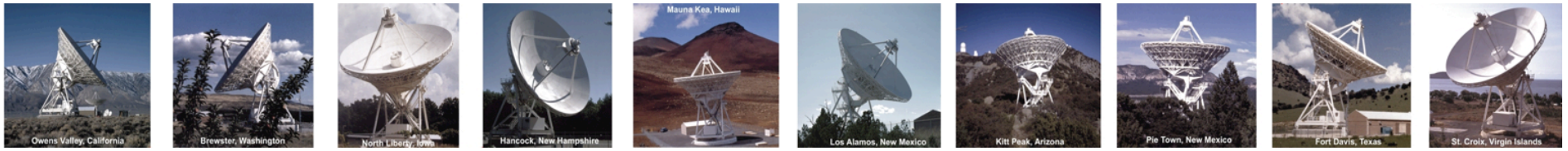
The Very Long Baseline Array



Gustaaf van Moorsel

NRAO Community Days

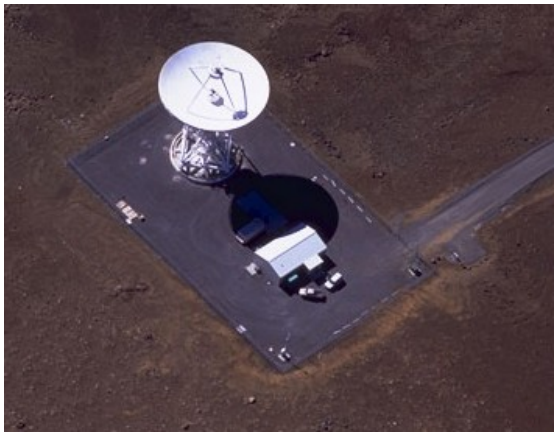
February 2013

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

NRAO

The VLBA stations

- Form a dedicated VLBI array
- Array dedicated in 1993
- Cover frequency range 310 MHz to 90 GHz
- 10 identical stations on U.S. territory:
  - Brewster WA, Hancock NH, Fort Davis TX, Kitt Peak AZ,
  - Los Alamos NM, Mauna Kea HI, North Liberty IA, Owens Valley CA,
  - Pie Town NM and Saint Croix, US Virgin Islands
- Each station has
  - 25-m Cassegrain antenna
  - Station building with maser, electronics, recorders
  - Weather station, GPS Rx, security camera
  - Staff of 2



The key capabilities of the VLBA

- **Long baselines yield high resolution**
  - 5 mas at 1.5 GHz
  - 80 μas at 90 GHz
  - Sensitive to brightness temperatures above about **10^5 K**
    - Sufficient only for non-thermal emission and some absorption work
- **Instrumental stability and long baselines → astrometry**
  - < 0.1 mas achievable with minor effort, cooperative sources
  - 0.01 mas demonstrated in some cases
    - Allows distance measurements at 1 kpc with 1% accuracy
- **10 identical 25-m antennas allow large field of view**
  - 30' at 1.5 GHz
  - Can image hundreds of sources in one pointing
- Full time operations
  - Suitable for transient response, dynamic scheduling, multi-epoch obs…

Rapid turnover to users: usually 2-3 weeks

VLBA Frequency bands and sensitivity

λ(cm)	ν(GHz)	σ(μJy/beam) in 4 hrs at 2Gbps
90 cm	0.312 - 0.342	277*
50 cm	0.596 - 0.626	782*
21 cm	1.35 - 1.75	13-14
13 cm	2.15 - 2.35	14
6 cm	4.6 - 5.1	13
6 cm (upgrade)	4.1 - 7.9	8
4 cm	8.0 - 8.8	13
2 cm	12.0 - 15.4	24
1 cm	21.7 - 24.1	18-22
7 mm	41.0 - 45.0	66
3 mm	80.0 - 90.0	316†

