A TOUR DE FORCE OF ALMA SCIENCE

Gergö Popping - European Southern Observatory
Spanish ALMA Days
Tenerife 18 - 20 February 2025

ESO
ALMA
EUROPEAN ARC
ALMA Regional Centre

ALMA HIGH-LEVEL SCIENCE GOALS

- 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 24h of observations

- Image the gas kinematics in a solar-mass protostellar/protoplanetary disk at a distance of 150 pc enabling the study of the physical, chemical and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation

- Provide precise (high fidelity) images at an angular resolution of 0.1″ (accurately representing the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness).

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CO AND [CII] IN A NORMAL HIGH-REDSHIFT GALAXY

Detection of CO emission across redshifts

ASPECS Large Programme, PI F. Walter

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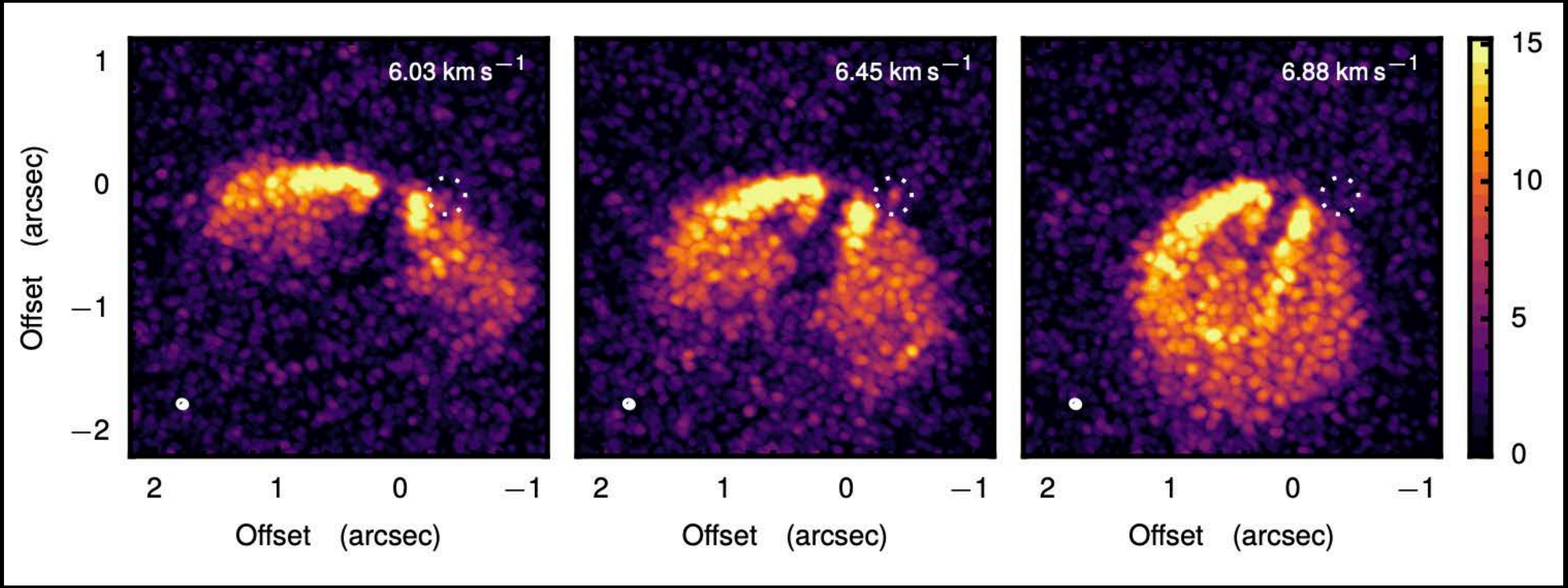
IMAGE THE GAS KINEMATICS IN A SOLAR-MASS PROTOSTELLAR/ PROTOPLANETARY DISK AT A DISTANCE OF 150 PC



0.07 arcsec observations of 12CO(3-2) towards PDS 70b revealing structured motions

Keppler+2019

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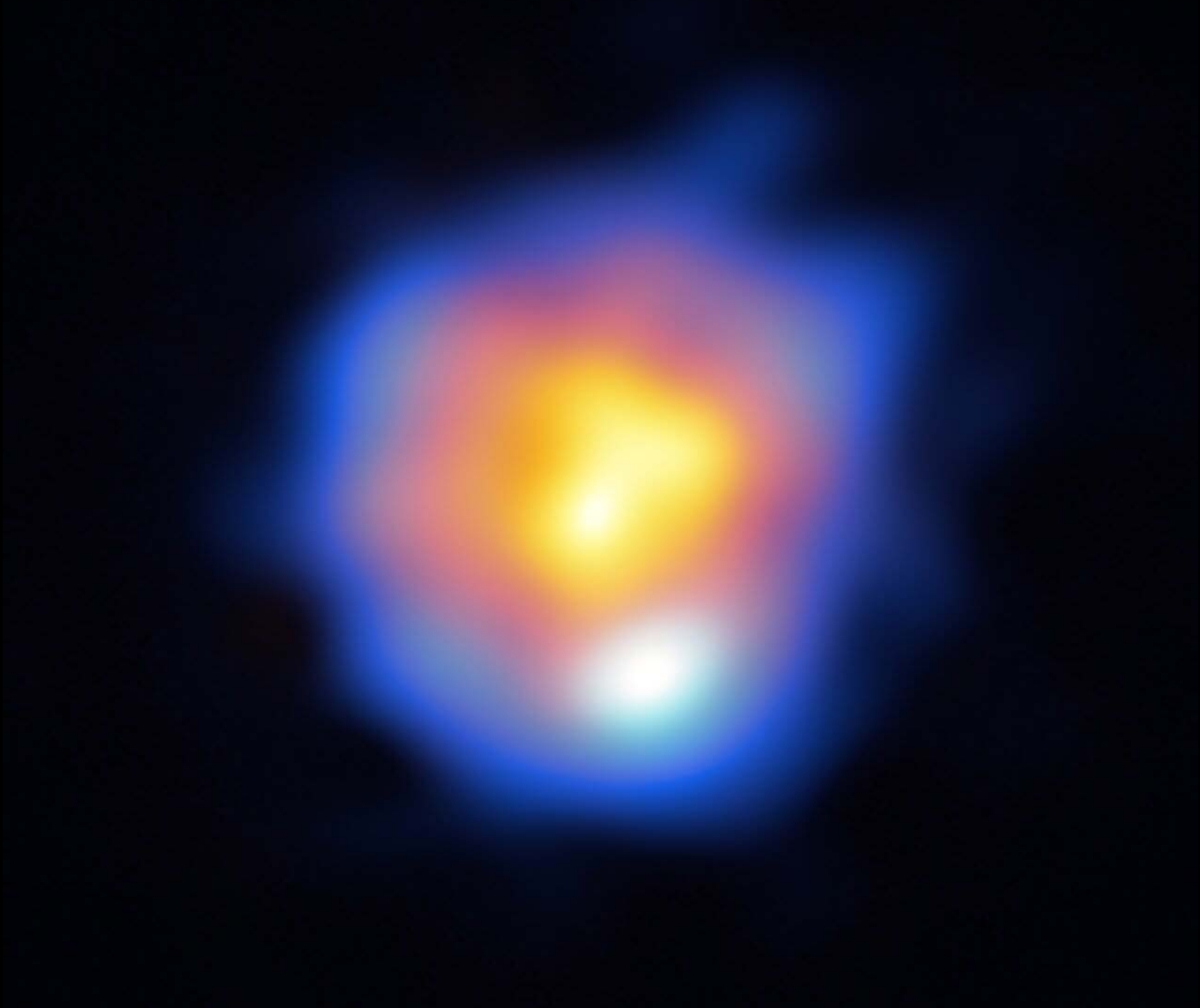
PROVIDE PRECISE (HIGH FIDELITY) IMAGES AT AN ANGULAR RESOLUTION OF 0.1′′

Angular resolution observations well below 0.1 arcsec. In this case continuum observations towards HL Tau down to 0.025 arcsec

ALMA (ESO/NAOJ/NRAO)

ALMA'S HIGHEST RESOLUTION OBSERVATIONS



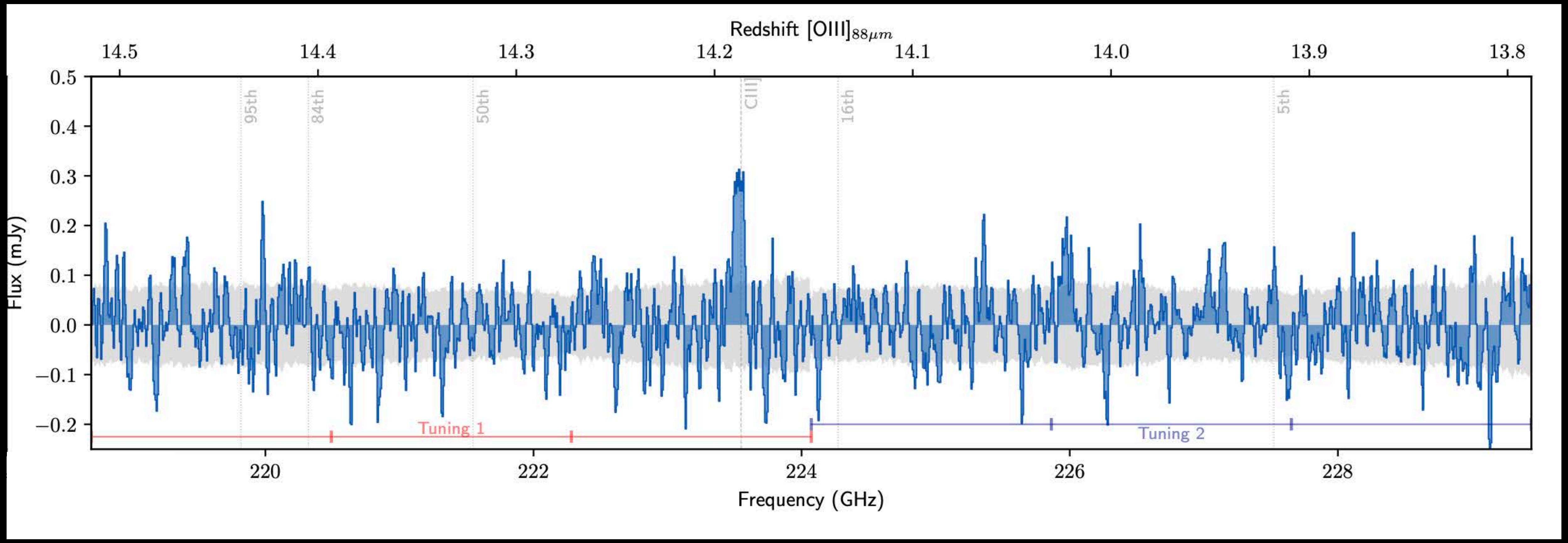
950 GHz observations with 16 km baselines to achieve 0.005 arcsec resolution towards R Leporis

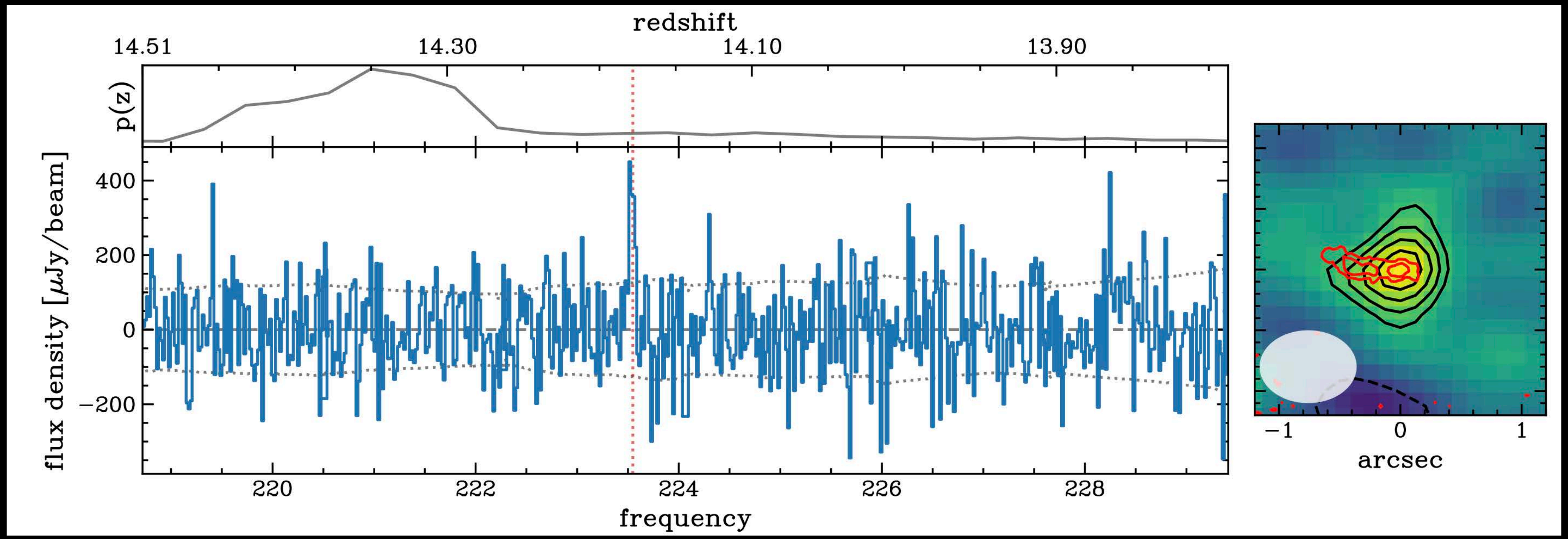
ALMA (ESO/NAOJ/NRAO)/Y. Asaki et al.

