Scientific priorities in the ALMA2030 roadmap

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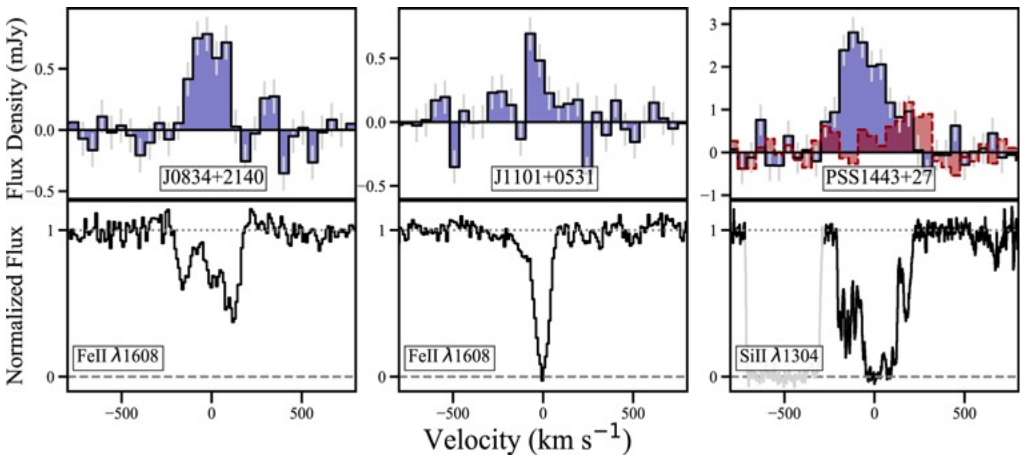
(ESO, Garching)

