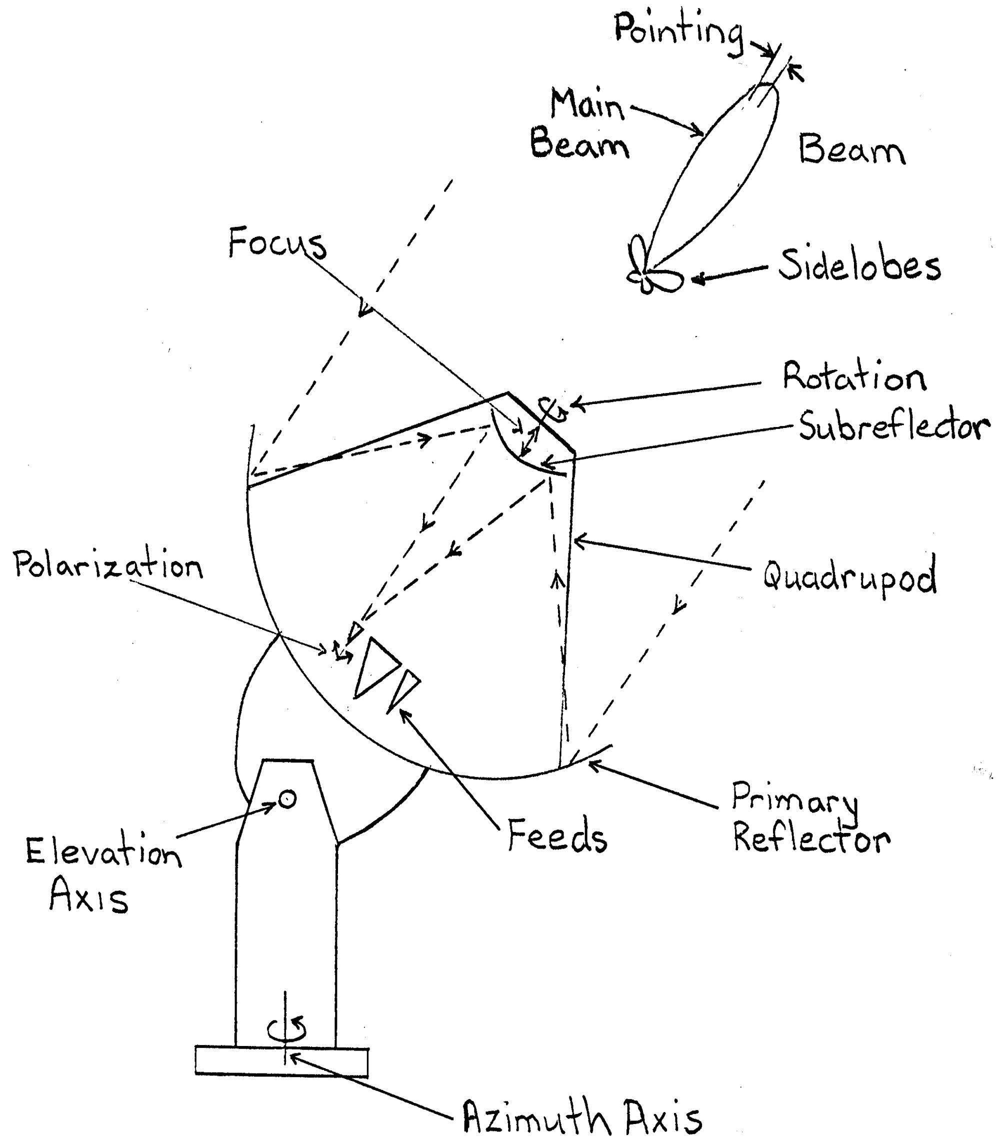


Backups

mm and sub-mm Telescopes



Antenna Key Features



Array Separations Are Usually Adjustable – Like a Zoom Lens...

Maximum Detail At Largest Antenna Separations...