Synergistic Science with the JVLA in the Epoch of the 30-m Telescopes and LSST

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Gratitude to Rick Perley and Steve Myers for slides

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

NRAO

Outline

- Properties of the Expanded VLA
- Science Capabilities of the VLA
  - Targeted Science
  - Survey Science with the VLASS
- Synergy with LLST and 30-m class telescope science

Properties of the Expanded VLA

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
- Designed as an imaging array
- Makes a pretty good 'light bucket' also.
- Also a decent surveying instrument.
- Recently upgraded.

Major Capabilities of the E-VLA

- **Nine Frequency Bands.**
  - Eight cryogenic bands, covering 1 – 50 GHz. Utilizes cassegrain subreflector.
  - One uncooled, prime-focus band, covering 50 – 450 MHz.
- **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.
- **Full polarization correlator with 8 GHz instantaneous BW**
  - Provides 64 independent 'sub-correlators', and 16384 spectral channels.
  - Many specialized operations modes (burst, pulsar binning, phased arrays …)
- **<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**
  - Requires higher level of software for calibration, imaging, and deconvolution.

Jansky VLA-VLA Capabilities Comparison

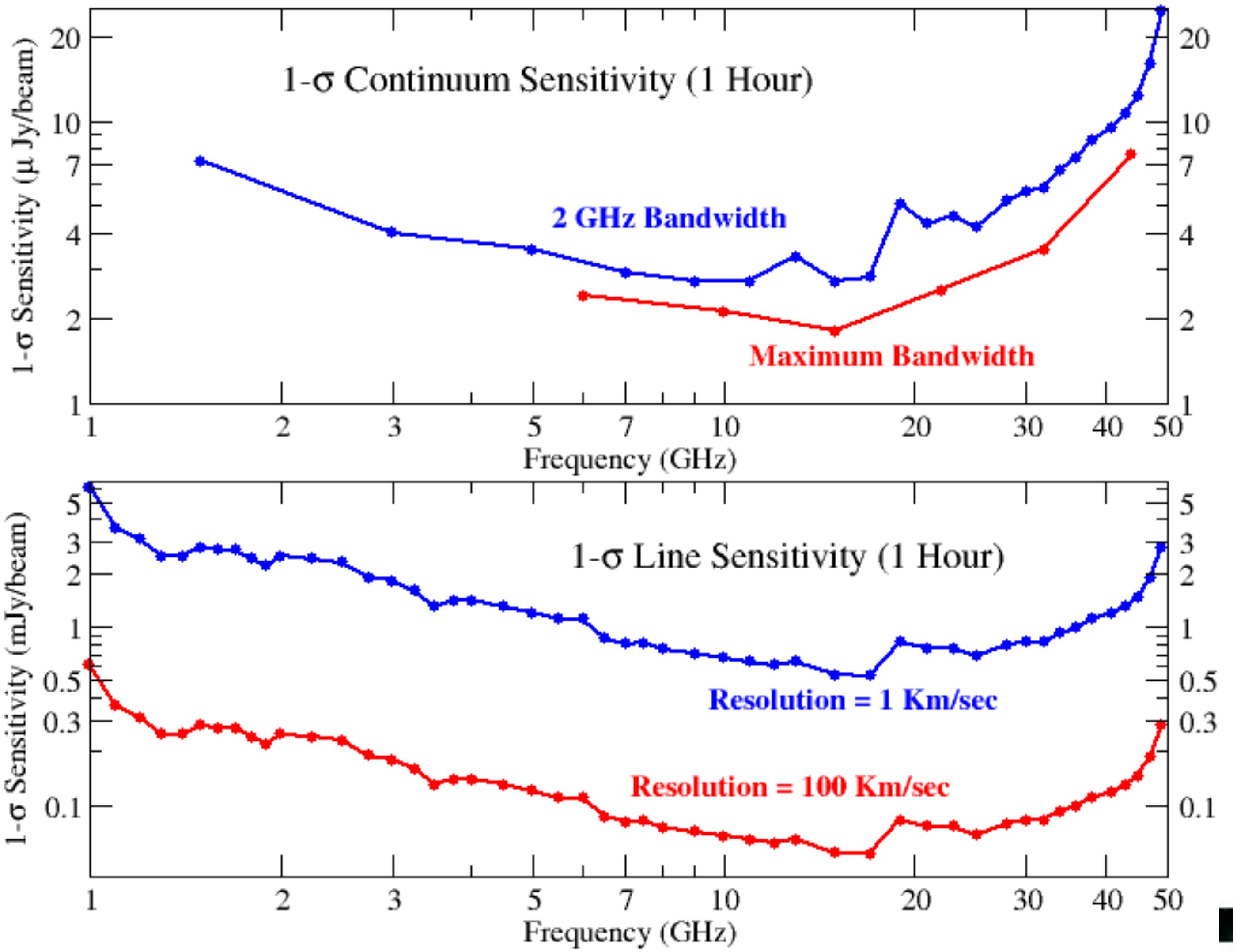
The upgraded VLA's performance is vastly better than the VLA's:

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%
Highest Time Resolution (all channels)	400 msec	<5 msec	**>80**	5*msec

* Limited number of channels

VLA Sensitivity (rms in 1 Hour)

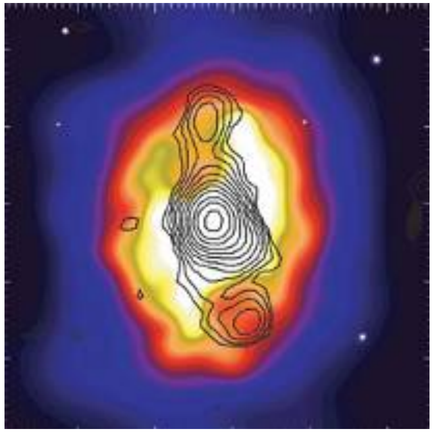
- Achieved sensitivities exceed project requirements at all frequencies above 8 GHz.
- Most sensitive region in continuum is 8 – 15 GHz.
- Most sensitive for spectral line is 10 – 25 GHz.



Targeted Science

Jansky VLA Science: Four Themes

Magnetic Universe



Measure the strength and topology of the cosmic magnetic field.

Obscured Universe

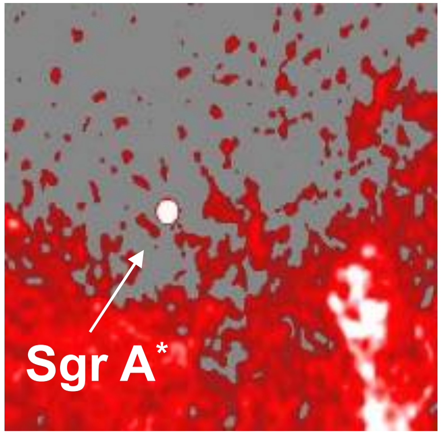
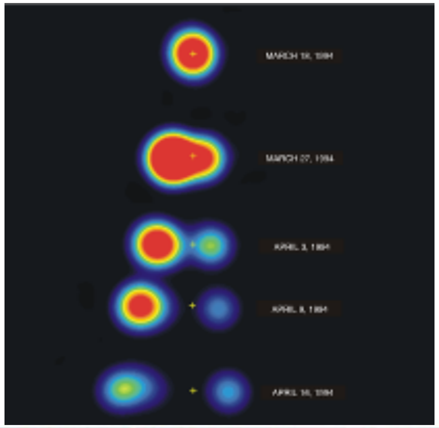


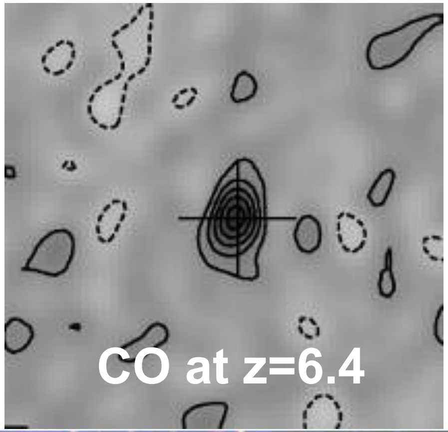
Image young stars and massive black holes in dust enshrouded environments.

Transient Universe



Follow the rapid evolution of energetic phenomena.

Evolving Universe



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

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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.

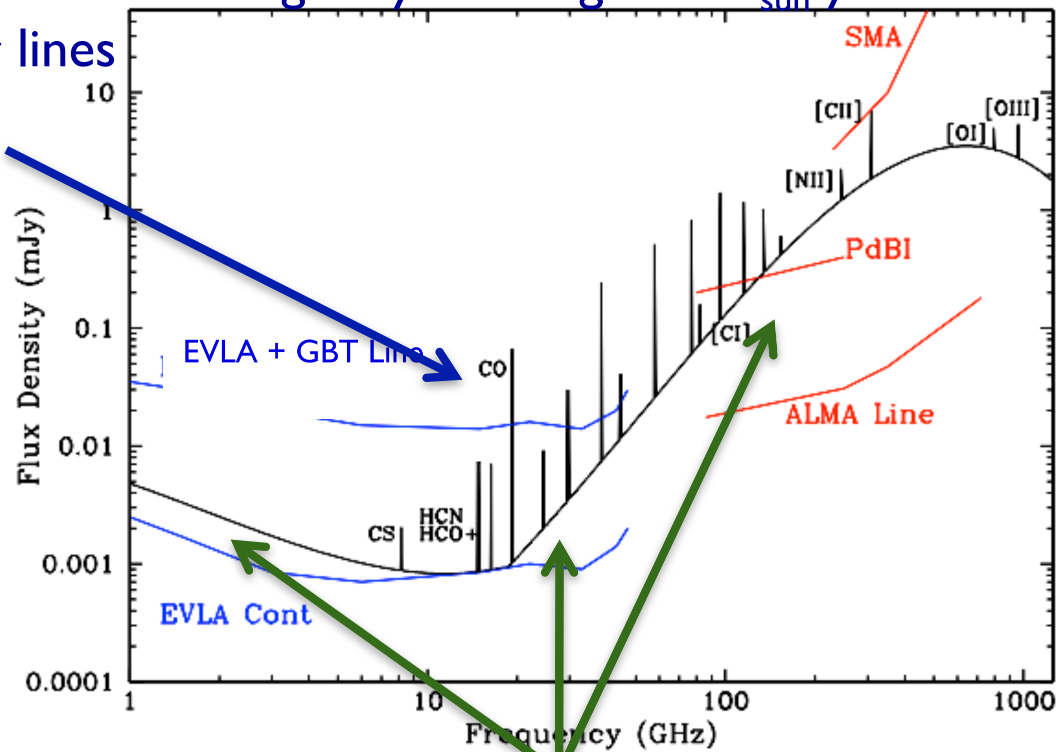
Evolving U: Key Line & Continuum Probes

1. Atomic Hydrogen (weak transition) :
   - "21cm" HI line (rest 1.42 GHz, z=0.42 at 1GHz, z=1.5 at 568 MHz)
   - single line in "clean" part of spectrum (beware OH interlopers)
2. Molecular CO (strong transition) :
   - CO ladder (1-0 rest 115.27 GHz, z=1.5 at 46.11 GHz, 230GHz,345GHz…)
   - no redshift ambiguity for multiple transitions, danger: forest of weaker lines
3. Other lines :
   - Masers like OH (1665/7 MHz), Methanol (6.7,19.9GHz), H_20 (22.2GHz)
   - Radio Recombination Lines (faint), other molecular lines (galactic)
4. Radio continuum :
   - Synchrotron (relativistic electrons), free-free (thermal electrons), anomalous microwave emission (spinning dust), thermal dust (cosmic grime)
   - Generally follows radio/FIR correlation for star formation

Evolving U: Line & SED Probes for Galaxy Evol

SED of galaxy forming 100 M_{sun} yr^{-1} at z=5

Low-J molecular lines
- Total H2
- Dense gas
- Dynamics



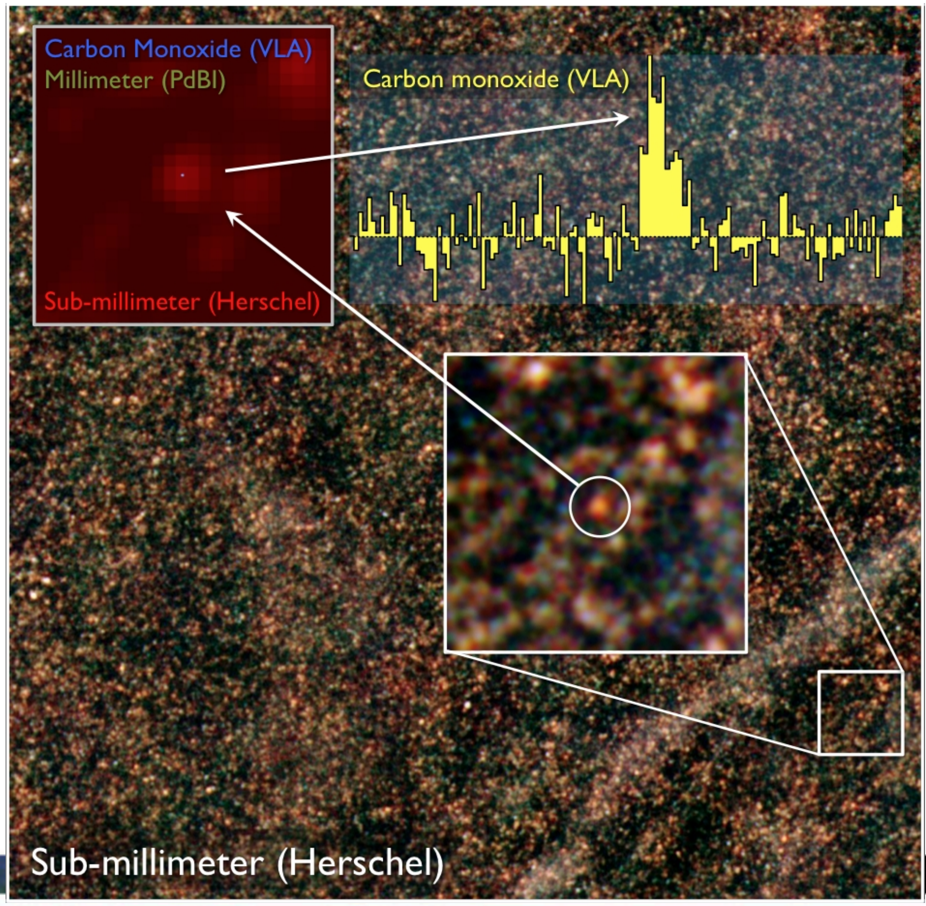
VLA = ALMA science at high redshift and in obscured regions!

Continuum (dust, free-free, synchrotron)
- SFR, ISM distribution, dust abundance

HFLS3 – Dust-Obscured Massive Maximum-Starburst Galaxy at z = 6.34

- Dominik Riechers et al. (64 coauthors, 32 institutions, 12 telescopes) have published (arXiv:1304.4256) an intensive study of HFLS3

- Source found as the strongest of 5 ‘ultra-red’ objects in Herschel/SPIRE
- Photometry done at 46 frequencies.
- 52 spectral lines from 11 atoms or molecules searched (21 detected).
- 10^{11} M_0 of highly excited chemically evolved ISM in the galaxy.
- ‘Maximum Starburst’ converting gas into stars 2000 times the MW (and 20 times more than Arp 220).



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VLA helps reveal the earliest extreme starburst

- The earliest extreme starburst galaxy has been discovered at z=6.3 through selection via red Herschel colors, plus follow-up spectroscopy at cm through submm wavelengths showing numerous lines from CO, ammonia, water…
- This system represents the formation of a massive galaxy in an extreme starburst within 800Myr of the Big Bang
- These results demonstrate the power of cm through submm spectroscopy to study the ISM in the earliest galaxies, and determine redshifts for the earliest, highly dust-obscured galaxies

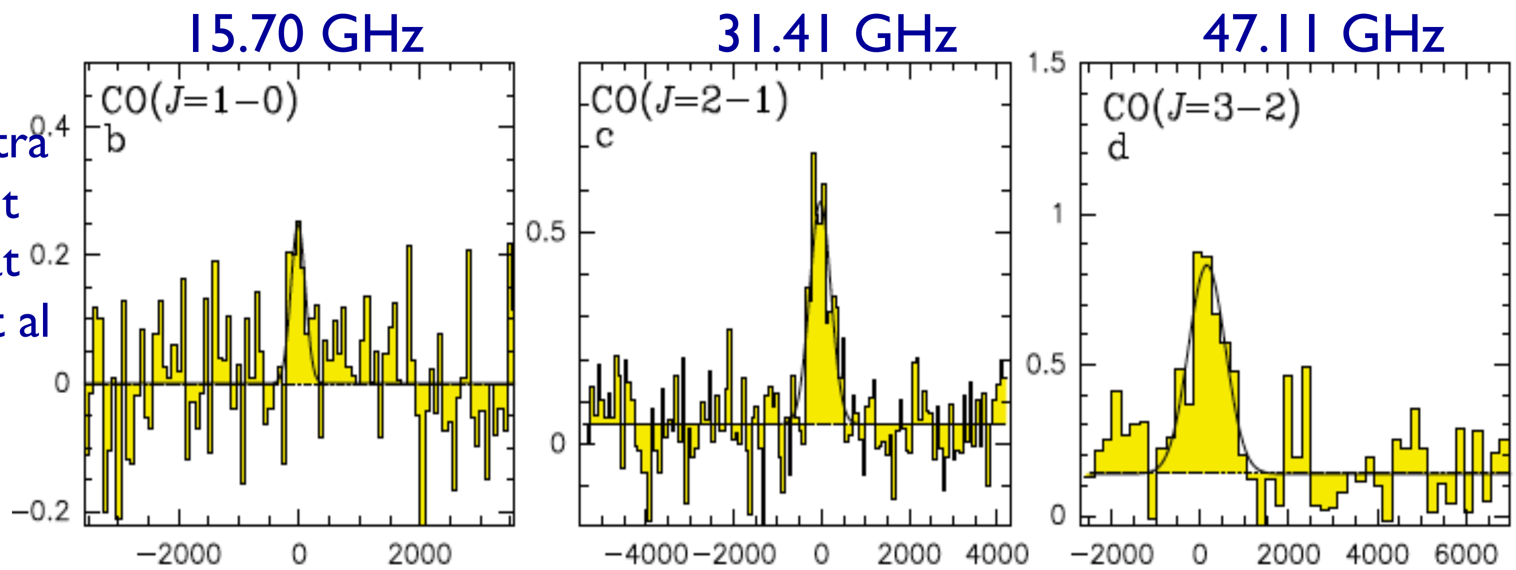


Figure: VLA CO spectra of the most distant starburst known at z=6.3 (Riechers et al 2013)

Binary HyLIRG HATLAS084933 in a Cluster

- Ivison et al. (arXiv:1302.4436) have identified a sample of non-lensed high luminosity sources from Herschel imaging surveys.
- Panchromatic (optical through cm radio, 11 facilities) imaging of the best candidate uncovers four luminous galaxies across a ~100 Kpc region at z = 2.41.
- Two brightest galaxies span 3 kpc (FWHM) in continuum and CO 4-3, and 6 kpc in CO 1-0.
- Two brightest galaxies are counter-rotating, with dynamical masses over 10^{11} M_0.
- Gas fractions exceed 40%.
- Star formation rates > 5 times the main sequence – difficult to reconcile with simple volumetric star-formation law.

The Four Galaxies, with CO Rotation Curves.

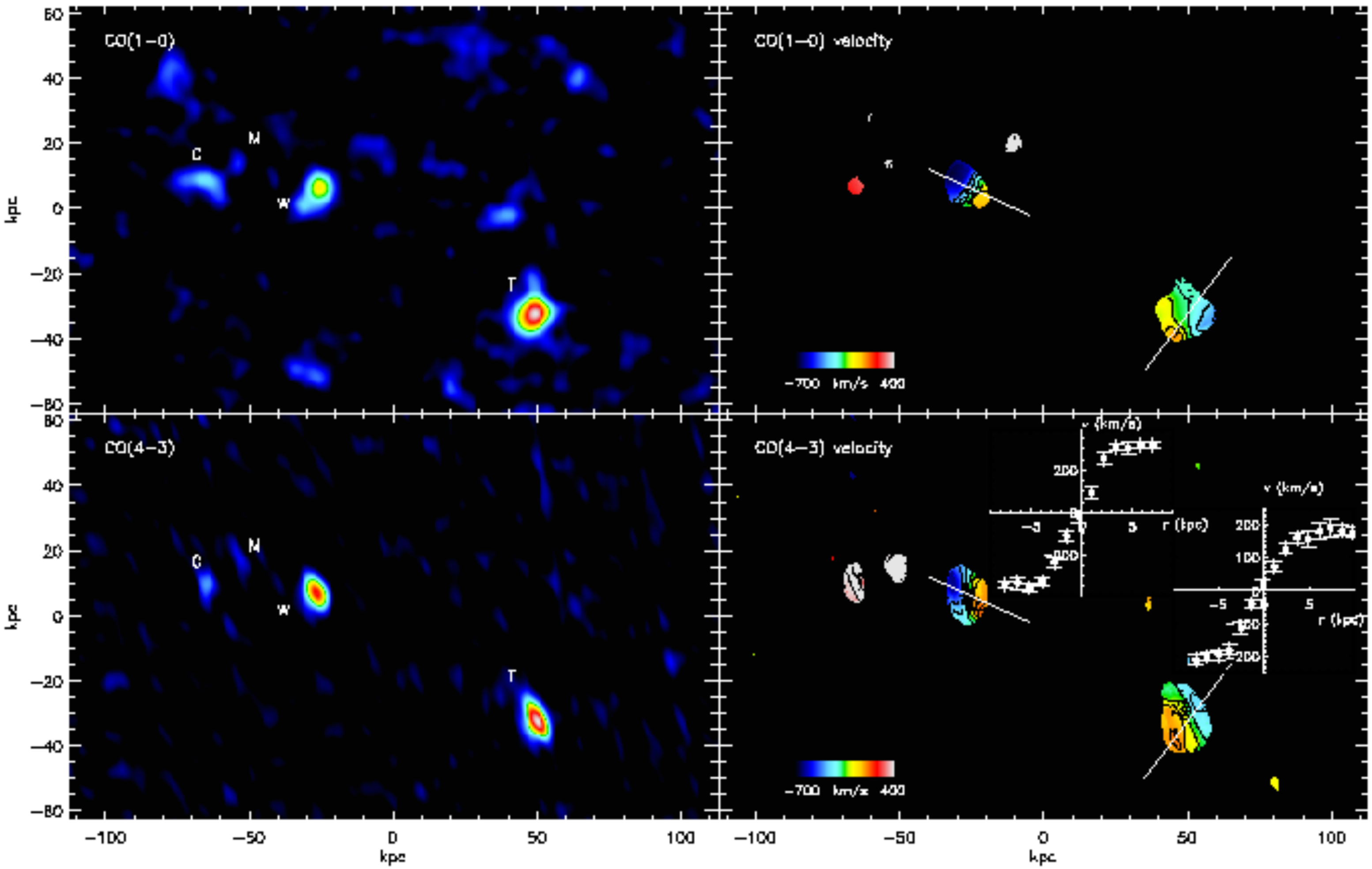
VLA

CO(1-0)

IRAM

PdBI

CO(4-3)



Rotation Curves – from CO 4-3.

Intensity Velocity Dispersion Model Fit

R

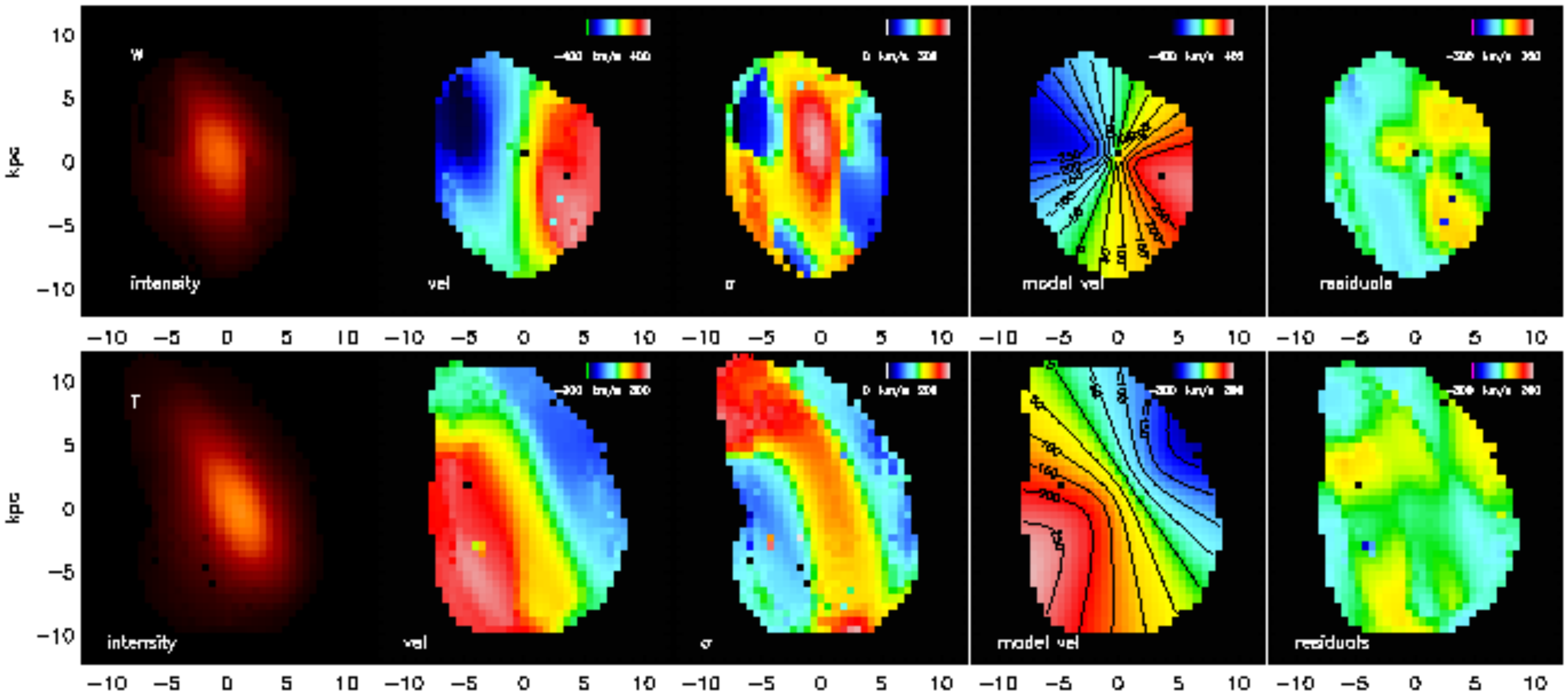
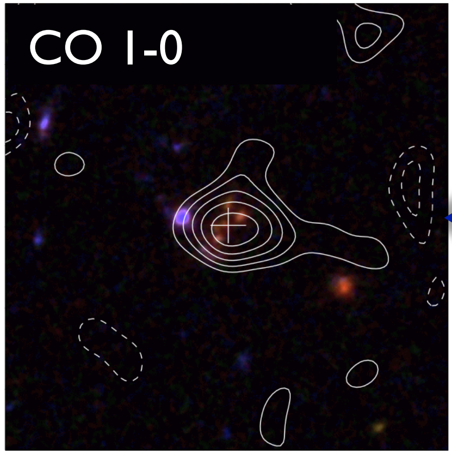


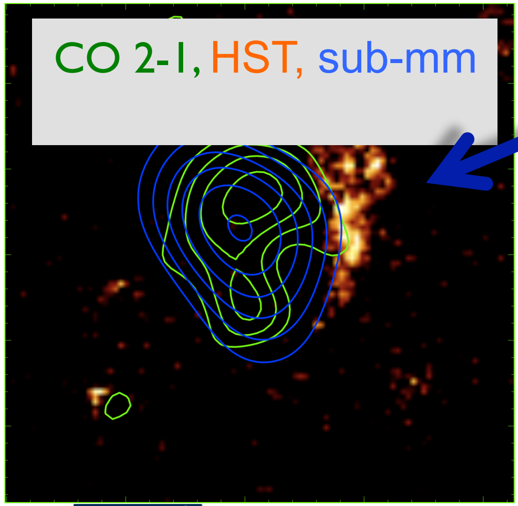
Figure 6. CO $J = 4 - 3$ imaging of galaxies W and T, showing *left to right* their intensities, resolved velocity profiles, line-of-sight velocity dispersions (σ), our best-fit kinematic model (see text) and the residuals. The color scale for the velocity fields is shown in each panel. We note that there is evidence for lensing shear in the velocity field and line-of-sight velocity dispersion for T.

