ALMA Presents a Transformational View of the Universe

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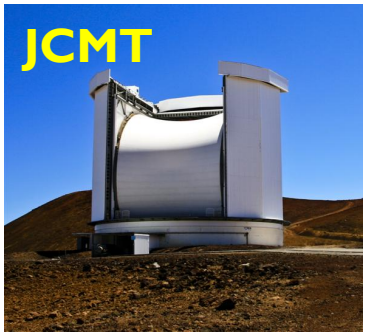
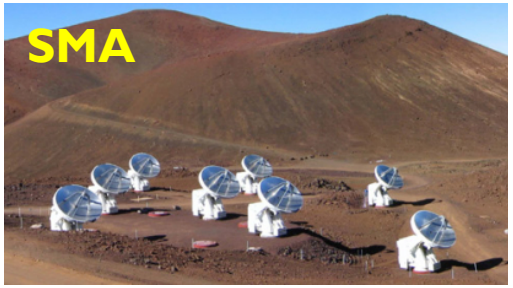
Presentation Outline

- Introduction
- A Brief History
- Key Design Elements
- Operations
- Science Goals
- Science
- Development Program
- Summary

Introduction

- ALMA is a revolutionary imaging & spectroscopic telescope system for mm & submm astronomy
- Builds on pioneering technical development & scientific research conducted at
  - Submillimeter Array (SMA)
  - Institut de Radioastronomie Millimétrique Plateau de Bure Interferometer (IRAM PdB)
  - Combined Array for Research in Millimeter Astronomy (CARMA)
  - James Clerk Maxwell Telescope (JCMT)





Introduction

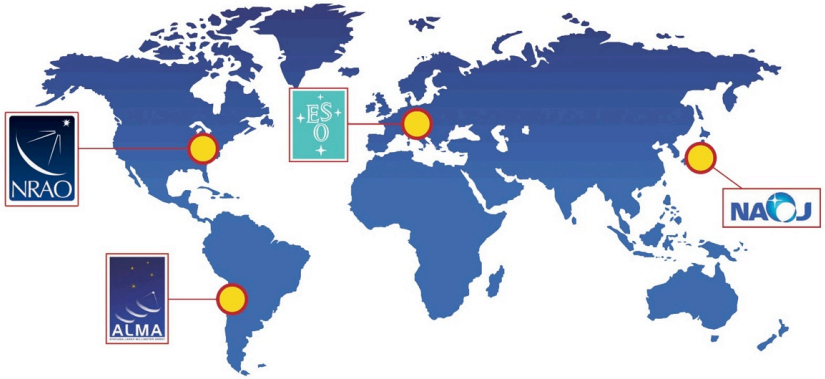
- 66 reconfigurable, high precision antennas
- $\lambda \sim 0.3 - 8.6$mm
- Array Operations Site is located at 5000m elevation in the Chilean Andes
- Provides unprecedented imaging & spectroscopic capabilities at mm/submm λ

Introduction

- Array configurations between 150 meters and 15 kilometers: 192 possible antenna locations
- Angular resolution to 0.005 arcsec (900 GHz)
- Ten frequency bands: 35 – 950 GHz
- All science data archived
- Pipeline processing
- ***ALMA is a telescope for all astronomers***

Introduction

A partnership of North America (37.5%), Europe (37.5%), and East Asia (25%), in cooperation with 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)

A Brief History of ALMA: I

- A fusion of ideas under development since the 1980s
  - Millimeter Array (MMA) — United States
  - Large Southern Array (LSA) — Europe
  - Large Millimeter Array — Japan
- NRAO & ESO agreed in 1997 to merge MMA and LSA → Atacama Large Millimeter Array
- ALMA Agreement signed 25 Feb 03 by North America & Europe
- Japan joined partnership Sep 2004, providing additional capabilities
  - Atacama Compact Array & very high frequency bands
- ALMA → Atacama Large Millimeter/submillimeter Array

A Brief History of ALMA: II

- Nov 2003 Groundbreaking in northern Chile
- Apr 2007 First ALMA Antennas arrive in Chile
- Oct 2011 Cycle 0 Early Science begins with 16 antennas
- May 2012 Cycle 1 Early Science Call for Proposals
- Oct 2013 Cycle 2 Call for Proposals
- Jun 2014 Cycle 2 Early Science begins
- Mar 2015 Cycle 3 Call for Proposals
- Oct 2015 Cycle 3 Early Science Begins

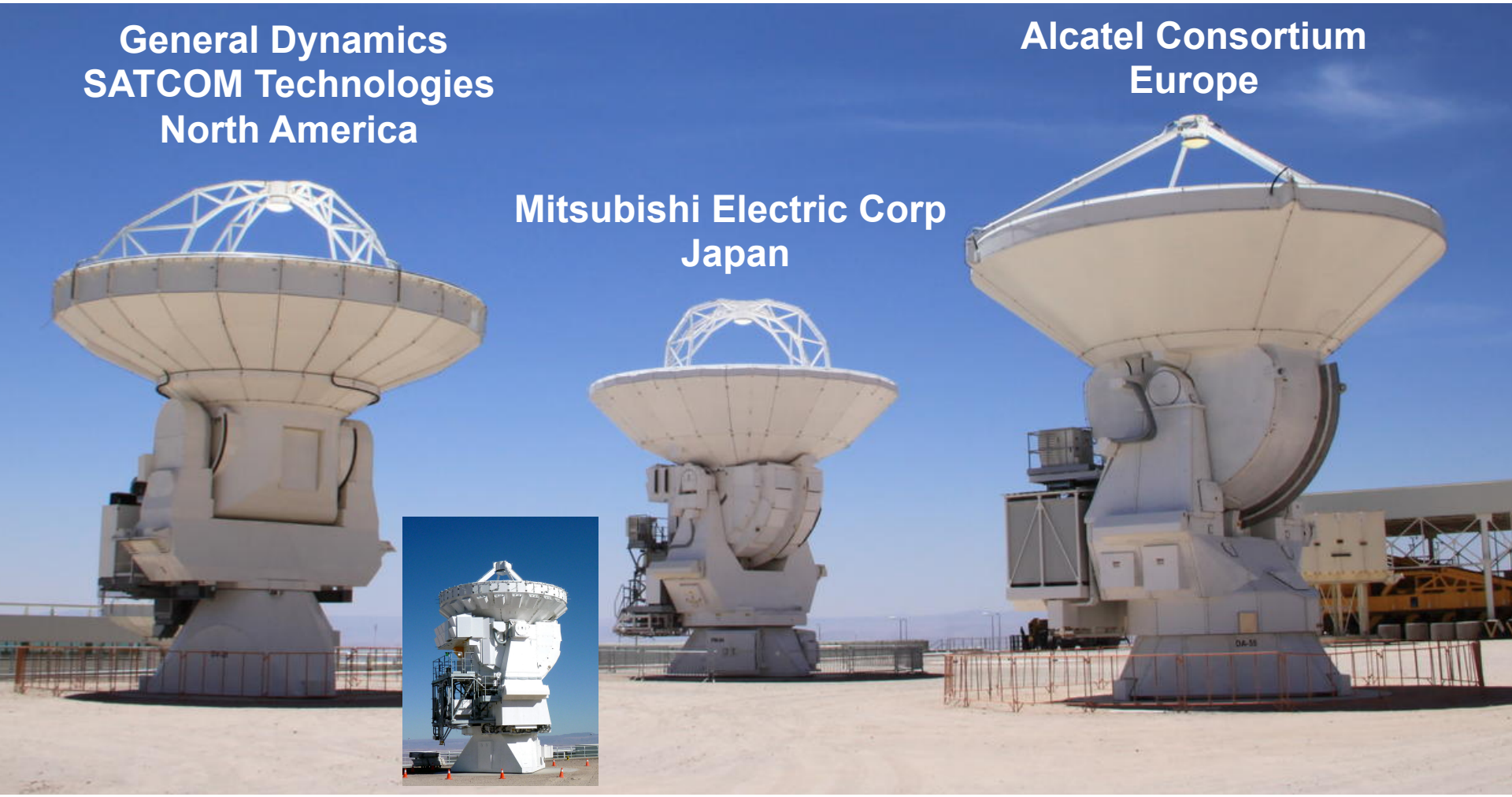
Key Design Elements

- ALMA improves available mm/submm sensitivity by ~ two orders of magnitude
  - Best accessible site on Earth
  - Highest performance antennas & receivers available
  - Enormous collecting area (1.6 acres or 6600+ m^2), huge number of baselines provides image fidelity
- Covers ten atmospheric windows with 50% or more transmission above 35 GHz
- Resolution improvement of nearly 100x
- Wavelength coverage improved by 2x
- Large bandwidths

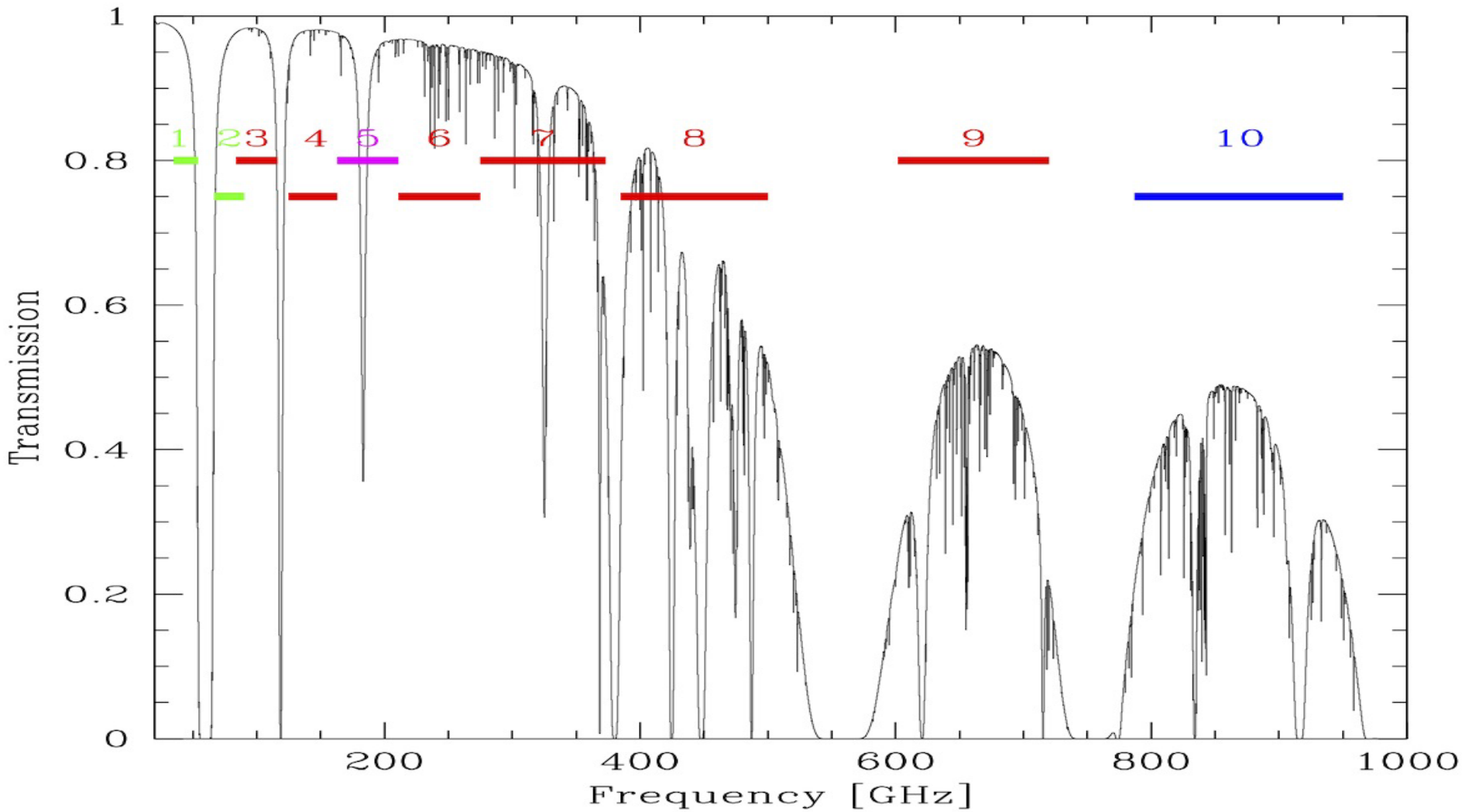
Key Design Elements: Antennas

- 66 high precision antennas operated as an imaging interferometer
  - 12m Array
    - Fifty 12m diameter antennas
  - Atacama Compact Array (ACA)
    - Twelve 7m diameter antennas
    - Four 12m antennas = “Total Power Array”
- 192 antenna stations

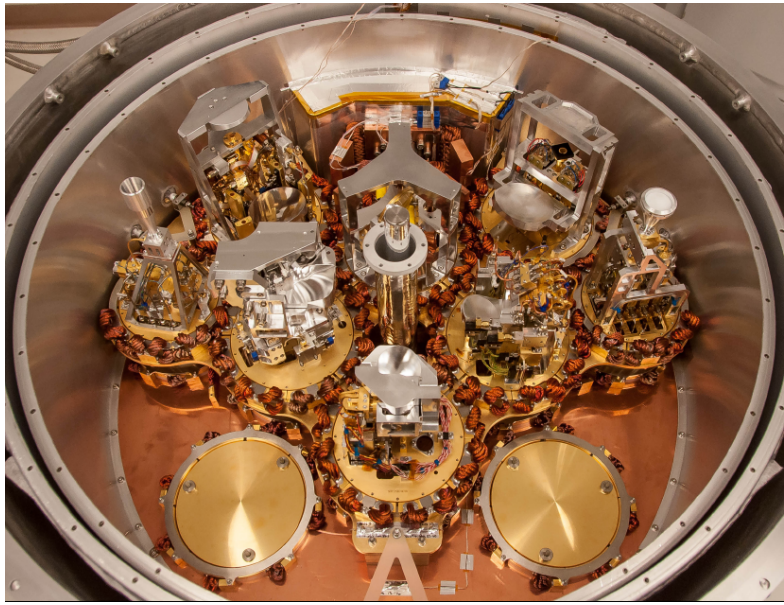
Key Design Elements: Antennas



Key Design Elements: ALMA Bands



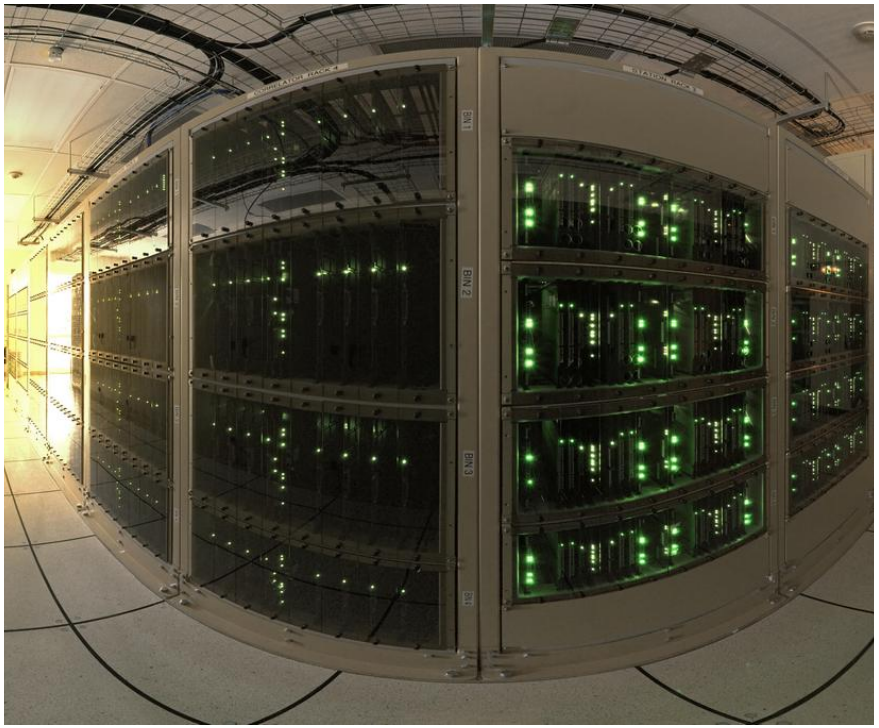
Key Design Elements: Receivers



- No moving parts: all electronically tunable
- State-of-the-art receiver performance: 35-950 GHz
- Dual linear polarization, 8 GHz per pol, 2 GHz basebands
- Ease of maintenance crucial → Line Replaceable Units
- Digitization: 4 Gbit/s, 3 bits, 8-level (96 Gbit/s per antenna)
- Signals cross-correlated for a large number of delays and all possible antenna pairs

Key Design Elements: Correlator

- ALMA correlator: special purpose supercomputer that combines the digital signals from each antenna
- Custom CMOS chips
  - 4096 processors
- 32,768 chips on 512 boards
- 17 Tera-operations/second



Designed & built by NRAO Central Development Laboratory in Charlottesville, VA

Operations

- ALMA Operations led on behalf of:
  - North America by NRAO
  - Europe by European Southern Observatory (ESO)
  - East Asia by National Astronomical Observatory of Japan (NAOJ)
- Joint ALMA Observatory (JAO) is responsible for ALMA operations in Chile
  - Operations Support Facility
  - Array Operations Site
  - Santiago Central Office

Operations: North America

North American ALMA Science Center (NAASC)

- North American science community's interface to ALMA
- Based at NRAO Headquarters in Charlottesville, VA
- Operated by NRAO with National Research Council of Canada
- Supports Extension of Capabilities efforts in Chile
- Supports ALMA proposal preparation by North American community
- Provides post-observation ALMA user support & tools
- Maintains ALMA websites, proposal guides, etc.