* Narrower bandwidths

† 8 stations

VLBA correlator

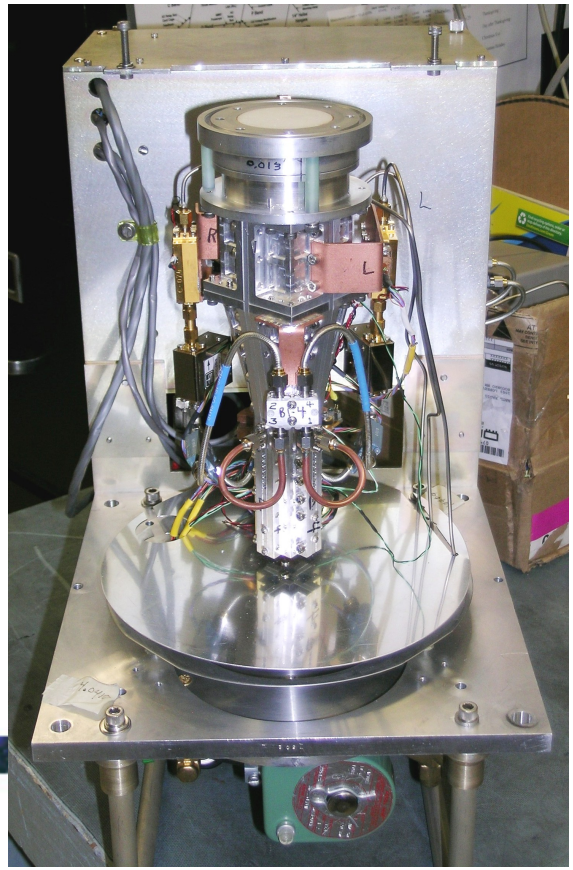
- NRAO Socorro hosts the VLBA DiFX software correlator
  - DiFX has a global collaborative development team
  - It is now used at many VLBI processing centers
- 15-20 Mark5 units available for playback
- Can process data from 10 stations at a rate of 1500 Mbps
- **Time resolution down to milliseconds (or less)**
- **Frequency resolution down to 2 Hz**
- Some special features
  - **Pulsar gating and binning**
  - Simultaneous correlation at many (hundreds) positions
  - Extraction of calibration information (phase tones, Tsys)
  - Can dump high time resolution spectra for commensal transient searching

C-band receiver upgrade

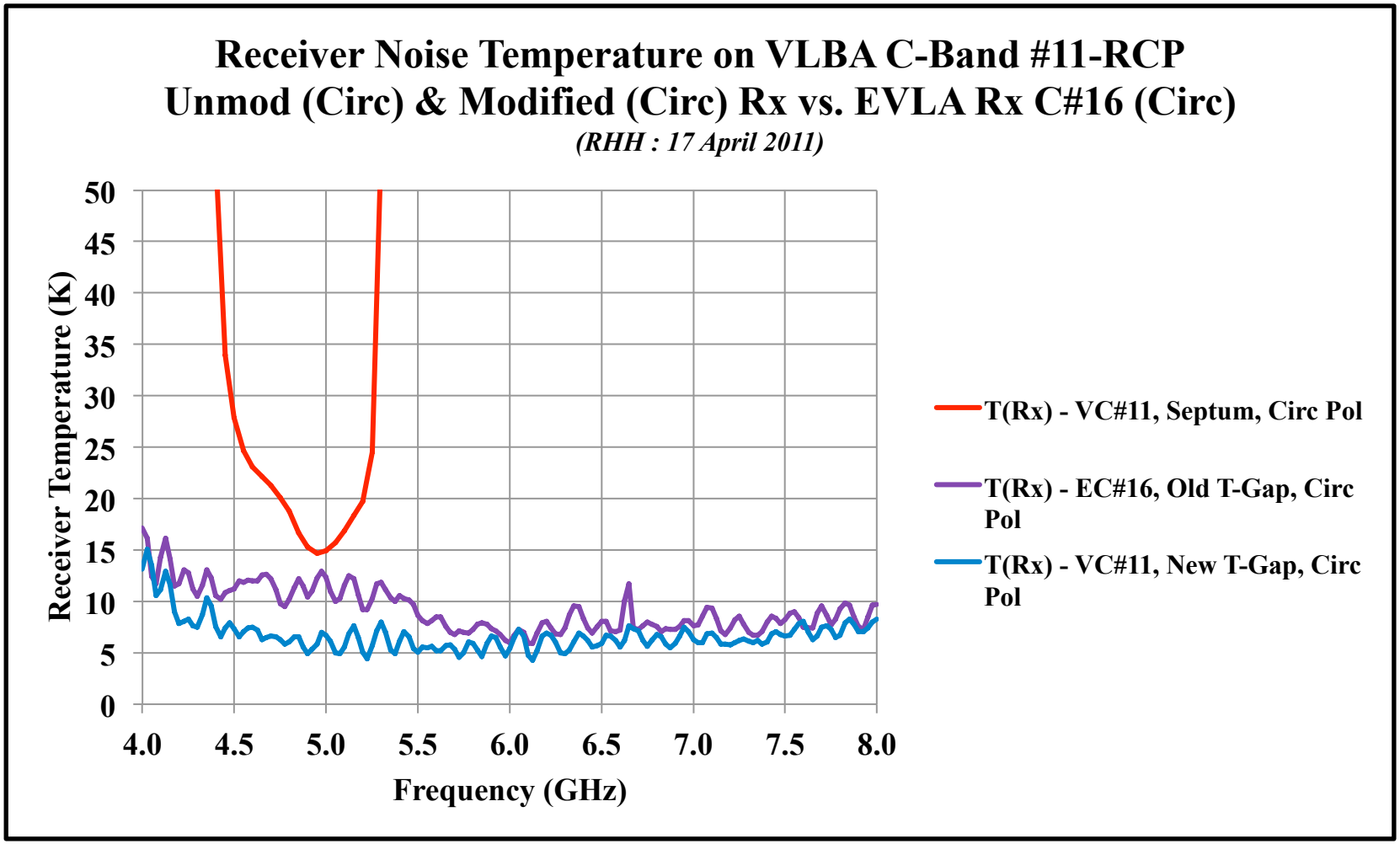
- Replace 4.5-5.1 GHz receivers with **4-7.9 GHz** upgraded units
- Primary science goal: **Astrometry of 6.7 GHz methanol** line found in star forming regions to map the structure of the Milky Way
- This project will bring more of the VLBA to EVLA standards
- Upgraded down-converter will allow **2 IF pairs** to attach to this receiver at widely separated frequencies
- **Upgrade is complete**

- **The best C-band receivers on Earth!**

- Thanks to MPIfR for funding to enable this!



