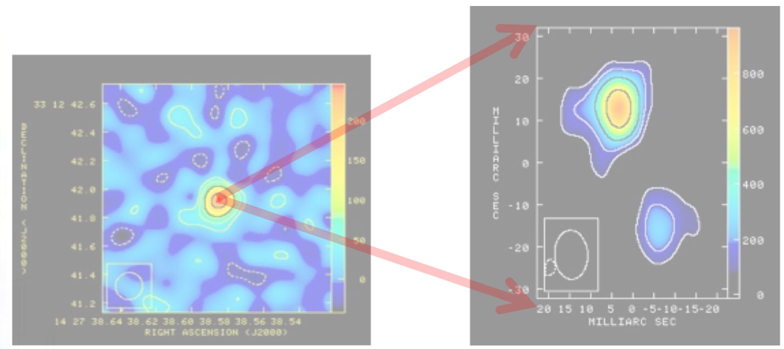
# Milliarcsecond Imaging of the Highest Redshift Radio-Loud Quasars




**Emmanuel Momjian**

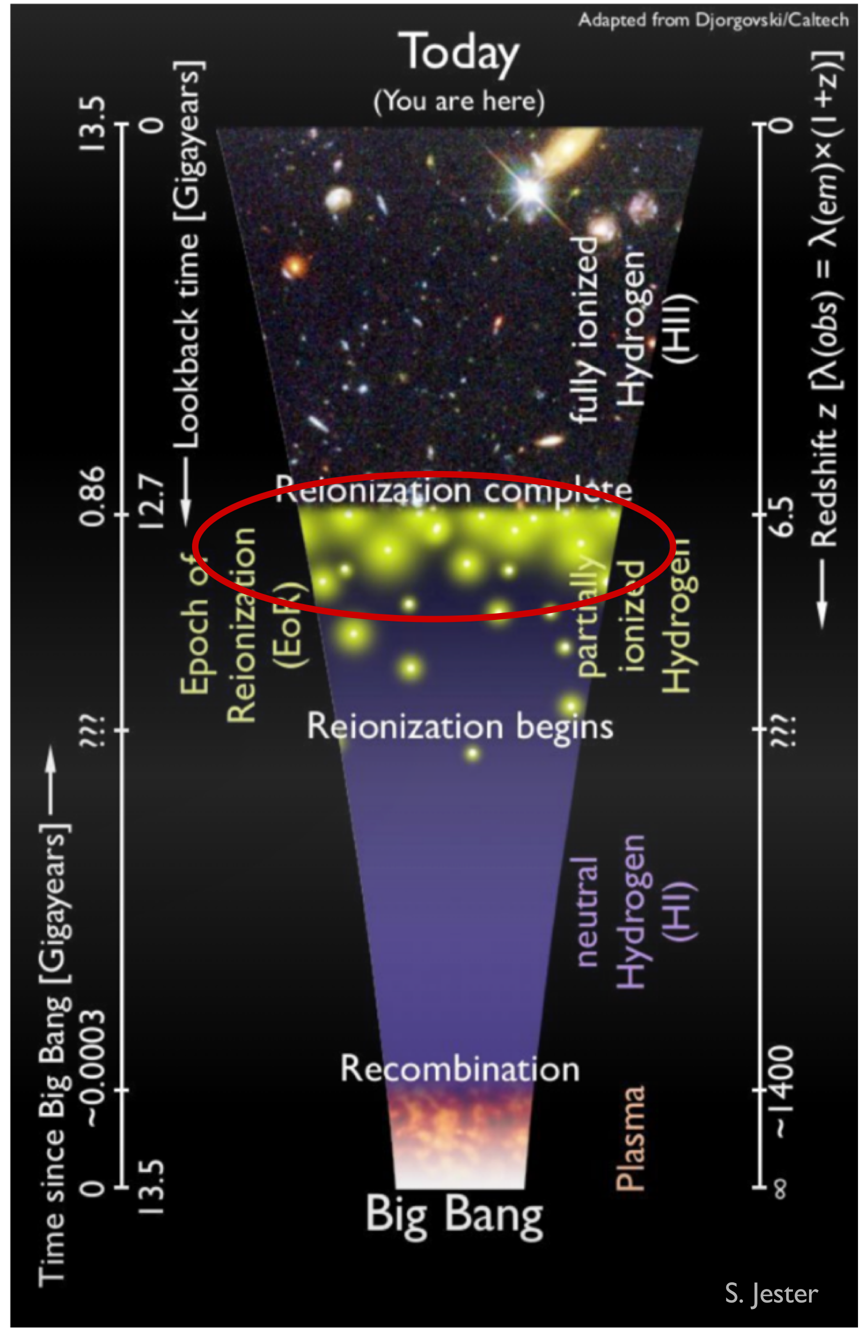
**NRAO**

**Collaborators**

Chris Carilli
Fabian Walter
Eduardo Bañados
Bram Venemans

# Introduction: High-z QSOs

- At $z \gtrsim 6$ we are probing the era near the end of the Cosmic Reinozation.
- Various surveys (e.g., SDSS, SHELLQs, Pan-STARRS1) found large samples of QSOs out to z~6 and beyond.
- To date, more than 150 quasars at $z \gtrsim 6$ have been identified.
- Only two at $z > 7$; the highest-z QSO known-to-date is at $z = 7.54$

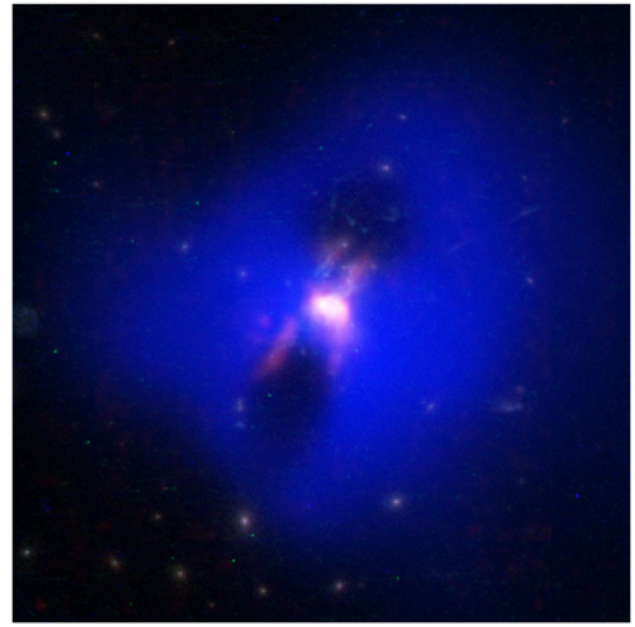


# RLQs

- Luminous radio quasars and radio galaxies are likely to reside in more massive galaxies and to harbor more massive central black holes.
- Roughly 10%-20% of all quasars are radio-loud (R>10)
- Evolution of the Radio Loud Fraction (RLF) with $z$
  - RLF of quasars decreases with increasing redshift and decreasing optical luminosity ($0 < z \leq 5$: Jiang et al. 2007).
- At high-z, may allow to probe the formation of radio jets in the first quasars.

# Powerful Radio Jets

- Thought to play a key role in the formation and growth of SMBH.
- Regulate (or suppress/quench?) star formation via negative, 'radio mode' feedback
  - and perhaps even induce star formation.

