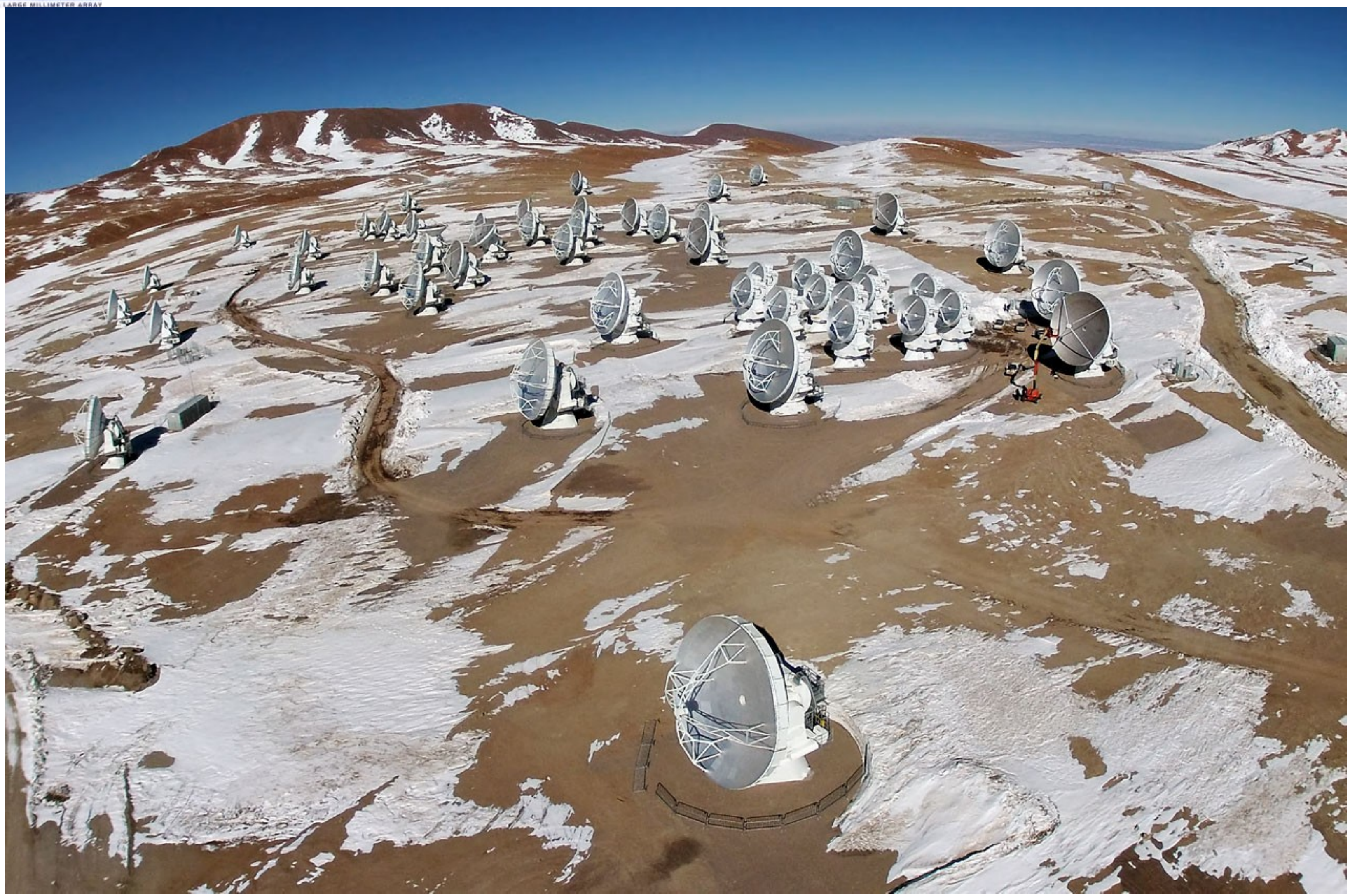
Ground-based opportunities for sub-mm heterodyne arrays: ALMA and large single dishes

Robert Laing, ESO

Outline

- What science is ALMA doing now?
- ALMA Development Programme
  - How do Focal-Plane Arrays fit in?
- Large sub-mm single dish
  - Early ideas on large antenna to complement ALMA
  - Important role for focal-plane arrays

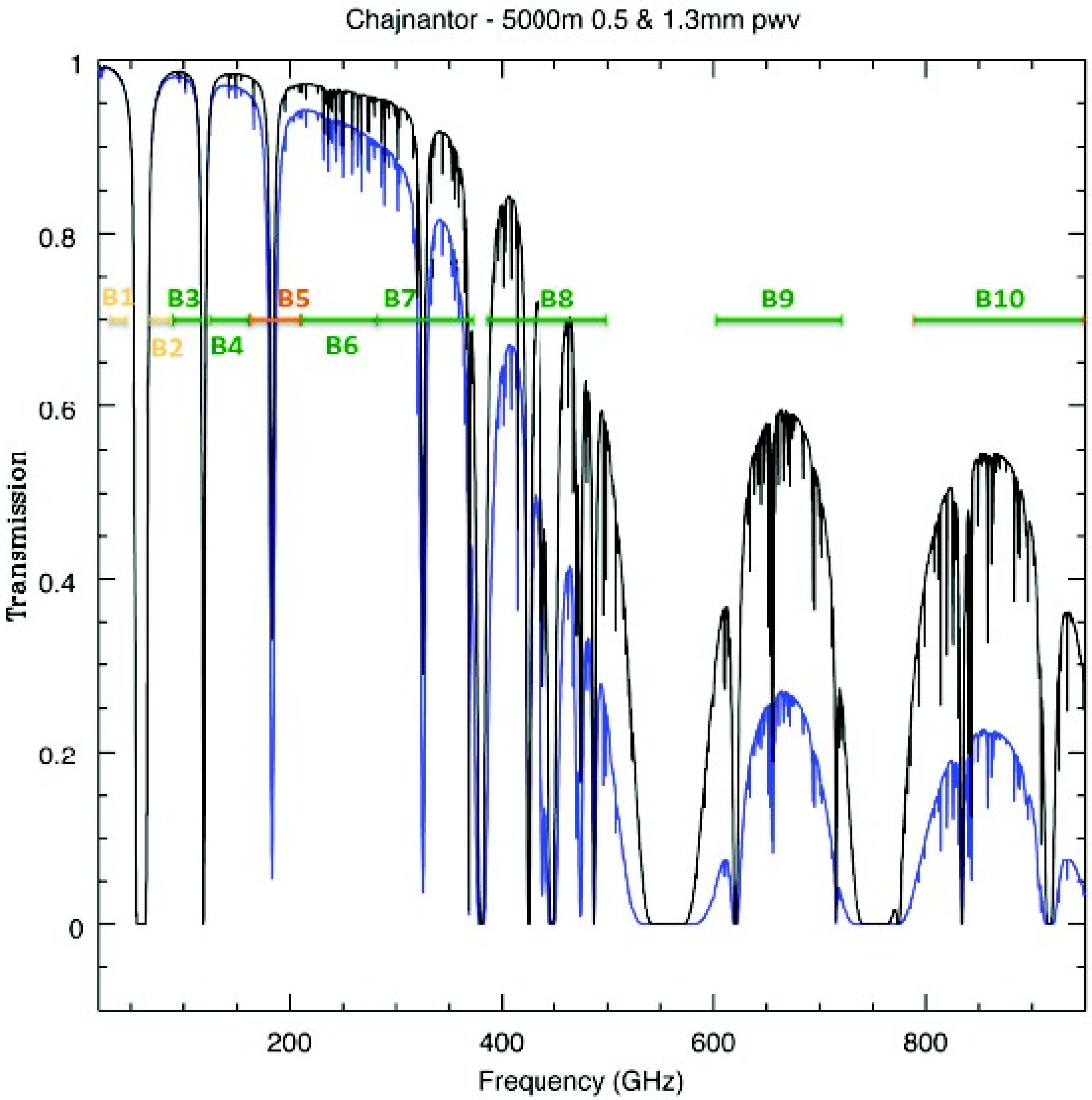
ALMA



ALMA in a nutshell

- **Atacama Large Millimeter/sub-millimeter 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 $\approx$ 0.2(λ/mm)/(max baseline/km)
- Field of view / arcsec $\approx$ 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 Transmission Windows



