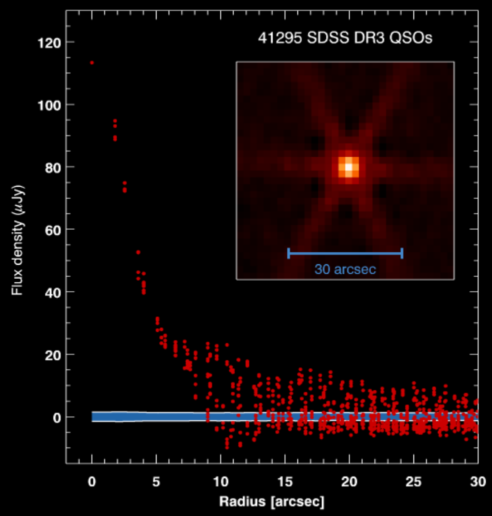
Radio Surveys



Richard L. White
Space Telescope Science Institute

HiPACC Summer School, July 2012

Overview

- Radio surveys: The universe through the looking glass
- Image stacking: Doing science with noise

The FIRST Survey

The FIRST Survey is a large-area, high-resolution radio survey using the VLA.

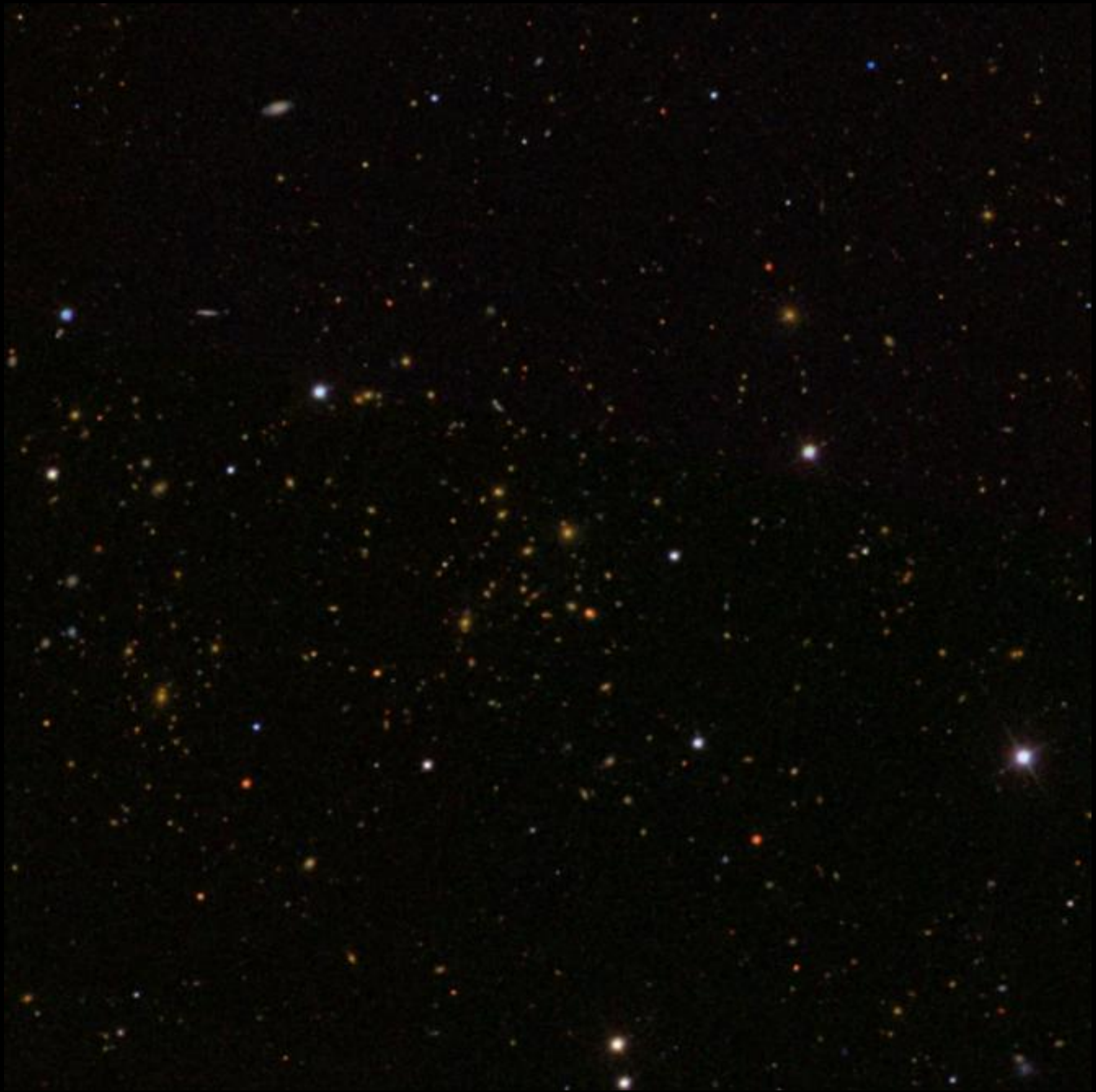
- 20 cm wavelength
- 5.4" FWHM resolution (B-configuration)
- 1 mJy detection limit
- 9,000 sq deg of north Galactic Cap

Becker, White & Helfand 1995, ApJ, 450, 559
http://sundog.stsci.edu

Radio Surveys: Invisible Stars, Distant Galaxies

- Sky looks completely different in the radio
  - Dominated by extragalactic sources
  - Almost all stars are dark
  - Emission mechanisms: non-thermal synchrotron, thermal free-free from ionized gas
- Cross-matches to find counterparts at other wavelengths (optical/IR/UV/X-ray) are essential for science
  - Median optical counterpart ~ 23.5 mag

SDSS
(10x10 arcmin)



FIRST
(10x10 arcmin)

SDSS
(10x10 arcmin)

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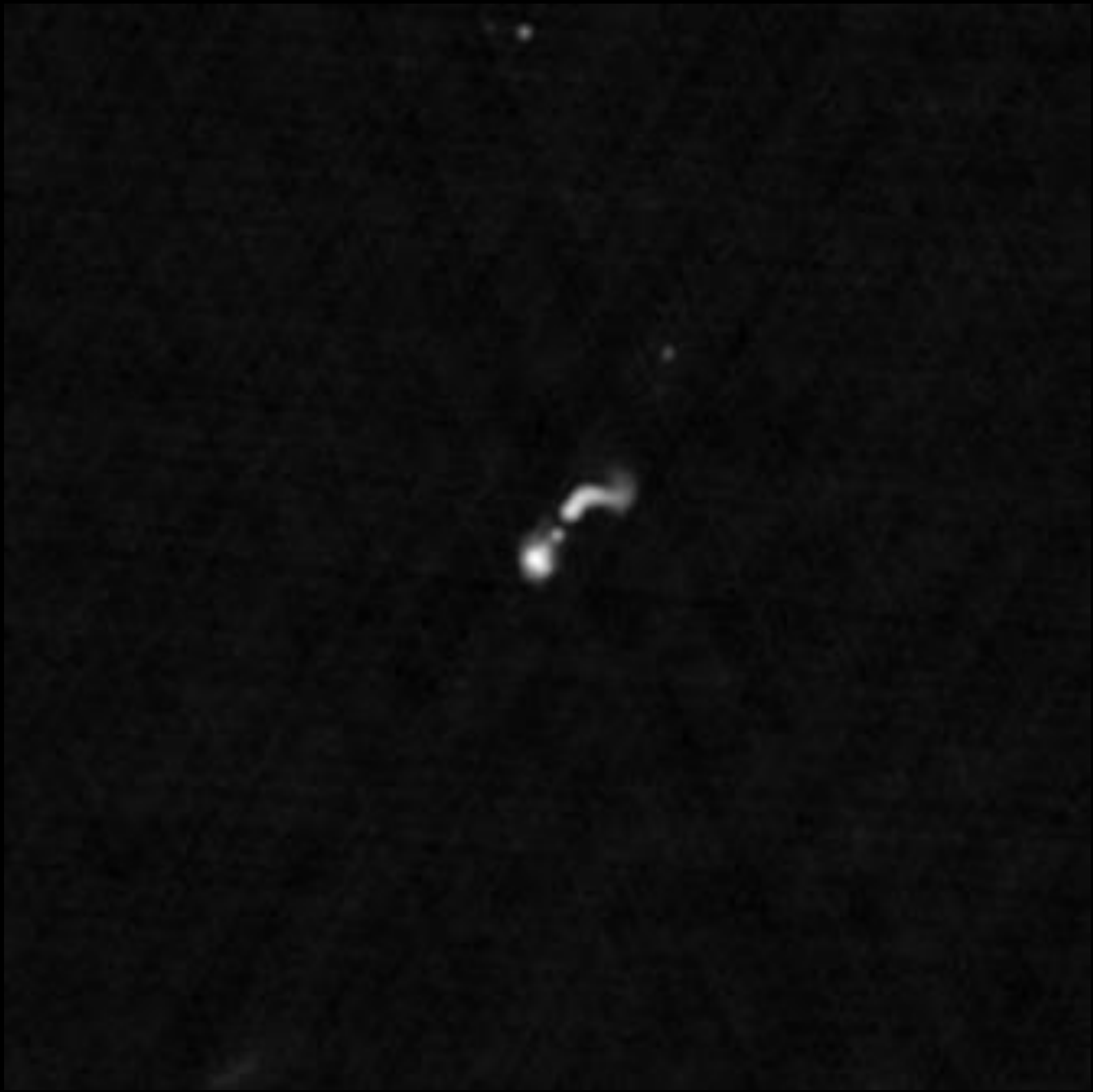
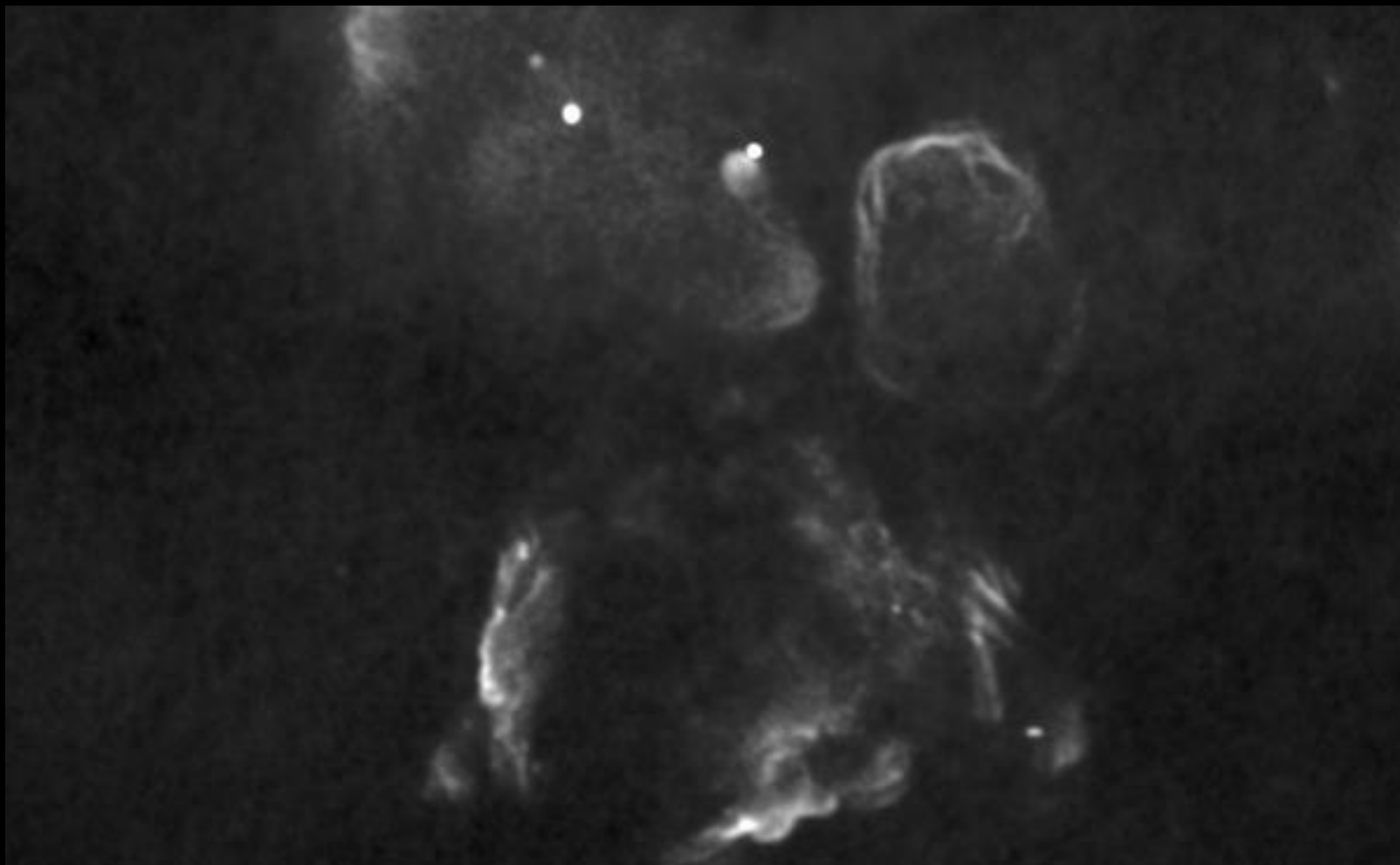
(10x10 arcmin)



Milky Way infrared λ=3.6 μm

Spitzer GLIMPSE survey (Churchwell et al.)

Milky Way radio λ=20 cm

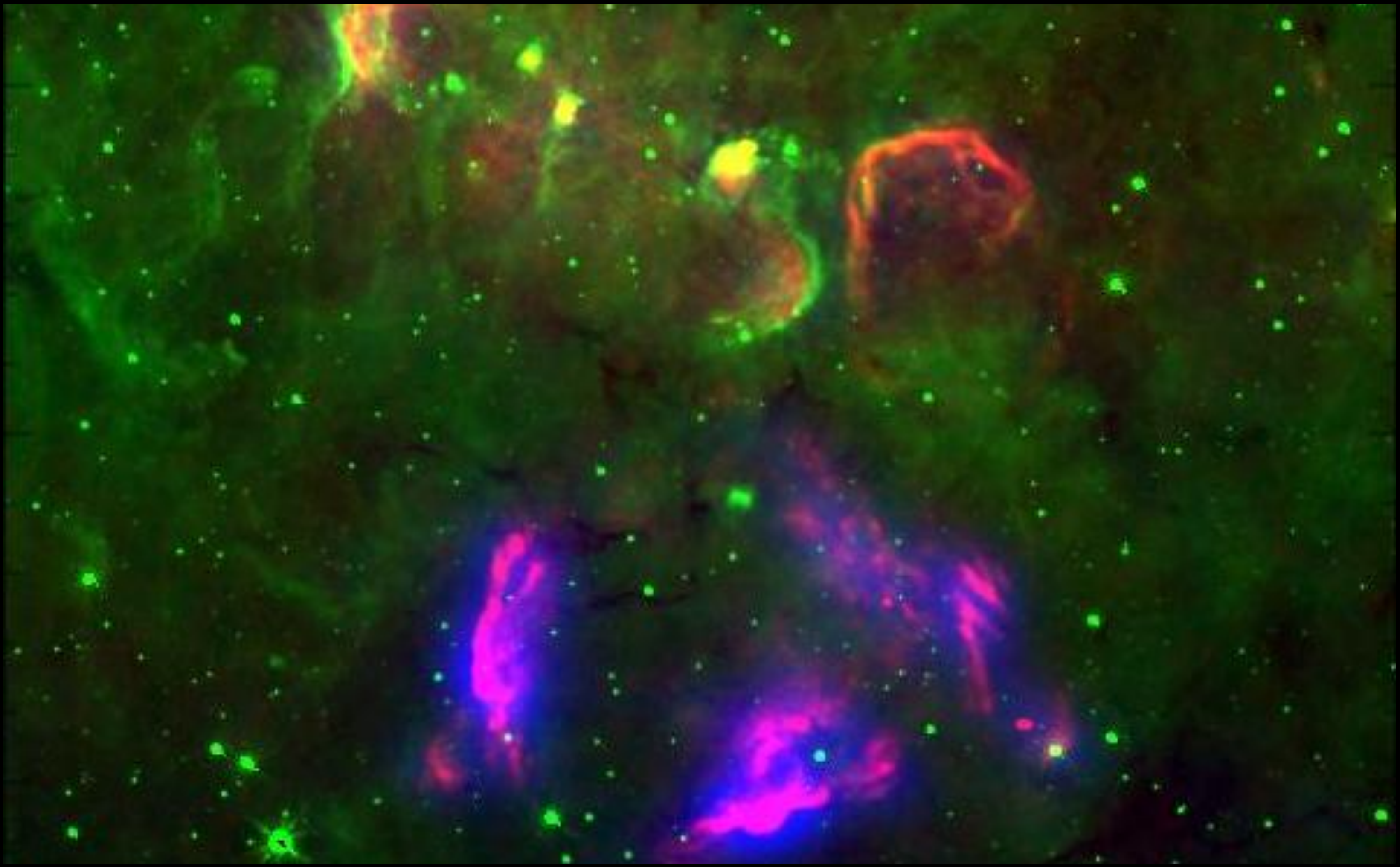


VLA MAGPIS survey (Helfand, Becker & White)

