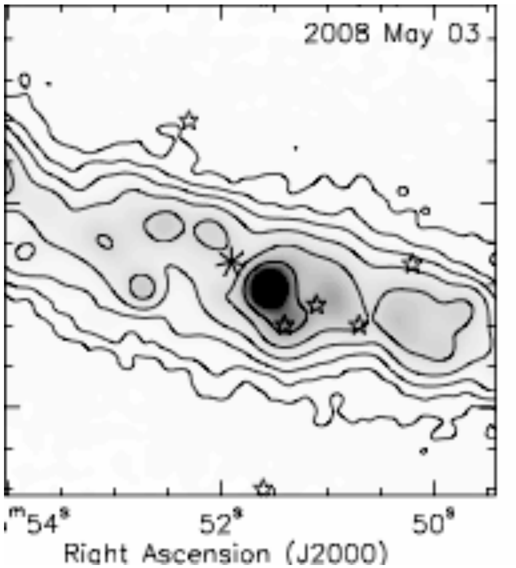
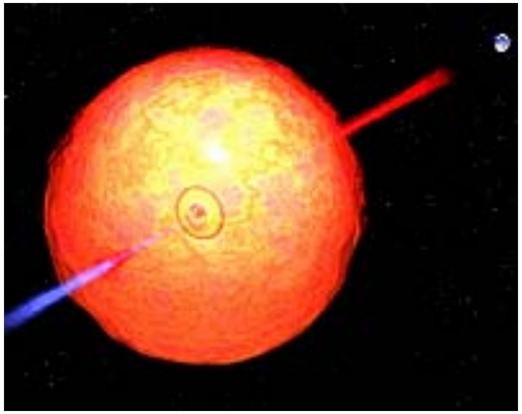
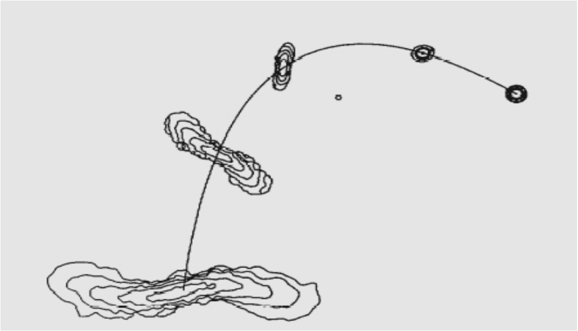
Radio Transient Surveys





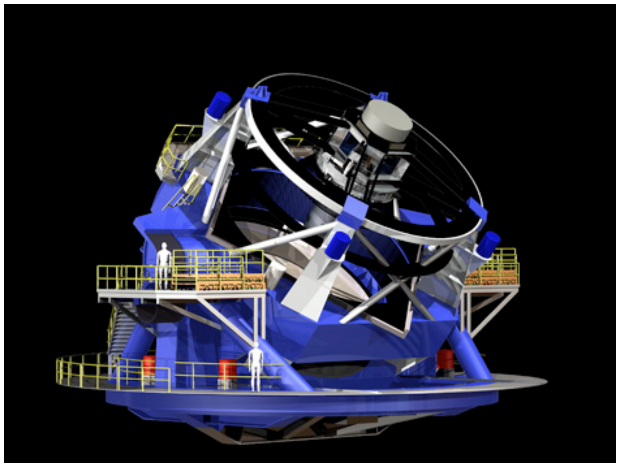


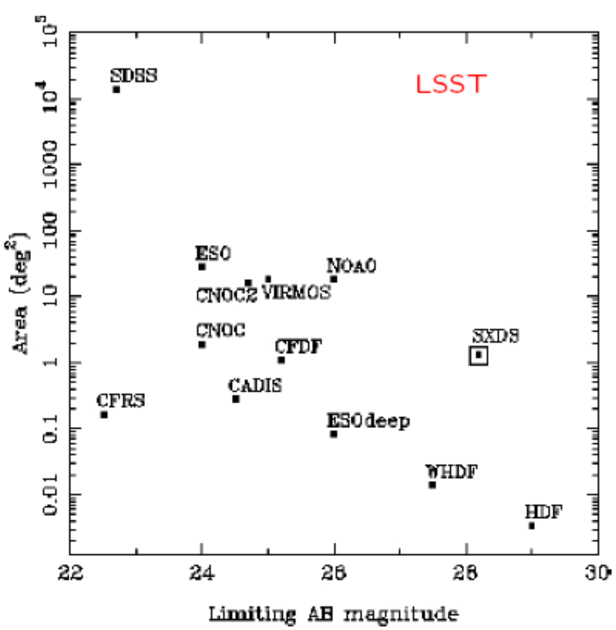
Geoffrey C Bower
(UC Berkeley)

New Worlds New Horizons

- Recognized *Time Domain* as a scientific frontier discovery area
- *KBOs* to *GRBs* to *Black Holes* to *Type Ia SNe*
- "only just begun to explore lively variations in the cosmos"
- The unexpected is expected
- LSST is number one ground-based priority

Optical Time Domain Science





- LSST: The whole observable sky every 3 nights in multiple filters. The same data serves many projects
- Enormous cameras and data volumes
- Builds on SDSS, PTF, PanStarrs, etc

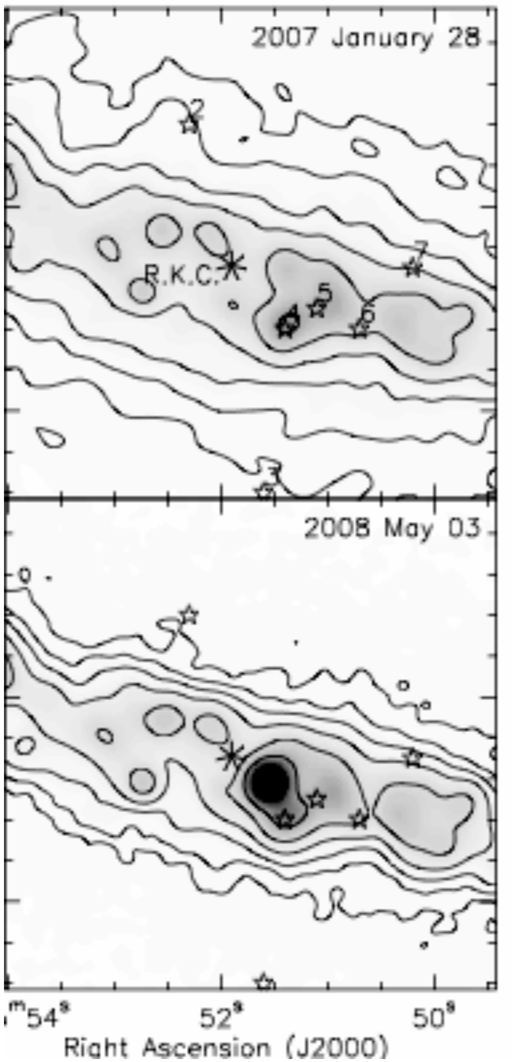
Why Radio Transient Surveys?

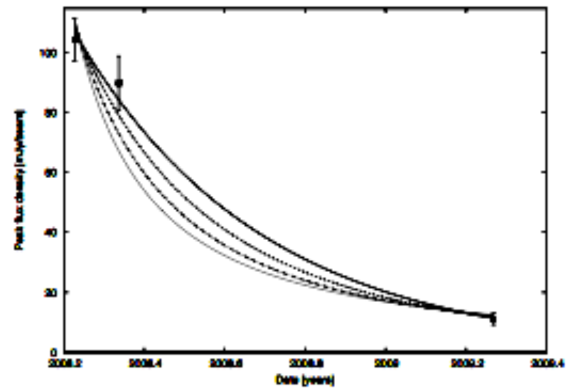
- In some cases, more optimal search technique than optical or high energy (dust, spectrum, duration)
- Study unbiased samples to discover new source classes
- Determine the variability ``foreground'' for rare events
- Simultaneous radio/optical surveys for rejection of optical foregrounds

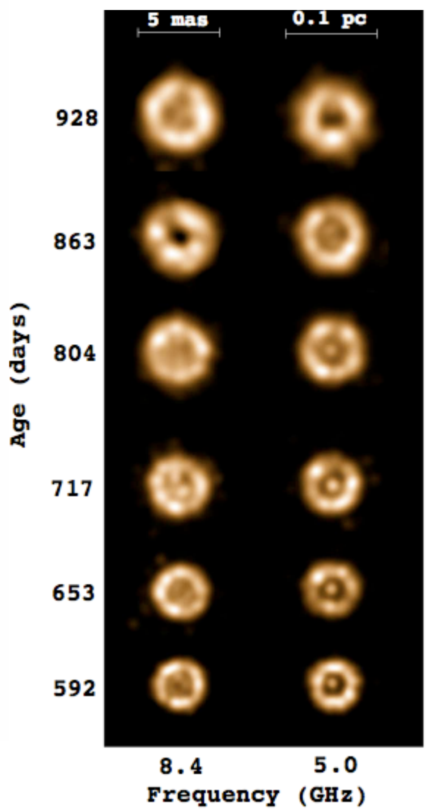
Long Duration Transients

- Orphan GRB afterglows
- Tidal disruption events
- Radio supernovae
- EM counterparts to GW sources