Performance of new C-band receiver



Performs even better than EVLA C-band receivers!

High Sensitivity Array

- Organized by NRAO
- HSA = VLBA + Phased VLA + GBT + Arecibo + Effelsberg
- 1-hr integration at 1.7 GHz gives S_{rms} = 5 μJy/beam with 512 Mbps recording rate
- Phased VLA is supported by the WIDAR correlator
  - Has not been available since the VLA correlator shutdown on Jan 2010
- Phased VLA returned to VLBI use in January 2013

- Routine 2 Gbps operation at other HSA antennas hoped during CY 2013

Future of the VLBA? (see http://www.nrao.edu)

- The NSF/AST Portfolio Review suggested **Divestment** of the VLBA and GBT (NRAO budget reduced by 35%) starting in 1-2 years.
  - Why?: Keep ALMA alive despite failure to double NSF budget
- NSF is not ignoring the report; conflicted regarding NRAO
- NRAO's response:
  - Note impact of premature VLBA closure
  - Point out that **today's VLBA is a new instrument with new science**
    - Significant evolution since input to decadal survey
- Possible outcomes for the VLBA:
  - We $urvive, $omehow (more N$F, partner$hips, …)
  - Full or partial closure
  - Completely new operating model that preserves long baseline science
  - Some mix of the above

VLBA

- Questions?

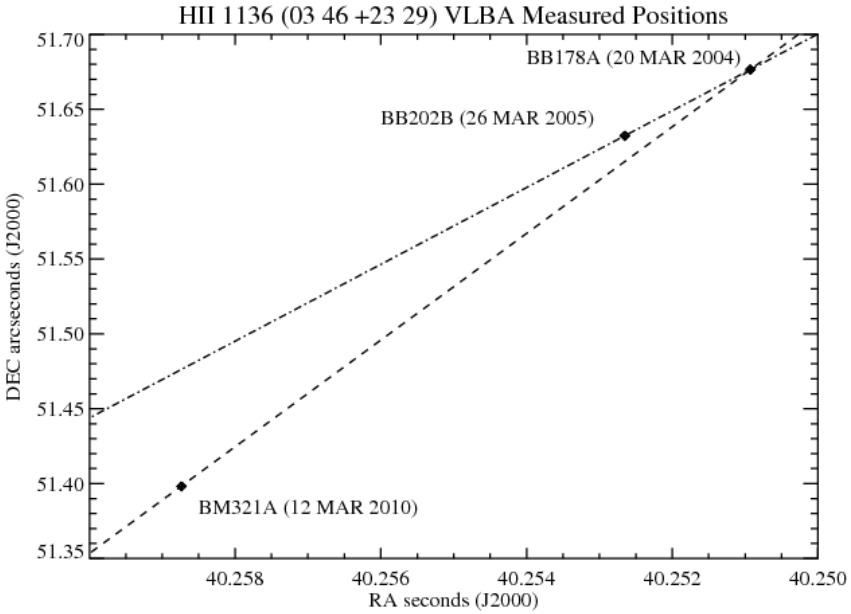
Bandwidth expansion project

- Goal: Increase the data rate from the VLBA from 512 Mbps to 2(4) Gbps
- Three major components, all developed collaboratively
  - New back-end electronics (collab. w/ Haystack)
    - Remove down-converters, samplers and formatter
    - Replace with FPGA-based ROACH (from CASPER group)
  - New recorder (Haystack, Conduant Corp.)
    - Mark5C unit with 10G Ethernet input port
  - New DiFX correlator (Adam Deller and global collaboration)
    - Replace VLBA hardware correlator with DiFX software correlator
    - Complete as of Dec 2009
- **Hardware is operational at all sites**
- **Final modes to be complete in 6 mo**
- First science is underway!

