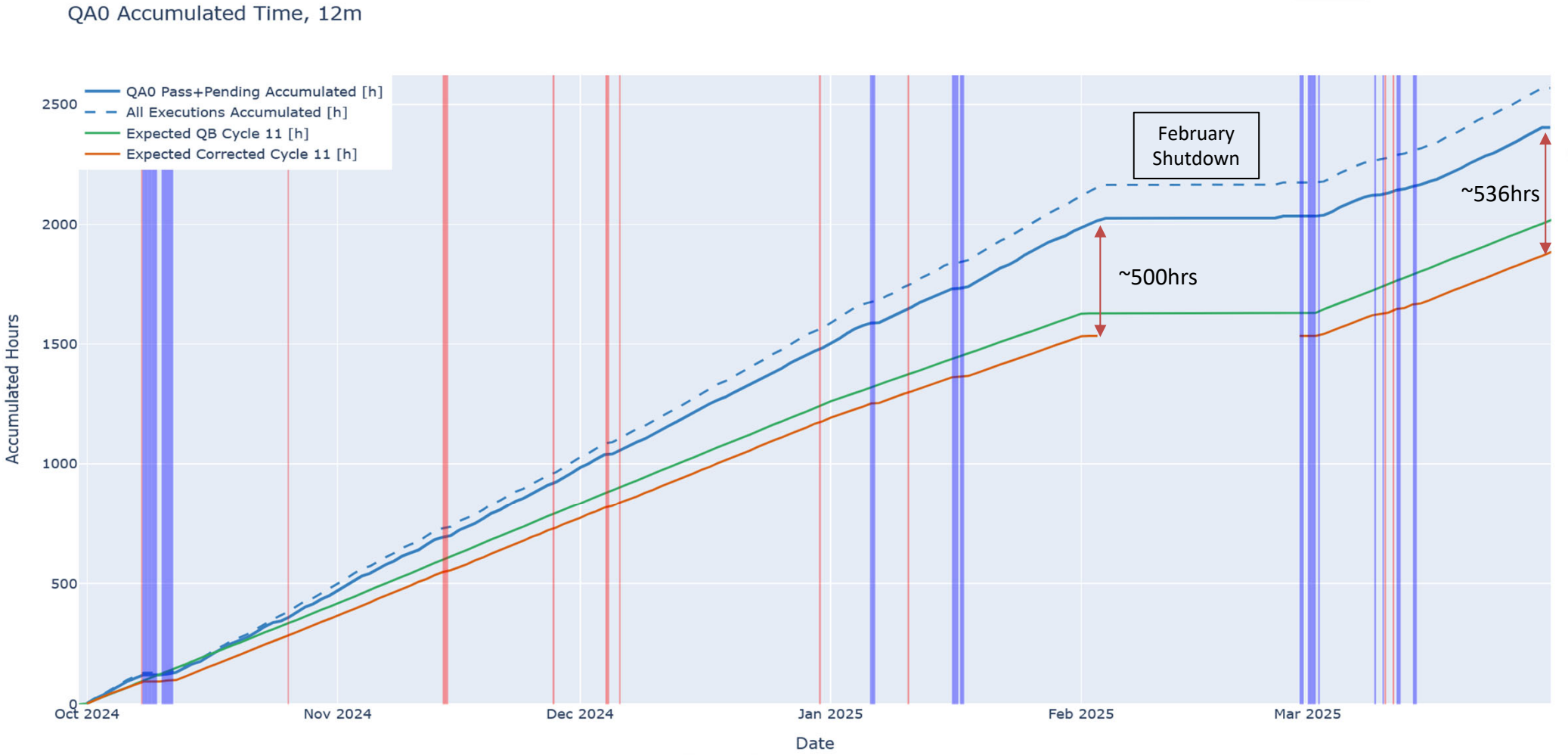
The ALMA Wide-band Sensitivity Upgrade

Sean Dougherty, ALMA Director

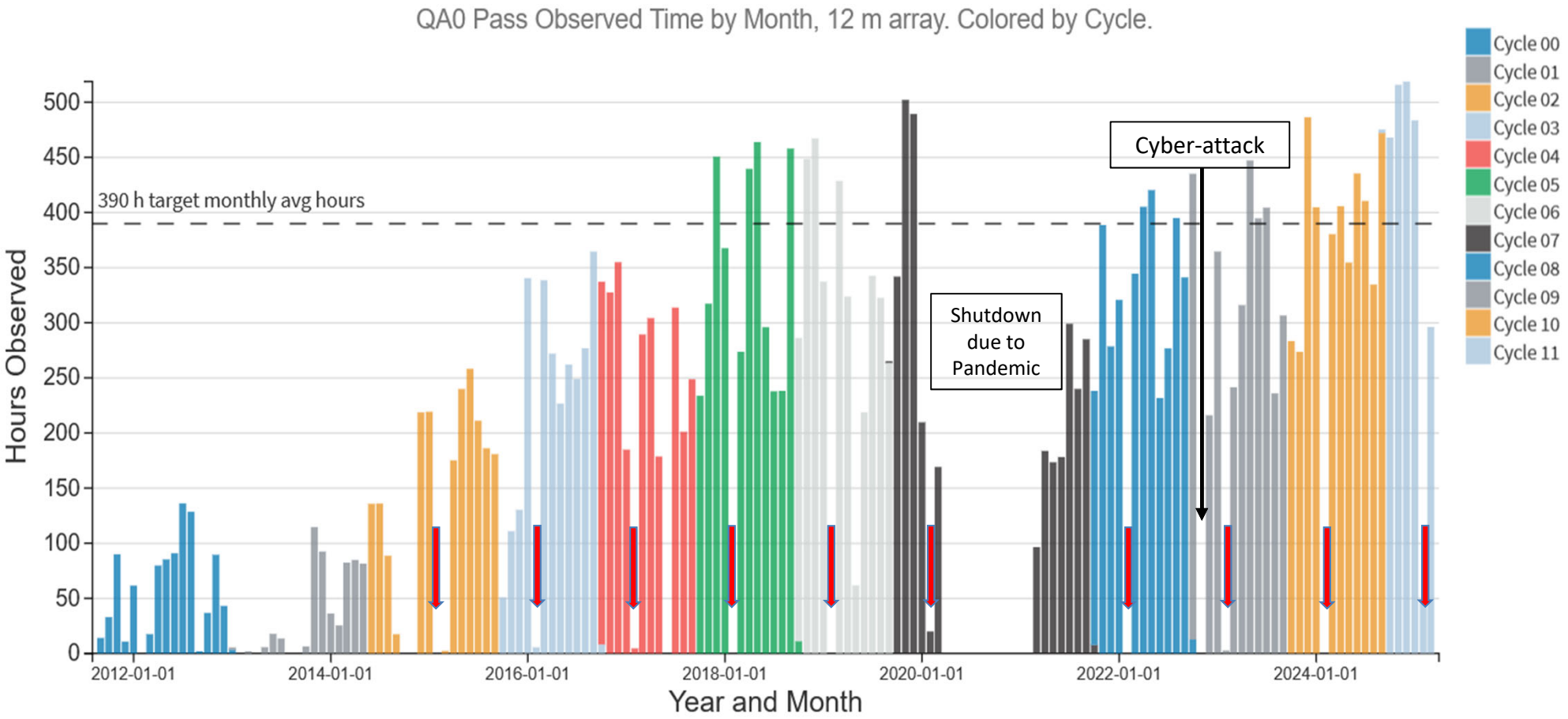
FIR 2025 Leiden, April 2025

Cycle 11 – the best ever ALMA cycle start



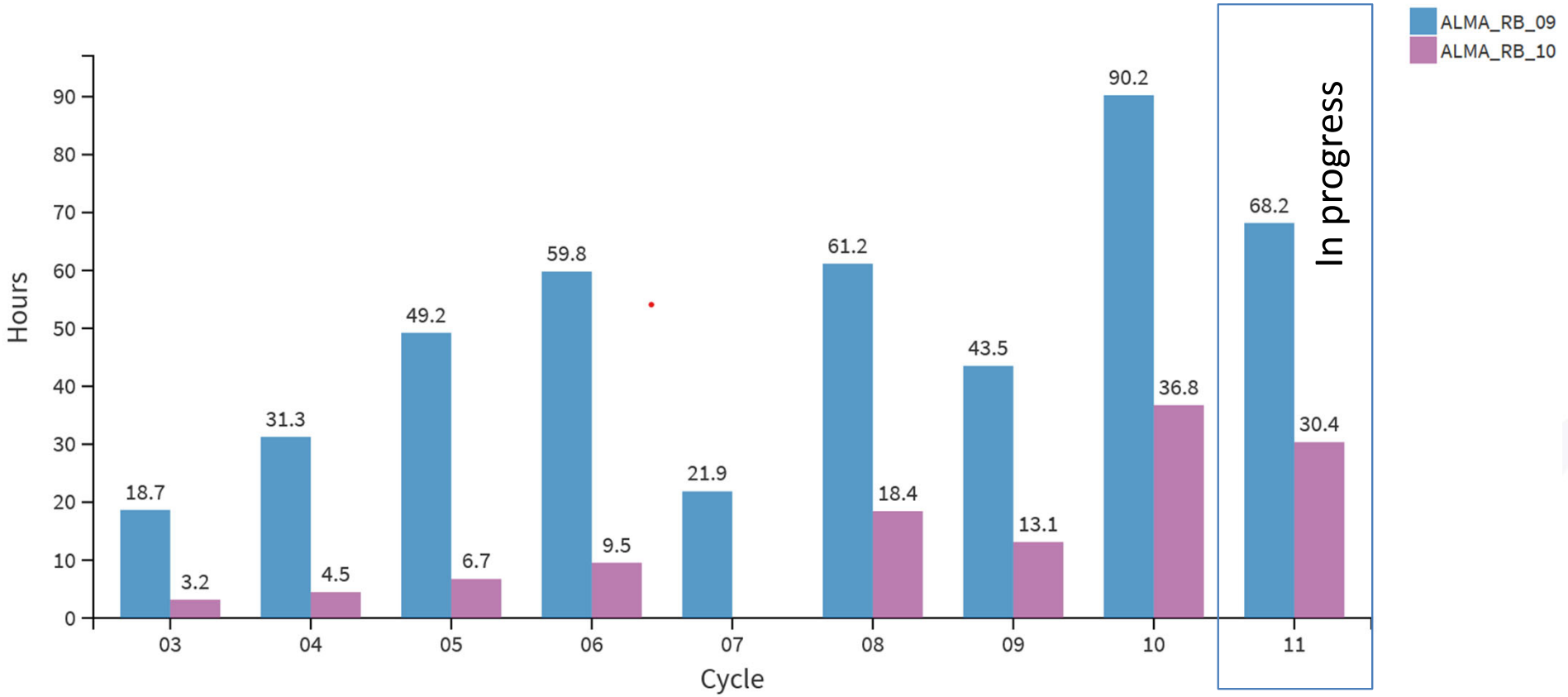
- ~536 hrs ahead of corrected planned cycle 11 schedule today
- Observing rate (slope of blue line) is consistent with those attained in previous 2 cycles when not impeded by weather or exclusive technical time (array handed to engineering and/or computing).
- Feb maintenance started on Feb 3 – severe weather started the same day (perfect timing for shutdown!)

