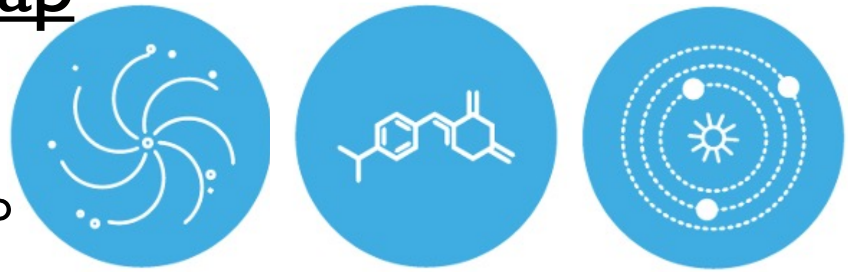
Atacama Large Millimeter/submillimeter Array
In search of our Cosmic Origins

ALMA2030
Wideband Sensitivity Upgrade (WSU)

Crystal Brogan (NA Program Scientist)
& the ALMA Integrated Science Team

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 widen the correlated bandwidth by at least a factor of 2

=> ALMA2030 Wideband Sensitivity Upgrade (WSU)

- Working Groups convened 2019-2022 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)

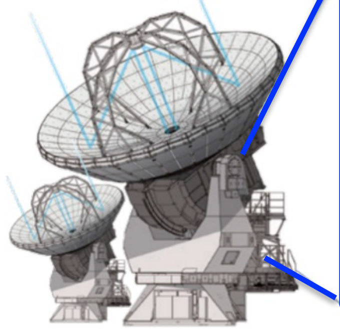
New or Upgraded Components are in blue

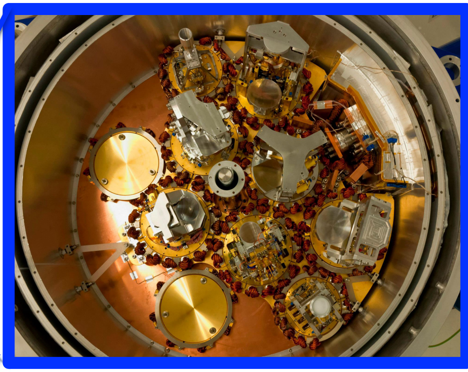
Goal: Expand system bandwidth by <u>at least</u> 2x with improved sensitivity

Front Ends (Receivers)

