Science with the Expanded Very Large Array and VLBA: a forwards look towards the SKA

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The Expanded Very Large Array

- The Expanded Very Large Array (EVLA) provides new and tremendously powerful capabilities for radio astronomical observations
  - science observations started 2 March 2010
  - increasing capabilities over the next 2 years
- When paired with the upgraded VLBA, we have the nucleus of a next-generation "high frequency" component of the SKA
  - EVLA+VLBA "trail-blazes" the path to the SKA-high, particularly in exploring the frontiers of SKA science

The Expanded Very Large Array

…is a major upgrade of the Very Large Array

- 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)
  - Up to 8 GHz instantaneous bandwidth
  - New digital correlator with unprecedented capabilities
  - ~3 μJy (1-σ, 1-Hr) point-source continuum sensitivity at most bands.
  - ~1 mJy (1-σ, 1 km/sec, 1 Hr) line sensitivity at most bands.
- Counting all sources, a $90M project.
- The Project began in 2001, and will be completed in 2012 – on time, on spec, on budget.
  - EVLA science observing (limited modes) started March 2010!

Overall EVLA Performance Goals

- Orders of magnitude performance improvement!

Parameter	VLA	EVLA	Factor
Continuum Sensitivity (1-σ, 1 hr.)	30 μJy	3 μJy	**10**
Maximum BW in each polarization	0.1 GHz	8 GHz	**80**
# of frequency channels at max. BW	16	16,384	**1024**
Maximum number of freq. channels	512	4,194,304	**8192**
Coarsest frequency resolution	50 MHz	2 MHz	**25**
Finest frequency resolution	381 Hz	0.12 Hz	**3180**
# of full-polarization spectral windows	2	64	**32**
(Log) Frequency Coverage (1 – 50 GHz)	22%	100%	**5**

The EVLA for Science Observing

- Spectral Coverage
  - 21cm HI line to z=0.4 (1.4-1GHz)
  - key molecular transitions, masers
  - radio recombination lines
  - redshifted CO
- Continuum Sensitivity
  - Synchrotron, free-free, dust
  - Polarimetry (magnetic fields)
- The Time Domain
  - 100ms integrations, dynamic spectra
  - Pulsar gating (future)

Wide-band spectral coverage
Wide field (e.g. with mosaicing)
High sensitivity
Full Polarization
Use for Surveys and Follow-up
Available staring March 1 2010!

