Observational evidences of AGN feedback

Chiara Feruglio
(IRAM, Grenoble)

AGN11, Trieste September, 23 2014

Outline

1- Observational evidences of AGN feedback in action (not outflows!) , near and far, review recent results

2- How they compare with model predictions

3- Open questions

4- What is needed to progress

Three key questions

Three key questions

- Why did galaxies during their evolution stop to form stars?

Three key questions

- Why did galaxies during their evolution stop to form stars?
- What are the mechanisms leading the transition from gas rich, star-forming, galaxies, to passive spheroids, deprived of most of their gas?

Three key questions

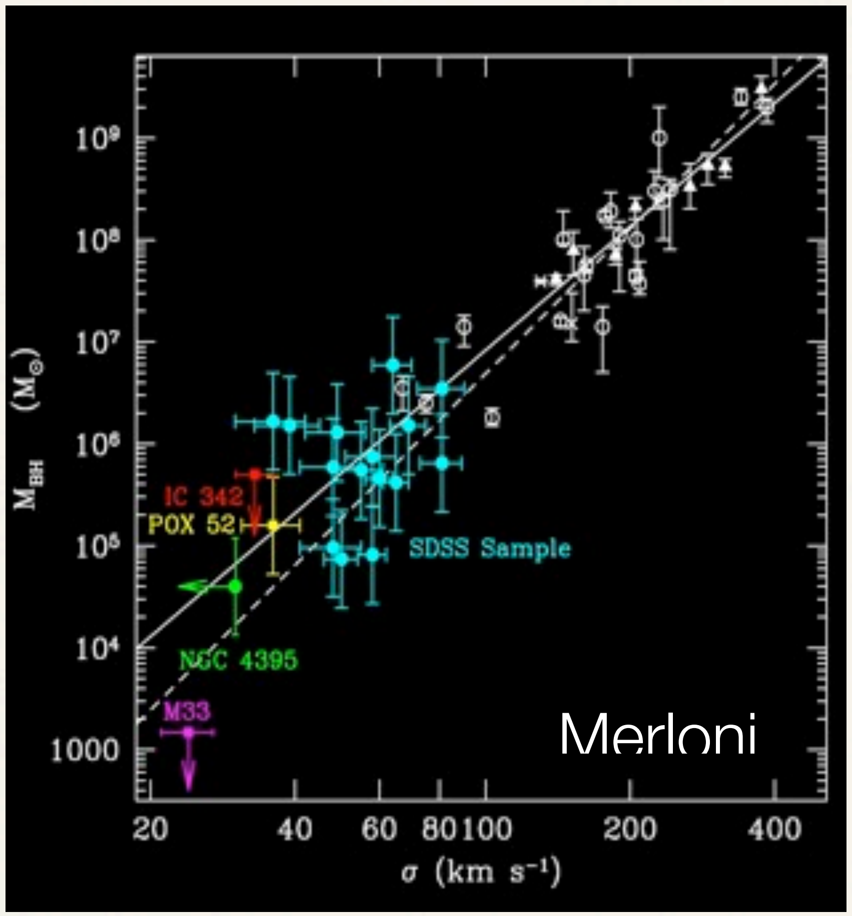
- Why did galaxies during their evolution stop to form stars?
- What are the mechanisms leading the transition from gas rich, star-forming, galaxies, to passive spheroids, deprived of most of their gas?
- Why black holes in galactic nuclei have masses proportional to spheroid masses?

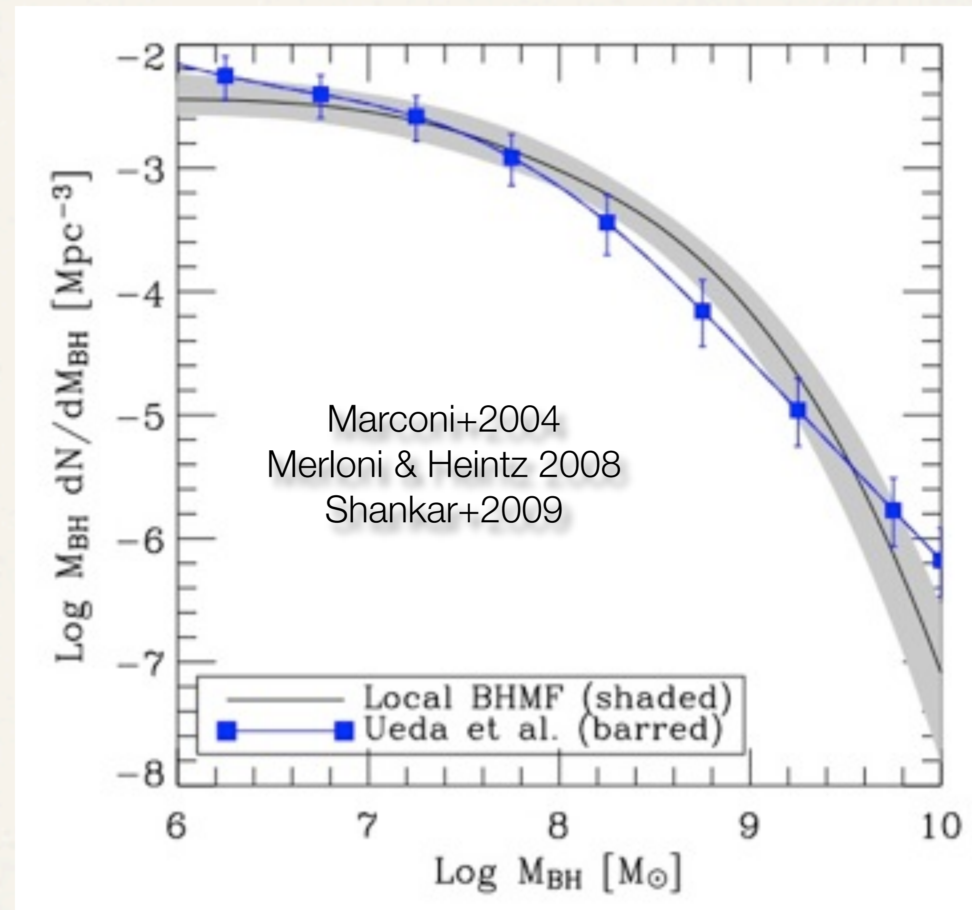
Three key questions

- Why did galaxies during their evolution stop to form stars?
- What are the mechanisms leading the transition from gas rich, star-forming, galaxies, to passive spheroids, deprived of most of their gas?
- Why black holes in galactic nuclei have masses proportional to spheroid masses?

One of the main candidate for driving these transformations are **powerful winds and shocks** launched from accreting black holes in active galaxy nuclei (i.e. feedback)

SMBH and stellar growth correlated





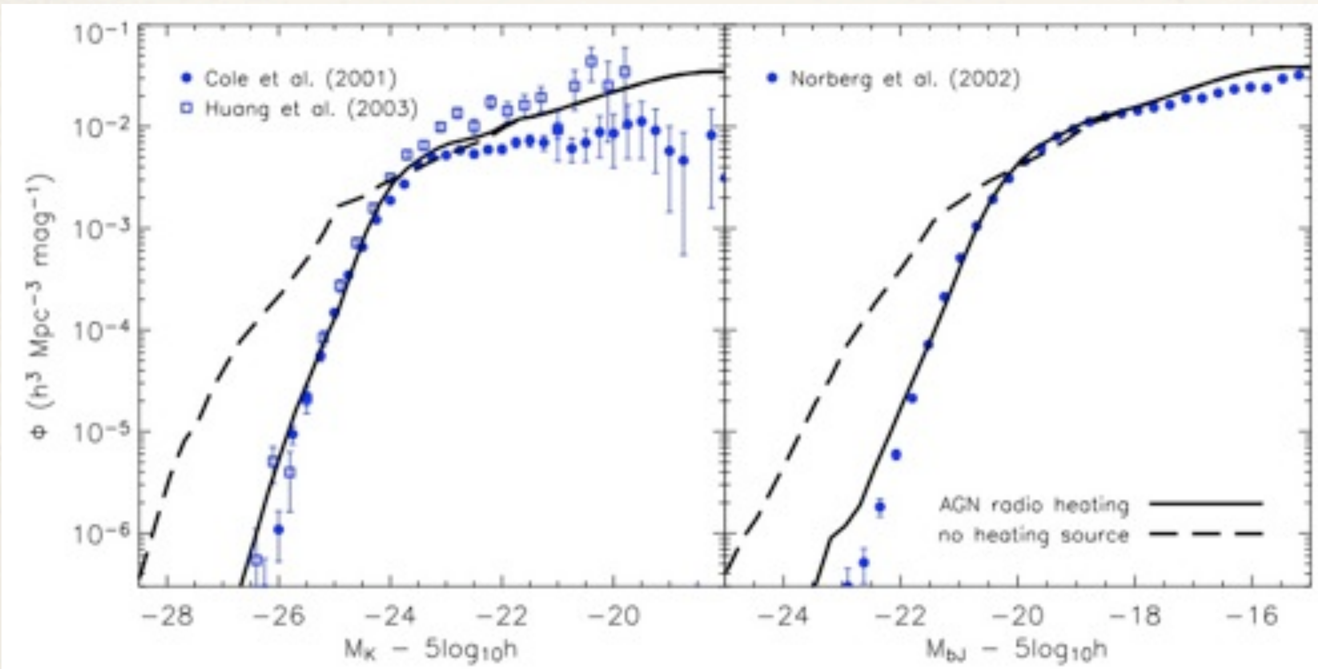
tight correlation between M_{BH} and bulge properties (*e.g. Richstone+ 1998)*

The BH mass density obtained integrating the AGN L.-F. and the CXB ~ that obtained from local bulges

How are they created: need to understand BH growth and feedback

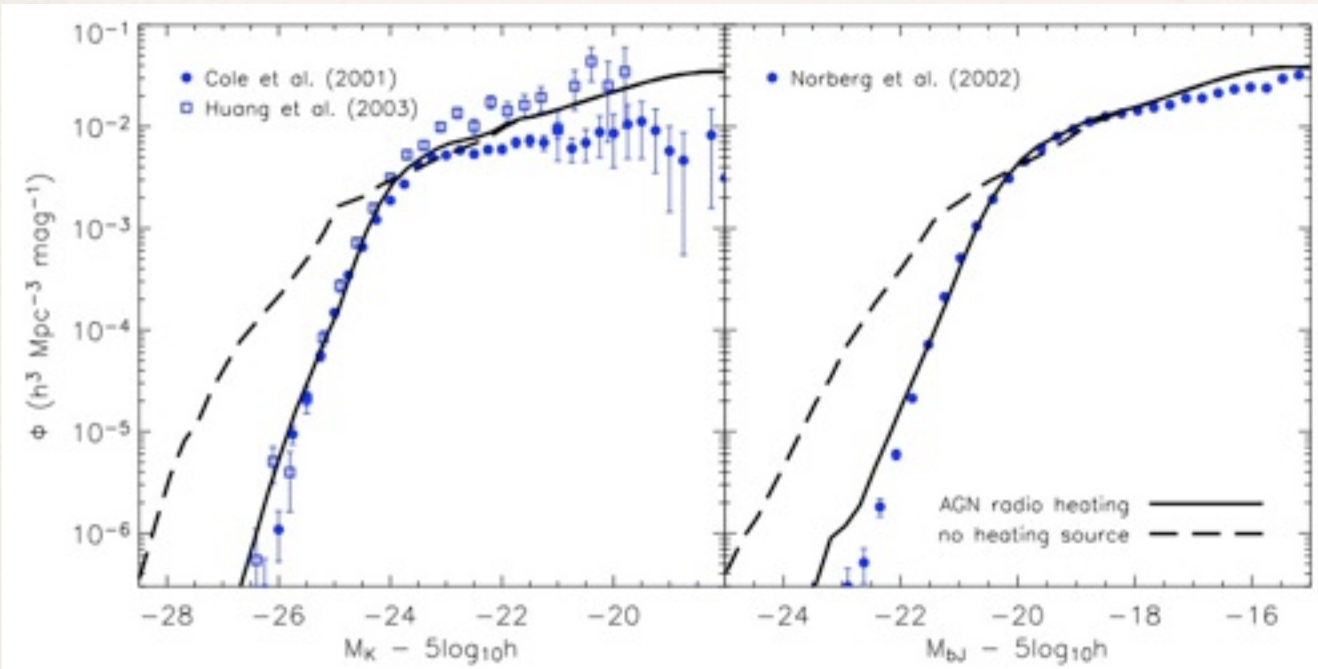
Massive galaxy density and colors: AGN feedback required

