WFIRST-ALMA Synergies

Al Wootten, NRAO

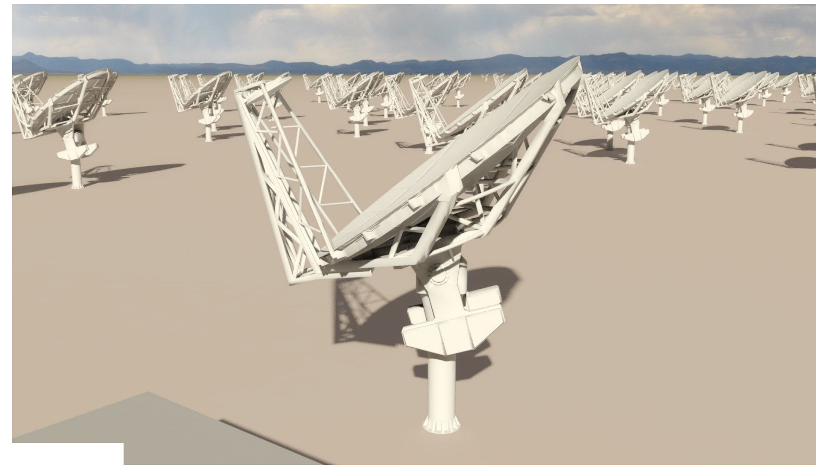
WFIRST and RMS Instrumentation Synergies

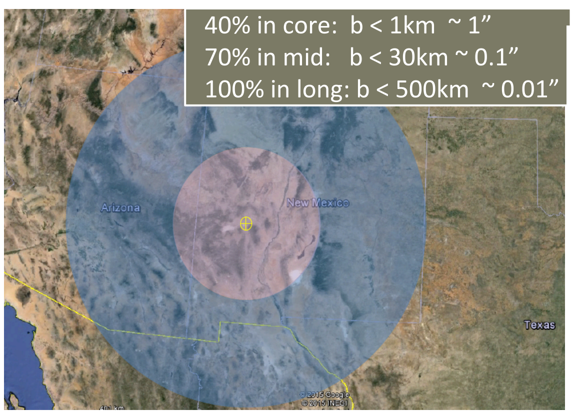
Radio, Millimeter, Submillimeter beyond 2020

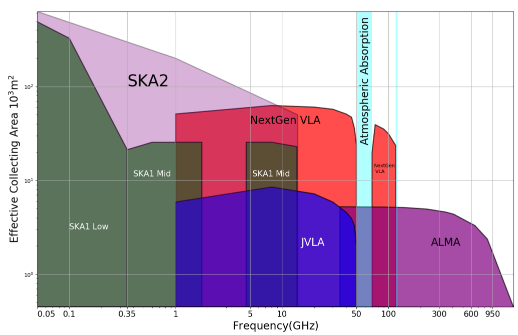
- Radio: JVLA/ngVLA: ***Thermal imaging with 10x effective collecting area of JVLA at milli-arcsec resolution***
- Millimeter: Green Bank Telescope, Large Millimeter Telescope and High Sensitivity Array: ***Thermal imaging with large collecting area and sensitive non-thermal imaging at milli-arcsec resolution***
- Submillimeter/Millimeter: ALMA moves toward ALMA2030: ***Increased Grasp of Spectrum and Sky, Increased Resolution and Sensitivity***

A next-generation Very Large Array (ngVLA)

- Scientific Frontier: ***Thermal imaging at milli-arcsec resolution***
- Sensitivity/Resolution Goal:
  - ***10x effective collecting area & resolution of JVLA/ALMA***
- Frequency range: ***1.2 –116GHz***
- Located in Southwest U.S. (NM + TX) & MX, centered on VLA
- Baseline design under development
- Low technical risk (reasonable step beyond state of the art)







Complementary suite from meter to submm arrays for the mid-21st century

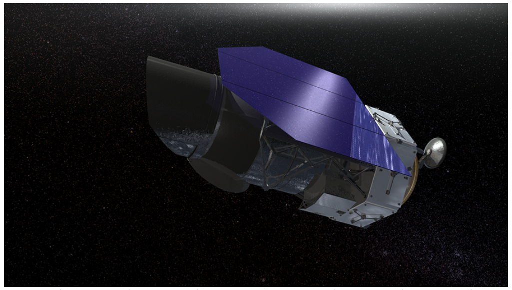
- **< 0.3cm:** ALMA 2030
- **0.3 to 3cm: ngVLA**
- **> 3cm:** SKA

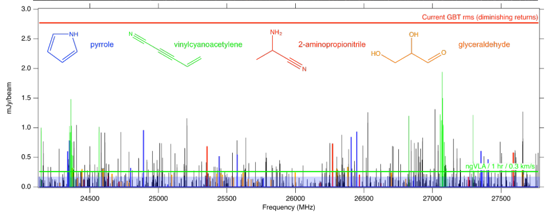
https://science.nrao.edu/futures/ngvla

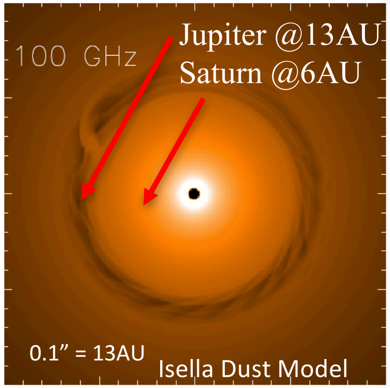
ngVLA: Highly Synergistic with WFIRST Science

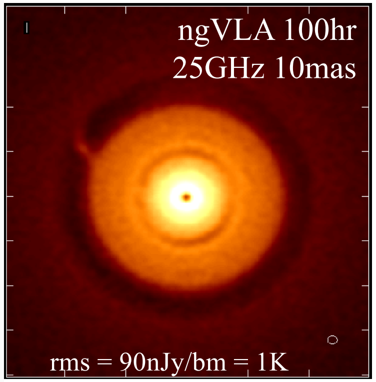
ngVLA Key Science

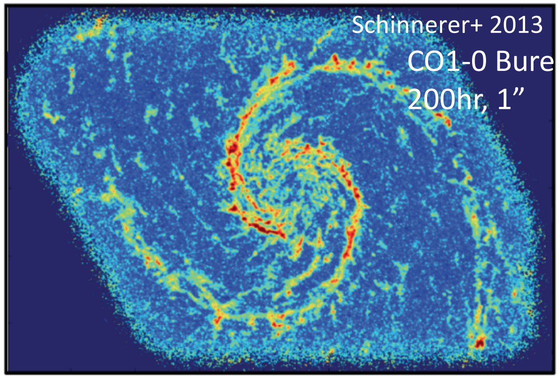
- Characterizing the Terrestrial Planet Forming Region in Nearby Young Solar Analogues *– Formation and characterization of planets*
- Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry – *Formation and characterization of habitable zones*
- Understanding How Galaxies Produce New Generations of Stars – *Assembly of galaxies and formation of Hubble sequence*

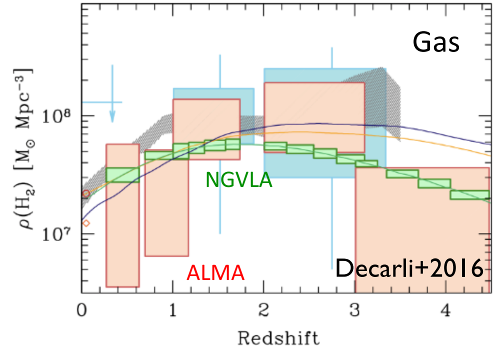








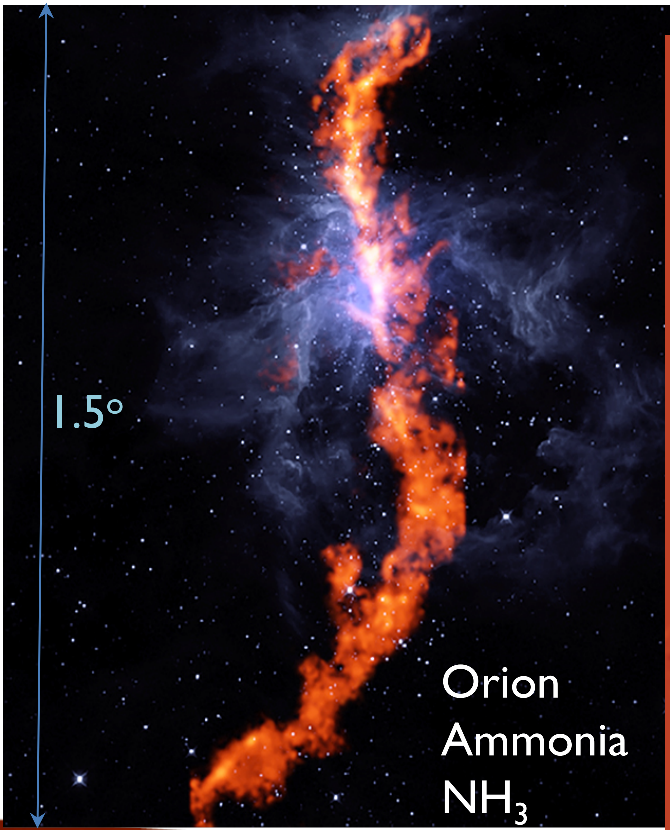


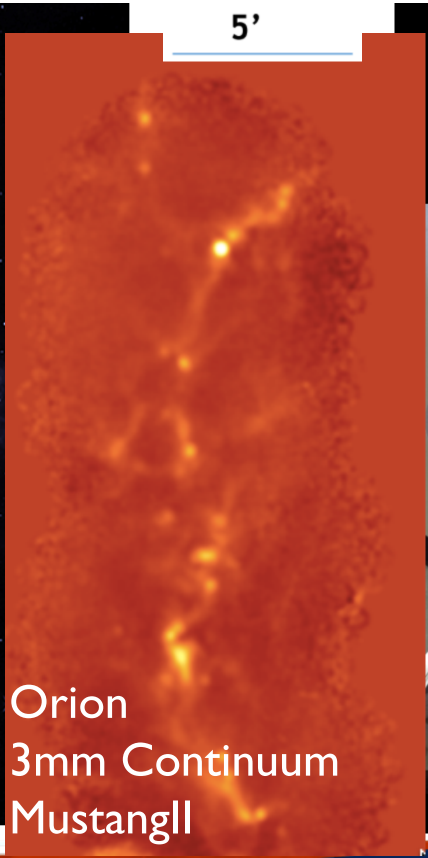


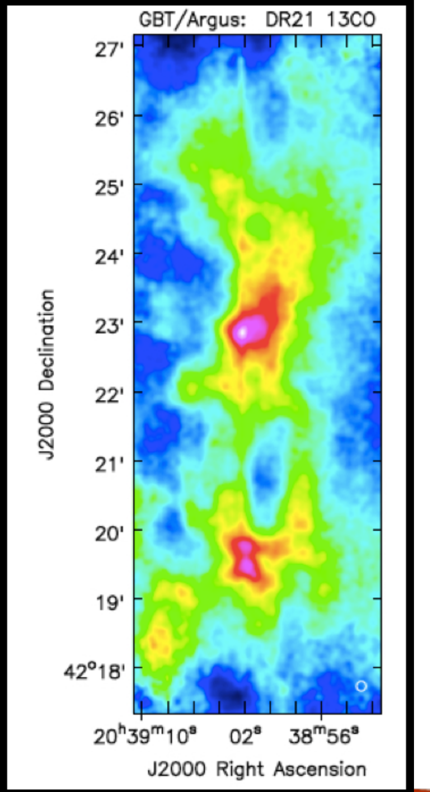
NRAO NSF Associated Universities, Inc.

