[Wideband Sensitivity Upgrade (WSU)]

Striving for perfection

Evanthia Hatziminaoglou
ESO / IAC

EUROPEAN ARC
ALMA Regional Centre

Many thanks to:
J. Carpenter, M. Zwaan for some of the material

SPANISH
ALMA Days
18-20 February 2025, La Laguna, Tenerife, Spain

ALMA original science drivers

The reason why ALMA was built

1. 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

2. 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

3. Ability to provide precise images at an angular resolution of 0.1″

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➢ Blind survey scan for CO and dust continuum in the HUDF; the deepest CO and continuum observations over a contiguous area on the sky

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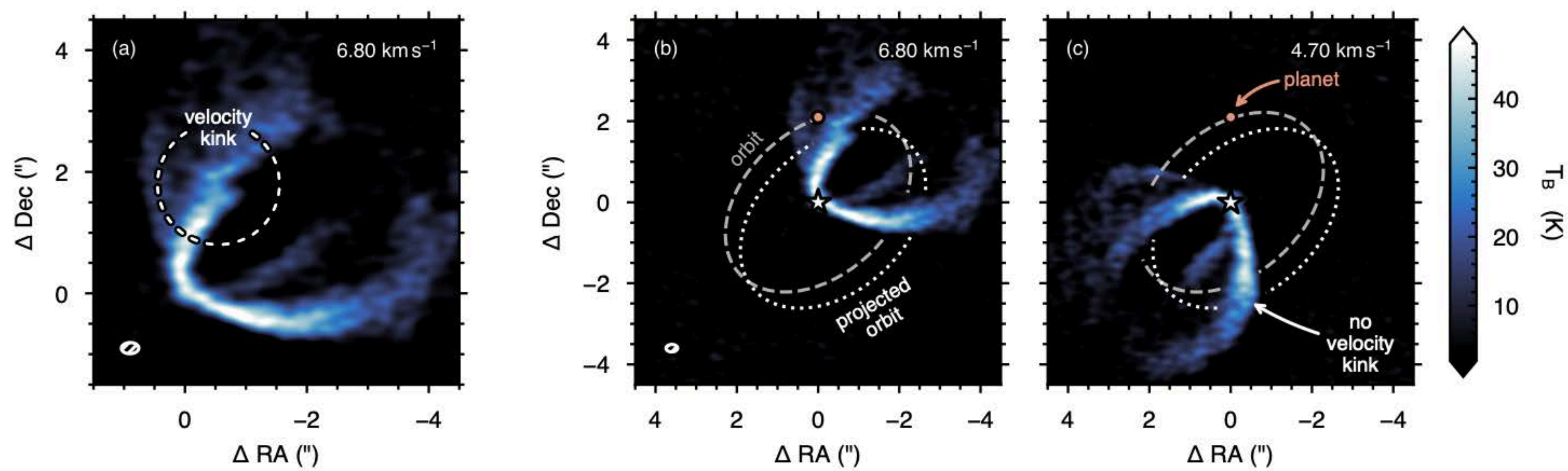

of 0.1″

Pinte et al. 2018b

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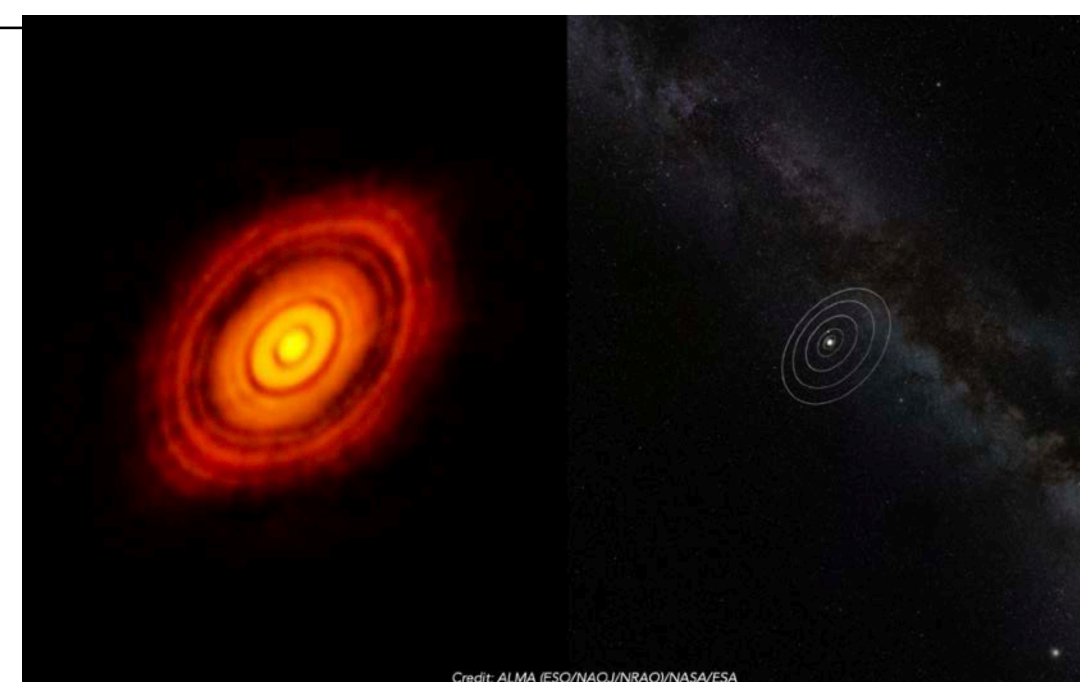
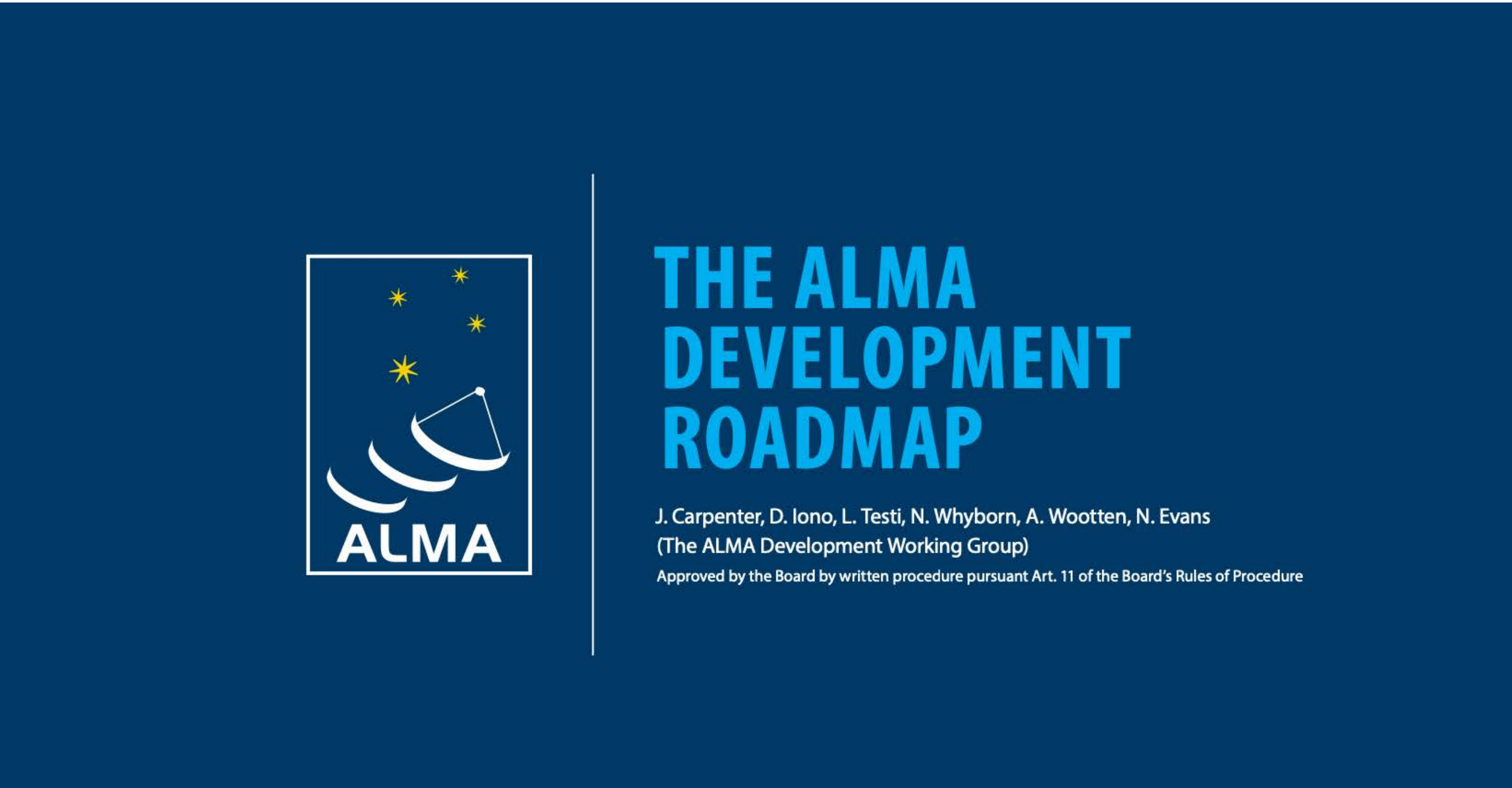



10+ Years of Amazing ALMA Science
Cold streams, or tidal streams from mergers
Starburst core
Turbulent reservoir
30 000 light-years
Dust
Sulfur Dioxide
1 light-year
Nitric Oxide
Formaldehyde
Cycle 1 started in January 2013

New and upcoming facilities

- JWST, Nancy Grace Roman, SKA, Vera Rubin, ELT, …
- Many science themes in common with ALMA: Origins of galaxies, stars, planets
- ALMA is and will be the only submm facility with such high sensitivity and angular resolution
- No replacement in the horizon

The ALMA 2030 Roadmap

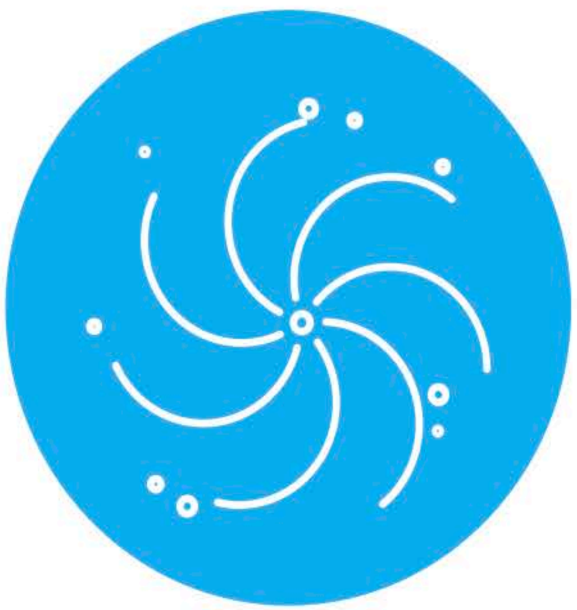

ALMA

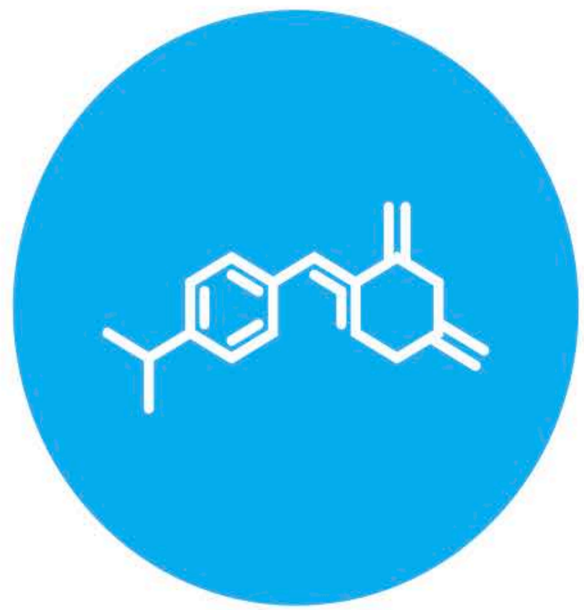
THE ALMA DEVELOPMENT ROADMAP

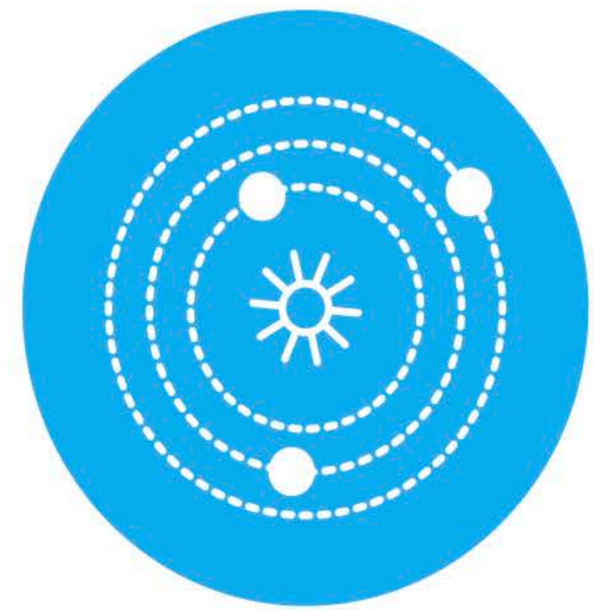
J. Carpenter, D. Iono, L. Testi, N. Whyborn, A. Wootten, N. Evans
(The ALMA Development Working Group)
Approved by the Board by written procedure pursuant Art. 11 of the Board's Rules of Procedure

The ALMA 2030 Roadmap

New science 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.