An Obscured Radio Supernova in M82





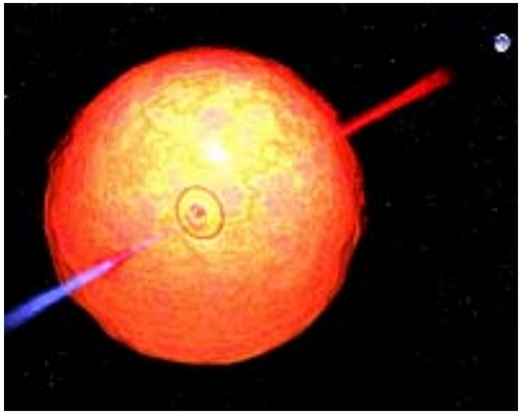


- Discovered serendipitously
- Not detected at optical, uv, nir, x-ray
  - What is the population of hidden SNe?
- Steep spectrum central source → compact object?
- Decelerating expansion → Probe of CSM
- Brunthaler et al. 2009, 2010

- <u>Radio Survey requirements</u>
- High frequency is optimal
  - Bright transient
  - Reduceds galaxy confusion, increases resolution
- Relatively low luminosity → Targeted search of nearby galaxies at arcsecond resolution

OGRBAs

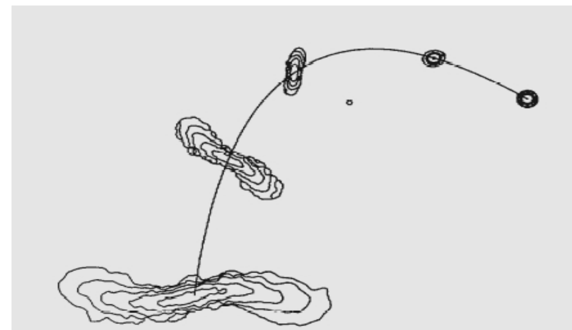
- Probes narrow jet model for GRBs
- Determines total number of GRBs
- High redshift galaxy and star formation tracer
- Universal Structured Jet Model: Rossi et al 2008



- <u>Radio Survey requirements</u>
- High frequency is optimal
  - Faster evolution, higher flux
  - Faint galaxy (confusion not important)
- $R=10^2\ y^{-1}\ sky^{-1}$ for 0.1 mJy radio survey
- Modest resolution for discovery is acceptable → High resolution follow-up

Tidal Disruption Events

- Probing accretion/jet dynamics & nuclear stellar and gas content
- Reverse shock model by Giannios & Metzger (2011)
  - F=2 mJy @ D=1 Gpc
  - ν_{max}=25 GHz
  - Delay ~ 1 year
  - Timescale ~ 1 month
  - R ~ 10^{-7} Mpc^{-3} y^{-1}
  - Radio limits ~ 8 x 10^{-7} Mpc^{-3} y^{-1}



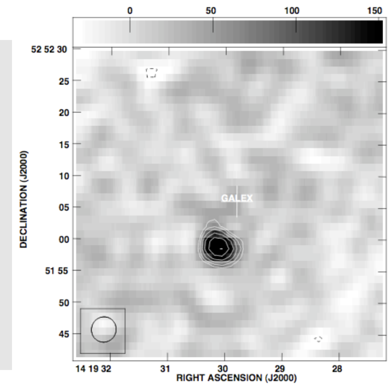


Table 1. Surveys with Long Timescale Sensitivity

Name	f (GHz)	F_{lim} (mJy)	Ω (sr)	N_e	N_{can}	D_{lim} (Gpc)	r_{TD} (10^{-7} y^{-1} Mpc^{-3})
VLA	5.0	0.1	3.9e-06	20	0	2.99	< 29
3C286	1.4	70.0	1.6e-04	23	0	0.08	< 29042
PiGSS-I	3.1	2.0	3.0e-03	1	0	0.59	< 96
ATATS-I	1.4	230.0	2.1e-01	1	0	0.05	< 3113
MOST	0.8	14.0	5.5e-01	1	4	0.16	< 34
FIRST-NVSS	1.4	6.0	1.9e-01	1	0	0.28	< 14

Bower 2011

- <u>Radio Survey requirements</u>
- High frequency is optimal
  - Bright transient
  - Faint galaxy (confusion not important)
- R=10^2 y^{-1} sky^{-1} for mJy radio survey
- Modest resolution for discovery is acceptable → High resolution follow-up

Radio Counterparts to GW Sources

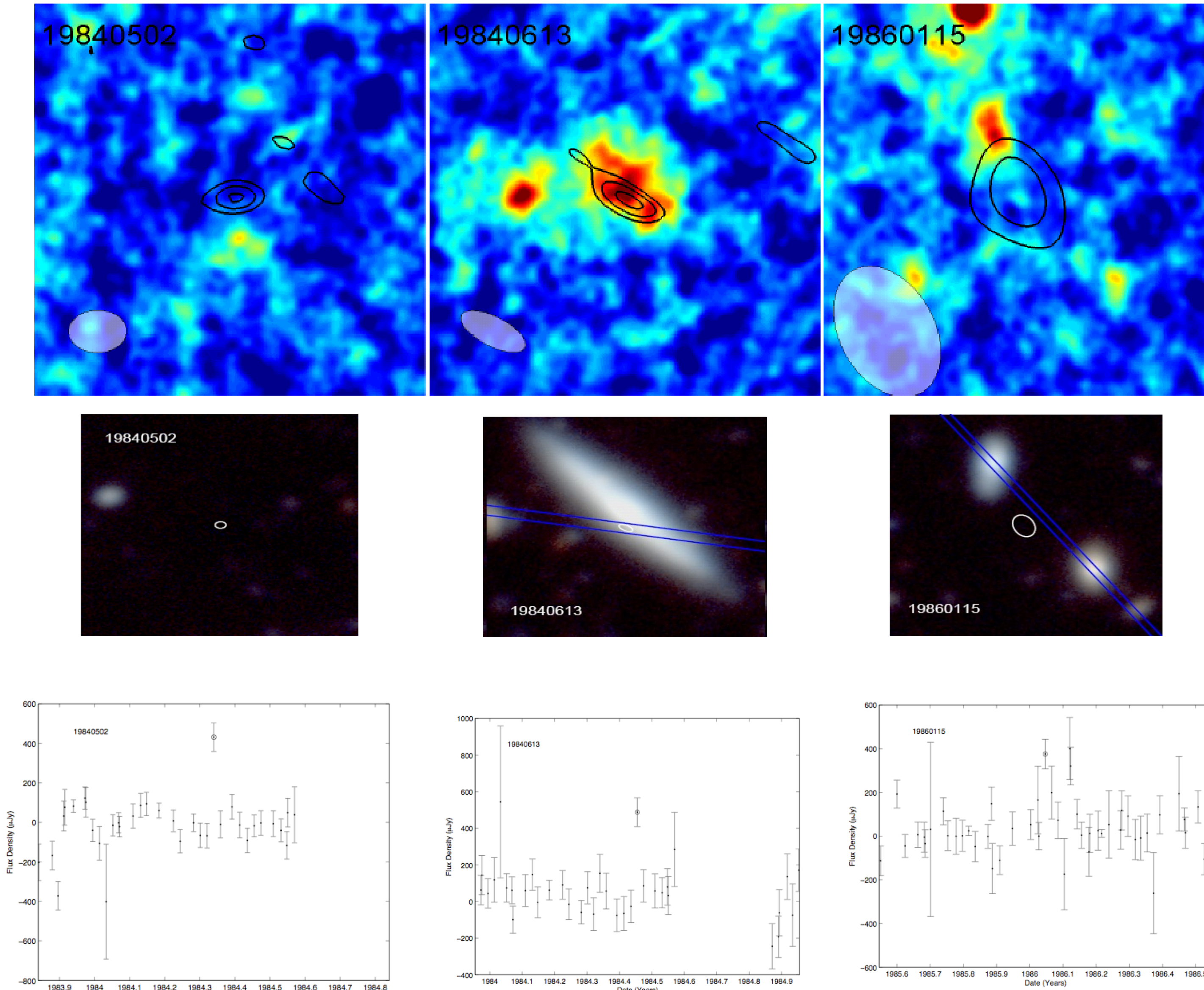
- Jet formation, shock waves, environments, progenitors of GW sources (NS^2 binaries)
- 10 times more luminous than RSNe
- ~1 GHz identified as optimal frequency
- Duration ~ weeks
- F~1 mJy at 1 Gpc
- Rate very uncertain
  - 20 --- 20,000 Gpc^{-3} y^{-1}
- Nakar & Piran 2011

- <u>Radio Survey requirements</u>
- GHz frequency may be optimal
  - Bright transient
  - Faint galaxy (confusion not important)
- R=10^{1--4} y^{-1} sky^{-1} for 0.1 mJy radio survey
- Modest resolution for discovery is acceptable → High resolution follow-up

What do we know now?

