New Surveys of the Universe with the Jansky Very Large Array (VLA)

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

NRAO

A New Sky Survey with the Jansky Very Large Array

From NRAO E-Newsletter (11 July 2013)

T. Beasley & D. A. Frail

[click to enlarge]

In the 20 years since the initial observations were made for the NRAO VLA Sky Survey (NVSS) and the Faint Images of the Radio Sky at Twenty-Centimeters (FIRST), these pioneering programs have defined the state-of-the-art in centimeter radio sky surveys and produced a steady stream of excellent science. Given the enhanced capabilities of the Jansky Very Large Array (VLA), now is an appropriate time to discuss the scientific potential of new centimeter-wavelength sky surveys.

The astronomy community has already recognized that several of the high priority science goals of the 2010 decadal survey *New Worlds, New Horizons in Astronomy and Astrophysics* could be addressed by a new VLA sky survey. At the May 2013 Radio Astronomy in the LSST Era held at NRAO-Charlottesville, for example, many scientists expressed keen interest in employing the VLA to conduct new, wide-area centimeter wavelength sky surveys in support of multi-wavelength synoptic surveys using existing and future facilities, such as the Large Synoptic Survey Telescope (LSST).

Thus, we are announcing a NRAO VLA Sky Survey (VLASS) initiative that will explore the science and technical opportunities of a new centimeter-wavelength survey. A community-led Science Survey Group (SSG) will define the science program and key components of VLASS, and NRAO will support its technical definition and implementation. All VLASS data will be available immediately to the North American community.

By 1 September, we will formally announce the formation of the SSG and identify opportunities for interested community members to join the group. We will also announce a white paper solicitation that will provide critical input to the SSG and NRAO regarding survey science goals, techniques development, and design.

Additionally, a VLASS workshop for all interested community members is being organized adjacent to the January 2014 American Astronomical Society meeting at National Harbor, MD. Stay tuned to eNews for further information.

0.
Radio Interferometry

Classic Radio Telescope

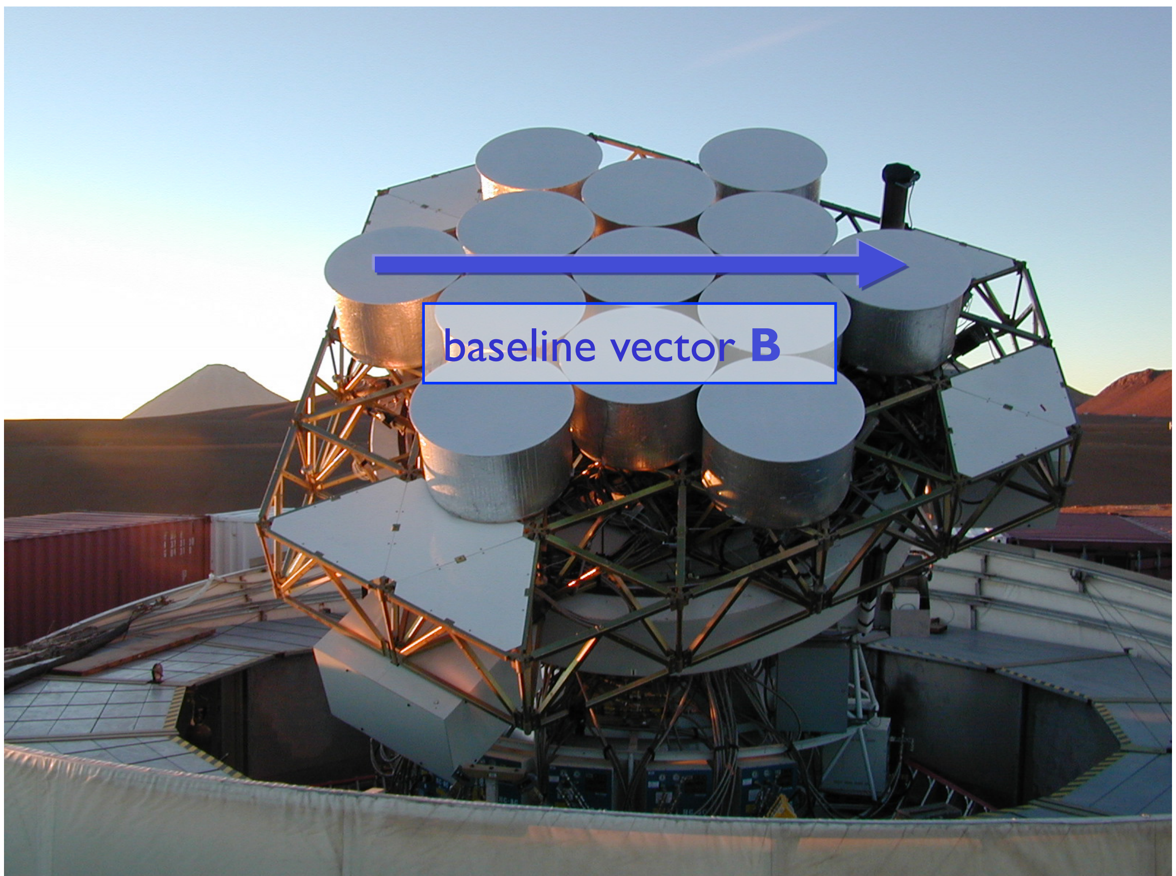
- Filled aperture (100m Green Bank Telescope in West Virginia)
- Resolution diffraction limited ~ λ/D (30cm/100m = 10' at 1GHz)

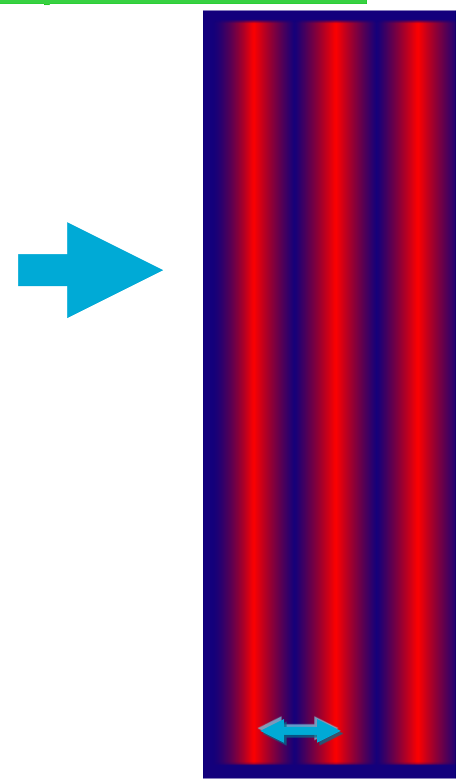
Off-axis paraboloid (Gregorian) reflector

Interferometer Baselines

- Baseline vector ***B*** in "aperture plane"
  - coherent signal applied to interferometer would produce plane-wave interference "fringe" on sky with angular period λ/B

interferometer naturally decomposes sky into plane waves!



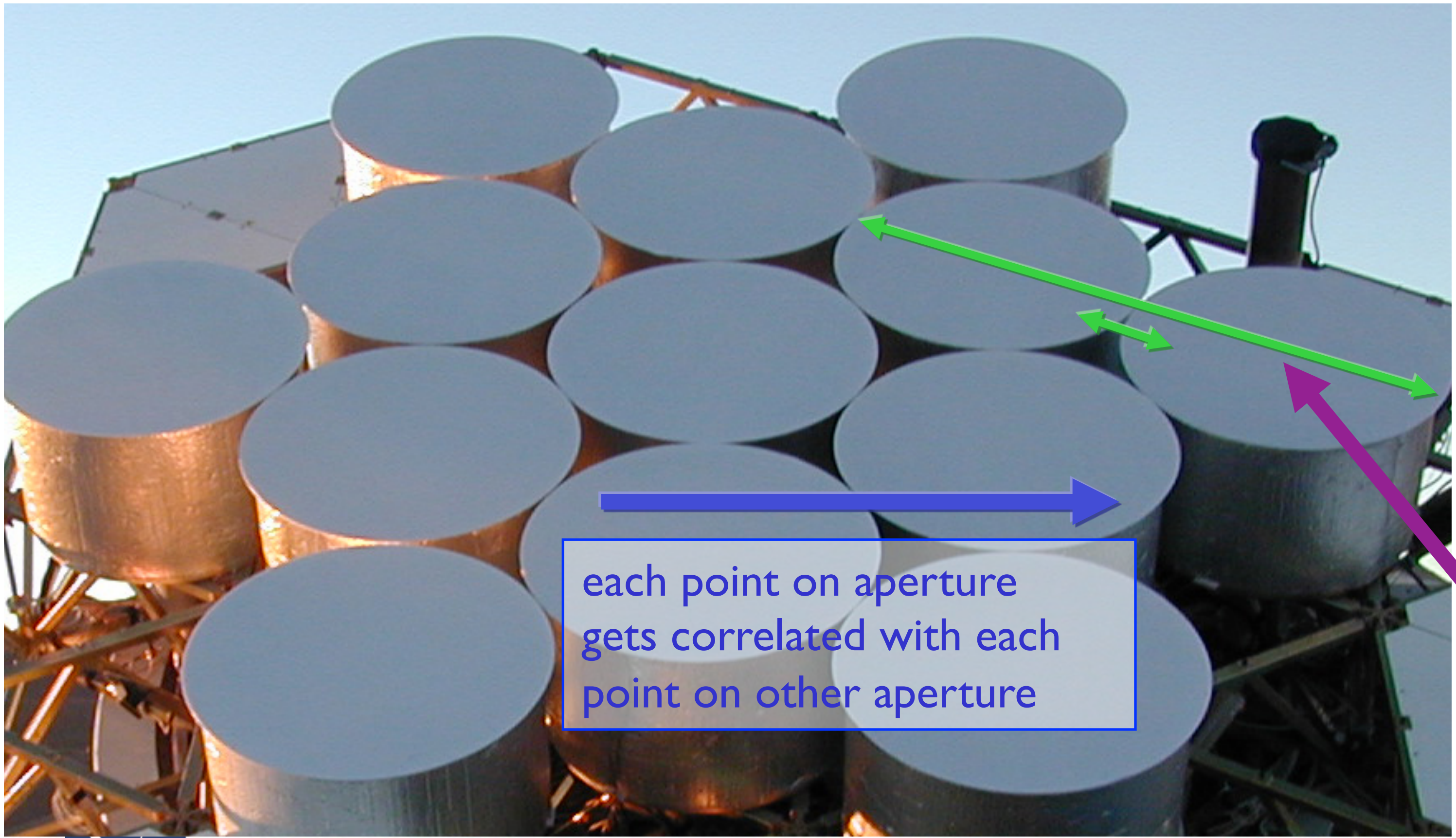


$\theta = \lambda / B$

The Aperture Plane

- Correlate wave-fronts in plane of apertures (Fourier transform of sky)
  - dish optics sum aperture plane at focus
  - visibility is cross-correlation of wavefronts of the 2 apertures

interferometer cannot measure "zero-spacing" w/o autocorrelations

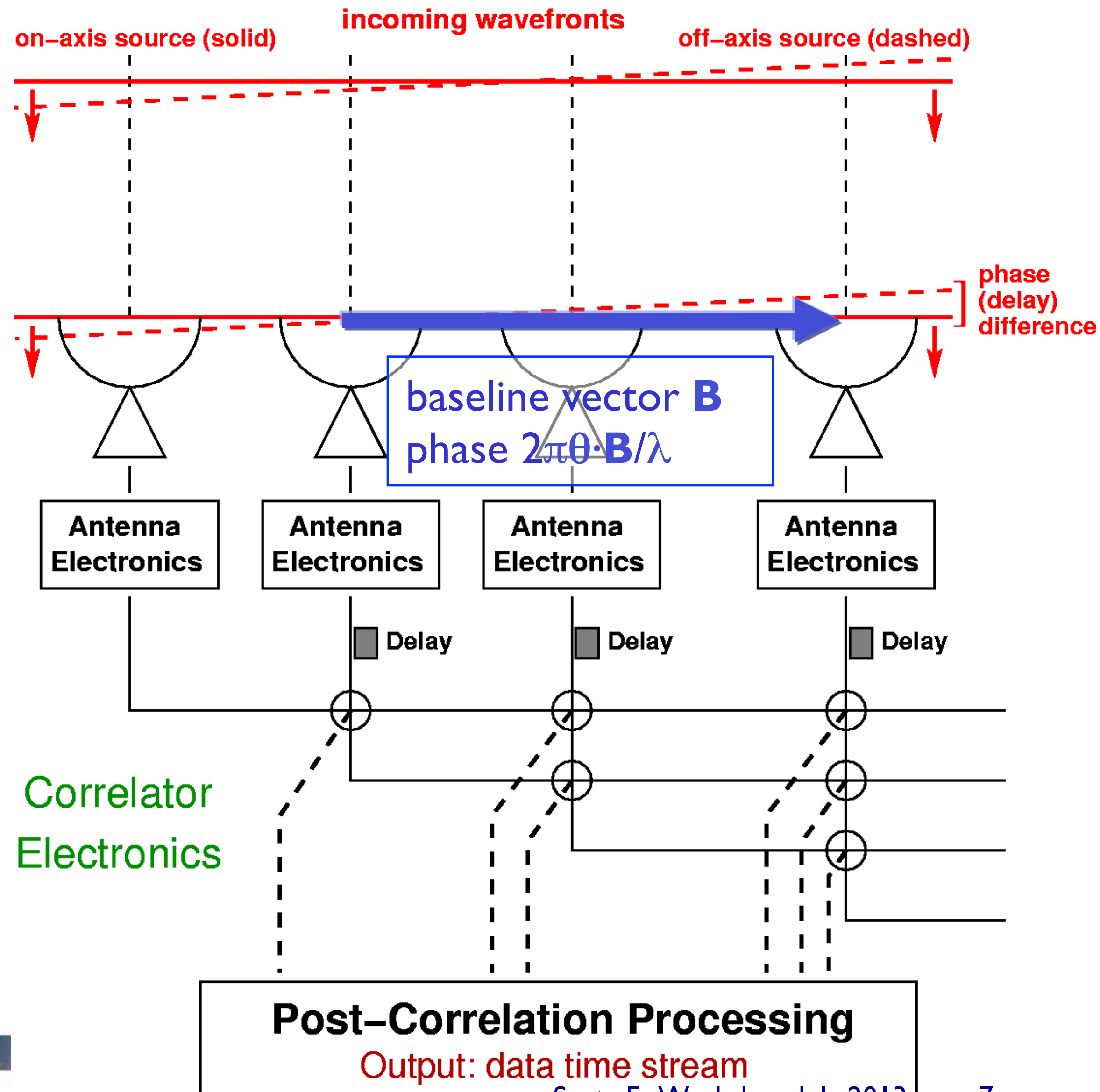


visibility contains range of baselines from closest to furthest parts of apertures

autocorrelations measure uv spacings inside D/λ

Radio Interferometer – schematic

- Spatial coherence of radiation
  - structure of source
- Correlate pairs of antennas
  - "visibility" = correlated fraction of total signal, calibrated as flux density
  - correlate real (cosine) and imaginary (90° shift=sine): amplitude and phase
- Function of baseline **B**
  - measures spatial frequencies $\boldsymbol{u} = \mathbf{B} / \lambda$
  - longer baselines = higher resolution
  - similar to double-slit interference and diffraction



Interferometric "Visibilities"

- Sum wavefronts over (incoherent) source distribution

$$V(u,v,w) = \iint \frac{d\xi\, d\eta}{1+\zeta} I(\xi,\eta)\, e^{i2\pi \boldsymbol{\xi}\cdot\mathbf{u}}$$

Visibility in *uv*-plane

Intensity field on sky

$$\boldsymbol{\xi} = (\xi,\eta,\zeta) \qquad \mathbf{u} = (u,v,w)$$

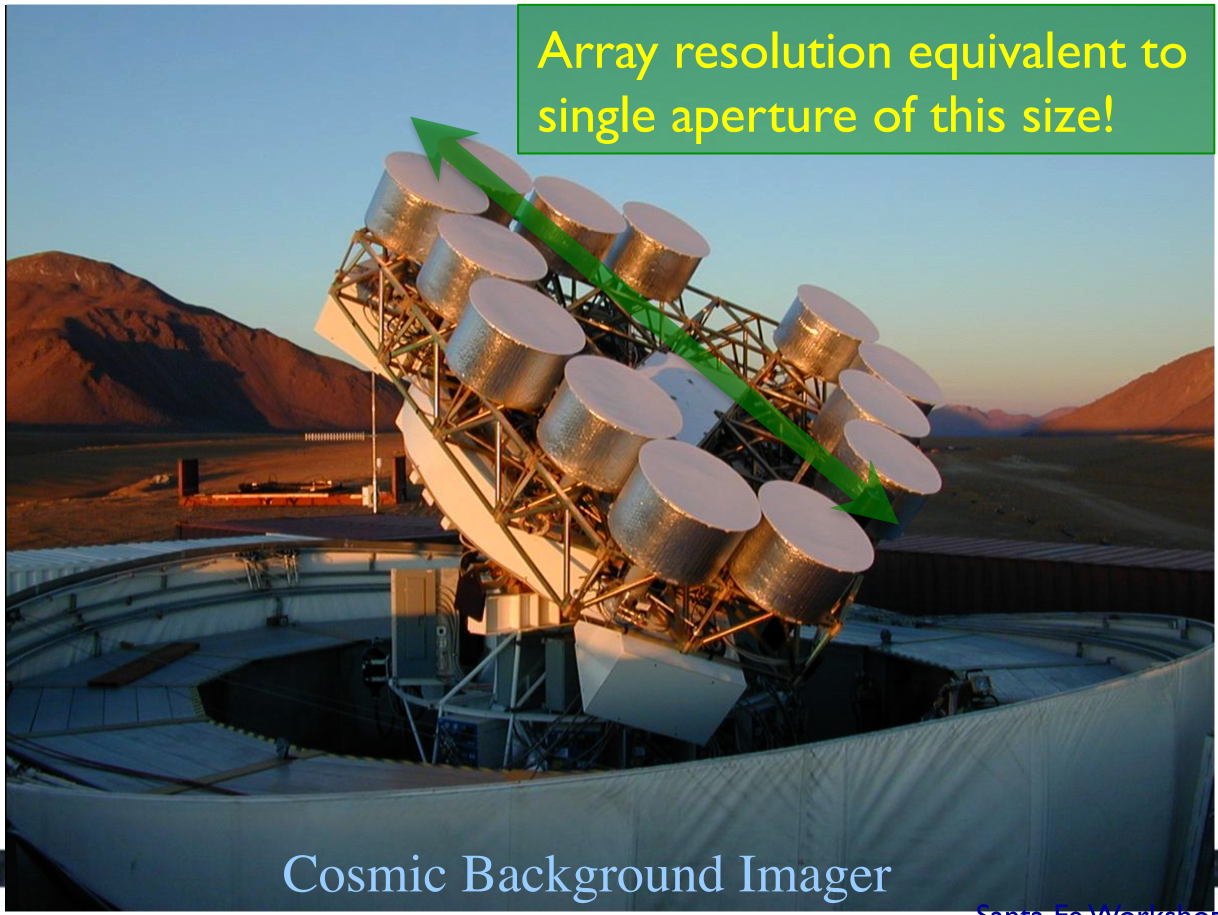
$$1+\zeta = \sqrt{1-\xi^2-\eta^2}$$

- for small fields-of-view can ignore w term, treat as 2D Fourier transform pair (Van Cittert-Zernicke theorem)

$$V(u,v) = \int dx\,dy\, I(x,y)\, e^{i2\pi(ux+vy)}$$

Interferometer vs. Filled Aperture

- Same resolution as single aperture ~size of the longest baseline
  - But aperture plane unfilled (holes in "uv" coverage)
  - Less surface brightness (e.g. mK) sensitivity than filled aperture



So … you could build this

Large filled aperture

- Good surface brightness sensitivity
- Poor resolution
- Impressive looking
- Massive!
- Liable to be taken by Bond supervillain for lair

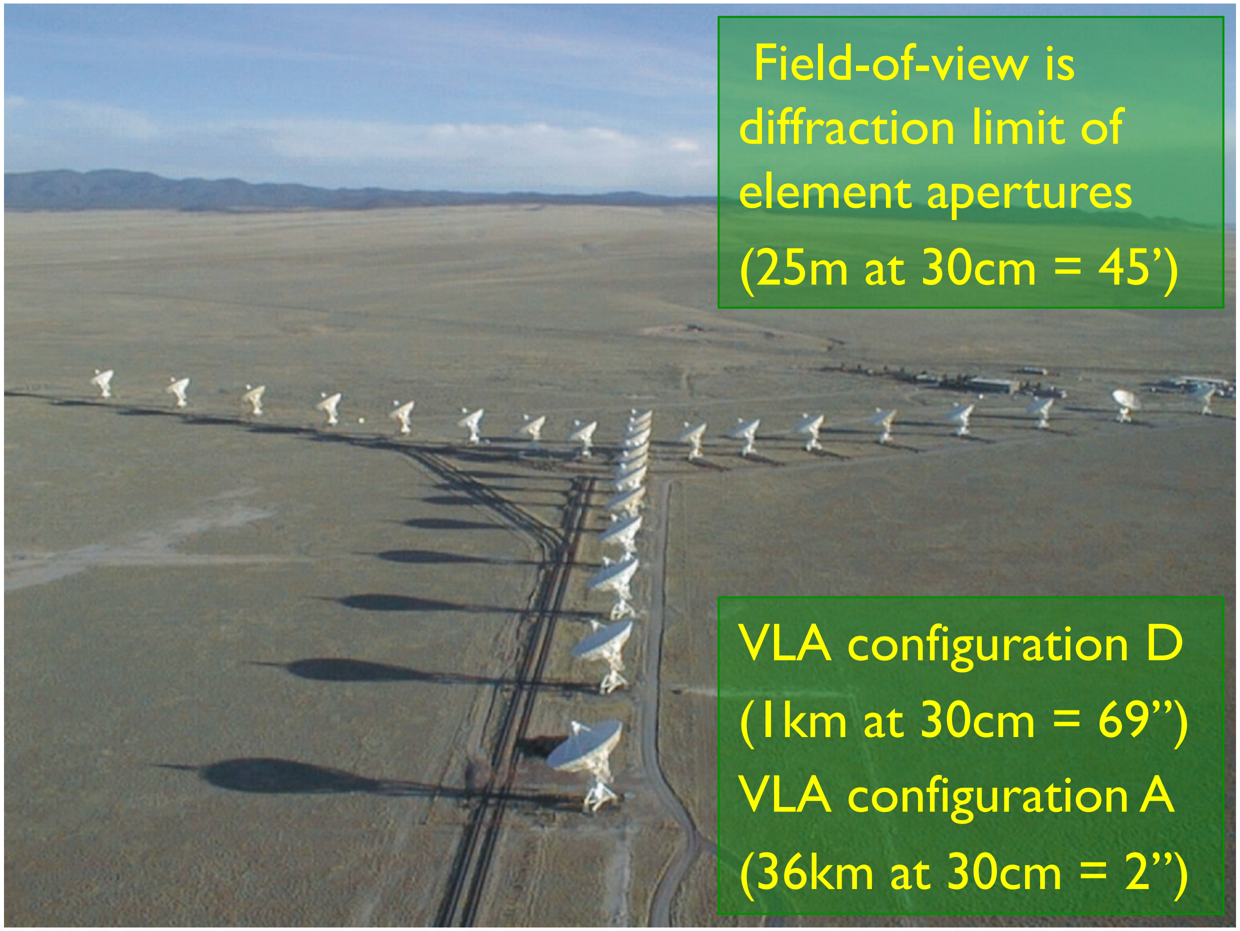
Arecibo Observatory, Puerto Rico 300m aperture

Or … you could build this!