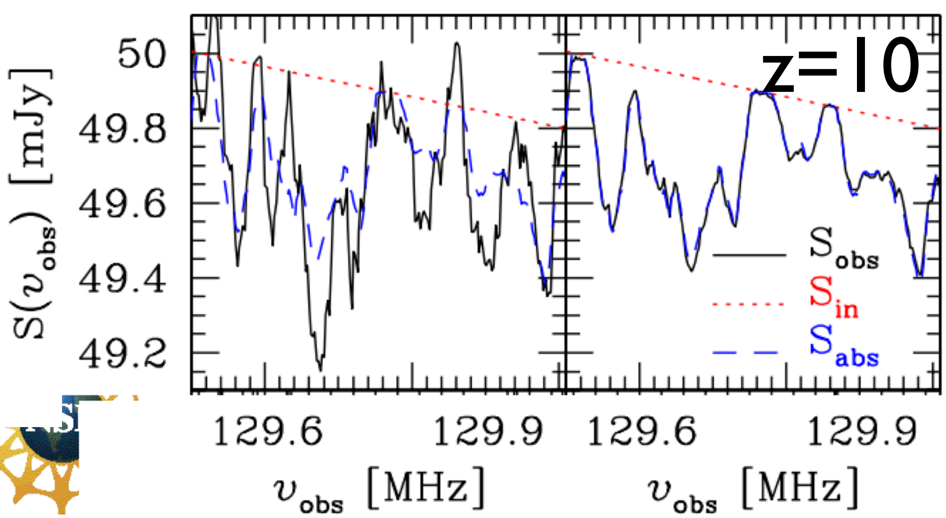


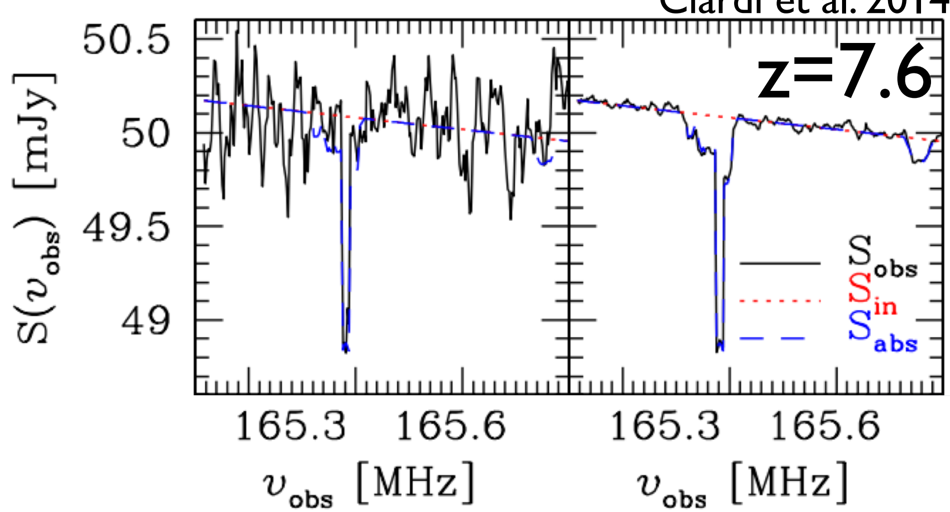
*Credit: ALMA (ESO/NAOJ/NRAO) H.Russell, et al.; NASA/ESA Hubble; NASA/CXC/MIT/M.McDonald et al.; B. Saxton (NRAO/AUI/NSF)*

# HI Absorption at High z

- Column density sensitivity for absorption: set by the surface brightness of the background source
- HI Absorption: Probes intermediate- to small-scale structures in the neutral IGM 'cosmic web', as well as HI in the first collapsed structures.
- What to expect:
  – An average suppression of the source flux (produced by diffuse HI in the IGM)
  – Isolated absorption lines due to overdense clumps of HI.

Ciardi et al. 2014



# Radio-loud QSOs @ z ~ 6

A total of seven known RLQs at $z > 5.8$, five imaged with VLBI

- J1609+3041 $z$=6.14 *No VLBI*
- J2053+0047 $z$=5.92 *No VLBI*

- J0836+0054 $z$=5.81 Frey et al. 2005
- J2228+0110 $z$=5.95 Cao et al. 2014
- J1429+5447 $z$=6.18 Frey et al. 2011

- J1427+3312 $z$=6.12 Frey et al. 2008, Momjian et al. 2008
- P352.15 $z$=5.84 Momjian et al. 2018

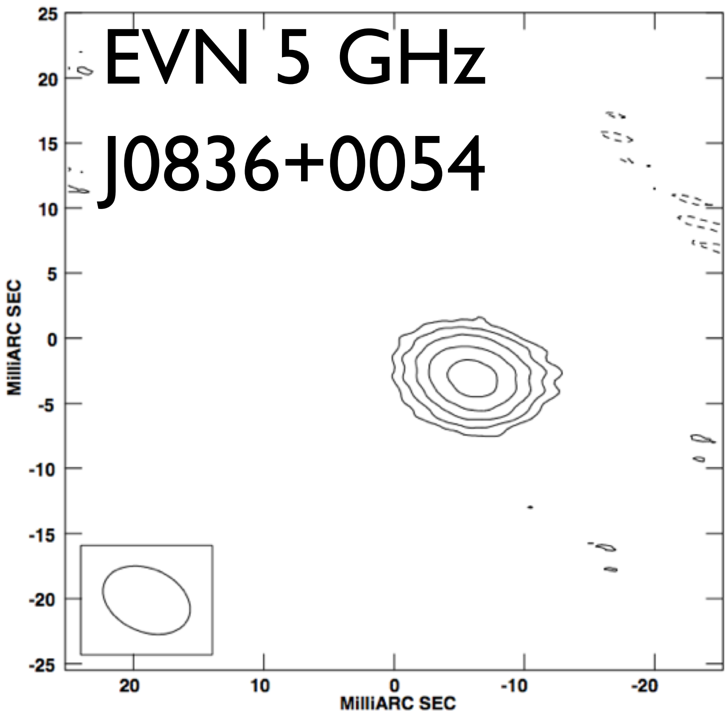
# VLBI and high-z QSOs

**Unmatched Angular resolution!**

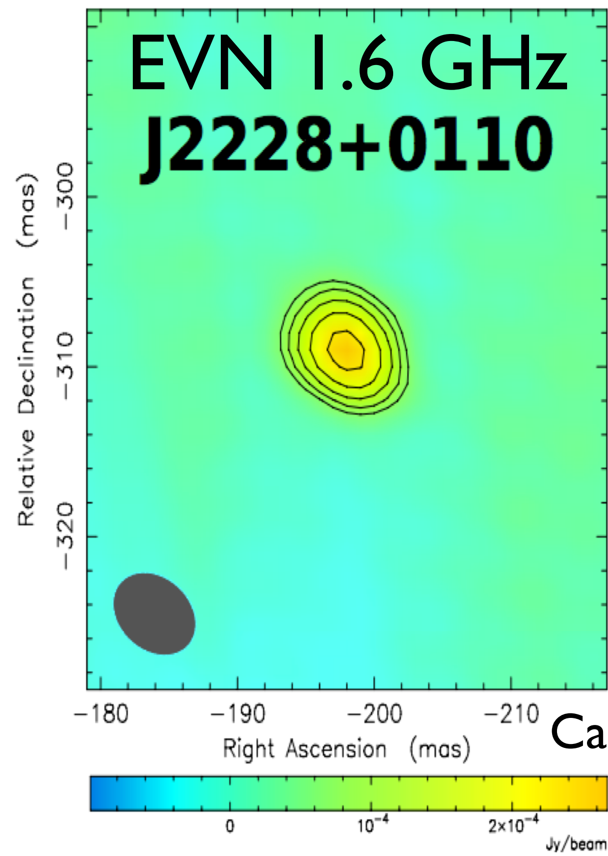
With VLBI's resolving power:

- Obtain a detailed look at the physical structures in the most distant objects
- Test for strong lensing
- Constrain the cosmic geometry
- Find the dominant power source at radio frequencies