λ=20 cm/8.0 μm/5.8 μm

MAGPIS/GLIMPSE

λ=20 cm/8.0 μm/90 cm



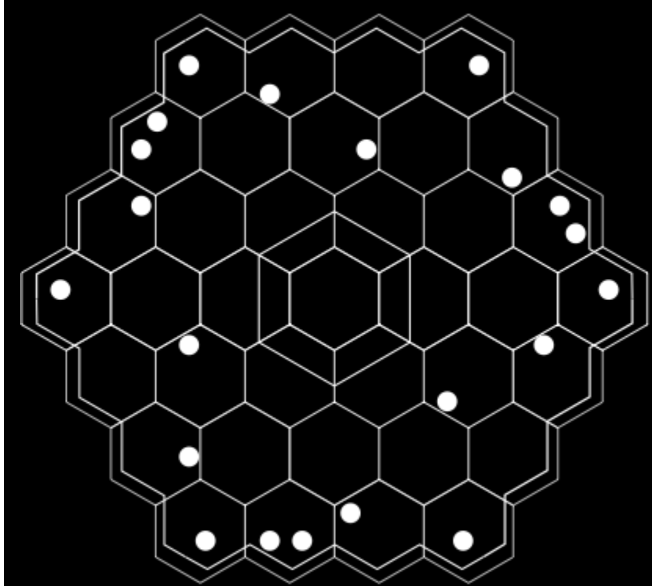
MAGPIS/GLIMPSE

POPULAR SCIENCE
MONTHLY

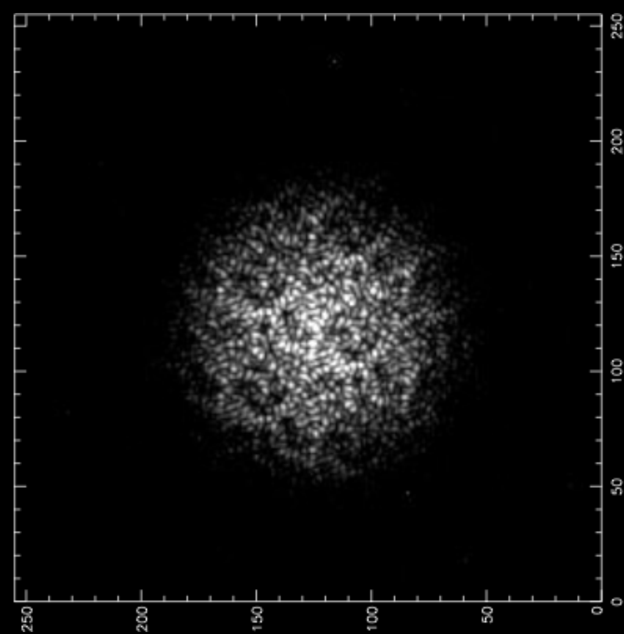
JAN. 1946
25 CENTS

IENCE LOOKS TO STARS AGAIN

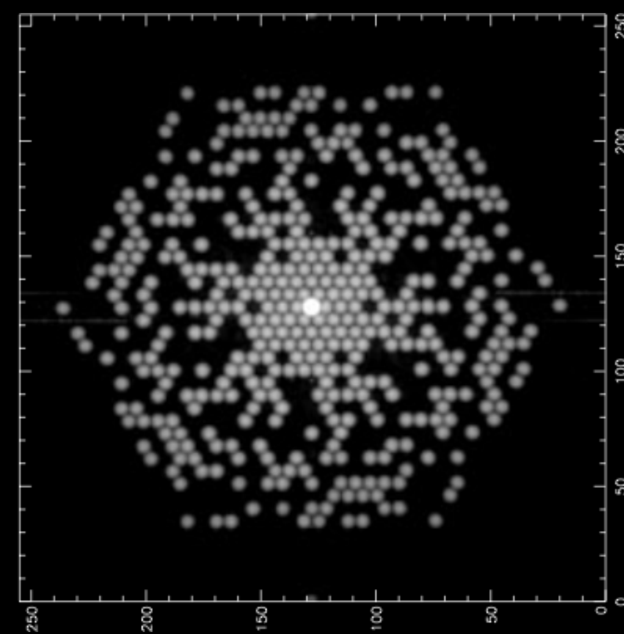
Keck Michelson interferometer



Aperture mask



Single interferogram

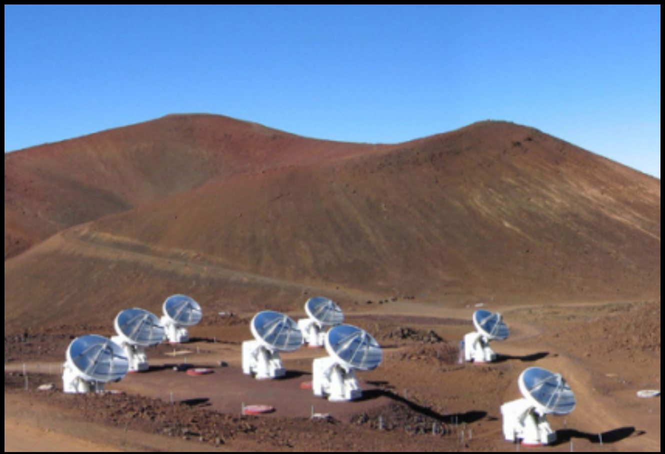


Power spectrum

Tuthill et al. 2000, PASP, 112, 555

Interferometer arrays

- Goal is to sample the visibility (Fourier) plane uniformly
  - Minimize sidelobe amplitudes and maximize signal-to-noise and resolution (e.g., Cornwell 1988)
- Redundancy in spacings is undesirable

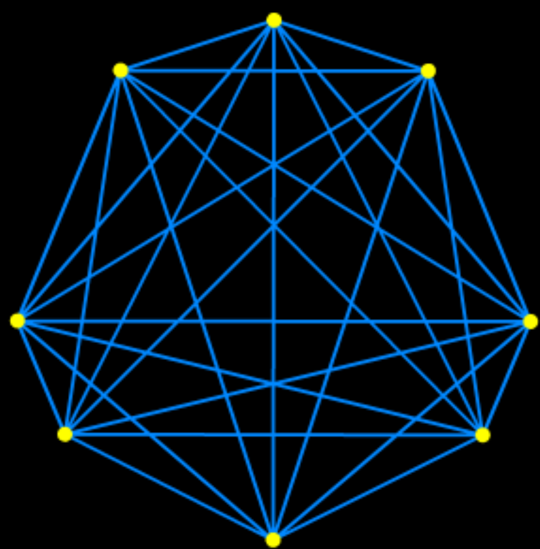


SMA, Mauna Kea

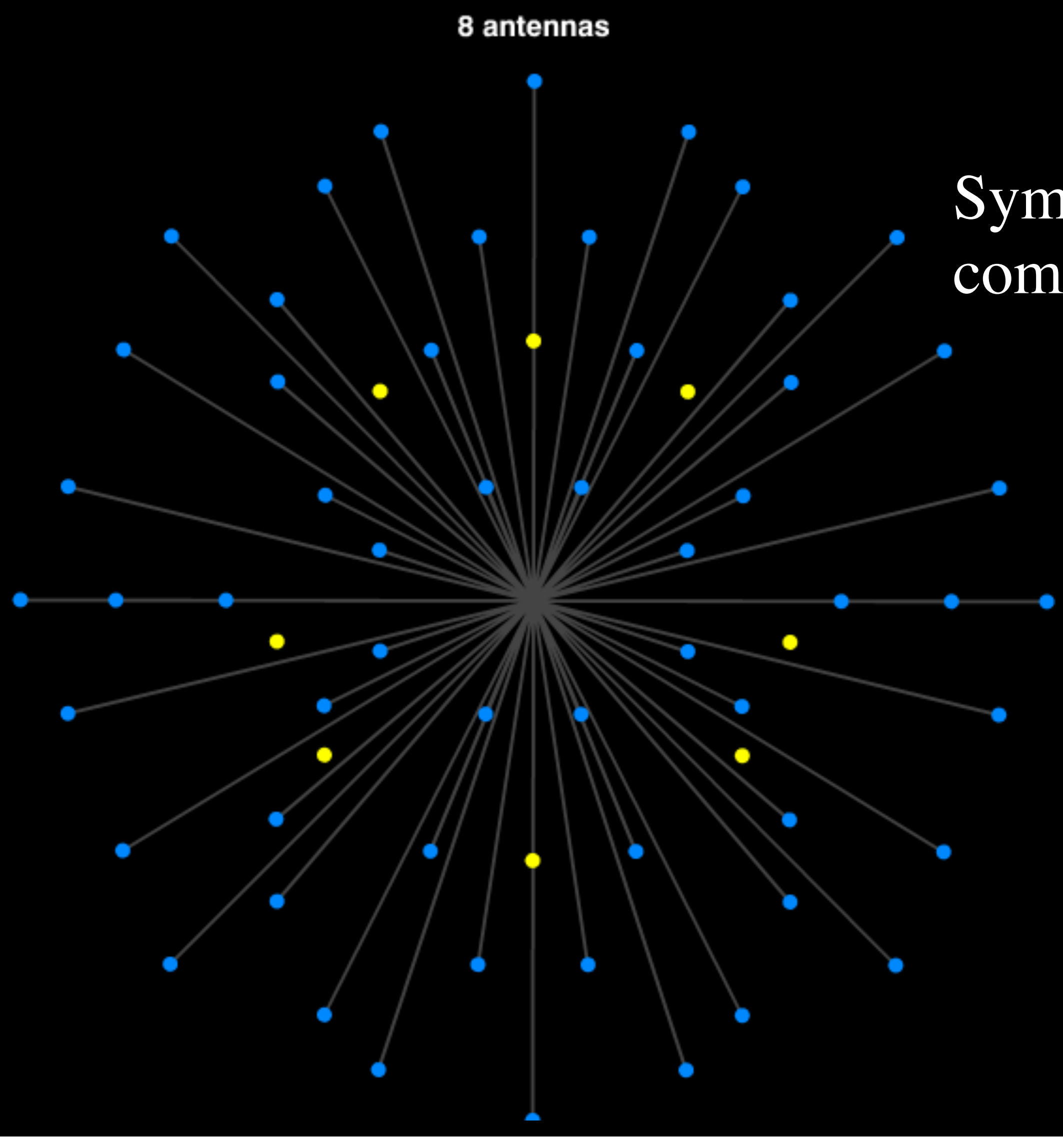
Antenna pair separations determine visibility coverage

8 antennas

N(N-1)/2 baselines

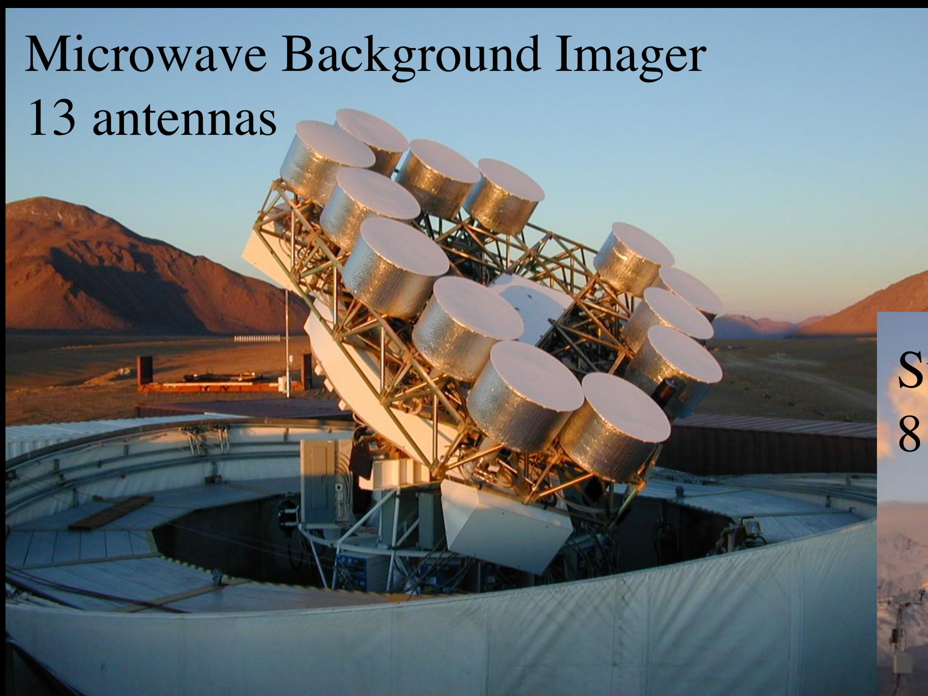


Antenna pair separations determine visibility coverage



Symmetric points complete coverage

Sub-Millimeter Array
8 antennas

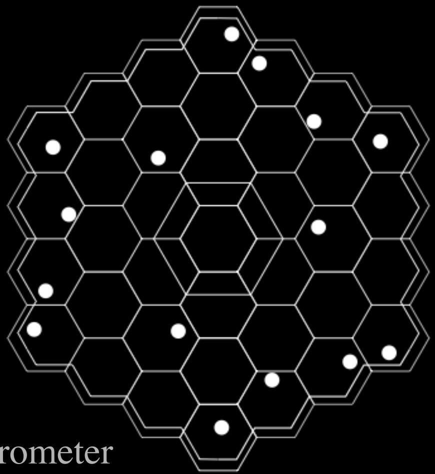


Microwave Background Imager
13 antennas

Sunayev-Zeldovich Array
8 antennas

Radio Image Curiosities

- Interferometers sample the Fourier transform of the radio image
  - Image construction/deconvolution a necessity
  - Artifacts (sidelobes) are global in image
  - Resolution ("synthesized beam") determined by array element spacing
  - Field of view ("primary beam") determined by antenna diameter
  - Choose your own pixel size
  - Noise is smoothed by PSF



Keck Michelson interferometer
Tuthill et al. 2000, PASP, 112, 555

Radio Imaging: Not a Solved Problem

- Current and future telescopes (EVLA, ALMA, LOFAR, SKA) produce wide-field, wide-bandwidth data
  - Everything varies with wavelength:
    - Field of view (smaller at shorter λ)
    - Resolution (better at shorter λ)
    - Source flux densities vary depending on spectral index
  - Existing algorithms have shortcomings
    - Computation and data rates are challenging
    - Biases get worse if data is processed in pieces
    - More complex algorithms have non-linear photometry
- Plenty of room for improvements!