- The Karl G. Jansky Very Large Array in 1km D-configuration
  - 27 antennas of 25m aperture, in New Mexico

Or … you could build this!

- The Karl G. Jansky Very Large Array in 1km D-configuration
  - Resolution of 1000-m aperture, area of 130m aperture



I.
The Jansky Very Large Array

The Karl G. Jansky Very Large Array 58MHz-50GHz in 35m-36.4 km

The Karl G. Jansky Very Large Array

- Located: plains of San Agustin, 50mi from Socorro NM (el. 2100m)
- 27 antennas, fiber-linked interferometer
  - Digitized at antenna(8/3bit), WIDAR correlator (NRC-DRAO)
- 25m diameter antennas – Field of View 45' at 1GHz (1' at 45GHz)
- Reconfigurable into 4 "array configurations"
  - D-configuration: B_{max} 1.03 km, θ_{res} 23" (at 3GHz, robust wt.)
  - C-configuration: B_{max} 3.4 km, θ_{res} 7.0"
  - B-configuration: B_{max} 11.1 km, θ_{res} 2.1"
  - A-configuration: B_{max} 36.4 km, θ_{res} 0.65"
- Cassegrain Focus: directed using rotating shaped subreflector
  - 1-50 GHz in 8 bands using "single-pixel" wide-band feeds
- 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?)

The Expanded Very Large Array (EVLA)

…is a major upgrade of the Very Large Array, now the **Karl G. Jansky VLA**

- improves all capabilities of the VLA -- except spatial resolution -- by at least an order of magnitude.
  - Full frequency coverage from 1 to 50 GHz (<1 GHz in bands)
  - New digital correlator (WIDAR) with unprecedented capabilities
  - Up to 8 GHz instantaneous bandwidth, 1K to 4M channels
  - ~100 μJy (1σ, 10sec, 1GHz) point-source continuum sensitivity at 5GHz
    - 100 square degrees to 100μJy (1σ) in 50ksec (14h) of integration
  - ~30 mJy (1σ, 1 km/sec, 10sec) line sensitivity at 5GHz
- The Project began in 2001, completed in 2012
  - Counting all sources, a $90M project.
  - EVLA science observing started March 2010

proposal deadlines Feb 1, Aug 1 (twice a year)

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

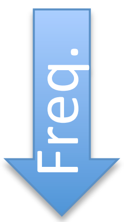
Using the Jansky VLA for Large Surveys

- Inherent strengths provided by the Expanded VLA Project
  - Wide instantaneous bandwidths (2 GHz@8bit and 8 GHz@3bit)
  - Full (dual circular from 1-50 GHz) 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!!)

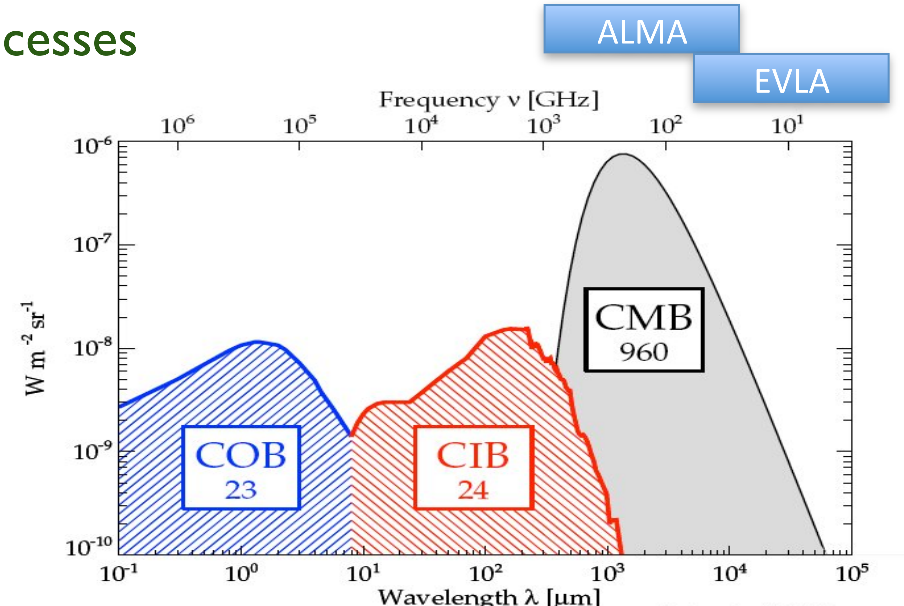
II.
Jansky VLA Survey Science

Radio astronomy in a Nutshell

Thermal & Non-thermal radiation processes



- Synchrotron emission. MeV-GeV electrons. HE astrophysics
- Plasma propagation phenomena (dispersion, Faraday rotation, interstellar scattering)
- Hyperfine atomic hydrogen line
- Thermal bremsstrahlung (ff) and atomic recombination lines
- Coherent maser lines
- Thermal dust continuum
- Molecular rotational lines (CO)
- Atomic cooling lines (e.g. redshifted C+ at 158 um)

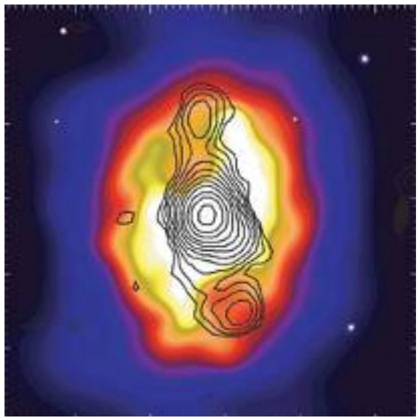


Dole et al 2006

- RMS window is 10 MHz to1THz i.e. five orders of magnitude
- Millimeter/submillimeter photons are the most abundant photons in the cosmic background, and in the spectrum of the Milky Way and most spiral galaxies.

The Universe as a Laboratory

Magnetic Universe



Measure the strength and topology of the cosmic magnetic field.

Obscured Universe

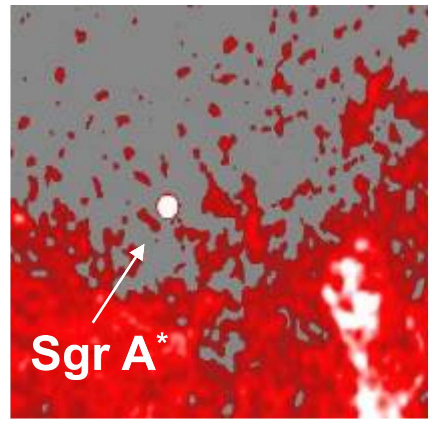
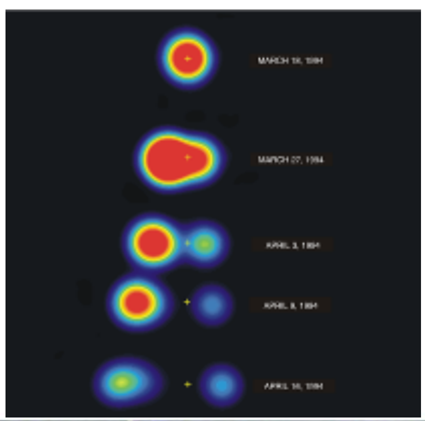


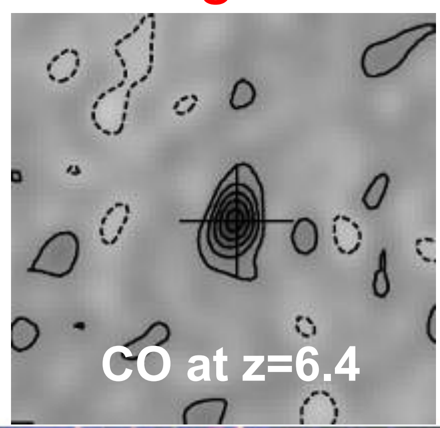
Image young stars and massive black holes in dust enshrouded environments.

Transient Universe



Follow the rapid evolution of energetic phenomena.

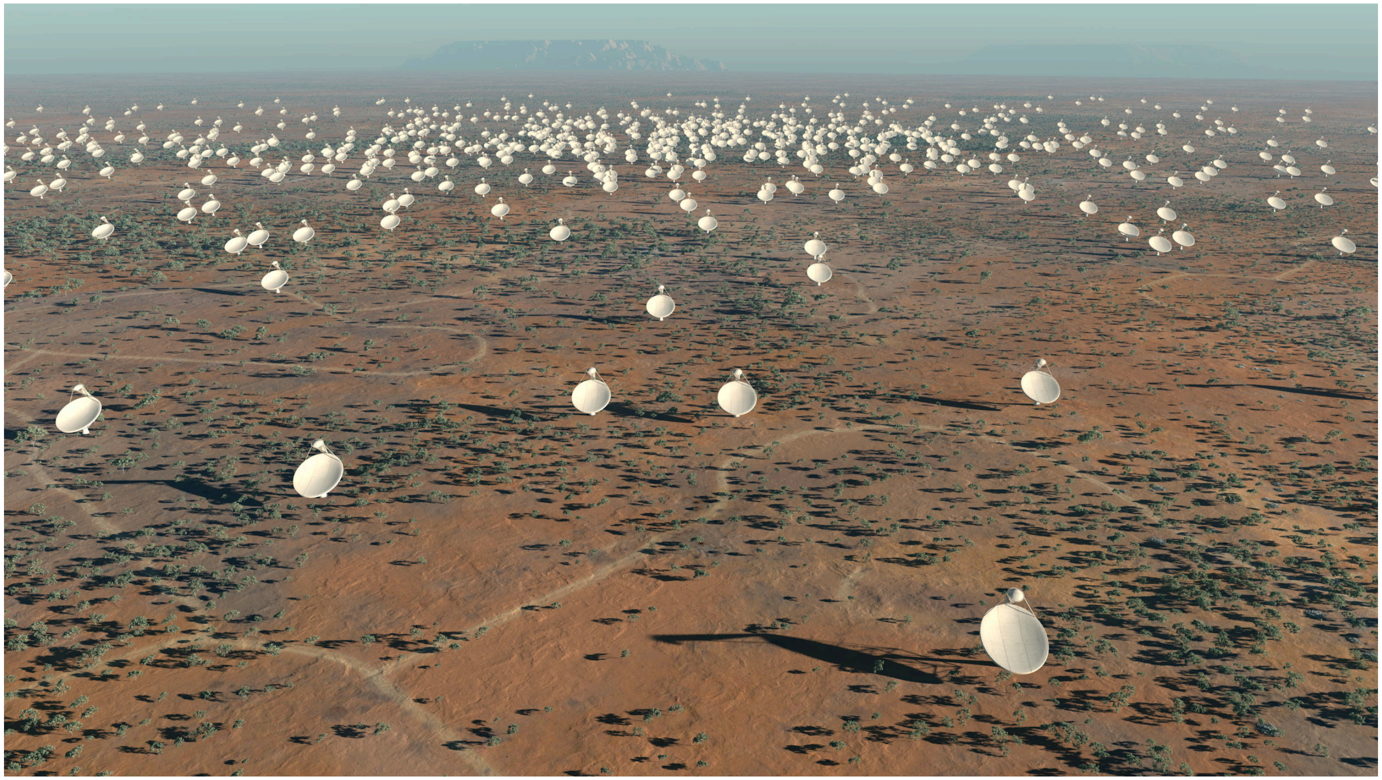
Evolving Universe



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

The Jansky VLA as a Proving Ground

- Science observing since March 2010 – from Lab to Sky
- Future possibilities – the road towards the Square Kilometre Array and the LSST next decade – the Jansky VLA is a SKA Science Proving Ground!



Artist's impression of the SKA dishes. Credit: SKA Organisation/TDP/DRAO/Swinburne Astronomy Productions

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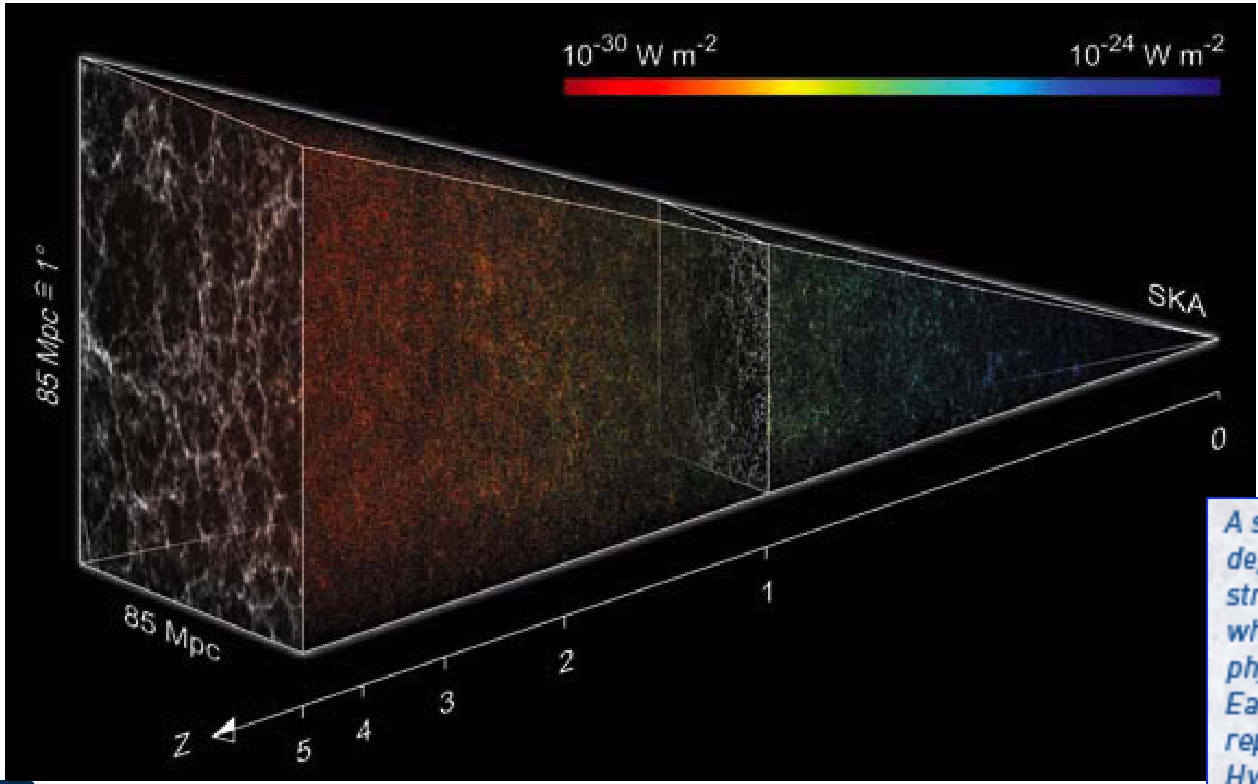


A simulated SKA observing cone depicting the complex filamentary structure of HI on cosmic scales, which encodes the mysterious physics of the "Dark Universe". Each coloured pixel in the cone represents a galaxy emitting neutral Hydrogen (HI, rest-frame 21-cm) radiation.
(Credit: Danail Obreschkow (Oxford)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

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

Key Radio Line & Continuum Probes

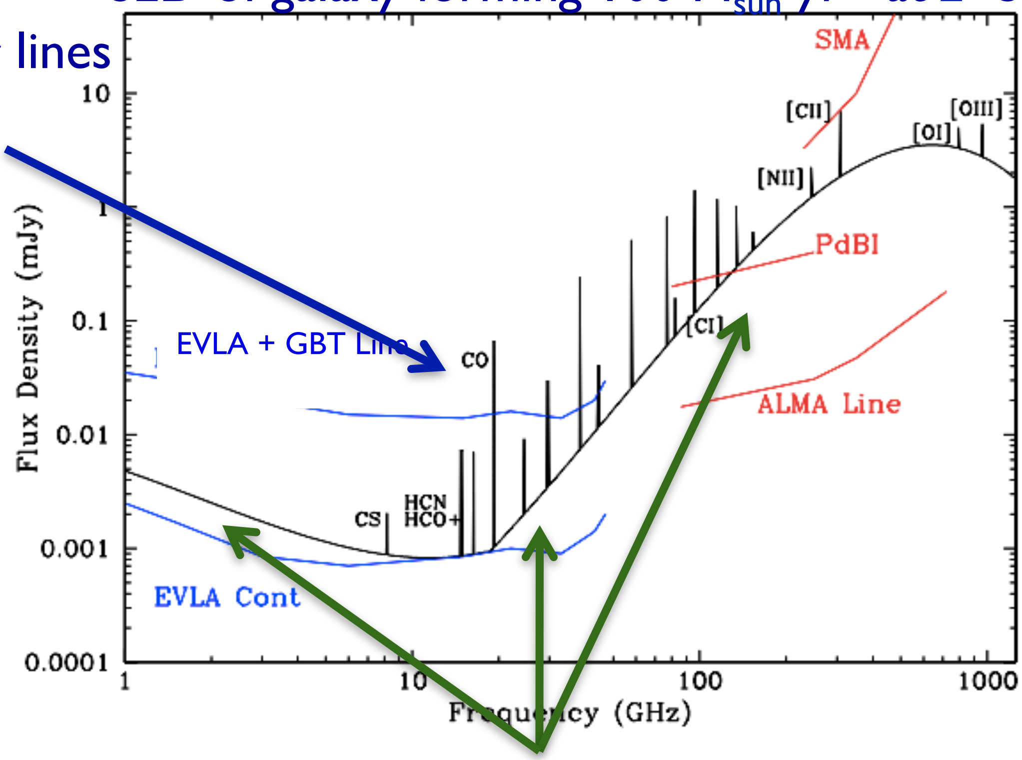
1. Atomic Hydrogen (weak transition) :
   - "21cm" HI line (rest 1.42 GHz, z=0.42 at 1GHz, z=1.5 at 568 MHz)
   - single line in "clean" part of spectrum (beware OH interlopers)
2. Molecular CO (strong transition) :
   - CO ladder (1-0 rest 115.27 GHz, z=1.5 at 46.11 GHz, 230GHz,345GHz…)
   - no redshift ambiguity for multiple transitions, danger: forest of weaker lines
3. Other lines :
   - Masers like OH (1665/7 MHz), Methanol (6.7,19.9GHz), $H_2 0$ (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

Cosmic Lab: Line & SED Probes for Galaxy Evolution

Low-J molecular lines

- Total H2
- Dense gas
- Dynamics

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



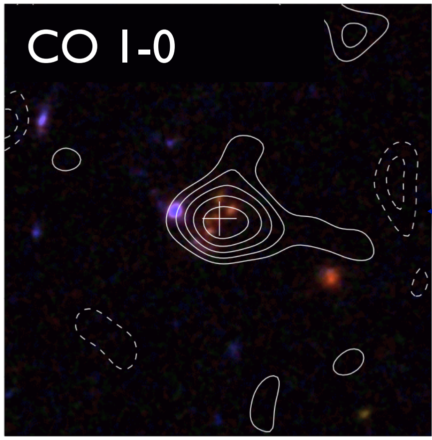
VLA = ALMA science at high redshift and in obscured regions!

