GBT Overview

David Frayer

GREEN BANK OBSERVATORY

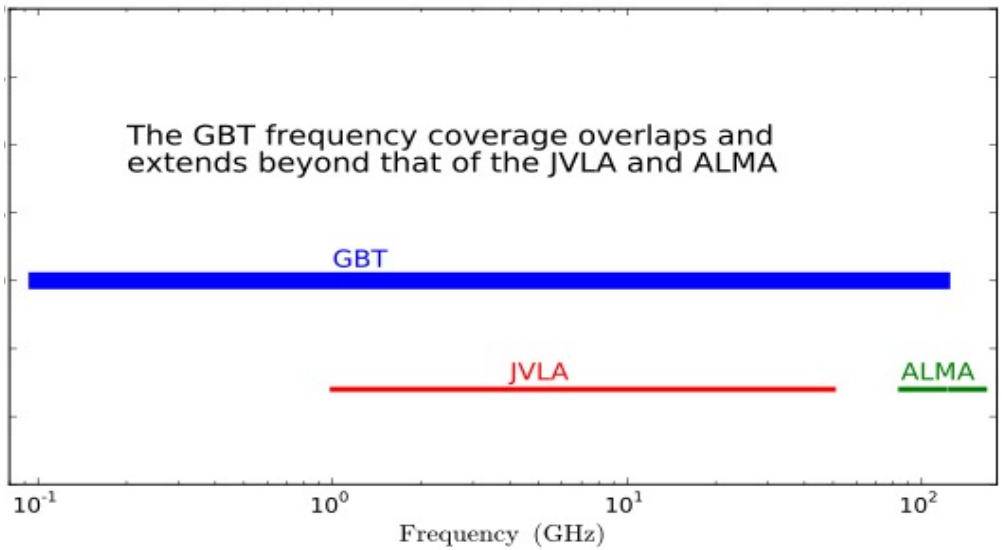
NSF

Outline

- Basic overview of the GBT
- Radio Astronomy 101
- GBT Science Areas
- Capabilities and Performance of the GBT
- Observing strategies

GBT Overview

- Largest fully moveable telescope
- 100 meter diameter unblocked
- Receivers cover 0.1 to 116 GHz
- >85% of total sky covered ($\delta \geq -46$)



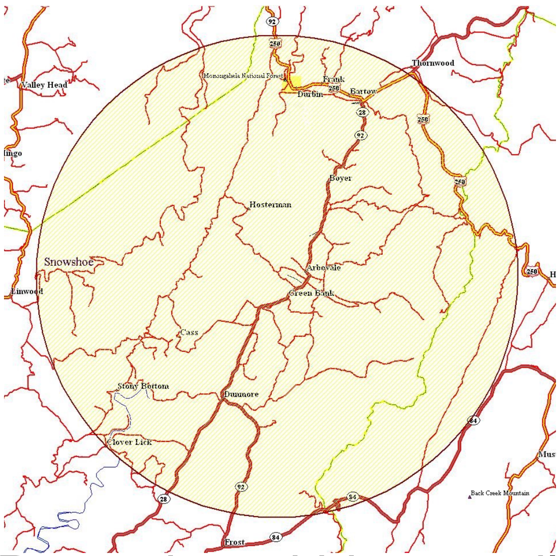
Key Characteristics of the GBT

- It is big; 100m class telescope (high sensitivity and resolution)
- Located in the National and WV Radio-Quiet Zone to minimize RFI
- OFF-axis/unblocked design allows for very faint observations of extended emission
- Active surface allows for observations up to 116 GHz

Site protected from Radio Interference

WV Radio Astronomy Zone

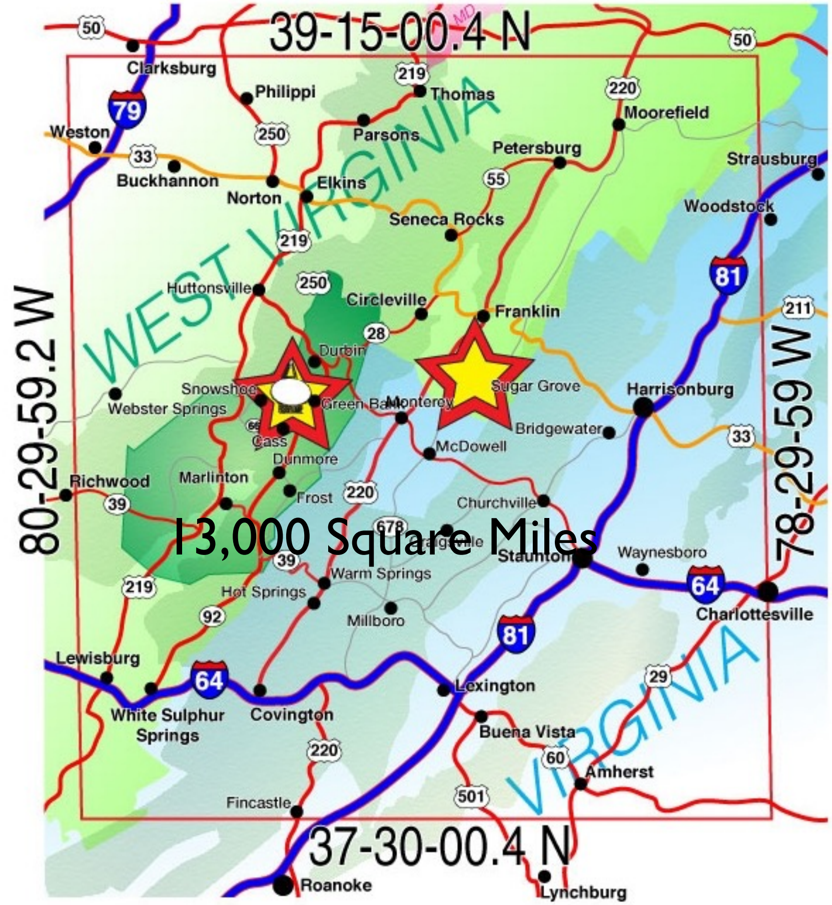
Established by the West Virginia Legislature (1956)



Protection within ten miles of the Observatory

National Radio Quiet Zone

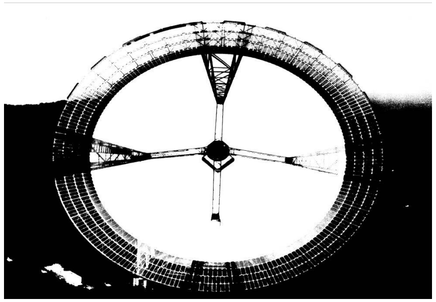
Established by the FCC and NTIA (1957)

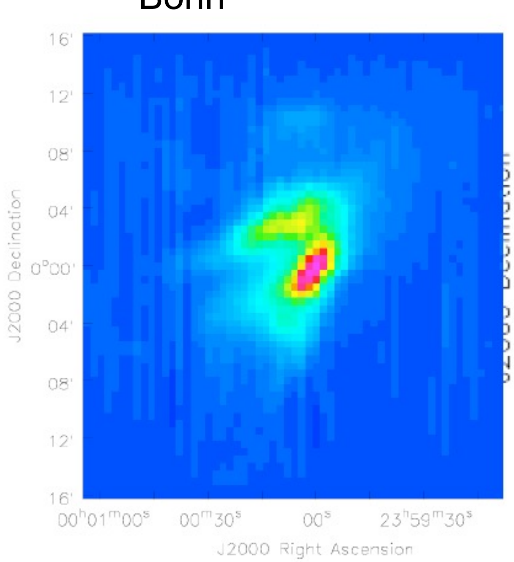


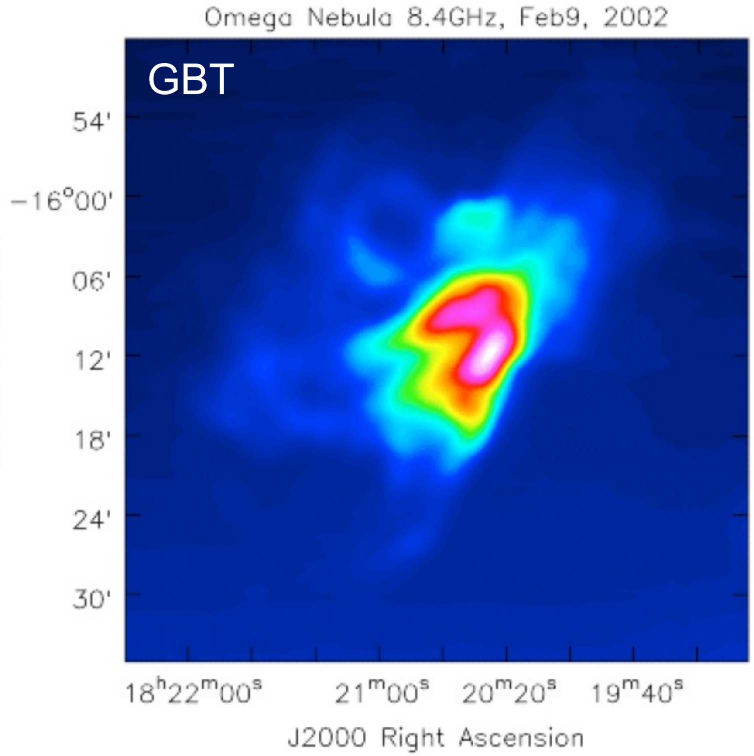
GBT: Unblocked dish

Image comparison of the Omega Nebula from the Bonn 100m and and the GBT at 8.4 GHz for the same expected sensitivity level (Tsys/time^0.5).

The superior GBT image is due to the clean GBT beam.



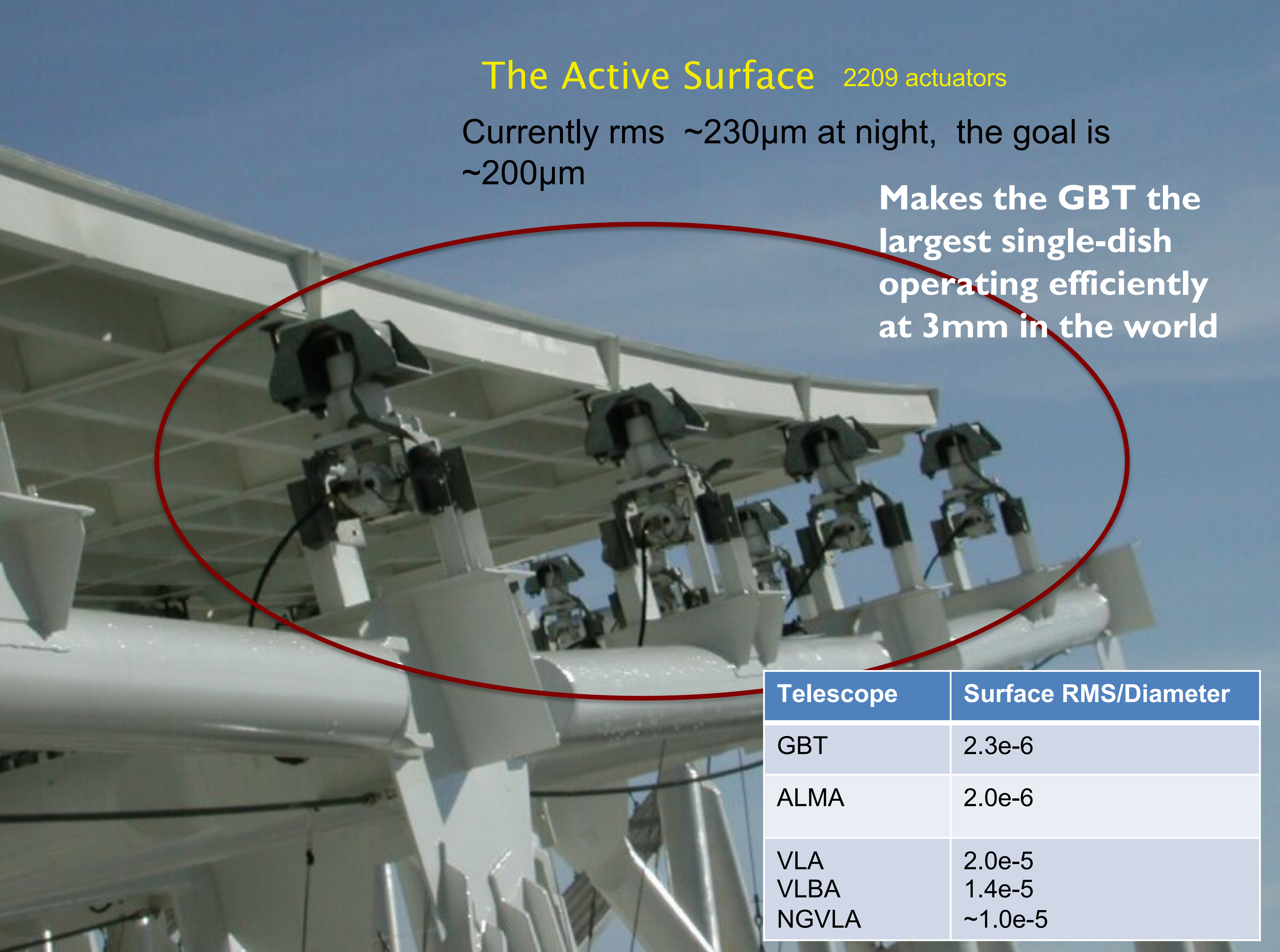




The Active Surface 2209 actuators

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

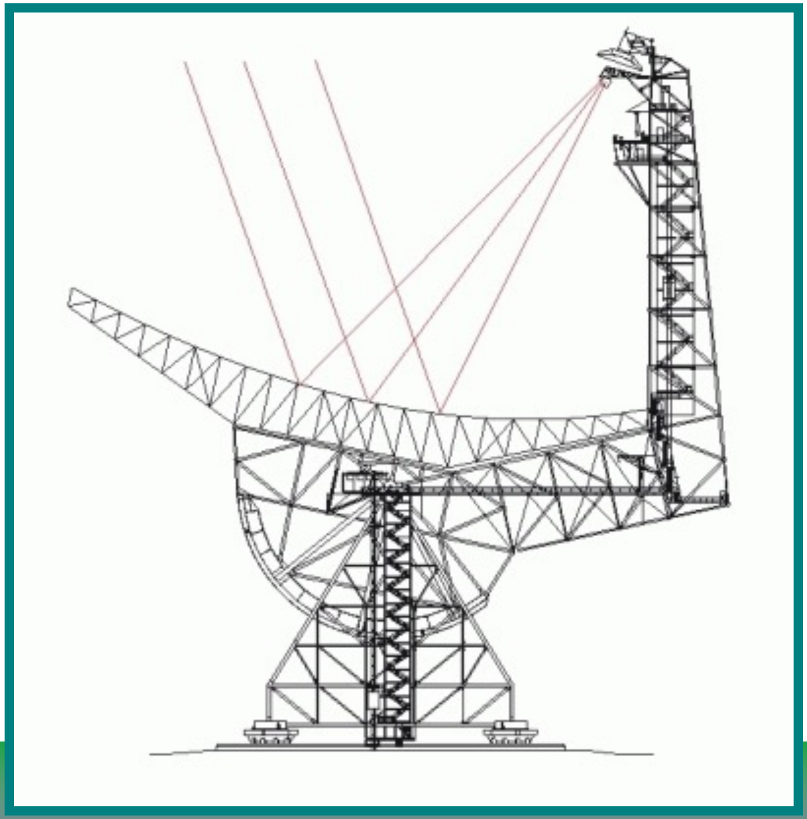
Makes the GBT the largest single-dish operating efficiently at 3mm in the world

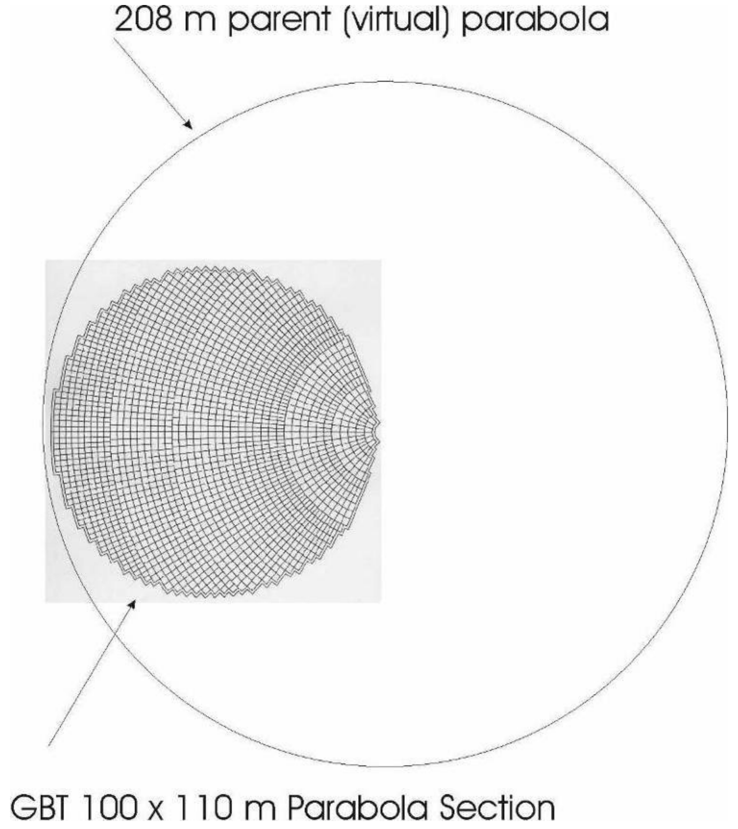


Telescope	Surface RMS/Diameter
GBT	2.3e-6
ALMA	2.0e-6
VLA VLBA NGVLA	2.0e-5 1.4e-5 ~1.0e-5

GBT Telescope Optics

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





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

Basic Radio Astronomy

Jansky flux density units

1 Jy = $10^{-26} Watts / m^2 / Hz$

dB units

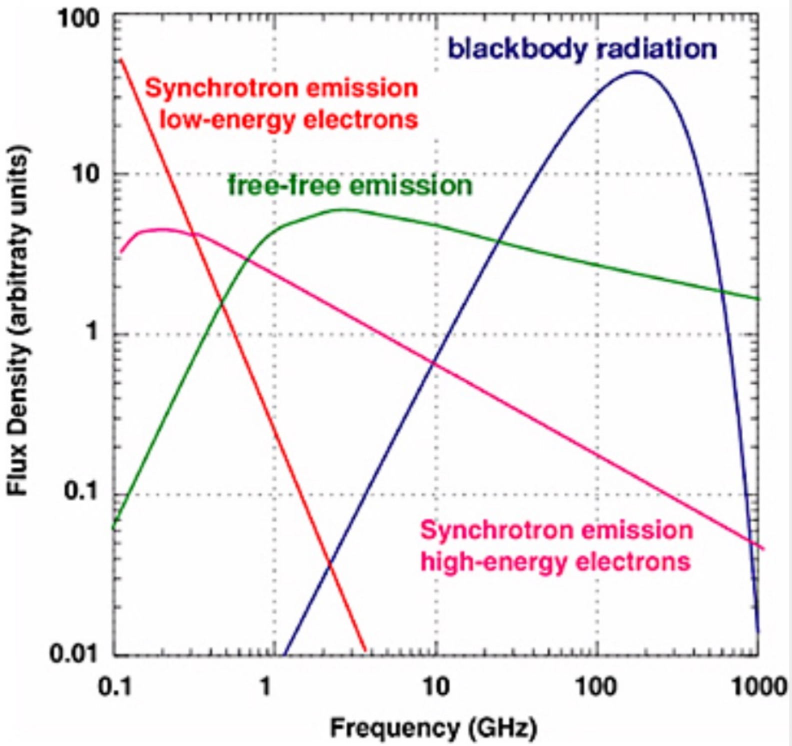
$$\Delta p(dB) = 10\log_{10}(\frac{P_1}{P_2})$$

