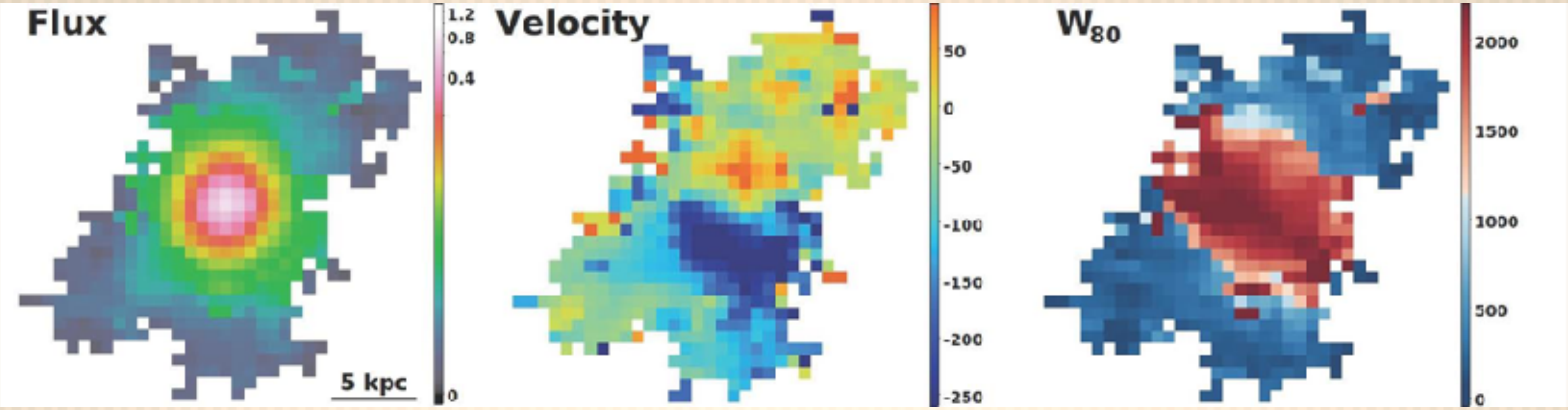
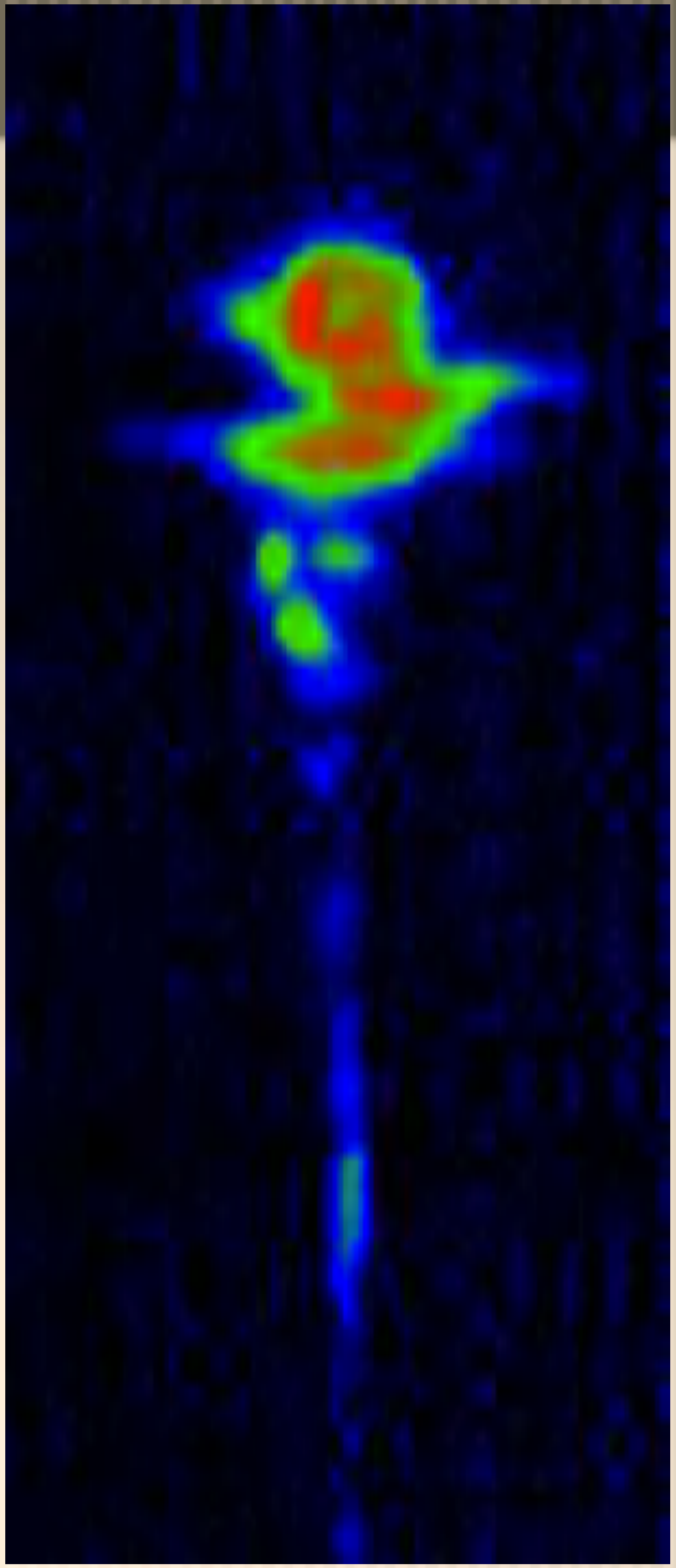
Observations of AGN-driven winds

Nadia Zakamska
Johns Hopkins University



AGN Feedback: definitions

- Feedback = strong effect that the black hole (tiny!) on the surrounding galactic and intergalactic environment (big!)
- Nontrivial that such a connection should exist
- Radiative feedback
- Stellar dynamical feedback
- Mechanical feedback (jet-driven or radiatively driven) = galactic gas outflows
- Impact on star formation



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(quasar OR agn) AND feedback

+Silk & Rees 1998 (1506 citations)

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4	2005MNRAS.361..776S Springel, Volker; Di Matteo, Tiziana; Hernquist, Lars	1106.000 Modelling feedback from stars and black holes in galaxy mergers	08/2005	A F G X R C U
5	2006ApJS..163....1H Hopkins, Philip F.; Hernquist, Lars; Cox, Thomas J.; Di Matteo, Tiziana; Robertson, Brant; Springel, Volker	970.000 A Unified, Merger-driven Model of the Origin of Starbursts, Quasars, the Cosmic X-Ray Background, Supermassive Black Holes, and Galaxy Spheroids	03/2006	A E F X R C S U
6	2004ApJ...600..580G Granato, Gian Luigi; De Zotti, Gianfranco; Silva, Laura; Bressan, Alessandro; Danese, Luigi	717.000 A Physical Model for the Coevolution of QSOs and Their Spheroidal Hosts	01/2004	A E F X R C S U H

Outline

1. Why do we think we need it?

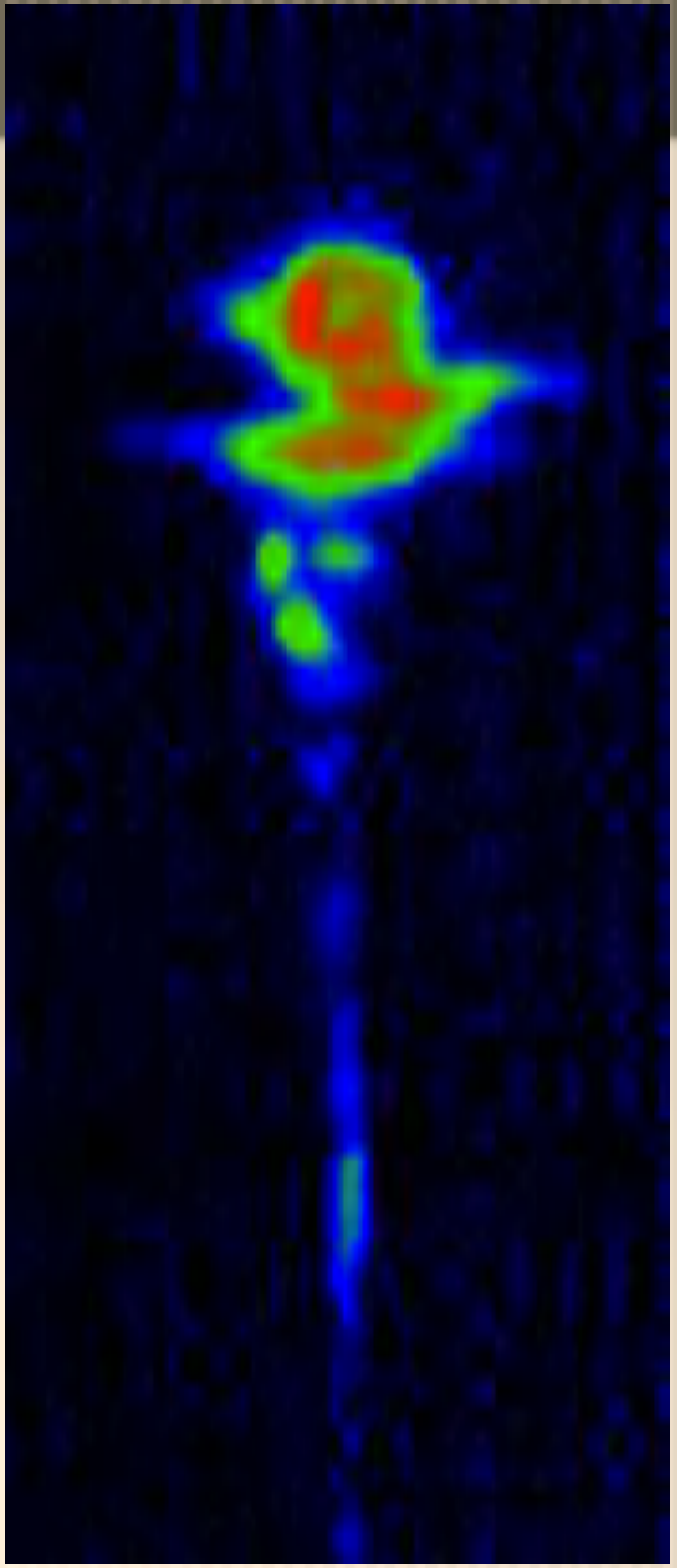
2. Mechanical feedback = outflows: Multi-phase phenomenon!

3. Established methods (>5 years): emission lines, absorption lines – molecular, neutral, ionized

4. New methods (<5 years): radio, Sunyaev-Zeldovich effect

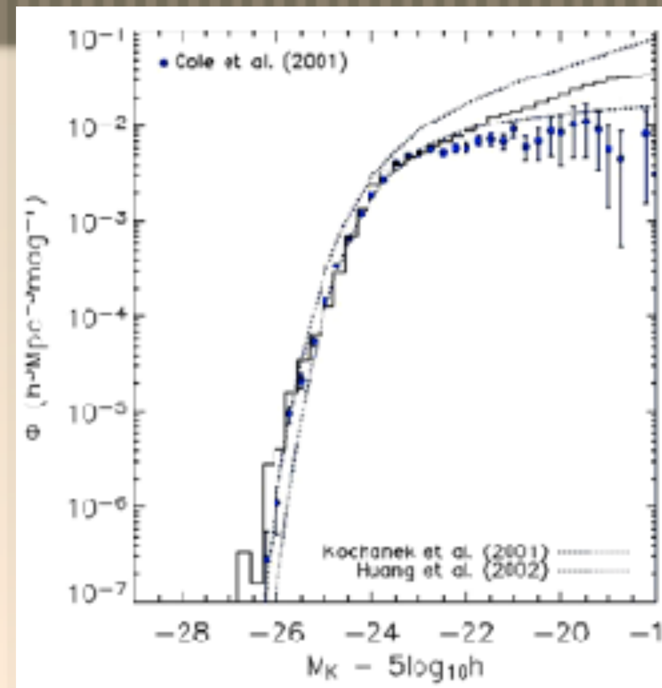
5. Impact on star formation

6. Unsolved issues, comparison with simulations

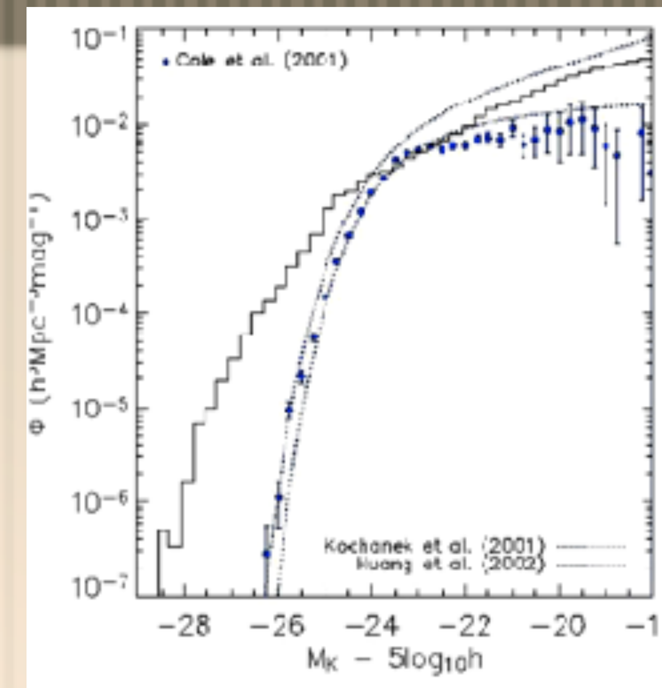


1. Why do we need AGN feedback?

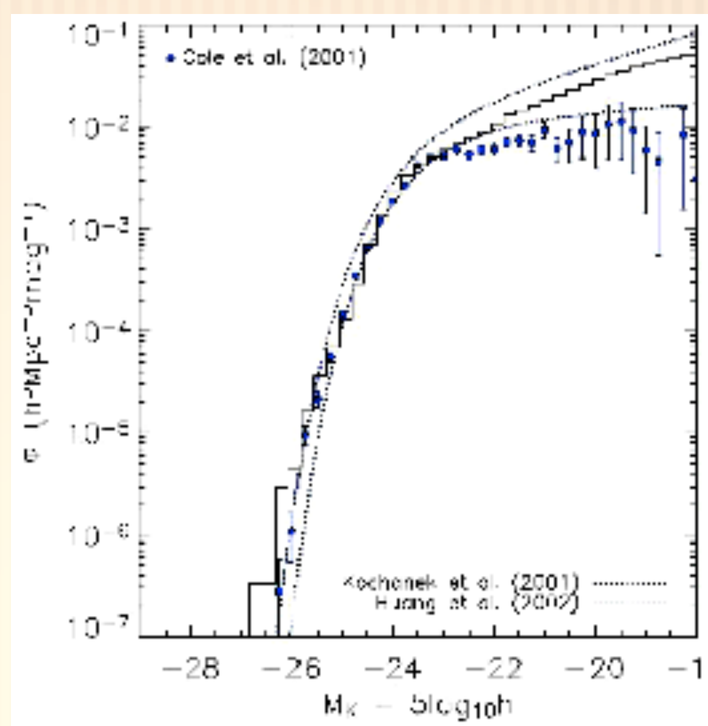
- Galaxy luminosity function: too few galaxies on the bright end
- Galaxy / black hole co-evolution, M-sigma relationship
- Intracluster medium
- Black hole feedback appealing: lots of binding energy available
- 1 gr accreted = enough energy to throw 10 kg out of the galaxy!



With reionization, AGN and SNe



With ~~reionization~~, ~~AGN~~ and SNe



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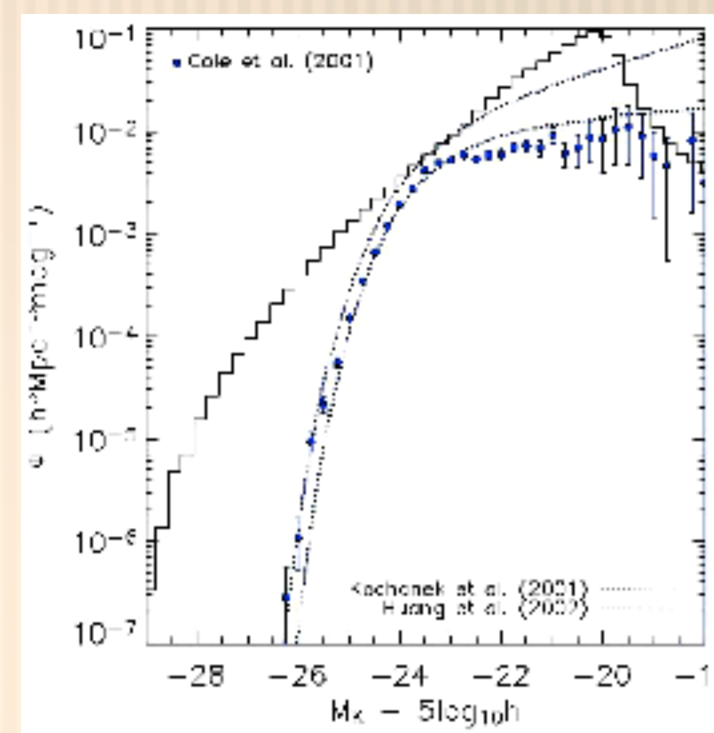


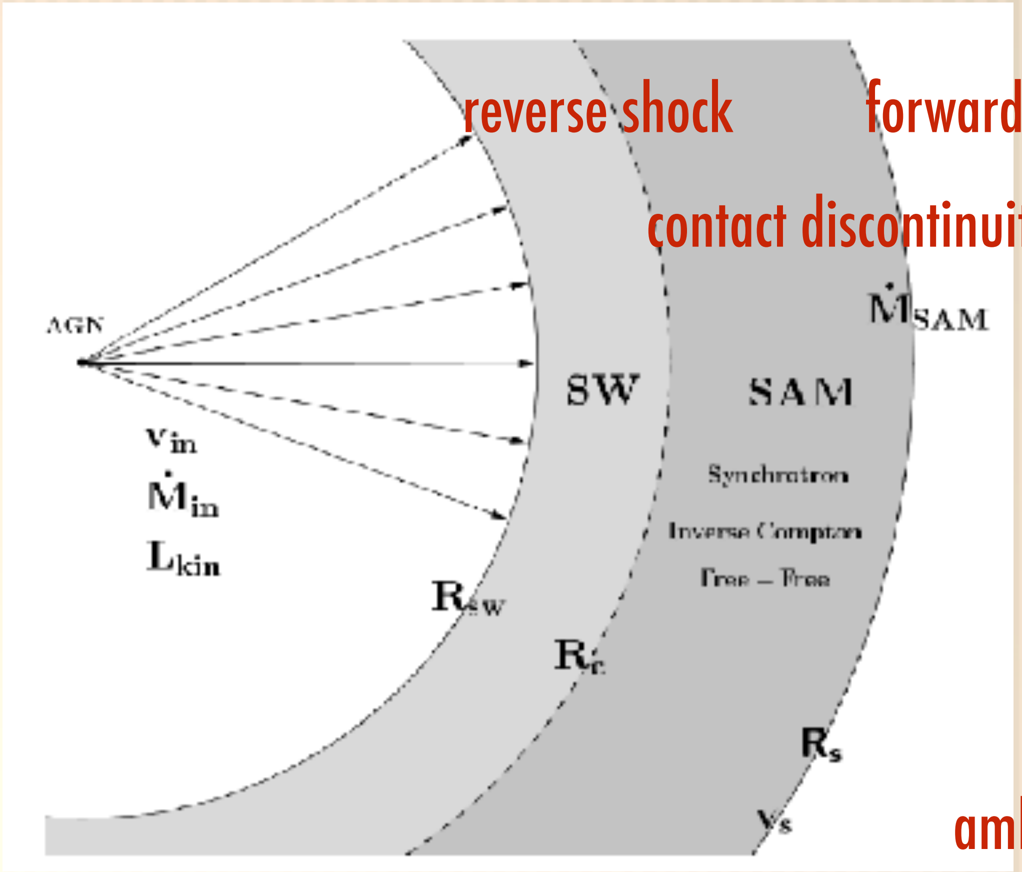
With ~~reionization~~, ~~AGN~~ and ~~SNe~~

Croton et al. 2006

2. How does feedback proceed?

- Energetics: a few per cent is a typical number which helps
- Needs to be coupled to the gas
- Radiatively driven winds ("line-driving")
- Jet-driven winds (bow-shock + cocoon)
- = 10^7 year bomb in a gas-rich medium, expect hot post-shock material
- Density distribution, clumping of the ISM crucial

Spherically symmetric models:
King, Zubovas & King,
Faucher-Giguere & Quataert:
typical velocities at large scales of 1000 km/sec.