Operational

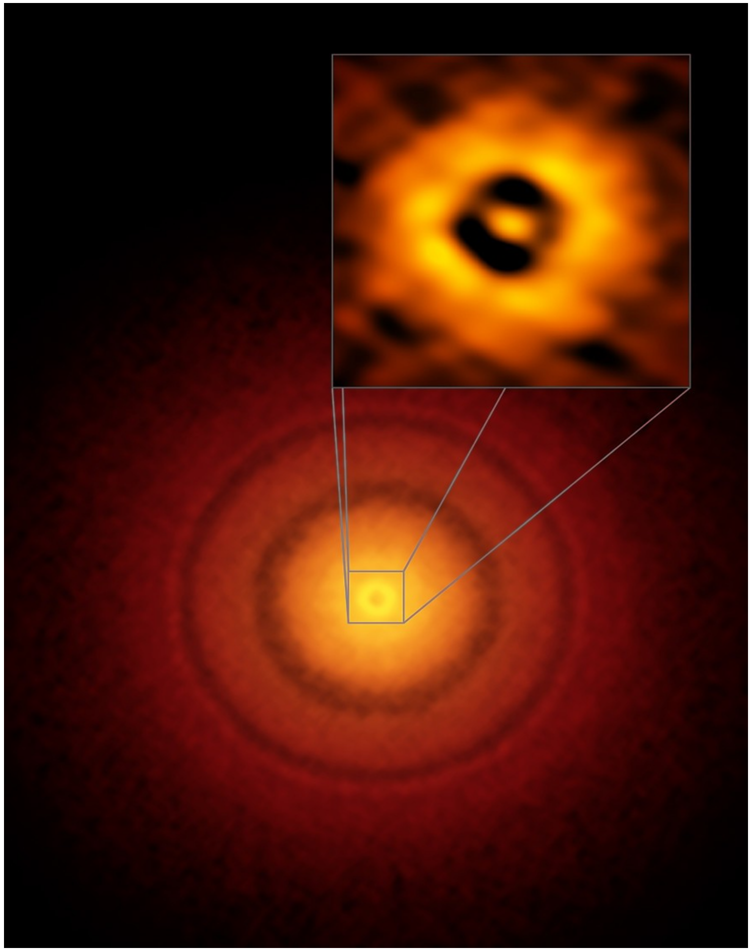
Integration

Development

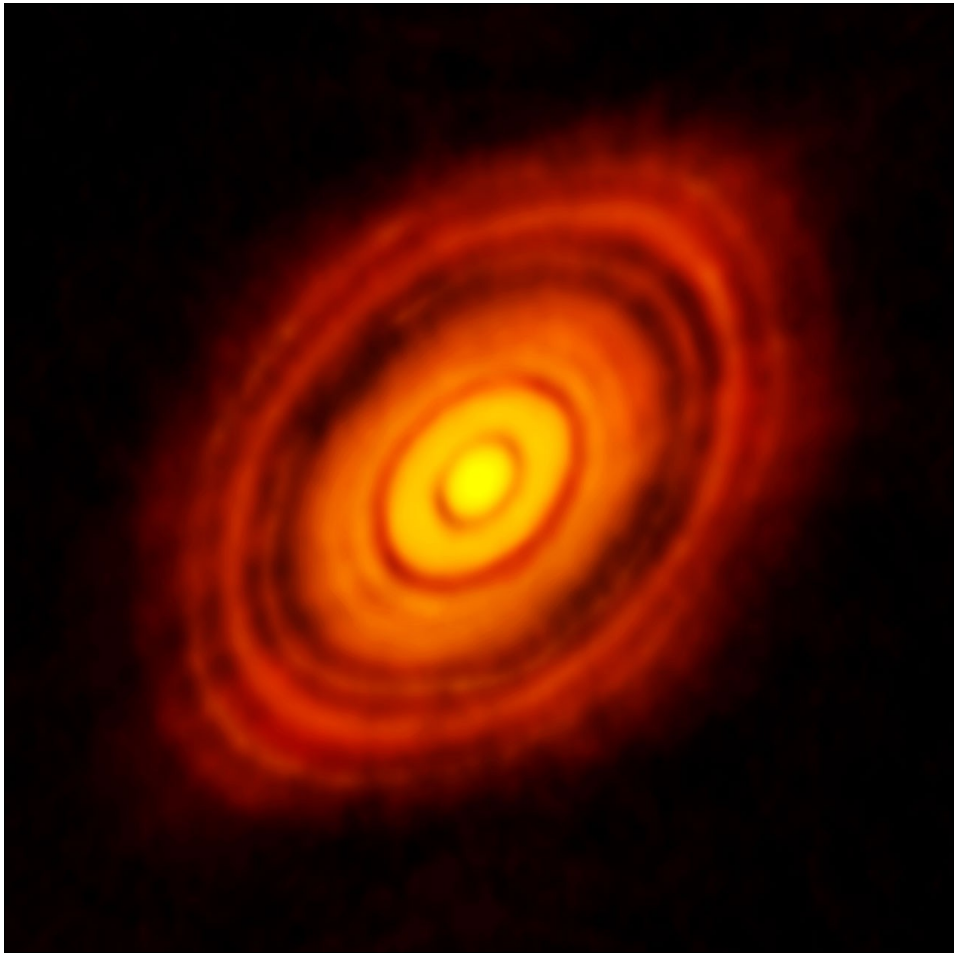
Original Top-Level ALMA Science Drivers

- Detect spectral-line emission from CO or C+ in a galaxy “like” the Milky Way at a redshift of 3
- Image the gas kinematics in a protostellar/protoplanetary disk at a distance of 150 pc (including gaps associated with forming planets)
- Provide “precise” images at a resolution of 0.1 arcsec.

Dust in protoplanetary disks

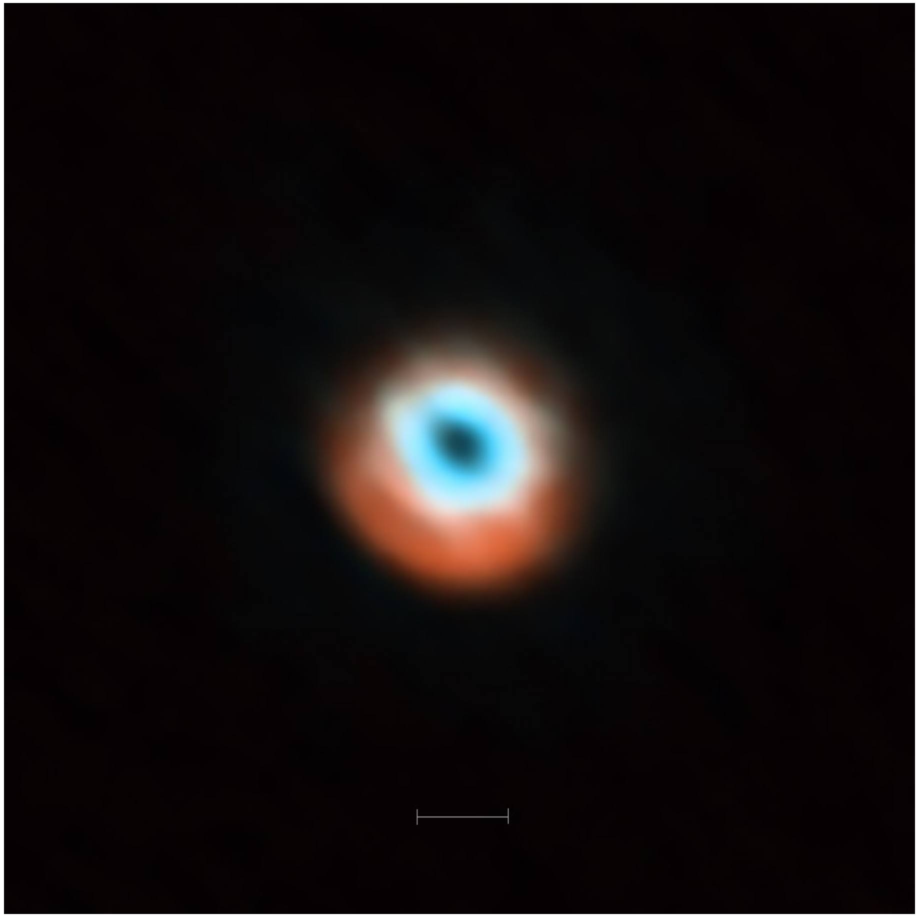


TW Hydrae
Andrews et al. (2016)



