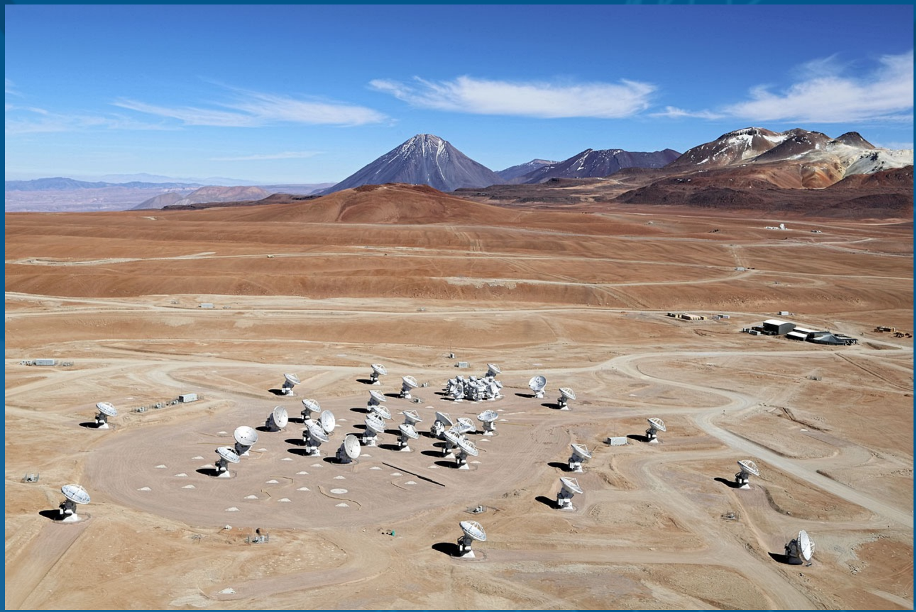
NRC·CNRC



What is ALMA?
An introduction to ALMA

Gerald Schieven
25 April, 2017
NRC Herzberg Astronomy & Astrophysics

ALMA: why do we care? (Or: Why ALMA Matters)

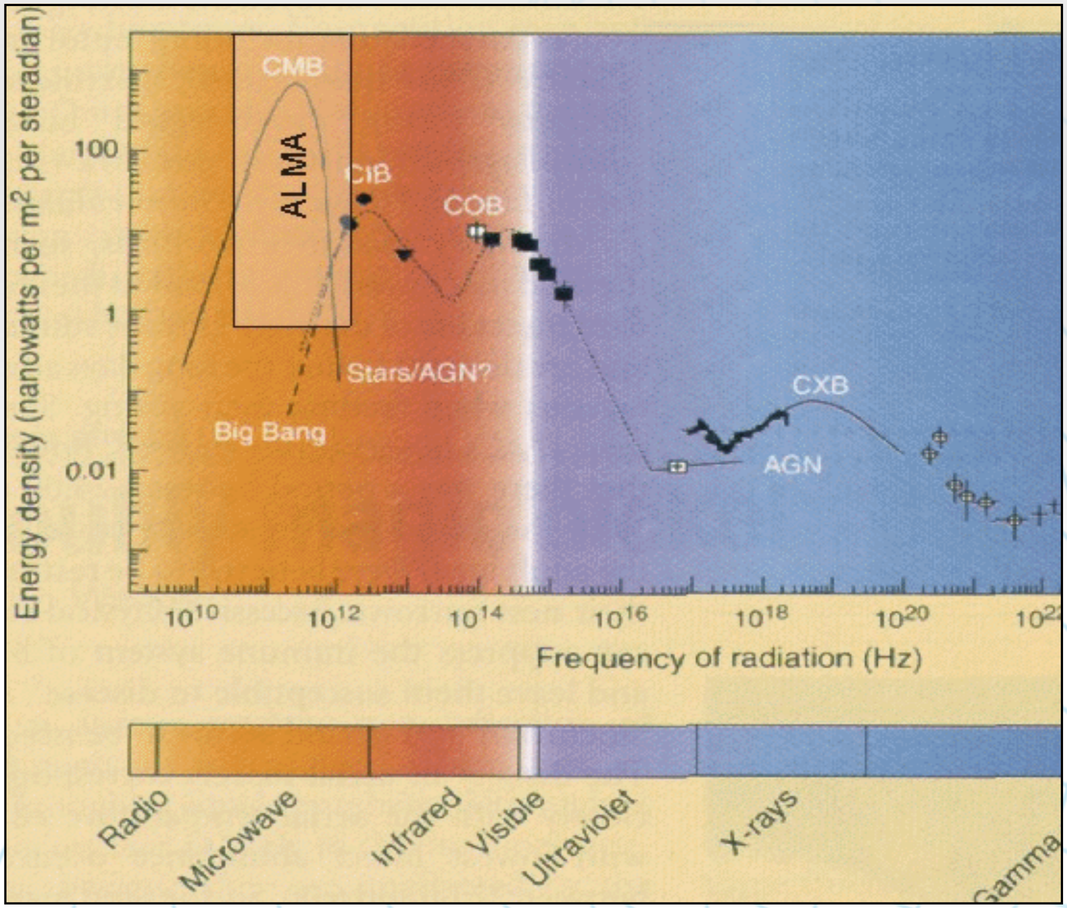
- After the 3 K cosmic background radiation, mm/submm photons carry most of the radiative energy in the Universe
  - 40% of Milky Way photons are in mm/submm

- Unique science because of the sensitivity to thermal emission from **dust** and **molecular lines**

Since $\Omega_b \sim \lambda / D$,

Ω_b (Hubble) ~ 0.0005 mm / 2.4 m
~ 0.05"

Ω_b (JCMT) ~ 0.850 mm / 15 m
~ 15"



- Hard to get ***detail*** in mm/submm!

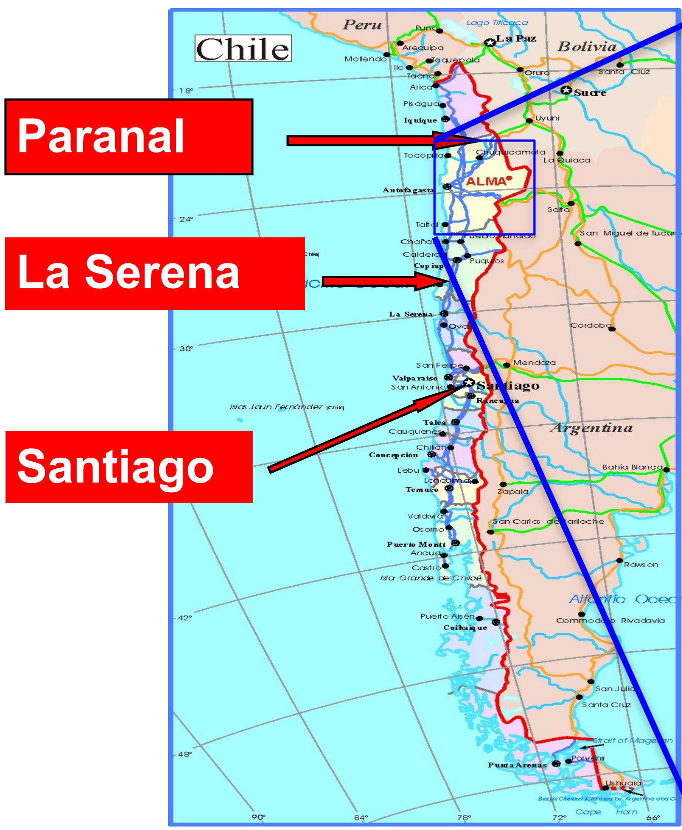
ALMA:
The Atacama Large Millimetre/submillimetre Array

ALMA Overview

- A global partnership to deliver a revolutionary millimeter/submillimeter telescope array
  - North America (US, Canada, Taiwan)
  - Europe (ESO)
  - East Asia (Japan, Taiwan)
  - In collaboration with Chile
- 5000 m (16,500 ft) site in Chilean Atacama desert
- 66 telescopes in full operation
  - Main 12m Array: 50 x 12m antennas
  - Atacama Compact Array (ACA; also called Morita Array)
    - 7m Array: 12 x 7m antennas
    - Total Power Array: 4 x 12m antennas

4

Where is ALMA?

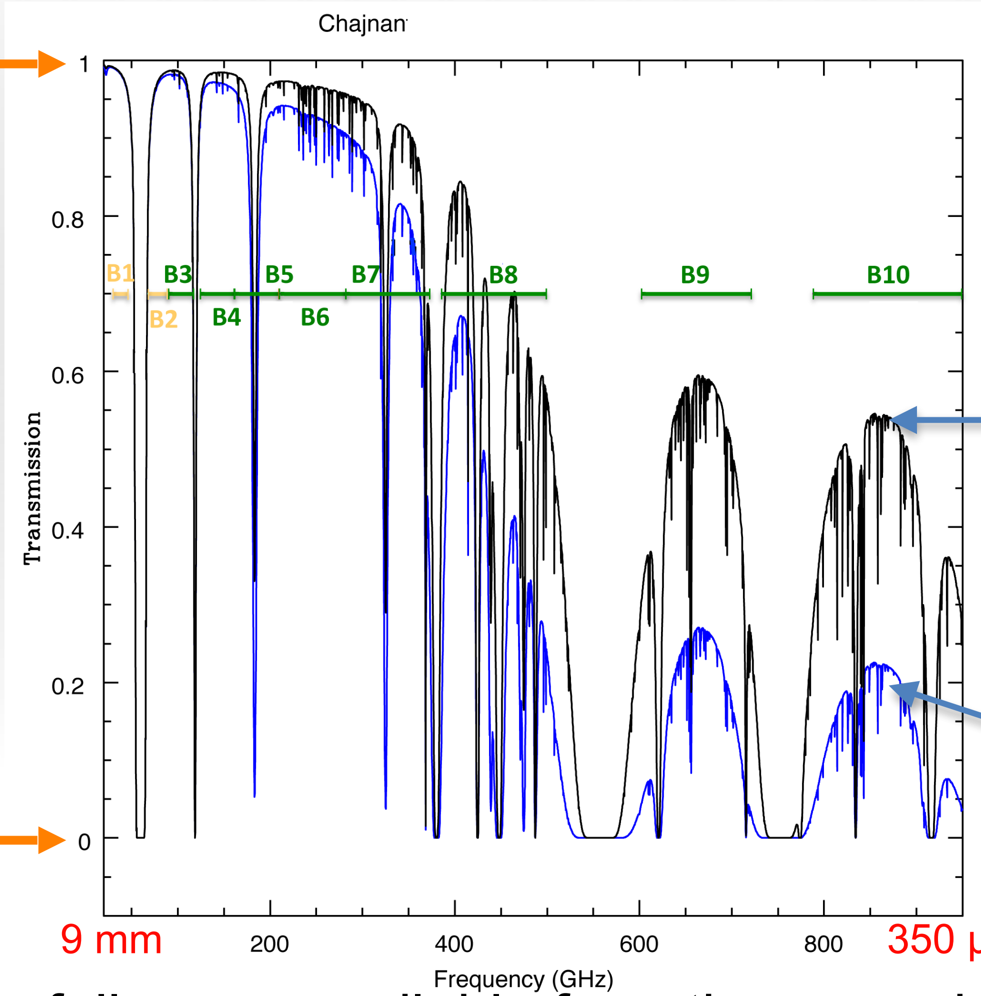


Atacama Desert,
Northern Chile

Receiver Bands

submillimetre wavelengths

transparent



opaque

9 mm

350 µm

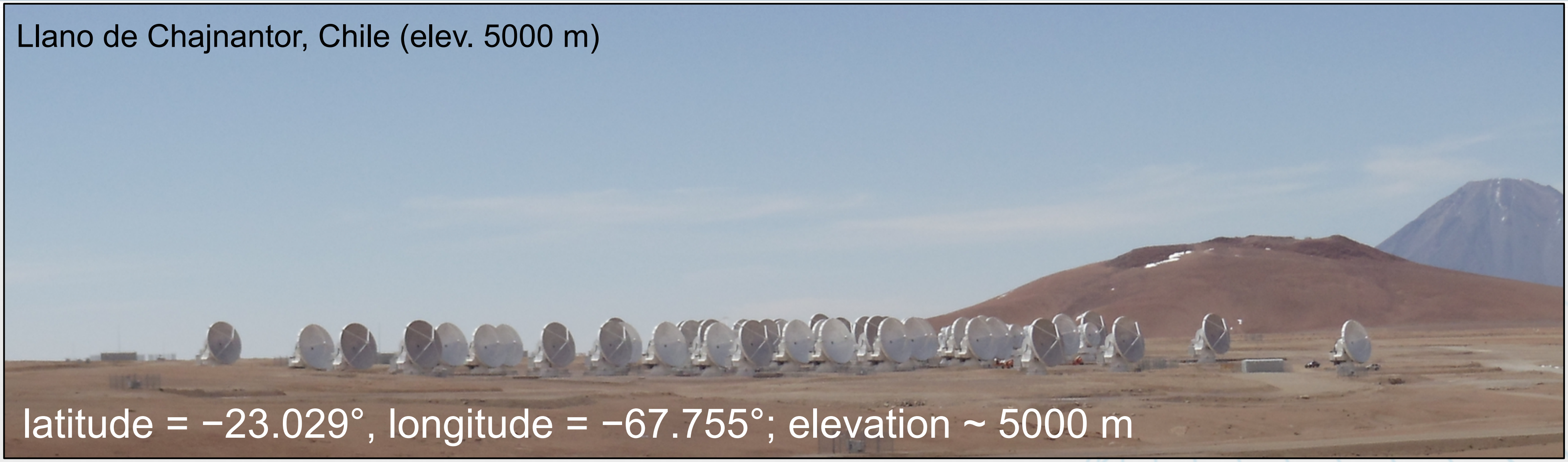
12.5% of the time better transparency than this

