Feedback in radio-quiet quasars

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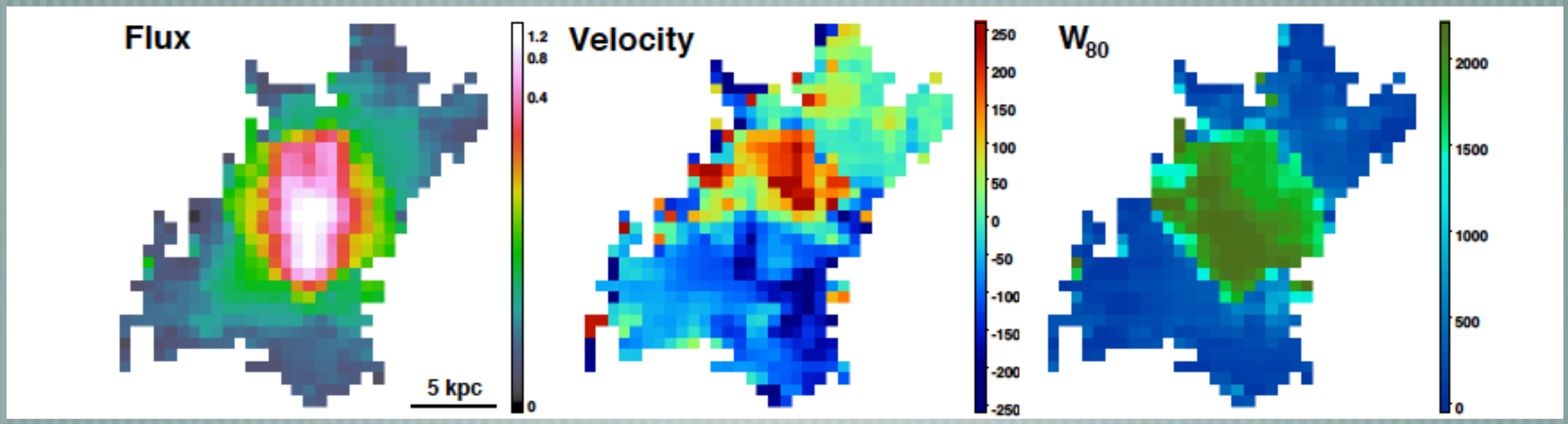
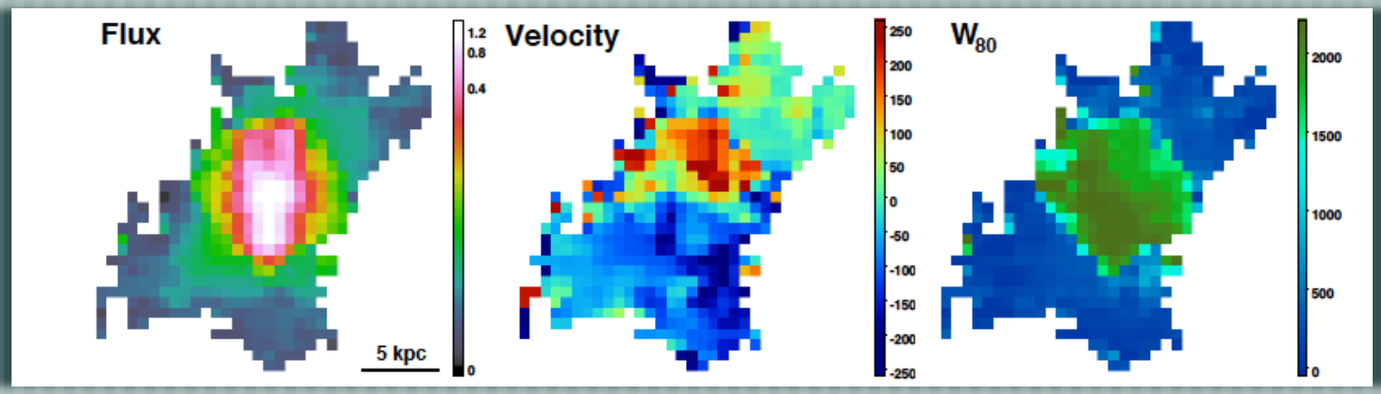


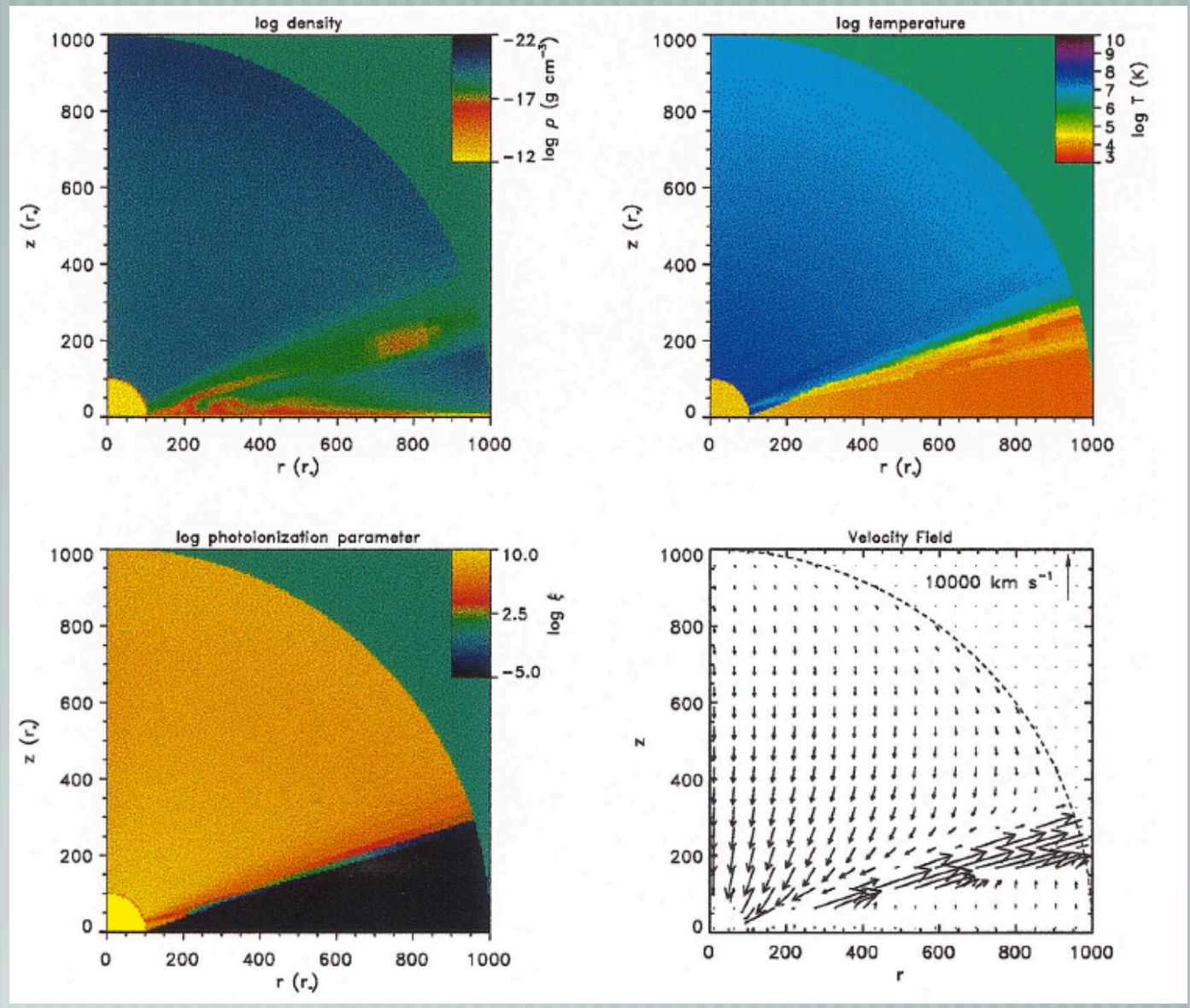
Overview



- From galaxy formation: Quasar feedback likely necessary for limiting maximal mass of galaxies, reheating intracluster medium
- Mechanism, energetics
- Strong observational evidence for radiatively-driven quasar winds on galaxy-wide scales
- Strong observational evidence for jet-driven feedback
- Which mechanism is more important in which situation?
- On the nature of the radio emission in radio-quiet quasars

1. Mechanism and energetics

- Energy is available! 1 g of matter accreted = radiation = enough energy to throw out 5 kg of matter
- Needs to be coupled to the gas
- Radiatively driven winds ("line-driving")
- Jet-driven winds (bow-shock + cocoon)
- Bomb in galaxy center



