

# The Green Bank Observatory

National Radio Astronomy Observatory



Anthony Remijan (NRAO)

Slides from: Braatz, Frayer, O'Neil, Lockman, Hunter, Langston, and input from other NRAO staff.

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

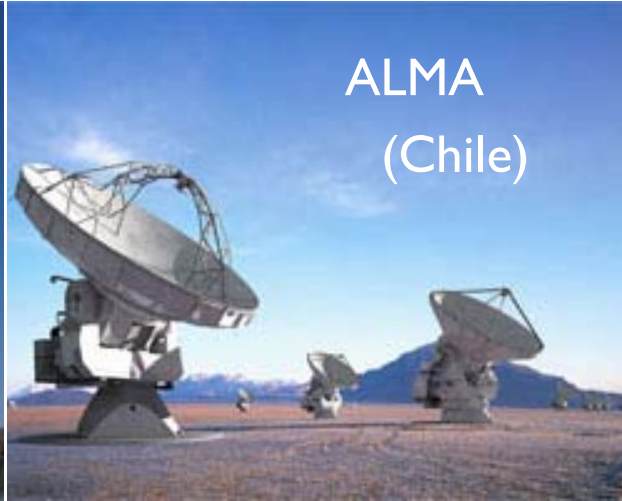


# NRAO has complementary suite of telescopes and facilities

Green Bank  
Observatory



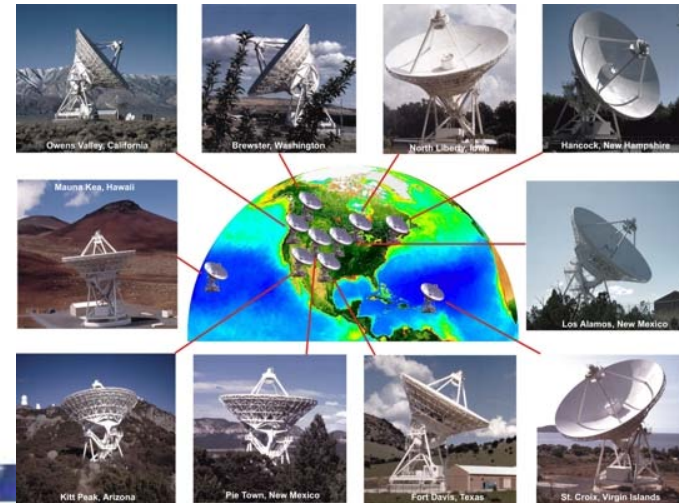
ALMA  
(Chile)



New Technology Center  
(Charlottesville, Virginia)



Expanded Very Large Array  
(Socorro, New Mexico)



Very Long Baseline Array



# Green Bank is original NRAO site, with world class telescopes for >50 years

Started 1958  
Completed 1959



Completed 1965



Completed 1995



Completed 2000



Completed 1994

Completed 1962



Completed 1962



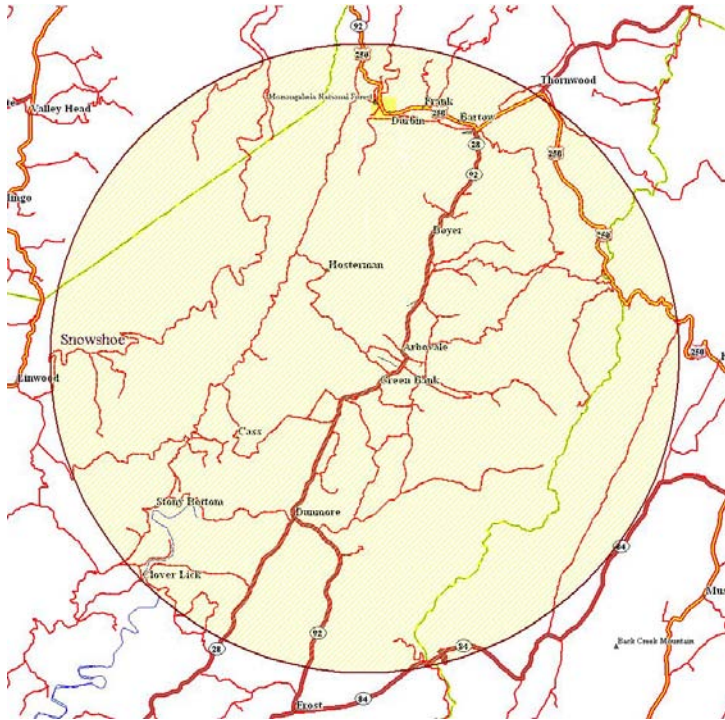
Completed 1967





# WV Radio Astronomy Zone

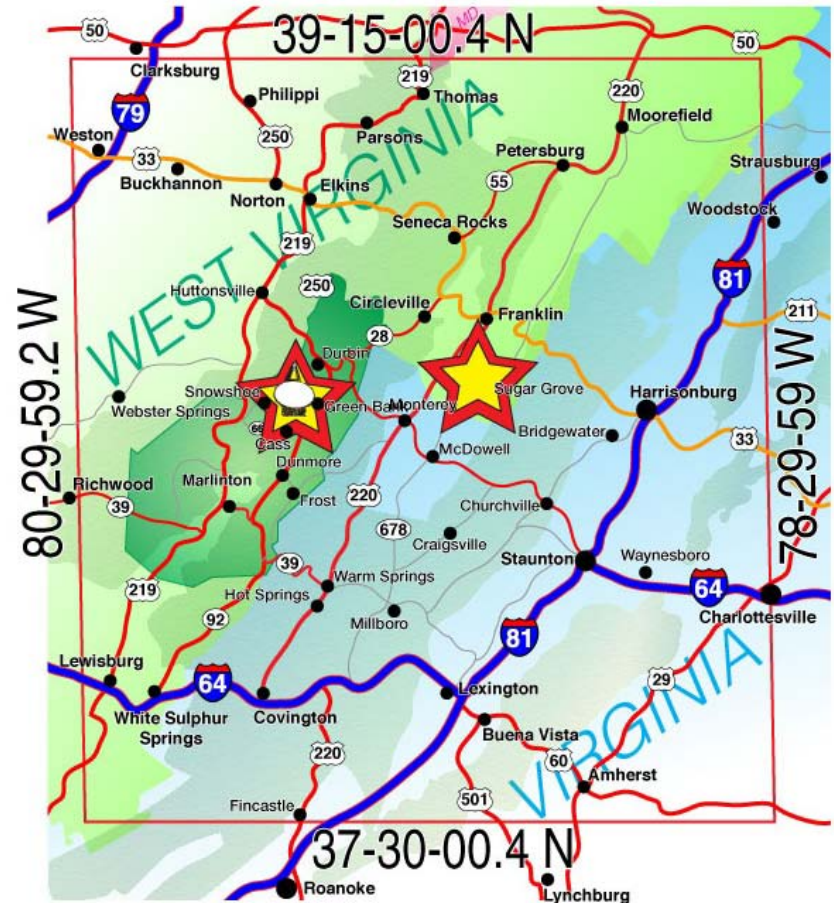
Established by the West Virginia Legislature  
(1956)



Protection within ten miles  
of the Observatory

# National Radio Quiet Zone

Established by the FCC and NTIA  
(1957)



13,000 Square Miles



# The Green Bank Telescope



100 meter Diameter

Unblocked Aperture

Active Surface

Operates from ~100 MHz to 100 GHz

Fully Steerable

>85% of total sky covered  $\delta \geq 46^\circ$

Pointing to 1"-2" accuracy

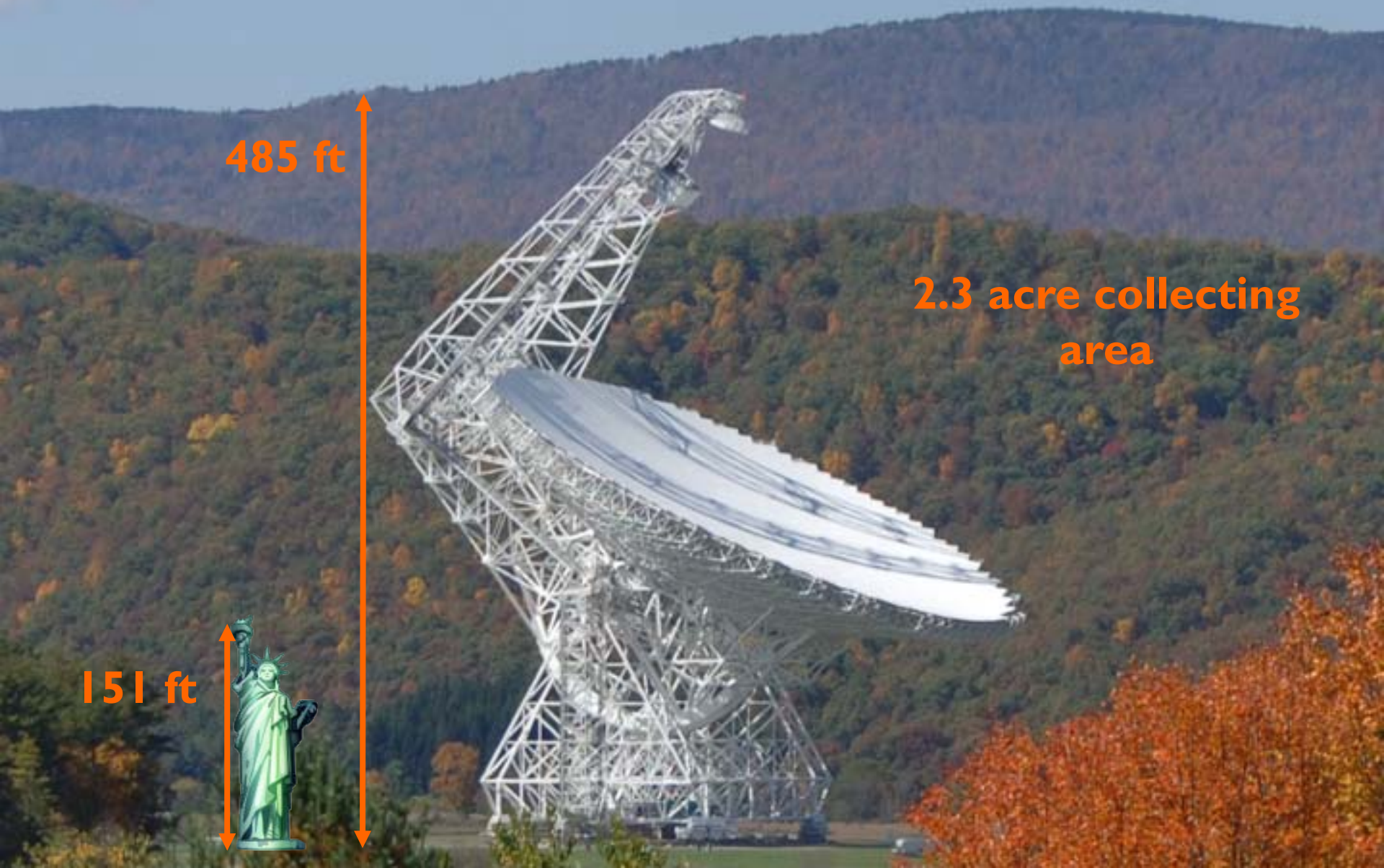
Surface good for 3mm work

Active Instrument Development Program

Site Protected by a 13000 km<sup>2</sup>  
Radio Quiet Zone



At 100 m, the GBT is the largest *fully steerable* telescope and the largest movable structure in the world.