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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.

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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.

The ALMA 2030 Roadmap

Preamble

- *"ALMA is approaching completion of its initially envisaged capabilities and, within the first five years of operations, the original fundamental science goals of ALMA have been essentially achieved. The ALMA Board established a Working Group to develop a strategic vision and prioritize new capabilities for the Observatory out to 2030 as part of the ALMA Development Program."*

- Roadmap approved by the ALMA Board in June 2018

- Vision was to:
  - broaden the receiver IF bandwidth by at least a factor two
  - upgrade the associated electronics and correlator

These developments will advance a wide range of scientific studies by significantly reducing the time required for blind redshift surveys, chemical spectral scans, and deep continuum surveys.

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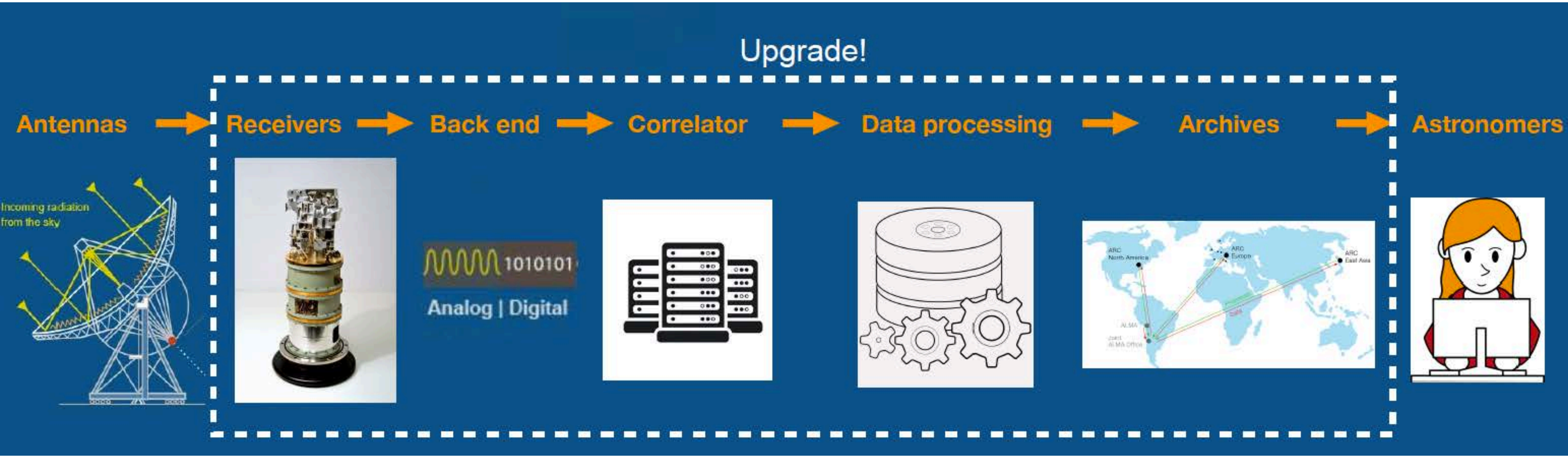
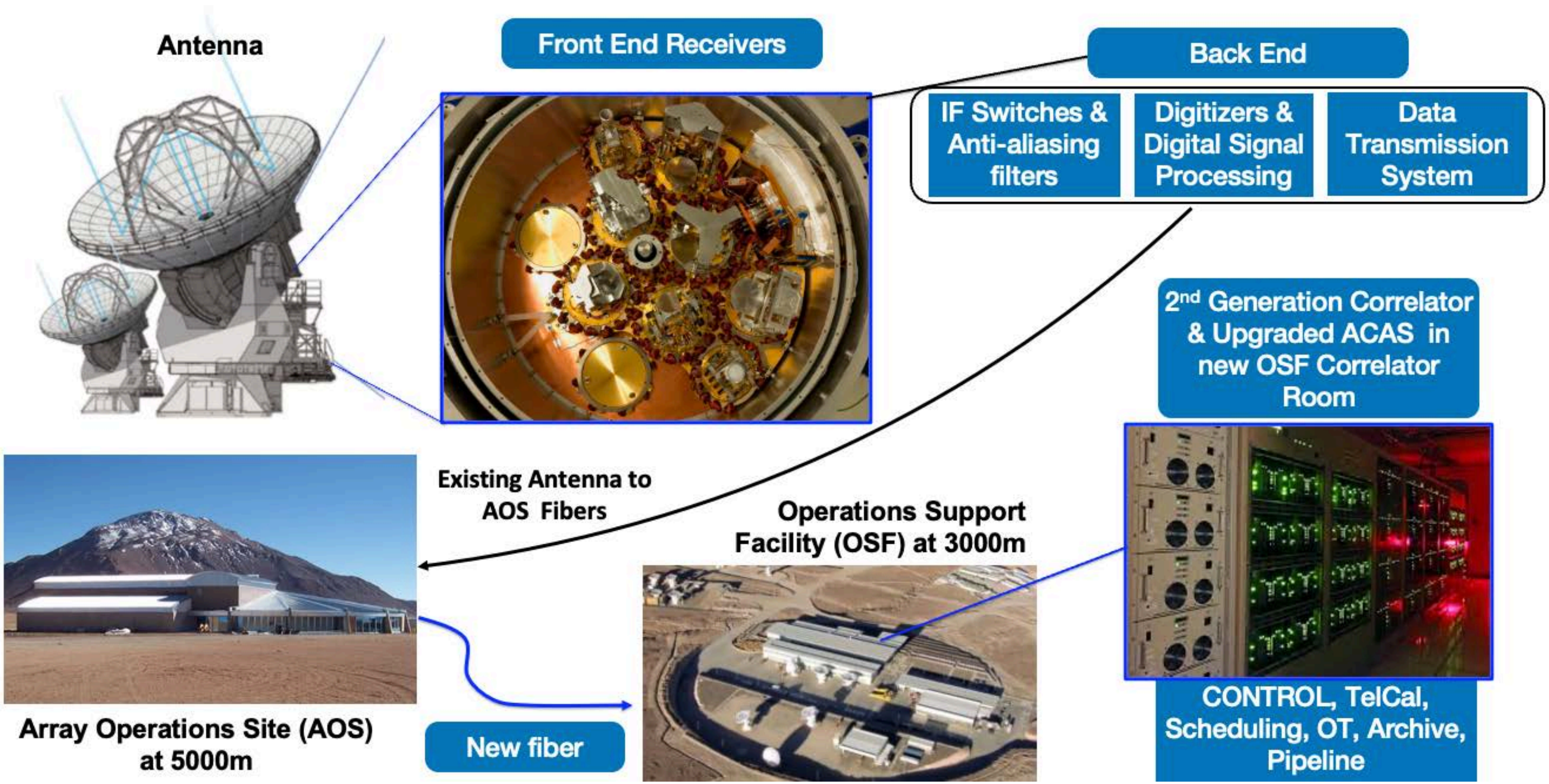


The ALMA 2030 Roadmap

Preamble

“Achieving these ambitious goals is currently impossible even with the outstanding capabilities of the current ALMA array. These science goals can be achieved with the upgrades […] that would make ALMA even more powerful and keep it at the forefront of astronomy by continuing to produce transformational science and enabling fundamental advances in our understanding of the universe for the decades to come.”

The Wideband Sensitivity Upgrade



Everything in blue is new!

The ALMA Development Program

Studies and Projects

- ➡ *Studies*
  - ➡ are intended for an initial exploration of concepts that may be of interest to ALMA development in near- or long-terms
  - ➡ are funded by and managed at the discretion of the regional executives
- ➡ *Projects*
  - ➡ are larger-scale programs
  - ➡ provide specific deliverables (hardware or software) to ALMA
- ➡ The detailed implementation of studies and projects varies between the regions

ESO's current WSU projects

➡ *Wideband IF Processors (WIFP)*

- ➡New antenna-based high-speed system to digitize analogue receiver outputs, and to process and format the resulting data stream before it is transferred to the central correlator
- ➡Contract with University of Bordeaux (F)

➡*Band 2*

- ➡ RF bandwidth: 67-116 GHz, first real wideband receiver (16 GHz per sideband)
- ➡Manufacturing ongoing, several production receivers already integrated
- ➡Contract with NOVA (NL) and many partners

➡*Fibre Optic Connection*

- ➡Project in definition. New trenches and fibre optics cable between high (5000) and low (3000m) site

ESO's current WSU projects

Band 2

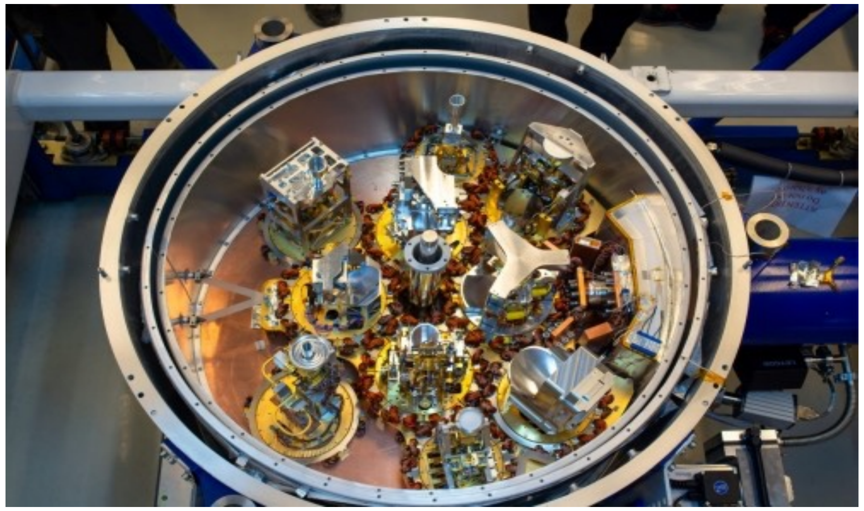
➡ Collaboration with NOVA/GARD/INAF and NAOJ

➡ RF bandwidth: 67-116 GHz, IF bandwidth: 2-18 GHz

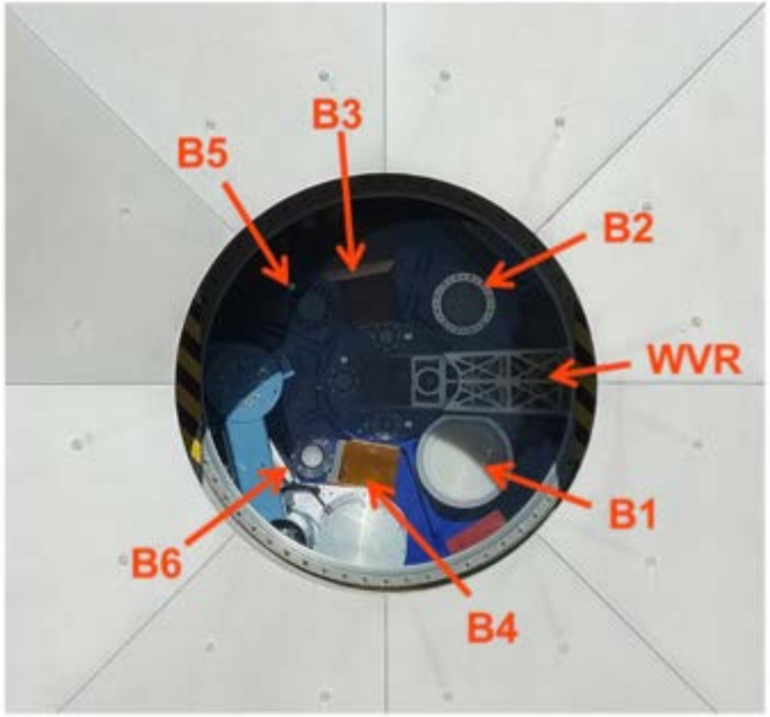
➡ 6 pre-production receivers (Q1 2024); 3 integrated in antennas; 2 more integrated in Q2 2024

