Atacama
Large
Millimeter/submillimeter
Array

ALMA 2030: The ALMA development vision and road map

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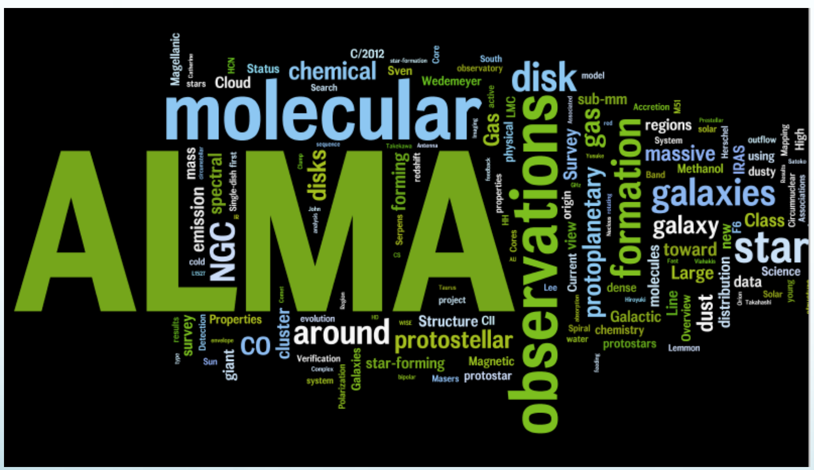
(with material from presentations by J. Carpenter, P. Cox, M. McKinnon, E. Murphy)

June 27, 2017

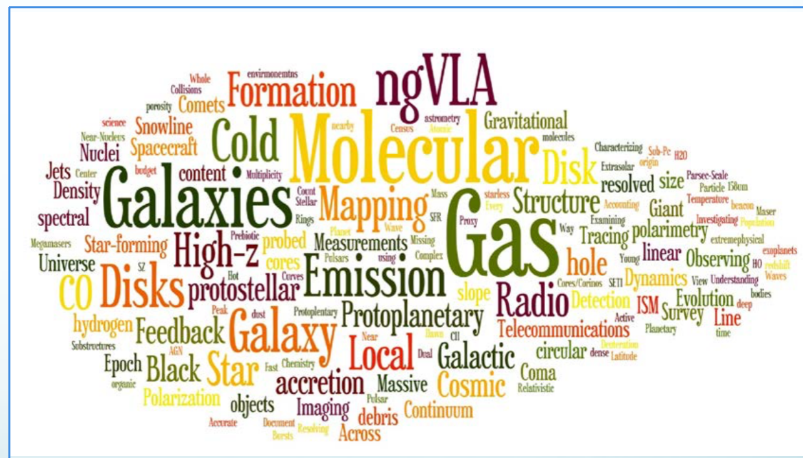
Complementary and overlapping science drivers

Revolution in astronomy with ALMA: the 3rd year (credit: C. Wilson)

Developing the ngVLA science program (credit: E. Murphy)

