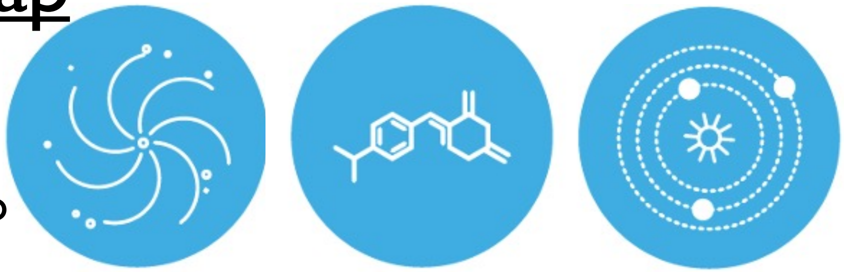
ALMA2030
Wideband Sensitivity Upgrade (WSU)

Anthony Remijan & the ALMA Integrated Science Team

ALMA Development Roadmap

- Published 2018 after several years investigation
- Three new key science "themes"
- All require increased bandwidth and sensitivity to keep ALMA at forefront of scientific discovery



ORIGINS OF GALAXIES ORIGINS OF CHEMICAL COMPLEXITY ORIGINS OF PLANETS

Topic: ALMA Wideband Sensitivity Upgrade and Other New Capabilities

The North American Science Center will hold a Webinar at 3pm 16 March in which speakers will describe ALMA news, capabilities, and expectations for ALMA performance and science in the next few years, and plans for its upgrade in the 2030 time-frame. In that period, ALMA will complete its frequency coverage of the millimeter window. Band 1 (8.6mm-6.0mm; 35-50 GHz), is being installed on the array now. Band 2 (4.5mm-3.3mm; 67-90 GHz) will follow, completing installation of the baseline ten bands.

A Band 6 upgrade, a part of the ambitious ALMA2030 Wideband Sensitivity Upgrade, is in early stages. This upgrade will improve ALMA's bandwidth and spectral line sensitivity in this most productive of ALMA bands. Eventually, ALMA's bandwidth will be increased to simultaneously enhance its spectral range and continuum sensitivity, even as its line sensitivity is increased via receiver upgrades, an upgraded correlator, and improvements of the systems connecting them. Higher resolution imaging is being explored, both on ALMA's 5000m exceptional site and as part of extremely long baseline imaging arrays. In the Webinar, ALMA Director Sean Dougherty will provide a status report, followed by Program Scientist C. Brogan on the planned upgrades.

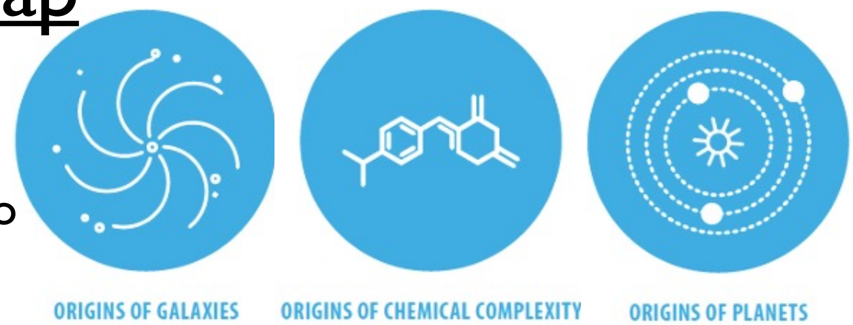
Anticipated Speakers:
Sean Dougherty (ALMA Director, JAO)
ALMA Status and Prospects for Cycles 9 & 10

Crystal Brogan (NRAO)
Keeping ALMA at the Forefront of Scientific Discovery: The Wideband Sensitivity Upgrade

Anthony Remijan (NRAO)
ALMA User Support for the NA Community
To register for the (free, no cost, no obligation) Webinar, please visit: https://nrao-edu.zoom.us/webinar/register/WN_burFLSqsQDGj-PkGWr7A8A

ALMA Development Roadmap

- Published 2018 after several years investigation
- Three new key science "themes"
- All require <u>increased bandwidth and sensitivity</u> to keep ALMA at forefront of scientific discovery



<u>Highest near-term priorities this decade</u> (envelope of existing development funding):

1. Increase receiver IF bandwidth and sensitivity
2. Increase the digital sensitivity and bandwidth by at least a factor of 2

=> ALMA2030 Wideband Sensitivity Upgrade

- Working Groups convened FY19-22 to recommend specifications/requirements in major technical areas: FE/Digitizers, Back-end/Data Transport, 2nd Generation Correlator; each sponsoring a Workshop to solicit community feedback
- Working Group recently convened to homogenize recommendations, and soon Ops Working Group to develop plan for downstream subsystems and operations
- Goal for completion by ~2030 (upgrade of some receiver bands will come later)

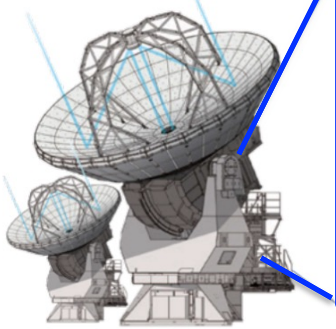
3. Improve usability of ALMA Science Archive and data products
    - Diverse efforts on both archive and tools across partnership

Wideband Sensitivity Upgrade (WSU)

