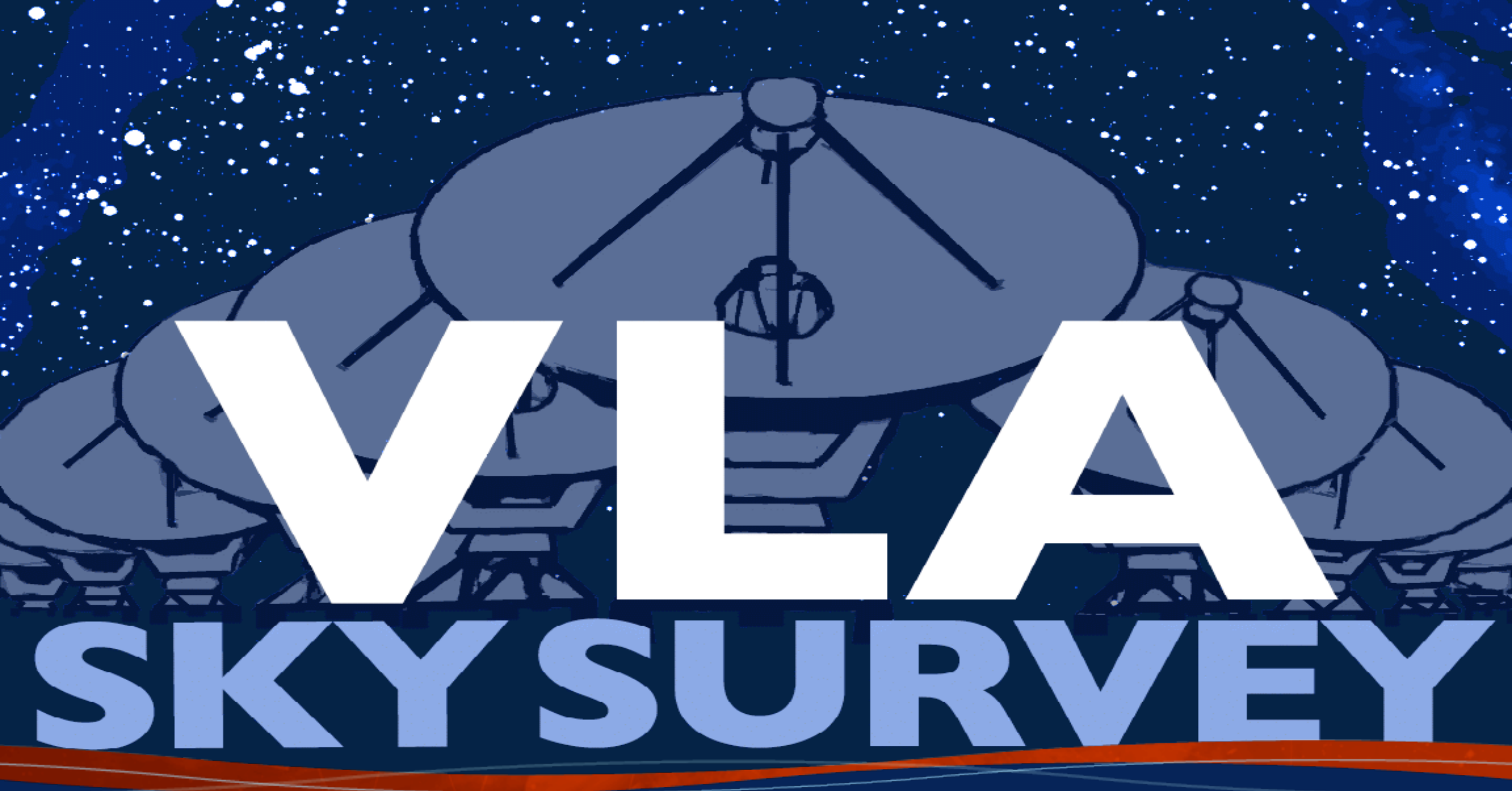


The VLA Sky Survey (VLASS):

A New Generation Radio Sky Survey with the VLA

Amy Kimball (NRAO)

for the VLA Sky Survey team and Survey Science Group

Karl G. Jansky Very Large Array

Very Large Array in 1km D-configuration:

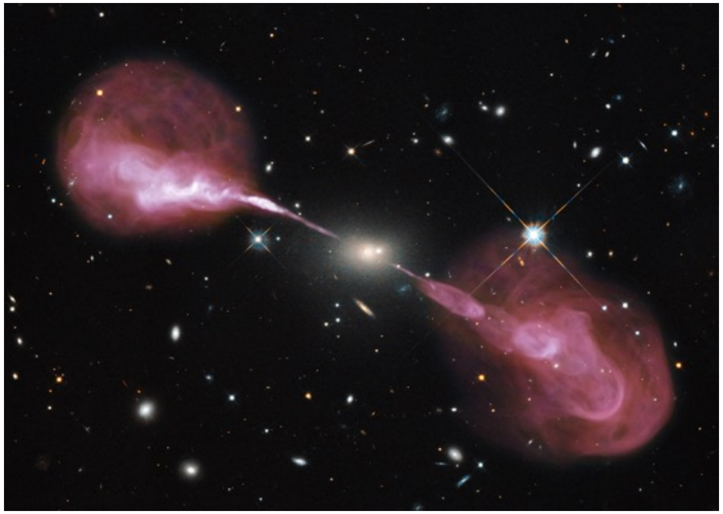
- Nine 25-m antennas along each of 3 arms extending up to 21 km from array center

Karl G. Jansky Very Large Array

- 27 antennas, fiber-linked interferometer
- 25m diameter antennas – Field of View 45' at 1GHz (1' at 45GHz)
- 4 configurations (A, B, C, D) covering range of spatial scales
  - D-config: B_{max} 1.03 km, θ_{res} 23" (at 3GHz, robust wt.)
  - C-config: B_{max} 3.4 km, θ_{res} 7.0"
  - B-config: B_{max} 11.1 km, θ_{res} 2.1" ← Used for VLASS
  - A-config: B_{max} 36.4 km, θ_{res} 0.65"
- Full frequency coverage, 1–50 GHz (in 8 receivers: L,S,C,X,Ku,K,Ka,Q)
- Up to 4.2e6 channels in up to 64 independent sub-bands
- *Up to 8 GHz/pol instantaneous BW*
- Fast dump times: several millisecond time resolution
- Prime Focus: low frequency dipoles (not truly in focus)
  - P-band 230-470MHz (available at all times)
  - 4-band 58-84 MHz (currently manually deployed, permanent soon?)

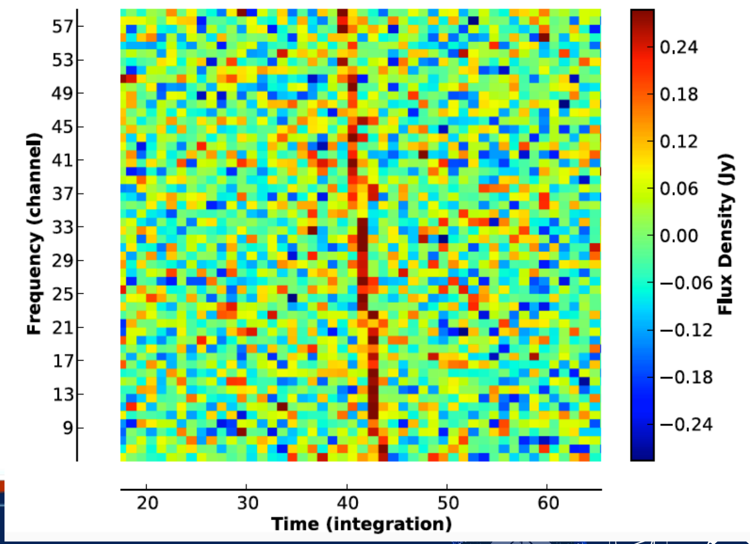
Scientific capabilities of the Jansky VLA relevant for a sky survey

- Wide bandwidths:
  - Continuum sensitivity
  - Spectral index information
  - Rotation measure studies
  - Survey speed for wide-field mosaics



Hercules A image credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

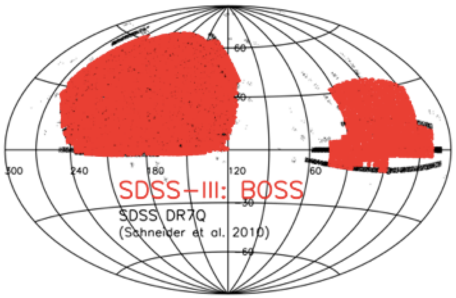
- Correlator flexibility:
  - Very fast (5ms) dumps for pulses, bursts, and transient searches

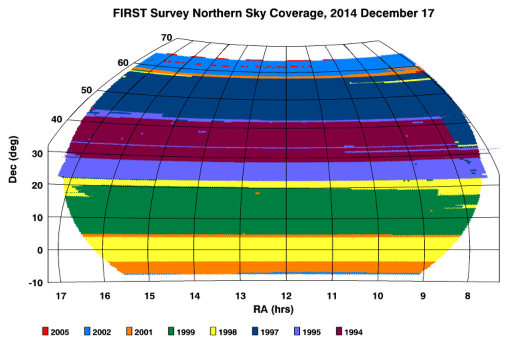


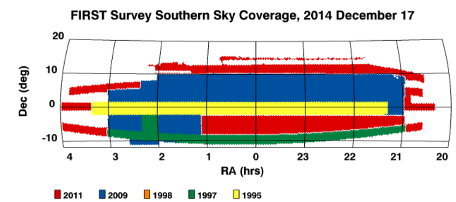
Spectrogram of dispersed pulse from RRAT J0628+0909, t_{int}=10ms (Law et al. 2012)

Why a VLA Sky Survey and why now?

- Science based on surveys comprise a steadily increasing fraction of VLA publications
- 20 years since VLA surveys NVSS and FIRST; 5+ years before SKA-1







- ***New scientific opportunities***
  - multi-messenger surveys need radio counterpart *with comparable or better resolution*
  - start now to build time series for time domain studies
- ***Community driven survey***
  - Astronomy community proposed a new radio survey taking advantage of VLA's new capabilities
  - Reviewed by independent panel, approved by NRAO Director in 2015

VLA Sky Survey (VLASS)

- Highest spatial resolution, all-sky radio survey to date
  - All-sky (33,885 deg^2 above declination –40°)
  - Frequency: 3 GHz (2-4 GHz, less RFI affected regions)
  - Angular resolution: 2.5” (VLA B-configuration)
  - Synoptic: 3 epochs separated by 32 months
  - Observing time: 920 hours per configuration cycle X 6 cycles

Area (deg^2)	Resolution (robust)	Rms (μJy/bm)	Density (deg^{-2})	Total Detections
33,885 (δ > -40°)	2.5”	120 \ 69	~290	9,700,000

10x FIRST yield, ~5x NVSS

- Pilot observations completed in Sep 2016 (200 hrs)
- Full survey, 7 years: September 2017 --- October 2024

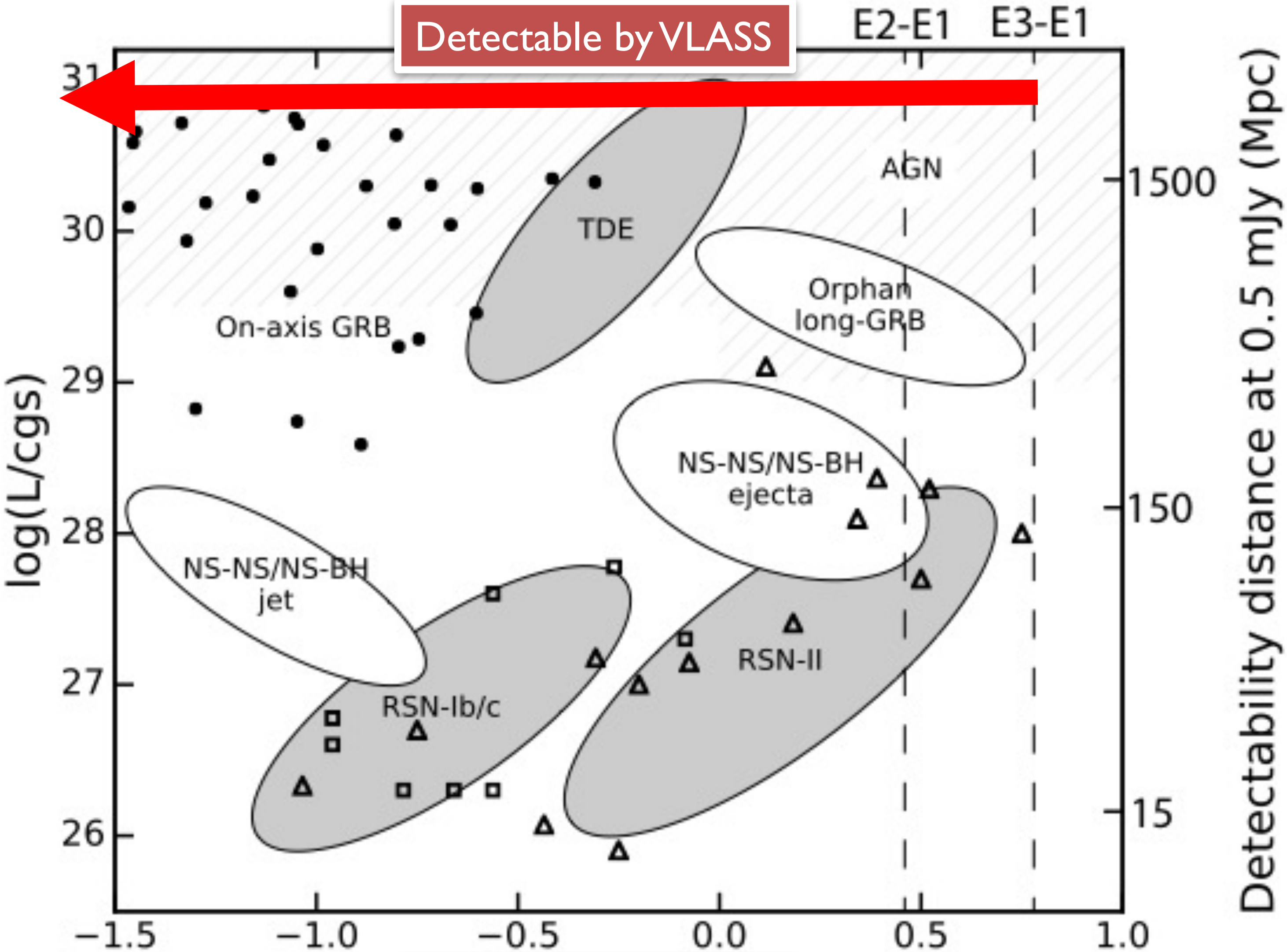
VLA Sky Survey Team

- VLASS Team (NRAO):
  - Claire Chandler (Project Director), Steve Myers (Technical Lead)
  - Rafael Hiriart (Architect), Drew Medlin (Lead DA: Ops/Pipeline/QA)
  - Chris McLaughlin (Project Management)
  - Amy Kimball, Frank Schinzel, Lorant Sjouwerman (Scientists)
- Survey Science Group Board
  - Stefi Baum (Manitoba), Shami Chatterjee (Cornell) (co-chairs)
  - Gordon Richards (Drexel), Amy Kimball (NRAO), Rachel Osten (STScI), Joe Lazio (JPL), Gregg Hallinan (Caltech), Gregg Sivakoff (Alberta), Susana Deustua (STScI), Jayanne English (Manitoba), Larry Rudnick (Minnesota), Bryan Gaensler (Toronto), Casey Law (Berkeley), Kunal Mooley (Oxford), Tracy Clarke (NRL), Jim Condon (NRAO), Jim Cordes (Cornell), Nicole Gugliucci (Anselm), Russ Taylor (Cape Town), Rick White (STScI), Ashley Zauderer (NYU)

Key science themes

- Imaging galaxies through time and space
  - AGN feedback, flares, BH merger events; synergies with surveys at other wavelengths (resolution is key!)
- Hidden explosions
  - VLASS will open new parameter space for finding dusty/unbeamed GRBs, SNe, compact object mergers
- Faraday tomography of the magnetic sky
  - Studies of magnetic fields throughout the universe: hot gas in galaxy clusters, magnetic fields within other galaxies, magnetic field in the Milky Way
- Peering through our dusty galaxy
  - Extreme pulsars, cool stars with active coronae, planetary nebulae, HII regions
- Missing Physics
  - Serendipitous discoveries that come from opening up new parts of observational parameter space.