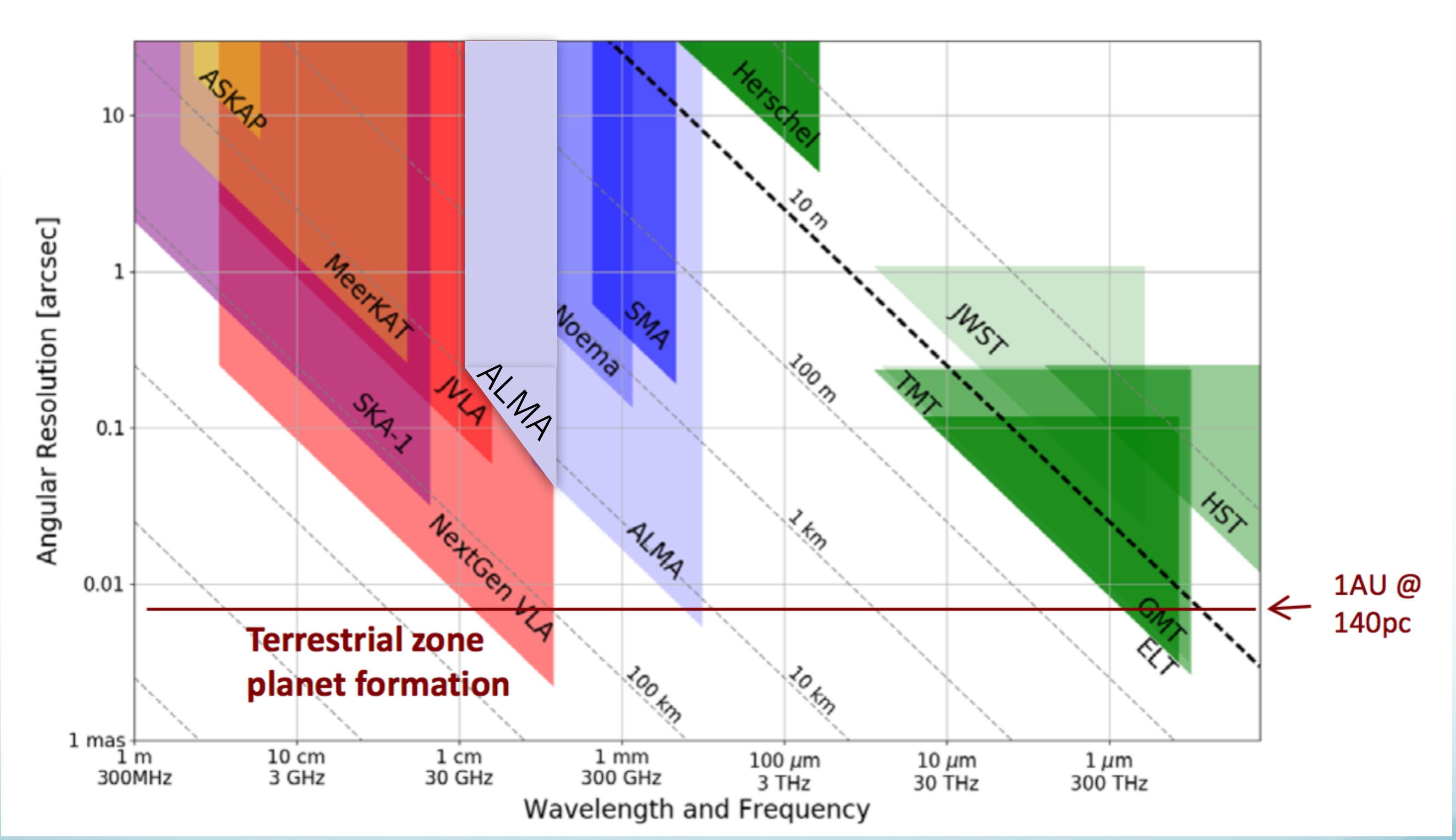


(credit: C. Wilson, 2014)



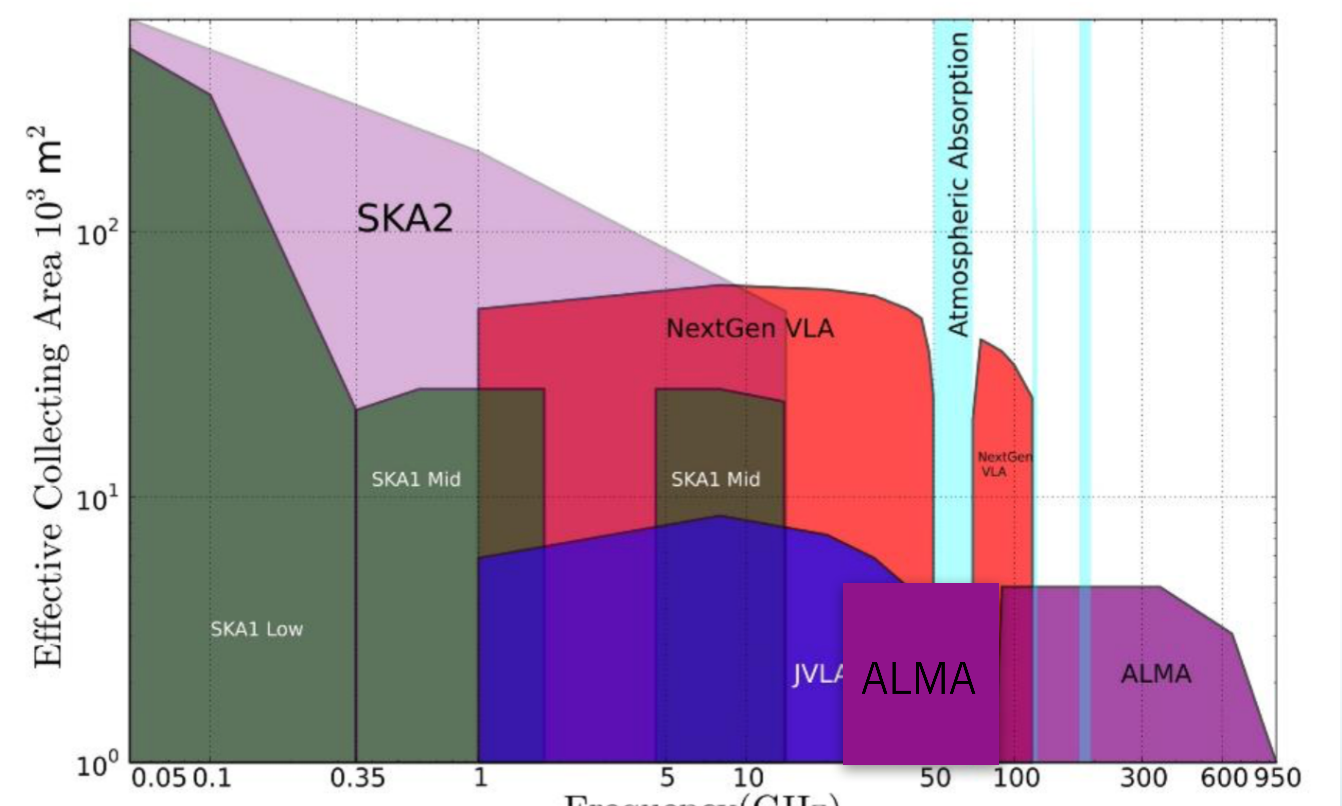
(credit: E. Murphy, 2017)

The landscape of ALMA, the VLA, and the ngVLA (1)



(credit: M.McKinnon, presentation to AUI Board)

The landscape of ALMA, the VLA, and the ngVLA (2)



SKA1 Baseline Design (2015)
SKA2 Baseline Design (2015)