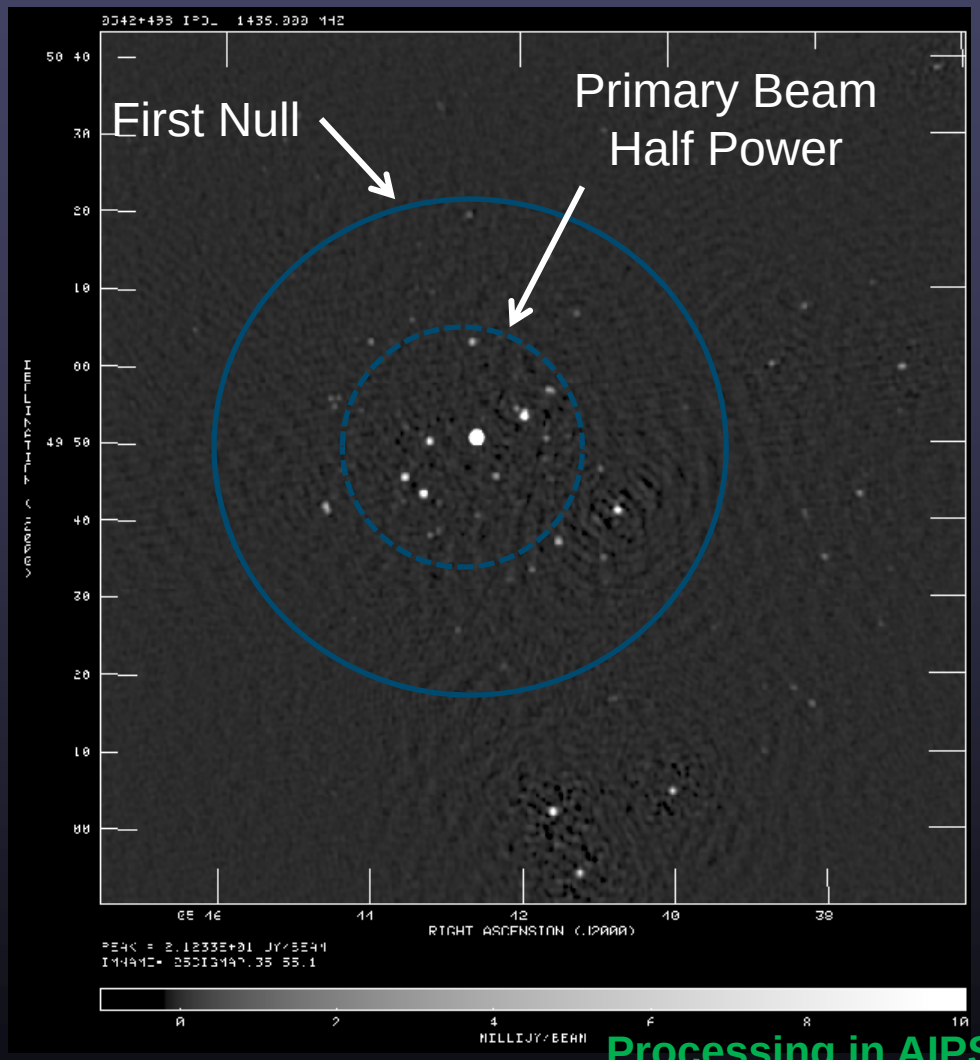
S. T. Myers

2009: Early EVLA Testing Results

- A 12-antenna sub-array was established to test correlator capabilities from the WIDAR-0 prototype.
- This test configuration provides:
  - 8192 channels
  - Full polarization
  - Up to eight adjacent spectral windows
- Test observations in 1—2 and 18 – 26 GHz bands are shown on subsequent slides.
  - Data processing in both AIPS and CASA possible

3C147 Deep Field @ 1440 MHz

- 12 antennas, 110 MHz bandwidth, 6 hours integration
  - Fidelity ~ 400,000:1
  - Peak/rms ~ 850,000:1
- artifacts are due to structure in the antenna primary beams
  - Advanced imaging software
- This is the highest fidelity image ever made with the VLA – using only a fraction of the upcoming capability!