Evolving U: A Molecule-Rich Protocluster @z~4

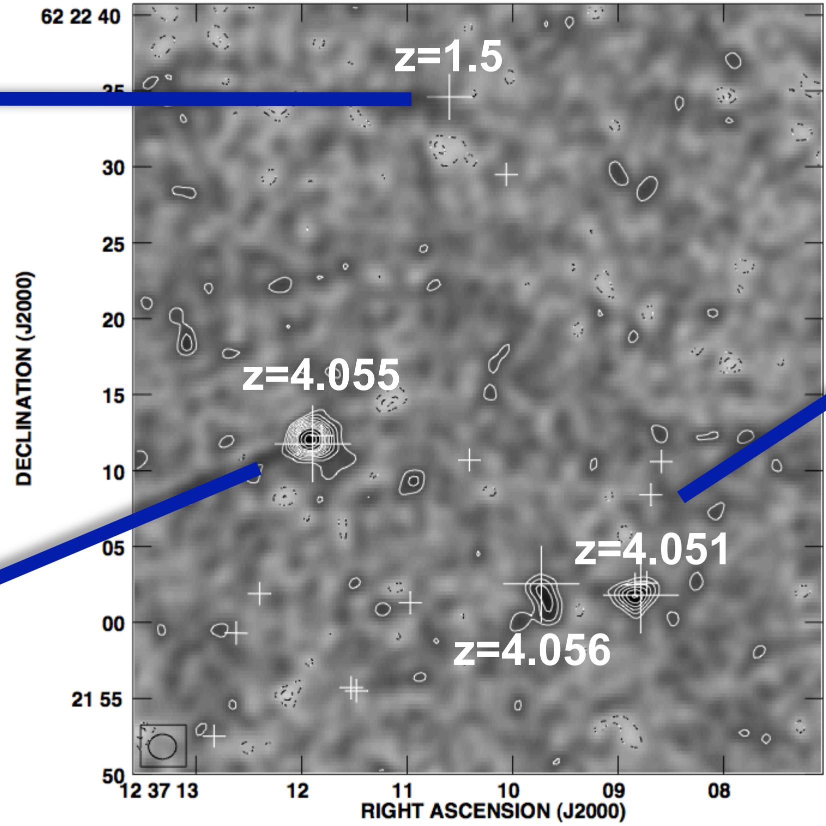
Foreground sBzK galaxy



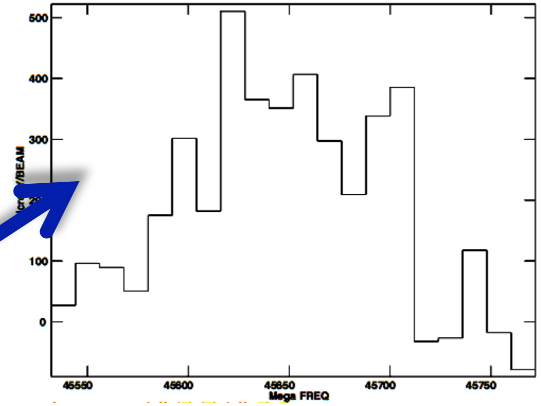
Imaging CO 2-1



46 GHz Observations of GN20



CO 2-1 Spectroscopy

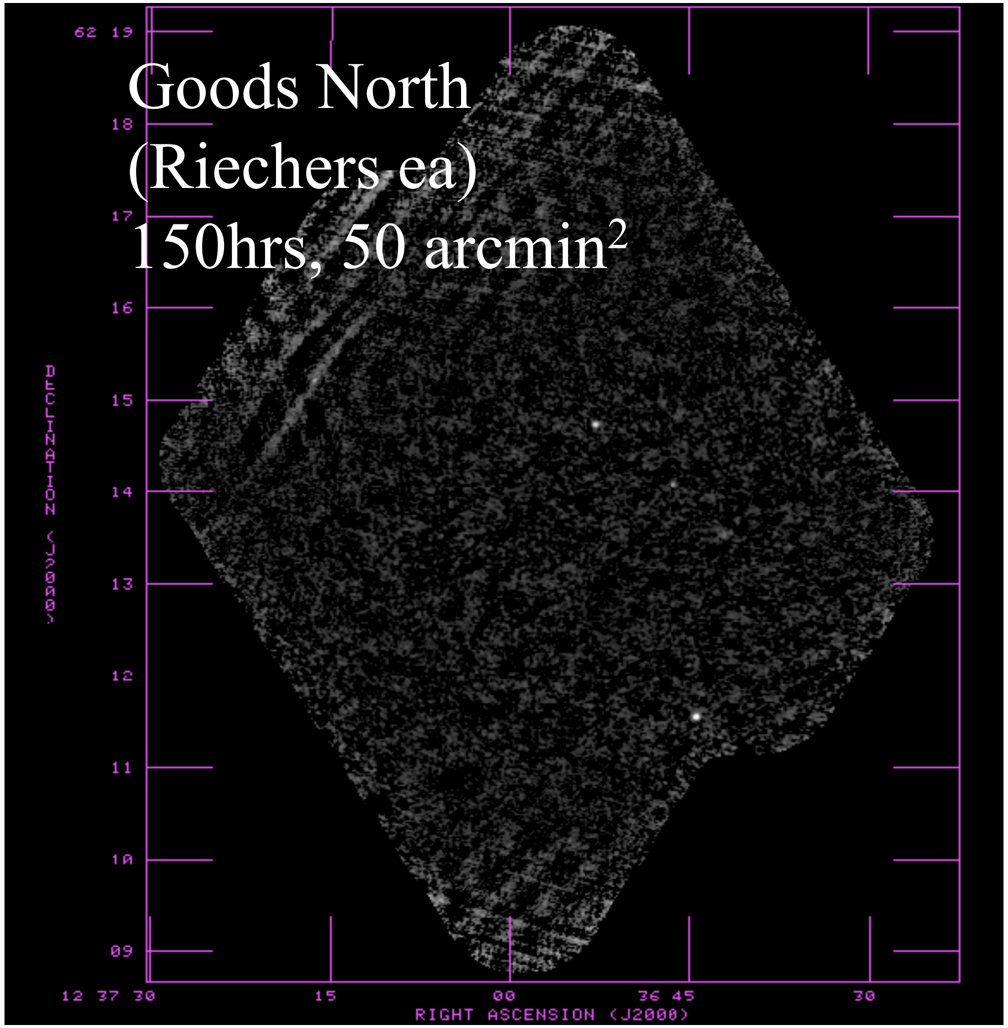


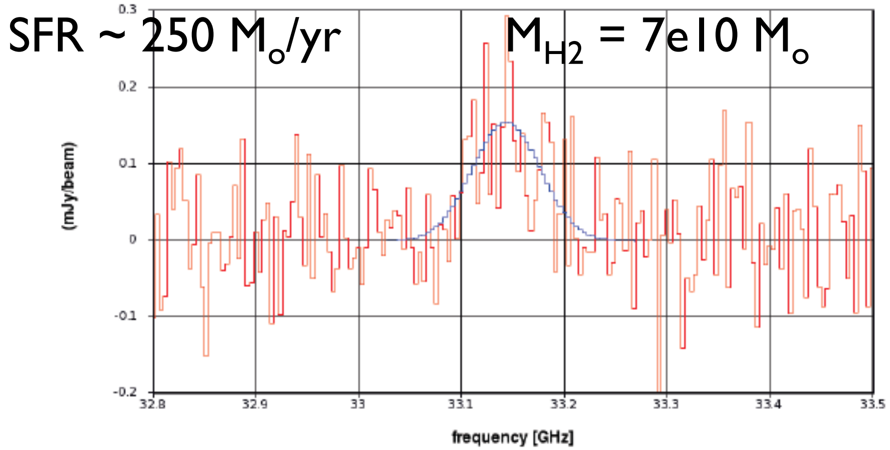
Wide Bandwidth = Large Redshift Range

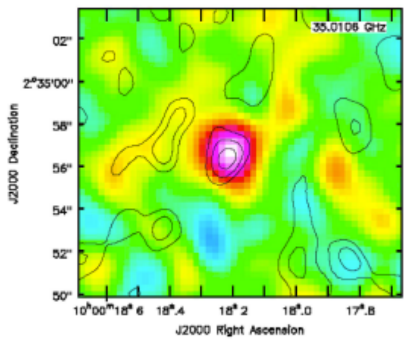
CARILLI ET AL. (2011)

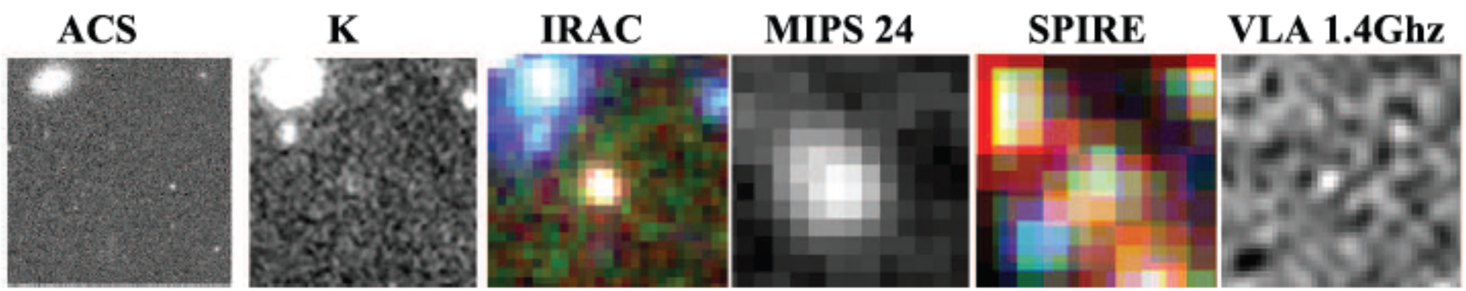
Line CO deep fields: VLA, ALMA

- 30 – 38 GHz =>
  - ➢ $z_{1\text{-}0}$ = 2-2.8
  - ➢ $z_{2\text{-}1}$ = 5-6.7
- Continuum rms = 5uJy
- Line rms(100km/s) < 0.1mJy => MH_2 = few e9 Mo



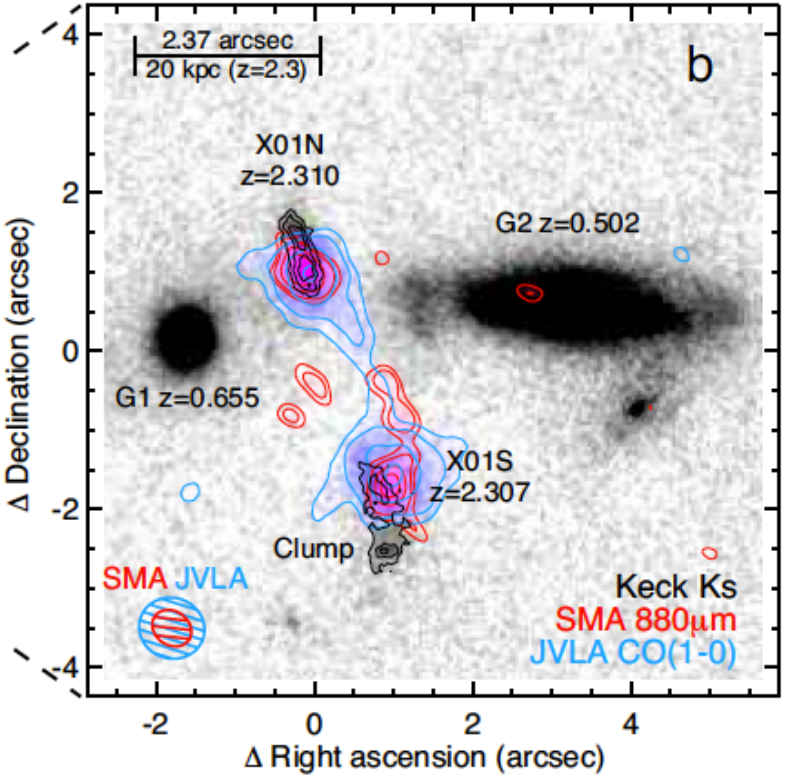






JVLA and GBT study rapid massive galaxy formation at high redshift

- High-resolution observations, including CO with the JVLA and GBT, reveal a rare merger of two massive starbursts at z = 2.3, currently forming stars at 2,000 M_o/yr. The gas reservoir will be exhausted in ~200 million years. At a projected separation of 19 kpc, the two massive starbursts are about to merge and form an elliptical galaxy with a stellar mass of $4x10^{11}$ M_o.
- The JVLA CO results show a tidal structure, direct evidence for a gas-rich major merger, driving the intense star formation during the rapid formation of the most massive elliptical galaxies by z ~ 1.5.



Composite of near-IR, HST, and JVLA CO observations of a z=2.3 starburst system (Fu ea. Nature)

Line CO deep fields: VLA, ALMA

- 30 – 38 GHz =>
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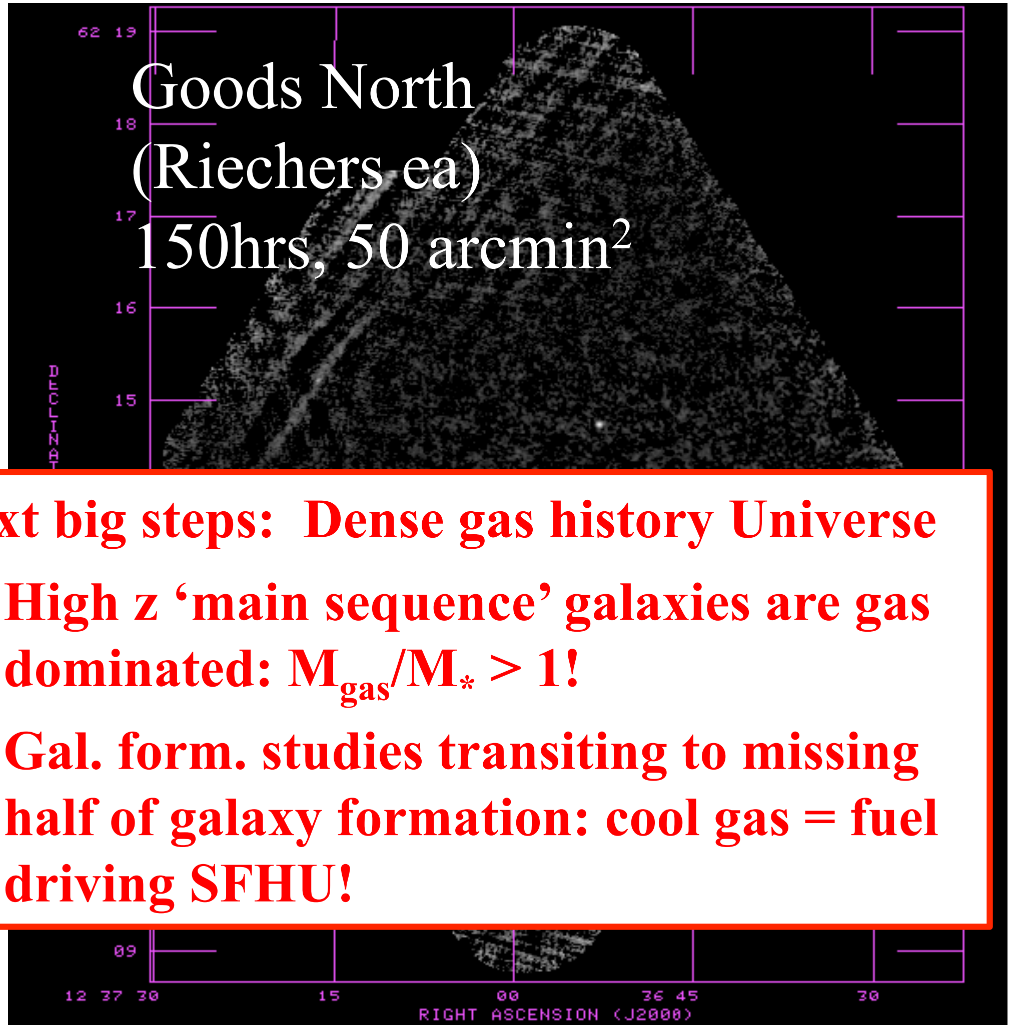
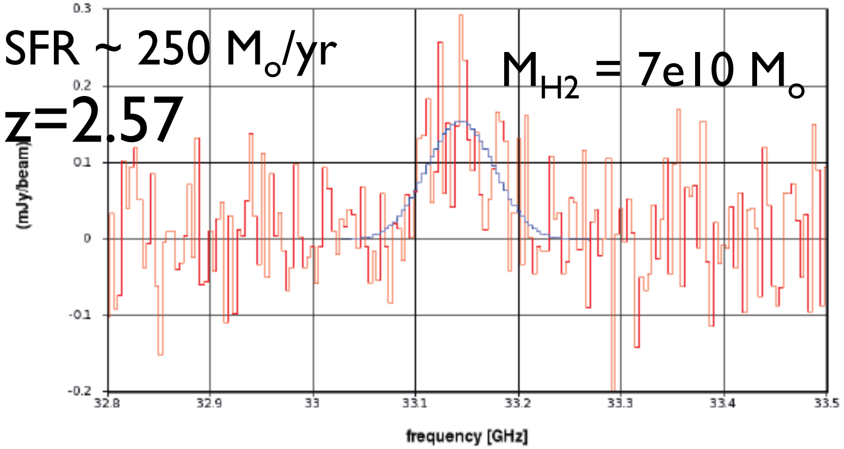
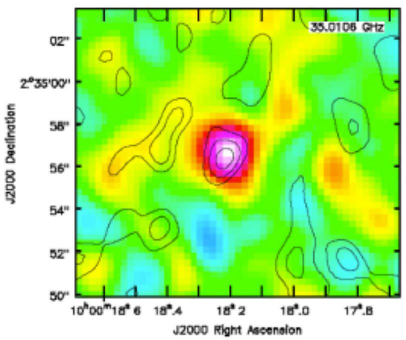
- $z_{2\text{-}1}$ = 5-6.7
- Continuum rms = 5uJy
- Line rms(100km/s) < 0.1mJy

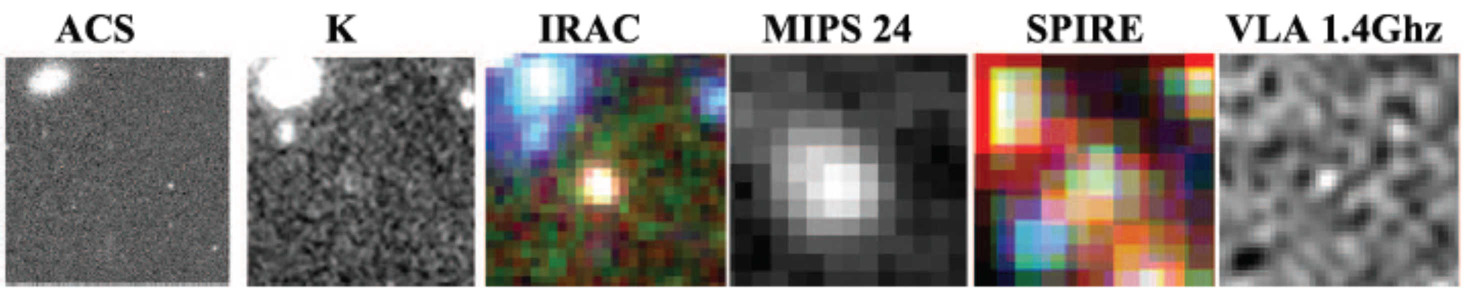


Next big steps: Dense gas history Universe

- **High z 'main sequence' galaxies are gas dominated: $M_{gas}/M_* > 1$!**
- **Gal. form. studies transiting to missing half of galaxy formation: cool gas = fuel driving SFHU!**



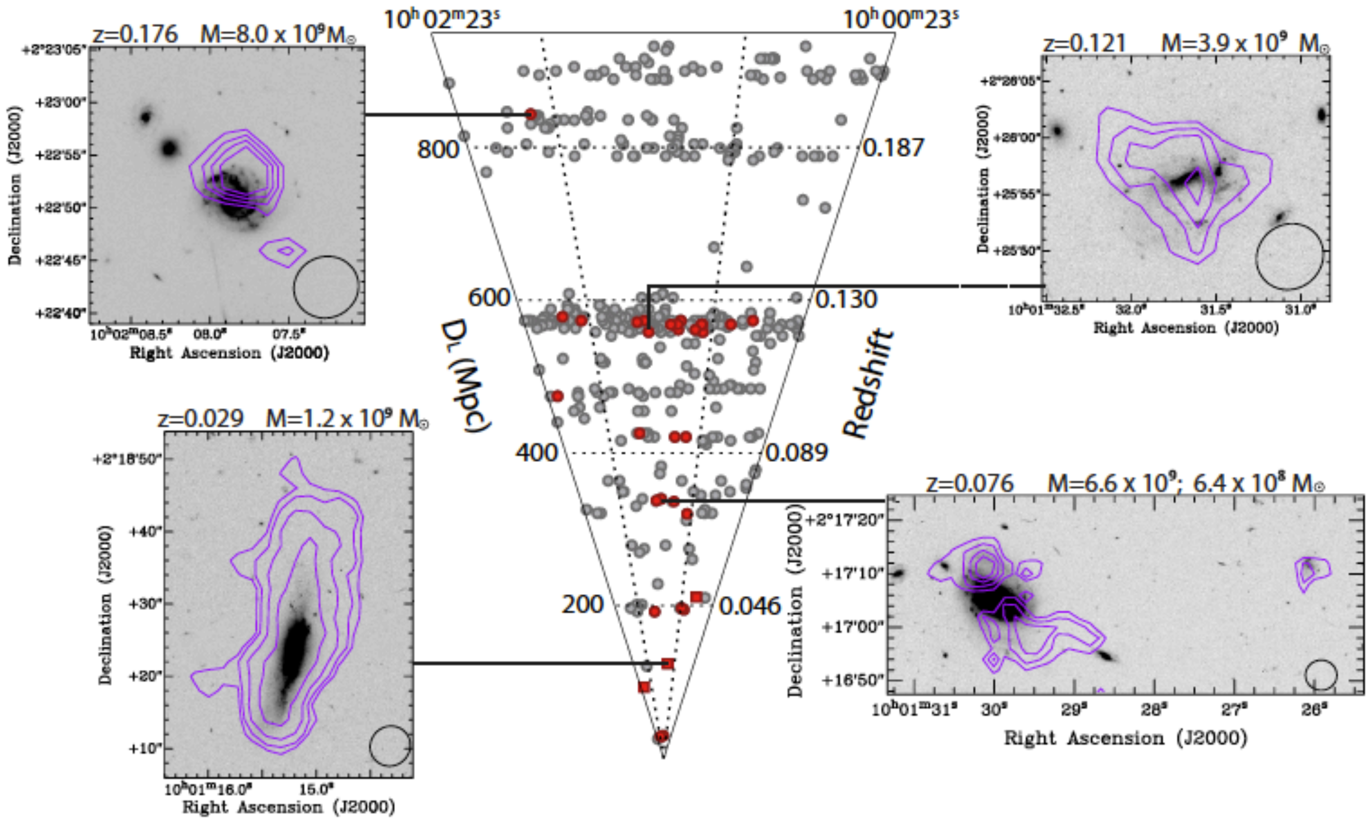




JVLA HI Pilot Deep Field

- The Cosmos field was observed for 50 hours as a pilot search for neutral hydrogen in distant galaxies. 33 galaxies were detected in HI at z=0 to 0.2, including three without a previously known spectroscopic redshift.
- These galaxies have a range of HI and stellar masses, indicating the diversity of galaxies probed. This pilot study shows that the VLA's B-array is the ideal configuration for H I deep fields, and that the VLA is ready to conduct a very deep HI survey.

Example HI detections in the JVLA pilot HI deep field (Fernandez ea. ApJ)



CHILES

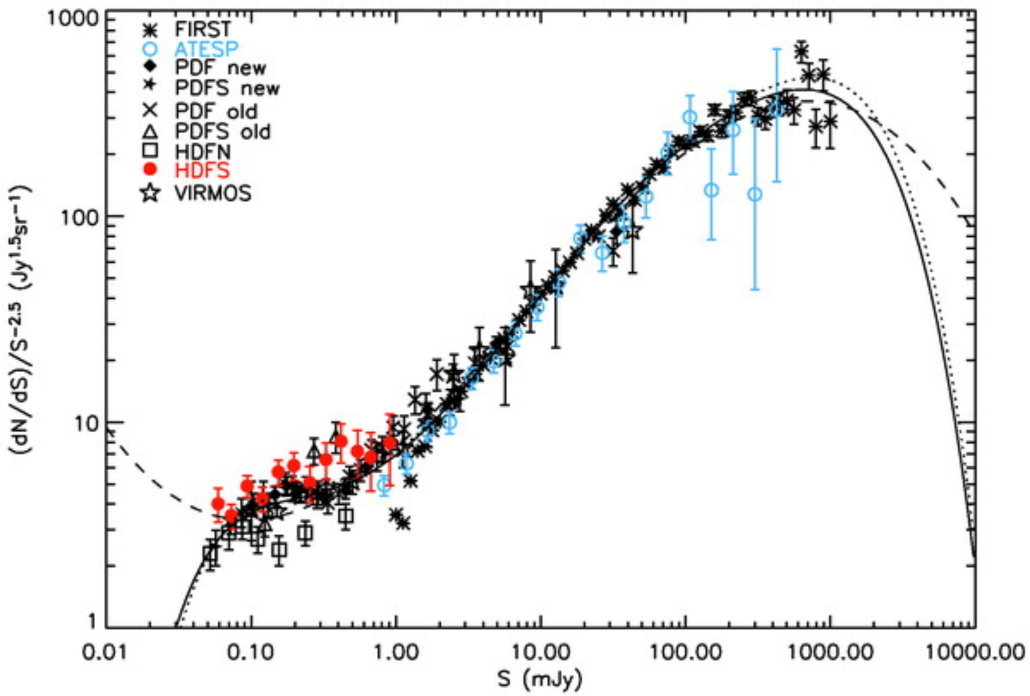
- CHILES (COSMOS HI Large Extragalactic Survey) is a large consortium effort led by Jacqueline van Gorkom (Columbia)
- 1000 hours, in three successive B-configurations (over 3 years), starting now.
- A single 40' pointing is centered on COSMOS field – lots of ancillary data.
- Will cover HI emission for z = 0 to z = 0.45. (1420 to 1000 MHz)
- HI mass limit of $3x10^{10}$ solar masses (5-sigma) at z = .45.
- Velocity resolution of 6 km/sec.
- Will image 300 galaxies
- Obtain integrated spectra for 500 galaxies
- Use stacking to determine mean HI properties as function of color, mass, environment.
- Goal to determine how gaseous properties evolve with z, and dependence upon environment.

Deep Continuum Imaging

- A number of projects are utilizing the VLA's new sensitivity.

