The ALMA Wideband Sensitivity Upgrade (WSU)

Arielle Moullet (NRAO/NAASC)

ALMA Today

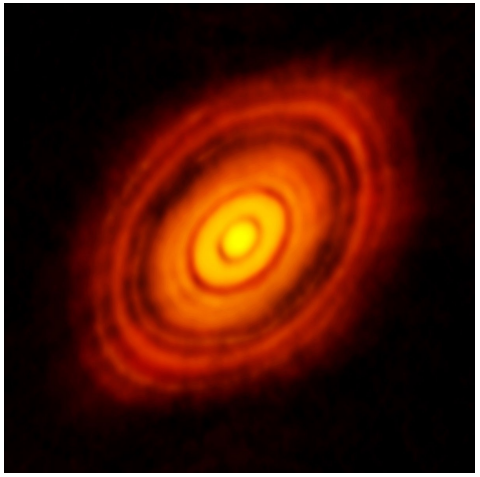
- Unique high and dry site at 5000m (16,500 ft) altitude
- 66 submillimeter/millimeter telescopes (50x 12m, 12x7m, 4x12m): 6600 m^2 collecting area
- Ten Frequency Bands: 35 to 950 GHz (7 to 0.32 mm) – 9 operating, Band 2 production
- Angular resolution as fine as 5 milliarcsec, baselines up to 16 km

"Full science" operations since 2014

ALMA has opened a new discovery space by offering unprecedented sensitivity, image fidelity, and angular resolution in the (sub)mm wavelength range.

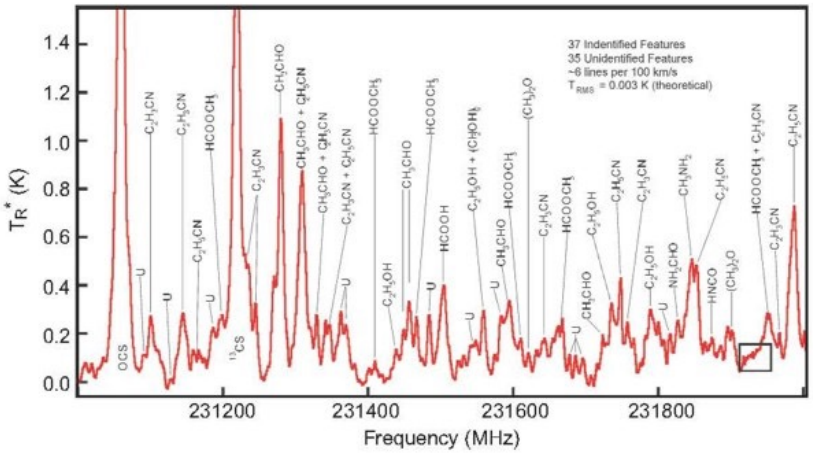
ALMA Today

Continuum

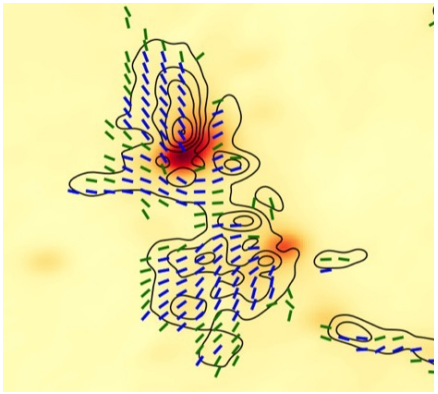


Imaging

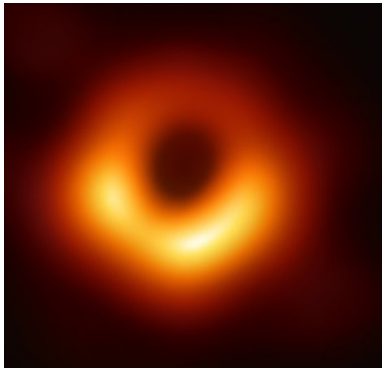
Spectroscopy



Polarization



VLBI

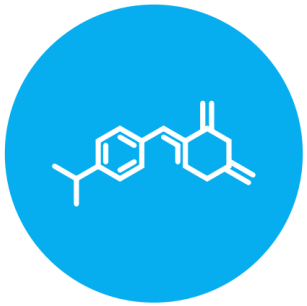


What's next?

The ALMA Development Roadmap identified three fundamental science drivers which require **increased bandwidth and sensitivity** to keep ALMA at forefront of scientific discovery

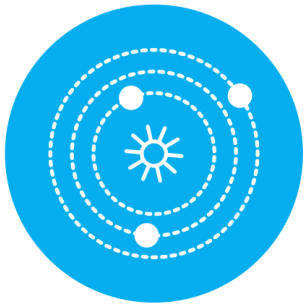
ORIGINS OF GALAXIES

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.

