ALMA capabilities: present and future

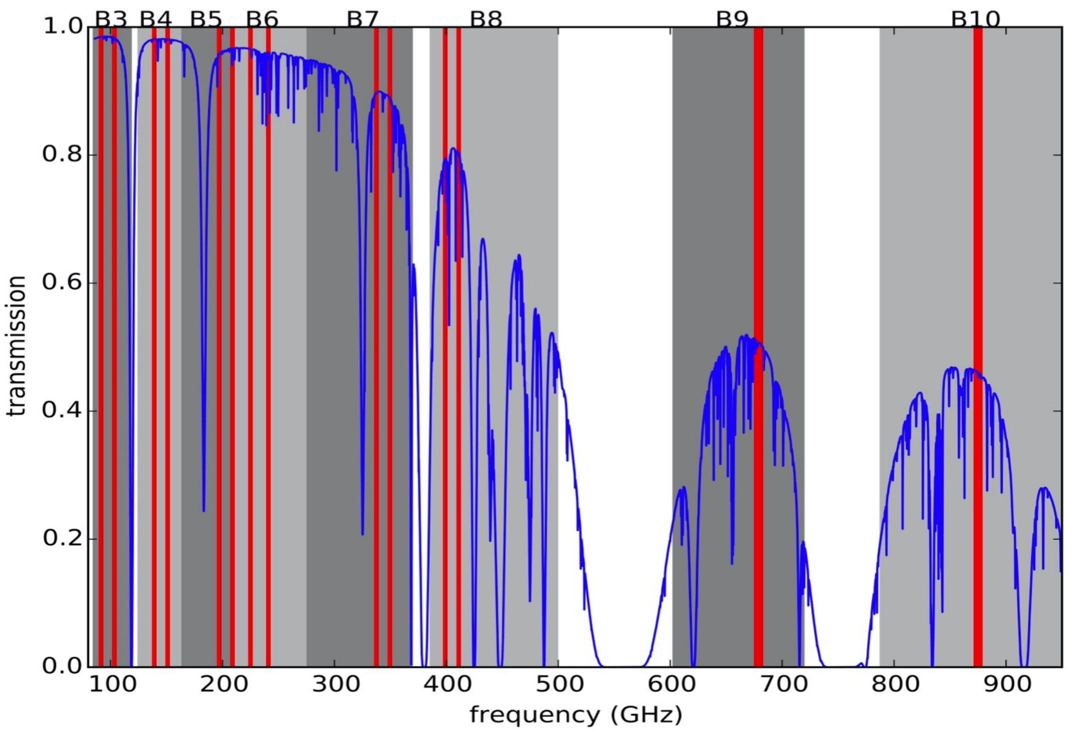
Carlos De Breuck/María Díaz Trigo

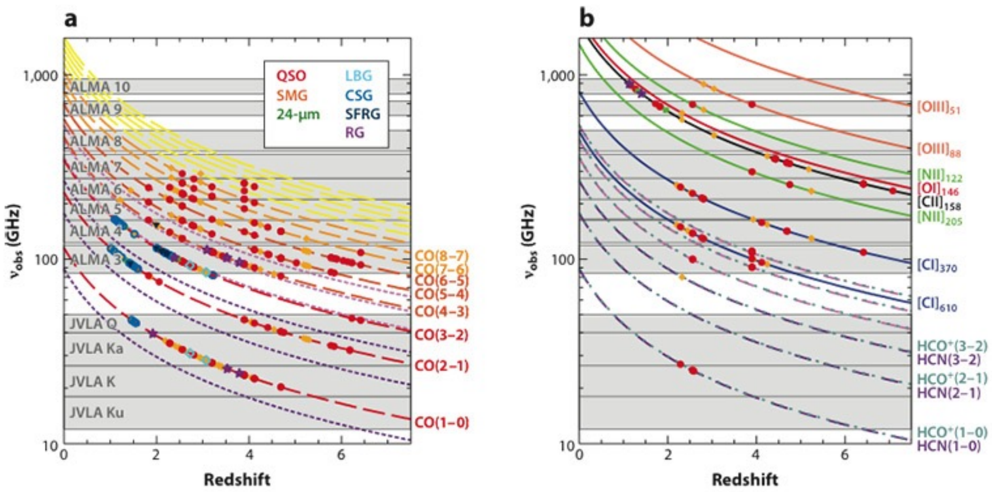
(ESO)

Atacama Large Millimeter/submillimeter Array

- Sixty-six antennas arranged in three different arrays at 5000 m altitude in the Atacama desert
- Start of operations in 2011

ALMA capabilities: frequency coverage





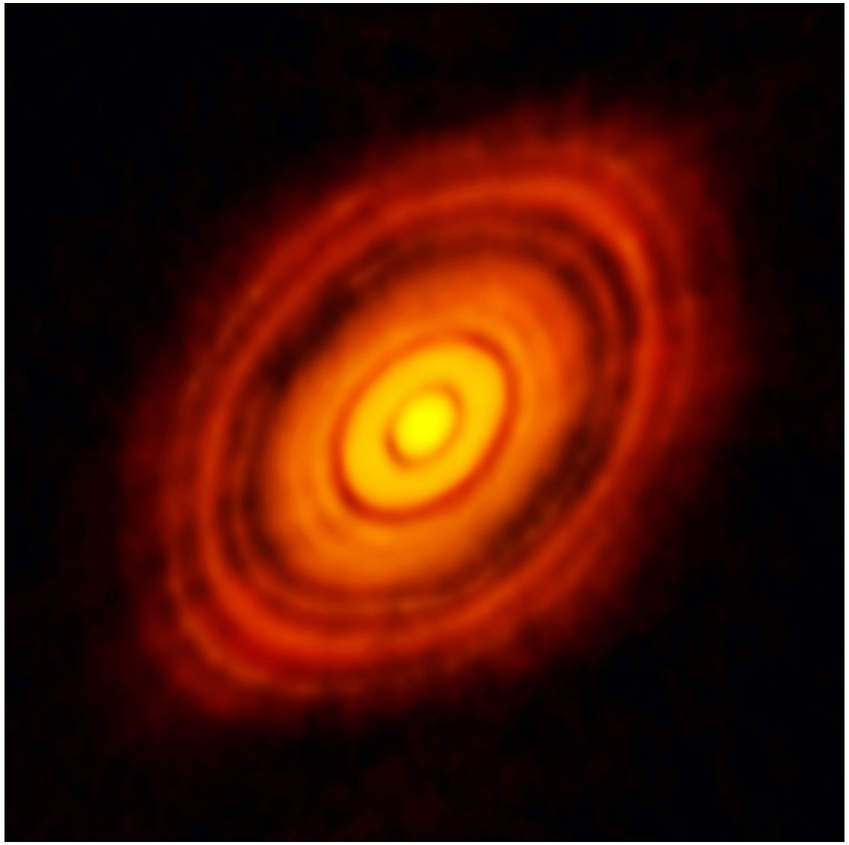
Carilli & Walter 2013

Spectral resolution: 30.5 kHz (equivalent to 0.079 km/s in Band 3 and 0.011 km/s in Band 10)

