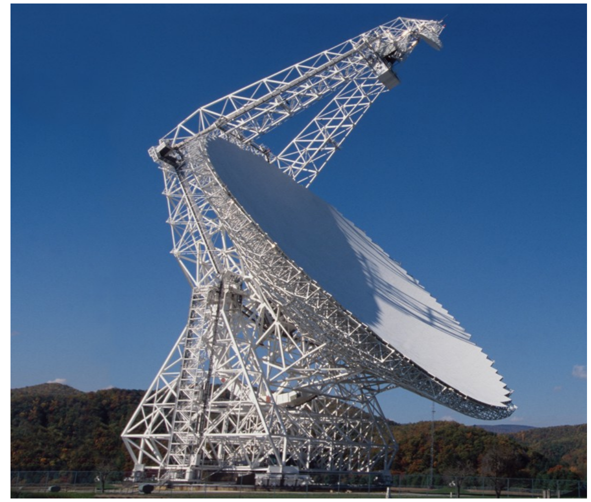
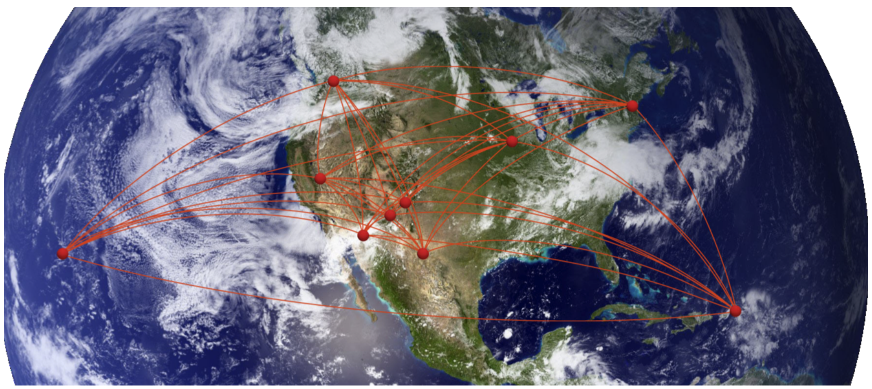
National Radio Astronomy Observatory





Phil Jewell
and the NRAO staff

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO:
One Observatory, Four Facilities

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One Observatory, Four Facilities

Atacama Large Millimeter/submillimeter Array:
a 66-antenna array in Chile

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Jansky Very Large Array:
a 27-antenna array in New Mexico

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Robert C. Byrd Green Bank Telescope: world's largest fully steerable radio telescope, in West Virginia

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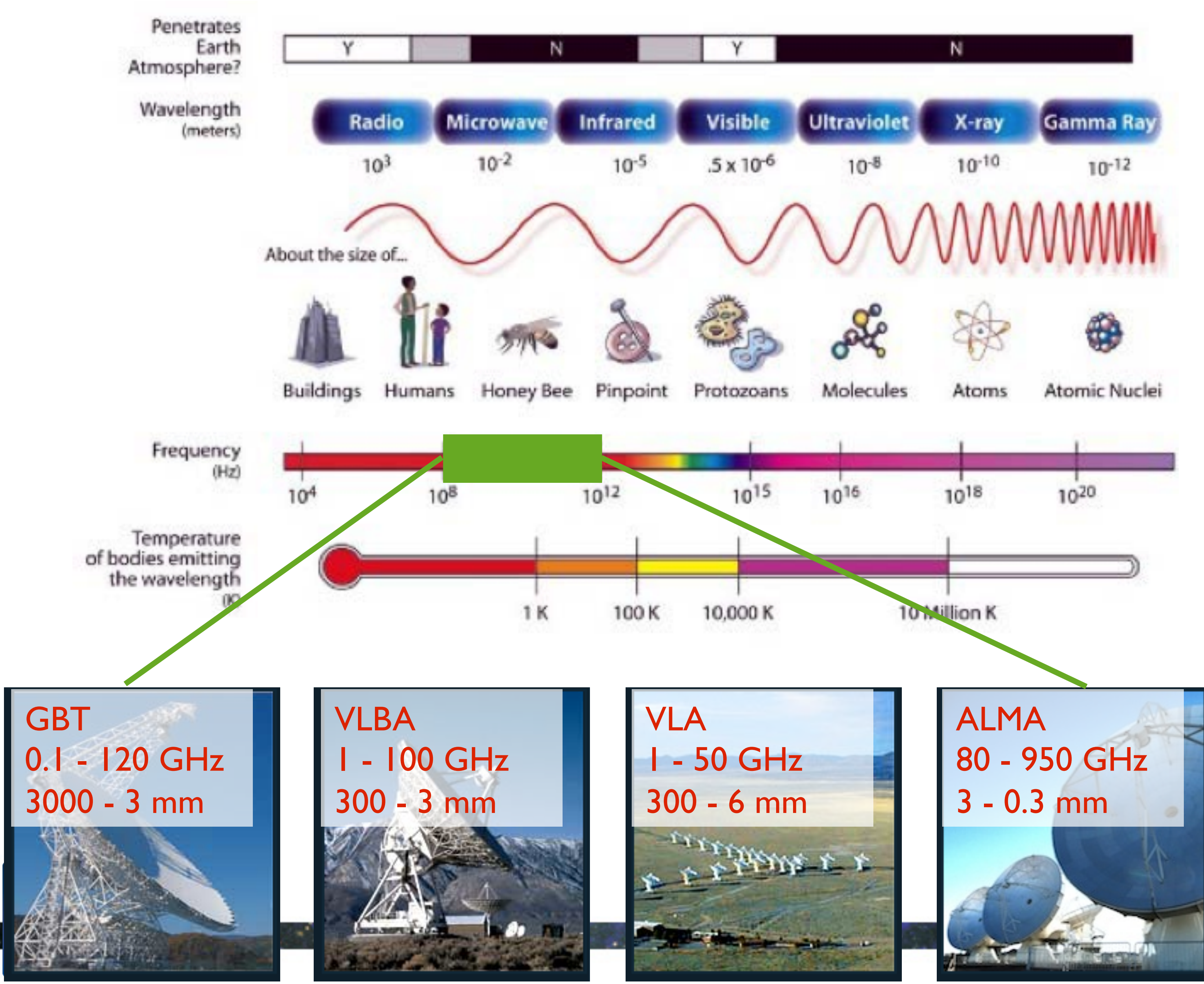
One Observatory, Four Facilities

Very Large Baseline Array:
ten radio antennas spanning 8000 km


Penetrates Earth Atmosphere?
Y
N
Y
N
Wavelength (meters)
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^3
10^{-2}
10^{-5}
$.5 \times 10^{-6}$
10^{-8}
10^{-10}
10^{-12}
About the size of...
Buildings
Humans
Honey Bee
Pinpoint
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
Temperature of bodies emitting the wavelength (K)
1 K
100 K
10,000 K
10 Million K
GBT
0.1 - 120 GHz
3000 - 3 mm
VLBA
1 - 100 GHz
300 - 3 mm
VLA
1 - 50 GHz
300 - 6 mm
ALMA
80 - 950 GHz
3 - 0.3 mm

Broad Science Topics with NRAO Telescopes

- Sun – coronal mass ejections, magnetic field activity
- Solar system, KBOs – atmospheres, astrometry, composition
- Star-forming regions – dust and gas environment, kinematics (infall, outflows, jets), proto-planetary disks, cores, chemistry, feedback, and natal cloud / star interactions
- Exoplanets – direct imaging, gaps in disks, kinematics
- Pulsars – neutron star physics, pulse morphology, gravity, ISM probe
- Galactic structure – spiral arms, bars, global atomic and molecular gas properties
- Nearby galaxies – molecular / atomic gas content and kinematics, dynamics of galaxies at high resolution, star formation, obscured SF, gas flow, astrochemistry
- Galaxy groups and clusters – atomic and molecular gas across systems, star formation efficiency, kinematics, dynamical mass measurements
- Black holes – mass measurements, kinematics
- High redshift galaxies – extragalactic background light, source counts, star formation history and efficiency, evolution of gas content (atomic and molecular)
- Cosmology – H_0 measurement, SZE

ALMA Overview

- A global partnership to deliver a revolutionary millimeter/submillimeter telescope array
  - North America (US, Canada, Taiwan)
  - Europe (ESO)
  - East Asia (Japan, Taiwan)
  - In collaboration with Chile
- 5000 m (16,500 ft) site in Chilean Atacama desert
- 66 telescopes in full operation
  - Main Array: 50 x 12m antennas
  - Total Power Array: 4 x 12m antennas
  - Atacama Compact Array (ACA): 12 x 7m antennas

Science Goals

ALMA design driven by three Key Science Goals:

- Detect spectral line emission from CO or [CII] in a normal galaxy like the Milky Way at $z = 3$ in less than 24 hours
- Image the gas kinematics in proto-stars and proto-planetary disks around young Sun-like stars in the nearest molecular clouds (150 pc)
- Provide precise high dynamic range images at an angular resolution of 0.1 arcsec

ALMA in a Nutshell…

- Angular resolution down to 0.015” (at 300 GHz)
- Sensitive, precision imaging 84 to 950 GHz (3 mm to 315 μm)
- State-of-the-art low-noise, wide-band receivers (8 GHz bandwidth)
- Flexible correlator with high spectral resolution at wide bandwidth
- Full polarization capabilities
- Estimated 1 TB/day data rate
- All science data archived
- Pipeline processing

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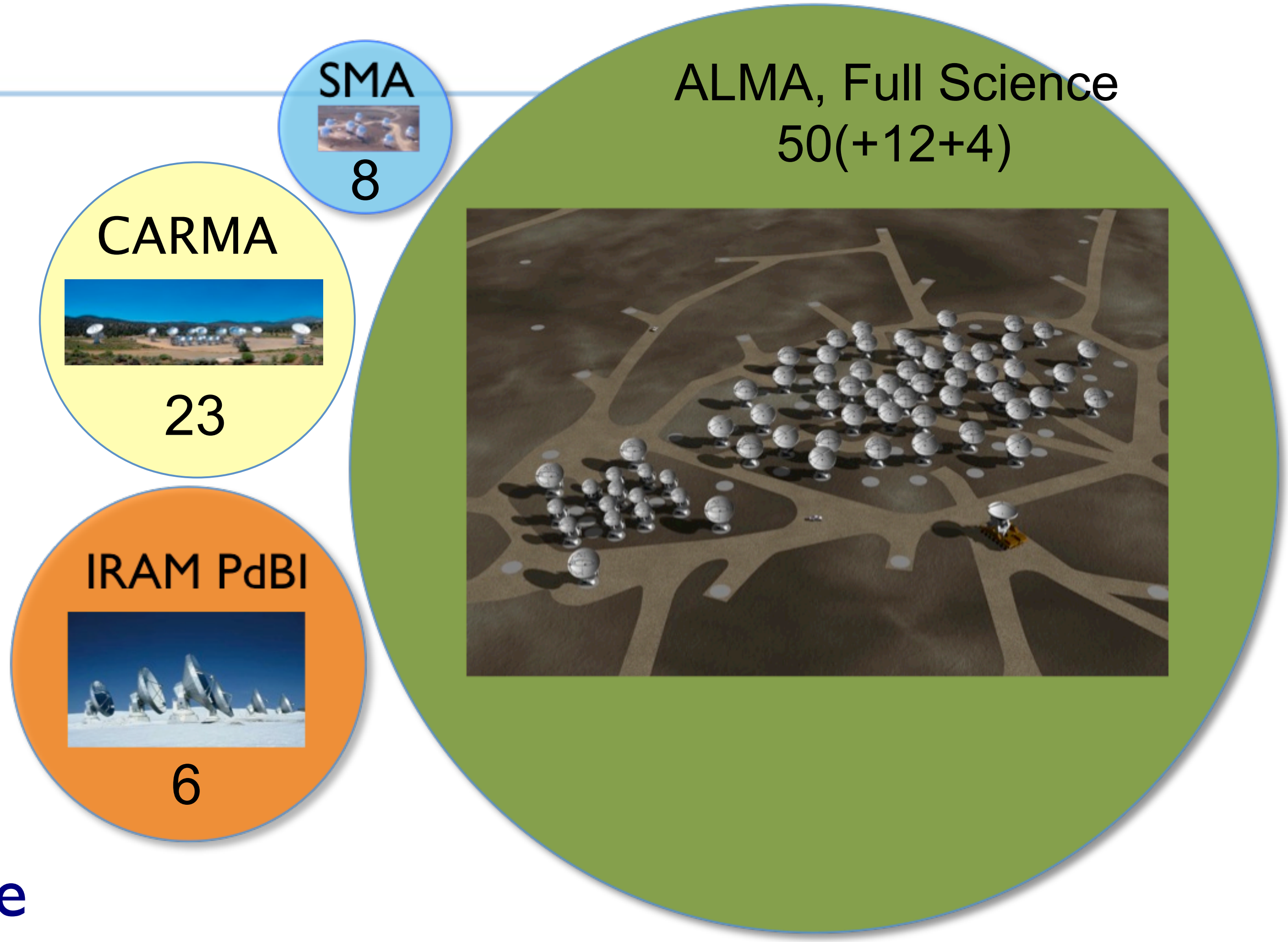
- Pipeline processing

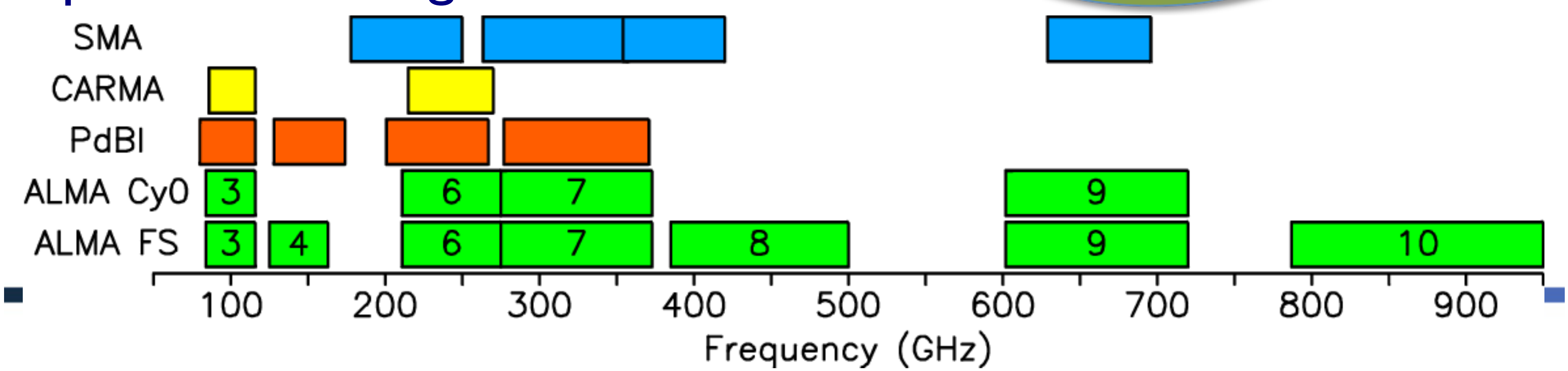
ALMA will be 10-100 times more sensitive and have 10-100 times better angular resolution than current mm interferometers

ALMA is a telescope for *all* astronomers

Collecting Area
~ sensitivity

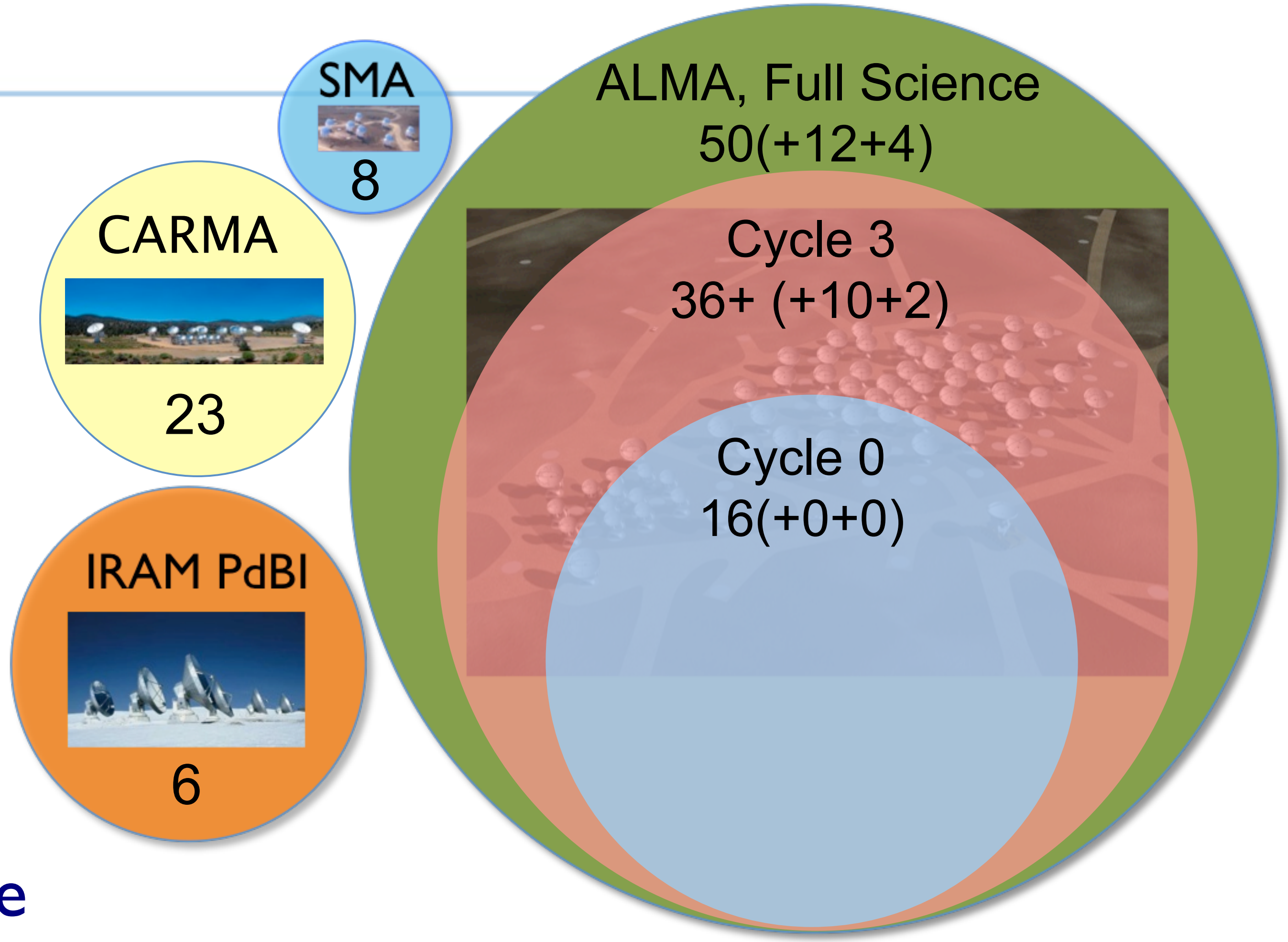


Spectral Coverage

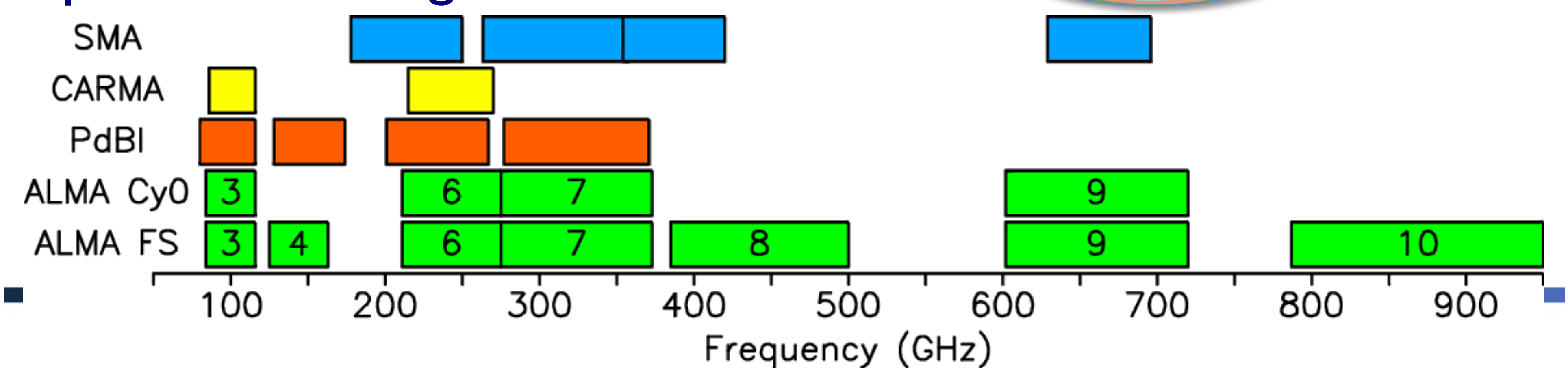


Collecting Area

~ sensitivity

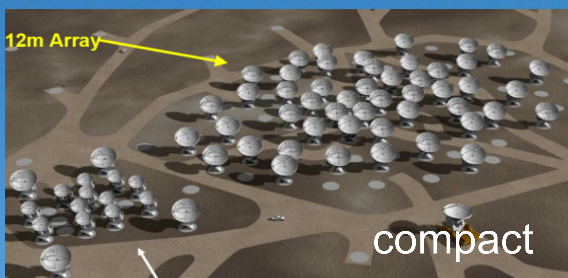


Spectral Coverage



ALMA

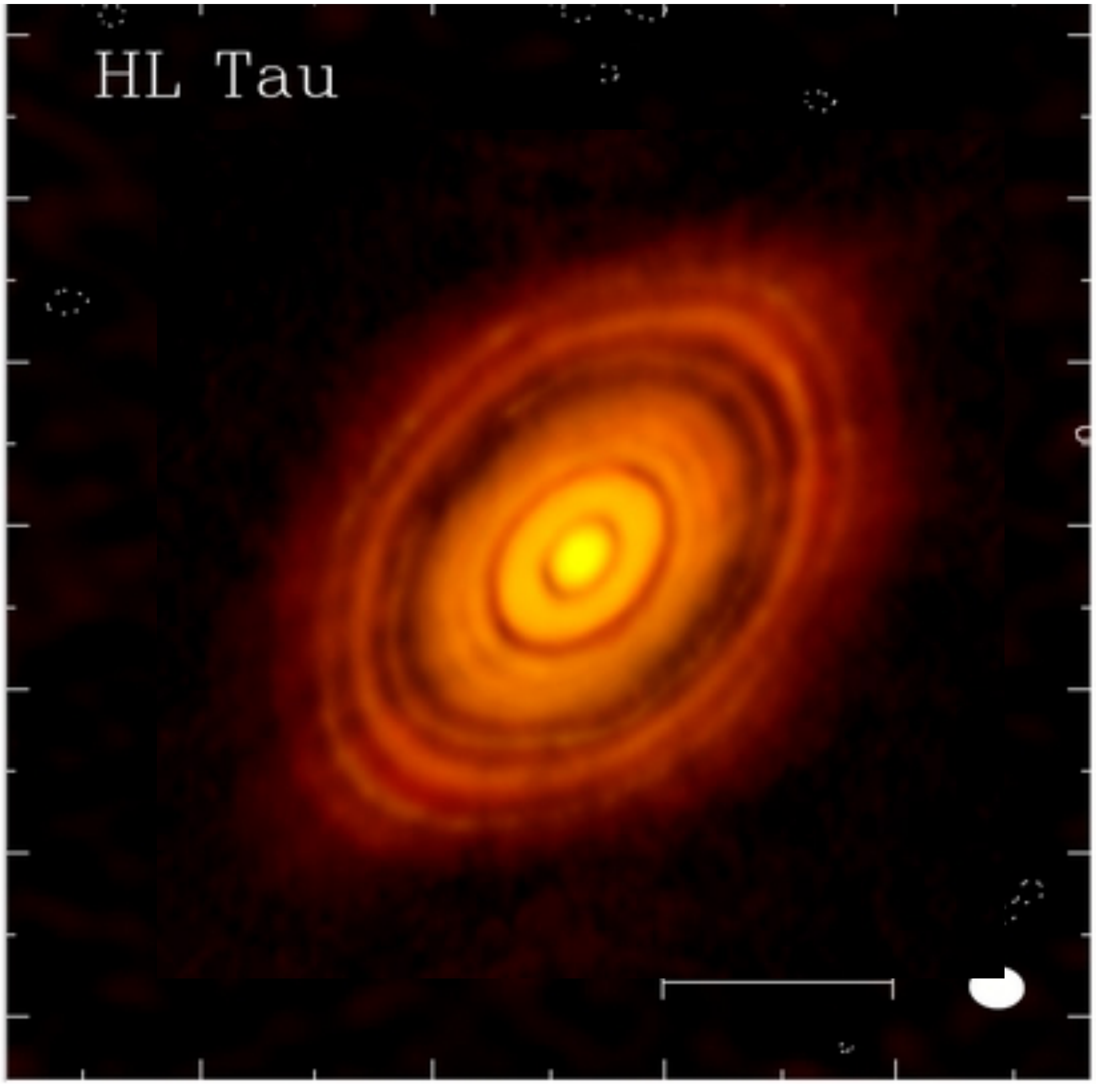
An array of **66 antennas,**
using *aperture synthesis*, *as a* "zoom telescope"
over the *entire accessible mm/submm* wavelength range
up to 1 THz