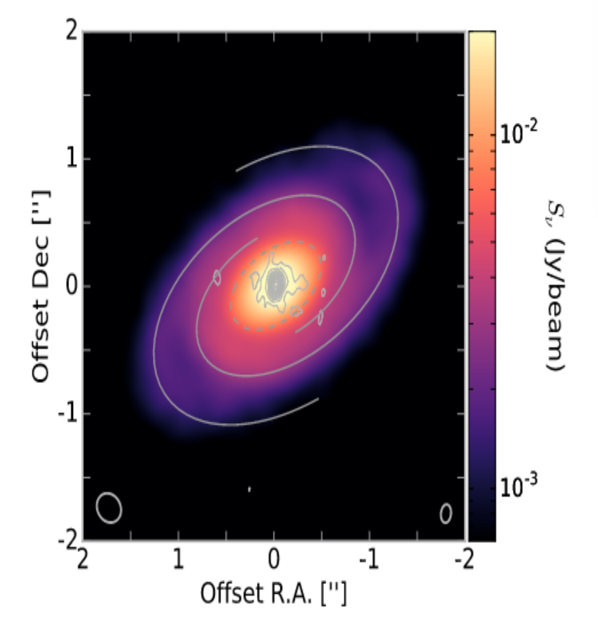
(credit: M.McKinnon, presentation to AUI Board)

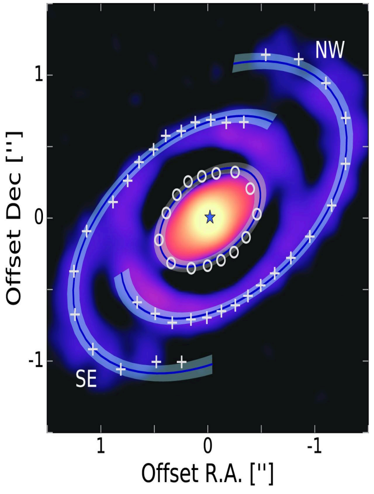
Original ALMA Science Drivers

- Most of the more important level-one science goals of the ALMA Baseline project have been essentially achieved in the first five years of ALMA operations.
- The three goals were:
  - ✓ *The 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;*
  - ✓ *The ability to image the gas kinematics in a solar-mass protostellar/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;*
  - ✓ *The ability to provide precise images at an angular resolution of 0.1"*

A Spiral Density Wave Observed in a Protoplanetary Disk

- Gravitational instabilities in protoplanetary disks excited by e.g. planet-disk interactions or gravitational instabilities
- Disk midplane structure provides a sensitive probe for these instabilities
- ALMA imaging (dust and CO, 33 AU resolution) reveals two symmetric spiral arms (r~150AU) emanating from an elliptical emission ring (r~71AU) in the disk Elias 2-27, in the nearby ρ Oph cloud
- spiral density wave fits the observations well
- fragmentation of such spirals is the only plausible formation mechanism for planets and companions at large disk radii



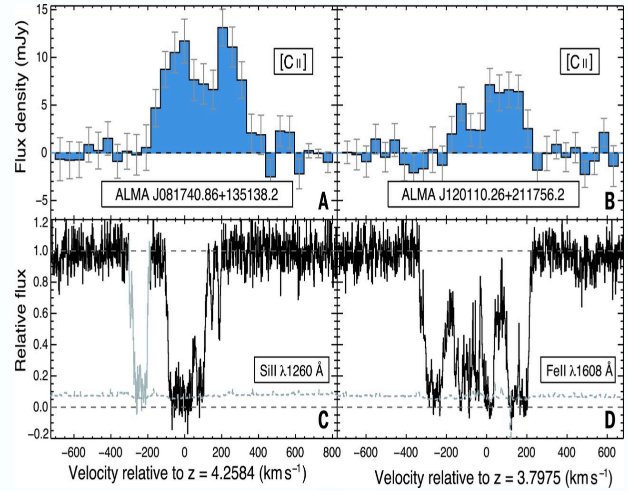


Top: ALMA 1.3mm image/VLA 9mm contours. Bottom: model

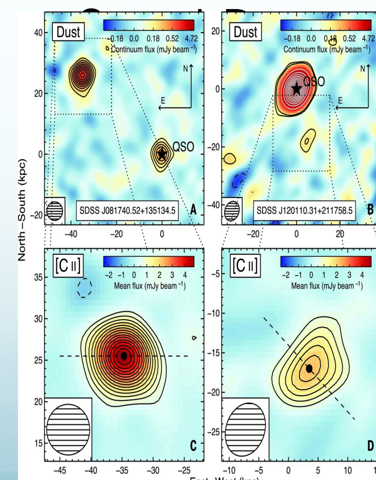
(Perez et al. 2016, Science)

Super-haloes surround early Milky-Way-like galaxies

- Using ALMA, astronomers observed young Milky-Way like galaxies at z~4 and probed their haloes by measuring even more distant QSOs through them.
- QSO-galaxy offsets probe the galaxy halo far beyond the ~5kpc extent of [C II] emission
  - The host galaxy has enriched its inner gaseous halo
  - The halo is bound to the host, will eventually be accreted and enrich star-forming gas.



Top: [C II] emission from the host galaxies A and B. Bottom: QSO absorption (Si II and Fe II) features



Top: 400-GHz continuum emission near two QSOs (black stars). Bottom: Mean flux density over the full [C II] line profiles; dashed line is the galaxy's major axis.

