Stellar Studies with ALMA's Wideband Sensitivity Upgrade

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contributions from C. Brogan (NRAO/NAASC) and J. Carpenter (ALMA/JAO)

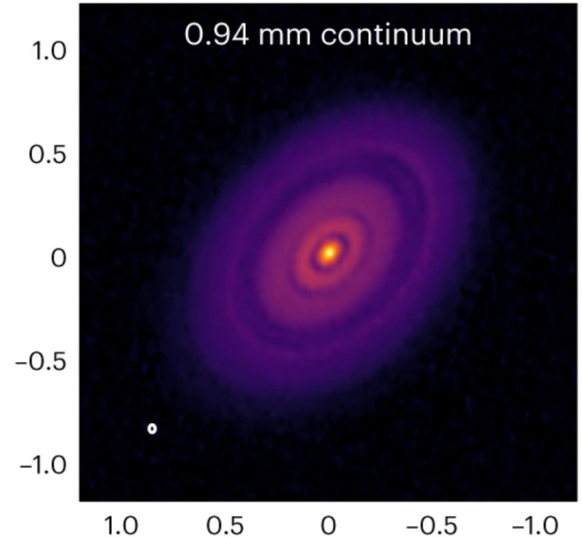
ALMA Today

- Unique high and dry site at 5000m (16,500 ft) altitude
- 66 submillimeter/millimeter telescopes (50x 12m, 12x7m, 4x12m): 6600 m^2 collecting area
- Ten Frequency Bands: 35 to 950 GHz (7 to 0.32 mm) – Band 2 in construction
- Angular resolution as fine as 5 milliarcsec, baselines up to 16 km

“Full science” operations since 2014

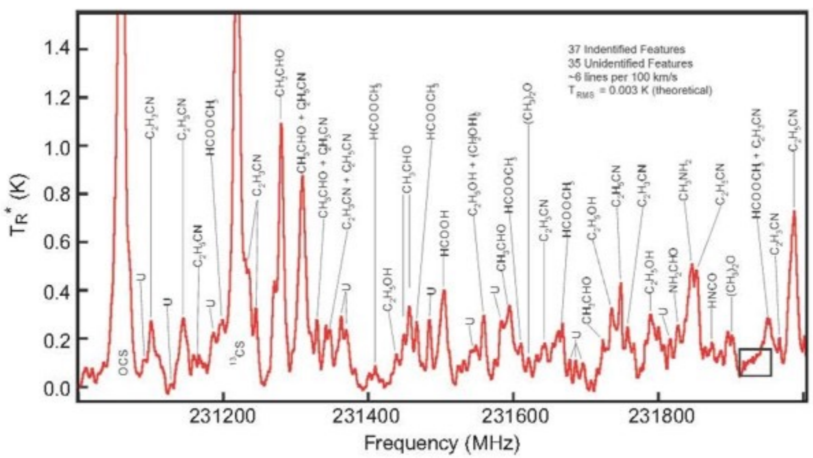
ALMA has opened a new discovery space by offering unprecedented sensitivity, image fidelity, and angular resolution in the (sub)mm wavelength range.