➡ Manufacturing of 67 production receivers (Q2 2024 - Q1 2026)

➡ Integration of production receivers in ALMA Front Ends at OSF and commissioning (Q3 2024 - Q3 2026)

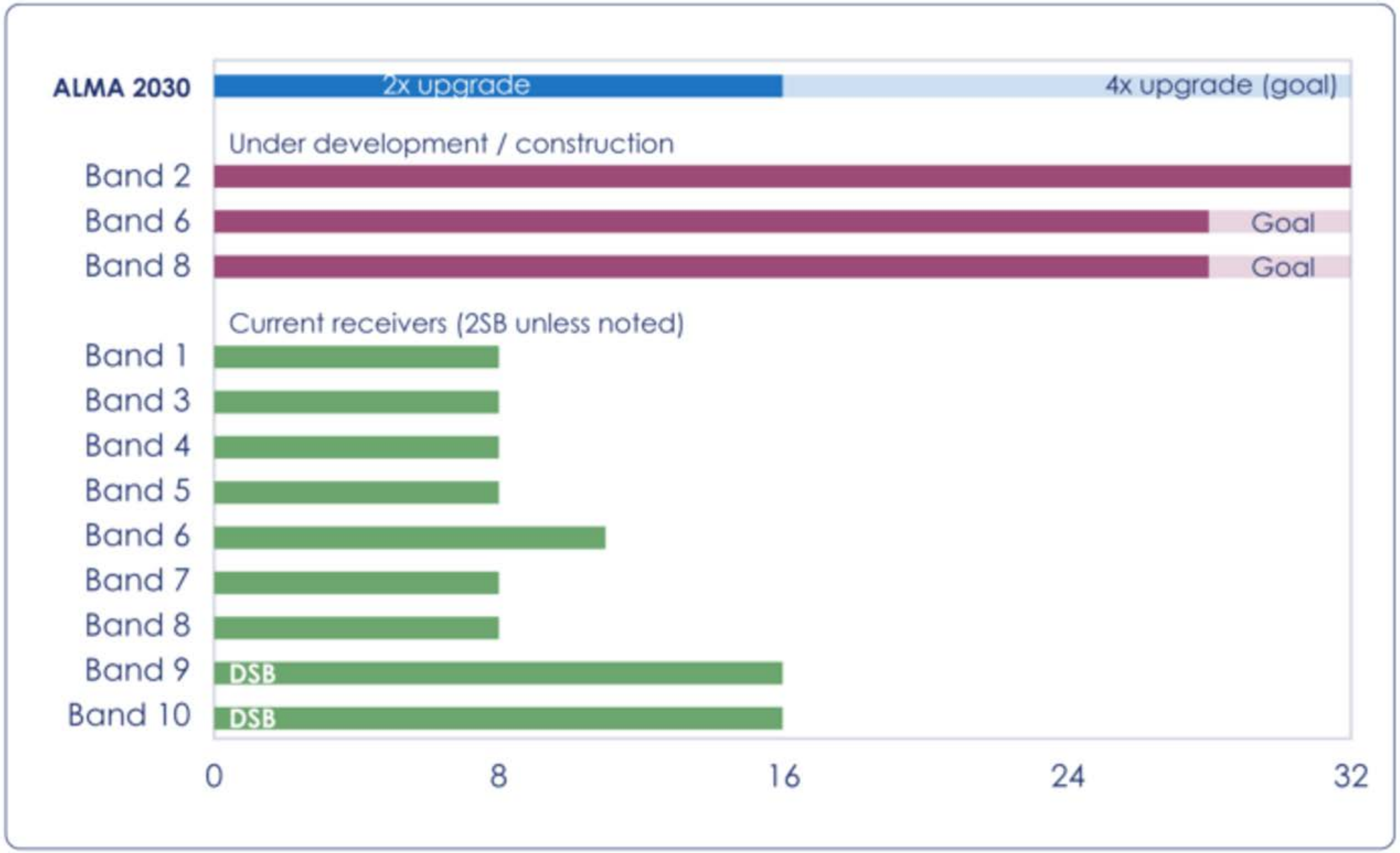


S. Otarola - ALMA (ESO/NAOJ/NRAO)



The Wideband Sensitivity Upgrade

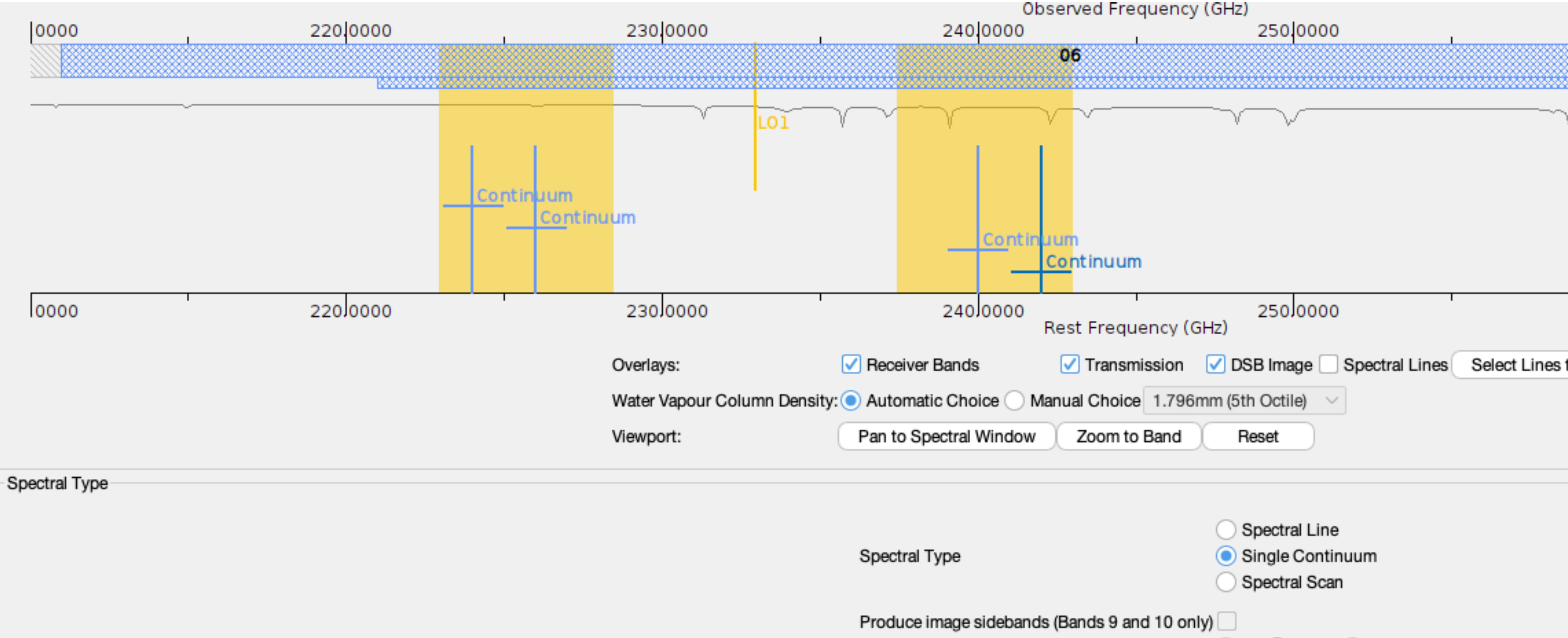
- ➢**Instantaneous bandwidth**
- ➢Correlated bandwidth
- ➢Observing speed



Increase of the available IF band width by a factor 2

The Wideband Sensitivity Upgrade

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



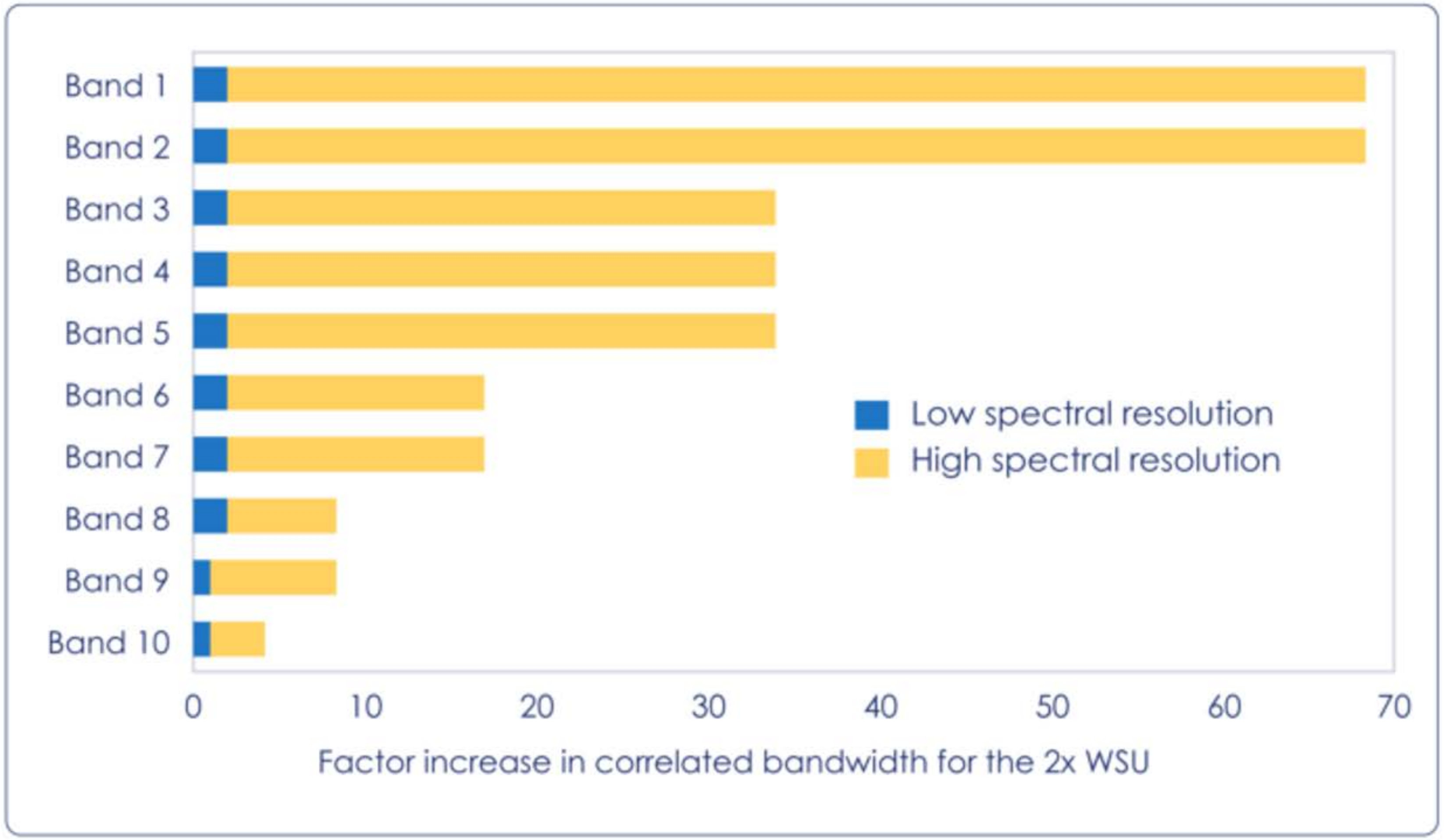
The Wideband Sensitivity Upgrade

- ➢ Instantaneous bandwidth
- ➢ **Correlated bandwidth**
- ➢ Observing speed

Increase of correlated bandwidth by factors 4 to 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