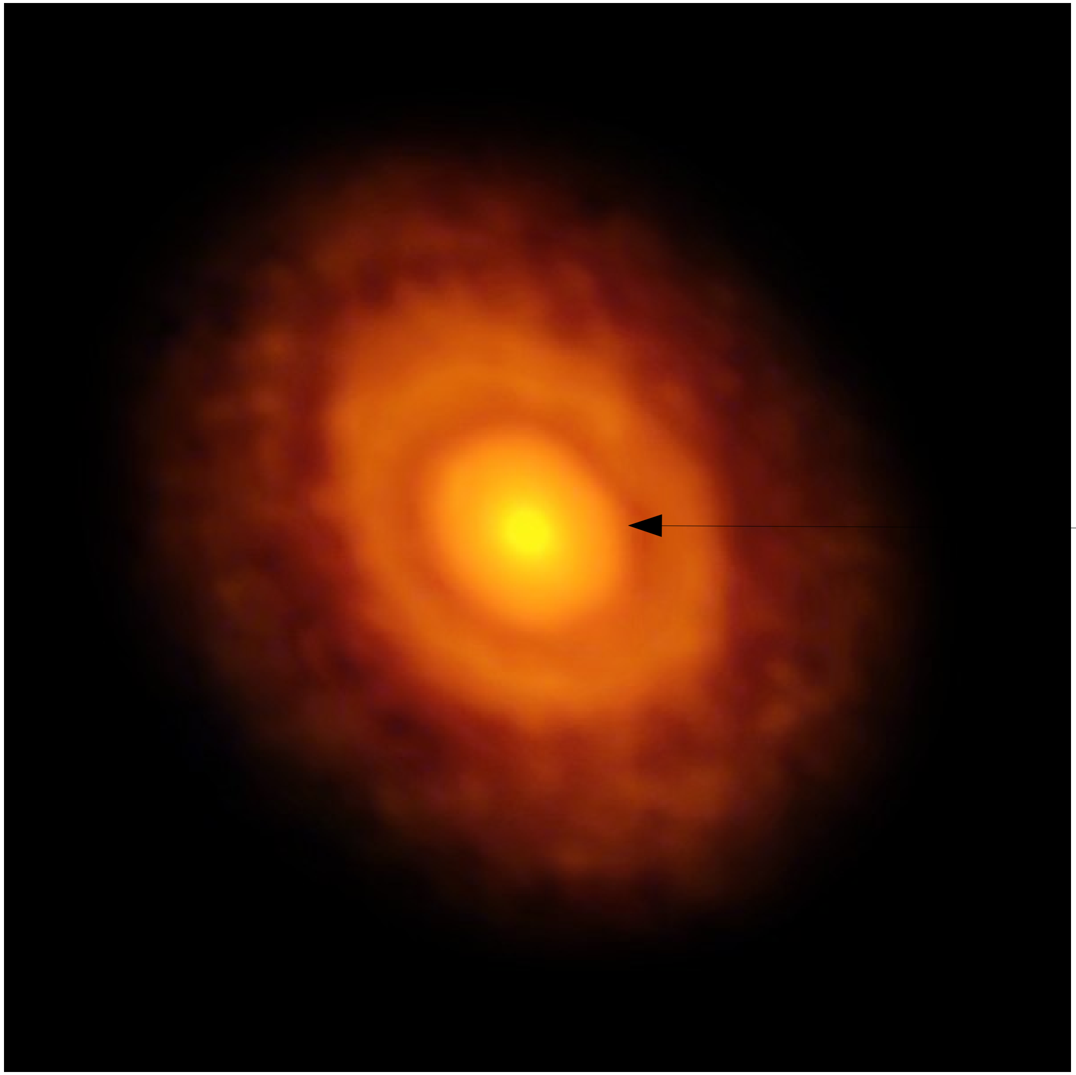
HL Tau
ALMA Partnership 2015

Gas in disks



Dust and CO (van der Marel et al. 2015)

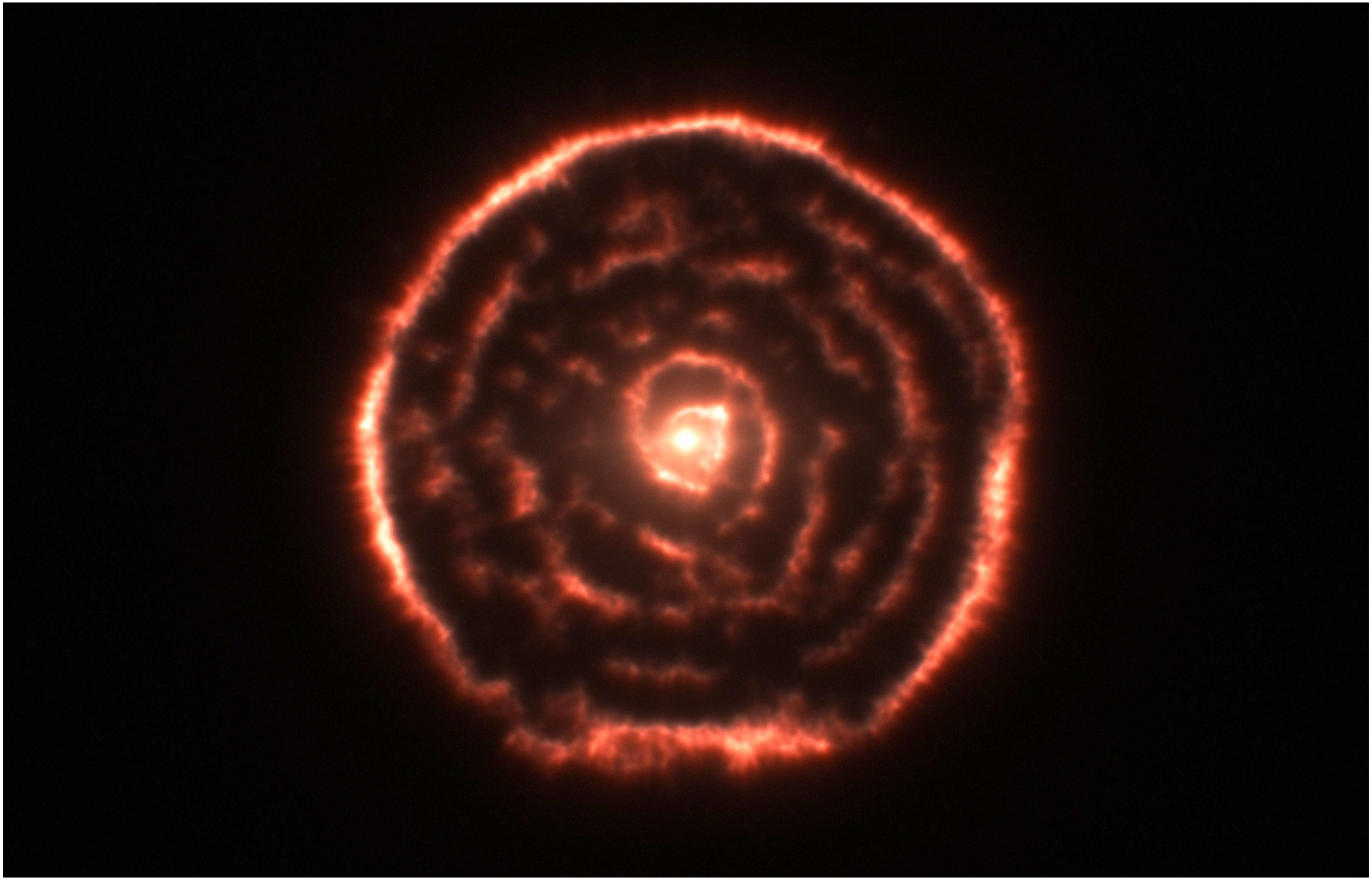
The water snow-line



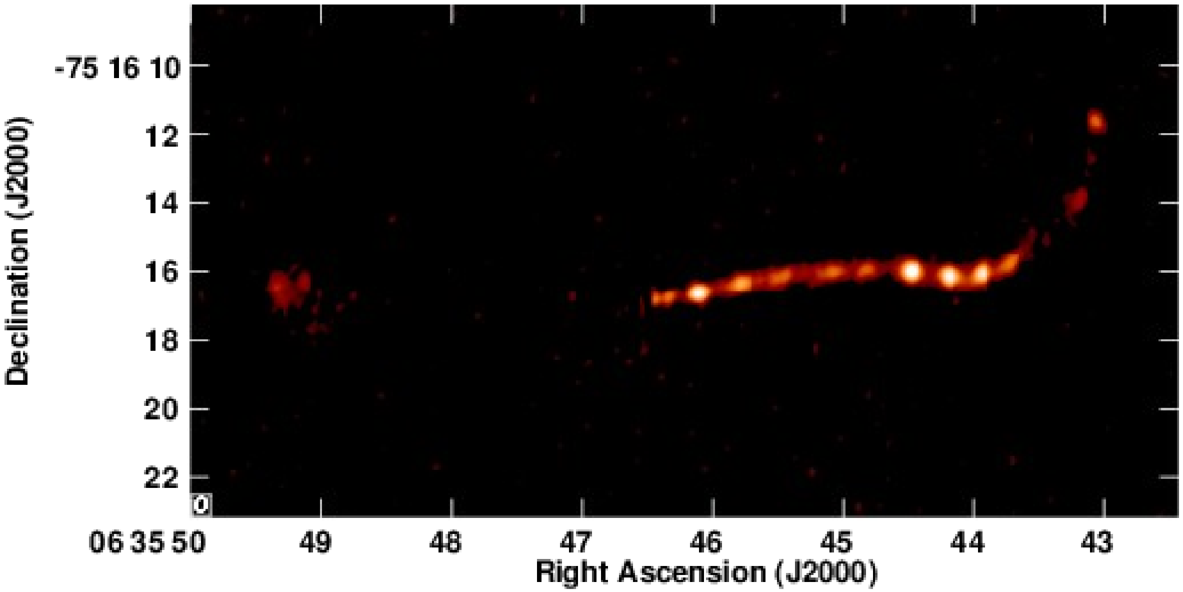
V883 Orionis
Cieza et al. (2016)