Green Bank Telescope: Sensitive Wide Field Imaging

- 16-pixel array provides 6.5” beam @ 2.6mm







NRAO

NSF

Associated Universities, Inc.

ALMA (Atacama Large Millimeter/submillimeter Array)

An array of **66 antennas,**
using *aperture synthesis*, *as a* "zoom telescope"
over the *entire accessible mm/submm* wavelength range up to 1 THz

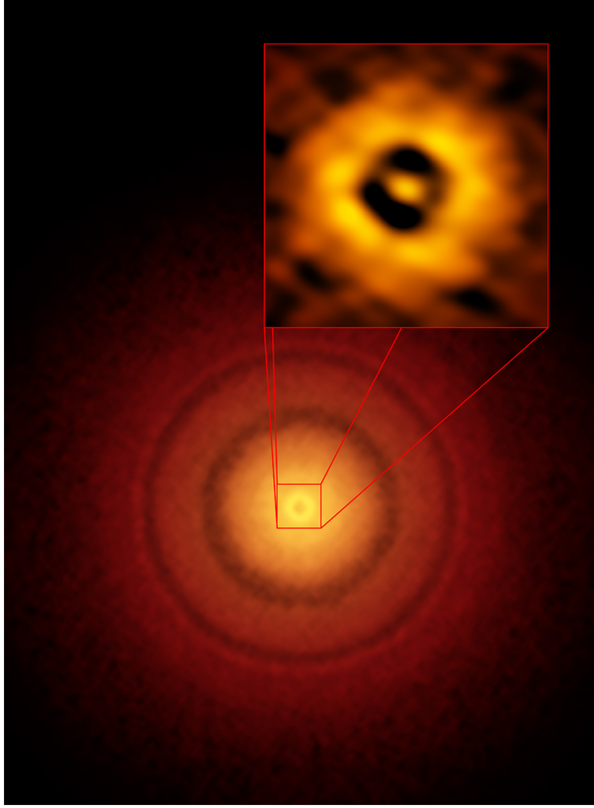
ALMA Key Science

- Planetary systems and the origins of life
- Birth of stars and protoplanetary systems
- Assembly and evolution of galaxies
- First light

Planetary Systems & Life's Origin

- Formation of planets
  - WFIRST directly images exoplanets; ALMA excels in imaging
    - local planetary bodies
    - natal disks in other systems
  - Disks provide both
    - fossil records of planet formation,
    - dynamical signposts of extant planets.
- Formation, imaging of habitable zones
  - High resolution
- Characterization of planets, atmospheres

  Measurement of Water, other molecules



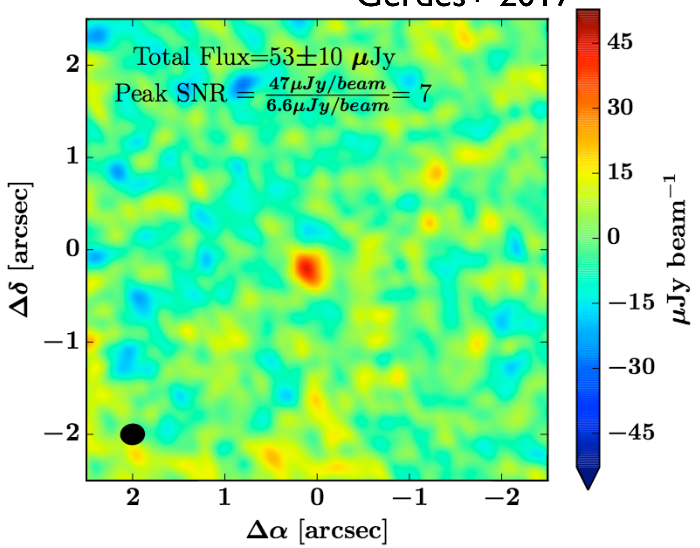
Narrow dark annulus 1 AU from TW Hya suggests planet-disk interaction Andrews et al 2016

Science: Exploring Our Own Planetary System

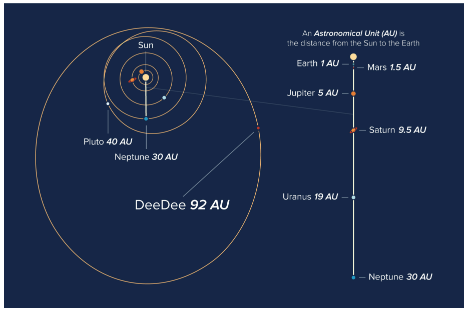
ALMA Characterizes TransNeptunian Object DeeDee

- ALMA imaged 2014 UZ224, or DeeDee, measuring its thermal properties
- DeeDee lies at 92AU from the Sun, the distance of Pluto, the 2nd most distant confirmed Solar System object, with a surface at 30K.
- ALMA data suggest a diameter of 635km, 2/3 that Ceres; DeeDee is a dwarf planet candidate.
- Very dark, its albedo is only 13%.

Gerdes+ 2017



Above: ALMA 1.3mm image

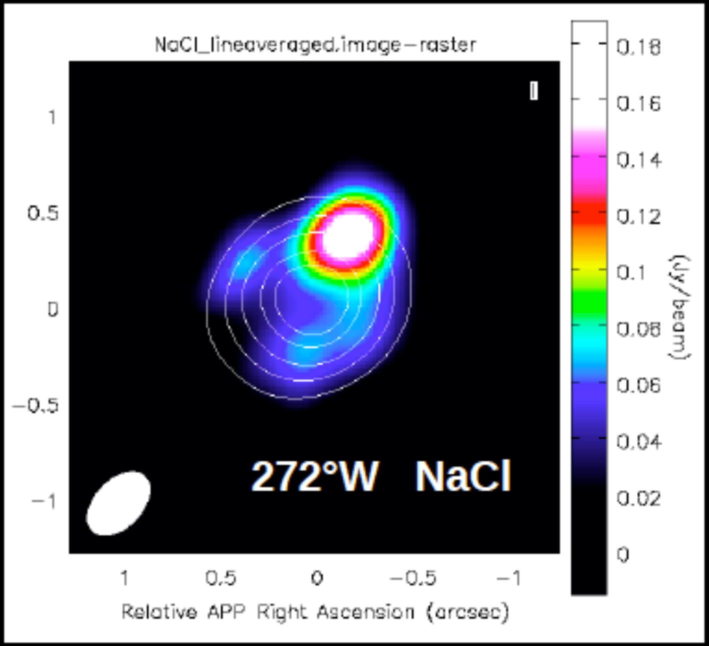


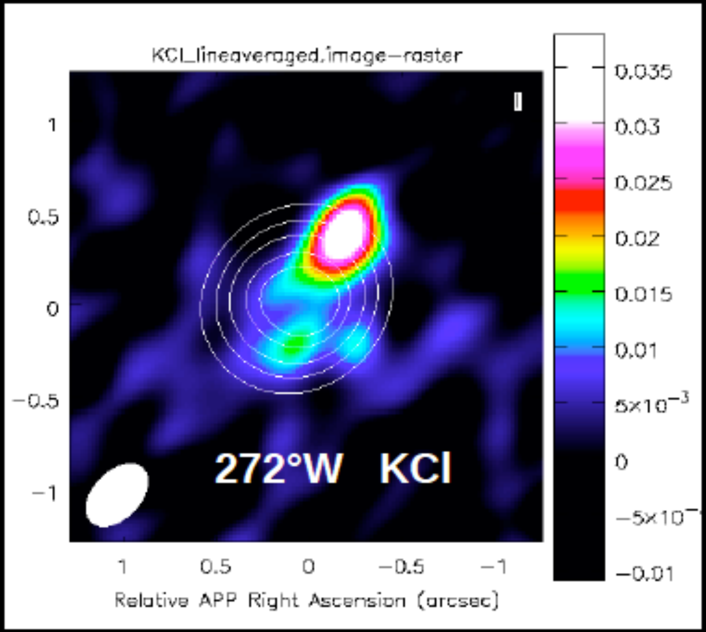
Left: DeeDee in the Solar System

NRAO NSF Associated Universities, Inc.