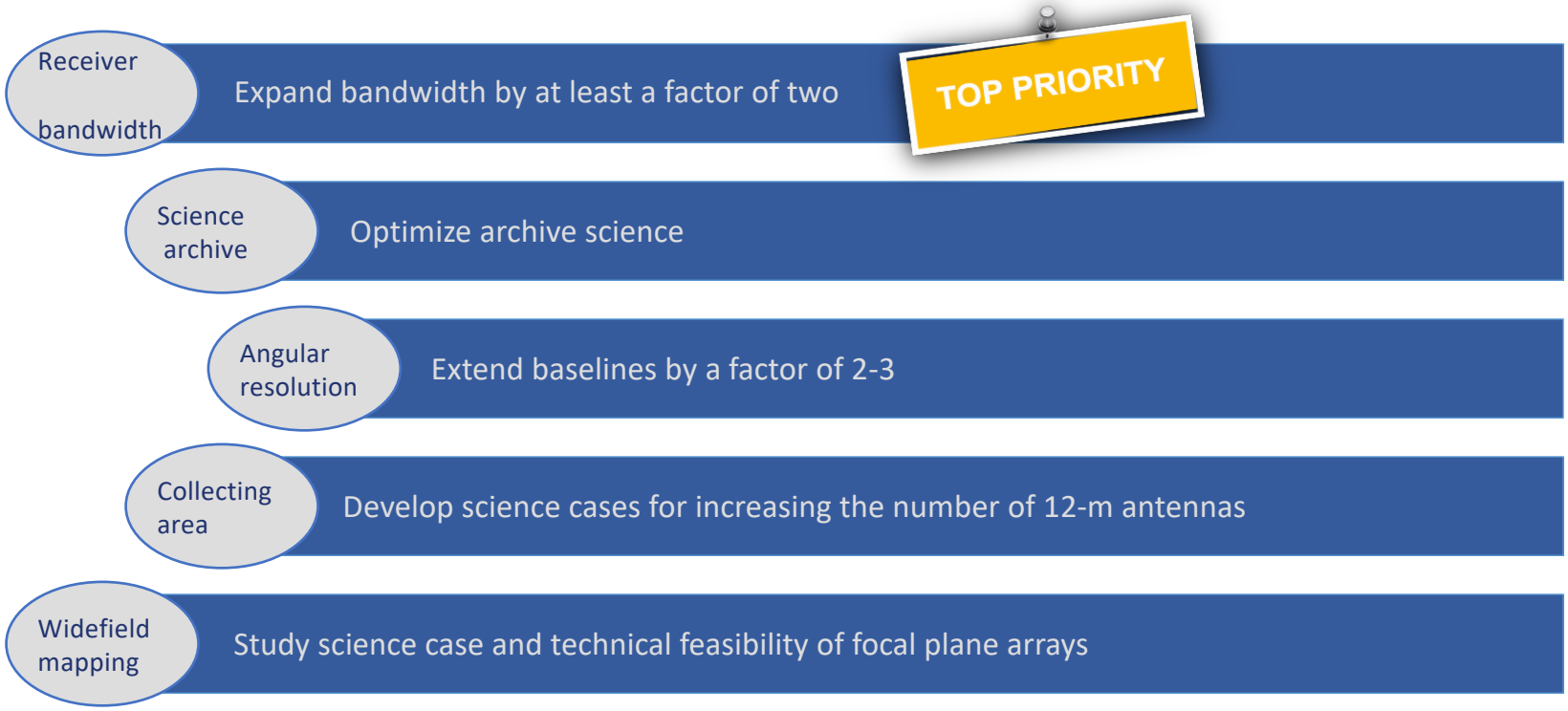


ORIGINS OF PLANETS

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.

What's next?

The ALMA Board has endorsed the proposed long-term development strategy



(from ALMA Integrated Science team)

The Wideband Sensitivity Upgrade

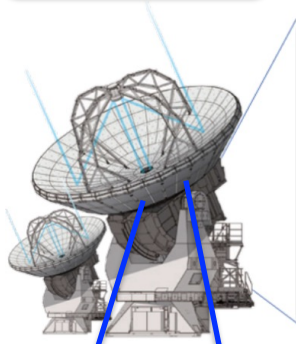
The ALMA Wideband Sensitivity Upgrade (WSU) is a partnership-wide initiative that will realize a **dramatic increase in correlated spectral bandwidth and sensitivity** across the entire ALMA's wavelength range

- Increase of receivers' spectral grasp
- Increase in correlator capabilities (throughput and flexibility)
- Increase in receiver performance
- Increase in digitizing / correlator efficiency
- Increased data reduction capacity

WSU consists in development and implementation of upgraded hardware components, with associated software and infrastructure