Snow line

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

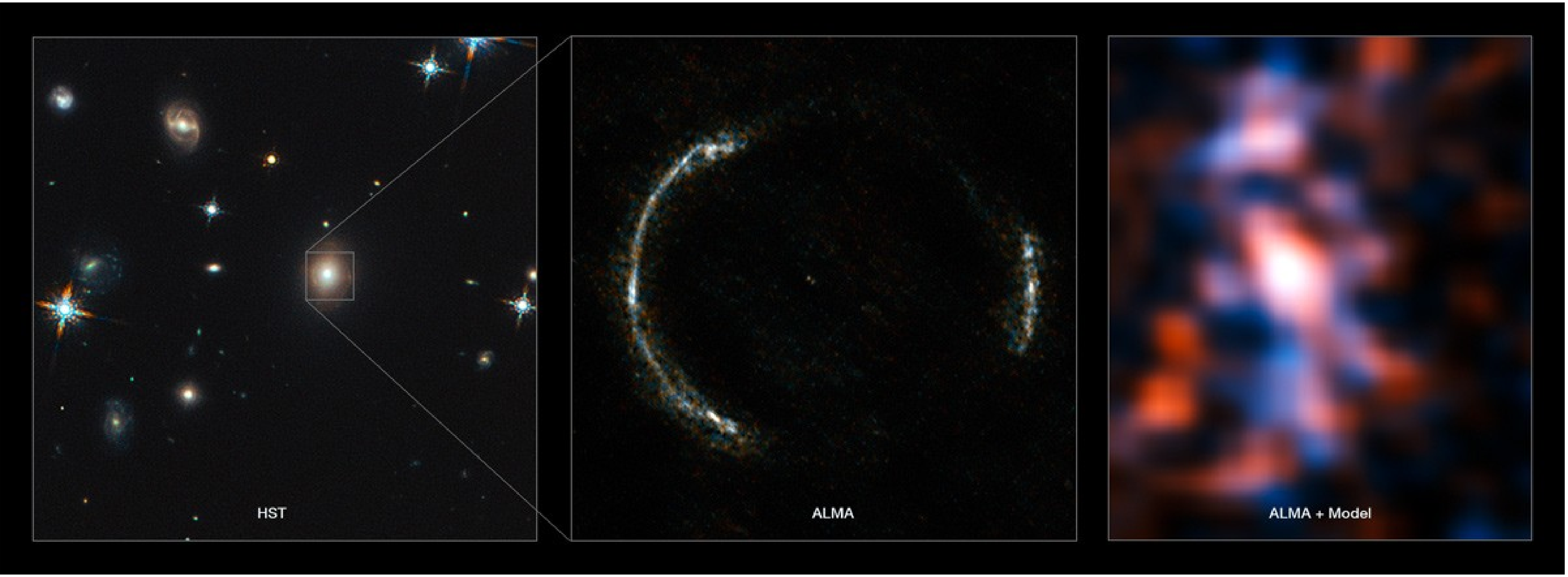


Relativistic jets



ALMA 230 GHz
Calibration source
Core subtracted
Meyer et al. (2017)

Gravitational Lensing



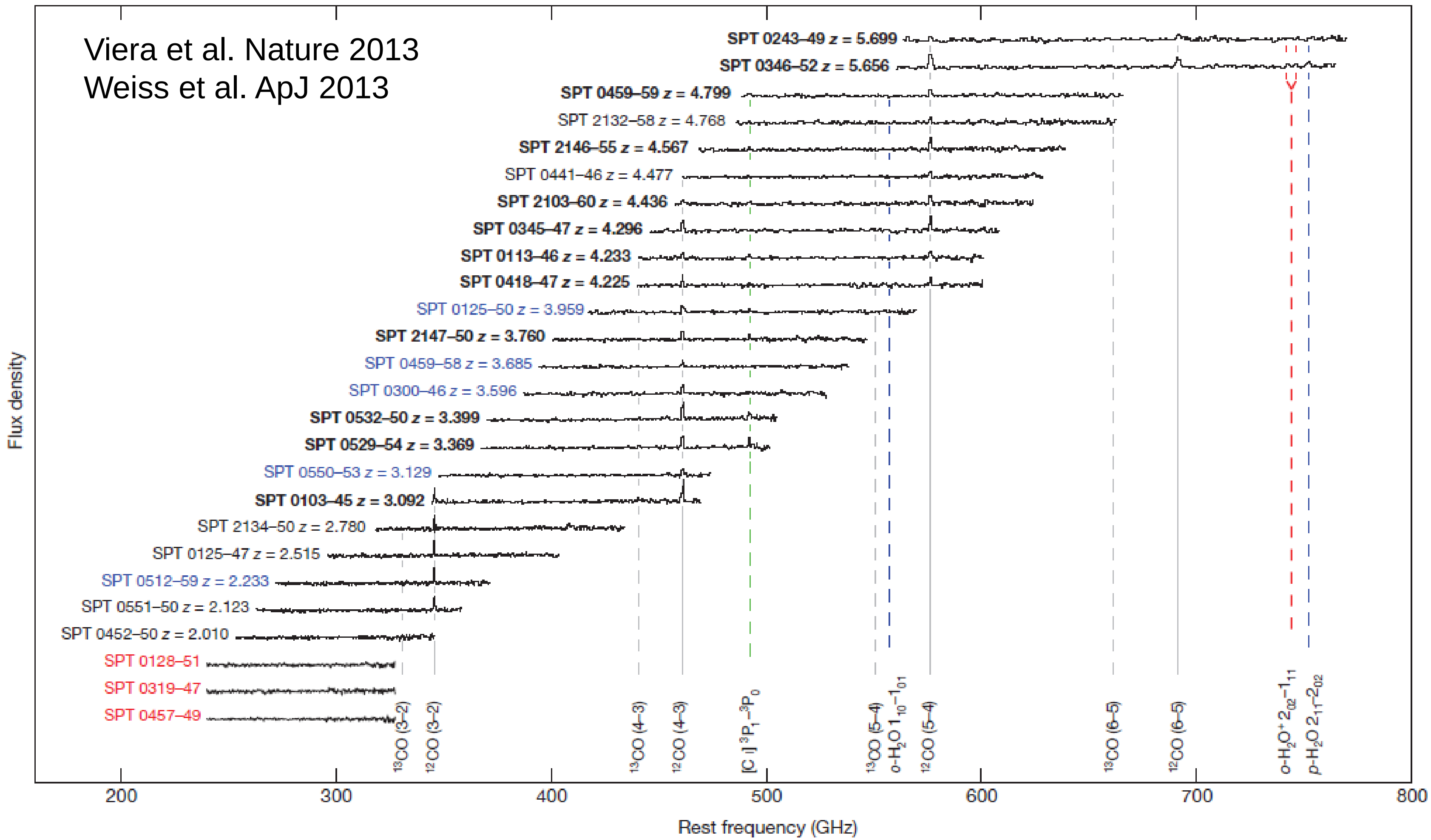
Lensing galaxy at z=0.3
(HST)

Lensed image
(ALMA, 1mm, 30mas)

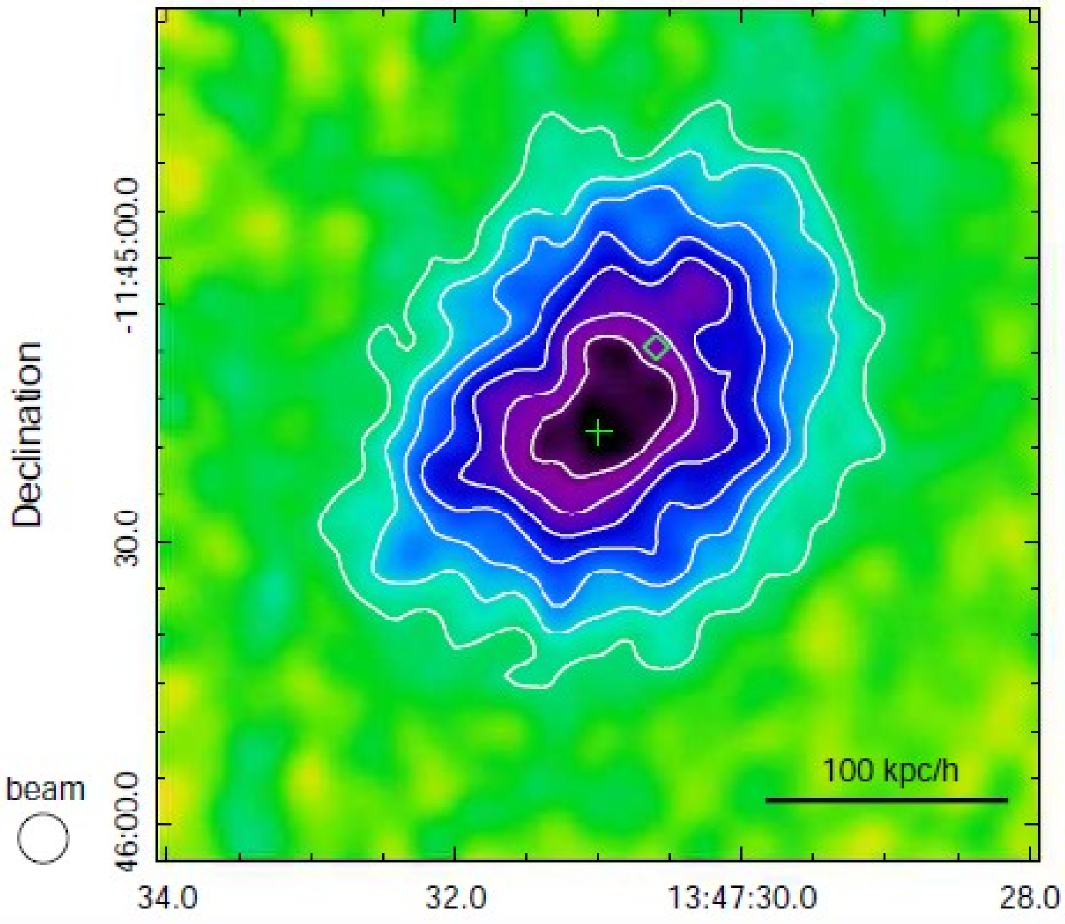
Background source, z=3.04
<100pc clumps in 2kpc disk