Data Classification: ESO PUBLIC

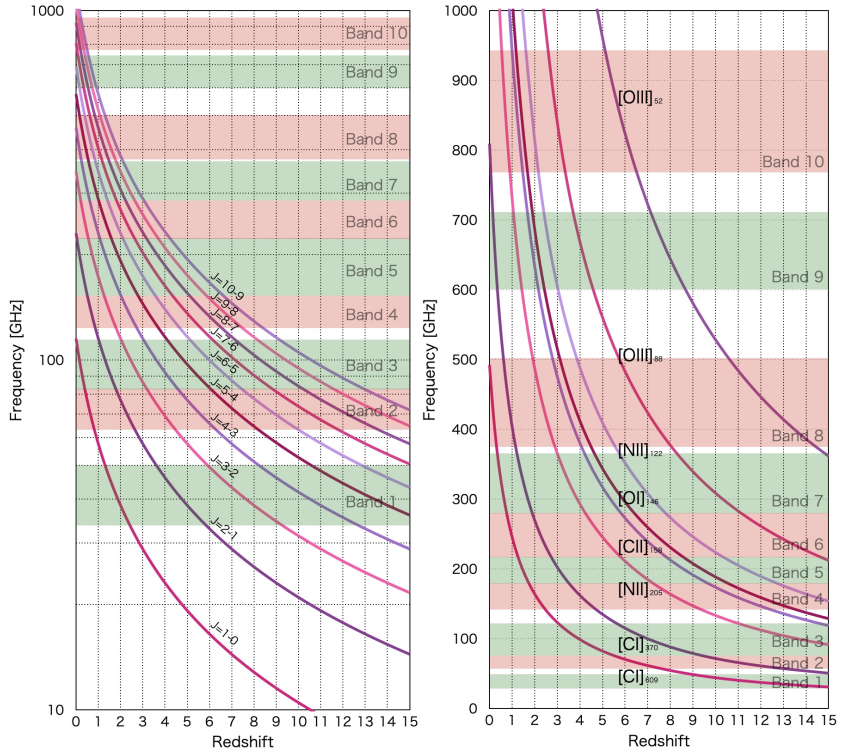
ALMA original science drivers

- 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



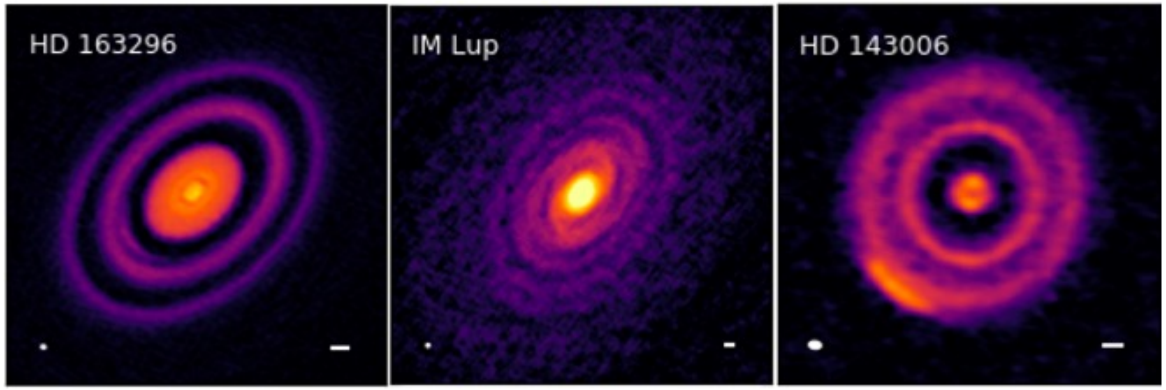
Carpenter et al. 2022

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

Luminosity ~ (0.36-30) 10^8 L_{sun}
Star Forming Rate: 7-110 M_{Sun}/yr

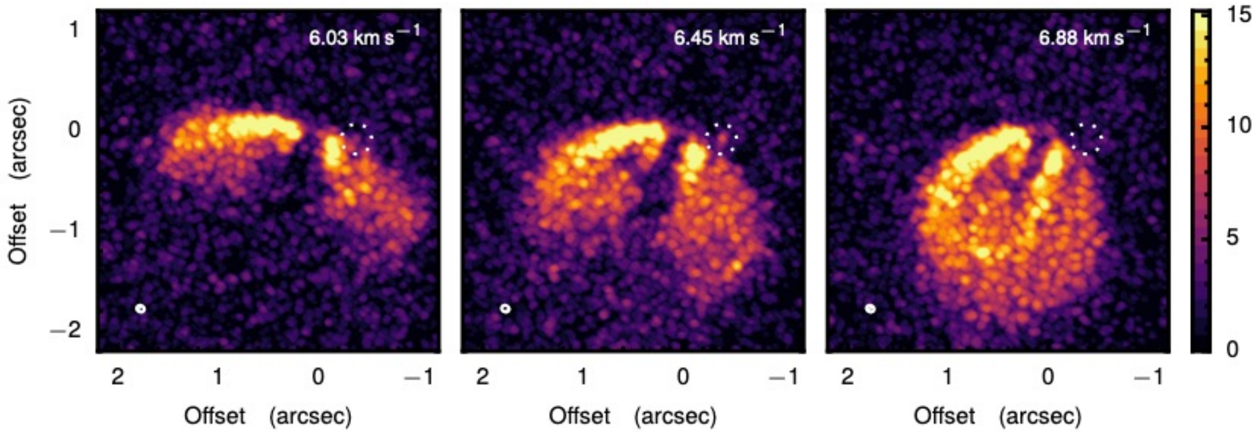
Superb imaging

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)

From Bolatto et al. (2015) …

- By 2015, the international ALMA community started to consider longer term goals and to identify the key upgrades that would sustain its scientific productivity into the 2030s and beyond

White Paper:

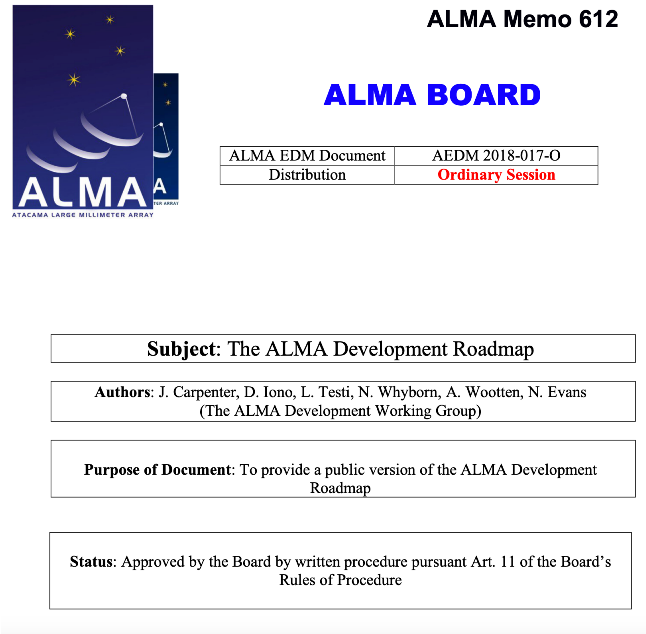
ASAC recommendations for ALMA 2030

Alberto D. Bolatto (chair), John Carpenter, Simon Casassus, Daisuke Iono, Rob Ivison, Kelsey Johnson, Huib van Langevelde, Jesús Martín-Pintado, Munetake Momose, Raphael Moreno, Kentaro Motohara, Roberto Neri, Nagayoshi Ohashi, Tomoharu Oka, Rachel Osten, Richard Plambeck, Eva Schinnerer, Douglas Scott, Leonardo Testi, & Alwyn Wootten

https://www.eso.org/sci/facilities/alma/developmentstudies/ALMA2030-Reports.pdf

… to Carpenter et al. (2019)

- And an ALMA Development Working Group was established to hone the recommendations into a plan


ALMA Memo 612

ALMA BOARD

ALMA EDM Document	AEDM 2018-017-O
Distribution	Ordinary Session

Subject: The ALMA Development Roadmap

Authors: J. Carpenter, D. Iono, L. Testi, N. Whyborn, A. Wootten, N. Evans
(The ALMA Development Working Group)

Purpose of Document: To provide a public version of the ALMA Development Roadmap

Status: Approved by the Board by written procedure pursuant Art. 11 of the Board's Rules of Procedure

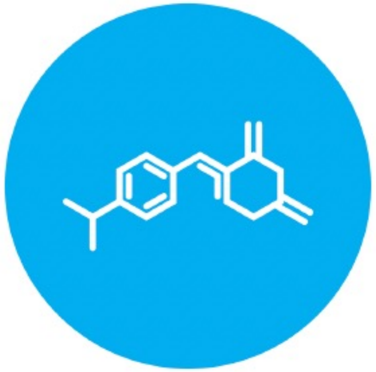
https://library.nrao.edu/public/memos/alma/main/memo612.pdf

The ALMA 2030 Roadmap

ALMA in the 2030s: scientific drivers

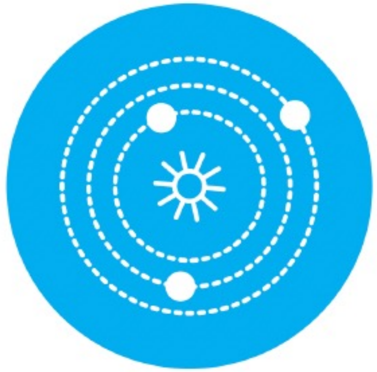
ORIGINS OF GALAXIES

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.



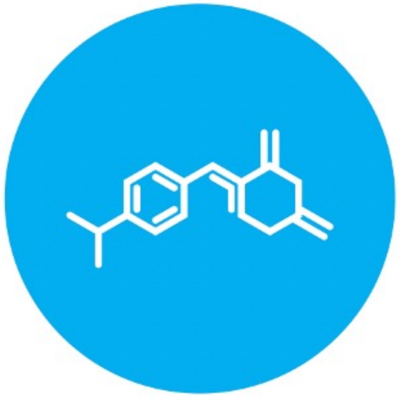
ORIGINS OF PLANETS

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.

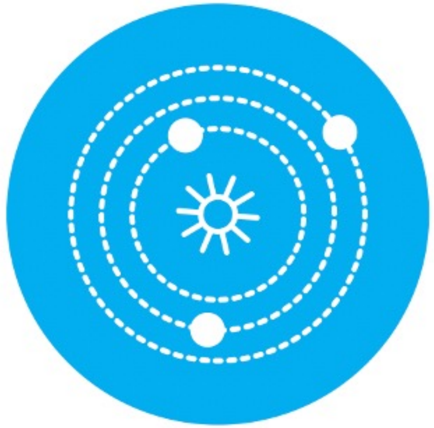
https://www.almaobservatory.org/en/publications/the-alma-development-roadmap