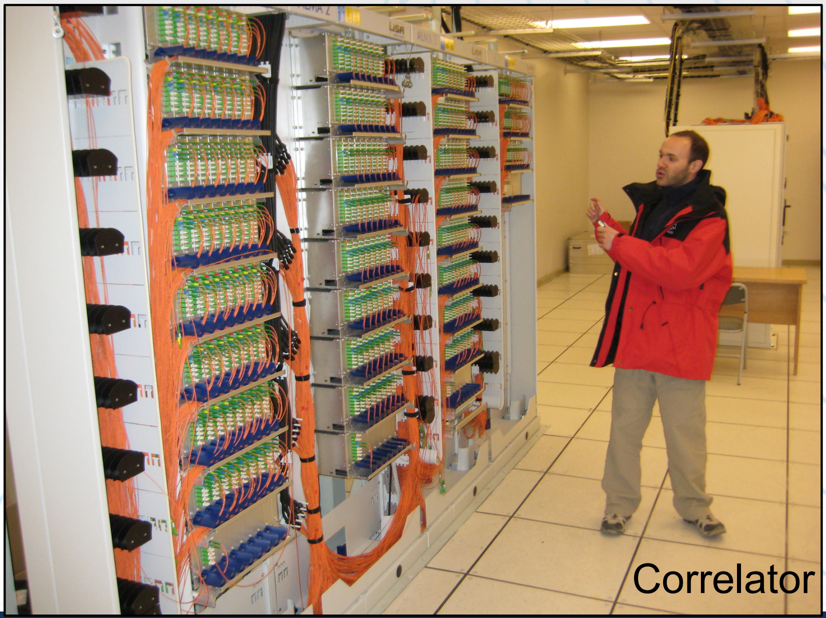
Half the time better transparency than this

ALMA covers the full range available from the ground at submm wavelengths

Where is ALMA?

ALMA Organization (Array Operations Site)

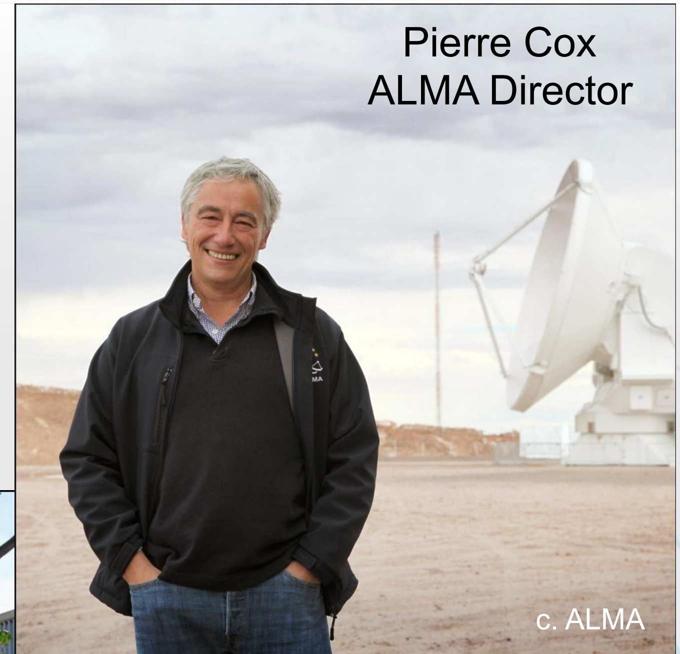




ALMA Organization (the Operations Support Facility)

ALMA Organization (Santiago Central Offices)

c. Chat Hull



c. ALMA


c. ALMA

Elev. ~520 m

ALMA Organization (ALMA Regional Centers)

NRAO Headquarters, Charlottesville, VA, USA
c. NRAO

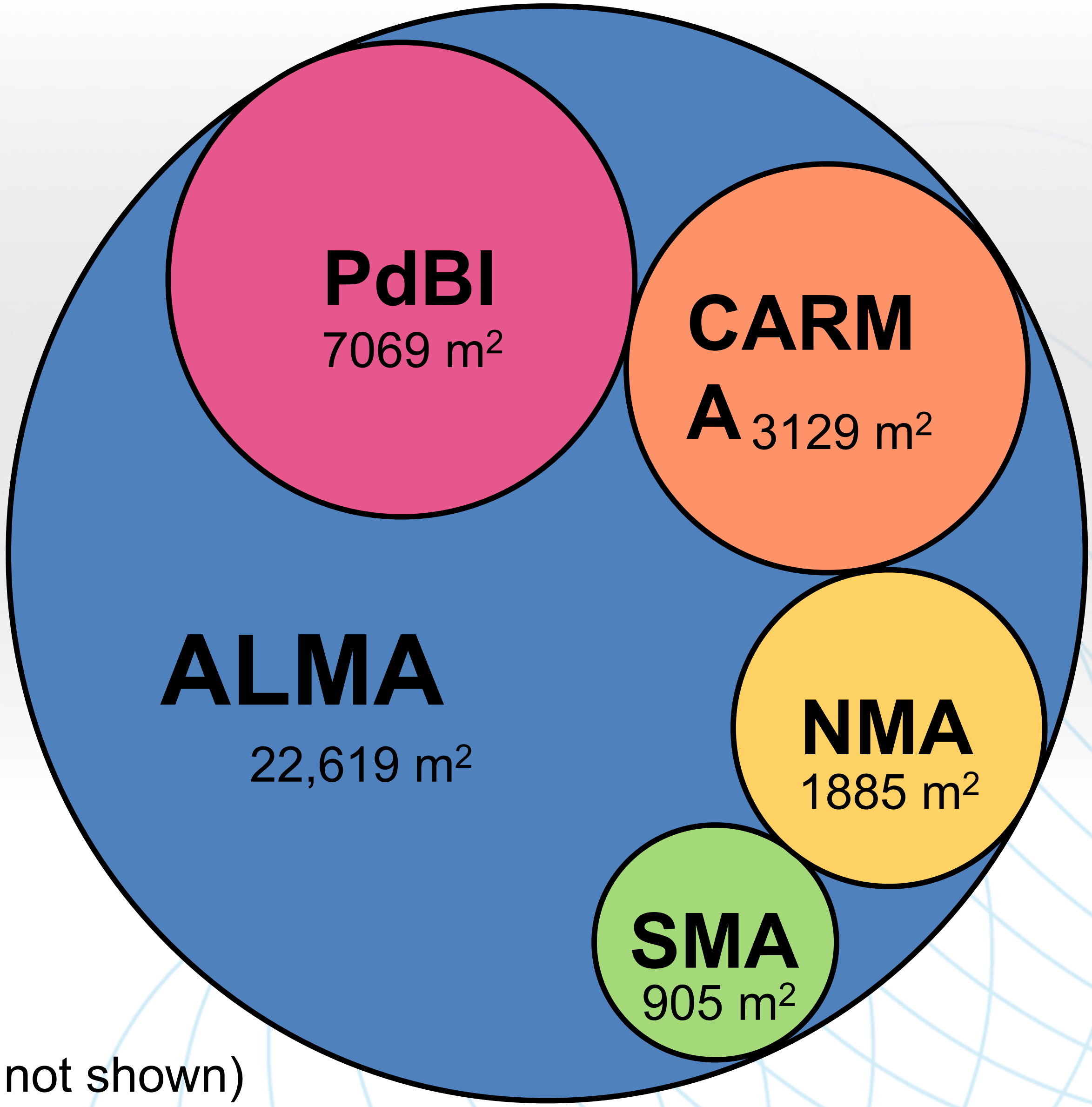
c. NRC
NRC Herzberg Victoria, BC, Canada

Basic Capabilities of ALMA

- At least fifty 12-meter antennas for sensitive, high resolution imaging
- The Morita Atacama Compact Array (ACA), comprised of twelve 7-meter antennas located very close together to provide short spacings, plus four additional 12-meter antennas providing total power, together enhancing the fidelity of wide field imaging
- Imaging ability in all atmospheric windows from 3.6 mm to 0.3 mm (84 GHz to 950 GHz), with coverage down to 10 mm (30 GHz) possible through future receiver development
- Array configurations with maximum baselines from approximately 150 meters to 16 km
- Ability to image sources many arcminutes across at arcsecond resolution
- Top spatial resolution of 5 milli-arcseconds (better than the VLA and HST)
- Top velocity resolution better than 0.05 km/s

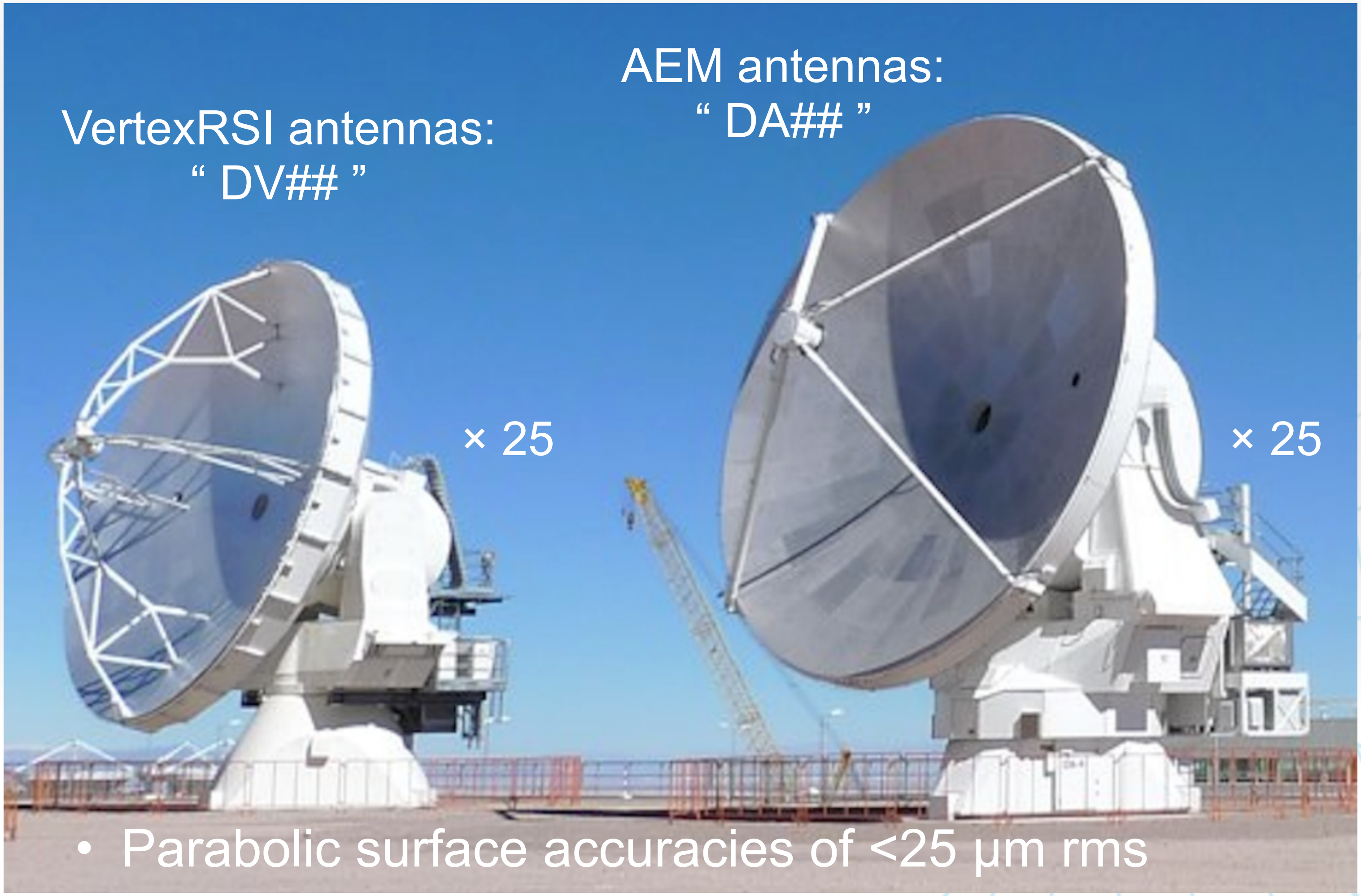
Comparisons with other mm interferometers

- Number of baselines N_B: $N(N-1)/2 = 1225$, much better instantaneous sampling of the uv plane, better overall image fidelity
- N_B (PdBI) = 45
- N_B (CARMA) = 253
- N_B (NMA) = 15
- N_B (SMA) = 27
- N_B (VLA) = 351



(VLA surface area of 53,014 m^2 not shown)