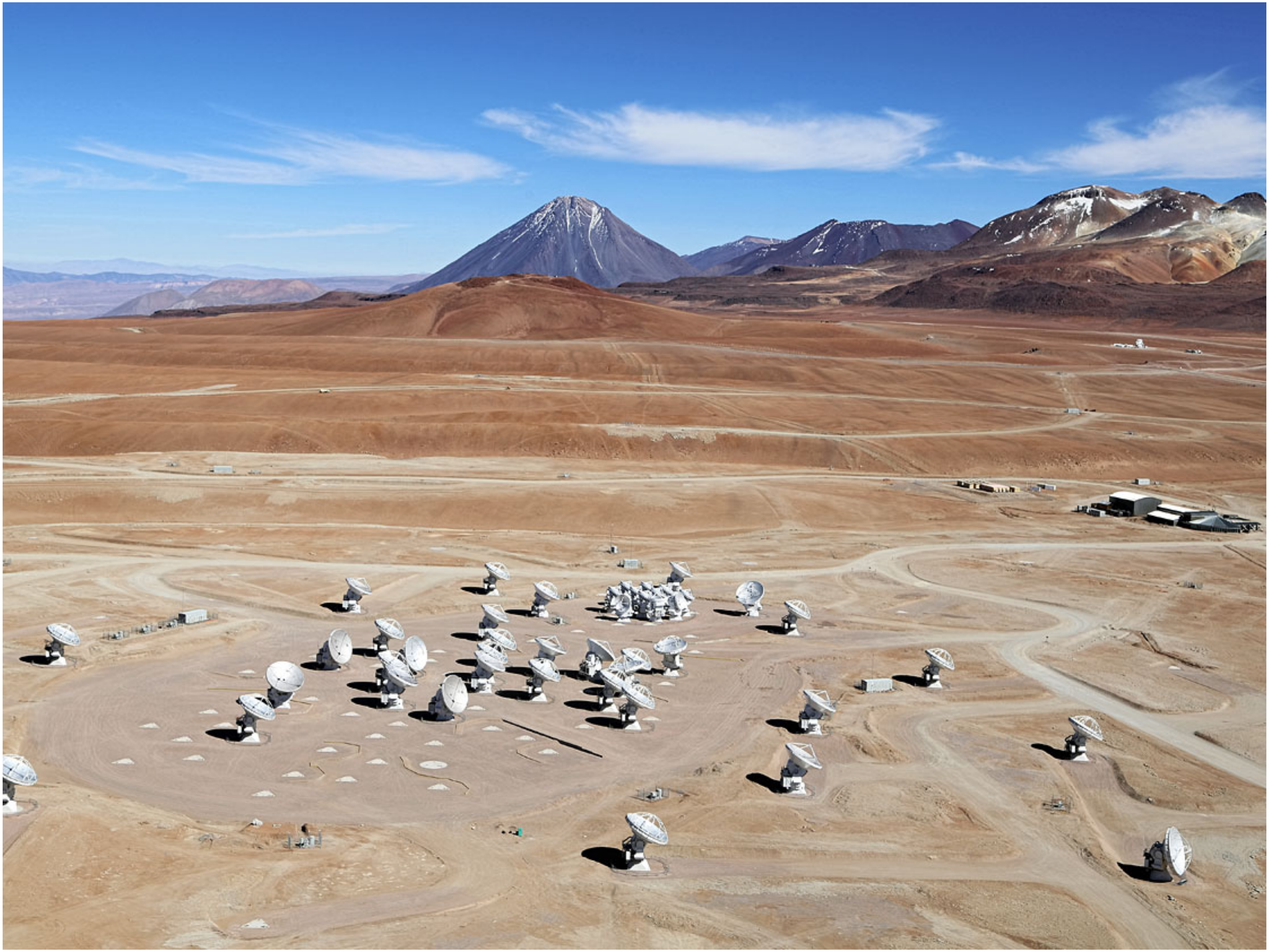


Built to operate
>30 years

Remotely operated from
OSF Control room

ALMA Long Baseline Campaign





ALMA Current Status

- Construction Project ended in September 2014
- Routine science observing has been limited to 1.5 km baselines (C34-7), but observations out to 15 km have been proven successful (thanks to the Long Baseline Campaign, ended December 2, 2014)
- **All 66 antennas accepted**
  - Currently 64 antennas are at the high site (AOS), of which ~47 on average (up to max ~54) are being used for Cycle 2 observations
  - Some construction and verification items remain to be finished (e.g., Bands 4, 8, 10; various observing modes)
- The ACA (Atacama Compact Array) or Morita-san Array – up to 12x7m antennas and 4x12m antennas for TP observations – has been accepted and is being used for Cycle 2 observations

ALMA Receivers: Current Status

- Receiver bands currently installed on all antennas
  - Band 3, 3mm (84-116 GHz)
  - Band 6, 1mm (211-275 GHz)
  - Band 7, 850 μm (275-370 GHz)
  - Band 9, 450 μm (602-720 GHz)
- Receiver bands partially installed and currently undergoing verification
  - Band 4, 2mm (125-163 GHz) 56/66 antennas
  - Band 8, 650 μm (385-500 GHz) 53/66 antennas
  - Band 10, 350 μm (787-950 GHz) 43/66 antennas

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Cycle 2 Snapshot (following the LBC)

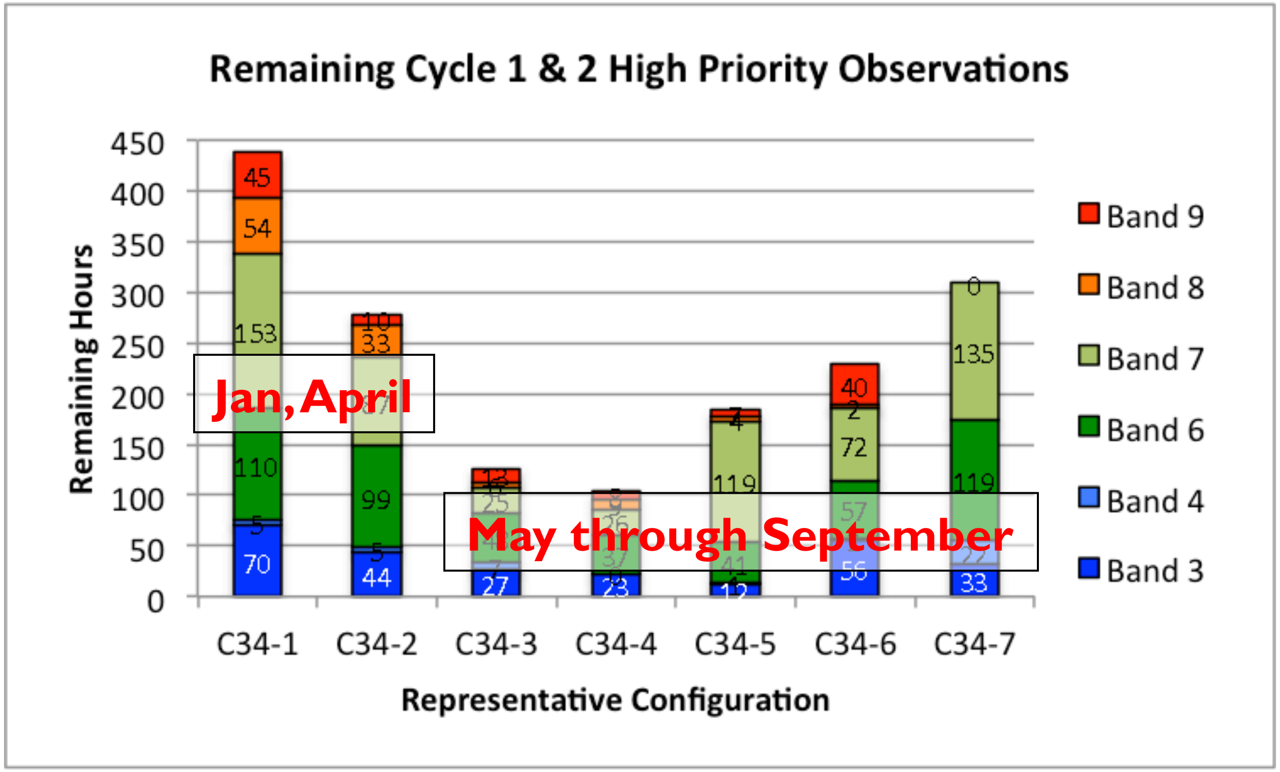
23 weeks of Cycle 2 science observations scheduled during 2015

Jan, Apr 2015 : Compact Configurations (C34-1, C34-2)

Feb – Mar 2015: Engineering/Computing (during the Altiplanic Winter)

May – Sep 2015: More extended configurations (C34-3 to C34-7)

Cycle 3 begins on October 1, 2015 – more details at end of talk



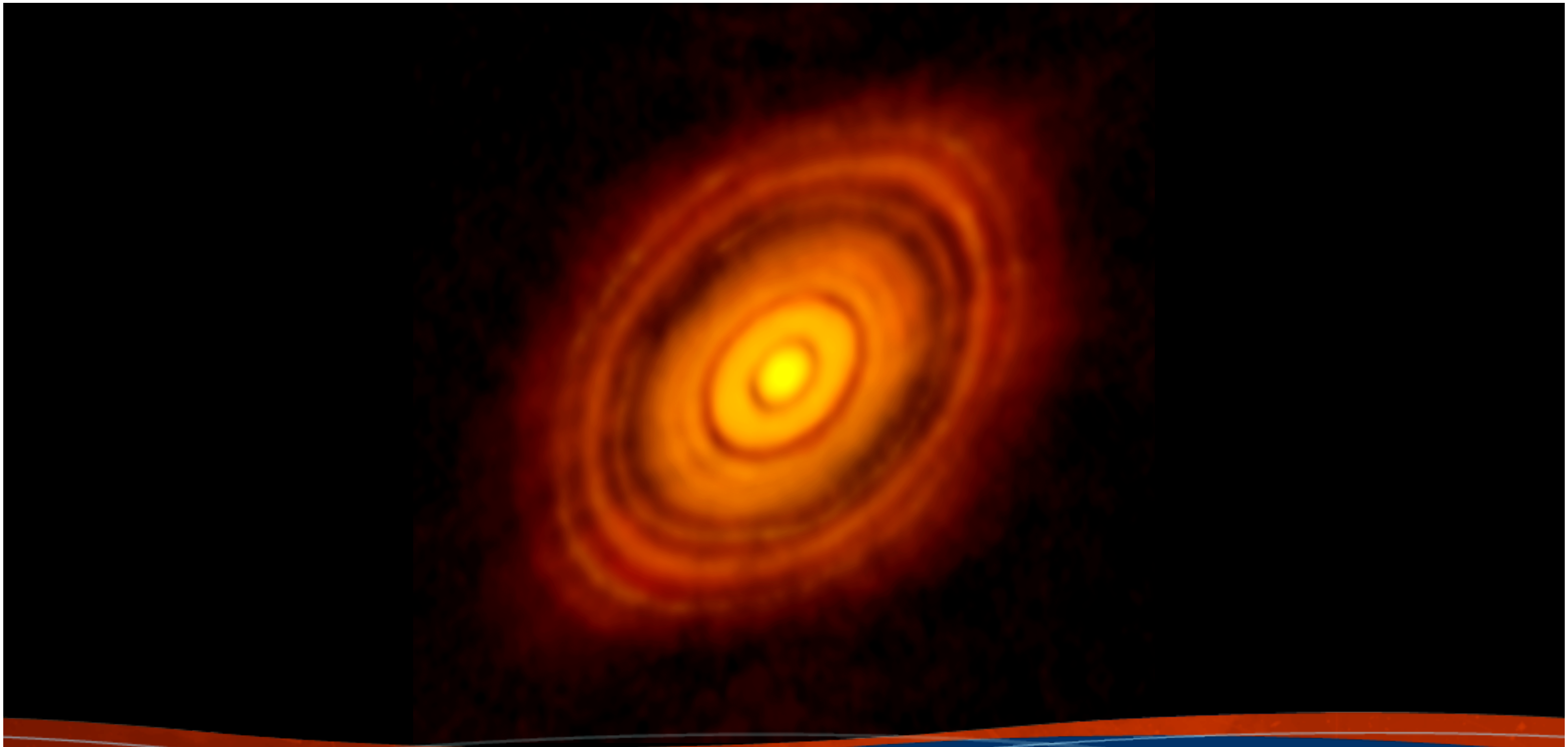
-- from November 2014 ALMA Status Update, ALMA Science Portal

ALMA Development Programs

- Optical Fiber project to connect OSF to Santiago
  - Completed as of the end of 2014
- ALMA Phasing Project (APP)
  - Full acceptance of all hardware in November 2014; commissioning observations to begin in 2015
- Production series for Band 5 (163-211 GHz)
  - Delivery of Band 5 receivers will begin in April 2015 (through 2017)
- Accepted and ongoing studies
  - Increased spectral coverage by designing, building and implementing a prototype receiver for ALMA Band 2 (67-90 GHz)
  - Prototype and production receiver for Band 1 (31-45 GHz)
  - Improved sensitivity and accuracy by decreasing gain variations in ALMA Band 3 receivers through modifications (magnets)
  - Increased flexibility through the addition of a 5^{th} sub-array
  - ALMA usability increased through implementation of new tools for data exploration and visualization.
  - Improved solar observing strategies

A robust development program, which has begun even as the baseline project is being completed, will result in an ALMA that will produce transformational science for many decades to come.

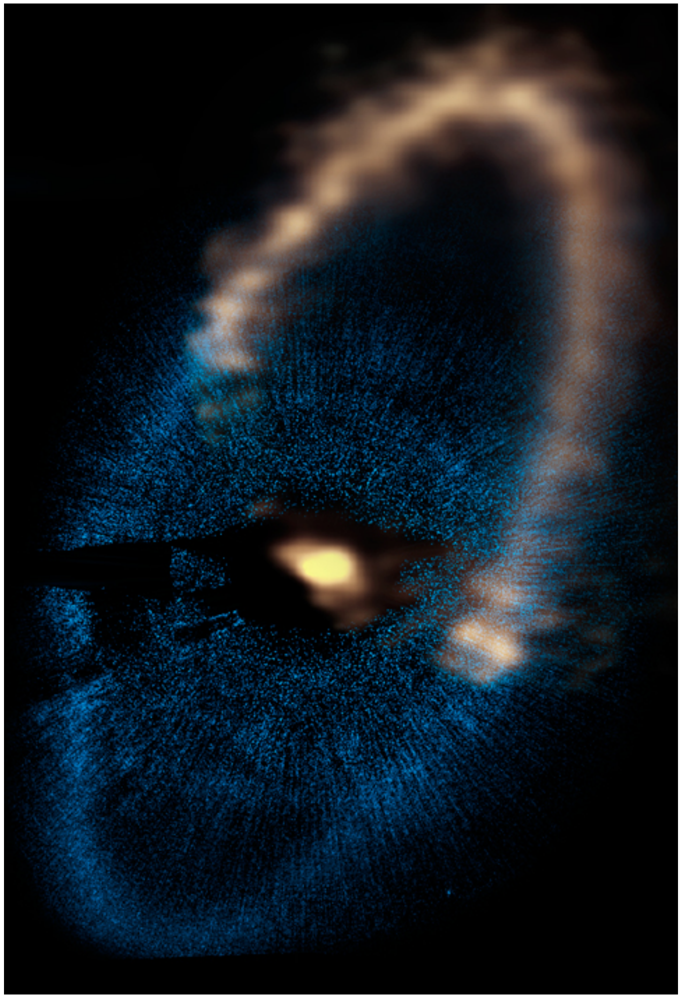
NRAO



ALMA Science Highlights

Formation of Planetary Systems

- 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

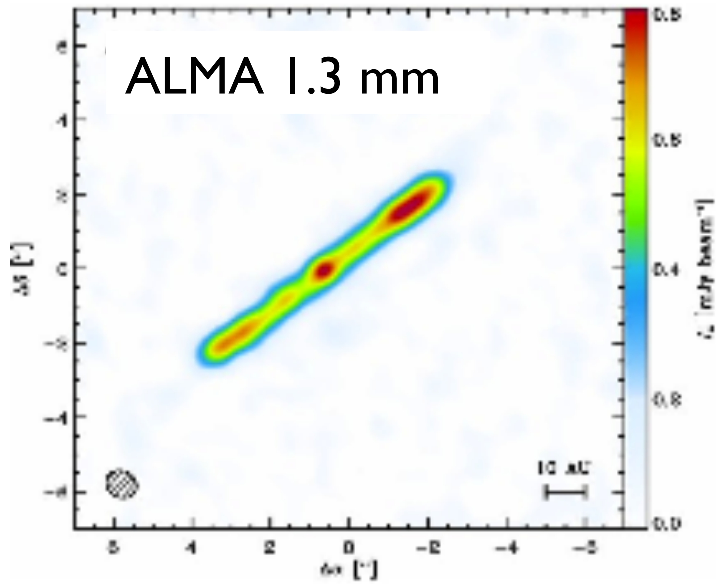


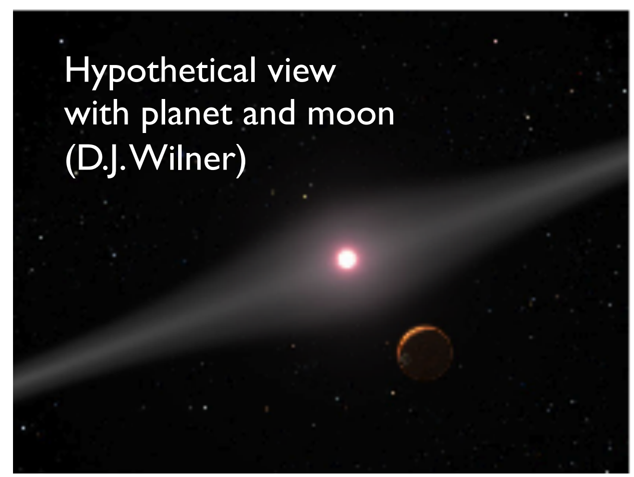
Boley et al. 2012

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

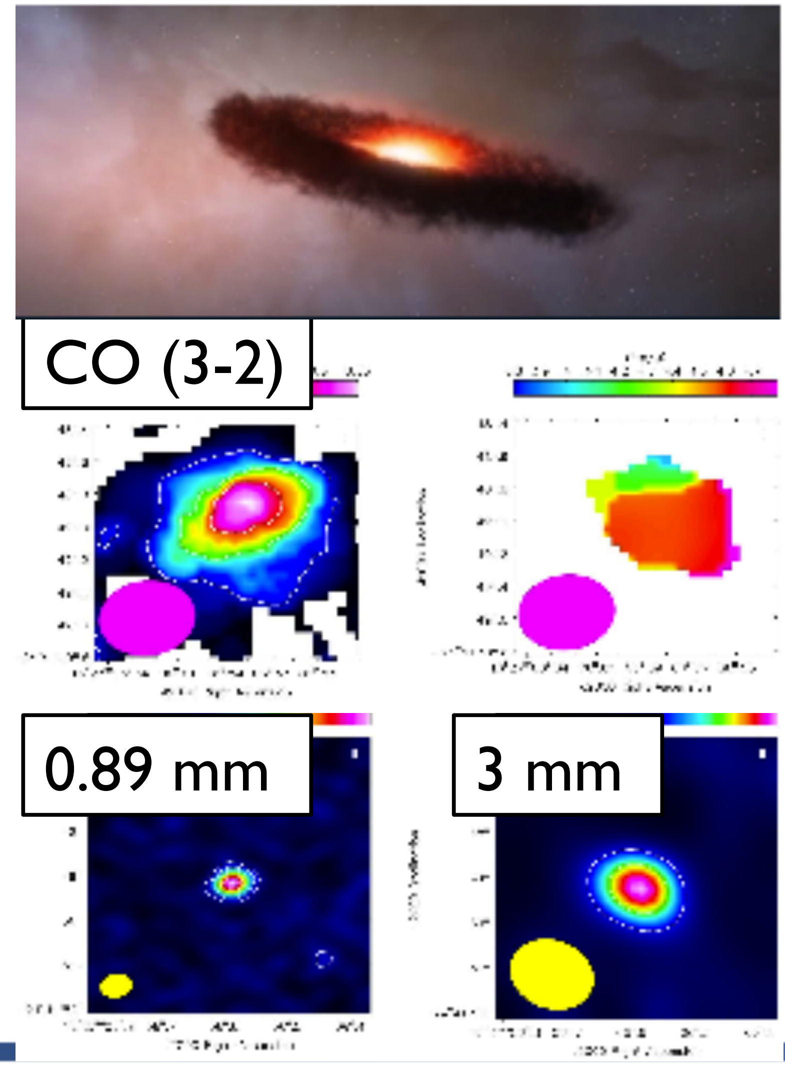
MacGregor et al. 2013





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

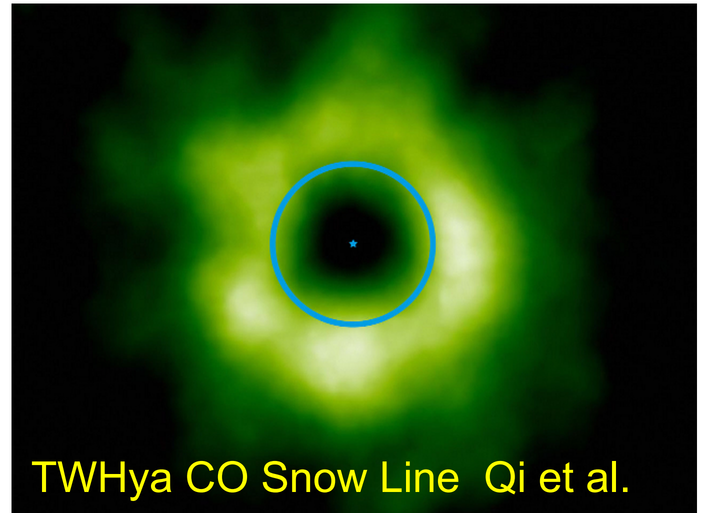
- Dusty disk < 40 AU around ρ Oph 102
- Surprisingly, dust grains are fairly large
- Molecular gas emission at brown dwarf location, indicating a gas-rich disk as typically found around young pre-MS stars
- Suggests brown dwarf stars may produce planets in a manner similar to normal stars

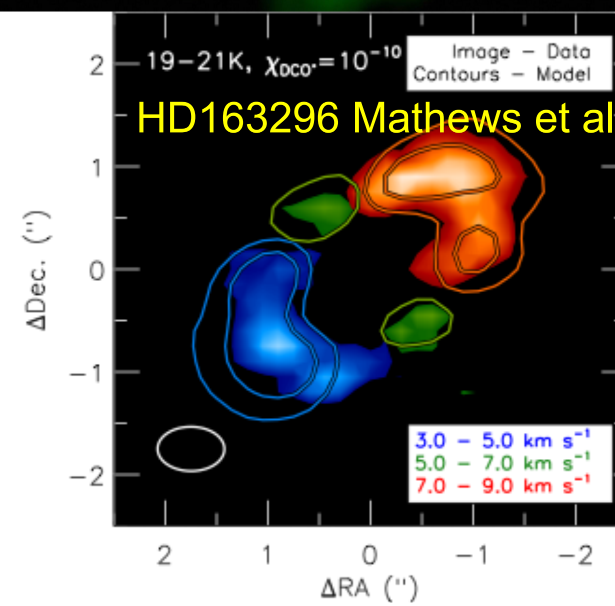


Ricci et al. 2012

ALMA Detection of 'Snow Lines' in Protoplanetary Disk Midplanes

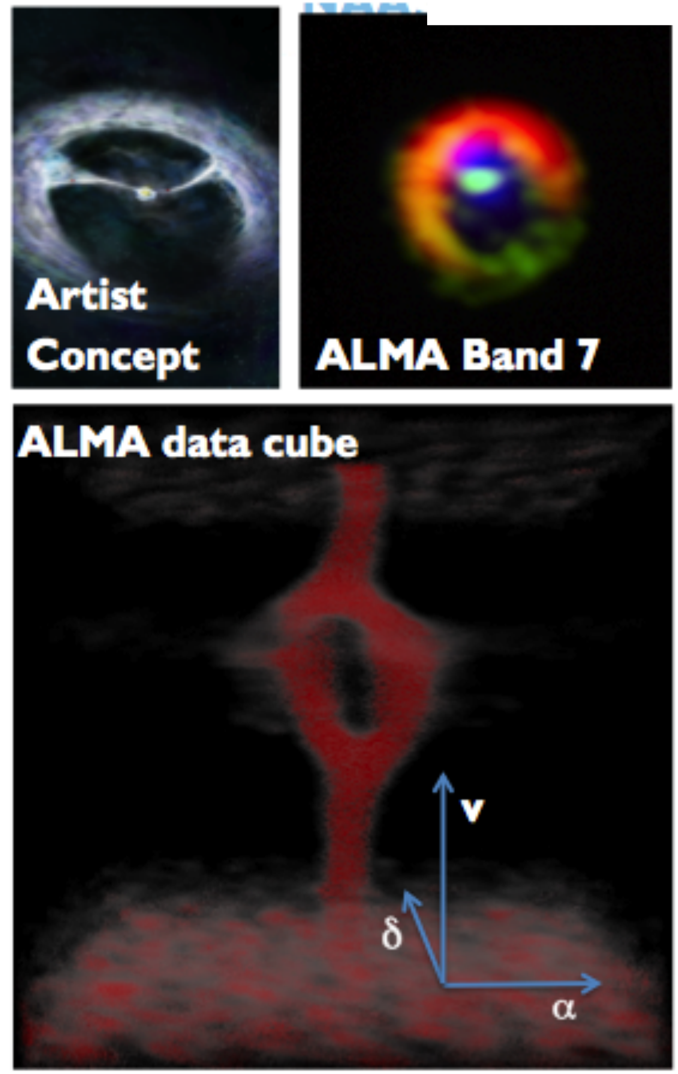
- Disk midplanes are
  - The sites of planet formation, the main reservoirs of mass and probable sources of complex organics
  - Cold—ices form; ices are sticky; good larger body seeds
  - Characterized by a range of low-energy lines of ions, deuterated molecules, isotopologues and organics
- Observational feature: 'Snow Line' which occurs where the temperature drops to where frost forms—in this case CO frost
- N_2H^+ is strong where CO is depleted by frosting out
- ALMA showed in the TW Hya disk a division between a region with no N_2H^+ closer than about 28 to 31 AU (Neptune's orbital radius, blue circle), and plentiful emission farther from the star (Qi et al 2013)
- ALMA showed in the HD163296 disk a similar ring of emission in DCO^+ again probably locating the CO snow line (Mathews et al 2013)