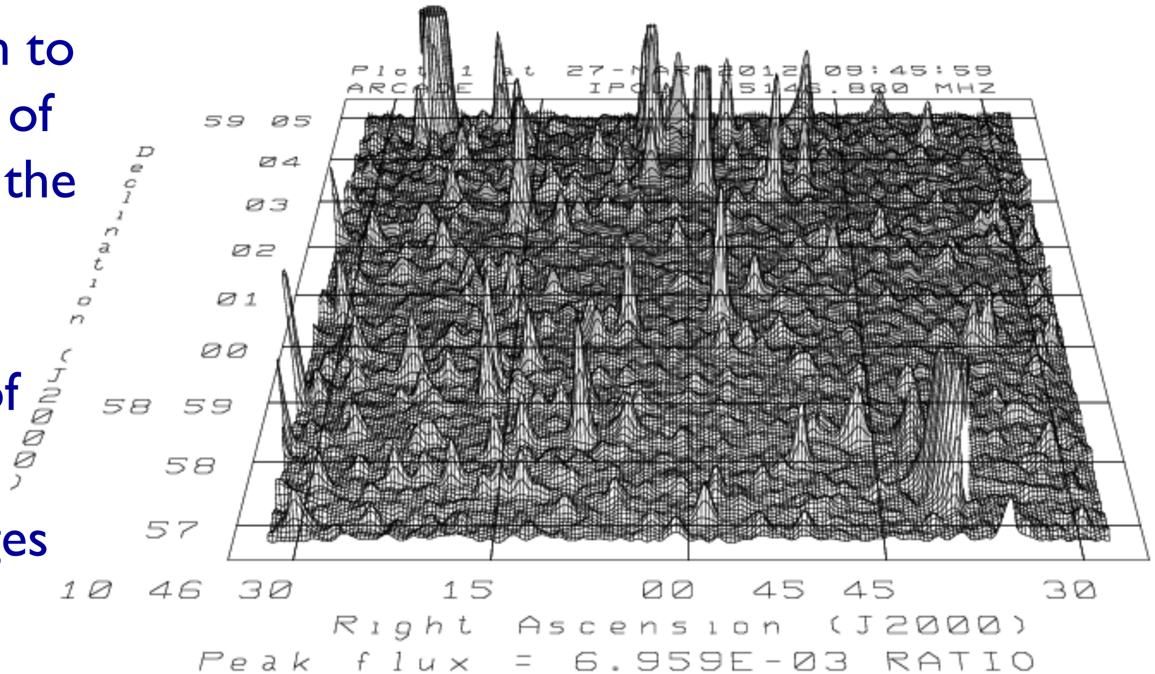
Exploring the Radio Sky at 1 uJy/beam

- 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)

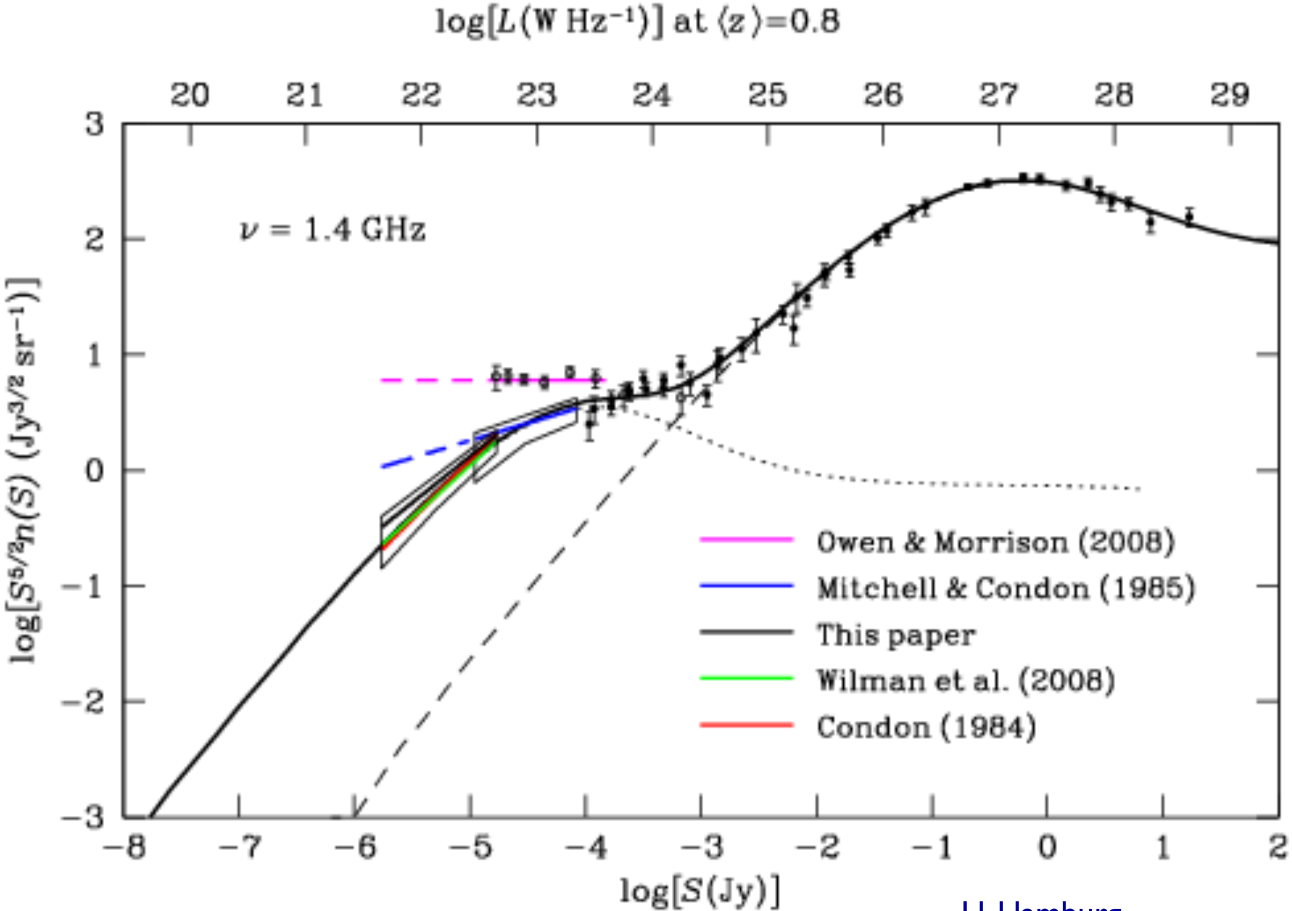


- The plot is clipped at 100 μJy/beam.
- The rms noise is 1% of this peak
- Every 'bump' in the map is real signal!
- About 50 hours on-source integration, with 21 antennas.

Results – No excess to 1 μJy/beam

- 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 1μJy, (1 – 100 nJy) with high surface density.



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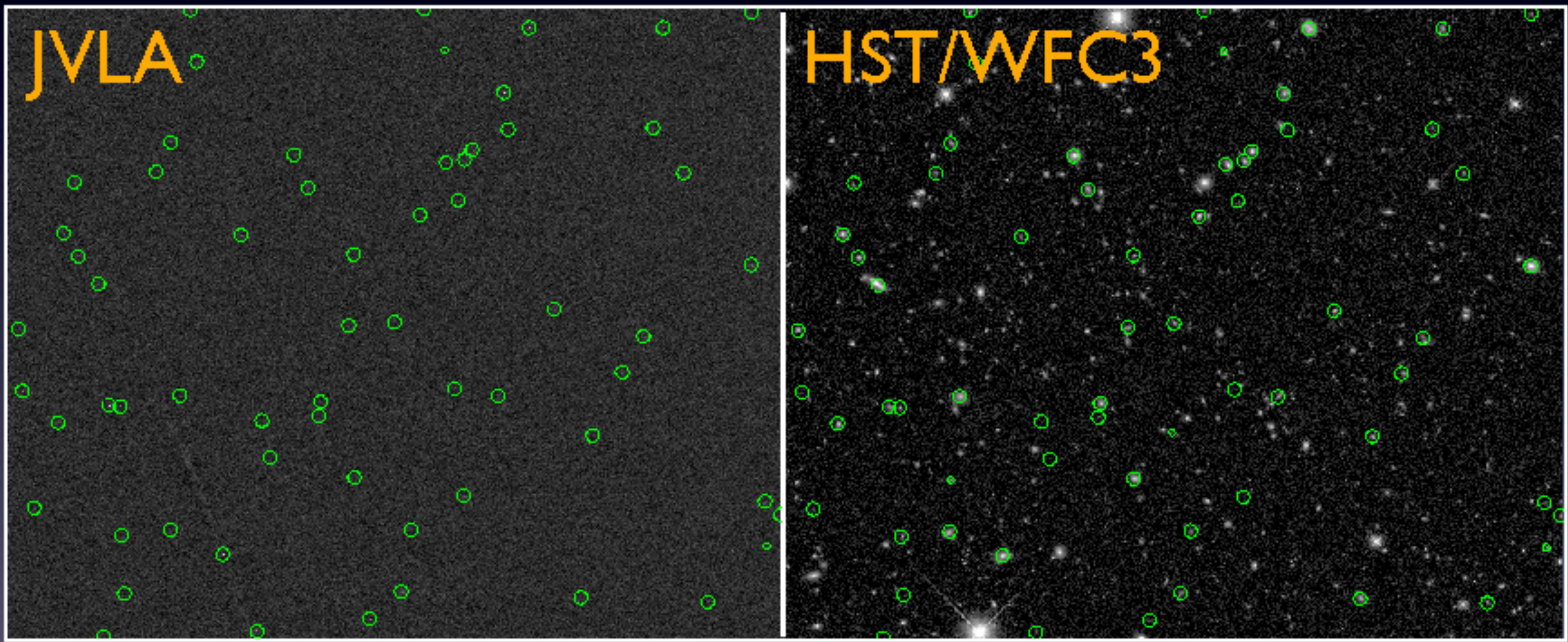
Some Conclusions from Confusion

- 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.

How Deep?

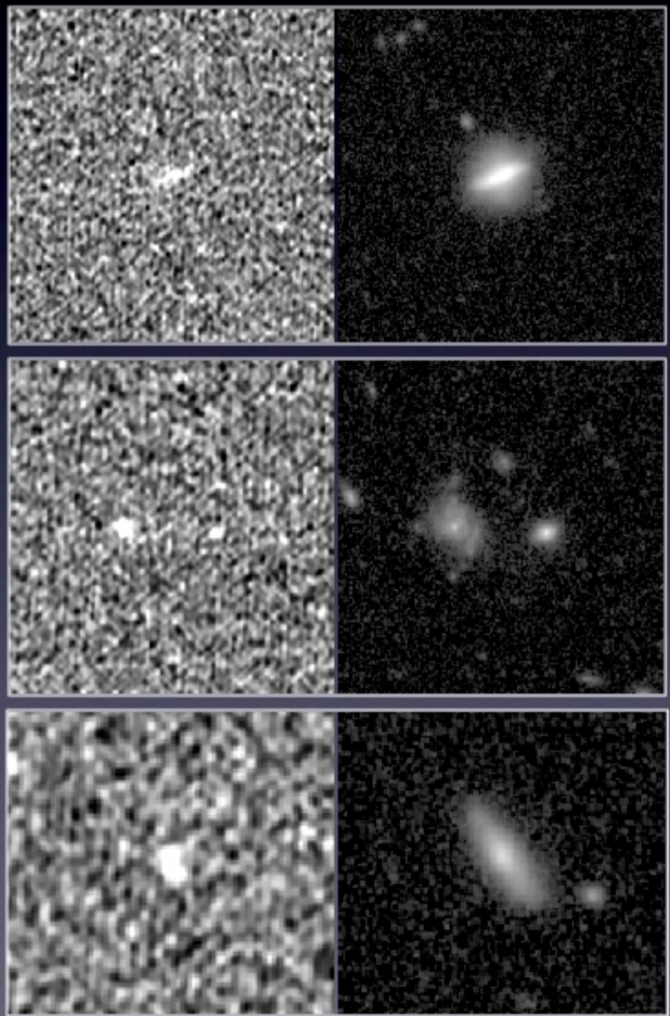
- Rujopakarn et al. have gotten 64 hours' observing at C-band in A-configuration on COSMOS field.
- Goal is to understand what drives star formation, and how galaxies assemble their mass, by imaging (with 3 kpc resolution) radio emission of star-forming galaxies out to z=3.
- Current image has 0.7 μJy/beam 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

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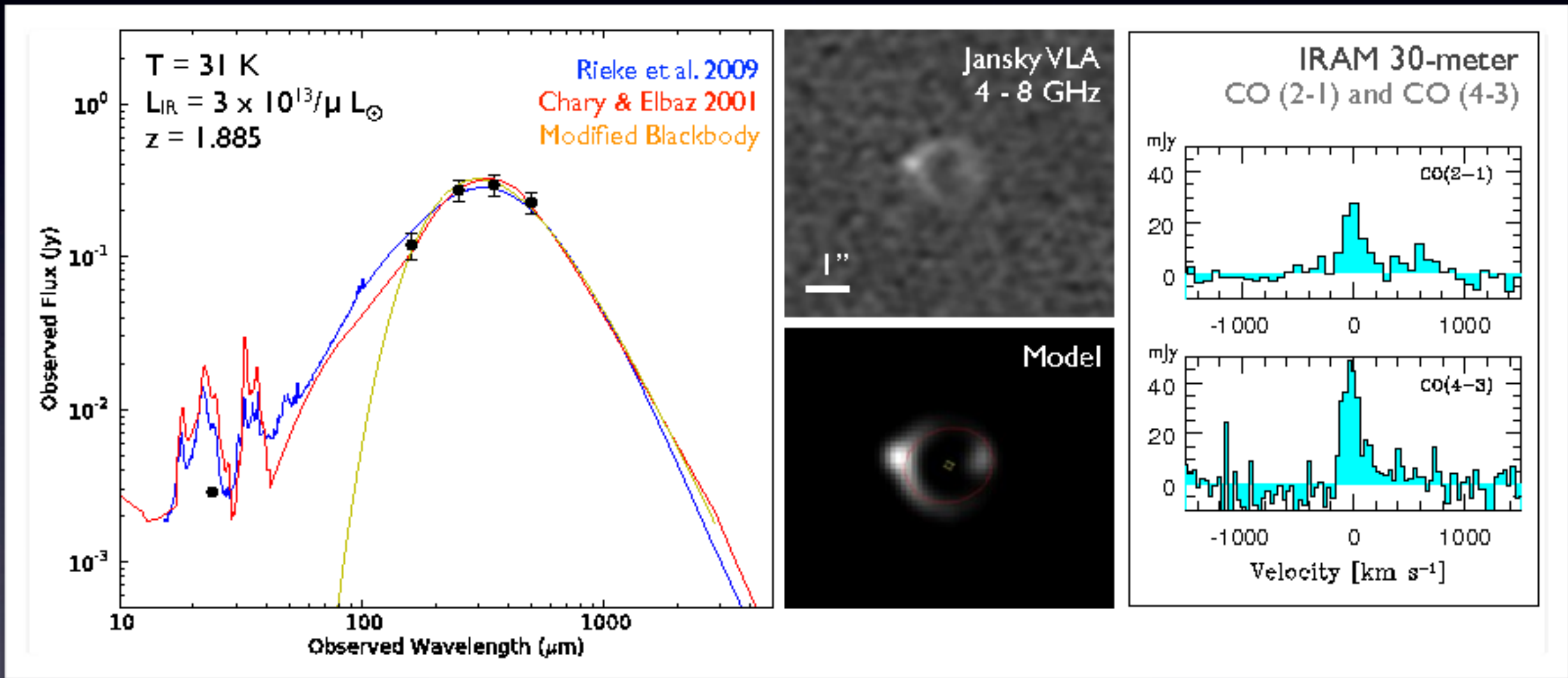
Strongly lensed, kinematically ordered ULIRG at z ~2 discovered with JVLA



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

Rujopakarn et al. 2013, in prep.

Evolving U: Untangling the Cosmic Web

Tracing Large-Scale Structure Formation

- Redshift surveys in CO and HI (e.g. Reichers et al. 13A-398 COSMOS-K_a)
- Characterizing source populations as part of structure hierarchy
- Cross-matching and cross-correlation with other wavelengths
  - e.g. w/Planck for ISW effect from Dark Energy

- Key Capabilities
  - High dynamic-range, high-fidelity mosaic imaging (with polarization)
  - High-sensitivity continuum and (medium resolution) spectral imaging
  - Wide-area survey, large number of sources
  - Cross-matching with surveys at other wavelengths
- Key Developments
  - High quality wide-field imaging, control of systematics
  - Robust extraction of survey catalogue from images & image cubes

Evolving U: Through a Lens Darkly

Strong and Weak Gravitational Lensing

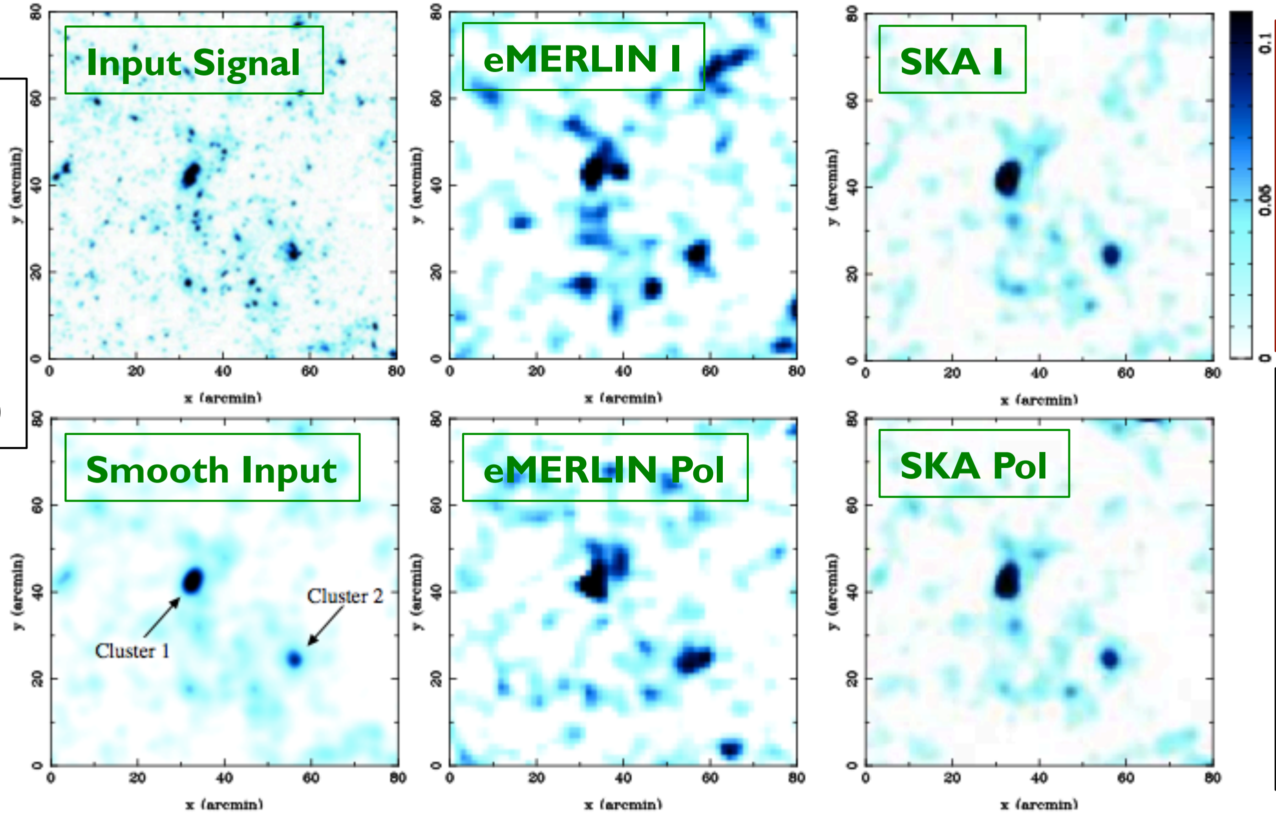
- Probes the amount of clumped matter (mass) – Dark Matter
- Strong Lensing (Multiple Images / Rings / Arcs) – galaxy to cluster scales
- Microlensing (strong lensing by very compact masses)
- Weak Lensing (Distortion of image shapes) – large scale structure
  - "killer-app" of SKA for Dark Energy characterization (e.g. DETF)

- Key Capabilities
  - High spatial resolution (particularly combined with eMERLIN)
  - High dynamic-range, high-fidelity mosaic imaging (with polarization)
  - Wide-area survey, high source density
- Key Developments
  - Ultra-high quality imaging, robust object finding
  - High-accuracy shape measurement (uv-plane and/or image based)
  - High-accuracy polarization imaging

Radio Weak Lensing

- For deep radio observations (<10mJy at 1.4GHz) there is high enough source density of galaxies (&AGN) to start doing weak lensing studies
  - Mass concentrations in Universe distort shapes (shear) of background galaxies, as well as magnify (convergence)

Now:
eMERLIN
plus VLA
SuperCLASS
(Brown et al.)



M. Brown 2012
arXiv:1206.4437

Brown & Battye
2011 ApJL 735 23

Simulated reconstruction of mass density in supercluster of ~10^{14} $M_\odot$ clusters

Obscured & Evolving U: The Unshrouding

Black Holes Near and Far, Then and Now

- Peering deep into galaxy cores
- Role of SMBH in early galaxy formation, magnetic field generation
- Linking AGN activity and star formation through cosmic time
- Astrophysical origin of jets and black hole physics

- Key Capabilities
  - Wide-band wide-field (multi-band) imaging
  - Observations of fields with good multi-wavelength coverage
  - Synoptic surveys for AGN variability characterization and monitoring
  - Deep observations for probing radio-quiet AGN population
- Key Developments
  - Multi-spectral term Multi-Frequency Synthesis imaging

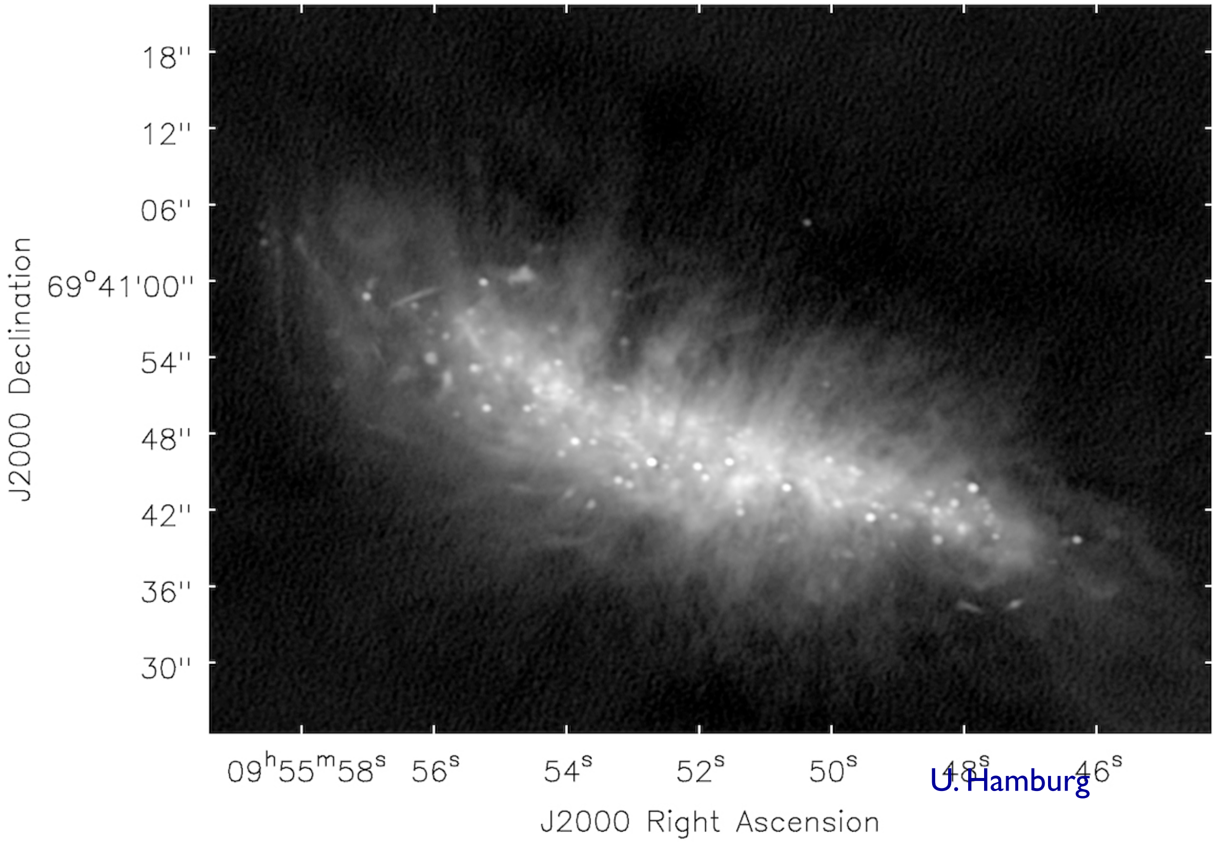
Obscured Universe Theme

- 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 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.

Josh Marvel, Owen, Eilek



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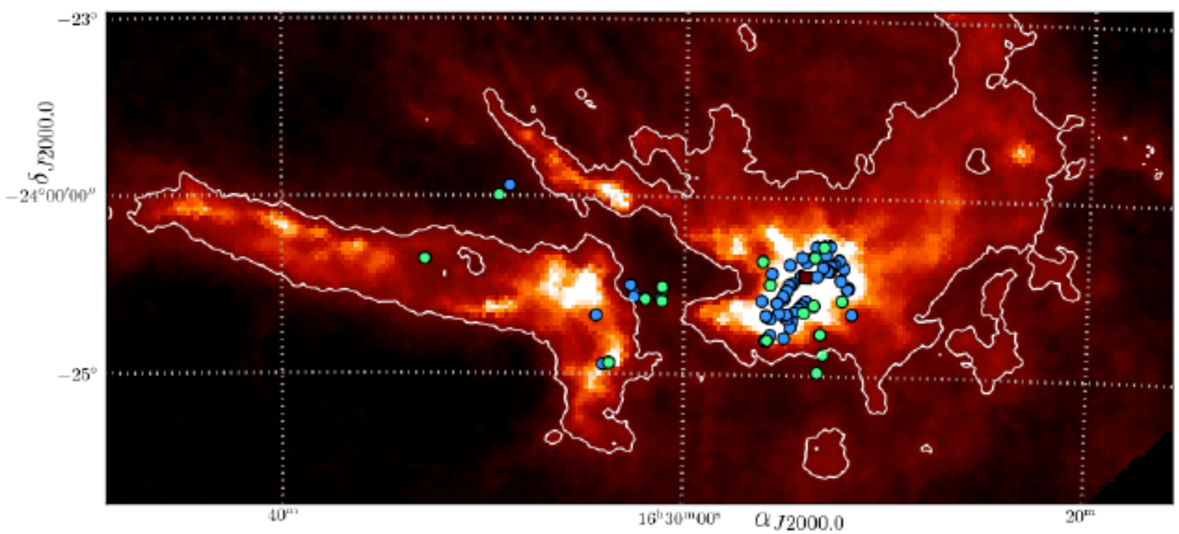
The Gould's Belt Very Large Array Survey I: The Ophiuchus Complex

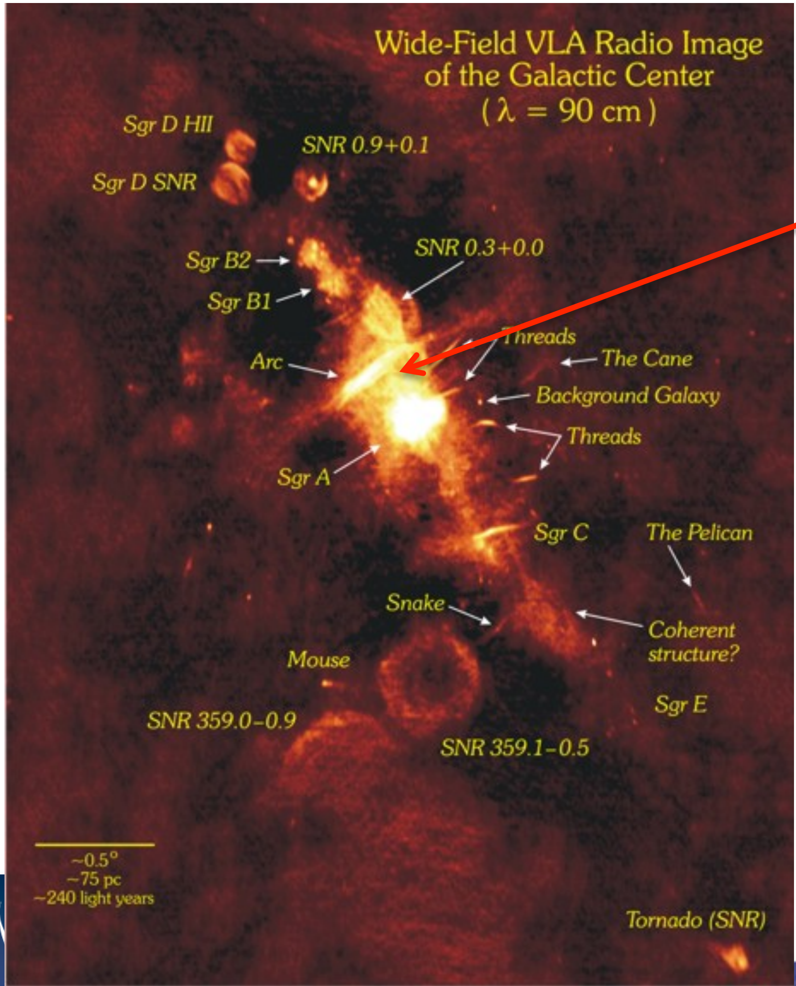
- Large-scale (2000 square arcmin), deep (20uJy), high-resolution (1”) observations of the Ophiuchus star-forming complex from 4 to 6 cm are presented. 189 sources were detected, 56 of them associated with known young stellar sources, and 4 with known extragalactic objects; the other 129 remain unclassified, but are likely background quasars.
- The vast majority of the young stars detected at radio wavelengths have spectral types K or M. At least half of these young stars are non-thermal (gyrosynchrotron) sources, with active coronas characterized by high levels of variability, negative spectral indices, and (in some cases) significant circular polarization.
- There is a clear tendency for the fraction of non-thermal sources to increase from the younger (Class 0/I or flat spectrum) to the more evolved (Class III or weak line T Tauri).

Location of the YSO (blue circles) and candidate YSO (green circle) onto the extinction map of the Ophiuchus complex. The position of the new is indicated as a brown square (Dzib ea ApJ).