(Marcel Neeleman et al 2017, Science)

ALMA Development Vision: Summary

The ALMA Development Working Group has recommended the following developments (in order of priority):

1. Broaden the receiver IF bandwidth and upgrade the associated electronics and correlator. The main bands considered for upgrades are Bands 7, 6, 3 and 9, with Band 7 and 6 deemed to have equal priority
2. Increasing the number of 12-m antennas within the baseline array by 14 to 30
3. Expanding the baseline length by a factor of 2-3
4. Focal Plane Arrays

Increased throughput with upgraded receivers and correlator

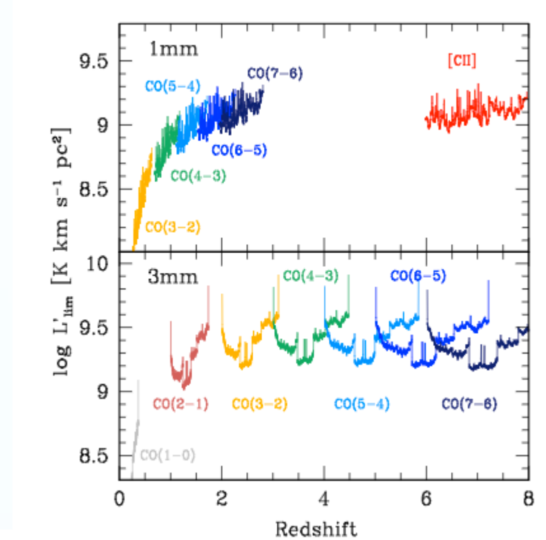
- The top ALMA development priority is to expand the bandwidth of the receivers and upgrade the digital system and correlator.

- This upgrade will benefit a wide range of science programs by:
  - Improving the continuum sensitivity
  - Increasing the ability to observe several molecular transitions simultaneously
  - Reducing the time to conduct blind redshift surveys or chemical spectral scans by at least a factor of 2 and a factor of 8-16 for high spectral resolution spectral scans

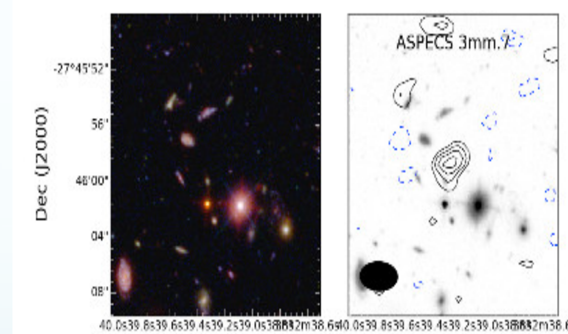
- Significant gains in the observing speed require upgrades to:
  - The receivers to deliver large IF bandwidths
  - The digitizers and digital processing to allow for large basebands and higher effective bandwidth coverage
  - The correlator to process larger bandwidths at higher spectral resolution

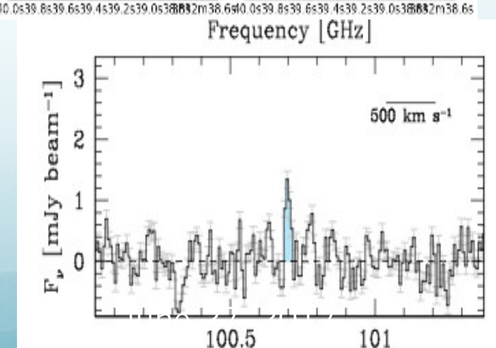
Evolution of Galaxies and Black Holes

- Science Drivers
  - Kinematics measure of nearby nuclear Black Hole mass
  - Kinematics characterize galaxies through cosmic time
  - Spectra characterize chemical content



- Instrumental needs
  - Sensitivity: detecting weak signals
  - High resolution, probing $R_{galactocentric}$<50pc regions
  - Spectral grasp covers appropriate redshifted lines





ASPECS: Spectral coverage deCarli et al. 2016, ApJ; weakest 3mm detection, Walter et al., 2016, ApJ

