The future of ALMA

María Díaz Trigo (ESO)

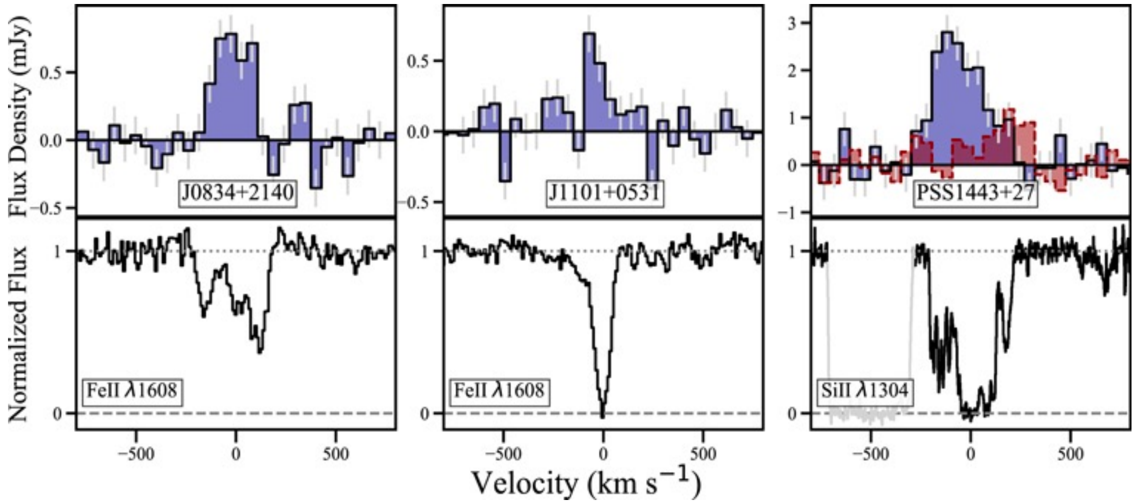
ALMA original science drivers

- Ability to detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation

- Ability to image the gas kinematics in a solar-mass protoplanetary disk at a distance of 150 pc, enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation

- Ability to provide precise images at an angular resolution of 0.1”

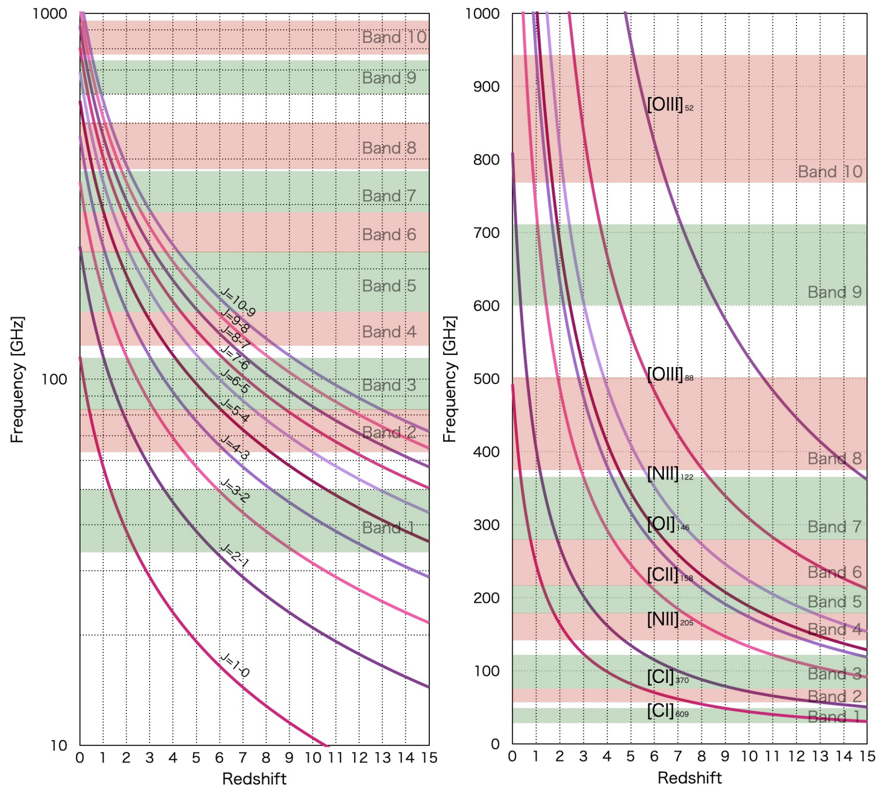
Sensitivity and frequency coverage



Neeleman et al. 2019

ALMA [CII] spectra of three damped Ly absorber galaxies at z ~ 4

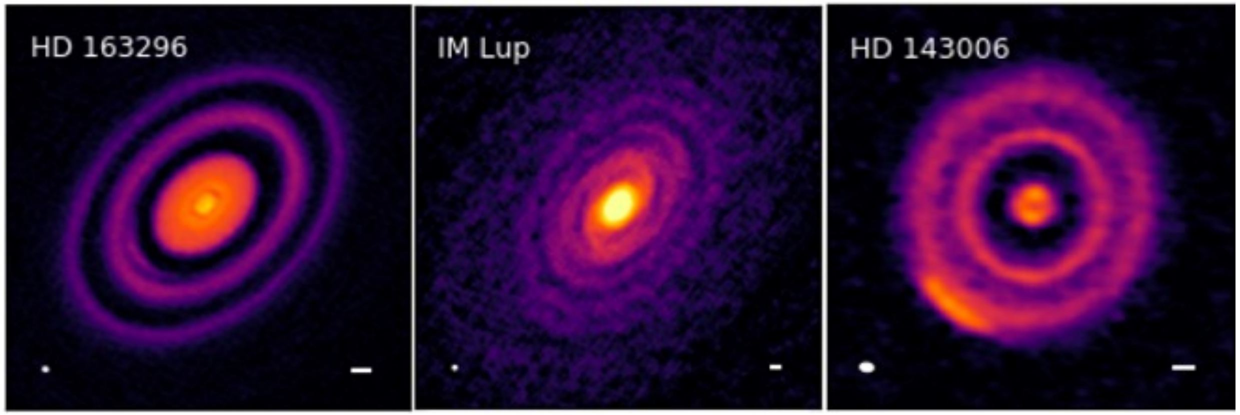
L ~ (0.36-30) 10^8 L_{sun} ;
SFR: 7-110 M_{Sun}/yr



