The VLA Sky Survey (VLASS):

A New Generation Radio Sky Survey with the VLA

Amy Kimball (NRAO)

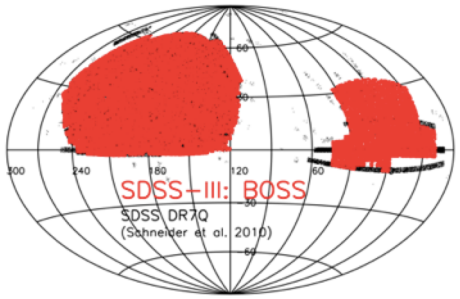
for the VLA Sky Survey team and Survey Science Group

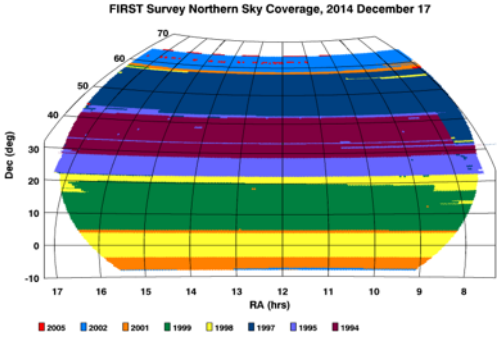
VLA array configurations

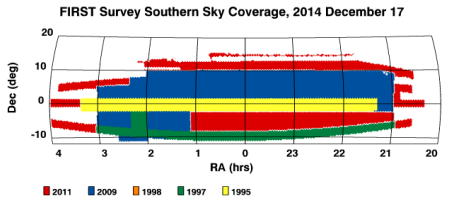
- Located: plains of San Agustin, 50mi. west of Socorro NM (elevation 2100m)
- 27 antennas, 25-m diameter reconfigurable into 4 “configurations”
  - A-config: B_{max} 36.4 km, θ_{res} 0.65” (3 GHz)
  - **B-config: B_{max} 11.1 km, θ_{res} 2.1”**
  - C-config: B_{max} 3.4 km, θ_{res} 7.0”
  - D-config: B_{max} 1.03 km, θ_{res} 23”

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



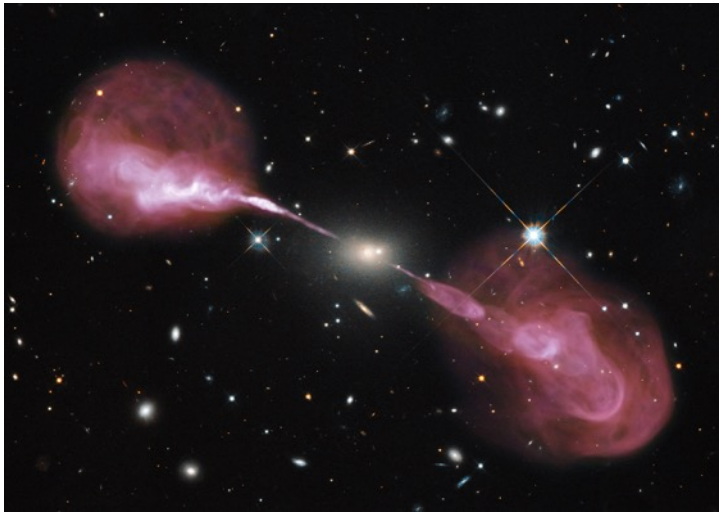




- ***New scientific opportunities***
  - multi-messenger surveys need radio counterpart *with comparable or better resolution*
  - start now to build time series for time domain studies
- ***Community driven survey***
  - Astronomy community proposed a new radio survey taking advantage of VLA's new capabilities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

Scientific capabilities of the upgraded VLA relevant for a sky survey

- Wide bandwidths:
  - Continuum sensitivity
  - Spectral index information
  - Rotation measure studies
  - Survey speed for wide-field mosaics
- Correlator flexibility:
  - Very fast dump times
  - High resolution, flexible tuning
- New "On-the-Fly" mosaicking mode:
  - Decreased overheads for large, relatively shallow surveys



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)

VLASS Survey Definition

- Captures snapshots of the radio sky unique in time and "space"
- 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) "S-band"
  - 64x2 MHz channels per spectral window, 16 spectral windows
  - High 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	5,000,000

- Full survey, 7 years: September 2017 --- October 2024

VLA Sky Survey Team

VLASS Team (NRAO):

- Claire Chandler (VLASS Director) Mark Lacy (Project Scientist)
  Steve Myers (Development Lead) Amy Kimball (Operations Coordinator)
- Scientific development team:
  Josh Marvil, Frank Schinzel, Lorant Sjouwerman, Joan Wrobel
- Also NRAO staff working on software, database, pipeline, quality assurance

Survey Science Group Board

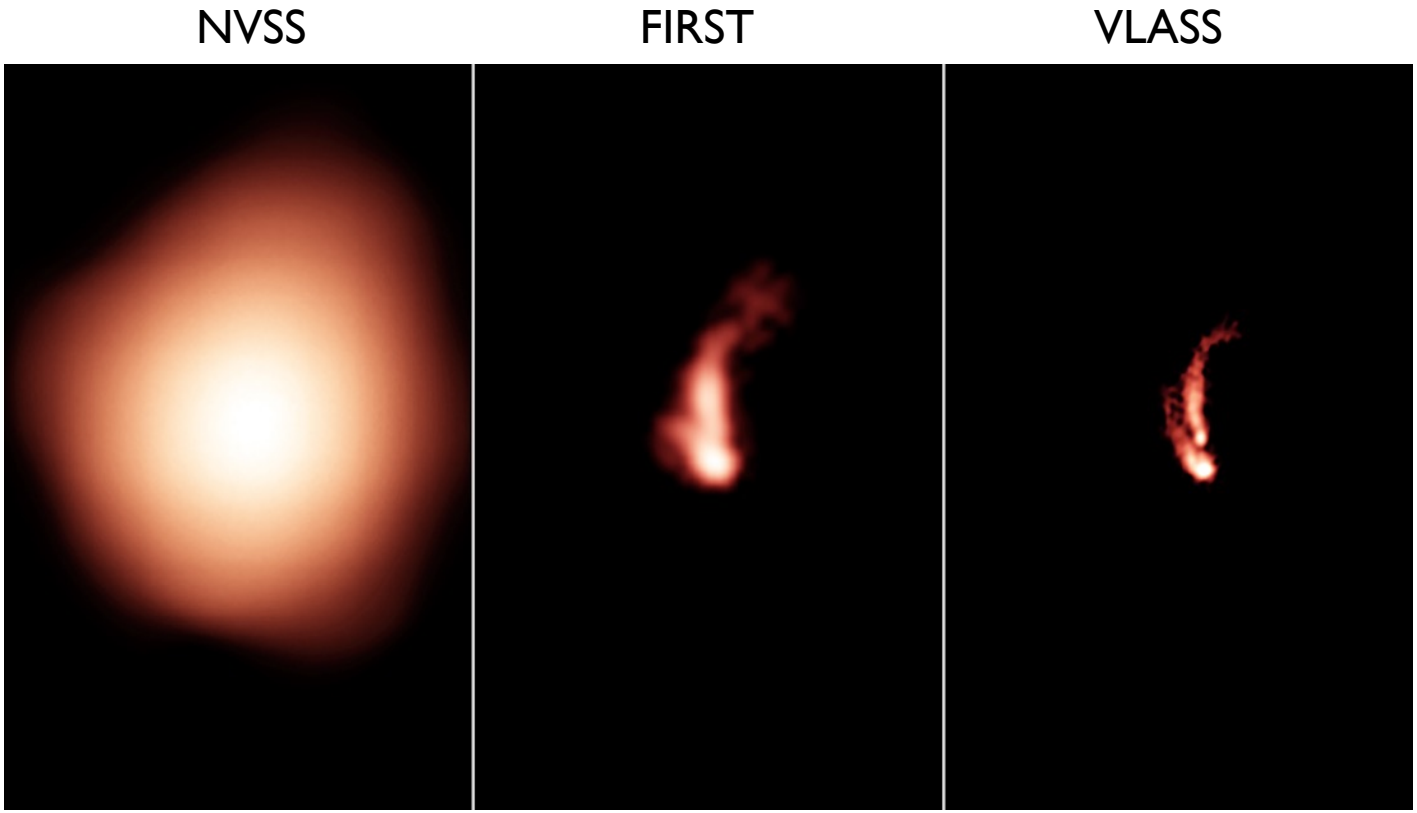
- Stefi Baum (Manitoba), Shami Chatterjee (Cornell) (co-chairs)
- Gordon Richards (Drexel), Amy Kimball (NRAO), Rachel Osten (STScI), Joe Lazio (JPL), Gregg Hallinan (Caltech), Gregg Sivakoff (Alberta), Susana Deustua (STScI), Jayanne English (Manitoba), Larry Rudnick (Minnesota), Bryan Gaensler (Toronto), 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)

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.

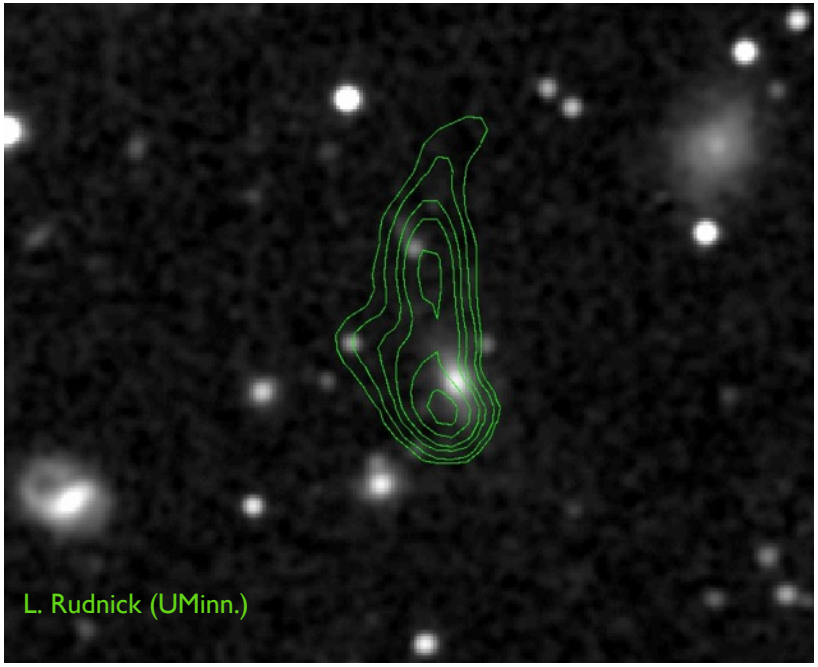
Imaging galaxies through time and space

Resolution of VLASS is key!