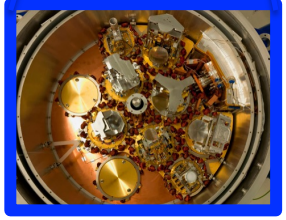
Receivers

Front End



Antenna

Receivers



Bands 2, 6v2, 8v2, 7v2
Other key bands may follow

Increased spectral grasp
Improved receiver temperature

Back End

IF Switches & Anti-

Digitizers & Digital Signal Processing

Digital Transmission

Array Operations Building at 5,000m

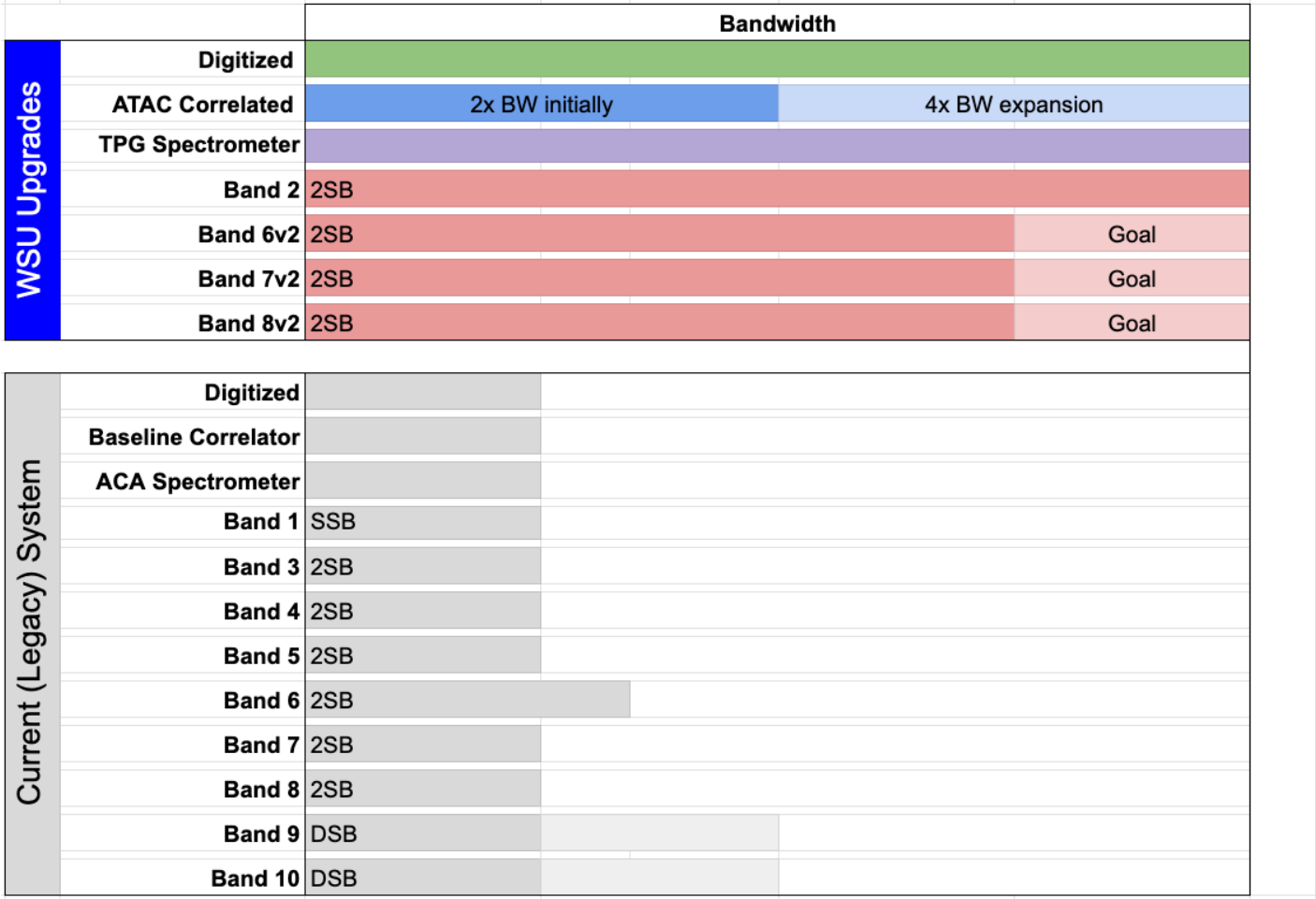
New Fiber

Operations Support Facility at 3,000m

New OSF Correlator Room

2nd Generation Correlator

CONTROL, TelCal, Scheduling, OT, Archive, Pipeline



Notes:

1. Legacy bands will be usable in the WSU System with their current IF bandwidth.

2. In the Legacy System DSB receivers are processed using 90 degree Walsh switching to recover the image sideband.

3. The maximum usable bandwidth in the Legacy System is 7.5 GHz, and is only available at relatively coarse minimum channel width 488.28 kHz (with a spectral resolution 2x poorer due to the need for Hanning Smoothing online).

4. The full ATAC and TPGS bandwidth is usable for channels as fine as 13.5 kHz, a factor of 72 better in spectral resolution.

Digital Signal Chain

Front End

Back End

IF Switches & Anti-aliasing filters

Digitizers & Digital Signal Processing

Digital Transmission System

Increased digitization efficiency

Operations Support Facility at 3,000m

New OSF Correlator Room

New Fiber

2nd Generation Correlator

CONTROL, TelCal, Scheduling, OT, Archive, Pipeline

Antenna

Receivers

Correlator

2nd Generation ALMA Correlator: ATAC

- Initially 2x (16 GHz/pol), readily expandable to 4x (32 GHz/pol)
- Up to 1.2 million spectral channels available (as well as flexible on-line channel averaging)
- Flexible subarrays to process 12m and 7m-array observations concurrently
- 13.4% improvement in correlation efficiency

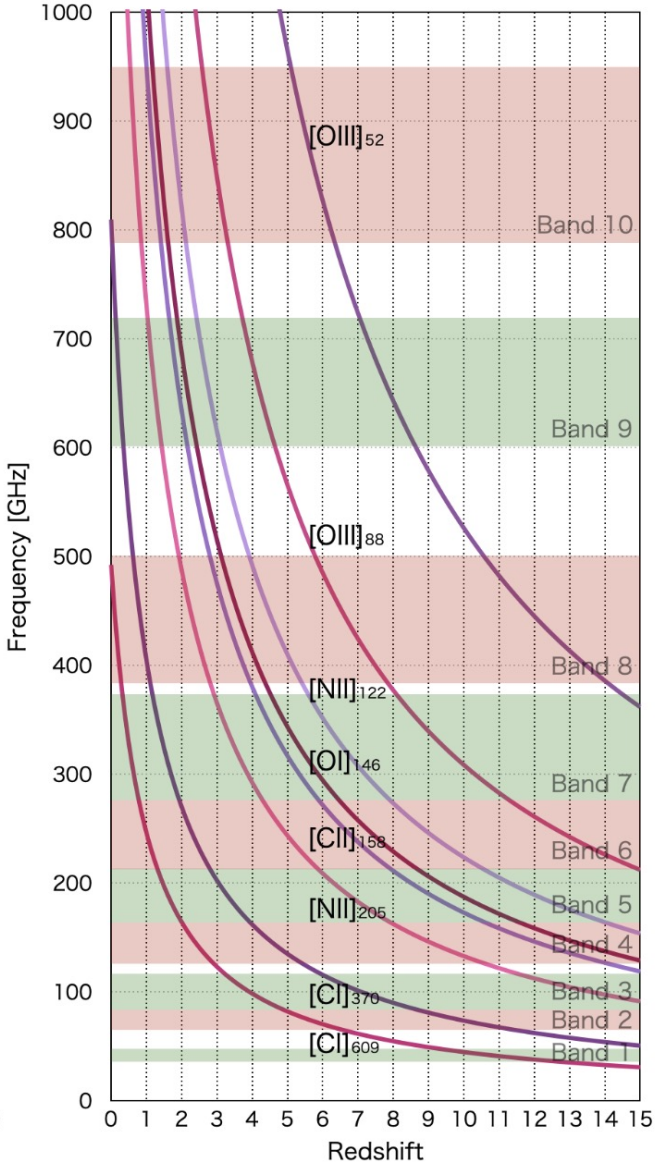
Overall 20% sensitivity improvement from signal chain + correlator