Continuum (dust, free-free, synchrotron)

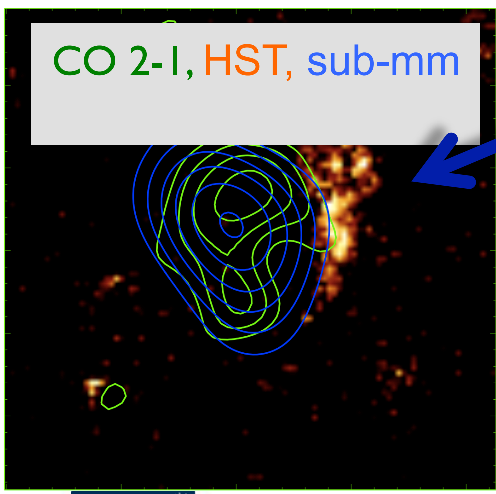
- SFR, ISM distribution, dust abundance

Cosmic Lab: A Molecule-Rich Protocluster @z~4

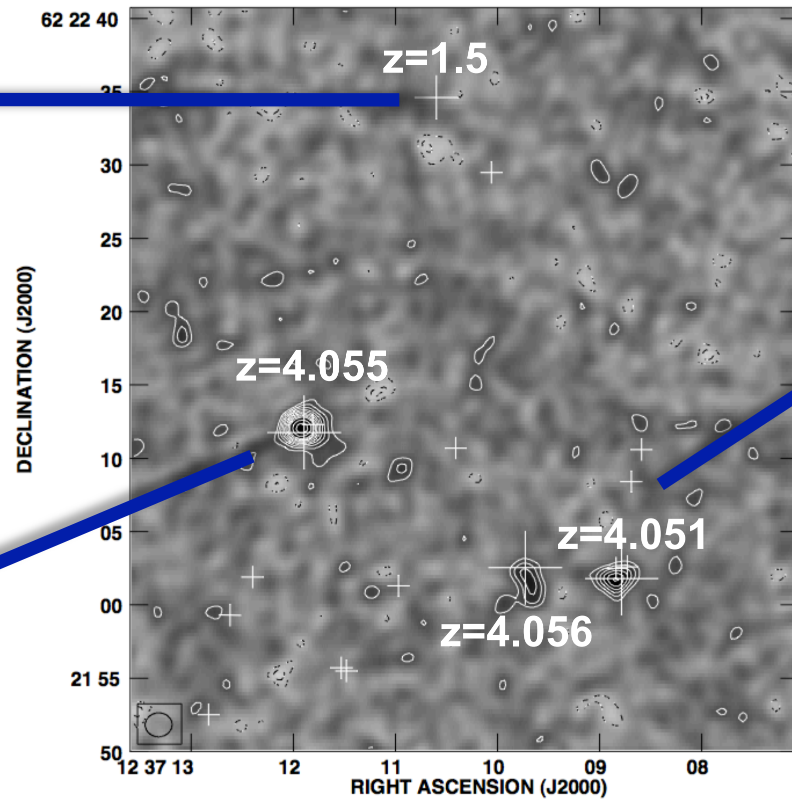
Foreground sBzK galaxy



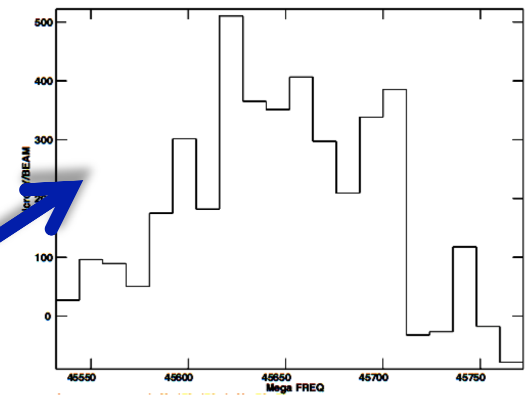
Imaging CO 2-1



46 GHz Observations of GN20



CO 2-1 Spectroscopy



Wide Bandwidth = Large Redshift Range

CARILLI ET AL. (2011)

Cosmic Lab: Late Integrated Sachs-Wolfe

- Decay of potentials in LCDM cause signature in CMB
  - Cross correlate CMB with large-scale structure tracers
  - WMAP and Planck (2013 Paper 19) used NVSS (3-5σ)

Planck Collaboration: The ISW effect with *Planck*

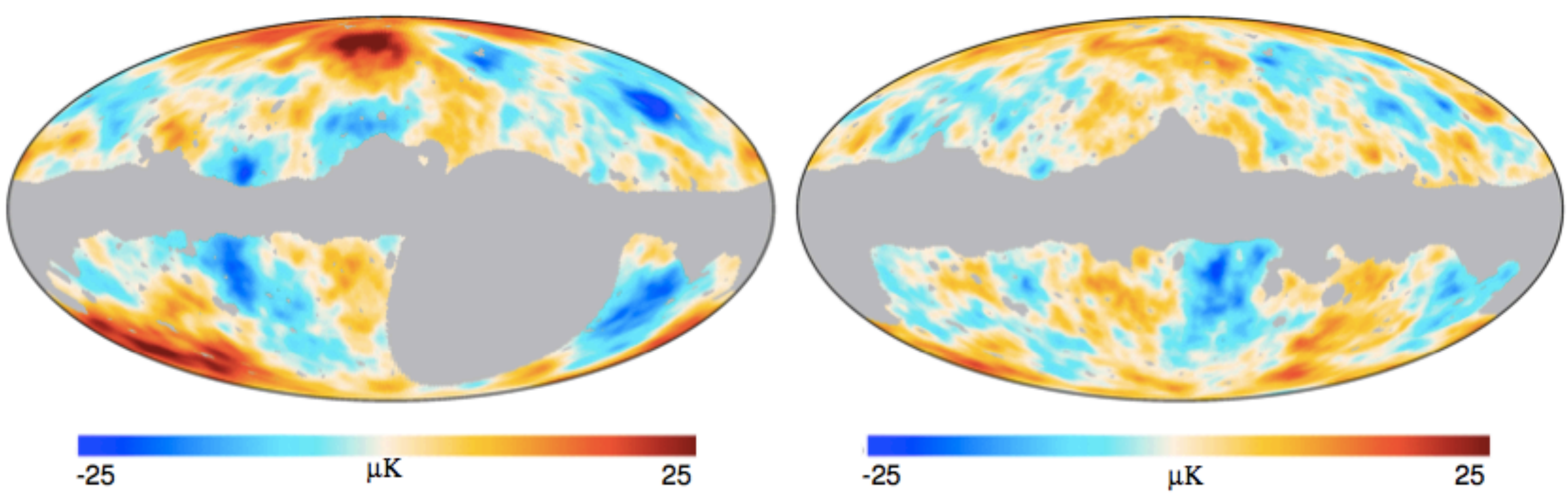
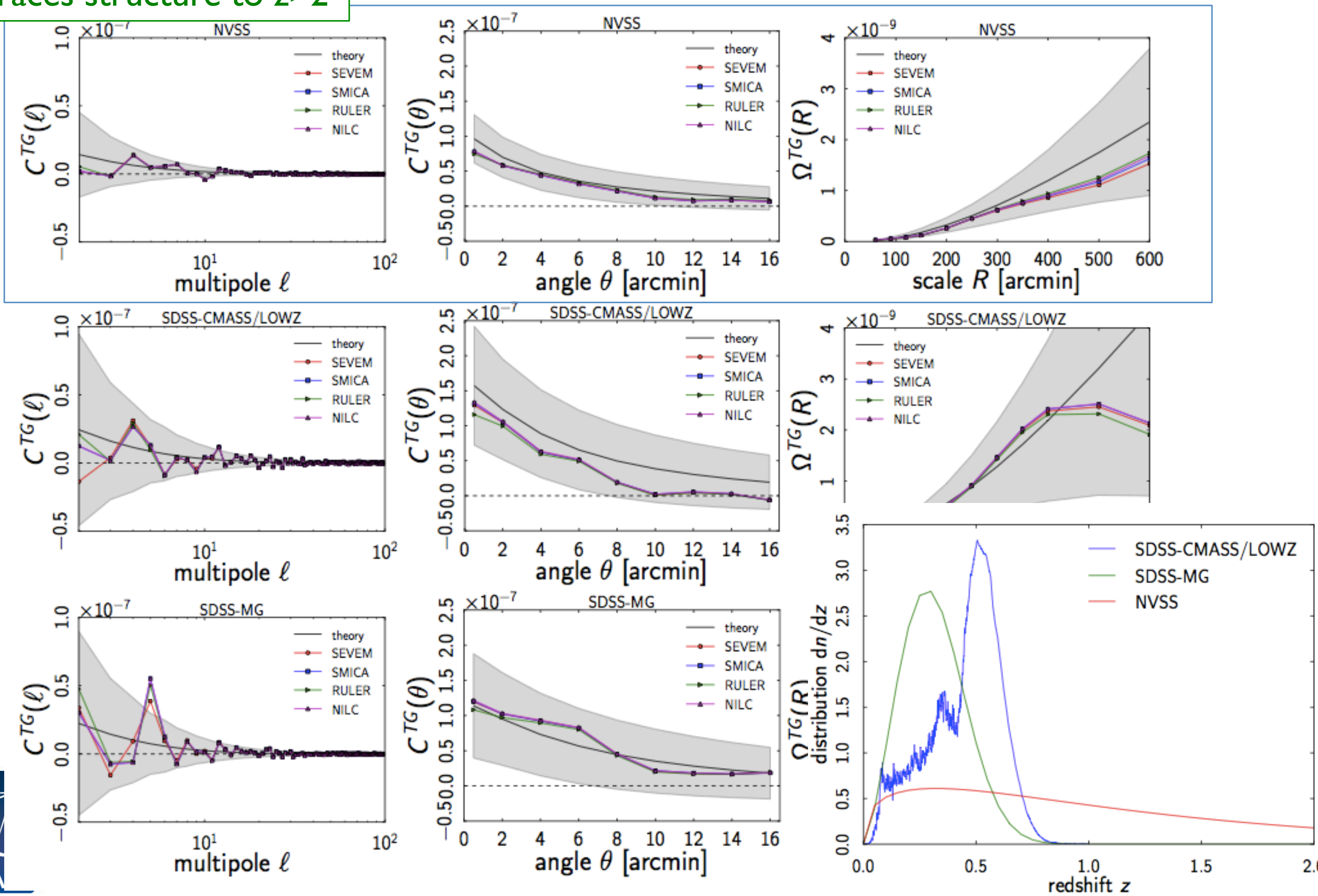


Fig. 11. Reconstructed ISW map from the *Planck* CMB and NVSS data (left) and from the *Planck* CMB and lensing potential maps (right). Note that the maps are not expected to look exactly the same, since each of them provides a partial reconstruction of the noisy ISW signal (see Sect. 6.2 for details).

Cosmic Lab: Late Integrated Sachs-Wolfe

NVSS traces structure to z>2

Planck Collaboration: The ISW effect with *Planck*



Cosmic Lab: Untangling the Cosmic Web

SKA Proving Ground – 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 object catalogue from images & image cubes
    - Identification of AGN versus star-forming and normal galaxies

NRAO

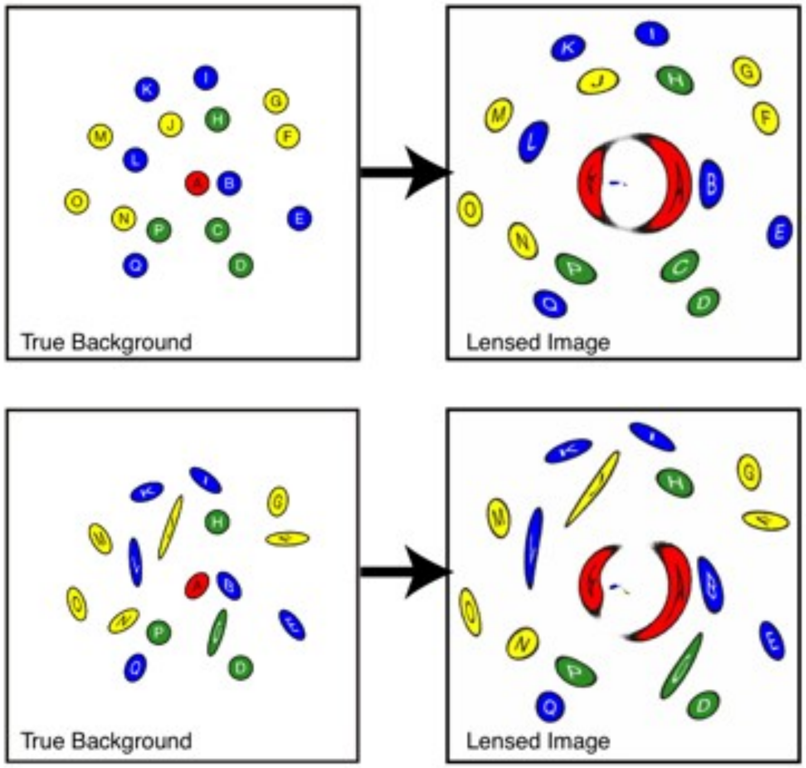
Cosmic Lab: Radio Weak Lensing

- 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)

Core of mass profile produces strong lensing arcs (Einstein radius)

Tangential shear (stretch) in outer weakly lensed regions

Look for presence of coherent shear signal above (random?) intrinsic shapes



From Williamson et al. 2007

Cosmic Lab: Radio Weak Lensing

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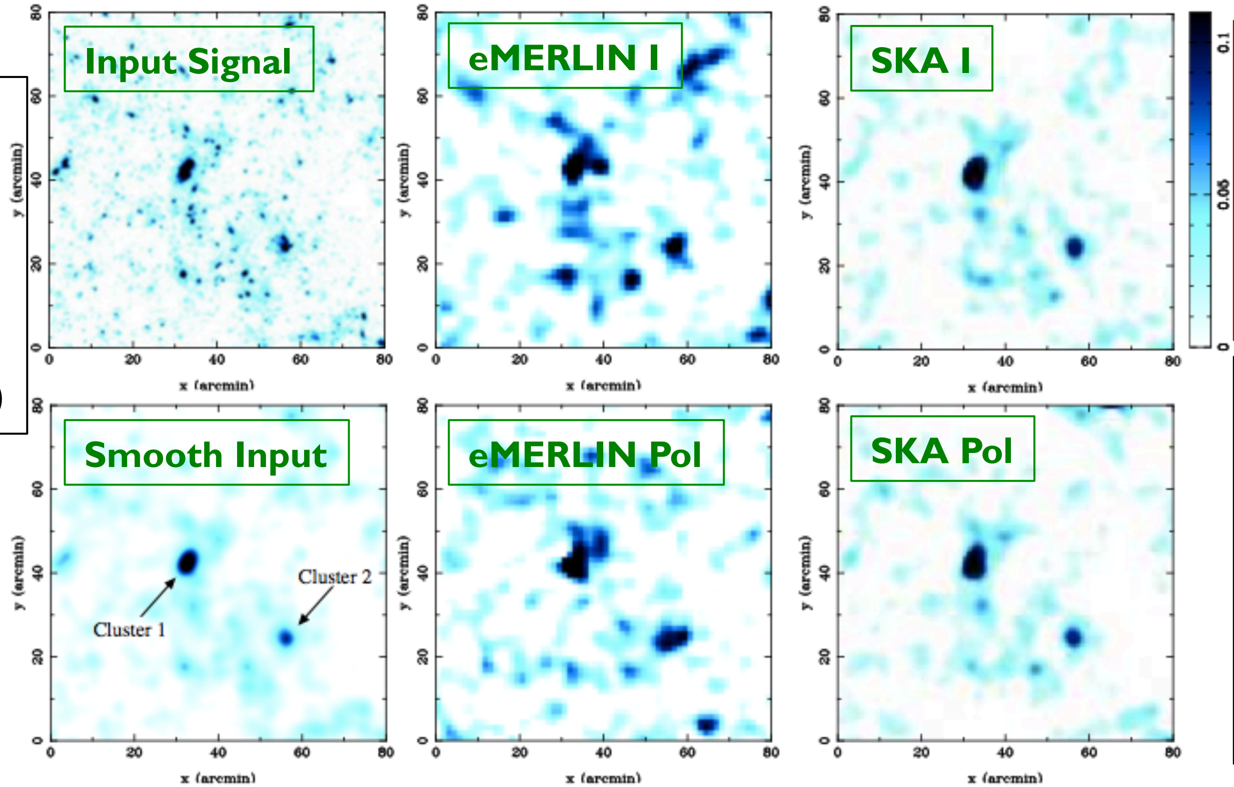
Now:
eMERLIN
plus VLA
SuperCLASS
(Brown et al.)



M. Brown 2012
arXiv:1206.4437

Brown & Battye
2011 ApJL 735 23

Simulated reconstruction of mass density in supercluster of $\sim10^{14}$ $M_\odot$ clusters

Cosmic Lab: Through a Lens Darkly

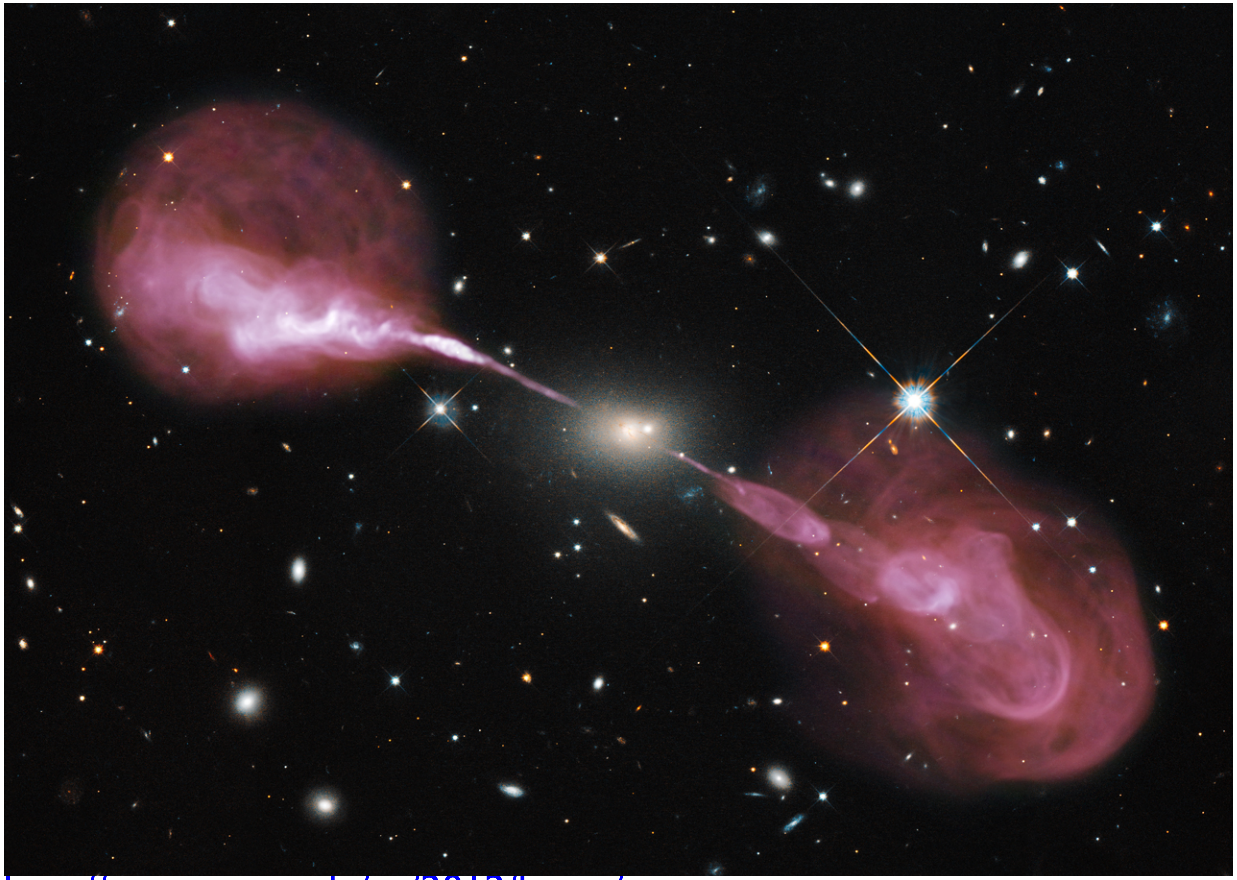
SKA Proving Ground – Strong and Weak Gravitational Lensing

- 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

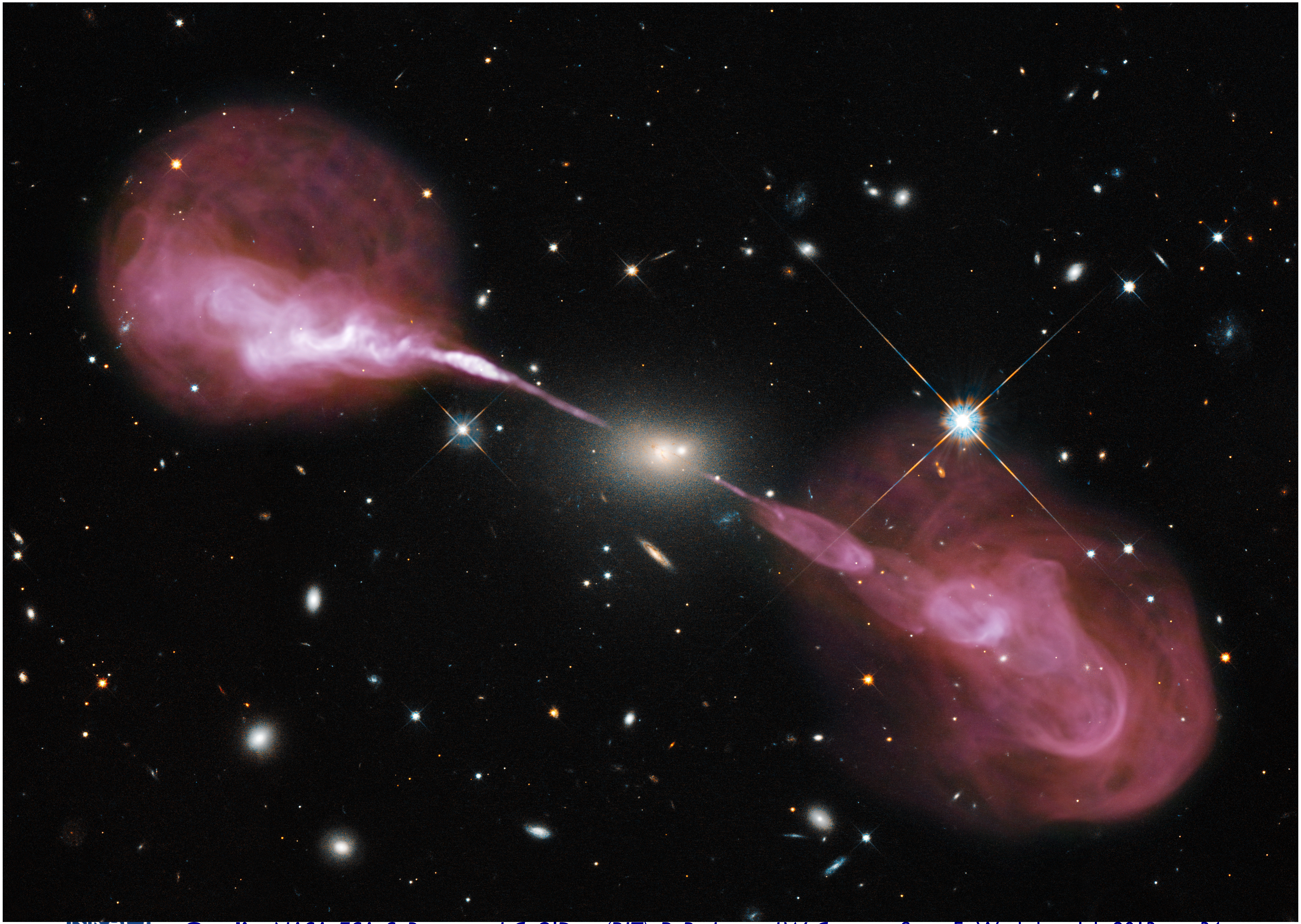
Black Hole Lab: The Case of Herc-A

- Hercules-A: distance ~700Mpc, size ~1Mpc
- Jets show unusual ring-like structures suggesting a history of multiple outbursts.