?

Unknown Radio Transients from VLA Archival Survey

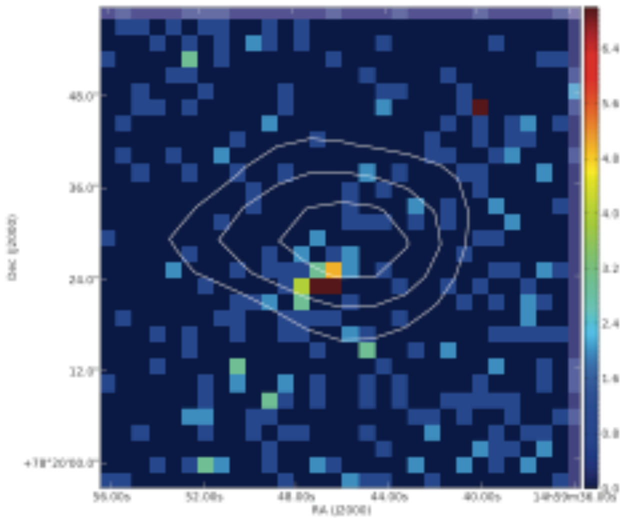


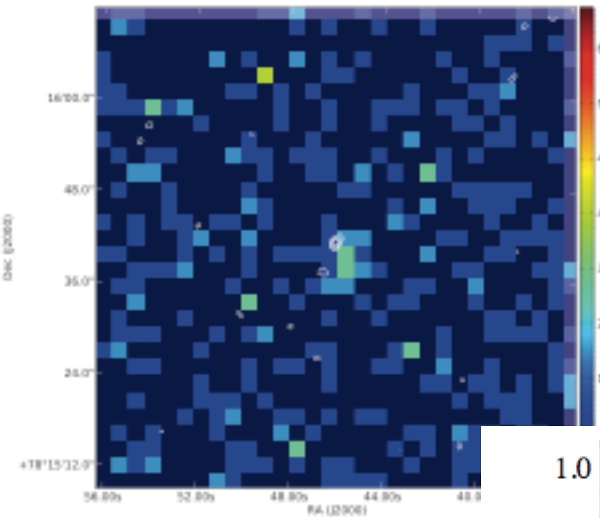
VLA
5 GHz

Keck
G,R

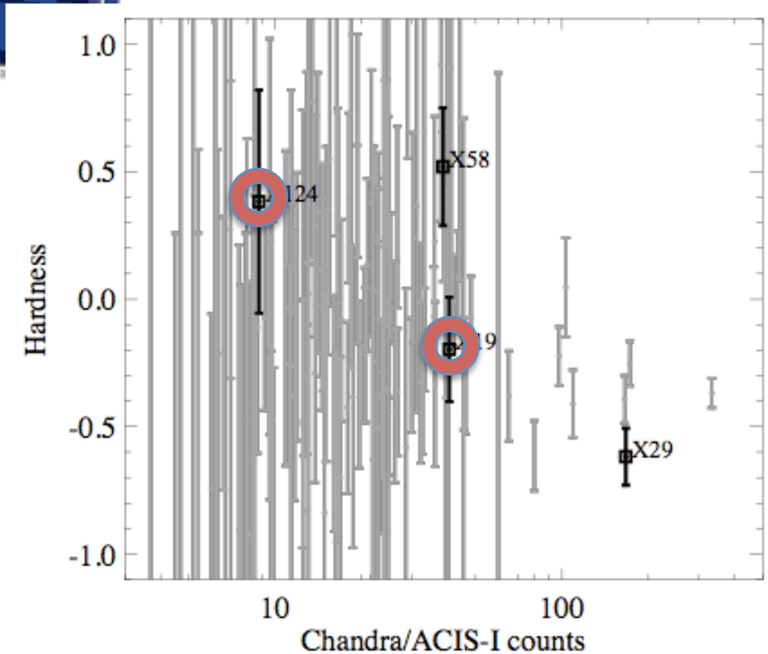
Bower et al 2007

X-ray Counterparts to RTs w/o Optical Hosts



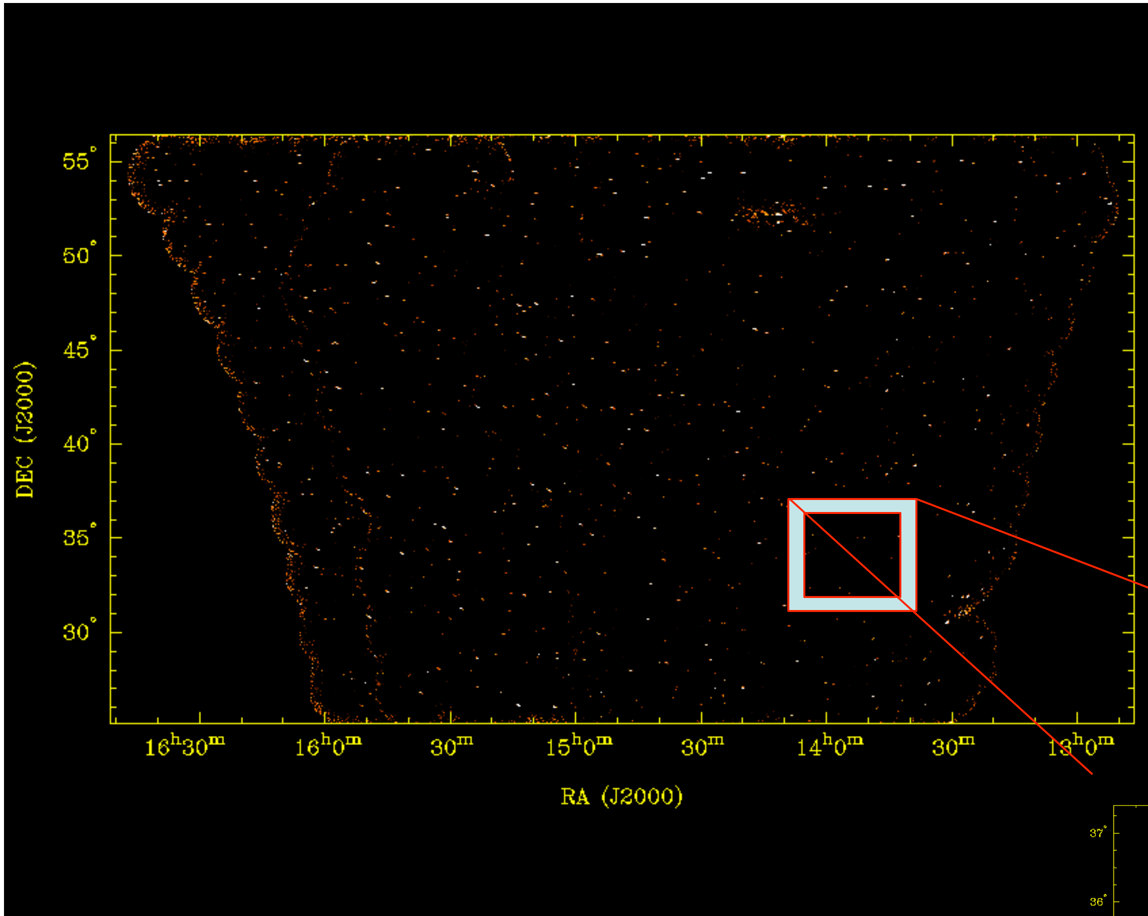


Preliminary results



- X-ray spectra marginally constrained
- Inconsistent with old NS (Ofek 2010)
- Consistent w/flare stars or brown dwarfs

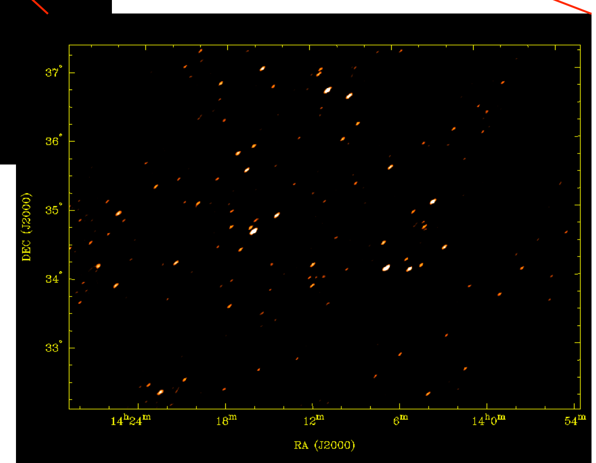
ATATS: ATA 20 CM Survey



Precursor to PiGSS

<u>690 square degrees</u>
<u>250 pointings</u>
<u>In 10 hours</u>
<u>>10 epochs</u>

