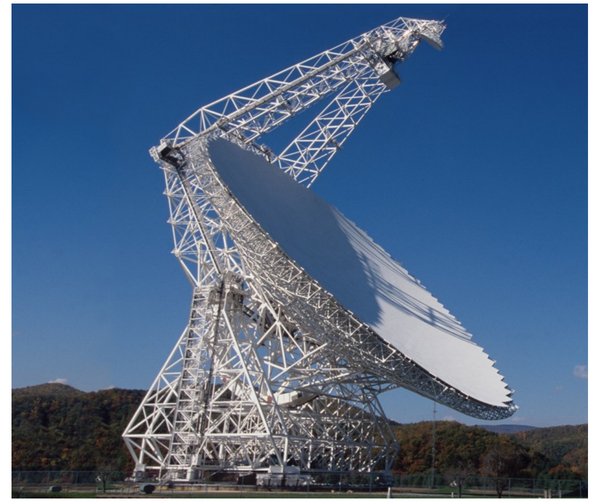
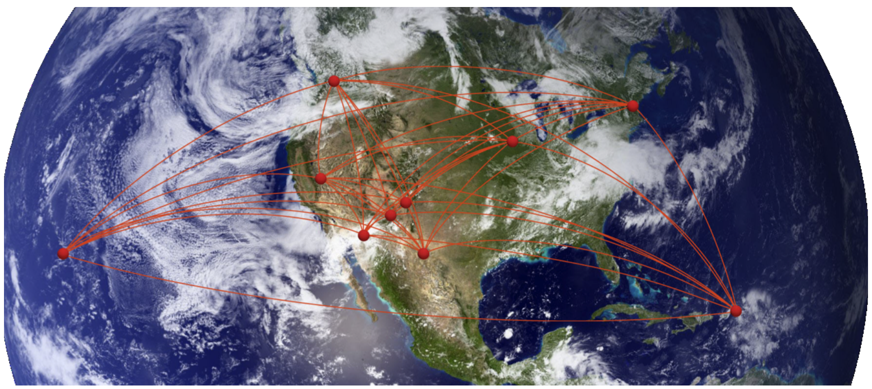
National Radio Astronomy Observatory





Jim Braatz 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

Associated Universities, Inc.

NSF

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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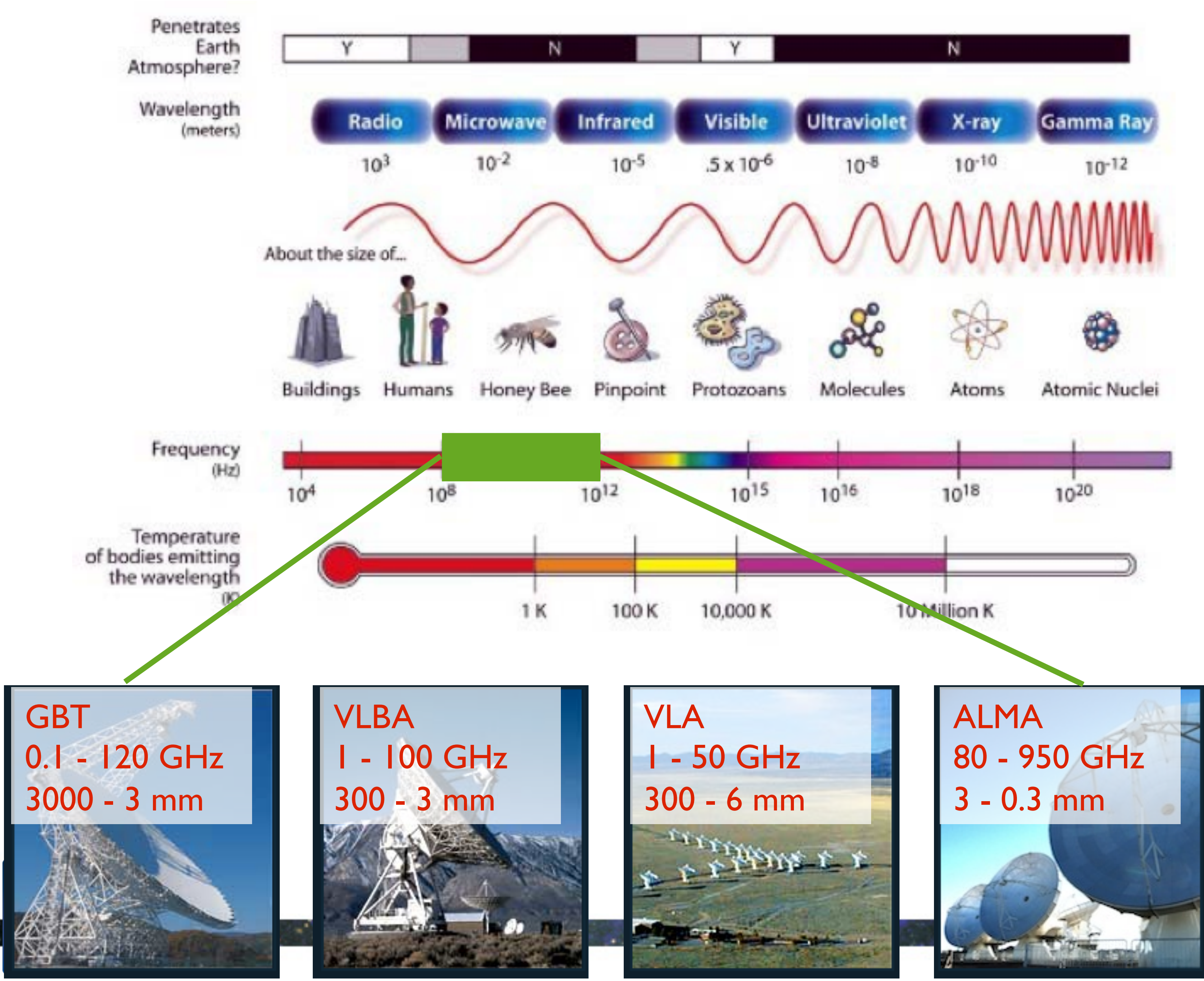
One Observatory, Four Facilities

Very Large Baseline Array:
ten radio antennas spanning 8000 km

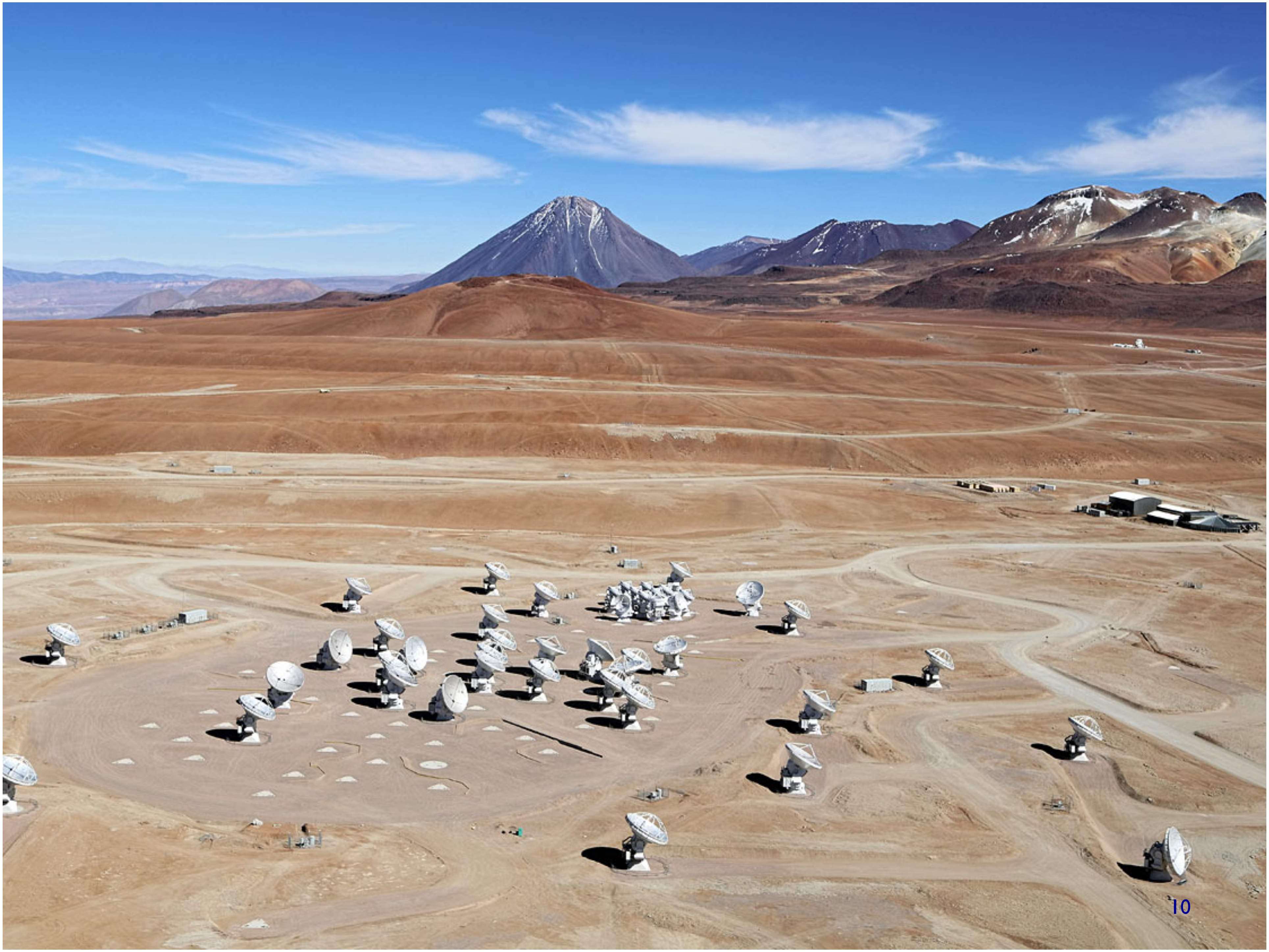

Penetrates Earth Atmosphere?
Y
N
Y
N
Wavelength (meters)
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^3
10^-2
10^-5
.5 x 10^-6
10^-8
10^-10
10^-12
About the size of...
Buildings
Humans
Honey Bee
Pinpoint
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^12
10^15
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



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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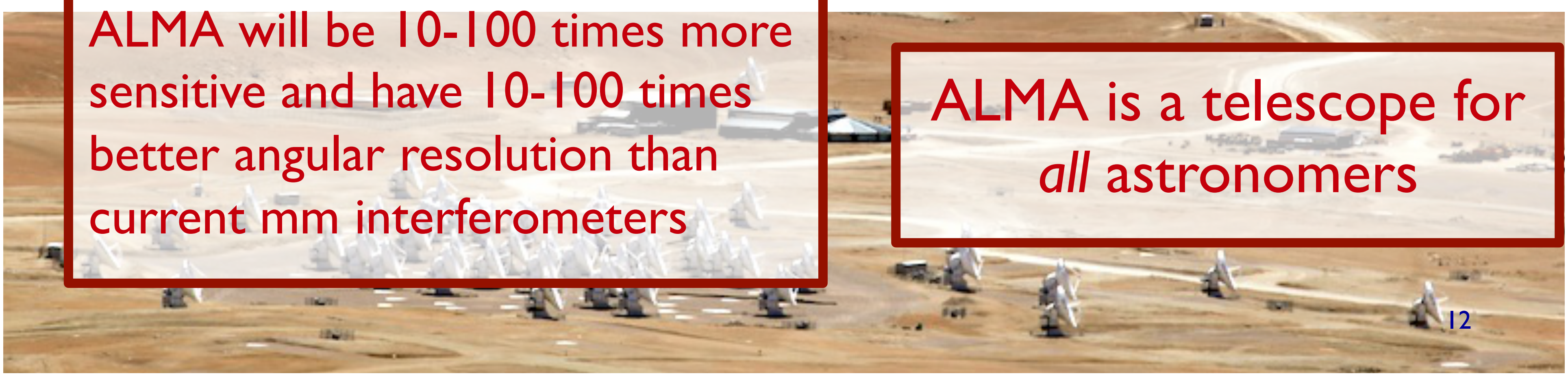
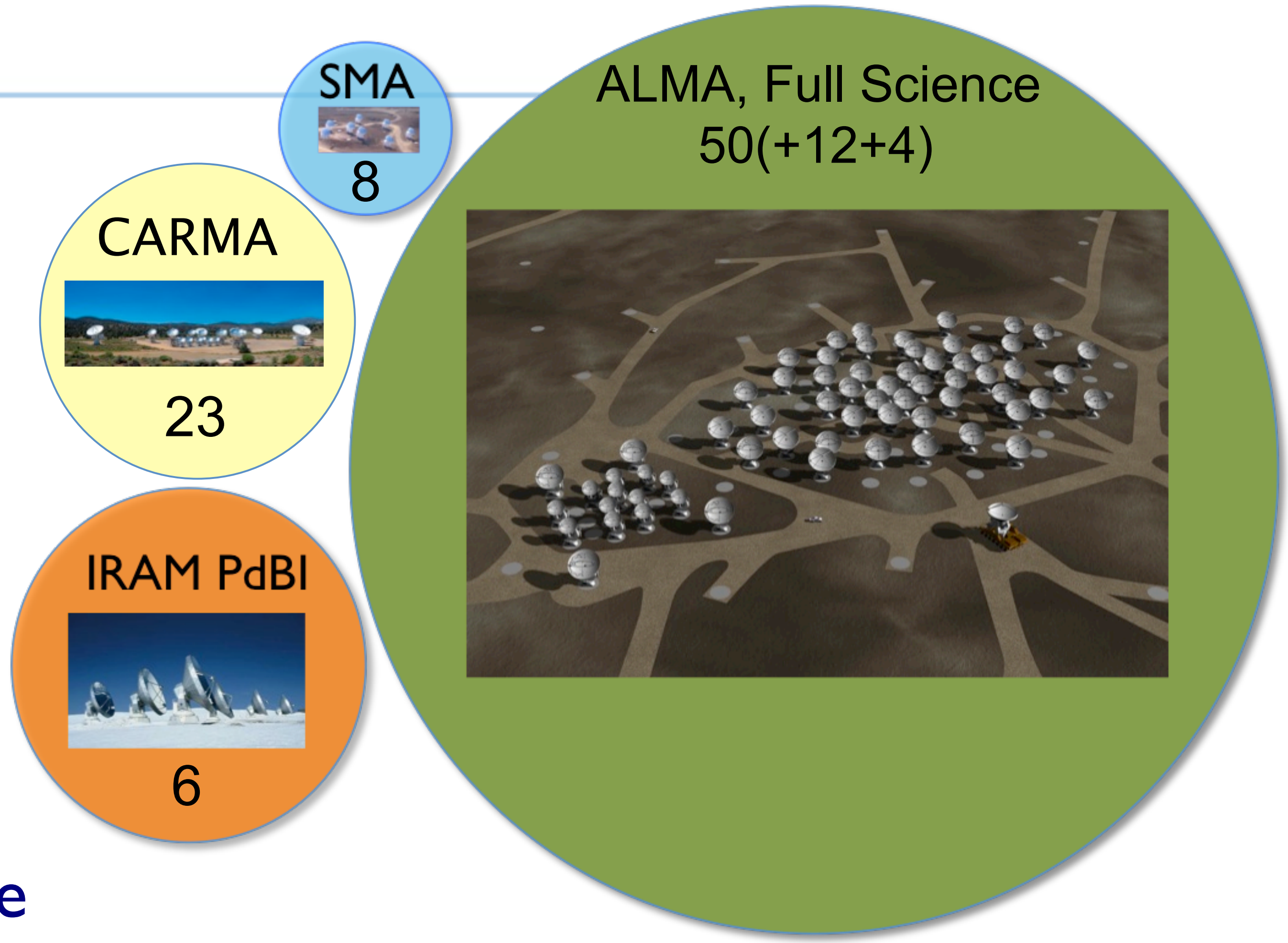