485 ft

2.3 acre collecting area

151 ft

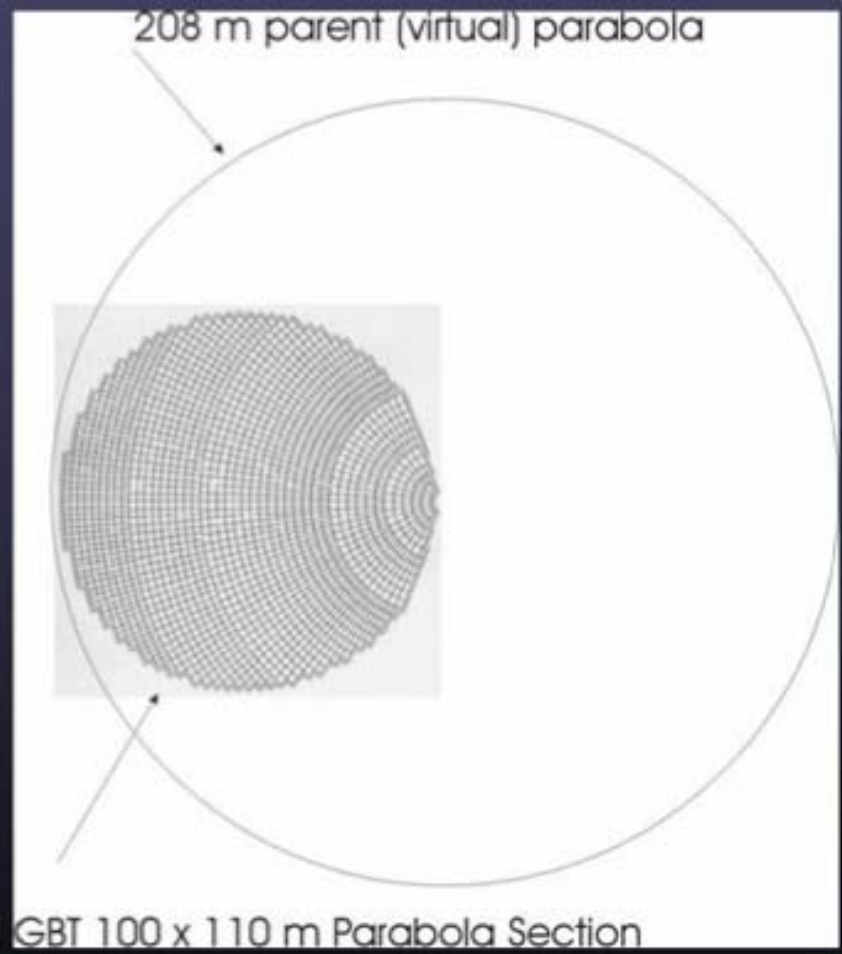


Eight slots in Gregorian receiver turret

Many projects are run each day



# The Offset Paraboloid





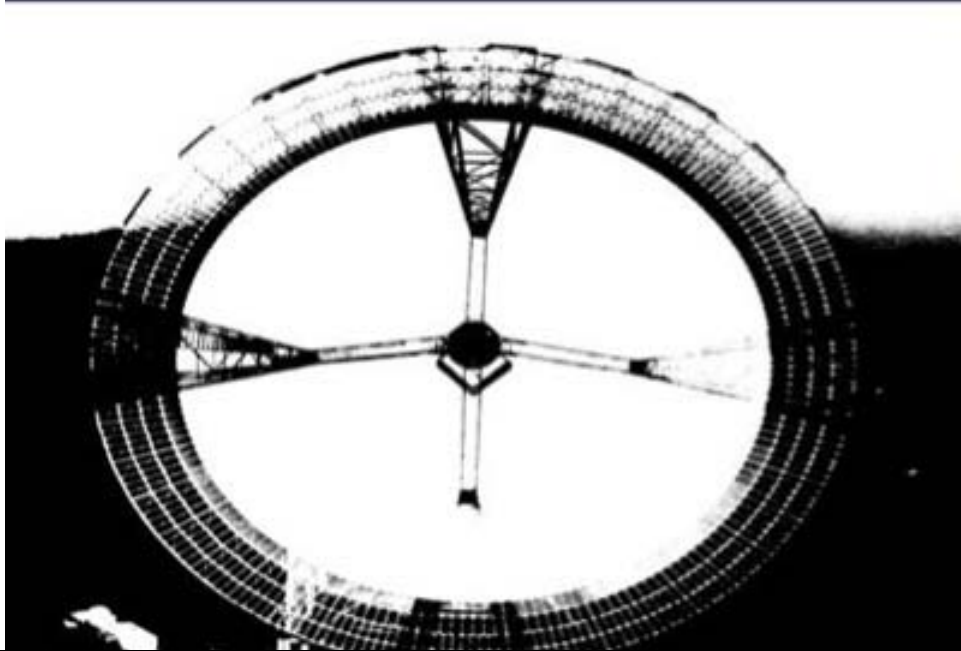
## The Active Surface

2209 actuators

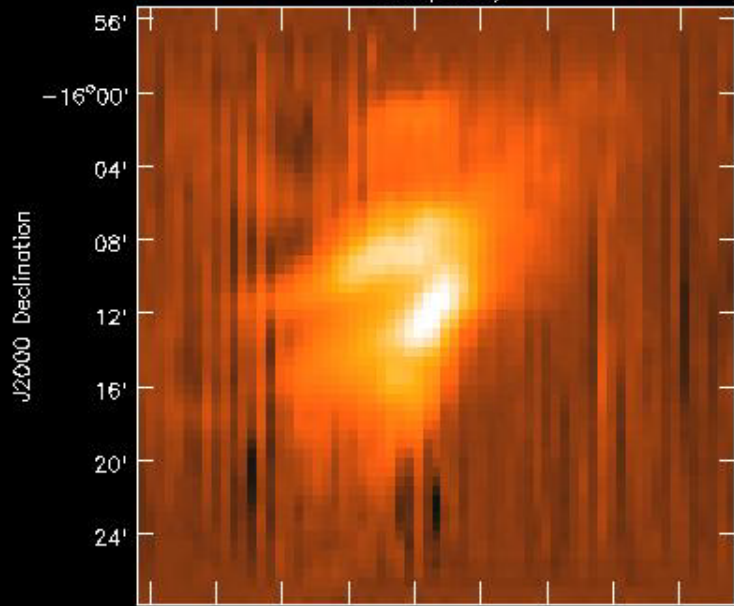
Currently rms  $< 240\mu\text{m}$  at night, the goal is  $210\mu\text{m}$



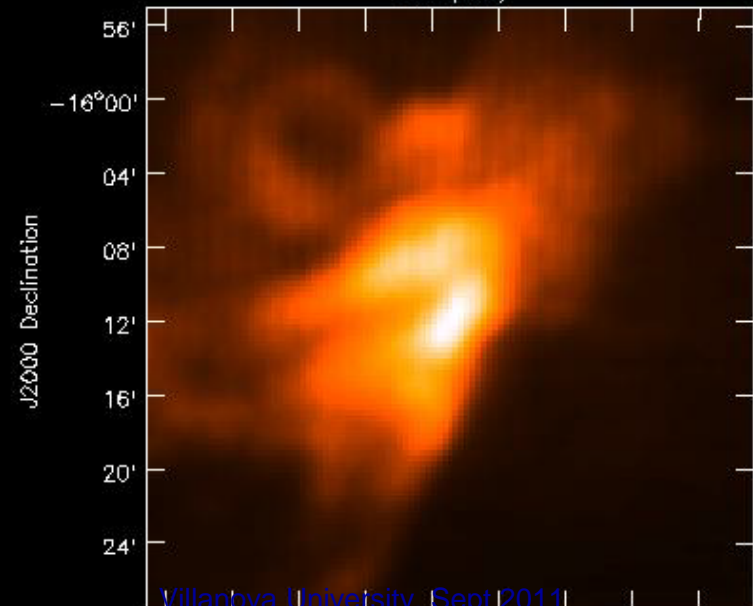
# Unblocked Optics for High Dynamic Range



M17 (MPIfR)



M17 (GBT)



Villanova University, Sept 2011



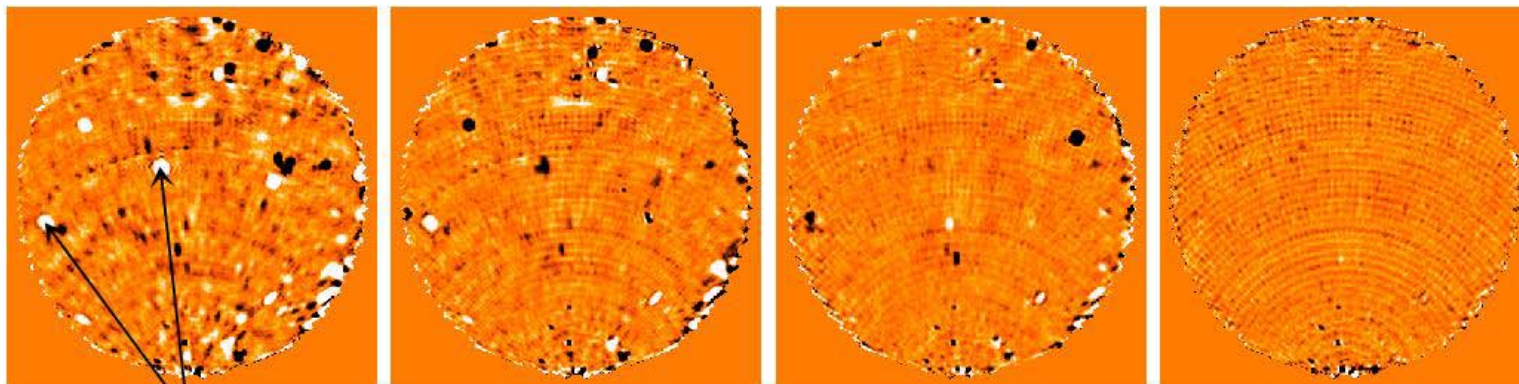
# Improvements to Surface Makes 3mm Possible

January 2009

February 2009

March 2009

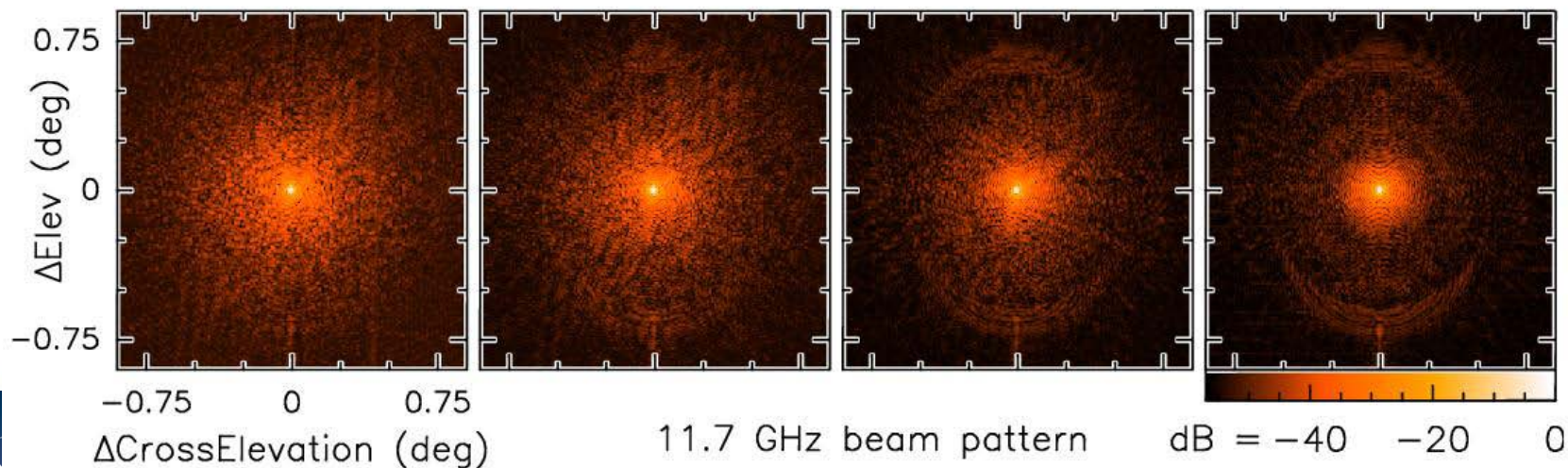
September 2009



Broken Actuators



-500 0 500 Microns



$\Delta$ Elev (deg)

$\Delta$ CrossElevation (deg)

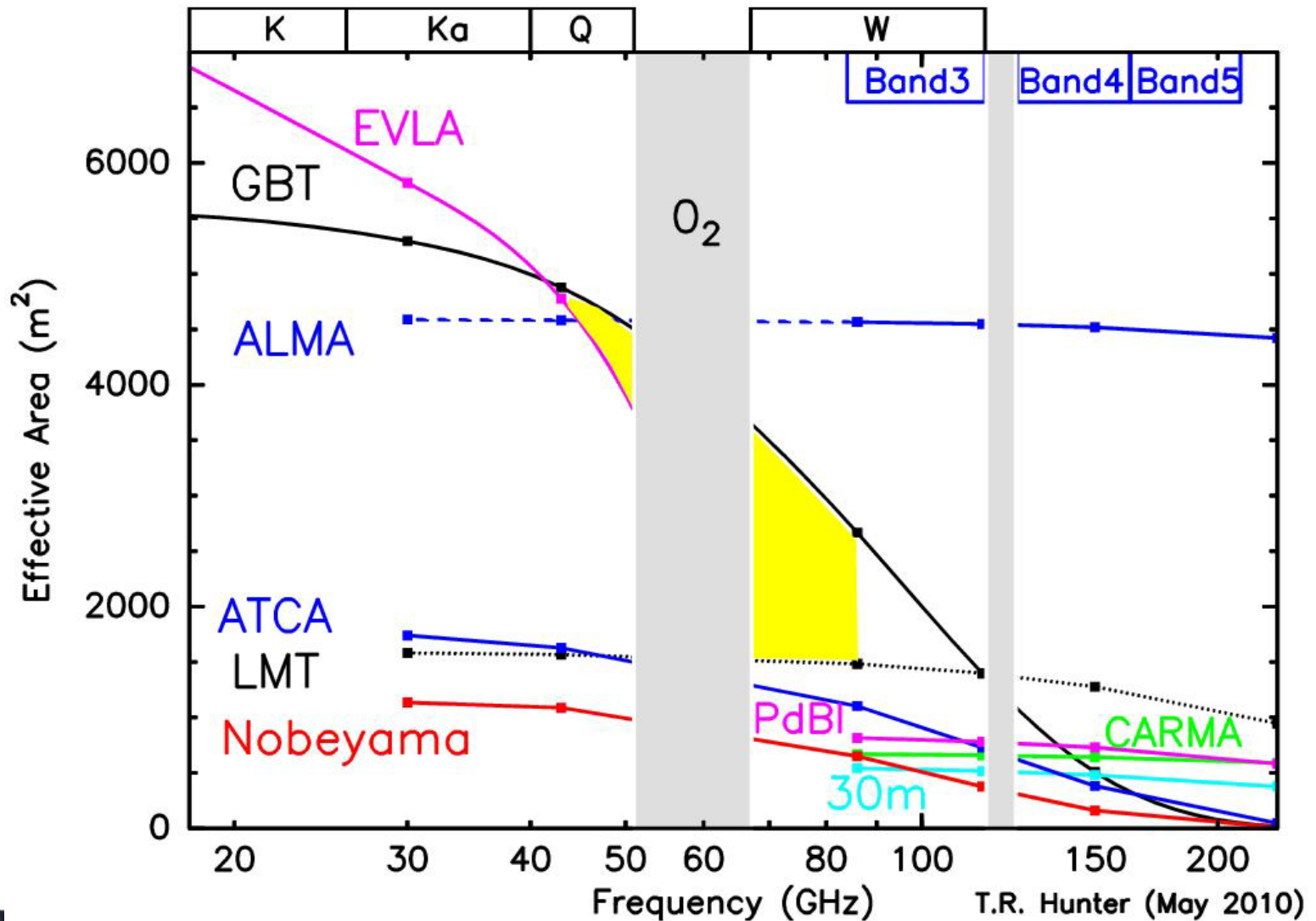
11.7 GHz beam pattern

dB = -40 -20 0

# GBT Effective Collecting Area ( $\eta_a * \text{Area}$ )

Assumes  
current  
~240um rms  
surface  
errors  $\rightarrow$  35%  
at 90 GHz  
(still room for  
more gains)

$\rightarrow$  most  
sensitive  
facility at Q  
and W-low  
(4mm).