Required scientific capabilities

- Spectral range
- Spectral grasp
- Spectral line sensitivity
- Continuum sensitivity



- Spectral range
- Spectral grasp
- Spectral line sensitivity
- Increased angular resolution



- Continuum sensitivity
- Increased angular resolution

Mapping scientific capabilities to technical capabilities

- Spectral range ✓

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

- Spectral grasp WSU
- Spectral line sensitivity WSU
- Continuum sensitivity WSU

Capability	Improvement
Instantaneous Bandwidth	• Factor of 2 to 4 increase in the *available* instantaneous bandwidth (16 to 32 GHz per polarization) compared to existing receivers.
Correlated bandwidth	• Factor of 4 to 68 increase in the *correlated* bandwidth at high spectral resolution (0.1–0.2 km s^{-1}), with larger gains in the lower frequency bands. • Observers will no longer need to trade off high spectral resolution for bandwidth.
Spectral scan speed	• Increase of at least a factor of 2, and up to a factor of 4 (Band 10) to 54 (Band 2) for a spectral resolution of 0.1–0.2 km s^{-1}.
Spectral line imaging speed	• Increased spectral line speed from lower receiver noise temperatures ($\sim$ 20%; up to $\sim$ 50% at edge of RF band in some receivers), improved digital efficiency ($\sim$ 20%), and upgrade to 2SB mixers (Bands 9 and 10 only). • Net gain in spectral line imaging speed of $\sim$ 2–3.
Continuum imaging speed	• Increase by at least a factor of 3 with 2× bandwidth increase and at least 6 for 4× bandwidth, including digital efficiency improvements. • Additional gains from improved receiver temperatures.
Ultra-high spectral resolution	• Provide for the first time unique access to ultra-high spectral resolution observations — better than 0.01 km s^{-1} at all ALMA frequencies.

- Increased angular resolution ✗

Carpenter et al. 2022

ALMA in the 2030s: development priorities

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)

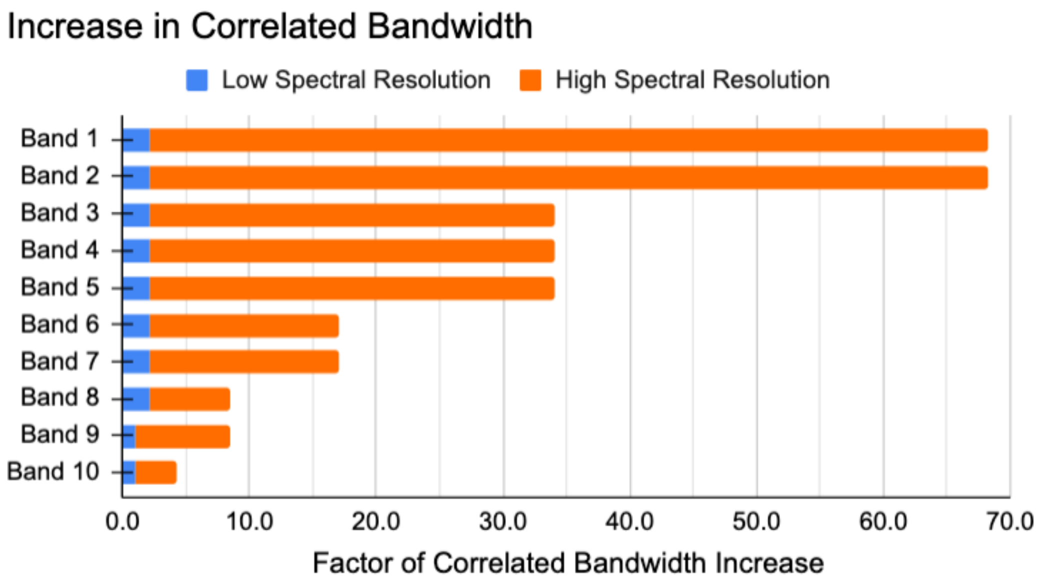
Near to mid-term goals:

- *Wideband Sensitivity Upgrade*: broaden receiver IF bandwidth by up to 4x, and upgrade of associated electronics and correlator for gains in speed (Science case arXiv:2211.00195, see M. Zwaan's and G. H. Tan's talks)
- *Archive*: increase usability/impact (Archive Vision WG, see F. Stoehr's and E. Villard's talks)

