The Jansky Very Large Array – New Capabilities, New Science

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Atacama Large Millimeter/submillimeter Array

Expanded Very Large Array

Robert C. Byrd Green Bank Telescope

Very Long Baseline Array

The Very Large Array -- Overview

- The Very Large Array is a 27-element, reconfigurable interferometer array, located in west-central New Mexico, USA. (lat = 34.1, long = 107.6).
- High elevation (2100 m), desert climate (~20 cm yearly precipitation, 76% sunny), means good observing conditions most of the year.
- There are four major configurations, offering a range of over 300 in imaging resolution.
  - e.g. 1.5" to 400" at λ=21cm
- The original VLA, commissioned in 1980, has now been upgraded.
- The new instrument – the Jansky Very Large Array, has hugely improved capabilities.

EVLA Project Overview

- The EVLA Project was a major expansion of the Very Large Array.
  - The upgraded telescope is now called the Jansky Very Large Array.
- Fundamental goal of the project: At least one order-of-magnitude improvement in all observational capabilities, except spatial resolution.
- The project began in 2001, and was completed early in 2013 – on budget and on schedule.
- Key aspect: A leveraged project, building on existing VLA infrastructure.
  - A sound strategy for these fiscally constrained times …

Major Goals for the VLA's Upgrade

- Full frequency coverage from 1 to 50 GHz.
  - Provided by 8 frequency bands with cryogenic receivers.
- In addition, the 50 – 450 MHz band is covered by a ninth receiver.
- Up to 8 GHz instantaneous bandwidth
  - Provided by two independent dual-polarization frequency pairs, each of up to 4 GHz bandwidth per polarization.
  - All digital design to maximize instrumental stability and repeatability.
- New correlator with 8 GHz/polarization capability
  - Designed, funded, and constructed by our Canadian partners, HIA/DRAO
  - Unprecedented flexibility in matching resources to science goals.
- <3 μJy/beam (1-σ, 1-Hr) continuum sensitivity at most bands.
- <1 mJy/beam (1-σ, 1-Hr, 1-km/sec) line sensitivity at most bands.
- Noise-limited, full-field imaging in all Stokes parameters for most observational fields.
  - Requires higher level of software for calibration, imaging, and deconvolution.

Jansky VLA-VLA Capabilities Comparison

EVLA

The upgraded VLA's performance is vastly better than the VLA's:

Parameter	VLA	Jy VLA	Factor	Current
Point Source Cont. Sensitivity (1σ,12hr.)	10 μJy	1 μJy	**10**	1 μJy
Maximum BW in each polarization	0.1 GHz	8 GHz	**80**	8 GHz
# of frequency channels at max. BW	16	16,384	**1024**	16384
Maximum number of freq. channels	512	4,194,304	**8192**	131072
Coarsest frequency resolution	50 MHz	2 MHz	**25**	2 MHz
Finest frequency resolution	381 Hz	0.12 Hz	**3180**	1 Hz
# of full-polarization spectral windows	2	64	**32**	64
(Log) Frequency Coverage (1 – 50 GHz)	22%	100%	**5**	100%

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The Jy VLA as a 'Leveraged Investment'

- The EVLA Project made maximum use of existing hardware and infrastructure.
- The EVLA utilizes the VLA's 25-meter parabaloids.
  - Off-axis Cassegrain optics.
  - Change band by rotating subreflector
- Disadvantages:
  - Big and slow
  - Not the best choice for fast wide-field surveys
- Advantages:
  - Paid for!
  - Work well up to 50 GHz.
- Also retained:
  - Configurations, buildings, basic infrastructure, people.

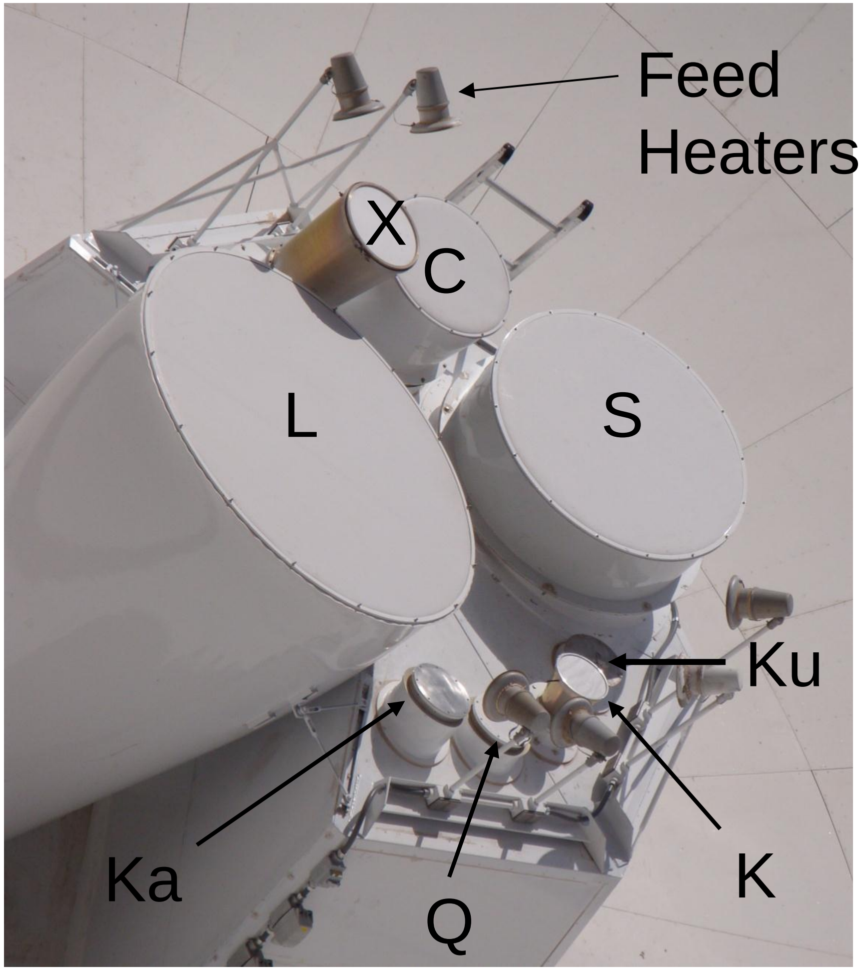
Antenna 24 – the first EVLA antenna outfitted with all eight feeds.

Full Frequency Coverage with Outstanding Performance

EVLA

- There are eight cassegrain focus systems, and one prime focus system.

Band (GHz)		SEFD (Jy) (27 antennas)
.05 -- .45	P	~60
1-2	L	13
2-4	S	9.5
4-8	C	8.5
8-12	X	8.1
12-18	Ku	8.1
18-26.5	K	13
26.5-40	Ka	22
40-50	Q	45



$$\sigma_I \approx \frac{SEFD}{7\varepsilon\sqrt{B_M T_{Hr}}} \quad \mu Jy / beam$$

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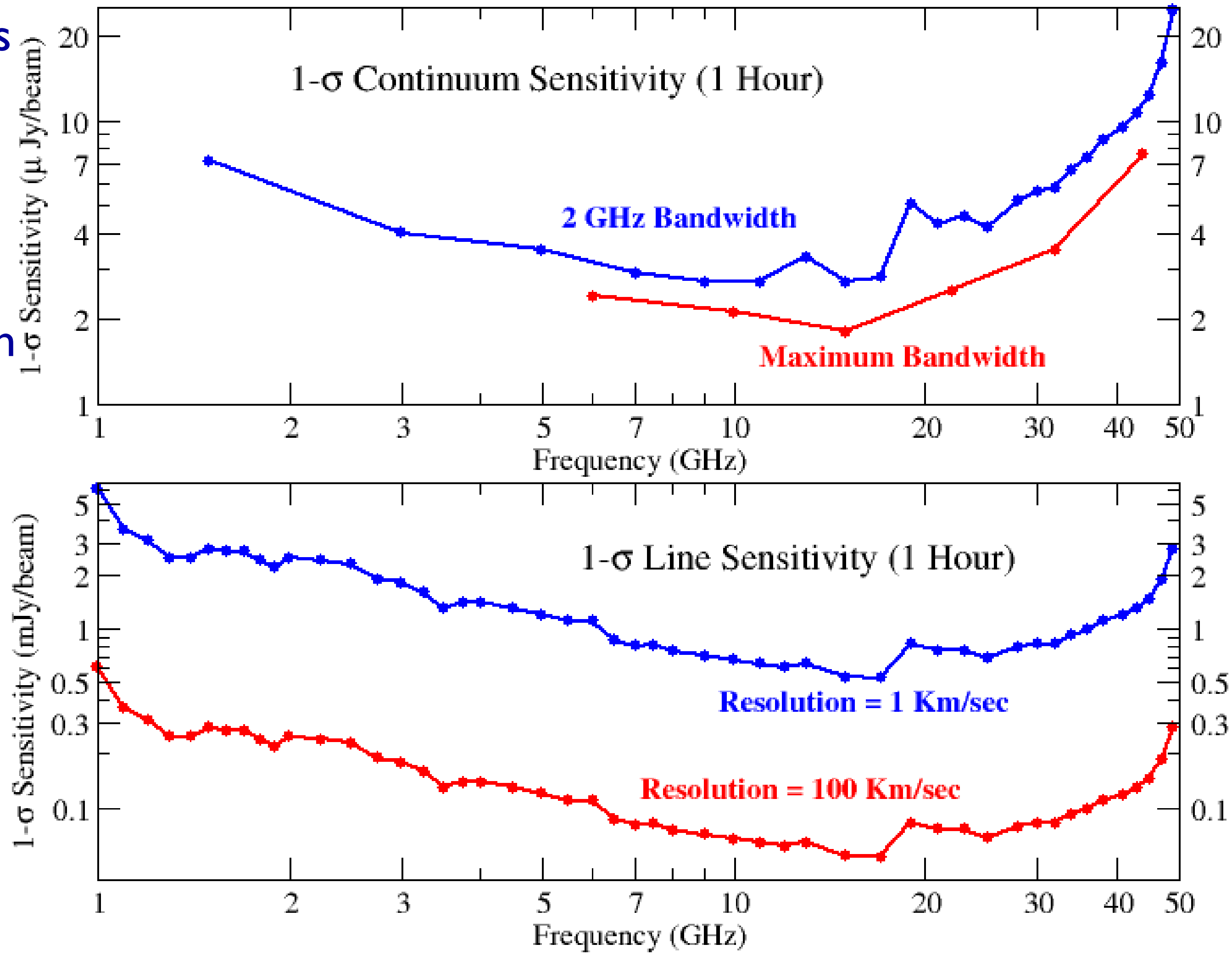
EVLA

VLA Sensitivity (rms in 1 Hour)

- Achieved sensitivities exceed project requirements at all frequencies above 8 GHz.
- Most sensitive region in continuum is 8 – 15 GHz.
- Most sensitive for spectral line is 10 – 30 GHz.



The 'WIDAR' Correlator's Special Modes

Some useful features (not all implemented yet):

- Each of the 64 spectral windows can be tuned to its own frequency, with its own bandwidth (128 MHz to 31.25 kHz) and spectral resolution (from 2 MHz to .12 Hz)
- 100 msec dump times with all 16384 channels and full polarization – and faster if spectral resolution is decreased. Fastest so far is 10 msec, for two polarizations, 2048 channels, and 1024 MHz bandwidth.
- > 44 dB (and up to 58 dB) isolation between spectral windows. (To prevent RFI leakage contamination)
- Up to 8 sub-arrays.
- Phased array capability for full bandwidth: – for pulsar and VLBI applications. Two different subarrays can be simultaneously phased.
- Special pulsar modes: 2 banks of 1000 time bins, and 200 μsec time resolution (all spectral channels), or 15 μsec (64 channels/sp.window)
- VLBI enabled

Ongoing VLA Developments

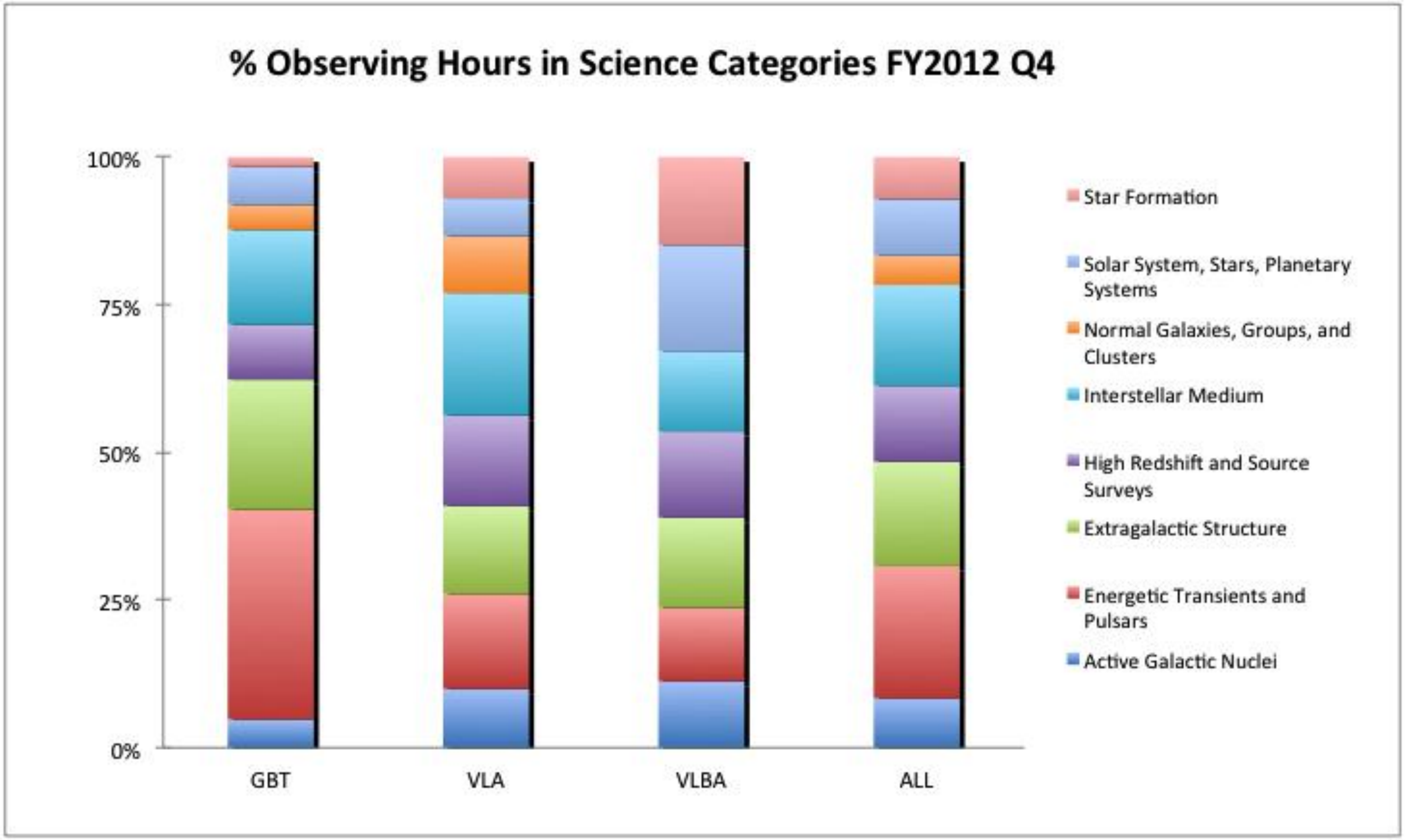
- Jansky VLA capabilities are constantly being improved.
- New capabilities to be offered by year's end:
  - Full bandwidths (3-bit samplers) at C, X, Ku bands.
  - More flexible tuning of spectral windows (non-contiguous, arbitrary widths)
  - Data output rates to 60 MB/sec (current max is 20 MB/s)
- Other capabilities – now available -- of interest:
  - Max. channels limited to 16384. (Recirculation modes disallowed).
  - All subband widths allowed (31.25 kHz through 128 MHz)
  - 3 simultaneous subarrays (8-bit mode only)
  - Integration times as short as 50 msec (Shared Risk)
  - P-band back on line (230 – 370 MHz), (Shared Risk)
  - 27-antenna Phased Array mode enabled for VLBI.

Who's Using the Jansky VLA, and for What Science?

- The Jansky VLA, like the VLA, was designed for flexibility.
- There were no 'key science' projects in the proposal.
- There are no 'guaranteed time' proposals or consortia.
- The Jansky VLA is an open skies instrument, with time granted solely on the basis of scientific merit.
- Approximately 200 proposals have been submitted for each semester. Of these, about 175 are accepted, at least in part.
- Oversubscription ratio ~2:1.
- Large increase in high frequency proposals (ν>20 GHz), driven by new availability of 8 GHz bandwidth, and hi-z studies.

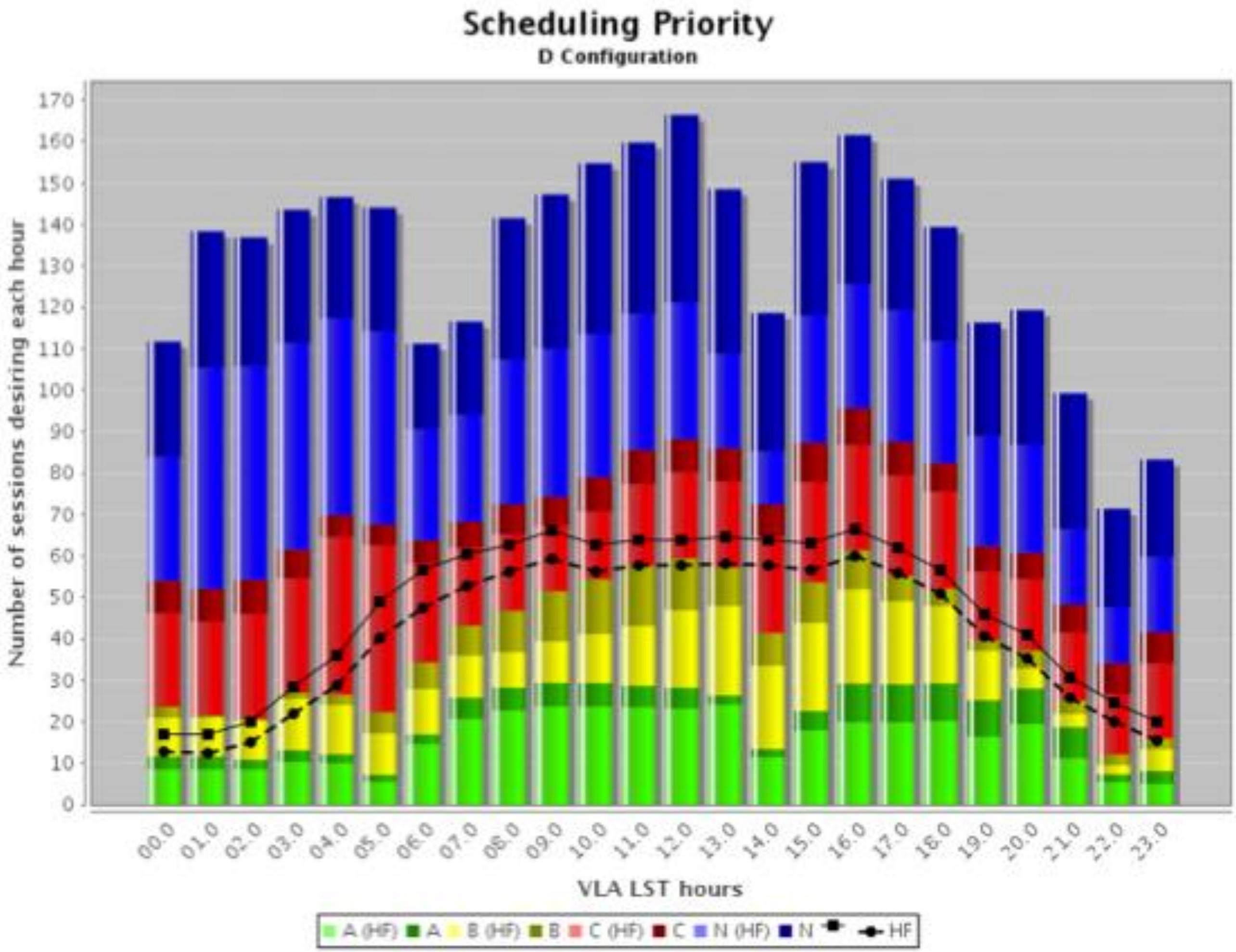
Observing Distribution by Category

- Shown here are the fractional usages of the NRAO's major instruments, categorized by major science category.



High Frequencies Observations Dominate

- 'Pressure Plot', showing the observing requests as function of LST and priority.
- Priority 'A'
- Priority 'B'
- Priority 'C' (filler)
- Rejected.
- Color Shadings indicate High/Low frequencies.



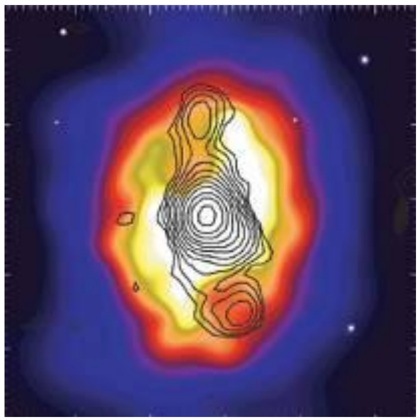
EVLA

Examples of Recent VLA Science

- The VLA was designed to be a general-purpose telescope. The upgrade maintains this philosophy.
- About 60% of the array time is now used for science observing – a fraction we expect to rise to 70% by next year.
- Daytime observing still at a premium, due to ongoing commissioning activities.
- The new science spans a remarkable range, with strong emphasis on 'thermal' science.
- Following are a number of brief summaries, contributed by a number of individuals.

EVLA Design Driven By Four Themes

Magnetic Universe



Measure the strength and topology of the cosmic magnetic field.

Obscured Universe

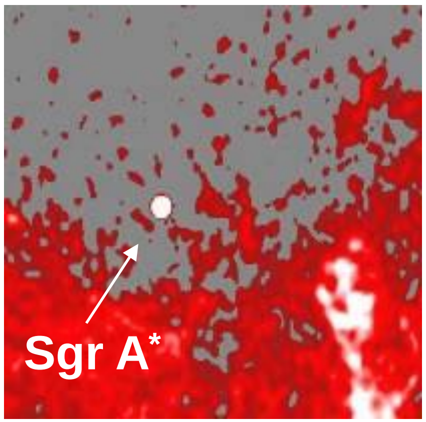
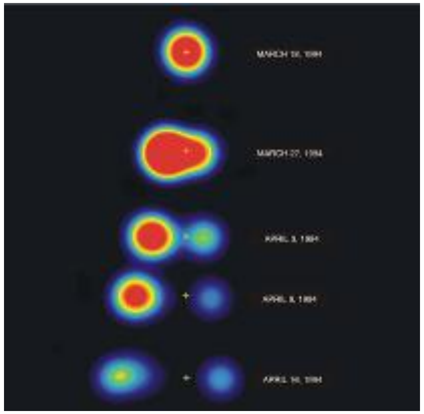


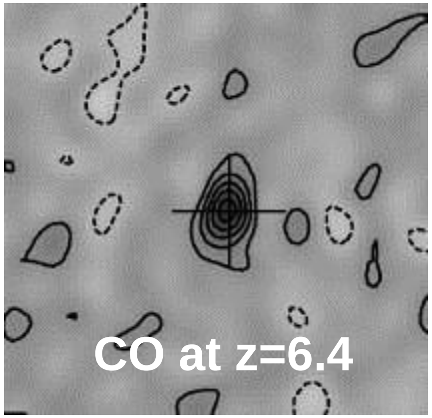
Image young stars and massive black holes in dust enshrouded environments.