Pleiades distance

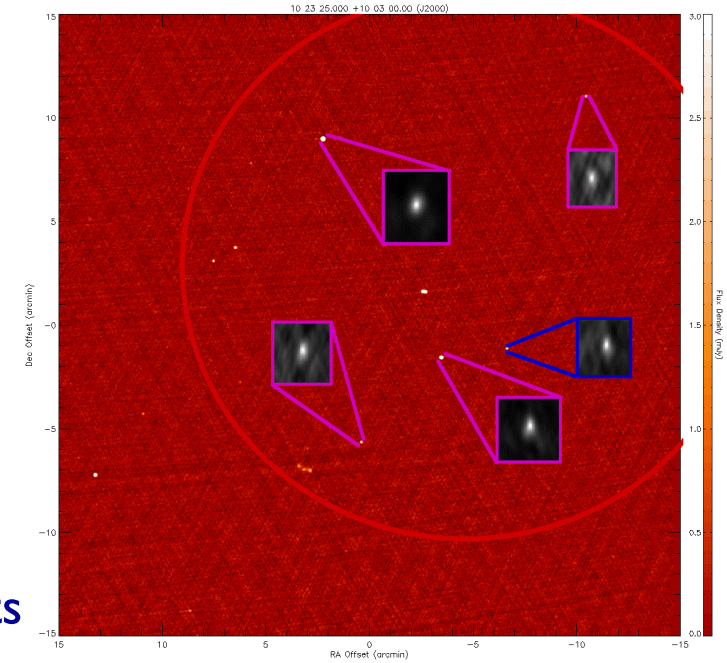
Melis et al.

- Pleiades are a key system for understanding stars in open clusters
  - It is close and young
- Pleiades distance controversy:
  - Hipparcos measured 120 pc
  - Other methods yield ~133 pc
- Goal: use VLBA to determine geometric distance
  - VLA being used to identify cluster members that are bright enough
  - Early VLBA results have demonstrated the feasibility
    - Non-linear stellar motion hints at multiplicity



PSRπ : pulsar astrometry

Adam Deller et al.

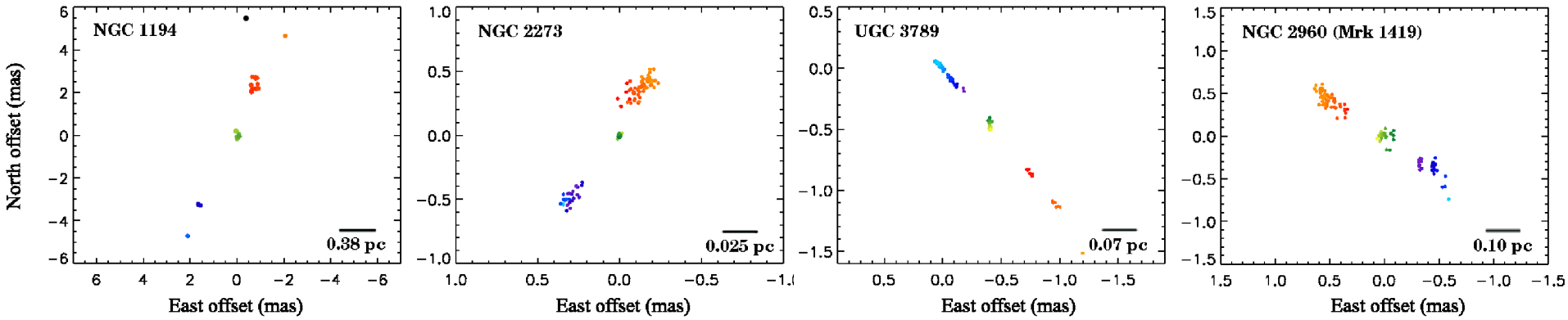


- Goal: 60 more parallax distances to pulsars
  - Proper motions come for free
- Luminosities can be calibrated
- Can connect pulsars with SNR or other objects
- Improve solar system to ICRF reference frame ties
- Used to better calibrate the Galactic electron density model
- Reduce covariances in pulsar timing array parameters
- Observing strategy
  - Use 1.5 GHz
  - Calibrate using background quasars in field of view
  - Make use of pulsar gating and multi-phase center correlation

Megamaser cosmology project

Braatz, Kuo et al.

- Goal: Measure Hubble constant
  - Determine geometric distance to AGNs hosting water maser disk through orbit modeling high velocity maser motions
  - Couple to redshift determined from systemic maser velocity
- Goal: Measure black hole masses precisely
- First results from galaxies within the Hubble flow suggest H_0=69±11 km/s
  - **Direct** measurement without intermediate distance ladder rungs