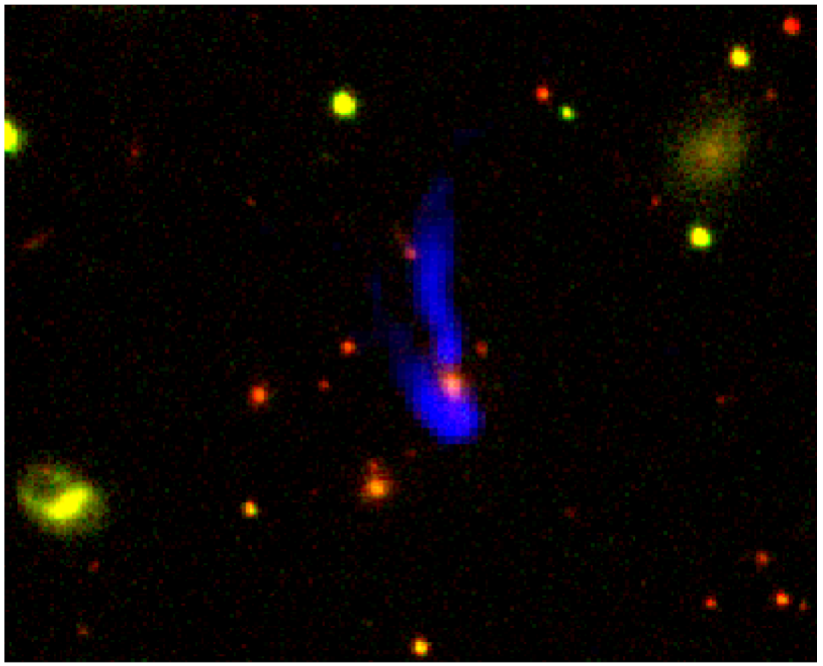


Imaging galaxies through time and space

Enables association with optical galaxy

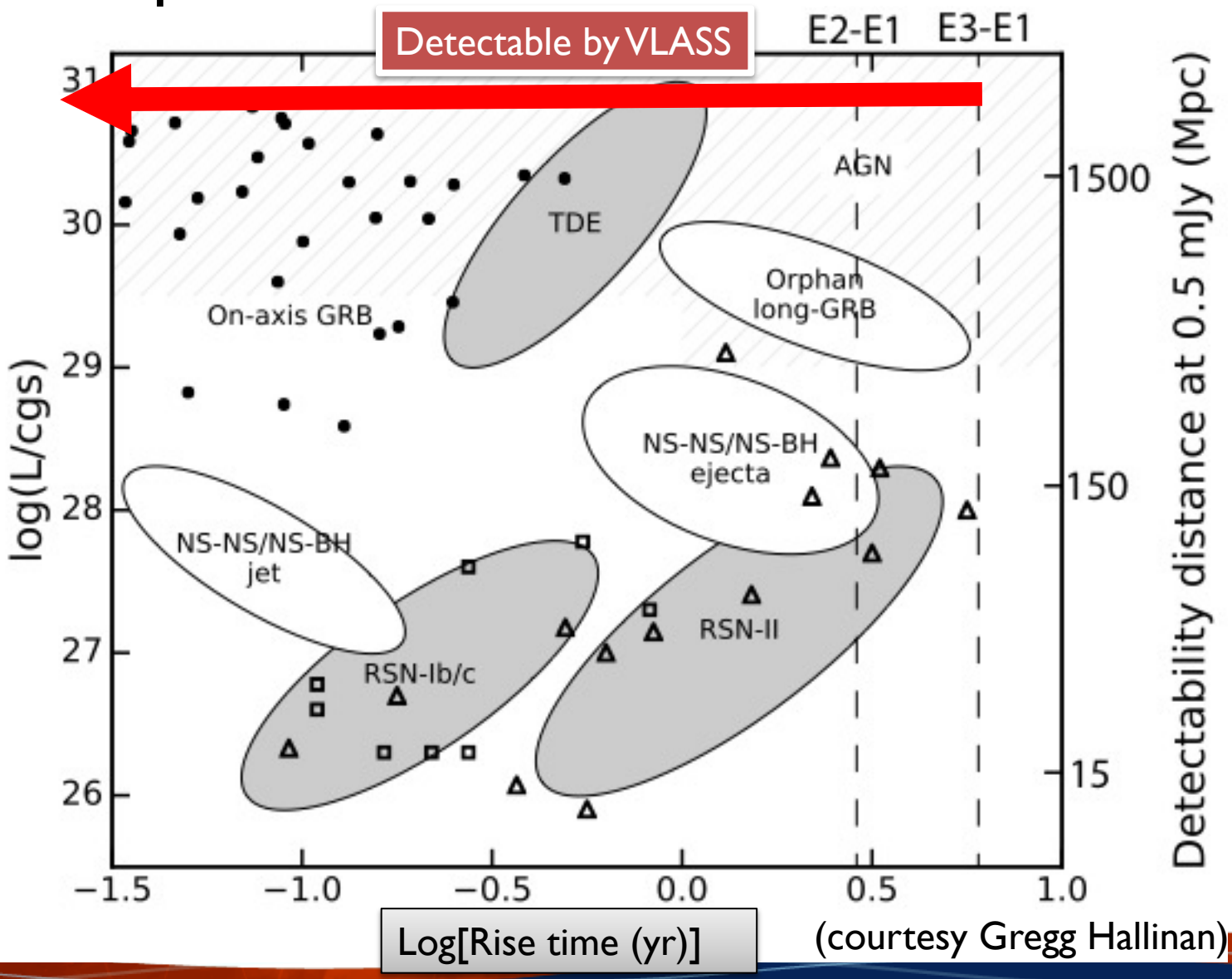


FIRST contours on SDSS



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.

Hidden explosions

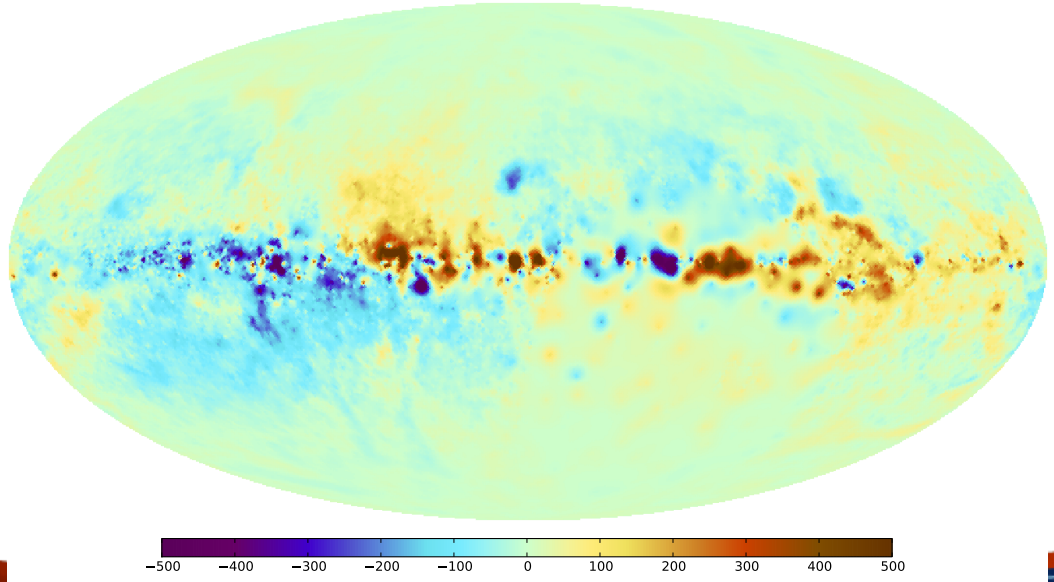


(courtesy Gregg Hallinan)

Faraday rotation studies

- How much thermal gas is entrained in 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

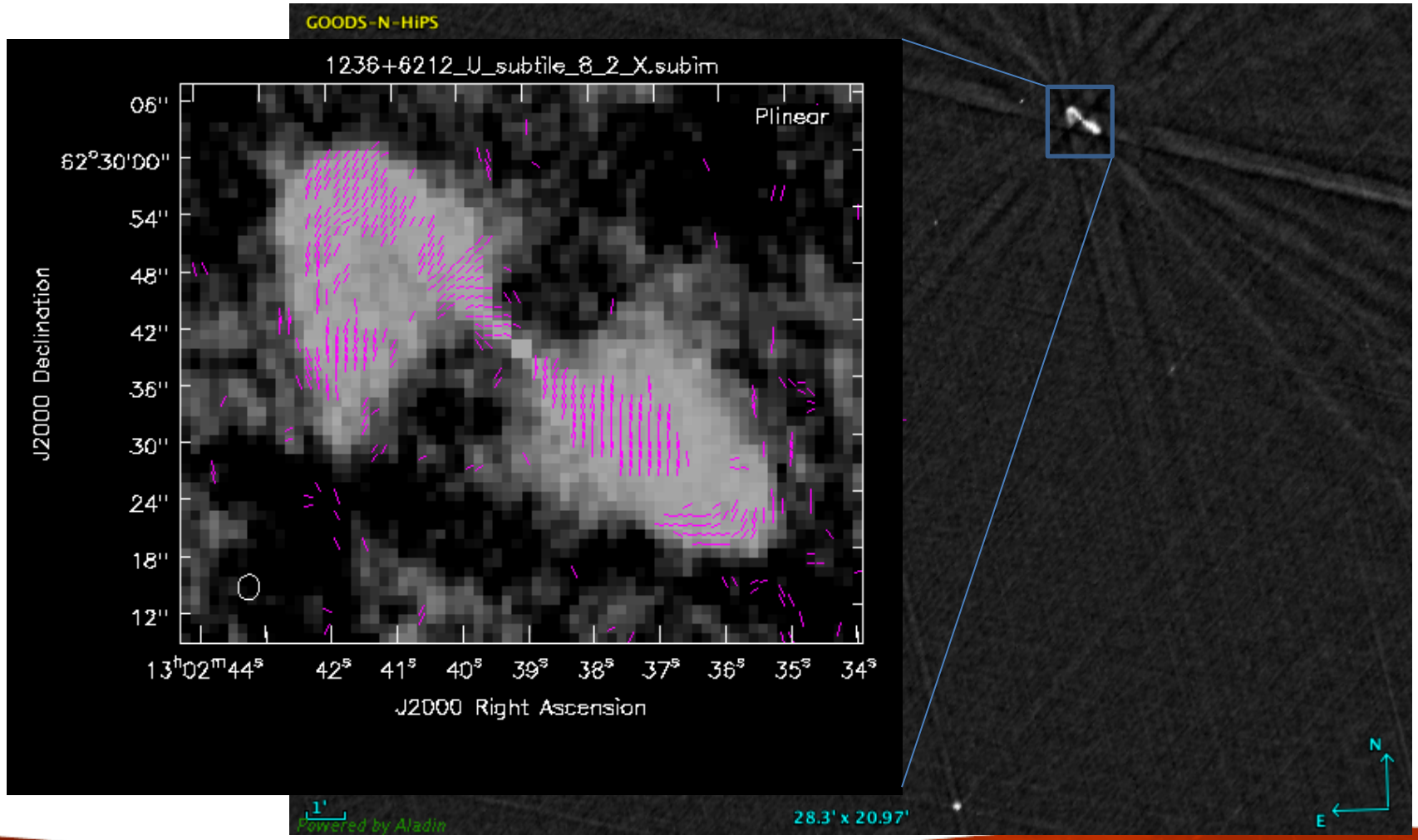
Factor ~10 increase in resolution of Milky Way Faraday rotation map



Linear Polarization Map:
Oppermann+ 2012 (NVSS)