ALMA successful observation evolution



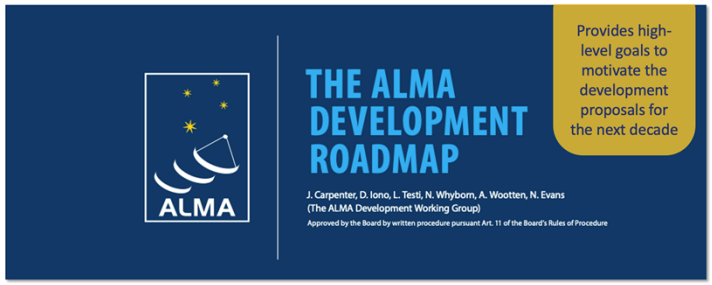
- Cycle 10 - record number of hours on all three arrays (12m – 4247h; 7m – 3769h; TP – 2708h)
- Cycle 11 - November and December 2024 – both the highest monthly hours ever (516hrs & 527hrs).
- Total hours observed by start of Feb maintenance: 2035hrs (47% of target in 4/11 months).
- In all 4 months, we are well ahead of the average monthly hours required for the 4300hr target

Cycle 11 – high-frequency observing



- Taking best advantage of excellent observing conditions for high-frequency observations
  - **When the right conditions prevail, ALMA observes at high frequency**.
- For Band 10, already approaching similar number of hours to last cycle.

Looking to the future – developing a science-driven vision



- Origin of Galaxies
- Origin of Complex Molecules
- Origin of Planets

Four ASAC Development priorities

- Improvements to archive
- Larger bandwidths and better receiver sensitivity
- Longer baselines
- Increased wide-field mapping

Development Working Group

ALMA Board charged the Director to form a Development WG

- Propose a science-driven vision for 5-15 years of ALMA development
- Prioritize the resulting plan
- **Within the anticipated ALMA Development budget**

2013

2015

2017

Community input

Working Group receives input from community conferences and development studies

Recommendations

ASAC provide the report to ALMA Board March 2015 with 4 development priorities

Board approval of ALMA2030

ALMA Board approves the ALMA Development Roadmap November 2017

ASAC ALMA 2030 report

ALMA Science Advisory Committee (ASAC) examine potential technical development for ALMA out to 2030

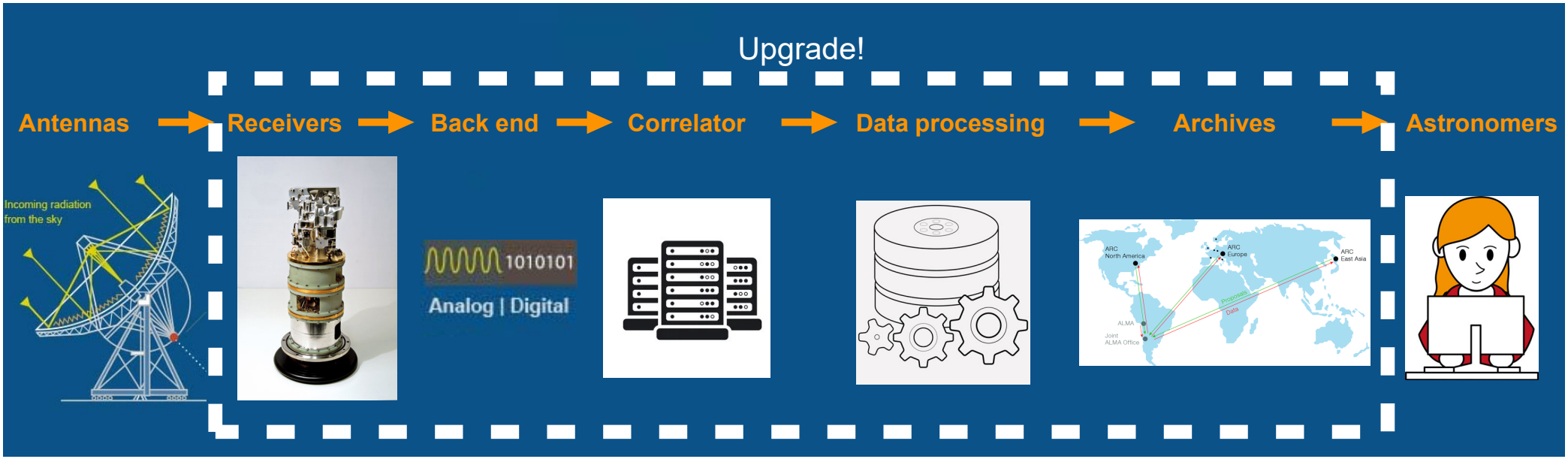
Carpenter et al. (2018) arXiv 1902.02856)