P1/P2	Δp(dB)
1	0
2	3
10	10
100	20
1000	30

Continuum Emission

- Broadband emission from a “continuum” of energies
  - Not specific frequencies
  - You could think of this as the “total brightness” of an object

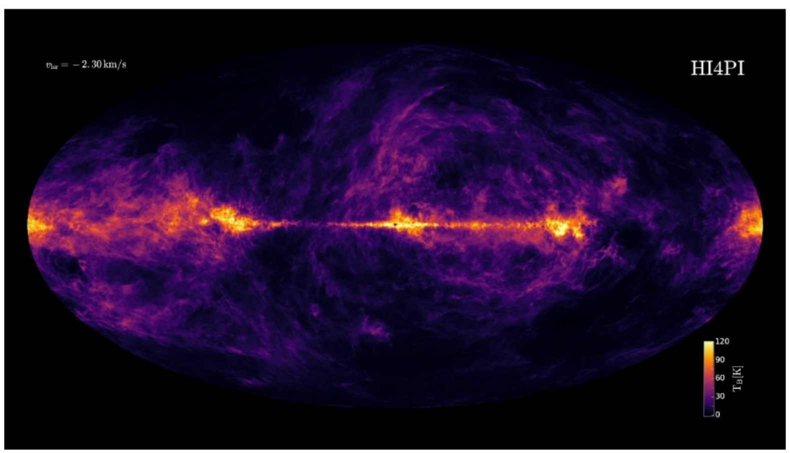
- Examples
  - Free-Free Emission
    - Electrons accelerating around ions
  - Synchrotron
    - Ions spinning around magnetic field lines

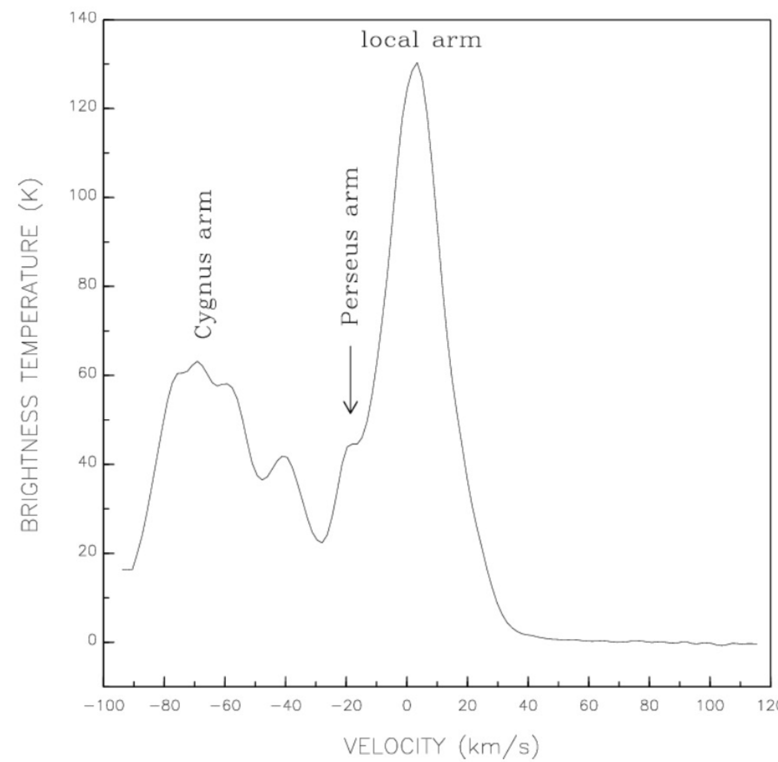


Spectral Lines

- Spectral features at specific frequencies from molecular or atomic transitions
  - These can be red or blue-shifted based on the source velocity

- Examples
  - Carbon Monoxide (115 GHz)
  - Neutral Hydrogen (1.421 GHz, shown)

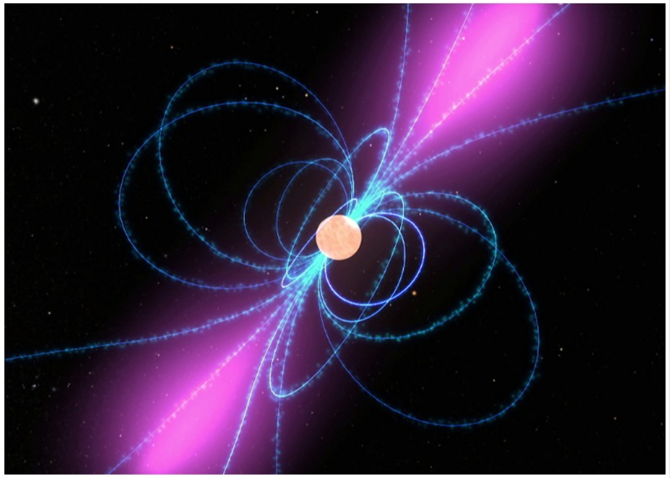




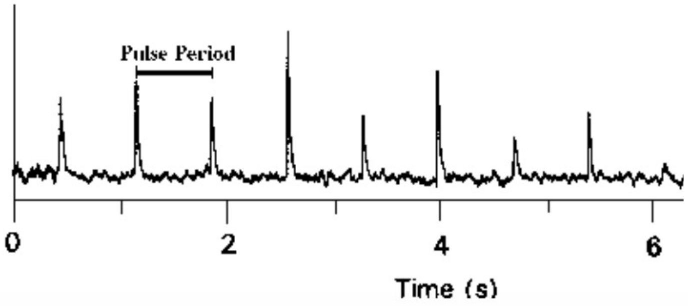
Time Variable / Transients

- Examples
  - Pulsars
  - Fast Radio Bursts

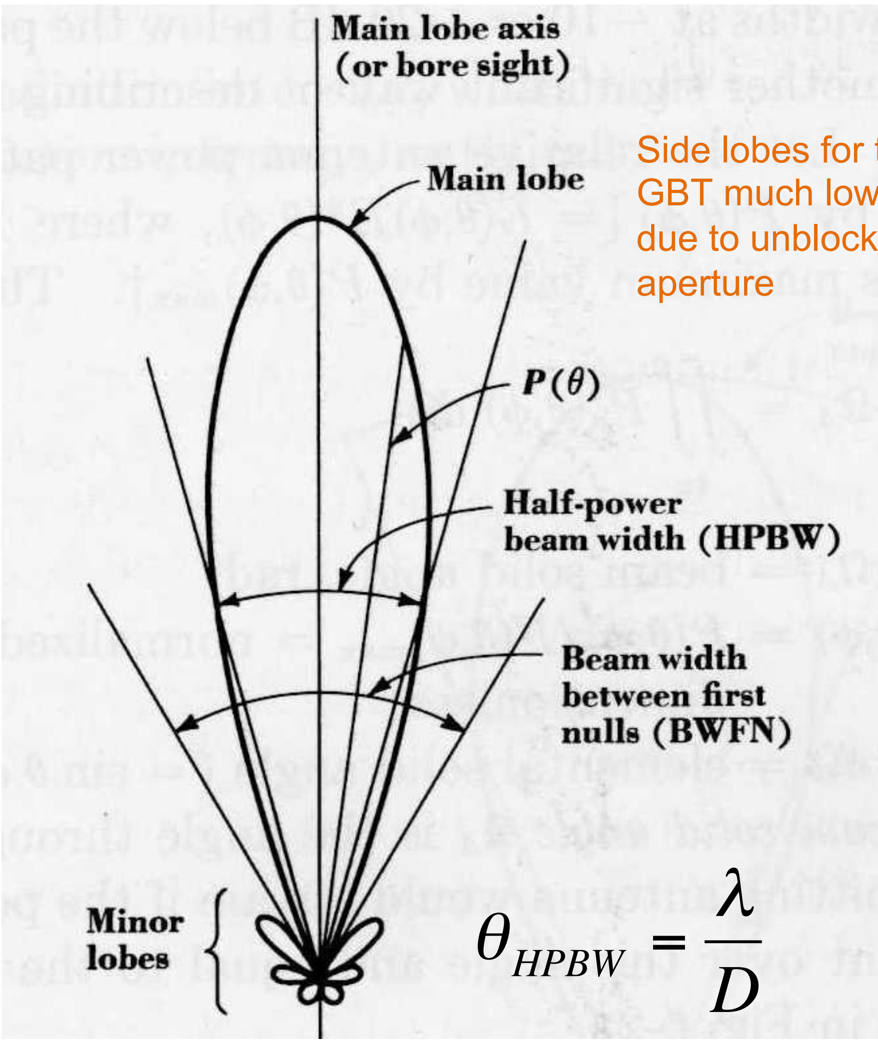
- What's important here?
  - Saving data very quickly (millisecond)
  - Time stamps on data
  - Ideally, wide bandwidth
    - See "pulse shape" across many frequencies



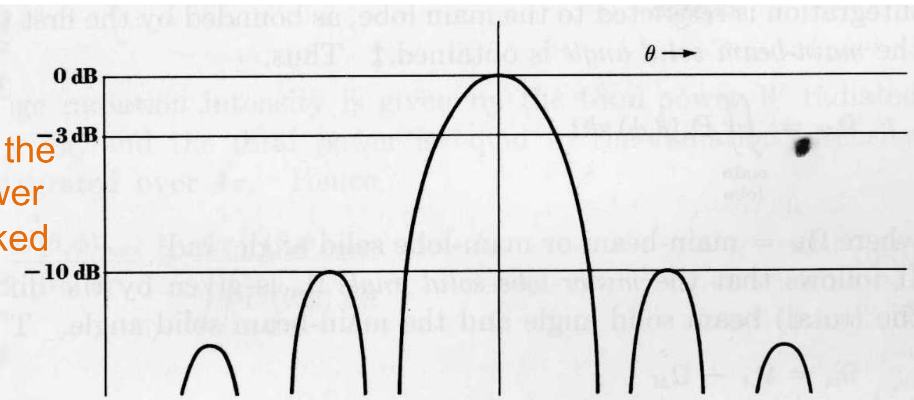
Pulsar Schematic (above), Pulsar Plot (below)



Antenna Beam Pattern (power pattern)



Side lobes for the GBT much lower due to unblocked aperture



$$\theta_{HPBW} = \frac{\lambda}{D}$$

Beam Solid Angle (steradians)

$$\Omega_A = \iint_{4\pi} P_n(\theta,\phi)\,d\Omega$$

Main Beam Solid Angle

$$\Omega_M = \iint_{\substack{main\\lobe}} P_n(\theta,\phi)\,d\Omega$$

P_n = normalized power pattern

Kraus, 1966. Fig.6-1, p. 153.

System Temperature

= total noise power detected, a result of many contributions

$$T_{sys} = T_{ant} + T_{rcvr} + T_{atm}(1 - e^{-\tau a}) + T_{spill} + T_{CMB} + \cdots$$

Thermal noise ΔT

"Radiometer Equation" for sensitivity

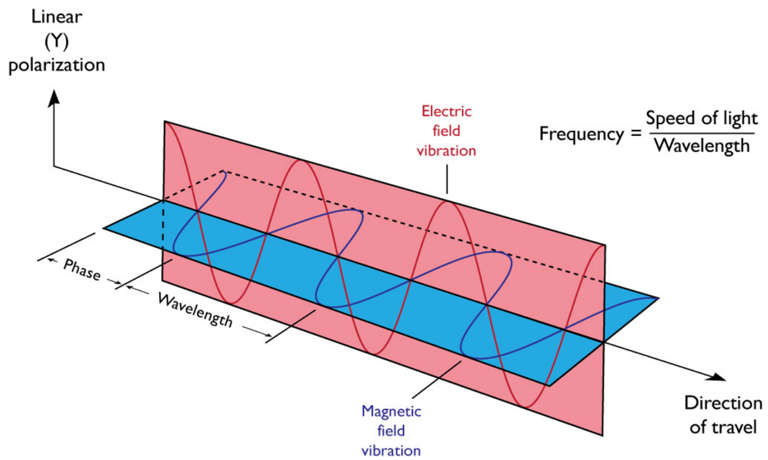
$$\Delta T = k_1 \frac{T_{sys}}{\sqrt{\Delta\nu \cdot t_{\mathrm{int}}}}$$

Radio Heterodyne Methods

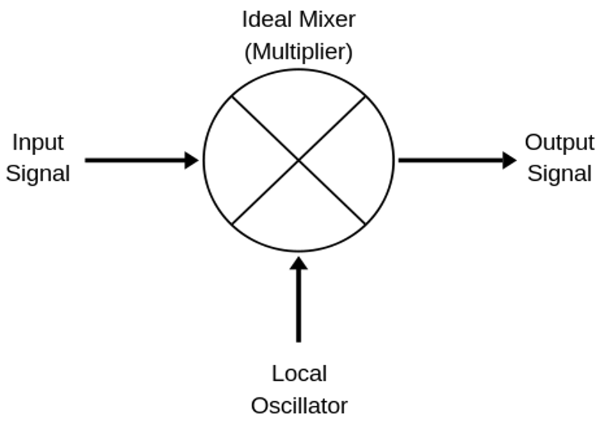
Heterodyne radio receivers use the wave-like properties of the radio electromagnetic radiation by measuring both the amplitude and phase of the signal (“coherent”).   This is different than most other astronomical techniques that treat incoming radiation as photons (”incoherent”), e.g., mm/sub-mm bolometers, IR Si/Ge detectors, optical/NIR CCDs, and X-ray and Gamma-ray detectors.

- Hetero – “other”, dyne – “power”
- Combine (“mix”) the signal of interest, with a second, precise frequency (the “***local oscillator (LO)***” to produce an output at a new frequency (the ***“intermediate frequency (IF)”***)

Electromagnetic Waves



Above only shows one polarization

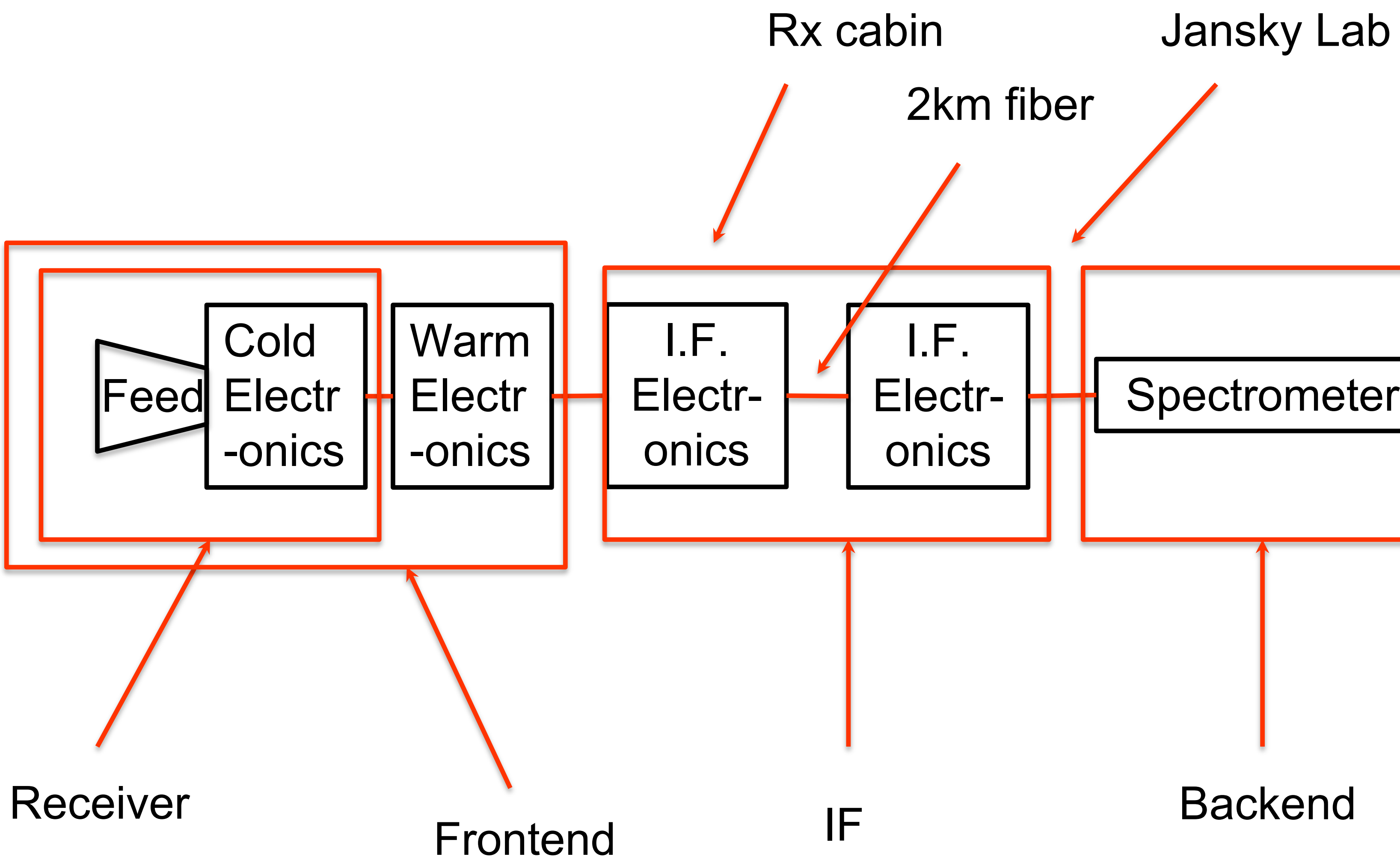


Stages in Heterodyne Signal Detection

- ***Gather*** the radiation — Antenna
- ***Convert*** the signal from free-space to electrical (feed horn)
- ***Amplify*** the signal (low noise amplifier – LNA)
- ***Mix*** the signal to convert to a different frequency

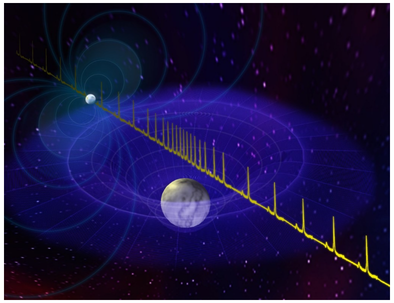
  (Convert, Amplify, Mix: Frontend Receiver)
- ***Transmit*** the signal to the "backend" — I.F. (Intermediate Frequency) System
- ***Measure*** the signal in the backend — Backend Spectrometer

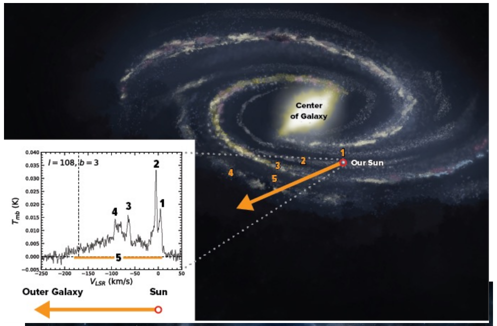
Parts of the system

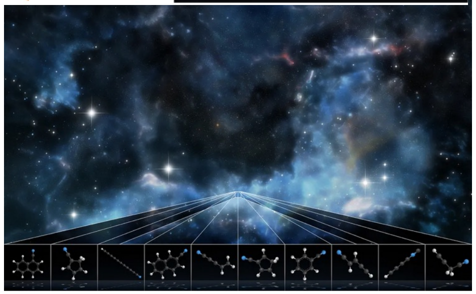


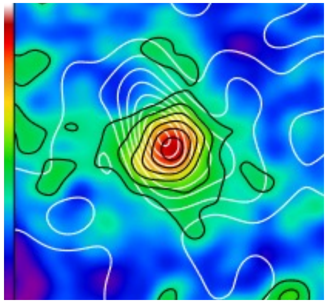
GBT Core Science

1. Gravitational waves and fundamental physics: Pulsar timing
2. Interstellar medium, star formation, galactic structure: Atomic and molecular spectroscopy, mm continuum
3. Astrochemistry: Molecular spectroscopy
4. SZ and Cosmology: mm continuum
5. Radar studies of solar system objects