WHAT EXCITING SCIENCE HAS ALMA ACHIEVED?

THE HIGH REDSHIFT UNIVERSE

[OIII] 88μm EMISSION AT Z = 14.1793

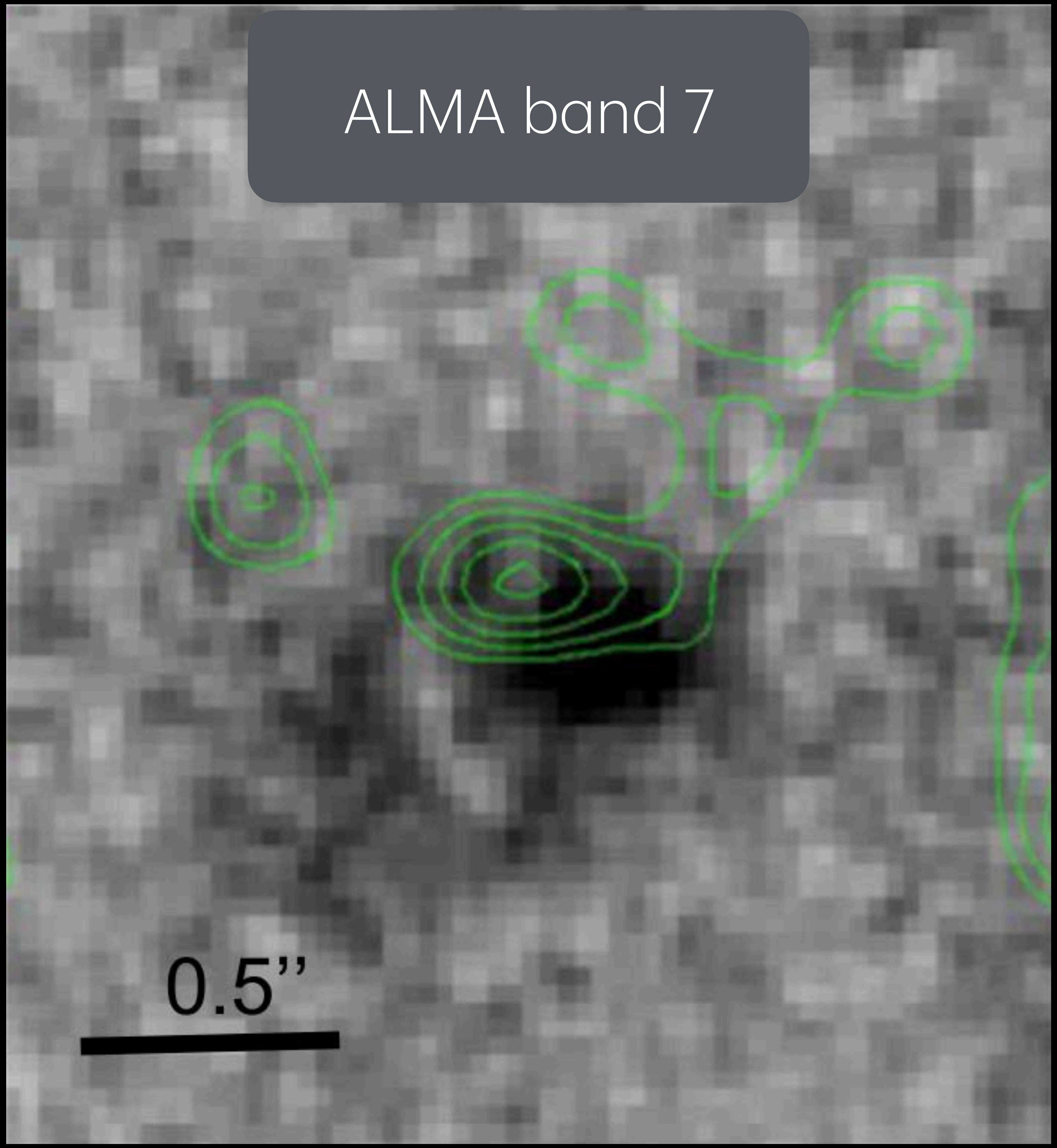




- [OIII] 88 μm emission from the highest-redshift spectroscopically observed galaxy to date
- More precise redshift than from JWST/NIRSpec
- Implications on the metal-enrichment of galaxies in the early Universe

Schouws et al. 2024, Carniani et al. 2024

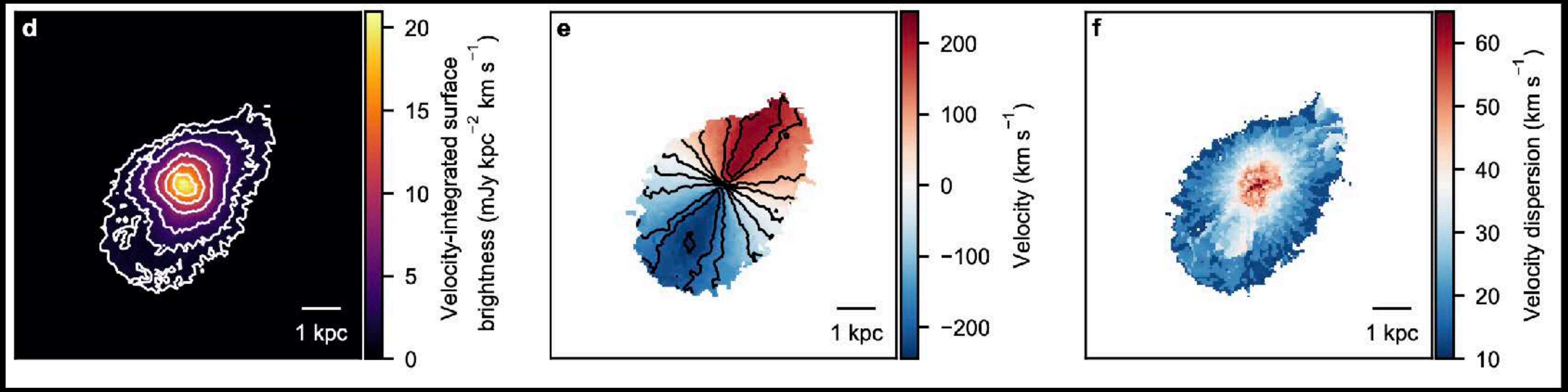
DUST RESERVOIR QUICKLY AFTER THE BIG BANG



- Signatures of dust when the Universe was only a few million years old
- How do you form large reservoirs of dust so quickly?

Laporte+2018

CO AND [CII] IN A NORMAL HIGH-REDSHIFT GALAXY

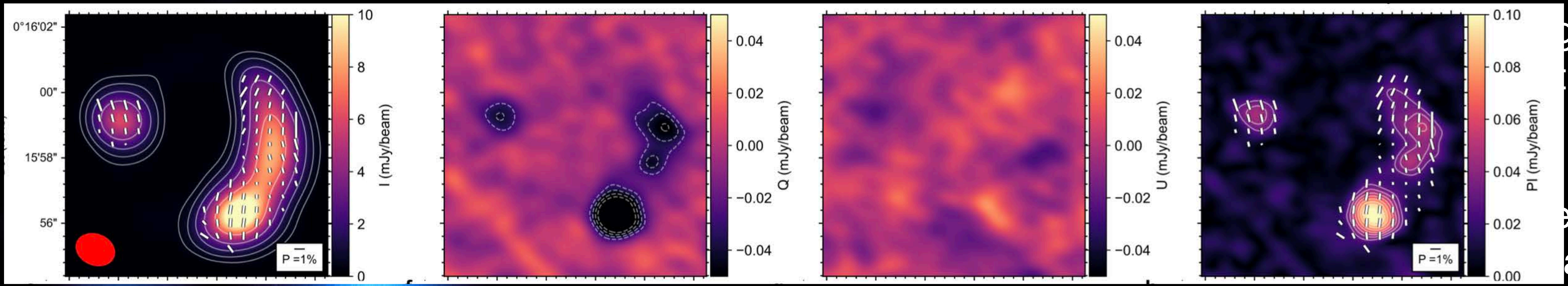


- [CII] 158 µm and band 7 continuum observations of SPT0418–47 at z=4.2
- Rotational motions dominate over random motions by a factor of 9.7
- Random motions expected to be (4x) more prominent in the early Universe
- Motions instead similar to the Milky Way

Rizzo et al. 2020

MAGNETIC FIELDS IN THE EARLY UNIVERSE

DETECTION OF POLARISED EMISSION IN A GALAXY 11 BILLION YEARS AGO

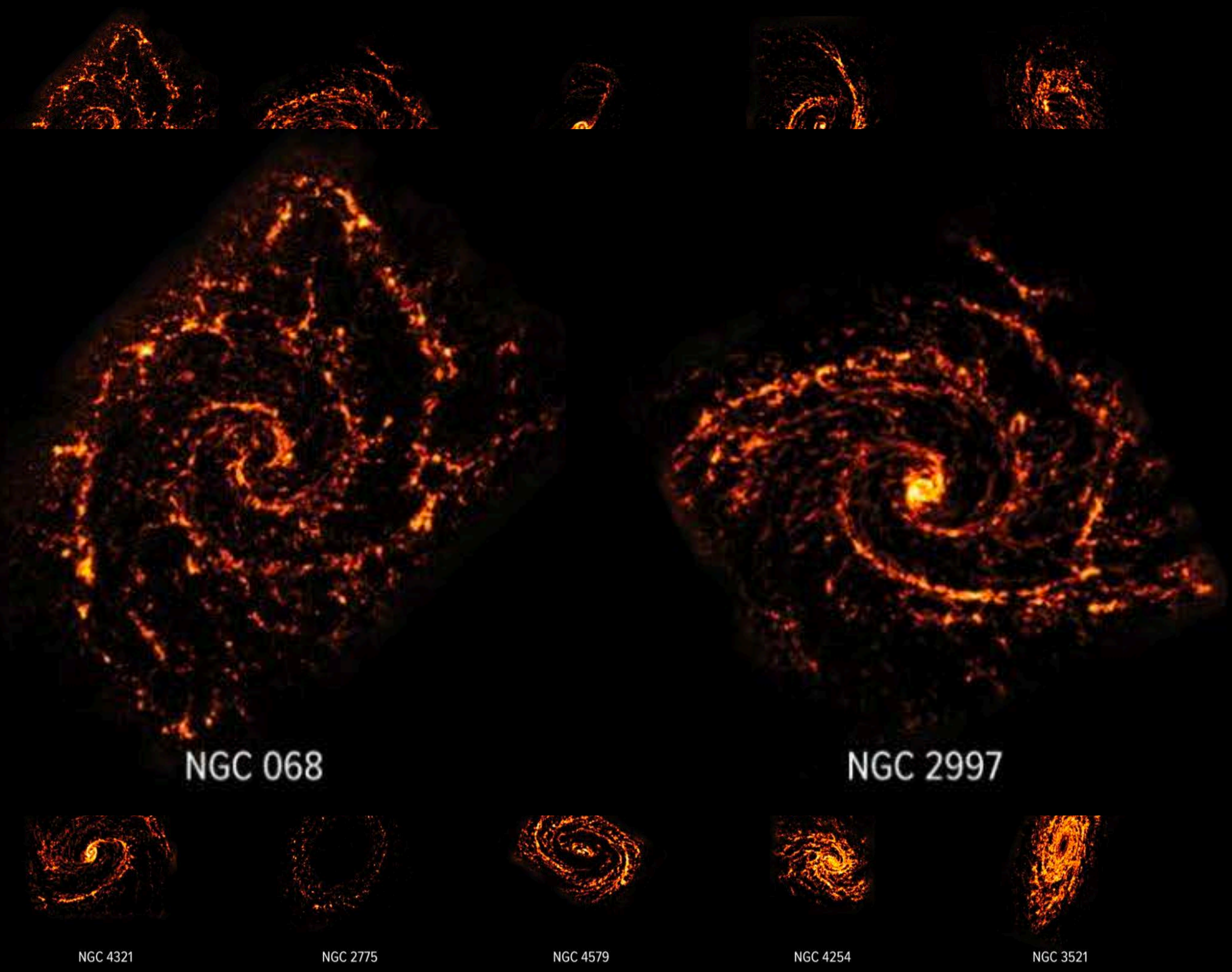


- Magnetic fields play an important role in the formation of galaxies
- galaxy at
  high
- erstanding
  alaxies
- ALMAs capability to observe polarisation in combination with high sensitivity allowed this new window on the early Universe

Geach+2023

NEARBY GALAXIES

MAPPING MOLECULAR CLOUDS IN NEARBY GALAXIES



- PHANGS: 1 arcsec CO 2-1 survey of nearby galaxies
- Prime example of combining 12m, 7m and TP observations
- Rich treasure trove to study the interplay between small-scale physics of gas and star formation and galactic structure and galaxy evolution