High-res imaging

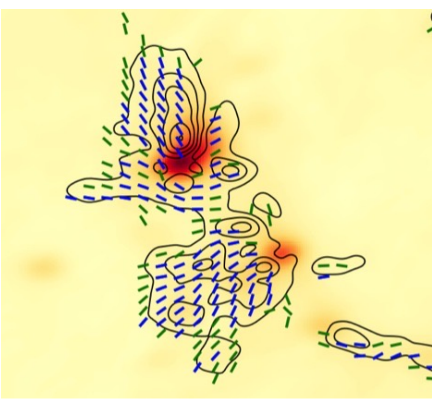


Large maps

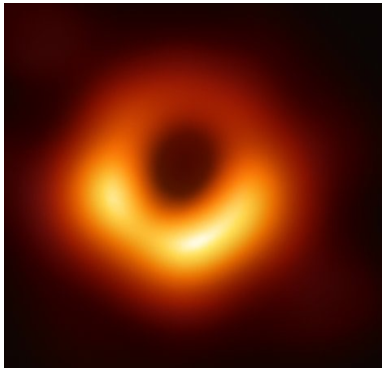
Spectroscopy



Polarization

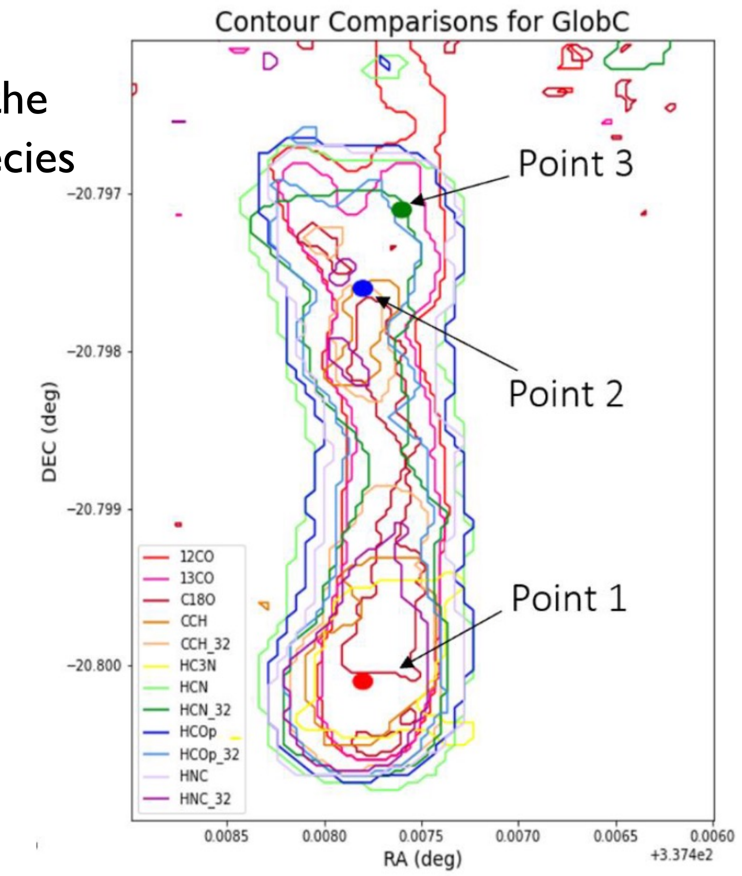


VLBI

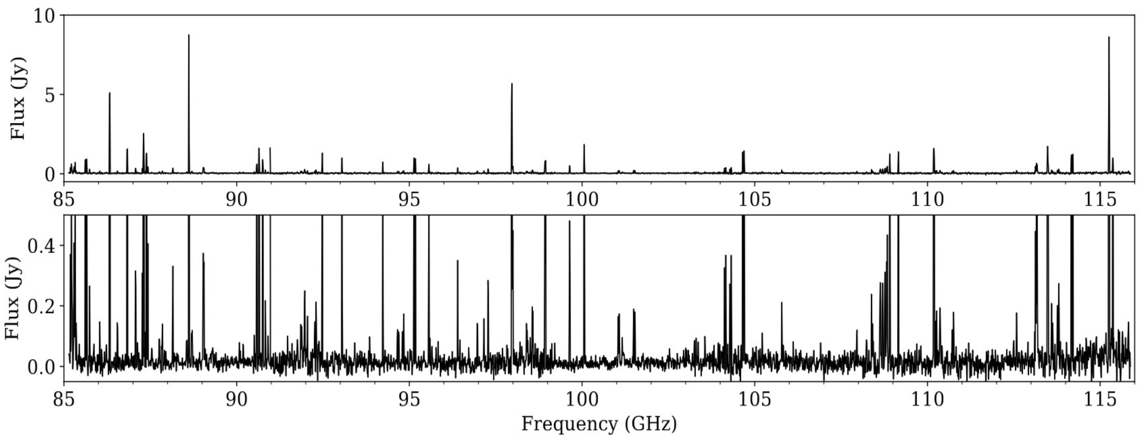


Spectral surveys for molecular composition overview

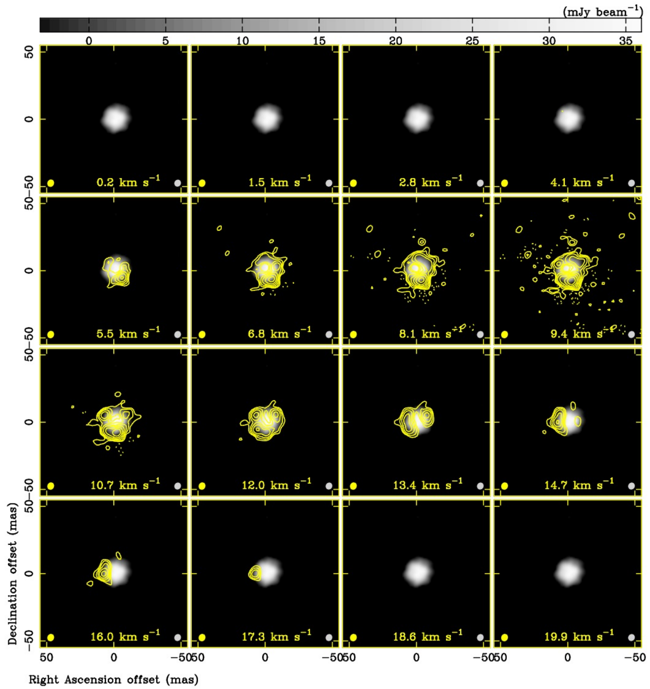
Steffes et Bublitz, 2022: Chemical Composition of Globules B and C in the **Helix Nebula (PN)**. 8 molecular species

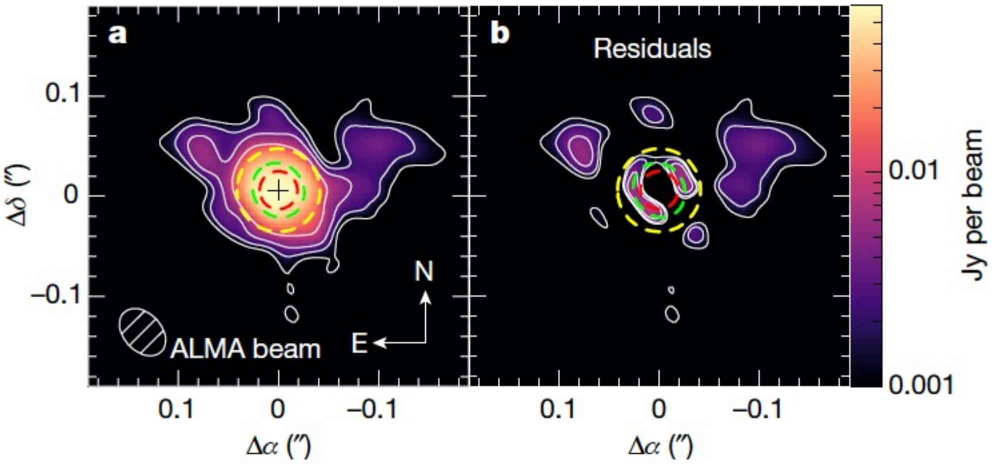


Unnikrishnan et al, 2024: Band 3 survey in CSE of **AGB star** IRAS 15194−5115. 49 molecular species