M33: EVLA 20 cm (1–2 GHz)

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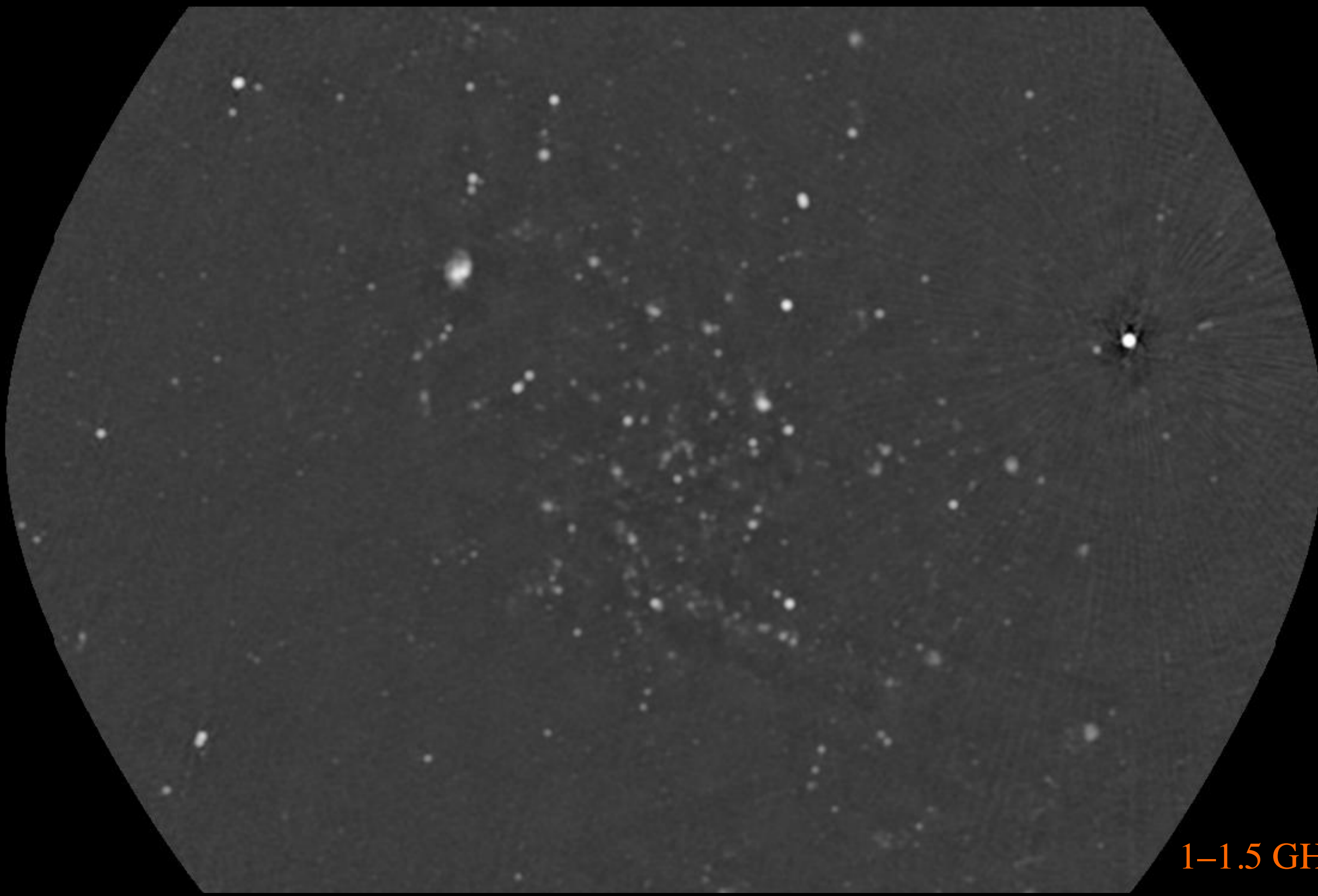

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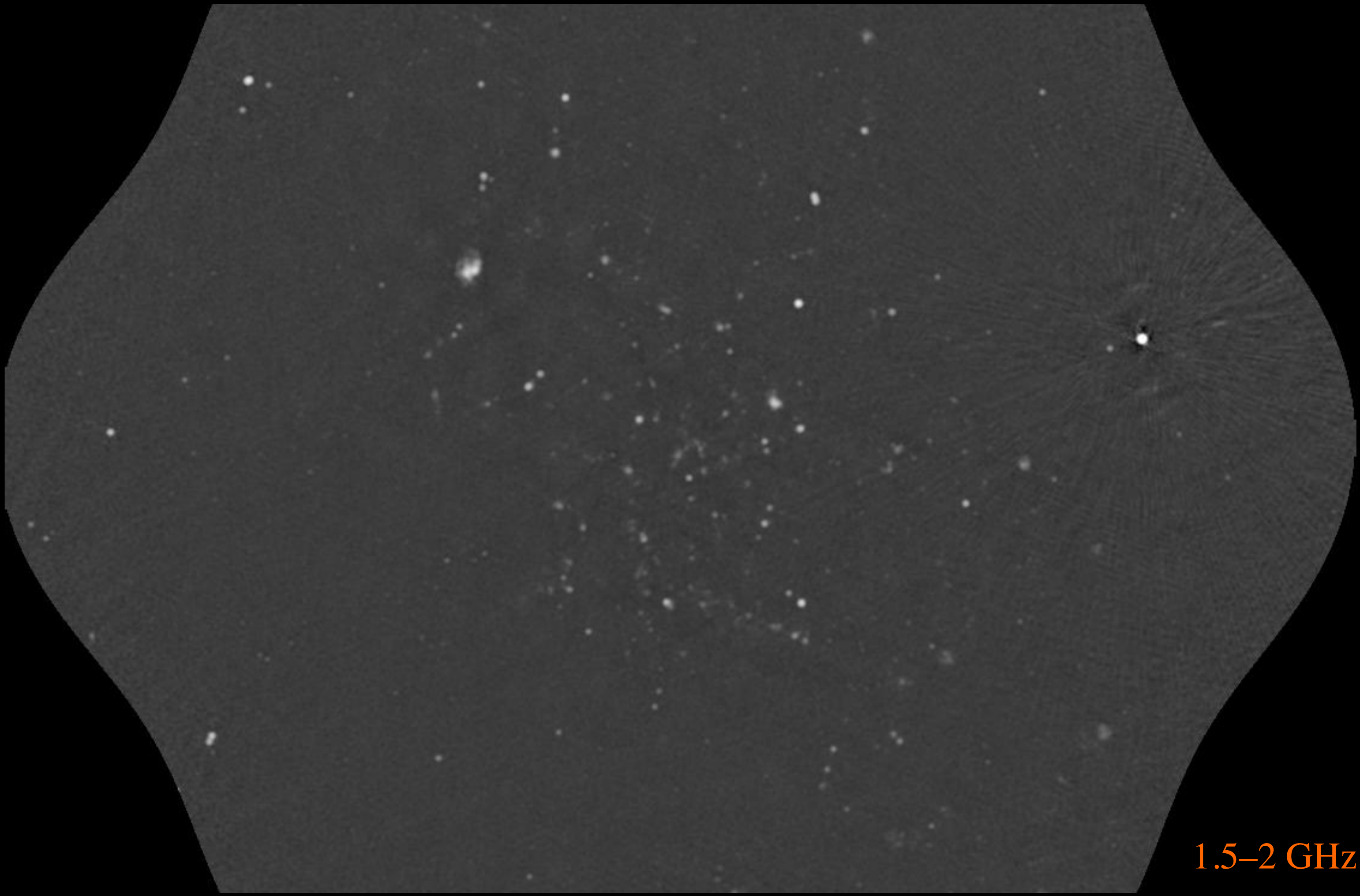

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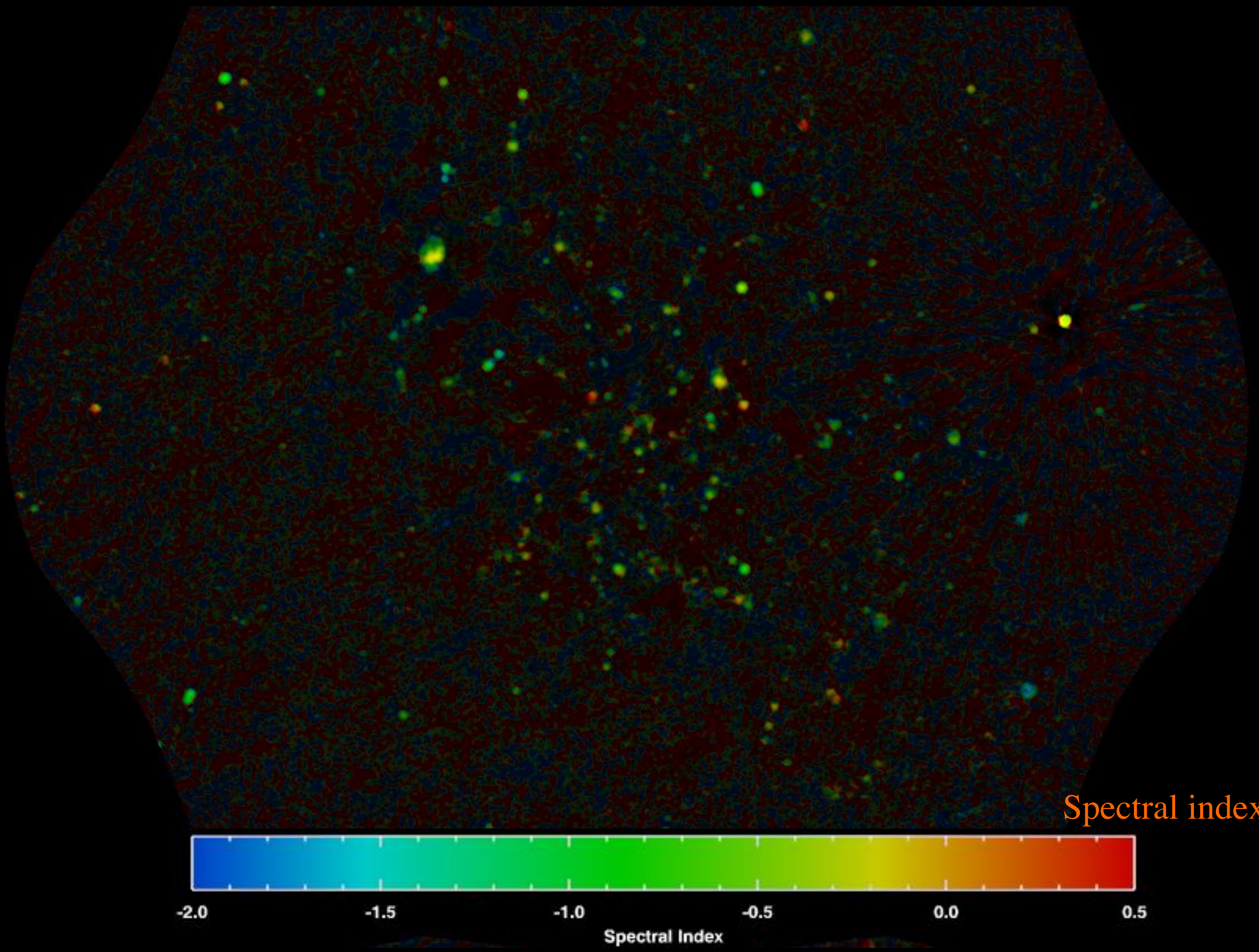


Signals from the Noise

- Catalogs are key tools for calibrating and using surveys
- … but some science requires access to the original data, not the catalog
  - Prime example: image stacking

Image Stacking

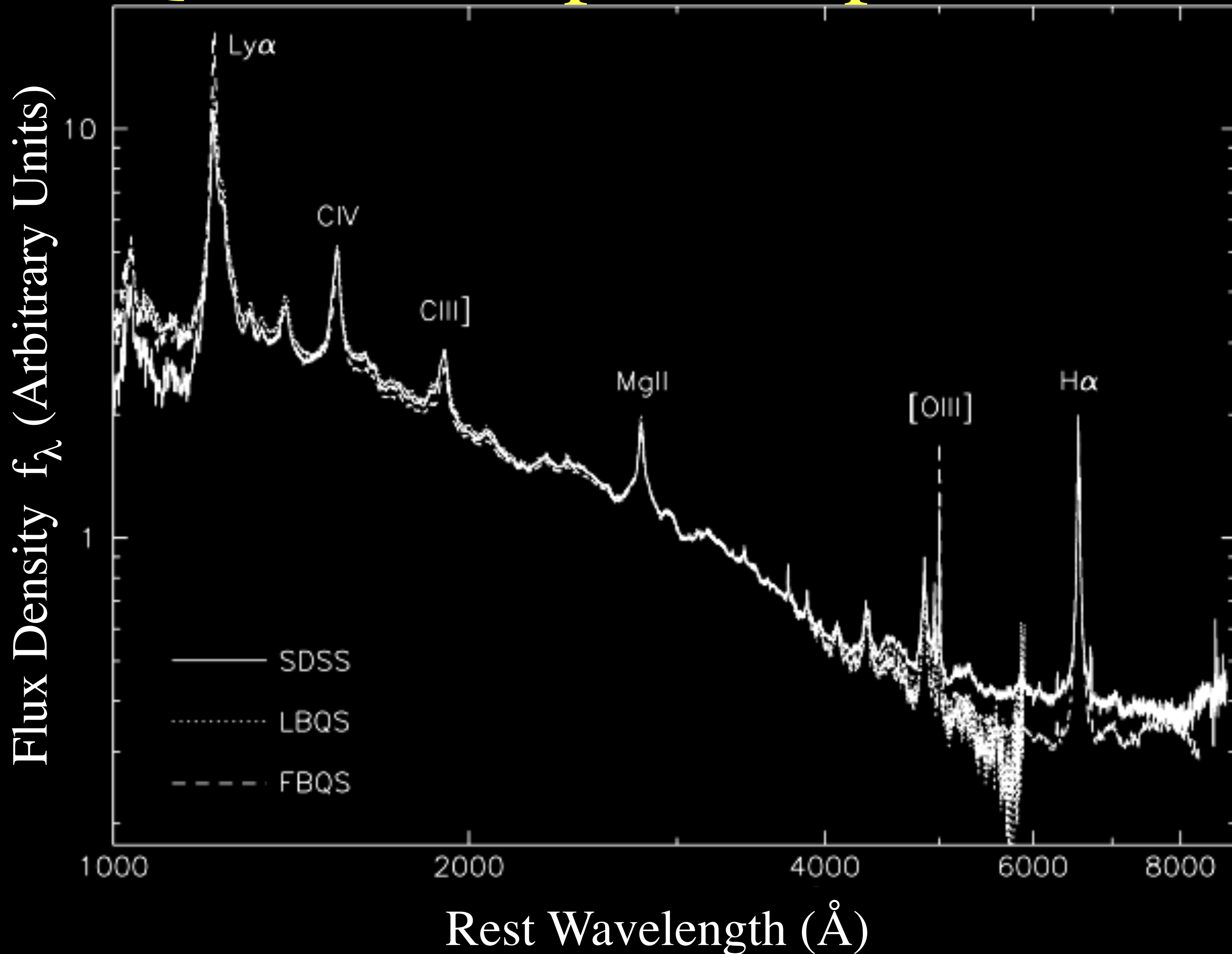
- Use image stacking to study the average radio properties of object classes that are usually undetected in radio
- FIRST survey is ideal for stacking
  - Wide area sky coverage
  - Excellent astrometry
  - Details:
    - Use median instead of mean (skewed distribution)
    - Correct for "snapshot bias" in VLA images
- Stacked images have no selection effects in the radio!

White et al. 2006, ApJ, 654, 99

Radio Quasars

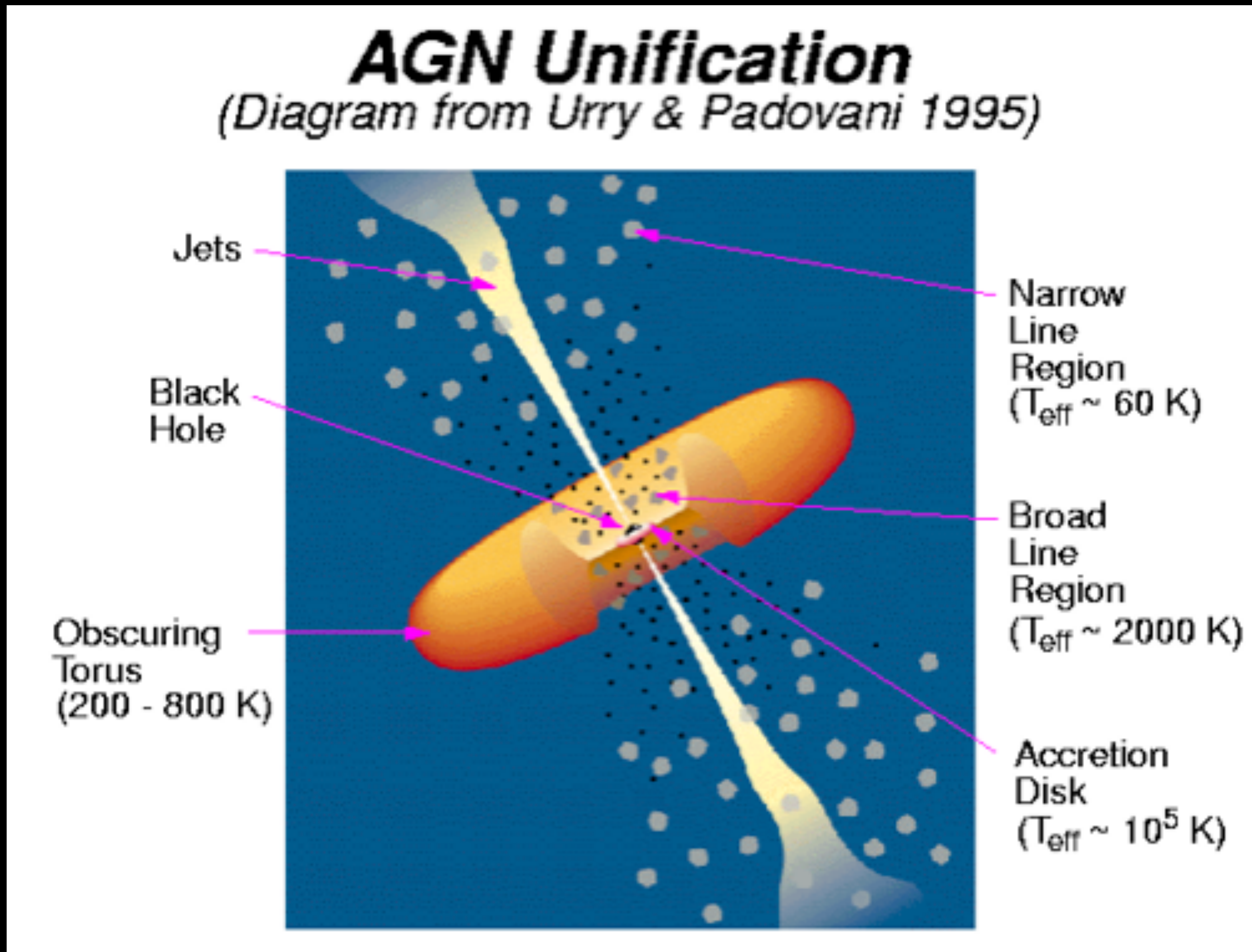
- Quasars were originally discovered as the optical counterparts of radio sources
  - But now the vast majority are optically discovered by their colors – only ~10% of quasars are radio-loud
- Why some (but not all) quasars are radio sources remains a mystery
- Goal: Use the largest radio and optical surveys to investigate QSO radio emission

