The Green Bank Observatory

National Radio Astronomy Observatory

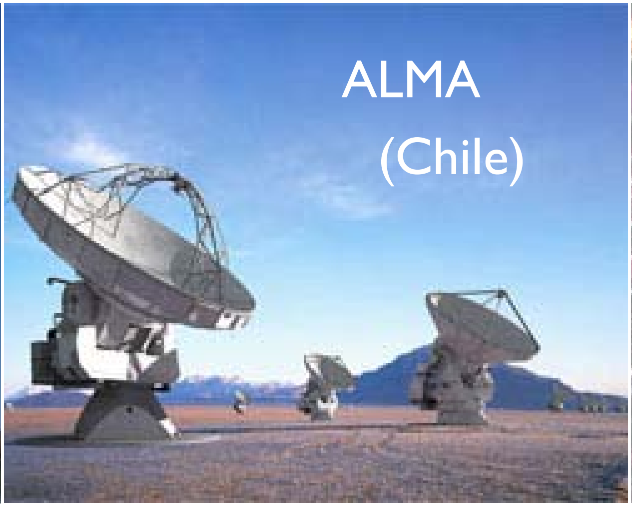
Anthony Remijan (NRAO)

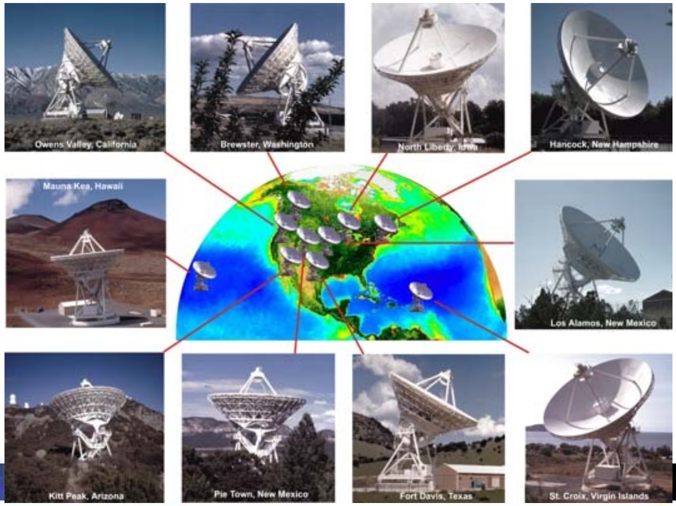
Slides from: Braatz, Frayer, O'Neil, Lockman, Hunter, Langston, and input from other NRAO staff.

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

NRAO

NRAO has complementary suite of telescopes and facilities



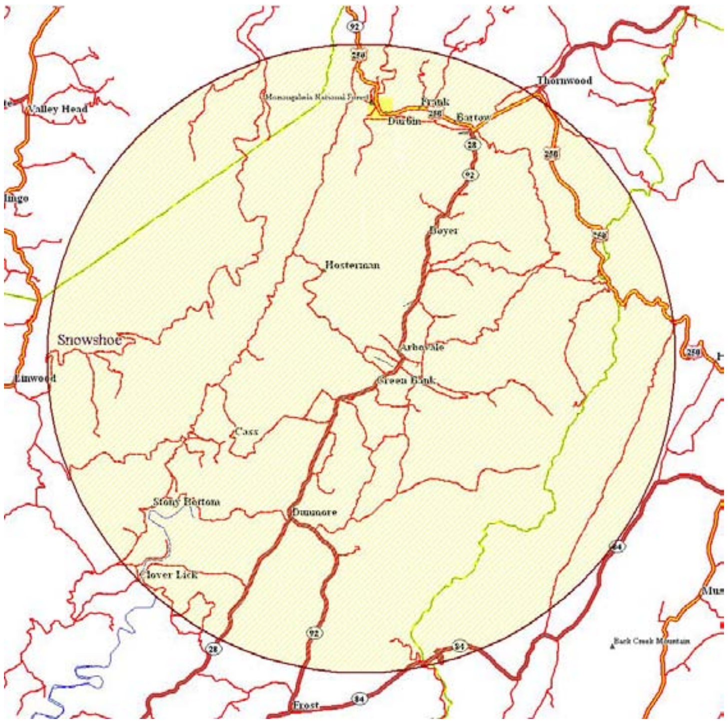


Very Long Baseline Array

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

WV Radio Astronomy Zone

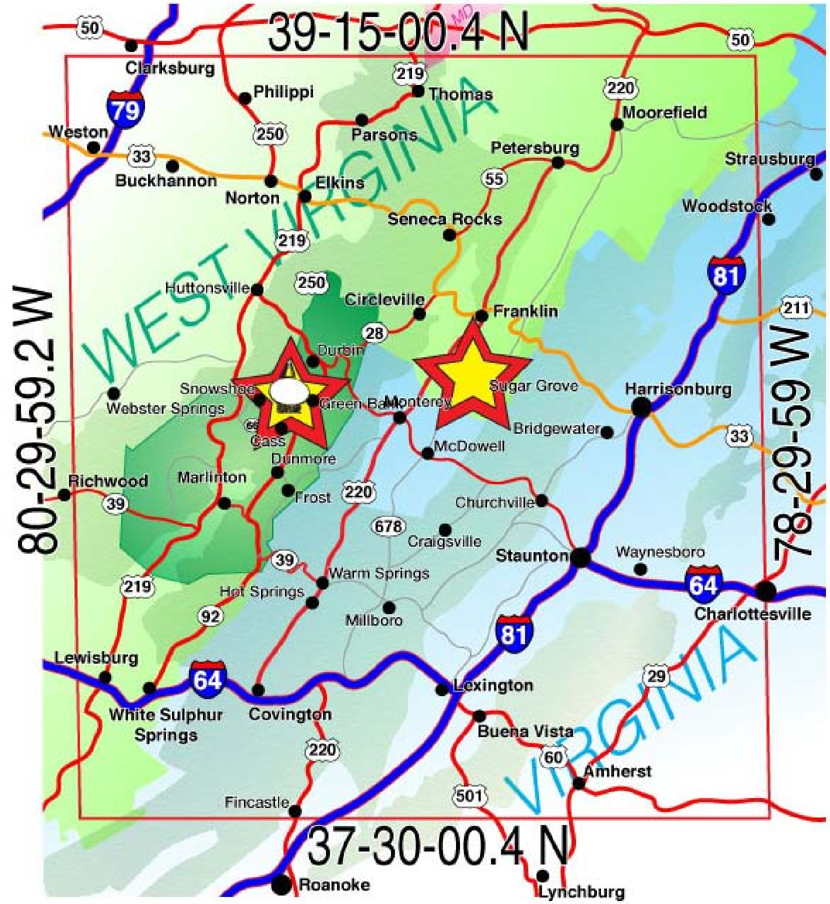
Established by the West Virginia Legislature (1956)



Protection within ten miles of the Observatory

National Radio Quiet Zone

Established by the FCC and NTIA (1957)



13,000 Square Miles

NRAO

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 $\delta \geq -46°$

Pointing to 1”-2” accuracy

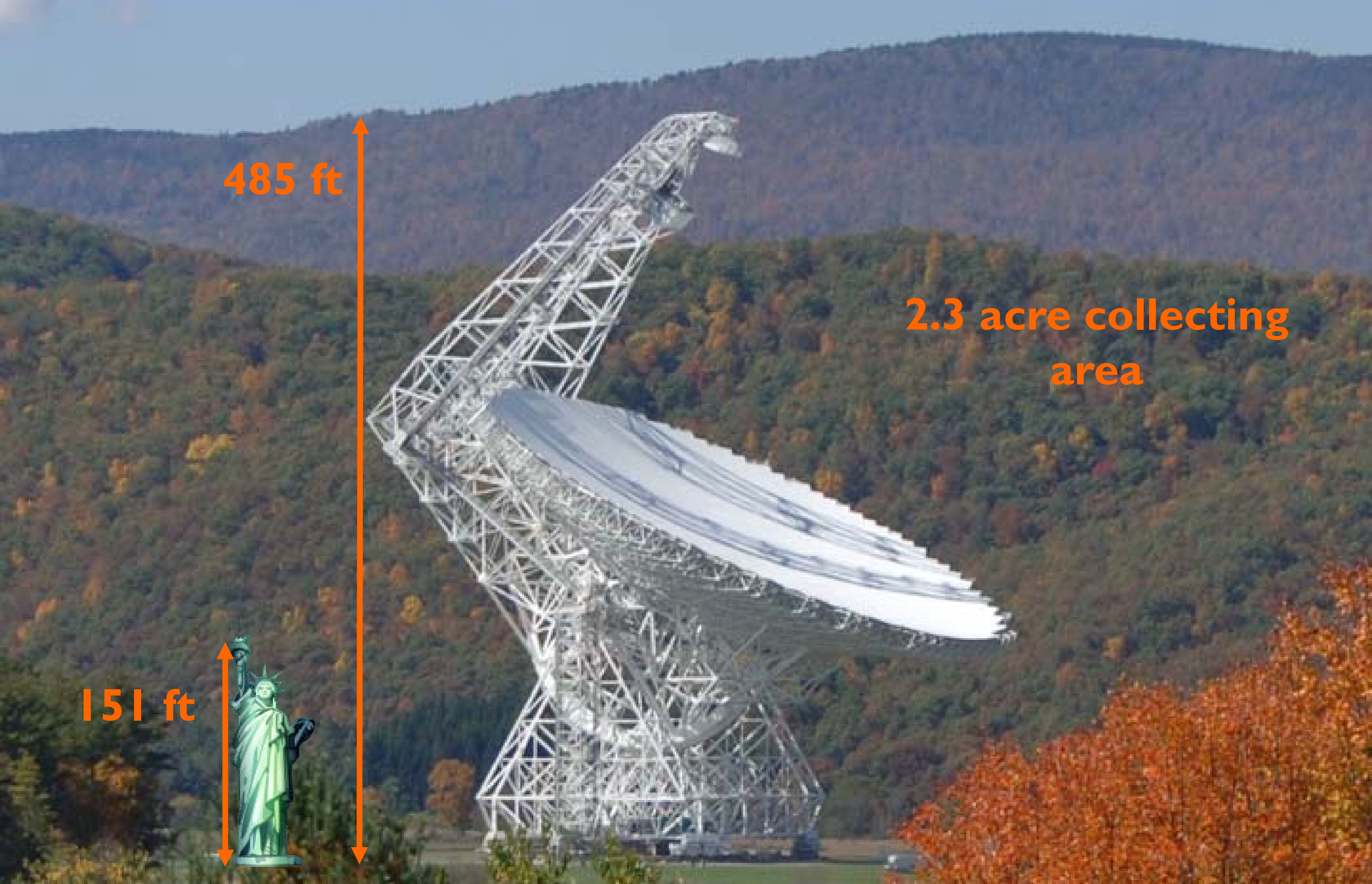
Surface good for 3mm work

Active Instrument Development Program

Site Protected by a 13000 km^2
Radio Quiet Zone

NRAO

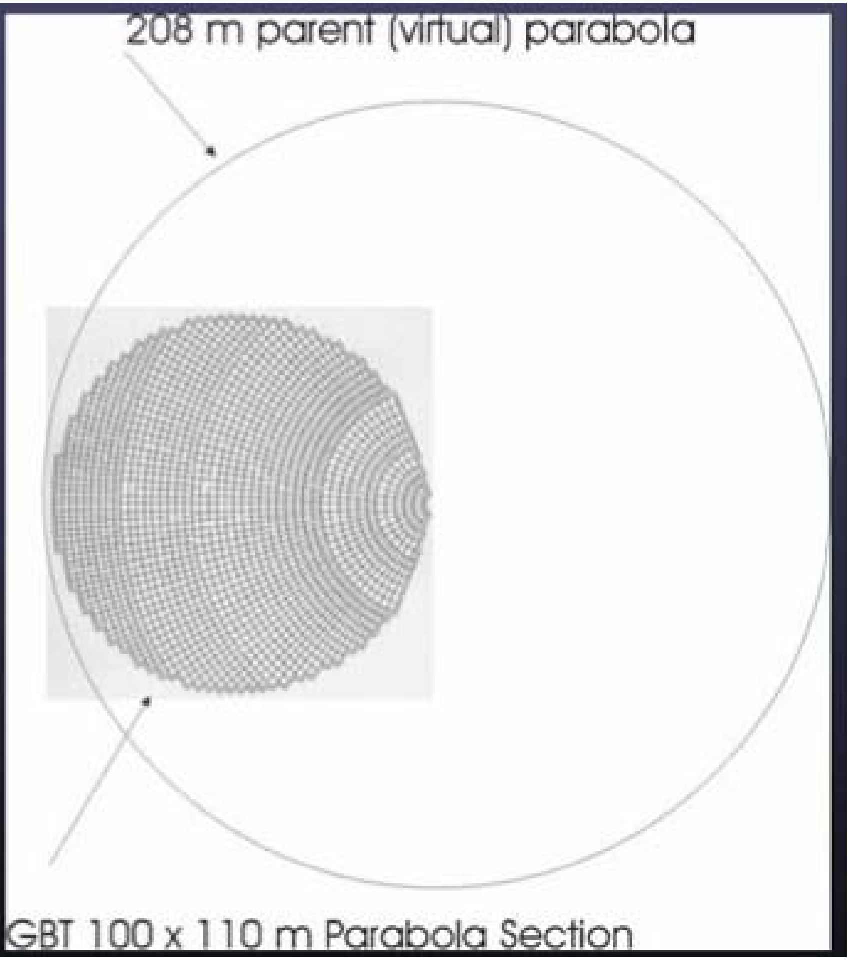
At 100 m, the GBT is the largest *fully steerable* telescope and the largest movable structure in the world.