See: http://www.nrao.edu/pr/2012/herca/

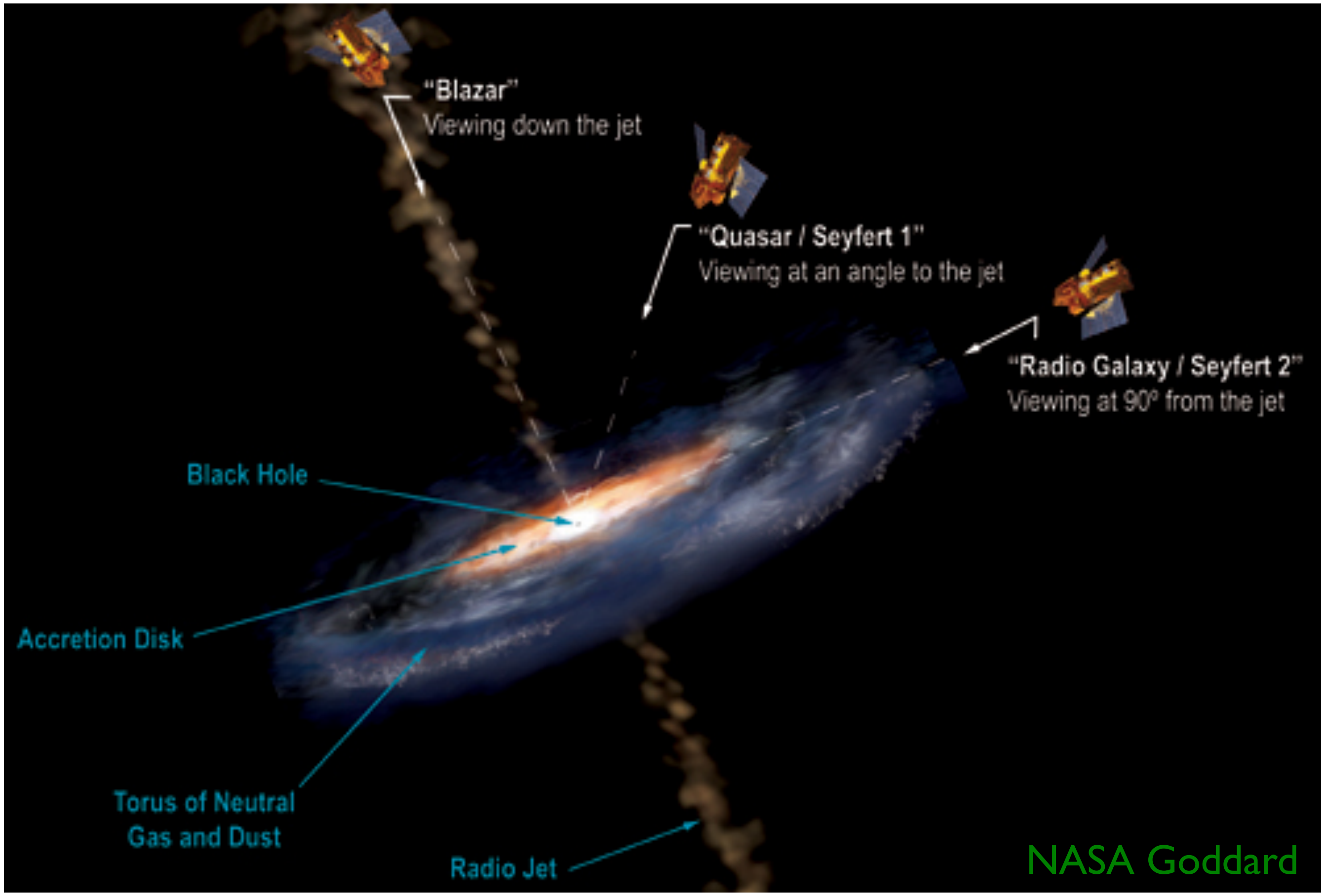
Credit: *NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)*



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)*

Black Hole Lab: AGN jets

- Magnetized Accretion Disk around spinning Black Hole
  - Polar jets of relativistic particles



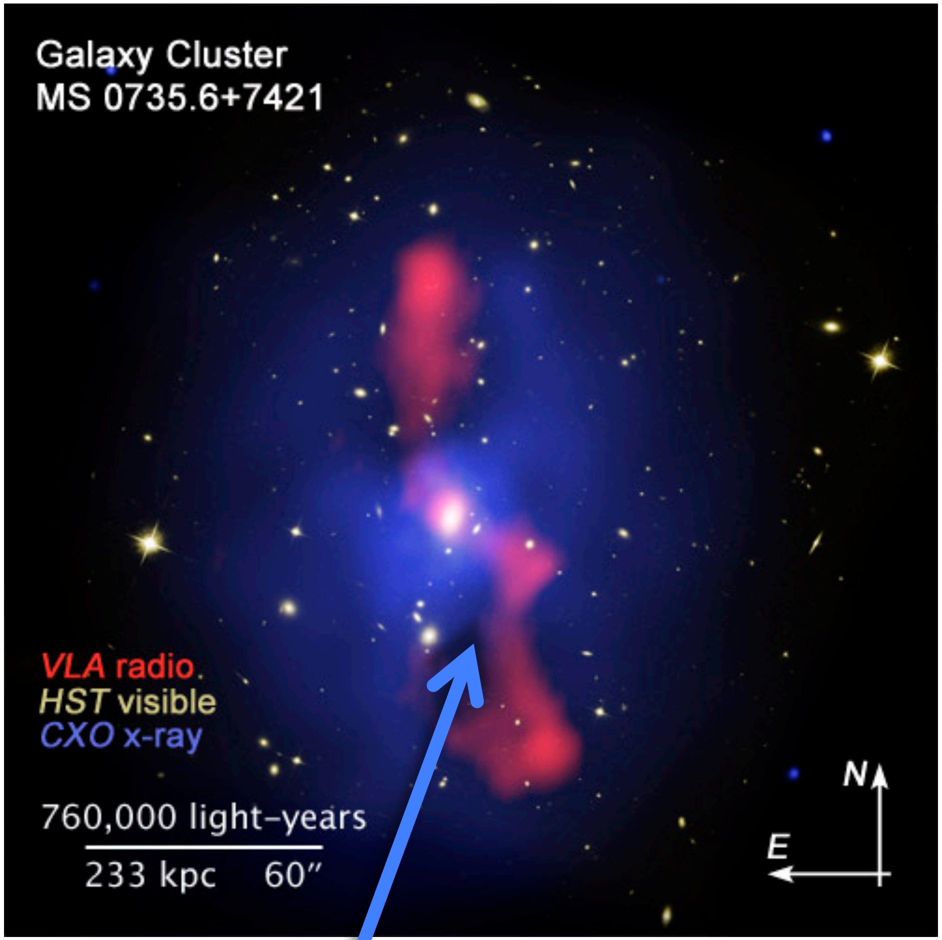
Black Hole Lab: The Unshrouding

SKA Proving Ground – Black Holes Near and Far, Then and Now

- Peering deep into galaxy cores
- Birth and Growth of Super-massive Black Holes (SMBH)
- 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

Cluster Lab: Role of B fields in the ICM



X-ray cavities correspond to radio lobes = feedback?

Deep ignorance on origin and evolution of cosmic B fields

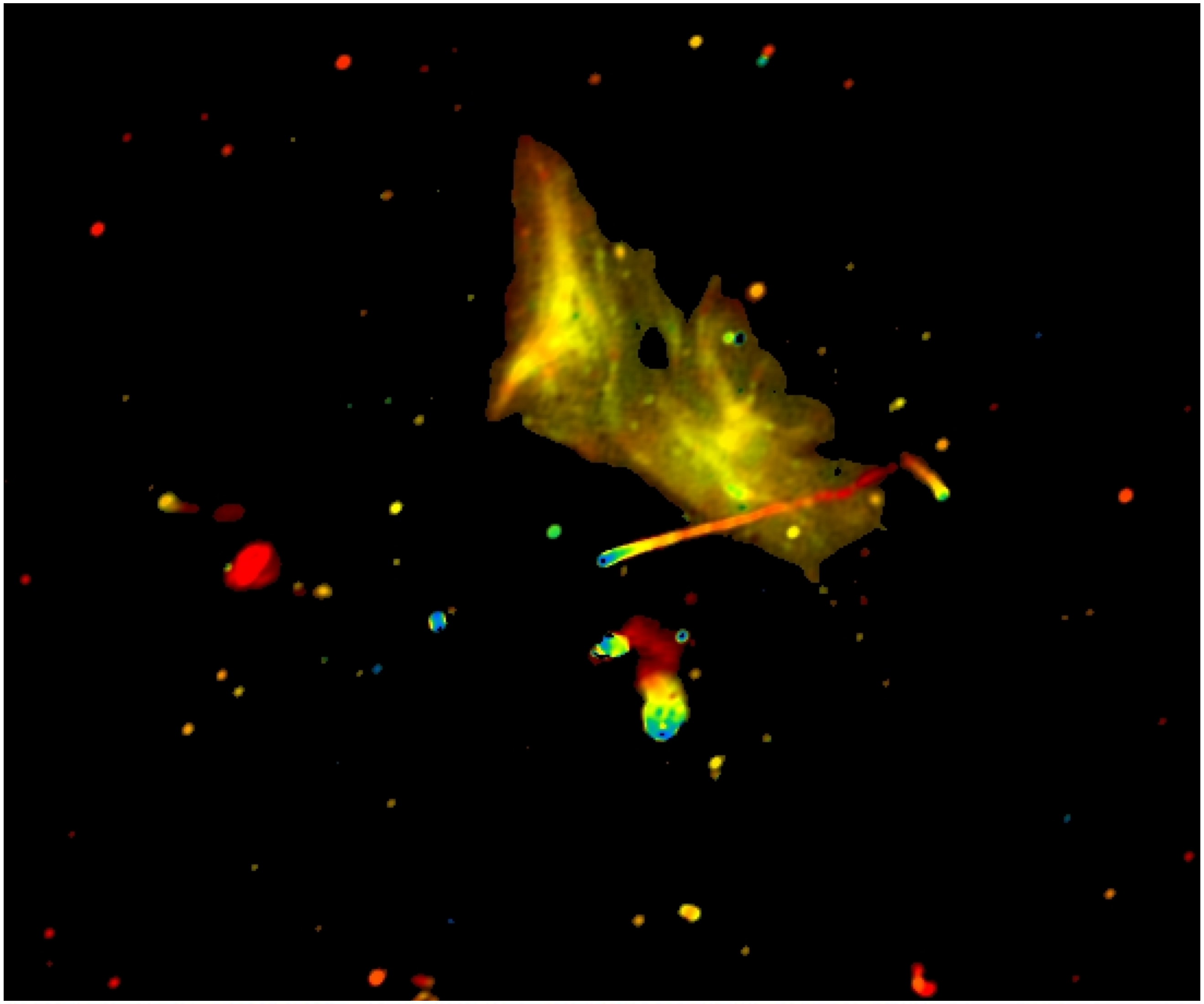
- Affects cosmic ray transport
- Role in cluster gas heating?
- Trace galaxy/cluster interactions

Jansky VLA capabilities

- Increased sensitivity to field direction and fractional polarization via synchrotron
- Increased spectral resolution allows field strength estimates via rotation measure

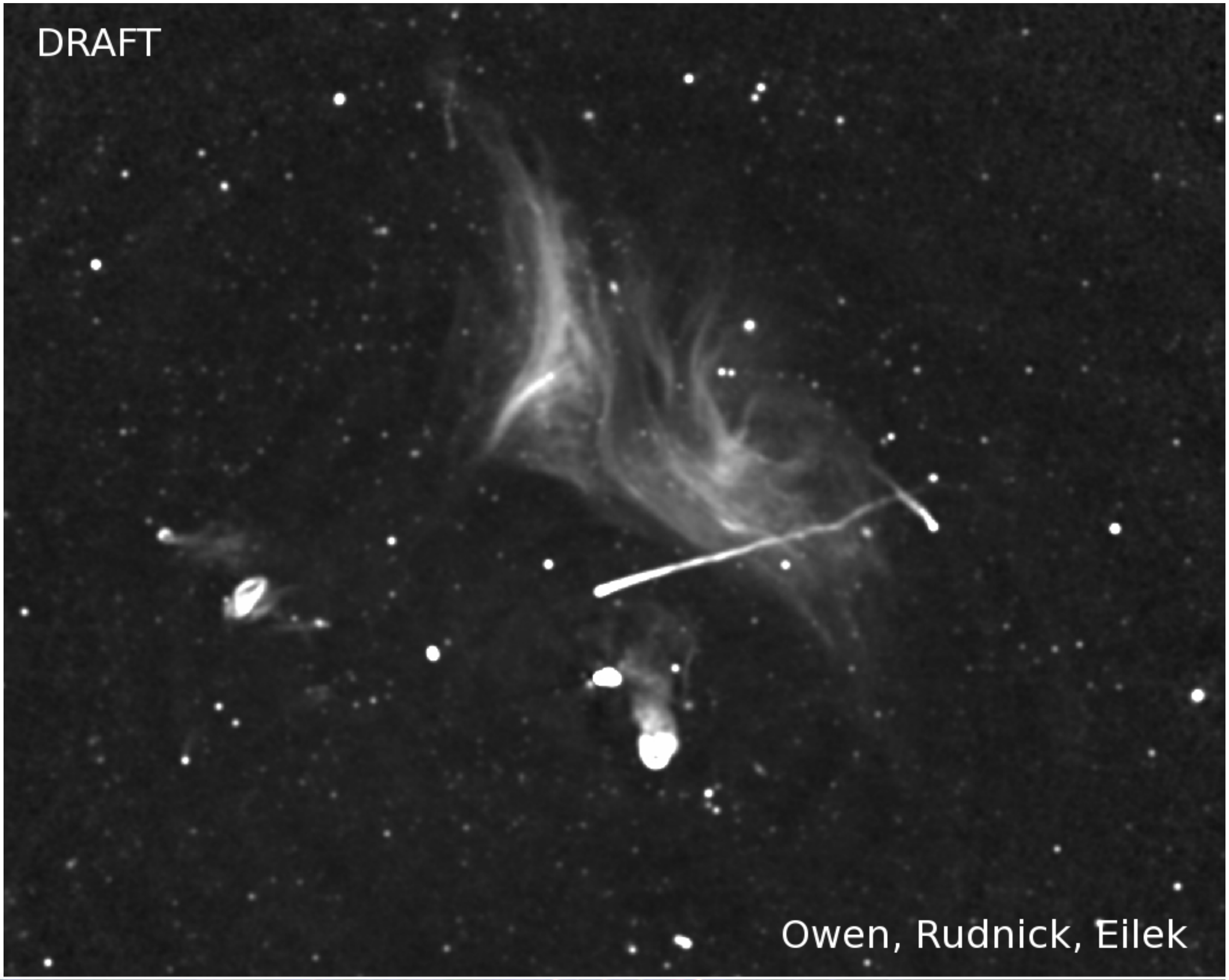
Cluster Lab: Relics and jets in Abell 2256

- Courtesy F. Owen, L. Rudnick, K. Eilek, U. Rau, S. Bhatnagar, L. Kogan
- 1–2 GHz, 20-arcmin on a side; color corresponds to spectral index (multi-term MFS)
- 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?



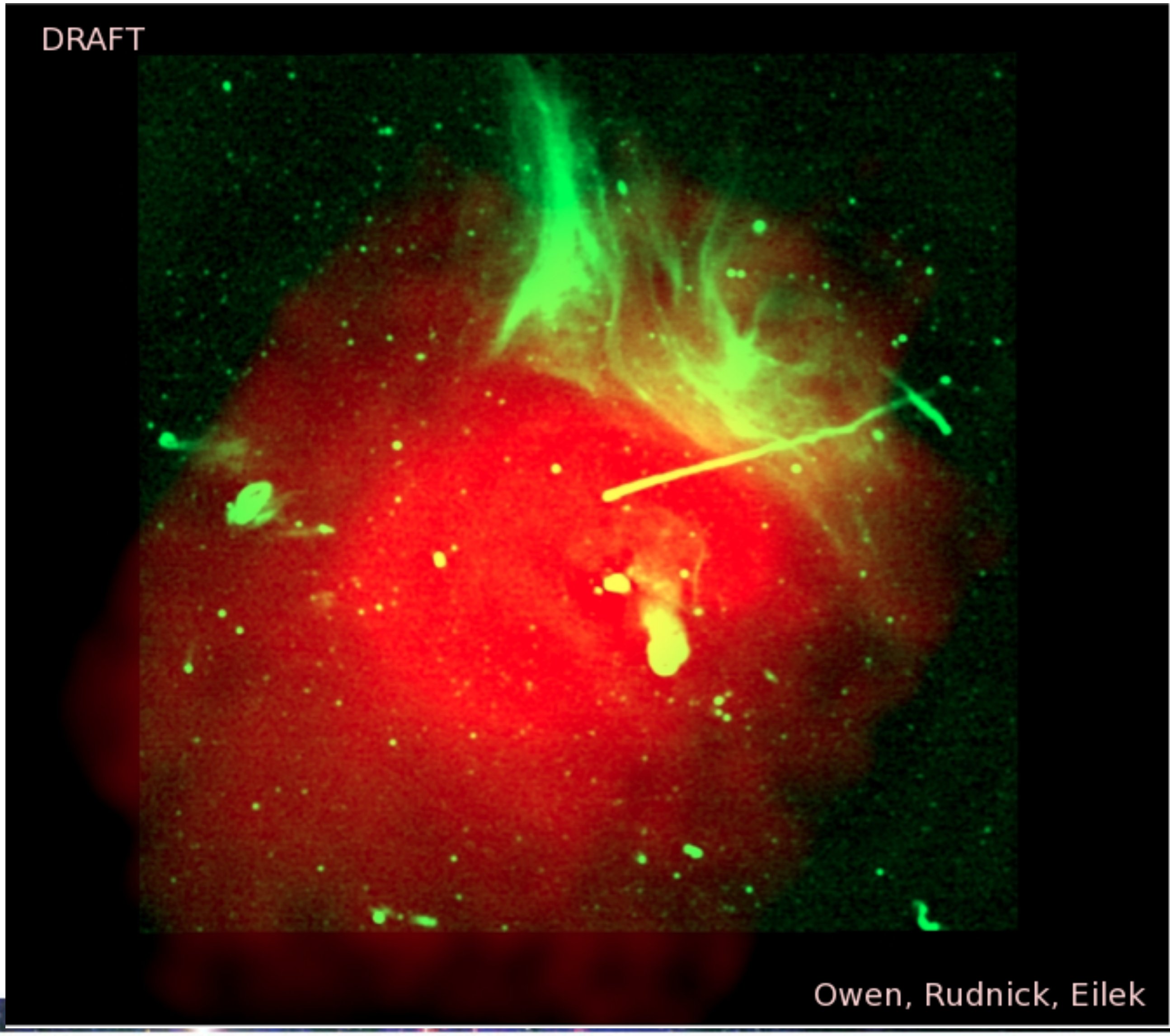
Cluster Lab: Relics and jets in Abell 2256

- Courtesy F. Owen, L. Rudnick, K. Eilek, U. Rau, S. Bhatnagar, L. Kogan
- High-resolution (A-configuration) radio
- Filamentary structure in large relic shock region
- Very long narrow jet unresolved



Cluster Lab: Relics and jets in Abell 2256

- Courtesy F. Owen, L. Rudnick, K. Eilek, U. Rau, S. Bhatnagar, L. Kogan
- High-resolution (A-configuration) radio
- X-ray ICM emission in red
- Filamentary shock region outside core of cluster. Merger?



Cluster Lab: Massive Attack

SKA Proving Ground – Spiders in the Cosmic Web

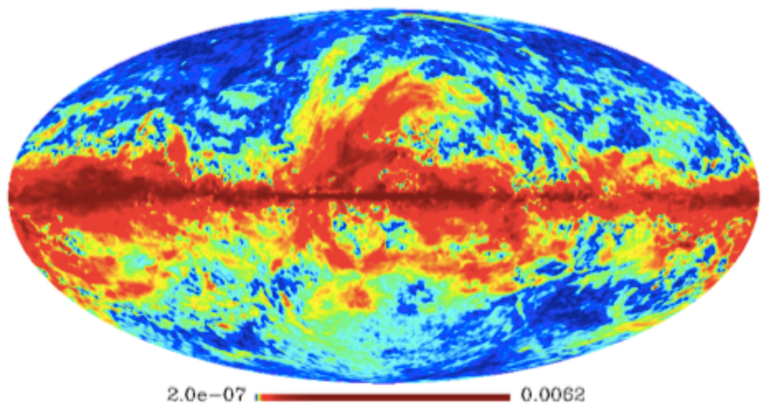
- Shocks due to merging clusters
- Linking AGN activity and feedback into cluster IGM
- Weighing clusters with Gravitational Lensing weak and strong

- Key Capabilities
  - Wide-band wide-field (multi-band) imaging
  - Observations of fields with good multi-wavelength coverage
  - Deep high-resolution observations for probing shocks
  - Deep high-resolution observations for weak lensing shapes
- Key Developments
  - Multi-spectral term Multi-Frequency Synthesis imaging

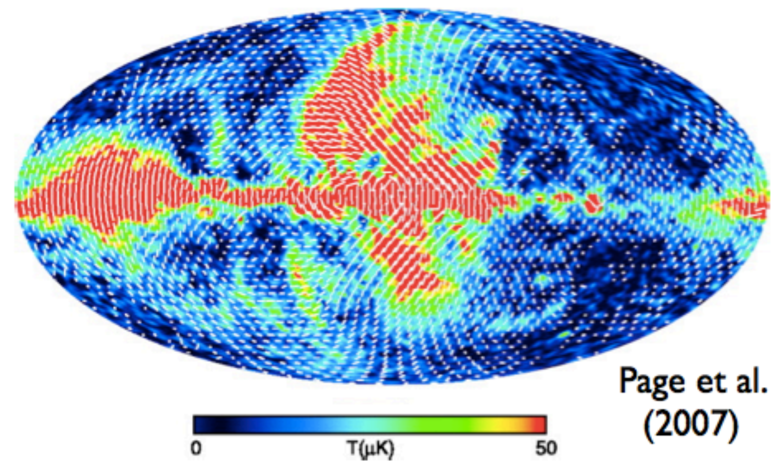
Magnetic Lab: Large-Scale Polarized Sky

- Degree-scale structure (WMAP, Planck, various)

P from Planck 353 GHz at 1° resolution

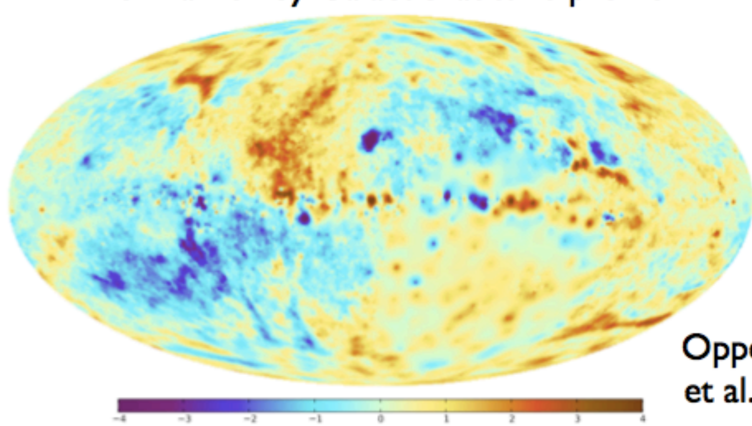


P from WMAP 23 GHz



Page et al. (2007)