T.R. Hunter (May 2010)



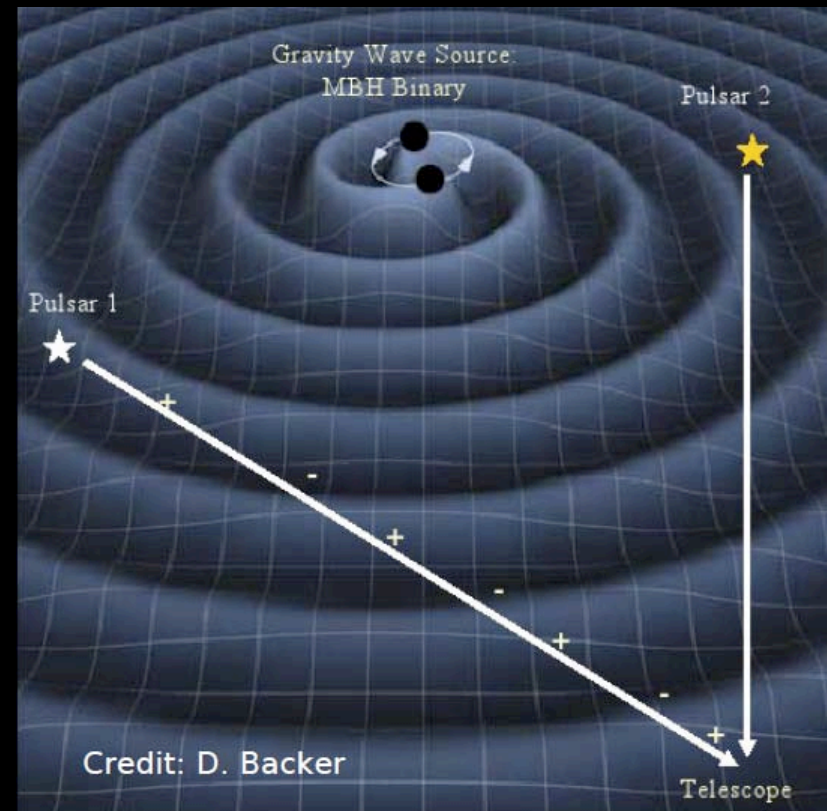
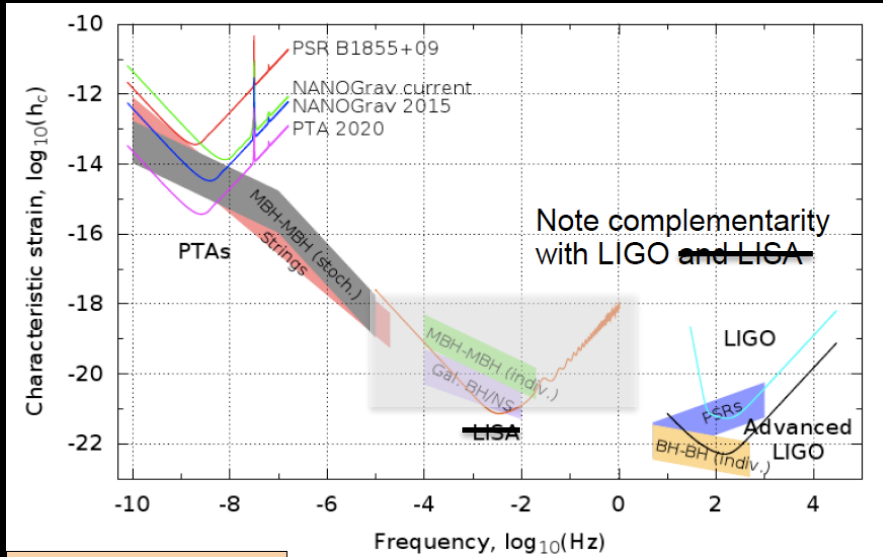


# Some Key GBT Science Areas:

- Pulsars: Surveys; 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-chemistry
- Masers: black hole masses, distances to galaxies
- Star Formation: NH<sub>3</sub> mapping
- Basic Physics: The search for Gravitational Radiation, Limits on Fundamental “constants”
- Solar system astronomy

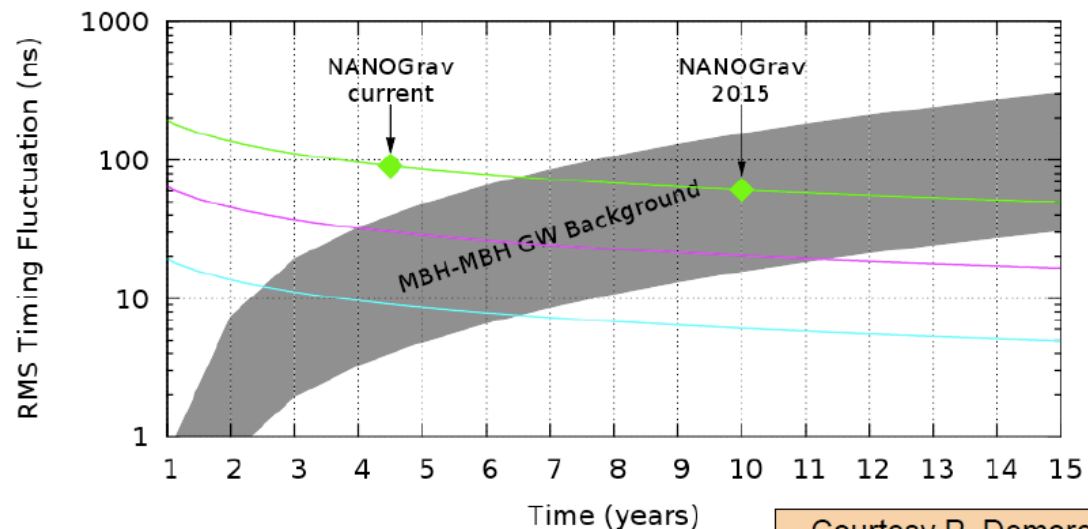
# Fundamental physics

## The race to detect gravitational waves



## NANOgrav

Need 40 pulsars with <100ns timing residuals



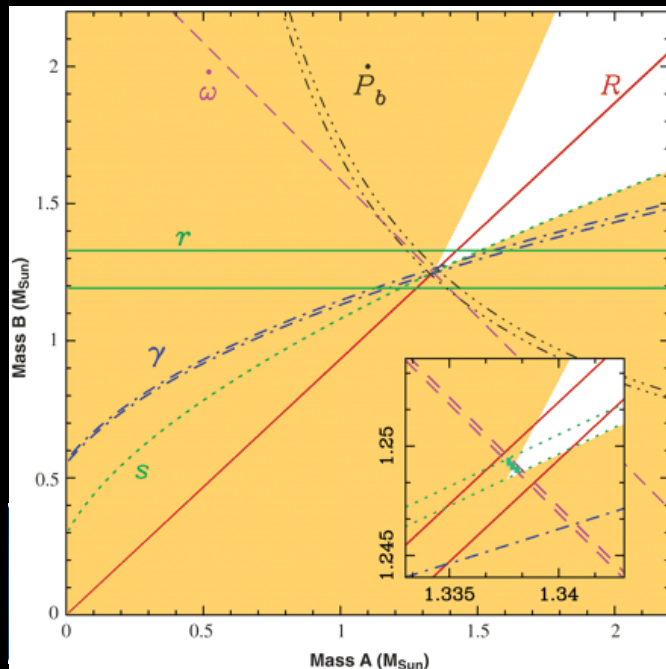
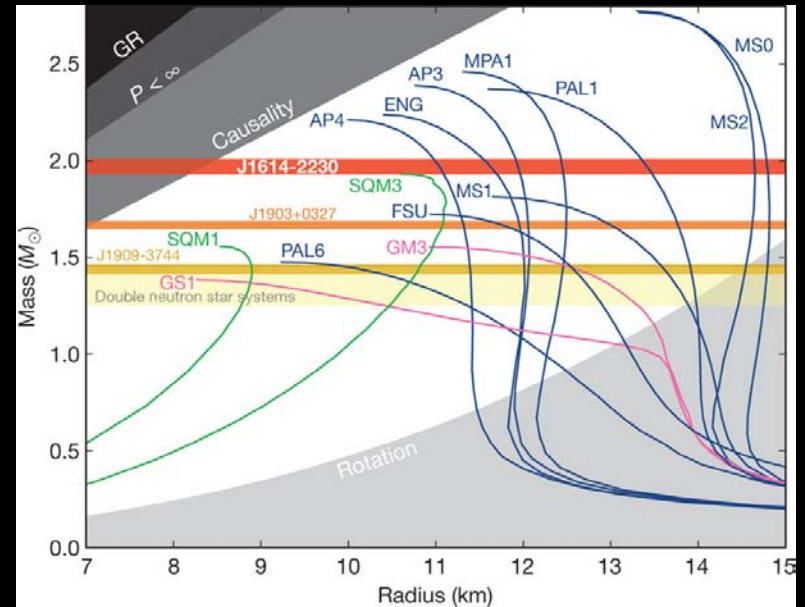
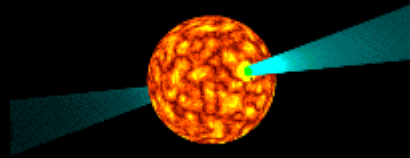
Courtesy P. Demers



# Fundamental physics

Testing matter at extreme densities

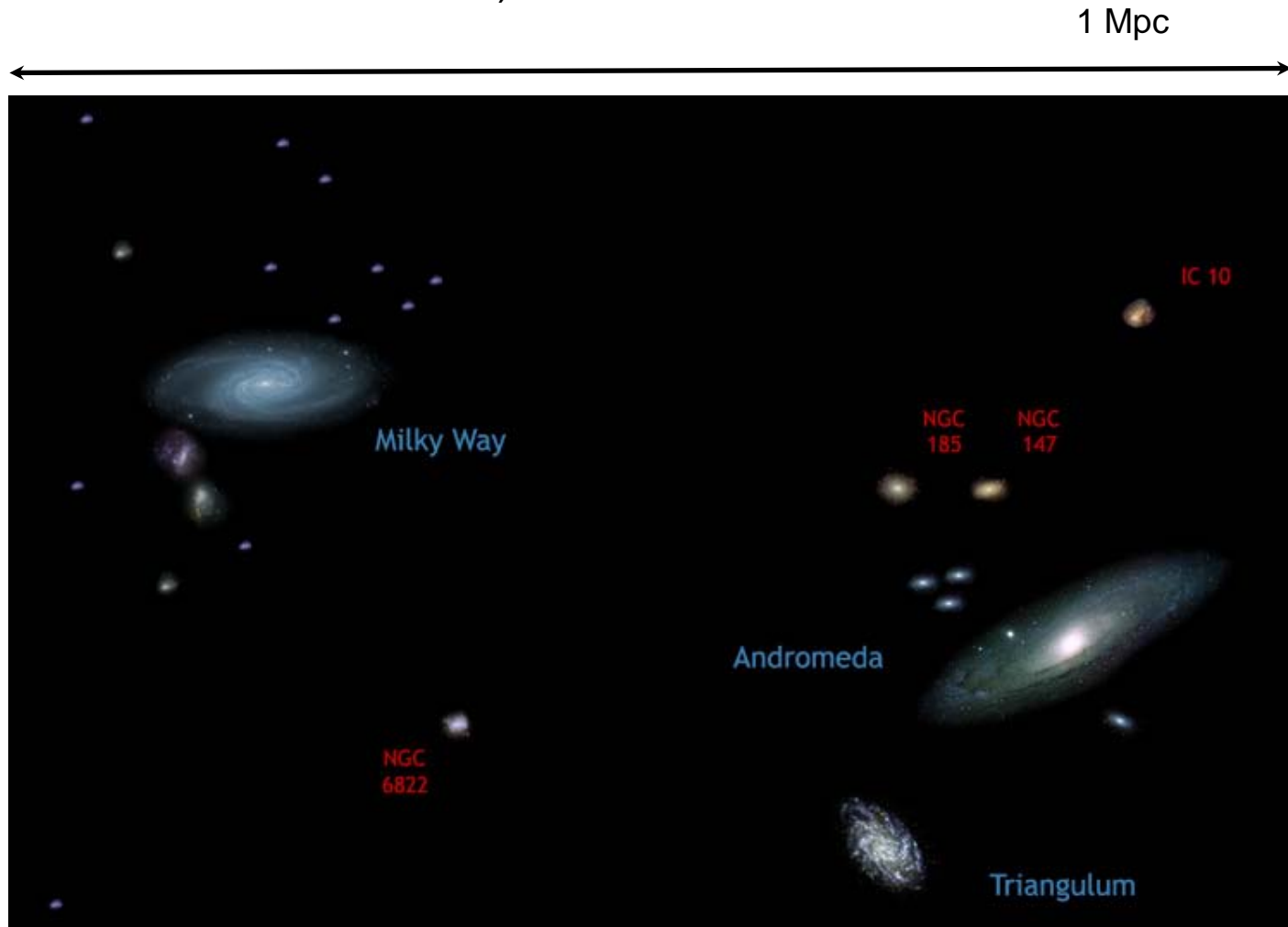
Additional pulsar timing results!