Key science theme: Hidden explosions

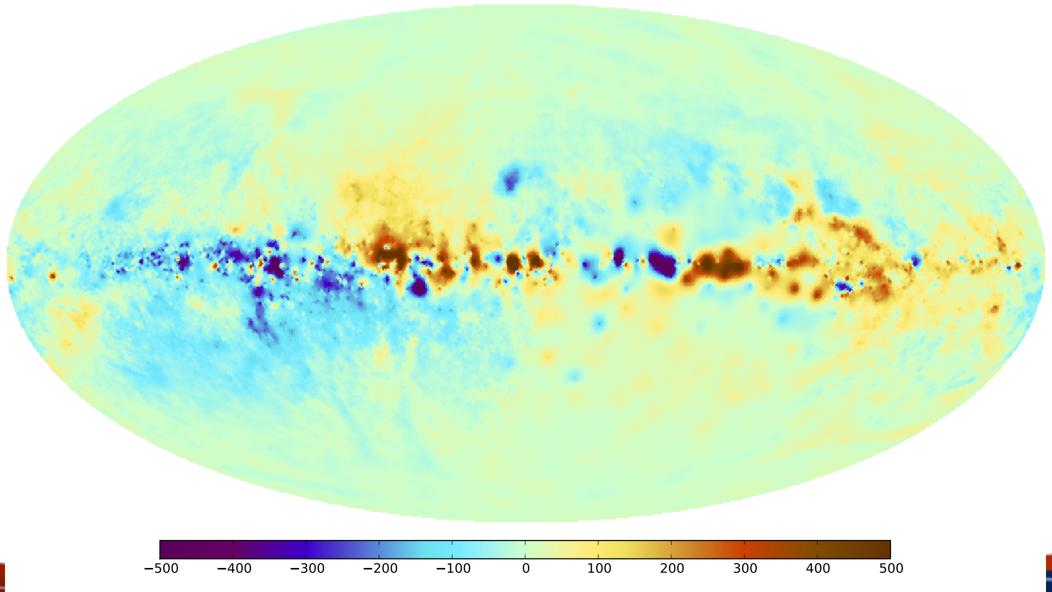


(courtesy Greg Hallinan)

Key science theme: Faraday tomography

- Faraday rotation studies:
  - How much thermal gas is entrained in the radio emitting material.
  - Magnetic field in surrounding group/cluster gas halo
  - AGNs, galaxies, damped Ly-α systems: expect rotation measure estimates for ~10^5 sources
  - Faraday rotation due to the magnetic field in the Milky Way

Factor ~10 increase in resolution of Milky Way Faraday rotation map



Linear Polarization Map:
Oppermann+ 2012 (NVSS)

VLASS Basic Data Products (public)

~1PB
Raw vis 523TB
Images 440TB

Product	Timescale for production	Notes
Raw visibility data	Immediate	In standard archive
Calibrated data	1 week	From standard archive
Quick Look Images	2 days	Stokes I wide-band continuum only
Single Epoch Images	6 months	Stokes I wide-band continuum
Single Epoch Images	12 months	Polarization and cubes
Single Epoch Catalogs	w/Single Epoch Images	By product
Cumulative Images	12 months	Stokes I wide-band continuum
Cumulative Images	12 months	Polarization and cubes
Cumulative Catalogs	w/Cumulative Images	By product

- CASA ALMA/VLA data calibration pipeline (VLASS "recipe")
- New imaging pipeline

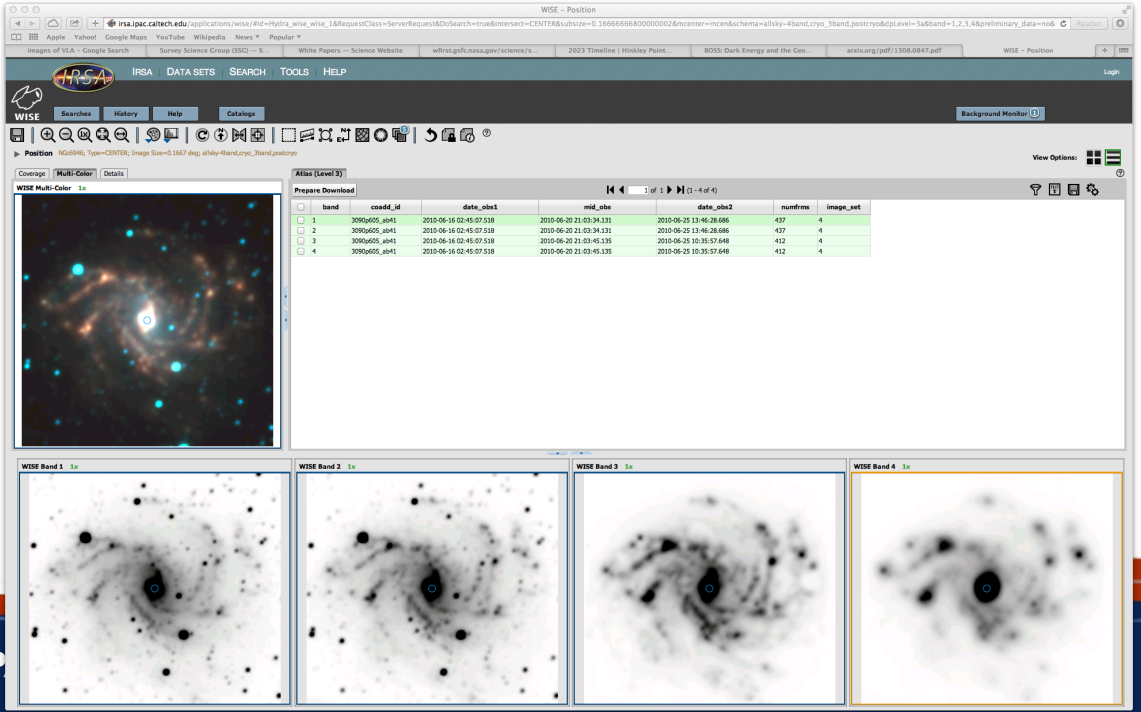
- NRAO → Science-Ready Data Products

Enhanced Data Products & Services

Community led effort

- Transient Object Catalogs & Alerts
- Multi-Wavelength Catalogs for VLASS sources
- Rotation Measure Images and Catalogs
- Light Curves (IQU)
- A hosted VLASS Archive with Image and Catalog Service

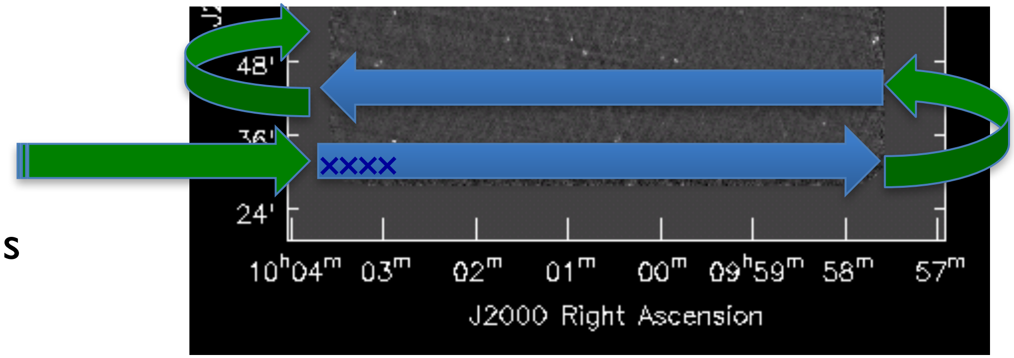
✧ e.g., as currently available by IPAC/IRSA allowing for VLASS to be integrated with Spitzer/Planck /WISE/Euclid/etc...



VLASS Challenges / Requirements

On-The-Fly-Mosaicking observations

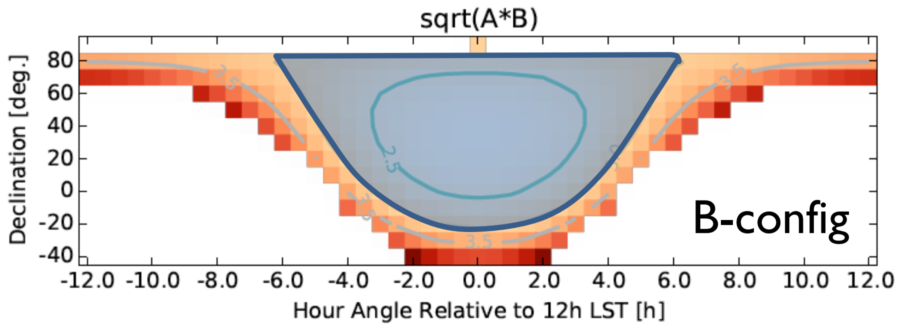
- Scan telescopes across sky while taking array data (step phase centers)
  - Net survey speed: ~20 deg^2/hr with calibration (Moon is ~0.2 deg^2)
  - Lose no data while scanning instead of 3-7s per step in standard mode
  - Efficient when dwell times on-sky are <25s (VLASS ~5s)
  - Correlator dump 0.45s avoids smearing
  - Scan rate 3.31'/s
  - 1.5'/integration
  - Row separation 7.2'
  - Equivalent time-on-source: 5s

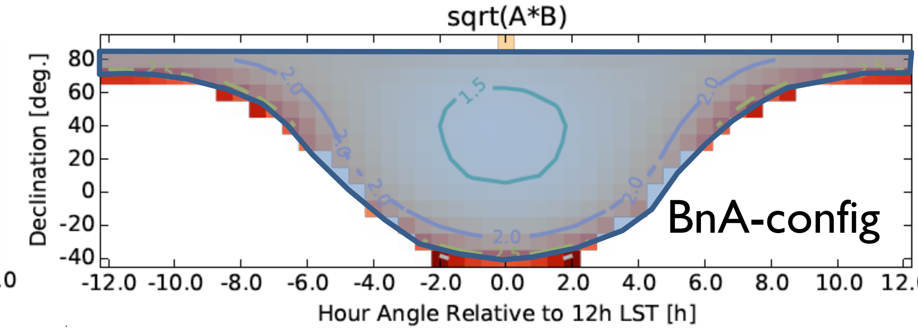


- New: antenna pointing positions recorded, can correct for minor errors

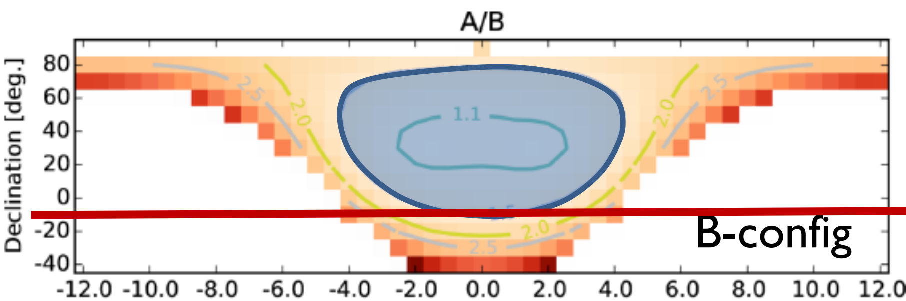
Beam shape requirements motivate configurations:

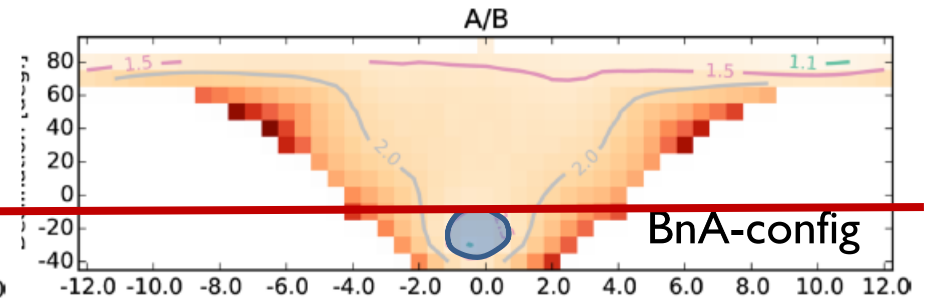
- Resolution requires the use of VLA B/BnA configurations
  - 3-arcsec (geometric mean) achieved over a large range of HA





  - Synthesized beam, major/minor axis ratio = 1.5 (contour)



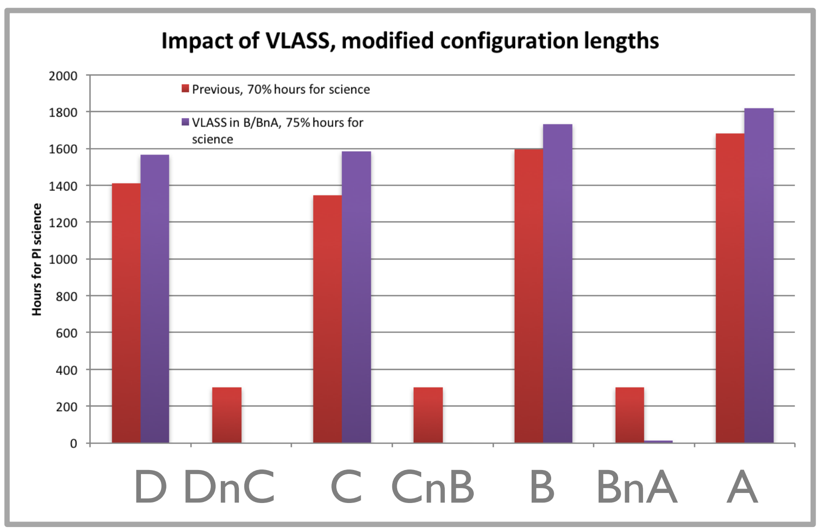


$\Longrightarrow$ B/BnA cutoff $\delta \sim -8^\circ$ to -16°, flexible

Requirement: small impact on normal operations

- VLASS must operate in same infrastructure as other VLA science observing
- Minimum impact on VLA Array Operations
  - Observe VLASS with standard tools (e.g., dynamic scheduler)
- Minimum impact on PI science
  - Fraction of time taken from PI science as small as possible
  - VLASS should be dynamically scheduled

