The ALMA Wideband Sensitivity Upgrade (WSU)

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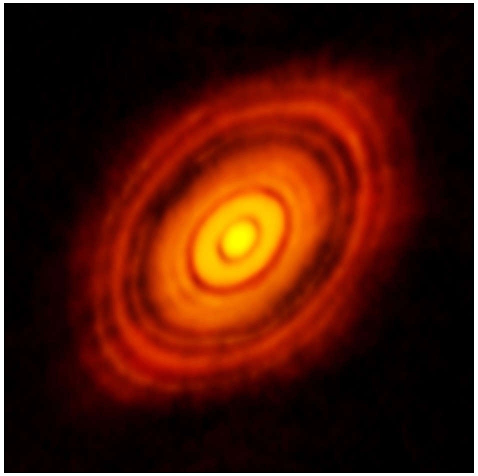
ALMA Today

- High and dry site at 5000m (16,500 ft) altitude
- Ten Frequency Bands: 35 to 950 GHz – 9 operating, Band 2 in production
- Interferometer with baselines up to 16 km: **angular resolution**
- 66 antennas (50x12m, 12x7m, 4x12m ‘single dishes’): **sensitivity , image fidelity**

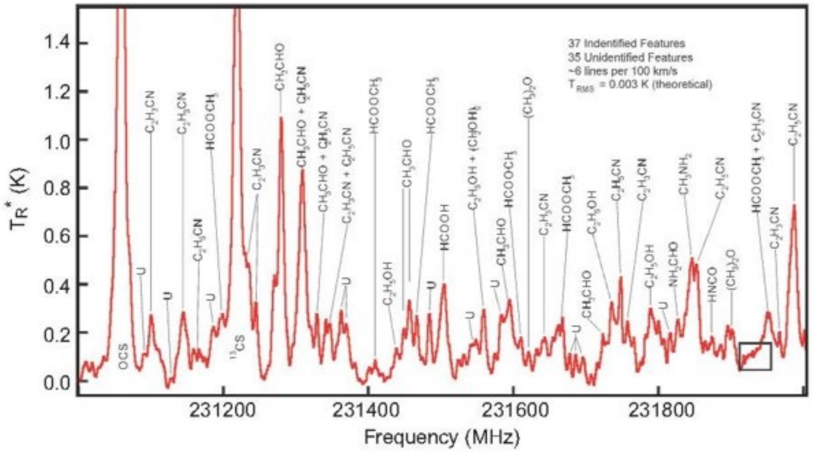
Since start of operations in 2012, ALMA has opened a new discovery space