Green Bank Telescope Surveys

As listed on GBO Science Web Pages [Feb. 2022]

Molecular Exploration of the Diffuse Interstellar mediUM (MEDIUM)

GBT EDGE: A Representative Survey of the z=0 Universe with Full IFU Spectroscopy

Green Bank Ammonia Survey (GAS)

HI-MaNGA

Drift Scan Survey for Pulsars, FRBs, Radio Transients, and Gas in Galaxies

The GBT Diffuse Ionized Gas Survey (GDIGS)

The GBT Diffuse Ionized Gas Survey at Low Frequencies (GDIGS-Low)

Dense Extragalactic GBT+Argus Survey (DEGAS)

GBT Observations of TMC-1: Hunting Aromatic Molecules (GOTHAM)

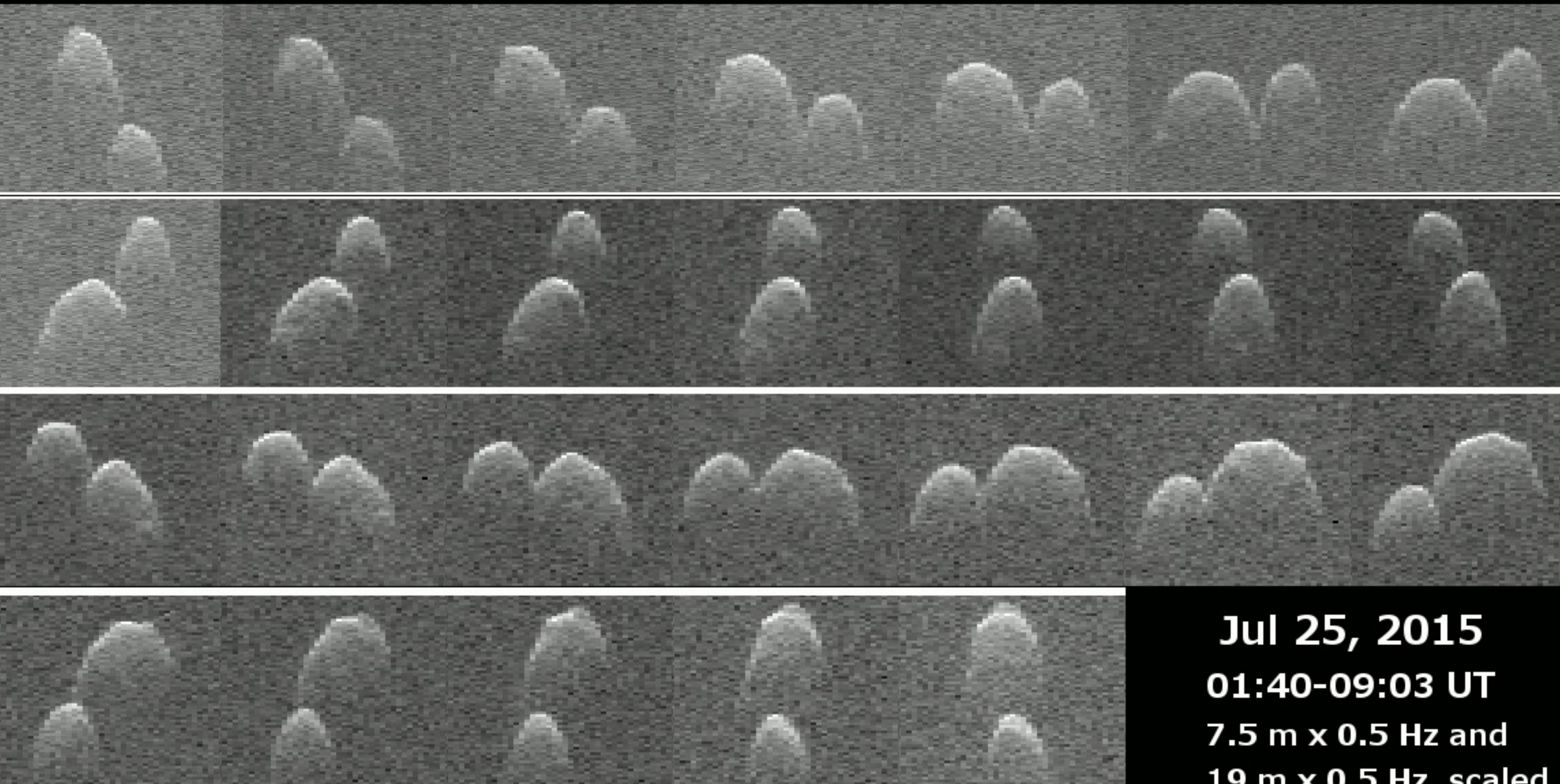
North American Nanohertz Observatory for Gravitational Waves (NANOGrav)

Green Bank North Celestial Cap (GBNCC) Survey

Dynamics in Star-forming Cores: a GBT-Argus Survey (DiSCo GAS)

The GBT L1544 Unbiased Complex Organics SurvEy (GLUCOSE)

(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

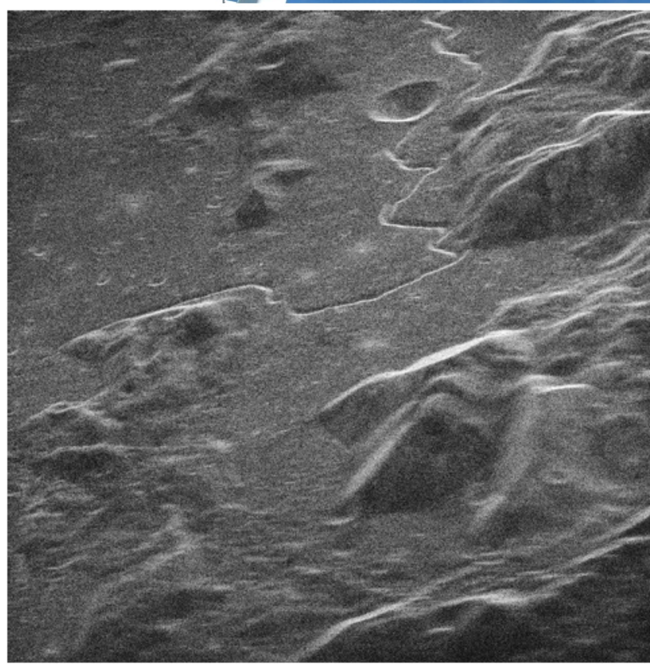
Goldstone-GBT bistatic radar images

~18x the distance to the Moon

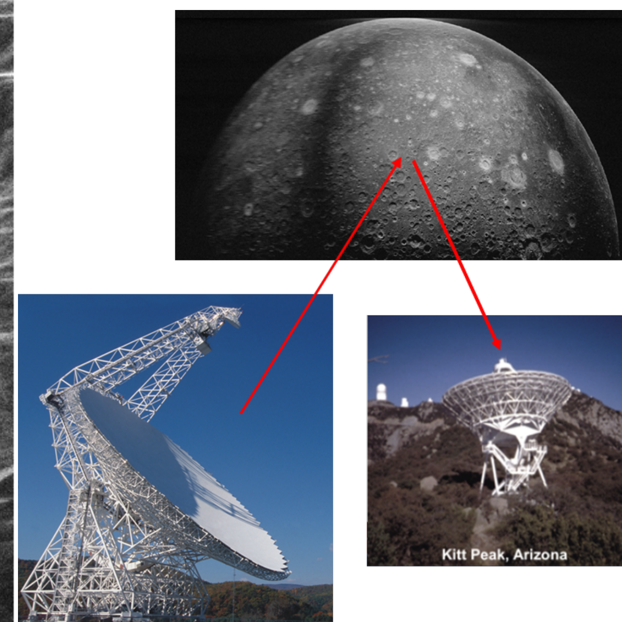
GBT Radar Systems

Test Ku-radar transmitter tests carried out last year.

Potential GBT radar systems are under investigation.



Apollo 15 landing site (5m resolution)

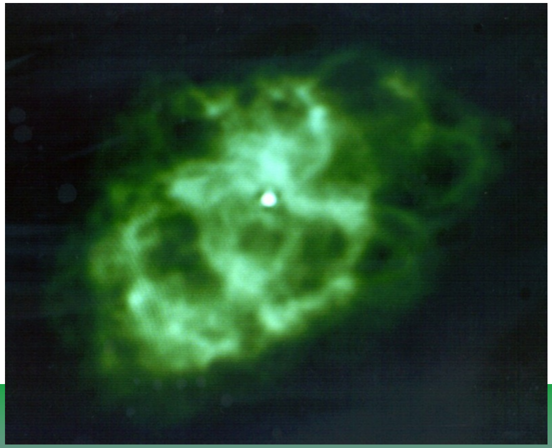


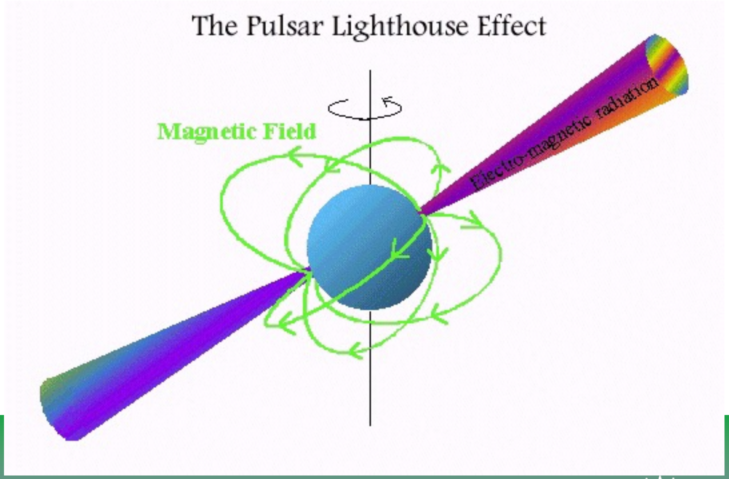
The GBT remains the world's premier pulsar observatory

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

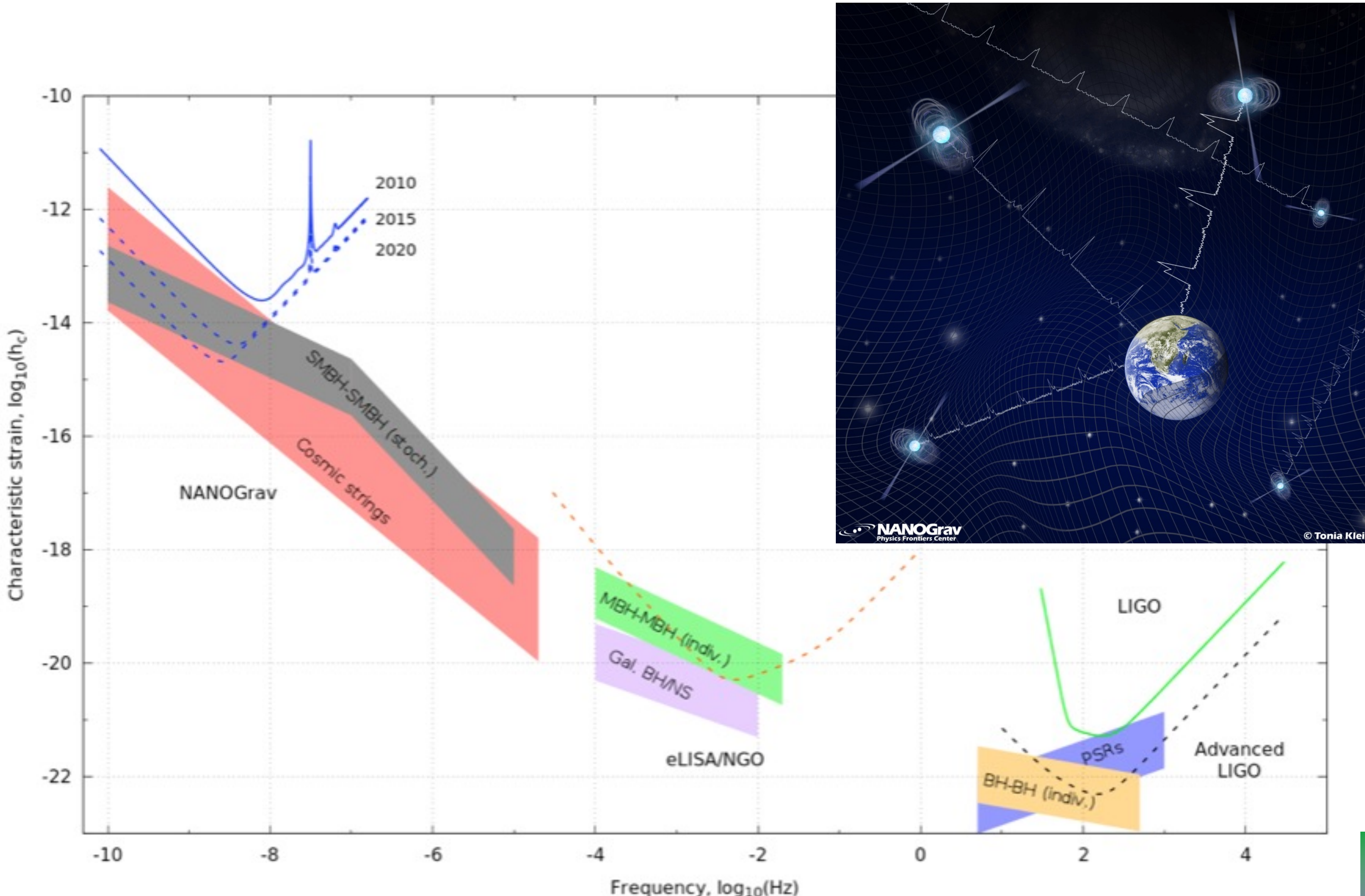
The Pulsar Renaissance:

- 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)



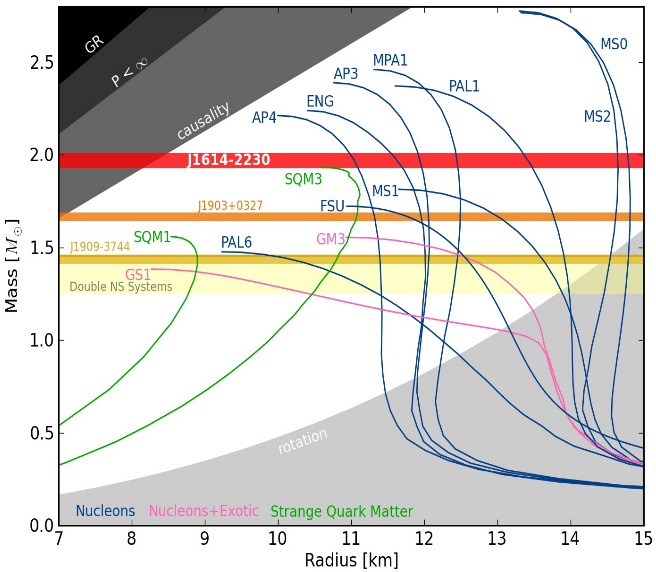


Searching for a detection of Gravitational Waves via Pulsar timing (NANOGrav)



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)

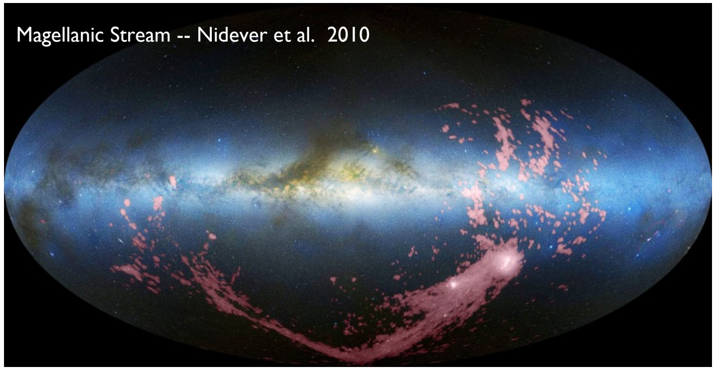
Lynch+2013; Antoniadis+2013

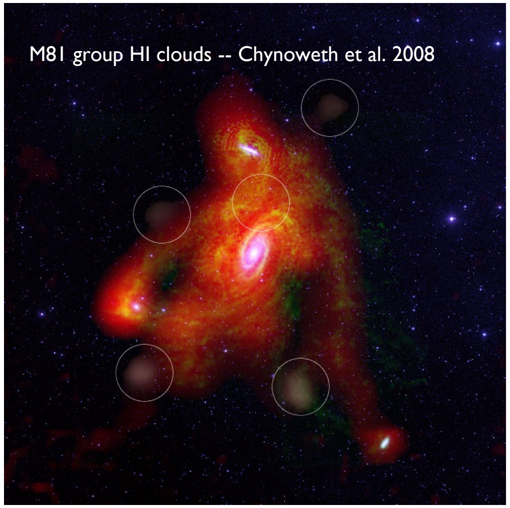
{artist impression of pulsar with WD companion}

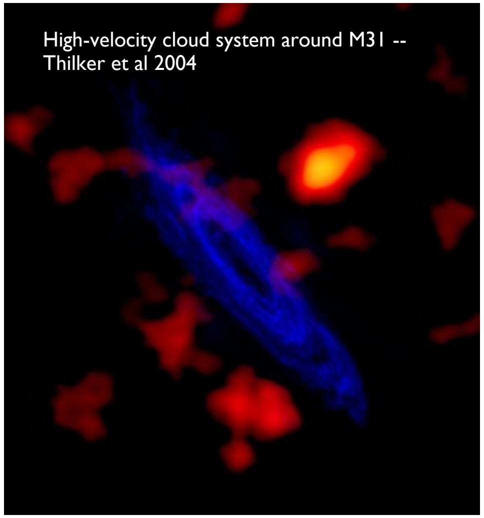
GBT Studies of faint HI -- unequalled sensitivity

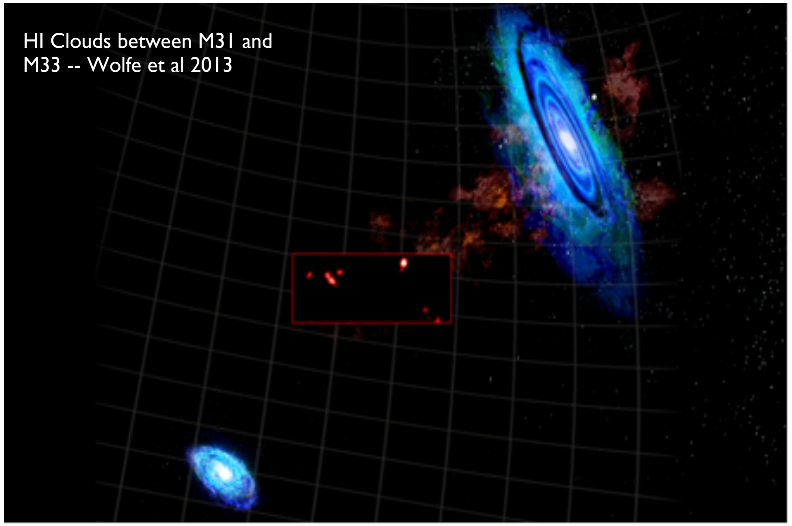
GBT offers ability to detect HI to $N_{HI} \sim 10^{17}$ cm^{-2}