Eight slots in Gregorian receiver turret

Many projects are run each day

The Offset Paraboloid

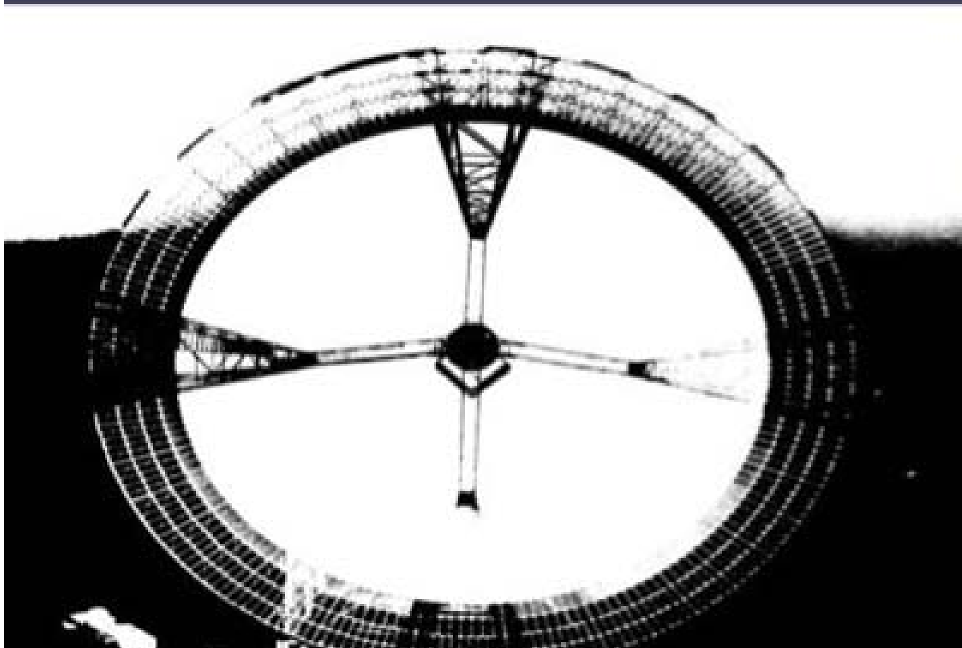


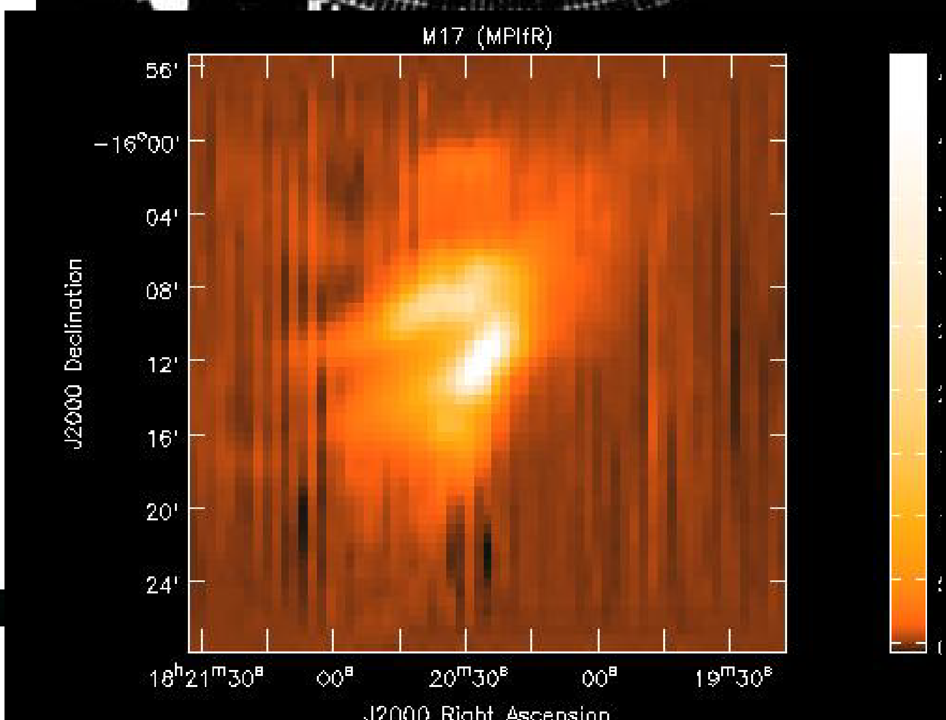
The Active Surface

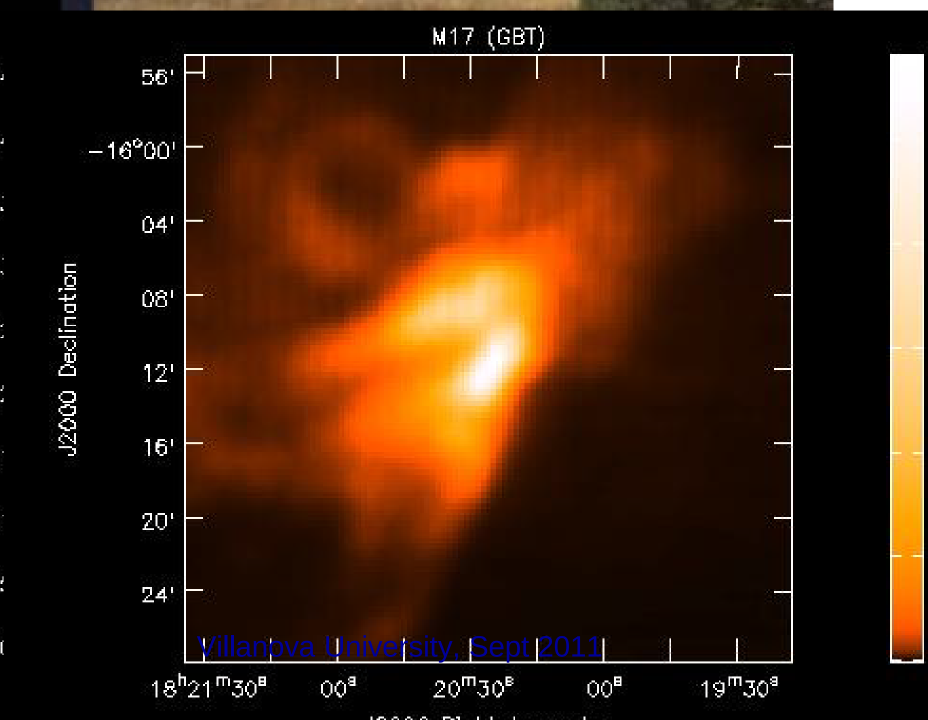
2209 actuators

Currently rms < 240μm at night, the goal is 210μm

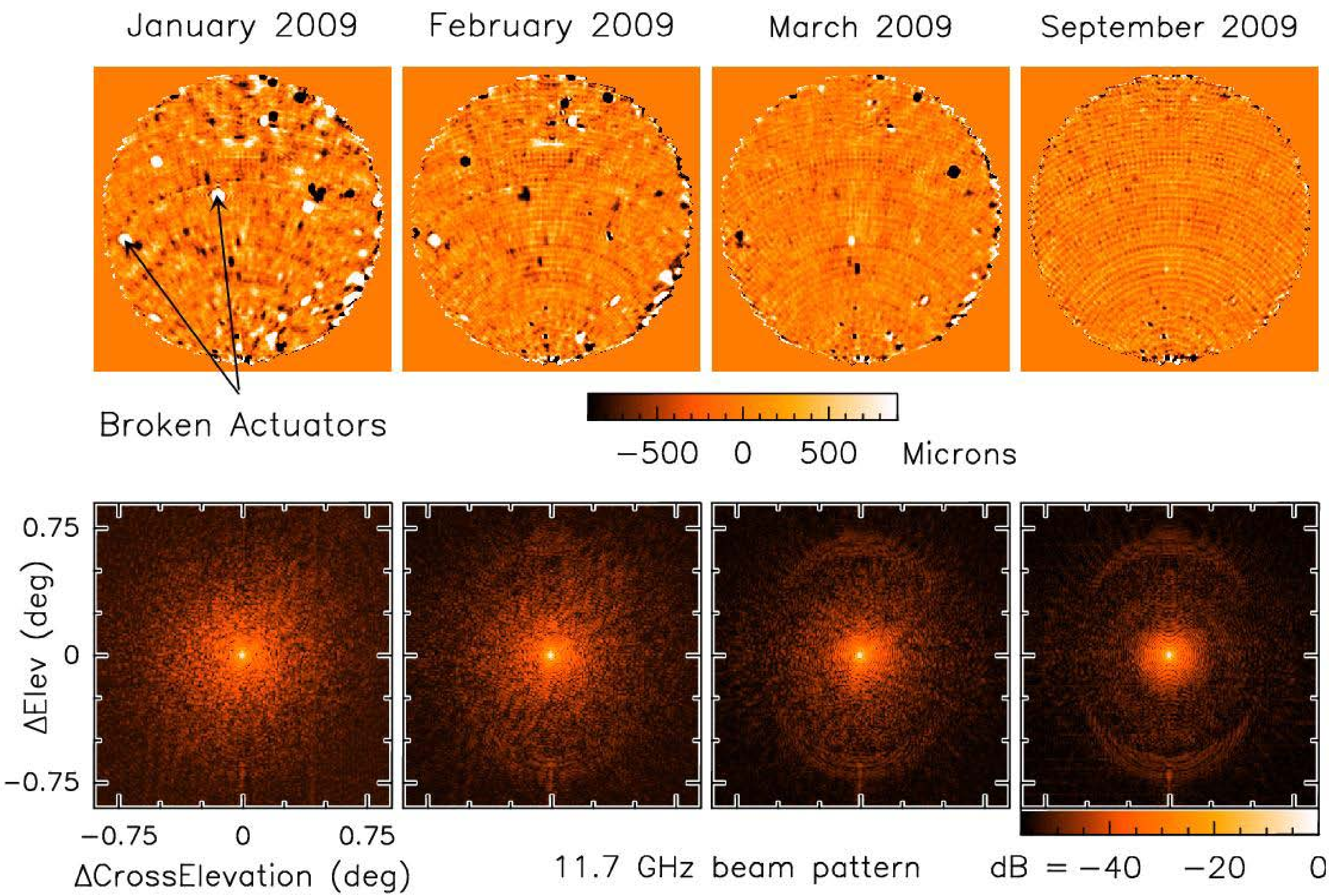
Unblocked Optics for High Dynamic Range







Improvements to Surface Makes 3mm Possible

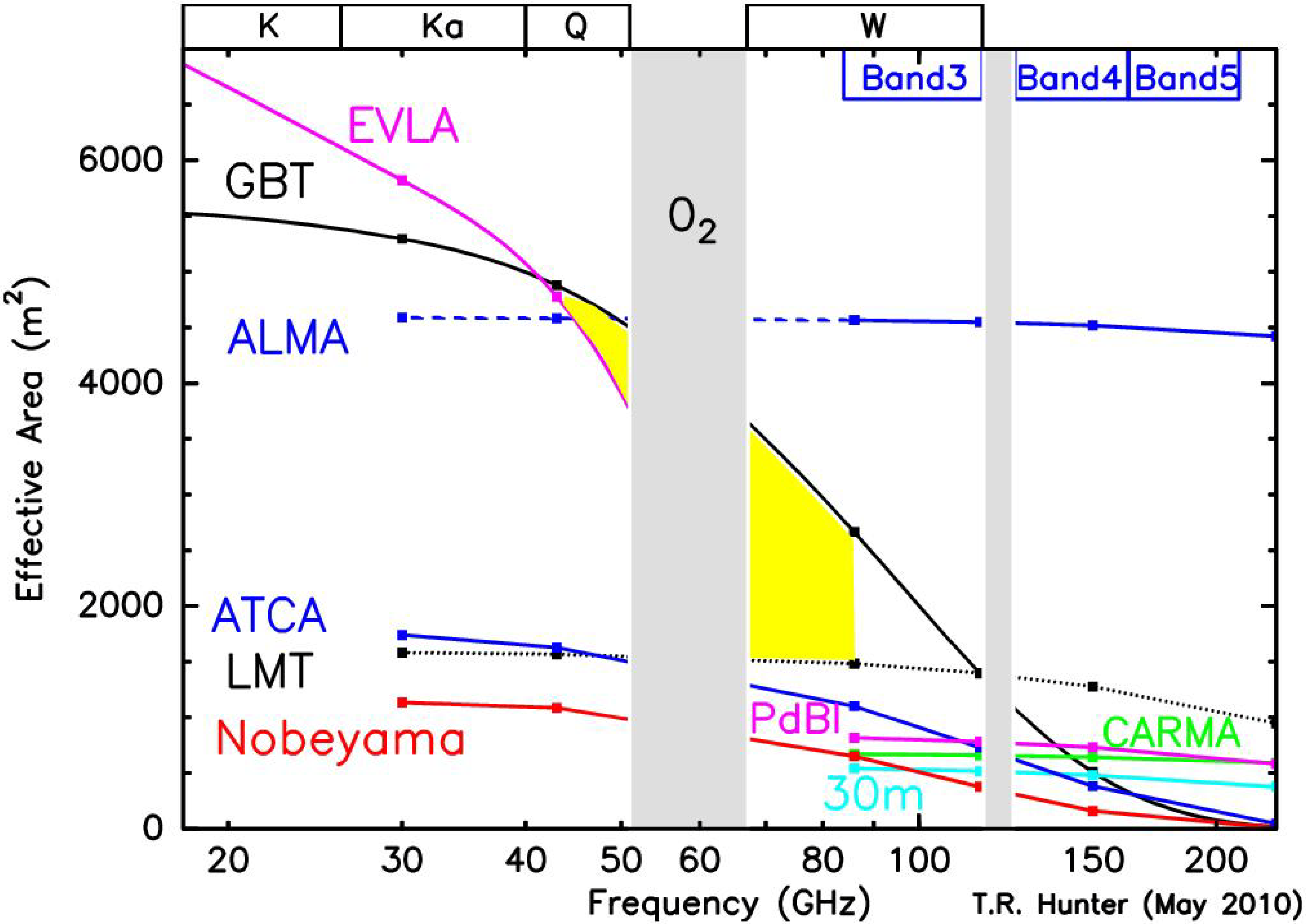


(From Todd Hunter, PTCS group)

GBT Effective Collecting Area (η_a * Area)

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

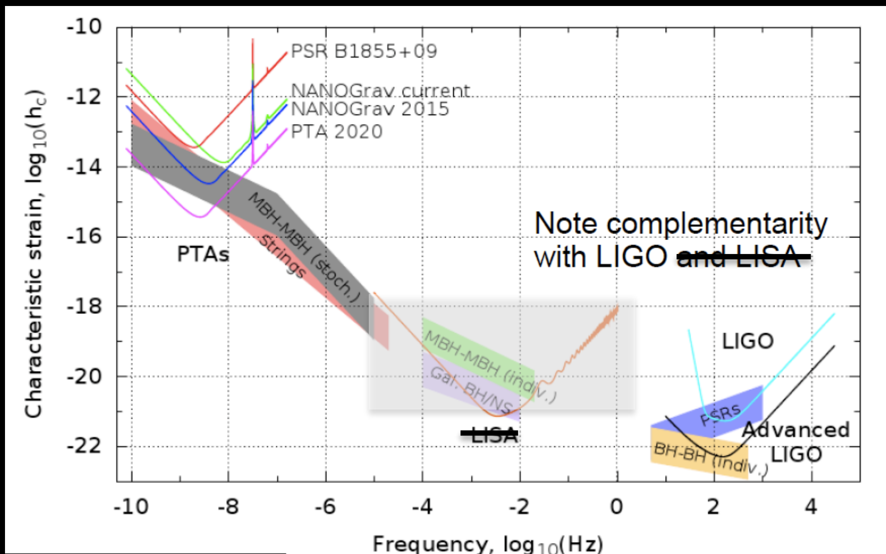
➔ most sensitive facility at Q and W-low (4mm).