Gas Flows through a Protoplanetary Disk Gap

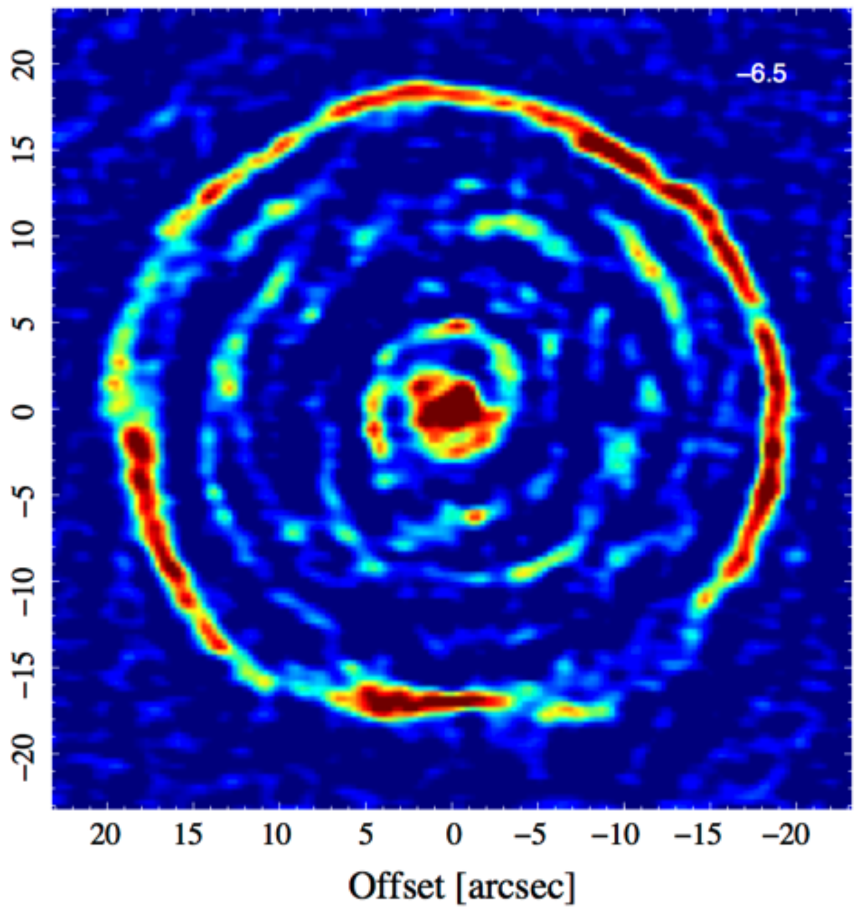
- HD142527: IR data shows 10 AU inner disk, 140 AU gap, disrupted outer disk attributed to unseen planetary mass at ~ 90 AU
- Sensitivity and spatial resolution enable images of dense gas in gap-crossing filaments and diffuse CO gas within gap – explains how high accretion maintained
- Dynamical models and data suggest outer disk gas channeled by putative protoplanets through gap-crossing bridges feeding the inner disk



Casassus et al. 2013

NRAO

Mass Loss in AGB Star R Sculptoris

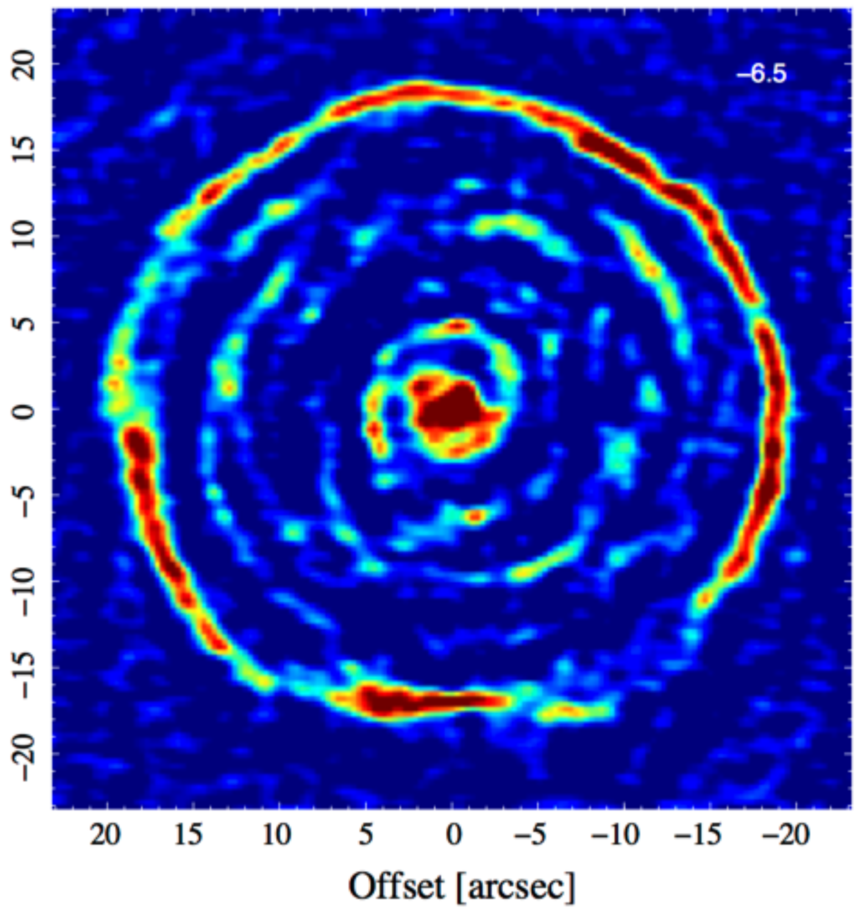


Maercker et al. 2012

Goals of study:

- Unique information on the structure and evolution of the gaseous-detached shell
- Changes in the physical stellar parameters during a He-shell flash
- Origin of highly episodic mass loss and the He-shell flash phenomenon
- Mass-loss mechanism of the AGB and structure of the circumstellar medium

Mass Loss in AGB Star R Sculptoris

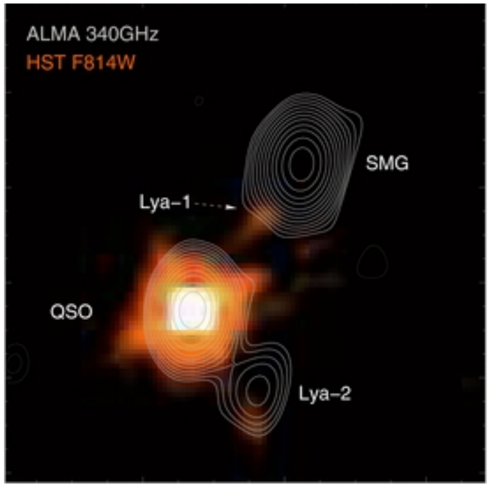


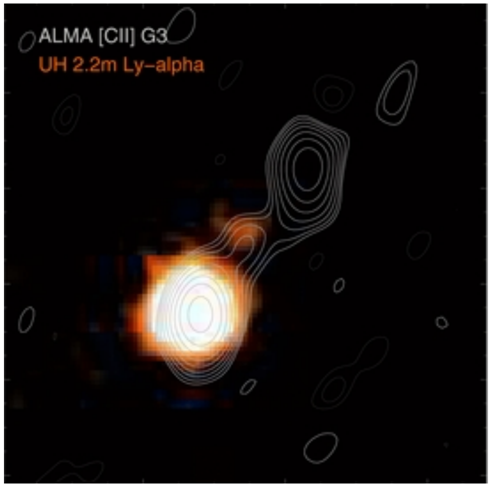
Maercker et al. 2012

- CO(3-2) map (16 ants, 1.4")
- **Unexpected spiral structure → previously undetected binary companion!**
- Shell created during a thermal pulse 1800 years ago

Anatomy of an Extreme Starburst

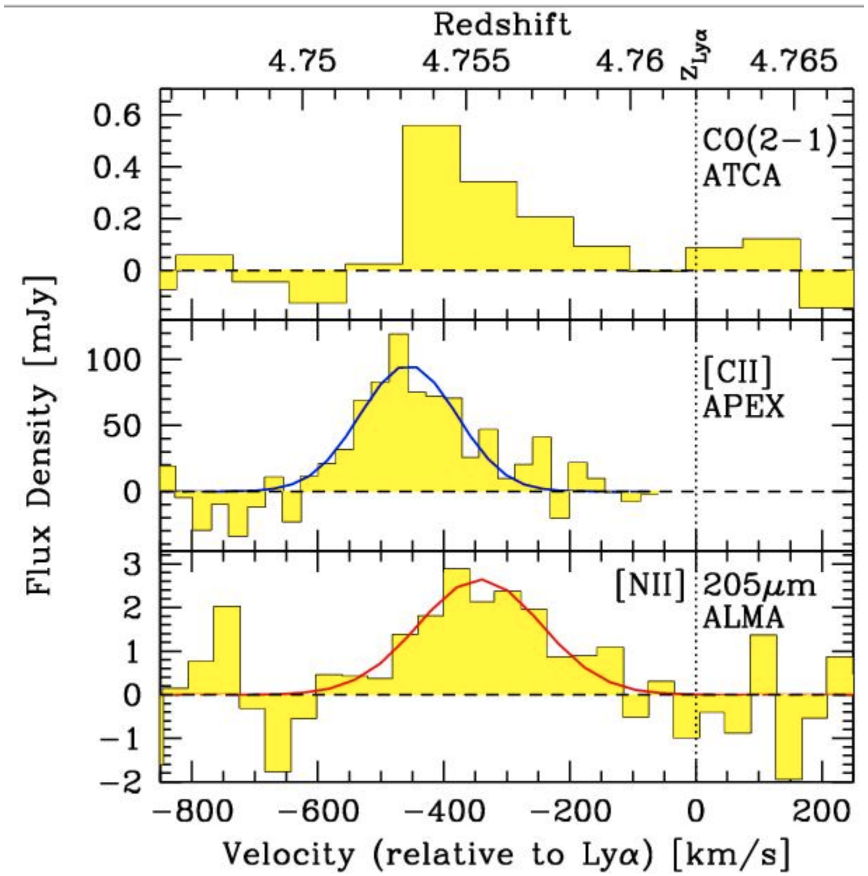
- ALMA science verification observation of compact group of galaxies BRI 1202-0725 (z = 4.7) acquired Jan 2012
  - Only 17 antennas and 25 min on-source
  - BRI 1202-0725: archetype extreme starburst/AGN group of galaxies in the early Universe
- 10x more sensitive than any previous submm observations of this system
- Rich laboratory for studying the myriad processes involved in clustered massive galaxy formation in early Universe





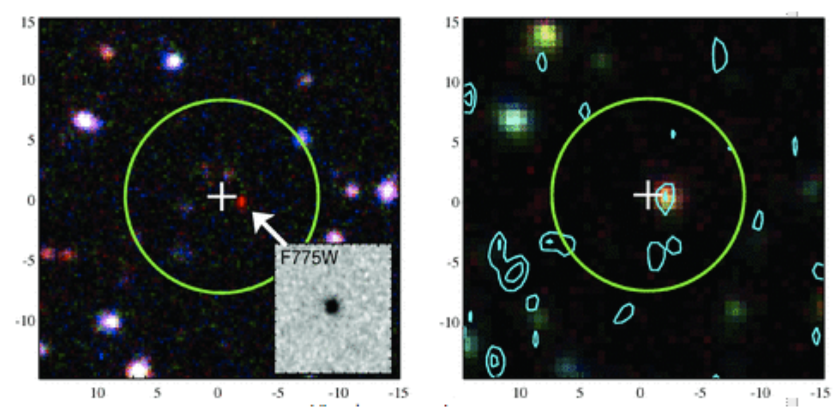
Carilli et al. 2013

Nitrogen in the Early Universe



Nagao et al. 2012

- ALMA observations of [N II] in J03329.4, a starburst submillimeter galaxy at z = 4.75
- [N II]/[C II]~0.043 in this galaxy, suggesting a solar nitrogen abundance, and consistent with values in local galaxies (e.g. 0.05 in M82)

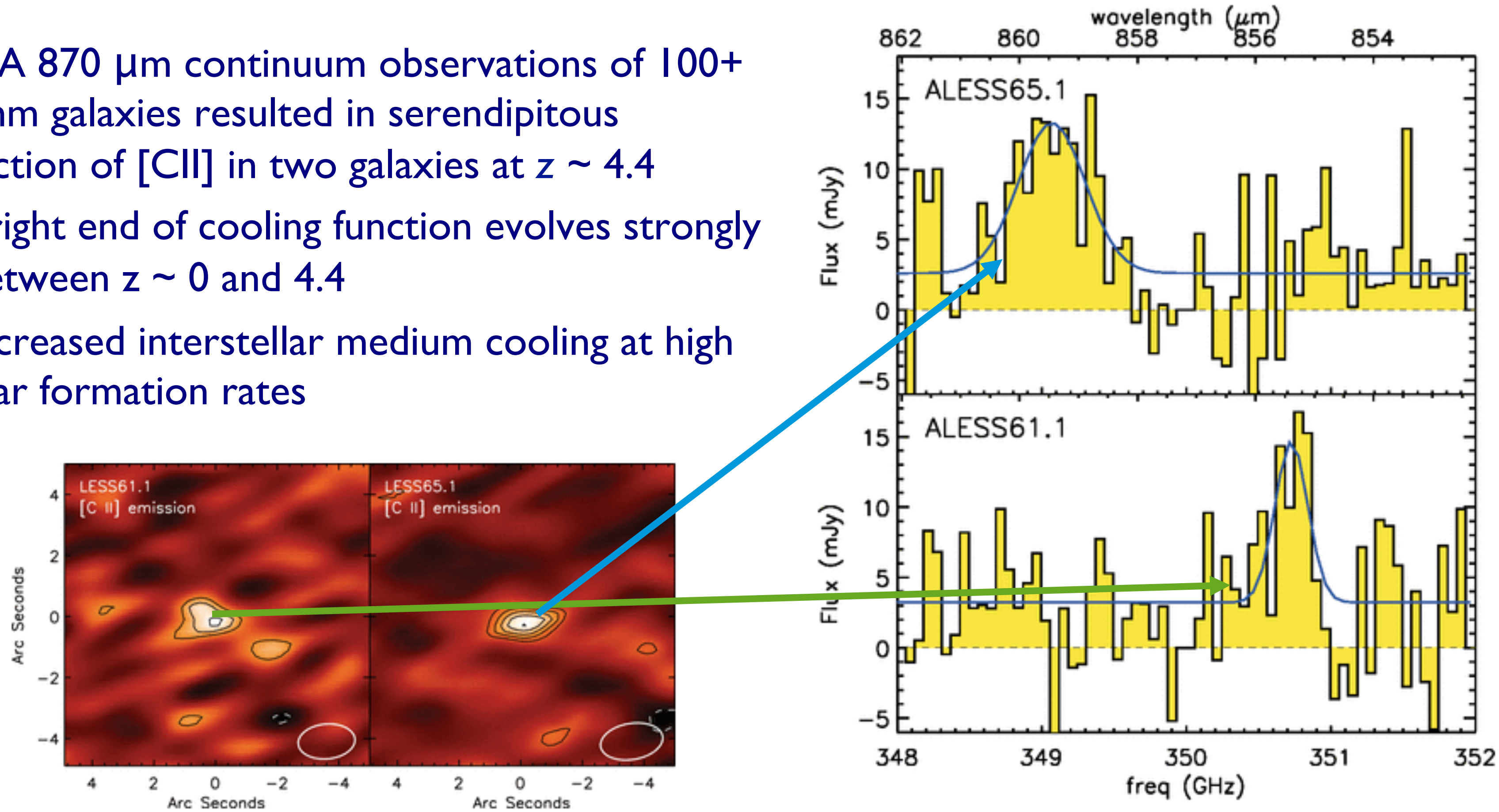


Coppin et al. 2009

Serendipitous [C II] Detection

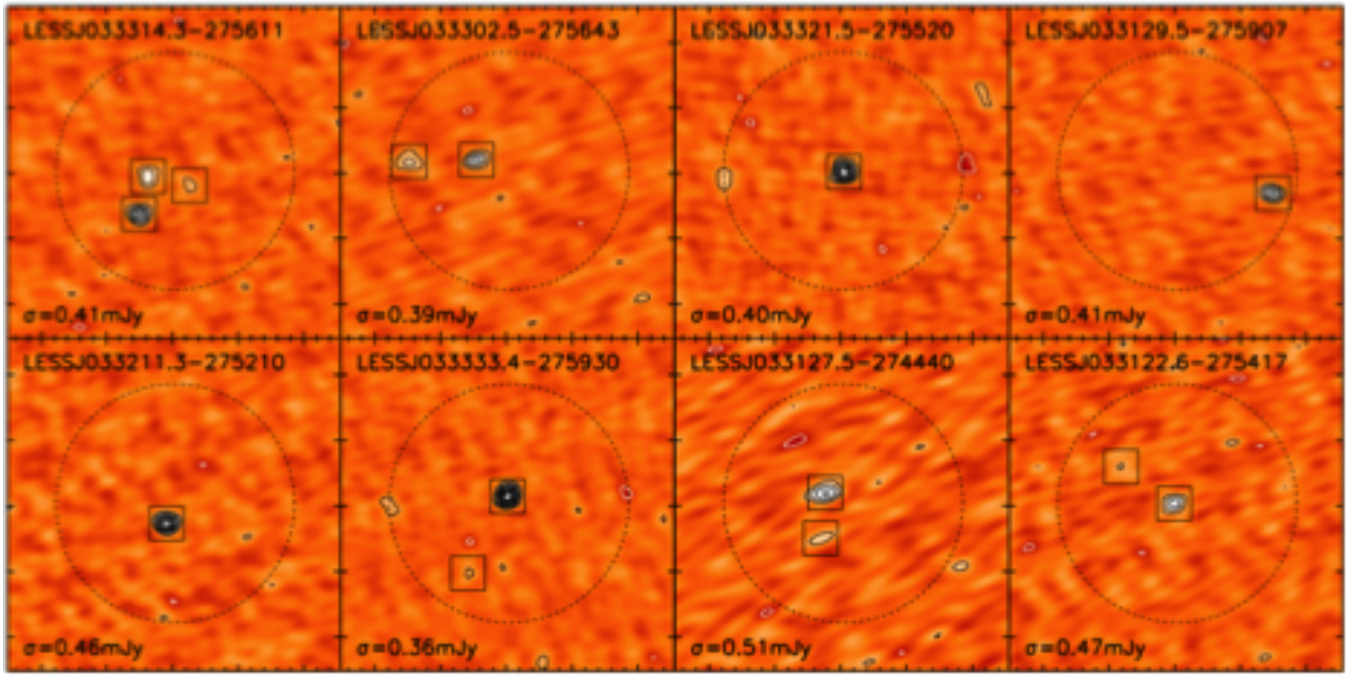
ALMA 870 μm continuum observations of 100+ submm galaxies resulted in serendipitous detection of [CII] in two galaxies at z ~ 4.4

- Bright end of cooling function evolves strongly between z ~ 0 and 4.4
- Increased interstellar medium cooling at high star formation rates



Swinbank et al. 2012

Resolving High-z Submm Galaxies

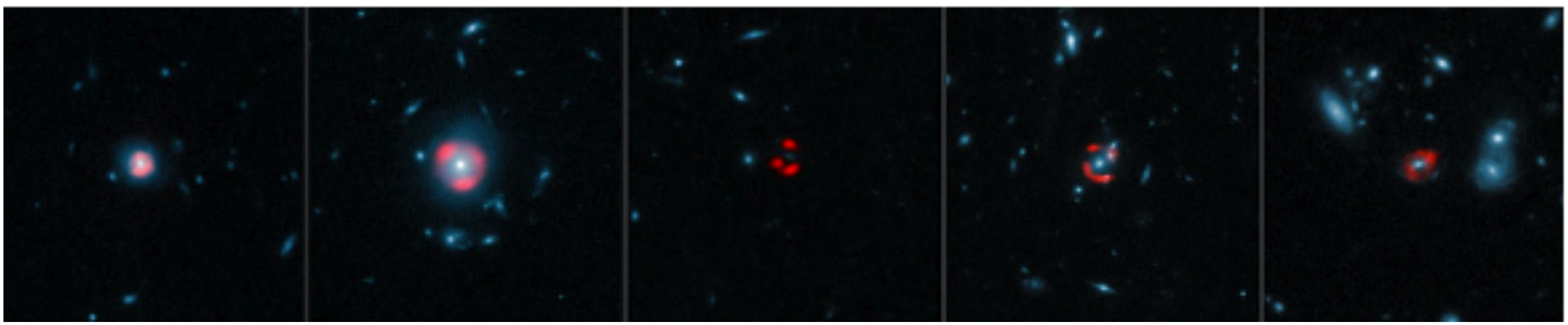


Hodge et al. 2013

- 126 submm sources observed with ALMA at 870 μ m
- 2x deeper, 10x higher angular resolution than previous surveys
- 99 sources detected in 88 fields, integration time ~120 sec
- Significant multiplicity (35-50%) found at 0.2” resolution

Lensing Reveals Starburst Galaxies

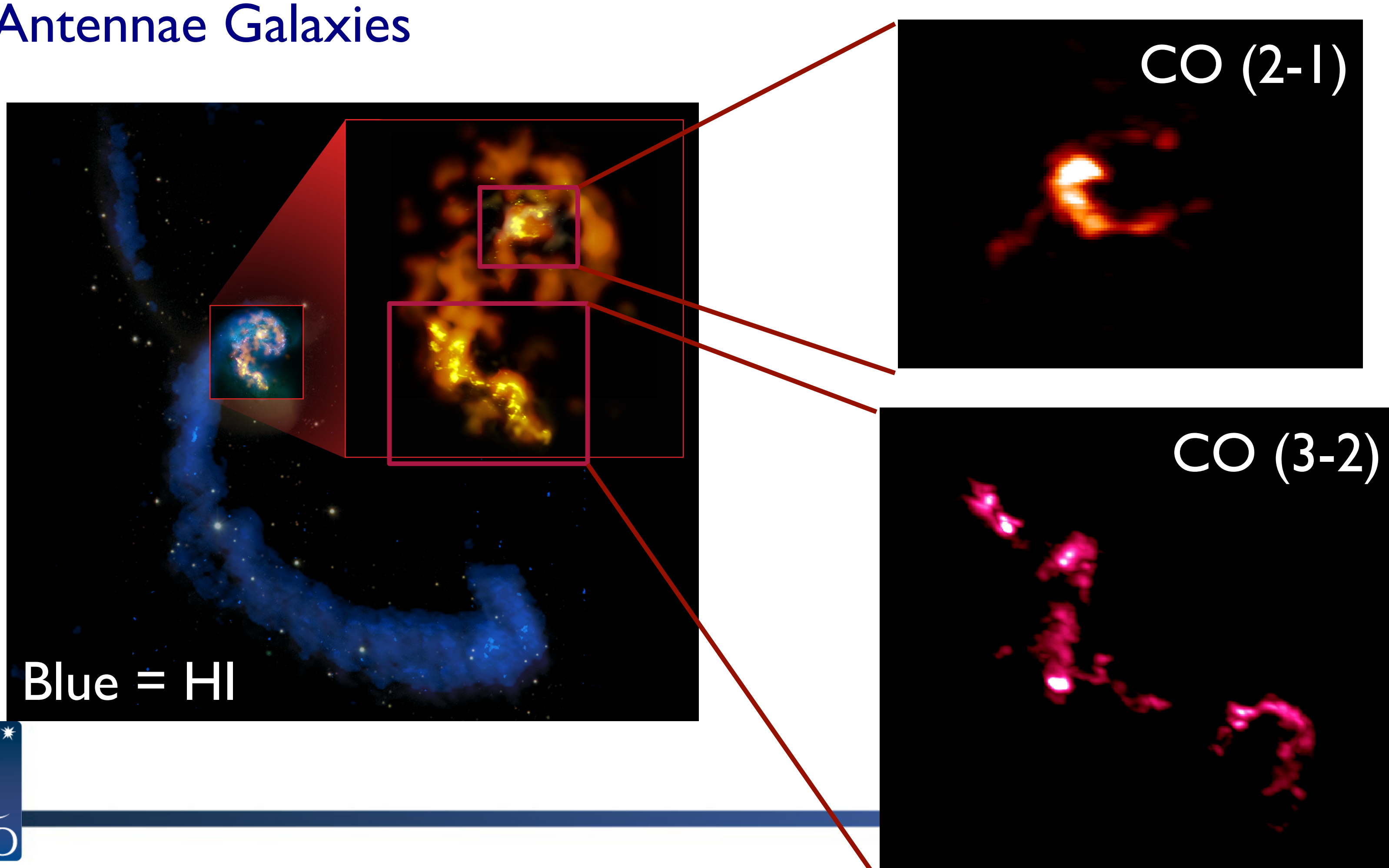
- Redshift survey targeted CO line emission from star-forming molecular gas toward bright mm sources
- ALMA imaging demonstrated that sources strongly gravitationally lensed by foreground galaxies
- Dusty starburst galaxy fraction at high z is greater than expected
- Models indicate that background objects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



Vieira et al. 2013

ALMA Images Nearby Galaxies

Science verification imaging of the
Antennae Galaxies

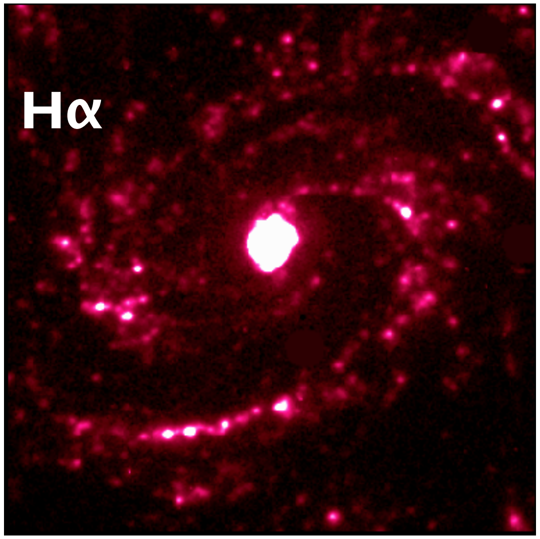


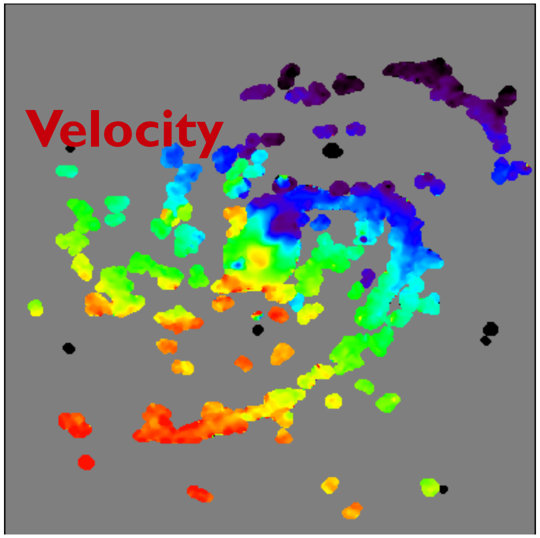
ALMA Images Nearby Galaxies

Science verification imaging of M100

CO 1-0

47-pt mosaic





ALMA Summary

- After three decades of planning/construction, ALMA is approaching full science operations
- ALMA offers unprecedented imaging and spectroscopic capabilities, orders of magnitude better than *any other* mm/submm system: high precision, high sensitivity, high dynamic range, and angular resolution
- Lessons from ALMA in science and technology, project development, and operations are valuable inputs for future projects including SKA and ngVLA
- Incredible range of science can be done in nearly any branch of astrophysics, astrochemistry, astrobiology

