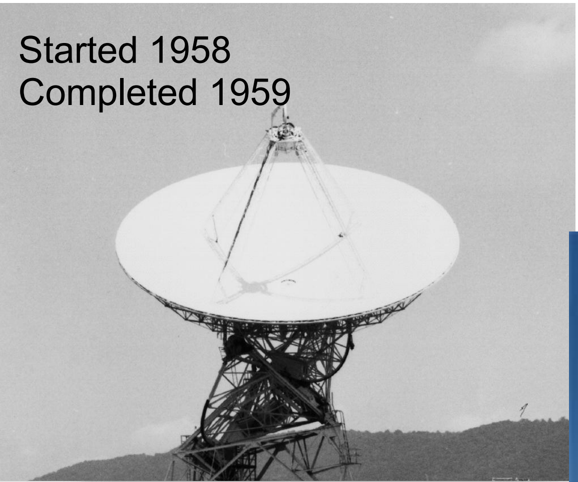
GBT Overview

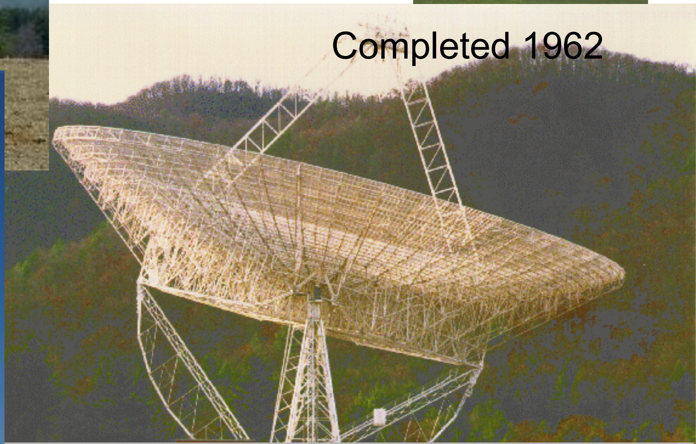
David Frayer

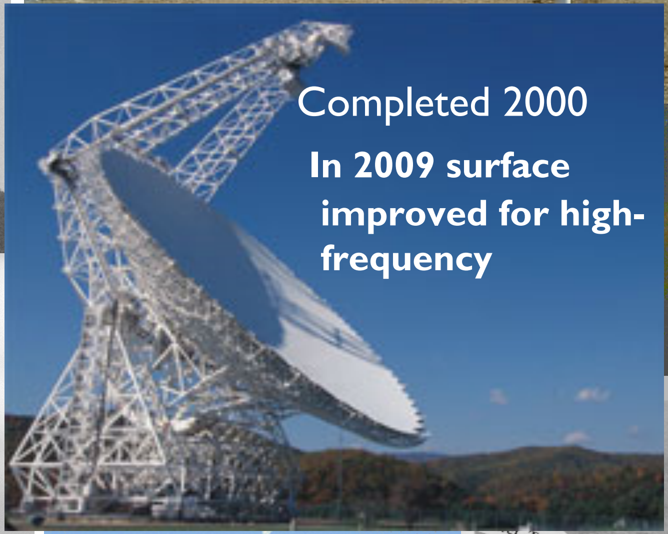
GREEN BANK OBSERVATORY

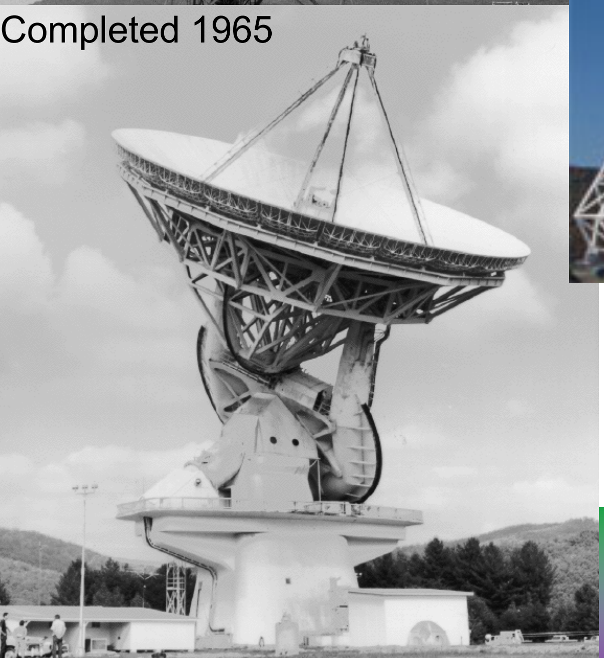
Green Bank is the original NRAO site and has been operating world-class radio telescopes for nearly 60 years…..

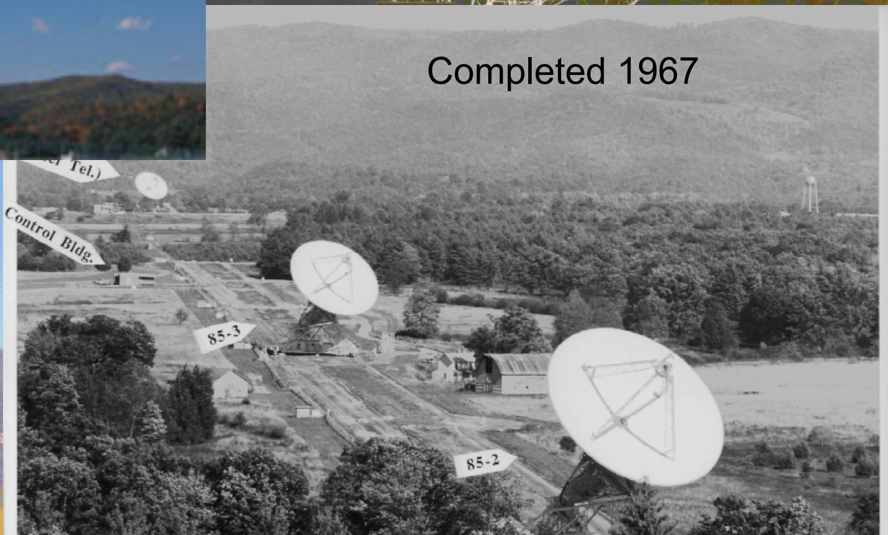


Completed
1962



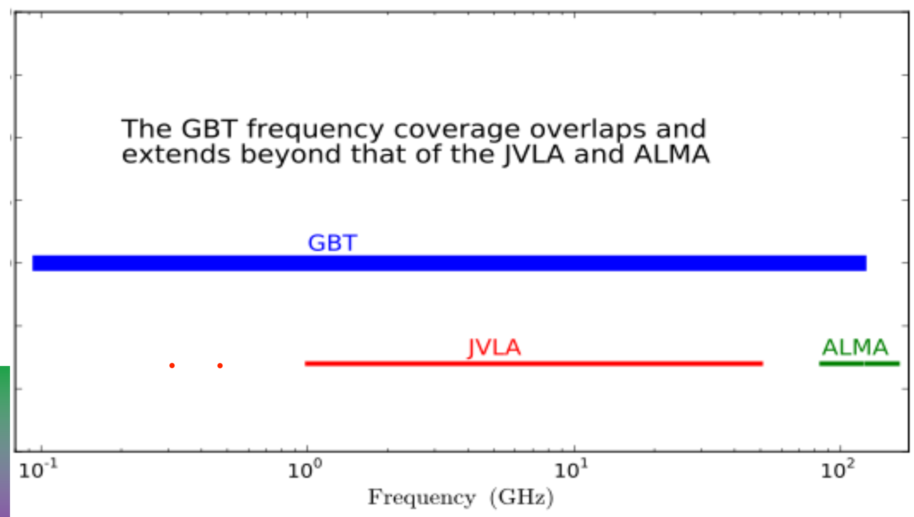






Key Capabilities of the GBT

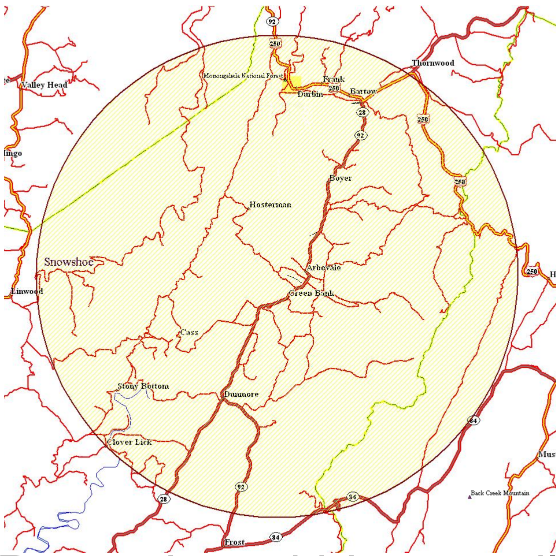
- 100 meter diameter unblocked
- Receivers cover 0.1 to 116 GHz
- Excellent point-source sensitivity
- Unsurpassed sensitivity for extended objects
- >85% of total sky covered (δ≥-46°)
- Location in the National Radio Quiet Zone



Site protected from Radio Interference

WV Radio Astronomy Zone

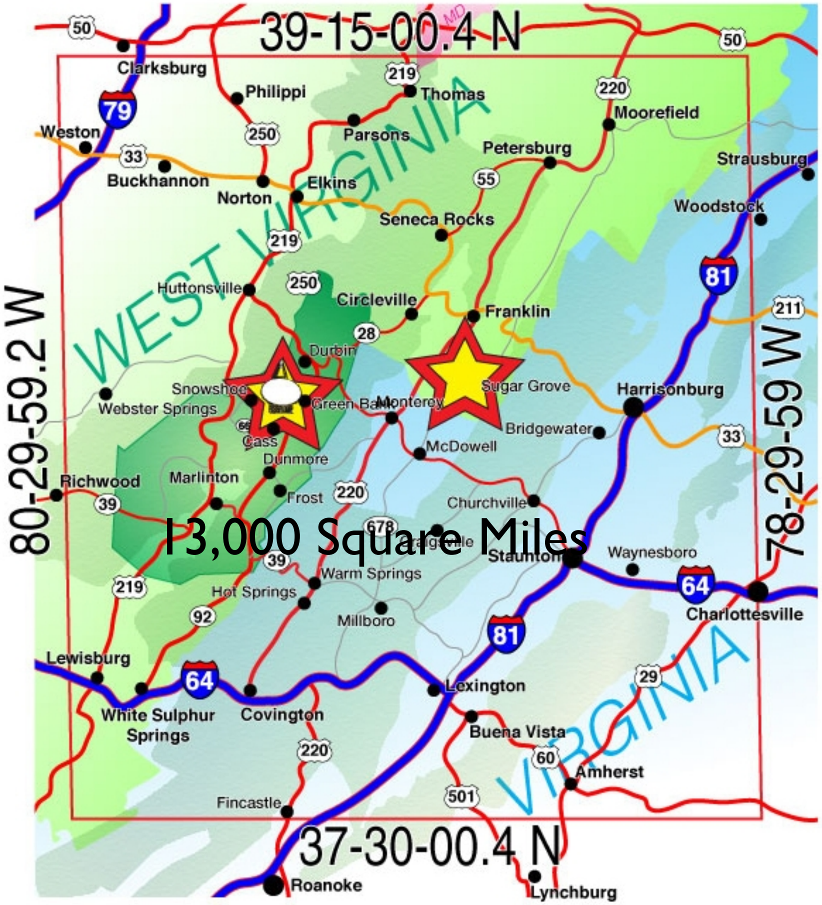
Established by the West Virginia Legislature (1956)



Protection within ten miles of the Observatory

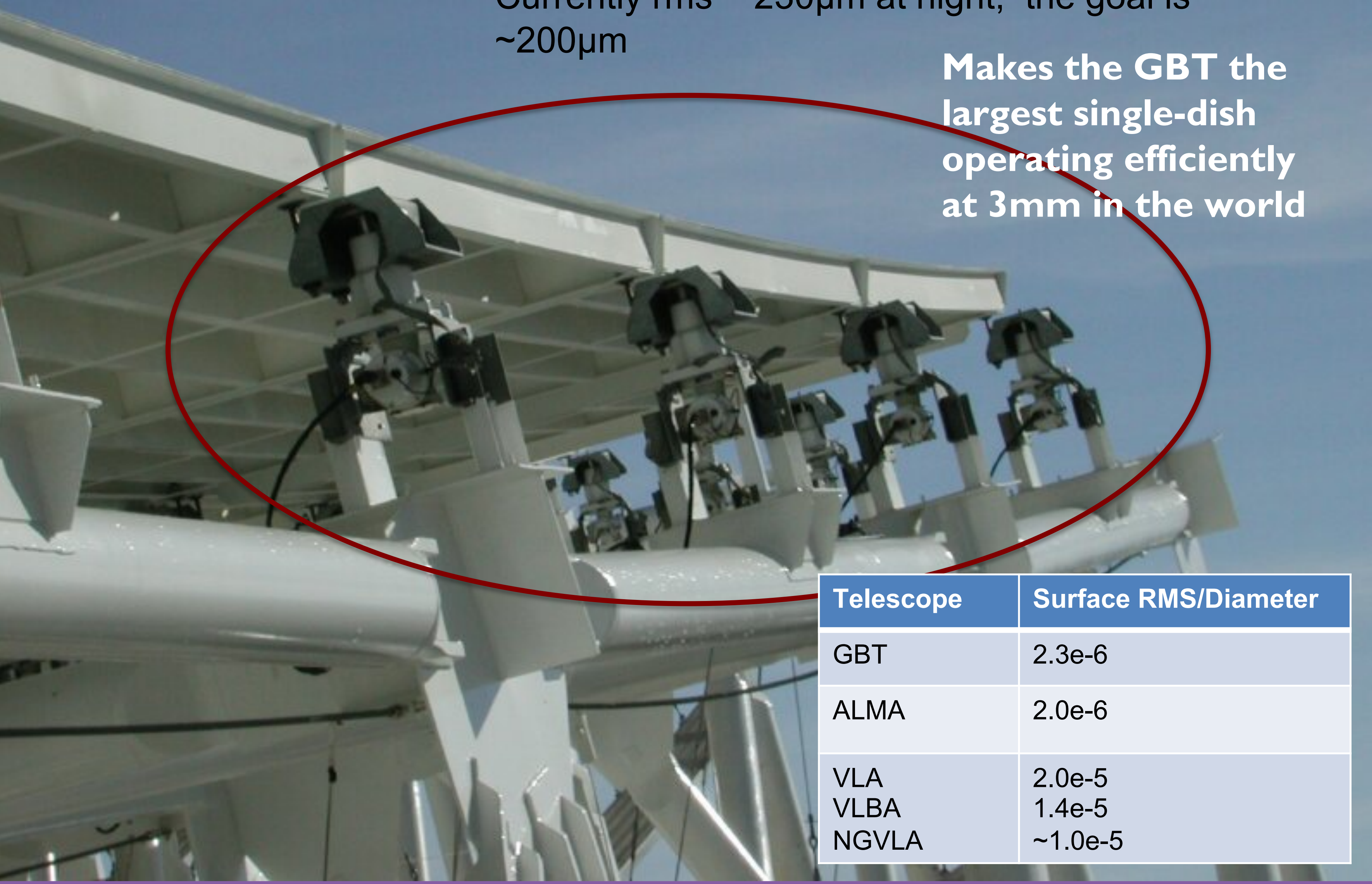
National Radio Quiet Zone

Established by the FCC and NTIA (1957)



The Active Surface 2209 actuators

Currently rms ~230μm at night, the goal is ~200μm

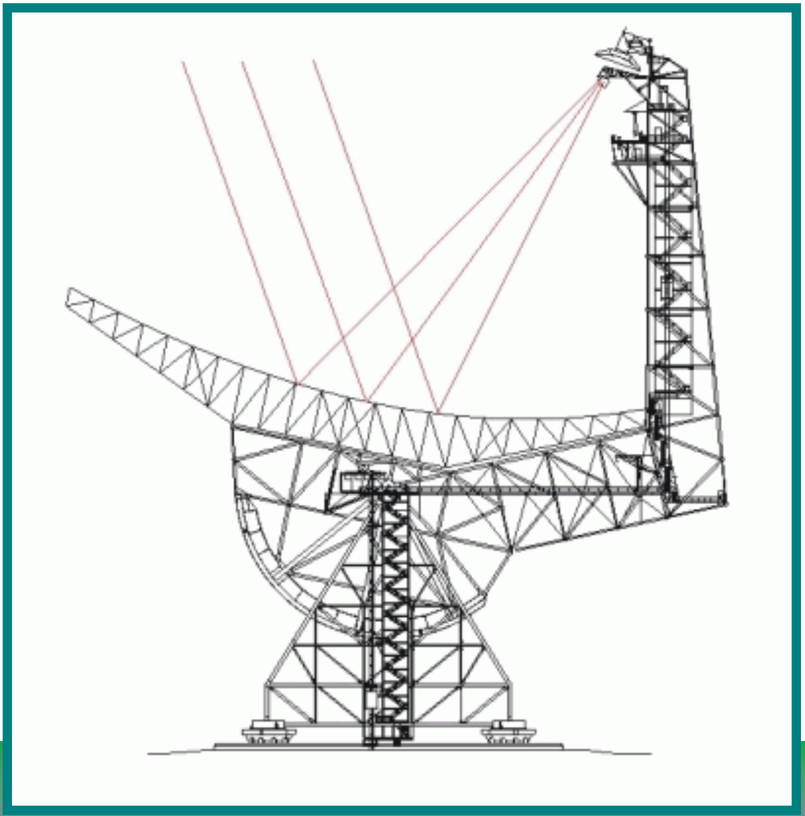


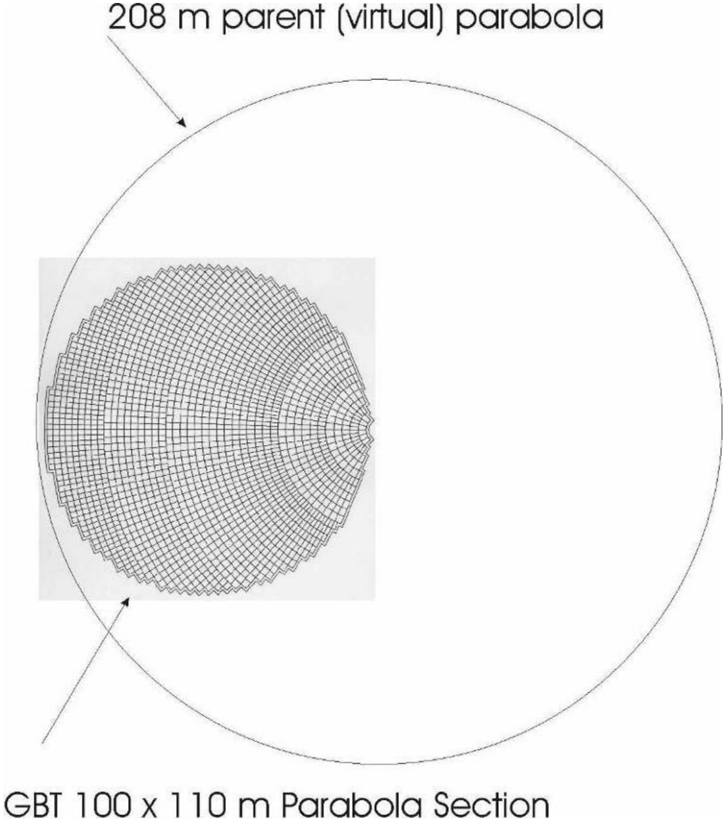
Makes the GBT the largest single-dish operating efficiently at 3mm in the world

Telescope	Surface RMS/Diameter
GBT	2.3e-6
ALMA	2.0e-6
VLA VLBA NGVLA	2.0e-5 1.4e-5 ~1.0e-5