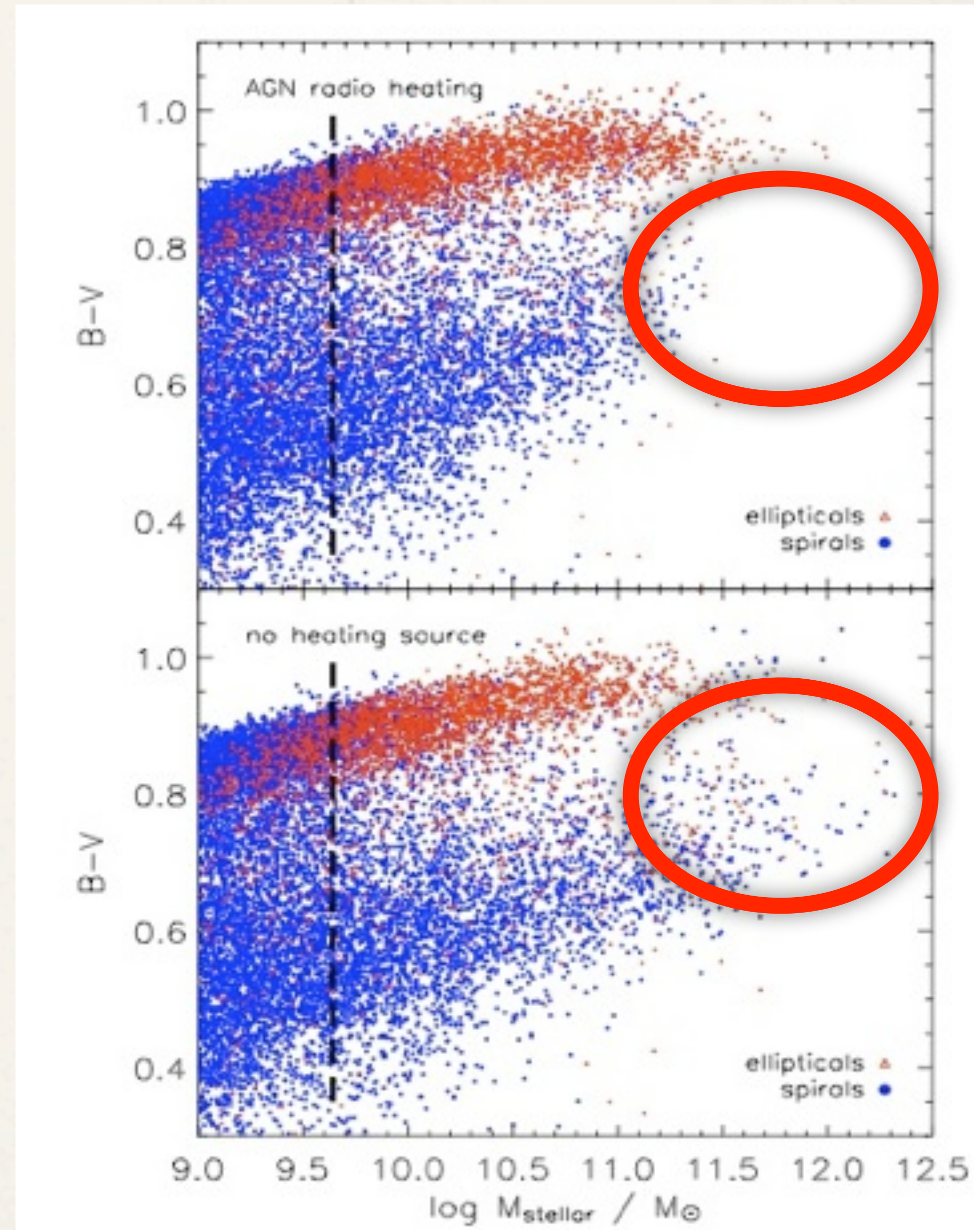
Menci+ 2006   Croton+2006



Massive galaxy density and colors: AGN feedback required

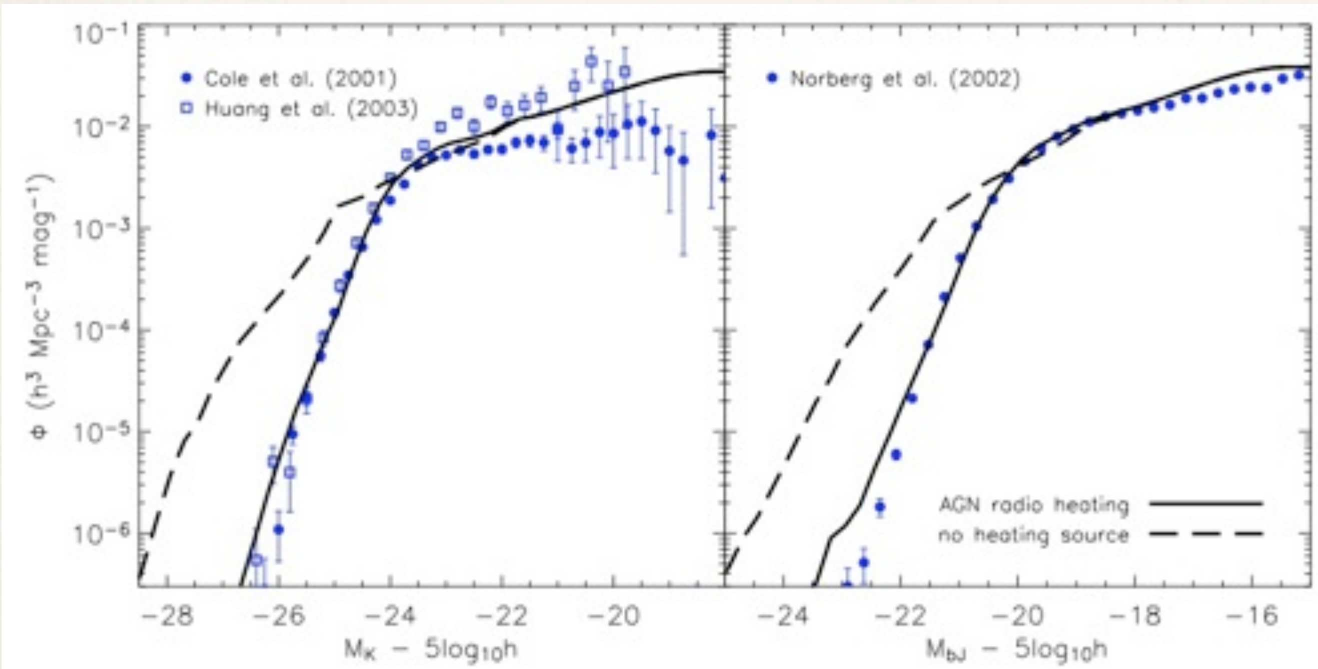
Menci+ 2006   Croton+2006

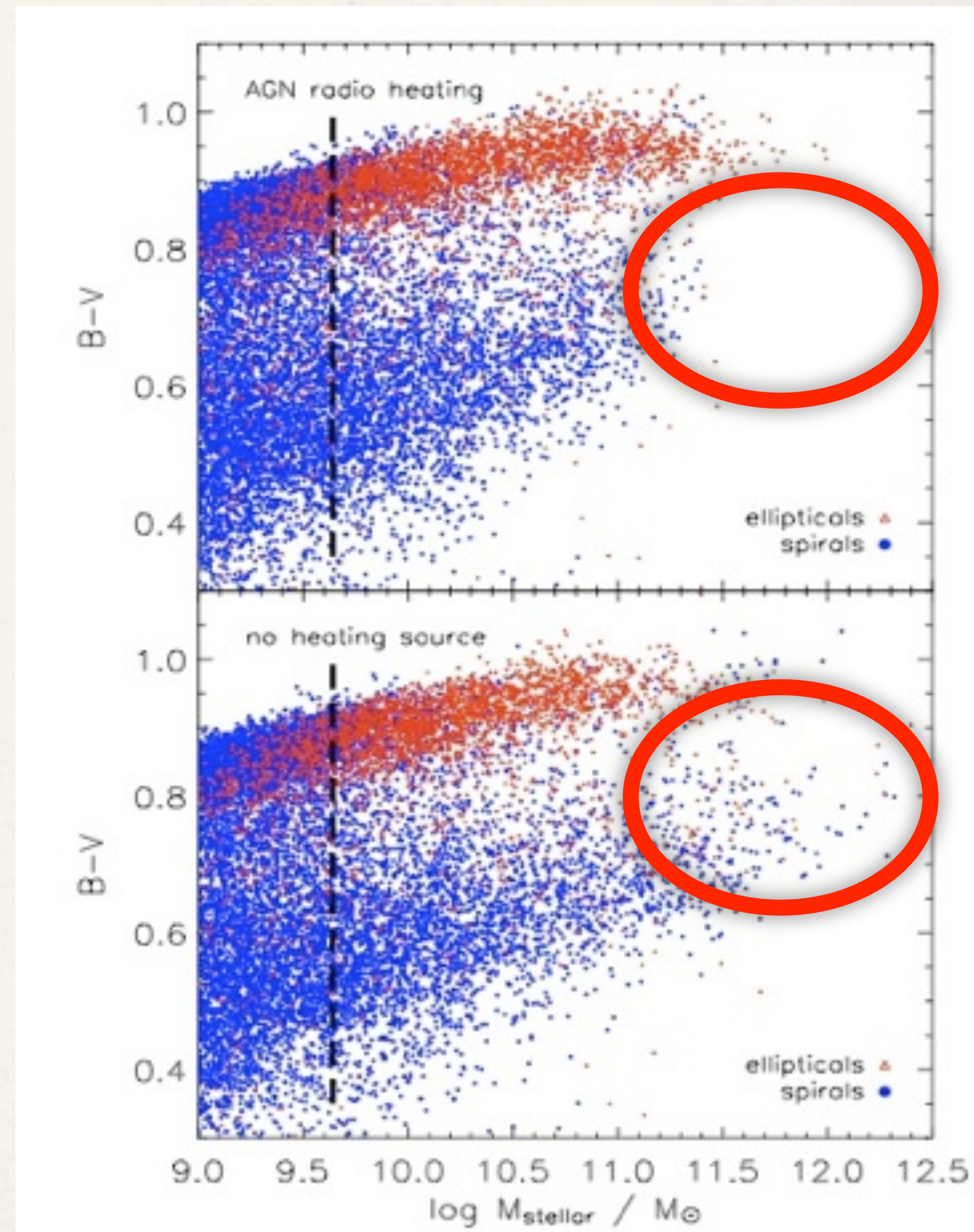




Massive galaxy density and colors: AGN feedback required

Menci+ 2006   Croton+2006

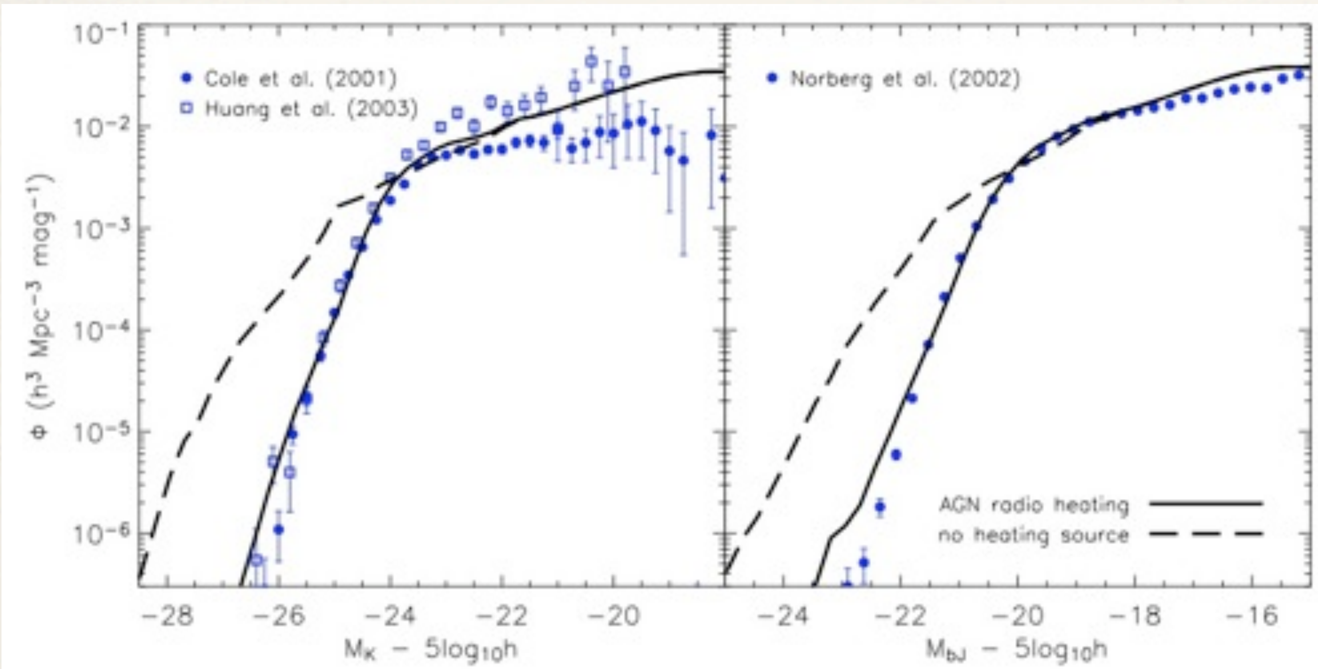


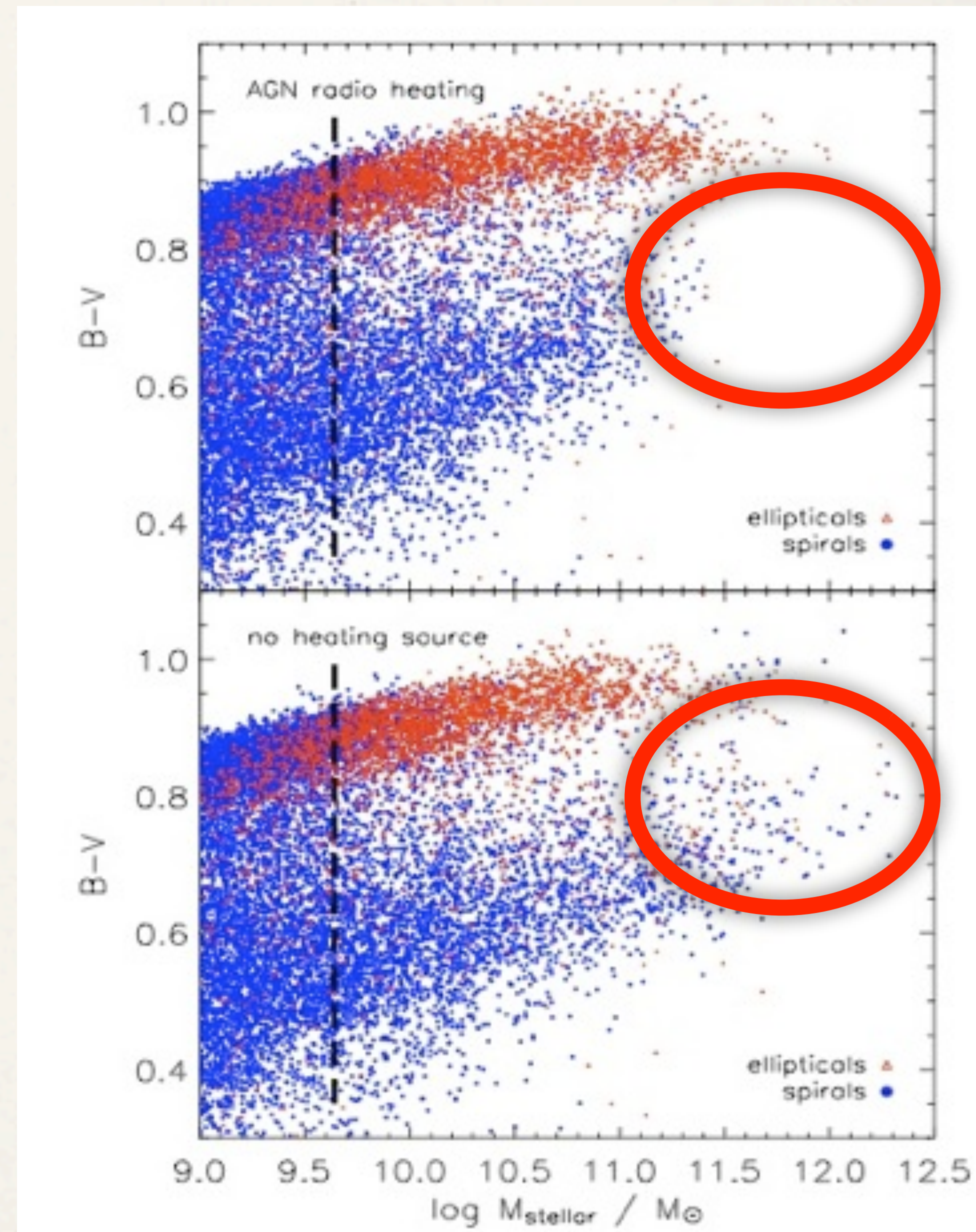


<u>Without AGN heating SAMs:</u>

Massive galaxy density and colors: AGN feedback required