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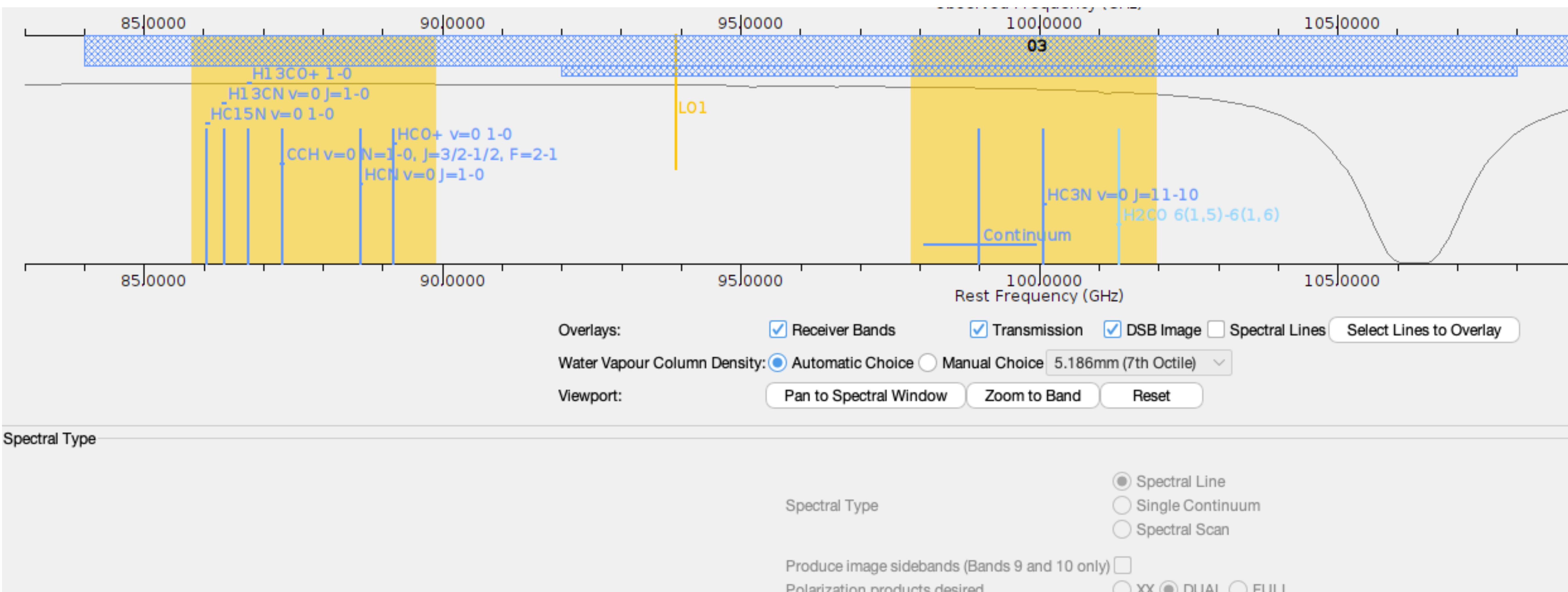
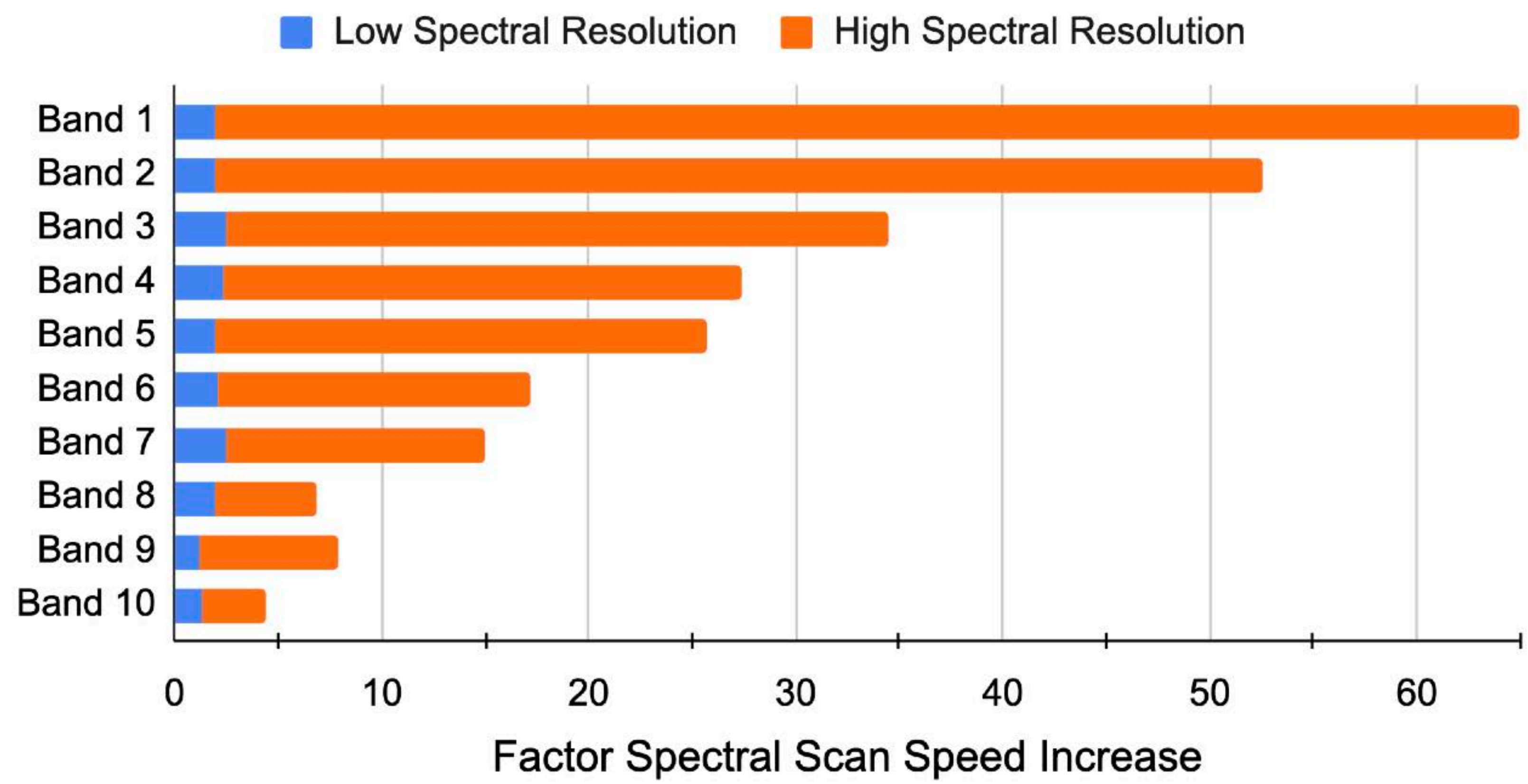


The Wideband Sensitivity Upgrade

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

Increase in spectral scan speed

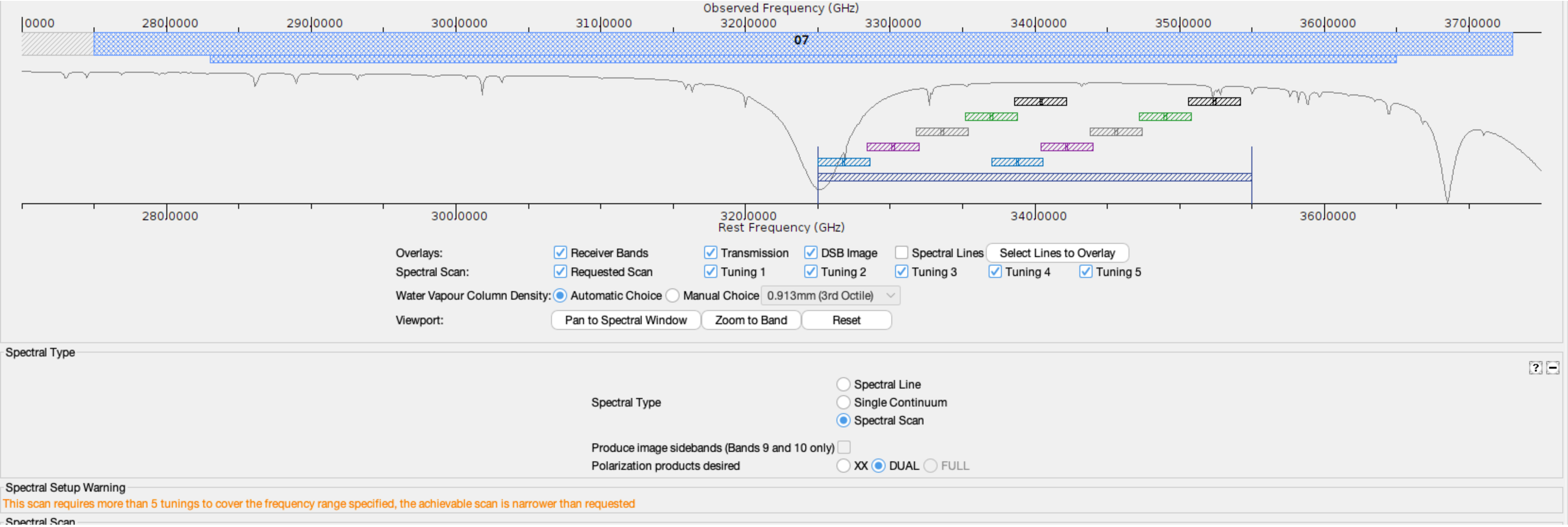


- ➢ Continuum imaging speed increase by x3 for x2 correlated bandwidth
- ➢ Spectral line imaging speed increase by ~ x2-x3
- ➢ Spectral scan speed increase by x2-x54

The Wideband Sensitivity Upgrade

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

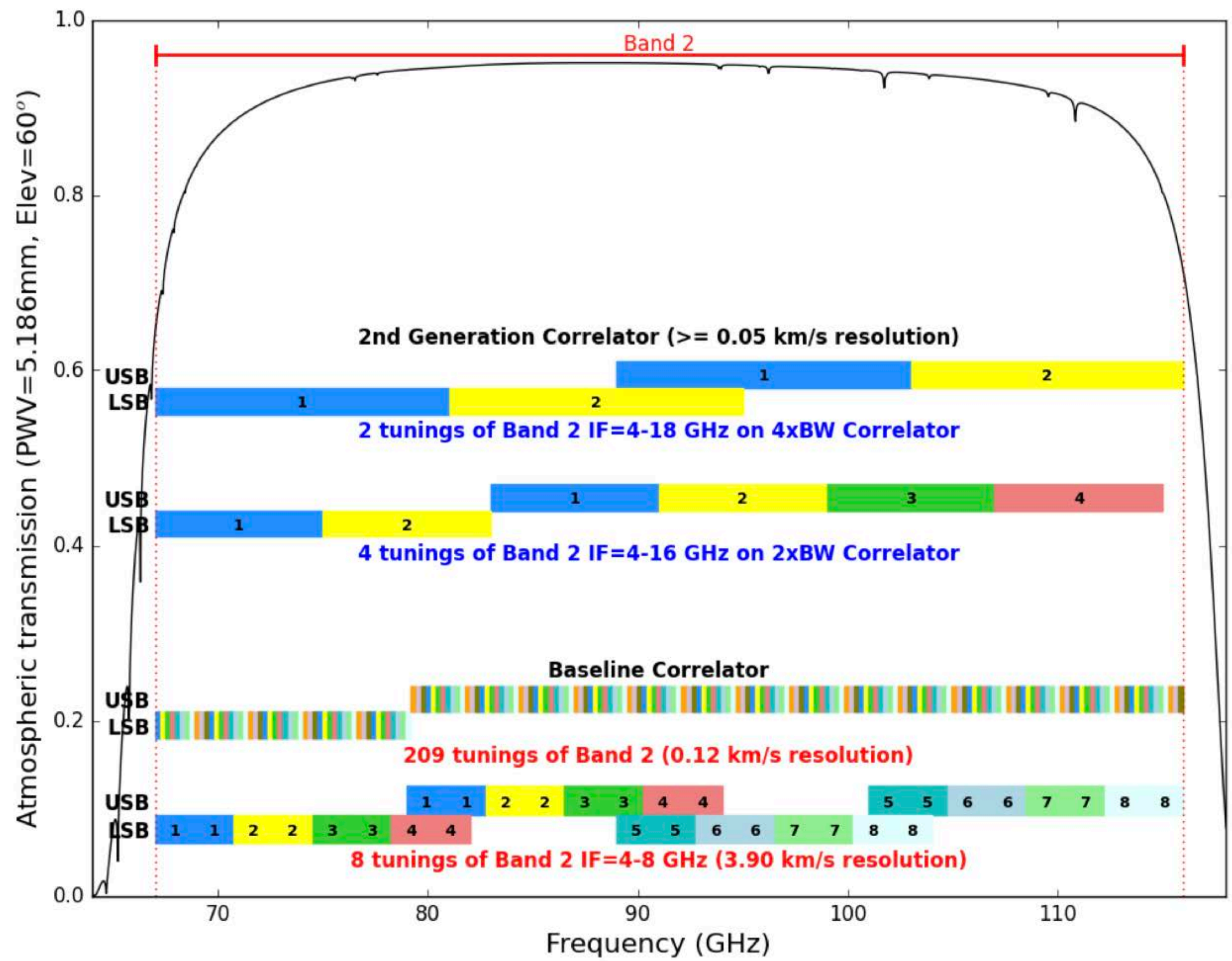
Increase in spectral scan speed



The Wideband Sensitivity Upgrade

Example: Band 2

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



The Wideband Sensitivity Upgrade

Improved sensitivity

A number of factors will enable the WSU to improve ALMA's overall spectral line and continuum sensitivity:

- ➢ Increase in the digital efficiency of the ALMA system: Increasing the number of correlation bits will improve sensitivity by x1.2
- ➢ Lower receiver noise temperatures: advances in receiver technology will allow the noise temperature of the future Band 3-8 receivers to be further reduced by ~20–30% (up to 50% at the edges for some of the receivers)
- ➢ Upgrading Bands 9 and 10 to sideband separation receivers will improve the spectral line sensitivity by ~70–80%
- ➢ Increased continuum bandwidth: sensitivity theoretically improved initially by a factor of 1.46 for 2× correlated bandwidth and eventually 2.06× after the final 4× correlated bandwidth goal is reached.