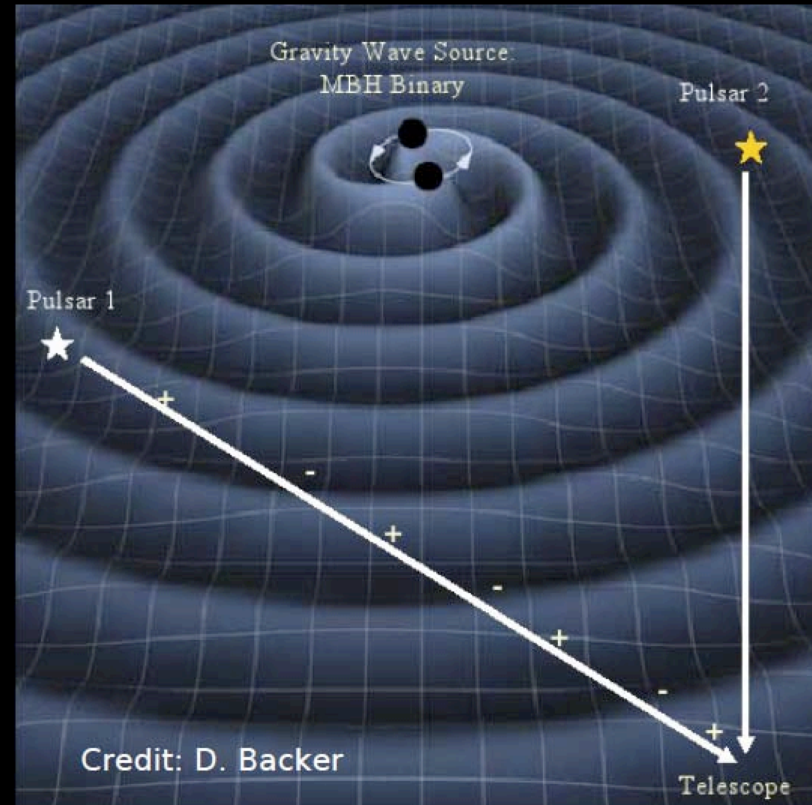


Some Key GBT Science Areas:

- 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-chemisty
- Masers: black hole masses, distances to galaxies
- Star Formation: NH_3 mapping
- Basic Physics: The search for Gravitational Radiation, Limits on Fundamental “constants”
- Solar system astronomy

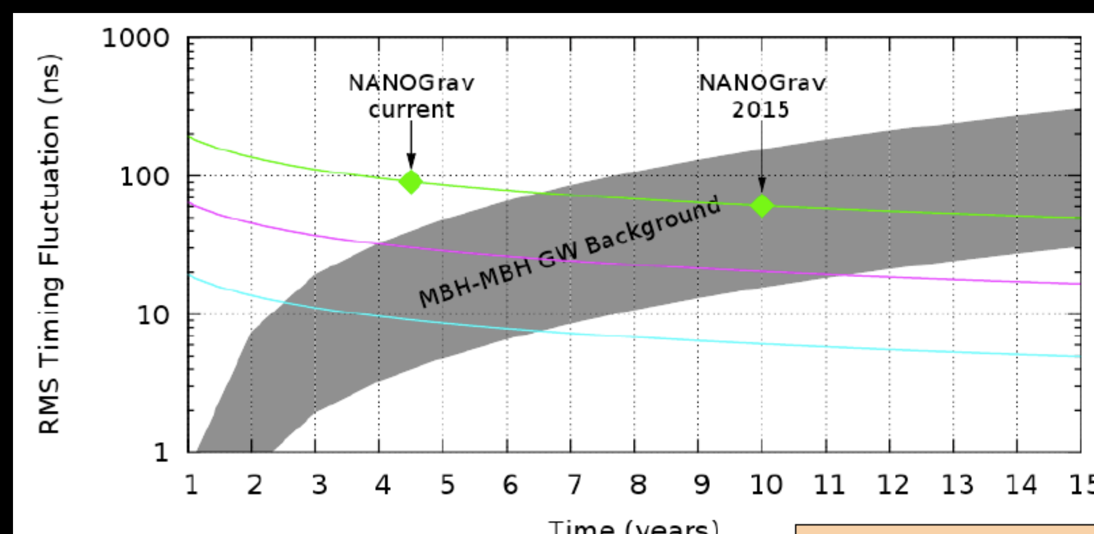
Fundamental physics
The race to detect gravitational waves





NANOgrav

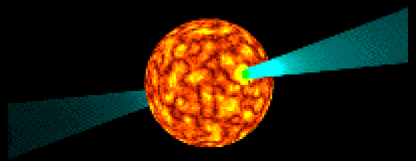
Need 40 pulsars with <100ns timing residuals

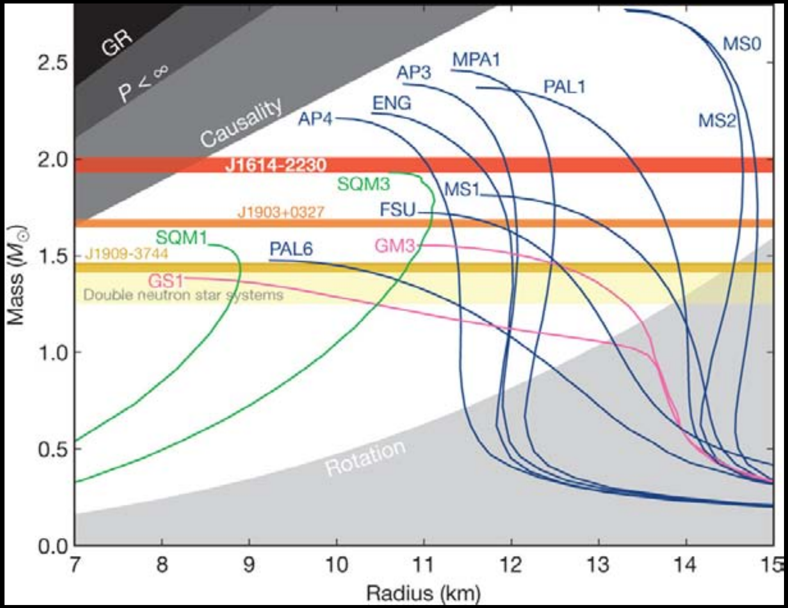


Fundamental physics

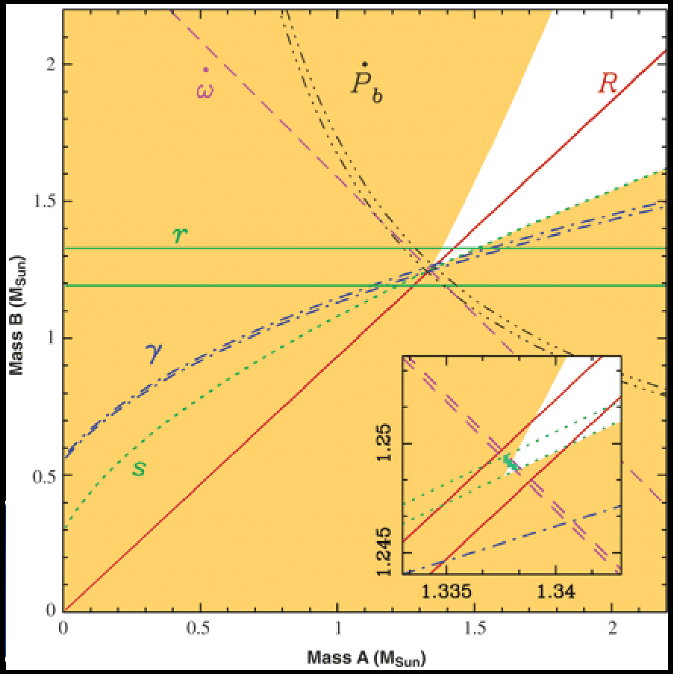
Testing matter at extreme densities

Additional pulsar timing results!