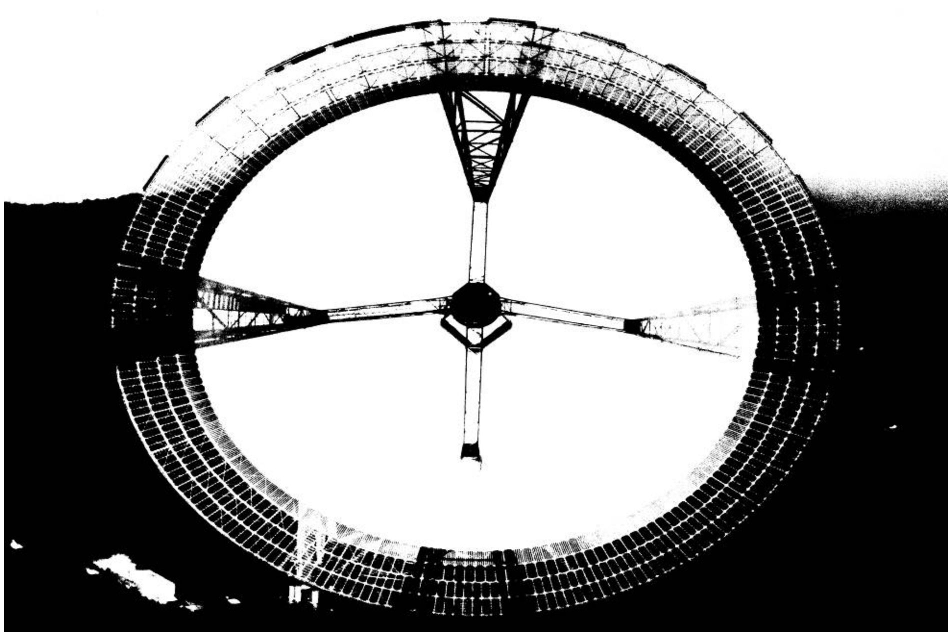
GBT Telescope Optics

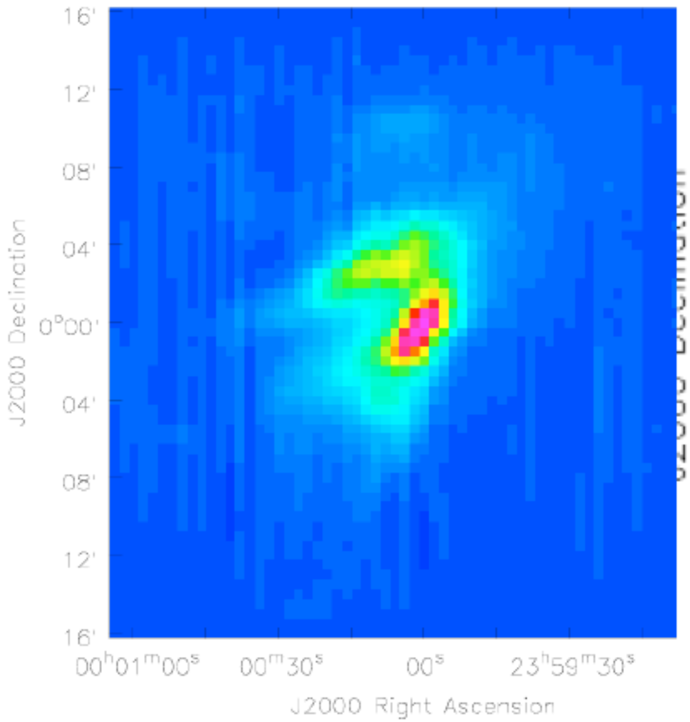
- 110 m x 100 m of a 208 m parent paraboloid
  - Effective diameter: 100 m
  - Off axis - Clear/Unblocked Aperture



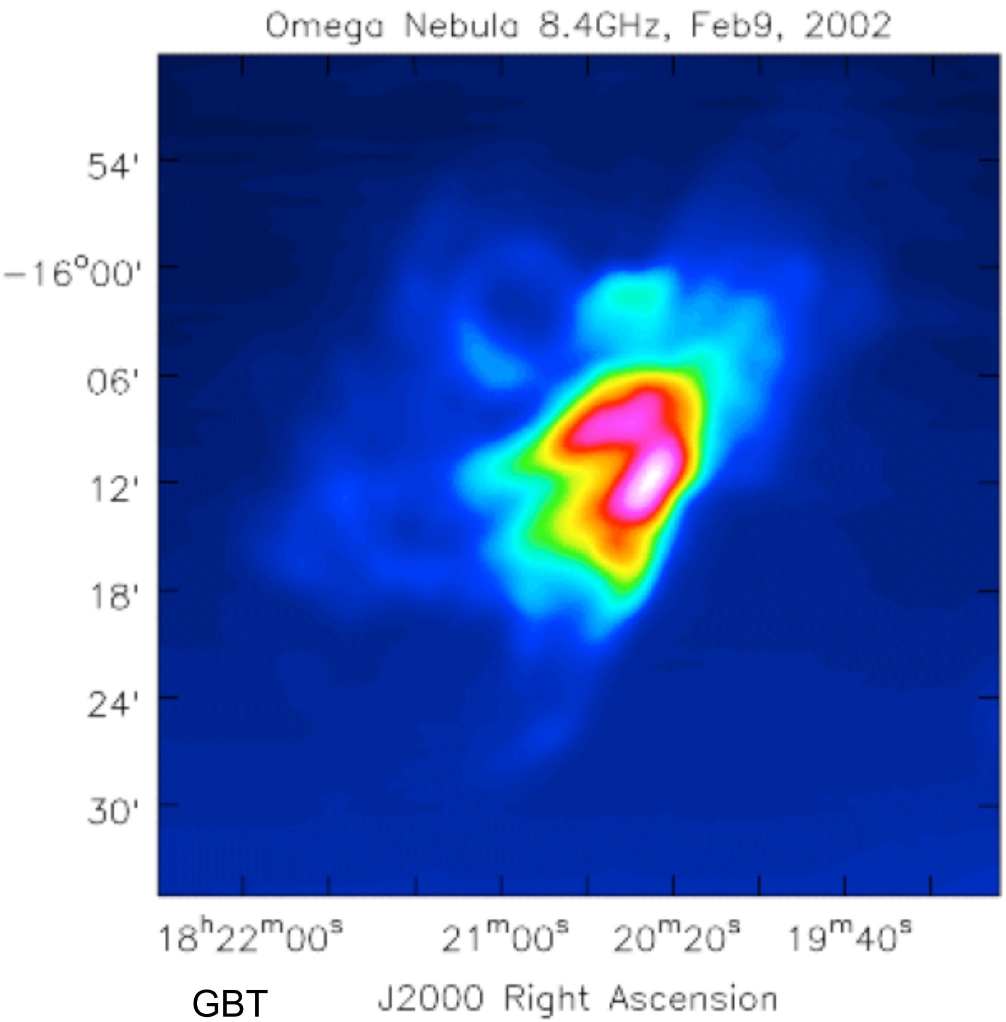


- High Dynamic Range
- High Fidelity Images




16'
12'
08'
04'
0°00'
04'
08'
12'
16'
J2000 Declination
00h01m00s
00m30s
00s
23h59m30s
J2000 Right Ascension

Bonn


Omega Nebula 8.4GHz, Feb9, 2002
54'
−16°00'
06'
12'
18'
24'
30'
18h22m00s
21m00s
20m20s
19m40s
J2000 Right Ascension

GBT

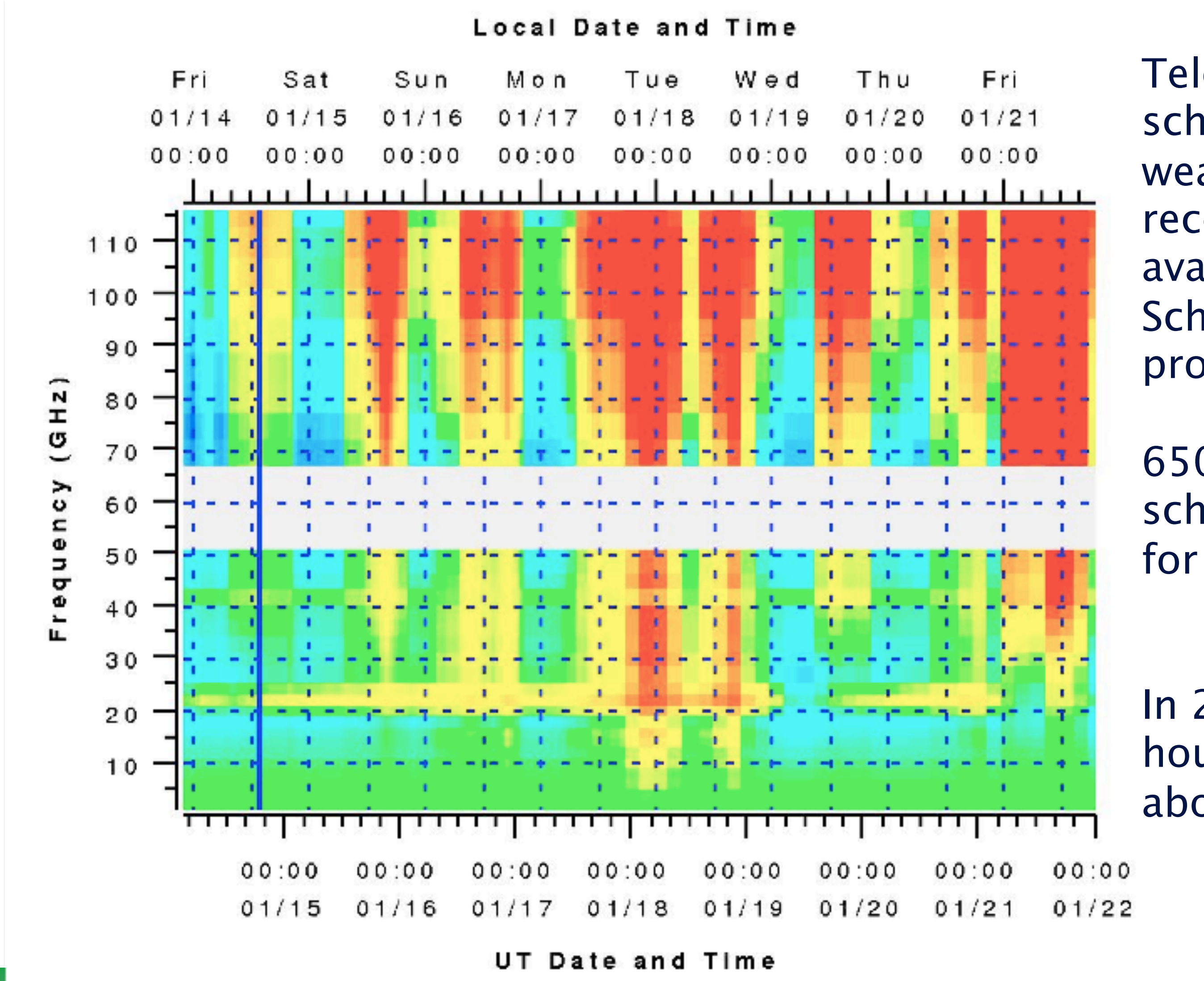
Prime Focus: Retractable boom

Gregorian Focus: 8-m subreflector - 6-degrees of freedom

Rotating Turret with 8 receiver bays

- Fully Steerable
  - Elevation Limit: 5º
  - Can observe 85% of the entire Celestial Sphere
- Slew Rates: Azimuth - 40º/min; Elevation - 20º/min

Dynamical Scheduling System allows efficient use of telescope at high frequency – based on weather model predictions that are updated every 6 hrs.

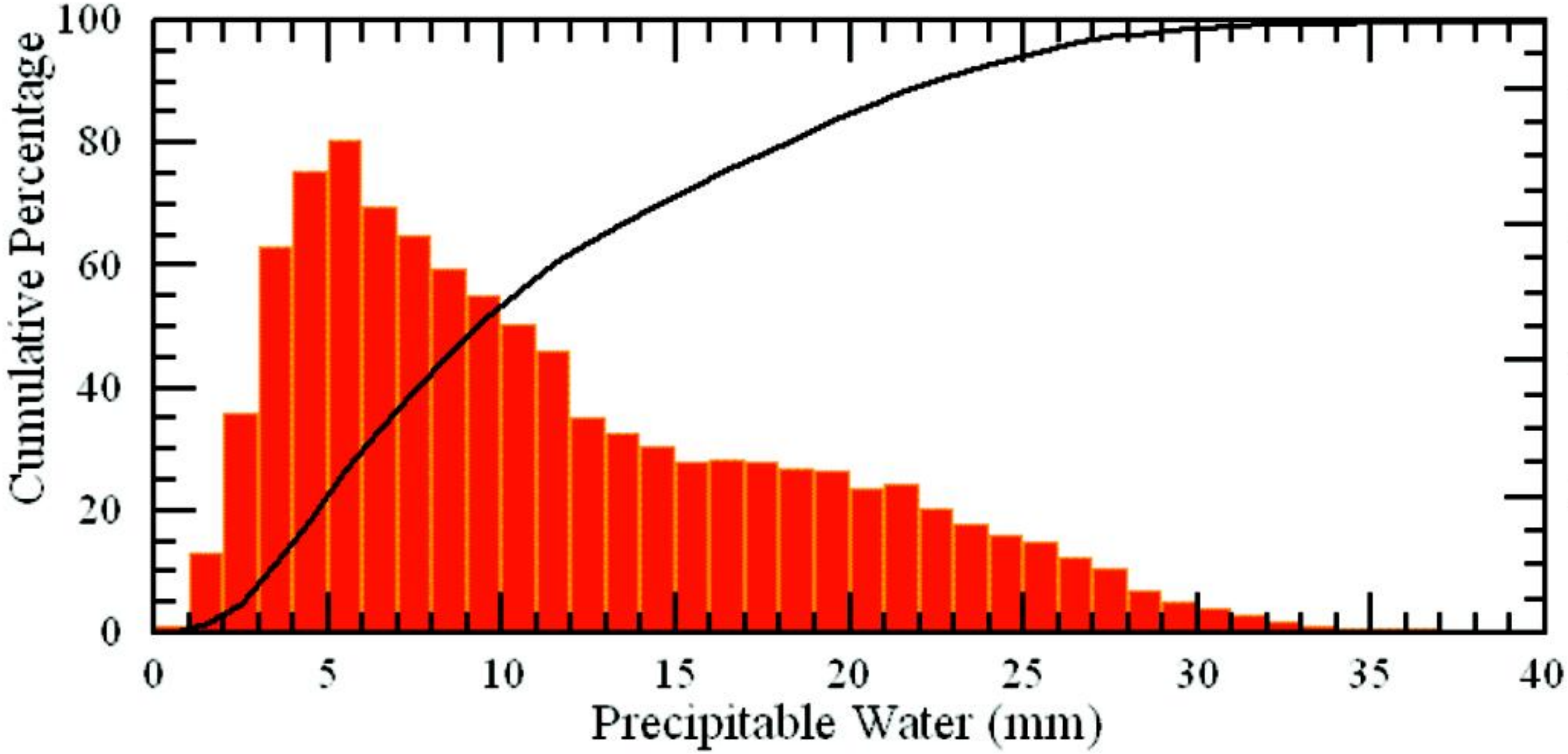


Telescope dynamically scheduled daily based on weather conditions and receiver and observer availability. Dynamic Scheduling matches the project to the weather

6500+ hours a year scheduled
for observations

In 2010 there were ~1800 hours used at frequencies above 18 GHz

~50% of time in Green Bank has less than 10mm of H_2O (acceptable for 3mm observations)

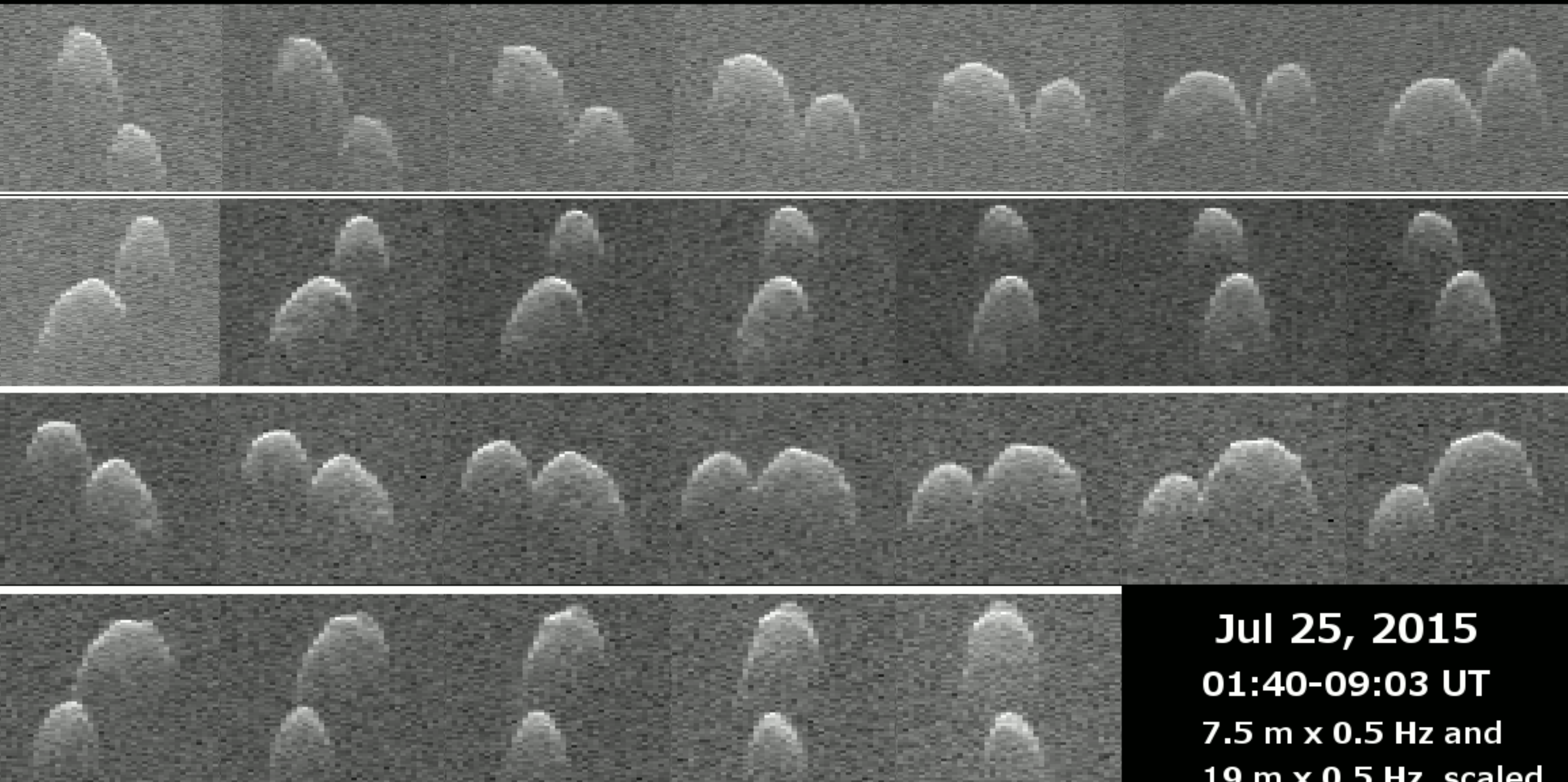


Wide Range of GBT Science Areas:

- Pulsars: Discovery of new pulsars, the most massive pulsar, gravity waves via pulsar timing
- Neutral Hydrogen HI: Masses of local galaxies, Kinematics of galaxy and local group/dark matter
- High-redshift/Cosmology: Galaxy clusters, CO in the early universe, HI intensity mapping at high-redshift
- Interstellar Organic Molecules/Astro-chemisty
- Masers: black hole masses, distances via proper motions and independent measurement of Ho
- Star Formation: NH3 mapping, cold and dense gas tracers at 3-4mm
- Basic Physics: The search for Gravitational Radiation, Limits on Fundamental "constants"
- Solar system astronomy -- planetary radar
- SETI – Breakthrough Listen