Make ALMA a research facility for all astronomers

Operations: Science Archive

Science Archive available from each of Santiago, NRAO-CV, ESO, and NAOJ

Science Goals

ALMA design driven by three Key Science Goals

1. Detect spectral line emission from CO or [CII] in a normal galaxy like the Milky Way at z=3 in less than 24 hours

2. Image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars in the nearest molecular clouds (150 pc)

3. Provide precise high dynamic range images at an angular resolution of 0.1 arcsec

Science

- Cycle 0 Early Science
  - 919 proposals received, began Oct 2011
  - Observations acquired for 113 projects
  - All data delivered, available in archive
- Cycle 1 Early Science
  - 1173 proposals received, began Jan 2013
  - Observations being acquired for 198 projects
  - ~2/3 of NA projects: some data delivered, some projects in archive

Science

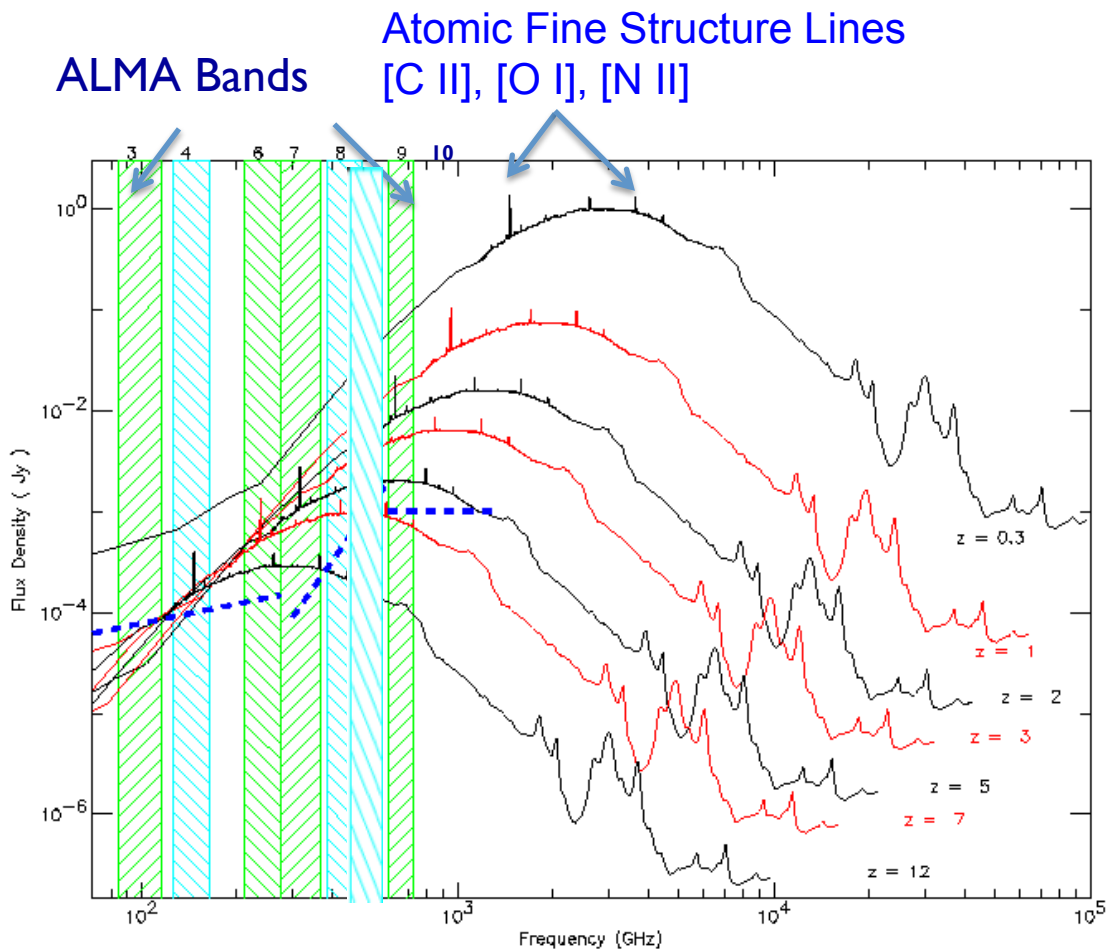
- Cycle 2 Early Science
  - 1381 proposals received, began 1 June 2014
  - Observations being acquired for 354 projects
  - ~25% of NA projects have some data delivered
- Cycle 3 Early Science
  - Begins 1 October 2015
  - Call for Proposals to be published March 2015

Science

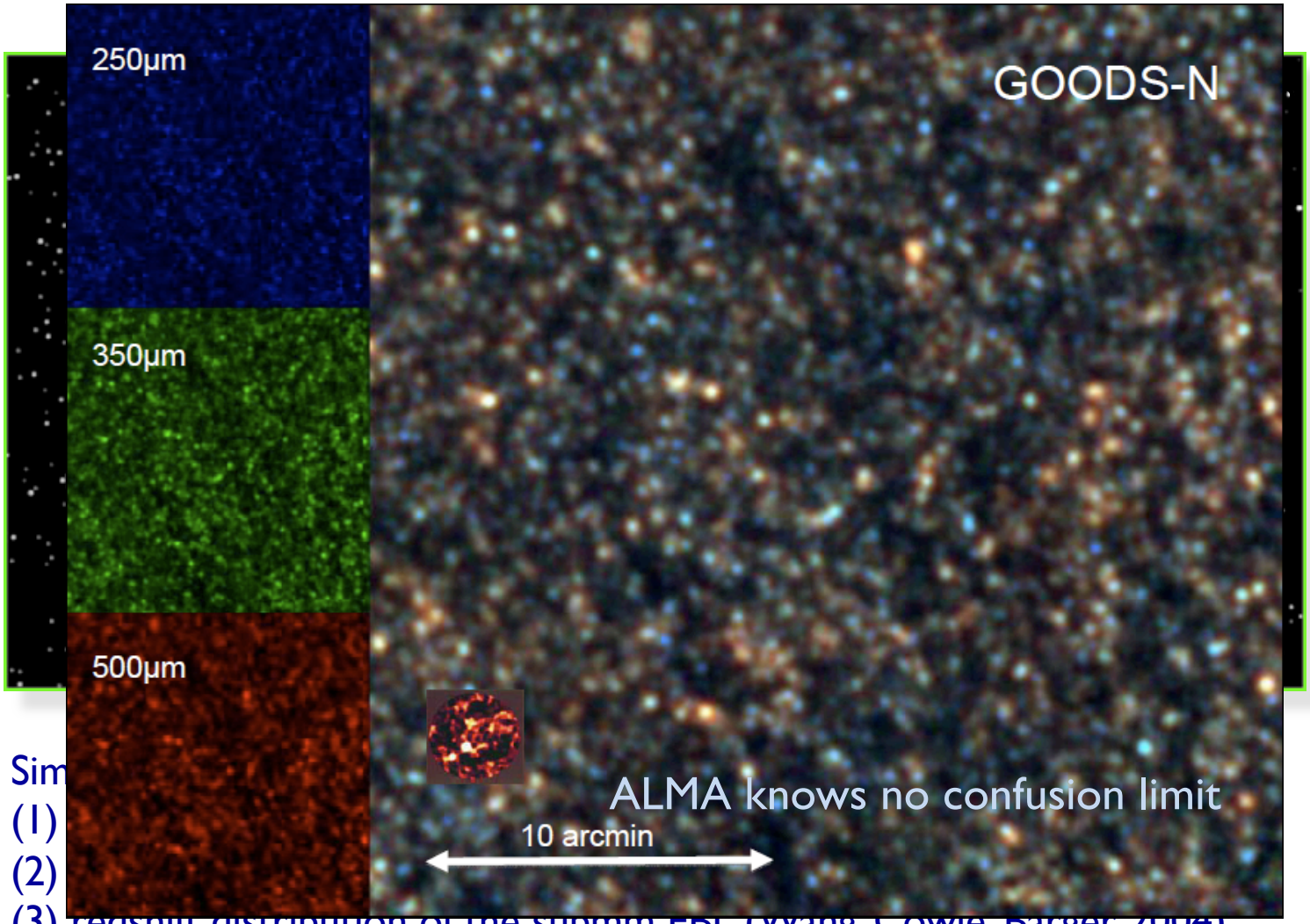
- **Revolution in Astronomy with ALMA – The Third Year**
- Tokyo, Japan: 8-11 December 2014
- 300 scientists from around the world

Distant Galaxies: Inverse K-correction

As galaxies get redshifted into the ALMA bands, dimming due to distance is offset by the brighter part of the spectrum being redshifted in. Hence, galaxies remain at relatively similar brightness out to high distances. This spectrum assumes solar metallicity of course; lower metallicity galaxies may be suppressed at higher z.

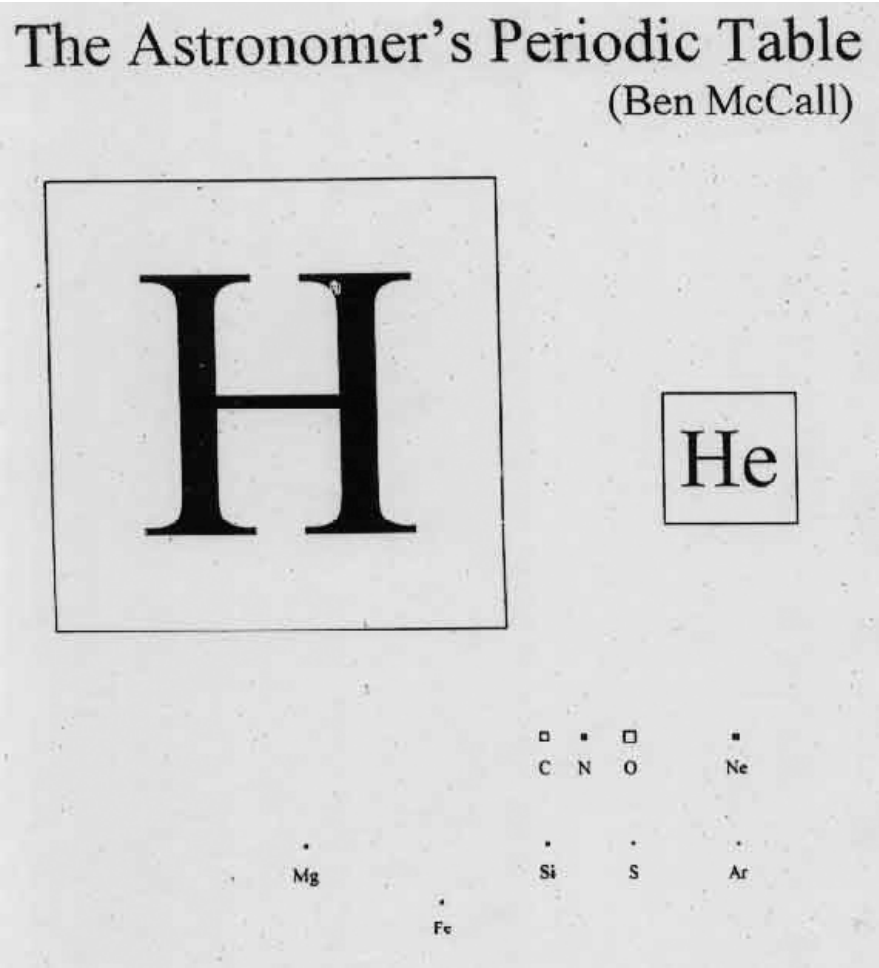


Submm Sources High and Low z



Sim
(1)
(2)
(3) redshift distribution of the submm EBL (Wang, Cowie, Barger 2004)

The Birth of Chemical Complexity



When chemistry got interesting

(H_3^+, H_2D^+, H_2, HD notwithstanding)

ALMA should be able to monitor the creation of

- O ([O I], [O III], OH, H_2O)
- C ([C I], [C II], CO, CH, CH^+, ^{13}C)
- N ([N II], NH, N_2H^+)
-

Submillimeter Continuum

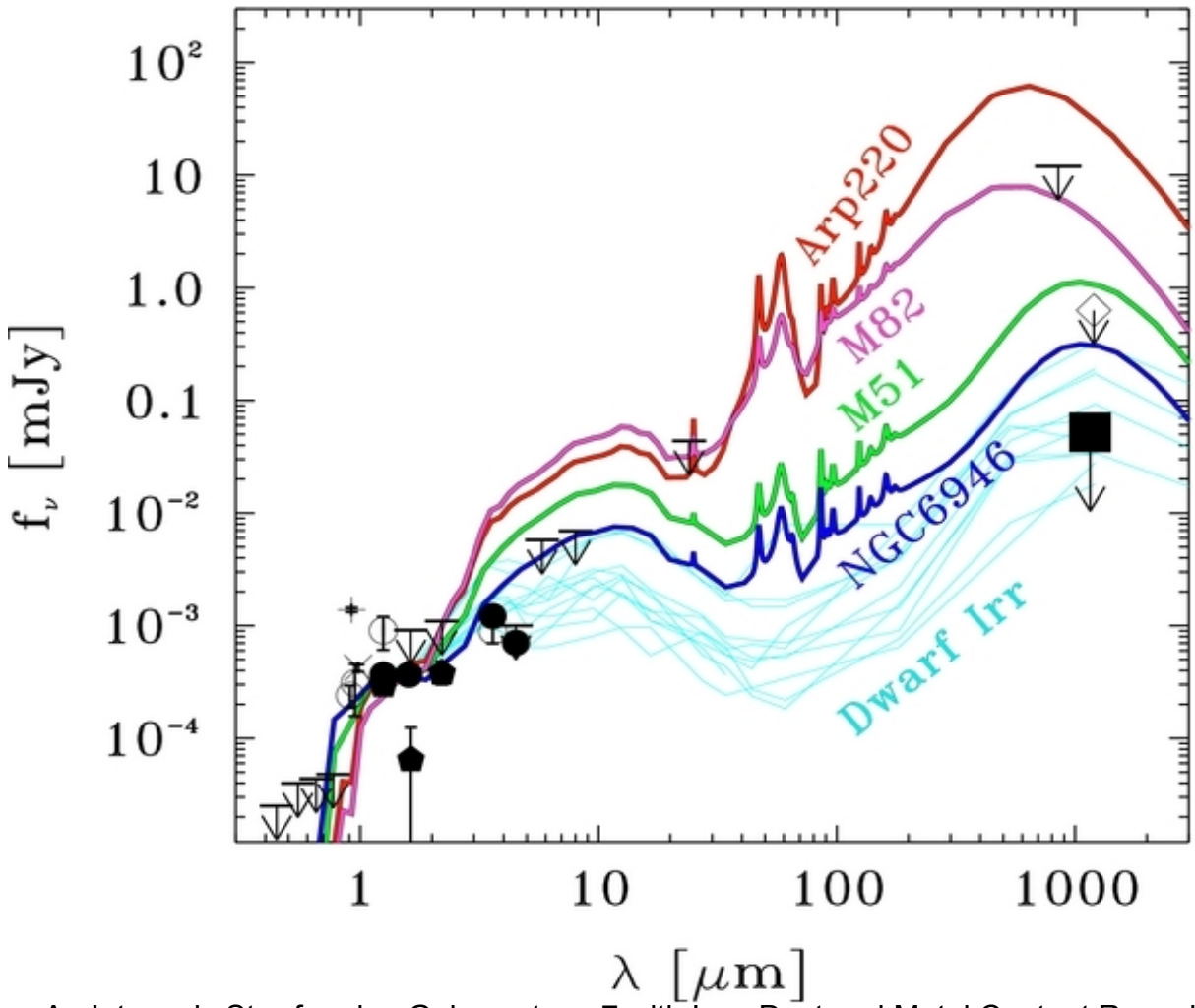
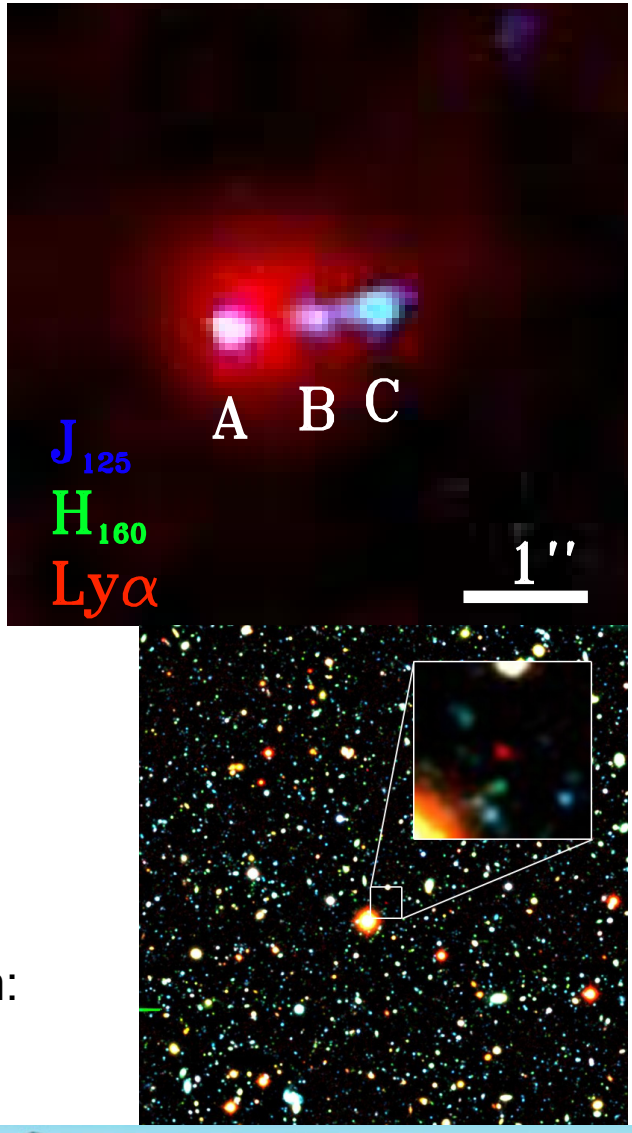


Figure 5 from An Intensely Star-forming Galaxy at z ~ 7 with Low Dust and Metal Content Revealed by Deep ALMA and HST Observations Masami Ouchi et al. 2013 ApJ 778 102 doi:10.1088/0004-637X/778/2/102

Formation of the 1st Galaxies

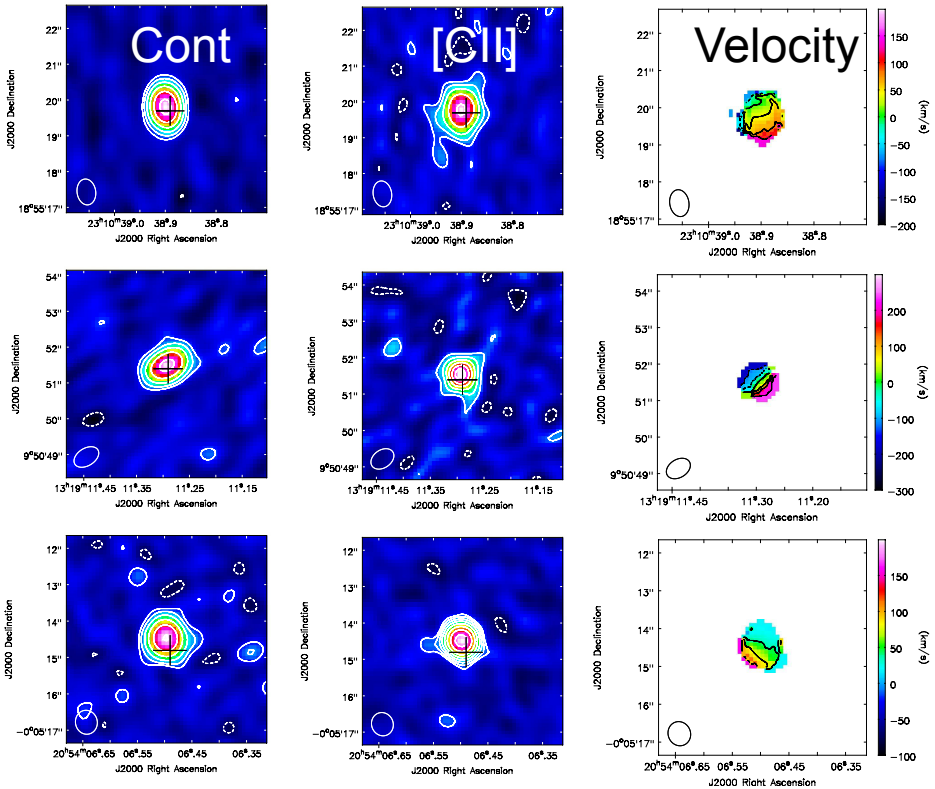
- ALMA observation of distant Lyα entities:
  - Deep non-detections in 250GHz continuum and [CII]
  - "Himiko" and IOK-1 have very low dust content and atomic carbon (e.g. metal poor system) – [CII] may not be the best tracer for 1st galaxies
- Possibly witnessing an assembly of 'first galaxy'

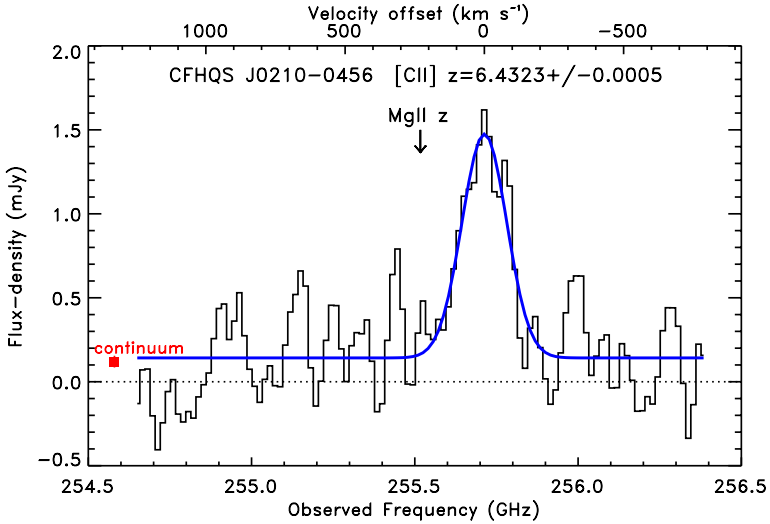


Top: Himiko Ouchi et al. (2013), Bottom: IOK-1 Iye, Ota, Kashikawa et al (2006), Ota and Walter et al. (2014)

[CII] strong in z~6 QSOs

- [C II] provides good dynamics, poorer for L, M
- Dynamical mass of [CII] emitting region ~$10^{10\text{-}11}$ Msun
- No other [CII] line emitters around the QSOs





Willott et al. (2013)

