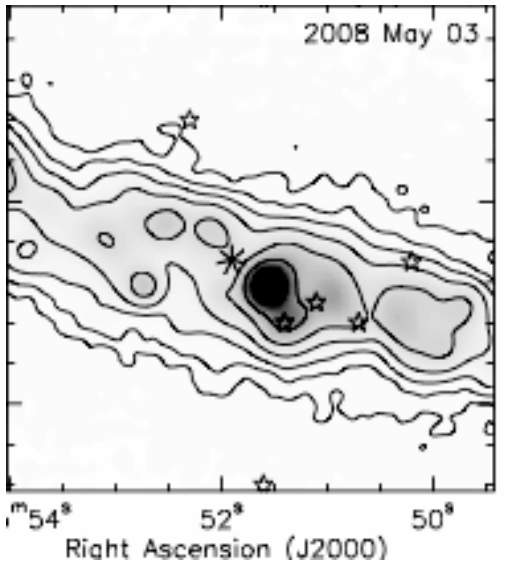
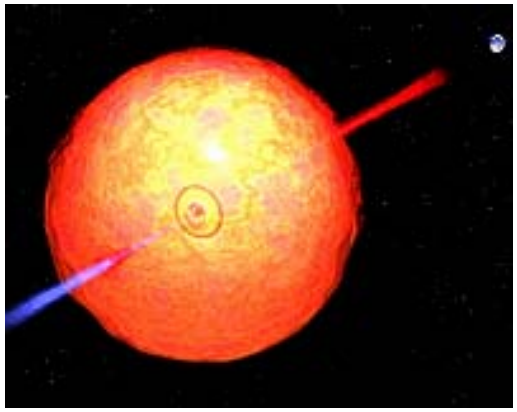
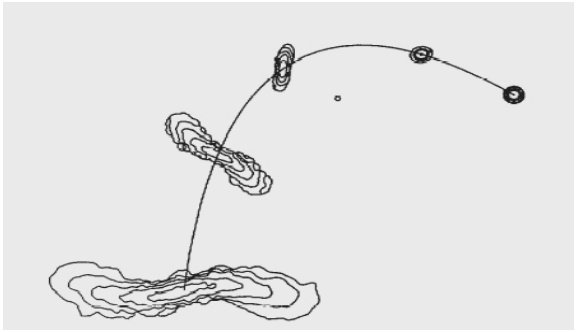
Radio Transient Surveys



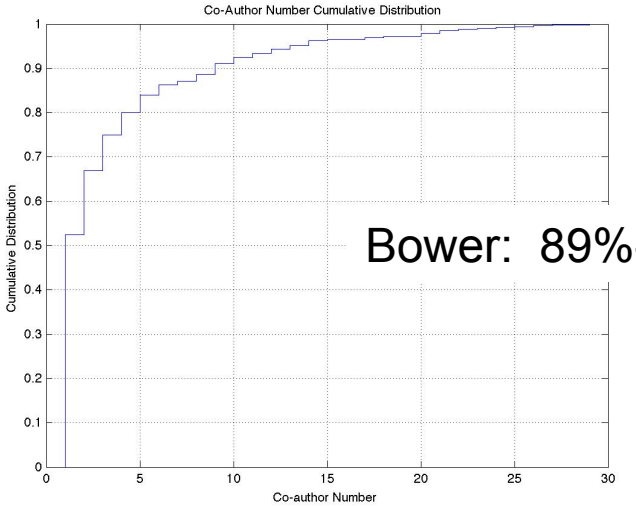




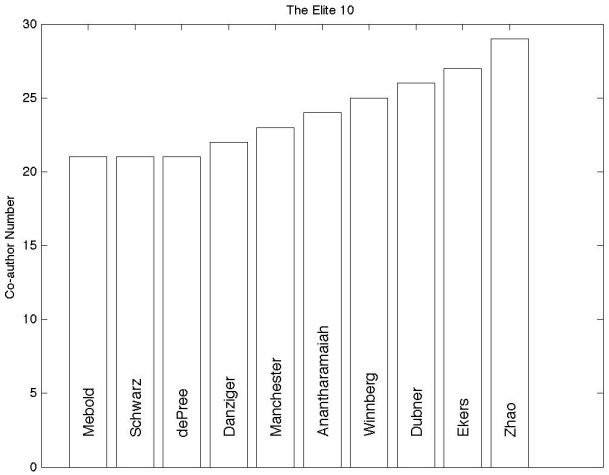
Geoffrey C Bower

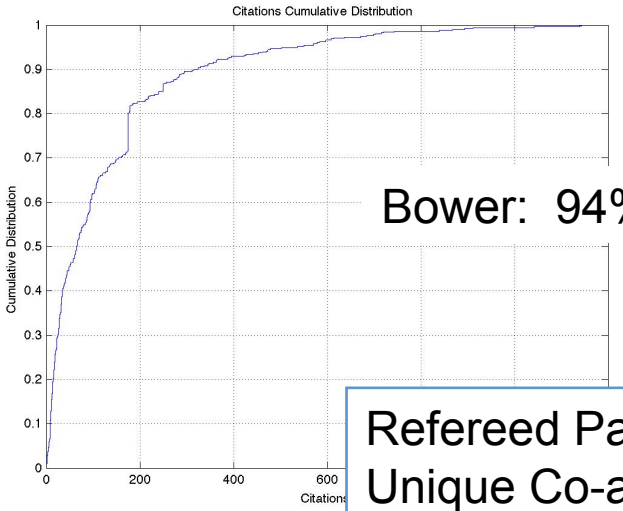
(UC Berkeley)