High-resolution imaging: outflow structure from molecular gas signatures

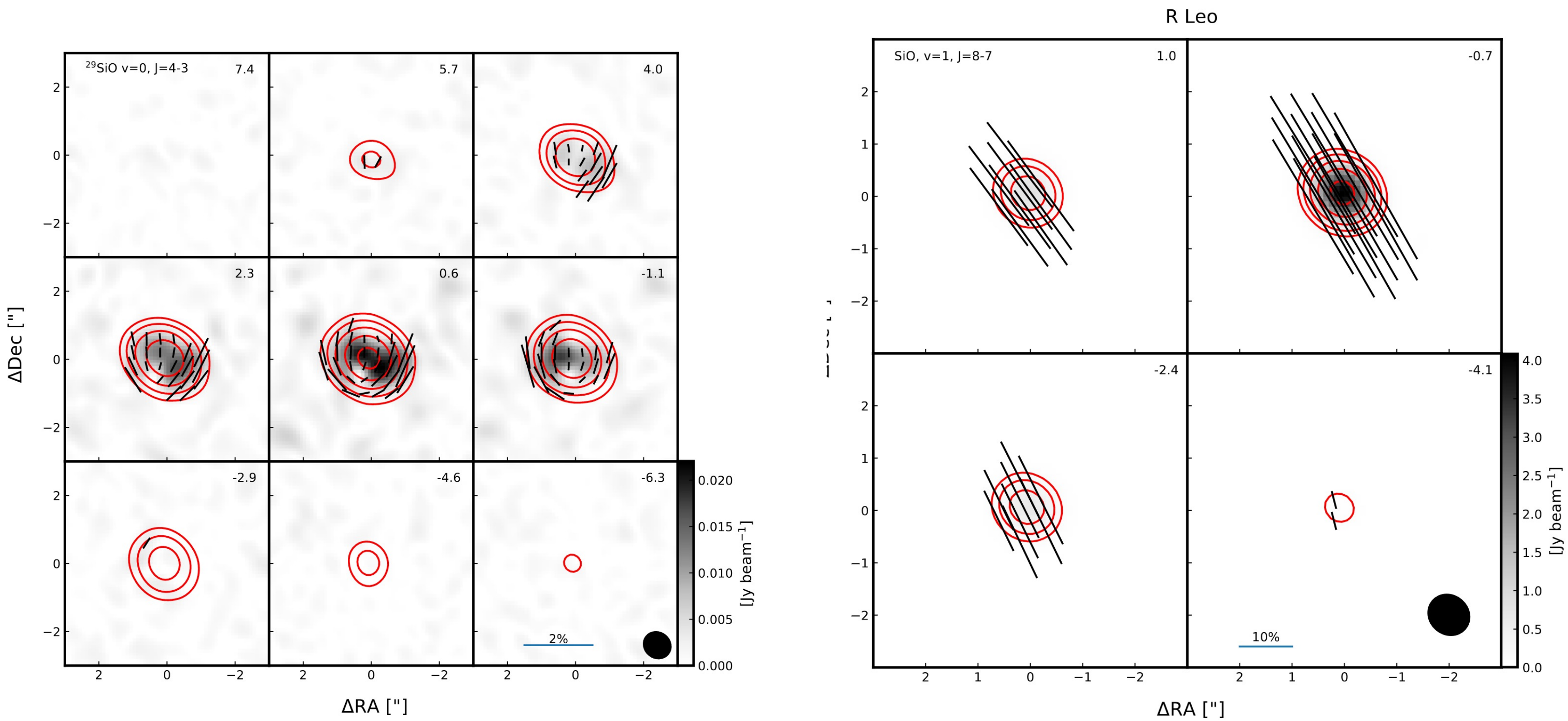




Velilla-Prieto et al., 2023: **Atmospheric Blobs around IRC+10216** HCN, SiS and SiC_2 : large convective photospheric cells. Stellar radius resolution!

Asaki et al, 2023 **Highest Angular Resolution in submm data (5 mas)** on R Lep HCN maser at 890.8 GHz

Polarization in lines : structure of magnetic fields



Vlemmings et al., 2024 : R Leo Polarization maps in SiO rotational line (left) and in SiO maser line (right)

What's next?

The ALMA Board has endorsed a 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)

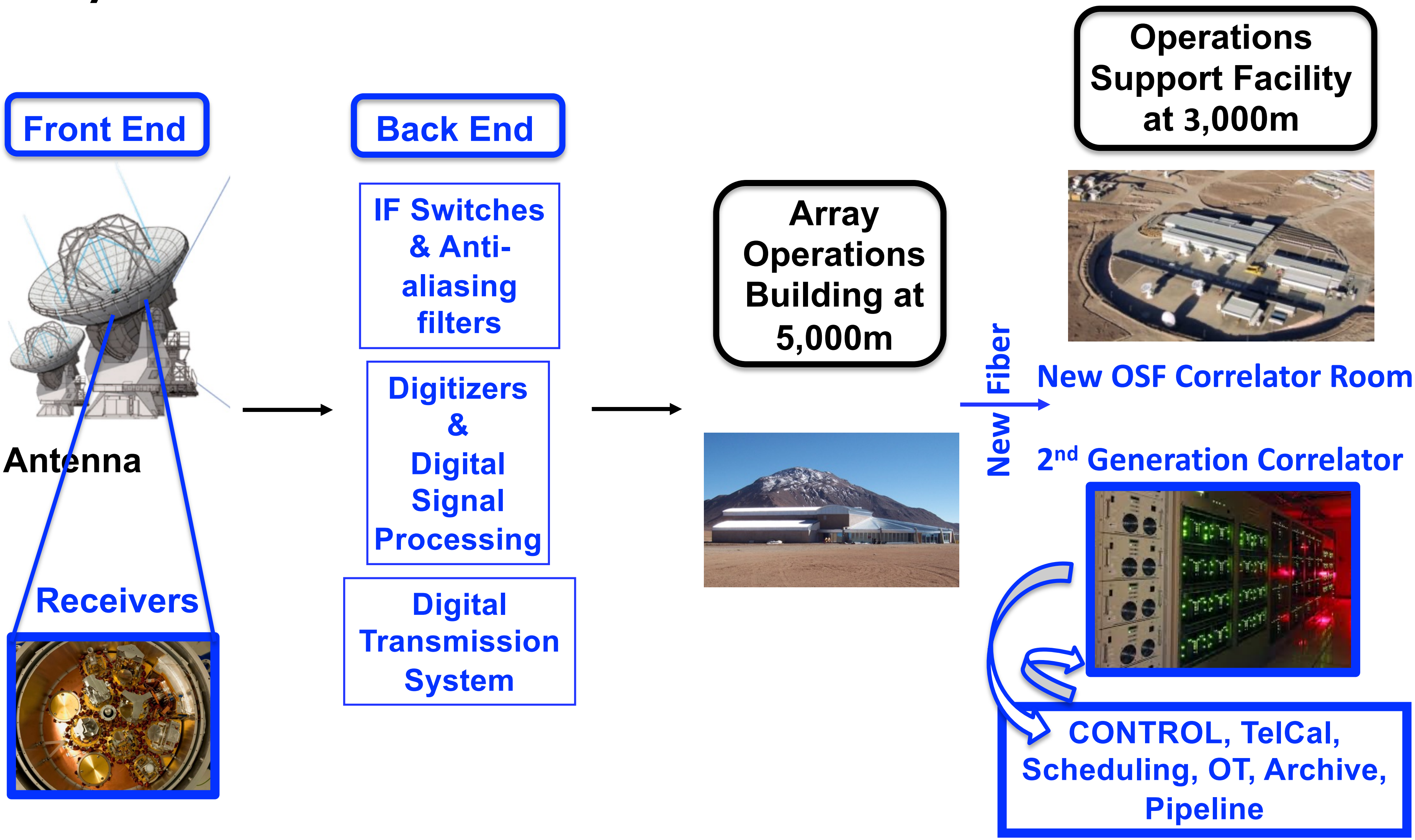
The Wideband Sensitivity Upgrade

The ALMA Wideband Sensitivity Upgrade (WSU) is the partnership-wide initiative that will realize this **dramatic increase in bandwidth (and sensitivity)** across the entire ALMA's wavelength range.