ALMA will be 10-100 times more sensitive and have 10-100 times better angular resolution than current mm interferometers

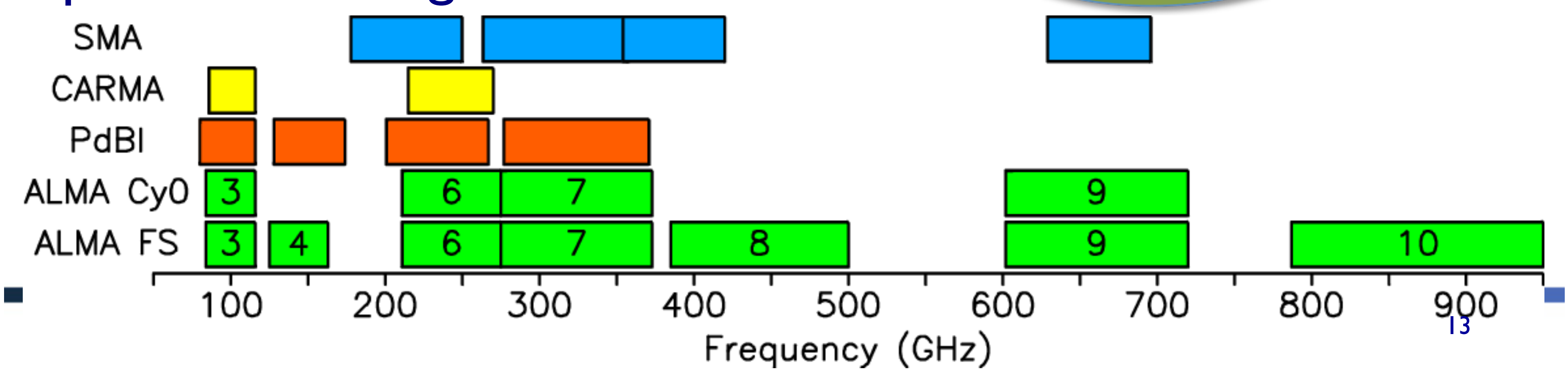
ALMA is a telescope for *all* astronomers