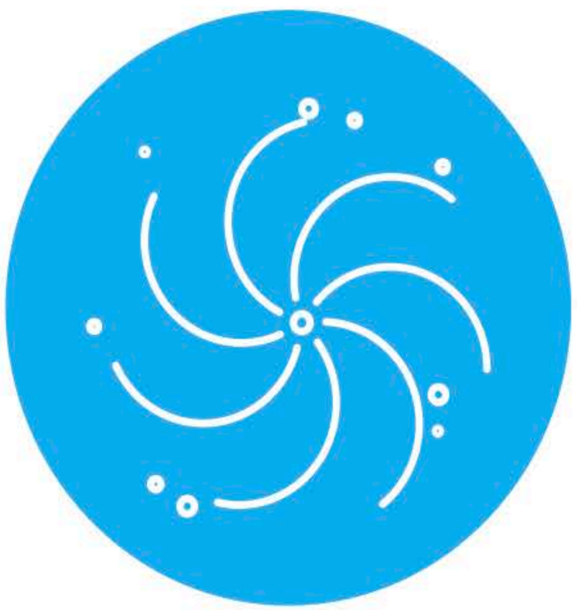
The Wideband Sensitivity Upgrade

The new correlation

- ➡ **Advanced Technology ALMA Correlator** (ATAC) [NRAO, NRC]
- ➡ Initially 2x bandwidth correlation, readily expandable 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 online channel averaging)
- ➡ 6-bit correlation for 13% improvement in sensitivity compared to the current correlator

New science drivers

The WSU will equip ALMA to pursue the ambitious science goals set for the next decade



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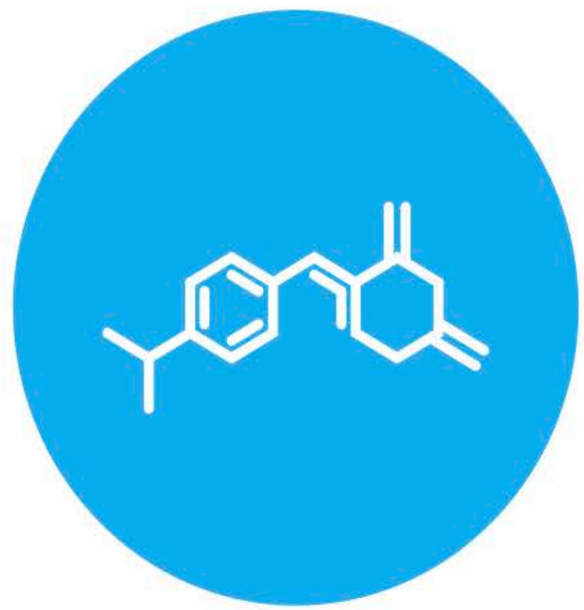

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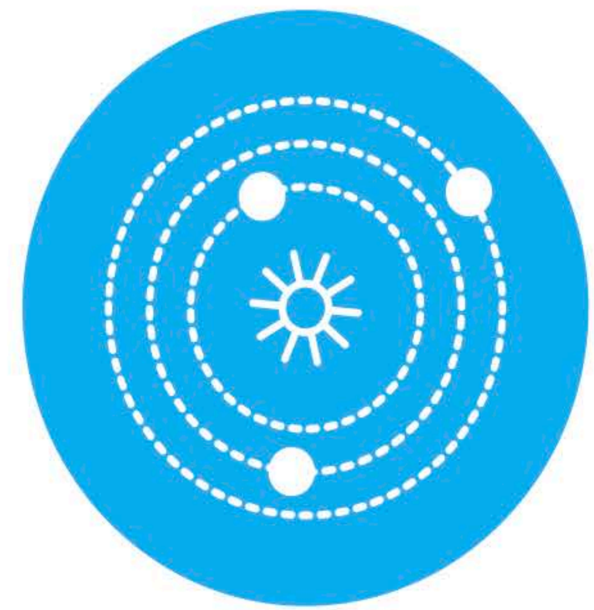

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Image protoplanetary disks in nearby (150 pc) star formation regions to resolve the Earth forming zone (~ 1 au) in the dust continuum at wavelengths shorter than 1mm, enabling detection of the tidal gaps and inner holes created by planets undergoing formation.

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Origins of galaxies

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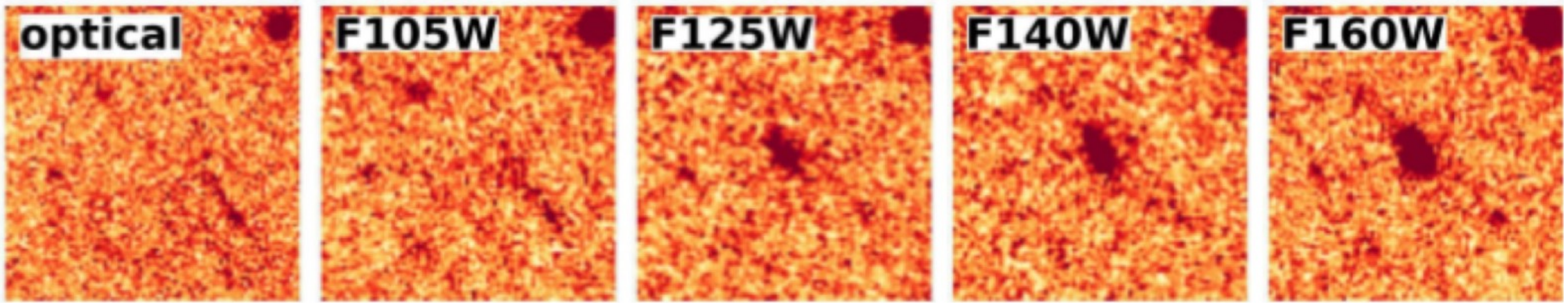
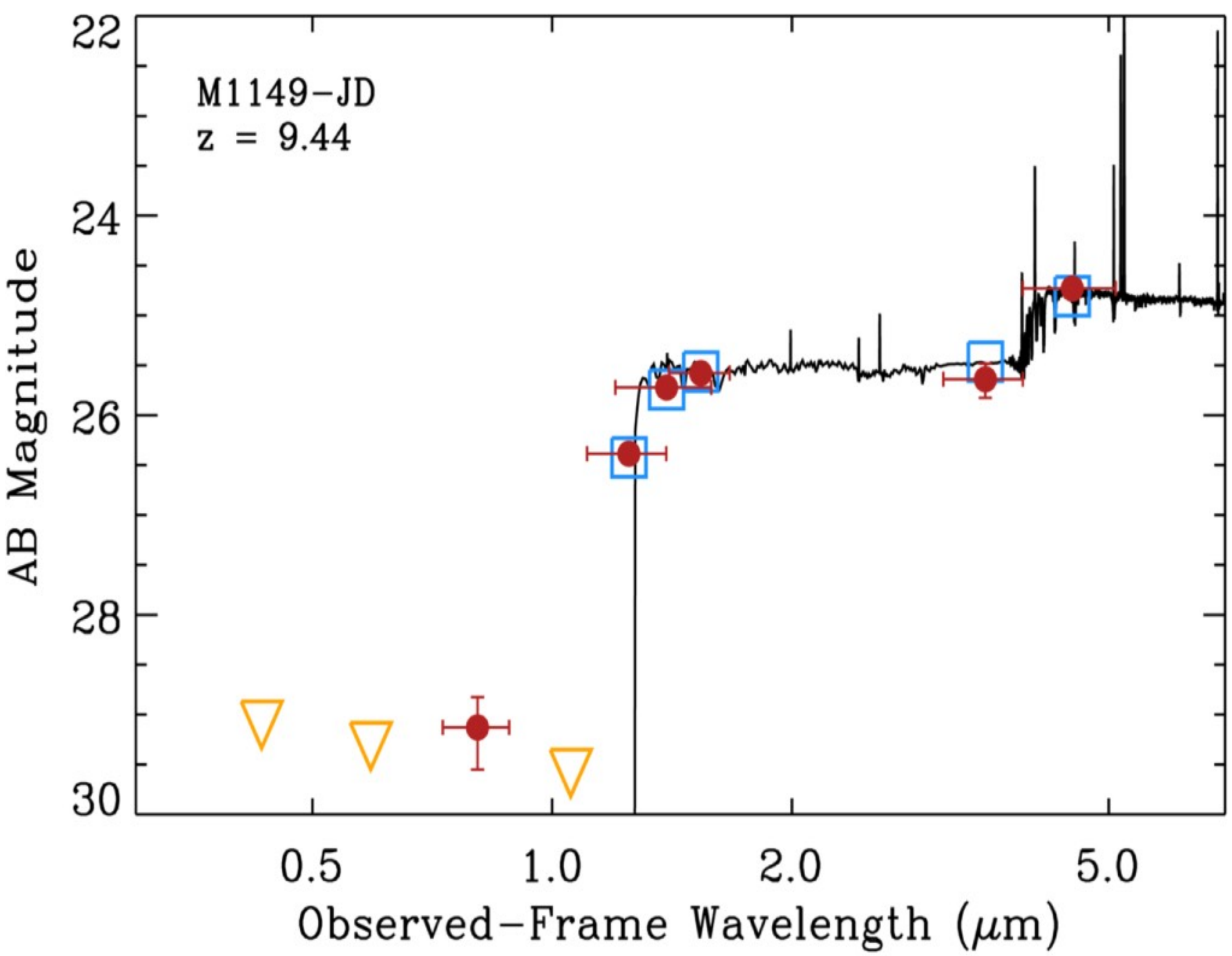
New science drivers

ALMA spectral scan search for Oxygen in MACS1149-JD





- ➢ Candidate galaxy at photometric redshift of *z*=9.4
- ➢ Universe only 500 Myr old!
- ➢ Spectroscopy needed to determine redshift
    - ➢ large uncertainties
    - ➢ contaminants at lower redshift

Zheng et al. (2017)
McLead et al. (2016)