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

- Increase in correlator capabilities (throughput and flexibility)
- Increase of the receivers' bandwidth by factor 2-4
- Increase in receiver performance
- Increase in digitizing / correlator efficiency

A system-wide rehaul

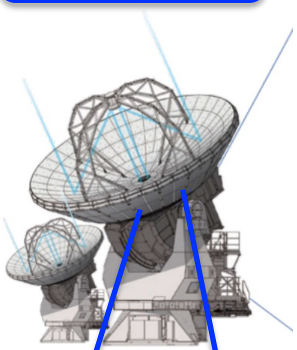


Receivers

Stage 1	Stage 2	Stage 3
Mid-decade	**Late-decade**	**Next decade**
Band 2	Band 7	Band 1
Band 6v2	Band 9	Band 3
Band 8	Band 10	Band 4/5

New or updated receivers for all bands. Improved receiver temperatures.

Front End



Antenna

Receivers

Digitizers & Digital Signal Processing

Digital Transmission System

New Fiber

New OSF Correlator Room

2nd Generation Correlator

CONTROL, TelCal, Scheduling, OT, Archive, Pipeline

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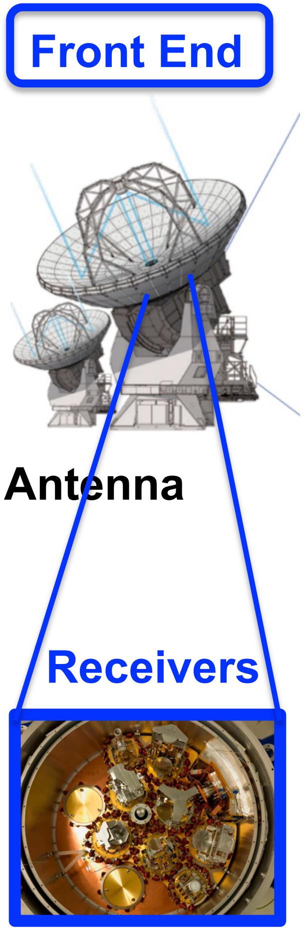
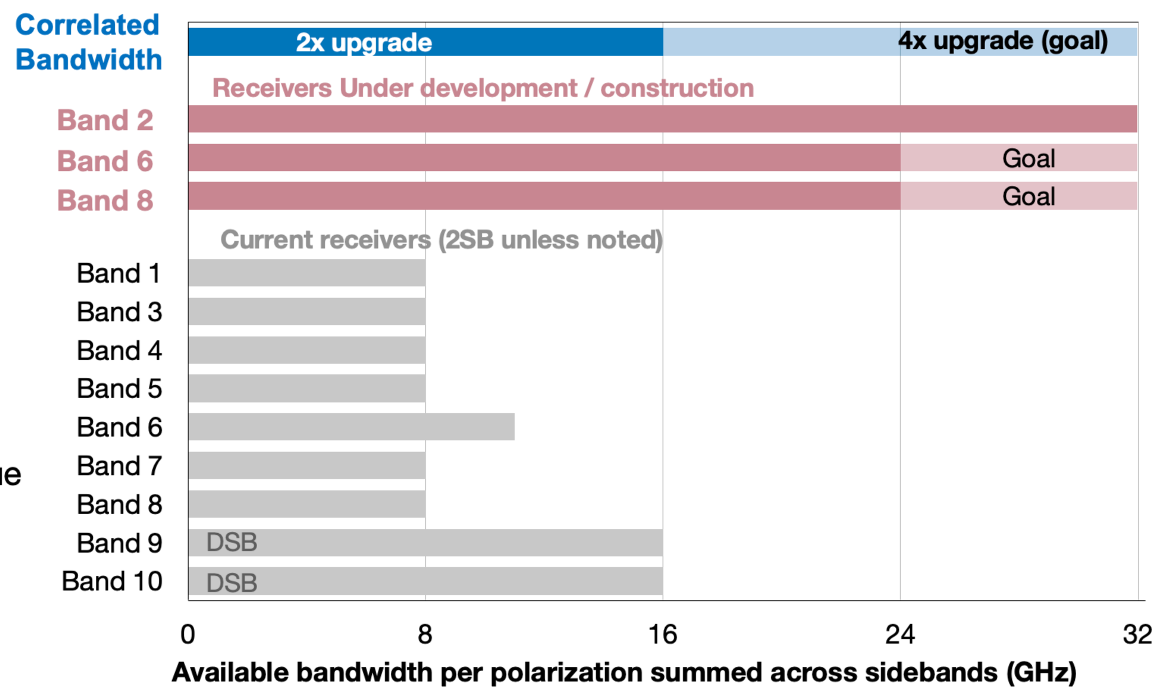




Correlator

Front End

Back End

IF Switches & Anti-aliasing

Array Operations Building at

Operations Support Facility at 3,000m

New OSF Correlator Room

New Fiber

2nd Generation ALMA Correlator: ATAC

- Initially 2x BW, readily expandable to 4x
- Up to 1.2 million spectral channels available (as well as flexible on-line channel averaging)
- Flexible subarrays to process 12m and 7m-array observations concurrently
- 13.4% improvement in correlation efficiency

2nd Generation Correlator

Transmission System

CONTROL, TelCal, Scheduling, OT, Archive, Pipeline

Observations in the WSU era: what to expect

New capabilities

- Larger receiver IF
- Improved correlator capabilities
- Better receiver performance
- Improved digitizer and correlator efficiency