ALMA Today

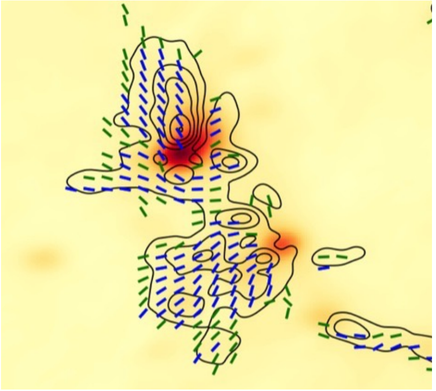
Imaging



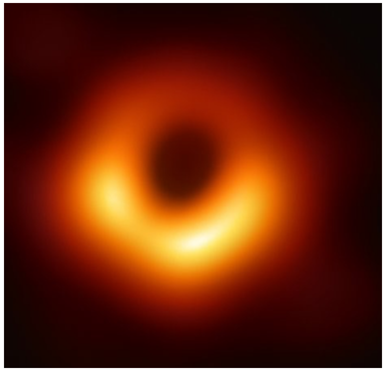
Spectroscopy



Polarization

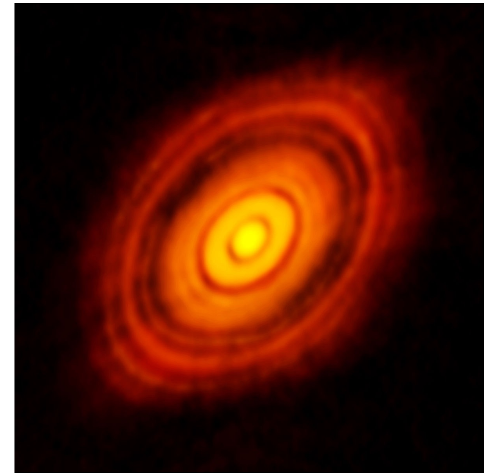


VLBI



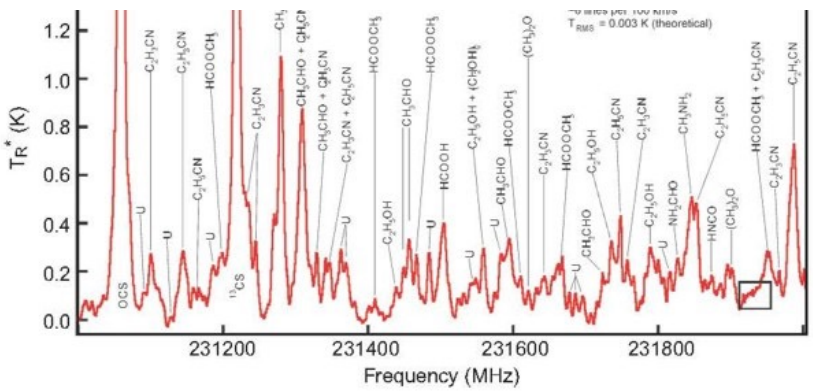
ALMA Today

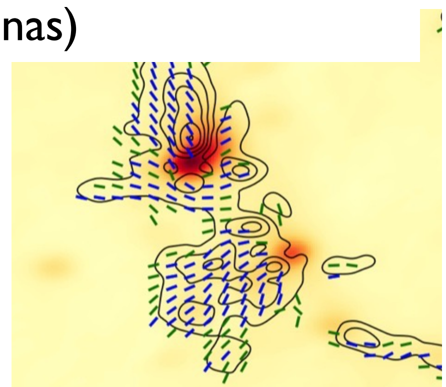
Imaging

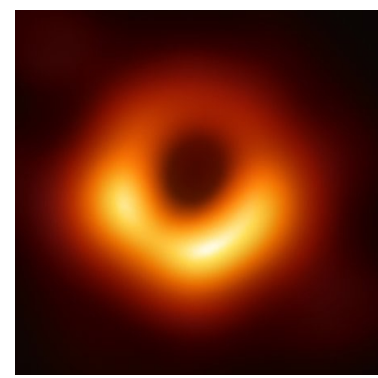


- Mapped fields ~ at most 100s arcmin^2
- Interferometer filters large scales >10-200 arcsec
  (in part recovered by Total Power antennas)

VLBI





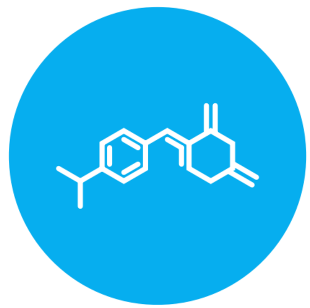


What's next?

(In 2015) The ALMA Development Roadmap identified three fundamental science drivers which require **increased bandwidth and sensitivity** to keep ALMA at forefront of scientific discovery

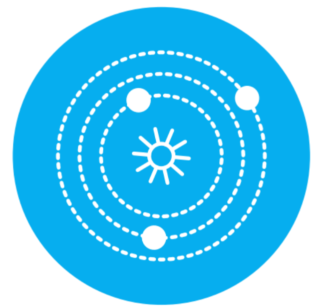
ORIGINS OF GALAXIES

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

Receiver bandwidth	Expand bandwidth by at least a factor of two — TOP PRIORITY
Science archive	Optimize archive science
Angular resolution	Extend baselines by a factor of 2-3
Collecting area	Develop science cases for increasing the number of 12-m antennas
Widefield mapping	Study science case and technical feasibility of focal plane arrays

(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

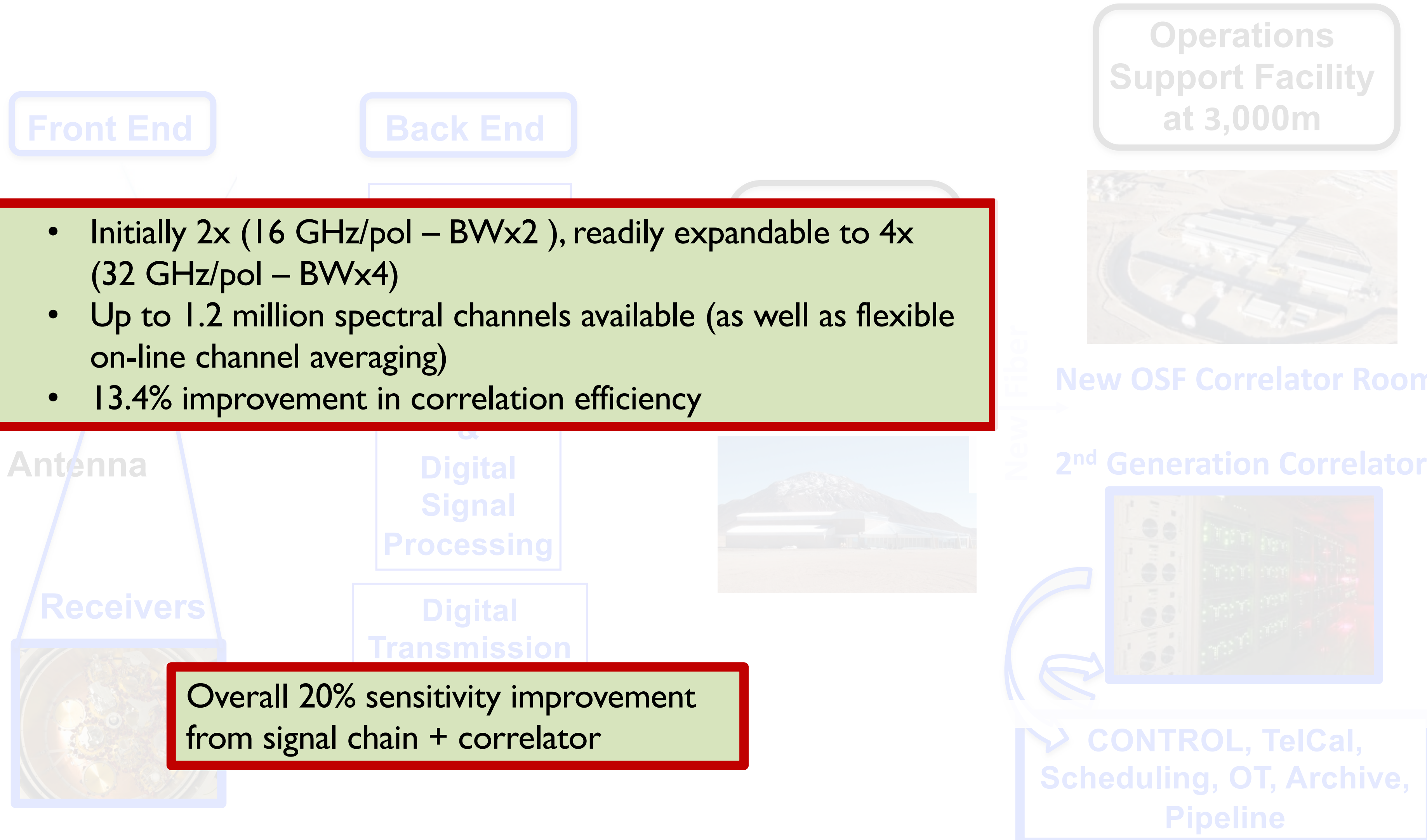
- Increase in correlator capabilities (throughput and flexibility)
- Increase of receivers' spectral grasp
- Increase in receivers' performance
- Increase in digitizing / correlator efficiency
- Increased data reduction capacity