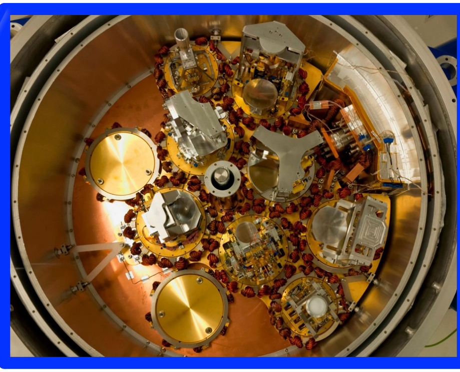
New or Upgraded Components are in blue

Goal: Expand system bandwidth by at least 2x with improved sensitivity

Antenna



Front Ends (Receivers)



Back Ends

- **IF Switches & Anti-aliasing filters**
- **Digitizers & Digital Signal Processing**
- **Digital Transmission System**

Existing Antenna to AOS Fibers

Array Operations Building at 5,000m

New Fiber

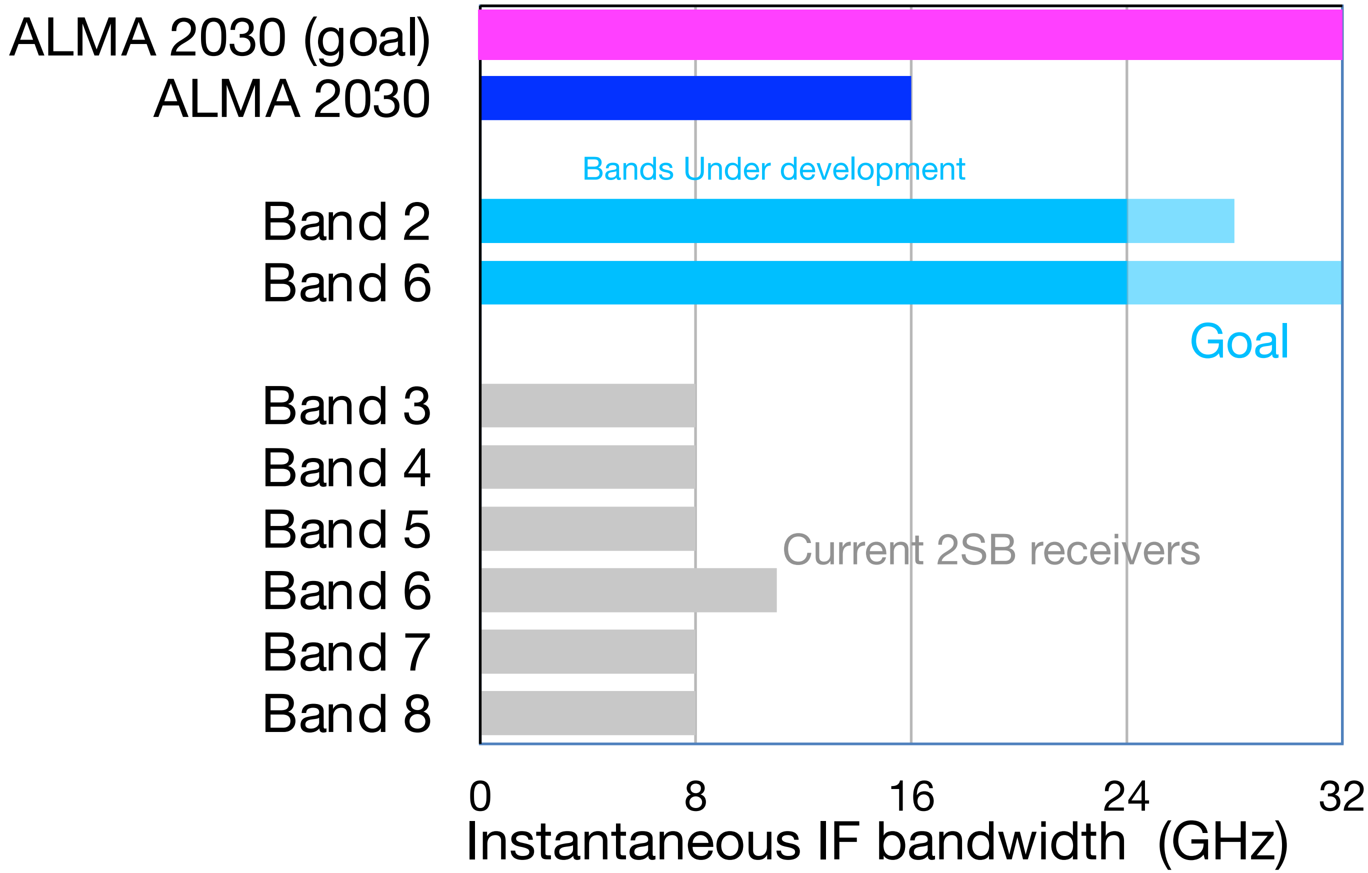
Operations Support Facility at 3,000m

2nd Generation Correlator & Upgraded ACAS in new OSF Correlator Room

CONTROL, TelCal, Scheduling, OT, Archive, Pipeline

Wideband Sensitivity Upgrade: Overview

- **Available bandwidth**
- Correlated bandwidth
- Observing speed

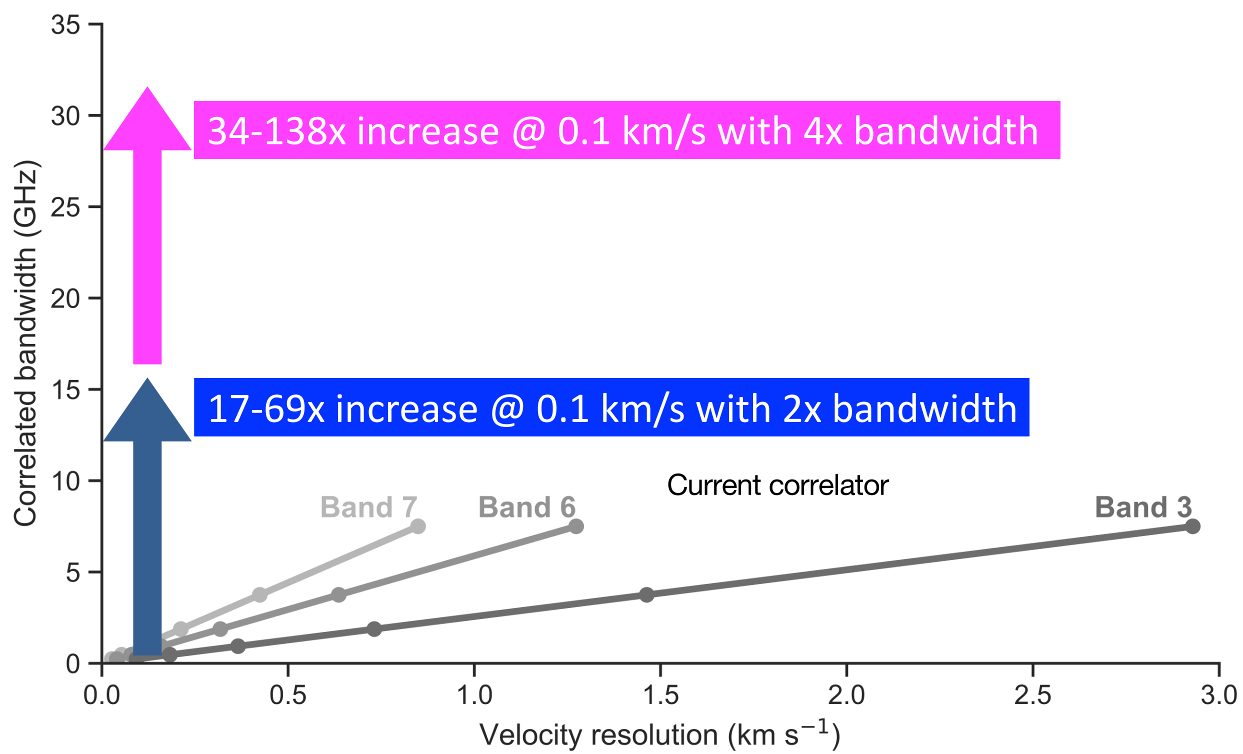


Factor of 2-4 increase in the available IF bandwidth.

Wideband Sensitivity Upgrade: Overview

Correlated bandwidth* vs. velocity resolution

- Available bandwidth
- **Correlated bandwidth**
- Observing speed



* per polarization

Never need to compromise spectral resolution for bandwidth again!

2nd Generation ALMA Correlator: ALMA TALON Central Signal Processor (AT.CSP)

Wideband Sensitivity Upgrade: Overview

- Available bandwidth
- Correlated bandwidth