Carpenter et al. 2022

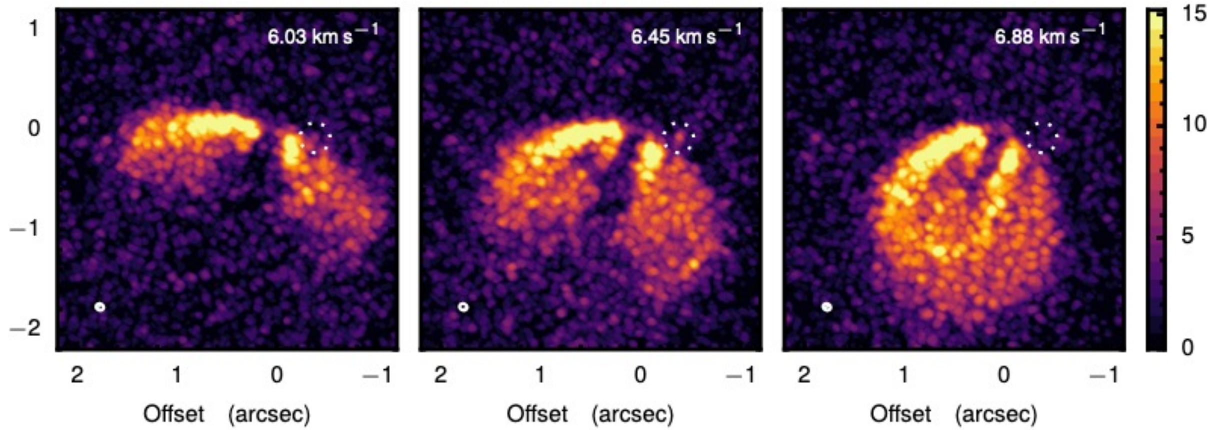
Superb imaging

Andrews et al 2018



Dust continuum (0.87 mm) at 35 mas (5 AU) angular resolution of protoplanetary disks at distances of 100-160 pc

Keppler et al 2019



ALMA 13 CO(3-2) images revealing the kinematics of the protoplanetary disk PDS 70 (d=113.4 pc), which harbours a planet imaged in the near-IR (PDS 70b)

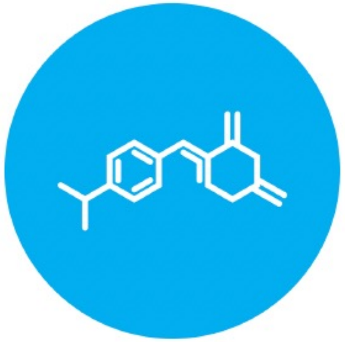
ALMA capabilities increase every cycle

- In upcoming Cycle 10:
  - Band 1 on the 12-m Array
  - Spectral scans that include Total Power observations
  - Solar observations in full polarization in Band 3 using only the 12-m Array
  - Phased array mode and VLBI in Bands 1, 3, 6 and 7
  - Band-to-band phase calibration for high frequency observations
  - 4x4-bit spectral modes for improved sensitivity on the 12-m Array (dual polarization)
- Joint proposals with JWST, VLA and the VLT

ALMA 2030 scientific drivers

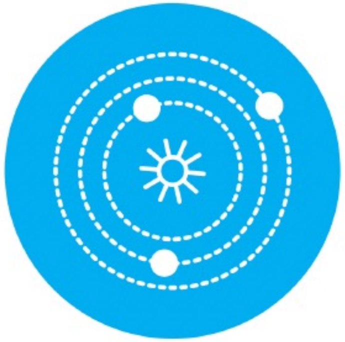
ORIGINS OF GALAXIES

Trace the cosmic evolution of key elements from the first galaxies (z>10) through the peak of star formation (z=2–4) by detecting their cooling lines, both atomic ([CII], [OIII]) and molecular (CO), and dust continuum, at a rate of 1-2 galaxies per hour.



ORIGINS OF CHEMICAL COMPLEXITY

Trace the evolution from simple to complex organic molecules through the process of star and planet formation down to solar system scales (~10-100 au) by performing full-band frequency scans at a rate of 2-4 protostars per day.