Band 1: 35-50 GHz coming soon!
Band 2: 67-116 GHz in construction

ALMA capabilities: superb imaging

ALMA partnership, 2015



Angular resolution of 0.025-0.075” (3.5-10 AU)

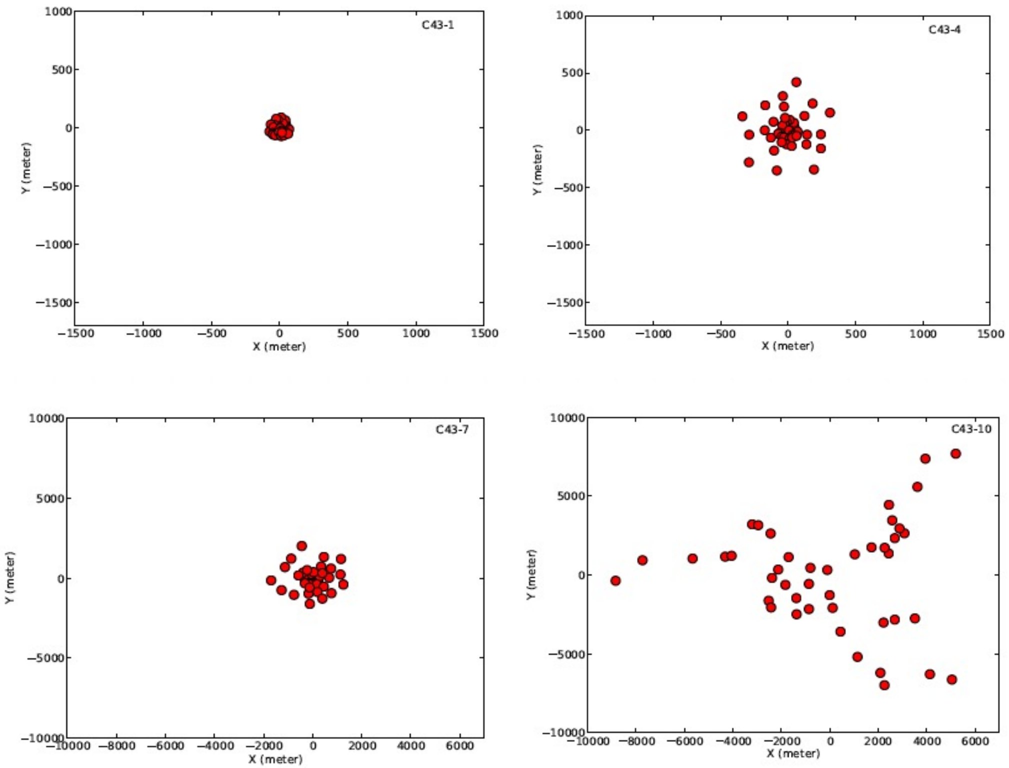
Baselines from 150 m up to 16.2 km

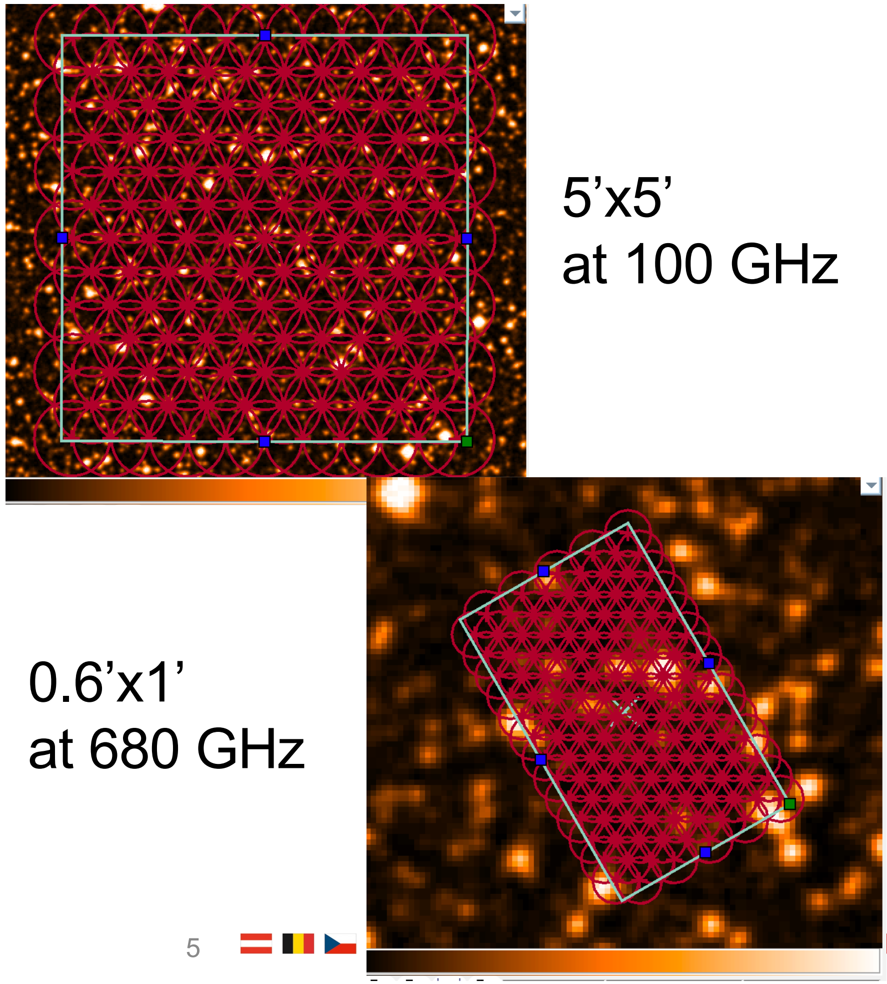
Angular Resolution: from 3.38” in Band 3 (C-1) to 0.009” in Bands 8 (C-10) and 9 (C-9)

But relatively modest **Field of View**: ~19" at 300 GHz for a 12-m antenna and a 33” for a 7-m antenna