Transient Universe



Follow the rapid evolution of energetic phenomena.

Evolving Universe



Study the formation and evolution of stars, galaxies and AGN.

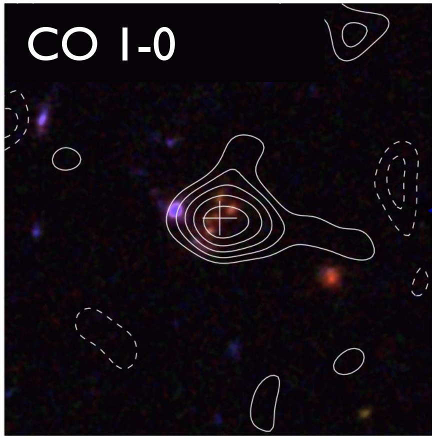
Evolving Universe Theme

- New micro-Jy sensitivity allows deeper continuum imaging.
  - Higher redshift continuum emission now within reach
  - More objects, more types, more classes, more extremes
- Wide spectral coverage, and full frequency coverage, allows studies of high-z molecular emission.
  - Can do 'double-blind searches' – no prior knowledge of specific transitions or specific sources.
  - 'Guaranteed' that there will be early galaxies, detectable in line emission, within a few hours integration, in any Ka or Q band beam!
  - Something of a 'gold rush' underway now.

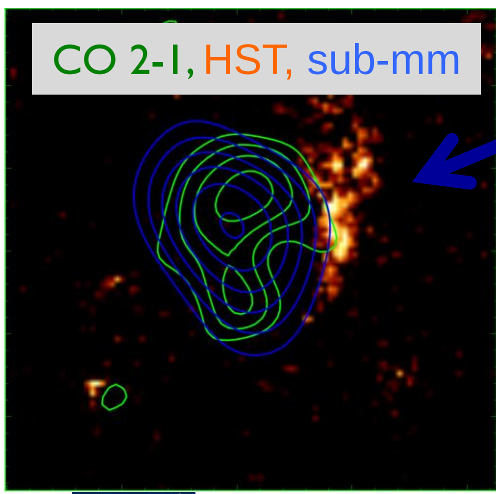
A Molecule-Rich Protocluster

EVLA

Foreground sBzK galaxy

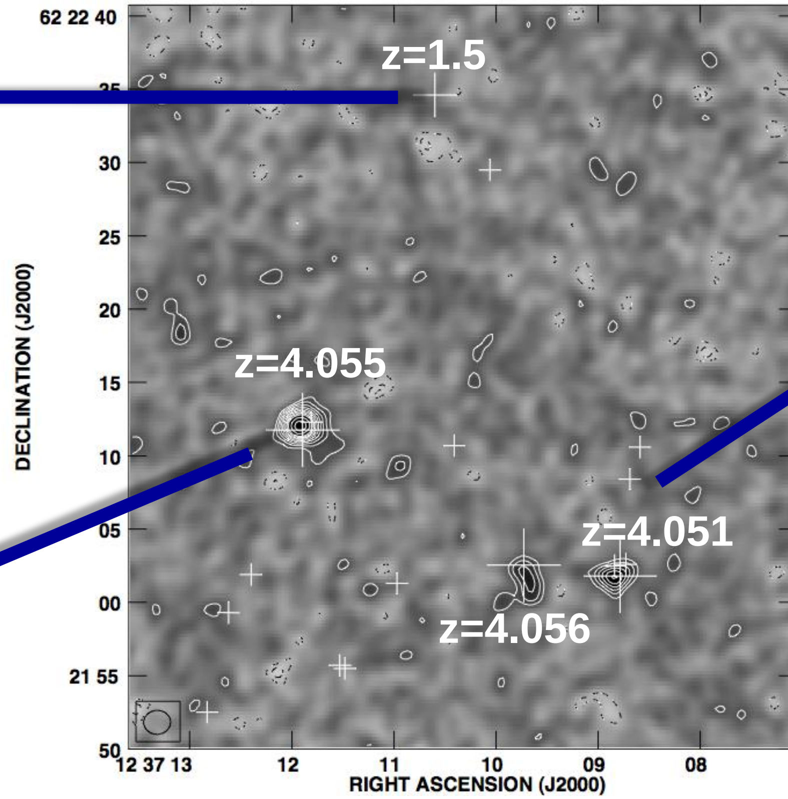


Imaging CO 2-1



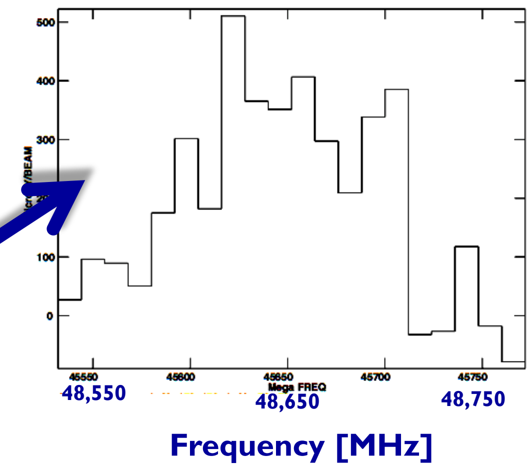
46 GHz Observations of GN20

Frequency Span = 256 MHz; FoV = 60"



CARILLI ET AL. (2011)

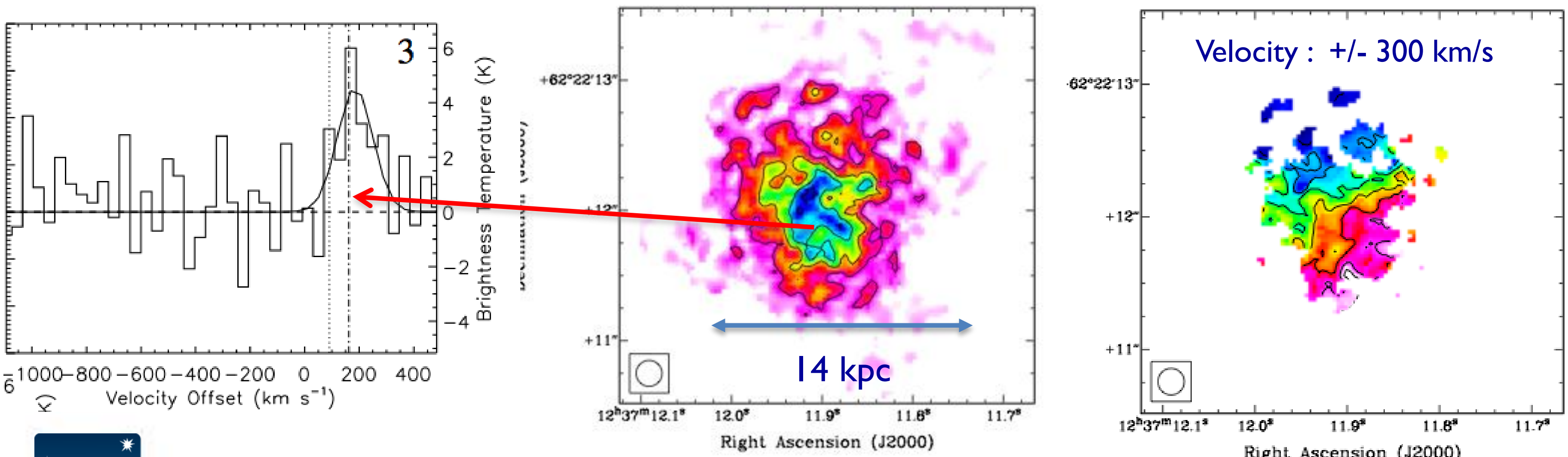
CO 2-1 Spectroscopy



Wide bandwidth=Large redshift range, e.g. *a single EVLA pointing at 30 GHz surveys a region at z=3 of 700 x 700 Mpc with Δz~1 in the CO (1-0) transition*

Imaging gas clumps in early galaxies EVLA

- The VLA has imaged the molecular disk of a galaxy within 1.6 Gyr of the Big Bang at ~ 1kpc resolution in the hyperstarburst galaxy GN20 (z=4.05)
- These observations reveal a rotating disk of molecular gas on a scale of 14 kpc, with a dynamical mass ~ 5e11 M_o. The disk is comprised of 5 massive molecular clumps, possibly self-gravitating, and is highly obscured.
- The gas distribution and dynamics is consistent with a disk formed via cold mode accretion from the IGM driving the extreme starburst

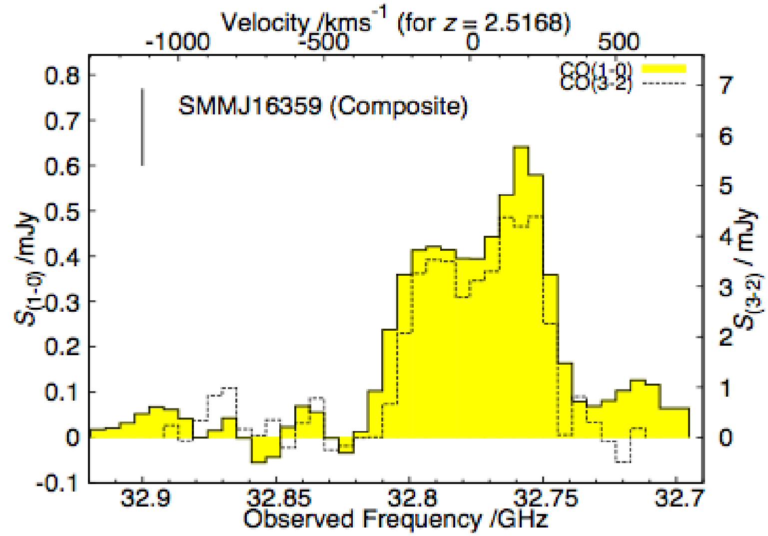


The CO 2-1 image at 0.15" resolution of the z=4.0 Submm Galaxy GN20 (Hodge et al 2012)

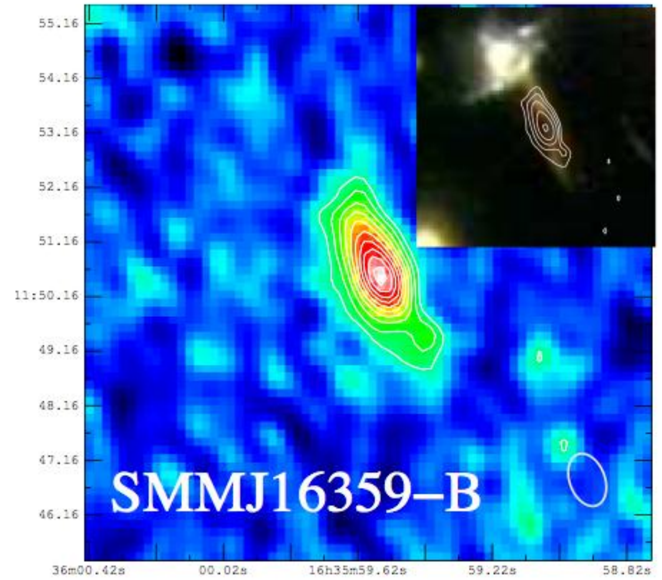
Molecular gas in early main sequence galaxies

- Herschel has identified large samples of gravitationally lensed, very dusty, FIR luminous star forming galaxies, but optical redshifts are difficult to obtain due to obscuration
- Wide bandwidth of VLA has become a powerful tool to obtain redshifts, and molecular gas properties
- VLA has imaged the molecular gas in a set of lower luminosity star forming galaxies at z~2.5. CO (1-0) used in this study.
- Large, rotating disks are seen, containing warm molecular gas
- They also detect thermal Free Free emission for the first time in distant galaxies, providing the best measure to date of star formation rates of 400 – 600 M_0/yr.

(Thompson et al. 2012)



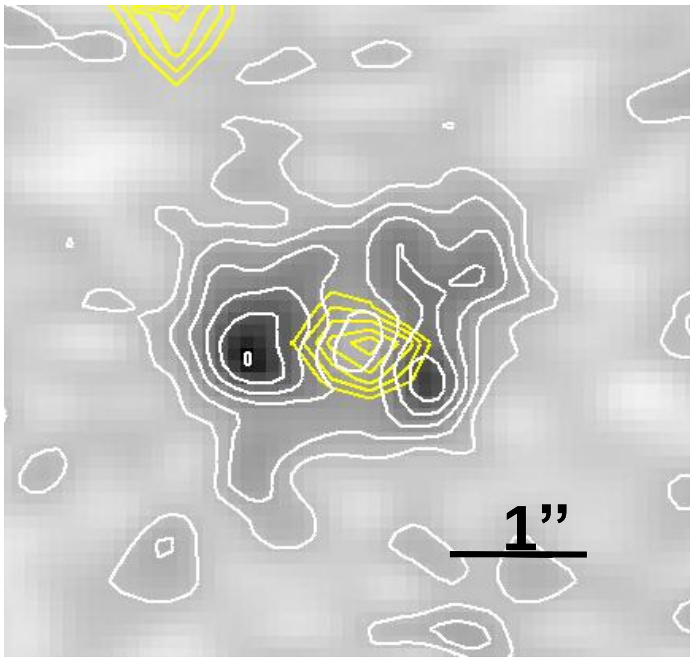
VLA CO (1-0) spectra and images of a star forming galaxy at z=2.5

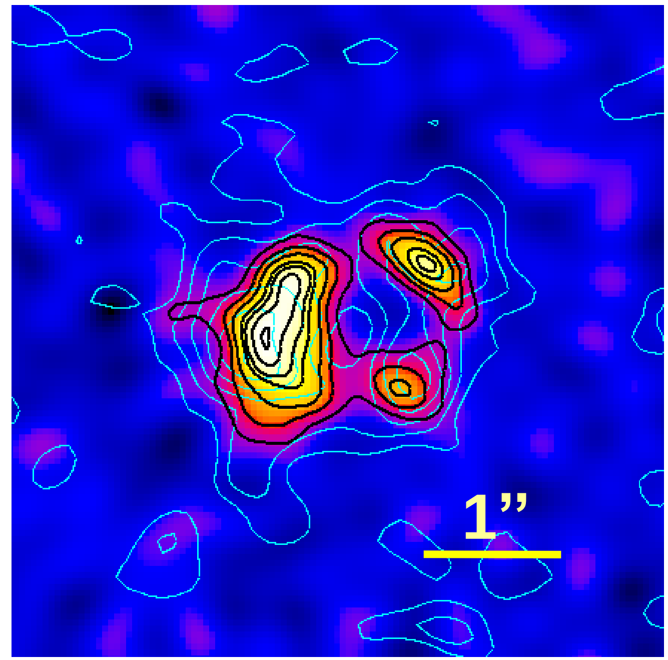


Sub-Millimeter Galaxy MM 18423+5938 at z=3.93 gravitationally lensed into an Einstein Ring.

The lens offers the prospect to study the morphology and kinematics of this galaxy at subkpc scale, 1.6 Gyr after the Big Bang .

(Lestrade et al., ApJL 739, L30, 2011)





JVLA : **CO(2-1)** velocity-integrated map (greyscale) CO(1-0) also observed
CFHT : **Lens galaxy** at z_{photo}=1.1 (yellow contours)

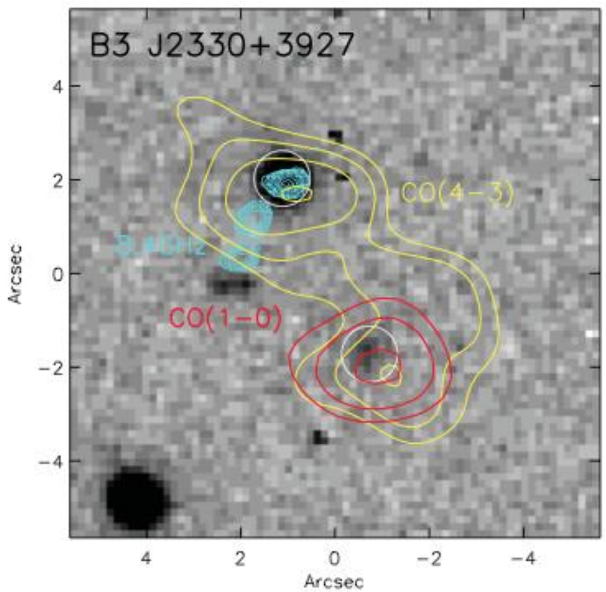
IRAM/PdBI : **Dust** emission in the 1mm band and EVLA CO(2-1) (contours)

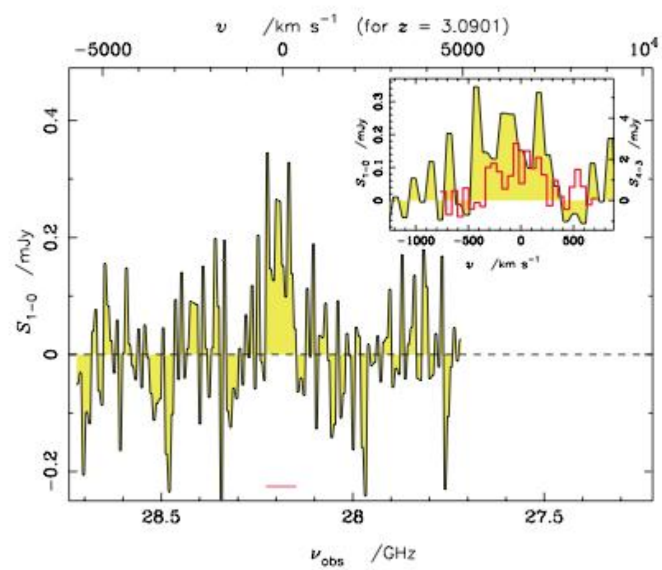
VLA: Imaging molecular gas in forming massive galaxies

- Ivison et al. imaged the CO (1-0) emission from two radio galaxies at z=3 using the VLA and PdBI
- The results indicate extreme, dense starbursts in complex, merging gas rich galaxies
- They see evidence for AGN feedback on the molecular gas through globally enhanced turbulence and high CO excitation

VLA CO (1-0) and PdBI CO (4-3) spectra and images of a radio galaxy at z=3.

(Ivison et al., MN 2012) ArXiv: 1206.4046





ALMA and EVLA – complementarity

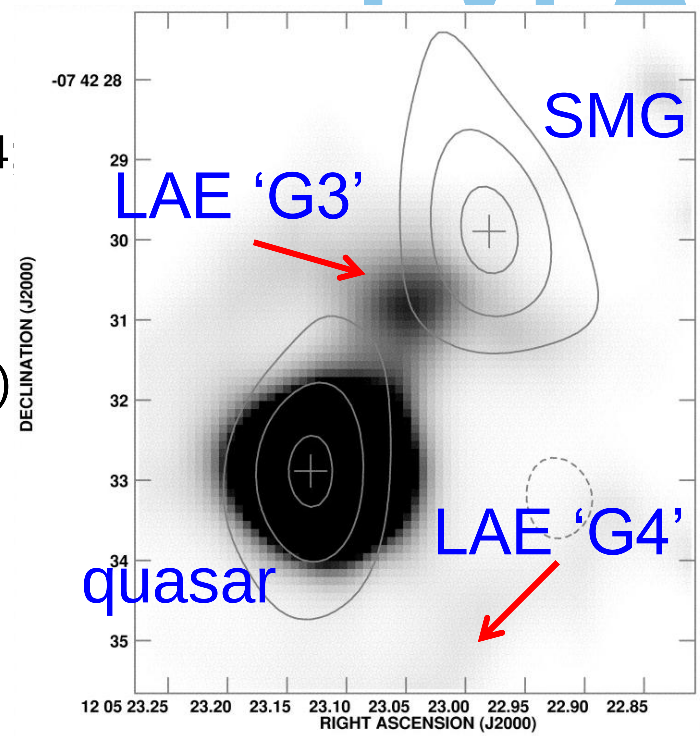
- Three of the four prior examples employed mm (PdBI) interferometer observations as well as VLA.
- The rise of ALMA will strengthen this complementarity, with stellar scientific results.
- New example – Wagg and Carilli combine VLA and ALMA for early forming galaxies:
  - Massive galaxies at z~2 must have formed at earlier epochs.
  - Formation phase seems to have been accompanied by high FIR luminosities, indicating large dust mass heated by star formation and/or quasar activity.
  - ALMA allows us to study FIR emission redshifted to submm bands, and FIR emission from C+, the main FIR cooling line in the ISM, which can be used to trace kinematics.
  - VLA is sensitive to cold molecular gas traced by CO line emission, telling us how much fuel these galaxies have to form stars.
  - Wagg and Carilli are studying BR1202-0725:

BR1202-0725: a laboratory for massive galaxy formation at z=4.7

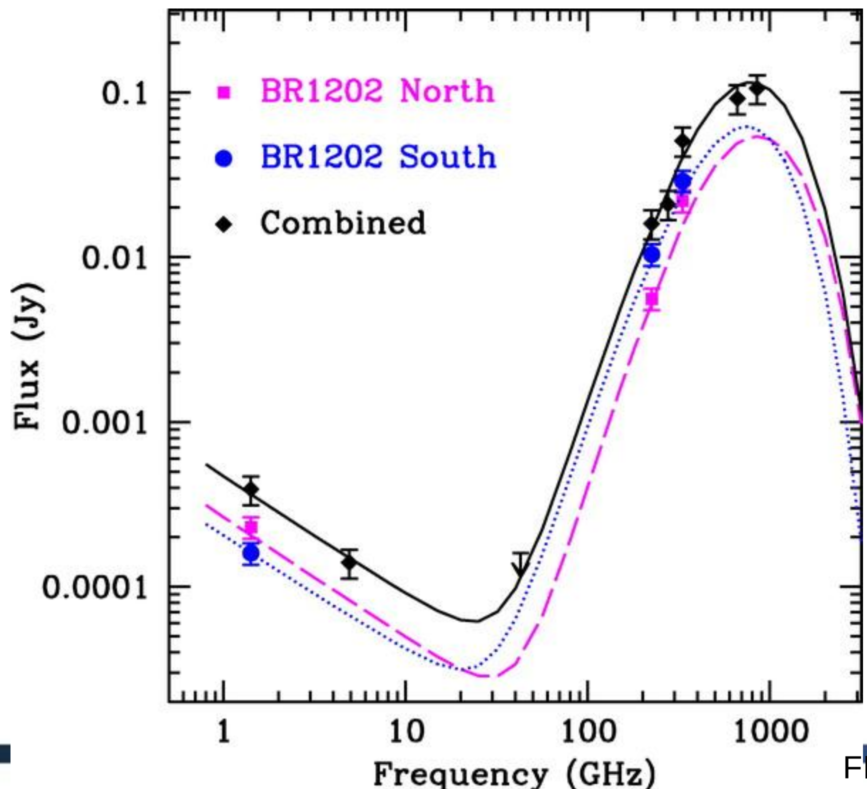
- quasar host galaxy at z=4.7 (t_{univ}~1.3 Gyr)