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



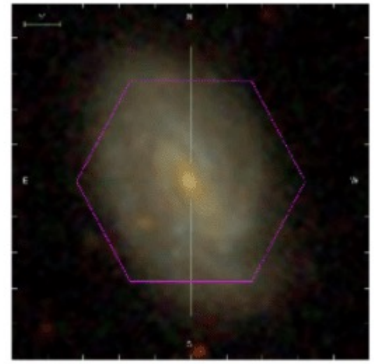


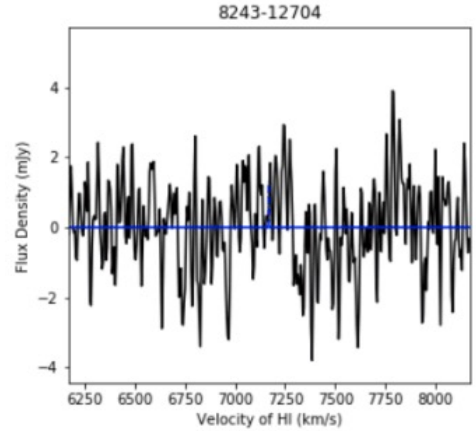


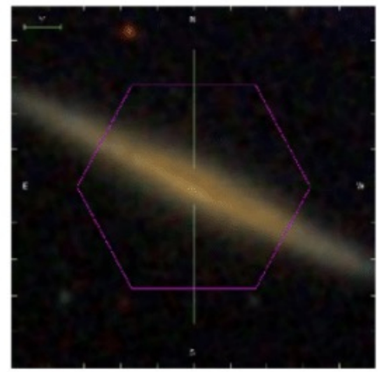


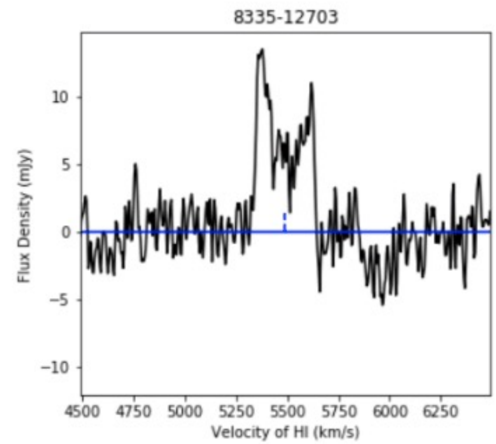
HI MaNGA Survey

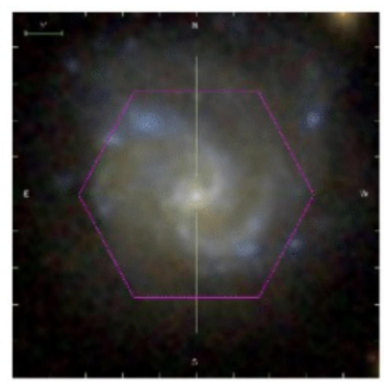
HI gas survey of 2000+ low-z galaxies;
PI: Karen Masters

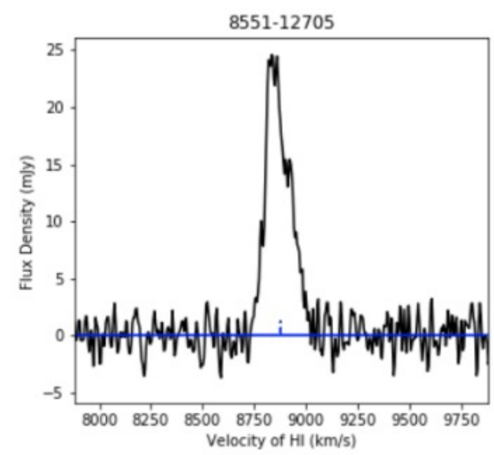






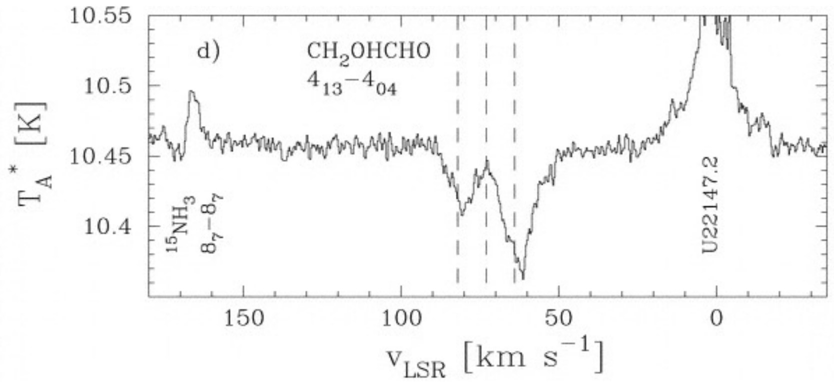






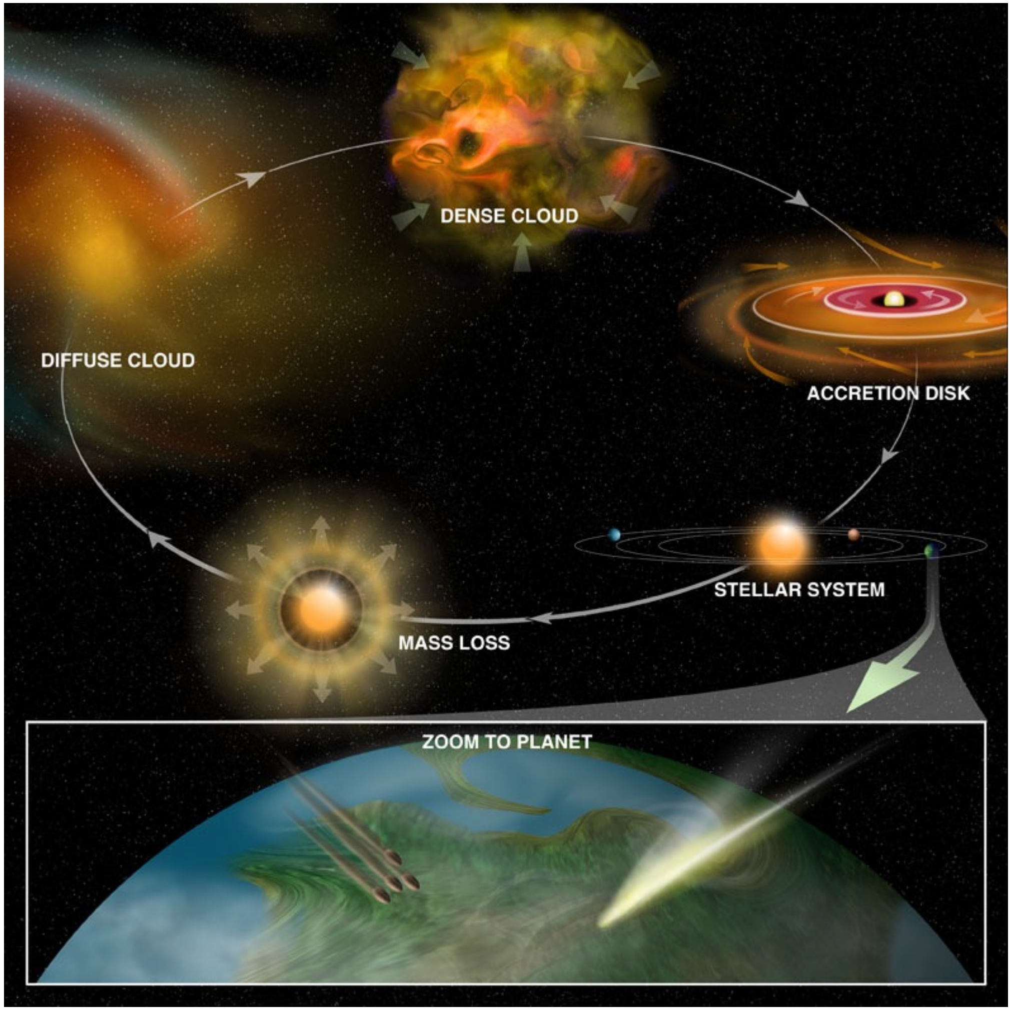
There are several GBT projects studying the chemistry of the ISM and solar system and the connections with life on Earth

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



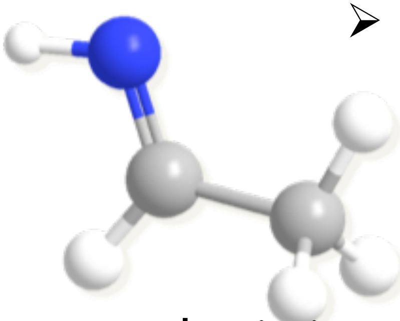
Low temperature sugar-related molecule

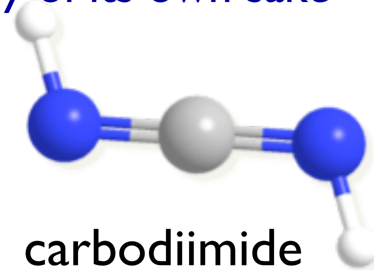
Courtesy Hollis, Jewell, Lovas, Remijan

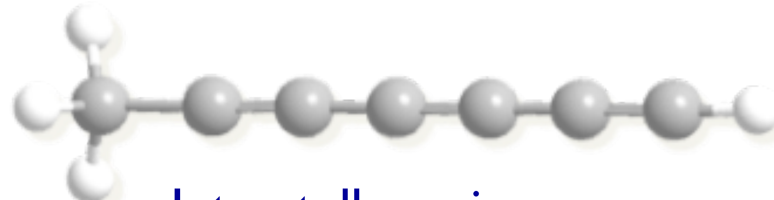


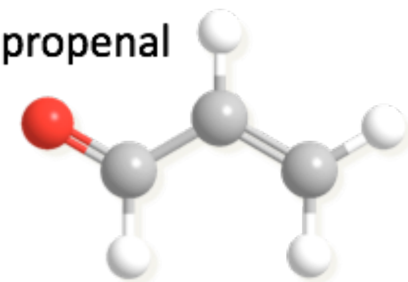
Some (of the ~20+) new molecules found by the GBT

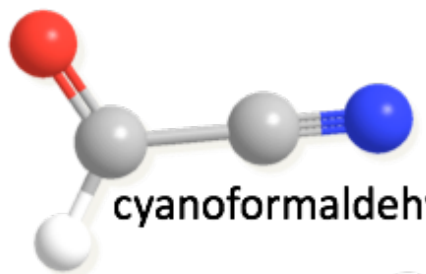
- Linking ISM chemistry to origin of life
- Chemistry as tool for understanding star-formation
- Chemistry of its own sake

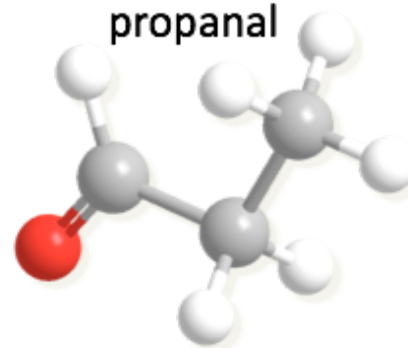

ethanimine

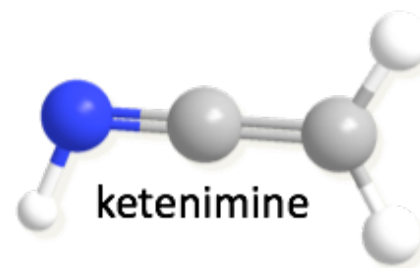

carbodiimide

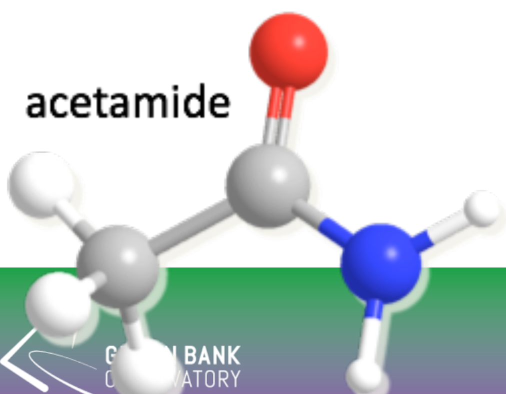

Interstellar anions

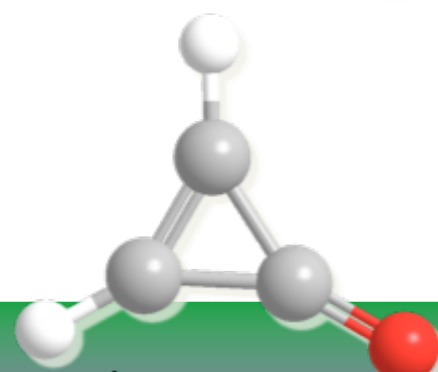
propenal


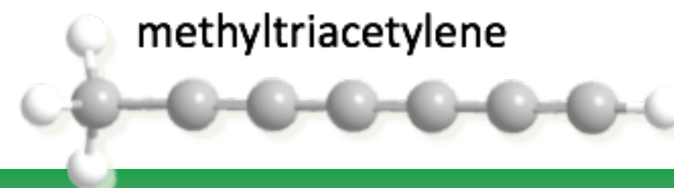

cyanoformaldehyde

propanal



ketenimine

acetamide


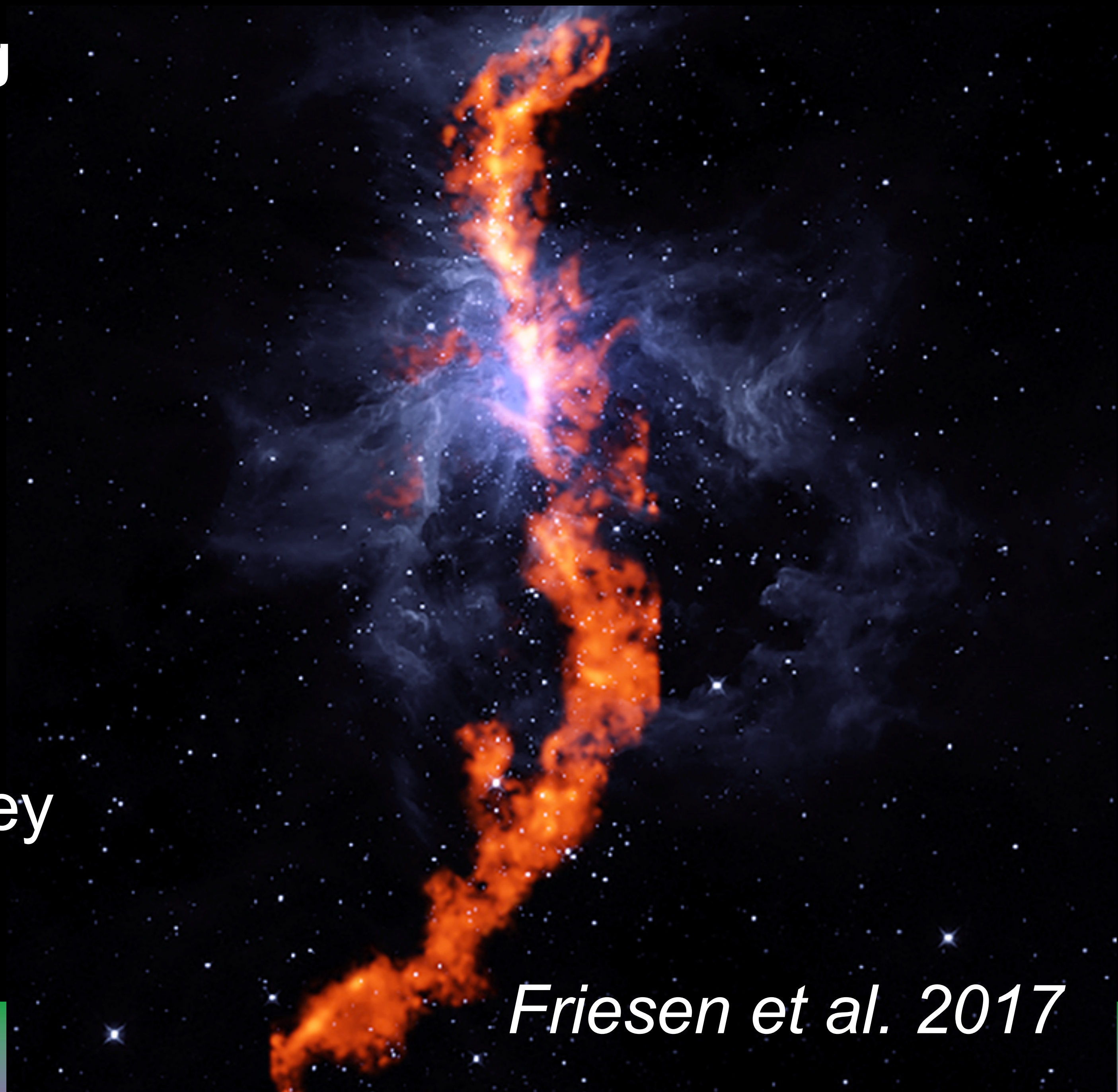

cyclopropenone


methyltriacetylene

Star forming regions

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

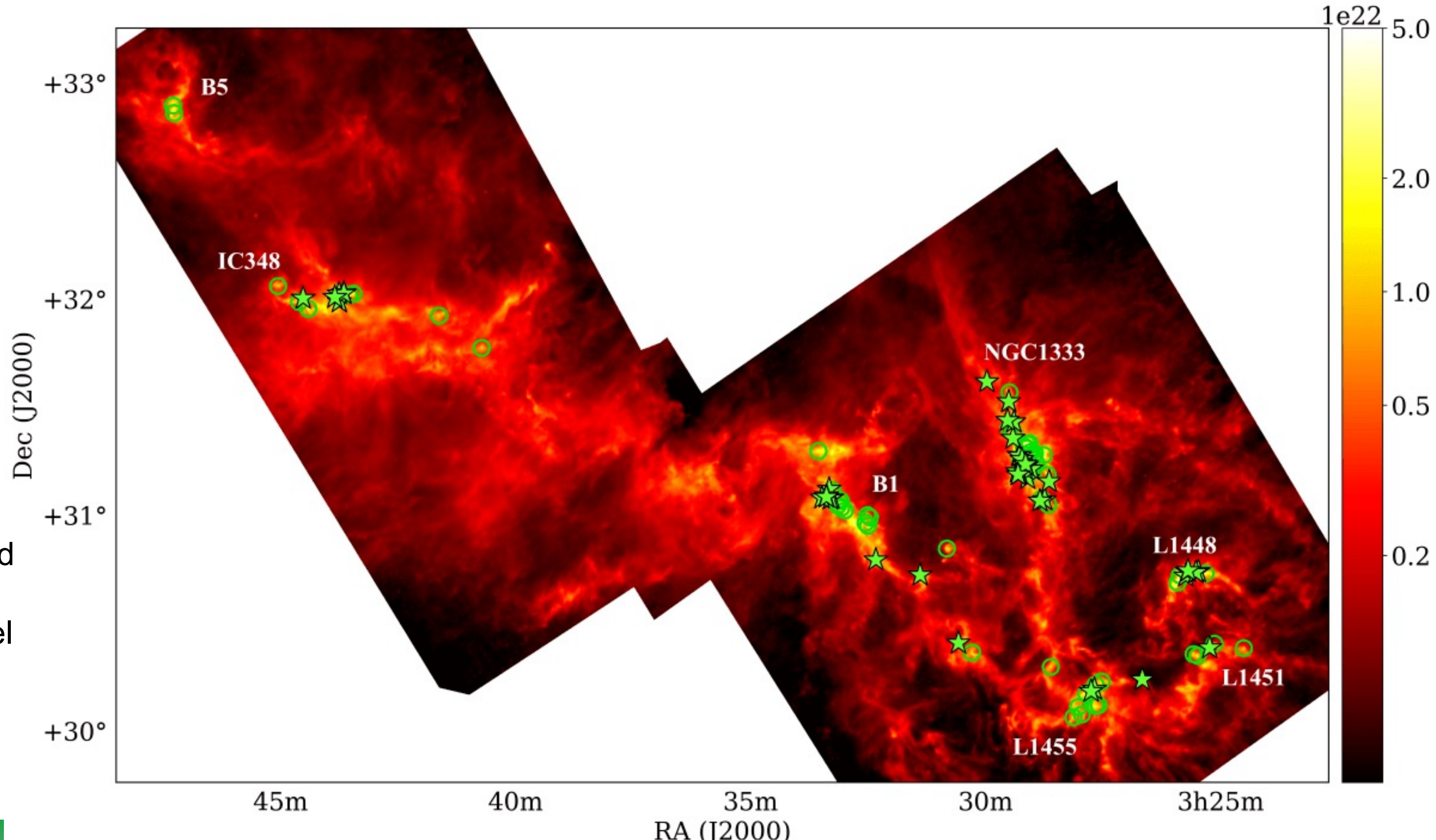
GAS Survey



Friesen et al. 2017

DiSCo GAS

Dynamics in Star-forming Cores: a GBT-Argus Survey;
100+ cores in Perseus; 93 GHz N2H+; PI Che-Yu Chen