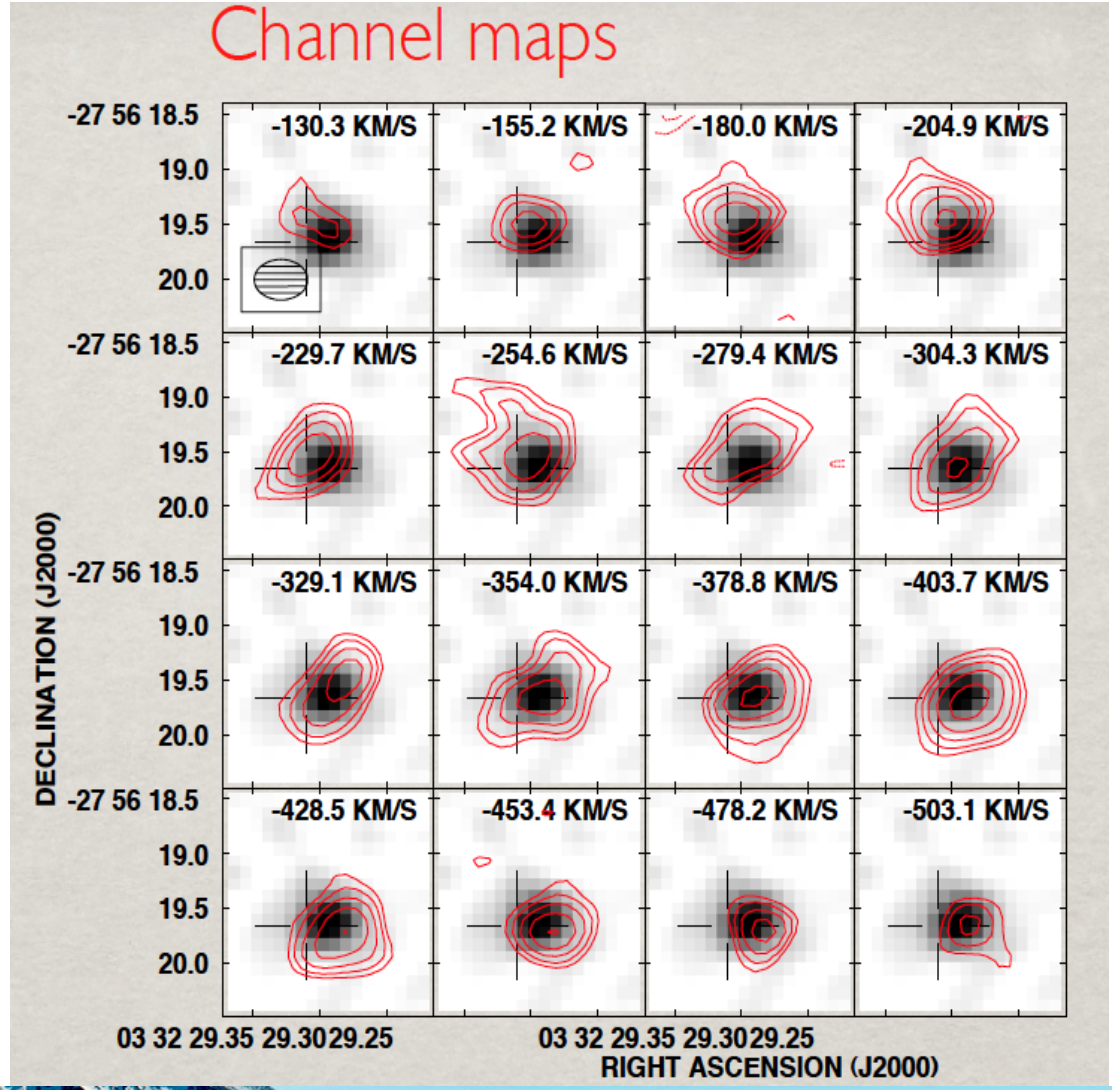
Wang et al. (2013)

Example: C^+ in ALESS73.1 at z=4.75

Contours: [CII]
Greyscale: dust emission
Cross: HST position

- ✓ Rotating disk (2.4 kpc)
- ✓ High turbulence v_{rot}/σ_{int} ~ 3.1
- ✓ Toomre $Q < 1$ → unstable
- ✓ Mdyn ~ 3 x 10^{10} M_{sun}
- ✓ Nascent galaxy undergoing its first major burst of star formation

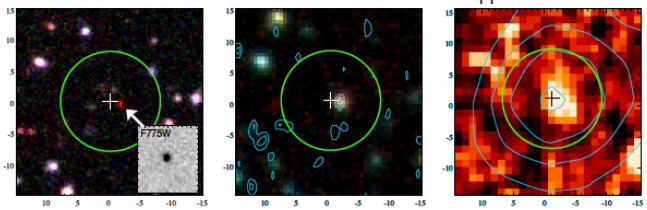
De Breuck et al (2014)



ALMA: Nitrogen in the Early Universe

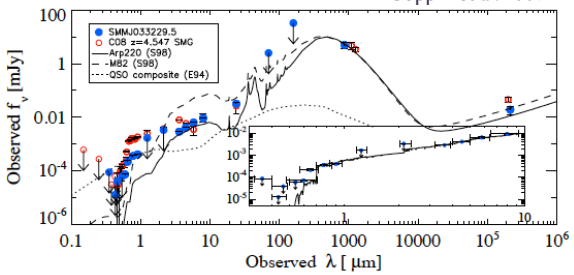
- Nitrogen is a secondary element, produced within low mass stars, hence its abundance rise in the Universe may be expected to lag that of O and C
- Spectrally, it is traced by the [N II] lines at 122 and 205 microns, which emit at about 5%of the [C II] intensity in the local Universe
- Nagao et al. (2012) report ALMA observations of [N II] in J033229.4-275619, a starburst submillimeter galaxy at an age since the Big Bang of 1.27 Gyr (z=4.75). [N II]/[C II]~0.043 in this galaxy, suggesting a solar nitrogen abundance (the ratio is 0.05 in M82). (see new [C II]/ALMA data from de Breuck et al 2014)

Coppin et al. 2009



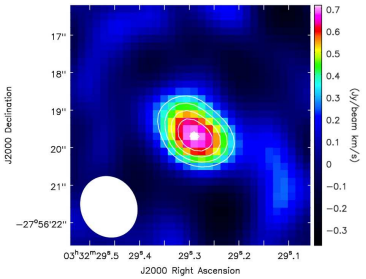
Visible, NIR/radio, FIR images

Coppin et al. 2009

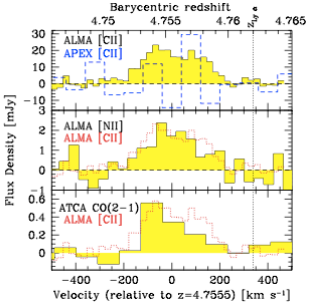


J03329.4 Spectral energy distribution

Nagao et al. 2012

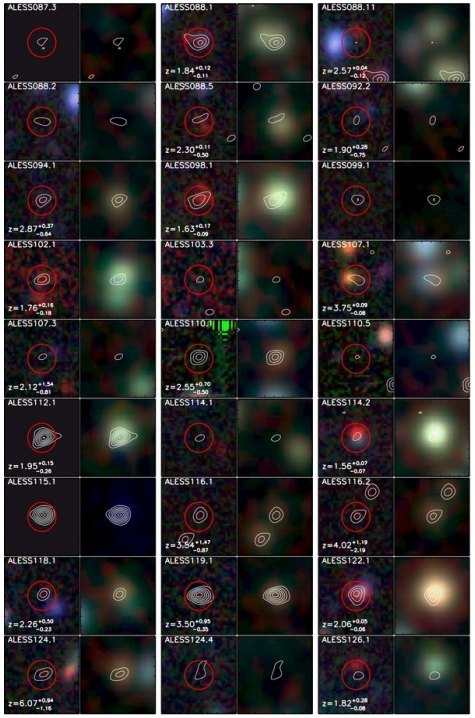


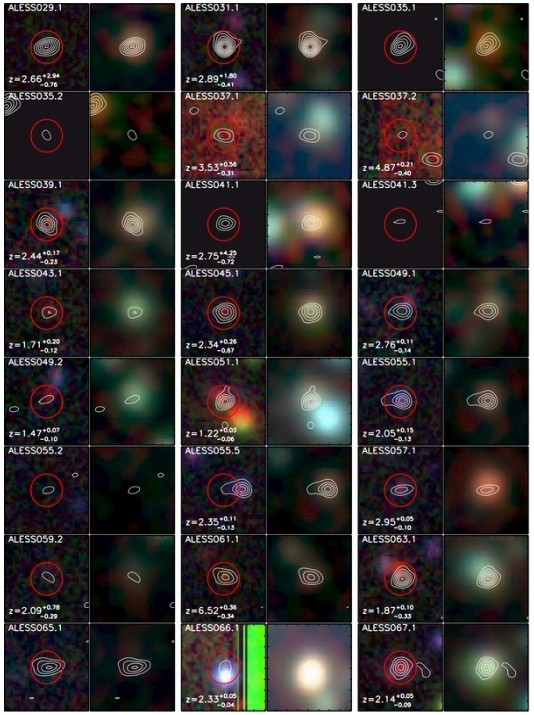
De Breuck et al 2014



ALMA Image, Spectrum

ALESS Sources
126 SMG targets



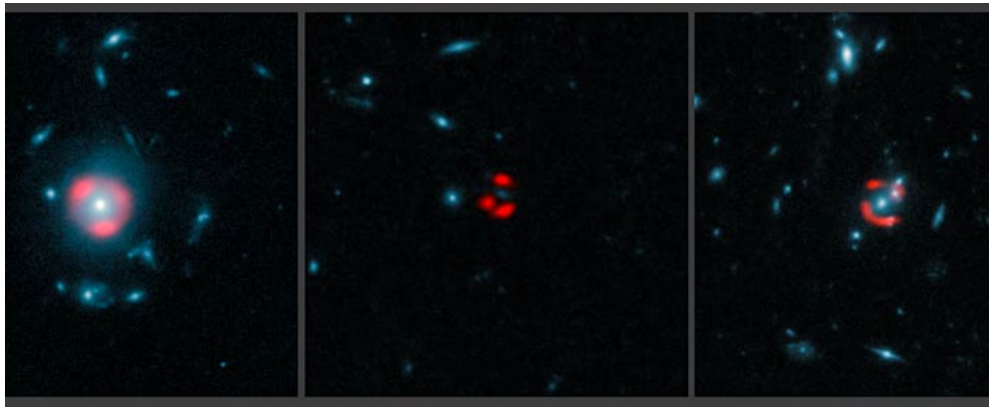


J. M. Simpson et al. 2014 ApJ 788 125

Hodge et al 2013, Karim et al 2013, Simpson et al 2014 and collaborators imaged 122 objects using 2 minute integrations to provide deeper (3x) higher resolution (10x) images of SMGs identified using LABOCA on APEX.

Distant Galaxies with ALMA

- 47 1.4mm-bright South Pole Telescope sources not coincident with IRAS/radio galaxies imaged ~1 min with ALMA at 3 and 0.8 mm. Many are lensed, excellent Einstein rings
- Blind spectroscopic observations of 26 sources followed; 23 showed high redshift CO; ten with z>4; doubling the number of such objects known
- The fraction of high redshift dusty starbursts is higher than previously thought.

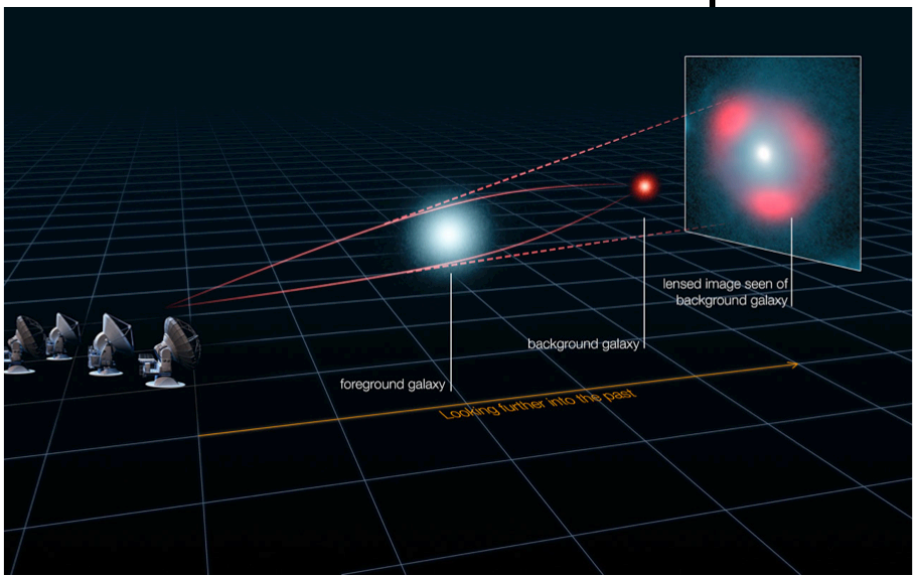


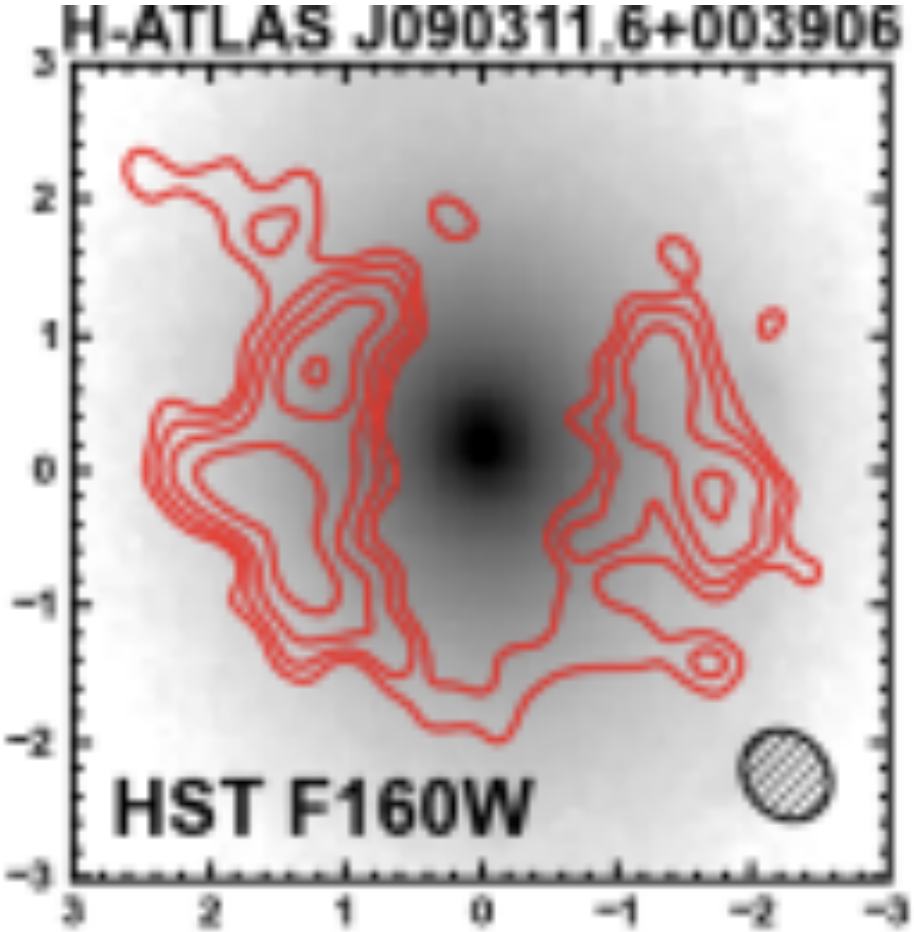
Vieira et al. 2013 Nature 495, 344; Weiss et al 2013 ApJ 767, 88, Hezaveh et al 2013 ApJ 767, 132

ALMA: The High Resolution Frontier

SMA Bussmann et al. 2013

Gravitational Lens Example



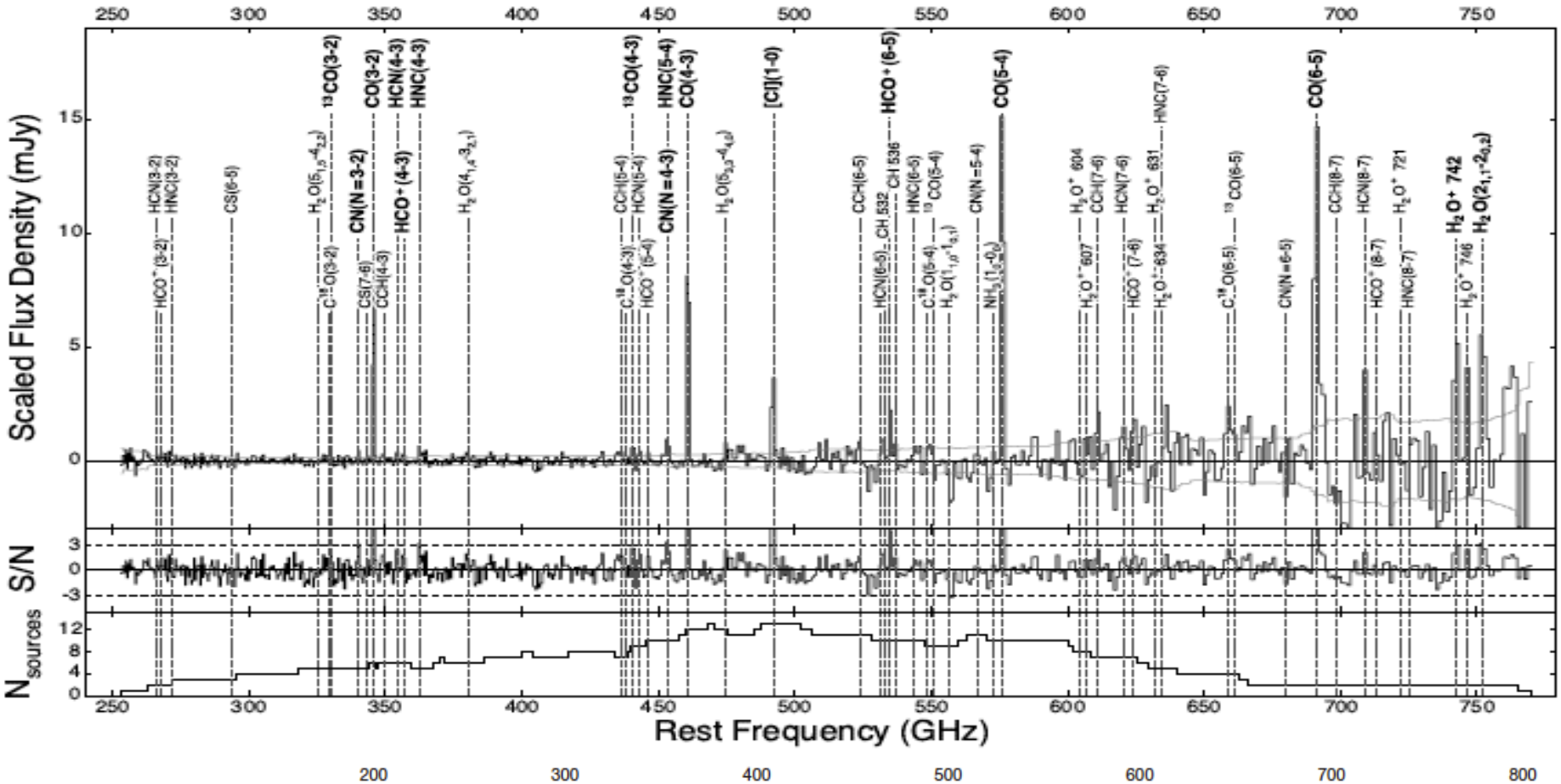


SDP.81 at z=3.04, lens at z=0.3

Einstein Ring

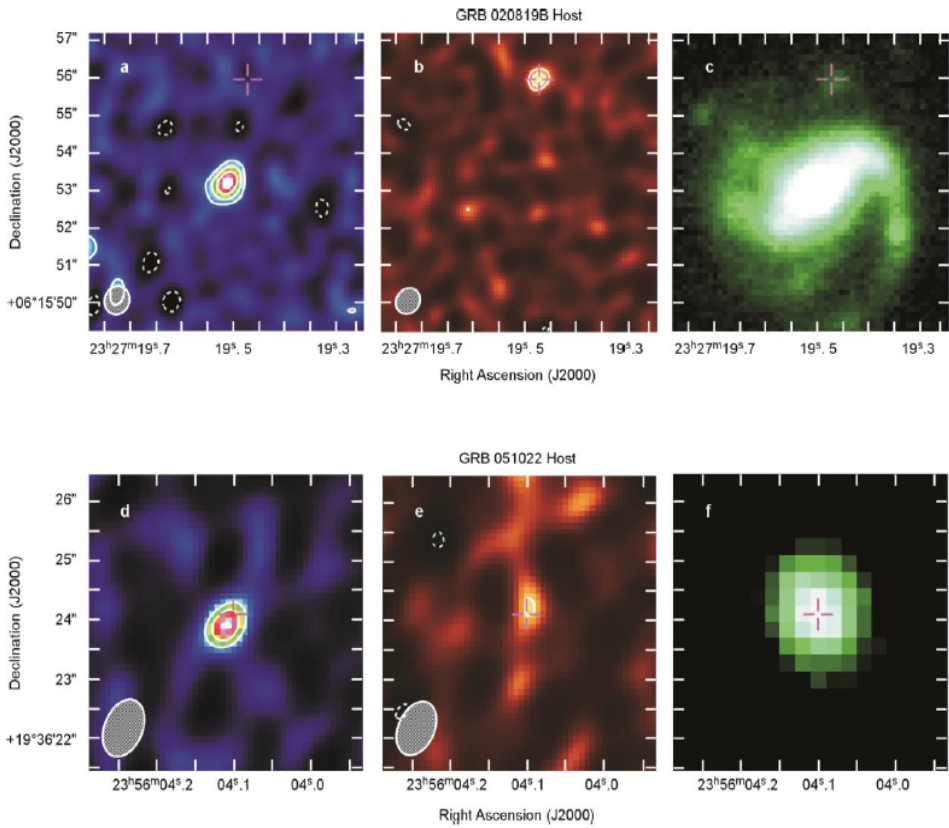
The Rest-Frame Submillimeter Spectrum of High-z, Dusty Star-Forming Galaxies