- L_{FIR} ~ 1013 $L_\odot$, SFR~1000 $M_\odot$/yr (Isaak et al 1994; Benford et al 1999)

- submm galaxy and quasar within ~5'' (25 kpc) (Omont et al 1996; Carilli et al 2002; Iono et al 2006)



VLA CO J=2-1 overlaid on Lyα (Carilli et al 2002; Hu et al 1996)



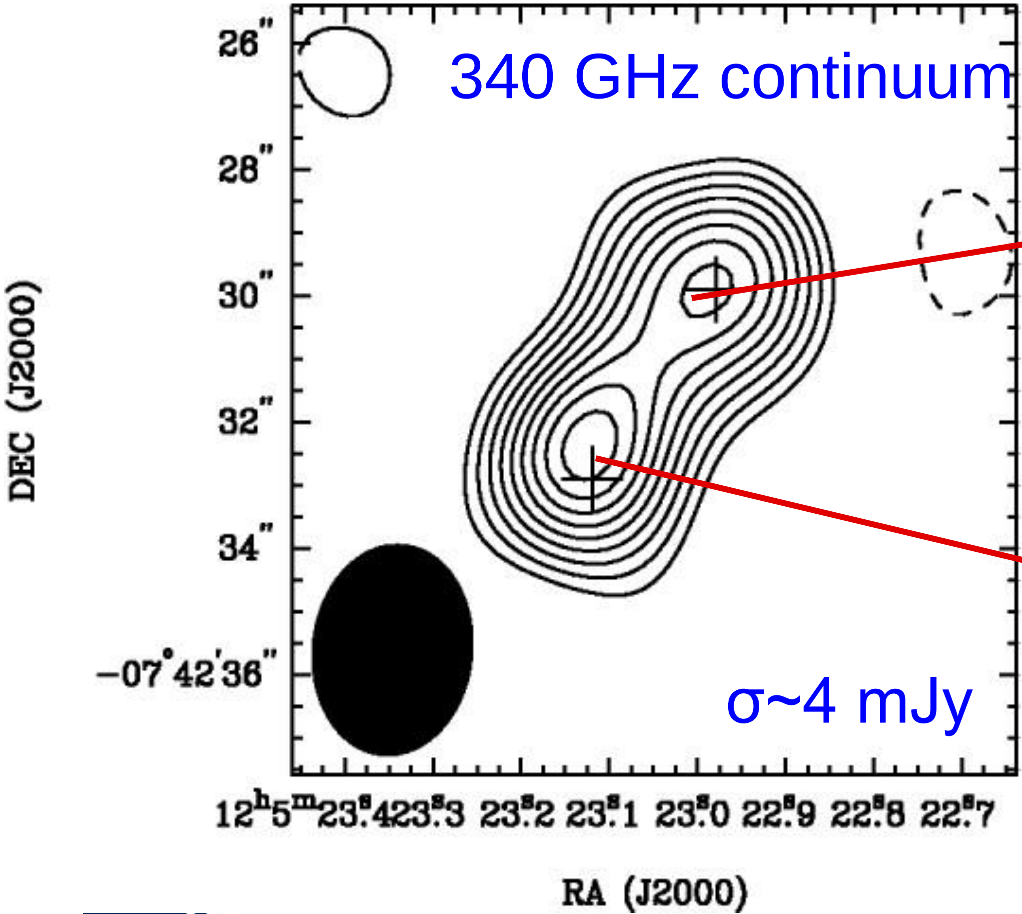
- CO molecular gas, ~8 × 1010 $M_\odot$ (Omont et al 1996; Guilloteau et al 1999; Carilli et al 2002; Riechers et al 2006)

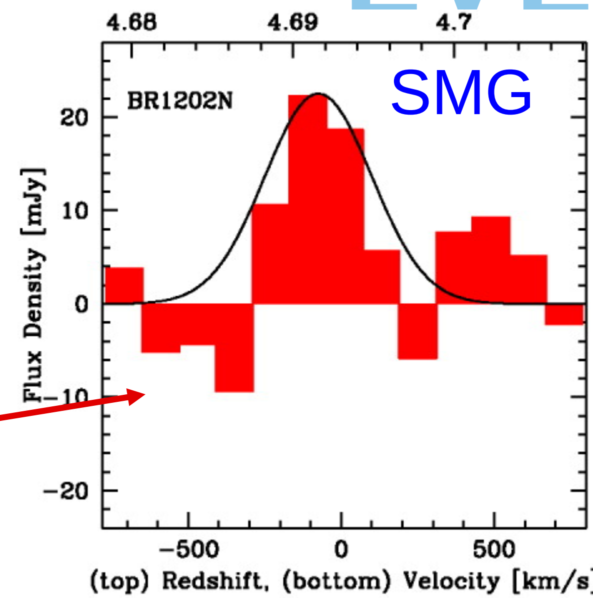
- two Lyα emitters at z~4.7 (Hu et al 1996)

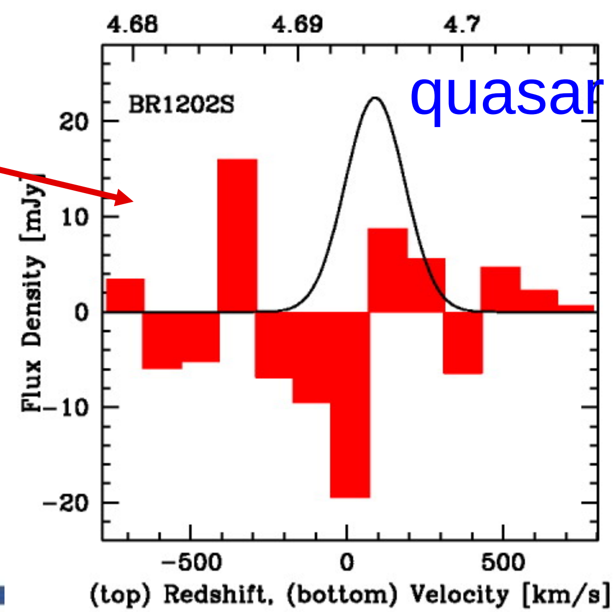
FIR to cm-wavelength SEDs: Benford et al 1999; McMahon et al 1999; Omont et al 1996; Carilli et al 2002; Iono et al 2006

BR1202-0725: FIR dust continuum and [CII] line emission

SMA Image: 7/8 antennas, 5 nights observing. (Iono et al., 2006)



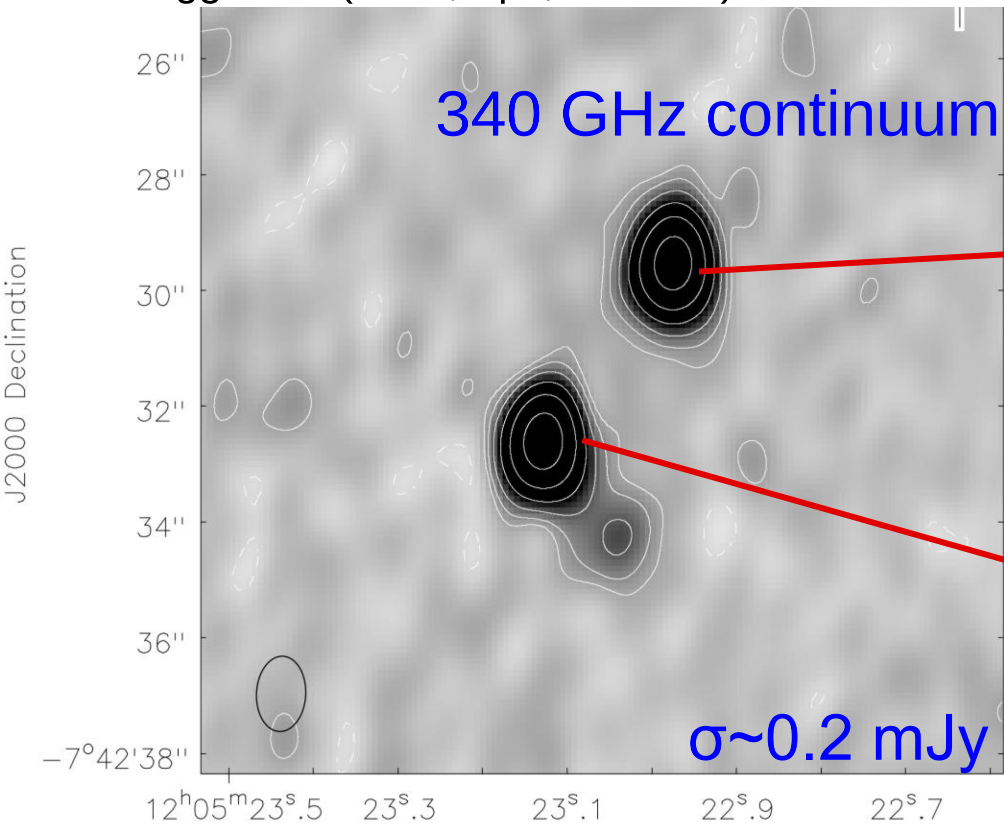


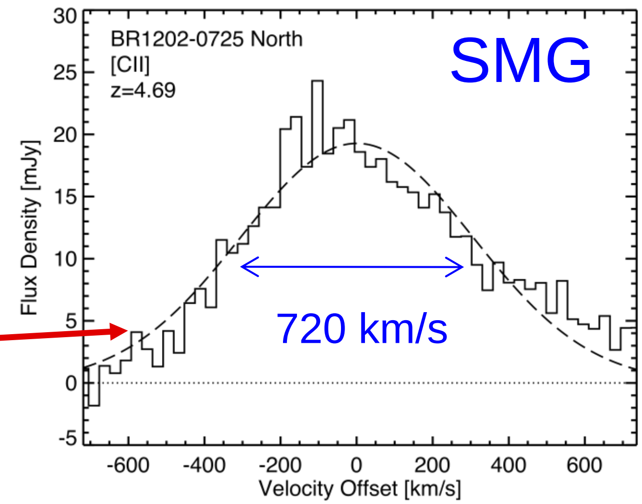


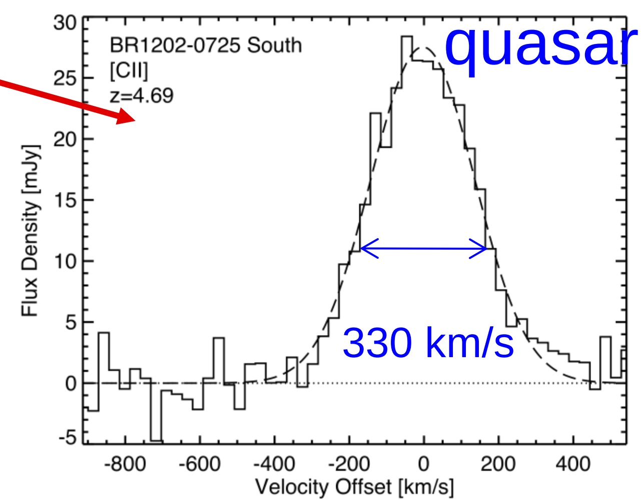
BR1202-0725: FIR dust continuum and [CII] line emission

EVLA

ALMA Image: 17 12m antennas, 12 minutes on source.
Data taken as part of science verification
Wagg et al. (2012, ApJ, 752 L30)







- S_{340GHz} = 43±6 mJy (SCUBA: 42±2 mJy)
- SMG: $L_{[CII]}/L_{FIR}$ ~ 8×10-4; quasar: $L_{[CII]}/L_{FIR}$ ~ 2×10-4

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JVLA: Molecular gas and thermal dust emission

EVLA

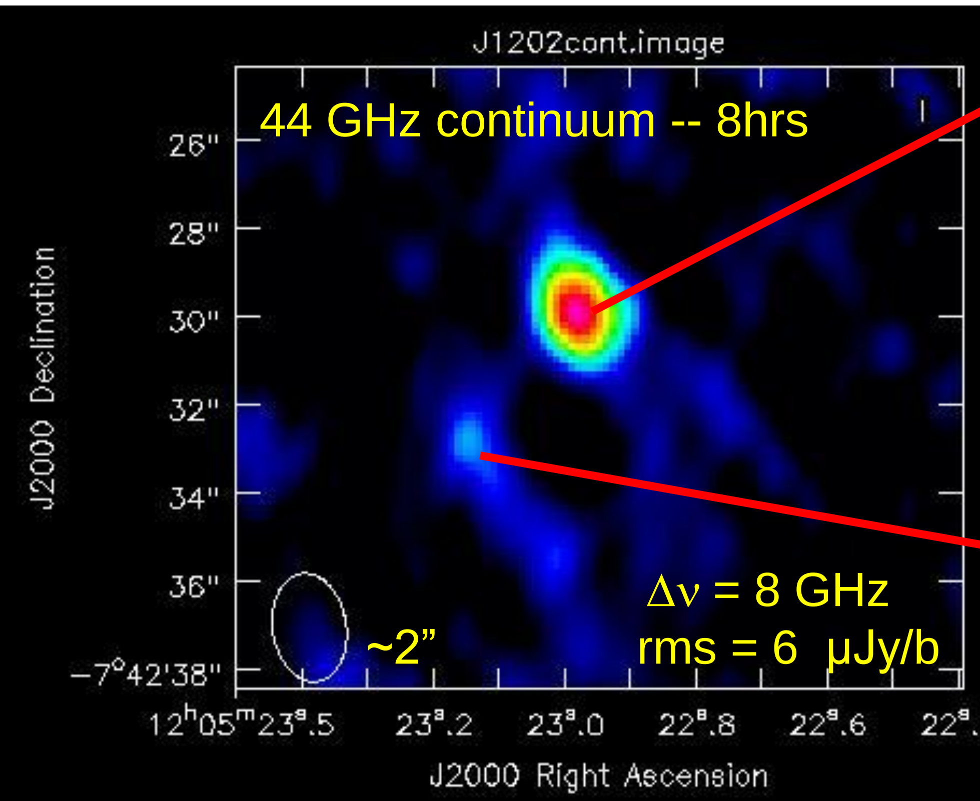
Wagg, Carilli et al. *in prep*

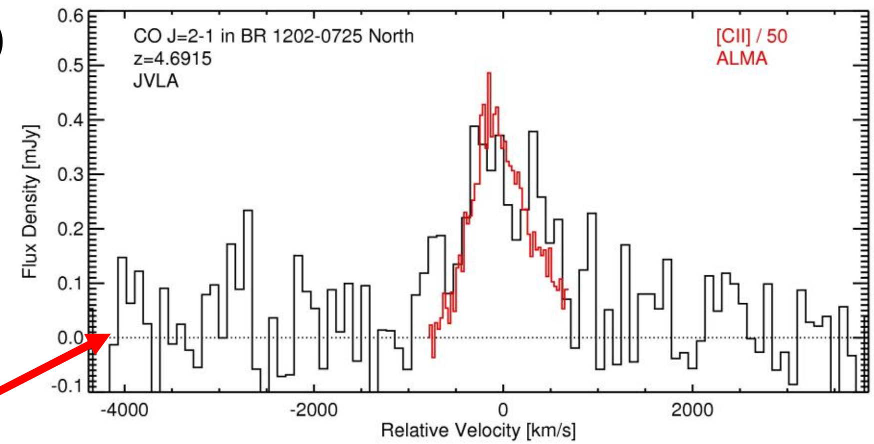
- SMG and QSO: $L'_{CO(J=5\text{-}4)} / L'_{CO(J=2\text{-}1)} \sim 1$

T_{kin}~40-50K, $n(H_2)$~2000cm^{-3} (Salome et al 2012)

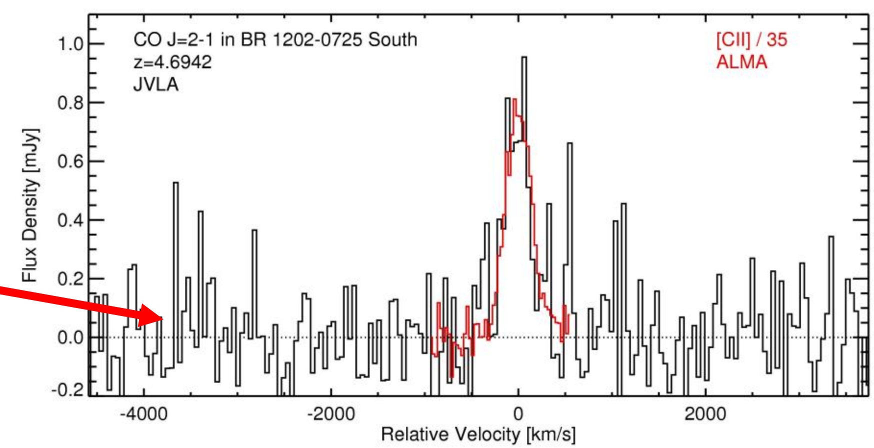
- SMG: $L_{[CII]}/L'_{CO} \sim 50\ L_\odot$ / [K km/s pc2]

  QSO: $L_{[CII]}/L'_{CO} \sim 35\ L_\odot$ / [K km/s pc2]





$L'_{CO(J=2\text{-}1)} = (7.6 \pm 0.8) \times 10^{10}$ [K km/s pc2]



$L'_{CO(J=2\text{-}1)} = (5.0 \pm 0.5) \times 10^{10}$ [K km/s pc2]

NRAO

JVLA: Molecular gas and thermal dust emission

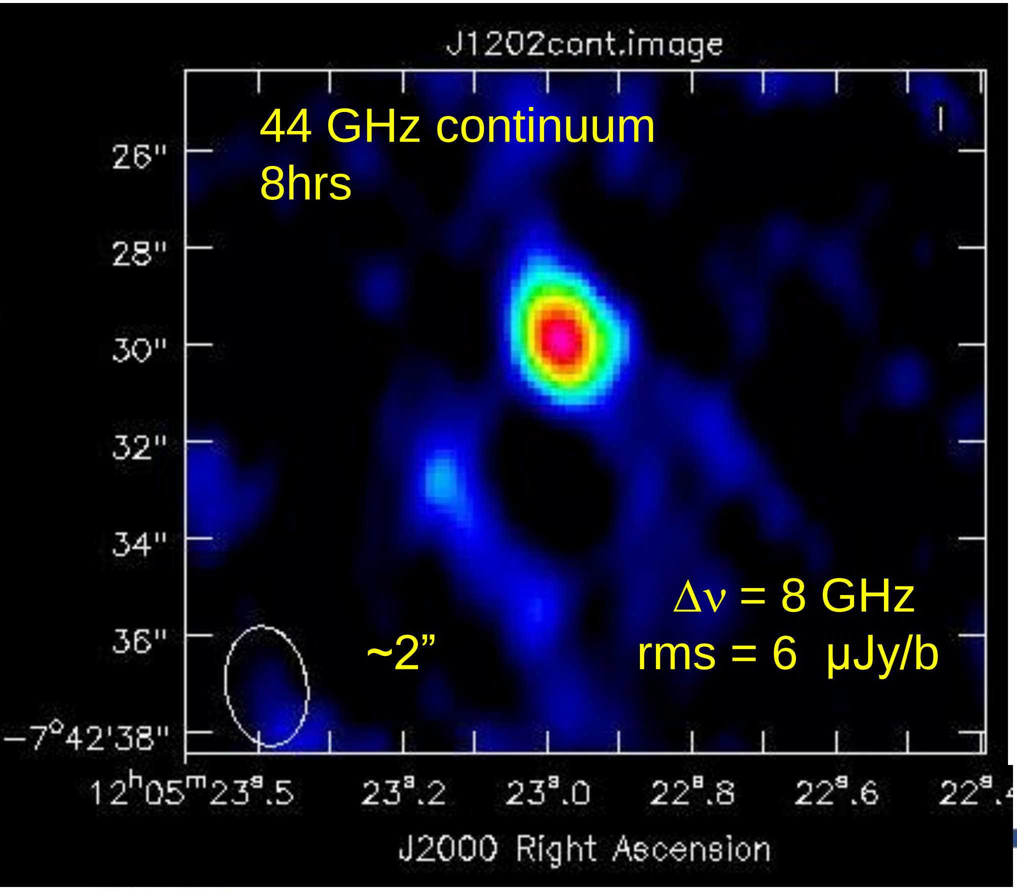
Wagg, Carilli et al. *in prep*

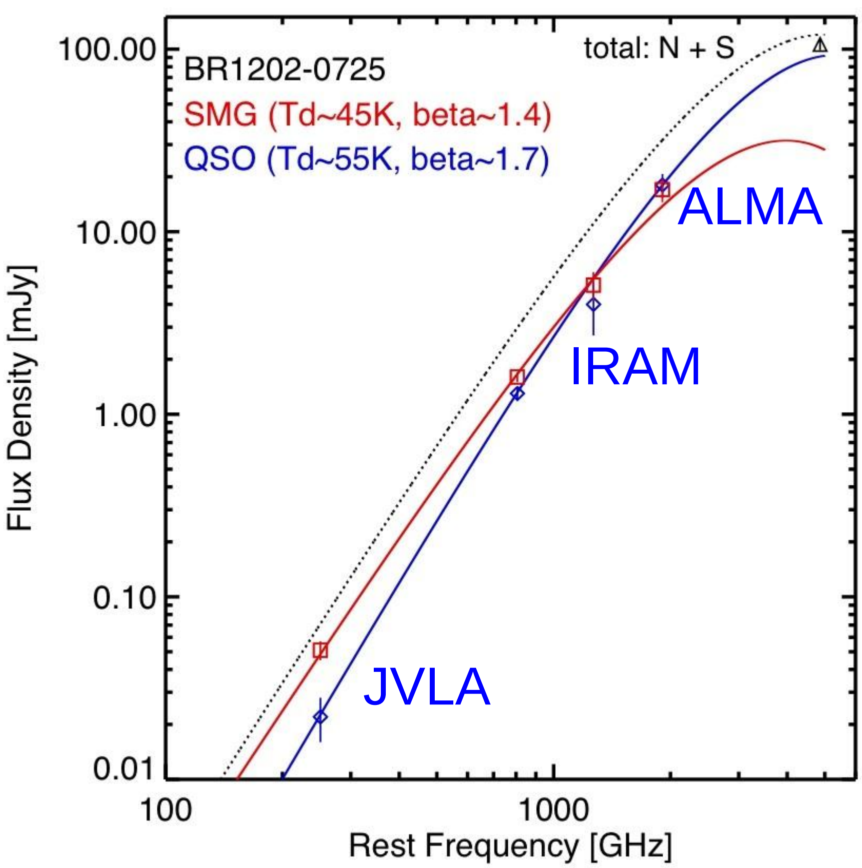
- SMG and QSO: $L'_{CO(J=5\text{-}4)} / L'_{CO(J=2\text{-}1)} \sim 1$

T_{kin}~40-50K, $n(H_2)$~2000cm^{-3} (Salome et al 2012)

- long-wavelength thermal dust continuum emission: different dust grain properties?