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

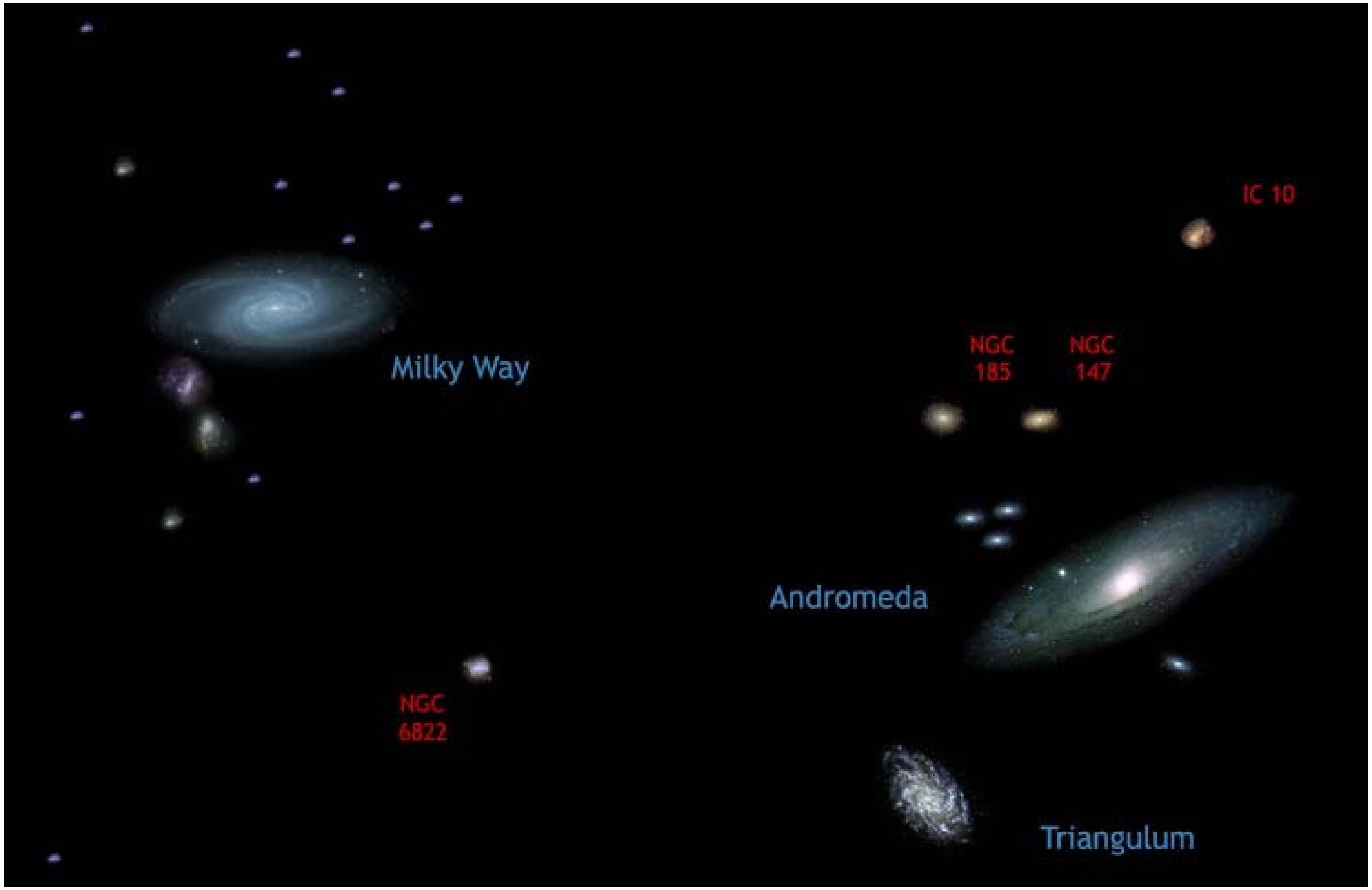


Measuring binary pair eccentricity to test general relativity

The Dynamics of the “Local Group” of Galaxies

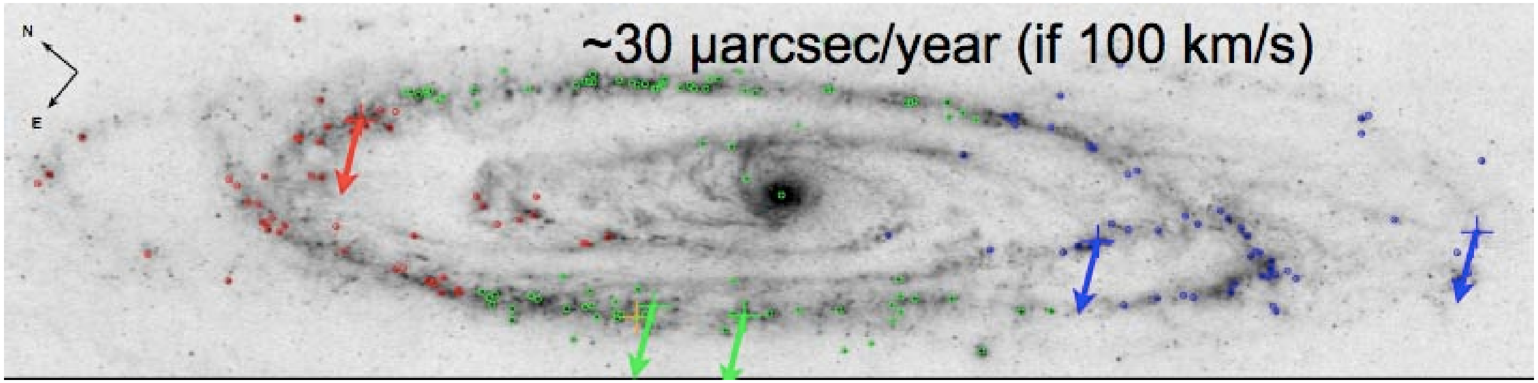
(where is the dark matter?)

1 Mpc



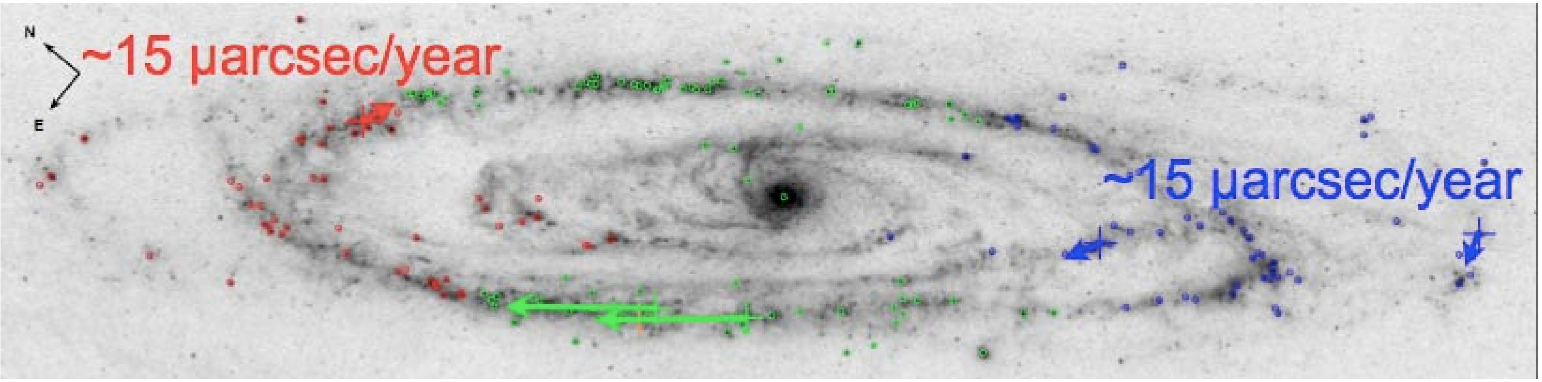
GBT Detection of H_2O Masers in M31

J. Darling (2011)



Expect 6σ detection of proper motion in ~3 years

arrows not to scale



~70 μarcsec/year

Proper <u>rotation</u> gives a geometric distance -- expect 10% uncertainty initially

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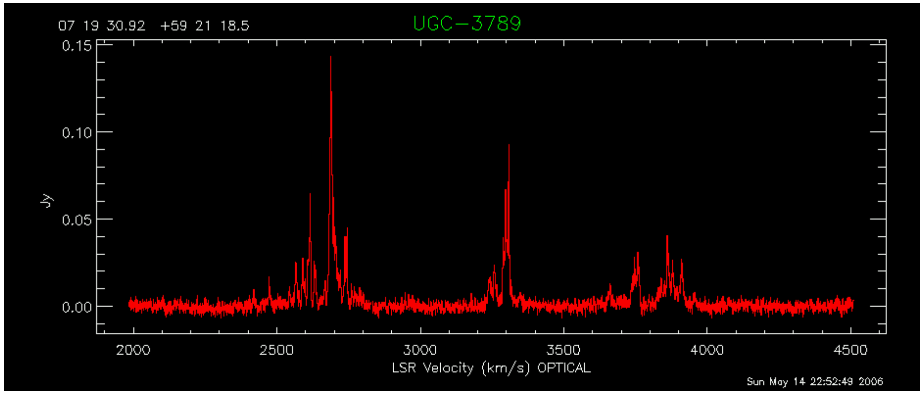
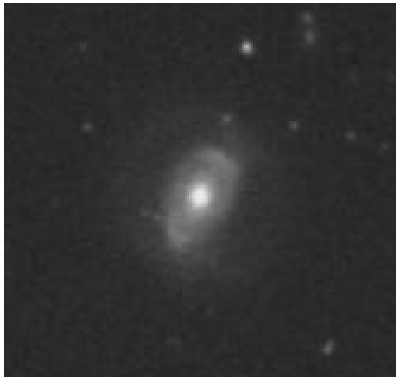
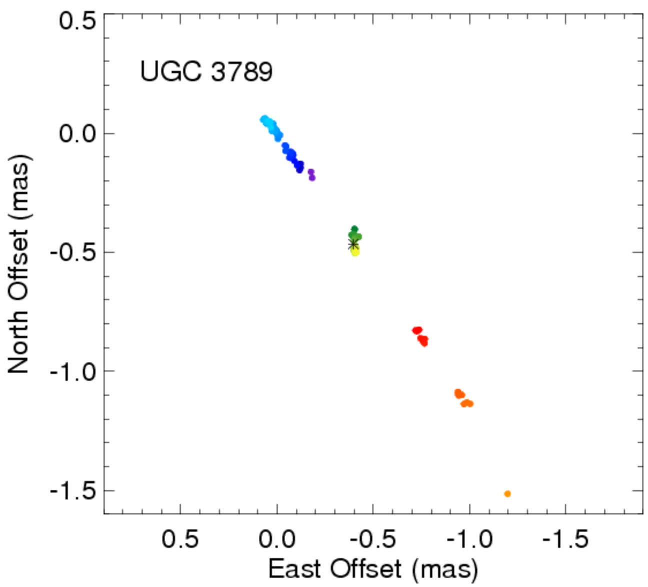
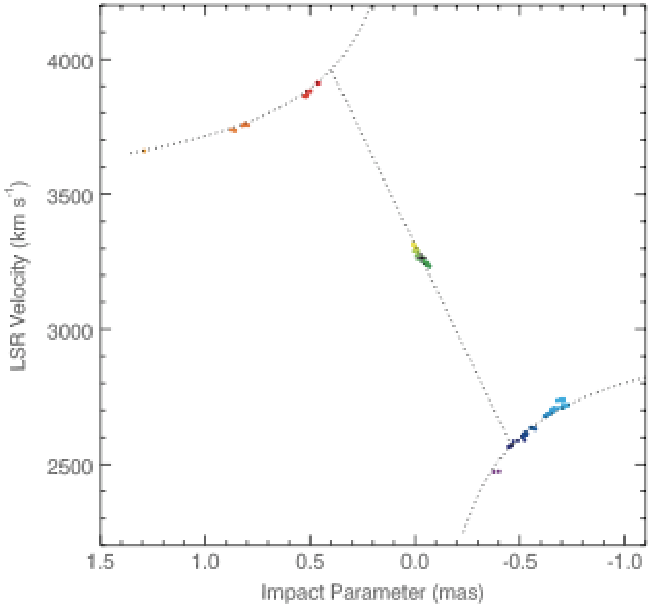
Megamasers provide gold standard M_{bh} and geometric measurement of H_0









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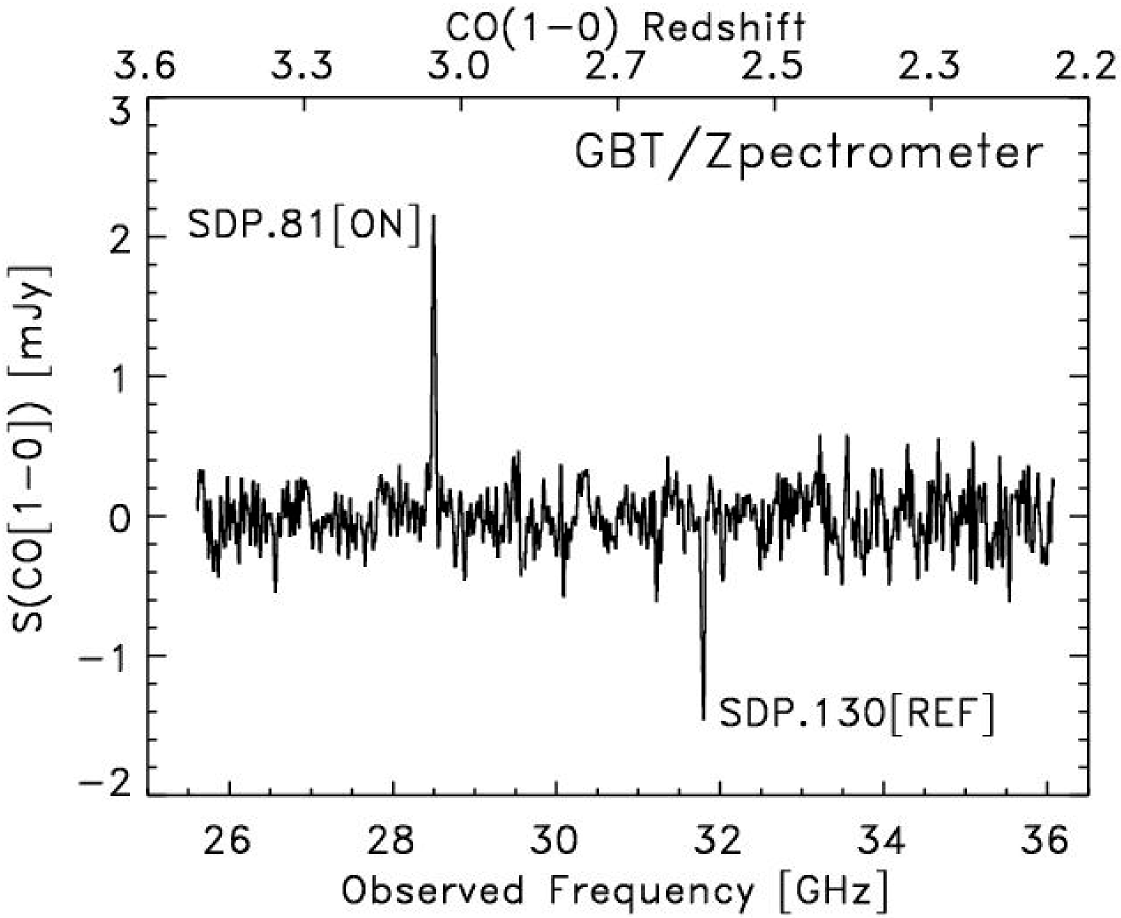
Braatz et al. 2010; Reid et al. 2009

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.