Polarization result from Pilot: GOODS-N

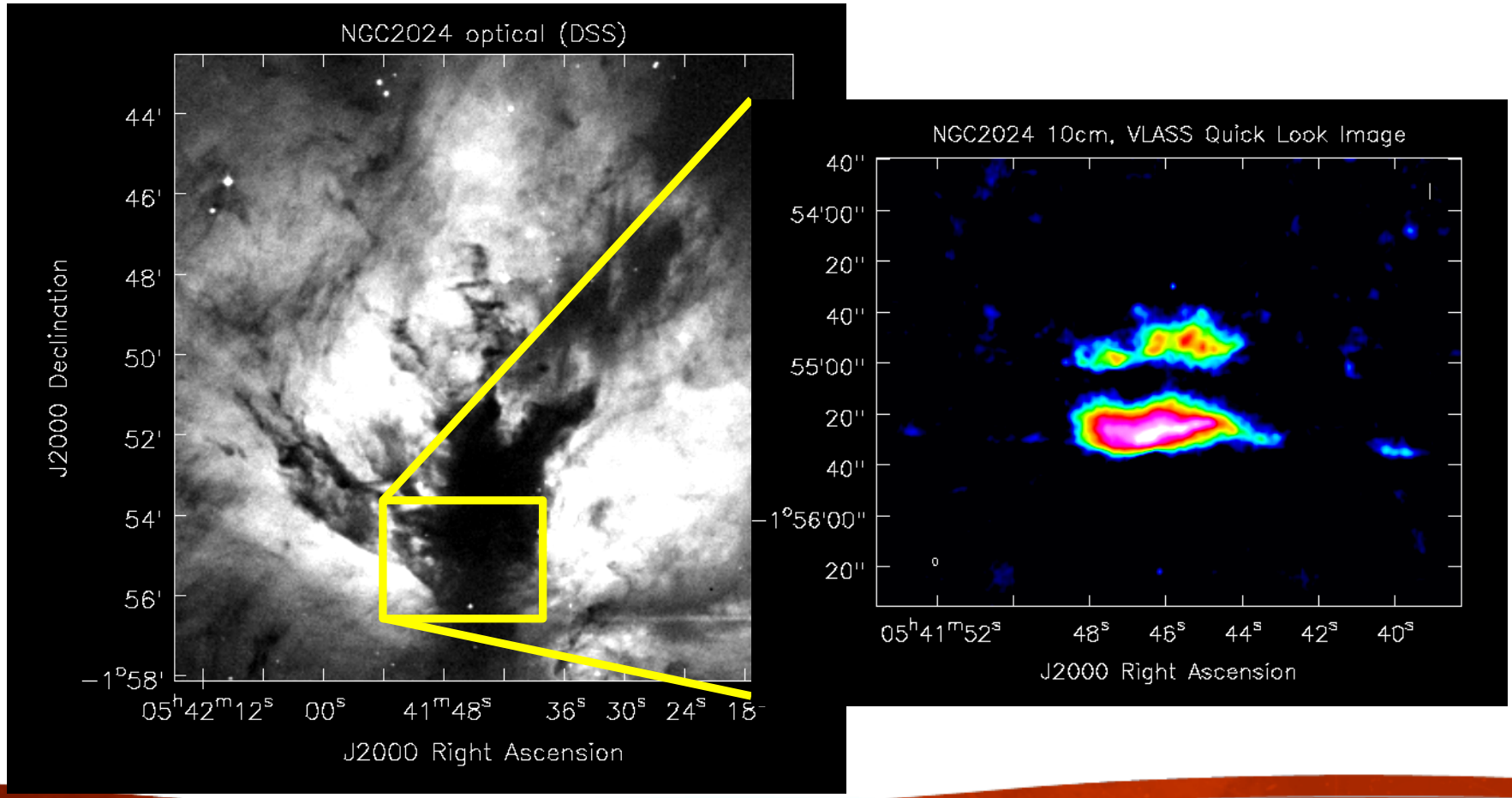
40 deg^2 QL imaged (1" pixels); **polarization**



Peering through our dusty galaxy

NGC2024 (Flame Nebula), Orion B (from VLASS Pilot)

- Survey has sensitivity to scales from 2.5” to 20”



VLASS Basic Data Products (public)

~1 PB
Raw data 523 TB
Images 440 TB

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

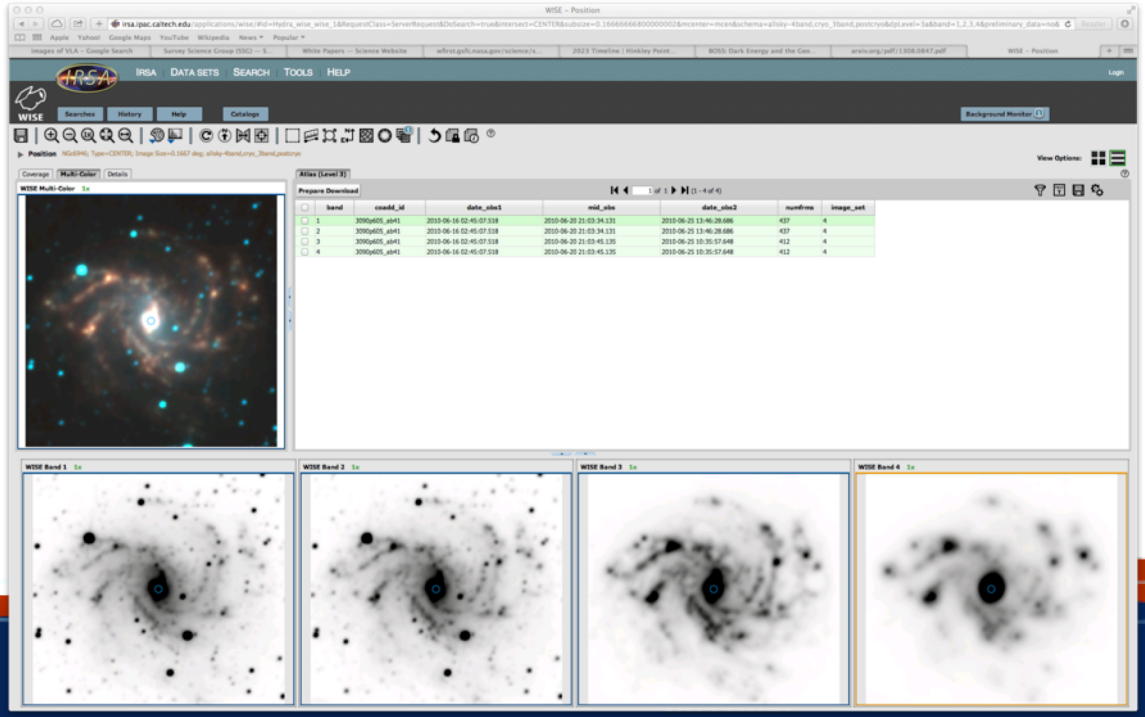
- NRAO → Science-Ready Data Products

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

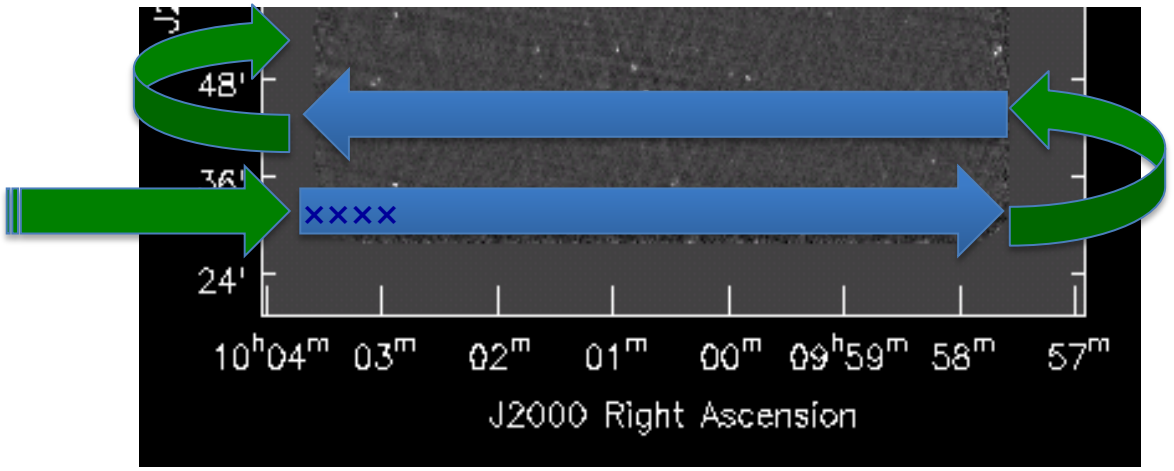
✧ **e.g., as currently available by IPAC/IRSA allowing for VLASS to be integrated with Spitzer/Planck /WISE/Euclid/etc…**



VLASS Challenges / Requirements

On-The-Fly-Mosaicking observations

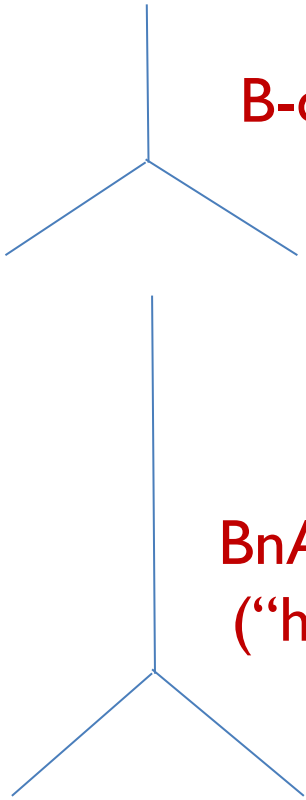
- Scan telescopes across sky while taking array data
  - Net survey speed*: ~20 deg^2/hr (Moon is ~0.2 deg^2)
  - Scan rate* 3.31'/s *(*slower at low declinations to mitigate increased noise)*
  - Correlator dump 0.45s (1.5')
  - ***Equivalent time-on-source: 5s***



7.2 arcmin row separation

Beam shape requirements motivate configurations:

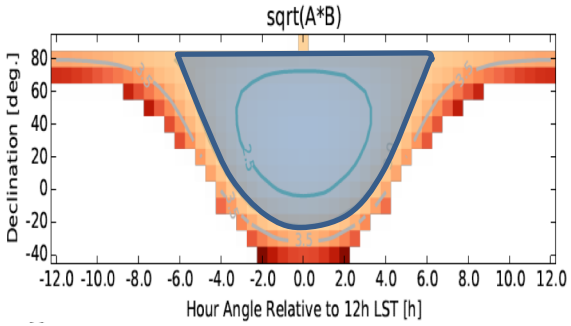
- Resolution requires the use of VLA B/BnA configurations
  - 3-arcsec (geometric mean) achieved over a large range of HA
  - Synthesized beam, major/minor axis ratio = 1.5 (contour)

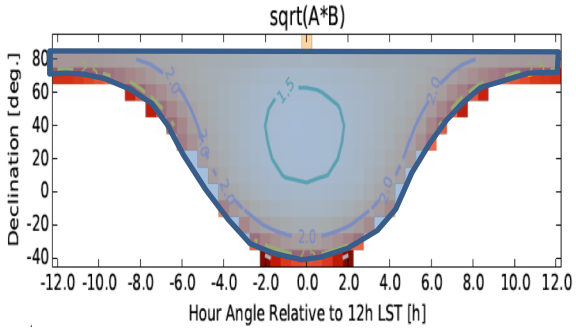


B-config

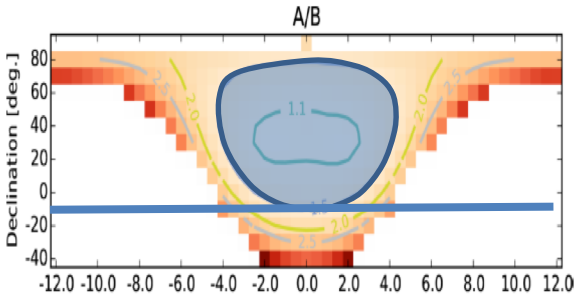
BnA-config
("hybrid")