Mosaics used to cover large areas

ALMA versatility in terms of imaging/maps



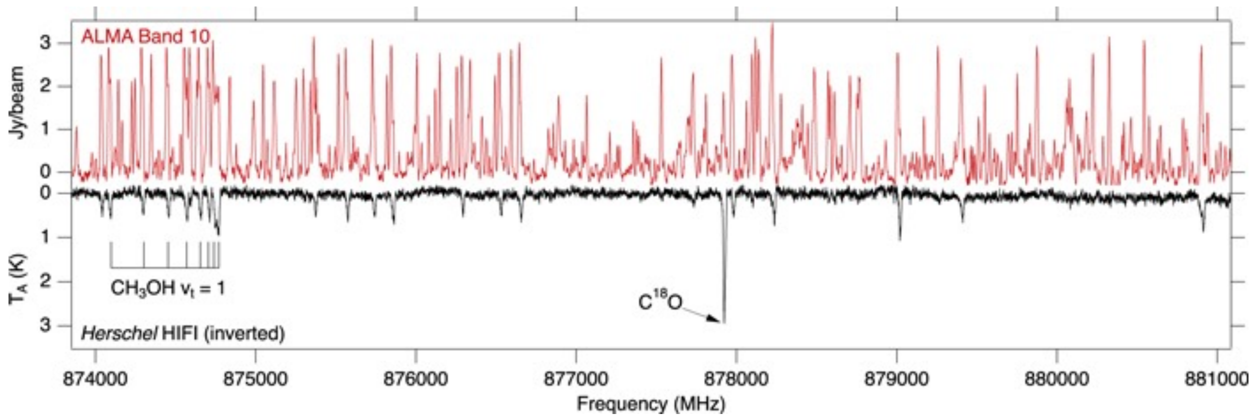


5’x5’
at 100 GHz

0.6’x1’
at 680 GHz

Antenna configurations with shorter baselines yield lower angular resolution, but there is also a dependence with frequency (**ALMA Technical Handbook**)

ALMA capabilities: line and continuum sensitivity



McGuire et al. 2018

Continuum sensitivity (8 GHz bandwidth)

Band (frequency GHz)	3 (98)	4 … 9 (145 … 679)	10 (870)
5 min (12-m)	40 uJy	…	2 mJy
30 min (12-m)	15 uJy	…	0.4 mJy
30 min (ACA)	0.2 mJy		6 mJy

ALMA capabilities: … and much more

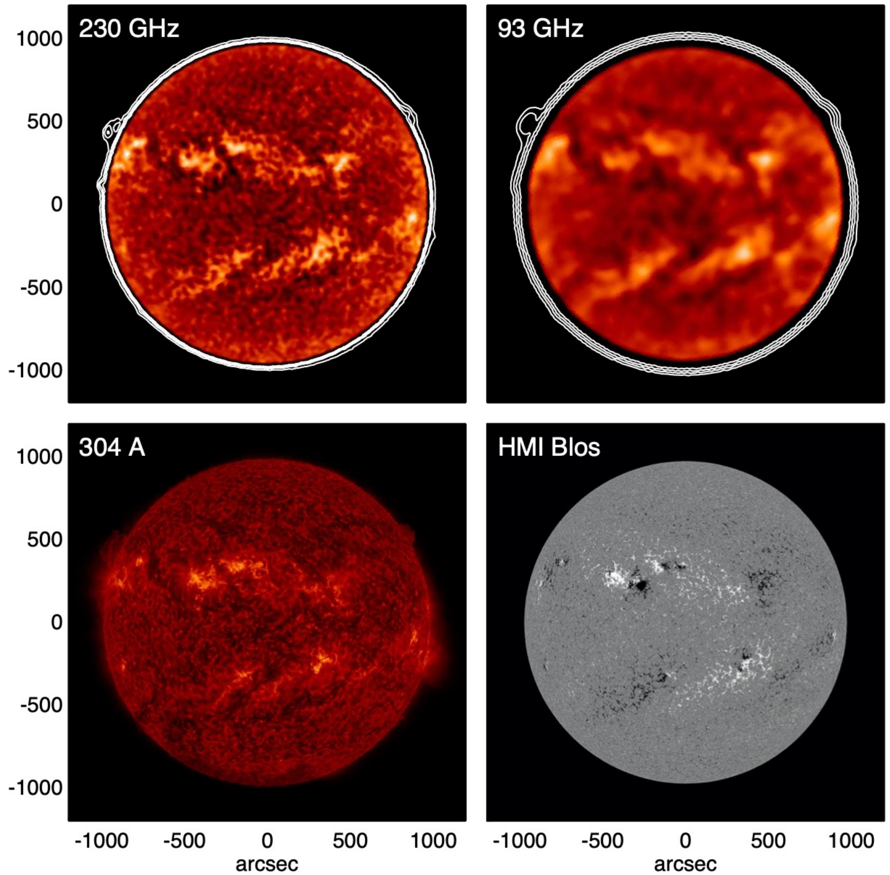
… and:

Full polarization up to Band 7

Solar observations

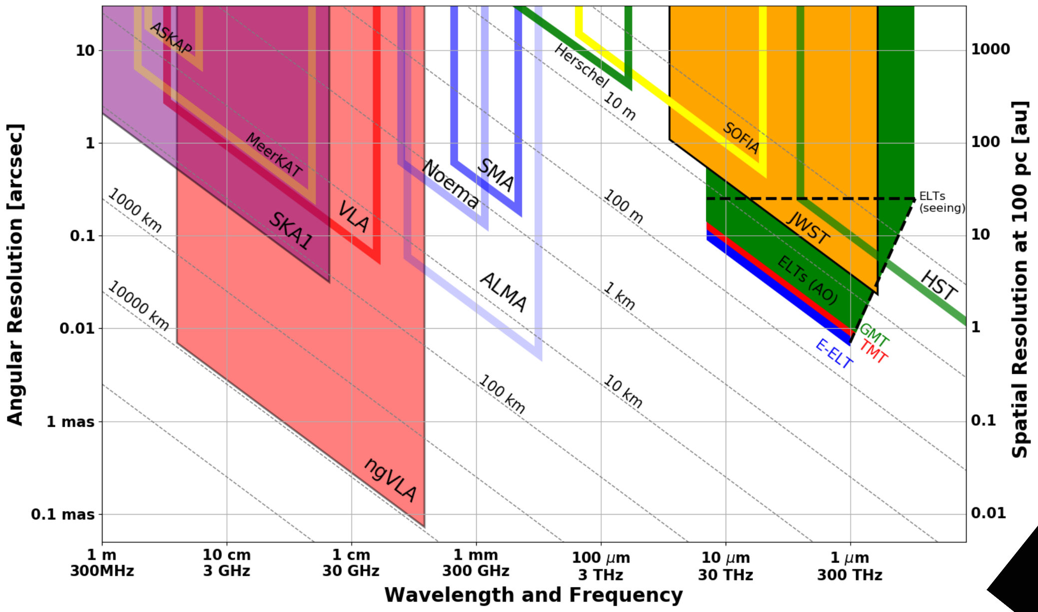
VLBI (GMV, EHT)