Menci+ 2006 Croton+2006



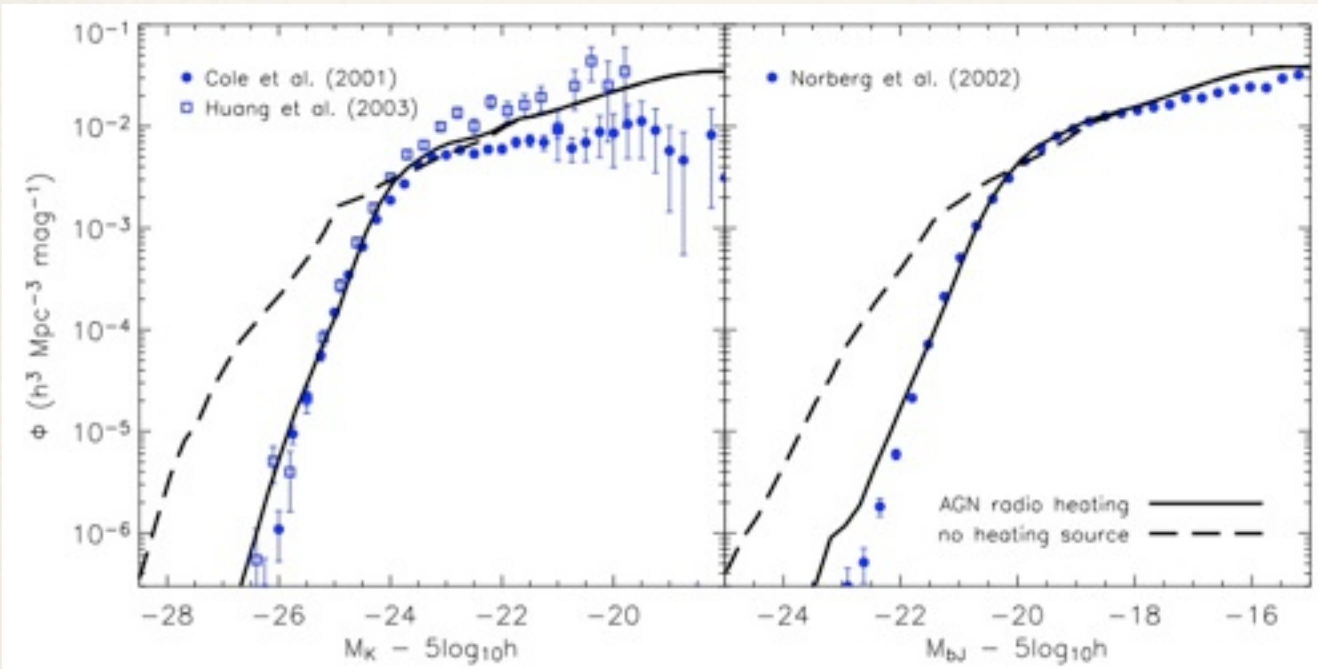


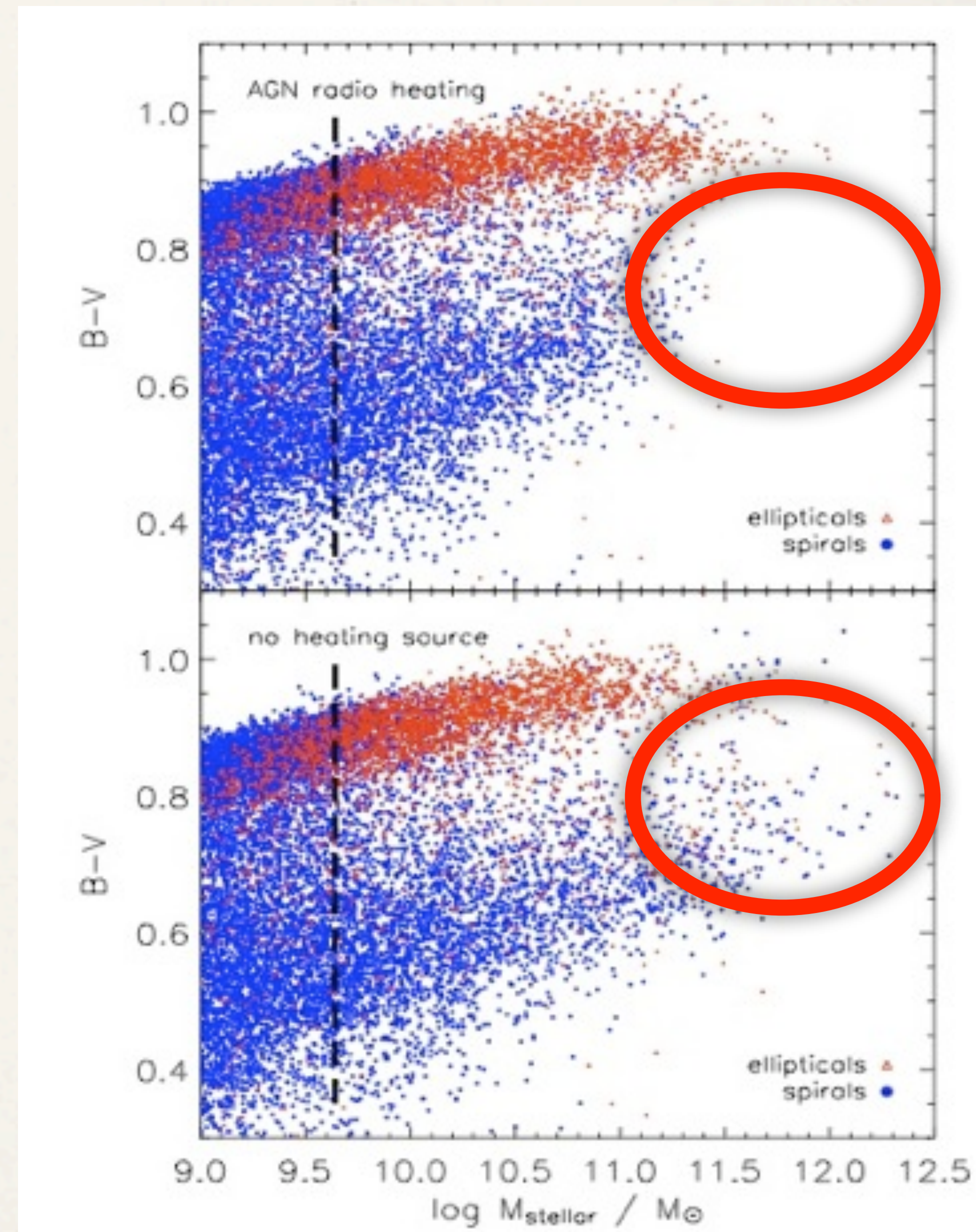
<u>Without AGN heating SAMs:</u>

1. overpredict luminosities of massive galaxies by ~2 mags

Massive galaxy density and colors: AGN feedback required

Menci+ 2006 Croton+2006





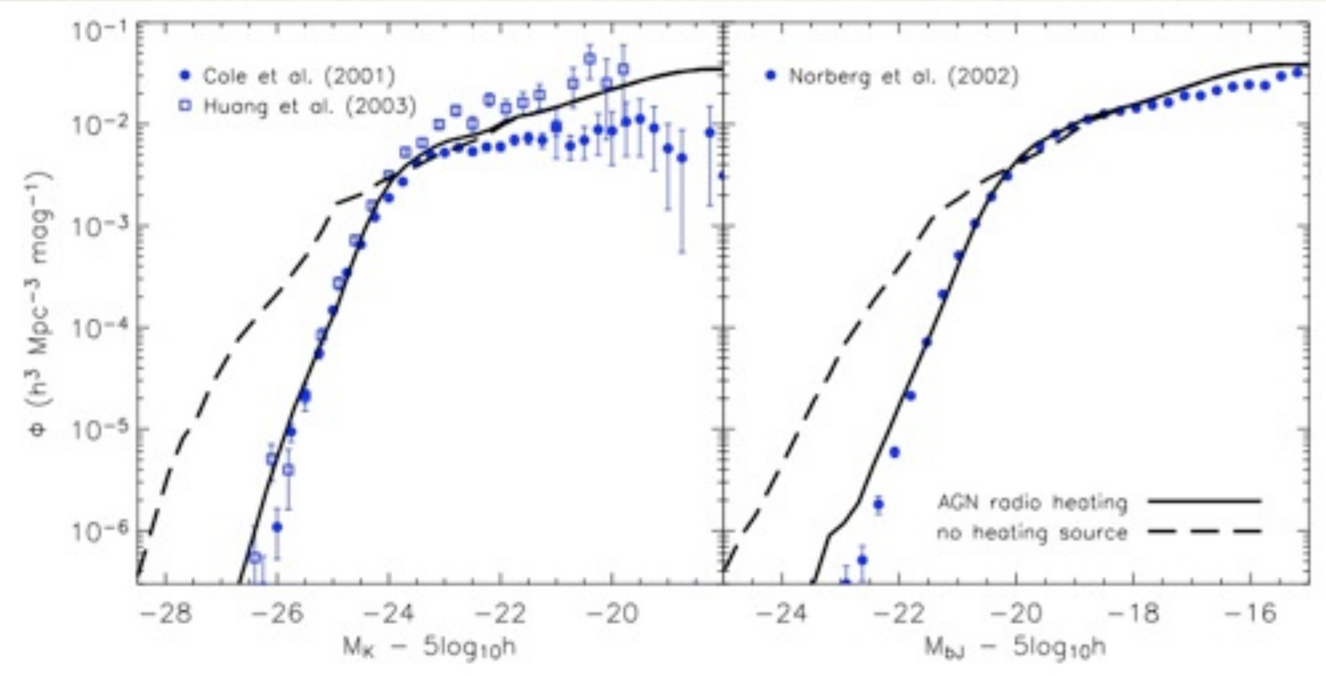
<u>Without AGN heating SAMs:</u>

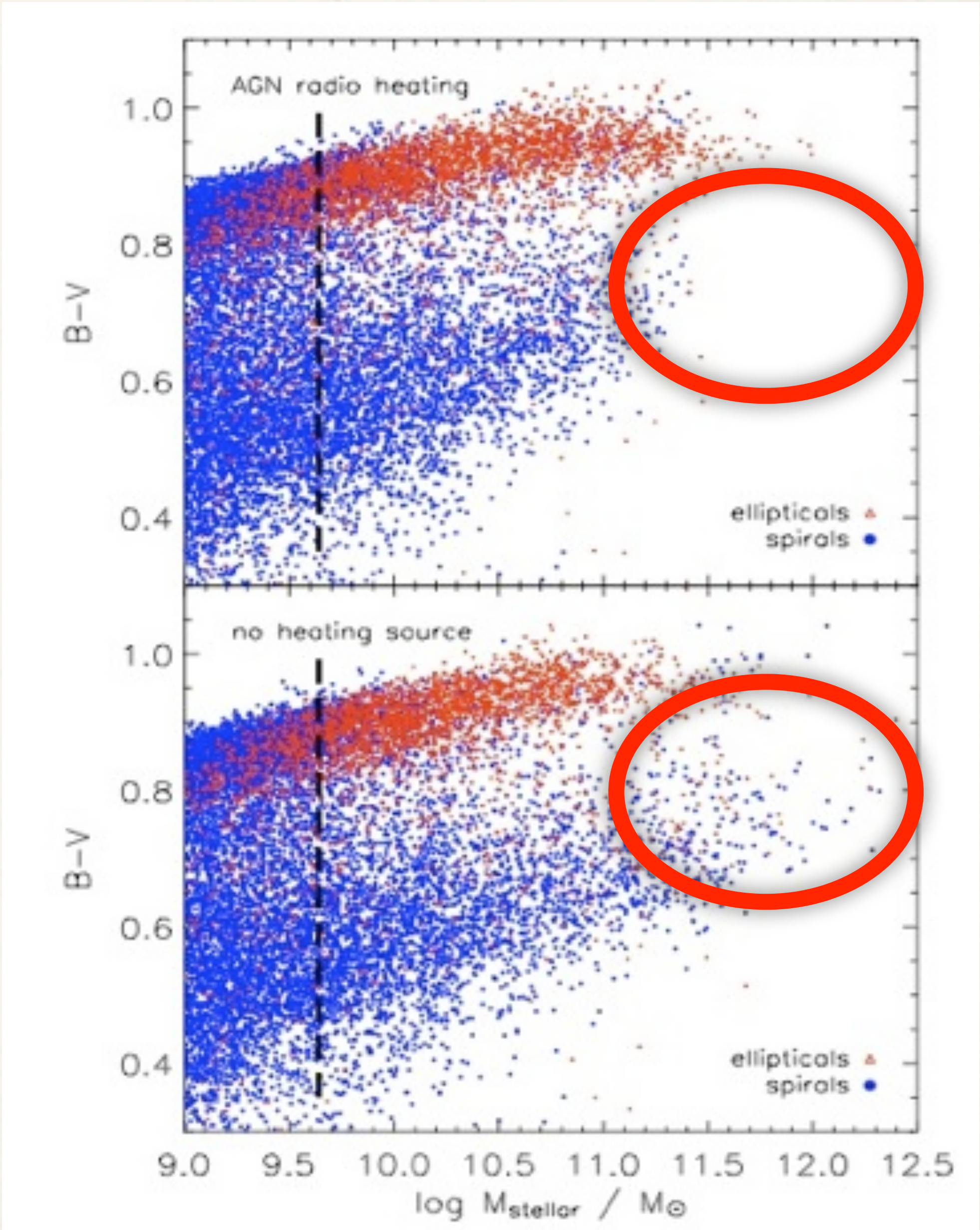
1. overpredict luminosities of massive galaxies by ~2 mags