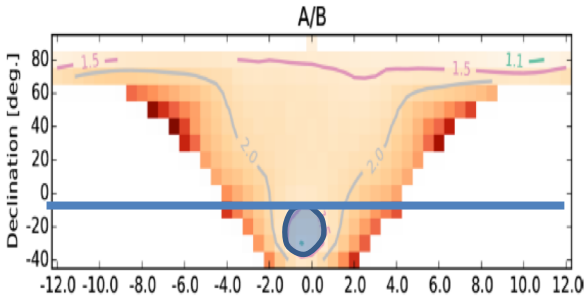
Beam: geometric mean





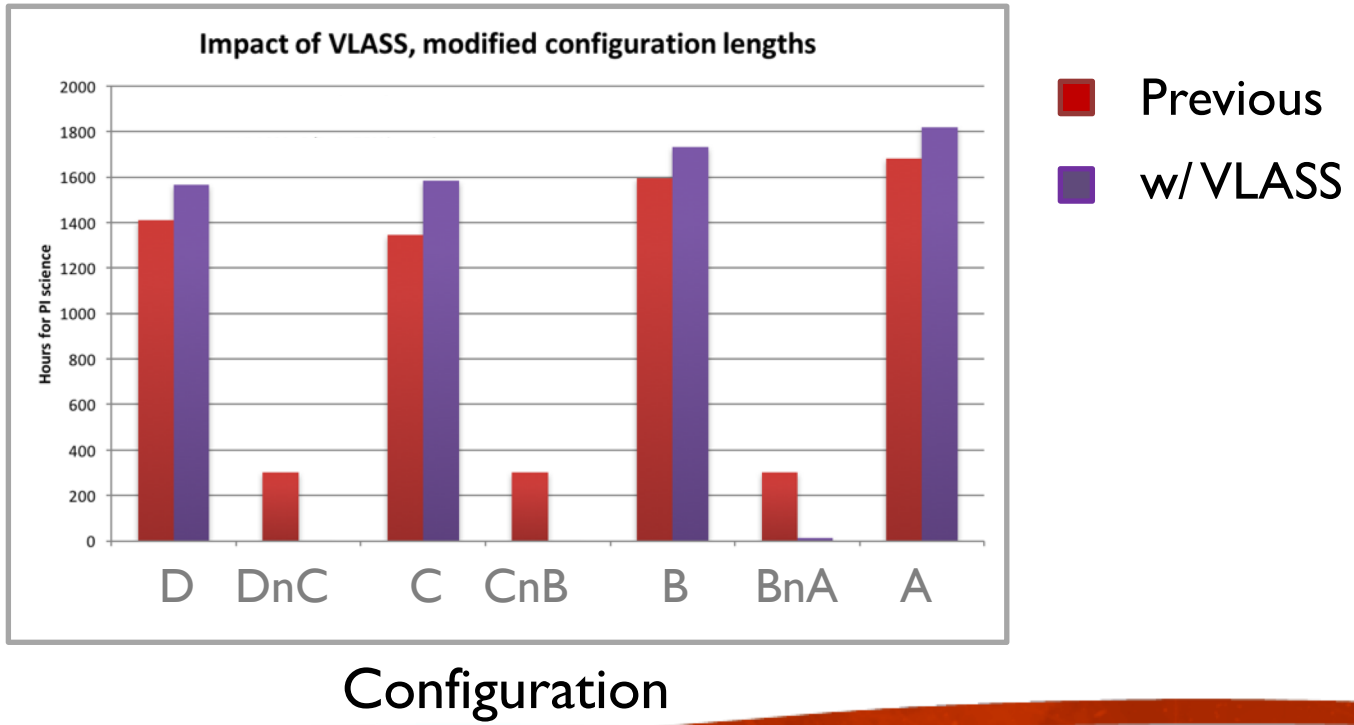
Beam: axis ratio





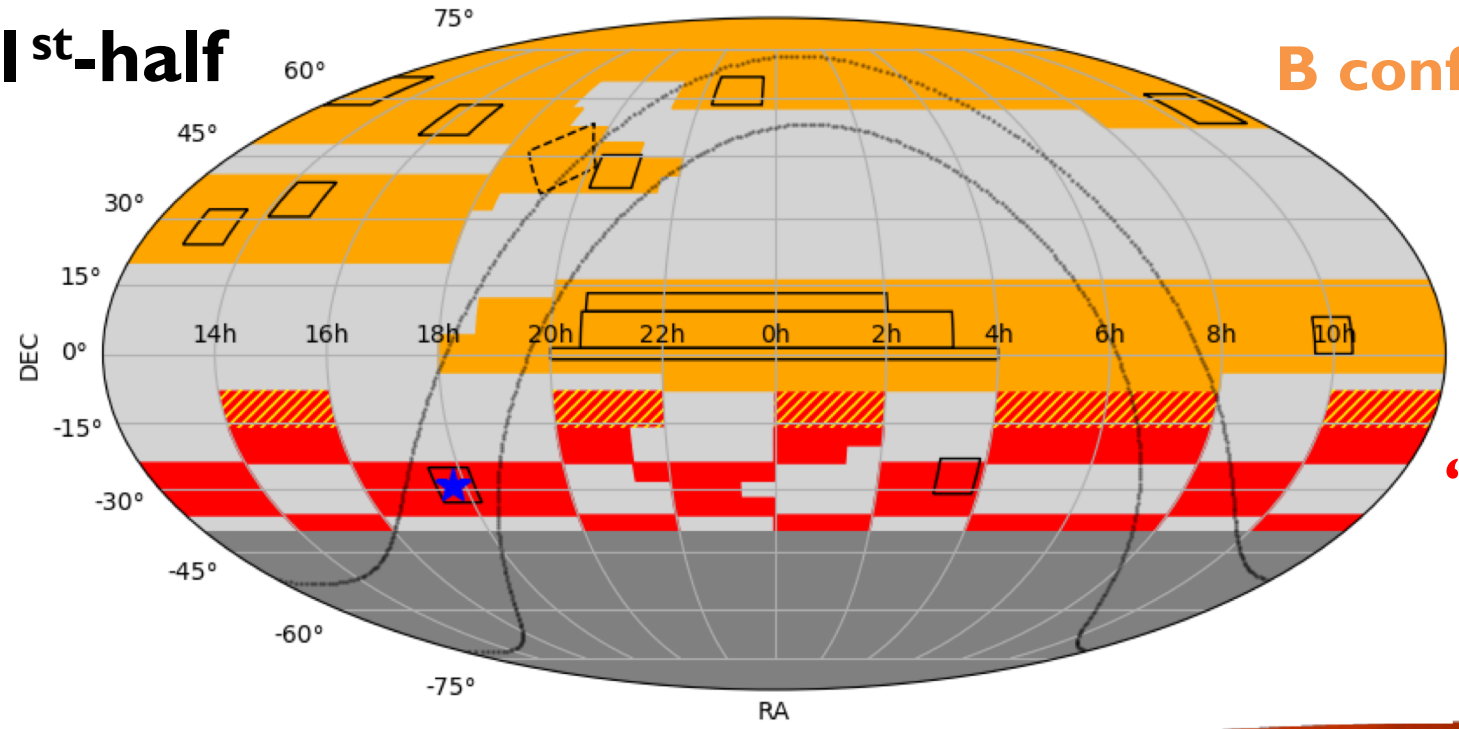
Requirement: small impact on normal VLA operations

- Observe VLASS with standard tools (e.g., VLASS dynamically scheduled)
- Fraction of time taken from PI science as small as possible



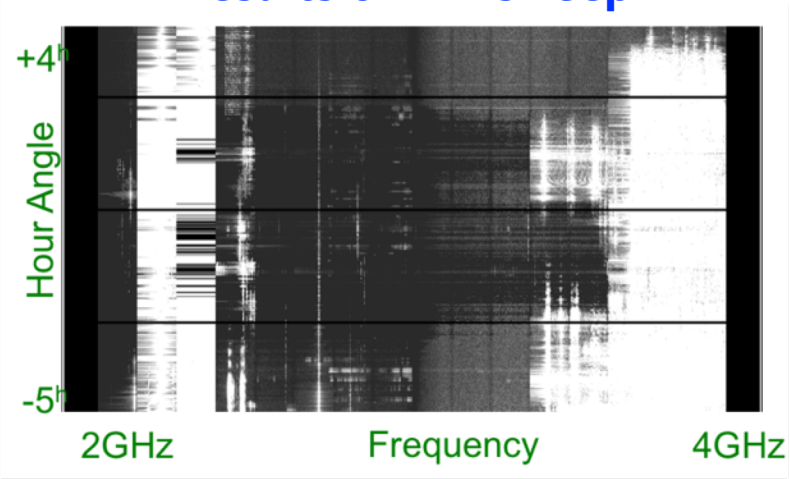
Sky Coverage: cadence and LST pressure

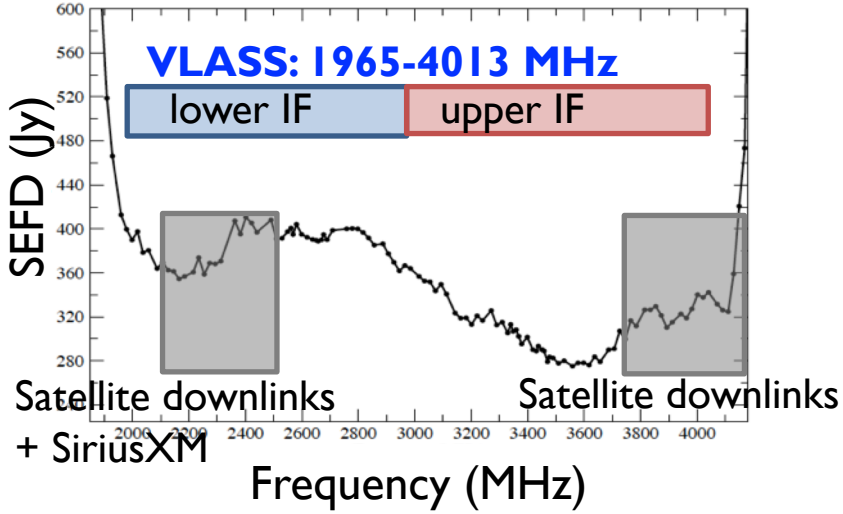
- Requirement: 16-month config cycle ⇒ 32-month cadence, same 1st/2nd half division per epoch
- Goal: re-observe Pilot tiles (and Kepler field) in 1st-half
- Goal: constant RA pressure per half-epoch (easiest to achieve LST flexibility)