Longer term goals:

- *Longer baselines* (ESO Internal development study)
- *Wide field mapping speed* (Ongoing development study)
- *Additional antennas*

WSU: Increase in correlated bandwidth (spectral grasp)



Increase of correlated bandwidth by factors 4-70

Current ALMA: need to choose narrow bandwidth for high spectral resolution

ALMA 2030: 0.1-0.2 km/s resolution across 16 GHz BW

"High spectral resolution" is defined here as ~0.1 km/s

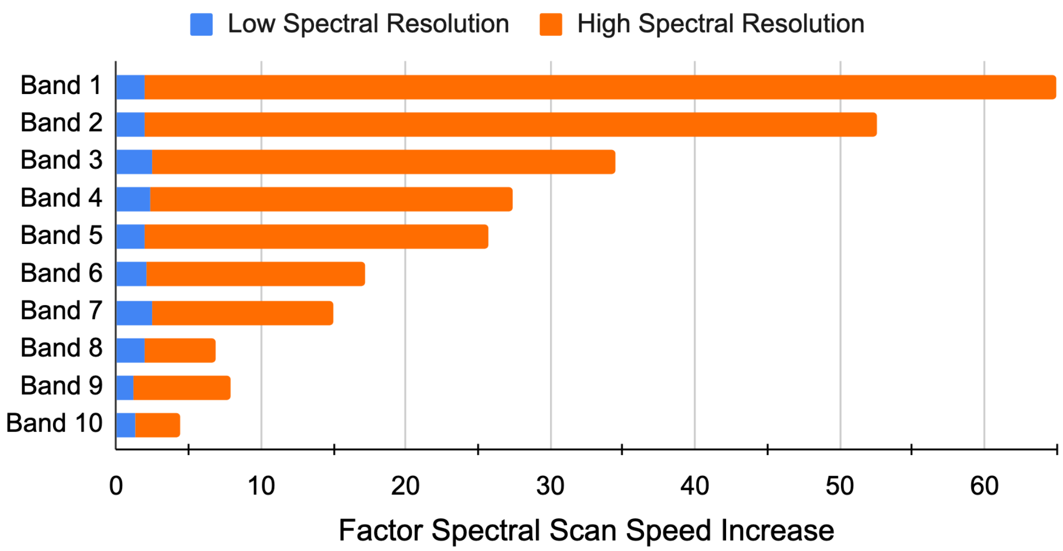
Plot is for the 16 GHz correlated bandwidth upgrade (2x bandwidth)

Table 2. Factor increase in the correlated bandwidth at high spectral resolution enabled by the WSU

Band	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Reference frequency (GHz)	**35**	**75**	**100**	**150**	**185**	**230**	**345**	**460**	**650**	**870**
Velocity resolution (km s^{-1})	0.26	0.12	0.18	0.12	0.10	0.16	0.11	0.16	0.11	0.17
BLC correlated bandwidth (GHz)	0.234	0.234	0.469	0.469	0.469	0.938	0.938	1.875	1.875	3.750
AT.CSP correlated bandwidth (GHz)	16	16	16	16	16	16	16	16	16	16
Channel averaging	2	2	4	5	5	8	10	14	18	32
Factor increase in correlated bandwidth	**68.3**	**68.3**	**34.1**	**34.1**	**34.1**	**17.1**	**17.1**	**8.5**	**8.5**	**4.3**

Carpenter et al. 2022

WSU: Increase in observing speed



"High spectral resolution" is defined here as ~0.1 km/s

Plot is for the 16 GHz correlated bandwidth upgrade (2x bandwidth)

Increase of observing speed

- Continuum imaging speed increase by x3 (x6) for x2(x4) correlated bandwidth*
- Spectral line imaging speed increase by ~ x 2-3**
- Spectral scan speed increase by x 2-64*

*Including digital efficiency improvements (~20%)
**Including digital efficiency improvements (~20%) and lower receiver noise temperatures (~20-30%)