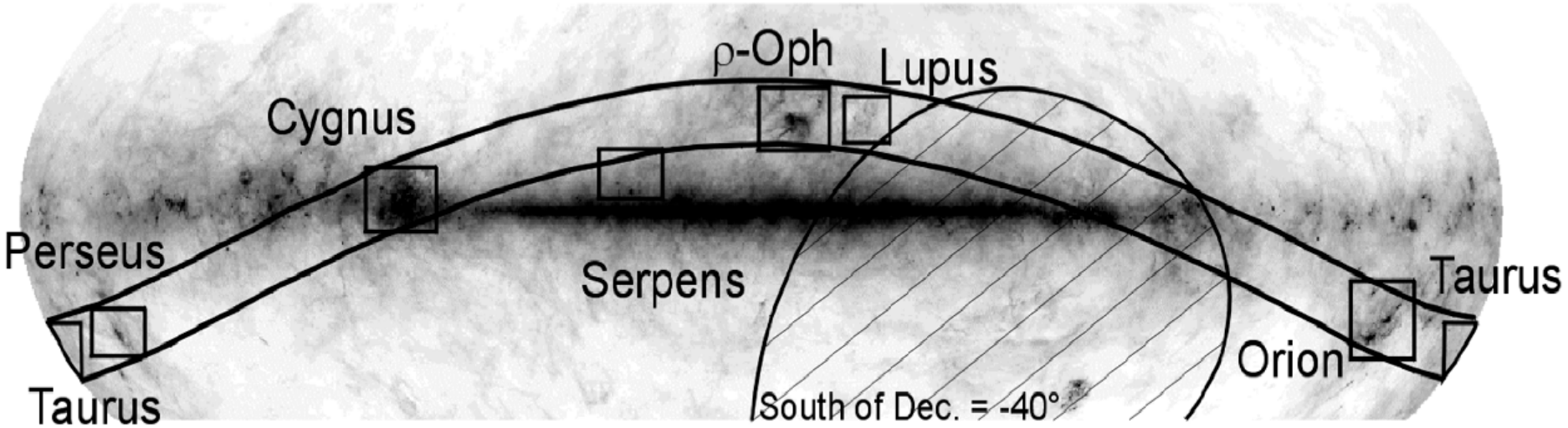


4 example maser spot maps

Gould's belt distance survey

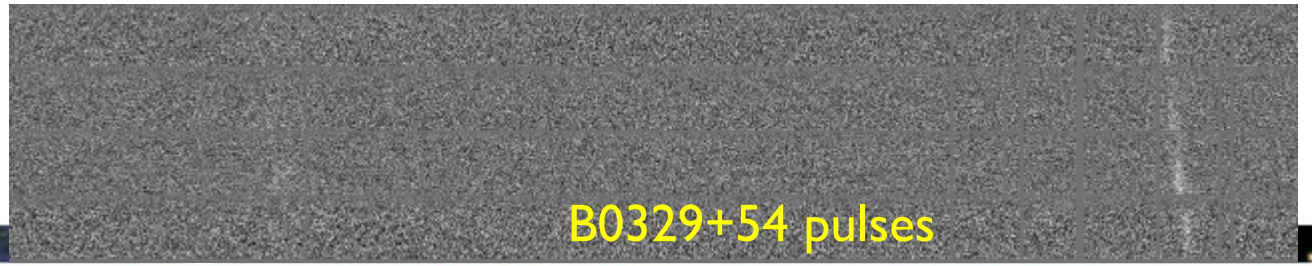
Loinard et al.

- Goal: determine distances to nearby star-forming regions
  - Perform parallax astrometry on young radio bright stars
  - EVLA used to identify suitable stars
- Results from studies of the Taurus star forming region are already mapping the three dimensional structure of the region
- Accurate distances to star forming regions is a new luxury



V-FASTR: Fast transient detection with the VLBA

- VLBA DiFX Software Correlator has been augmented with a transient detection pipeline
  - Looks for "Lorimer" type events
  - Commensally searches all projects correlated in Socorro
  - Short term (~2ms) accumulated spectra sent to processor
  - Data are reordered, flattened, and searched for dispersed pulses
- Machine-learning algorithms exploited (Thompson et al., 2011, ApJ, 735, 98)
  - 10 separated antennas used as coincidence detectors
  - Artificial pulses injected constantly to assess/set thresholds
- Pulsar test datasets prove the concept (Wayth et al., 2011, ApJ, 735, 97)
  - Regular pulses from PSR B0329+54 detected
  - Giant pulses from the Crab Pulsar detected



VLBA Astrometry of Cassini at Saturn

- 8 measurements of the position of Cassini were made between 2006 and 2009; each measurement was accurate to ~0.3 mas (2 km) relative to the quasar reference frame (ICRF).
- This new data is contributing to the new DE422 planetary ephemeris. Ongoing observations will ultimately reduce uncertainty in Saturn's position by a factor of about 3 as more of Saturn's orbit is probed.
- This will have implications for spacecraft navigation, solar system dynamics, relativity research, pulsar timing, and frame ties connecting the solar system to the ICRF.