Simultaneous alkali detection on Io

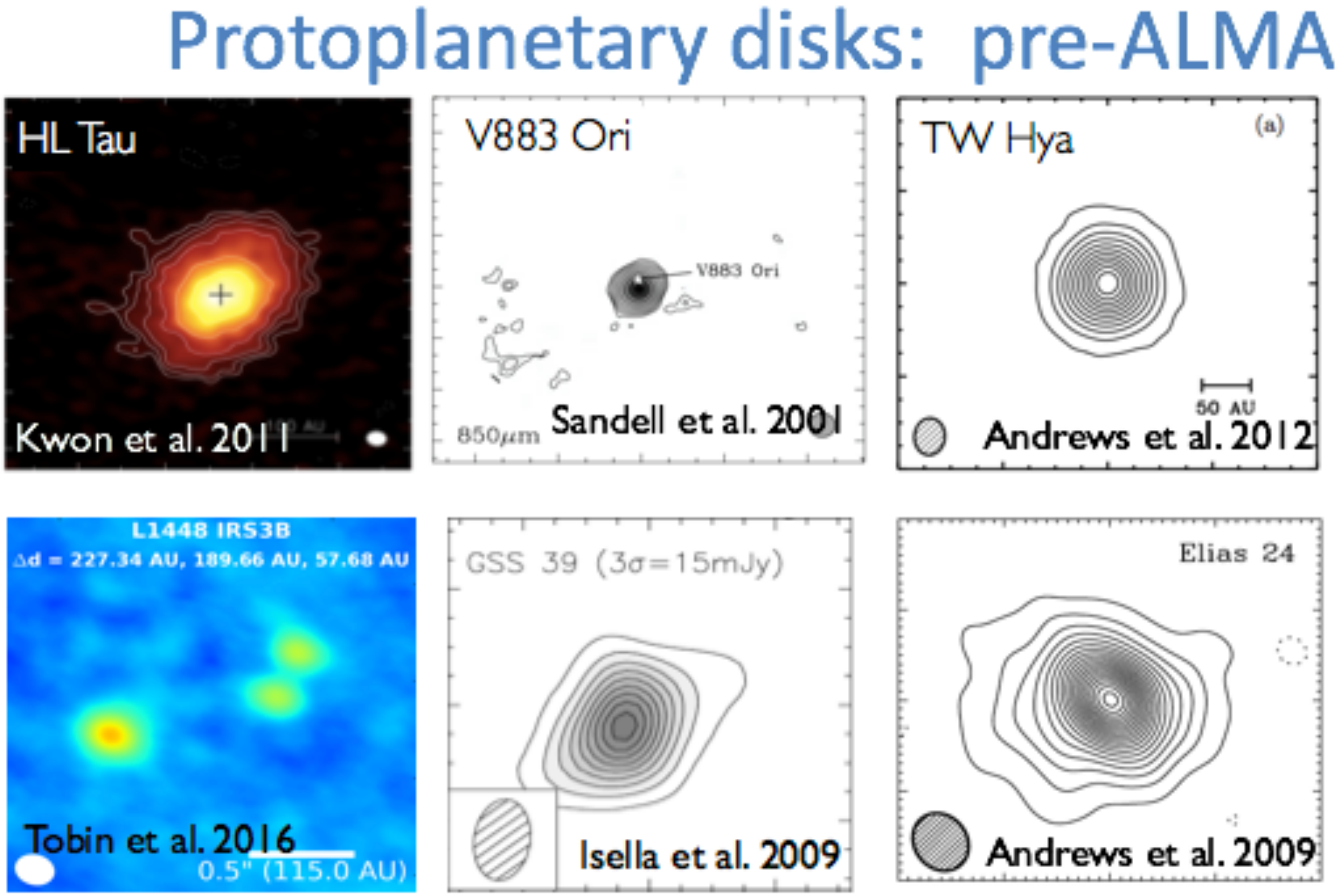
PI. Moullet: **Alkali (KCl, NaCl)** emission distributed in small and co-located regions → active volcanic plumes





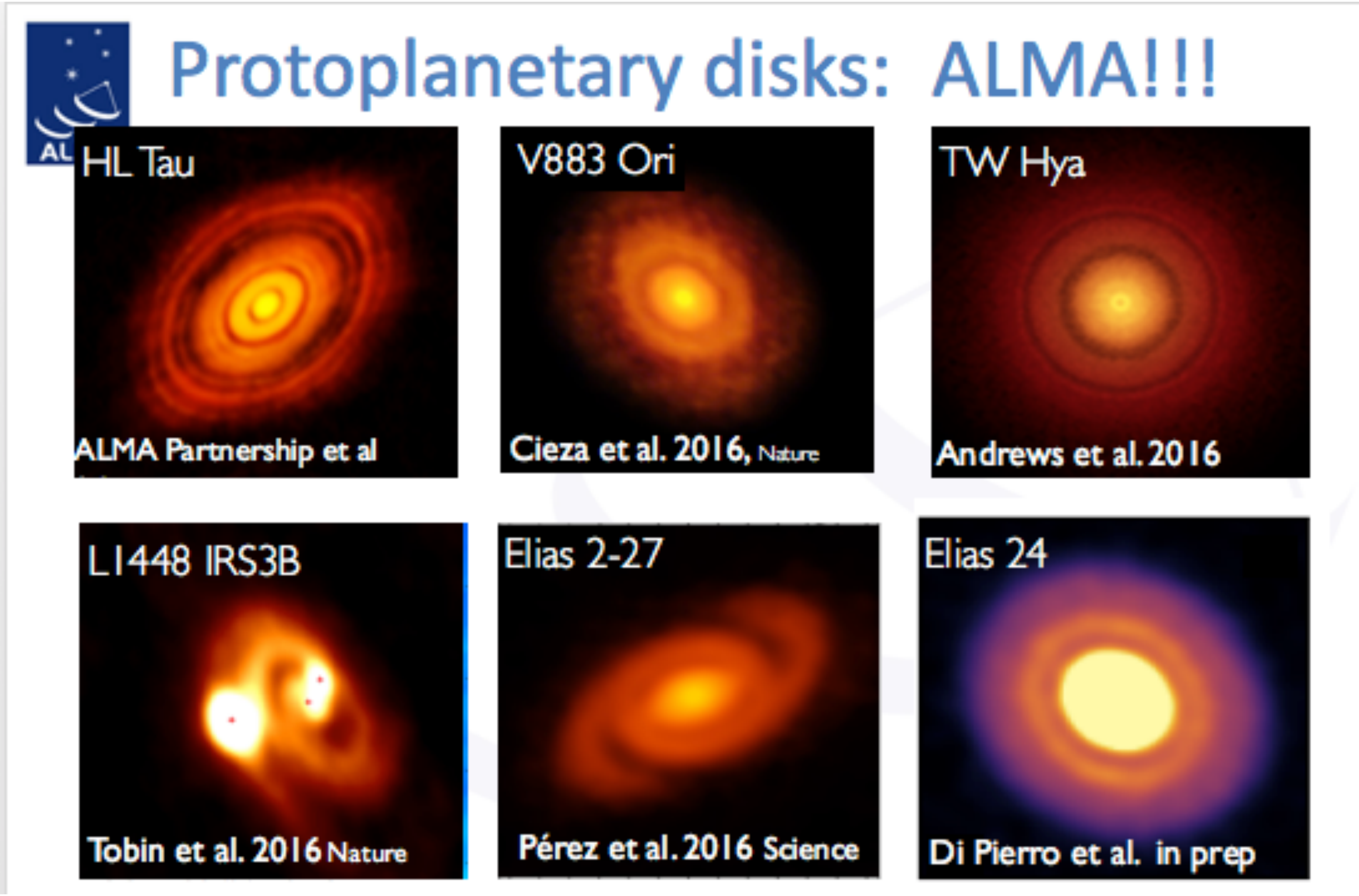
Potassium-rich atmosphere: KCl/NaCl ~ 5 (cosmic 16)