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

ALMA as a redshift machine



Sunyaev-Zeldovich Effect

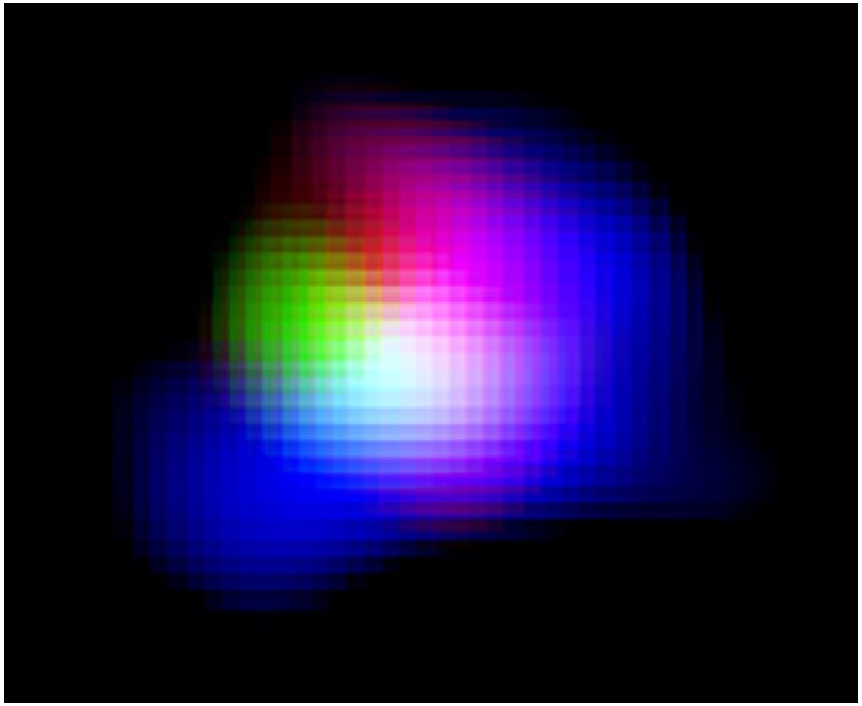


Kitayama et al. (2016)

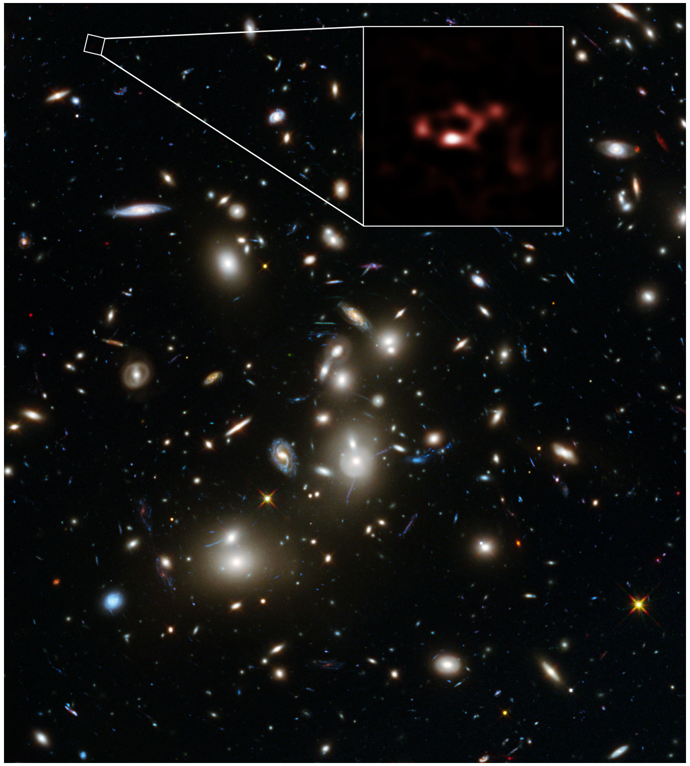
z = 0.451

12m + 7m Arrays

Early Oxygen and Dust

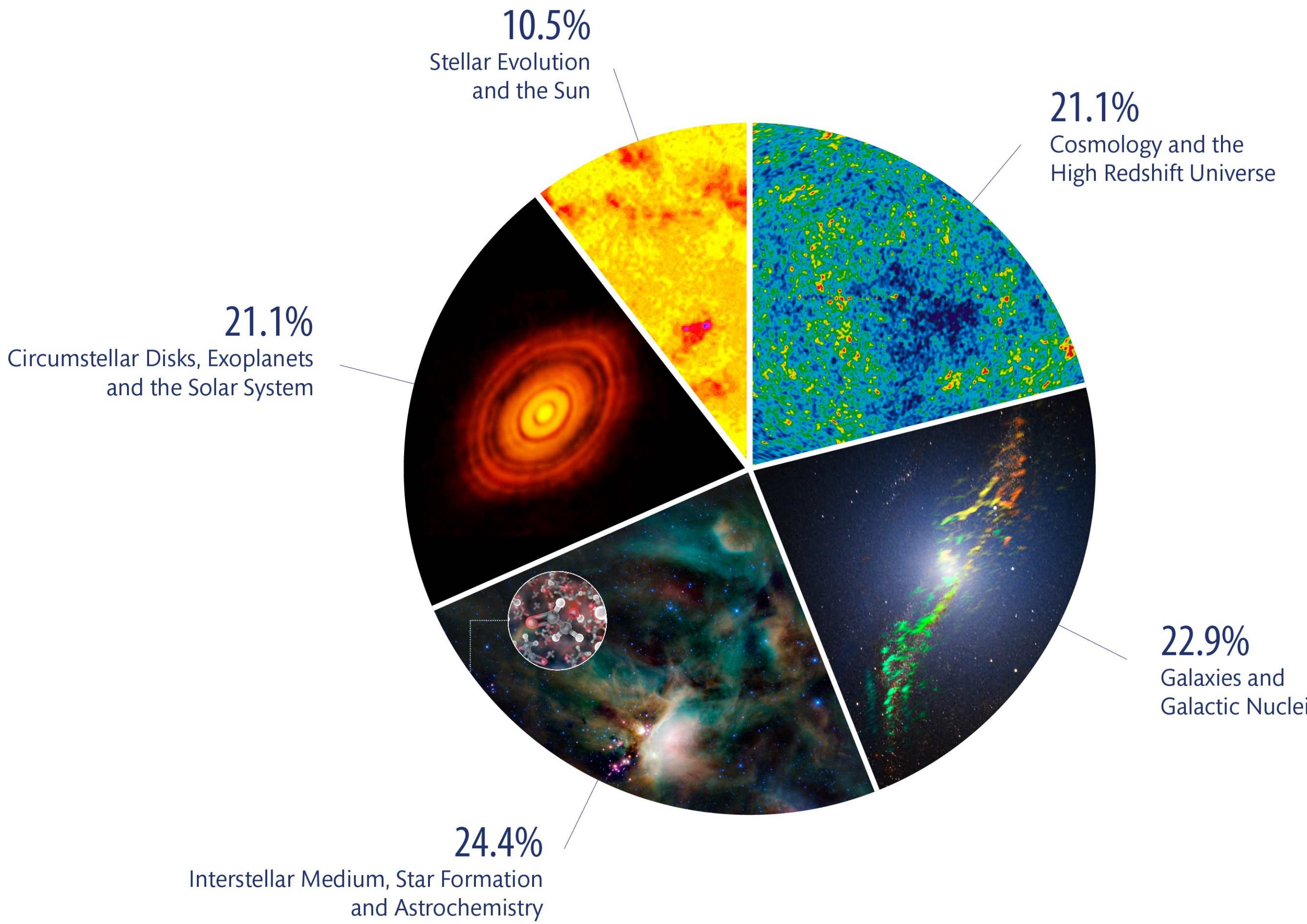


Inoue et al. (2016)
z = 7.2
Ionized oxygen (green)
Lyman alpha (blue)
IR continuum (red)