ORIGINS OF PLANETS

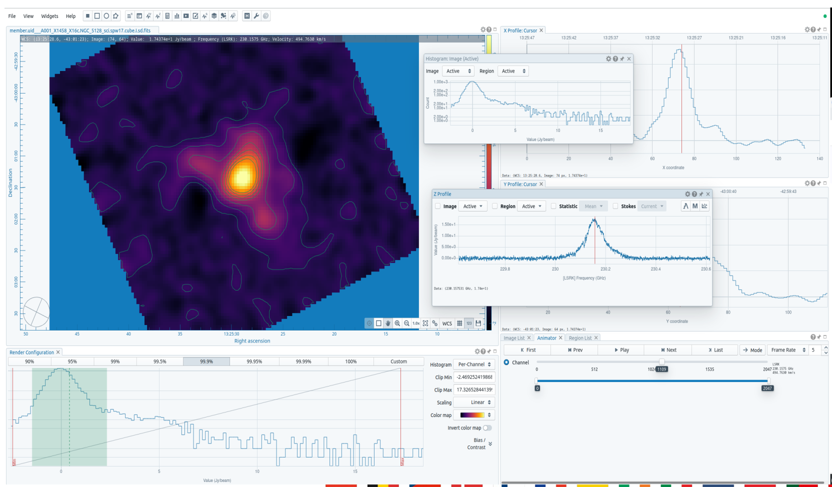
Image protoplanetary disks in nearby (150 pc) star formation regions to resolve the Earth forming zone (~ 1 au) in the dust continuum at wavelengths shorter than 1mm, enabling detection of the tidal gaps and inner holes created by planets undergoing formation.

https://www.almaobservatory.org/en/publications/the-alma-development-roadmap

ALMA in the 2030s: development roadmap

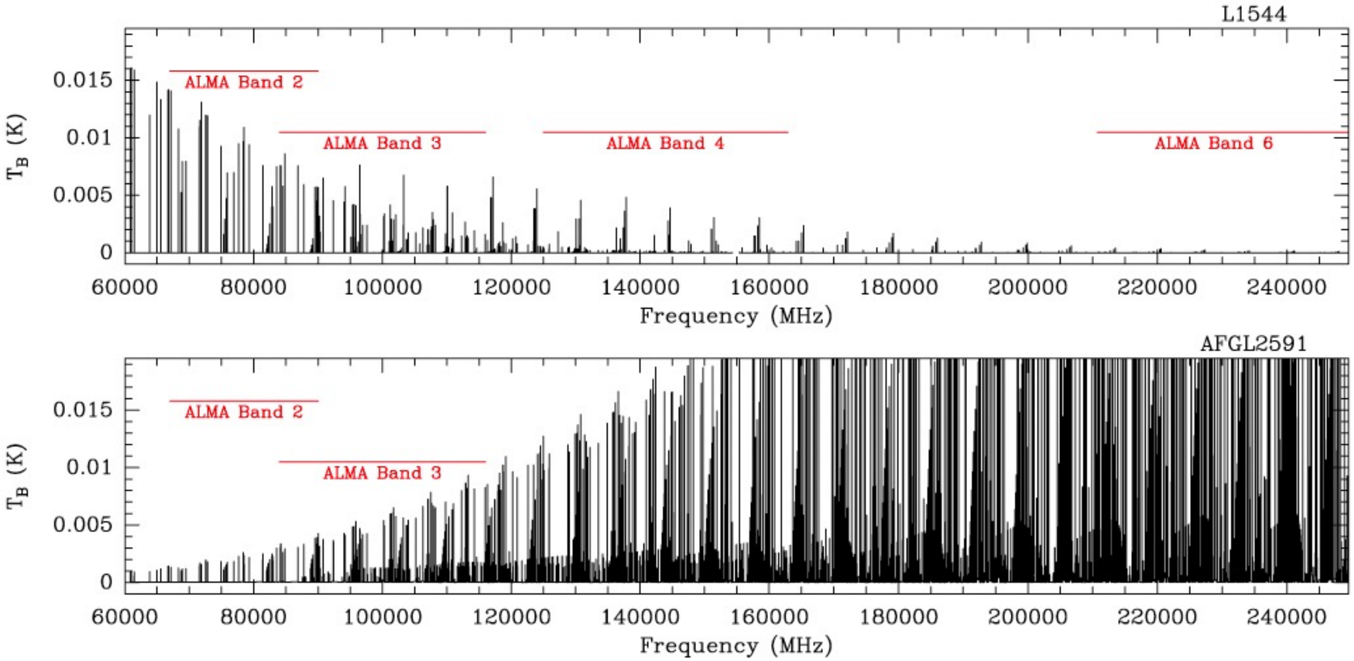
- Short term upgrades:
  - Band 1 (35-50 GHz) from 2023 on: adding $1.3 < z < 2.3$ range for CO(1-0)
  - Band 2 (67-116 GHz) from ~2026 on: adding $0.37 < z < 0.7$ for CO(1-0)

- Near to mid-term goals:
  - Wideband sensitivity upgrade: broaden receiver IF bandwidth by up to 4x, and upgrade of associated electronics and correlator for gains in speed
  - Archive: increase usability/impact



- Longer term goals:
  - Longer baselines
  - Wide field mapping speed
  - Additional antennas