Collecting Area

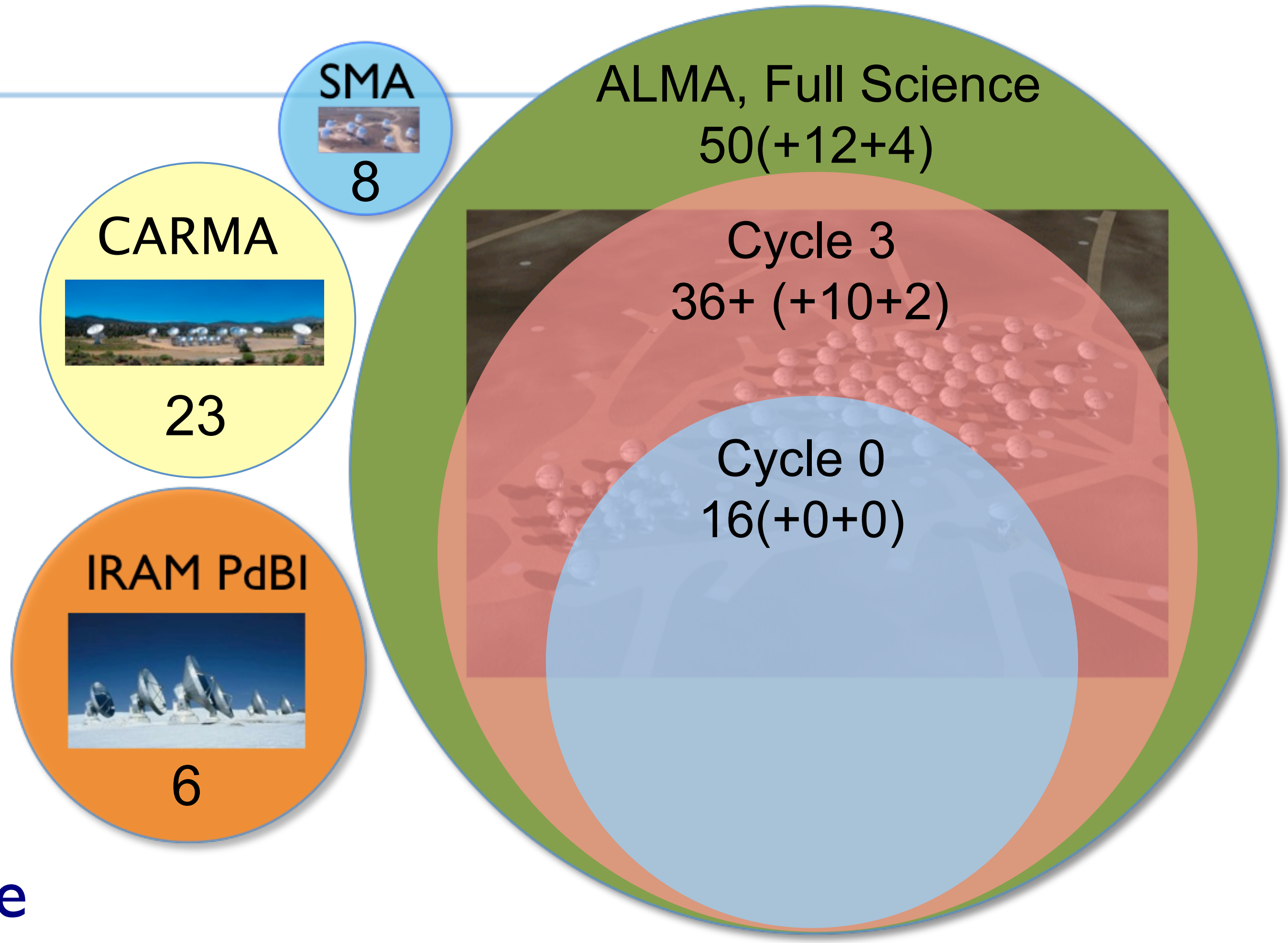
~ sensitivity



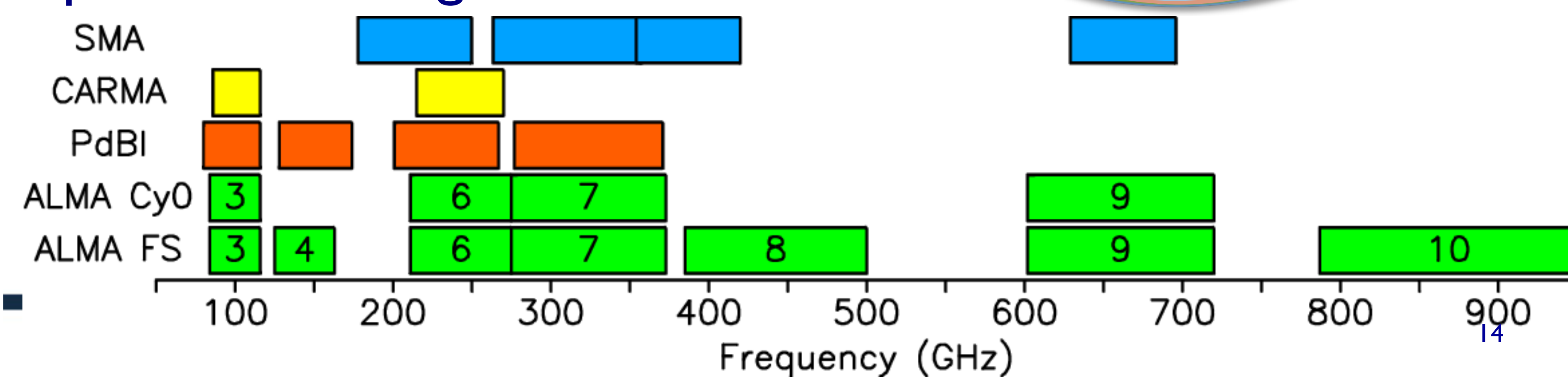
Spectral Coverage



Collecting Area
~ sensitivity

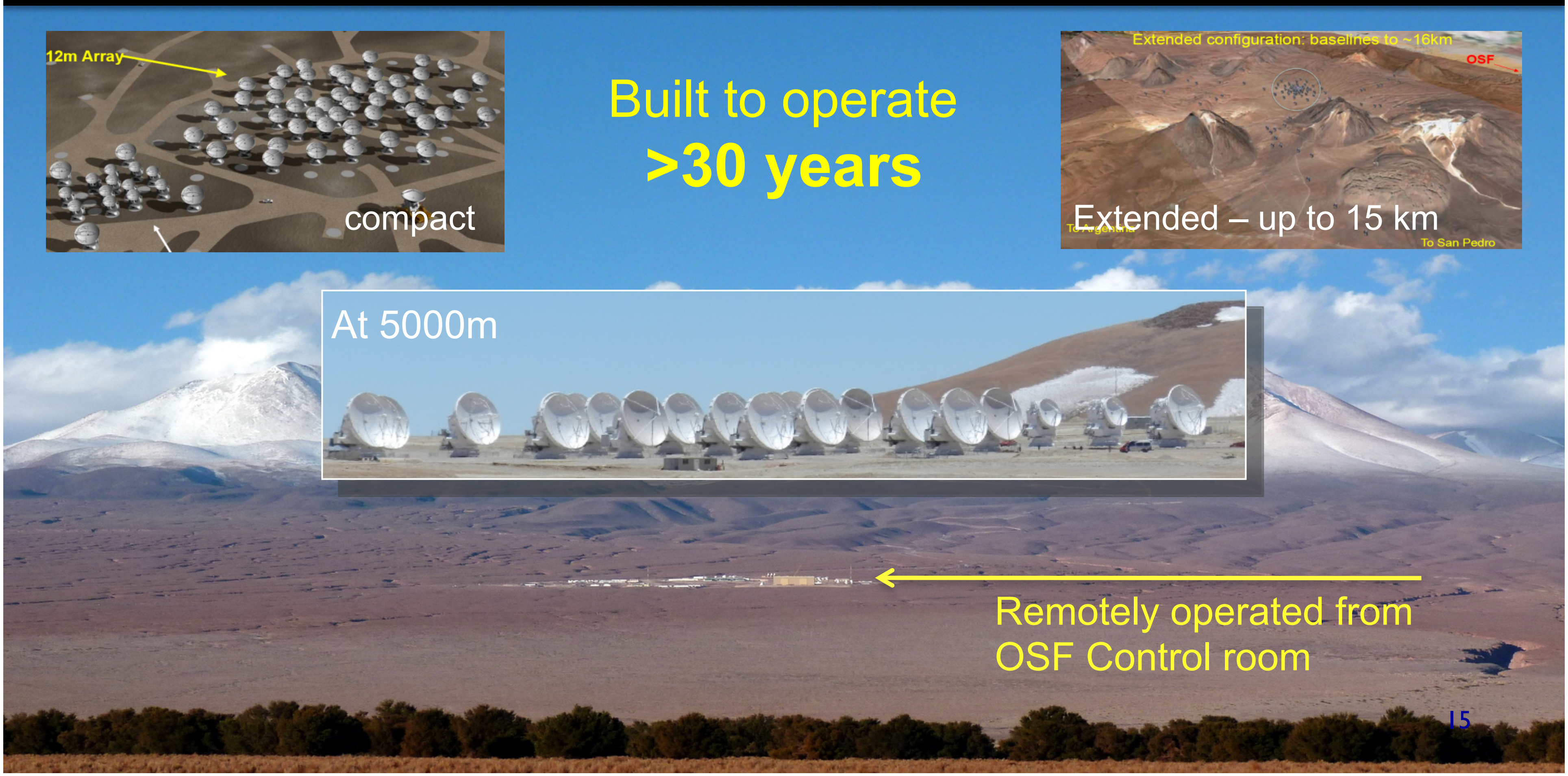


Spectral Coverage



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



ALMA Current Status

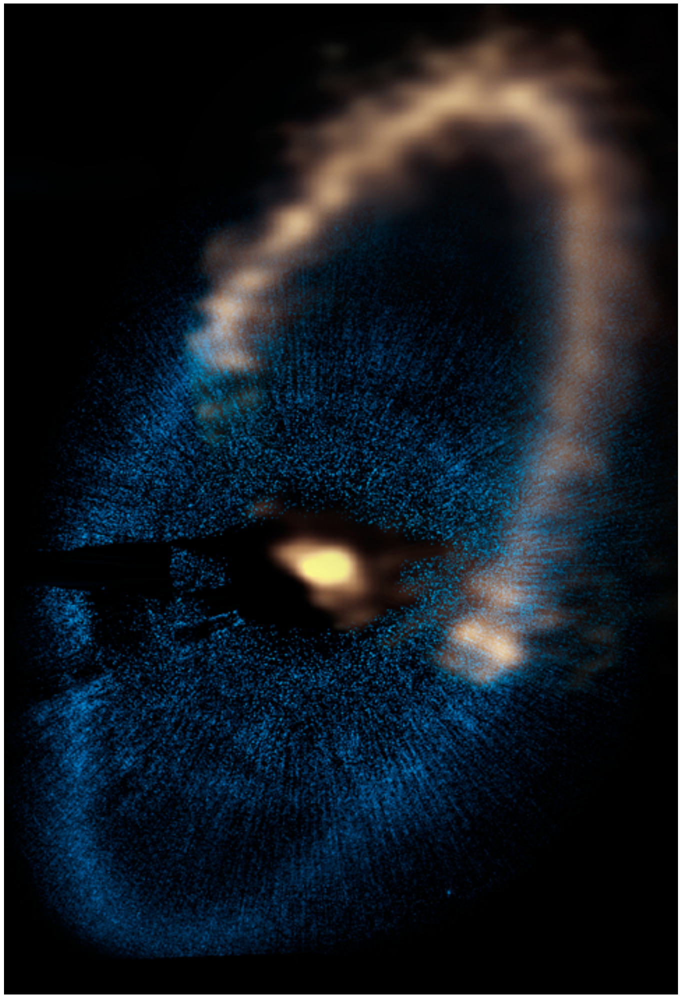
- Construction Project ended in September 2014
- Routine science observing has been limited to 1.5 km baselines (C34-7), but observations out to 15 km have been proven successful (thanks to the Long Baseline Campaign, ended December 2, 2014)
- **All 66 antennas accepted**
  - Currently 64 antennas are 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

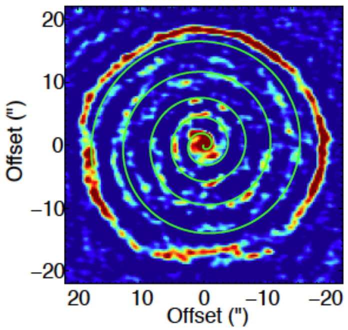
Formation of Planetary Systems

- 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

ALMA Measures Stellar Feedback

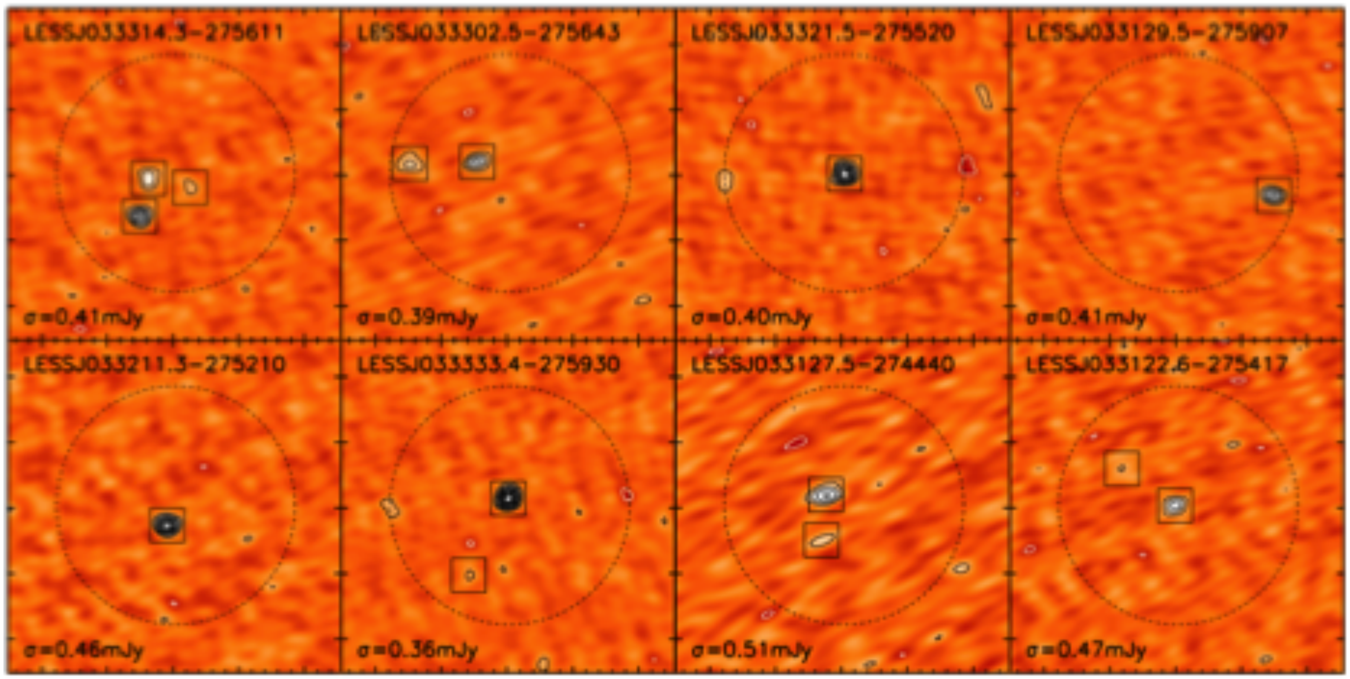


Maercker et al 2012

- ALMA's high sensitivity high resolution CO image measures the mass (0.003 M_{sun} and timescale (200 years) of feedback to the interstellar medium from the AGB star R Sculptoris and reveals the star to be a binary

NRAO

Resolving High-z Submm Galaxies



Hodge et al. 2013

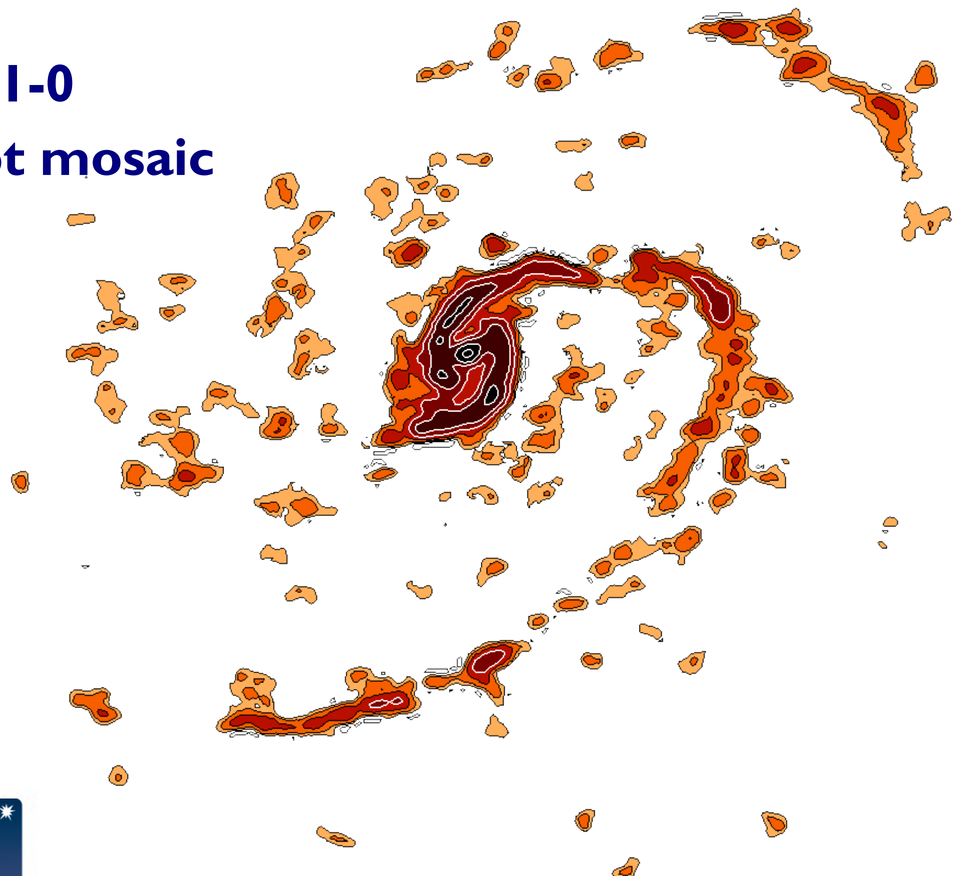
- 126 submm sources observed with ALMA at 870 μm
- 2x deeper, 10x higher angular resolution than previous surveys
- 99 sources detected in 88 fields, integration time ~120 sec
- Significant multiplicity (35-50%) found at 0.2" resolution