Goss-ography

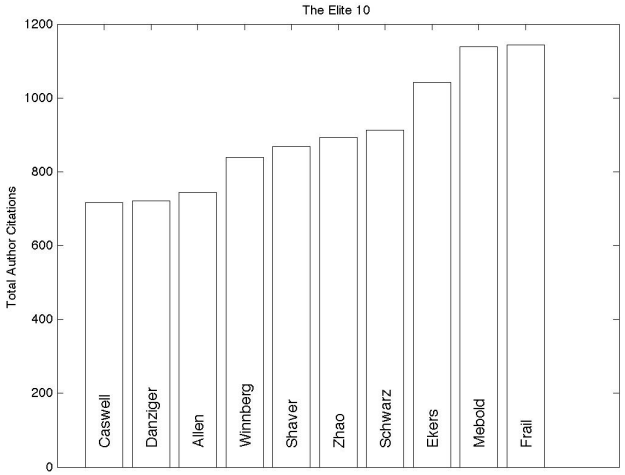


Bower: 89%-ile





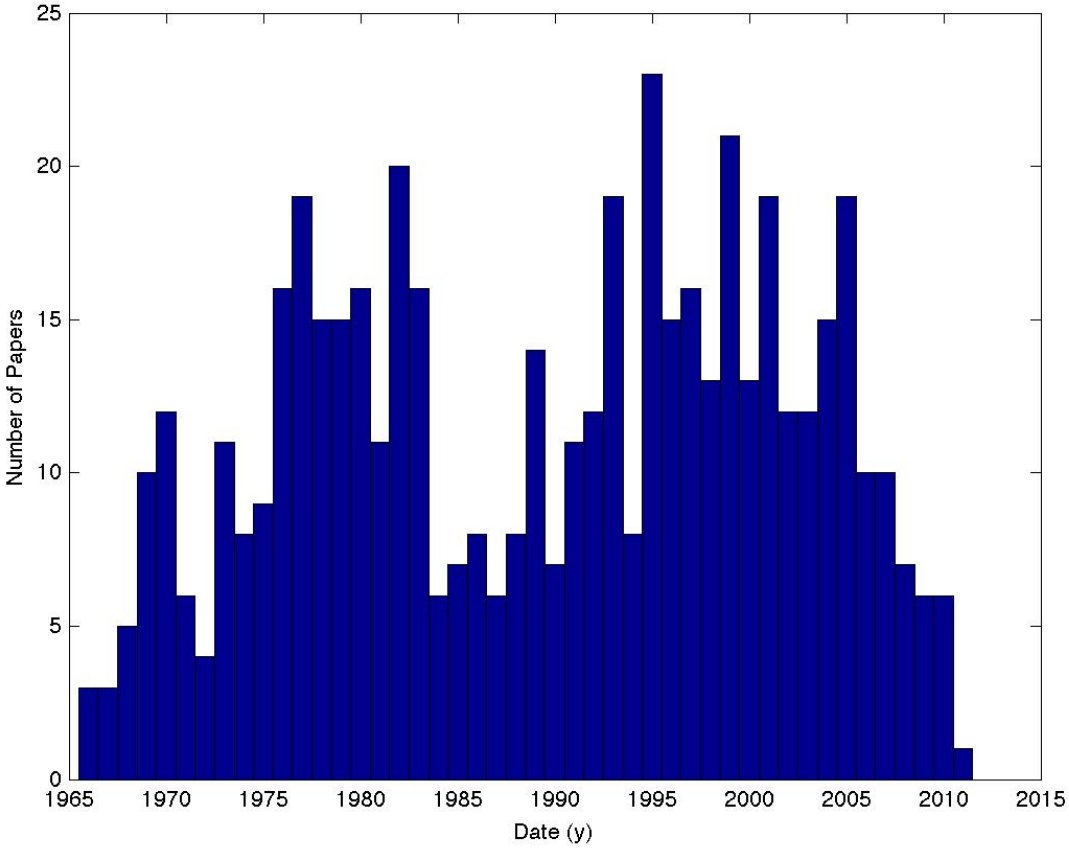
Bower: 94%-ile



Refereed Papers: 523
Unique Co-authors: 511
Median Co-author Number: 1

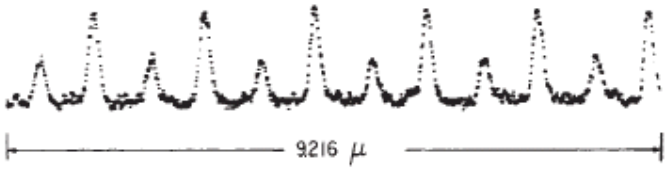

Verkhodanov
Schwarz
Winnberg
Robinson
Palmer
Wellington
Ekers
Dubner
Mebold
Dickel
Danziger
Anantharamaiah
Giacani
Gorkom
Viallefond
Green
Manchester
Frail
Johansson
Pree
Caswell
Zhao
Shaver
Claussen
Allen
Roelfsema
Fruchter
Matthews
Peterson
Smith
Kassim
Heiles
Lockhart
Gathier
Linz
Lang
Parijskij
Cordes
Davis
Frater
Brogan
Lyne
Kopylov
Thorsett
Arnal
Cappa
Knowles
Diamond
Dwarakanath
Rodr
Longmore
Bower
Hawarden
Woerden
Fomalont
Reynoso
Troland
Winkler
Churchwell
Brooks
Murdin
Habing
Lazio
McAdam
Temirova
Holdaway
Radhakrishnan
Johnston
Roberts
Fosbury
Wallace
Soboleva
Brisken
Kalberla
Hartley
Mehringer
Gaume
Boksenberg
Wright
Morris
Johnson
Whiteoak
Richards
Moffett
Anderson
Olmi
Kurtz
Zhelenkova
Kulkarni
Duric
Skellern
Pottbasch
Haynes
Subrahmanyan
Yusef-Zadeh
Taylor
Wilson
Murray
Batchelor
Backer
Forster
Chatterjee
Hoffman
Araya
Roy
Mohan
Hofner
Werf
Lacey
Cowan
Crutcher
Beasley
Sramek

Time History



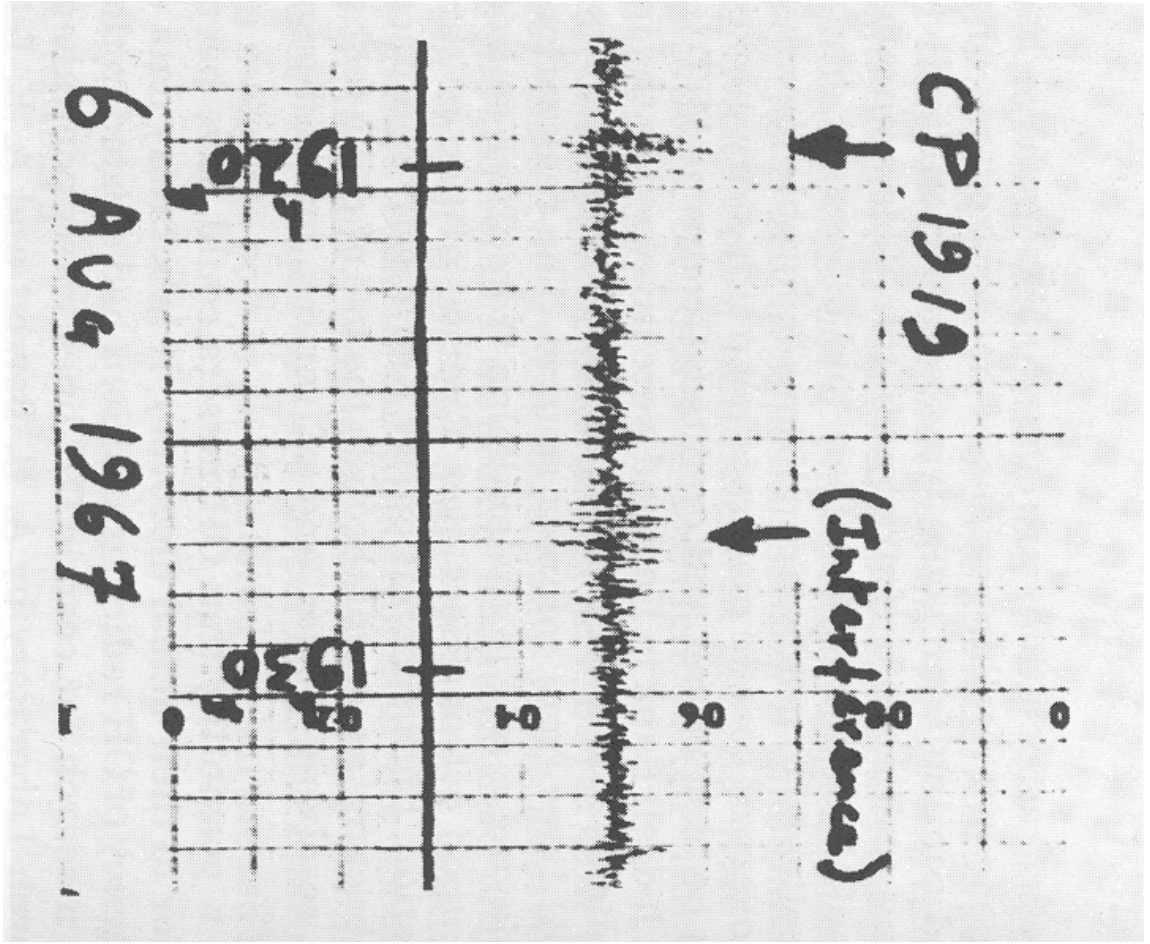

Observations
observations
Radio
radio
OH
NGC
VLA
Galactic
MHz
Supernova
supernova
Sagittarius
recombination
Recombination
galaxy
galactic
galaxies
Emission
emission
absorption
Absorption
toward
remnant
remnants
Remnant
Remnants
sources
source
Sources
Array
synthesis
survey
Survey
II
Large
southern
Center
pulsar
Pulsar
Masers
masers
Maser
Line
line
Lines
lines
Centimeter
Detection
hydrogen
H2CO
Ionized
ionized
region
Region
regions
Regions
New
W3
PSR
IC
Neutral
neutral
near
cm
CM
direction
Direction
Compact
Optical
optical
Interstellar
Structure
VLBA
Gas
gas
Galaxy
High-Resolution
resolution
continuum
Continuum
Aperture
spiral
complex
study
giant
B2
Star
Westerbork
Medium
PKS
Formaldehyde
alpha
High
Imaging
Long
distance
around
RATAN-600
Zeeman
Study
M33
Cluster
Clusters
Baseline
H2O
Infrared
Star-forming
Spectrum
pulsars
globular
planetary
Telescope
Molecular
Variability
Erratum
Three
search
Search
Galaxies
dark
clouds
OrionHI
W28
X-Ray
new
MERLIN
3C
Source
W4
Investigation
Cassiopeia
plane
large
Distance
GHz
AU
West
Cloud

Discovery of the Millisecond Pulsar



- Backer, Kulkarni, Heiles, Davis, Goss 1982
- 1.5 msec period
- Search driven by polarization & steep spectrum
- Missed by earlier searches with less time resolution

Pulsar Discovery



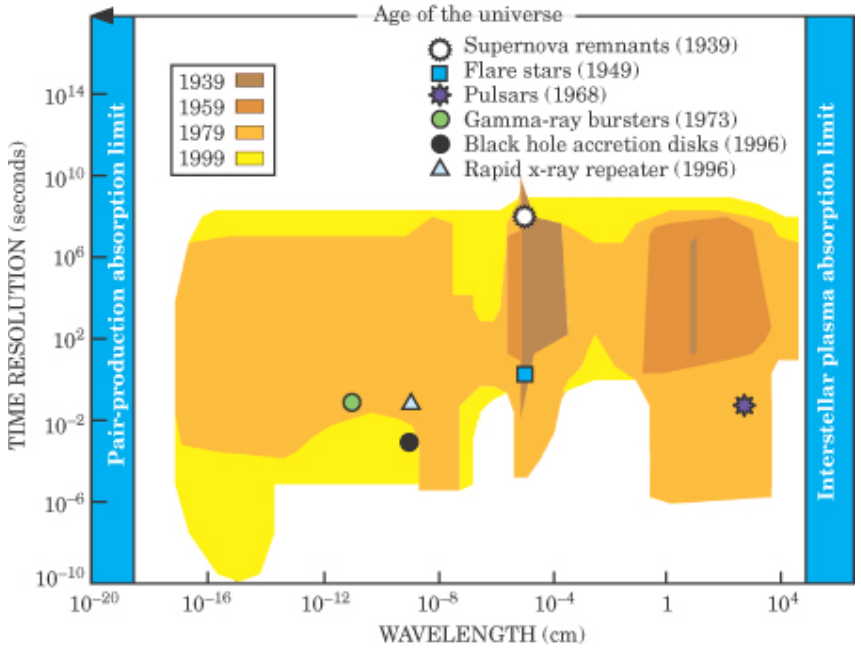
"a bit of scruff"
-J Bell

The Unknown

As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also unknown unknowns,
The ones we don't know
We don't know.
—Feb. 12, 2002, Department of Defense news briefing