- **Observing speed**

Increase in Band 6v2 observing speed with ALMA 2030

Observing mode	Increase in speed over current system*
Continuum	4.8x (with goal of 9.6x)
Spectral line	2.25-4.7x

* To reach same sensitivity as current system with single tuning

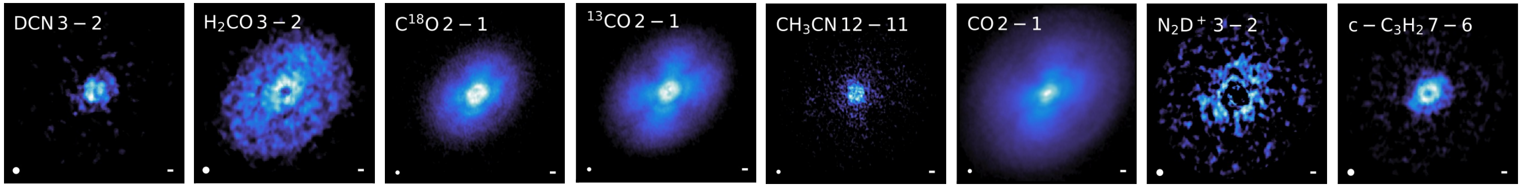
Increase in observing speed results from

- Improved receiver temperatures
- Increased digital efficiency
- Wider bandwidth (continuum)

Spectral scans will see further speed increases due to larger correlated bandwidth.

The ALMA 2030 Advantage

Using the MAPS (Molecules at Planetary Scales) Large Program (Oberg et al. 2021) science as example:



								DCO^+ J=3-2	NO J=5/2-3/2
SO_2 10(5,5)-11(4,8)	H_2S 2(2,0)-2(1,1)	SiO J=5-4	c-C_3H_2 6(0,6)-5(1,5)	HC_3N J=24-23	H_2CO 3(2,1)-2(2,0)	$C^{15}N$ N=2-1	SO 3Σ 6(5)-5(4)	SO_2 11(1,11)-10(0,10)	$C^{17}O$ J=2-1
t-HCOOH 10(4,6)-9(4,5)	H_2CO 3(1,2)-2(1,1)	H_2CS 7(0,7)-6(0,6)	H_2CS 7(1,6)-6(1,5)	CN N=2-1	c-C_3H_2 4(3,2)-3(2,1)	c-C_3H_2 3(2,1)-2(1,2)	CS J=5-4	HC_3N J=25-24	HC_3N J=27-26
13CS J=5-4	$C^{34}S$ J=5-4	t-HCOOH 11(2,10)-10(2,9)	SO 3Σ 2(3)-3(2)	c-C_3H_2 5(2,3)-4(3,2)	SO 3Σ 5(6)-4(5)	SO 3Σ 8(9)-8(8)	HC_3N J=28-27	c-C_3H_2 5(3,3)-4(2,2)	$HC^{18}O^+$ J=3-2