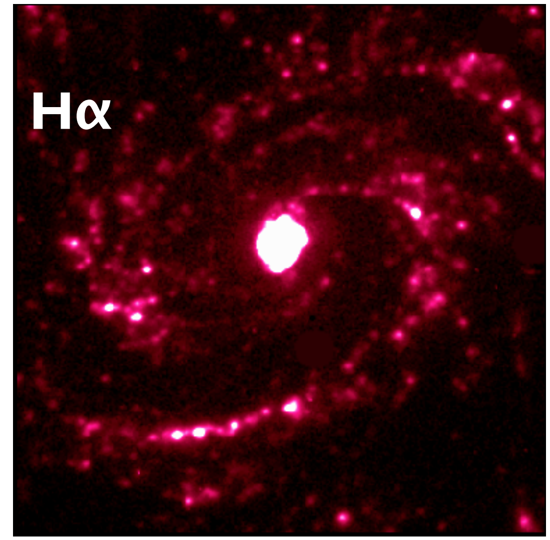
ALMA Images Nearby Galaxies

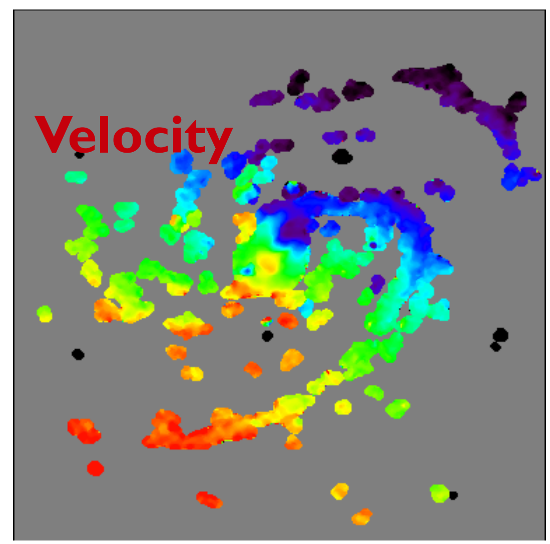
Science verification imaging of M100

CO 1-0

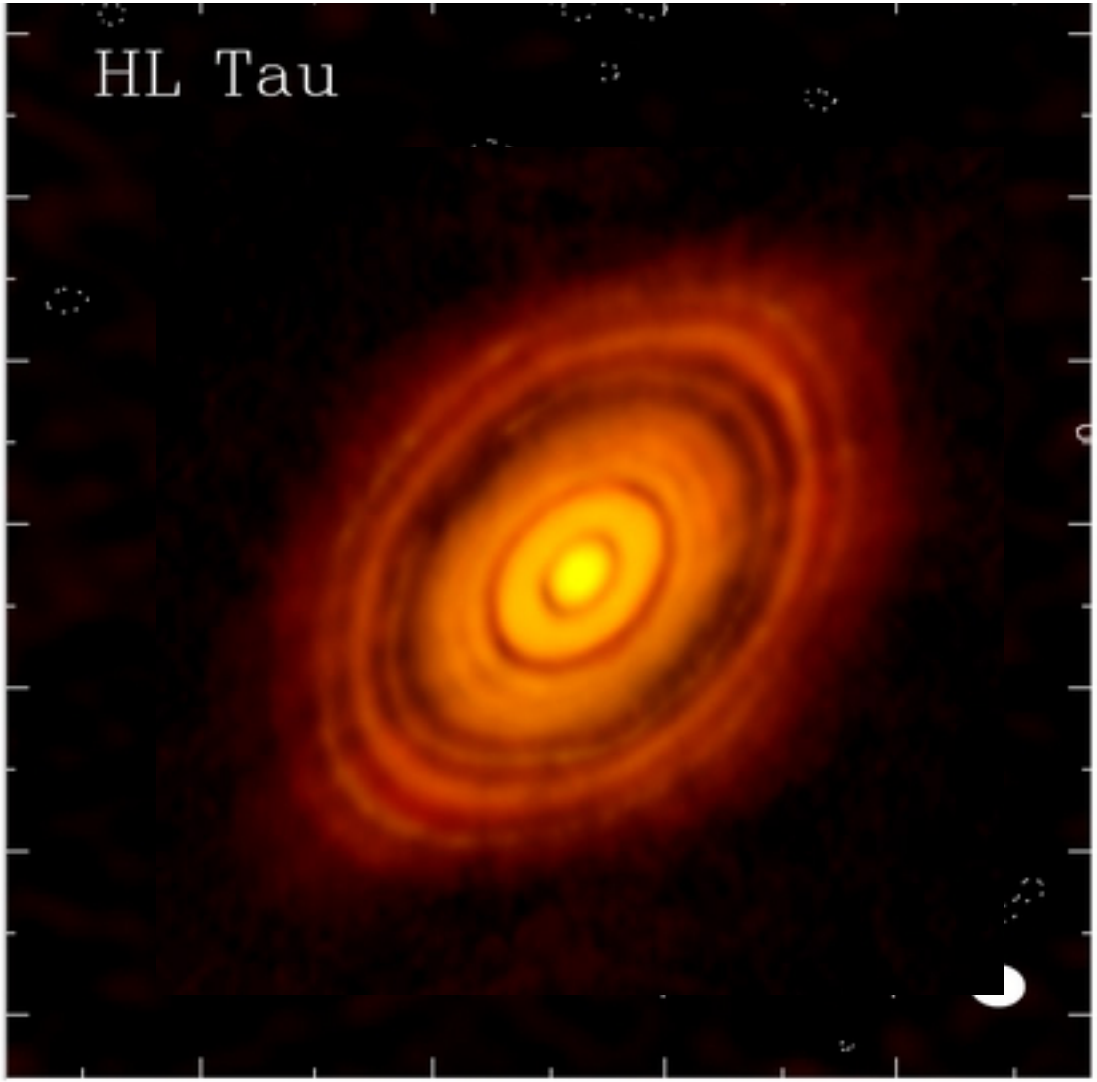
47-pt mosaic







ALMA Long Baseline Campaign



CARMA Observation of HL Tau, resolution of ~25AU

The Green Bank Telescope in 2015

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

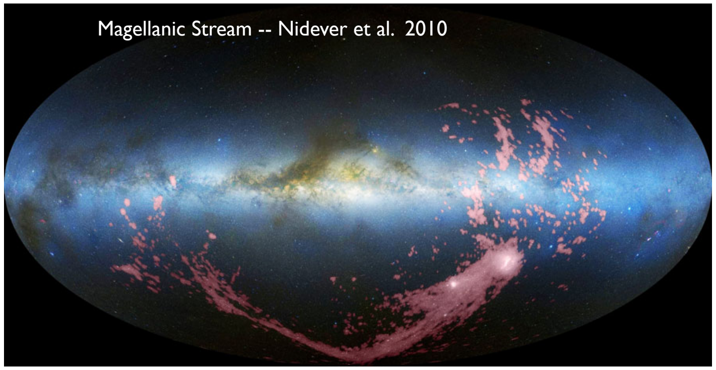
August 03, 2015 at 5pm EST

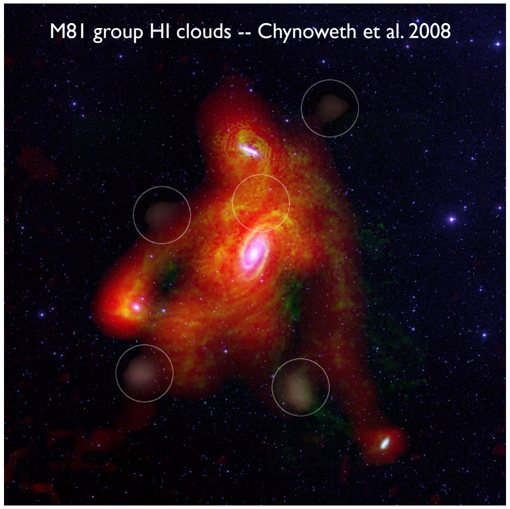
which is for semester "16A" (Feb 2016 – Aug 2016 observations)

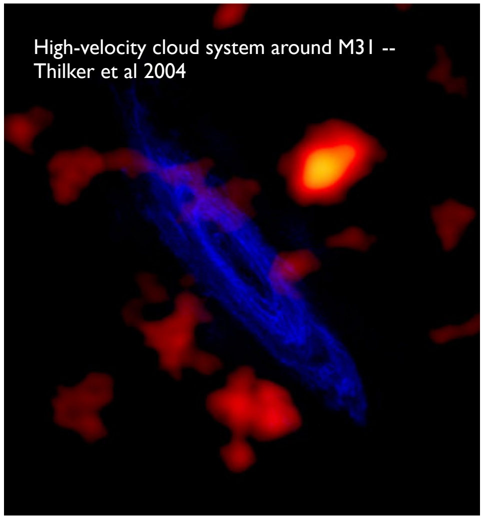
GBT Studies of faint HI -- unequalled sensitivity

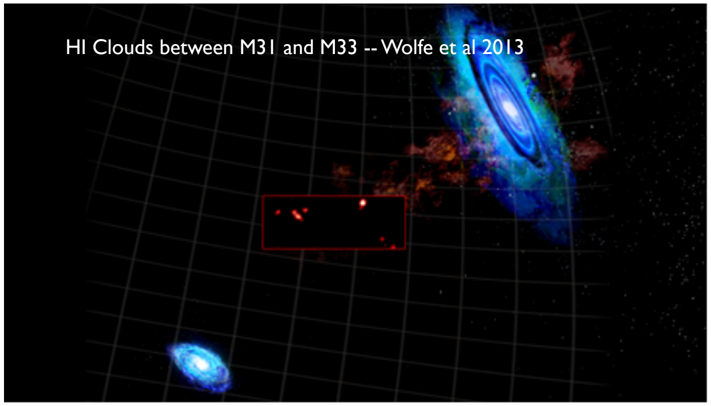
GBT offers ability to detect HI to N_{HI} ~10^{17} cm^{-2}

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







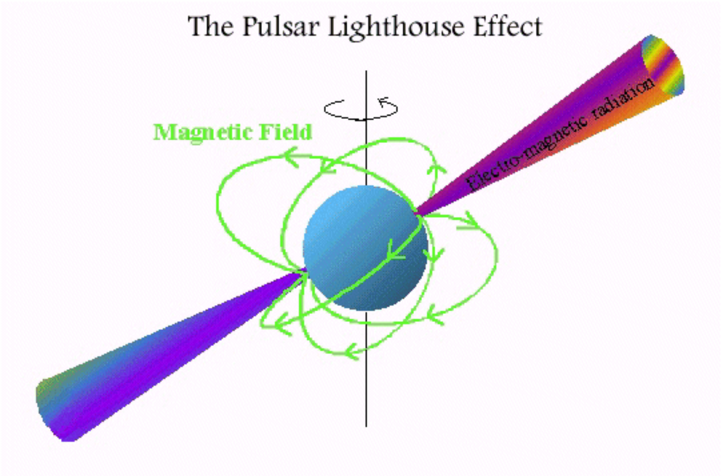


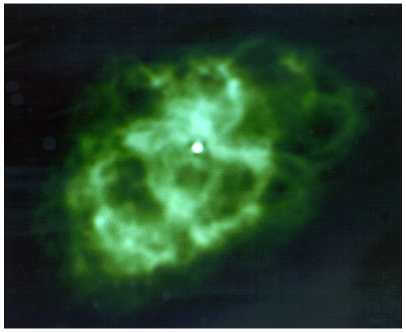
The GBT remains the world's premier pulsar observatory

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

The Pulsar Renaissance:

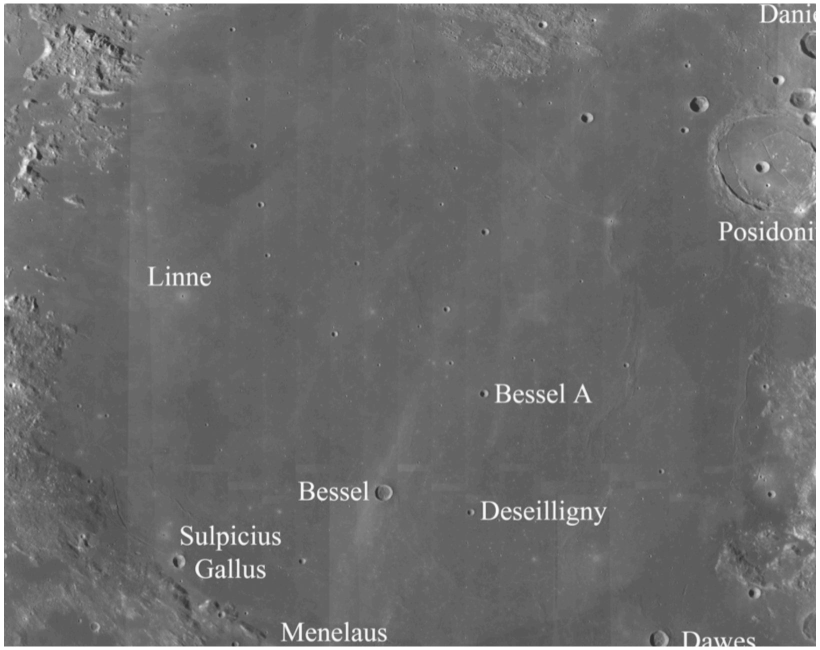
- Fastest Pulsar
- Most Massive Pulsar
- Pulsars in Globular Clusters
- Tests of General Relativity
- Relativistic Spin Precession
- Pulsar in a three-body system
- Coolest white dwarf star (a diamond as big as the Ritz)