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

New Receivers: Bands 2, 6v2, 8v2, 7v2

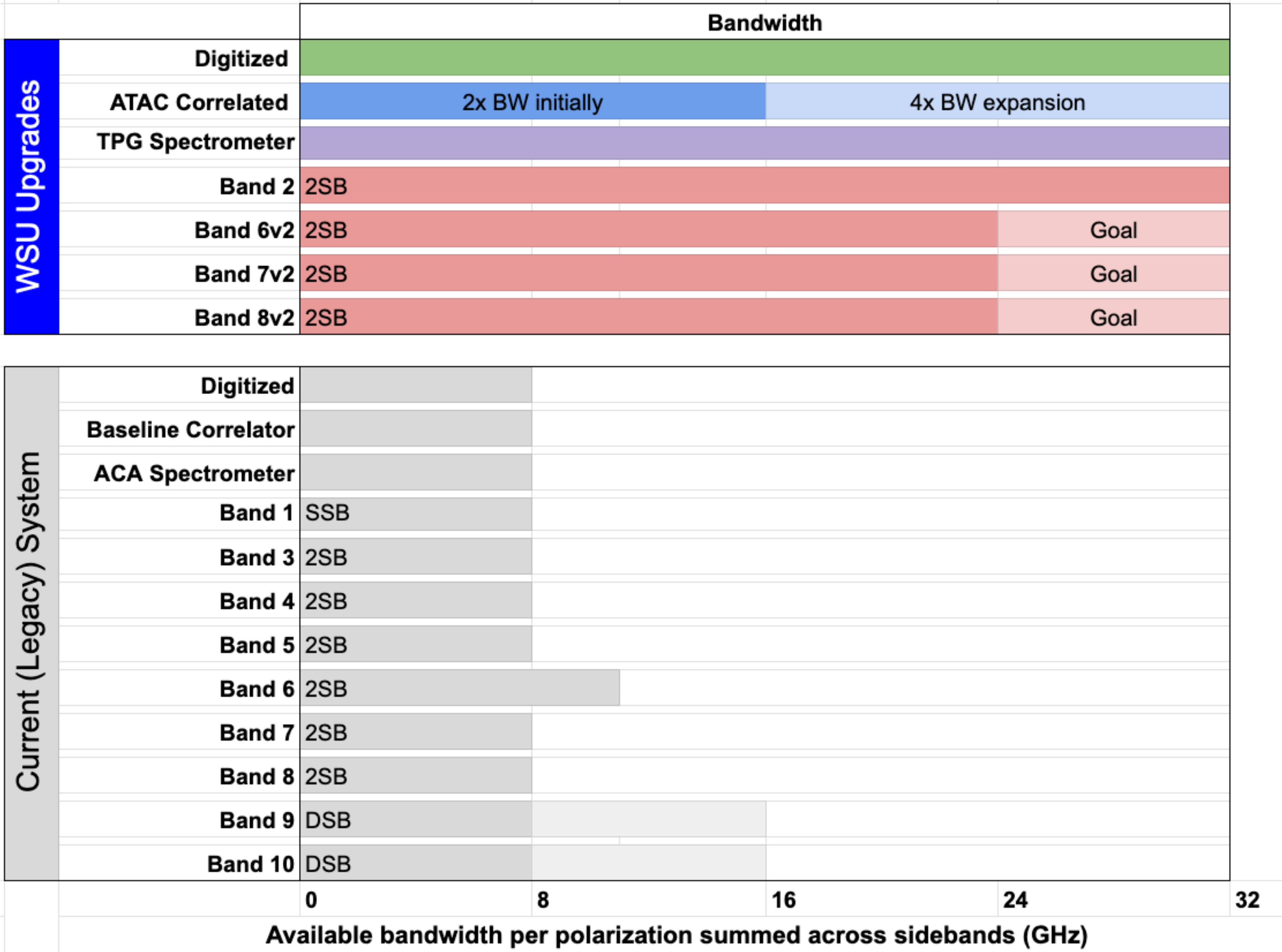
Other key bands may follow

2nd Generation ALMA Correlator: ATAC



- Initially 2x (16 GHz/pol – BWx2), readily expandable to 4x (32 GHz/pol – BWx4)
- Up to 1.2 million spectral channels available (as well as flexible on-line channel averaging)
- 13.4% improvement in correlation efficiency

Overall 20% sensitivity improvement from signal chain + correlator



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.