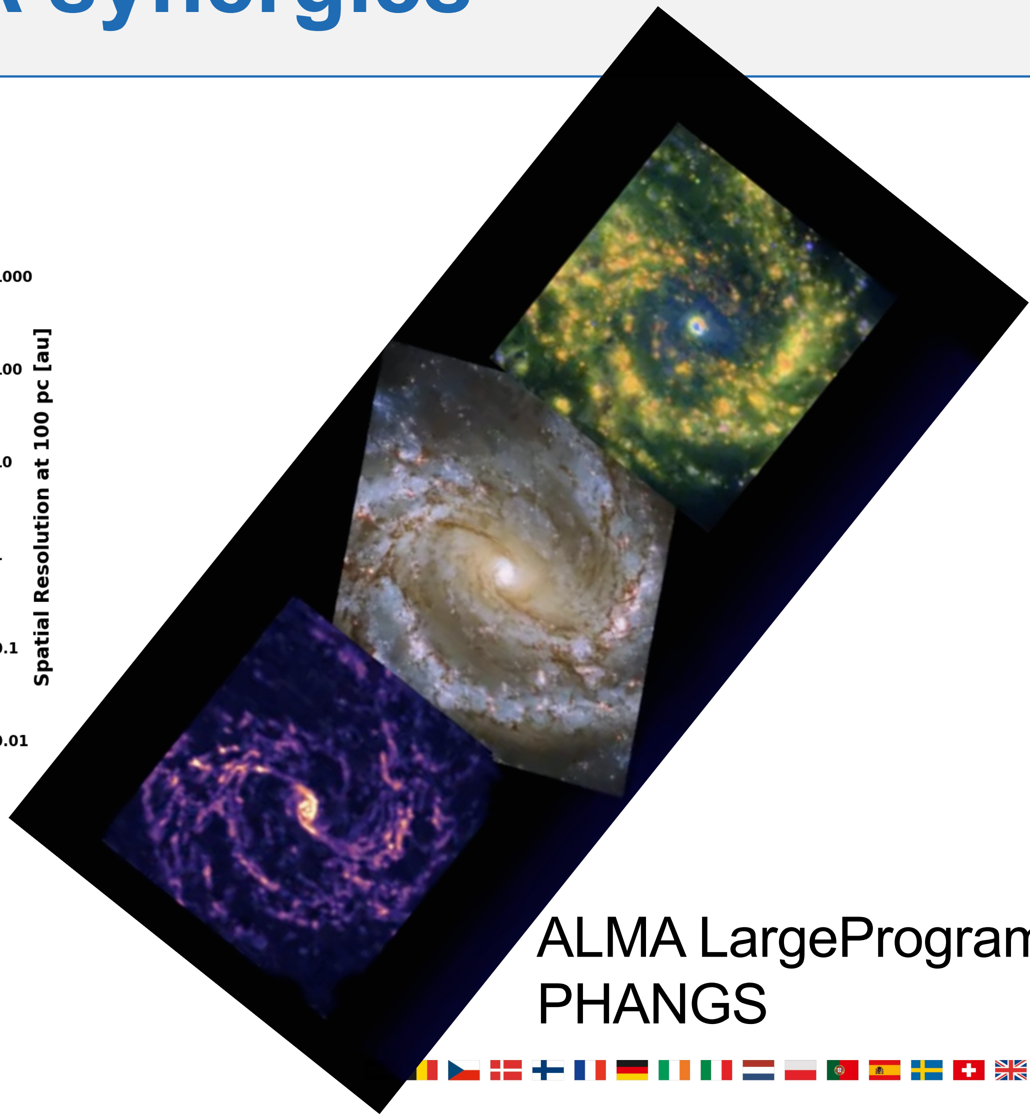
Phased array observations



White et al. 2017

ALMA synergies





ALMA LargeProgramme PHANGS

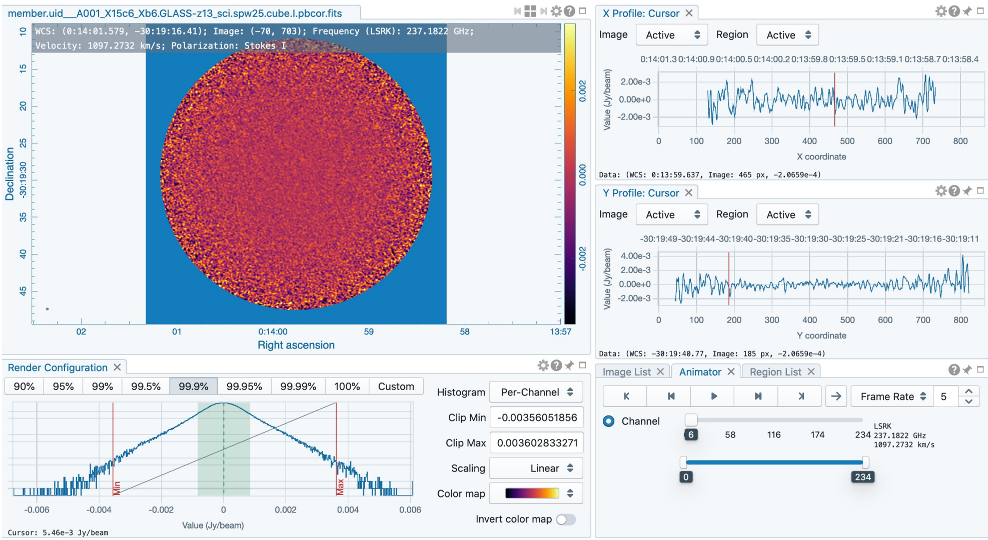
ALMA synergies

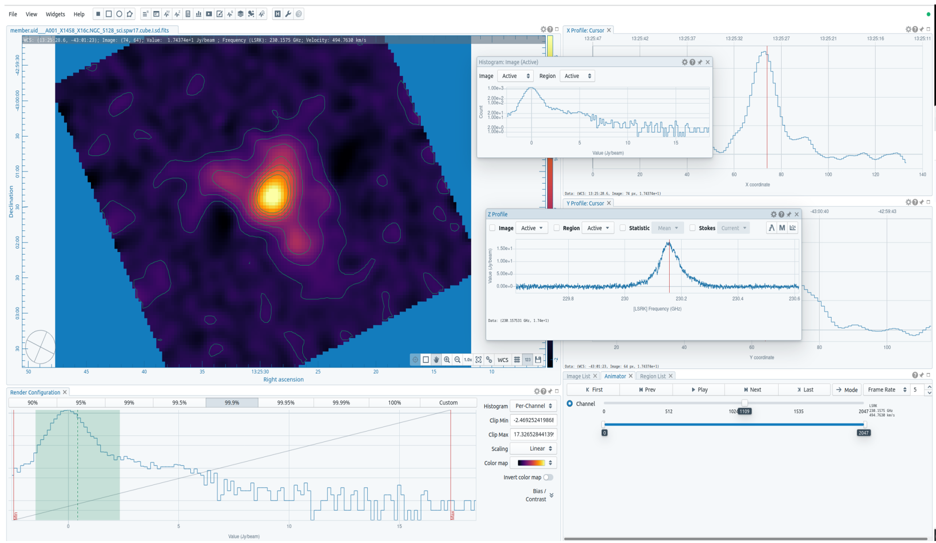
Science topics (non-exhaustive list):