Radar: Protecting Planet Earth -- Chelyabinsk, Russia -- Feb. 15, 2013

(85989) 1999 JD6

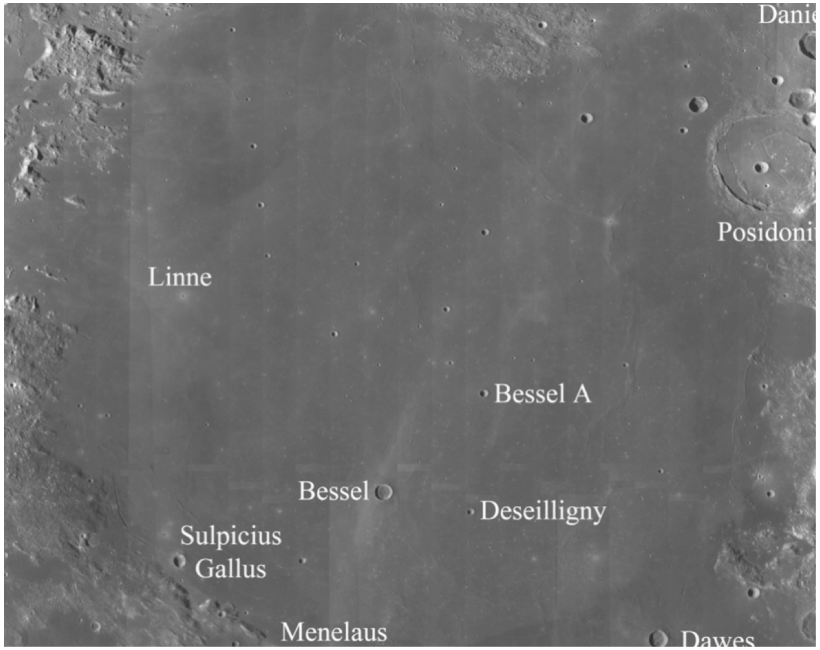


Jul 25, 2015
01:40-09:03 UT
7.5 m x 0.5 Hz and
19 m x 0.5 Hz, scaled

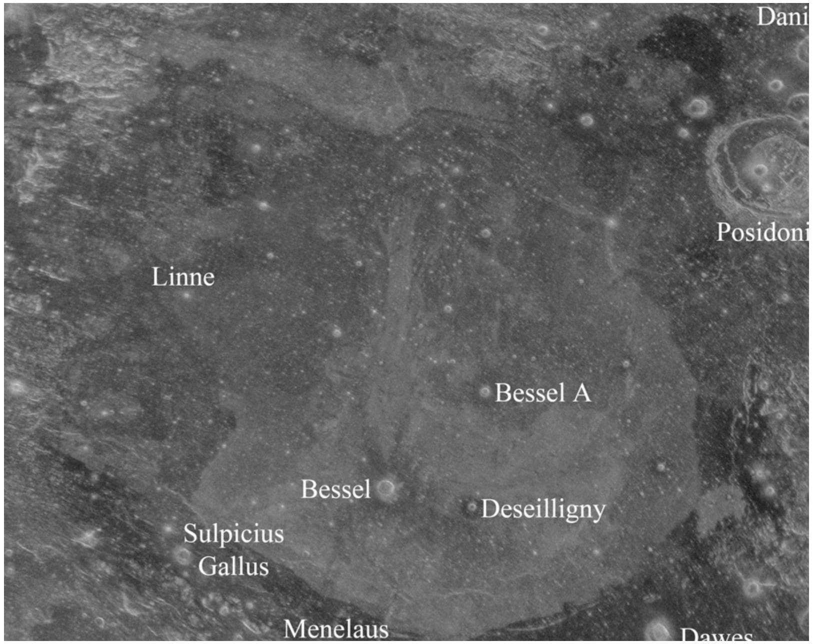
Goldstone-GBT bistatic radar images

~18x the distance to the Moon

Radar image of the moon



Optical



70cm radar

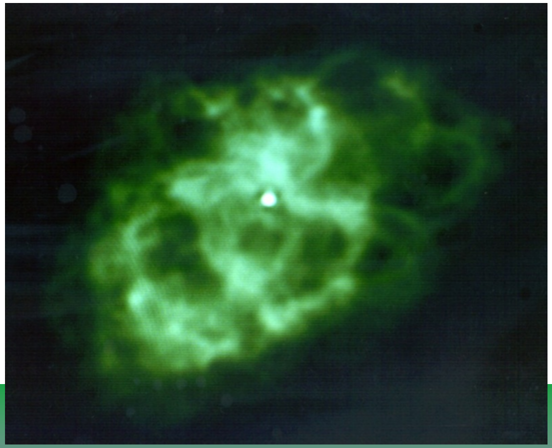
"The 70 cm backscatter differences provide a view of mare flow-unit boundaries, channels, and lobes unseen by other remote sensing methods."
-- Campbell, B.A. et al. JGR-P 2014

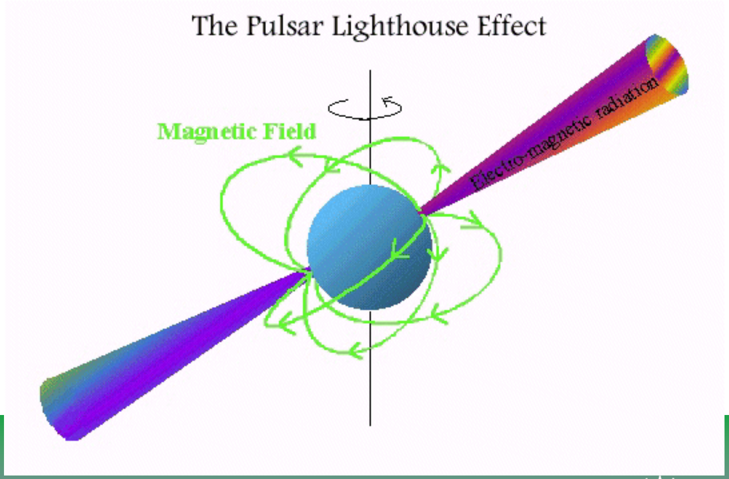
The GBT remains
the world's premier pulsar observatory

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

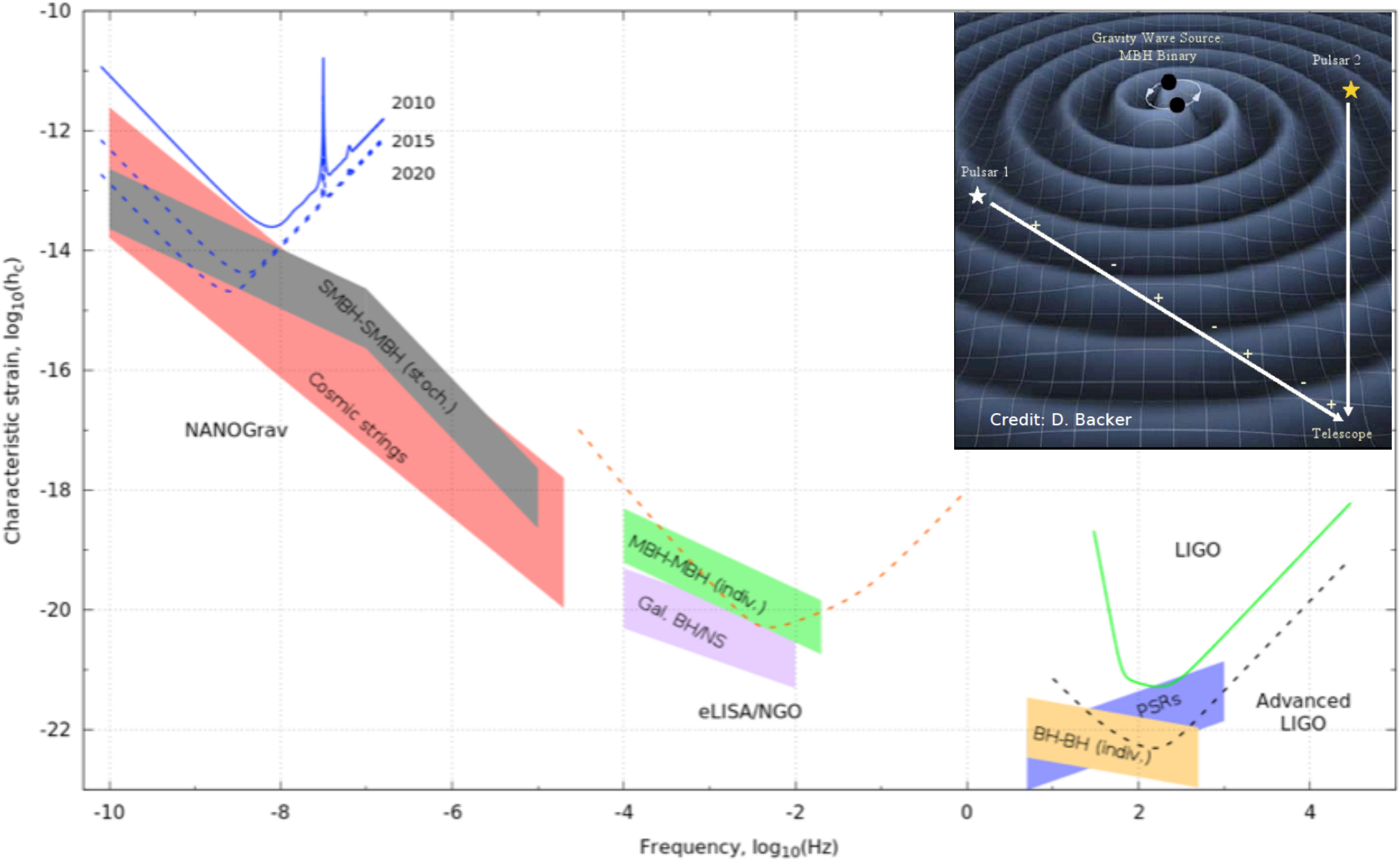
The Pulsar Renaissance:

- Fastest Pulsar
- Most Massive Pulsar (constrains equation of state of matter)
- Pulsars in Globular Clusters
- Tests of General Relativity
- Relativistic Spin Precession
- Pulsar in a three-body system
- Coolest white dwarf star (carbon – diamond star)



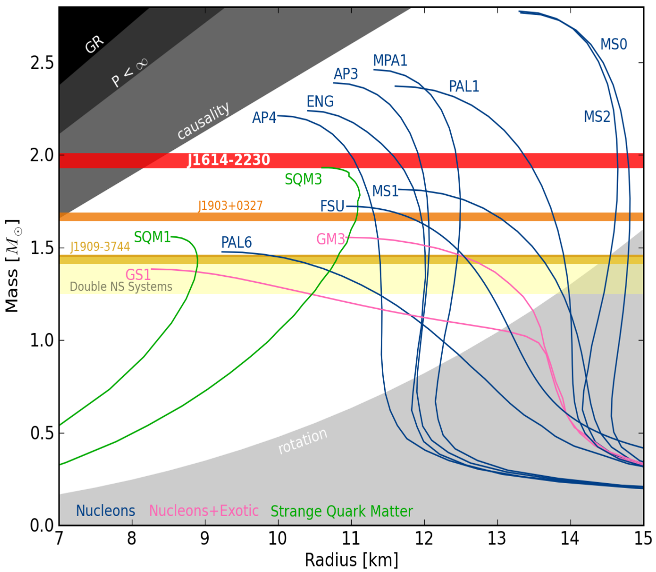


Searching for a detection of Gravitational Waves via Pulsar timing (NANOGrav)



Massive pulsars, M~2M$_\odot$

J1614-2230



The new mass determination for PSG J1614-2230 makes it the most massive pulsar known, and rules out a number of soft equations of state for nuclear matter including many “exotic” hyperon, kaon models.

(Demorest et al. 2010)

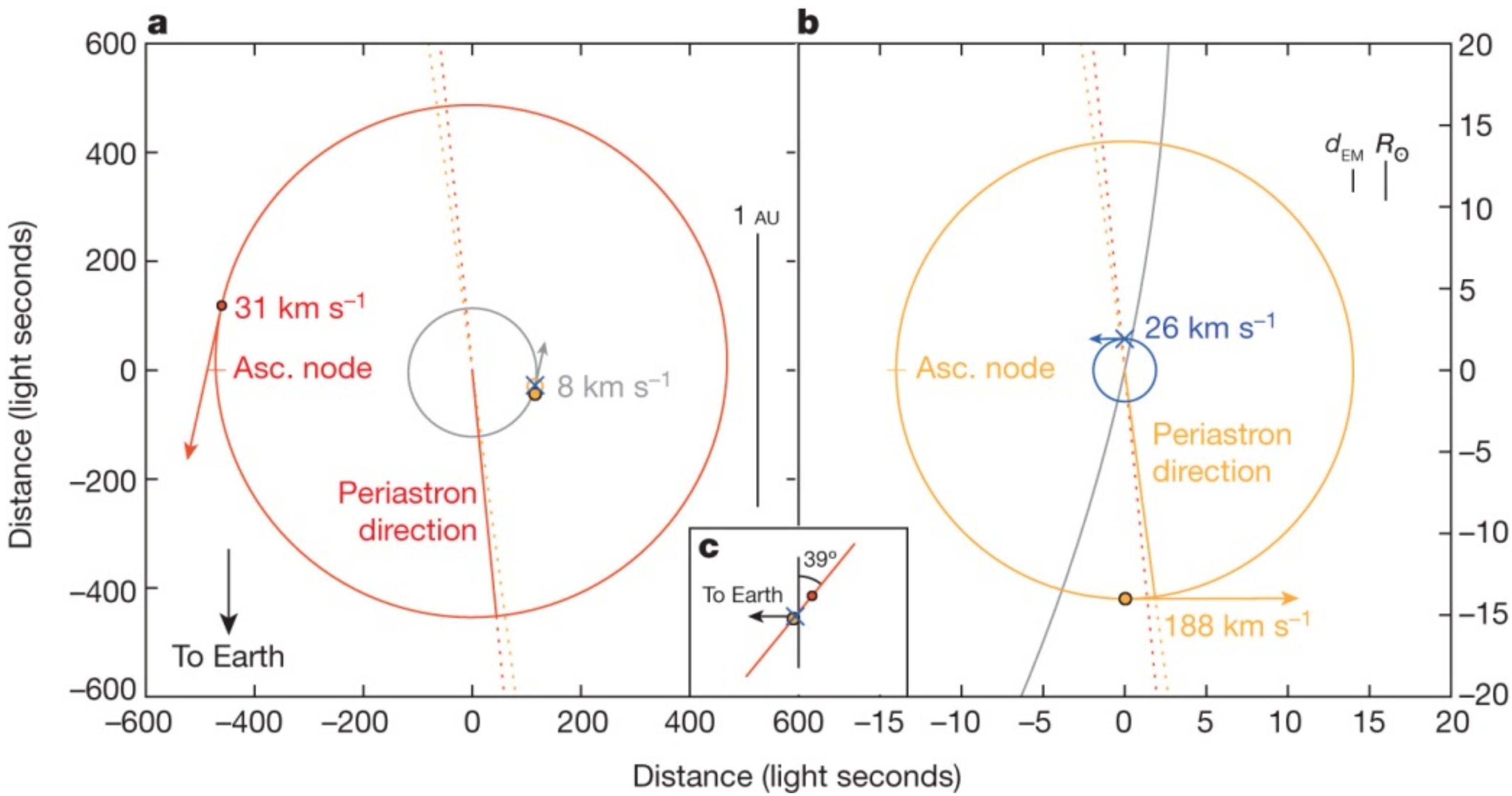
PSR J0348+0432 (2.01+/-0.04 Msun)

Lynch+2013; Antoniadis+2013

{artist impression of pulsar with WD companion}

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

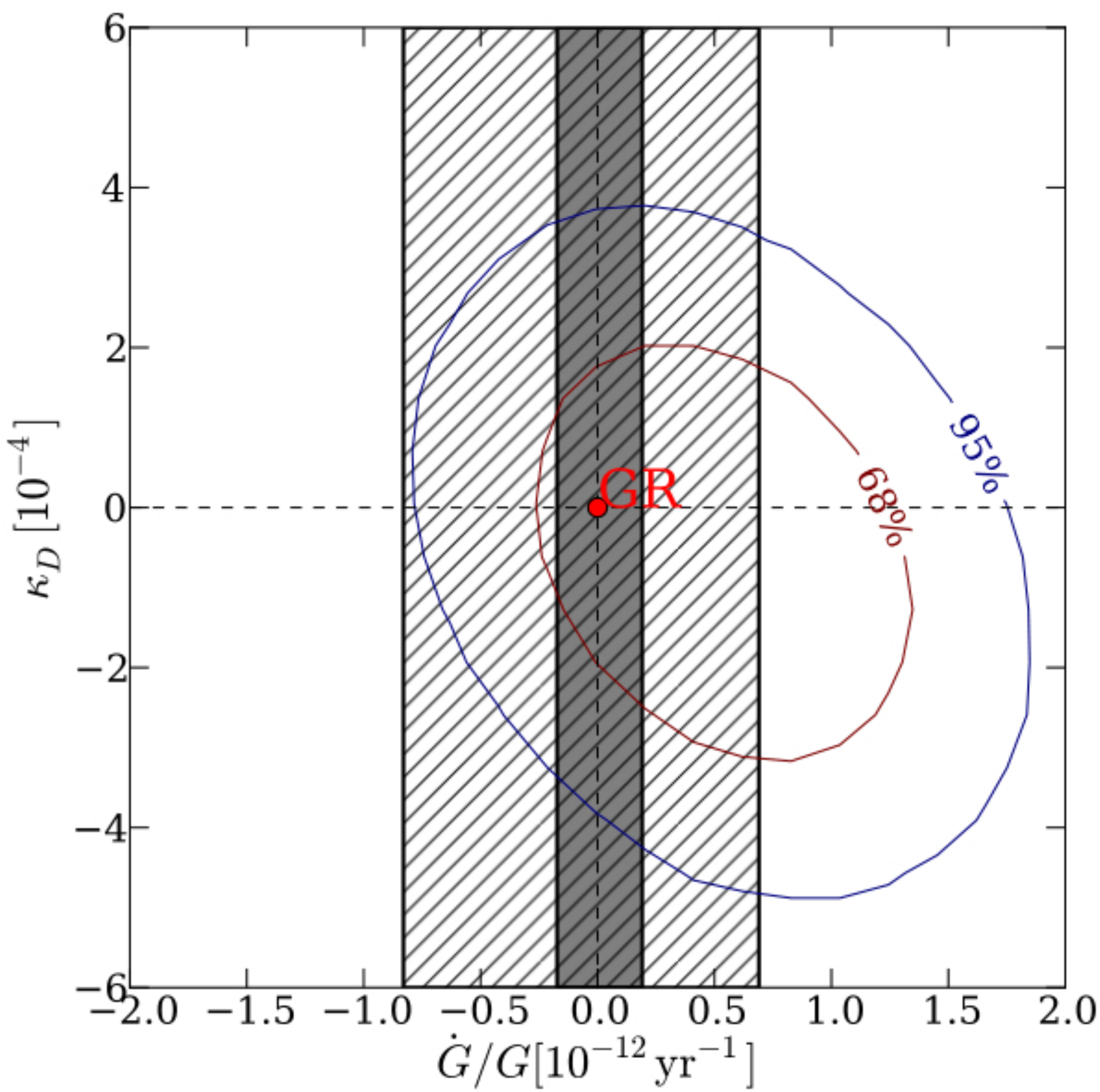
Testing the Equivalence Principle (gravitational and inertial mass)

F=ma = GMm/r^2

Fundamental Physics: Constraining Gravity

Stringent limits to variation of the Gravitational constant using a pulsar binary, (J1713+0747)

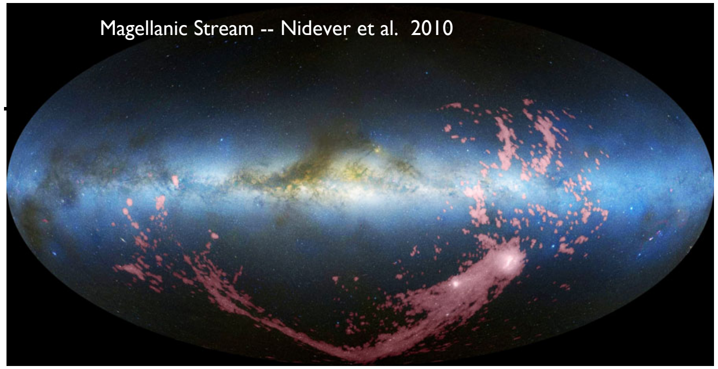
Zhu+2015

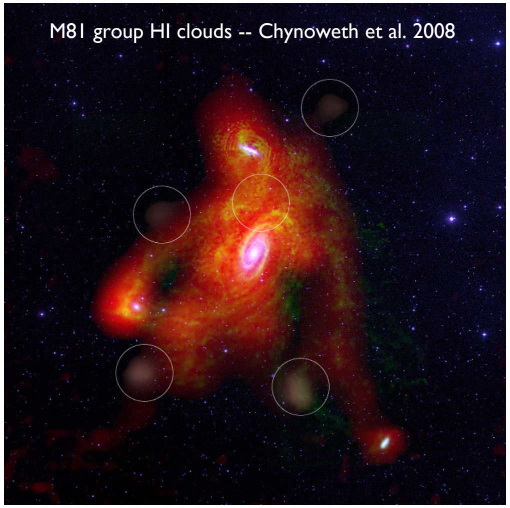


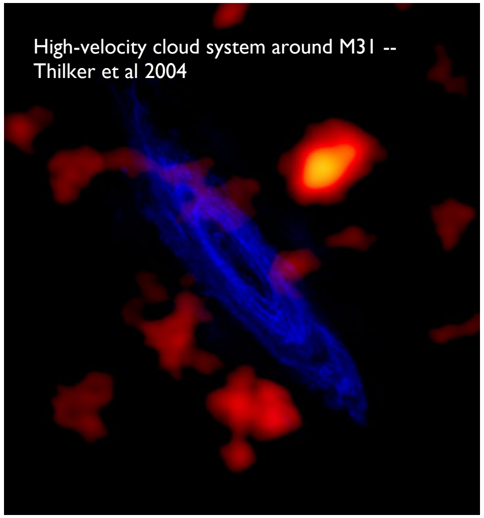
GBT Studies of faint HI -- unequalled sensitivity