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

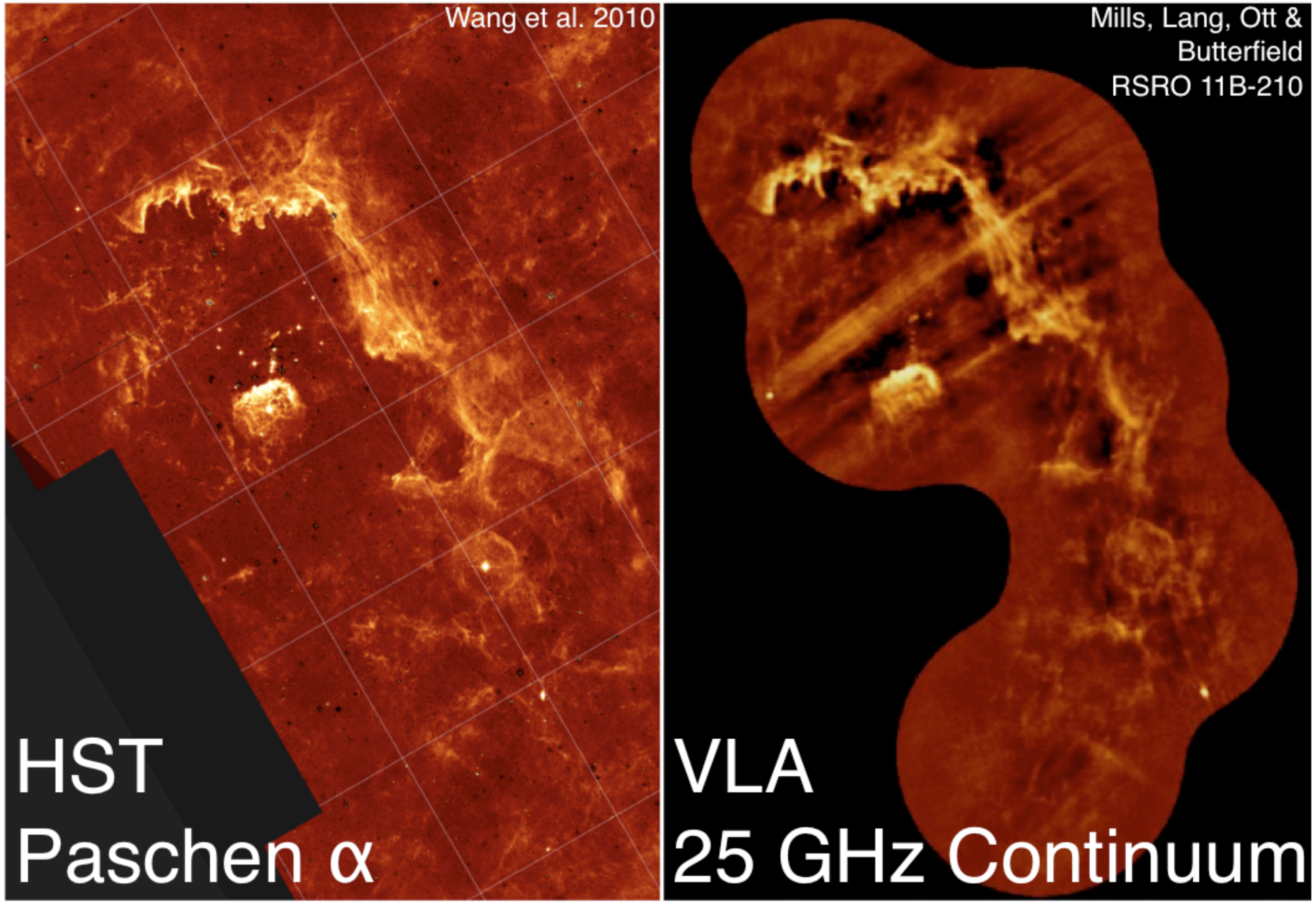
The Galactic Center: A Busy Neighborhood!



Area of interest: The 'Sickle'

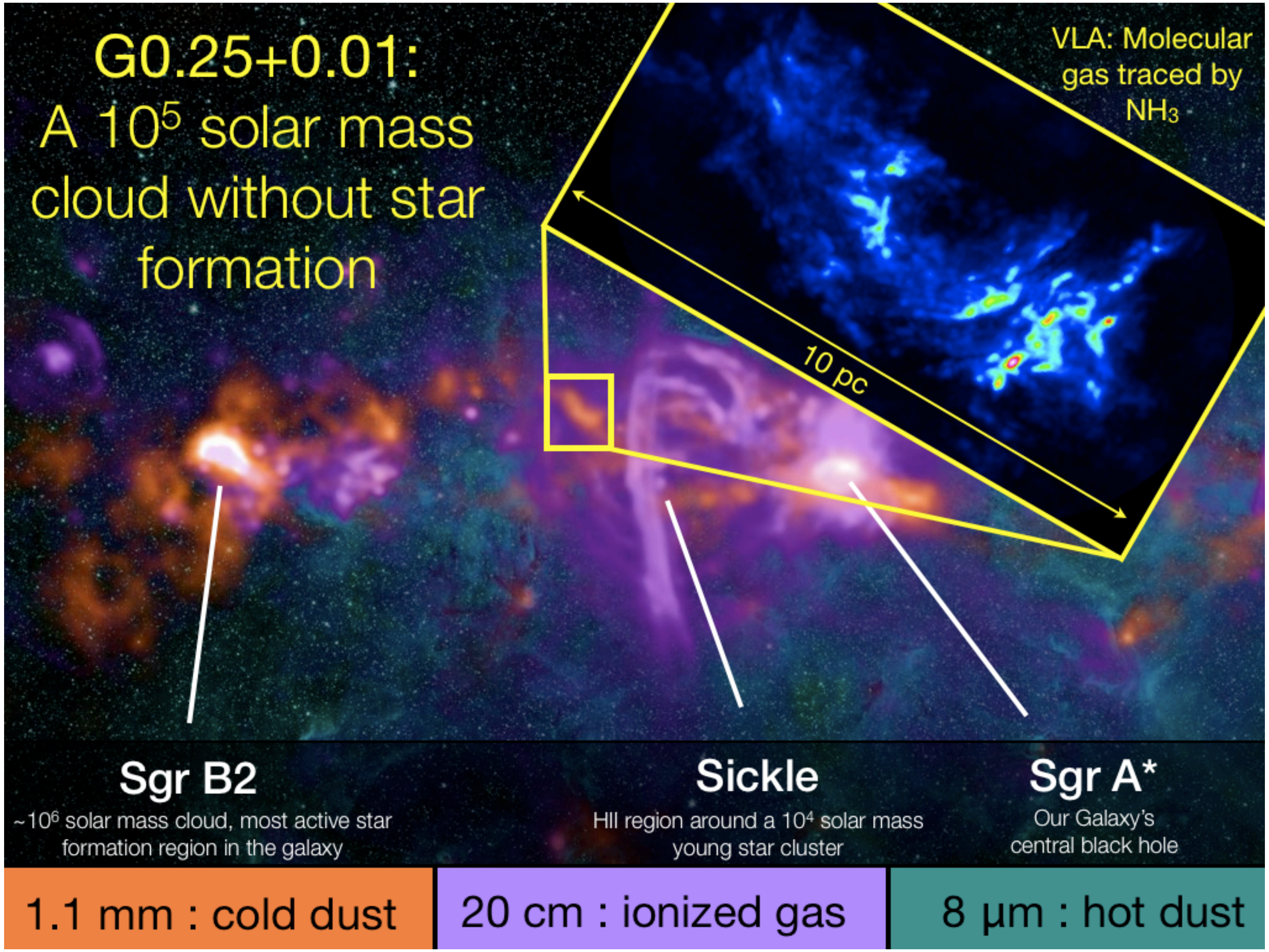
25 pc

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

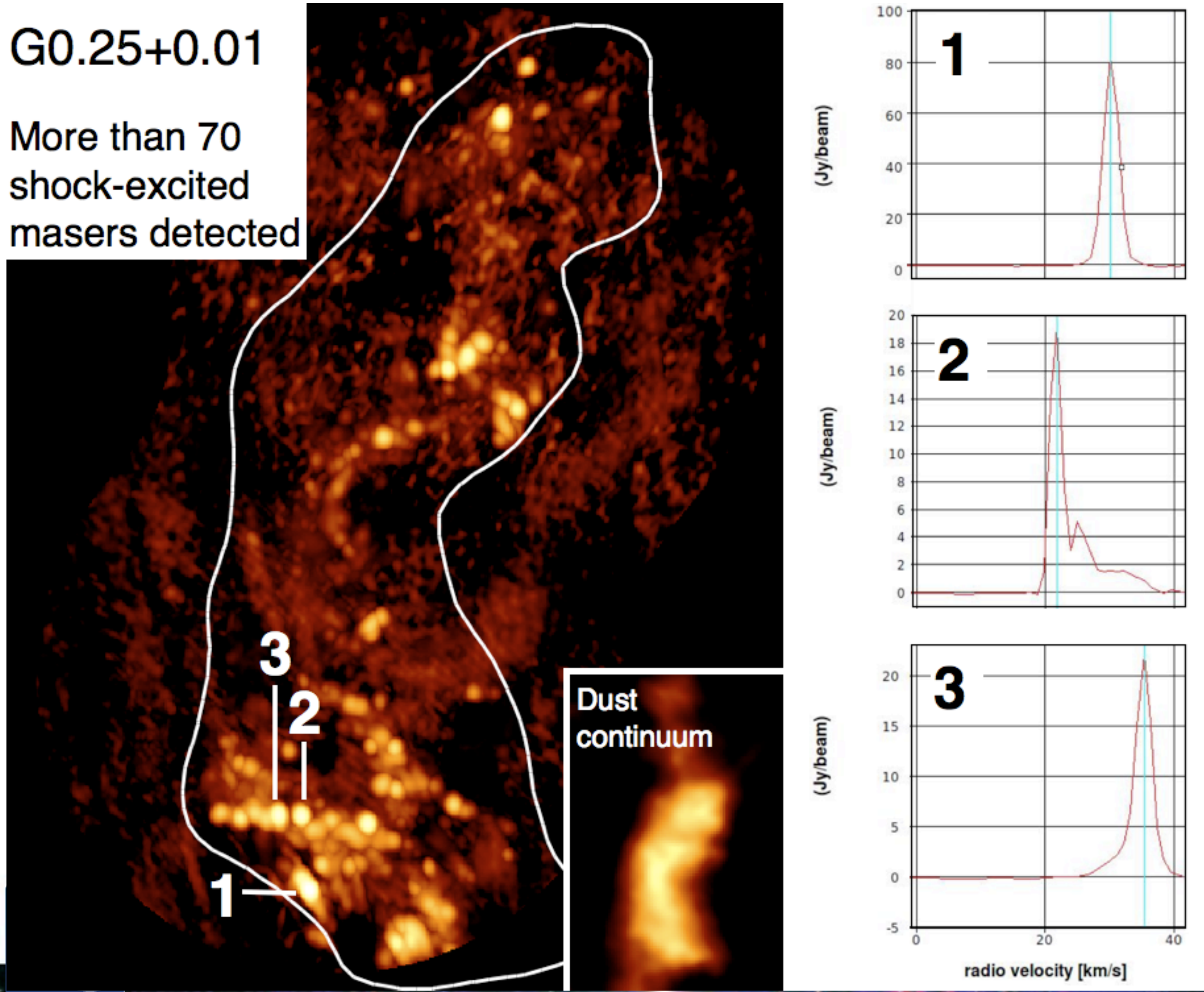


G0.25+0.01 – a uniquely dense dark IR cloud

- 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?



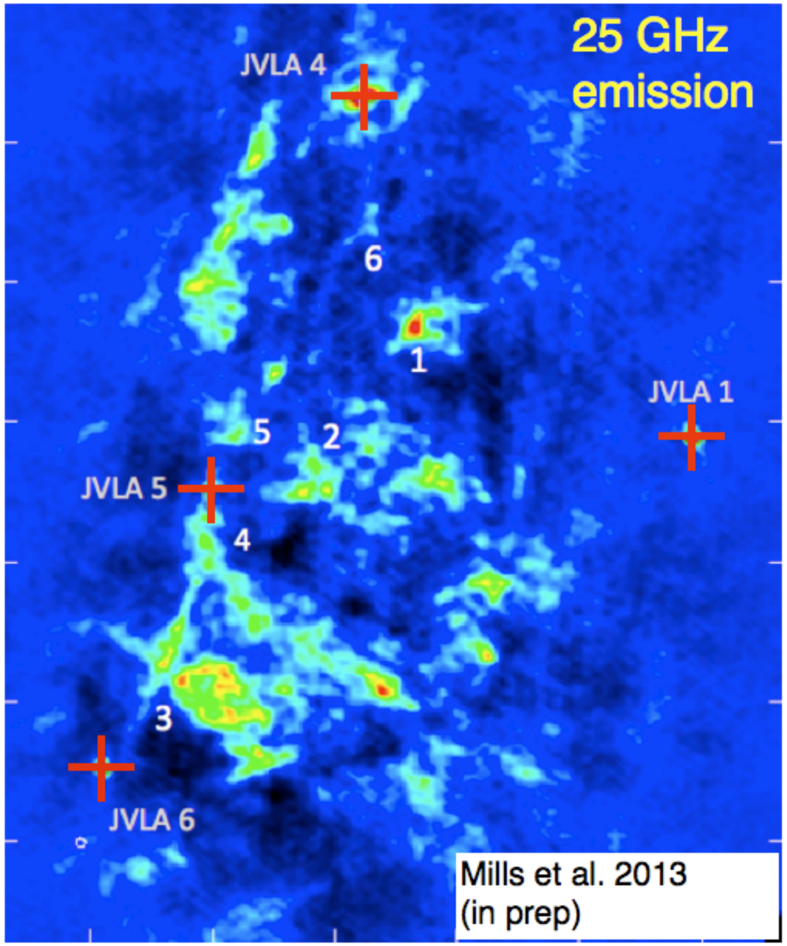
> 70 methanol masers in this cloud!



- 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

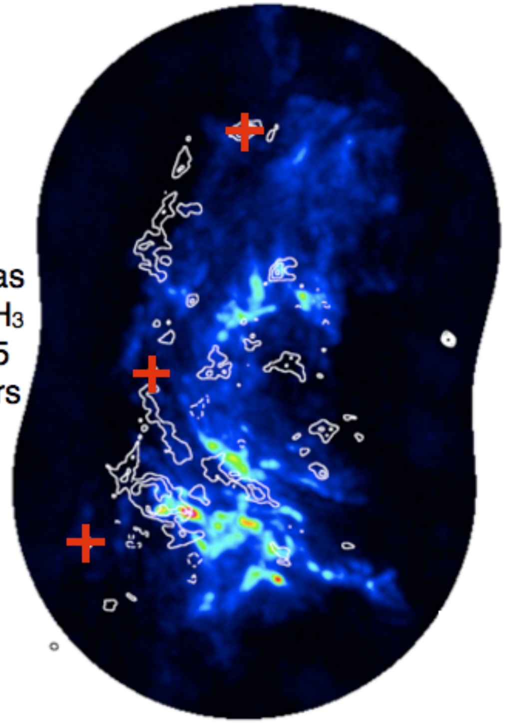
Thermal and nonthermal continuum emission in the quiet molecular cloud G0.25+0.01



Mills et al. 2013 (in prep)

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

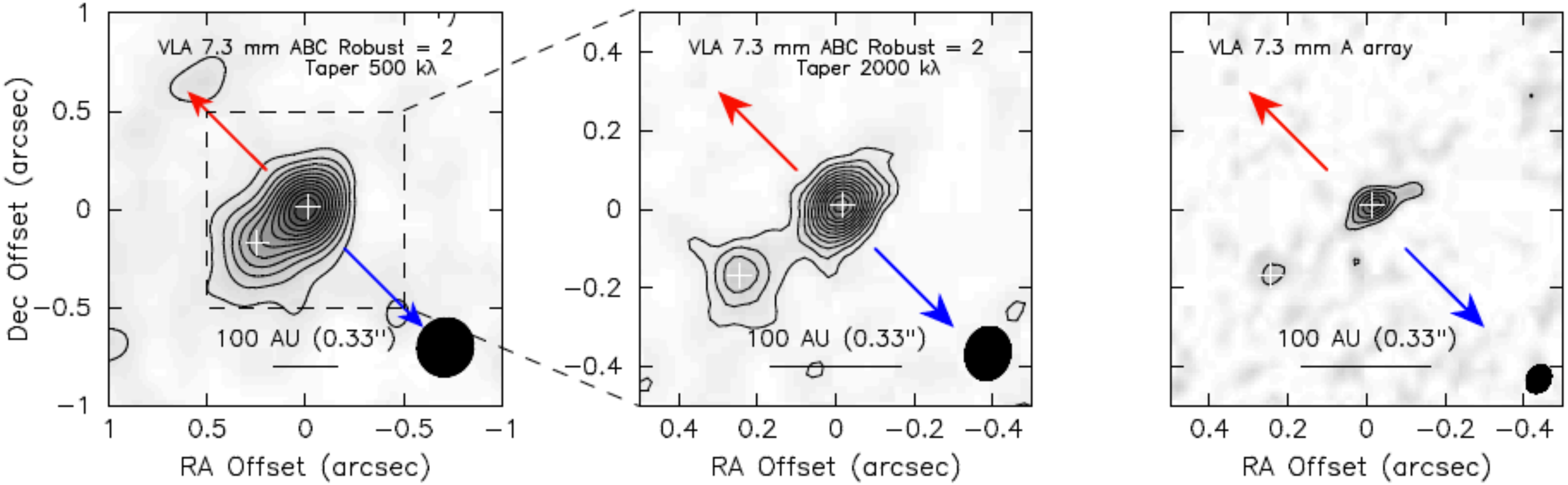
Molecular gas traced by NH_3 (3,3), with 25 GHz contours



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

VLA images fragmenting disks in protostars

- VLA and CARMA images Class 0/I protostars at 0.06" (18 AU) show two sources with binary companions at separations of 100 AU. The binary position angles orthogonal to bipolar outflows => consistent with protostellar disks.
- Suggests that binary formed from disk fragmentation; turbulent fragmentation would not arrange the binary companions to be orthogonal to the outflow direction.
- One source shows a large (R > 100 AU) disk, others show structures consistent with 20 AU radius disks.



Images of a protostar with the JVLA at 7mm (Tobin ea. 2014).

Magnetic U: Faraday Tomography

Jansky VLA Faraday Rotation Survey

- Measure magnetic fields in galaxies and in the Cosmic Web
- Role of B-fields in ISM, IGM, and ICM
- Impact of B-fields on star, galaxy, SMBH, and structure formation
- Origin and evolution of cosmic magnetism

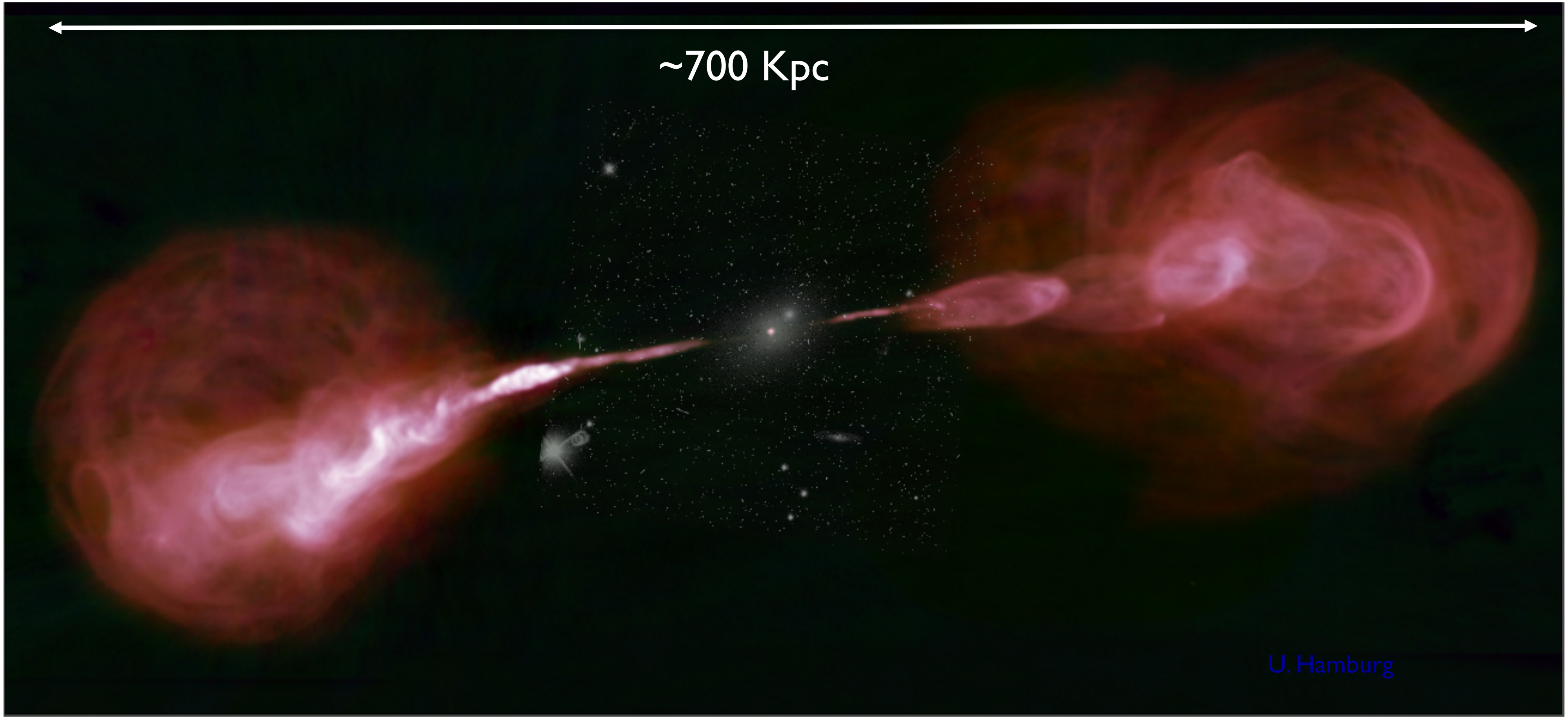
- Key Capabilities
  - Wide VLA bandwidths (1-2, 2-4, 4-8, 8-12 GHz)
  - High-quality polarimetry
  - Wide-area survey, high source density
- Key Developments
  - Wide-field polarization calibration and imaging
  - High dynamic-range high-fidelity mosaic imaging
  - Faraday Rotation Synthesis imaging

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 (Cotton and Perley, O'Dea et al.)

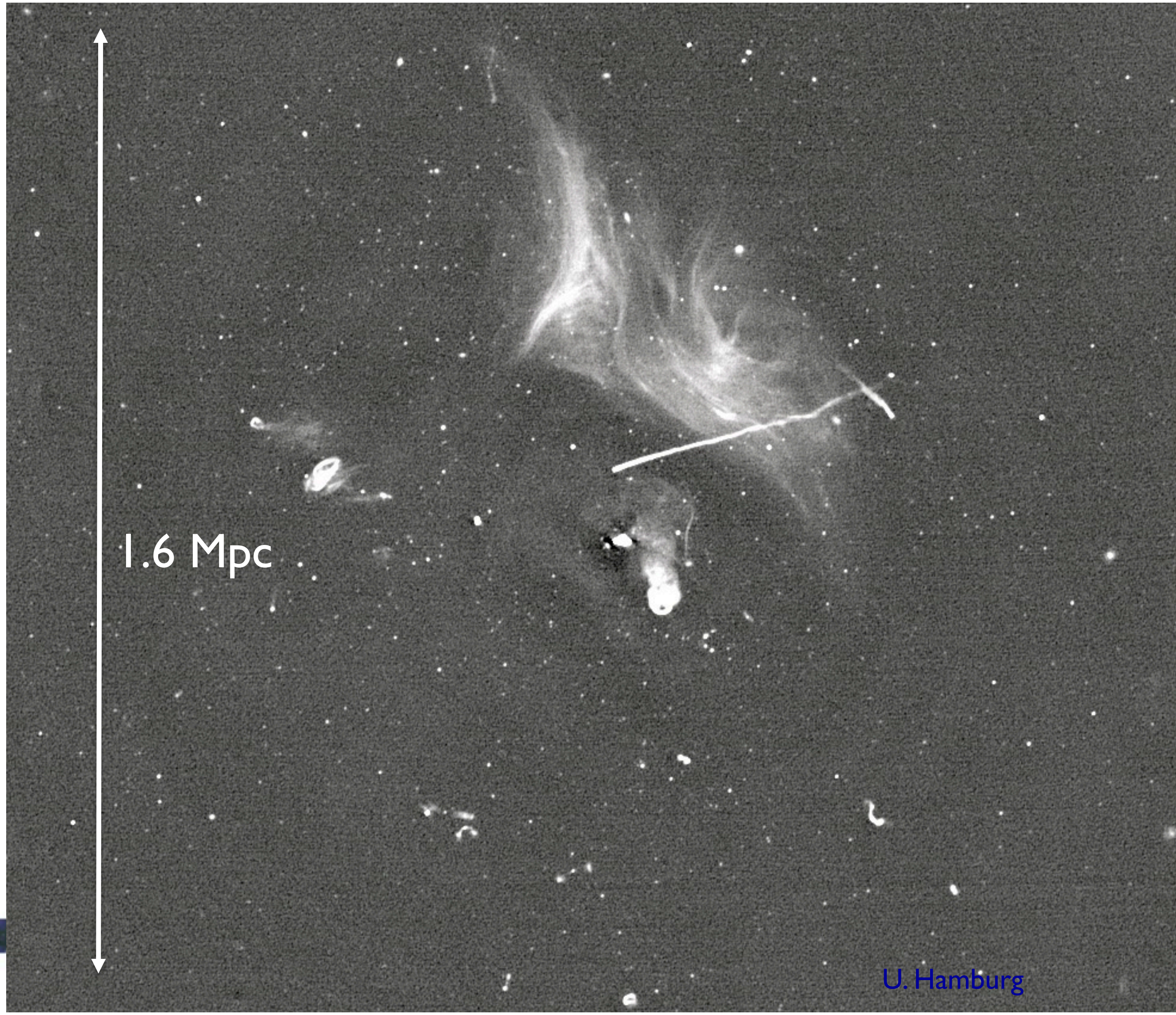
- z = 0.154, radio galaxy. D = 710 Mpc, 1arcsec = 3.4 Kpc.
- 4-9 GHz color-code spectro-intensity image (redder = older). 1 Kpc res^{n}.
- EVLA data: 1 through 9 GHz, all four configurations, 1Kpc resolution.
- Shocks in western lobe indicate repeated ejection.



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?