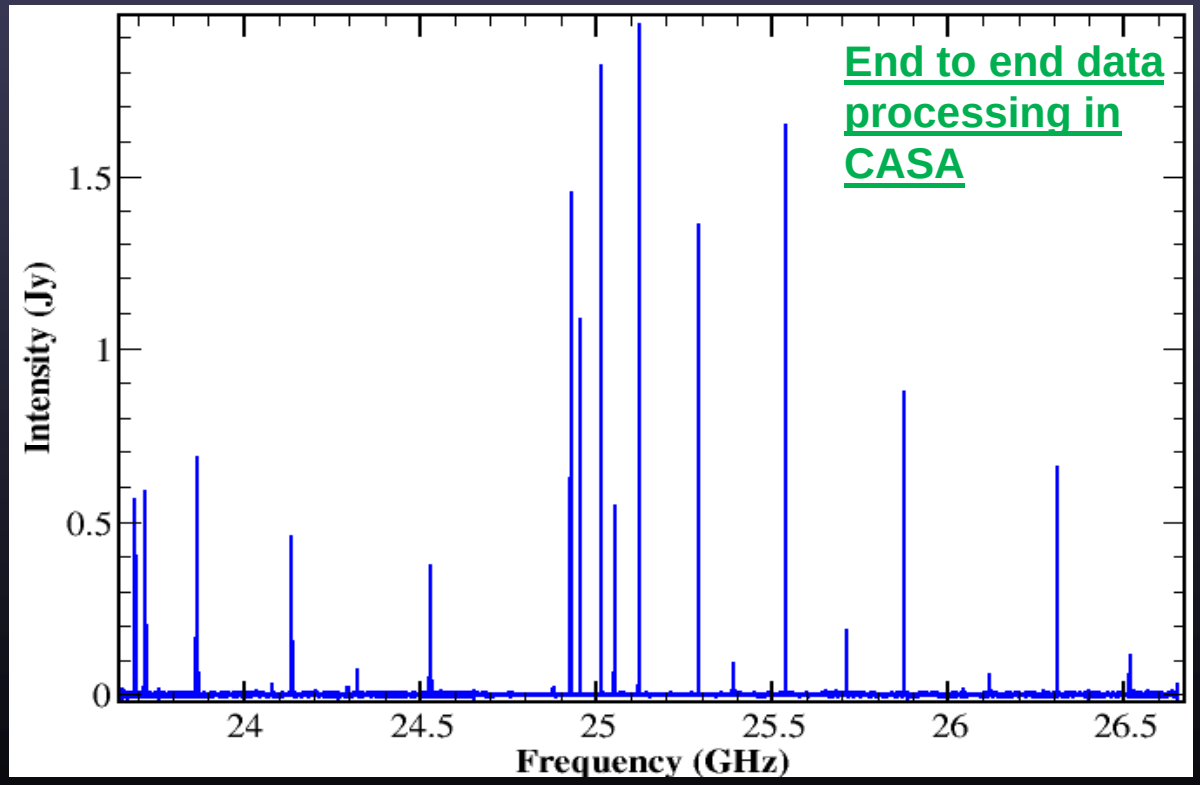


Processing in AIPS

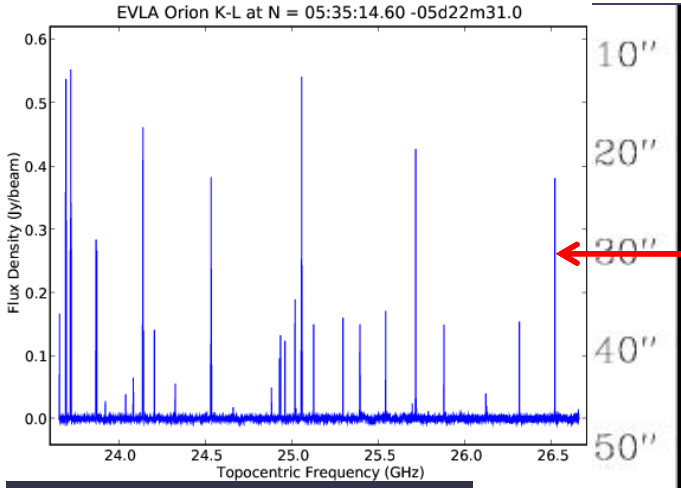
The Spectrum of Orion-KL – 3 GHz Wide

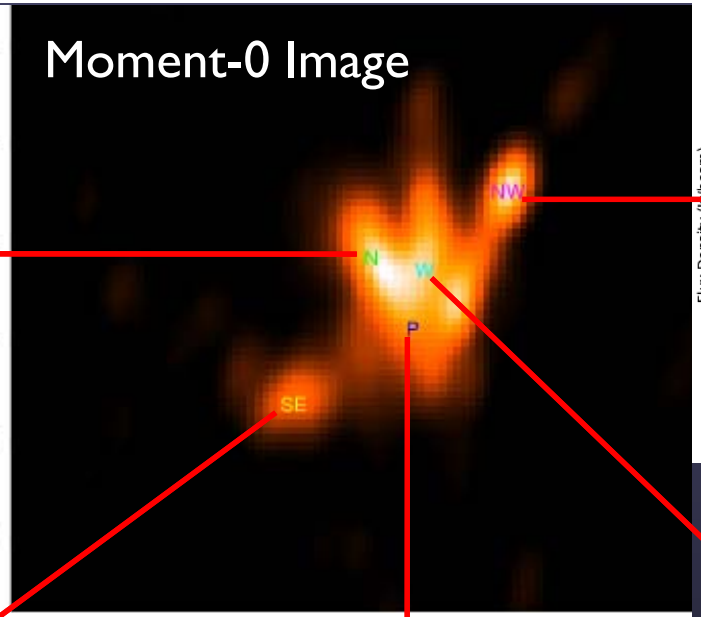
- Three short (90m,90m,30m) observations of the hot core of Orion, each 1024 MHz wide, ~1.5 km/sec velocity and 2.5" spatial resolution
- From NH_3 are the 8 lowest meta-stable inversion transitions (J,K) = (1,1) to (8.8), two meta-stable (9,8) and (10,9) lines, the (6,6) line from $^{15}NH_3$ isotopologue, and the 4(1,4)-4(0,4) line from singly deuterated ammonia, NH_2D.

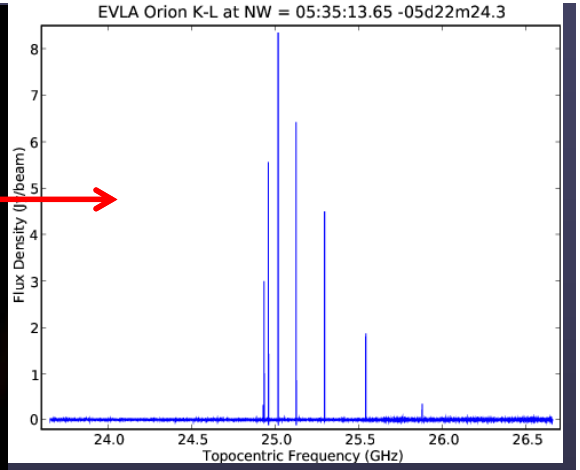
- Two E/A doublets of methyl formate: CH_3CHO
- OCS 2-1
- Three unidentified lines
- Ten strong methanol maser lines from $J_{k=2} - J_{k=1}$ E-type series (J=2 – 11).
- Clear spatial segregation of oxygenated vs. nitrogenated molecules.