The ALMA WSU will benefit all observations

Enhanced Capability	WSU Improvement for 2x BW Correlation (16 GHz per pol)	Future Improvement with 4x BW
Receiver bandwidth increase (grasp)	**2-4x** in instantaneous bandwidth (as receiver bands are upgraded)	…
Correlated Bandwidth increase	• 16 GHz/pol, then 32 GHz/pol • **2x** for low spectral resolution • Up to **4x** (Band 10) and **68x** (Band 1) for 0.1 km/s spectral resolution	Up to Additional 2x
Spectral scan speed increase	• **2x** for low spectral resolution • Up to **4x** (Band 10) and **64x** (Band 1) for 0.1 km/s spectral resolution	Up to Additional 2x
Spectral line Imaging speed	**~2.2x** from improved receiver noise temperatures and digital efficiency for upgraded bands, ~1.4x for all bands	…
Continuum Imaging speed	**≥ 4.8x** from correlated bandwidth increase, improved receiver noise temperatures and digital efficiency	Up to Additional 2x
Ultra-high spectral resolution	Access to **0.01 km/s** at all ALMA frequencies for the first time	…

Equivalent to adding 1000 additional hours of observing time per cycle

IRFSLs at high red-shifts



Carpenter et al. 2023

IRFSLs at high red-shifts

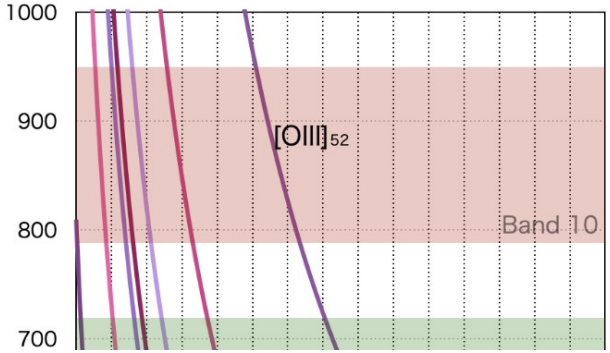
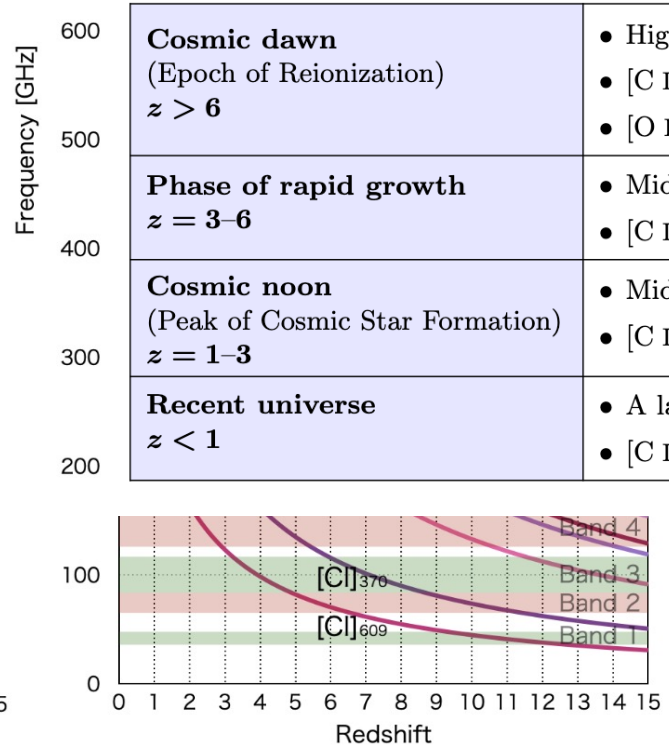


Table 5. Spectral line diagnostics at each cosmic epoch

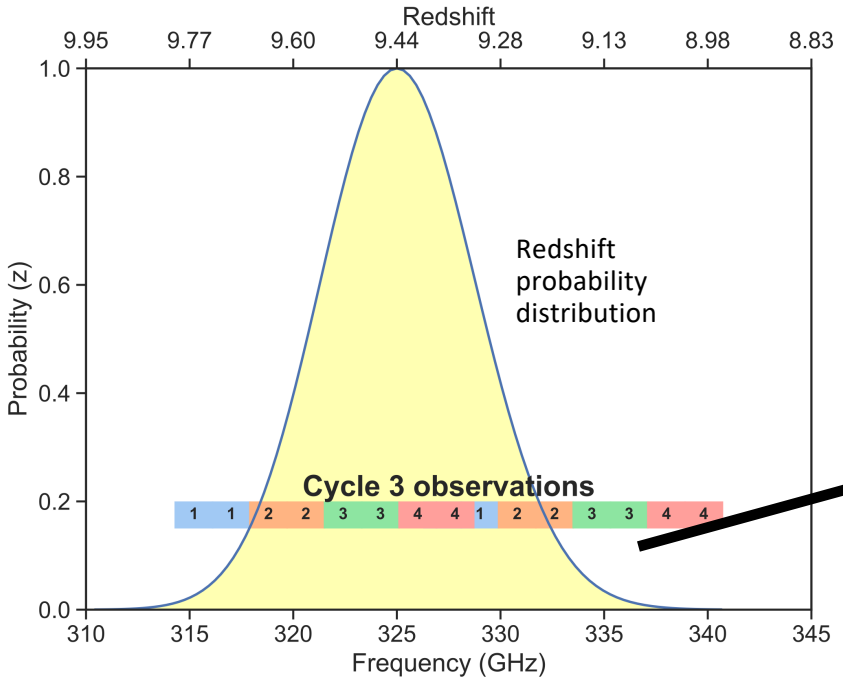
Cosmic dawn (Epoch of Reionization) **$z > 6$**	• High-J CO ($J_{up} \geq 6$) in Bands 3–4, mid-J CO ($J_{up} = 3$–5) in Bands 1–2 • [C II] in Band 6 for $6 < z < 8$, Band 5 for $8 < z < 10$, lower bands for $z > 10$ • [O III] (88 μm) in Bands 7–8, [O III] (52 μm) in Bands 9–10
Phase of rapid growth **$z = 3$–6**	• Mid to high-J CO in Bands 3–5, $J_{up} = 3$–4 in Band 2, CO $J = 2 - 1$ in Band 1 • [C II] in Band 7–8, [C I] in Bands 2–4
Cosmic noon (Peak of Cosmic Star Formation) **$z = 1$–3**	• Mid to high-J CO ($J_{up} \geq 3$) in Bands 4 or higher, low-J CO ($J_{up} \leq 3$) in Bands 1–3 • [C II] in Band 9, [C I] in Bands 4–7
Recent universe **$z < 1$**	• A large range of CO J_{up} are available • [C I] (370 and 609 μm) in Bands 7–10