New science drivers

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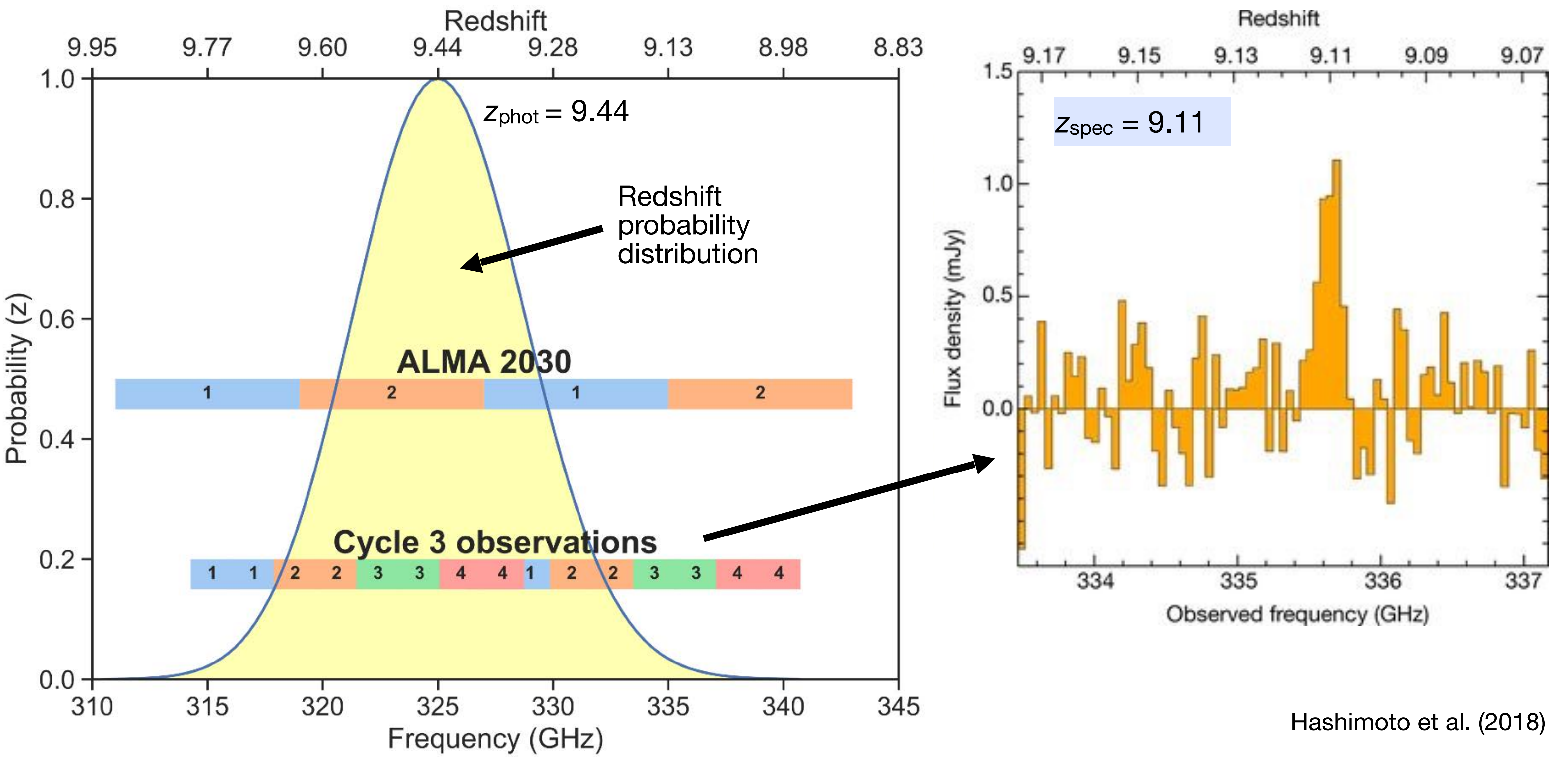

Hashimoto et al. (2018)

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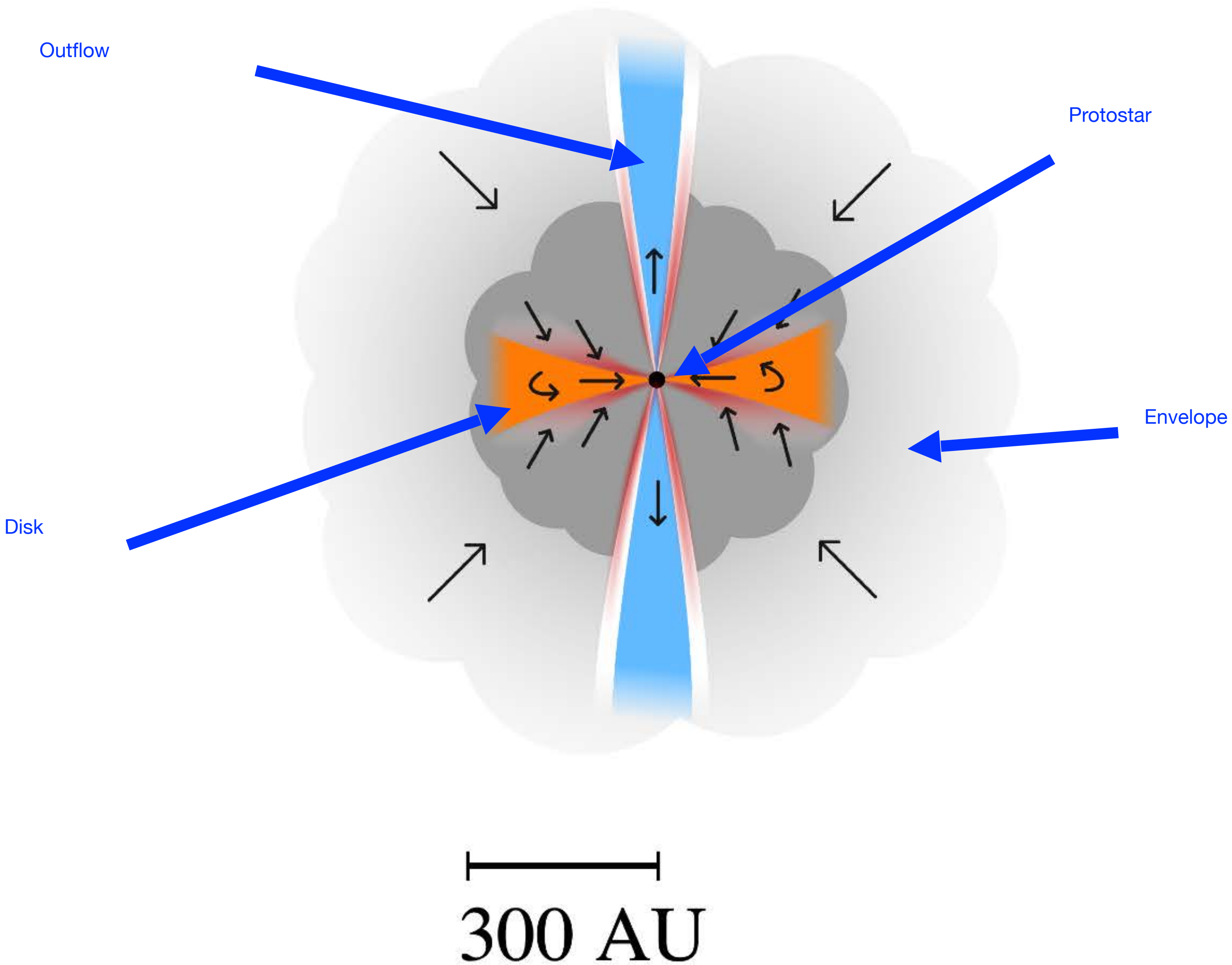
New science drivers

Star formation in molecular clouds



- *Why do some regions of clouds collapse to form stars, while others do not?*
- *Why are some stars 100 times **more** massive than the Sun, while others are 10 times **less** massive?*
- *What determines the distribution of stellar masses?*

New science drivers

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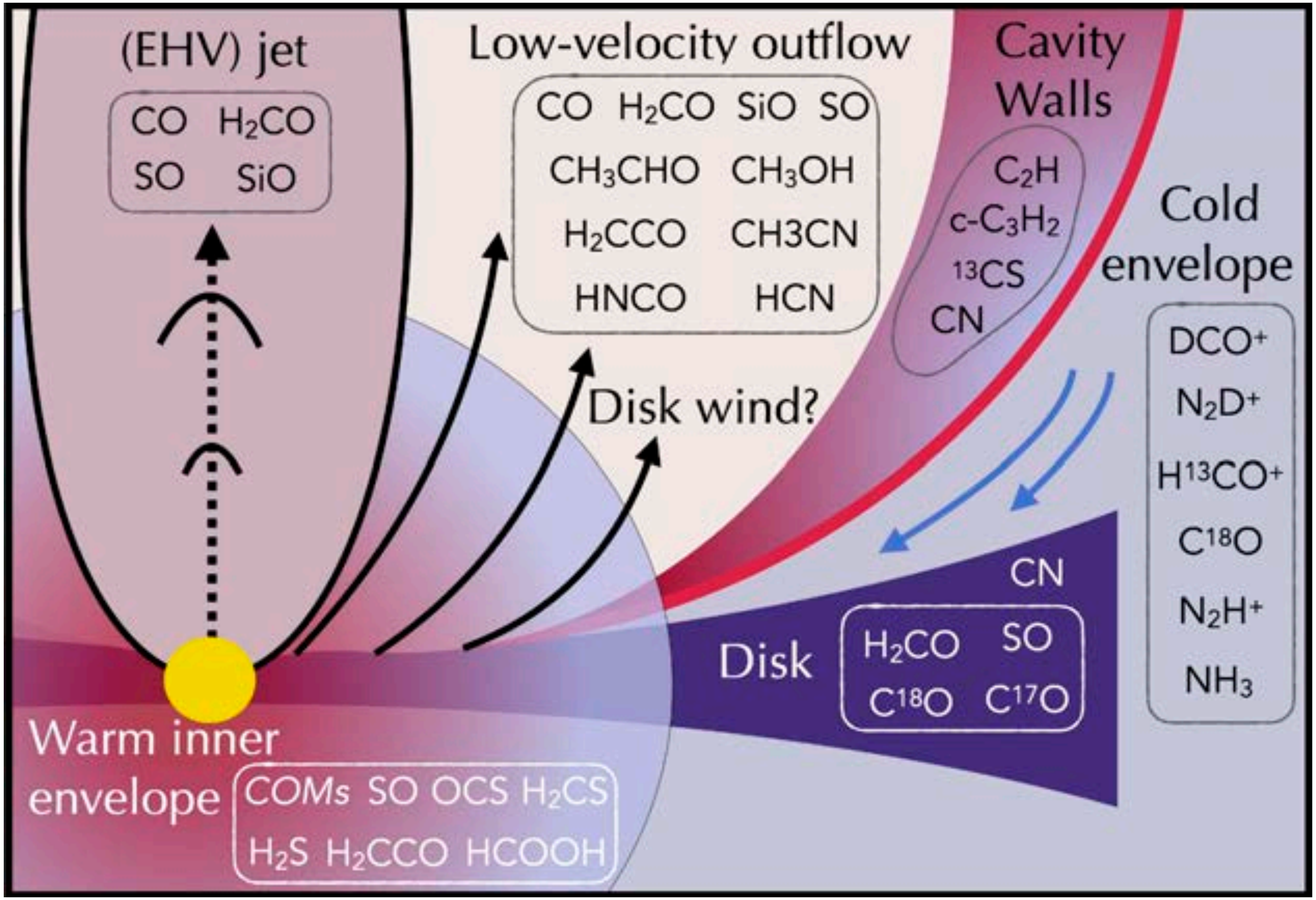

Tychoniec et al. (2021)