→

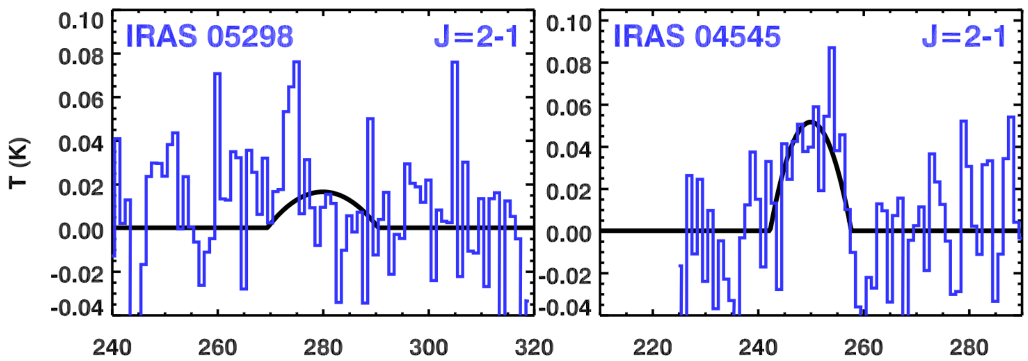
Dramatically improved observing efficiency

- Instantaneously correlated spectral bandwidth, at all spectral resolutions
- Continuum sensitivity
- Line sensitivity
- Spectral grasp
- Ultra-high spectral resolution

Line Sensitivity

Better receiver performance + better digitizer/correlator efficiency
➔ line sensitivity better, factor ~0.7

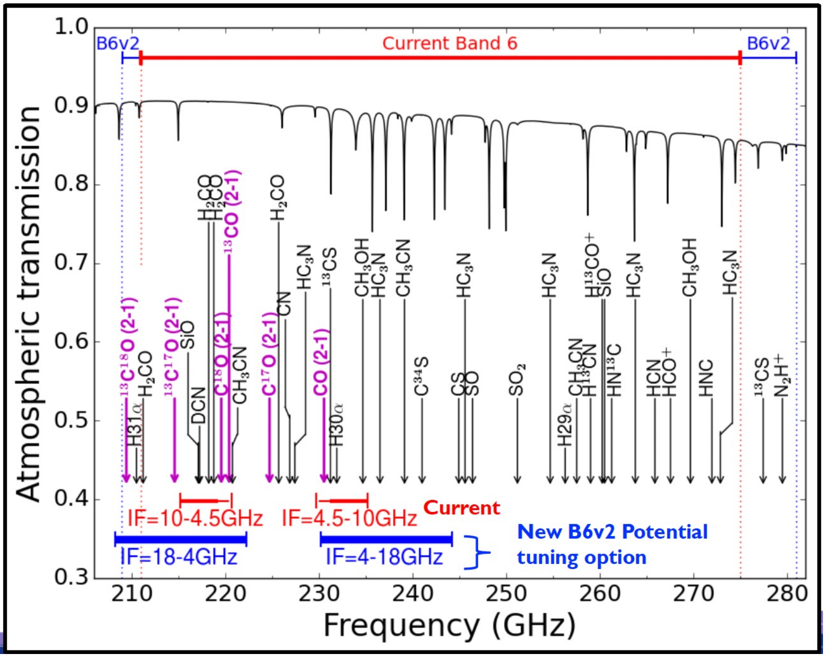
Access to fainter (distant) sources and less abundant molecules.



Groenewegen et al. 2016:
CO in LMC OH/IR stars.
First attempt to spectrally resolve CO in LMC stars to measure expansion velocity

Spectral grasp

Larger receiver IF
-> 16-24 (32) GHz of spectrum range can be **accessed in one spectral setting.**



- Simultaneous access to strategic line combinations: Full suite of CO isotopologues in one go in Band 6
- Easier study of molecular lines temporal variations in CSEs over pulsation cycle

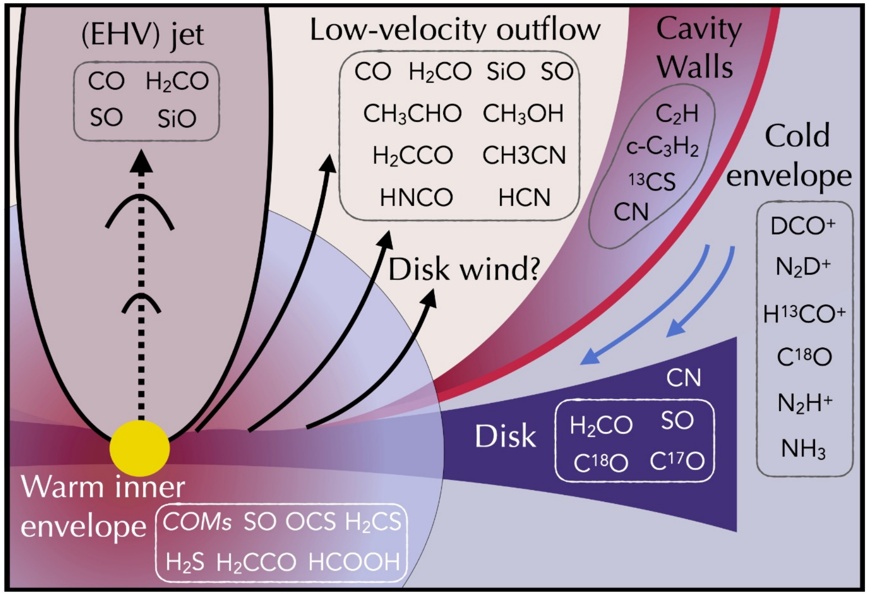
Adapted from ALMA Memo 621: Band 6v2 IF options

Instantaneously correlated spectral bandwidth

Larger receiver IF + Improved correlator capabilities:
-> 16 (32) GHz of spectrum can be processed simultaneously, **at (almost) any spectral resolution**. (No more trading 'resolution for bandwidth')