Proga et al 2000
Murray et al. 1995

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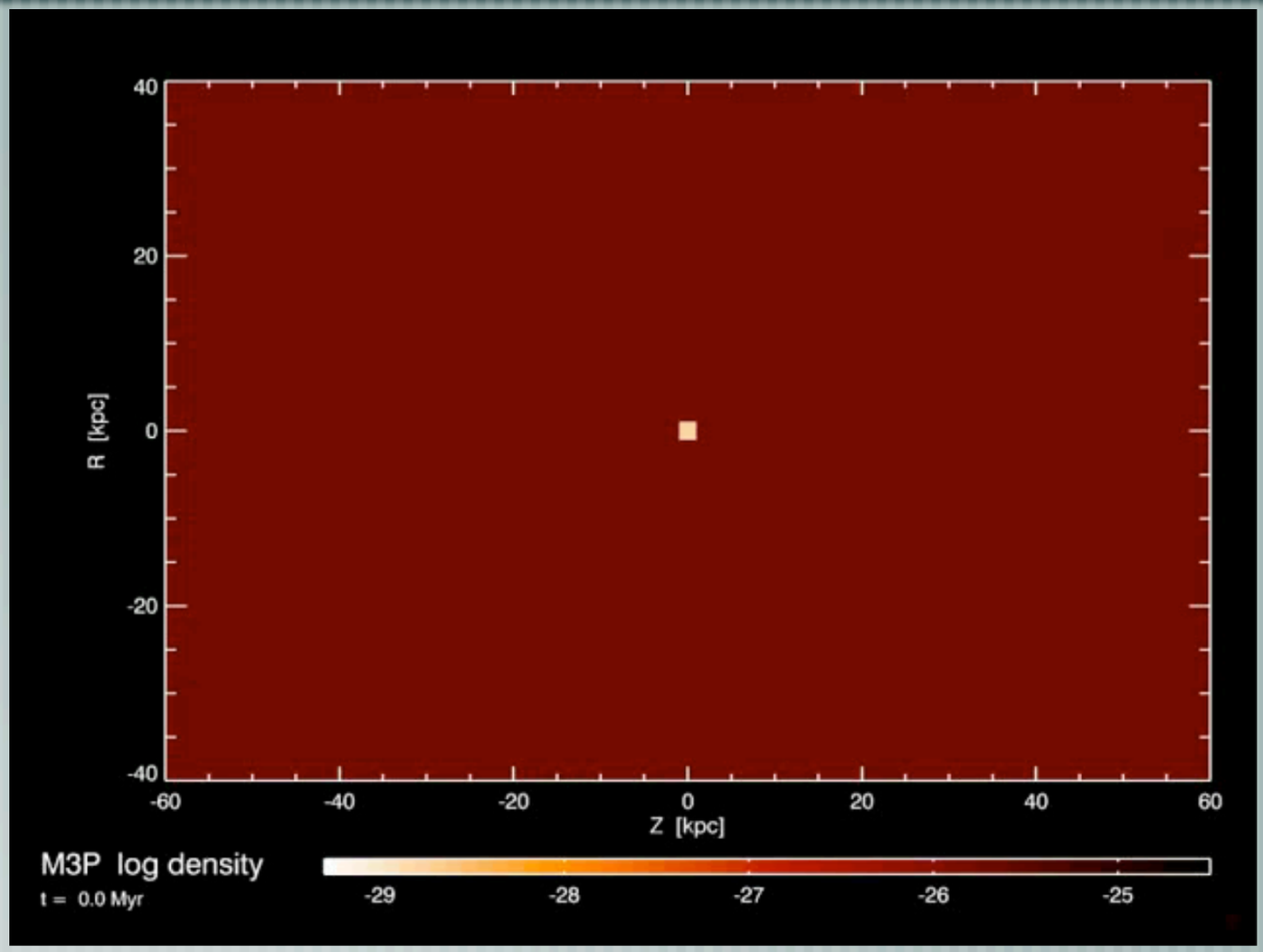
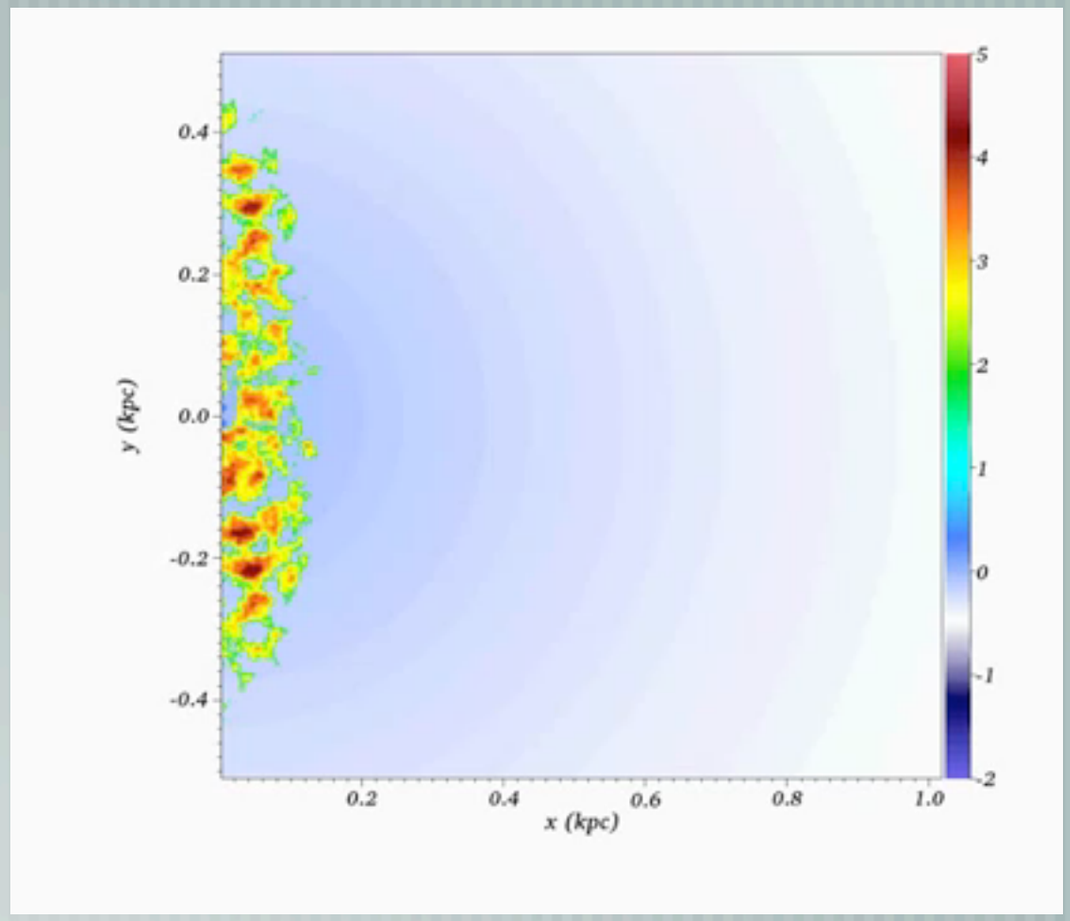


V.Gaibler et al.

1. Mechanism and energetics

- Initial high velocity wind slams into clumpy ISM
- Carves channels through clouds, propagates along paths of least resistance
- Clouds accelerated, destroyed, recreated
- Multi-phase wind
- For galaxy formation: typically 1-5% of L_{bol} needs to be converted to L_{wind} in simulations



Wagner et al. 2013

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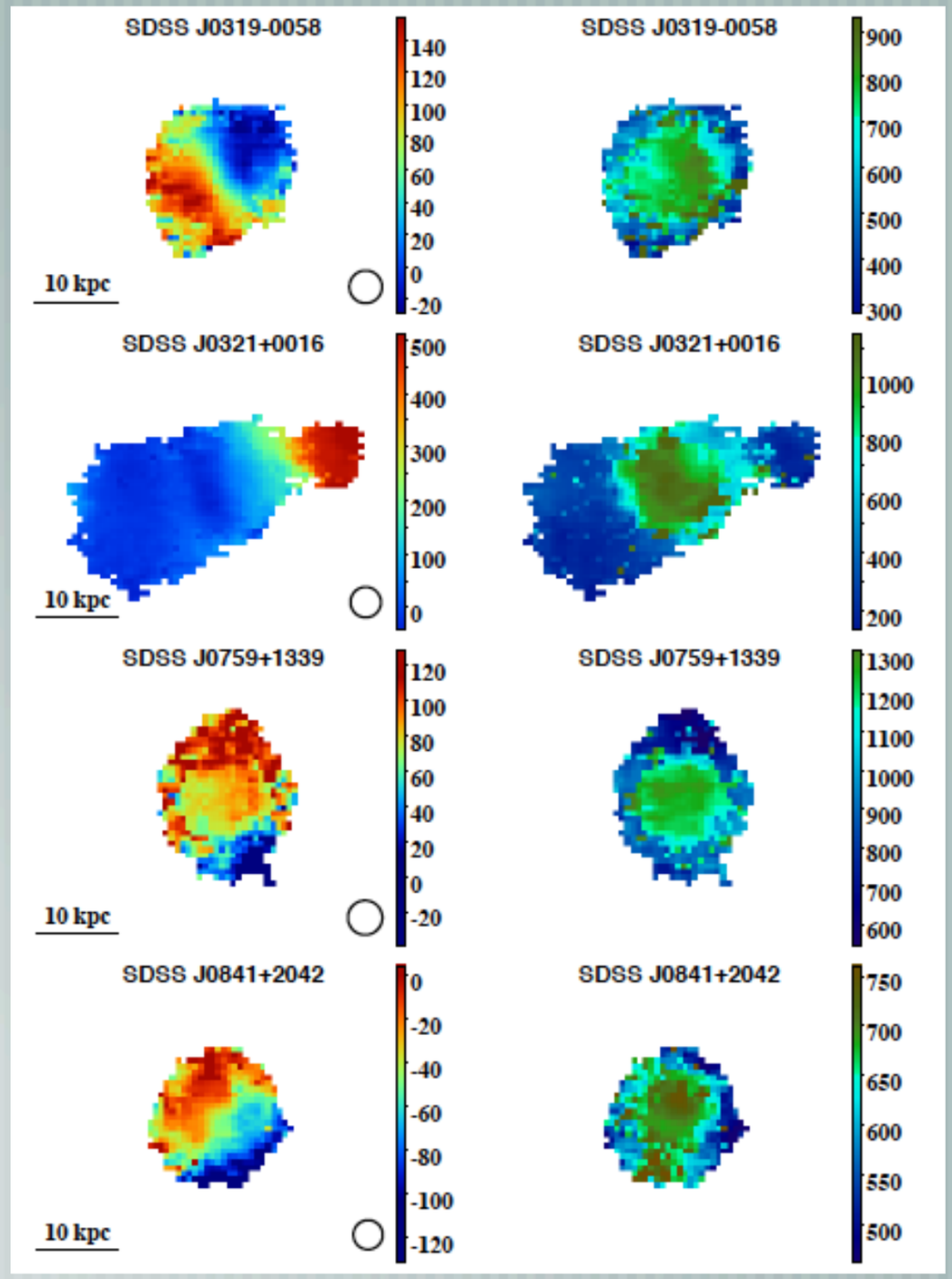
Springel, Hopkins, DiMatteo, Cox, Hernquist et al.