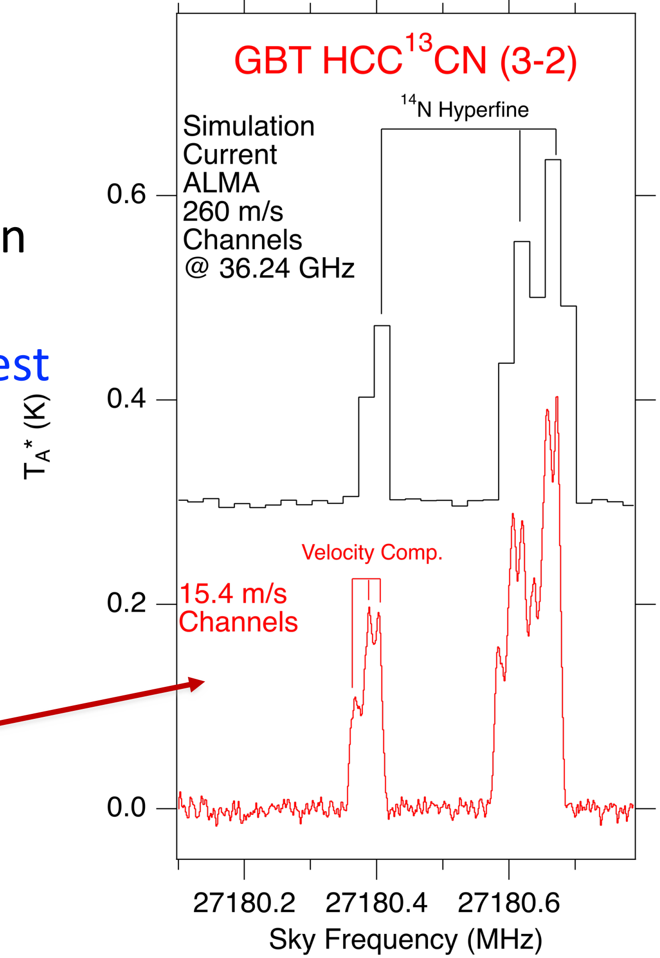
… and up to 40 additional spectral windows!

Unique Access to Ultra-High Spectral Resolution

- Original ALMA requirement for finest spectral resolution has not been met: 10 m/s at 100 GHz
- Re-interpreted for ALMA2030 as 10 m/s at ALMA's lowest operating frequency of 35 GHz (stretch goal)
  - ➢ Easily met with AT.CSP zoom windows

Science use cases for ultra-high spectral resolution:

- Measuring subtle deviations from Keplerian rotation towards the mid-plane of protoplanetary disks
- Probing the kinematics of very cold (starless) clouds and cores
- Detecting infall signatures (in absorption) toward the cold molecular envelopes of protostars
- Characterizing the line-of-sight magnetic field strength using the molecular Zeeman effect
- Spectrally resolving the motions of atmospheric winds in Solar System objects



GBT HCC^{13}CN (3-2) spectrum toward TMC-1 with 15.4 m/s channels (McGuire et al. 2021).

Simulation of HCC^{13}CN (4-3) at 36.24 GHz at current best Band 1 spectral resolution: 260 m/s.

=> The hyperfine structure can be resolved but the complex < 200 m/s kinematics are completely lost.

Continuum Sensitivity & Fidelity

- **Increased sensitivity** -- For 2x correlated BW = ([16 GHz/7.5GHz]$^{0.5}$) x 1.2 (digital) improvement x receiver improvement
- **Improved image fidelity** – increased uv-plane coverage from multi-frequency synthesis
- **More sensitive estimation of spectral index** – increased fractional bandwidth
- **Enhanced calibration options** – use weaker, closer calibrators or less time and channel averaging for improved calibration

1.3mm model and simulations with 50mas resolution of a protoplanetary disk similar in morphology to IM Lup.