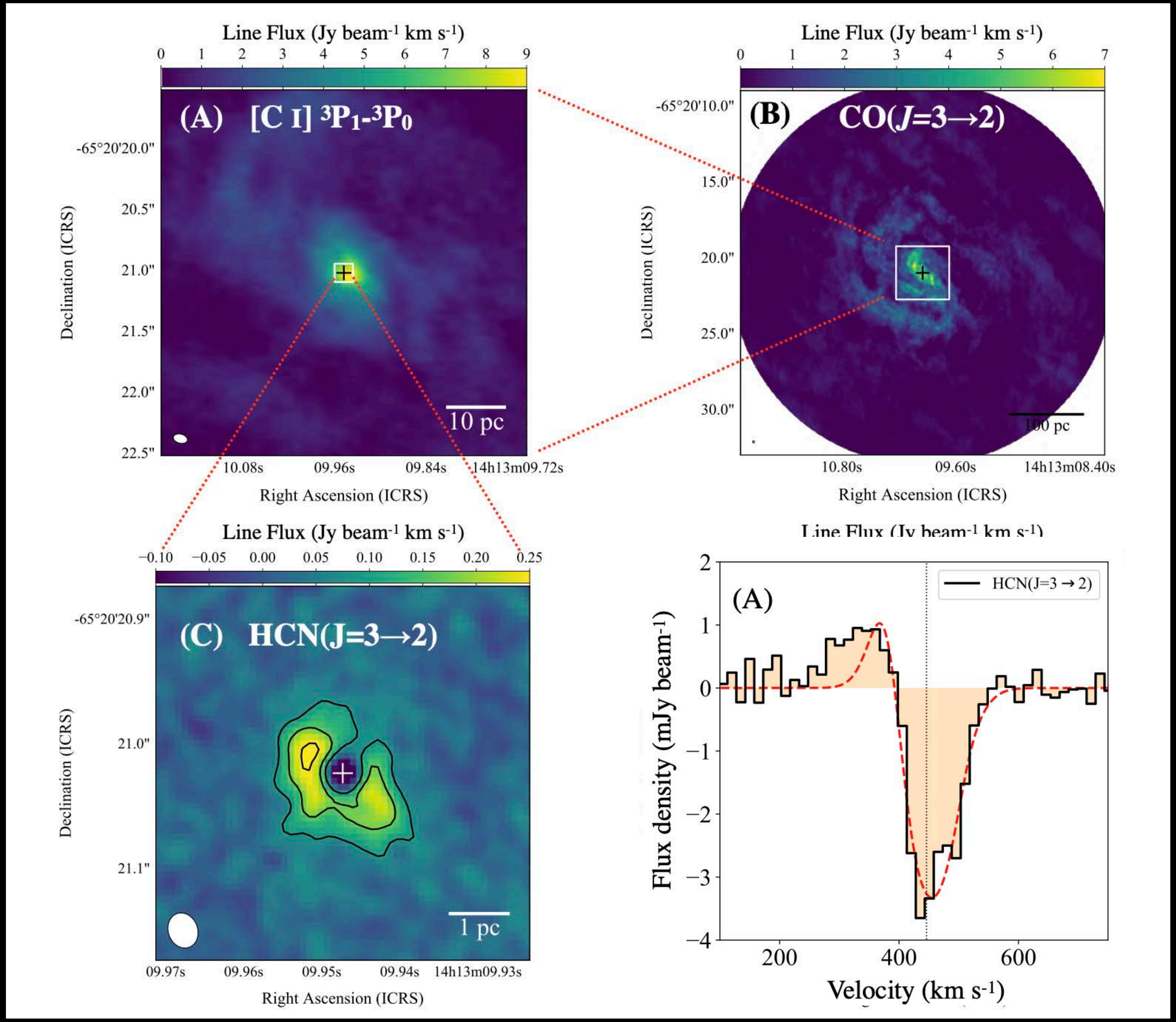
Leroy+2021

STAR FORMATION IN 30 DORADUS IN THE LMC

- Molecular clouds within the intense star-forming region 30 Doradus
- Study of molecular cloud properties in regions experiencing different feedback strengths
- Even in environments with active feedback from recent stars, very dense pockets of molecular clouds can form.

Wong+2022

ACCRETION OF GAS ONTO A BLACK HOLE

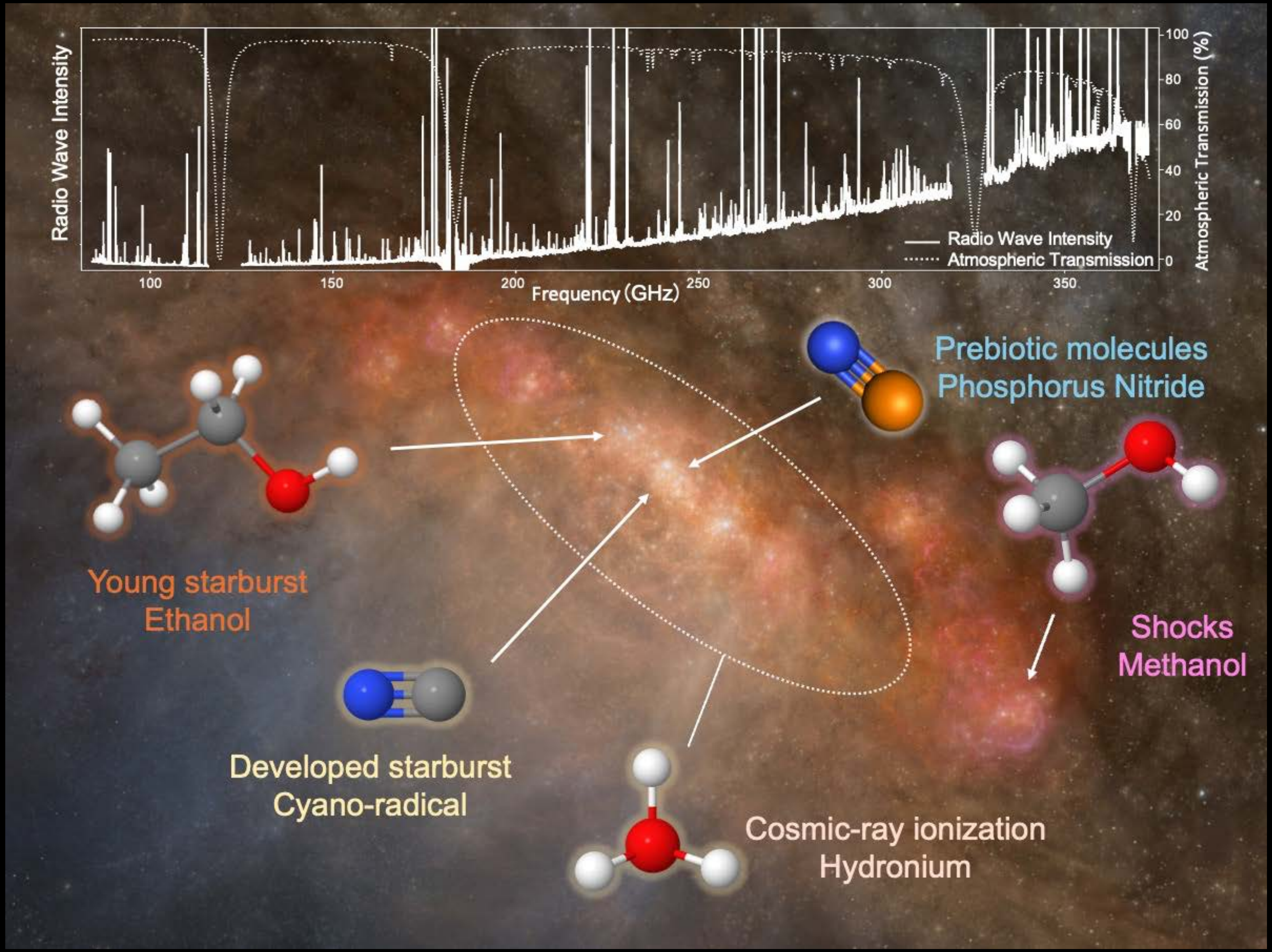


- AGN within the Circinus galaxy observed with 1 lightyear resolution
- Detection of dense HCN gas in absorption accreting onto the black hole
- Detection of [CI] and CO (atomic and molecular) outflows

Izumi+2023

CHEMISTRY IN NEARBY GALAXIES

ALMA COMPREHENSIVE HIGH-RESOLUTION EXTRAGALACTIC MOLECULAR INVENTORY



- ALMAs sensitivity allows for the detection of faint molecular lines in nearby galaxies
- More than 100 molecular species detected in nearby starburst
- First detection of ethanol and phosphorus-bearing species outside of the MW
- Collision of clouds in starburst environment may drive the formation of densest clouds

Harama+2024

ALMA AS PART OF THE EVENT HORIZON TELESCOPE

Event Horizon Telescope Collaboration et al., 2022, ESO/L. Calçada, N. Risinger (skysurvey.org), DSS, VISTA, VVV Survey/D. Minniti DSS, Nogueras-Lara et al., Schoedel, NACO, GRAVITY Collaboration, EHT Collaboration (Music: Azul Cobalto)

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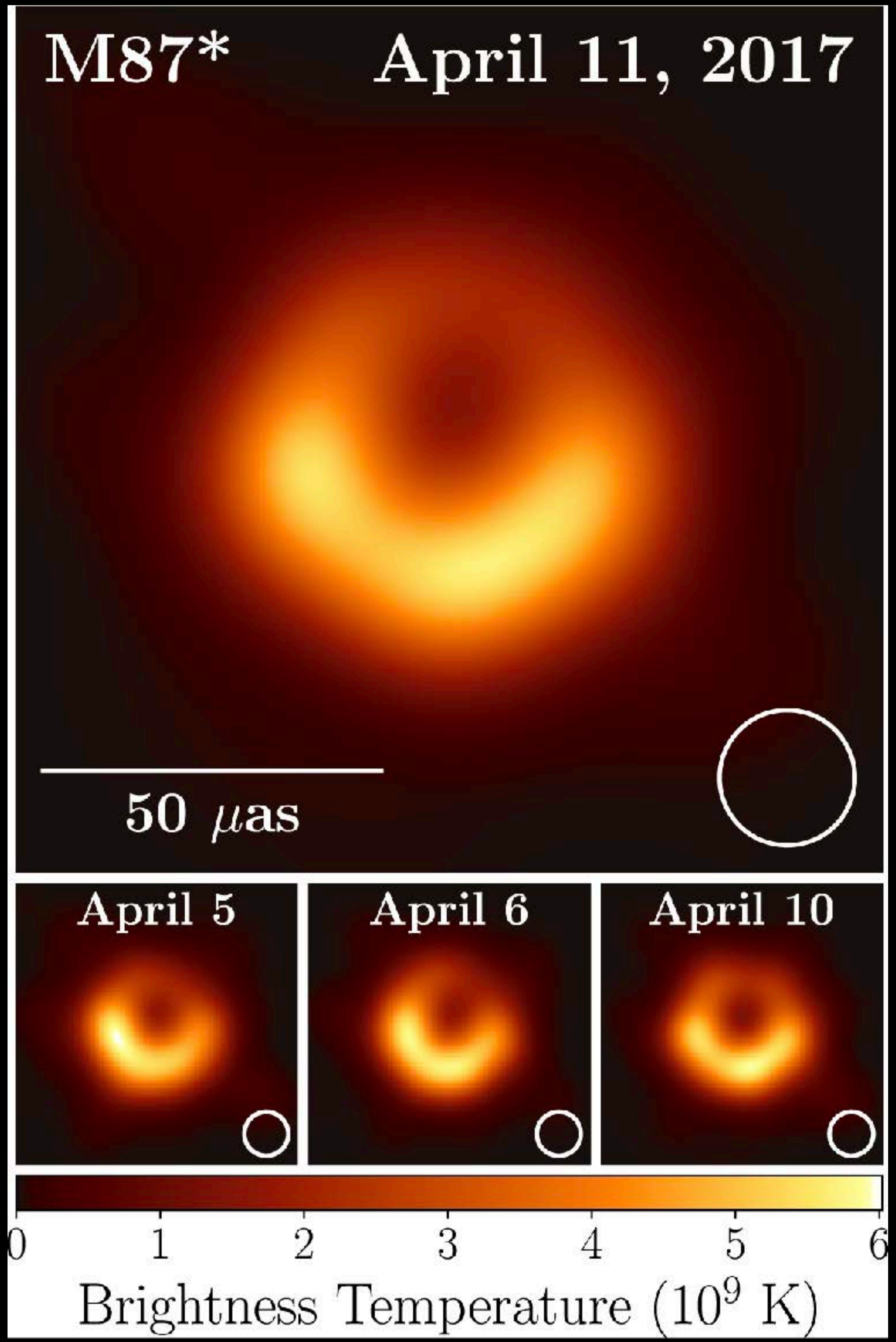
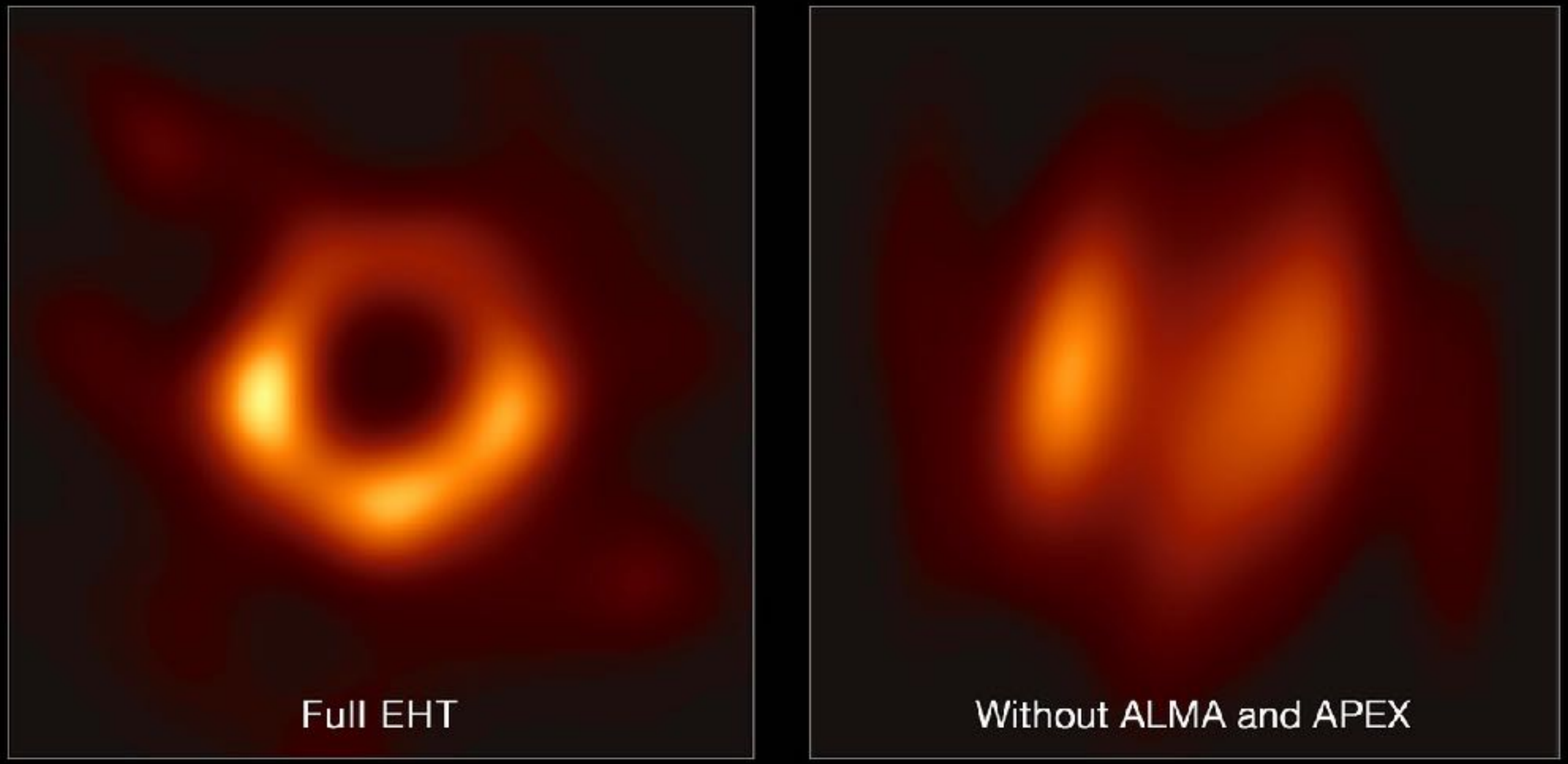