Vieira et al. 2013 / Spilker et al. 201



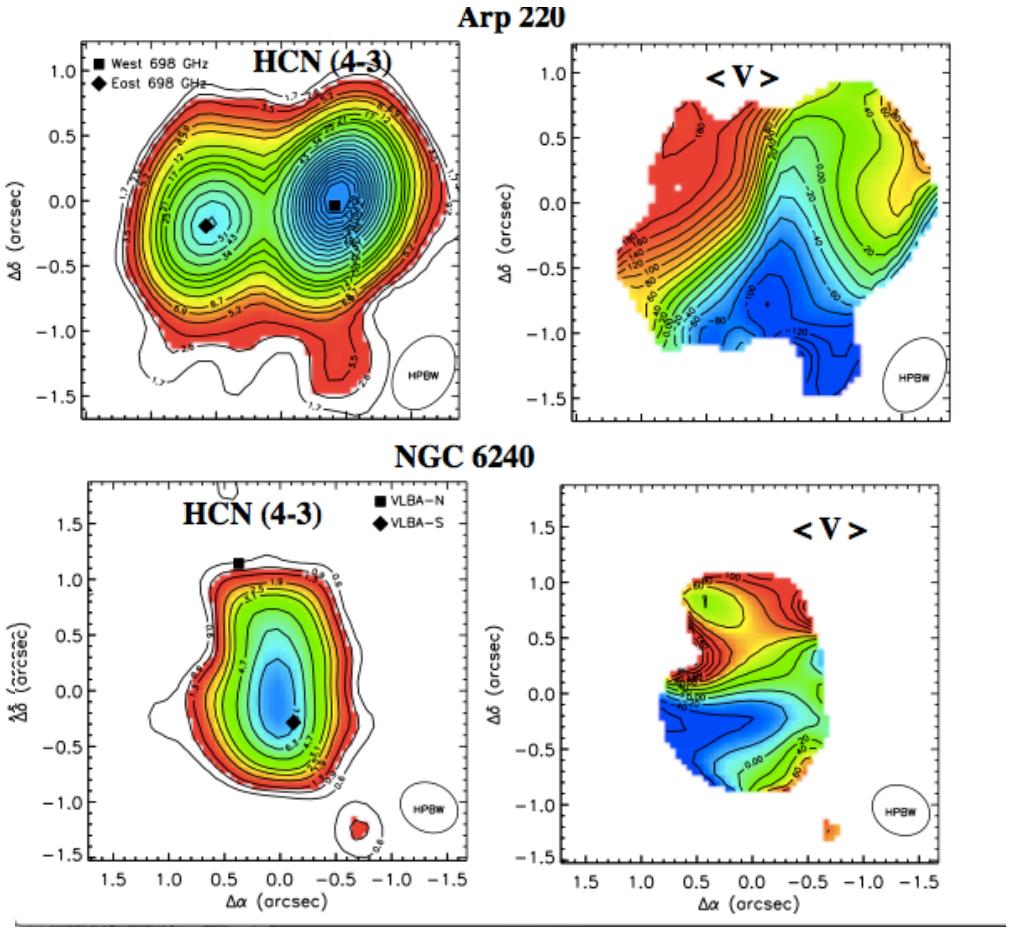
CO in Gamma-Ray Host Galaxies

- Occurred in regions rich in dust, but not particularly rich in molecular gas, at z=0.4 and 0.8.
- The ratio of molecular gas to dust (< 9 - 14) is significantly lower than in star-forming regions of the Milky Way or nearby star-forming galaxies
- Suggesting that much of the dense gas has been dissipated by newly formed massive stars



Hatsukade et al (2014) Nature 510, 247

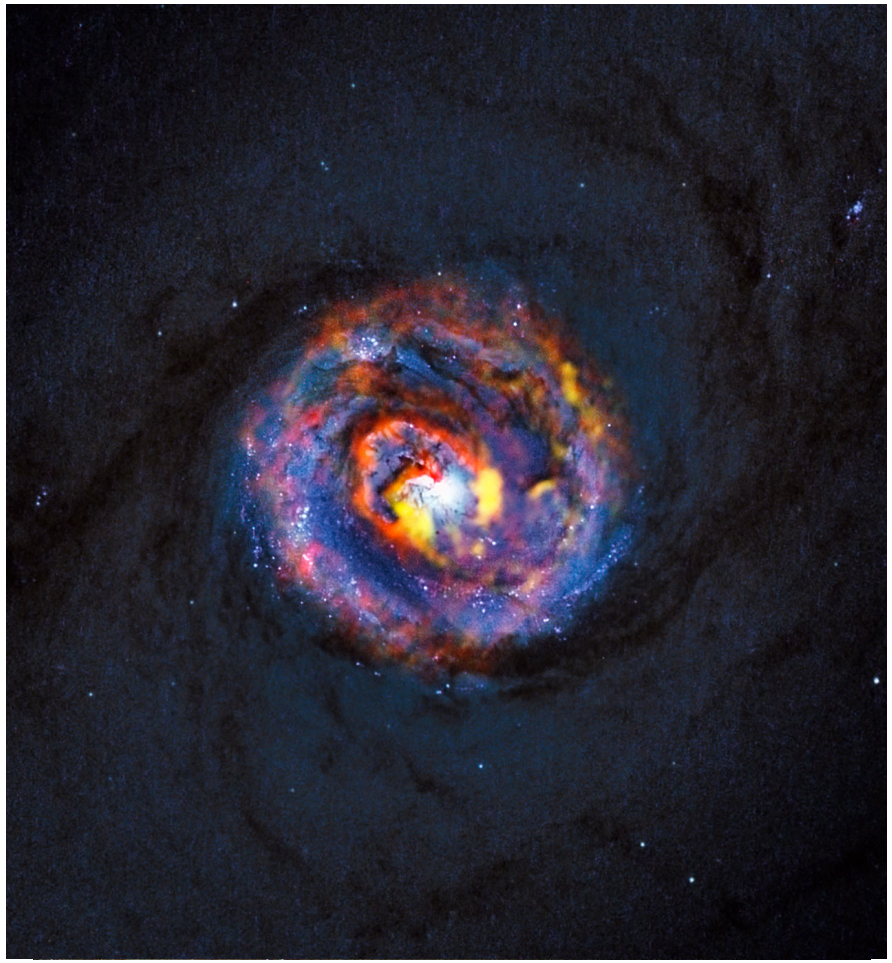
Arp220/NGC6240



Scoville et al 2014

Outflow near Galactic Nuclei

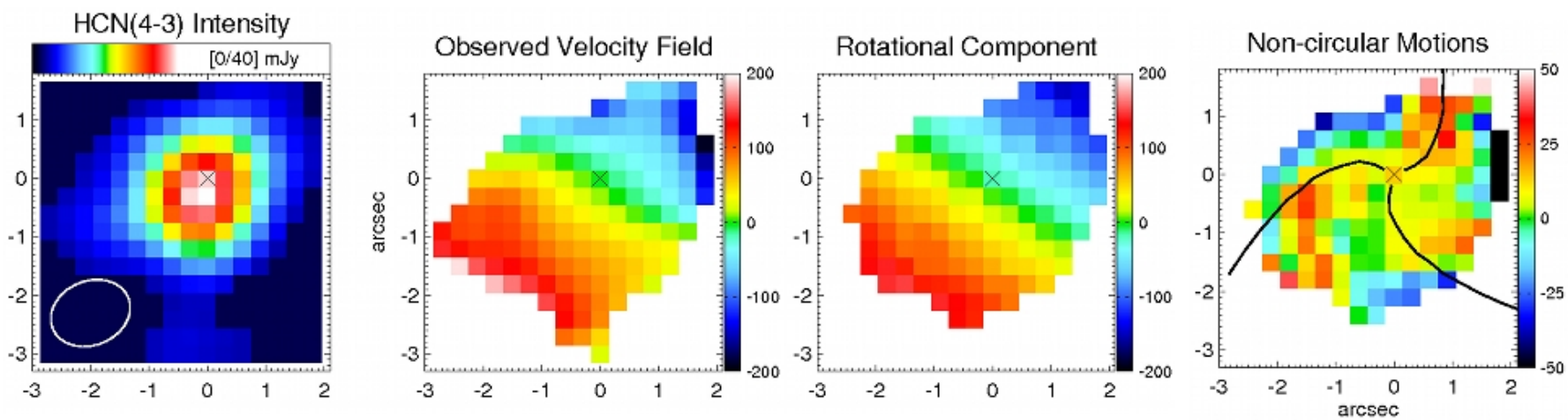
- NGC1413: angular resolution of 0.5” ~ 24 pc
  - The colored structures near the center are from ALMA observations that reveal a spiral shape, as well as an unexpected outflow, for the first time—entrained by radio flow?
- NGC3256: molecular gas may reach ~1800 km s^{-1}, for an average $M_{outflow}$ 20 $M_{sun} yr^{-1}$ (Emonts et al 2014)
- NGC1266: CO shows outflow 500 km/s. Losing gas >110 $M_{sun} yr^{-1}$ (Alatalo 2015)
- Need better mass estimators for flows



NGC1413 Combes et al., 2013 A&A 558, L124

Nearby Galaxies

- Discovered a hint of streaming gas toward the central black hole in NGC1097
- Central chemistry: HNCO in well shielded disk gas, HC_3N traces X-ray exposed gas, SiO may trace innermost dense gas (also in NGC 1068 Takano et al '14)

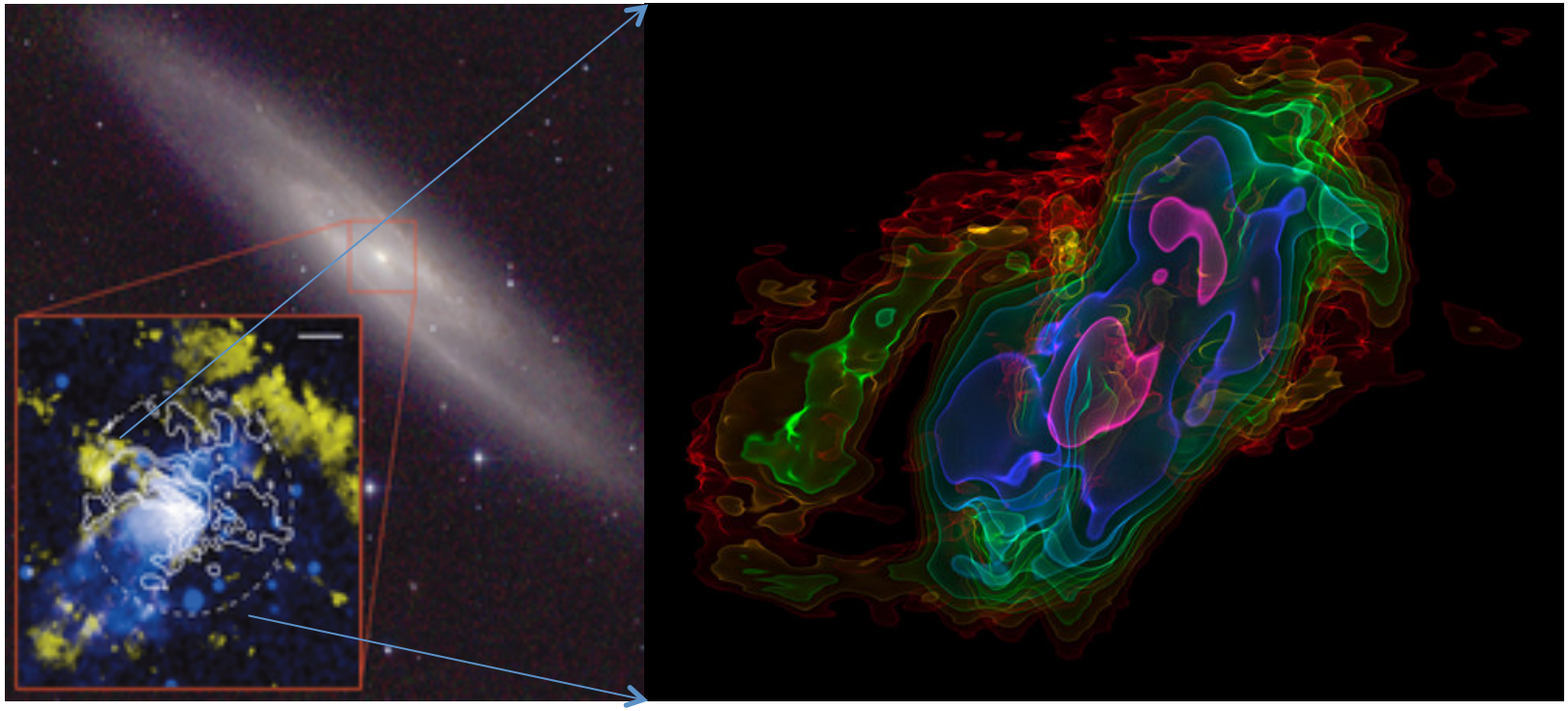


Fathi et al. (2013), Martin et al (2014)

Suppression of Star Formation in NGC 253

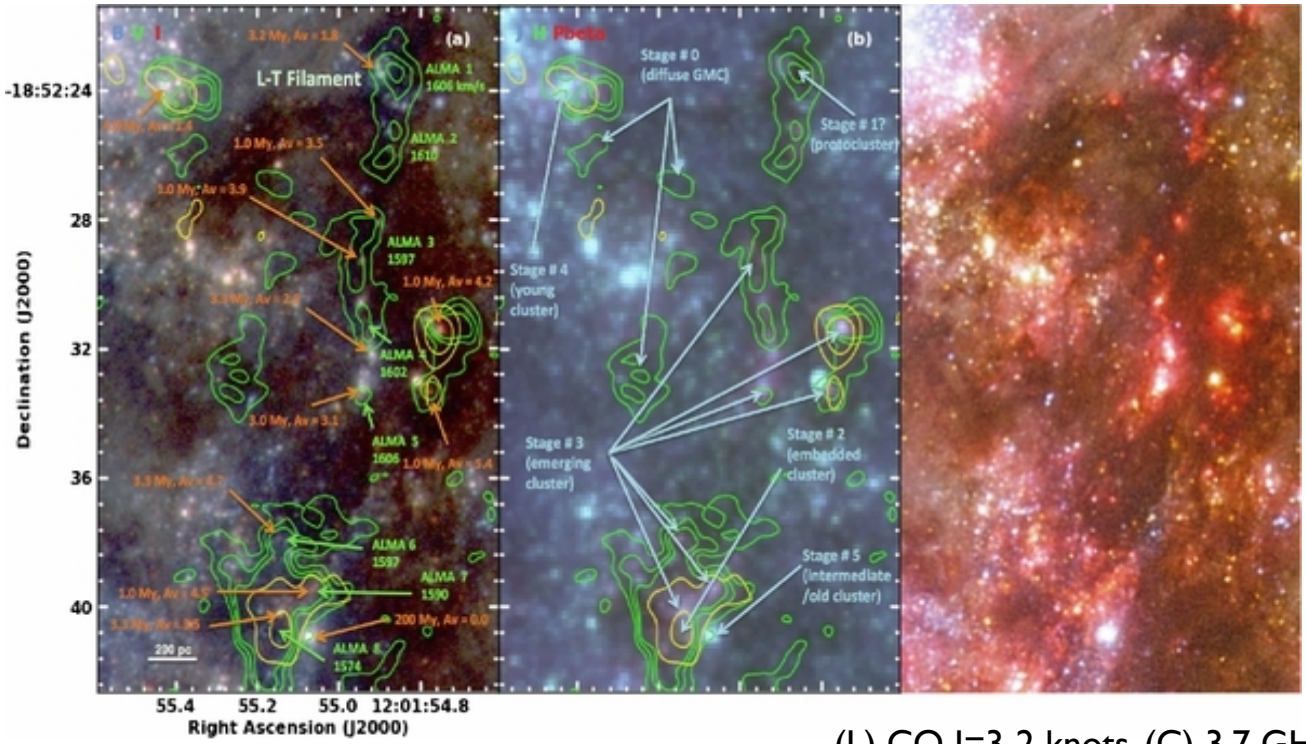
- Starburst-driven molecular wind
- Molecular outflow rate is greater than 3 – 9 M_{sun}/yr
- Starburst-driven wind limits the star-formation activity

Bolatto et al 2013



THE ANTENNAE GALAXIES. I. A NEW WINDOW ON A PROTOTYPICAL MERGER

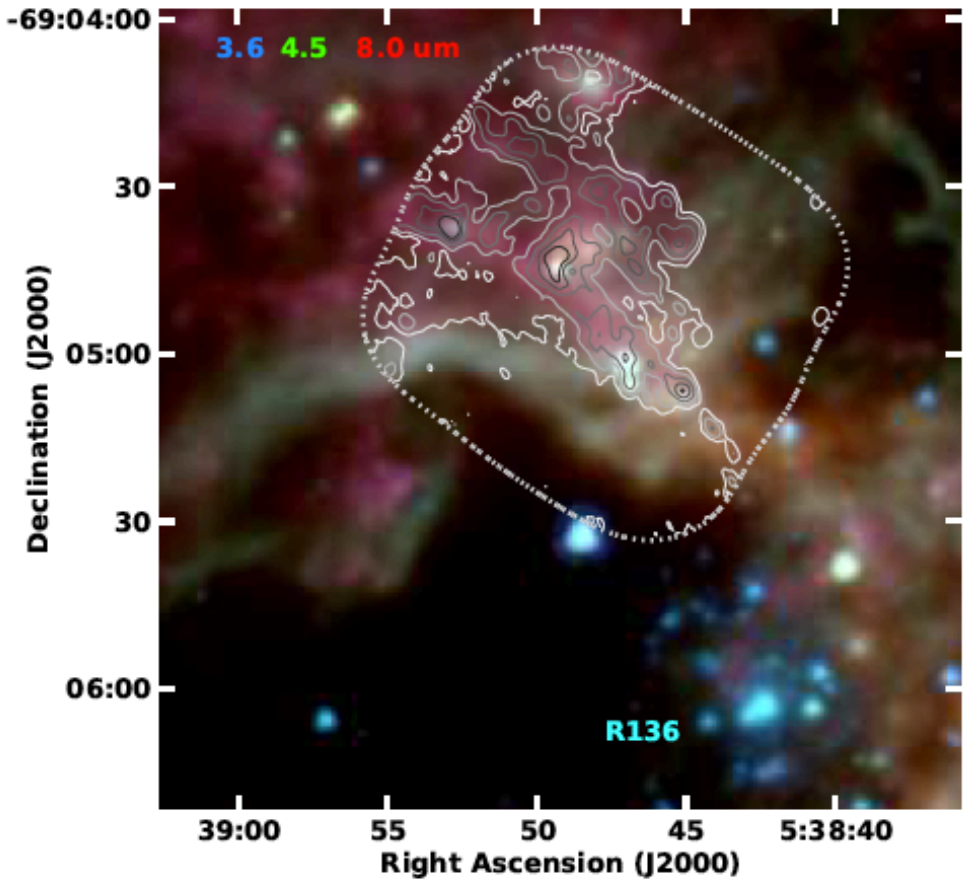
Bradley C. Whitmore et al. 2014 ApJ 795 156



(L) CO J=3-2 knots, (C) 3.7 GHz emission, (R) optical clusters in the Long-Thin filament

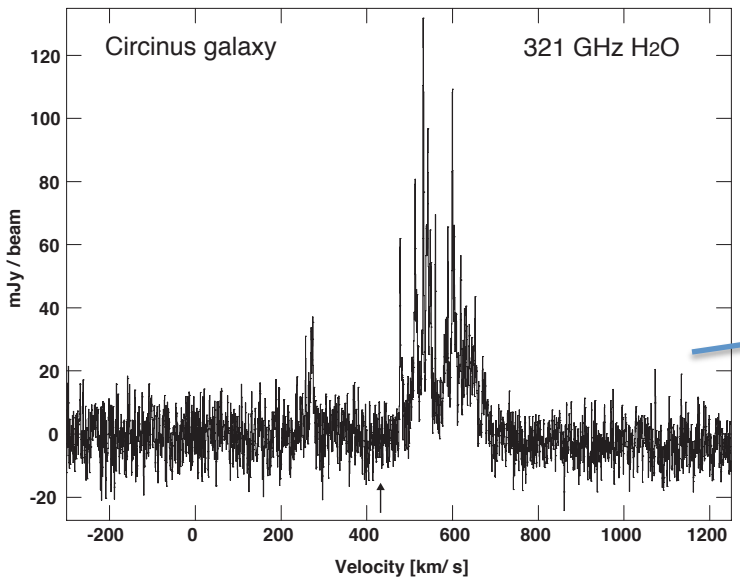
Green contours (20, 40, 60 K km s^{-1}) show CO emission; **yellow contours (50, 150 μJy beam^{-1}) show radio emission**; and orange provides information about the optical clusters.