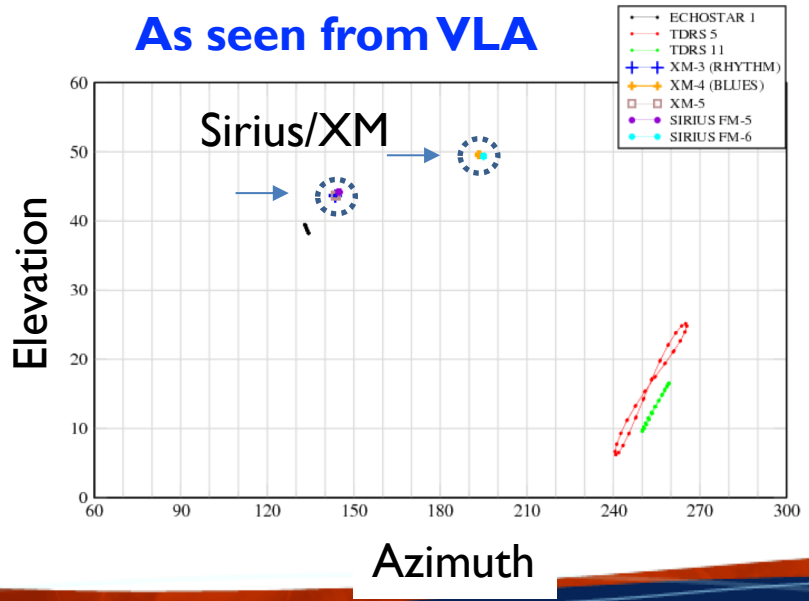
Challenges: RFI / satellite avoidance

Results of RFI sweep

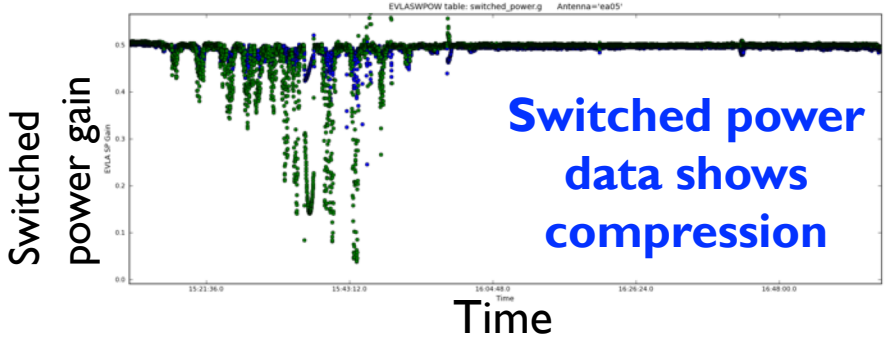




As seen from VLA



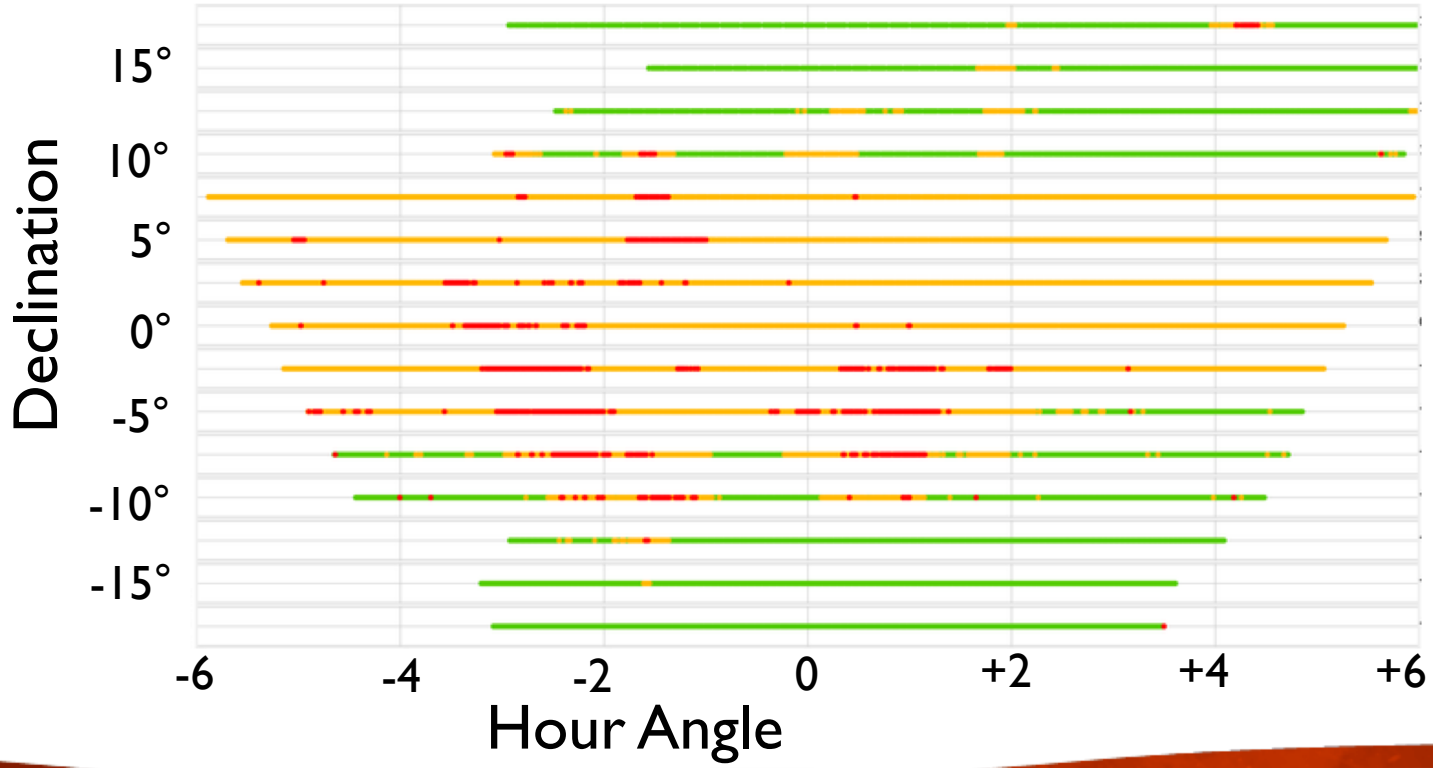
Strong RFI leads to gain compression



1-5 % compression

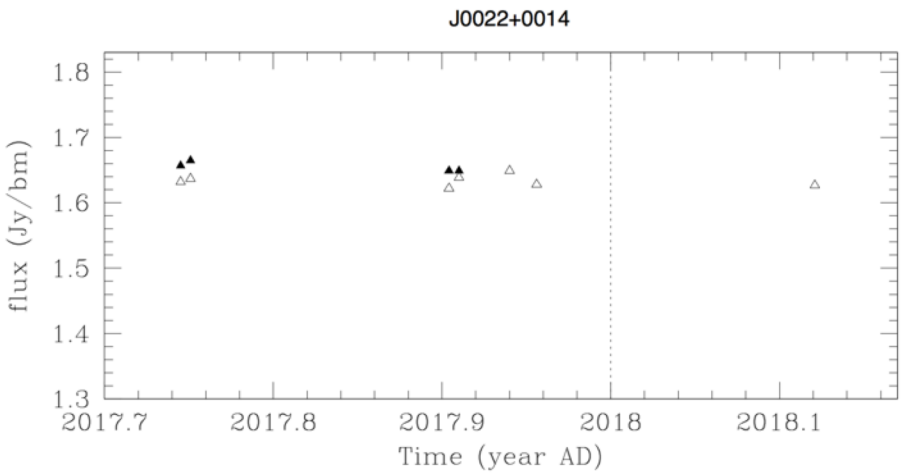
5-20 % compression

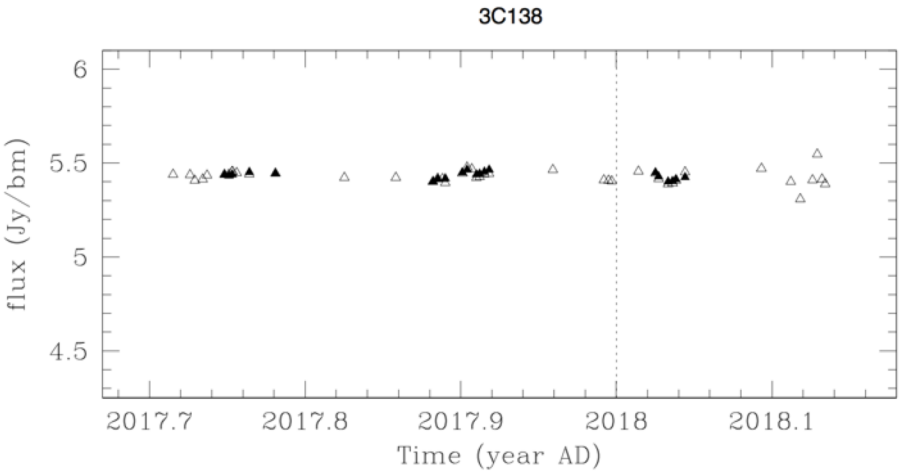
> 20 % compression

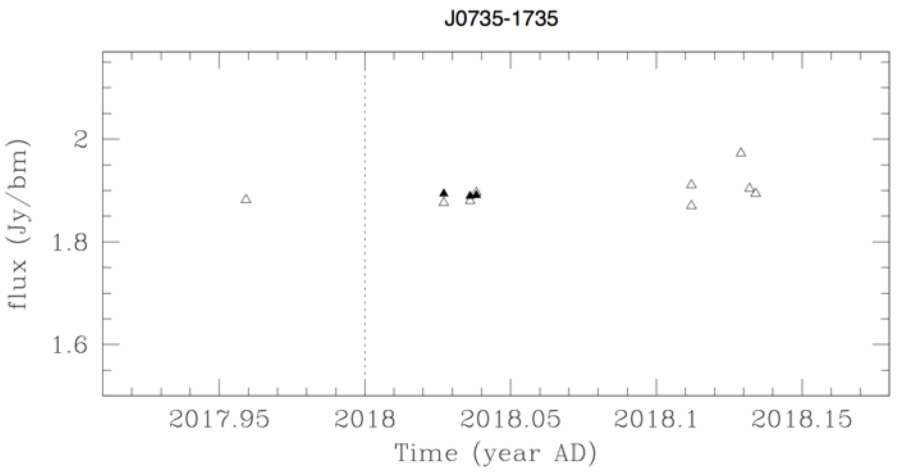


Work by Frank Schinzel

Flux density consistency





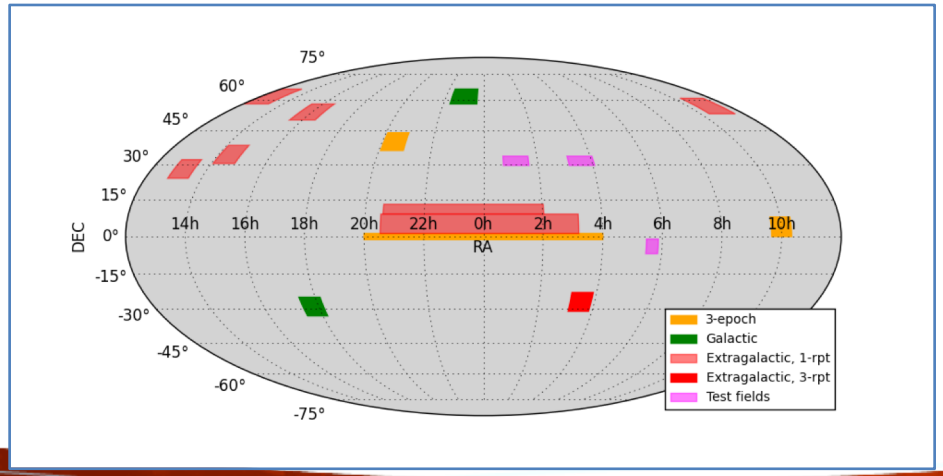


△ With compression

▲ After compression fix

Pilot Survey and Test Fields

- ~200hr pilot survey observed May-Sep 2016
  - Prototype survey execution and data reduction
- 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

Current VLASS status

- Observations of VLASS 1.1 completed (Sep '17-Feb '18)
  - 12,921 deg^2 in B config: 130 data sets
  - 3910 deg^2 in BnA config: 35 data sets
  - Total of 916.5 hours ~ 16,831 deg^2

- All data sets available to public:
  - [old] NRAO archive, Project code "VLASS1.1":
  - https://archive.nrao.edu/archive/advquery.jsp
  - > 94,000 GB of *raw* data
  - **~16,800 deg^2 of "QuickLook" images published**

Sky tiling and Observing method

- Sky divided into "Tiers" from -40 decl to +90 decl
  - "Tiers" are mostly 4-deg tall in decl (and two are 5-deg tall)

- Each Tier divided into integral number of "tiles"
  - "tiles" are roughly 10-deg/cos(decl) long in R.A.