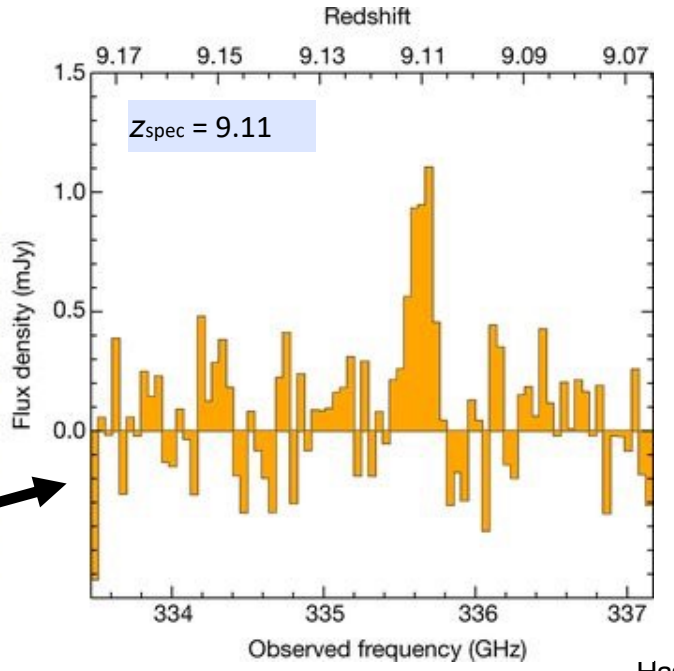


Carpenter et al. 2023

Increased correlated spectral bandwidth/grasp

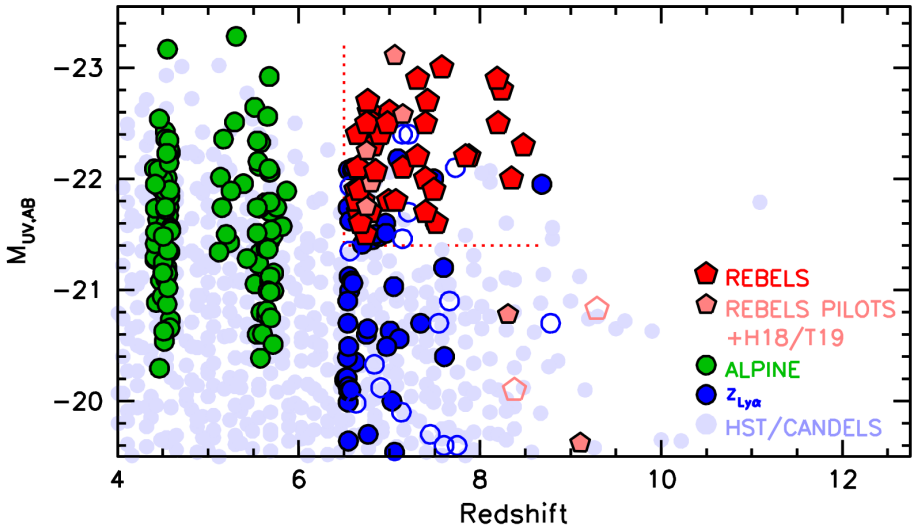
- large efficiency gain for spectral redshift surveys (x2-6 depending on band)





Hashimoto et al. (2018)

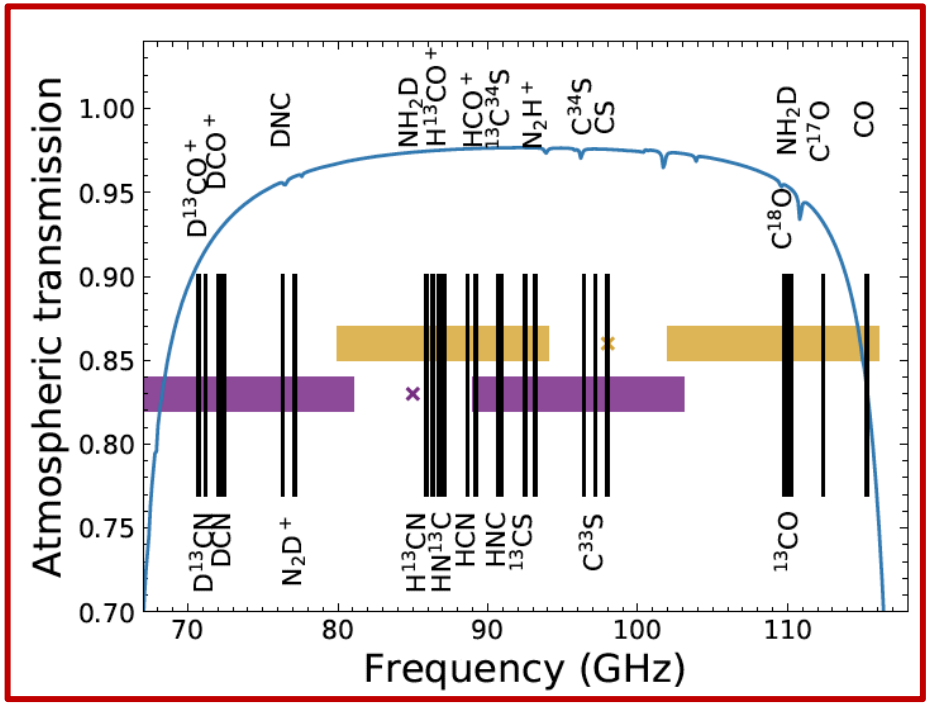
- The large ALMA REBELS project – 70 h of observations ([CII], [OIII] and continuum in z~7 sources) - would be done in just 21h with WSU, or 3x as many targets, or access to fainter targets