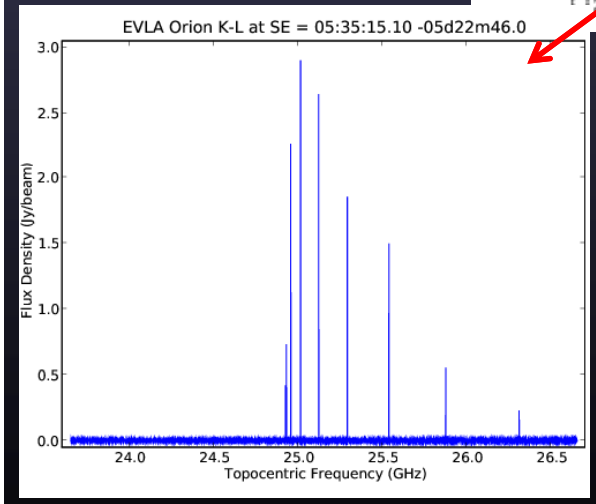
Spectra from 96x96x24012 image cube

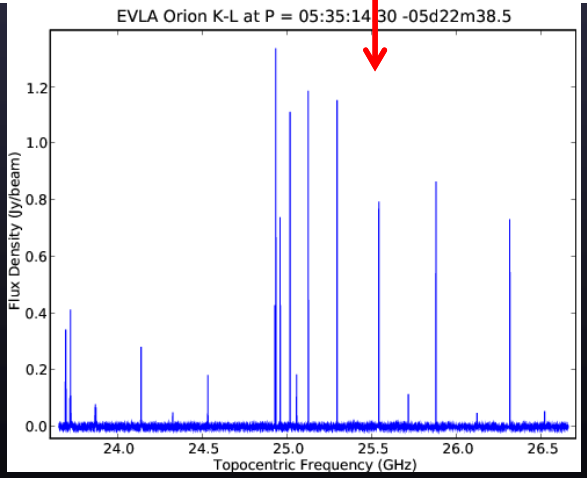


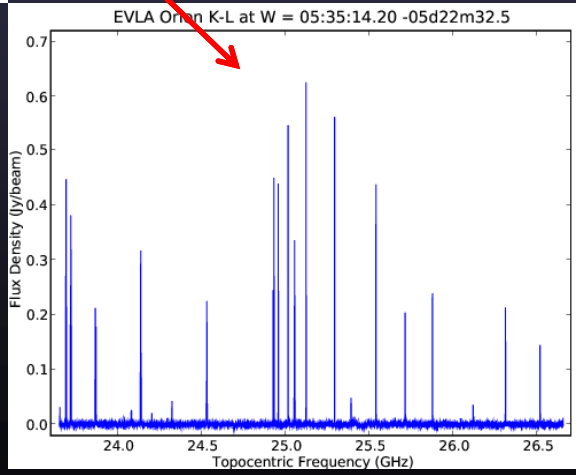




[End to end data processing in CASA]