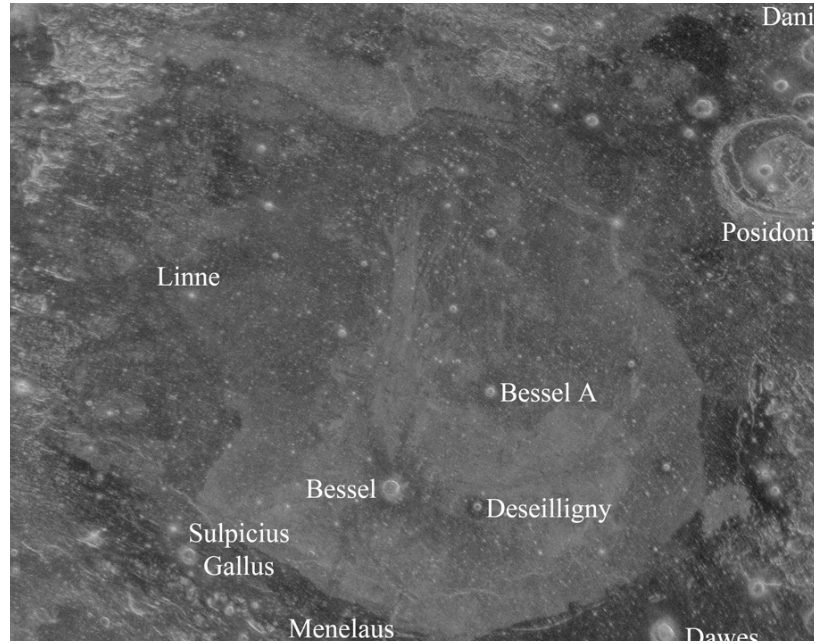


GBT Bi-static radar studies with Arecibo

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

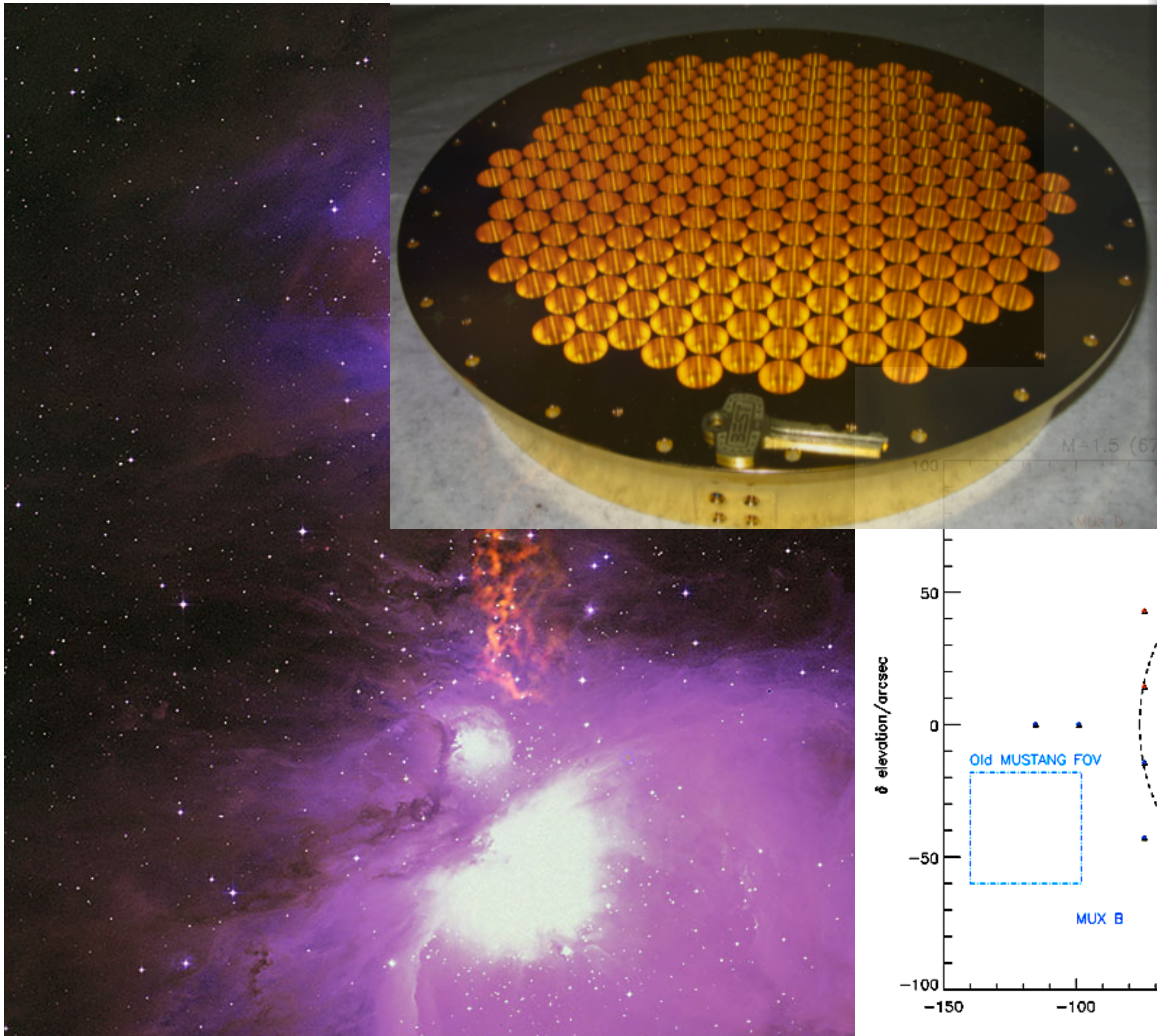
GBT Support Staff

December 19, 2013

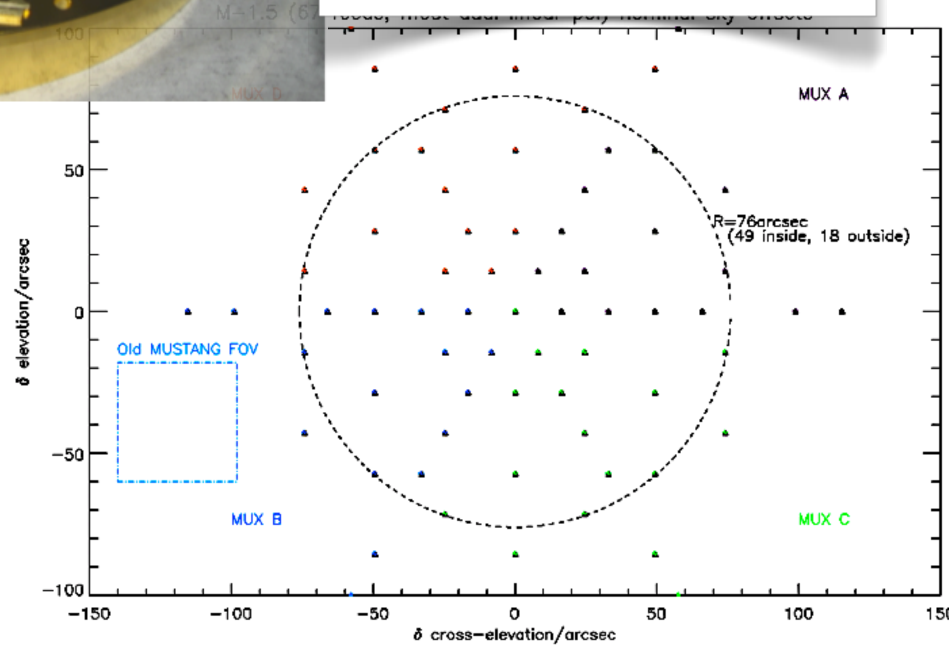
This guide provides essential information for the preparation of observing proposals on the Green Bank Telescope (GBT). The information covers the facilities that will be offered in Semester 14B.

9″ MUSTANG-1.5 Bolometer Array (UPenn)

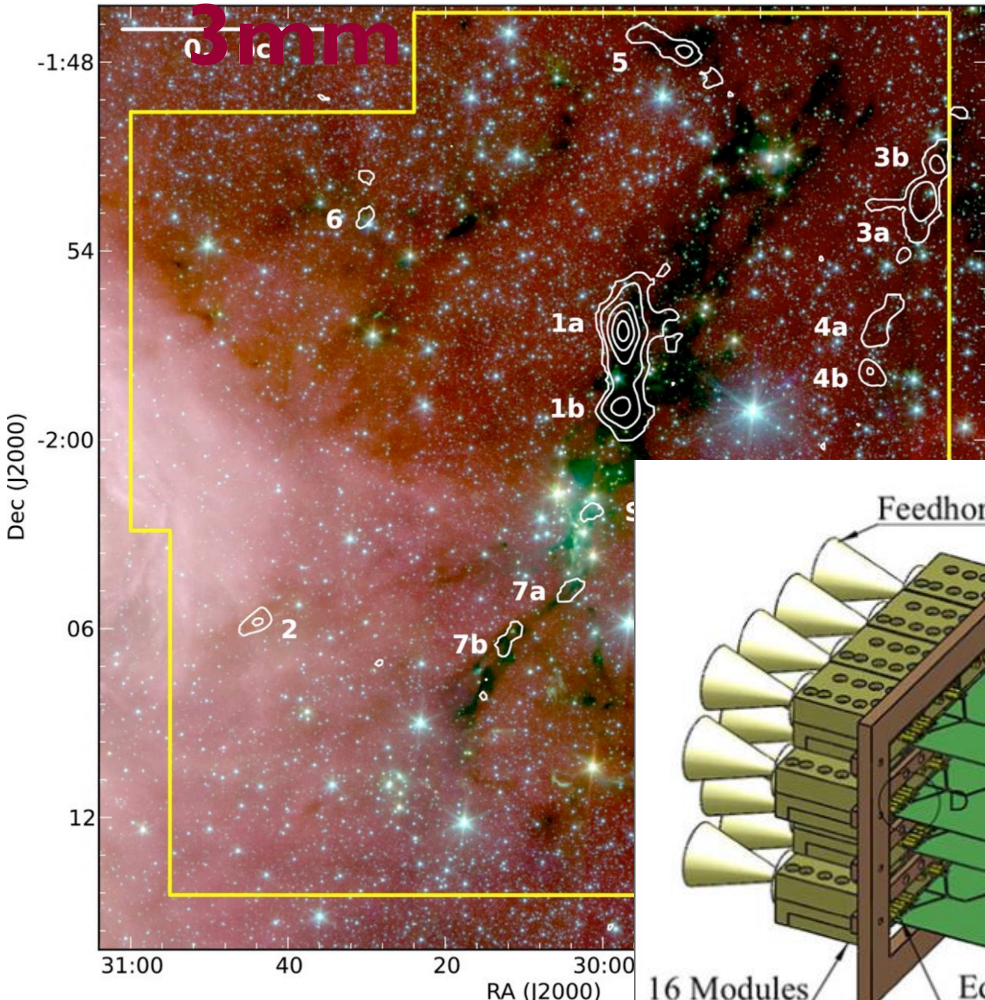
Dicker et al. (2014)



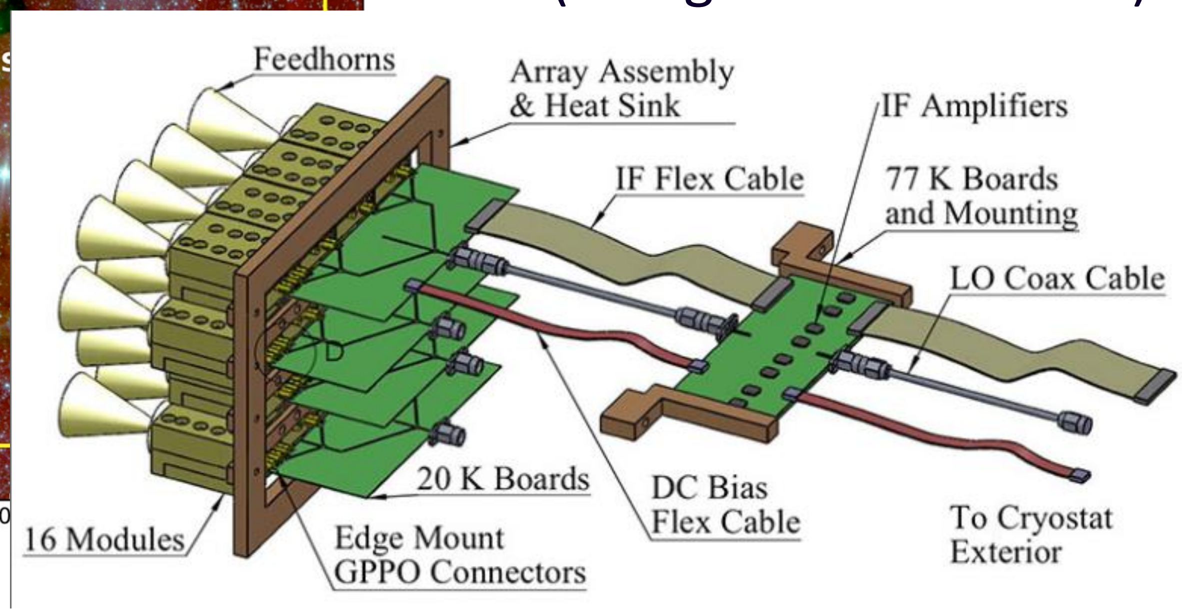
- 223 feed horns
- 64 dual-pol currently populated
- 4’ FOV
- 3x more sensitive than MUSTANG



ARGUS -- 8″ GBT spectroscopy at 3mm

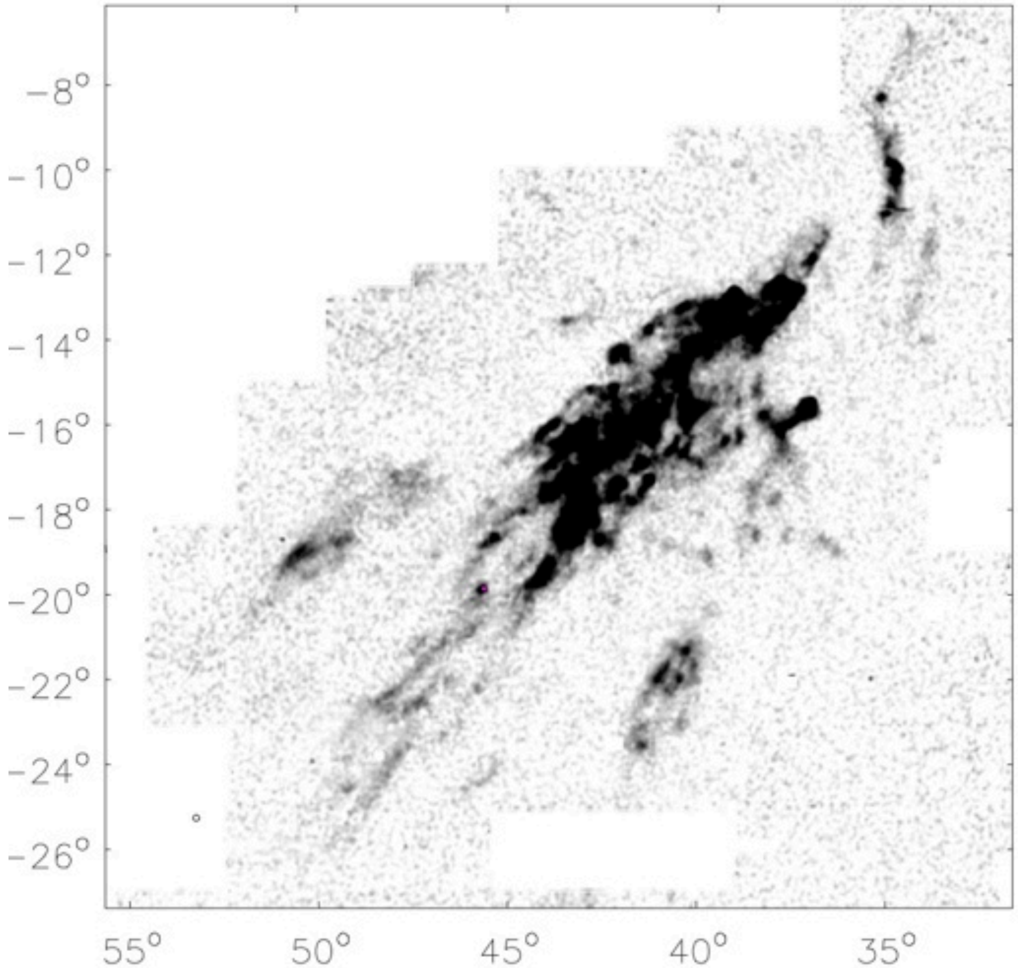


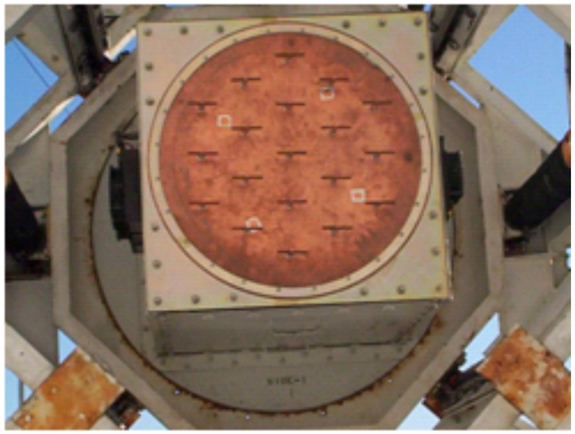
- 16 element scalable 75-115 GHz Focal Plane Array (Spring 2015)
- Stanford/CIT-JPL/UMd/ Miami/NRAO
  (NSF grant to Stanford)