- Time-domain aspects:
  - Planet formation (e.g. interplay of stellar flares in chemical composition of protoplanetary disks), transients (e.g. hosts of Fast Radio Bursts, GWs)…
- With instrumentation that matches ALMA angular resolution (e.g. JWST, VLT/ERIS, VLT/MAVIS, ELT):
  - Galaxy evolution and star formation (ionised/cold gas), AGN feedback (ionized/molecular outflows), planet formation, photometric/spectroscopic redshifts…
- With upcoming sensitive radio facilities (e.g. SKA):
  - Chemical complexity (Complex Organic Molecules: SKA + ALMA Band 1)…

ALMA synergies

Follow-up of JWST high-redshift targets already happening via DDT programmes (quick look of ALMA cubes possible at the ALMA archive)

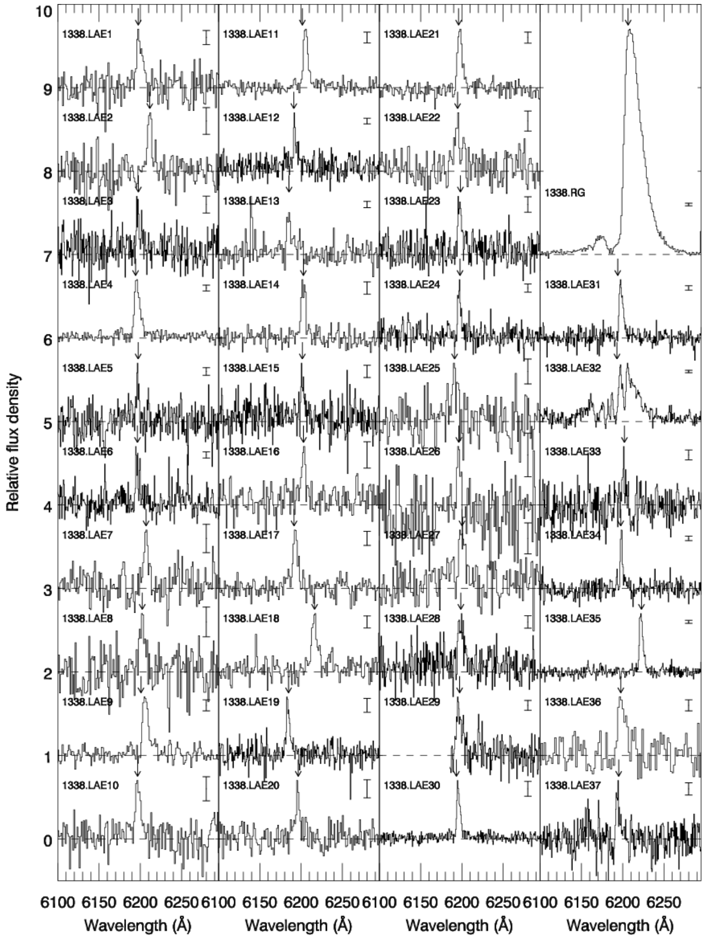




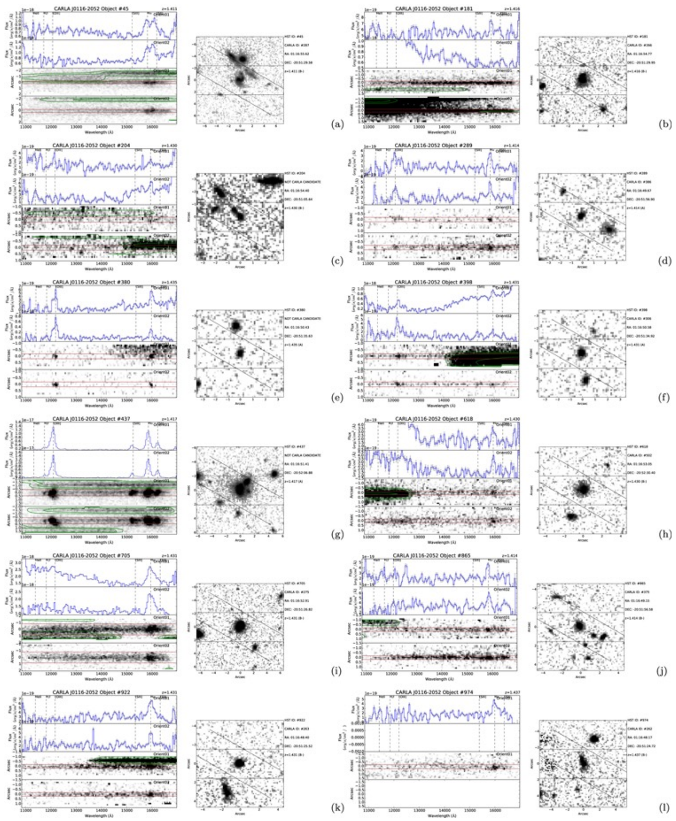
Joint programmes with JWST, VLT and the VLA starting soon!