Back Ends

Antenna





IF Switches & Anti-aliasing filters

Digitizers & Digital Signal Processing

Digital Transmission System

Existing Antenna to AOS Fibers

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

Array Operations Building at 5,000m

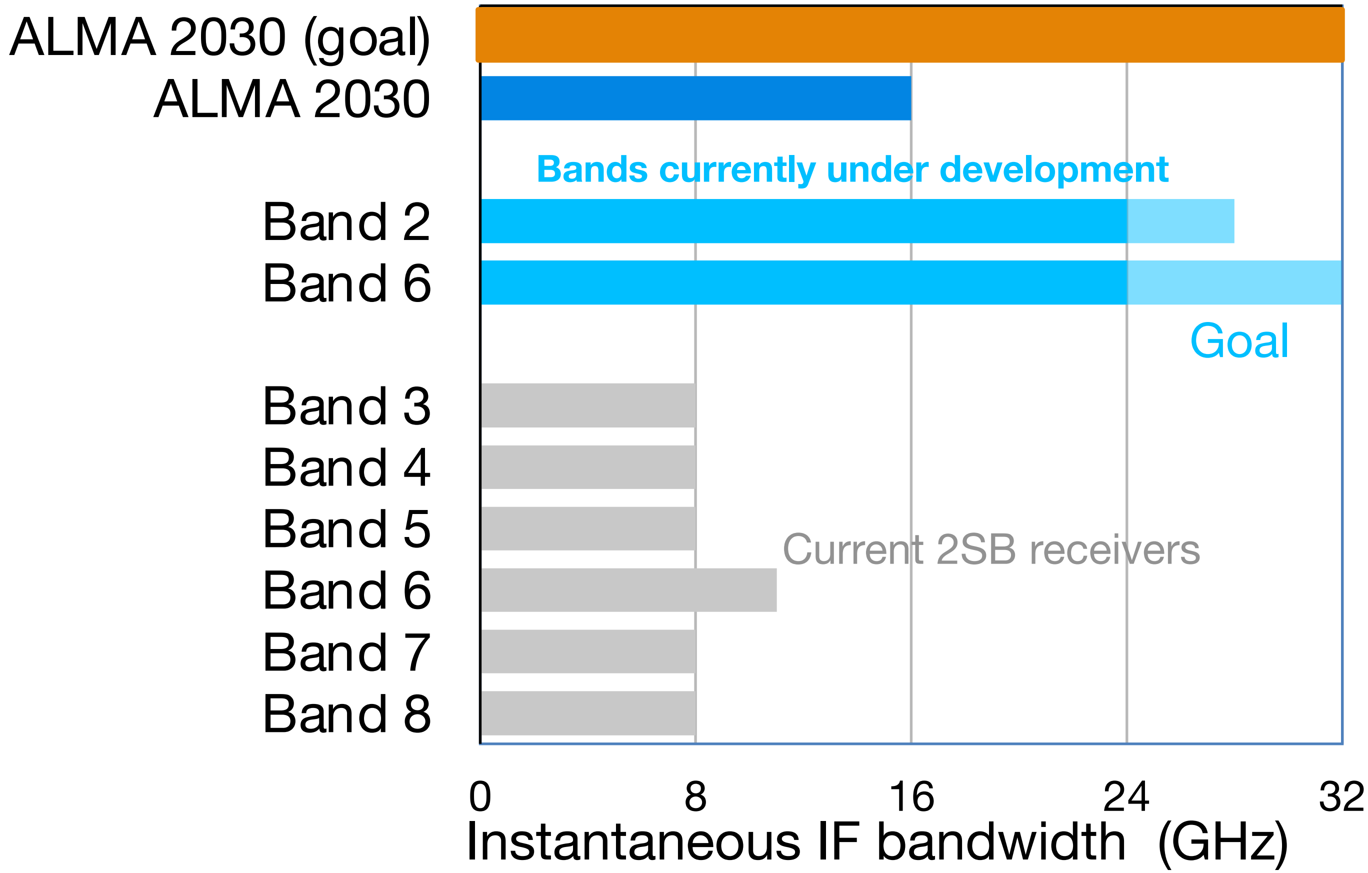
New Fiber

Operations Support Facility at 3,000m

CONTROL, TelCal, Scheduling, OT, Archive, Pipeline

Wideband Sensitivity Upgrade: Overview

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



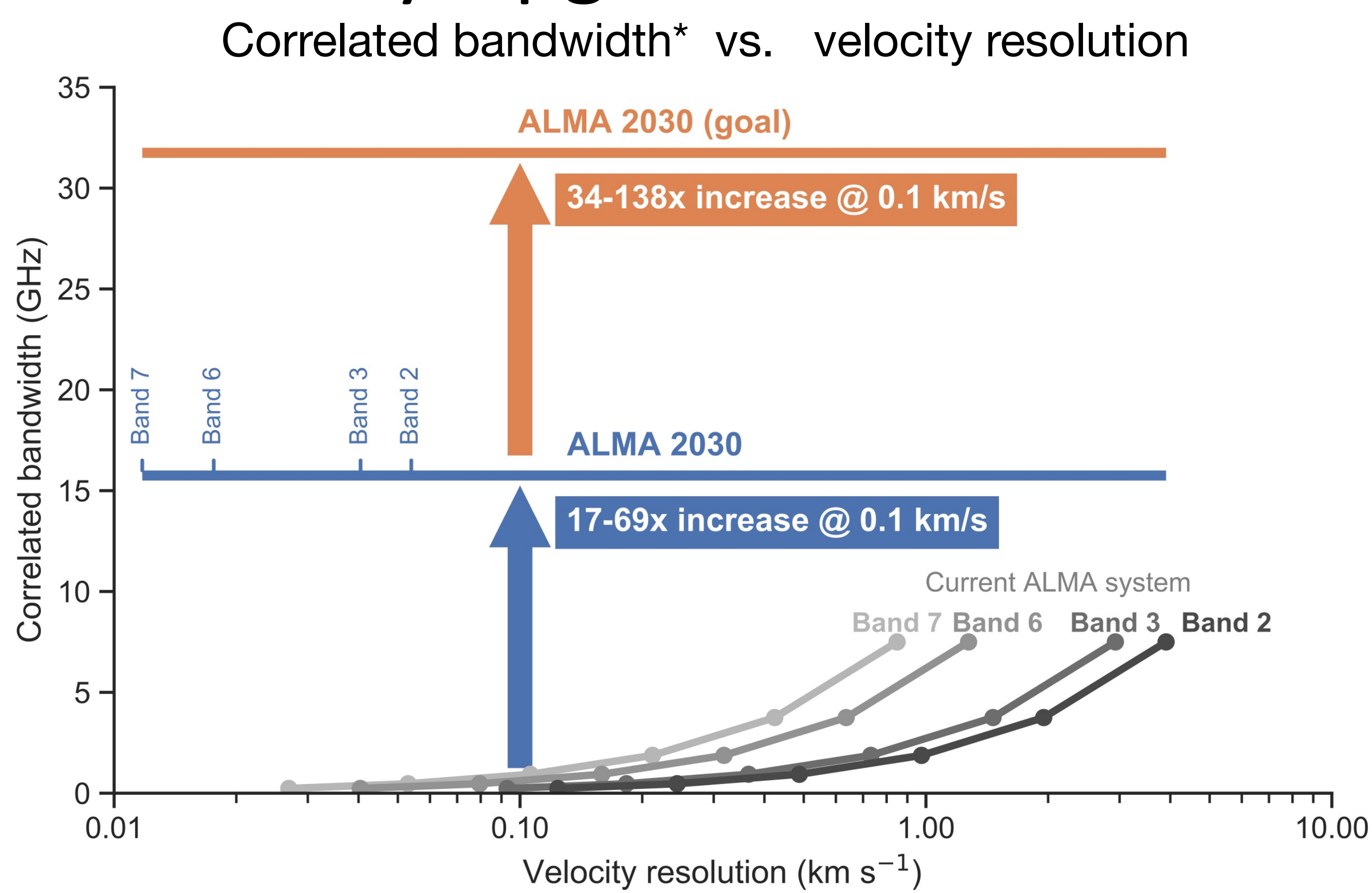
Factor of 2-4 increase in the available IF bandwidth.