and/or

Massive galaxy density and colors: AGN feedback required

Menci+ 2006 Croton+2006





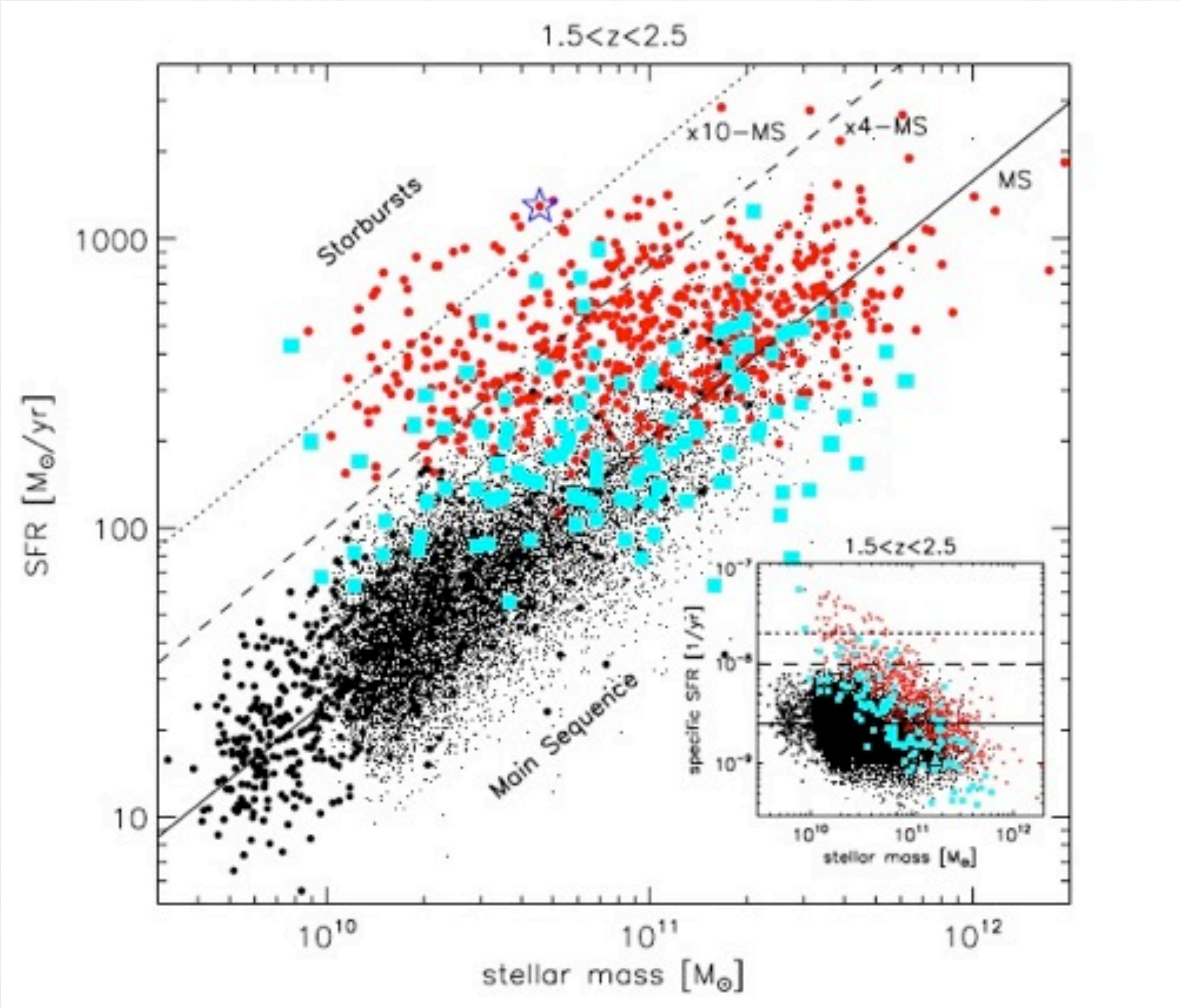
<u>Without AGN heating SAMs:</u>

1. overpredict luminosities of massive galaxies by ~2 mags

and/or

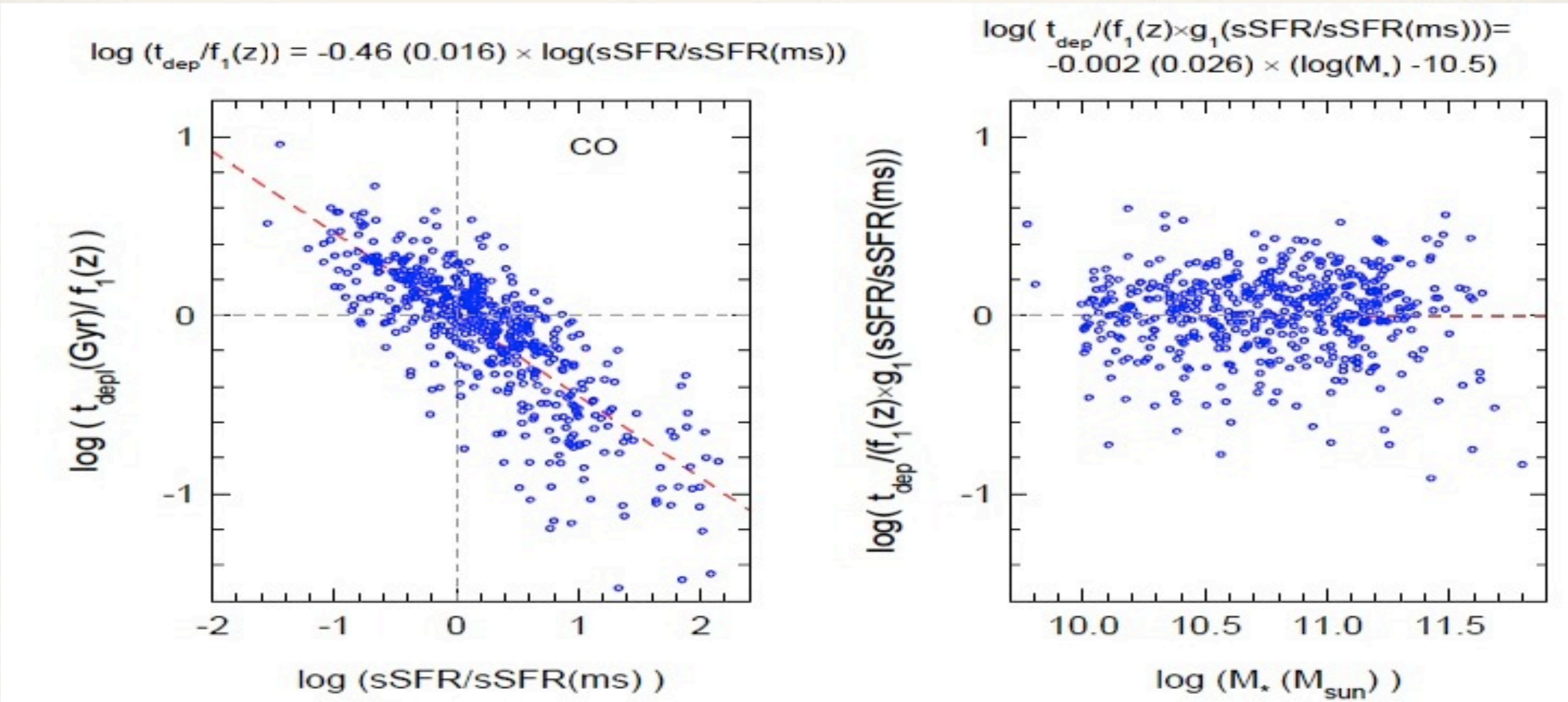
2. predict a number of massive blue galaxies higher than observed

Scaling relations

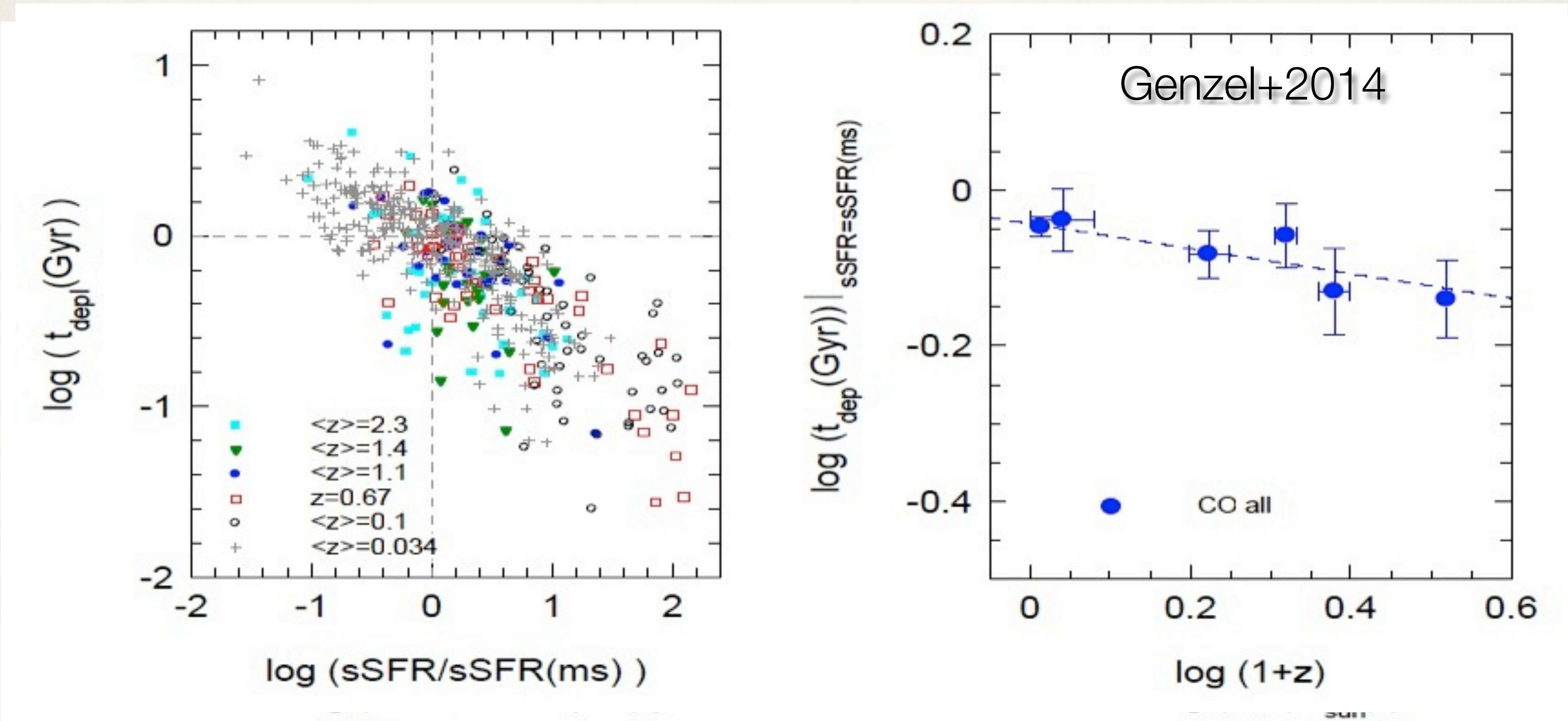


Star-forming galaxy *main sequence*: a nearly linear relationship between stellar mass and SFR, flattening at the highest stellar masses and evolving with the redshift.

Scaling relations

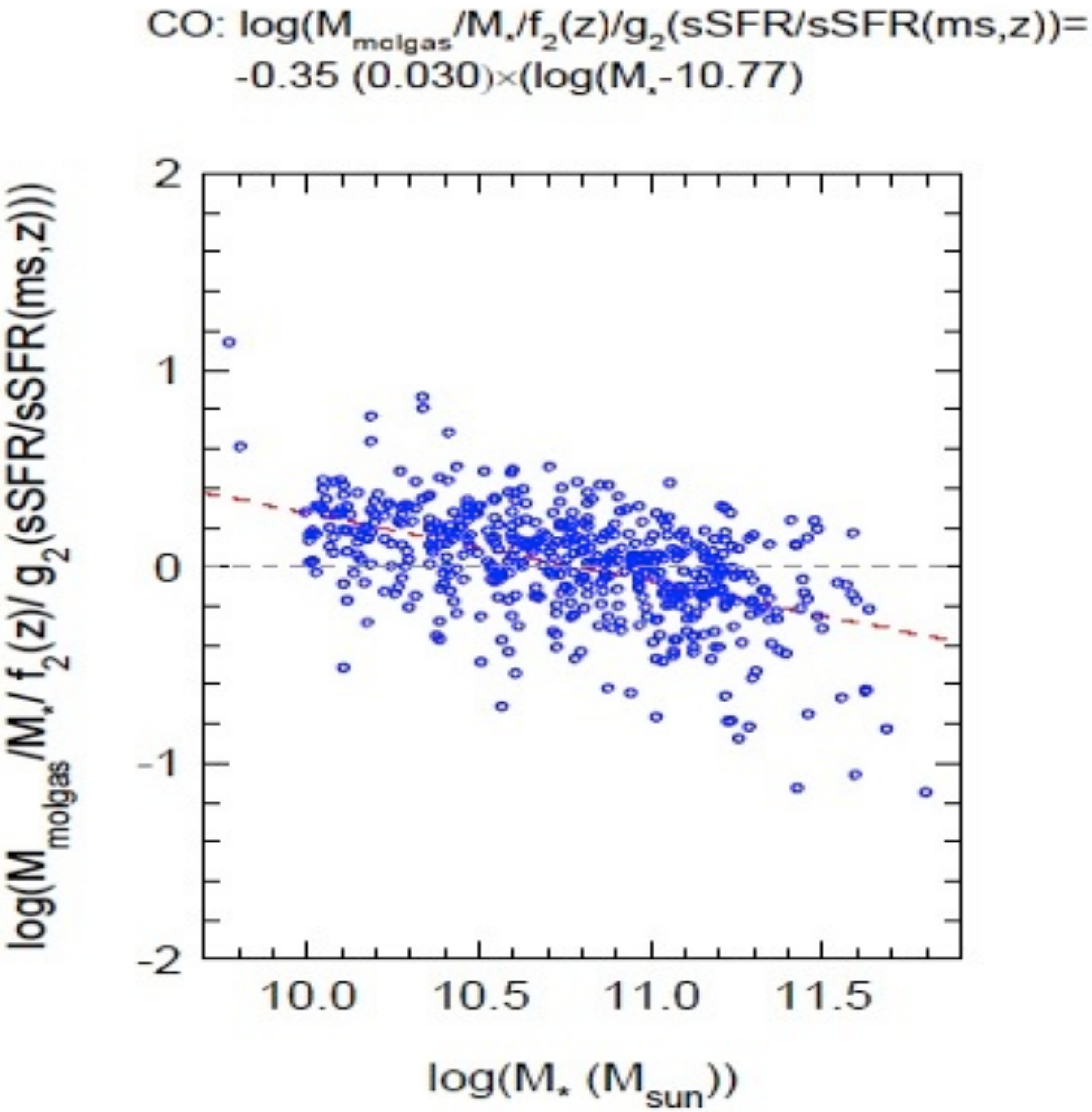


Scaling relations



$sSFR = SFR/M_{star}$; $t_{depl} = M_{gas}/SFR$

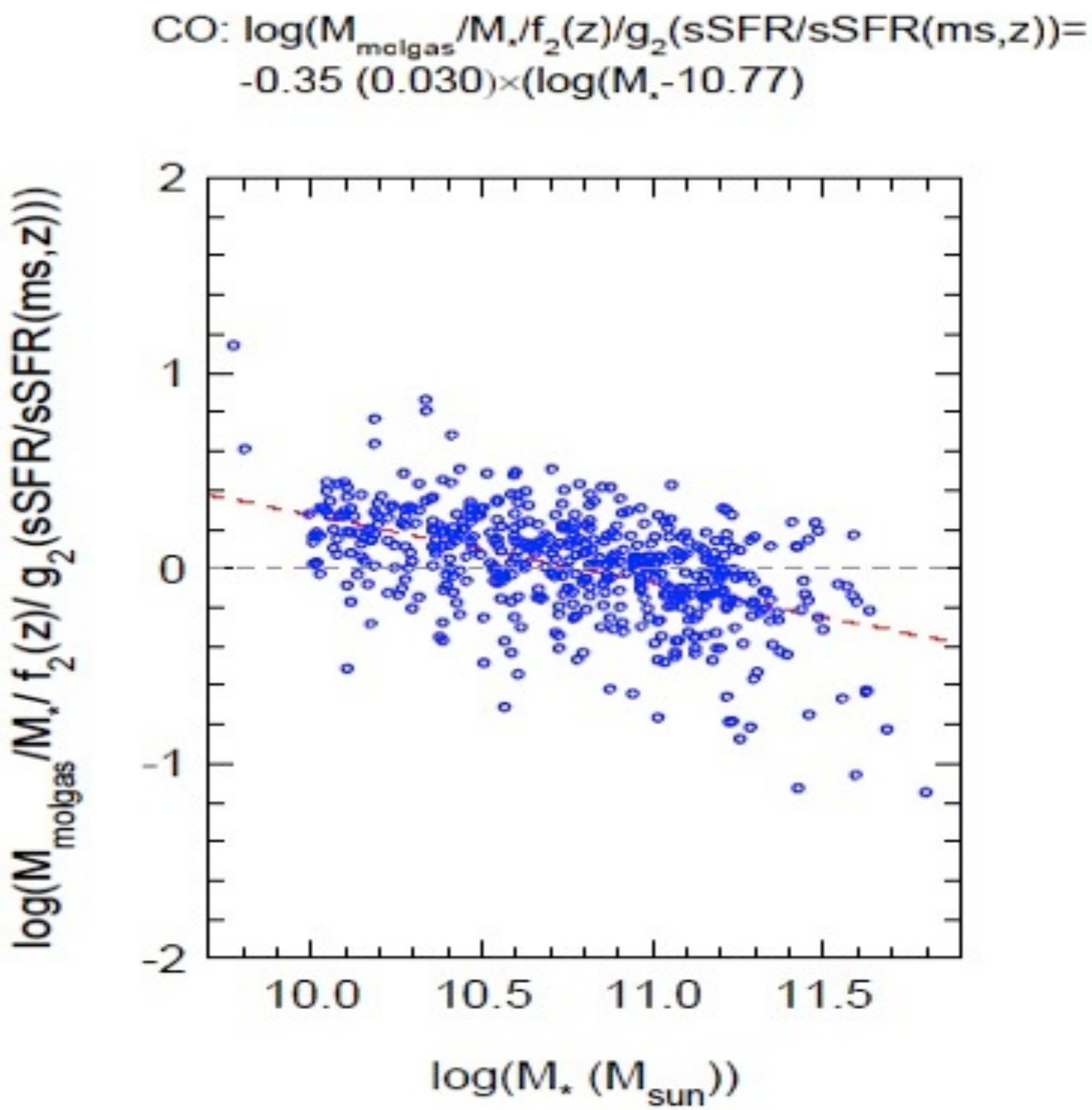
Scaling relations



Gas fraction=M_{gas}/M_{star}

AGN feedback may be the driver for the decrease of the gas fraction and for the quenching of SFG at **$\log M_{star}$>1.8**