$L_{FIR\text{-}QSO} \sim 2 \times L_{FIR\text{-}SMG}$

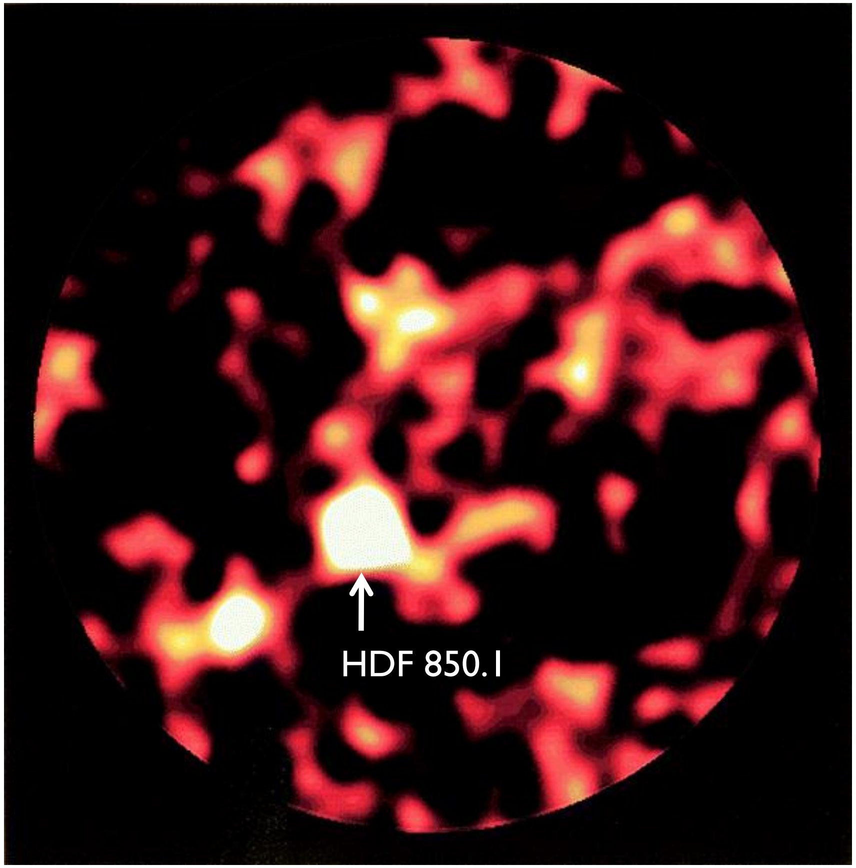




An Old Mystery in the High z Universe

Hughes et al (1998)

- The strongest submm source (850 microns) in the HDF lacked a counterpart or redshift for decade.
- Known as HDF850.1, no identification with any optical/IR image was made for many years following its discovery in 1998.
- Dunlop et al. (2002) proposed an identification with deep imaging done with Subaru.
- Estimated redshift: 4.1

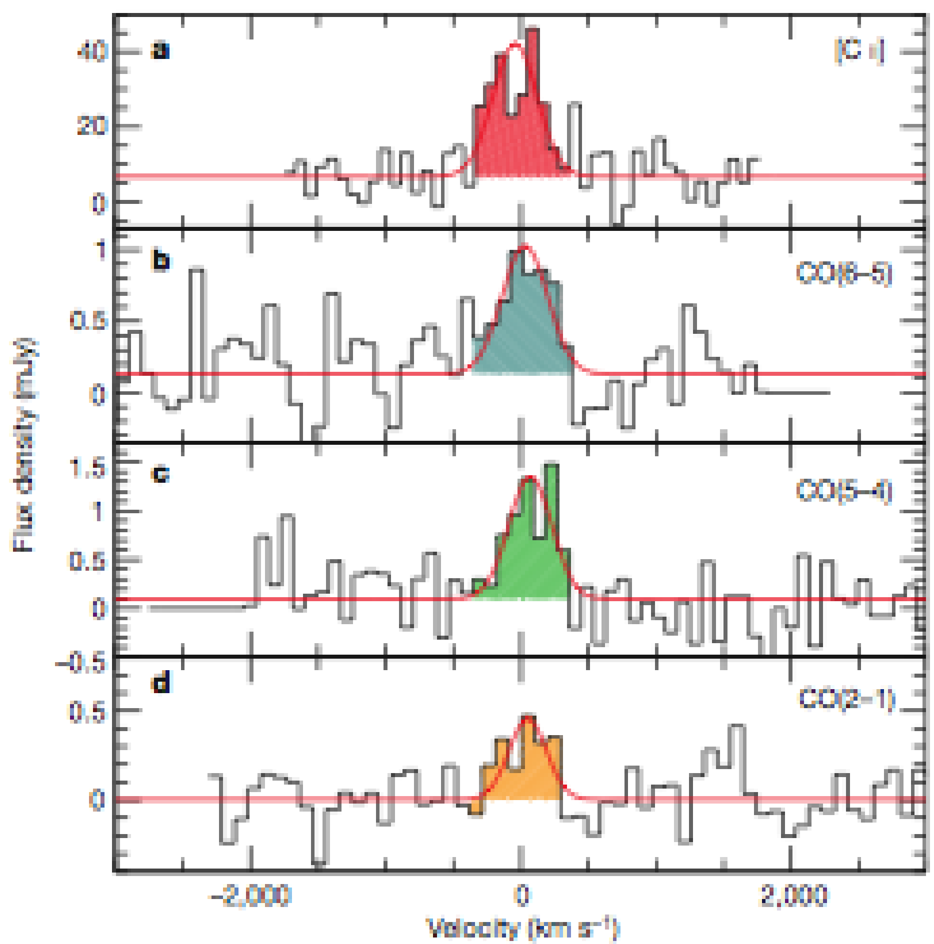


Redshift found by PdBI and VLA:

EVLA

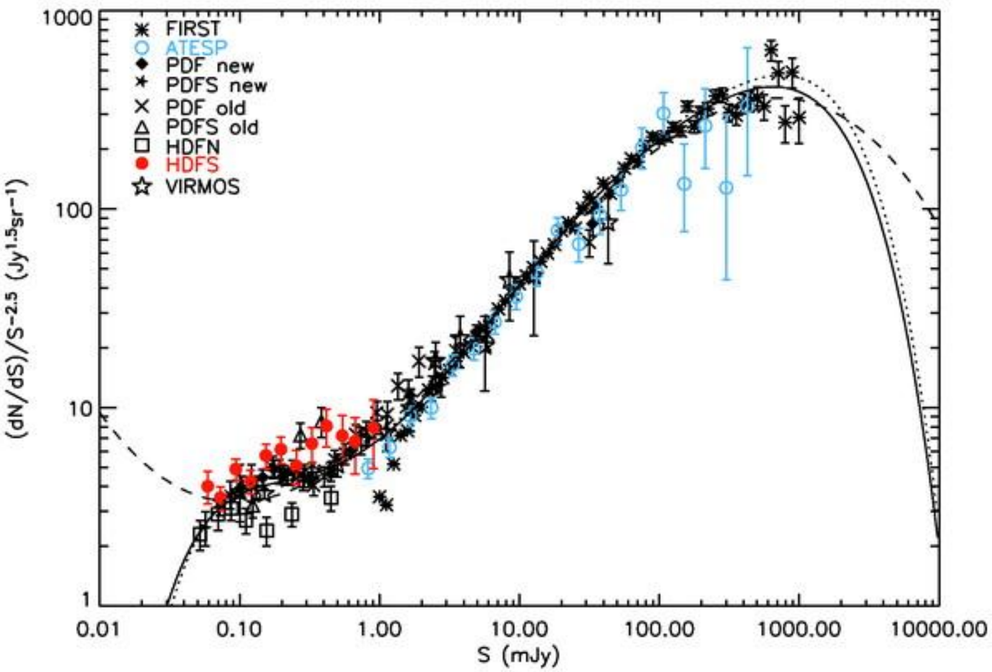
- Blind molecular line survey of HDF with PdBI identified redshift with CO (6-5) and (5-4).
- Confirmed with EVLA CO(2-1), and PdBI CII.
- HDF 850.1 is a rare ultraluminous starburst galaxy:
  - z=5.183 (further than predicted)
  - In galaxy over-density at z=5.2
  - 850 $M_{\odot}$/year, $M_{dyn}=10^{11}$ $M_{\odot}$
- Still no optical/NIR counterpart
- Highlights the value of blind surveys and future ALMA and EVLA synergy

Walter et al, Nature in press (2012)



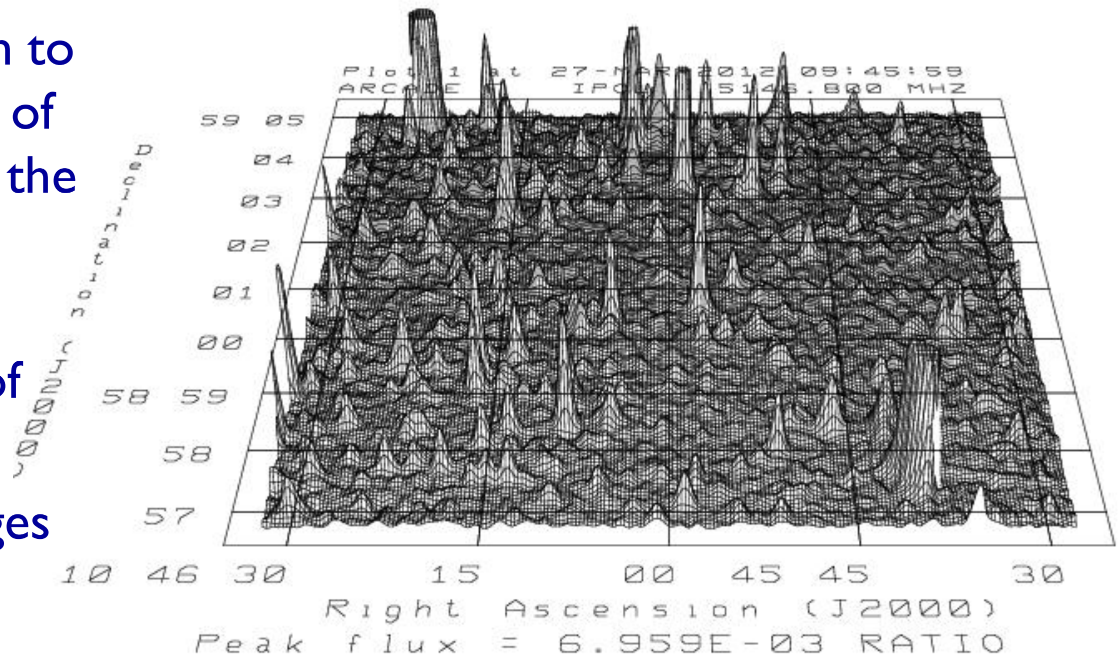
Exploring the Radio Sky at 1 uJy/beam

- The Balloon-borne instrument ARCADE 2 measured a sky brightness of 54 +/- 6 mK at 3.3 GHz.
- The known population of radio sources can only provide ~10 mK.
- Support from Owen and Morrison (2008) who saw flat normalized source counts down to 17 uJy
- Is the excess ~45 mK real?
- If so, is it due to a new population?
- If so, will SKA key science be limited by source confusion?
- Condon et al. have investigated this with VLA's new S-band system.



Deeper Knowledge Through Confusion

- "Confusion" is the term given to fluctuations caused by blends of faint sources not resolved by the point-source response
- Image brightness fluctuations P(D) yield statistic "counts" of sources
- Confusion-limited EVLA images will be able to constrain the population of extragalactic sources as faint as 1 microJy at 1 GHz .
- A 3 GHz project was recently carried out by Condon et al. (ApJ 2012)



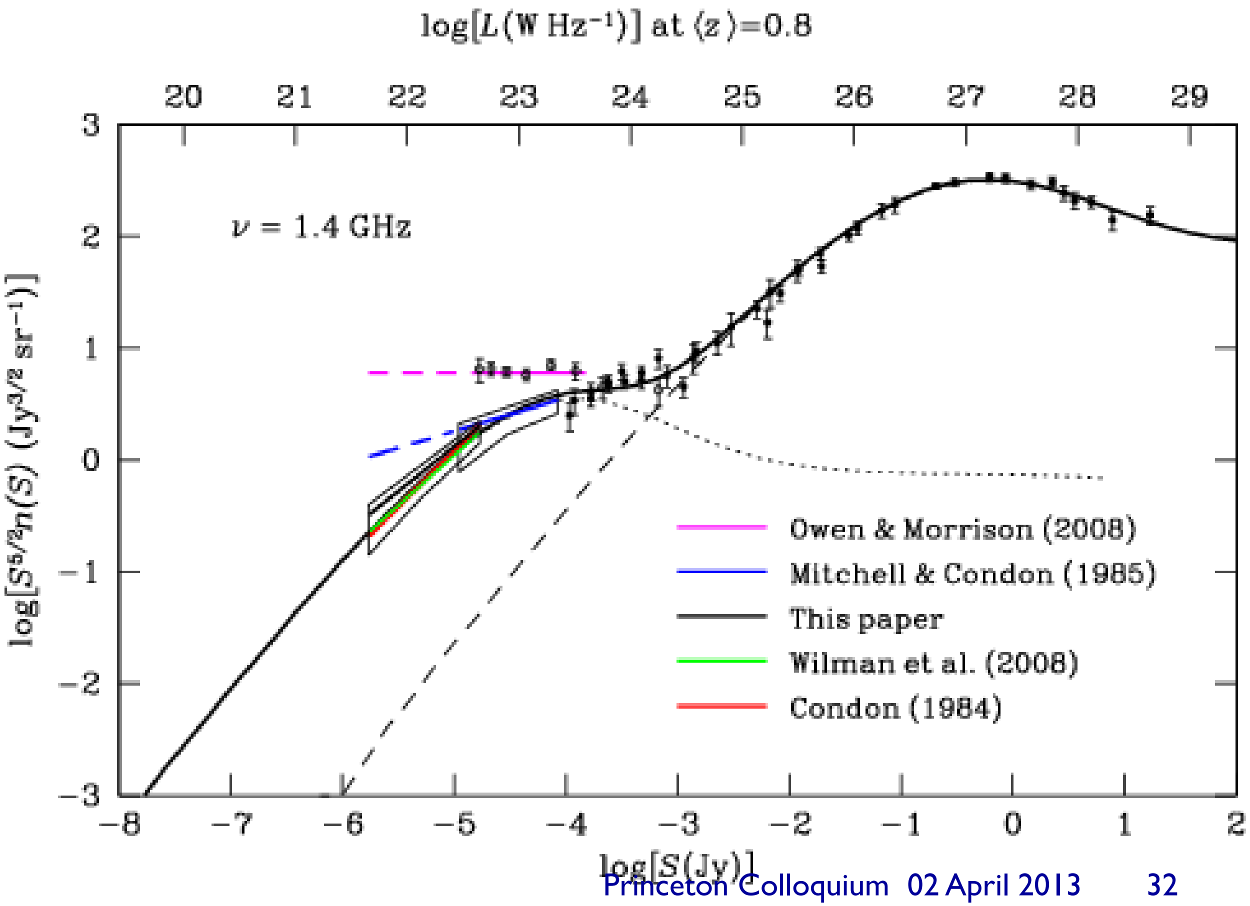
- The plot is clipped at 100 μJy/beam.
- The rms noise is 1% of this peak
- Every 'bump' in the map is real signal!
- About 50 hours on-source integration, with 21 antennas.

Results – No excess to 1 μJy/beam

EVLA

- P(D) analysis shows number count heading downwards, as predicted by models.
- No excess of faint sources visible.

- If the ARCADE result is right, the responsible objects are much weaker than 1 μJy, (1 – 100 nJy) with high surface density.



Some Conclusions from Confusion

EVLA

- At these flux density levels (1 – 10 μJy):
  - Brightness-weighted differential count is converging rapidly
  - Faintest sources are star-forming galaxies
  - ~96% of the background originating in galaxies has been resolved into discrete sources.
  - 63% of the radio background is produced by AGN, the remaining from star-forming galaxies that obey the FIR/radio correlation and account for most of the FIR background at 160 microns.
  - Radio sources powered by AGN and star formation evolve at about the same rate, consistent with AGN feedback and the rough correlation of black hole and bulge stellar masses.
  - Confusion level at cm wavelengths is low enough that the planned SKA will not be confusion limited. Natural confusion is at the level of 10 nJy at 1.4 GHz.

NRAO

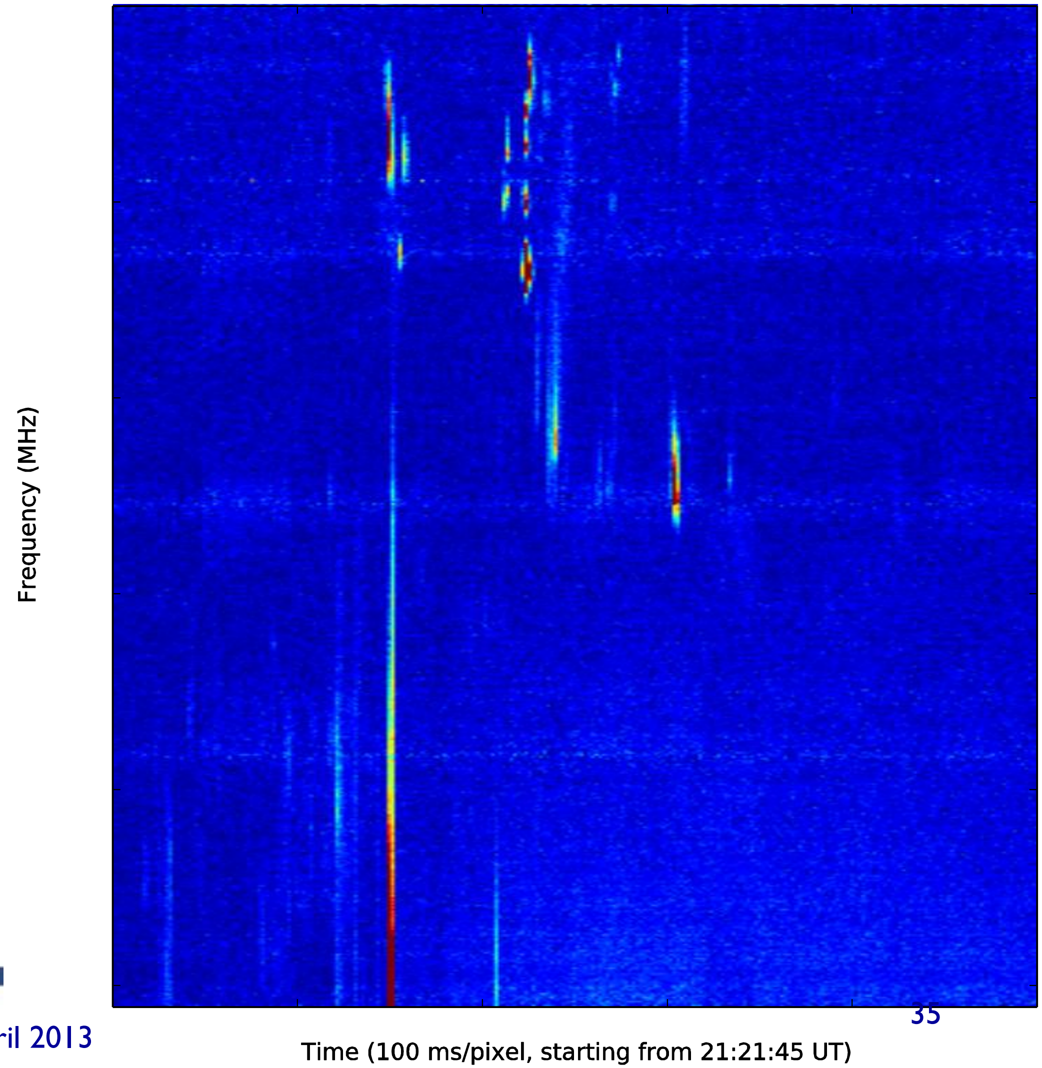
Transient Universe Theme

- Searching for Rotating Radio Transits (RRATs) – pulsars with sporadic pulses.
- Solar flare science.
  - Radio studies ongoing since late 1940s.
  - Provides insight into particle acceleration and energy release.
  - Important role in discovery of CMEs.
- Flare star science
- Brown Dwarfs

Solar Transient Science: Suprathermal Electron Beams in the Solar Corona

EVLA

- Shown here is a dynamic spectrum, time to the right, frequency vertical.
- Time resolution is 100 ms.
- Data taken at 1 – 2 GHz, in Nov 2011, during a modest flare.
- Vertical lines are Type III bursts.
- An image can be made for each (frequency, time) pixel.



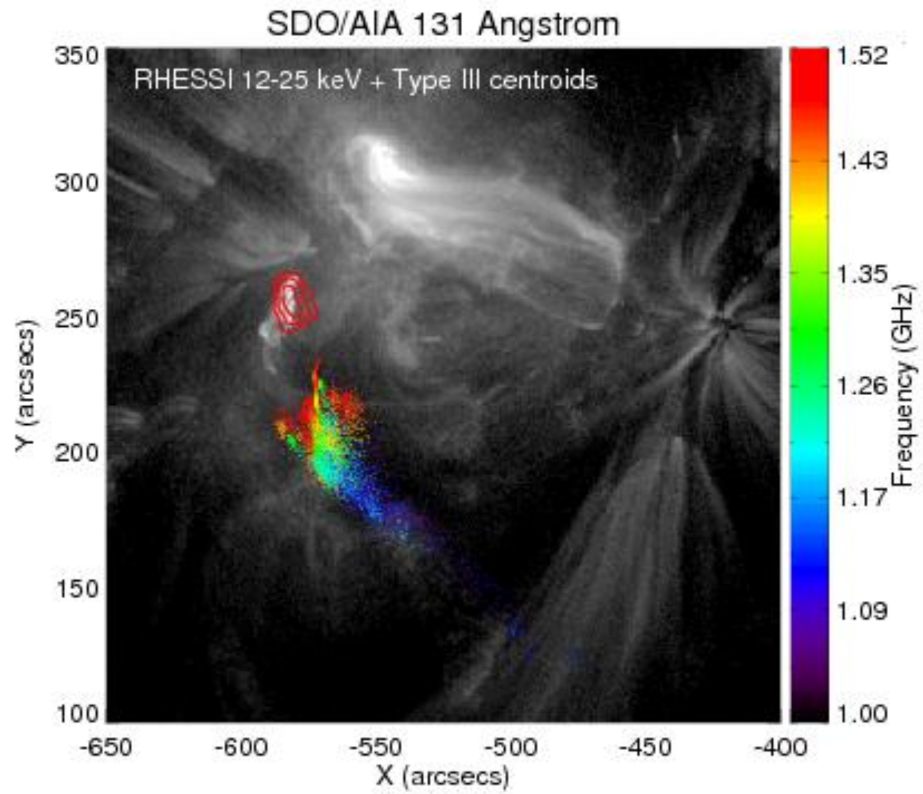
Chen et al. (2012)

NRAO

Suprathermal Electron Beams in the Solar Corona

EVLA

- Each color 'dot' shows centroid position of radio burst, color coded for frequency.
- Background is EUV image of the sun at the same time.
- Emission at different frequencies originates from different places in the corona
- Progression plots the electron beam trajectories, representing the topology of the magnetic fields.
- Contours show HXR emission.