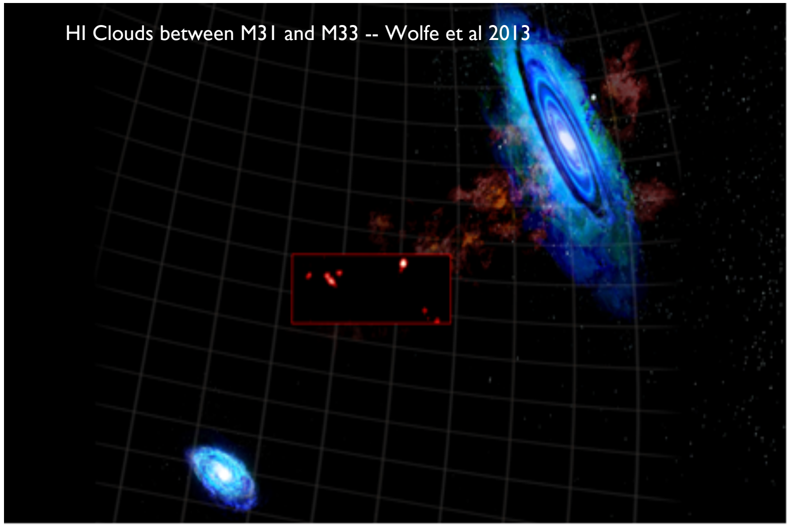
GBT offers ability to detect HI to N_{HI} ~10^{17} cm

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





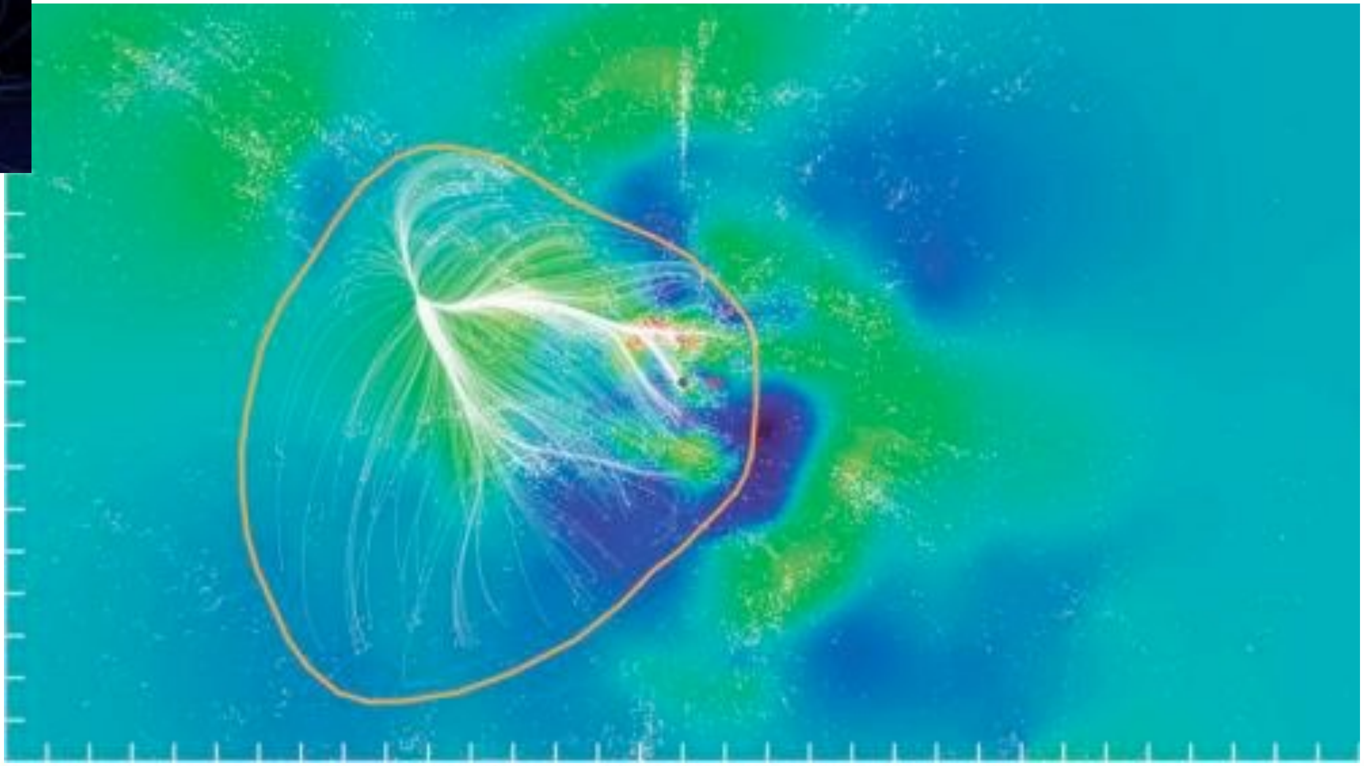




GBT Hydrogen measurements show the structure of the local Universe

(Tully et al. 2014)

Local Super Cluster (~10^{17} Msun) Laniakea – Hawaiian for immeasurable Heaven



HI "Intensity Mapping"

At large redshift the HI from individual galaxies cannot be seen, but their collective signal is detectable.
This technique was developed on the GBT by
Ui-Le Pen, Jeffrey B. Peterson et al.

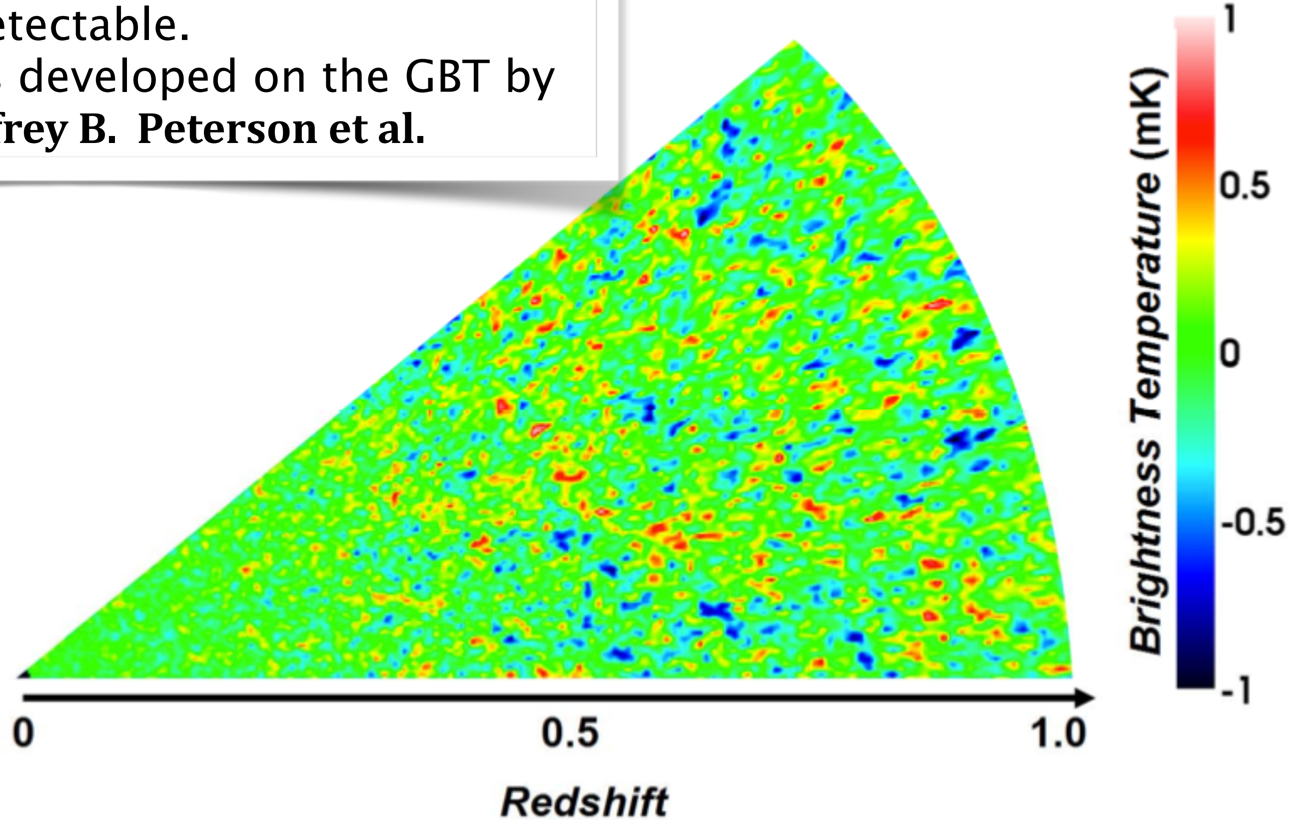


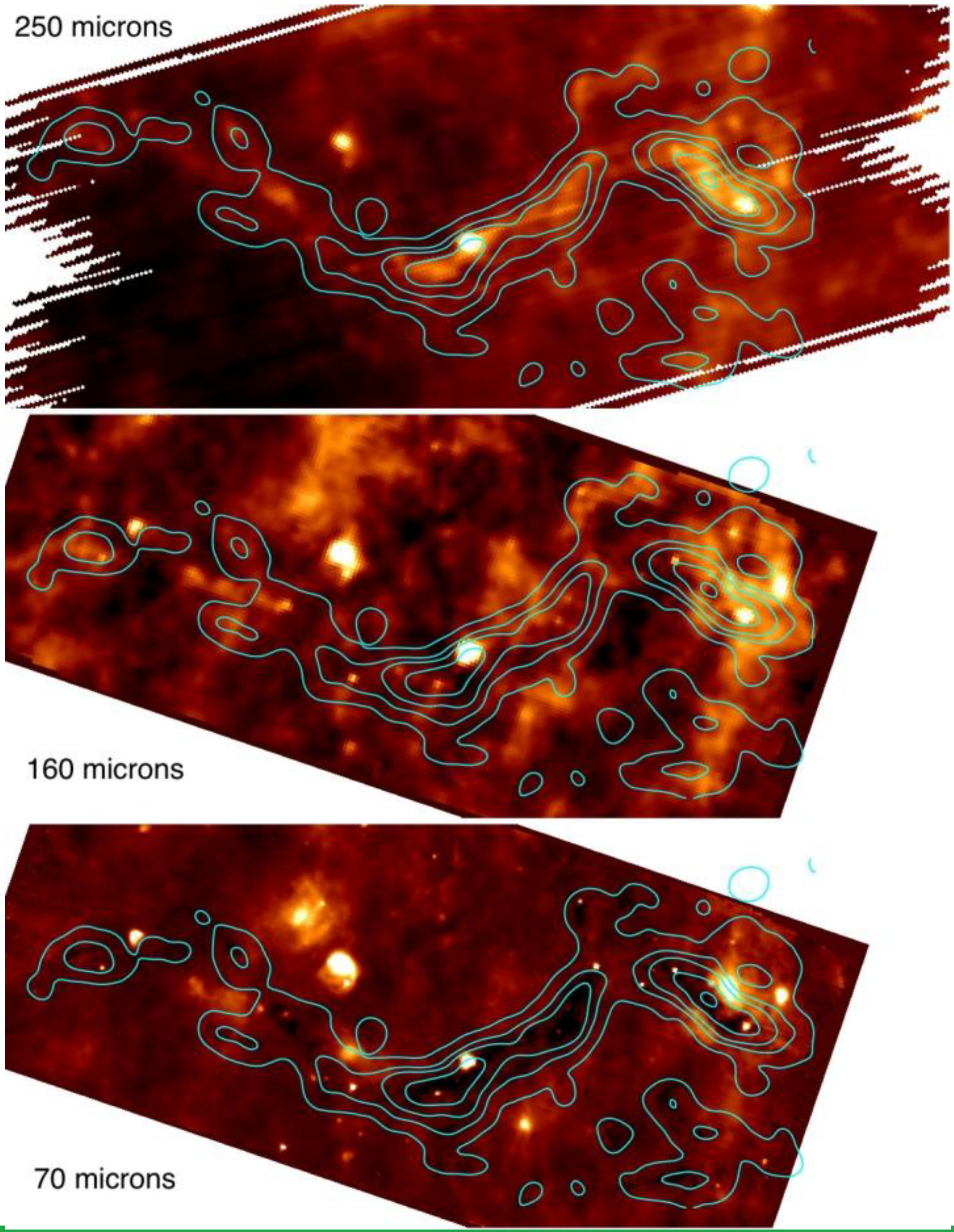
Figure 2: Simulated fluctuations in the brightness temperature of 21cm emission from galaxies in a slice through the universe. The emission is smoothed over 8/h Mpc. The redshift, z, translates to frequency: ν=1.42GHz/(1+z). Red indicates overdensity and blue underdensity.

How do star clusters form and evolve?

What is the role of filaments?

Where do high mass stars form?

GBT NH3 contours on top Infrared images of IRDC ("The Snake") *Courtesy J. Jackson*



GREEN BANK OBSERVATORY

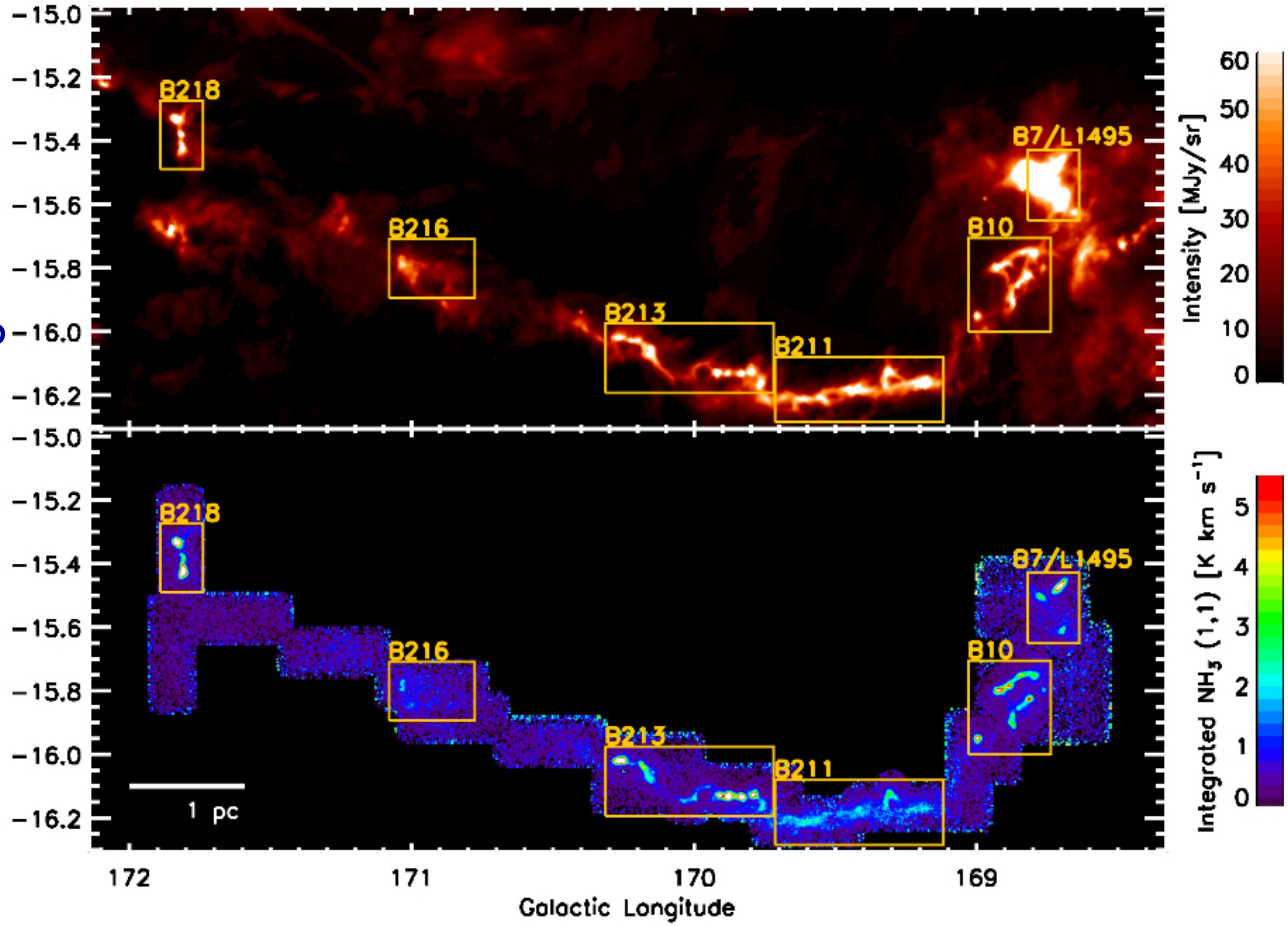
Studies of Star-Forming Filaments via NH_3

Taurus filament.

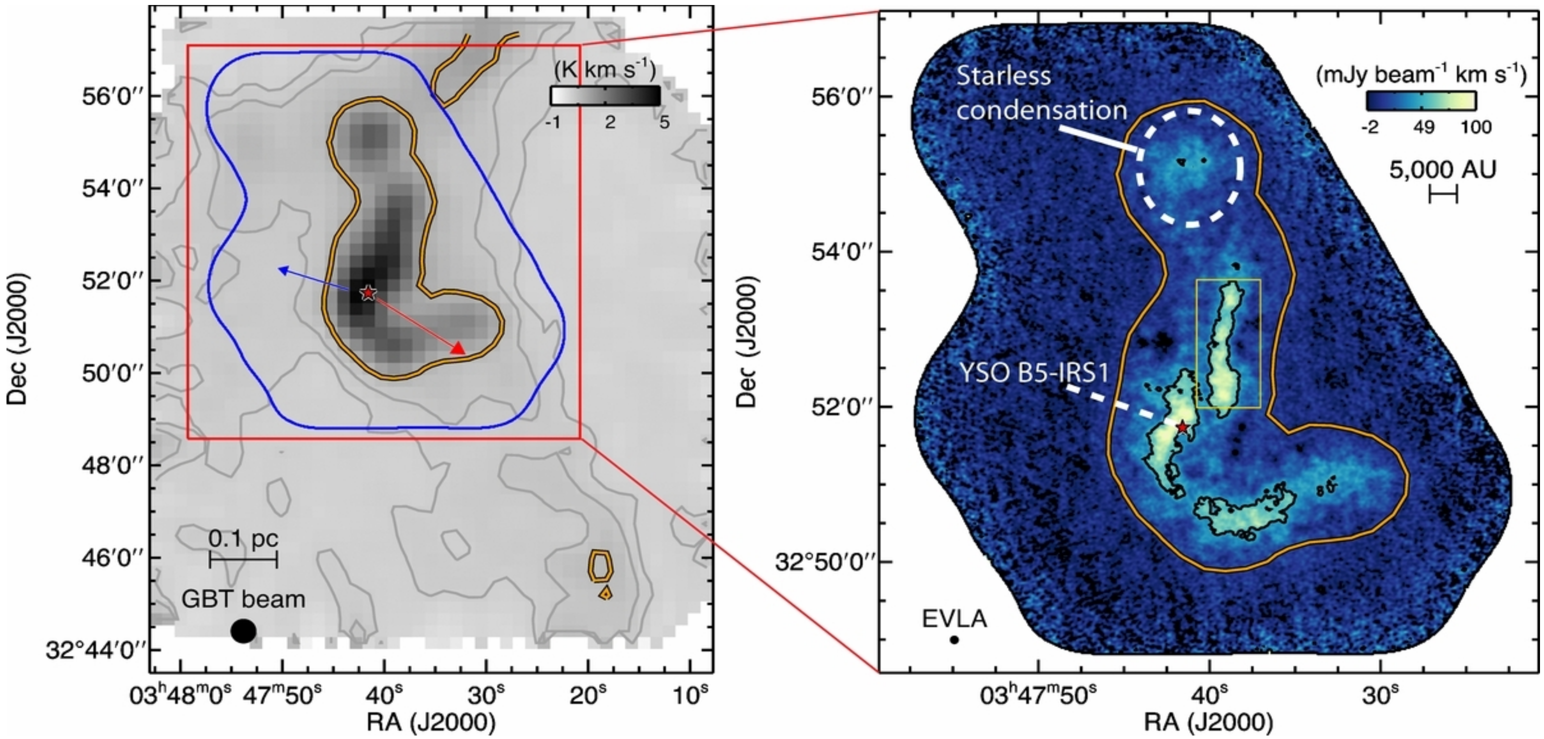
Herschel 500um (top – Dust image)

and GBT NH3 (bottom)