Detection of  $2M_{\text{sun}}$  neutron star  
Rules out many theories of matter  
at high density

Measuring binary pair eccentricity  
to test general relativity

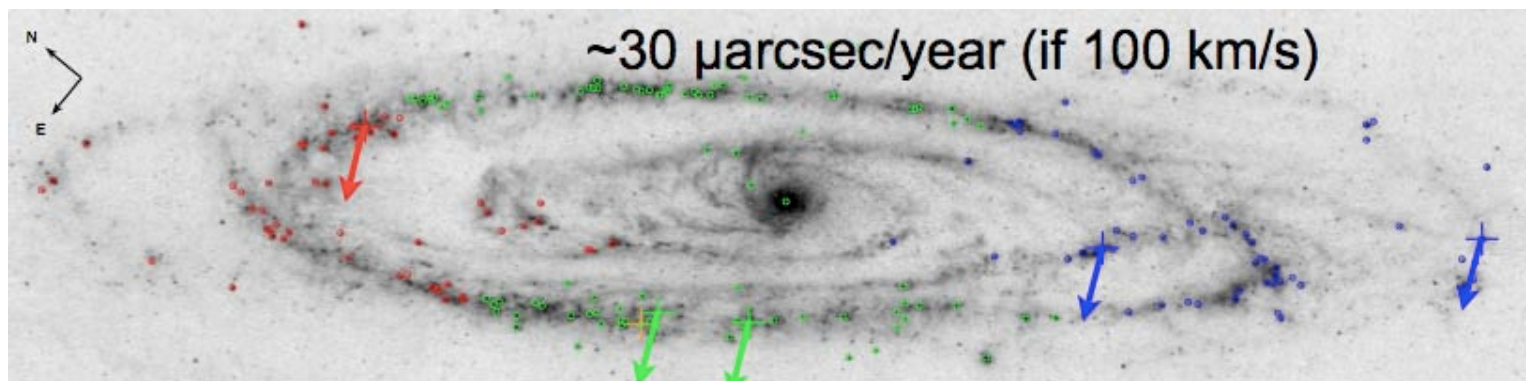
# The Dynamics of the “Local Group” of Galaxies (where is the dark matter?)





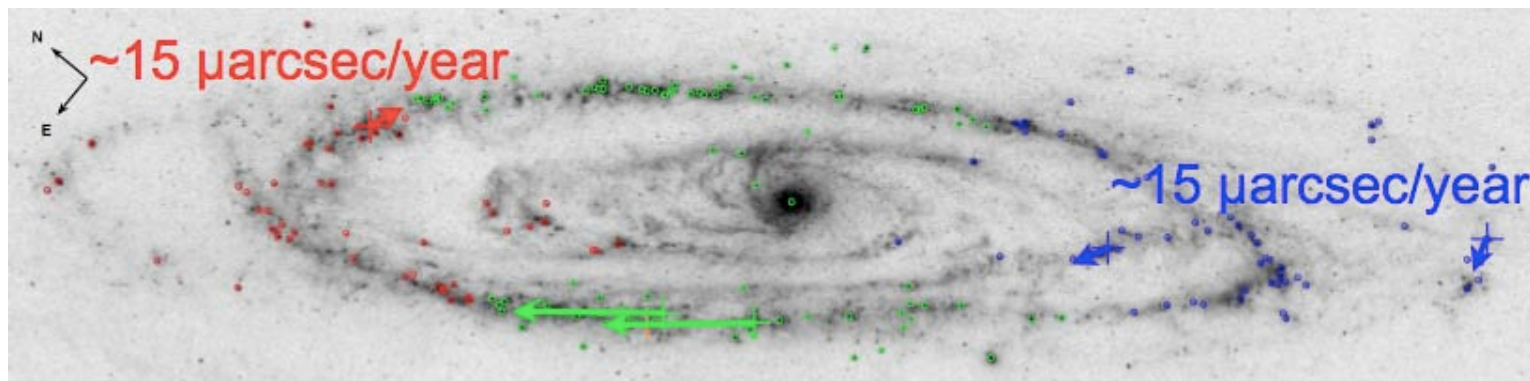
# GBT Detection of H<sub>2</sub>O Masers in M31

*J. Darling (2011)*



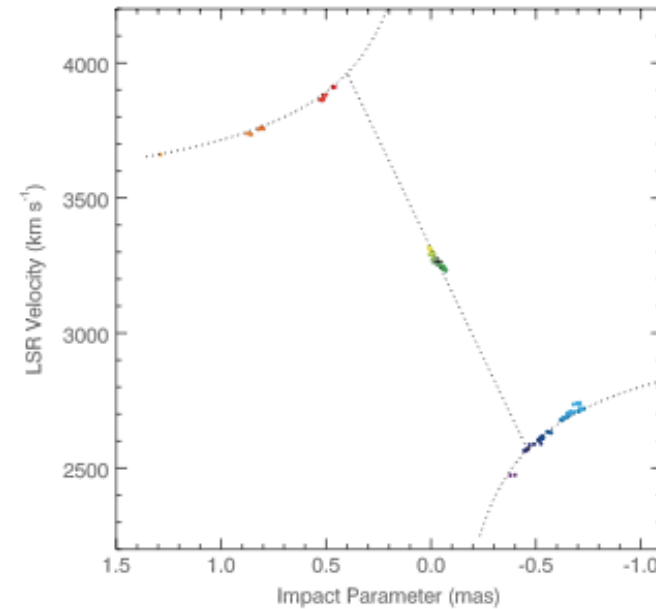
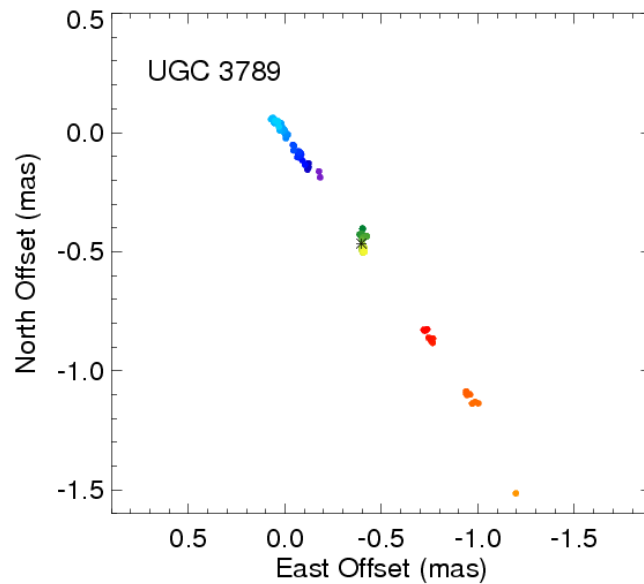
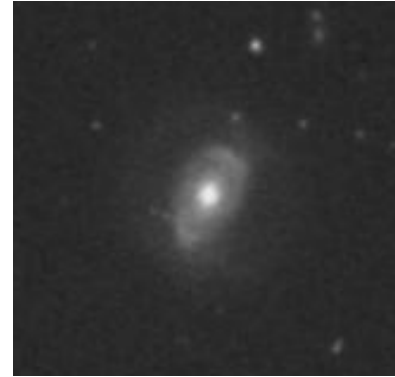
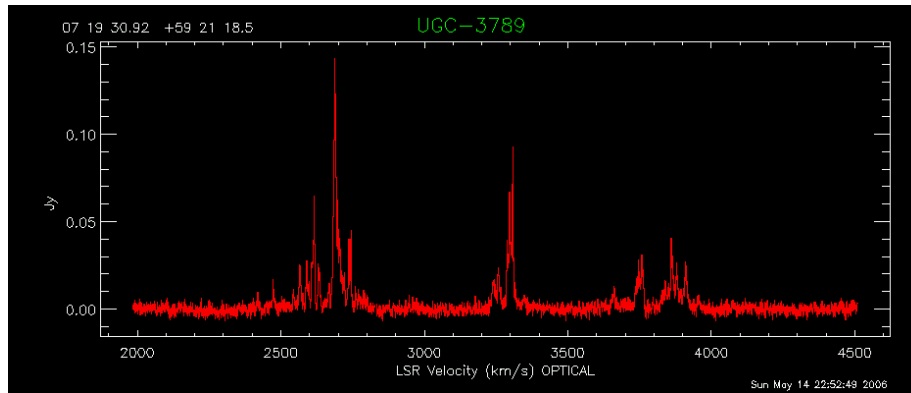
Expect  $6\sigma$  detection of proper motion in  $\sim 3$  years

*arrows not to scale*



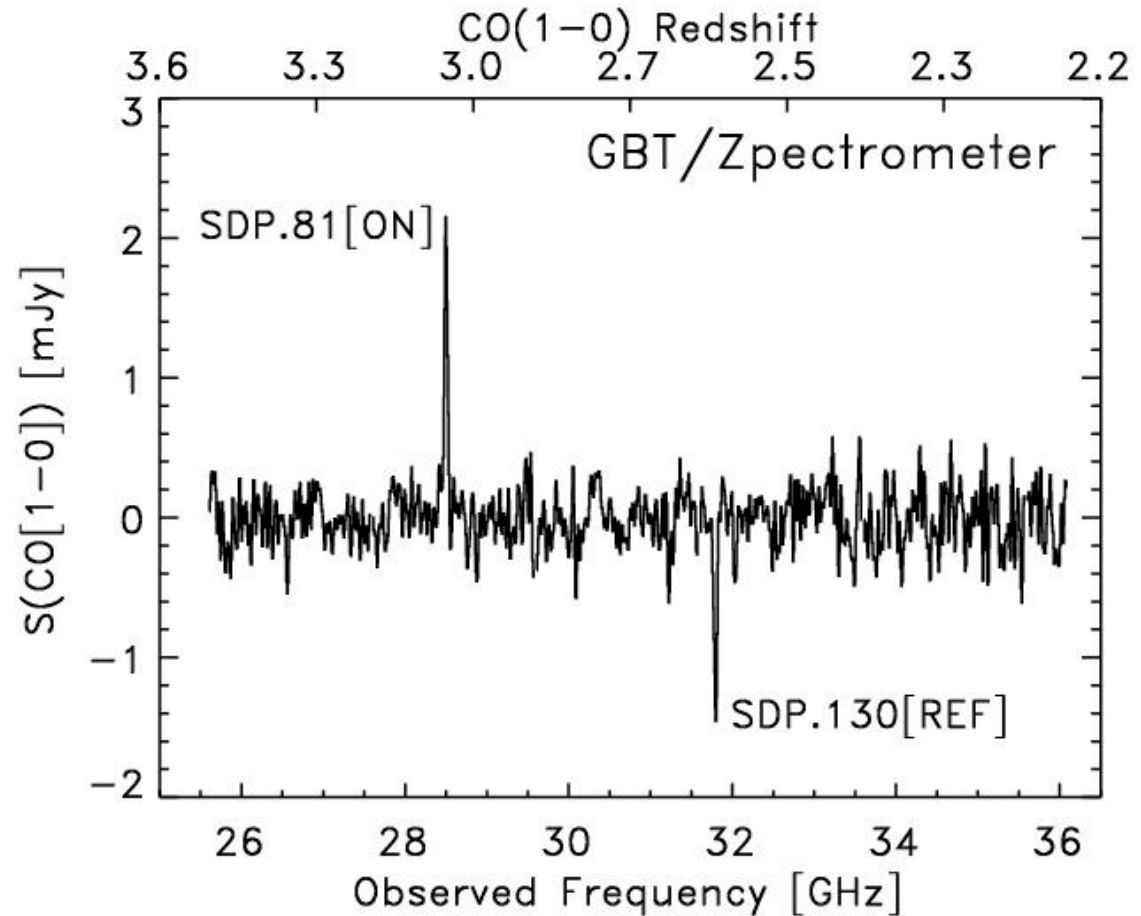
Proper rotation gives a geometric distance -- expect 10% uncertainty initially

# Megamasers provide gold standard $M_{\text{bh}}$ and geometric measurement of $H_0$



# Studying star formation in the early universe via high-redshift CO

Frayer et al. 2011:  
Molecular gas  
measurements and  
redshifts of ultra-  
luminous infrared  
galaxies discovered  
by Herschel with the  
GBT/Zpectrometer.