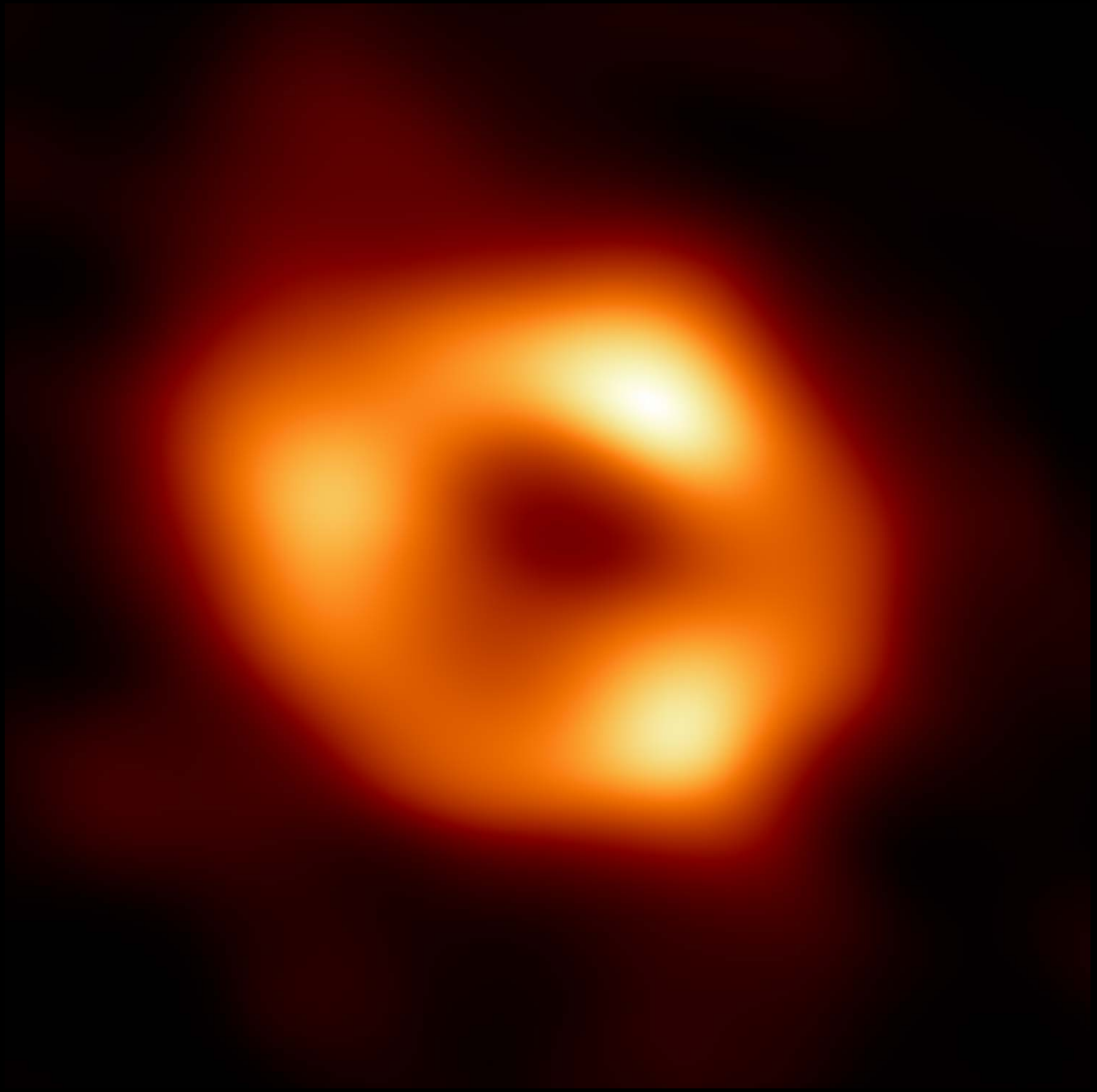


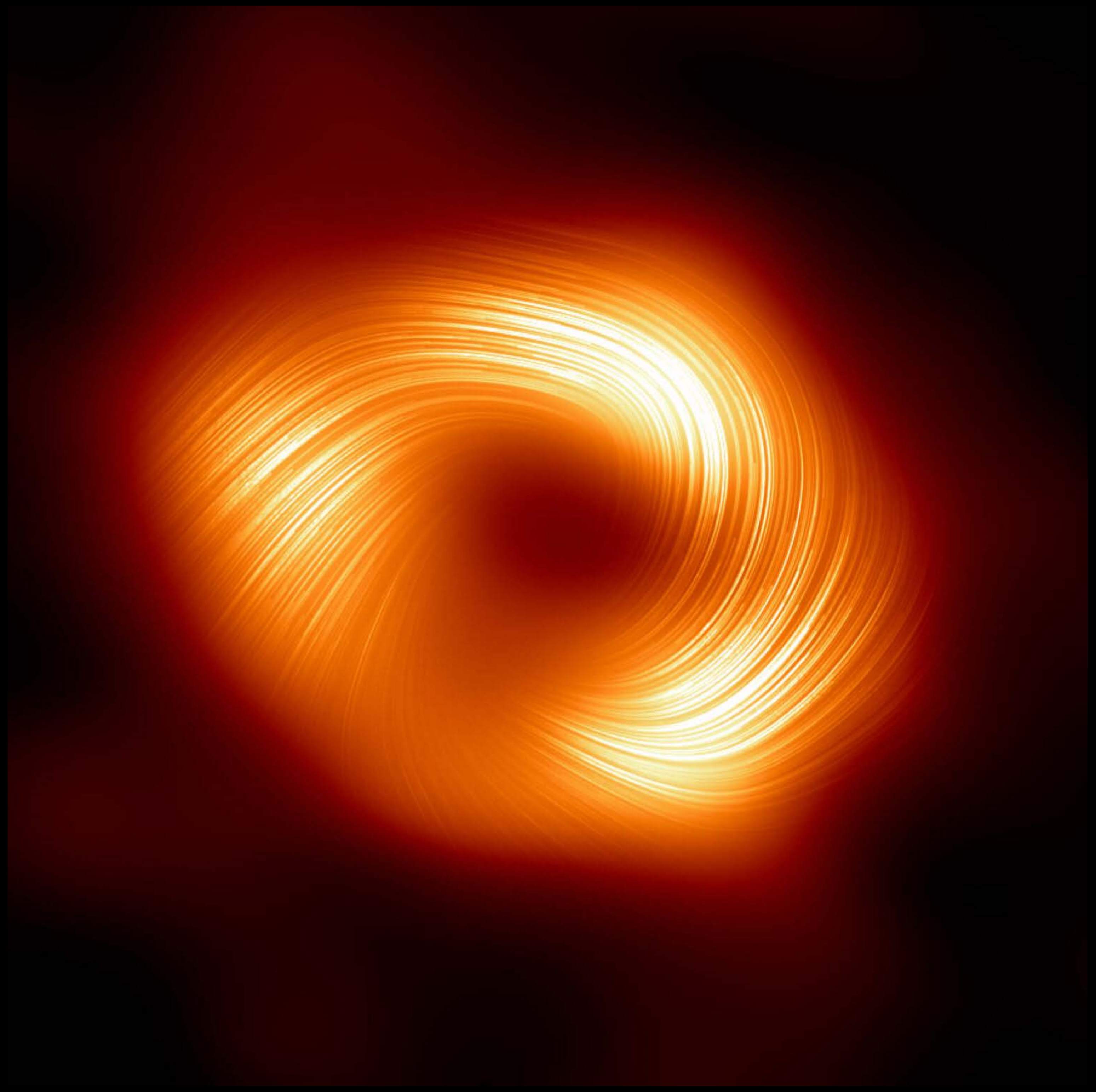
The crucial contribution of ALMA and APEX to the EHT
Credit: EHT Collaboration

Event Horizon Telescope Collaboration et al., 2022, ESO/L. Calçada, N. Risinger (skysurvey.org), DSS, VISTA, VVV Survey/D. Minniti DSS, Nogueras-Lara et al., Schoedel, NACO, GRAVITY Collaboration, EHT Collaboration (Music: Azul Cobalto)

ALMA AS PART OF THE EVENT HORIZON TELESCOPE

THE MW BLACK HOLE IN POLARISED LIGHT





Credit: EHT Collaboration

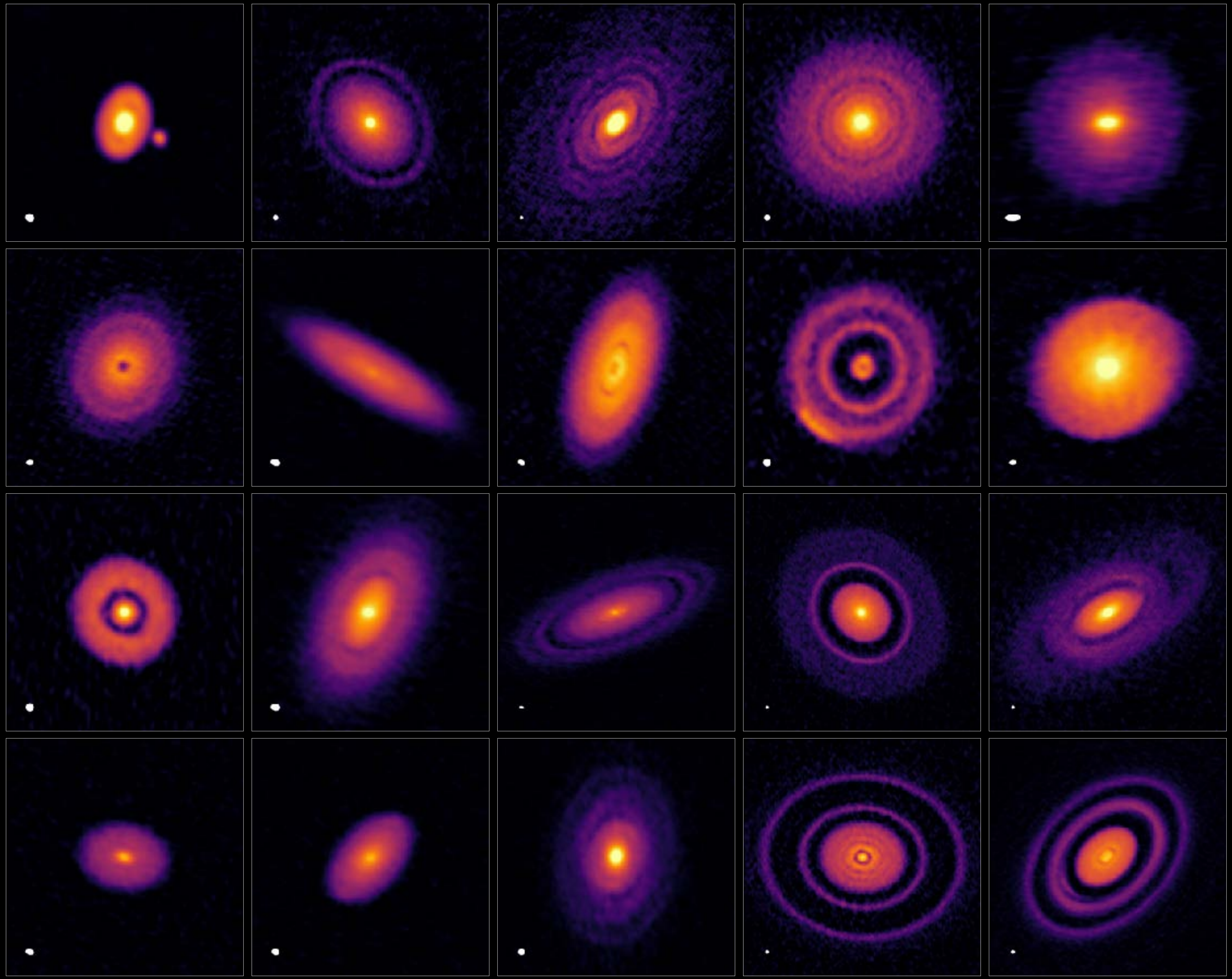
PROTO PLANETARY DISCS

HL TAU

ALMA (ESO/NAOJ/NRAO)