Nims & Quataert 2015

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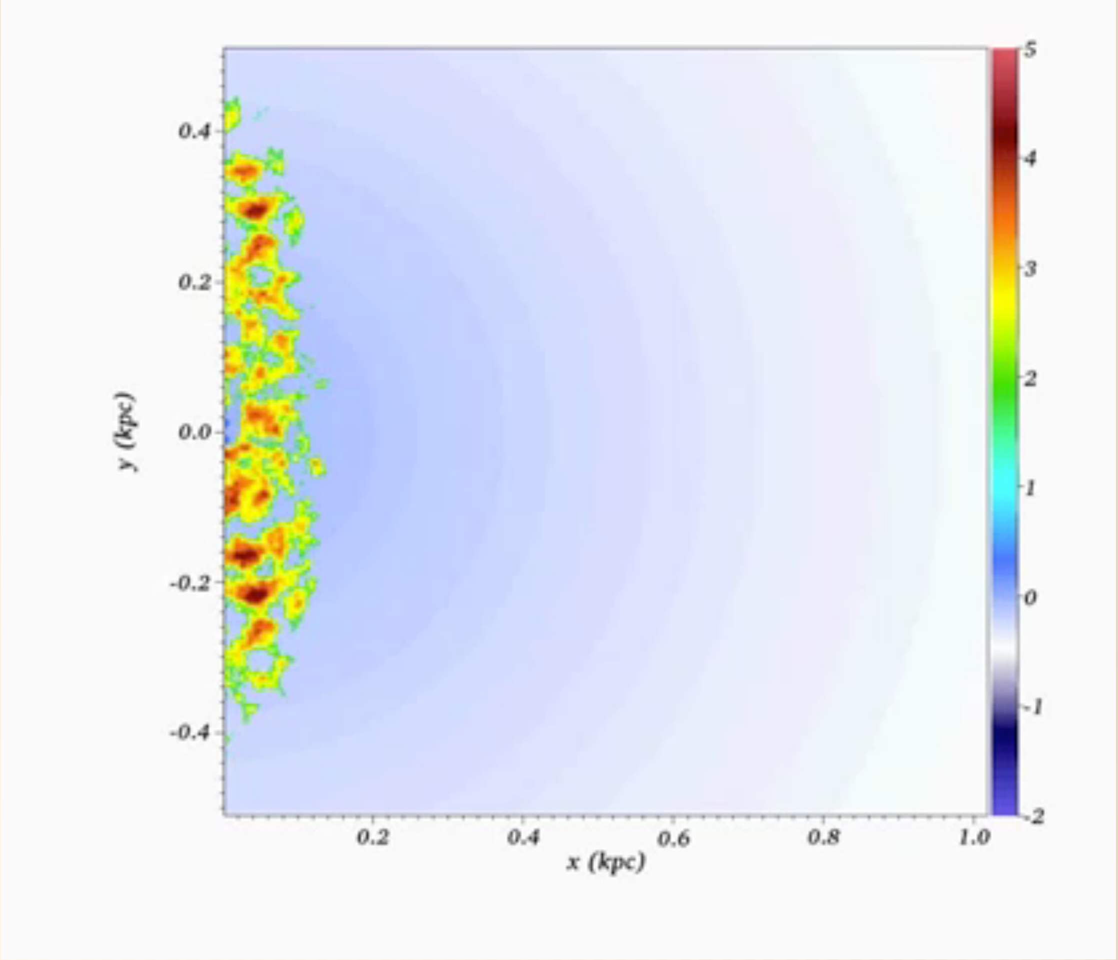
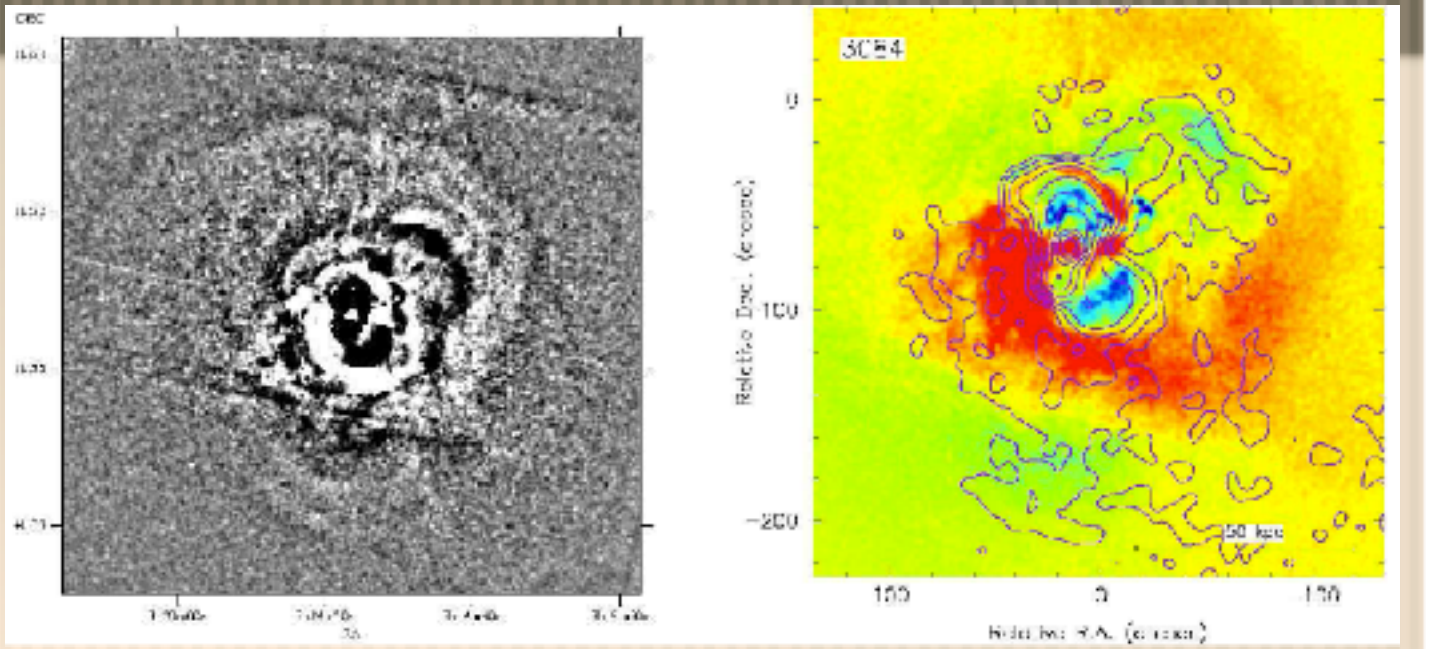


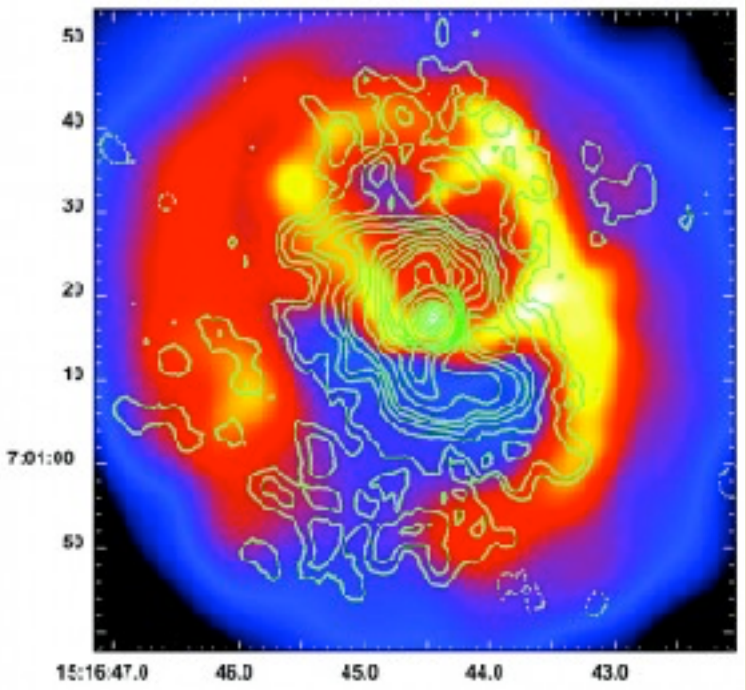
Wagner et al. 2013

3. Observations of feedback in RL AGN: established methods

- Until ~15 years ago little direct evidence for AGN feedback
- Earliest: radio-loud = powerful jets
- Interactions between jet and intra-cluster medium, jet and galaxy gas
- Bubbles: how is the energy transferred?
- Ionized gas outflows
- Neutral gas outflows



Fabian et al. 2000, 2003, Perseus cluster



Blanton et al. (A2052)

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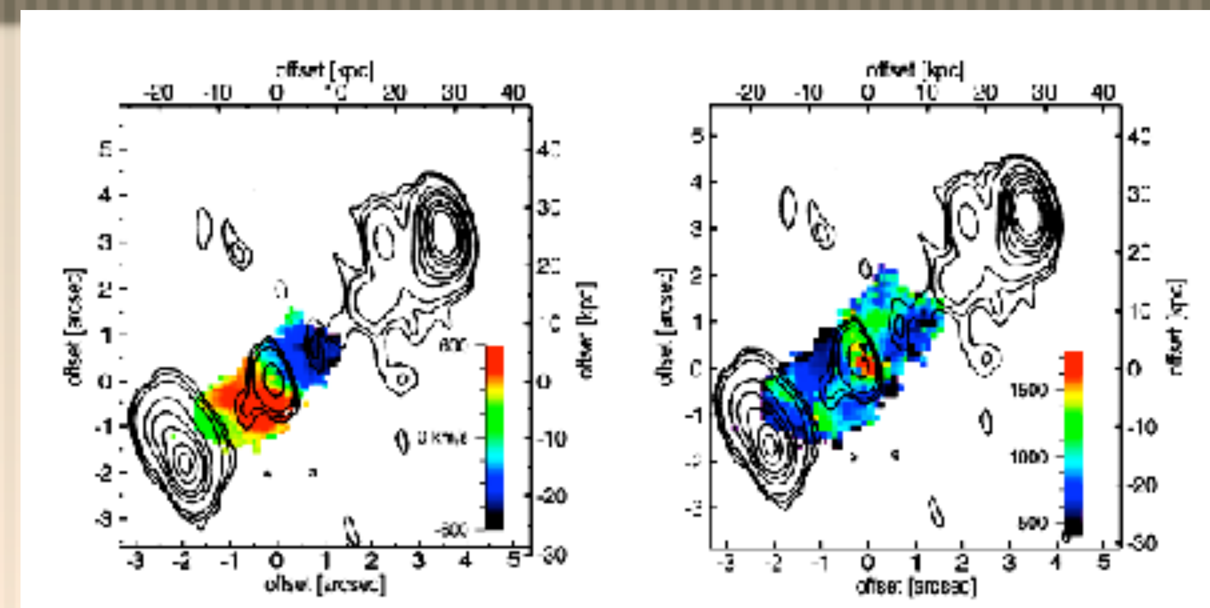
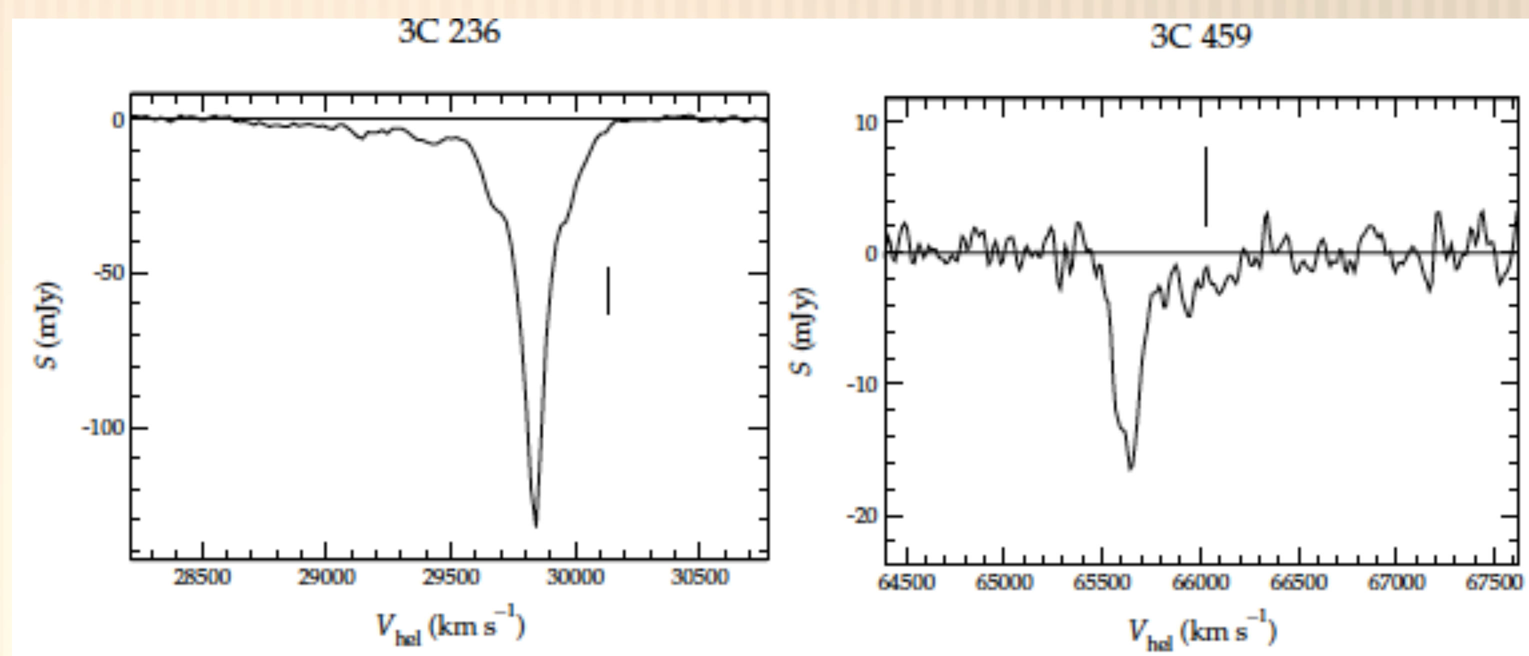


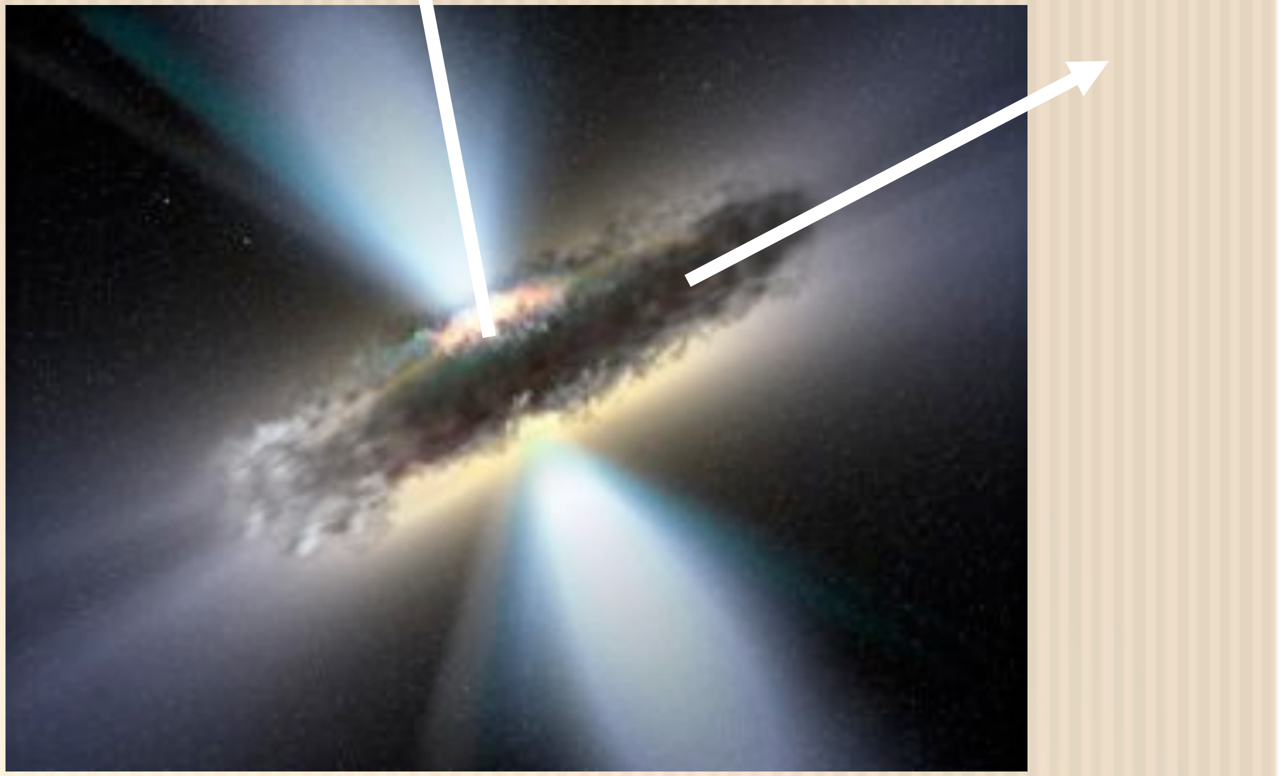
Observations of extended ionized gas, z=2-3
Nesvadba et al. 2006/08, $M=10^{10}$Msun, v>800km/s



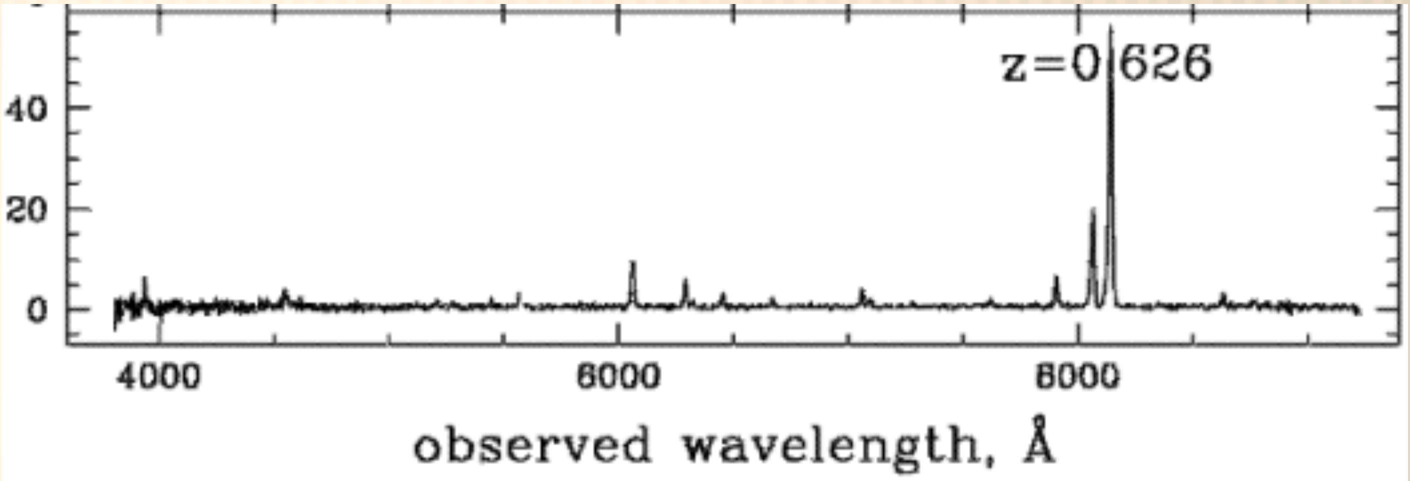
Morganti et al. 2005, HI absorption, $dM/dt=50\ M_{sun}$/year

3. Observations of feedback in RQ quasars: ionized gas

- Radio-quiet = no evidence for jets
- Majority of quasar population
- Look for winds at several kpc from the nucleus
- Use kinematics of forbidden emission lines
- Now the standard method of studying ionized gas winds

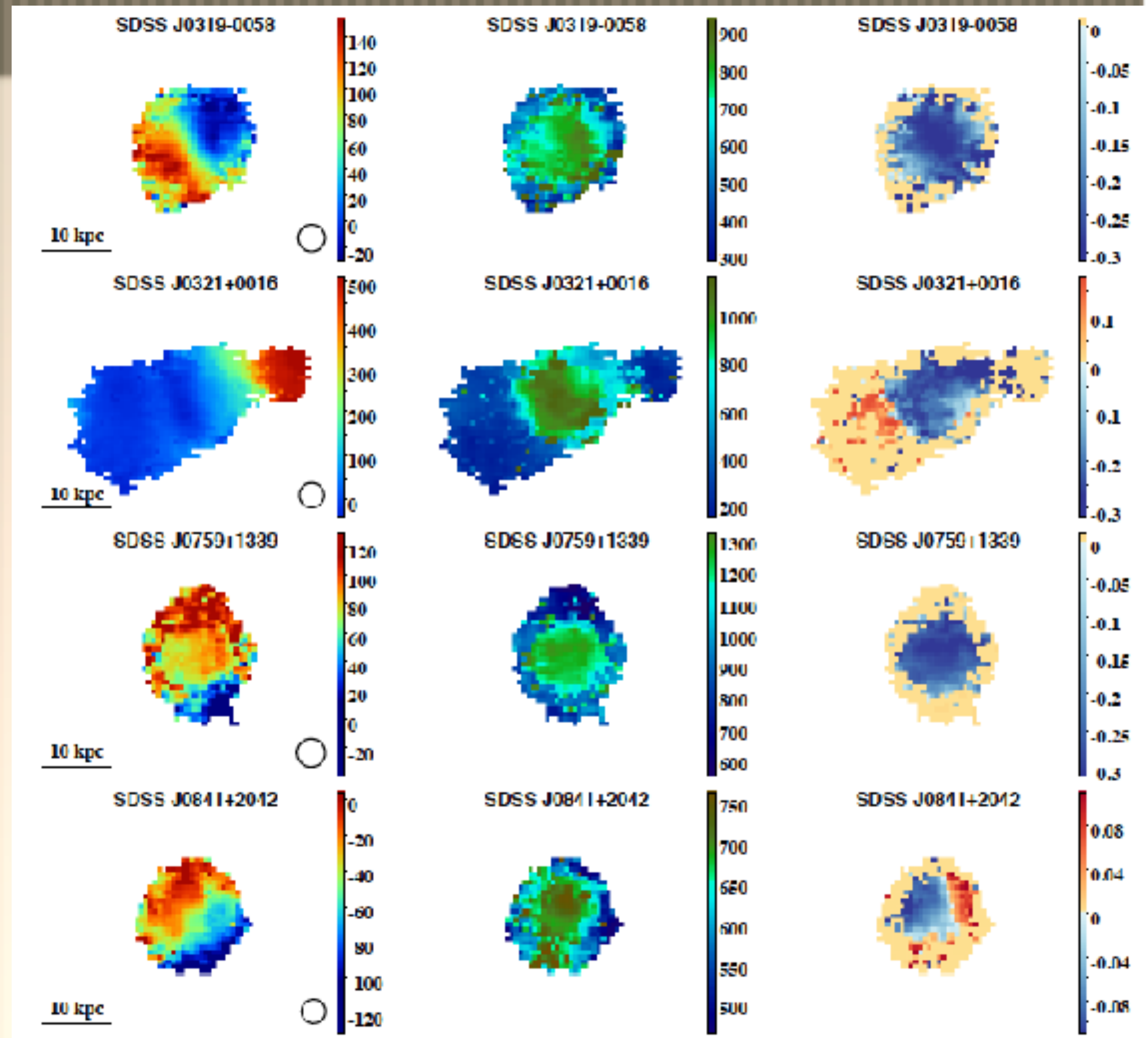


"Geometric unification model"