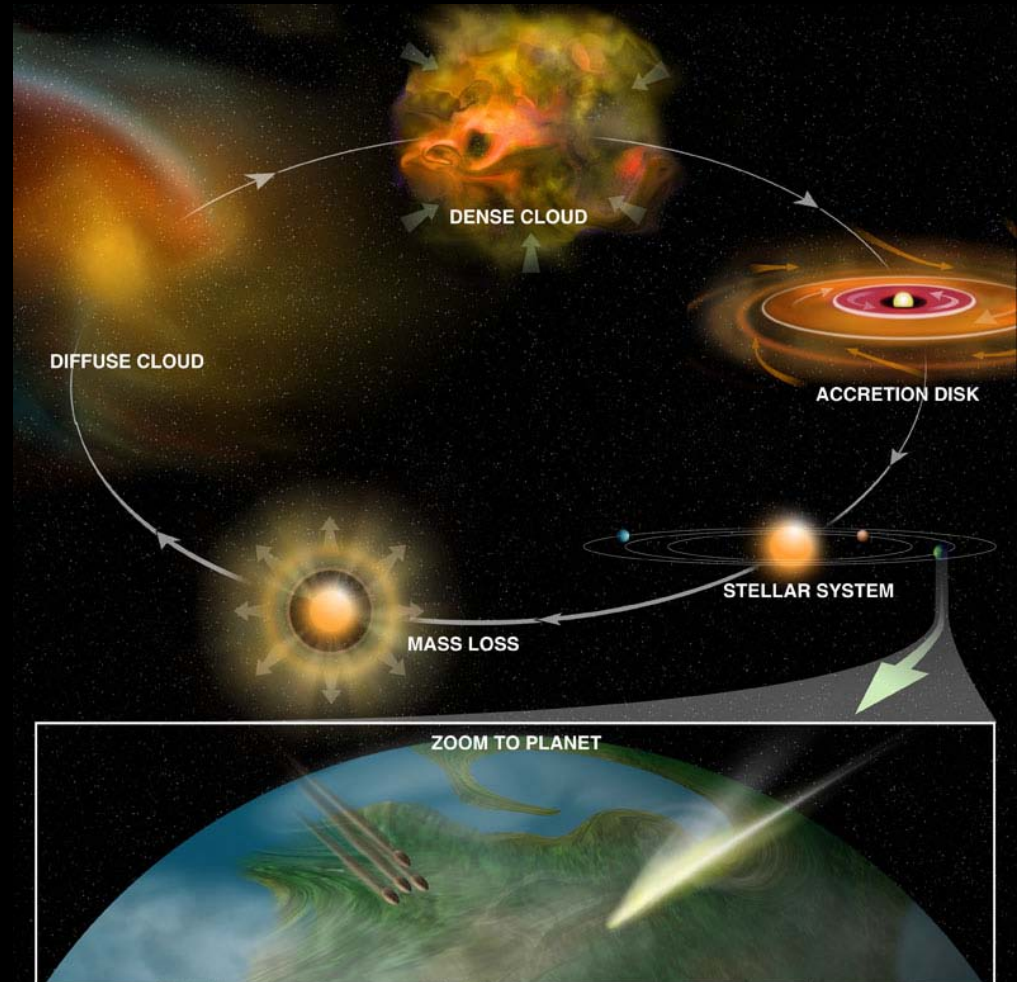


# A telescope for interstellar chemistry

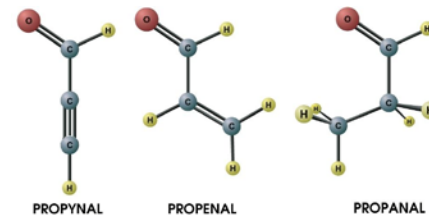
Connecting the chemistry of interstellar space with the chemistry of the solar system and the origin of life on earth.

“Like no other science, astrophysics cross-pollinates the expertise of chemists, biologists, geologists and physicists, all to discover the past, present, and future of the cosmos - and our humble place within it.”

- N. deGrasse Tyson



# Organic chemistry in interstellar clouds



H<sub>2</sub>O (water)  
H<sub>2</sub>CO (formaldehyde)  
NH<sub>3</sub> (ammonia)  
CO (Carbon monoxide)  
HCOOH (formic acid)  
CNCHO (cyanoformaldehyde)  
CH<sub>3</sub>OH (methanol)  
CH<sub>2</sub>CHCN (vinyl cyanide)  
HOCH<sub>2</sub>CH<sub>2</sub>OH (ethylene glycol)  
CH<sub>3</sub>CO<sub>2</sub>H (acetic acid)  
CH<sub>3</sub>CH<sub>2</sub>OH (ethyl alcohol)  
CH<sub>2</sub>OHCHO (glycolaldehyde)

The GBT has detected 14 new interstellar organic molecules including the first interstellar anions: C<sub>6</sub>H<sup>-</sup> & C<sub>8</sub>H<sup>-</sup> (McCarthy et al 2006; Cordiner et al 2011)

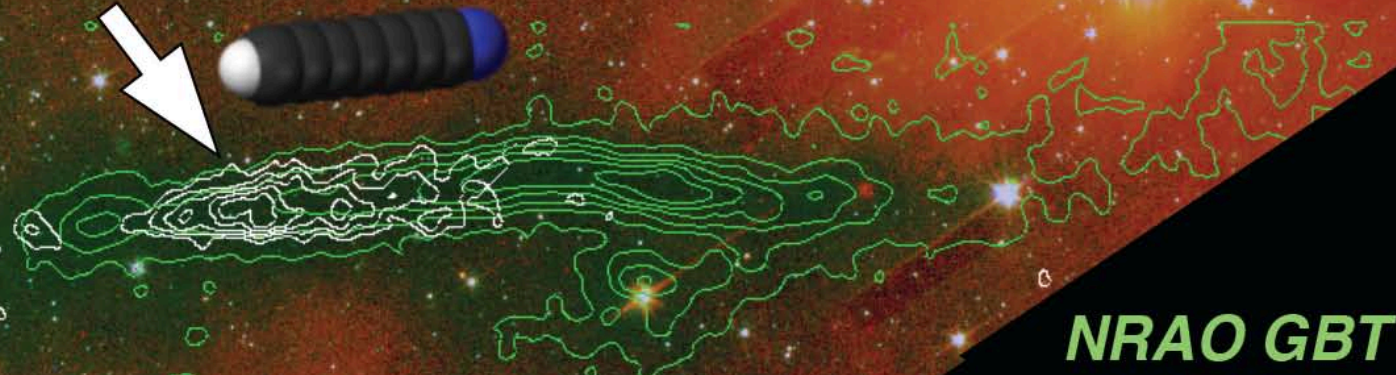


# Mapping of Star-Formation Regions with the K-FPA

## Taurus Molecular Cloud

Nearby site of formation of large molecules in our Galaxy

Cyanotriacetylene ( $\text{HC}_7\text{N}$ )



Ammonia ( $\text{NH}_3$ )

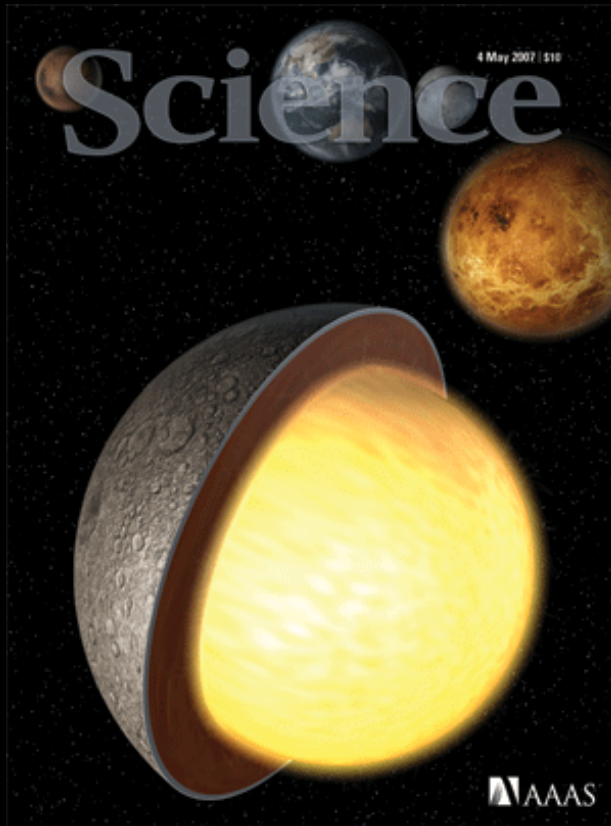
NRAO GBT  
18-27.5 GHz  
Focal Plane Array

Moon image included for scale comparison, showing the large size of molecular clouds.

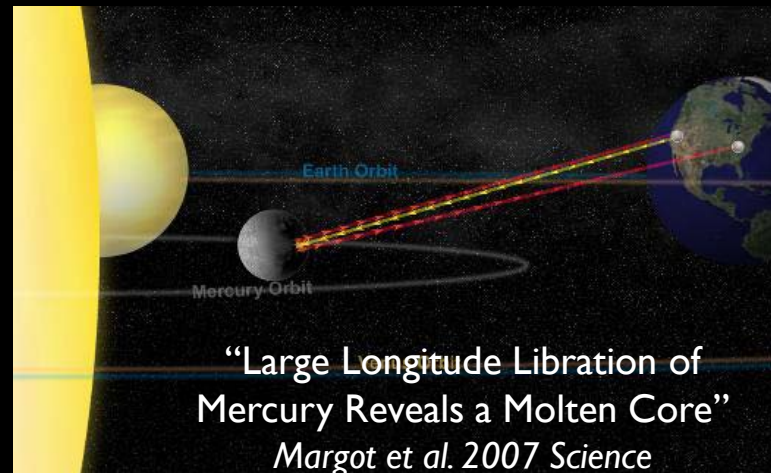
Contours show molecular chemistry dynamics in cold, dark, star forming clouds. White contours mark molecule  $\text{HC}_7\text{N}$ . Green contours mark ammonia distribution. Background image is a color composite of Spitzer Space Telescope IRAC channels 1, 2 and 4 (Langston et al. 2011).

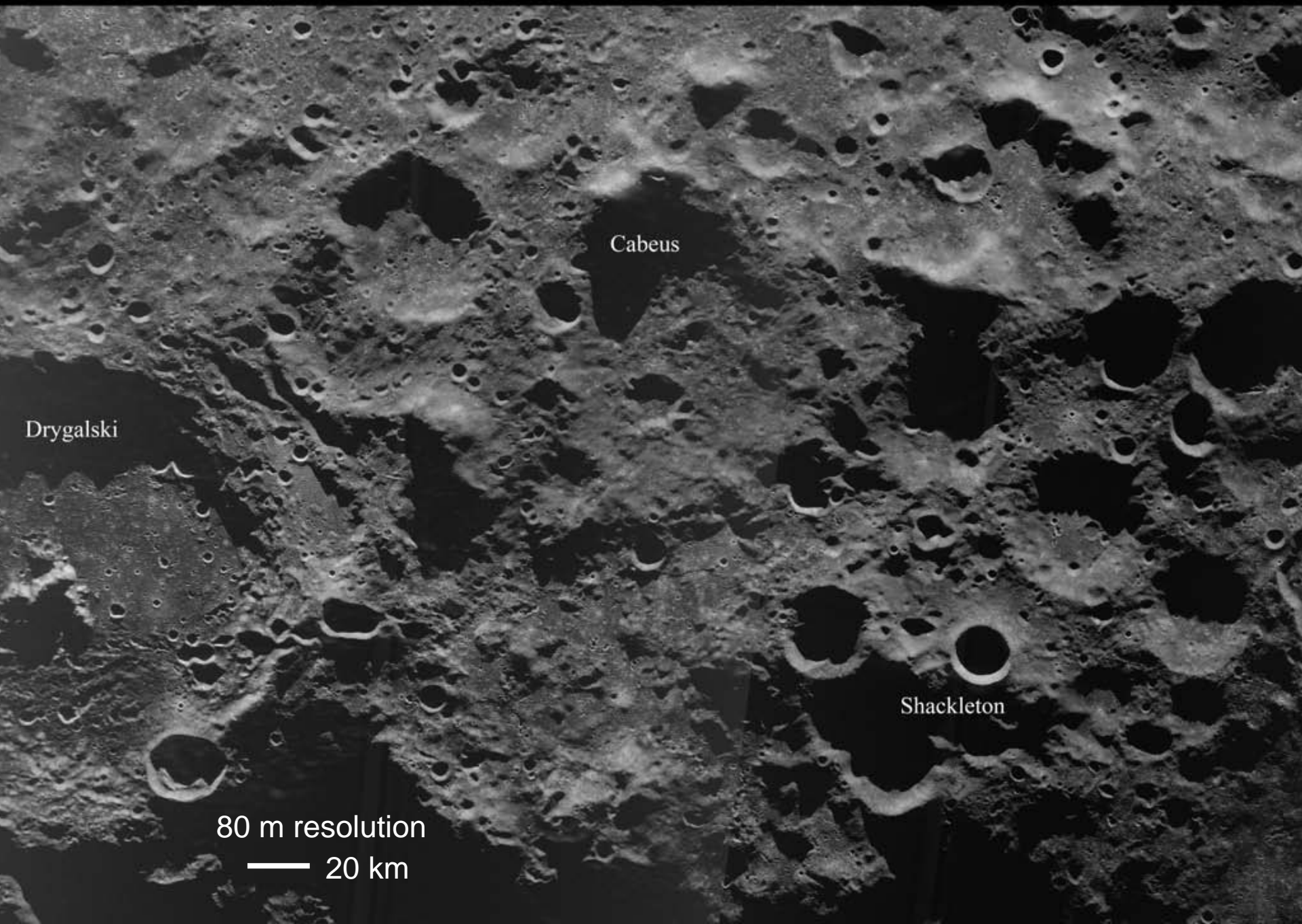


# Radar observing to study the solar system



“No Evidence for Thick Deposits of Ice at the Lunar south Pole”  
*Campbell et al 2006 Nature*