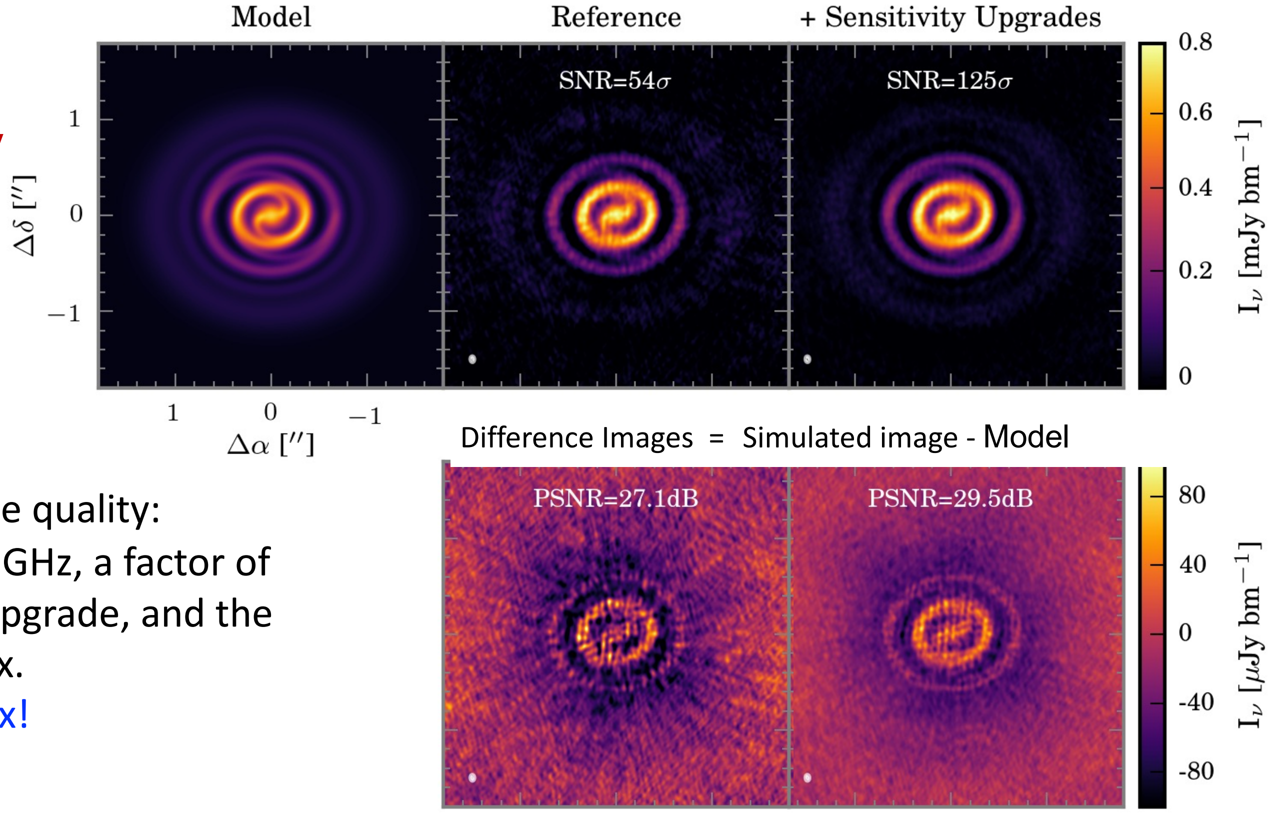
- **Reference** today's image quality:

3.75 GHz of BW per sideband, with a gap of 12 GHz.

- **+Sensitivity Upgrades** ALMA2030 image quality:

8 GHz of BW per sideband, with a gap of 16 GHz, a factor of 1.25x better sensitivity from the Band 6v2 upgrade, and the digital sensitivity improvement factor of 1.2x.

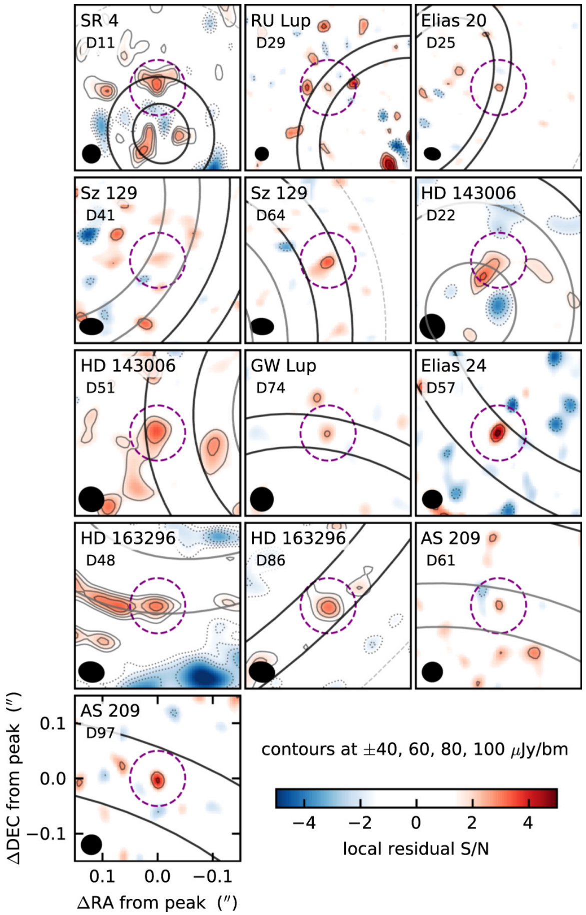
- Signal-to-noise improved by factor 2.3x!