Map of Faraday rotation measure normalized by Galactic latitude profile

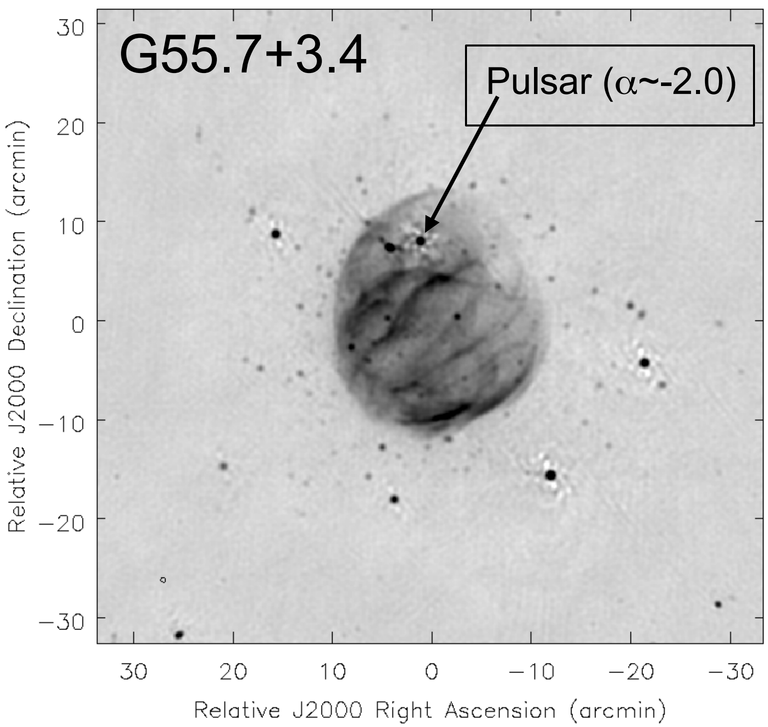


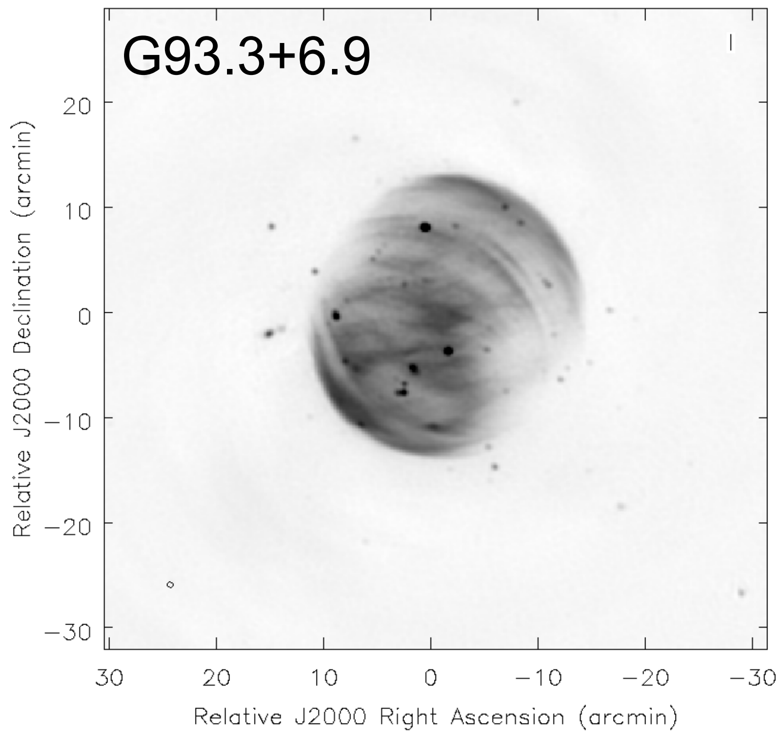
Oppermann et al. (2012)

From presentation by F. Boulanger (courtesy Google search)

Dominated by our galaxy…

Magnetic Lab: Supernova Remnants

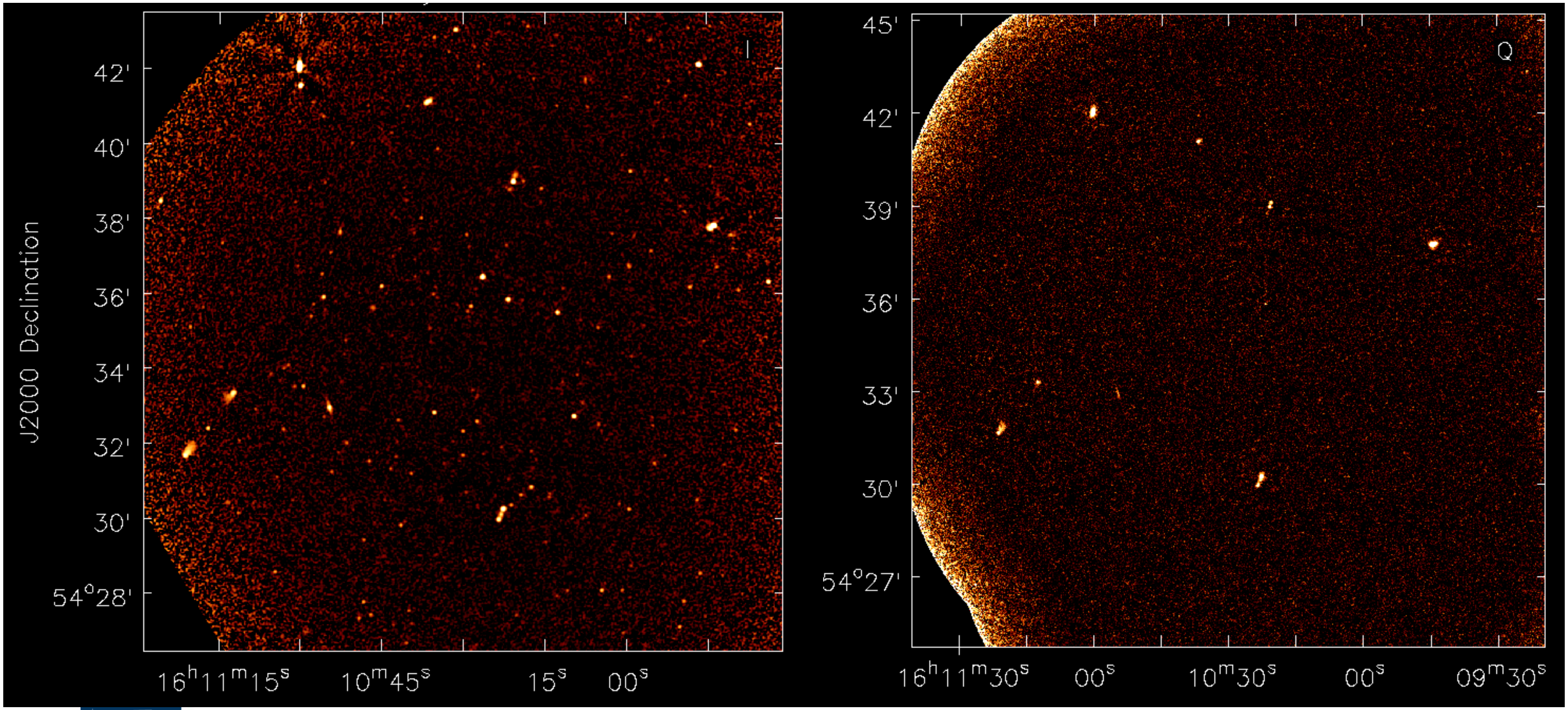




- Wide-band Galactic Plane survey pilot (Bhatnagar, Green, Rau, Golap, Rupen & Perley)
  - Stokes-I images with EVLA @ L-Band, BW~600MHz (RMS ~30 μJy/Beam)
  - Imaging done using MS-MFS (Rau, PhD thesis, 2010) and A-Projection in CASA

Magnetic Lab: Polarization Surveys

- C-array 4-6GHz Survey ELAIS N1 (P. Jagannathan, R. Taylor, UCalgary)
  - 10 pointings, 84 hours, image rms 1.9μJy (*left:* I, *right:* P)



Magnetic Lab: Faraday Tomography

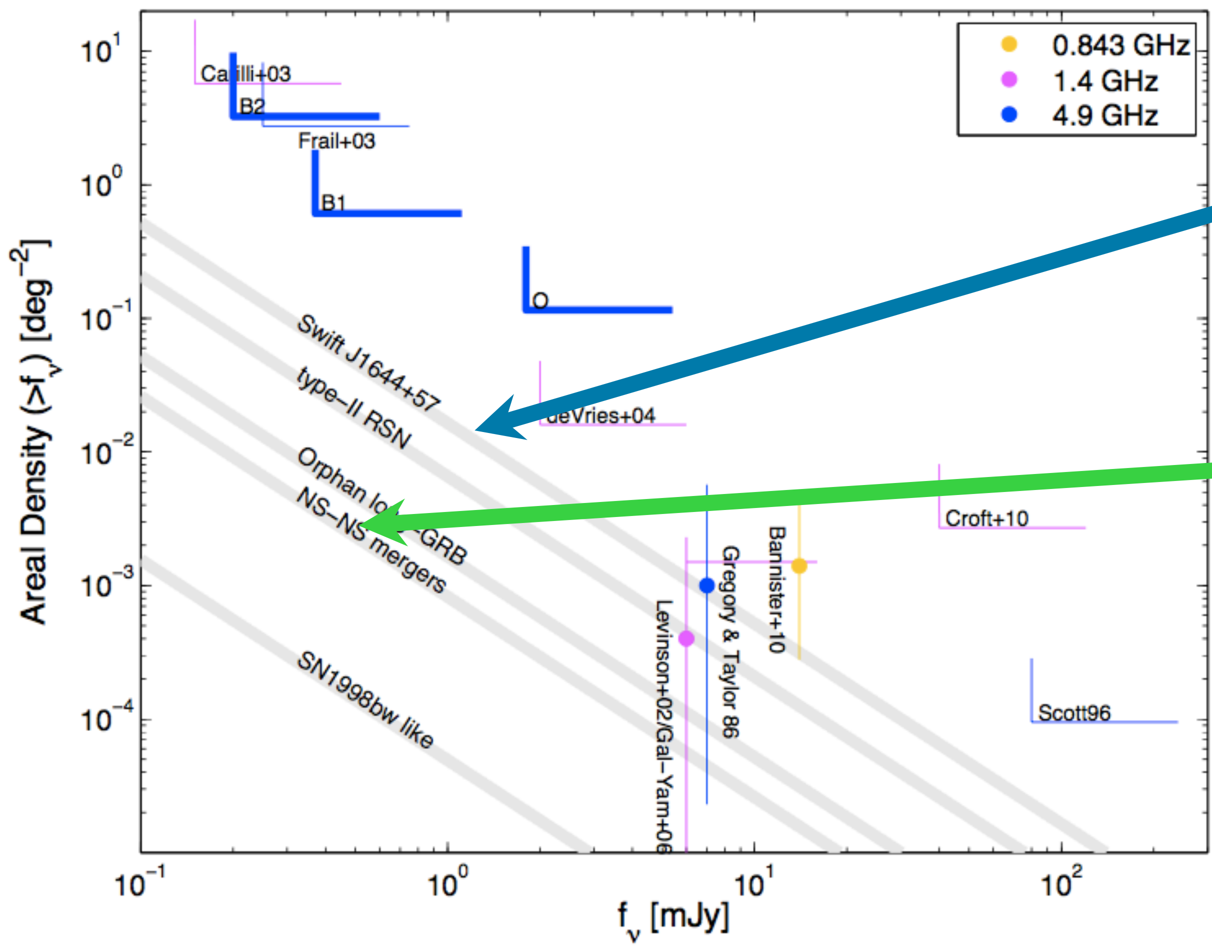
SKA Proving Ground – Jansky VLA Faraday Rotation Survey
  - Measure magnetic fields in galaxies and in the Cosmic Web
  - Role of B-fields in ISM, IGM, and ICM
  - Impact of B-fields on star, galaxy, SMBH, and structure formation
  - Origin and evolution of cosmic magnetism
- Key Capabilities
  - Wide 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

Transient Lab: Radio Transients and Bursts

- Many radio sources show variability on ranges of timescales due to intrinsic and propagation effects (pulsars, AGN, stars)
  - Timescales generally tied to rotation period or light travel time (Doppler corrected) across emitting region for intrinsic variability
  - Timescales for refractive and scintillation effects much shorter and due to interference of "rays" from object to us through ISM (or IPM)
- Some sources, particularly due to energetic explosive events, show a radio burst and/or transient afterglow (SNe, GRB, etc.) then fade away = transient
- We generally consider observational classes of transients:
  - Fast transients: timescales seconds or less (prompt bursts)
    - You see the explosive event itself
  - Long-duration transients: timescales days or longer (e.g. afterglows)
    - You see the aftereffects of the event as it expands and interacts

Transient Lab: Long Duration RTs

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



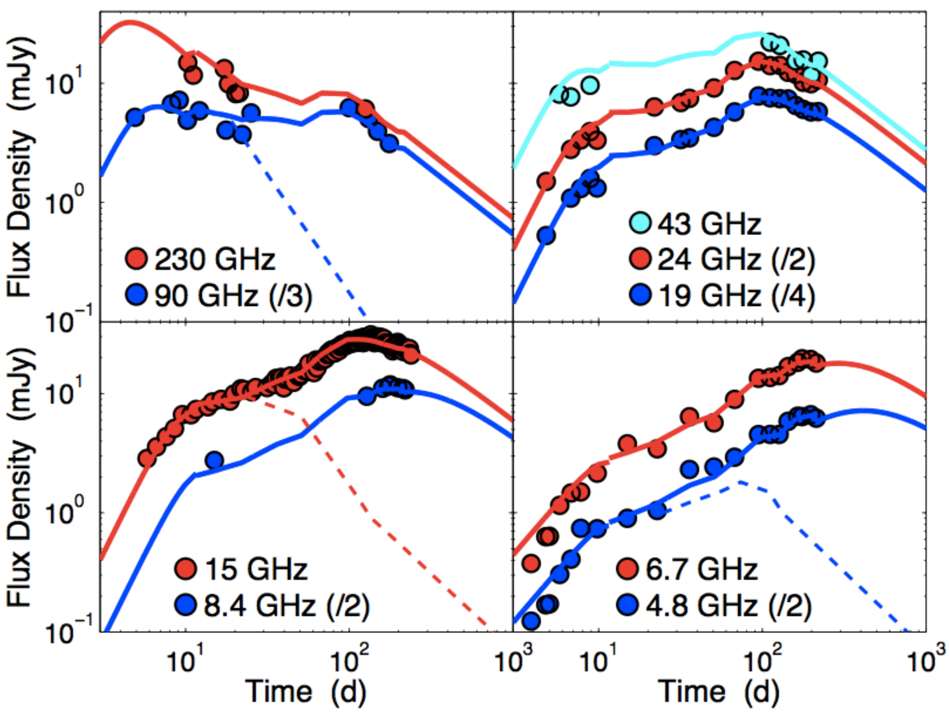
TDE: Zauderer etal. 2011, Berger etal. 2011 (timescale mos. to yrs.)
Only the tip of the iceberg!

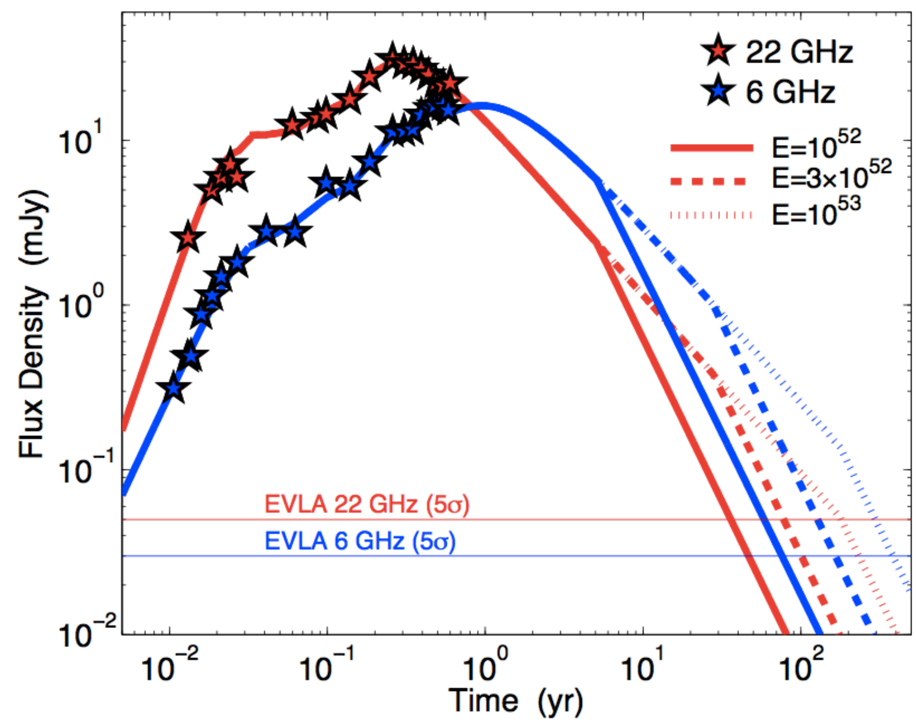
13B-370 Hallinan etal.
300 deg^2 at 80μJy
B-config 150hrs
3 epochs, 46μJy added

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

Transient Lab: 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 of explosion (kinetic) energy





Transient Lab: A Multiwavelength Approach

- A multi-wavelength and/or multi-messenger approach is needed to identify and characterize the explosion sites, progenitors, and aftereffects of the bursts.
  - Future example: the EM counterparts to Gravity Wave events
  - Classic example: Gamma-Ray Bursts and afterglows (localization & ID!)
  - Current example: properties of unusual Supernovae and TDEs

Now showing: VLA monitoring of SDSS Stripe 82!

  - Proof of concept and prototype for larger VLASS sub-surveys
  - Example of multi-wavelength co-observing and triggering

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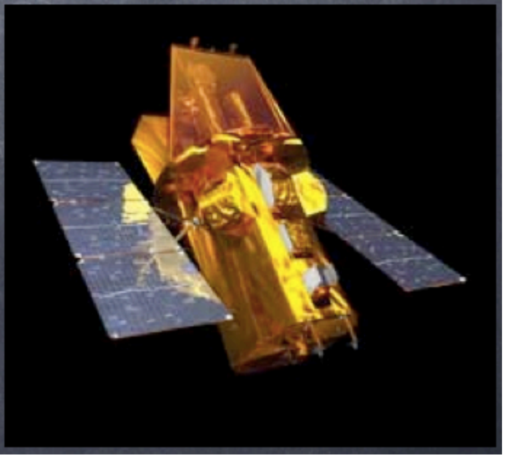
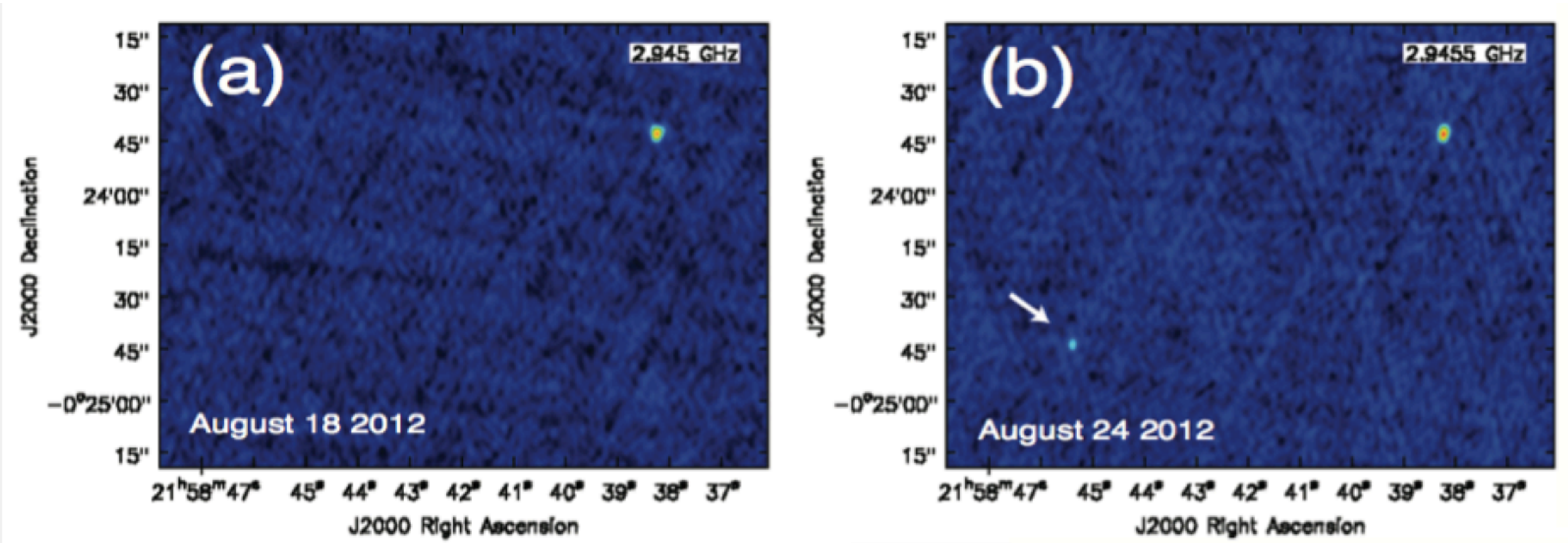
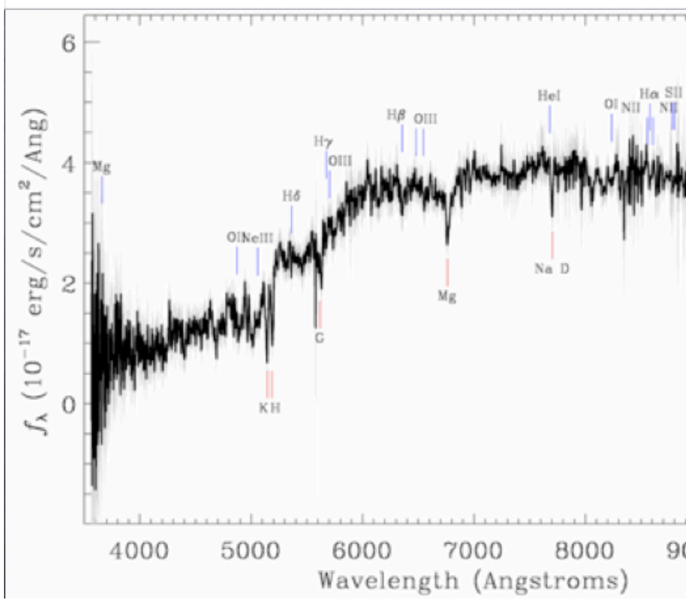
Transient Lab: A Multiwavelength Approach