Receiver Band Upgrades

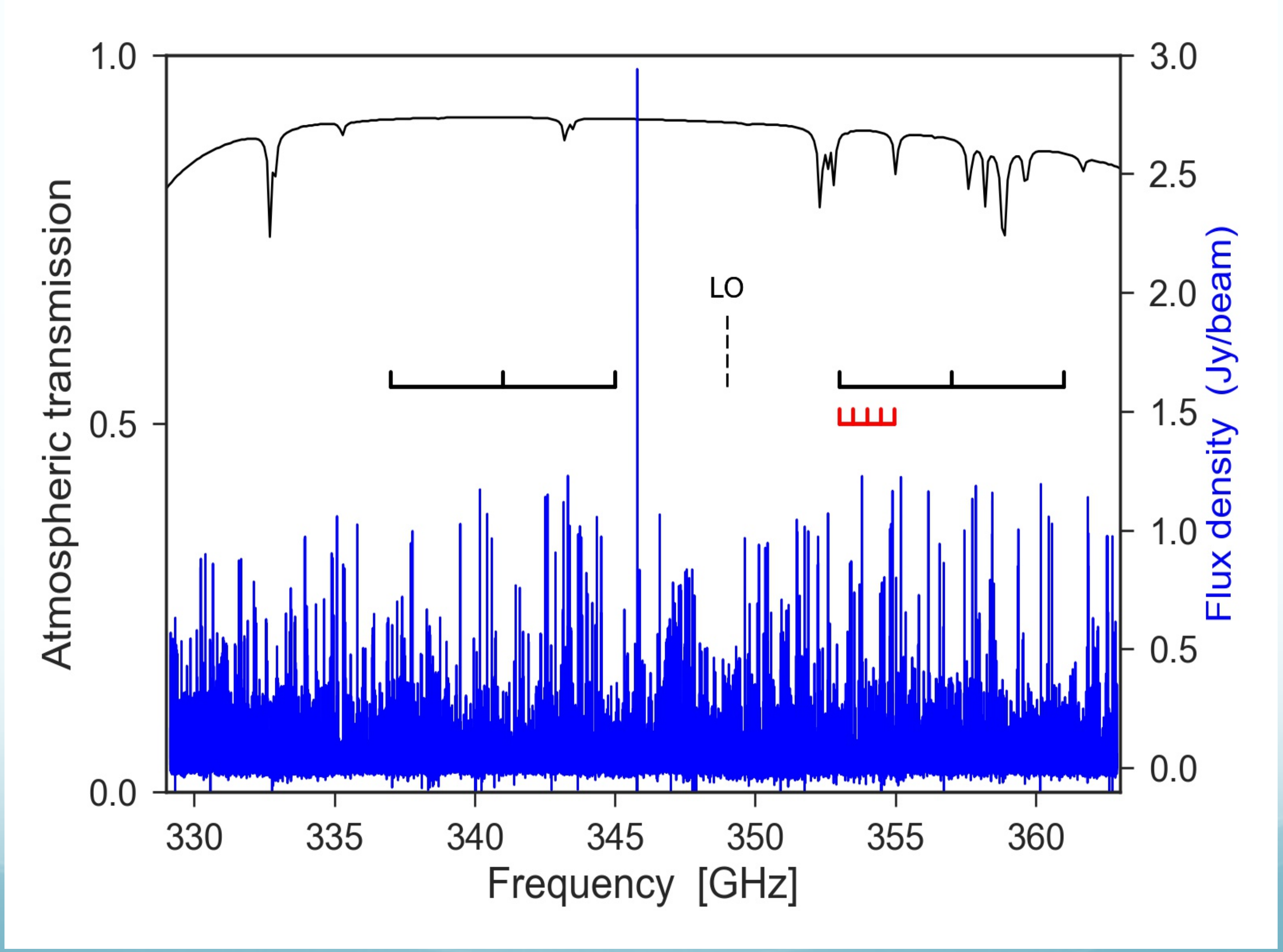
- The following receivers are recommended for upgrades assuming 8 GHz bandwidth per sideband and polarization in a 4-12 GHz IF

- **Band 6 (211-275 GHz) and Band 7 (275-373 GHz)**
  - Cover all isotopologues (^{12}CO, ^{13}CO and $C^{18}O$) in a single setting; increase in the efficiency of spectral surveys, reducing the required observing time by a factor ~8, for high spectral resolution (0.25 km/s) surveys; both bands are the choice for continuum studies (improvement on calibration); probing galaxies at the epoch of re-ionization (e.g., Band 6 can probe C^+ at z=5.9 to 8)

- **Band 3 (84-116 GHz)**
  - Important for the study of high-*z* galaxies and the structure of interstellar medium; all Band 3 can be covered in 2 settings only; probing molecular complexity in cold galactic sources with an order of magnitude greater efficiency; continuum science (thermal and non-thermal)

- **Band 9 (602-720 GHz)**
  - Provides the smallest spatial scales at long baselines, reaching 1 AU in the nearest star-forming regions; if single-side band, spectral line observations in Band 9 will benefit tremendously; probing C^+ at the peak of star formation at z=2; self-calibration for fainter sources