3. Observations of feedback in RQ quasars: ionized gas

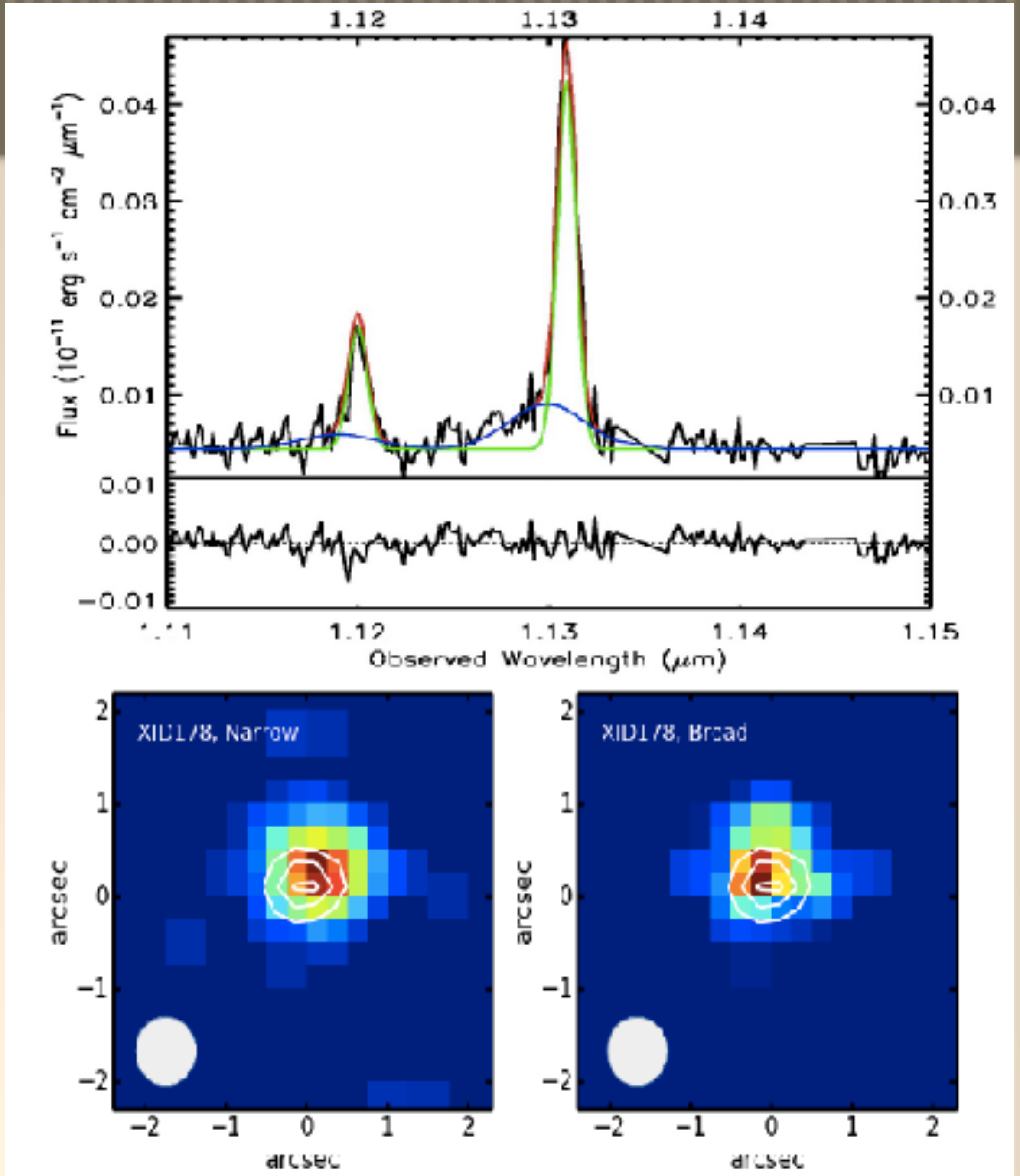
- Key observations: the entire galaxy is affected
- Line-of-sight velocity ⇒ one side approaching, one side receding.
- Line-of-sight velocity dispersion ⇒ typical outflow velocity=800 km/sec
- Likely will escape from the galaxy
- Blue-shifted asymmetries = classical outflow signatures



Liu, Zakamska et al. 2013a, 2013b, 2014

3. Observations of feedback in RQ quasars: ionized gas

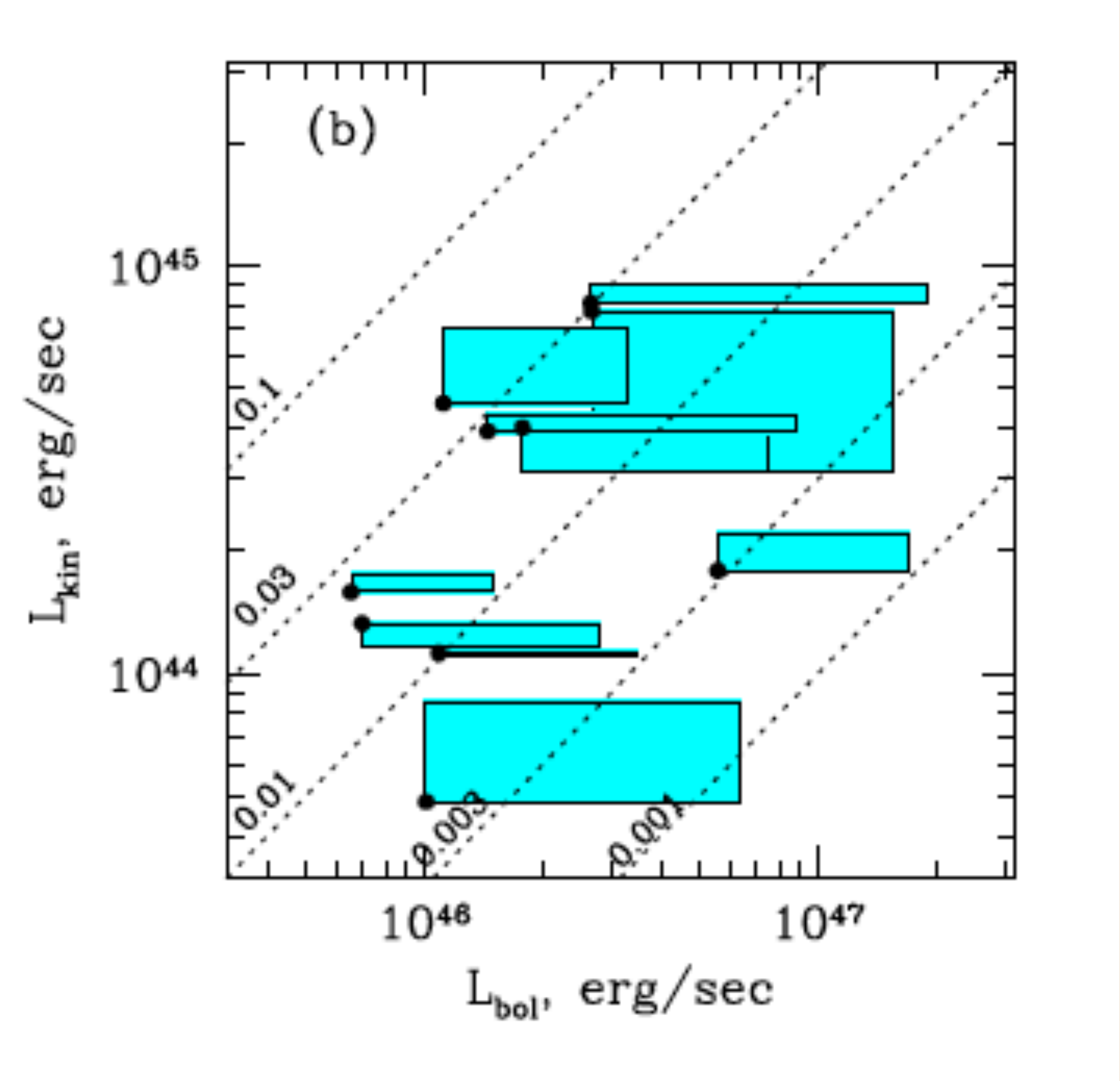
- Now seen by many groups in type 1 and type 2 quasars (e.g., Harrison et al., Rupke & Veilleux, Husemann et al., Villar-Martin et al., Hainline et al., Alexander et al., Cano-Diaz et al., Brusa et al., Perna et al., Greene et al.)
- IFU and long-slit spectroscopy
- PSF decomposition methods: Rupke et al. 2018
- How to convert to masses, energies?



Kakkad et al. 2016

3. Observations of feedback in RQ quasars: ionized gas

- Small dense clouds produce emission lines
- Much of the wind is invisible in these observations, density / mass very uncertain
- Methods to estimate the energetics of the process (transition to matter bounded clouds)
- Find 2% efficiency for conversion from luminosity to wind.
- Major component of feedback! 1000 Msun/year outflow rates



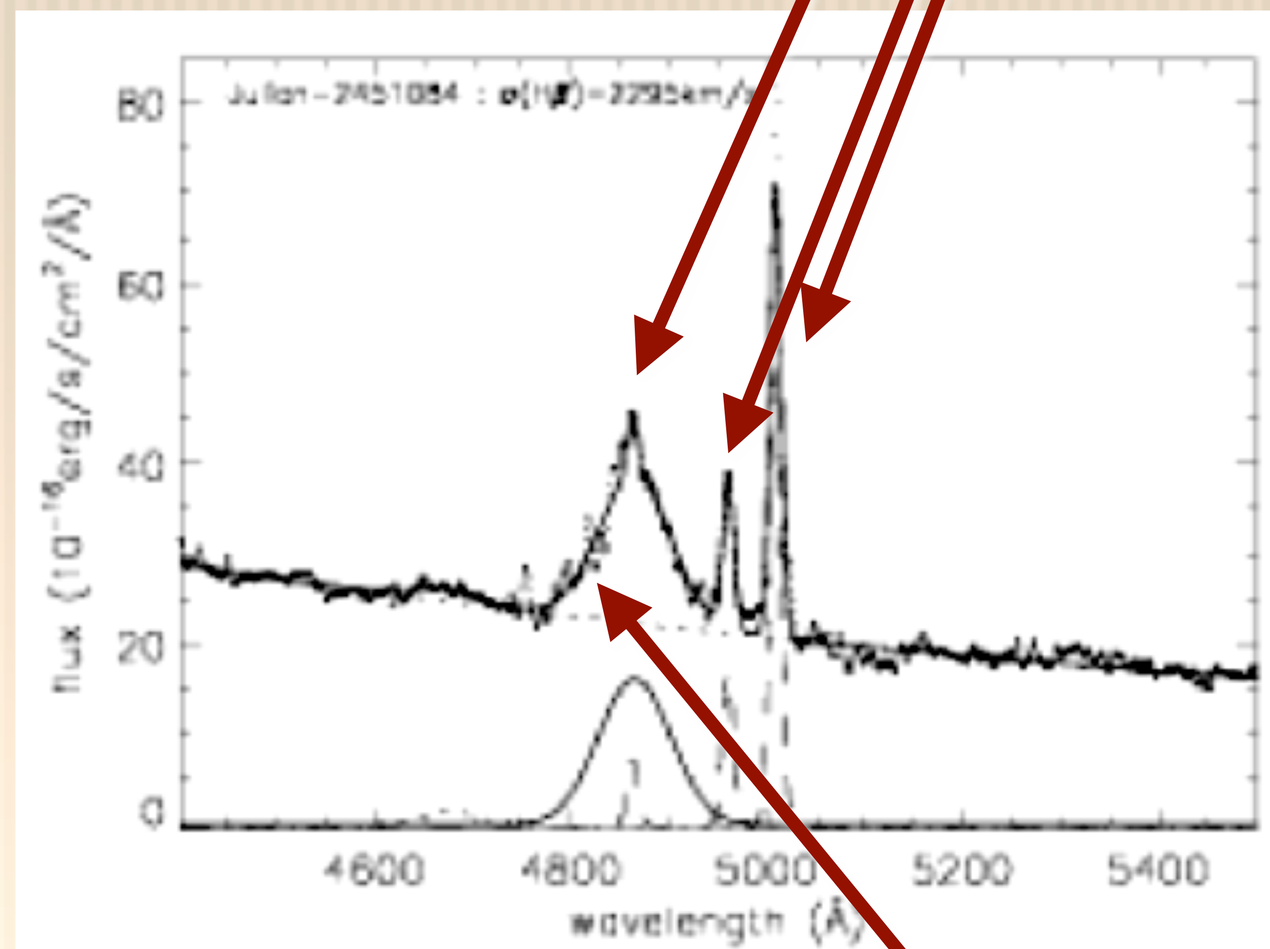
Liu, Zakamska, Greene, Nesvadba, Liu 2013b

Dempsey & Zakamska 2018 on mass correction factors

3. Observations of feedback in RQ quasars: the most extreme ionized gas outflows

kinematics of extended gas = host galaxy

- Spatial mapping of winds in [OIII] = gold standard
- Integrated velocity profiles also suggestive!
- [OIII] has critical density ~ a few x 10^5 cm^{-3}, so has to be extended, >>100 pc
- High velocities of [OIII] ~ galactic winds??
- Population with extreme [OIII] outflows!
- Extremely red quasars (ERQs): optical - WISE selected, z=2.5
- L_{bol} up to 10^{48} erg/sec, highly obscured ($N_H=10^{24}cm^{-2}$) – Goulding et al. 2018



Zhang et al. 2017

BLR / NLR refresher

kinematics of BH sphere of influence

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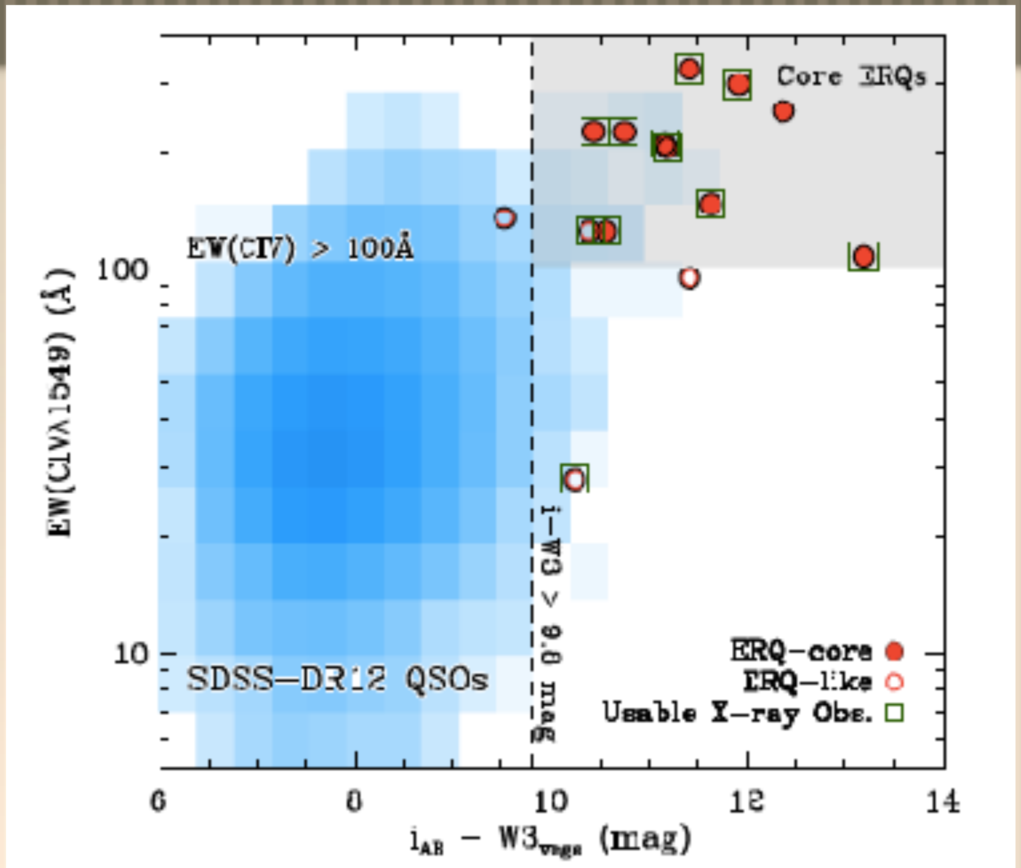

Ross et al. 2015 MNRAS 453 3932
Zakamska et al. 2016 459 3144
Hamann et al. 2017 MNRAS 464 3431
Hwang et al. 2018 MNRAS 477 830
Goulding et al. 2018 ApJ 856 4
Alexandroff et al. 2018 in press, arxiv 1806.10138
Sun et al. 2018 in prep
Perrotta et al. 2018 in prep

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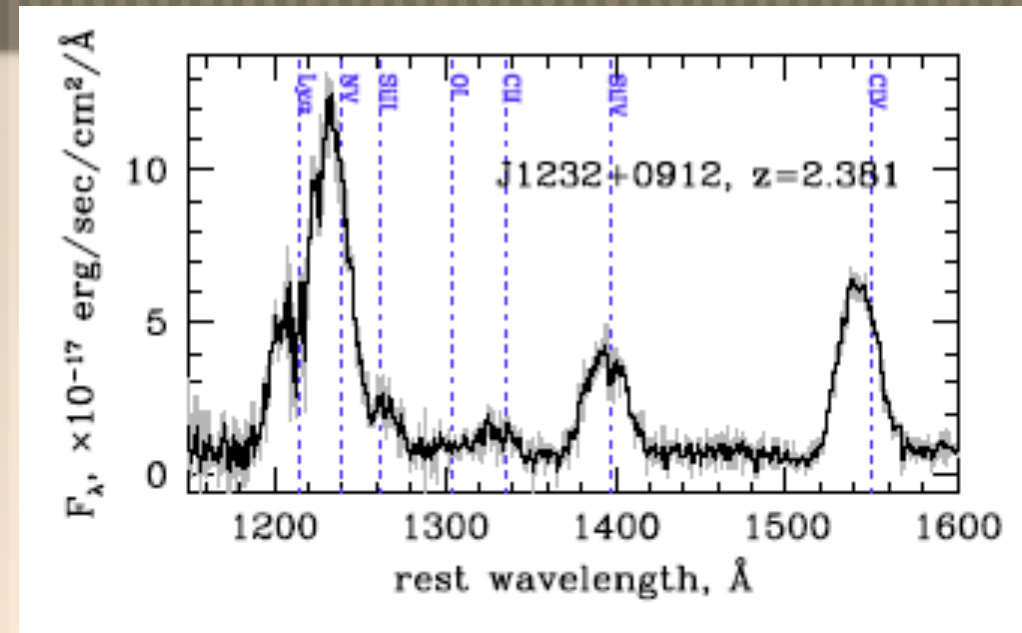
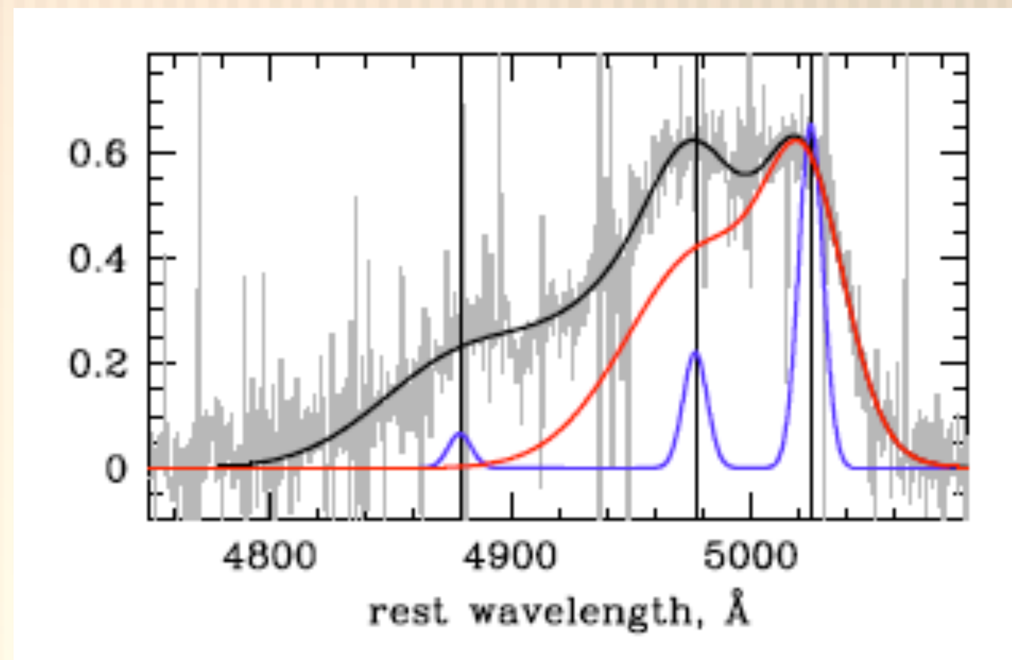


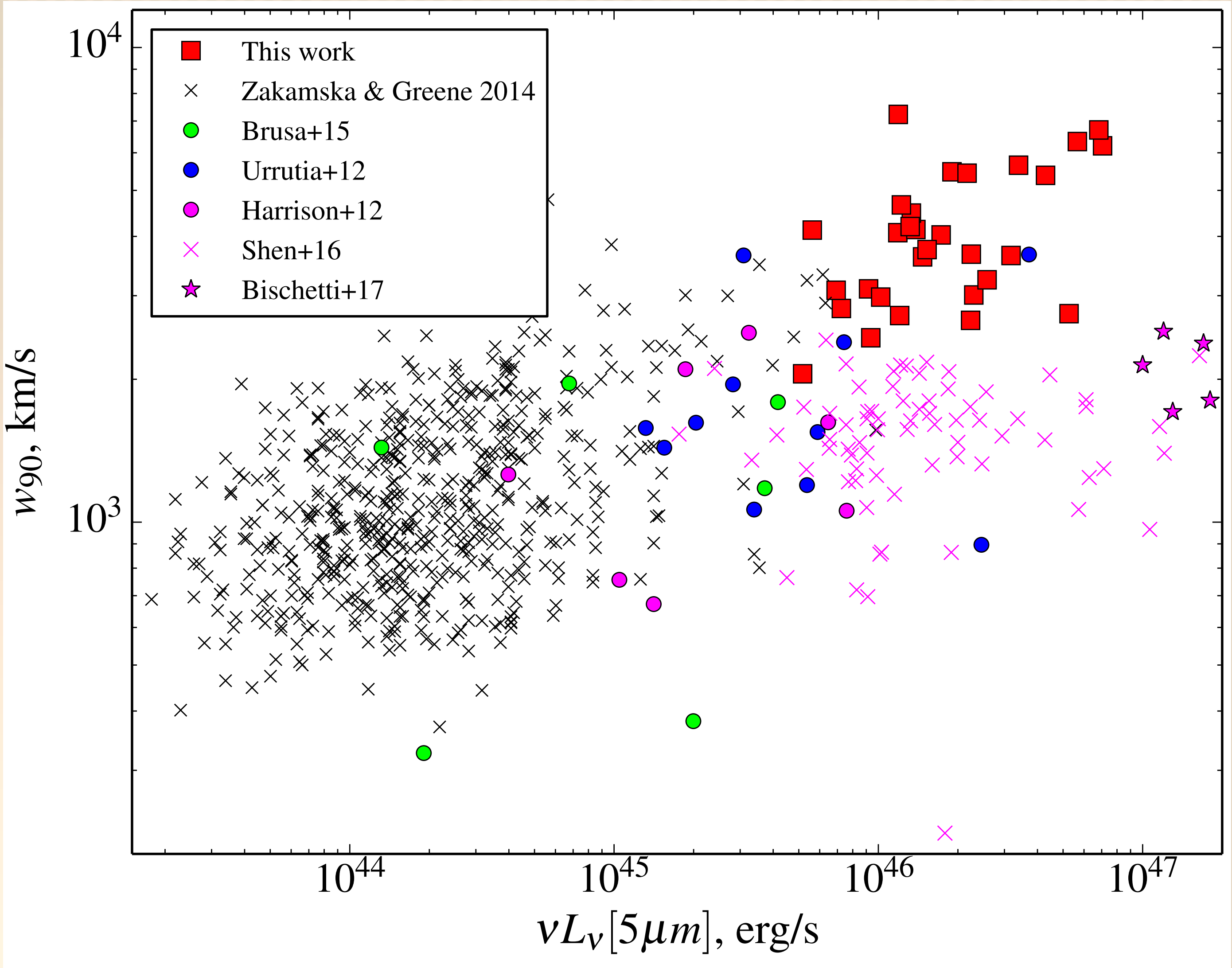
Ross et al. 2015



Zakamska, Hamann, Paris et al. 2016b

3. Observations of feedback in RQ quasars: the most extreme ionized gas outflows

- Unprecedented widths of [OIII]
- Defy the standard BLR / NLR definitions (FWHM=5000 km/sec)
- [OIII] outflow velocities are related both to the luminosity and to the color, the most extreme population
- Also spectropolarimetry of CIV, NV, Lyalpha
- Equatorial winds at several thousand km/sec on 10 pc scales!
- Super-Eddington quasars with extreme outflows on all scales, blowing up the host galaxy?