Hours for PI science

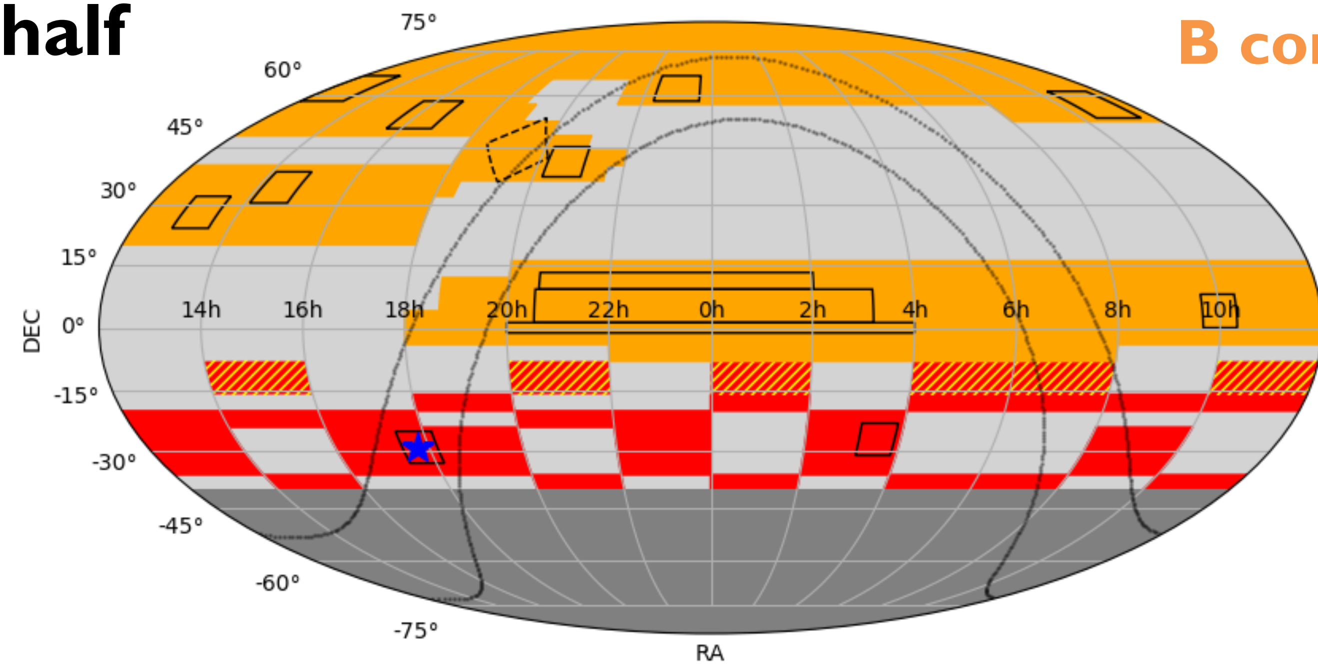


Configuration

Sky Coverage: cadence and LST pressure

- Requirement: 16-month config cycle ⇒ 32-month cadence, same 1st/2nd half division per epoch
- Goal: re-observe Pilot tiles (and Kepler field) in 1st-half
- Requirement: constant RA pressure per half-epoch (easiest to match LST pressure that varies on16-month configuration cadence)

1st-half

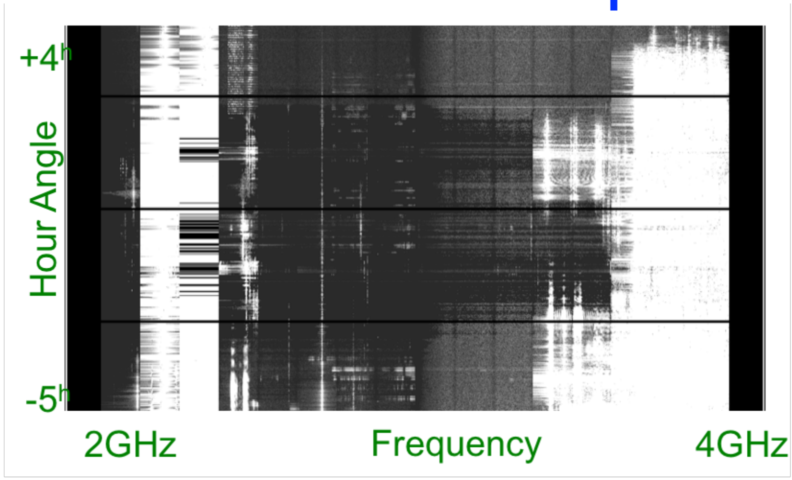


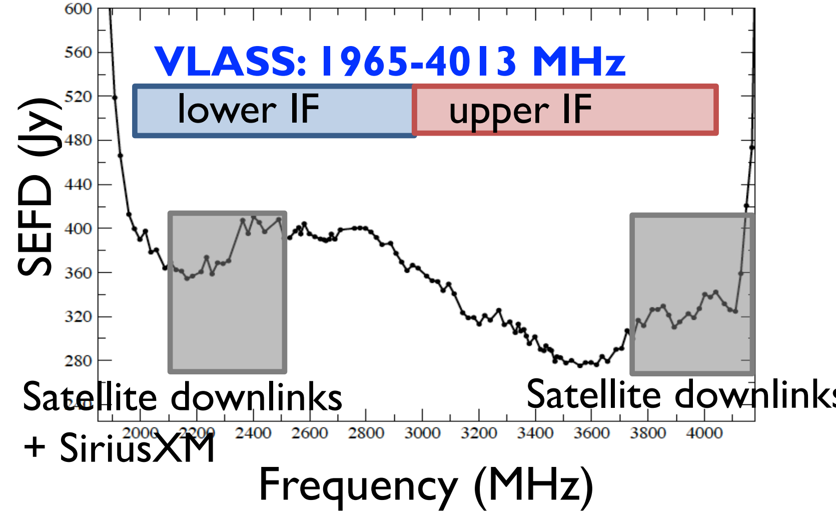
B config

BnA hybrid

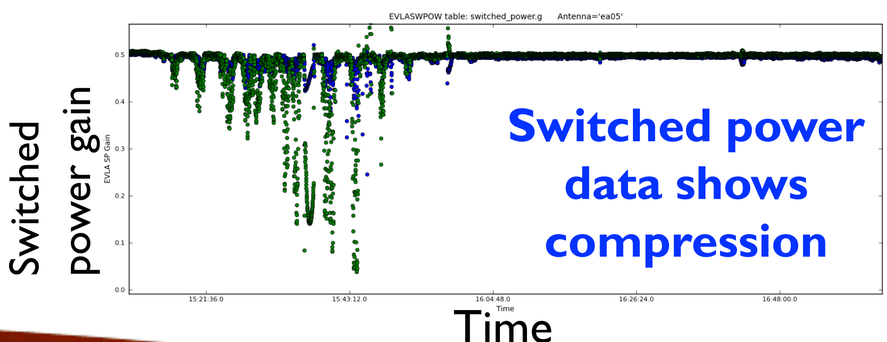
Challenges: RFI / satellite avoidance

Results of RFI sweep

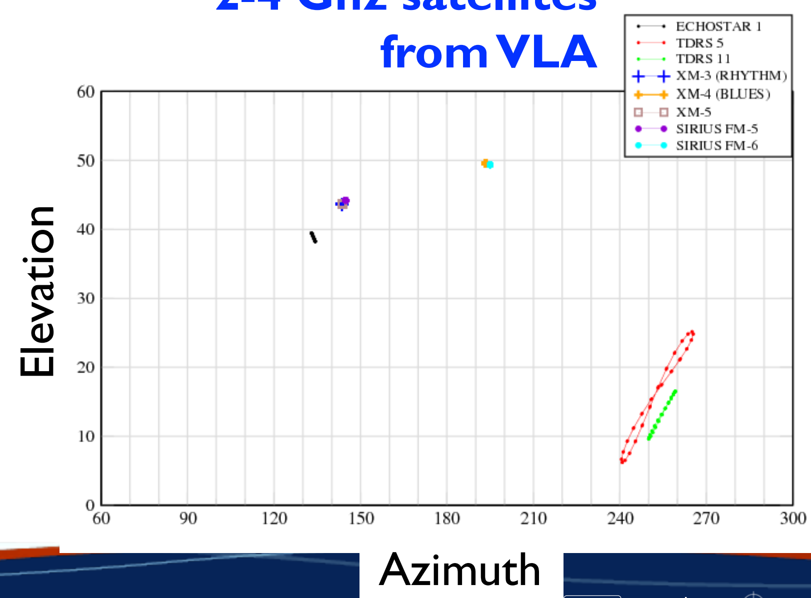




- Clarke Belt is at $\delta \sim -5°$ from the VLA; test shows compression when encountering a geostationary satellite

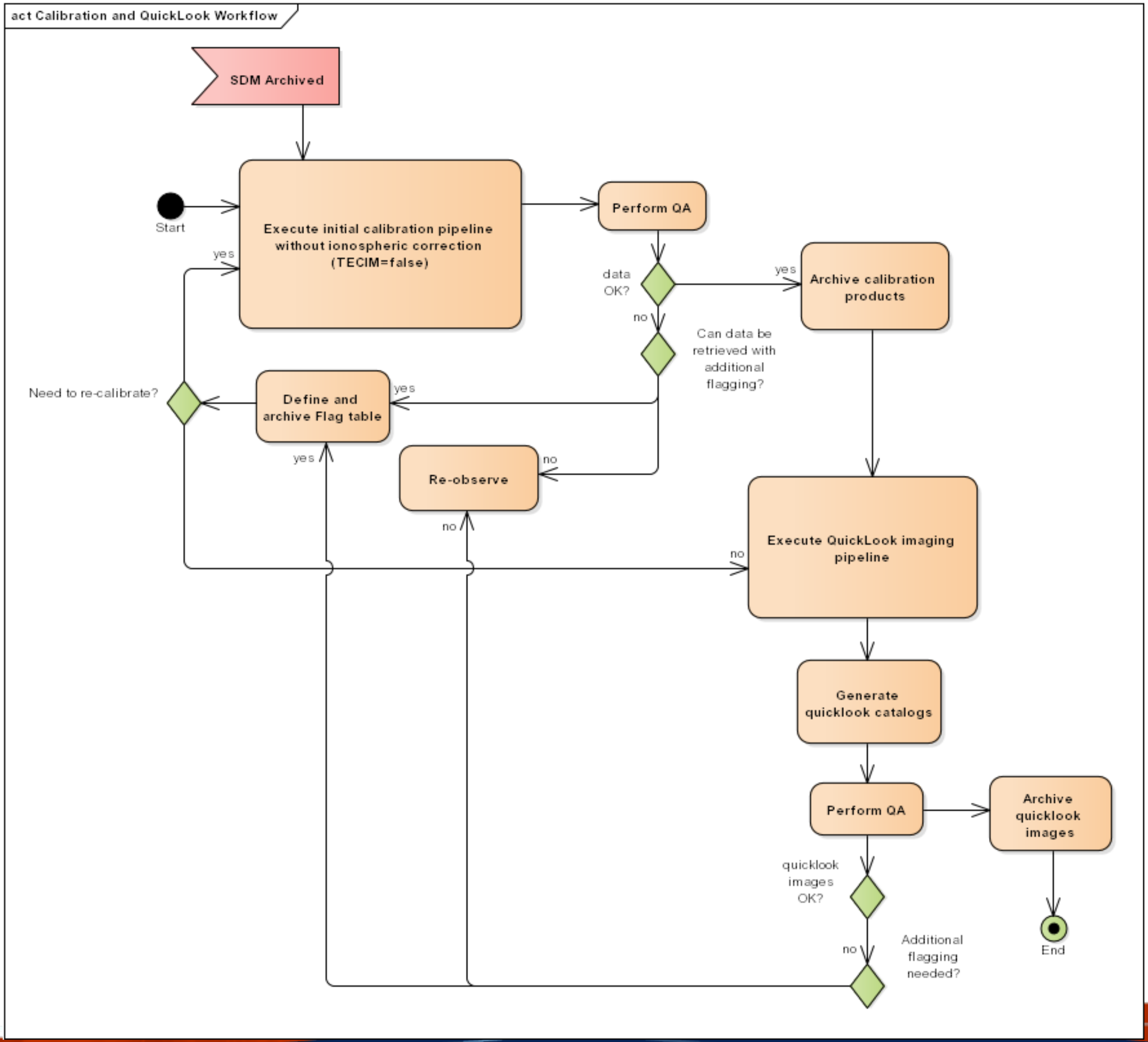


2-4 Ghz satellites from VLA



Survey workflow (QuickLook example):

- raw data
  - → calibrated data
  - → images
- calibration/imaging
  - – automated pipelines (ALMA/VLA)
  - – uses CASA
- Survey Data Base
  - – track workflow
  - – trigger workflow
- Archive
  - – new VLA archive (under development)



Ongoing commissioning

- Automating the workflow (incl./esp. scheduling)
- Imaging algorithms in CASA
  - AW-projection
  - Full Mueller treatment for polarisation calibration
  - PSF subtraction when PSF varies over large image
  - auto-boxing (speed)
  - self-calibration
- Source finding: (same problem, different survey)
  - PyBDSF, Aegean

VLASS Pilot Status / Results

Pilot Survey and Test Fields

- ~200hr pilot survey observed May-Sep 2016
  - Prototype survey execution and data reduction processes
- 1st pass for transients; overlap with FIRST/SDSS, representative extragalactic Deep fields, Galactic Center
- ~2400 deg^2 covered
- Some areas repeated 3x to demonstrate sensitivity of full survey
- Raw data public immediately, image products available after validation through archive

Field	RA	Dec	Observation type	Area (sq. deg.)	# hrs
COSMOS	10.0h	+2°	3 epoch OTF (3x4hr)	80	12
Cygnus	20.5h	+40°	3 epoch OTF (3x4hr)	80	12
Cepheus	23.0h	+62°	3 repeat OTF (3x4hr)	80	12
CDFS	3.5h	−27°	3 repeat OTF (3x4hr)	80	12
Galactic Center	17.8h	−29°	3 repeat OTF (3x4hr)	80	12
Stripe 82	21h–03h	0°	3 epoch OTF (12x4hr)	320	48
SDSS SGC	21h–03h	0° to 15°	1 repeat OTF (17x4hr)	1360	68
SDSS NGC	10h–17h	50° to 60°	1 repeat OTF (5x4hr)	400	20