The Poetry of Donald Rumsfeld and Other Fresh American Art Songs
Elender Wall and Bryant Kong

Astronomical parameter space



- Sensitivity
- wavelength
- angular resolution
- spectral resolution
- time resolution←
- polarization
- particle mode

Harwit 1984

A Very Broad Parameter Space

- Nanoseconds to Years (10^{16})
  - Crab pulsar giant pulses (nanosec)
  - Radio Supernovae (years)
- 10 MHz to 1 THz (10^{5})
- From the Sun to Gigaparsecs (10^{14})

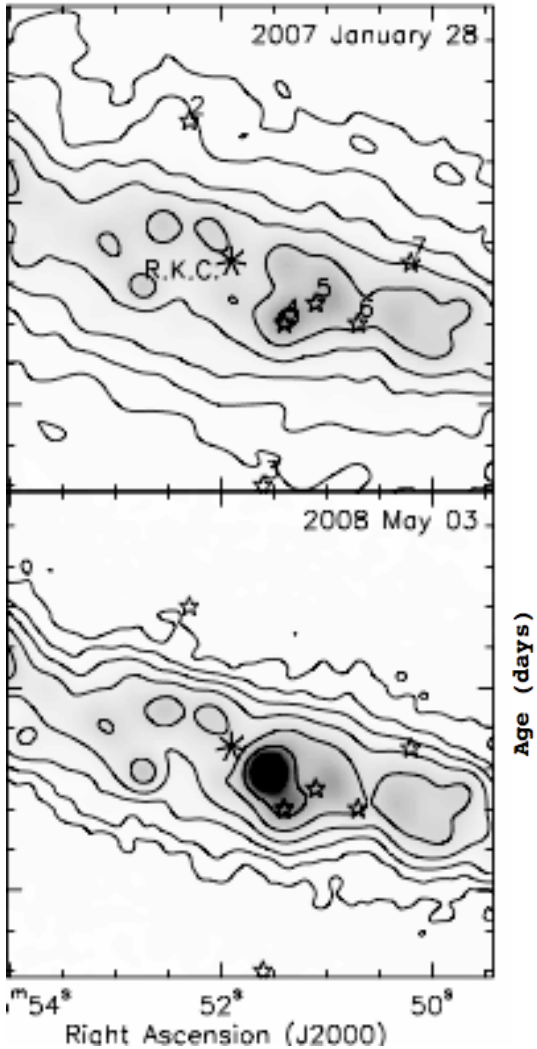
Why Radio Transient Surveys?

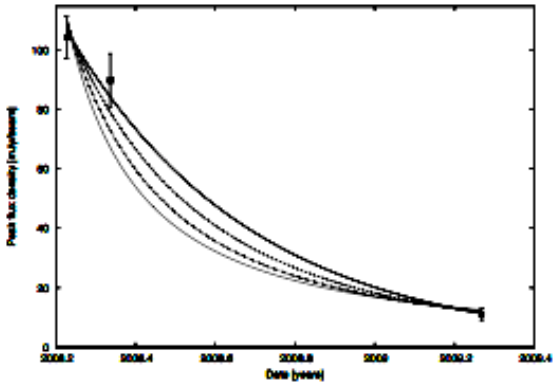
- In some cases, more optimal search technique than optical or high energy (dust, spectrum, duration)
- Study unbiased samples to discover new source classes
- Determine the variability ``foreground'' for rare events
- Simultaneous radio/optical surveys for rejection of optical foregrounds

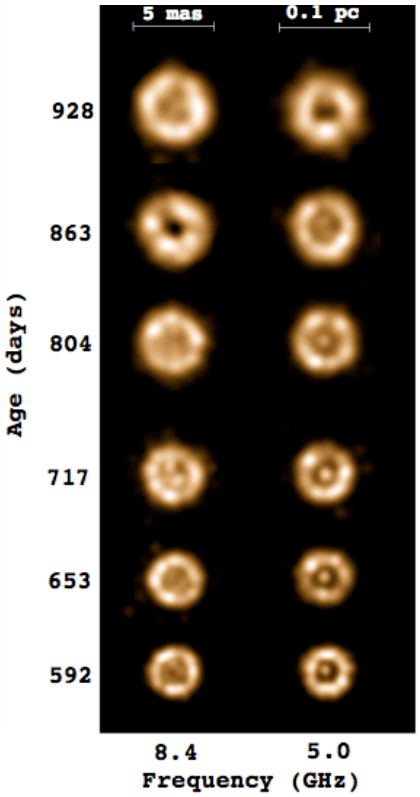
Long Duration Transients

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

An Obscured Radio Supernova in M82





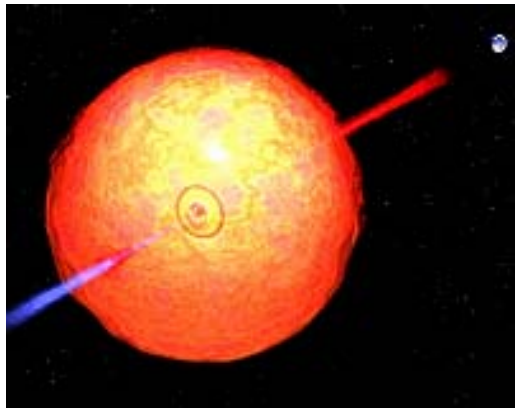


- Discovered serendipitously
- Not detected at optical, uv, nir, x-ray
  - What is the population of hidden SNe?
- Steep spectrum central source → compact object?
- Decelerating expansion → Probe of CSM
- Brunthaler et al. 2009, 2010

- <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

Orphan GRB Afterglows

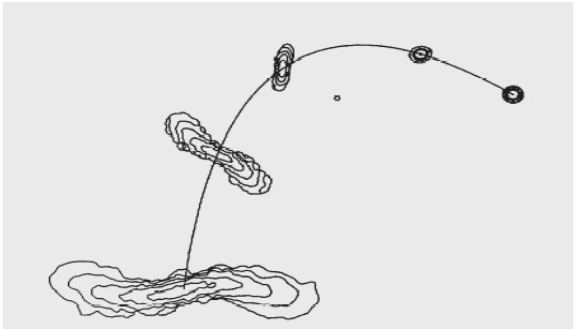
- Probes narrow jet model for GRBs
- Determines total number of GRBs
- High redshift galaxy and star formation tracer
- Universal Structured Jet Model: Rossi et al 2008



- <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 ~ 10^{-6} Mpc^{-3} y^{-1}