# VLBI: RLQ at z~6




Frey et al. 2005

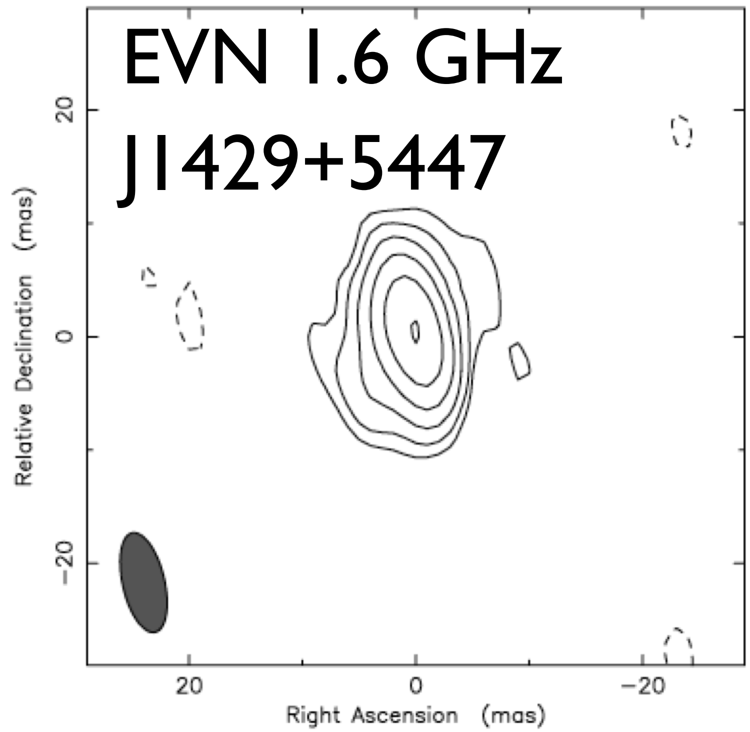


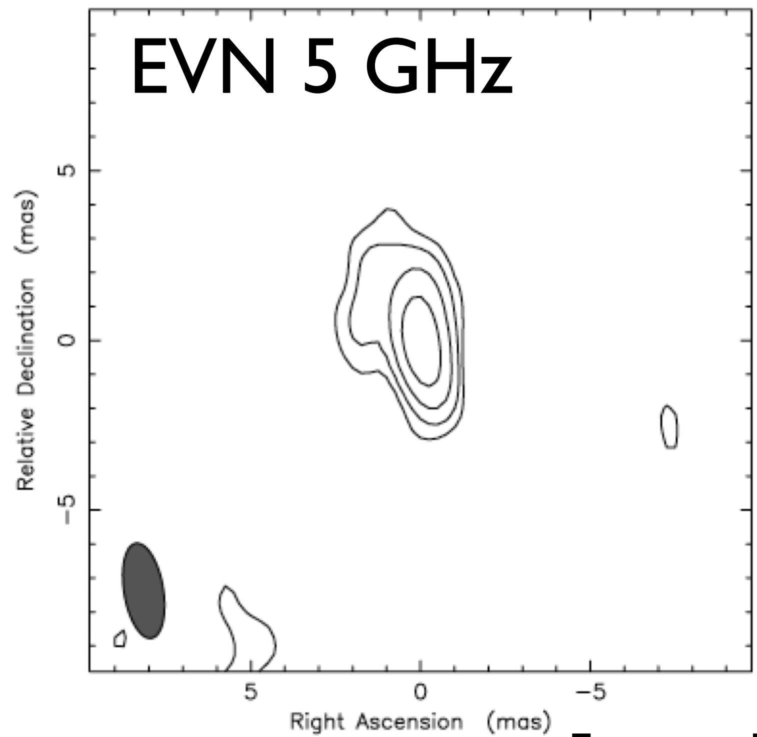

Cao et al. 2014

- $z$=5.81
- Peak: 333 μJy/beam
- A few mas size → $T_b \sim 10^6$ K

- $z$=5.95
- Peak: 267 μJy/beam
- A few mas size → $T_b > 10^8$ K

# VLBI: RLQ at z~6



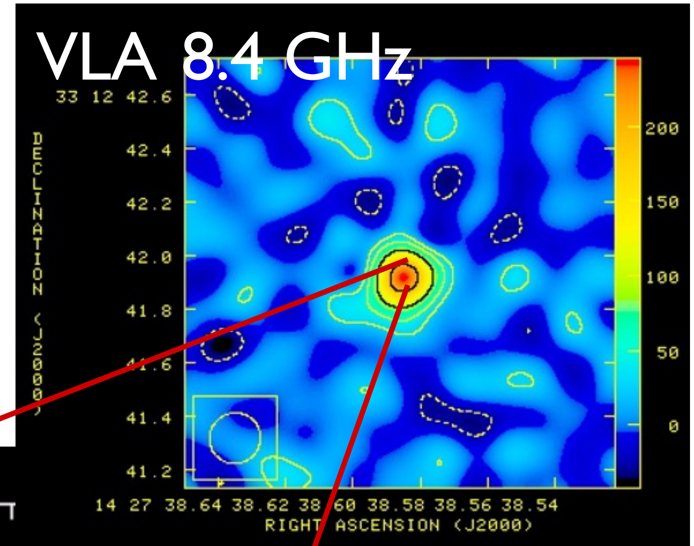



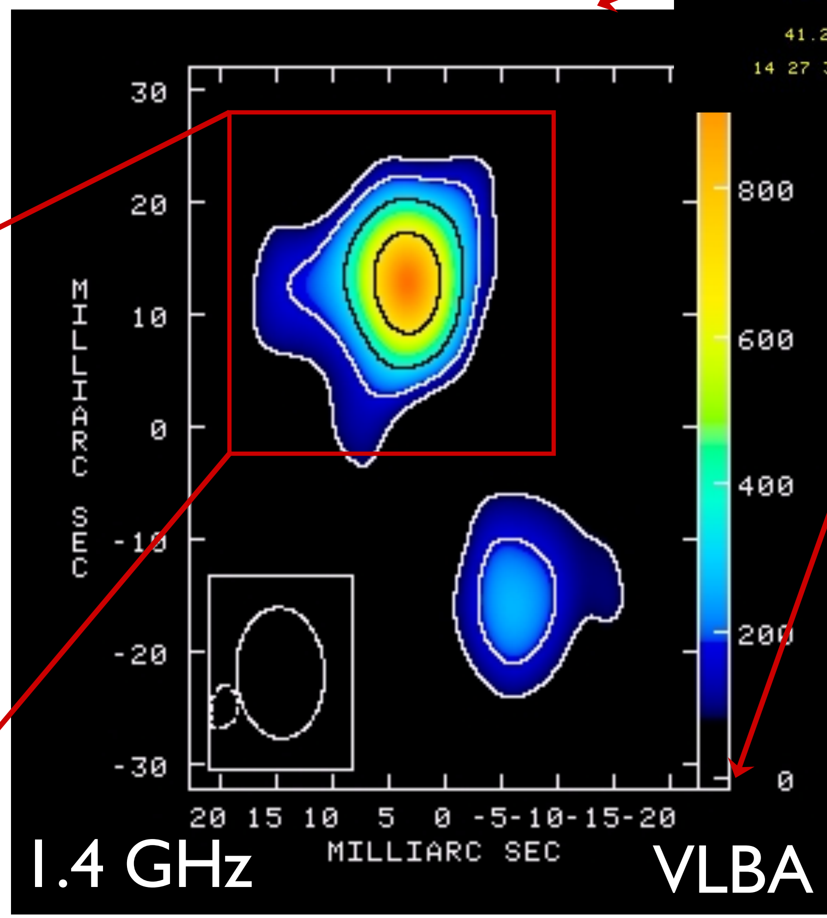

Frey et al. 2011

- $z$=6.18
- Peak: 2.3 mJy/b at 1.6 GHz, 0.67 mJy/b at 5 GHz.
- A few mas size => $T_b > 10^9$ K
- The entire emission region is confined to within 10 pc at 5 GHz