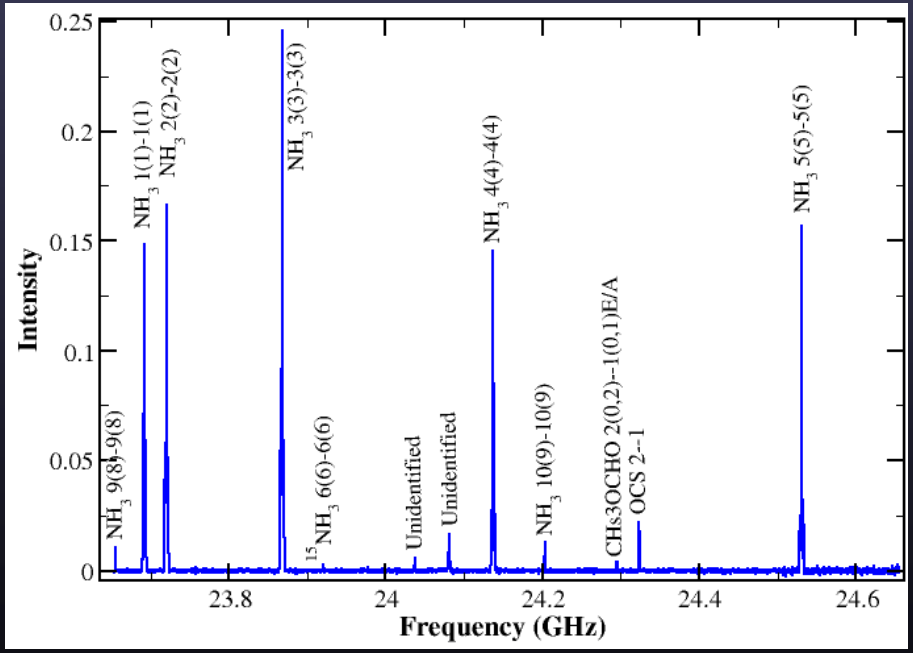


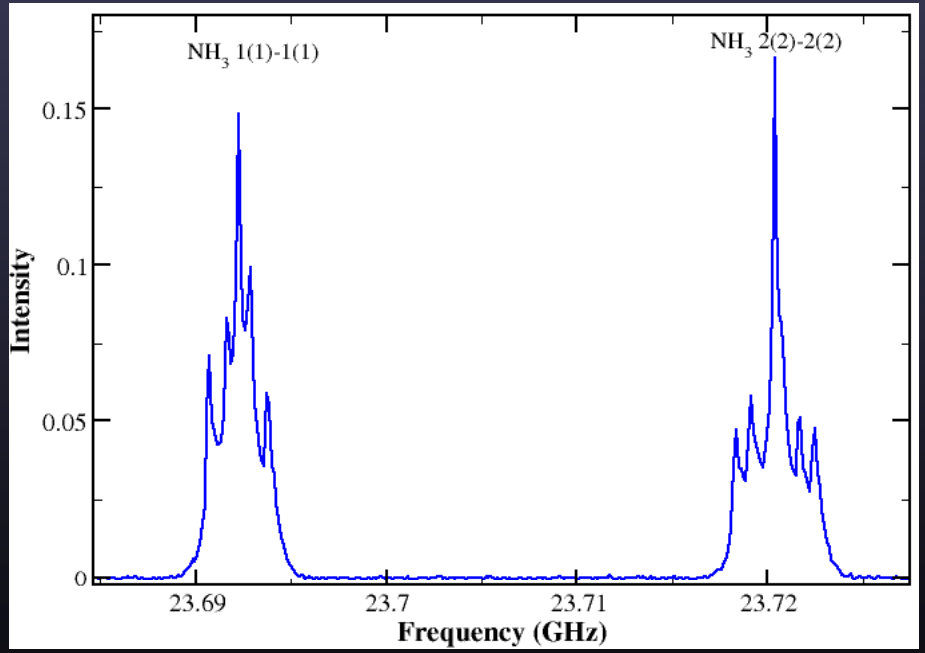




Orion: Expanding the Frequency Scale

- Left Side: The lowest 1.0 GHz, showing some of the identifications.
- Right Side: A close-up of the two lowest meta-stable transitions, showing the 5 main groups of hyperfine structure which are blended in the Orion-KL spectrum.

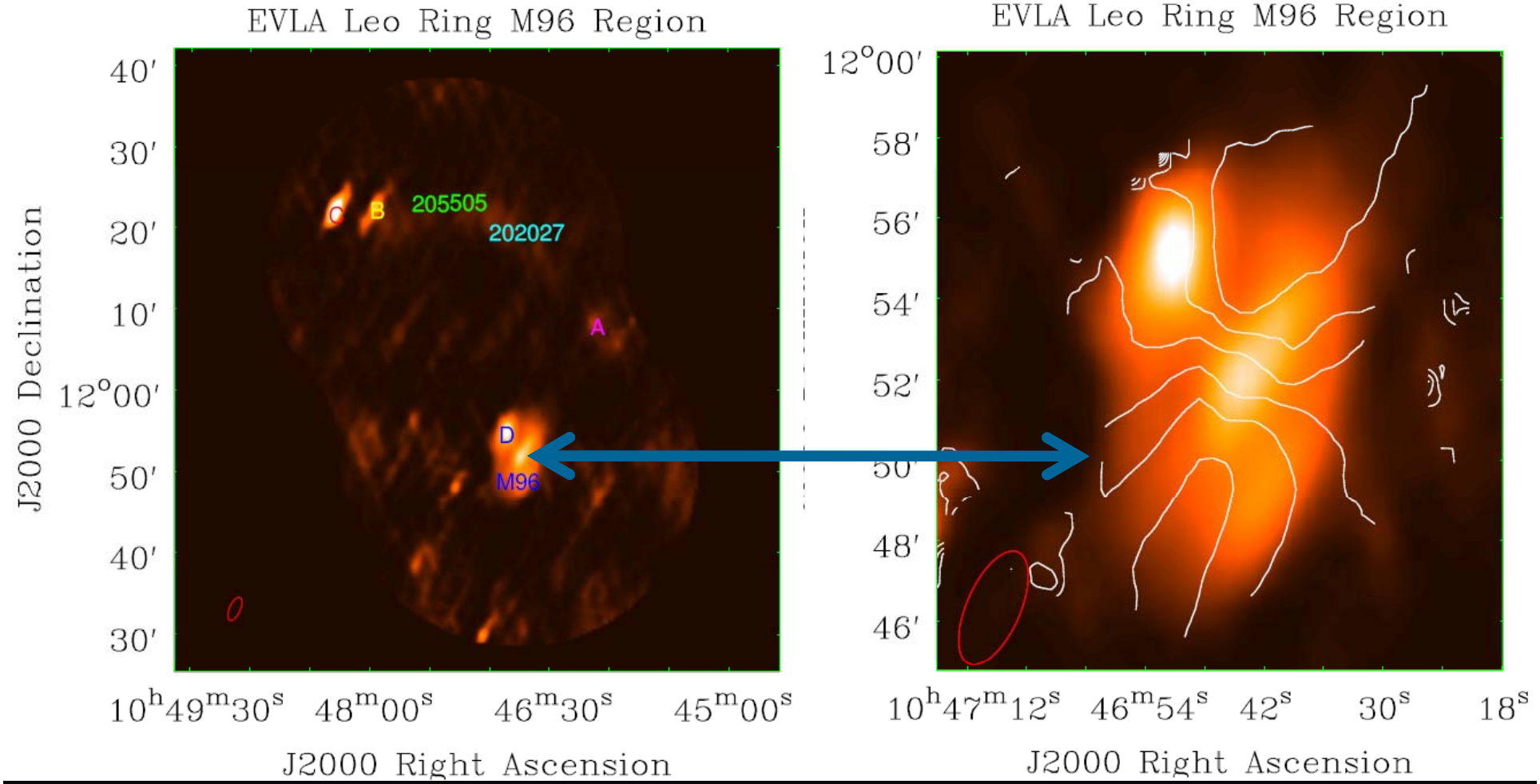




HI in Leo Group (Ring) Region

End to end data processing in CASA

- "OSRO"-mode observation (Aeree Chung et al.)
  - 1 sub-band, 256 channels, 2MHz BW, 2 pol