The Green Bank Telescope in 2015

NRAO

Next GBT, VLA, VLBA/HSA/VLBI proposal deadline is

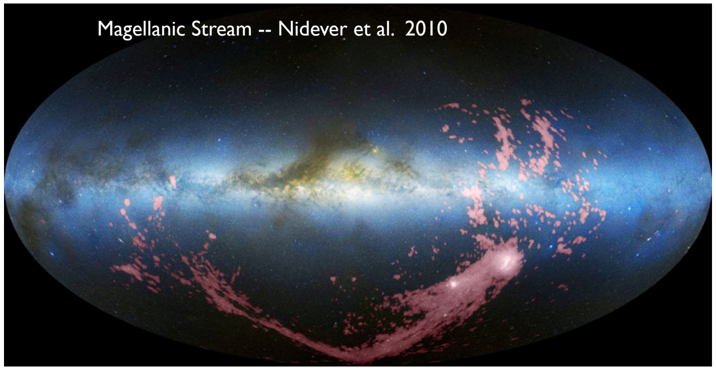
August 03, 2015 at 5pm EST

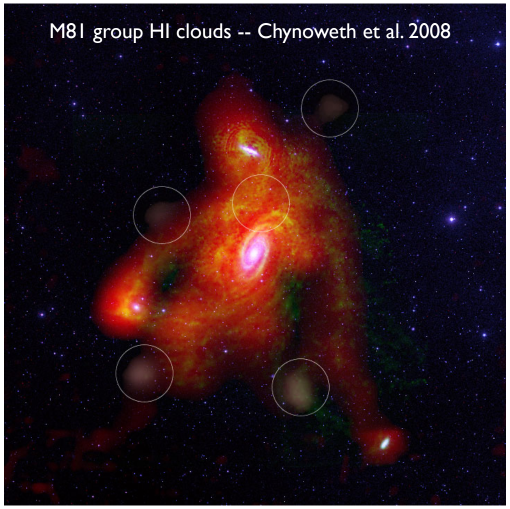
which is for semester "16A" (Feb 2016 – Aug 2016 observations)

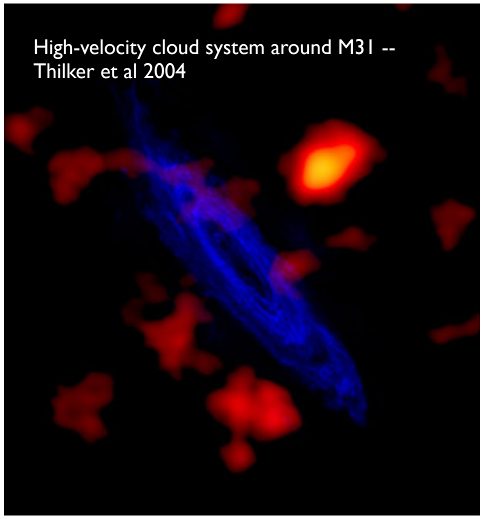
GBT Studies of faint HI -- unequalled sensitivity

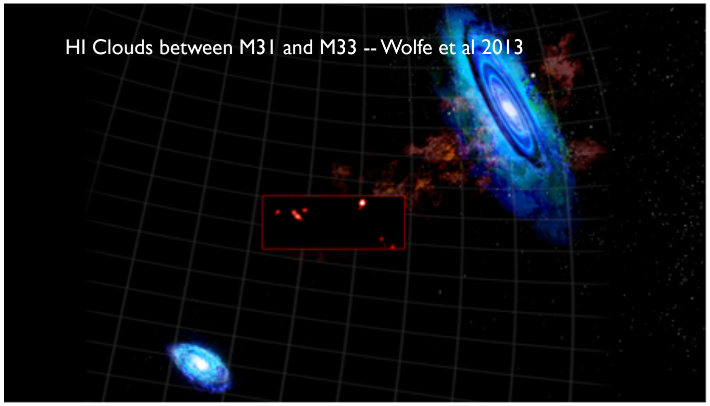
GBT offers ability to detect HI to $N_{HI} \sim 10^{17}$ cm^{-2}

- Interactions
- Outflows from winds and fountains
- Cool gas accretion









GBT Finds No Neutral Hydrogen in the Milky Way's Dwarf Galaxies

(Spekkens et al. 2014)

Ursa Minor dwarf galaxy
(Capella Observatory)

Galaxy	L ($L_\odot$)	M_{HI} ($M_\odot$)
Segue I	340	<11
UMa II	41,000	<74
Bootes II	1,000	<38
Coma Ber	3,700	<62
Ursa Mi	2.80E+05	<63
Draco	2.80E+05	<133

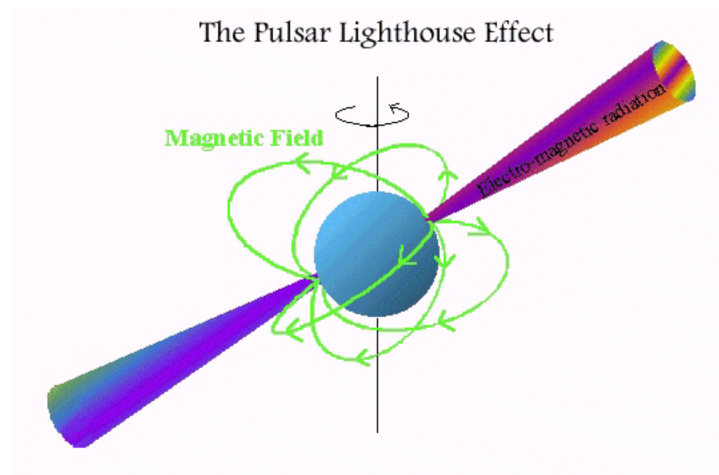
"Spitzer" diffuse HI cloud: 400 $M_\odot$

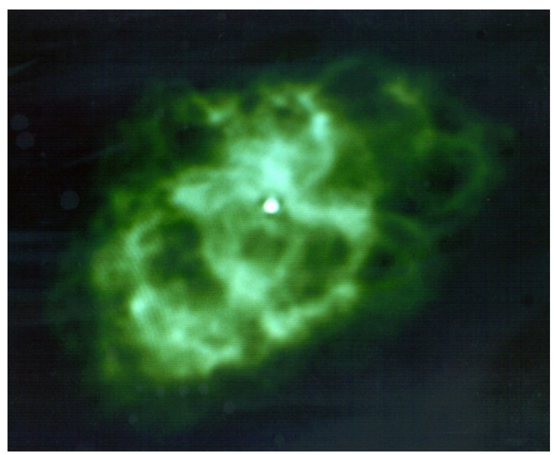
The GBT remains
The world's premier pulsar observatory

(Quiet Zone, collecting area, receivers, detectors, sky coverage)

The Pulsar Renaissance:

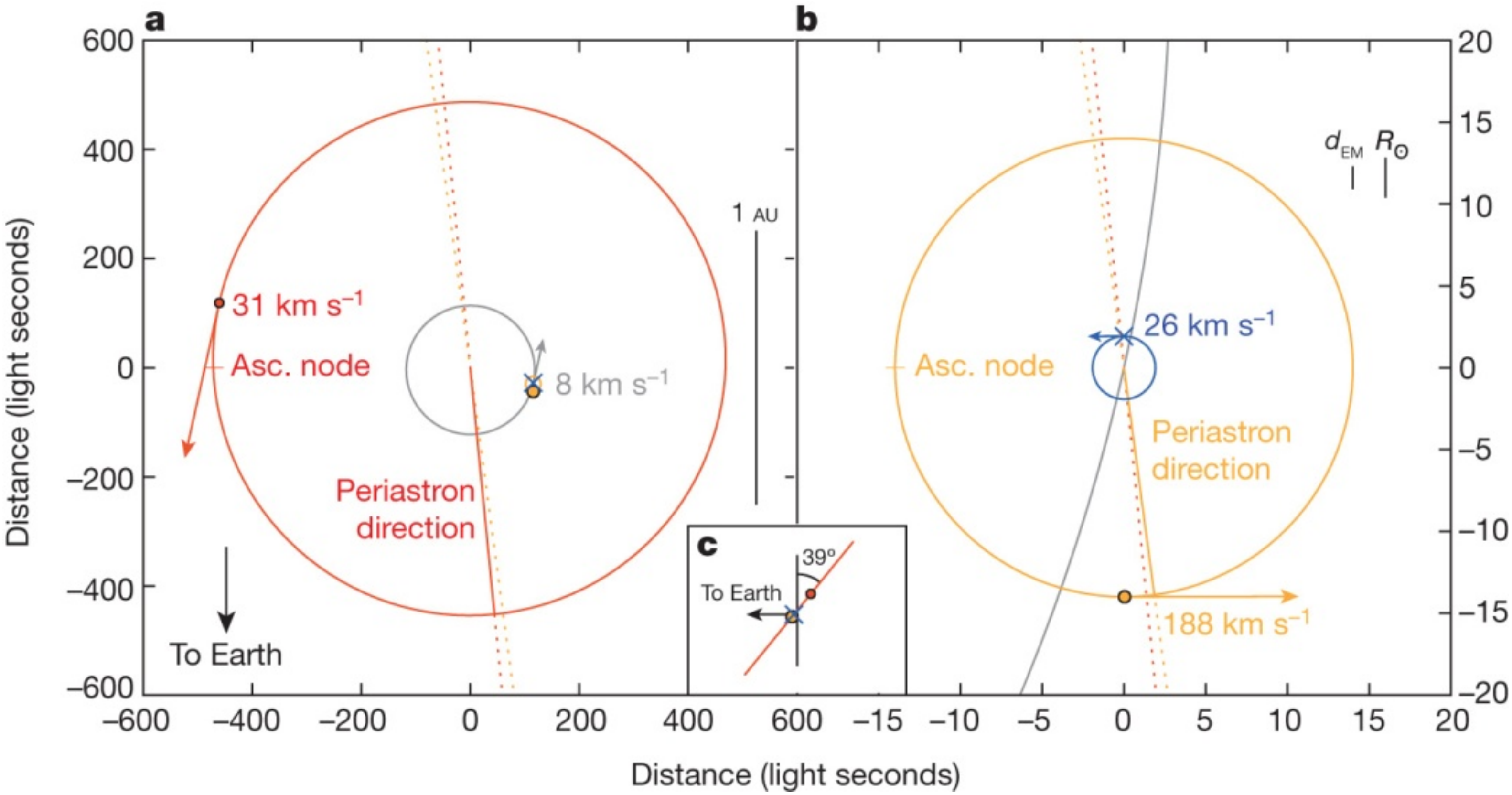
- Fastest Pulsar
- Most Massive Pulsar
- Pulsars in Globular Clusters
- Tests of General Relativity
- Relativistic Spin Precession
- Pulsar in a three-body system
- Coolest white dwarf star (a diamond as big as the Ritz)





GBT Discovery of a Pulsar in a Triple System

Ransom et al. Nature (2014)



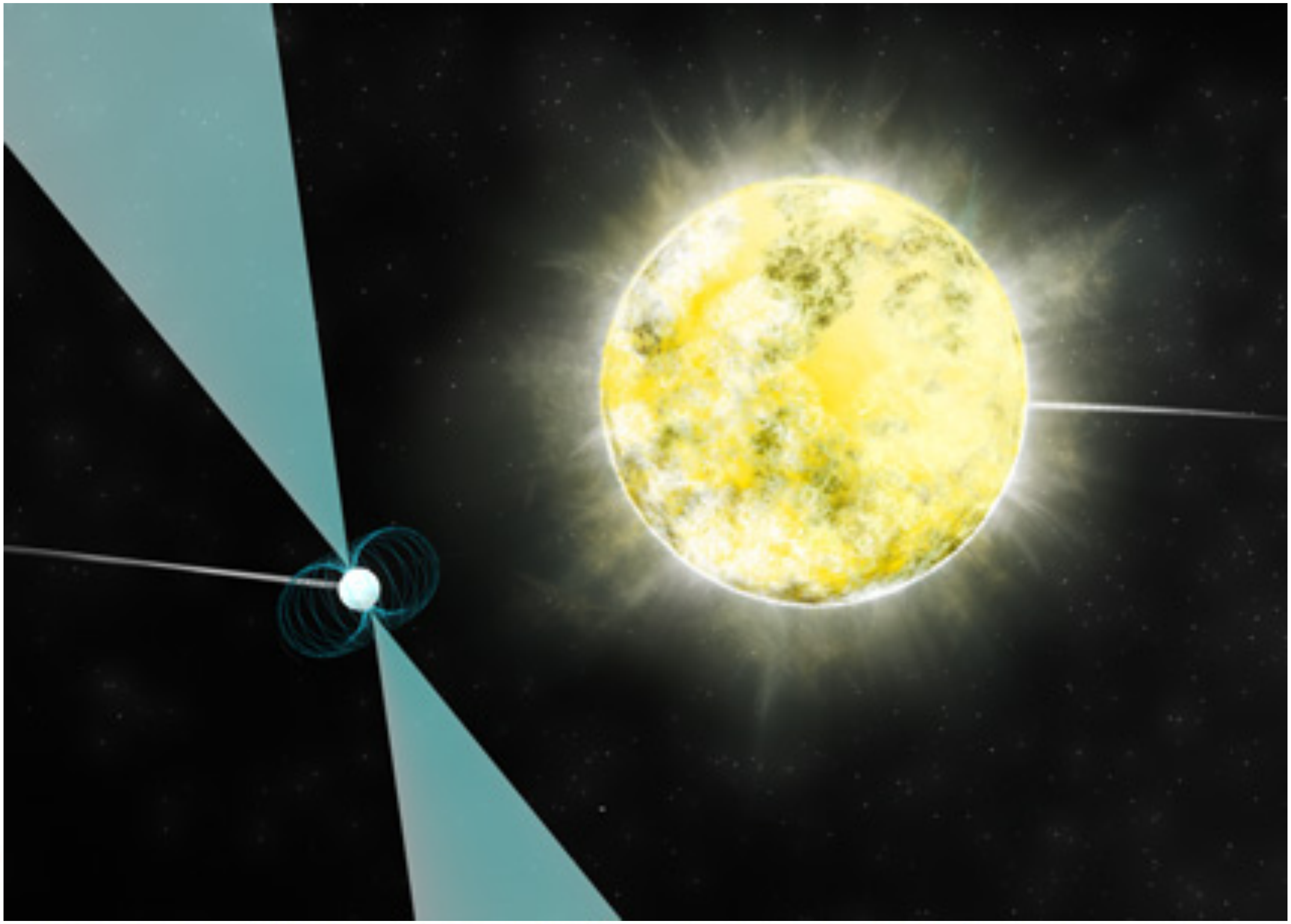
Masses: 1.4378(13), 0.19751(15), 0.4101(3) M⊙

Angle between orbital planes: 1.20(17)x10^{-2} deg

Testing the Equivalence Principle

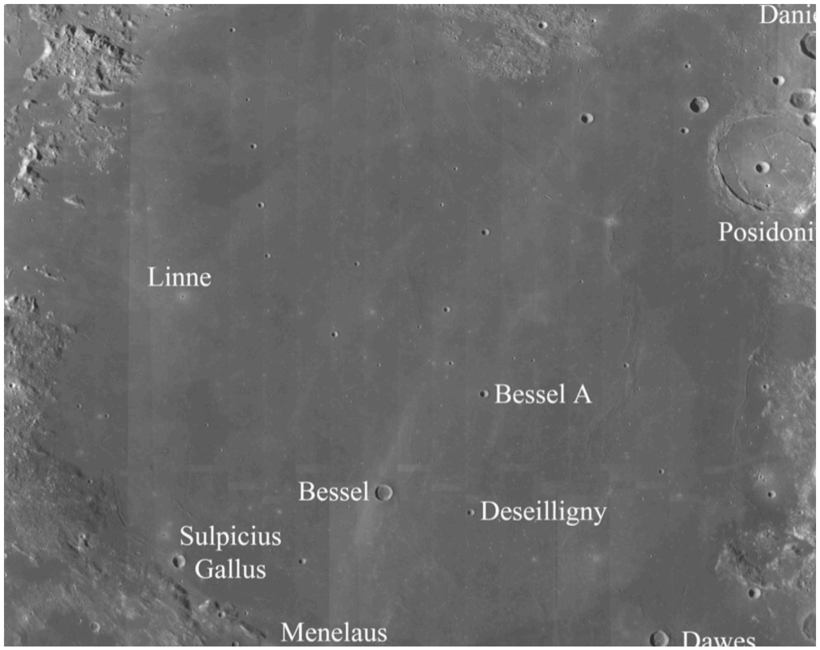
A Solid Carbon "Diamond" Star Orbiting a Pulsar

Kaplan et al. (2014)

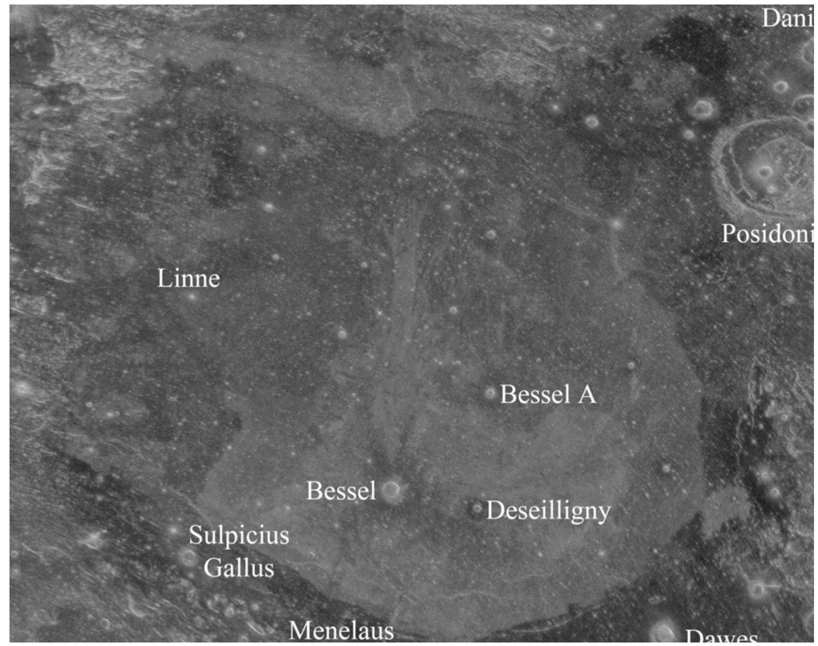


GBT Bi-static radar studies with Arecibo

Campbell, B.A. et al. 2014 JGR-P



Optical



70cm radar

"The 70 cm backscatter differences provide a view of mare flow-unit boundaries, channels, and lobes unseen by other remote sensing methods."
-- Campbell, B.A. et al. JGR-P 2014

New GBT radar backend in 2014 from JPL

NRAO

News for Semester 15B

- VEGAS has replaced the GBT spectrometer and spectral processor
- C-band upgrade to cover 3.95-8 GHz frequency range (shared-risk)
- Mustang-1.5, a 90 GHz bolometer array (shared-risk)
- ARGUS 16 element array 75-115.5 GHz (shared-risk)

The Proposer's Guide for the Green Bank Telescope

GBT Support Staff

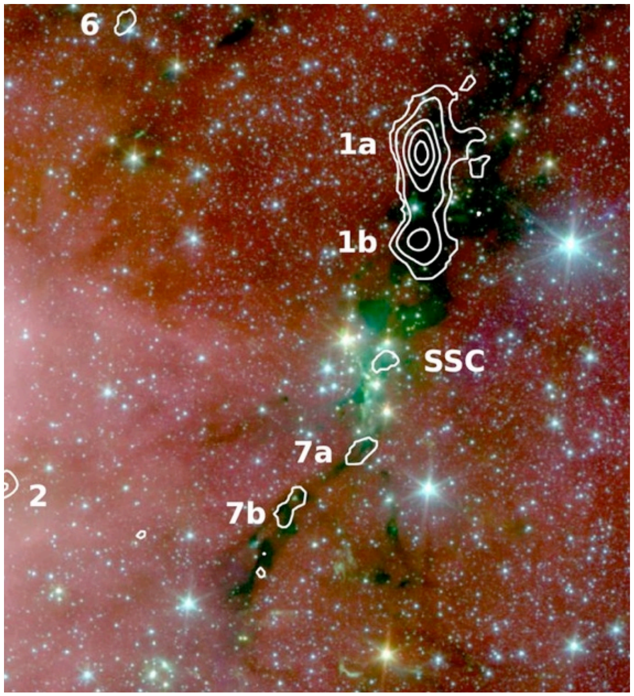
December 19, 2013

This guide provides essential information for the preparation of observing proposals on the Green Bank Telescope (GBT). The information covers the facilities that will be offered in Semester 14B.

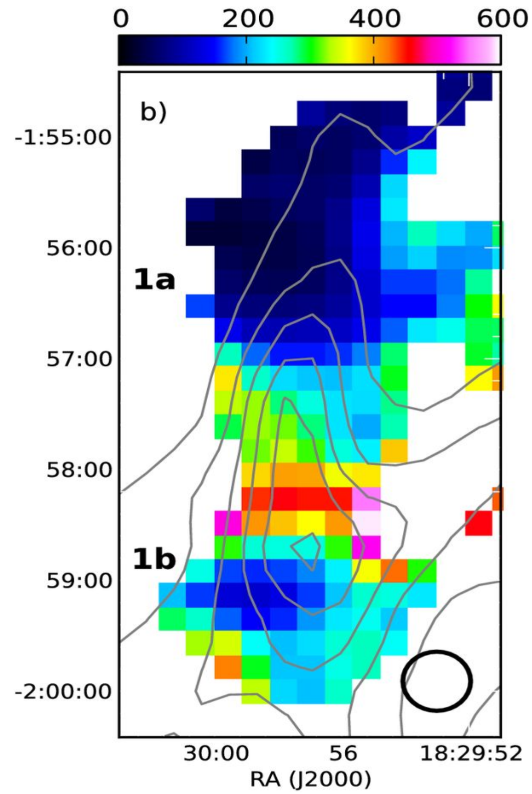
NRAO

HC_7N: A Chemical “Clock” in a Molecular Cloud?