PLANET FORMING DISCS

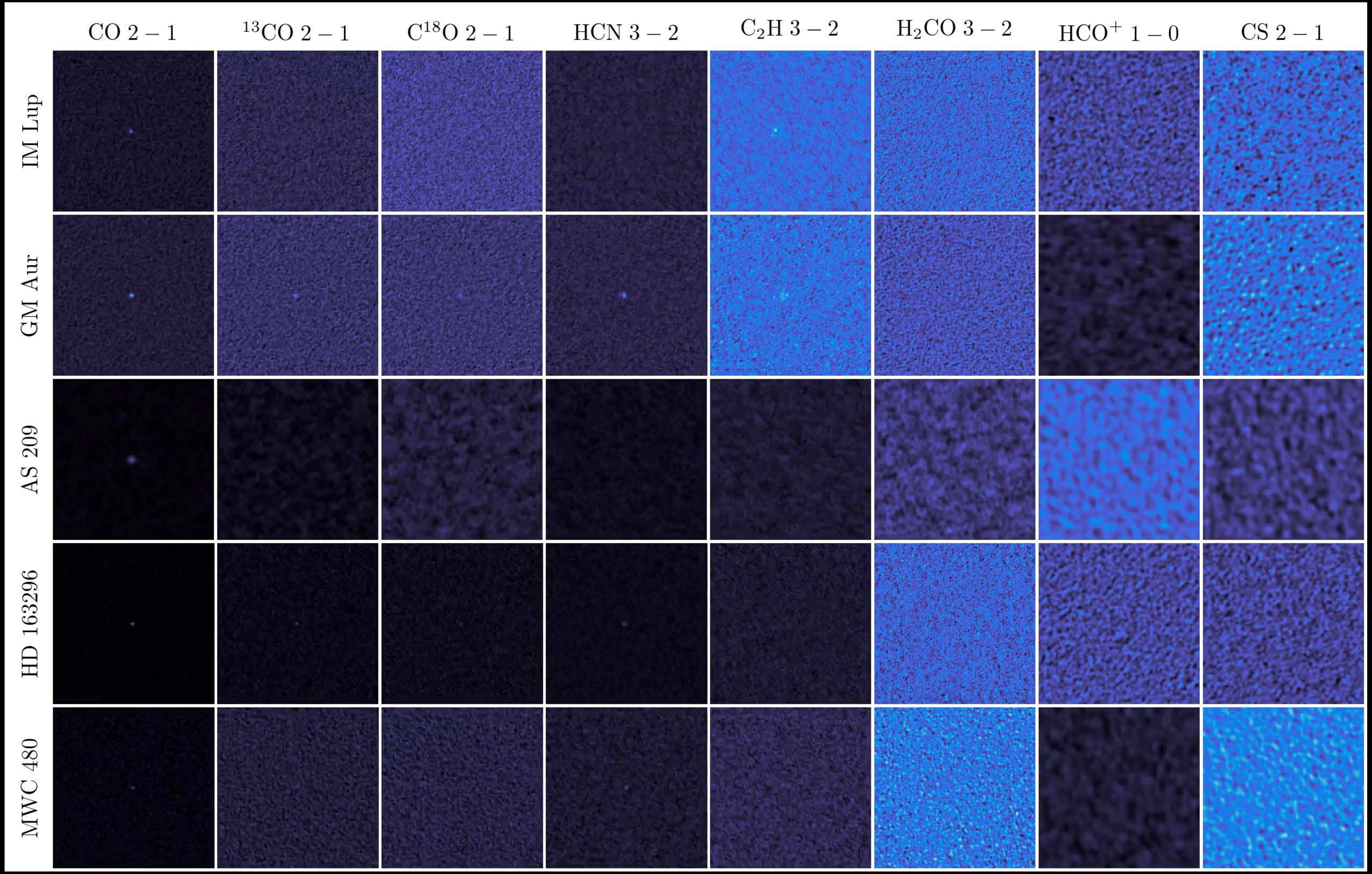
A WIDE VARIETY IN DISCS



- Homegenous survey in resolution and sensitivity, 5 AU resolution (35 mas)
- Find and characterise substructures in the spatial distributions of solid particles in 20 nearby protoplanetary disks
- Rings/gaps most common sub-structures; less common are spiral structures (3)
- Multiple systems (2) **and** single stars

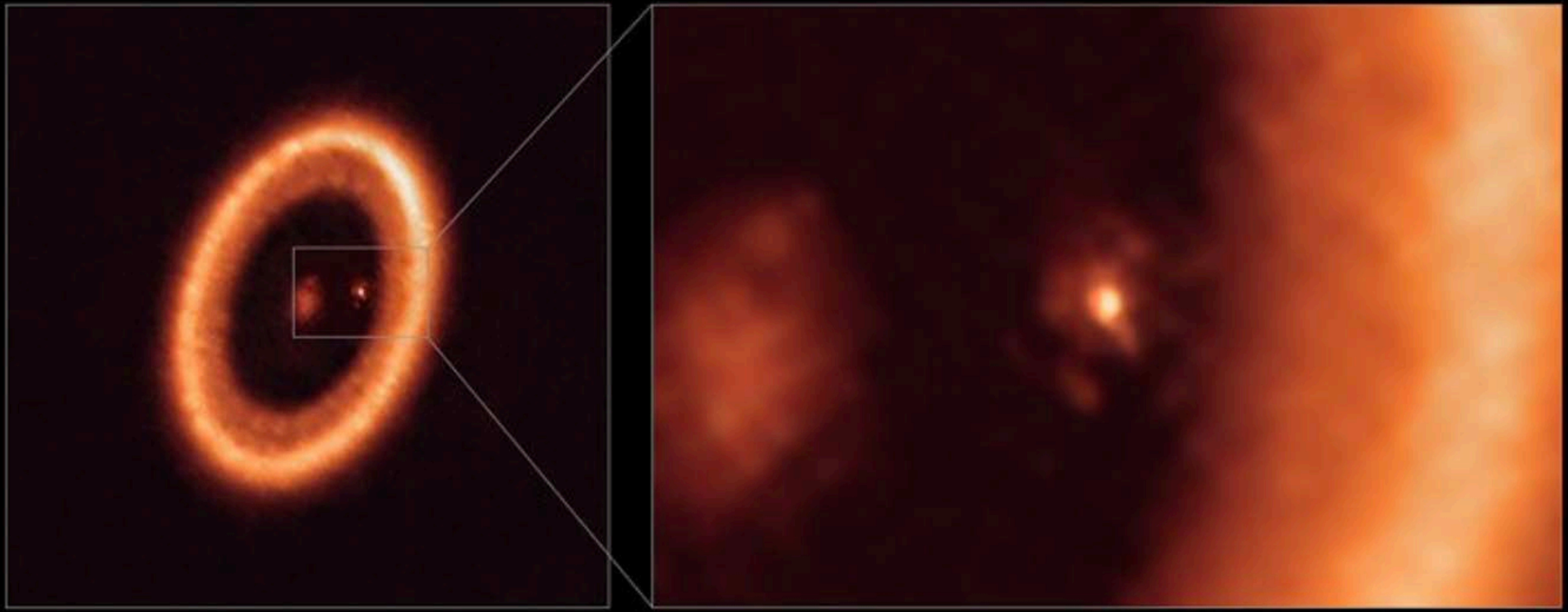
DSHARP Large Programme,
Andrews+2018

MOLECULES WITH ALMA AT PLANET-FORMING SCALES



MAPS Large Programma:Öberg+2021

MOON-FORMING DISC AROUND AN EXOPLANET



0.02 arcsec resolution ALMA dust continuum observations identified a disc structure around a protoplanet

Benisty+2021

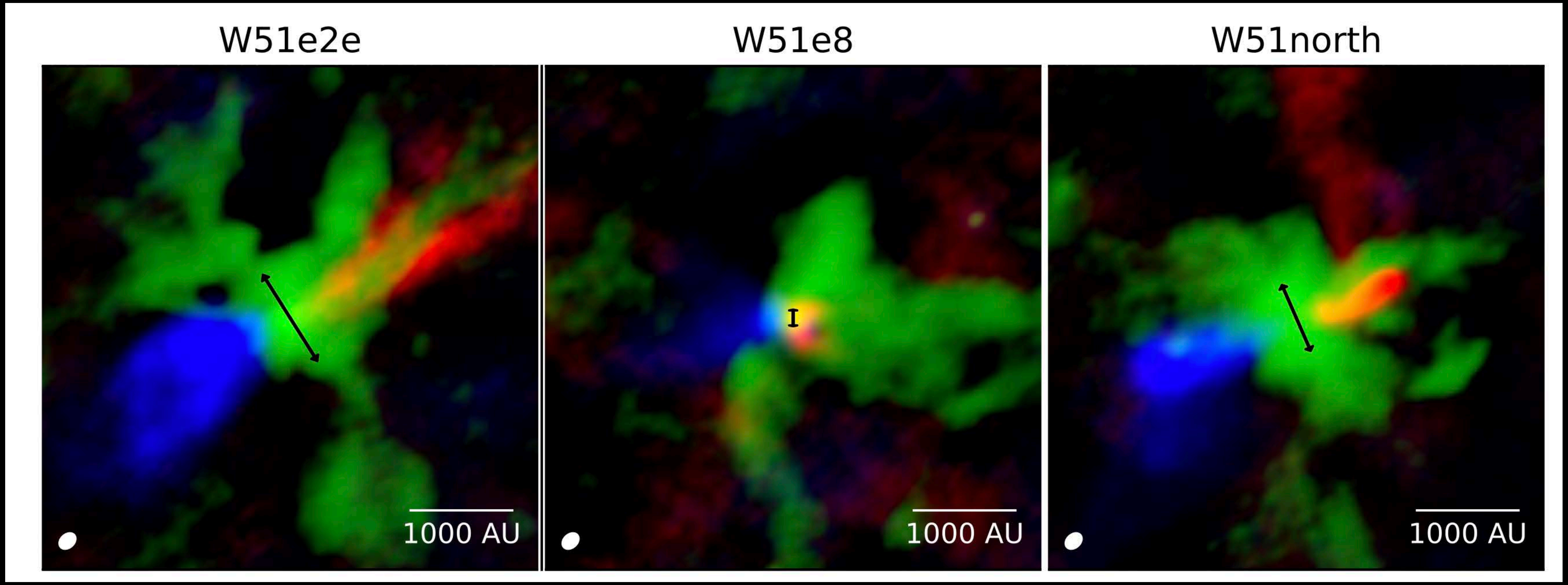
WATER VAPOUR IN A PLANET FORMING DISC

- Detection of water vapour in planet forming disc
- Water molecules being released from ices
- Water vapour at same location as gaps where a planet could potentially be forming
- Water vapour can influence the chemistry of the planet