<u>Sensitive to bright, rare transients</u>



Croft & Bower et al 2010, 2011

ATATS: Validation of ATA Flux Scale and Imaging Capabilities

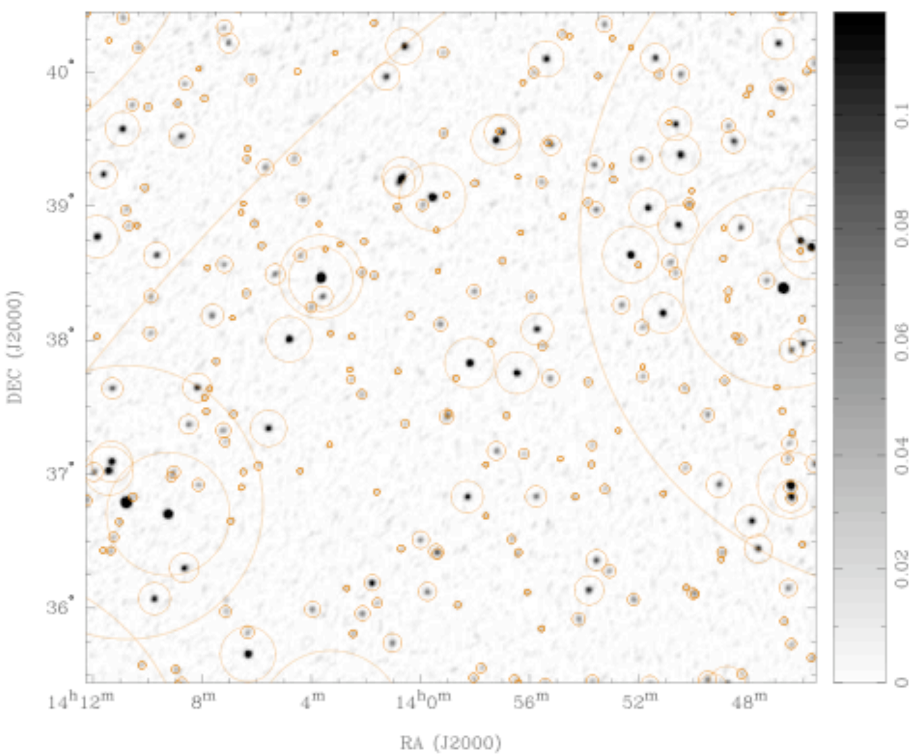


Fig. 5.— A 25 square degree region of the deep field shown in Fig. 3, shown at a larger scale (and slightly different stretch) so that the structure of individual sources may be seen. All NVSS sources brighter than 20 mJy (corresponding to 5 times the RMS of the ATATS image) are plotted as circles; the size of the circle is proportional to the NVSS flux density. The greyscale runs from zero to 118.2 mJy beam^{-1}(30σ).

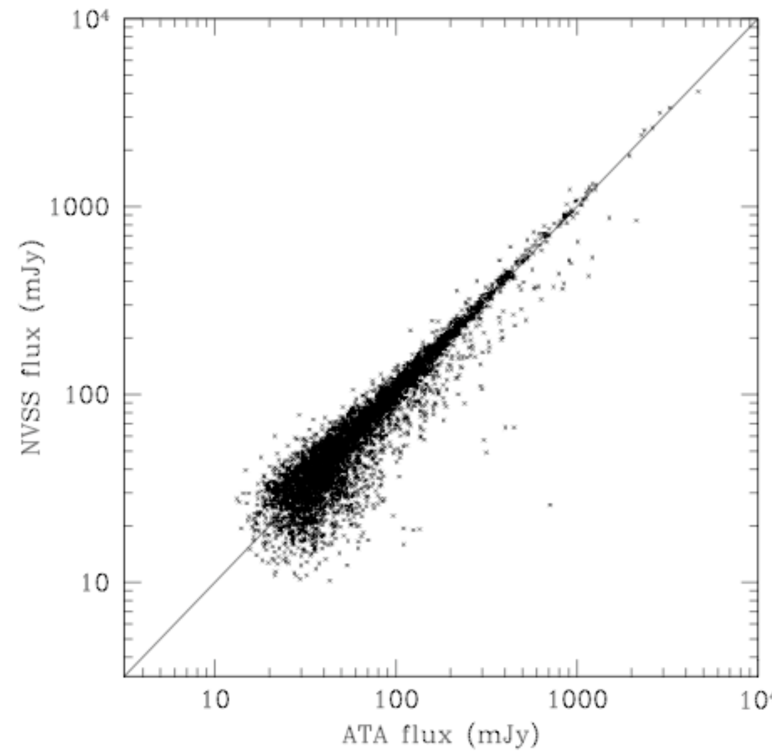


Fig. 7.— Comparison of the flux densities of sources from the ATATS catalog, with the sum of fluxes of all NVSS sources within 75″ of the ATATS positions.

ATATS: No Very Bright Transients or Strongly Variable Sources

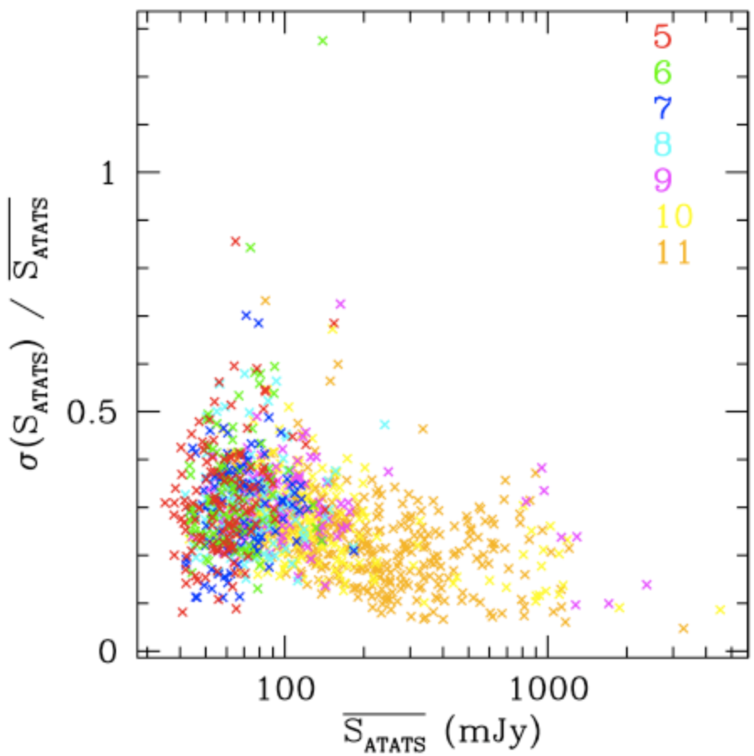
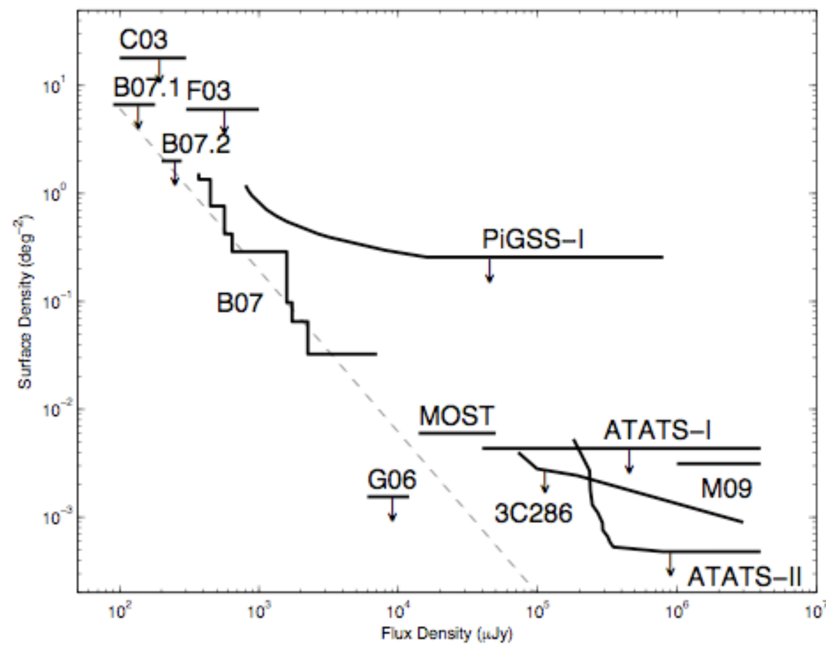


Fig. 8.— The ratio of the standard deviation of flux densities of sources detected in ATATS, $\sigma(S_{ATATS})$, to the mean flux density of the sources, $\overline{S_{ATATS}}$, plotted as a function of $\overline{S_{ATATS}}$, for sources with detections in 5 or more ATATS epochs. Points are color coded according to the number of ATATS epochs in which they were detected.