‘Pillars of creation’ in 30 Doradus in LMC

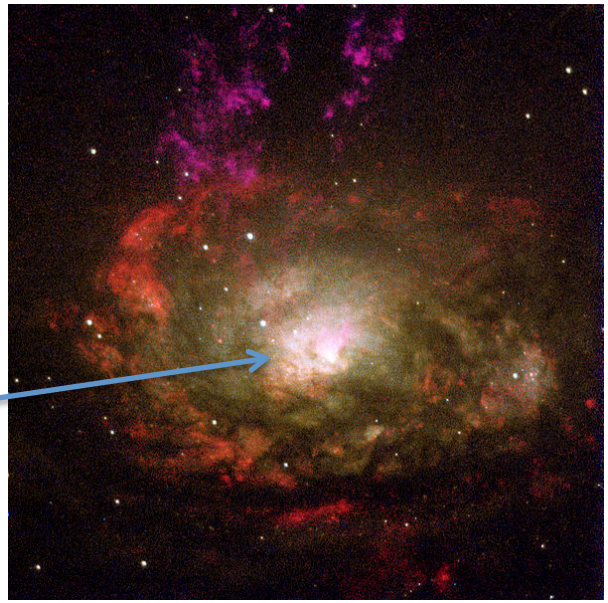


ALMA CO 2-1 contours plus Spitzer multicolor imaging of 30 Dor (Indebetouw ea. ApJ).

Mm/Submm Water Masers



Hagiwara et al. (2013)

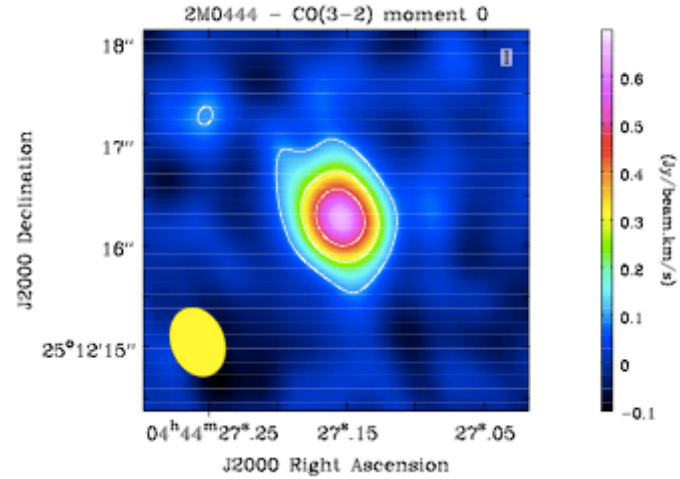


HST
Closest AGN to the MW

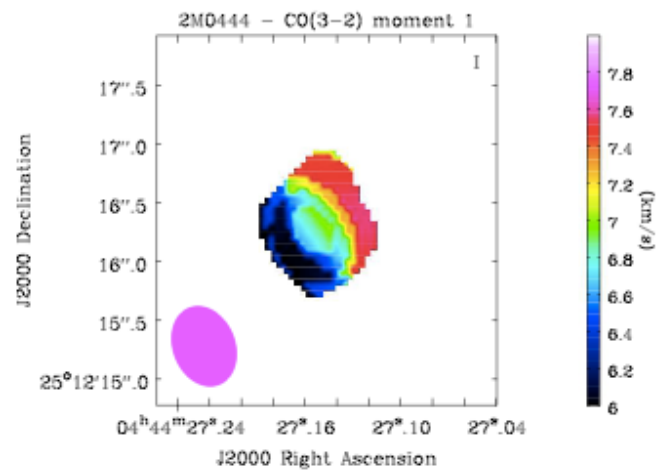
First Submm H_2O maser detection in Circinus galaxy – tracing the warm/dense material around the AGN

ALMA observations of disks in young stars

- Sensitivity provides gas images —chemistry, dynamics
- ALMA extends knowledge of low mass disks to lower masses, finer scales, chemistry
  - Subsolar mass stars
  - Brown dwarfs



Brown Dwarf 2M0444



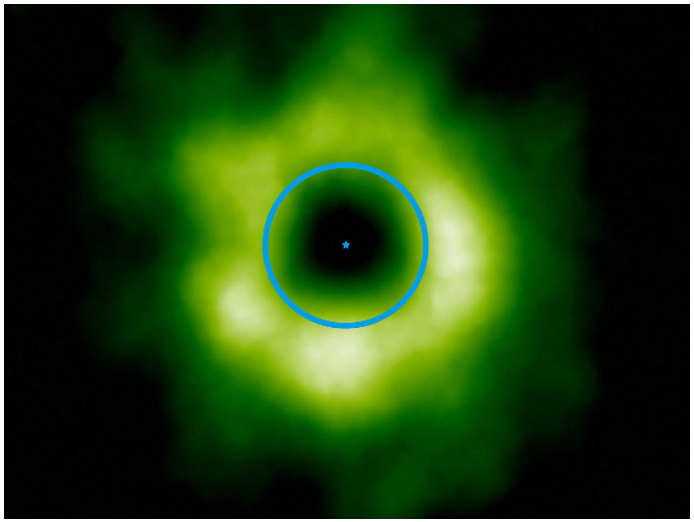
Ricci et al 2014

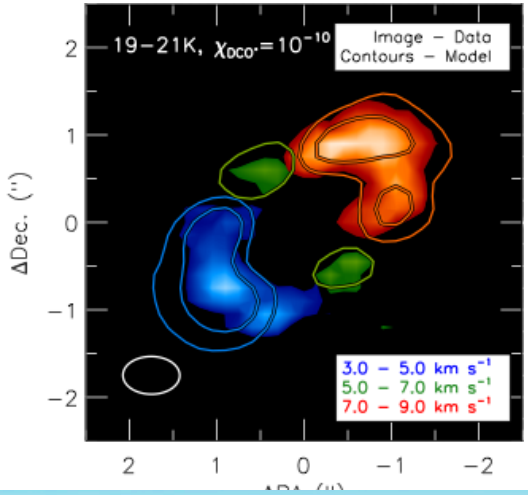
*L1527 (Sakai et al '14), HH212 (Codella et al '14), VLA1623A (Murillo et al '13), RCrA IRS7b(Lindberg et al '14) ⋆ ρ Oph 102 Ricci et al '12, M0444, CIDA 1, and CFHT Tau4 (Ricci et al '14)

Protoplanetary Disk Midplane Snow Lines

- Disk midplanes are
  - The sites of planet formation, the main reservoirs of mass and probable sources of complex organics
  - Cold—ices form; ices are sticky; good larger body seeds
  - Characterized by a range of low-energy lines of ions, deuterated molecules, isotopologues and organics
- Observational feature: 'Snow Line' which occurs where the temperature drops to where frost forms—in this case CO frost

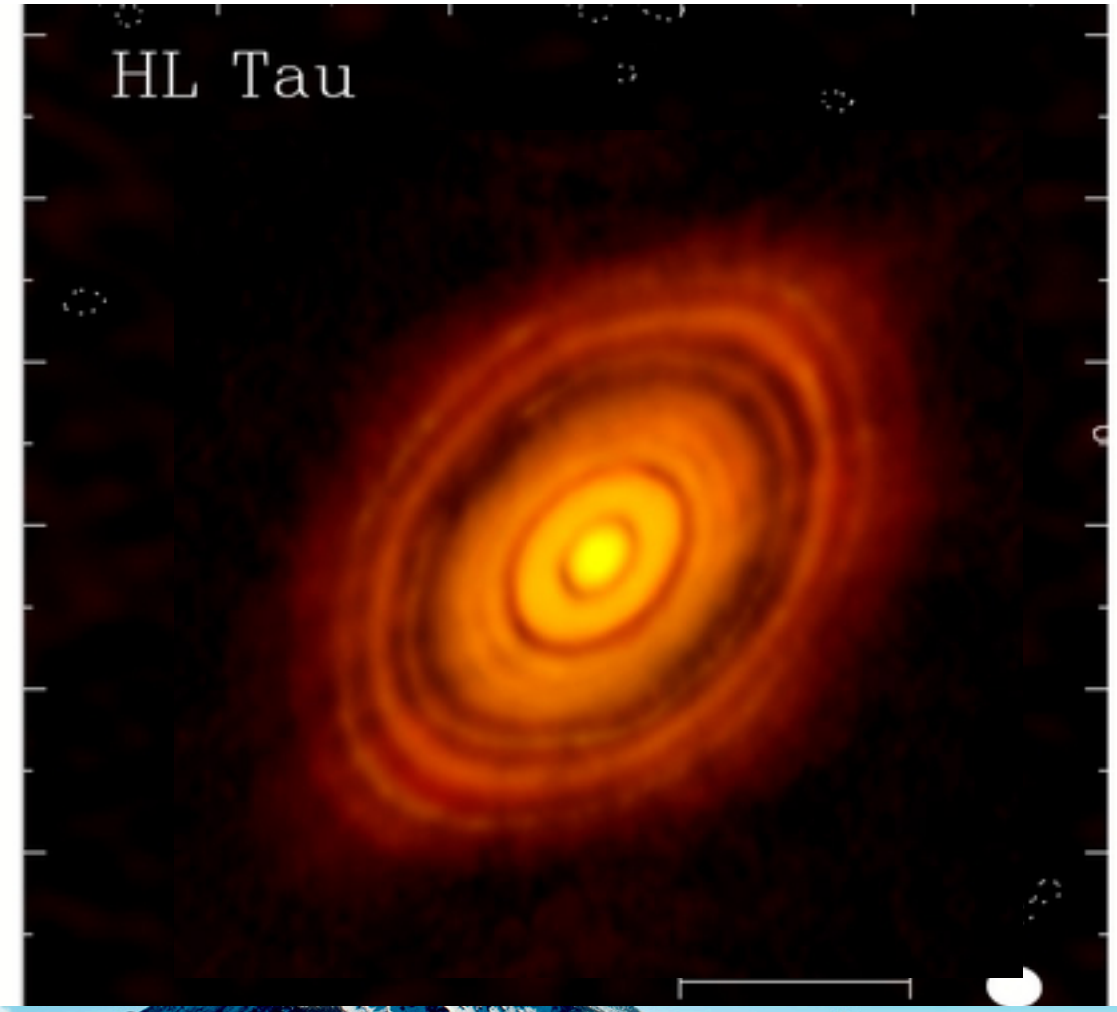
TWHya CO Snow Line Qi et al.



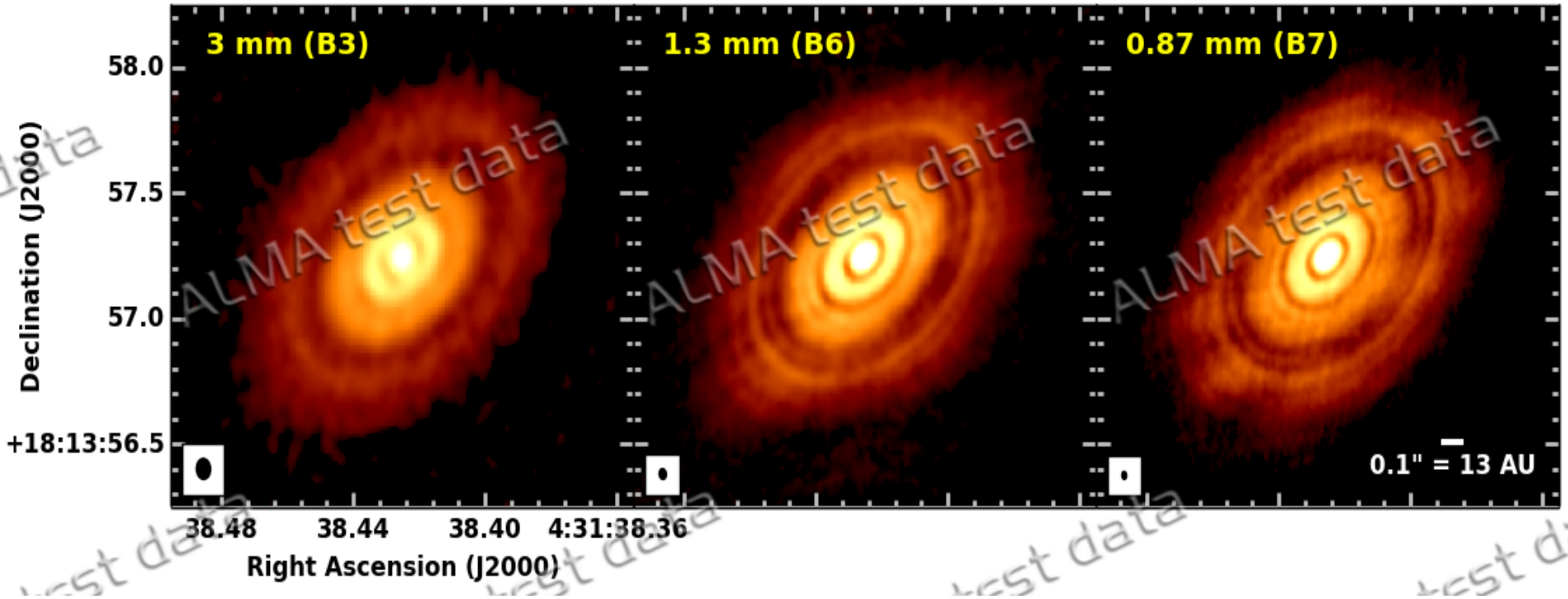


HD163296 Mathews et al.

Power of Many Long Baselines: HL Tau

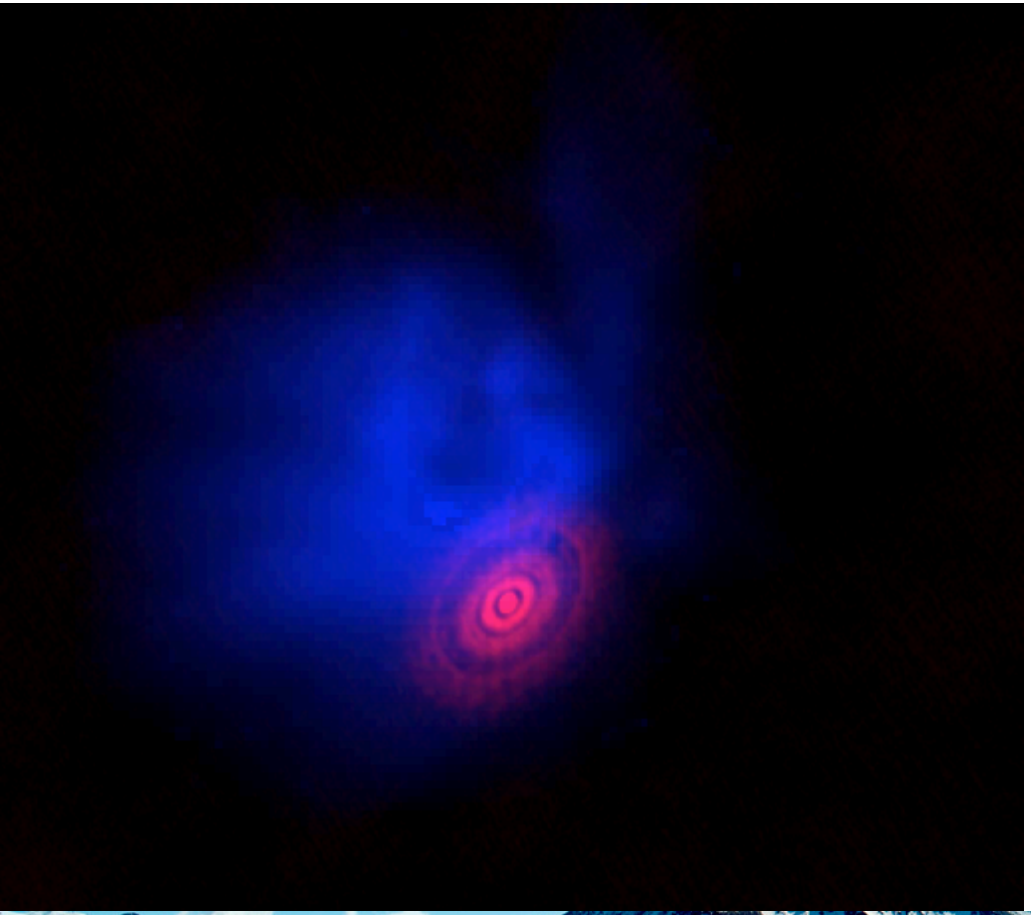


Long Baseline Campaign: HL Tau



ALMA HL Tau SV data at 3, 1.3, and 0.87 mm. The images were made from 14 executions x 4 GHz bandwidth (BW), 9 executions x 8 GHz BW, and 10 executions x 8 GHz BW and Bands 3, 6, and 7, respectively. Beam sizes are 83x60, 42x30 and 31x19 mas at Bands 3, 6, and 7, respectively.

Long Baseline Campaign: HLTau



- Complementary to Hubble (blue—scattered light from unseen star).
- Presence of several planets at such a young age is “disturbing” to planet formation theories

- Press Release Impact/News Circulation

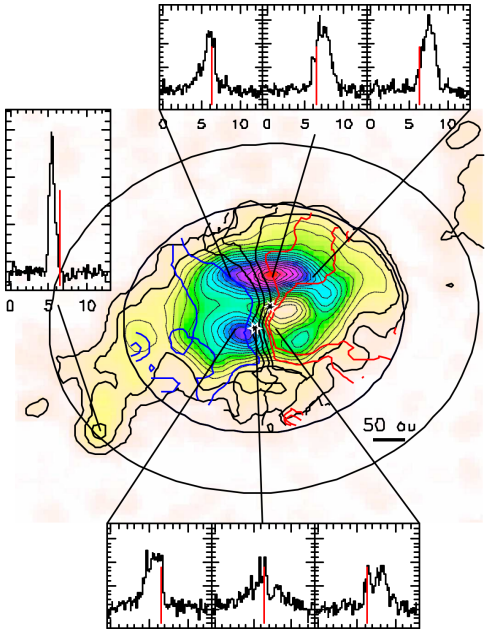
HL Tau ALMA Image 455 Million views

Interconnecting Streamer in Binary GG Tau

Can nature form planets in multiple star systems?
ALMA revealed a streamer channeling gas from a massive outer disk to the inner disk in this hierarchical triple system

- Flow appears capable of sustaining the 1 $M_{jupiter}$ inner disk beyond the accretion lifetime, leaving time for planet formation to occur there.
- Planets may form here!