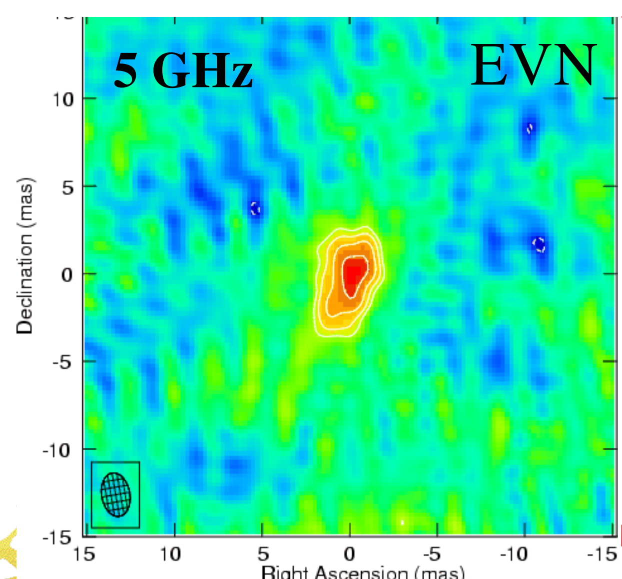
# The z=6.12 QSO J1424+3312

- $T_b \sim 10^7$ to $10^8$ K.
- The flux density ratio is ~3:1, separated by 31 mas; 174 pc.
- $\alpha(5-1.4) = -0.67$




Momjian et al. 2008




Frey et al. 2008

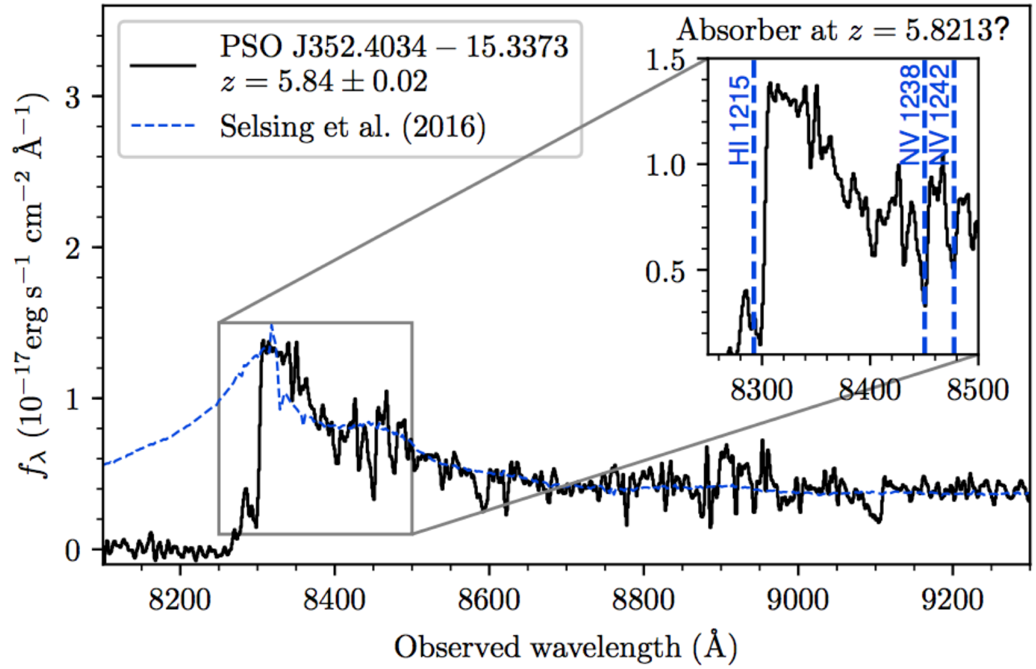
# Powerful RLQs near z~6?

- There seems to have been a lack of powerful radio quasars at $z > 5.5$
  - $S_{1.4} > 10$ mJy ($L_{\nu,1.4GHz} > 10^{27}$ W/Hz)
- This changed in September 2017 with the discovery of

PSO J352.4034–15.3373 (**P352-15)**

# The Discovery of P352-15

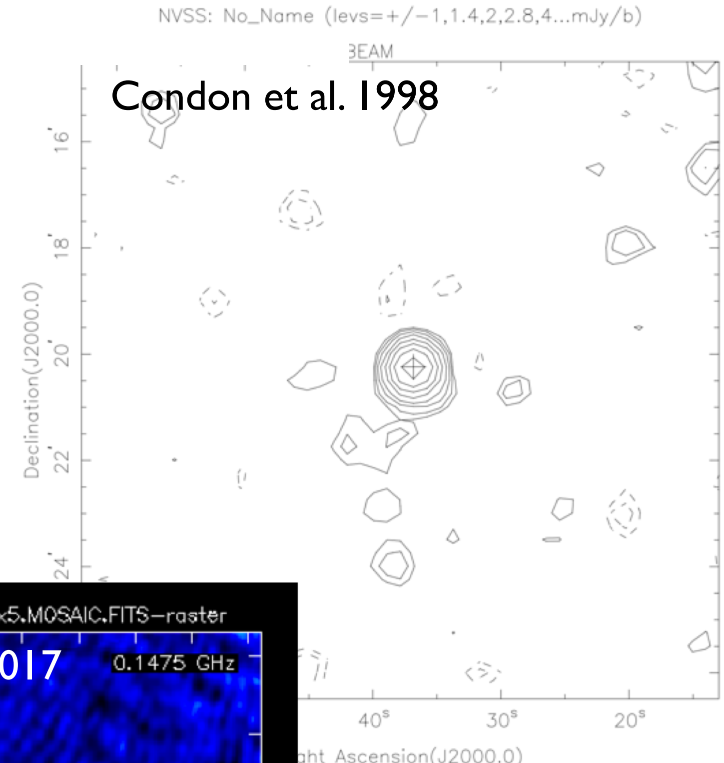
- z ~ 6 quasar candidate from PanSTARRS1
- Confirmed as a quasar on Sep. 26, 2017, using Magellan Clay telescope in Las Campanas Observatory.
- z = 5.84 ± 0.02
- Also, a tentative detection of an associated absorber at *z*=5.8213 (dense local environment, or outflow)