- Tiles roughly 40 deg^2 in area; observed in roughly 2 hours (including calibration)

- Scheduling Blocks observe 2, 3, or 4 tiles (roughly 4, 6, 8 hours) (including calibration overheads)

Calibrator observations

- Flux calibrator: (observed ≥ 2 min)

  3C 286 or 3C 48

- Polarization angle calibrator : (observed ≥ 2 min)

  3C 286 or 3C 48 / J1800+7828 / 3C 138

- Polarization leakage calibrator: (observed ~few min)

  Complex gain calibrator or known "unpolarized" source

  Complex gain calibrator observed every 16-20 minutes

  Leakage calibrator observed once if unpolarized, otherwise observed ≥ 3x with Parallactic Angle range $\gtrsim 60°$

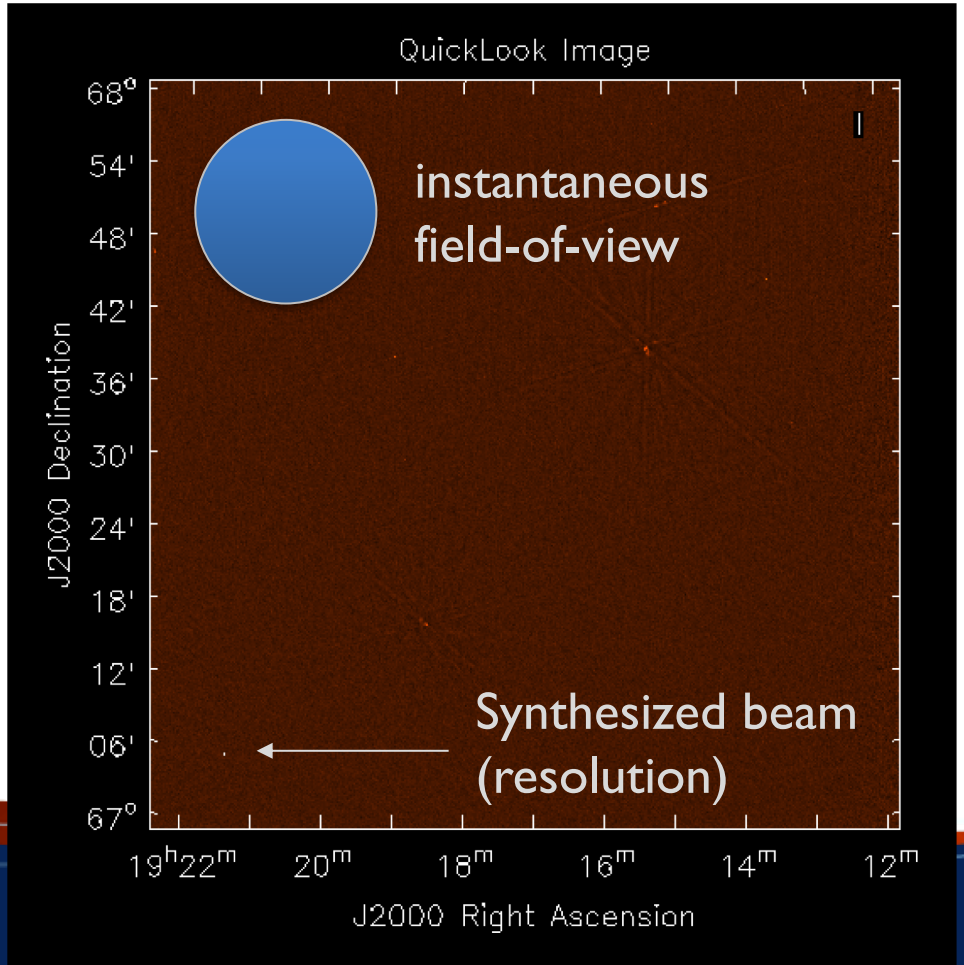
Data flow after the observations

- Raw data:
  - immediately ingested into archive
- Calibrated data:
  - obtained via [compression] pipeline (see Frank's talk)
- QuickLook (QL) images:
  - each tile divided into ~40 1x1deg^2 images
  - Imaging pipeline (VLASS specific for now → wider use for future)
    - Image 2x2deg^2; take central quarter (1x1deg^2) for QL
    - CASA's mosaic gridder
    - Multi-frequency synthesis (2-4 GHz) with curvature (nterms=2)

Individual QuickLook images

- https://archive-new.nrao.edu/vlass/quicklook/VLASS1.1/

  a QuickLook image at the edge of a tile (centered 1917+6730)