Perrotta et al. 2018 in prep.
Zakamska et al. 2016

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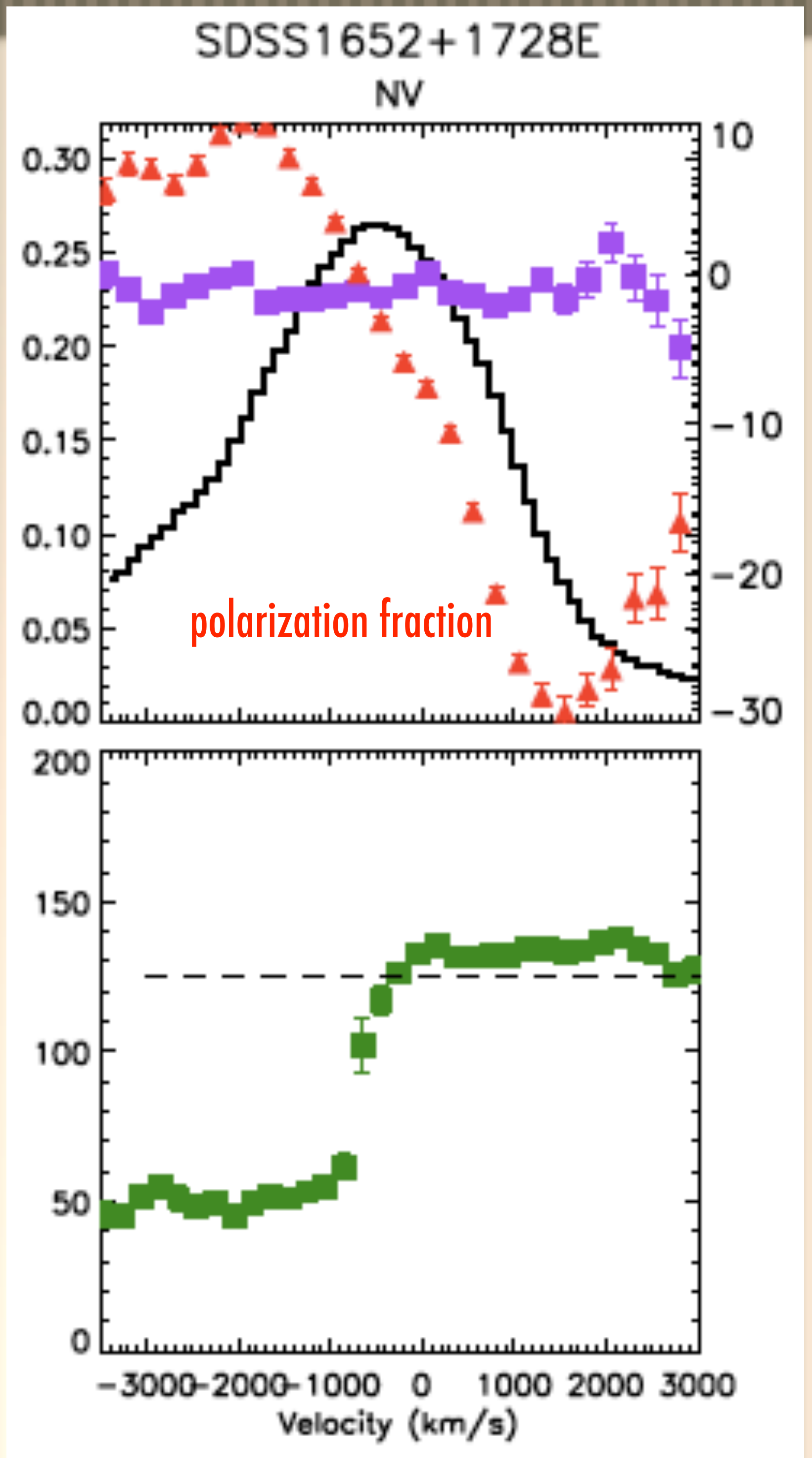
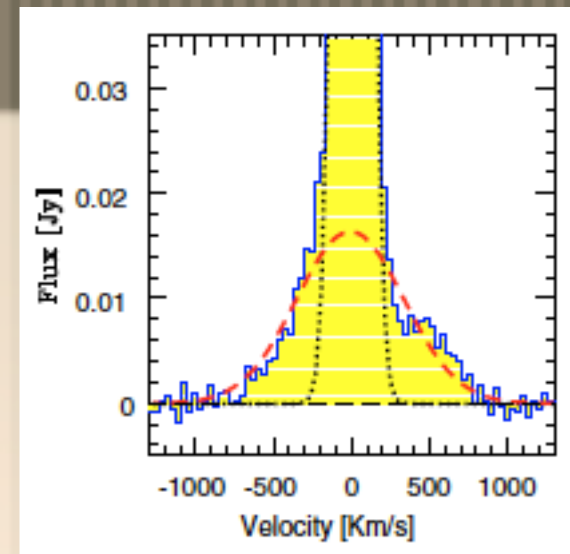


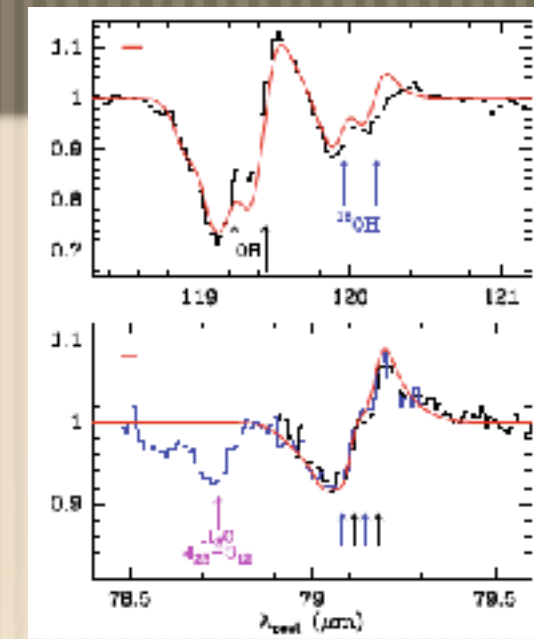
Alexandroff et al. 2018, arxiv: 1806.10138

3. Observations of feedback in RQ quasars: molecular outflows

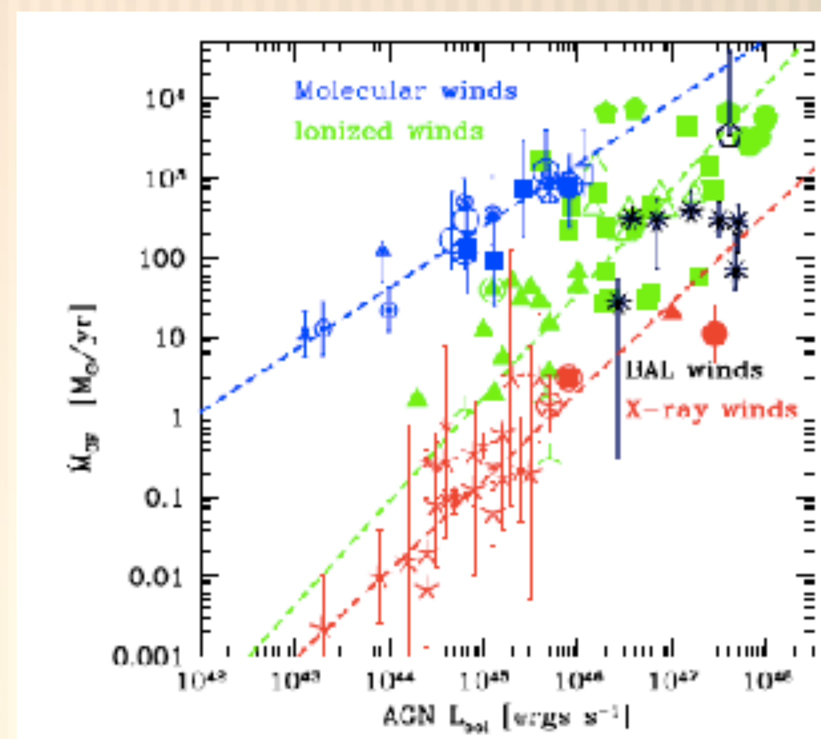
- Both in absorption and in emission
- CO, OH, NIR and MIR lines of warm H_2
- Velocities inconsistent with galactic potential = escaping gas
- CO: Potentially the component that carries most of the mass
- Origin of this component? Richings & Faucher-Giguere 2018: formation of molecules in situ



Mrk 231: Feruglio et al. 2010
CO emission, $dM/dt=710\ M_{sun}/year$
$E_{kin}=4.4\times10^{44}$ erg/s, extended (3kpc)



Mrk 231: Fischer et al. 2010
PCygni profiles



Fiore et al. 2017

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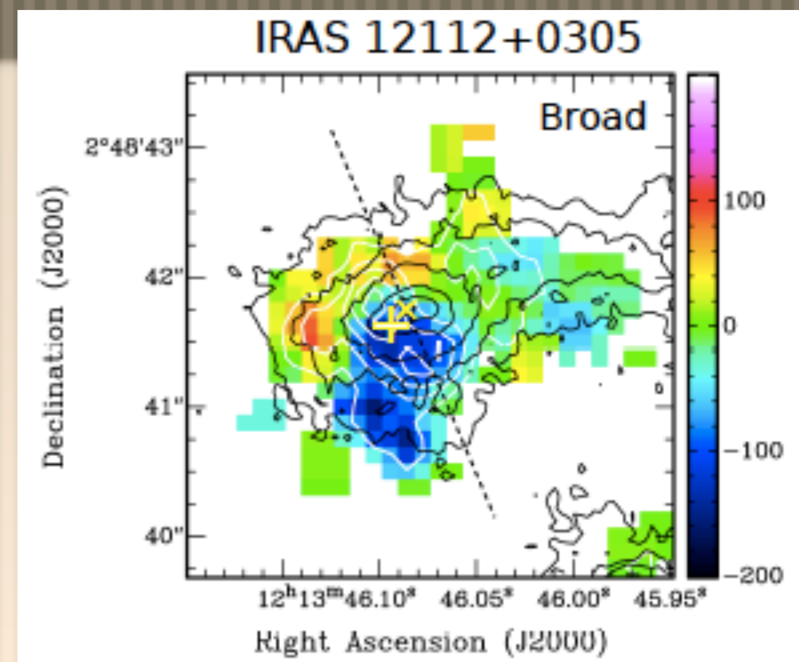

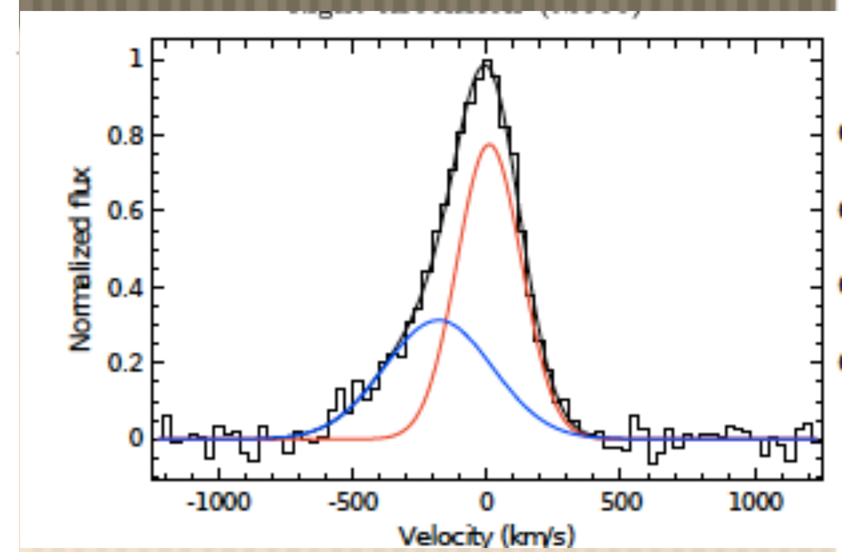

Emonts et al. 2017

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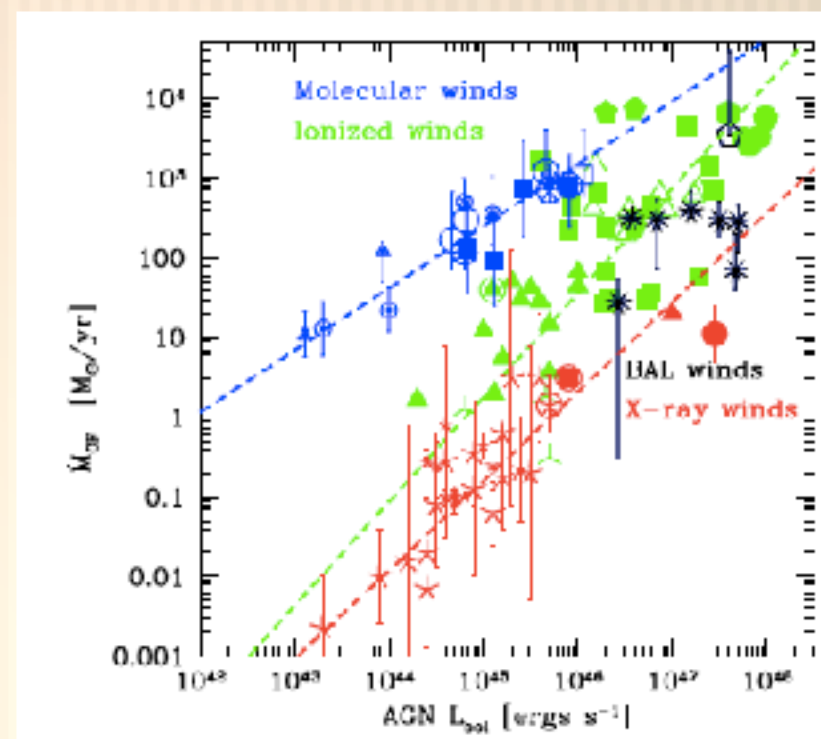
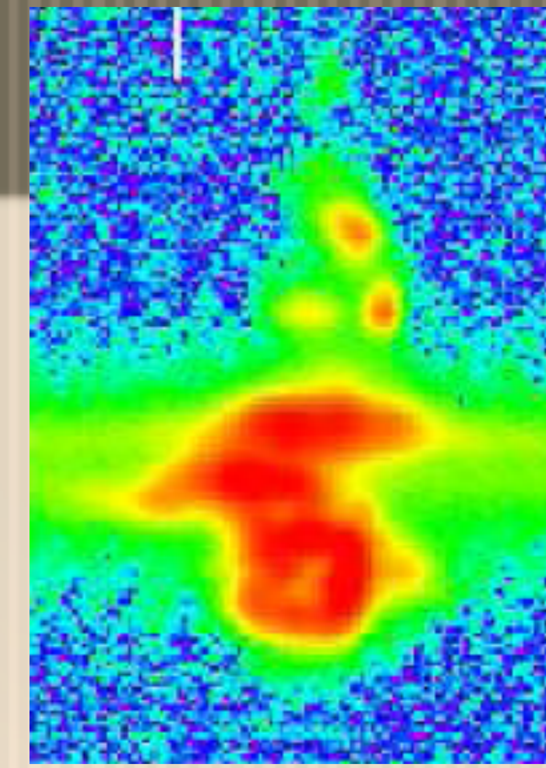


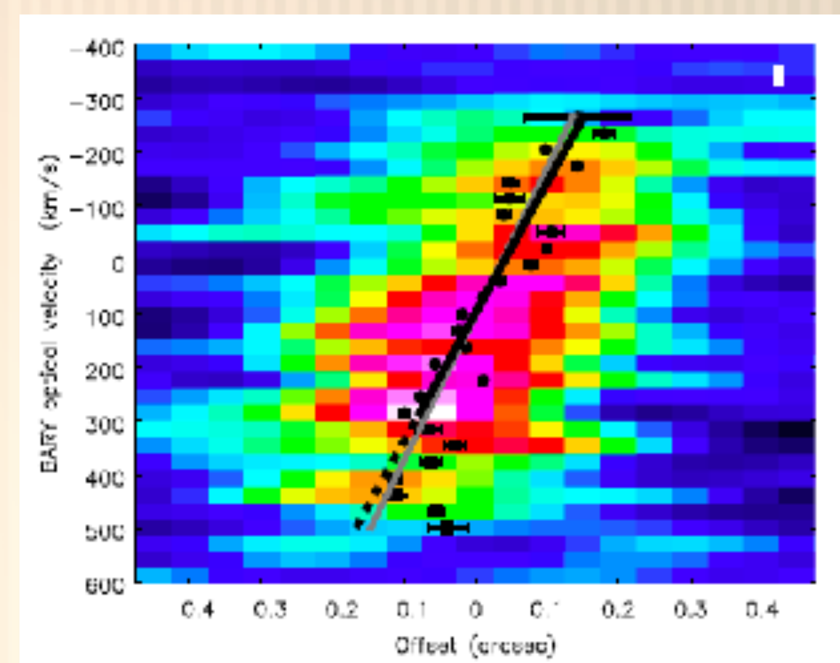
Fiore et al. 2017

3. Observations of feedback in RQ quasars: relationship between phases

- Which phase carries most mass / energy / momentum?
- Ionized gas component is probably underestimated…
- Do different tracers "see" the same outflow?
- No: The Bubble (SDSS1356)
- Ionized gas outflow, 1000 km/sec, 20 My, 20 kpc
- Molecular gas outflow, 500 km/sec, <Myr, 300 pc, different direction
- Two different AGN episodes?