Friesen et al. (2013)



$[NH_3]/[HC_7N]$



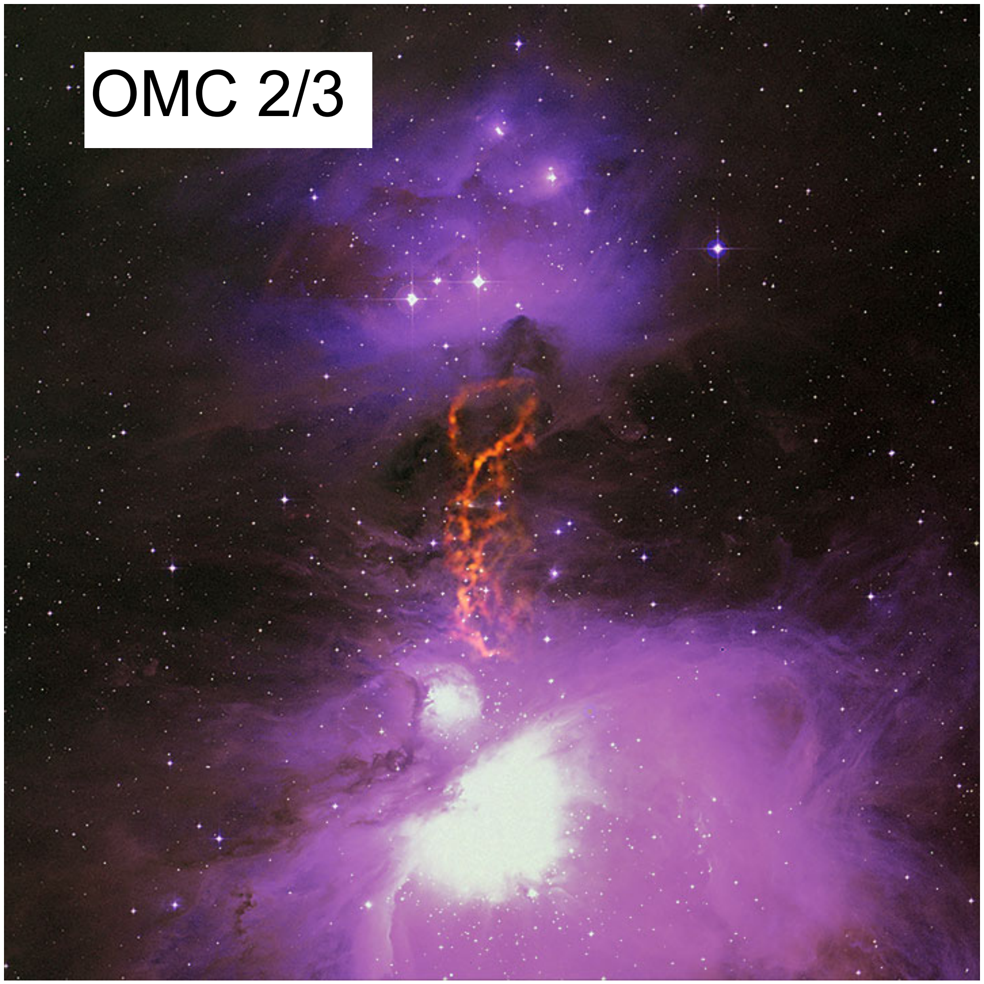
VEGAS

(NSF grant to UC Berkeley)

- Up to 16 spectrometers
- Up to 8 spectral windows per spectrometer
- Up to 1.25 GHz per spectrometer

GBT Detection of mm-cm sized particles in Orion

Schnee et al. (2014)



← 5 ‘ →

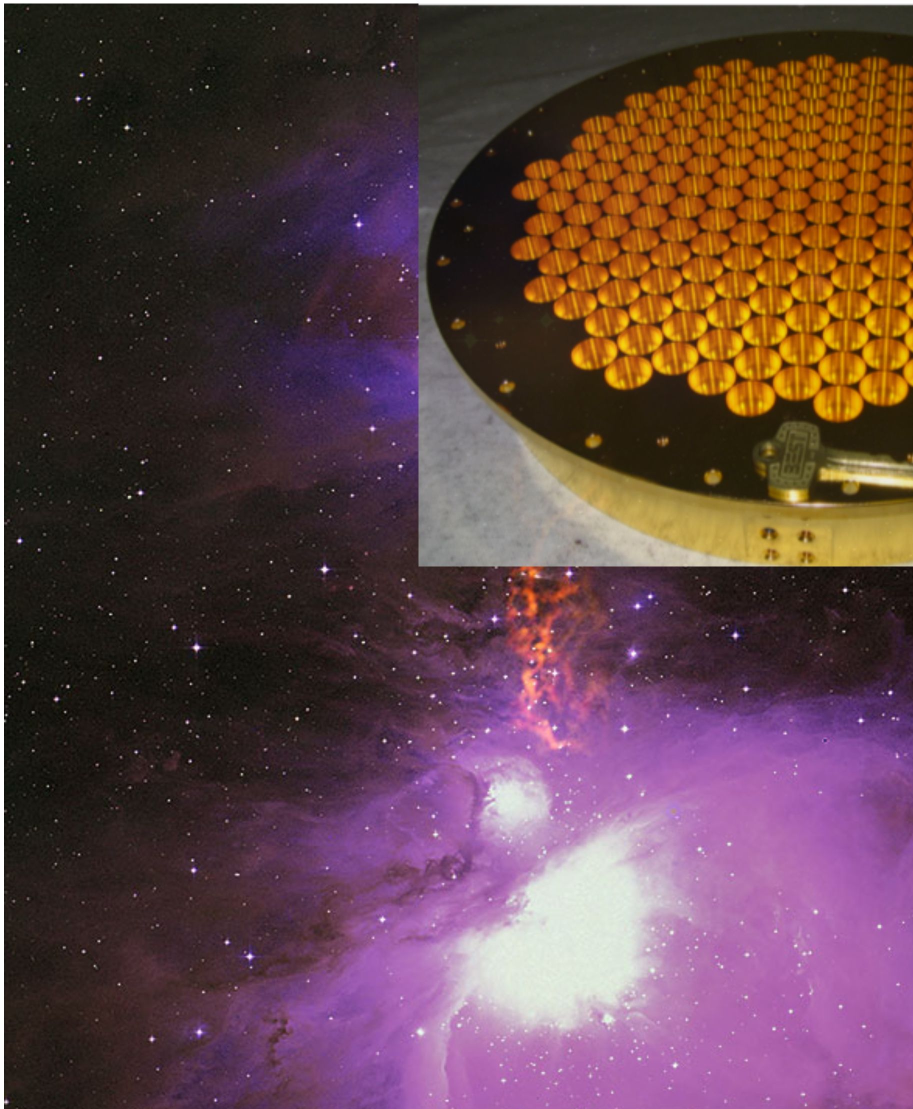
MUSTANG

- Bolometer Array
- 3.3mm
- 81–96 GHz
- 14 hours

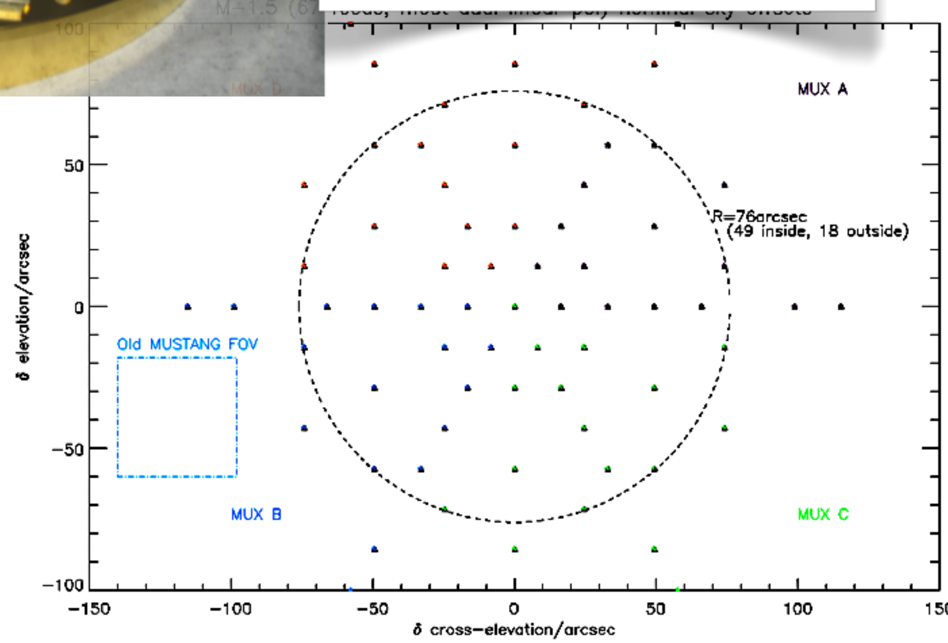
Brighter emission at 3.3mm implies either the existence of “pebbles” or a new model for dust emissivity

9″ MUSTANG-1.5 Bolometer Array (UPenn)

Dicker et al. (2014)

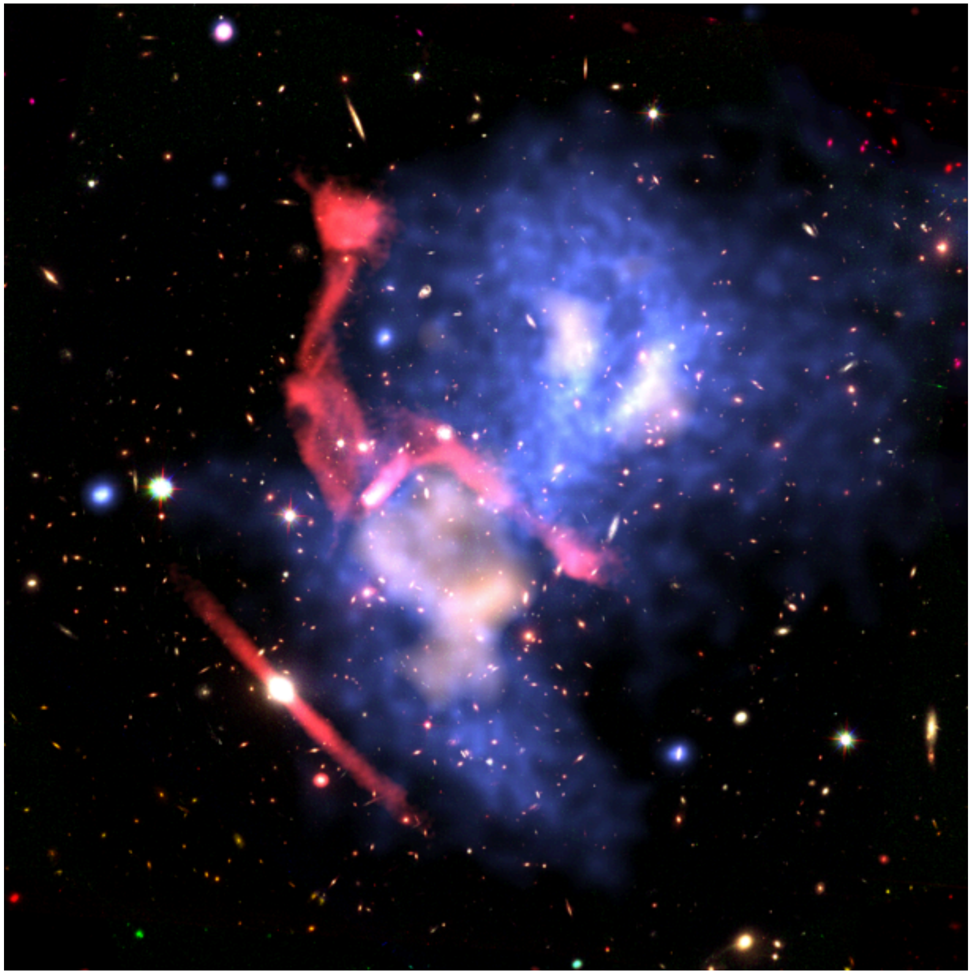


- 223 feed horns
- 64 dual-pol currently populated
- 4’ FOV
- 3x more sensitive than MUSTANG



GBT measurements of the SZE in galaxy clusters

Mroczkowski et al. (2012)

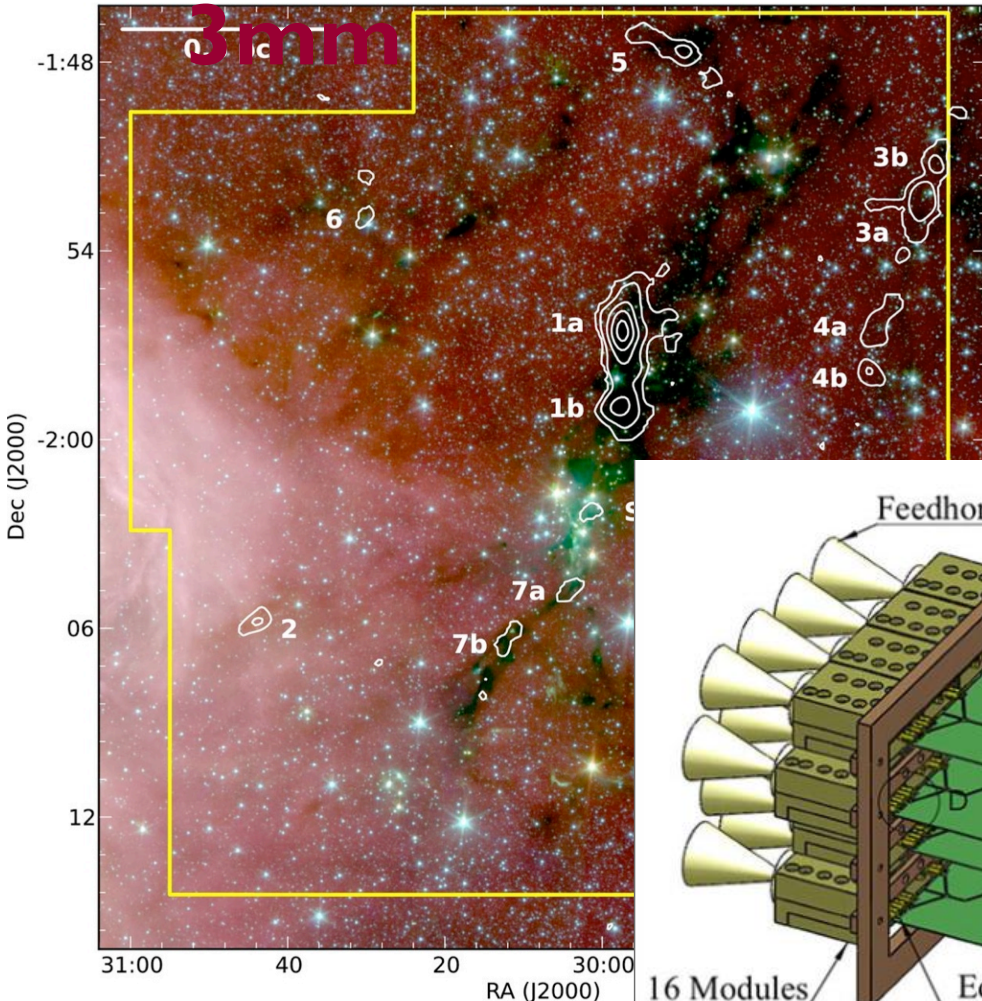


X-ray hot gas

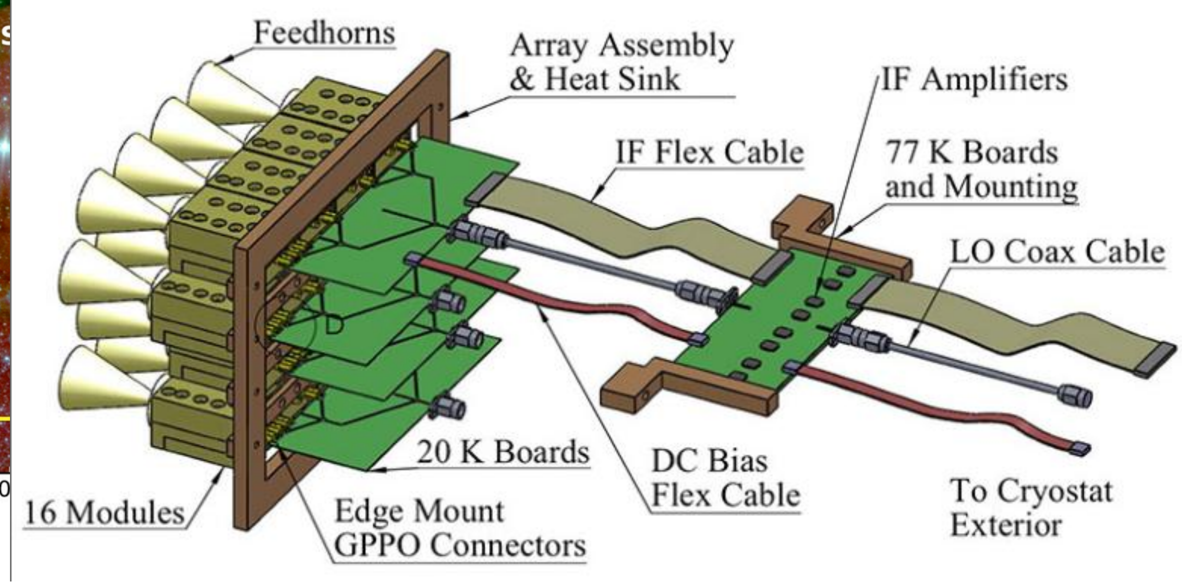
VLA nonthermal

GBT 90 GHz hot gas SZE

ARGUS -- 8″ GBT spectroscopy at 3mm



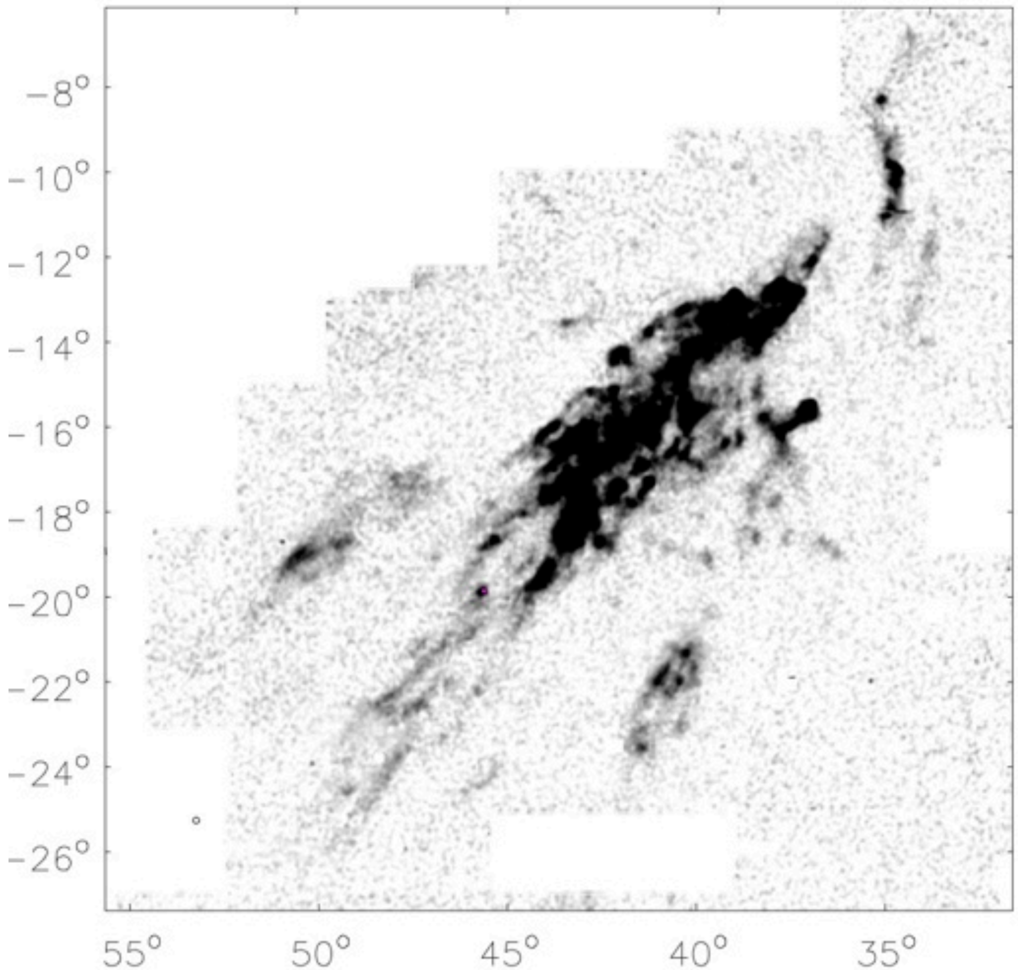
- 16 element scalable 75-115 GHz FPA (Spring 2015)
- Stanford/CIT-JPL/UMd/ Miami/NRAO (NSF grant to Stanford)

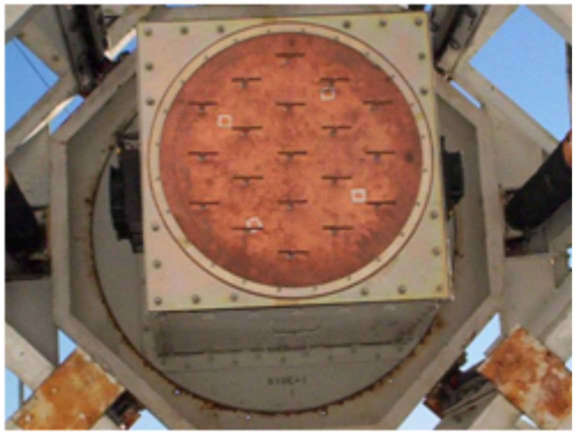


The GBT in 2015 and Beyond

GBT HI mapping of the Smith Cloud, a “failed” galaxy?

Nichols et al. (2014)





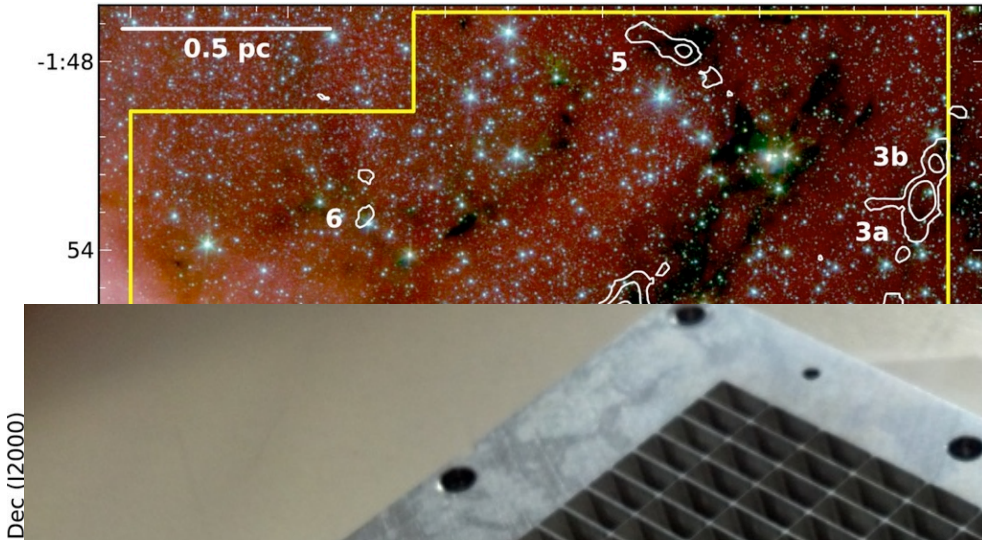
FLAG

19-element phased-array feed [PAF] (7beams) at 21cm

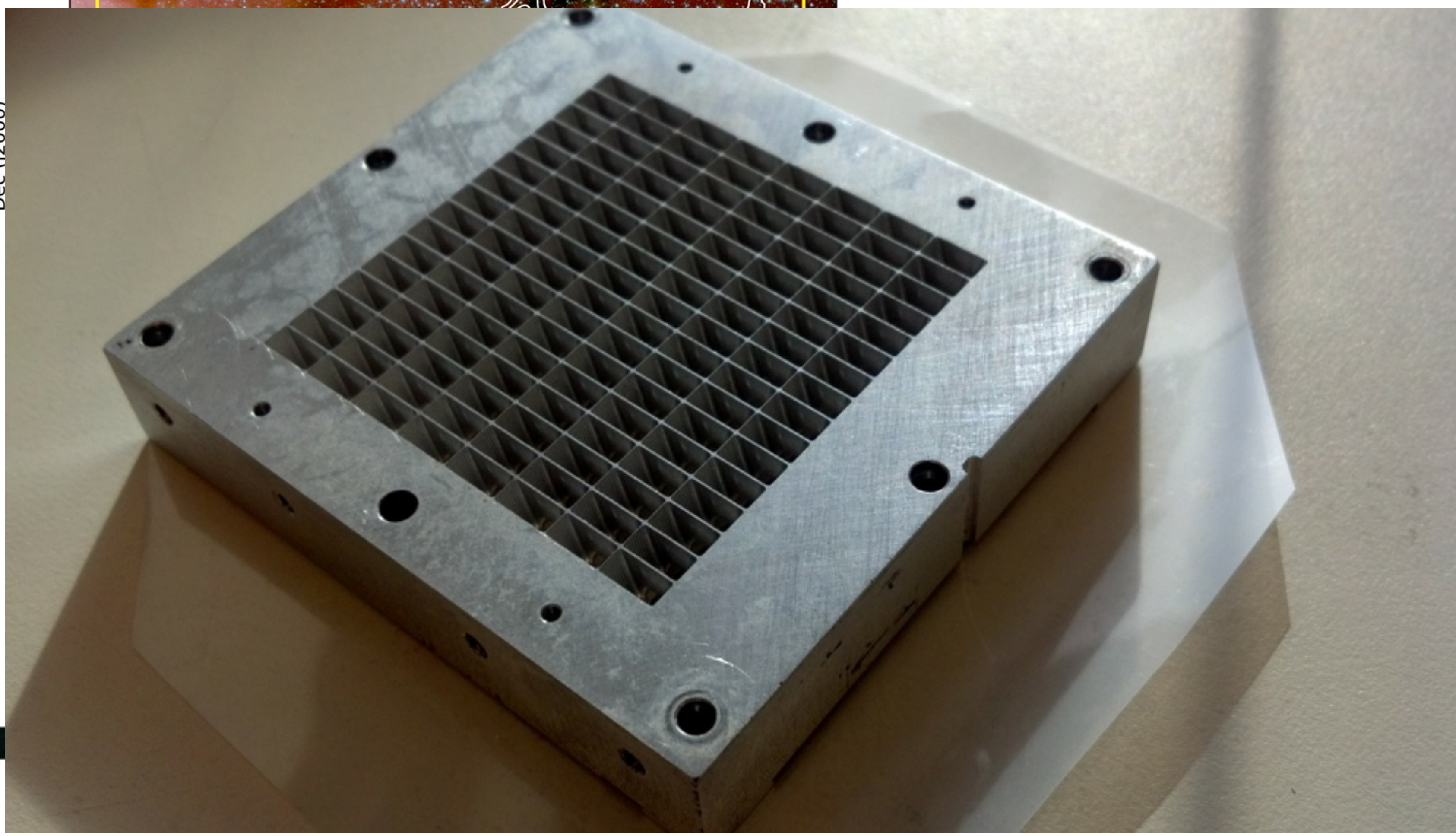
(NSF grant to BYU/WVU)

Planned future 20 beam PAF

UMass 3mm PAF (W-PAF)



Scalable 75-115 GHz PAF
Summer 2015
(NSF grant to UMass Amherst)



The GBT in 2015

- The GBT is a powerful instrument – single-dish flexibility, filled-aperture sensitivity, wide-frequency coverage, accessible for a vast range of science
- NSF-supported development ongoing to enhance the capabilities of the GBT well into the future (higher frequency coverage, multi-pixel receivers, ...)
- VEGAS new versatile spectrometer
- New receivers coming for 3mm: MUSTANG-1.5, ARGUS, W-PAF

The GBT is just beginning to realize its scientific potential at high frequencies

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Available GBT receivers for 15B