Receivers: Band 2



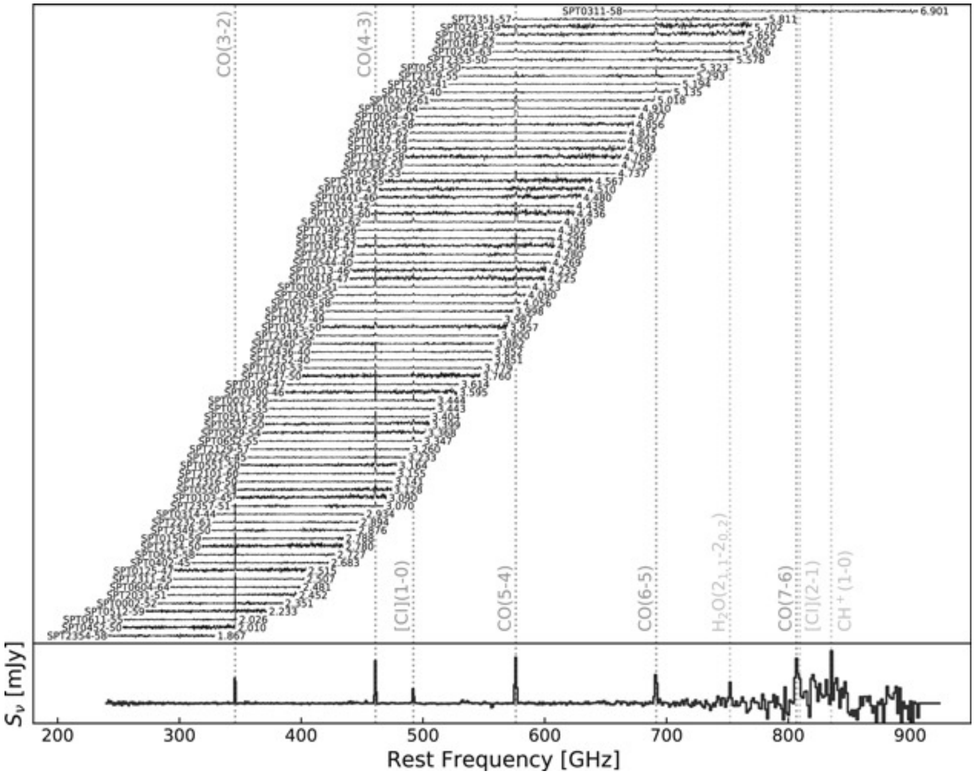
Pre-stellar core

Hot molecular core

Simulations of Glycine spectra (Jimenez-Serra et al. 2014)
Glycine is the simplest amino acid relevant to life

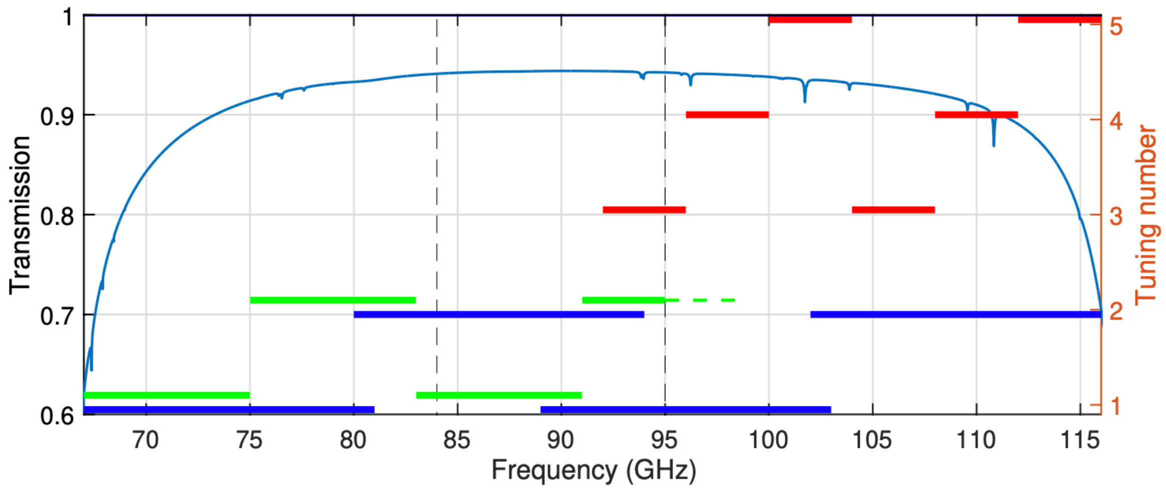
RF bandwidth: 67-116 GHz (coverage of original bands 2 and 3)

Receivers: Band 2



Reuter et al. 2020 ApJ 902, 78

Full range of spectral scan can be covered in just 2 spectral setups compared to currently 5 setups for 84-116 GHz Band 3