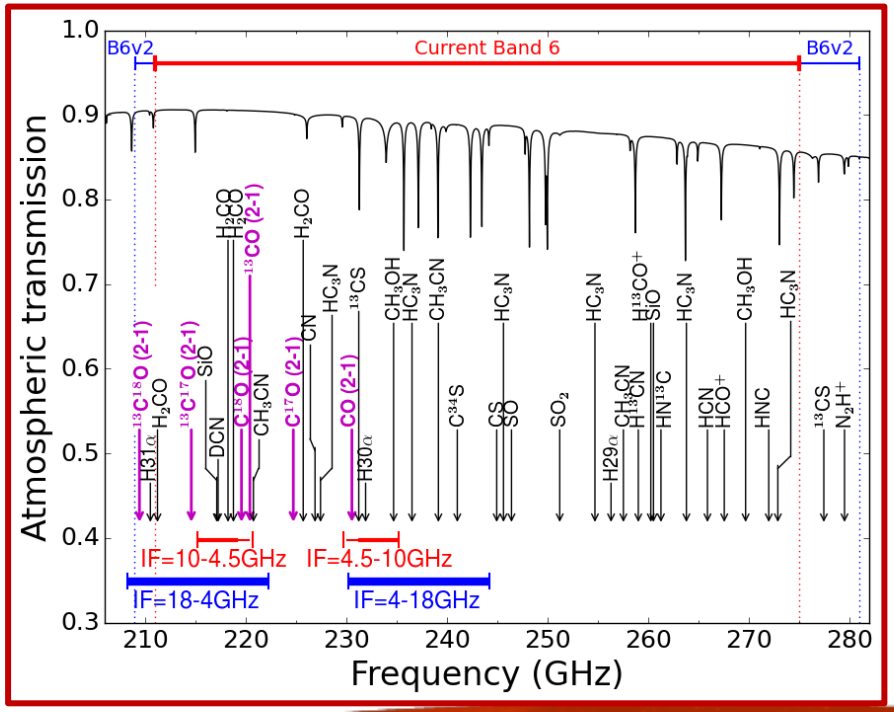
Bouwens et al. 2022

- simultaneous access to strategic line combinations
- simultaneous access to multiple high-velocity components in outflows (10,000s -1000s km/s)

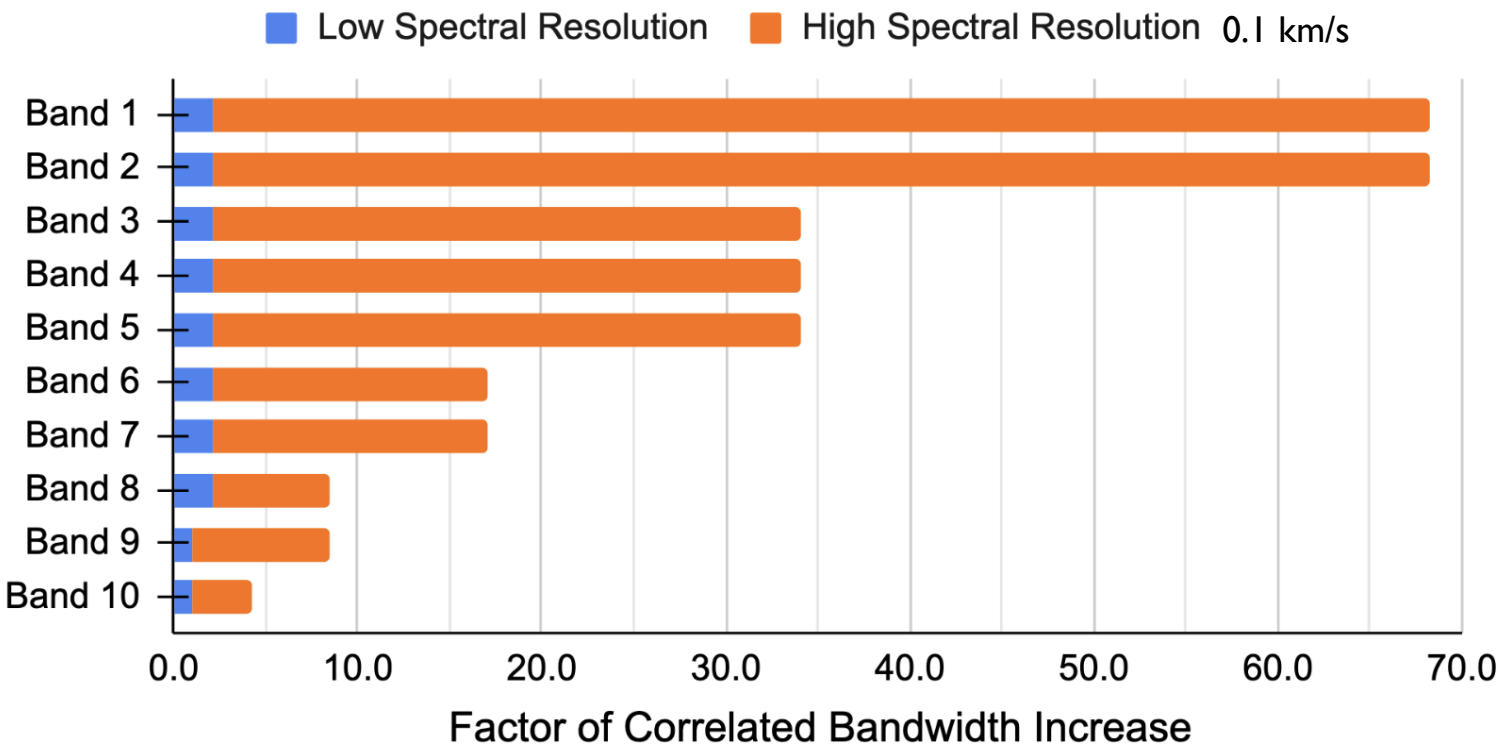
Band 2: 67-116 GHz
Two promising tunings (purple + yellow)