A Dutrey *et al. Nature* **514**, 600-602 (2014)

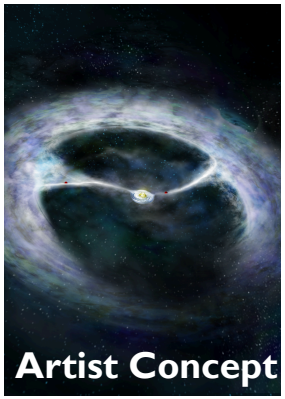


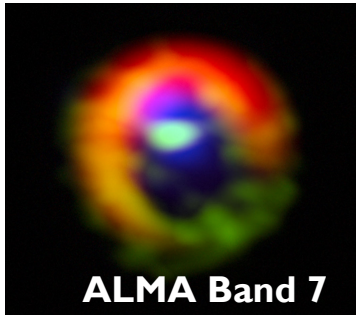
CO J=6-5 data. Black: integrated area, blue: approaching gas, red: receding gas, Stars: Aa (south) and Ab (north). Ellipses: ring edge. Spectra illustrate velocities.

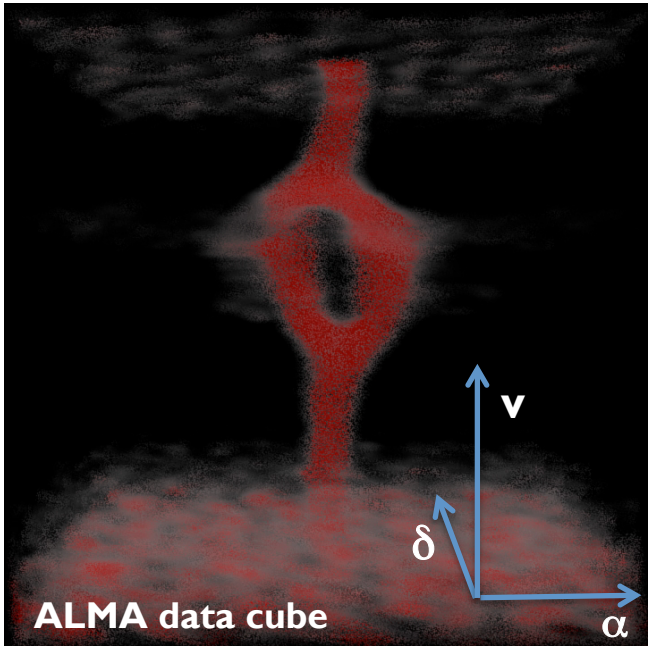
Gas Flows thru a Protoplanetary Gap

- HD142527: IR data shows 10 AU inner disk, 140 AU gap, disrupted outer disk, attributed to unseen planetary mass at 90 AU
- Sensitivity & spatial resolution enable images of dense gas in gap-crossing filaments & diffuse CO gas within disk
- Dynamical models & data suggest outer disk gas channeled by putative protoplanets

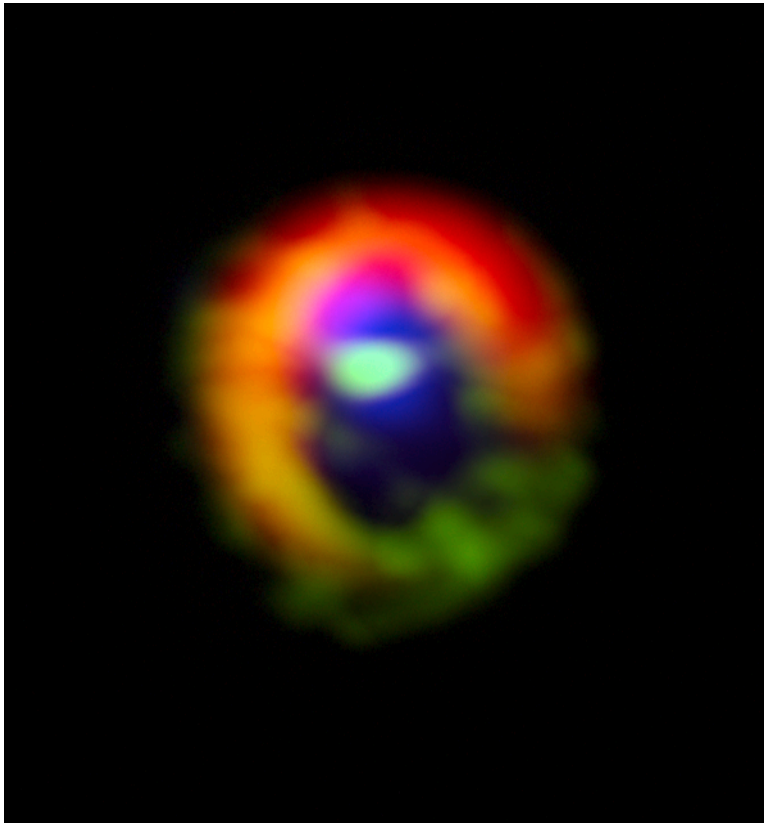
Casassus (Chile)+, 2013 Nature, 493, 191



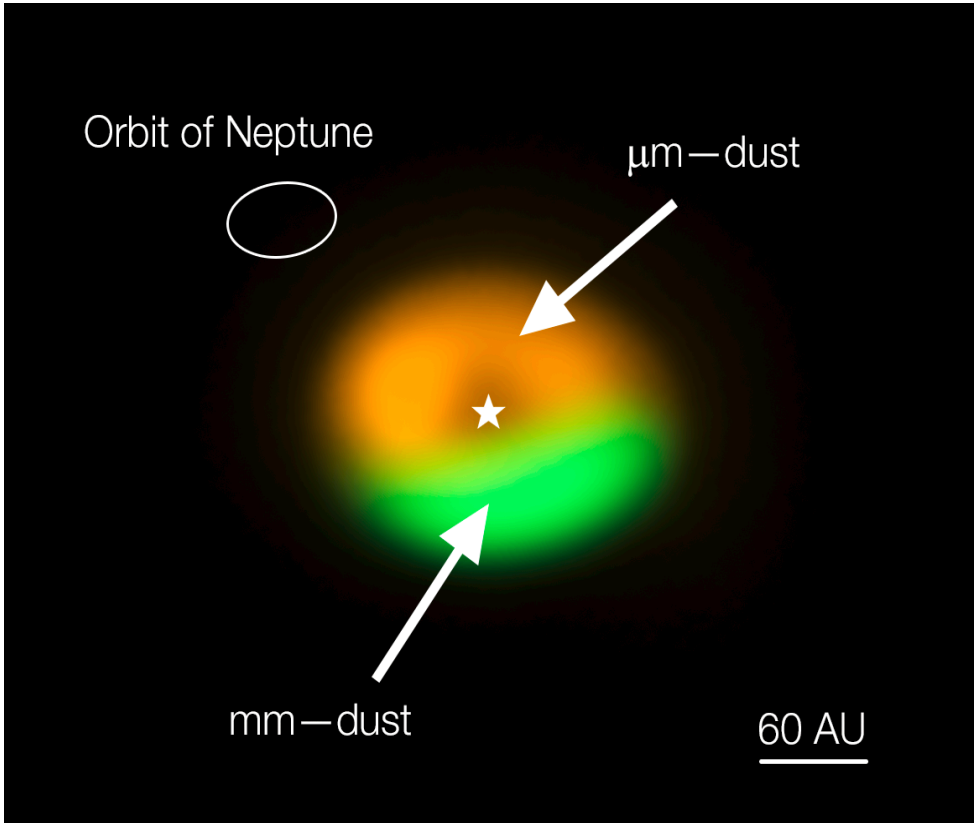




Transitional Disks:
Gas Flows and Dust Evolution



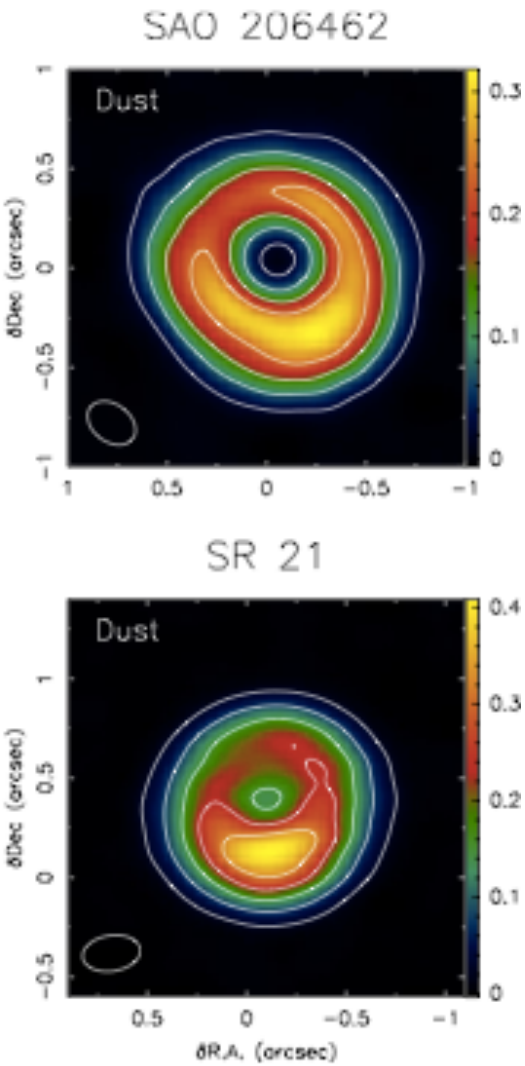
Gas Flow and Dust Trap in HD 142527
Casassus et al. (2013)



Dust Trap in Oph IRS 48
van der Marel et al. (2013)

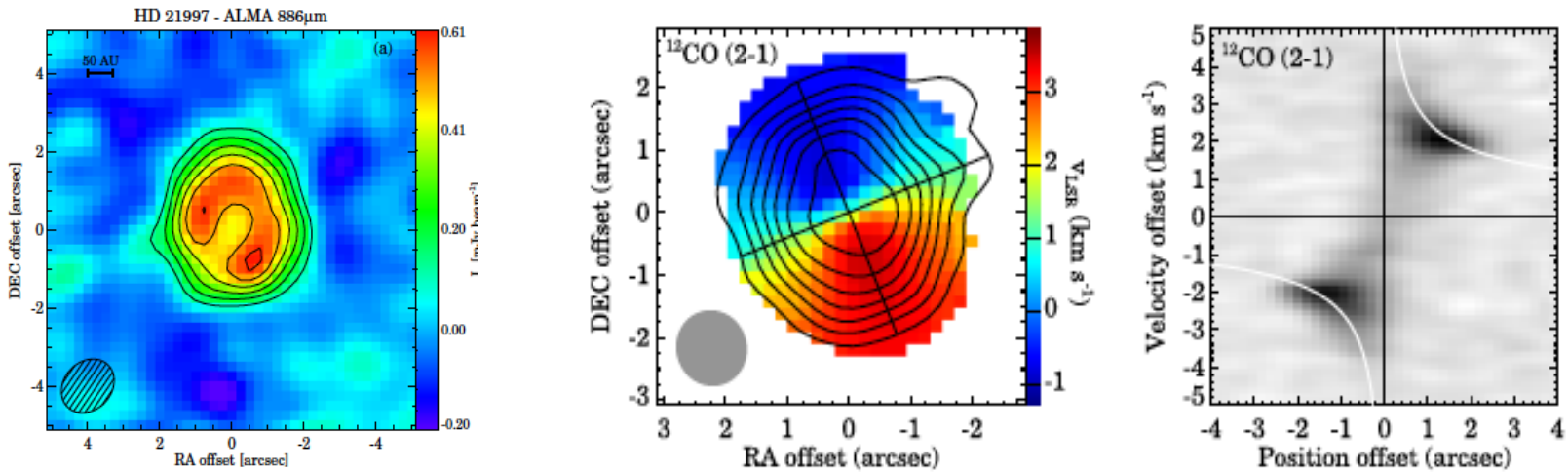
‘Dust Traps’ in Transition Disks

- An annular gap is created in the gas disk (perhaps owing to a planet)
- A high-pressure vortex forms at the gap edge, collecting and trapping millimeter-sized dust particles that would otherwise spiral rapidly inward through the disk.



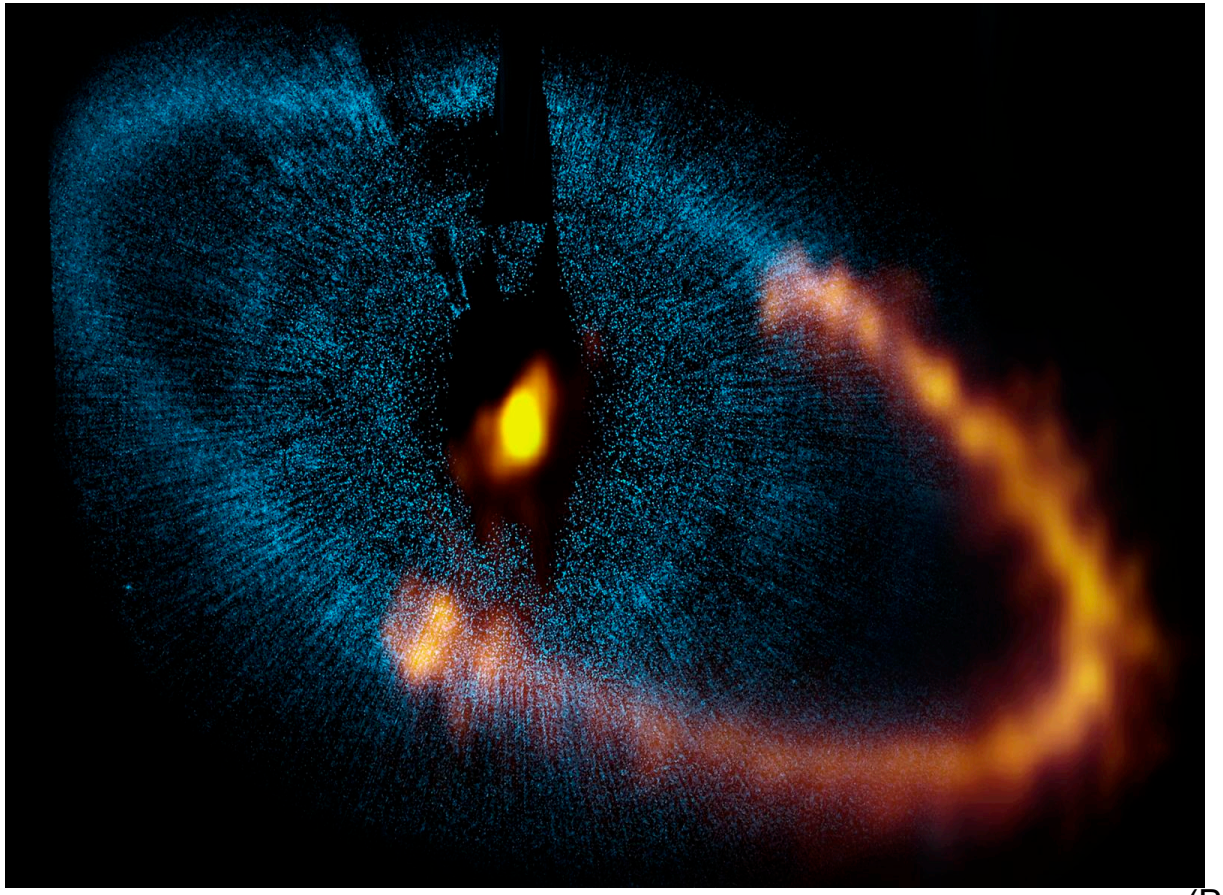
Perez et al 2014

Debris Disks



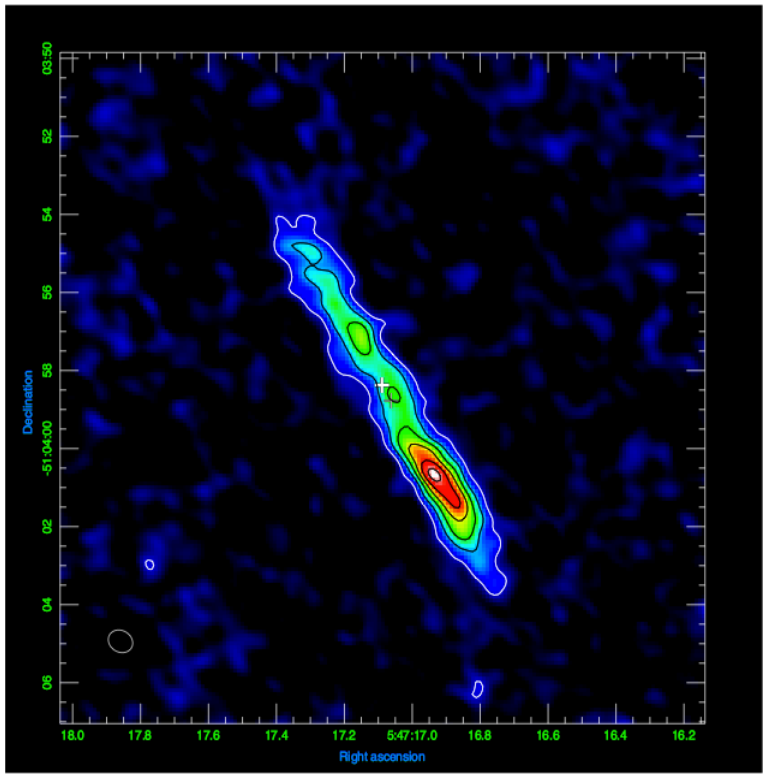
HD 21997 A debris disk with a measurable amount of cold molecular gas, dust-free inner gas disk within 55 AU of the star. Kospal et al., Moor et al. (2013)

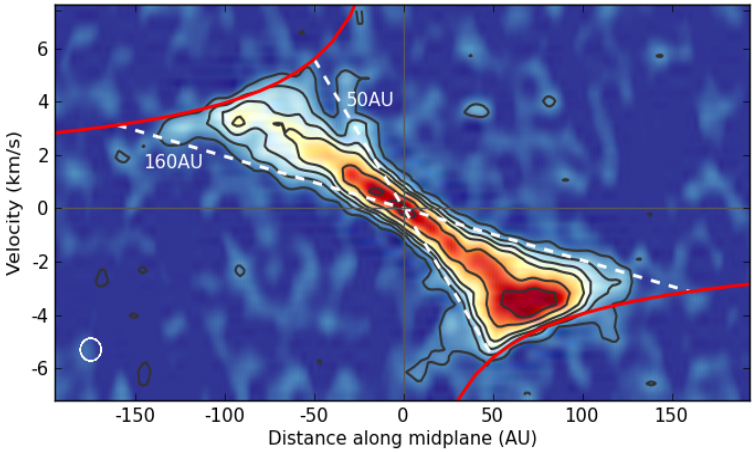
Probing mm-sized dust grains in Fomalhaut's Debris Disk



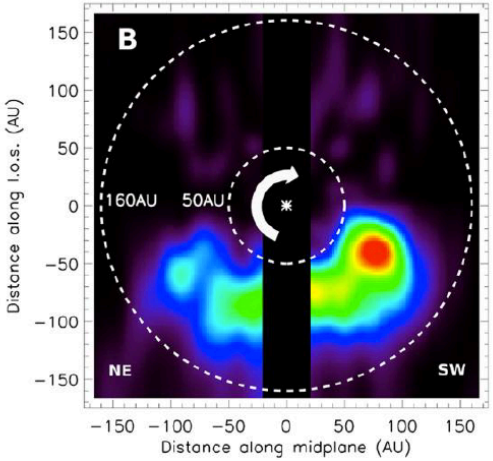
(Boley et al., 2012)