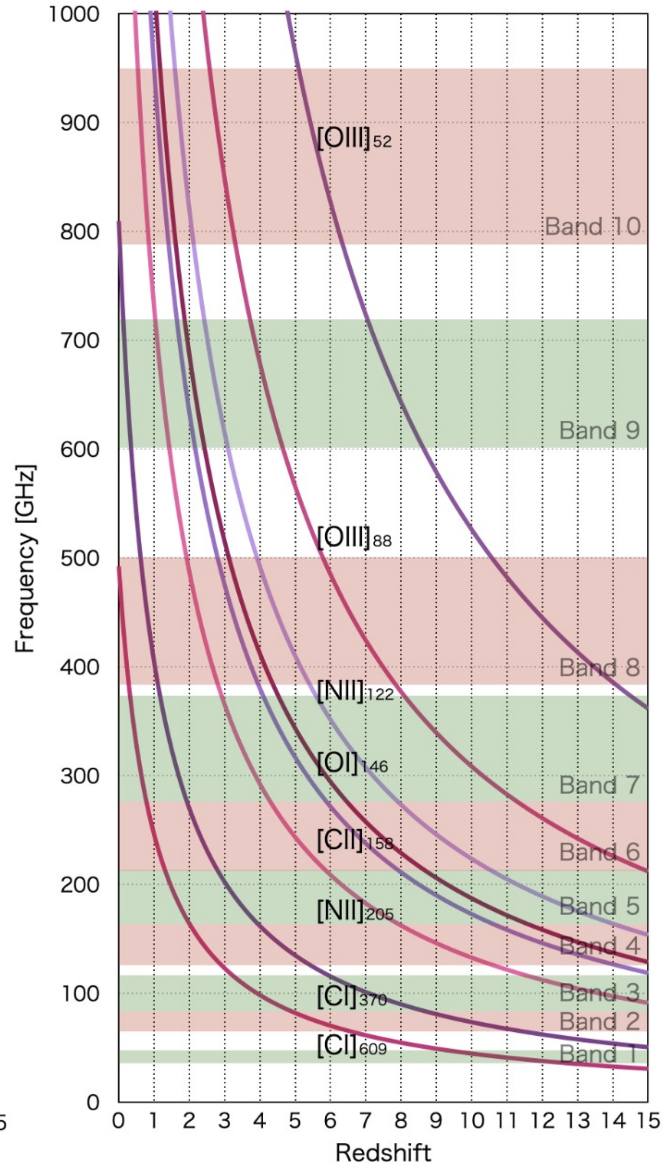
3. The maximum usable bandwidth in the Legacy System is 7.5 GHz, and is only available at relatively coarse minimum channel width 488.28 kHz (with a spectral resolution 2x poorer due to the need for Hanning Smoothing online).

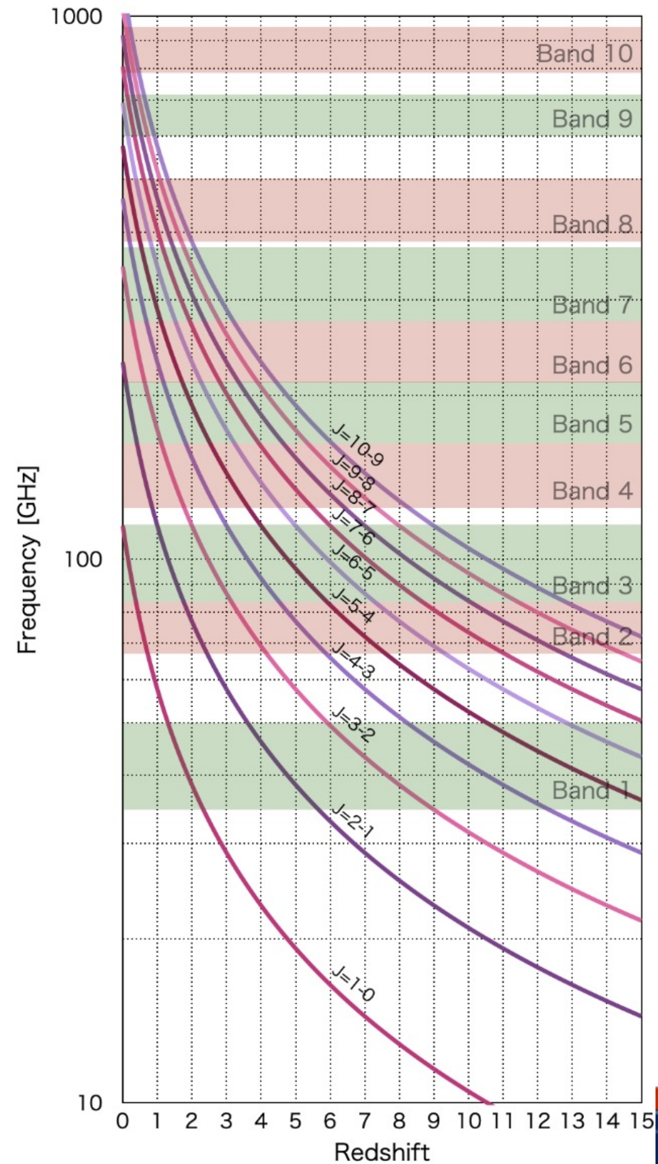
4. The full ATAC and TPGS bandwidth is usable for channels as fine as 13.5 kHz, a factor of 72 better in spectral resolution.

The ALMA WSU will benefit all observations

Enhanced Capability	WSU Improvement for 2x BW Correlation (16 GHz per pol)	Future Improvement with 4x BW
Spectral line Imaging speed	**~2.2x** from improved receiver noise temperatures and digital efficiency for upgraded bands, ~1.4x for all bands	…
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 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
Continuum Imaging speed	**> 4** 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	…