ALMA2030 Development Priorities

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

Wideband Sensitivity Upgrade (WSU): Highest-Priority of the ALMA2030 Roadmap

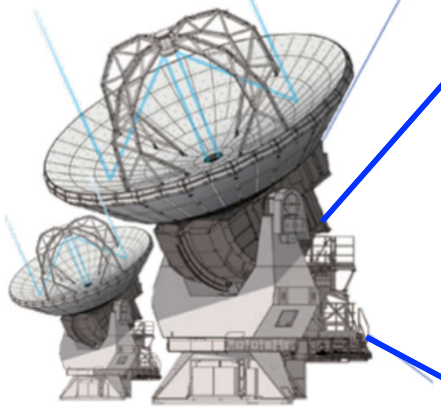
- Upgrade of the bandwidth and throughput of the ALMA system by at least a factor of 2 (**goal: 4 times**)
  - upgraded receivers with increased bandwidth and improved receiver temperatures
  - more powerful correlator
  - increased data reduction capacity



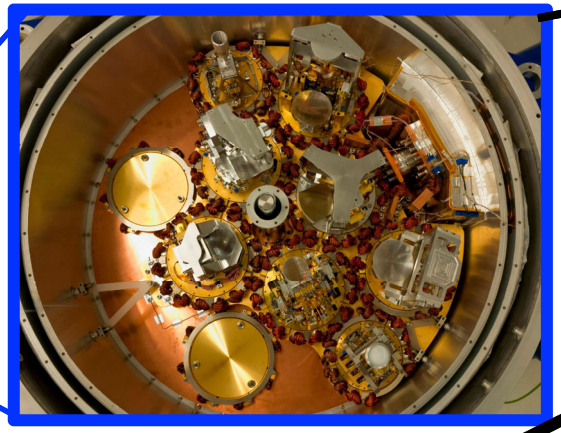
The Wideband Sensitivity Upgrade

New or upgraded components are in blue

Antenna



Front End Receivers



Back End

IF Switches & Anti-aliasing filters

Digitizers & Digital Signal Processing

Data Transmission System

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

CONTROL, TelCal, Scheduling, OT, Archive, Pipeline

Existing Antenna to AOS Fibers

Array Operations Site (AOS) at 5000m

New fiber

Operations Support Facility (OSF) at 3000m

WSU Status

First wideband receivers

- Band 2 (67-116 GHz) in production [ESO, NAOJ]
- Band 6v2 (209-281 GHz) in development [NRAO]
- Band 8v2 (385-500 GHz) in development [NAOJ]
- Other receivers under study

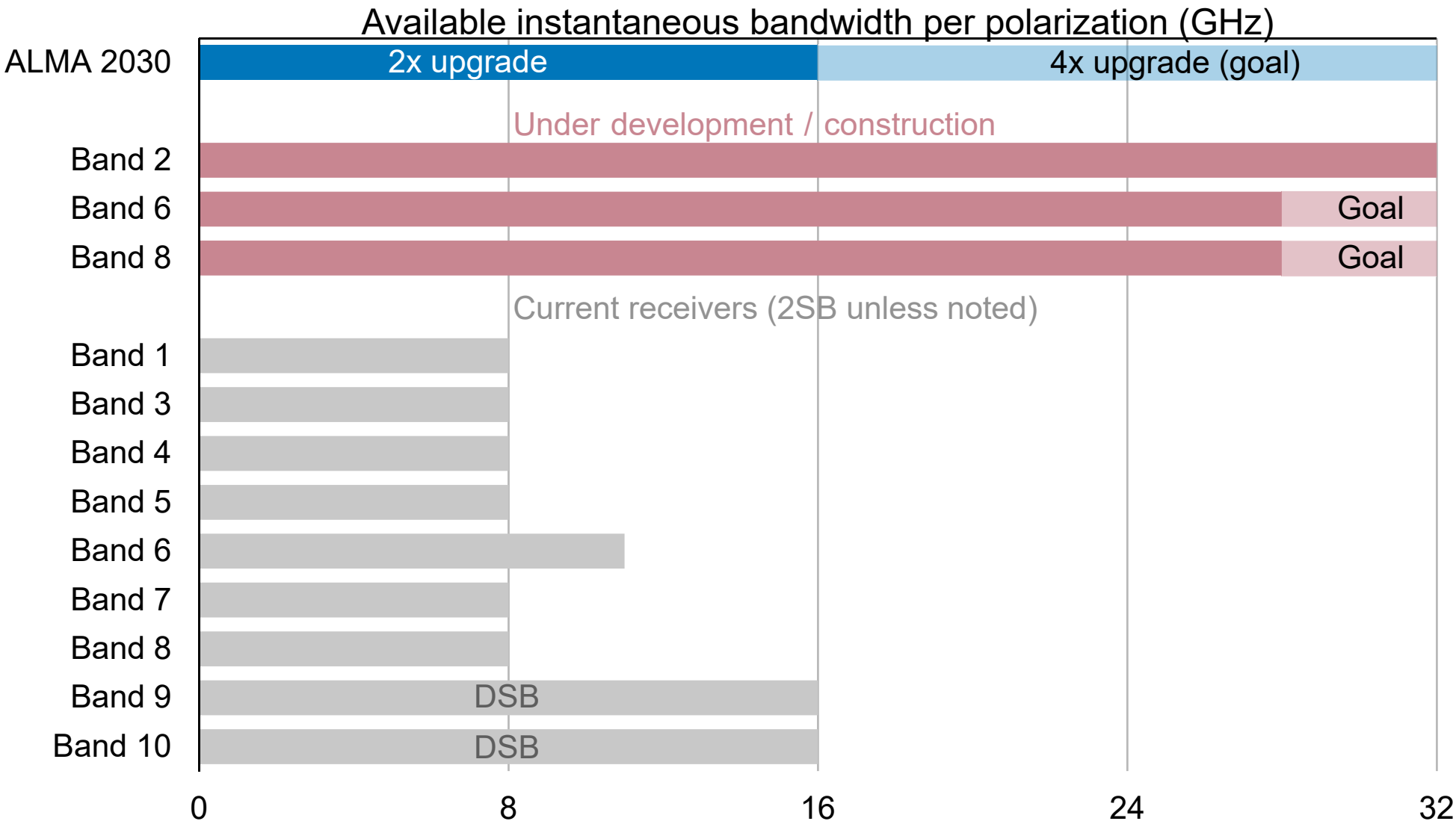
Digital Signal Chain

- Digitizer project for 4x bandwidth underway [ESO, Bordeaux]
- Data Transmission System (DTS) prototype development underway [NAOJ, NRAO]
- AOS to OSF fiber – in approval process [ESO]