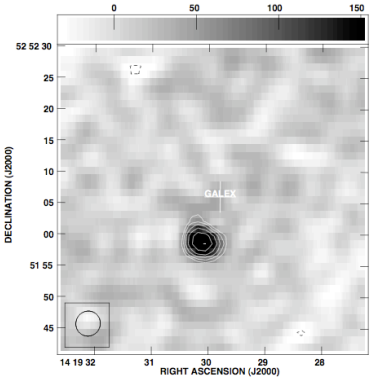


Table 1. Surveys with Long Timescale Sensitivity

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

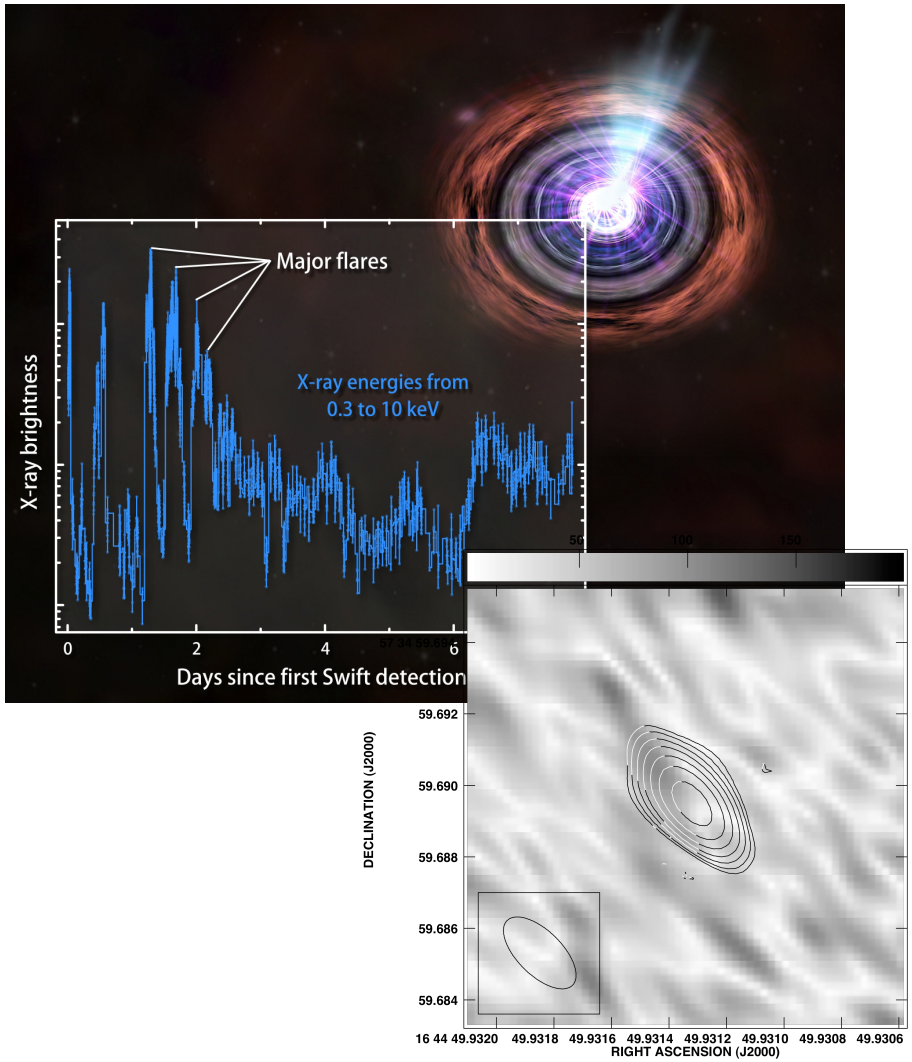
Bower 2011

- <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

Tidal DisruptionEvents
The Surprising Swift 1644+57

- Long duration, highly variable X-ray activity (> 10 days) → Not a GRB
- $L \sim 10^{45}$ erg/s ~ L_{edd} $(M/10^7 M_{sun})$
- Associated with nucleus of galaxy at z=0.3 with no indication of AGN activity
- Point-like, variable,bright radio emission
- → Beamed relativistic jet in direction of the Earth from tidal disruption of a star
- Once in 30 year event!

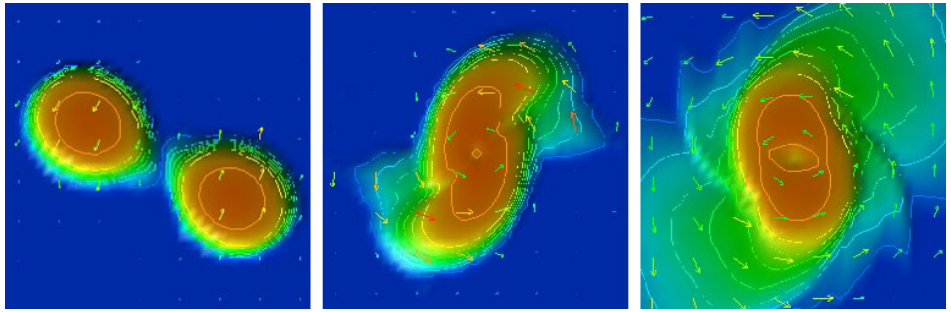
Bloom et al 2011, Levan et al 2011



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

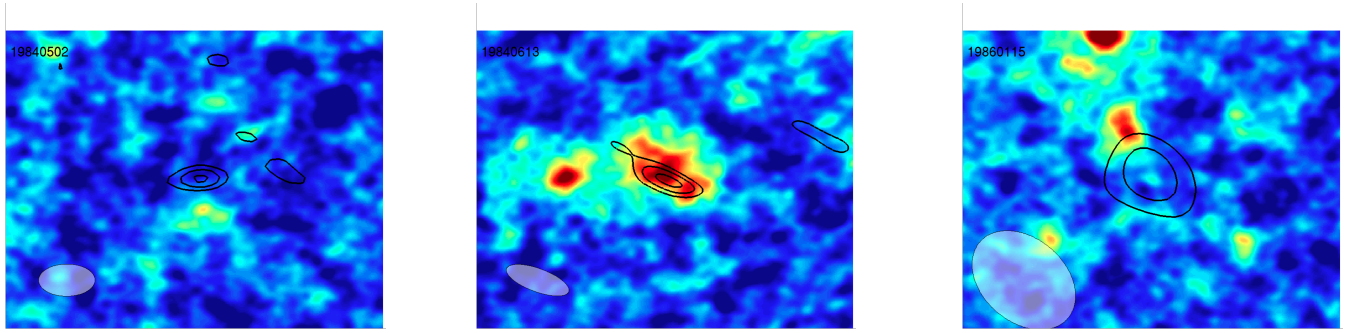
- <u>Radio Survey requirements</u>
- GHz frequency may be optimal
  - Bright transient
  - Faint galaxy (confusion not important)
- $R=10^{1-4}\ y^{-1}\ sky^{-1}$ for 0.1 mJy radio survey
- Modest resolution for discovery is acceptable → High resolution follow-up



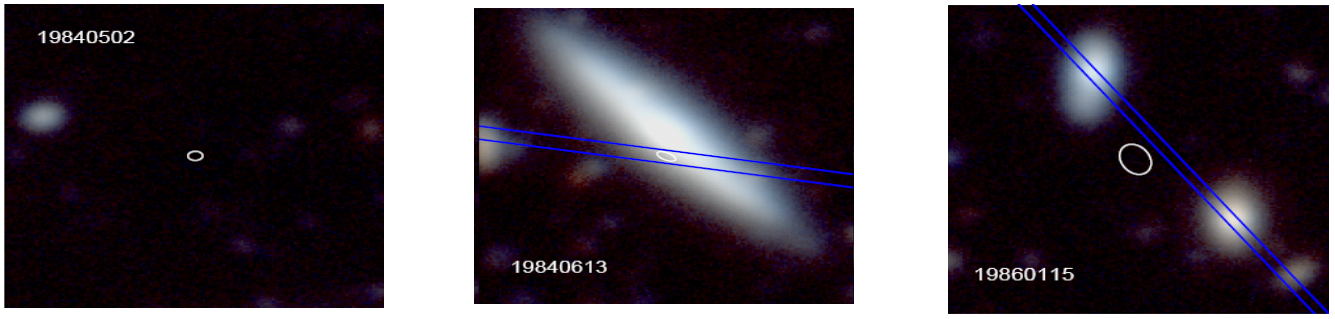
What do we know now?

?

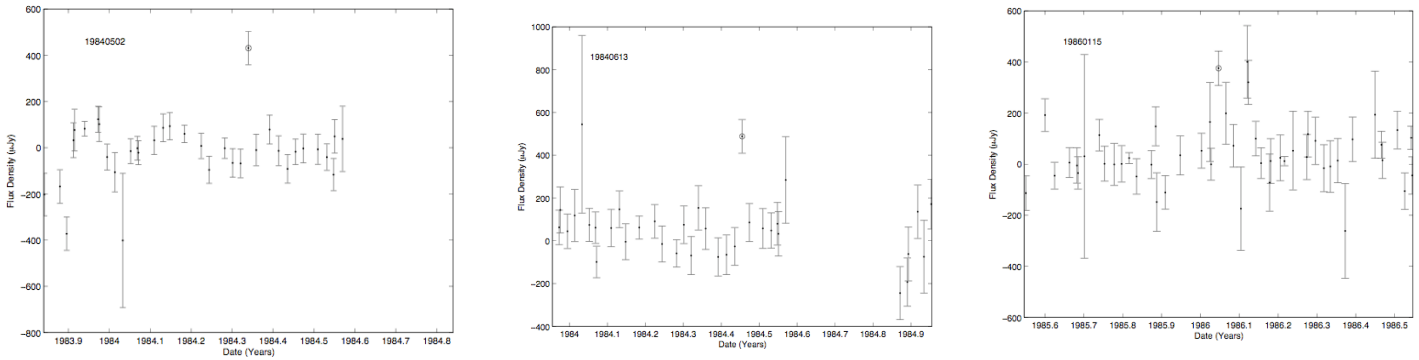
Unknown Radio Transients from VLA Archival Survey