Lensed, dusty galaxy at z = 8.38
Laporte et al. (2017)

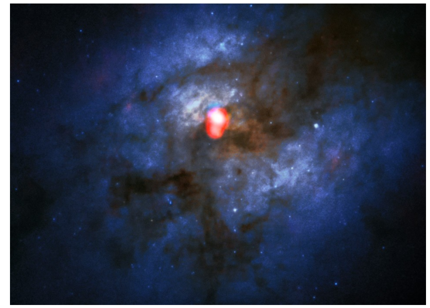
Accepted Proposals by Science Categories

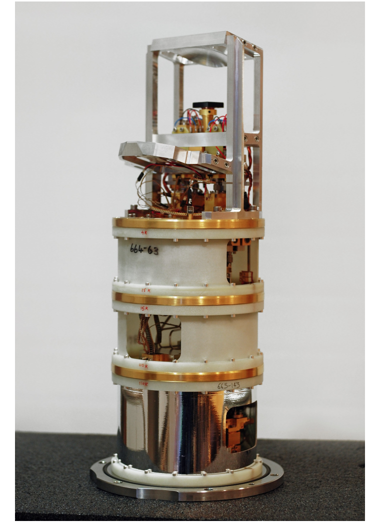


What's next for ALMA?

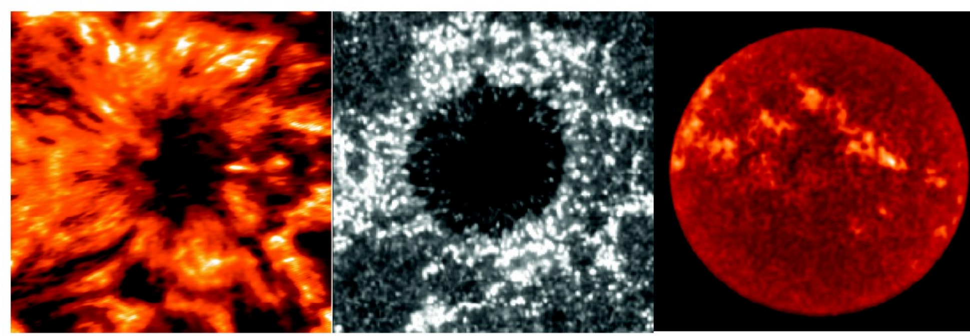
- Finish ALMA as originally conceived
- Receiver noise and bandwidth: higher sensitivity and spectral range
- Longer baselines: higher resolution
- Wider fields of view (e.g. focal plane arrays): increased mapping speed
- Extending the frequency range

Finish ALMA





- Band 5 (163-211 GHz)
  - Offered in Cycle 5
  - GARD/NOVA/NRAO
- Band 1 (35-50GHz)
  - Under construction
  - ASIAA+
- Band 2/2+3
  - 67-90 or 67-116GHz
  - Under development
- VLBI, Pulsars
- Solar



Improve Throughput and Spectral Coverage

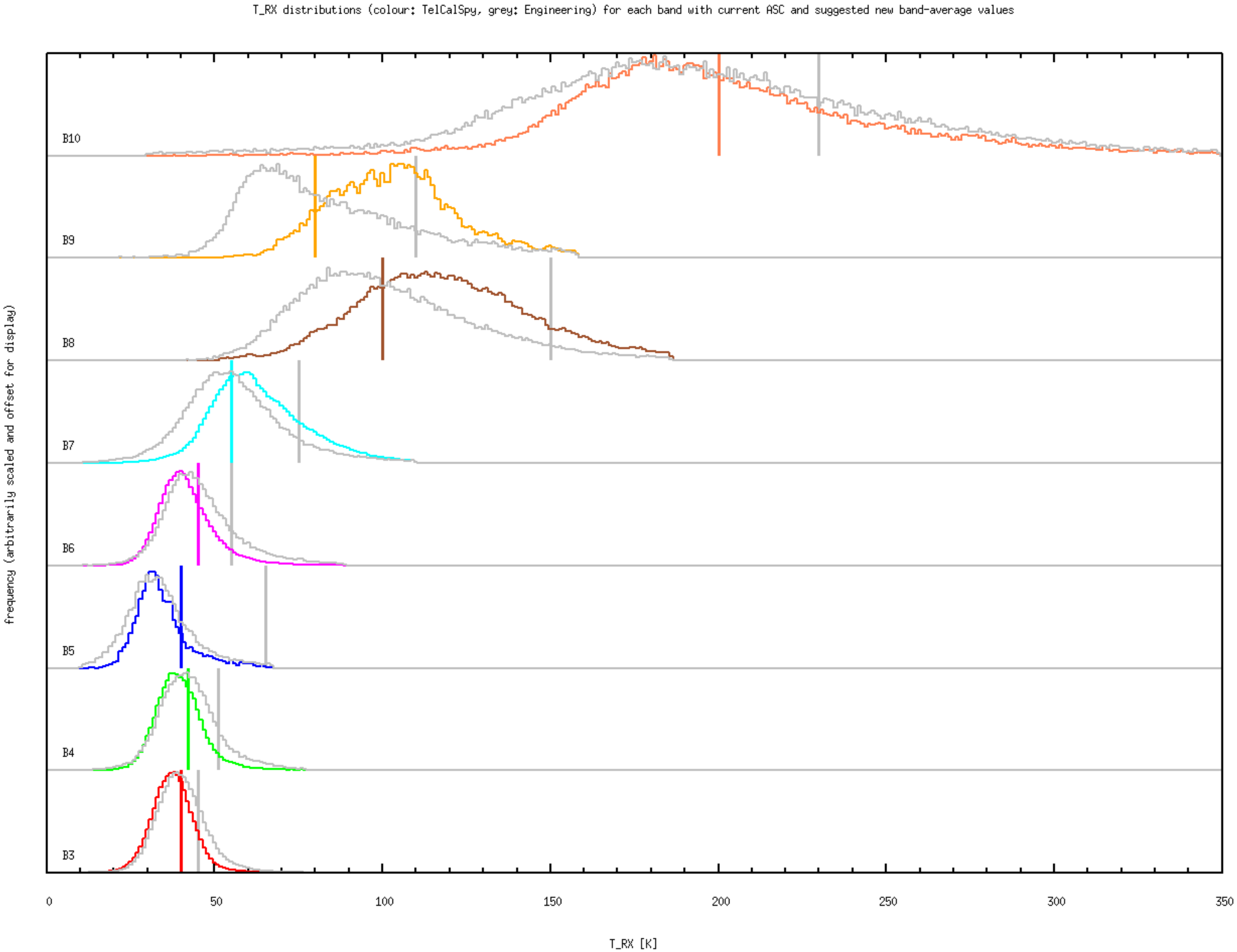
- Increase IF bandwidth
  - At least 8 GHz per sideband (from current 4 GHz)
  - All sideband-separating receivers except Band 1
  - Improve noise level for continuum ($\propto \Delta\nu^{-1/2}$)
  - Increased spectral range
  - Simultaneous observation of multiple molecular transitions
  - Particularly effective for redshift surveys
  - Understand noise-bandwidth tradeoffs: what is the right figure of merit?
- Implications
  - Major upgrade of back-end, correlator and software, as well as the receivers themselves

Currently the focus of several studies and projects within the ALMA partnership.