Scaling relations

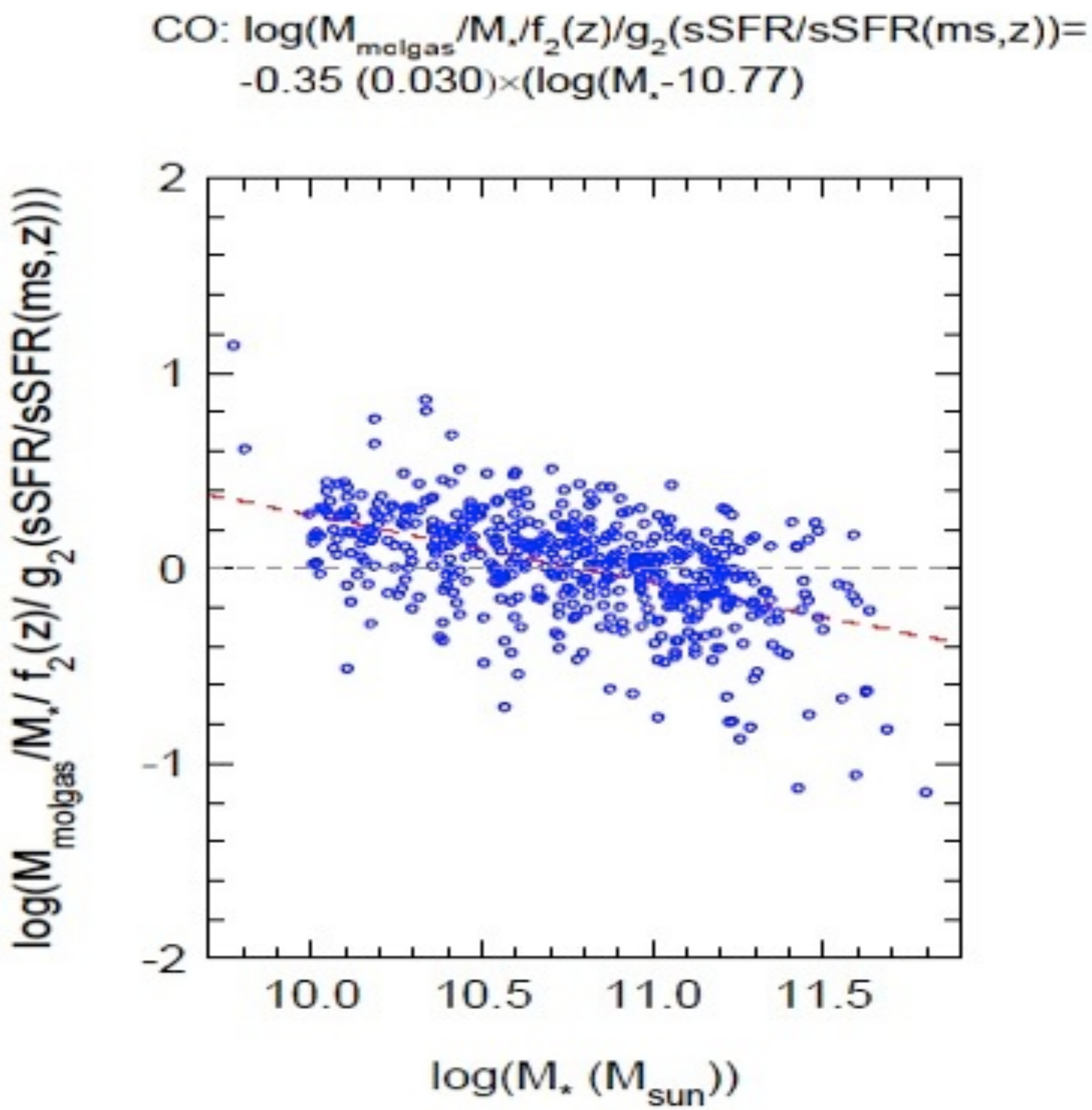


Gas fraction=M_{gas}/M_{star}

AGN feedback may be the driver for the decrease of the gas fraction and for the quenching of SFG at **$\log M_{star}$>1.8**

sSFR=SFR/M_{star}; t_{depl}=M_{gas}/SFR

Scaling relations



Gas fraction=M_{gas}/M_{star}

AGN feedback may be the driver for the decrease of the gas fraction and for the quenching of SFG at **$\log M_{star}$>1.8**

sSFR=SFR/M_{star}; t_{depl}=M_{gas}/SFR

AGN Feedback & accretion mode

AGN Feedback & accretion mode

Quasar mode

- Major mergers
- Minor mergers
- Galaxy encounters
- **Activity periods are strong, short and recurrent**

AGN density decrease at z<2 is due to:

- decrease with time of galaxy merging rate
- Decrease with time of encounters rate
- Decrease with time of galactic cold gas left available for accretion

Feedback is driven by AGN radiation

Somerville+2003

Menci+ 2003,2004,2006,2008

AGN Feedback & accretion mode

Quasar mode

- Major mergers
- Minor mergers
- Galaxy encounters
- **Activity periods are strong, short and recurrent**

AGN density decrease at z<2 is due to:

- decrease with time of galaxy merging rate
- Decrease with time of encounters rate
- Decrease with time of galactic cold gas left available for accretion

Feedback is driven by AGN radiation

Somerville+2003

Menci+ 2003,2004,2006,2008

Radio mode

- Low accretion-rate systems tend to be radiatively inefficient and jet-dominated
- Feedback from low luminosity AGN dominated by kinetic energy
- **Low level activity can be ~continuous**

Croton+ 2006

AGN winds and outflows are ubiquitous

- **radio jets (relativistic)**
- **ultra fast outflows (UFO, moderately relativistic)**
- **ionized gas outflows (BAL, NAL, [OIII], [CII] v~1000-30000 km/s, massive)**
- **atomic gas outflows (absorption NaI, HI, v~100-1000 km/s)**
- **molecular outflows**

(OH, CO, HCN,

v~200-2000 km/s,

MASSIVE

Sturm+2011,

Spoon+2008,2011)

AGN winds and outflows are ubiquitous

- **radio jets (relativistic)**
- **ultra fast outflows (UFO, moderately relativistic)**
- **ionized gas outflows (BAL, NAL, [OIII], [CII] v~1000-30000 km/s, massive)**
- **atomic gas outflows (absorption NaI, HI, v~100-1000 km/s)**
- **molecular outflows**

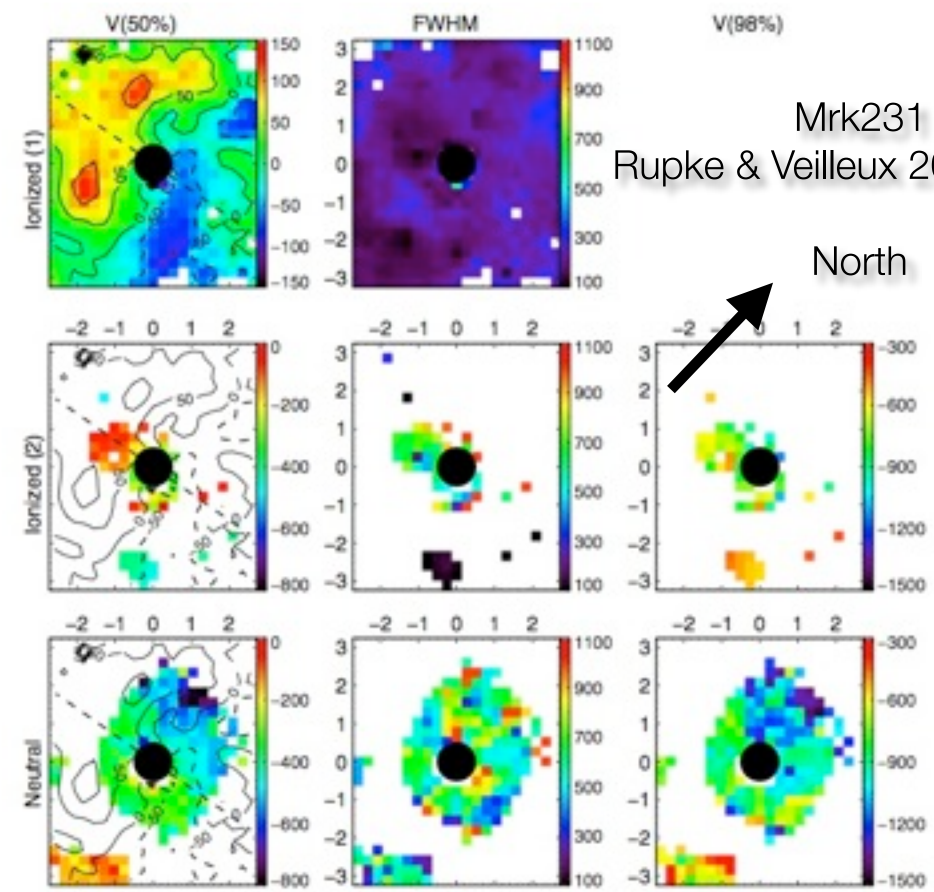
(OH, CO, HCN,

v~200-2000 km/s,

MASSIVE

Sturm+2011,

Spoon+2008,2011)



Mrk231
Rupke & Veilleux 2011, 2013

AGN winds and outflows are ubiquitous

- **radio jets (relativistic)**
- **ultra fast outflows (UFO, moderately relativistic)**
- **ionized gas outflows (BAL, NAL, [OIII], [CII] v~1000-30000 km/s, massive)**
- **atomic gas outflows (absorption NaI, HI, v~100-1000 km/s)**
- **molecular outflows**

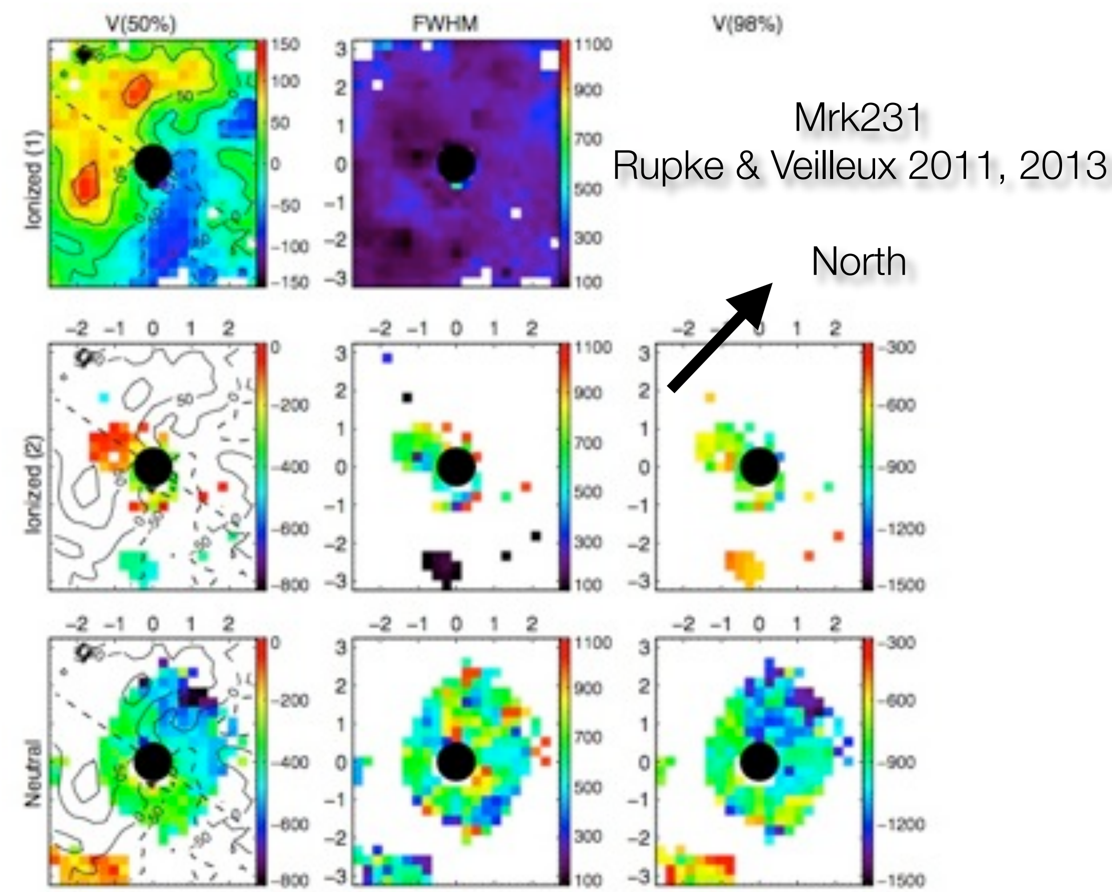
(OH, CO, HCN,

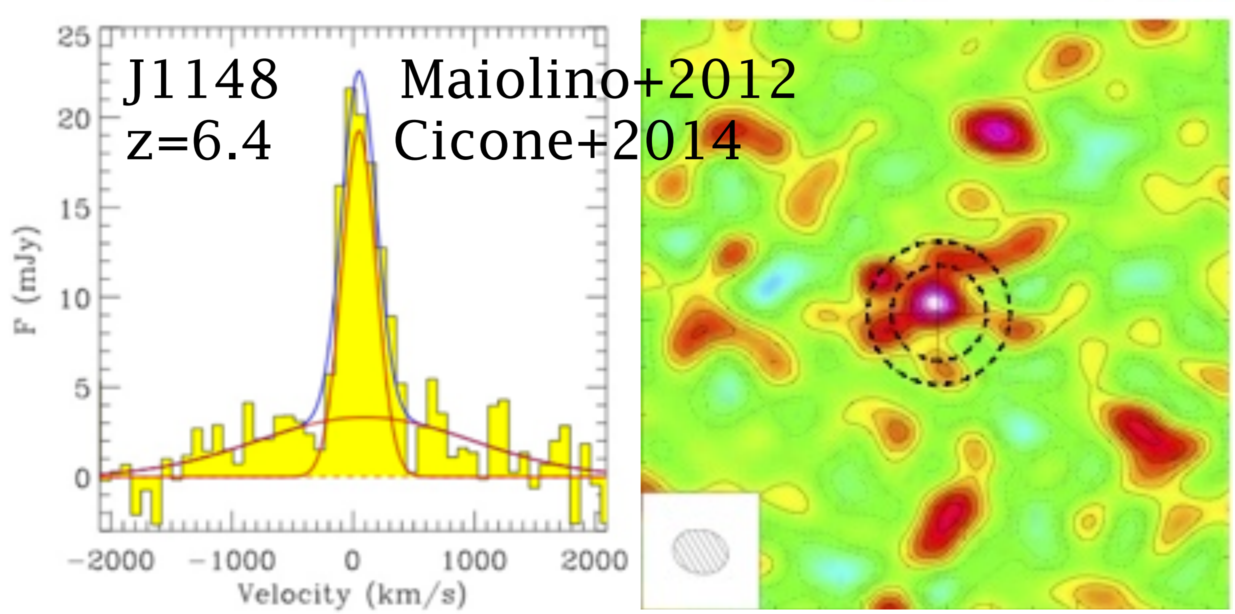
v~200-2000 km/s,

MASSIVE

Sturm+2011,

Spoon+2008,2011)





AGN winds and outflows are ubiquitous

- **radio jets (relativistic)**
- **ultra fast outflows (UFO, moderately relativistic)**
- **ionized gas outflows (BAL, NAL, [OIII], [CII] v~1000-30000 km/s, massive)**
- **atomic gas outflows (absorption NaI, HI, v~100-1000 km/s)**
- **molecular outflows**