VLA
5 GHz

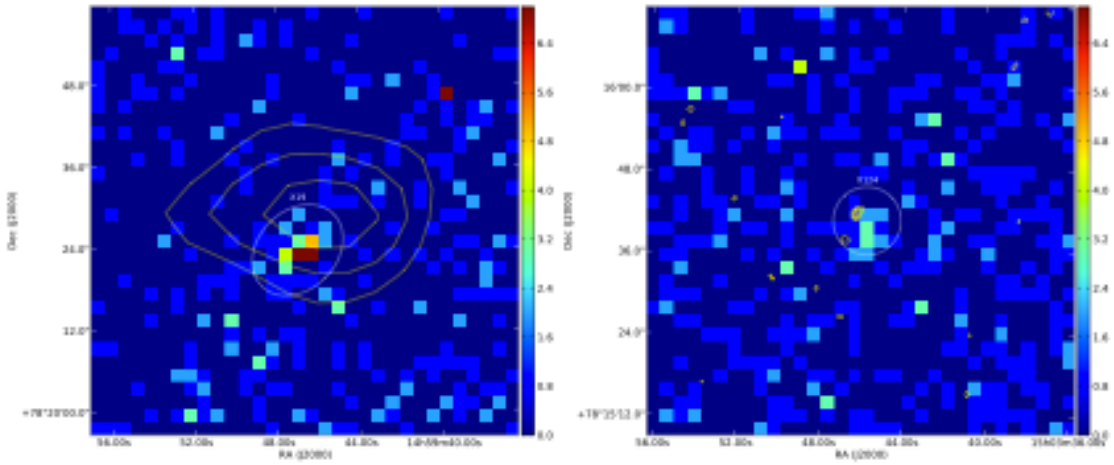


Keck
G,R

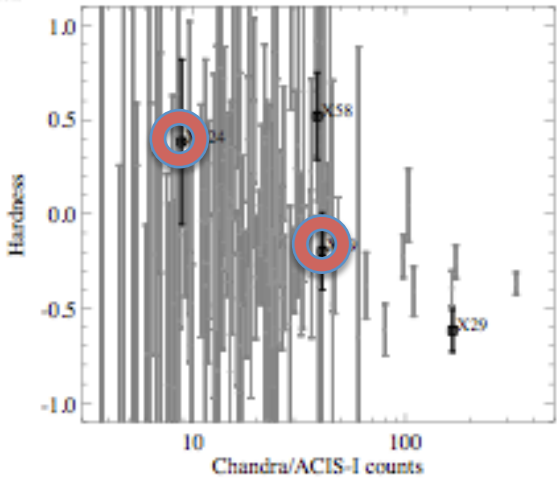


Bower et al 2007

X-ray Counterparts to RTs w/o Optical Hosts



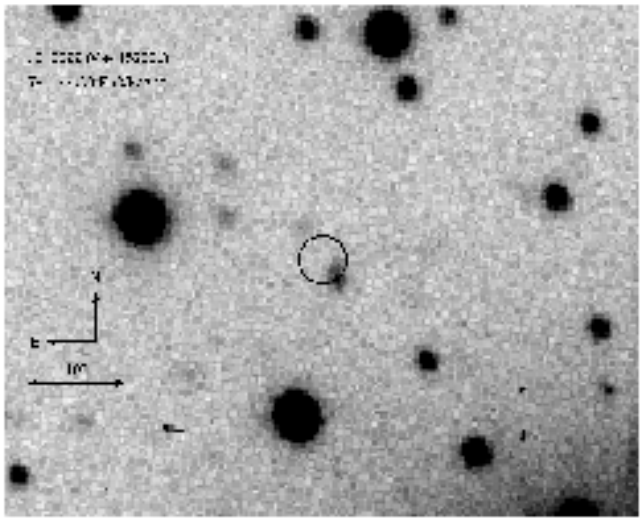
- X-ray spectra marginally constrained
- Inconsistent with old NS (Ofek 2010)
- Consistent w/flare stars or brown dwarfs



Croft, Tomsick, and Bower, 2011, ApJ, submitted

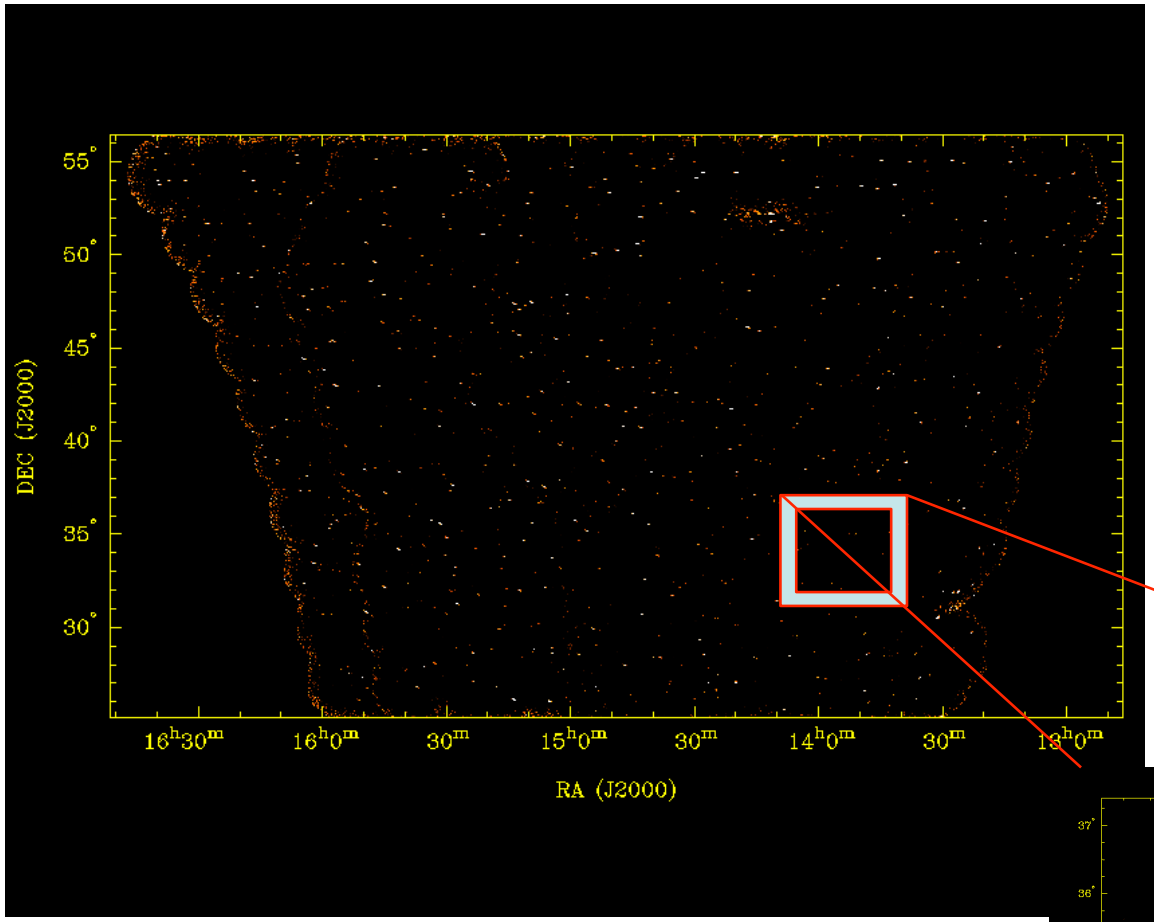
VLA Search Confirms RT Population

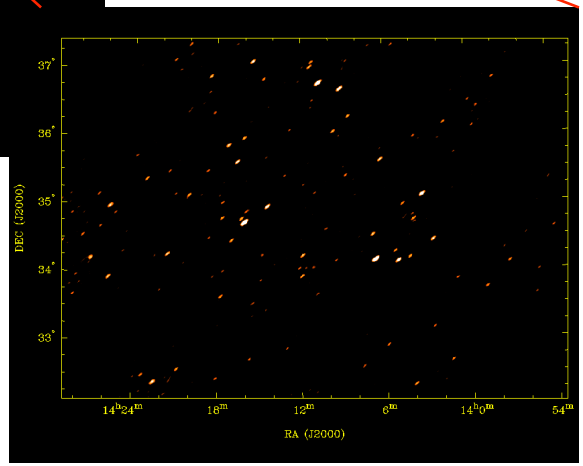
- 16 epoch VLA survey at 5 GHz found one RT without an optical counterpart
- Rate is consistent with Bower et al 07
- Ofek et al. 2011