Quasar composite spectra



Vanden Berk et al. 2001, AJ, 122, 549

Quasar schematic model



Sloan Digital Sky Survey Quasar Catalog

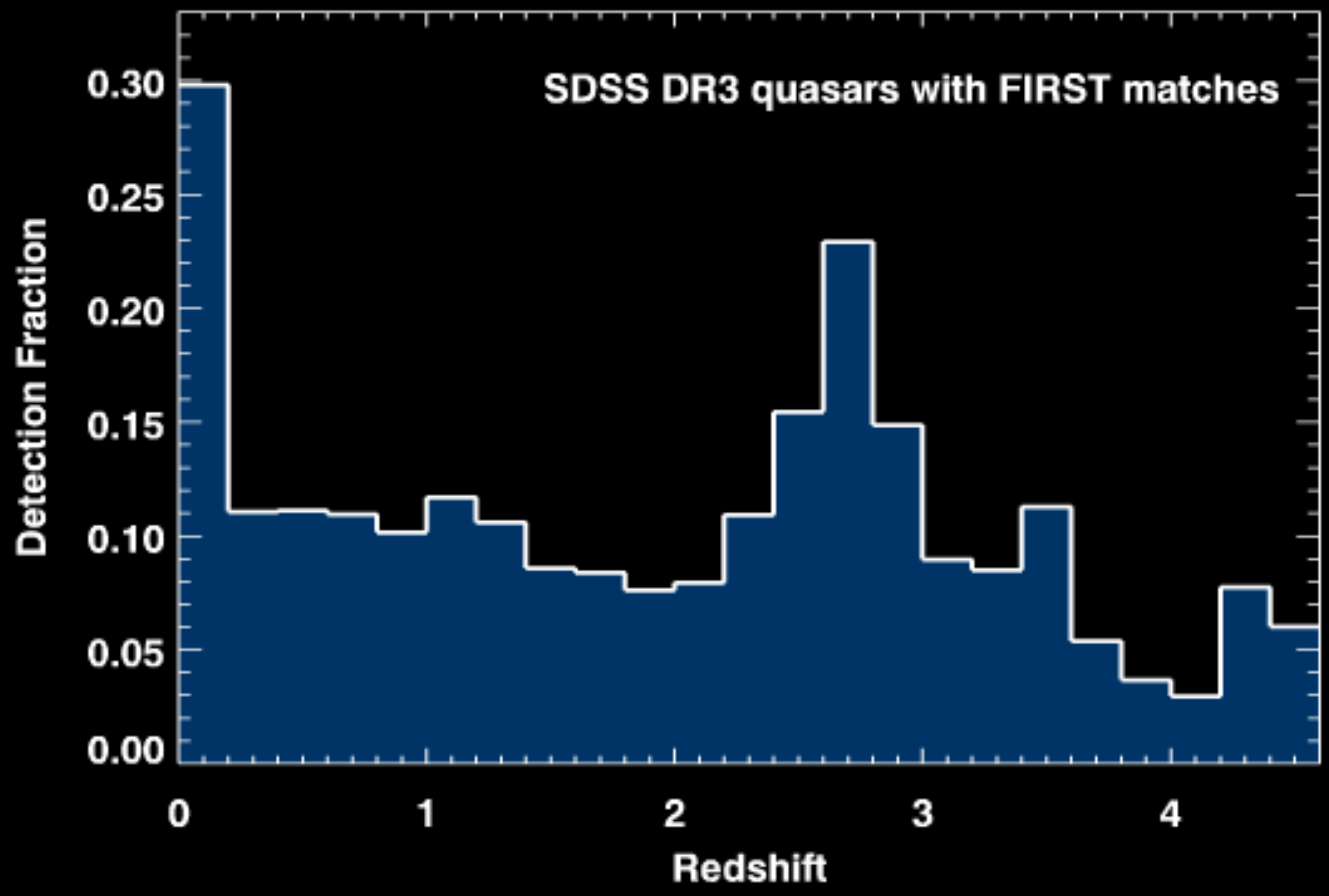
Schneider et al. 2005, AJ, 130, 367

- Used SDSS DR3 quasar catalog
  - 46,420 quasars with spectroscopic redshifts
    - 41,295 in FIRST survey area
  - All objects have accurate 5-color photometry (*ugriz* filters)
  - Selected as outliers from stellar sequence
    - Efficient except for z ~ 2.5–3

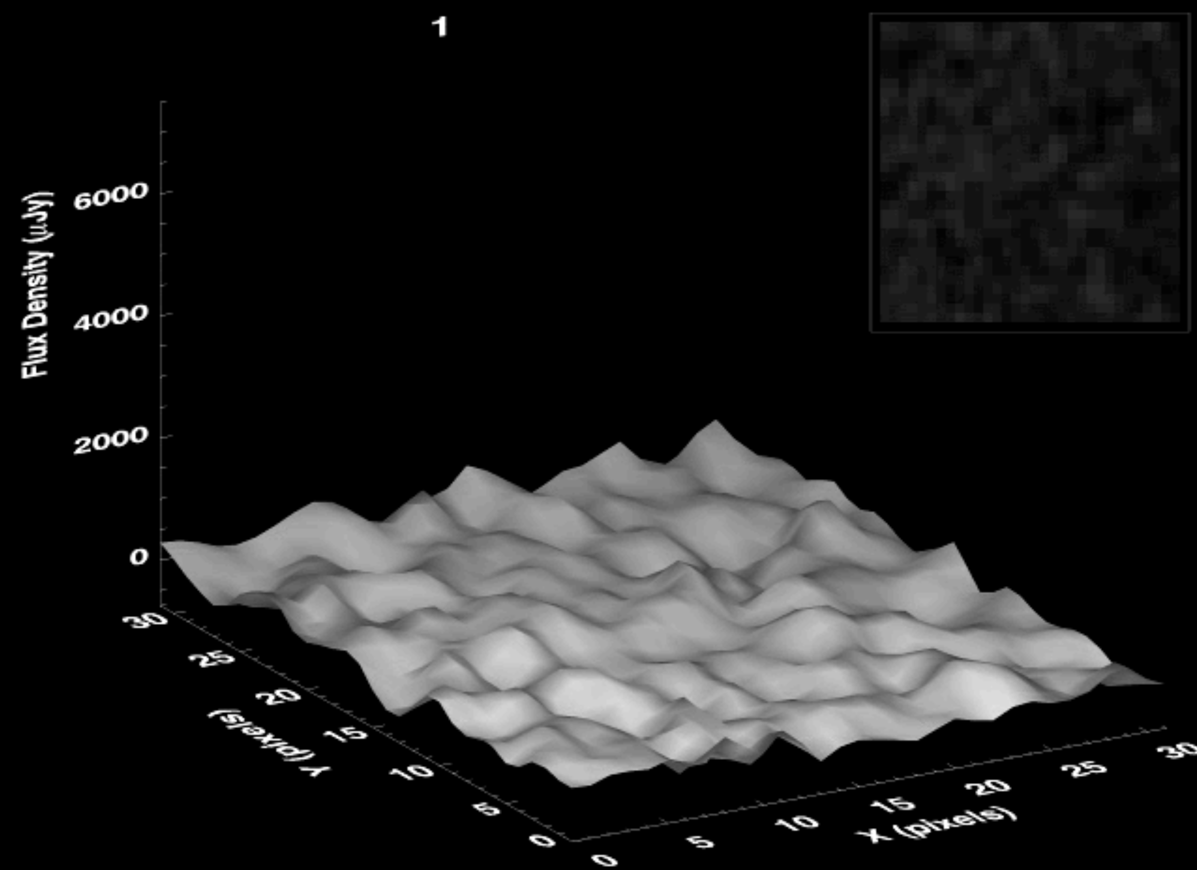
SDSS Radio Quasars

- 10% of SDSS quasars are detected in FIRST survey (F_ν(20cm) > 1 mJy)

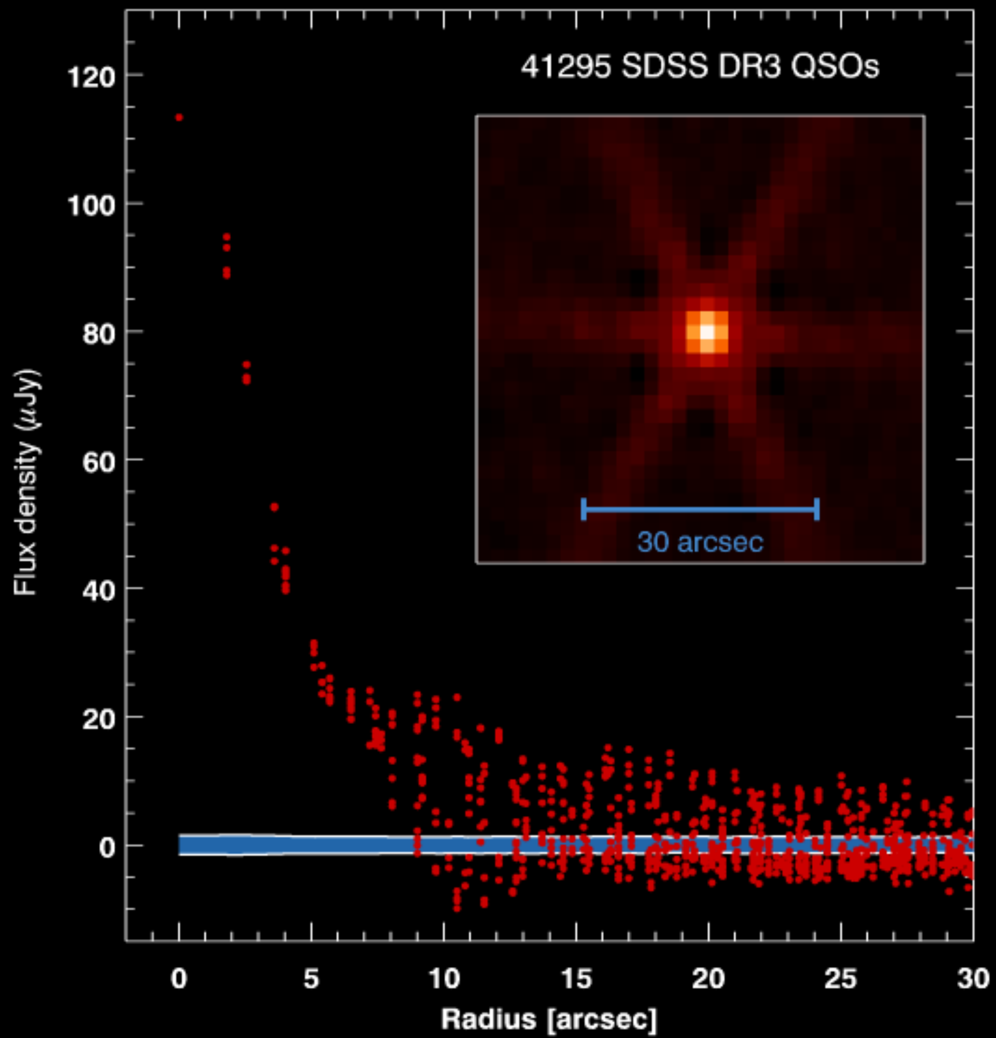
Redshift variations will be discussed later