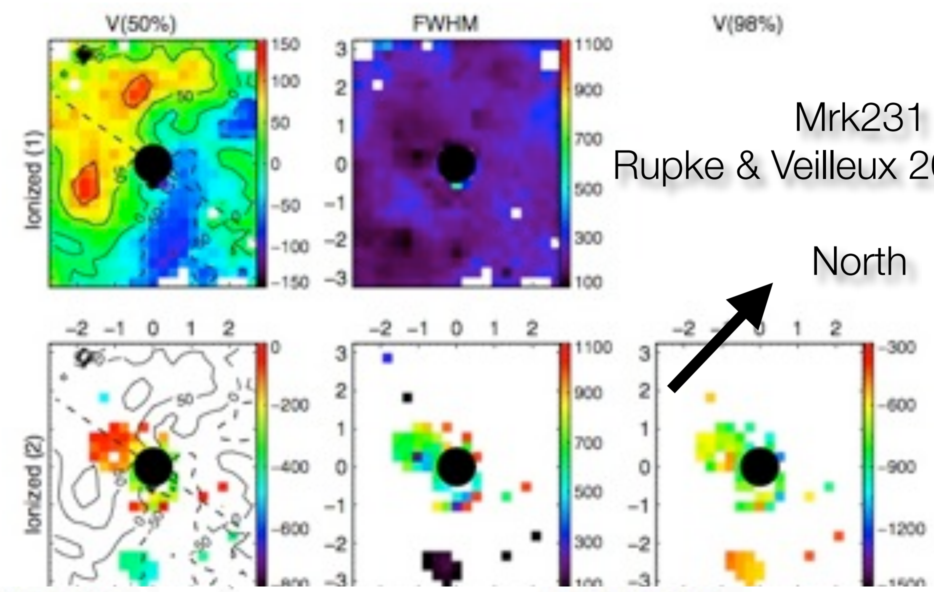
(OH, CO, HCN,

v~200-2000 km/s,

MASSIVE

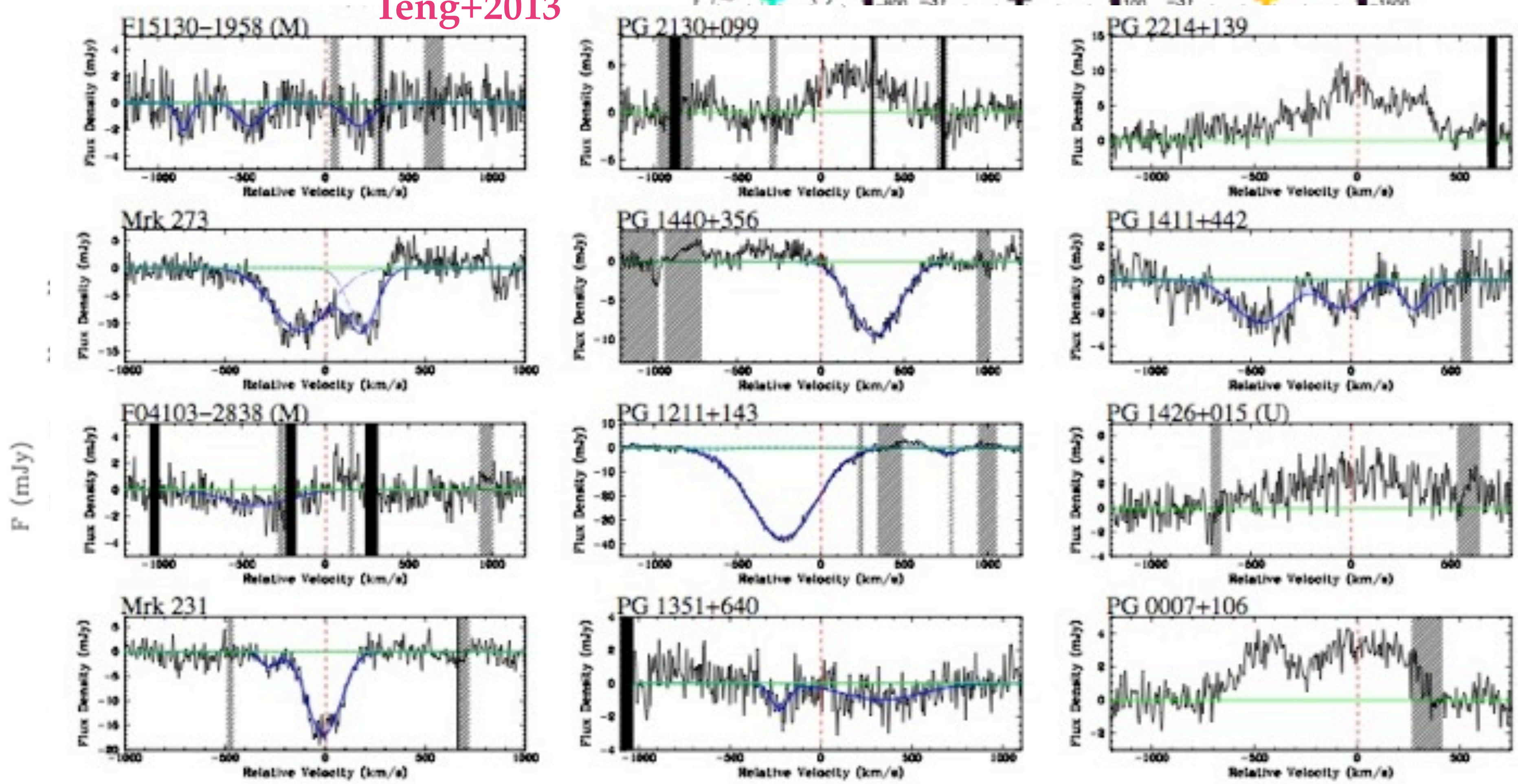
Sturm+2011,

Spoon+2008,2011)



Mrk231
Rupke & Veilleux 2011, 2013

Teng+2013



AGN winds and outflows are ubiquitous

- **radio jets (relativistic)**
- **ultra fast outflows (UFO, moderately relativistic)**
- **ionized gas outflows (BAL, NAL, [OIII], [CII] v~1000-30000 km/s, massive)**
- **atomic gas outflows (absorption NaI, HI, v~100-1000 km/s)**
- **molecular outflows**

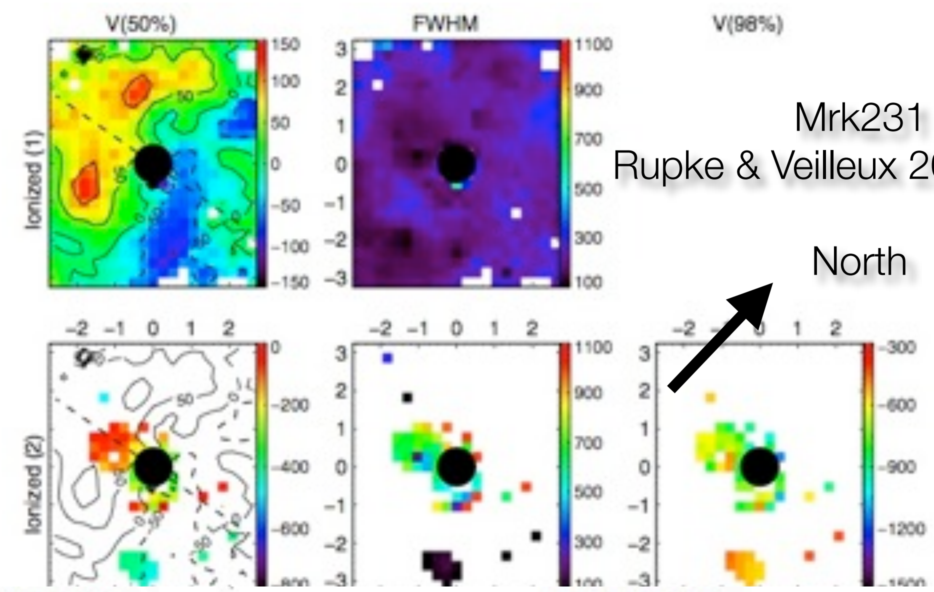
(OH, CO, HCN,

v~200-2000 km/s,

MASSIVE

Sturm+2011,

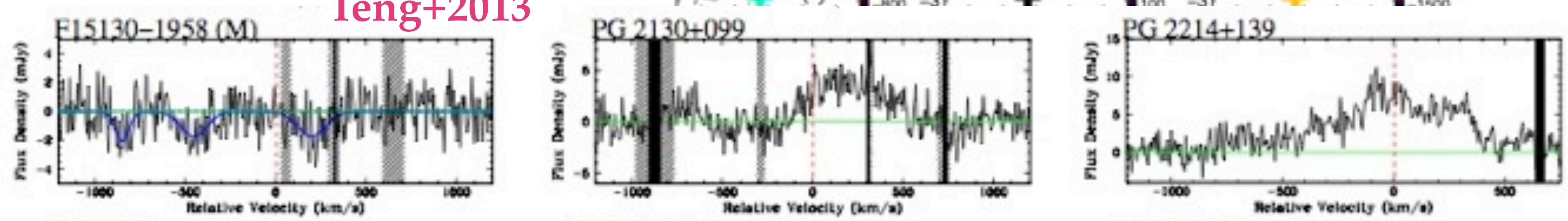
Spoon+2008,2011)

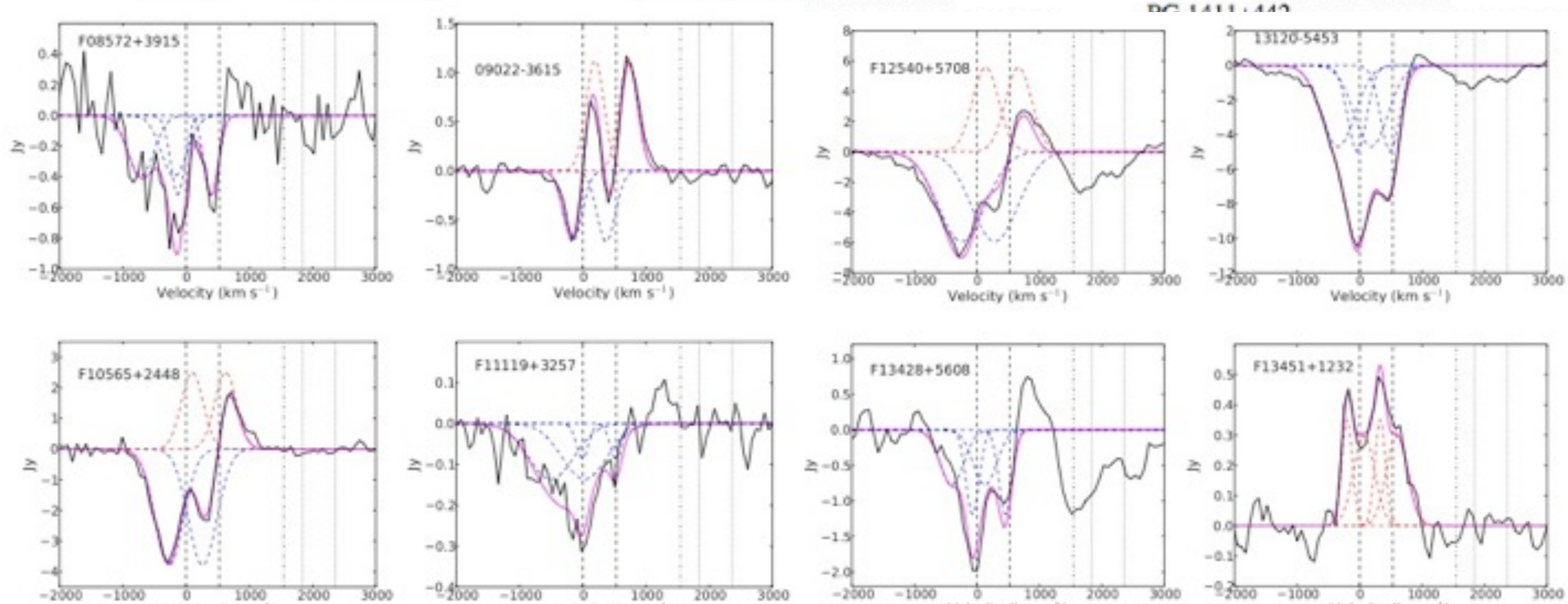


Mrk231
Rupke & Veilleux 2011, 2013

North

Teng+2013





AGN winds and outflows are ubiquitous

- **radio jets (relativistic)**
- **ultra fast outflows (UFO, moderately relativistic)**
- **ionized gas outflows (BAL, NAL, [OIII], [CII] v~1000-30000 km/s, massive)**
- **atomic gas outflows (absorptio v~100-1000 km/s)**
- **molecular outflows**

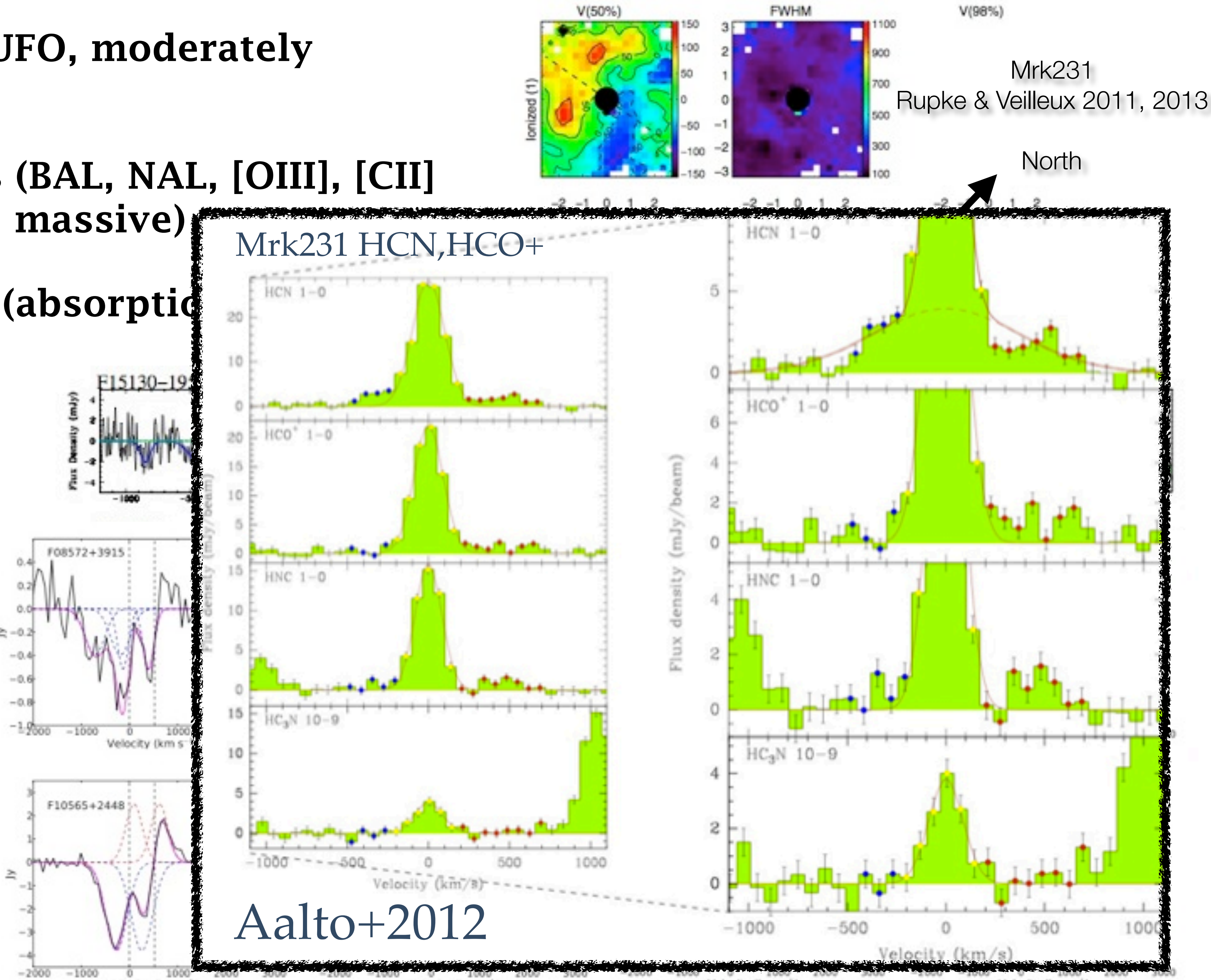
(OH, CO, HCN,

v~200-2000 km/s,

MASSIVE

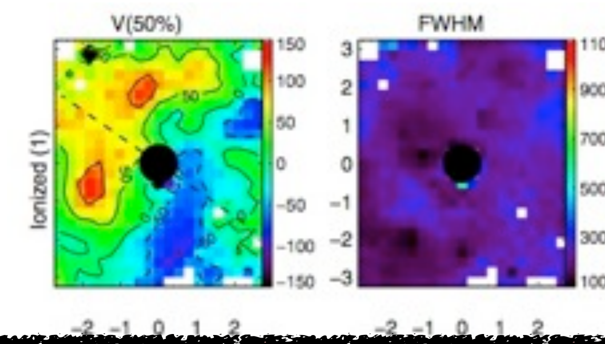
Sturm+2011,

Spoon+2008,2011)