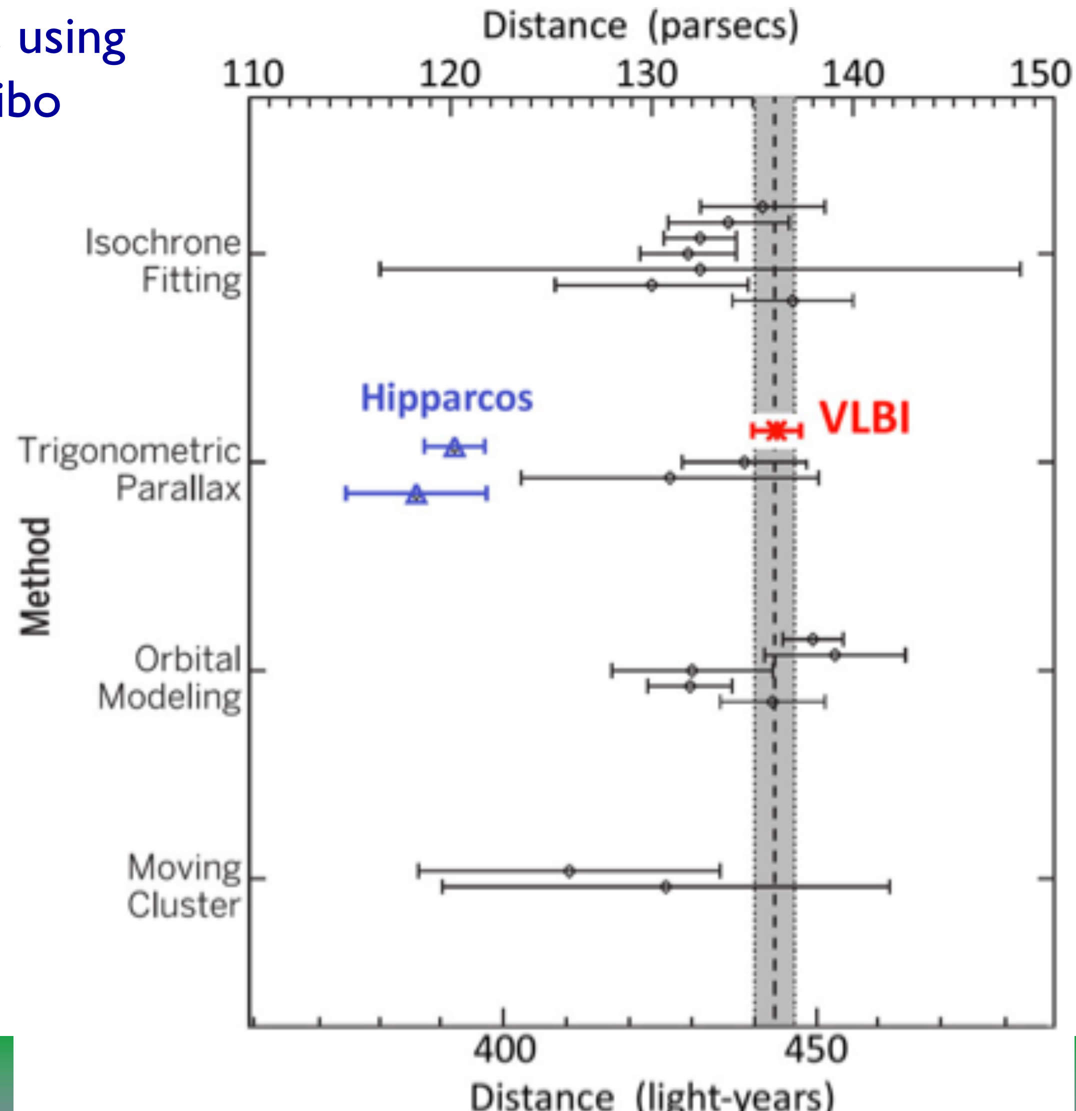


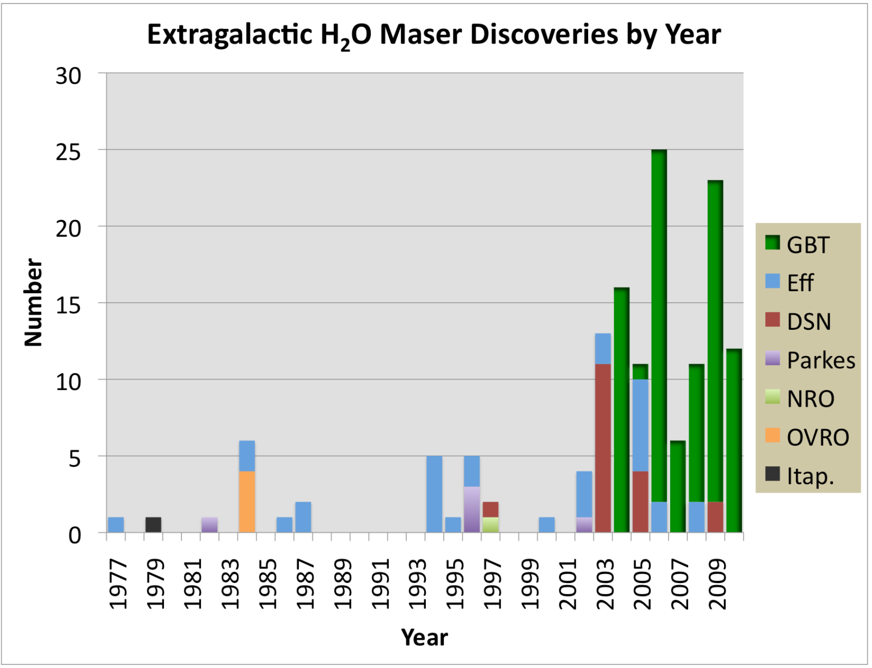
Cores identified from Herschel infrared images

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

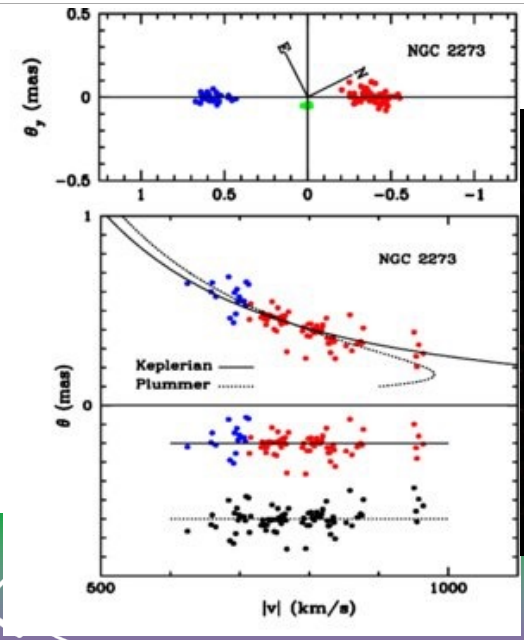


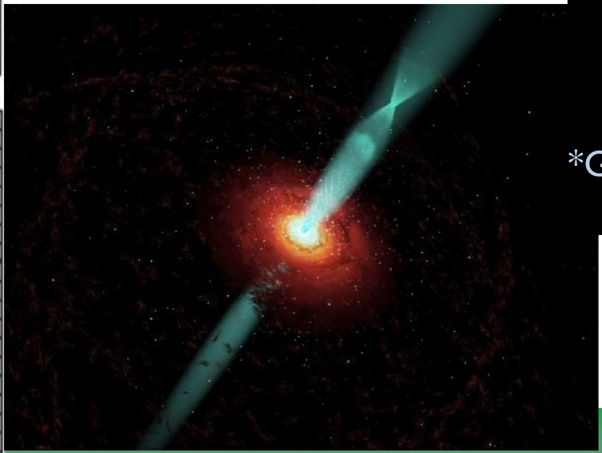


Over 80 masers discovered with the GBT (K-band 22GHz)

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

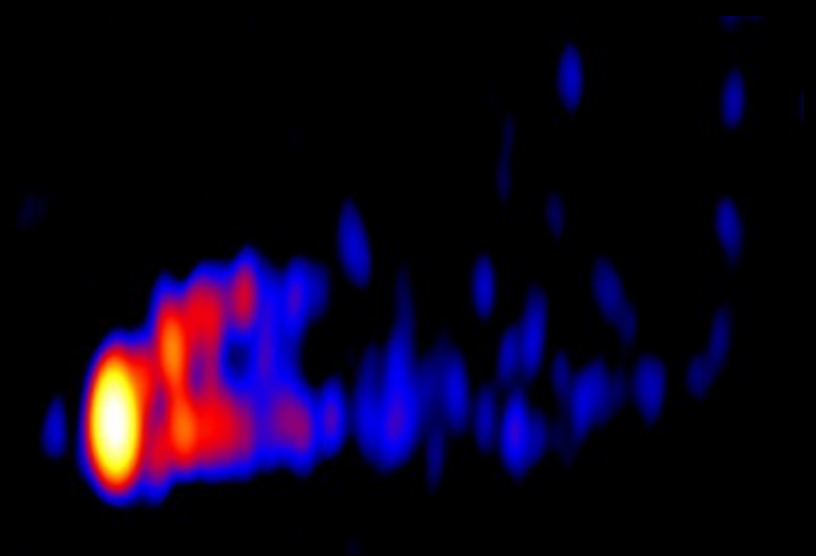
Measuring precise masses of the black holes in megamaser disk galaxies*





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

M87 3mm VLBI Jet

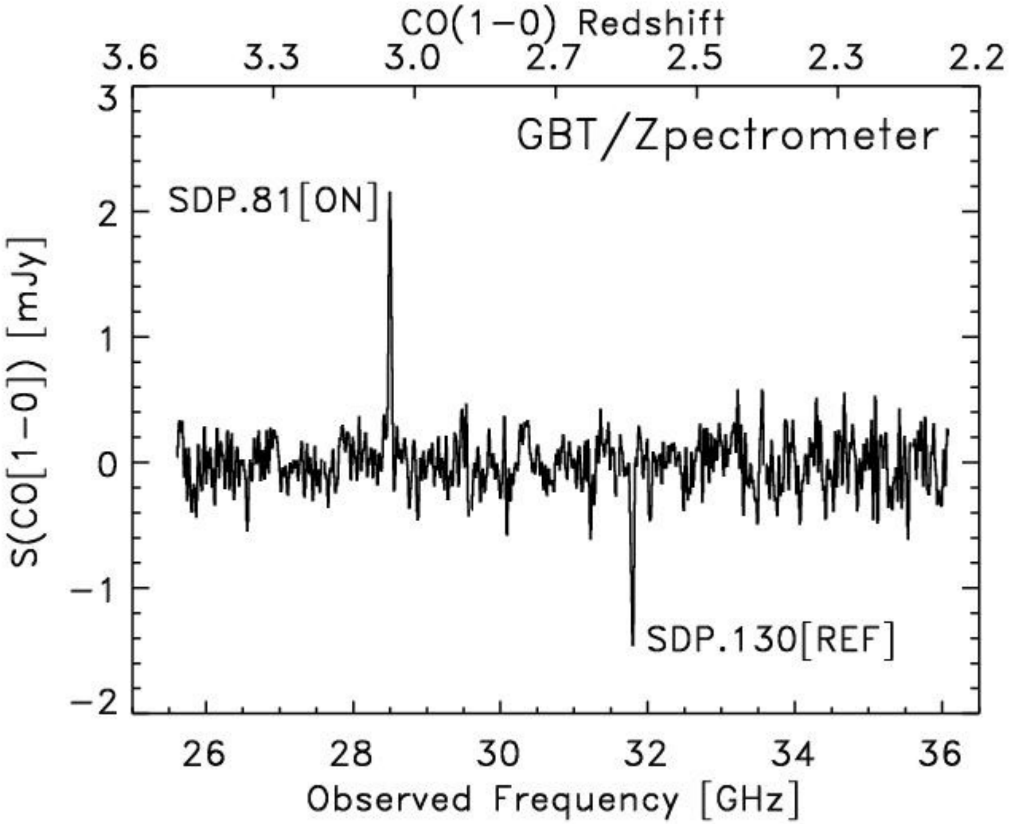


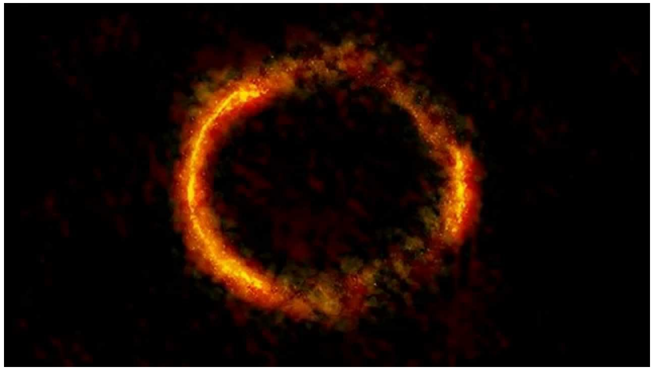
The M87 jet at an angular resolution of 0.25x0.08 mas (~10 Schwarzchild radii) in 3mm VLBI (Hada et al 2016)

High-Redshift Molecular Gas with the GBT

Measurements of molecular gas from young galaxies in formation (Frayer+2011; Harris+2012).

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





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

Mustang 3mm Observations of Clusters

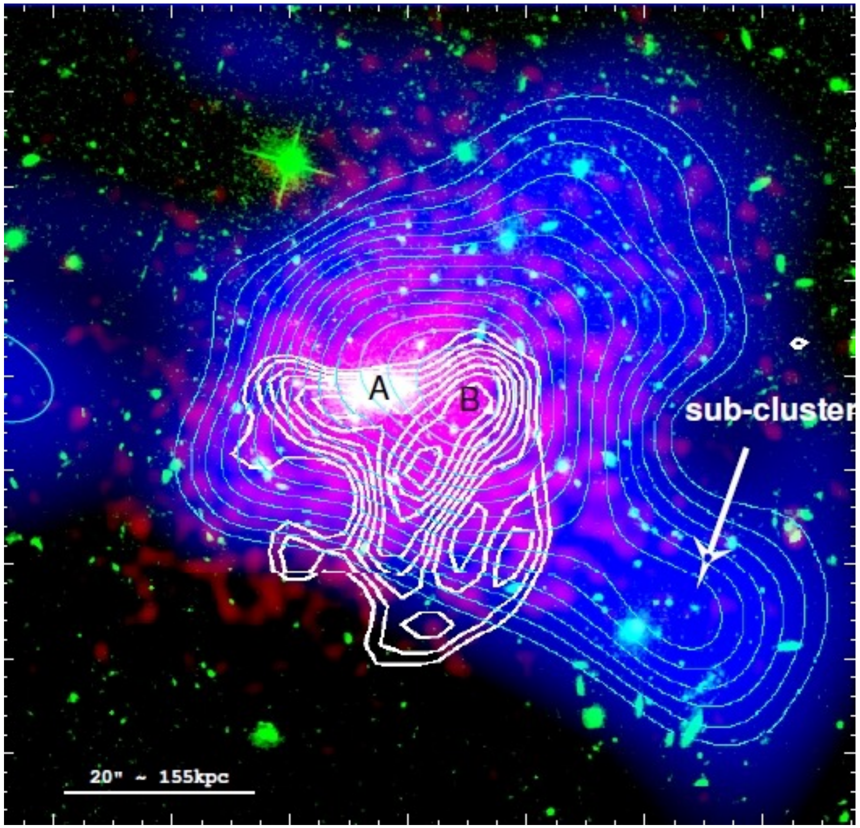
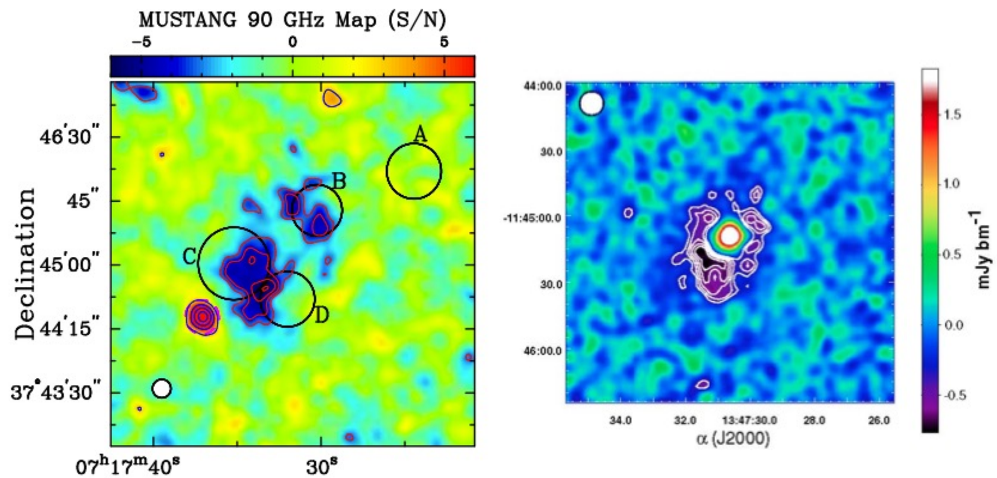


Image of CL1226.9+3332 (z = 0.89); White is MUSTANG; Green is optical (HST); Red is X-ray (Chandra); Blue is mass density (HST) *Courtesy Korngut, et al.*



(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).