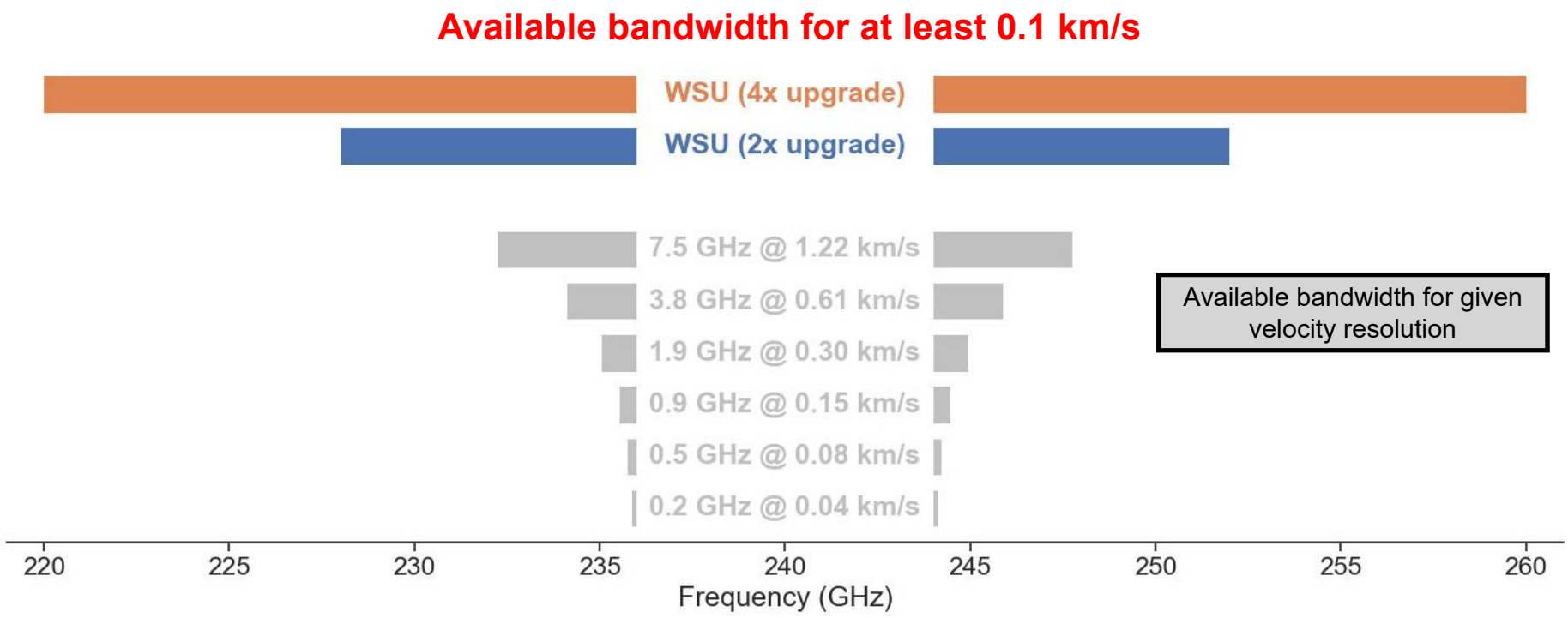
Advanced Technology ALMA Correlator (ATAC) [NRAO, NRC]

- Ingest of 4x bandwidth; currently costed for 2x bandwidth correlation; readily scaled to 4x bandwidth
- Flexible subarrays to process 12-m and 7-m array observations concurrently
- Up to 1.2 million spectral channels available (as well as flexible on-line channel averaging)
- Subarrays; array phasing; VLBI; spectral flexibility
- 6-bit correlation for **13.4% improvement in sensitivity –** equivalent to 7 antennas
- **Not necessary to trade bandwidth for spectral resolution** - full-resolution across the whole band