Atomic and molecular lines at high redshifts





Carpenter et al., 2023

Atomic and molecular lines at high redshifts

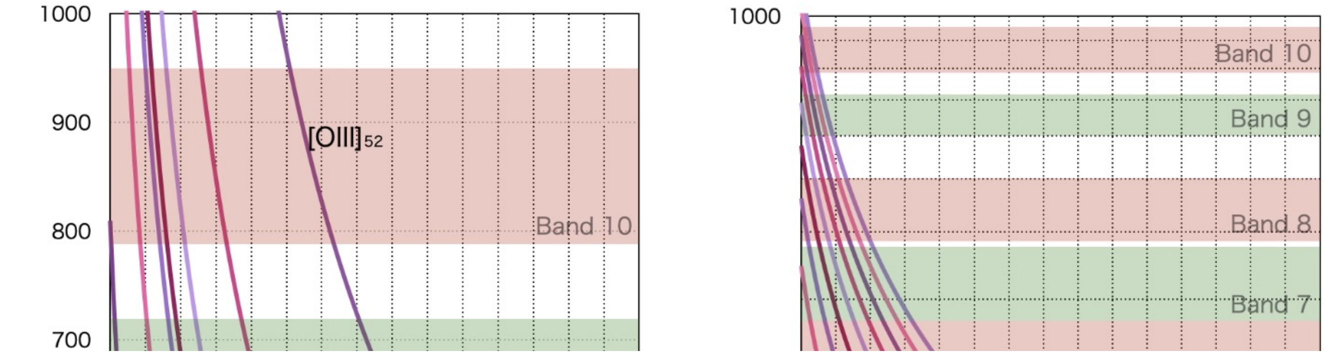
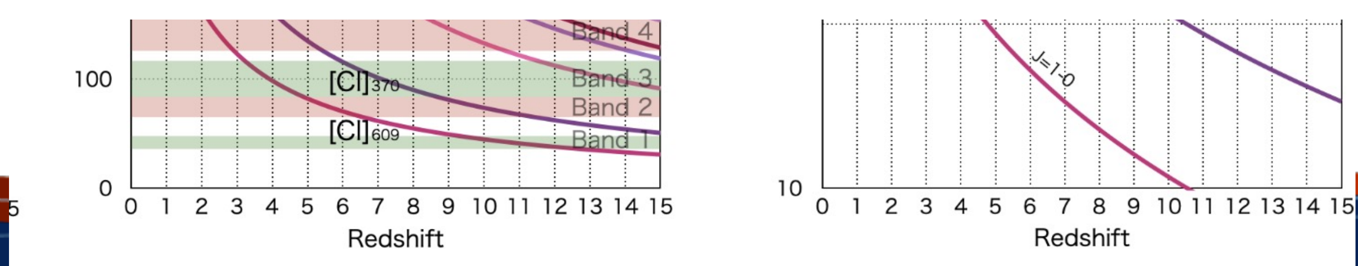


Table 5. Spectral line diagnostics at each cosmic epoch

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



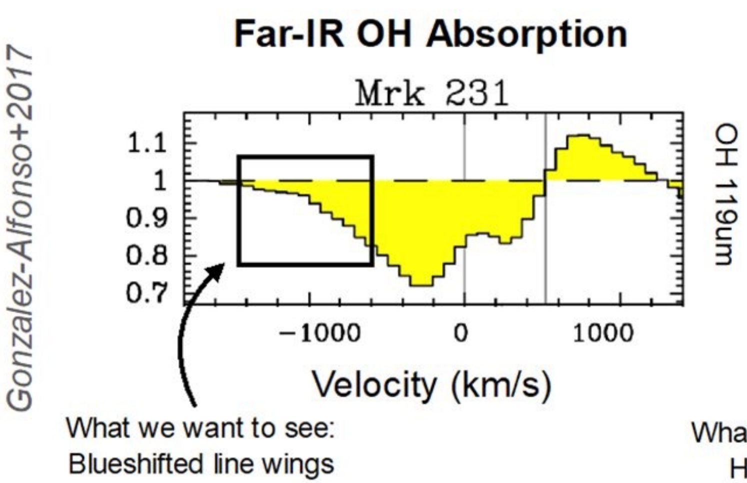
Carpenter et al., 2023

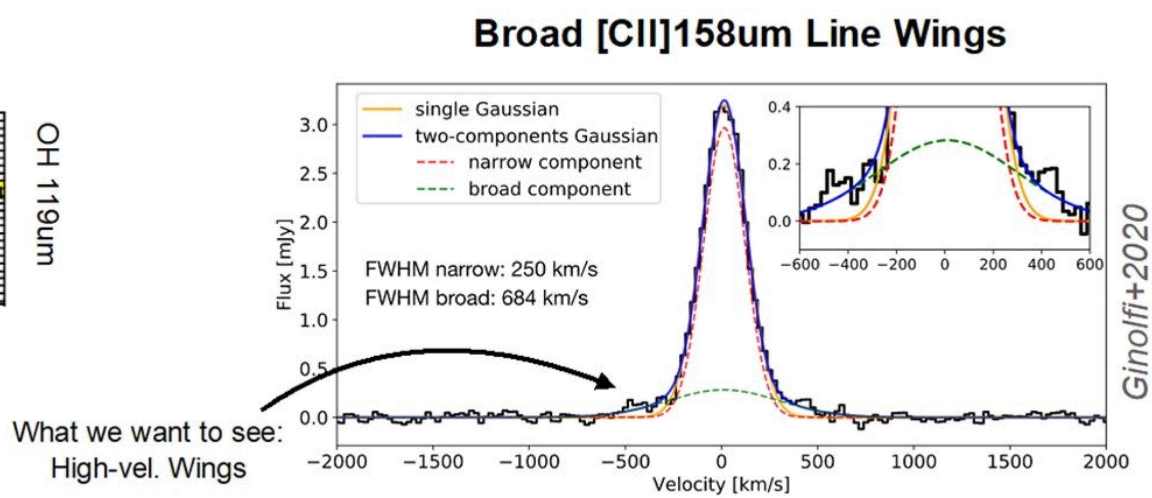
Increased spectral grasp

- simultaneous access to strategic line combinations, probing different environments

- access to multiple high-velocity outflow components (1000s-10,000 km/s)