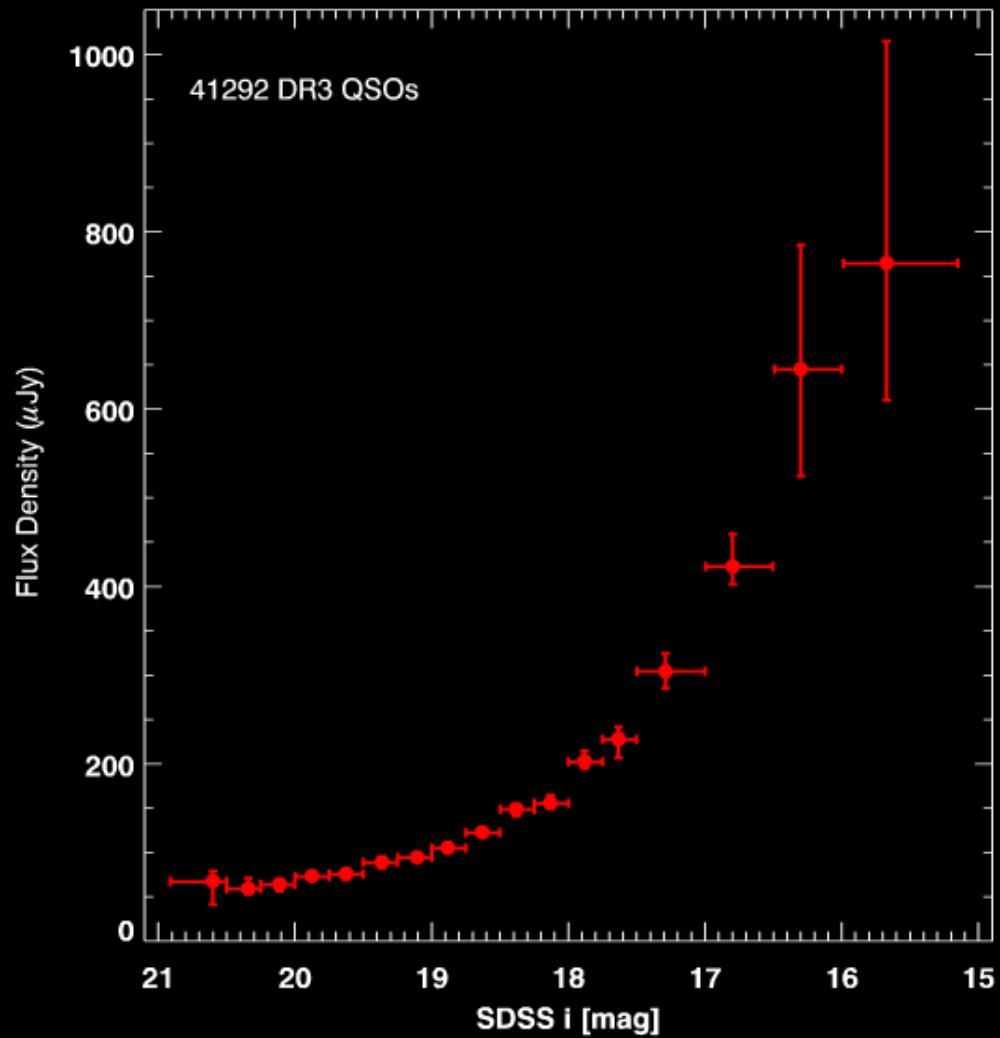
Stacking Quasars



Median Radio Image for 40,000 Quasars

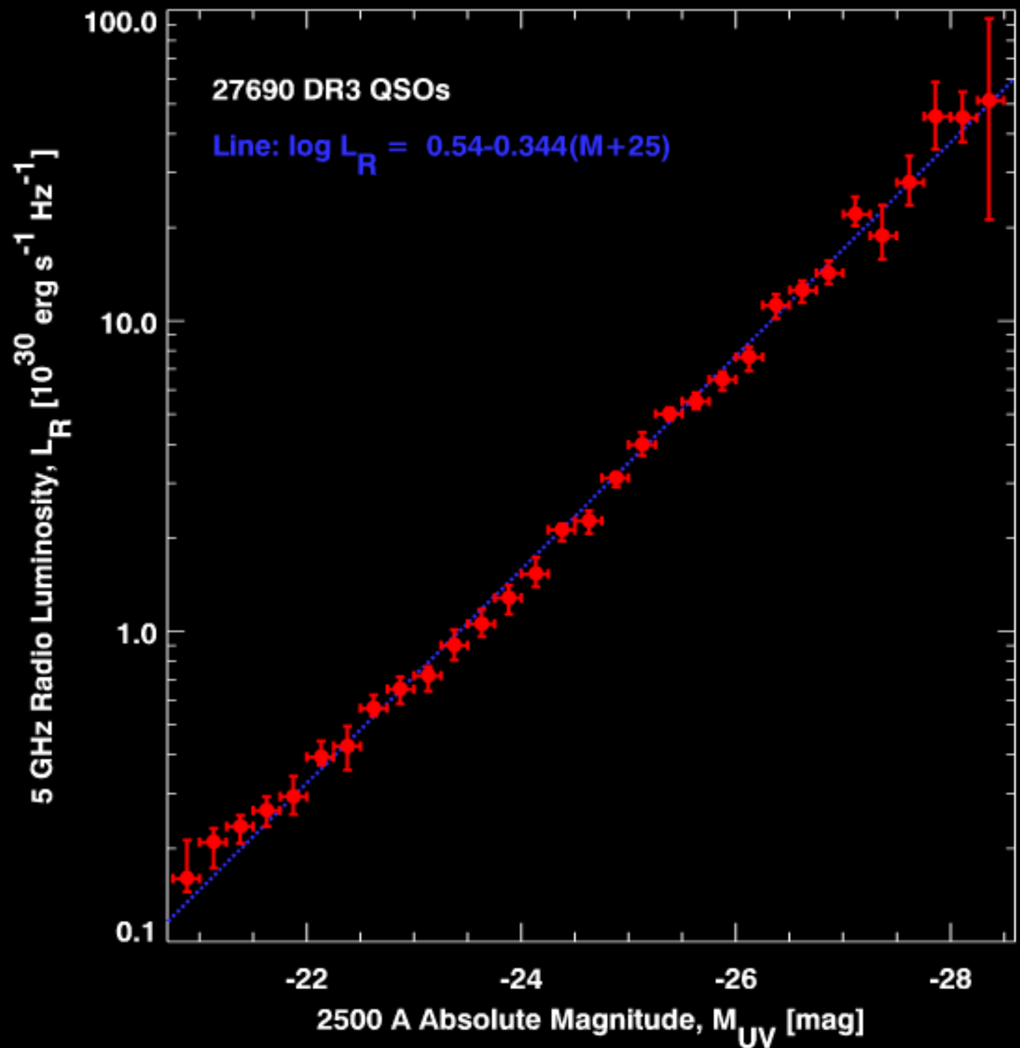


F_ν(20cm) vs. *i* Magnitude



Median for bright quasars is close to FIRST 1 mJy detection limit

Radio Luminosity L_R vs. Absolute UV Magnitude M_{UV}

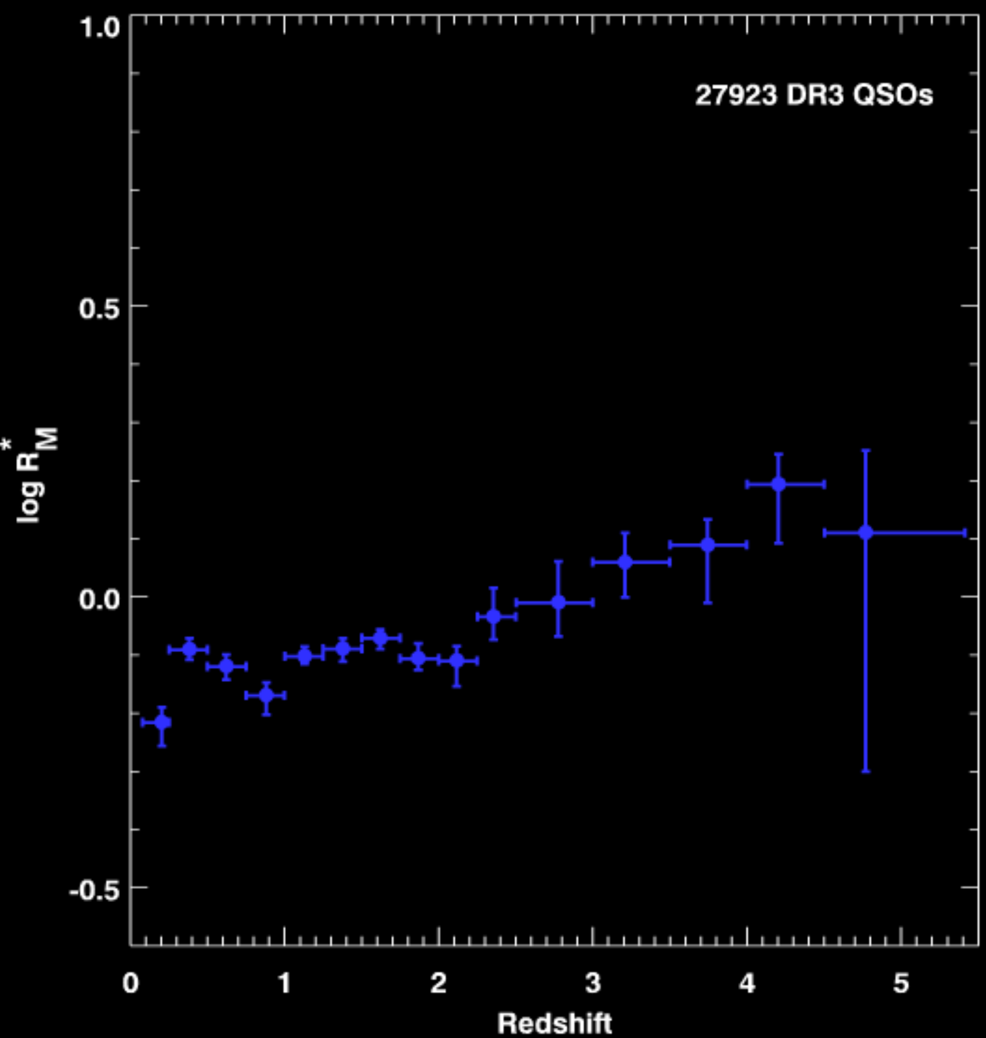


Radio images are scaled to luminosity before stacking.

Radio luminosity increases more slowly than optical luminosity:

$$L_R \sim L_{opt}^{0.85}$$

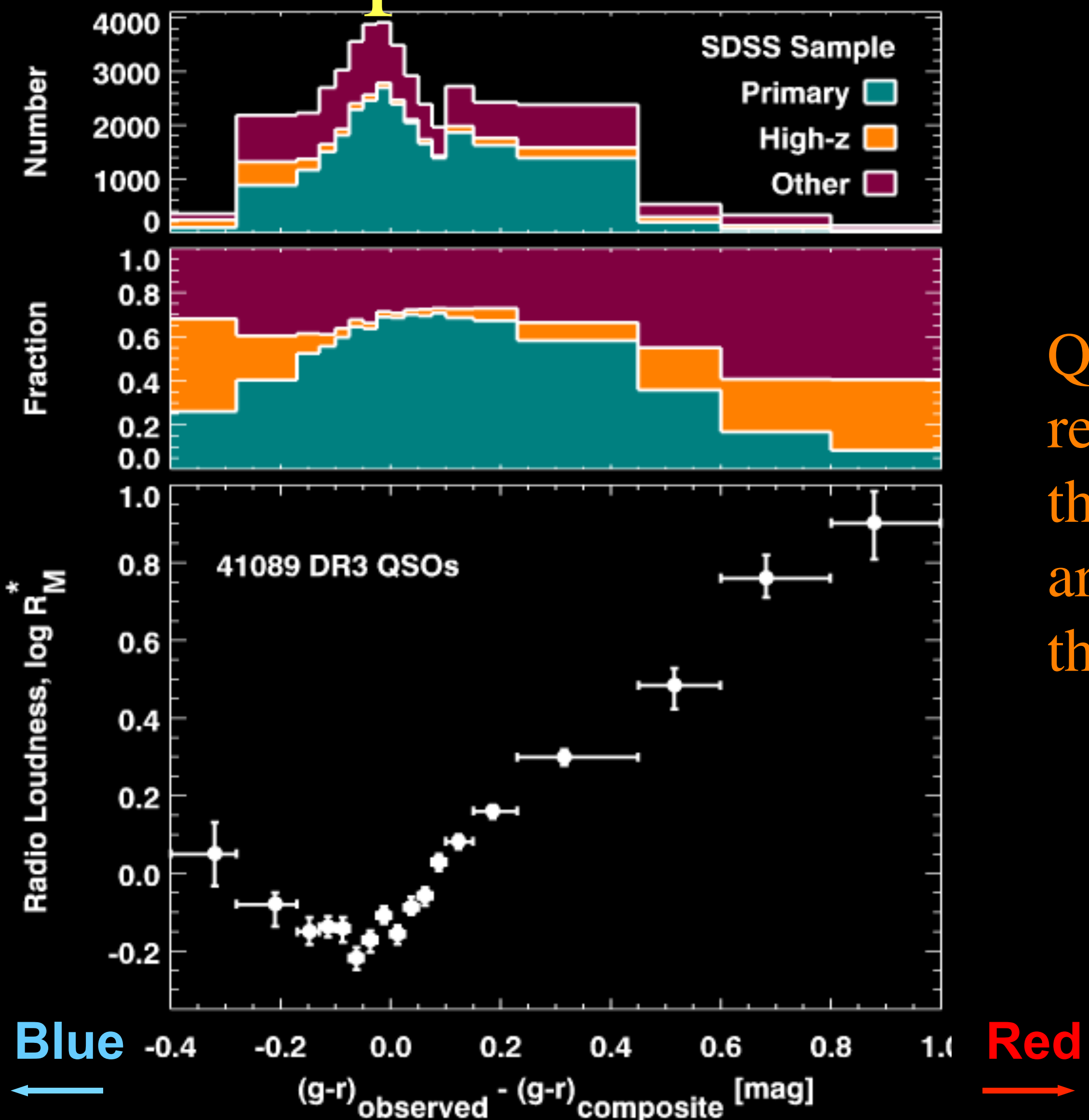
M-adjusted Radio Loudness R^*_M vs. Redshift



Radio loudness adjusted to remove M dependence

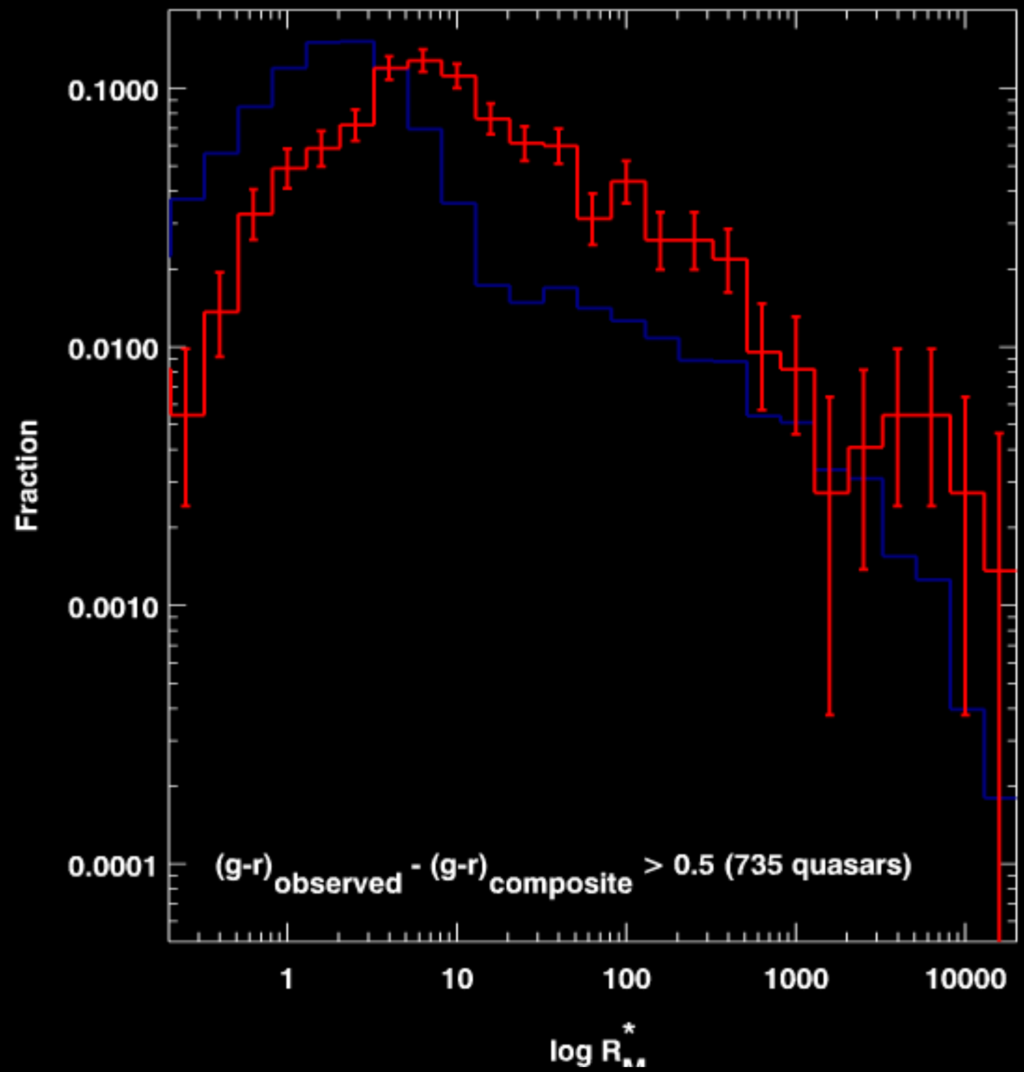
"Radio loud" is usually defined as log R^* > 10

Radio Loudness Depends on Color



Quasars either redder or bluer than the norm are brighter in the radio

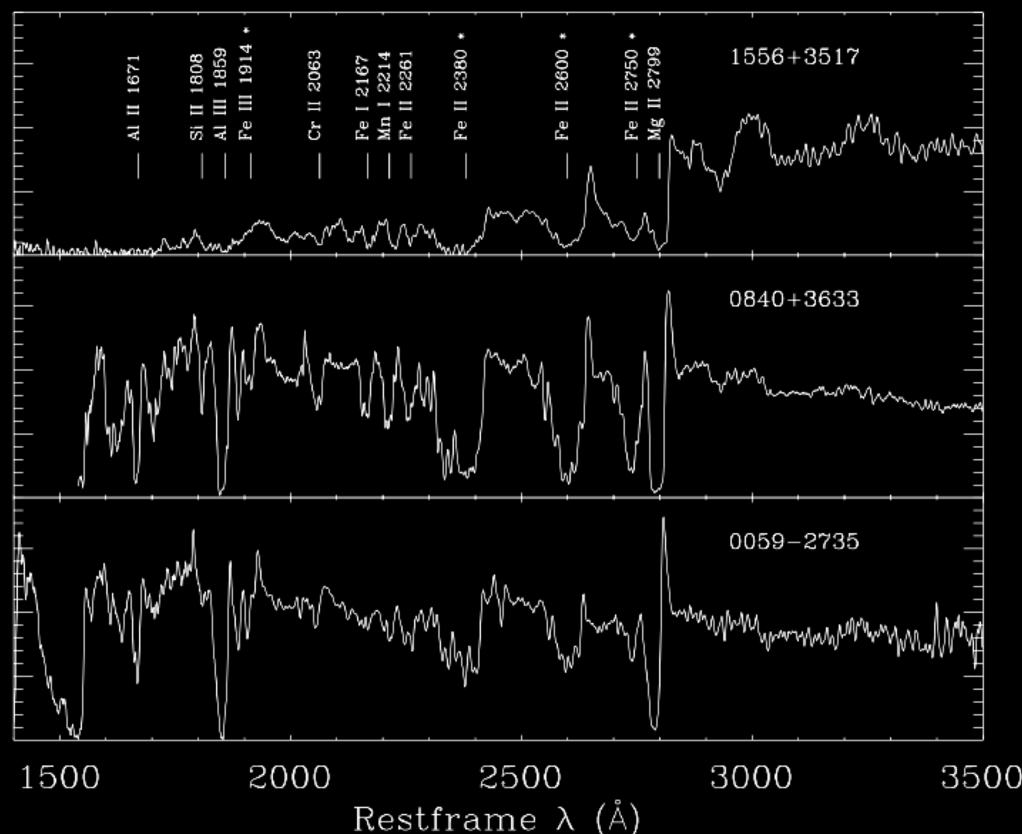
Radio Loudness Distribution is Sculpted by Selection Effects