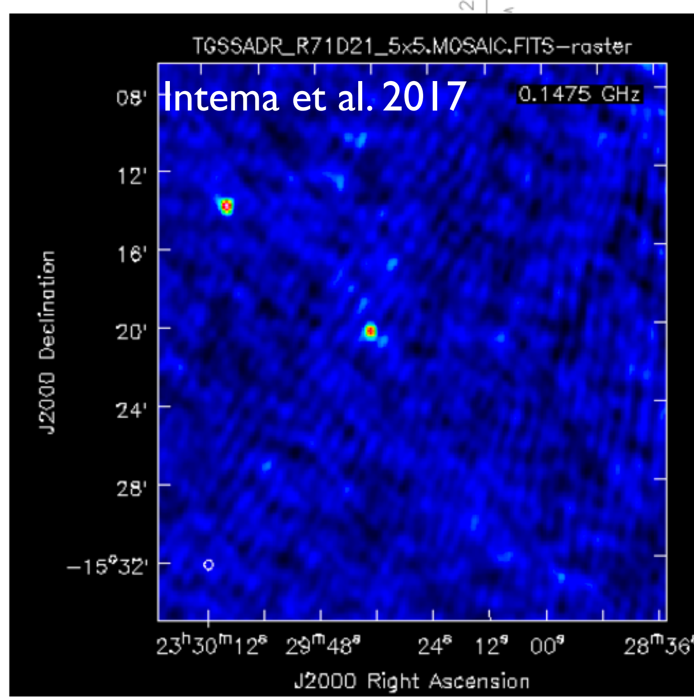



Bañados et al. 2018

# Matching with Existing Radio Surveys

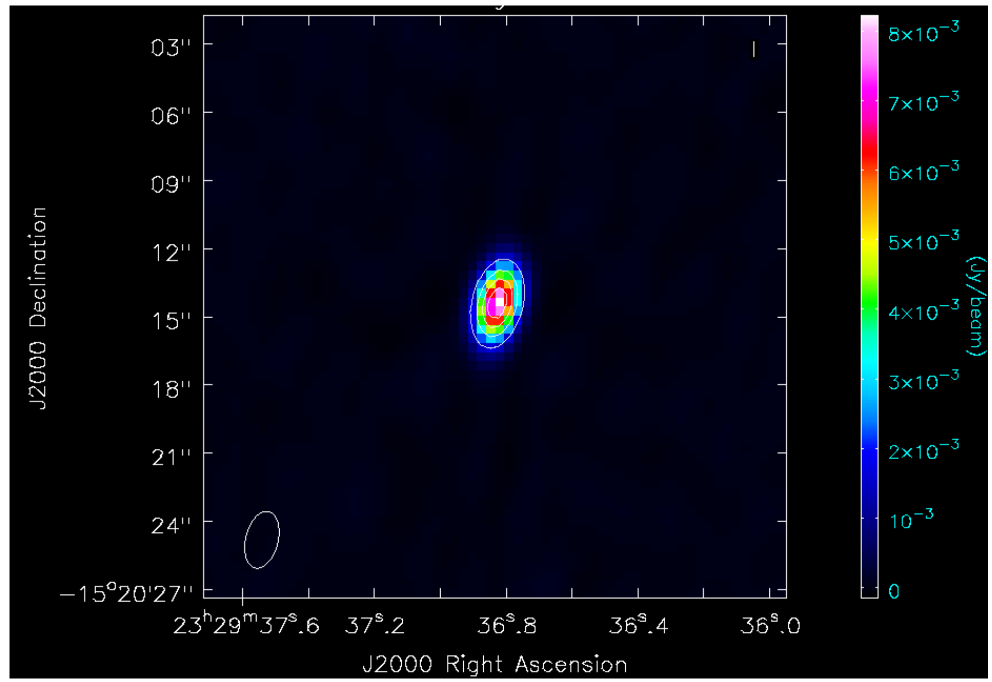
- NVSS (1.4 GHz)
  14.9 ± 0.7 mJy
- GLEAM WIDE (200 MHz)
  87.8 ± 6.9 mJy
- TGSS peak (150 MHz)
  110.6 ± 13.8 mJy
- TGSS total (150 MHz)
  163.1 ± 20.7



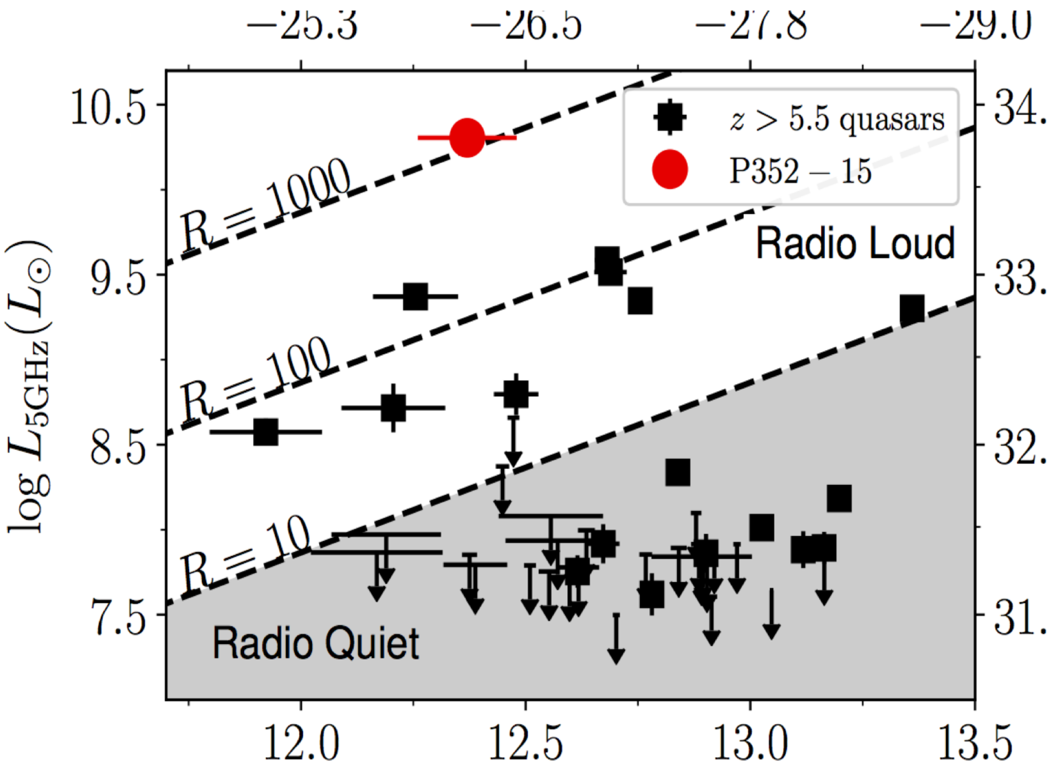
# VLA High Angular Resolution Follow-up: The Confirmation

- B-configuration
- S-band (2-4 GHz)
- Jan. 13, 2018 (B-config)
- Resolution: 2.6” x 1.4”
- Unresolved (≤ 0.5”)
- $S_{3GHz}$= 8.2 ± 0.25