Not shown:

- ❖ Band 1 coming Cycle 10, is 1SB
- ❖ Plans to also upgrade Bands 9 & 10 to 2SB and 2x BW

Wideband Sensitivity Upgrade: Overview

- Available receiver 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)

⇒ Straightforward expansion path to 4x BW

Wideband Sensitivity Upgrade: Overview

- Available receiver 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

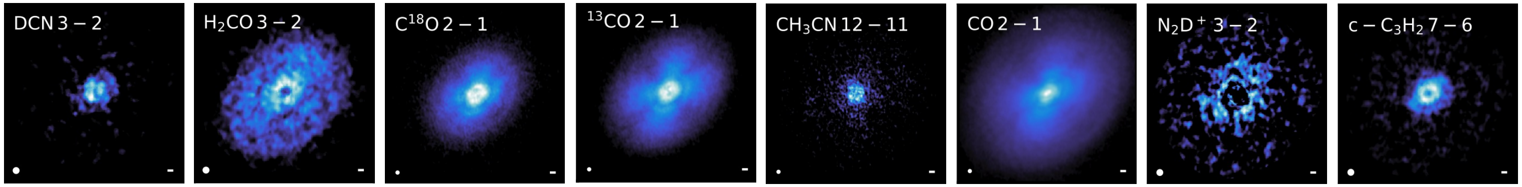
Increase in observing speed results from

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

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

The ALMA WSU 2030 Advantage: High Spectral Resolution at Wide Correlated Bandwidth

Using the MAPS (Molecules at Planetary Scales) Large Program (Oberg et al. 2021) 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!

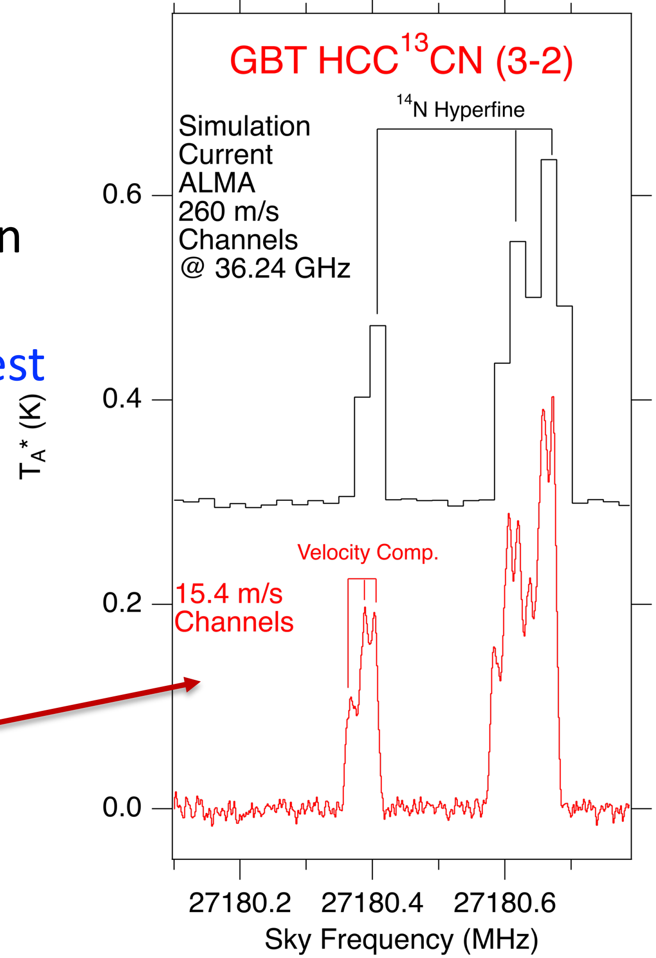
GREEN BANK OBSERVATORY NRAO NSF AUI

ALMA2030 WSU: 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.

ALMA2030 WSU: Improved 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.

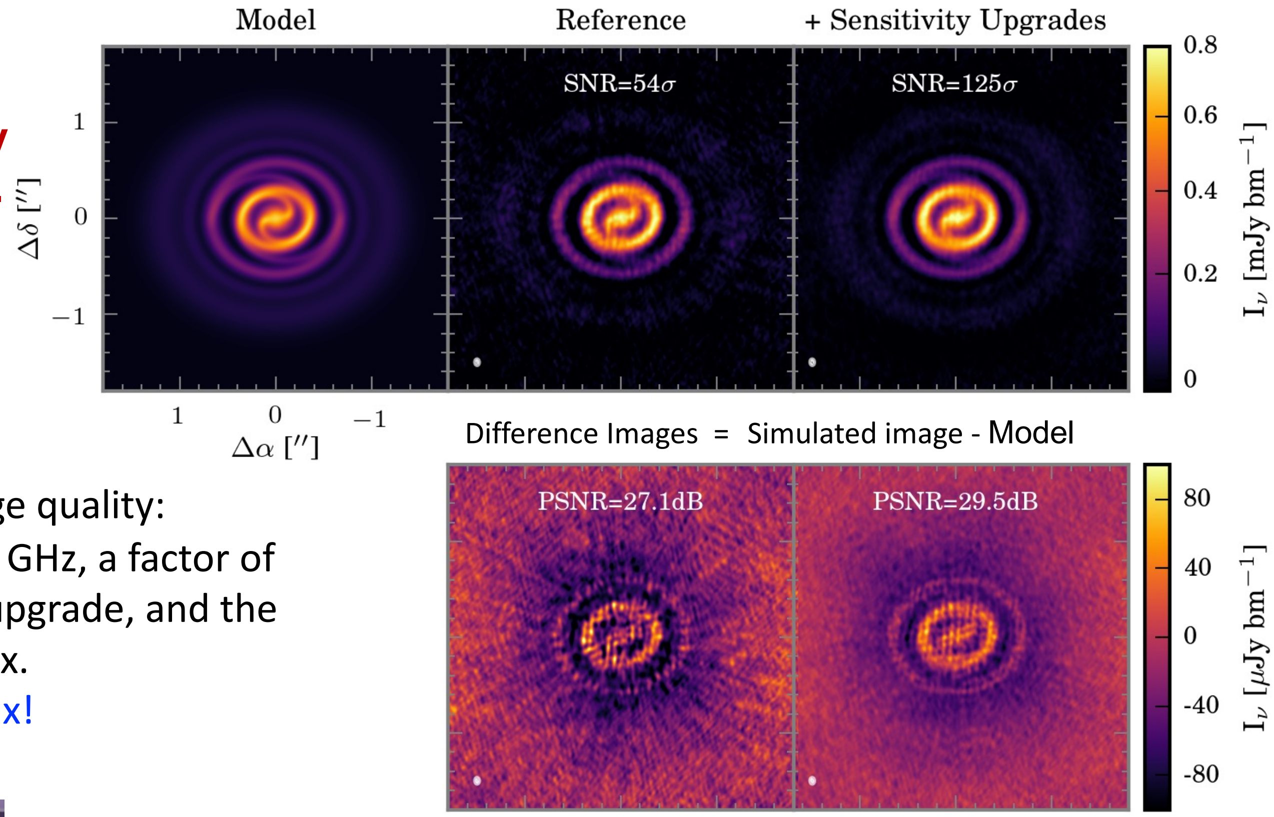
- **Reference** today's image quality:

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.

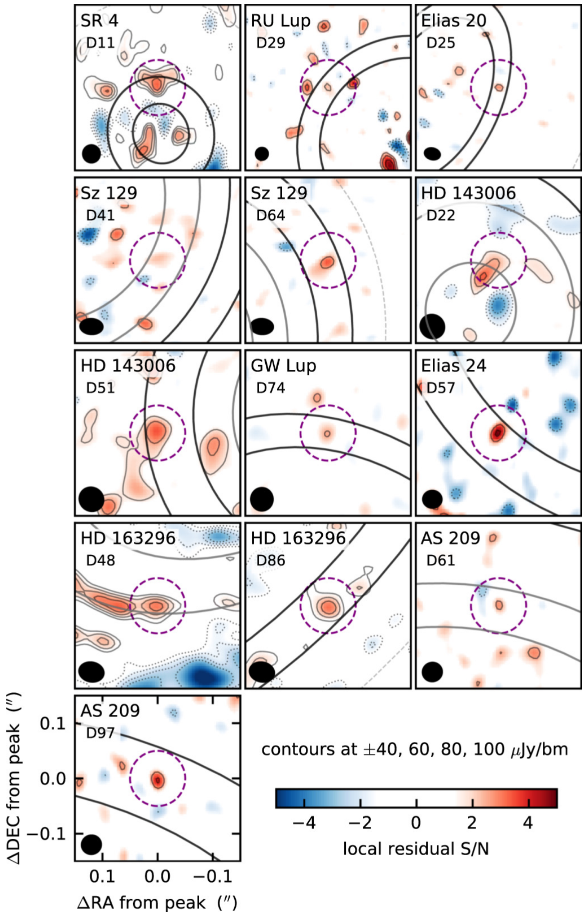
  - Signal-to-noise improved by factor 2.3x!