WSU: Available Bandwidth – Receiver developments



WSU: Correlated Bandwidth and Spectral resolution – correlator development



Example of correlated bandwidth in Band 6

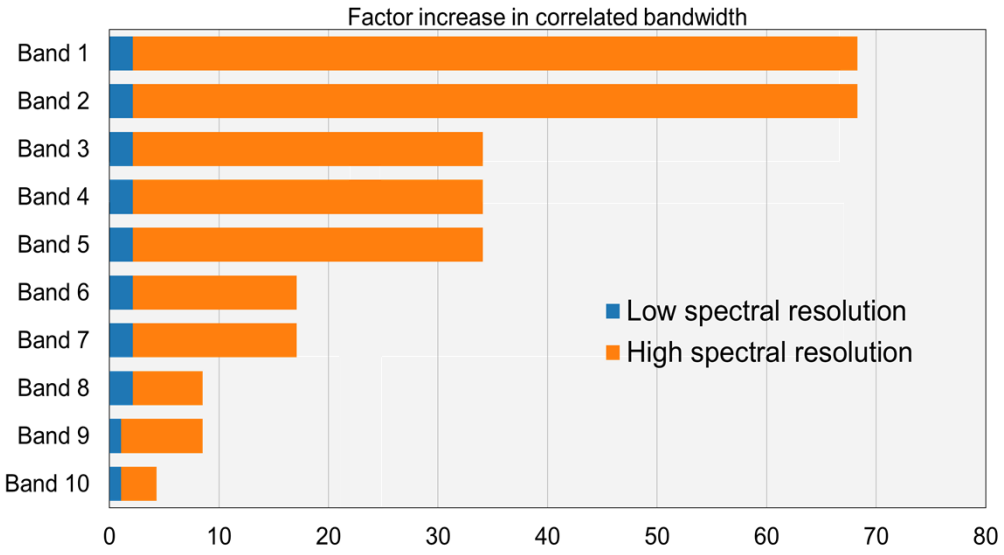
WSU: Observing Speed at band 6

Observing mode	Increase in speed over current system*
Continuum	4.8x (with goal of 9.6x)
Spectral line	2.2-4.7x

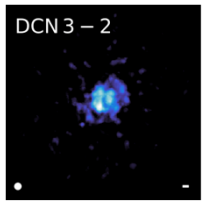
* To reach same sensitivity as current system with single tuning

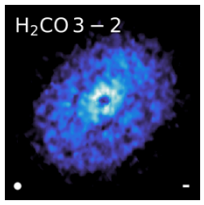
Increase in observing speed results from
- improved receiver temperatures
- improved digital efficiency
- wider bandwidth (continuum)

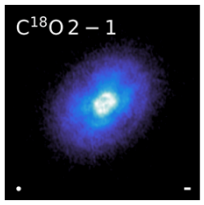
Spectral scans will see further speed increases due to larger correlated bandwidth.

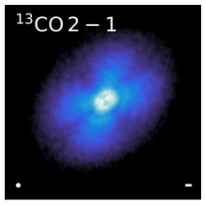


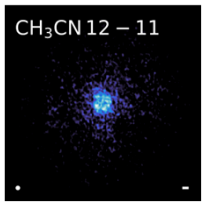
Example of WSU Advantage – protoplanetary disks (MAPS)