Pilot Survey and Test Fields

- ~200hr pilot survey observed May-Sep 2016
  - Prototype survey execution and data reduction processes
- 1s
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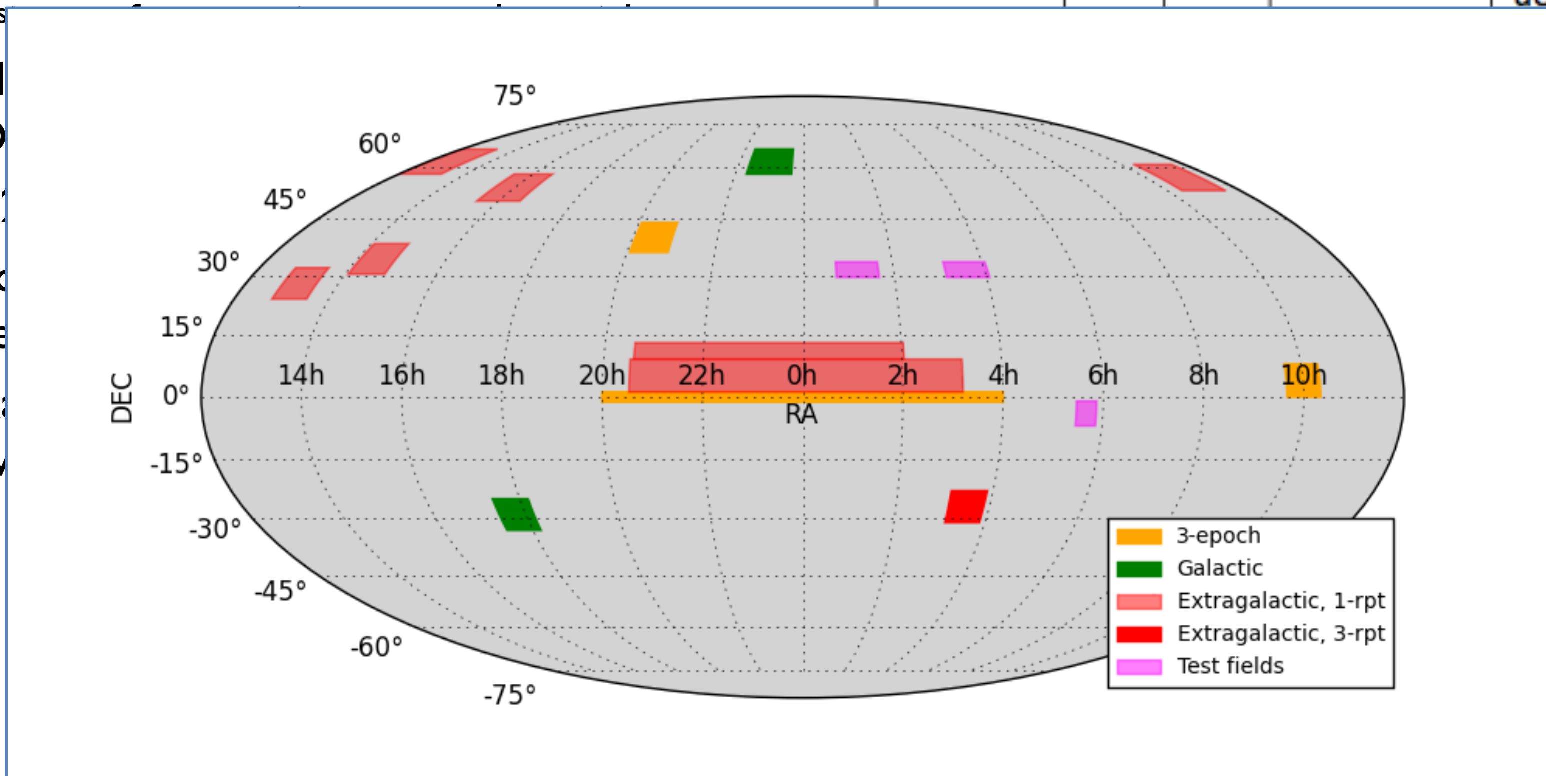
Field	RA	Dec	Observation type	Area (sq. deg.)	# hrs
				[illegible]	12
				[illegible]	12
				[illegible]	12
				[illegible]	12
				[illegible]	12
				0	48
				0	68
				0	20



Pilot Survey Results - ongoing

- In process of imaging more tiles and testing pipelines and imaging software
- Difficult to display tiles of 80 deg^2 at 1” resolution!

- Check out some Aladin-Lite images on the web:

  http://www.aoc.nrao.edu/~smyers/vlass/pubimages/

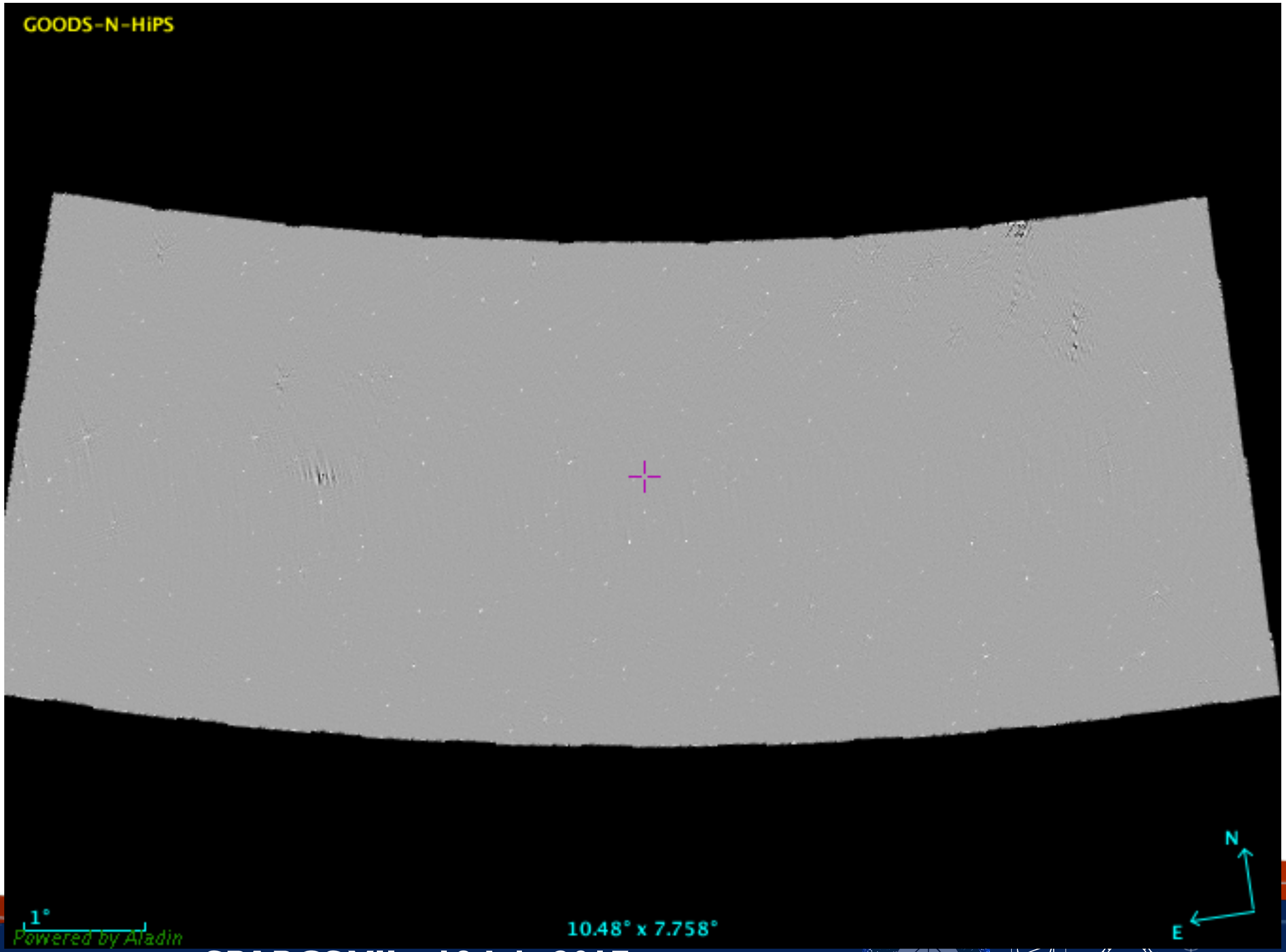
Pilot Results – GOODS-N

- 40 deg^2 QL imaged (1” pixels)

Full Mosaic
40 deg^2
2 hours observing

Constructed
From 40 individual
sub-mosaics

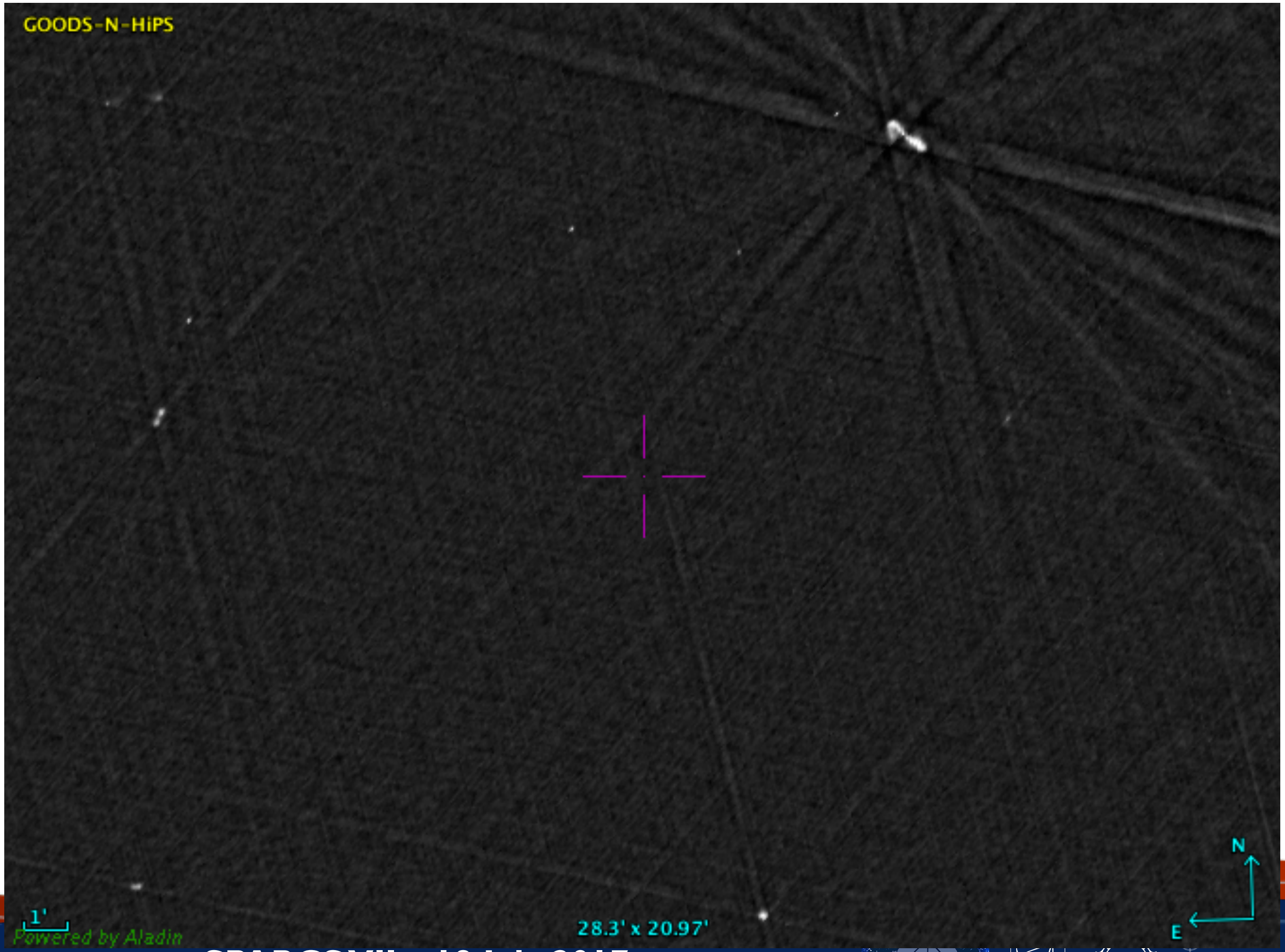
This is centered on
the much smaller
“GOODS-N” area
and the Hubble
Deep Field.



Pilot Results – GOODS-N

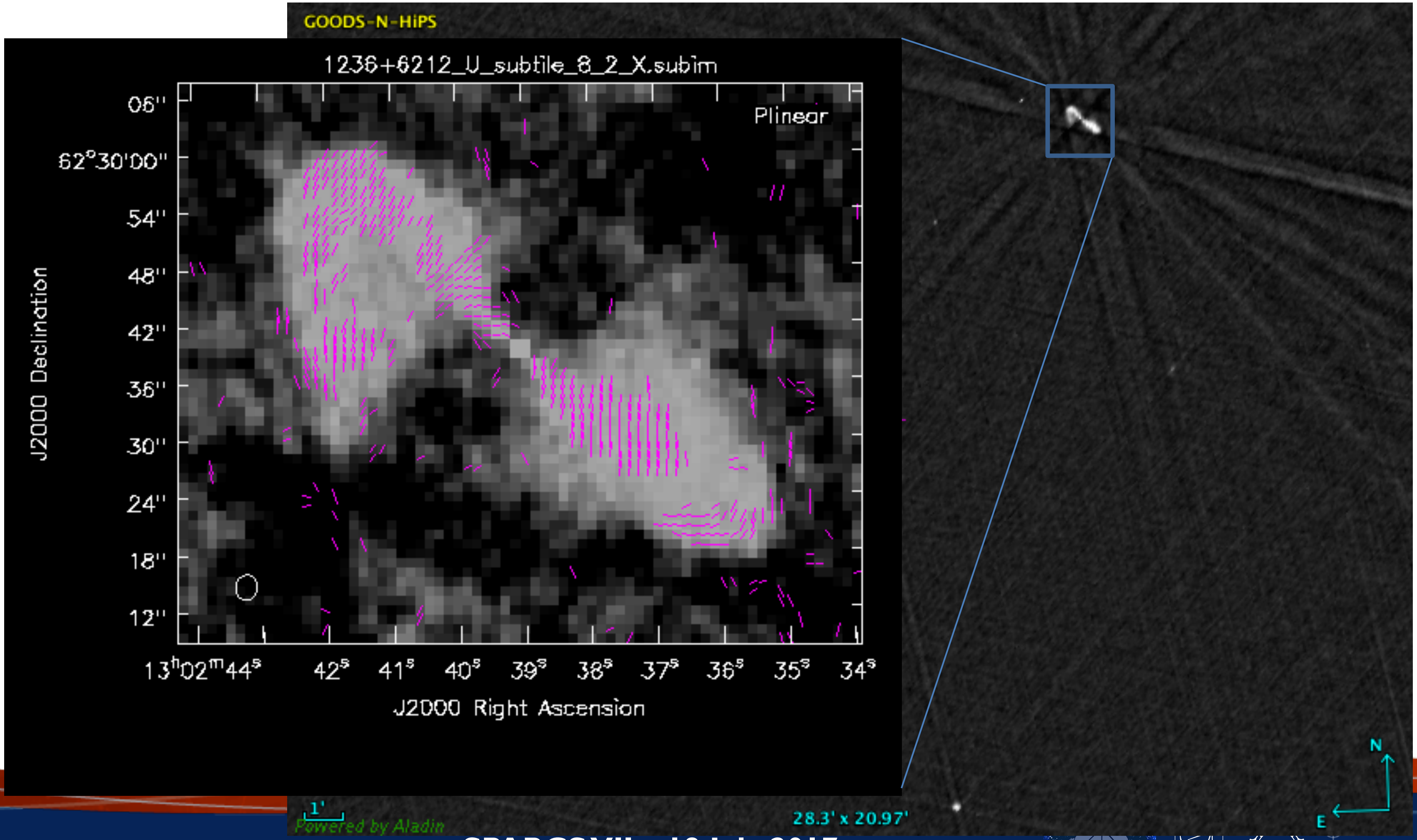
- 40 deg^2 QL imaged (1” pixels)

Zoomed-in region around bright extended radio galaxy; sidelobes! This is meant for “Quick Look”.