ALMA arrays: the 12-m Array



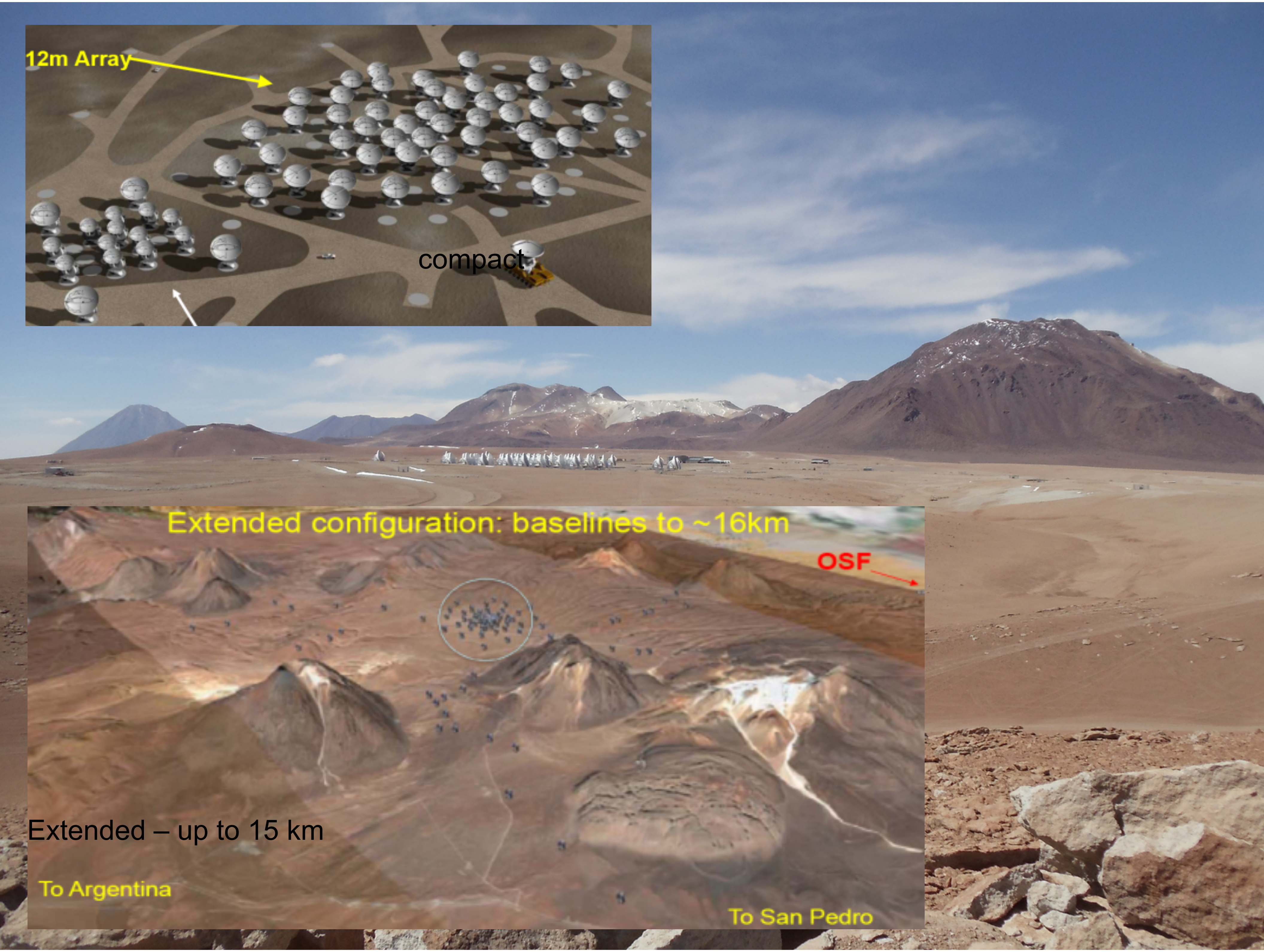
- Parabolic surface accuracies of <25 μm rms
- Minimum 43 antennas available for Cycle 5

- Number: 50 × 12-m antennas
- Composition: steel, CFRP, aluminum, and Invar
- Weight: >100 tons
- Max slew rate: 0.5° s^{-1}
- Pointing: <2" (absolute) all sky; <0.6" in 2° rad (offset)

ALMA arrays: the 12-m Array

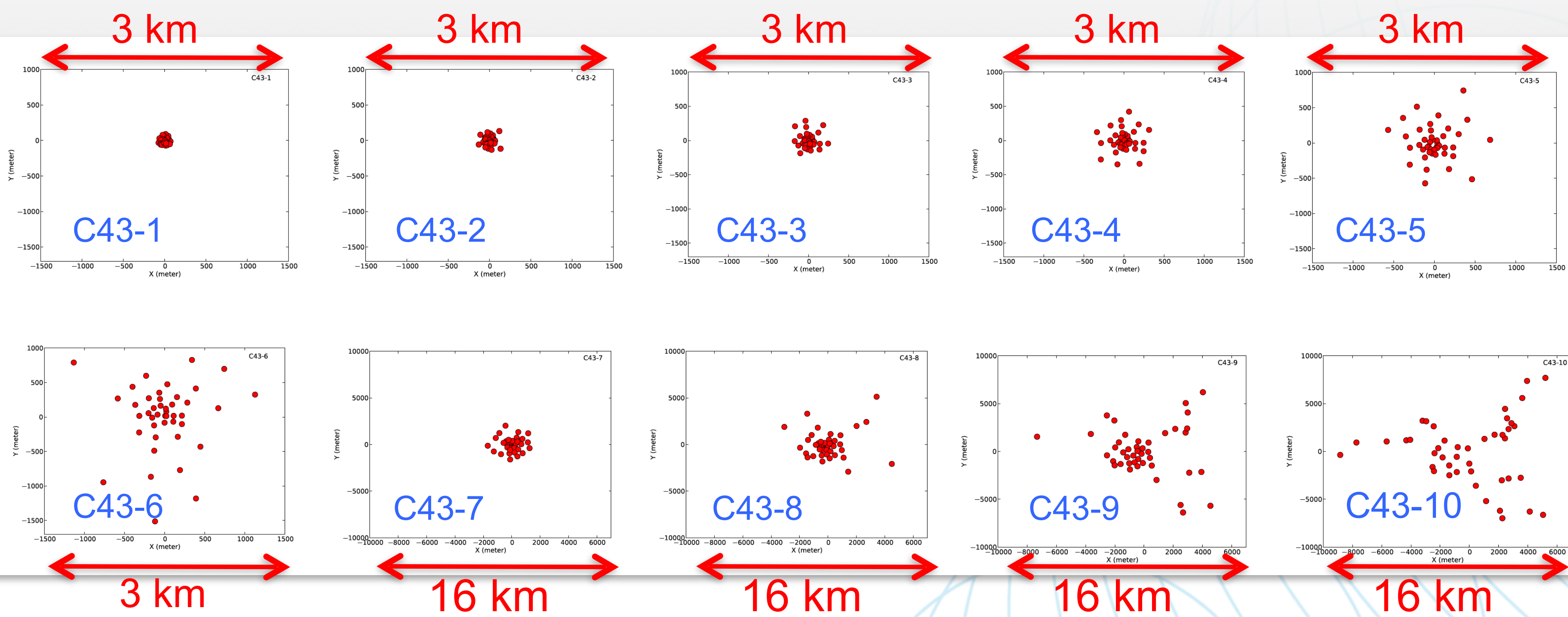
- 12-m antennas are movable to various stations across the Chajnantor plateau
- Specialized trans-porters (named "Otto" and "Lore") are used to move antennas around (also return them to the OSF for maintenance visits)

"Lore"
Credit: ESO/P. Martinez


12m Array
compact
Extended configuration: baselines to ~16km
OSF
Extended – up to 15 km
To Argentina
To San Pedro

ALMA arrays: the 12-m Array

Cycle 5 configurations: min baseline = 14.7 m, max baseline = ~16 km



ALMA will progress through these configurations throughout the Cycle

ALMA arrays: the ALMA Compact Array (ACA)

- Number: 12 × 7-m antennas
- Antennas are fixed in position
- Min / Max baselines: 8.7 m / 32 m
- Surface accuracy: <20 µm rms
- Used for low spatial frequency data

ALMA arrays: the Total Power “Array” (TPA)

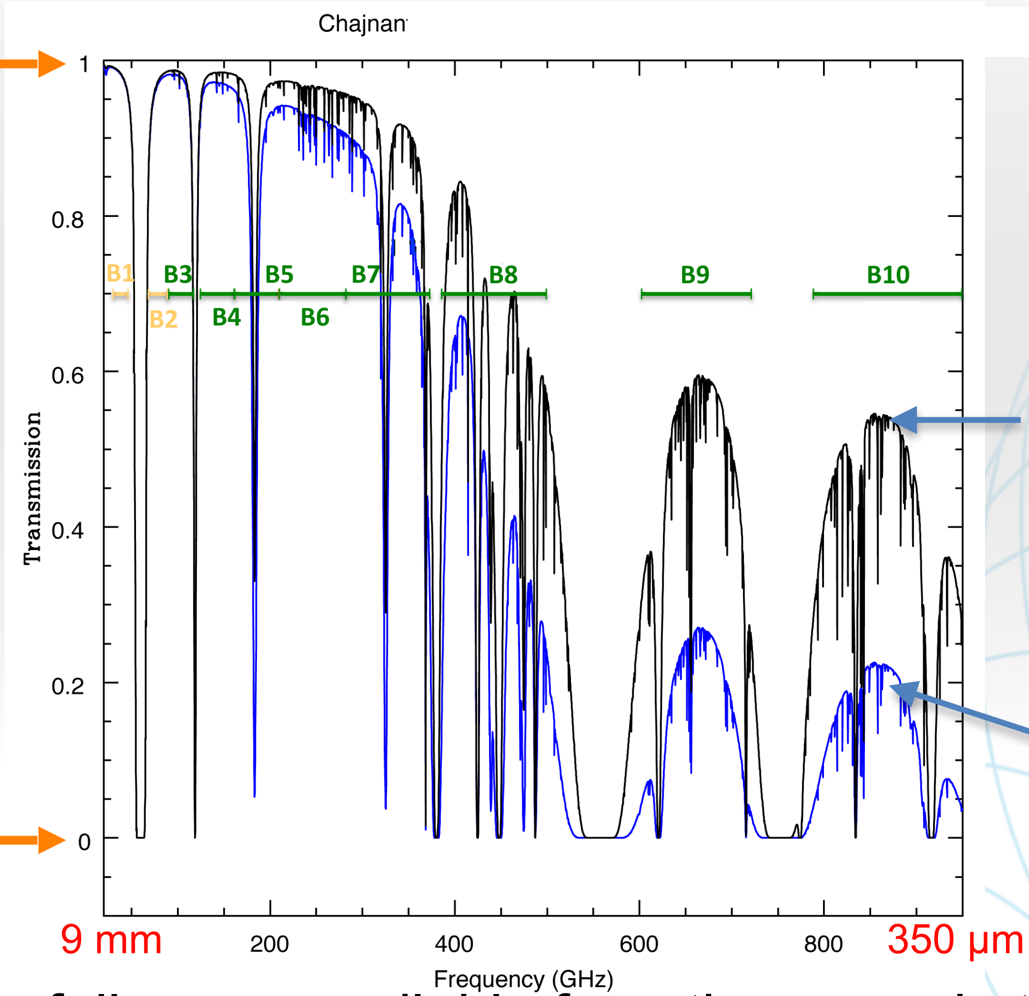
- Number:
  4 × 12-m antennas
- Antennas are also fixed in position
- Nutating secondaries may or may never be available for sky subtraction
- Signals not necessarily correlated but signals can be combined with those from the ACA if needed
- Used to obtain zero-spacing spatial frequency data by acting as single-dish telescopes that observe simultaneously

Receiver Bands

submillimetre wavelengths

transparent →

opaque →



12.5% of the time better transparency than this

Half the time better transparency than this

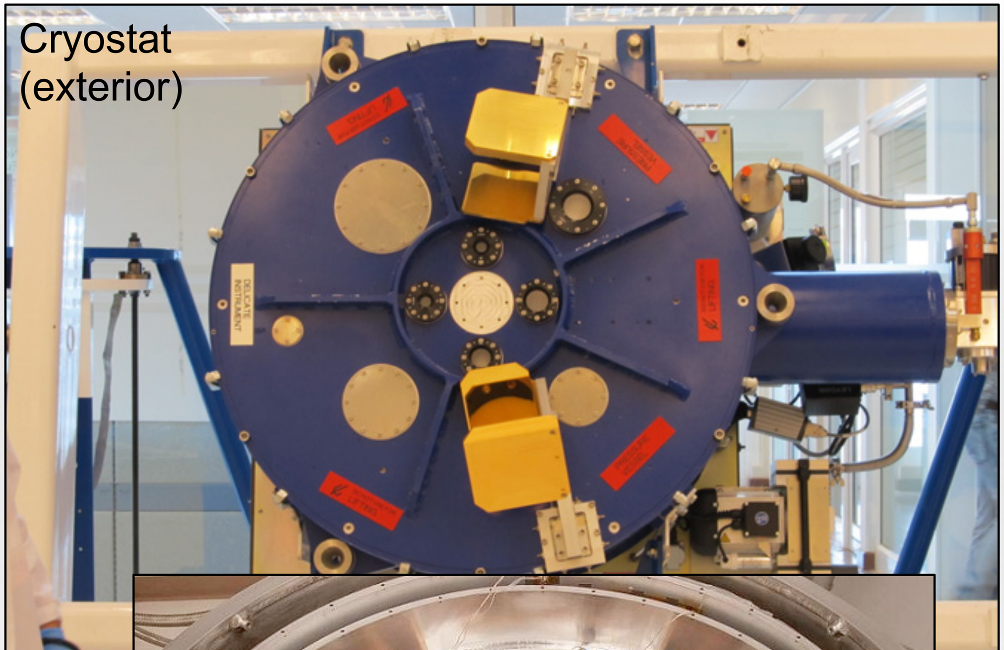
ALMA covers the full range available from the ground at submm wavelengths