Seo+2015



Yellow contour from the GBT (left) shows where the molecular gas has a subsonic velocity dispersion undergoing large-scale collapse/fragmentation. GBT combined with VLA shows (right) shows starless core and YSO outflow regions



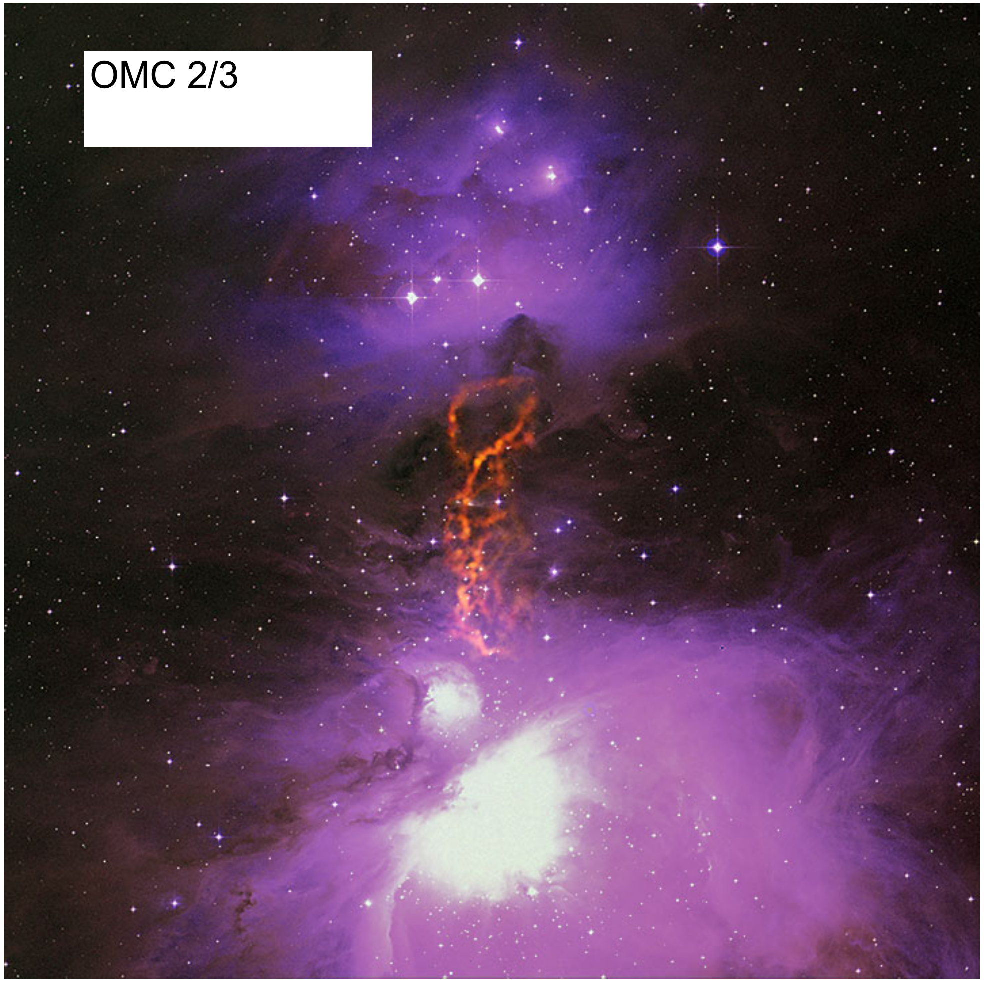
NH_3 intensity of Baranard5 with the GBT (left) and GBT+EVLA (right)

Courtesy Pineda, et al

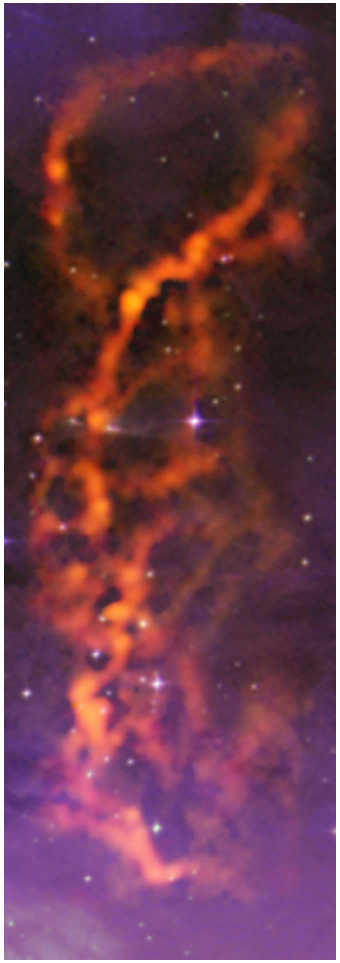
GBT NH3 image of Orion molecular cloud (red, 1.5deg) with WISE infrared image in blue showing warm dust

GBT Detection of mm-cm sized particles in Orion

Schnee et al. (2014)



← 5' →



MUSTANG

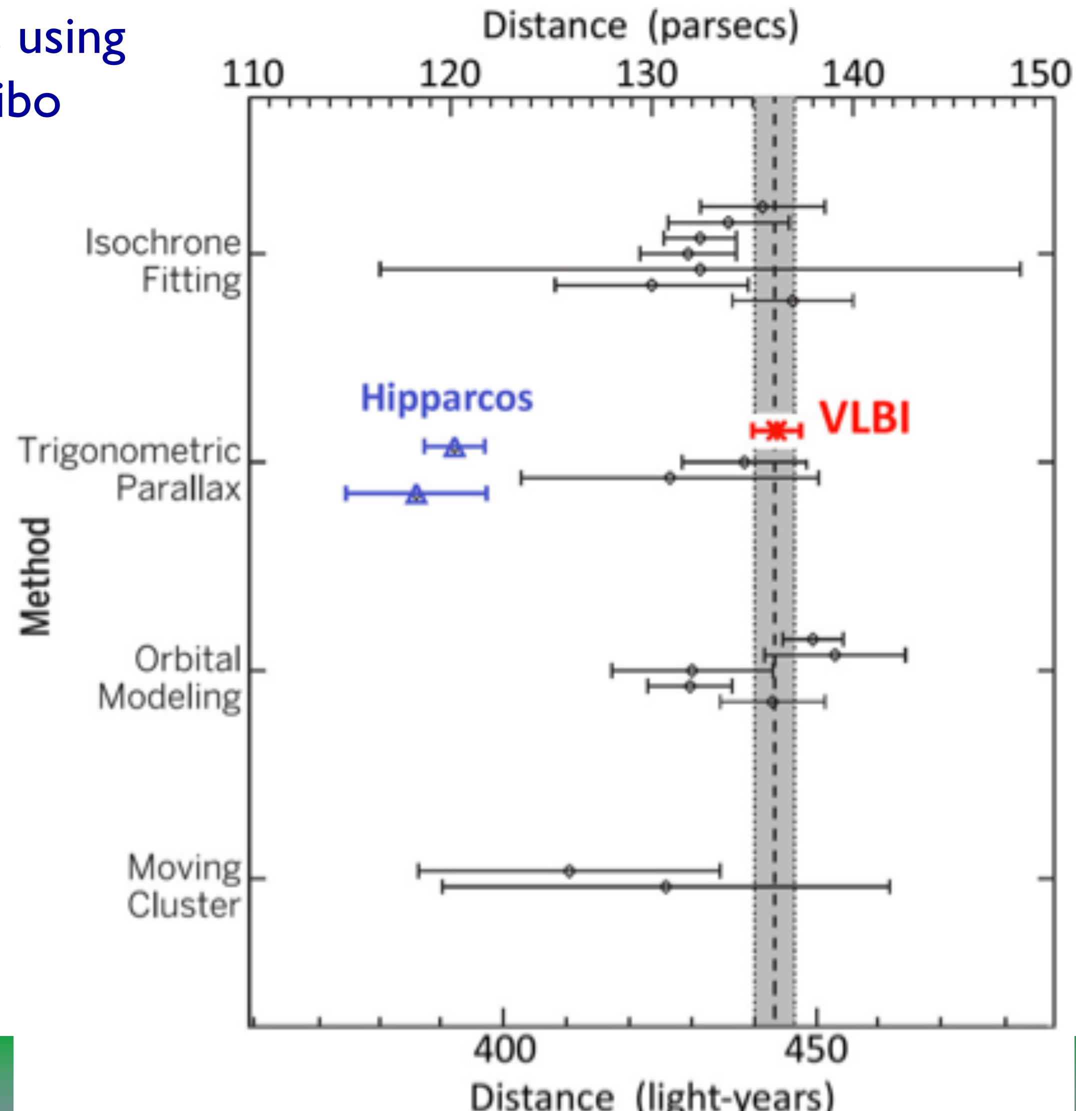
- Bolometer Array
- 3.3mm
- 81-96 GHz
- 14 hours

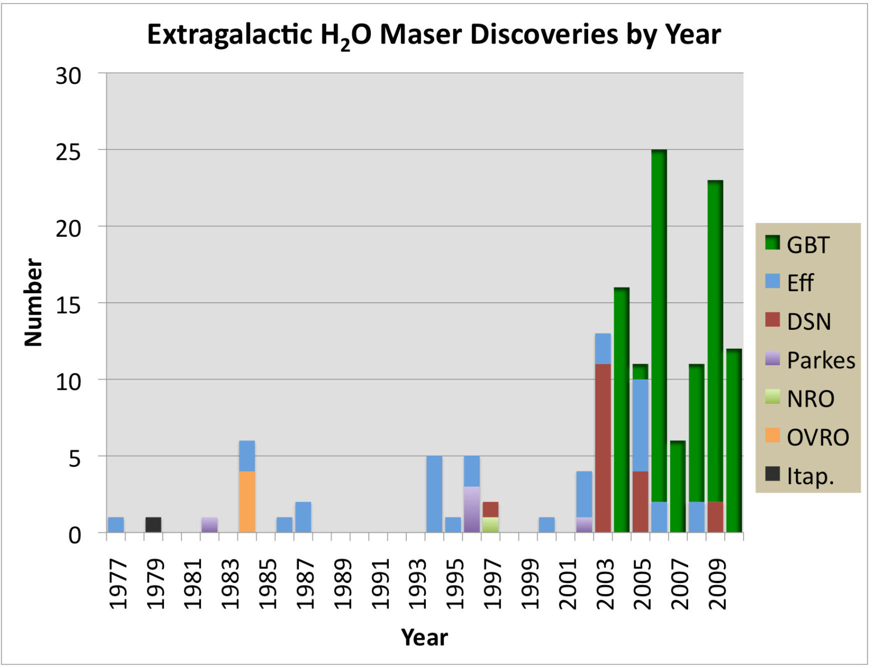
Brighter emission at 3.3mm suggests the existence of “pebbles” which may jump start planet formation {or a new model for dust emissivity}

GBT used with VLBA/HSA/GMVA

e.g., VLBI Resolution of the Pleiades Distance Controversy (Melis et al. 2014)

Trigonometric parallex of radio stars using the VLBA +GBT + Effelsberg + Arecibo

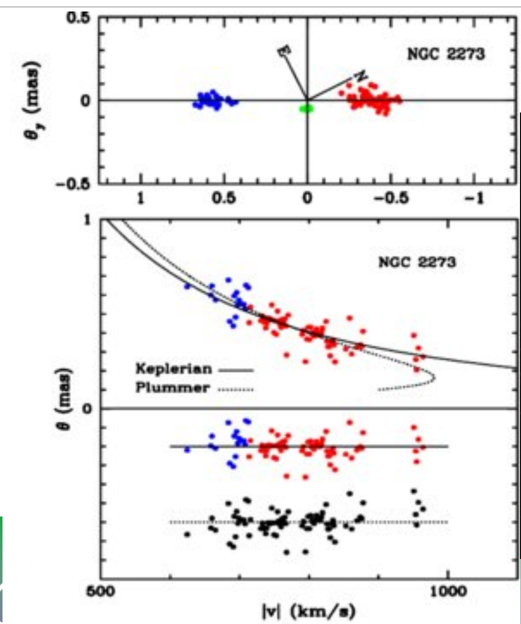


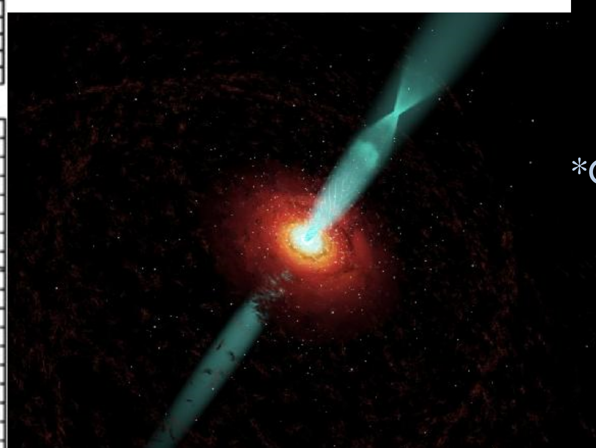


Over 80 masers discovered with the GBT (k-band 22GHz)

Measuring H_0 within 3% precision by obtaining geometric distances to water masers in other galaxies*

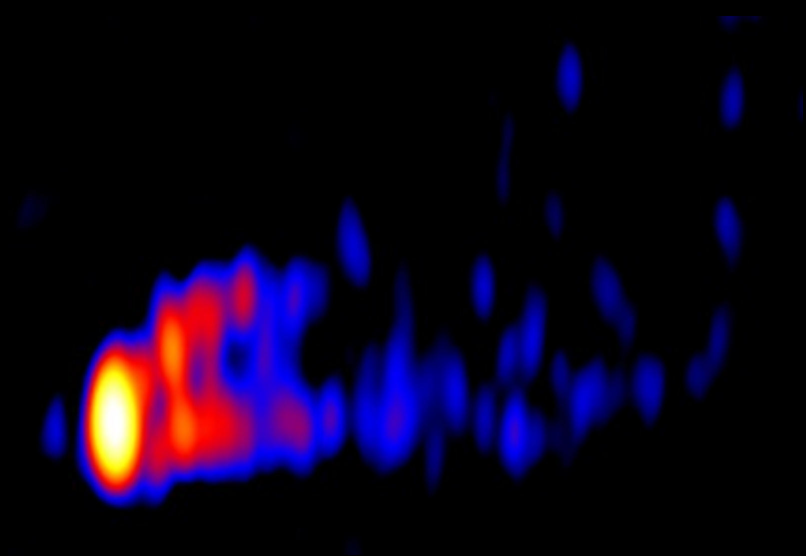
Measuring precise masses of the black holes in megamaser disk galaxies*





*GBT used both for Maser discovery and providing necessary sensitivity to VLBA

M87 3mm VLBI Jet



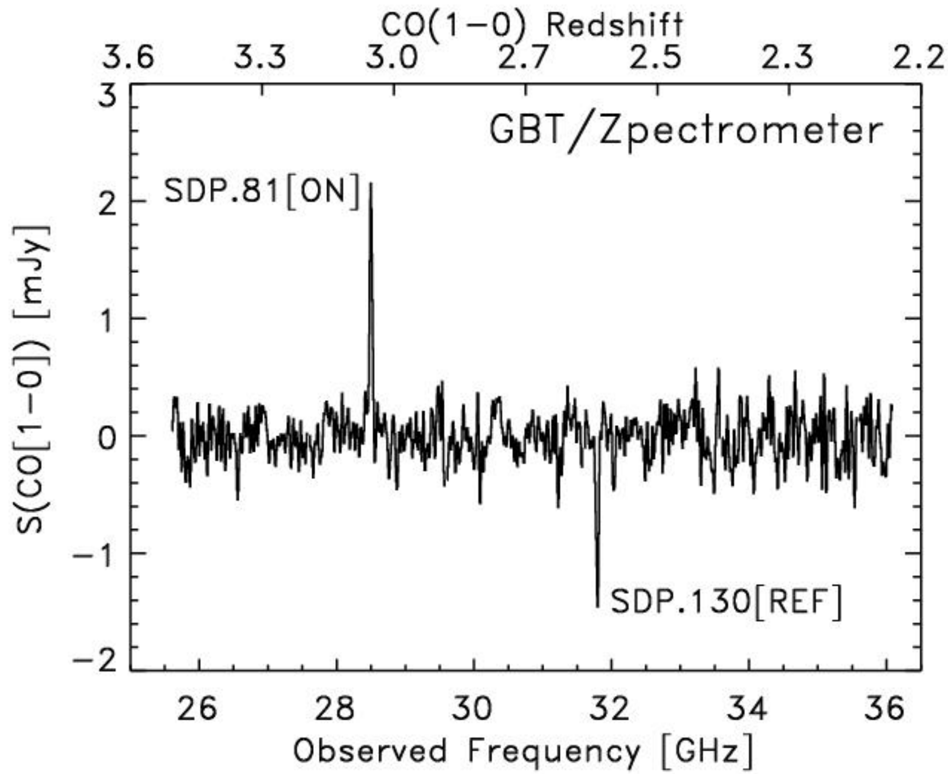
The M87 jet at an angular resolution of 0.25x0.08 mas (~10 Schwarzchild radii) in 3mm VLBI (Hada et al 2016)

GBT High-Redshift Molecular Gas

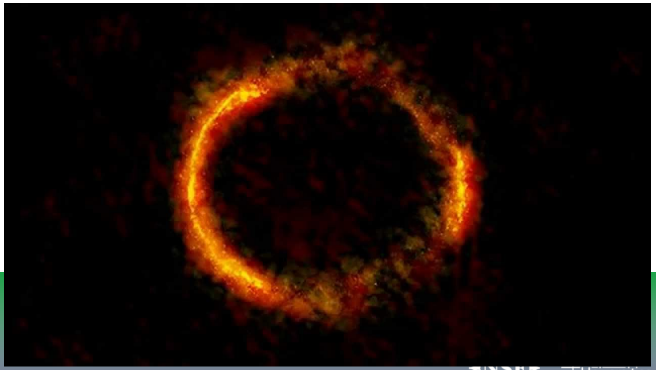
Measurements of molecular gas from young galaxies in formation.

About 30 Herschel sources with GBT CO(1-0) redshifts.

Groups also pursuing CO(3-2) searches at z~7 with the GBT in Q-band (40-45GHz) as well as confirming high-redshift sources from the LMT with CO(1-0) on the GBT.