Increased throughput with upgraded receivers and correlator



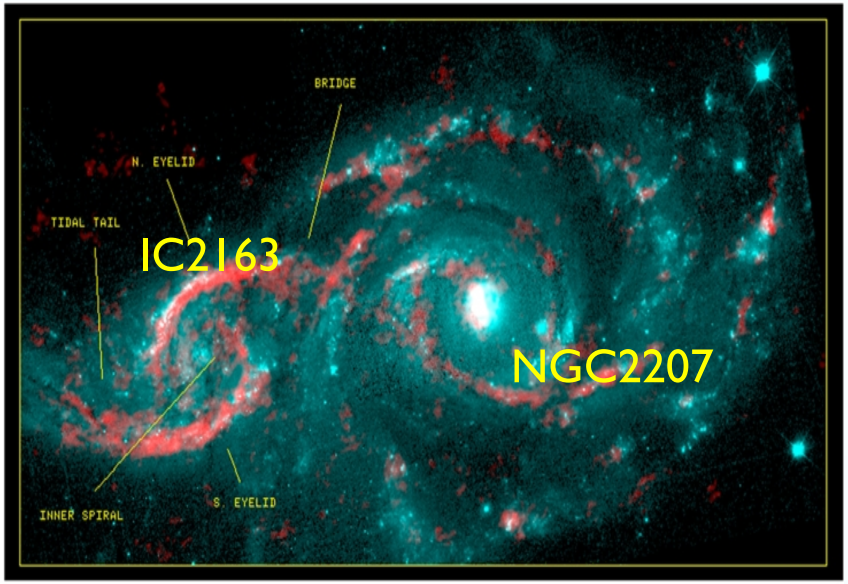
Additional 12-m Antennas

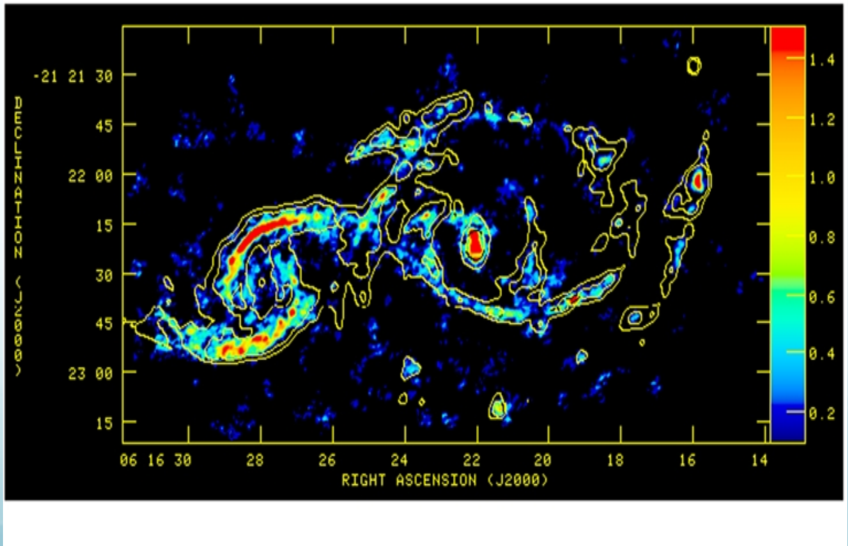
- Adding 12-m antennas to the array benefits all science programs
- Adding 30 antennas to the baseline array will:
  - Improve the sensitivity by 60%
  - Shorten the integration times by 150%
  - Enhance image fidelity due to 160% increase in the number of baselines
  - Significantly improve the uv coverage for longest baseline configurations, enabling to image complex emission regions with high resolution, especially at high frequencies
- These improvements will impact new science drivers significantly:
  - For spectral surveys of proto-planetary disks, the increase in observing speed would correspond to factor of 20-40 in addition to the gain of the receiver/correlator upgrade, enabling far more efficient mapping of the gas and hence their chemical composition.
  - For high-z galaxies, blind spectral surveys would be done 5-10 times more quickly when combined with the 8 to 16 GHz IF bandwidth per sideband and polarization.

Ocular Shock Front in the Colliding Galaxy IC 2163

Interaction compresses CO, stimulates star formation

- Tsunami of stars and gas crashes midway through the IC2163 spiral disk
  - triggered when IC 2163 sideswiped spiral galaxy NGC 2207
  - produced dazzling arcs of intense star formation
- Direct measurement of compression shows how the encounter between the two galaxies drives gas to pile up, spawn new star clusters





(Kaufman et al 2016, ApJ)

Additional 12-m Antennas

- Additional antennas also bring numerous operational and imaging capabilities with large science benefits
  - Antenna configurations can cover a wider range of resolution so that a greater number of programs can be accommodated with any given configuration; saves time and utilizes more efficiently the best weather conditions during the year
  - Better sensitivity can make more calibrators accessible closer to the source; allows for better phase correction, which is crucial for high frequency observations
  - Robustness and availability of the self-calibration technique will be increased
- Clearly, the addition of 30 antennas to the current ALMA interferometer, which will result in an array of 96 antennas in total, combined with the upgrade of the receivers/correlator, will keep ALMA at the forefront of astronomical observations for the decades to come.

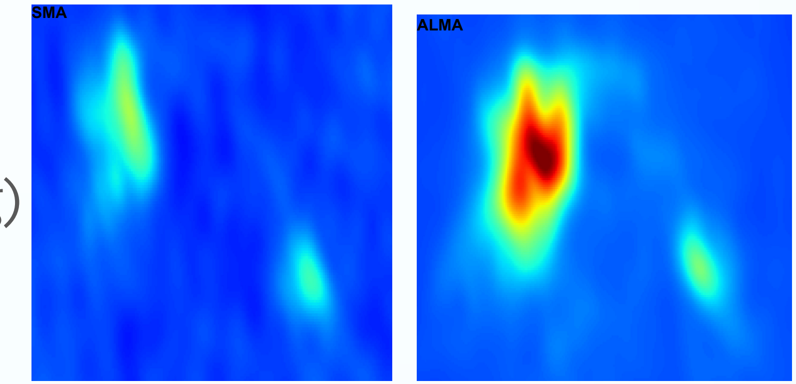
ALMA Catches, Characterizes Massive Star Outburst

Recent outbursts in YSOs show similar features:

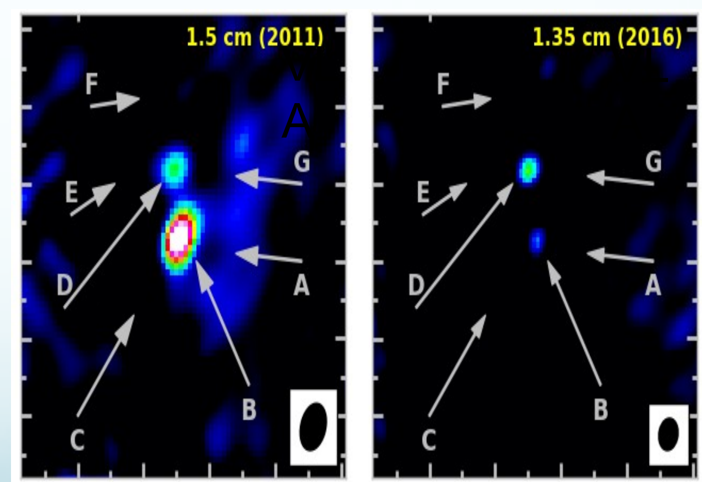
- Factors of 6-70x increase in L
- Sustained for many years (ongoing)