Protoplanetary Disks: Views before ALMA and Now



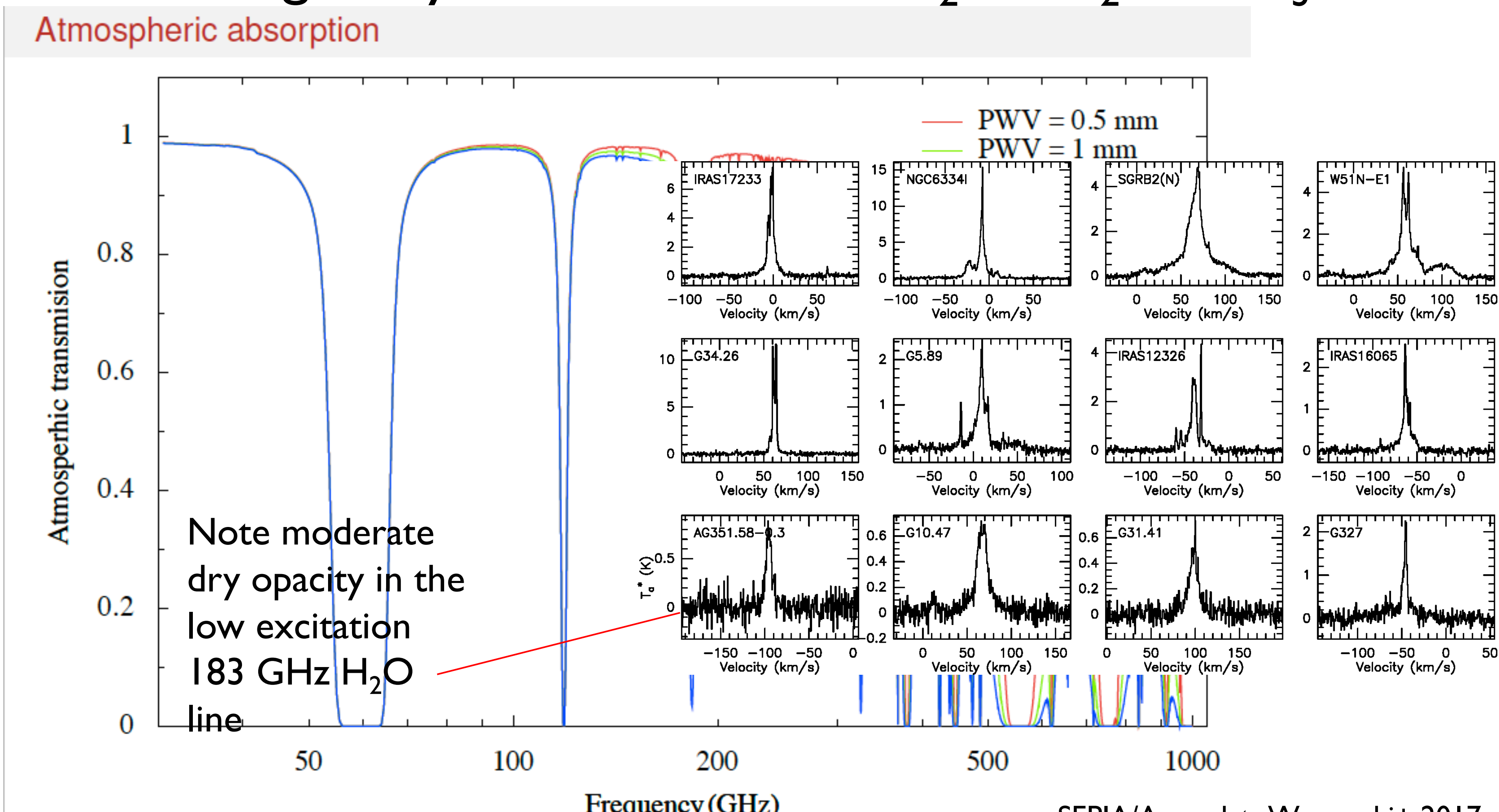
Carpenter 2017

Protoplanetary Disks: Views before ALMA and Now



Following Water

ALMA's High Dry Site: Above most H_2O; O_2 and O_3



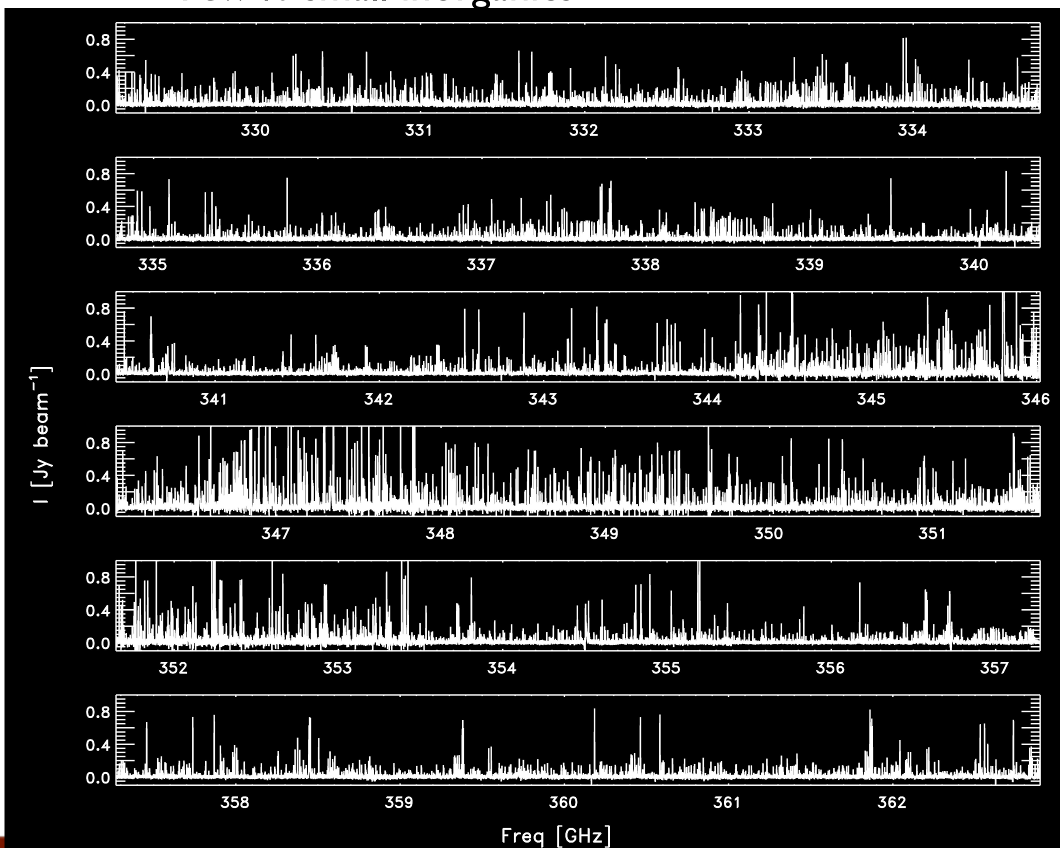
SEPIA/Apex data Wyrowski+ 2017

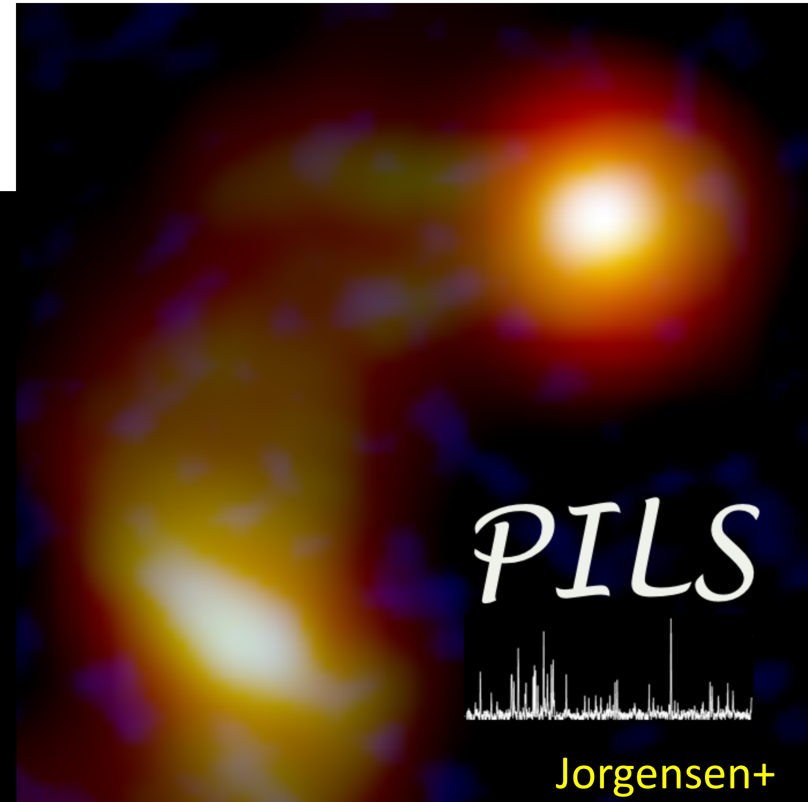
Warm water is directly observable

ALMA Detections of complex organics, prebiotics

Seen from solar-type protostars to giant molecular clouds

- 1mm Spectral Survey: >10000 lines
  - 30% saturated organics, 30% isotopic variants
  - Few % small inorganics





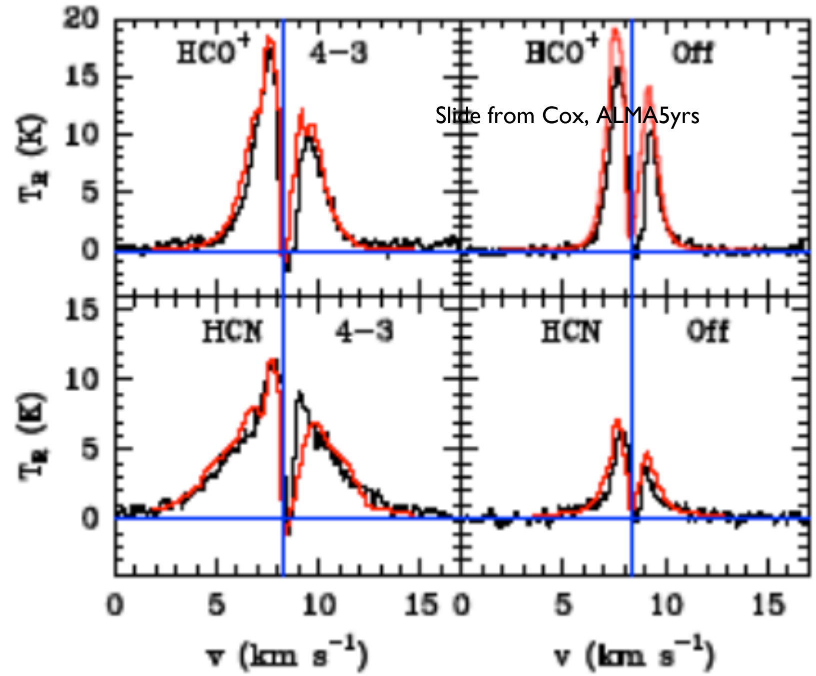
Star and Protoplanetary System Birth

- Protostellar cloud collapse
- IMF at sub-stellar masses
- Formation of protoplanetary systems
- Dust and gas life cycle

Detection of Infall in the Proto-star B335

- Isolated globule B335 at 100pc
- Absorption features against the continuum that are red-shifted from the systemic velocity.
- Unambiguous evidence for infall towards the central luminous source.

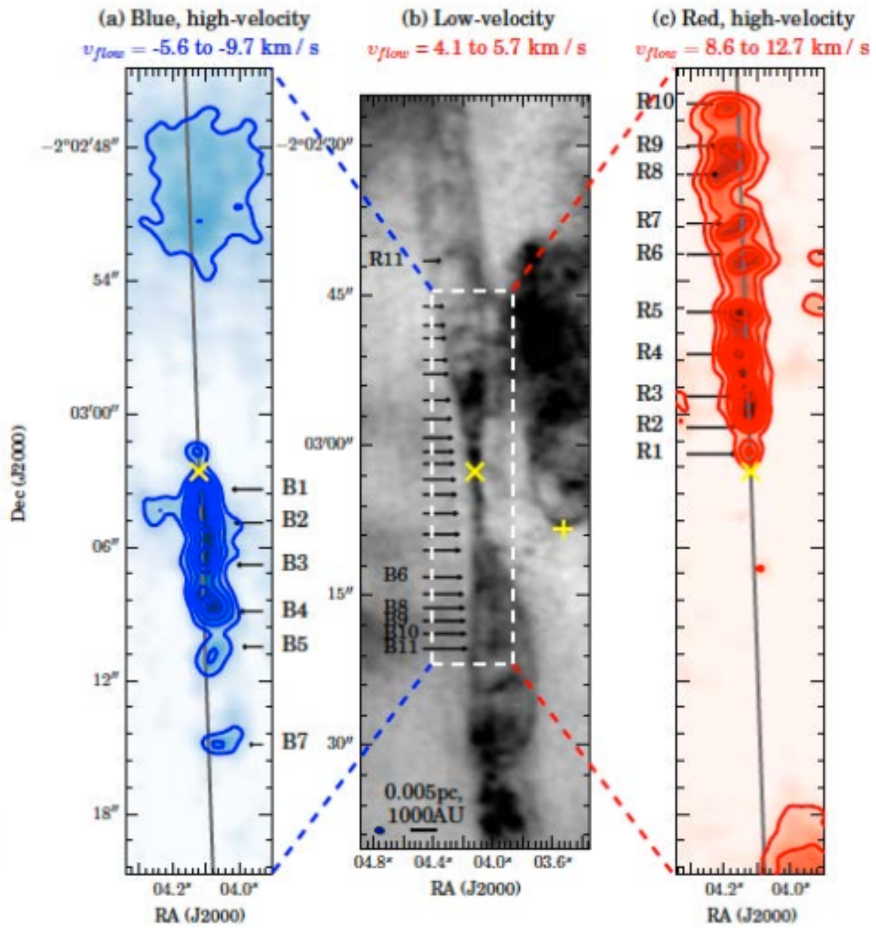
- Infall radius is 0.012 pc
- Mass infall rate 3 x 10^{-6} $M_{\odot} yr^{-1}$
- Age is $5x10^4$ yr and accumulated mass is 0.15 $M_{\odot}$