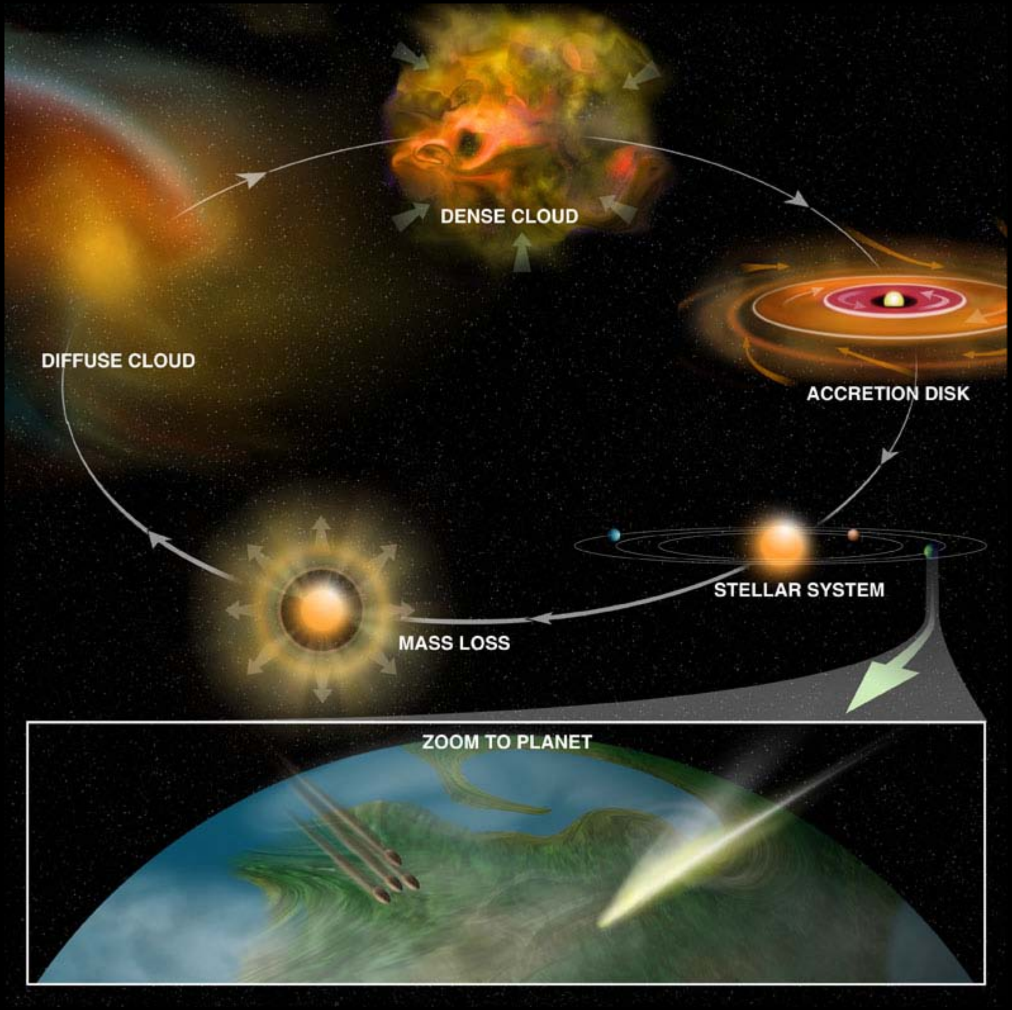


A telescope for interstellar chemistry

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



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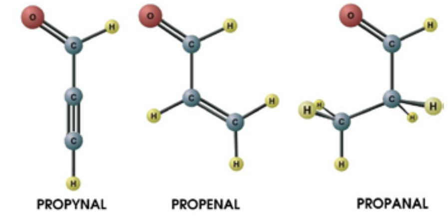
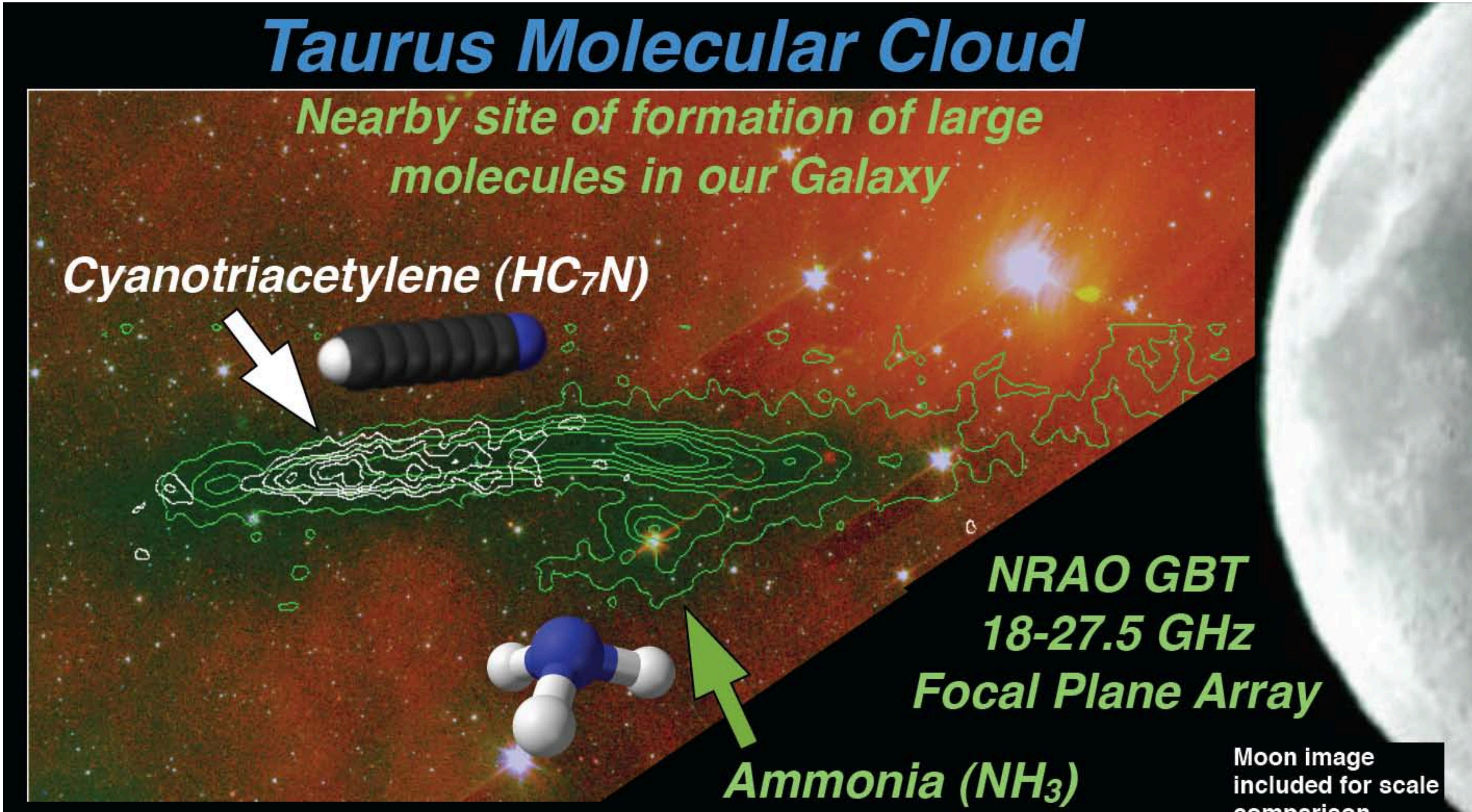
Organic chemistry in interstellar clouds



H_2O (water)
H_2CO (formaldehyde)
NH_3 (ammonia)
CO (Carbon monoxide)
HCOOH (formic acid)
CNCHO (cyanoformaldehyde)
CH_3OH (methanol)
CH_2CHCN (vinyl cyanide)
$HOCH_2CH_2OH$ (ethylene glycol)
CH_3CO_2H (acetic acid)
CH_3CH_2OH (ethyl alcohol)
CH_2OHCHO (glycolaldehyde)

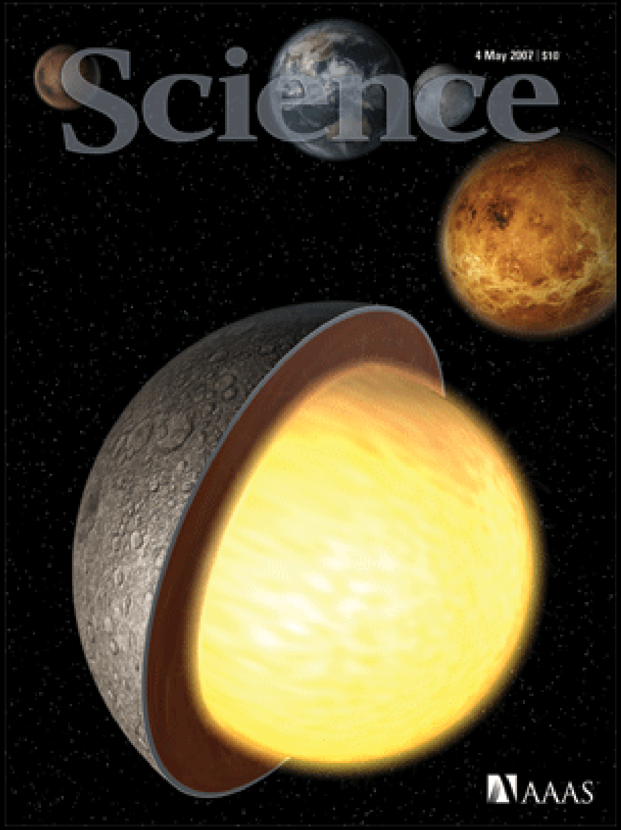
The GBT has detected 14 new interstellar organic molecules
including the first interstellar anions:
C_6H^- & C_8H^-
(McCarthy et al 2006;
Cordiner et al 2011)

Mapping of Star-Formation Regions with the K-FPA

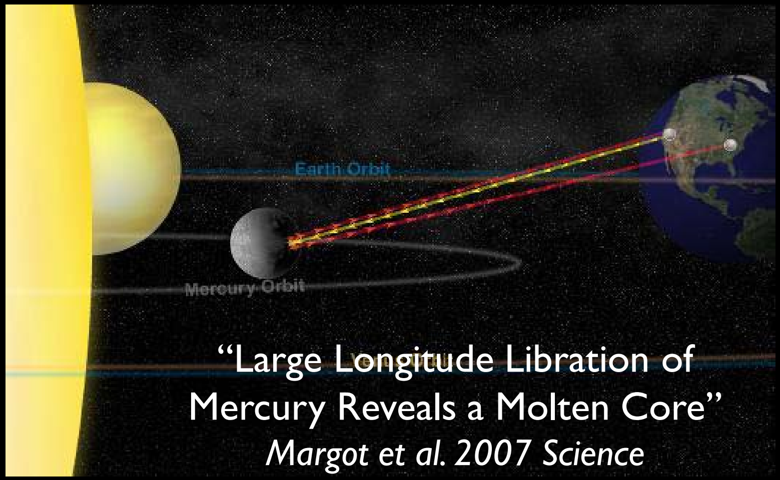


Contours show molecular chemistry dynamics in cold, dark, star forming clouds. White contours mark molecule HC_7N. Green contours mark ammonia distribution. Background image is a color composite of Spitzer Space Telescope IRAC channels 1, 2 and 4 (*Langston et al. 2011*).