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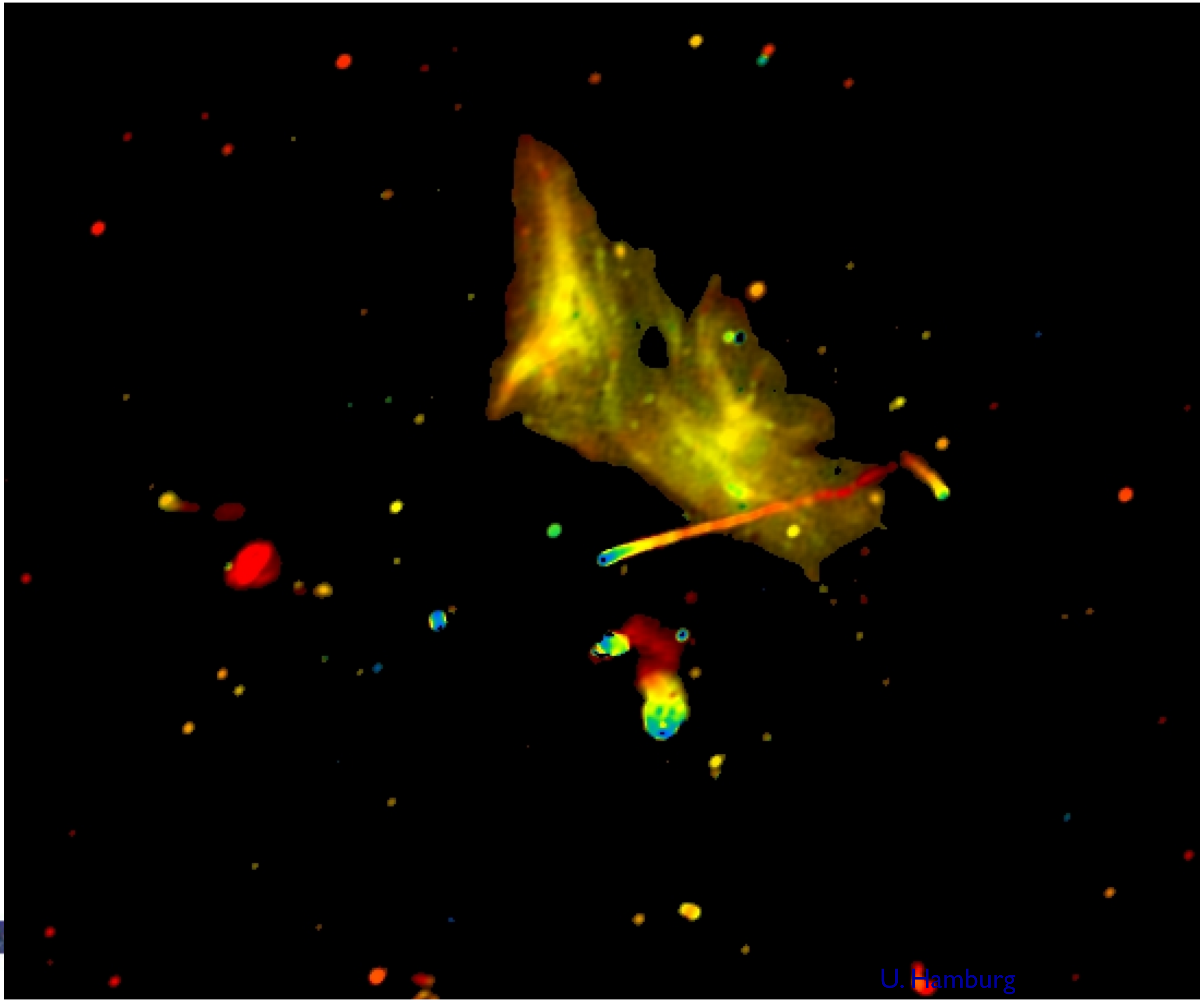
A2256 – Spectral Index - Intensity

- 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)

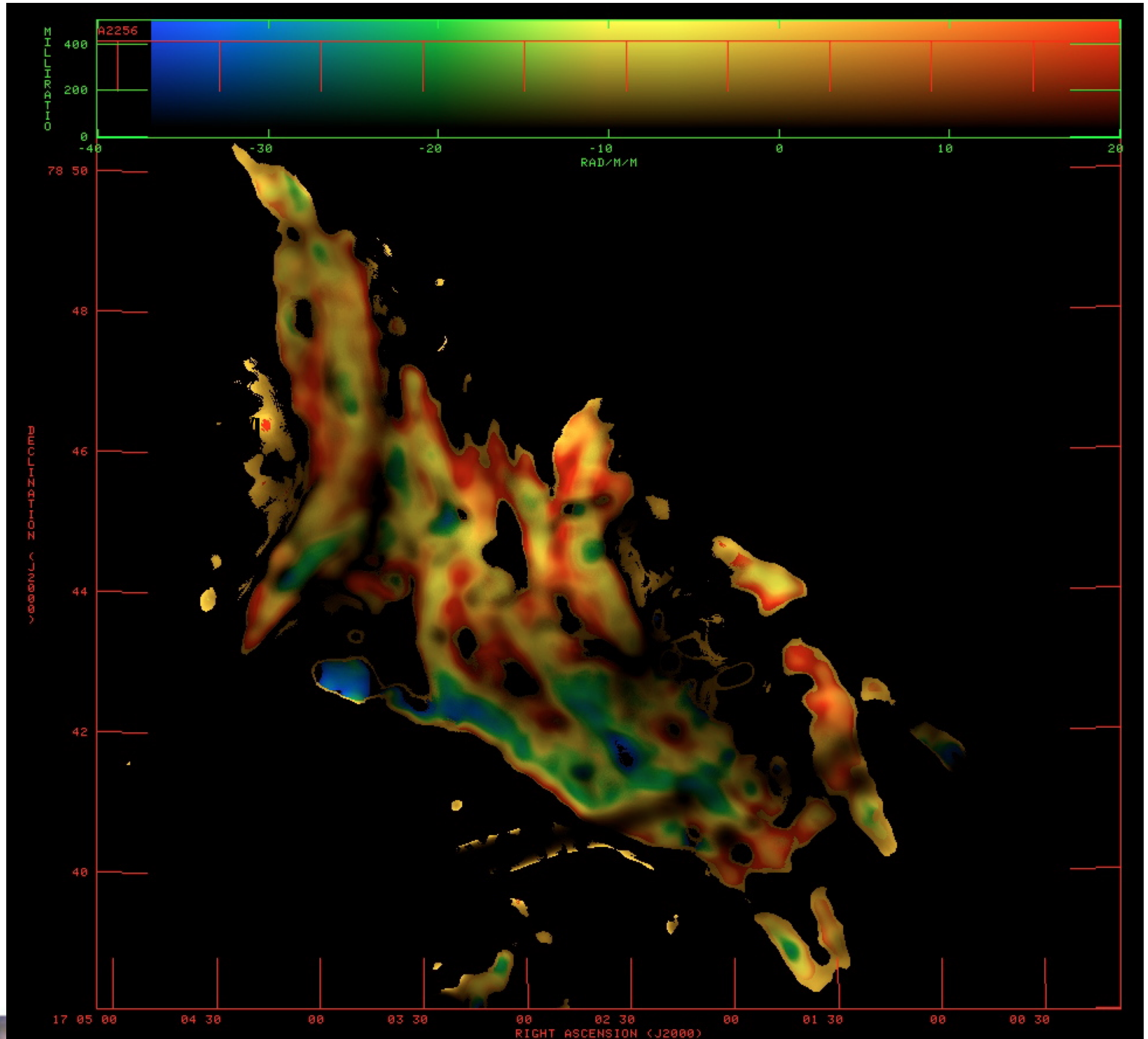


Faraday Rotation in A2256

- 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.



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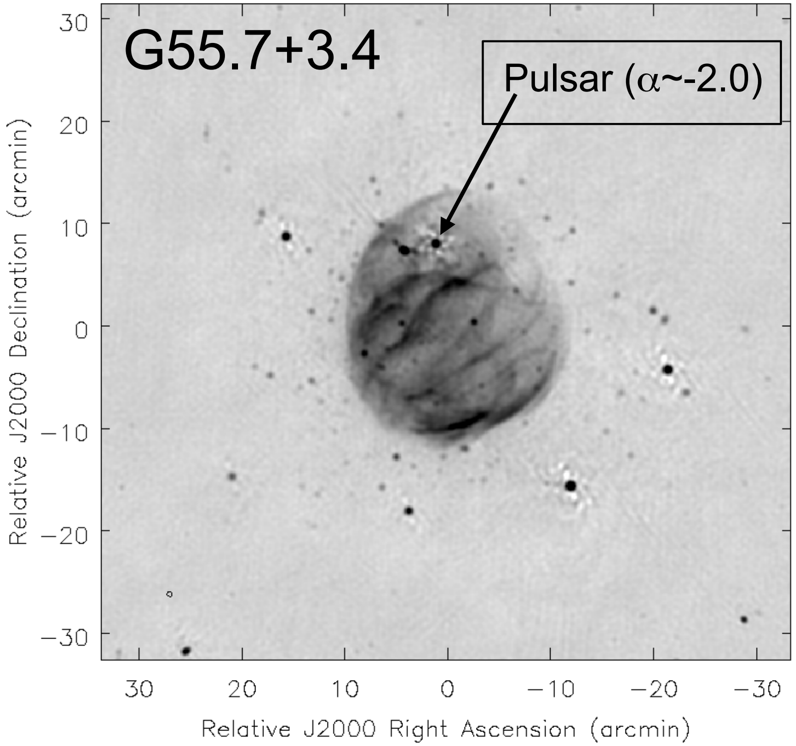
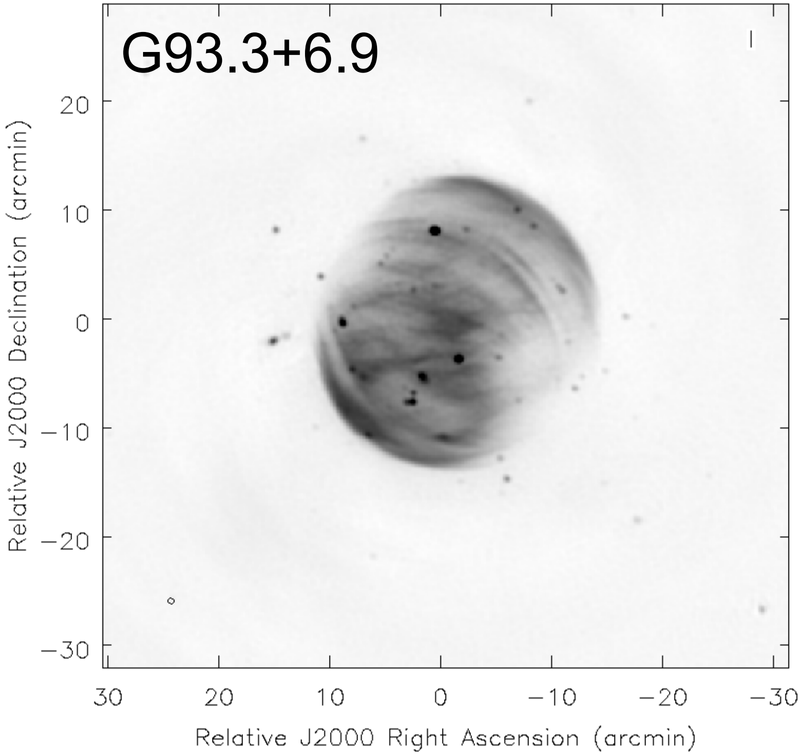
Magnetic U: Galactic SNR Close to Home

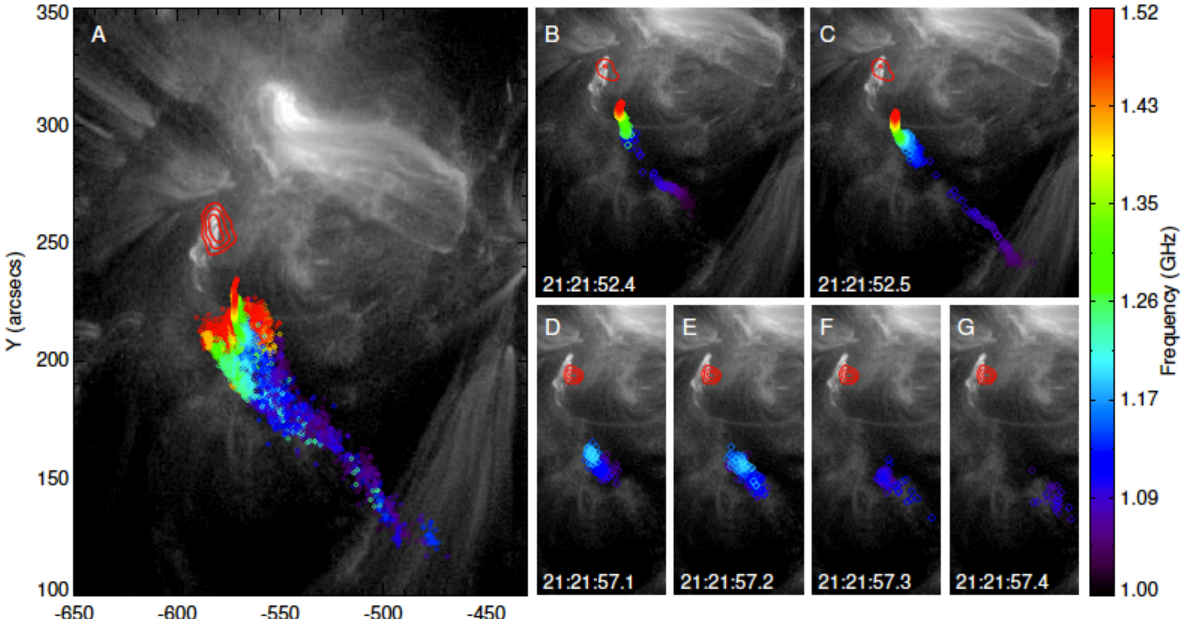




- Wide-band Galactic Plane survey pilot (Bhatnagar, Green, Rau, Golap, Rupen & Perley)
  - Stokes-I images with EVLA @ L-Band, BW~600MHz (RMS ~30 μJy/Beam)
  - Imaging done using MS-MFS (Rau, PhD thesis, 2010) and A-Projection in CASA

Magnetic U: Imaging magnetic reconnection on the Sun

- Type III radio bursts = thermal electron beams propagating in the low corona. The VLA has imaged these bursts on times scales ~ 100ms.
- Beams emanate from 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. Over-dense and ultra-thin loops reveal the fibrous structure of the corona.
- Localized energy release is highly fragmentary in time and space => bursty reconnection model involving secondary magnetic structures for energy release and particle acceleration.



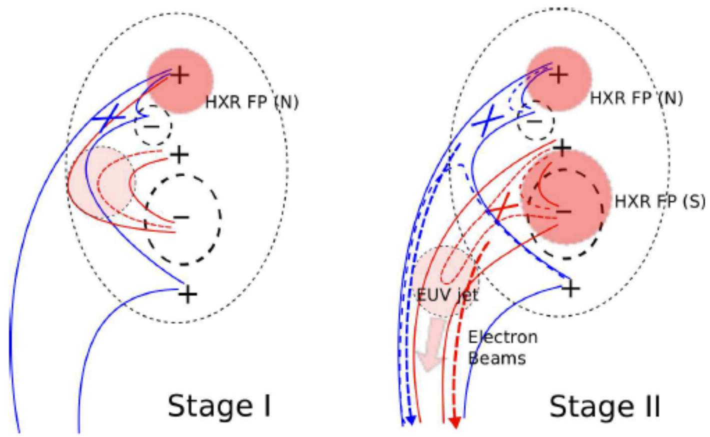
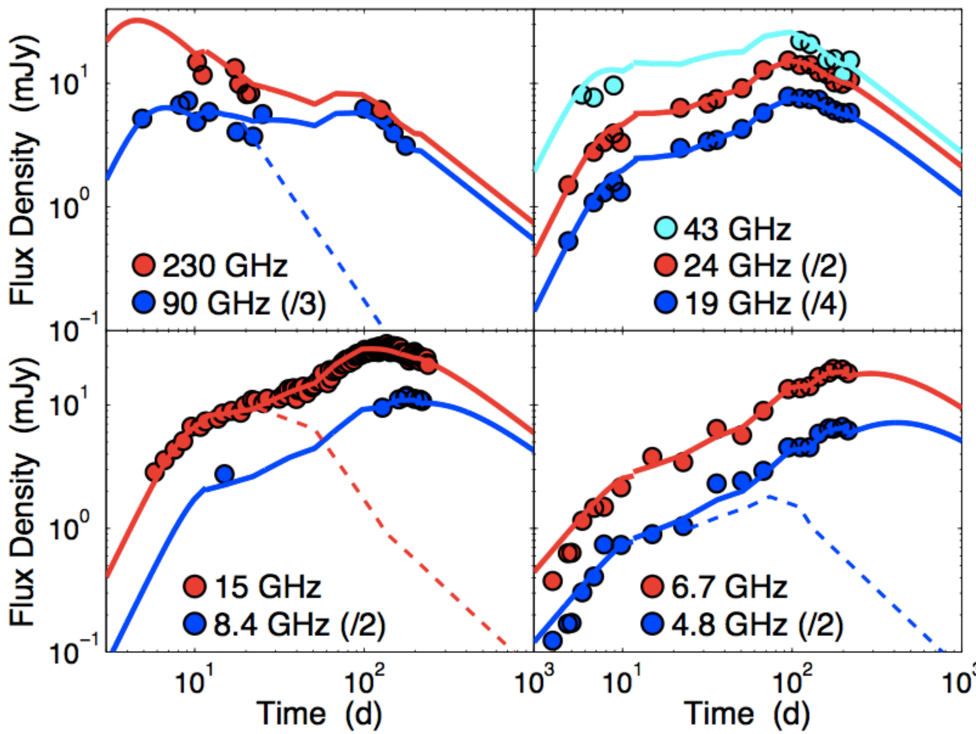


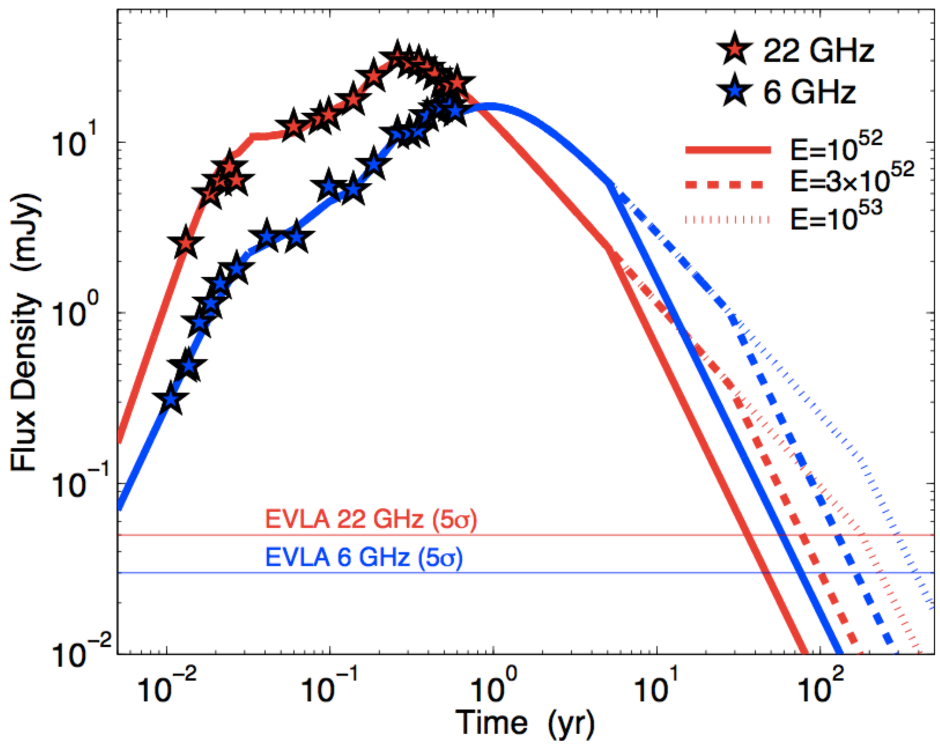
FIG. 5.— Schematic illustration of the magnetic field evolution, reconnection, EUV jet, and generation of the electron beams and HXR footpoint sources during the impulsive energy release event.

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

Transient U: A Tidal Disruption Event?

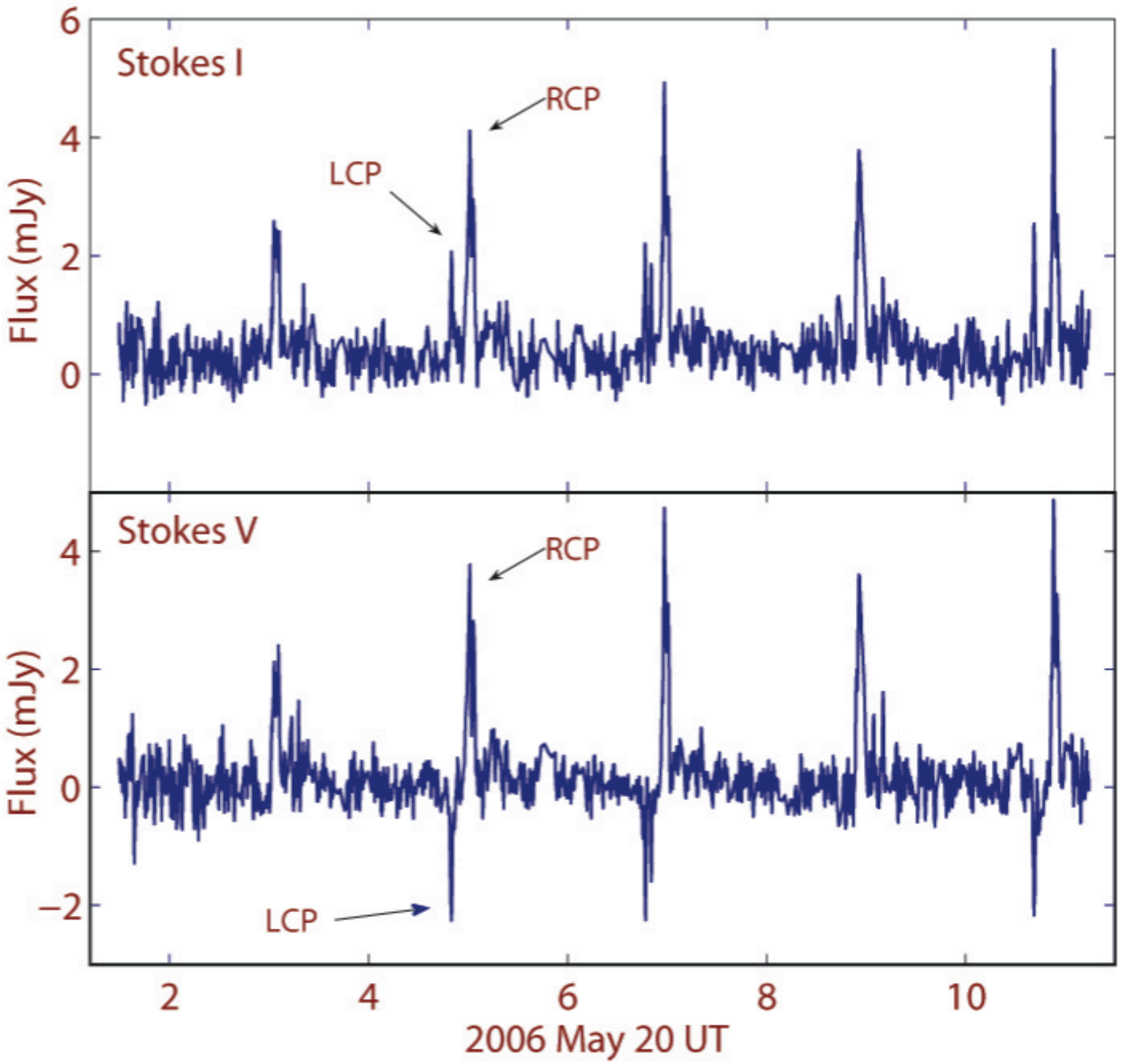
- Swift J164449.3+573451 TDE candidate
  - Radio: Zauderer etal. 2011, Berger etal. 2011 (figs below)
  - Chain of evidence points to transient accretion of stellar mass onto SMBH in a galaxy core
  - Radio emission eventual calorimeter



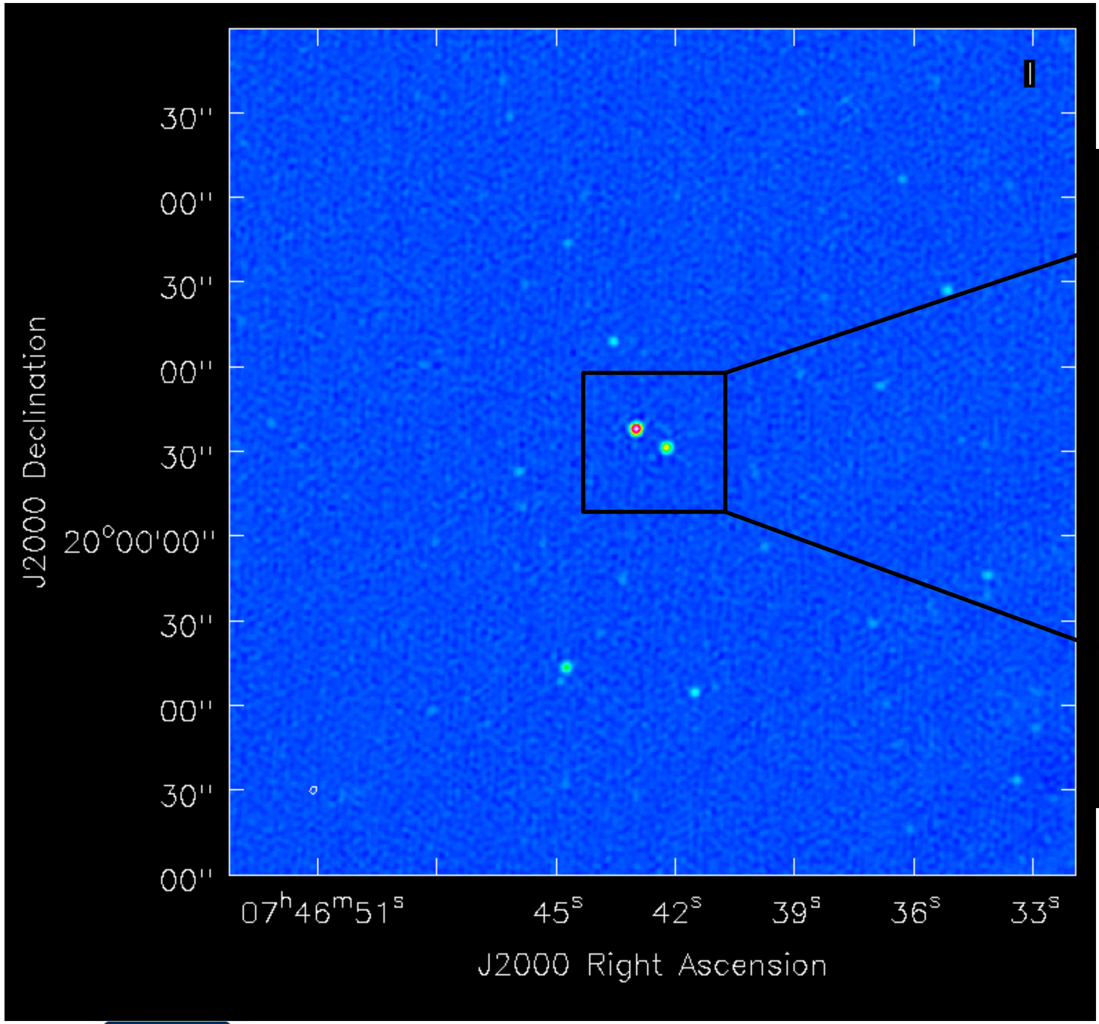


The VLA established that brown dwarfs pulse

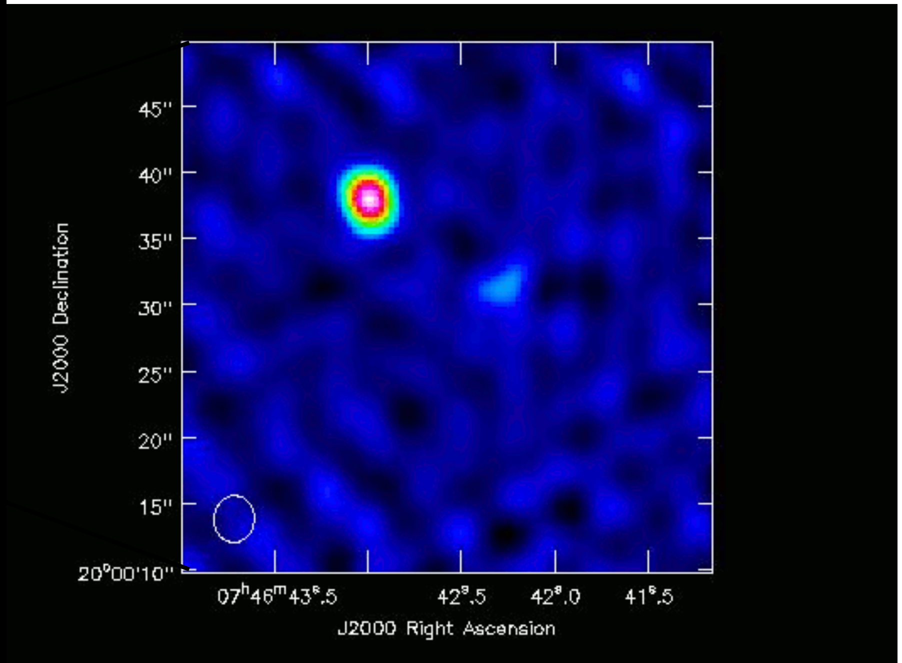
- The M9 dwarf TVLM 513-46546 - Hallinan et al. (2007)
- X-band observations , period 1.96 h, 100% circularly polarized.
- Emission by electron cyclotron maser emission, in kG fields.
- Period set by stellar rotation, emission is highly beamed.
- Emission region ~1/5 stellar radius.
- Emission coherent,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