Greene, NZ, Smith 2012; Greene, Pooley, NZ, et al. 2014



Sun, Greene, Zakamska, Nesvadba 2014

3. Observations of feedback in RQ quasars:
ionized / neutral gas + molecular gas data still on increase!

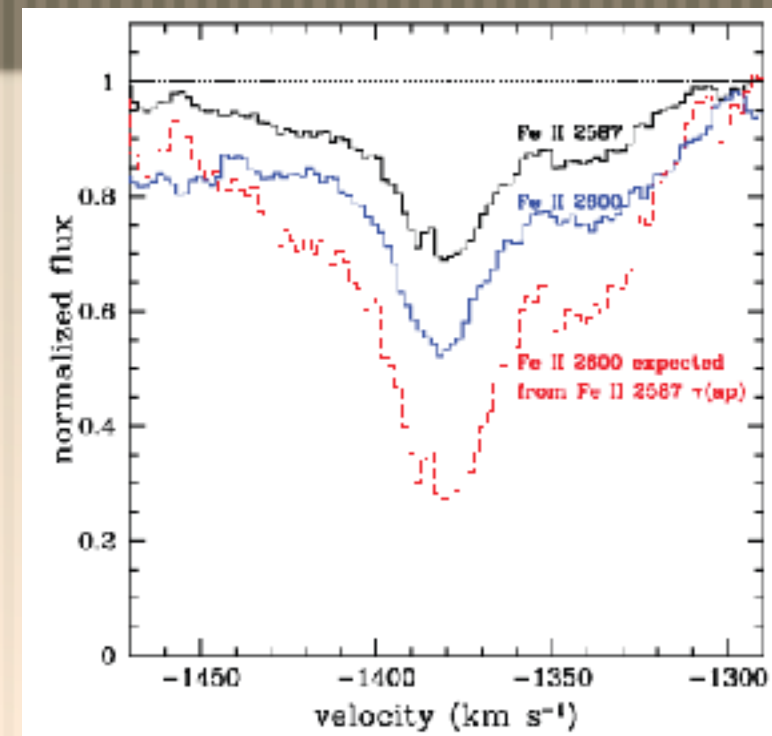
- Enormous number of IFU observations / facilities / surveys
- Califa, SAMI, MaNGA, DYNAMO, CARS, SINS, KMOS 3D, FROSS, VIRIAL
- Power of ALMA
- JWST: allow to probe high-redshift feedback, impact on host galaxy
- Approved Early Release Science program – PI Wylezalek

http://www.eso.org/~dwylezal/q3d

Q3D: PI: Wylezalek, CoPIs: Zakamska, Veilleux

3. Observations of feedback in RQ quasars: absorption line troughs

- 20% of RQ quasars show blue-shifted UV absorption lines
- Problem: to get E_{kin}, need n, r and v and f. Only v is a direct measurement.
- n, r from detailed photo-ionization models
- Detailed models ⇒ **Large E_{kin} for 25% of absorption line quasars!**



Arav et al. 2008

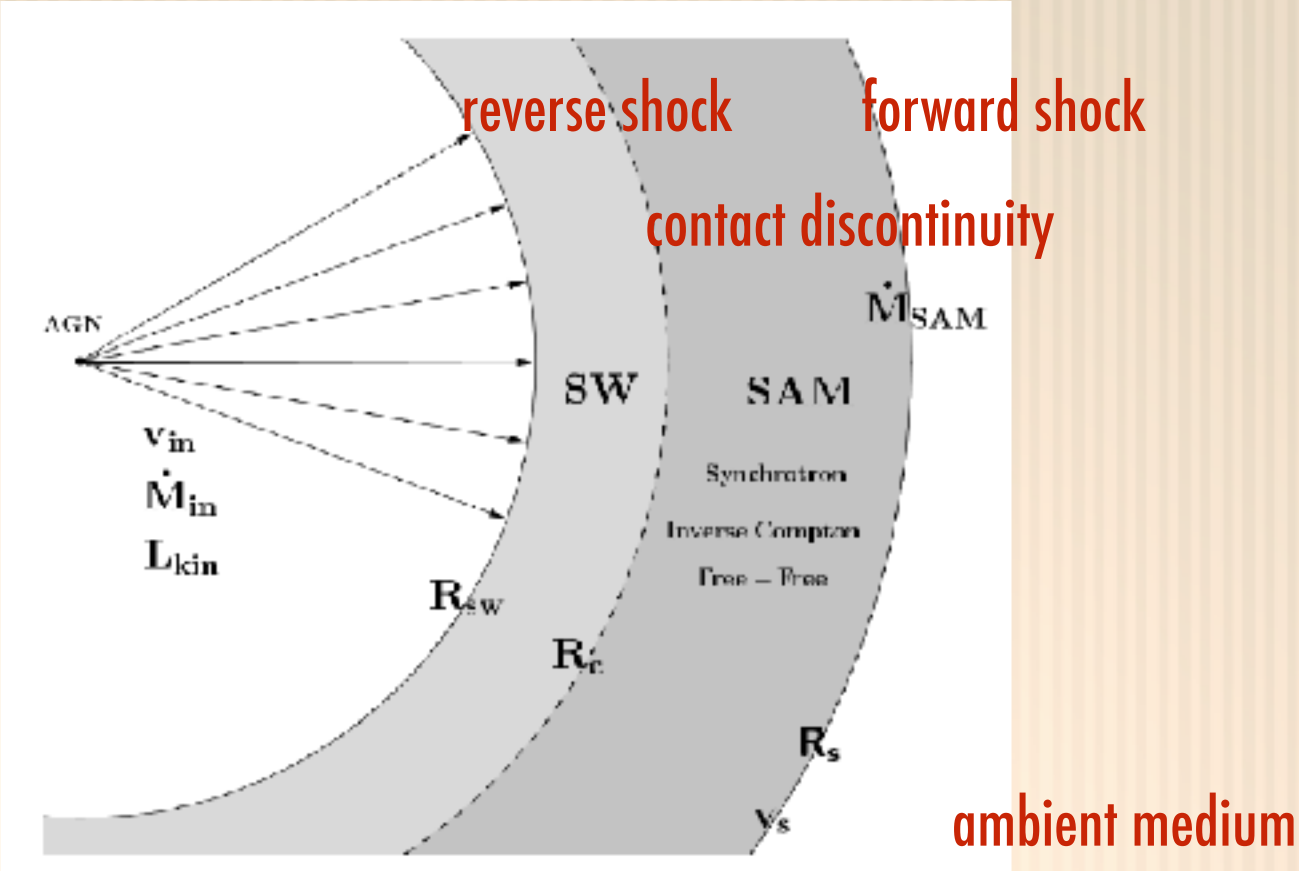
P_{kin}=4.5x10^{45} erg/sec (Moe et al. 2009)

Table 6
Outflows with Published Distances Based on High-ionization Dignostics.

Object (1)	Distance Diagnostic	log(N_H) (cm^{-2})	R (pc)	Ref
SDSS J0831+0354	S IV	22.5	110	1
SDSS J1106+1939	S IV	22.1	320	2
SDSS J1512+1119A	S IV and C III	21.9	10-300	2
SDSS J1111+1437	S IV	21.5	880	3
HE0238–1904	O IV	20.7	1700	4
SDSS J1206+1052	N III and S III	20.5	840	5
SDSS J1512+1119B	S IV	20.1	>3000	2
FBQS J0209–0438	O IV	20.0	4000	6

Arav + 2018

4. Observations of feedback in RQ quasars:
New methods to probe the volume-filling phase



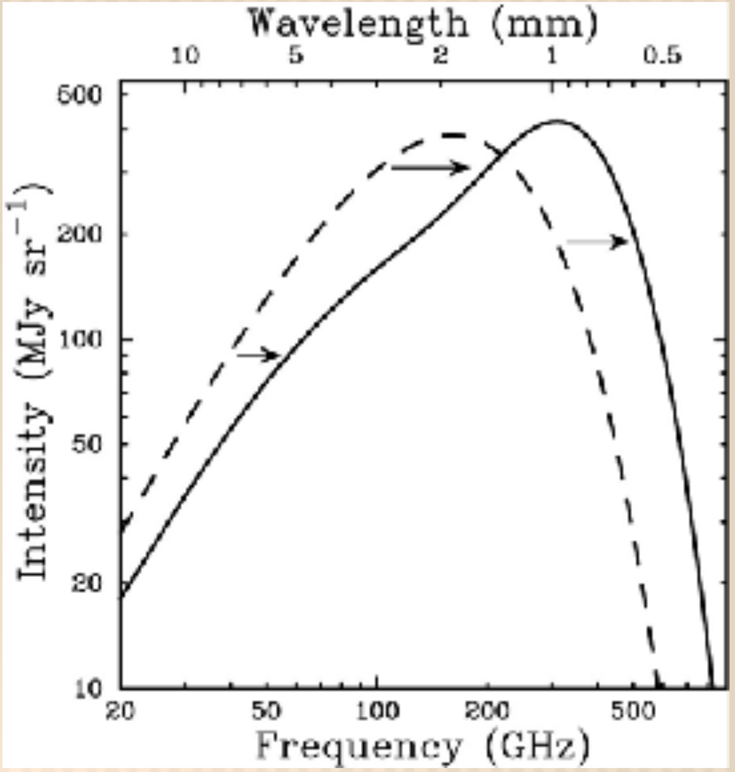
Nims & Quataert 2015

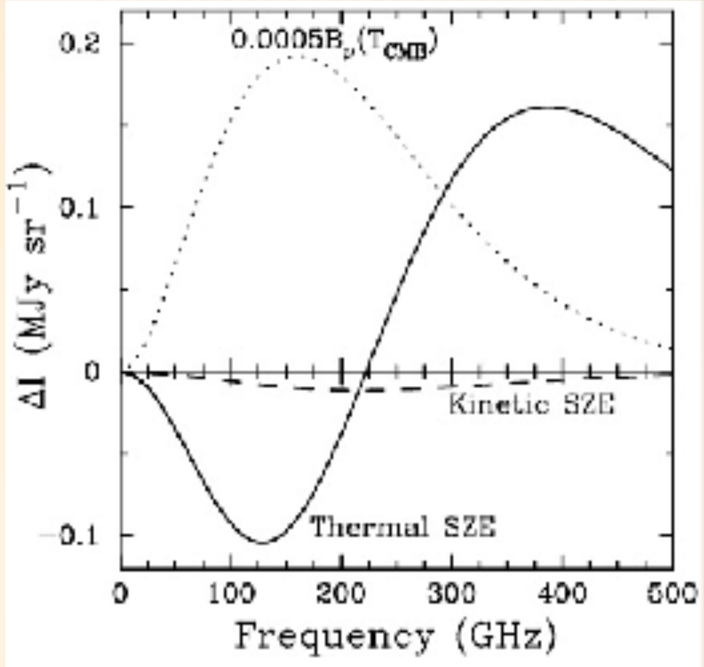
4. Observations of feedback in RQ quasars: Sunyaev-Zeldovich effect

- SZ effect: spectral distortion of the CMB photons as they scatter off hot gas
- For point sources in CMB data, sensitive to total thermal energy

$$S_{SZ}(\nu, z, \textstyle\int p dV) = I_0 g(\nu) \frac{\sigma_T}{m_e c^2} \frac{\int p dV}{D_A^2(z)}.$$

- Stacked ACT, Herschel data for 20,000 quasars in z, L bins
- Looking for extremely hot, low-density component ("bubble") invisible via other means





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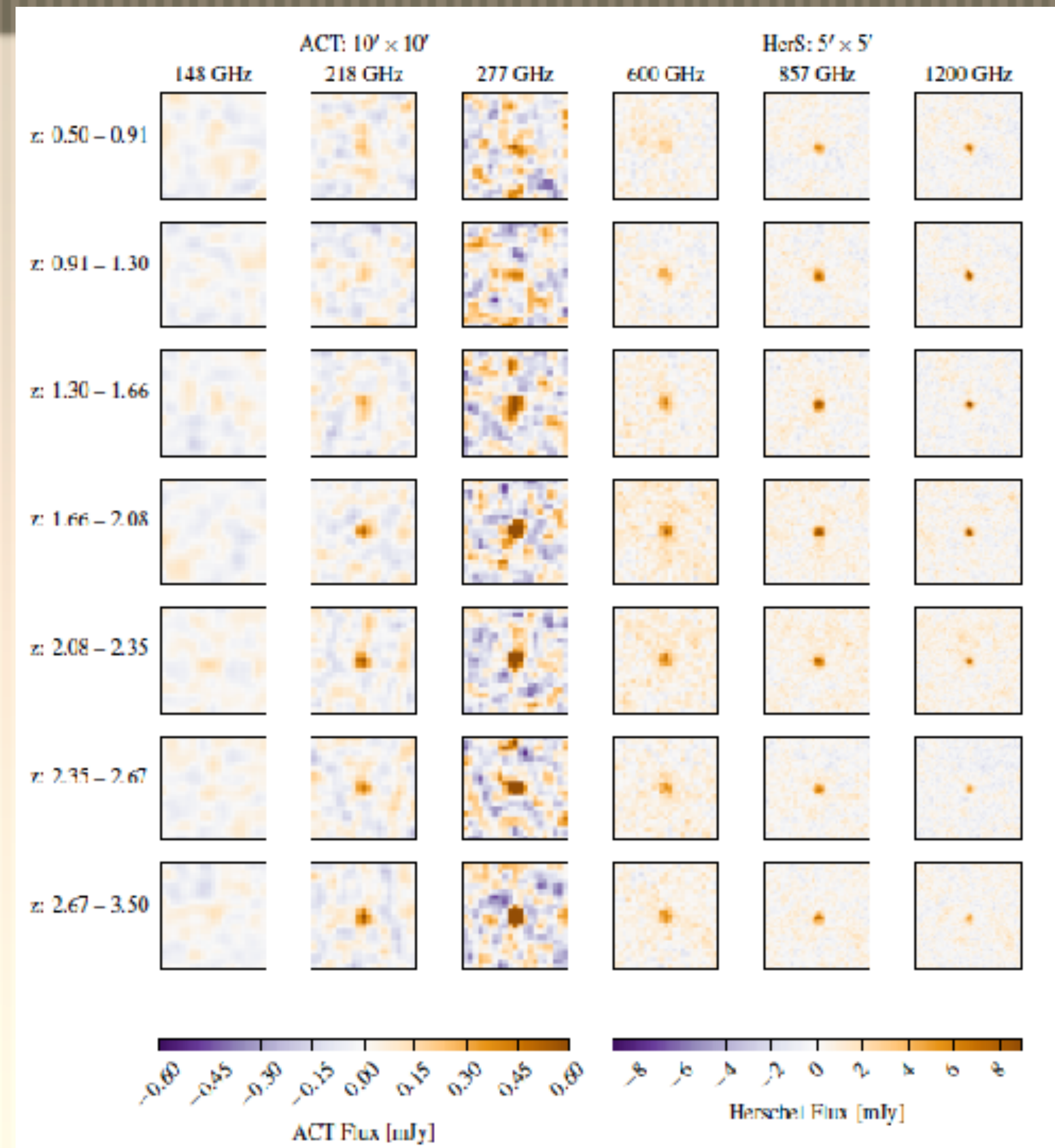
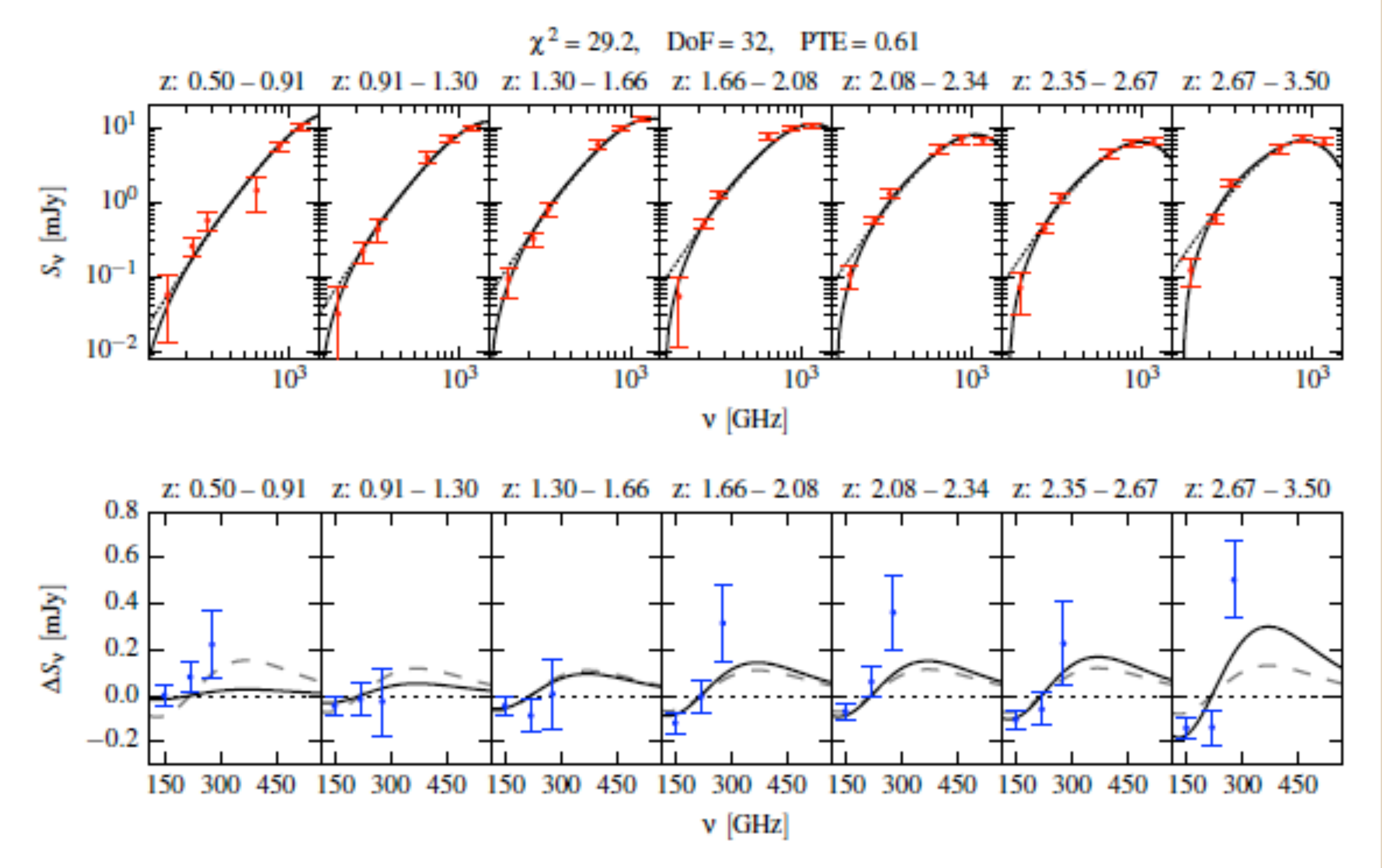
- Stacked ACT, Herschel data for 20,000 quasars in z, L bins
- Looking for extremely hot, low-density component ("bubble") invisible via other means



Crichton et al. 2016

4. Observations of feedback in RQ quasars: Sunyaev-Zeldovich effect

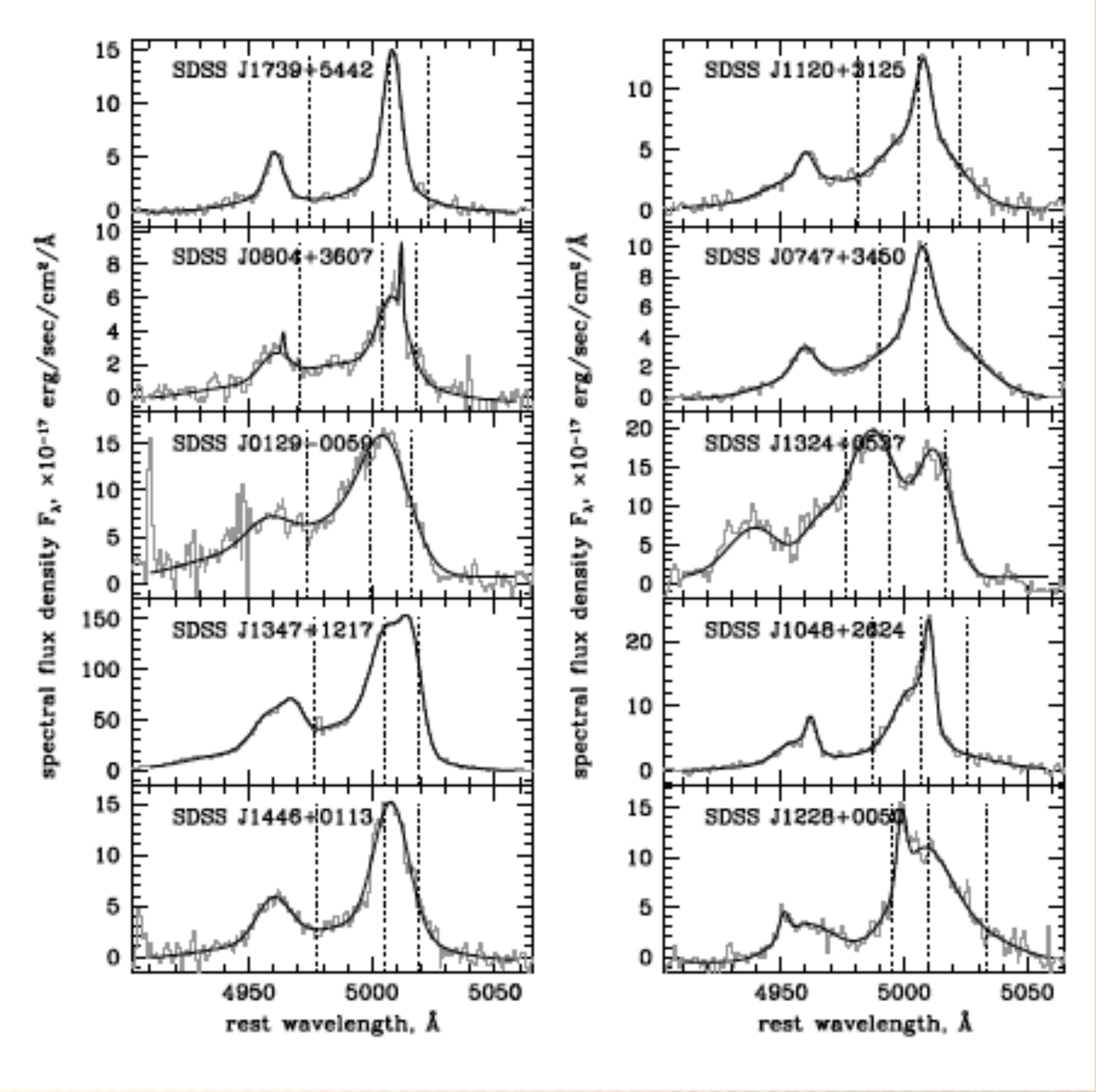
- Look for g(ν) deviations from "normal" spectral energy distribution
- 3-4 sigma detection!
- Independently achieved at the same time by Planck collaboration, different set of quasars (Verdier et al. 2016), similar amplitude
- Up to 15% of quasar luminosity goes into the hot bubble!
- This method will see enormous growth



Crichton et al. 2016

4. Observations of feedback in RQ quasars: radio emission

- Forbidden line ([OIII]) kinematics = galactic outflows
- Measure width of the 90% of line power
- In z<1 type 2 quasars, correlation between line width (=outflow velocity) and radio luminosity
- Also found by Mullaney et al. 2013 for lower luminosity AGN (stacking)
- Compact jets drive gas outflows?
- Zakamska & Greene: radiatively driven outflows produce radio as bi-product