Wideband Sensitivity Upgrade

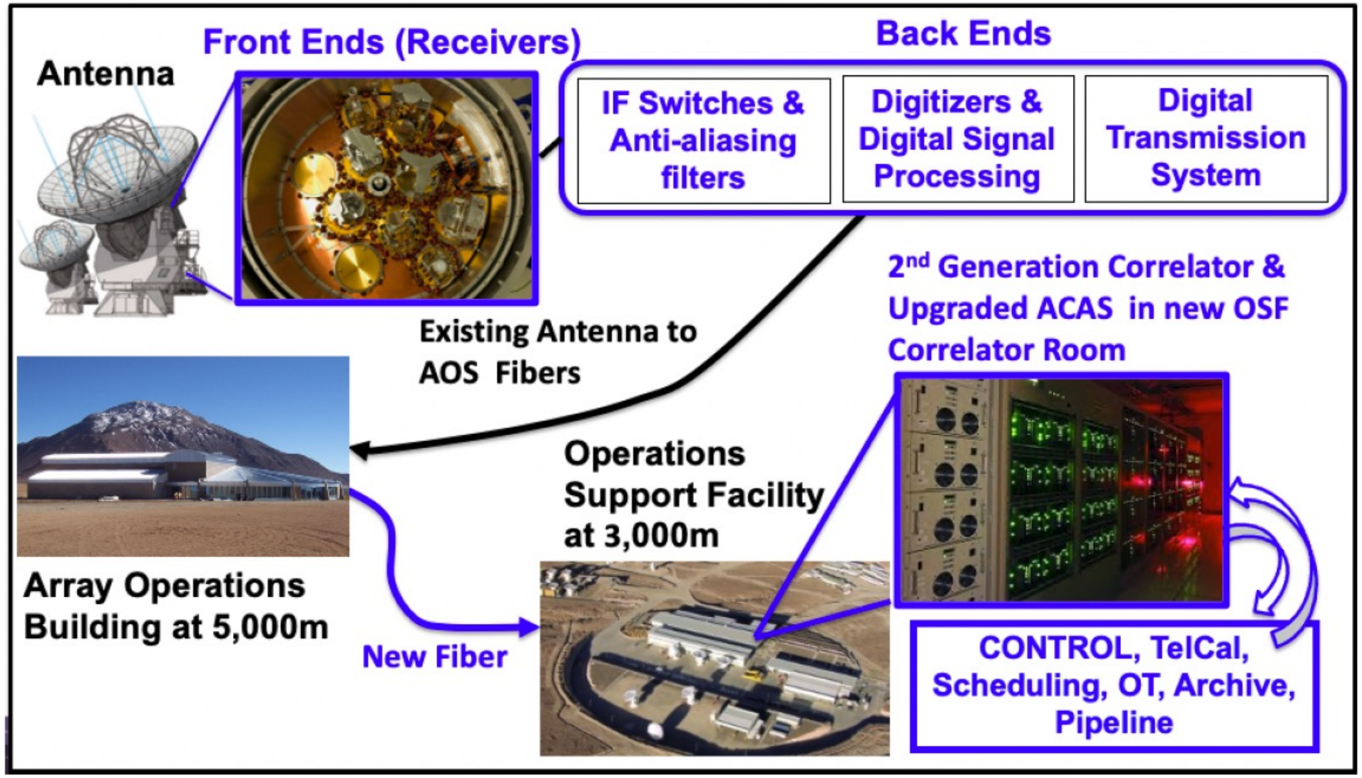
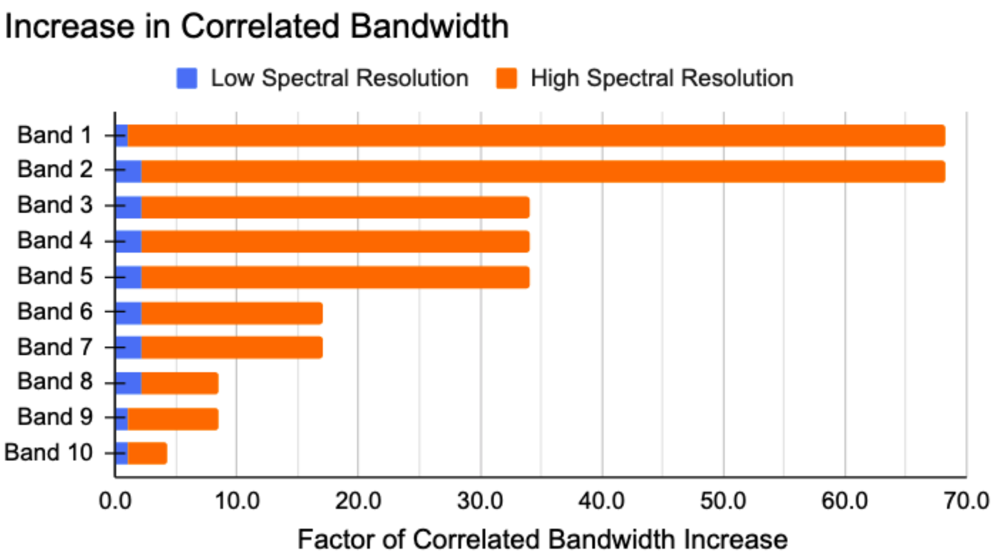
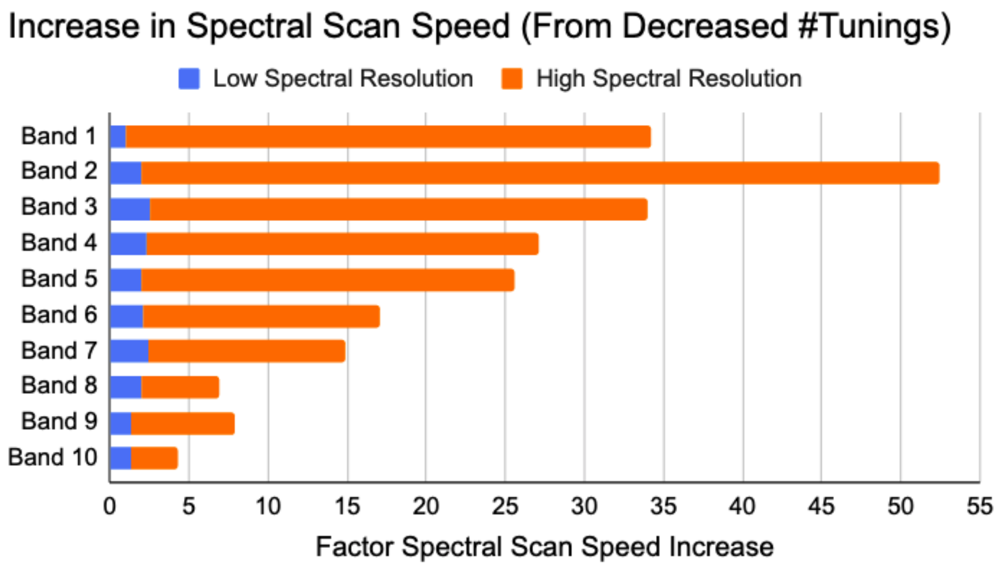


Figure 1. Simplified overview of the ALMA signal chain post-WSU upgrade. Components that are either new or will be upgraded are shown in blue.