PSNR is measure of image fidelity

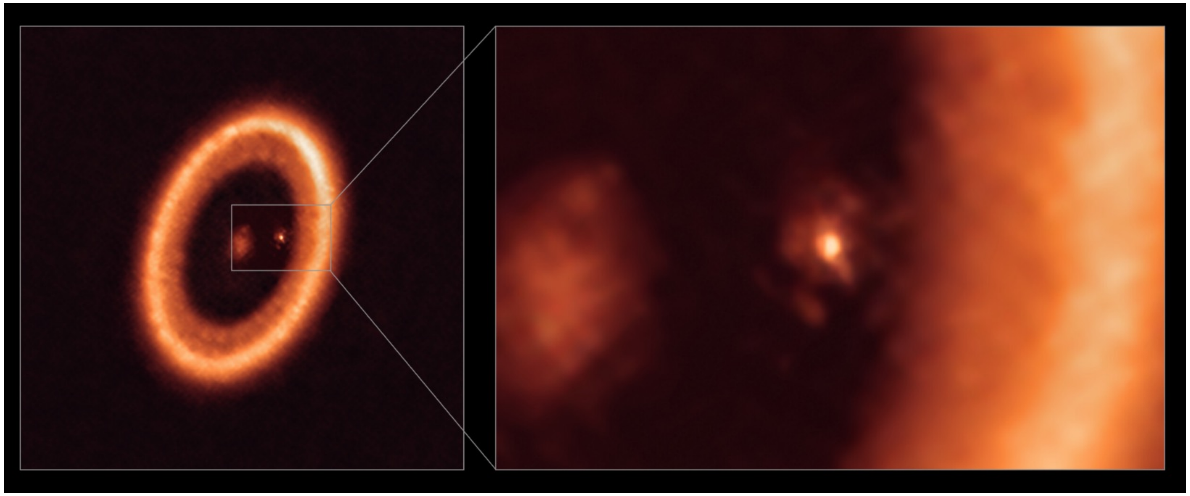
Circumplanetary disks

Search for circumplanetary disks in DSHARP



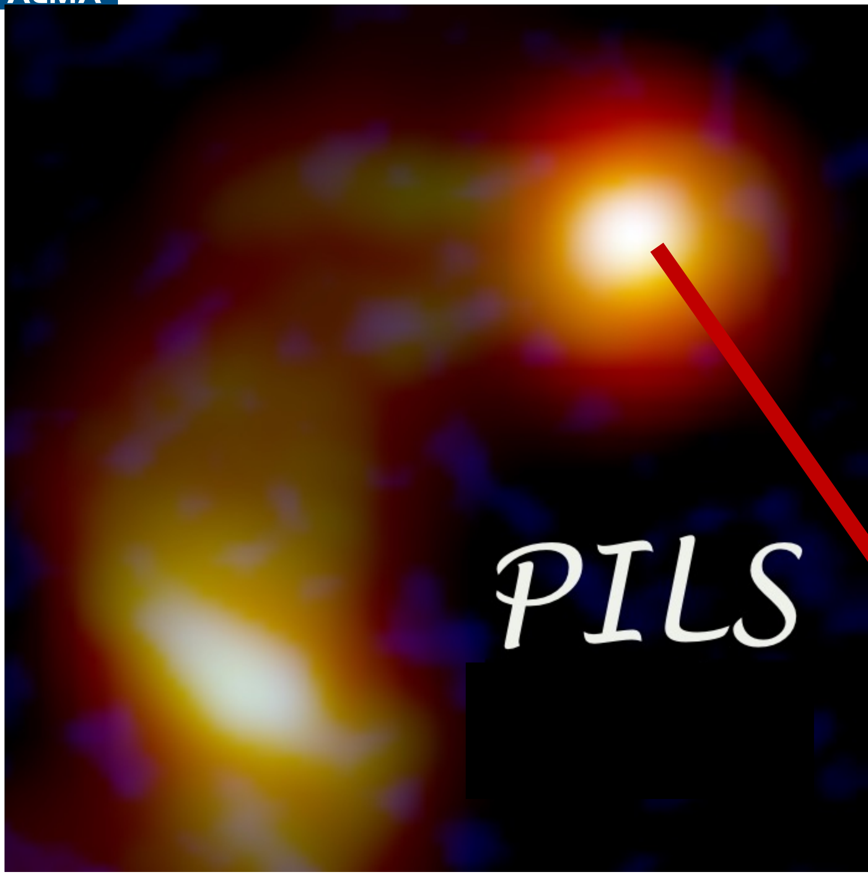
- Detection of circumplanetary disks in PDS 70c
- Search circumplanetary disks in the DSHARP sample
  - Several 3-5$_\sigma$ peaks, but no convincing detections
  - Wideband sensitivity upgrade will improve signal to noise by 2.2x
  - Improved uv-coverage from wider bandwidth imaging synthesis will help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

Circumplanetary disk around PDS 70c

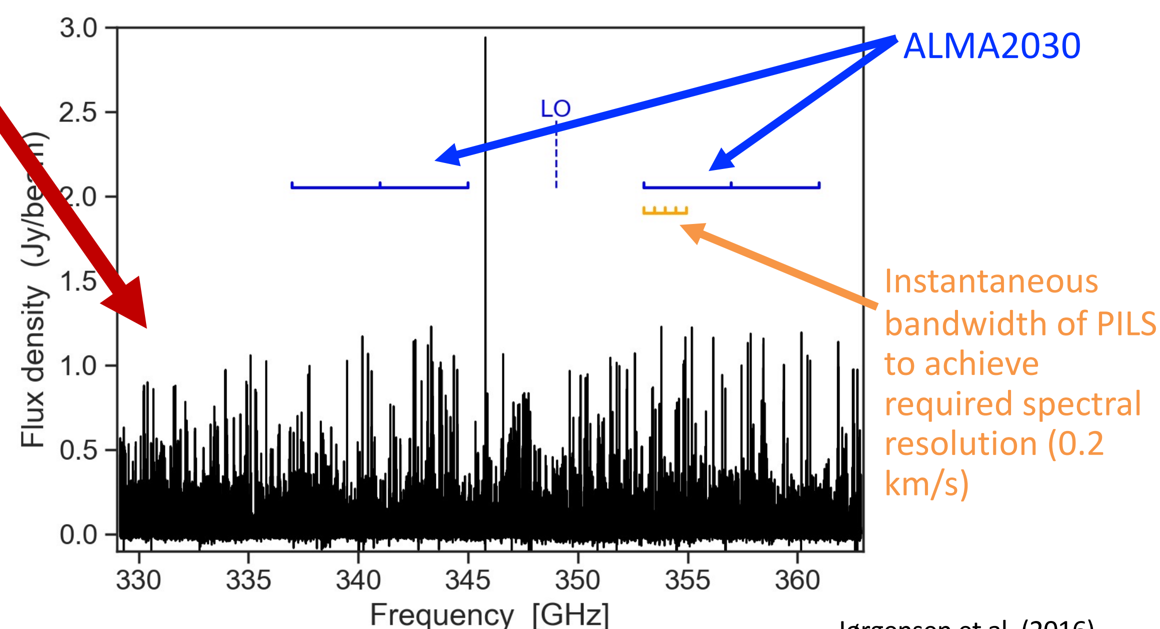


Benisty et al. (2021)
Andrews et al. (2021)