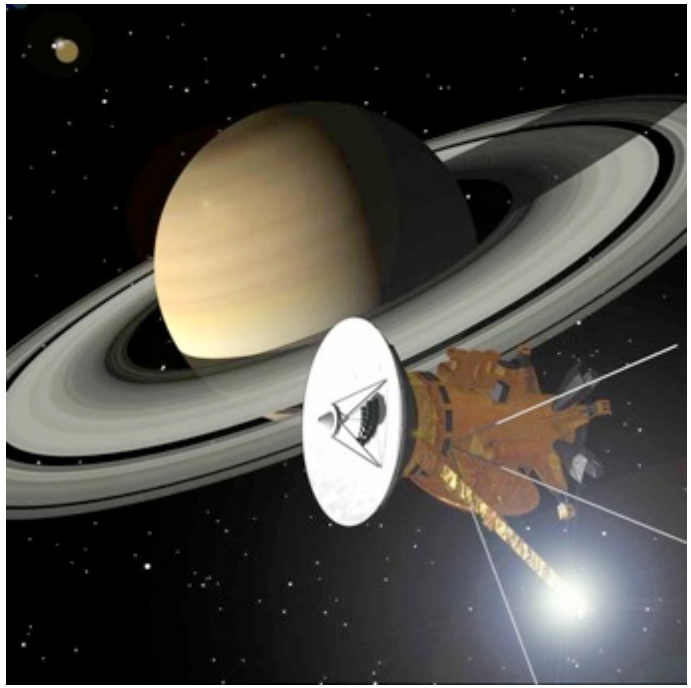


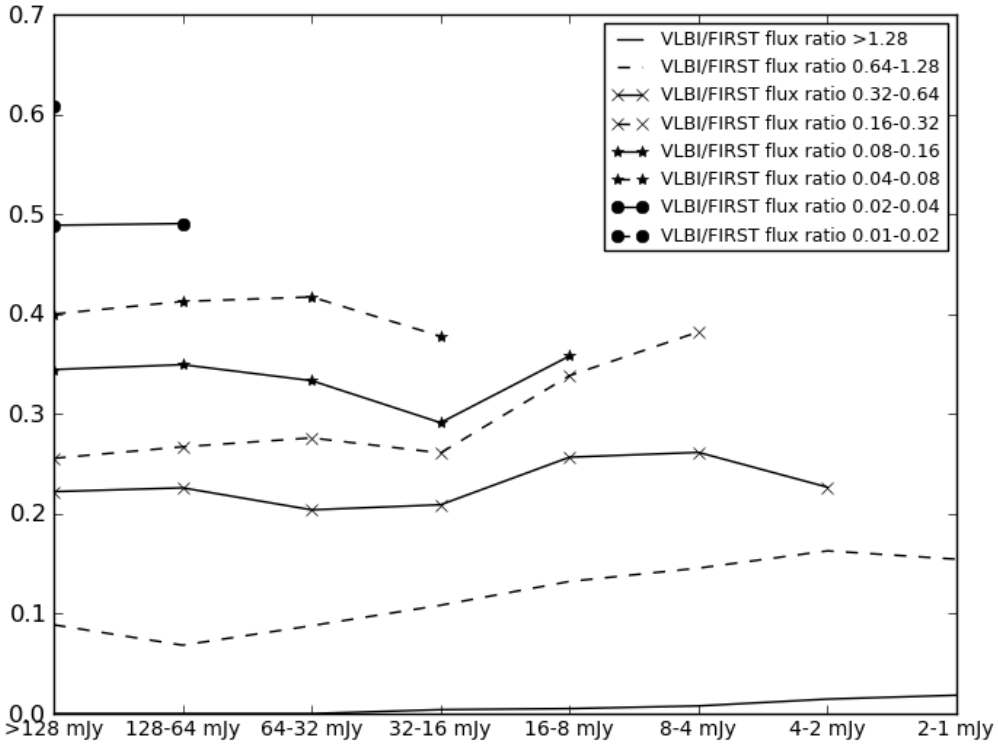
Image: NASA

Jones et al., 2011, ApJ, 141, 29

mJIVE-20

(Adam Deller et al.)

- Correlate at positions of all FIRST sources surrounding known calibrators
- Look for compact source fraction
- 200 hours of observing to date
- About 21% of ~10000 sources detected at < 10 mas resolution
  - Due to selection effects, the real value is likely ~30%
- One new VLBI source every 6 minutes of observing!
- There is some hint of detection fraction for fainter sources



Daily UT1-UTC observations

- US Naval Observatory is contributing to VLBA operations in exchange for daily 1 hour observations using 2 VLBA antennas: Mauna Kea and Pie Town
- High speed network links have been installed at these two sites
  - MK and PT to Washington D.C. at ~250 Mbps
- Daily ~1 hour observations began in July
  - Observations make use of 2 Gbps capability
- VLBA science may be interrupted
- Users have been contacted with tips to reduce impact on observing