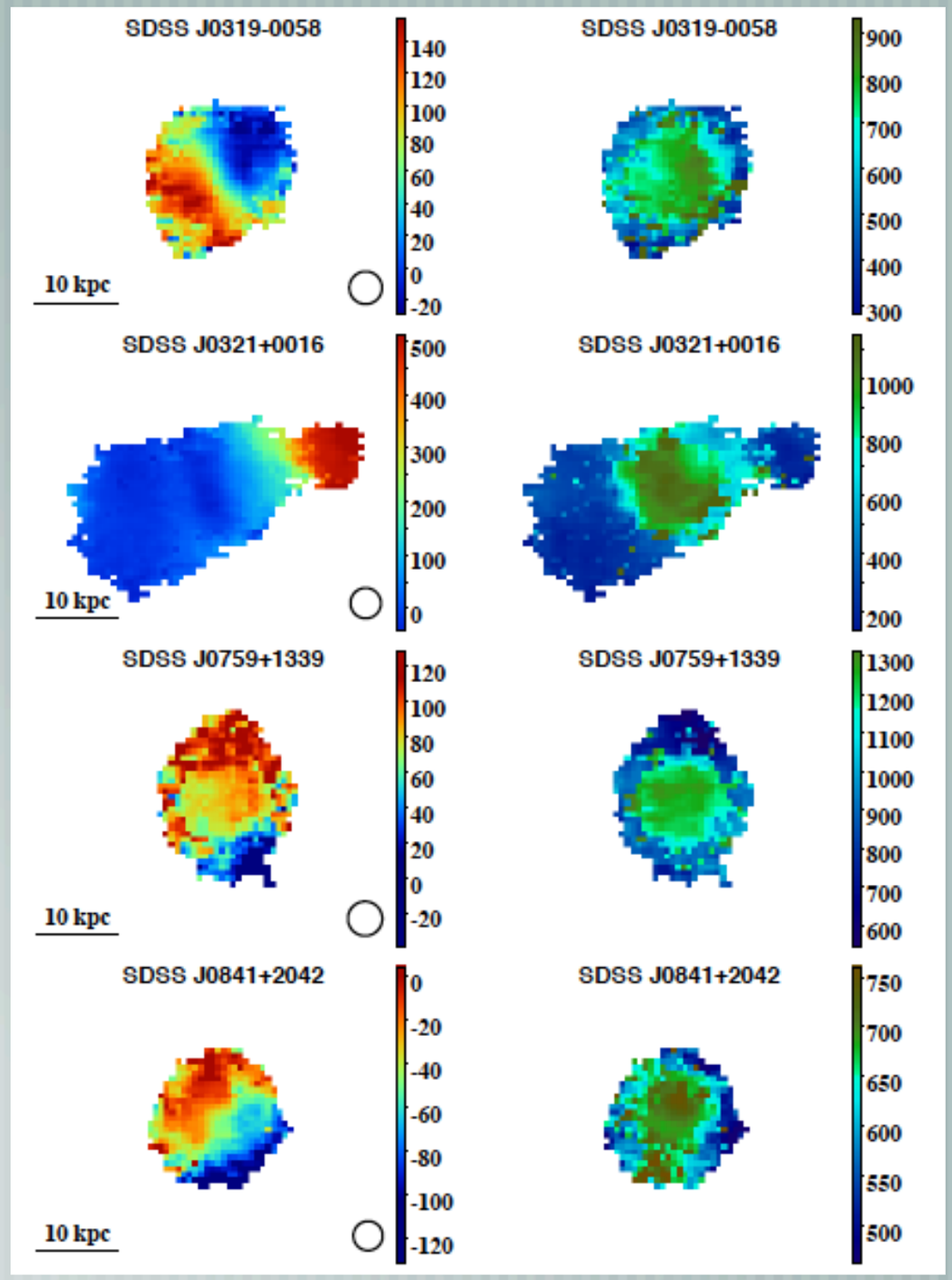
2. Feedback in radio-quiet quasars: ionized gas

- Radio-quiet quasars z=0.5
- Integral field spectroscopy: obtain a spectrum at every point in field of view
- Emission lines ⇒ Doppler effect ⇒ Kinematics of gas in 2D
- Guilin Liu & NZ et al. 2013a, 2013b, 2014a, 2014b in prep.
- Gemini telescope (obtained through NOAO)



2. Feedback in radio-quiet quasars: ionized gas

- Key observations: the entire galaxy is affected
- Line-of-sight velocity ⇒ one side approaching, one side receding.
- Line-of-sight velocity dispersion ⇒ typical outflow velocity=800 km/sec
- Likely will escape from the galaxy
- Line asymmetries characteristic of outflows



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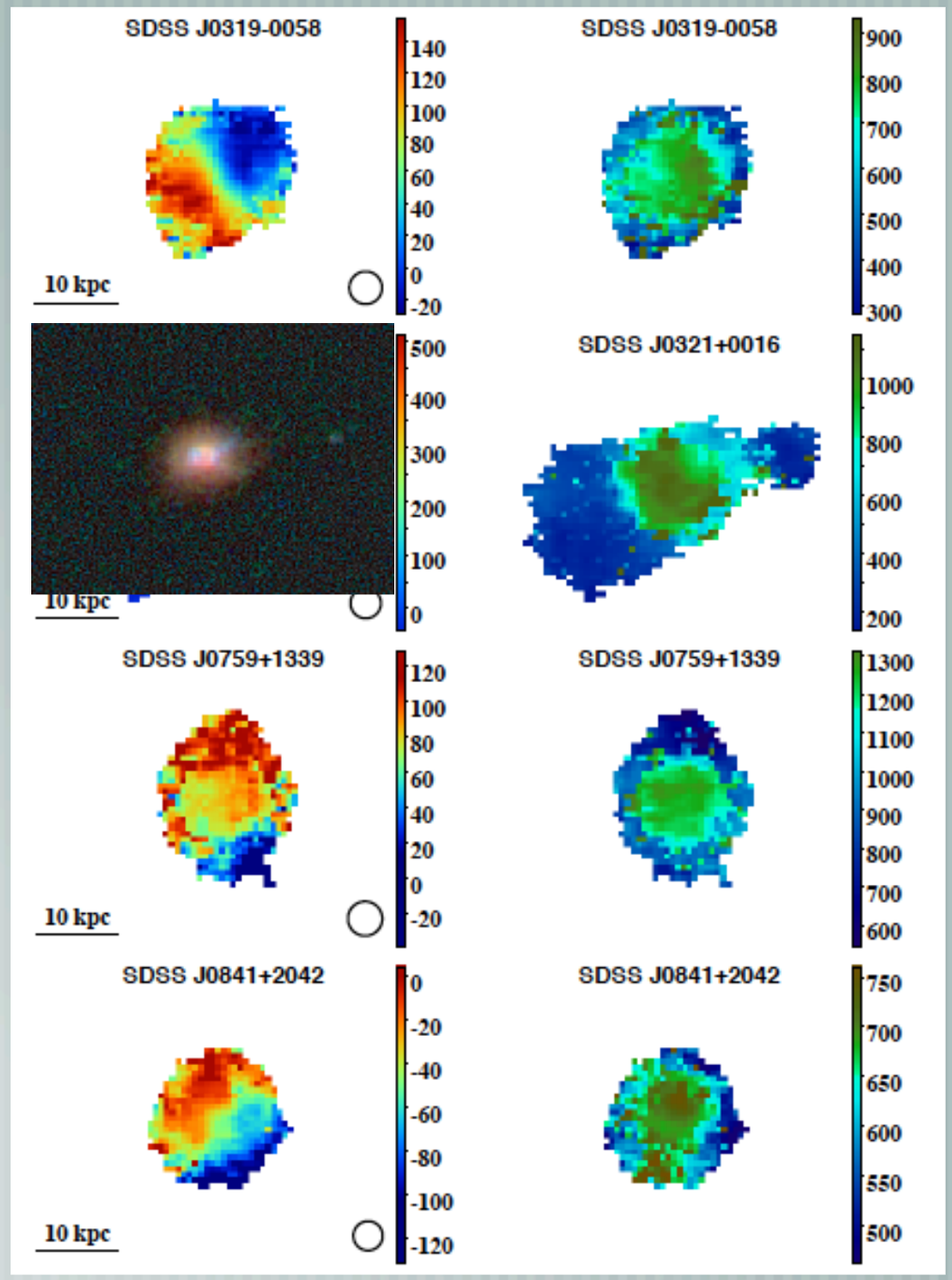