NGC6334I-MM1 dust continuum outburst is accompanied by:

- Dimming of the HCHII region by a factor of 4: suppression of UV photons
- Candidate compact disk/outflow system
  - disk traced by hot SO_2, outflow traced by $C^{34}S$ and 6 cm jet direction, and maser flare
- consistent with B4 ZAMS star accreting >= $0.1M_{\odot}$ in a short period
- further monitoring and modeling required to understand details



Pre-outburst Post-outburst



T. Hunter et al. 2017 ApJL

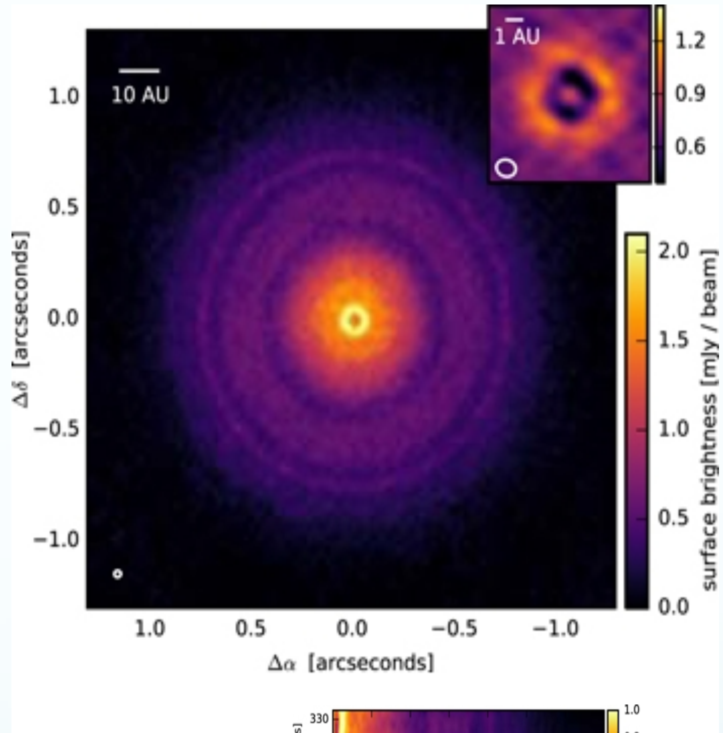
Very long baselines

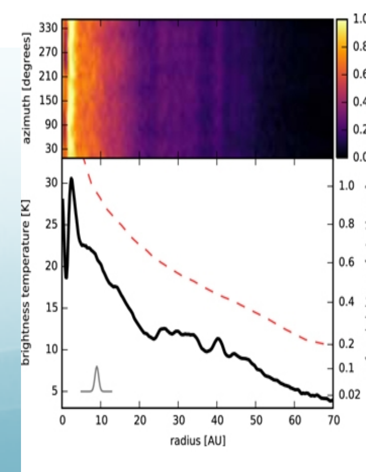
- Expanding the longest baselines by factor of 2-3 (to 30 to 50 km) will enable ALMA to probe astronomical sources with exquisite detail
  - provides tantalizing possibility to image dust continuum in nearby proto-planetary disks at 1 AU scales (~10 mas), down to habitable zones, at low frequencies where dust optical depths are low
- Very long baselines will also enable ALMA to:
  - Resolve the morphology of evolved stars to probe the mass loss process and trace the regions of dust formation (nucleation and growth).
  - Measure at the smallest scales the dust and molecular emission of the torus around AGN, including maser emission.
- Working Group assumed at least six additional antennas, permanently stationed on new pads, would be needed to provided minimal *uv* coverage on the longest baselines.
- Further studies are required to determine if 6 are sufficient to achieve necessary image fidelity and sensitivity in brightness temperature to probe at 1 AU scale nearby proto-planetary disks at low frequencies.

Ringed Substructure and a Gap at 1 AU in TW Hya

- 870 µm continuum, 20mas (1AU resolution)
- Bright zones, narrow (1-6 AU) dark annuli of modest contrast trace concentrations of solids halted in inward radial drift, perhaps at local gas pressure maxima
- Related to condensation fronts of major volatile species?
- Disk-young planet interaction: Narrow dark annulus at ~1AU?

(S. Andrews et al., 2016, ApJL)





Focal plane arrays

- Focal Plane Arrays could significantly increase ALMA's wide-field mapping speed, thereby contributing significantly to the new science drivers
  - Imaging entire GMCs (~10 deg^2) probes how gas and dust evolves from the largest to the smallest scales, from filaments onto protostars and protoclusters
  - Imaging nearby galaxies (0.1-few deg^2) provides global view on how galactic environment influences star formation efficiency in individual GMCs
  - Wide-field cosmology surveys (up to ~2 deg^2) are necessary to overcome cosmic variance and measure evolution of gas and dust over cosmic time
- Deep mosaics rather prohibitive today
  - imaging 1 deg^2 at Nyquist sampling with ALMA requires 19,000 pointings in Band 3 and 208,000 in Band 7
  - About 100 hours of telescope time would be needed to image a 1 deg^2 area in Band 3 to 0.15 mJy continuum sensitivity
- A significant increase in mapping speed presents an opportunity to expand ALMA's science reach