The Allen Telescope Array

ATATS: ATA 20 CM Survey





Precursor to PiGSS

690 square degrees
250 pointings
In 10 hours
>10 epochs

Sensitive to bright, rare transients

Croft & Bower et al 2010, 2011

ATATS: No Very Bright Transients or Strongly Variable Sources

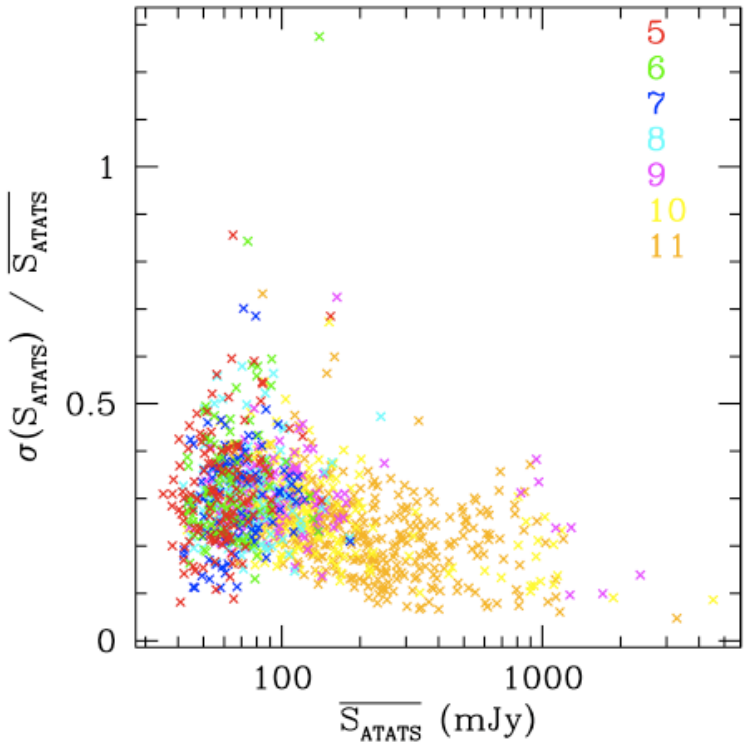
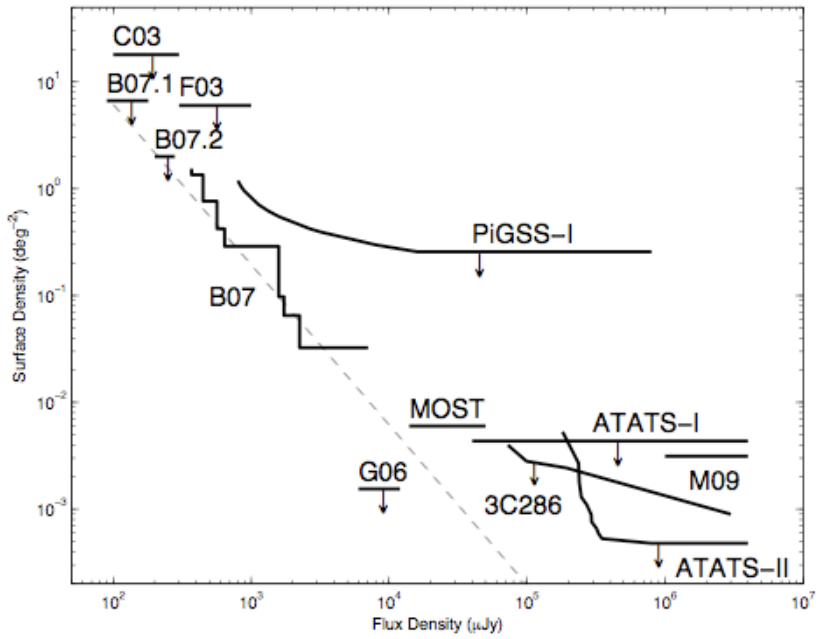
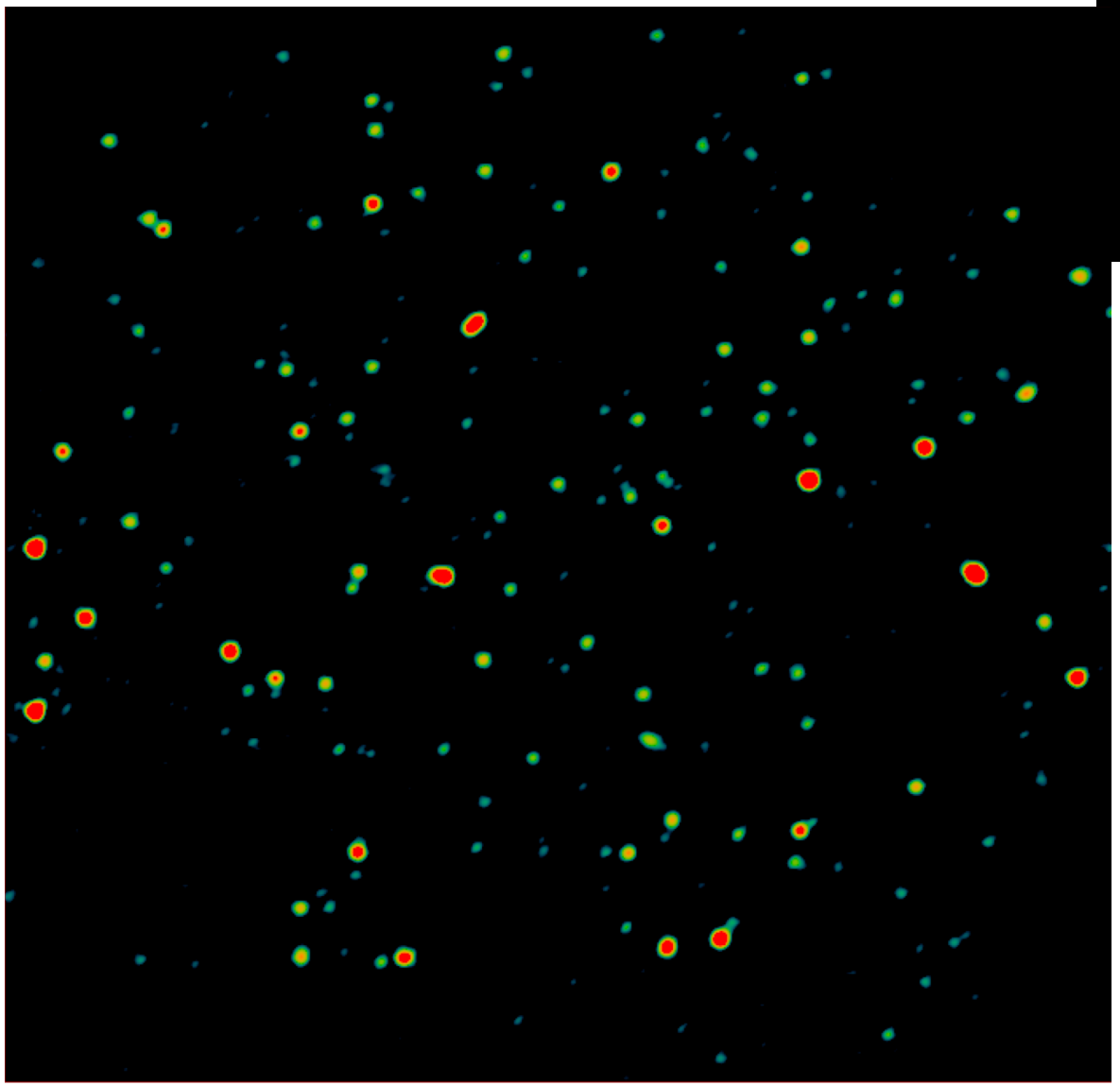


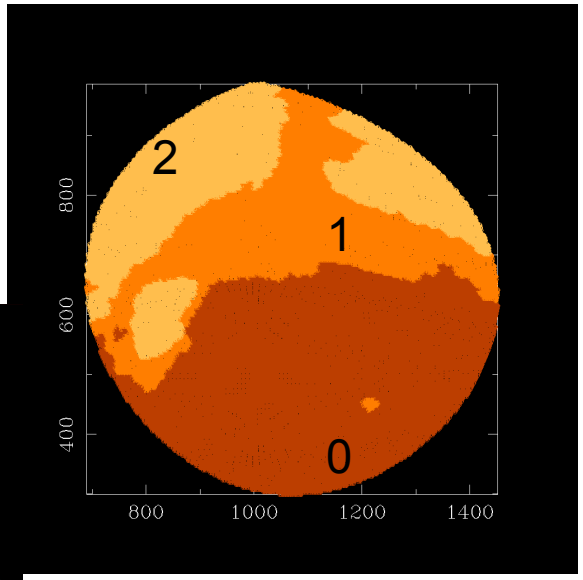
Fig. 8.— The ratio of the standard deviation of flux densities of sources detected in ATATS, $\sigma(S_{ATATS})$, to the mean flux density of the sources, $\overline{S_{ATATS}}$, plotted as a function of $\overline{S_{ATATS}}$, for sources with detections in 5 or more ATATS epochs. Points are color coded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



Rejects Nasu 1-Jy Transients (M09)