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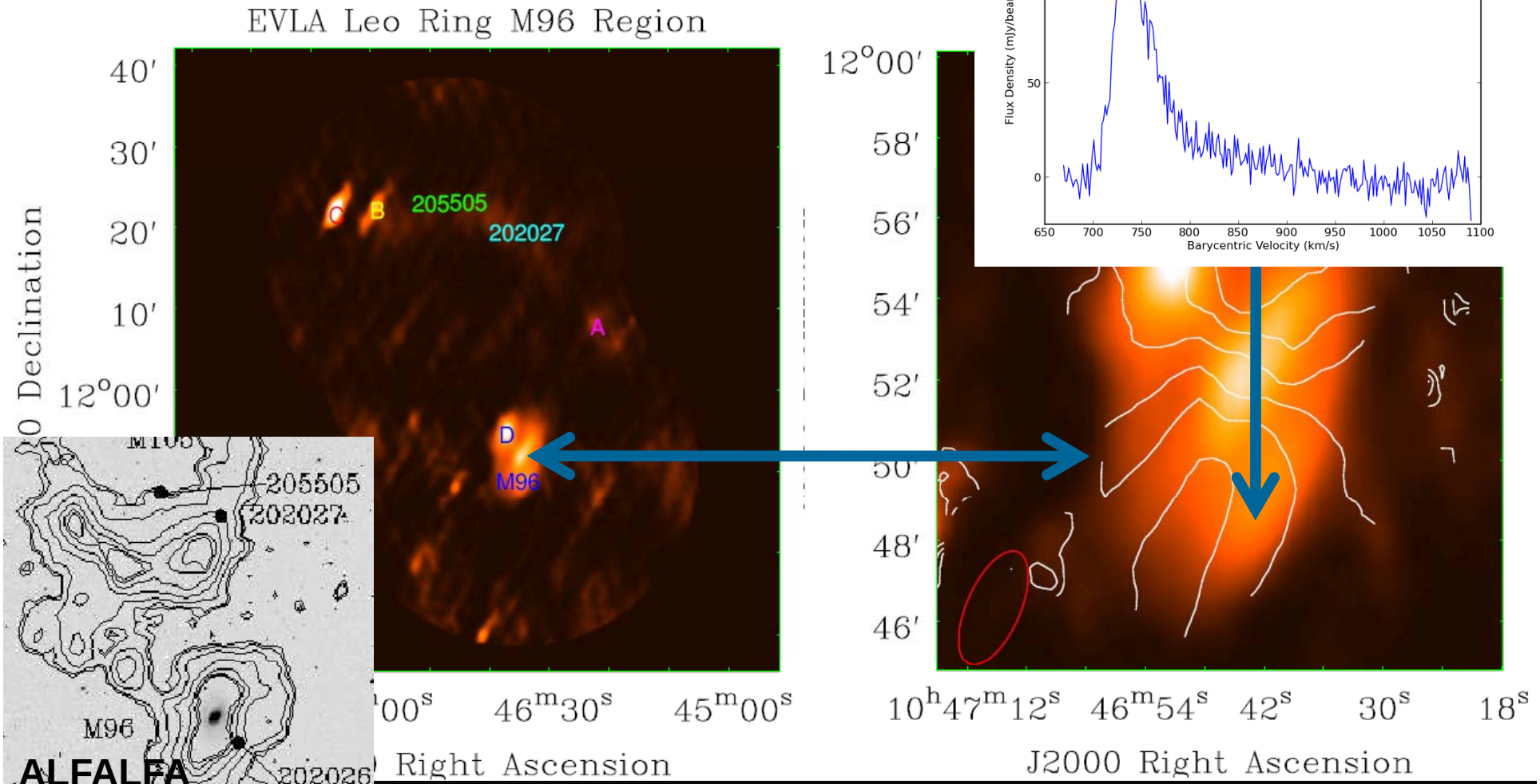