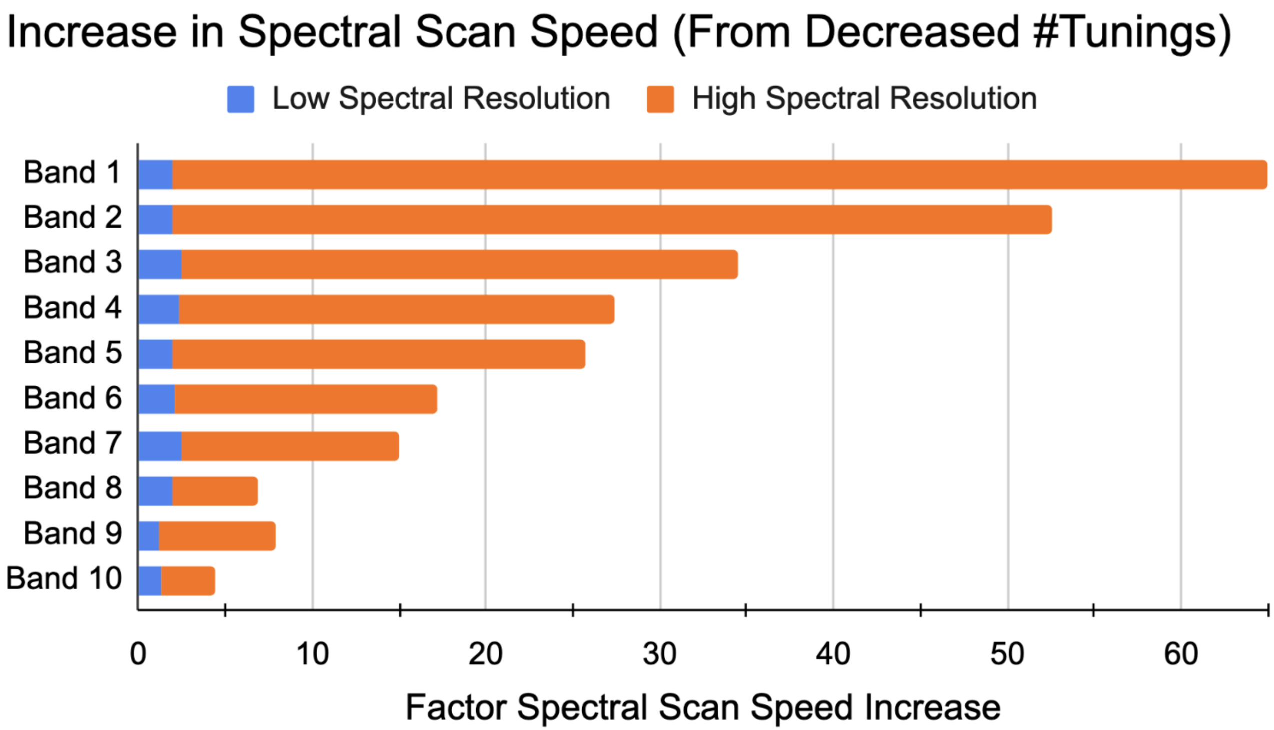
Characterizing all protostellar components at a glance at relevant spectral resolution (~0.1 km/s):
A single ALMA Band 6 tuning will capture 70 (over 80 identified) diagnostic transitions

For CSEs: mapping dust parent molecules



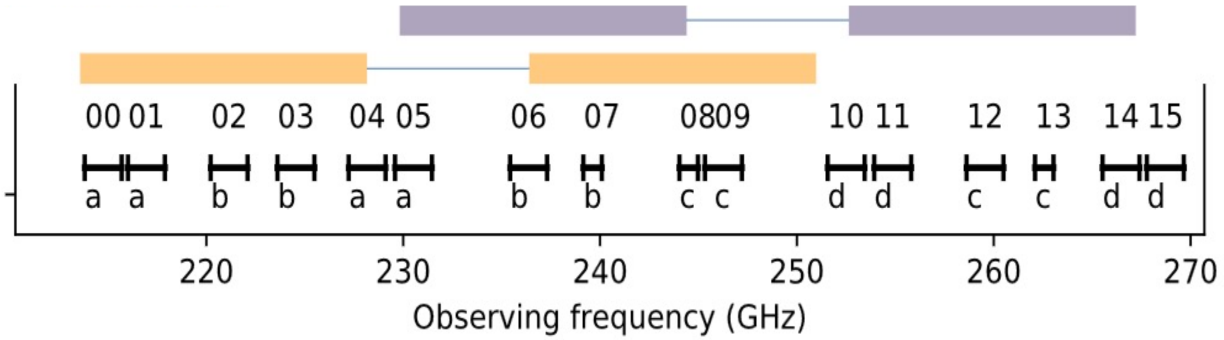
Tychoniec et al., 2021: protostellar environment tracers

High spectral resolution astrochemistry surveys: spectral scanning speed improved by factor 5-64 (*not even accounting for improved line sensitivity)



ALMA Memo 621

ATOMIUM survey (Gottlieb et al., 2022, previous presentation)
Four spectral tunings at resolution 1.3 km/s