EVLA

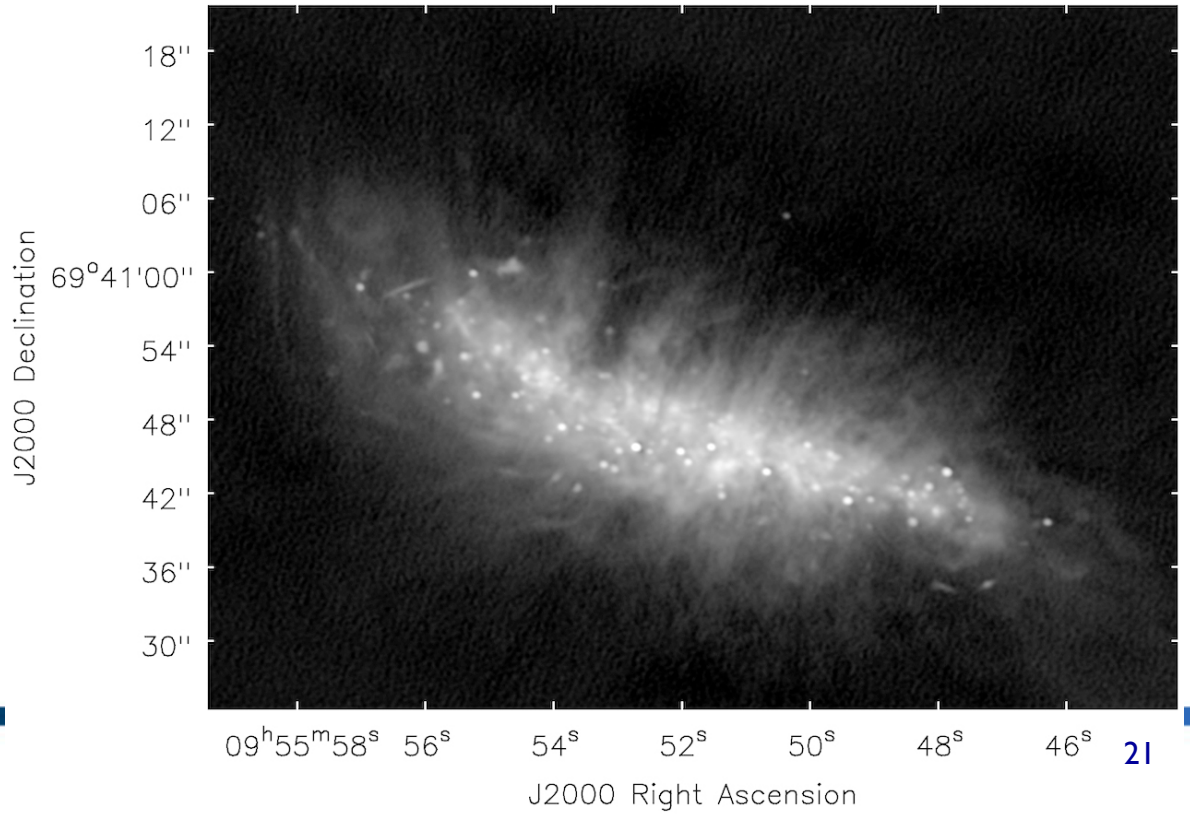
Hercules A (Perley and Cotton, demo)

- z = 0.154, radio galaxy. D = 710 Mpc, 1arcsec = 3.4 Kpc.
- 4-9 GHz color-code spectro-intensity image (redder = older). 1 Kpc res^{n}.
- EVLA data: 1 through 9 GHz, all four configurations, 1Kpc resolution.
- Shocks in western lobe indicate repeated ejection.

M82 – The Prototype Nearby Starbust Galaxy

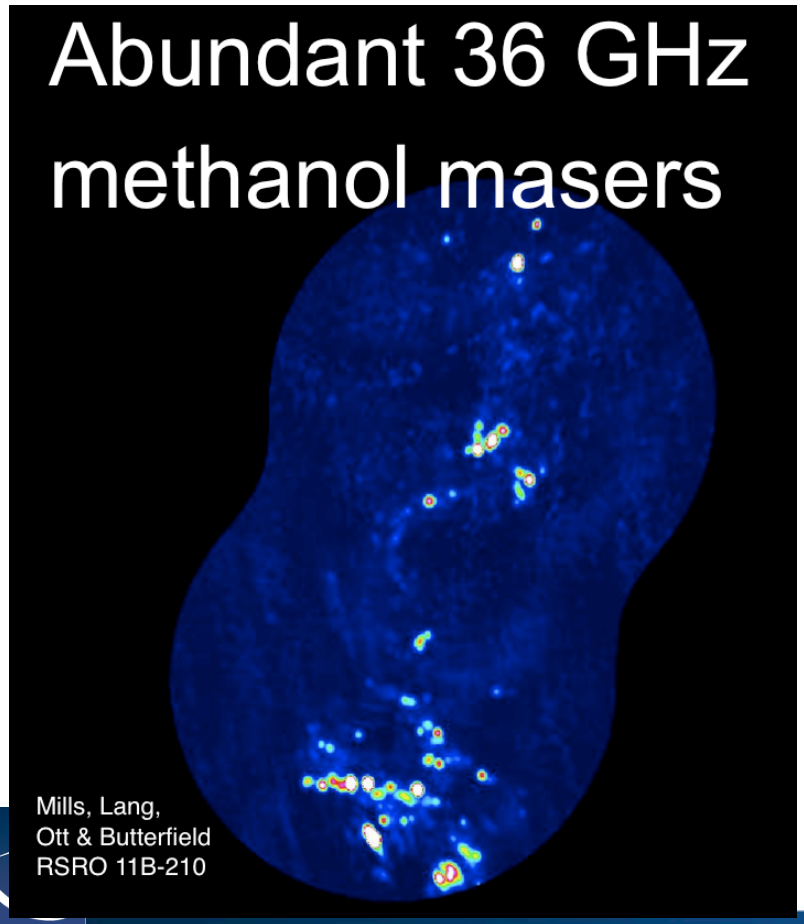
- Shown is a deep C-band VLA image, combining A and B configuration data.
- Resolution is 0.35 arcseconds (5 pc at distance of M82).
- Extreme nuclear starburst driving a superwind > 1Kpc above disk.
- Visible are: SNR and some HII regions throughout star forming disk.
- Synchrotron radio halo shows filamentary structures
- Matches H-alpha and Xray images.
- Inhomogenous distribution of super-star clusters drives multiple outflow channels.