Receiver Bands + Sensitivities

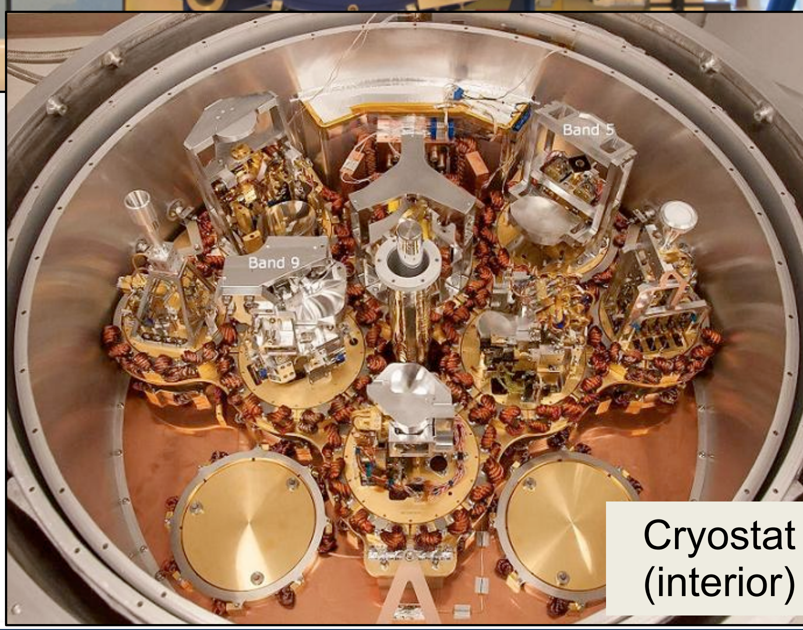
Cycle 5 Receiver Bands				
Band	Frequency (GHz)	Wavelength (mm)	Primary Beam (FOV; ")	Continuum Sensitivity (mJy/beam)
3	84-116	2.6-3.6	73-53	0.088
4	125-163	1.8-2.4	49-38	0.12
5	163-211	2.4-1.1	38-22	0.12
6	211-275	1.1-1.4	29-22	0.12
7	275-373	0.8-1.1	22-16	0.22
8	385-500	0.6-0.8	16-12	0.42
9	602-720	0.4-0.5	10-8.5	2.0
10	787-950	0.3-0.4	7.8-6.5	4.6

- Also in the works:
  - Band **1**: 35-52 GHz
  - Band **2**: 67-90 GHz
  - Band **11?** : 1.0-1.6 THz
- Continuum sensitivities estimated from a total of 7.5 GHz dual polarization band width in 60 seconds

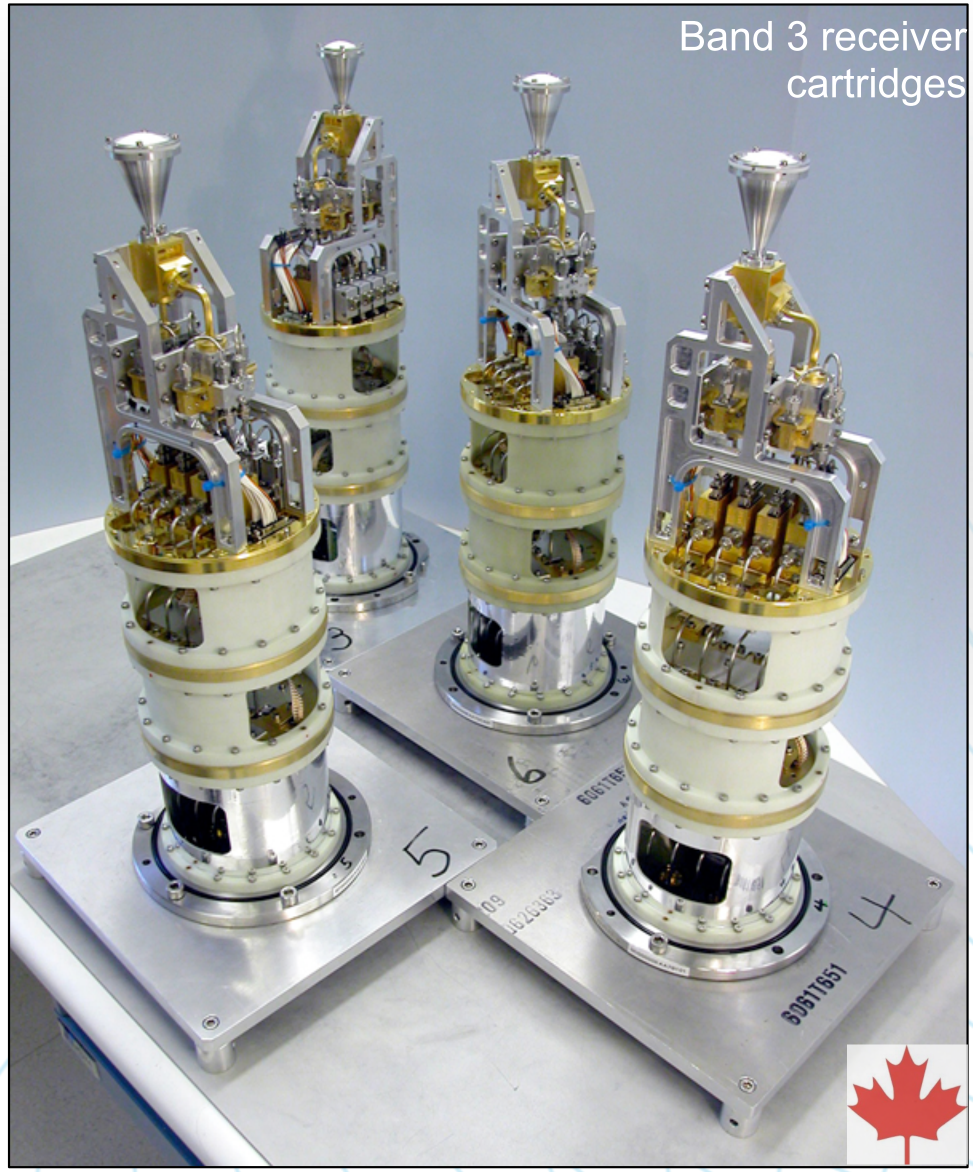
Receiver Bands



Cryostat (exterior)



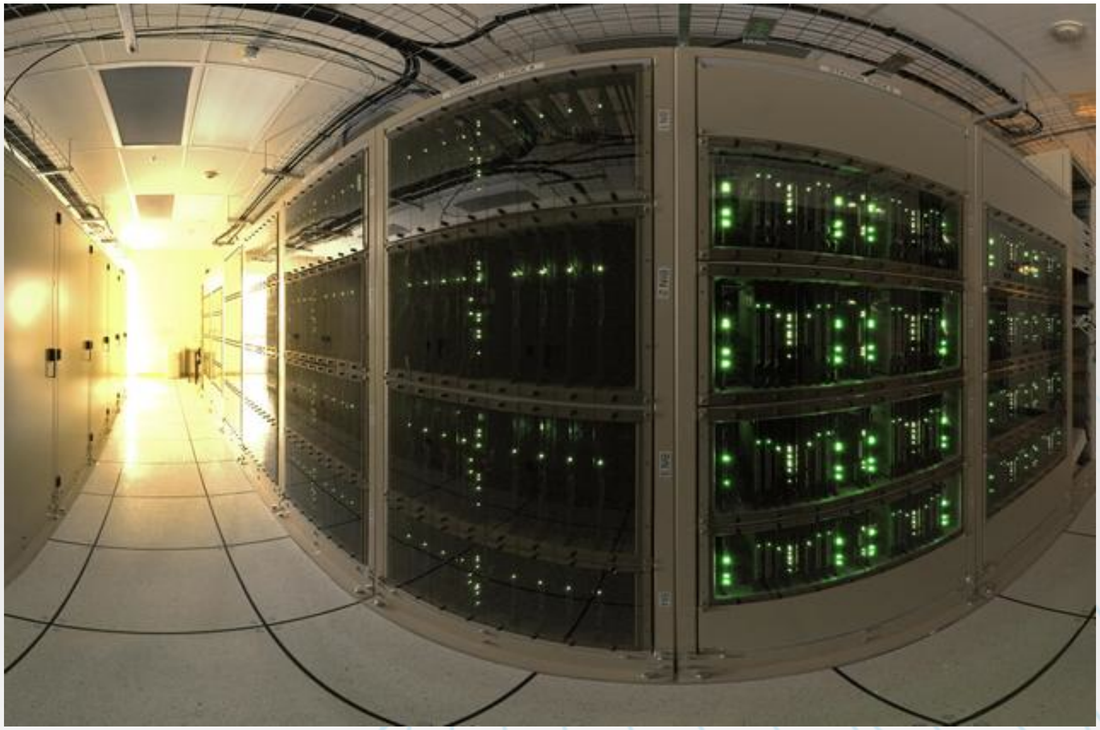
Cryostat (interior)



Band 3 receiver cartridges

Correlators: the 64-input Correlator

Digital Filter Circuit Boards (ALMA)



Correlator Exterior (ALMA)

A state-of-the-art FXF “correlator” (signal combiner) with 134 million processors capable of performing 17 quadrillion operations per second ➔ produces “visibilities”

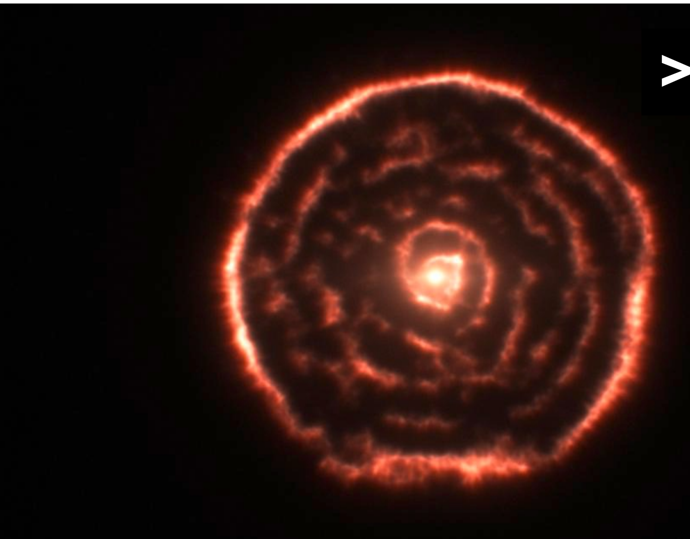
Correlators: the 64-input Correlator

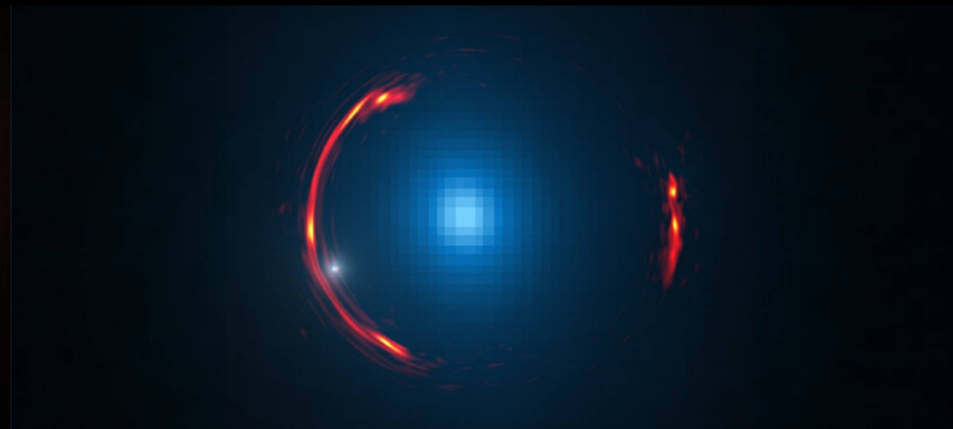
ALMA Baseband Options (Cycle 5)