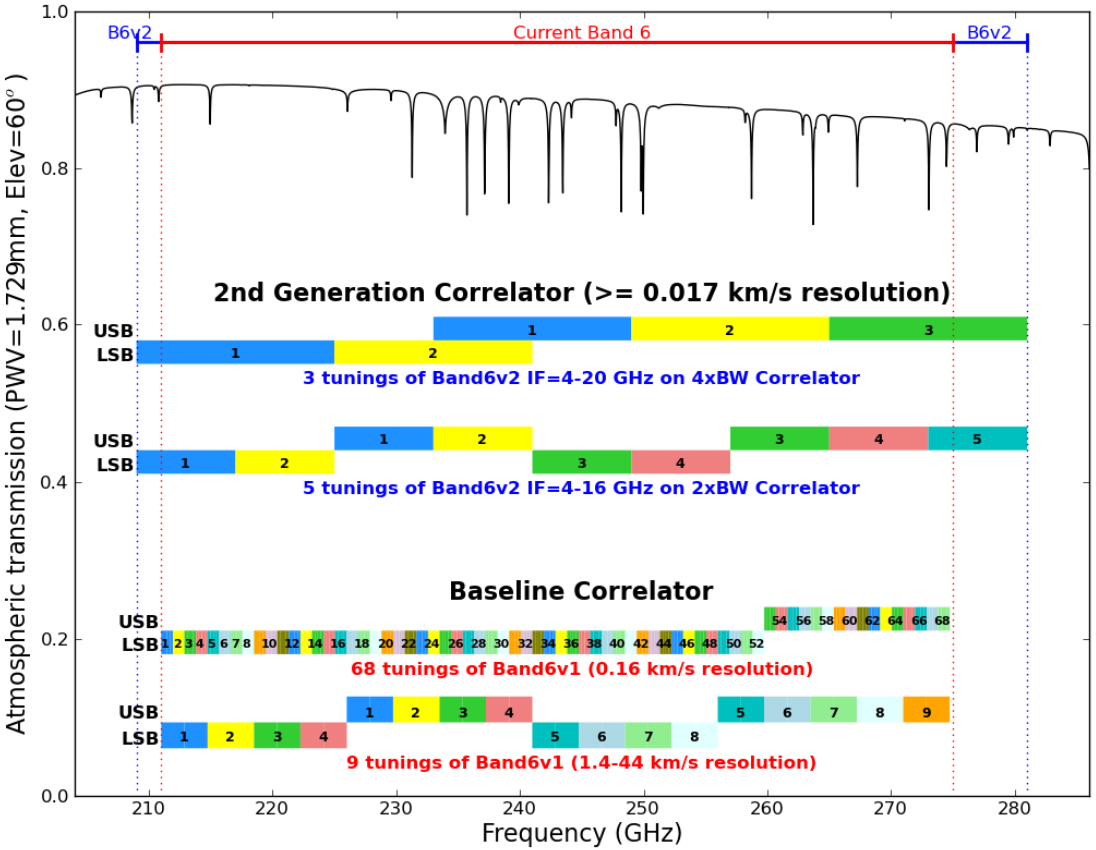
Band 6v2: 209 - 281 GHz
Red: B6 BW, IF Blue: B6v2 BW, IF



- entire instantaneous correlated bandwidth (16-32GHz) can be processed simultaneously at (almost) any spectral resolution. **No more trading 'resolution for bandwidth'**



- High spectral resolution astrochemistry surveys on protoplanetary disks (and more): spectral scanning speed improved by a factor >10



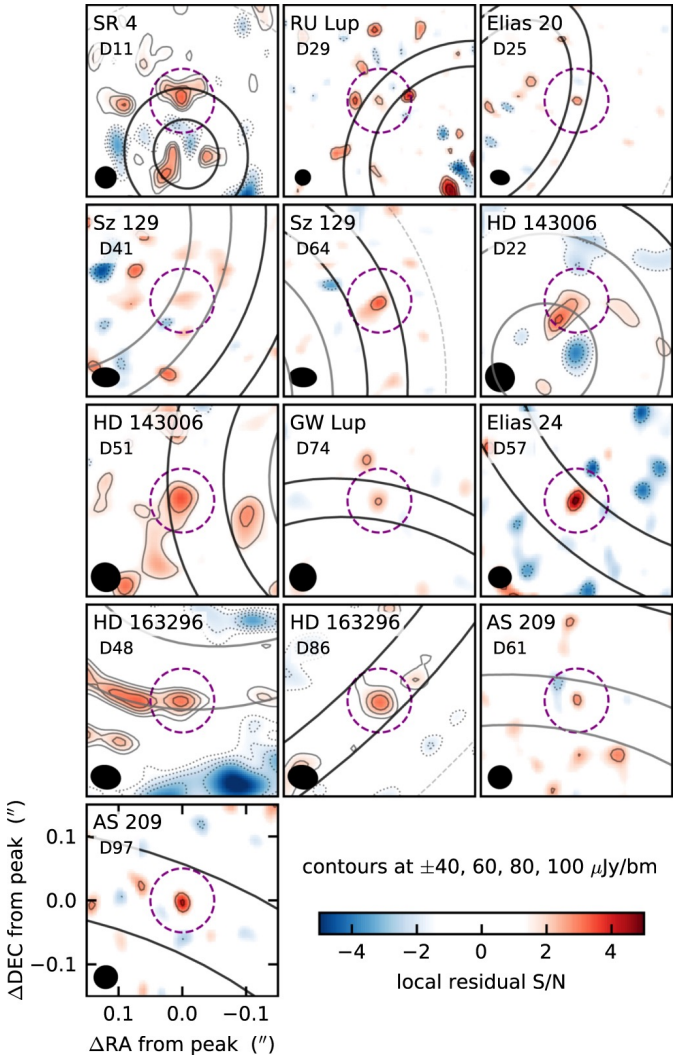
Carpenter et al. (2023)