- Footprint HXR sources, hot EUV loop topology, and type III burst trajectories show a consistent picture of flare energy release, particle acceleration, and flare energy release.

NRAO

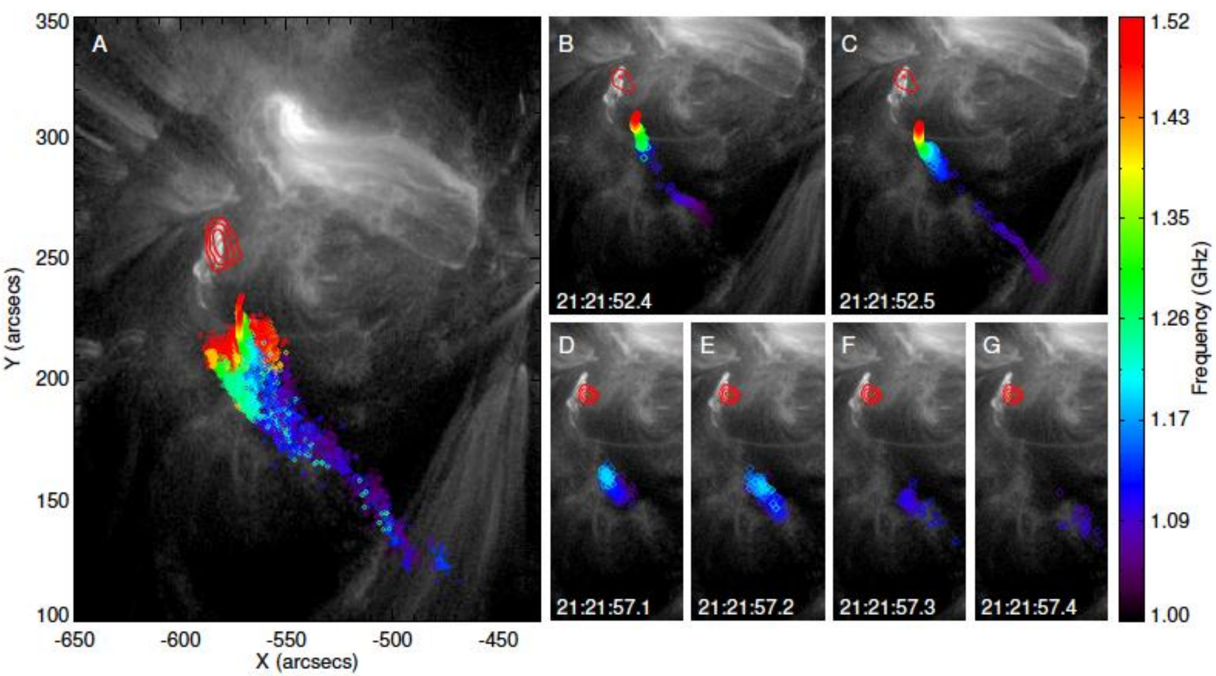
Imaging magnetic reconnection on the sun

EVLA

•Type III radio bursts from the Sun correspond to thermal electron beams propagating in the low corona. The VLA has imaged these bursts on times scales ~ 100ms.

•The beams emanate from an energy release site located in the low corona and propagate along a bundle of discrete magnetic loops upward into the corona. The diameter of these loops is less than 100 km. These over-dense and ultra-thin loops reveal the fibrous structure of the Sun’s corona.

•The localized energy release is highly fragmentary in time and space, supporting a bursty reconnection model that involves secondary magnetic structures for magnetic energy release and particle acceleration.



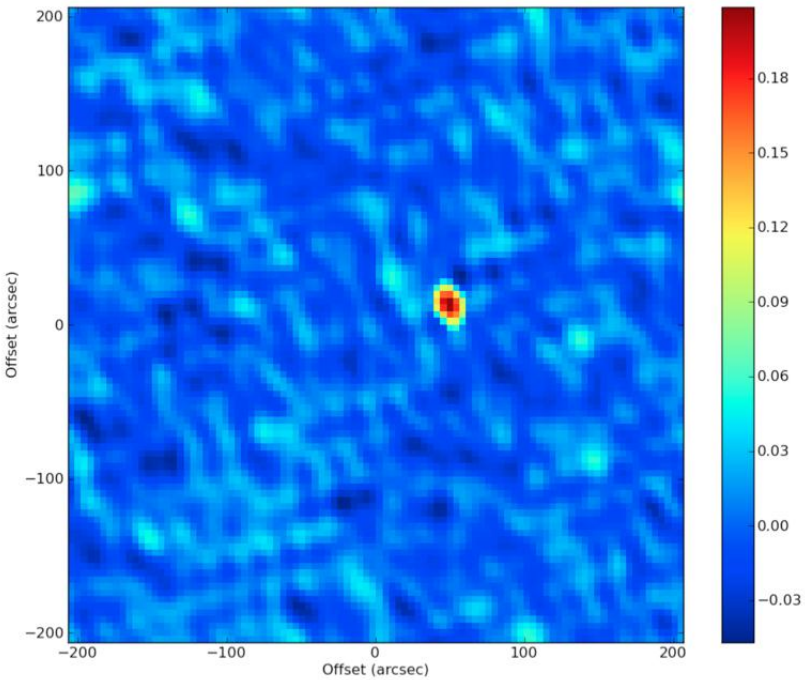
Emission centroids of type II bursts vs. frequency measured on timescales of 100ms. Chen et al. 2013

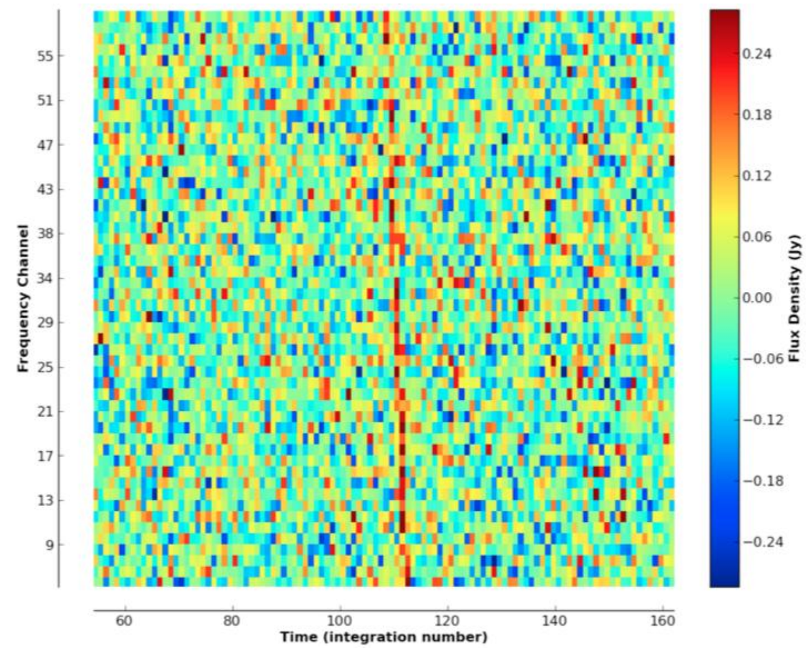
(B, C) sequential separation 100 ms.

(D through G) four sequential images, separated by 100 ms.

Transient Science – RRATs at the VLA

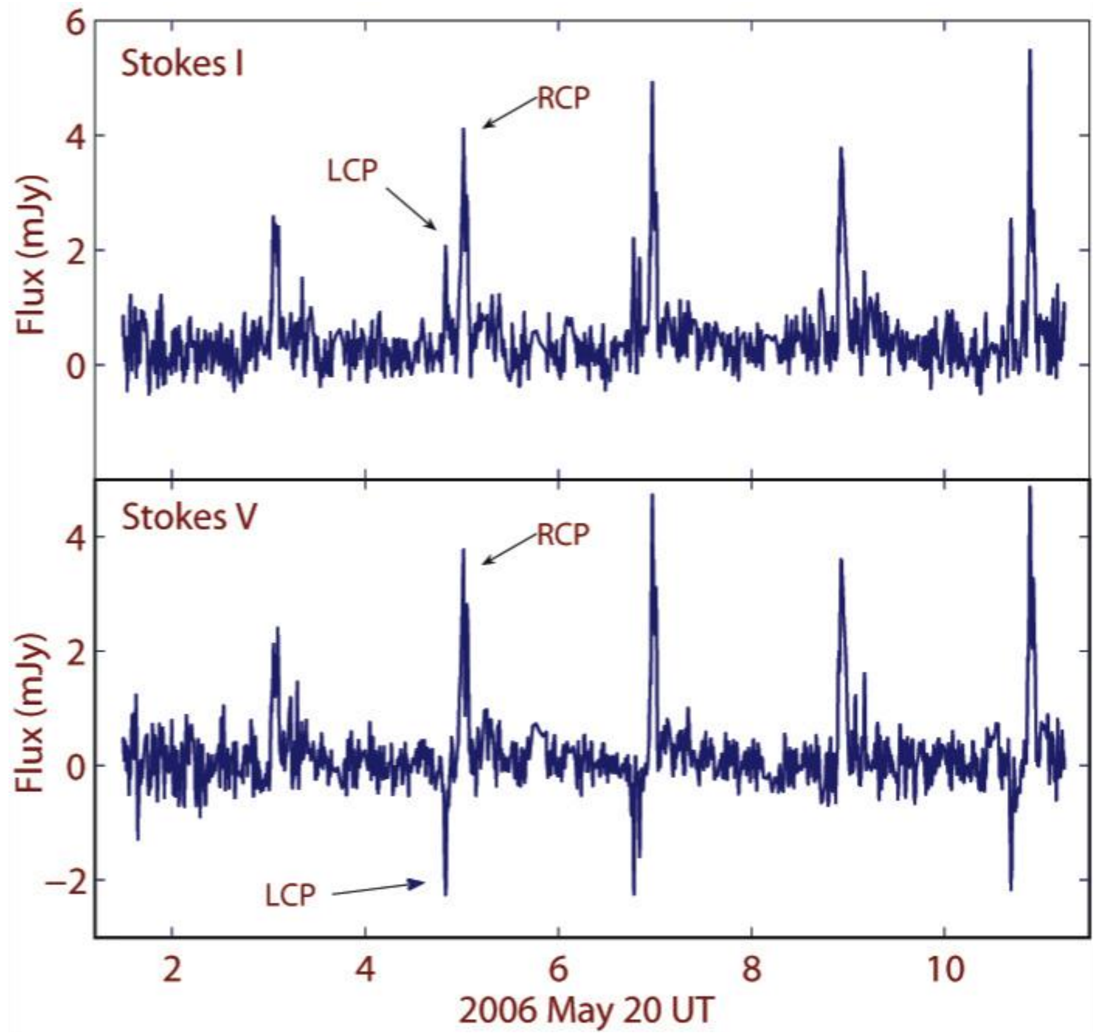
- Law and Bower (UCB) have taken 16 minutes of VLA data with 10 ms time resolution on J0628+0909, known as an RRAT from Arecibo observations.
- Bispectrum analysis (Law & Bower, 2012) of raw data found a single pulse.
- Image of a single time interval, and its dispersion function shown below.
- No optical counterpart.





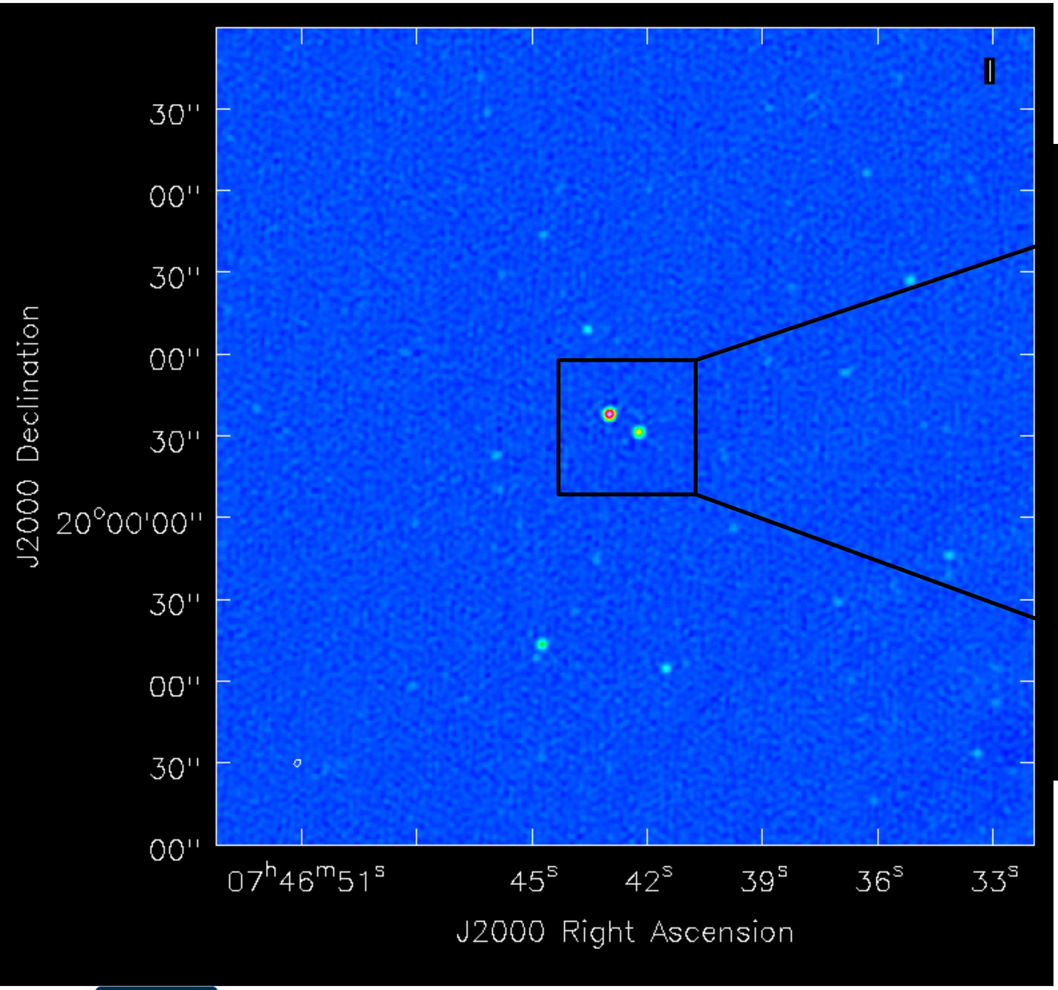
The VLA established that brown dwarfs pulse

- The M9 dwarf TVLM 513-46546 - Hallinan et al. (2007)
- X-band observations , period 1.96 h, 100% circularly polarized.
- Emission by electron cyclotron maser emission, in kG fields.
- Period set by stellar rotation, emission is highly beamed.
- Emission region ~1/5 stellar radius.
- Emission coherent, with Tb ~ 10^{11} K

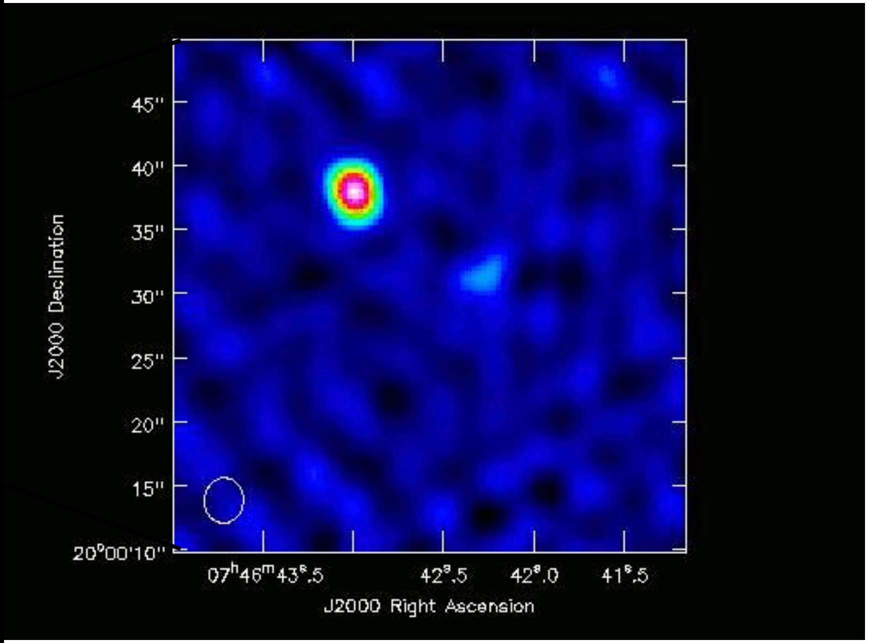


The upgraded Jansky VLA can do a lot more...

EVLA



2MASS J0746+20



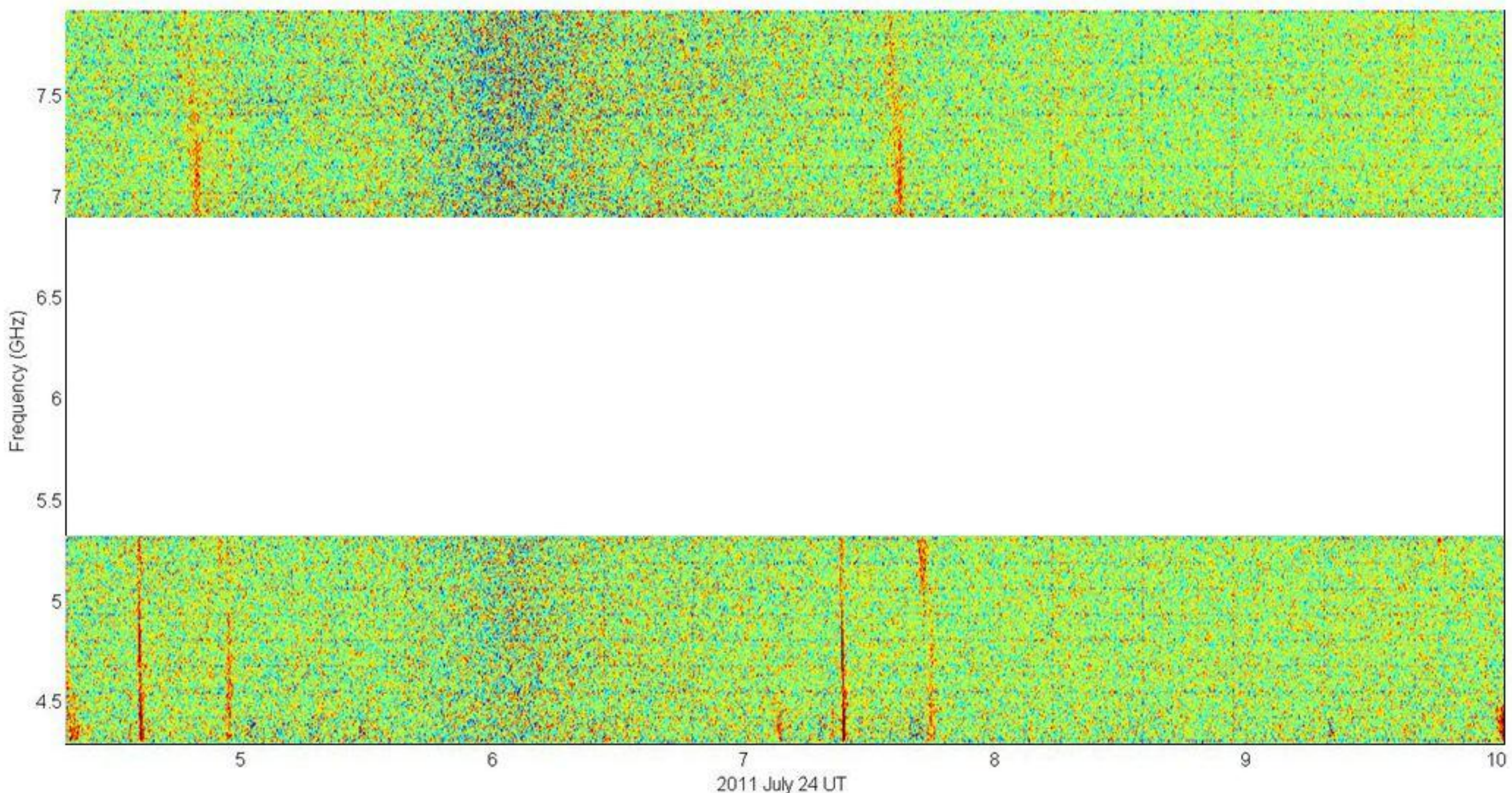
12.5 hours of data with 2 GHz bandwidth

RMS noise ~1.6 μJy/beam

NRAO

EVLA

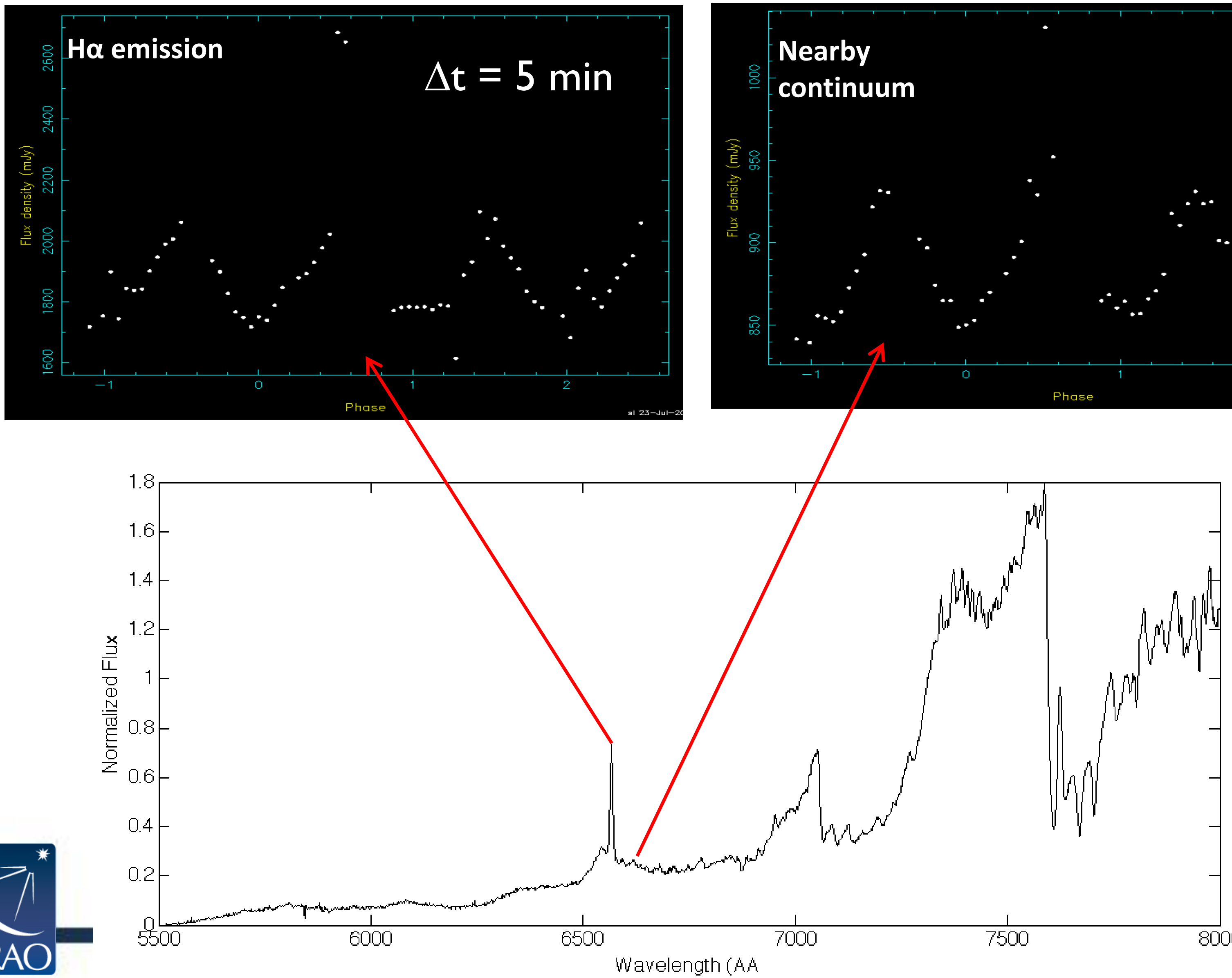
Dynamic spectra reveal large-scale source structure