Table 1: GBT Receivers

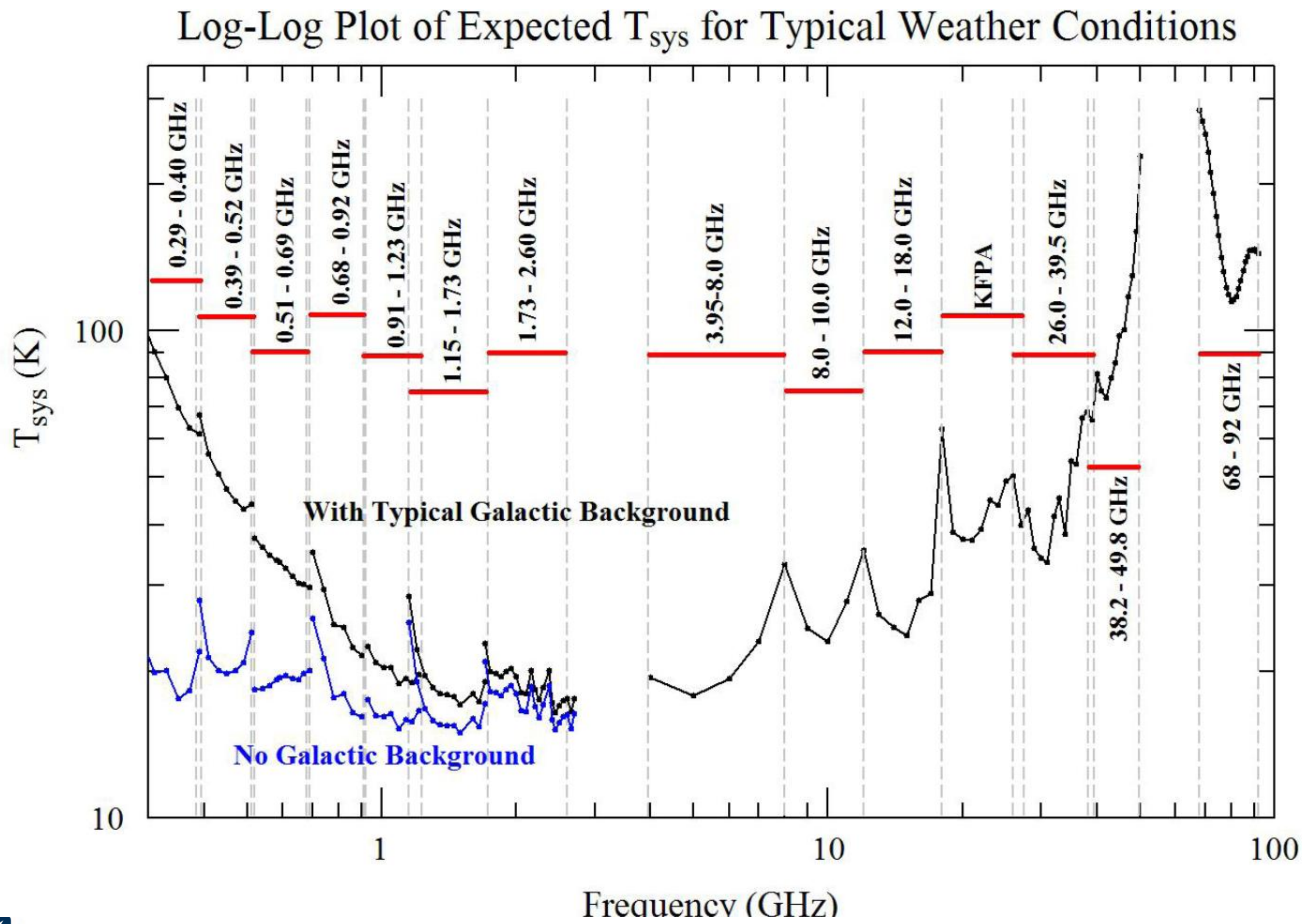
Receiver	Frequency Range
Prime Focus 1	290-920 MHz
Prime Focus 2	910-1230 MHz
L-band	1.15-1.73 GHz
S-band	1.73-2.60 GHz
C-band (shared risk)	3.8-8.0 GHz
X-band	8.0-11.6 GHz
Ku-band	12.0-15.4 GHz
K-band Focal Plane Array (7 pixels)	18.0-26.0 GHz
Ka-band	26.0-39.5 GHz
Q-band	38.2-49.8 GHz
W-band	67-93.3 GHz
MUSTANG 1.5 bolometer array (shared risk)	80-100 GHz
ARGUS (shared risk)	75-115.3 GHz, Private PI instrument

Available GBT Backends for 15B

Table 2: GBT Backends and Observing Modes

Backend	Observing Modes
Versatile Green Bank Astronomical Spectrometer (VEGAS)	Continuum, pulsar, spectral line
Digital Continuum Receiver (DCR)	Continuum
Green Bank Ultimate Pulsar Processing Instrument (GUPPI)	Pulsar
Mark V Very Long Baseline Array Disk Recorder	Very Long Baseline Interferometry
Caltech Continuum Backend (CCB) • (Ka-band)	Continuum
Zpectrometer • (Ka-band)	Private PI instrument
Radar	Private PI instrument

Noise Levels (Tsys) for Typical Weather



The Karl G. Jansky Very Large Array

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

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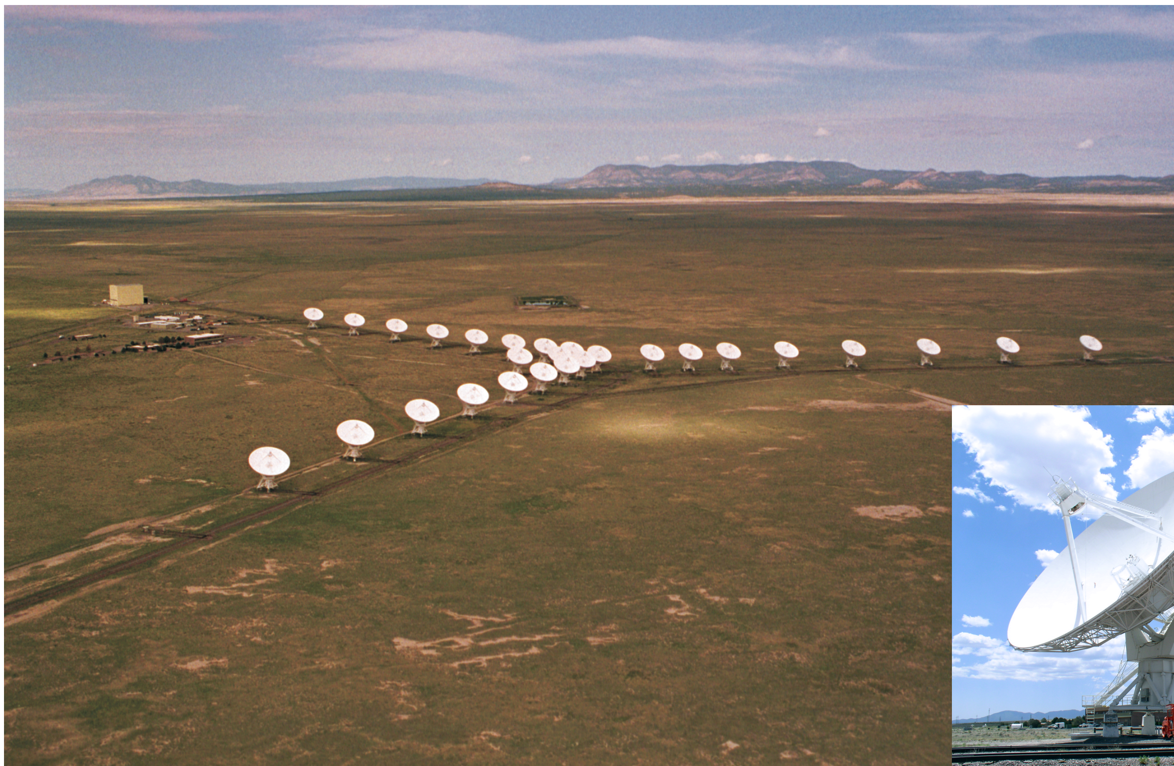
The (Jansky) VLA

- 27x25m antennas (antennas in the shape of a Y) reconfigurable on baselines 35m to 36km
- located in New Mexico at 2100m altitude



Spatial Resolution

- With reconfiguration of the antennas, the array can vary its spatial resolution by a factor of ~40.
- Configuration sequence: D (B_{max}~ 1 km) → C → B → A (B_{max}~ 36 km).
- Reconfiguration every ~4 months.
- Hybrid configurations (DnC, CnB, BnA) extend for about 2 weeks in between regular configurations.
- The August 2015 deadline is for the C, CnB, and B configurations.

Configuration	A	B	C	D
B_{max} (km[1])	36.4	11.1	3.4	1.03
B_{min} (km[1])	0.68	0.21	0.035[5]	0.035
	Synthesized Beamwidth θ_{HPBW}(arcsec)[1,2,3]			
74 MHz (4 band)	24	80	260	850
1.5 GHz (L)	1.3	4.3	14	46
3.0 GHz (S)[6]	0.65	2.1	7.0	23
6.0 GHz (C)	0.33	1.0	3.5	12
8.5 GHz (X)[7]	0.23	0.73	2.5	8.1
15 GHz (Ku)[6]	0.13	0.42	1.4	4.6
22 GHz (K)	0.089	0.28	0.95	3.1
33 GHz (Ka)	0.059	0.19	0.63	2.1
45 GHz (Q)	0.043	0.14	0.47	1.5

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The VLA

- Nine Frequency Bands
  - Eight cryogenic bands, covering 1 – 50 GHz. Utilizes cassegrain subreflector.
  - One uncooled, prime-focus band, covering 50 – 450 MHz.
- Up to 8 GHz instantaneous bandwidth
  - Provided by two independent dual-polarization frequency pairs, each of up to 4 GHz bandwidth per polarization.
  - All digital design to maximize instrumental stability and repeatability.
- Full polarization correlator with 8 GHz instantaneous BW
  - Provides 64 independent 'sub-correlators', and 16384 spectral channels.
  - Many specialized operations modes (burst, pulsar binning, phased arrays …)

Full Frequency Coverage with Outstanding Performance

There are eight cassegrain focus systems, and one prime focus system.

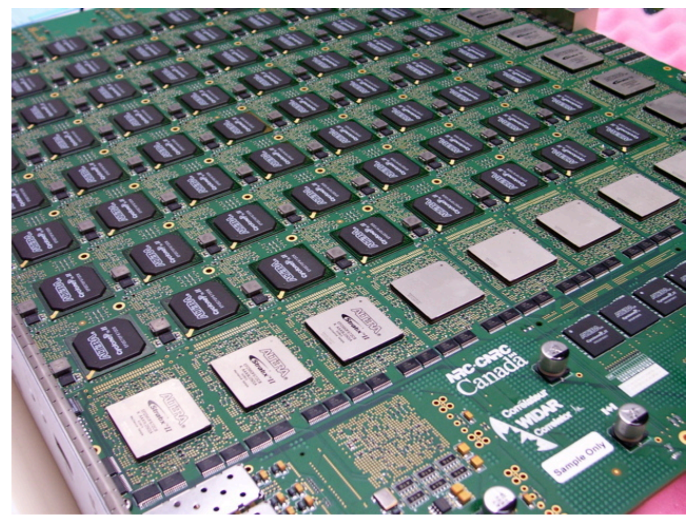
Band (GHz)		SEFD (Jy) (27 antennas)
.05 -- .45	P	~60
1-2	L	13
2-4	S	9.5
4-8	C	8.5
8-12	X	8.1
12-18	Ku	8.1
18-26.5	K	13
26.5-40	Ka	22
40-50	Q	45

Eight feeds around the cassegrain secondary focus ring.

The ‘WIDAR’ Correlator

The VLA’s correlator was built to NRAO’s requirements by the DRAO correlator group, located at the NRC-Herzberg facility near Penticton, BC.

This ‘WIDAR=**W**ideband **I**nterferometric **D**igital **AR**chitecture’ correlator was paid for by the Canadian government, as part of an agreement between NRC and NSF.



CNRC-NRC

Corrélateur WIDAR Correlator

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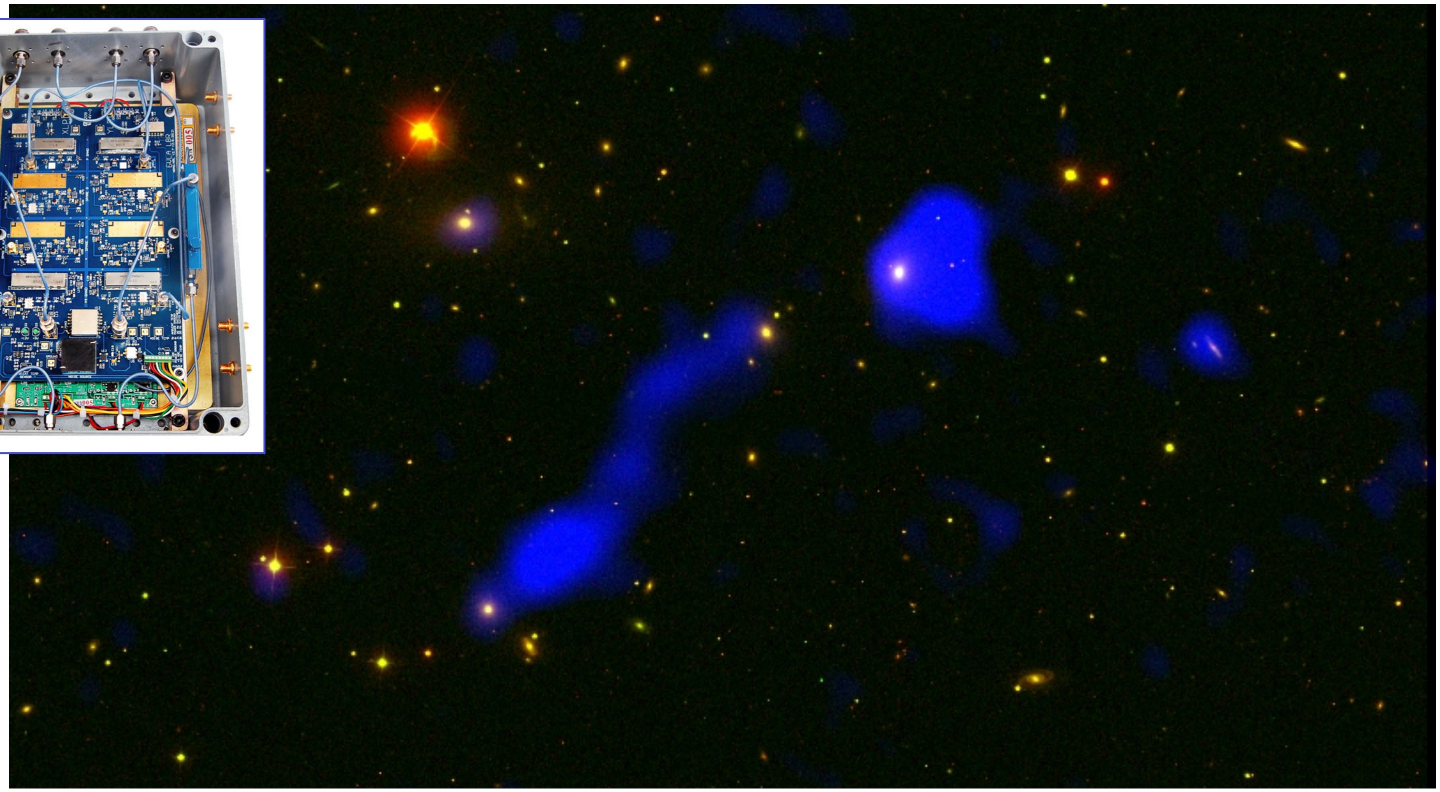
Basic Features of the 'WIDAR' Correlator

The correlator's basic features (not all implemented yet):

- **64 independent full-polarization subbands**
  - Each can be tuned to its own frequency, with its own bandwidth (128 MHz to 31.25 kHz) and spectral resolution (from 2 MHz to .12 Hz)
- **100 msec dump times with 16384 channels and full polarization**
  - Faster if spectral resolution, BW, or number of antennas is decreased.
- **Up to 8 sub-arrays**. Maximum to date is three.
- **Phased array capability** with full bandwidth – for pulsar and VLBI applications. Two different subarrays can be simultaneously phased.
- **Special pulsar modes**: 2 banks of 1000 time bins, and 200 μsec time resolution (all spectral channels), or 15 μsec (64 channels/sp.window). Undergoing testing; See RSRO.

Two Telescopes in One

VLITE (VLA Ionospheric and Transient Experiment)

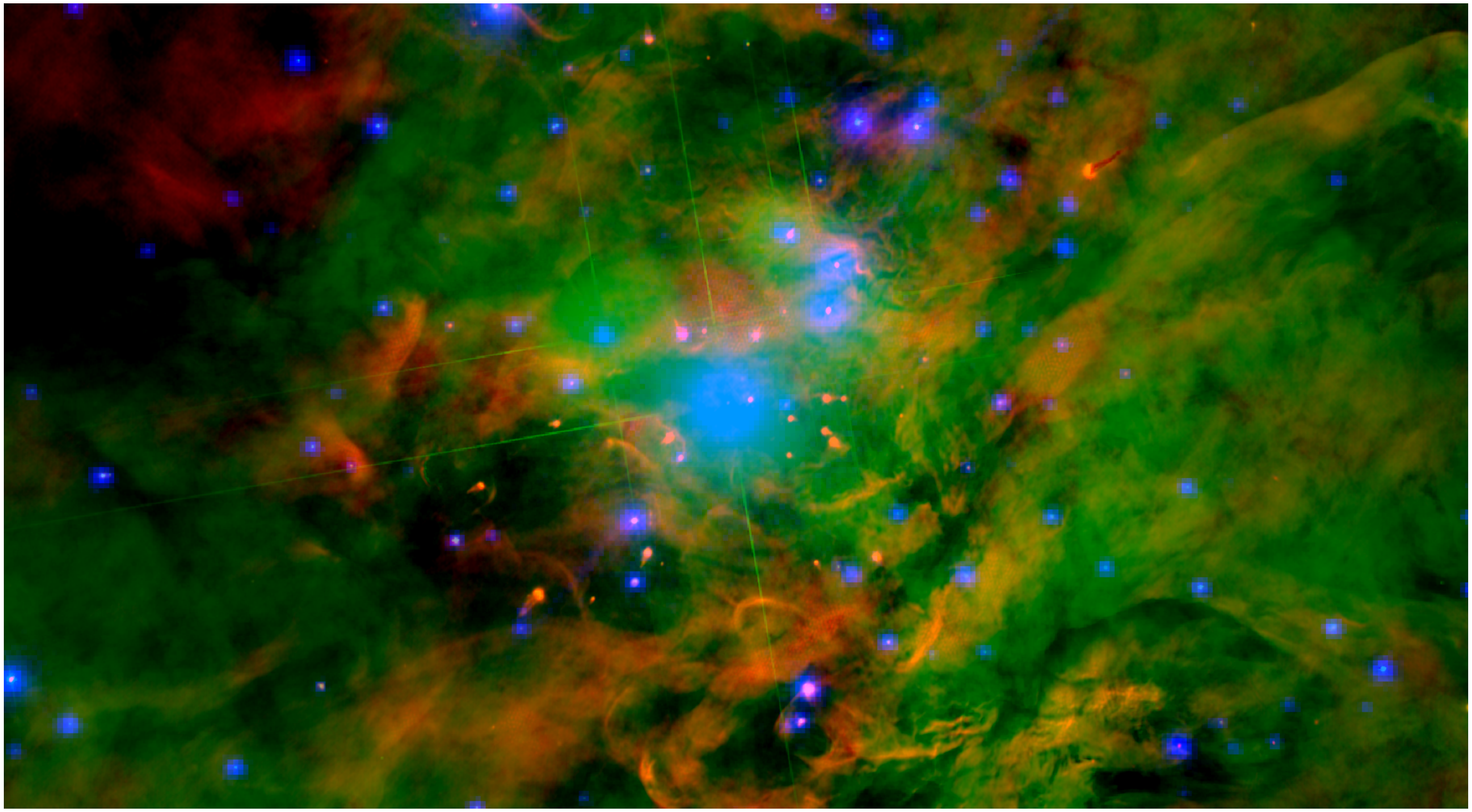


A VLITE pipeline-processed image of the giant radio galaxy IC 711 in the galaxy cluster Abell 1314

Credit: Radio (blue) from VLITE on the NRAO VLA.
Optical (red and green) from the Sloan Digital Sky Survey.
U.S. Naval Research Laboratory/Dr. Tracy Clarke

Time-Domain Astronomy

A multiwavelength study of the Orion nebula searches for young stellar variability

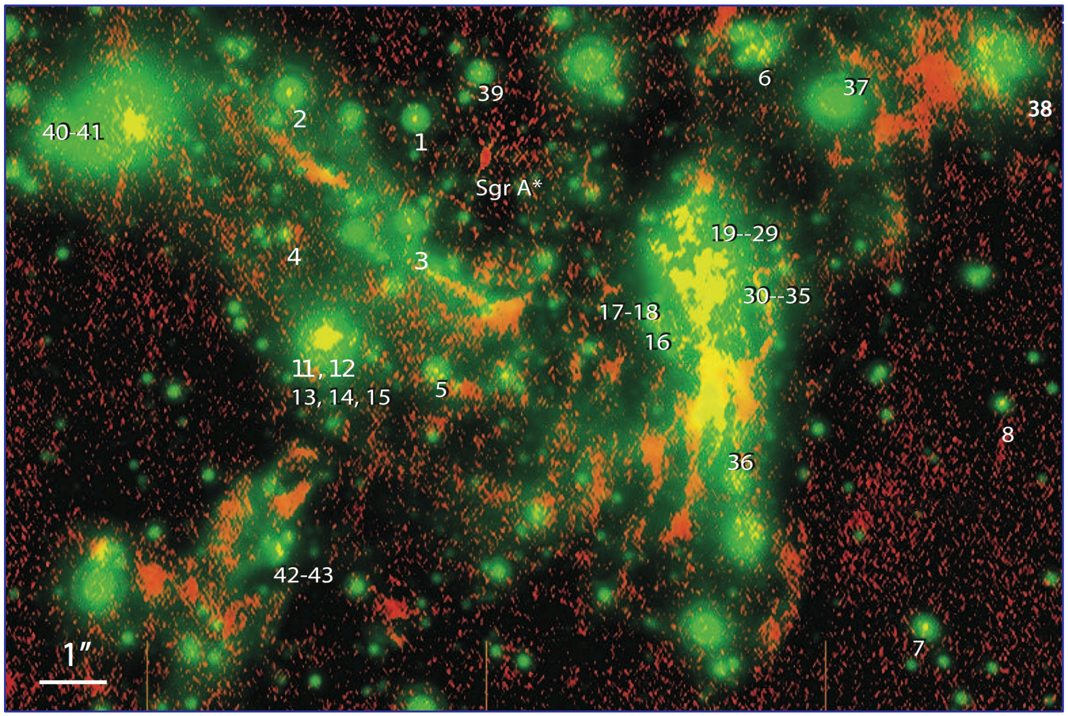


Credit: Red: VLA 6 cm continuum, J. Forbrich et al.
Green: Optical data, Hubble Space Telescope, Robberto et al. 2013
Blue: X-rays, Chandra, Getman et al. 2005

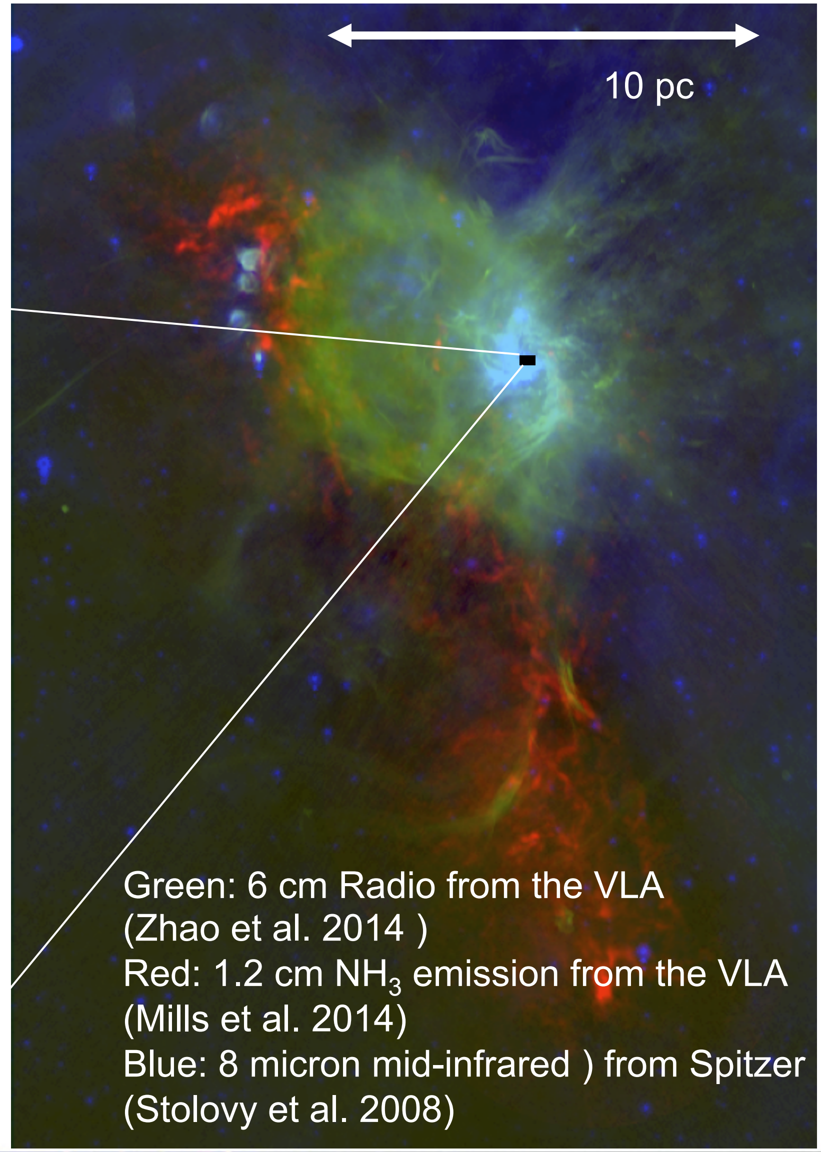
NRAO

A Sensitive view of the Invisible Universe

Ionized and molecular gas around the supermassive black hole in the center of our Galaxy



Red: 7mm radio VLA observations
Green: 3.8 um adaptive optics image from the VLT
(Yusef-Zadeh et al. 2014)



Green: 6 cm Radio from the VLA
(Zhao et al. 2014)
Red: 1.2 cm NH_3 emission from the VLA
(Mills et al. 2014)
Blue: 8 micron mid-infrared) from Spitzer
(Stolovy et al. 2008)

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Capabilities of Interest (for 2015B)
General Observing (GO)

- Full 8 GHz bandwidth with 16384 spectral channels – 2 MHz spectral resolution (full pol), 1 MHz resolution (Stokes I)
- All 64 subband pairs can be separately tuned, and set to any of 128, 64, 32, 16, … ,0.03125 MHz widths.
- Up to 16384 spectral channels (no recirculation), or up to 65536 (with recirculation)
- Three simultaneous, fully independent subarrays.
- Mix 3-bit and 8-bit modes.
- Phased Array (for VLBI).