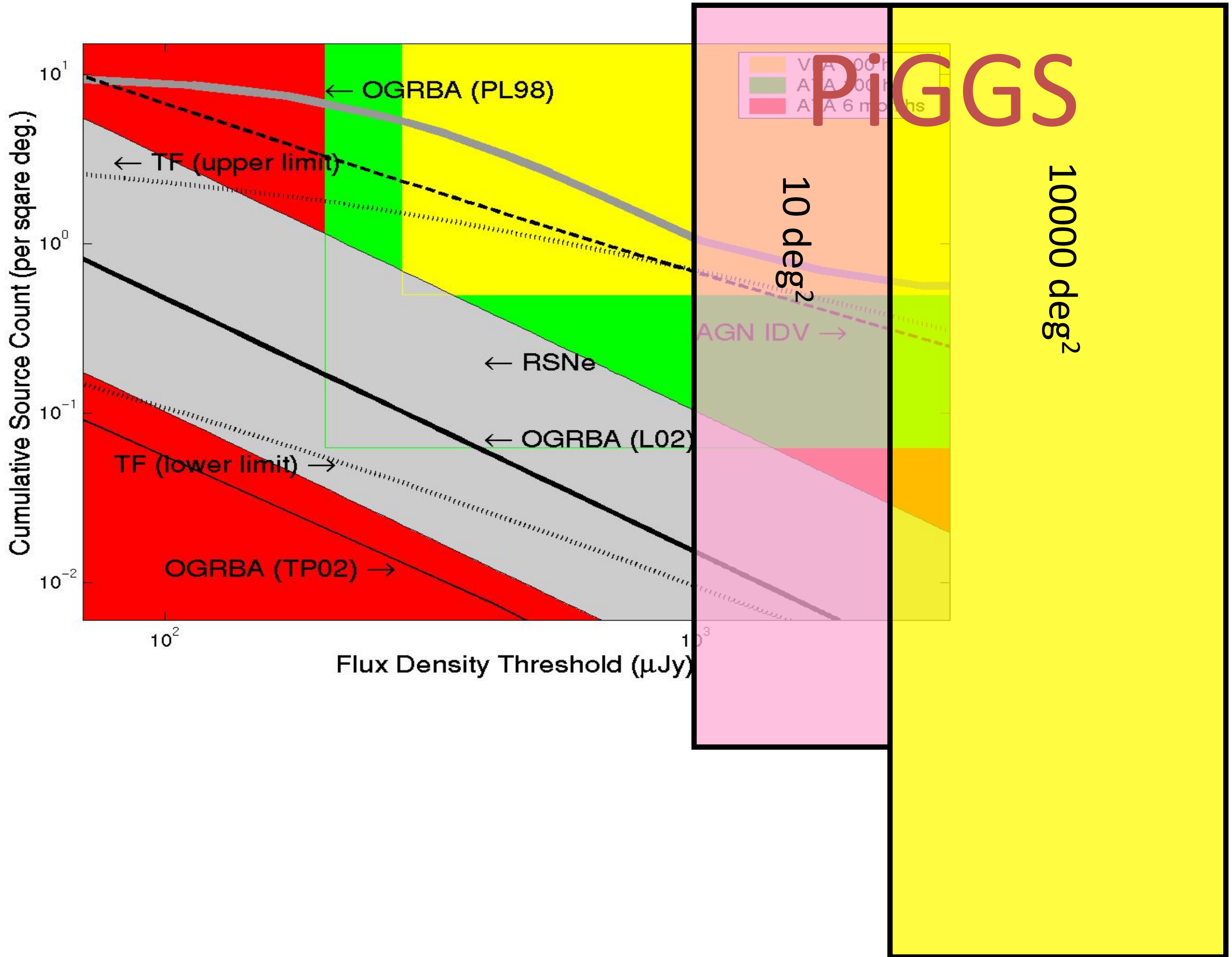


Rejects Nasu 1-Jy Transients (M09)

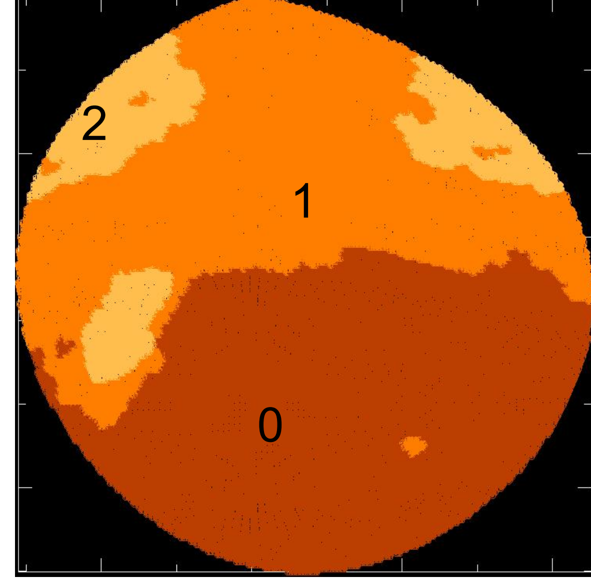
ATA PiGSS
Pi GHz Sky Survey

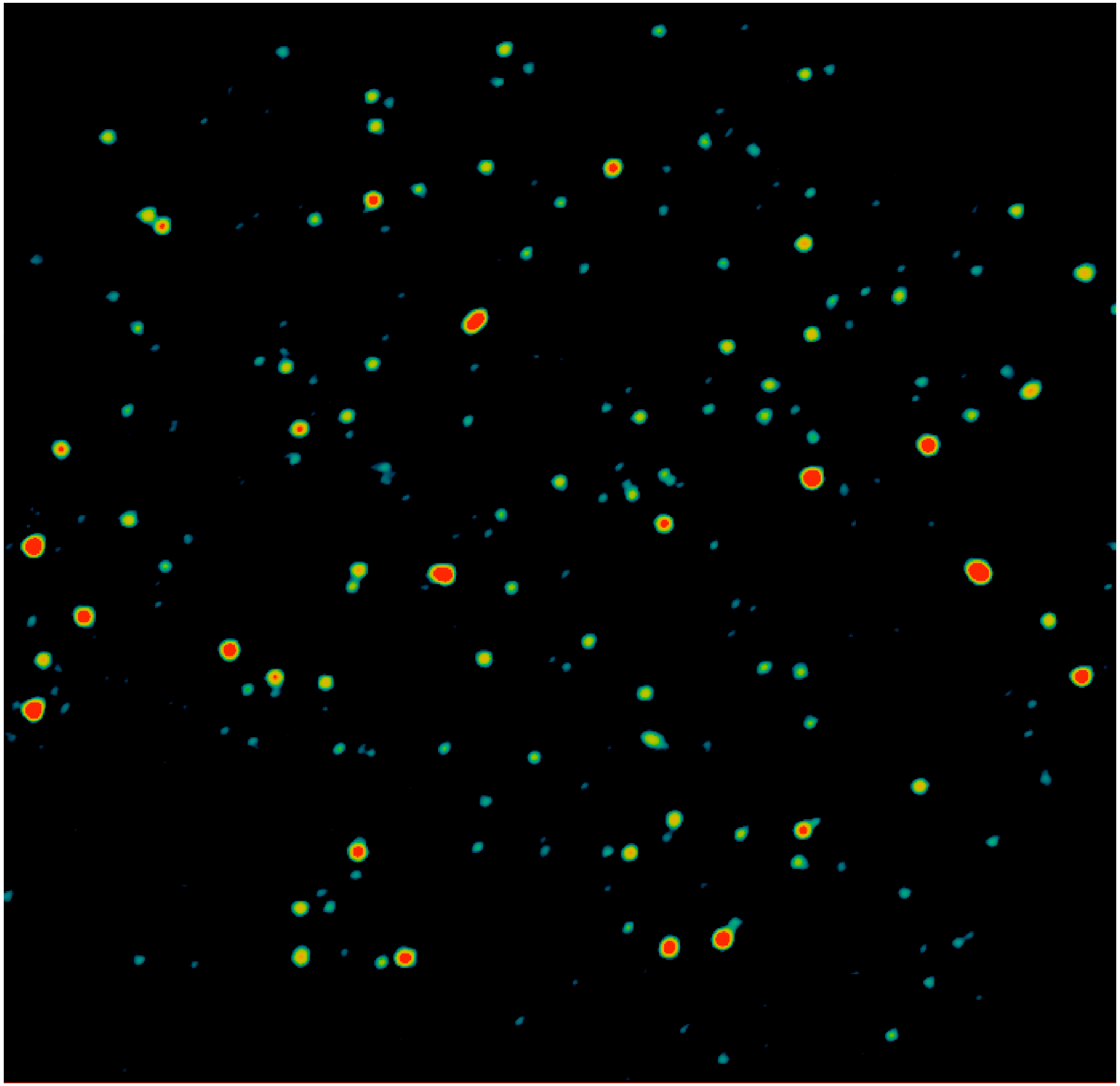
- Radio Counterpart to Sloan Digital Sky Survey
  - Overlap with NVSS, FIRST & SDSS
  - 10^4 Square degrees
  - Arcminute resolution
- Highest Frequency Deep, Large Radio Survey
  - 1 mJy rms
  - Factor of ~10 more sensitive than GB6 (5 GHz)
- Smaller, deeper fields
  - 10 sq deg repeated every day
- 24 calendar months to complete with ATA-42
- Broad science case