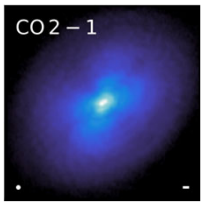


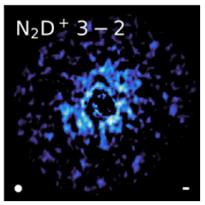


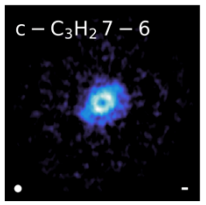








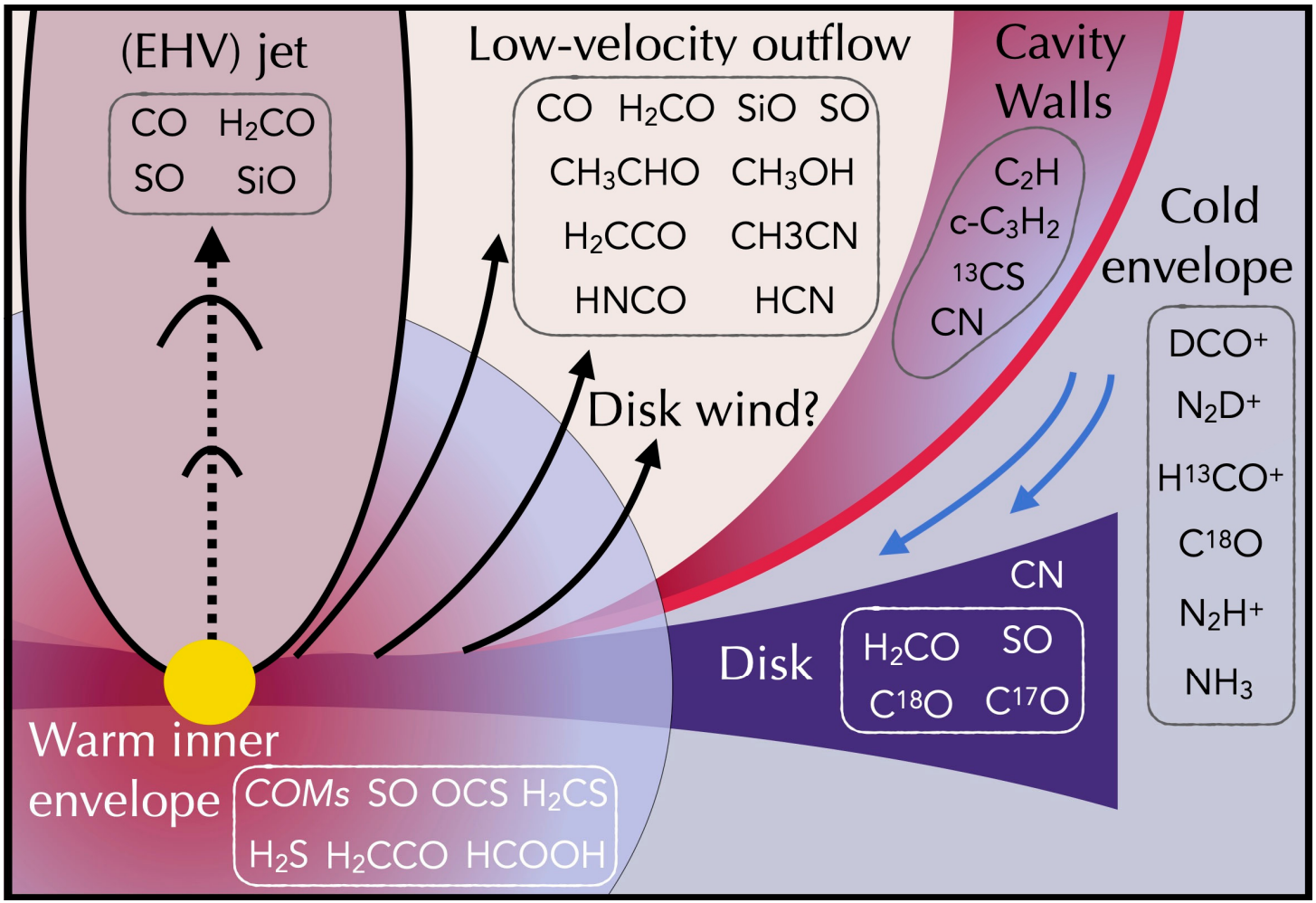




								DCO^+ J=3-2	NO J=5/2-3/2
SO_2 10(5,5)-11(4,8)	H_2S 2(2,0)-2(1,1)	SiO J=5-4	c-C_3H_2 6(0,6)-5(1,5)	HC_3N J=24-23	H_2CO 3(2,1)-2(2,0)	$C^{15}N$ N=2-1	SO 3Σ 6(5)-5(4)	SO_2 11(1,11)-10(0,10)	$C^{17}O$ J=2-1
t-HCOOH 10(4,6)-9(4,5)	H_2CO 3(1,2)-2(1,1)	H_2CS 7(0,7)-6(0,6)	H_2CS 7(1,6)-6(1,5)	CN N=2-1	c-C_3H_2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

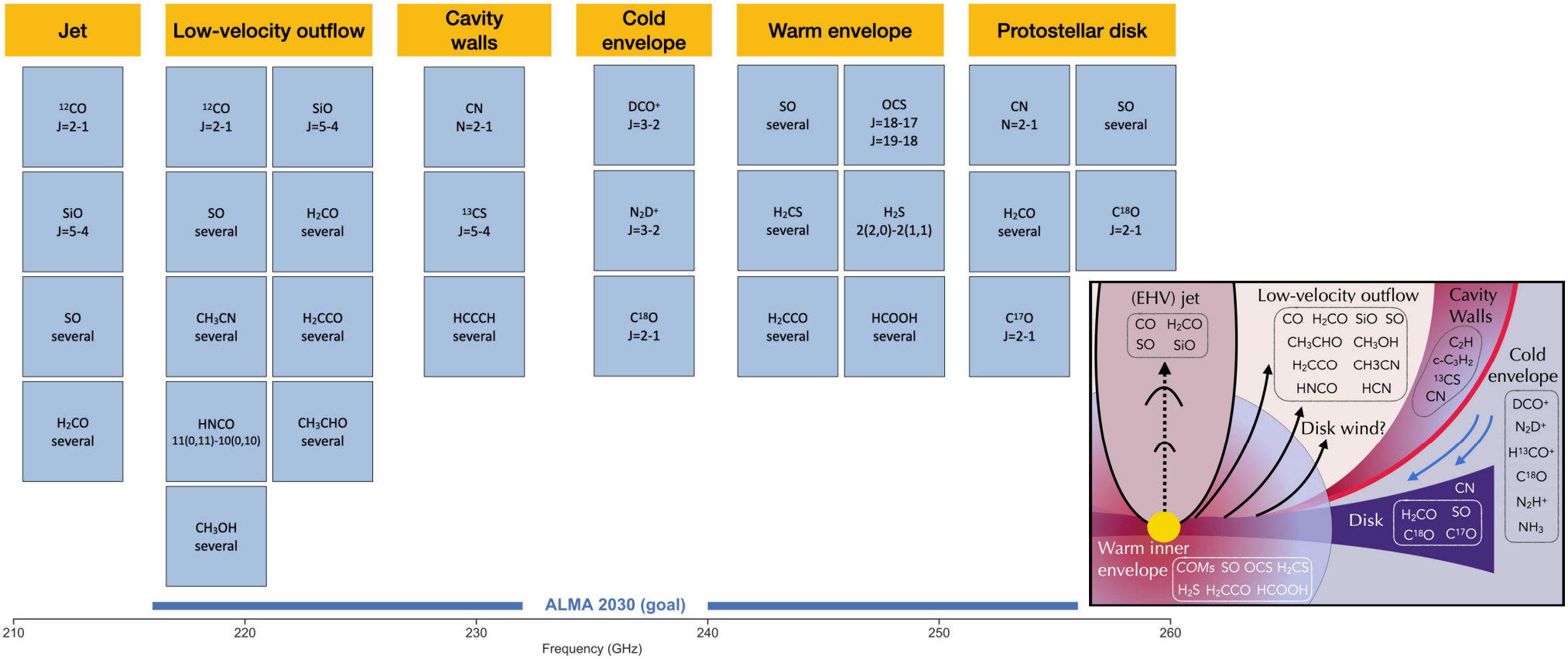
… and up to 40 additional spectral windows!