Evans et al. 2015 ApJ 814, 22

The Episodic Molecular Outflow in the Cluster Serpens South

- Episodic outflow observed in very young cluster
- Class 0 outflow showing episodic events
- The CO(2-1) emission reveals 22 distinct outflow ejecta features, with the most recent having the highest velocities
- The bipolar outflow originates from the peak of the 1 mm continuum emission – kinematics are consistent with rotation and infall
- Momentum and energy transfer to the environment

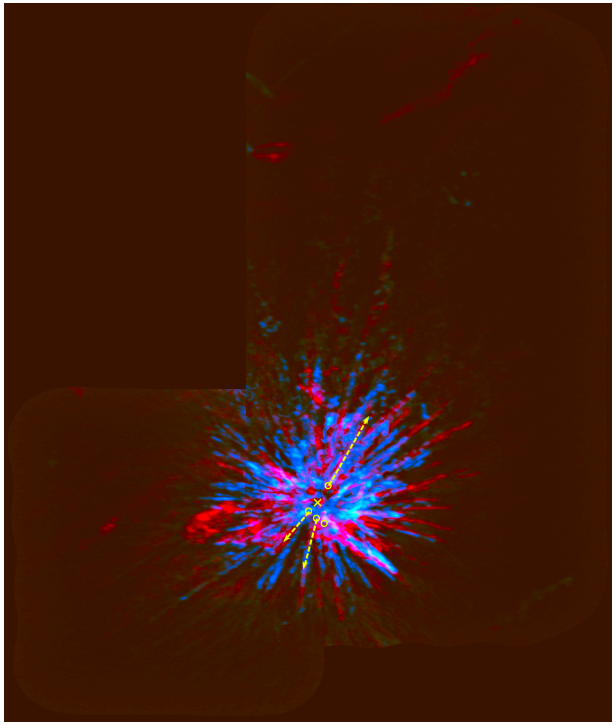


Plunkett et al. 2015 Nature 527, 70

Recent Highlights – Science (3)

ALMA Images the Explosion in Orion MC1- The BN-Source I Event Seen in CO

- Dramatic evidence of the importance of gravity in dense massive star-forming regions
- Over 100 linear streamers of CO emission +/- 100 km s^{-1}
- 500 yr dynamical age coincides with Source I, the BN object, and Source n close approach.
- Event energy estimated at 10^{48} erg released in compact binary formation or protostellar merger.