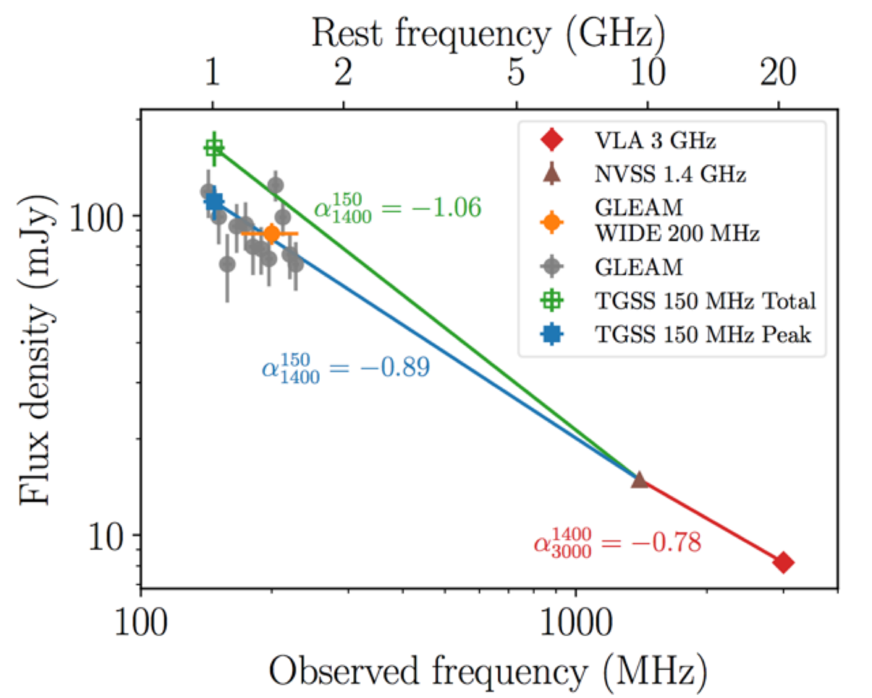



Bañados et al. 2018

# Radio Loudness and SED



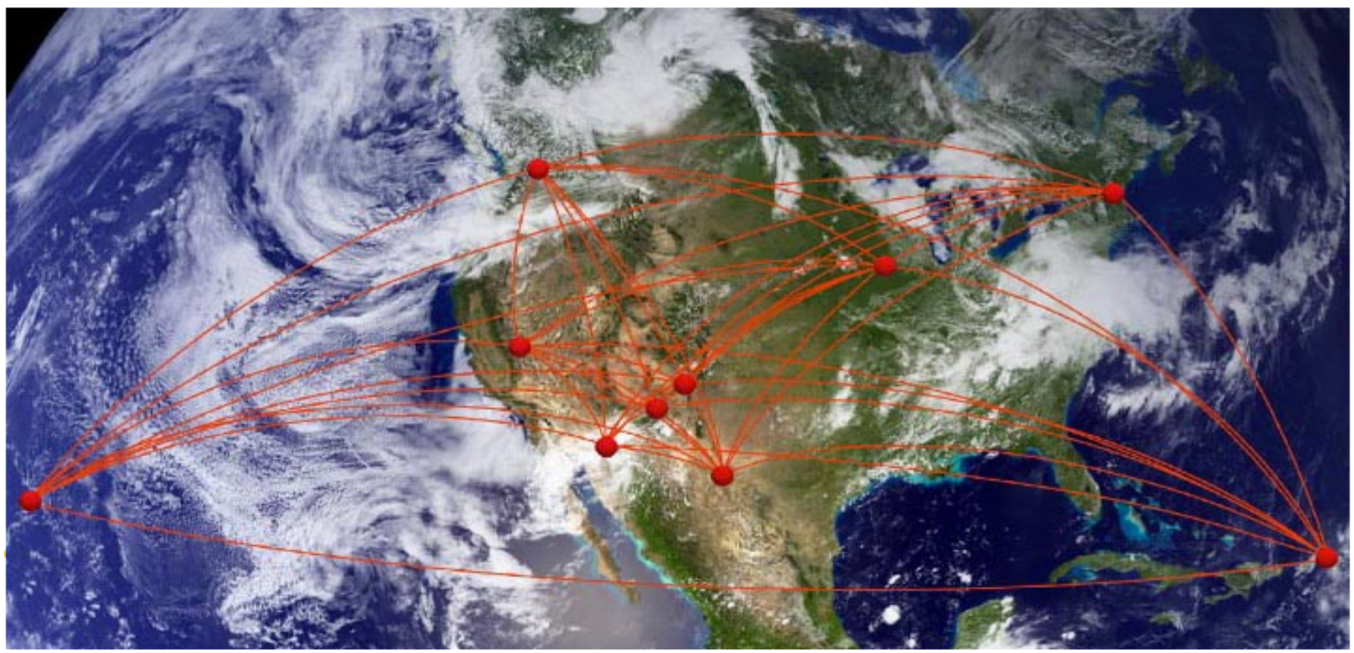

Bañados et al. 2018



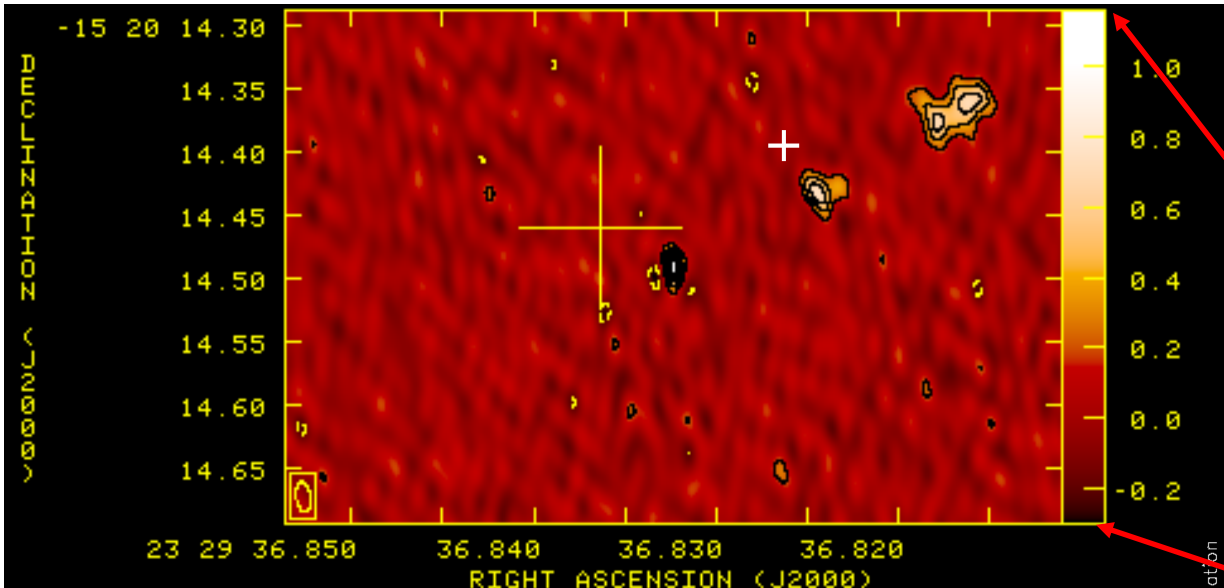

- R $\gtrsim$ 1000; one order of magnitude more radio loud than any other source at *z* > 5.5
- $L_{\nu,1.4}$= 4.5 – 6.3 x $10^{27}$ W/Hz: the most powerful radio source at *z*~6

# VLBA Follow-up

- January 23, 2018
- L-band (1.5 GHz)
- Dual pol, 256 MHz bandwidth (2 Gbps recording)
- Time: 2 hrs
- Phase referenced (calibrator 0.7 degrees away)