AGN winds and outflows are ubiquitous

- **radio jets (relativistic)**
- **ultra fast outflows (UFO, moderately relativistic)**
- **ionized gas outflows (BAL, NAL, [OIII], [CII] v~1000-30000 km/s, massive)**



Mrk231
Rupke & Veilleux 2011, 2013

North

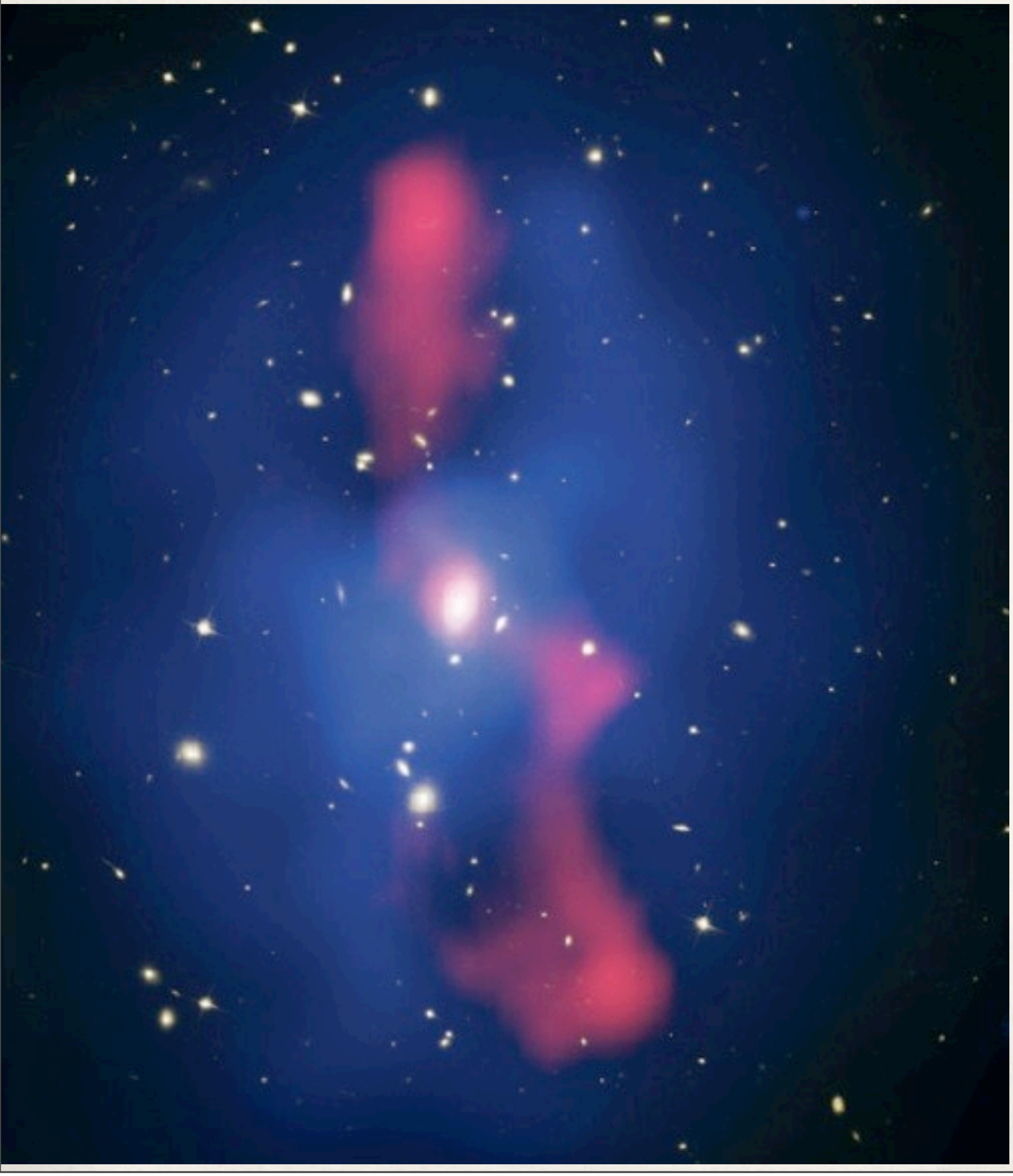
Mrk231 HCN,HCO+

Bad news: <u>Feedback</u> observations are difficult

Radio-mode (jet driven) strong evidence of *feedback,* observed frequently

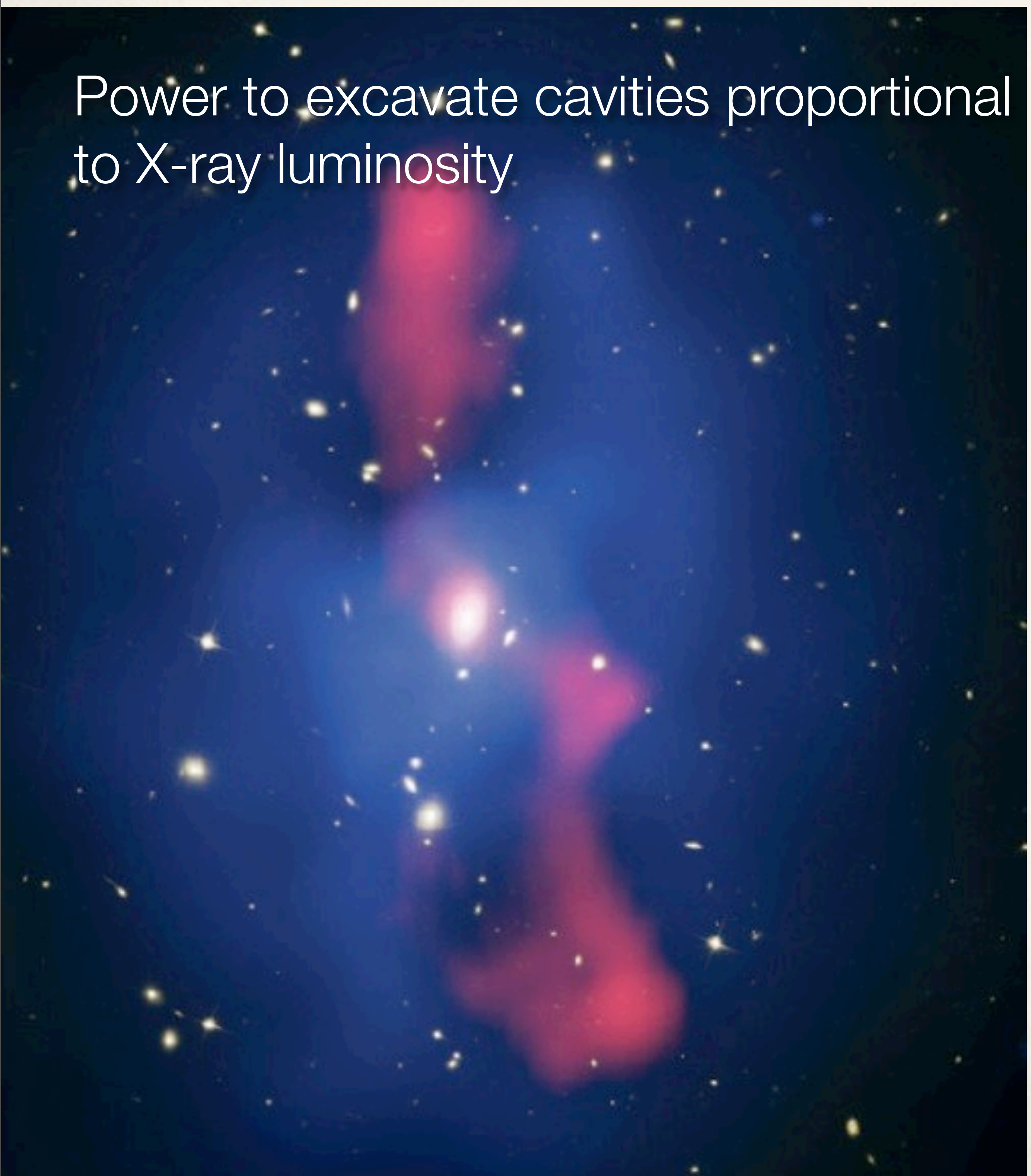
But quasar-mode *feedback* observations are still rare. both in single objects and statistical samples.