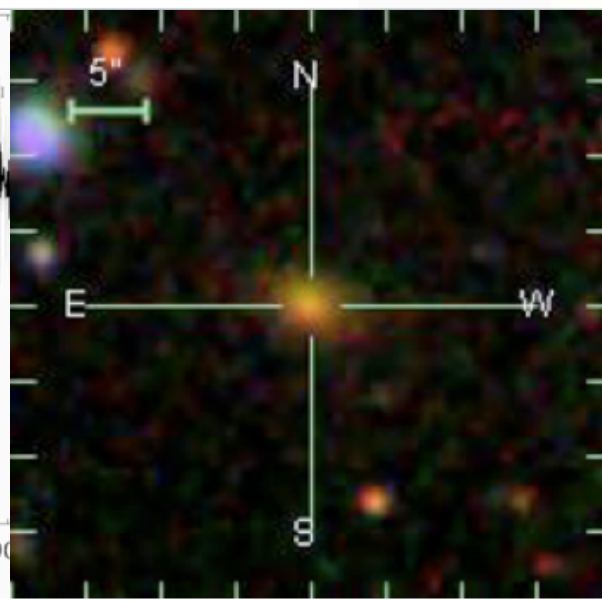
PALOMAR TRANSIENT
FACTORY

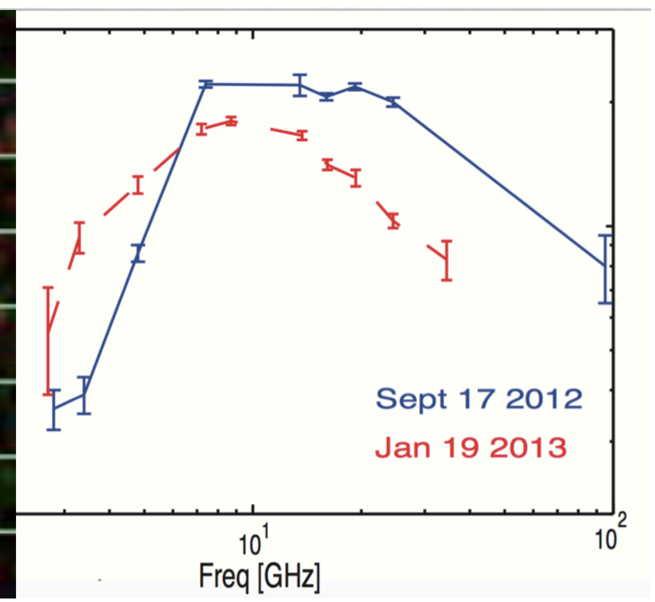


Transient Lab: A Multiwavelength Approach



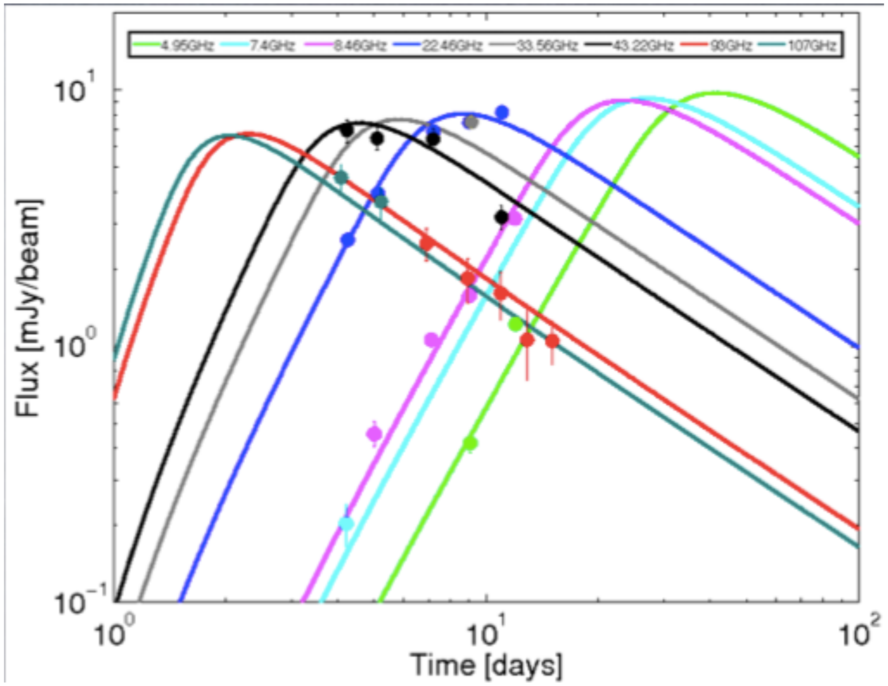






Galaxy Lab: M51

- PTF-VLA transient SN2011dh!



SN2011dh PTF,VLA,CARMA
Type 11b core-collapse
Horesh et. al 2012

M51 (VLA HI in red, HST)

Transient Lab: The Singing Sky

SKA Proving Ground – 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

Galaxy Lab: M51

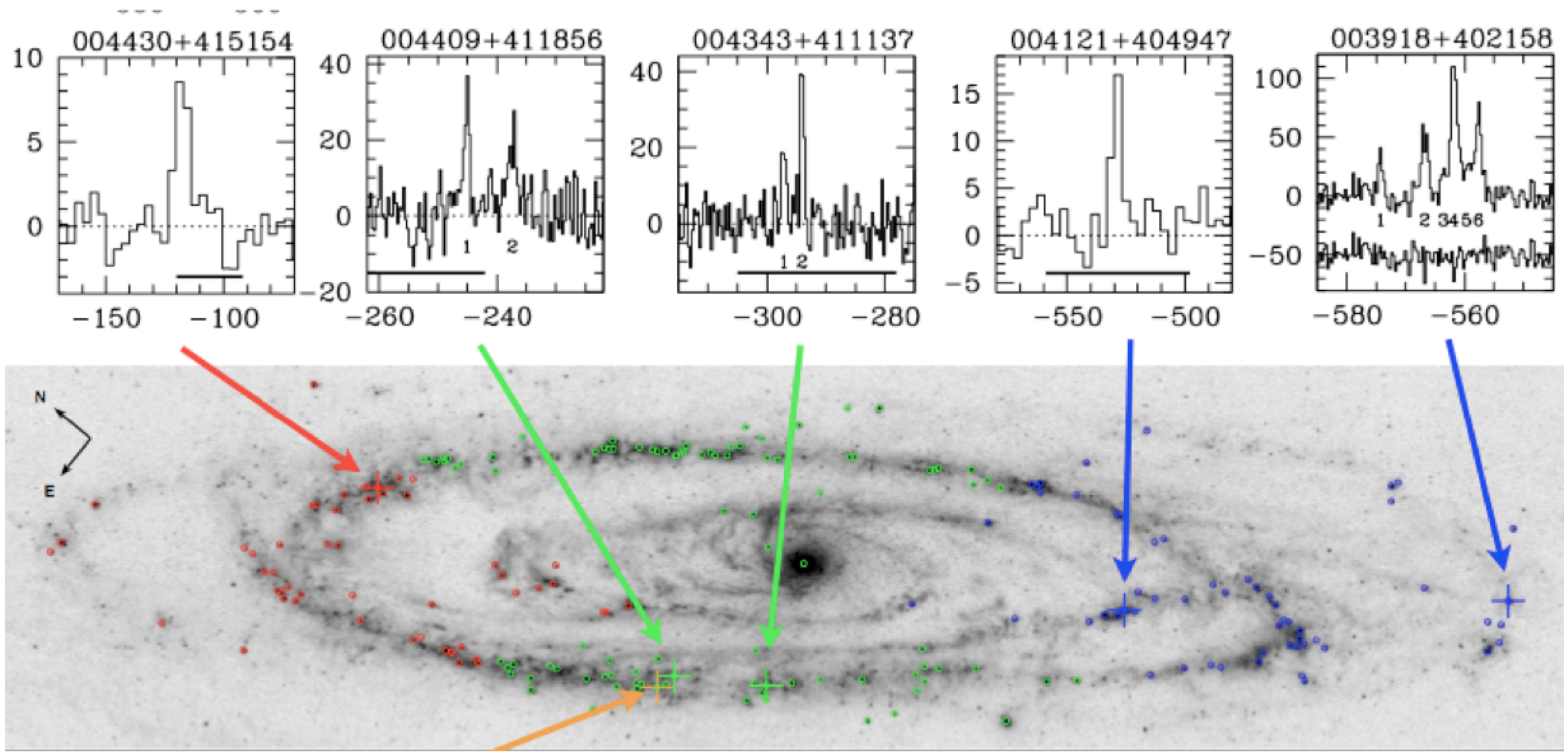
- The VLA can efficiently map galaxies near and far
- Map HII regions (around active high-mass star formation), SNR, X-ray binaries, HI in ISM, central AGN, anomalous microwave emission (spinning dust)

M51 (VLA HI in red, HST)
Image courtesy J.Ott (NRAO)

NRAO

Galaxy Lab: M31

- The VLA can efficiently map galaxies near and far
- Map gas and masers (H_2O, methanol), use VLBA for astrometric studies giving proper motions



M31 Spitzer 24μm, GBT H_2O & VLA methanol masers *Courtesy J.Darling (UColorado)*

Galaxy Lab: Where the Cold Baryons Roam

SKA Proving Ground – Galaxies Through Cosmic Time

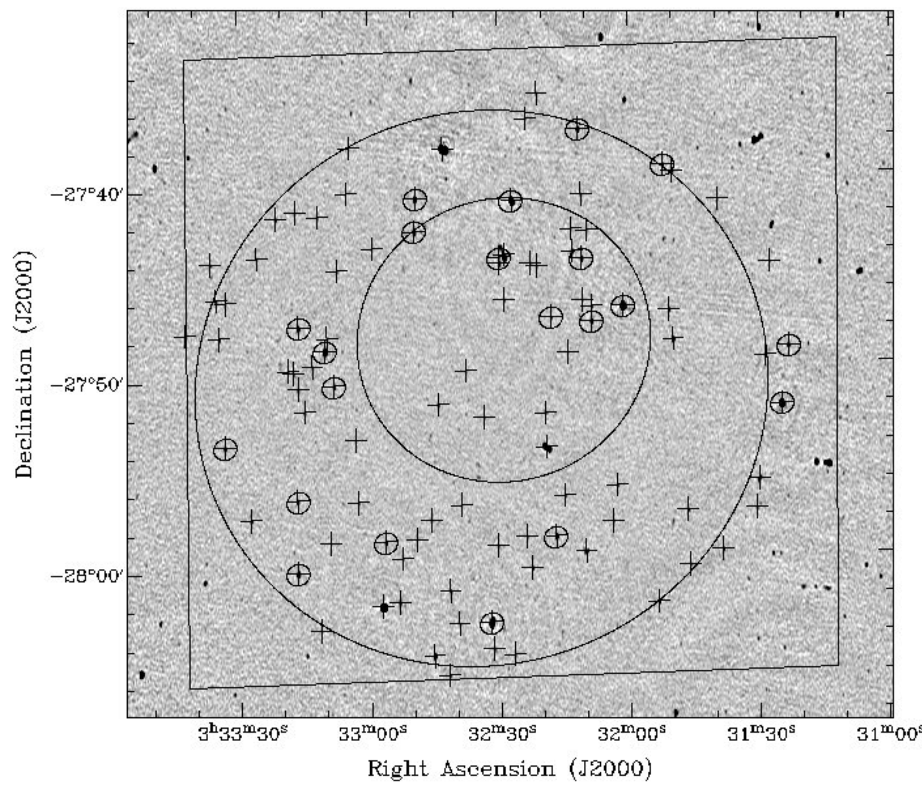
- Role of particles, B-fields, shocks, gas, turbulence in IGM
- Masers and compact objects for astrometry
- Measure anomalous microwave emission in galaxies

- Key Capabilities
  - Wide VLA bandwidths (1-50 GHz with 2/8GHz bandwidth)
  - High-quality polarimetry
  - Wide-area survey, range of angular scales and surface brightnesses
  - Ultra-high Resolution and Astrometric accuracy (e.g. using VLBA)
- Key Developments
  - Wide-field polarization calibration and imaging
  - High dynamic-range high-fidelity mosaic imaging

Beyond the Jansky VLA and SKA-1

- 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
  - Next-Gen Centimeter-wave Array

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



III.
A New Jansky VLA Sky Survey

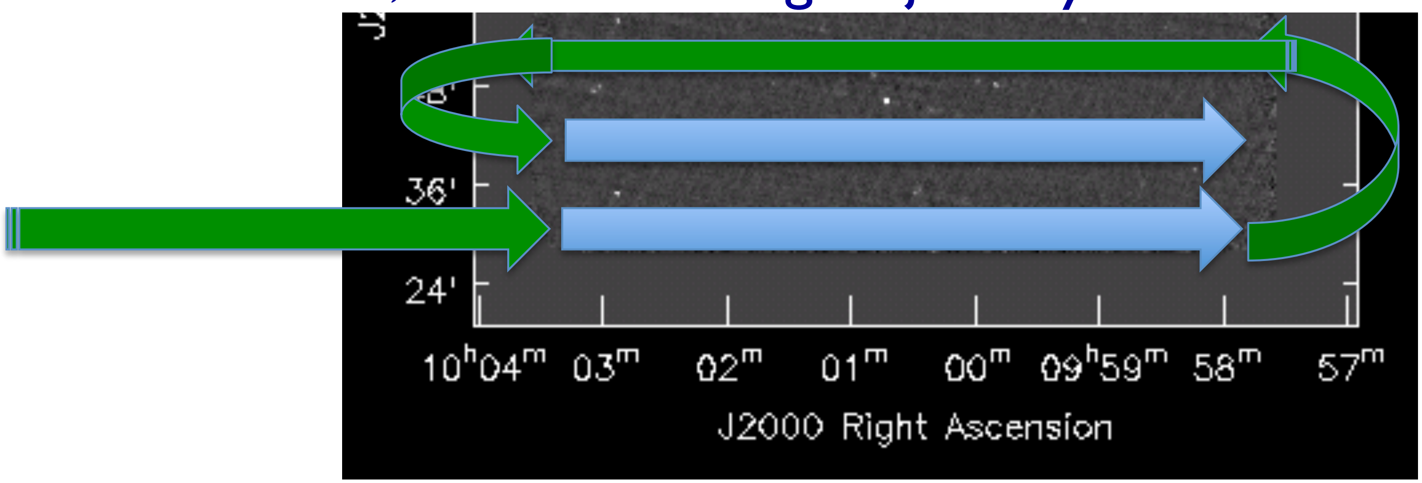
Key VLA Development: OTF Mosaicking

- "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 3-7s standard mode
    - Efficient when dwell times on-sky are <25s
  - Currently available only as part of Resident Shared Risk (RSRO)
    - Will be available for GO projects in 2014?
    - Currently under extensive development and testing…
- Image Processing support for OTF Mosaicking (in CASA)
  - Can process like normal data at moderate dynamic range
    - Errors are from moving primary beam
  - CASA imager can correct for offset pointing and phase centers if information given in POINTING table (not populated by VLA)

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

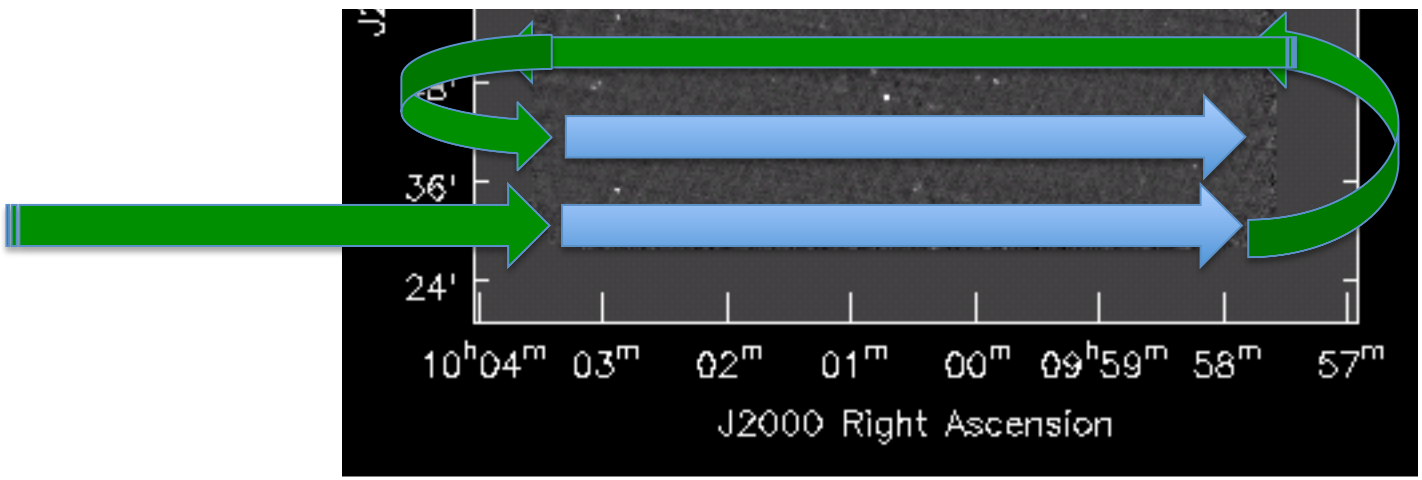
OTF scanning

- Atomic Element: "OTF Scan" of length Duration in time
  - StartPosition (RA,Dec) ➔ EndPosition (RA,Dec)
    - COSMOS Field Example: 2 square degrees = 85' x 85'
    - COSMOS-C example: 150sec for 85' = 34"/s = 2x sidereal w.r.t. sky = 1x sidereal net w.r.t. ground (same as track)
  - Usually at fixed Dec, scan forwards in RA (counter-sidereal)
    - Use uniform RA,Dec rate during trajectory



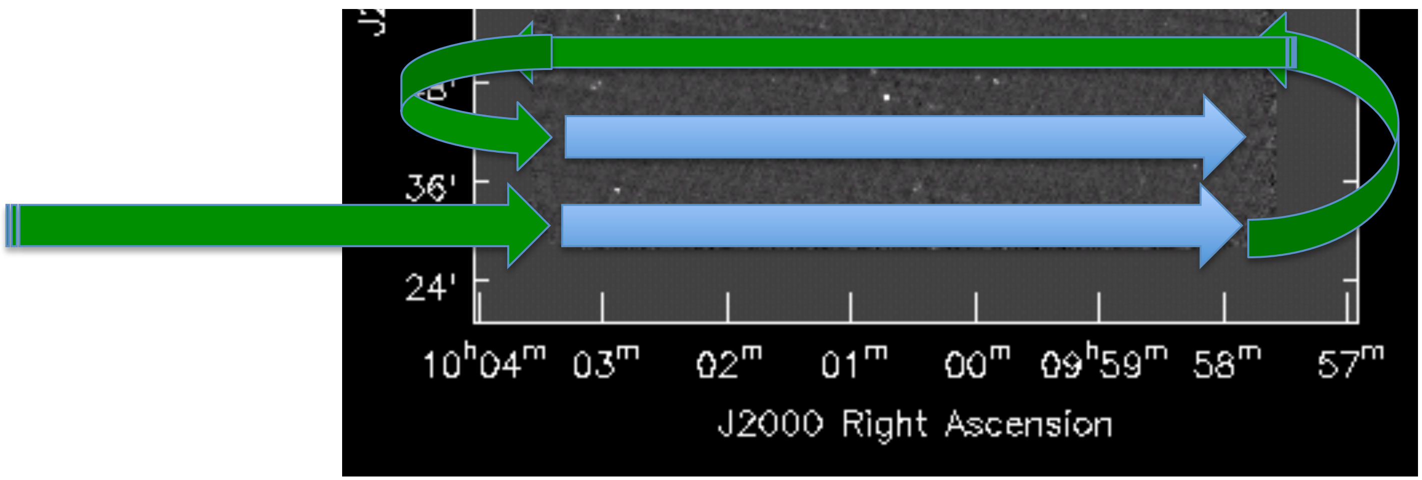
OTF scanning

- Atomic Element: "OTF Scan" of length Duration in time
  - During scan step phase center every PhaseStep integrations
    - COSMOS-C example: phase center step every 5 integrations (5 sec) = 5 sec at 34"/sec = 170"/step = 0.5xFWHM (8GHz)
    - Intrinsic beam smearing 34"/sec = 0.1xFWHM (8GHz)
      - Could really use shorter integration times even at these modest scanning rates!