Capabilities of Interest (for 2015B)
Shared Risk Observing (SRO)

Access to extra capabilities that have not been well tested, e.g.,

- On-the Fly mosaicking
- 32 subbands per baseband with the 8-bit samplers
- Recirculation of up to a factor of 64

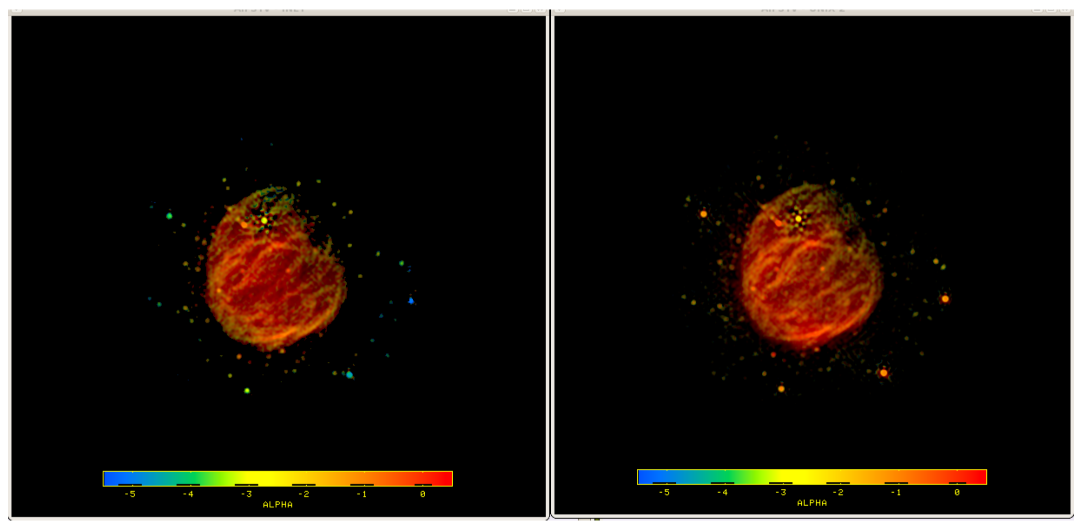
Capabilities of Interest (for 2015B)
Resident Shared Risk Observing (RSRO)

- Access to extended capabilities that require more testing
  - In exchange for a period of residence
- Correlator dump times < 50 msec
  - Including as short as 5 msec for transient detection
- Pulsar observations
- Data rates above 60 MB/s
- Recirculation beyond a factor of 64
- P-band (230-470 MHz) polarimetry and spectroscopy
- 4-band (58-84 MHz) commissioning and testing
- More than 3 subarrays with the 8-bit samplers
- Subarrays with the 3-bit samplers
- Complex VLBI observing modes with the phased array

Post processing

- Data reduction software: CASA
  - Handles complex observing set-ups
  - Task interface to suite of C++-based reduction tools
  - Python interface provides access to data for manipulation
  - Effective platform for algorithm development (e.g., handling effect of wide fractional bandwidths, $\Delta\nu/\nu$)

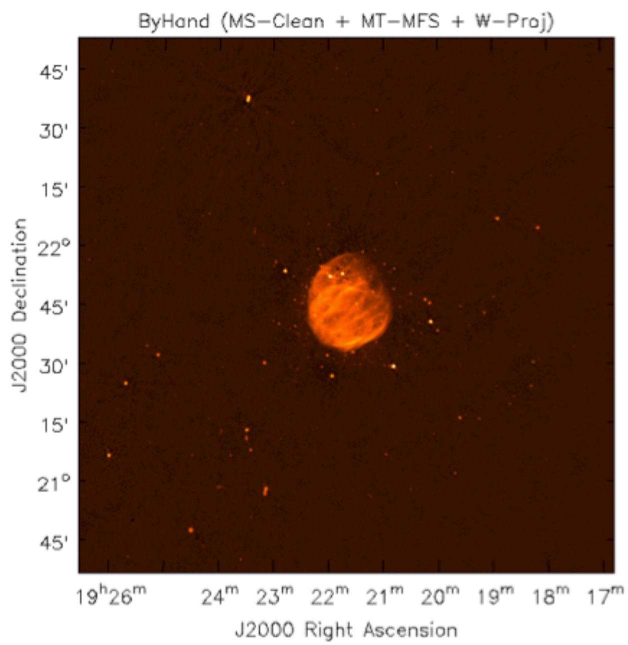
Spectral index of 1–2 GHz emission from SNR G55.7+3.4, before correction for the frequency-dependence of the primary beam (left), and after correction (right)



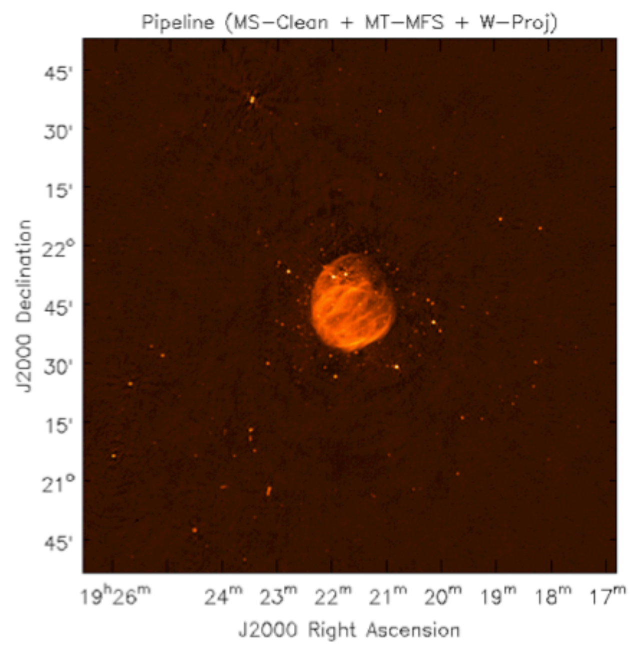
VLA Calibration Pipeline

- Designed for Stokes I continuum
- Scripts can be modified to work for other science goals as well

The supernova remnant
G55.7+3.4



hand-flagged and calibrated



pipeline-calibrated

RMS is within 10%

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Important Links

NRAO Help Desk

https://help.nrao.edu

VLA Observational Status Summary

https://science.nrao.edu/facilities/vla/docs/manuals/oss

VLA Exposure Calculator

https://obs.vla.nrao.edu/ect/

Proposal Submission Tool

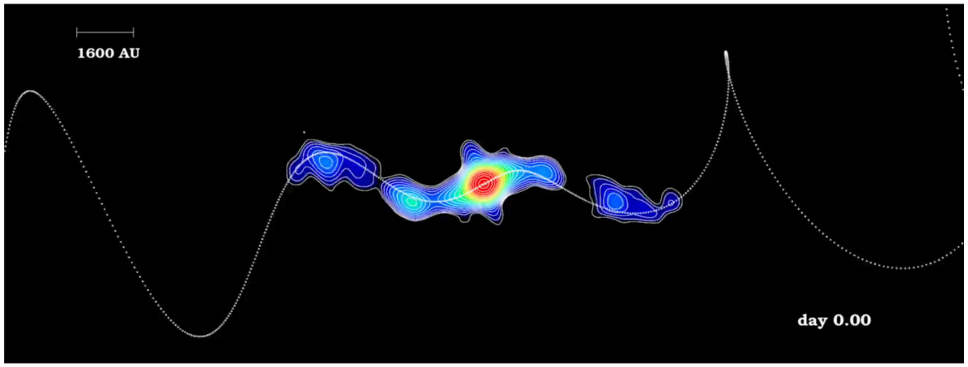
my.nrao.edu

CASA– data reduction software

http://casa.nrao.edu/

VLA Calibration Pipeline

https://science.nrao.edu/facilities/vla/data-processing/pipeline



SS433 at 26 GHz (0.095"; 520 AU resolution)
Credit: Miodusweski & Miller-Jones, EVLA demo science

NRAO

Next Generation Very Large Array

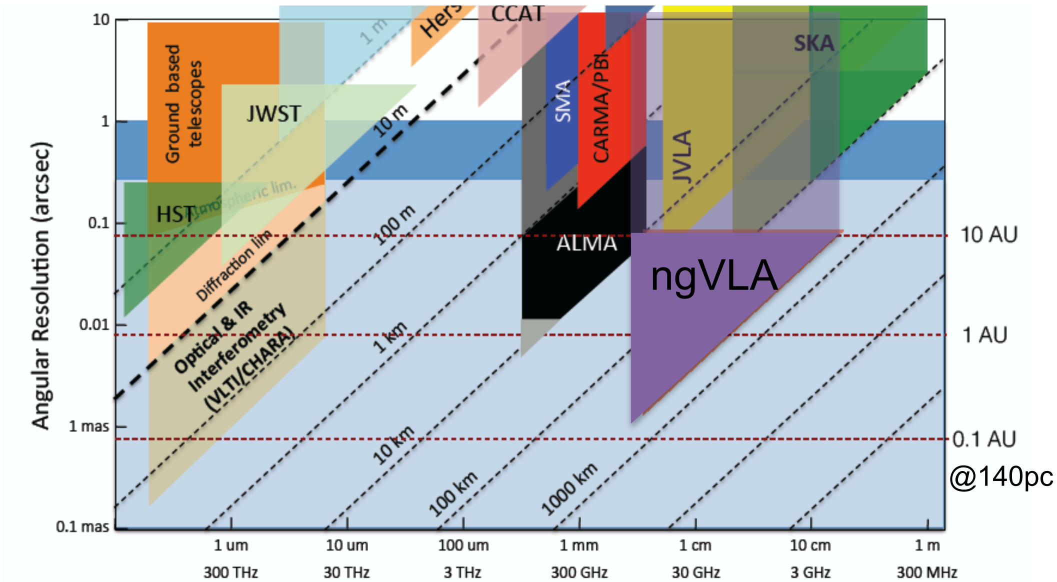
Killer Gap: *Thermal imaging on milliarcsecond scales at λ ~ 0.3cm to 3cm*

Notional Specifications
- Collecting area: spec = 5x VLA; goal = 10x VLA
- Frequency range: 1– 50 GHz + 70–115 GHz
- Configuration: 50% to 3km; 40% to 200km; 10%? to 3000km

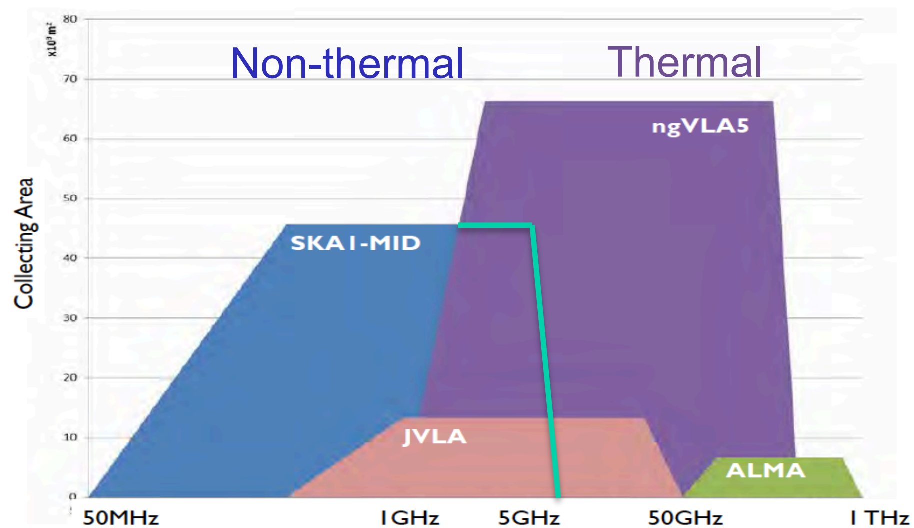
Killer Gap: Opening parameter space

Order of magnitude improvements

- Resolution ~ 15mas @ 1cm (180km)
- Sensitivity ~ 0.2uJy (1cm, 10hr, 8GHz)
- T_B ~ 1K @ 15mas, 1cm

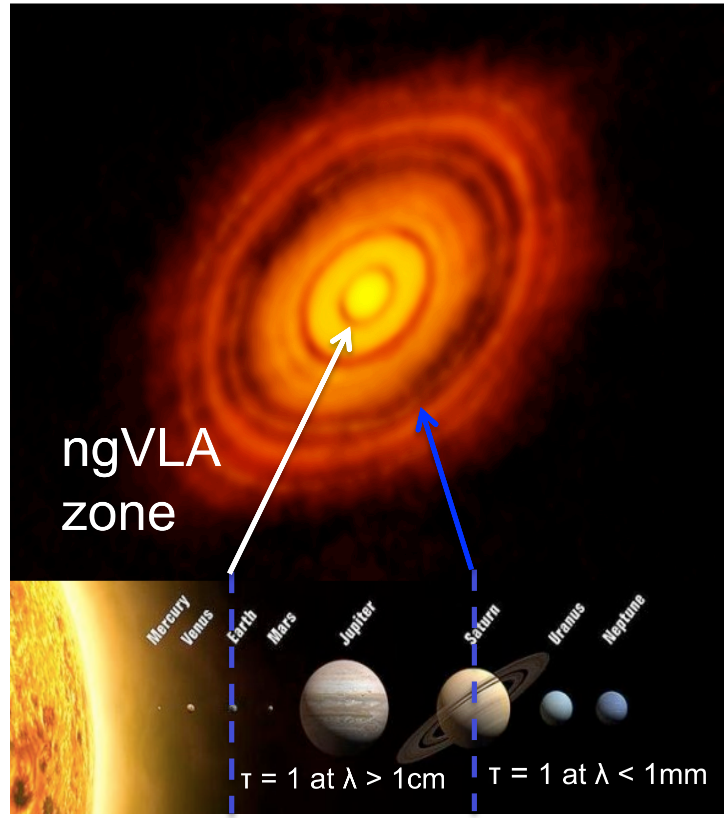


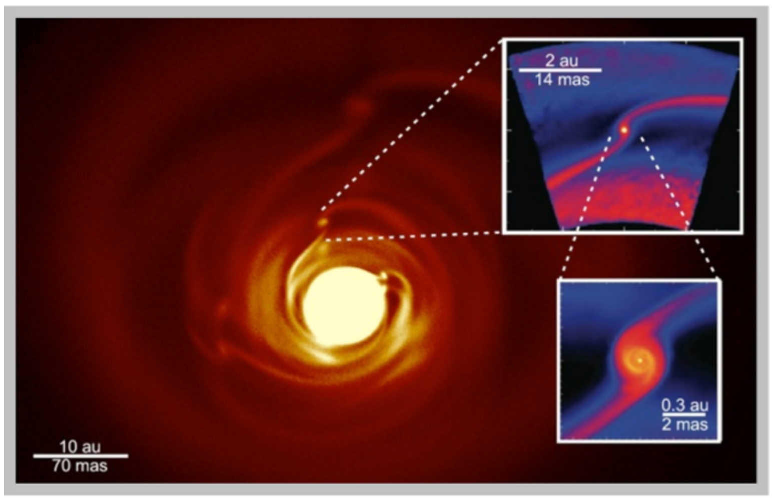
Next-generation VLA – x5



Terrestrial planet formation imager: seeing through dust to rocks on AU scales (Isella et al. SWG1)

- Grain size stratification at 0.3cm to 3cm
  - ➢ low optical depth inner disk (optically thick in submm)
  - ➢ Traces pebbles and rocks throughout the disk = poorly understood transition from dust to planetesimals



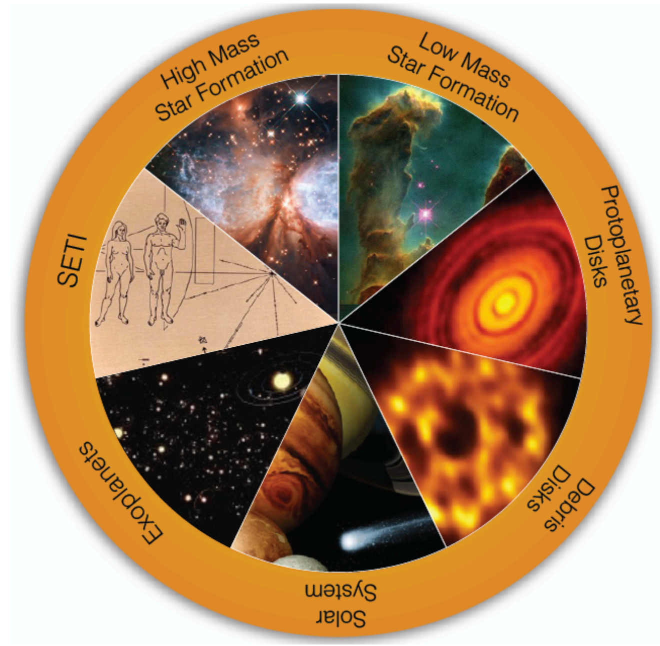


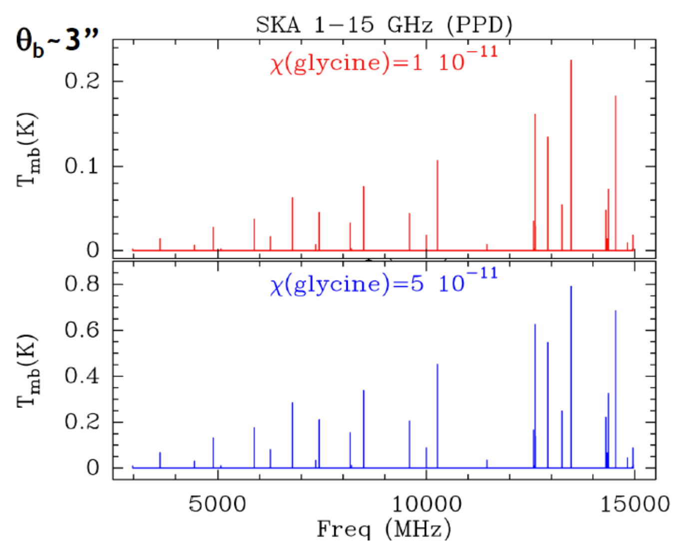
- Access to terrestrial planet-forming zone ~ 1AU @140pc: annual variability!
- Circumplanetary disks: imaging accretion onto planets!

ngVLA: origin stars, planets, life

- Chemistry in PP disks on AU-scales, peer deep into planetary atmospheres, comets, asteroids
  - ➢ Complex organics: ice chemistry in cold regions
  - ➢ Pre-biotic molecules: rich chemistry in 0.3cm to 3cm regime [Need new glycine spectrum at 1 to 50GHz]
  - ➢ Ammonia and water

- Star formation
  - ➢ High mass star formation: in Galactic center, resolving accretion in dust-obscured early phases
  - ➢ Origin of stellar multiplicity

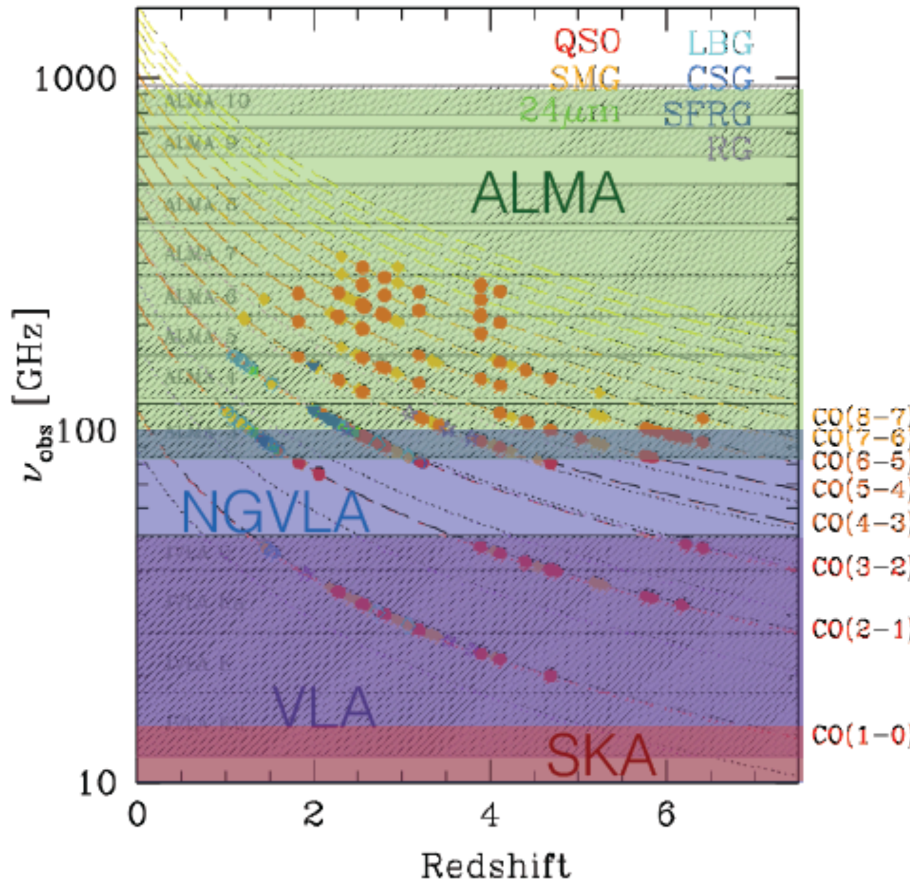




NRAO

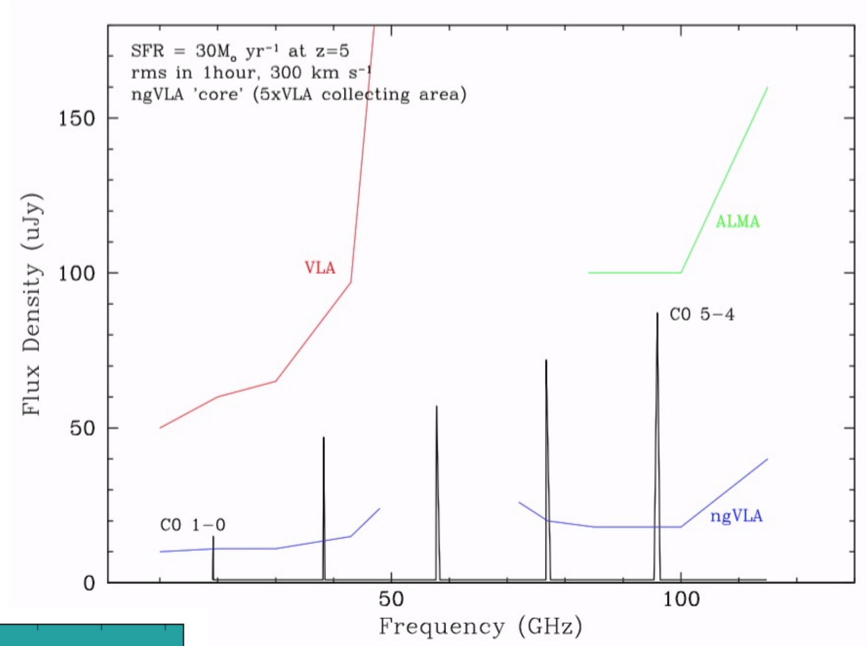
The Missing Half of Galaxy Formation: Tracing the cosmic evolution of cool gas from which stars form (Hodge et al. SWG3)

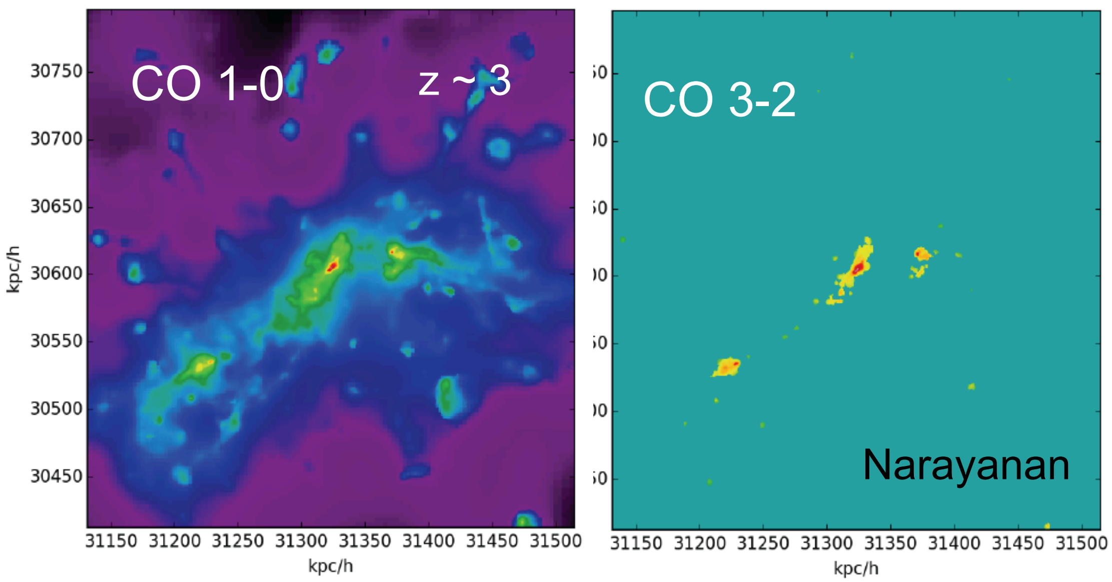
- Low order molecular transitions missed by ALMA and SKA-1 for high z galaxies.
- Low order => critical diagnostics
  - ➢ Total gas mass w/o excitation uncertainty [high order lines may not be excited]
  - ➢ Dense gas tracers associated w. SF cores: HCN, HCO+…
  - ➢ Comparative astrochemistry wrt nearby galaxies



Galaxy formation: cool gas

Sensitive to CO emission from typical star forming, 'main sequence' galaxies at high z (~ 10 M_o $year^{-1}$)

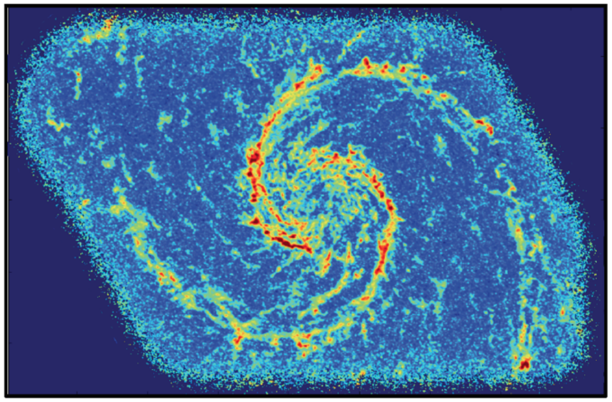


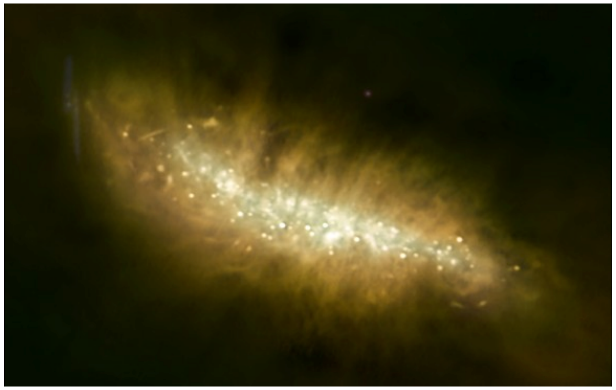


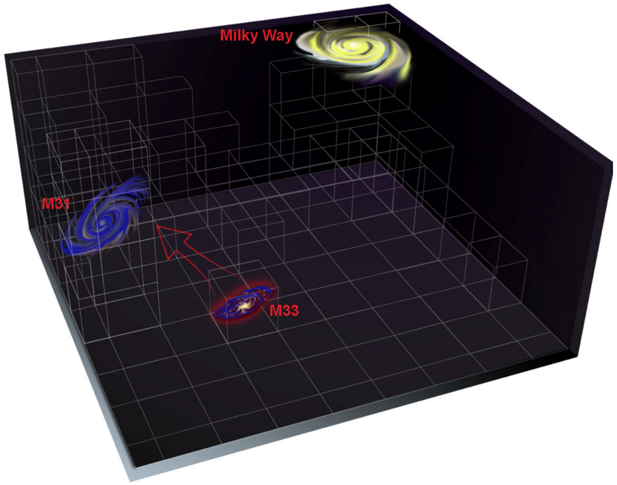
Imaging on kpc scales

- Low order: distributed gas dynamics, not just dense cores
- Resolved star formation laws