Molecular probes of star formation



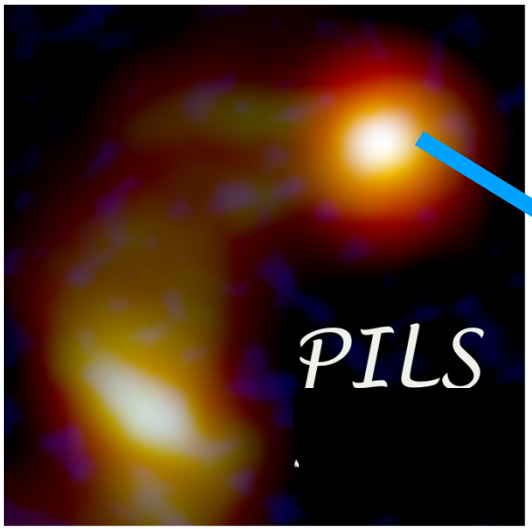
Tychoniec et al. (2021)

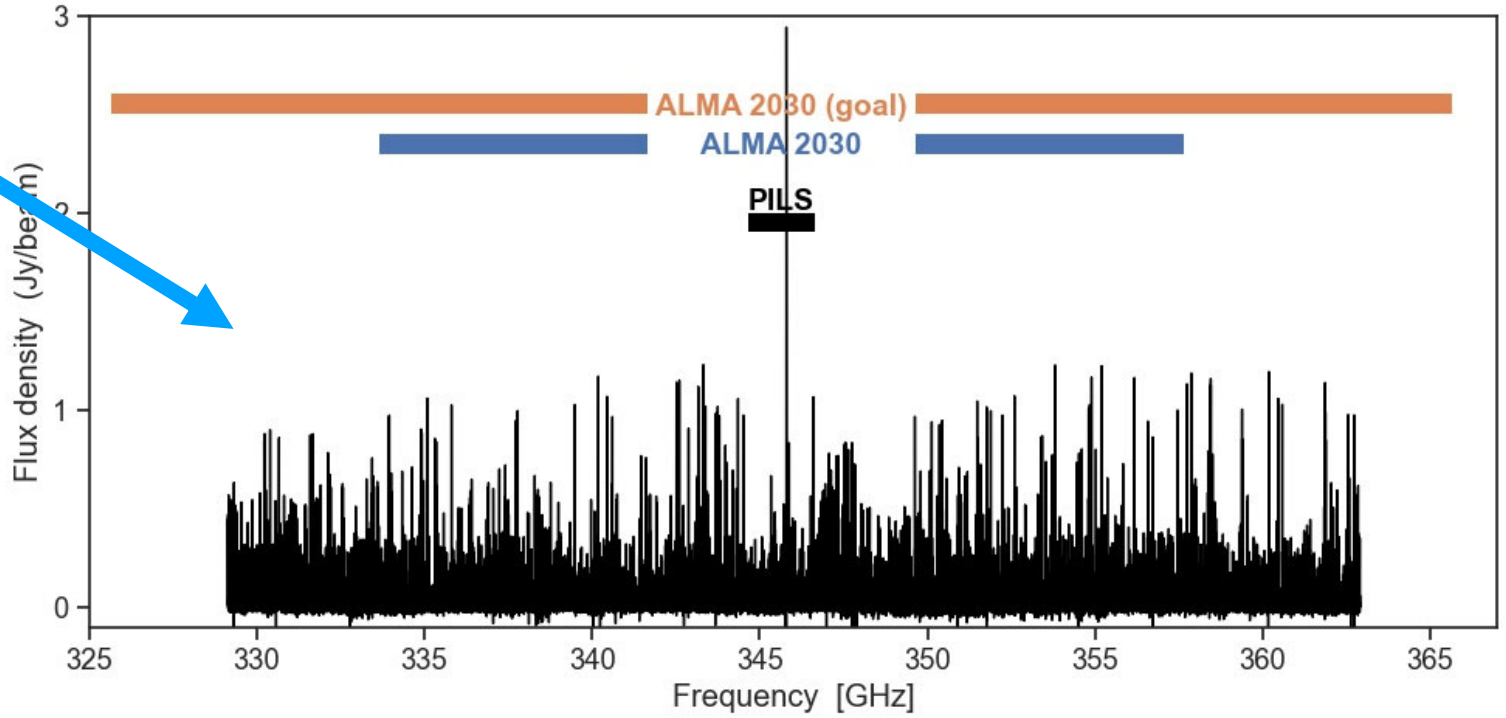
WSU and molecular probes of star formation



Tychoniec et al. (2021)

WSU and efficient spectral scans of protostars e.g. PILS





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

Jørgensen et al. (2016)

- ALMA is observing at it highest effectivity ever – 4300 hrs per year; will continue through Cycle 13.
- Looking to the future –wideband sensitivity upgrade
  - Improved receiver sensitivity
  - Increased digital efficiency – 6 –bit correlation – 13.4% more sensitivity (equivalent to 6 antennas)
  - Observed bandwidth : factor of 2-4 increase
  - Correlated bandwidth : more than an order of magnitude increase **with ~ 0.1 km / s resolution**
    - **Never need to trade correlated bandwidth for spectral resolution**
  - Observing speed : 2.2-4.7x faster for spectral lines, 4.8x faster for continuum (Band 6 upgrade)
- 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
  - Redshift surveys will be significantly faster (2-3x)
  - Lots of synergy with other leading facilities.
  - See https://arxiv.org/abs/2211.00195
- First wideband receivers for ALMA
  - Band 2 : installation underway
  - Band 6 : prototype under development
- Digital signal chain
  - Correlator (ATAC), Data Transmission System (DTS), and Digitizers under development;
  - new AOS-OSF fibre optic system – to be proposed to the Board next week.
- **Keeps ALMA at the forefront of astrophysics** – synergies with the other new leading facilities

To the amazing people who make ALMA such a success

Thank you all!