PSNR is measure of image fidelity

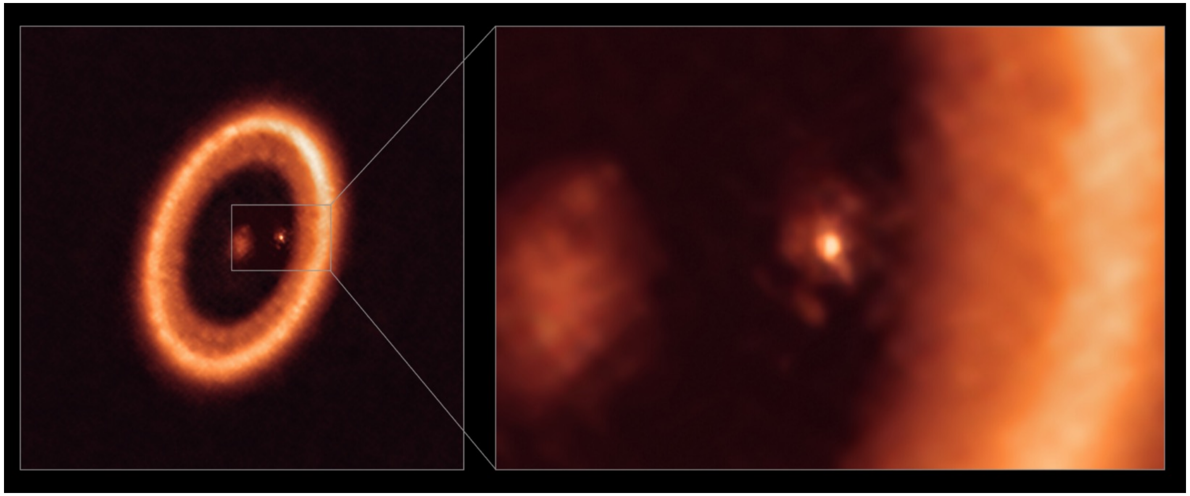
Circumplanetary disks

Search for circumplanetary disks in DSHARP



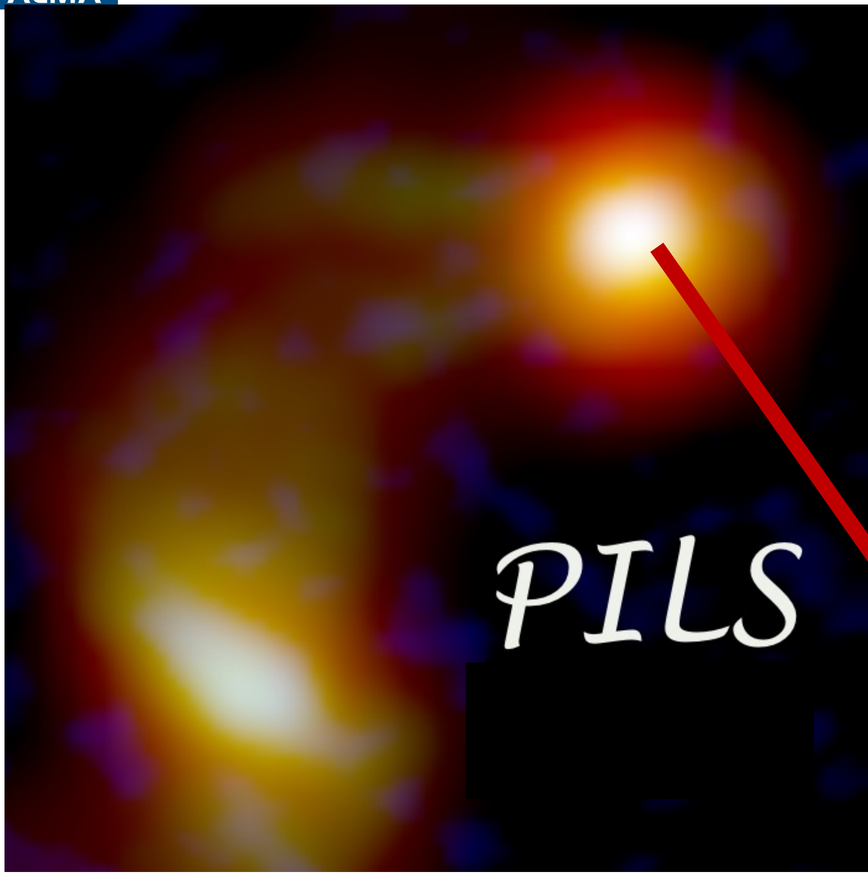
- Detection of circumplanetary disks in PDS 70c
- Search circumplanetary disks in the DSHARP sample
  - Several 3-5$_{\sigma}$ peaks, but no convincing detections
  - Wideband sensitivity upgrade will improve signal to noise by 2.2x
  - Improved uv-coverage from wider bandwidth imaging synthesis will help suppress imaging artifacts

Circumplanetary disk around PDS 70c



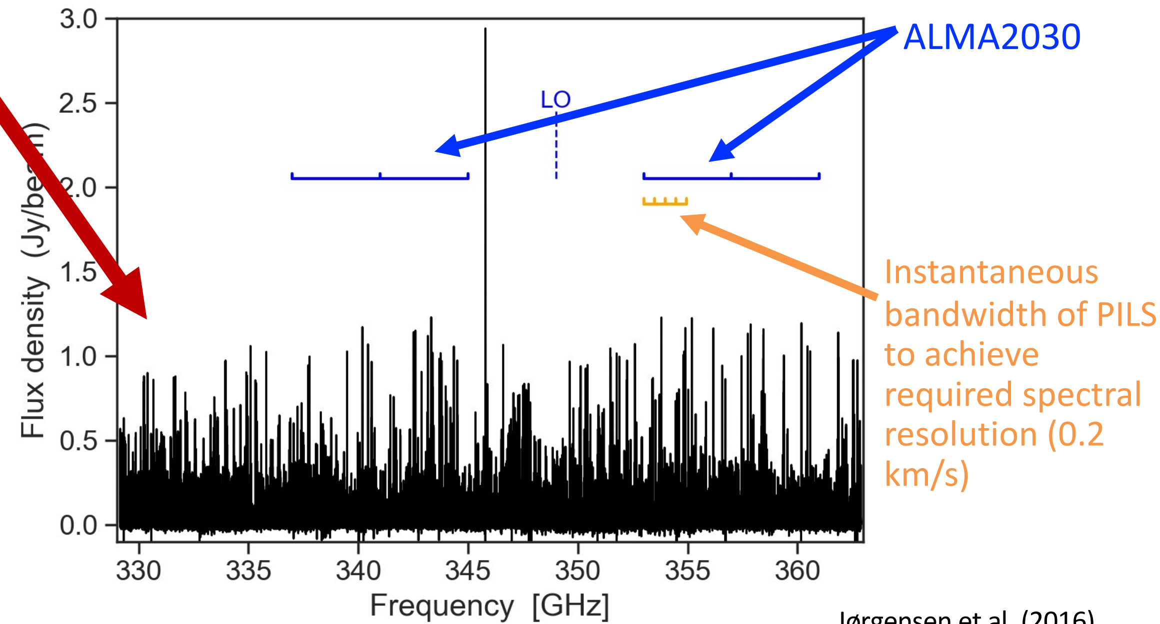
Benisty et al. (2021)
Andrews et al. (2021)