Continuum mapping speed

-> continuum mapping speed improved by factor ~4 for BWx2, up to (8) in upgraded bands

- For DSHARP project – search for circumplanetary disks resulting in borderline detections: with WSU, in the same amount of time, can confirm detections with SNRx2, or increase sample by ~5.

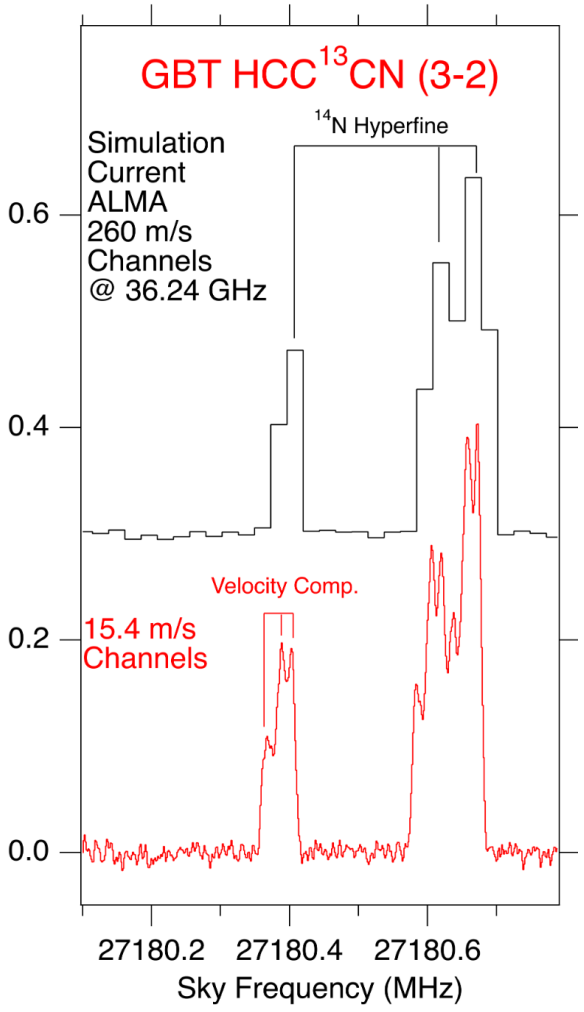
Andrews et al. (2021)



Ultra-high spectral resolution

Spectral resolution down to ~10-15 m/s at all bands

- Direct evidence of the kinematics in dark and cold molecular clouds/ protostar envelopes need such spectral + angular resolution to connect low-velocity components to spatial features



GBT HCC13CN J = 3 − 2 spectrum from the GOTHAM survey (Mc Guire et al., 2020) toward the cold dark molecular cloud TMC-1 with a spectral resolution of 15.4 m/s; the black spectrum shows a simulation at ALMA's current best resolution. Carpenter et al., 2022

Status

Wideband receivers

- Band 2 (67-116 GHz) in production
- Band 6 (209-281 GHz) in development
- Band 8 (385-500 GHz) in development
- Band 7v2 (275 – 373 GHz) in study

Signal Chain/correlators

- Digitizer in development passed PDR
- Data Transmission System passed PDR
- ATAC Correlator passed PDR
- Total Power spectrometer passed CoDR

Infrastructure:

- Correlator room in construction
- AOS to OSF fiber project in progress

Proposed WSU Implementation Milestones *

*Subject to review outcome /ALMA Board approval

Milestone 1: Initial WSU scientific observations

At least 36 antennas retrofitted and connected to WSU Signal Chain, DTS, Digitizer, new optical fibers and ATAC; OCRO, Band 2; necessary updates to software and infrastructure in place.

Currently targeted for 2030

Milestone 2: End of WSU System AIV

All antennas retrofitted and connected; TP spectrometer ; Scientific observations with 2x bandwidth offered for Band 2.

WSU BWx2 system and observing in place

Milestone 3: End of WSU System Commissioning

All ALMA observing modes offered with legacy system commissioned for WSU (2x bandwidth).

Milestone 4: End of Data Processing Transition

Upgrades to data flow and data management architecture, WSU/next generation data processing software is in place, enabling full utilization of ATAC for Scientific observations.

Full scientific vision of the WSU achieved

Milestone 5: Top scientific priorities achieved

Completion of receiver bands: 6v2, 7v2 and 8v2; ATAC upgrade to 4x system bandwidth. Upgraded computing, communication and archival systems for increased data rates.

Additional receiver band updates can be achieved in future development studies (following current practice), subject to funding availability.

What next?

During WSU commissioning, regular science operations will continue with some adjustments. Detailed deployment schedule in preparation

Goal is WSU first science by 2030

Keep informed

- WSU Details in White Paper
  ALMA Memo 621 (arXiv:2211.00195)

- ALMA Observatory WSU project page
  almaobservatory.org/en/scientists/alma-2030-wsu

WSU webpage on North American ALMA website

www.nrao.edu
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