ALMA image of SDP.81 ("ALMA's ring of fire")



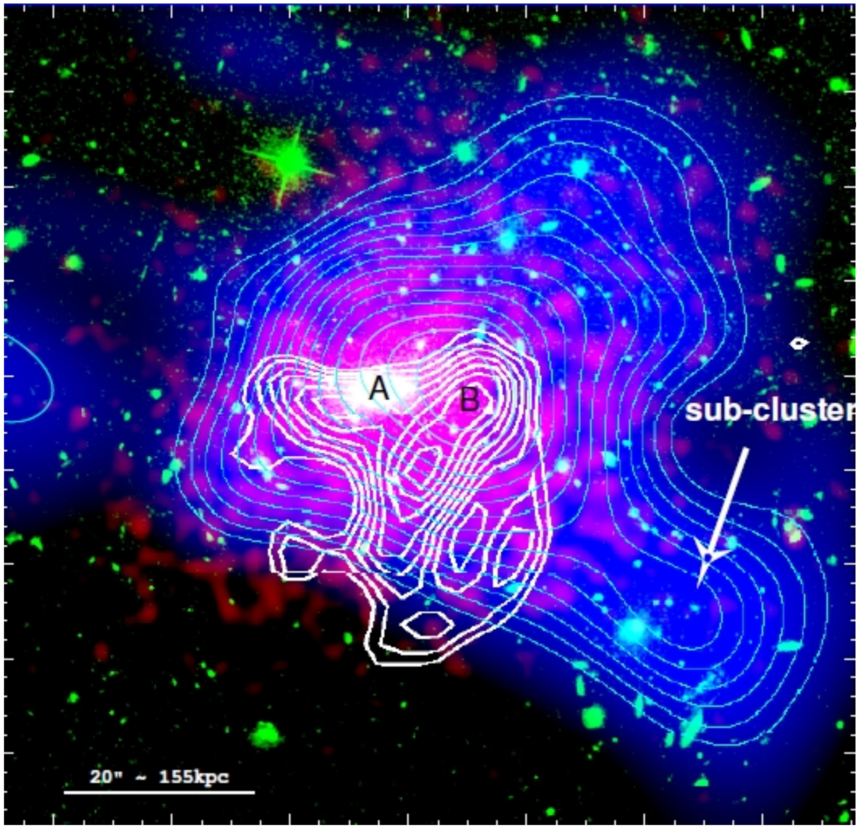
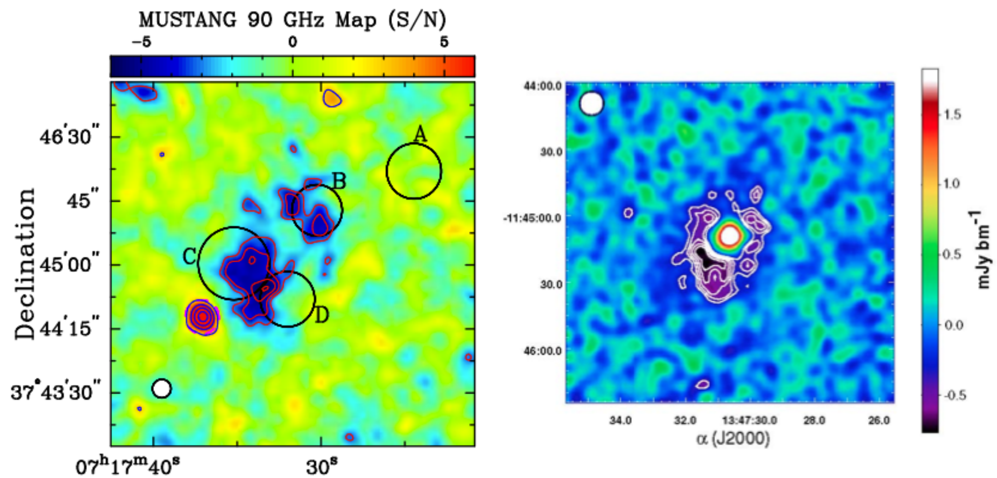


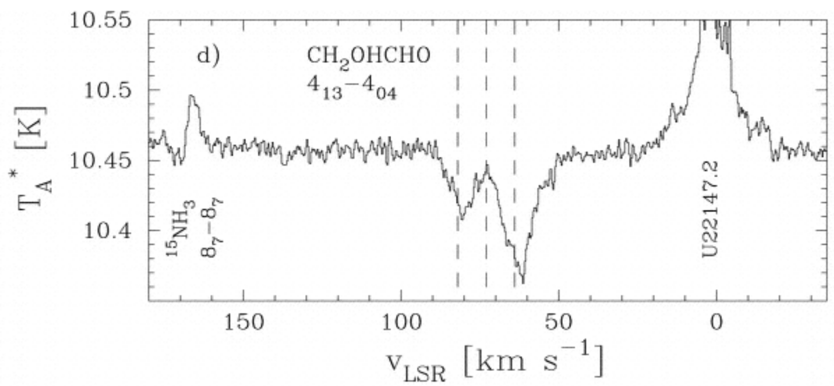
Image of CL1226.9+3332 (z = 0.89); White is MUSTANG; Green is optical (HST); Red is X-ray (Chandra); Blue is mass density (HST) *Courtesy Korngut, et al.*



(Left) Mustang SZE image of the triple merger MACSJ0717+3745 (Mroczkowski 2012). (Right) Mustang image of RXJ1347-1145 which shows deviations from equilibrium first shown by high angular resolution SZE measurements (Mason et al. 2010).

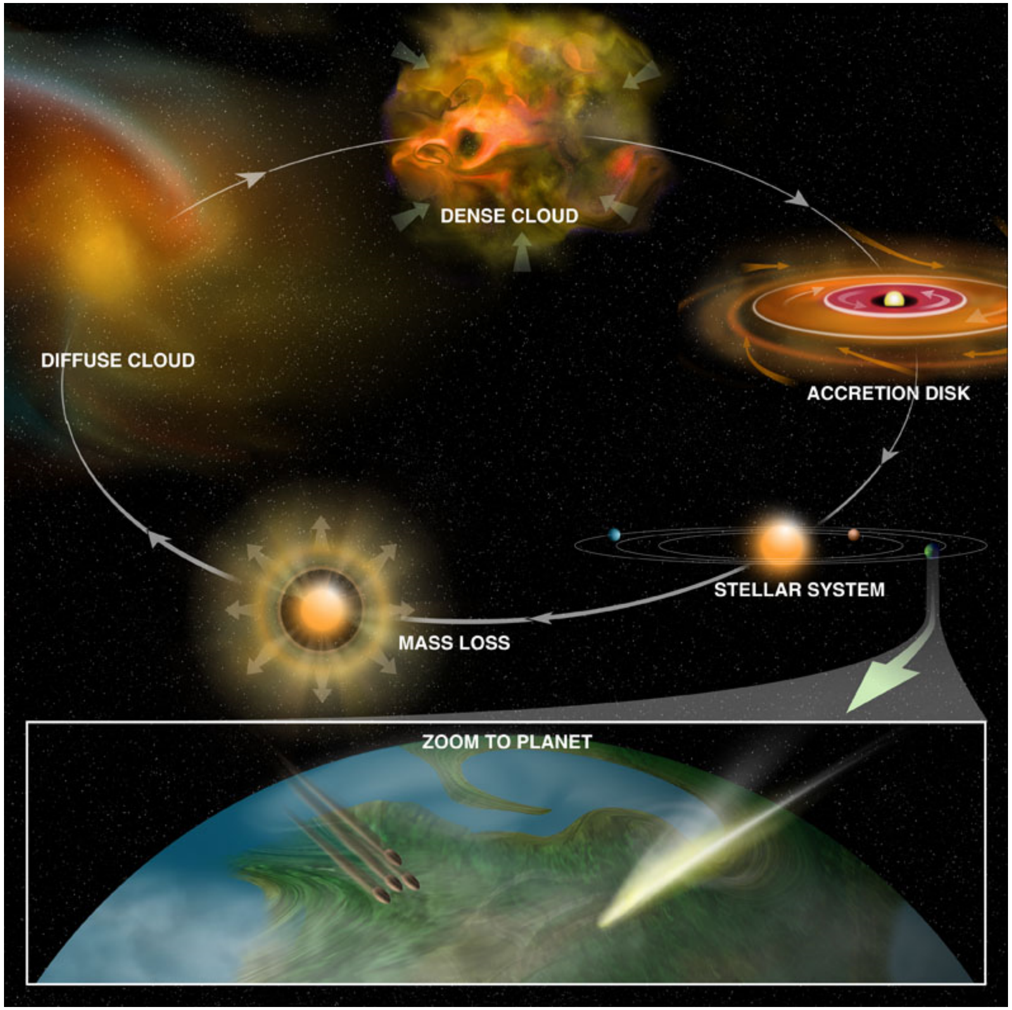
Connect Organic Chemistry in Space with Life on Earth

Measure interstellar chemical processes to determine the characteristics of pre-biotic chemistry in star-forming regions



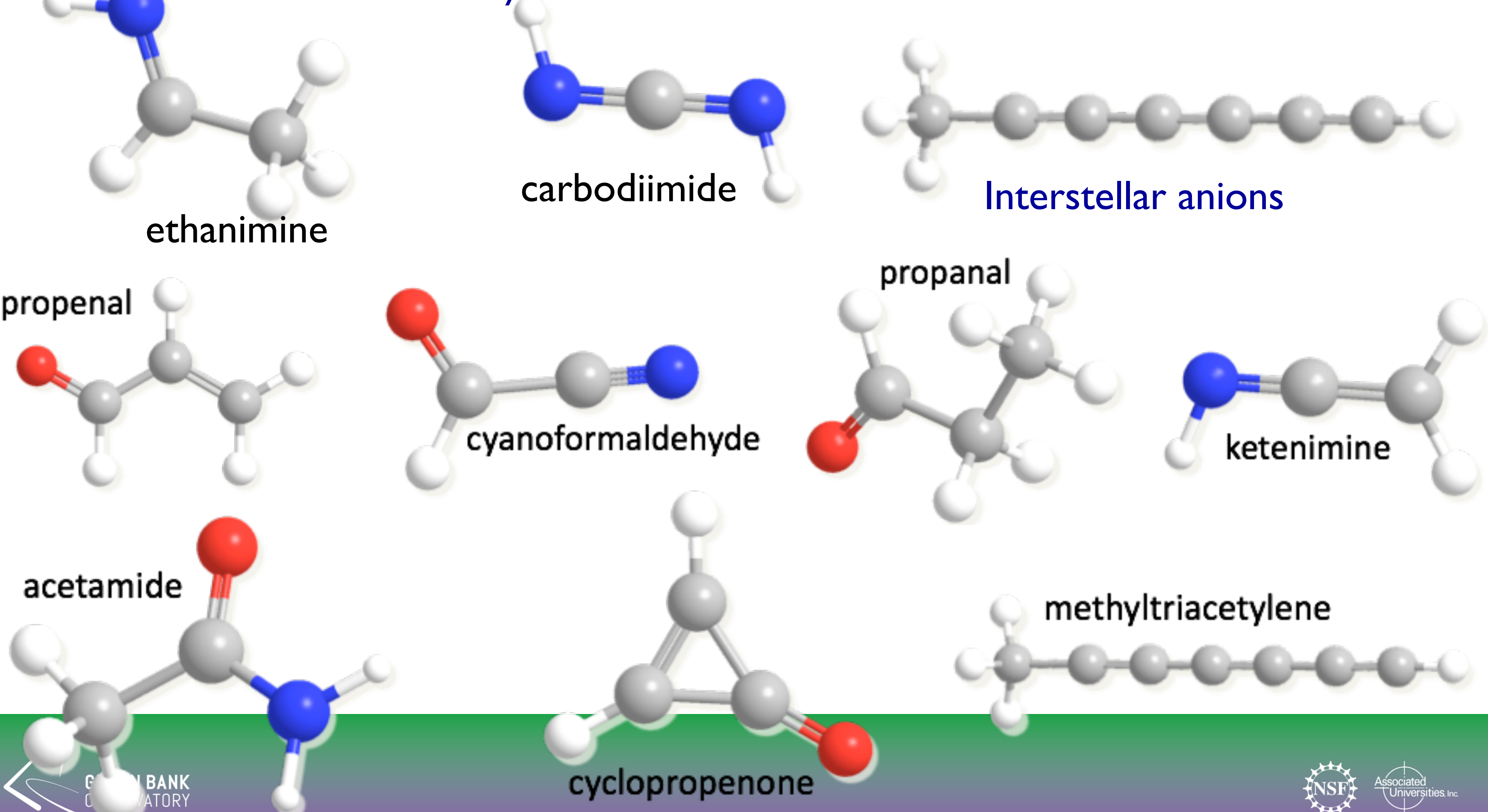
Low temperature sugar-related molecule

Courtesy Hollis, Jewell, Lovas, Remijan



Some (of the ~20) New GBT Molecules

- Linking ISM chemistry to origin of life
- Chemistry as tool for understanding star-formation
- Chemistry of its own sake



Capabilities and Performance of the GBT

Available GBT receivers

Receiver	Band	Frequency Range (GHz)	Focus	Polarization	Beams	Polarizations per Beam
PF1	342 MHz	.290-.395	Prime	Lin/Circ	1	2
	450 MHz*	.385-.520	Prime	Lin/Circ	1	2
	600 MHz*	.510-.690	Prime	Lin/Circ	1	2
	800 MHz	.680-.920	Prime	Lin/Circ	1	2
PF2*	——	.910-1.23	Prime	Lin/Circ	1	2
L-Band	——	1.15-1.73	Greg.	Lin/Circ	1	2
S-Band	——	1.73-2.60	Greg.	Lin/Circ	1	2
C-Band	——	3.95-8.0	Greg.	Lin/Circ	1	2
X-Band	——	8.00-11.6	Greg.	Circ	1	2
Ku-Band	——	12.0-15.4	Greg.	Circ	2	2
KFPA	——	18.0-27.5	Greg.	Circ	7	2
Ka-Band	MM-F1	26.0-31.0	Greg.	Circ	2	1
	MM-F2	30.5-37.0				
	MM-F3	36.0-39.5				
Q-Band	——	38.2-49.8	Greg.	Circ	2	2
W-Band 4mm	MM-F1	67-74	Greg.	Circ	2	2
	MM-F2	73-80	Greg.	Circ	2	2
	MM-F3	79-86	Greg.	Circ	2	2
	MM-F4	85-93.3	Greg.	Circ	2	2
Mustang2	——	80-100	Greg.	—-	200	—-
ARGUS	——	80-115.3	Greg.	Circ	16	1

Performance and Bandwidth

Receiver	Band	Beam Separation	FWHM	Gain (K/Jy)	Aperture Efficiency	Maximum Instantaneous Bandwidth (MHz)
PF1	342 MHz 450 MHz* 600 MHz* 800 MHz	—— —— —— ——	36′ 27′ 21′ 15′	2.0 2.0 2.0 2.0	72% 72% 72% 72%	240
PF2*	——	——	12′	2.0	72%	240
L-Band	——	——	9′	2.0	72%	650
S-Band	——	——	5.8′	2.0	72%	970
C-Band	——	——	2.5′	2.0	72%	3800
X-Band	——	——	1.4′	2.0	71%	2400
Ku-Band	——	330”	54”	1.9	70%	3500
KFPA	——	96”	32”	1.9	68%	1800,8000
Ka-Band	MM-F1 MM-F2 MM-F3	78”	26.8” 22.6” 19.5”	1.8	63-67%	4000
Q-Band	——	58”	16”	1.7	58-64%	4000
W-Band 4mm	MM-F1 MM-F2 MM-F3 MM-F4	286”	10”	1.0	30-48%	6000 4000 4000 4000
Mustang2	——	—-	10”	—-	35%	20000
ARGUS	——	30.4”	8”	—-	20-35%	1500

Available GBT Backends

- VEGAS Spectral-Line
- VEGAS Pulsar
- Digital Continuum Receiver (DCR)
- Caltech Continuum Backend (CCB, Ka-band only)
- Mark 6 VLBA Disk Recorder
- JPL Radar Backend

VEGAS Spectral-line Modes:

16 separate spectrometer channels (8 dual polarization channels) that can be divided between beams and different frequencies as needed and can support up to 8 spectral sub-windows per spectrometer.

Maximum data rate ~160GB/s, but most projects at <1MB/s

Table 4: VEGAS modes.

Mode	Spectral Windows per Spectrometer	Bandwidth per Spectrometer (MHz)	Number of Channels per Spectrometer	Approximate Spectral Resolution (kHz)
1	1	1500[a]	1024	1465
2	1	1500[a]	16384	92
3	1	1080[b]	16384	66
4	1	187.5	32768	5.7
5	1	187.5	65536	2.9
6	1	187.5	131072	1.4
7	1	100	32768	3.1
8	1	100	65536	1.5
9	1	100	131072	0.8
10	1	23.44	32768	0.7
11	1	23.44	65536	0.4
12	1	23.44	131072	0.2
13	1	23.44	262144	0.1
14	1	23.44	524288	0.05
15	1	11.72	32768	0.4
16	1	11.72	65536	0.2
17	1	11.72	131072	0.1
18	1	11.72	262144	0.05
19	1	11.72	524288	0.02
20	8[c]	23.44	4096	5.7
21	8[c]	23.44	8192	2.9
22	8[c]	23.44	16384	1.4
23	8[c]	23.44	32768	0.7
24	8[c]	23.44	65536	0.4
25	8[c]	16.875	4096	4.1
26	8[c]	16.875	8192	2.0
27	8[c]	16.875	16384	1.0
28	8[c]	16.875	32768	0.5
29	8[c]	16.875	65536	0.26

[a] The useable bandwidth for this mode is 1250 MHz.
[b] The useable bandwidth for this mode is 850 MHz.
[c] For modes 20-24, the spectral windows must be placed within 1500 MHz with a useable frequency range of 150 to 1400 MHz. For modes 25-29, the spectral windows must be placed within 1000 MHz with a useable frequency range of 150 to 950 MHz.

VEGAS Pulsar Modes:

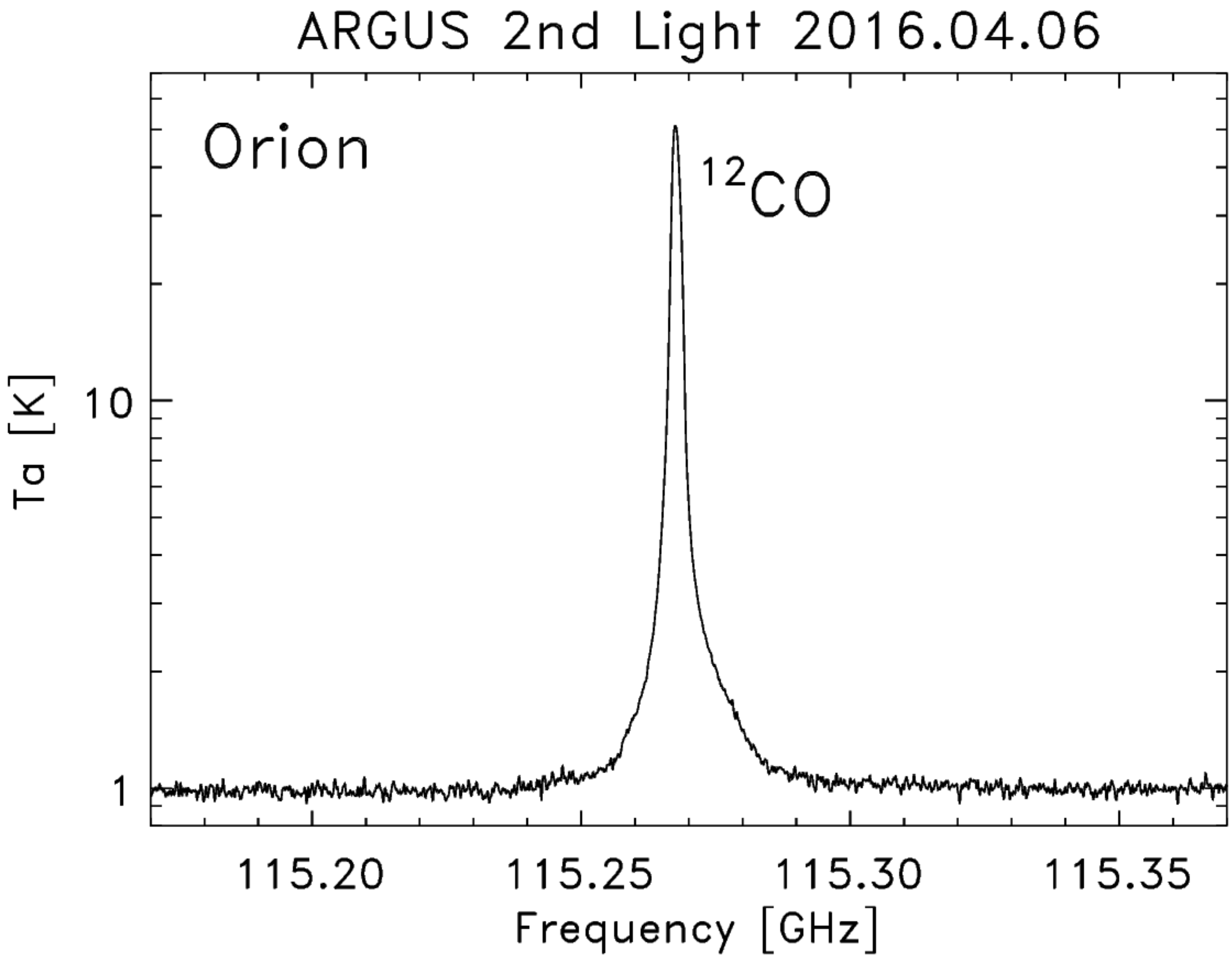
Coherent and Incoherent
Bandwidth: 100-1500MHz
Nchannels: 64-4096