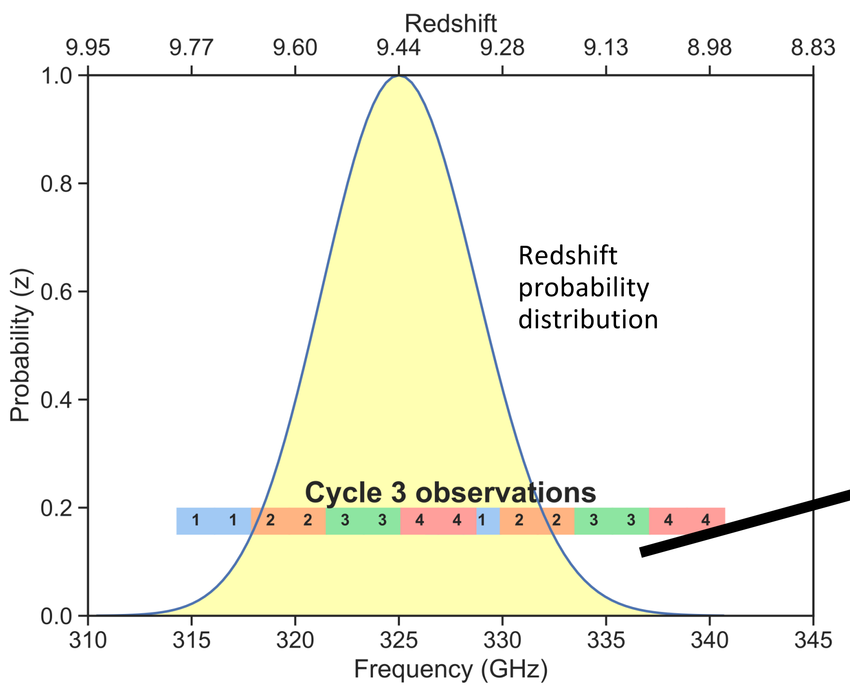
- access to redshifts of cluster components (can be 1000s km/s apart)

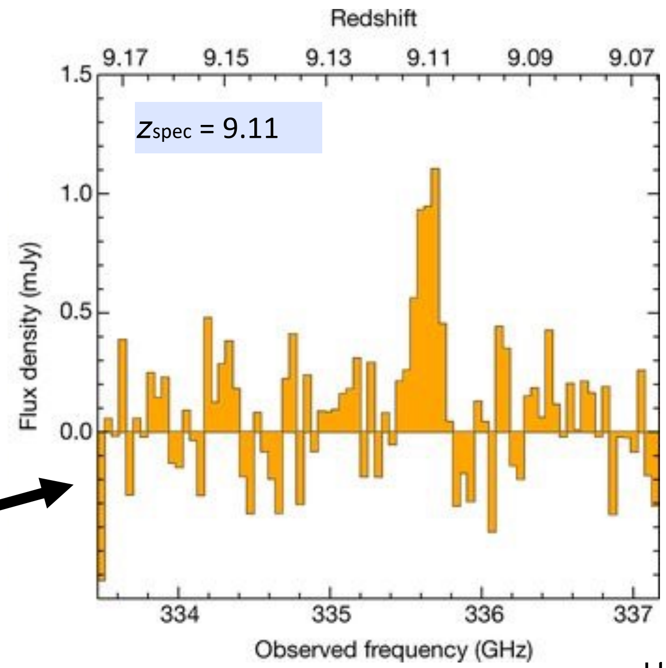




Increased spectral scan speed

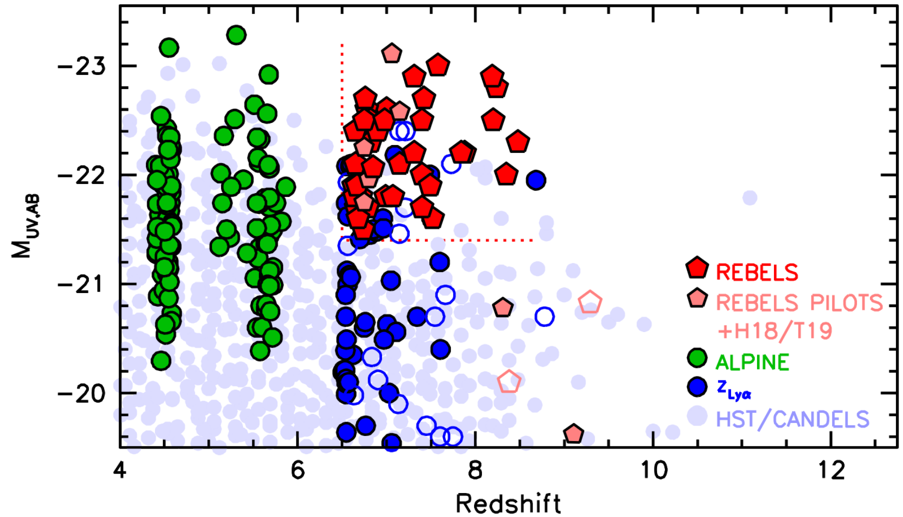
Spectroscopic redshift surveys : **3-6 times faster with BWx2** (and twice as fast with BWx4); efficient follow up of 1000s of candidates from large surveys



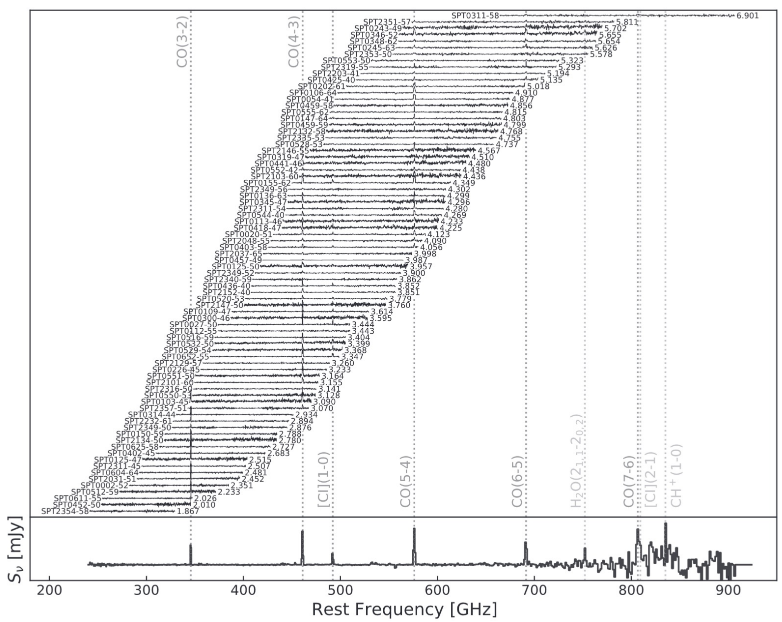


Hashimoto et al. (2018)