Pilot Results – GOODS-N

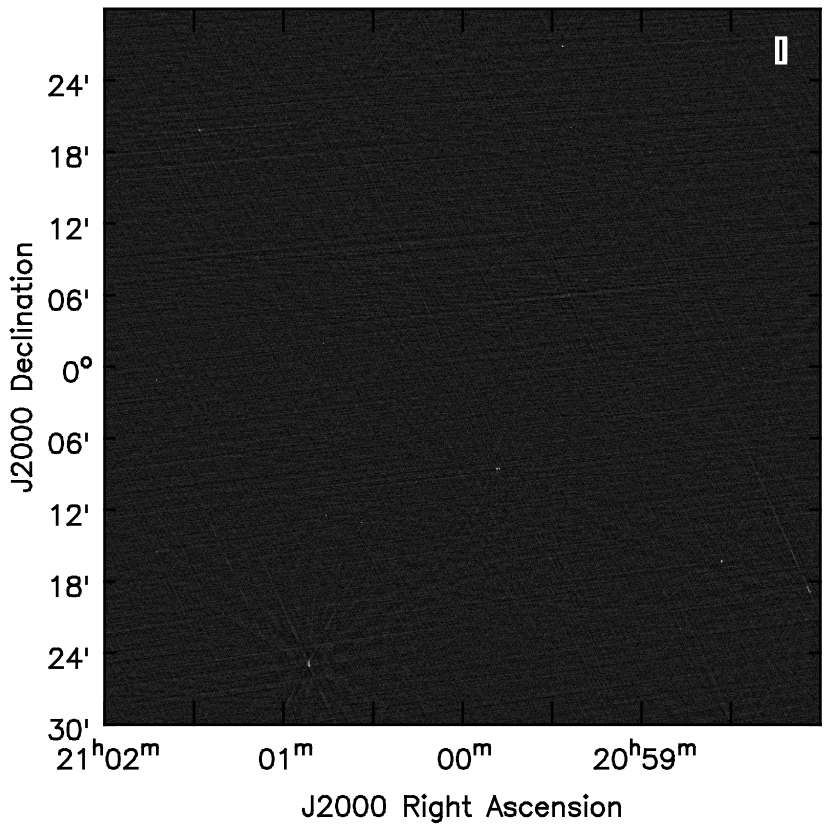
- 40 deg^2 QL imaged (1” pixels); **polarisation**



Progress: "Quick-Look" Images

Results from test & pilot observations

- 1st Pilot observation June 2016, 1°x1° sub-mosaic : Stripe-82 at 2100+0000

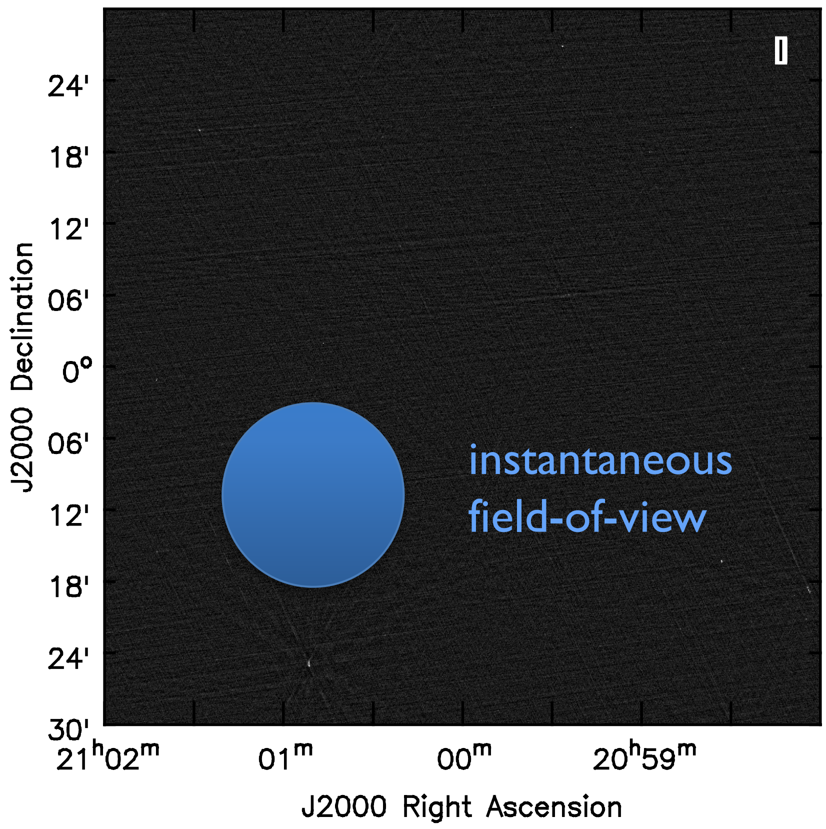


VLASS QuickLook Image
1°x1° subimage (full 2°x2°)
1" pixel size, 2.5" resolution (13Mpix)
416 phase-centers (2 x 0.45sec integ)
~10GB vis. data
MTMFS nterm=2
σ_I=134μJy/beam
max I = 137mJy/beam (~1000:1)

Progress: "Quick-Look" Images

Results from test & pilot observations

- 1st Pilot observation June 2016, 1°x1° sub-mosaic : Stripe-82 at 2100+0000



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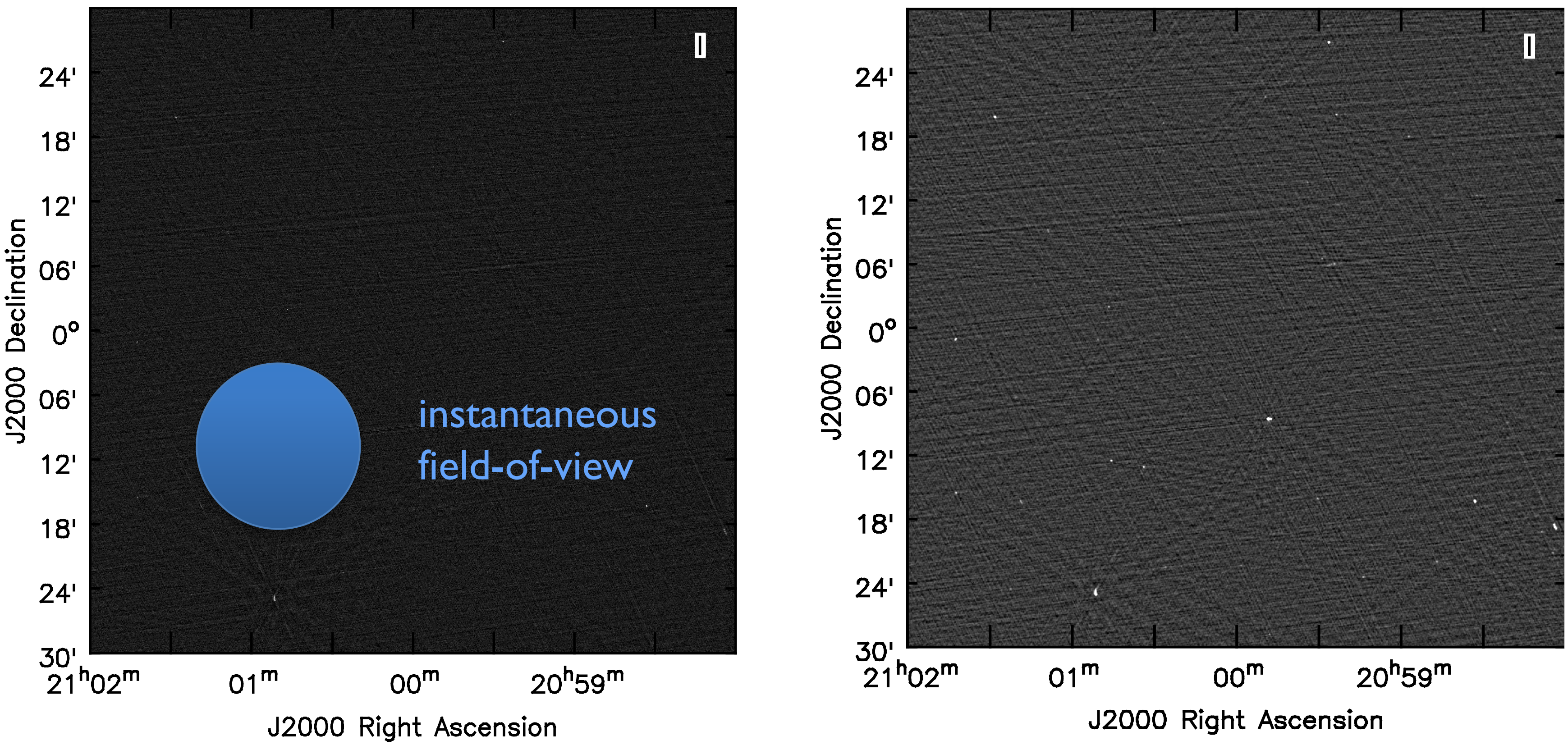
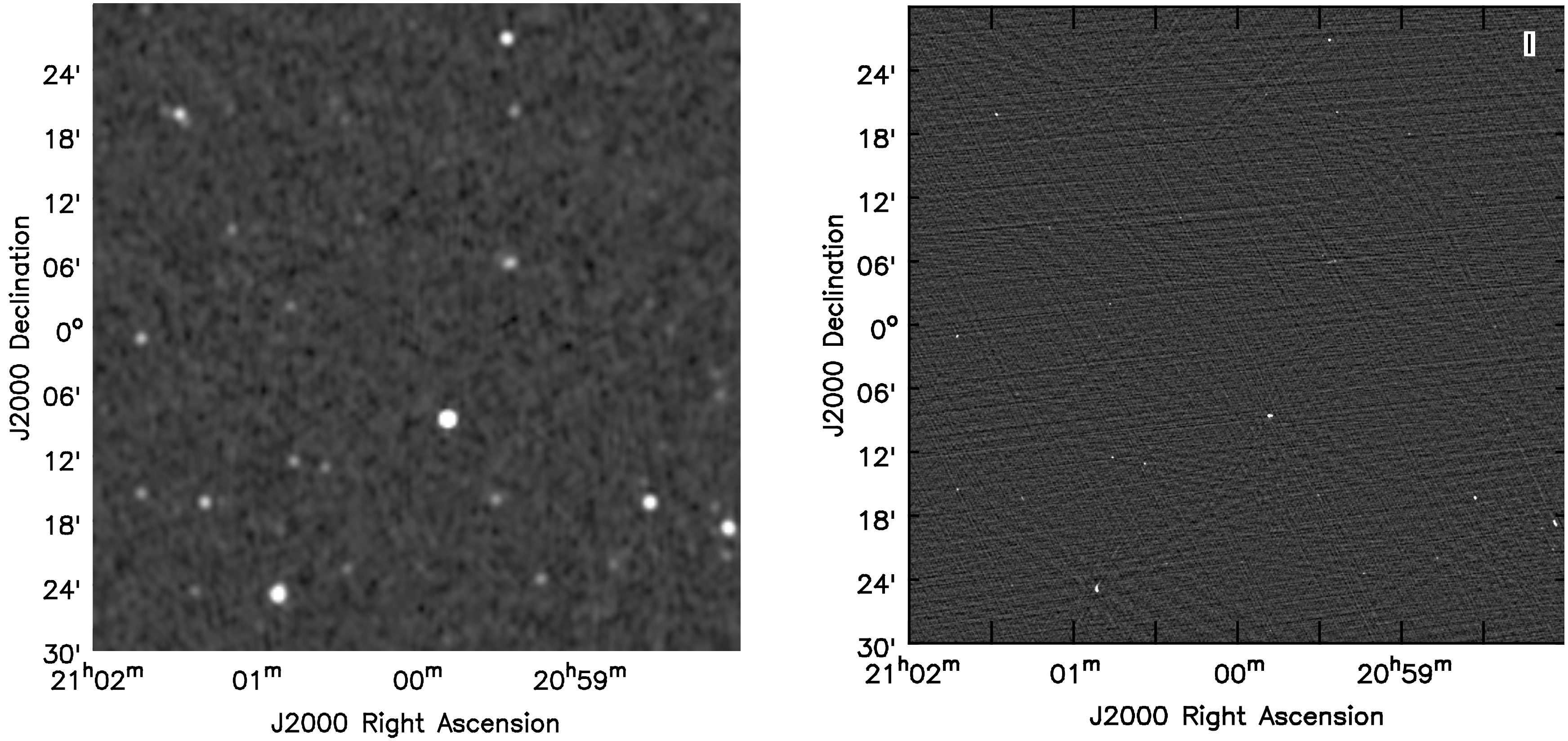


(left) VLASS 2.5" resolution, full image; (right) VLASS uv-tapered to 7.5" resolution to enhance low surface-brightness extended emission

Comparison: NVSS + tapered VLASS image

Results from test & pilot observations

- 1st Pilot observation June 2016, 1°x1° sub-mosaic : Stripe-82 at 2100+0000

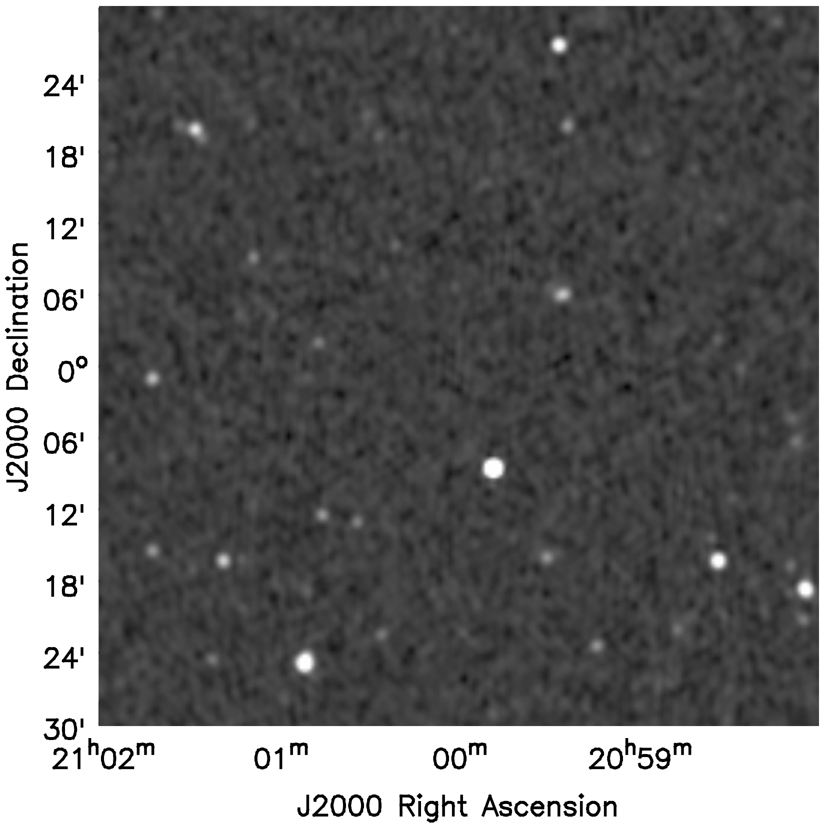


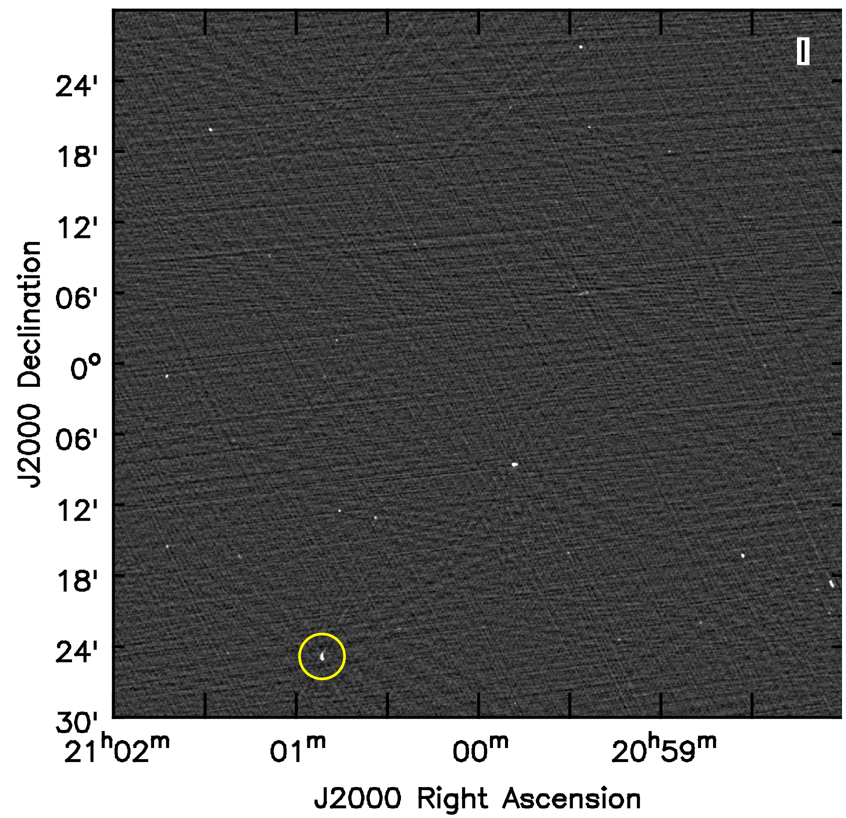
(left) NVSS at 45” resolution, full image; (right) VLASS uv-tapered to 7.5” resolution. Good correspondence for many point-like sources.