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

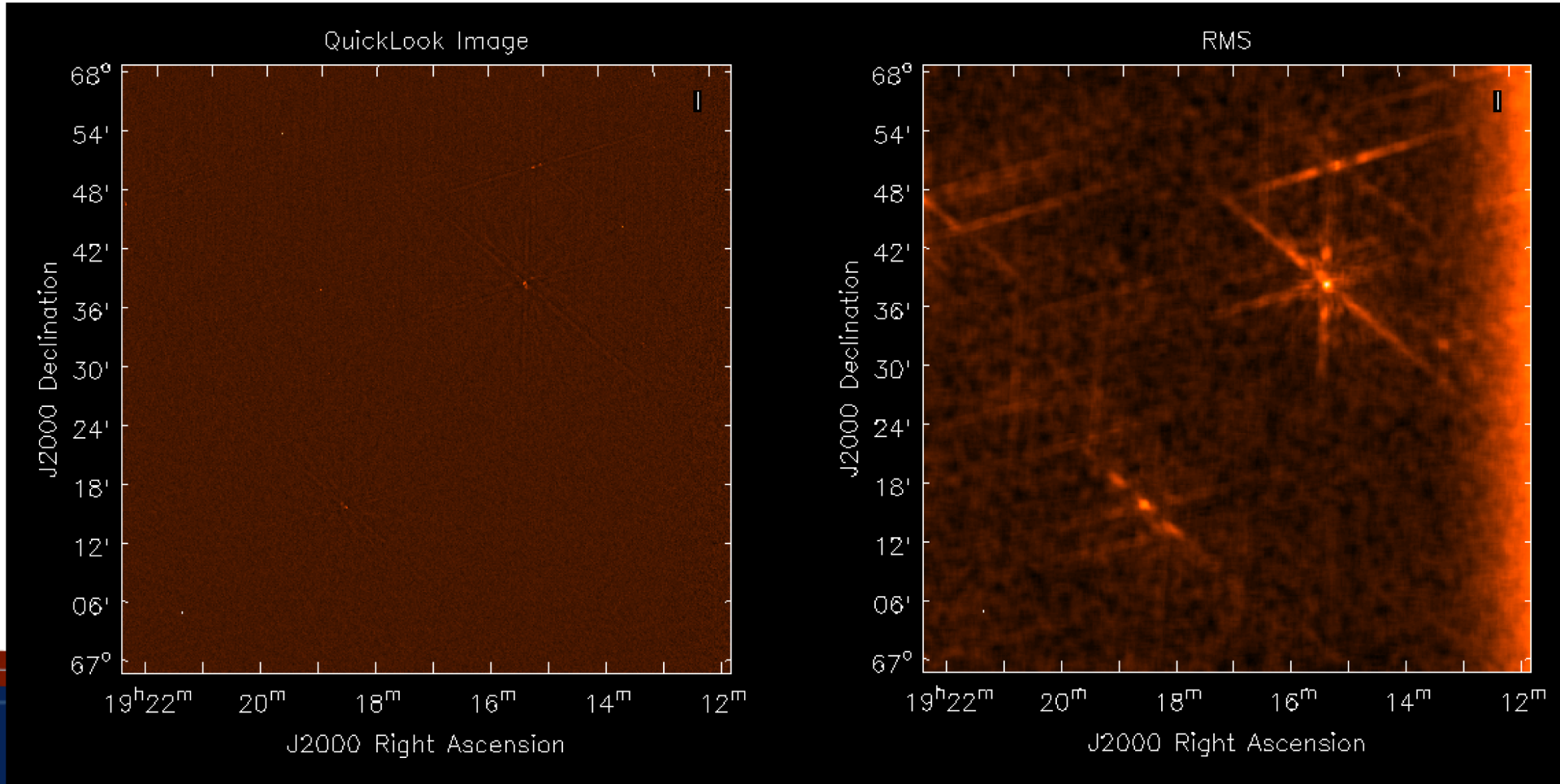
MTMFS nterm=2

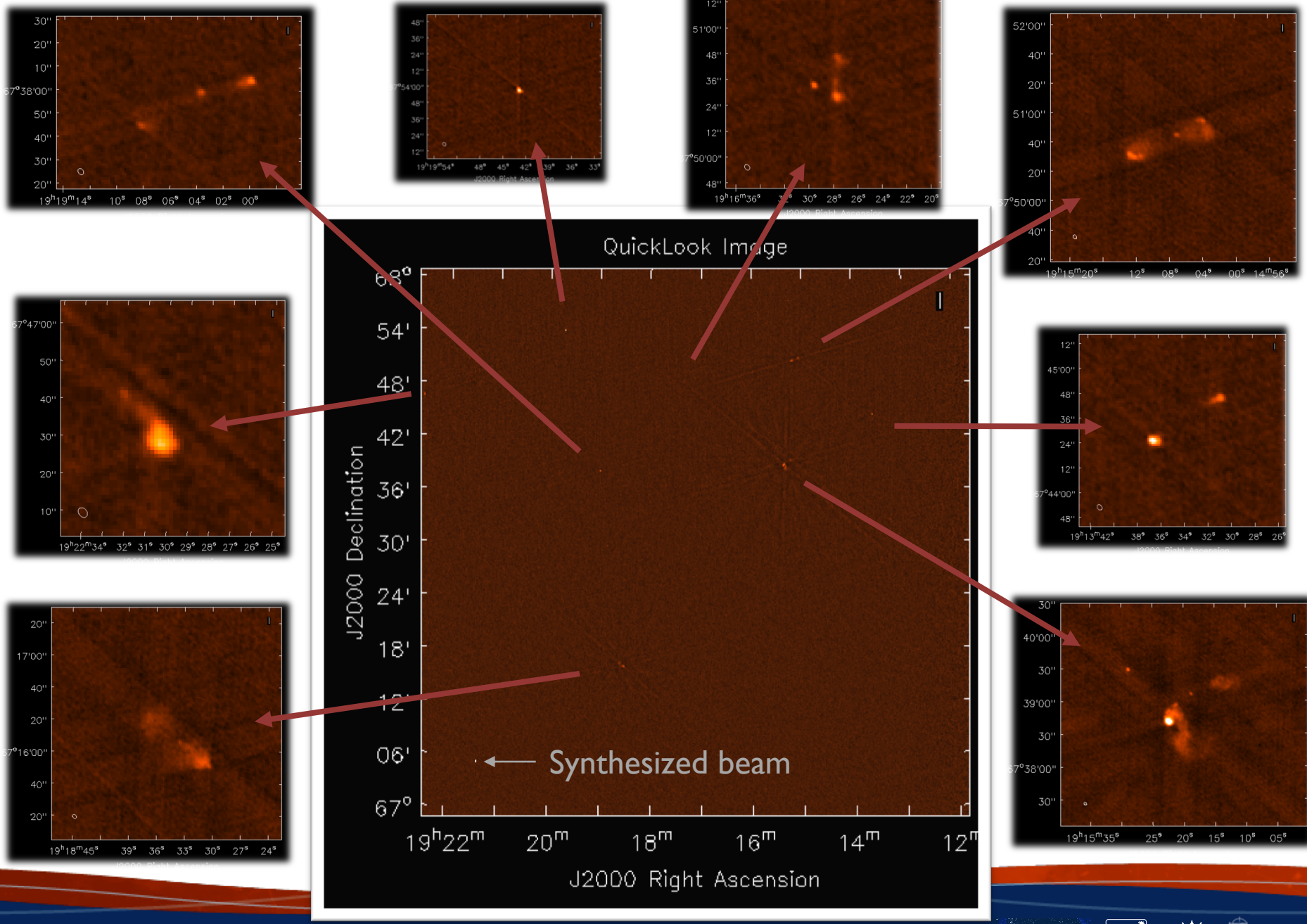
σ_I=130μJy/beam

Individual QuickLook images

- https://archive-new.nrao.edu/vlass/quicklook/VLASS1.1/

  a QuickLook image at the edge of a tile (centered 1917+6730)

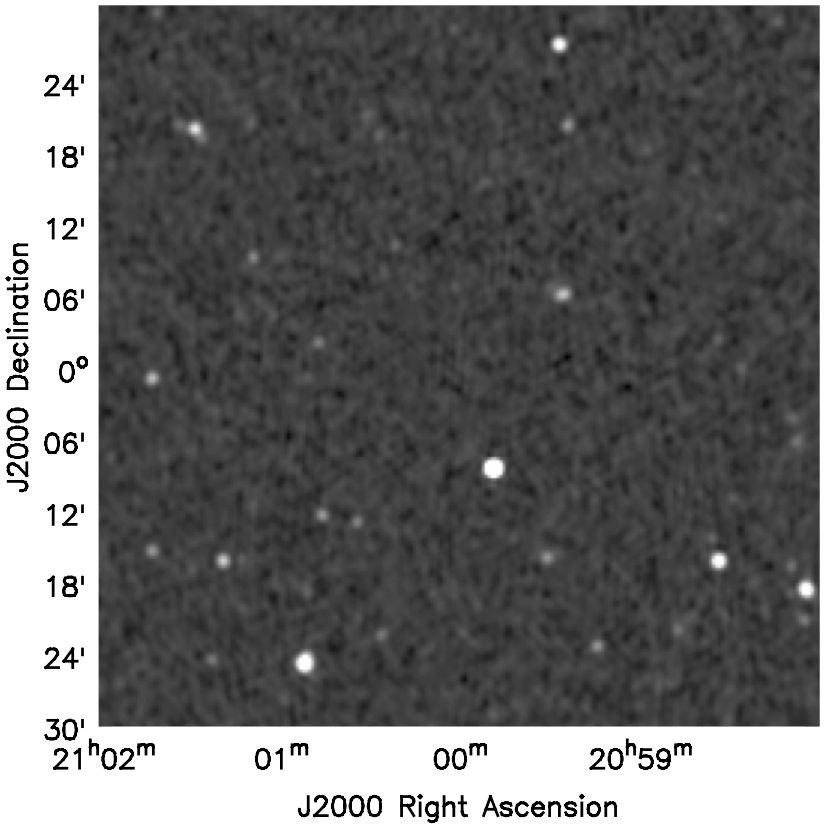


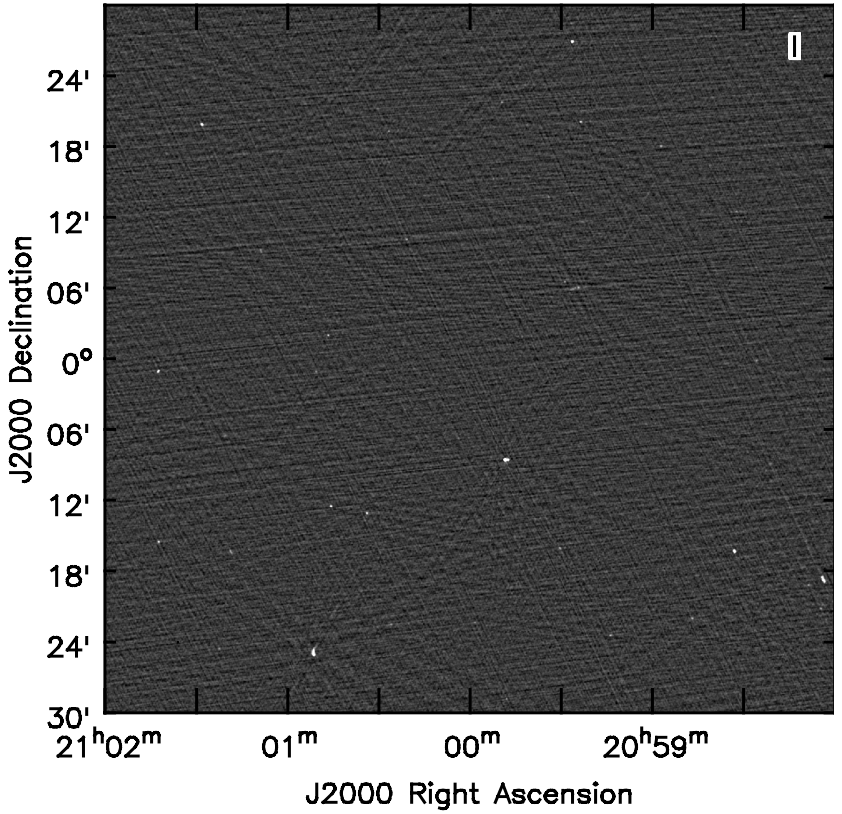

QuickLook Image
J2000 Declination
J2000 Right Ascension
Synthesized beam

Comparison: NVSS + tapered VLASS image

Results from test & pilot observations

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

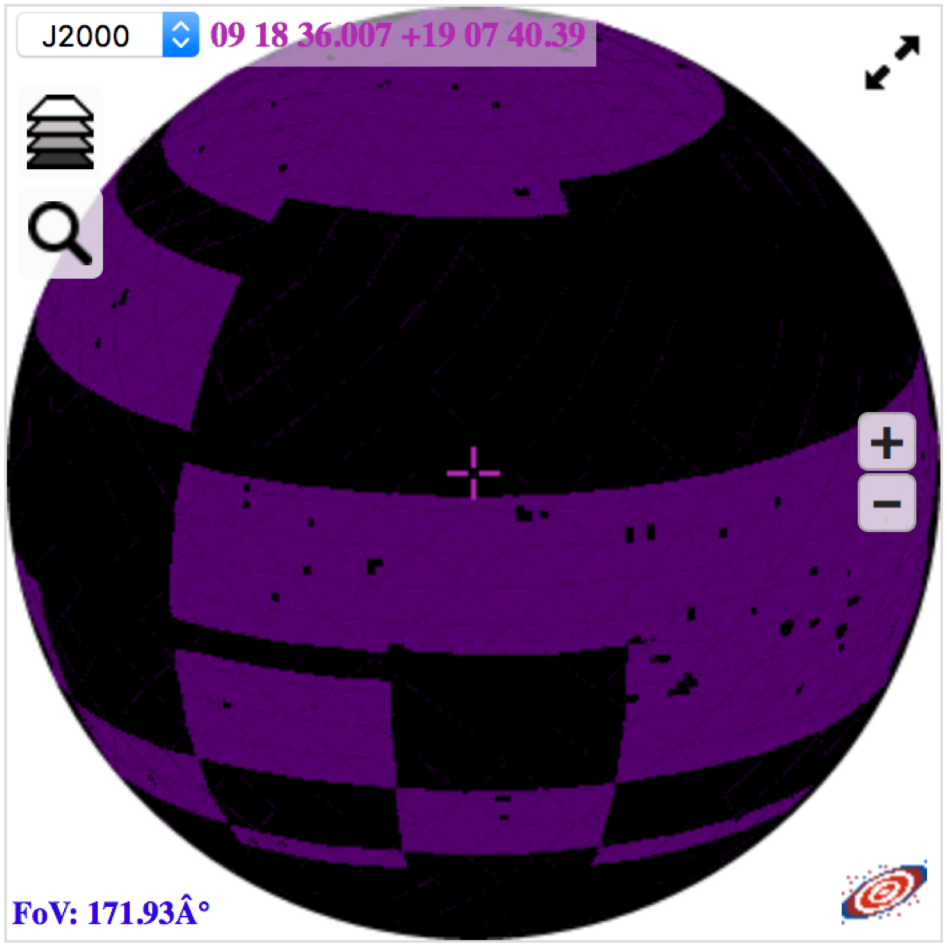




(left) NVSS at 45" resolution, full image; (right) VLASS uv-tapered to 7.5" resolution to enhance low surface-brightness extended emission.