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



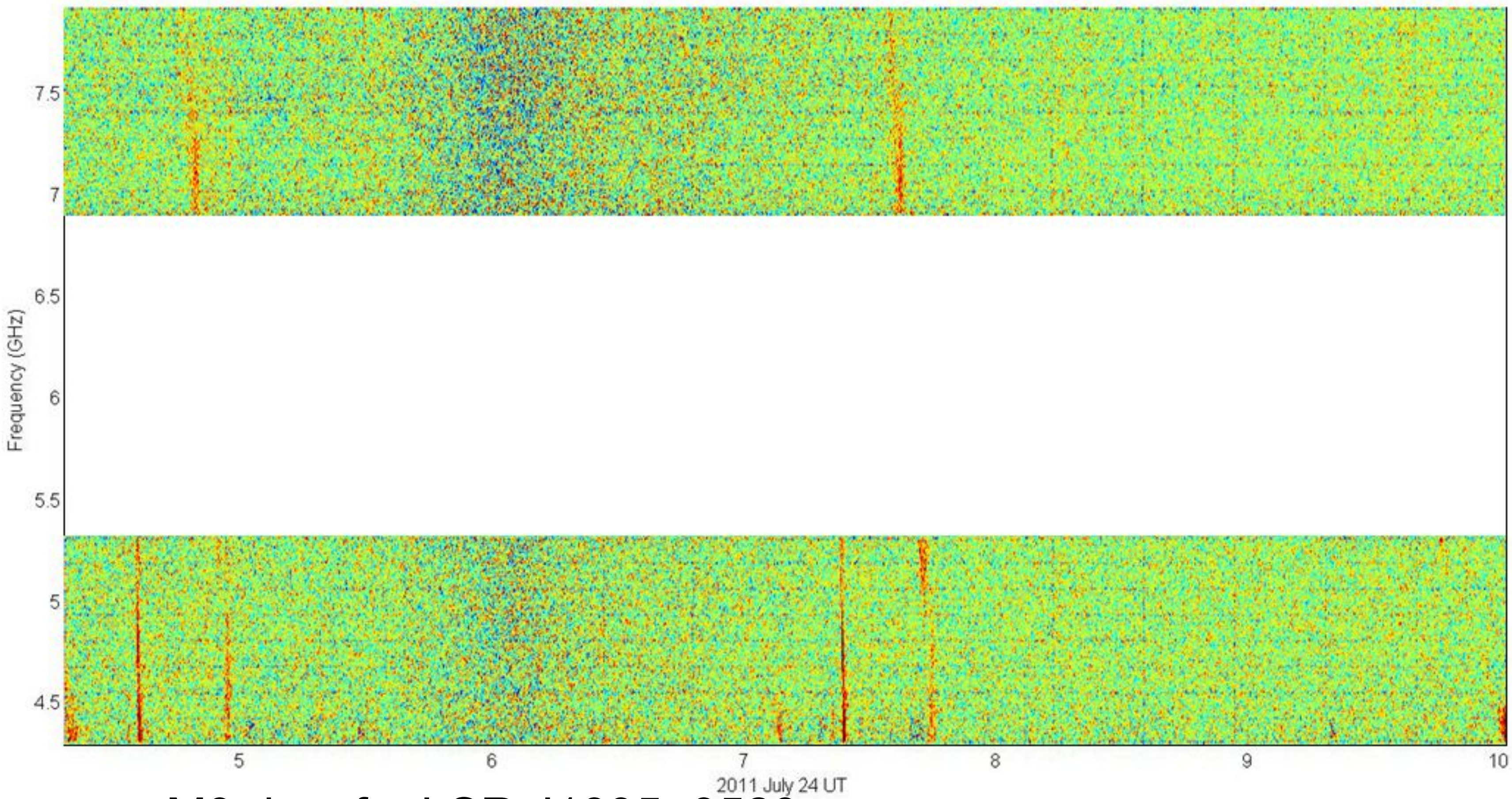
2MASS J0746+20



12.5 hours of data with 2 GHz bandwidth

RMS noise ~1.6 μJy/beam

Dynamic spectra reveal large-scale source structure



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

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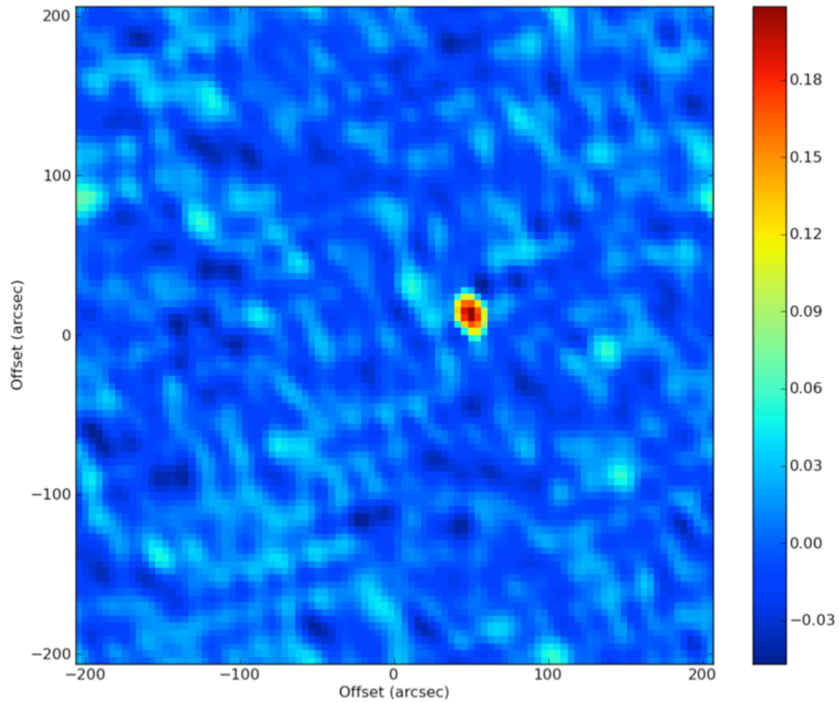
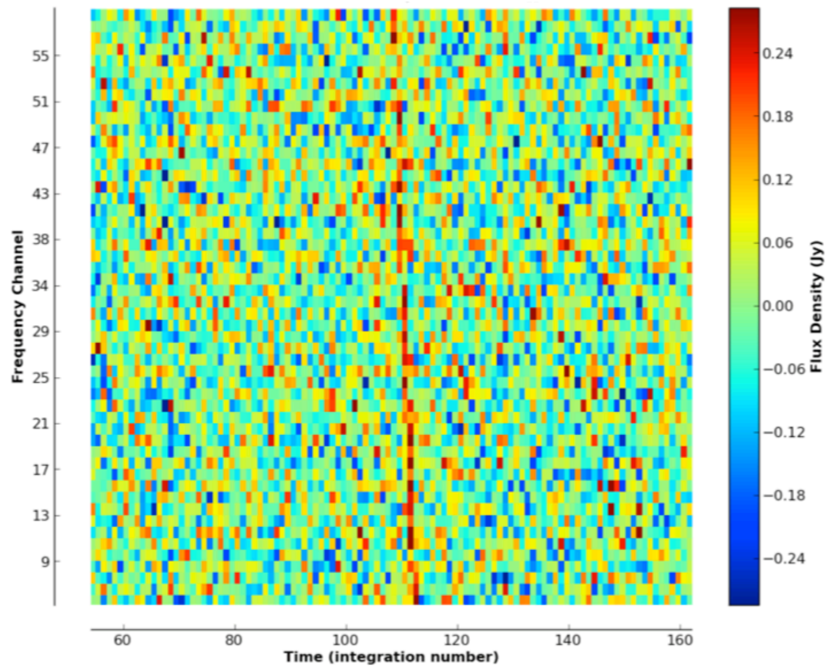
Transient Science – RRATs at the VLA

- 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.



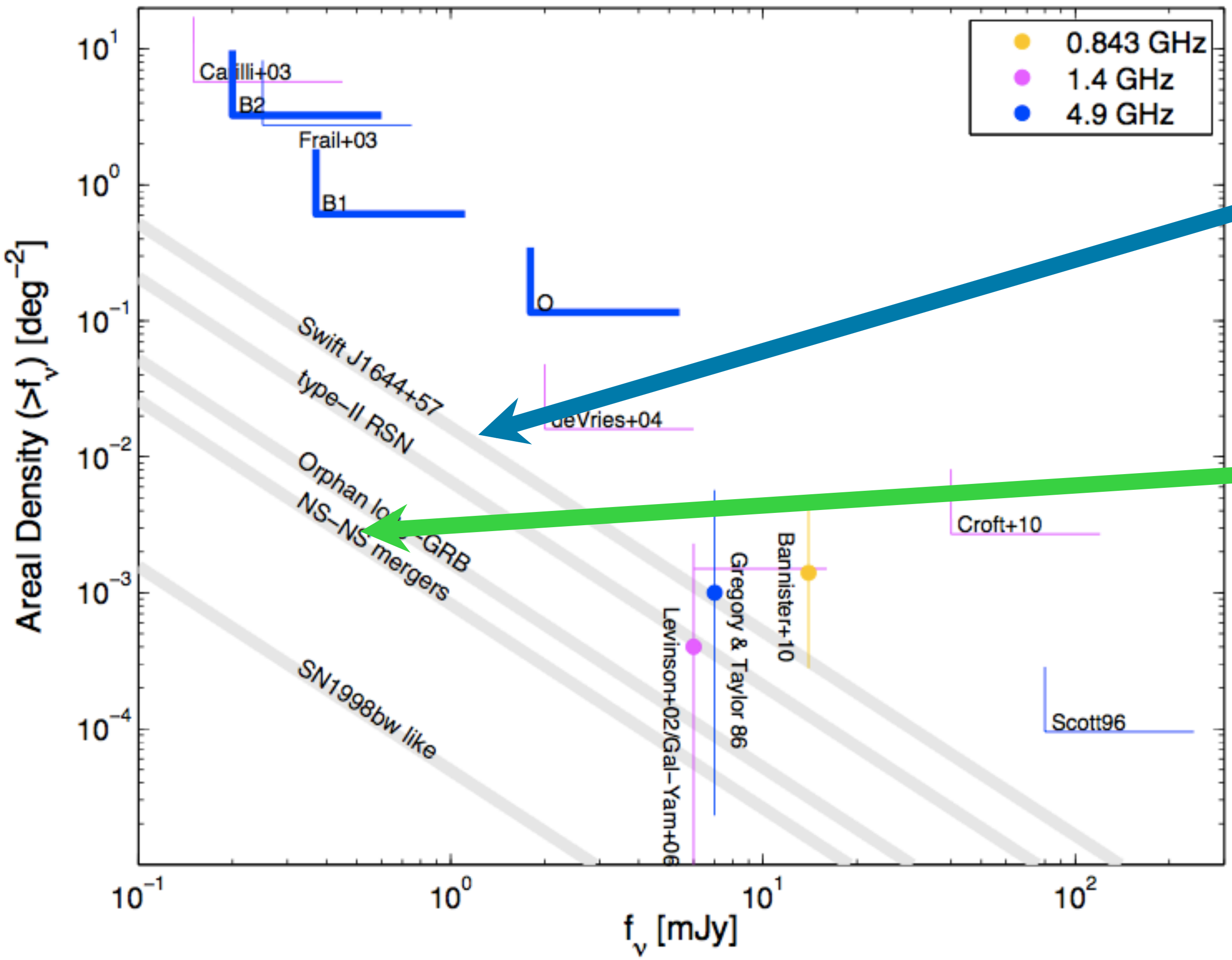


Extragalactic millisecond pulses?

- Law and Bower are continuing development of techniques to find rapid transients.
- Recent survey: 20 hours to detect possible highly dispersed extragalactic millisecond pulses in blind survey.
- Used 5 msec integration, 256 channels, covering 256 MHz bandwidth.
- Generates 1 TB/hour.
- Data downloaded to VLA's cluster (at the AOC)
- Data are de-dispersed, and spatially imaged with special software (every 5 ms!) to look for flashes.
- Nothing found yet … but useful limits will be set.

Transient U: Synoptic Radio Surveys

- Areal density vs. Flux density (Frail et al. 2011)



TDE: Zauderer etal. 2011, Berger etal. 2011 (timescale mos. to yrs.)

Only the tip of the iceberg!

13B-370 Hallinan etal.

300 deg^2 at 80μJy

B-config 150hrs

3 epochs, 46μJy added

Lessons Learned

Need careful control of survey and imaging systematics! >8σ

Transient U: The Singing Sky

Jansky VLA Time Domain Surveys

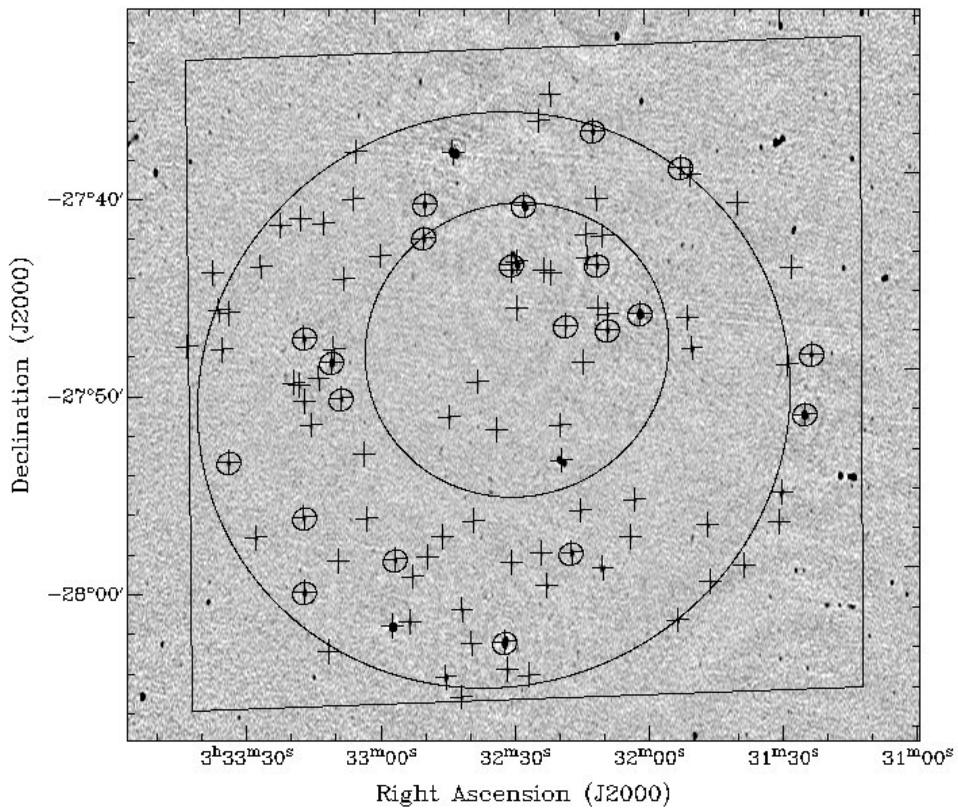
- Prompt and afterglow emission from cosmic explosions
- Electromagnetic counterparts to Gravity Wave events
- Radio flares from low-mass stars and Jovian exo-planets
- Explore new classes of events (e.g. "Lorimer bursts")

- Key Capabilities
  - Synoptic wide-area surveys for long-duration transients
  - Fast scanning and imaging for short-duration transients
  - High-resolution for source localization
- Key Developments
  - High-throughput robust pipeline processing, control of systematics
  - Efficient and robust wide-band wide-field imaging
  - Fast response to triggered events, fast event reporting

Beyond the Jansky VLA

- High-Resolution Counterparts to the Jansky Very Large Array
  - eMERLIN e.g. Legacy Surveys (eMERGE, SuperCLASS)
  - VLBA (newly upgraded, future uncertain)
  - Other VLB arrays (EVN, etc.)
  - mm VLBI: ALMA & EHT
- LB and VLB component of SKA
  - SKA Phase 1 baselines 200km
- Beyond SKA Phase 1
  - VLB and high-frequencies

VLBA Chandra Deep Field South
Multi-phase-center correlation
Middelberg et al., 2011, A&A 526, 74



Jansky VLA Survey Science (VAST)

Pioneers: Pre-Jansky VLA Surveys

- The D-configuration (resolution 45”) NVSS covered ~30000 square degrees in two 42 MHz bandwidth IF channels centered around 1.4 GHz to an image rms level of around 450 μJy/beam in Stokes I. The source catalog completeness limit was stated as 2.5 mJy and contained around 2×10^6 discrete sources (Condon et al. 1998, AJ, 115, 1693). A total of 2932 hours* was allocated to this project in 1993-1996.
- The B-configuration (resolution 5”) FIRST covered 10635 square degrees in two 42 MHz bandwidth IF channels centered around 1.4 GHz to around an image rms level of around 150 μJy/beam in Stokes I. The source catalog completeness limit was stated as 1 mJy and the 2012Feb16 version of the catalog contained around 950000 discrete sources. (Becker et al. 1995, ApJ, 450, 559; 2012yCat.8090). A total of 3200 hours* was allocated to this project in 1993-2002.
- A total of ~6000 hours was devoted to these projects from 1993-2002.

*From https://science.nrao.edu/observing/largeproposals/largeproposals

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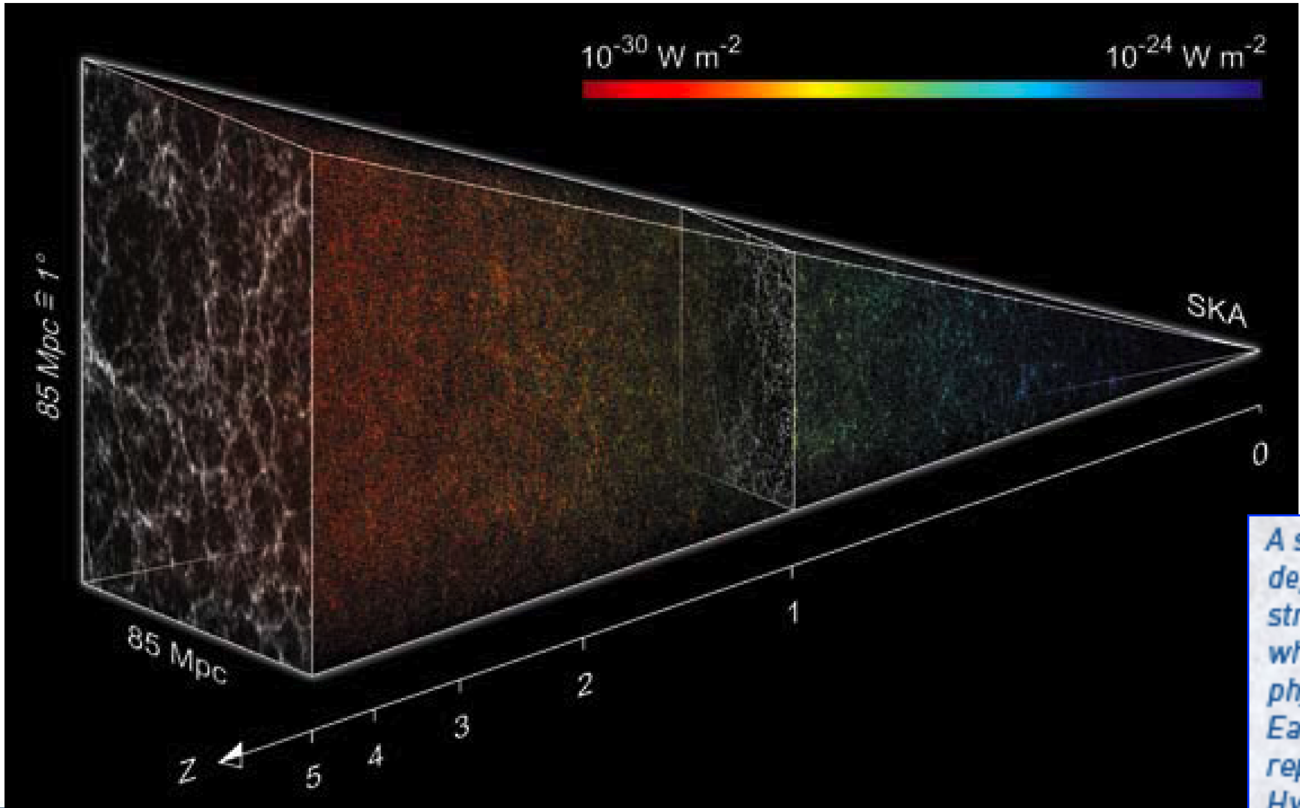
Using the Jansky VLA for Large Surveys

- Past and current results – science observing since March 2010
- Future possibilities – the road towards the Square Kilometre Array and the LSST next decade – the Jansky VLA is a SKA Science Proving Ground!



A simulated SKA observing cone depicting the complex filamentary structure of HI on cosmic scales, which encodes the mysterious physics of the "Dark Universe". Each coloured pixel in the cone represents a galaxy emitting neutral Hydrogen (HI, rest-frame 21-cm) radiation.
(Credit: Danail Obreschkow (Oxford) and the SKADS Sky Simulation team.)

Astro2010 white paper: Myers et al. (**arXiv:0903.0615**)

Using the Jansky VLA for Large Surveys

- Inherent strengths provided by the Expanded VLA Project
  - Wide instantaneous bandwidths (2 GHz@8bit and 8 GHz@3bit)
  - Full (dual circular) polarimetry
  - Flexible correlator (WIDAR), can trade bandwith and polarization for increased spectral resolution (from 2MHz/channel on down)
- Developments are underway to enable large synoptic surveys
  - "On-the-Fly" (OTF) mosaicking for efficient area coverage (Act 111)
  - Higher time-resolution modes (<1sec)
  - Image-processing algorithms for wide-field wide-band data
- Limitations of VLA and EVLA technology
  - Performance <5GHz limited by optics (subreflector too small)
  - Many modes (high time & spectral resolution) limited by data rates
    - Current GO limits are 25MB/s (archive disk space budget)
    - WIDAR capable of much higher rates (10-100x!!)

Key VLA Development: OTF Mosaicking

- "On-the-Fly" (OTF) mosaicking for efficient coverage of large areas
  - Scan telescopes (e.g. in RA counter-sidereal) stepping phase centers
  - Lose only 1s (possibly none) on step instead of 6-7s standard mode
    - Efficient when dwell times on-sky are <25s
  - Can process like normal data at moderate dynamic range
    - Errors are from moving primary beam
  - Currently available only as part of Resident Shared Risk (RSRO)
  - STM working on getting this into the OPT for scheduling
    - Now requires special conversion obs-to-script
- Image Processing support for OTF Mosaicking (in CASA)
  - CASA imager can correct for offset pointing and phase centers if information given in POINTING table (not populated by VLA)
  - Testing on higher quality data needed to show limitations of this

See https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/mosaicking

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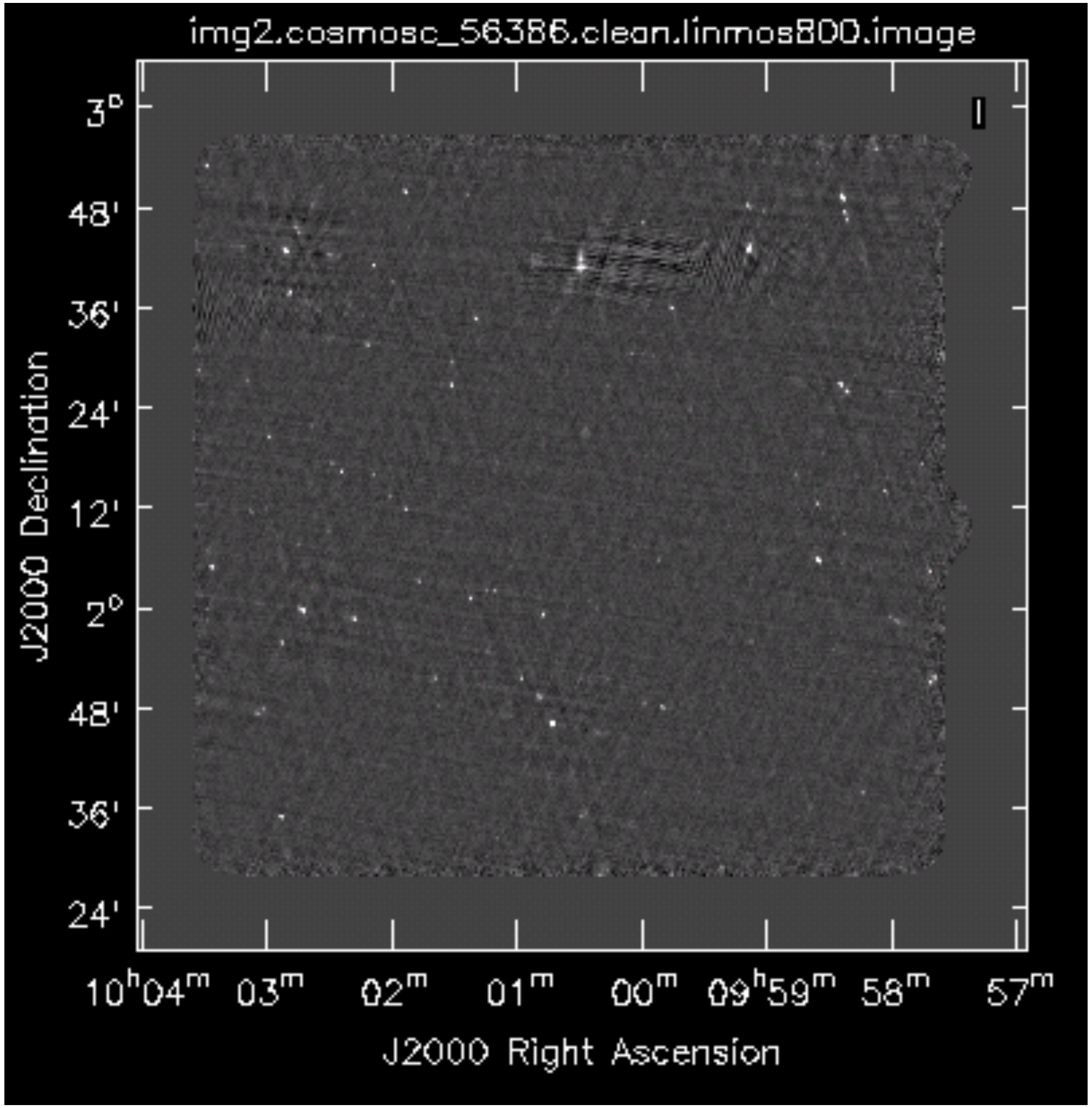
On-the-Fly Mosaicking with the VLA Now

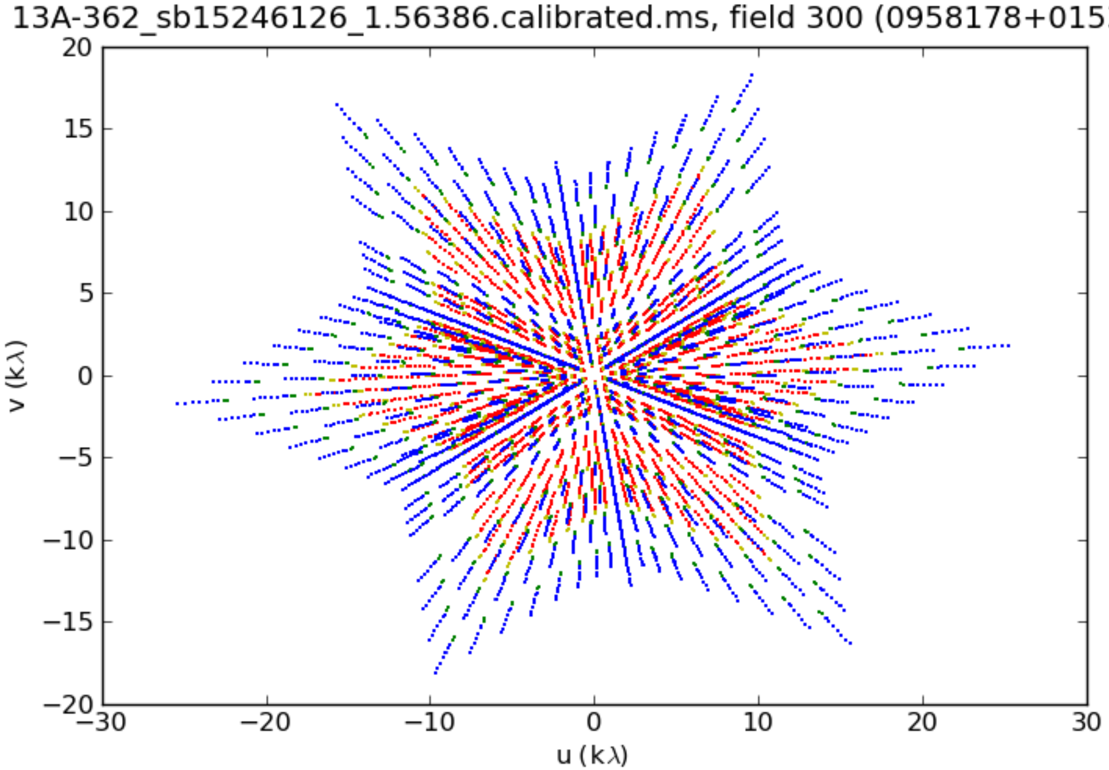
- C-band OTF 8bit 2GHz
  - cover wide area quickly ~30m on-src
  - Now: simple linear mosaic after clean (CASA)
  - Striping/defects: RFI, missing data, unboxed cleaning, spectral index



COSMOS field
13A-362 (Myers)
C-band 1hr SB
4.2-5.2 + 6.5-7.5GHz
2 square degrees
OTF scans in RA
432 phase centers
95μJy rms
Repeat monthly.

Multi-Frequency Synthesis

- The wide (2:1 in some bands) VLA bands allow determination of spectral index and curvature (and rotation measure) for single observation
- Snapshot uv-coverage is excellent (2:1 fills in most gaps)
  - Observations near celestial equator OK (Stripe82, COSMOS, etc.)