Comparison: NVSS + tapered VLASS image

Results from test & pilot observations

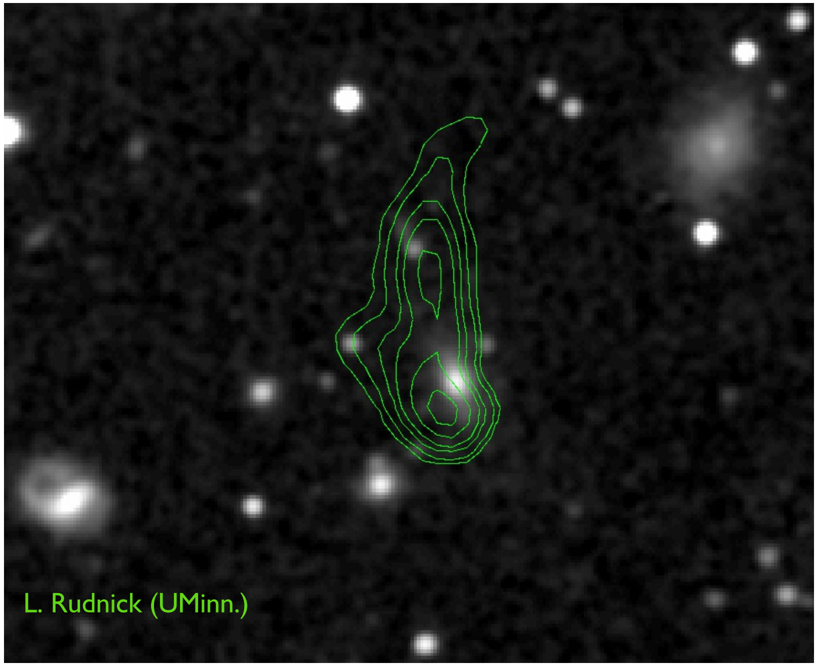
- 1st Pilot observation June 2016, 1°x1° sub-mosaic : Stripe-82 at 2100+0000



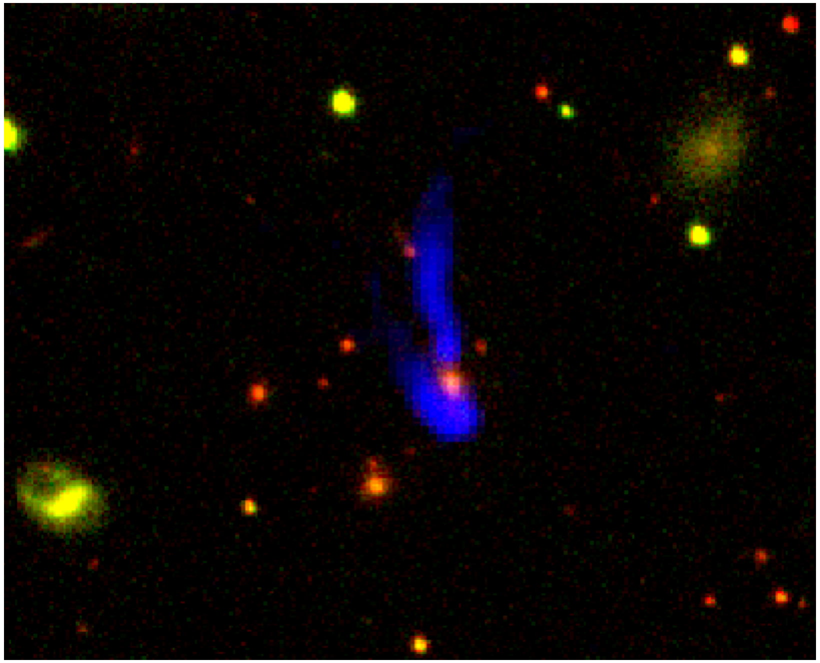


(left) NVSS at 45" resolution, full image; (right) VLASS uv-tapered to 7.5" resolution. Good correspondence for many point-like sources.

Resolution of VLASS enables association with optical galaxy



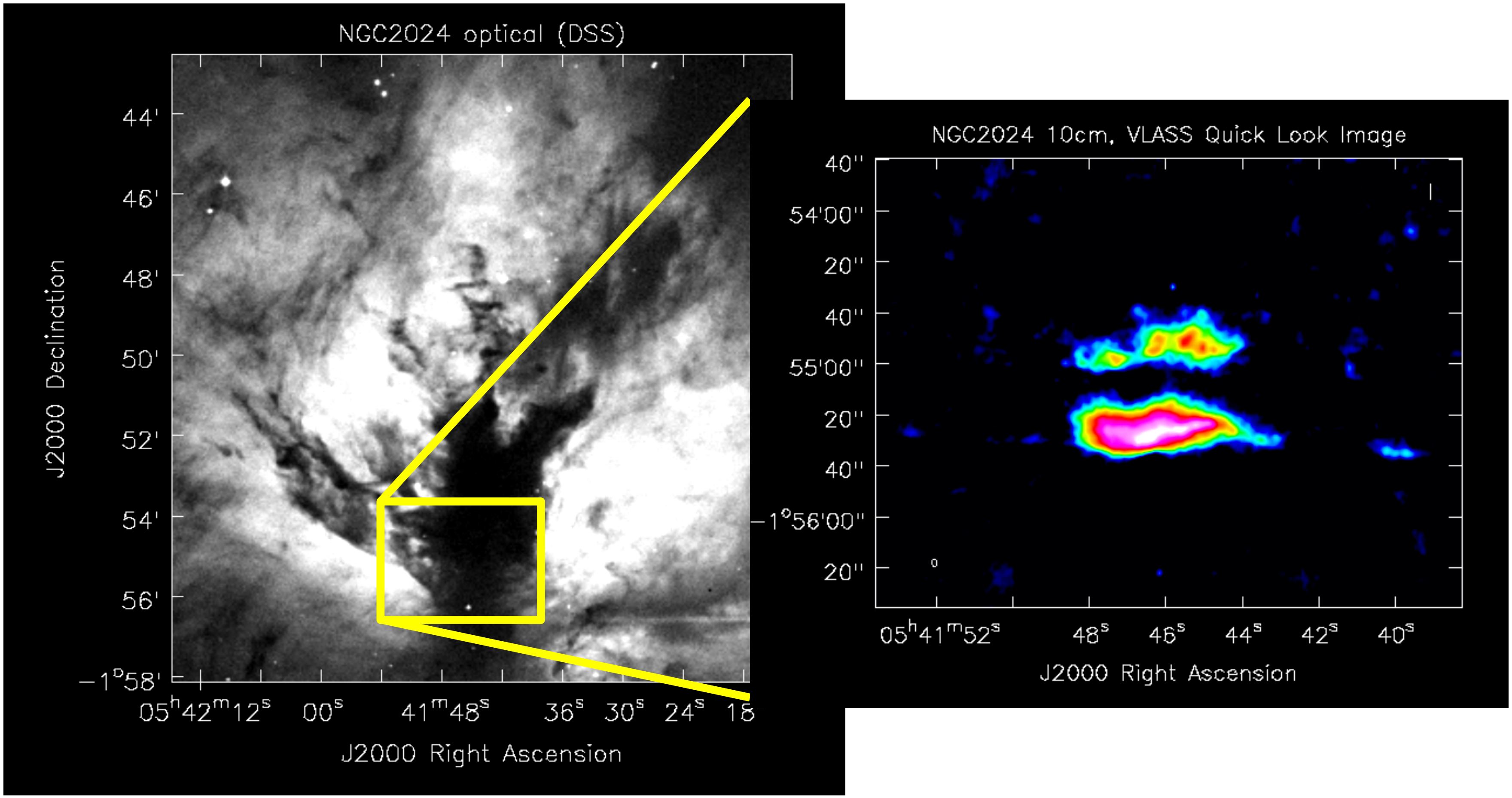
FIRST contours on SDSS



SDSS (red/green) image overlay on VLASS (blue). Improved VLASS resolution allows us to classify the radio source as a galaxy at z=0.25, possibly in a cluster.

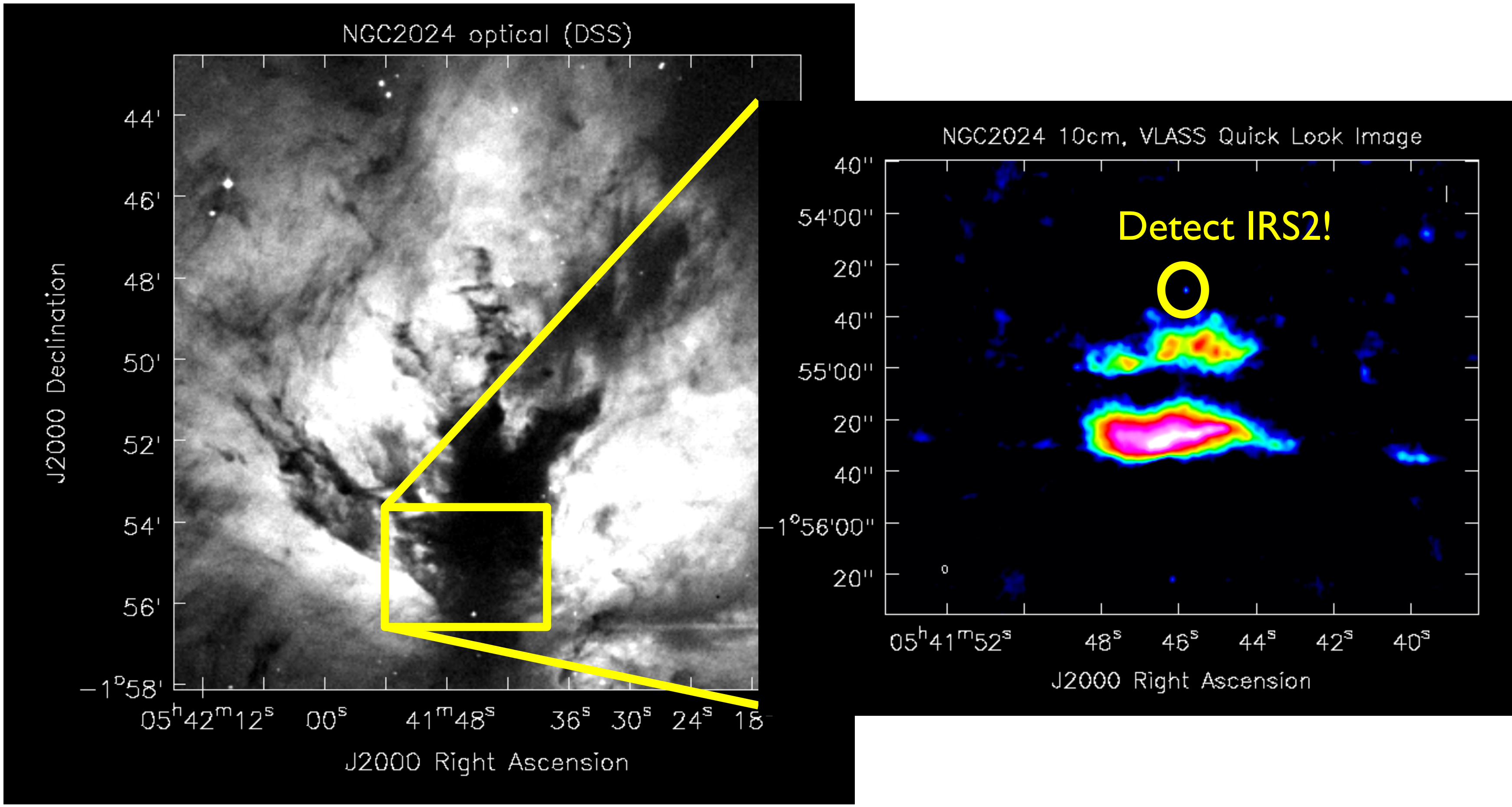
Survey has sensitivity to scales from 2.5" to 20"