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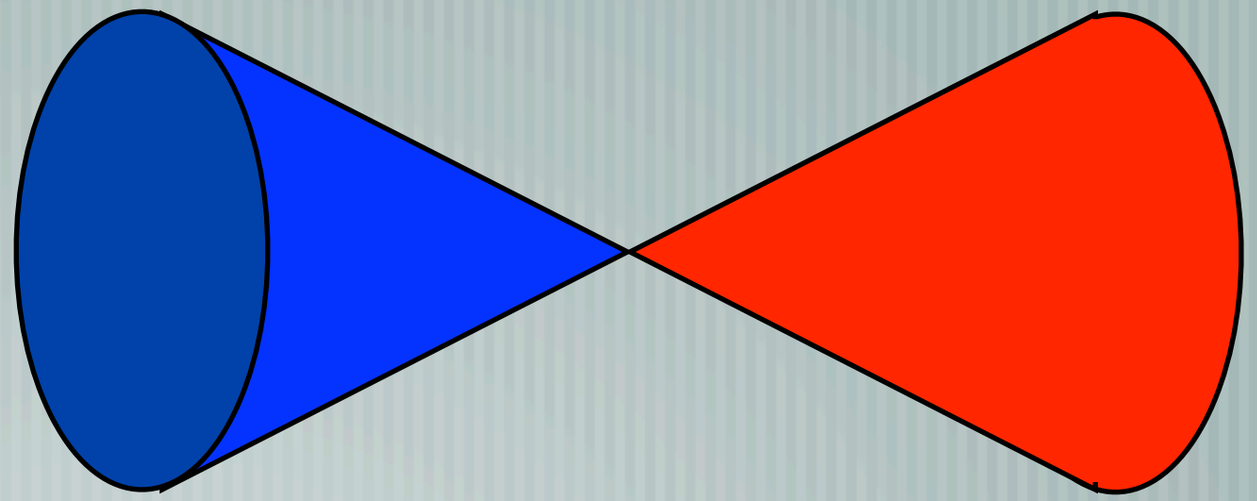

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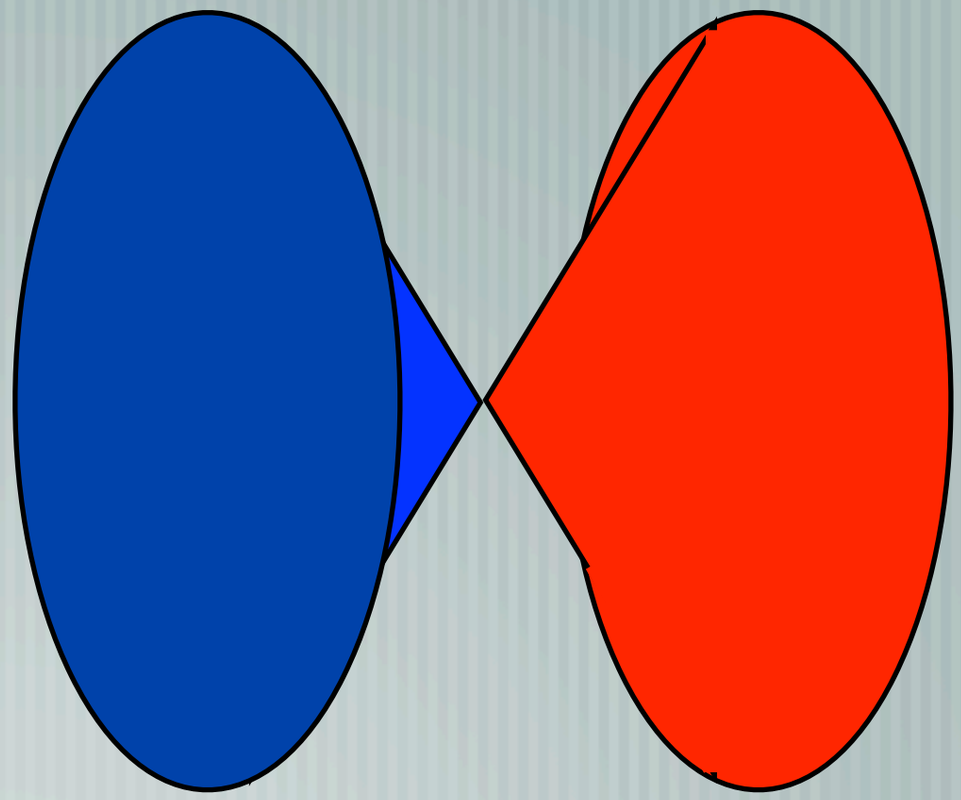

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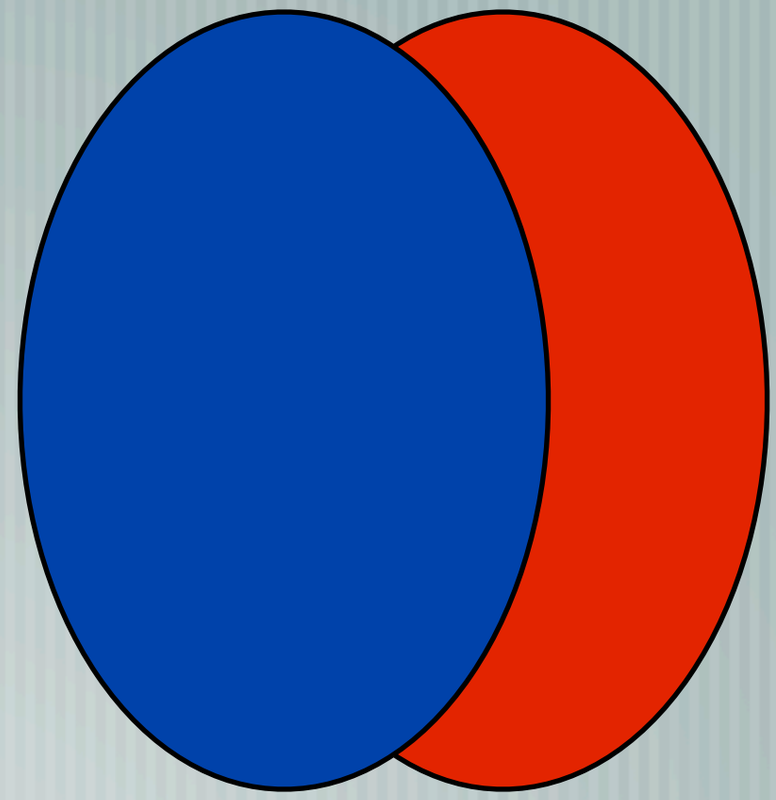

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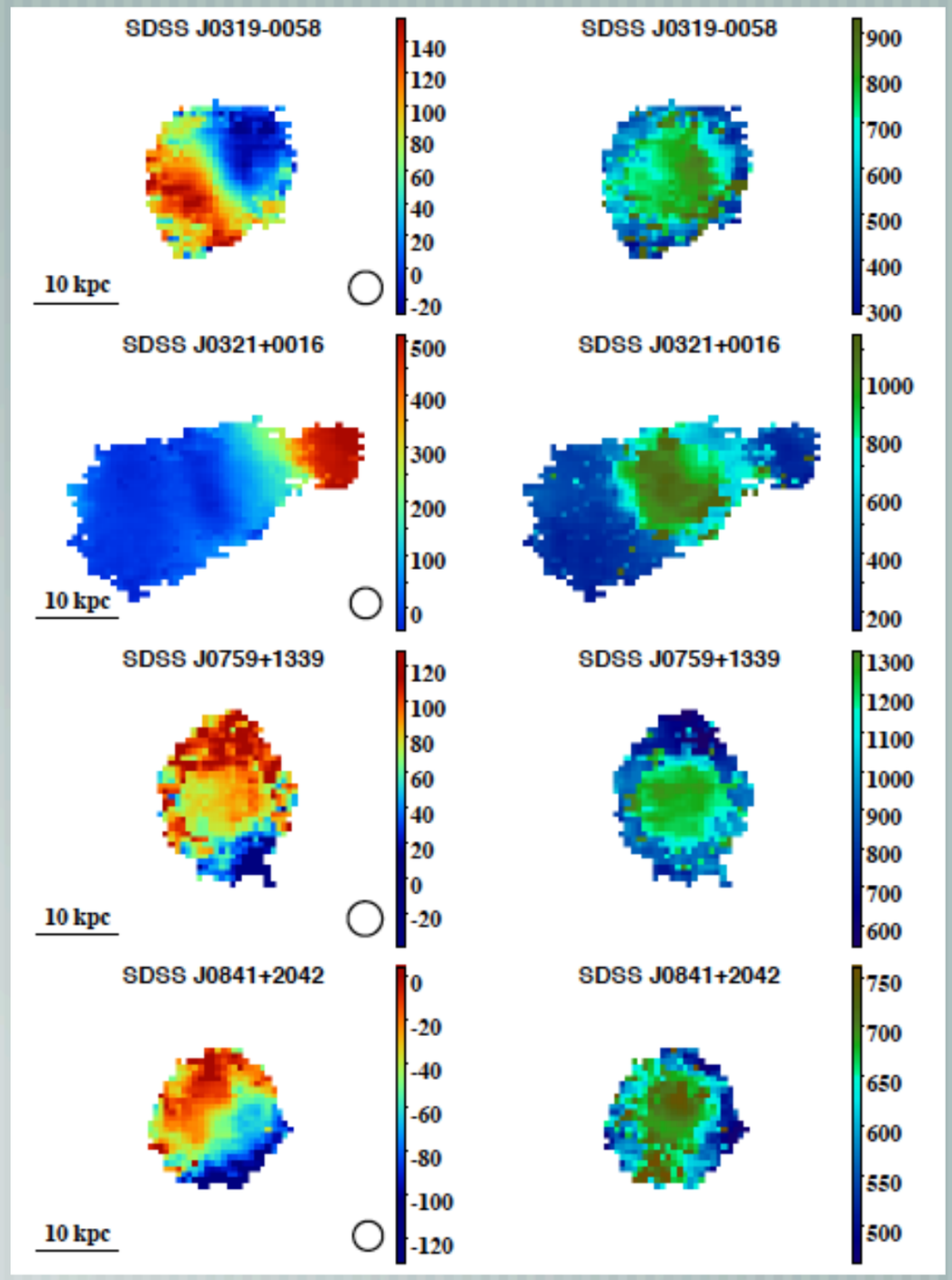
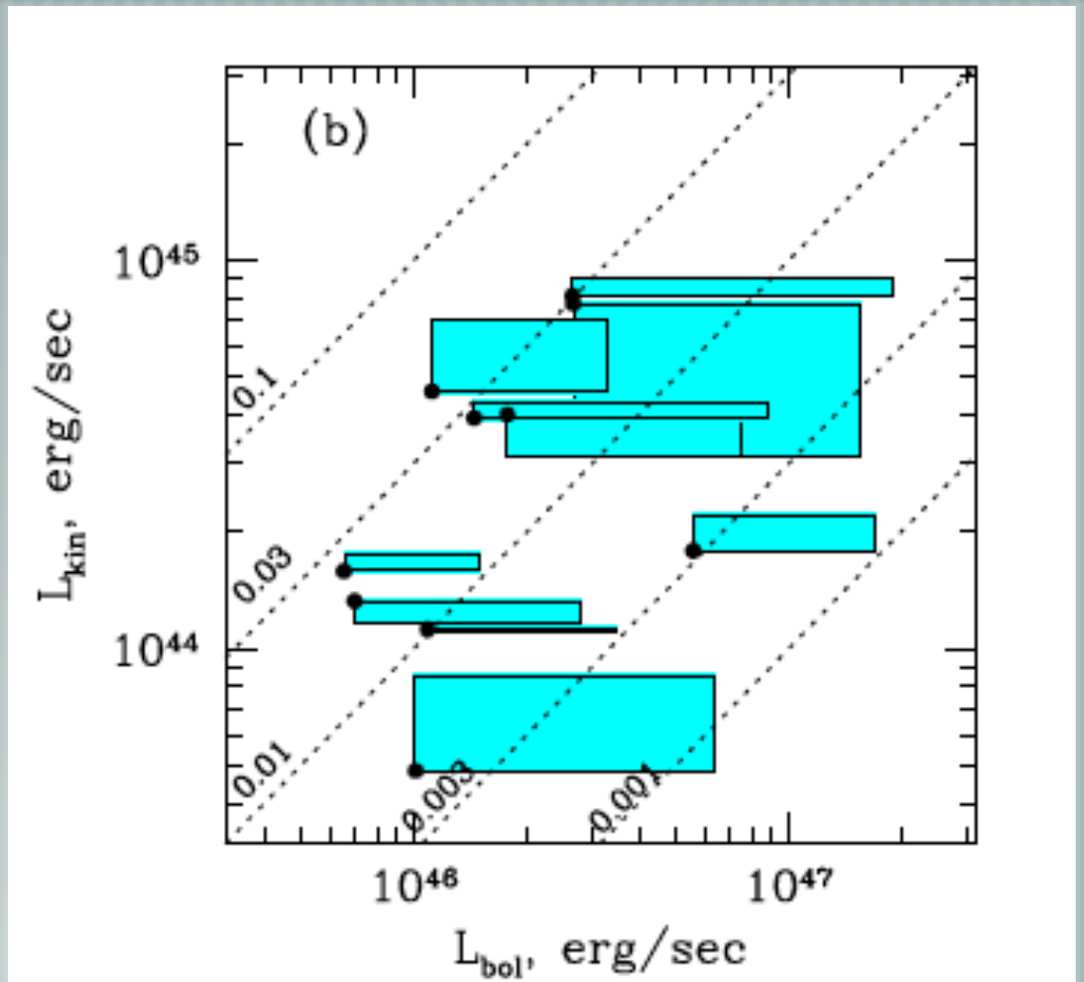