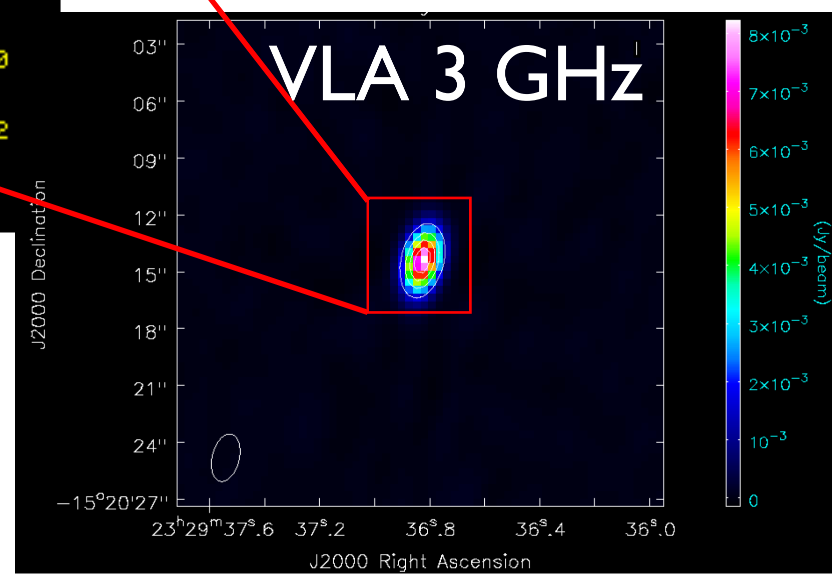


# Resolving the Radio Emission




Momjian et al. 2018

Bañados et al. 2018




- Beam size 23.9 x 11.3 mas (139 x 66 pc at z=5.84)
- RMS noise 67 μJy/beam

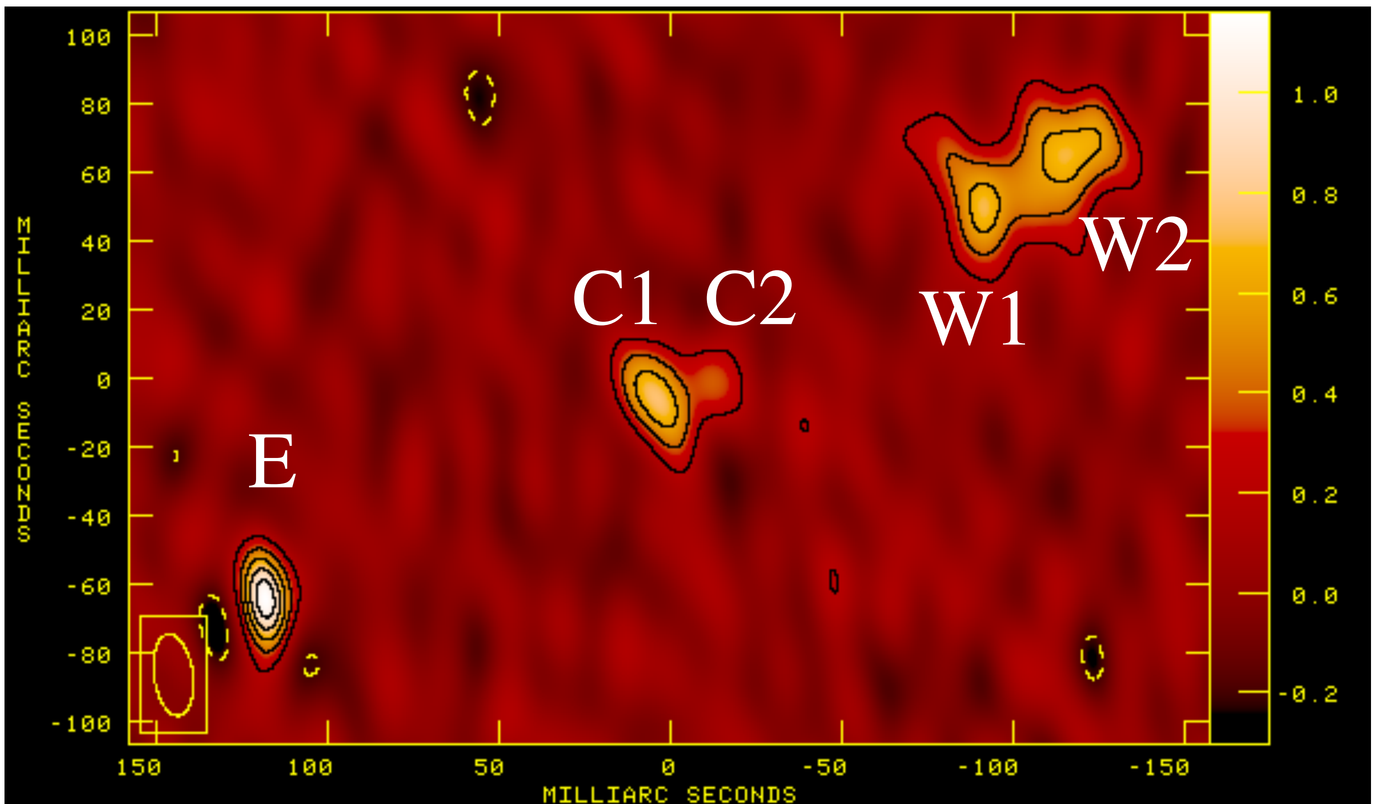
# VLBA Results

- Three distinct emission regions.
- Total extent: 1.62 kpc (0.28")
- Total flux density: 6.57 ± 0.38 mJy; ~50 % recovered.
- $T_b$: 1x $10^7$ to > 13 x$10^7$ K

E ~ 1.2 mJy

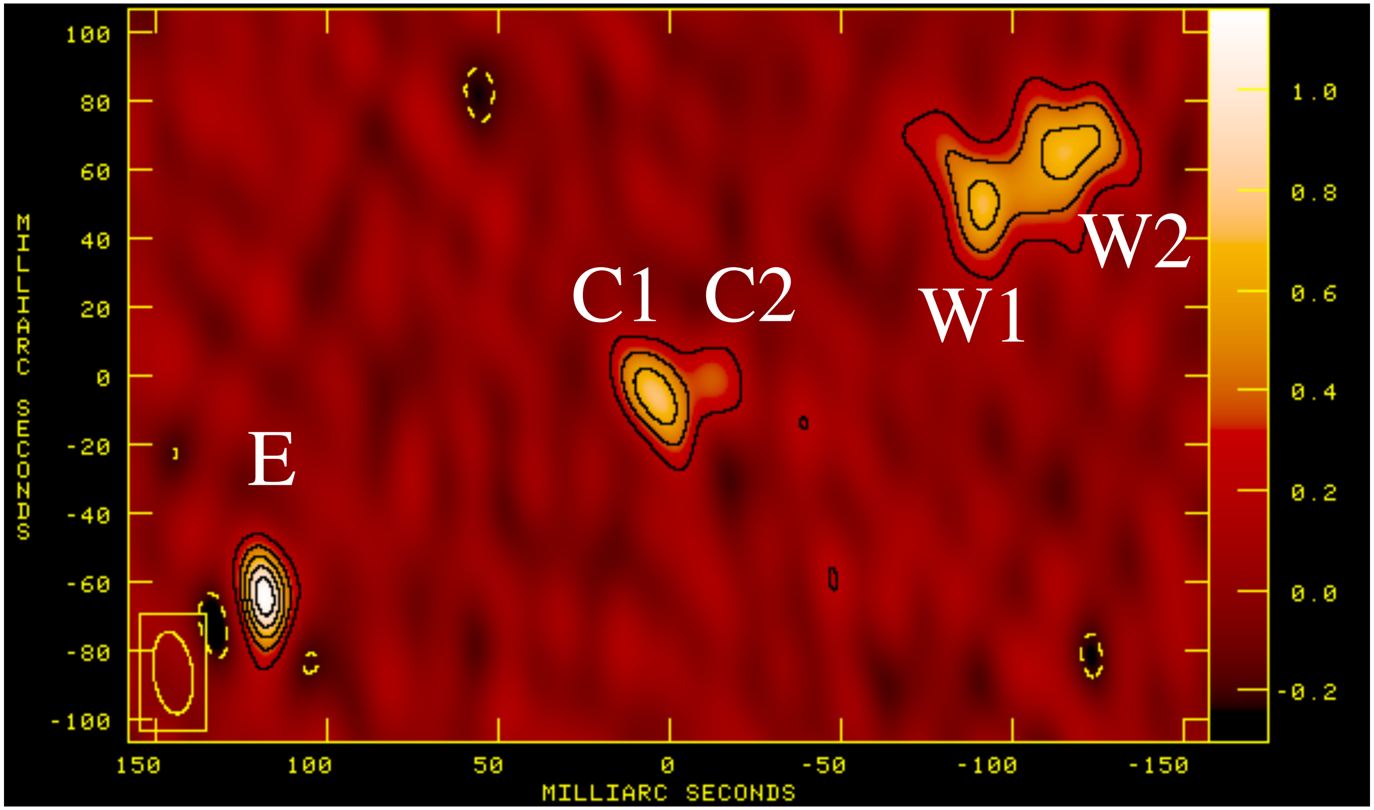
C1+C2 ~ 1.5 mJy

W1+W2 ~ 3.9 mJy



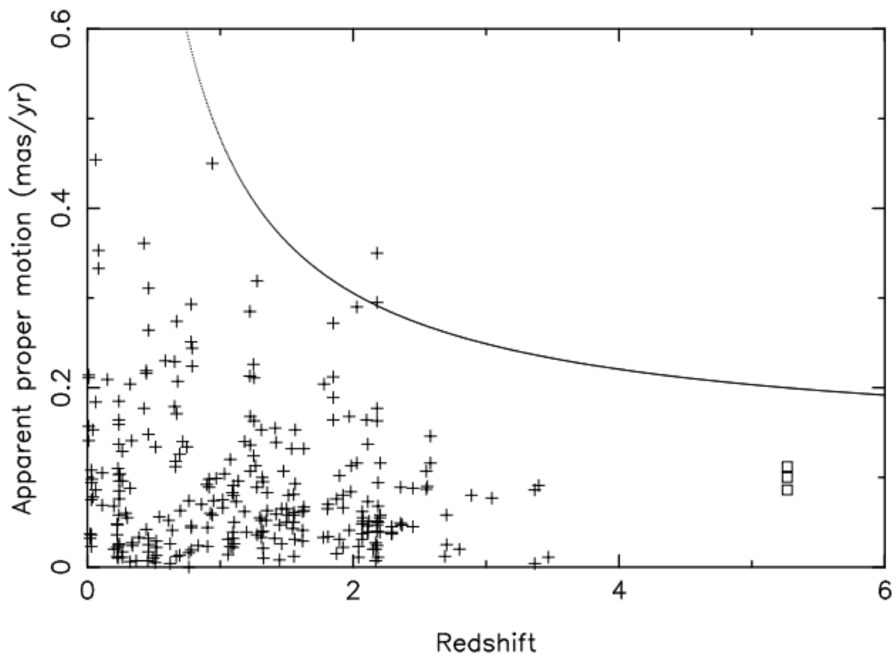
# Two Scenarios

- Two possible interpretations with the existing data:
  1. A core with a one sided jet
  2. A classic but compact FRII source
- Need multi-frequency VLBI data to identify a core