Radar observing to study the solar system



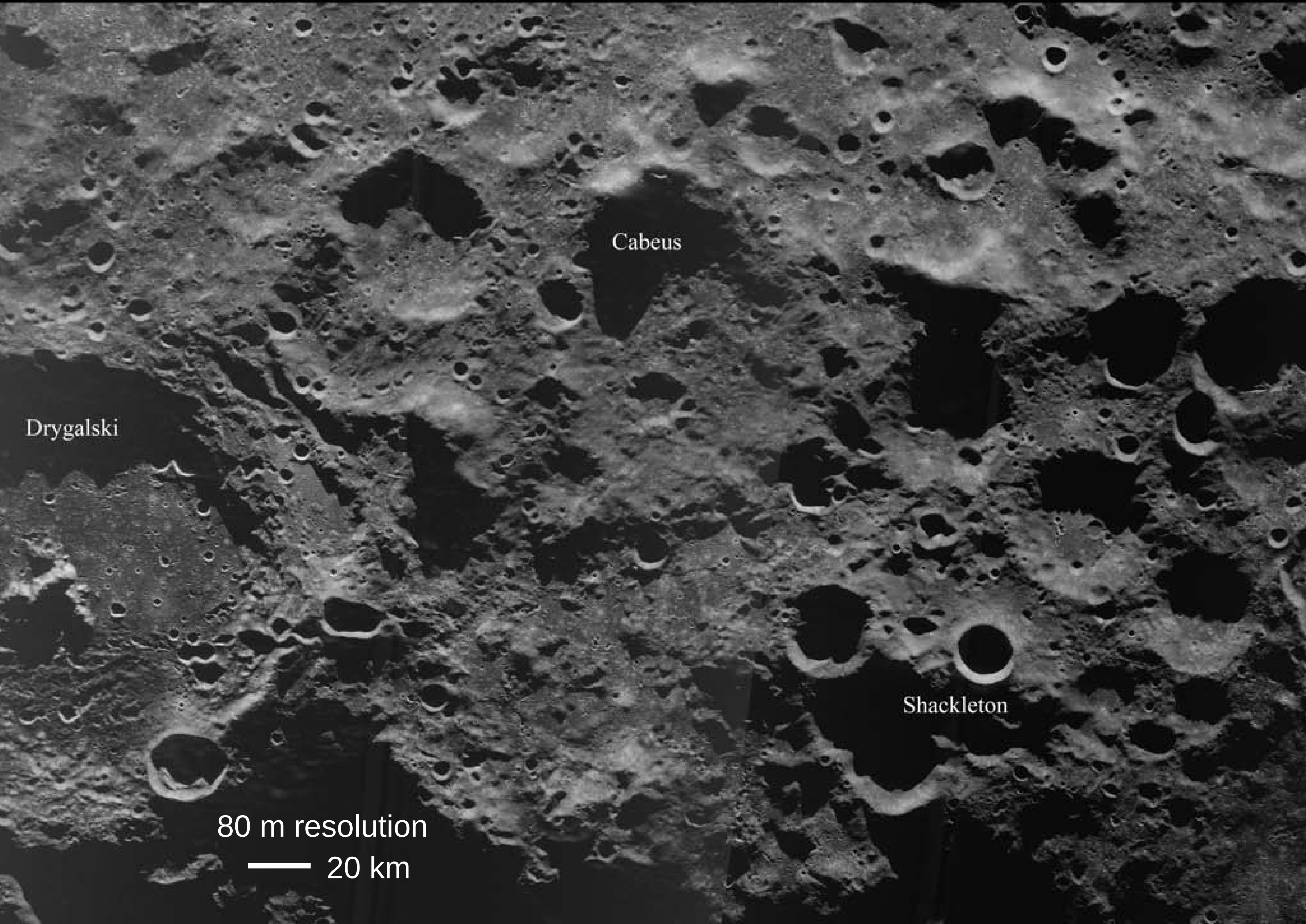
"No Evidence for Thick Deposits of Ice at the Lunar south Pole"
Campbell et al 2006 Nature

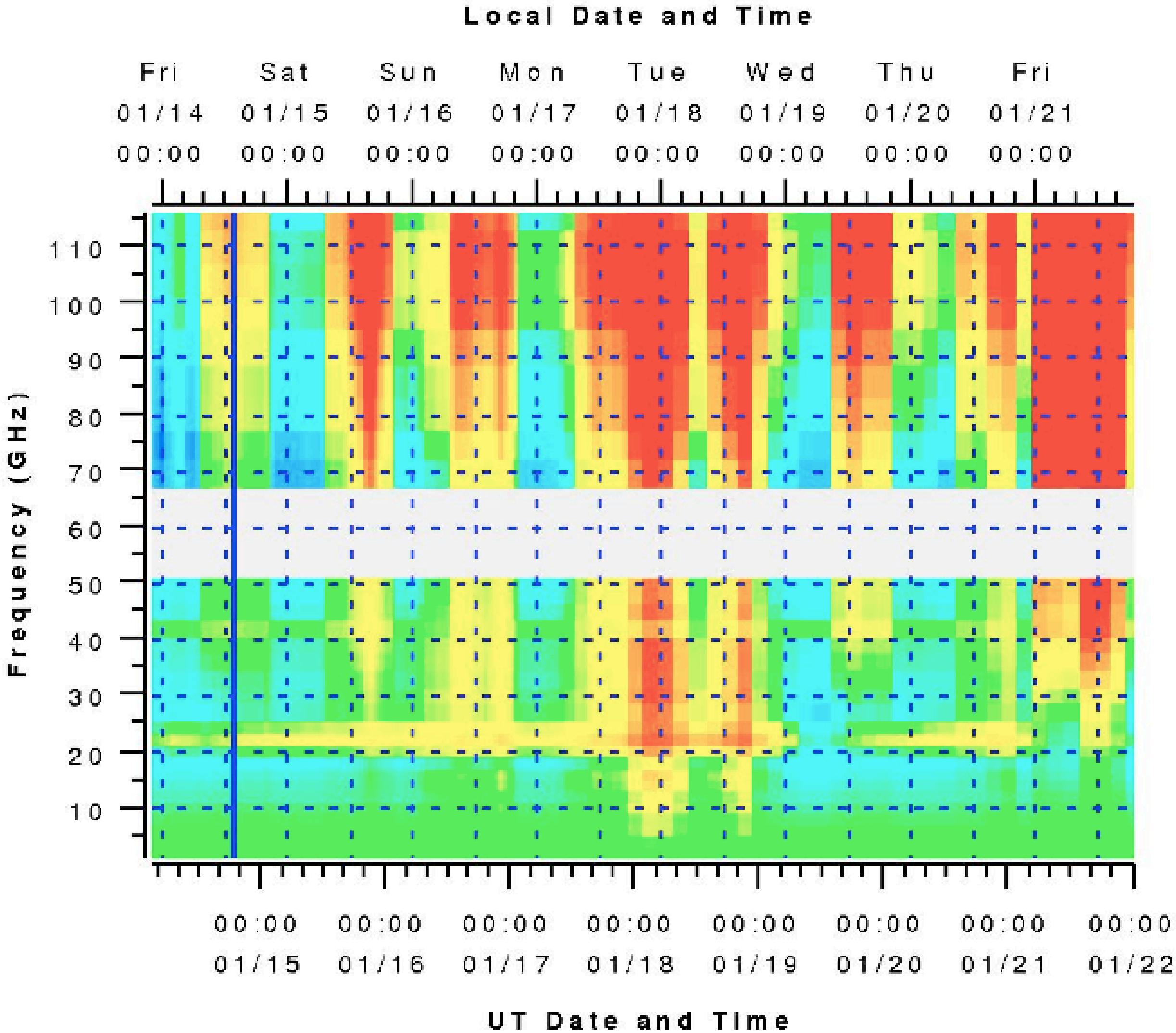


"Large Longitude Libration of Mercury Reveals a Molten Core"
Margot et al. 2007 Science

Campbell & Campbell 2008

Arecibo-Green Bank Telescope Radar View of the Moon's South Pole (Courtesy Cornell University/Smithsonian Institution)





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	1
C-Band	——	3.95-6.1	Greg.	Lin/Circ	1
X-Band	——	8.00-10.0	Greg.	Circ	1
Ku-Band	——	12.0-15.4	Greg.	Circ	2
K-Band	lower	18.0-22.4	Greg.	Circ	~~2~~ 7 KFPA
	upper	22.0-26.5	Greg.	Circ	2
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
{W-band (4mm Rx)		67-93.2	Greg.	Lin/Circ	2}

Example lines:

HI, OH → L-Band

NH3, HC5N, C2S, H2O → K-Band

HCN, HNC, HCO+, HDO, DCN, SiO, SO2, H2CO, N2H+, N2D+, CH3CN, C2H → W-band

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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	67% → 68%	23	21	$30 - 40 + T_{sky}$
	$30''$	1.5	65% → 67%	24	21	$30 - 40 + T_{sky}$
Ka-Band	$26.8''$	1.5	56-64% → 65%	27	20	$45 + T_{sky}$
	$22.6''$			20		$35 + T_{sky}$
	$19.5''$			43		$70 + T_{sky}$
Q-Band	$16''$	1.0	47-56% → 60%	67-134	40-70	$67 - 134 + T_{sky}$
Mustang	$10''$	—-	20% → 35%	—-	—-	—-

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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 (VErsitile 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)	Mininum 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.

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.

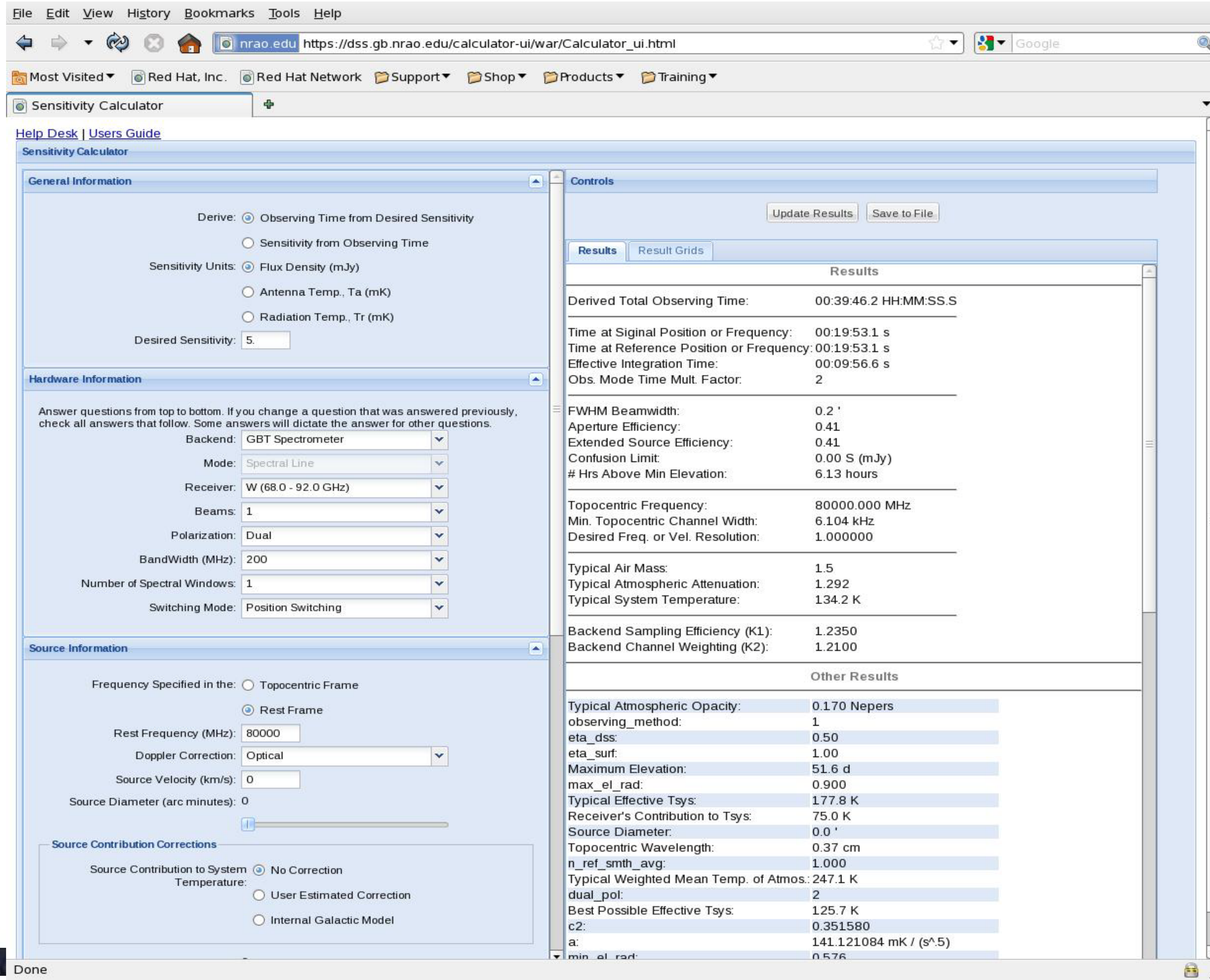
Bandwidth (MHz)	Number of Spectral Windows	Number of Beams	Channels - Approximate Resolution (kHz)	Mininum Integration Time (sec)	Notes
250	1 or 2	1	32768 – 7.629	10	
250	1	2	32768 – 7.629	10	
100	1 or 2	1	32768 – 3.052	10	
100	1	2	32768 – 3.052	10	
50	1 or 2	1	32768 – 1.526	10	
50	1	2	32768 – 1.526	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)	Mininum 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	