- M9 dwarf – LSR J1835+3529
- Period: 2.84 hours
- Magnetic field range: 1500 Gauss – 2800 Gauss

NRAO

Keck observations of the same M9 dwarf reveal periodic variability across the optical spectrum



- Radio observations were the first clue that magnetic activity complete changes at the end of the main sequence
- Emissions (X-ray, H-alpha, radio) associated with the presence of a high temperature corona, ubiquitous for cool stars like the Sun, are largely absent for cool L and T dwarfs
- Replaced by auroral emissions analogous to those detected on Jupiter, but 10^6 times more powerful – present in radio, optical and infrared
- Powered by large-scale currents in the brown dwarf magnetosphere

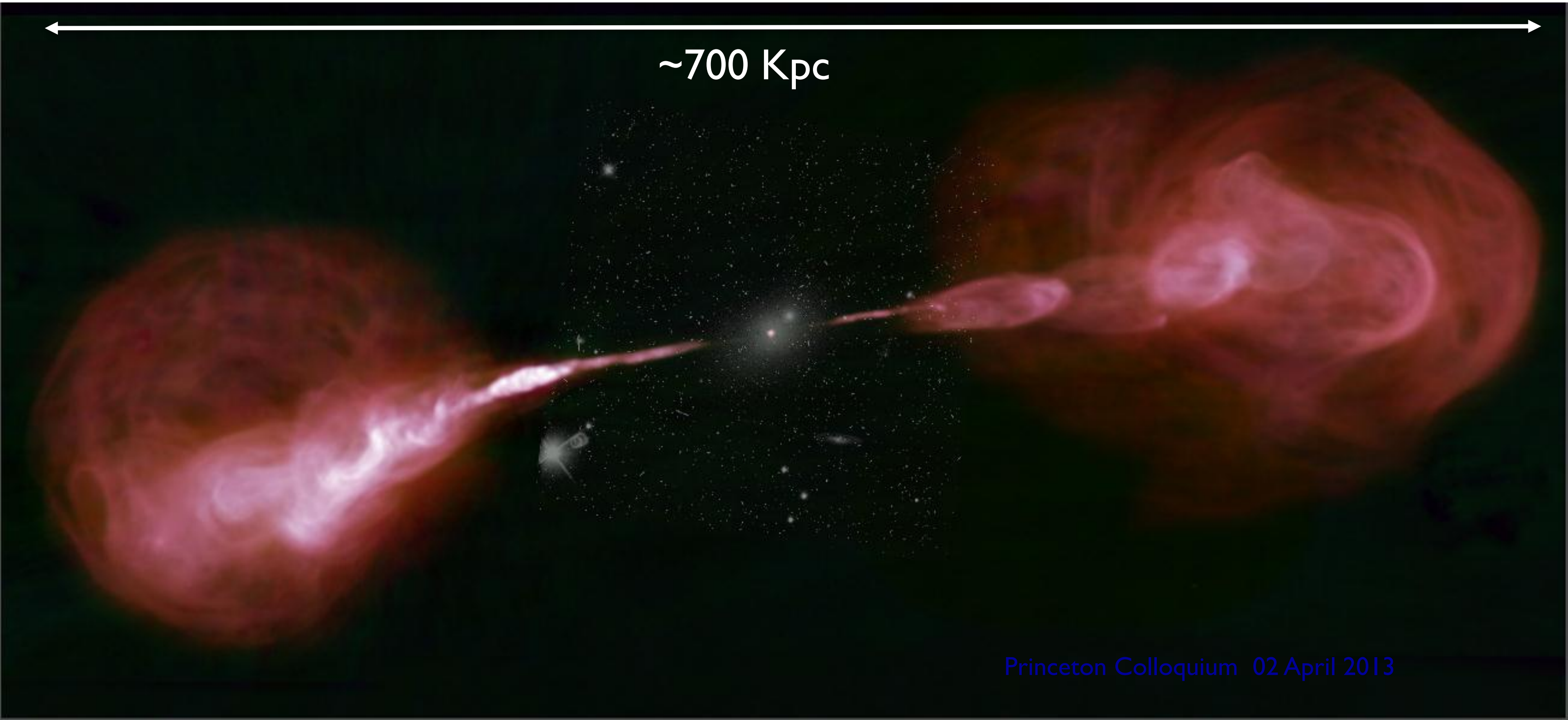
Magnetic Universe Theme

- Synchrotron emission from radio galaxies, quasars, SNR
  - Maps magnetic fields within sources
  - Provides age estimates of structure
- Faraday Rotation Studies
  - Plane of polarized emission is rotated by magneto-ionic medium, give estimate of line-of-sight magnetic field strength and structure.
- Zeeman Splitting Studies
  - Spectral transitions split into hyperfine structure by magnetic field.
  - Allows direct measurement of magnetic fields in line-emitting environments.

Hercules A (Perley and Cotton, demo science)

EVLA

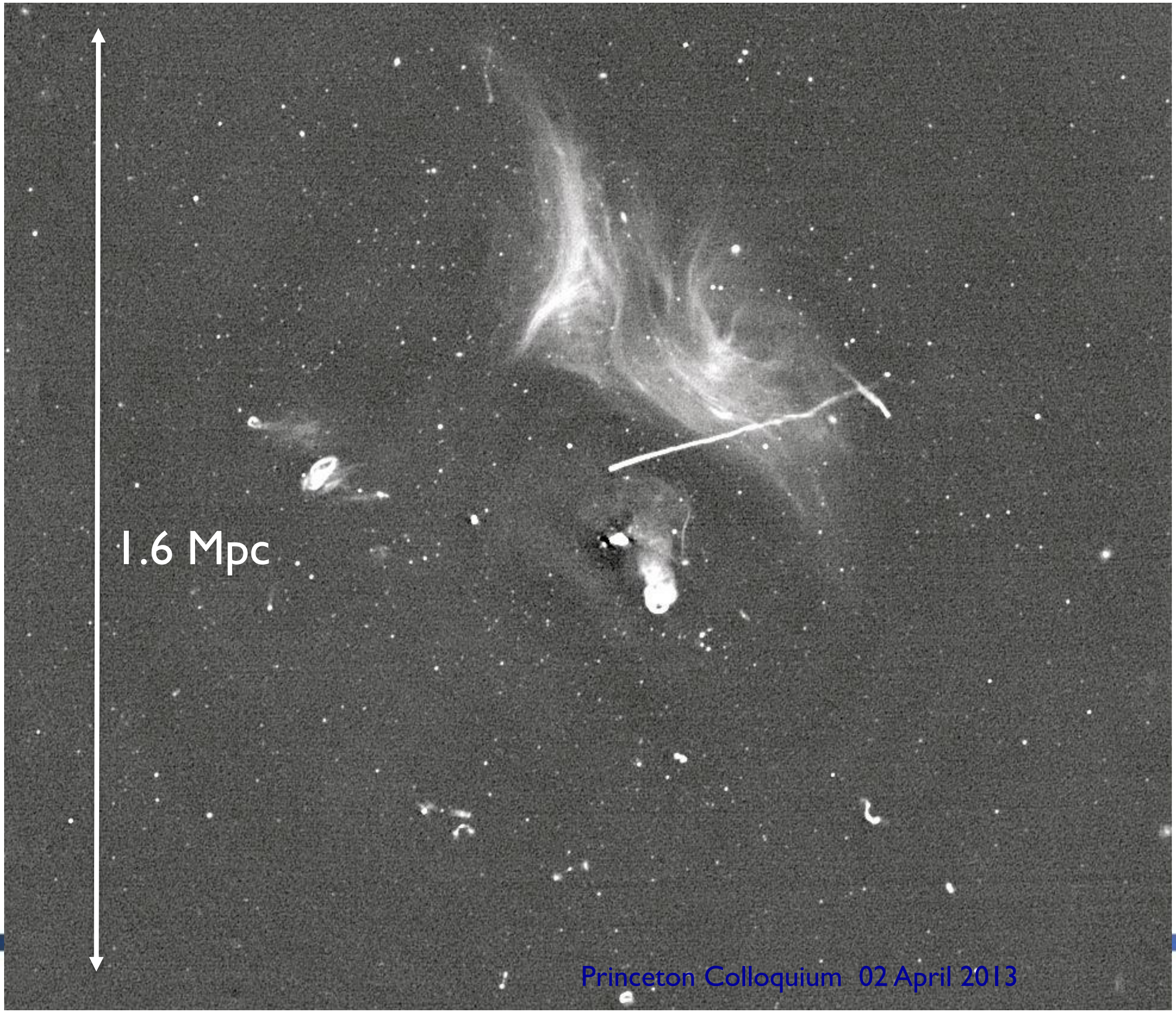
- $z = 0.154$, radio galaxy. D = 710 Mpc, 1arcsec = 3.4 Kpc.
- 4-9 GHz color-code spectro-intensity image (redder = older). 1 Kpc res^{n}.
- EVLA data: 1 through 9 GHz, all four configurations, 1Kpc resolution.
- Shocks in western lobe indicate repeated ejection.



Relics and Jets in Abell 2256 at λ = 20cm

Owen, Rudnick, Eilek, Rau, Bhatnagar, Kogan)

- A merging rich cluster of galaxies
- z = .058, D = 270 Mpc.
- 1–2 GHz, 20-arcmin on a side (1.6 Mpc)
- Studies of the complex interactions between galaxies, AGN feedback, ICM, magnetic fields, and dark matter content of clusters
- Role of radio galaxies and relics in cluster evolution?



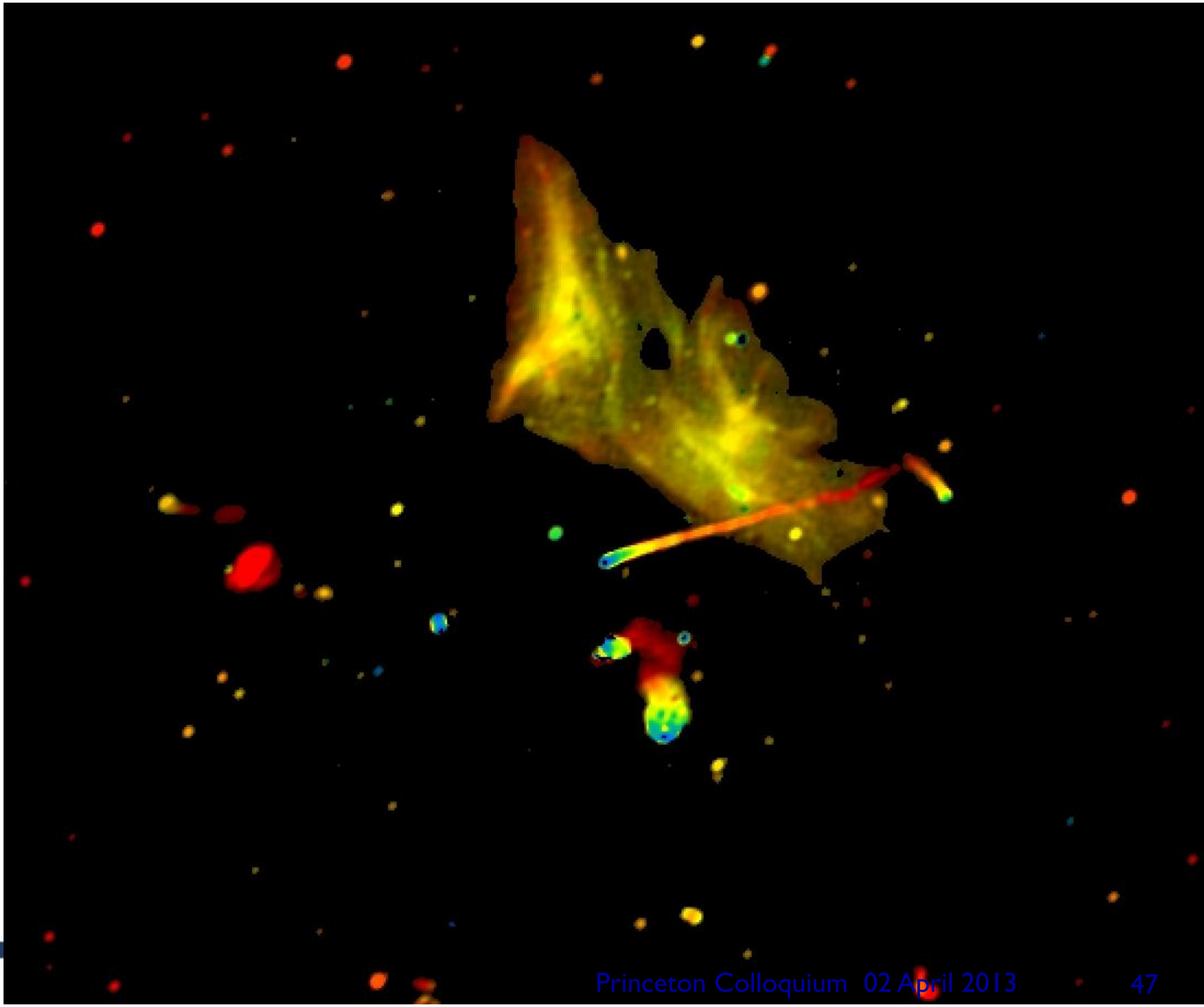
A2256 – Spectral Index - Intensity

EVLA

- Wideband data permits simultaneous calculation of spectral index.
- Combined with estimate of B-field, gives estimate of electron age since last acceleration.

Red = steep (old)

Blue = flat (young)



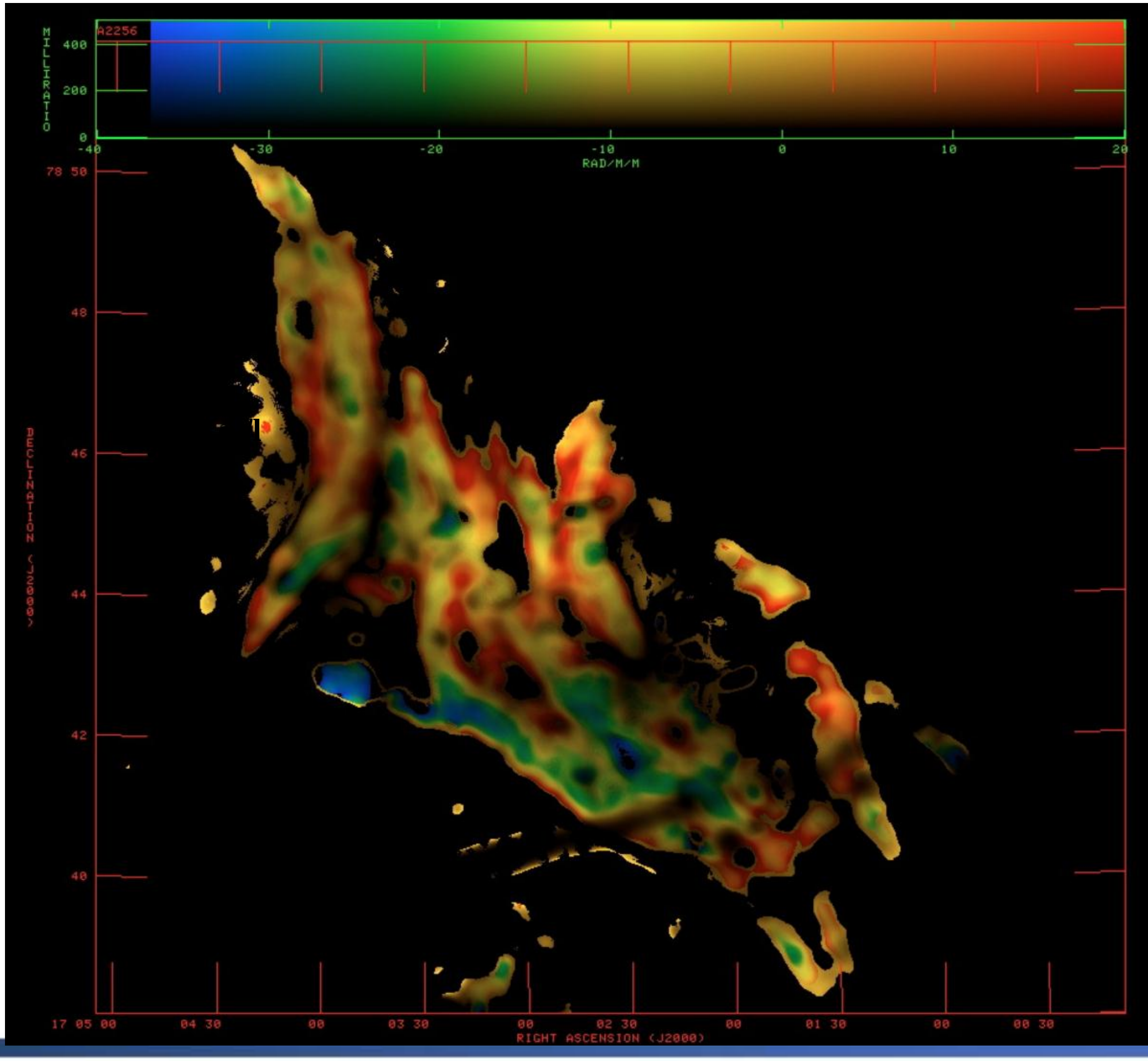
EVLA

Faraday Rotation in A2256

- Shown is the RM

$$\propto \int n_e \mathbf{B} \bullet d\mathbf{l}$$

- VLA's wide bandwidths and narrow frequency resolution will be a boon to Faraday rotation studies.
- New technique for Faraday Rotation Synthesis provides information on B-fields along line of sight, for regions where emission is within the thermal gas.



NRAO

Obscured Universe Theme

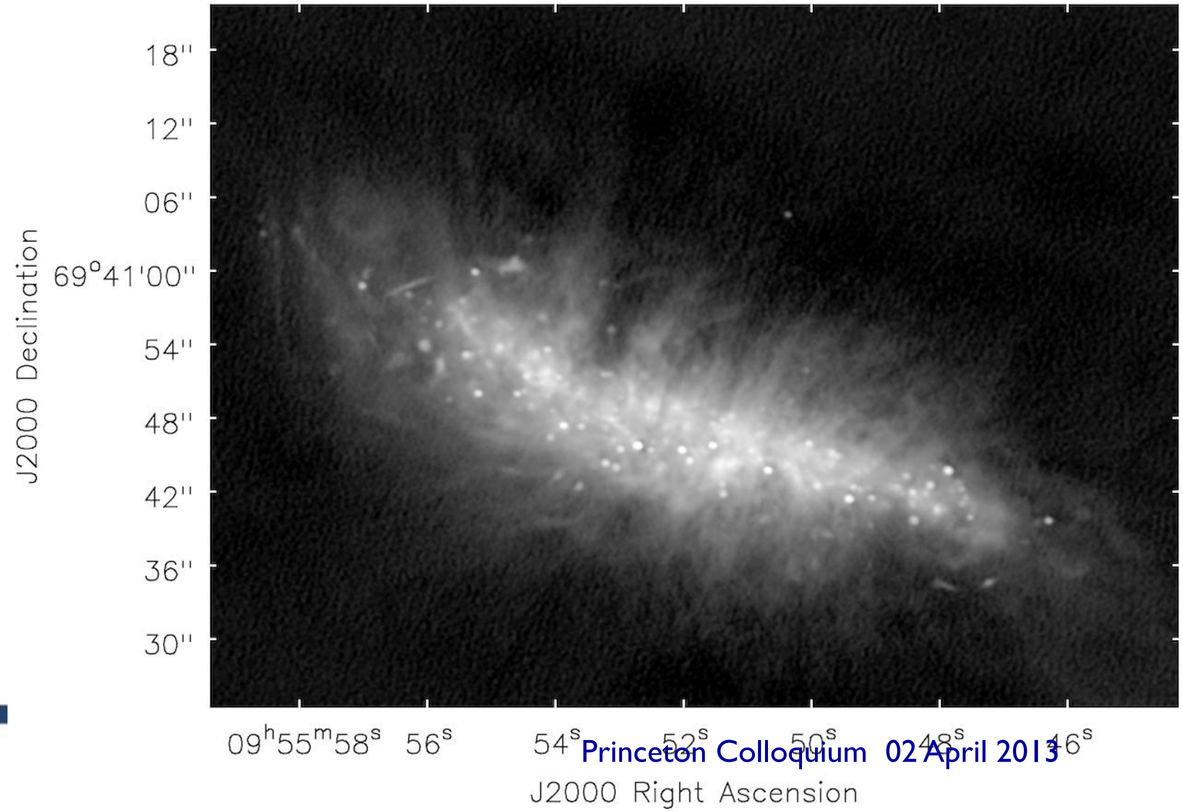
- Cm-wavelength observations nearly unattenuated by dust.
- VLA can detect regions too optically thick for visible, IR, and mm-wave instruments.
- Star-forming regions, protoplanetary disks, proto-stellar objects, HII regions, and much more are likely targets for high-resolution cm-wave studies with the VLA.