Efficient spectral scans with ALMA 2030



- PILS survey of IRAS 16293 protostar
  - required 18 tunings

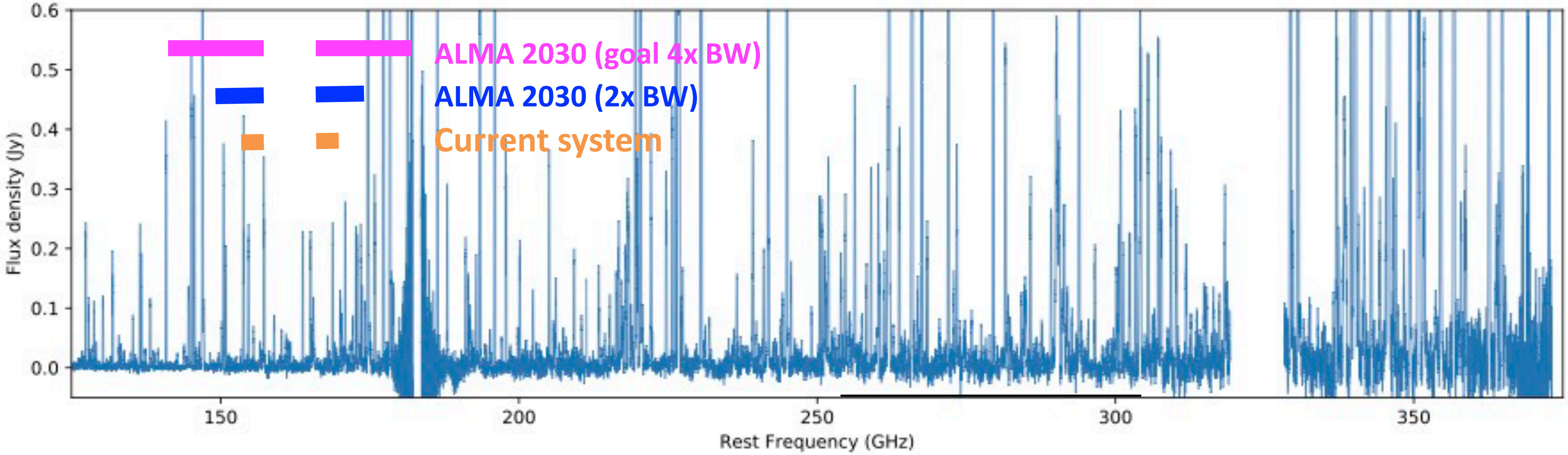
- ALMA 2030 will need only 2 tunings!



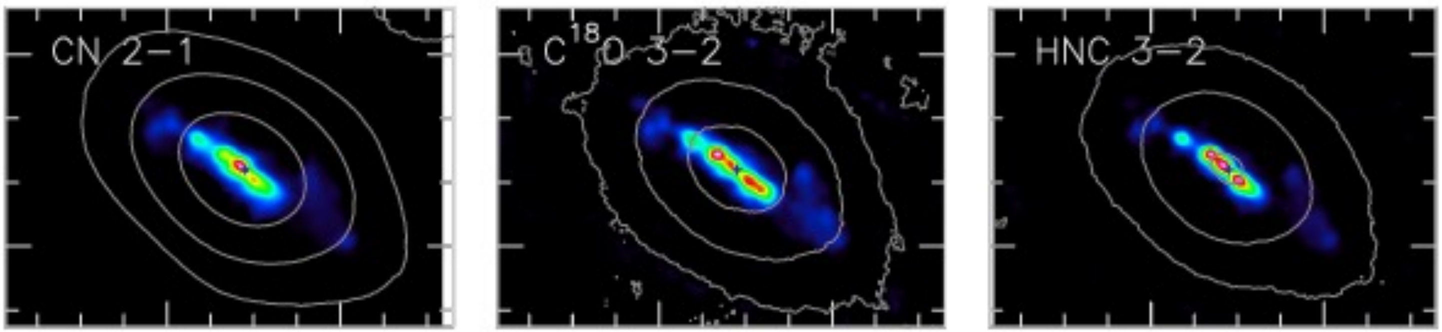
Jørgensen et al. (2016)

ALCHEMI survey of Starburst Galaxy NGC 253

Martín et al. (2021)



Example of observed chemical differentiation



- Survey speed with ALMA 2030 will increase a factor of 3-6 plus any gains from improved receiver temperatures.