Capabilities and Performance of the GBT

→ Available for the Feb 2022 workshop

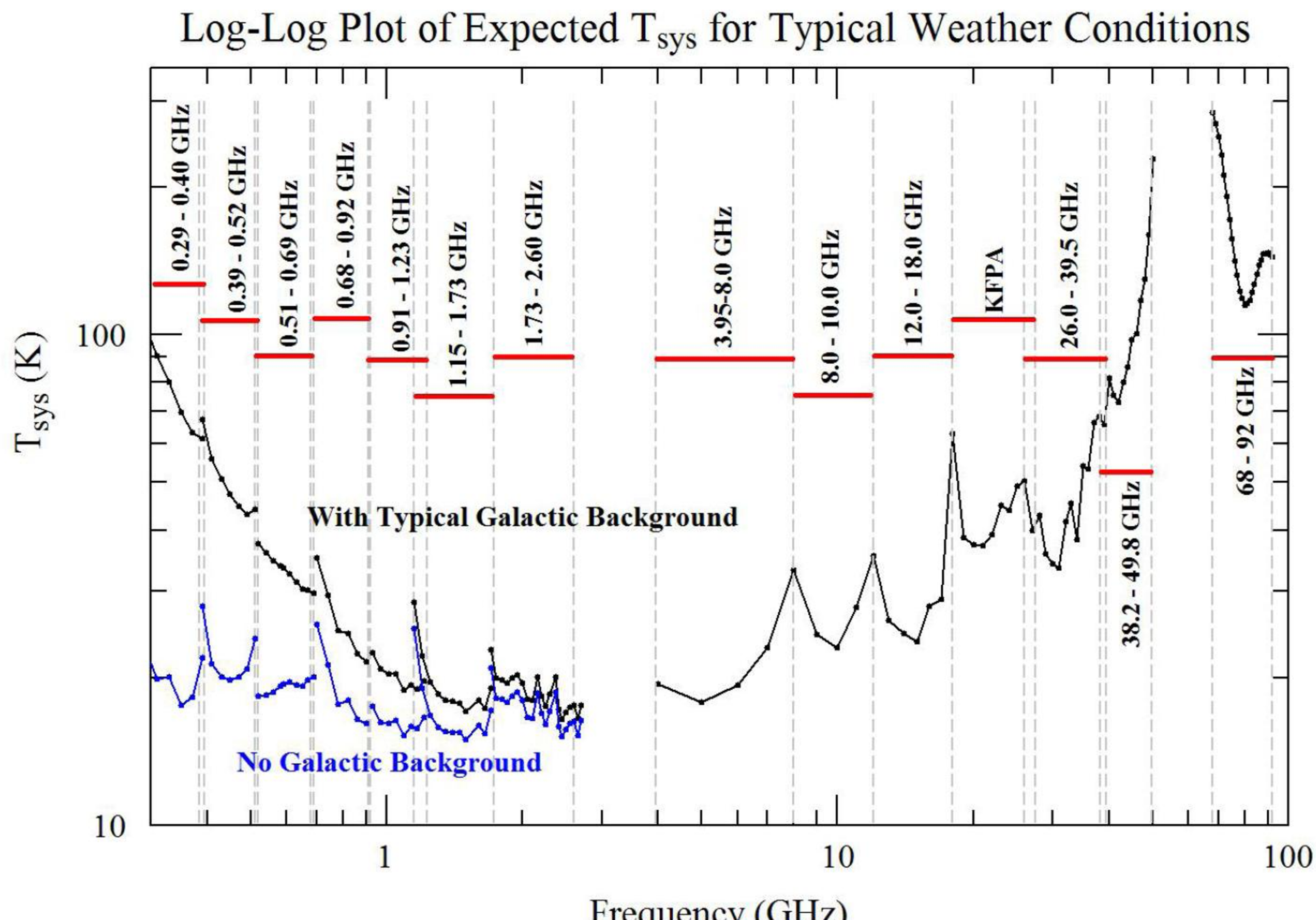
GBT receivers

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

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

Noise Levels (Tsys) for Typical Weather

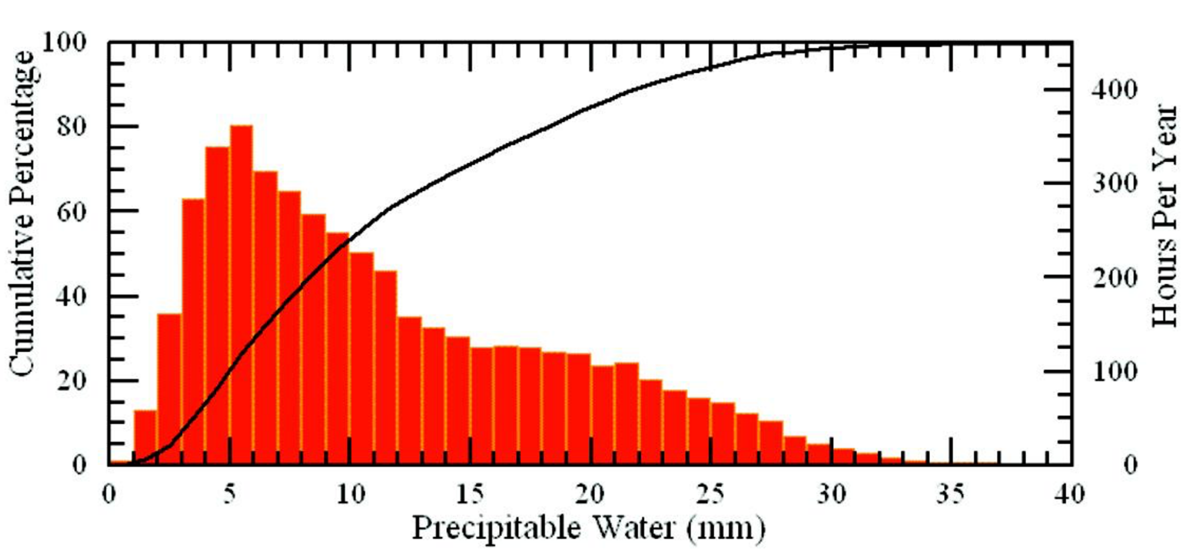


The atmosphere is important at high frequency (>10 GHz)

- 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°)

- 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



~50% of time in Green Bank during the high-frequency season (Oct thru April) has less than 10mm of H2O (acceptable for 3mm observations)
GBT Memo#267

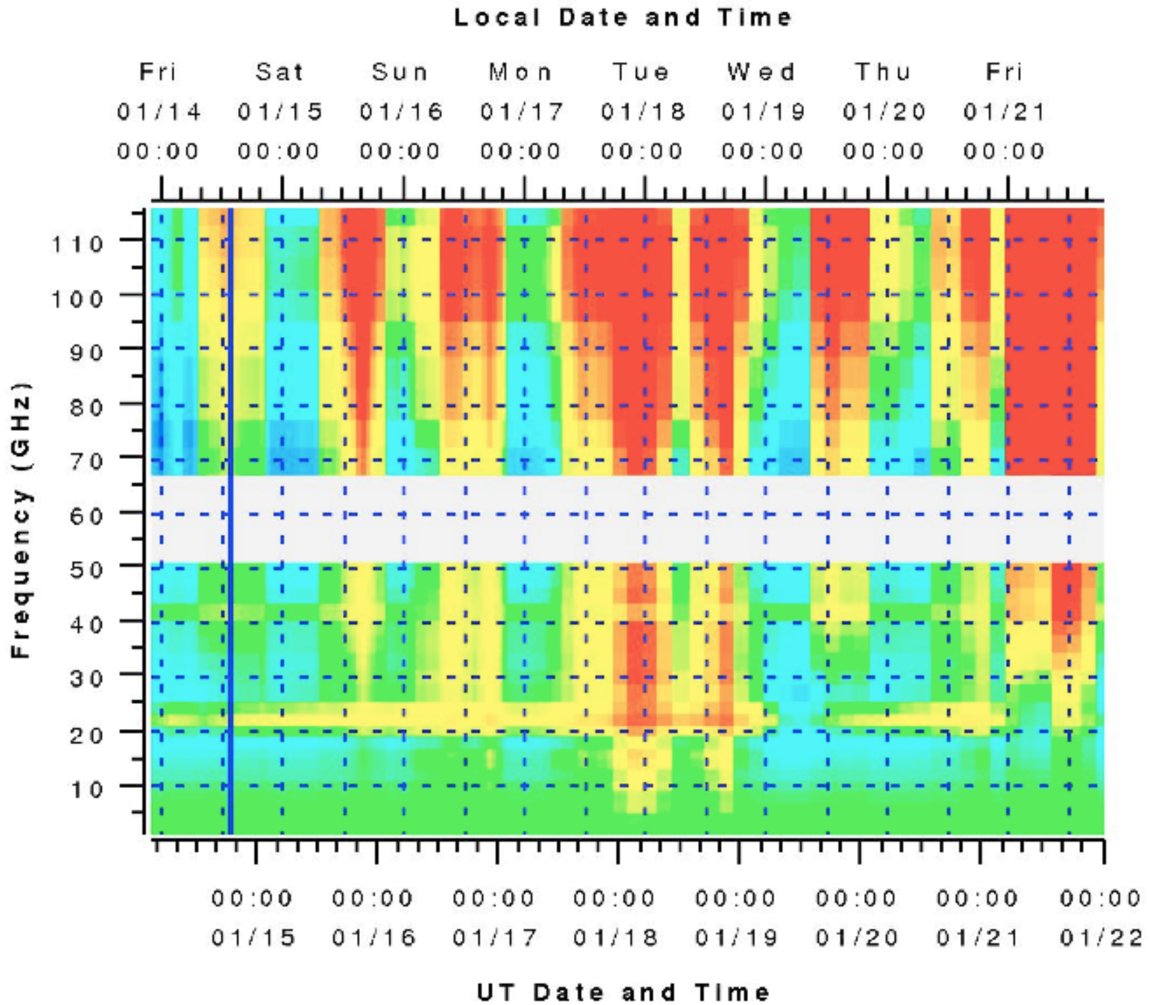
Effects of Winds

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

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)

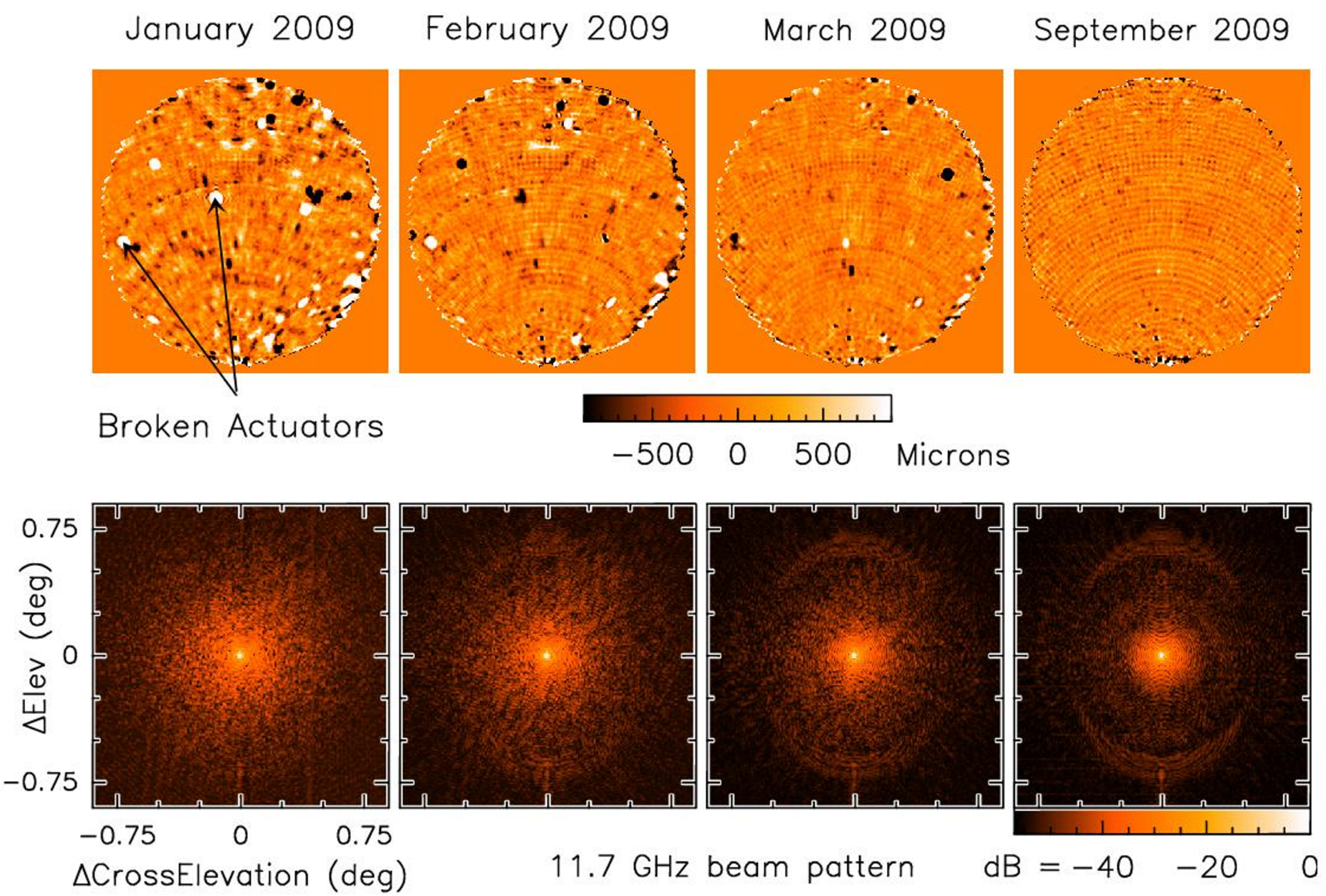
Dynamical Scheduling System allows efficient use of telescope at high frequency – based on weather model predictions that are updated every 6 hrs.



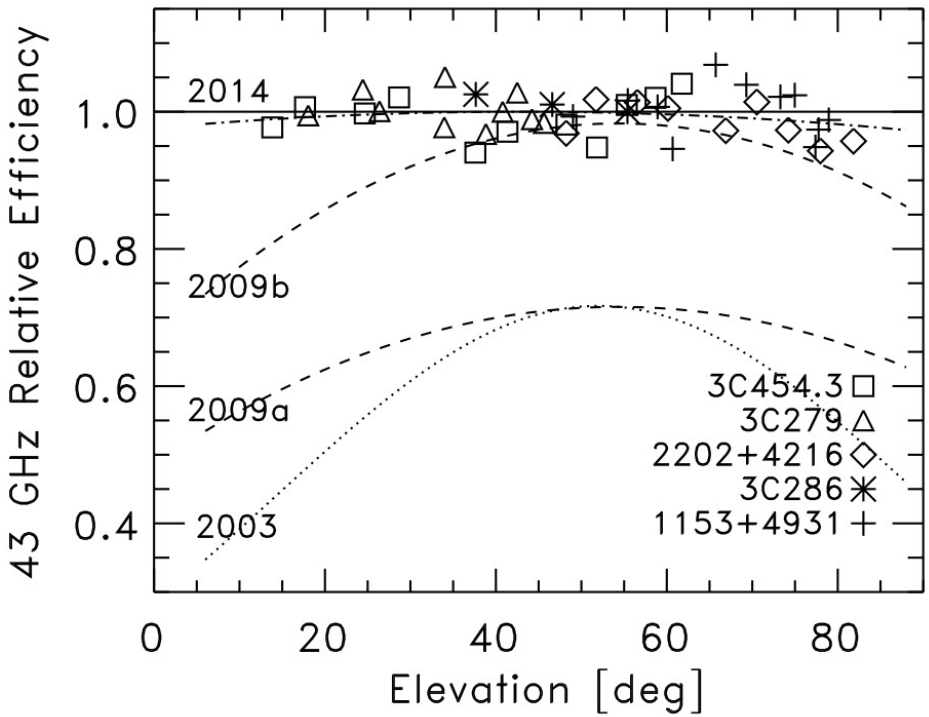
Telescope dynamically scheduled daily based on weather conditions and receiver and observer availability. Dynamic Scheduling matches the project to the weather

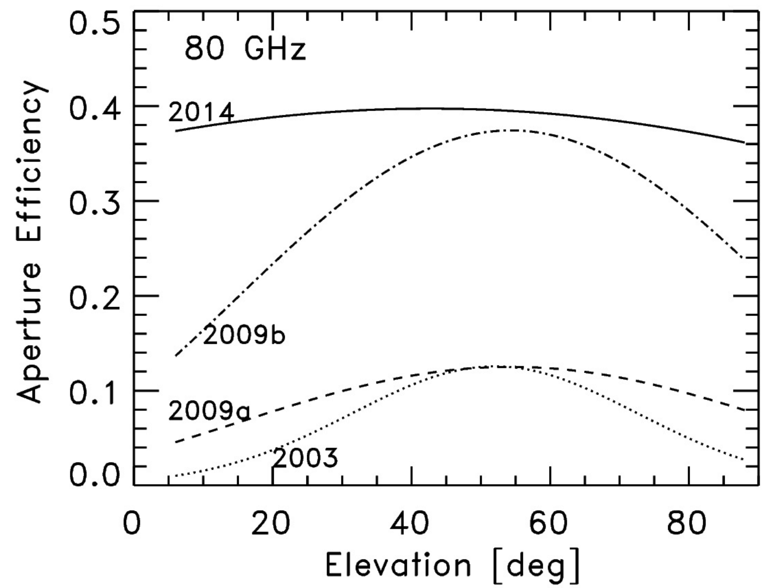
There are about 450 hrs per semester for high-frequency observations (factoring in all constraints, i.e., opacity, winds, NSF open skies time).

GBT Surface Improved in 2009

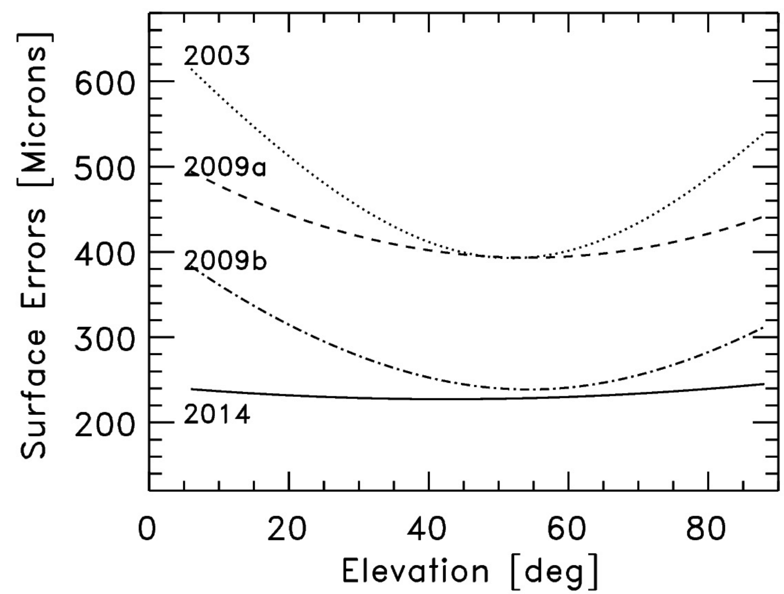


History of Surface Improvements

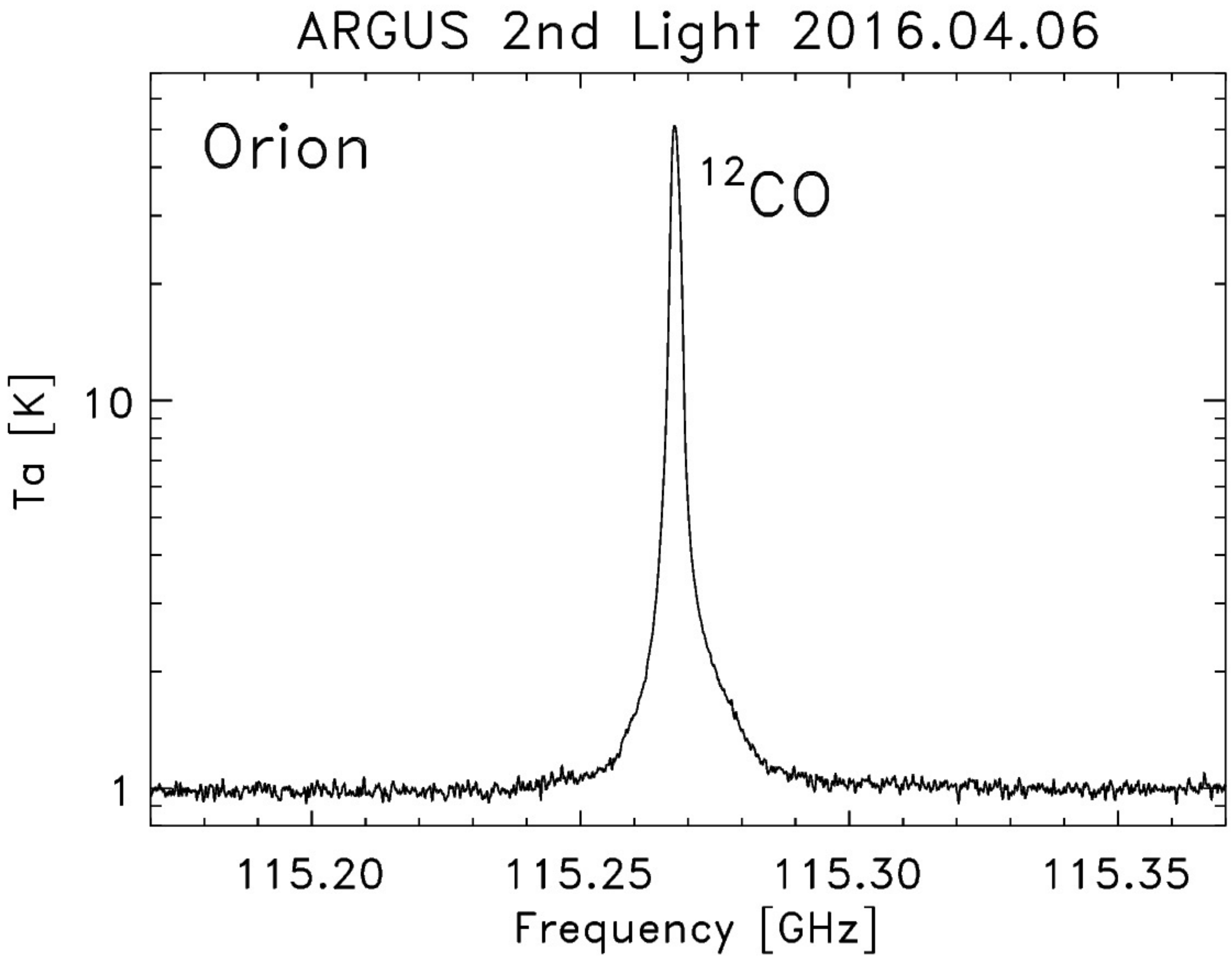




Improvements to the Zernike-Gravity model in 2014 yields a flat gain curve with elevation and has significantly improved the GBT performance at high-frequency **(GBT Memo#301)**