M82 – The Prototype Nearby Starburst Galaxy

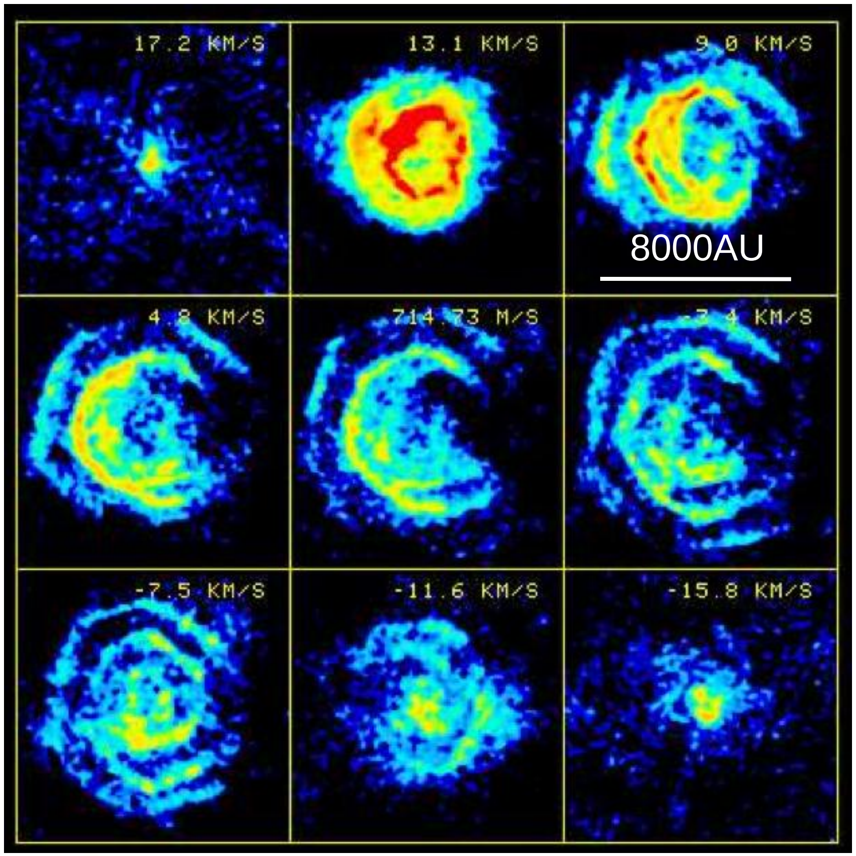
EVLA

- 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



18 to 40 GHz imaging line survey of Two Asymptotic Giant Branch stars, RW Lmi and IK Tau.



Claussen et al. 2011, ApJ 729, L5

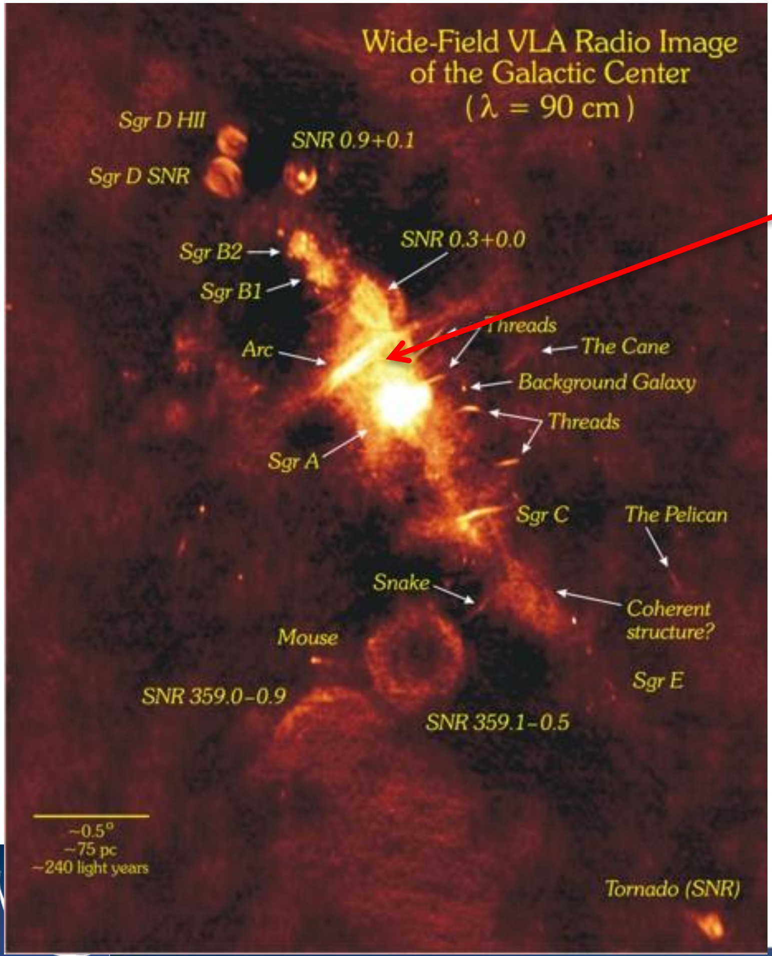
- AGB outflows are key to ISM molecule and dust enrichment (Mass loss rate ~ 10^{-4} M_o/yr)
- 7 hours integration, 0.6 arcsec
- Source here is RW LMi = CIT6, with 9 of 34 spectral channels.
- Pilot study w. new 36 GHz band: HC_3N reveals multiple shells tracing episodic circumstellar envelope evolution, on road to PNe
- Shell radii ~ 800 to 4000 AU, v_{exp} ~ 13 km/s => age date outbursts over last 1200 yrs

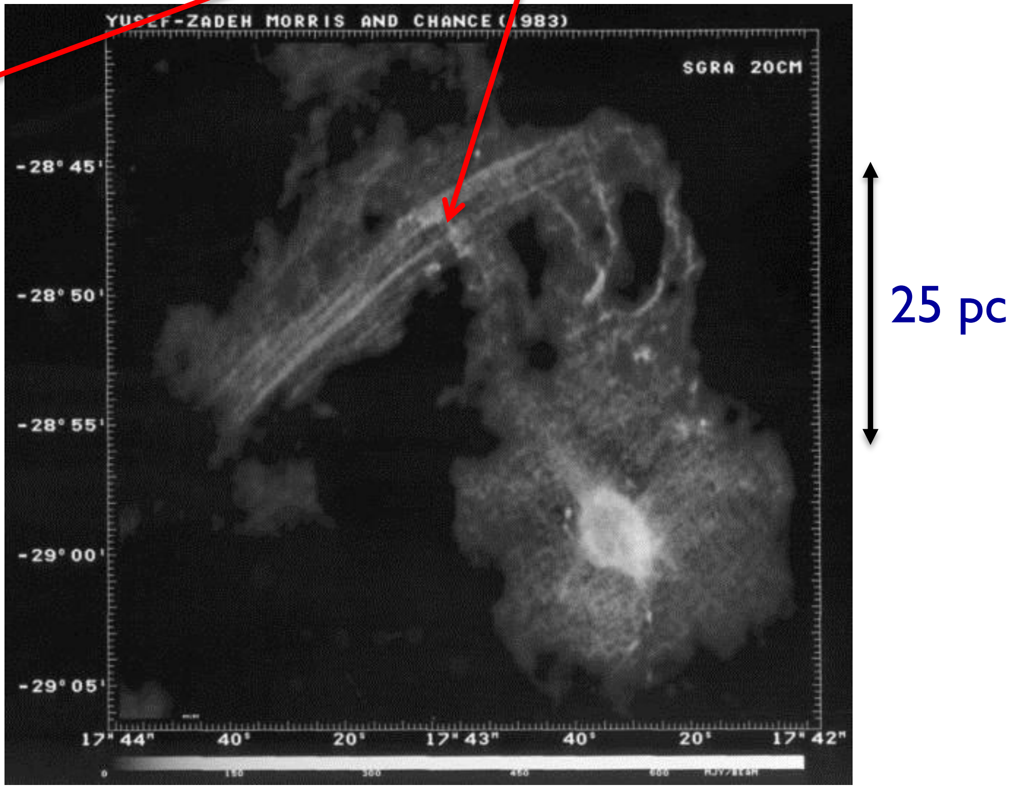
New K, Ka-band Observations of the Galactic Center (Mills et al.)

EVLA

The Galactic Center: A Busy Neighborhood!

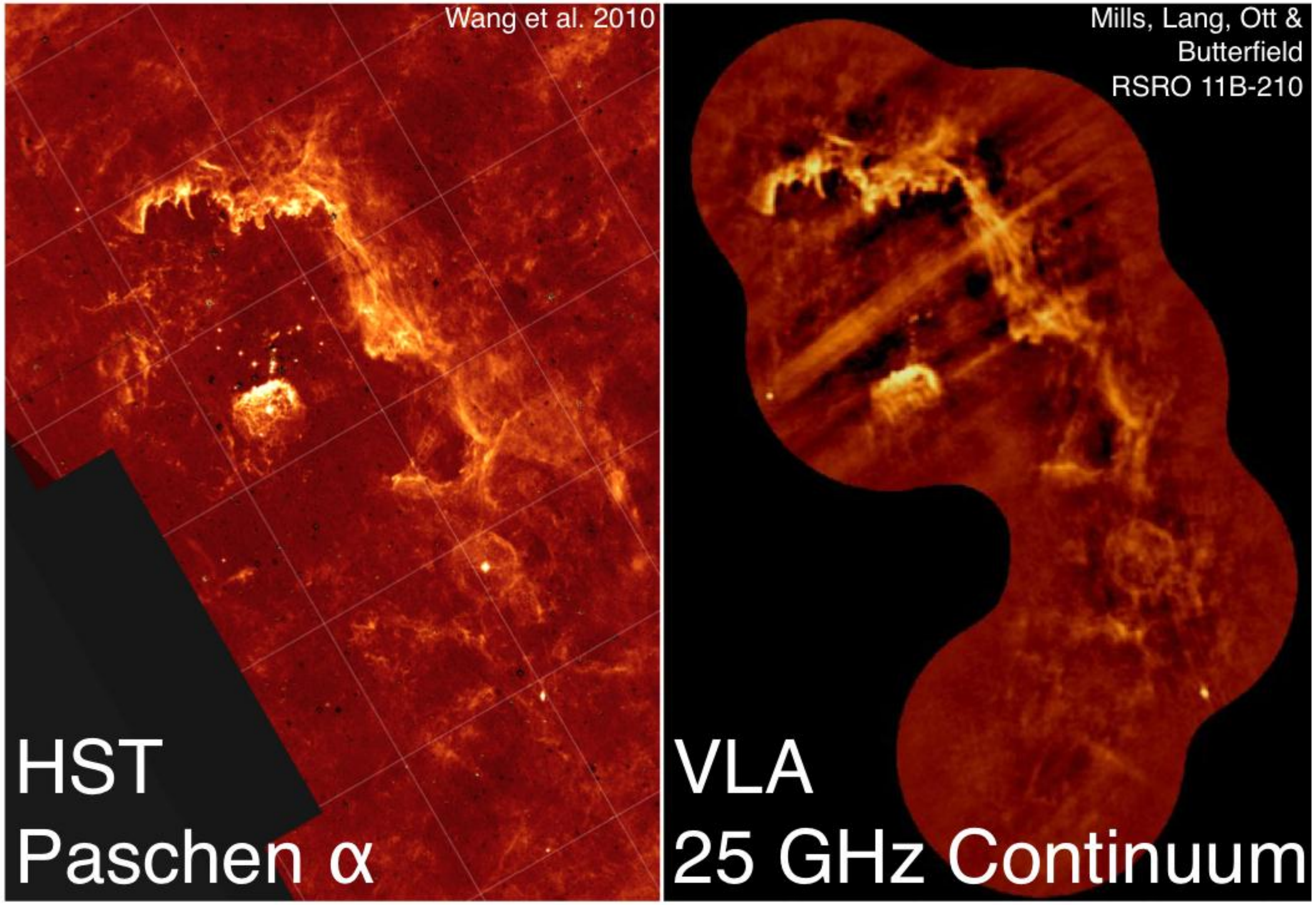
Area of interest: The 'Sickle'





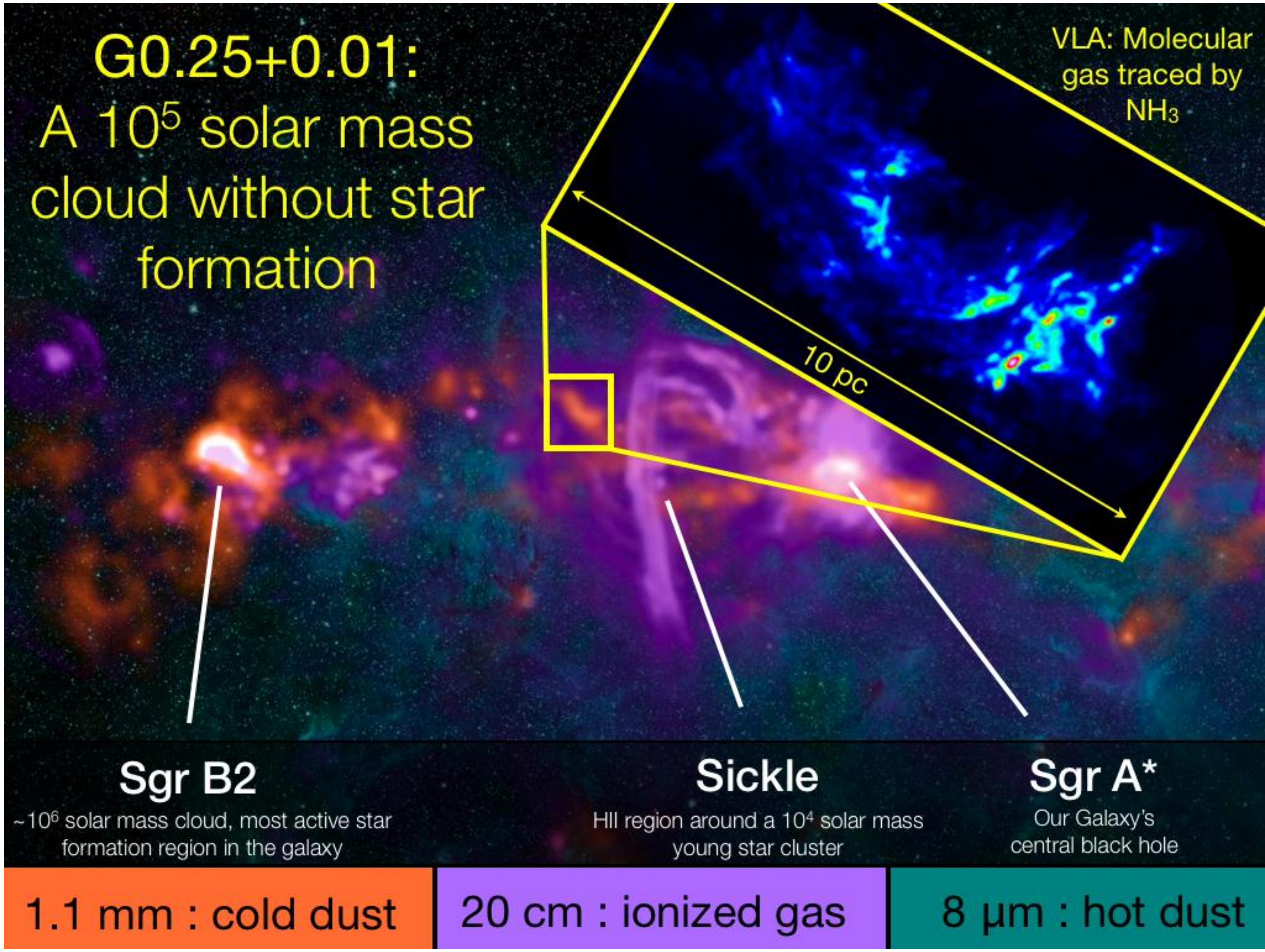
EVLA

The Sickle Region in Paschen α (IR, 1870 nm) and 25 GHz (radio, 1.2 cm)

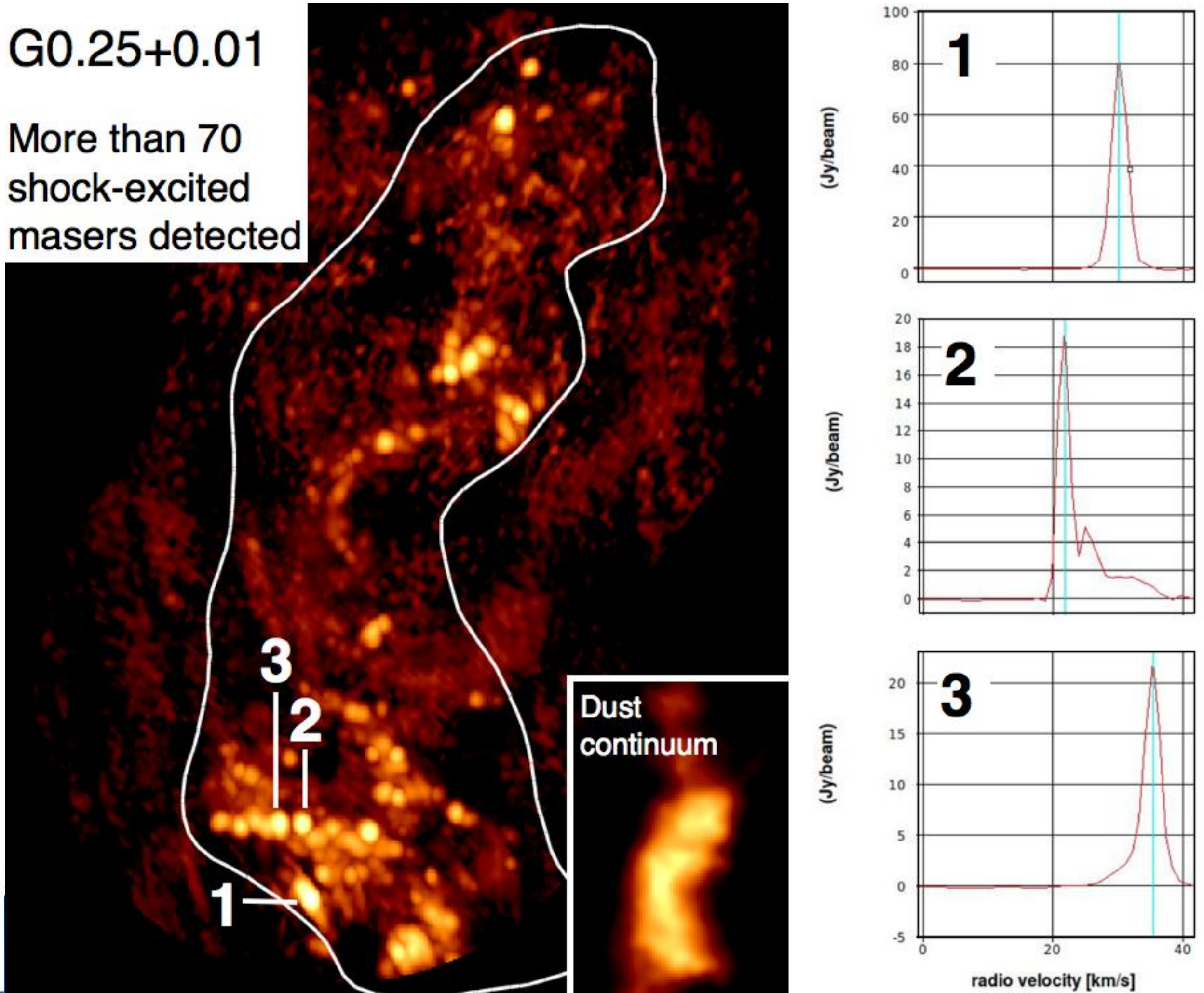


G0.25+0.01 – a uniquely dense dark IR cloud

- An extremely massive dense IR-dark cloud with almost no evidence for ongoing starformation.
- A single H_2O maser. No hot dust or IR sources to indicate star formation.
- Why is there no star formation here?



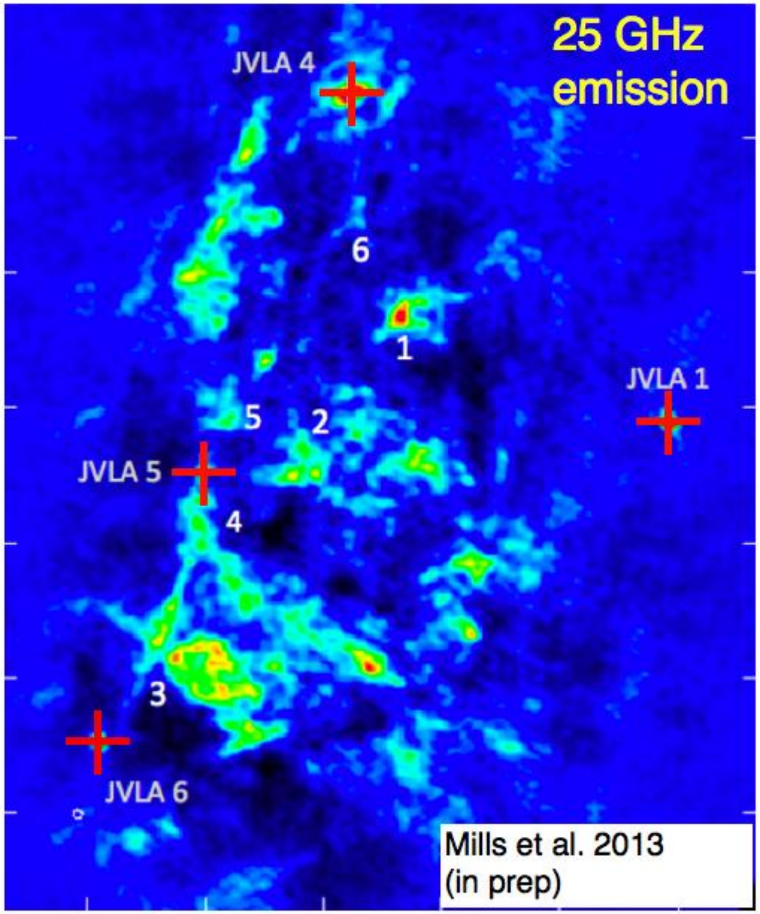
> 70 methanol masers in this cloud!



- Mills et al. (2013) will report on these new results – more masers in this cloud than in a lower-resolution survey of the entire Galactic center!