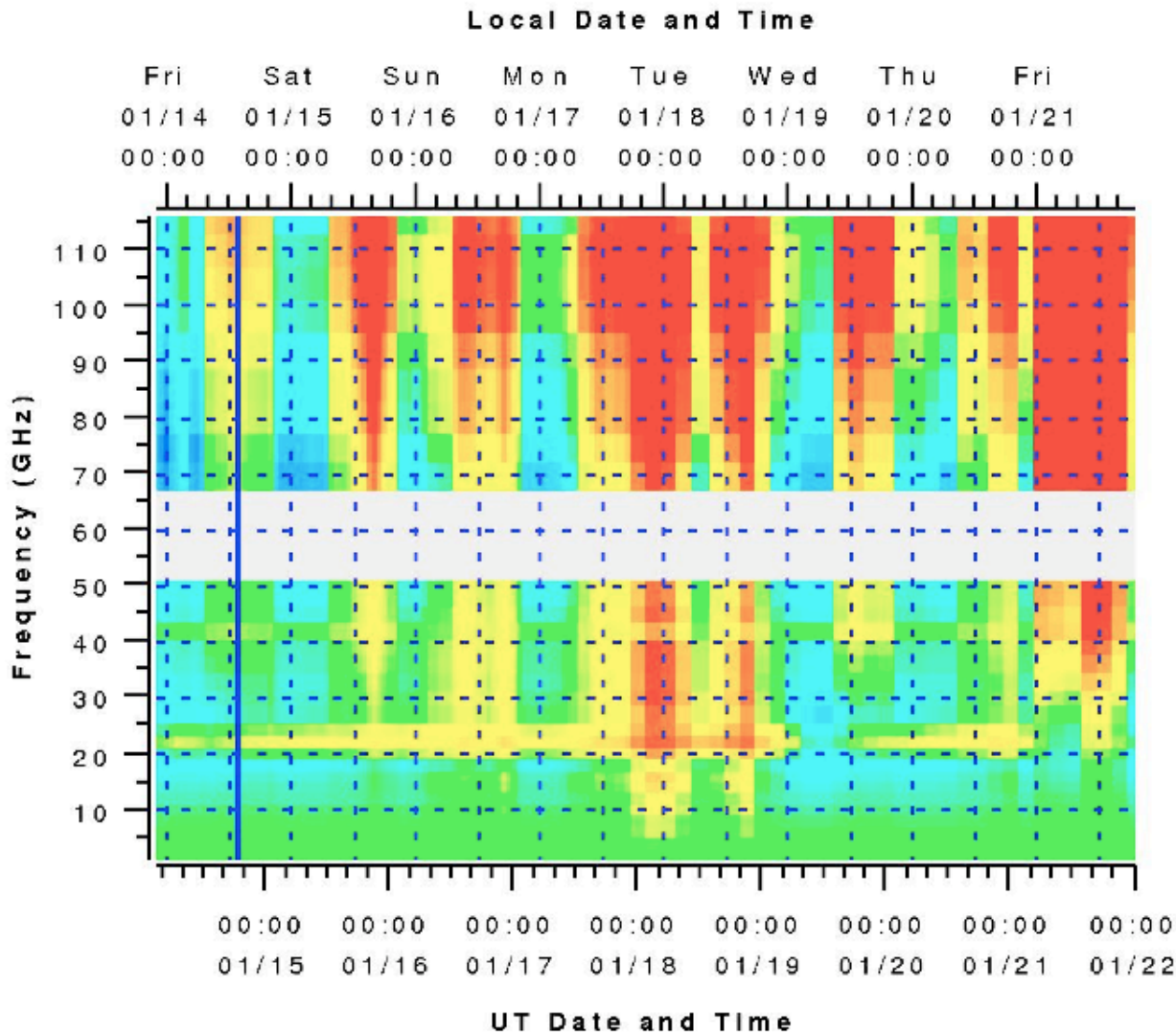
Cabeus

Drygalski

Shackleton

80 m resolution

— 20 km



6500 hours a year scheduled for astronomy

Dynamic Scheduling matches the project to the weather

In 2010 there were 1776 hours used at frequencies above 18 GHz



# Current Instruments – Front Ends

Receiver	Band	Frequency Range (GHz)	Focus	Polarization	Beams
PF1	342 MHz	.290-.395	Prime	Lin/Circ	1
	450 MHz	.385-.520	Prime	Lin/Circ	1
	600 MHz	.510-.690	Prime	Lin/Circ	1
	800 MHz	.680-.920	Prime	Lin/Circ	1
PF2	----	.910-1.23	Prime	Lin/Circ	1
L-Band	----	1.15-1.73	Greg.	Lin/Circ	1
	S-Band	----	1.73-2.60	Greg.	Lin/Circ
C-Band	----	3.95-6.1	Greg.	Lin/Circ	1
	X-Band	----	8.00-10.0	Greg.	Circ
Ku-Band	----	12.0-15.4	Greg.	Circ	1
	K-Band	lower	18.0-22.4	Greg.	Circ
		upper	22.0-26.5	Greg.	Circ
Ka-Band	MM-F1	26.0-31.0	Greg.	Circ	2
	MM-F2	30.5-37.0			
	MM-F3	36.0-39.5			
Q-Band	----	38.2-49.8	Greg.	Circ	2
Mustang	----	80-100	Greg.	---	64

Example lines:

HI, OH

NH<sub>3</sub>,  
HC<sub>5</sub>N,  
C<sub>2</sub>S, H<sub>2</sub>O

HCN, HNC,  
HCO<sup>+</sup>, HDO,  
DCN, SiO,  
SO<sub>2</sub>, H<sub>2</sub>CO,  
N<sub>2</sub>H<sup>+</sup>, N<sub>2</sub>D<sup>+</sup>,  
CH<sub>3</sub>CN, C<sub>2</sub>H

KFPA

2 7

{W-band (4mm Rx) 67-93.2 Greg. Lin/Circ 2}



# Current Instruments – Front Ends-2

Receiver	FWHM	Gain (K/Jy)	Aperture Efficiency	SEFD (JY)	$T_{rec}$ (K)	$T_{sys}$ (K)
PF1	36'	2.0	70%	23	12	$46 + T_{bg}$
	27'	2.0	70%	22	22	$43 + T_{bg}$
	21'	2.0	70%	11	12	$22 + T_{bg}$
	15'	2.0	70%	15	21	$29 + T_{bg}$
PF2	12'	2.0	70%	9	10	$17 + T_{bg}$
L-Band	9'	2.0	70%	10	6	$20 + T_{bg}$
S-Band	5.8'	1.9	70%	11	6-10	$20 + T_{bg}$
C-Band	2.5'	1.85	70%	8	5	$18 + T_{bg}$
X-Band	1.4'	1.8	70%	15	13	$27 + T_{sky}$
Ku-Band	54''	1.7	70%	18	14	$30 + T_{sky}$
K-Band	37''	1.5	<del>67%</del> 68%	23	21	$30 - 40 + T_{sky}$
	30''	1.5	<del>65%</del> 67%	24	21	$30 - 40 + T_{sky}$
Ka-Band	26.8''	1.5	<del>56-64%</del> 65%	27	20	$45 + T_{sky}$
	22.6''			20		$35 + T_{sky}$
	19.5''			43		$70 + T_{sky}$
Q-Band	16''	1.0	<del>47-56%</del> 60%	67-134	40-70	$67 - 134 + T_{sky}$
Mustang	10''	—	<del>20%</del> 35%	—	—	—

# Backends/Spectrometers

- Spectrometer with bandwidths: 800, 200, 50, 12.5 MHz. Maximum resolution is 49 Hz with 12.5MHz bandwidth. Minimum integration times 1-2 sec.
- Spectral Processor (FFT spectrometer) for high-time resolution data (useful at low freq where RFI is an issue).
- Continuum with DCR (digital continuum receiver) for most bands, CCB used for continuum at Ka, and Mustang for continuum at 90GHz.
- GUPPI used for Pulsar Observations
- VEGAS (VErsatile GBT Astronomical Spectrometer) is the new replacement for the Spectrometer available in 2012 (FPGA based).



Bandwidth (MHz)	Number of Spectral Windows	Number of Beams	Channels - Approximate Resolution (kHz)	Minimum Integration Time (sec)	Notes
1500	1 or 2	1	1024 – 1464.844	0.5	1st priority mode
1500	1	2	1024 – 1464.844	0.5	1st priority mode
1000	1 or 2	1	2048 – 488.281	0.7	
1000	1	2	2048 – 488.281	0.7	
800	1 or 2	1	4096 – 195.313	1.3	
800	1	2	4096 – 195.313	1.3	
500	1 or 2	1	8192 – 61.035	2.5	
500	1	2	8192 – 61.035	2.5	
400	1 or 2	1	16384 – 24.414	5.0	
400	1	2	16384 – 24.414	5.0	

Table 7: VEGAS Large Bandwidth, Few Spectral Window Modes.

Bandwidth (MHz)	Number of Spectral Windows	Number of Beams	Channels - Approximate Resolution (kHz)	Minimum Integration Time (sec)	Notes
250	1 or 2	1	32768 – 7.629	10	
250	1	2	32768 – 7.629	10	
100	1 or 2	1	32768 – 3.052	10	
100	1	2	32768 – 3.052	10	
50	1 or 2	1	32768 – 1.526	10	
50	1	2	32768 – 1.526	10	
25	1 or 2	1	32768 – 0.763	10	
25	1	2	32768 – 0.763	10	
10	1 or 2	1	32768 – 0.305	10	3rd priority mode
10	1	2	32768 – 0.305	10	3rd priority mode
5	1 or 2	1	32768 – 0.153	10	
5	1	2	32768 – 0.153	10	
1	1 or 2	1	32768 – 0.031	10	4th priority mode
1	1	2	32768 – 0.031	10	4th priority mode

Table 8: VEGAS Small Bandwidth, Few Spectral Window Modes.

Bandwidth (MHz)	Number of Spectral Windows	Number of Beams	Channels - Approximate Resolution (kHz)	Minimum Integration Time (sec)	Notes
30	8 or 16	1	4096 – 7.324	10	
30	8	2	4096 – 7.324	10	
15	8 or 16	1	4096 – 3.662	10	2nd priority mode
15	8	2	4096 – 3.662	10	2nd priority mode
10	8 or 16	1	4096 – 2.441	10	
10	8	2	4096 – 2.441	10	
5	8 or 16	1	4096 – 1.221	10	
5	8	2	4096 – 1.221	10	
1	8 or 16	1	4096 – 0.244	10	
1	8	2	4096 – 0.244	10	

Table 9: VEGAS Small Bandwidth, Many Spectral Window Modes.

**VEGAS:**  
**Supports 8 beams, dual polarization (e.g., K-FPA). Up to 16 windows (one beam), 8 windows (two beams). Maximum continuous bandwidth of 10 GHz, eventually.**



# GBT Sensitivity Calculator for proposal estimates, also good for verifying available modes.

File Edit View History Bookmarks Tools Help

← → ↻ × 🏠 nrao.edu https://dss.gb.nrao.edu/calculator-ui/war/Calculator\_ui.html

Most Visited Red Hat, Inc. Red Hat Network Support Shop Products Training

Sensitivity Calculator

Help Desk | Users Guide

### Sensitivity Calculator

#### General Information

Derive:  Observing Time from Desired Sensitivity  
 Sensitivity from Observing Time

Sensitivity Units:  Flux Density (mJy)  
 Antenna Temp., Ta (mK)  
 Radiation Temp., Tr (mK)

Desired Sensitivity:

---

#### Hardware Information

Answer questions from top to bottom. If you change a question that was answered previously, check all answers that follow. Some answers will dictate the answer for other questions.