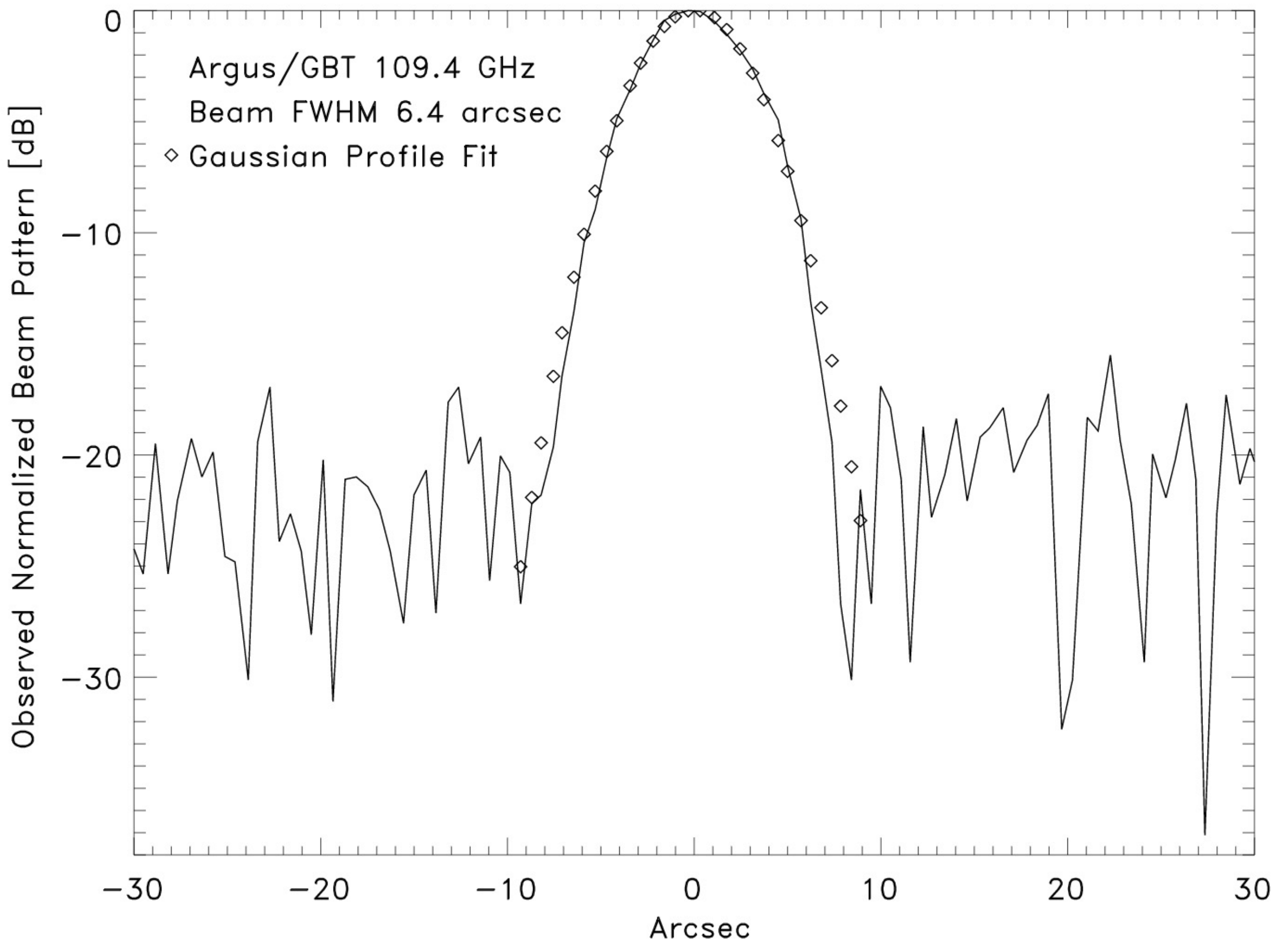
GBT can observe up to 116 GHz



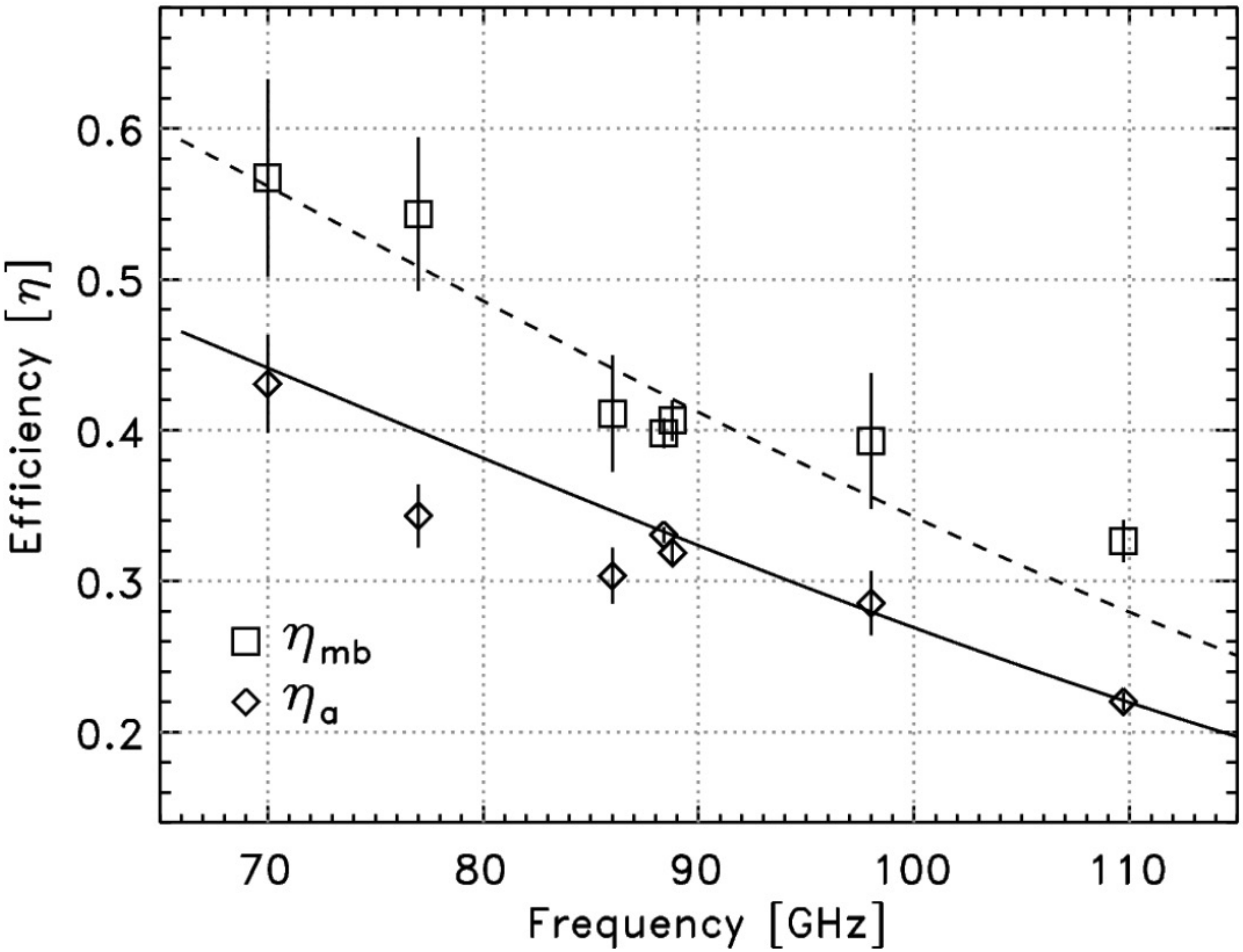
GBT Achieves Theoretical Beam with Argus GBT Memo#296

GBT at 109.4 GHz reaches same beam size one would expect from extrapolating from the performance at 9GHz.

With Argus, the GBT achieves beam sizes of ~1.15--1.25 λ/D (in good conditions after OOF).



Quasar Calibration Results



Average effective surface error is 0.235mm which determines the aperture efficiency (solid line). The point-source main-beam efficiency scales with the aperture efficiency as:

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

which is consistent with a Gaussian beam and a beam-size parameter of:

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

GBT Memo #302 Frayer+ 2019

3mm Calibration Parameters GBT Memo#302

Results derived from hundreds of 4mm and Argus Observations over several seasons.

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)	$\eta_{\rm Jupiter}$	0.53 ± 0.05
Moon Beam Efficiency (32′ diameter)	$\eta_{\rm Moon}$	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.

GBT Performance (PTCS-PN78)

- ~10 arcsec blind pointing
- ~5 arcsec all-sky offset pointing
- ~1 arcsec nearby offset pointing
- ~0.5 arcsec tracking accuracy (still needs measurements)

- 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

Observing Strategies

- Your observing strategies depends on your science goals.

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 (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

Radio telescopes measure:
Ta = "antenna temperature"

- Ta(total) = Tsource + {Trx + Tbg + Tatm + Tspill}
- Where {….} = other contributions
- Want Tsource, so carry out ON – OFF
- Ta(ON) =Tsource + {….}
- Ta(OFF) = {….}
- So Ta(ON)-Ta(OFF) = Tsource

➔ Need to carry out ON-OFF observations, and there are different observing techniques for measuring ON-OFF

Different Observing Modes to derive the reference data (OFF)

Types of reference observations

➢ Frequency Switching (FSW)

– In or Out-of-band

➢ Position Switching (PS)