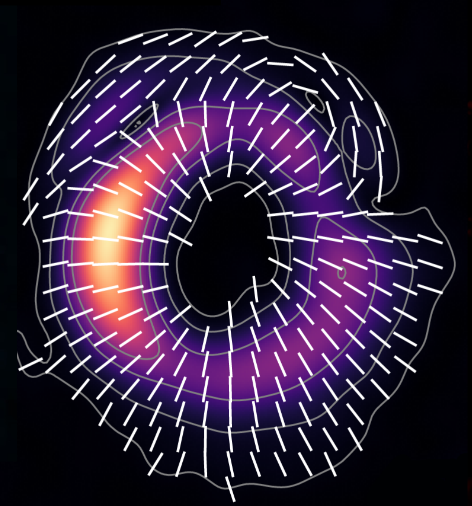
Mode	Polar-ization*	Band width (MHz)	Nchan	Chan. Spacing (MHz)	Spectral Resolution† 300 GHz (km/s)
FDM	*Dual*	*1875*	*3840*	*0.488*	*0.98*
FDM	*Dual*	*938*	*3840*	*0.244*	*0.49*
FDM	*Dual*	*469*	*3840*	*0.122*	*0.24*
FDM	*Dual*	*234*	*3840*	*0.061*	*0.12*
FDM	*Dual*	*117*	*3840*	*0.0305*	*0.061*
FDM	*Dual*	*58.6*	*3840*	*0.0153*	*0.031*
TDM	*Dual*	~~*2000‡*~~ 1875 (due to filtering)	*128*	*15.625*	*31.2*

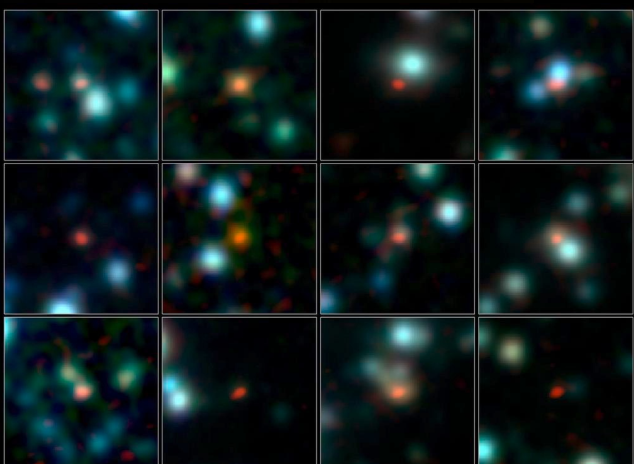
- Actual spectral resolution is **2× channel spacing** due to the correlator performing Hanning smoothing on the data
- Single pol'n modes also available, yield double the channel number and half the channel spacing
- 4 x "2 GHz" basebands = 8 GHz dual-pol band width
- More baseband options to be commissioned later

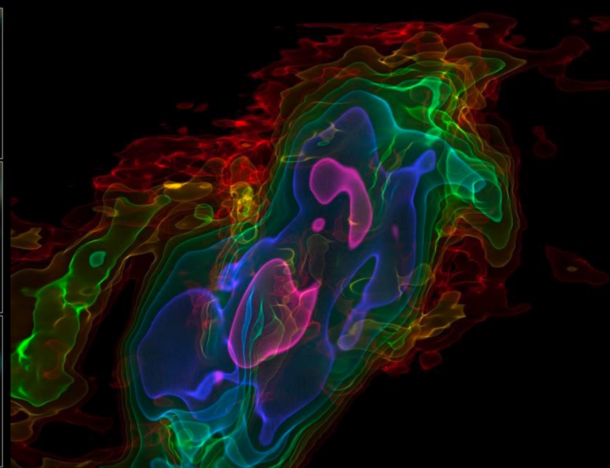
>638 refereed publications as of mid-April

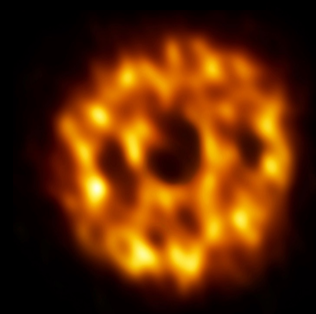


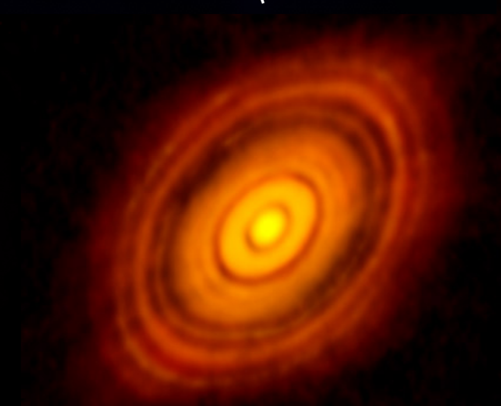




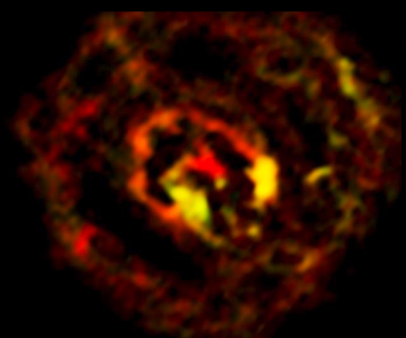


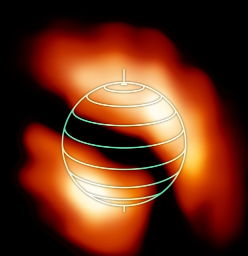


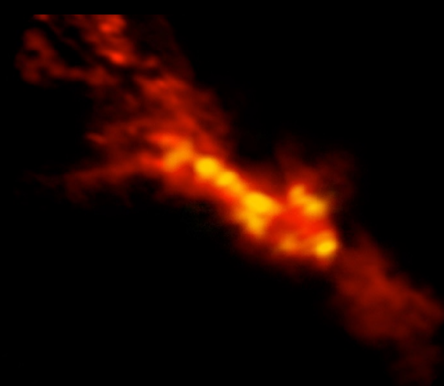




…and hundreds of unpublished datasets remaining in the archive!

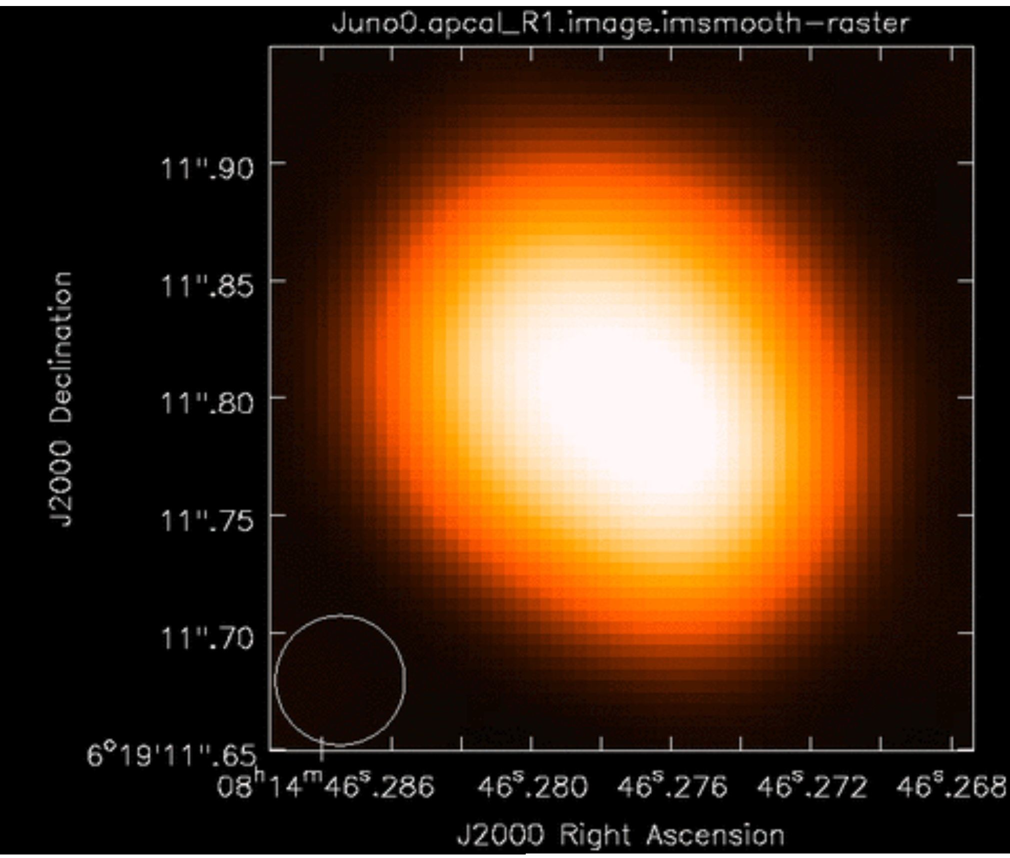


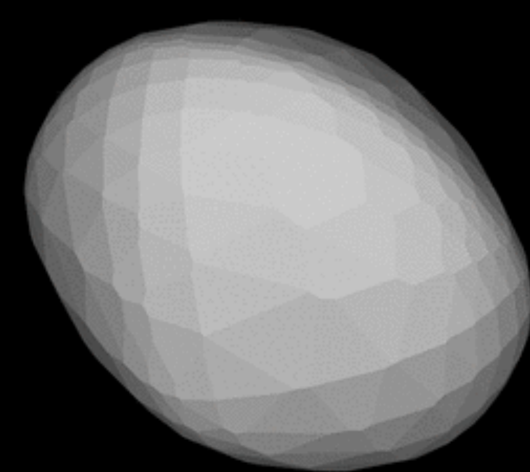




ALMA Science Highlights: Solar System

Band 6 Observations of Juno: Frequency = 233 GHz (Science Verification)
Five consecutive executions over 4.4 hours
Beamsize ~ 0.04” x 0.03” (~60 x 45 km)
Model: Durech et al. 2010: **Database of Asteroid Models from Inversion Techniques**



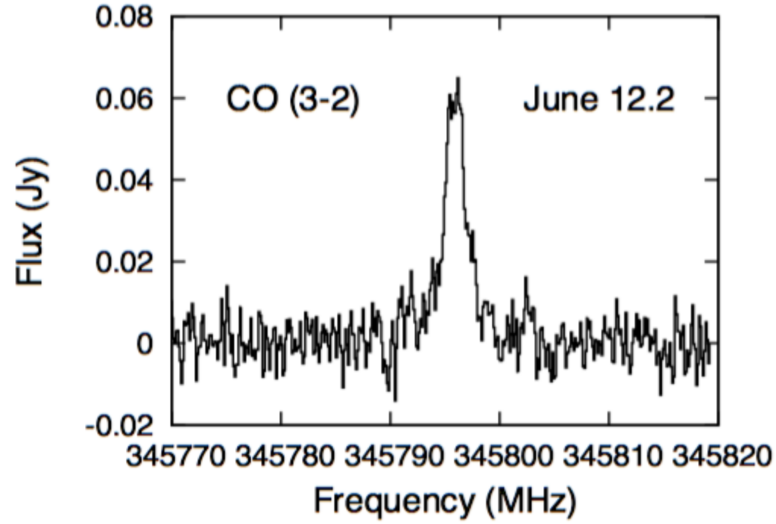


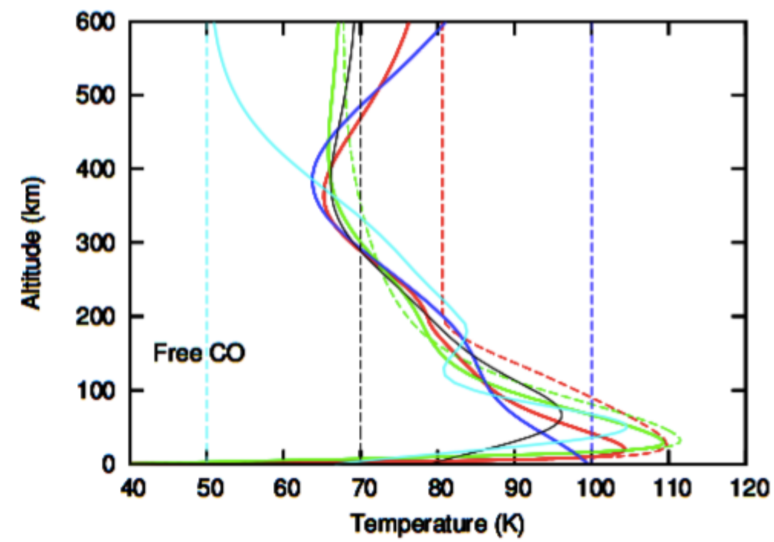
ALMA Image of Juno (ALMA Partnership, Hunter et al. 2015)