2. Feedback in radio-quiet quasars: ionized gas

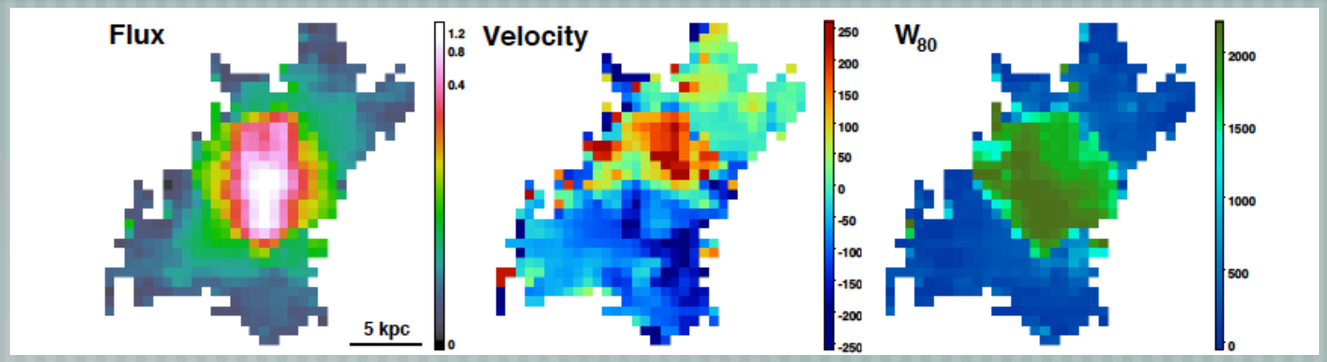
- Getting mass, energy estimates is very difficult
- Small dense clouds produce emission lines
- Much of the wind is invisible in these observations, density / mass uncertain
- Methods to estimate the energetics of the process
- Find 2% efficiency for conversion from luminosity to wind.



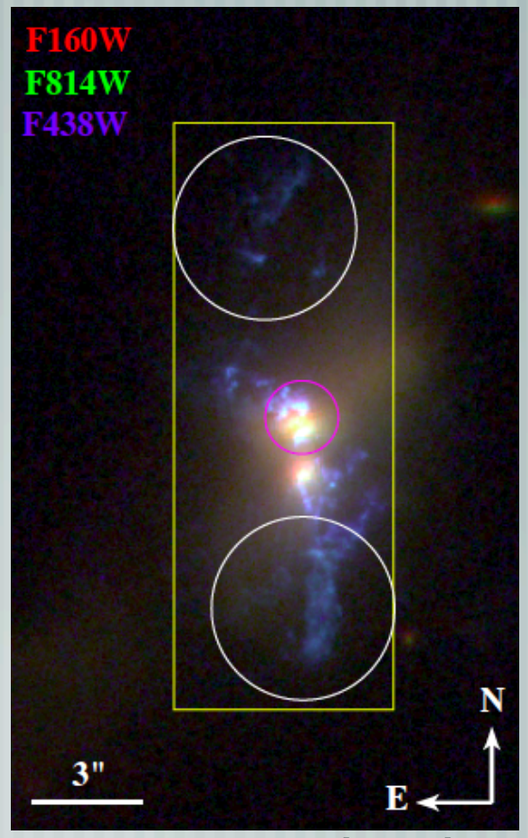
Liu, NZ, et al. 2013b

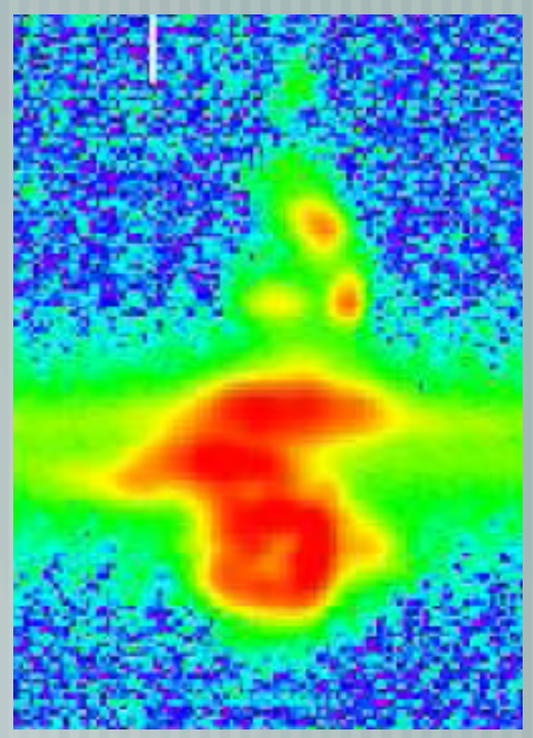
2. Feedback in radio-quiet quasars: super-bubbles

- Winds look for the path of least resistance
- In disk galaxies, expect them to "break out" perpendicular to galaxy plane
- Have several candidates
- Energy estimates using completely different method: also a few % (still large uncertainty)