ALMA2030 WSU: Efficient spectral scans



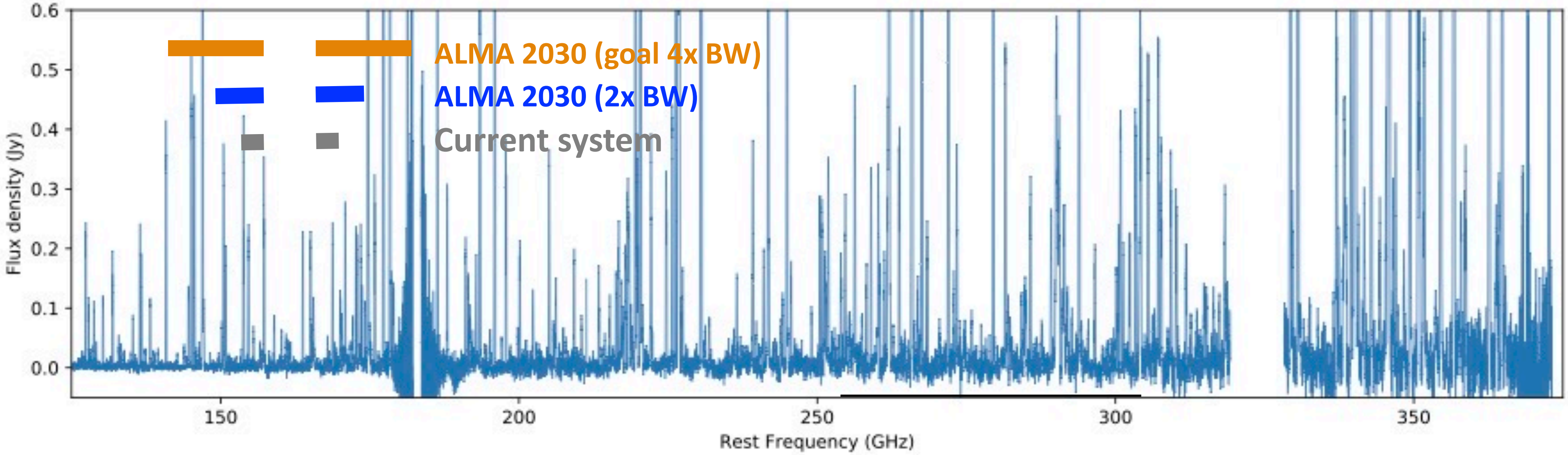
- PILS survey of IRAS 16293 protostar
  - required 18 tunings
- ALMA 2030 will need only 2 tunings!



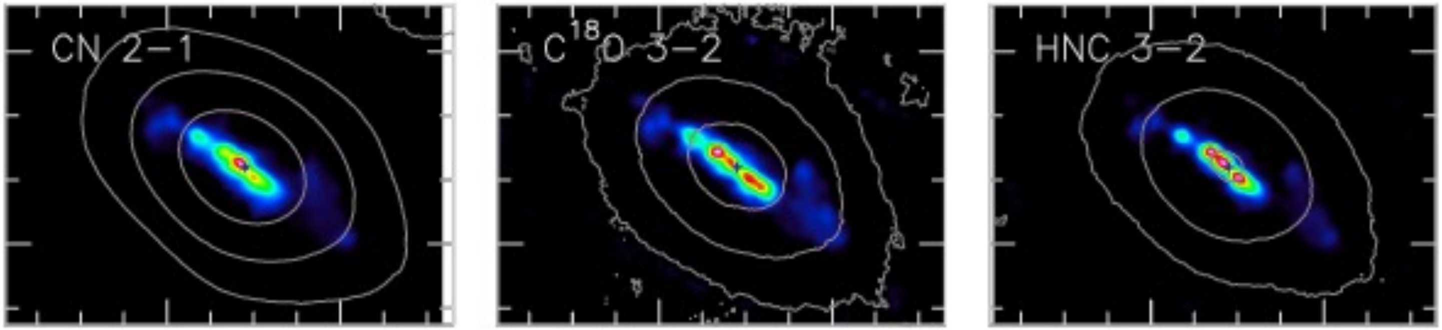
Jørgensen et al. (2016)

ALCHEMI survey of Starburst Galaxy NGC 253

Martín et al. (2021)