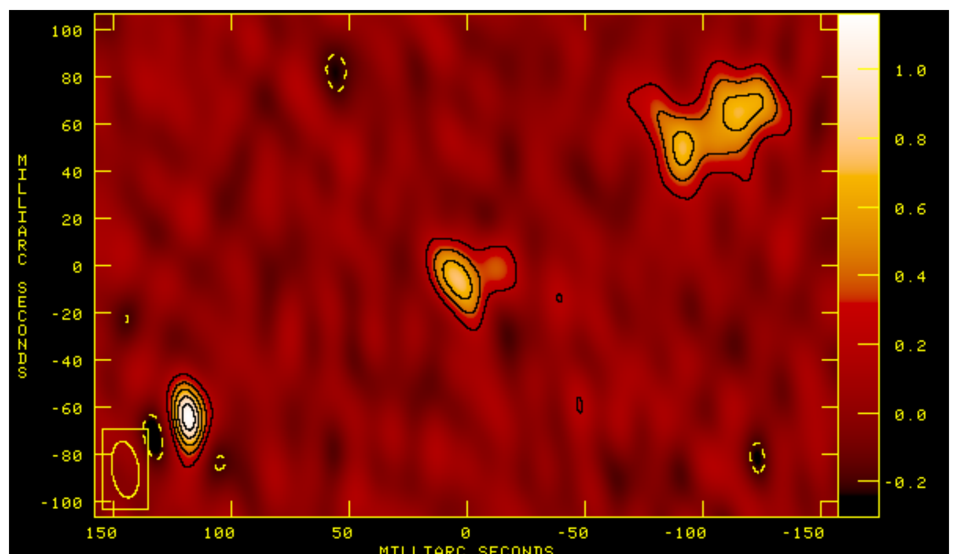
# A Core with a One-sided Jet

- E is the core, C and W are part of the jet structure.



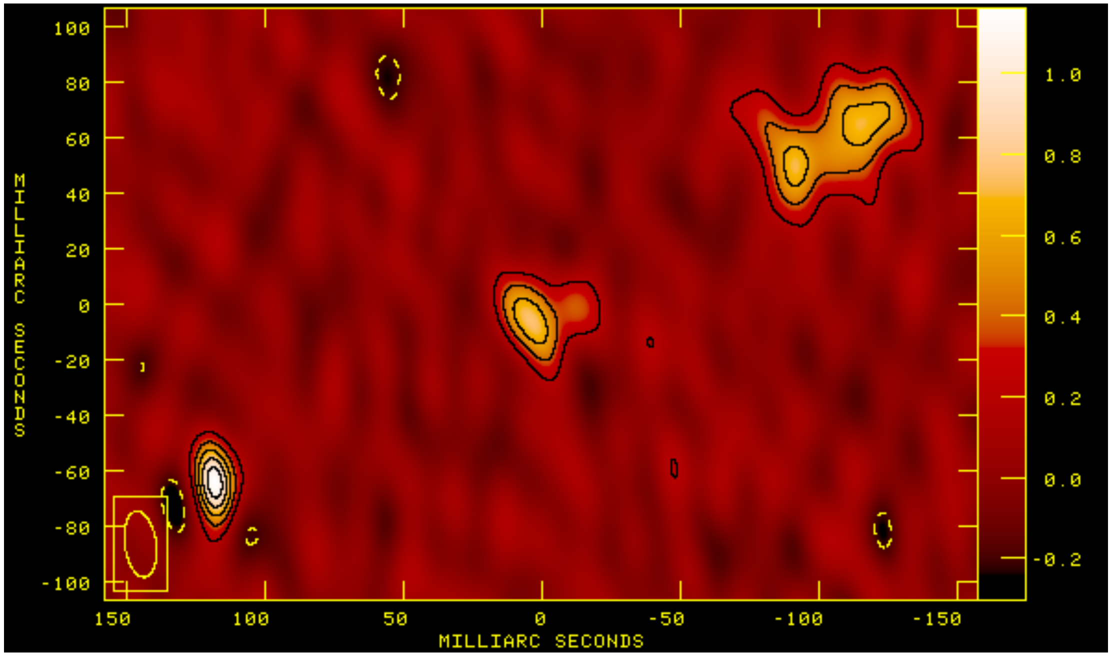

Frey et al. 2015

$\mu_{max} \sim 0.2$ mas/yr



# A Compact FR II Source

- The core is in C, and E and W are the lobes/hotspots.
- A CSO/MSO
- Assuming a typical advance speed of 0.2*c* for CSOs
  - Age of source: $10^4$ years
  - Separation between hotspots ~ 20 μas/yr



# Open Questions and Future Observations

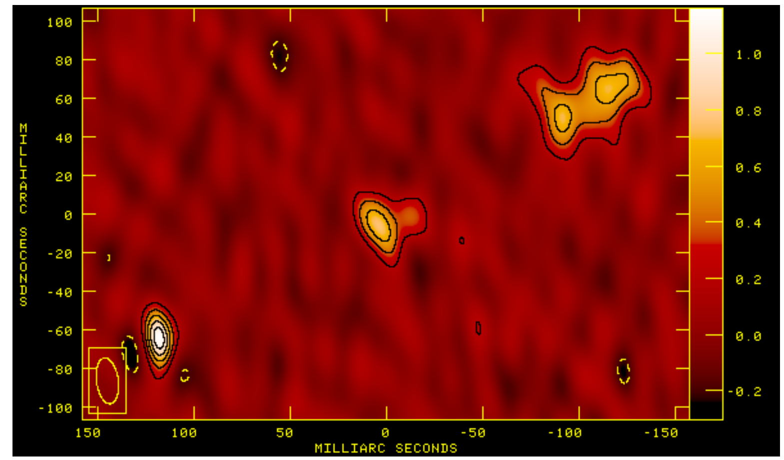
- Is it a core+jet or a CSO/MSO?
  - VLBA multi frequency observations
- Associated HI absorption if CSO/MSO
  - GMRT (DDT time approved, also assess the system)
- Probe the neutral IGM in HI absorption (21cm forest)
  - ~10% neutral fraction at z~6 (Greig and Mesinger 2017)
  - GMRT: ~100 hr needed (1% optical depth, 10 km/s)

# Open Questions and Future Observations

- X-ray properties
  - Chandra
- Estimate the mass of the SMBH, accretion rate, confirm the associated absorber (may indicate dense environment or strong outflow)
  - Gemini
- Dust and [CII] emission; search for (anti-) correlation between radio and mm dust emission.
  - ALMA

# Summary

- Recently discovered the radio-loudest quasar at z~6.
- A resolved radio source with a 1.62 kpc linear extent.
- May be
  - Core with one-sided jet
    - measure the proper motion
  - CSO/MSO → age of source ~ $10^4$ yr




- Multiple follow-up observations planned
  - From X-ray, to searching for redshifted HI
- The new discoveries of quasars at z $\gtrsim$ 6 and follow-up studies (including VLBI) are key to understand and constraint the feedback processes in the earliest galaxies.