Liu, Zakamska, et al. 2013b

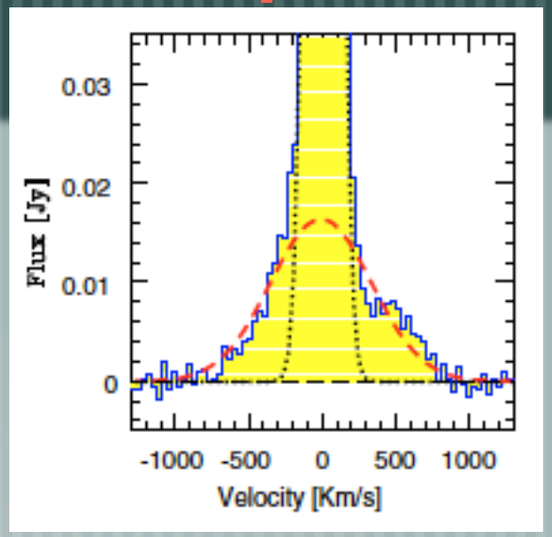




Greene, Zakamska, Smith 2012,
Greene, Pooley, Zakamska, et al. 2014

2. Feedback in radio-quiet quasars: multi-phase

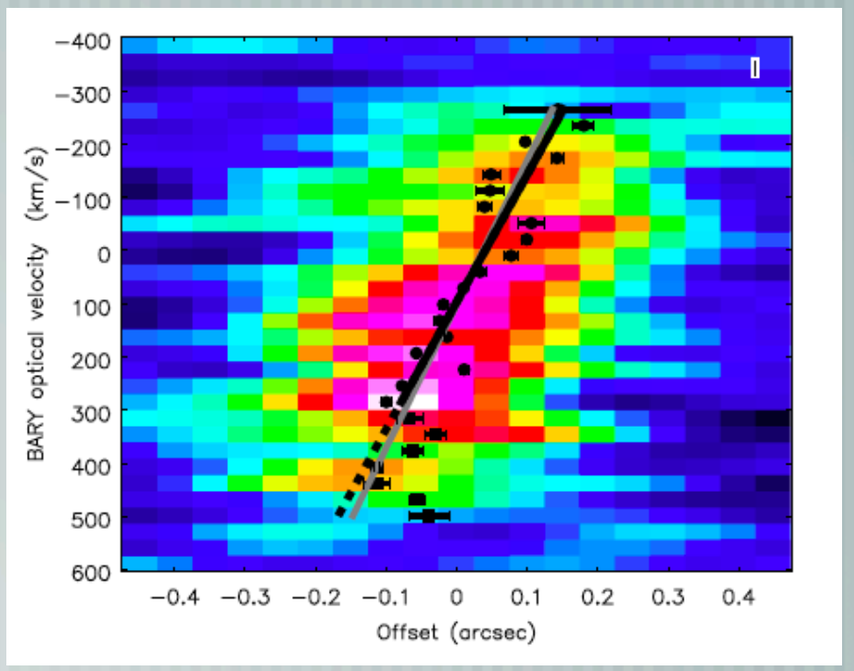
- Multi-phase winds:
  - hot, volume filling, invisible component
  - cooler denser clumps (ionized, neutral, molecular)
  - Ionized – emission lines
  - Molecular – ALMA!
  - 350 Msun/year, will deplete in 10^6 years



Mrk 231: Feruglio et al. 2010

CO emission, $dM/dt=710\ M_{sun}$/year

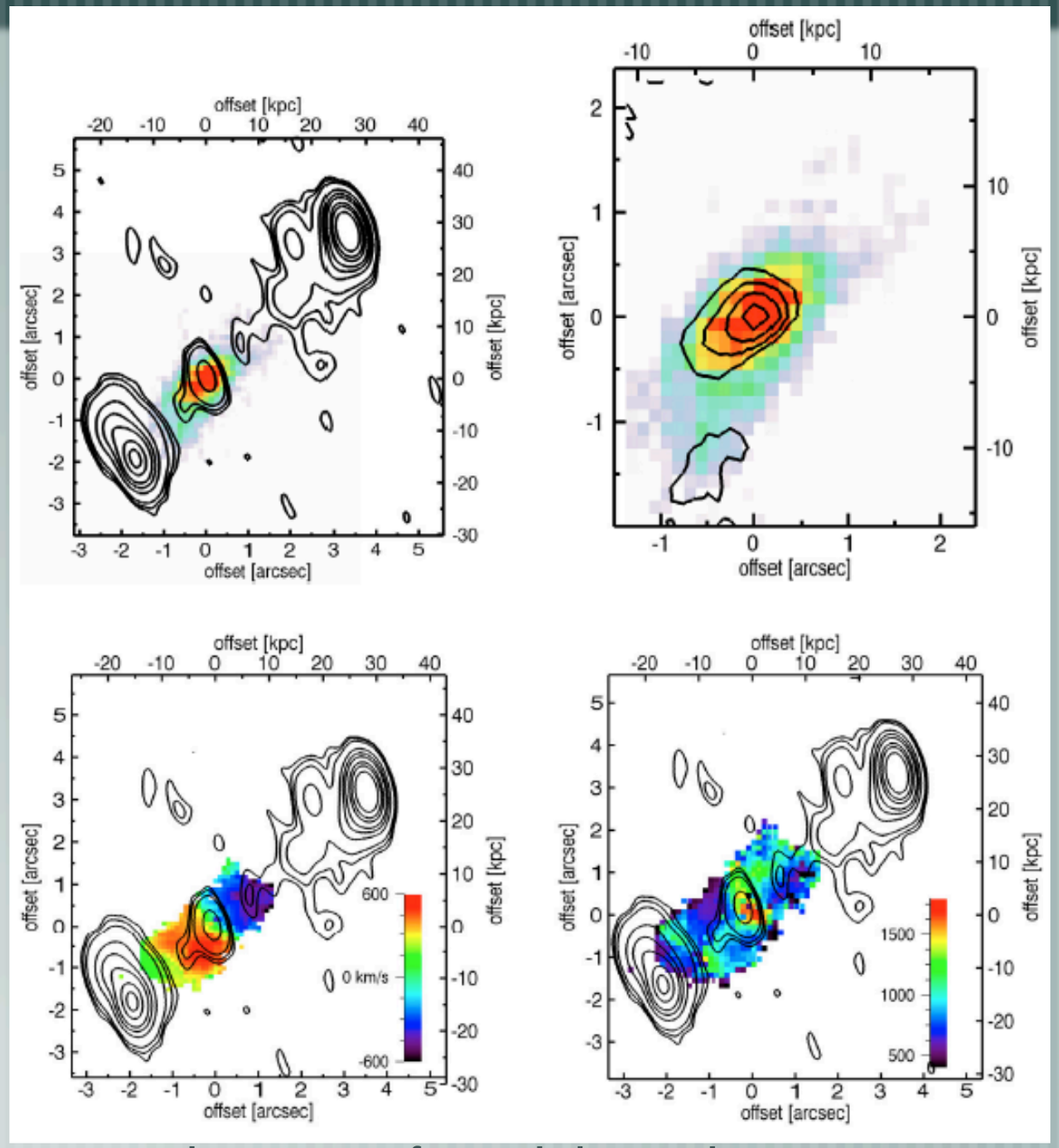
$E_{kin}=4.4 \times 10^{44}$ erg/s, extended (3kpc)



Sun, Greene, Zakamska, Nesvadba 2014

3. Observations: radio-loud quasars and radio galaxies

- Direct evidence of jet expelling galaxy gas (especially high z)
- Interactions between radio lobes and cluster gas
- Do radio galaxies solve all our problems?
- Yes for clusters? What about galaxy luminosity function?
- (1) minority of AGN population
- (2) very interesting differences between hosts of RL and RQ quasars



Observations of extended ionized gas, z=2-3
Nesvadba et al. 2006/08, $M=10^{10}$Msun, v>800km/s

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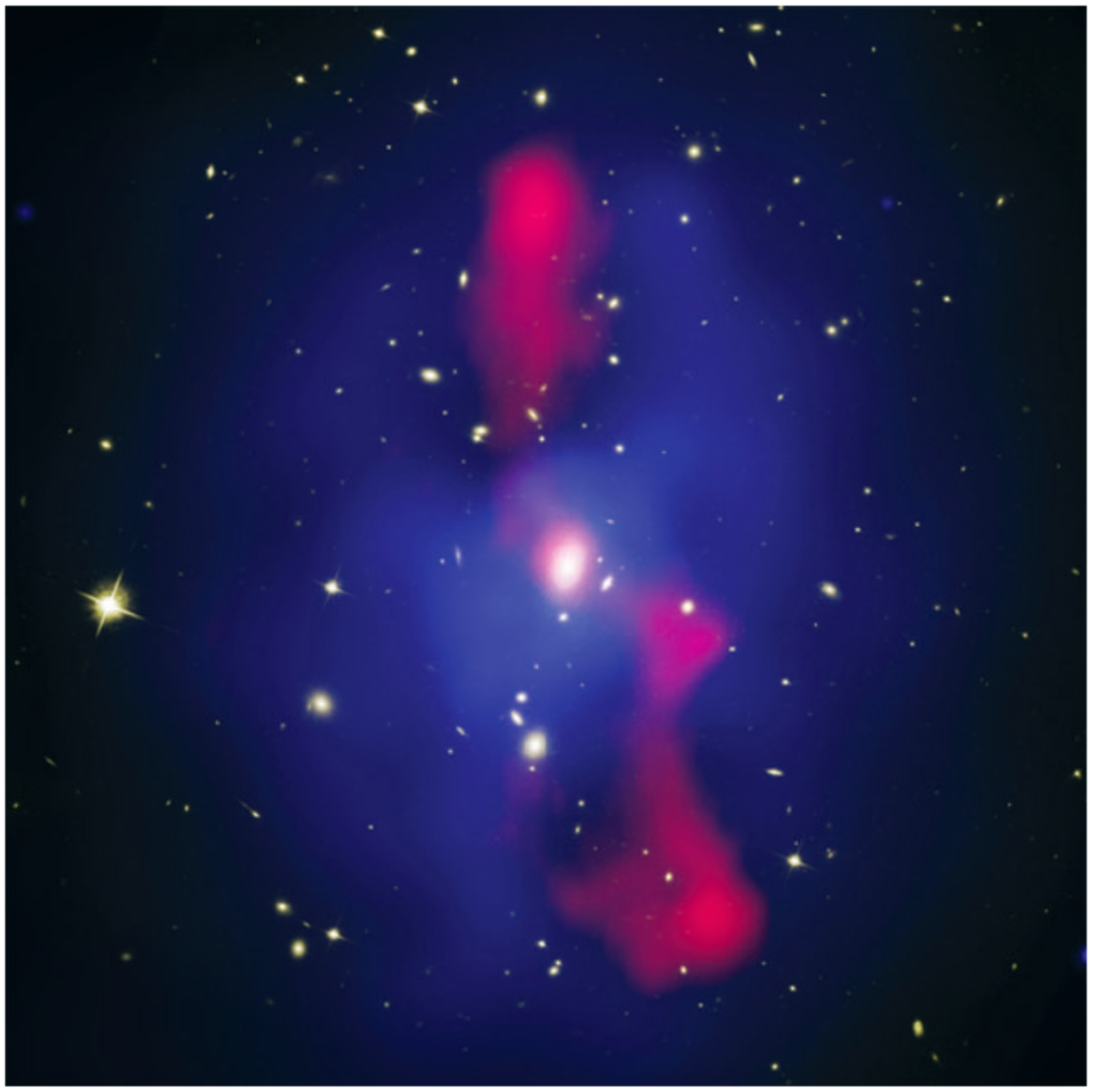
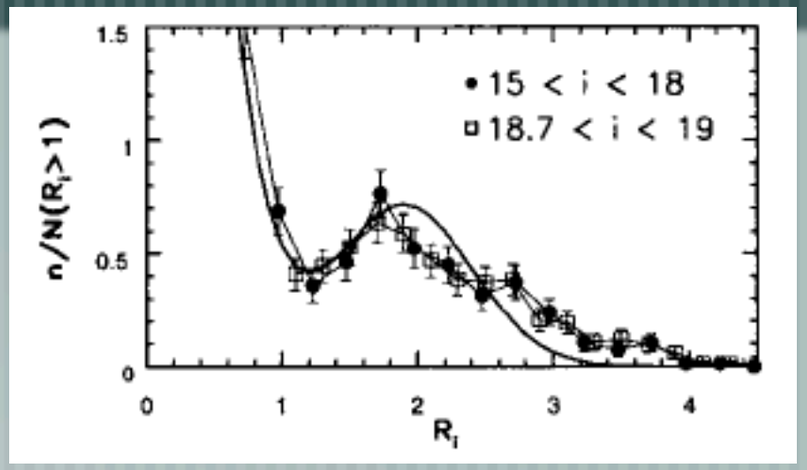