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

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

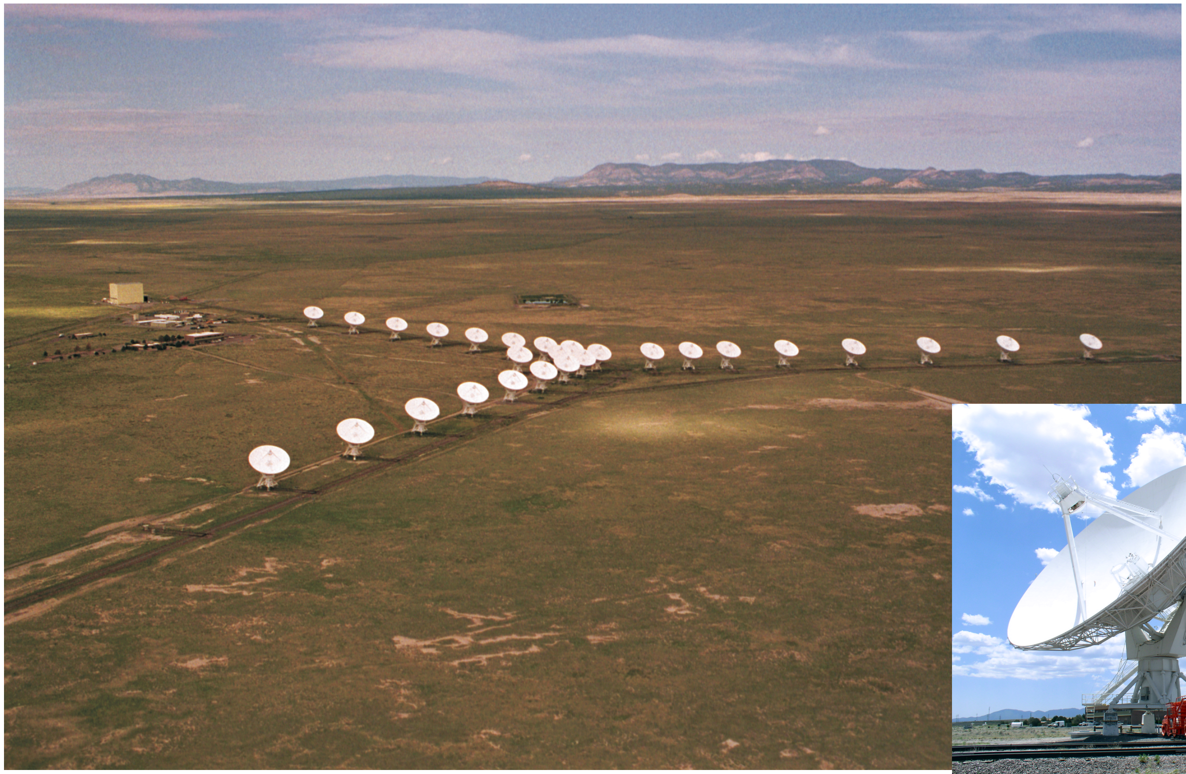
The GBT is just beginning to realize its scientific potential at high frequencies

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

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



NRAO

Angular 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

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.

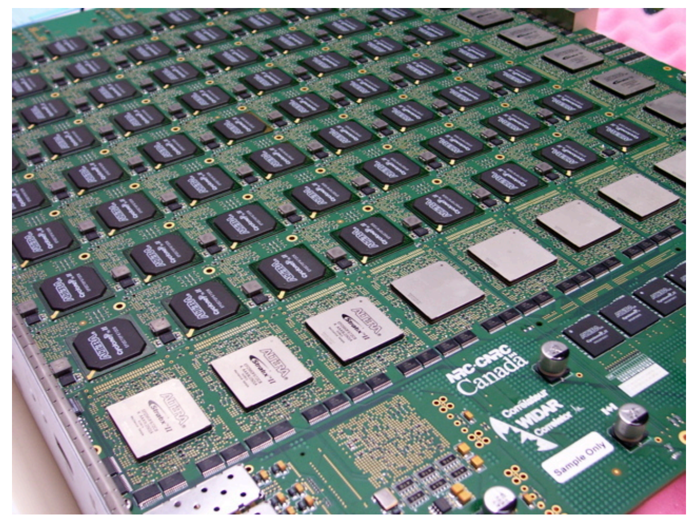
Band (GHz)		SEFD (Jy) (27 antennas)
.05 -- .45	P	~60
1-2	L	13
2-4	S	9.5
4-8	C	8.5
8-12	X	8.1
12-18	Ku	8.1
18-26.5	K	13
26.5-40	Ka	22
40-50	Q	45

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

NRAO

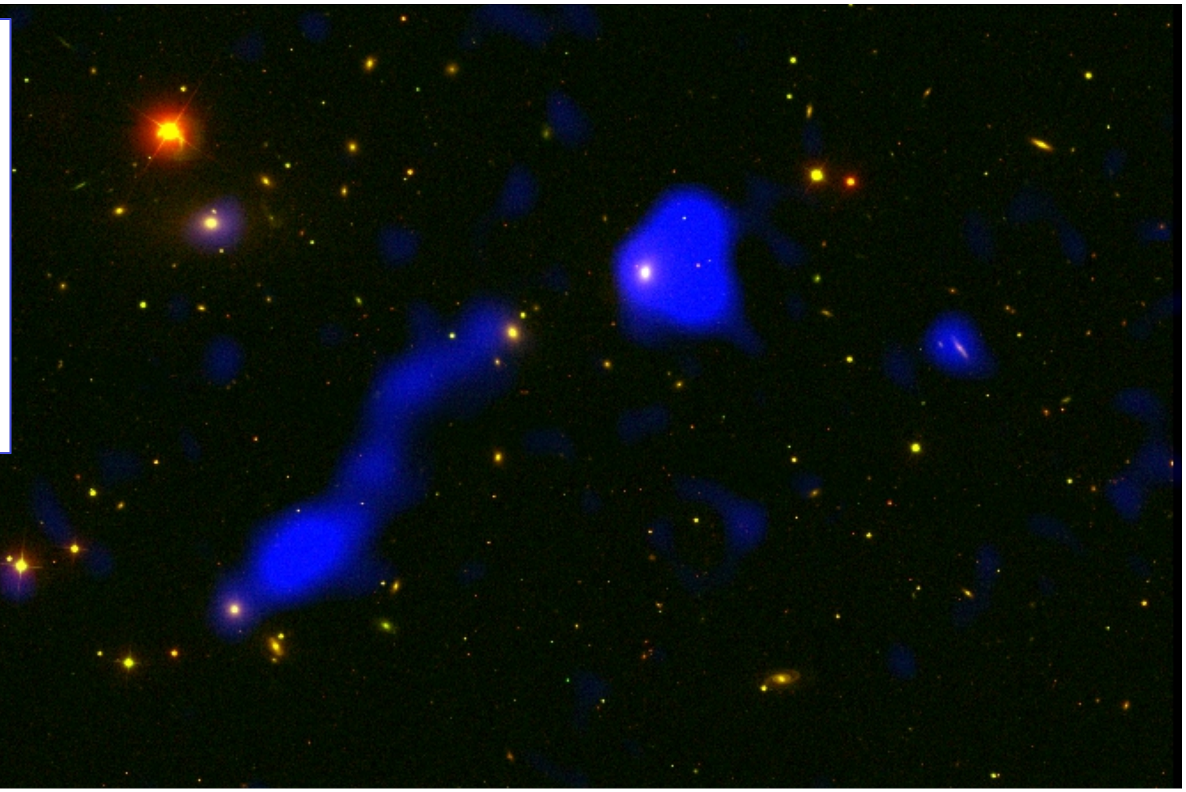
Basic Features of the 'WIDAR' Correlator

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)

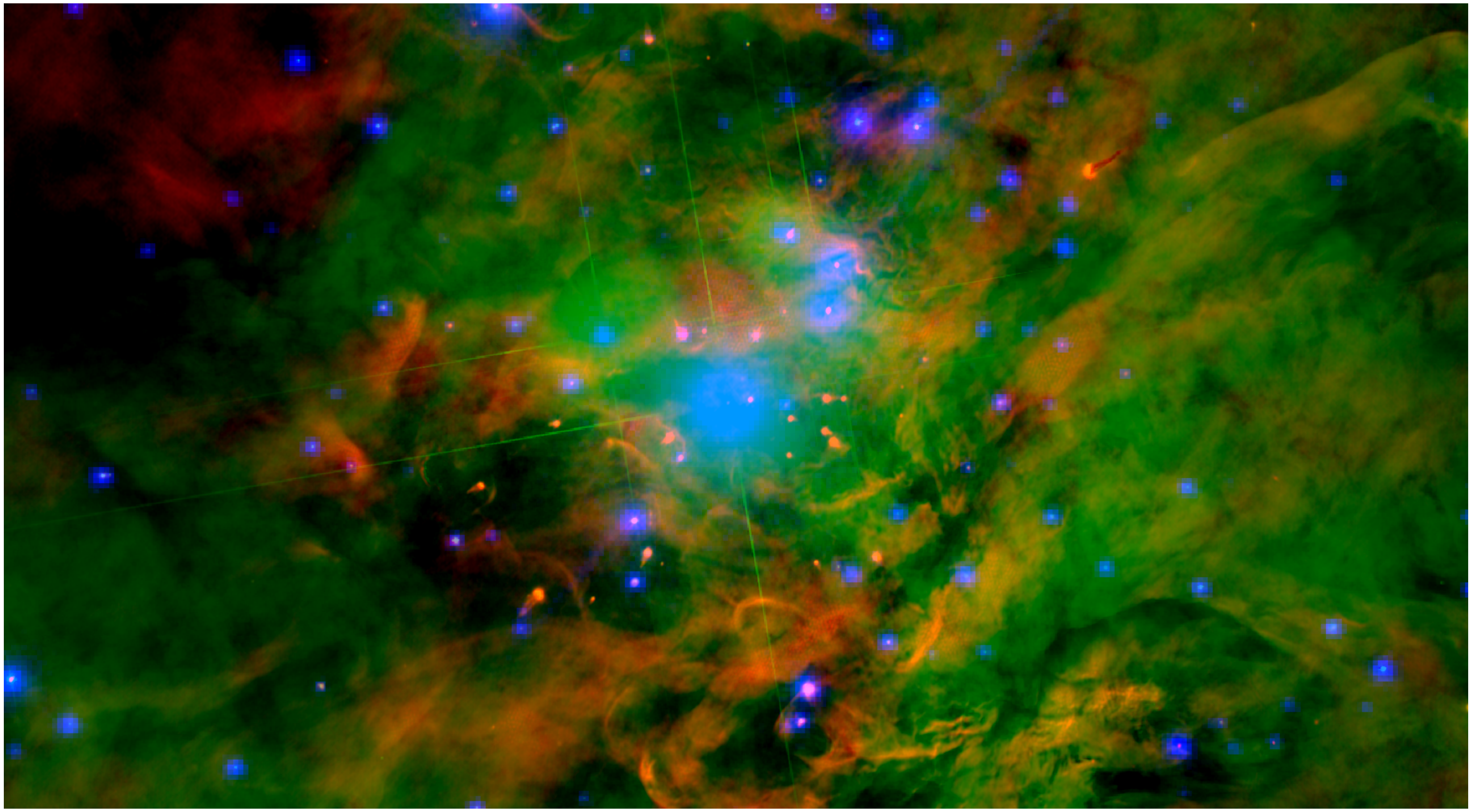


A VLITE pipeline-processed image of the giant radio galaxy IC 711 in the galaxy cluster Abell 1314

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

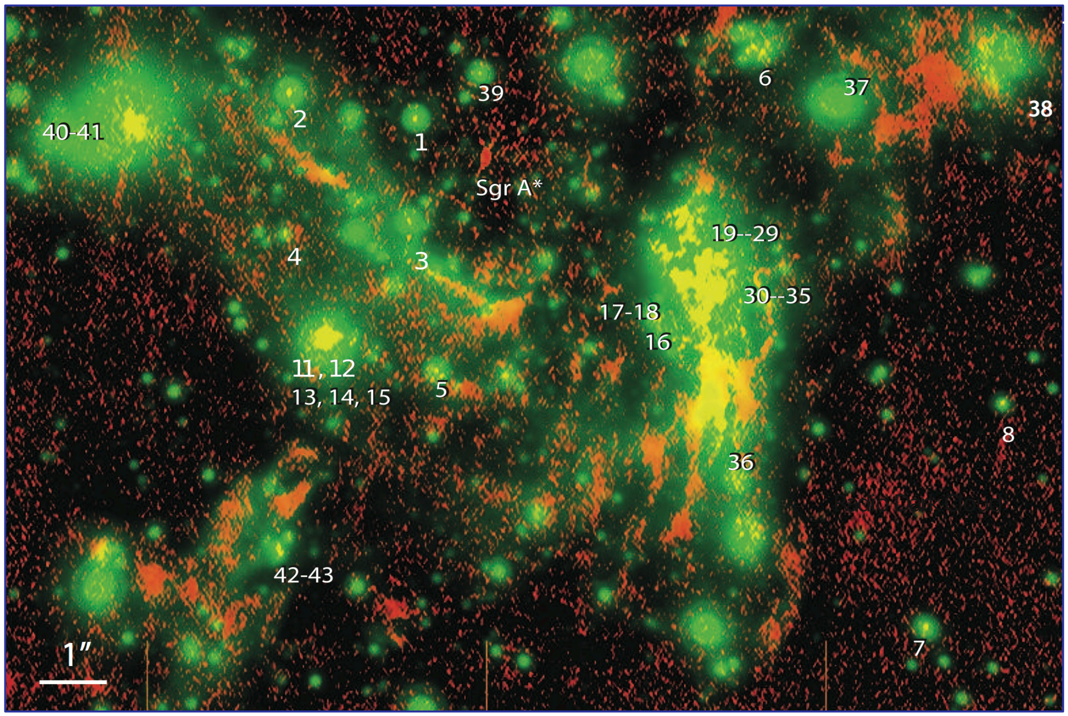
A multiwavelength study of the Orion nebula searches for young stellar variability