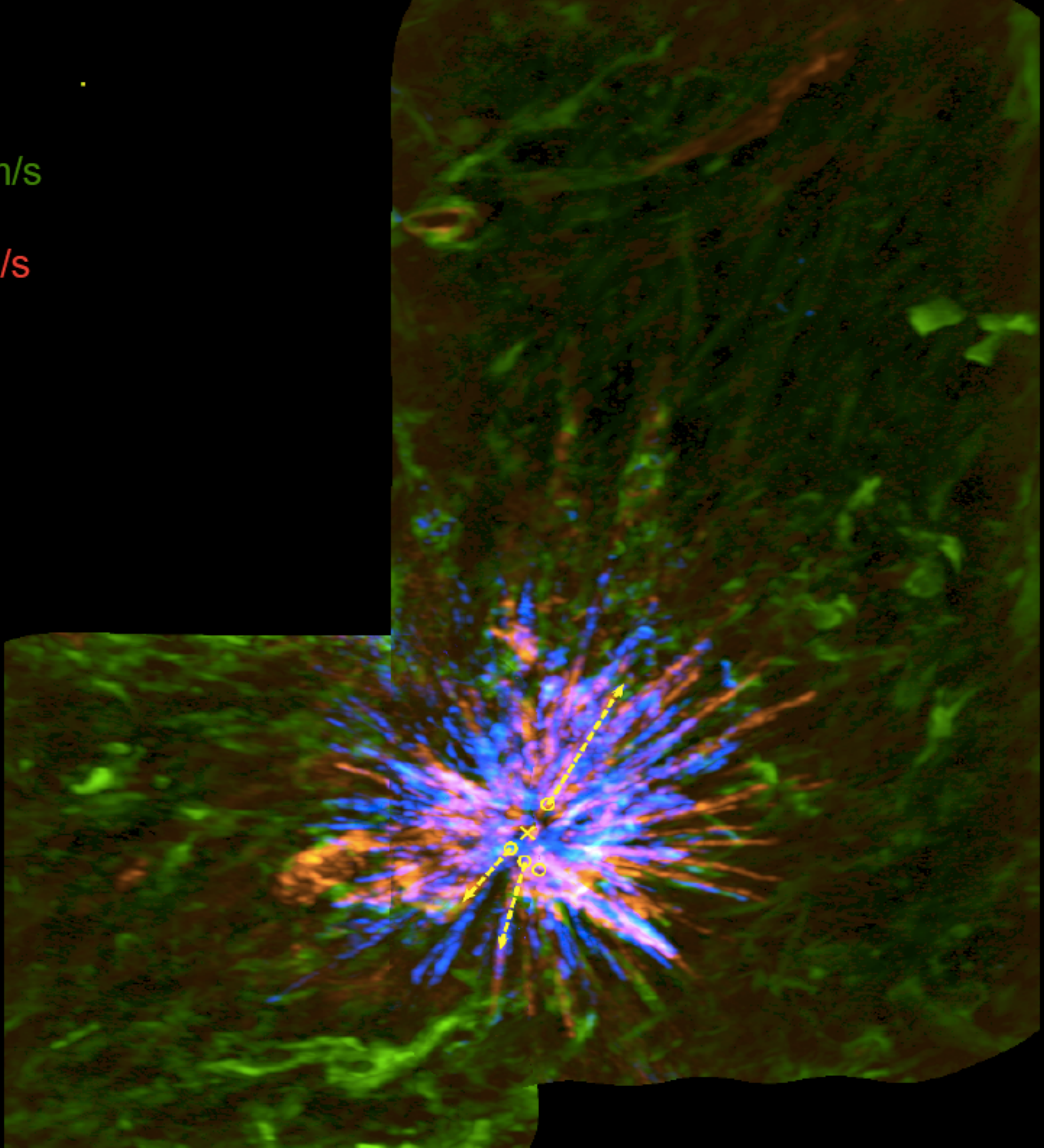
Bally et al. 2017 arXiv:1701.01906

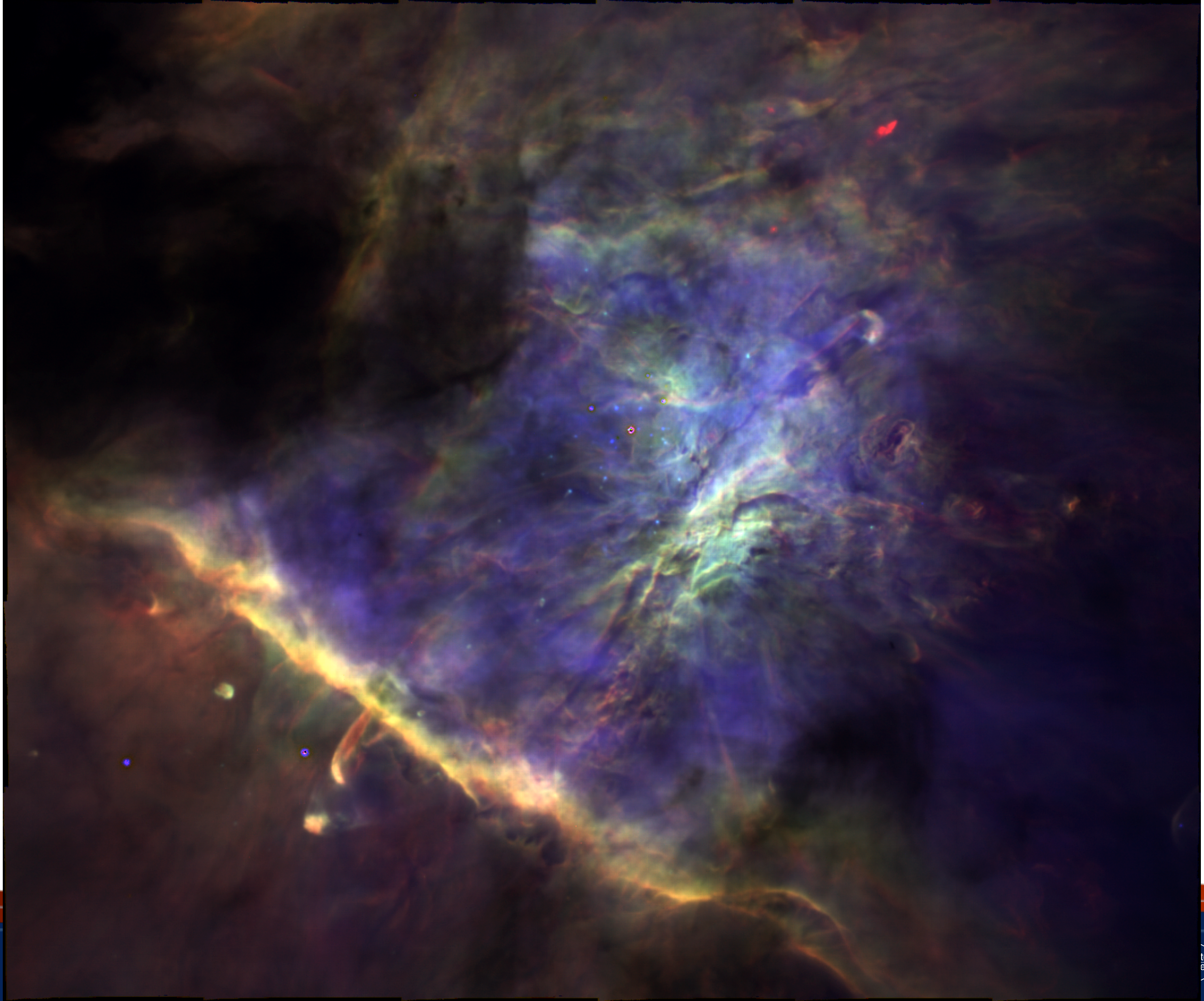
T_{max}

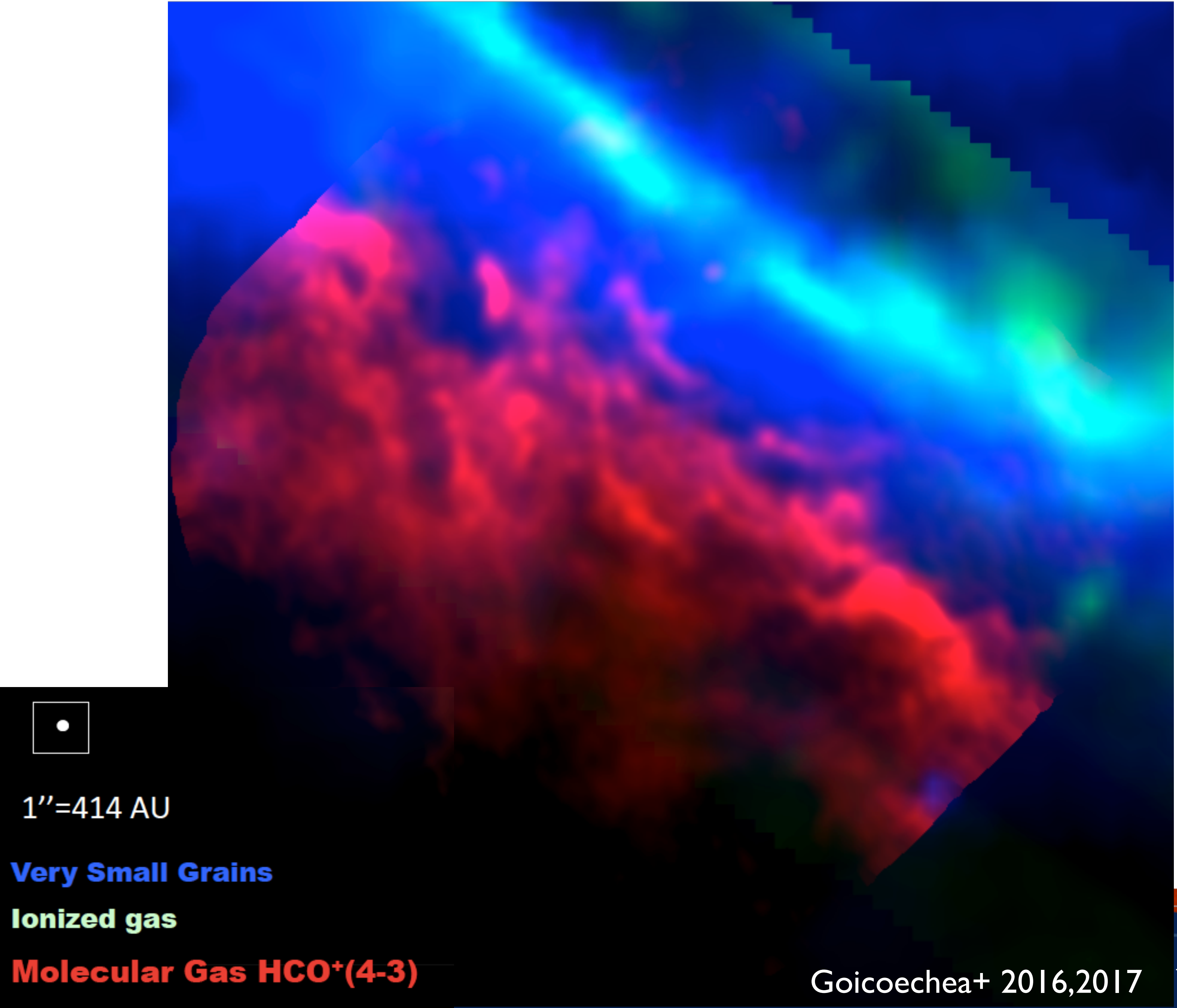
-100 to 120 km/s

-100 to 0 km/s

+20 to 120 km/s





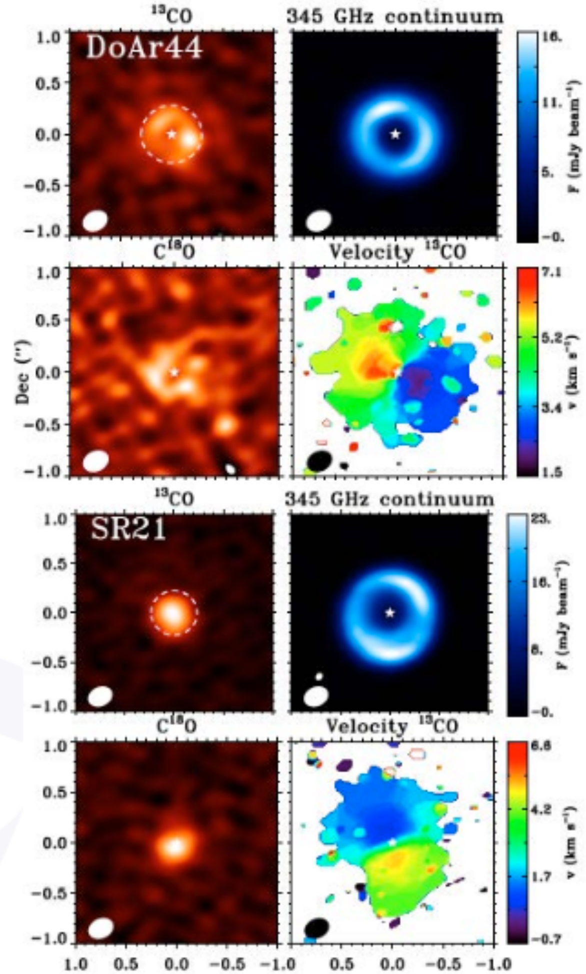

1''=414 AU
Very Small Grains
Ionized gas
Molecular Gas HCO⁺(4-3)
Goicoechea+ 2016,2017

Resolving Gas Cavities in Transitional Disks

- ^{13}CO and $C^{18}O$ 3-2 and 6-5 lines in four disks with large dust cavities
- Constraints on the gas surface density (cavity size and density drop): the gas cavities are 3 to 4 times smaller than dust cavities

➢ Results support the predictions of models describing how planet-disk interactions sculpt gas disk structures and influence the evolution of grains

➢ Suggest the presence of giant planetary companions in transition disk cavities at small orbital radii