Summary

- Wideband sensitivity upgrade will benefit all observations

- Technical upgrades
  - Available bandwidth : factor of 2-4 increase
  - Correlated bandwidth : more than an order of magnitude increase with ~ 0.1 km/s resolution
  - Digital Efficiency: greater bit-depth at all stages will result in factor of 1.2 sensitivity improvement
  - Observing speed : 2.2-4.7x faster for spectral lines, 4.8x faster for continuum (Band 6 upgrade)

➢ Never need to give up correlated bandwidth for spectral resolution again (except for ultra-high spectral resolution Zoom mode)

- Scientific impact
  - Planet formation : comprehensive studies of physical, kinematic, and chemical structure of disks
  - Star formation : efficient surveys of all stages in the star formation process
  - Galaxy formation : probe the formation and evolution of galaxies across cosmic time

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Overview of AT.CSP Capabilities

- Increase maximum correlated bandwidth to 16 GHz per polarization. Expandable to 4x BW.
- Correlates up to 70 antennas (66 deployed initially)
- Up to 1.2 million channels across 80 x 200 MHz frequency slices, and flexible channel averaging available

Comparison of the BLC and AT.CSP in Imaging Correlation Mode

	BLC (2x2 bit[1] FDM)	AT.CSP (6x6 bit)
# Antenna inputs	64	70
Maximum Correlated Bandwidth (Max CBW)	7.5 GHz per pol	16 GHz per pol
# Channels (per pol) Dual Pol	4 x 3840	2 x 40 x 14880
# Channels (per pol) Full Pol	4 x 1920	
Channel Width[2] at Max CBW Dual Pol	488 kHz	13.5 kHz
Channel Width[2] at Max CBW Full Pol	976 kHz	
Finest Channel Width[2] Dual Pol	15.25 kHz	13.5 kHz / (2, 4, 8 ...64)
Finest Channel Width[2] Full Pol	30.5 kHz	
Zoom Windows[3]	4 x 4	2 x 40
Internal Channel Averaging[4]	None	2, 3, 4, 6, 8, 12, 16, 24, 48
Correlator Efficiency	0.8810	0.99887

- Flexible subarrays will enable independent observations with ALMA's three arrays: Main 12m-array, ACA 7m-array, and ACA TP-Array
- Applies all-digital, virtually perfect delay and phase tracking with no delay rate-dependent anomalies in visibilities and no post-correlation corrections needed
- Provides significant improvements to current VLBI and pulsar observing modes, including simultaneous coarse resolution visibilities, and ability to observe with a single antenna in VLBI mode (A1-VLBI) without disturbance to interferometric observing.

Unprecedented Spectral Resolution at Wide Bandwidth

=> (Almost) never need to give up BW for spectral resolution

New ALMA2030 requirements ensure at minimum:

- Spectral resolution of <200 m/s at 16 GHz BW per polarization at f>35 GHz (goal 100 m/s)
- Spectral resolution of <20 m/s at 1.6 GHz BW per polarization at f>35 GHz (goal 10 m/s)

Achievable Velocity Widths with AT.CSP in Imaging Correlation Mode

					1	2	3	4	5	6	7	8	9	10
Band					1	2	3	4	5	6	7	8	9	10
Frequency (GHz)					35	75	100	150	185	230	345	460	650	870
Zoom Factor[1] all spw	1	Max CBW per pol	16 GHz	Velocity Width[2] (m/s)	115.6	54.0	40.5	27.0	21.9	17.6	11.7	8.8	6.2	4.7
	2		8 GHz		57.8	27.0	20.2	13.5	10.9	8.8	5.9	4.4	3.1	2.3
	4		4 GHz		28.9	13.5	10.1	6.7	5.5	4.4	2.9	2.2	1.6	1.2
	8		2 GHz		14.5	6.7	5.1	3.4	2.7	2.2	1.5	1.1	0.8	0.6

Comparison with BLC at max and min FDM CBW

BLC	Max CBW dual pol	7.5 GHz	Velocity Width[2] (m/s)	8364.9	3903.6	2927.7	1951.8	1582.6	1272.9	848.6	636.5	450.4	336.5
		0.234 GHz		261.4	122.0	91.5	61.0	49.5	39.8	26.5	19.9	14.1	10.5

The native spectral resolution of AT.CSP is 13.5 kHz, but even higher spectral resolution can be achieved per 200 MHz frequency slice using "Zoom Windows"

CBW = Correlated Bandwidth

More BW & Channels = Efficient Spectral Scans

(Super efficient at high spectral resolution)

Band Properties			Low Spectral Resolution			High Spectral Resolution (0.1-0.2 km/s)			
			Current with 7.5 GHz CBW		WSU 16 GHz CBW	Current with Indicated CBW			WSU 16 GHz CBW
Band	Rep Freq (GHz)	RF BW (GHz)	Velocity Res (km/s)	#Tunings	#Tunings	Velocity Res (km/s)	Max CBW GHz	#Tunings	#Tunings
1	40	15	7.32	2	1	0.23	0.234	64	2
2+3	75	49	3.90	7	3	0.12	0.234	209	3
4	150	38	1.95	5	2	0.12	0.468	81	2
5	185	48	1.58	6	3	0.10	0.468	103	3
6v2	230	72	1.27	10	5	0.16	0.938	77	5
7	345	98	0.85	13	6	0.11	0.938	105	6
8	460	115	0.64	15	7	0.16	1.875	61	7
9	650	118	0.45	16	7	0.11	1.875	63	7
10	870	163	0.34	22	10	0.17	3.75	43	10

At 2x BW, with all 8 GHz per sideband (per pol) of science quality, there are no gaps

The ability to efficiently do spectral scans at moderate to high spectral resolution will be unprecedented.

CBW = Correlated Bandwidth