Zakamska & Greene 2014

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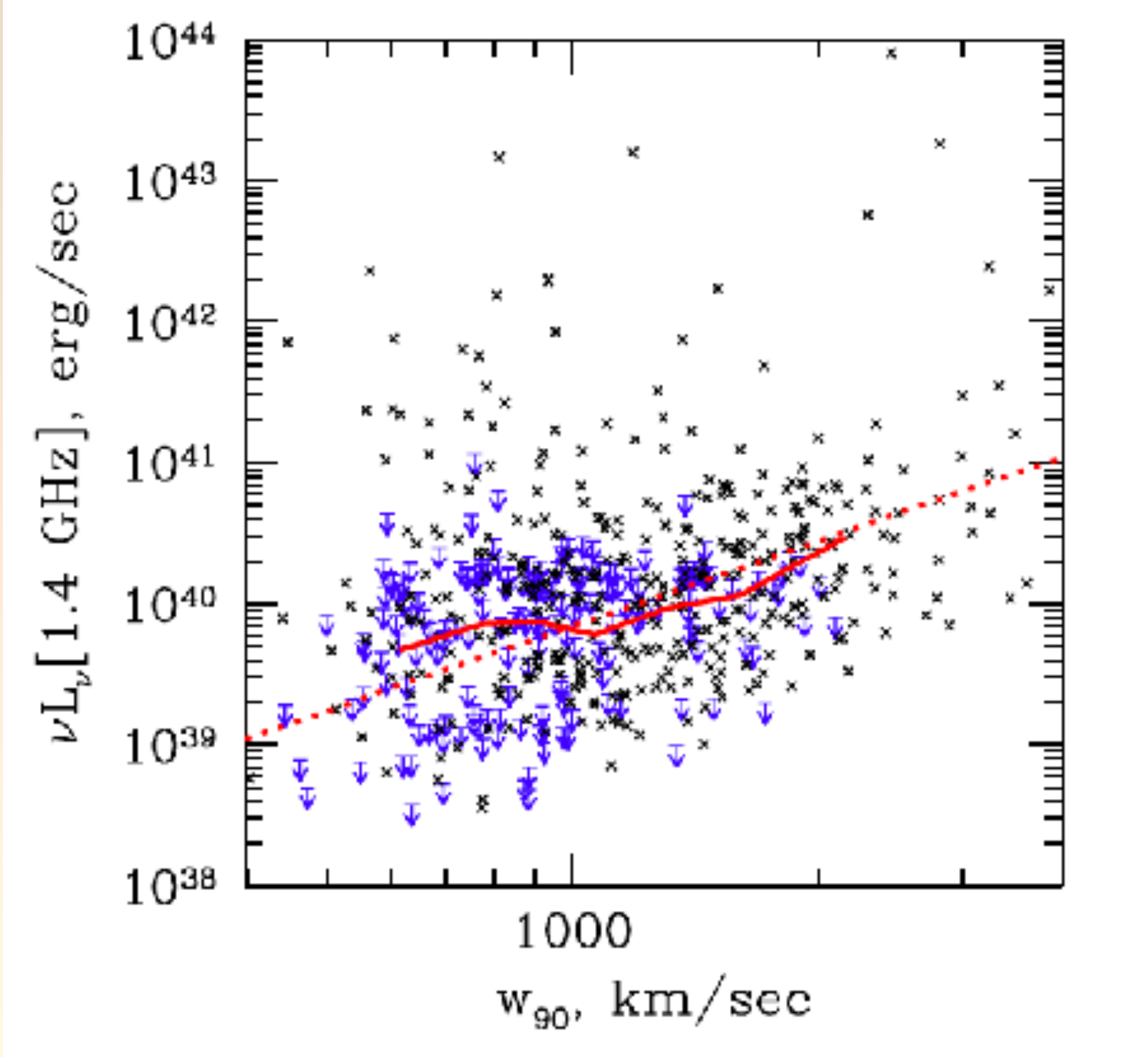

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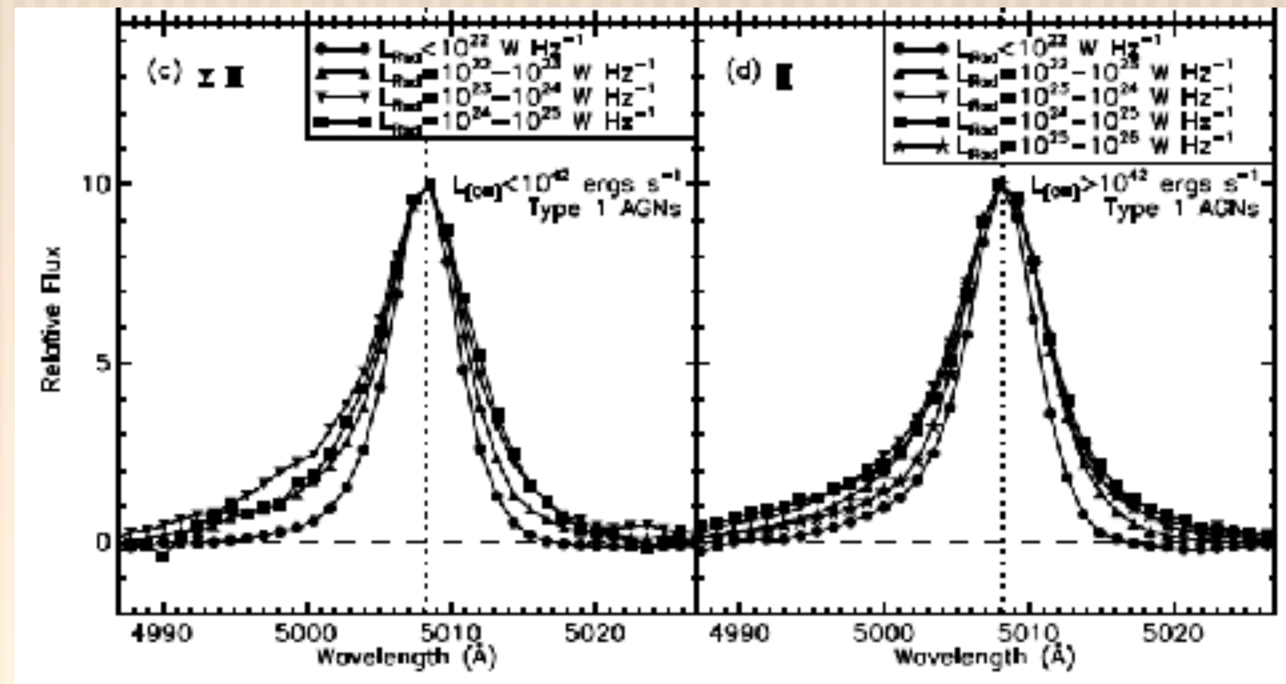

Mullaney et al. 2013

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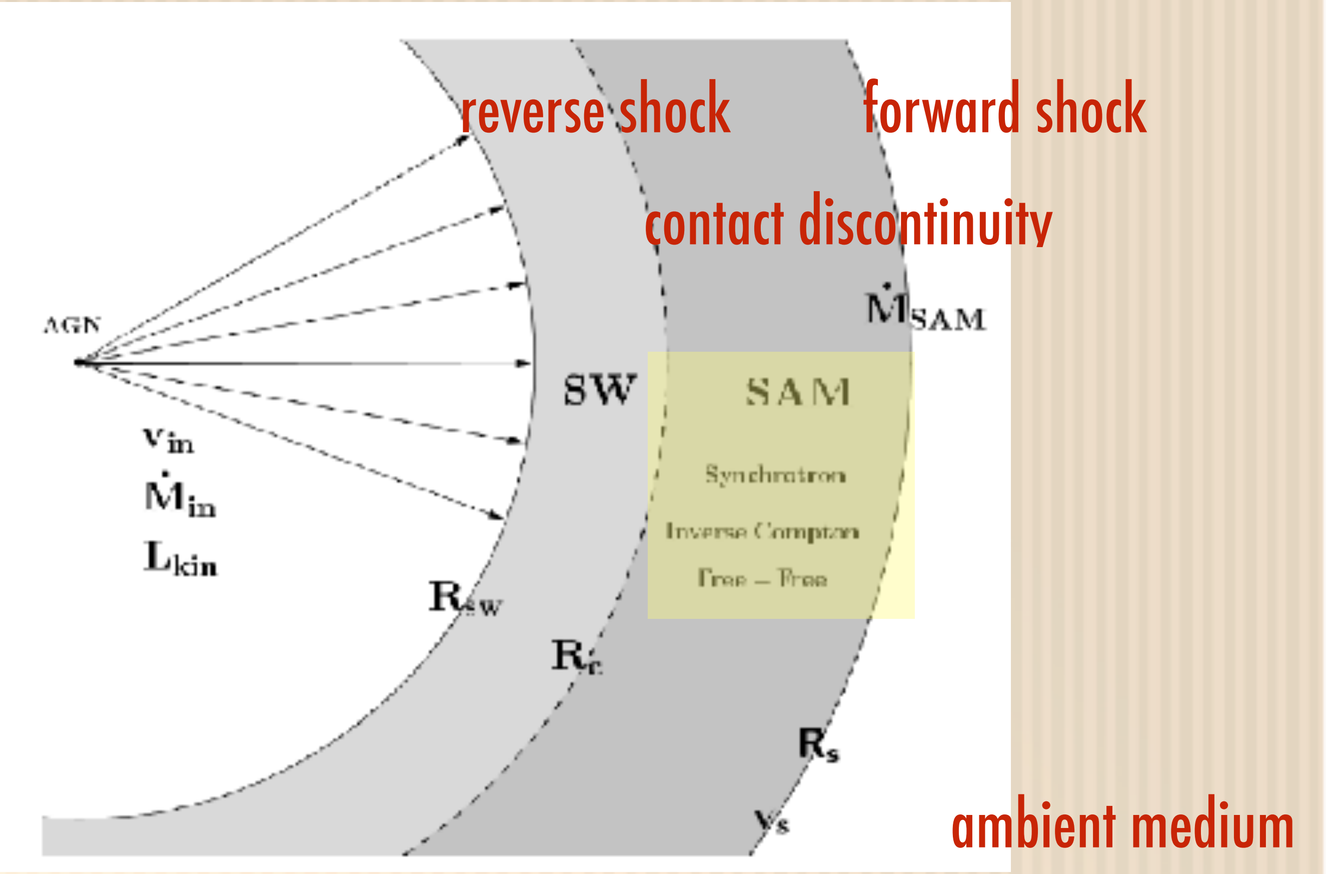
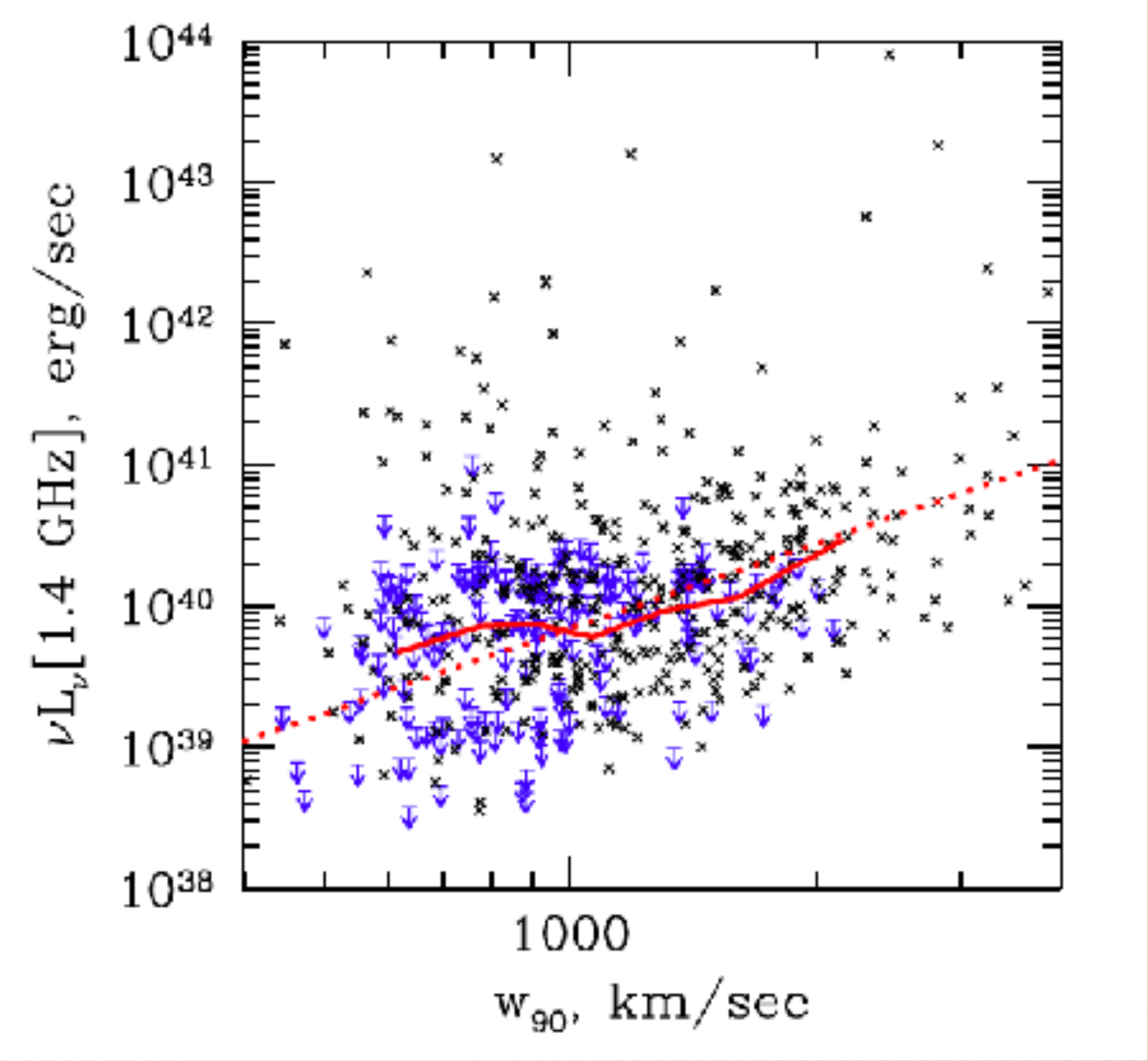


Nims & Quataert 2015

4. Observations of feedback in RQ quasars: radio emission

- Dotted line is not a formal fit
- L_{radio} proportional to w_{90}^2: conversion of kinetic energy to radio emission?
- Morphologies: point-like in FIRST
- Extended glow in high-resolution VLA!
- Need detailed radio+ionized-gas morphologies
- Tea-cup object would look like core+lobes!
- Entirely consistent with a wind



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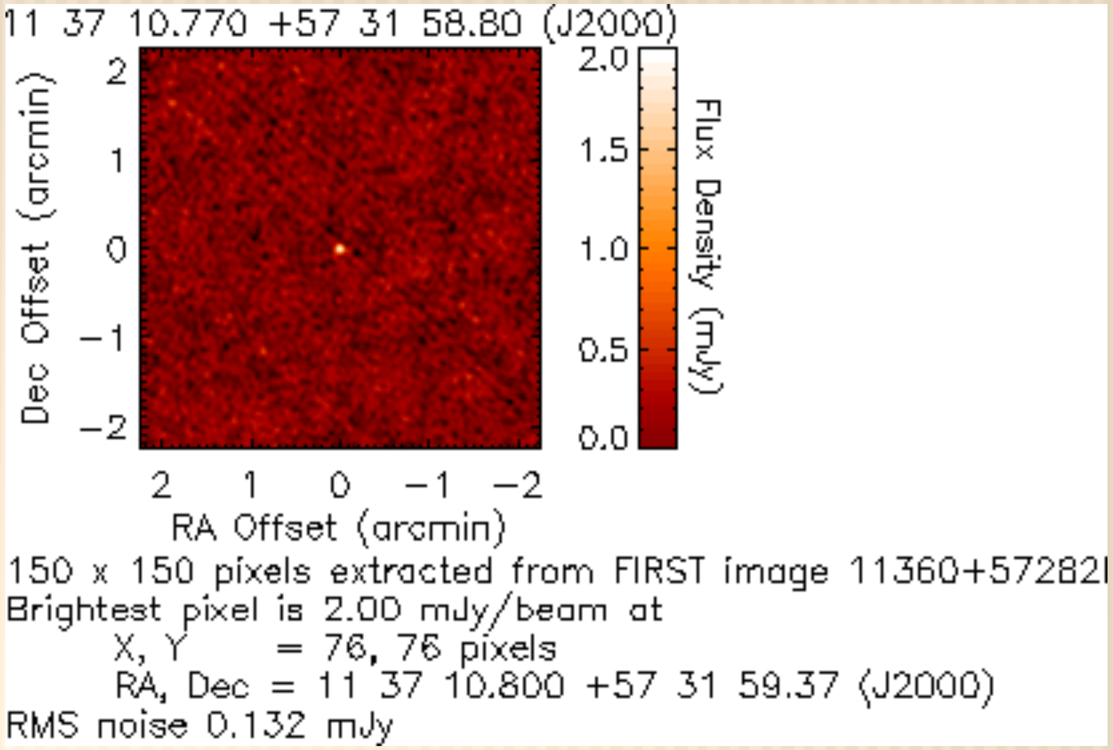

This is a very interesting object!

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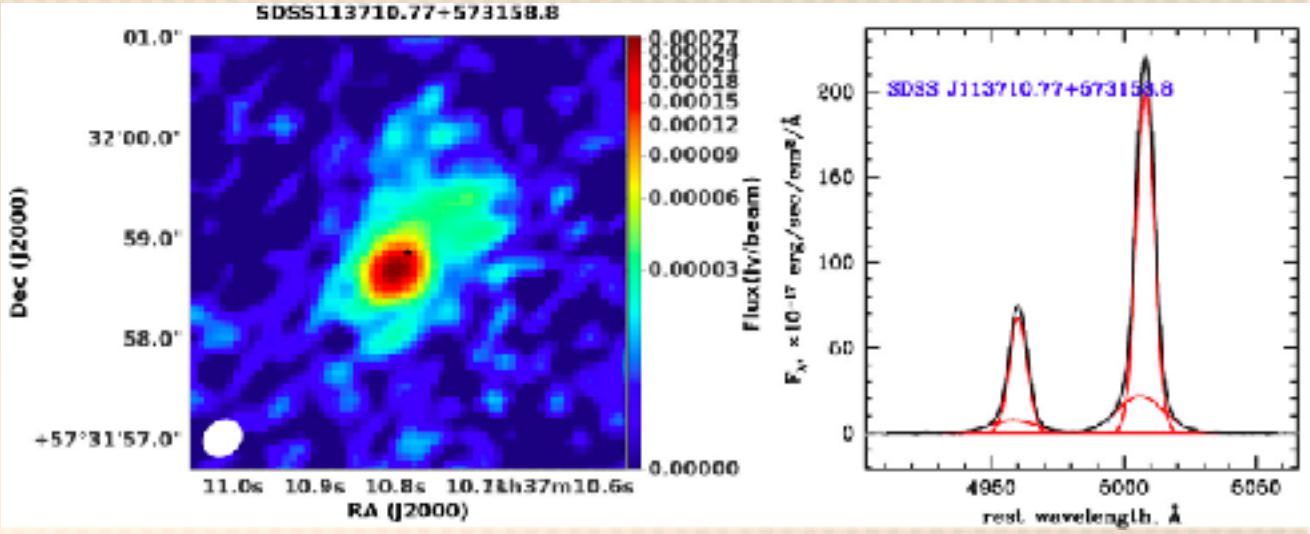

Alexandroff, Zakamska et al. 2016

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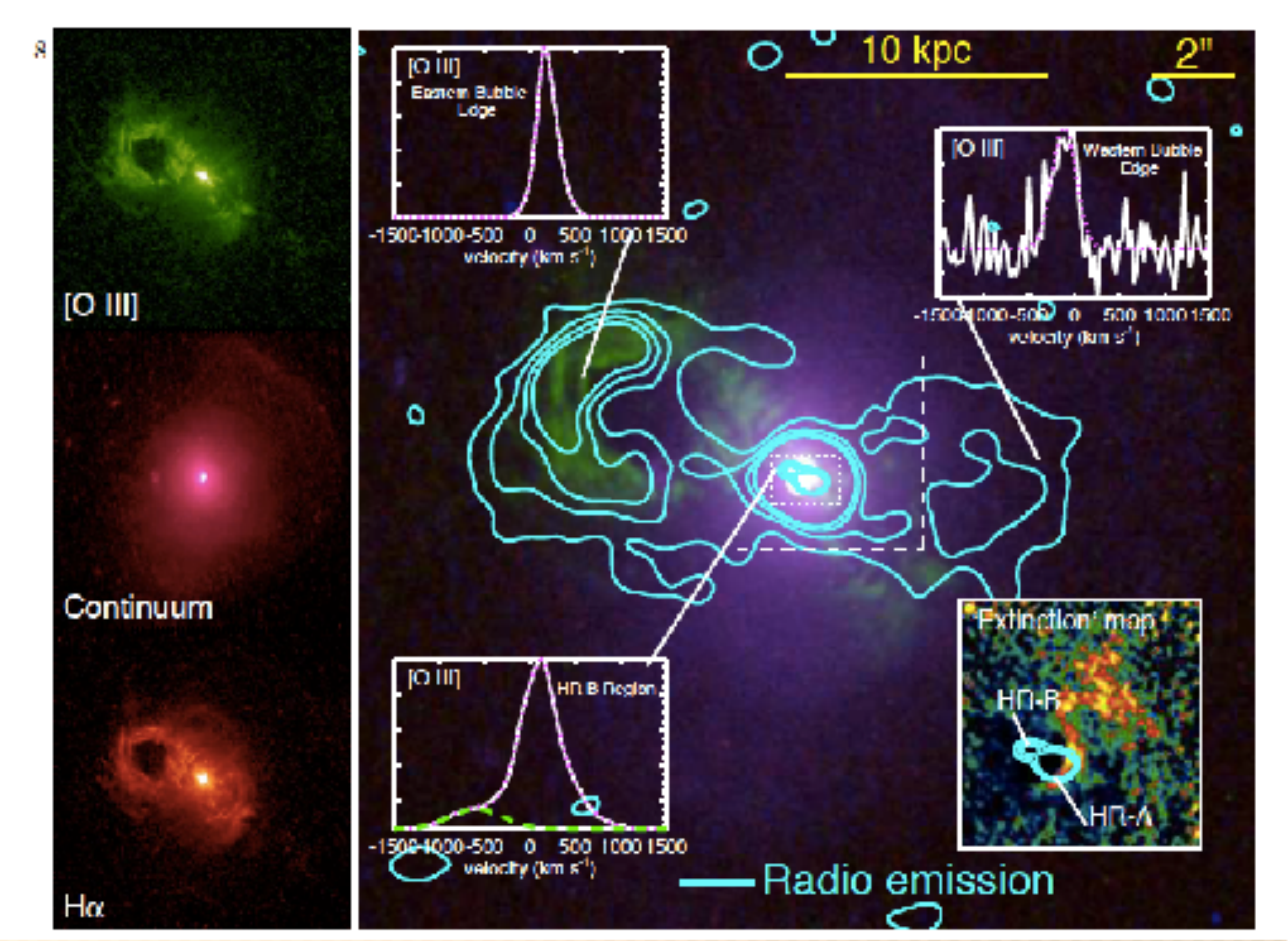