- 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

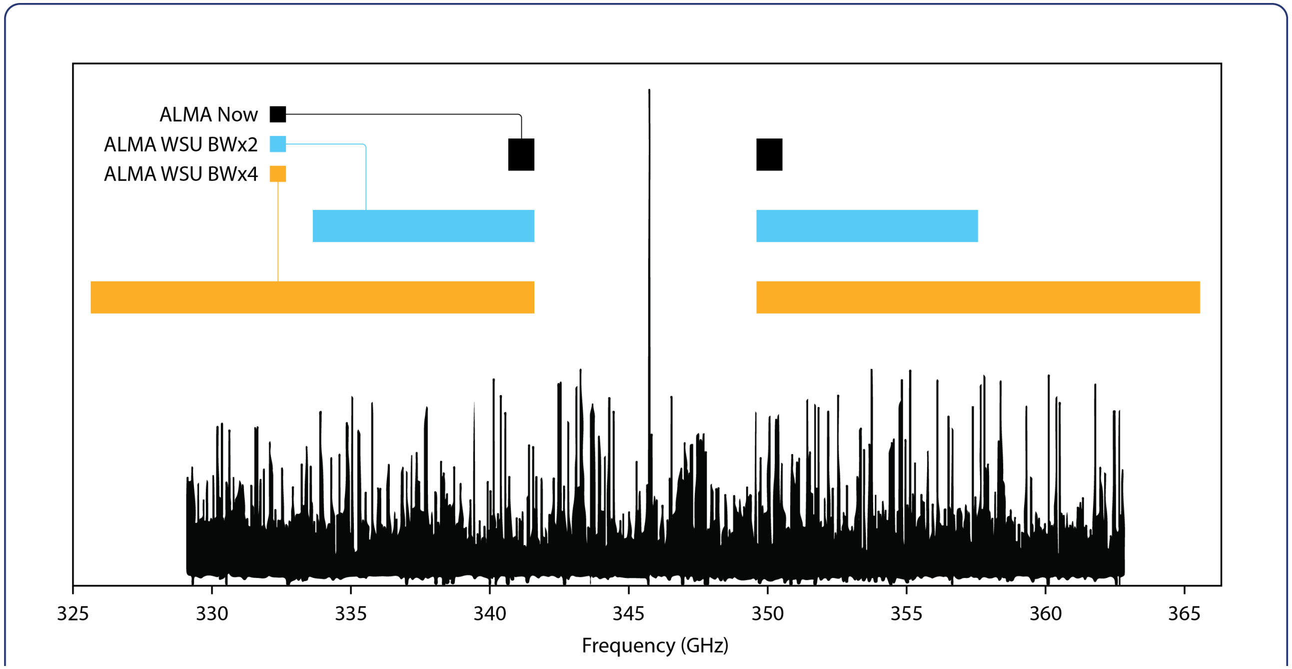


- Follow-up survey of 80 SPT-SZ DSFGs, 2<z<7. Blind surveys required 5 spectral setups ; only 2 needed for WSU, with factor 3 shorter integration time.

Reuter et al. 2020

- Entire instantaneous correlated bandwidth (16-32GHz) can be processed at (almost) any spectral resolution.

High spectral resolution astrochemistry surveys on galactic sources / nearby galaxies: spectral scanning speed improved by a factor >10

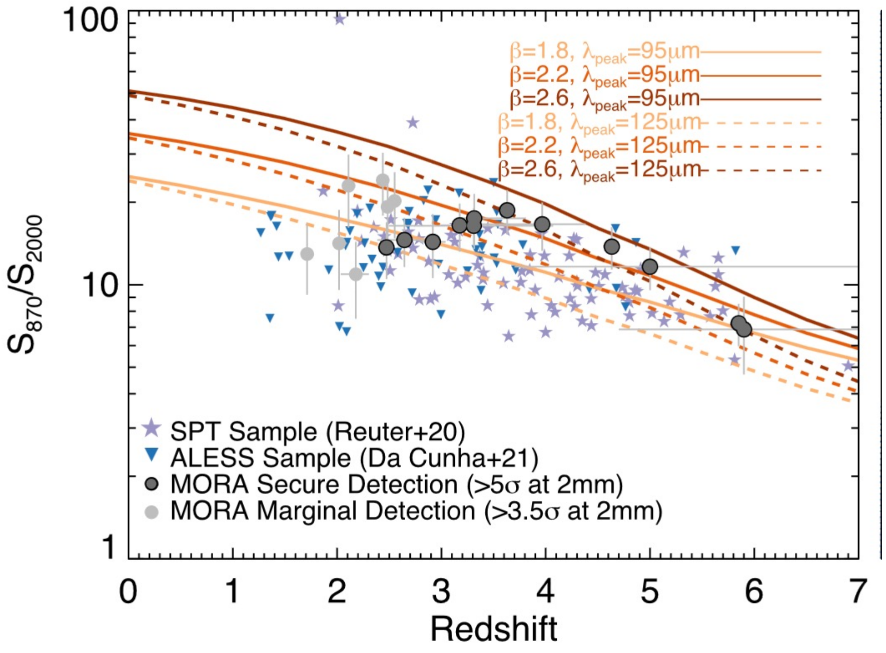


Jorgensen et al. (2016)