ALMA (ESO/NAOJ/NRAO)/S. Facchini et al.2024

STAR FORMING REGIONS

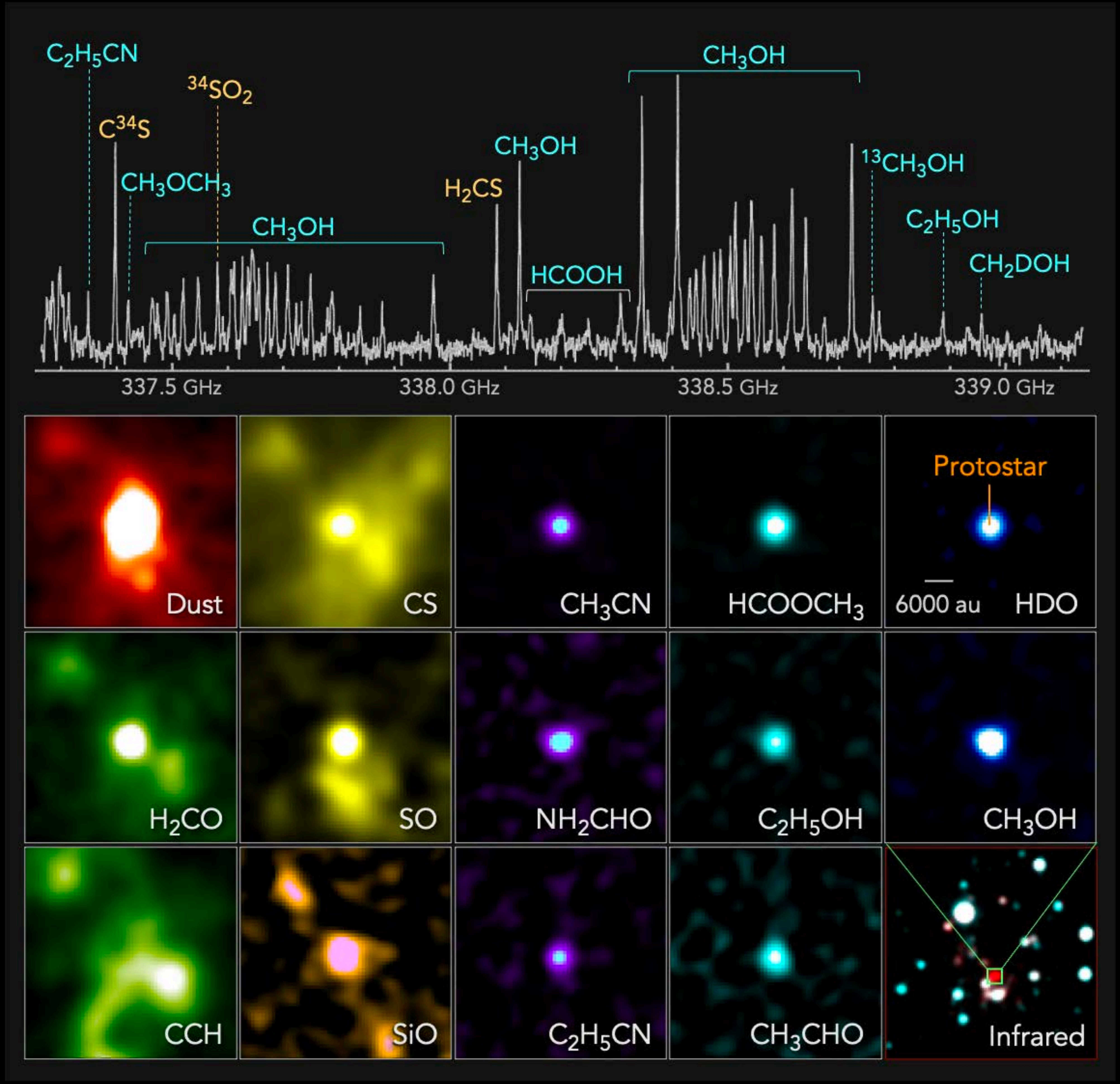
MASSIVE STAR FORMATION: A CHAOTIC PROCESS



- High angular resolution observations revealed complex and filamentary structures arising from star-forming cores
- Different from the ordered disks seen around low-mass star-forming regions
- This supports a scenario were massive protostars accrete material from multiple massive flows with different angular momentum vectors.

Goddi+2020

MOLECULAR COMPLEXITY OF STAR-FORMING REGIONS



- Spectrum of protostar in extreme outer Galaxy
- A variety of carbon-, oxygen-, nitrogen-, sulfur-, and silicon-bearing molecules, including complex organic molecules containing up to nine atoms
- The relative abundances of complex organic molecules are similar to objects in inner Galaxy.
- Complex organic molecules are formed with similar efficiency even at the edge of our Galaxy, where the environment is very different from the solar neighbourhood.

ALMA (ESO/NAOJ/NRAO), Shimonishi et al. 2021

FILAMENTARY STAR FORMATION

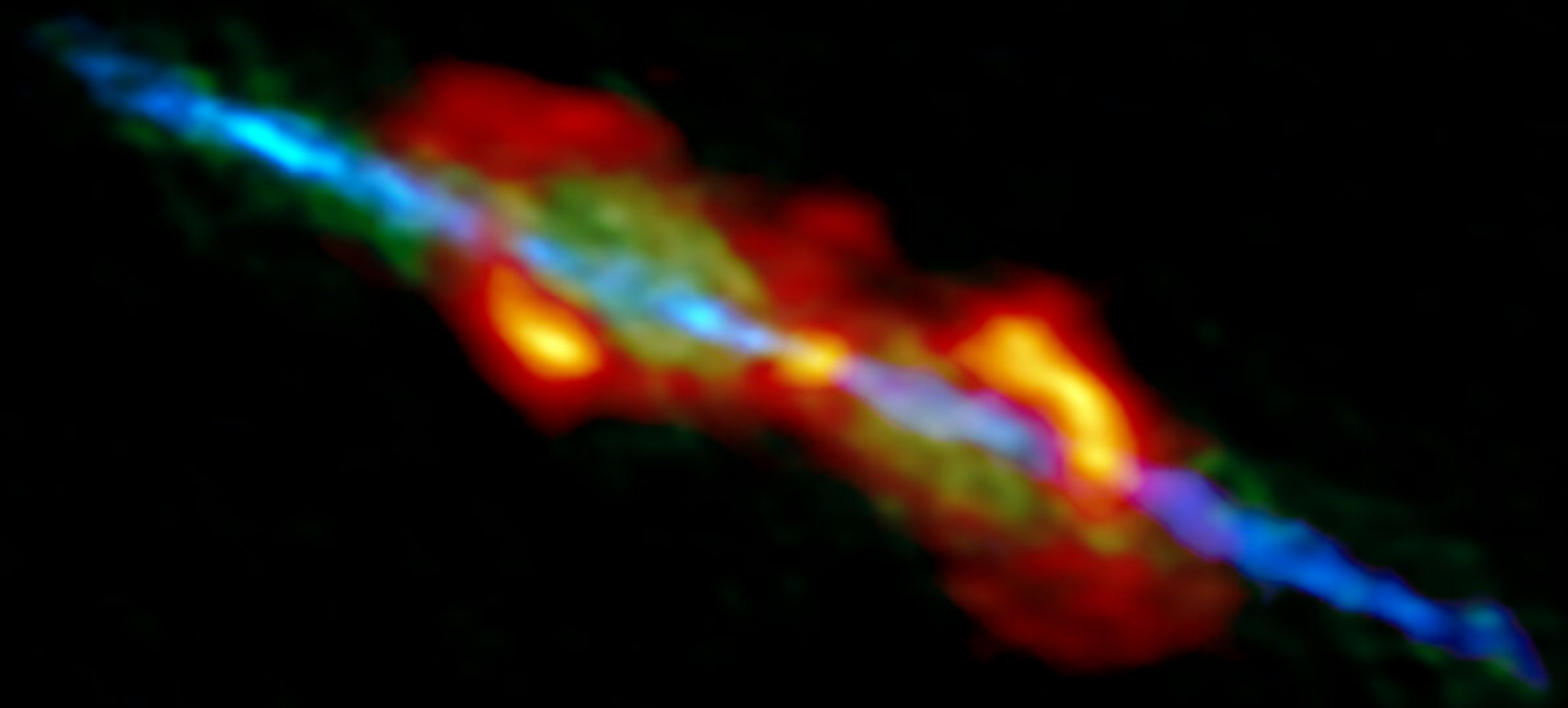
- N2H+ observations of filaments in the Orion
- Complex bundles of fibres within the filament
- Strong similarities between the internal substructure of this massive filament and previously studied lower-mass objects
- Beautiful example of combination of 12m, 7m and single dish data (IRAM 30m)

Hacar+2018

STELLAR EVOLUTION

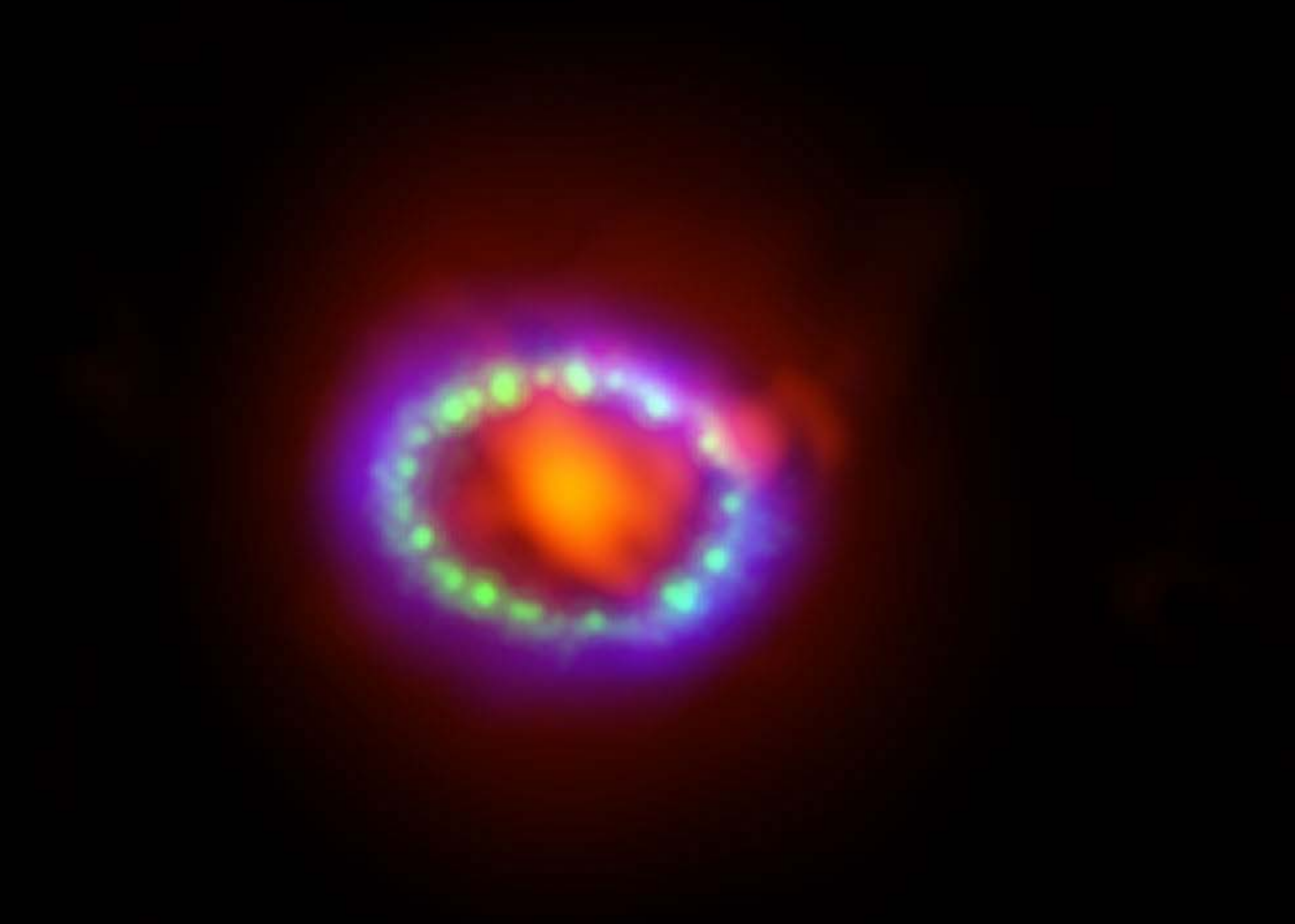
A STAR ALTERING ITS ENVIRONMENT

- A jet from an evolved star with an age less than human-life span (~60 yr)
- Key initial conditions for the theoretical models that aim to explain the formation of bipolar morphologies in the circumstellar envelopes of low- and intermediate-mass stars
- Dusty clouds entrained by the jet, indicative of the jet interacting with its surroundings
- Signs of emission from water molecules