ALMA Science Highlights: Solar System

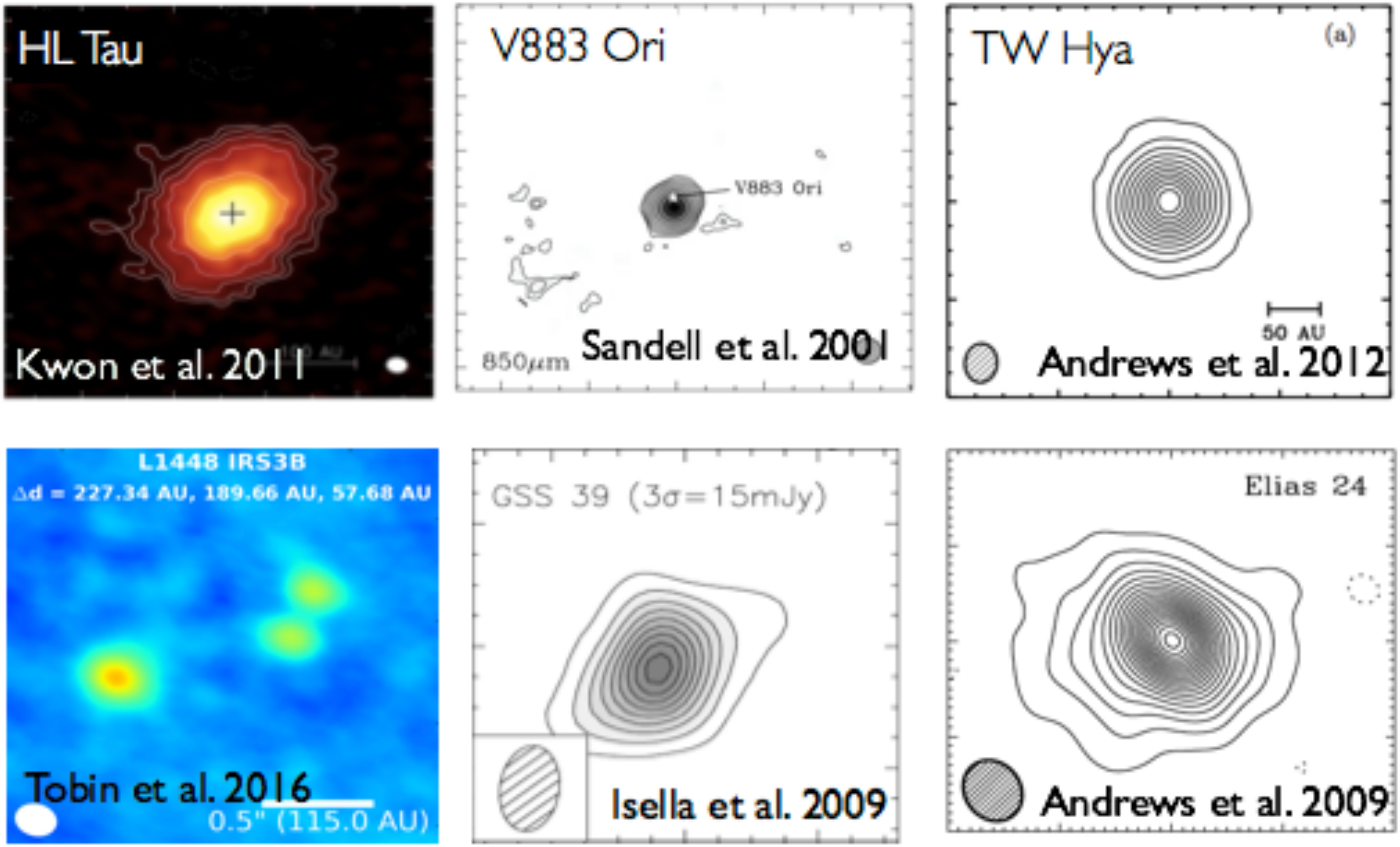
ALMA detects organics above Pluto

- ALMA has detected CO (3-2) and HCN (4-3) on Pluto (Lellouche et al. 2016)
- The lines probe the abundances and temperature of Pluto's atmosphere up to ~450 km and ~900 km.
- The dayside temperature profile shows a well-marked temperature decrease (i.e., mesosphere) above the 30-50 km stratopause, with T= 70 K at 300 km
  - In agreement with New Horizons solar occultation data.
- The HCN line shape implies a high abundance in the upper atmosphere (450 – 800 km)
  - Suggests a warm (>92 K) upper atmosphere





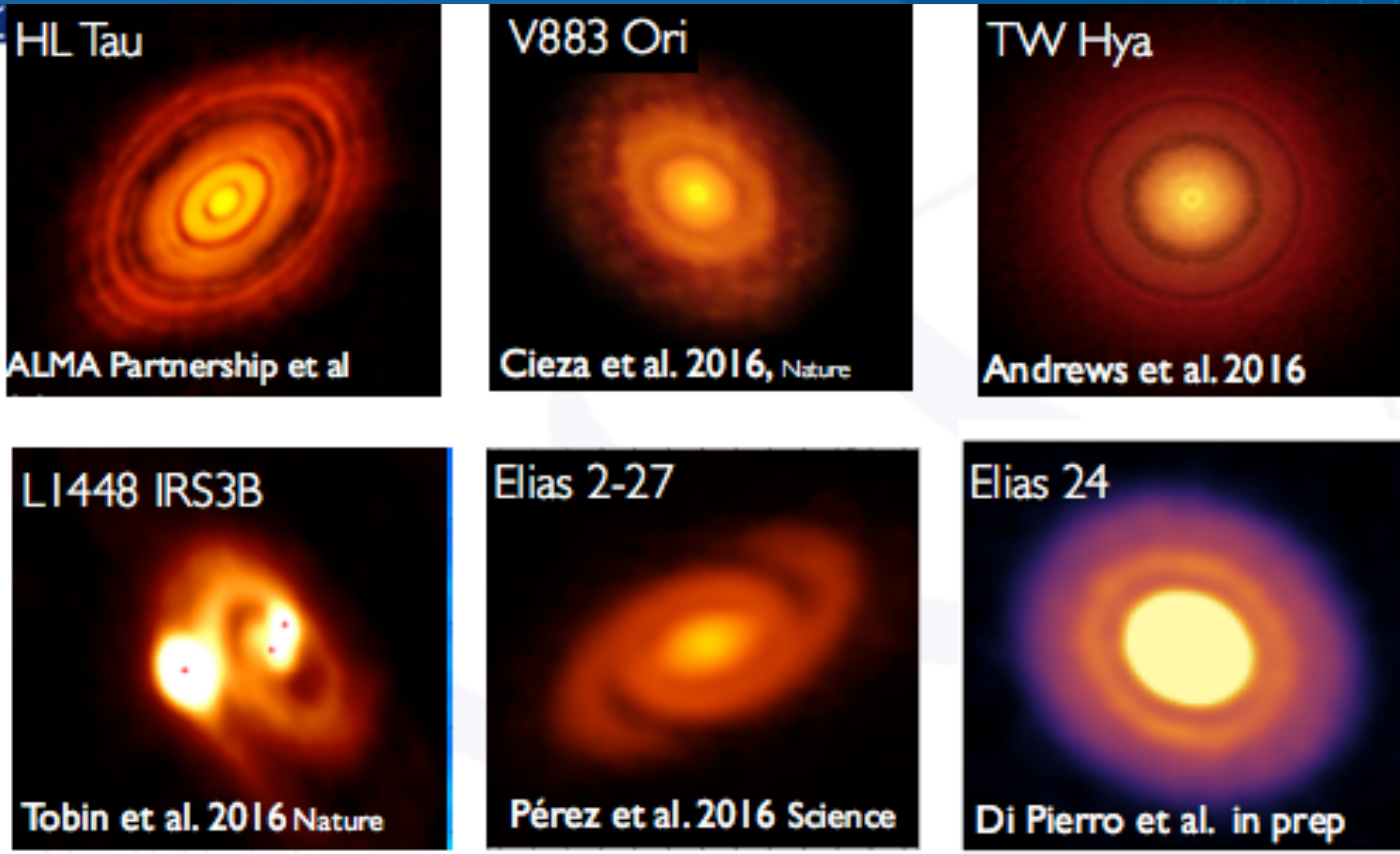
ALMA Science Highlights: Protoplanetary Disks



Composite image courtesy J. Carpenter / A. Wootten (ALMA / NRAO)

Pre- ALMA

ALMA Science Highlights: Protoplanetary Disks



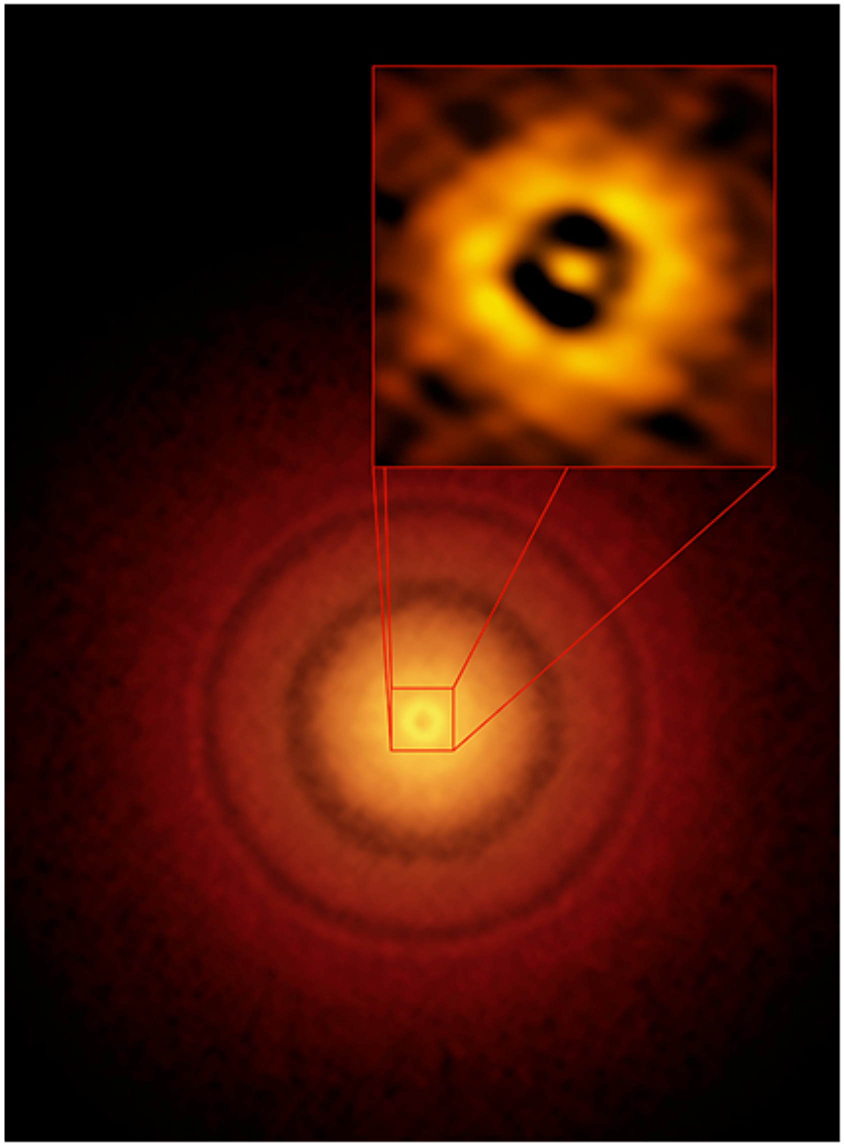
Composite image courtesy J. Carpenter / A. Wootten (ALMA / NRAO)

With ALMA

ALMA Science Highlights: Protoplanetary Disks

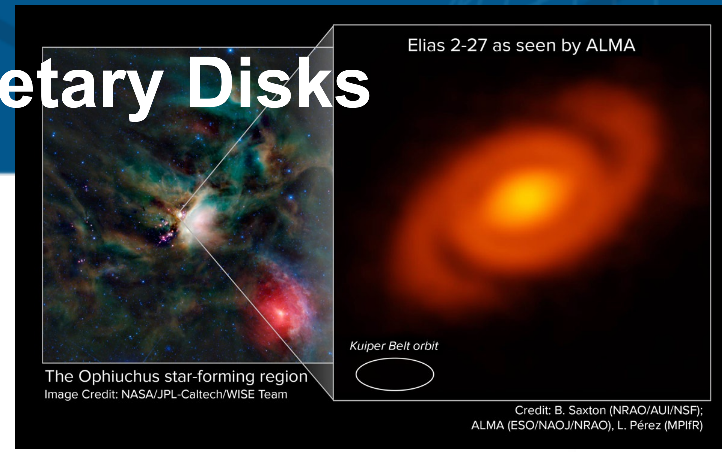
TW Hydrae

With ALMA's better-than Hubble resolution, details as small as the Earth's distance from the Sun (1 au) may be discerned in this young (10 Myr) nearby (175 light years) planet-forming, Sun-like star



Andrews et al. (2016)

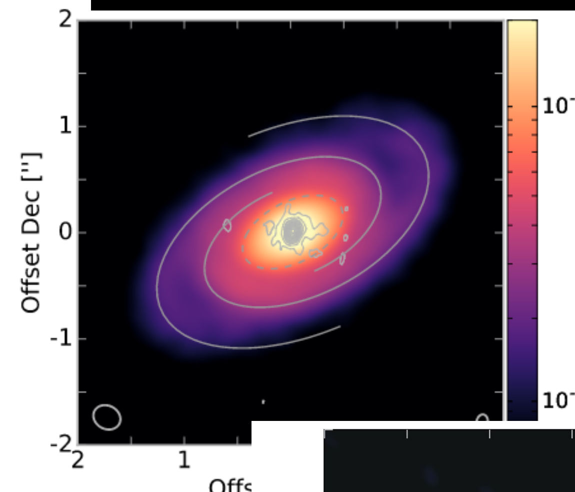
ALMA Science Highlights: Protoplanetary Disks