Beta Pictoris





CO (3-2) velocity field



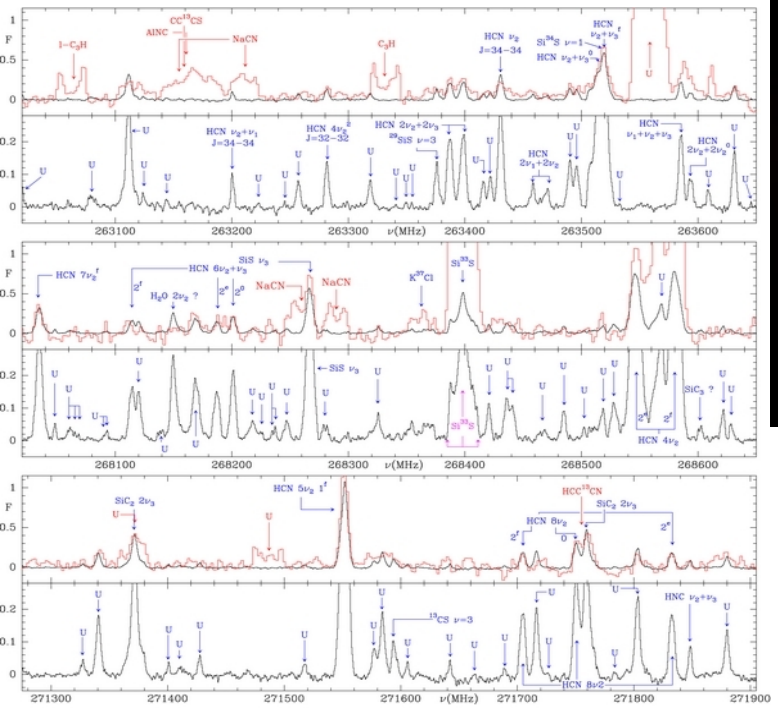
Polar view

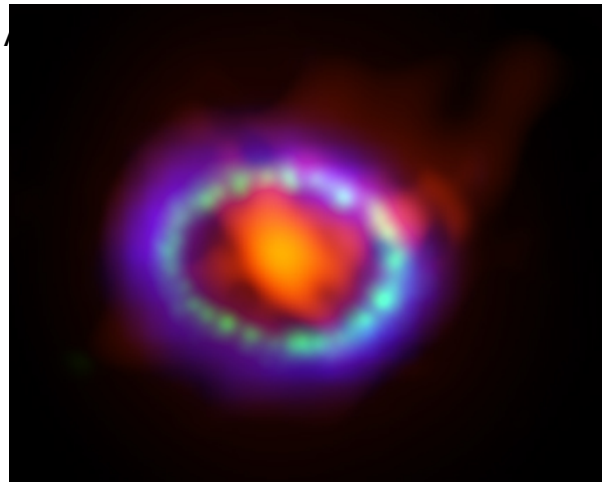
Dust, then CO
Dent et al. (2014) Science

Stellar evolution, the Sun and the solar system

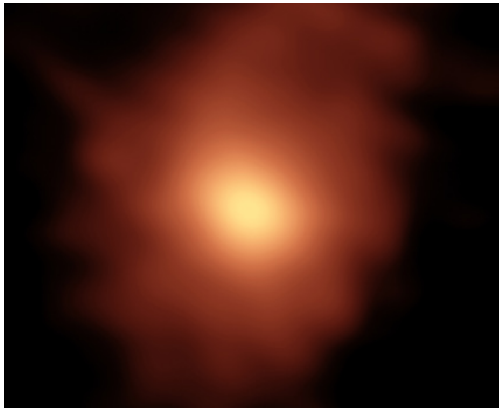
- Dust nucleation zone unveiled by ALMA in AGB star and SN87A
- η Car, Comet papers, Pluto observations

IRC+10216, J. Cernicharo et al. 2013



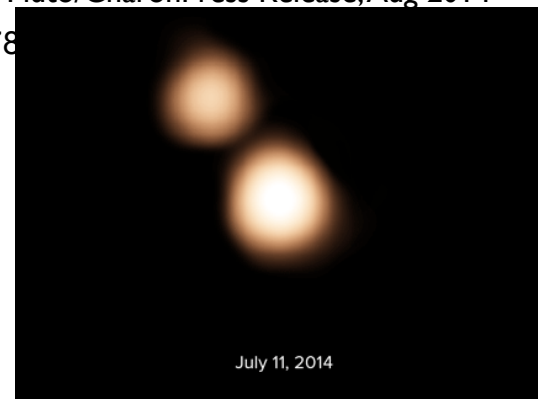


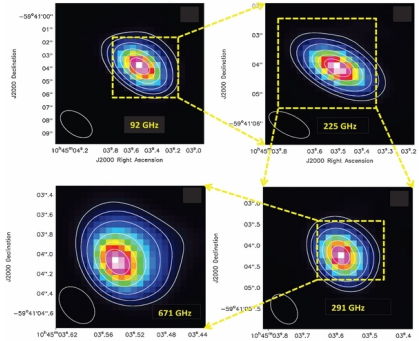
SN87A, Indebetouw et al 2014ApJ,78



C/ISONCordiner et al, 2014ApJ,792

Pluto/CharonPress Release, Aug 2014

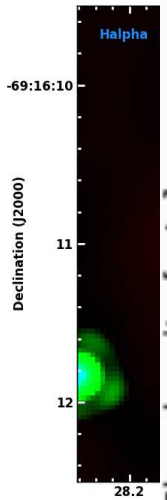


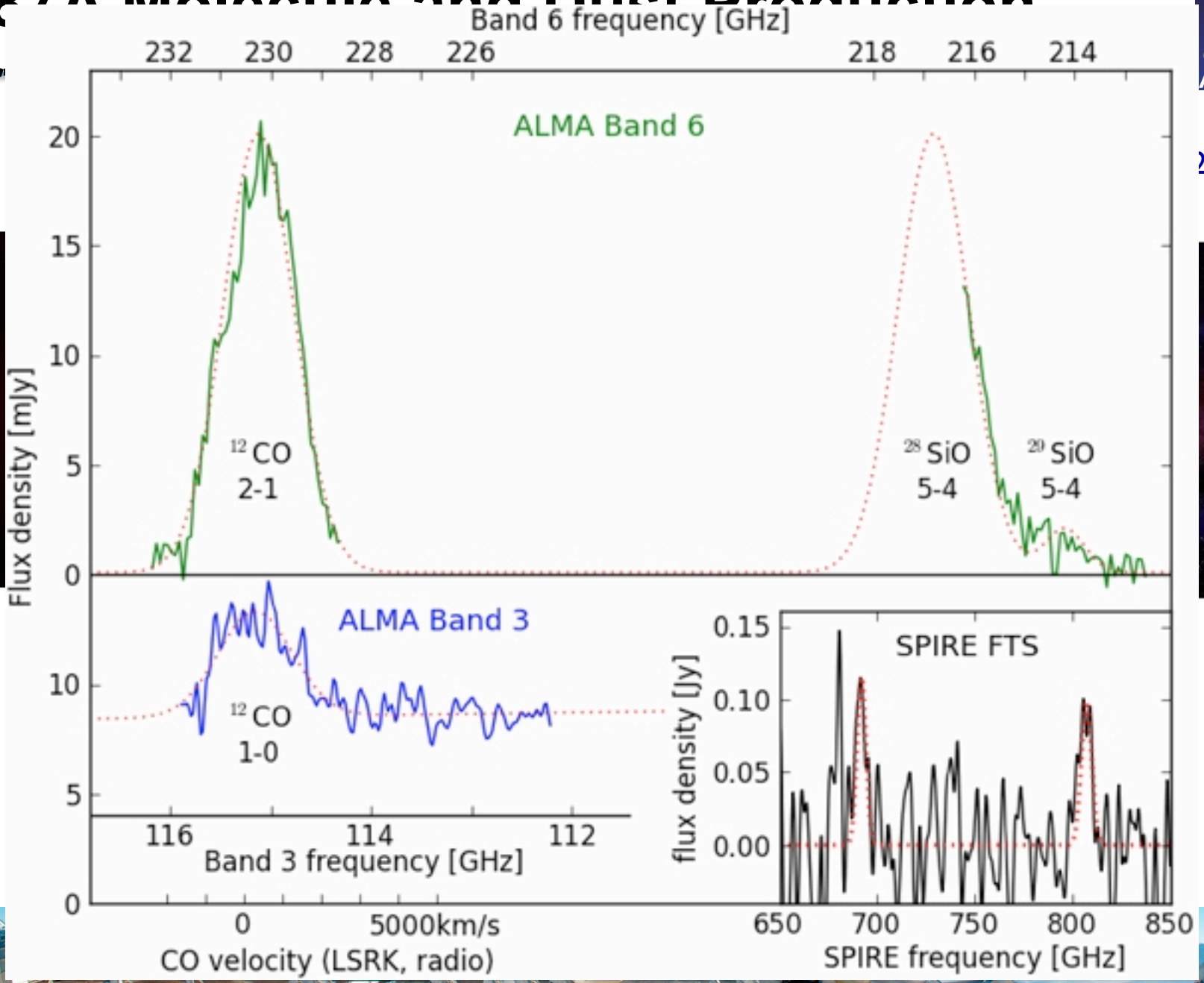


Eta Car Abraham et al. 2014

SN87A Molecule and Dust Production Par

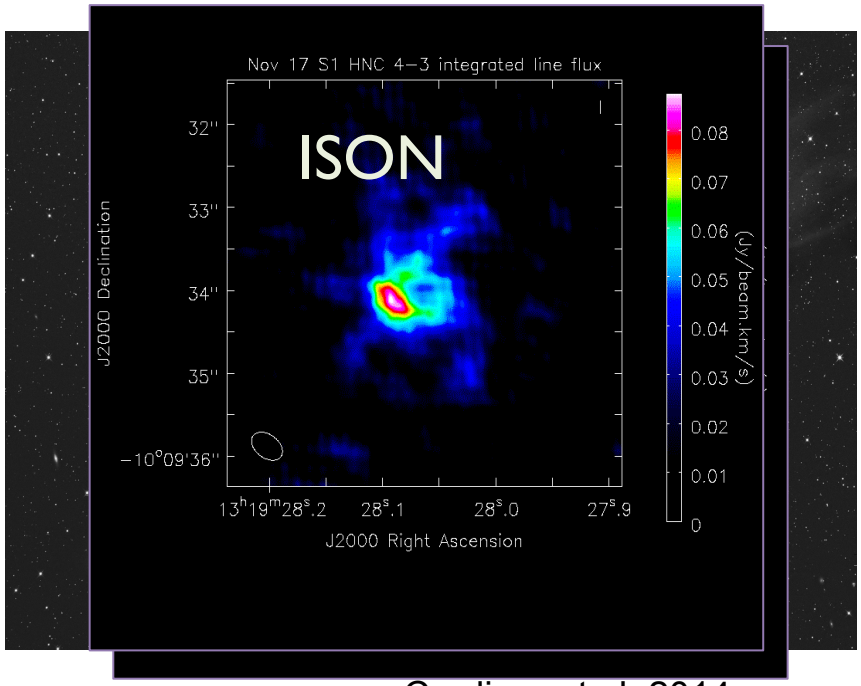
2013





ALMA Observations of Comet ISON

- Pre-perihelion (r_H = 0.4 – 0.7 AU)
  November 12 – 21, 2013
  Observed November 15, 16, 17, 2013



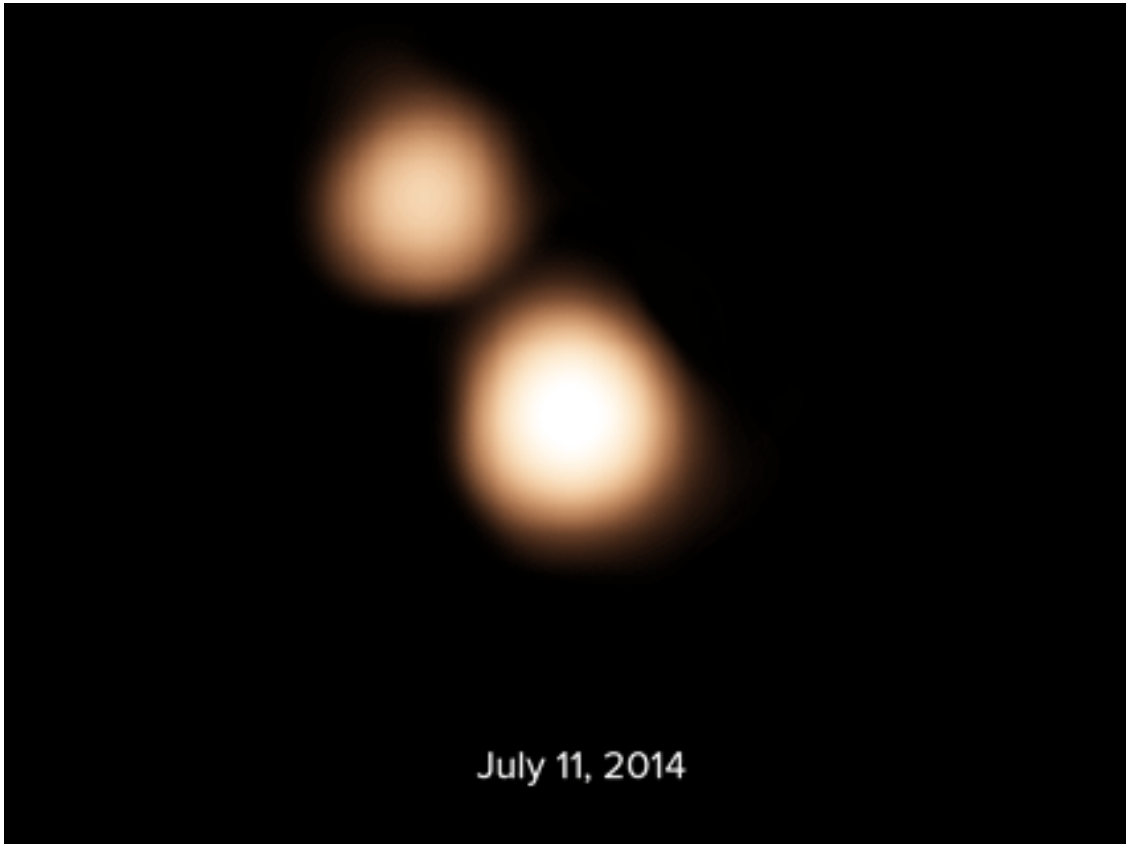
Cordiner et al. 2014

- Hydrogen cyanide (HCN), hydrogen isocyanide (HNC), and formaldehyde (H_2CO) were used to produce 3D images of Comets Lemmon and ISON.
- HCN flows evenly from nucleus
- HNC, H_2CO concentrates in clumps and jets, showing they actually form within the coma
- ALMA may follow comets close to the Sun owing to its capacity for solar observations.

Pluton & Charon Observations

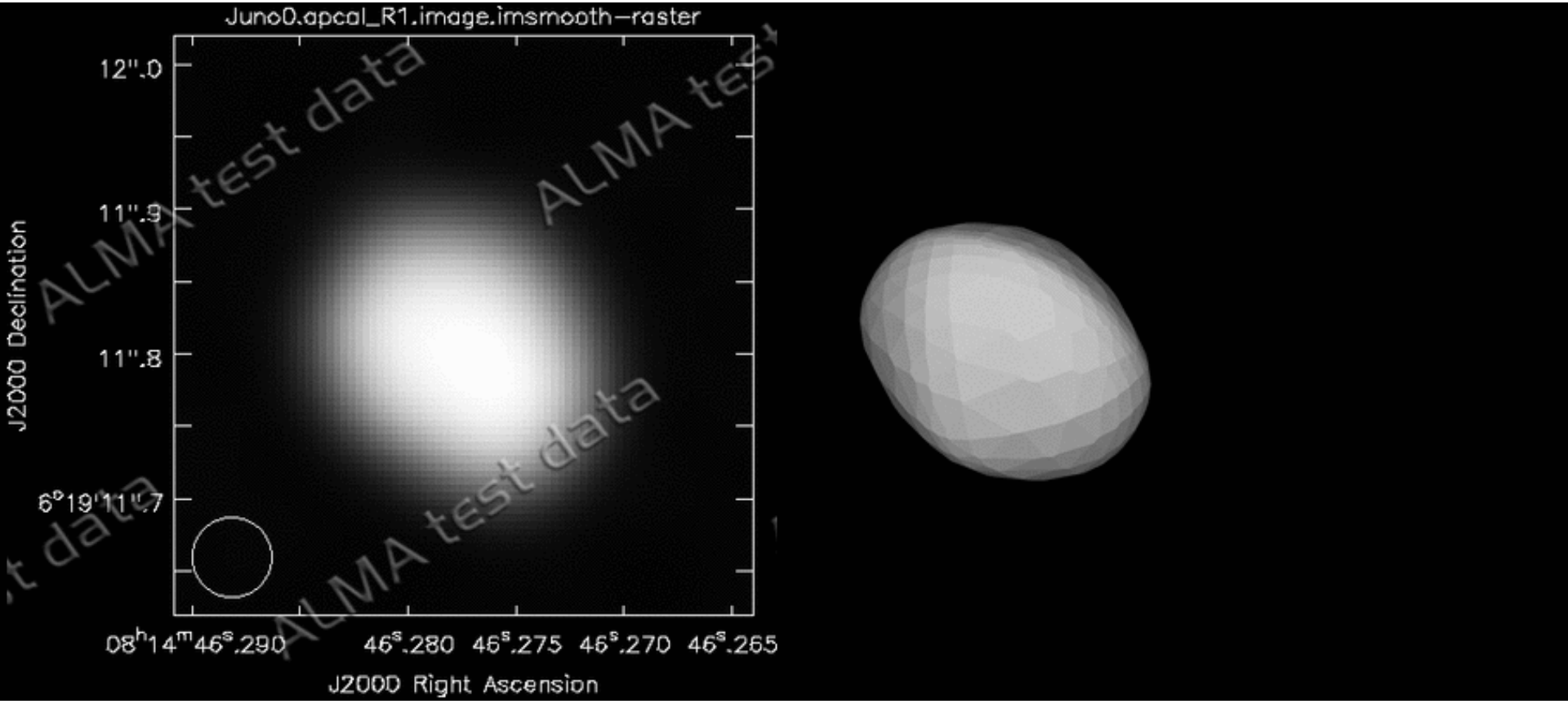
Astrometry using a reference network of neaby QSOs achieved Astrometric accuracy of 4 mas

ALMA data improved targeting of New Horizons spacecraft



Fomalont et al, in prep

Juno at High Resolution



1.3 mm (Band 6) ALMA SV continuum images of Juno—3x15 minute snapshots (l) compared to model (r) from online software DAMIT (Durech et al 2013)

Development Program

- Development of post-construction receivers, phasing hardware, and new data analysis tools underway
  - 1st Development Studies program call issued Nov 2011
  - After external review, 8 proposals funded, now coming to completion
- New Call for FY2016 Development Studies April/May 2015
  - $1.0M will be available (subject to the FY 2015 and FY2016 Federal Budget and allocation of funds). The NRAO expects to fund several Studies in FY 2016; no individual Study will be funded in excess of $200K.
  - Notification of awards will be made prior to 30 September 2015.
- New Call for FY2017 Development Projects in April 2016 for projects to begin in FY 2017 (subject to the FY 2017 Federal Budget and allocation of funds).

Summary

- After three decades of planning/construction, ALMA is approaching full science operations
- US: major partner in international governance of the facility
- Early Science has been hugely successful
  - Regular observing cycles underway
- Further technical/scientific development via community involvement: in progress

- On behalf of NRAO, AUI and our international partners – encourage everyone to consider using ALMA for your research.