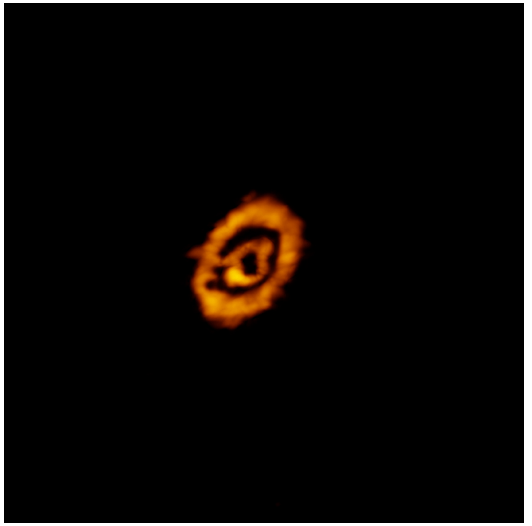
September 25, 2016

van de Marel et al. 2016 AA 585, A58

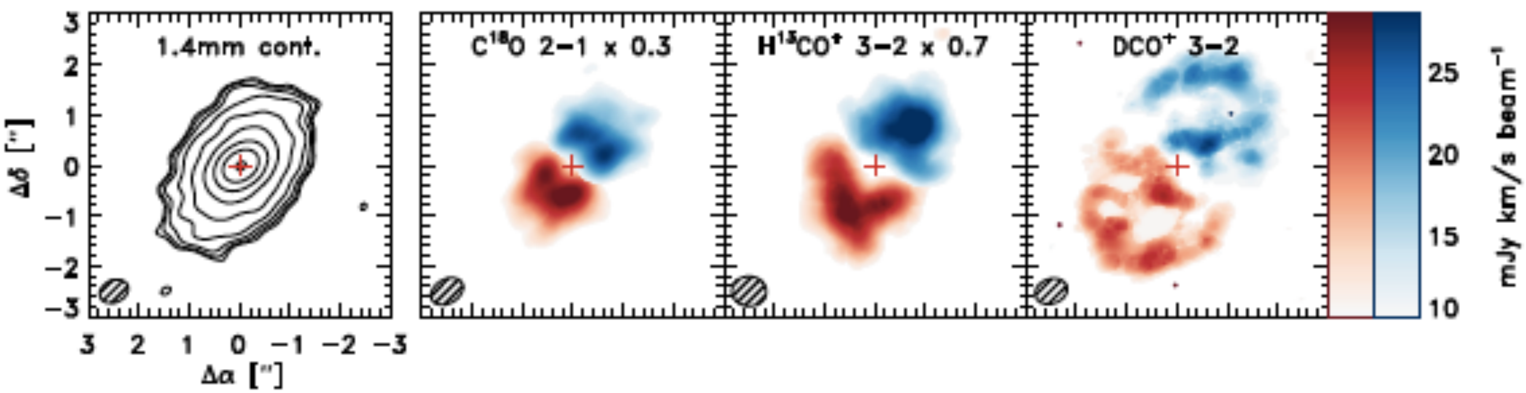
In Search of our Cosmic Origins

The Double DCO+ Loops of IM Lupi

Oberg+ 2015



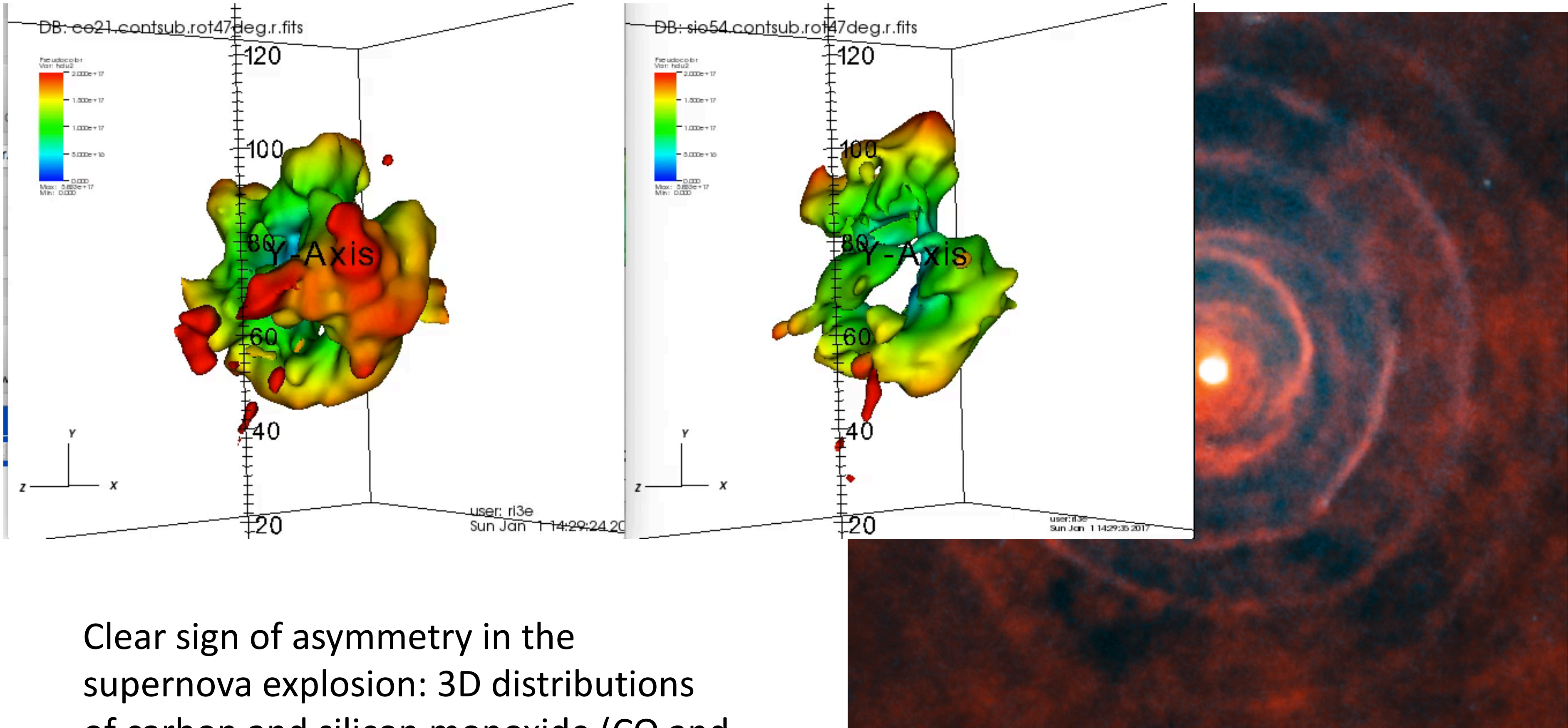
- In cold gas where CO is present, DCO^+ readily forms from the reaction of CO and H_2D^+.
  - In the cold disk midplane, CO freezes out onto grains at the distance from the central star where T is sufficiently low: ~25AU in th
  - In th free incre incre



Dust and Gas Life Cycle

Abellán+ 2017

LL Pegasi Kim+ 2017



Clear sign of asymmetry in the supernova explosion: 3D distributions of carbon and silicon monoxide (CO and SiO) emission differ markedly.

AGB Star Dust and Gas recycles to ISM

Assembly of galaxies

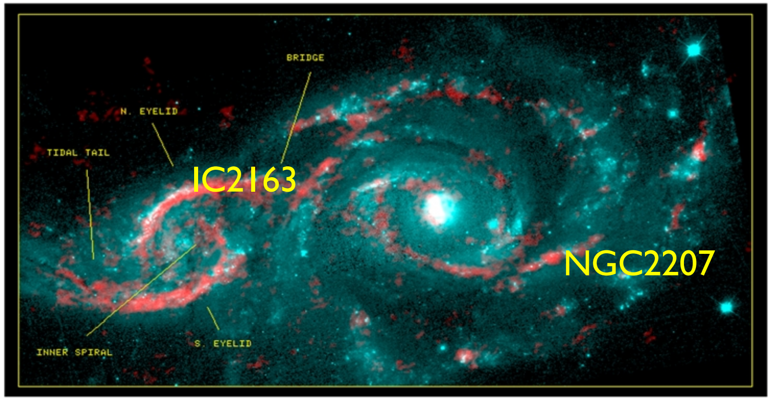
- Formation of the Hubble sequence
- Metallicity evolution
- Role of starbursts and black holes
- Clusters/SZ

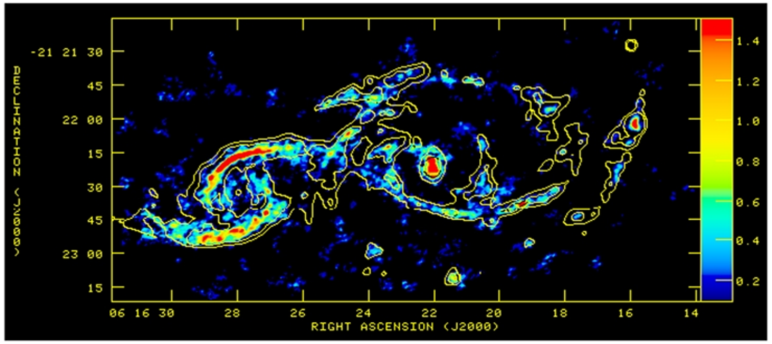
Mergers Stimulate Star Formation, Galaxy Evolution

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 that resemble a pair of eyelids.
- 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...831..161

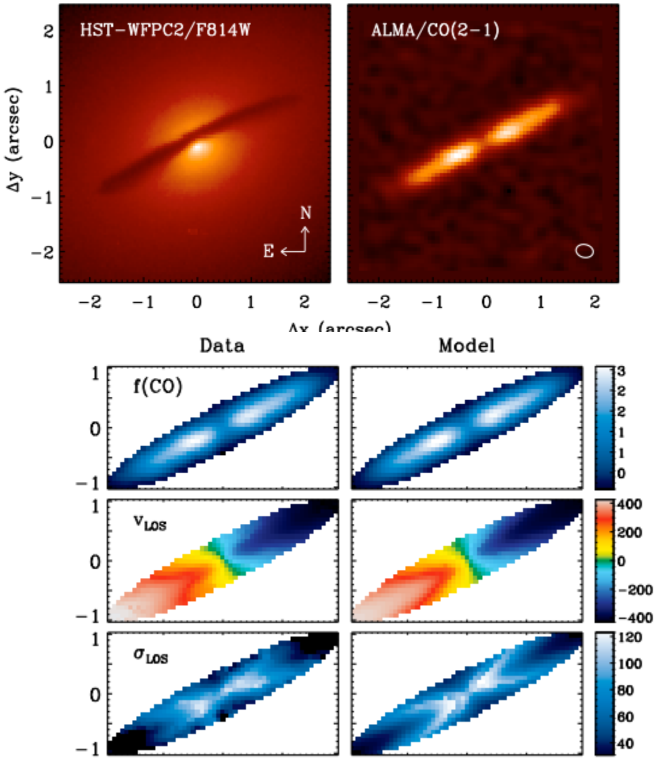




ALMA Measures the Black Hole in NGC 1332

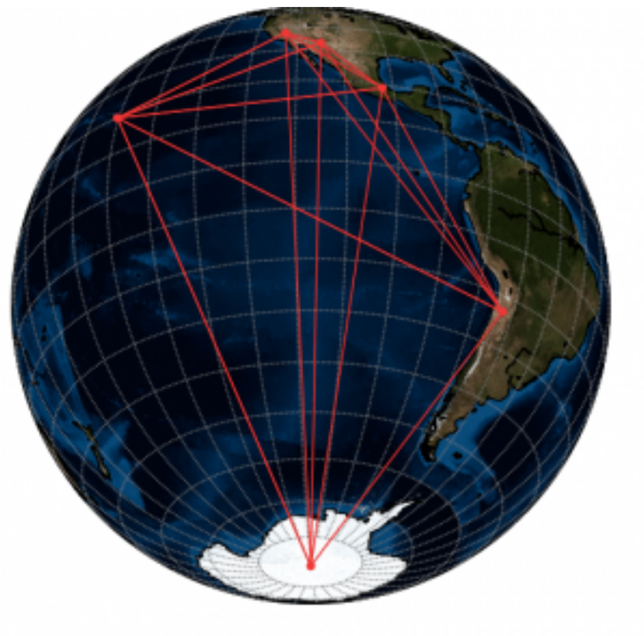
- CO J=2-1 emission measured in the circumnuclear disk of NGC1332.
- Resolution of 0.044" (4.8pc) resolution at 22.3Mpc demonstrates ALMA imaging, high resolution
- Disk shows regular rotation with central high velocity component suggesting a compact central mass
- Authors find

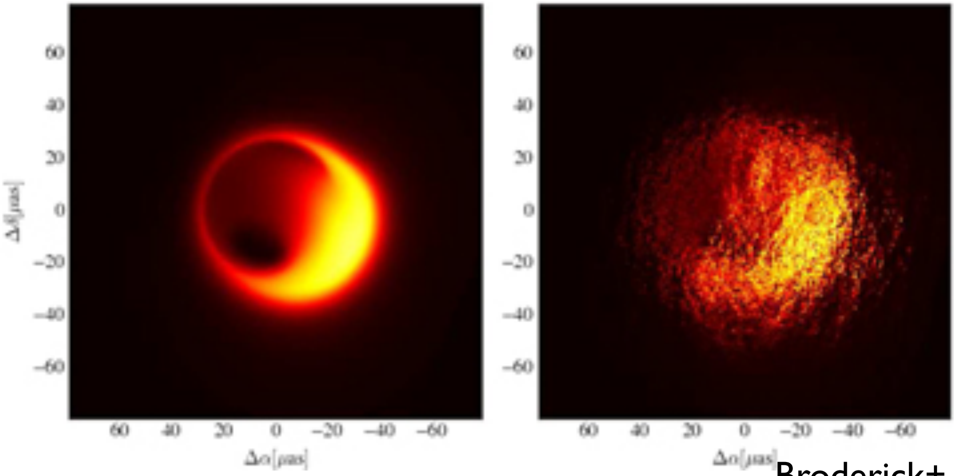
  $M_{BH} = (6.64^{+0.65}_{-0.63}) \times 10^8 M_\odot$
- ALMA is poised to make a major contribution to understanding Black Hole demographics.
  - Through ***better-than HST resolution***
  - ***ALMA sensitively images massive accretion disks***, the most sensitive probe of kinematics available near galactic nuclei.