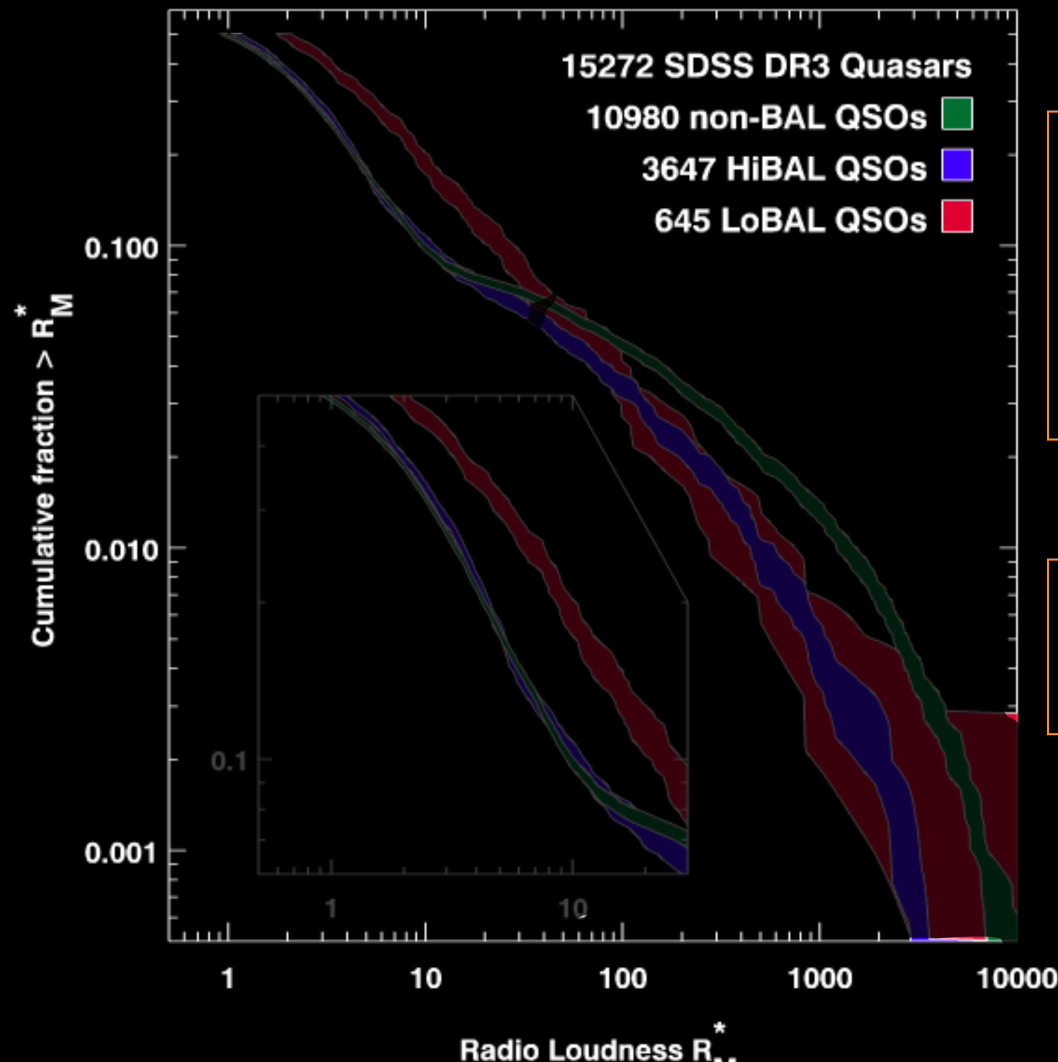
Radio dichotomy is probably created by color selection effects

Broad Absorption Line Quasars

- One of few known connections between optical spectra and radio properties is the tendency of BAL quasars to be radio quiet
  - Radio-loud BALs rare but do occur
- Stacking results are exactly opposite: BAL QSOs are brighter in the radio



Radio-Loudness Distribution for BAL, non-BAL Quasars



But radio-faint BAL QSOs have brighter radio emission

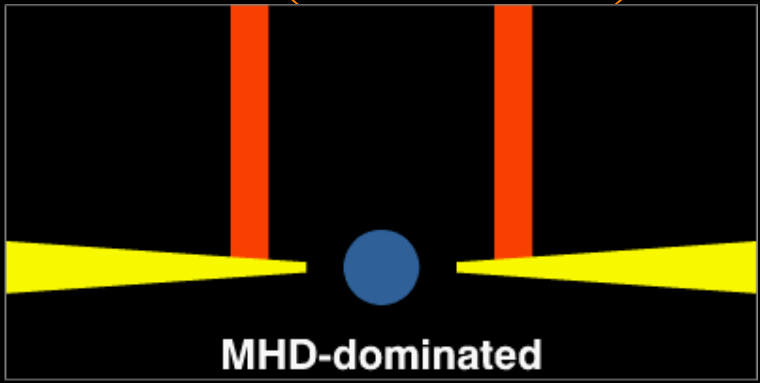
Radio-loud BAL Quasars are rare

Summary

- Radio surveys are unusual both in scientific content and data characteristics
  - Content of images very different from optical data
  - Image characteristics are also strange
  - Wide-field, wide-band interferometric imaging is not a solved problem
- Stacking FIRST survey images enables the study of source classes with fluxes in the microJansky regime
- Stacking completely eliminates selection biases in the stacked images, greatly simplifying analysis of the data
- Stacking 40,000 SDSS quasars reveals many interesting characteristics that illuminate the radio & BAL phenomena

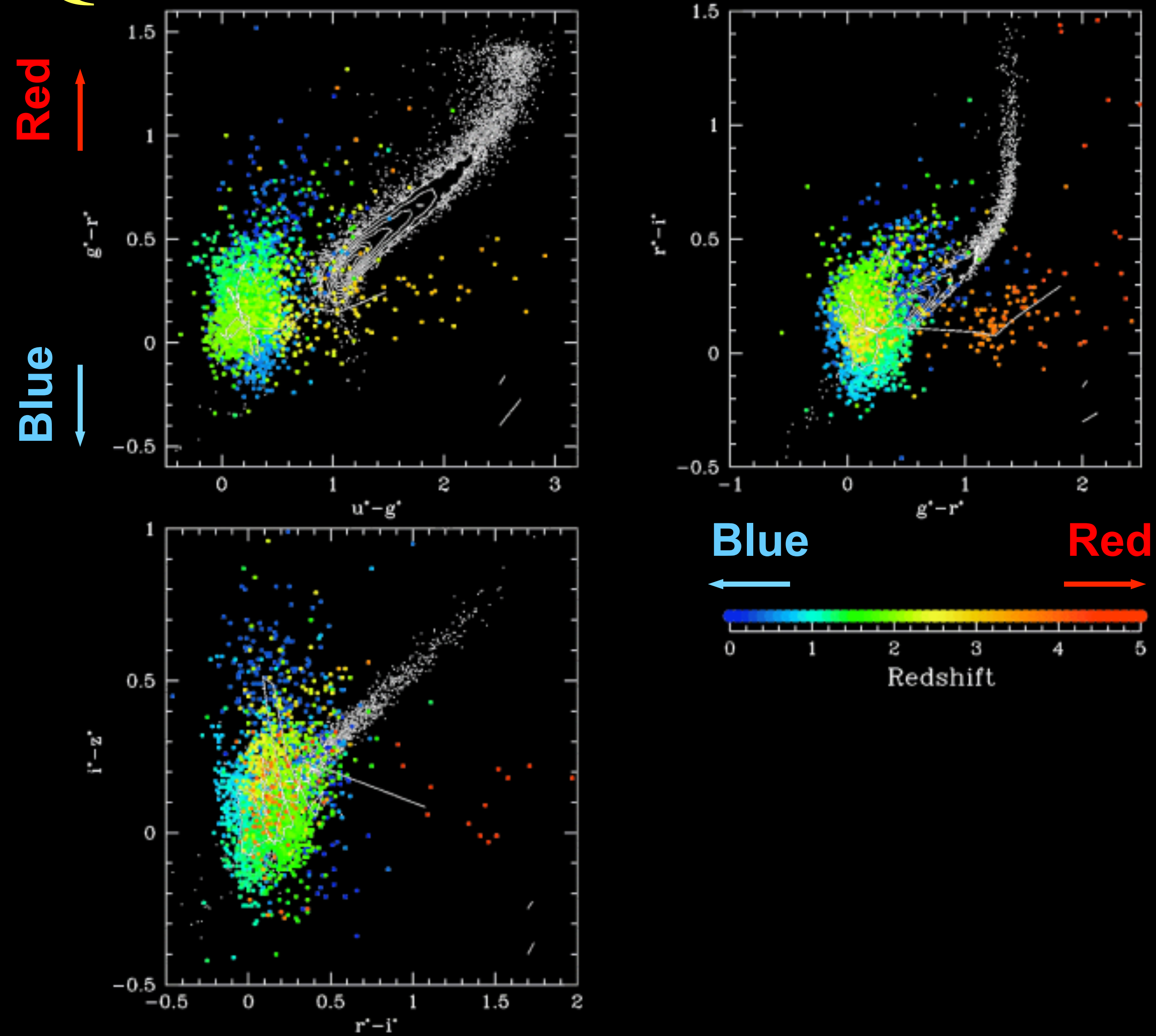
The BAL/Radio Connection

- BAL-radio correlation is inconsistent with simple orientation models for BAL QSOs
- Alternative models:
  - Low-level radio emission confined near nucleus is a stage accompanied by absorption clouds (evolutionary unification)
  - Outflow transition from MHD-driven (radio-loud) to radiatively driven (radio-quiet) with changing geometry



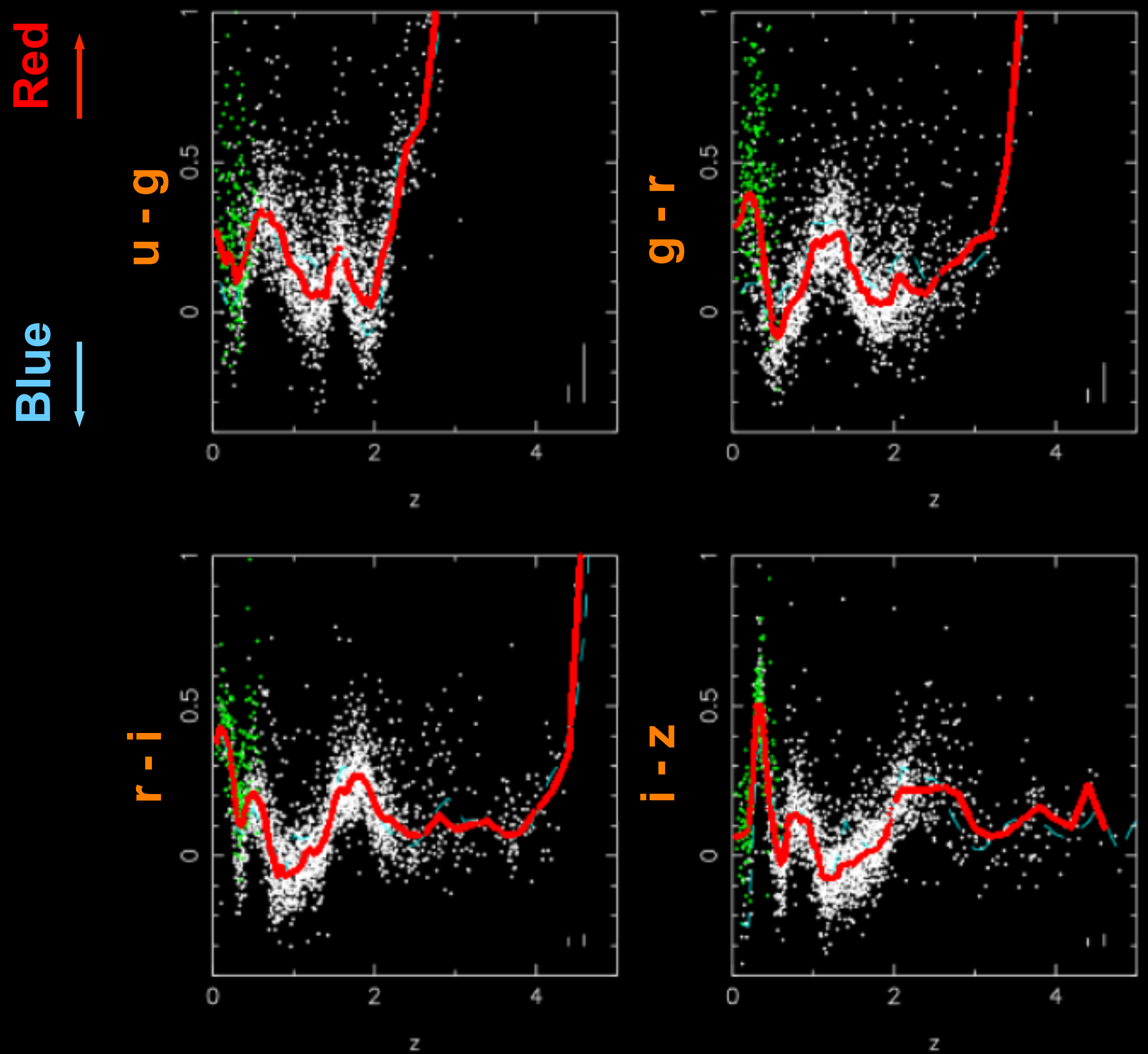
Adapted from Richards et al. 2004, ASP Conf Ser 311