Radio Transient Source Counts



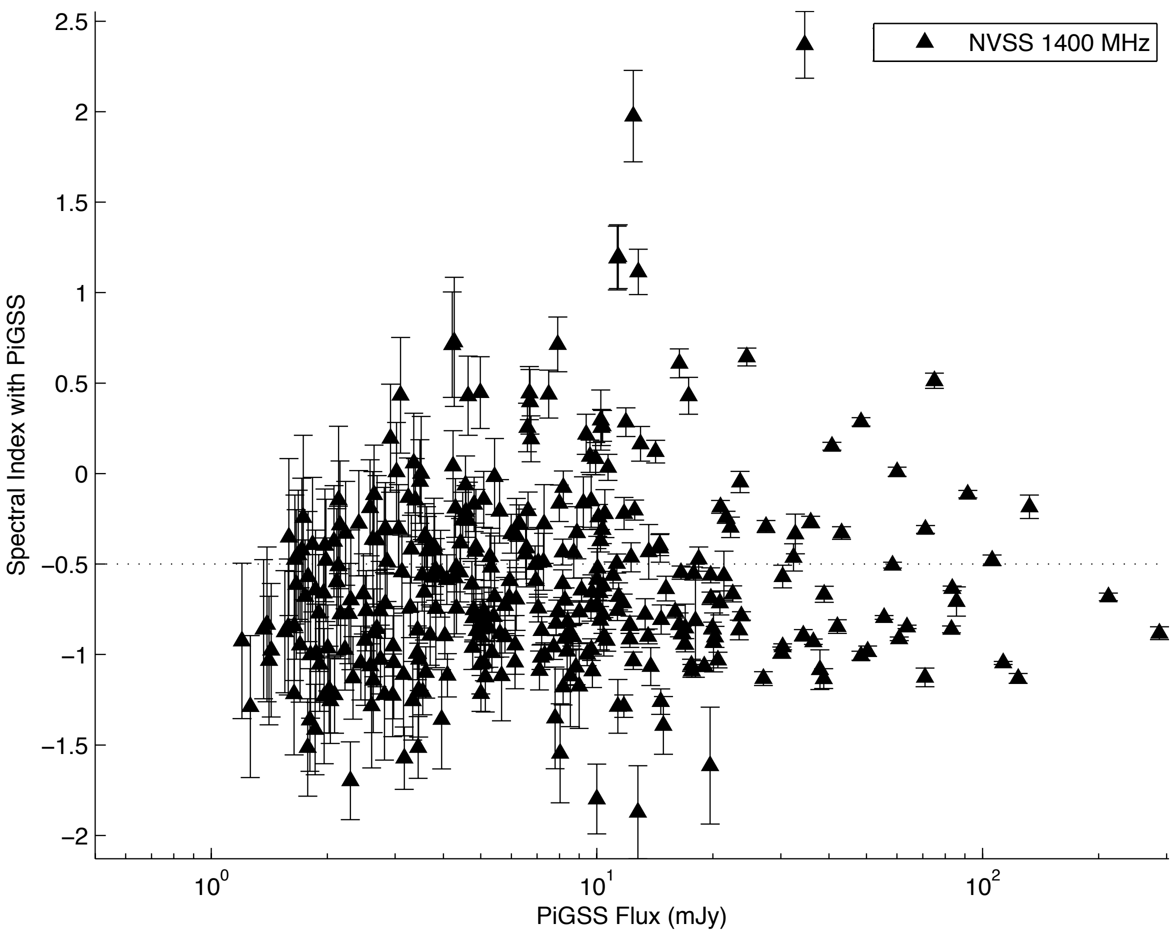
PiGSS Status





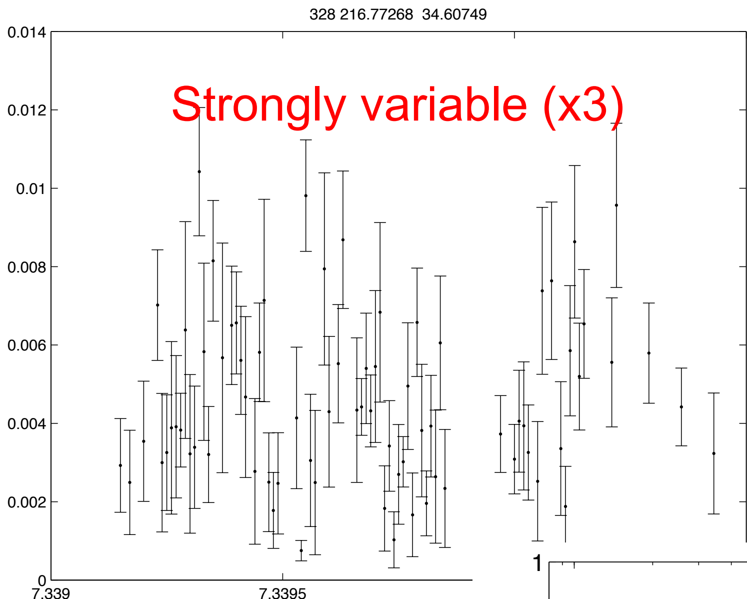
- 5000 sq deg campaign
  - First pass complete
  - Second pass underway
- 300 epochs of 10 sq degree imaging
  - 1 mJy rms
- Deep image from 80 daily images of 10 sq deg fields
  - 0.2 mJy rms
- Two epochs of 250 sq deg images
  - 1 mJy rms
  - 2 month separation