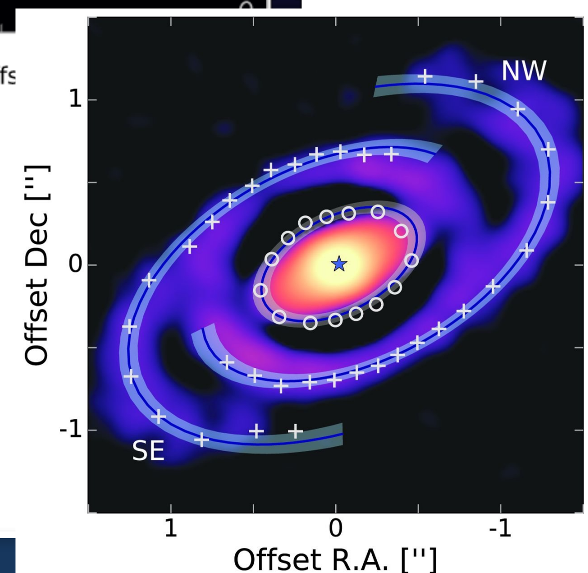
A Spiral Density Wave Observed in a Protoplanetary Disk

Perez et al. Science 353, 1519 (2016)

- Gravitational instabilities in protoplanetary disks might be excited by e.g. planet-disk interactions or gravitational instabilities
- Disk mid-plane structure provides a sensitive probe for these instabilities; optical observations probe the disk surface but radio wavelength observations probe the disk density structure.
- ALMA imaging (dust and CO, 33 au resolution) reveals two symmetric spiral arms (r~150 au) emanating from an elliptical emission ring (r~71 au) in the disk Elias 2-27, in the nearby ρ Oph cloud
- A spiral density wave fits the observations well. Fragmentation of such spirals remains the only plausible formation mechanism for planets and companions at large disk radii, where core-accretion becomes inefficient.



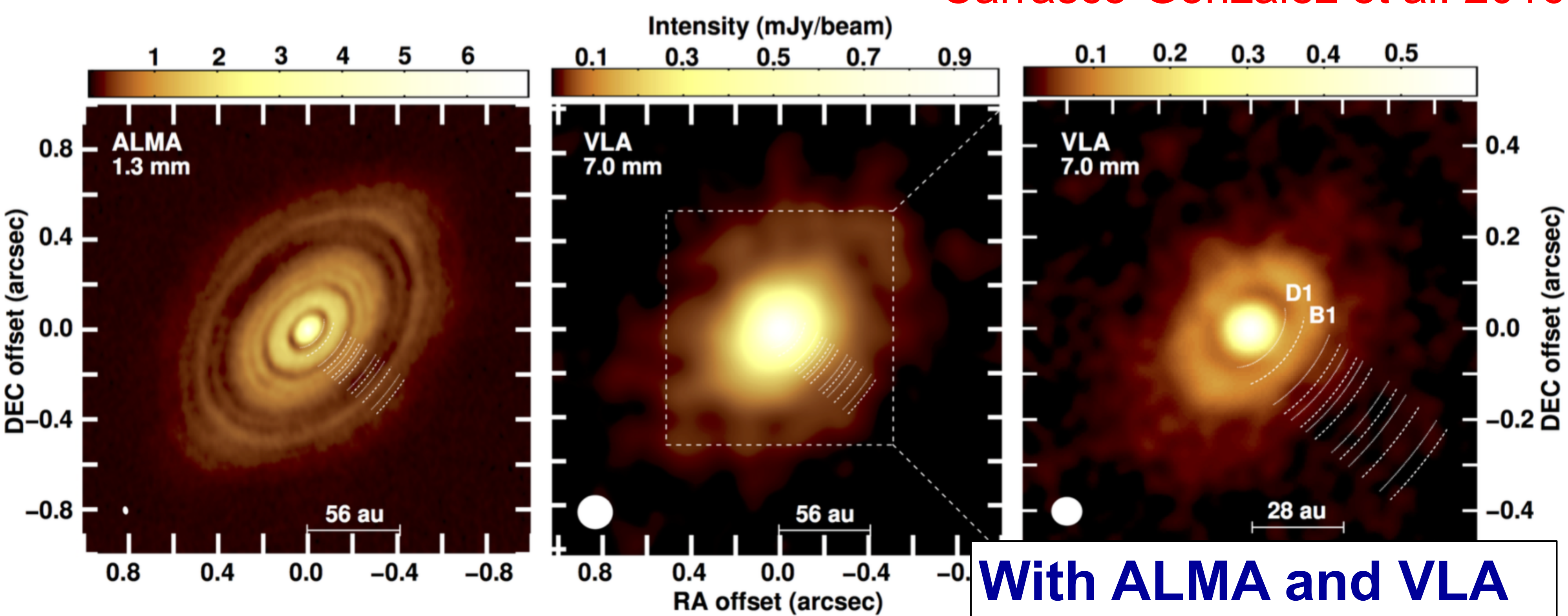
With ALMA



ALMA Science Highlights: Protoplanetary Disks

- Emission from inner regions of HL Tau still optically thick at ALMA wavelengths
- VLA can image the disk at comparable resolution to ALMA at 7 mm where emission is optically thin
- Combination of ALMA+VLA helps differentiate between formation theories with info on grain growth, fragmentation, and formation of dense clumps: suggest HL Tau disk is in very early stage of planet formation with planets not yet in the gaps but set for future formation in the bright rings

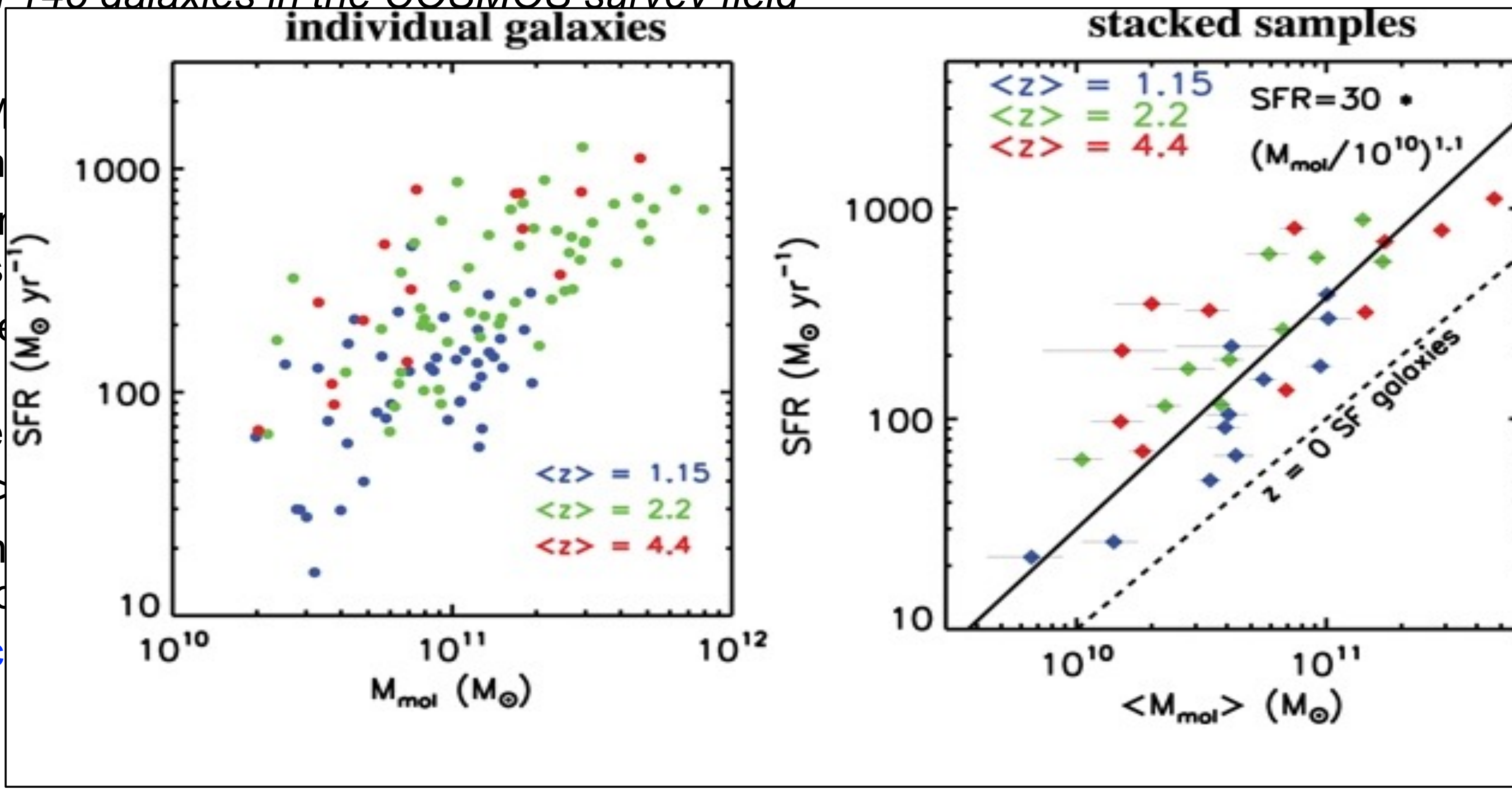
Carrasco-González et al. 2016



With ALMA and VLA

ALMA Science Highlights: Star Formation Peak

- Scoville et al. (2016 ApJ 820 83)
  - *“ISM Masses and the star formation law at z = 1 to 6: ALMA observations of dust continuum in 145 galaxies in the COSMOS survey field”*



- ALM… evolution of th…
- Four… ISM mas…
- Seve…
- At z… pletion time…
  - =…
  - m… tural c…
- 36 c…

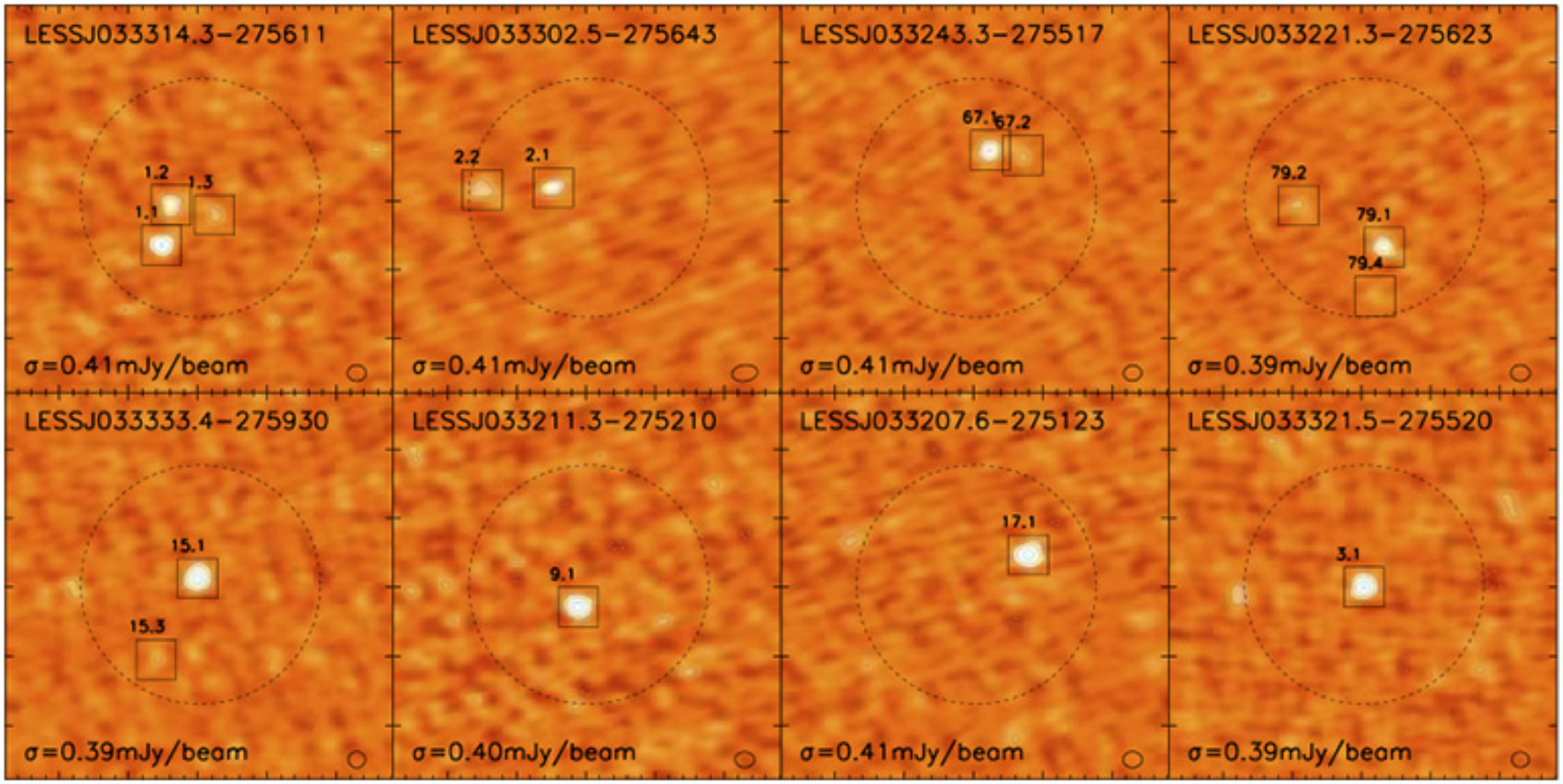
ALMA Science Highlights: Star Formation Peak