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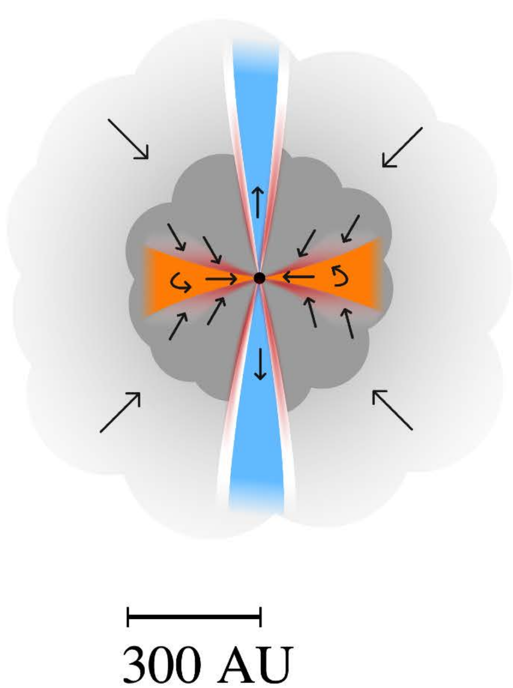
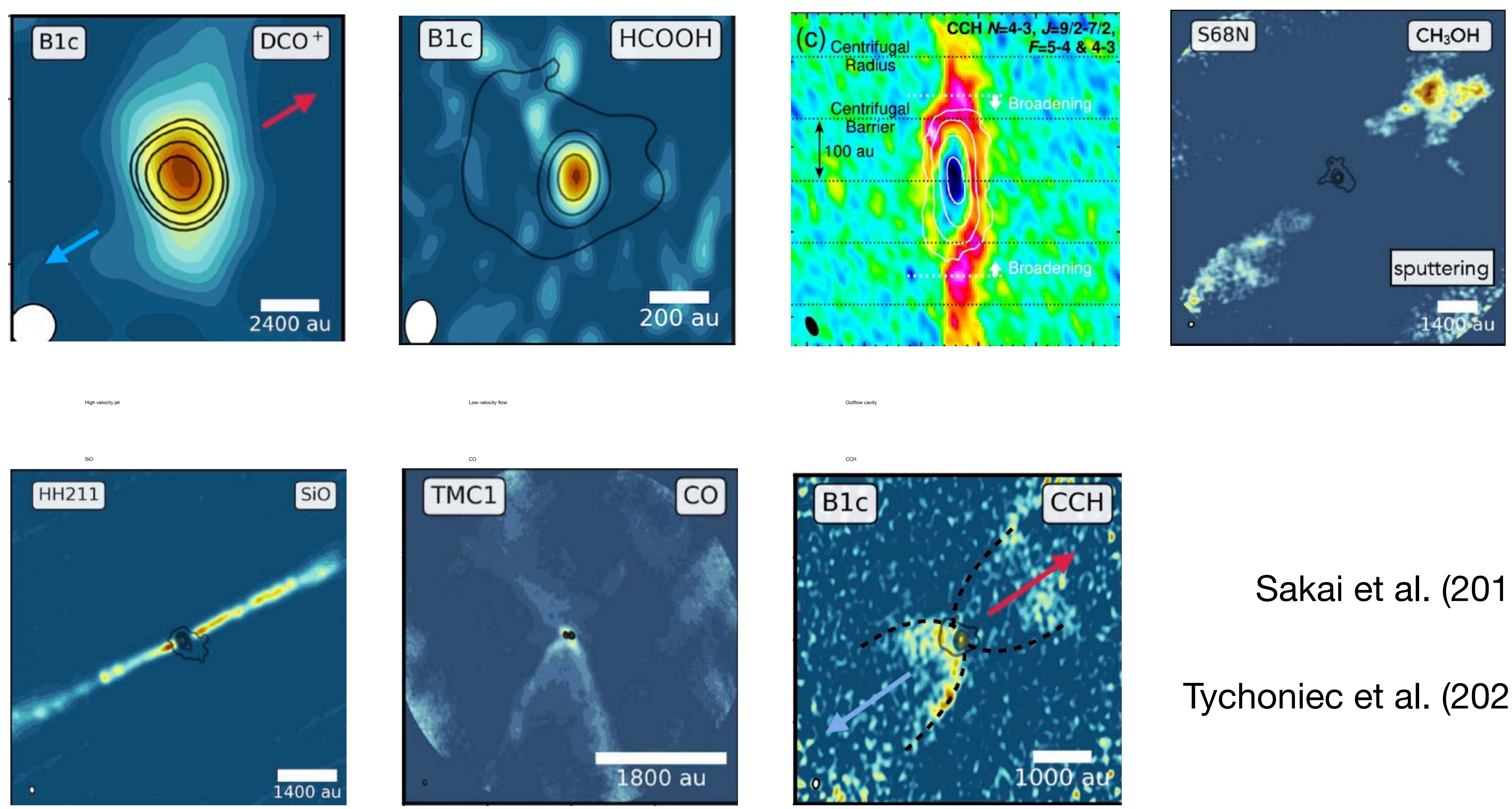


Envelope
DCO+

Hot core
HCOOH

Centrifugal barrier
CCH

Sputtering
CH_3OH



Sakai et al. (2017)

Tychoniec et al. (2021)

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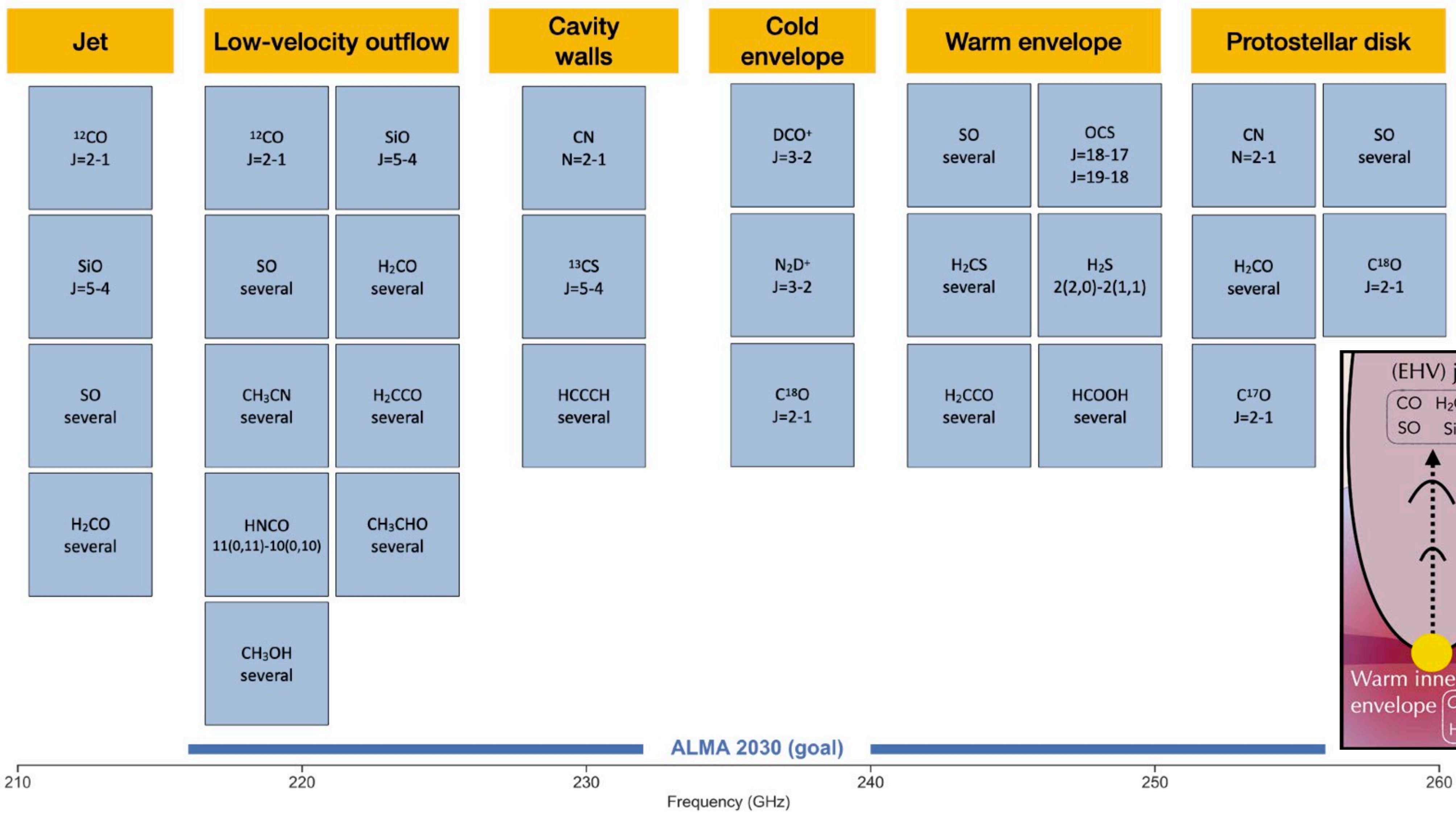

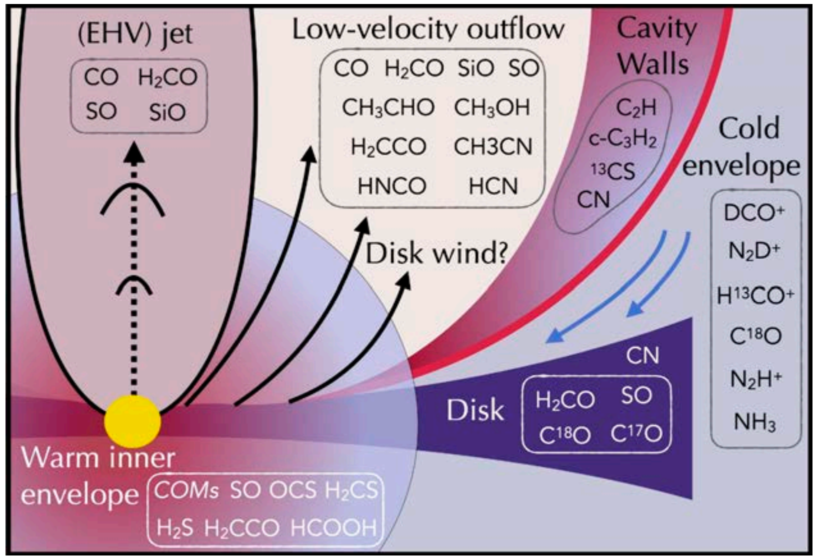

Tychoniec et al. (2021)

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Origins of planets

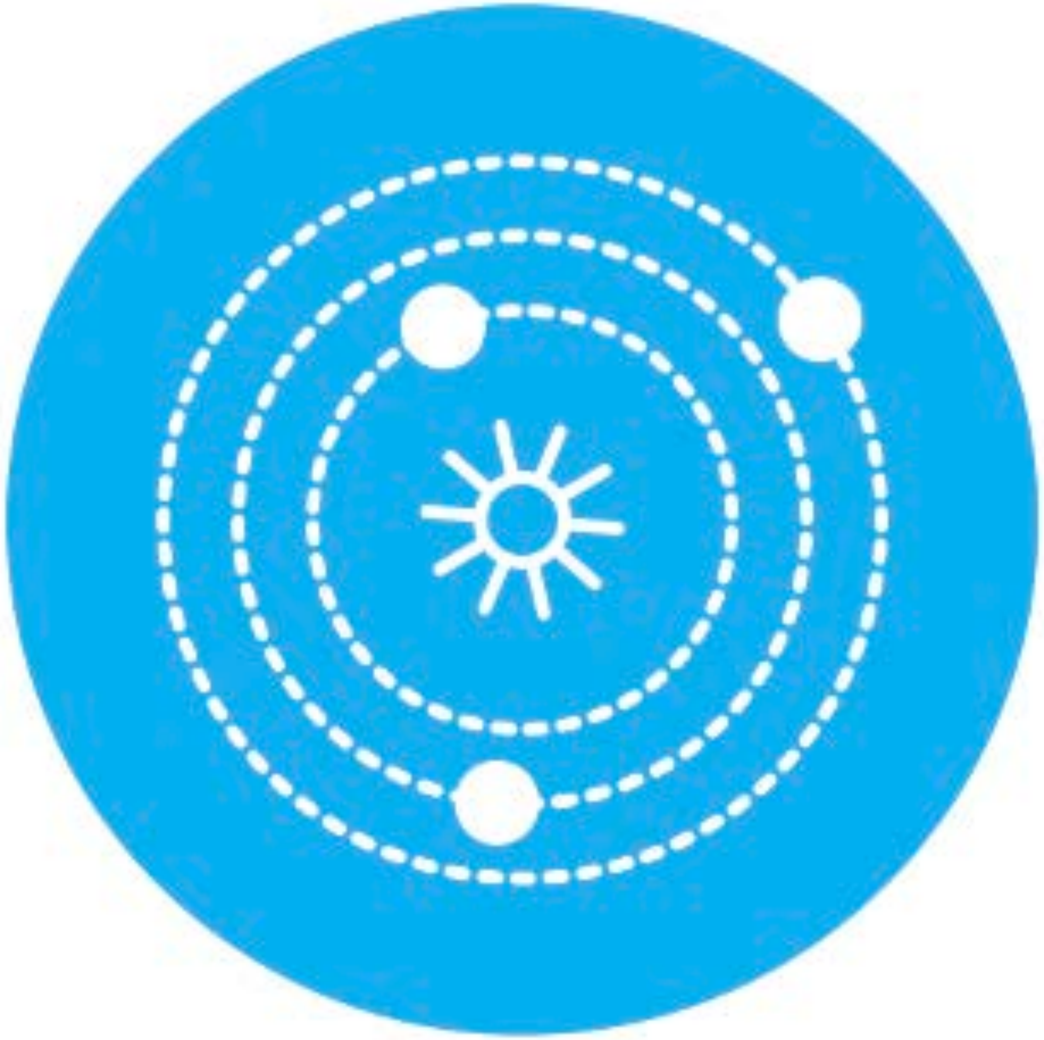
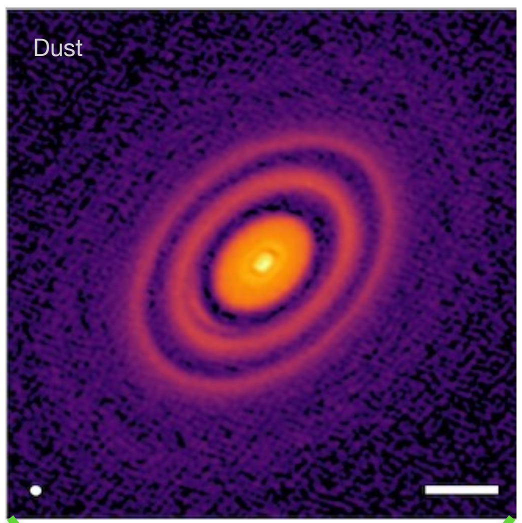


Image protoplanetary disks in nearby (150 pc) star formation regions to resolve the Earth forming zone (~ 1 au) in the dust continuum at wavelengths shorter than 1mm, enabling detection of the tidal gaps and inner holes created by planets undergoing formation.