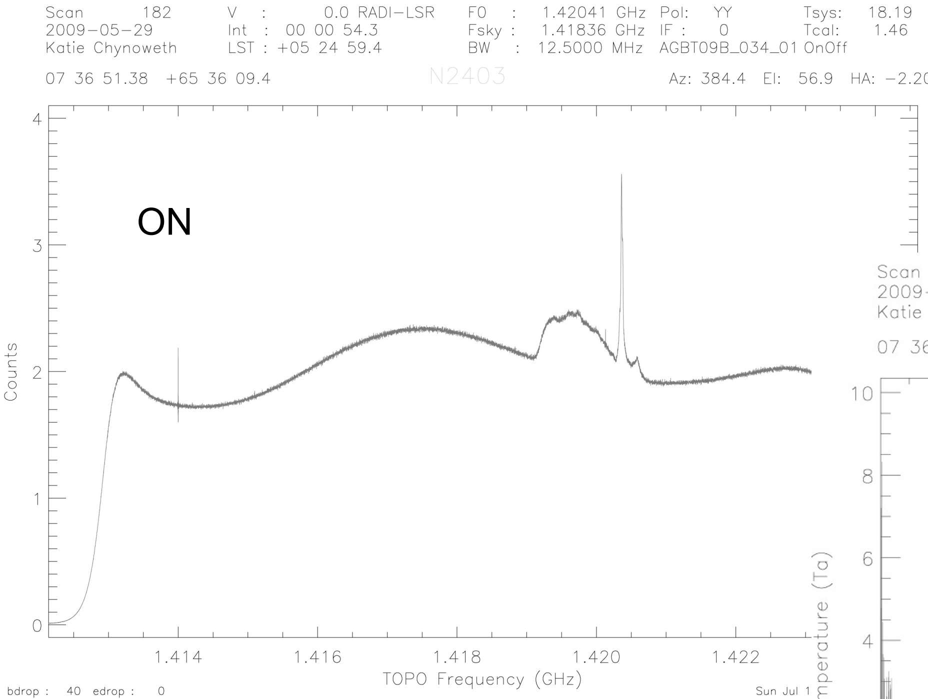
– Reference-Off

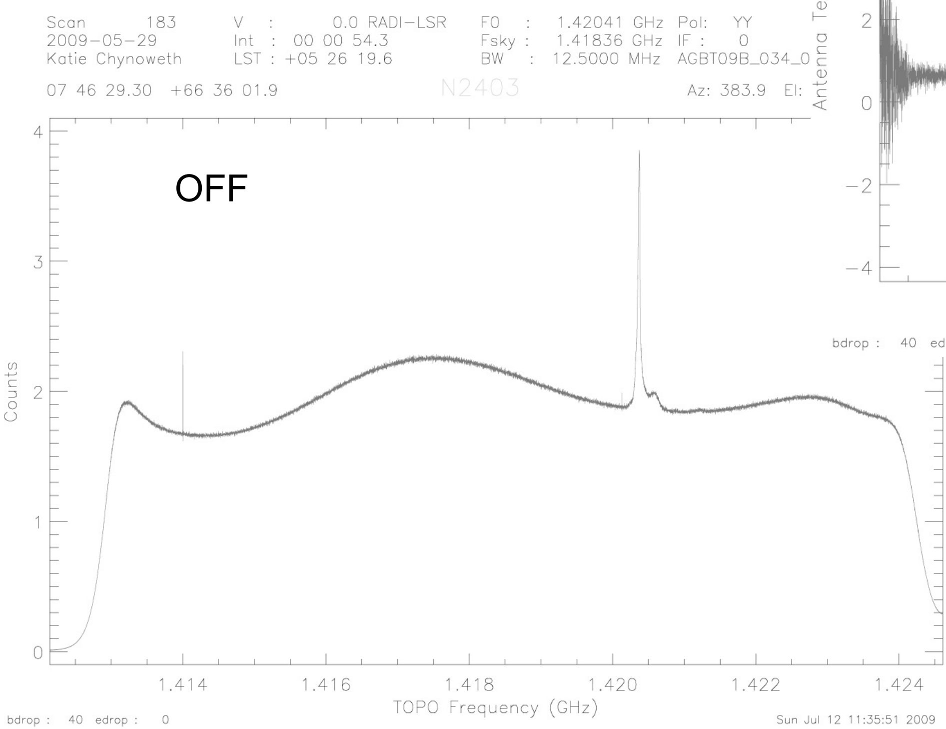
– Mapping-Off

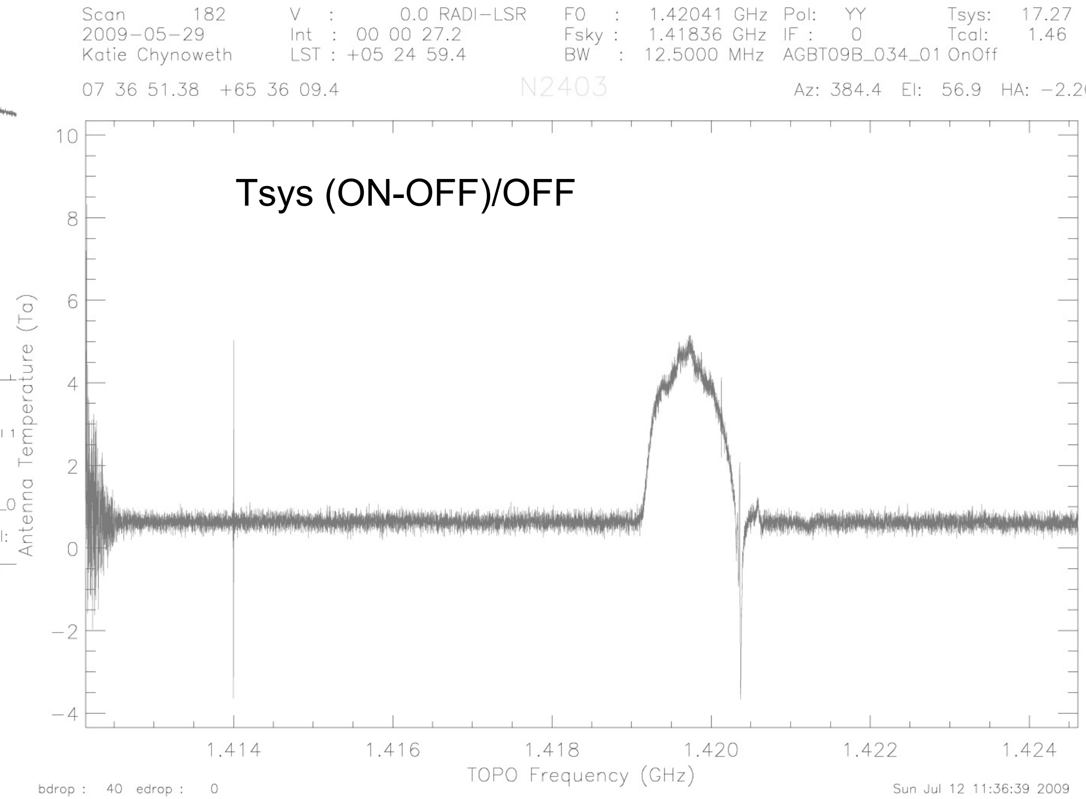
➢ Dual-Beam Position Switching

- **Nod** -- Move telescope
- **SubBeamNod** -- Move Subreflector

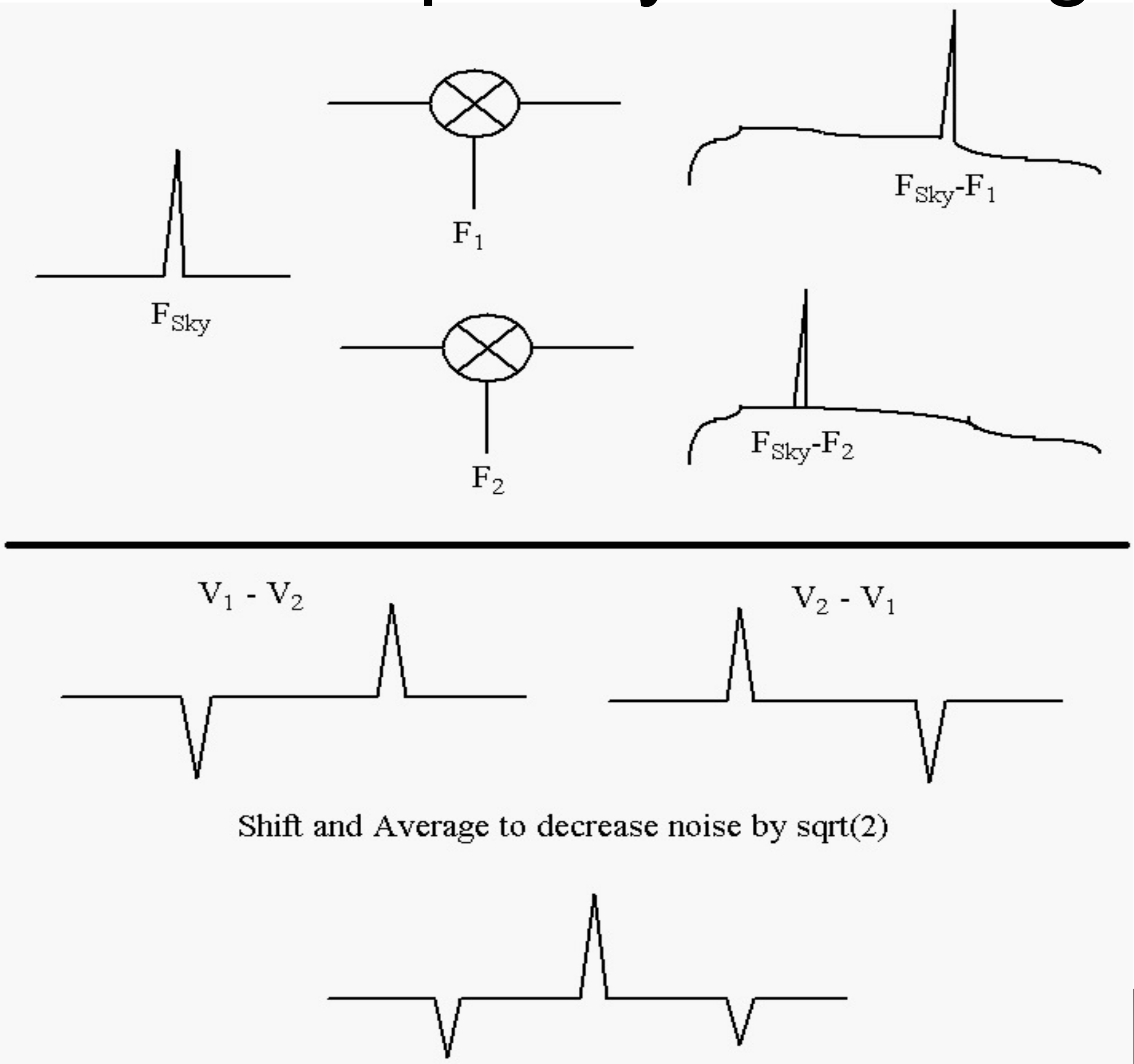
Position switching



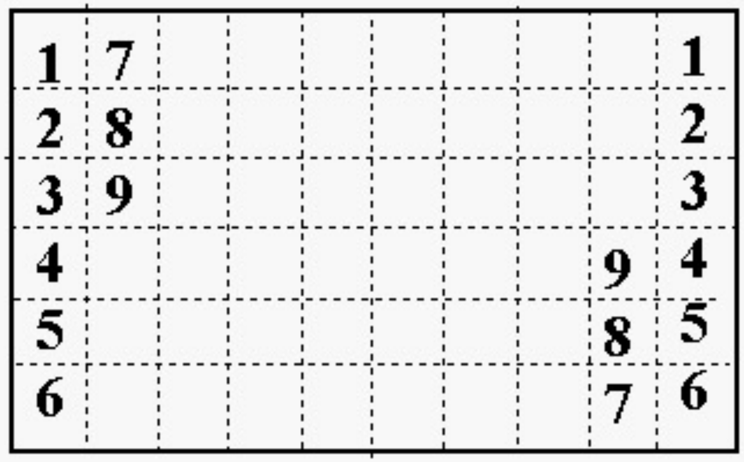




In-Band Frequency Switching



Mapping Techniques



- **Point map**

•Sit, Move, Sit, Move, etc.

- **On-The-Fly Mapping**

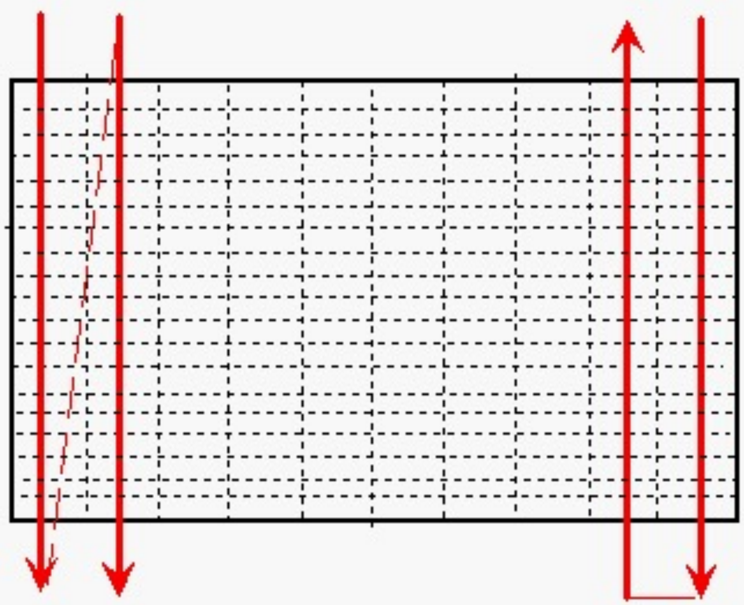
•Slew a column or row while collecting data

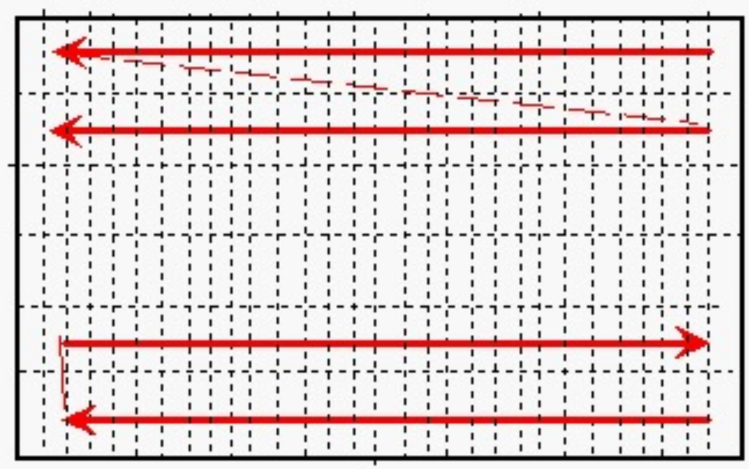
•Move to next column row

•Basket weave

•Should oversample ~3x Nyquist along direction of slew

Reference/OFF from a “source-free” map position or separate “OFF” spectrum taken.

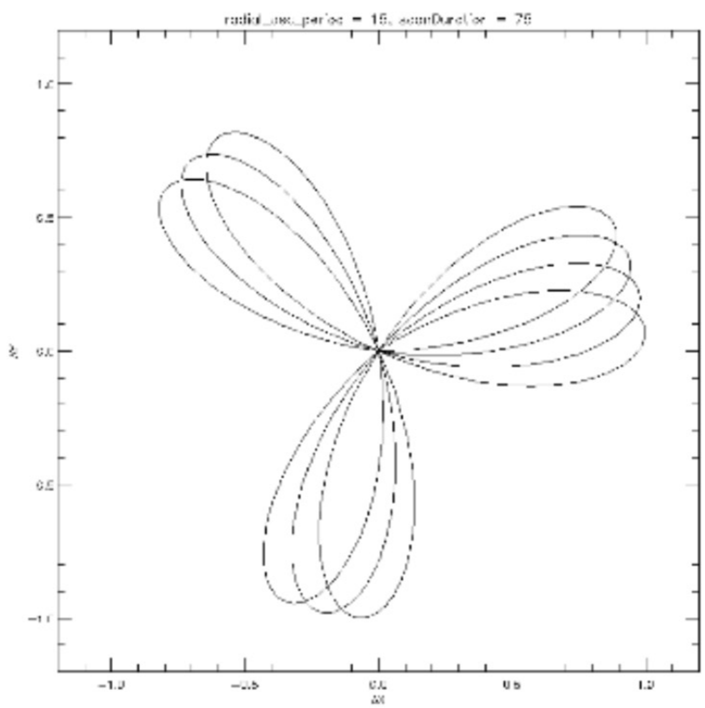




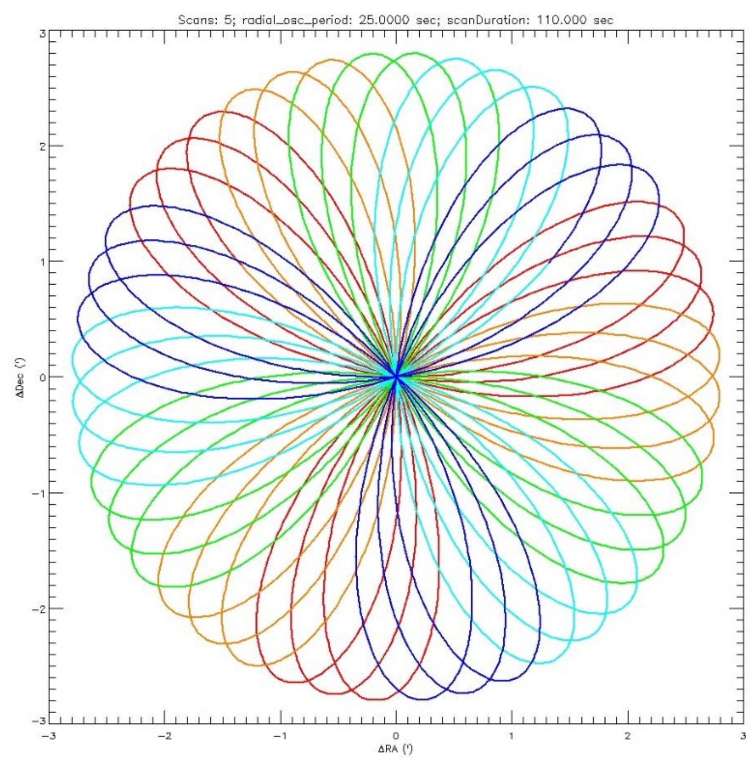
Mapping Techniques

Daisy Map

- Useful for multi-beam arrays
- Best for smaller regions (6’)
- Most sensitive towards the center of the daisy



(a) Daisy scan with scanDuration = 5×radial_osc_period.



How to pick your observing mode?......

(Q1) 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

(Q2) Small Source vs Large 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)

{bold = GBT astrid observing commands}

Mapping Modes – Large Source (Q3) Map size vs FOV

➢ 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

Calibration

GBT Definition of Ta

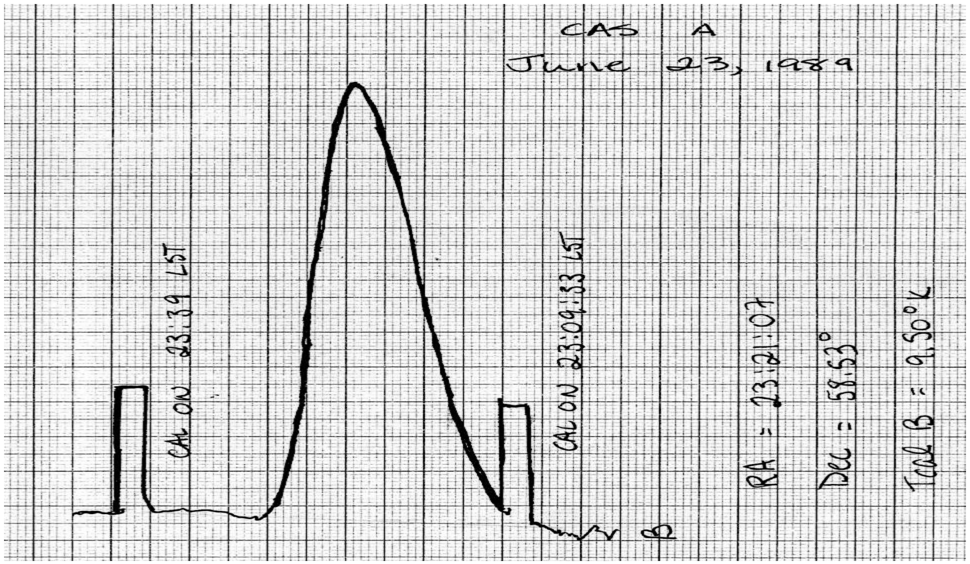
$$T_a = \frac{(ON - OFF)}{OFF} T_{system}$$

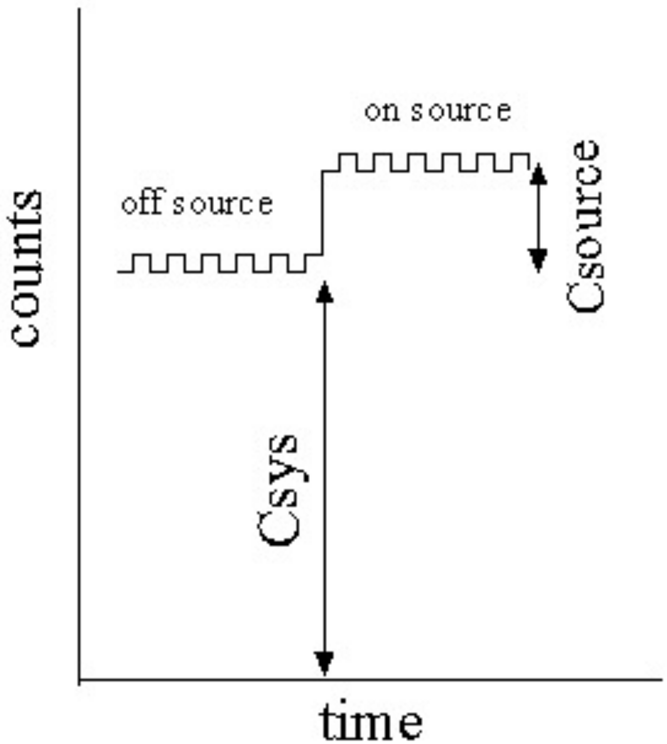
Blank Sky or other

From diodes, Hot/Cold loads, etc.

Noise Diodes

Example noise-diode signal from drift scans using the educational telescope

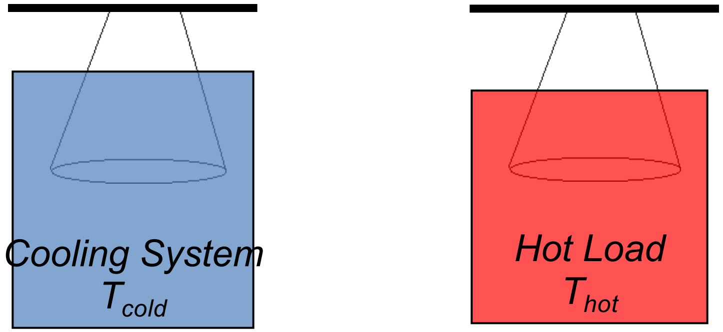




(left) For the GBT, we typically flicker the noise-diodes on/off during the observations.

Noise diodes are used for relative calibration and are stable for many months.

Hot & Cold Loads



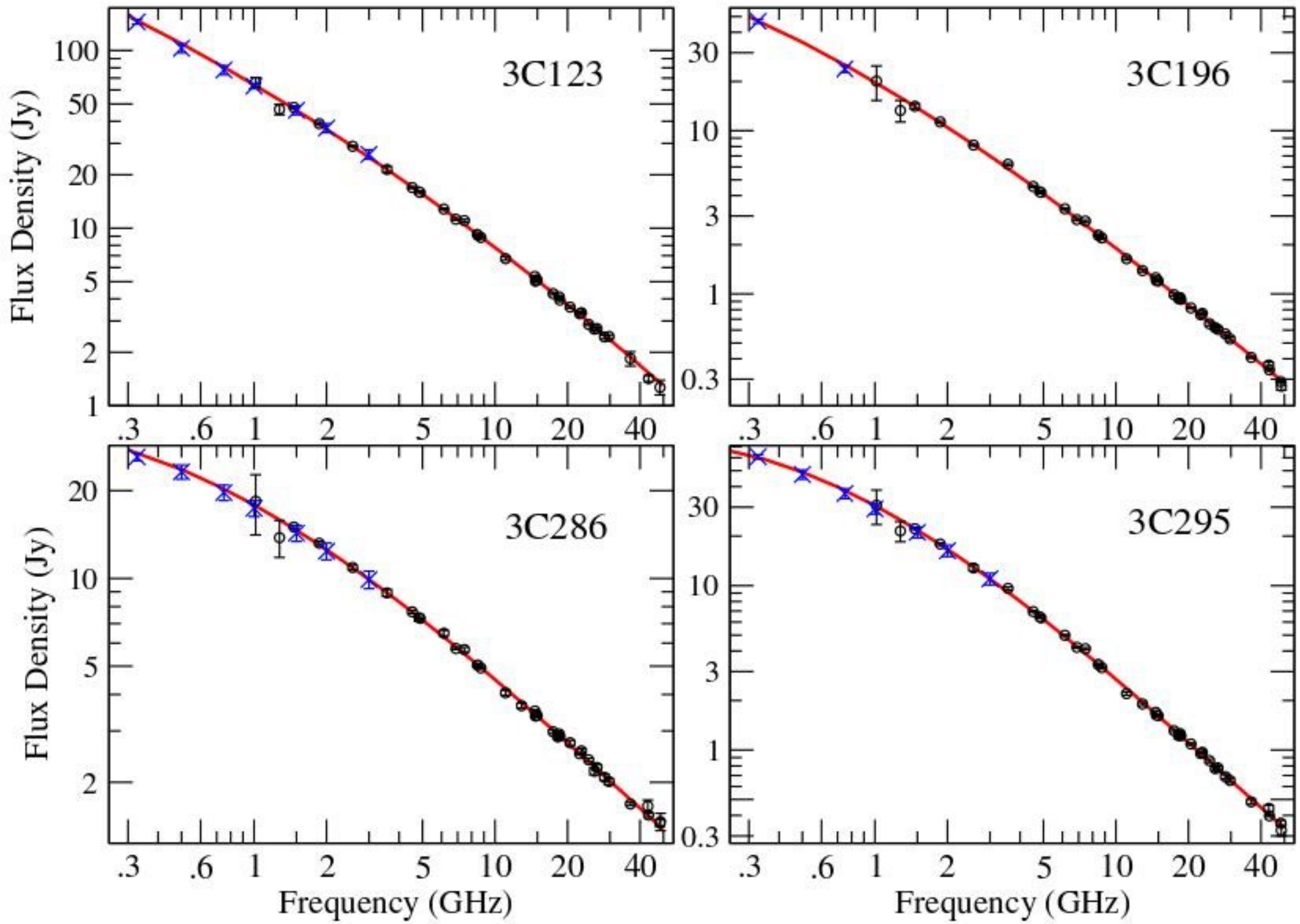
Gain: g =(Thot – Tcold)/(Vhot –Vcold) [K/Volts]

Tsys = g Voff

Example GBT 4mm Rx

VLA Stable Calibrators

GBT to VLA calibration scale for 1-50 GHz, and we use ALMA for 3mm absolute calibration.



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).

GREEN BANK
OBSERVATORY

greenbankobservatory.org

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

NSF Associated Universities, Inc.