McNamara (ARAA)

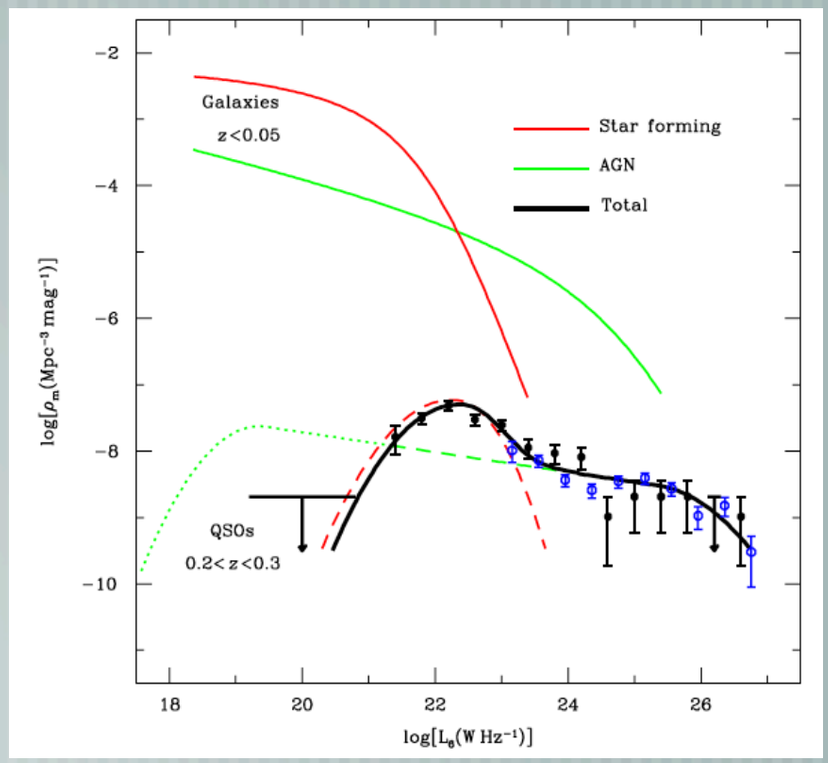
4. The nature of the radio emission in RQ quasars

- Distribution of radio power is very broad
- many (>5) orders of magnitude (faint end hard to probe)

- Is it a smooth or a bi-modal function?
- Is the mechanism of production of radio emission the same (just scaled up and down) or different?
- Why do we care? – Is every black hole capable of producing a jet? Or are jet-producing BH special?



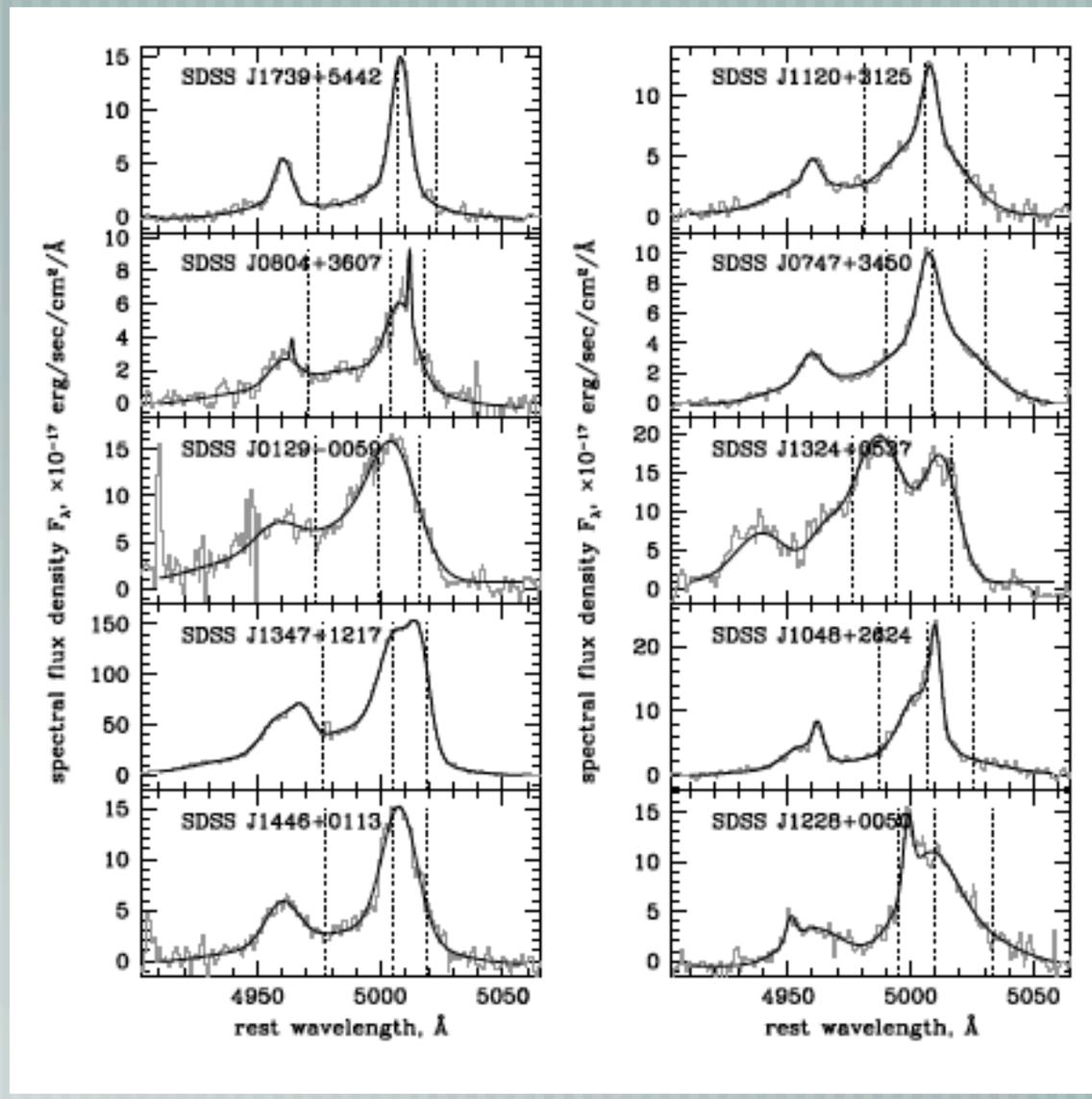
Ivezic et al. 2002
distribution of radio-to-optical ratios



Kimball et al. 2011

4. The nature of the radio emission in RQ quasars

- Correlation between line width (=outflow velocity) and radio luminosity
- These are “the 90%”: faint point sources (so-called “radio-quiet”), not much known about these
- We propose that quasar-driven shocks accelerate particles, produce radio emission
- Different from the usual assumption that jets accelerate gas