Quasar colors in SDSS filters



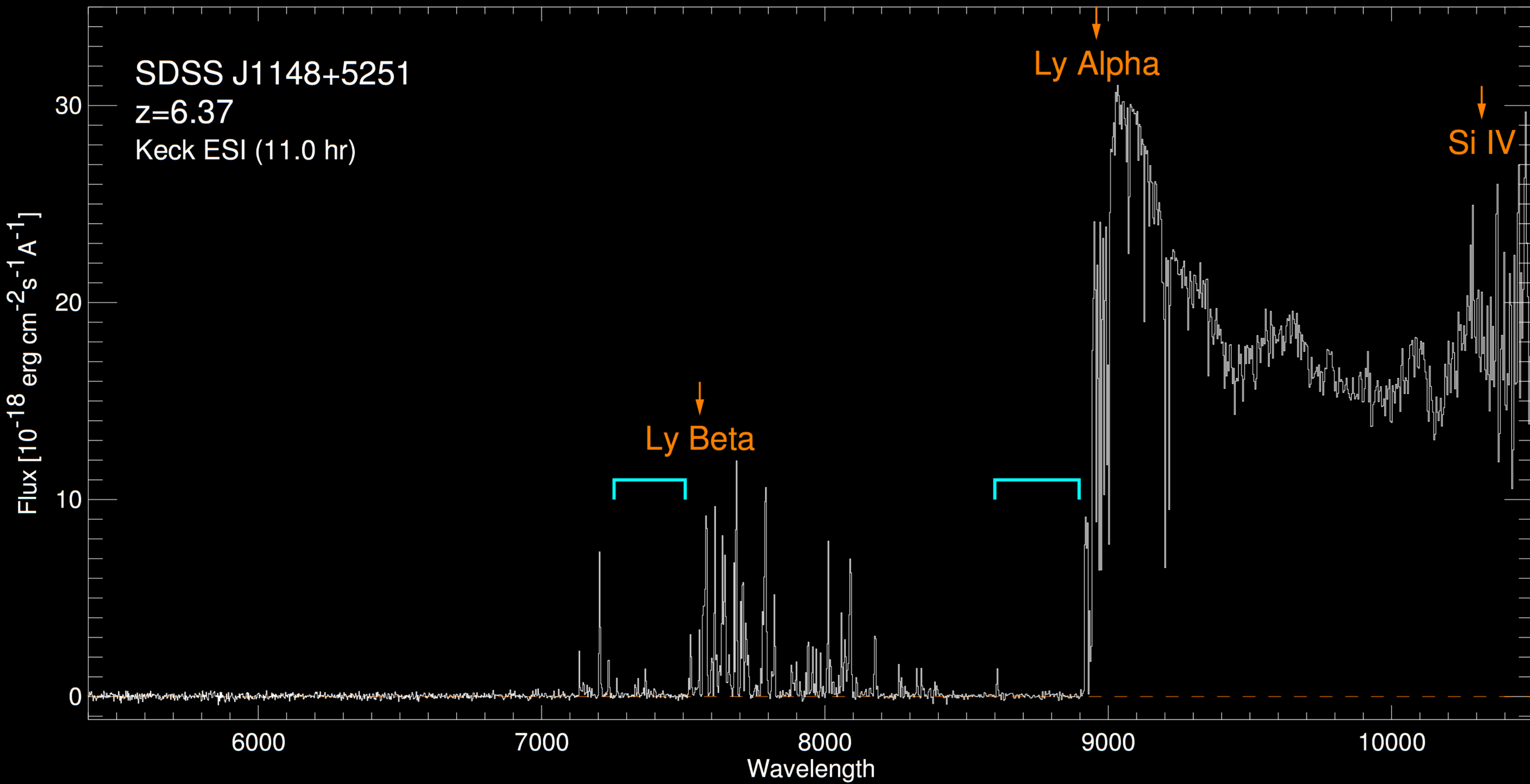
Richards et al. 2001, AJ, 121, 2308

Quasar colors vs. redshift



Richards et al. 2001, AJ, 121, 2308

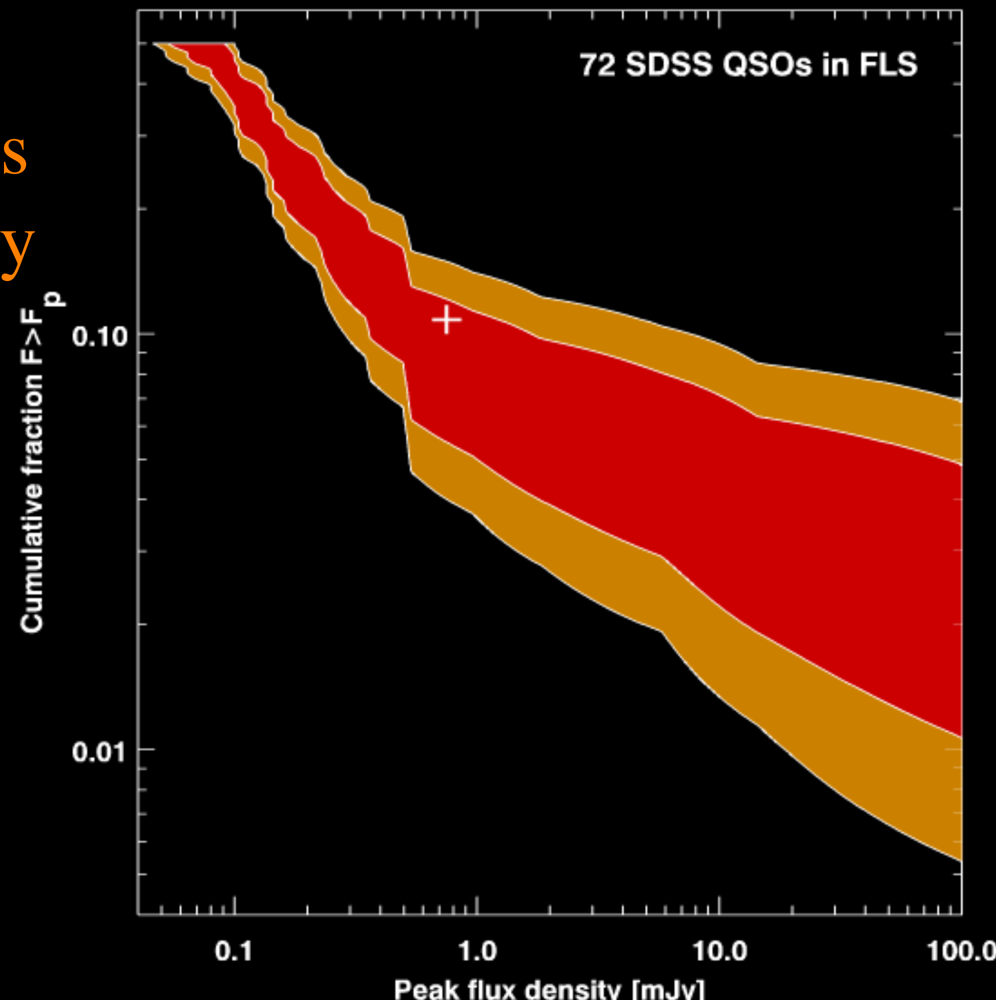
SDSS J1148+5251 z=6.42



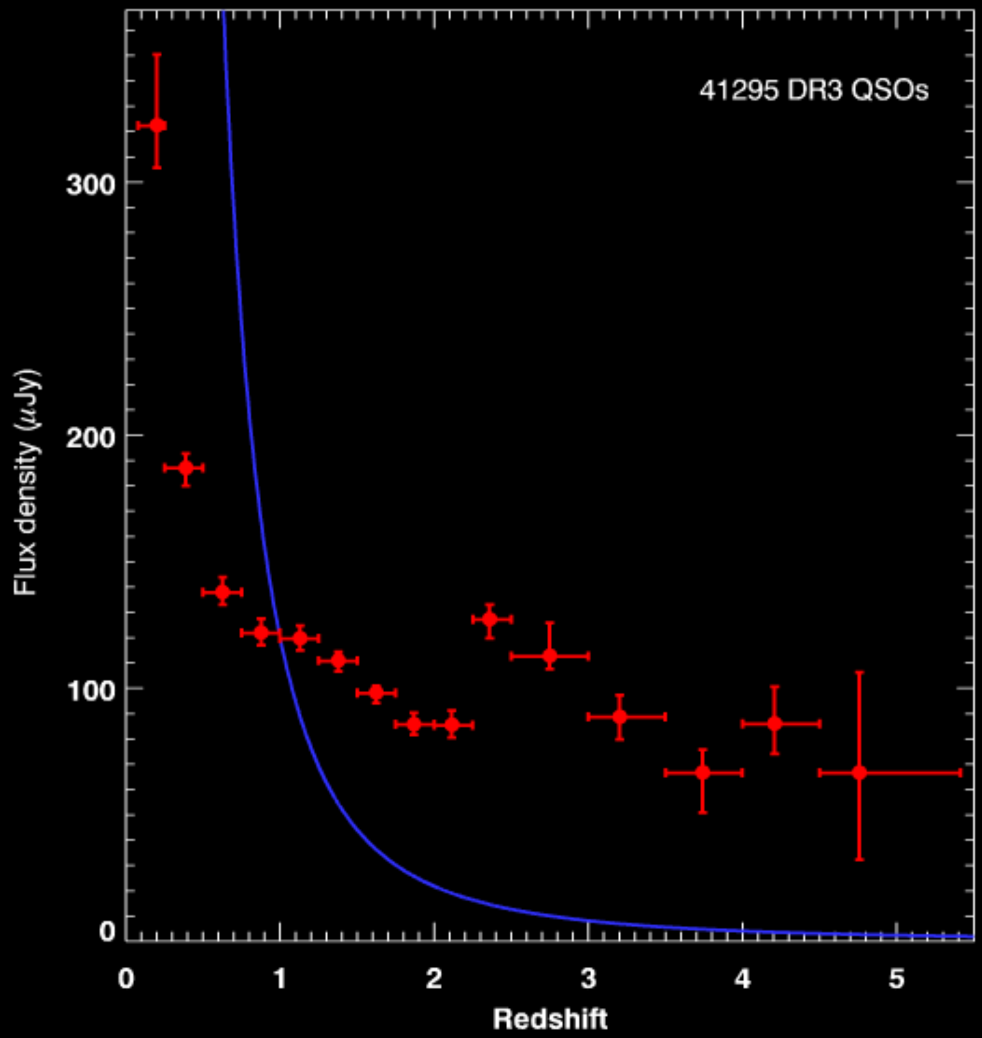
White et al., 2003, AJ, 126, 1

SDSS Radio Quasars

- Much deeper radio surveys are required to detect half of quasars
  - FLS survey detects less than half at F > 0.1 mJy (10x deeper than FIRST survey)
  - FLS area only 5 deg^2