Wideband Sensitivity Upgrade





Carpenter et al. 2022

- Continuum imaging speed increase by x3 (x6) for x2(x4) correlated bandwidth (including digital efficiency improvements)
- Spectral line imaging speed increase by ~ x2-3
- Spectral scan speed increase by x2-54

WSU Science case

The ALMA2030 Wideband Sensitivity Upgrade

John Carpenter,[1] Crystal Brogan,[2] Daisuke Iono,[3] and Tony Mroczkowski[4]

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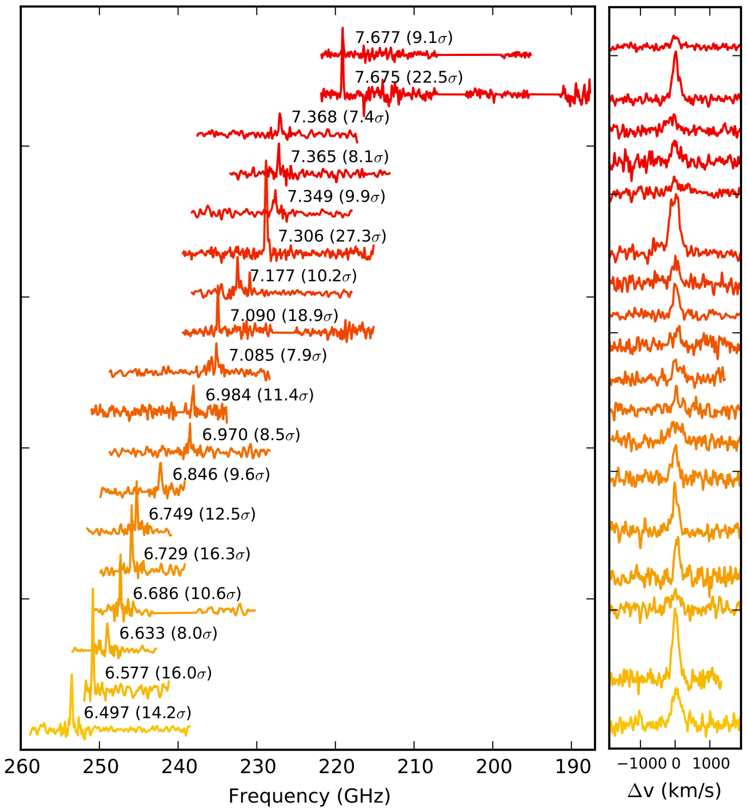
[2] *National Radio Astronomy Observatory (NRAO), 520 Edgemont Road, Charlottesville, VA 22903, USA*
[3] *National Astronomical Observatory of Japan (NAOJ), 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*
[4] *European Southern Observatory (ESO), Karl-Schwarzschild-Str. 2, 85748, Garching bei Munchen, Germany*

See arXiv:2211.00195

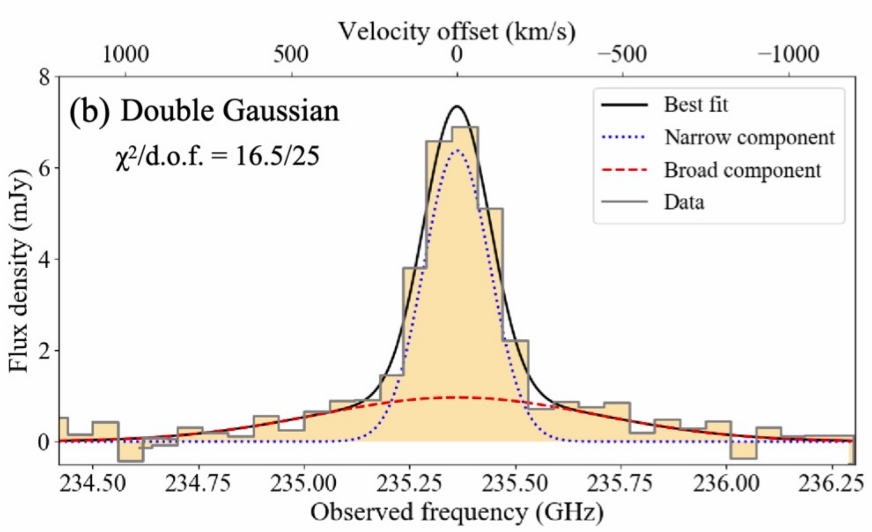
WSU Science case: origin of galaxies



Bouwens et al. 2021

- Unbiased redshift surveys
- Spectroscopic redshifts for photometric redshift candidates (synergy with JWST!)
- Cluster membership
- High redshift QSO outflows (broad lines with high velocities)