ALFALFA

Stierwalt et al. 2009

1-2 GHz on the EVLA

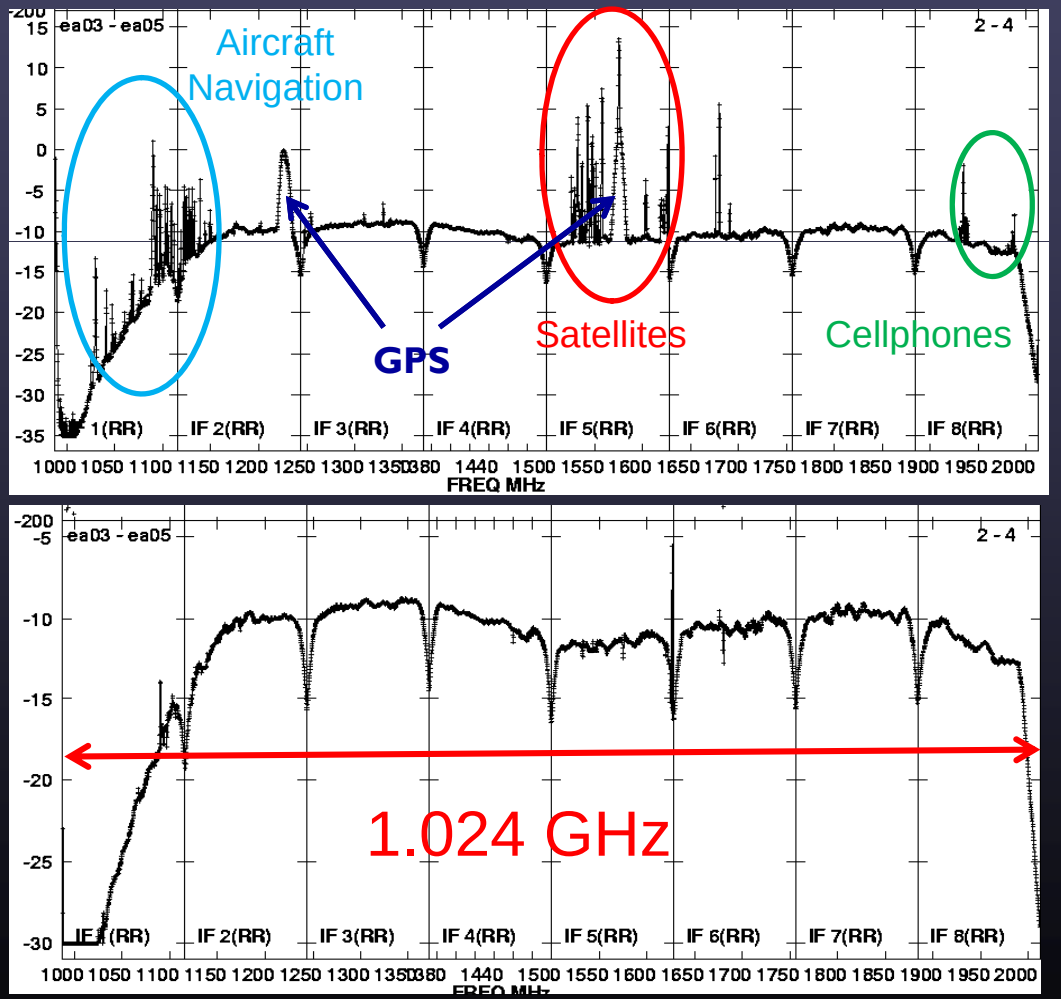
- With great power (from WIDAR) comes…

  …great responsibility (to deal with nasty RFI)

8 sub-bands each 128 MHz spanning 1 – 2 GHz band.

Single baseline, "ampscalar" average, showing RFI, but also extensive 'empty space'. These are raw data, with no bandpass correction.

Same data, vector average, showing how RFI is de-cohered over a few minutes integration.



The VLBA this decade

- Upgrade (512MHz bandwidth expansion) underway
  - **2007-2010:** Development of a new, wider-band digital backend and recording system, in collaboration with MIT Haystack Observatory, the UC-Berkeley CASPER and South African KAT groups, and with Conduant Corporation. Integration of the Swinburne University DiFX software correlator into the VLBA operational environment. Together, these three developments enable fully digital processing of the entire span of the VLBA dual-polar 500 MHz intermediate frequency channels.
  - **2008:** Replacement of the low-noise amplifiers in the VLBA 22-GHz receivers, resulting in 30% sensitivity improvement, in partnership with the Max-Planck-Institut fuer Radioastronomie.
  - **2009:** Commissioning of the software correlator, and beginning of full-time use for VLBA scientific observations.
  - **2010:** Deployment of digital backends and new recording system at VLBA stations. Initiation of conversion of VLBA to subscriber facility, with emphasis on Key Science Projects.
  - **2010-2011:** Expansion of data recording media pool and software correlator processor cluster.
  - **2011:** Full VLBA conversion to 4 Gbit/sec data rate, allowing full-time observations in dual polarization over the entire 500 MHz IF bandwidths.
- Future upgrade plans in decadal white paper
  - "Measuring the Milky Way and the Universe with the VLBA"
    - Romney et al. (*http://science.nrao.edu/A2010/rfi/VLBA-edited.pdf*)
    - 4GHz/pol (32Gbps) bandwidth, EVLA 4-8GHz Rx, WVRs
  - We are working hard (with partners) to ensure a VLBA future
    - With EVLA, the VLBA is the springboard to the North America Array…