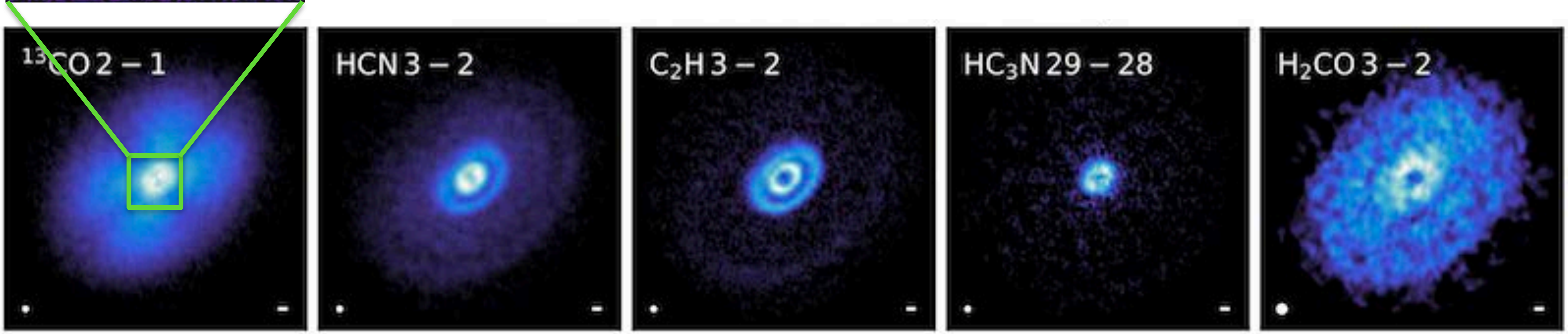
New science drivers

The power of molecular spectroscopy in disks

HD 163296



- ➢Gas mass: Dust only traces ~1% of the total disk mass; use molecules to trace the dominant disk component (H_2)
- ➢Chemistry and the chemical compositions of planets
- ➢3D velocity and temperature structure of disks
- ➢Detect embedded planets through velocity distortions



Öberg et al. (2021)

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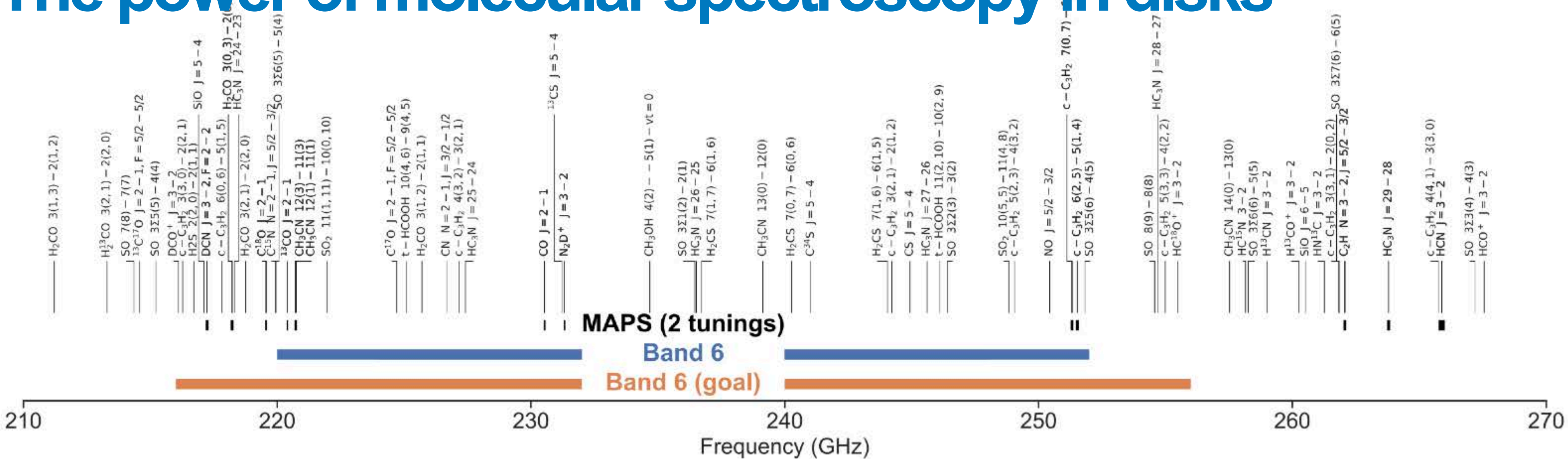
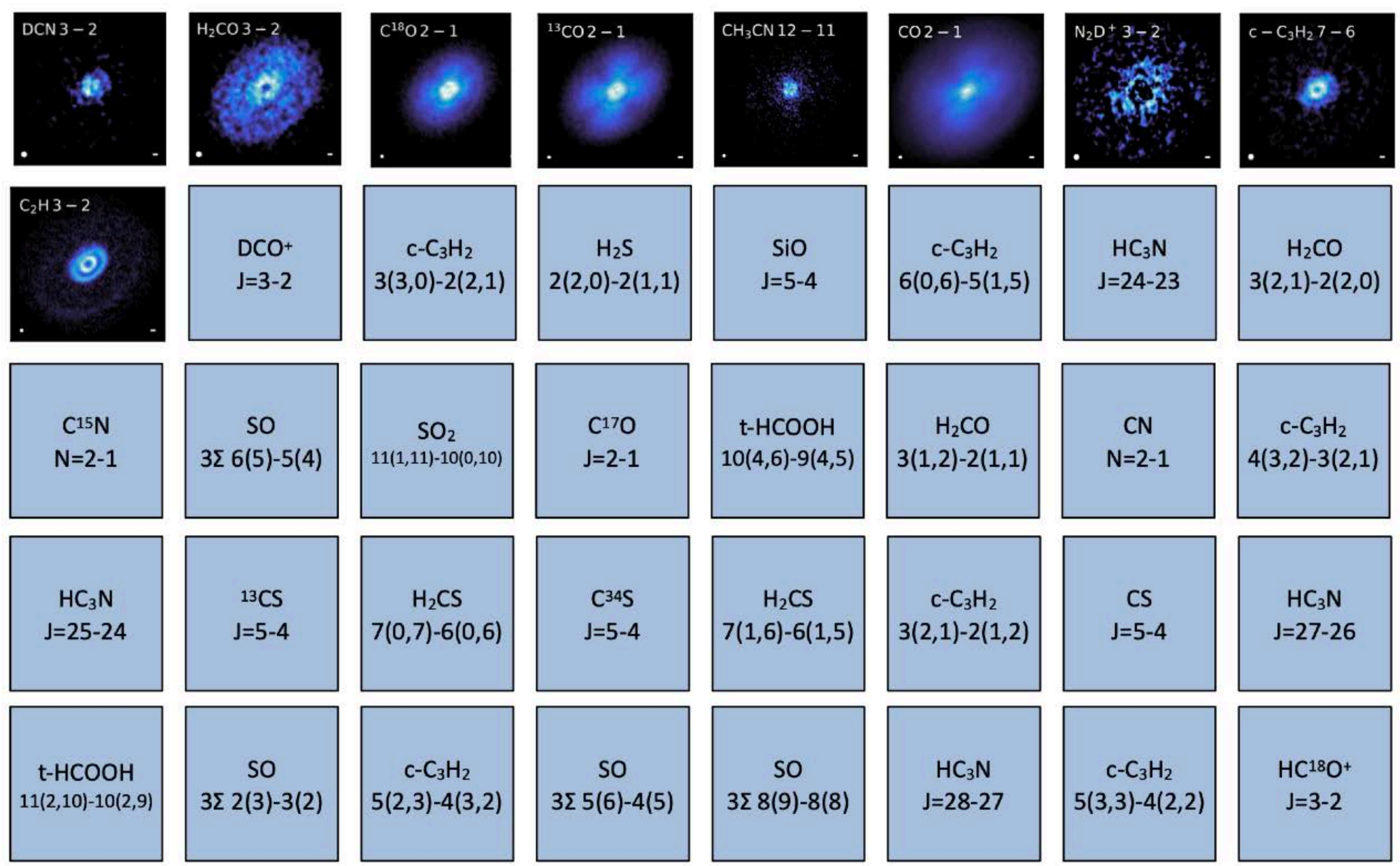




The ALMA 2030 Roadmap

Beyond the WSU

- *"Extending the maximum baseline length by a factor of 2-3 provides the exciting opportunity to image the terrestrial planet-forming zone in nearby protoplanetary disk"*

- *"Focal plane arrays could significantly increase ALMA's wide-field mapping speed"*

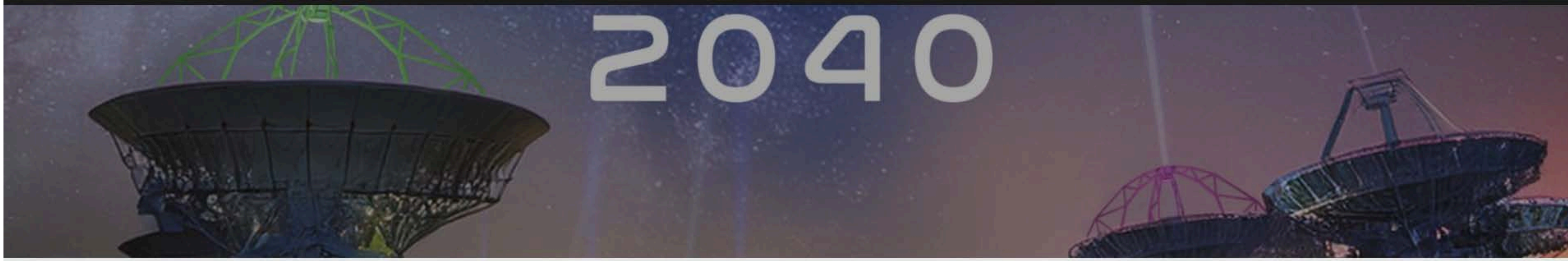
- *"Increasing the number of 12-m antennas would benefit all science programs by improving the sensitivity and image fidelity"*

- *"A large single dish submillimeter telescope of a diameter of at least 25-m would enable deep, multi-wavelength images of the sky and provide many scientific synergies with ALMA*"*

*(*not within the scope of current ALMA operations)*

European ALMA2040

European ALMA2040 | Home | Workshops | Contributing | Timeline | Working Groups | Contact



Transformational science with a (sub-)mm interferometer in the 2040s

Towards a radical upgrade of ALMA

Following the announcement from ESO about the start of the search for its next astronomical ground-based programme for the 2040s (ESO Expanding Horizons), the community is getting organized to prepare the science case for a new millimeter/sub-millimeter facility in the 2040s ("ALMA2040") which builds upon the successes of the current ALMA Observatory.

A series of workshops will take place in Europe in 2025 to discuss the scientific interest of the ESO community in such a facility, identify the key scientific questions to be addressed, and ultimately define the needed technical capabilities. ESO will issue a Call for Ideas in Q3/2026 with a deadline of 2027 June 1 (and a deadline of 2026 December 1 for Letters of Intent).

Here we aim to help coordinate the interests of the millimeter/sub-millimeter community.

Interested in contributing? Fill out this form to join a working group and/or submit a science pitch (<1 page).

Working Groups work on the following topics.

Workshops related to ALMA2040 are listed here.

Useful links

ALMA Observatory

White Paper: ASAC Recommendations for ALMA2030

Report of the Kavli-IAU Workshop on Global Coordination "Probing the Universe from far-infrared to millimeter wavelengths: future facilities and their synergies"

ESO Expanding Horizons -- Transforming Astronomy in the 2040s

Thank you for your attention