- NGC2024 (Flame Nebula), Orion B



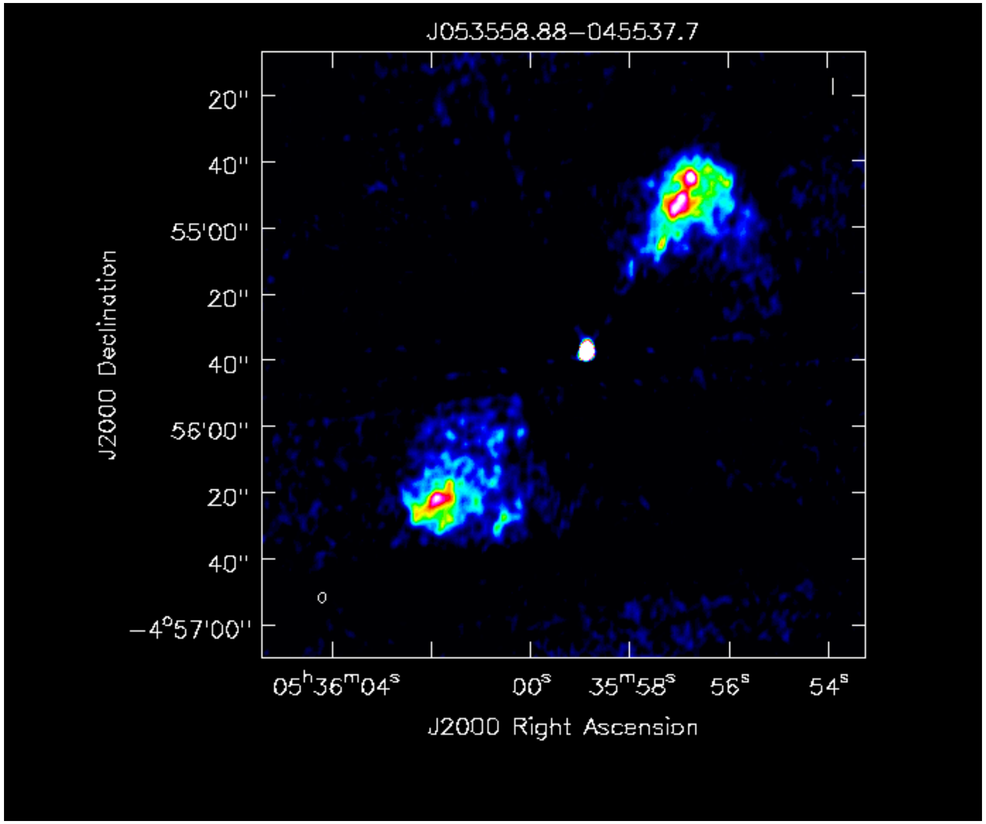
Survey has sensitivity to scales from 2.5” to 20”

- NGC2024 (Flame Nebula), Orion B



J053558.88–045537.7

- Identified as candidate Young Stellar Object in the literature, based on previous 6cm observations
  - Kounkel et al. (2014)
- VLASS pilot/test data show it is an FRII radio galaxy
  - 10cm data reveal the steep-spectrum radio lobes



VLA SKY SURVEY NRAO NSF

VLASS references and more information

- Survey science website
  https://science.nrao.edu/science/surveys/vlass
- Public wiki with Technical Implementation Plan, memo series:
  https://safe.nrao.edu/wiki/bin/view/JVLA/VLASS

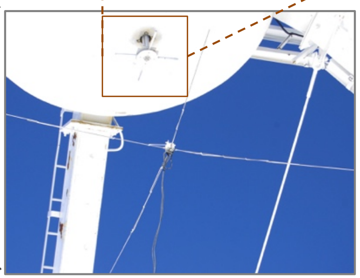
- Next steps
  – Full processing of pilot data
  – Technical & Pilot results publications in preparation
  – Final software testing and bug fixes
  – Preparing for operational readiness assessment (Aug 2017)
  – Start observing in the next B-configuration, September 2017!

Commensal surveys with the VLA

Ongoing Commensal Surveys with the VLA

VLA Low Band Ionosphere and Transient Experiment (VLITE)

- uses the VLA "P-band" dipoles installed at the primary focus
- independent optical stream and correlator



- real-time transient searches at the VLA
- independent data stream; native 5ms time resolution

realfast's transient search pipeline

regular path: VLA PI

Why Build a Low Frequency Commensal System?

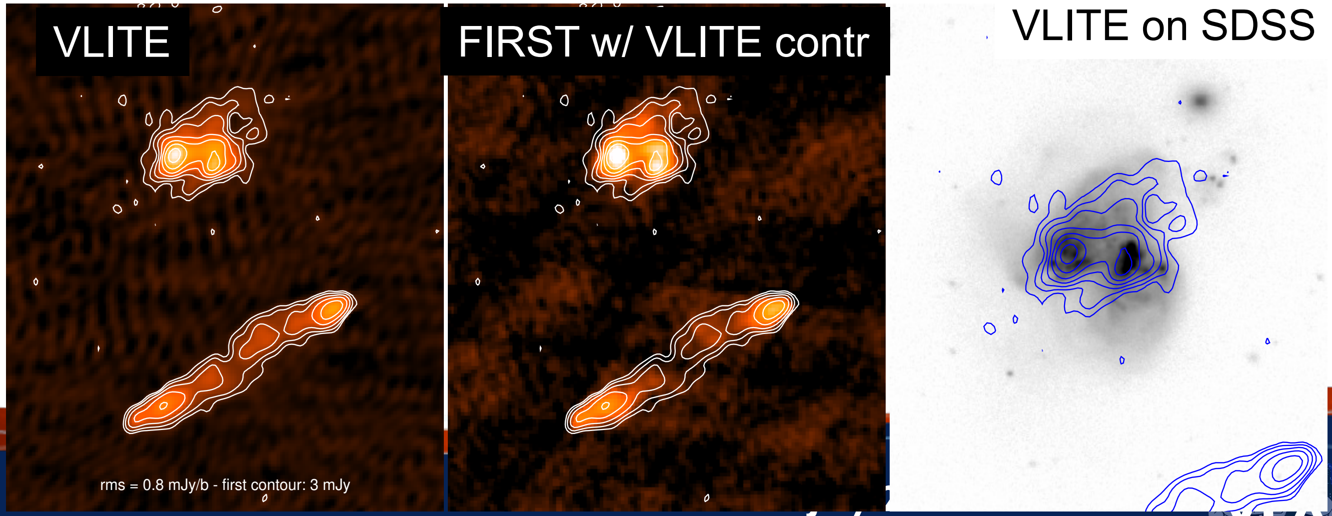
It is an experiment designed to demonstrate:

1) ionospheric monitoring – funds VLITE/eVLITE! (Helmboldt et al. 2017)

2) open phase space for transients (Polisensky et al. 2016)

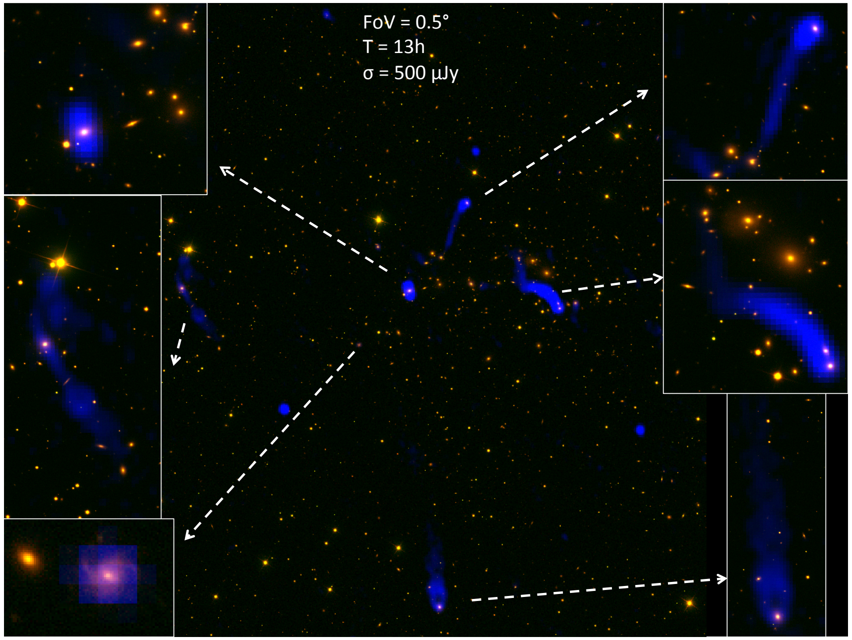
3) broad scientific payoff (e.g. Giacintucci et al. 2017, Ogrean et al. 2015, Straal et al. 2016, Helmboldt et al. 2015)

Ultimate goal is broadband capabilities on the full 27 VLA antennas – the LOw Band Observatory (LOBO).



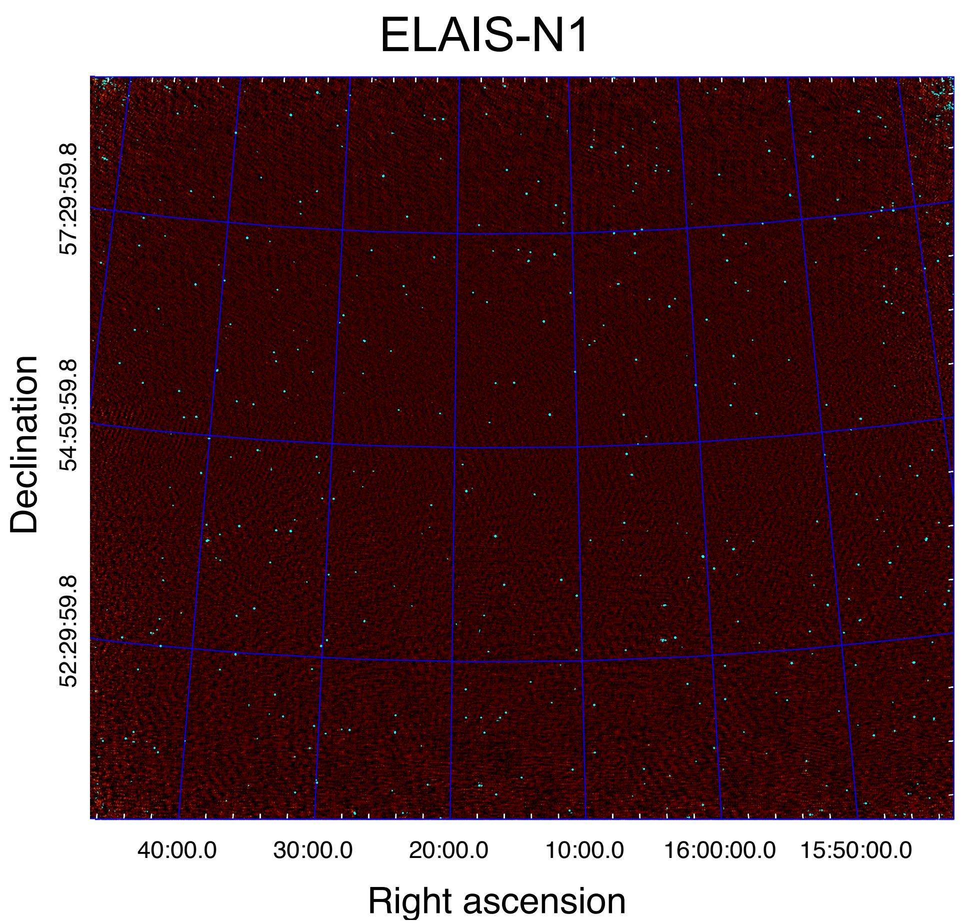
VLA Low Band Ionosphere and Transient Experiment (VLITE)

- Uses 10 antennas in 330 MHz band (upgrading to 15)
  - 320 – 384 MHz, $\Delta\nu$ = 100 kHz
  - $\Delta\tau$ = 2s (2 GB/hr data rate)
  - Full polarisation (linear)
  - Field of view: > 5 square degrees
  - 5" – 3' resolution, up to 1° scales
- Pipeline
  - 1 day lag, post processing
  - 3-15 hours to process 1 day's data
- Science-ready data products
  - calibrated UV data
  - single plane images
  - image cubes
  - catalogs



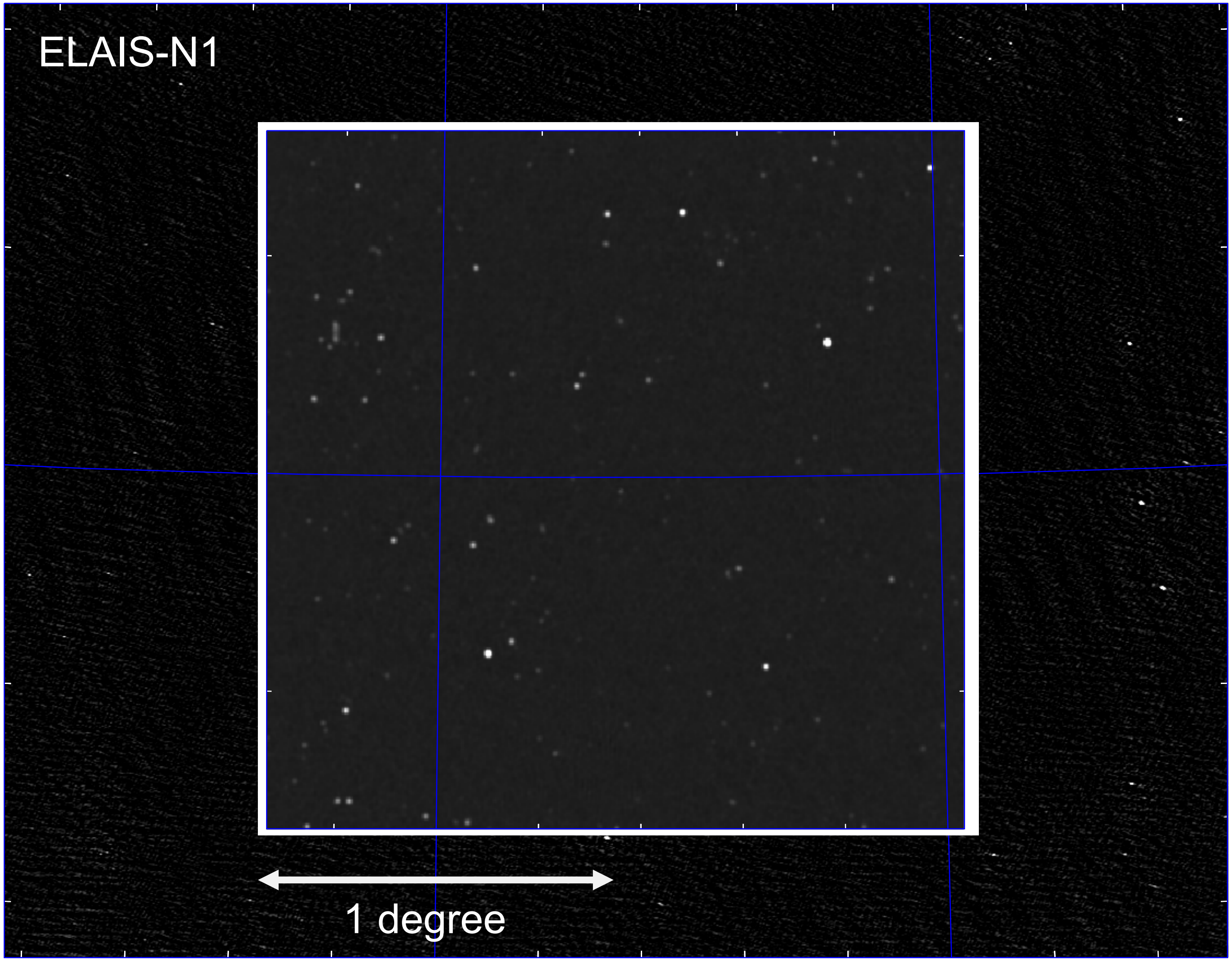
* Clarke et al. (2016)