Harrison et al. 2015

Take-home message:
Core + lobes is ≠ jet

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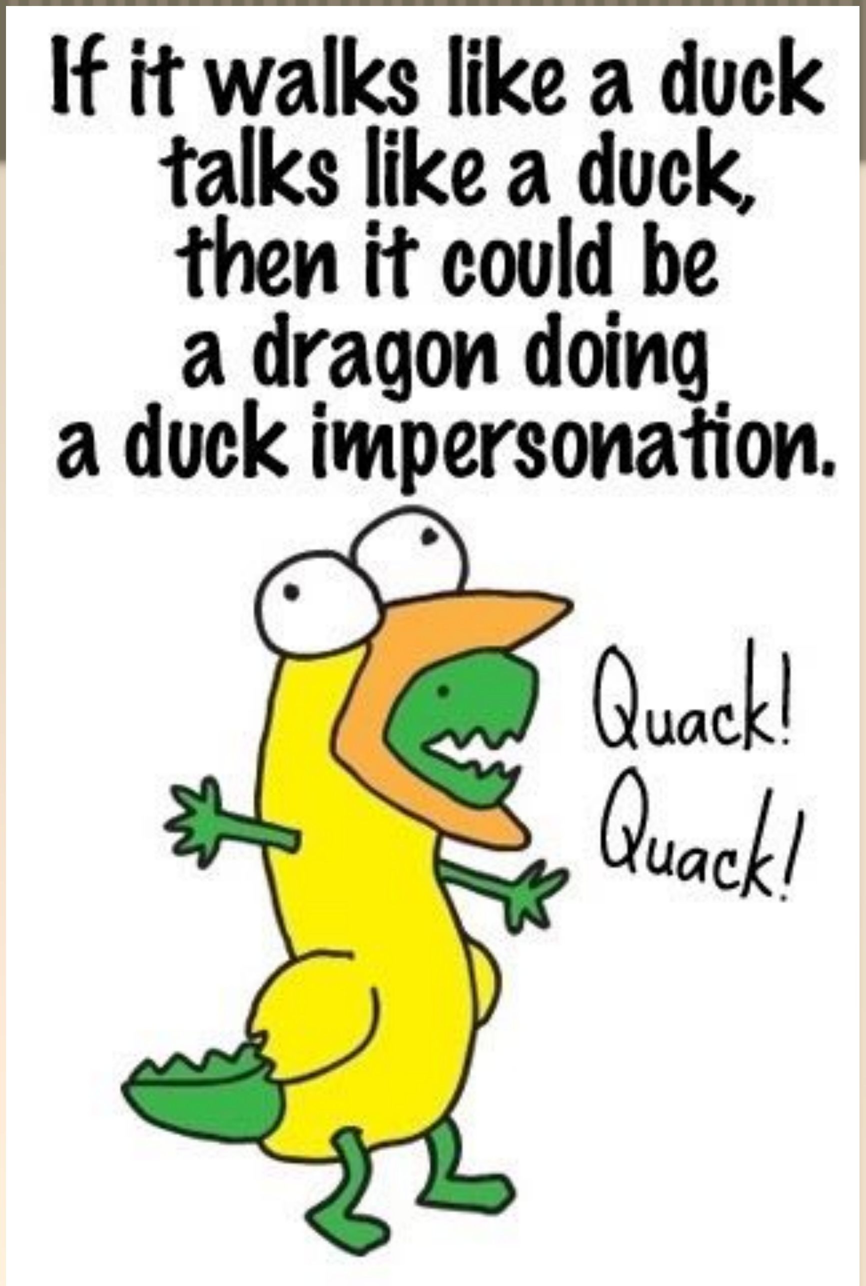
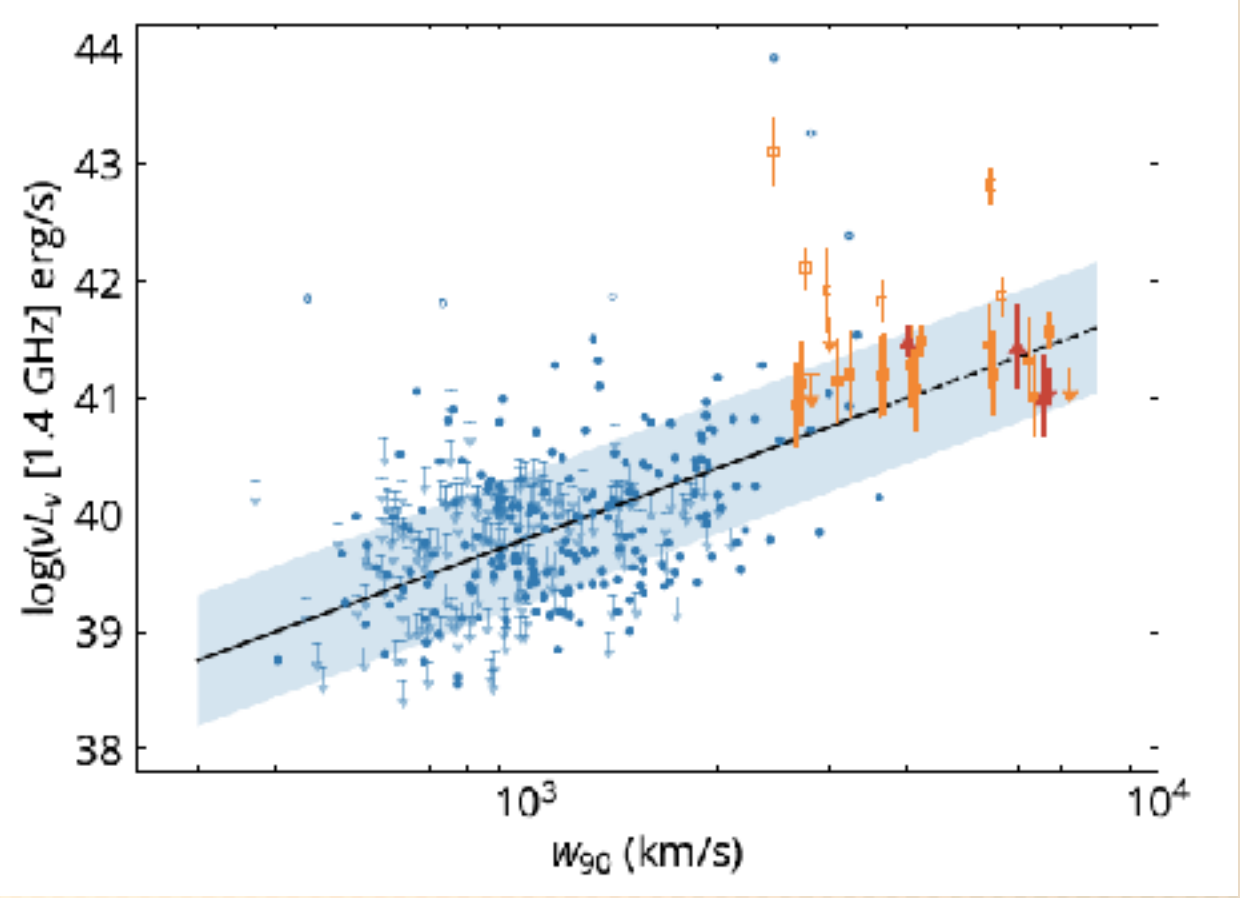


Take-home message:
Core + lobes is $\neq$ jet

4. Observations of feedback in RQ quasars: radio emission

- z<1 type 2 quasars:
- Energetics: bolometric luminosity 8e45 erg/sec ⇒ 4% conversion to wind (3e44 erg/sec) ⇒ standard ratio for star forming galaxies (1e40 erg/sec)
- z=2.5: Quasars with extreme [OIII] outflows have correspondingly high radio luminosities
- Quasars at z=2.5 without extreme [OIII] outflows are also on the correlation
- Hypothesis: In powerful RQ quasars radio emission is a bi-product of quasar-driven winds



Hwang, Zakamska et al. 2018
Alexandroff, Zakamska et al. 2016

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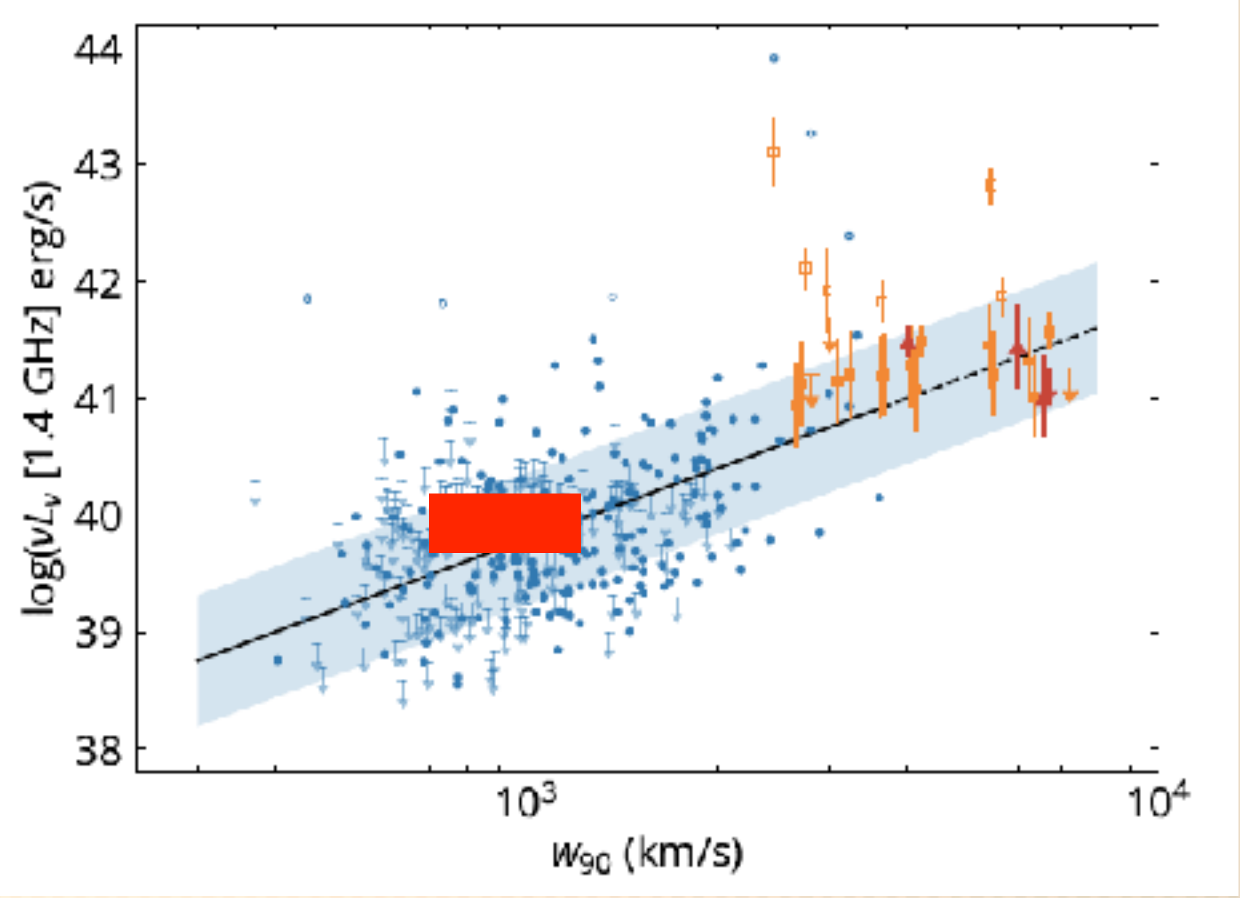
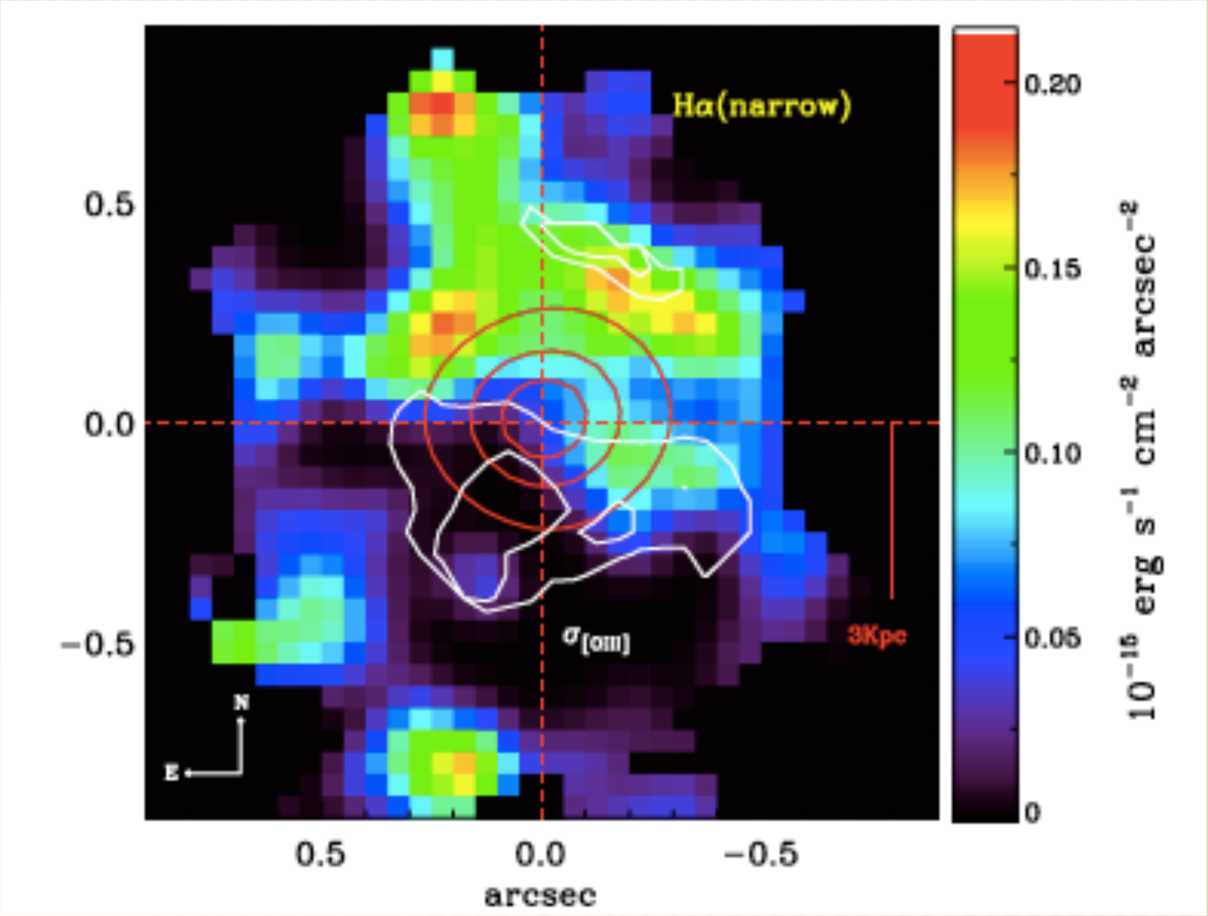


Hwang, Zakamska et al. 2018
Alexandroff, Zakamska et al. 2016

5. What is the impact of quasar winds on galaxies?

Options

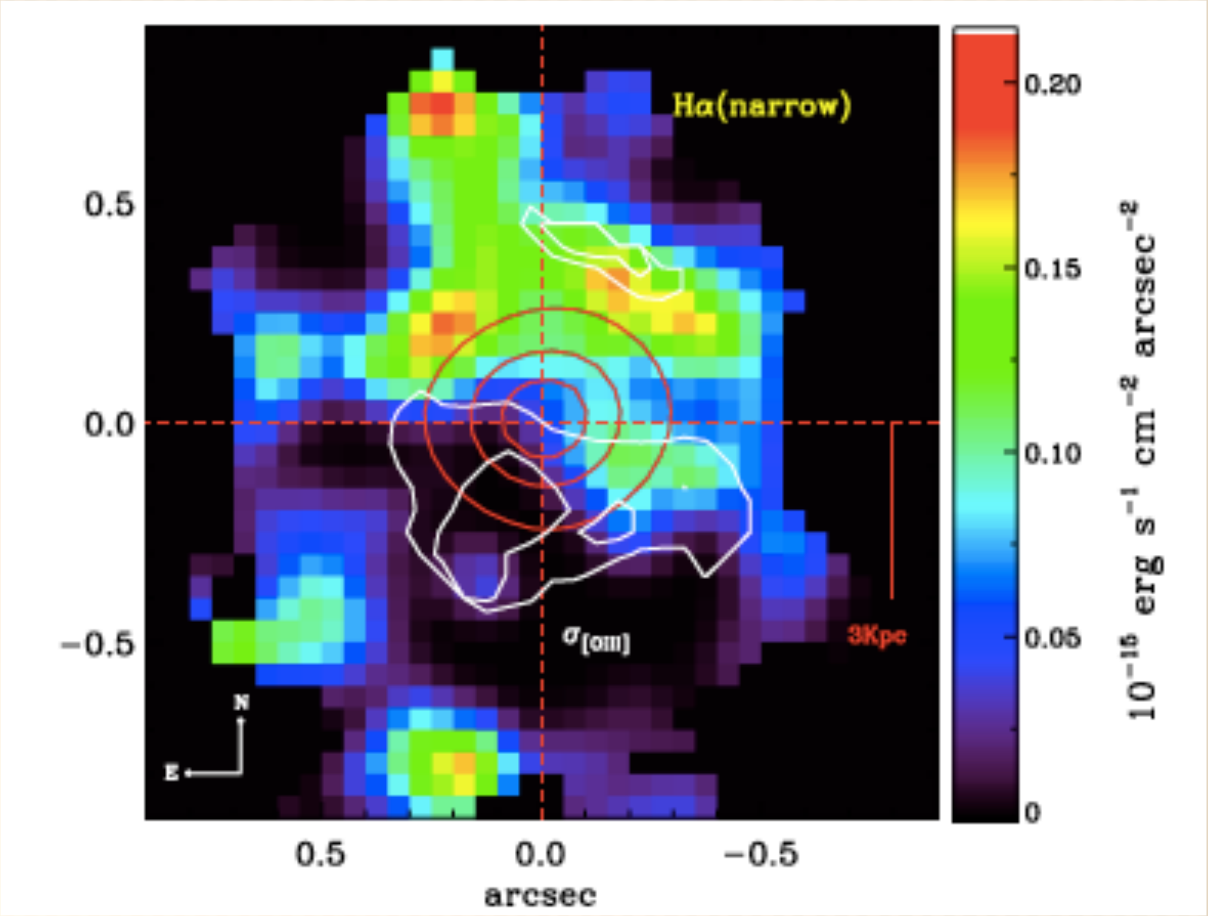
- Negative feedback: star formation suppressed (gas reheated, removed)
- Positive feedback: star formation enhanced (clouds are pressure-collapsed)
- Galaxy formation says: negative feedback should dominate!



Cano-Diaz et al. 2012

5. What is the impact of quasar winds on galaxies?

- Examples of negative feedback: Cano-Diaz et al. 2012
- Examples of positive feedback: "alignment effect" in radio jets, also Maiolino et al. 2017 for RQ
- Measuring star formation rate in quasar host galaxies is very difficult!