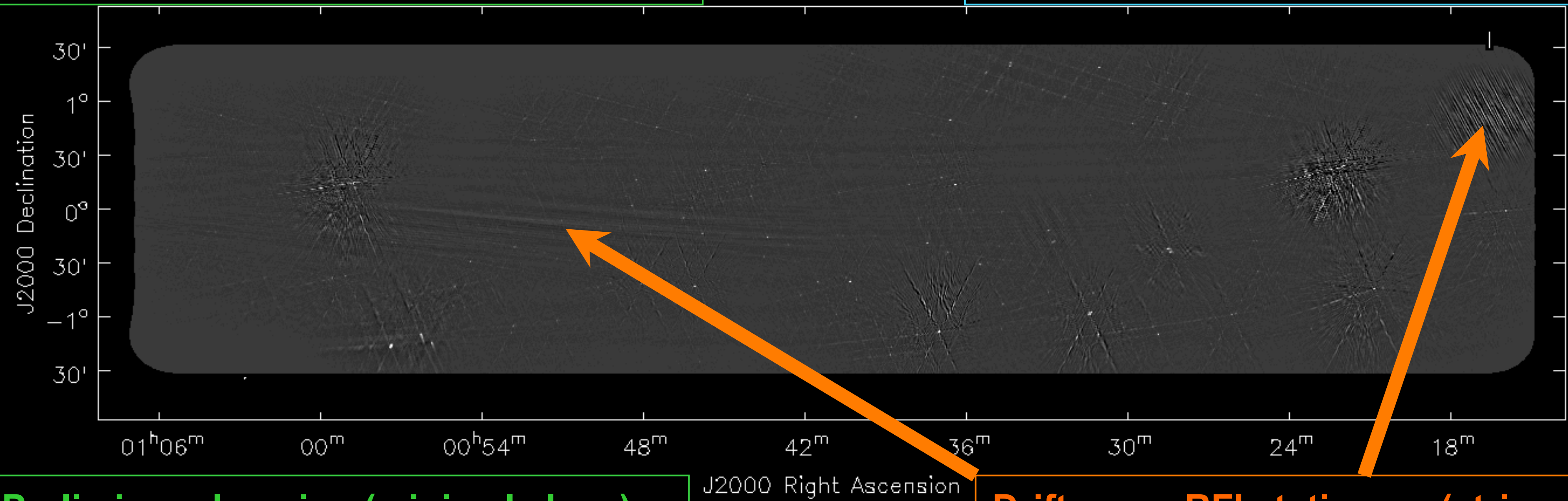
13A-362 *uv*-coverage
Single "field", 4 sec
C-band D-configuration
16 spectral windows
4.25-5.25 & 6.5-7.5 GHz

Drift-scan Pilot Project: Stripe 82

- EVLA project 11B-203 (S. Myers, J. Sievers etal.)
  - 12.5deg x 3deg ACT/SDSS equatorial stripe (37.5 sq.deg)
  - Raw imaging only, full reduction still in progress

Eventual Goal:
120deg x 3deg = 360 sq.deg

11B-203 L-band 8hr 1400MHz
12.5deg x 3deg
On-the-Fly (OTF) drift scan 15'/min



Preliminary Imaging (minimal clean)
128MHz our of 1GHz only
~1mJy rms (artifacts dominate)

Drift scan: RFI stationary (stripes)
Danger from geo-sync satellites
Affects shortest baselines

Key VLA Development: Mosaic Imaging

- Other Wide-field Image Processing Development (in CASA)
  - Joint mosaicking algorithms (in CASA *clean* task & toolkit)
    - Need combined joint and linear algorithms (peeling)
  - Multi-Taylor term MFS imaging (also multi-scale)
  - Auto-boxing needed for snapshot deconvolution (only in Python now)
  - Auto-object detection for catalogs (borrow from others if possible)
- Convolutional gridding algorithm for mosaicking ("A-projection")
  - Grid mosaic data into single uv-plane using aperture function
    - Phase gradient for pointing & phase center offsets (shift theorem)
  - Gridding kernel is aperture cross-correlation for each baseline
    - Naturally handles heterogeneous arrays (ALMA,CARMA,eMERLIN)
  - CPU expensive (GPU?)
  - Use true beam response at major (Cotton-Schwab) cycles
    - Knowledge of beam limited in outskirts (peeling-like algorithm?)

Classic VLA Surveys (1993-2002): 1.4GHz NVSS 30000 deg^2 45" 450mJy / FIRST 10000 deg^2 5" 150mJy rms

Specs: Jansky VLA Survey Capabilities

- VLA performance for large-area mosaics (100 μJy rms*, natural weighting):

*Using VLA sensitivity calculator

Band (freq)	Bandwidth	t_{int} sec	θ_{PB}	θ_{res} (B)	SS deg^2/hr	$\dot{\theta}$ arcmin/s
P (230-470 MHz)	200MHz	8553	122′	24.0″	0.98	0.01
L (1-2 GHz)	600MHz	37	30.00′	5.6″	13.90	0.65
S (2-4 GHz)	1500MHz	7.7	15.00′	2.7″	16.53	1.56
C (4-8 GHz)	3.03GHz	4.4	7.50′	1.3″	7.21	1.36
X (8-12 GHz)	3.50GHz	3.9	4.50′	0.78″	2.96	0.93
K_u (12-18 GHz)	5.25GHz	3.5	3.00′	0.55″	1.45	0.68
K (18-26.5 GHz)	7.20GHz	7.0	2.05′	0.36″	0.34	0.23
K_a (26.5-40 GHz)	7.20GHz	9.5	1.45′	0.25″	0.12	0.12
Q (40-50 GHz)	7.20GHz	50	1.00′	0.18″	0.011	0.02

FAQ: Effective beam area for mosaicking speed is ½ PB area: $\Omega_B = 0.5665\ \theta_{PB}^2$

Sampler mode, RFI-free bandwidth

Integration time to reach 100μJy

Primary beam FWHM

Resolution, A-config, natural wt.

Survey Speed in deg^2 /hr at 100μJy image rms

On-the-fly scan rate

VLASS Timeline & Schedule (provisional)

Target is <u>December 2014 approval</u> to start in 2015B

- Jan 2014 – public workshop at AAS Meeting (National Harbor)
- Feb – Apr 2014 SSG Working Groups "met" and defined survey
- May – Jul 2014 – SSG writes Science Proposal (NOW)
- May - Jul 2014 – SDG develops technical design & plan (NOW)
- Early Aug 2014 – Full Proposal to NRAO director for review
- Aug - Nov 2014 – Proposal Review by NRAO & NSF
- Dec 2014 – Approval (all/part/none), develop schedule 2015+
- Late 2015 – first pilot or production observations in A/B-array?
- 2015-2020 – VLASS observations

VLASS organization

- Survey Science Group (SSG) formed in Feb 2014 comprising several working groups, open to entire community, advertised in multiple eNews articles:
    - Galactic
    - Extragalactic
    - Transients and variability
    - Programmatics
    - Communcation/Education/Outreach
    - Technical
  - WG co-chairs comprise SSG Governing Council
  - Council co-chairs are Stefi Baum (RIT) and Eric Murphy (IPAC)
- Contributions are via VLASS Discussion Forums, material posted to public wiki
  - https://science.nrao.edu/science/surveys/vlass/vlass-discussion-forums
  - https://safe.nrao.edu/wiki/bin/view/JVLA/VLASS
- Survey Design Group (SDG) NRAO + community, lead Steve Myers
  - SDG will do technical design, testing, and implementation (continuation of the Technical Working Group, after science has been defined)
- VLASS Project Director: Claire Chandler

The VLA Sky Survey: why now?

- Science:
  - The cosmic view:
    - Radio galaxy surveys need wide areas at substantial depth
    - Arc-second or better resolution for identification
    - Other multi-wavelength surveys, co-observing opportunities
  - The dynamic view:
    - Synoptic surveys need time baseline (3+ years), OTF ⇒ rapid sky coverage
    - Characterize the "null" (static+variable) sky
      - Lay groundwork for LIGO & LSST era
  - Prepare for the future – science proving ground for SKA
- Astro2020:
  - Starts ~2019, need strong case for continued support of radio astronomy by the entire US astronomy community ~2018 ⇒ start survey ~2015 to minimize impact on PI science and maximize transient science

Key science cases: highlights from the White Papers

- Medium/Deep Fields for Galaxy Evolution & Cosmology
  - AGN and Clusters of Galaxies, Feedback
  - Star-forming Galaxies
  - Weak Lensing

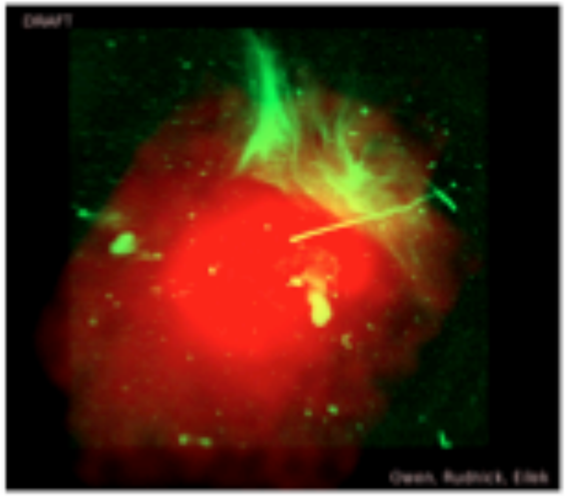
Cosmology & AGN: Brown et al., Mao et al., Spoalor et al.,

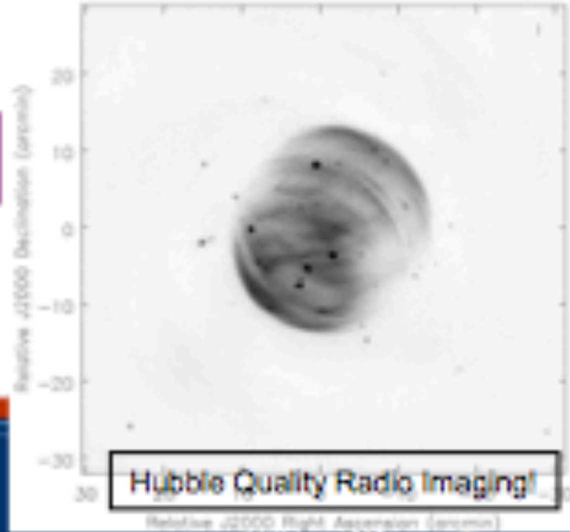
Clusters & Polarization: Clarke et al., Edge et al., Mao et al.
Cosmic Deep Fields: Hales et al., Jarvis et al., Richards et al., Wang et al.

- Large Area Survey for Transients & Faraday Tomography
  - Full Polarimetry for B-field Studies
  - EM Counterparts to GW events (LIGO/VIRGO)
  - Radio Bursts on timescales from 1ms to >1 year
- Galactic Plane and Center
  - Atomic and Molecular Lines from 0.2-50 GHz
  - Stars and Stellar Systems

Transients: Chatterjee et al., Hallinan et al., Kamble et al., Law et al., Wilson et al.

Galactica: Bastian et al., Bhatnagar et al., Sjouwerman et al., Mills et al.





Radio Survey Landscape 2015-2020+

Target flux density limits 1-20μJy at 1.4GHz

Norris et al. 2012 (arXiv:1210.7521)

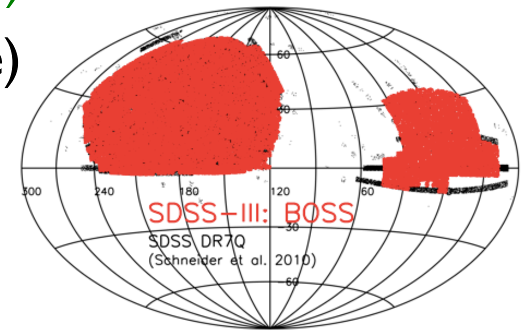
- MeerKAT Continuum Surveys
  - 64 x 13.5m
  - Tier 1: 10^3 deg^2 to 5μJy at 1.4 GHz (6" resolution)
  - Tier 2: 35 deg^2 to 1μJy at 1.4 GHz (2.5" resolution w/20km baselines)
  - Tier 4: 0.25 deg^2 to 1μJy at 12 GHz (0.3" resolution)
- ASKAP EMU Surveys
  - 36 x 12m 30 deg^2 FOV camera, 300MHz band
  - 3×10^4 deg^2 to 10μJy at 1.4 GHz (10" resolution)
- APERTIF WODAN Survey
  - 10^4 deg^2 to 10μJy at 1.4 GHz (15" resolution, confusion 20μJy)
- SKA Phase 1 dish array (2020+) :
  - 190 x 15m dish array + 64 x 13.5m MeerKAT dish array
  - Survey speed 53 deg^2/hr at 10μJy rms (!!) in band 2 (0.95-1.76GHz)

SKA Baseline Design 2013-03-12

VAST: A Survey of Four Intertwined Tiers

VLASS: S-Band 2-4GHz 16.53deg^2/hr at 100μJy

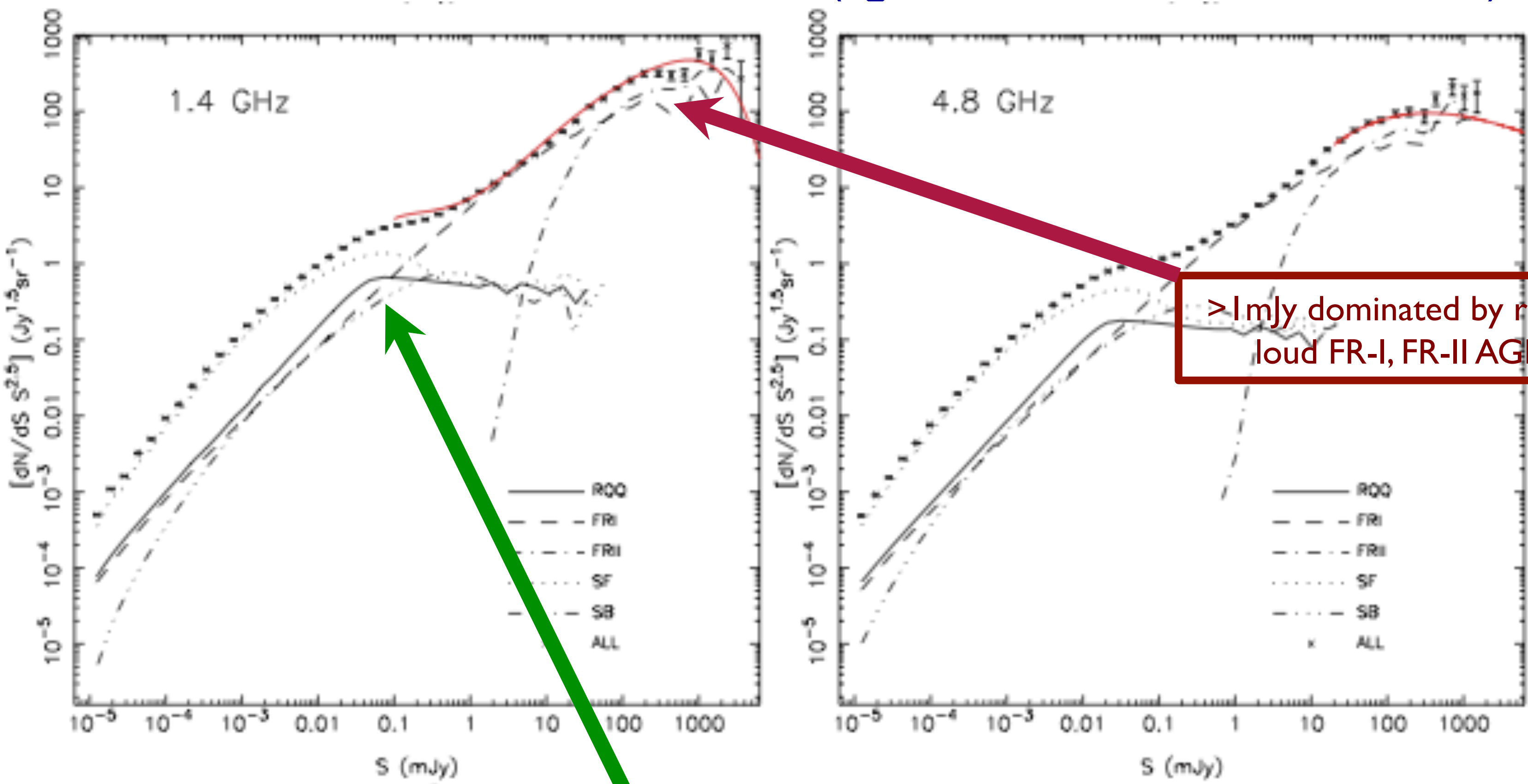
- All-Sky: 34000 deg^2 (all the Northern sky, e.g. NVSS)
  - 100 μJy rms, B-configuration, two epochs (each 140 μJy)
  - Highest source yield at a given band
- Wide- Exgal: 10000 deg^2 (e.g. SDSS and FIRST footprint)
  - 50 μJy rms, B-configuration, 4 epochs (each 100 μJy)
- Galactic - Gal: 3160 deg^2 (Galactic Central Bulge, Plane)
  - 50 mJy rms, in A & B configurations, 8 epochs
  - Galactic Bulge: -10° < *l* < 10° , -14° < *b* < 14°
  - Galactic Plane: -20° < *l* < 260° , -5° < *b* < 5°
- Deep: 10 deg^2 (deep fields)
  - 1.5 μJy rms (!!), in A & B configurations, 10 epochs (4.7 μJy)
  - in 3 Deep Fields – COSMOS, ECDFS, Elias-N1 (prelim)



VLASS: 7200 hrs observing, 9000 hrs total (25% overhead)

Radio Source Counts and Populations

- Wilman et al. 2008 SKADS diff. counts (agrees with Condon et al. 2012)

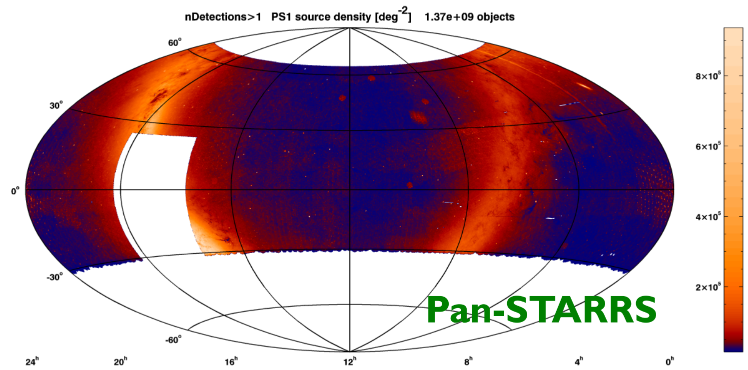


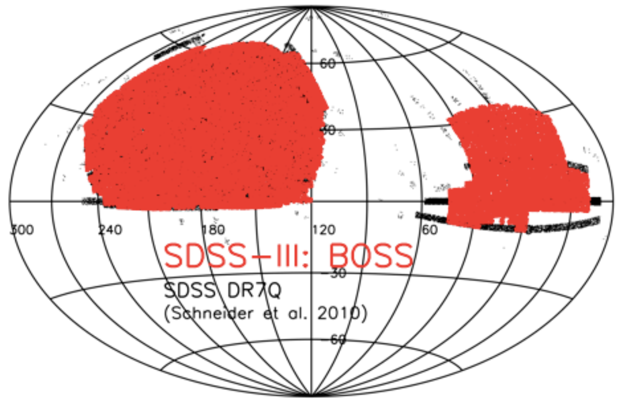
>1mJy dominated by radio-loud FR-I, FR-II AGN

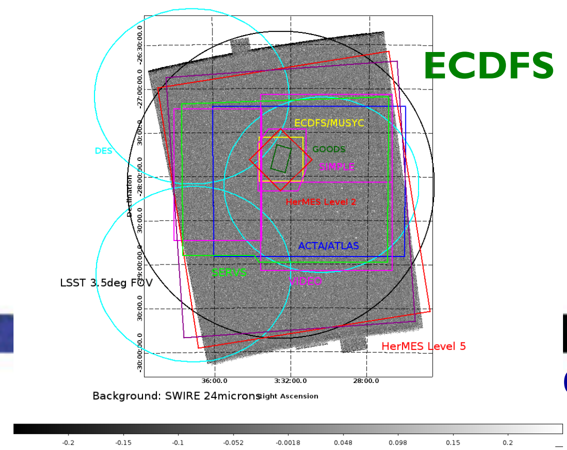
<1mJy dominated by radio-quiet (all) AGN and star-forming galaxies (roughly equal)

Science with the VLASS

- All-Sky (Tier 1)
  - 2” resolution over Northern sky
  - includes spectral index, polarization
  - new catalog for ISW, RM surveys, etc.
- Wide (Tier 2)
  - SDSS, HSC, DESI area
    - radio matches to optical
- Galactic (Tier 3)
  - Galactic Plane & Central Bulge
    - pulsars, SNR, PNe, radio stars
- Deep (Tier 4)
  - well-studied Deep Fields
  - weak lensing, star forming galaxies
  - radio correlation function and bias

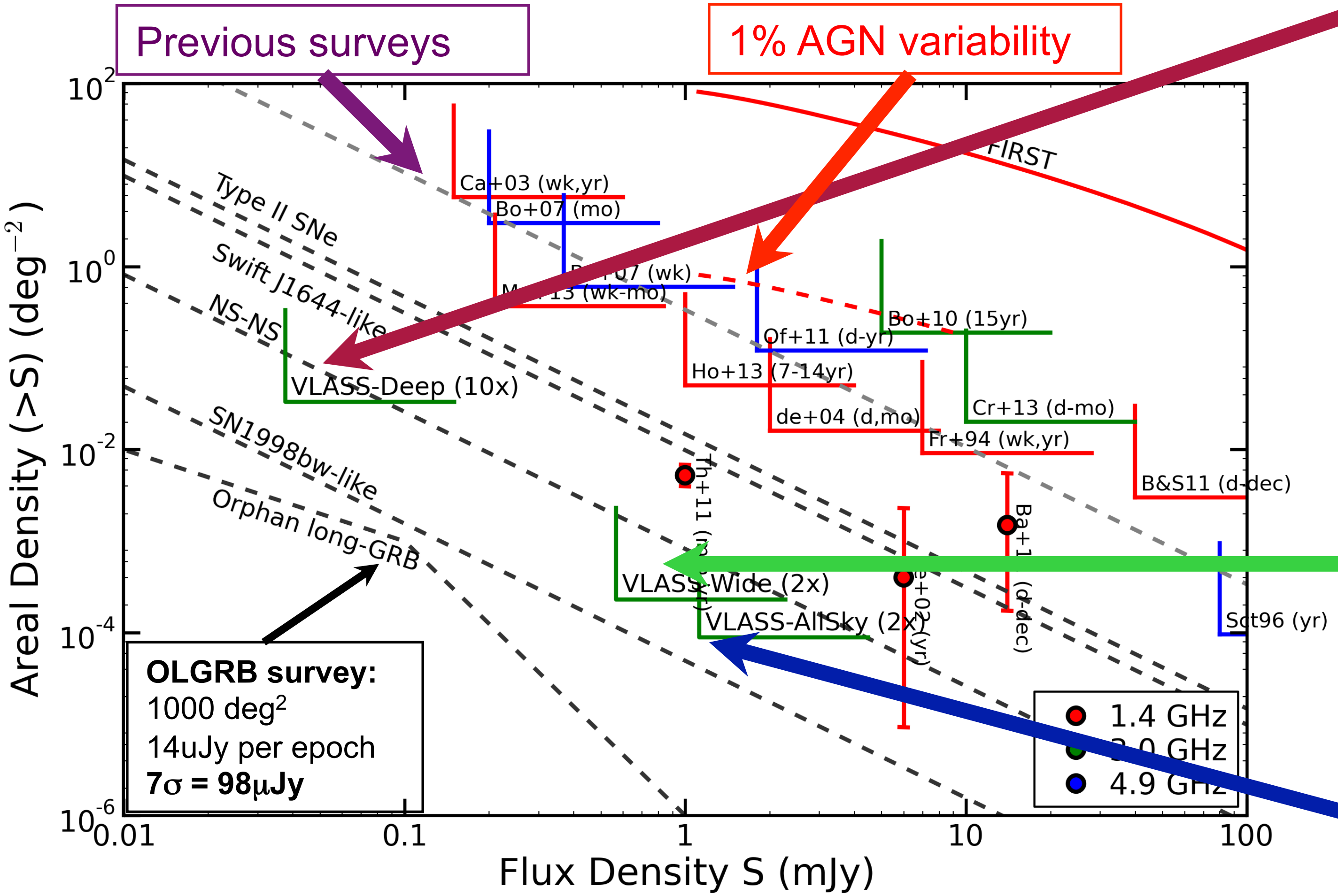






Extragalactic Transients in the VLASS

- Areal density vs. Flux density (from Mooley & Hallinan)



Deep Fields
10deg^2
4.7μJy in 10 epochs
8σ = 38μJy

Gal
3160 deg^2
140μJy in 8 epochs
8σ = 1.12mJy

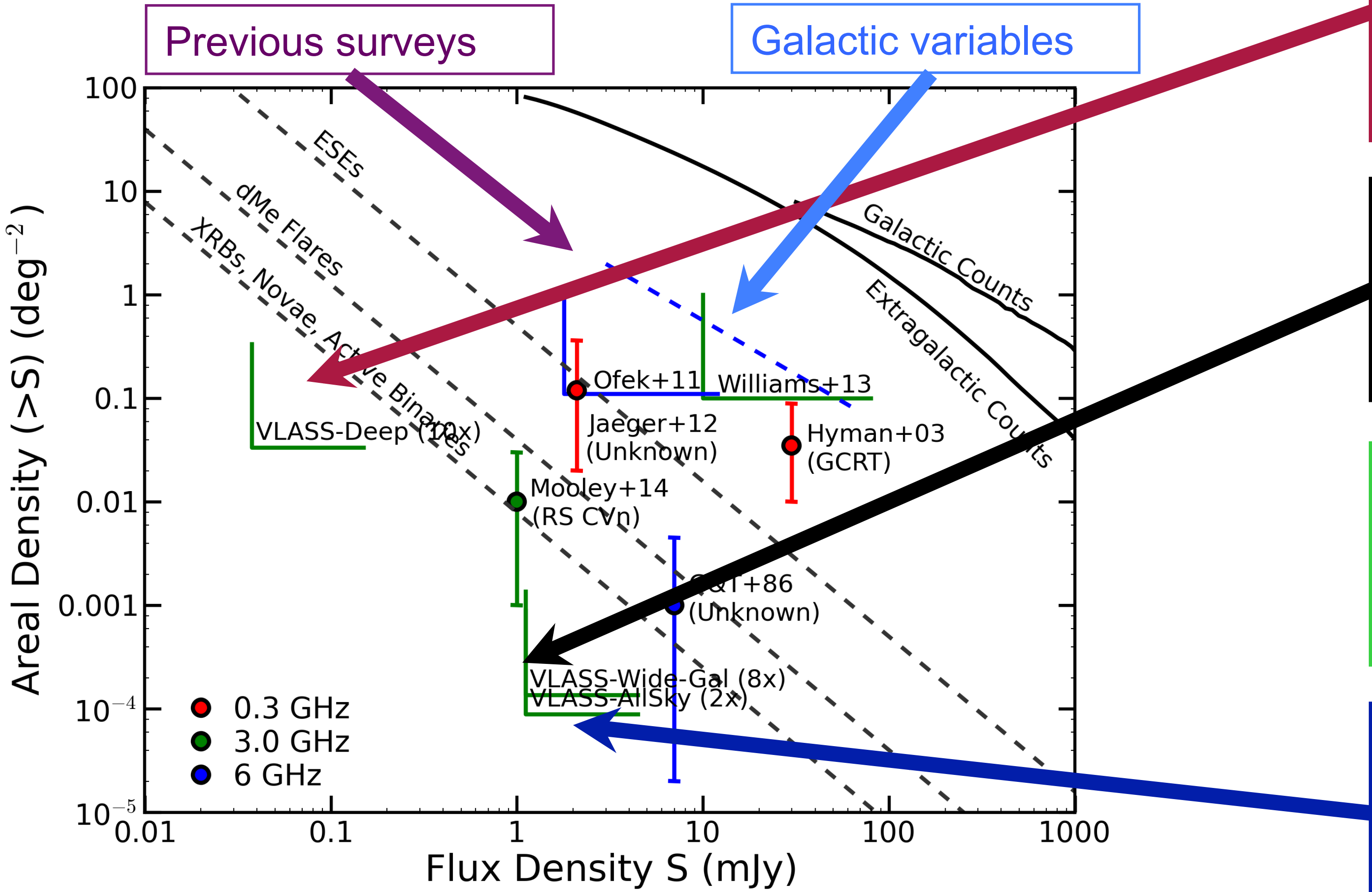
Wide-Exgal
10^4deg^2
100μJy in 4 epochs
8σ = 0.8mJy

All Sky
3.4×10^4deg^2
140μJy in 2 epochs
8σ = 1.12mJy

NRAO

Galactic Transients in the VLASS

- Areal density vs. Flux density (from Mooley & Hallinan)