OTF (VLASS) Imaging with VLITE



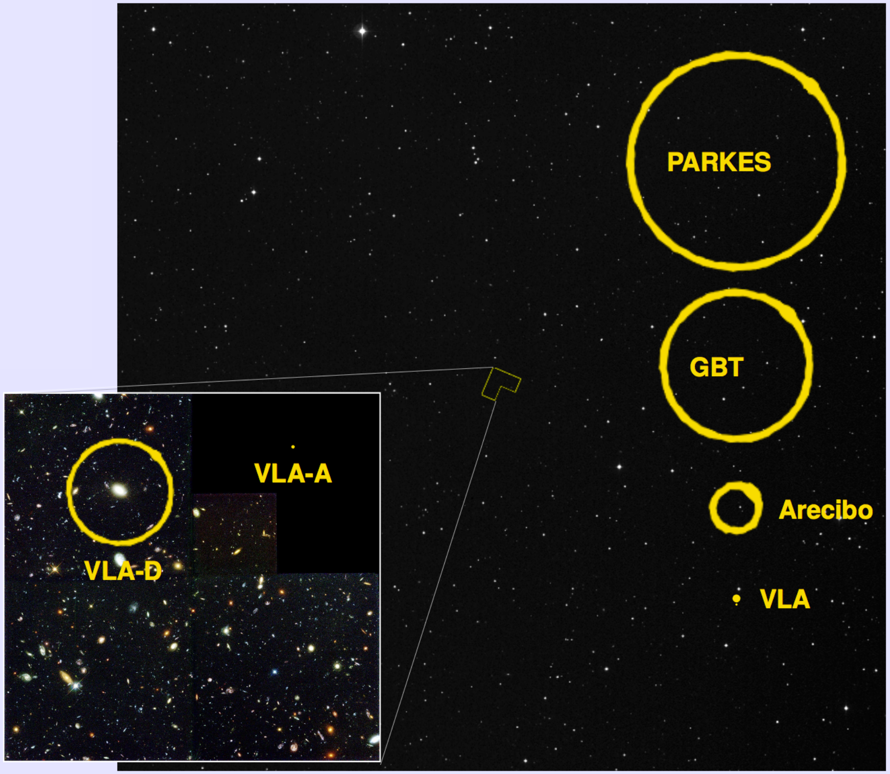
- Observational mode:
  - Correlate data collected per 2° of antenna motion (~30 s)
- ~1 day for calibration/imaging
- Correct/weight images with elongated "effective primary beam" → mosaic
- Declination offset ~15' gives huge overlap:
  - Combination = improvements in both sensitivity and artifact rejection
  - (Combination software is not automated)

OTF (VLASS) Imaging with VLITE



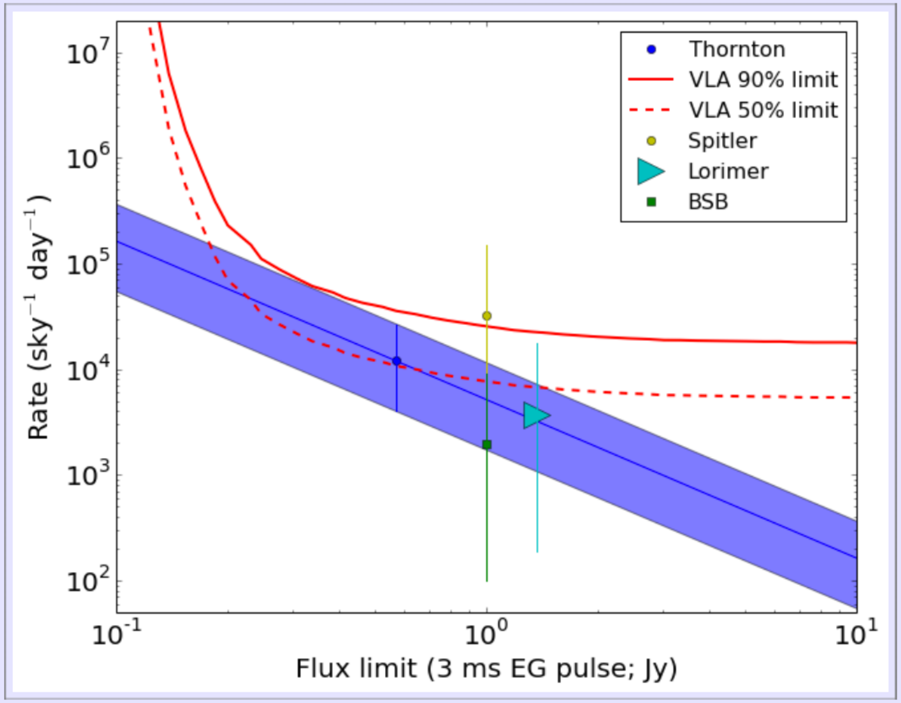
VLA transient pipeline search

VLA has best sensitivity and angular resolution to directly localise FRBs



(plot: S. Burke-Spolaor)

FRBs are ***rare***:
estimate ~600 VLA hours per FRB!



(Law et al 2015)

Challenges

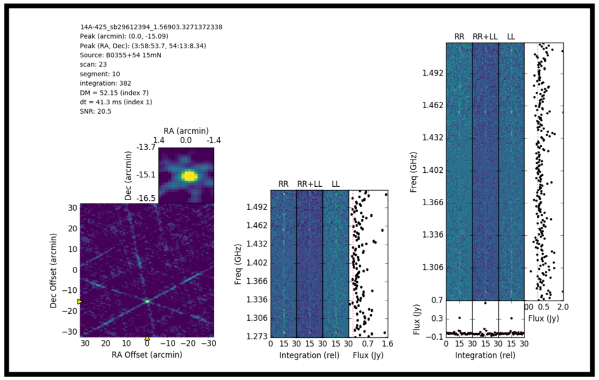
- data rates!
  - VLA sampling at 5-milliseconds
  - 280 GB/s → 1 TB/hr!
  - 1σ → 5 mJy, S-band (VLASS frequency)

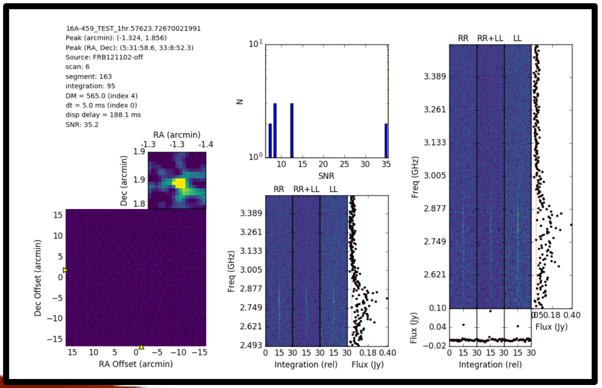
- detection and selection algorithms: http://realfast.io
  - dispersion & resampling
  - RFI filtering
  - simple imaging of candidates (individual 5ms integration)

~6000 observing hours / year (1-50 GHz)

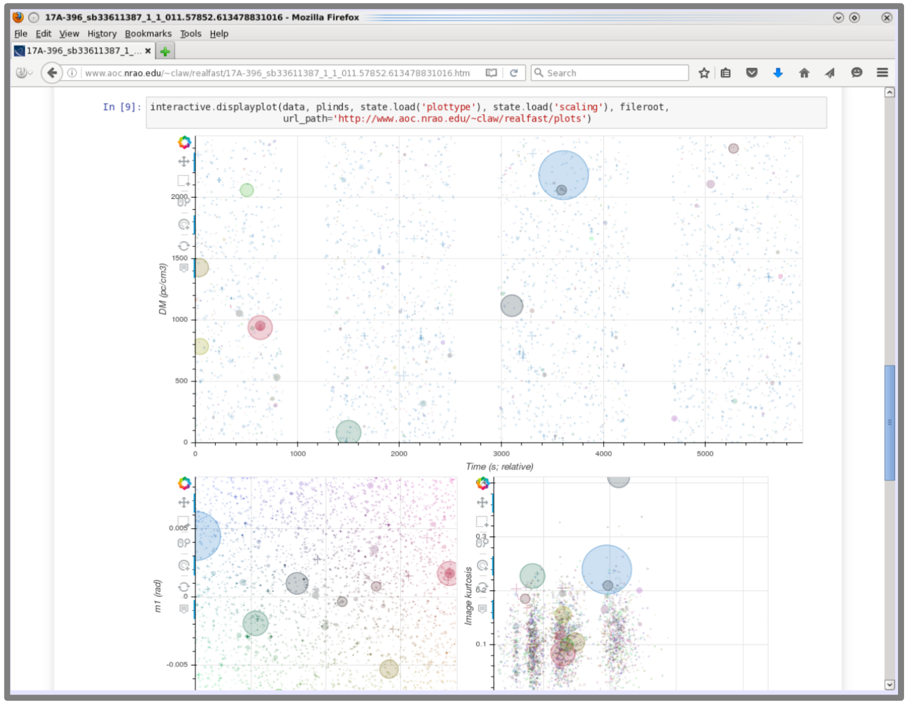
- C Law (PI), B Butler (NRAO lead), S Burke-Spolaor, G Bower, P Demorest, S Khudikyan, J Lazio, M Pokorny, J Robnett, M Rupen

Candidate plots (examples):





Web-based "portal" to inspect candidates:

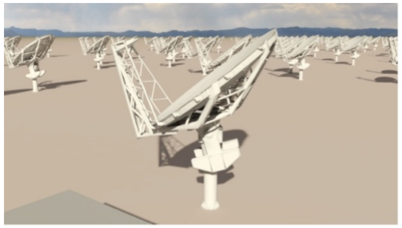


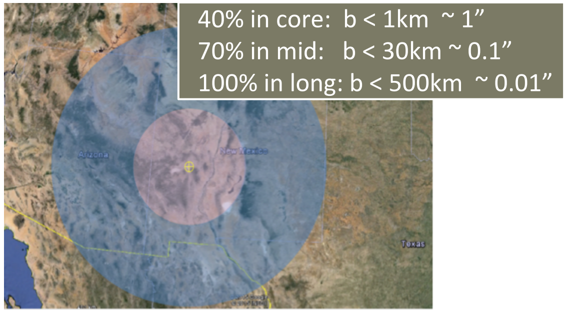
Looking ahead:

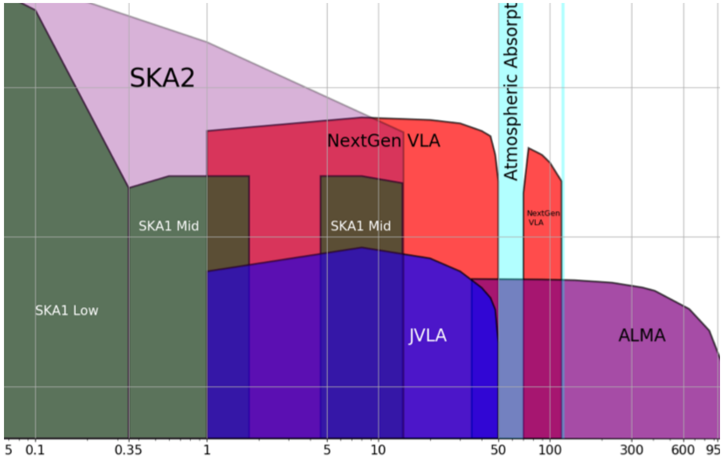
Next-Generation VLA (ngVLA)

A next-generation Very Large Array (ngVLA)

- Scientific Frontier: ***Thermal imaging at milli-arcsec resolution***
- Sensitivity/Resolution Goal:
  - ***10x effective collecting area & resolution of JVLA/ALMA***
- Frequency range: ***1.2 –116 GHz***
- In southwestern U.S. (NM+TX+?) & MX, centered on VLA
- Baseline design under development
- Low technical risk (reasonable step beyond state of the art)







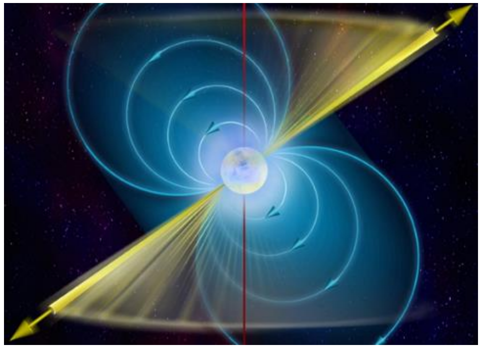
Complementary suite from meter to submm arrays for the mid-21st century

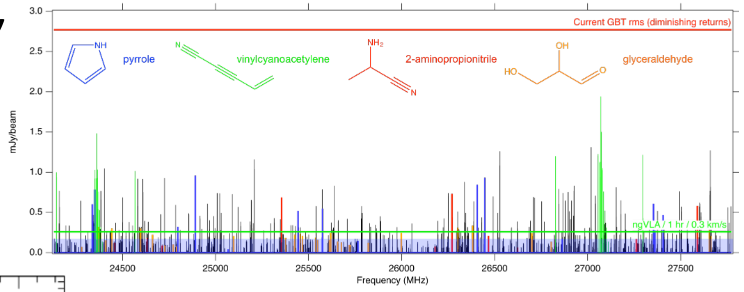
- **< 0.3cm:** ALMA 2030
- **0.3 to 3cm: ngVLA**
- **> 3cm:** SKA

https://science.nrao.edu/futures/ngvla

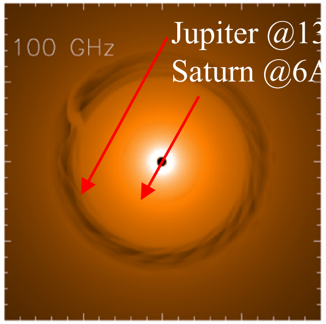
ngVLA Key Science Mission

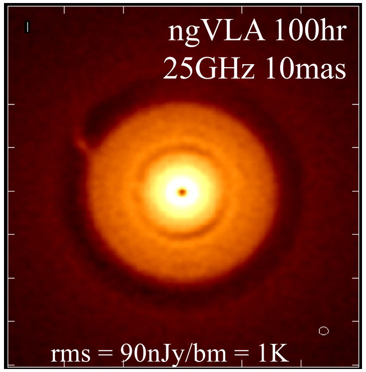
- ***Characterizing Terrestrial Planet Formation in Nearby Young Solar Analogues***
- ***Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry***
- ***Understanding How Galaxies Produce New Generations of Stars***
- ***Pulsars in the Galactic Center as Fundamental Tests of Gravity***
- ***High Precision Astrometry to Determine the Size of the Galaxy & Scale of the Universe***

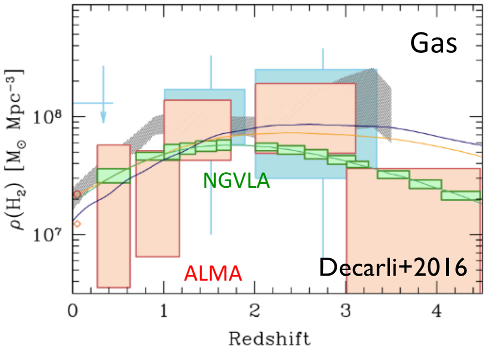


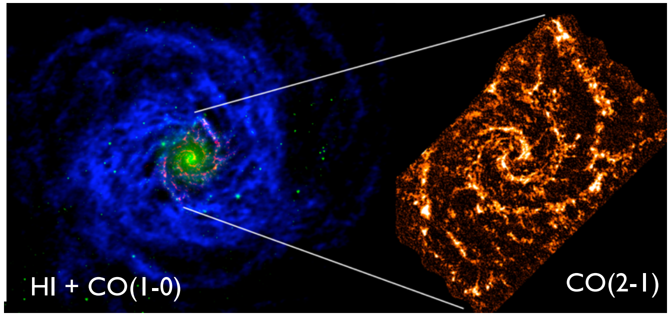


Highly synergistic with next-generation ground-based OIR and NASA missions.









June 2017, Socorro, NM: "*Developing the ngVLA Science Program*" workshop

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