AARON J. BARTH, BENJAMIN D. BOIZELLE, JEREMY DARLING, ANDREW J. BAKER, DAVID A. BUOTE, LUIS C. HO, and JONELLE L. WALSH ArXiv:1605.01346

SgrA* Black Hole Event Horizon/Hot Spot Models





Broderick+

Above: EHT Network

Observations taken in April

Right above: Artists impression

Right below: Broderick and Loeb model

left: input

right: with IS scattering model

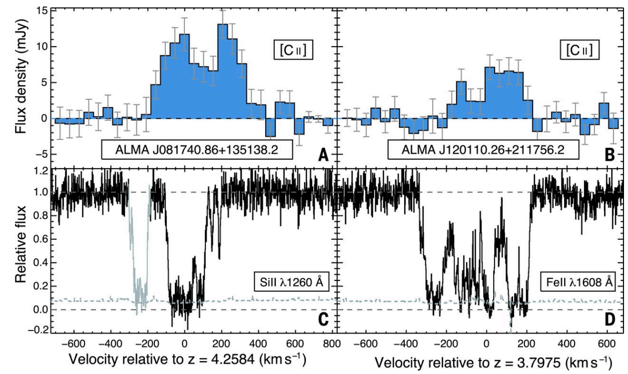
First Light

- First galaxies
- Sources of re-ionization
- Formation of first metals

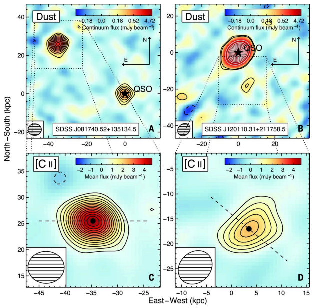
ALMA: SuperHaloes Surround Early Milky-Way-like Galaxies

- With ALMA, US 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.

Marcel Neeleman et al. Science 2017;355:1285-1288

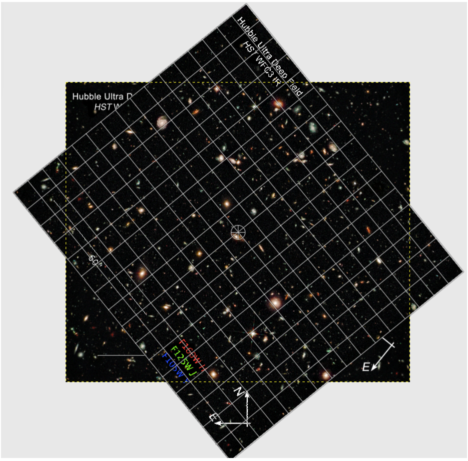


Host emission ([C II]) from the host galaxies A and B and QSO absorption (Si II and Fe II) features C and D.

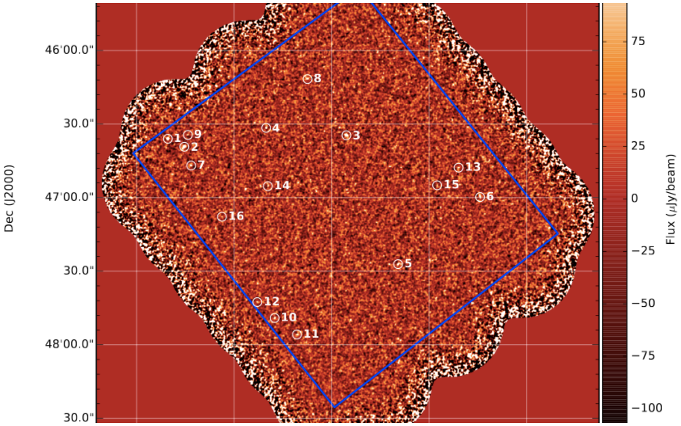


Above: The ≈400-GHz continuum emission near two QSOs (black stars). Axes give the relative physical (proper) distance at the DLA. Below: Mean flux density over the full [C II] 158-μm line profile displayed above. The dashed line is the measured major axis of the galaxy.

Evolution of Galaxies: Deep Field Surveys



WFC3/IR on HST



Dunlop et al (2016)

Instrumental needs

- Sensitivity: detecting weak signals
- Spectral grasp covers appropriate redshifted lines
- Field of View to include varied sources
    - Synergy with WFIRST

Probing the Early Universe

z~1000
0.0003 Gyr

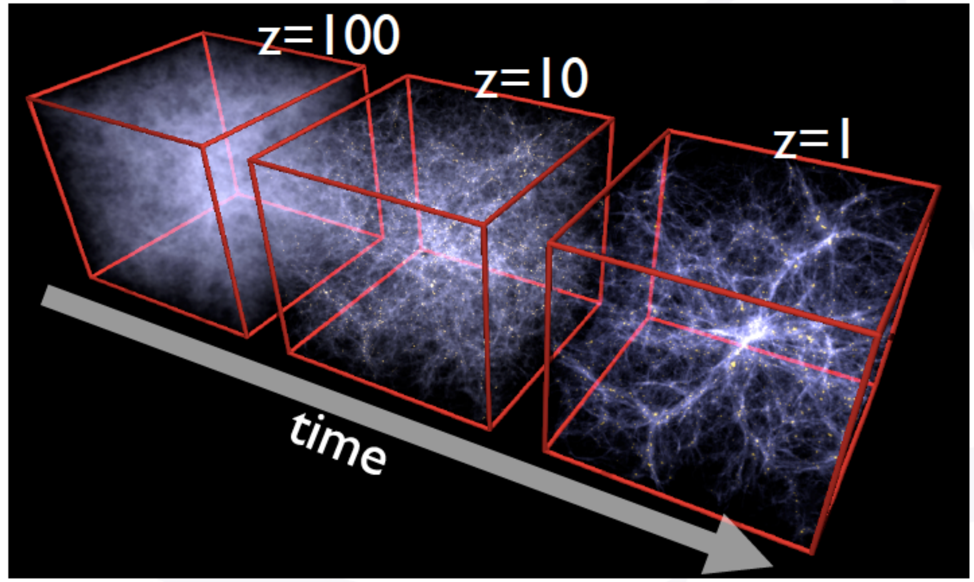
z~15-1000
0.0003-0.3 Gyr

z~8-15
0.3-1 Gyr

z<~8
>1 Gyr

z~0
14.3 Gyr

Simulations of structure formation



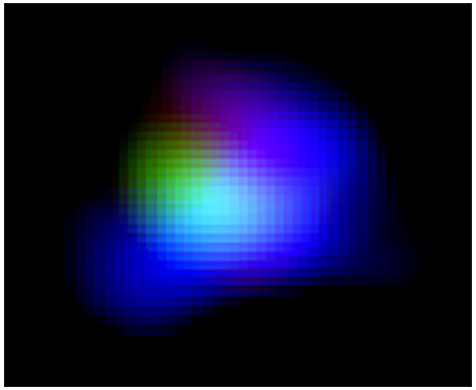
e.g., Springel et al.

Galaxies grow through gas accretion...

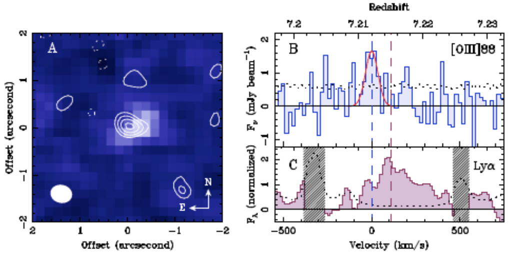
...but the gas supply is currently largely unconstrained observationally

The First Billion Years: Metals, Dust, First Galaxies

- Science Drivers
  - Creation of the Metals, monitored through atomic and molecular lines
  - The first cosmic 'dust'
  - These tracers enable characterization of the development of structures in the early Universe
- Instrumental needs
  - Sensitivity, to detect weak signals
  - Spectral grasp, to cover appropriate redshifted lines



[O III] 88µm @z=7.2 in SXDF-NB1006-2 imaged by ALMA (Inoue et al 2016). Blue: Lyα,



New Science Drivers for ALMA: 2030

- To sustain ALMA's science into the next decade, new science drivers are being developed to guide instrumentation upgrades.
- The ALMA Development Working Group proposes the following two fundamental science drivers to lead the vision for the future developments for ALMA for the next decades.

- **Disks & Planets**
  - *The ability to explore the chemical composition and evolution of disks, including around planets, down to scales of 1 AU*
- **First Galaxies**
  - *The ability to investigate the early universe from the formation of metals (first stars) to the peak of star formation and to identify the first galaxies and image their surroundings*

- Achieving these ambitious goals today remains difficult even with the outstanding capabilities of the current ALMA array.
- Reaching the above science drivers can only be achieved by significantly improving ALMA's sensitivity, observing speed, *uv* coverage and image quality, as well as fully utilizing the longest baselines capabilities and the high frequency atmospheric windows that are available at the Chajnantor plateau

Development Vision: Summary

- Outline of a vision for future developments that will significantly expand ALMA's capabilities and enable it to produce further groundbreaking and transformational science in the coming decades

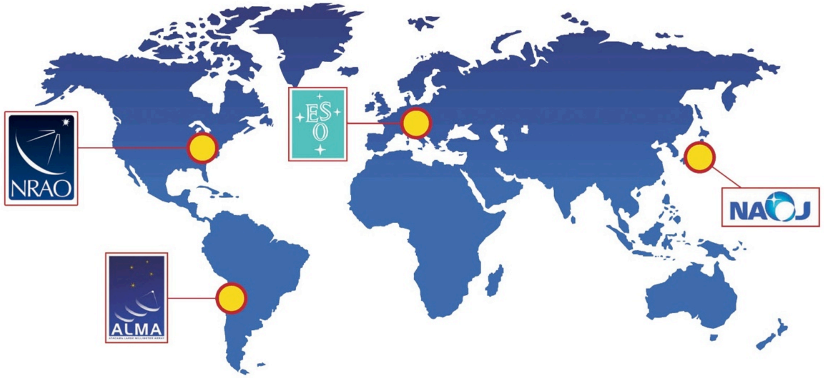
- The Working Group recommends the following developments that will enable the achievement of new level-one science goals in the next decades. Ranked in order of priority, they are:
  1. **Broaden the receiver IF bandwidth and upgrade the associated electronics and correlator. The main bands considered 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**

WFIRST – Radio Synergies

- Investigating the chemical and structural evolution of stars and planets
- Tracing the evolution of galaxies from first light to the present era
- Detailing the era of first light through measurement of atomic and molecular emission from the earliest entities
- Measuring Black Holes, from distant quasars to imaging the central black hole of the Milky Way

Cooperation between many countries

A partnership of North America (37.5%), Europe (37.5%), and East Asia (25%), in cooperation with and located within the Republic of Chile



Funding

- North America: National Science Foundation (US), in cooperation with National Research Council (Canada) and National Science Council (Taiwan)
- Europe: European Organisation for Astronomical Research in the Southern Hemisphere (ESO)
- East Asia: National Institute of Natural Sciences (Japan) in cooperation with Academia Sinica (Taiwan) and the Korea Astronomy and Space Science Institute (KASI).

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