Backend:

Mode:

Receiver:

Beams:

Polarization:

BandWidth (MHz):

Number of Spectral Windows:

Switching Mode:

---

#### Source Information

Frequency Specified in the:  Topocentric Frame  
 Rest Frame

Rest Frequency (MHz):

Doppler Correction:

Source Velocity (km/s):

Source Diameter (arc minutes):

---

#### Source Contribution Corrections

Source Contribution to System Temperature:  No Correction  
 User Estimated Correction  
 Internal Galactic Model

#### Controls

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#### Results

Results  Result Grids

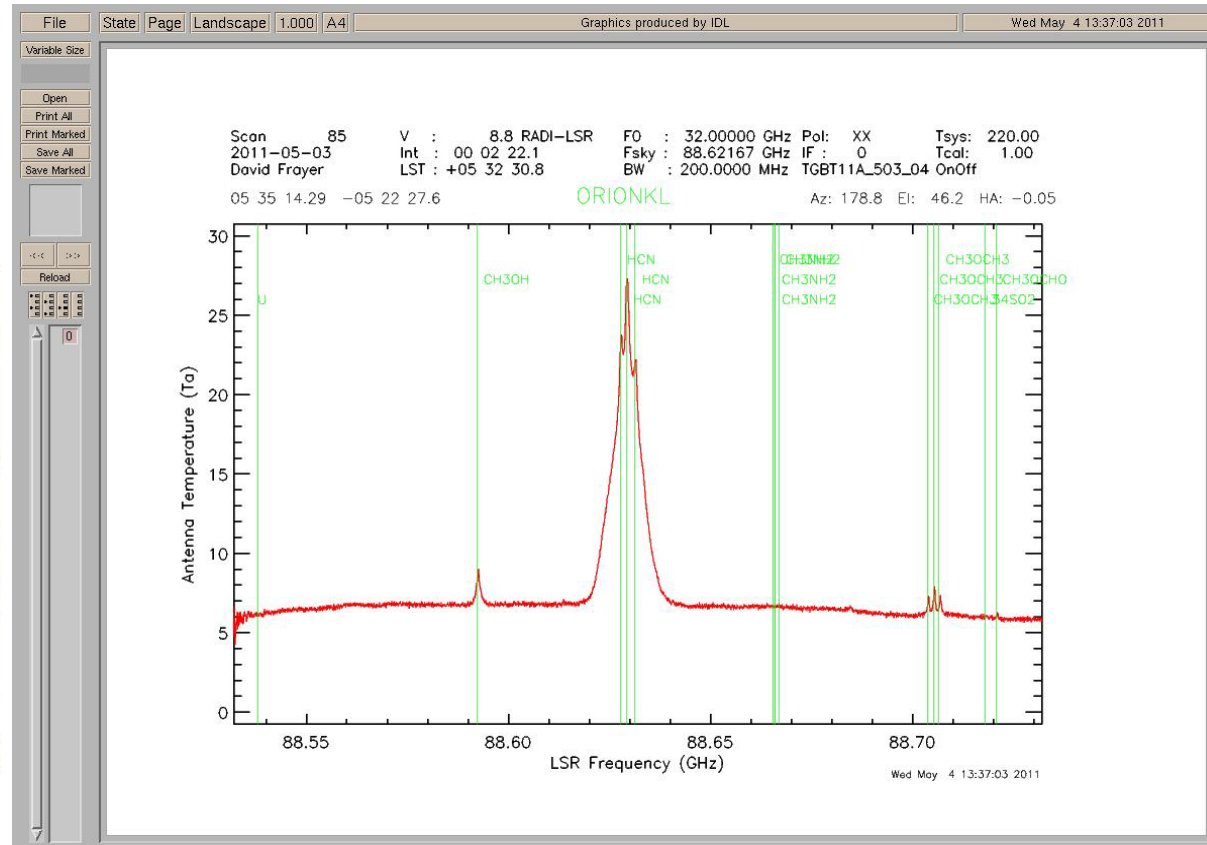
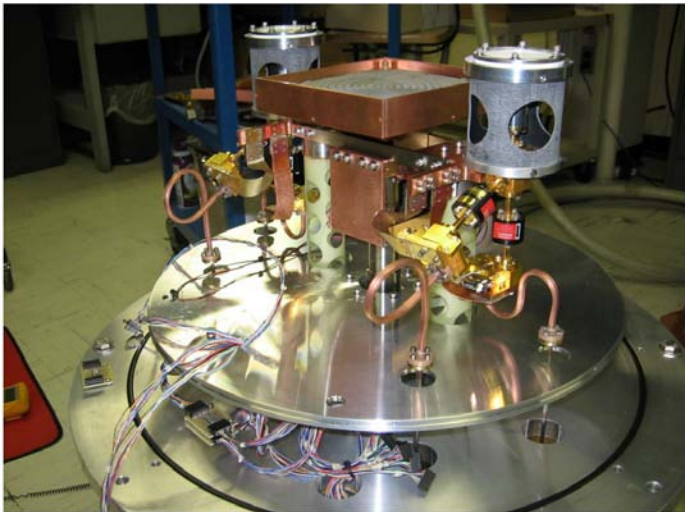
Results	
Derived Total Observing Time:	00:39:46.2 HH:MM:SS.S
Time at Signal Position or Frequency:	00:19:53.1 s
Time at Reference Position or Frequency:	00:19:53.1 s
Effective Integration Time:	00:09:56.6 s
Obs. Mode Time Mult. Factor:	2
<hr/>	
FWHM Beamwidth:	0.2'
Aperture Efficiency:	0.41
Extended Source Efficiency:	0.41
Confusion Limit:	0.00 S (mJy)
# Hrs Above Min Elevation:	6.13 hours
<hr/>	
Topocentric Frequency:	80000.000 MHz
Min. Topocentric Channel Width:	6.104 kHz
Desired Freq. or Vel. Resolution:	1.000000
<hr/>	
Typical Air Mass:	1.5
Typical Atmospheric Attenuation:	1.292
Typical System Temperature:	134.2 K
<hr/>	
Backend Sampling Efficiency (K1):	1.2350
Backend Channel Weighting (K2):	1.2100
<hr/>	
Other Results	
Typical Atmospheric Opacity:	0.170 Nepers
observing_method:	1
eta_dss:	0.50
eta_surf:	1.00
Maximum Elevation:	51.6 d
max_el_rad:	0.900
Typical Effective Tsys:	177.8 K
Receiver's Contribution to Tsys:	75.0 K
Source Diameter:	0.0'
Topocentric Wavelength:	0.37 cm
n_ref_smth_avg:	1.000
Typical Weighted Mean Temp. of Atmos.:	247.1 K
dual_pol:	2
Best Possible Effective Tsys:	125.7 K
c2:	0.351580
a:	141.121084 mK / (s <sup>2</sup> )
min_el_rad:	0.576

Done



# GBT's Newest receiver: The 4mm Receiver (67-93.3 GHz). First Light, May 2011: HCN in Orion-KL

Commissioning  
2011 Oct, Dec



See <http://www.gb.nrao.edu/4mm> for more details.



# GBT Instrumentation: Enabling a Wide-Range of Science.

- Next Proposal Deadline 2012 Feb 01. Accepting shared-risk proposals for new instruments (see call for details posted on Jan 6, 2012).
  - 67-93.2 GHz spectral line observations
  - 80-90 GHz GBT+VLBI observations
  - More flexible spectrometer capabilities with VEGAS
  - New Ku 12-18 GHz Receiver
  - Expanded C-band coverage for 6-8 GHz (uncertain)

# Outreach Opportunities:

- Educators:

- Ongoing teacher training workshops
- Science education material for elementary through college levels

- Students:

- Summer research programs, co-ops, internships
- Pulsar search collaboratory, Governor's school
- NSF-NRAO REU summer research program

- University research groups:

- Contact NRAO to collaborate on any of the planned/ongoing development programs



[www.gb.nrao.edu](http://www.gb.nrao.edu)