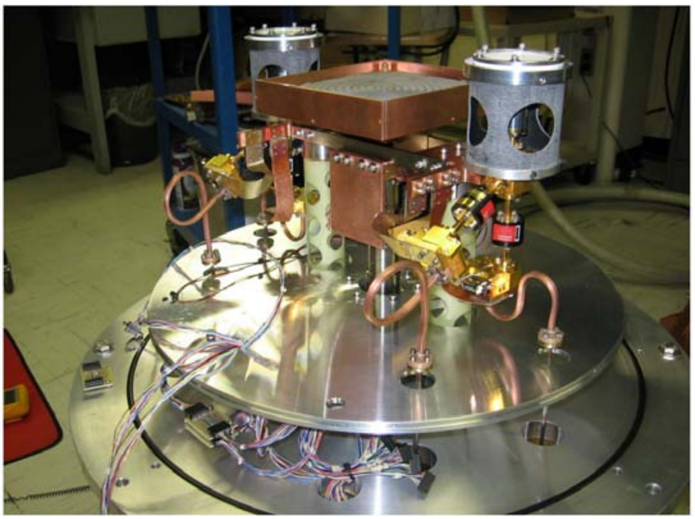
Table 9: VEGAS Small Bandwidth, Many Spectral Window Modes.

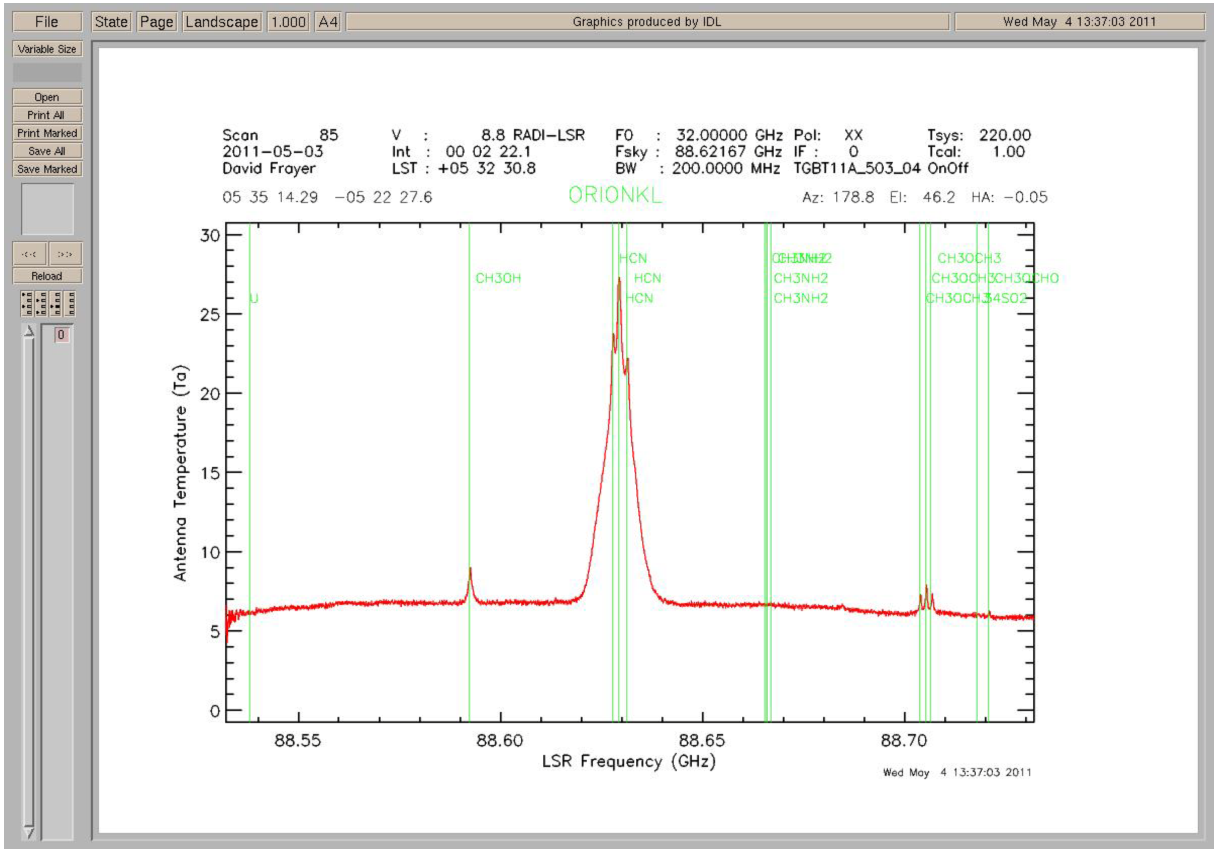
GBT Sensitivity Calculator for proposal estimates, also good for verifying available modes.



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:

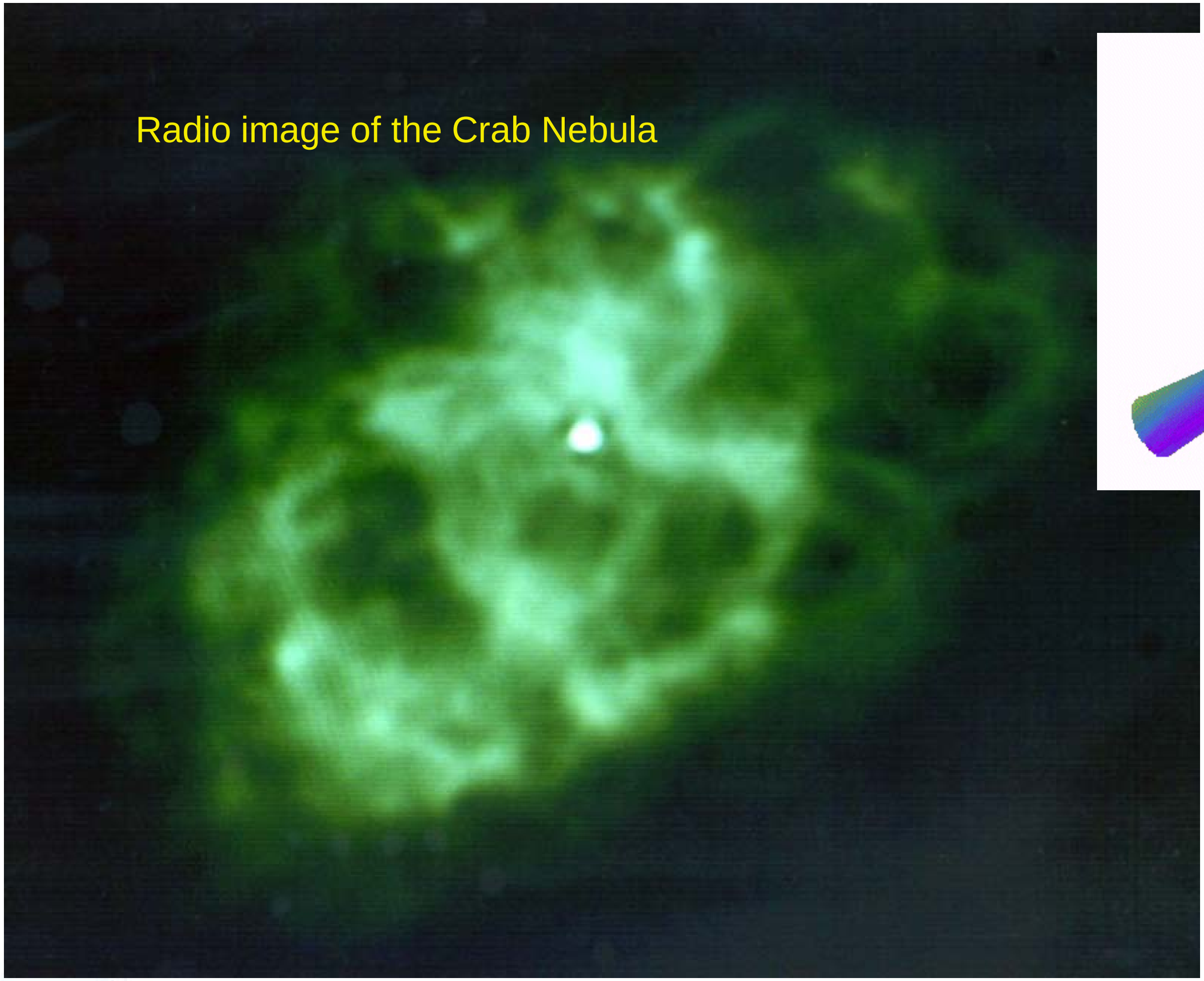
- Educators:
  - Ongoing teacher training workshops
  - Science education material for elementary through college levels

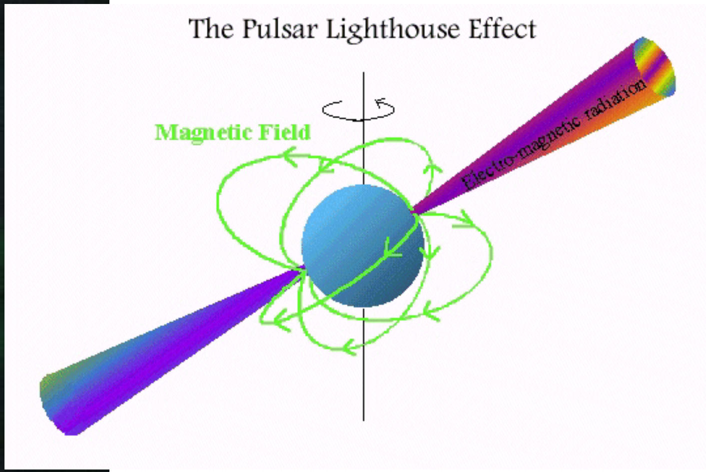
- Students:
  - Summer research programs, co-ops, internships
  - Pulsar search collaboratory, Governor's school
  - NSF-NRAO REU summer research program
- University research groups:
  - Contact NRAO to collaborate on any of the planned/ongoing development programs

www.gb.nrao.edu

The End

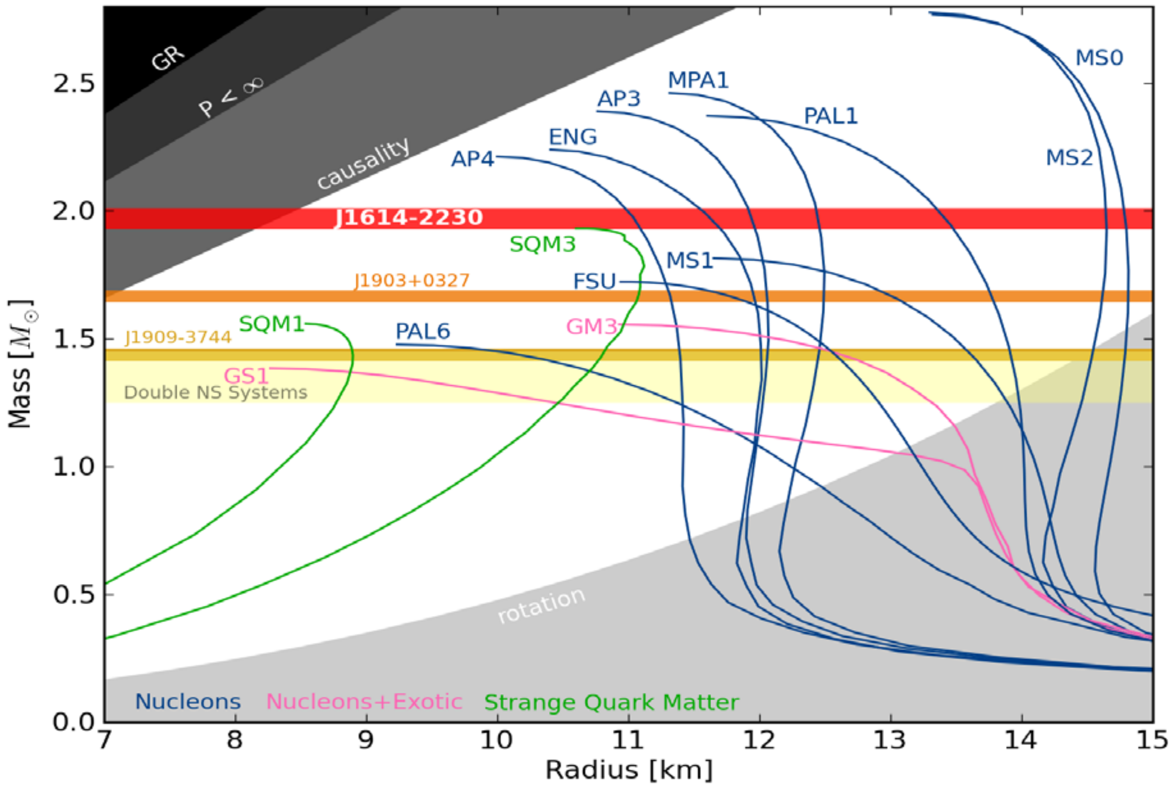
Pulsars: neutron stars that are remnants of massive stars that became supernovae