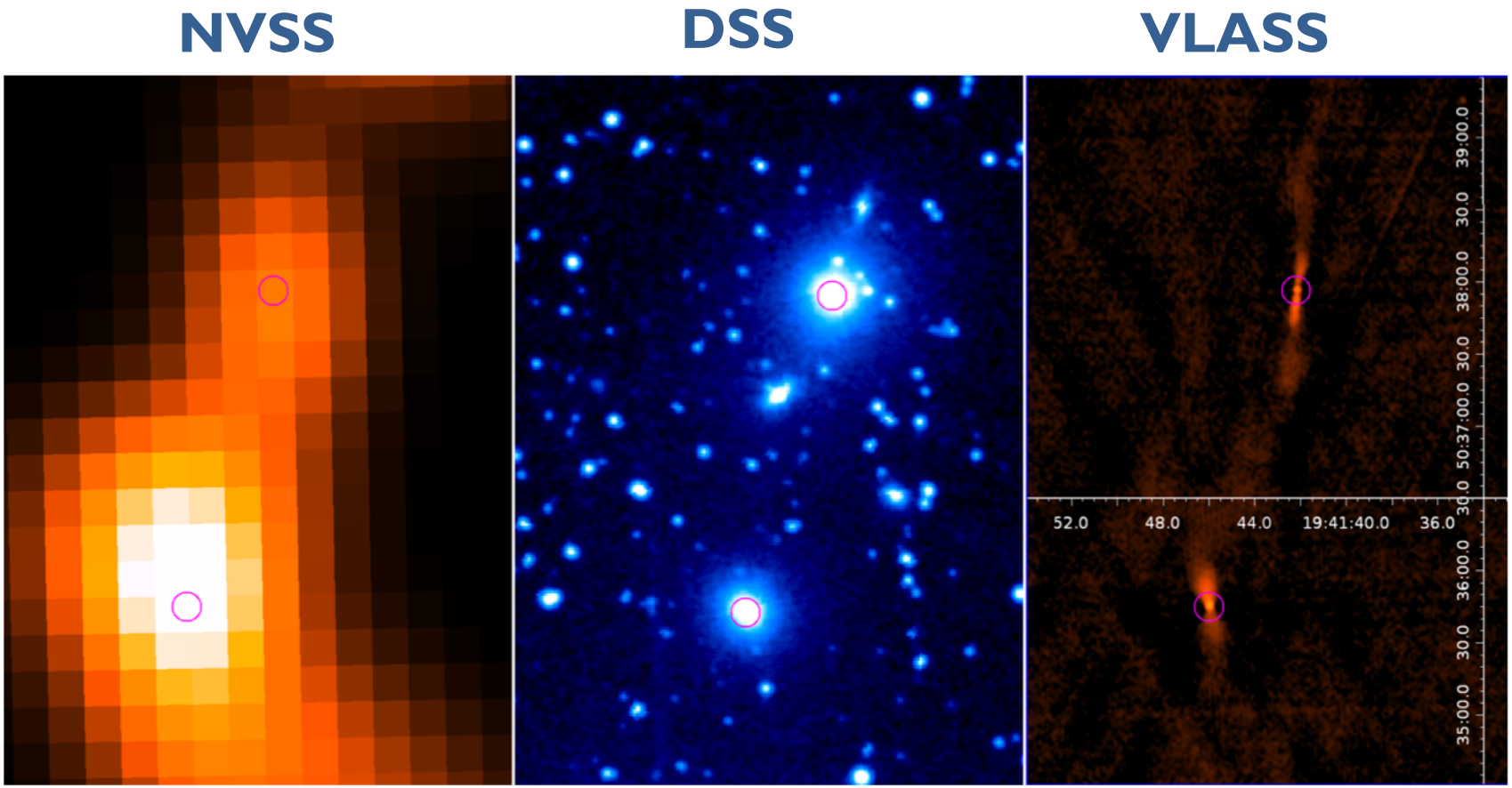
VLASS QuickLook Image Mosaic

- http://archive-new.nrao.edu/vlass/HiPS/VLASS1.1/Quicklook/
  - HiPS (HEALPix) image displayed by AladinLite



VLASS resolution advantage

Radio “galaxy” 3C 402

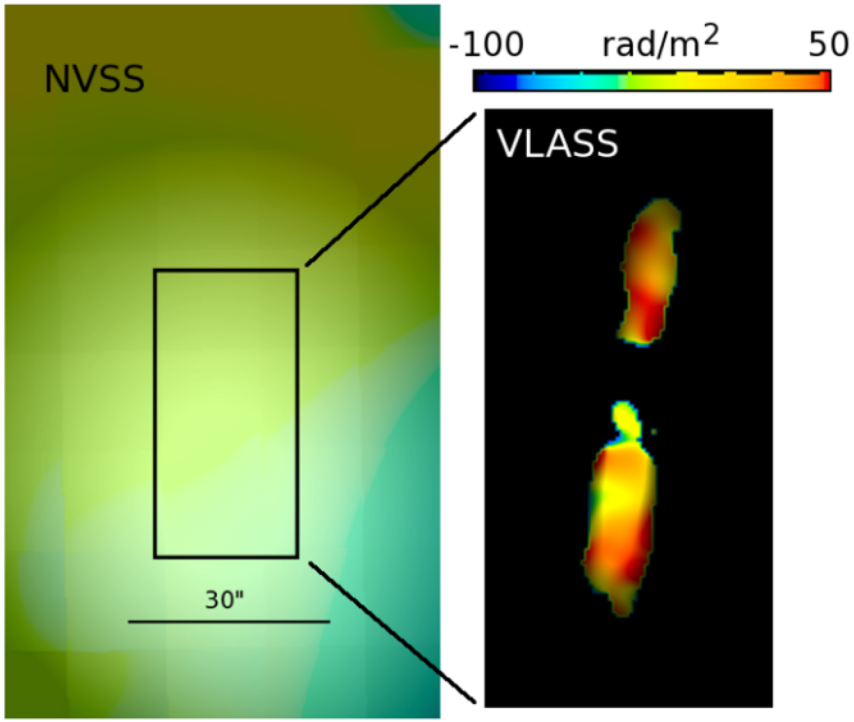


M. Lacy et al. (in prep)

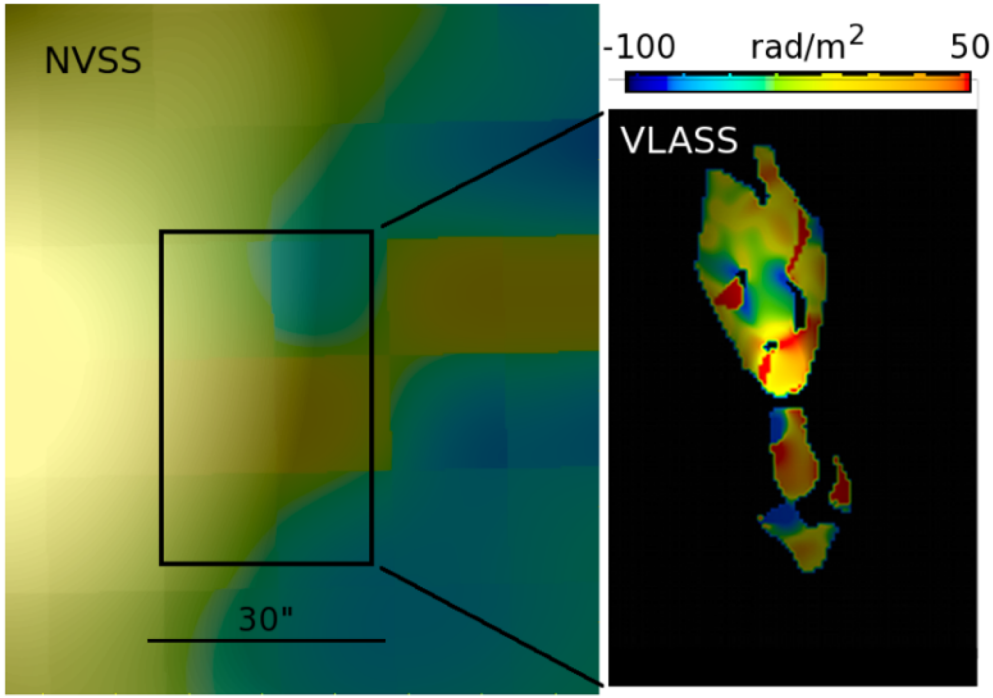
VLASS resolution advantage

Polarization mapping

3C 402 North



3C 402 South



M. Lacy et al. (in prep)

Ongoing commissioning / improvements

- Further increase automation (schedule, calibration, imaging)
- Improve CASA algorithms for Single-Epoch imaging
  - widefield imaging, beam rotation, polarization, PSF subtraction, etc.
- Source finding:
  - Using 3rd party package PyBDSF (Python Blob Detection and Source Finder developed at Astron for the LOFAR survey

    http://www.astron.nl/citt/pybdsm/

Community Effort:

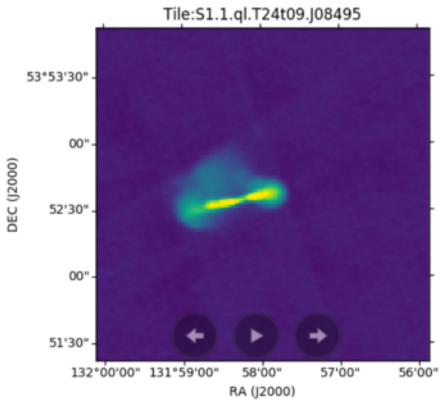
- Led by Shea Brown (*U. Iowa*)

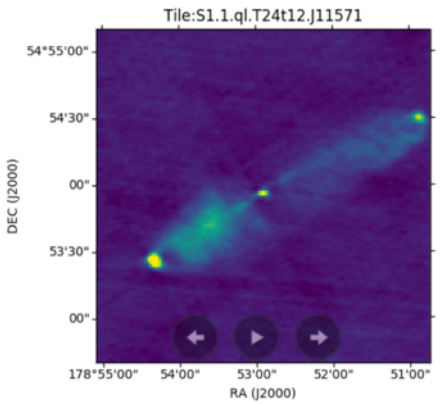
  https://bablai.com/vlass

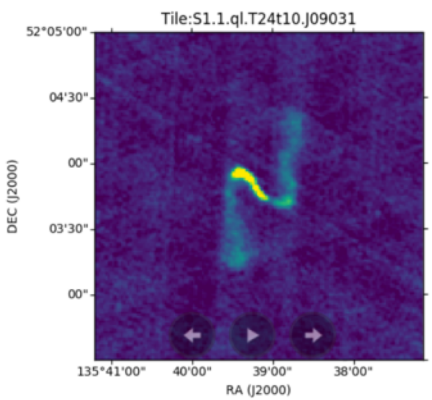
  – Machine Learning for source classification

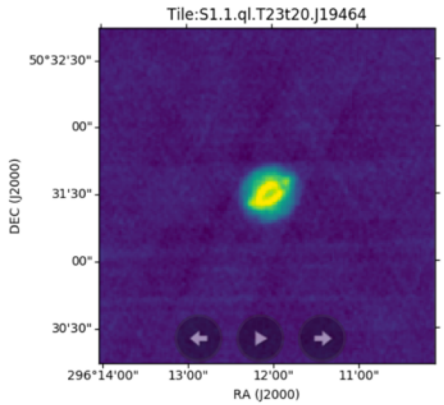
  – Training on VLASS QuickLook images (prep for cubes)

  – Basic catalogs and postage-stamp images









CIRADA:

Canadian Initiative for Radio Astronomy Data Analysis

- Led by Prof Bryan Gaensler (Director, *Dunlap Institute*)
- Canadian Foundation for Innovation (CFI) award
  - $3.5 million (CFI) + $6 million partner funds (w/ NRAO in-kind)

With VLASS: produce rotation measure images and catalogs

CIRADA

CANADIAN INITIATIVE FOR RADIO ASTRONOMY DATA ANALYSIS

VLASS references and more information

- Survey science website
  https://science.nrao.edu/science/surveys/vlass
- Education & Public Outreach website
  https://public.nrao.edu/vlass
- Public wiki with Technical Implementation Plan, memo series:
  https://safe.nrao.edu/wiki/bin/view/JVLA/VLASS
- Technical & Pilot results publication near submission (*Lacy et al.*)

Summary

- The new VLA Sky Survey will be the highest spatial resolution, all-sky radio survey ever undertaken
  - Resolution critical for cross-identification with other wavelengths
  - Multi-epoch for identifying transients obscured at other wavelengths
  - Polarimetry to reveal the magnetic universe

- First observing cycle complete:
  - Half of sky observed
  - QuickLook images available (tomorrow's talks)
  - Ongoing development of single-epoch products

www.nrao.edu
science.nrao.edu
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