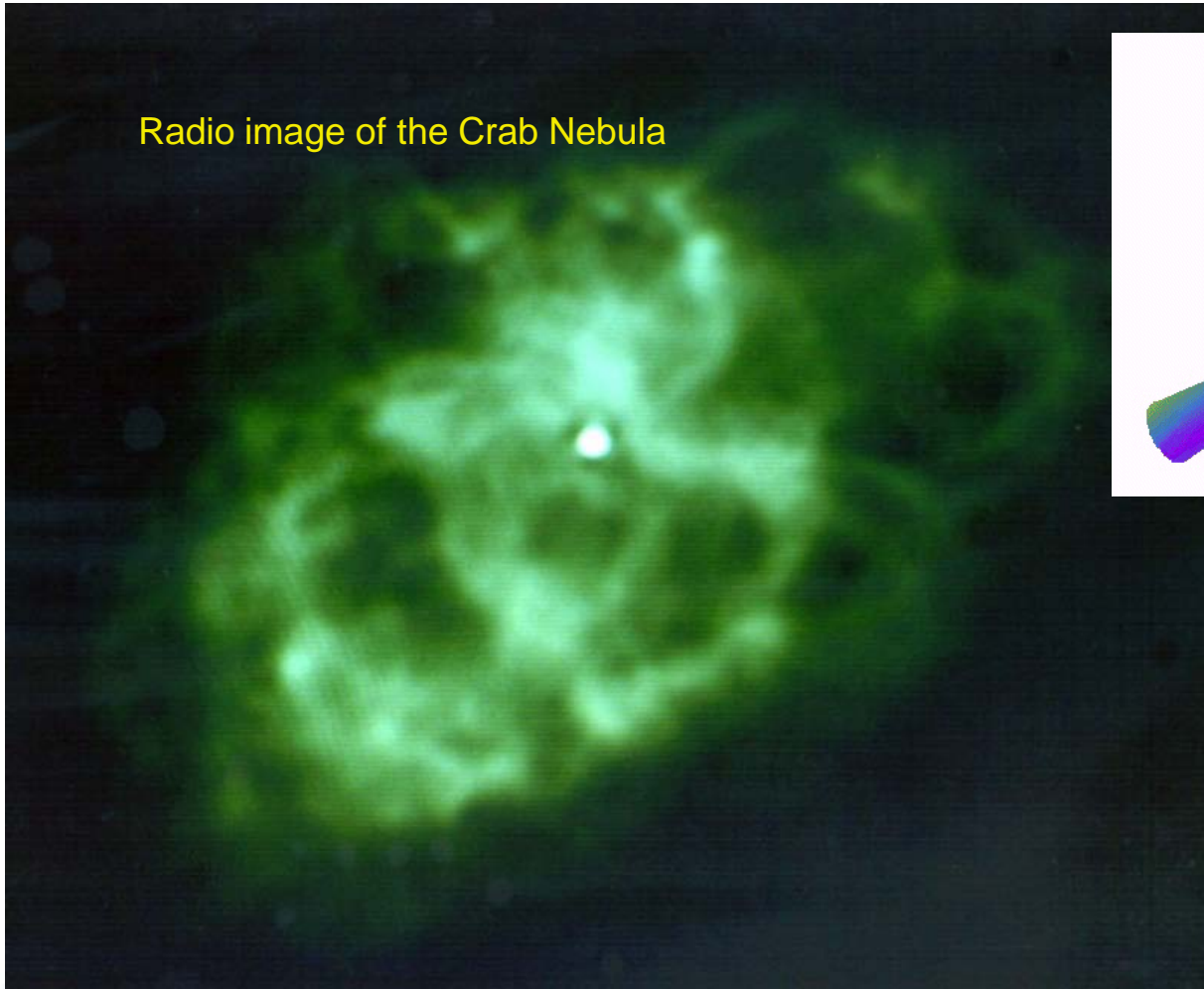
**The End**



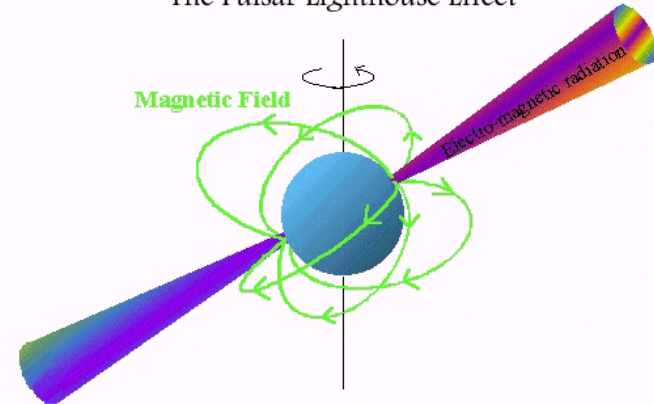


Pulsars: neutron stars that are remnants of massive stars that became supernovae

Radio image of the Crab Nebula

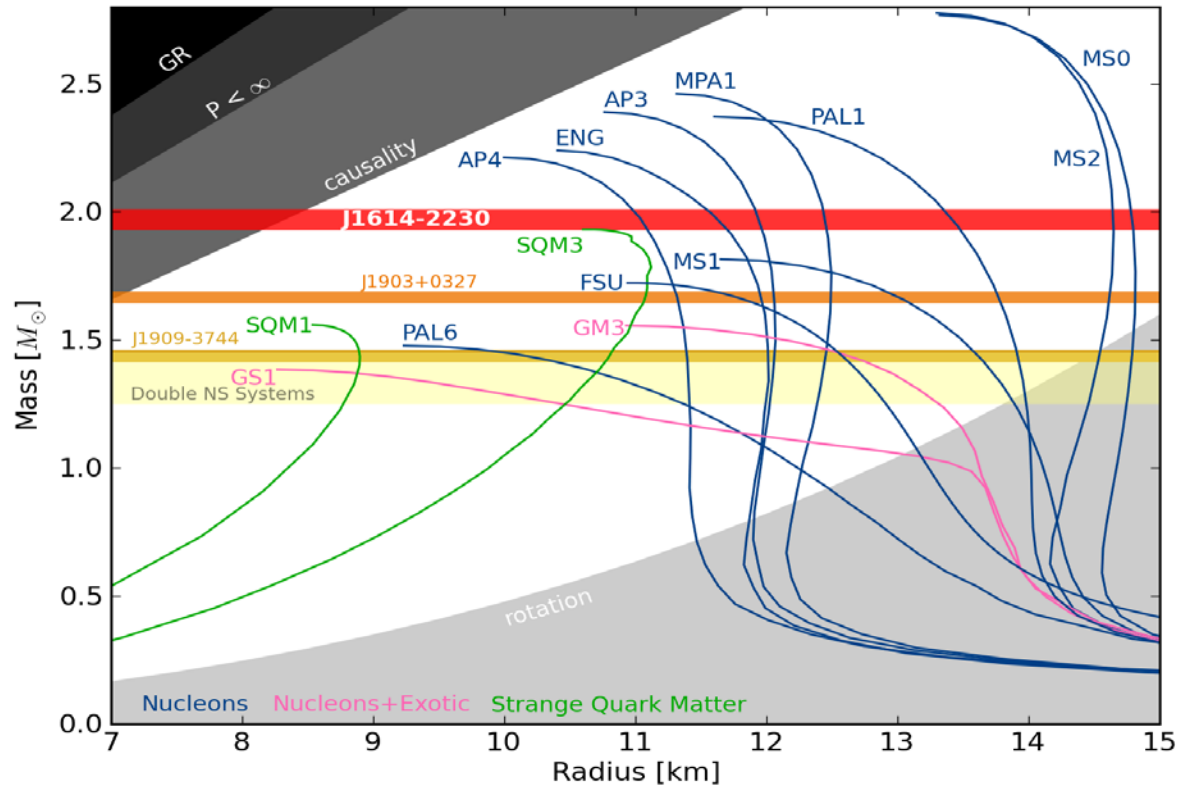


The Pulsar Lighthouse Effect



With a period  $\sim 10^{-3}$  s  
over one year  $3 \times 10^7$  s  
timing to a part in  $10^{11}$

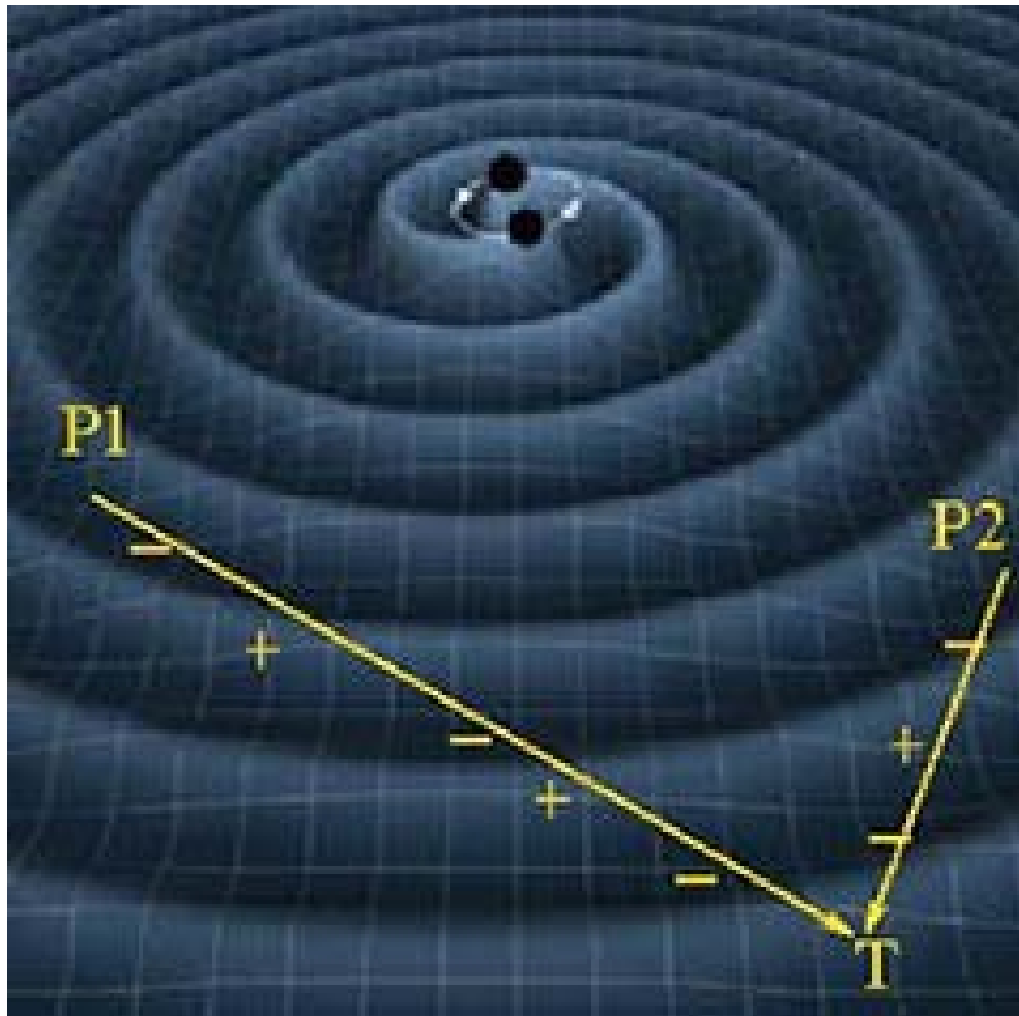
# The most massive known pulsar, J1614-2230



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)*

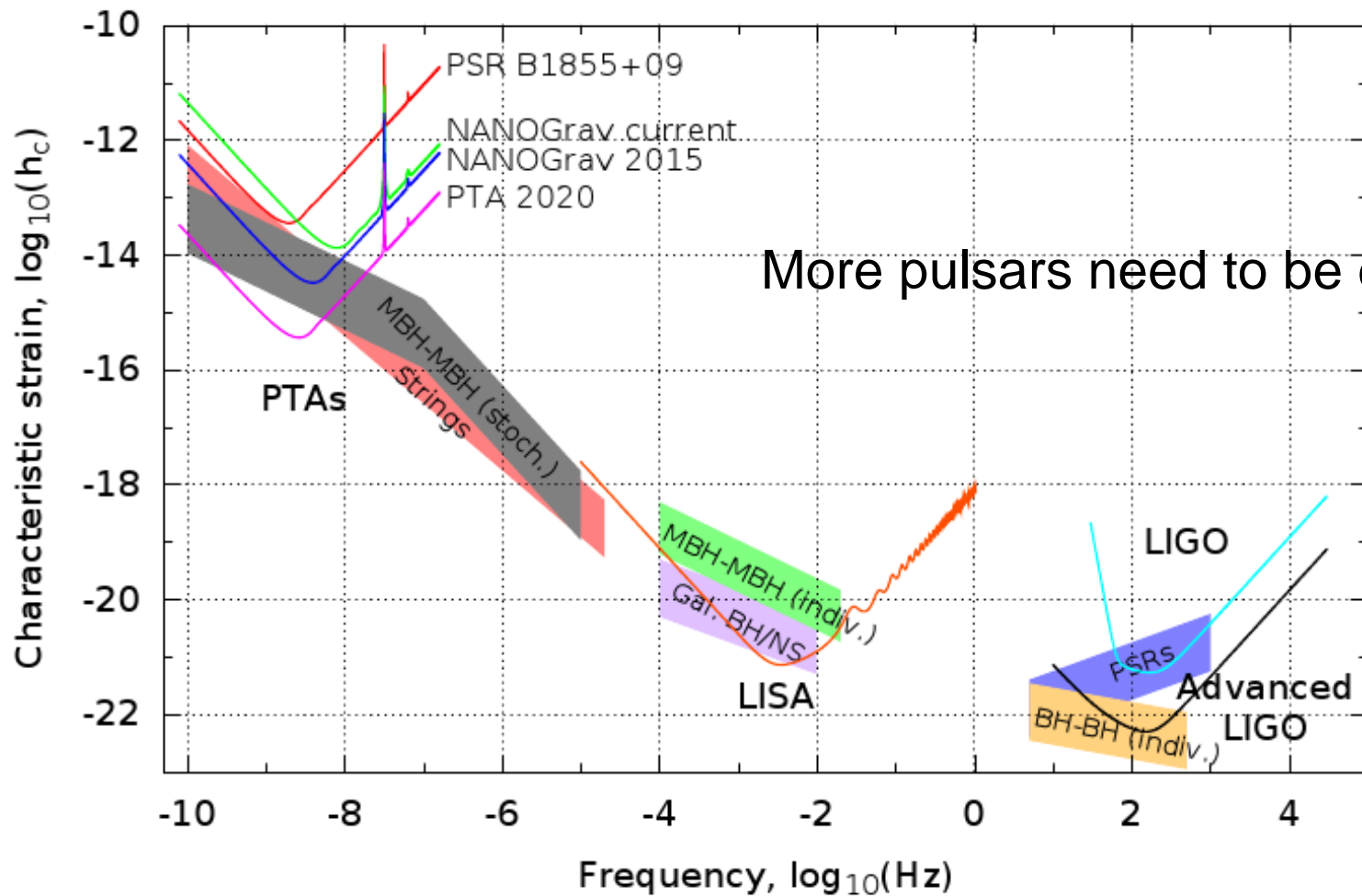
# Using pulsars to detect gravitational radiation





# The NANOGrav Collaboration

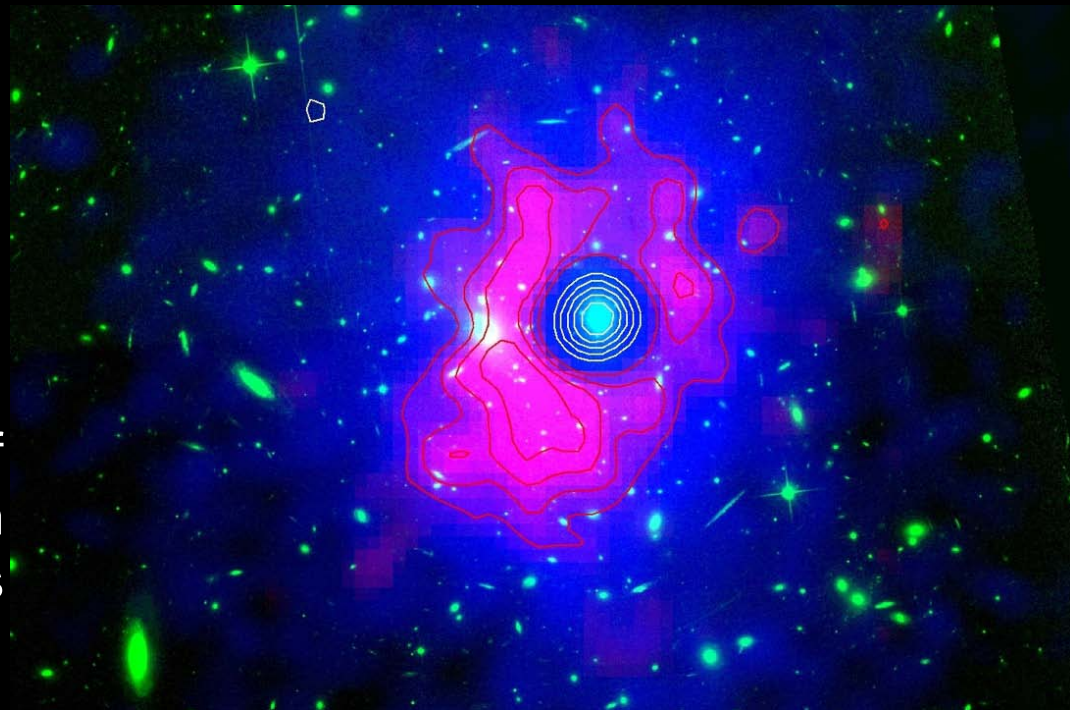
[nanograv.org](http://nanograv.org)



# Black Holes in the centers of galaxies and structure of galaxy clusters → constraints on Cosmology

Measurement of black hole masses in centers of galaxies and independent measurements of  $H_0$  (age and size scale of the universe) via H<sub>2</sub>O masers

Measurement clusters of galaxies via 3mm continuum observations



# More than just the GBT on site...

## Eight Large Telescopes:

- GBT: 100m telescope open to all observers
- 43m (140'): Bistatic radar experiments (MIT/Lincoln Labs)
- 45': Solar Radio Bursts monitoring (NSF ATM)
- 40': Education telescope, open to anyone (school/college groups)
- 20m: Being recommissioned as part of RadioSkyNet (education!)
- 85': **Three** telescopes currently not in use

## Additional Instruments:

- PAPER: Low frequency array (Berkeley/NRAO/UVa)
- Atmospheric monitoring array (FM signals)
- RFI monitoring station: monitor radio frequency interference
- Geomagnetic sensors (WVU)