Improve Throughput (2)

- Additional antennas
  - Conceptually straightforward
  - Baseline correlator can cope with 64 antennas
  - Very expensive
- Improve noise levels
  - Very hard at the lowest ALMA frequencies
  - Some scope at higher frequency
- Bands 6 and 7 seen as the current priority
  - "Workhorse" ALMA bands
  - Redshift surveys
  - Molecular diagnostics
  - Long-baseline line and continuum

Measured noise levels on the sky



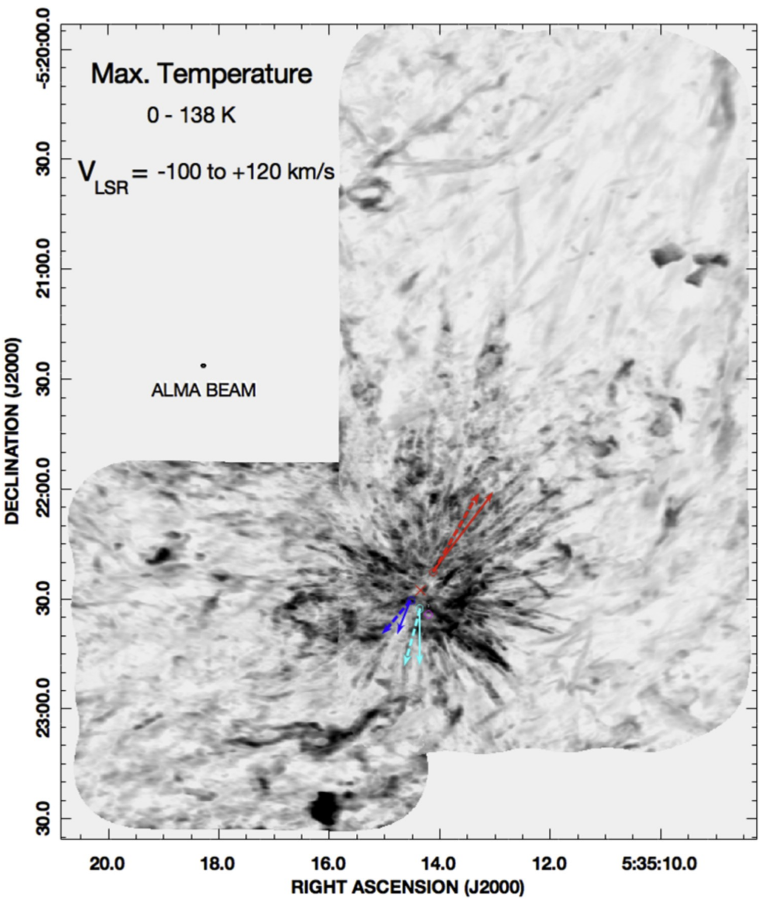
Improve Resolution

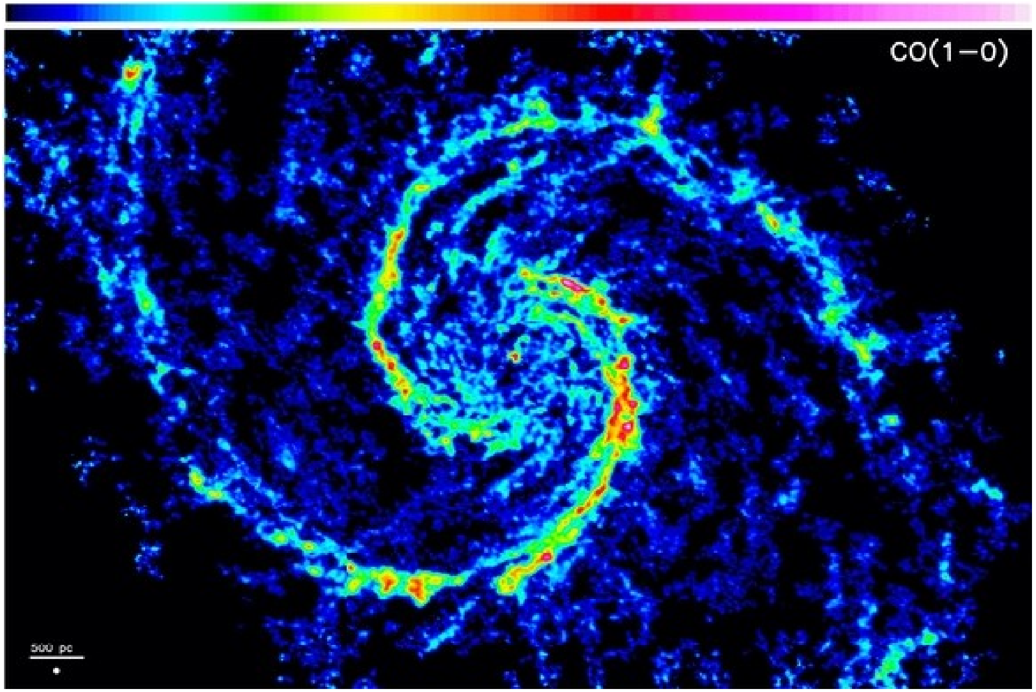
- Baseline increase of factors of 2-3 (to 50 km)
  - Protoplanetary disks (continuum and high-excitation lines; Earth-like orbits)
  - AGN torus, absorption lines, SiO and water masers
  - Evolved stars, molecular outflows, masers
  - Shocks in PNe
  - Gravitationally lensed high-z galaxies
- New antennas on fixed locations
  - Expensive
  - Improve LO distribution
  - Enough collecting area on long baselines?

Increasing the Field of View

- Focal Plane Arrays or Phased-array feeds
  - PAF's are now in use at 1-2 GHz frequencies (ASKAP, APERTIF)
  - Interferometry can be done over a much larger field of view (at the cost of extra processing)
- ALMA science priorities for wider fields
  - Deep surveys (e.g. HUDF): currently very inefficient because many of the fields are blank
  - Very complex fields (nearby galaxies; Galactic star formation)

Science Cases for Focal Plane Arrays: Complex Fields

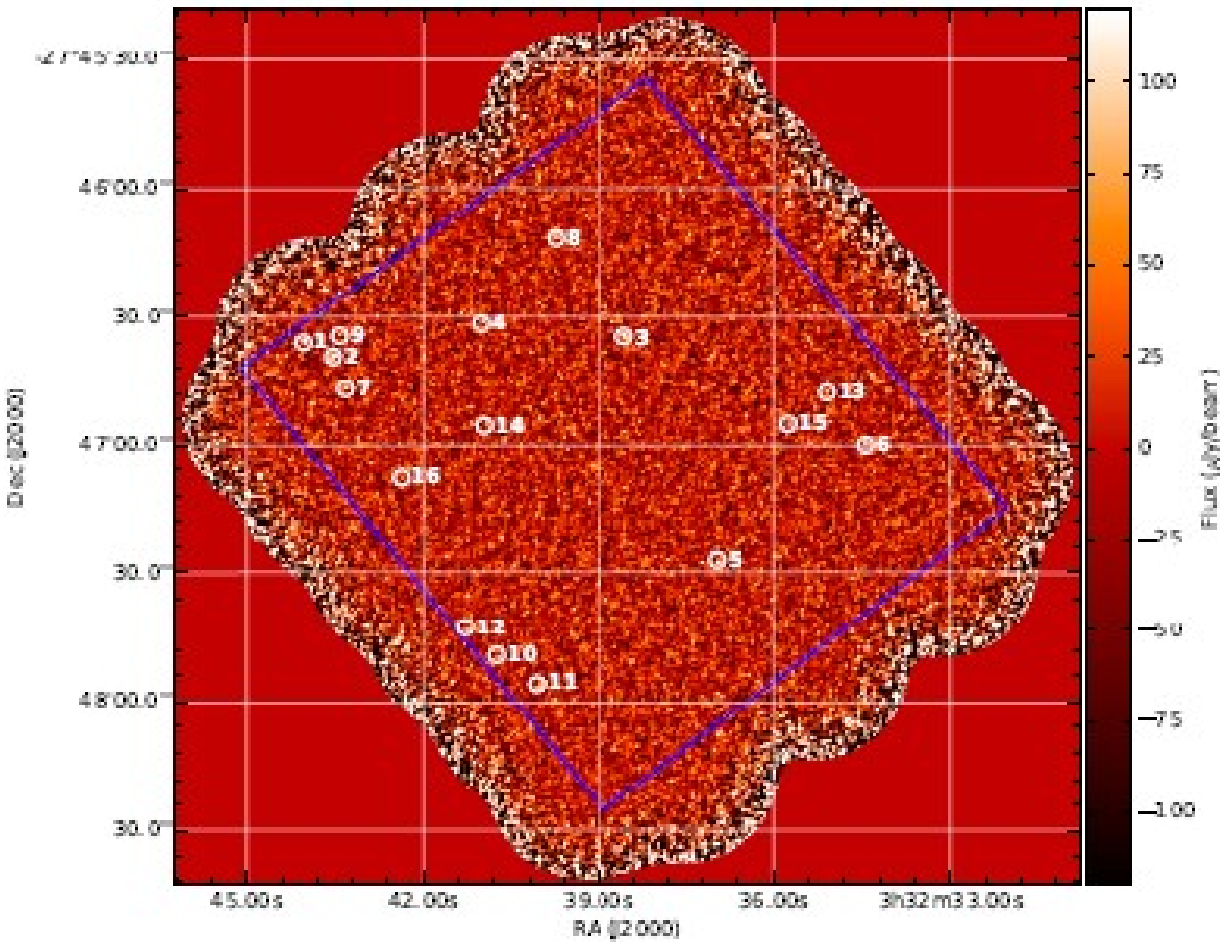




M51 CO(1-0) IRAM Plateau de Bure
Schinnerer et al. (2013)

High-velocity CO in OMC1
Bally et al. (2017)

Science Cases for Focal-Plane Arrays: Deep Surveys



ALMA Band 6
Hubble Ultra-Deep Field

Dunlop et al. (2016)

Deep surveys are currently possible, but take a very long time.

Which Frequency?

- High (>400 GHz)
  - Primary beams are small
  - Map a larger field all at once to take advantage of good conditions
  - May be possible without wrecking the existing focal plane
- Low (<400 GHz)
  - Primary beams are larger
  - Classic large, complex targets (e.g. low-order CO transitions)
  - Workhorse frequencies for deep surveys
  - Hard to implement without compromising other unique ALMA capabilities?