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

ALMA Science Portal almascience.nrao.edu

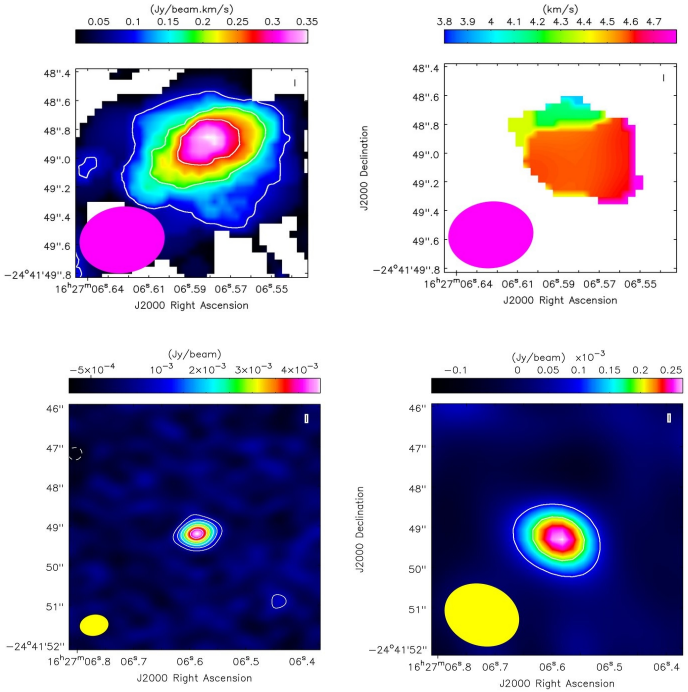
North American ALMA Science Center science.nrao.edu/facilities/alma

Unexpected Large Mass Loss During a Red Giant Thermal Pulse Cycle

Maerker+, 2012 Nature, 490, 232

Grain Growth & Molecular Gas in the Disk around a Young Brown Dwarf

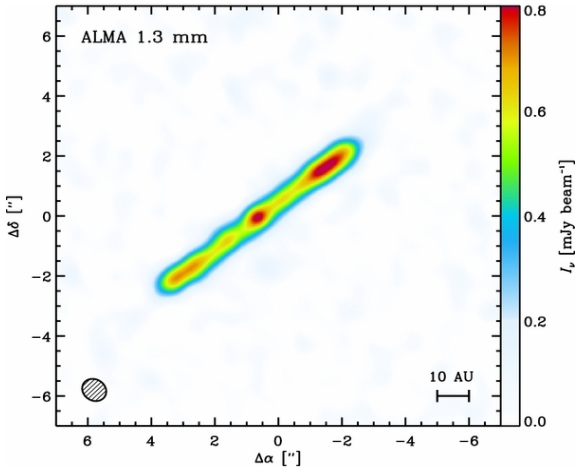
- Dusty disk <40 AU around ρ Oph 102
- Surprisingly, dust grains are fairly large
- Molecular gas emission at brown dwarf location → a gas-rich disk as typically found around young pre-MS stars
- Suggests brown dwarf stars may produce planets in a manner similar to normal stars

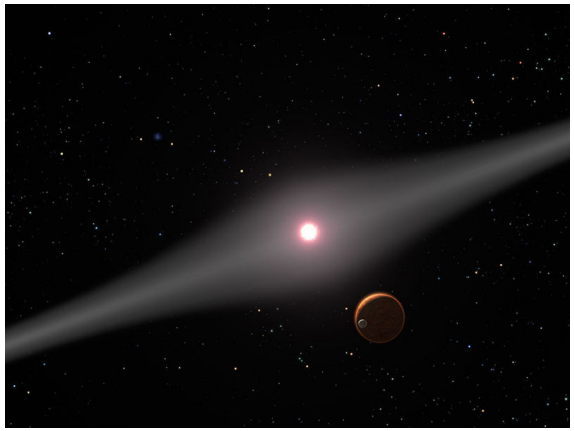


Ricci (Caltech)+, 2012 ApJ, 761, L20

AU Mic: Young Solar System Analog

- Two debris emission components
- Central peak: Stellar photosphere + asteroid-like belt at a few AU?
- Outer dust belt extends to 40 AU, to break in scattered light profile
  - truncated, reminiscent of classical Kuiper Belt
  - no detectable asymmetries in structure or position: compatible with Uranus-like planet

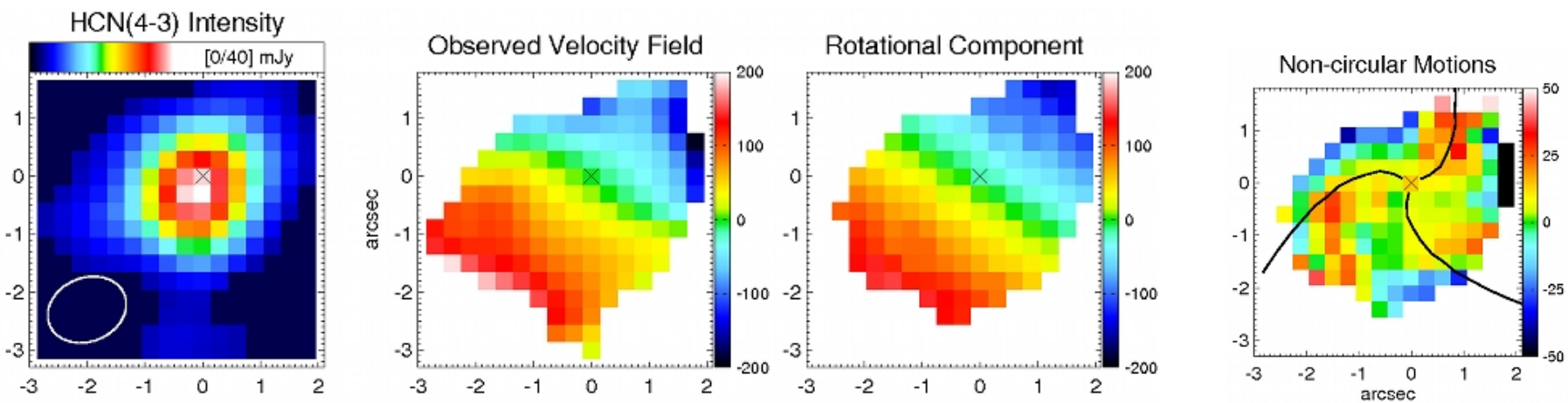




MacGregor (CfA)+, 2013 ApJL, 762, L21

Nearby Galaxies: NGC 1097

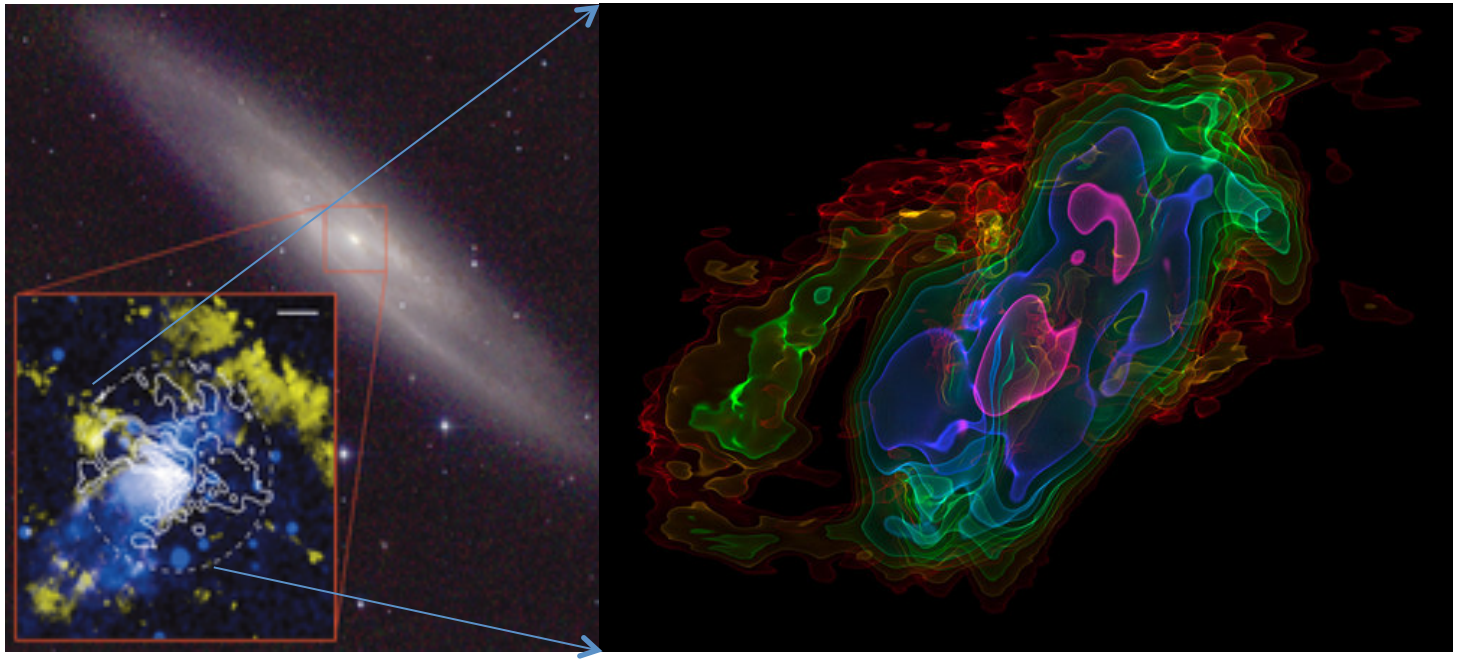
- Discovered a hint of streaming gas toward the central black hole in NGC1097
- Central chemistry: HNCO in well shielded disk gas, HC_3N traces X-ray exposed gas, SiO may trace innermost dense gas (also NGC 1068 Takano+ 2014)



Fathi+ (2013), Martin+ (2014)

Nearby Galaxies: NGC 253

- Suppression of star formation in NGC 253
  - Starburst-driven molecular wind
  - Molecular outflow rate is greater than 3 – 9 M_{sun}/yr
  - Starburst-driven wind limits the star-formation activity
- Bolatto+ 2013



TBD

- TBD
- et al

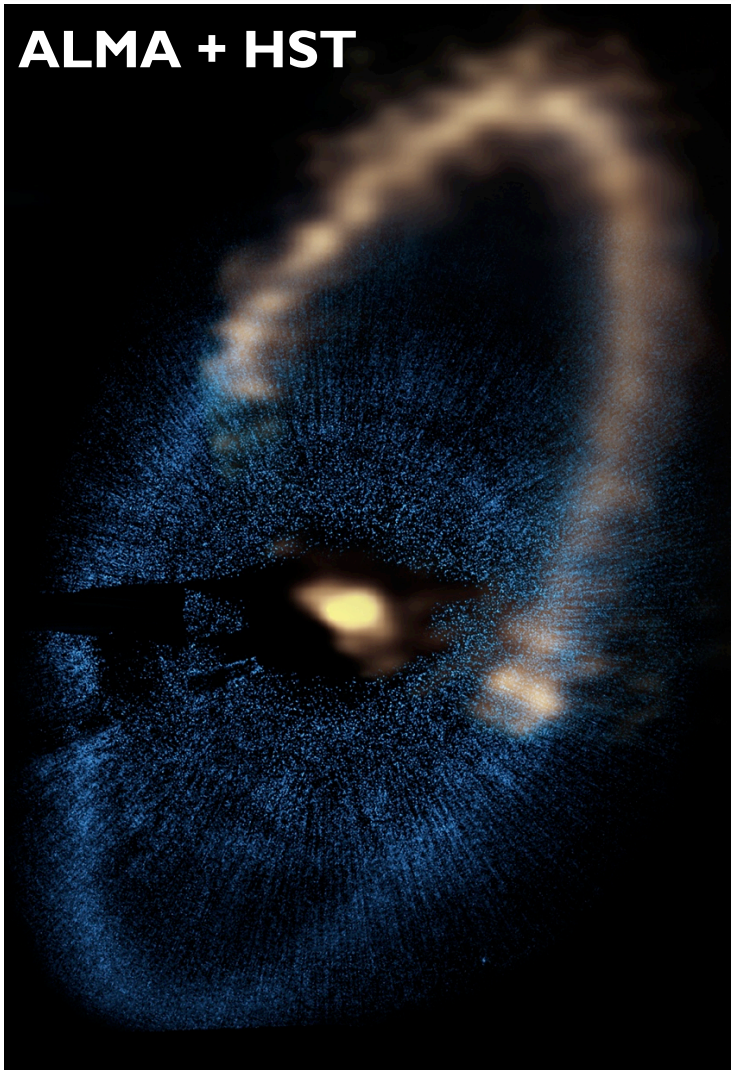
TBD

- TBD
- et al

TBD

- TBD
- et al

Science



- Remarkably thin, sharp-edged Fomalhaut debris disk: 13-19 AU wide
- Two shepherding planets likely corral the disk on either side
  - Each exoplanet < 3 Earth masses
- Data acquired with only 15 ALMA antennas

A. Boley (Florida)+, 2012 ApJ, 750, L21

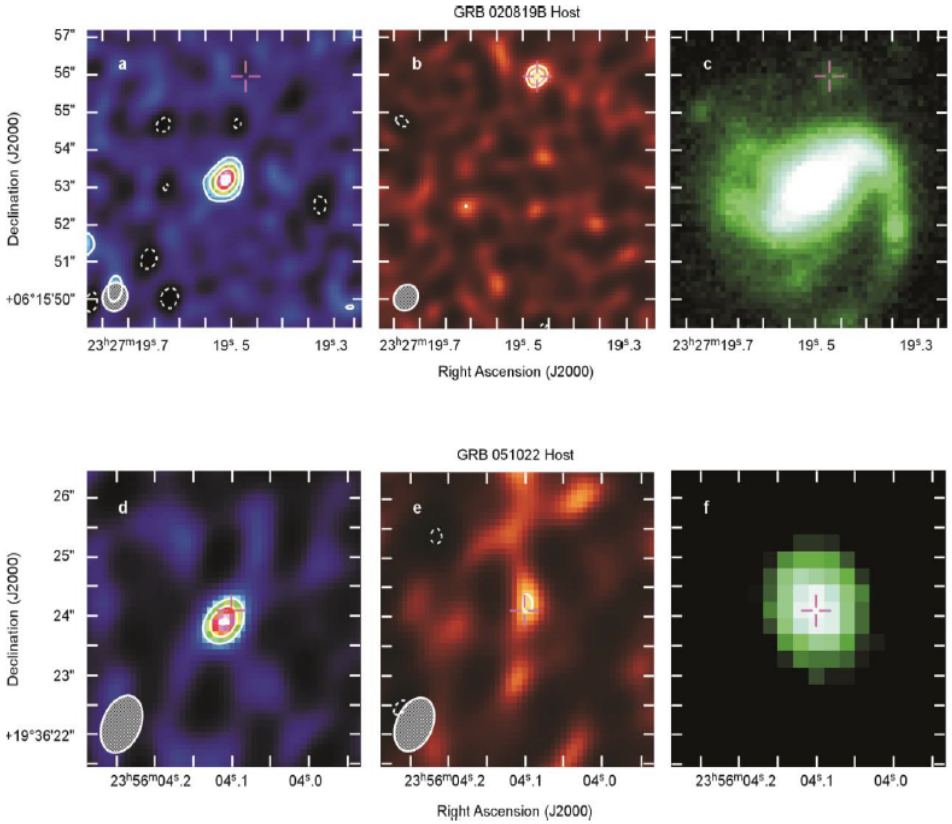
Outflow near Galactic Nuclei

- NGC 1413
  - ✓ 0.5” resolution ~ 24 pc
  - ✓ Structures near center reveal a spiral shape & unexpected outflow
  - ✓ entrained by radio flow?
- NGC 3256
  - ✓ molecular gas may reach ~1800 km/s
  - ✓ average $M_{outflow}$ ~ 20 M_{sun}/yr
- NGC 1266
  - ✓ CO shows outflow 500 km/s
  - ✓ Losing gas >110 M_{sun}/yr
- Need better mass estimators for flows

NGC 1413: Combes et al., 2013 A&A 558, L124

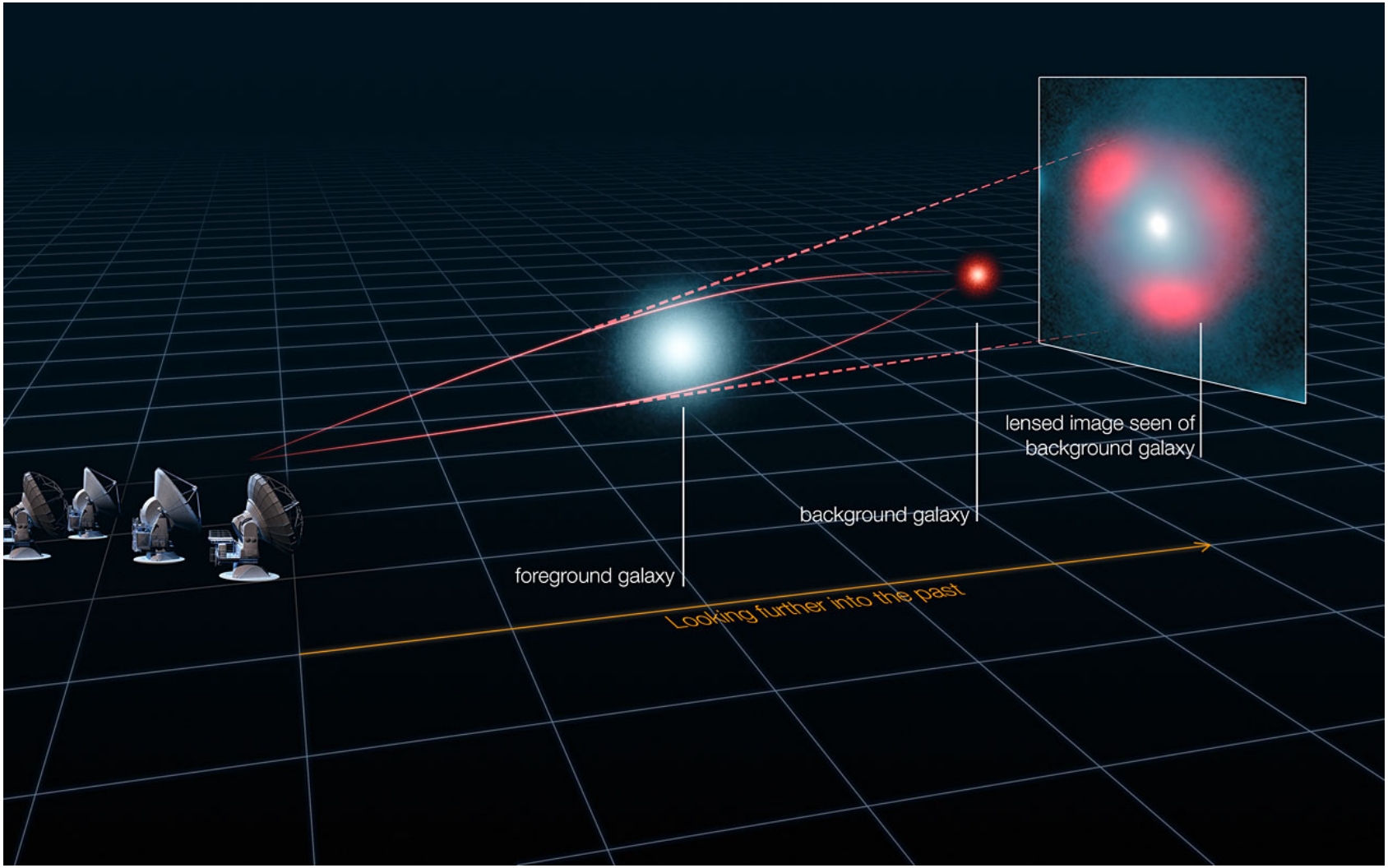
CO in γ-Ray Host Galaxies

- In regions rich in dust, but not molecular gas, at z = 0.4 & 0.8
- Molecular gas to dust ratio is much than in star-forming regions in Milky Way or nearby star-forming galaxies
- Suggesting that dense gas has been dissipated by newly formed massive stars

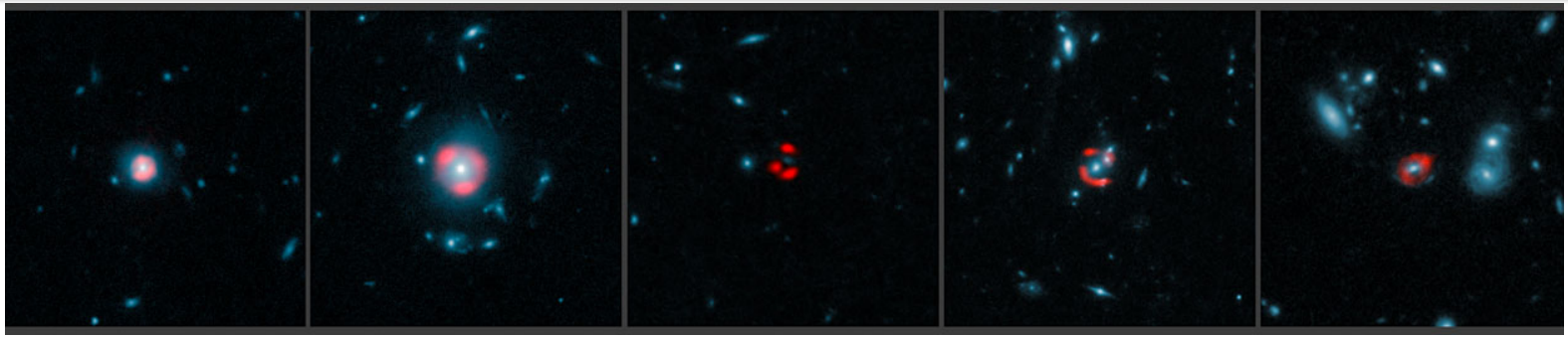


Hatsukade+, 2014, Nature 510, 247

Lensing Reveals Starburst Galaxies



Lensing Reveals Starburst Galaxies



- Redshift survey targeted CO line emission from star-forming molecular gas toward bright mm sources
- ALMA imaging demonstrated that sources strongly gravitationally lensed by foreground galaxies
- Greater dusty starburst galaxy fraction at high z than expected
- Models → background objects are ULIRGs powered by extreme bursts of star formation.

Vieira (Caltech) et al., 2013 Nature, 495, 344