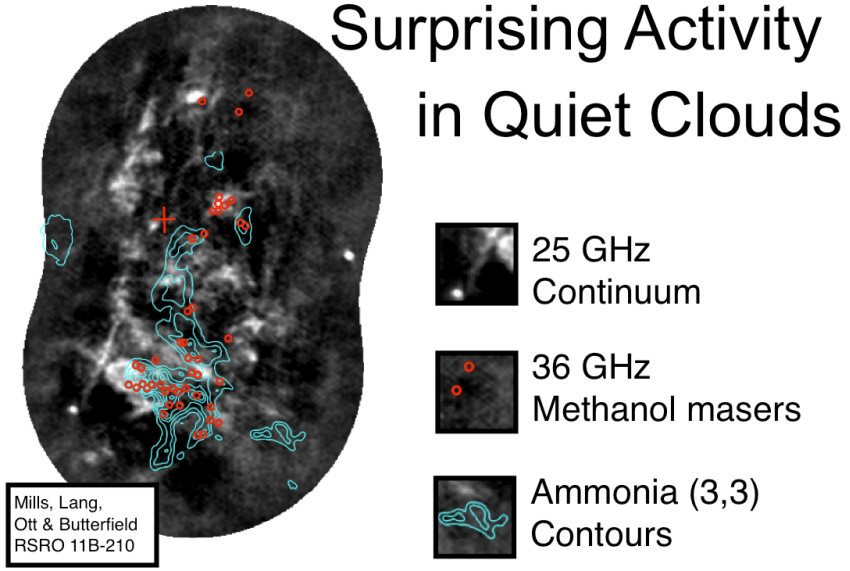
J. Marvel, Owen, Eilek



36 GHz Methonal Masers – everywhere!

- Tracers of shocks. Abundant, even in apparently quiet clouds.
- Shown is methanol masers, ammonia (3,3), and continuum, all from VLA.





Questions?

Bonus material…

EVN + VLBA : Global VLBI

- Add telescopes from the European VLBI Network (EVN) to the VLBA.
- The EVN has many large sensitive telescopes adding them increases the sensitivity as well as improving *uv* coverage (e.g., EVN has many more short baselines so can be more sensitive to larger structures.)

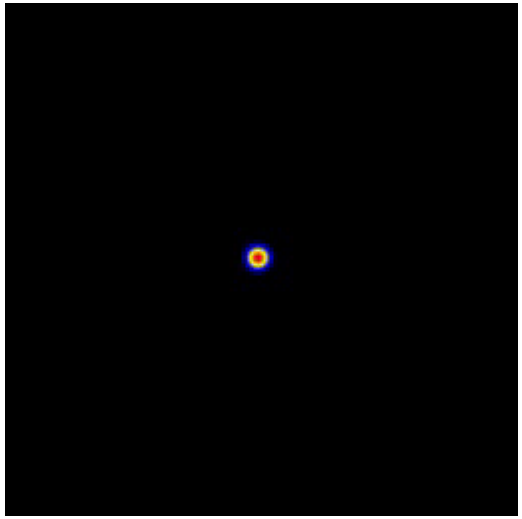
Global Millimeter VLBI Array (GMVA)

- Special high-sensitivity session-based VLBI network
- Observing at 3mm (86-90 GHz) wave-band
  - Yields highest resolution ground-based images in astronomy
- Stations:
  - VLBA
  - Effelsberg
  - Metsahovi
  - Onsala
  - Plateau de Bure
  - Pico Valeta
  - Yebes
- Coordinated and correlated by MPIfR in Germany
- Typically two 5-day sessions per year

Important Links

- NRAO Help Desk
  https://help.nrao.edu
- VLBA Observational Status Summary
  http://www.vlba.nrao.edu/astro/obstatus/current/
- EVN Sensitivity Calculator
  http://www.evlbi.org/cgi-bin/EVNcalc
- Proposal Submission Tool
  my.nrao.edu
- SCHED – observation preparation software
  http://www.aoc.nrao.edu/software/sched/index.html
- AIPS – data reduction software
  http://www.aips.nrao.edu/index.shtml
- 13th Synthesis Imaging Workshop (next one in 2014)
  http://www.aoc.nrao.edu/events/synthesis/2012/

SN1993J in M81



Bartel et al. 2000