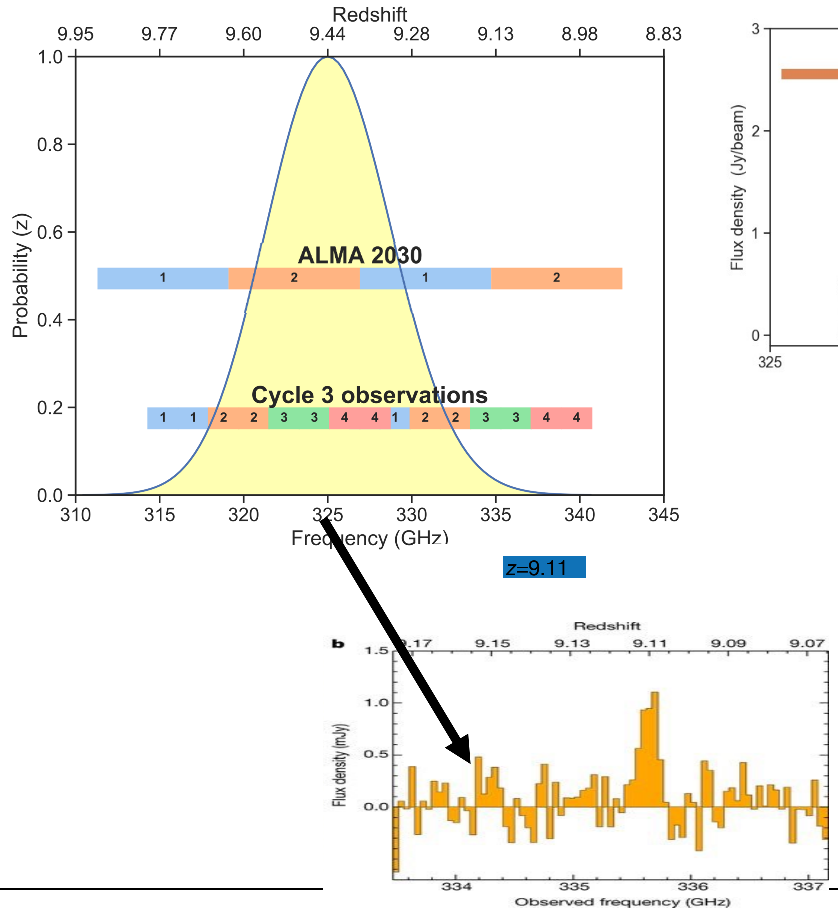
Table 4. Increase in the spectral scan speed with the 2× bandwidth WSU

Band Properties			Low Spectral Resolution				High Spectral Resolution (0.1–0.2 km s^{-1})				
			Current		WSU		Current			WSU	
Band	Rep. Freq. (GHz)	RF BW (GHz)	Velocity Res. (km s^{-1})	Number Tunings	Number Tunings	Time Savings Factor	Velocity Res. (km s^{-1})	Max CBW (GHz)	Number Tunings	Number Tunings	Time Savings Factor
1	35	15	8.36	2	1	2.0	0.26	0.234	64	1	64.0
2	75	49	3.90	8	4	2.0	0.12	0.234	209	4	52.3
3	100	32	2.93	5	2	2.5	0.19	0.469	68	2	34.0
4	150	38	1.95	7	3	2.3	0.12	0.468	81	3	27.0
5	185	48	1.58	8	4	2.0	0.10	0.468	103	4	25.8
6v2	230	64	1.27	9	4	2.1	0.16	0.938	68	4	17.0
7	345	98	0.85	17	7	2.4	0.11	0.938	105	7	15.0
8	460	115	0.64	18	9	2.0	0.16	1.875	61	9	6.8
9	650	118	0.45	10	8	1.3	0.11	1.875	63	8	7.9
10	870	163	0.34	13	10	1.3	0.17	3.75	43	10	4.3