Arrays for Interferometry: pros and cons

- Pro
  - Efficiency of mapping for deep surveys
  - Particularly important at higher frequencies where the ALMA primary beam is small
  - Large field of view for complex (primarily Galactic) fields
- Con
  - Is the single-field performance compromised (for example for long-baseline imaging)?
  - Do we have to drop some frequency bands?
  - Field rotation issues (ASKAP implements field rotation; APERTIF is on an equatorial telescope)
  - Complication and expense of the arrays/digital/correlator/software system

A Large Single Dish to complement ALMA

- Origins
  - At the ESO2020 meeting, several of the (sub-)mm users said “we want CCAT”
  - Further investigation revealed that this was not what they really meant ...
  - ... actually, they wanted a large single dish to provide a wide-field survey capability to feed ALMA ...
  - .. to which large-format focal-plane arrays are crucial
- Next
  - ESO Large Single Dish Working Group
  - Report is available
  - Workshop at ESO this year
  - Find the money!?

Conclusions of the WG

- Conversion of existing ALMA “total-power” antennas to full-time stand-alone single dishes with array detectors is not cost-effective: ALMA should be optimised as an interferometer.
- By the late 2020's there will be a strong case for a 40m class single dish on the Chajnantor plateau, with at least the inner 25m capable of working to 350µm or a 25m dish on Chajnantor peak with THz capability.
- Until then, APEX, with new instrumentation, will remain competitive.

Example Science Cases for a Large Single Dish

- Wide-field surveys for sub-mm galaxies
  - Search for rarer sub-populations impossible with ALMA alone
  - Continuum affected by confusion; hence 40m diameter
  - Line
  - HIgh frequencies select z ~ 2-3 (U)LIRG's at the peak of their SED's; also redshifted atomic transitions – [CII], [NII], [OI], [OIII]
- Galactic surveys
  - Continuum Galactic Plane surveys – improve on ATLASGAL; confusion
  - Atomic (e.g. [CI]) and molecular line surveys of the Galactic Plane: complement ongoing HI surveys
  - LMC and SMC
  - Census of high-mass star formation

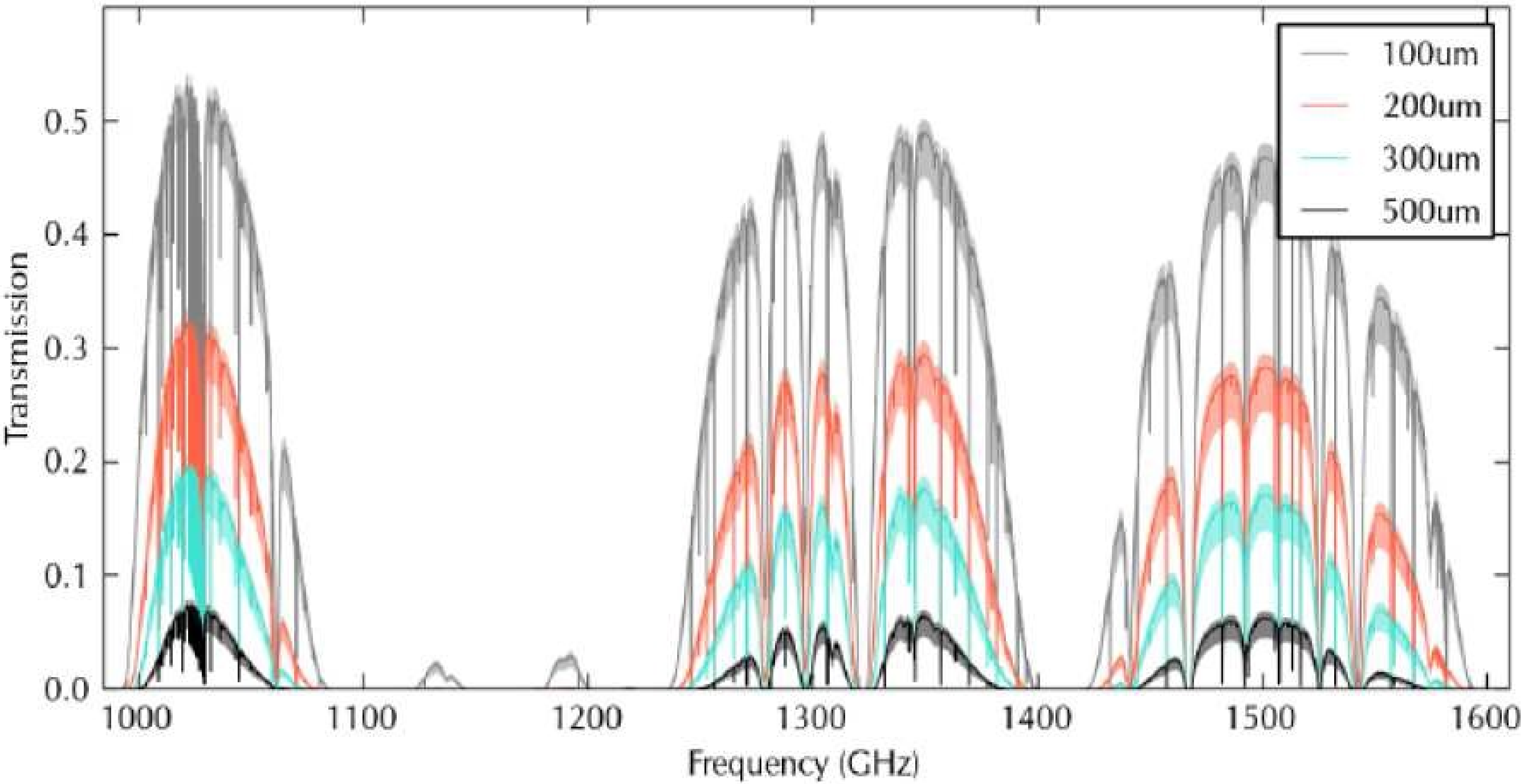
Essentially all applications require large-format arrays

Supra-THz Observing

- ALMA site is marginal for observations at >1 THz
- Phase stability and sensitivity are both problematic for interferometry
- Many of the science cases identified are in any case just as appropriate for a large single dish
  - Shocked CO in molecular outflows from protostars
  - Para ground state transition of H_2D^+
  - Interstellar hydrides
  - Coldest prestellar cores at the peak of their SED's
  - [OI] and [OIII] at moderate redshifts
- Driver for a higher site (Chajnantor peak)

40m on ALMA site or 25m on Chajnantor peak?

THz transmission on the ALMA site



Sarah Graves, Band 11 Meeting
<270µm for 5% of the time

What do we need?

- 10µm surface accuracy (full/25m or inner/40m)
- Switchable instruments (Nasmyth/Cassegrain)
- Advanced mapping modes
- Continuum camera(s): at least 100, 350, 650 GHz; 10^5 – 10^6 pixels
- Heterodyne cameras: at least 16x16 pixels; 32 GHz bandwidth, 0.2 kms^{-1} velocity resolution; 350, 450, 650 GHz bands
- Low-resolution broad-band spectrograph

	APEX+	ALMA-SD+	40m 5000m	12m 5600m	25m 5600m	E-ELT
2.1.1 cont. exgal survey	Red	Red	Green	Red	Green	Yellow
2.1.2 gal line survey	Red	Red	Green	Red	Green	Yellow
2.1.3 atomic FS lines	Red	Red	Yellow	Yellow	Green	Red
2.2.1 Continuum Milky Way surveys	Red	Red	Green	Red	Yellow	Red
2.2.2 Molecular and atomic line galactic surveys	Red	Red	Green	Yellow	Green	Yellow
2.2.3 Magellanic clouds	Red	Red	Green	Yellow	Green	Yellow
2.2.4 Nearby galaxies	Yellow	Yellow	Green	Yellow	Green	Yellow
2.2.5 Massive star formation	Red	Red	Green	Red	Yellow	Green
2.2.6 Magnetic fields	Green	Green	Green	Green	Green	Yellow
2.2.7 Astrobiology	Red	Red	Green	Red	Green	Yellow
2.2.8 Protoplanetary and debris disks	Red	Red	Yellow	Red	Yellow	Red
2.3.1 Stellar winds and ISM	Red	Red	Green	Red	Yellow	Yellow
2.3.2 Dust in supernova remnants	Red	Red	Green	Green	Green	Yellow
2.4.1 Planetary atmospheres	Green	Green	Green	Green	Green	Green
2.4.2 TNOs and Asteroids	Red	Red	Green	Red	Yellow	Yellow
2.4.3 Comets	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
2.5 mmVLBI	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
2.6 SupraTHz	Red	Red	Yellow	Yellow	Green	Red

Questions for Discussion

- What are the pros and cons of focal-plane arrays used for interferometry on ALMA?
- What are the opportunities for large-format heterodyne arrays on a 25-40m class single dish?