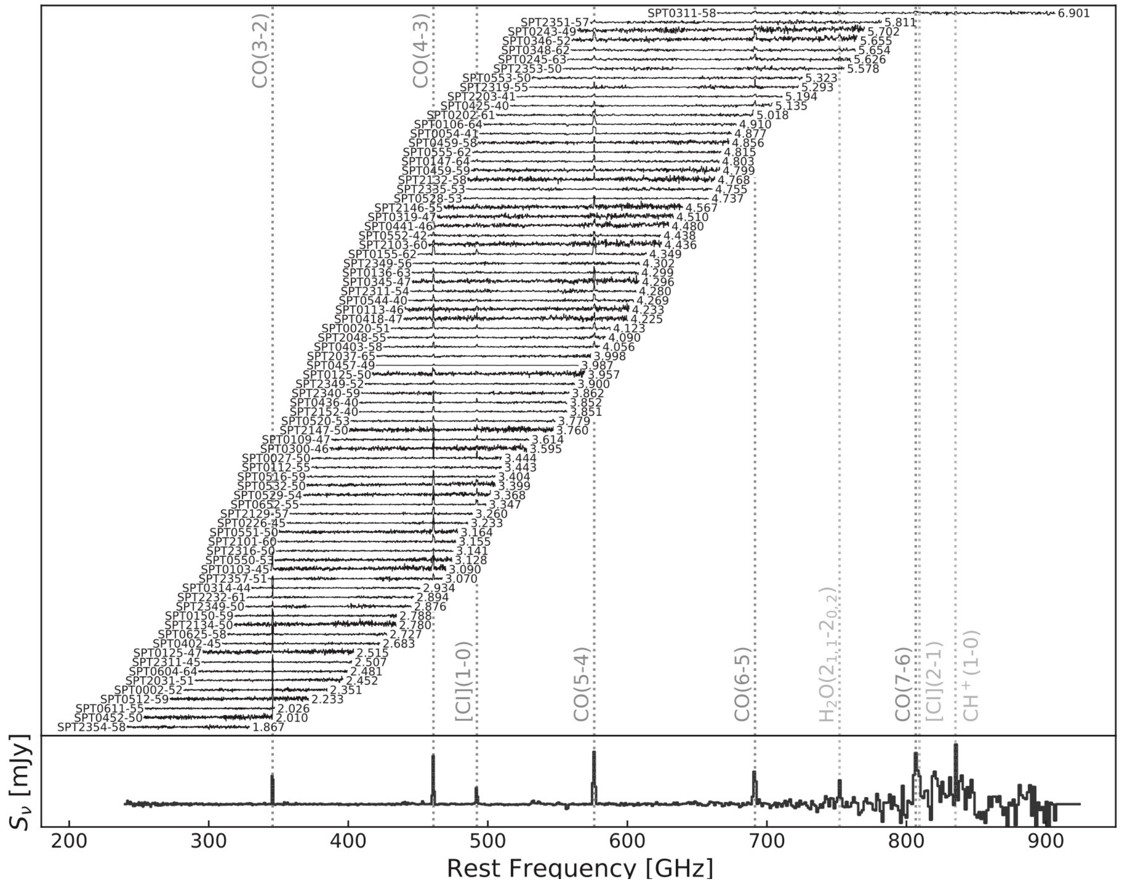


Example of observed chemical differentiation



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

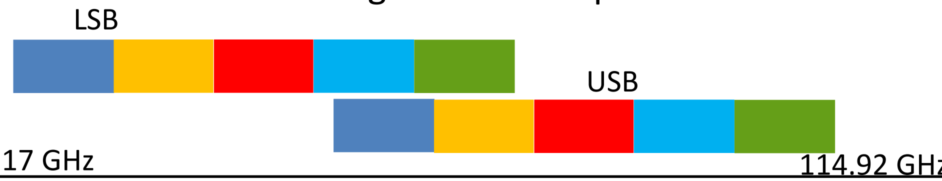
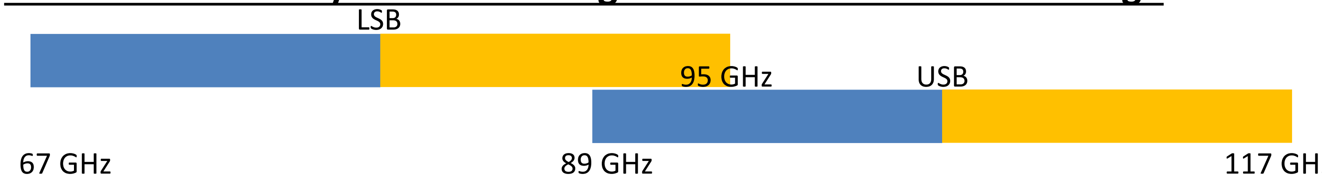
ALMA redshift survey of SPT sources



- ALMA survey of 81 sources discovered by the South Pole Telescope (SPT)
- 5 tunings in Band 3
  CO 3-2, 4-3, 5-4, 6-5, 7-6
  [C I]
  H_2O
  CH^+
- Identify galaxies spanning $1.9 < z < 6.9$

Unbiased redshift survey of SPT sources.
Reuter et al. (2020)

ALMA2030 WSU:
Efficient Redshift surveys

	IF [GHz]	BW [GHz]	Tuning setup
Current ALMA	4-8	3.75	SPT survey was carried out in 5 tunings with overlap in 96-103GHz  LSB USB 84.17 GHz 114.92 GHz
ALMA 2030	4-12	8	**<u>The SPT tuning can be covered with two tunings</u>**  LSB USB 84.17 GHz 114.92 GHz
	4-18	14	**<u>Scan entire Band 2/3 in two tunings for broader redshift coverage</u>**  LSB 95 GHz USB 67 GHz 89 GHz 117 GHz

Summary: ALMA2030 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 = 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

- Significant challenges remain (sequencing of upgrades, data rates, downstream subsystems) but we are optimistic
  - Hope to complete digital upgrades and and several receiver bands by late this decade

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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 <200 m/s at 16 GHz CBW per polarization at f>35 GHz (goal 100 m/s)

Achievable Velocity Widths with AT.CSP in Imaging Correlation Mode

Band				1	2	3	4	5	6	7	8	9	10
Frequency (GHz)				35	75	100	150	185	230	345	460	650	870
AT.CSP	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

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

=> Achieve better spectral resolution with 68x more bandwidth!

- ❖ Finest spectral resolution <20 m/s at 1.6 GHz BW per polarization at f>35 GHz (goal 10 m/s)

Zoom Factor[1]	2	Max CBW per pol	8 GHz	Velocity Width[2] (m/s)	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

CBW = Correlated Bandwidth

More BW & Channels = Efficient Spectral Scans

(Super efficient at high spectral resolution)

Assumed Band Properties			Low Spectral Resolution				High Spectral Resolution (0.1-0.2 km/s)				
			Current with 7.5 GHz CBW		WSU 16 GHz CBW	Time Savings	Current with Indicated CBW			WSU 16 GHz CBW	Time Savings
Band	Rep Freq (GHz)	RF BW (GHz)	Velocity Res (km/s)	#Tunings	#Tunings	Factor	Velocity Res (km/s)	Max CBW GHz	#Tunings	#Tunings	Factor
1	40	15	7.32	2	2	1	0.23	0.234	64	2	34.2
2+3	75	49	3.90	8	4	2.0	0.12	0.234	209	4	52.4
4	150	38	1.95	7	3	2.3	0.12	0.468	81	3	27.1
5	185	48	1.58	8	4	2.0	0.10	0.468	103	4	25.6
6v2	230	64	1.27	9	4	2.1	0.16	0.938	68	4	17.1
7	345	98	0.85	17	7	2.4	0.11	0.938	105	7	14.9
8	460	115	0.64	18	9	2.0	0.16	1.875	62	9	6.9
9	650	118	0.45	16	8	2.0	0.11	1.875	63	8	7.9
10	870	163	0.34	22	11	2.0	0.17	3.75	43	11	4.0