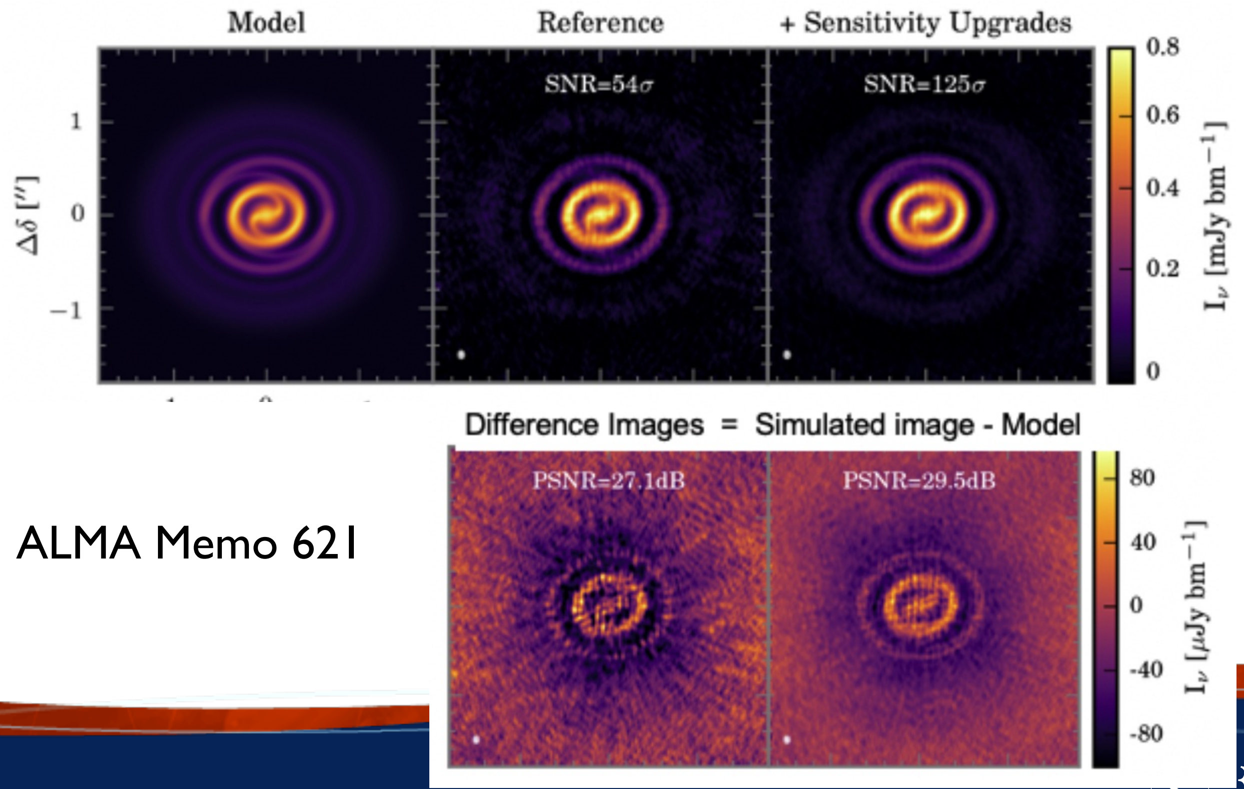


After WSU:
- only 2 tunings needed
- completion in ¼ of observing time
- or 4 x more targets
- or 2x deeper

Continuum Sensitivity

Increased spectral grasp + better receiver performance + better digitizer/correlator efficiency
➔ continuum sensitivity down x 0.4 (0.3 for 4x upgrade) at least

Also to consider: improved continuum image fidelity from denser uv-coverage

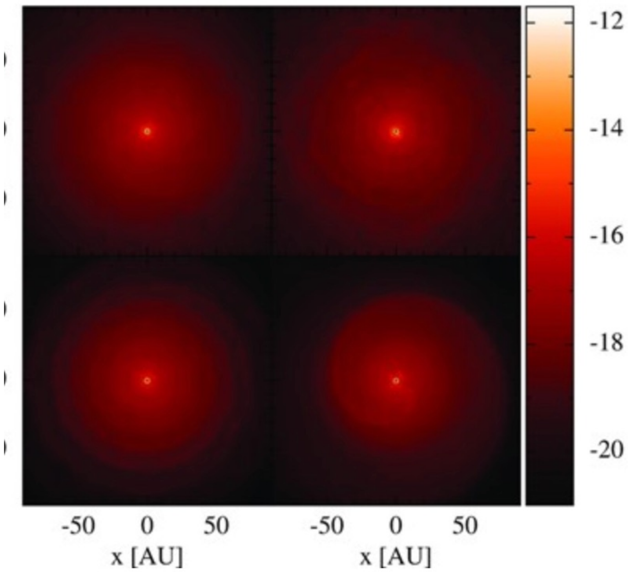


ALMA Memo 621

Continuum Sensitivity: maps

Identify subtle continuum features in the environment of AGB and WR stars to:

- detect and characterize companions
- evidence outflows further out than gas; massive dust clumps
- constrain gas/dust coupling



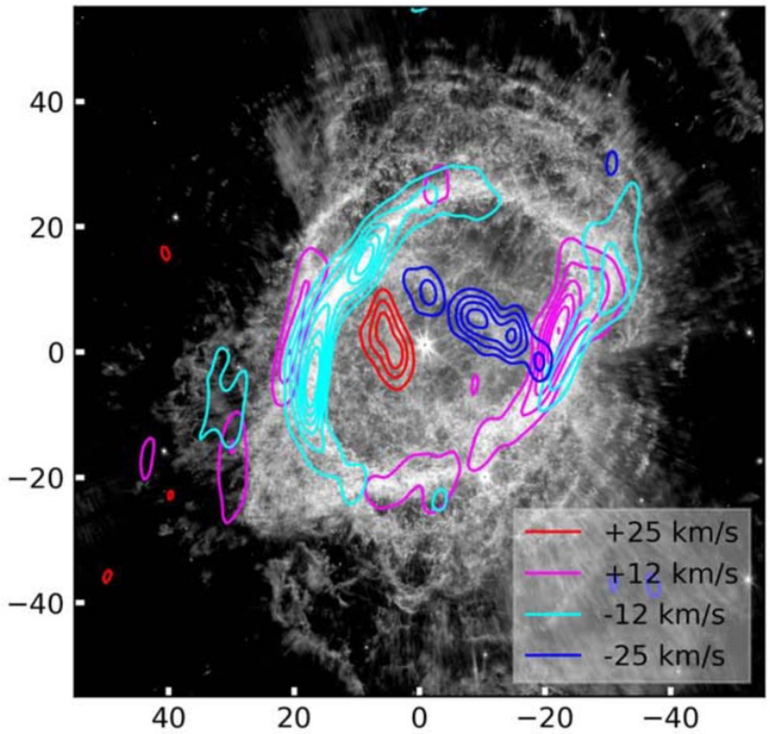
Aydi et al., 2022: models of CSE density distribution varying w companion separation

CO emission map, RSG R Sculptoris, Maercker et al., 2012

Continuum Sensitivity: maps

- In - often dust poor - PNs, continuum features in the form of torus / discs can point to progenitor companions

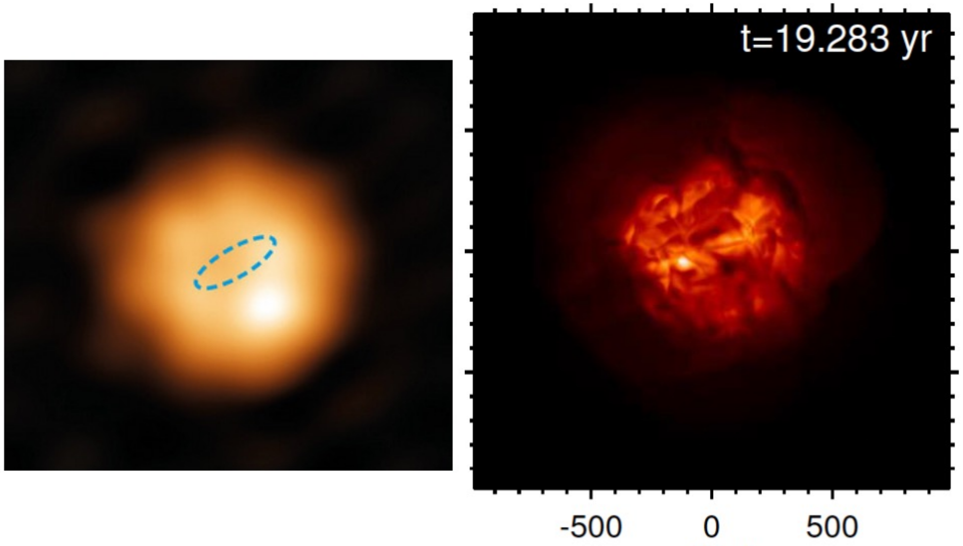
- More sensitivity: access to sources and features 2-3 x fainter, to explore the continuum of separation of stars / progenitors