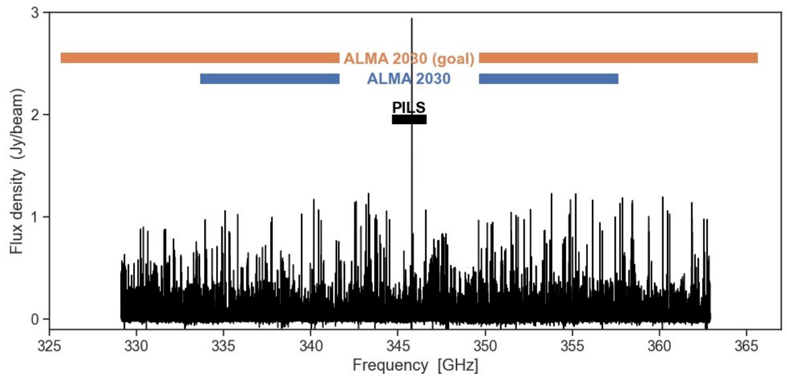
Notes: Comparison of the number of spectral tunings currently required to span each band's RF range, for the "low" and "high" spectral resolution regimes. The exact spectral resolution is defined by what the BLC can achieve. The time savings only considers the efficiency of spectral scan tunings, and does not included the expected improvements in the digitizer and correlator efficiencies or receiver performance.

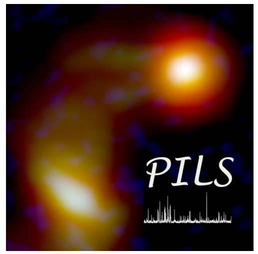
Carpenter et al. 2022

Gain in spectral scans

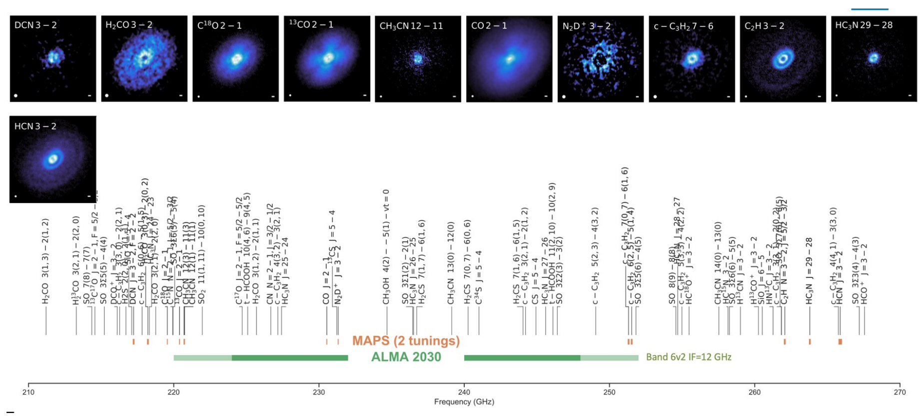


Hashimoto et al. (2018)





Jørgensen et al. (2016)

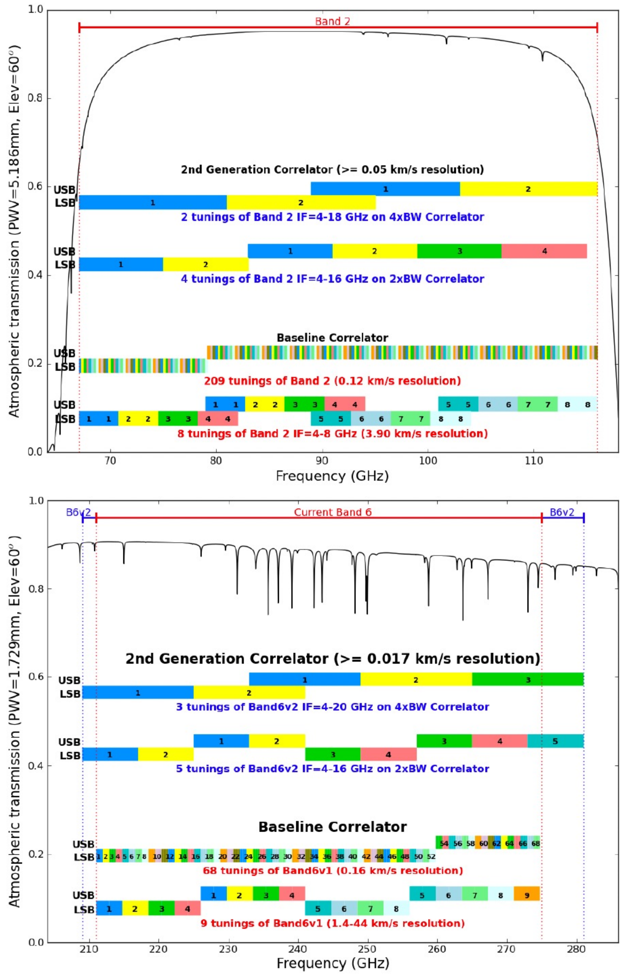


Öberg et al. (2021)