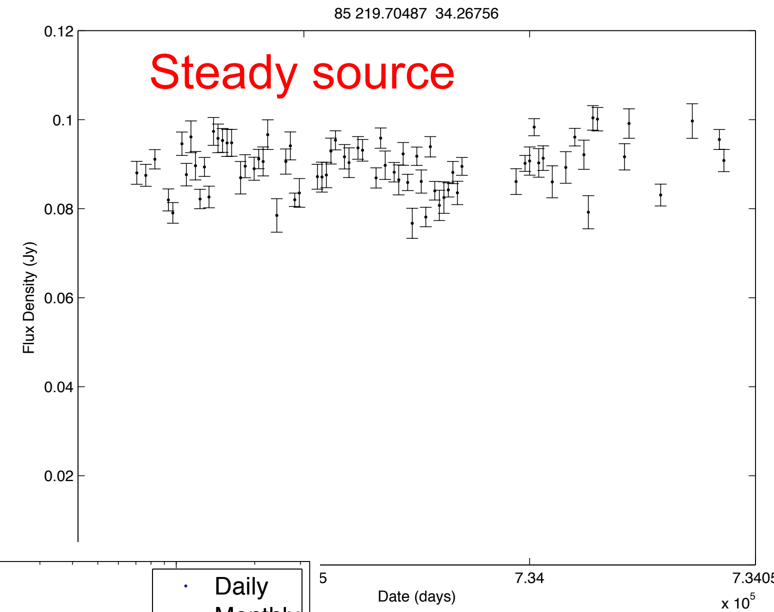
PiGSS Spectral Indices

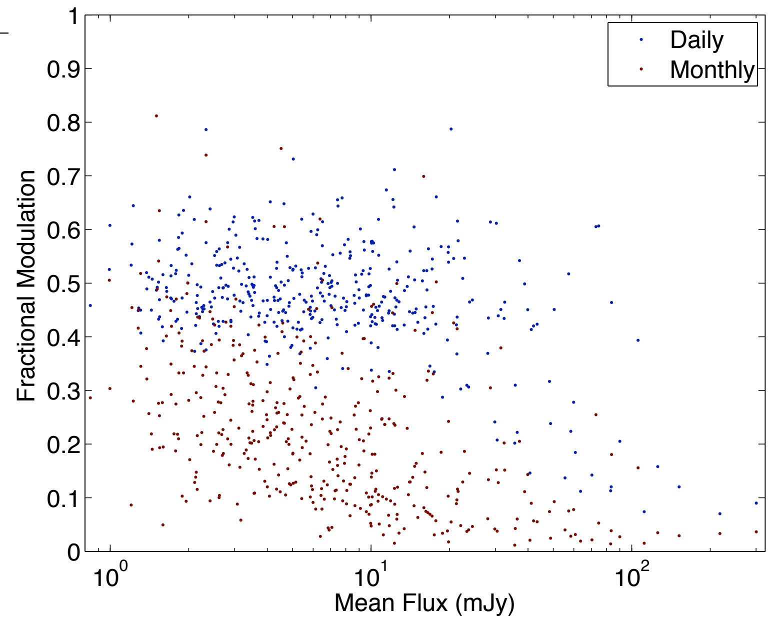


Bower et al 2010

PiGSS Light Curves



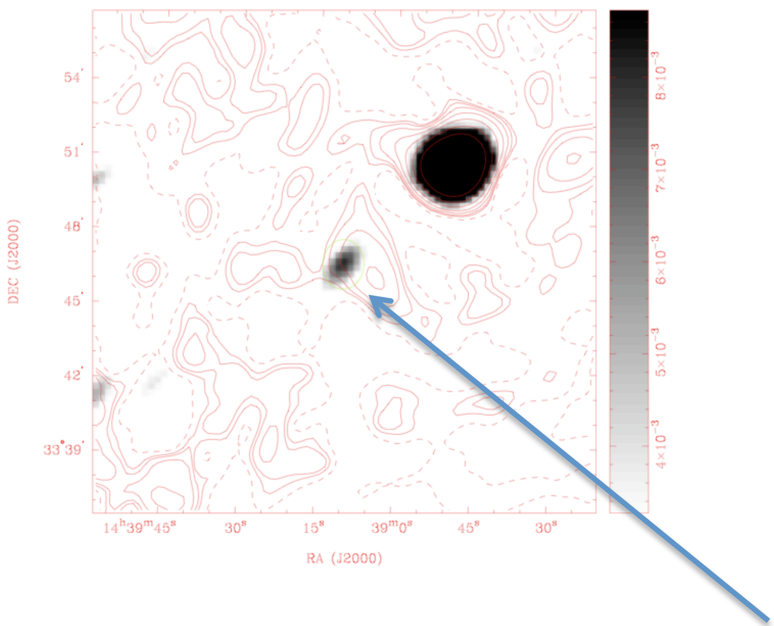


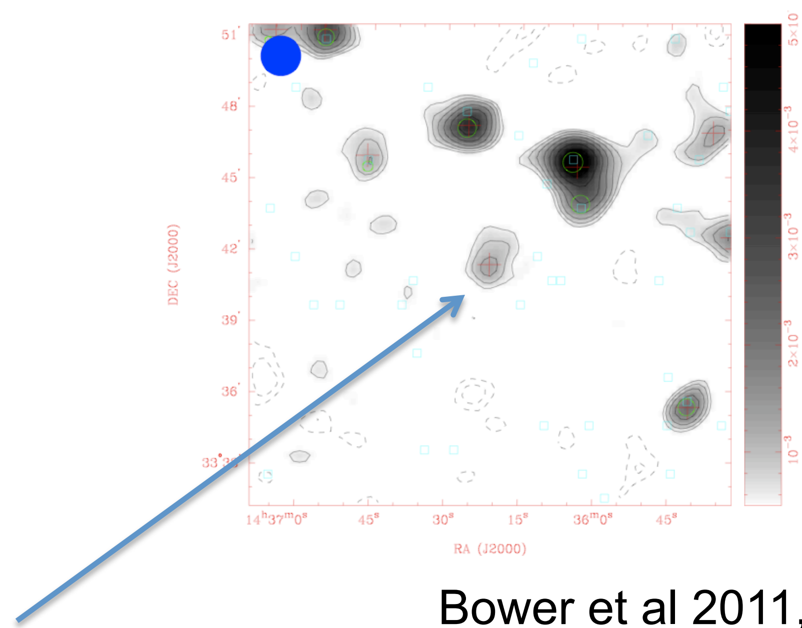


Bower et al 2011, in prep

Transient Candidates from PiGSS

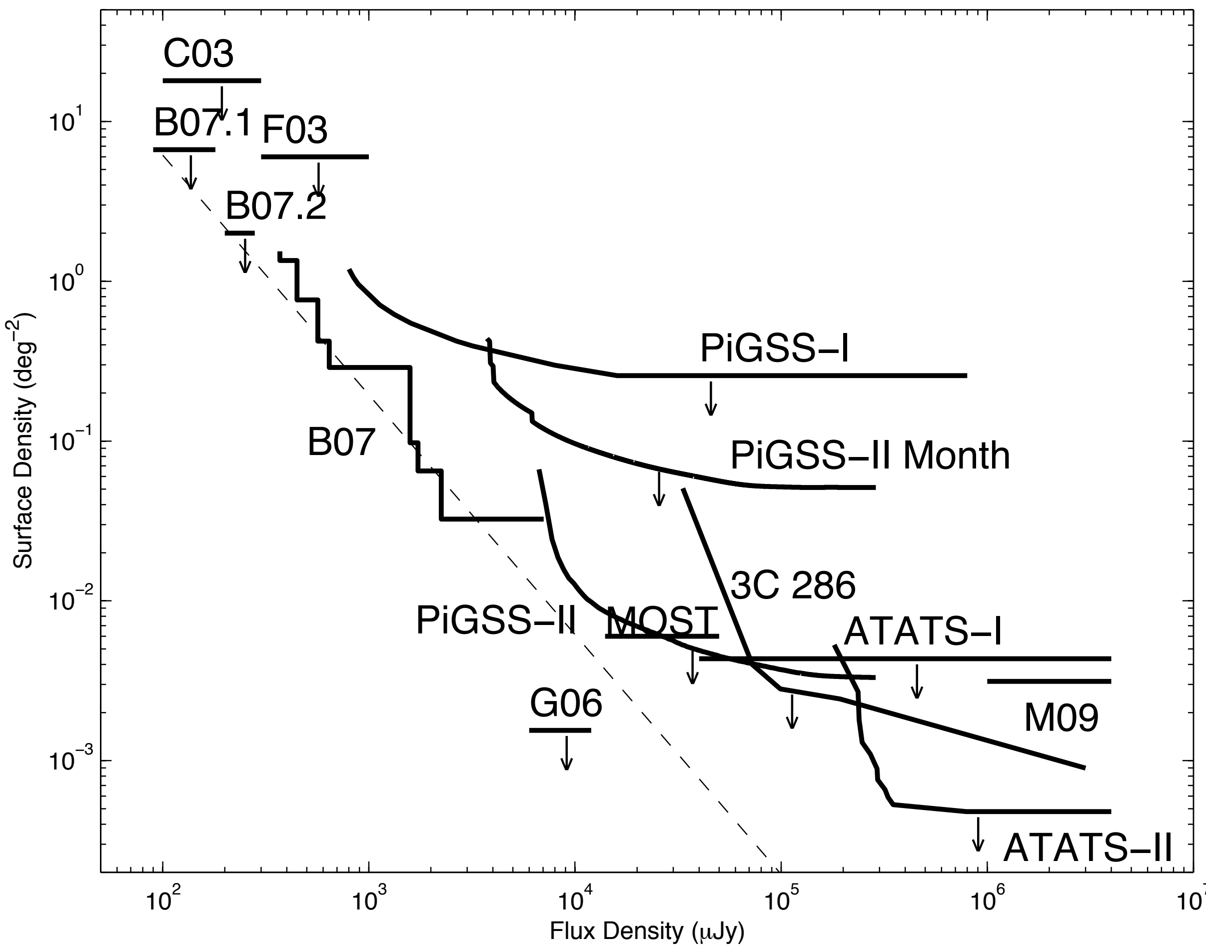
- Single epoch
  - Single epoch gray scale
  - Deep image contours
  - 1 day timescale
- Deep image but not in previous catalog (NVSS, FIRST, etc)