The Future: EVLA to SKA

- The EVLA will be “complete” in 2012
  - Small enhancements planned for 2010-2019 decade such as compact E-configuration, improved receivers below below 1 GHz, WVR for high-frequency observing.
  - Synergy with Allen Telescope Array (ATA)
- Beyond EVLA – the SKA-high and NAA
  - “North America Array” (NAA) submitted to US Decadal Survey as a Design, Development, and Prototying project (Myers et al.).
  - Part of the international “Square Kilometre Array” (SKA) program as the high-frequency counterpart to the mid-frequency (Cordes et al.) and low-frequency (Backer et al.) SKA components.

NAA High-Level "Design" and Goals

- NAA concept
  - 1-50 GHz capability
    - "core" 5-45 GHz, two 3:1 bands (5-15, 15-45 GHz)
  - At least 10 x EVLA sensitivity
    - 5 x EVLA on baselines < 500km and 500-3800+ km
  - Grow from EVLA + VLBA + GBT + ATA?
- Science Goals
  - Drivers: megamasers (dark energy, BH masses), weighing dark matter (lensing), imaging galaxies in early Universe (lines, continuum), protoplanetary disks, super-star clusters and supernovae, SNe and GRB, obscured pulsars and motions, Local Group motions (astrometry)
  - For more information: *http://www.nrao.edu/nio/naa/*

NAA/SKA-high Decadal Activity

- Subject of RFI response to RMS Program Prioritization Panel (Myers et al.)
  - Asked to submit RFI-2 response for costing (28Jul09)
  - Final costing estimate: $39850K (FY09)
- NAA Components:
  - Continue and expand SKA TDP (TDP-II), extending to SKA-high antenna evaluation and NAA preparatory R&D
    - 3 years (2012-2015) Cost: $18350K
  - Construct a NAA Prototype Antenna Station connected to EVLA, develop SKA-high costing model and NAA site concept
    - 4 years (2015-2019) Cost: $21500K

EVLA+VLBA➔SKA: Lessons Learned

- 10 year project, even with modest goals
  - We kept the VLA running until very end
  - As with ALMA, would be difficult/expensive to do faster
- Large data rates and volumes stress the post-processing systems
  - Disk access speeds ~25MB/s cause I/O bottleneck
  - Example: 5 hours “VLA-like” OSRO1 mode
    - 2 sub-bands x 64 channels (128MHz) x 1s = 20GB raw data
  - More reliance on scripts and proto-pipelines
    - Hard to examine (visualize) all the data
    - Auto-flagging (e.g. for RFI) or correction will be key
    - Change in “paradigm” for user-based processing

EVLA+VLBA➔SKA: more lessons

- High Dynamic Ranges are difficult
  - Non-closing effects dominate above 50,000:1
    - e.g. non-linear polarization leakage terms in RR,LL
    - mostly affects continuum imaging (including polarimetry)
  - Need to account for some effects to higher precision
    - geodetic vs. geocentric zenith for parallactic angle calculations
    - direction dependent effects like pointing, ionosphere
    - if an effect is present, you have to deal with it (-10db not enough)
  - but, spectral imaging is spectacular (50,000:1 is enough)
- Digital Systems are good (mostly)
  - timing is everything (bad timing causes bad effects)
  - data is much cleaner (fewer subtle issues)
    - our intuition from “old” analogue systems may not apply

EVLA+VLBA➔SKA : Lessons to learn

- We will get more real-life experience
  - with very large (100GB to 1TB+) datasets
  - with users interacting with this data
  - making >1,000,000:1 continuum images
  - making wide-band high-res spectra (also with ALMA)
  - big surveys with pipelines (also ALMA)
  - data-mining for time-domain studies (transient events)
  - supporting non-“black-belt” and non-radio astronomers
- We can carry out SKA-oriented programs
  - joint EVLA/ATA observing campaigns
  - testing of SKA software/algorithms
  - what do YOU want from the EVLA and VLBA?

For more information…

- Project Websites
  - Expanded Very Large Array (EVLA) *http://science.nrao.edu/evla/*
  - Very Long Baseline Array (VLBA) *http://science.nrao.edu/vlba/*
  - North America Array (NAA) *http://www.nrao.edu/nio/naa/*
- Astro2010 Decadal Submissions
  - NRAO Decade2010 *http://www.nrao.edu/A2010/*
    - Includes links to many science and technology white papers
  - "Great Surveys of the Universe" S.T. Myers *http://arxiv.org/abs/0904.2593*
- Proposing for EVLA and VLBA (and ALMA, GBT)
  - Proposal deadlines Feb 1, June 1, Oct 1
  - EVLA Open (OSRO) and Resident (RSRO) shared-risk programs
  - Large Proposals and Key Projects
- NRAO SKA Program Office up and running (mostly)
  - would like to have a community workshop late 2010 or early 2011