- Scoville et al. (2016 ApJ 820 83)
  - *“ISM Masses and the star formation law at z = 1 to 6: ALMA observations of dust continuum in 145 galaxies in the COSMOS survey field”*

- ALMA Cycle 2 observations of long-wavelength dust emission were used to probe the evolution of the star-forming interstellar medium (ISM). Sample size: 145 galaxies
- Found a single high-z star formation law -- an approximately linear dependence on the ISM mass and an increased star formation efficiency per unit gas mass at higher redshift.
- Several notable conclusions from the survey – among them:
- At $z > 1$, the entire population of star-forming galaxies has ~2–5 times shorter gas depletion times than low-z galaxies.
  - => **different mode of star formation in the early universe**
  - most likely dynamically driven by compressive, high-dispersion gas motions—a natural consequence of the high gas accretion rates.
- 36 citations to date (power of well-designed surveys)

ALMA Science Highlights: The Distant Universe

Resolving High-z Submm Galaxies



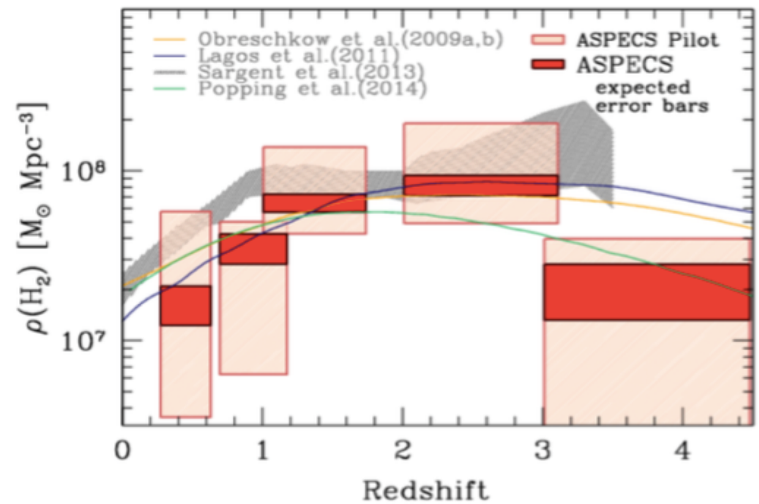
- 126 submm sources observed with ALMA at 870 μm
- 2x deeper, 10x higher angular resolution than previous surveys
- 99 sources detected in 88 fields, integration time ~120 sec (!!)
- Significant multiplicity (35-50%) found at 0.2” resolution

Hodge et al. 2013

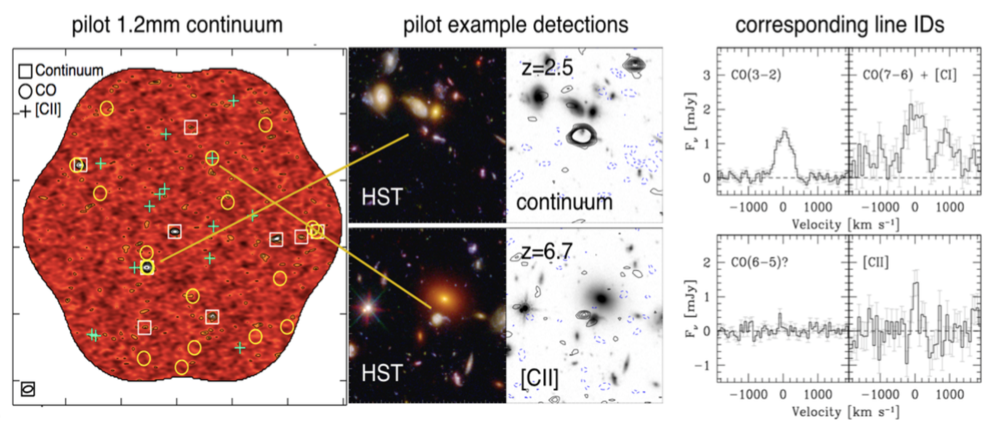
ALMA Science Highlights: The Distant Universe

ALMA Deep Fields: a new era of cosmological surveys

- ALMA has opened a new window on the cosmos: large volume surveys for cold gas throughout the Universe = the fuel for star formation. ASPECS is the first line deep field, involving full frequency scans of Band 3 and 6 in the Hubble UDF.
- 21 candidate line galaxies were detected, including CO emission from galaxies at z=1 to 5, and [CII] at z > 6, plus 9 dust continuum sources at 1.2mm
- These data determine the dense gas history of the Universe, the necessary complement to the star formation history of the Universe.

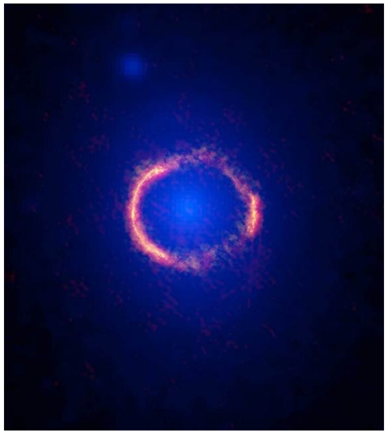


Examples of line and continuum sources from the ASPECS program, plus constraints on the dense gas history of the Universe (see papers by Walter, Decarli, Aravena)



ALMA Science Highlights: The Distant Universe

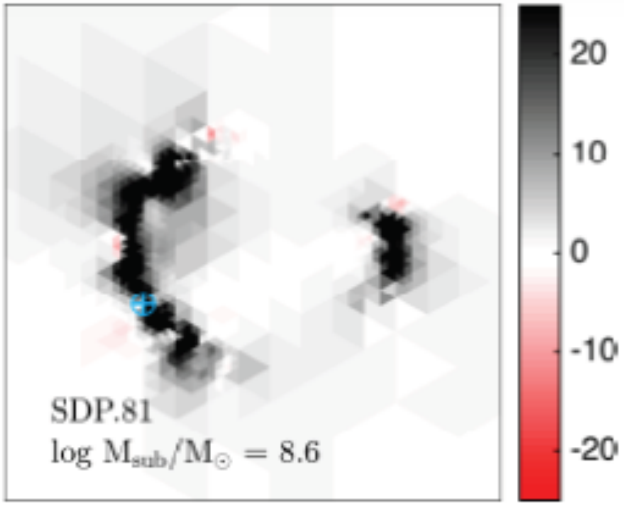
- Hezaveh et al. (2016) show ALMA's potential to advance understanding of dark matter substructures
- ALMA's SDP.81 observations are analyzed to detect a subhalo with a mass of $10^{8.96\pm0.12}$ M_{sun}
- Consistent with theoretical expectations

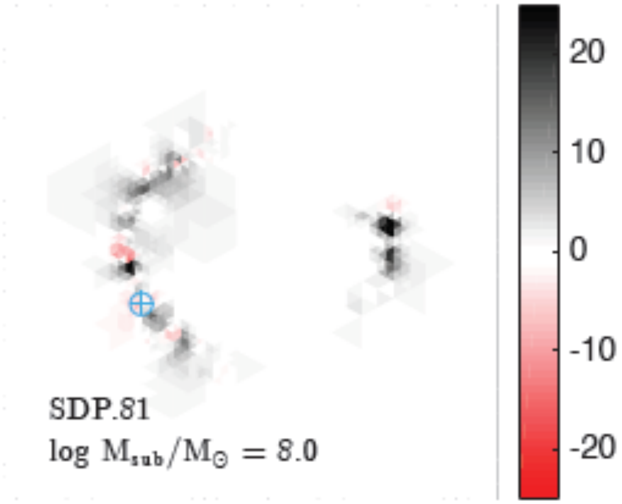


The SDP.81 system.

Blue: HST/WFC3 F160W data shows lensing elliptical at z~0.3

Red: ALMA Bands 4/6/7 combined emission.





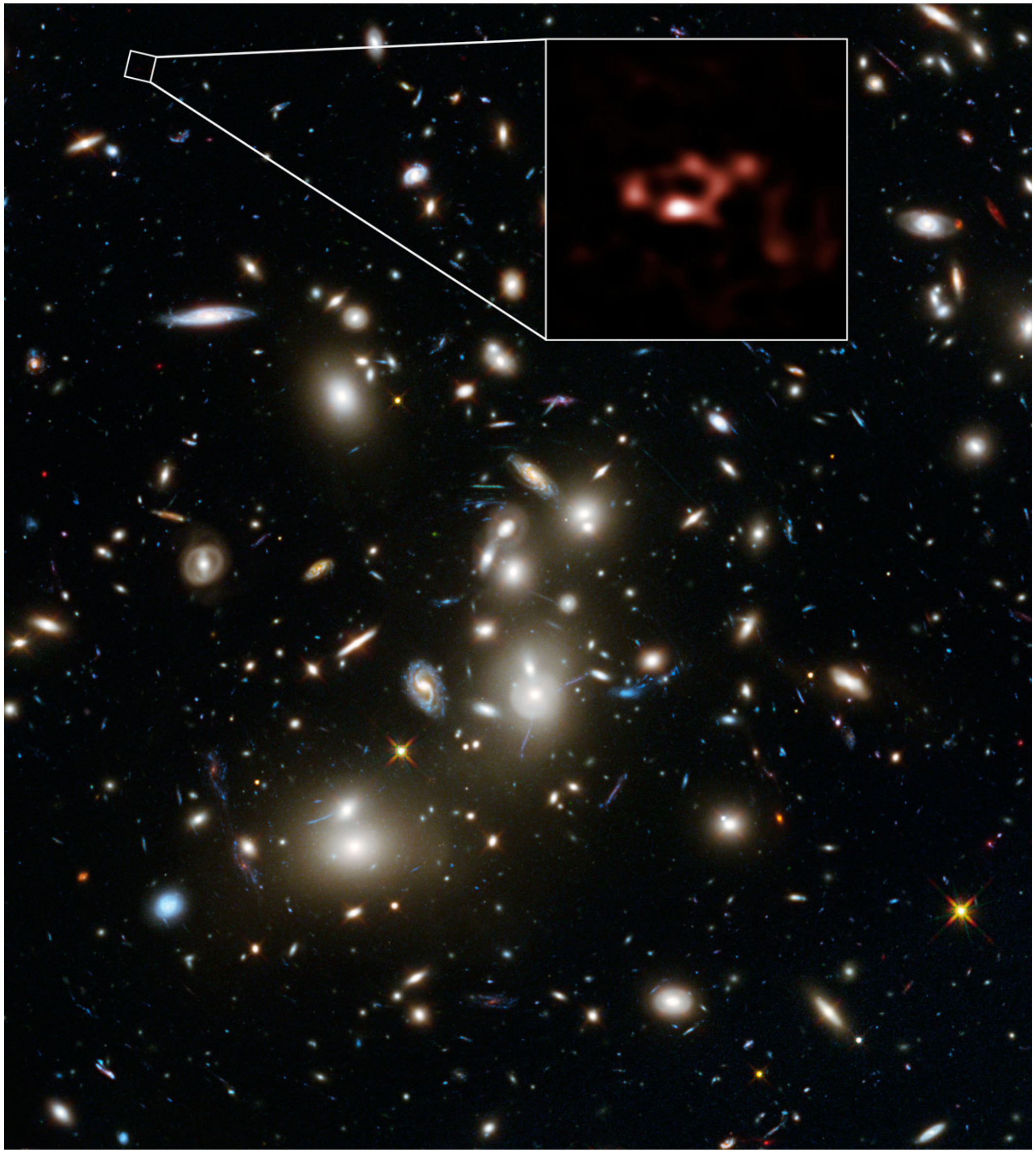
(Right Top) a map of parameter for a second subhalo of mass $10^{8.6}$ M_{sun} after inclusion of one subhalo of mass 10^{9} M_{sun} at the location of the blue symbol.
(Bottom) results from similar analysis for a lower mass subhalo, showing marginal improvement at another point near the first detection.

ALMA Science Highlights: The Distant Universe

- Laporte et al. (2017) observes lensed galaxy at Z = 8.38

- A2744_YD4
- $M_{dust} = 6 \times 10^6 M_{sun}$
- $M_{star} = 2 \times 10^9 M_{sun}$

- SFR ~ 20 M_{sun} / yr



Summary

- ALMA is a versatile transformational observatory that is now in the process of breaking new ground in a host of astrophysical contexts
- ALMA is emerging from its “Early Science” phase and entering more standard operations for many modes of observing
- ALMA is the future instrument for mm/submm observations, now entering the 6^{th} proposal round (“Cycle 5”)

Check out the ALMA Primer!
Find it on the ALMA Science Portal (almascience.org)

Thank you

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