With a period ~10^{-3} s
over one year 3×10^{7} s
timing to a part in 10^{11}

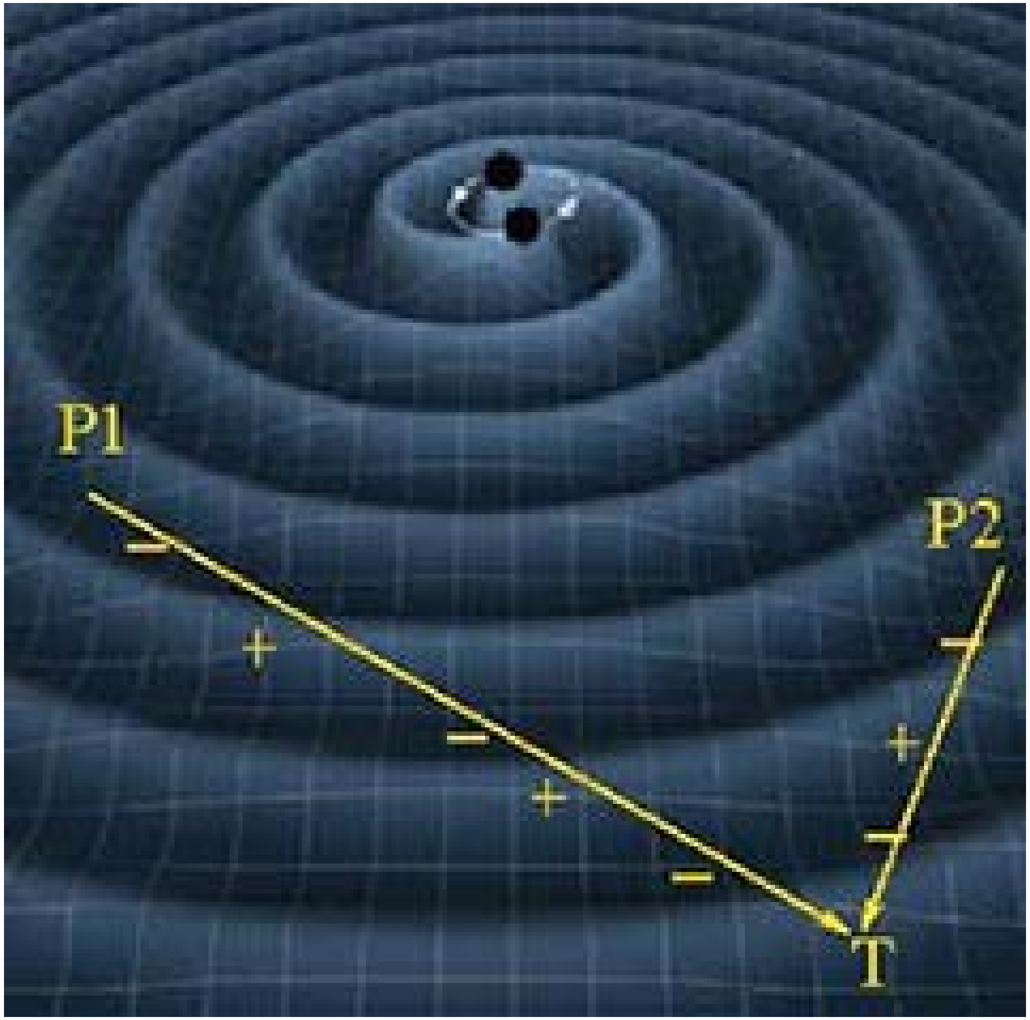
The most massive known pulsar, J1614-2230



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.

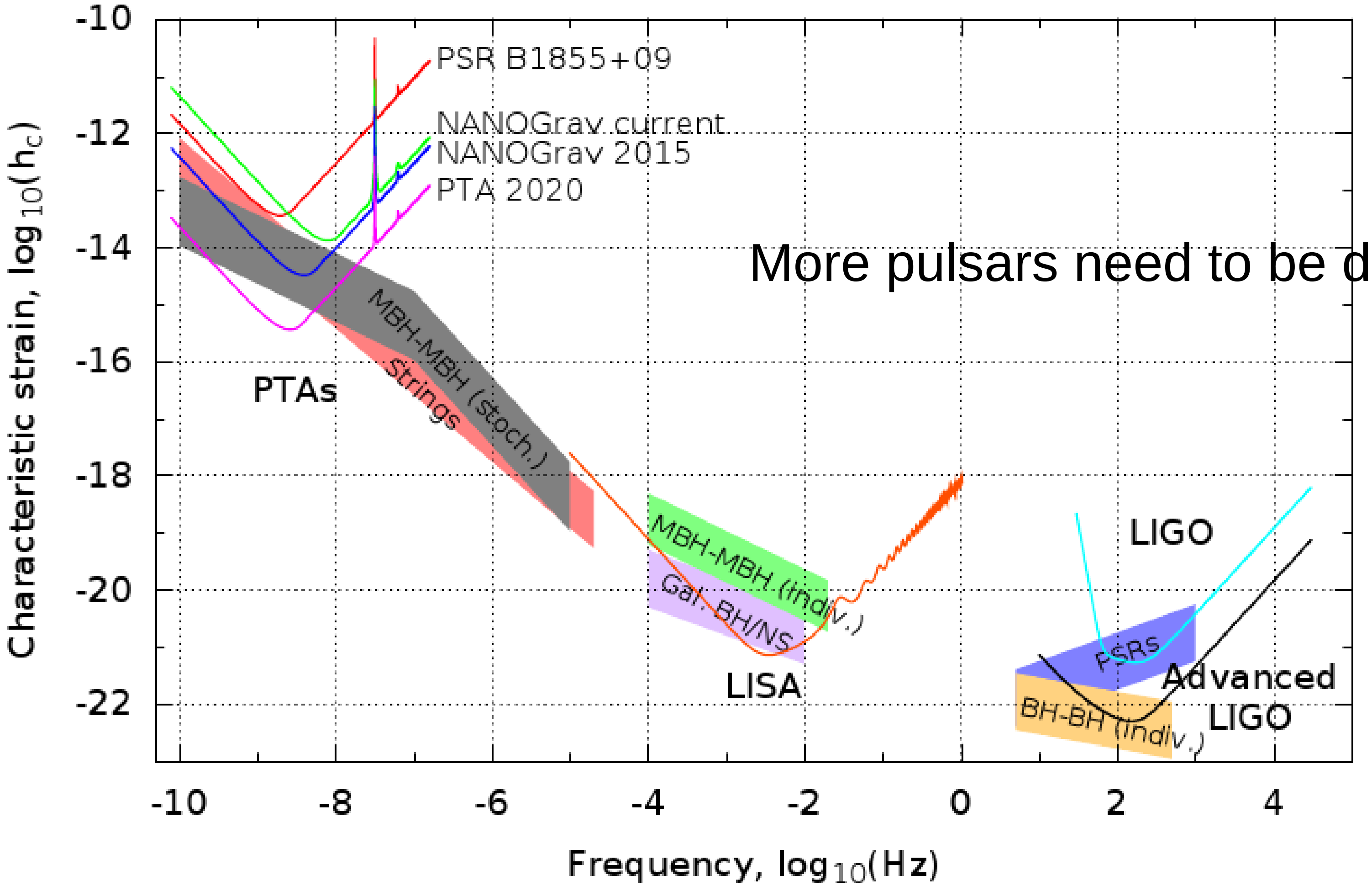
(Demorest et al. 2010)

Using pulsars to detect gravitational radiation



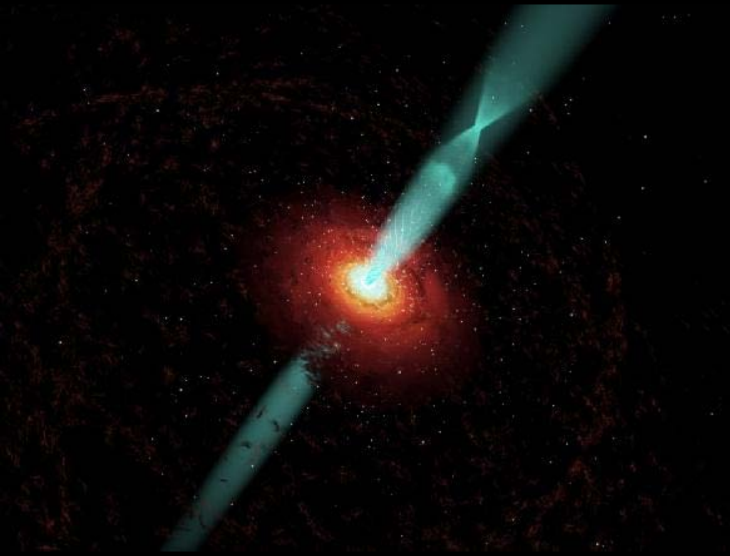
The NANOGrav Collaboration

nanograv.org

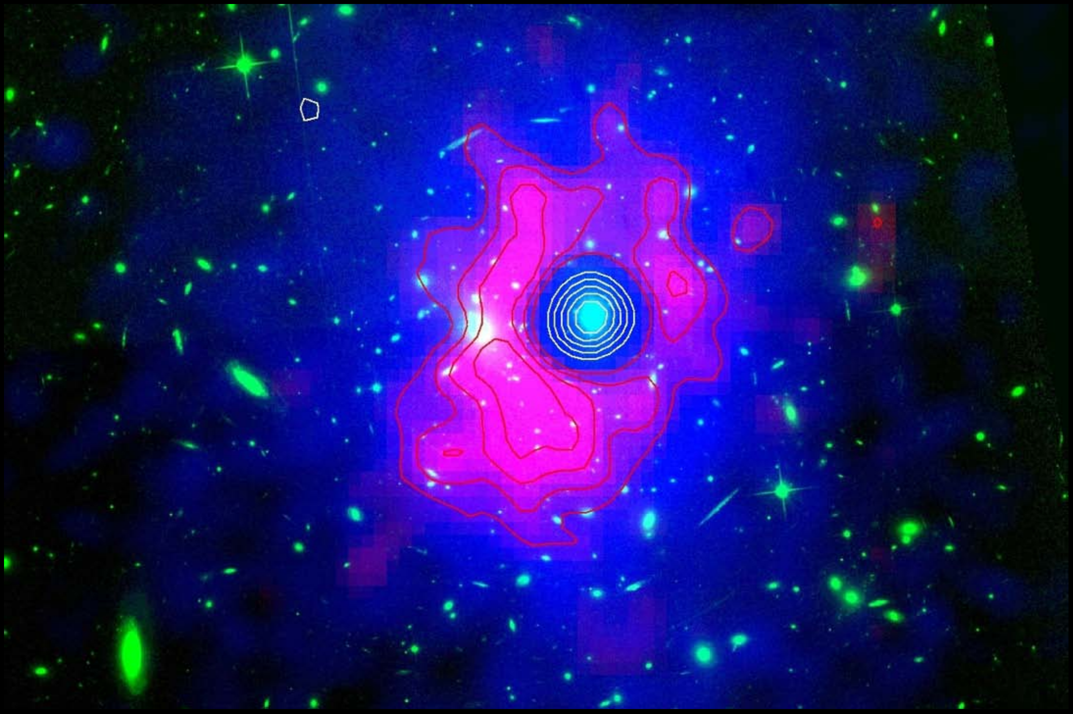


More pulsars need to be discovered

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 Ho (age and size scale of the universe) via H20 masers



Measurement clusters of galaxies via 3mm continuum observations

NRAO

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)

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