Name	Dedispersion Mode	Bandwidth (MHz)	nchan	Notes
c0100x0064	Coherent	100	64	Full Stokes only
c0100x0128	Coherent	100	128	Full Stokes only
c0100x0256	Coherent	100	256	Full Stokes only
c0100x0512	Coherent	100	512	Full Stokes only
c0200x0064	Coherent	200	64	Full Stokes only
c0200x0128	Coherent	200	128	Full Stokes only
c0200x0256	Coherent	200	256	Full Stokes only
c0200x0512	Coherent	200	512	Full Stokes only
c0200x1024	Coherent	200	1024	Full Stokes only
c0800x0128	Coherent	800	128	Full Stokes only
c0800x0256	Coherent	800	256	Full Stokes only
c0800x0512	Coherent	800	512	Full Stokes only
c0800x1024	Coherent	800	1024	Full Stokes only
c0800x2048	Coherent	800	2048	Full Stokes only
c0800x4096	Coherent	800	4096	Full Stokes only
c1500x0128	Coherent	1500	128	Full Stokes only
c1500x0256	Coherent	1500	256	Full Stokes only
c1500x0512	Coherent	1500	512	Full Stokes only
c1500x1024	Coherent	1500	1024	Full Stokes only
c1500x2048	Coherent	1500	2048	Full Stokes only
c1500x4096	Coherent	1500	4096	Full Stokes only
i0100x0512	Incoherent	100	512	Total intensity available in search-mode
i0100x1024	Incoherent	100	1024	Total intensity available in search-mode
i0100x2048	Incoherent	100	2048	Total intensity only
i0100x4096	Incoherent	100	4096	Total intensity only
i0100x8192	Incoherent	100	8192	Total intensity available in search-mode
i0200x1024	Incoherent	200	1024	Total intensity available in search-mode
i0200x2048	Incoherent	200	2048	Total intensity only
i0200x4096	Incoherent	200	4096	Total intensity only
i0200x8192	Incoherent	200	8192	Total intensity only
i0800x0128	Incoherent	800	128	Total intensity available in search-mode
i0800x0256	Incoherent	800	256	Total intensity available in search-mode
i0800x0512	Incoherent	800	512	Total intensity available in search-mode
i0800x1024	Incoherent	800	1024	Total intensity available in search-mode
i0800x2048	Incoherent	800	2048	Total intensity available in search-mode
i0800x4096	Incoherent	800	4096	Total intensity available in search-mode
i1500x0128	Incoherent	1500	128	Total intensity available in search-mode
i1500x0256	Incoherent	1500	256	Total intensity available in search-mode
i1500x0512	Incoherent	1500	512	Total intensity available in search-mode
i1500x1024	Incoherent	1500	1024	Total intensity available in search-mode
i1500x2048	Incoherent	1500	2048	Total intensity available in search-mode
i1500x4096	Incoherent	1500	4096	Total intensity available in search-mode

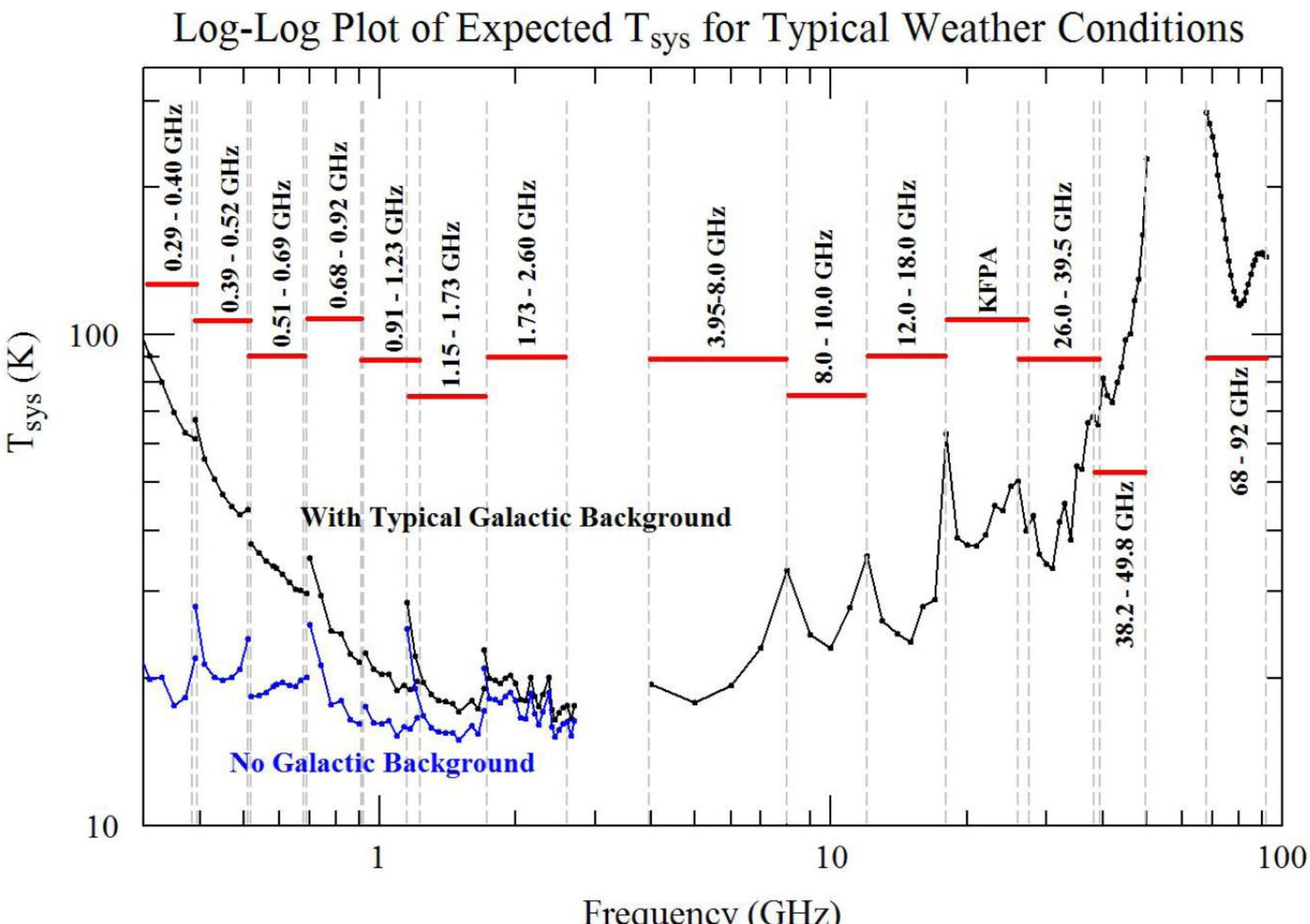
GBT Specs:

Location	Green Bank, West Virginia, USA
Coordinates	Longitude: 79°50′23.406″ West (NAD83) Latitude: 38°25′59.236″ North (NAD83) Track Elevation: 807.43 m (NAVD88)
Optics	110 m x 100 m unblocked section of a 208 m parent paraboloid Offaxis feed arm
Telescope Diameter	100 m (effective)
Available Foci	Prime and Gregorian f/D (prime) = 0.29 (referred to 208 m parent parabola) f/D (prime) = 0.6 (referred to 100 m effective parabola) f/D (Gregorian) = 1.9 (referred to 100 m effective aperture)
Receiver mounts	Prime: Retractable boom with Focus-Rotation Mount Gregorian: Rotating turret with 8 receiver bays
Subreflector	8-m reflector with Stewart Platform (6 degrees of freedom)
Main reflector	2004 actuated panels (2209 actuators) Average intra-panel RMS 68 μm
FWHM Beamwidth	Gregorian Feed: $\sim 12.60/f_{GHz}$ arcmin Prime Focus: $\sim 13.01/f_{GHz}$ arcmin (see Section 3.1.1)
Elevation Limits	Lower limit: 5 degrees Upper limit: $\sim$ 90 degrees
Declination Range	Lower limit: ~ -46 degrees Upper limit: 90 degrees
Slew Rates	Azimuth: 35.2 degrees/min Elevation: 17.6 degrees/min
Surface RMS	Passive surface: 450 μm at 45° elevation, worse elsewhere Active surface: $\sim$ 250 μm, under benign night-time conditions
Pointing accuracy	1σ values from 2-D data 5″ blind 2.7″ offset

GBT can observe up to 116 GHz



Noise Levels (Tsys) for Typical Weather



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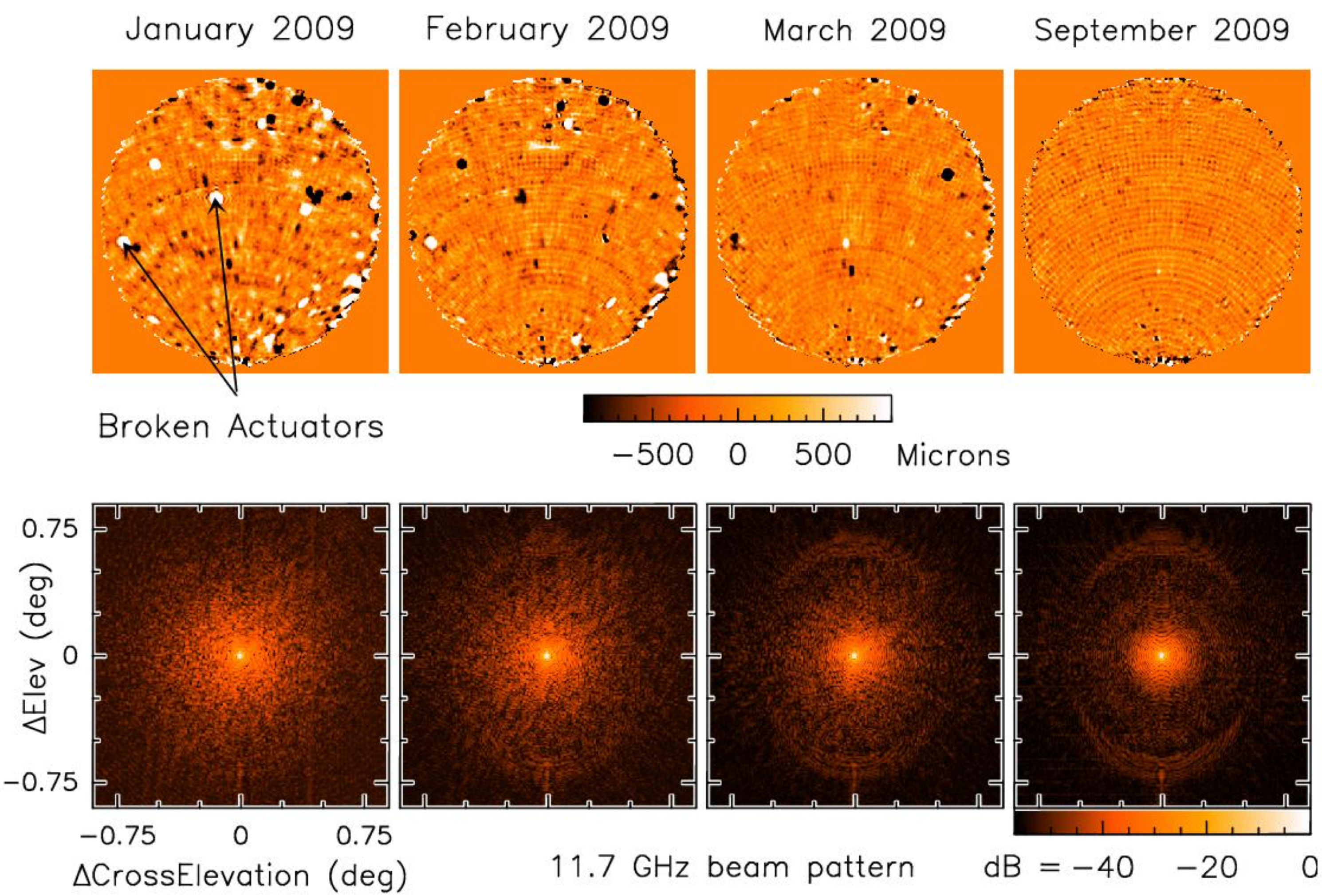
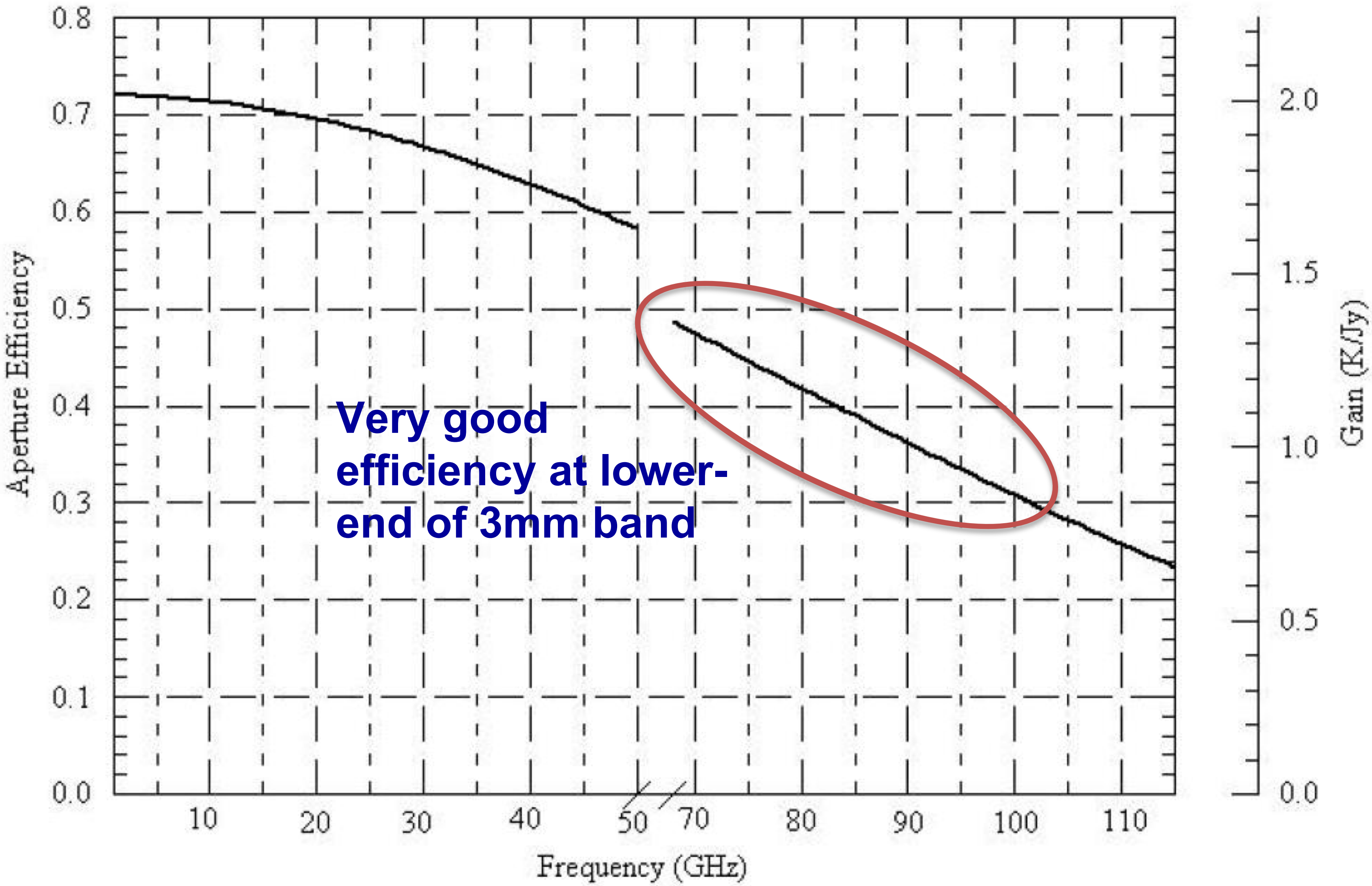
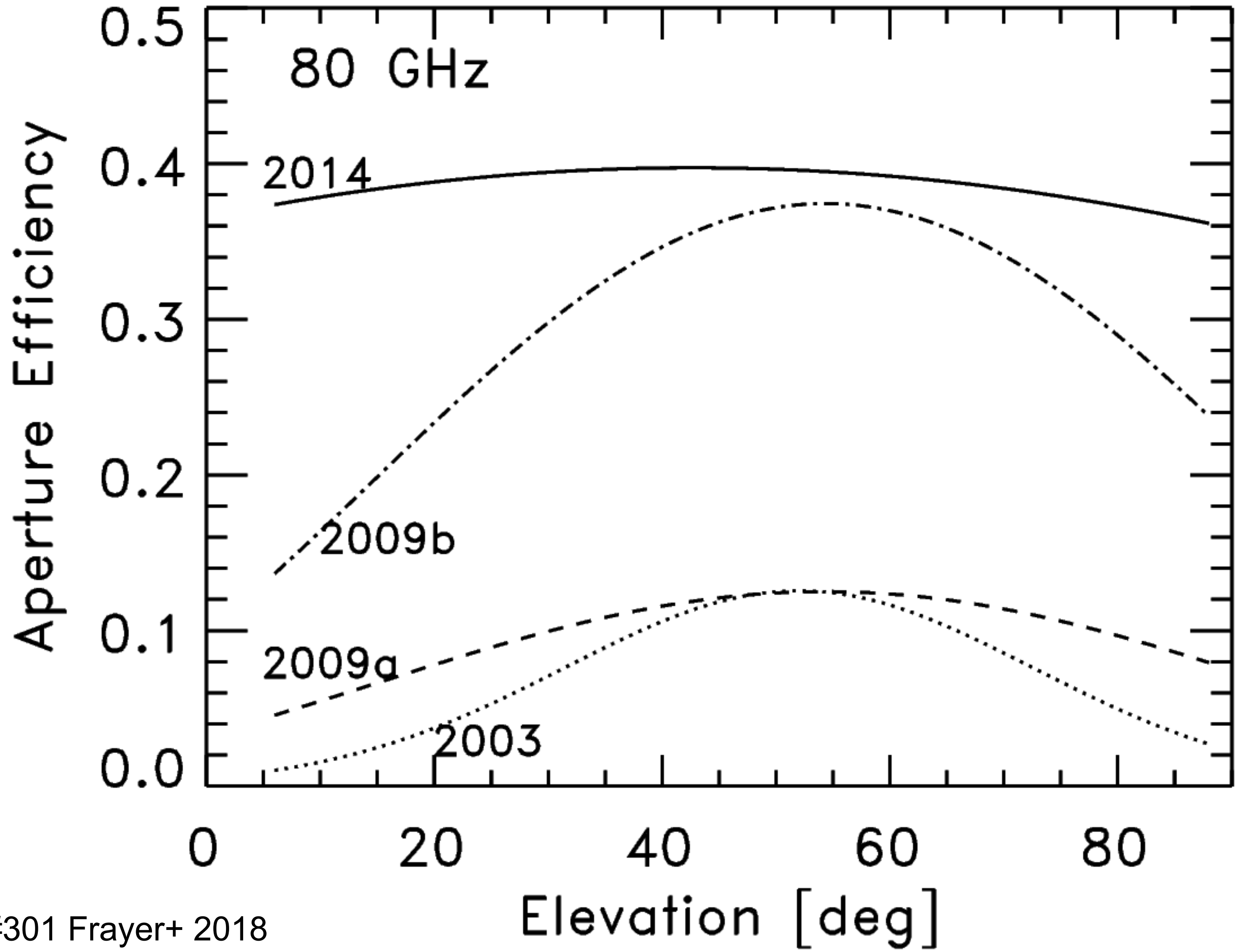
GBT Surface Improved in 2009



GBT Aperture Efficiency and Gain (K/Jy)