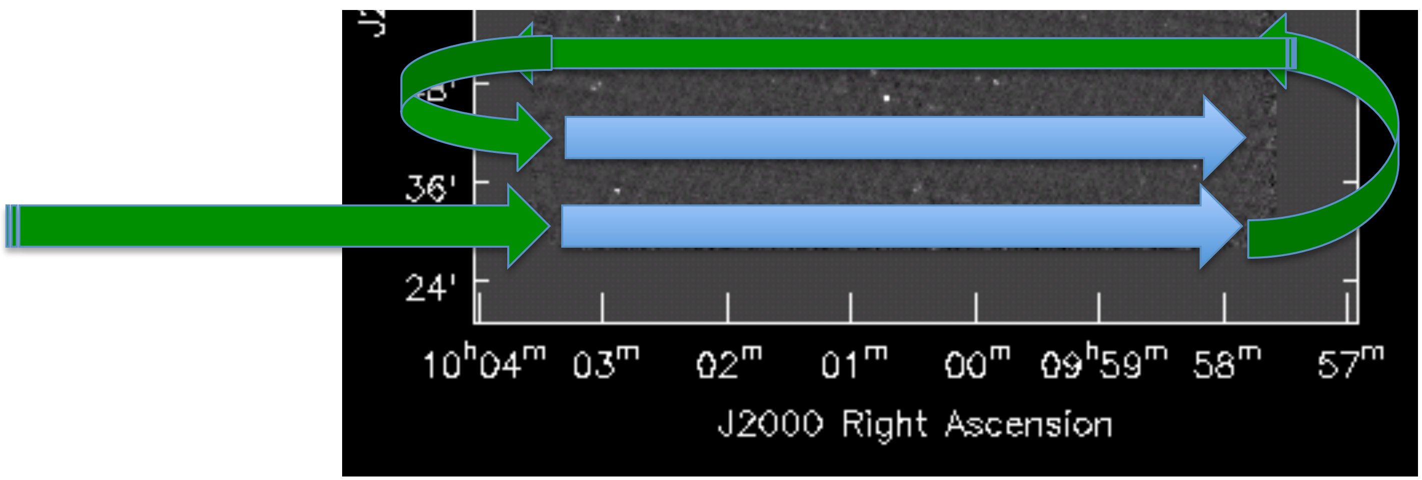
OTF scanning

- Building the schedule: combining "OTF Scans" of length Duration
  - Scan "stripes" should have optimal separation of FWHM/√2
    - Current recommendation is FWHM/√2 at mid-band
      - Closer stripes = more uniform but faster scans needed
    - COSMOS-C example: stripe separation 5.3' = 318"
      - Span 85' = 16 stripes (in Declination)



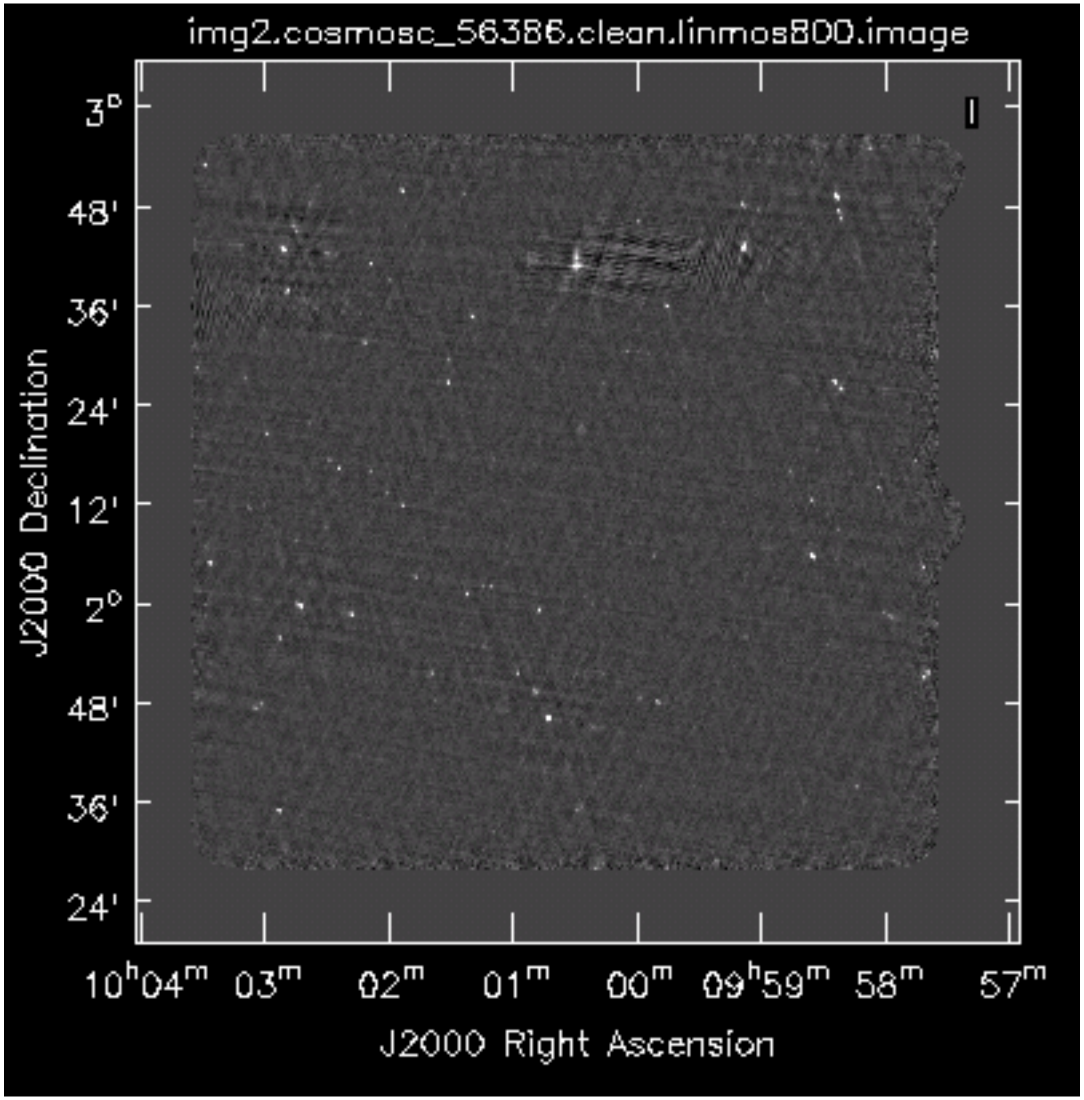
OTF scanning

- Building the schedule: combining "OTF Scans" of length Duration
  - Observe consecutive stripes until time to break for calibrator
    - Band-dependent. COSMOS-C every 8 scans = 20m
  - Rasters: unidirectional (e.g. RA++) or weaving (zig-zag)
    - Simpler conceptually to always advance in RA (or Dec)



OTF Now – COSMOS C-band D-config

- D-config C-band OTF
  - 800x800 8" cells
  - 8bit 2GHz, 95μJy rms
  - <30m on-src
  - Now: simple linear mosaic after clean of each 4s "field" (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

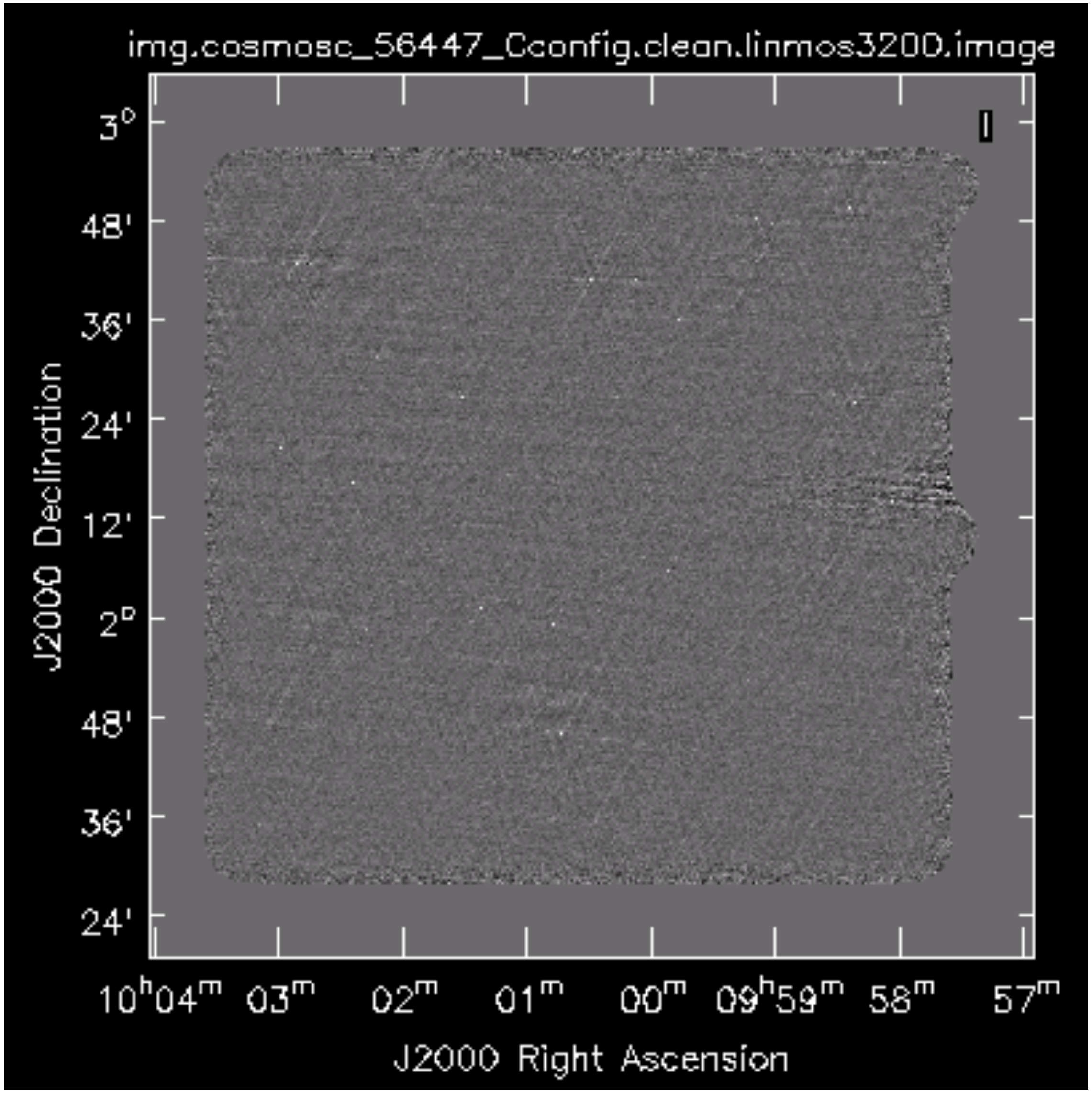
OTF scans in RA

432 phase centers

Repeat bi-monthly.

OTF Now – COSMOS C-band C-config

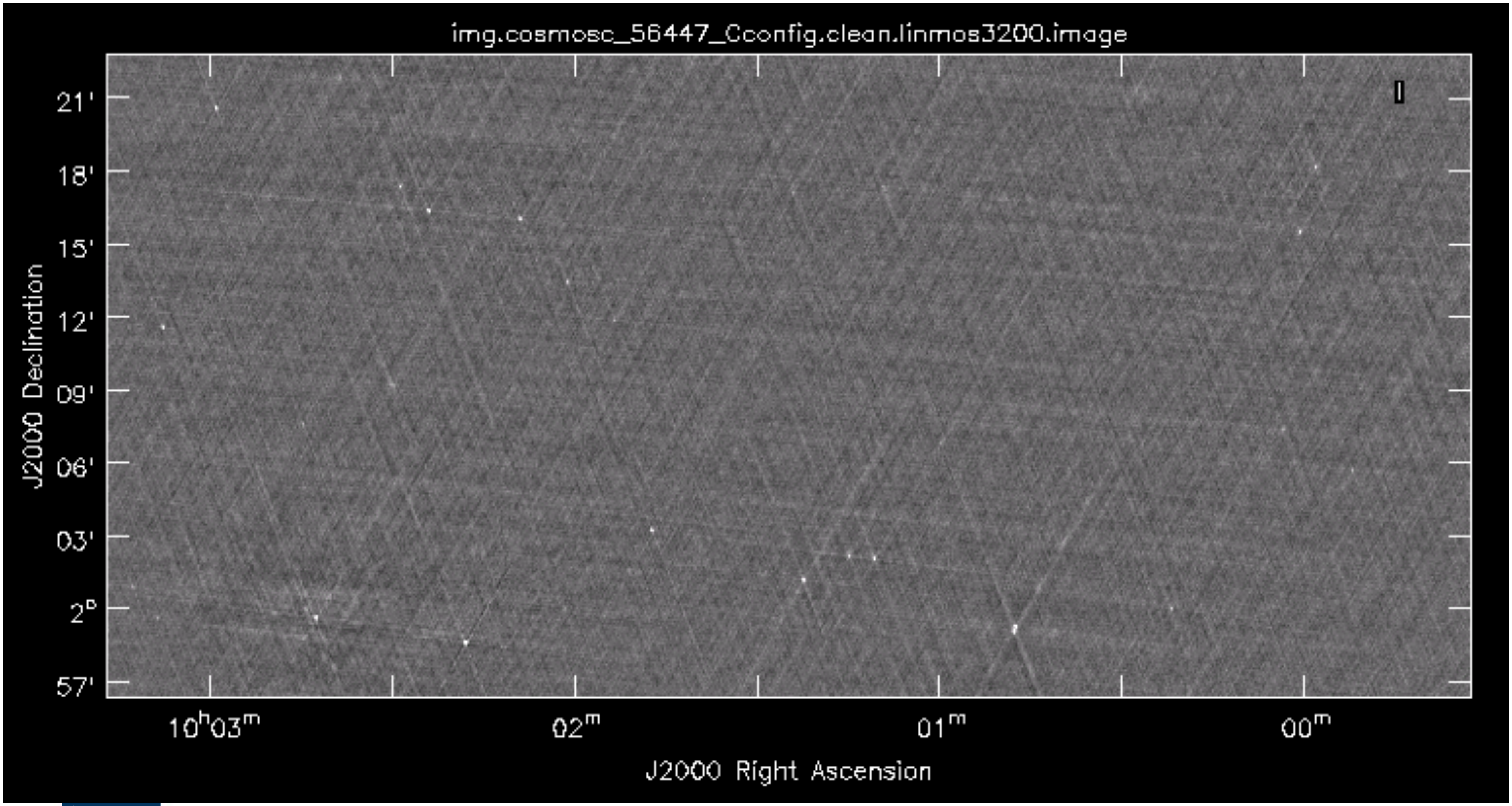
- C-config C-band OTF
  - 3200x3200 2" cells
  - 8bit 2GHz, 84μJy rms
  - <30m on-src
  - Now: simple linear mosaic after clean of each 4s "field" (CASA)
  - Striping/defects: RFI, missing data, unboxed cleaning, spectral index



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
Repeat bi-monthly.

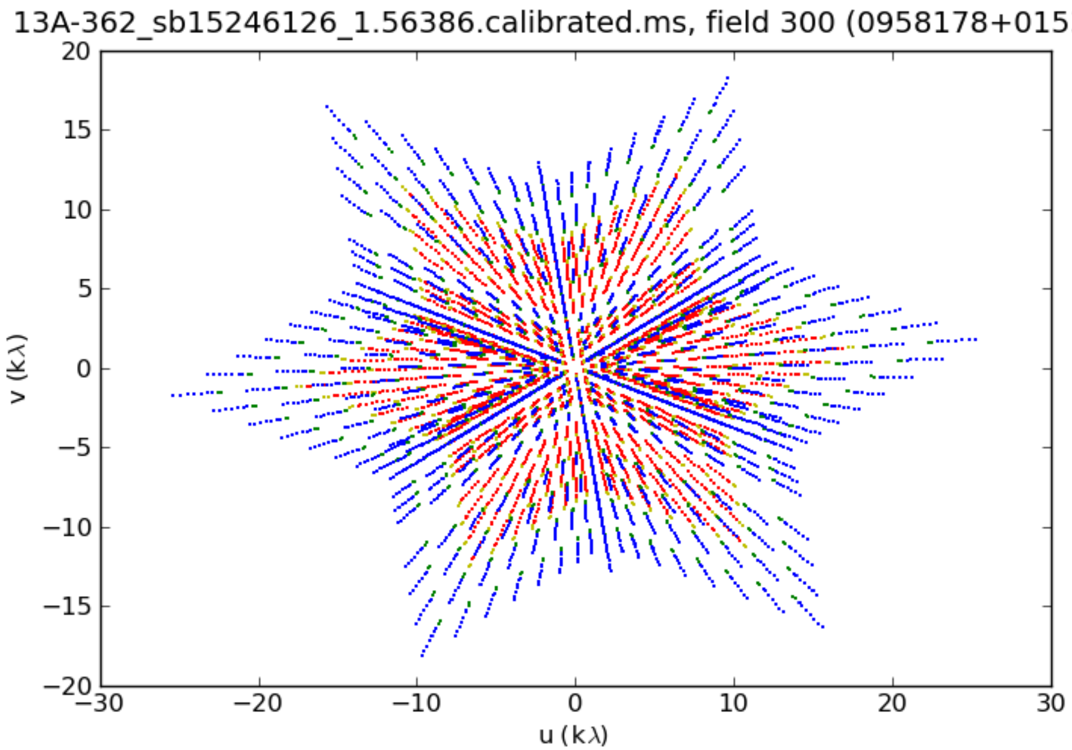
OTF Now – COSMOS C-band C-config

- D-config C-band – OTF 3200x3200 2" cells - 8bit 2GHz, 84μJy rms (ZOOM IN)



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

COSMOS & SDSS Stripe-82 VLA Surveys

- COSMOS (2 square degrees)
  - 1.4GHz Schinnerer et al. 2007 (old VLA)
  - 1-2GHz 13B-266 (van Gorkom, HI line)
  - 2-4GHz 12B-158 (Smolcic)
  - 4-8GHz TRSR0015, 13A-362, 13B-248 (Myers)
  - 26-36GHz 13A-398 (Riechers)
- SDSS Stripe-82 (270 square degrees total)
  - 1.4GHz Hodge et al. 2011 (old VLA)
  - 1-2GHz 11B-203 36□° (Myers), 13B-272 (Jarvis)
  - 2-4GHz 12A-371 (50□° Kulkarni), 13B-370 (Hallinan)
  - 8-12GHz 13B-380 (50□° Myers)
- Upshot: these surveys are proof-of-concept for VLA sky surveys as described here! No insurmountable bottlenecks yet…

200+ hours in semester 13B (BnC,B) starting Sep 2013!

NRAO

Survey Banquet: Wide vs. Deep Fields

- Wide-field Surveys
  - Cover large area of sky to "shallow" depth
    - Yields the largest number of sources for fixed observing time
  - Characterized by Survey Speed (area per time at fixed depth)
    - Limited by scanning speed and dump time of array
    - Example W1: VLA 2-4GHz 300 □° to 100μJy in 18 hours
    - Example W2: VLA 12-18 GHz 300 □° to 100μJy in 207 hours
- Ultra-Deep Fields
  - Focus on single fields or small mosaics (e.g. HDF, clusters)
    - Best when particular (small) target regions interesting
  - Characterized by raw sensitivity (depth for given time)
    - Limited by dynamic range (<1μJy rms near 10mJy source >10^4:1)
    - Example D1: VLA 2-4GHz to 1μJy in 21 hours (15' FOV)
    - Example D2: VLA 12-18GHz to 1μJy in 10 hours (3' FOV)

Stacking of objects in wide surveys can reach deep levels

Specs: Jansky VLA Capabilities for Surveys

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

*Using VLA sensitivity calculator

Band (freq)	Mode (width)	t_{int} sec	θ_{PB}	θ_{res} (A)	SS deg^2/hr	$\dot{\theta}$ deg/m
P (230-470 MHz)	8bit, 200MHz	8553	122′	8.40″	0.980	0.01
L (1-2 GHz)	8bit, 600MHz	36.69	30.00′	1.95″	13.896	0.65
S (2-4 GHz)	8bit, 1500MHz	7.71	15.00′	0.98″	16.532	1.56
C (4-8 GHz)	3bit, 3.03GHz	4.42	7.50′	0.50″	7.209	1.36
X (8-12 GHz)	3bit, 3.50GHz	3.87	4.50′	0.30″	2.964	0.93
K_u (12-18 GHz)	3bit, 5.25GHz	3.51	3.00′	0.20″	1.452	0.68
K (18-26.5 GHz)	3bit, 7.00GHz	7.09	2.05′	0.13″	0.336	0.23
K_a (26.5-40 GHz)	3bit, 7.00GHz	9.75	1.45′	0.09″	0.122	0.12
Q (40-50 GHz)	3bit, 7.00GHz	50.42	1.00′	0.065″	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

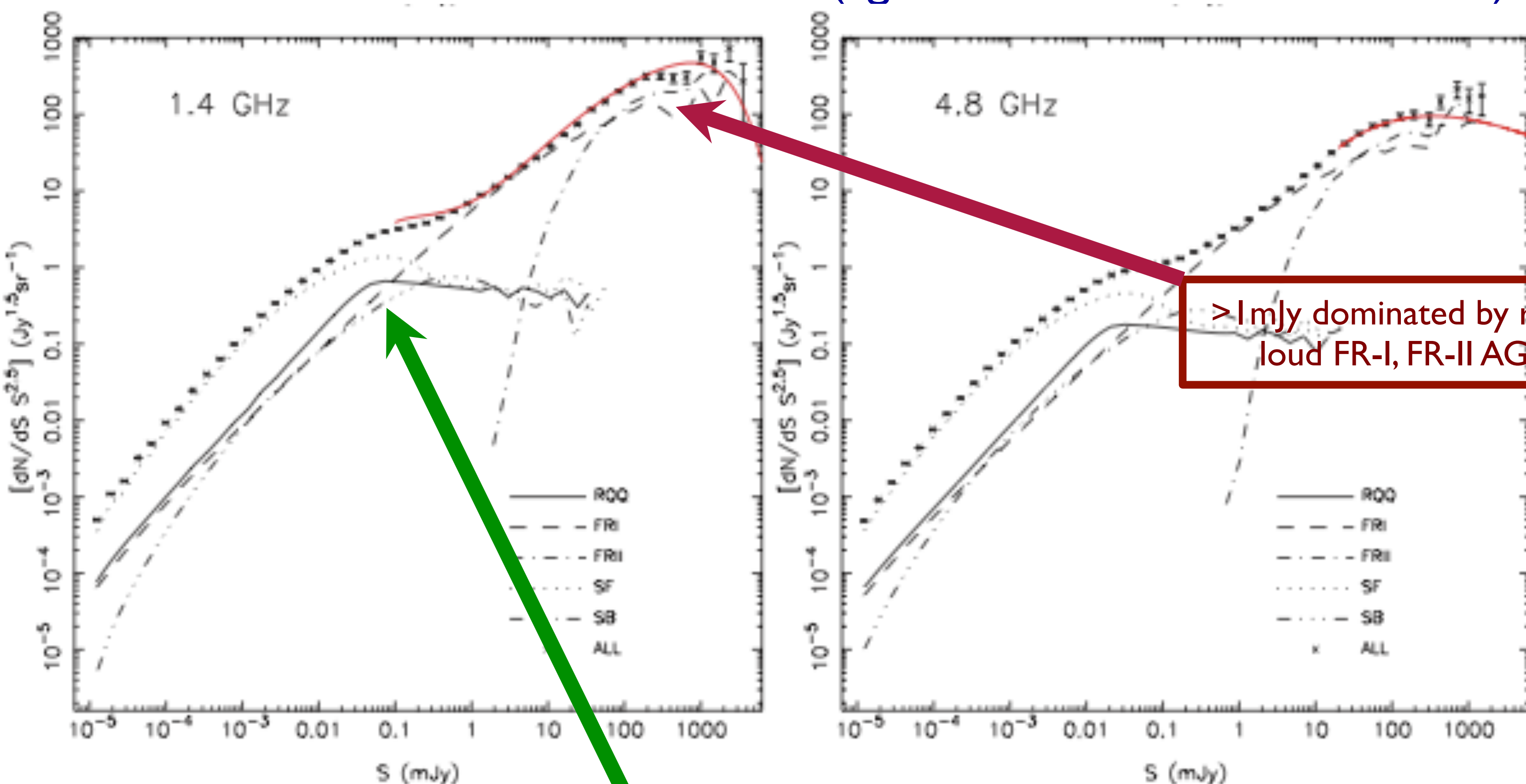
Resolution, A-config, natural wt.