ALMA (ESO/NAOJ/NRAO), Tafoya et al.+2020

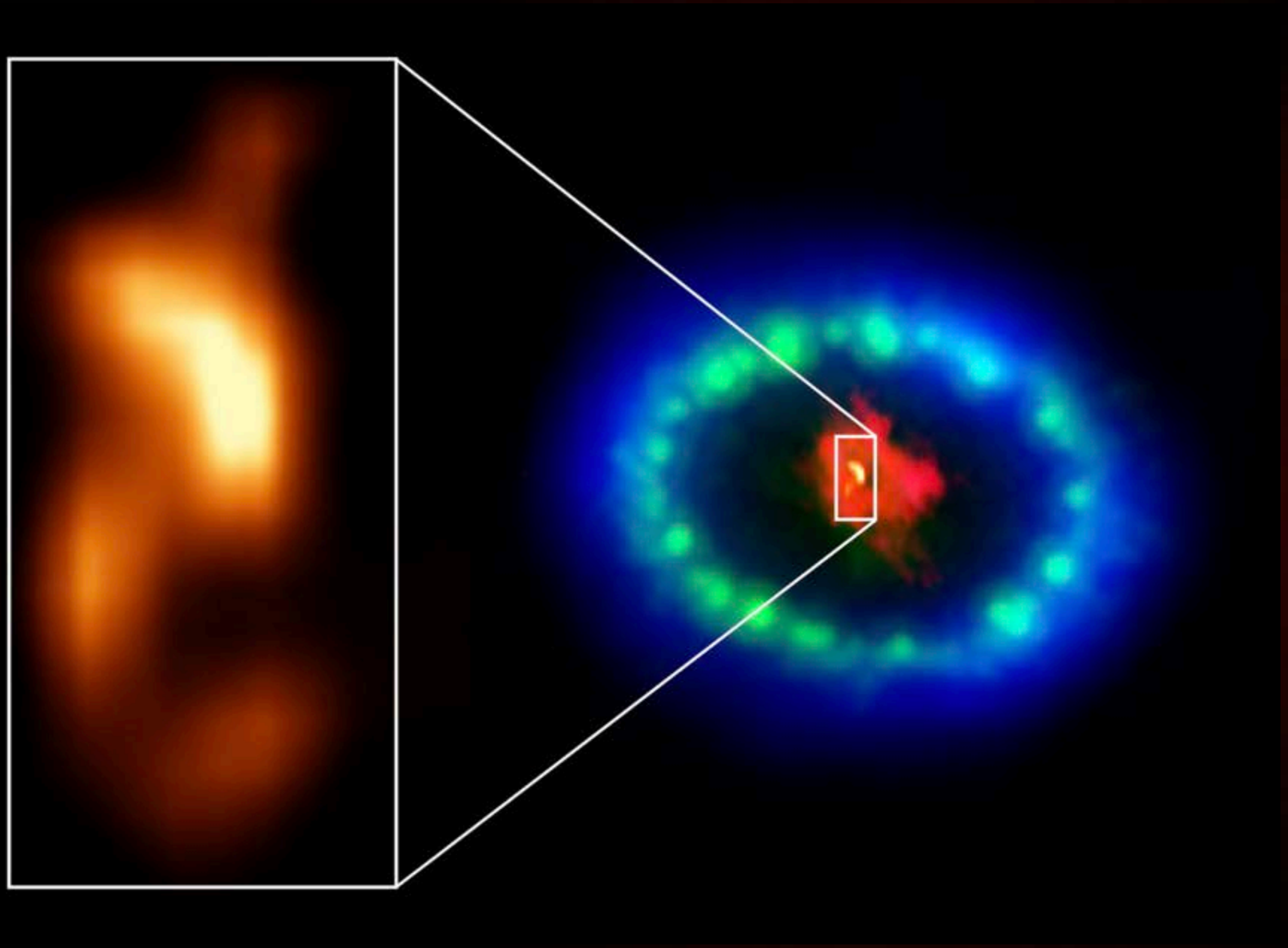
SN1987A



- Large dust mass concentrated in the central part of the ejecta from a relatively young and nearby supernova
- Image the exact location where dust is forming
- Key information to understand the formation of dust in SNe and couple this to the dust buildup of the Universe

ALMA (ESO/NAOJ/NRAO)/A. Angelich. Visible light image: the NASA/ESA Hubble Space Telescope. X-Ray image: The NASA Chandra X-Ray Observatory. Indebetouw+2014

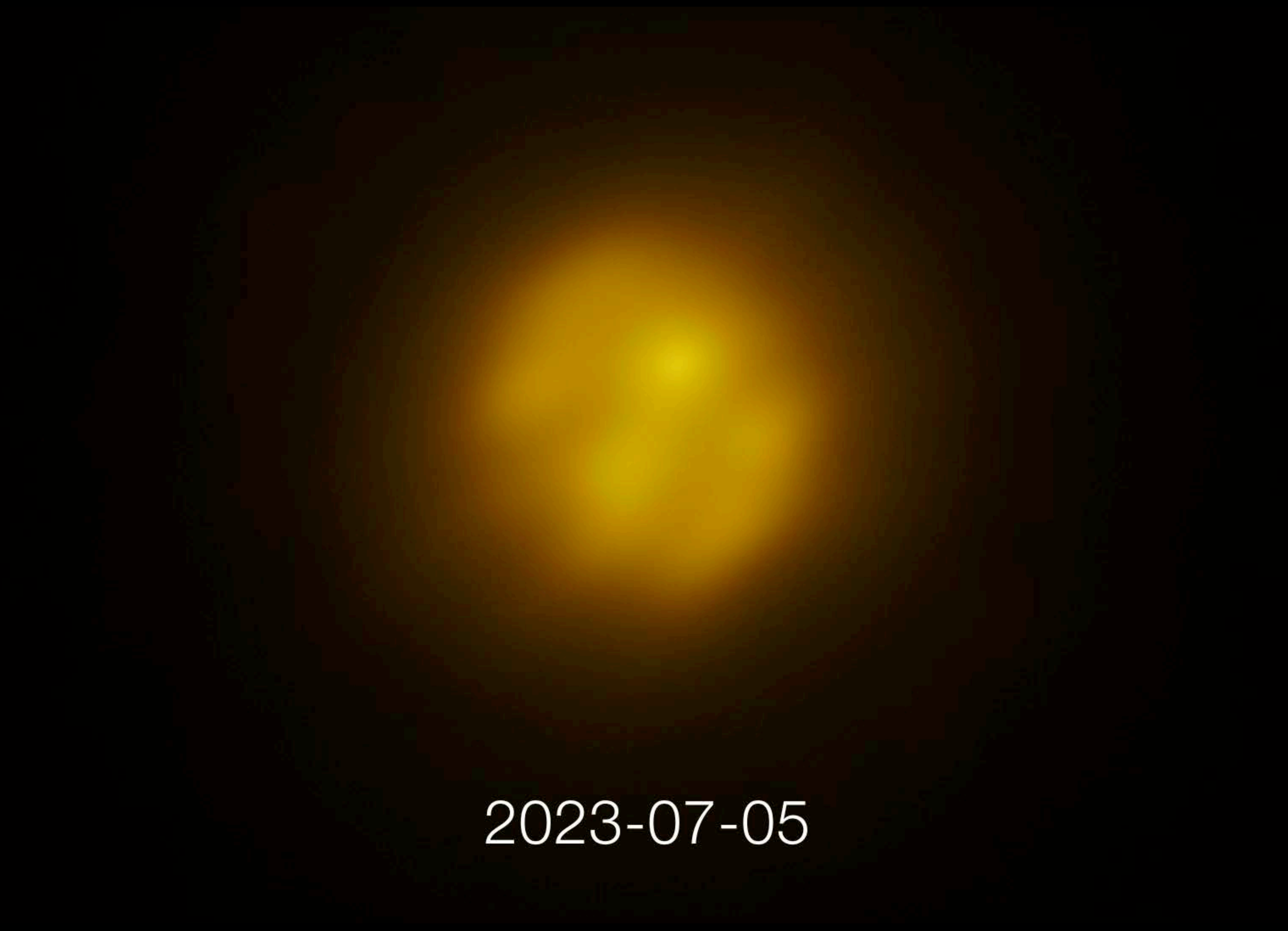
SN1987A HARBOURING A NEUTRON STAR?



- A bright continuum blob with was detected in the centre of SN1987A
- CO and SiO line transitions indicate warm gas
- The brightness and temperature can be explained by a neutron star heating the dust and gas

ALMA (ESO/NAOJ/NRAO), P. Cigan and R. Indebetouw; NRAO/AUI/NSF, B. Saxton; NASA/ESA, Cigan+2019

STELLAR BUBBLES IN R DORADUS



- First measures of convection motions in a star other than our Sun
- Convection bubbles are larger than in our Sun and have a faster cycle

ALMA (ESO/NAOJ/NRAO)/W. Vlemmings et al.

SOLAR SYSTEM (AND SLIGHTLY BEYOND)

ALMA TARGETING INTERSTELLAR COMETS

NRAO/AUI/NSF, S. Dagnello

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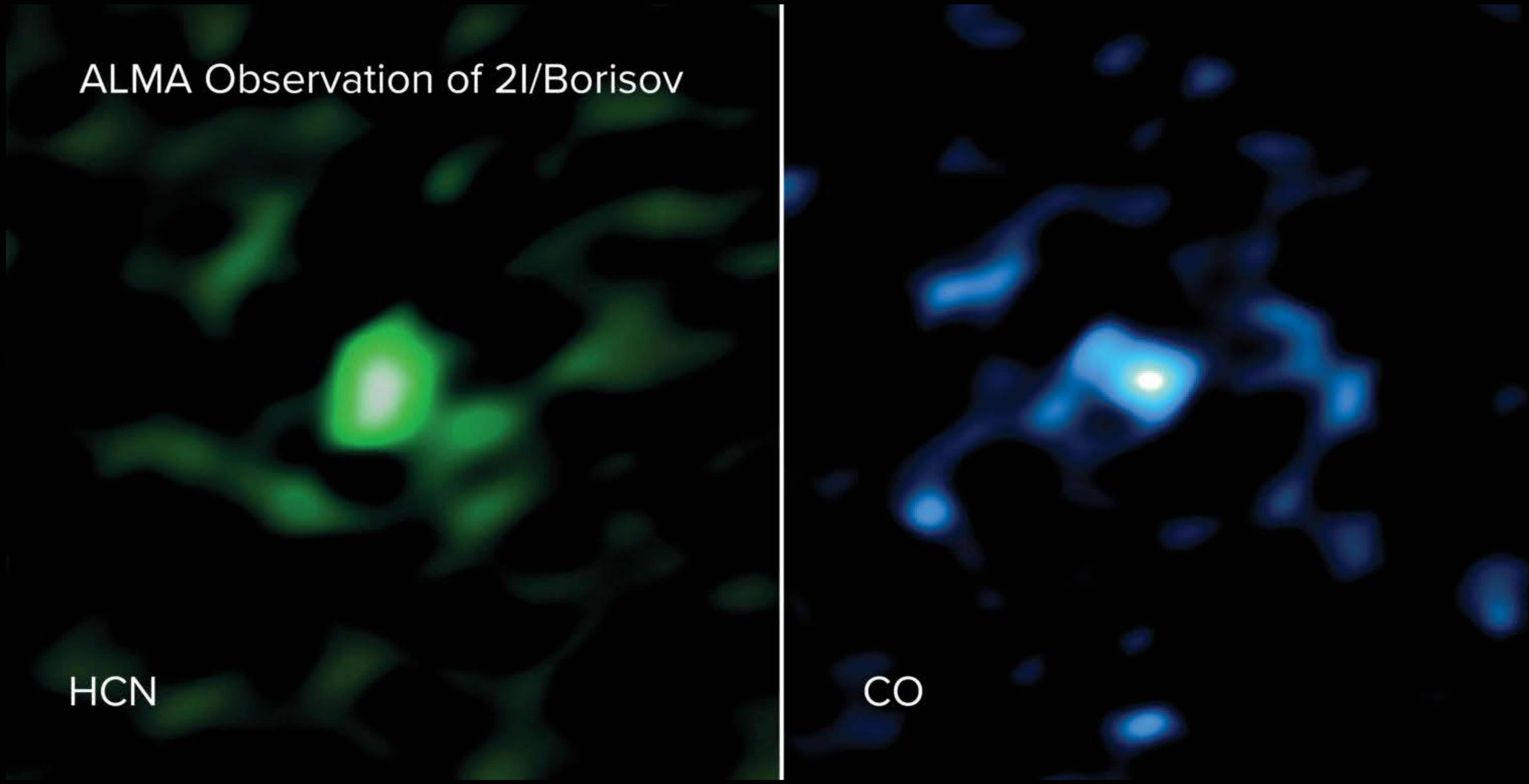
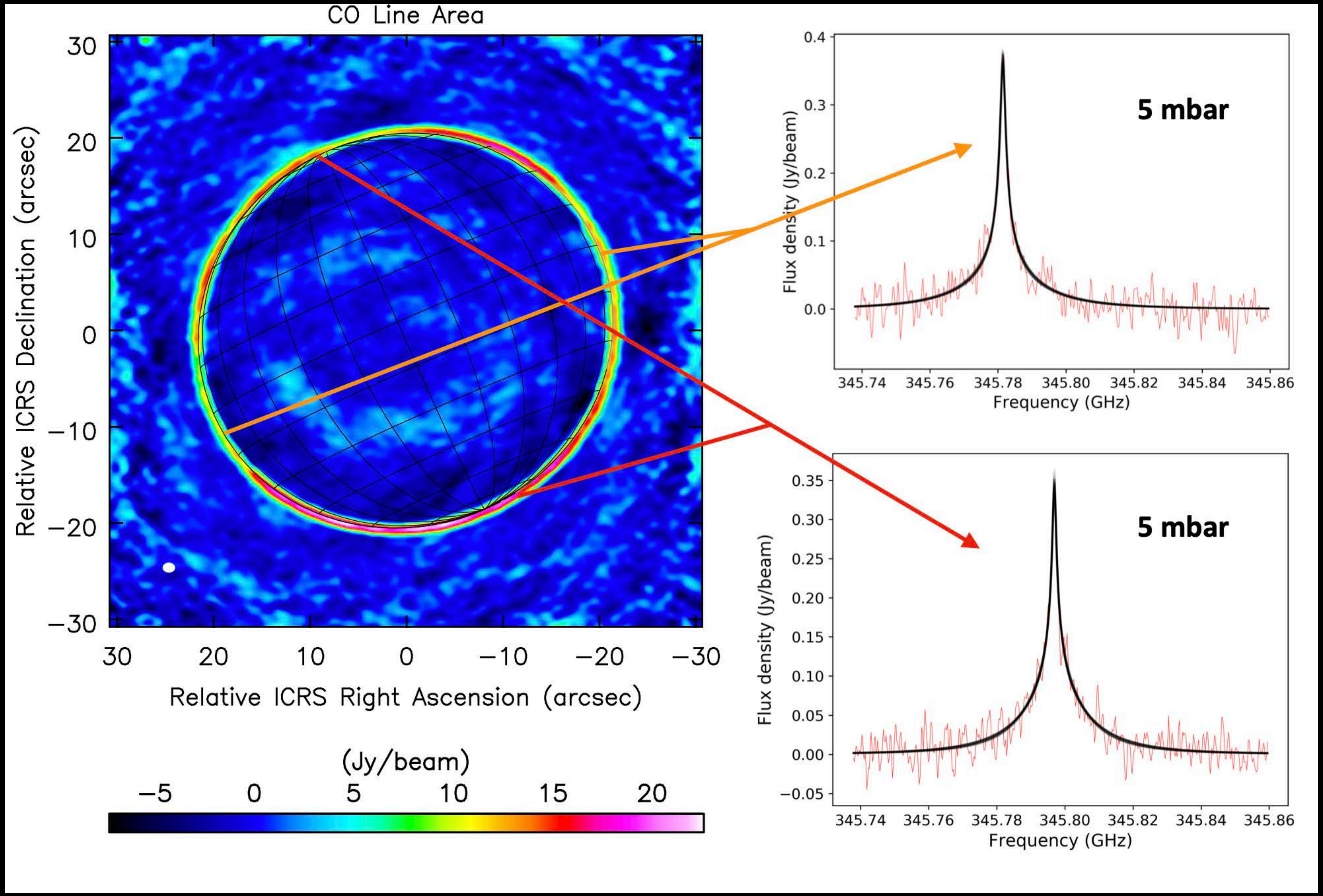