Optical / near-IR observations of protoclusters

- Confirmation of overdensities:
  - Optical/near-IR multi-object spectroscopy
  - HST grism spectroscopy
- Euclid will revolutionize this field with many more clusters
- ALMA has been a very complementary follow-up telescope to study molecular mass content



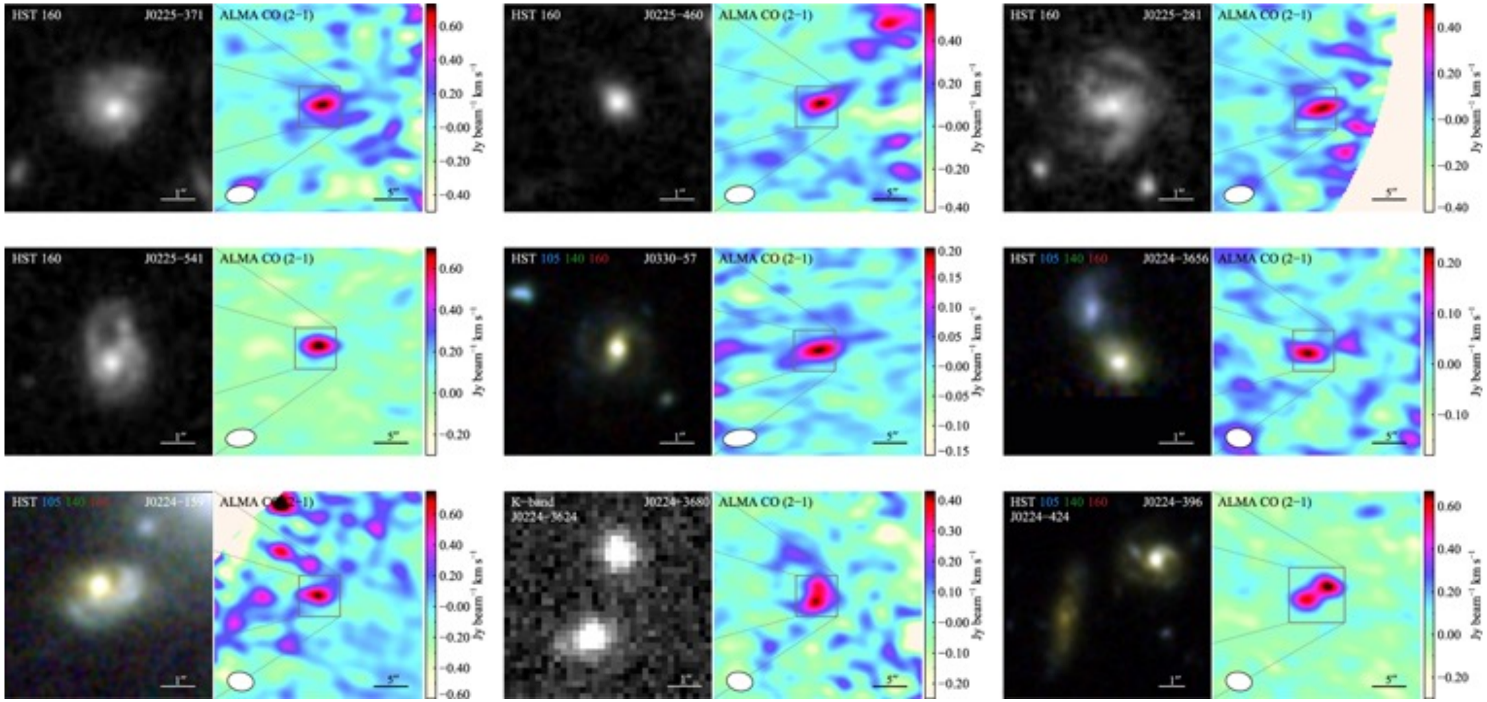
Z=4.1 cluster; Venemans et al. 2007 A&A 461, 823



Z=1.4 cluster; Noirot et al. 2018 ApJ 859, 38

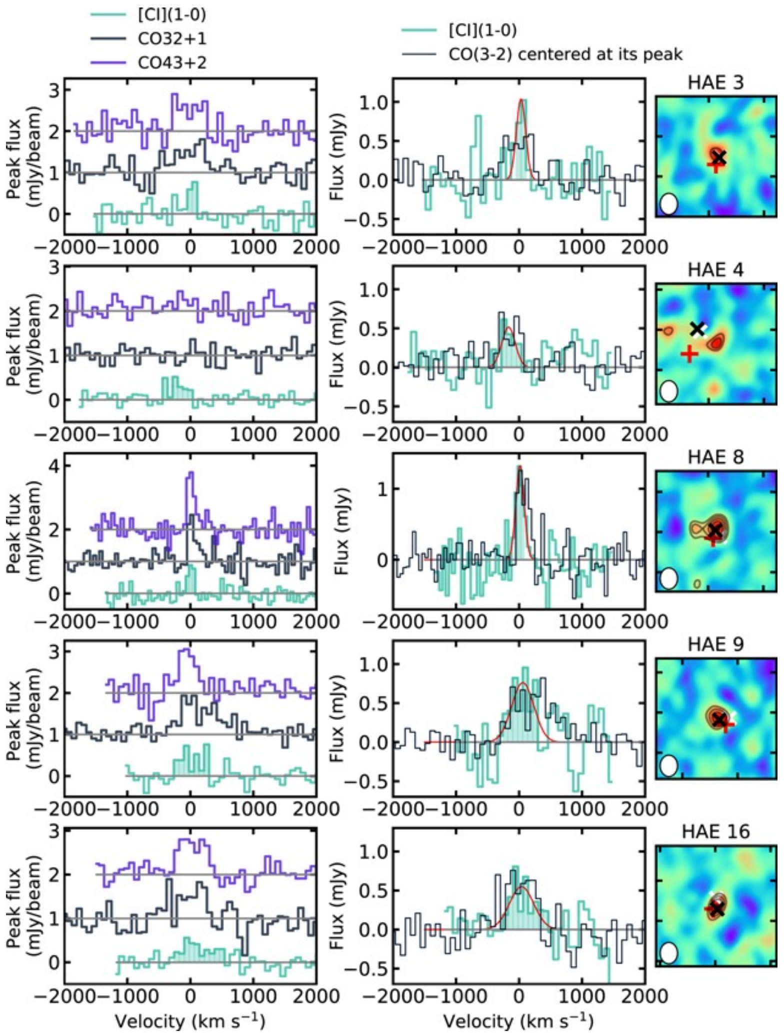
ALMA CO observations of galaxy clusters

- CO observations of galaxy clusters:
  - Provices H_2 mass using α_{CO} factor
  - Euclid will provide stellar masses
  - Study gas fractions
  - Low-J CO in lower ALMA bands has larger primary beam (Field of View)