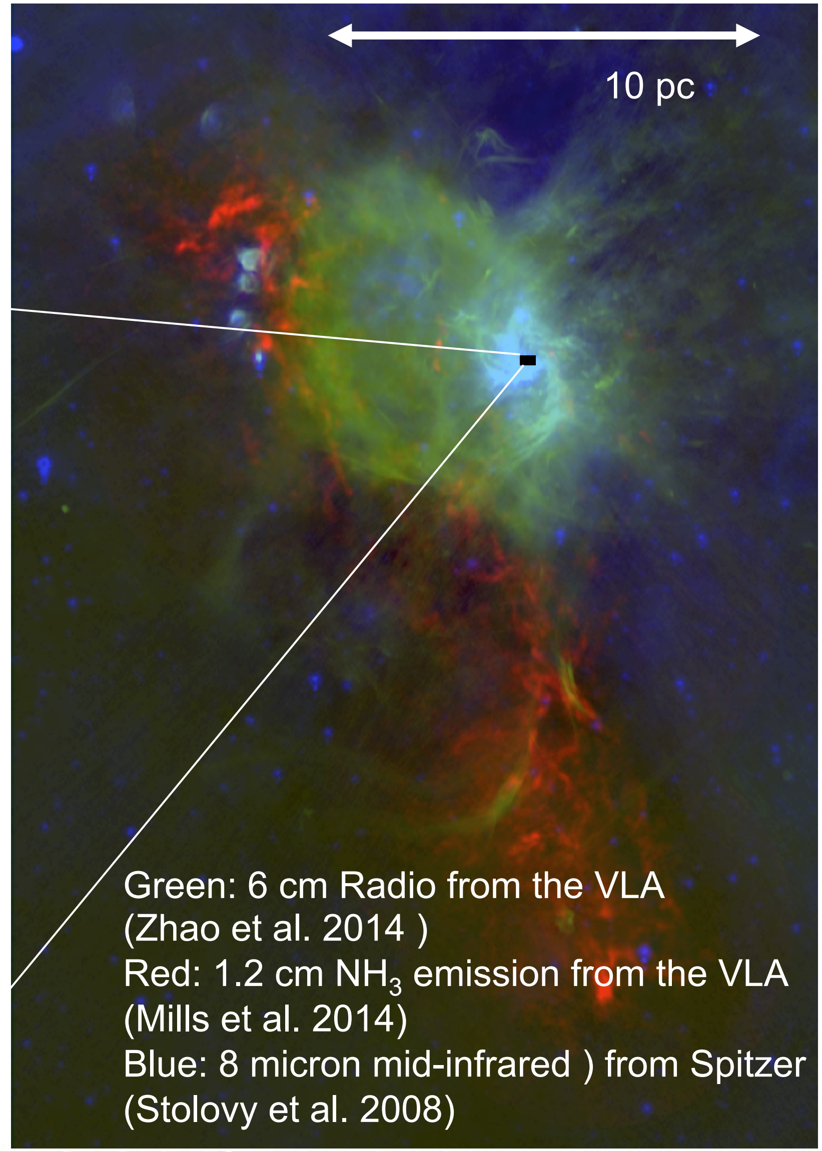
Credit: Red: VLA 6 cm continuum, J. Forbrich et al.
Green: Optical data, Hubble Space Telescope, Robberto et al. 2013
Blue: X-rays, Chandra, Getman et al. 2005

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)

NRAO

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)
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

Next Generation Very Large Array

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

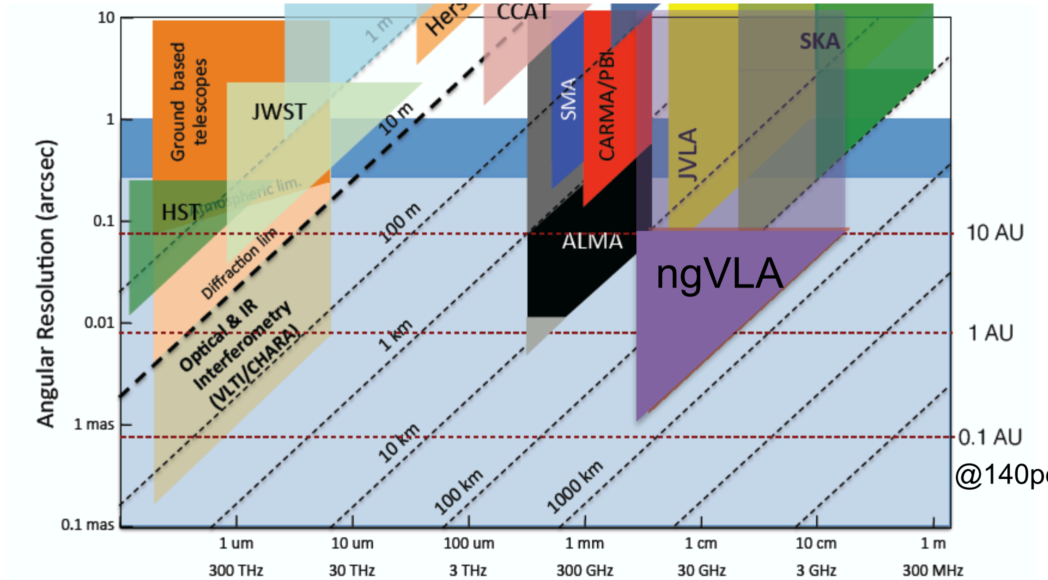
Notional Specifications

- 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

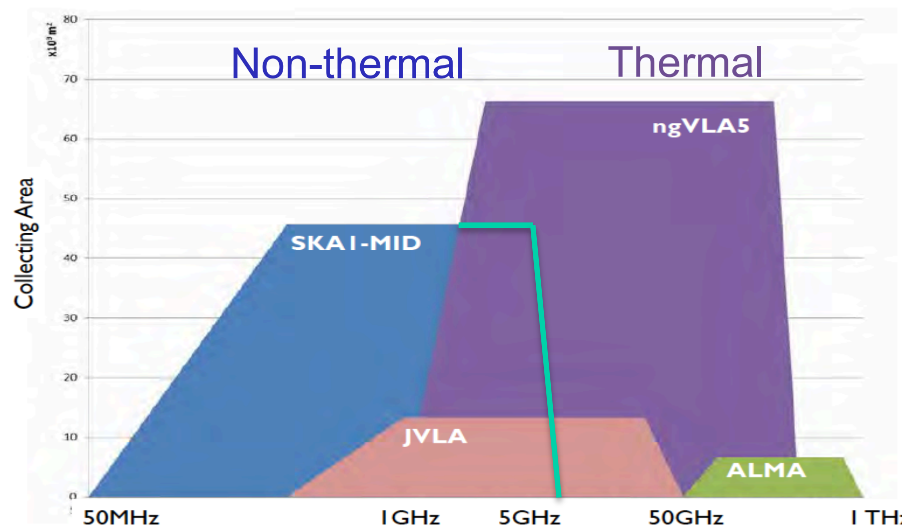
Killer Gap: Opening parameter space

Order of magnitude improvements

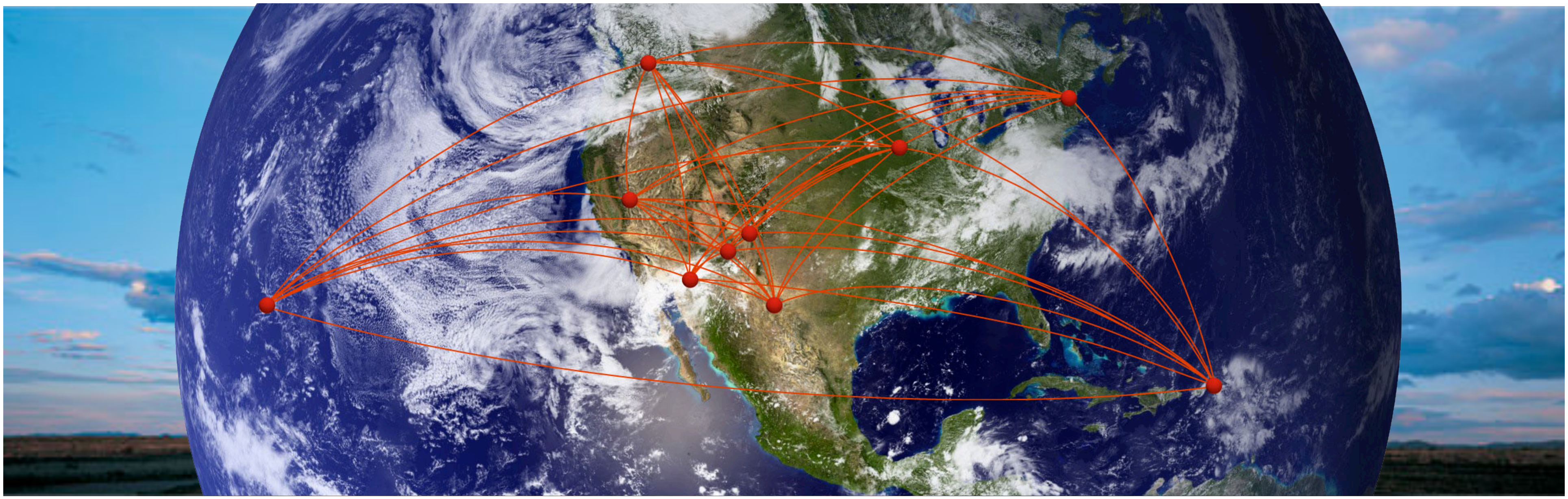
- Resolution ~ 15mas @ 1cm (180km)
- Sensitivity ~ 0.2uJy (1cm, 10hr, 8GHz)
- T_B ~ 1K @ 15mas, 1cm



Next-generation VLA – x5



The Very Long Baseline Array



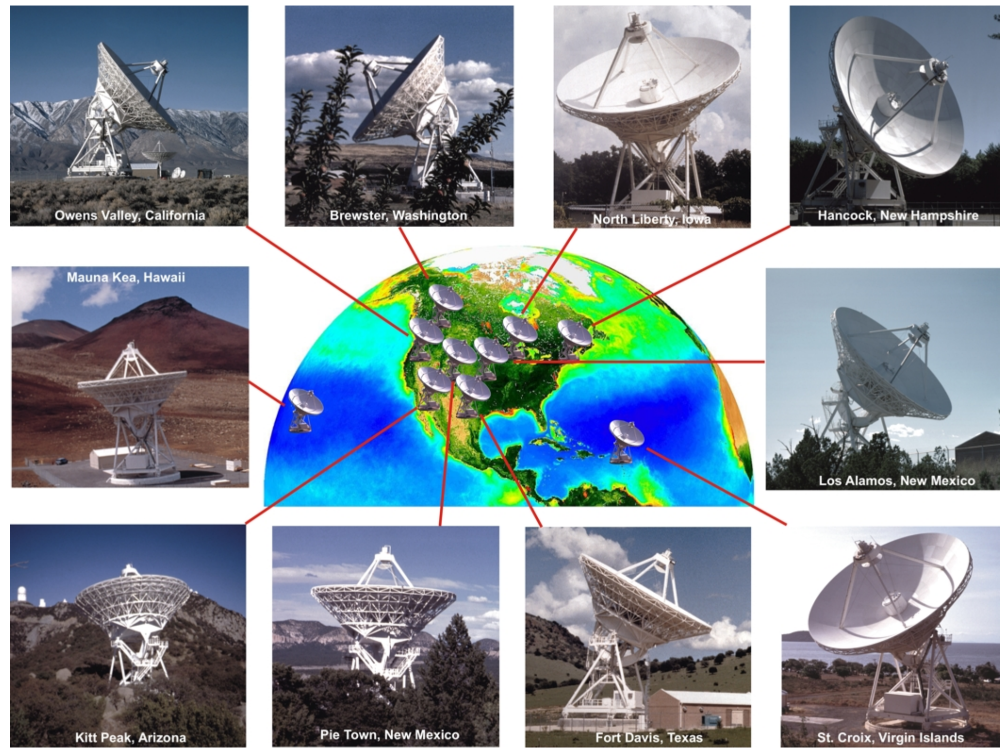
Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO

NRAO

The VLBA

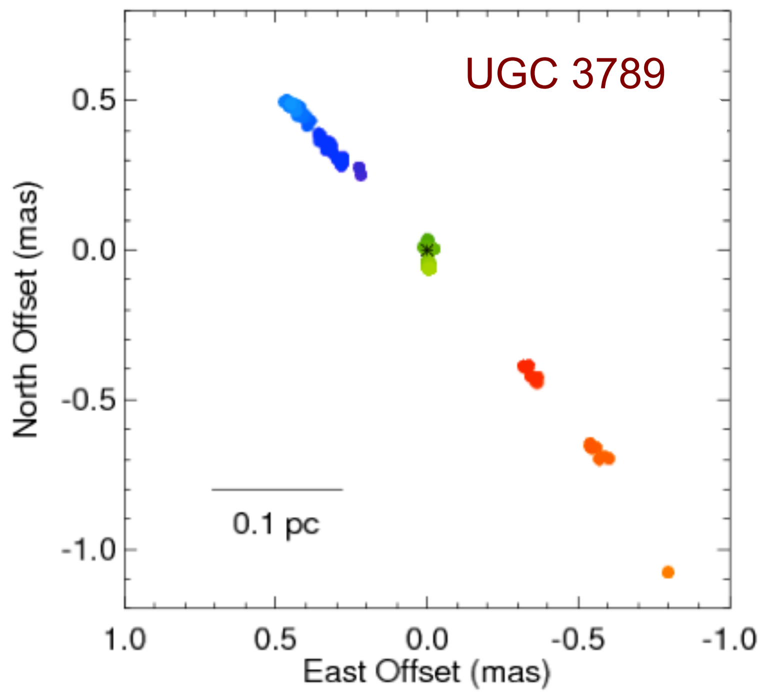
- A dedicated VLBI array
- 10 identical 25-m antennas.
- Spanning Mauna Kea to St. Croix
- Baselines 200 to 8600 km
- Frequencies 310 MHz to 90 GHz
- Sensitive to compact structures with $T_b > 10^5$ K
- Software correlator, DiFX



Resolution!