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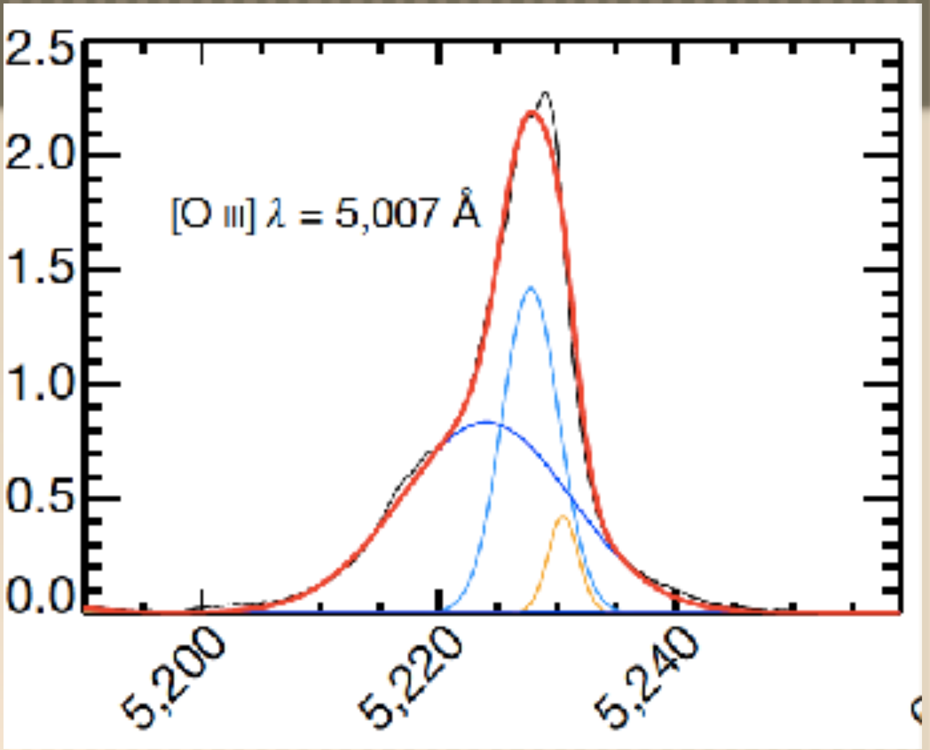

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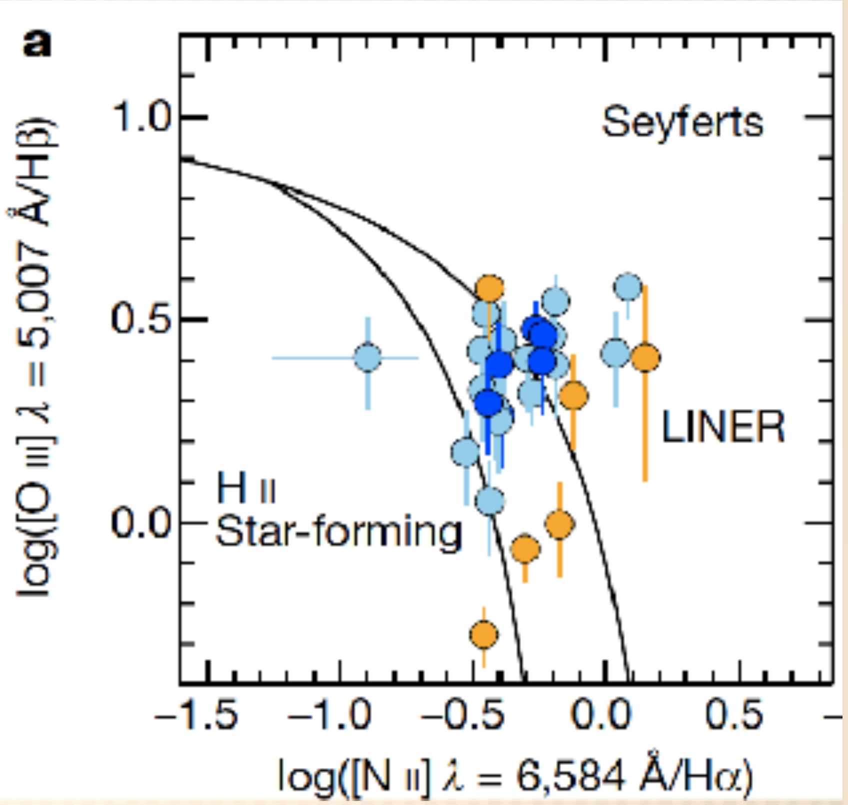
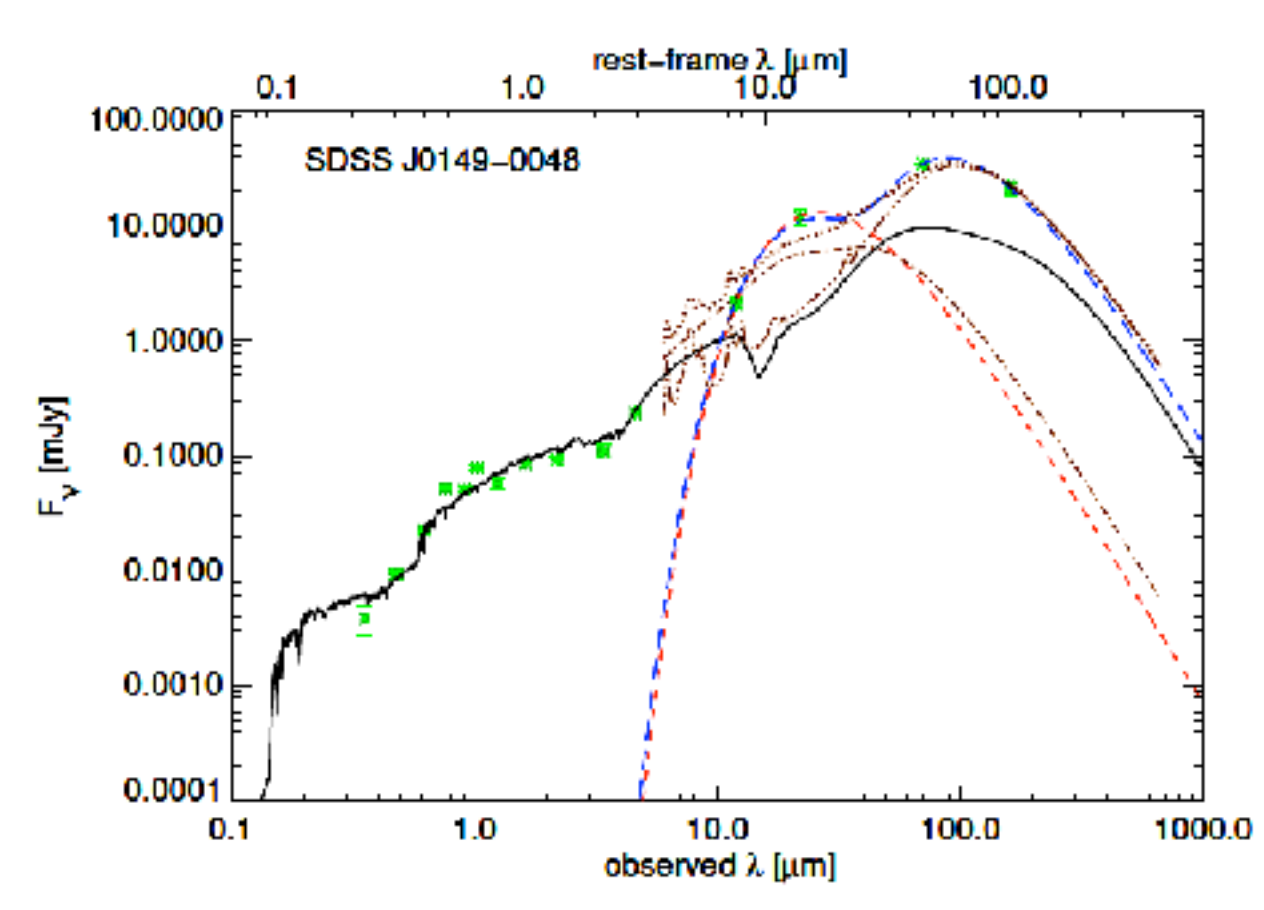


Maiolino et al. 2017

5. What is the impact of quasar winds on galaxies?

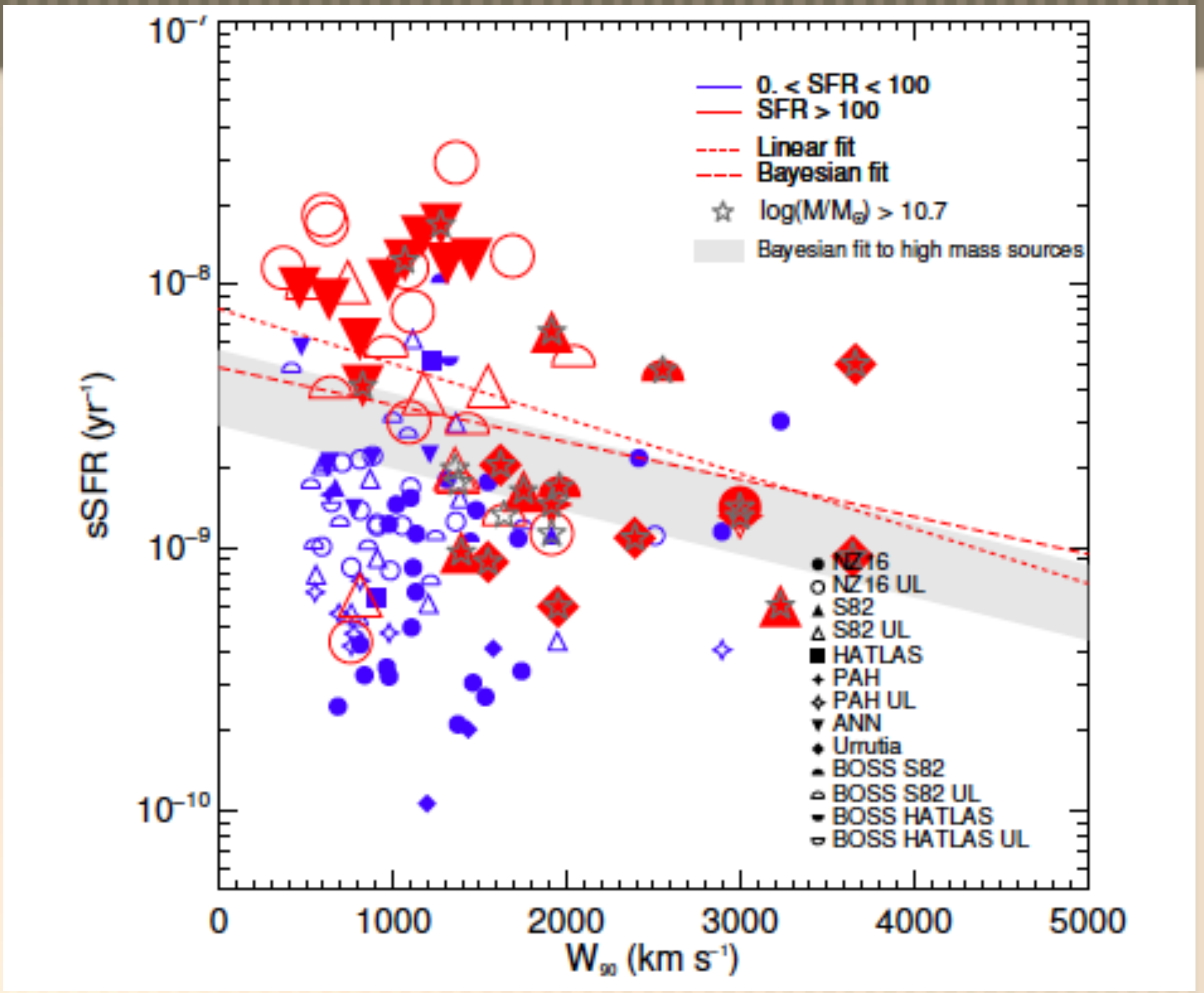
- Measuring star formation rate in quasar host galaxies is very difficult!
- Ionized gas diagnostics = "fried" (optical, NIR, MIR)
- PAHs suppressed by destruction (Diamond-Stanic et al.)
- The lesser evil: SED decomposition + FIR luminosities (Zakamska et al. 2016a)
- Usually dominated by SFR, but there are exceptions on the luminous end



Wylezalek, Zakamska et al. 2016
Zakamska et al. 2016a

5. What is the impact of quasar winds on galaxies?

- Despite molecular outflows, surprisingly little evidence of negative feedback on SFR! (Balmaverde et al. 2016)
- Wylezalek & NZ: Collected a large sample of quasars with good SEDs
- Strong suppression of specific star formation rate
- As a function of wind kinematics
- But only for the most gas-rich objects
- (perhaps the best coupling?..)

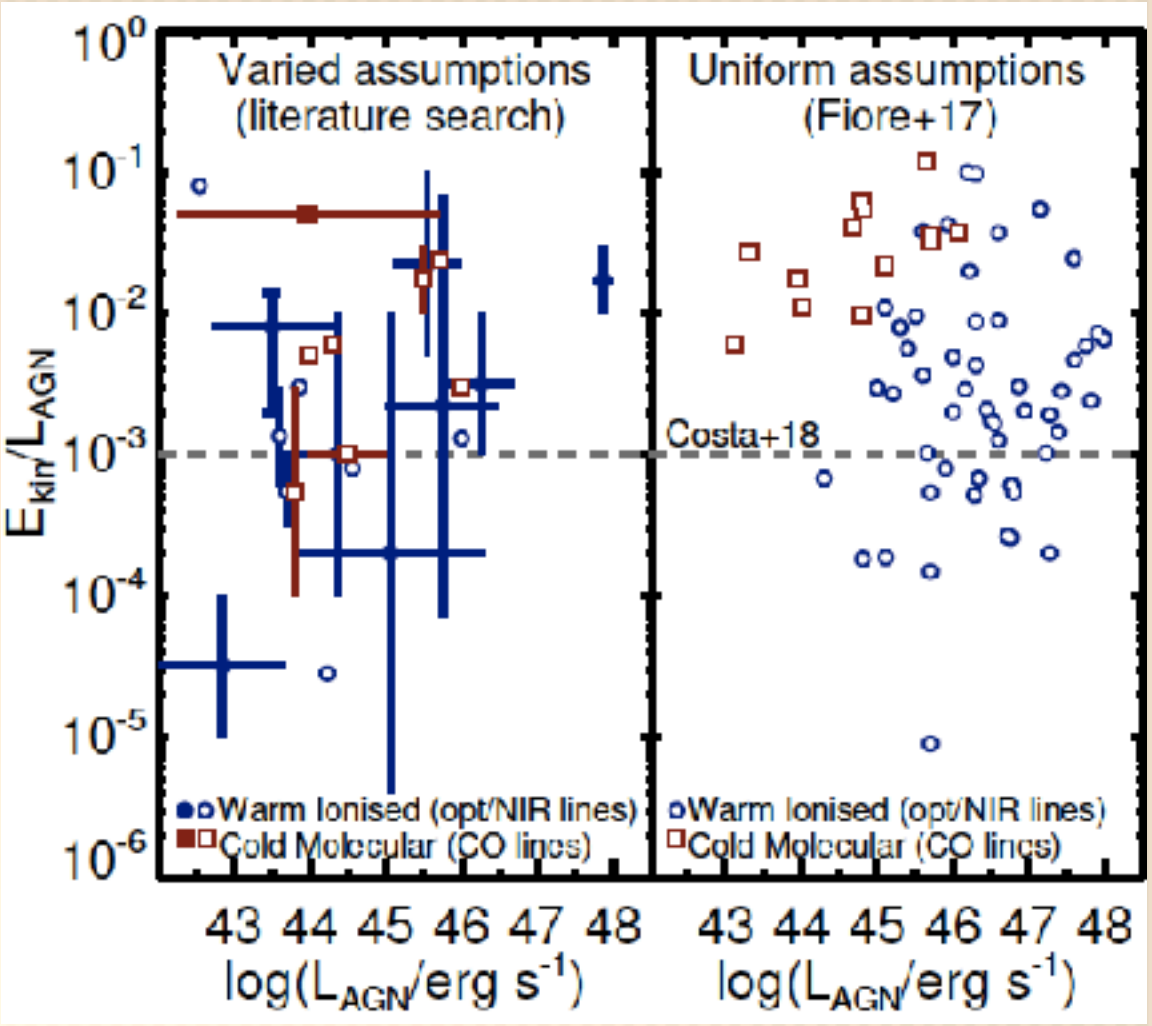


wind kinematics, km/sec

Wylezalek & Zakamska 2016

6. Unsolved issues, comparison with simulations

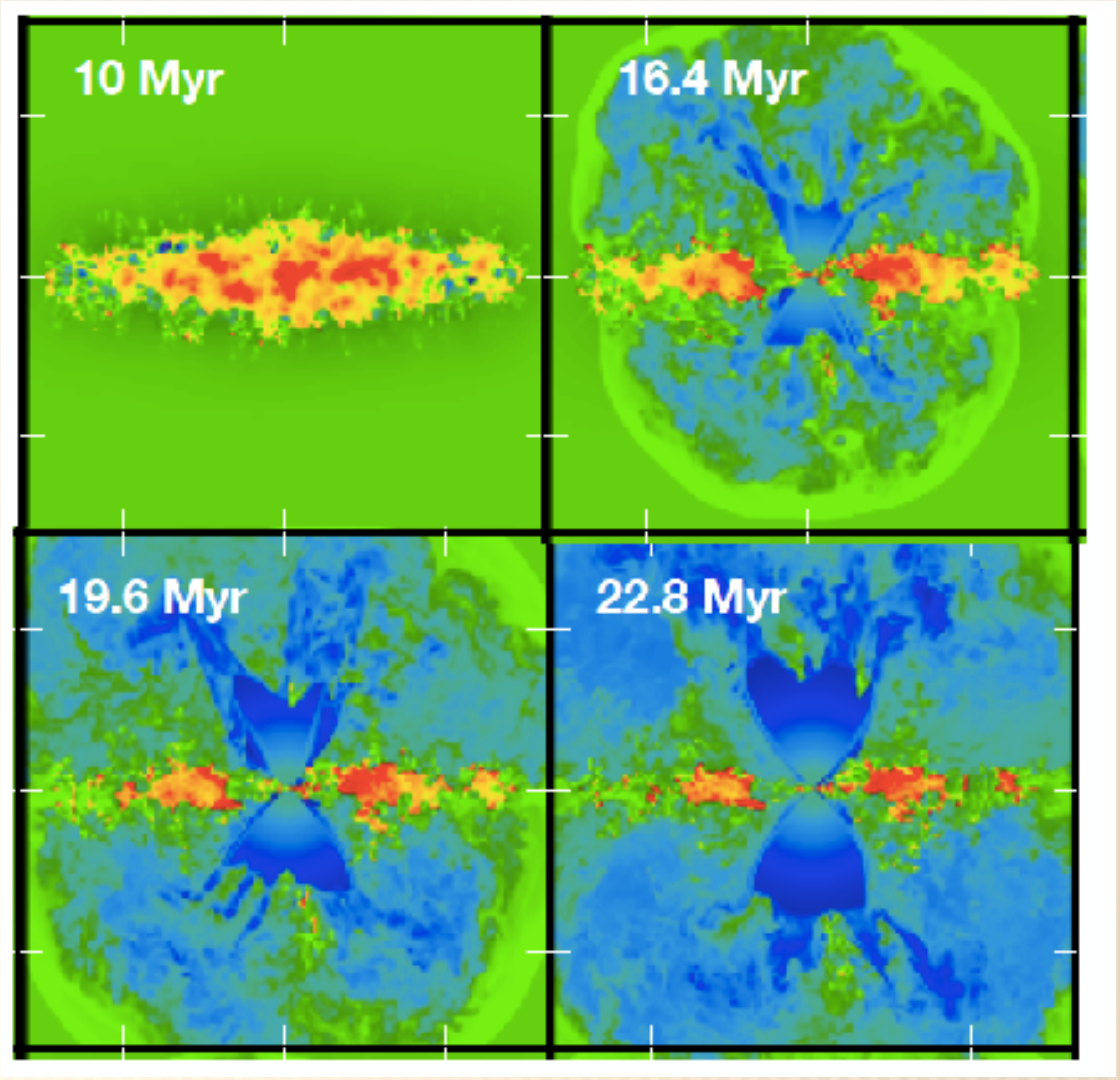
- Mass, energy measurements remain a problem for every observational method (Harrison et al. 2018 Nature Astronomy)
- Several methods available for [OIII], use them all and compare! (talk to me!)
- Also difficult for molecular gas (the X-factor, the AGN affects the excitation diagram, optical depth)
- Compare different tracers in the same objects! Different episodes?
- SZ effect, radio are promising new methods



Harrison et al. 2018

6. Unsolved issues, comparison with simulations

- Comparison with simulations:
- With emission, absorption lines we are observing the densest clouds in low-density faint medium
- 100-1000 cc: Not yet accessible to (most?) galactic simulations?
- I think velocity fields can be directly compared (test the convergence first)
- Ideally include photo-ionization into your simulations (again density is a problem)
- Additional physics being put in for molecular outflows (Richings & Faucher-Giguere 2018)



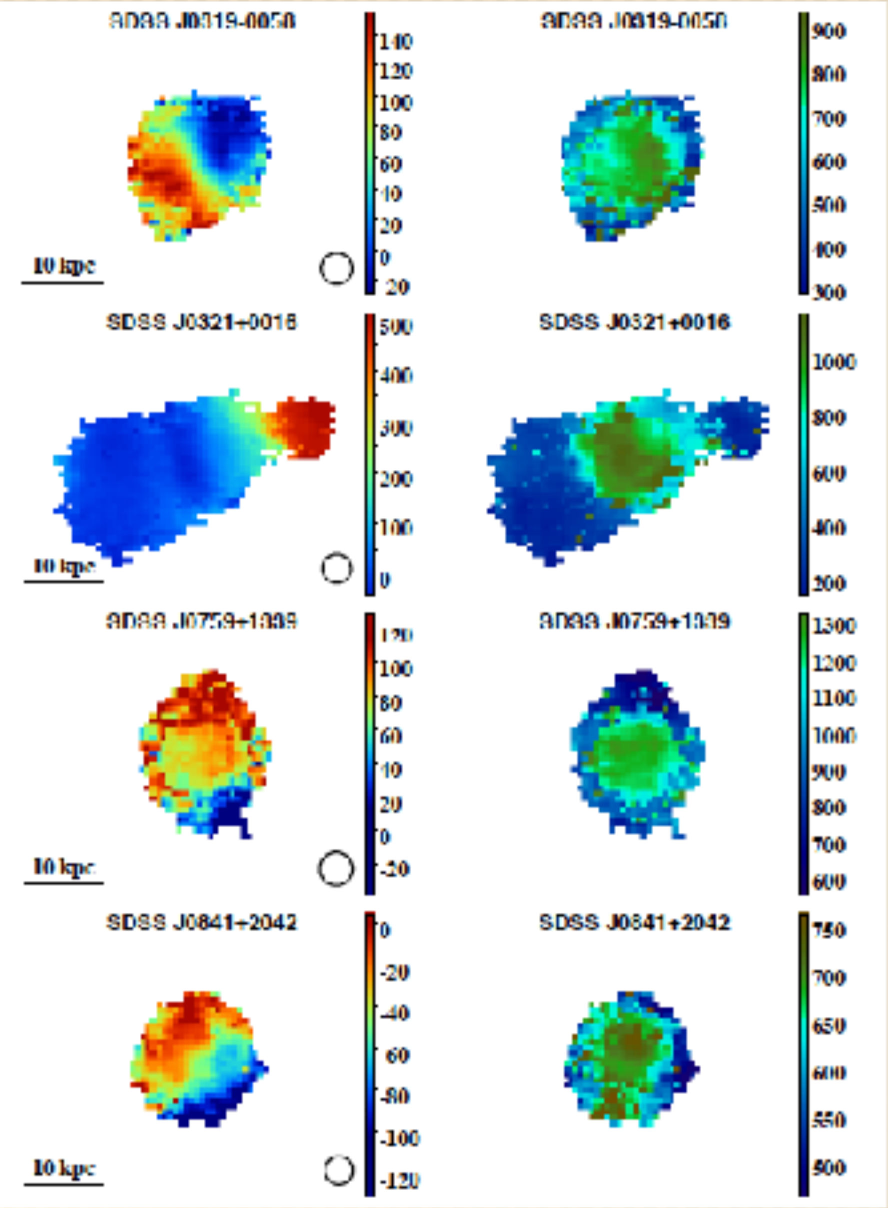
Dugan et al. 2017

6. Unsolved issues, comparison with simulations

- SZ observations can and should be compared to simulations
- Simulations are ahead of observations, but more groups are getting involved
- Radio: very little known about the theory, all spherically symmetric (Jiang et al. 2010, Nims & Quataert 2015)
- Observed energies in good agreement with theory
- But need better theory

Summary

- Powerful galactic winds with P_{kin} of a few per cent of L_{AGN} have been detected!
- RL and RQ quasars
- Emission line, absorption line diagnostics of ionized, neutral and molecular phases – extremely rapidly growing field
- Example – Extremely red quasars: on the extreme end of the velocity if ionized gas winds
- Mass / energetics still uncertain!
- New interesting probes: SZ, radio – these phases are not detectable in other ways.



Liu, Zakamska et al. 2013