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

On-the-fly scan rate

Radio Source Counts and Populations

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

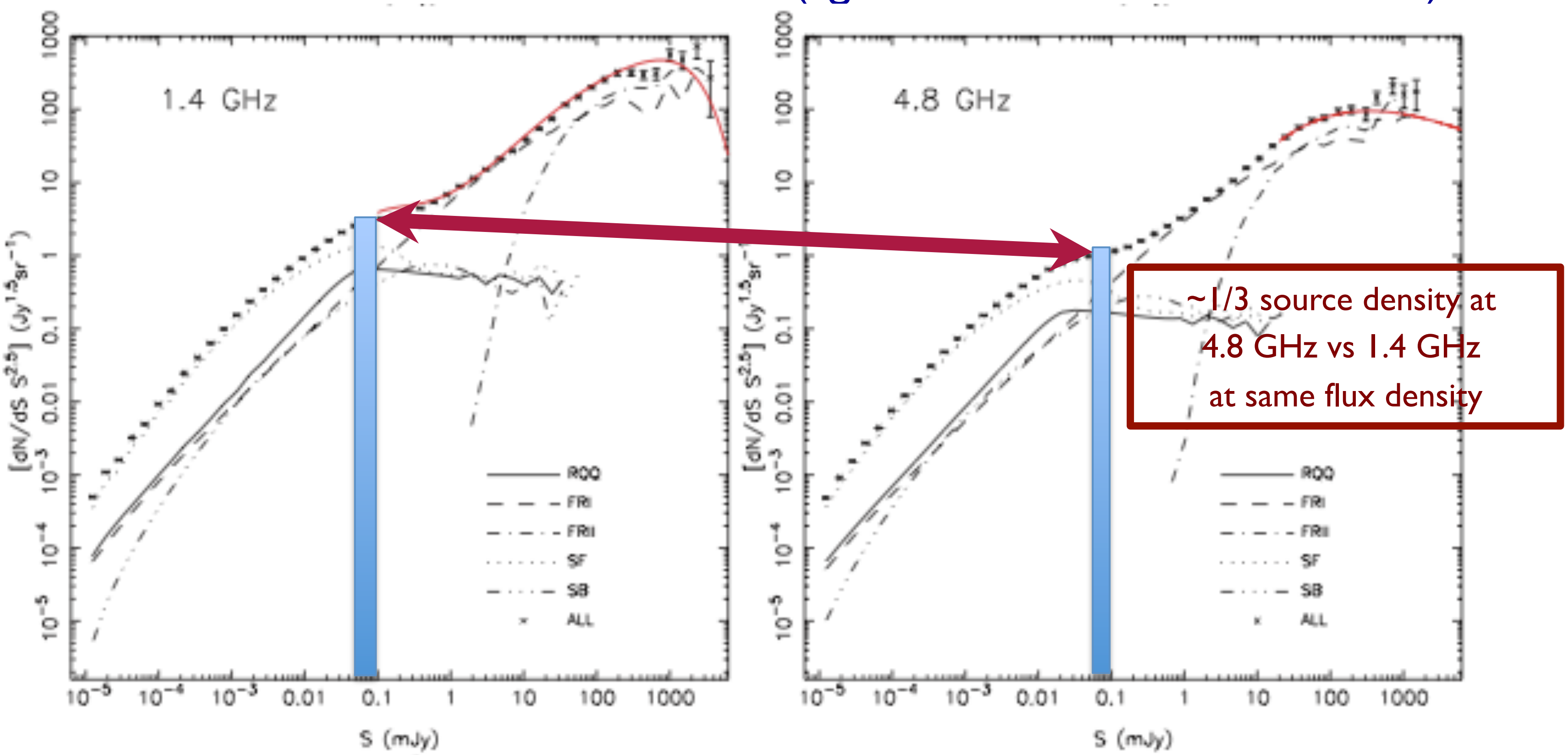


>1mJy dominated by radio-loud FR-I, FR-II AGN

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

Radio Source Counts and Populations

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

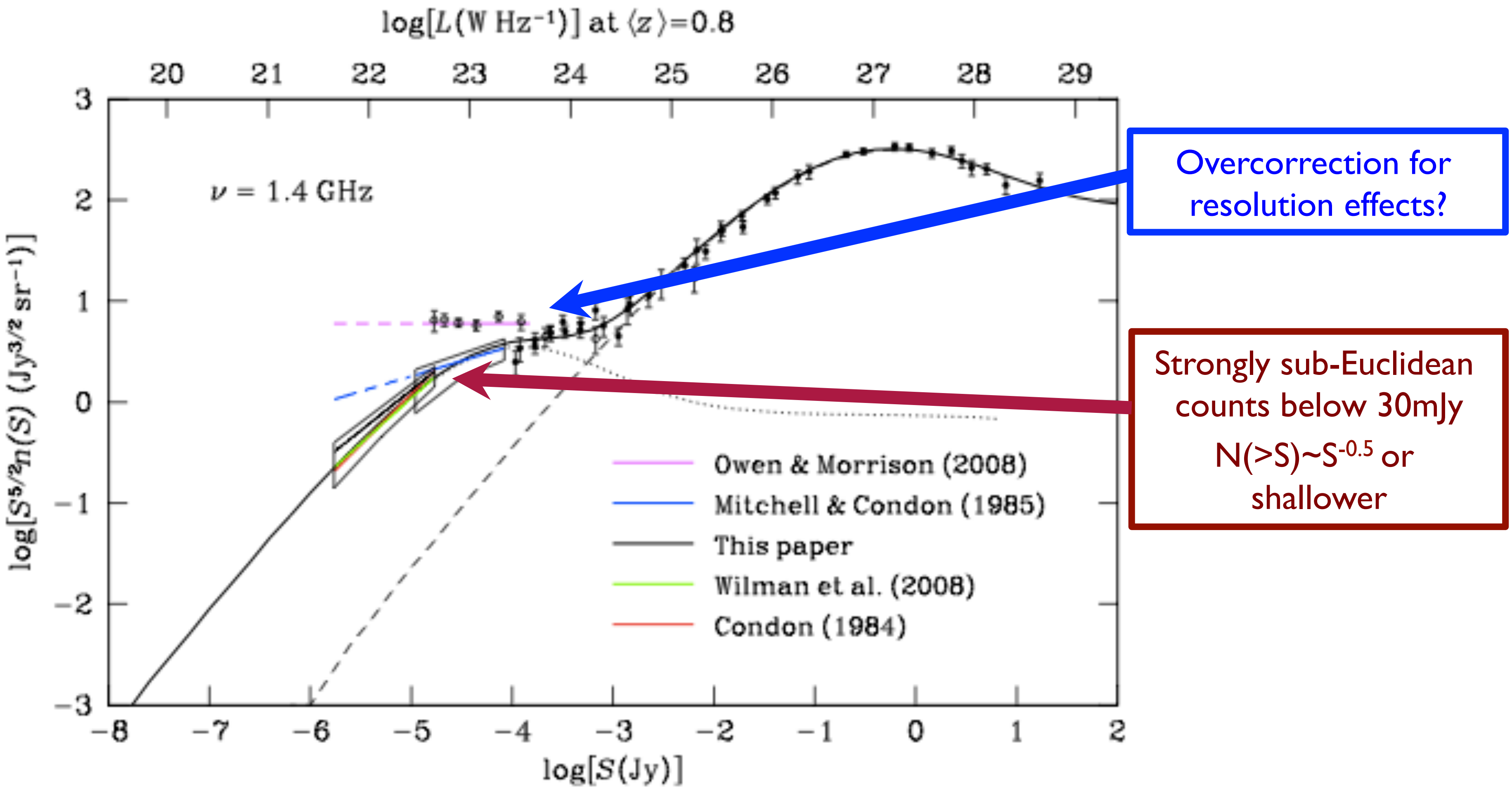


100μJy 3GHz vs 450μJy 1.4GHz (NVSS) ~ 4.3x more srcs
50μJy 3GHz vs 150μJy 1.4GHz (FIRST) ~ 2.3x more srcs

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

Radio Source Counts and Populations

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



Commensal Science Opportunities

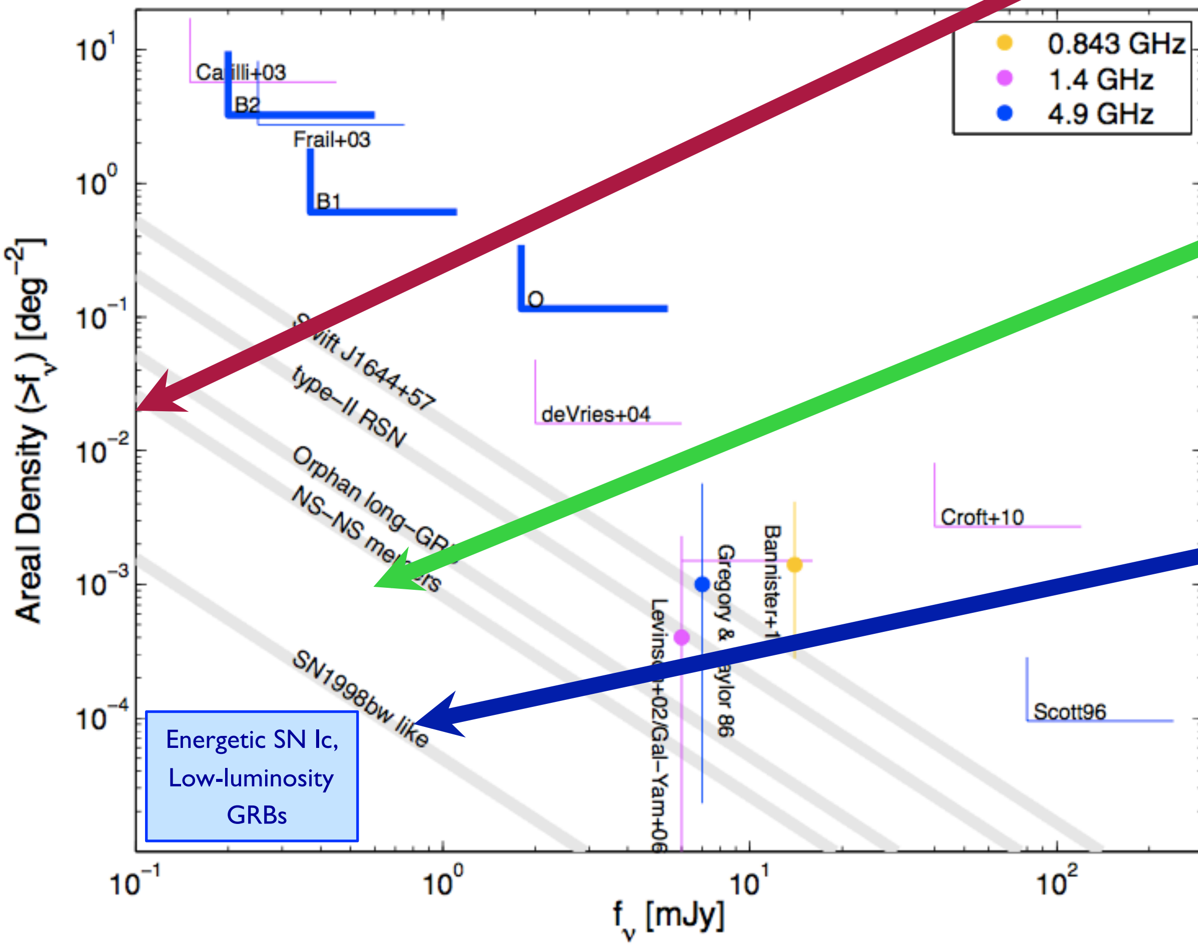
- Line and Continuum Science
  - For maximal continuum sensitivity, would use wide-band modes with channel resolution of 2 MHz (1MHz at L-band), corresponding to a velocity resolution of ~200 km/s (1.4GHz) to 40 km/s (15 GHz).
  - At the cost of higher data rates and volumes, could include higher-resolution "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 (V-LITE, LOBO)
  - It is likely that by the time this survey commences the VLA will have a commensal low-band observing system for 230-470 MHz (P) and possibly 58-84 MHz (4) band data from a subset of antennas.

A Multi-Tiered Survey Program

- Tier 1: 30000 deg^2 (all the Northern sky, e.g. NVSS)
  - Cover in single band, one or two configs/epochs
  - Highest source yield at a given band
- Tier 2: 10000 deg^2 (e.g. SDSS and FIRST footprint)
  - Cover in multiple epochs and array configurations, bands
- Tier 3: 1000 deg^2 (selected areas, stripes)
  - Three areas/stripes (e.g. SDSS 300 deg^2 Stripe82 on celestial equator)
    - High Galactic Latitude (Galactic Cap), overlap Tier 2 & 1
    - Medium Galactic Latitude range (Stripe82), overlap Tier 2 & 1
    - Galactic Plane, overlap Tier 1 (maybe 2)
- Tier 4: 100 deg^2 (medium deep fields)
  - Sub-patches of Tier 2/3, e.g. 10 x 10 deg^2 (LSST DDF, M31, Virgo, Coma)
  - Could include under JVLASS if critical (e.g. long-term monitoring)

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

Getting the Survey on the Telescope

- NVSS+FIRST had ~6000 h total duration over 3-9 yrs
- Total of ~6000 h integration
  - 7500-9000 h duration w/+25-50% overhead
  - "upper end" of what is practical to get approved?
- Span of 5-8 years, start late 2014 or early 2015
  - 7500 h / 6 yrs = 1250 h / yr (52 days per year)
  - Oct 2014 (C), Feb 2014 (B), June 2015 (A)
- Work into or adjust the VLA configuration cycle
  - Currently DCBA every 16 months (4 months/config)
  - Might be beneficial to make special hybrid (A+B+C) configuration
- Dynamic versus fixed (LST block) scheduling
  - Dynamic blocks can be integrated into normal observing
  - Fixed blocks have more predictability in HA (preferred)

Band & Configuration?

- Band (higher frequency is newer territory w.r.t. NVSS/FIRST/pre-SKA but…)
  - Survey speed limited by FOV, gain from bandwidth & performance
    - Lose around a factor of 2 each band from S to Ku
  - Example 10000 square degrees to 100 μJy (continuum rms)
    - S band 605 hrs
    - C band 1390 hrs
    - X band 3380 hrs
    - Ku band 6890 hrs
  - OTF scanning speed limiting, cannot go much shallower
- Configuration
  - Need sub-arcsecond resolution for cross-id with O/IR surveys etc.
  - Want some sensitivity to larger scale emission (A + C config? B+D?)
  - Can we devise a new survey hybrid array to use MFS?

Assembling the Puzzle - 1

- **Wide Survey** (times are integration/dwell) **Total 6000 hours**
  - Tier 1 : 30000 deg^2 all-sky
    - S1 – 2-4GHz in 2 config at 100μJy (1800h)
    - C1 – 4-8GHz in 2 config at 100μJy (4200h)

Assembling the Puzzle - 2

- **Broad Survey** (times are integration/dwell) **Total 6620 hours**
  - Tier 1 : 30000 deg^2 all-sky
    - S1 – 2-4GHz in 1 epoch to 100μJy (1800h)
  - Tier 2 : 10000 deg^2
    - S2 – 2-4GHz in 3 epoch at 100μJy (1800h) [50 μJy S2+S1]
    - C2 – 4-8GHz in 1 epoch at 100μJy (1400h)
  - Tier 3 : 1000 deg^2 , e.g. in 3 x 330 deg^2 fields (GP,GC,Eq)
    - S3 – 2-4GHz in 12 epochs at 100μJy (720h) [25 μJy S3+S2+S1]
    - C3 – 4-8GHz in 3 epochs at 100μJy (420h) [50 μJy C3+C2]
    - X3 – 8-12GHz in 1 epoch at 100μJy (340h)
    - L3 – 1-2GHz in 1 epoch at 100μJy (140h)
  - Tier 4 – can trade some above area/time for Tier 4 deep fields

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Assembling the Puzzle - 3

- **Medium Survey** (times are integration/dwell) **Total 6290 hours**
  - Tier 2 : 10000 deg^2
    - S2 – 2-4GHz in 4 epochs at 100μJy (2400h) [50 μJy all S2]
    - C2 – 4-8GHz in 1 epoch at 100μJy (1400h)
  - Tier 3 : 1000 deg^2 , e.g. in 3 x 330 deg^2 fields (GP,GC,Eq)
    - S3 – 2-4GHz in 12 epochs at 100μJy (720h) [25 μJy S3+S2]
    - C3 – 4-8GHz in 3 epochs at 100μJy (420h) [50 μJy C3+C2]
    - X3 – 8-12GHz in 1 epoch at 100μJy (340h)
    - U3 – 12-18GHz in 1 epoch at 100μJy (700h)
    - L3 – 1-2GHz in 1 epoch at 100μJy (140h)
  - Tier 4 – 100 deg^2 in 10 x 10 deg^2 fields
    - C4 – 4-8GHz in 12 epochs at 100μJy (170h) [25 μJy C4+C3+C2]

Assembling the Puzzle - 4

- **Extreme-C Survey** (times are integration/dwell) **Total 7000 hours**
  - Tier 2 : 10000 deg^2
    - C2 – 4-8GHz in 1 epoch at 100μJy (1400h)
  - Tier 4 – 100 deg^2 in 10 x 10 deg^2 fields
    - C4 – 4-8GHz in 100 epochs at 50μJy (5600h) [5μJy all epochs]
      - cadence ~monthly (36 days) over 10 years

Note: 2-4GHz (S-band) would take 3000 h at same flux density rms, or 6000 h for 3.5μJy rms all epochs

Radio Survey Landscape 2015-2020+

Target flux density limits 1-20μJy at 1.4GHz

- 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)

Norris et al. 2012 (arXiv:1210.7521)

- 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

Carrying Out a VLASS Program

- A proposed structure for carrying out a Jansky VLASS program
  - Alternatives are possible (e.g. a general call for proposals)
- "Survey Science Group" (SSG) – community led
  - Broad community-based group (multi-wavelength, science areas)
  - Solicit (write) and evaluate "white papers" on survey components
  - Define survey science goals, design and plan survey
- "Survey Implementation Team" (SIT) – NRAO led
  - 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. Involves community + NRAO in both groups.
- 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, prompt with levels of quality assured
  - More advanced products as added value by community

Survey Data Products - When

- To be produced by NRAO (by the SIT) with some level(s) of Quality Assurance (QA) with levels of promptness after observing

Warning: These are my own opinions at this point, not policy!

- QA0 – "You get what you get"
  - Raw data (visibilities) appear in archive as usual, no proprietary time
- QA0.5 – "We did the best we could on short notice"
  - Quick-look images and transient alerts (publicly available ASAP)
- QA1 – "Seems to be OK at first glance"
  - Calibrated data, images, catalogs (<1wk after observing)
- QA2 – "Passed our tests, looks quite good"
  - Refined images, catalogs for each epoch (<3mo after obs)
- QA3 – "This is the very best we can do now given all we have"
  - Final version of lower QA products & Combined epoch/configuration

Survey Data Products - What

- Raw data – it's whats in the archive by default!
- Calibrated data – each SB
  – best current output of pipeline (with release notes)
- Quick-look images and events – prompt processing
  – Simple intensity images for SB, transient object location
- Reference images and catalogs – each "epoch"
  – Intensity and Spectral Index (& curvature?) images
  – Polarized QUV, intensity, angle
  – Source catalog IQUV, size&shape, spectral index/curv, rotation measure
- Refined images and catalogs – each "epoch"
  – As above, plus cross-ids from other wavelengths – anything else?
- Final combined images – over epoch and configuration
  – As above, plus time-series from epochs
  – Multi-scale, multi-config source fitting

The Jansky VLA Sky Survey Data Challenge

- A "Big Data" problem?!
  - The raw (post-correlation) raw data rate from current VLA is ~50MB/s (currently throttled by decree) or ~200GB/hour (4TB/day). Becomes a big data problem at high time/spectral resolution (10-100x at 100-10ms).
  - However, to image the FOV in A-config from 1-2GHz out to first sidelobe (common) takes 1 Gpix. You can get one of these every 1 second (or faster). In 1024 channels (w/o averaging). That's potentially a 1 Tpix/sec!
  - For reference LSST has 3.2Gpix that can be read out every 2 sec but a single "channel".
  - EVLA imaging is even now potentially a "huge data" problem when looking for fast transients! Opportunity for innovative approaches (e.g. Law et al. for real-time transient detection).
  - Opportunities for community involvement and innovation in new survey techniques, analysis pipelines, etc., in particular for the more difficult imaging problems (wide-band wide-field high-dynamic range, e.g. SKA)

Upcoming Workshop

- **NRAO Very Large Array Sky Survey Science Planning**
  - We are planning a workshop for the science definition and planning of the VLASS at the January 2014 AAS meeting in Washington, DC area (Cold Harbor)
  - More information available soon. If interested in participating in the VLASS Program, contact:
    - Stefi A. Baum (baum@cis.rit.edu)
    - Steven T. Myers (smyers@nrao.edu)
  - Discussion of community-written White Papers
  - Official website to open soon.

Epilogue: Possible Discussion Topics

- Key Science / Missing Science
  - Galactic Plane Survey
  - Key Spectral Lines
- Survey Design & Implementation
  - Survey depth vs. area
  - Band and configuration? Special Hybrid config?
  - Cadences and Scheduling
  - Tier 3 & 4 fields? Ultra-deep fields?
  - What data products & when?
- Community Involvement
  - **White Papers on aspects of survey**
  - Input to planning, websites/wikis/media, info materials
  - Spin-off science, follow-up, enabling research funding
  - Contributed software and effort

This is a new model for VLA surveys. Wide participation is a key to success.

New ideas welcome!

Consider submitting White Papers