Example: spectral scan in bands 2/6

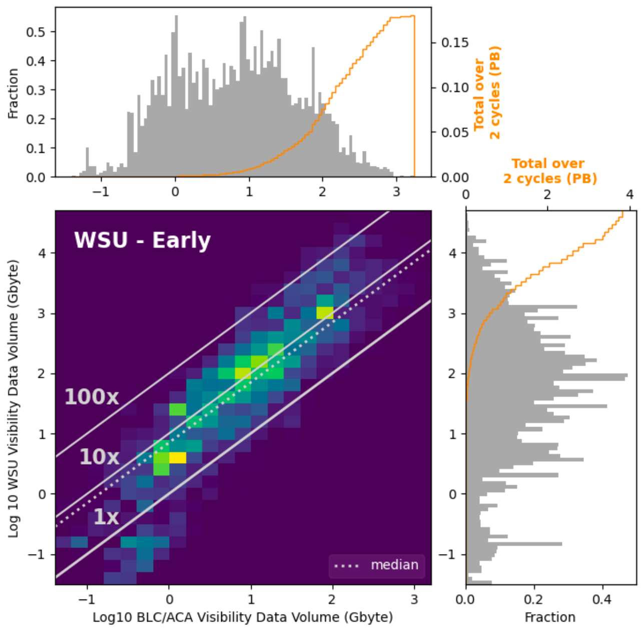
- Band 2:
  - Current ALMA: 209 tunings at 0.12 km/s
  - ALMA 2030 (2x BW): 4 tunings
  - ALMA 2030 (goal): 2 tunings

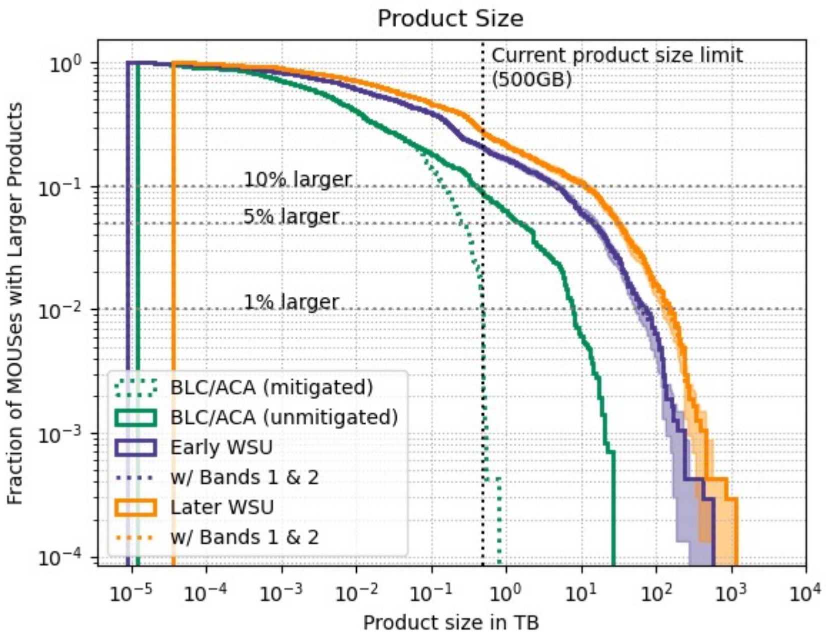
- Band 6:
  - Current ALMA: 68 tunings at 0.16 km/s
  - ALMA 2030 (2x BW): 5 tunings
  - ALMA 2030 (goal): 3 tunings



Carpenter et al. 2022

WSU: Peak data rates and volumes





Kepley et al. 2024 (ALMA Memo 626)

- Peak data rates will increase by factors up to 30x, although rates are below current limit in 70% of cases
- Values in the long tail dominate requirements for transfer, storage, and processing of data

In summary…

- The next development studies should help in the implementation of the ALMA 2030 Development Roadmap priorities including but not limited to:
  - Development of new receiver components allowing an expansion to 4x the current IF bandwidth
  - ...
  - Software initiatives that enable and maximize the science output of the WSU (data processing or ADPs)
  - Archive development
- See next talks for details!

Thank you!

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