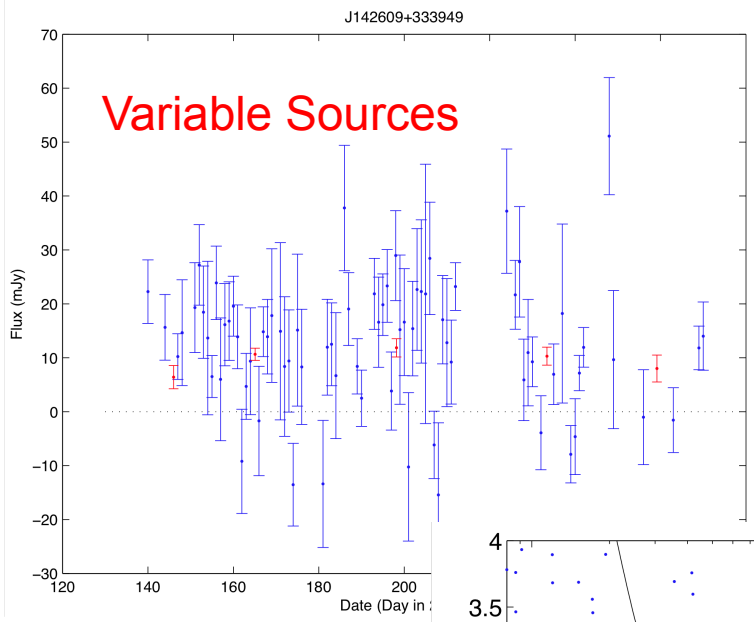
PiGSS Status

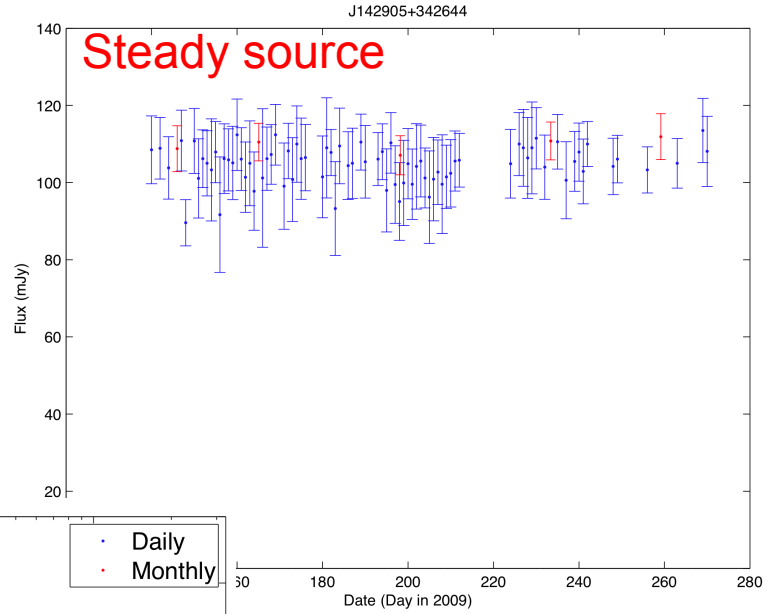


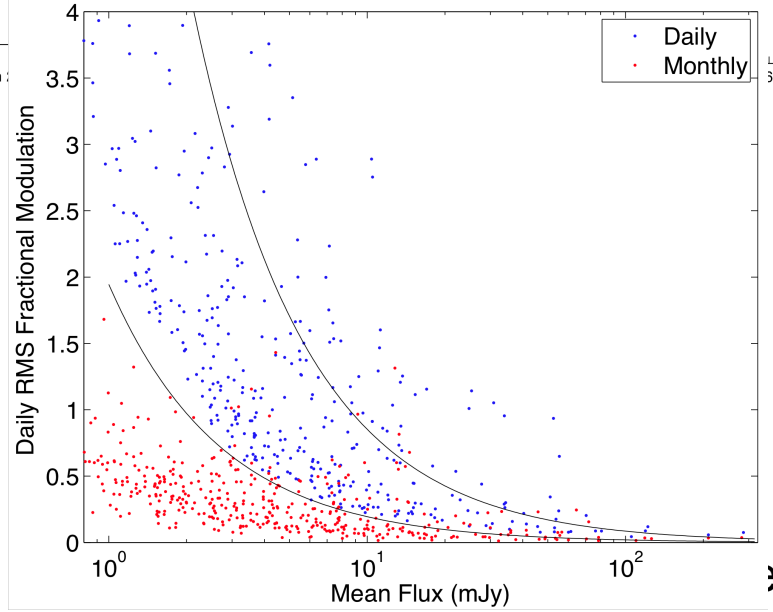


- 5000 sq deg campaign
  - First pass complete
  - Second pass at 2500 sq deg
- 300 epochs of 10 sq degree imaging
  - 2 mJy rms
- Deep image from 80 daily images of 10 sq deg fields
  - 0.2 mJy rms
- Two epochs of 250 sq deg images
  - 2 mJy rms
  - 2 month separation

PiGSS Light Curves



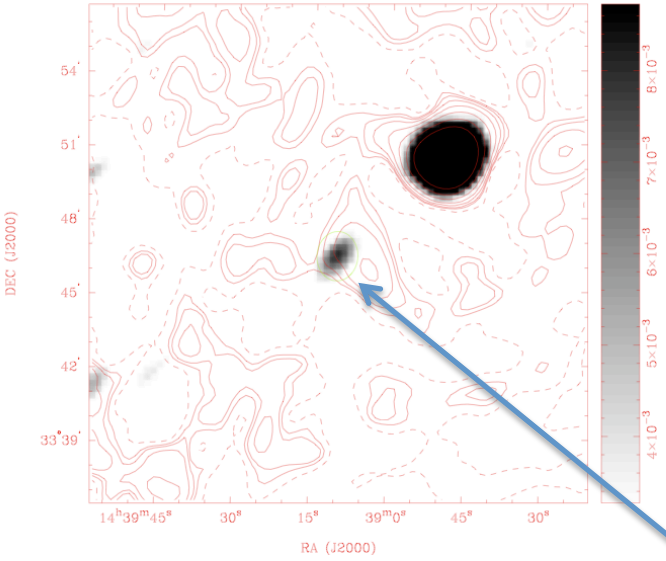


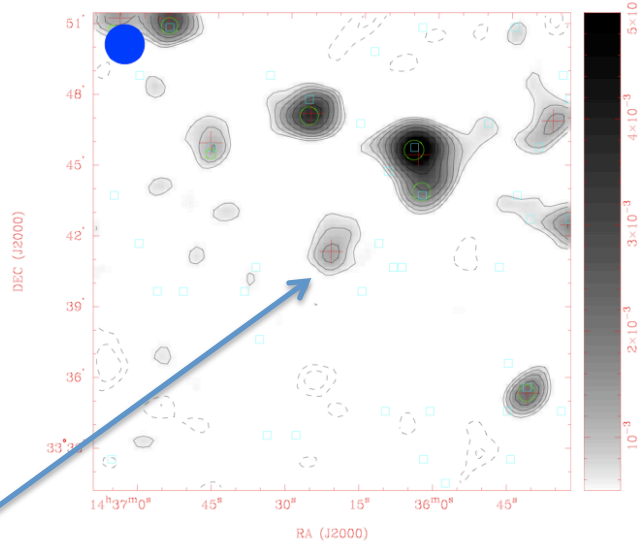


er et al 2011, ApJ, submitted

Transient Candidates from PiGSS

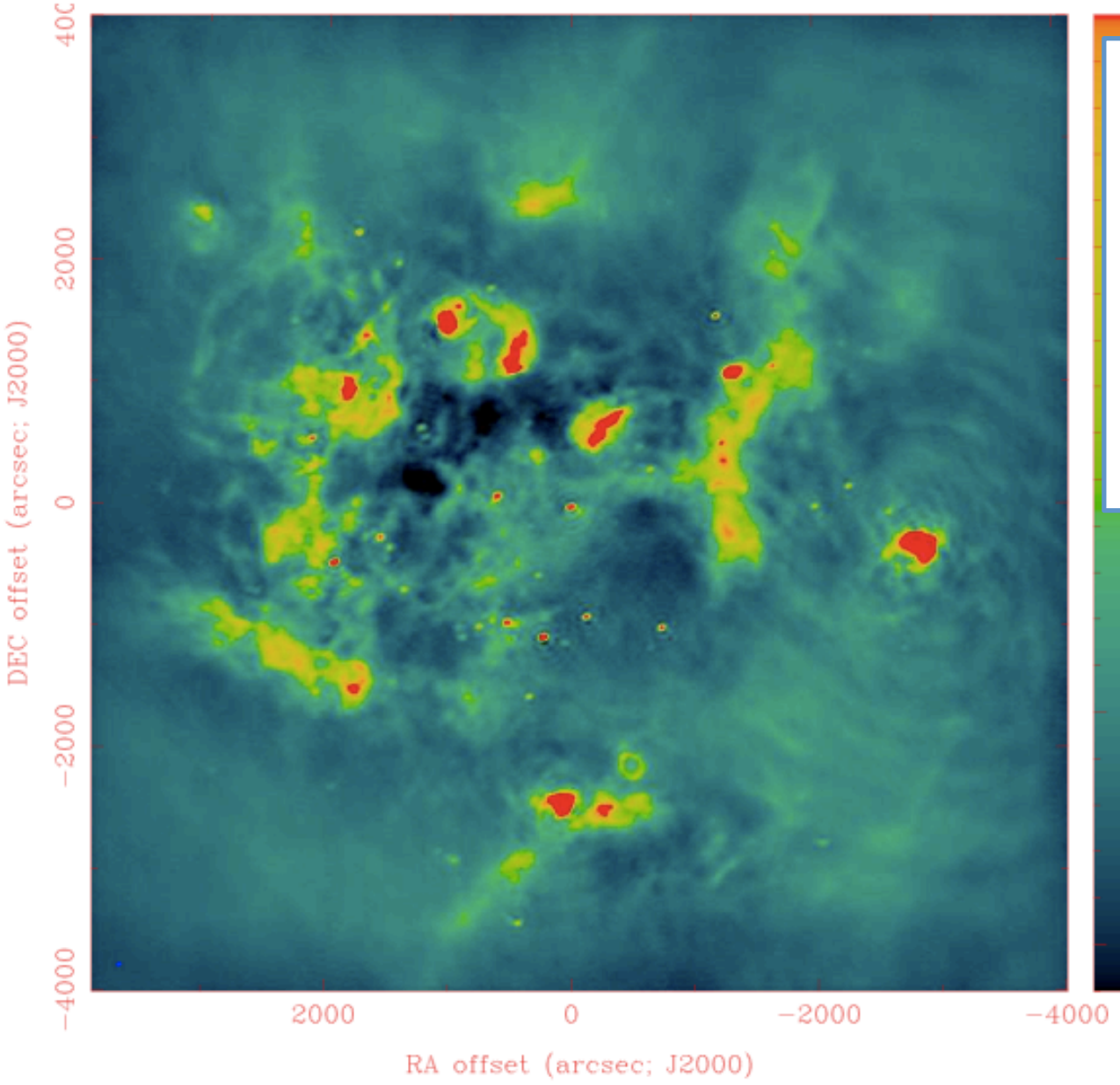
- Single epoch
  - Single epoch gray scale
  - Deep image contours
  - 1 day timescale
- Deep image but not in previous catalog (NVSS, FIRST, etc)
  - Timescale > 4 months