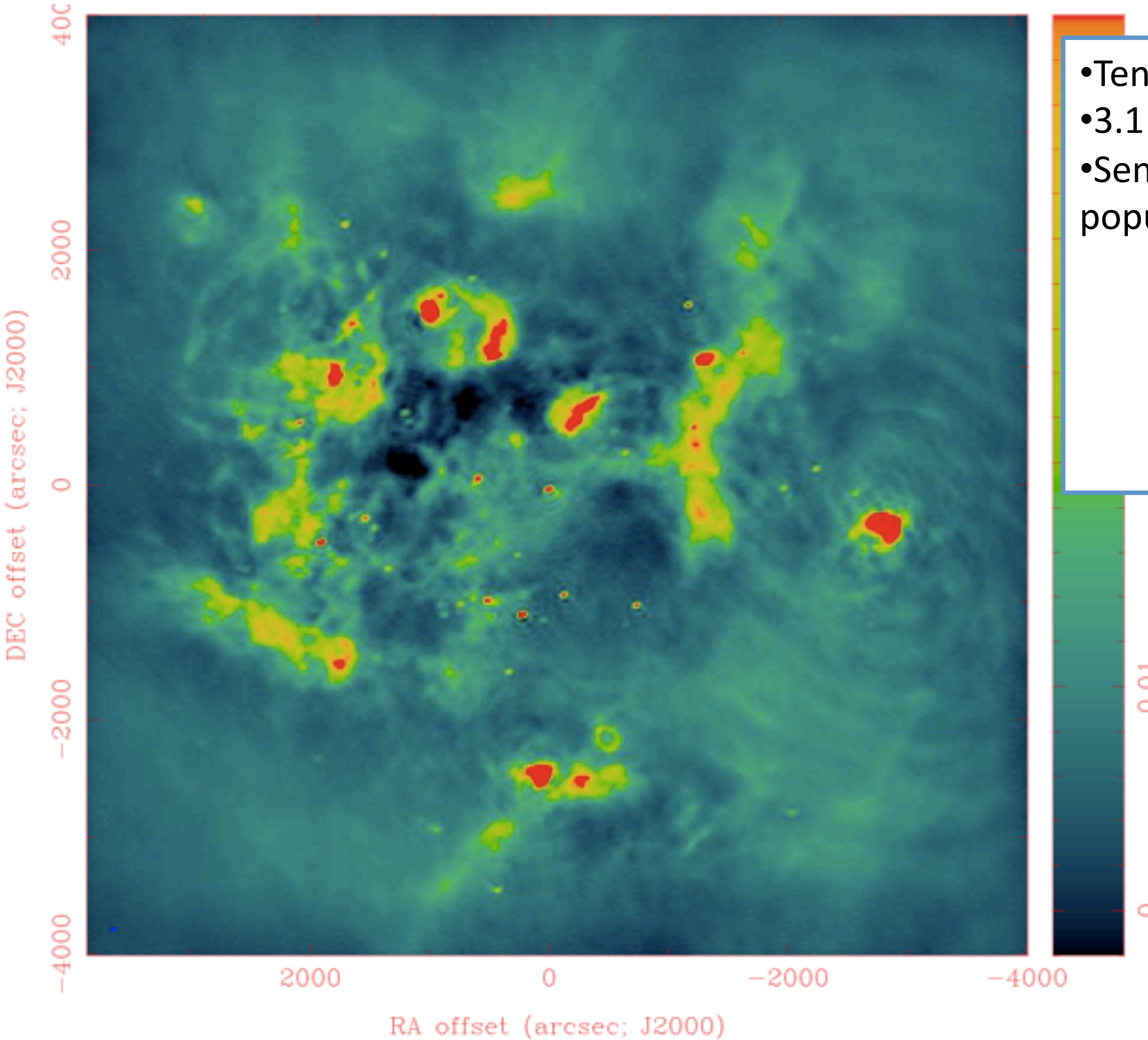
Bower et al 2011, in prep

Transient Parameter Space



Bower et al 2011, in prep

Commensal Transient Search in Cygnus



- Tens of epochs
- 3.1 GHz
- Sensitive to different populations than PiGSS
  - E.g., Becker et al 2009
  - Cyg X-3
  - XRBs, Low-mass stars

Williams, Bower, et al

Some Lessons & Questions from ATA Surveys

- Archival searches have been very effective
- Real time detection very powerful but very difficult to achieve
- Deep images are very useful tool for characterization of variable and transient population
- Low angular resolution makes imaging and searching easy but makes multi-wavelength, multi-survey identification difficult
- Finding sources in nearby galaxies very difficult --- requires high angular resolution to eliminate confusion
- Commensal modes are effective way to get a lot of observing time
  - Piggyback on pulsar-timing observations?
- What is the right balance between shallow-and-wide, deep-and-narrow, and targeted?
- What is the best frequency to search?
  - Higher frequencies are more strongly variable
  - Higher frequencies exclude galactic structure
  - But smaller beam area and slower survey speed

Where are we going?

?

Survey Requirements

	Frequency	Localization	Timescale	Survey Type	Rate
OGRBA	>10 GHz	10 arcsec	< 1 month	Blind	10^2 y^{-1} sky^{-1}
Tidal disruption	>10	10	1	Blind	10^2
RSNe	>10	1	>1	Targeted	10 y^{-1}
GWs	<10	10	<1	Blind	10^{1-4} y^{-1} sky^{-1}
Optimal Survey	≥10 GHz	10 arcsec	≤1 month	Blind	1 day^{-1}

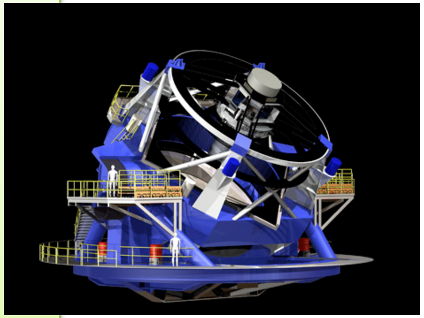
Survey Requirements
- 0.1 mJy
- 100 deg^2 day^{-1}
- 10 day cadence

Survey Strategies

EVLA targeted surveys of large sample of nearby galaxies

Blind surveys of local volume with high cadence

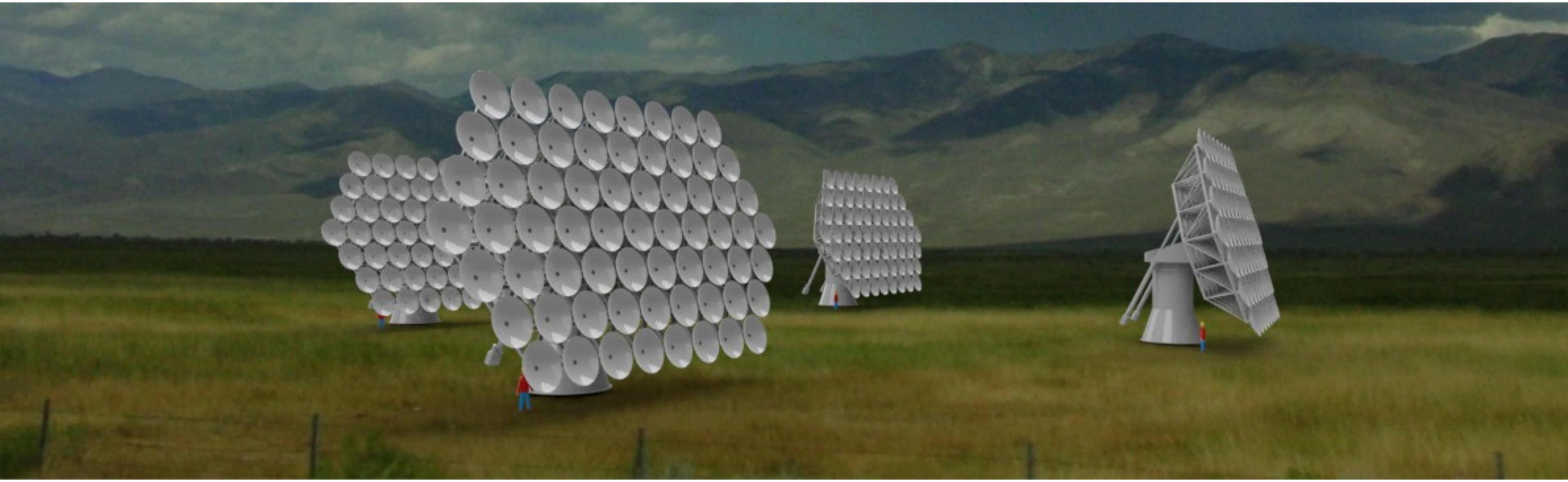
Joint radio/optical survey campaigns



ASKAP

- 36 x 12m antennas
- Focal plane arrays provide 30 sq deg instantaneously
  - Enormous survey speed
  - Technically ambitious
  - Major computing and calibration challenges
- 0.7 --- 1.8 GHz
- Operational >2013
- VAST survey
  - Targets ESEs, RSNe, GRBs, …
  - Tiered search strategy @ mJy levels

DACOTA



- Transients
- CO at redshift of EOR
- SZ Effect
- Galactic Water and Ammonia
- Other…

- Dense array of 4 x 64 x 2m antennas
- 10 – 40 GHz (2 feed horns)
- T_{sys} ~ 25 - 50 K
- 8 GHz Bandwidth, 8k channels
- Spatial FFT Correlator
- Resolution: 1’ – 22’
- Survey speed ~ EVLA speed
- 2 years to complete 100 deg^2 CO survey