Galaxy eco-systems: Milky Way and the nearby Universe (Murphy et al. SWG2)







- Spectral Line Mapping @ 10GHz to 100GHz: Map cool ISM 10x faster than ALMA => Baryon cycle: following life cycle of gas to stars to gas
- Broad-Band Continuum Imaging: simultaneously capture all radio emission mechanisms (synchrotron, free-free, dust, SZ effect) => physics of cosmic rays, ionized gas, dust, and hot gas around galaxies.
- uas astrometry: complete view of the large scale structure of MW; 3D imaging of dynamics of local group galaxies

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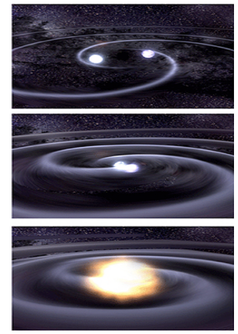
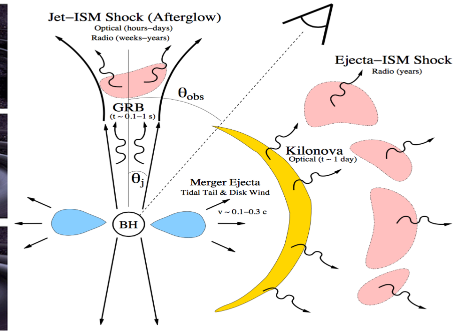
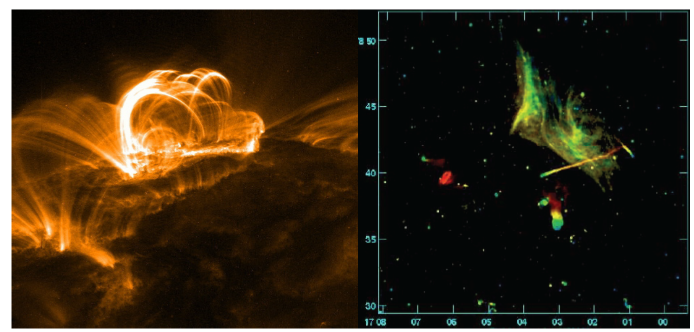
Physics and cosmology (Bower et al. SWG4)

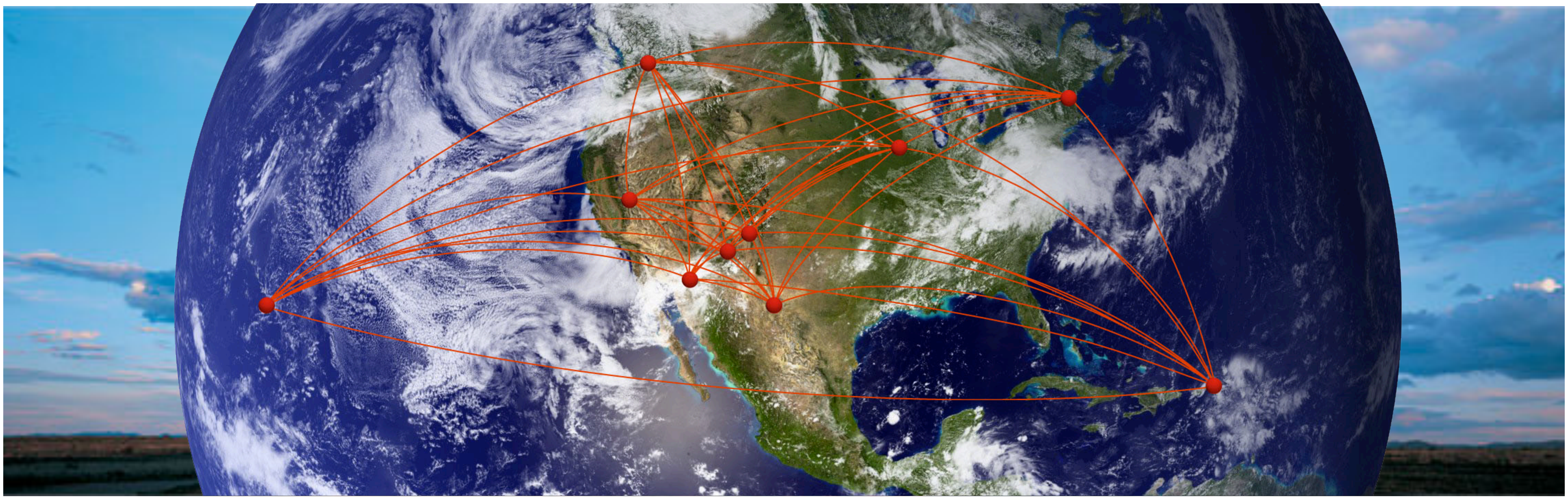
- Time domain: phenomena peaking @ 0.3cm to 3cm
  - ➢ Radio counterparts to GW events
  - ➢ FRBs, TDEs
  - ➢ Solar bursts
  - ➢ Novae: 'peeling onion'
- Stellar photospheres
- Galactic Center pulsars: strong field GR
- Evolution fundamental constants via. Quasar absorption lines
- Megamasers: SMBH and precision cosmology: 1% H_o
- The plasma Universe: solar flares to galaxy clusters

NRAO

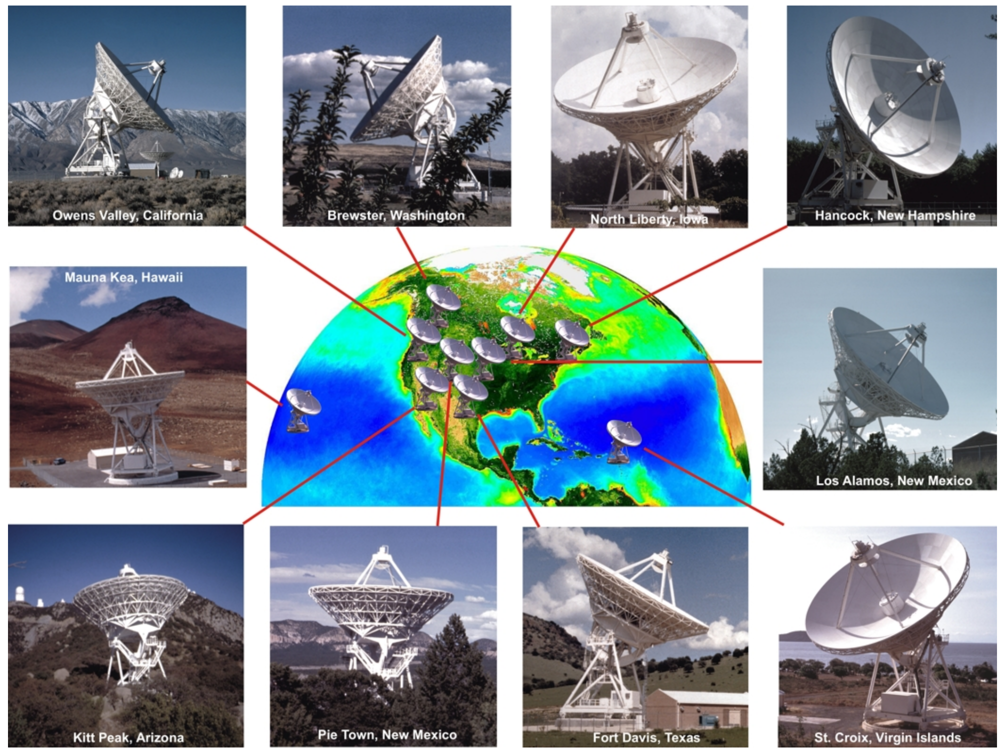
The Very Long Baseline Array



Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

The VLBA

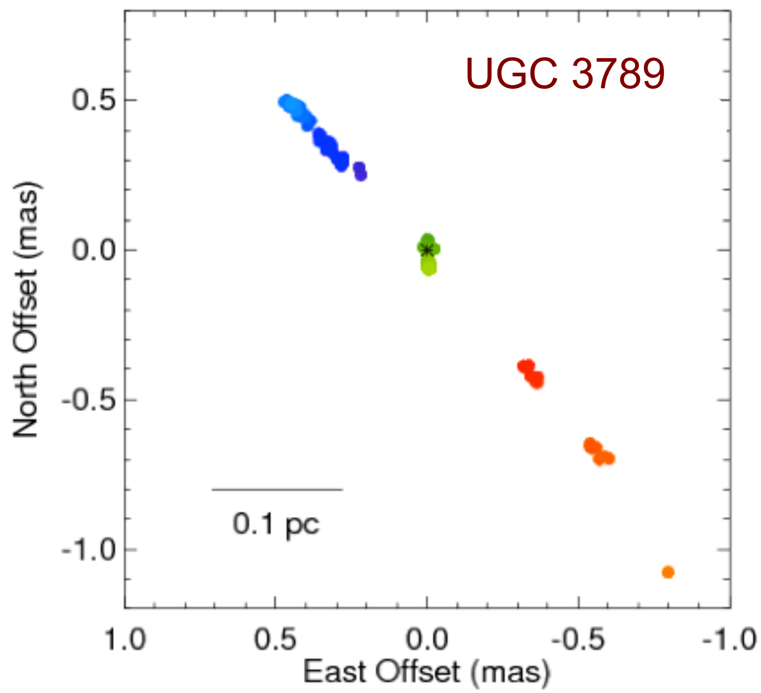
- A dedicated VLBI array
- 10 identical 25-m antennas.
- Spanning Mauna Kea to St. Croix
- Baselines 200 to 8600 km
- Frequencies 310 MHz to 90 GHz
- Sensitive to compact structures with $T_b > 10^5$ K
- Software correlator, DiFX



Resolution!

- 25 *milli* arcsecond at 330 MHz.
- 80 *micro* arcsec at 90 GHz.

- 1 mas is
  - 0.1 AU at 100 pc (Galactic)
  - 10 AU at 10 kpc
  - 1000 AU at 1 Mpc (Extragal)
  - 5 pc at 1 Gpc



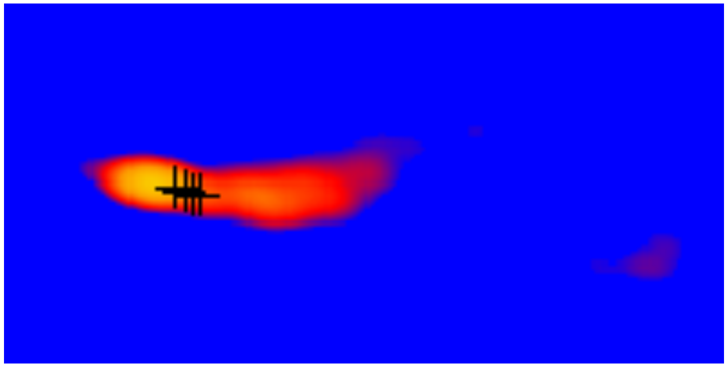
The Megamaser Cosmology Project
(Braatz et al.)

Mapping H_2O maser disks in AGNs
to measure H_0 and determine SMBH masses

NRAO

Fast Response & Monitoring

- Dedicated array
- Targets of Opportunity
- Monitoring



AGN 1222+216

Example: The MOJAVE project (Lister et al.)

Examining the evolution of AGN jets and their magnetic fields, and the medium into which the jets are expanding

NRAO

Astrometry

- Astrometry: parallax and proper motions.
  - Instrumental stability with long baselines
  - < 0.1 mas positions are routine
  - 0.01 mas demonstrated in some cases
  - Allows 1% distance measurements at 1 kpc

Example: Distance to Pleiades
(Melis et al. 2014)

d = 136.2 ± 1.2 pc (1%)

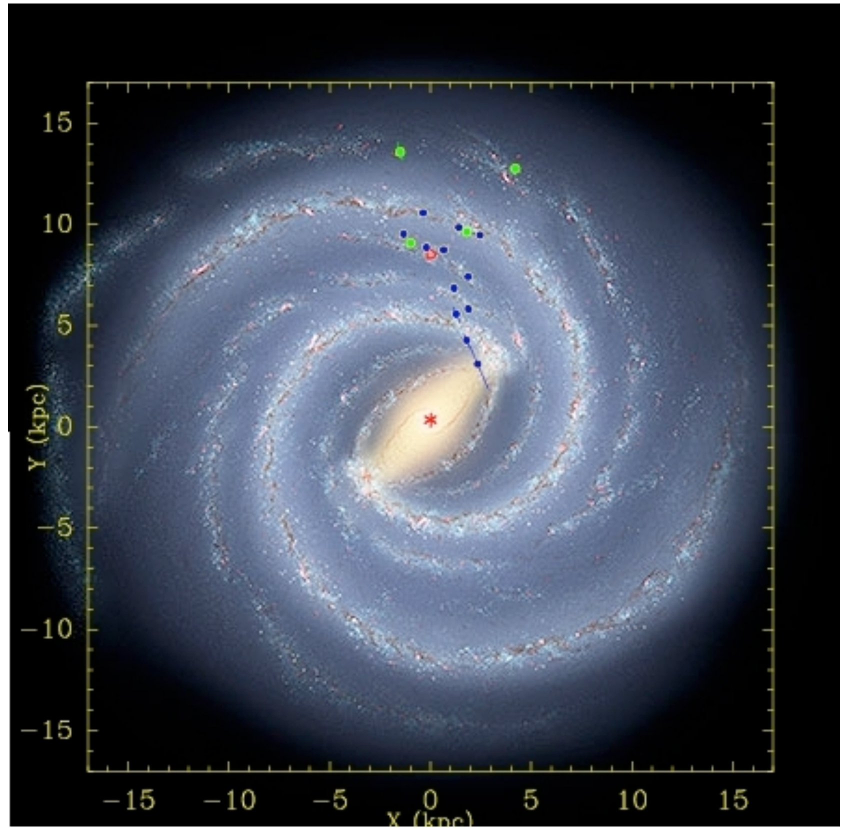
Astrometry

- Astrometry: parallax and proper motions.
  - Instrumental stability with long baselines
  - < 0.1 mas positions are routine
  - 0.01 mas demonstrated in some cases
  - Allows 1% distance measurements at 1 kpc

Example: BeSSeL (Reid et al. 2014)

Mapping Galactic structure and measuring fundamental parameters by measuring parallaxes and proper motions of SF regions

R_0 = 8.4 ± 0.6 kpc
Θ_0 = 254 ± 16 km/s



VLBA Frequency bands and Sensitivity

λ(cm)	ν(GHz)	σ(μJy/beam) in 8 hrs at 2Gbps
90 cm	0.312 - 0.342	266*
50 cm	0.596 - 0.626	681*
21 cm	1.35 - 1.75	10-12
13 cm	2.15 - 2.35	12
6 cm (upgrade)	3.9 - 7.9	6-9
4 cm	8.0 - 8.8	11-15
2 cm	12.0 - 15.4	18
1 cm	21.7 - 24.1	18-22
7 mm	41.0 - 45.0	40
3 mm	80.0 - 90.0	180†

- 2 Gbps recording delivers a bandwidth of 256 MHz with two polarizations.
- 90 cm band assumes 32 MHz of bandwidth.
- 50 cm band assumes 4 MHz of bandwidth.

* Narrower bandwidths

† 8 stations

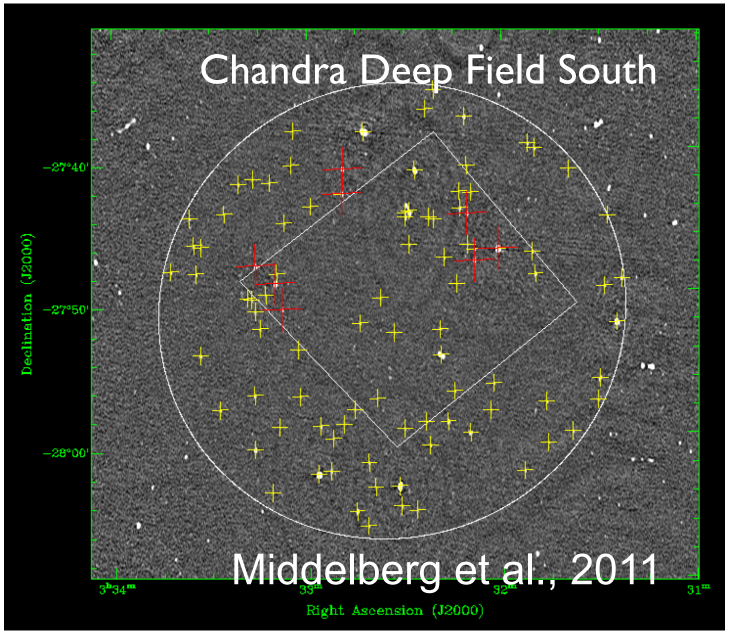
VLBA Correlator (DiFX) Capabilities I
Spectral Resolution

- DiFX is a software correlator in Socorro, NM
  - 1-8 sub-bands up to 128 MHz wide
  - Up to 4096 channels per sub-band routinely
  - Up to 132096 channels possible

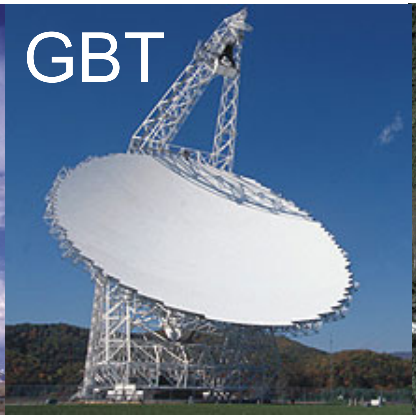
- Spectral zooming to achieve higher spectral resolution.
- Useful for:
  - Masers with in-beam continuum calibrators: wide bands for maximum sensitivity on calibrator + high spectral resolution for the masers.
  - Masers with multiple transitions: wide bands to cover a large number of widely separated maser transitions + high spectral resolution for each transition.

VLBA Correlator (DiFX) Capabilities II: Wide-field and Multi-field Imaging

- The sky is almost entirely empty at VLBI resolution
  - "full beam" imaging not needed; rather, many small "fields" are imaged
  - DiFX images many fields in one correlator pass
  - Low overhead (~2.5X) is only weakly dependent on the number of fields
  - e.g. 200 fields require only 20% more correlator time than 2 fields.

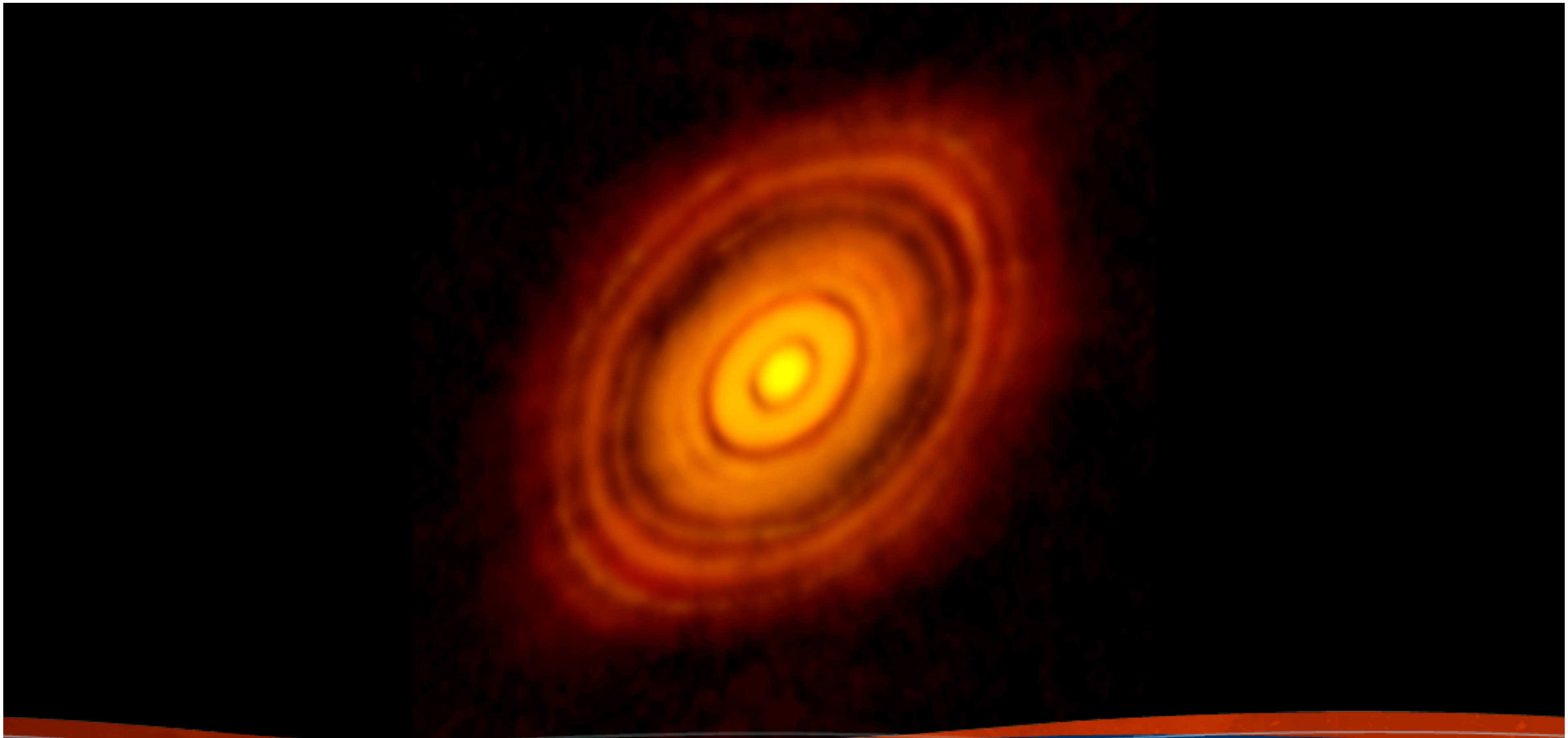


The High Sensitivity Array (HSA):
To boost the sensitivity of the VLBA by an order of magnitude



The High Sensitivity Array at 3mm

VLBA+LMT+GBT offered under the VLBA RSRO program



ALMA Cycle 3 Preparations

Timeline for Cycle 3

- Call for proposals: March 24, 2015
- Deadline for submission: April 23, 2015
- Proposal Review meetings: June 22-26, 2015
- Communication of Outcome of Review Process: August 2015
- Start of Cycle 3: October 1, 2015 – **12 months**

Capabilities for Cycle 3

- At least 36x12m antennas in the main array, and 10x7m antennas (for short baselines) and 2x12m antennas (for making single-dish maps) in the Morita-san Array (ACA)
- Receiver bands 3, 4, 6, 7, 8, 9, & 10
- Baselines up to 10 km for Bands 3, 4 and 6
- Baselines up to 5 km for Band 7
- Baselines up to 2 km for Bands 8, 9, and 10
- Both single-field interferometry and mosaics
- Spectral-line observations with all Arrays and continuum observations with the 12m Array and the 7m Array (except in Bands 9 and 10)
- Polarization at PI-specified frequencies (on-axis, continuum in Bands 3, 6 and 7 - no ACA, no mosaics, no spectral line, no circular polarization)
- Mixed correlator modes (both high and low frequency resolution in the same observation)

In Cycle 3 we expect:

- 75% of the time awarded will go to “standard modes”: projects using mature capabilities with an established reduction path using the pipeline
- 25% of the time awarded will go to “non-standard modes”: newly offered capabilities or modes not yet incorporated in the pipeline
  - Projects that require manual data processing by ALMA staff at this time

In Cycle 3 we expect:

- 75% of the time awarded will go to "standard modes": projects using mature capabilities with an established reduction path using the pipeline
- 25% of the time awarded will go to "non-standard modes": newly offered capabilities or modes not yet incorporated in the pipeline
  - Projects that require manual data processing by ALMA staff at this time
  - All observations in Bands 8, 9 & 10 and narrow (< 100 MHz) spectral window observations in Band 7
  - Long baselines (> 2km)
  - Polarization
  - Spectral Scans
  - External ephemeris observations
  - Non-standard calibrations

NRAO Important Links

NRAO Help Desk

https://help.nrao.edu

VLBA Observational Status Summary

https://science.nrao.edu/facilities/vlba/docs/manuals/oss

EVN Sensitivity Calculator

http://www.evlbi.org/cgi-bin/EVNcalc

Proposal Submission Tool

my.nrao.edu

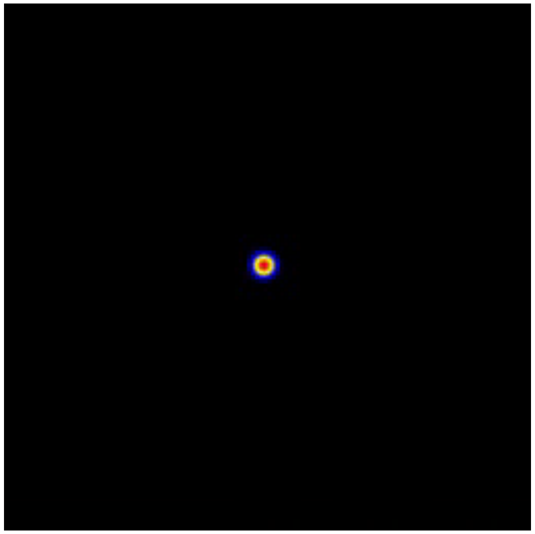
SCHED – observation preparation software

http://www.aoc.nrao.edu/software/sched/

AIPS – data reduction software

http://www.aips.nrao.edu/index.html

SN1993J in M81



10 mas

36,000 AU

Bartel et al. 2000

www.nrao.edu

science.nrao.edu