Z=1.6 cluster; Noble et al. 2017 ApJ 842, 2

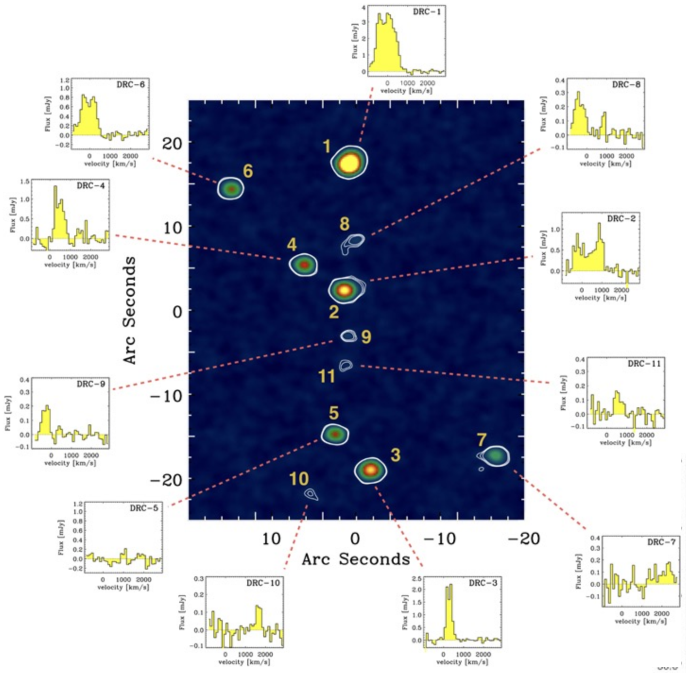
ALMA [CI] observations of galaxy clusters



- [CI] as an alternative gas mass tracer
  - Not metallicity dependent like CO
  - Still needs Euclid to provide stellar masses
  - Two [CI] lines allow to observe at almost any redshift
  - Disadvantage is the smaller primary beam as the [CI] lines are at higher frequency

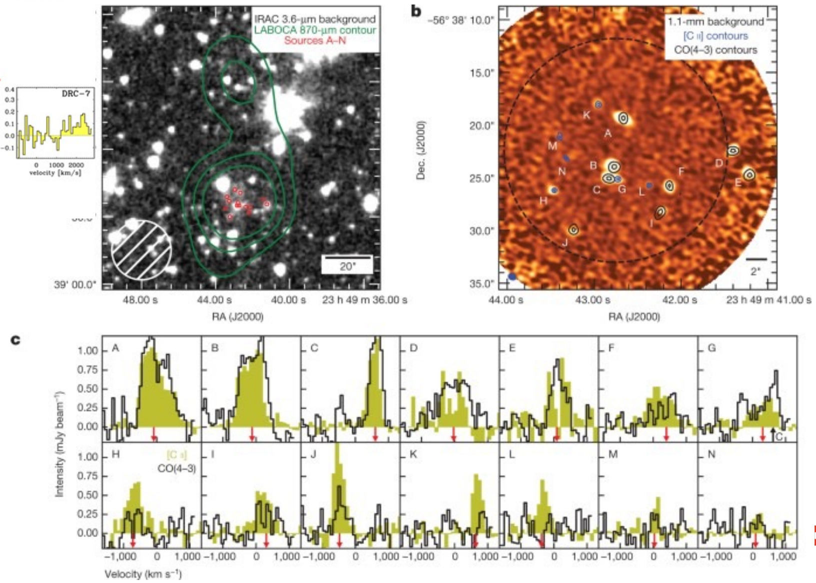
Z=2.5 cluster; Lee et al. 2021 ApJ 909, 181

ALMA [CII] observations of galaxy clusters



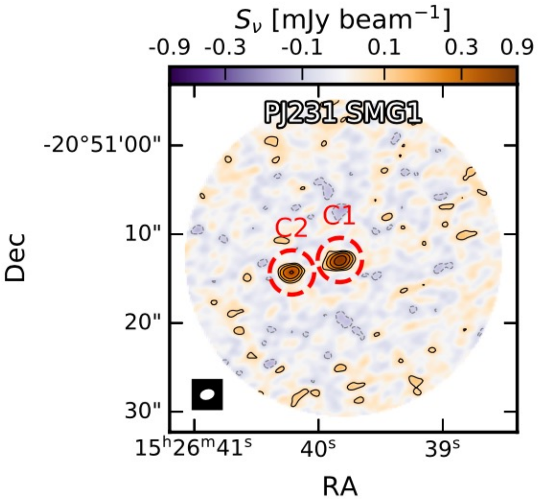
Z=4.0 cluster; Oteo et al. 2018 ApJ 856, 72

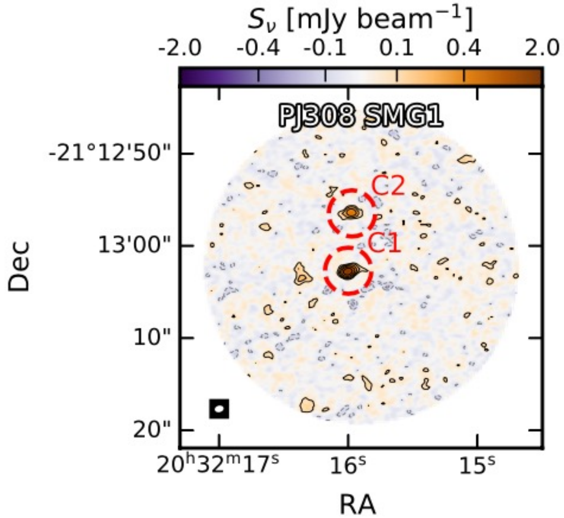
Z=4.3 cluster; Miller et al. 2018 Nature 556, 469

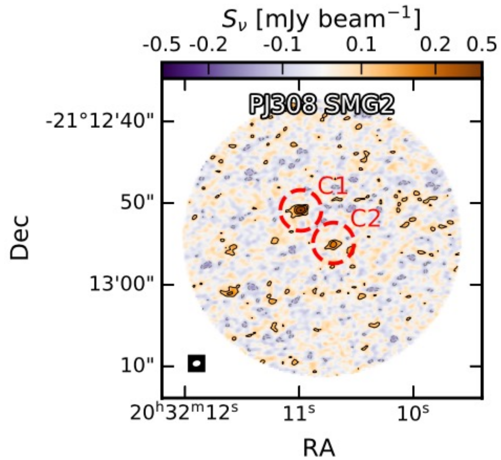


- [CII] confirmations of protoclusters
  - Selected from very wide-field Herschel and SPT surveys
  - [CII] is an ideal line to confirm z>3 targets thanks to its brightness
  - Cores of forming protoclusters

Pushing to even higher z with [CII]







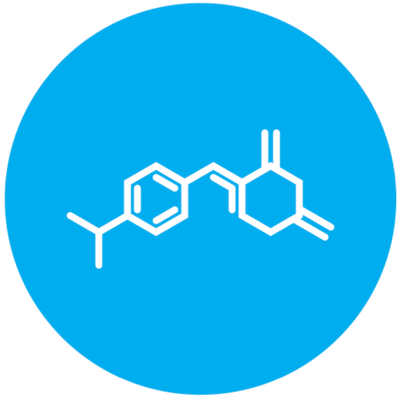
Z=6.6 quasars; Meyer et al. 2022 ApJ 927, 141

- [CII] imaging of fields surrounding z>6 quasars
  - Several quasar fields show a statistical overdensity of [CII] emitters
  - ASPIRE ALMA Cycle 9 large programme will target 25 z~7 quasars, covering an area of 45 arcmin^2

ALMA in the 2030s: science drivers

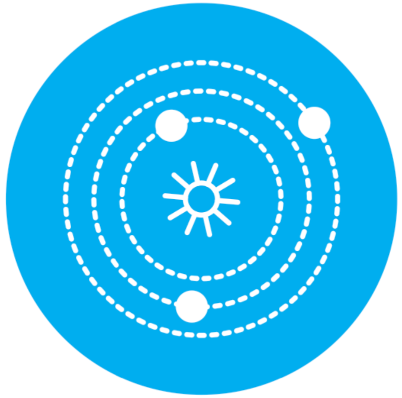
ORIGINS OF GALAXIES

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.