WSU Science case: origin of galaxies



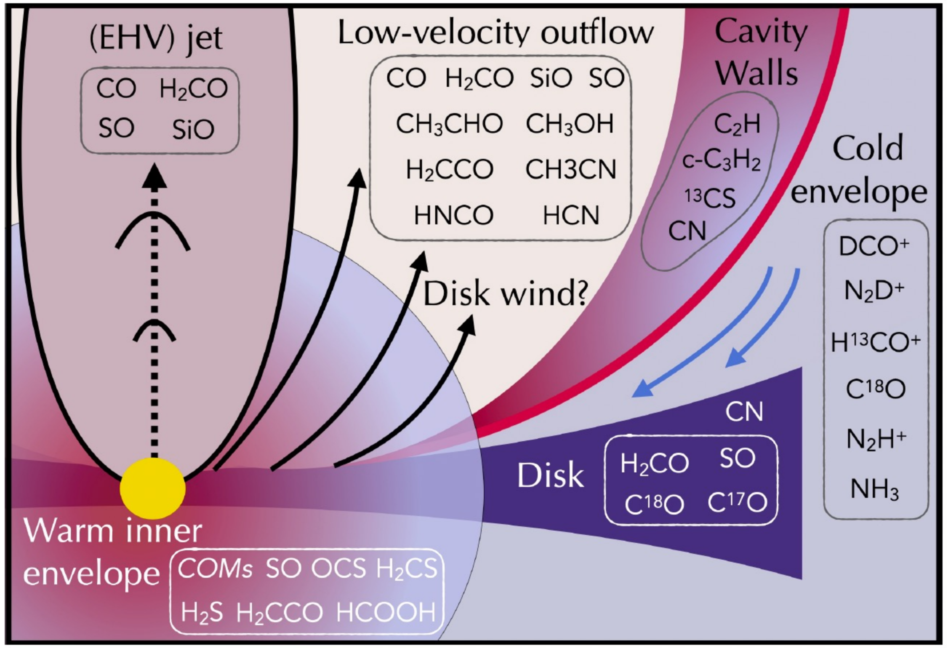
Fast large-scale [C II] gas outflow from a z = 7.07 quasar (Izumi et al. 2021)

Table 7. Velocity bandwidths per sideband of the current and WSU correlators

	Velocity width (km s^{-1})		
	Current Bandwidth=3.75 GHz	WSU Bandwidth=8 GHz	WSU Bandwidth=16 GHz
Band 1	26,500	56,500	112,900
Band 2	14,300	30,600	61,100
Band 3	11,300	24,000	48,000
Band 4	7800	16,700	33,300
Band 5	6000	12,800	25,700
Band 6	4600	9900	19,800
Band 7	3500	7400	14,800
Band 8	2500	5400	10,800
Band 9	1700	3600	7300
Band 10	1300	2800	5500

Note: Velocity bandwidth is for the middle of the receiver band and one sideband.

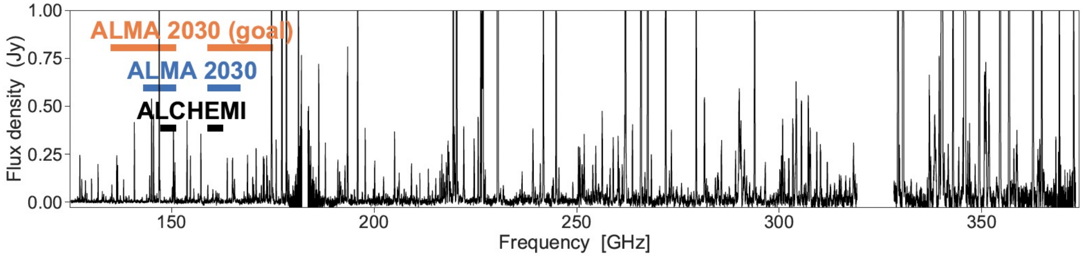
WSU Science case: origin of chemical complexity



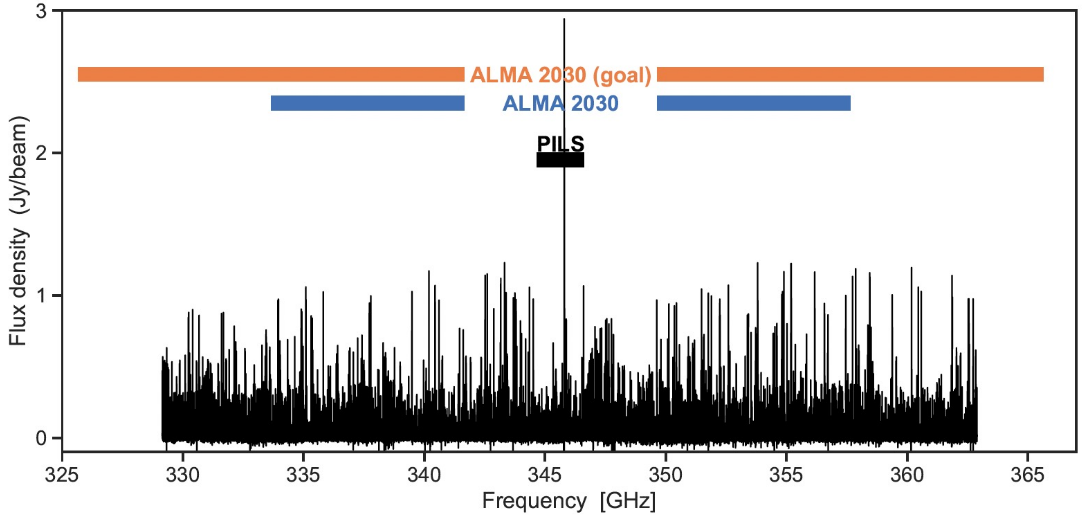
Molecules probed in a protostellar environment (Tychoniek et al. 2021)

- Understand how stars form in molecular clouds (from cores to protostars): vast range of spatial scales (0.0001 pc to ~100 pc) accompanied by orders of magnitude in density and temperature
- Disentangle different physical and chemical mechanisms in play within the central region of galaxies
- Chemistry of circumstellar envelopes in evolved stars