Deep Fields
10deg^2
4.7μJy in 10 epochs
8σ = 38μJy

Gal
3160 deg^2
140μJy in 8 epochs
8σ = 1.12mJy

Wide -Exgal
10^{4}deg^2
100μJy in 4 epochs
8σ = 0.8mJy

All-Sky
3.4×10^{4}deg^2
140μJy in 2 epochs
8σ = 1.12mJy

Headline Transient Science in VAST

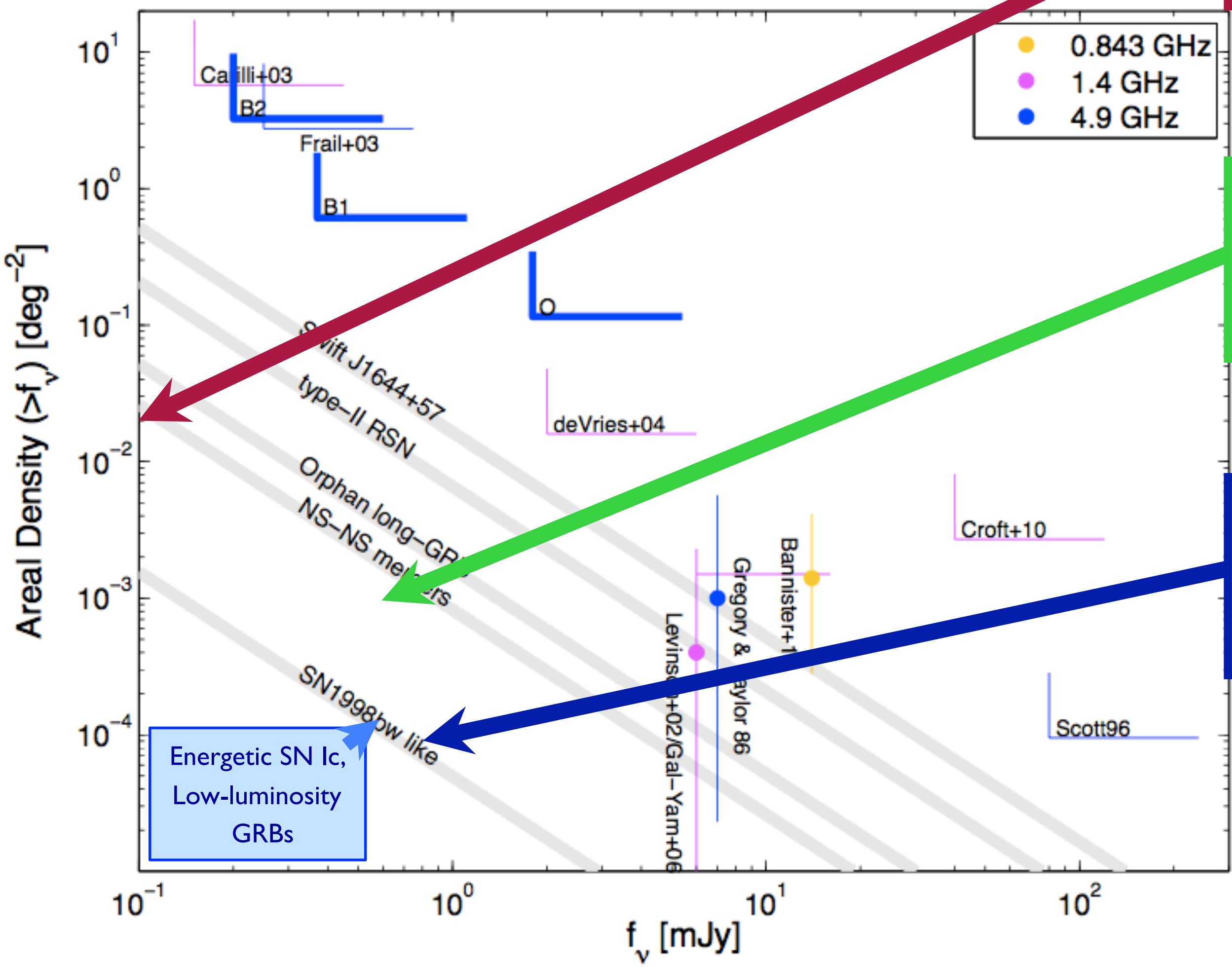
- A new era of wide-area high-resolution radio synoptic surveys

- Detection of dual Neutron Star merger event
- Exotic Neutron Stars (Chatterjee white paper)
- Determination of the Tidal Disruption Event (TDE) rate
- Determination of the rate of obscured supernovae in local Universe
- Discovery of other Galactic Center radio transients
- Determination of the rate of other Radio Transients (Galactic & Ex-gal)
- Detection of off-axis (orphan) GRB only if higher than model

- High quality high resolution radio maps and catalogs as basis ("Epoch Zero") for future radio transient surveys and follow-up of multi-wavelength transient events (Gravity Waves, LSST, etc.)

Science Case: Synoptic Radio Surveys

- Areal density vs. Flux density (Frail et al. 2011)
  - $N/t = S^{-1.5} / S^{-2} = S^{0.5}$ (shallow wins)



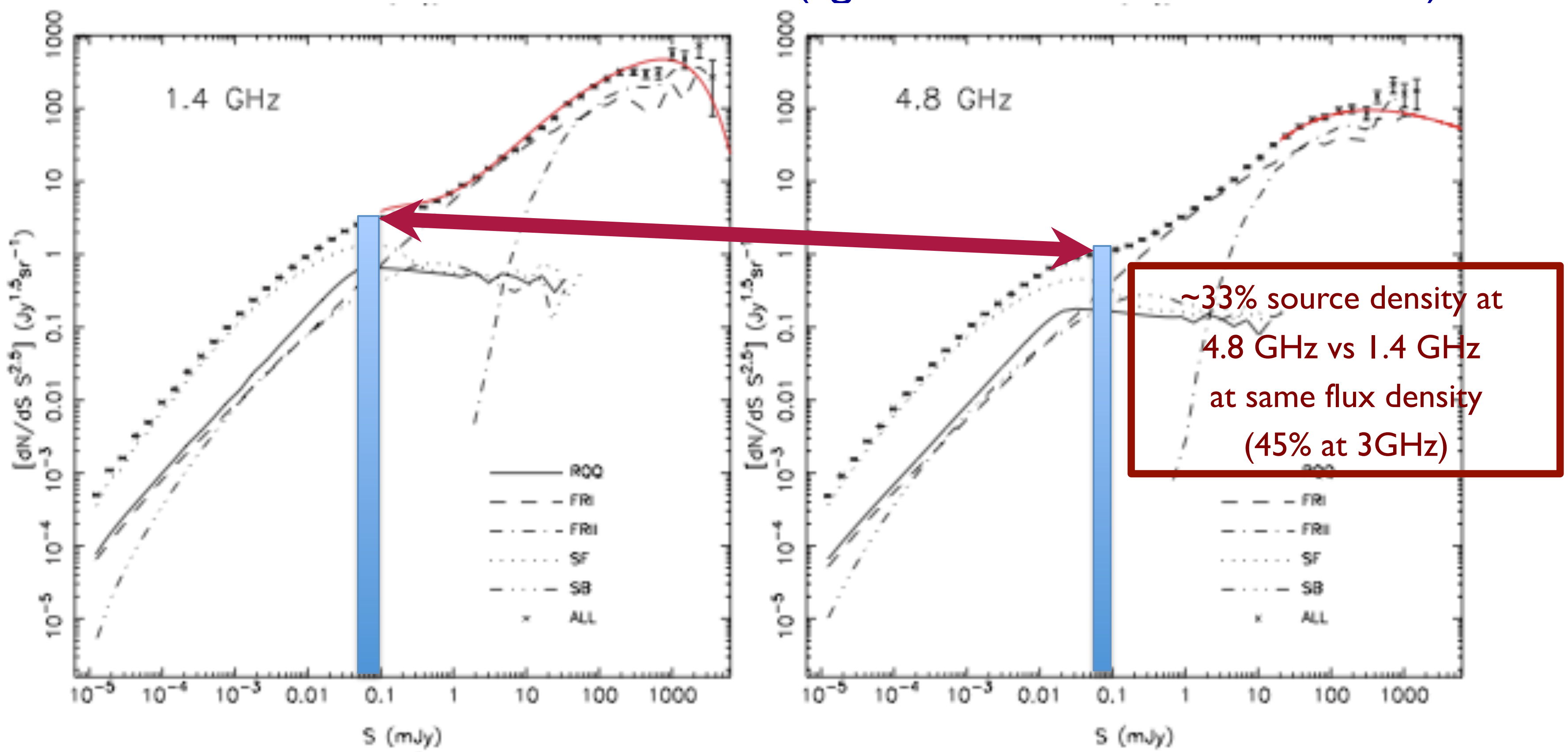
Deeper Narrower Survey
50sq.deg at 12.5μJy rms
2-4GHz in 194 hours

Medium-Wide Survey
10^3sq.deg at 75μJy rms
2-4GHz in 107 hours

Wide-Shallow Survey
10^4sq.deg at 100μJy rms
2-4GHz in 605 hours

Radio Source Counts and Populations

- Wilman et al. 2008 SKADS diff. counts (agrees with Condon et al. 2012)



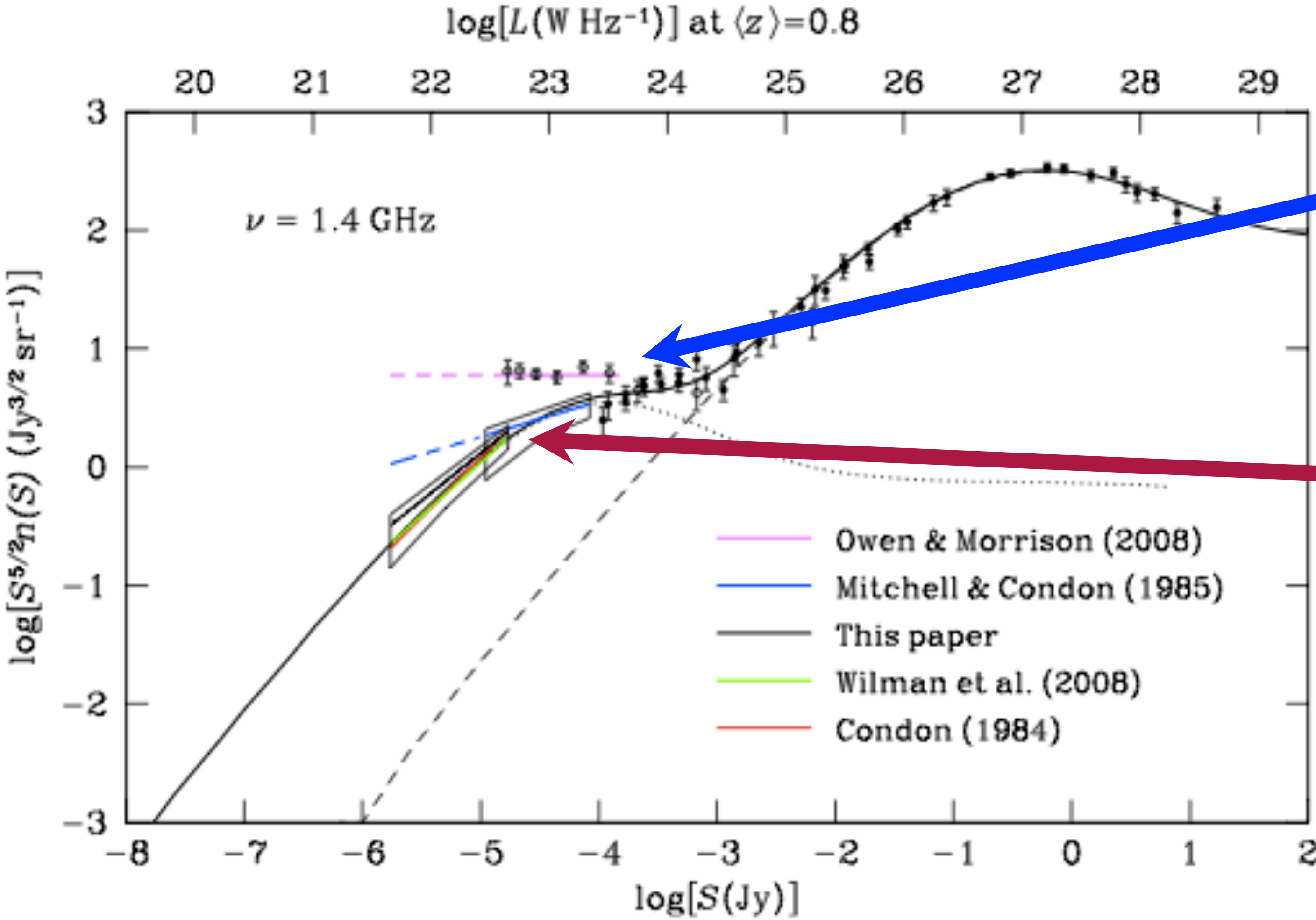
100μJy 3GHz vs 450μJy 1.4GHz (NVSS) ~ 4.3x more srcs
50μJy 3GHz vs 150μJy 1.4GHz (FIRST) ~ 2.3x more srcs

$N(>S) \sim (S/S_0)^{-1.5}(\nu/\nu_0)^{1.5<\alpha>}$
$<\alpha>\sim-0.7$

NRAO

Radio Source Counts and Populations

- Condon et al. 2012 Jansky VLA at 3GHz D-config (confusion limited)



Overcorrection for resolution effects?

Strongly sub-Euclidean counts below 30mJy $N(>S) \sim S^{-0.5}$ or shallower

Commensal Science Opportunities

- Line and Continuum Science
  - For maximal continuum sensitivity, would use wide-band modes with channel resolution of 2 MHz (1MHz at L-band), corresponding to a velocity resolution of ~200 km/s (1.4GHz) to 40 km/s (15 GHz).
  - At the cost of higher data rates and volumes, could include higher-resolution "line" windows on key lines (e.g. OH and HI in L-band, Methanol at C-band). This has cost impact and must be justified.
- Transient Science
  - If practical should observe at highest standard time resolution (1sec), or at higher resolution (0.5sec) if feasible. Will also be needed for wide-field imaging in A-configuration.
- Low-Frequency Commensal System (LOBO)
  - It is likely that by the time this survey commences the VLA will have a commensal low-band observing system (LOBO) for 230-470 MHz (P) and possibly 58-84 MHz (4) band data from a subset of antennas.

Assembling the Puzzle

- A "Baseline Survey Program" : Total of ~6000 h integration (7500-9000 h duration w/+25-50% overhead) over 6 years (1500 h = 2 months per year)
- The breakdown: (times are integration/dwell) **Total 6620 hours**
  - Tier S1 – 30000 deg^2 S-band in 2 conf to 100μJy combined (1800h)
  - Tier S2 – 10000 deg^2 S-band in 1 conf x 3 epochs at 100μJy (1800h)
    - Reaches 50 μJy with 3 x S2 + 1 x S1 epochs
  - Tier S3 - 1000 deg^2 S-band in 1 conf x 12 epochs at 100μJy (720h)
    - In 3 x 330 deg^2 fields, reaches 25 μJy with overlap S2 + S1
  - Tier C2 – 10000 deg^2 C-band in 1 conf x 1 epoch at 100μJy (1400h)
  - Tier C3 – 1000 deg^2 C-band in 1 conf x 3 epochs at 100μJy (420h)
    - For same S3 fields, reaches 50 μJy including C2
  - Tier X3 – 1000 deg^2 X-band in 1 conf x 1 epochs at 100μJy (340h)
  - Tier L3 – 1000 deg^2 L-band in 2 conf x 1 epoch at 100μJy (140h)
  - Tier 4 – can trade some above area/time for Tier 4 deep fields

A Jansky VLA Sky Surveys Program

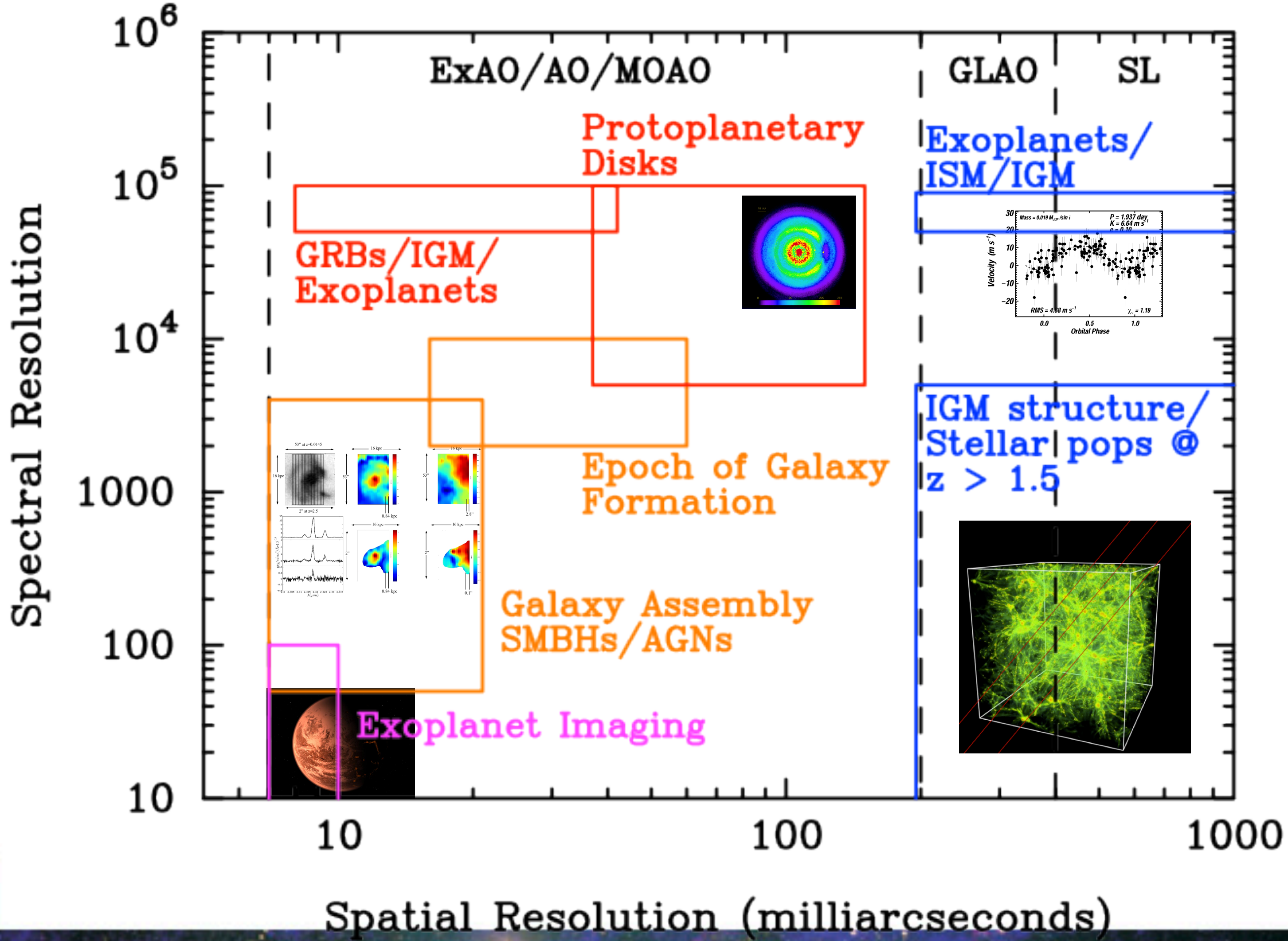
- In order to maximize the utility of the JVLASS Program for the astronomical community, and to involve the widest cross-section of potential users in the planning, prosecution, and processing of the data products, we are setting up:
- "Survey Science Group" (SSG) – Stefi A. Baum, RIT
  - Broad community-based group (multi-wavelength, science areas)
  - Define survey science goals, design and plan survey
- "Survey Implementation Team" (SIT) – Steven T. Myers, NRAO
  - Smaller team to carry out survey observations, quality assurance
  - Basic Data products: pipeline calibration and imaging, basic catalogue
- Group and team members will be accreted through solicitations and community workshops.
- The survey data taken under this program will have no proprietary period, following the tradition of the FIRST and NVSS surveys.

Maximizing the Science

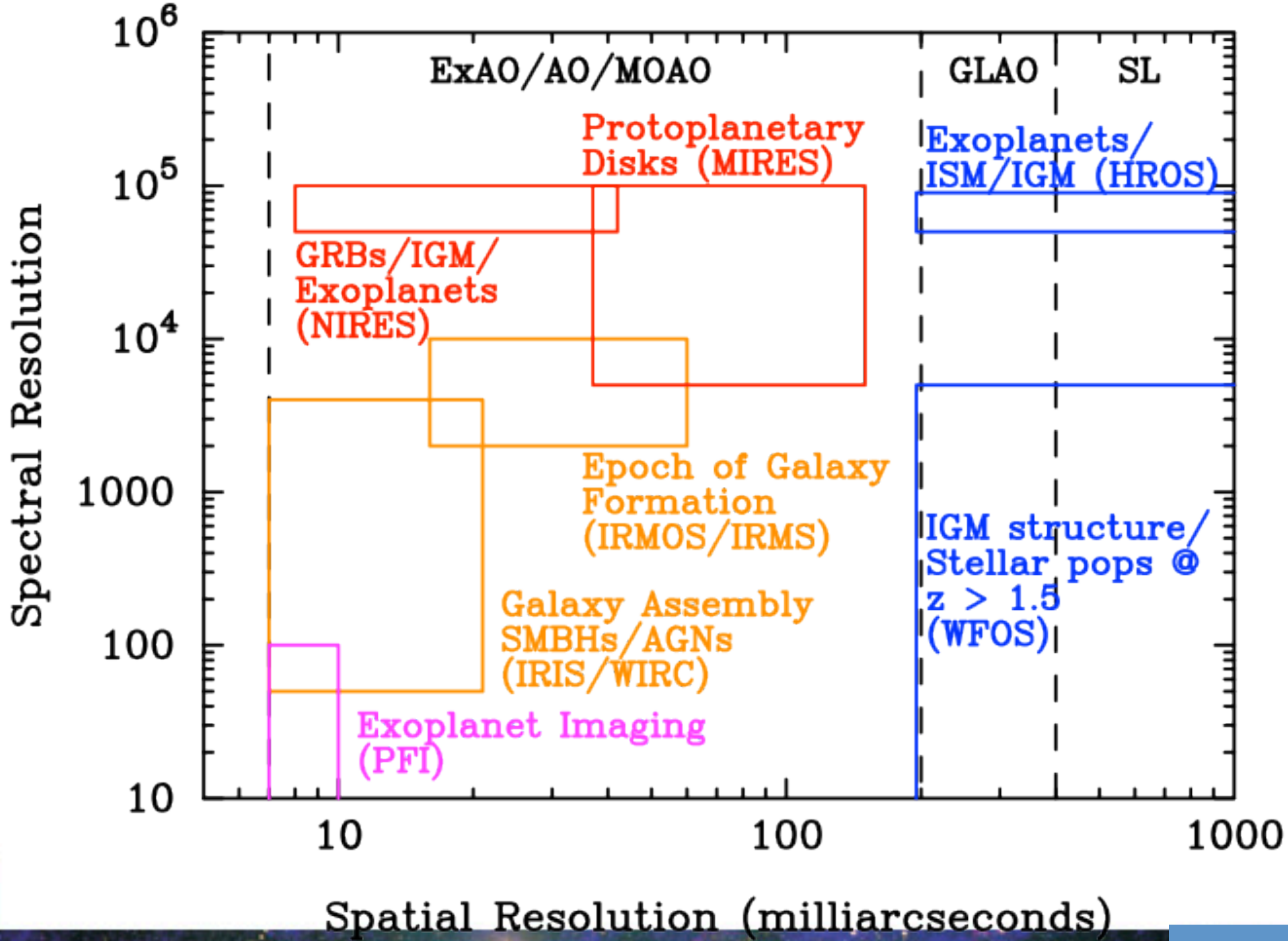
- Cultivating a Multi-wavelength View
  - Involve a broad community of astronomers
  - Open process, no proprietary data
  - Range of available data products for science-ready utility
- Enabling principles
  - Coordinate observations of key fields
  - Enable co-observing by publishing survey schedules
  - Flexible scheduling in response to events and opportunities
  - Prompt analysis and publication of transient event alerts
  - Quality control and assurance
- Data Products
  - Calibrated uv data
  - Basic images and catalogs
  - More advanced products as added value by community

Synergy

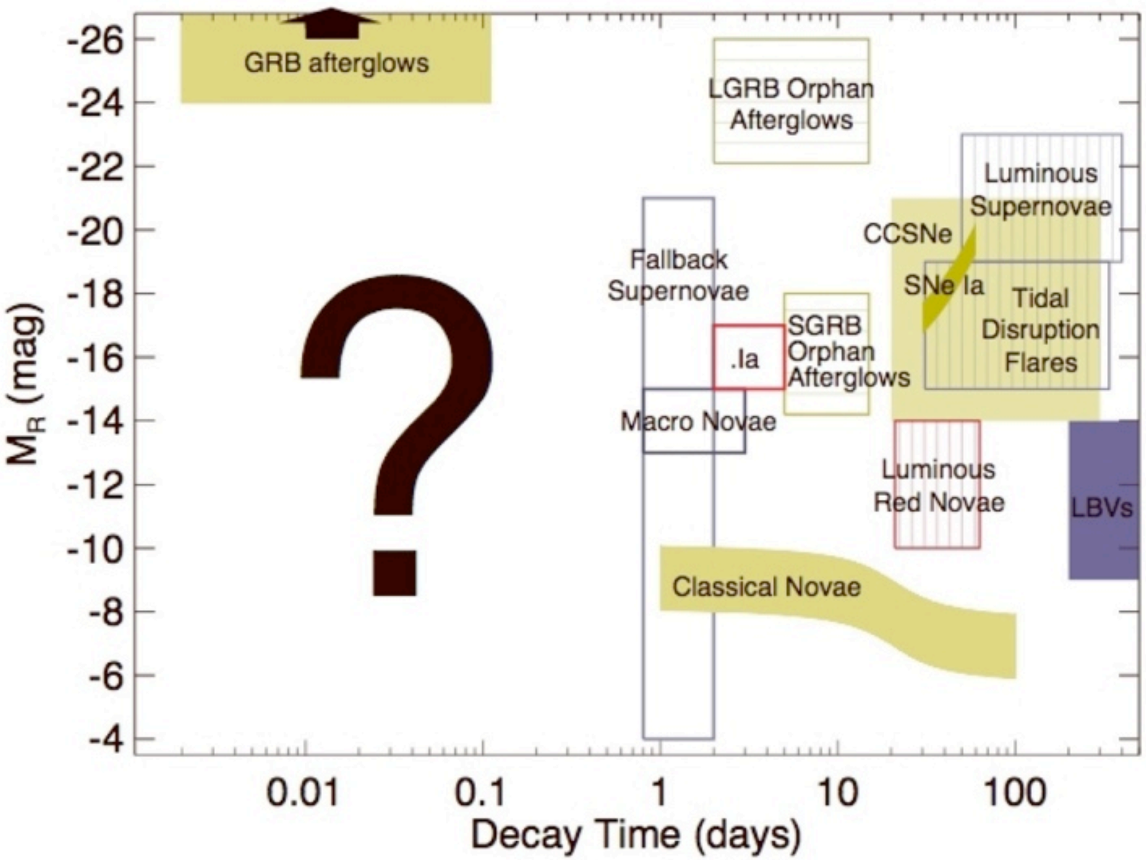
Defining Capabilities in the TMT Discovery Space



Defining Capabilities in the TMT Discovery Space



TMT as an Agile Telescope: Catching The “Unknown Unknowns”



TMT target acquisition time requirement is 5 minutes
(i.e., 0.0034 day)

TMT is the only agile extremely large telescope

Source: Figure 8.6, LSST Science Book

30-m, LSST and JVLA Science

30-m and LSST

- Cosmology and Large Scale Structure

- Galaxy Formation and Evolution

JVLA

- Radio Continuum: Sachs-Wolfe effect, power spectrum of radio source population , cosmic magnification bias.
- Radio Weak Lensing

- Radio continuum of star formation
- Molecular and hydrogen line studies of gas content and kinematics
- AGN populations + feedback

30-m, LSST and JVLA Science

30-m and LSST

- Star and Planet Formation

- Transient Science

JVLA

- Thermal and Non-thermal continuum and emission lines from Young stellar objects and proto-planetary disks
- Magnetic properties of stars
- Gas cloud properties

- Sample different emission processes in the radio, deect different populations and different phases. Independent confirmations.

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, fast dumps, and the most flexible spectral modes) are still under development.
  - Users can, and should express their preferences for future development.
- New and very exciting results are now being produced – with topics across the entire range of astronomy.

A Brief Summary II

- The Jansky Very Large Array is capable of making significant contributions to the key areas of science targeted by the LSST and the 30-m class telescopes:
  - Cosmology and Large Scale Structure
  - Galaxy Formation and Evolution
  - Star and Planet Formation
  - Transient Science
- The synergy between the JVLA and ground based telescopes should be considered going forwards for maximum scientific impact, including the design and execution of surveys.