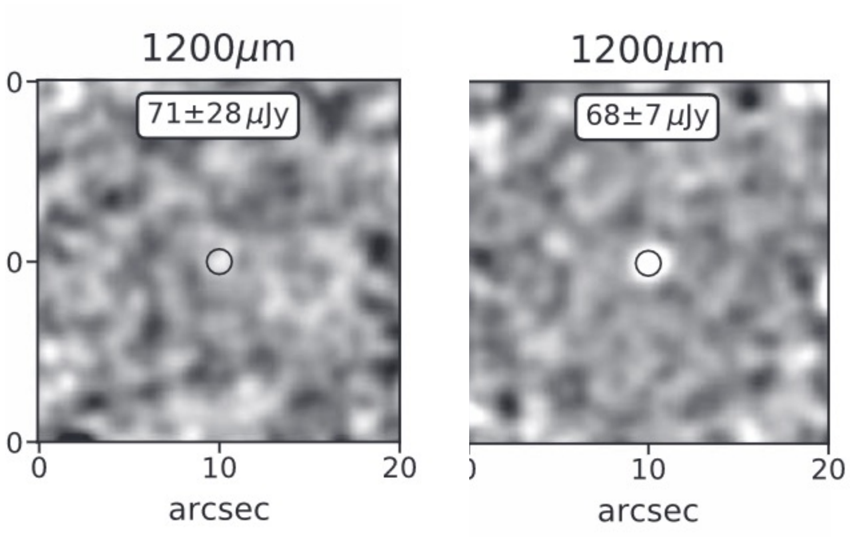
Continuum detection / mapping

Continuum mapping speed improved by factor > 3 (6) for BWx2 (BWx4)

Currently challenging high-z continuum measurements become more accessible



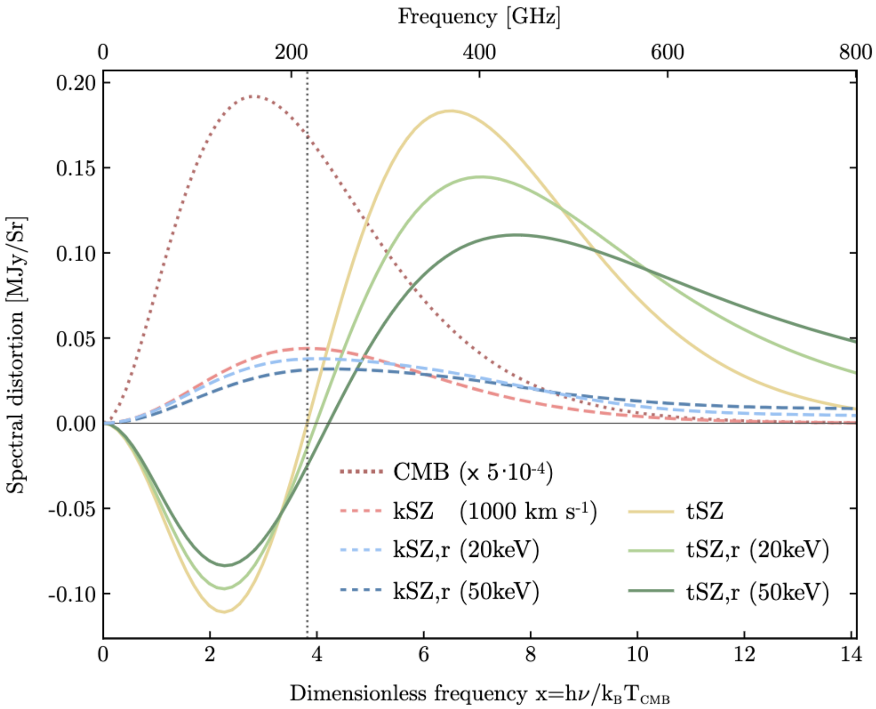
MORA DSFGs survey Casey et al. (2021)



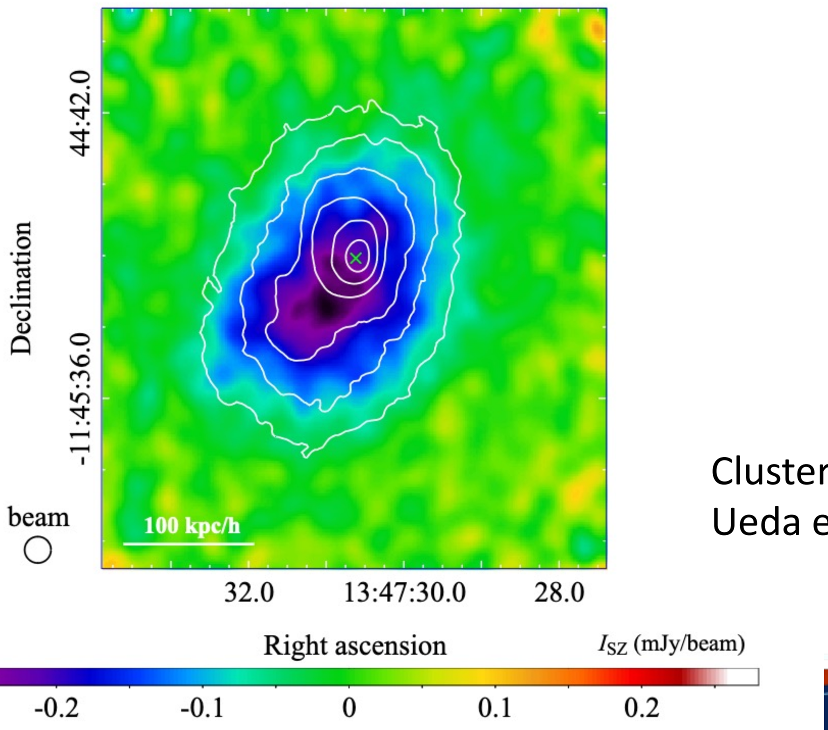
Stacked LIRG detections Shivaei et al. (2022)

Continuum detection / mapping

Mroczkowski et al. (2020)



Extended spectral coverage + improved sensitivity (especially Bands 2-6) can help to separate synchrotron thermal (dust) emission / tSZ Vs kSZ components



Cluster MRX J1347.5–1145 – Ueda et al., 2018

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.

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

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
science.nrao.edu
public.nrao.edu

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

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