Bower et al 2011, ApJ submitted

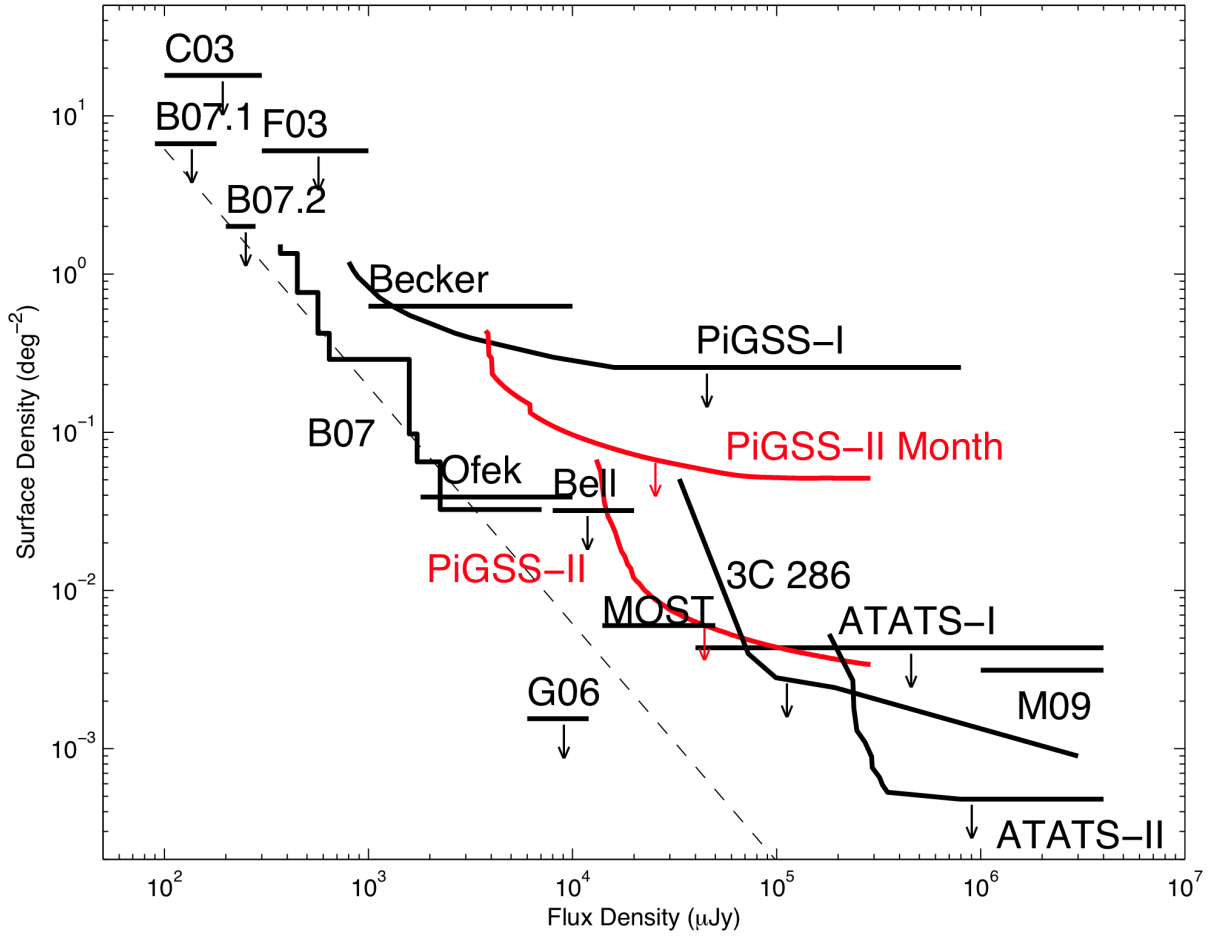
Commensal Transient Search in Cygnus



- 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

Transient Parameter Space



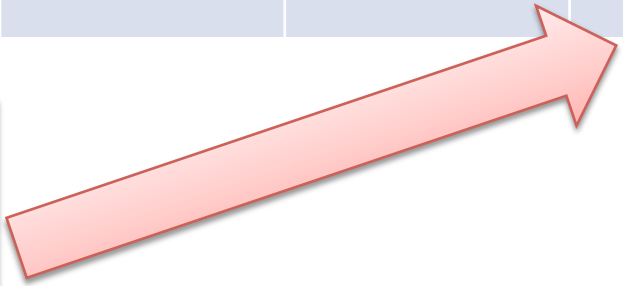
Bower et al 2011, in prep

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

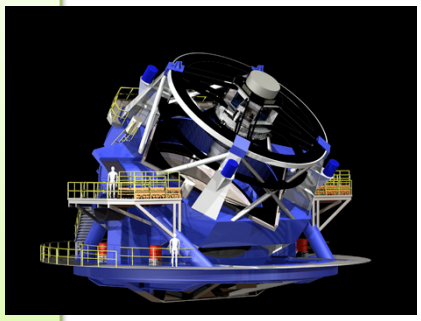


Survey Strategies

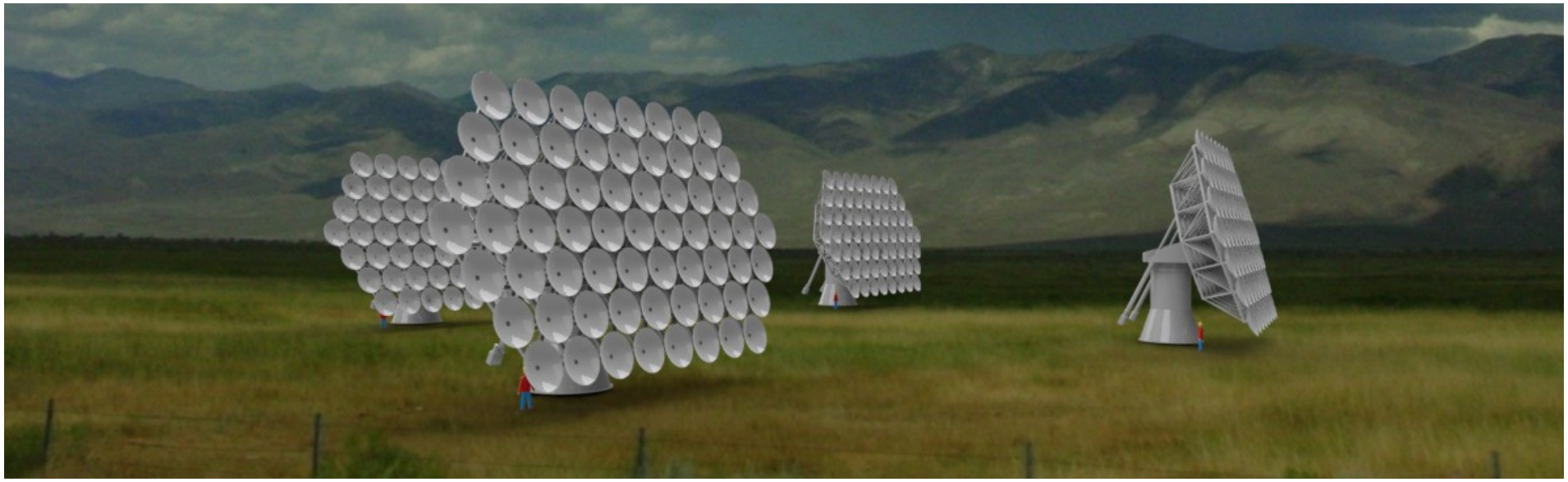
EVLA targeted surveys of large sample of nearby galaxies

Blind surveys of local volume with high cadence

Joint radio/optical survey campaigns



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

A New Era of Radio Transient Science

- Transient parameter space is wide open
- New discoveries indicate rich phenomena that can serve as probes of wide range of astrophysical problems
- ATA surveys address a broad parameter space
- Next generation instruments will be powerful tools
- Huge challenges in data throughput, automated processing, archiving