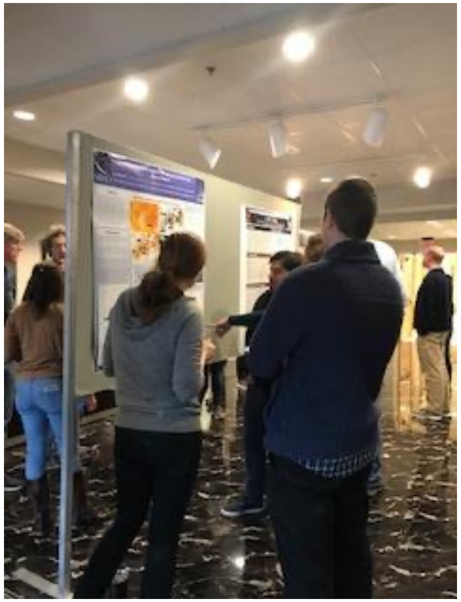
Assumes all bands will be upgraded to at least 4-16 GHz IF 2SB (apart from Band 1)

At 2x BW, with 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

NAASC – Your Source of Support



Timeline for ALMA Cycle 9

- **24 March, 2022** — **Call for Proposals**
- **21 April, 2022 @ 15UT** — **Proposal Deadline!**
- **August 2022** — **Results are sent to PIs**
- **October 2022** — **Start of Cycle 9**
- **September 2023** — **End of Cycle 9**

NAASC – Your Source of Support

ALMA Helpdesk: User support is a priority so questions are usually answered within 48 hours (with around the clock staffing in the week leading up to the proposal deadline) - https://help.almascience.org.

Also can ask for a “NAASC Chat” through the f2f department which is more than a ticket but less than a full virtual f2f visit!

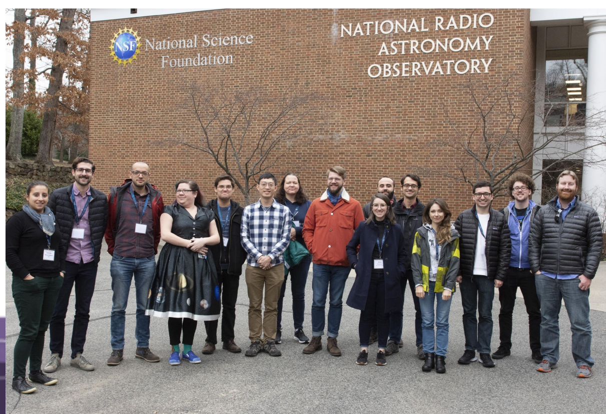
Face-to-face Visitor Support: Upon request NRAO will cover the travel expenses of up to 2 people from 2 teams per week to come to the NAASC to get support for data reduction, proposal preparation, etc… We also have long term visitor support as well - https://science.nrao.edu/facilities/alma/visitors-shortterm

NAASC Financial Support for Workshop/Conferences: The NAASC invites scientists to apply for funding in support of upcoming conferences and workshops. - https://science.nrao.edu/facilities/alma/community1/NAASC-Conference-and-Workshop-Support

NAASC – Your Source of Support

Page Charges: Upon request NRAO covers page charges for authors at US institutions when reporting results from ALMA/VLA/VLBA - https://library.nrao.edu/pubsup.shtml

Student Observing Support: Successful ALMA proposals and archival researchers will be invited to apply for up to $35k to support undergraduate or graduate student involvement - https://science.nrao.edu/opportunities/student-programs/sos



ALMA Ambassadors: You can become an ALMA Ambassador! For program eligibility visit - https://science.nrao.edu/facilities/alma/ambassadors-program

ALMA Ambassadors Proposal Preparation Events

https://science.nrao.edu/facilities/alma/community/

Ambassador	Location	Date
Wren Suess	Stanford University	28 March
Nathan Roth	University of Maryland	29 March
Hansung Gim	Montana State University	29 March
Cheng-Han Hsieh	Yale University	30 March
Tarraneh Eftekhari	Northwestern University	1 April
Hansung Gim	University of Alabama	2 April
Allison Towner	University of Florida	5, 7, 8 April
Fengwu Sun	University of Arizona	8 April

The ALMA Ambassadors will also host several webinars for people unable to attend one of the workshops. The talks, dates, and registration links for the webinars are listed below.

Title	Date
ALMA Basics and Cycle 9 Capabilities	30 March @ 4pm ET
Cycle 9 Proposal Preparation & the Proposal Review Process	31 March @ Noon ET
ALMA Basics and Cycle 9 Capabilities	05 April @ 2pm ET
Cycle 9 Proposal Preparation & the Proposal Review Process	05 April @ 4pm ET

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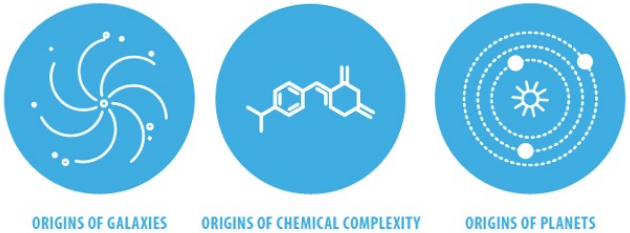

ALMA Development Program: The ALMA Development program will open a new call for studies in **May 2022** - https://science.nrao.edu/facilities/alma/facilities/alma/science_sustainability/NADevelopmentProgram

Contact the NAASC Early and Often! Especially if you are planning for an ALMA Large Program. The better informed we are, the better support you will be provided when your proposal is accepted.

If there is a service or support that you need but didn't see it listed here, contact us – submit an ALMA Helpdesk ticket!

Finally…

THERE IS NO SUCH THING AS A "LATE" PROPOSAL

"My internet is down…"
"My proposal won't validate…"
"My power went out…"
"I thought the time was 16UT not 15UT…"
"My dog ate my proposal…"

There is no excuse for a late proposal UNLESS the Observatory grants an extension.

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