Gain-Curve: Improvements to Surface Models over time

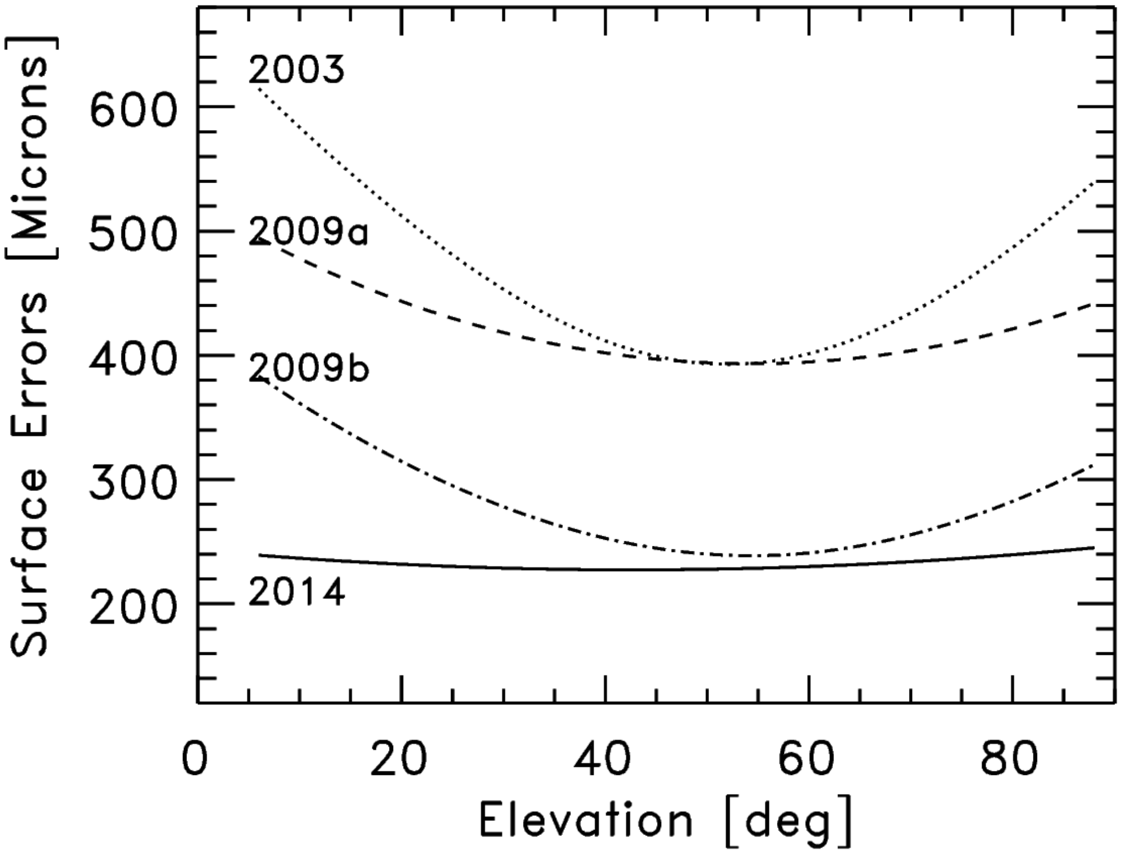


GBT Memo #301 Frayer+ 2018

Ruze Equation

$$\eta_a = \eta_0 \exp[-(4\pi\epsilon/\lambda)^2)],$$

History of GBT Performance

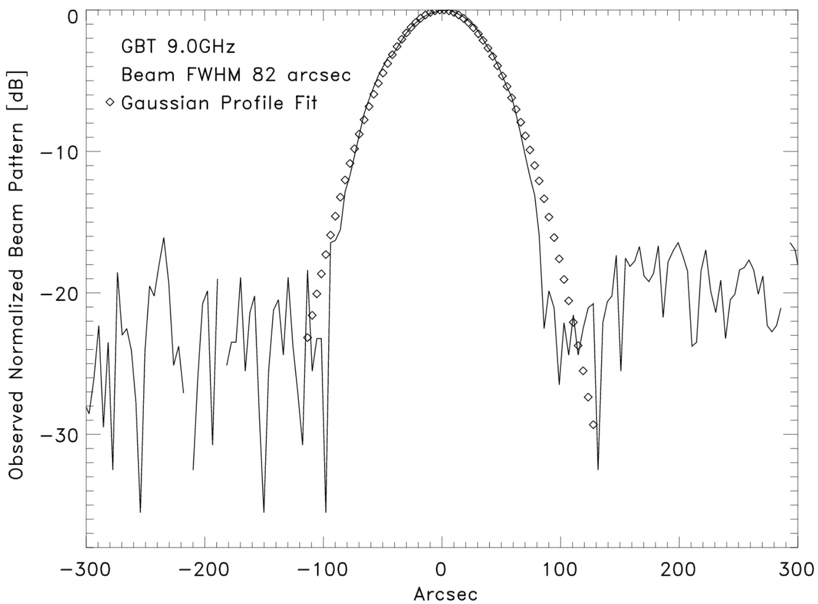


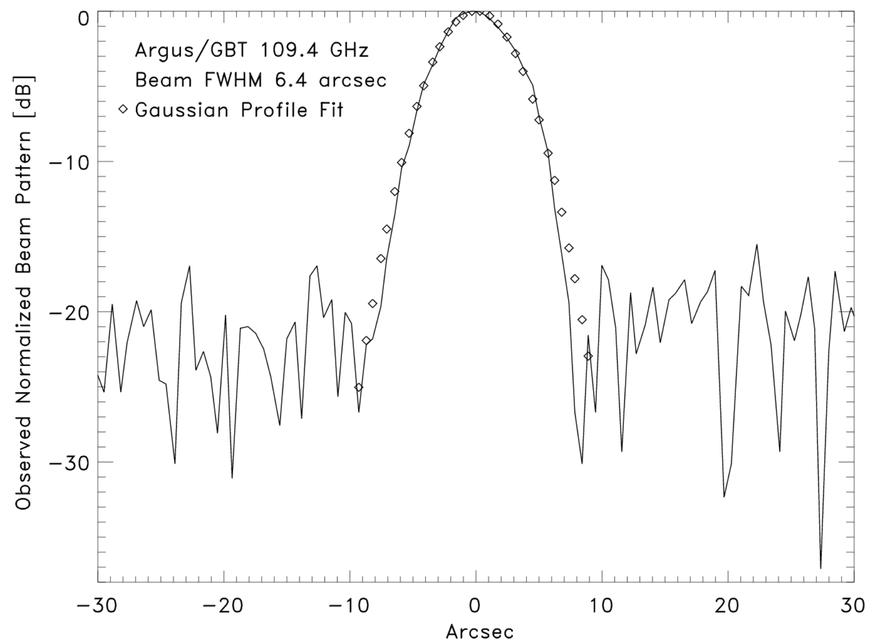
Effective surface errors determines the aperture efficiency.

Surface errors of 235+/-15 microns were measured for 2017-2019 observing seasons

GBT Achieves Theoretical Beam with Argus at 109 GHz

(GBT memo#296)

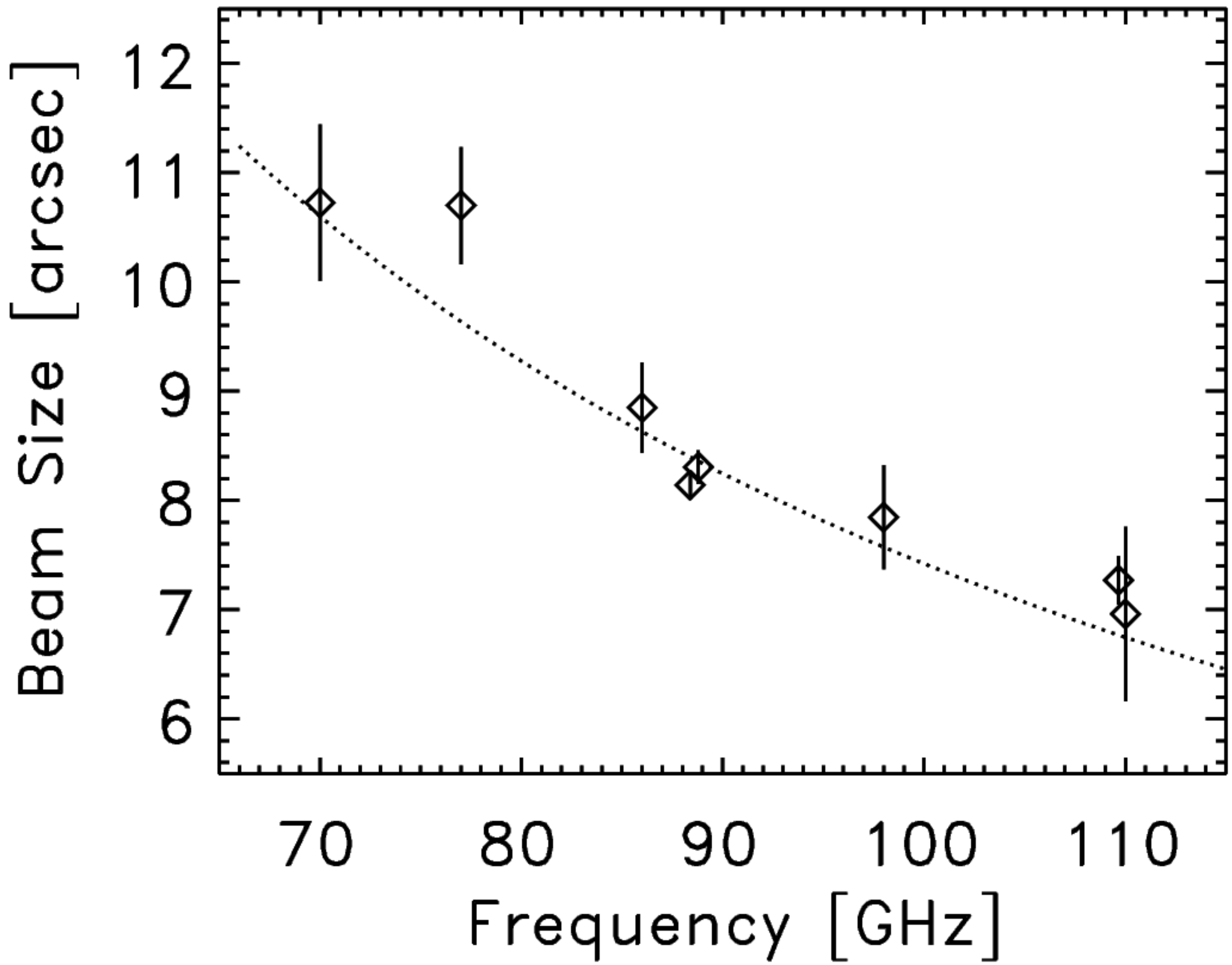




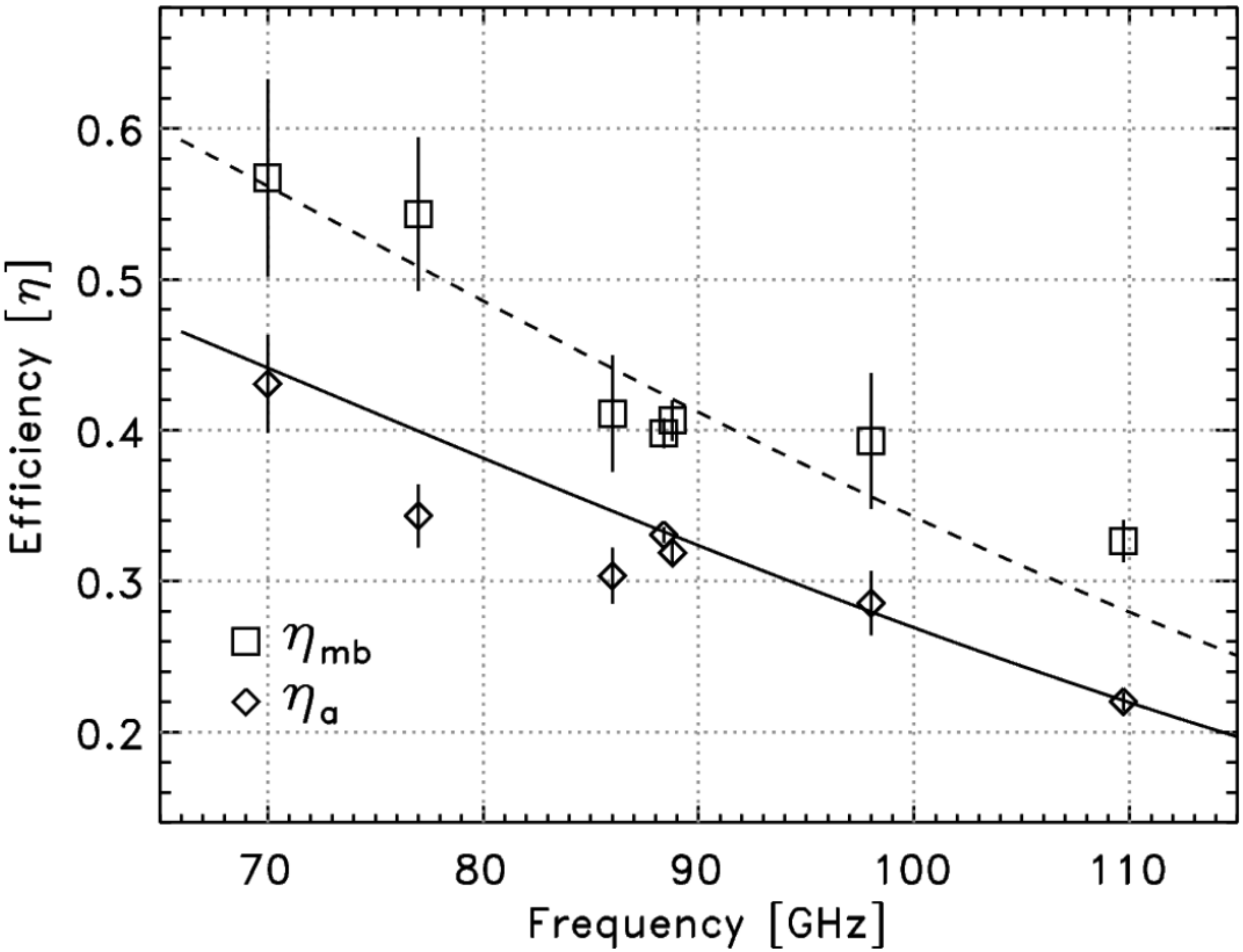
Left is the GBT beam at 9.0 GHz and **Right** GBT at 109.4 GHz.
With Argus, the GBT can achieve beam sizes of ~1.15--1.2 Lambda/D (in good conditions after OOF).

GBT Beam Size

FWHM ~= 1.2 Lambda/D



Calibration Results



$$\frac{\eta_{mb}}{\eta_a} = 1.274 \pm 0.035.$$

Average beam-size parameter:

$$\kappa \equiv \theta_{\rm FWHM} \left(\frac{D}{\lambda}\right) = 1.20,$$

GBT Memo #302 Frayer+ 2019

GBT Pointing and Surface Performance

- ~5-10 arcsec blind pointing
- ~1-2 arcsec offset pointing
- ~0.5-1 arcsec tracking accuracy

- rms(surface) ~0.45mm without the active surface
- rms (surface) ~ 0.35mm – no OOF corrections during day
- rms (surface) ~ 0.3mm – no OOF corrections during night
- rms(surface) ~0.23mm with OOF corrections at night
- Long-term Goal: rms(surface)~0.20mm

Effects of Winds

$$\sigma_{tr}^2 = \sigma_0^2 + \left(\frac{s}{3.5}\right)^4$$

where s is wind speed in m/s.
sigma_o ~1" during night
sigma_o~2" during day

Frequency	Beam Size	Wind speed limit to track within 1/10 beam size ; sigma_tr=(s/3.5)^2
1 GHz	740"	30 m/s (67 mph, but telescope in survival at 35 mph)
10 GHz	74"	9.5 m/s (20 mph)
100 GHz	7.4"	3 m/s (6 mph)

The atmosphere is important at high frequency (>10 GHz)

- Opacity attenuates the signal and adds to the Tsys:

Tsys = Trcvr + Tspill +Tbg * exp(-tau*A) + Tatm * [exp(-tau*A) – 1]

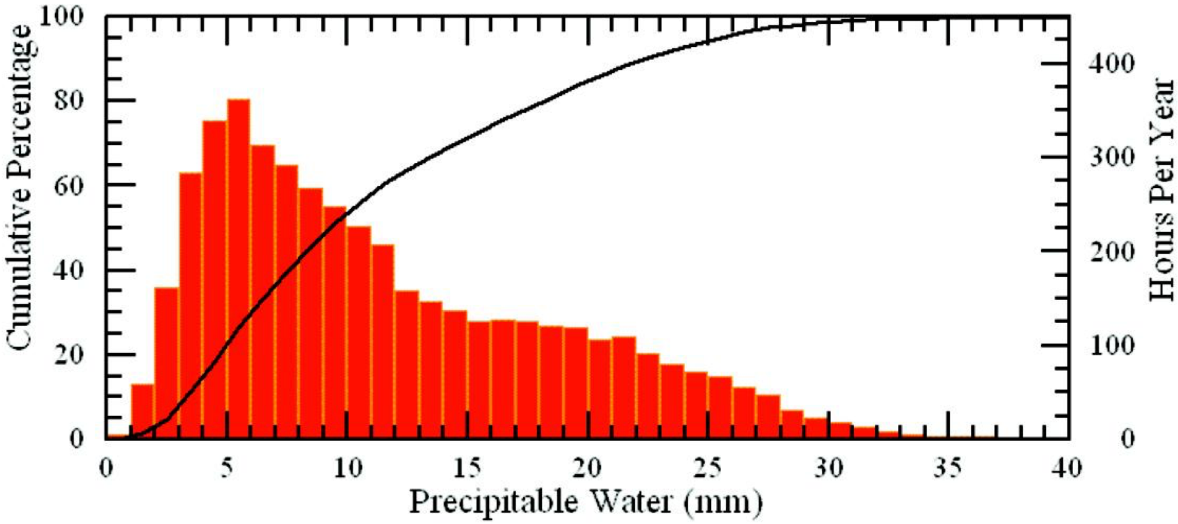
Air Mass A~ 1/sin(Elev) (for Elev > 15°)

- Stability

Tsys can vary quickly with time

Worse when tau is high

- Atmosphere is in the near-field so the tau observed is similar for all beams for multi-beam receivers



GBT site has many days with low water vapor per year (<10mm H_2O are ok for 3mm, 50% of time)

GBT 86 GHz Performance

Table 2: 86GHz GBT Efficiency and Calibration Parameters

Dish Diameter	D	100 m
RMS Surface Accuracy	ϵ	$235 \pm 15\,\mu$m
Beam Size Parameter	κ	1.20 ± 0.02
Aperture Efficiency	η_a	0.347 ± 0.032
Main-Beam Efficiency	η_{mb}	0.442 ± 0.043
Corrected Main-Beam Efficiency	η_M^*	0.465 ± 0.035
Jupiter Beam Efficiency(43″diameter)	η_{Jupiter}	0.53 ± 0.05
Moon Beam Efficiency (32′ diameter)	η_{Moon}	0.814 ± 0.029
Rear Spillover Efficiency[a]	η_l	0.985 ± 0.015
Forward Spillover Efficiency[b]	η_{fss}	0.965 ± 0.020

[a]Power in the forward 2π direction. [b]Factional power in the forward direction inside the $\sim 1^\circ$ diameter error pattern.

Observing Strategies

The GBT provides a lot of observing options – multiple instruments and several observing modes

- Pick receiver based on frequency
- Pick backend based on observing type (spectral line, continuum, pulsar, ….)
- Pick observing techniques based on science goals (point source, large field, narrow lines vs broad lines….)
- Calibration strategies depend on receiver and science needs

Different Observing Modes to derive the reference data (OFF)

Types of reference observations

- ➢Frequency Switching (FSW)
  - – In or Out-of-band
- ➢Position Switching (PS)
  - – Reference-Off
  - – Mapping-Off
- ➢Dual-Beam Position Switching
  - **Nod** -- Move telescope
  - **SubBeamNod** -- Move Subreflector

Frequency vs Position Switching

- Narrow line in non-crowded spectrum ➔ Frequency Switching (FS)
- Narrow line in crowded spectral region or significant RFI ➔ Position Switching (PS)
- Broad line ➔ PS

➢ Narrow line < 10 km/s

➢ Broad line > 100 km/s

Observing Mode – Small Source

If source size < beam, Line Obs, and for **PS**:

- Nod {two beams} – if not limited by baselines
- SubBeamNod {two beams} – for Ka, Q, and Argus (use Nod for K-band and W-band)
- OnOff {one beam}
- Track (with and w/o offset)

If source size < beam, Line Obs and for **FS**:

- Track

If source size < beam, Continuum Obs:

- Daisy map (efficient way to deal with 1/f noise)

Observing Mode – Large Source

- ➢ Map > FOV of instrument
- RaLongMap and/or DecLatMap
- ➢ Map <~ FOV of instrument (optimal method depends on several factors)
- RaLong/DecLat mapping (significant overheads for turn arounds)
- Daisy (if only interested in central point)
- Box scans
- PointMap (Grid) if needing a deep spectrum

Observing: Antenna Optimization

- Should point+focus every 30min-1hr depending on frequency and time of day (point+focus takes ~5min).
  - C/X-band every 1hr during day; 2-3hr at night
  - Ku/K-band every 1hr during day; 1-2hr at night
  - Ka/Q-band every 30-40min during day; 1hr at night
  - W-band every 20-30min during day; 40-50min at night
- AutoOOF (which takes ~30min) is used to correct the surface for thermal effects for Q-band and W-band at night. OOF solutions good for 2-6hrs at night.
- Daytime surface changes <1hr time scales and the AutoOOF solutions can cause more harm than good after ~1hr from the AutoOOF (so it is typically not useful to use the “thermal” corrections during the day).

Absolute Calibration on known astronomical sources (point sources)

➔ Corrects for any errors in the adopted Tdiode/gains measured in the lab and corrects for the telescope response

Observe and process target source and known calibrator (3cX) in the same way, then the flux density of the source S(source) is simply:

S(source)/S(3cX) = T(source)/T(3cX),

where S(3cX) is known and T(source) and T(3cX) are observed.

If done carefully, absolute calibration can be done to 10-15%.

At high-frequency and if not pointing often enough, one can correct for systematic pointing/focus drifts by looking at changes of pointing/focus solutions.

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