WSU Science case: origin of chemical complexity



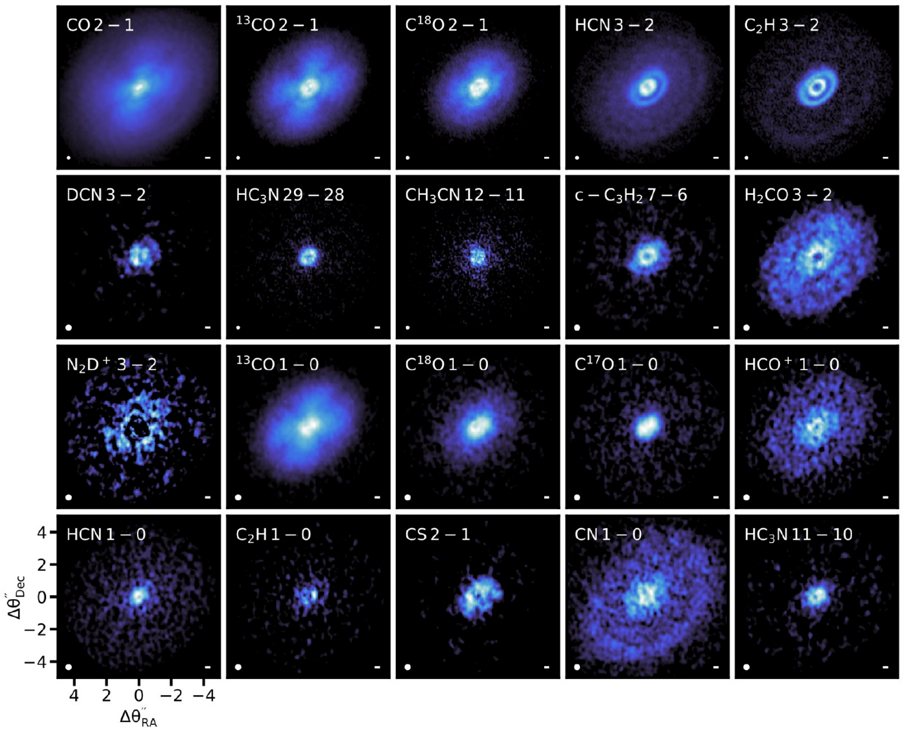
Nuclear region of the galaxy NGC 253 (Martin et al. 2021)



Protostellar binary IRAS 16293-2422B (Jorgensen et al. 2016)

The WSU will allow to do chemical inventories of cores and protostars

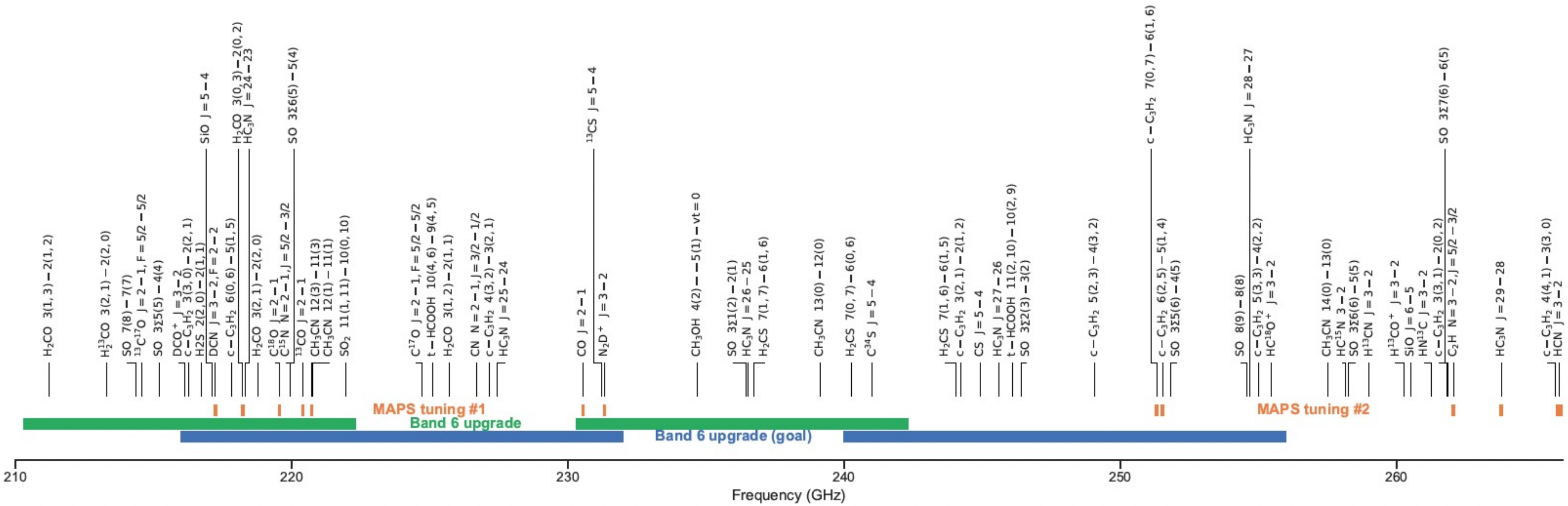
WSU Science case: origin of planets



Oberg et al. 2021

- Properties of discs have a direct impact on the planet formation process (e.g. planet location and mass)
- Radial and vertical chemical structure affects planet composition and formation
- Kinematic signatures of planet formation
- Circumplanetary discs

WSU Science case: origin of planets



In Band 6, at 0.1 km/s resolution, the WSU allows to correlate 64x more bandwidth

Save the date!

ALMA at 10 years: Past, Present, and Future

Puerto Varas, Chile, from **December 4 to 8, 2023**

Summary

- Ten years after start of operations, ALMA continues to be the leading observatory in mm/submm wavelengths
- Key contributions to a large number of science topics
- New capabilities available every cycle
- In the 2030s: the Wide Sensitivity Upgrade will double (and ultimately quadruple) the bandwidth resulting in factors 4 to 68 in correlated bandwidth at high spectral resolution