Kastner et al. (2024), with SMA: structures most likely sculpted by an unseen companion or companions. No dust detected

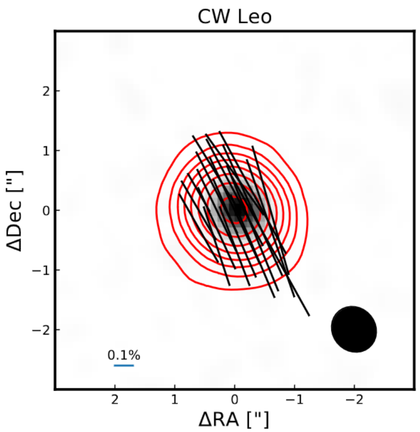
Continuum Sensitivity: maps (high-res)

- Faster monitoring of hot spots on the spatially-resolved surfaces of AGB stars
- Constraints on expansion at a few stellar radii

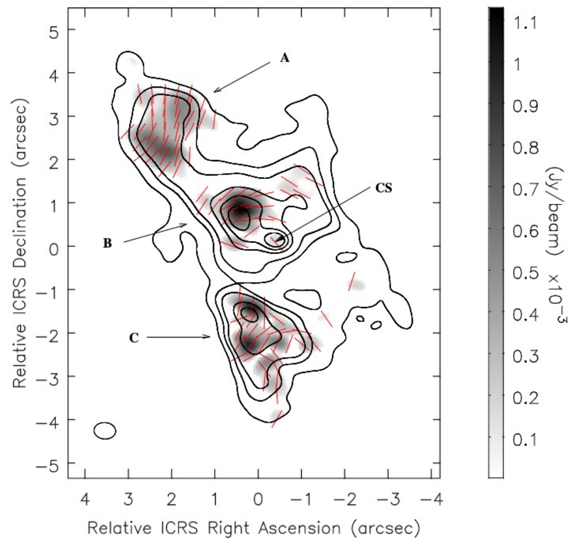


(left) Vlemmings et al., 2017: W Hya with ALMA.
(right) Hofner et al., 2019: surface model

Continuum Sensitivity: polarization



Vlemmings et al., 2024:
R Leo



Sabin et al., 2020:
PNe OH 231.8+4.2

Improvement by factor 2 (3) of noise in Stokes Q, U, V and fractional polarization:
-> identification of fainter B-fields
-> Improved distinction of polarization processes: radiative alignment Vs grain alignment to B-field Vs self-scattering

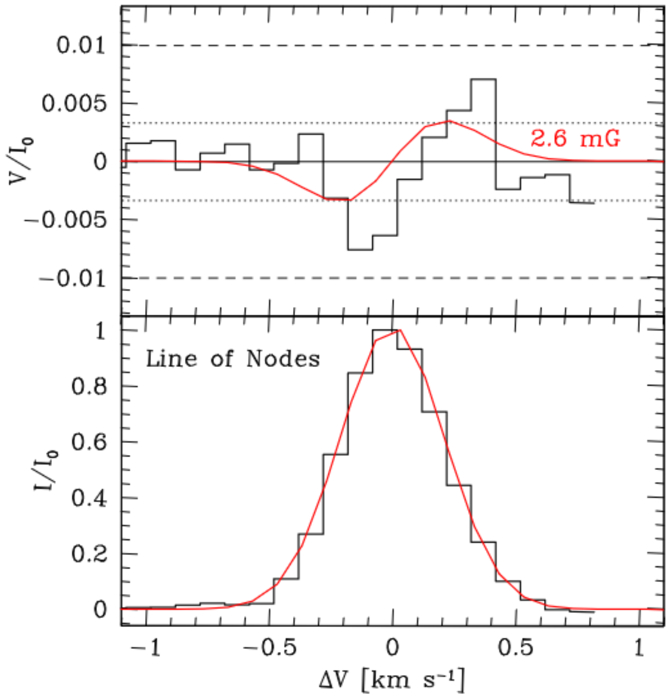
Ultra-high spectral resolution

Spectral resolution down to ~10 m/s at all bands

- **Zeeman-induced circular polarization pattern** more accessible (lower frequencies / fainter magnetic fields): direct measurement of B-field strength

- Spectral profile analysis of **non-thermal maser lines** for spot characterization (size / position / kinematics)

- Detailed kinematics exploration of **low-velocity outflows / infall** in cold environments



Vlemmings et al., 2019: Hint of Zeeman-induced pattern in TW Hya disk from CN maser

The ALMA WSU will benefit all observations

Enhanced Capability	WSU Improvement for 2x BW Correlation (16 GHz per pol)	Future Improvement with 4x BW
Receiver bandwidth increase	**2-4x** in instantaneous bandwidth (as receiver bands are upgraded)	…
Correlated Bandwidth increase	• **2x** for low spectral resolution • Up to **4x** (Band 10) and **68x** (Band 1) for 0.1 km/s spectral 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
Spectral line Imaging speed	**~2.2x** from improved receiver noise temperatures and digital efficiency*	…
Continuum Imaging speed	**≥ 4.8x** 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	…

All details in WSU White Paper : ALMA Memo 621 (arXiv:2211.00195)

WSU status

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

Digital Signal Chain
- Digitizer project with 4x current bandwidth underway [ESO, Bordeaux]
- Data Transmission System (DTS) prototype development underway [NAOJ, NRAO]
- AOS to OSF fiber under study [ESO]

Correlator [NRAO, NRC]
- Under construction
- Initially 2x bandwidth correlation, readily expandable to 4x bandwidth

WSU Status

Goal is WSU first science by the end of the decade (upgrade of some receiver bands will come later)**.** Detailed deployment schedule in preparation; during commissioning, regular science operations will continue (adjusted).

Stay informed!

Subscribe to NRAO e-news for announcements →

WSU workshop June 24-28, 2024 at ESO Garching
https://www.eso.org/sci/meetings/2024/wsu.html

Reach out to the North American ALMA Science Center (NAASC) through the ALMA Helpdesk: https://almascience.nrao.edu

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