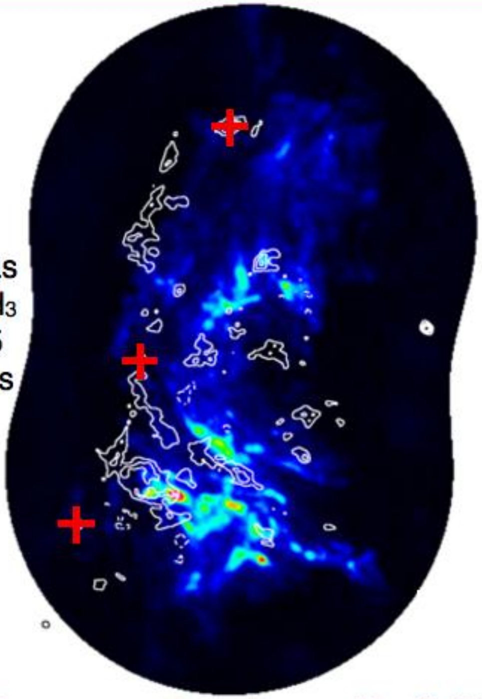
Continuum Emission

Thermal and nonthermal continuum emission in the quiet molecular cloud G0.25+0.01



Extended sources 1, 2 and 3 have flat spectral indices, consistent with being thermal emission from HII regions

Molecular gas traced by NH_3 (3,3), with 25 GHz contours

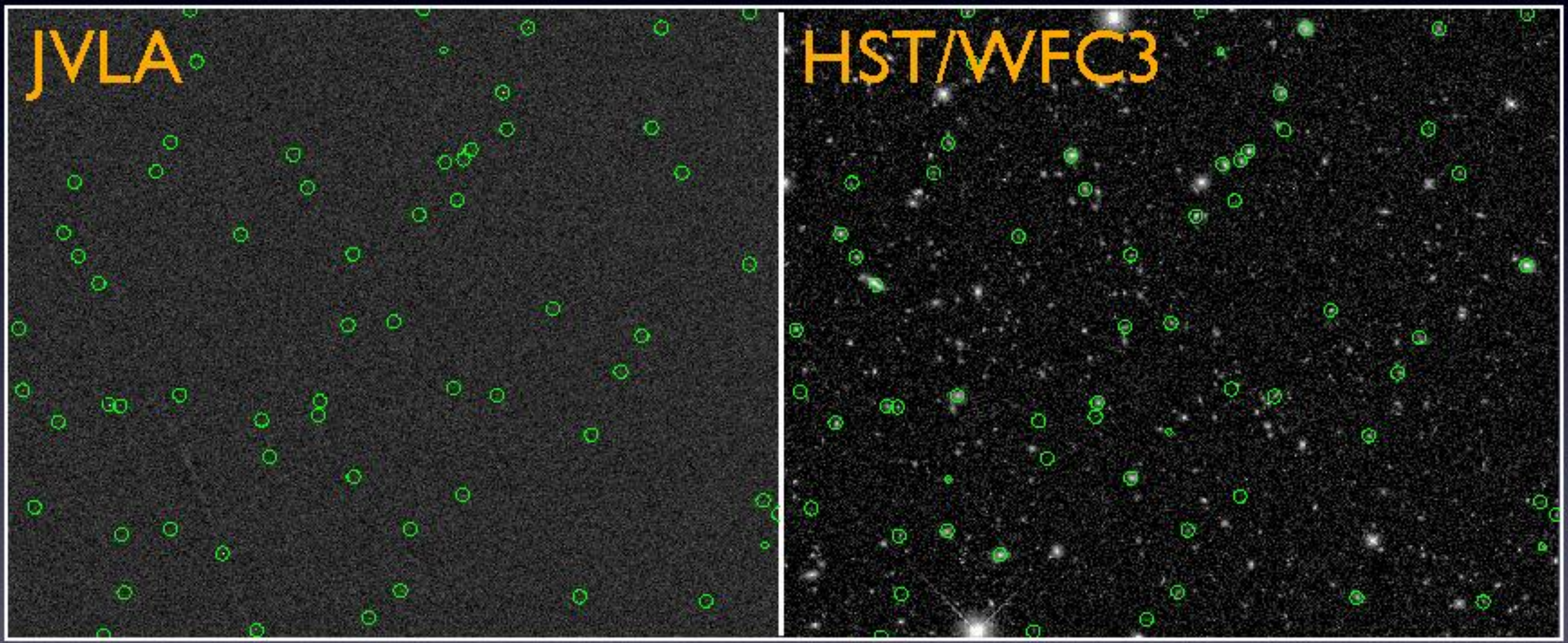


JVLA 4-6 are compact thermal sources identified by Rodriguez et al. 2013. They mostly lie **outside** of the cloud, so it is unclear if they represent embedded star formation

How Deep?

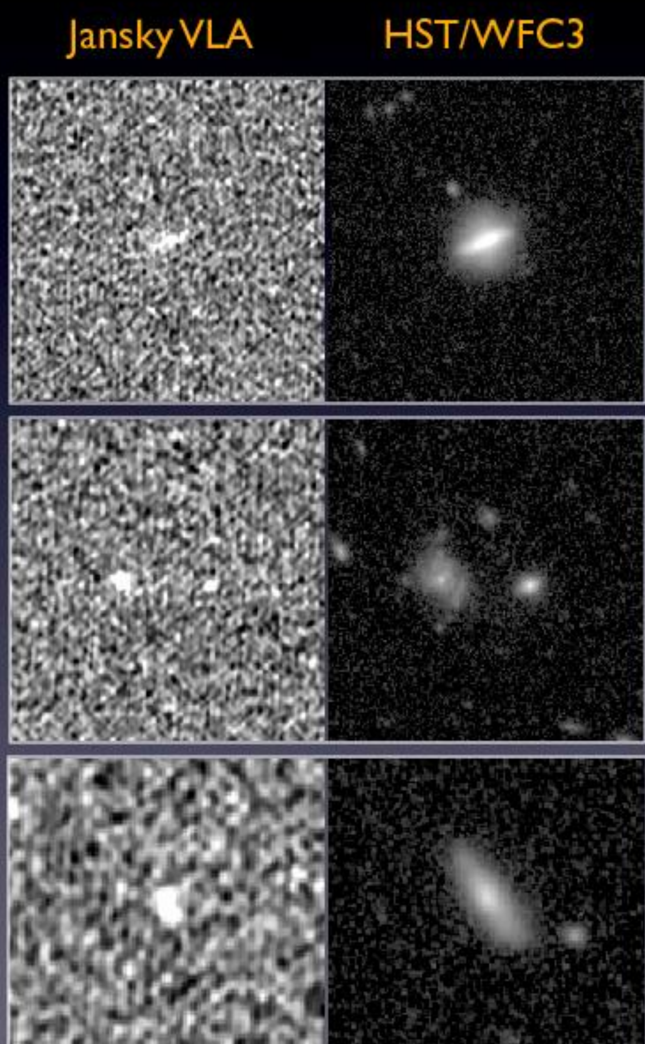
- Rujopakarn et al. have gotten 64 hours' observing at C-band in A-configuration on COSMOS field.
- Goal is to understand what drives star formation, and how galaxies assemble their mass, by imaging (with 3 kpc resolution) radio emission of star-forming galaxies out to z=3.
- Current image has 0.7 μJy/beam noise – the lowest I'm aware of so far.
- Expect to reach 0.5 μJy/beam.
- In another program, he is using the VLA to survey ~ 600 massive galaxy clusters for lensed galaxies, using Herschel/SPIR in the 'Herschel Lensing Survey' (HLS).

6cm radio and HST images



Sources density comparison between
4-8 GHz radio (green circles) and HST/WFC3 F160W from CANDELS

A total of 200 galaxies detected in 36 hrs data (55%) so far, e.g.



Local, z = 0.1 star-forming galaxy

z = 2 SF/AGN in spiral core?

Extended, ~8 kpc
star forming regions at z = 1

Lensed Radio Emission discovered

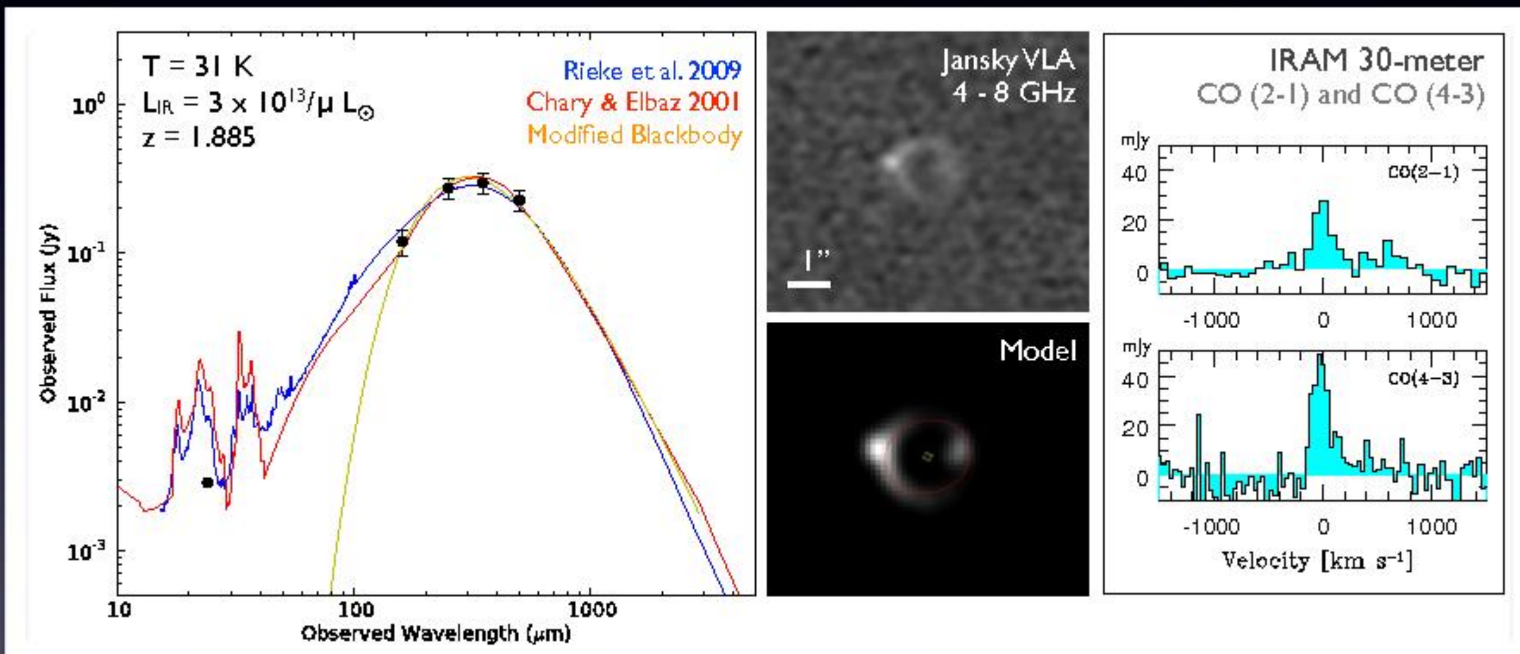
EVLA

- Strong IR galaxy (300 mJy at 350 micron) is 10’ from cluster core.
- Lensing not due to cluster – is a galaxy-galaxy lens system.

- Lensing galaxy not detected in radio or IR
- In optical, Subaru shows it is an elliptical, located at center of the ring.
- MMT z=0.65.
- Background object z=1.885 (CO).

EVLA

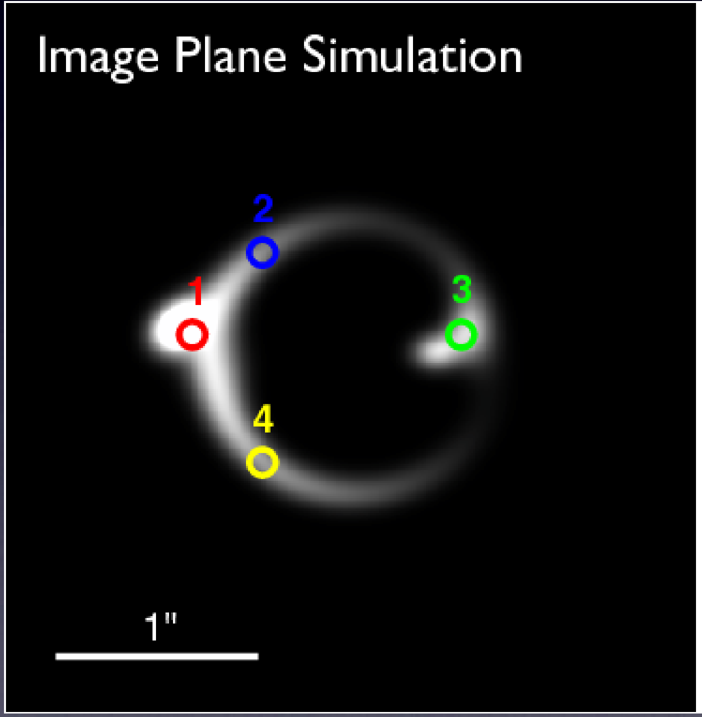
Strongly lensed, kinematically ordered ULIRG at z ~2 discovered with JVLA



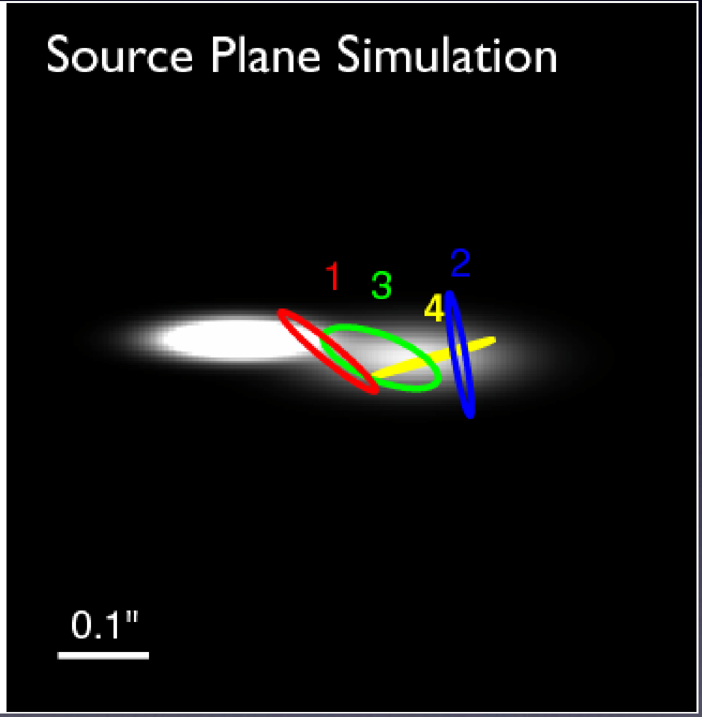
Narrow CO line widths suggest a kinematically-ordered system (e.g., disk) despite its extreme luminosity

Rujopakarn et al. 2013, in prep.

Dissecting the intensely star-forming clumps in a z ~ 2 Einstein ring



Simulated HST WFC3 beams



... physical area probed

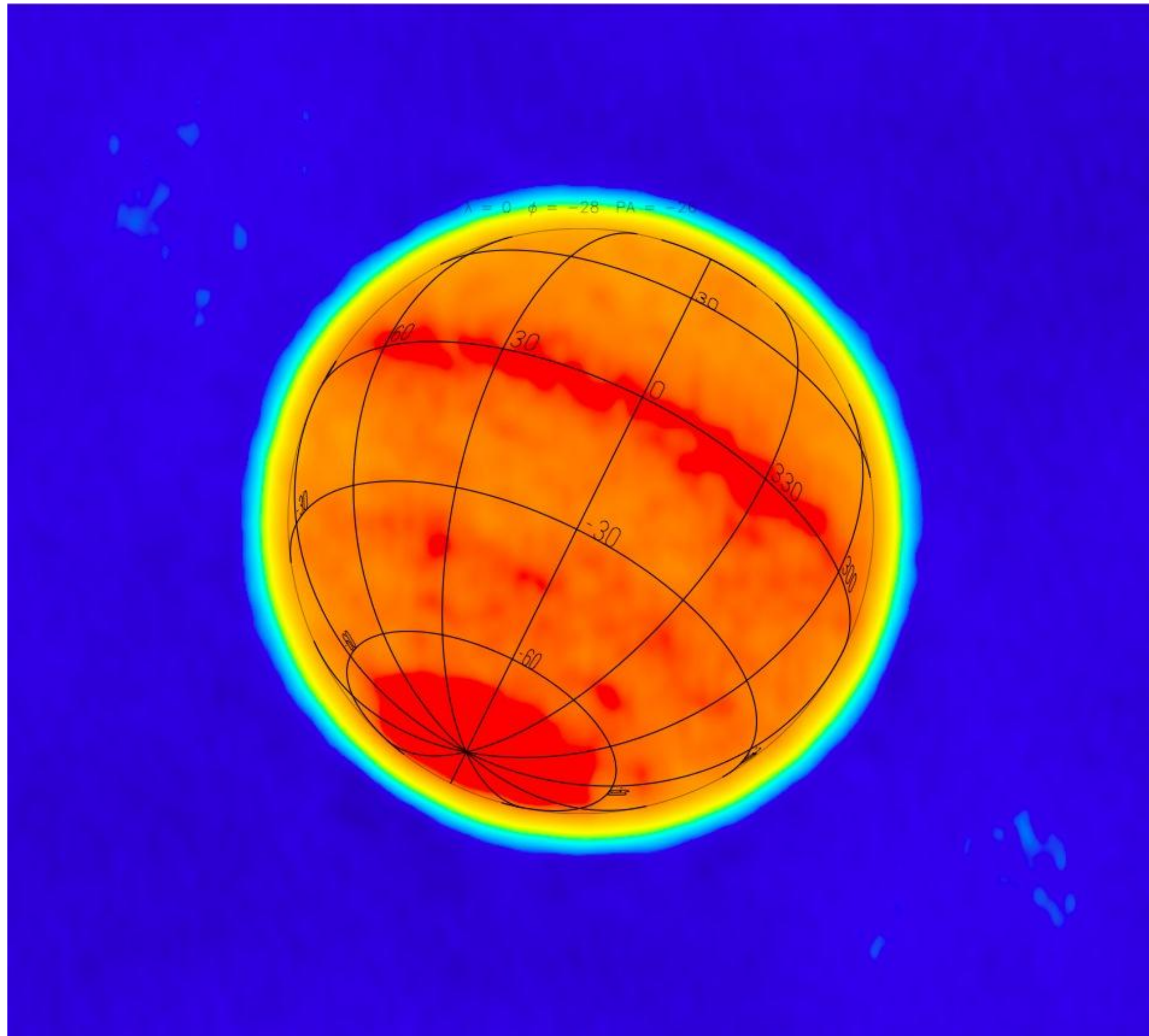
Scaling relations in these clumps can be studied down to ~40 pc with HST and ALMA

EVLA

Planetary Physics – Neptune (Butler et al.)

- 1 cm wavelength
- A-config – 0.1" resolution
- Average T_b = 135 K
- Noise ~ 15 uJy/bm ~ 1.8 K

- Note brightenings at the south pole (~20 K), equator (~10 K), and mid-southern latitudes (a few K).
- South polar enhancements have been seen before at both radio and thermal infrared wavelengths, but equatorial and mid-latitude enhancements have not been seen before.
- Brightening due to optical depth effect – we're seeing deeper into the atmosphere.



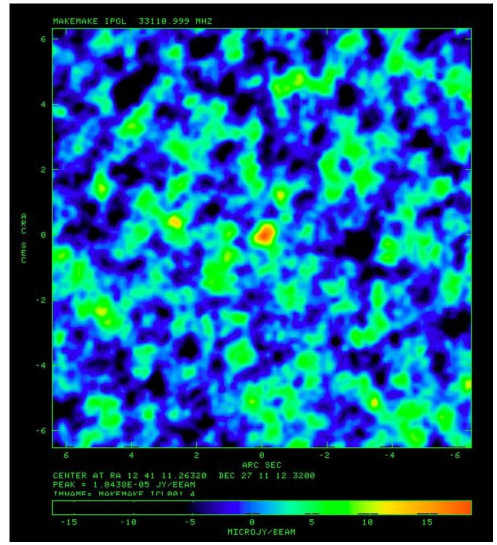
NRAO

EVLA

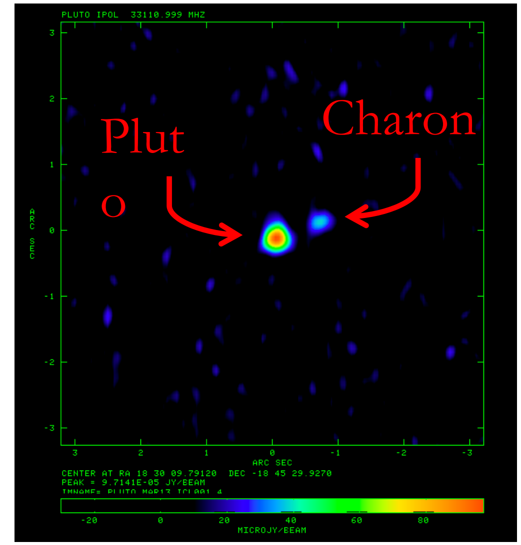
Trans-Neptunian Objects

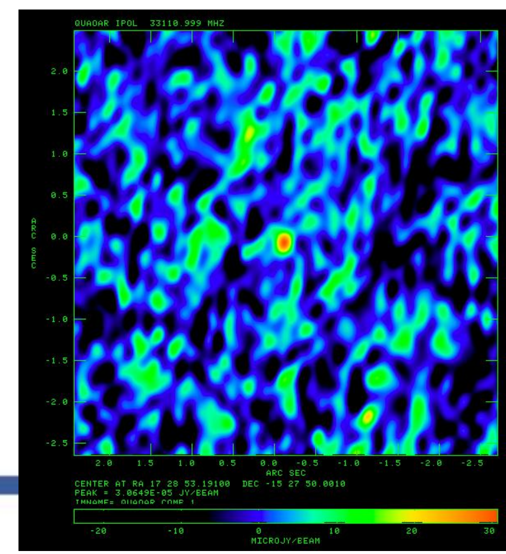
- 1 cm wavelength
- Winter/Spring 2011
- Noise ~ 3-5 uJy/bm ~ 2-4 K

These icy outer solar system bodies are at temperatures from 25 to 40 K, so very faint. For Pluto/Charon, a measurement of temperature constrains surface composition (what kind of ice?); for the others, a size constraint is obtained. These are the longest wavelength observations of these bodies, by an order of magnitude.



Makemake





Quaoar

NRAO

A Brief Summary

- The Jansky Very Large Array is a flexible imaging spectroscopic array with 1 to 4 orders of magnitude improved performance over the pre-existing Very Large Array.
- The construction phase of the project is now completed, and science observing with the new capabilities is now in place.
- Most promised capabilities are available – some (such as pulsar modes and the most flexible spectral modes) are still under development.
- New and very exciting results are now being produced – with topics across the entire range of astronomy.