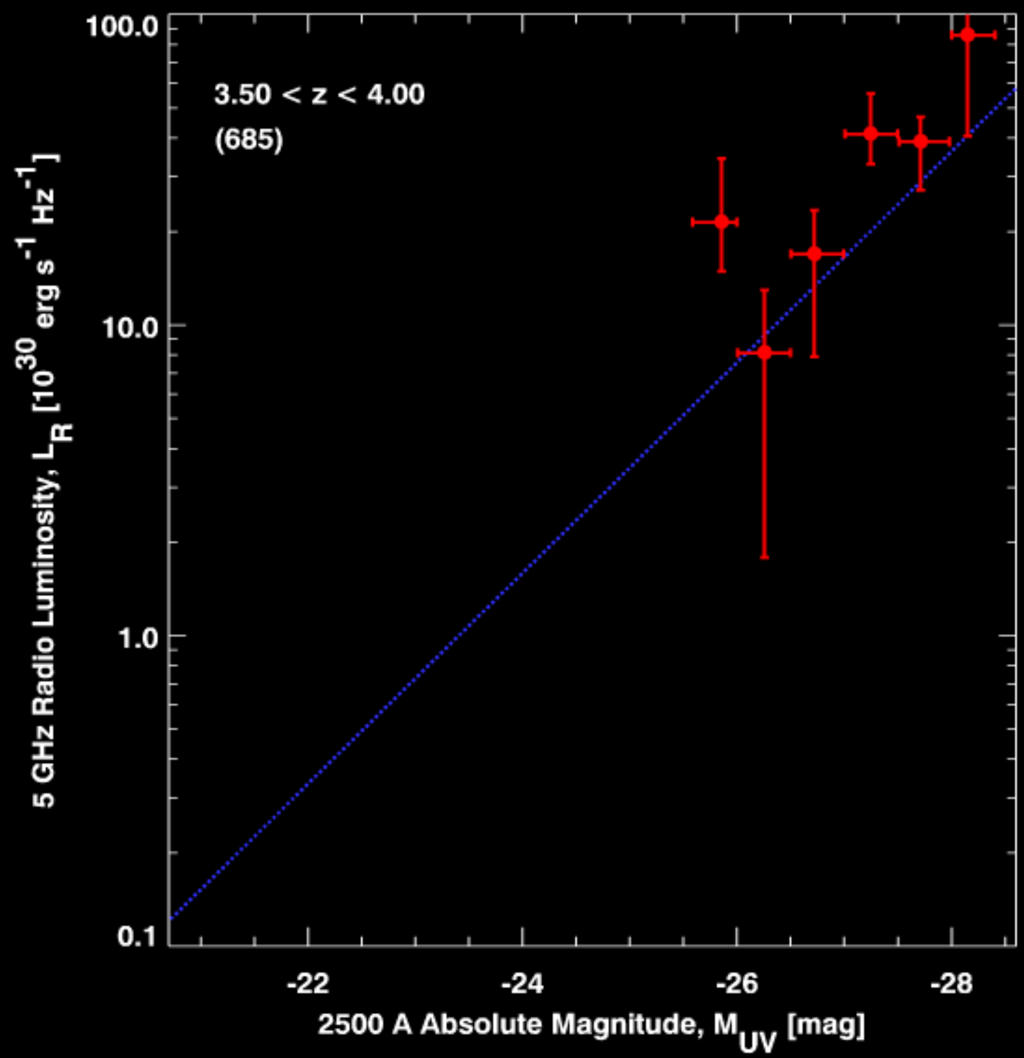


20 cm Flux Density vs. Redshift

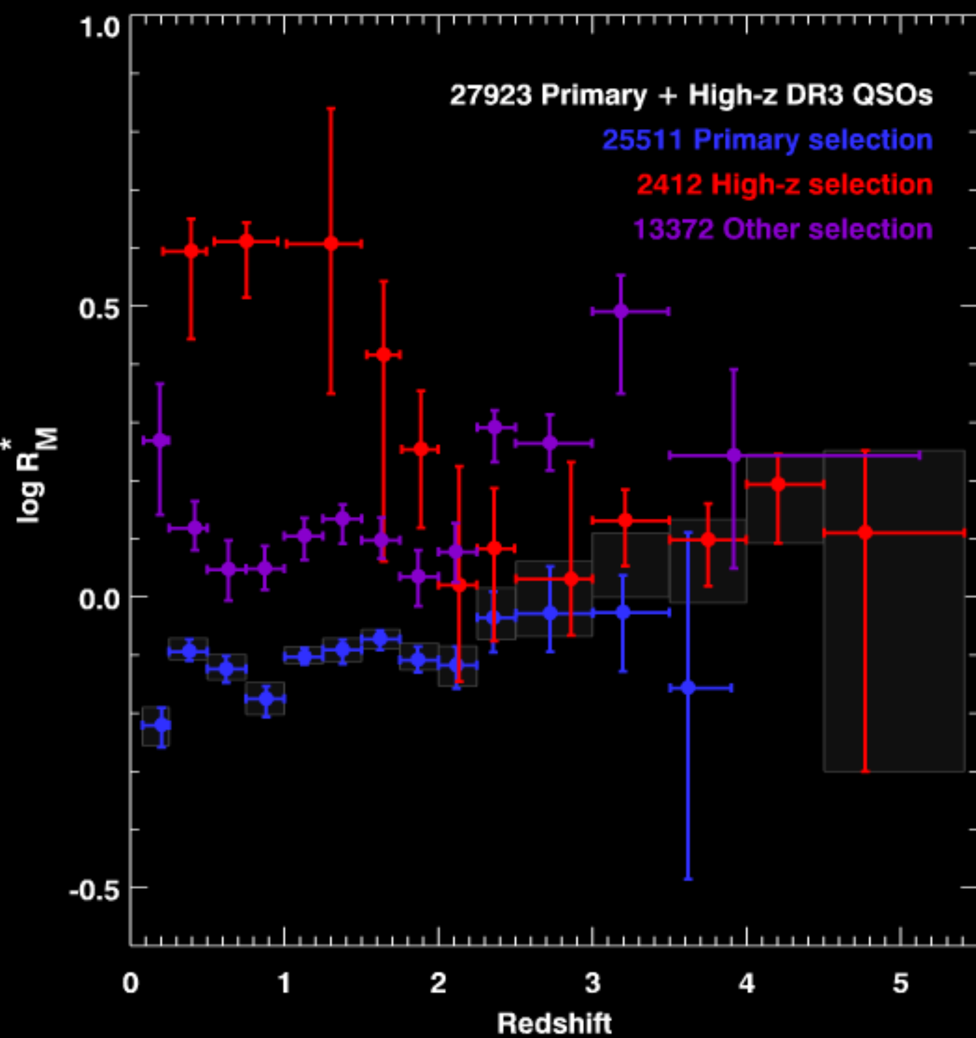


Much flatter than a simple distance dependence

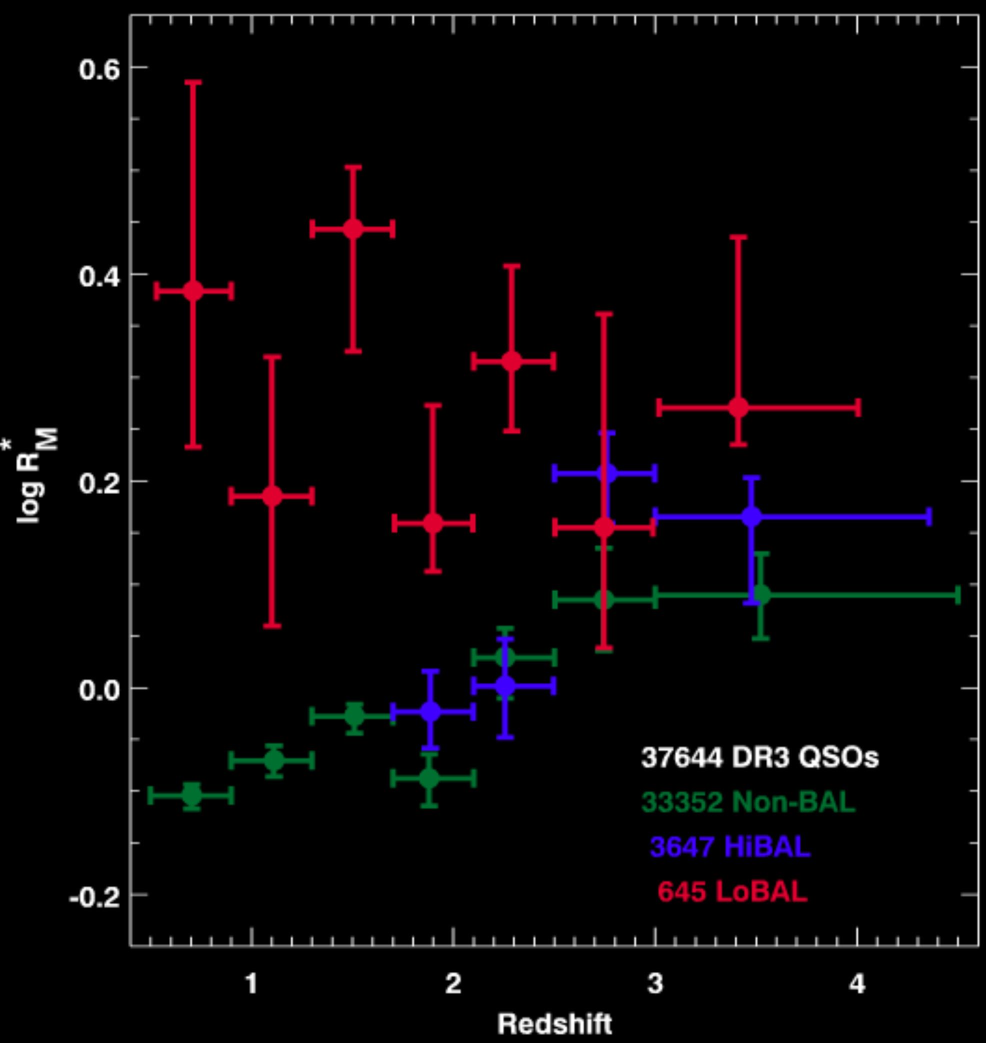
L_R vs. M_{UV} in redshift bins



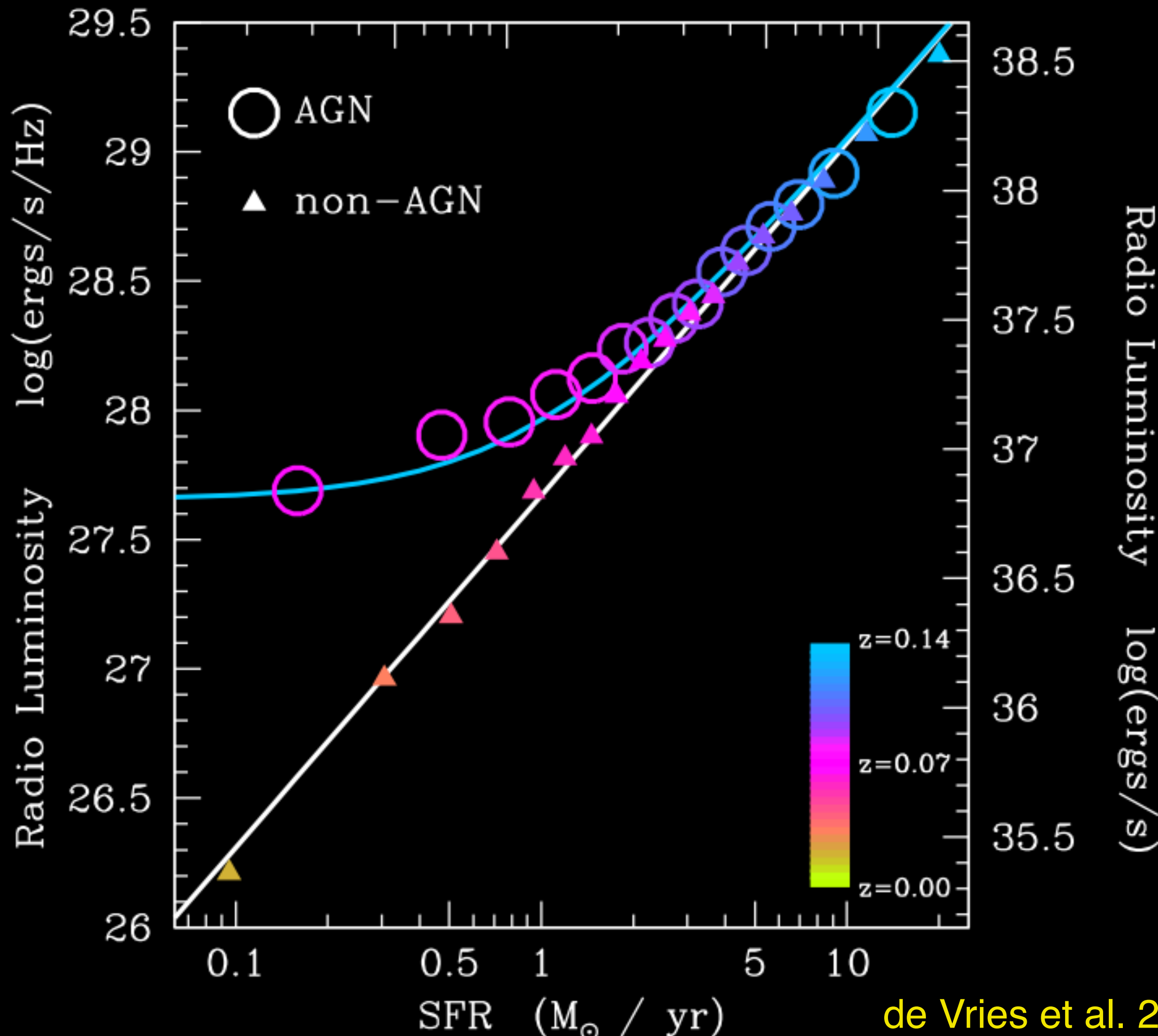
R^*_M Depends on SDSS Quasar Selection Criteria



BAL Quasars are Radio Louder



Radio Luminosity vs. Star Formation Rate



de Vries et al. 2007, AJ, 134, 457

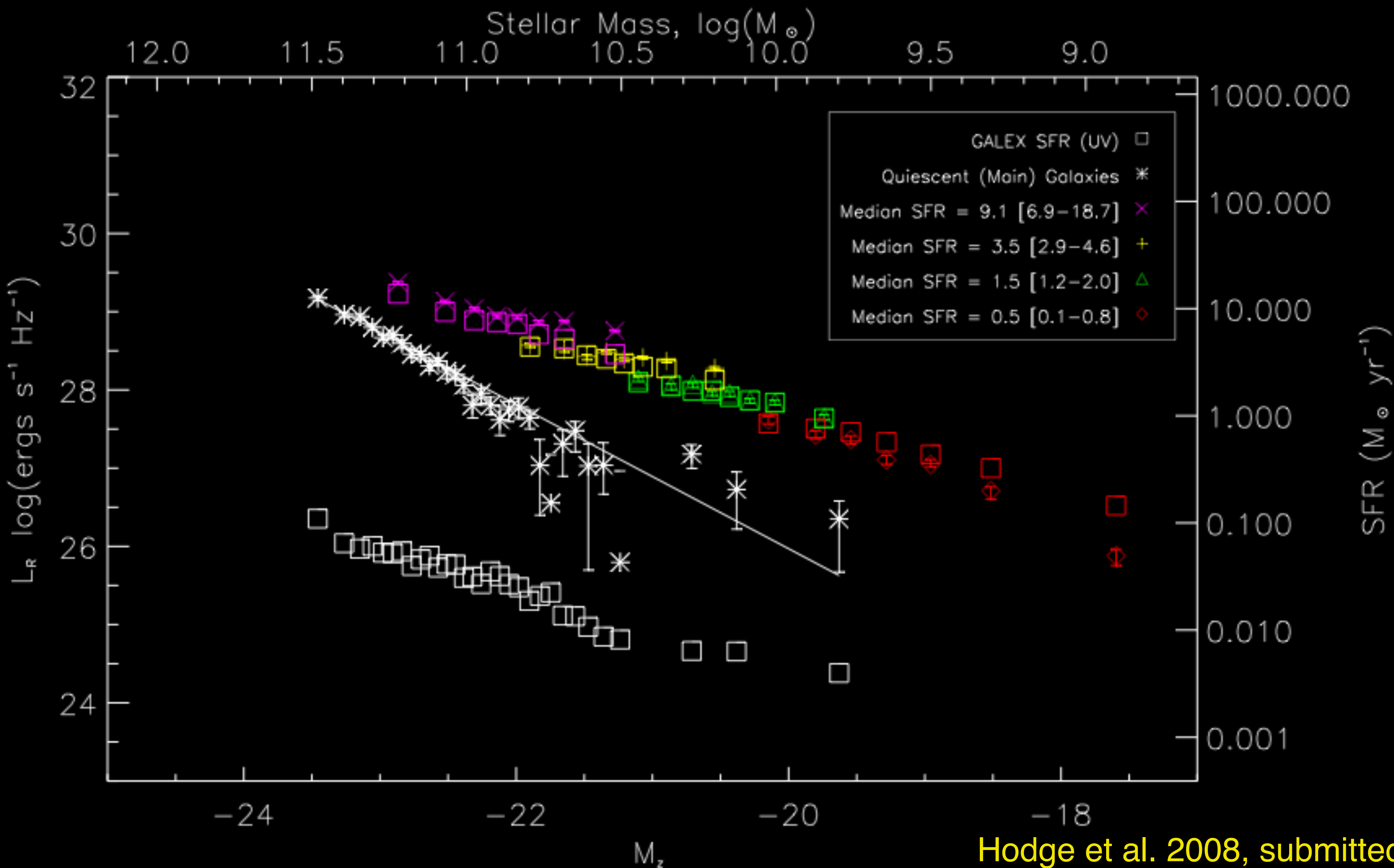
Signals from the noise in the FIRST Survey

Richard L. White
Space Telescope Science Institute

Northwestern University, 2008 April 22

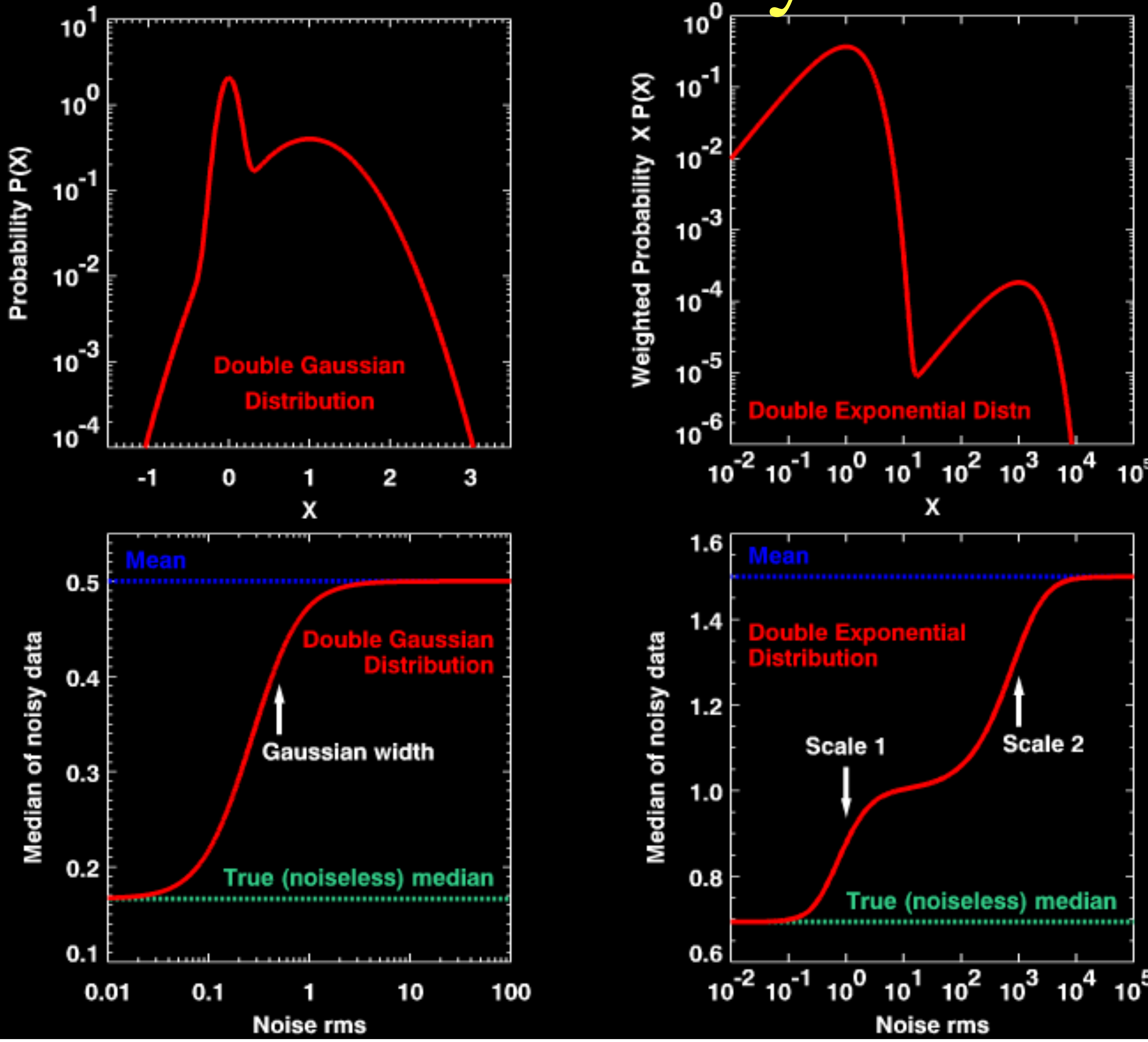
Collaborators:
R. Becker (UC-Davis), D. Helfand (Columbia),
E. Glikman (Caltech), W. de Vries (LLNL),
J. Hodge (UC-Davis)

AGN or Star Formation in "Quiescent" Galaxies

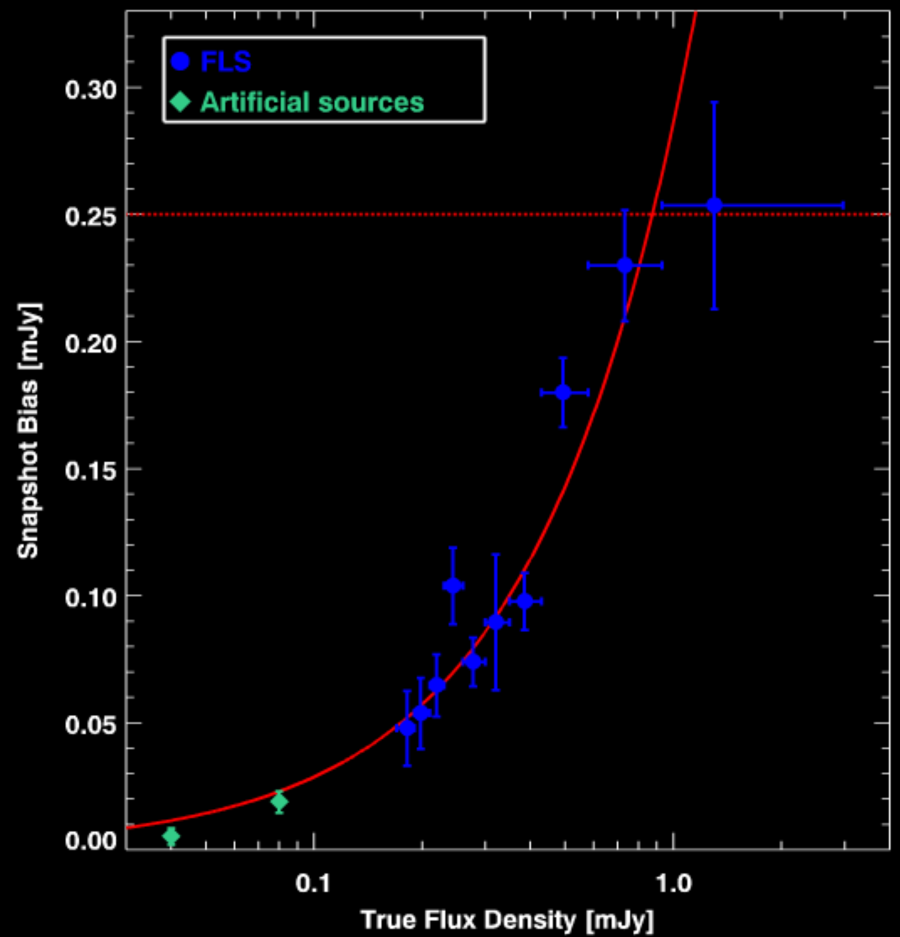


Hodge et al. 2008, submitted

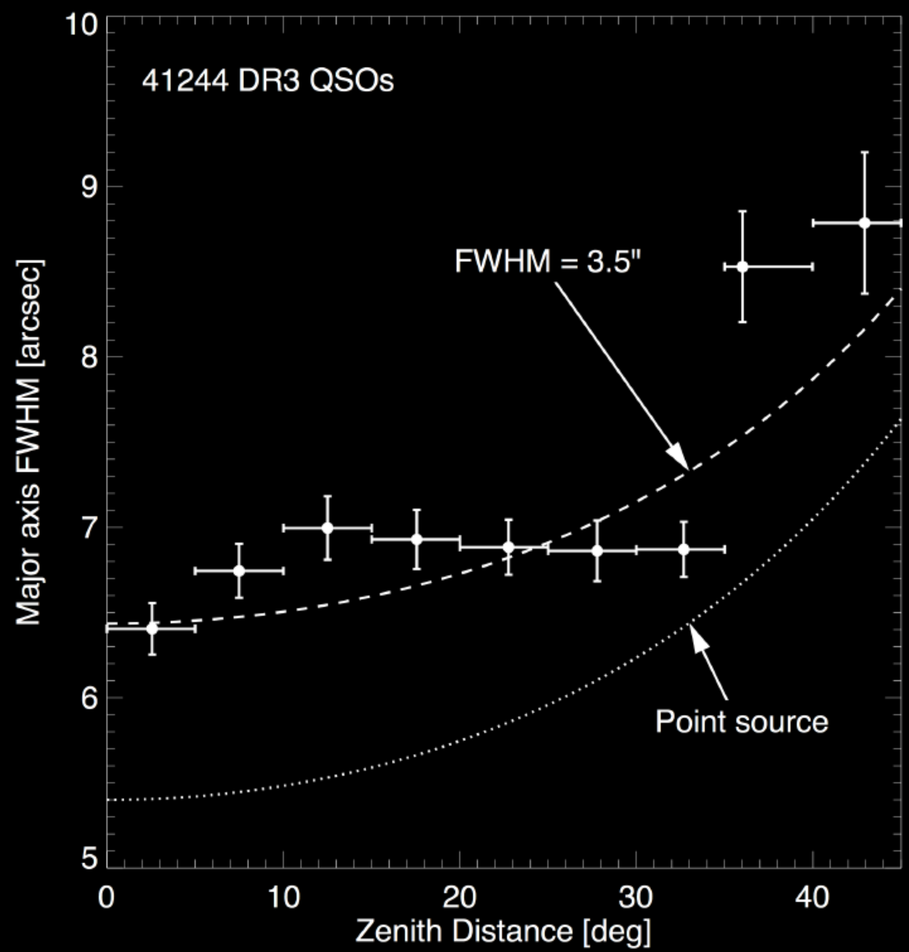
Median of Noisy Data



Snapshot Bias in Radio Images



Size vs. Zenith Distance



SDSS BAL Sample Heavily Influenced by Selection Effects