ALMA 2030: looking to the future

- The future developments recommended by the Working Group will have profound impacts on many aspects of the ALMA activities
  - careful planning is necessary; for example, requirements of the next generation correlator will depend on the upgraded IF bandwidth and the number of additional antennas.
- Many of the recommended developments need further scientific and/or technical studies.
  - Technical requirements and goals for the receivers upgrade and the new generation correlator should be actively pursued to explore and define the best solutions in view of available and anticipated technology
- Some developments require a more detailed scientific case
  - the case for longer baselines needs to be further assessed to determine the number of antennas needed to achieve the requested brightness temperature sensitivity
  - a more solid science case for the Focal Plane Arrays would enable technical choices to be made for future studies.
- **It is urgent that the scientific and development communities collaborate to set the technical requirements and goals for the next generation developments for ALMA**

Thank you!

Christine Wilson, McMaster University

A Large Single-Dish Submillimeter Telescope

- A Large, Single-Dish submillimeter telescope (LSD) of diameter between 25 to 50-m would provide many scientific synergies with ALMA. Such a telescope, equipped with large format cameras, will survey the sky thousands times faster than ALMA and allow to:
  - Measure the production of metals and the build-up of the interstellar medium from the earliest galaxies to the present time.
  - Identify large samples of star-forming galaxies in the early universe to probe the epoch of re-ionization and the formation of the first galaxies.
  - Map out large-scale filamentary structures in clouds and trace the flow of gas from the diffuse molecular clouds, to filaments, to dense cores and protoclusters.
- A LSD will have powerful synergies with ALMA, due to its high efficiency at identifying large samples of sources and performing wide area high- and low-spectral resolution mapping, which will allow ALMA to focus on the high-resolution, high-sensitivity follow-up studies. E.g., extragalactic spectral surveys, mapping galactic scales in the Milky Way and nearby galaxies, large-scale mapping at high frequencies, large-scale polarization of the ISM.
- It is noted that the mode of operation of a LSD, with the emphasis on large scale sky surveys that are independent of direct interferometer observations, is not within the scope of current ALMA operations. A re-definition of the scope of the ALMA projects by the ALMA Partners would be necessary to consider a LSD as appropriate for the ALMA development line.

Process

- The ALMA2030 document provided the initial framework for the scientific vision and technical possibilities and recommended four development paths, namely:
  - ✓ *Improvements to the ALMA Archive: enabling gains in usability and impact for the observatory.*
  - ✓ *Larger bandwidths and better receiver sensitivity: enabling gains in speed.*
  - ✓ *Longer baselines: enabling qualitatively new science.*
  - ✓ *Increasing wide field mapping speed: enabling efficient mapping.*

- The Working Group also considered additional antennas and a large single dish

- The goal of the new document is to review and prioritize the developments suggested, advance major ideas that are science driven, and outline a roadmap for development over the next decades.

- Over the past year, the Development Vision Working Group has been seeking advice from throughout the ALMA community through workshops, conferences (Indian Wells) and individual meetings.

- The ASAC provided additional scientific guidance by prioritizing which receiver bands should be upgraded as well as further insight into the scientific benefits of increasing the large baselines.

Technical Challenges and Operational Impact

Project	Technical Challenges	Operational Impact
Increased Throughput	✓ Band 3, 6, 7: increasing bandwidth ✓ Band 9: improving T_{sys} and/or bandwidth ✓ IF expansion vs receiver noise increase ✓ Upgraded signal transport chain, correlator, software and data flow	✓ Relatively low impact (reduction pipeline, increase in data processing speeds and archive capacity)
Additional Antennas	✓ More than 64 antennas requires a new correlator design ✓ Sufficient density of pads within concession ✓ Restart production lines of antennas/receivers	✓ Basic mode of operation will remain unchanged and energy consumption within the current capacity ✓ Increase in maintenance costs
Long Baselines	✓ New pads and associated infrastructure; permanently mounted isolated antennas ✓ Identify suitable locations ✓ At least six antennas (further studies needed) ✓ Role when ALMA is in compact configuration	✓ Obtaining permission to build and operate outside of concession ✓ New stations (power, cables) and access roads ✓ Maintenance and protection
Focal Plane Array	✓ Cryostat space availability ✓ Number of pixels and frequency bands ✓ Correlator capacity	✓ Further investigations needed to evaluate operational impact ✓ Starting with TP antennas
Large Single Dish	✓ Large aperture (25 to 50 meters) to achieve high sensitivity and angular resolution, wide field-of-view and high	✓ Located on Chajnantor plateau ✓ Major expansion of ALMA operations (control system

Note on the Archive

- The Working Group concurs with the ASAC's remarks that the ALMA Science Archive will become the source of probably the majority of future publications based on ALMA results.
- Therefore the ability to efficiently mine the archive contents is vital to the community and ALMA's future.
- The current archive provides the basic functionality to facilitate archival research and the 5-year archive development plan will provide additional functionality to facilitate archival research.
- However, the heterogeneity of the archive contents and the current approach to restore calibrated visibilities hinder archival research, and must be solved to secure the future efficient use of the archive, in particular with the increased volume of data that will results from the here described developments.
- The funds allocated to archival improvement are modest and ALMA needs a long-term solutions to the above issues as soon as possible.