Zakamska & Greene 2014

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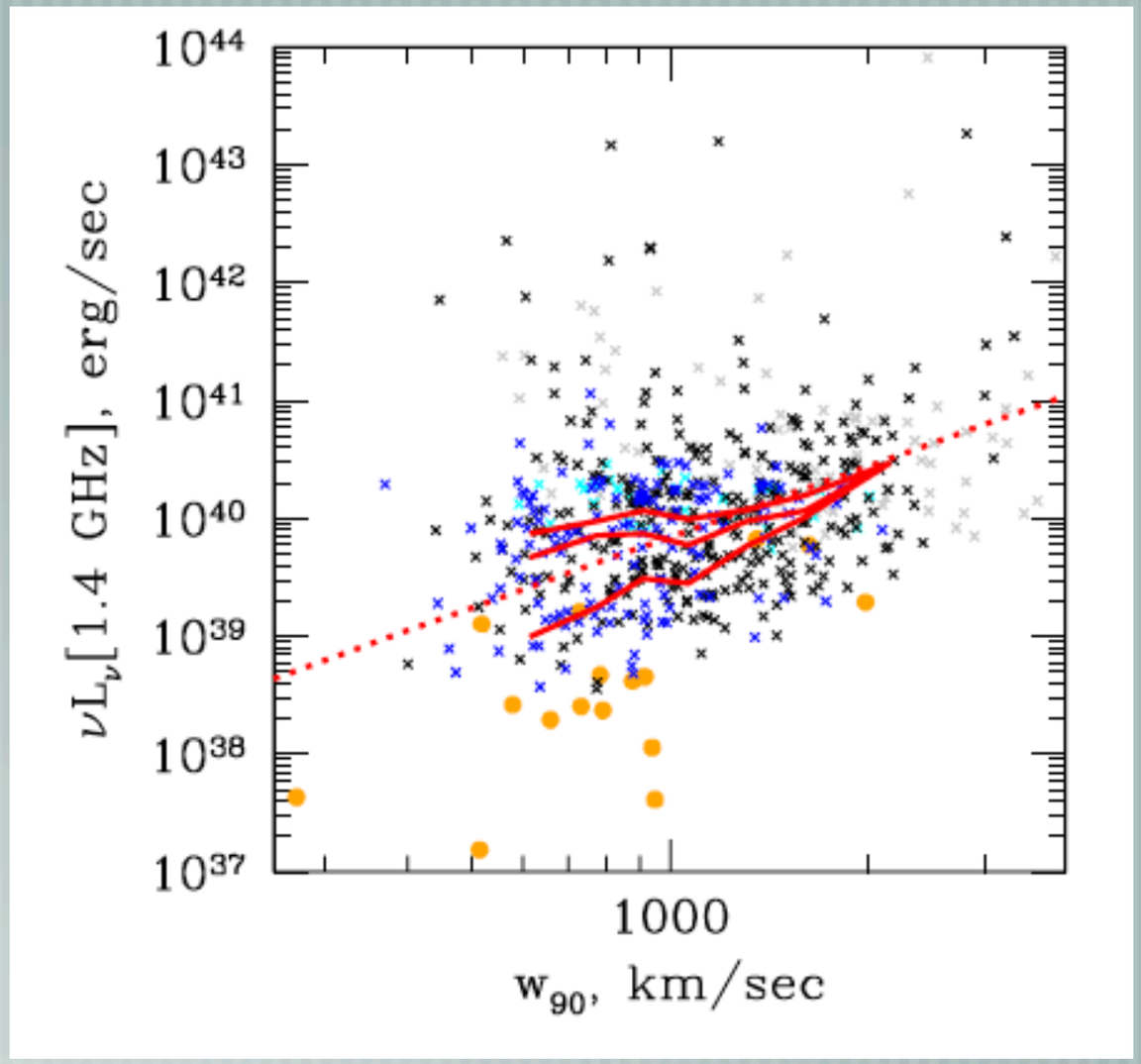

Zakamska & Greene 2014

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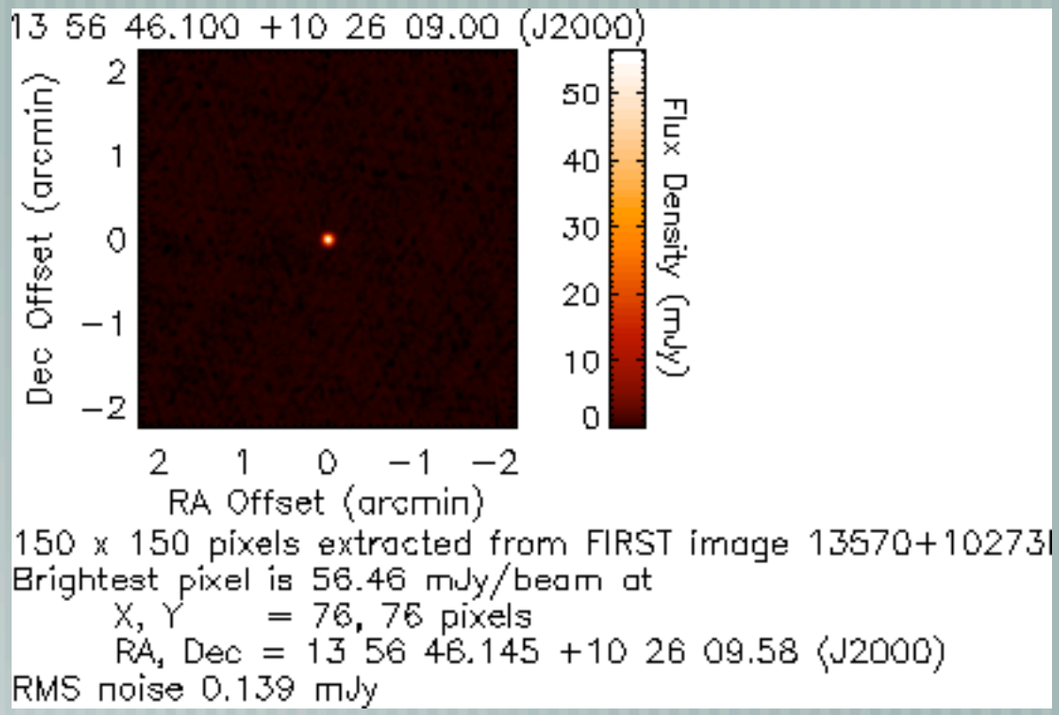
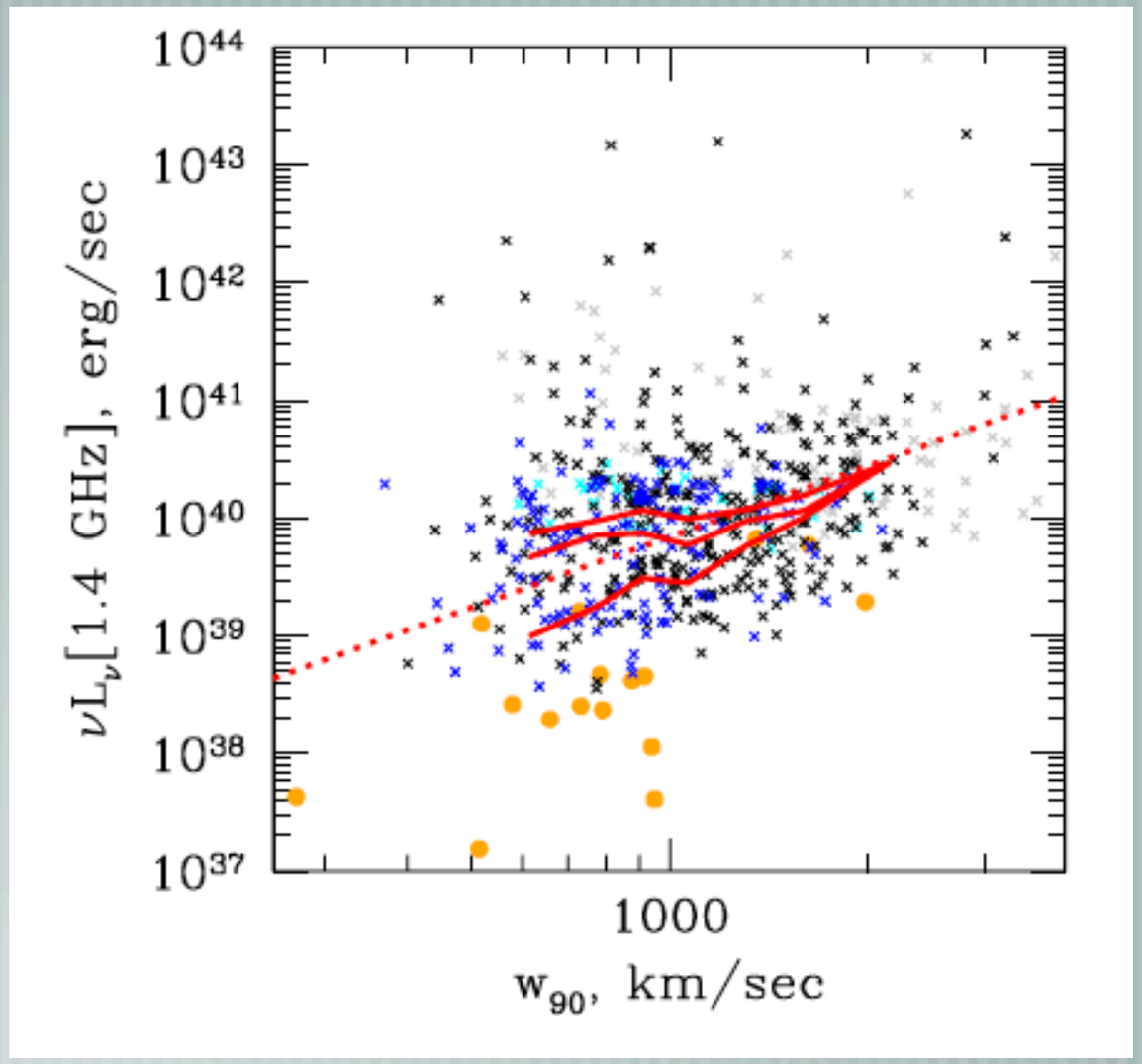


This is a very interesting object!

4. The nature of the radio emission in RQ quasars

- Energetics: bolometric luminosity 8e45 erg/sec ⇒ 4% conversion to wind (3e44 erg/sec) ⇒ standard ratio for star forming galaxies (1e40 erg/sec)
- Star formation insufficient by a factor of 2-10.
- Difficult to distinguish from compact jets (although see luminosity function...)



Zakamska & Greene 2014

Summary

- Radiatively-driven or jet-driven winds propagate into gas-rich host galaxy: shocks, cloud acceleration / destruction
- Recent observations of quasar winds across different wavelengths
- Indicate wind power up to a few per cent of the bolometric luminosity