- A high CO abundance in Comet 2I/ Borisov
- Comet likely formed in a different way than our own solar system comets, in an extremely cold, outer region of a distant planetary system
- A glimpse into the chemistry in other planetary systems

NRAO/AUI/NSF, S. Dagnello

RAPID WINDS ON JUPITER

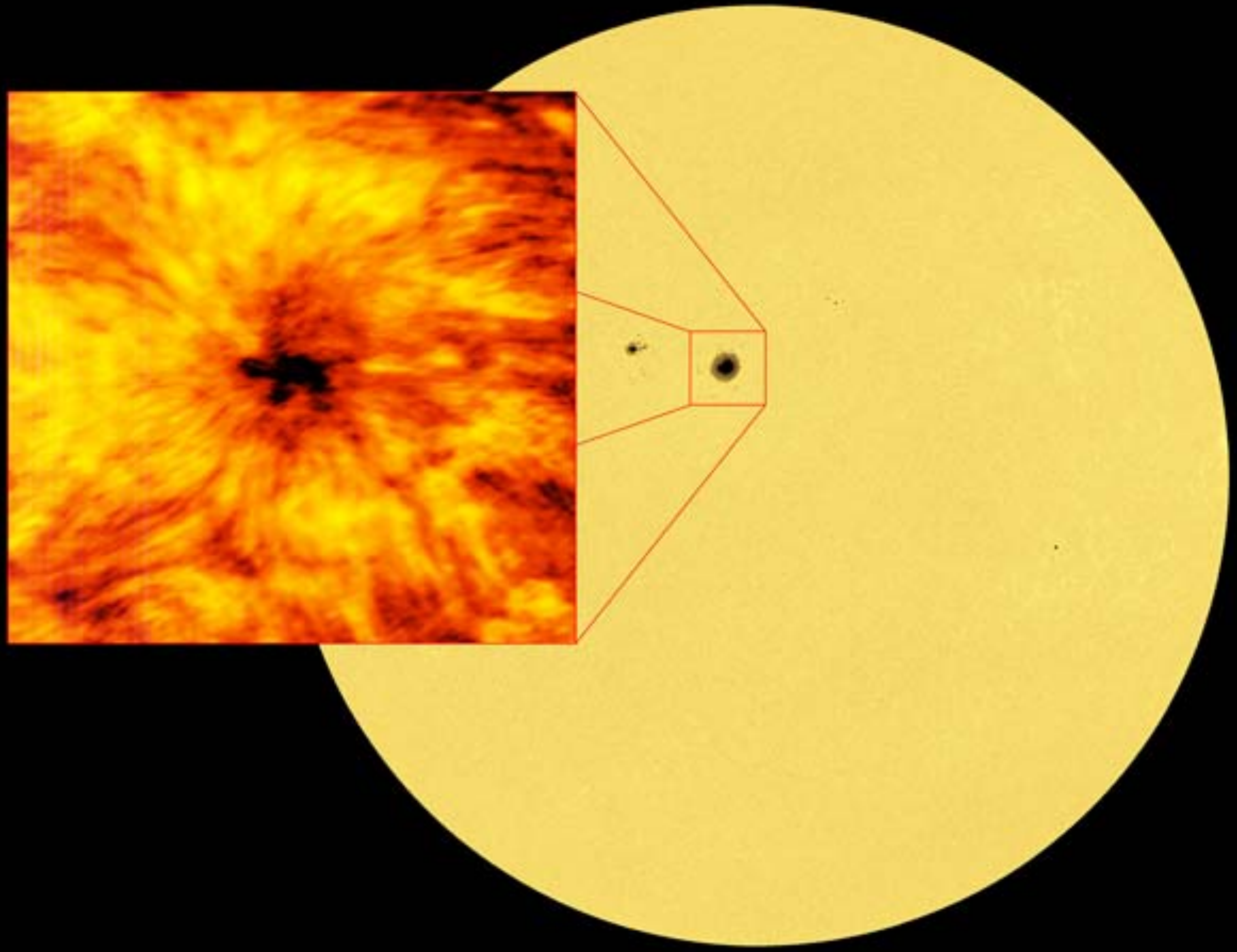


- CO and HCN measurements of the stratosphere of Jupiter
- Doppler shift of the lines indicate winds with speeds up to 400 m/s (1450 km/h) in the stratosphere close to the poles of Jupiter

Cavalié+2021

ALMA OBSERVES THE SUN

The sun at 1.25 mm



Millimetre emission originates in different regions of the solar atmosphere, and trace physical mechanisms other than produced at longer and shorter wavelengths

ALMA (ESO/NAOJ/NRAO); NASA

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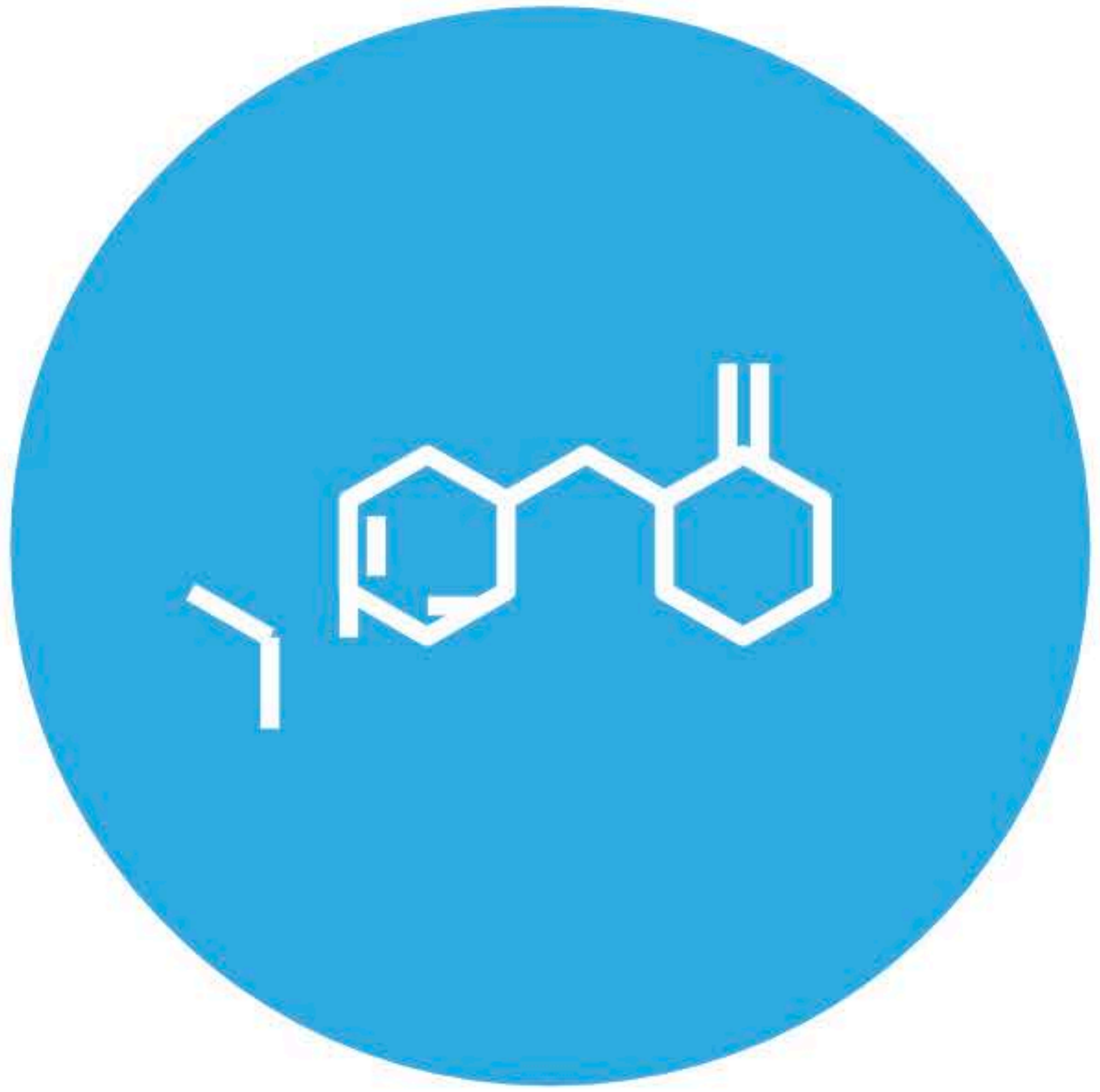
EXCITING ALMA SCIENCE IN 2030s

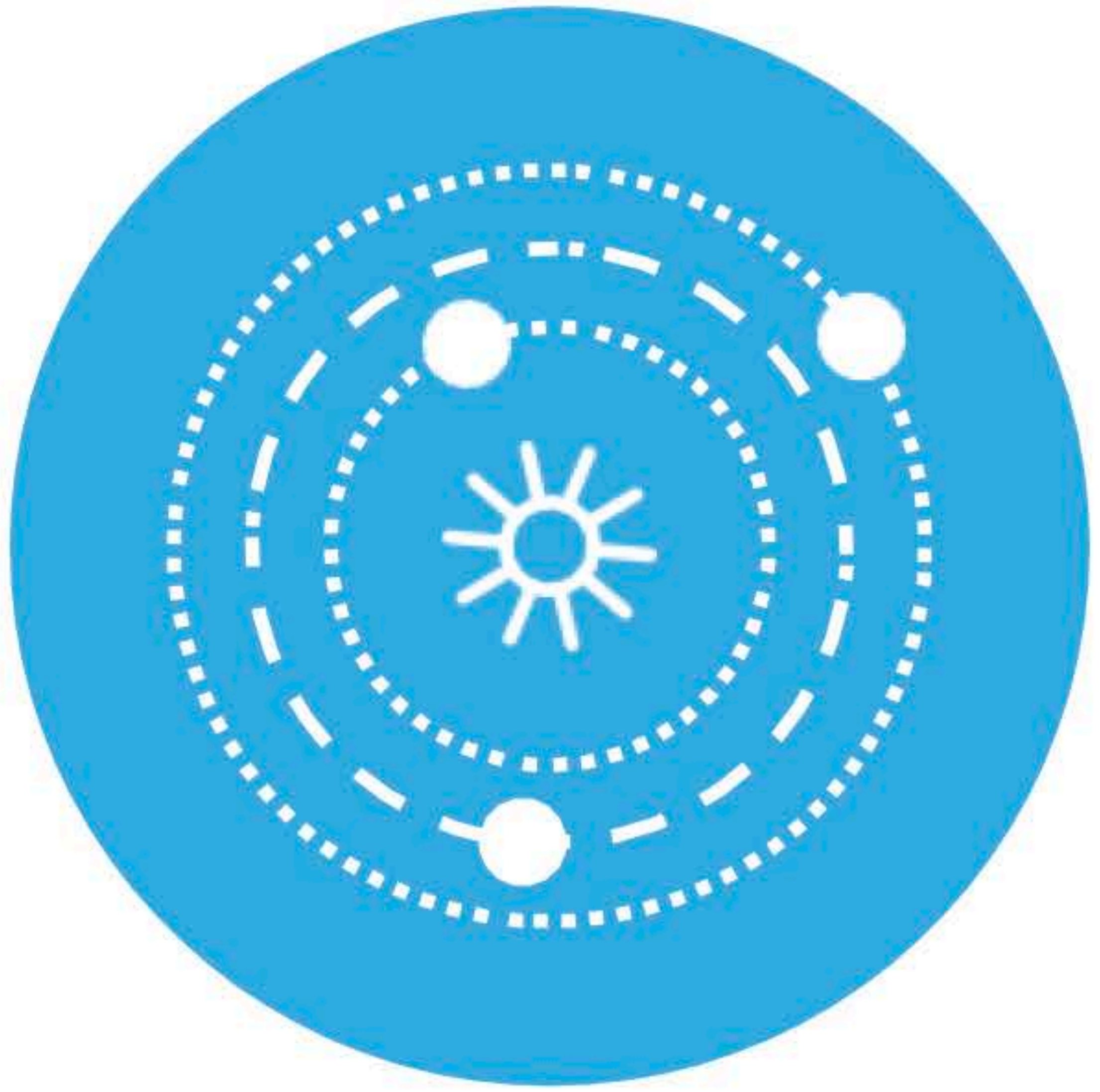
ORIGINS OF GALAXIES

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.

10 years of exciting ALMA science

and many more to come!