ORIGINS OF CHEMICAL COMPLEXITY

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.



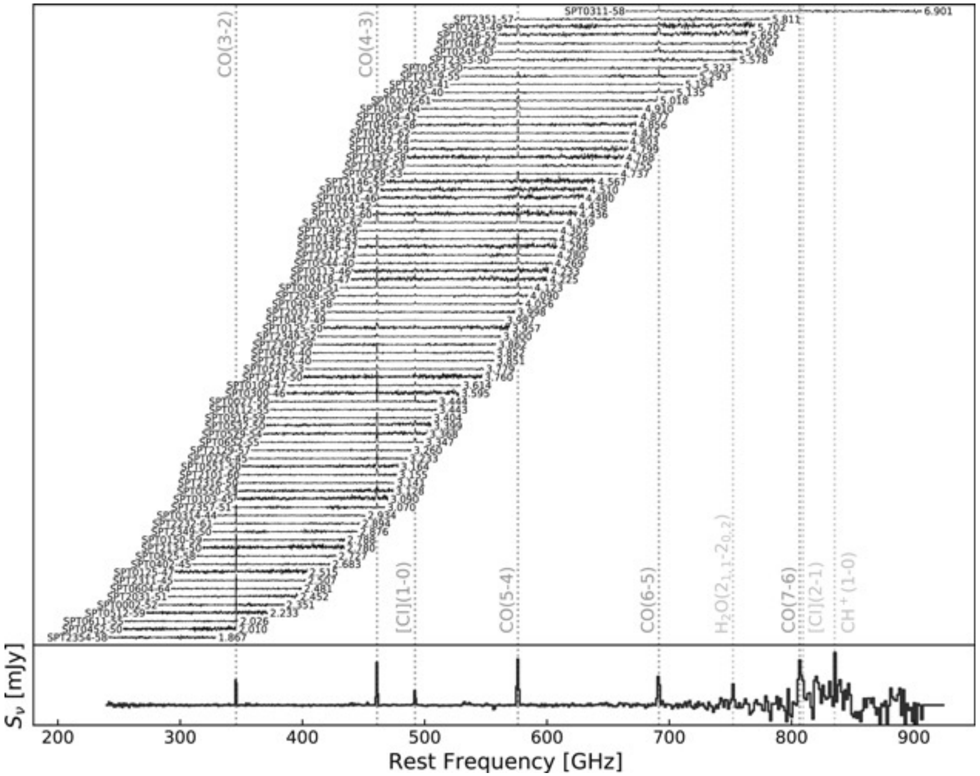
ORIGINS OF PLANETS

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.

ALMA in the 2030s: development roadmap

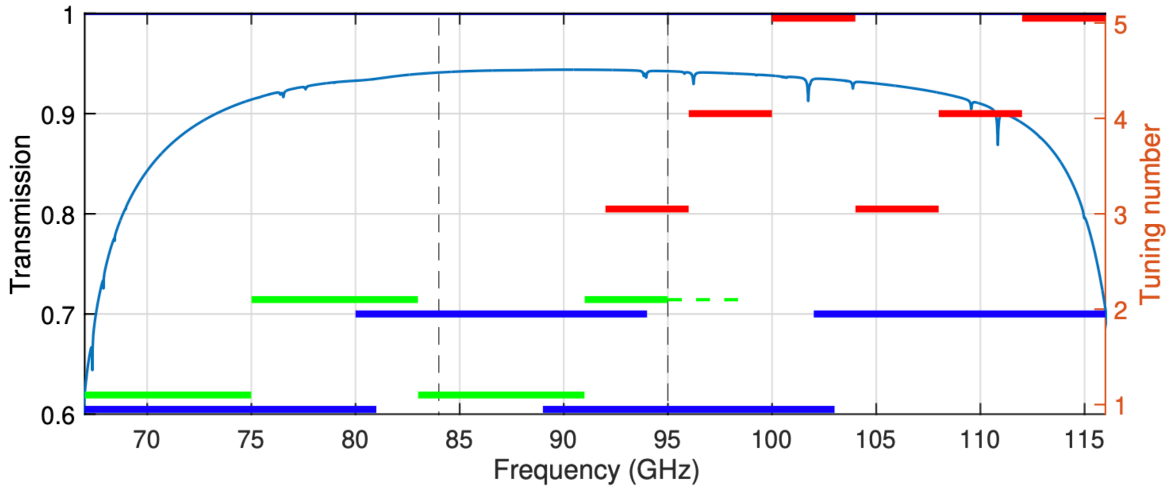
- Short term upgrades:
  - Band 1 (35-50 GHz) coming online in 2023: adding $1.3<z<2.3$ range for CO(1-0)
  - Band 2 (67-116 GHz) coming online in 2026: adding $0.37<z<0.7$ for CO(1-0)
- Near to mid-term goals:
  - Wide sensitivity upgrade: broaden receiver IF bandwidth by up to 4x, and upgrade of associated electronics and correlator for gains in speed
    - Widening of spectral grasp for high spectral resolution by up to a factor of 50 is a game changer for redshift searches!
  - Archive: increase usability/impact
- Longer term goals:
  - Longer baselines
  - Wide field mapping speed

ALMA for redshift determinations



Reuter et al. 2020 ApJ 902, 78

- Band 2 (67-116 GHz): full range can be covered in just 2 spectral setups compared to currently 5 setups for 84-116 GHz Band 3.



Conclusions

- ALMA is a versatile follow-up instrument, e.g. for molecular mass determinations of overdense fields
- Several far-IR lines are available: CO, [CI], [CII]
- Field of view is limited, but can be extended using mosaicking.
- Future upgrades will make ALMA a lot more powerful:
  - Bands 1 & 2
  - Increase of instantaneous bandwidth by up to 4x
- Important synergies with EUCLID, especially for follow-up