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

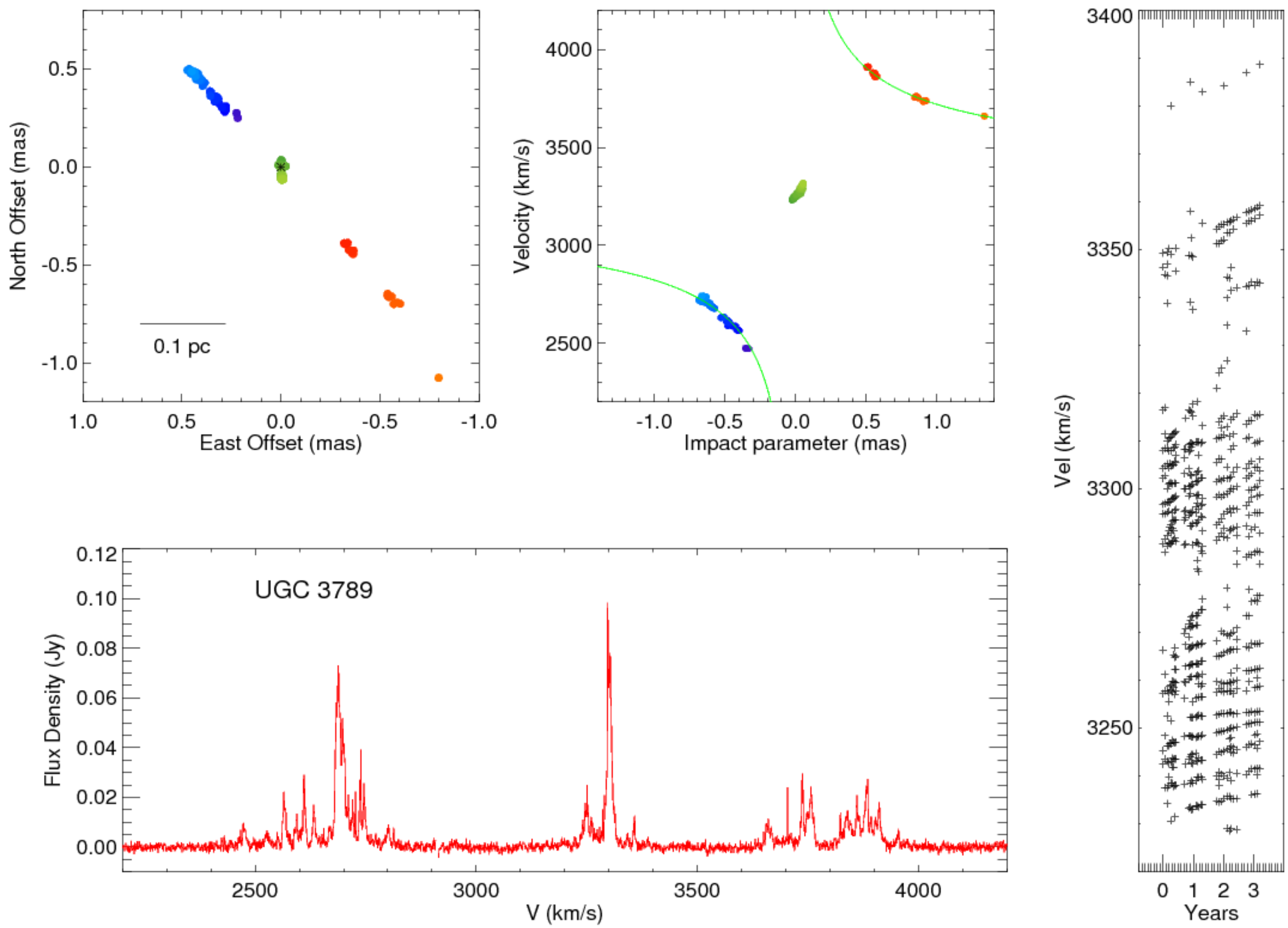
- 1 mas is
  - 0.1 AU at 100 pc (Galactic)
  - 10 AU at 10 kpc
  - 1000 AU at 1 Mpc (Extragal)
  - 5 pc at 1 Gpc



The Megamaser Cosmology Project
(Braatz et al.)

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

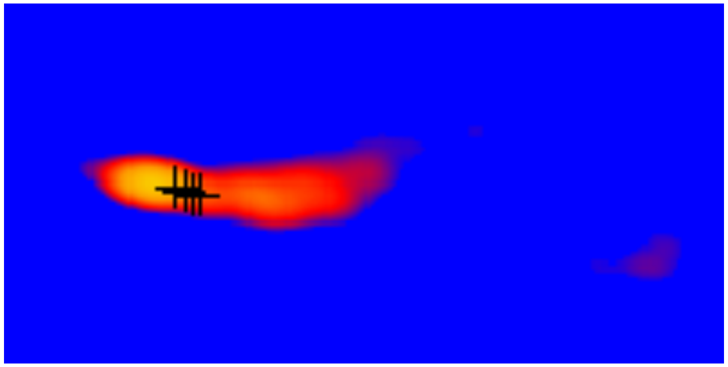
The H_2O Megamaser in UGC 3789



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

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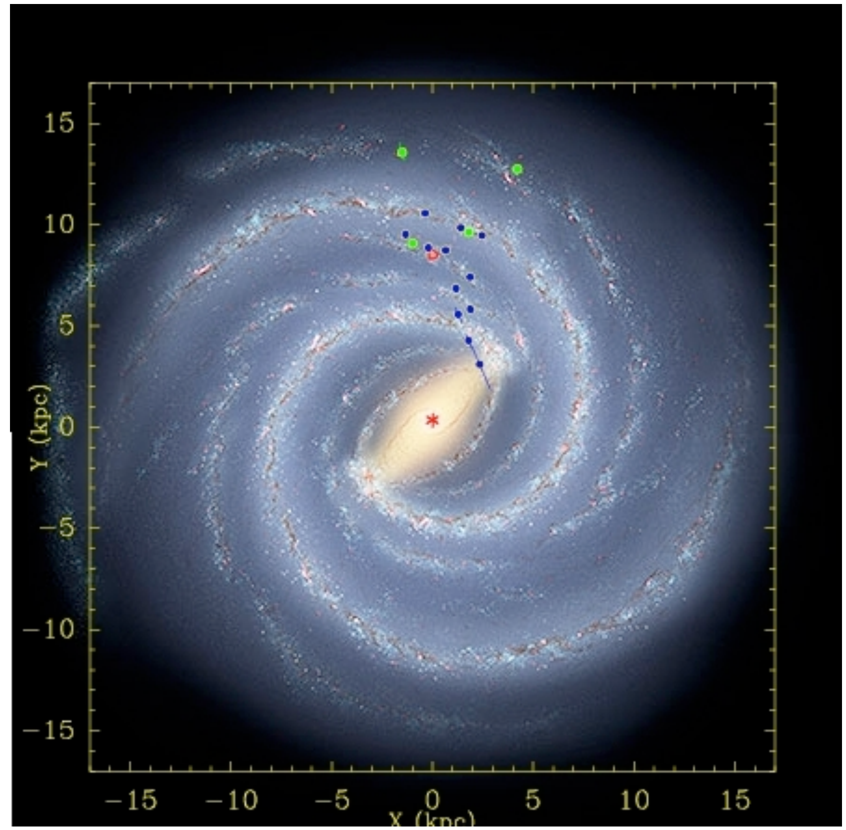


Example: BeSSeL (Reid et al. 2014)

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

NRAO

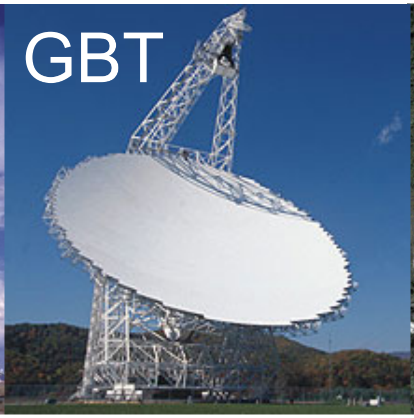
VLBA Frequency bands and Sensitivity

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

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

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

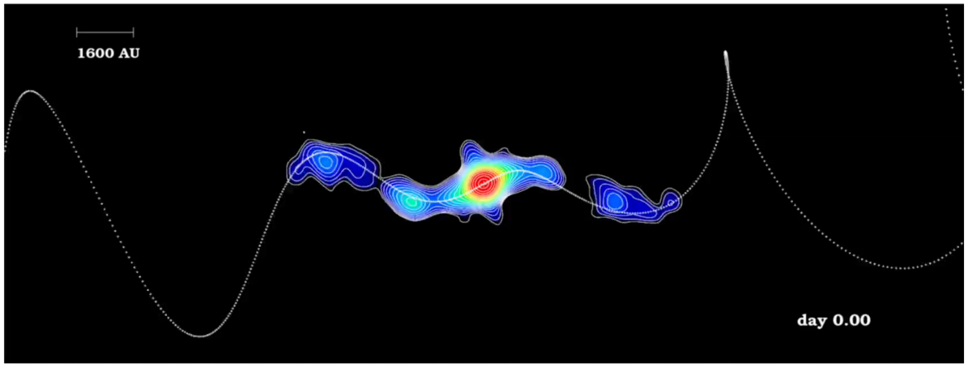
my.nrao.edu

CASA– data reduction software

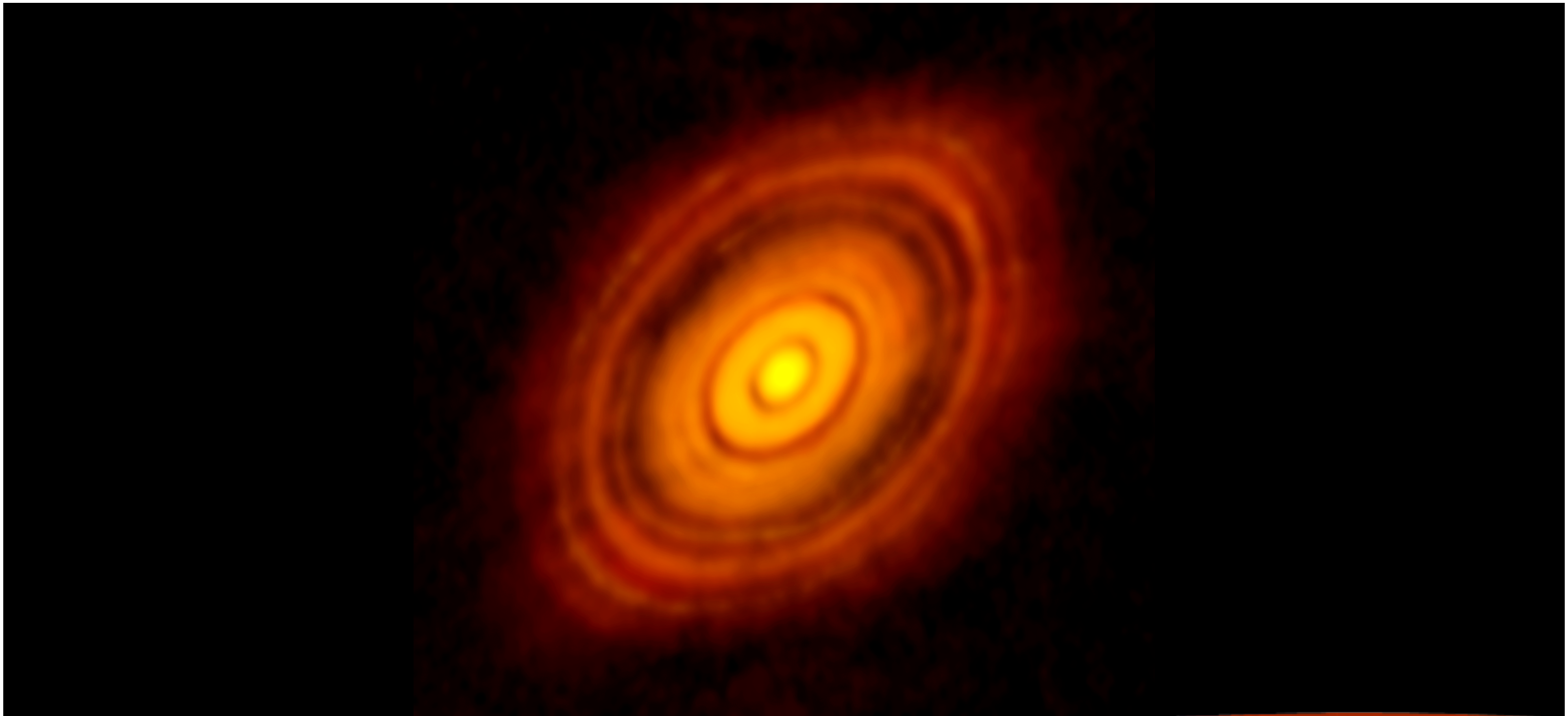
http://casa.nrao.edu/

VLA Calibration Pipeline

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



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



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
  - 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

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