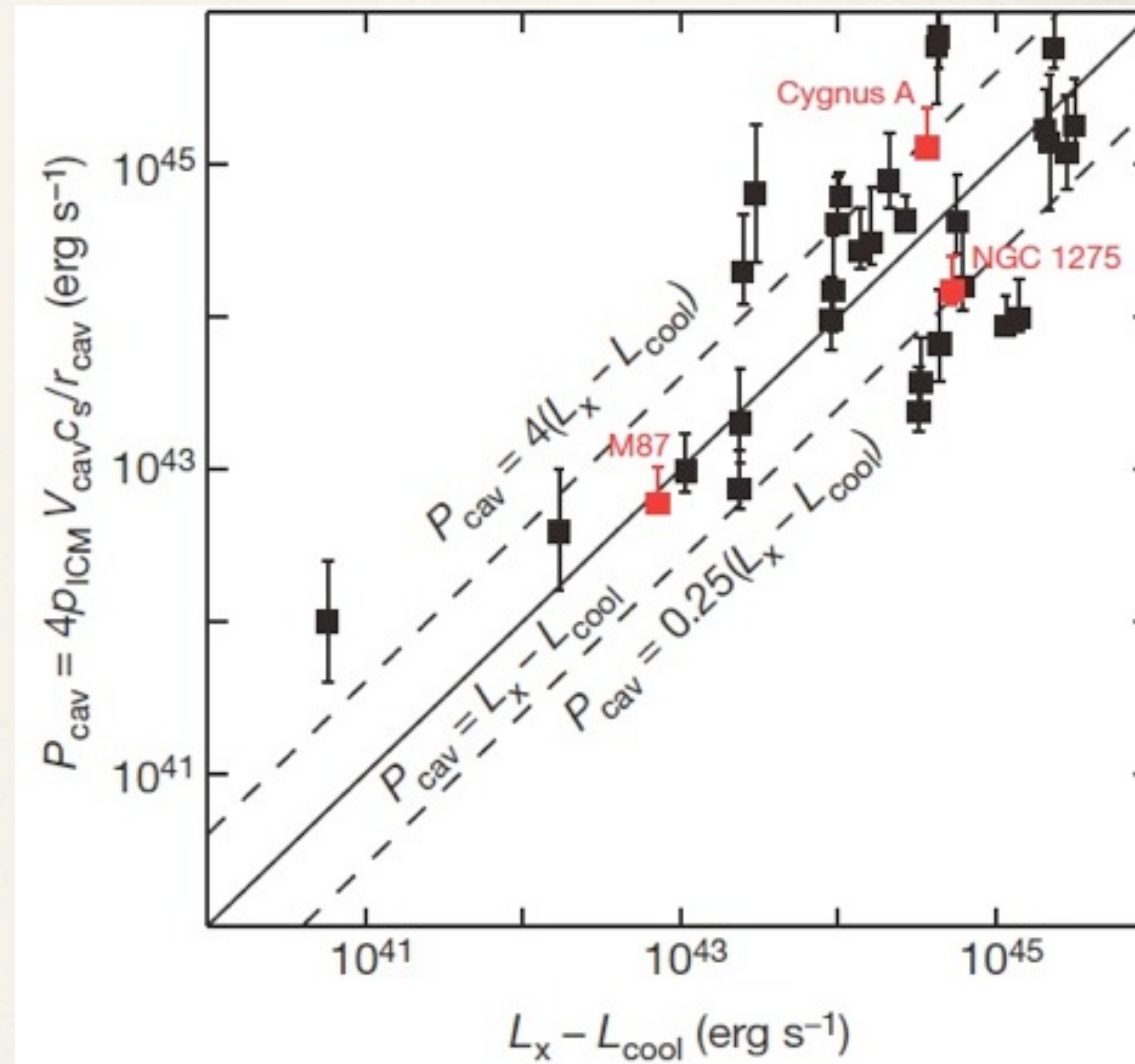
Radio-mode feedback



Radio-mode feedback

Power to excavate cavities proportional to X-ray luminosity

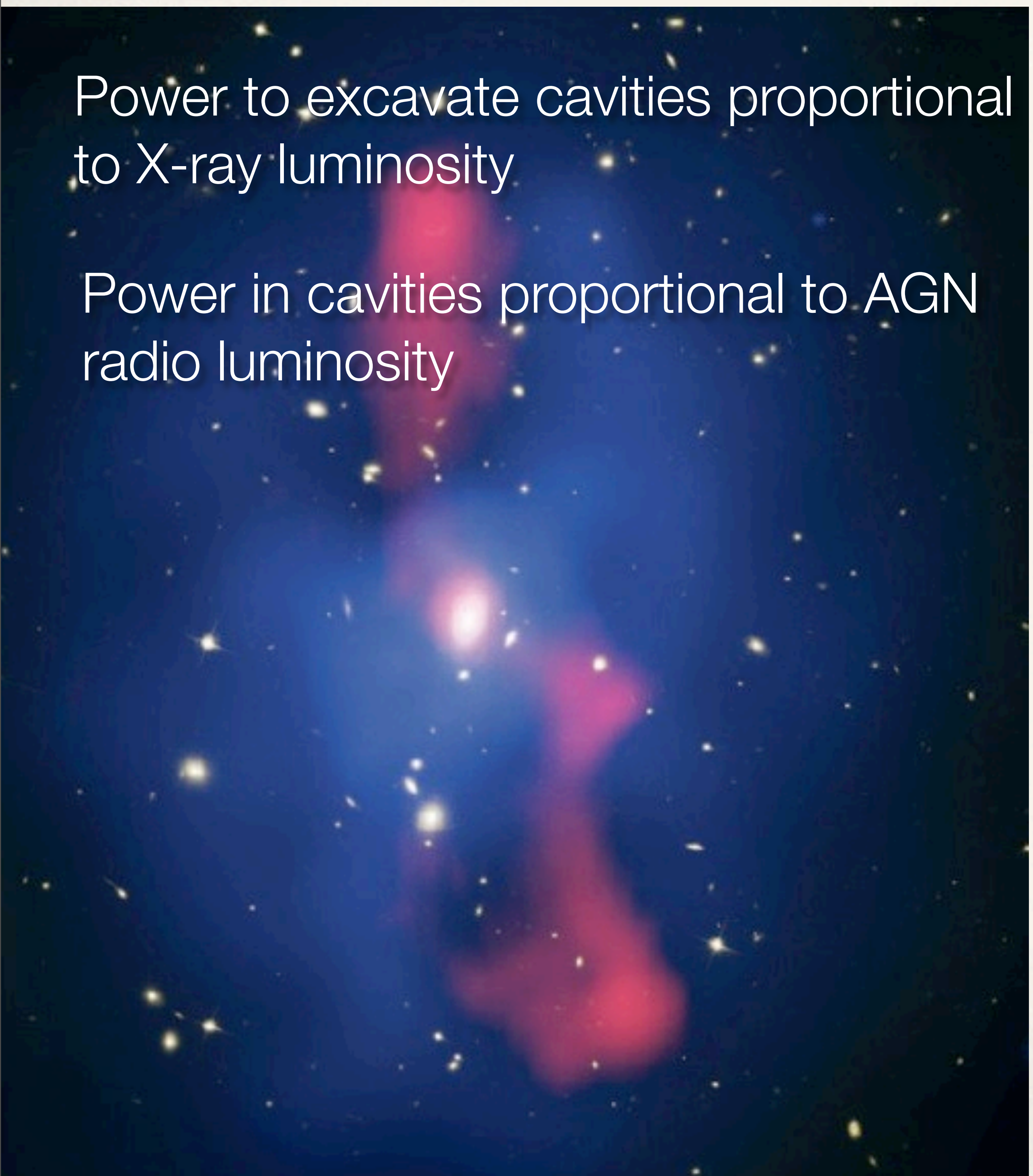


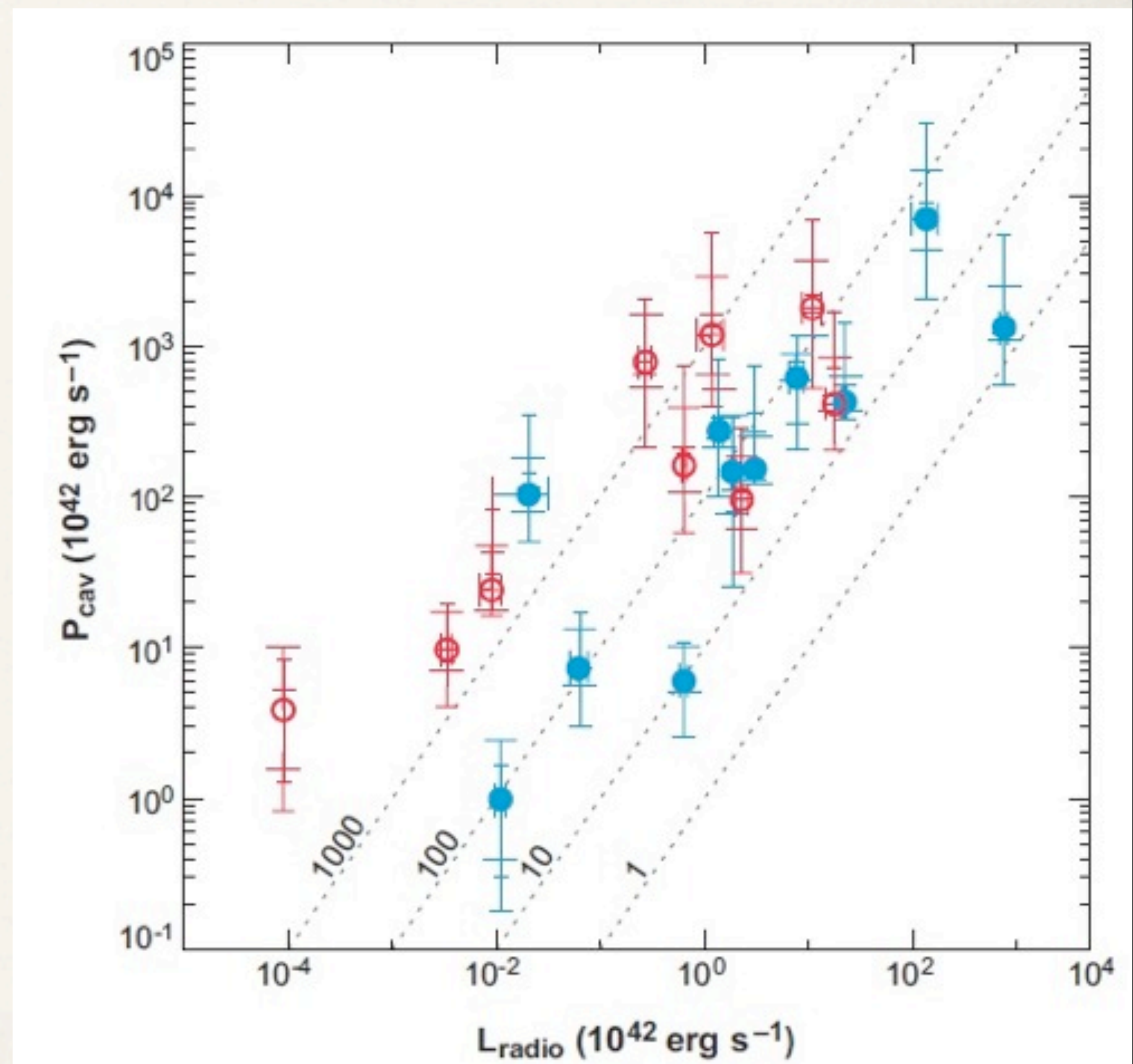


Radio-mode feedback

Power to excavate cavities proportional to X-ray luminosity

Power in cavities proportional to AGN radio luminosity



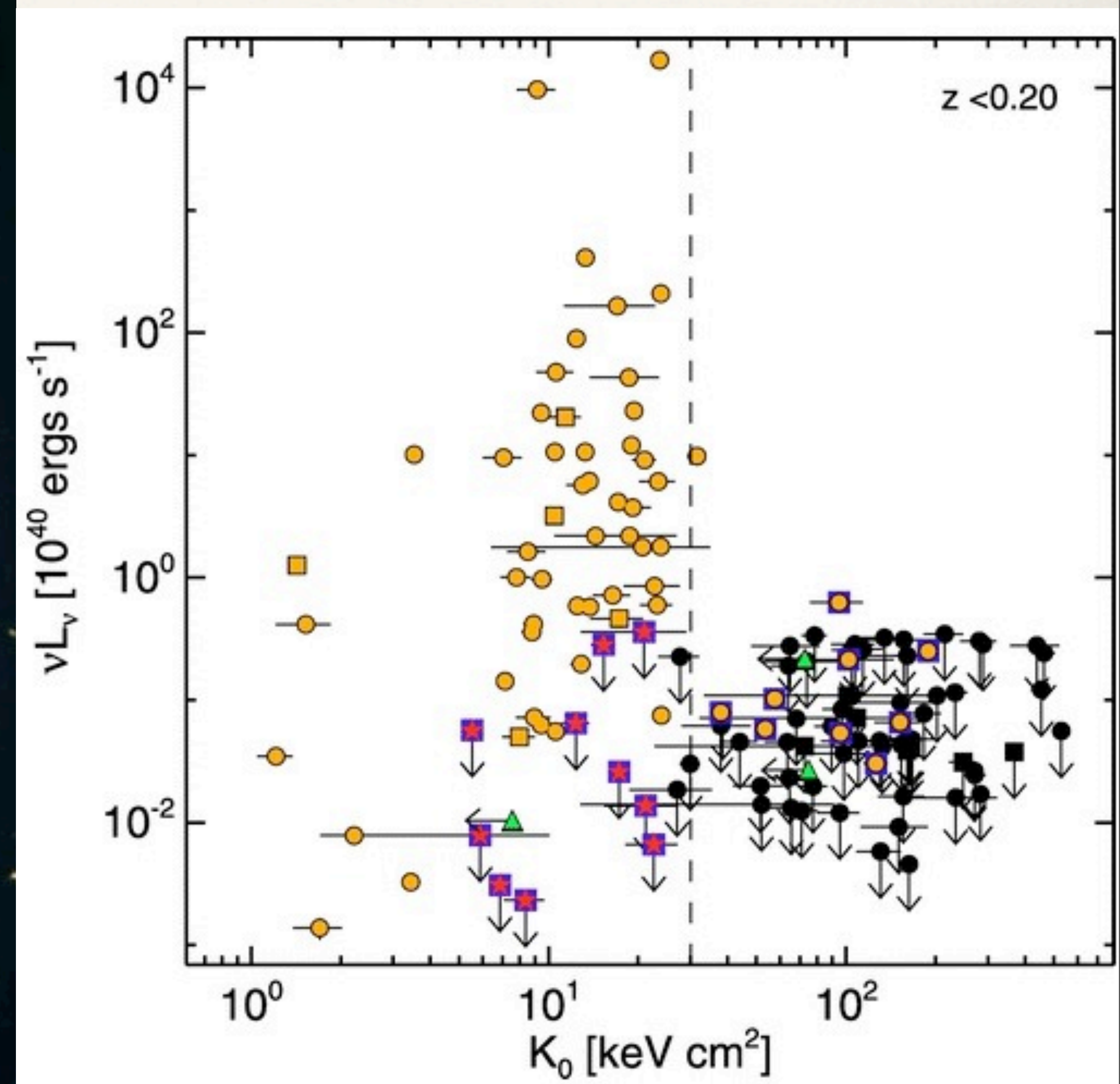


Radio-mode feedback

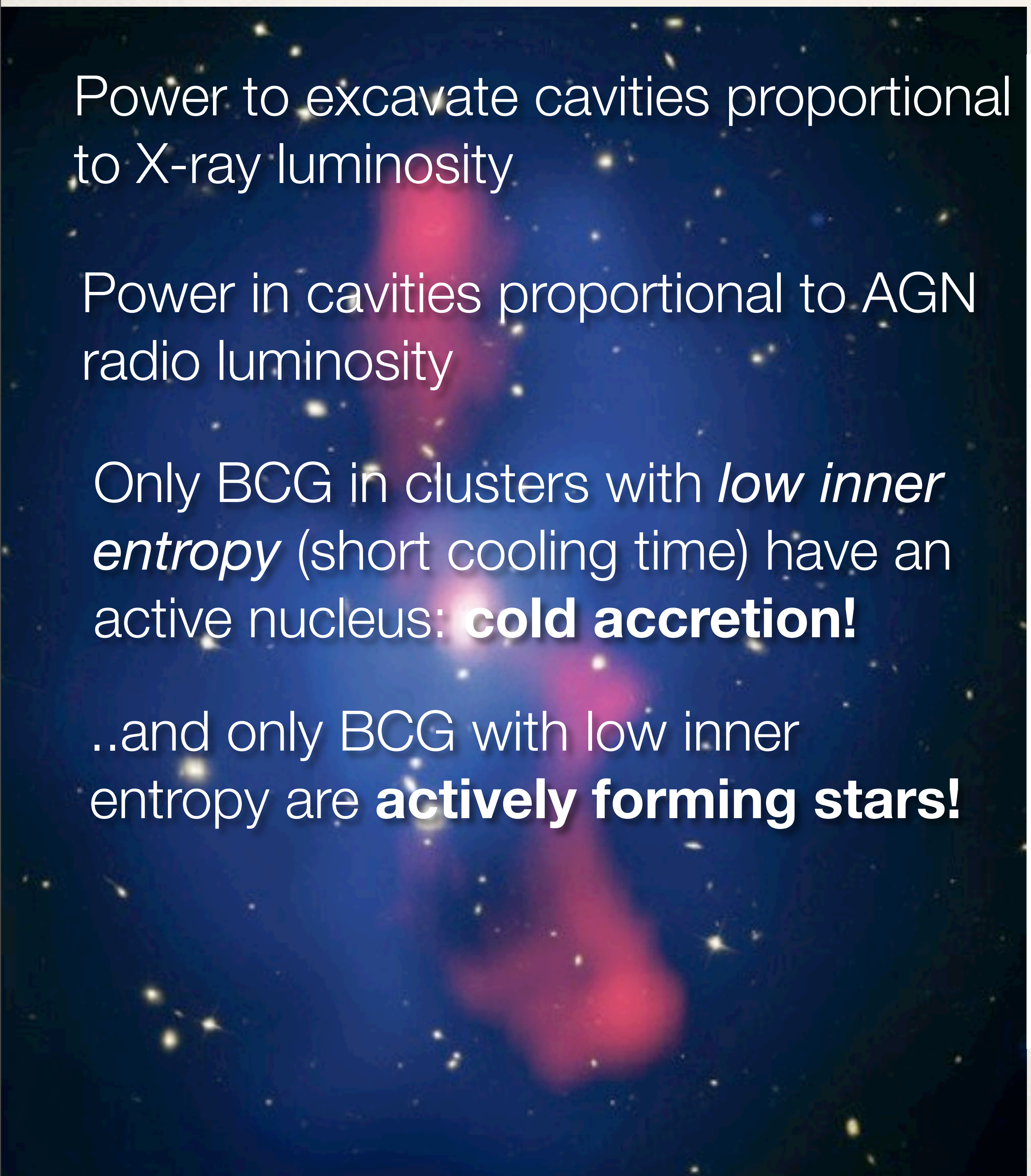
Power to excavate cavities proportional to X-ray luminosity

Power in cavities proportional to AGN radio luminosity

Only BCG in clusters with *low inner entropy* (short cooling time) have an active nucleus: **cold accretion!**



Radio-mode feedback

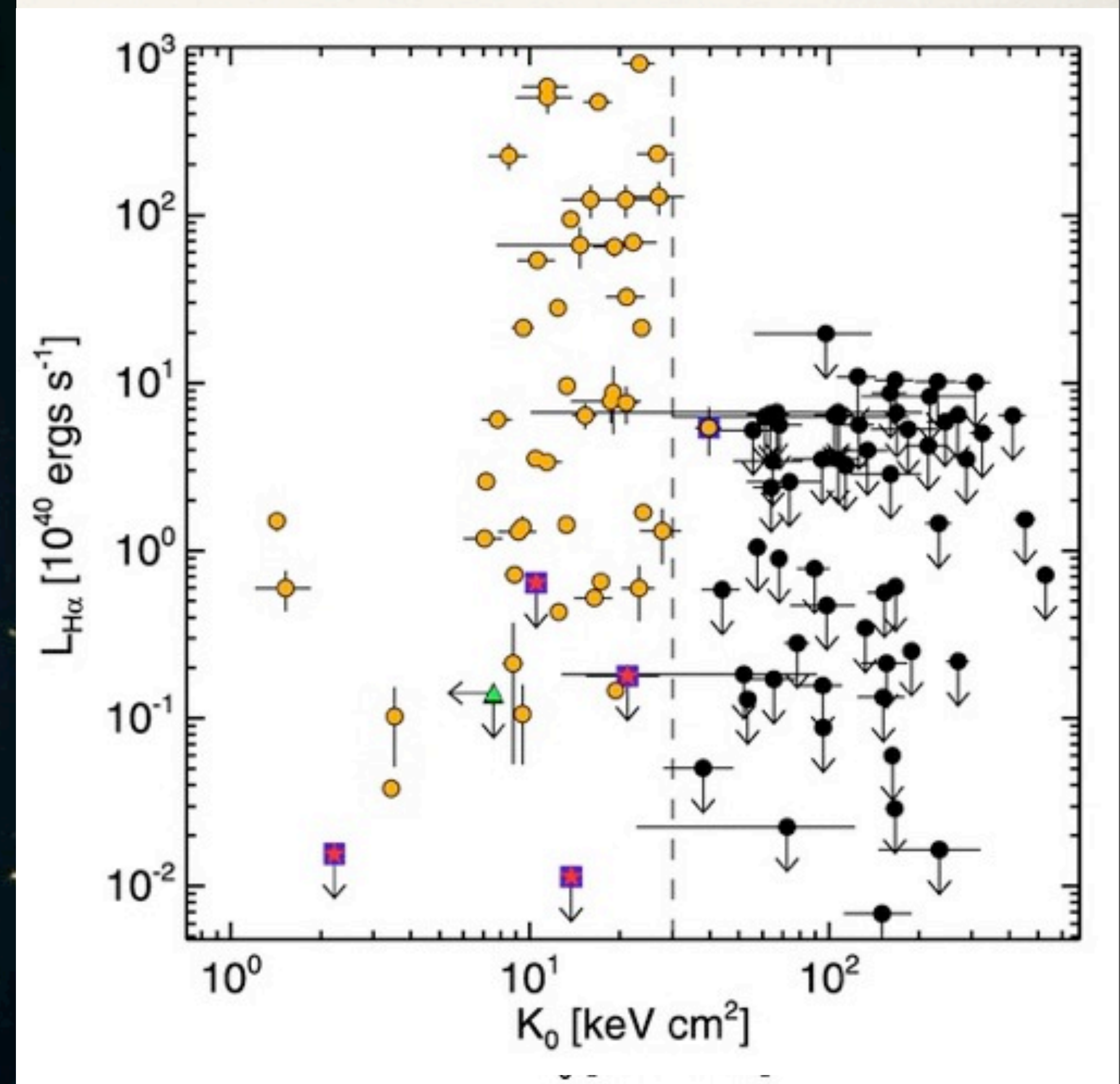


Power to excavate cavities proportional to X-ray luminosity

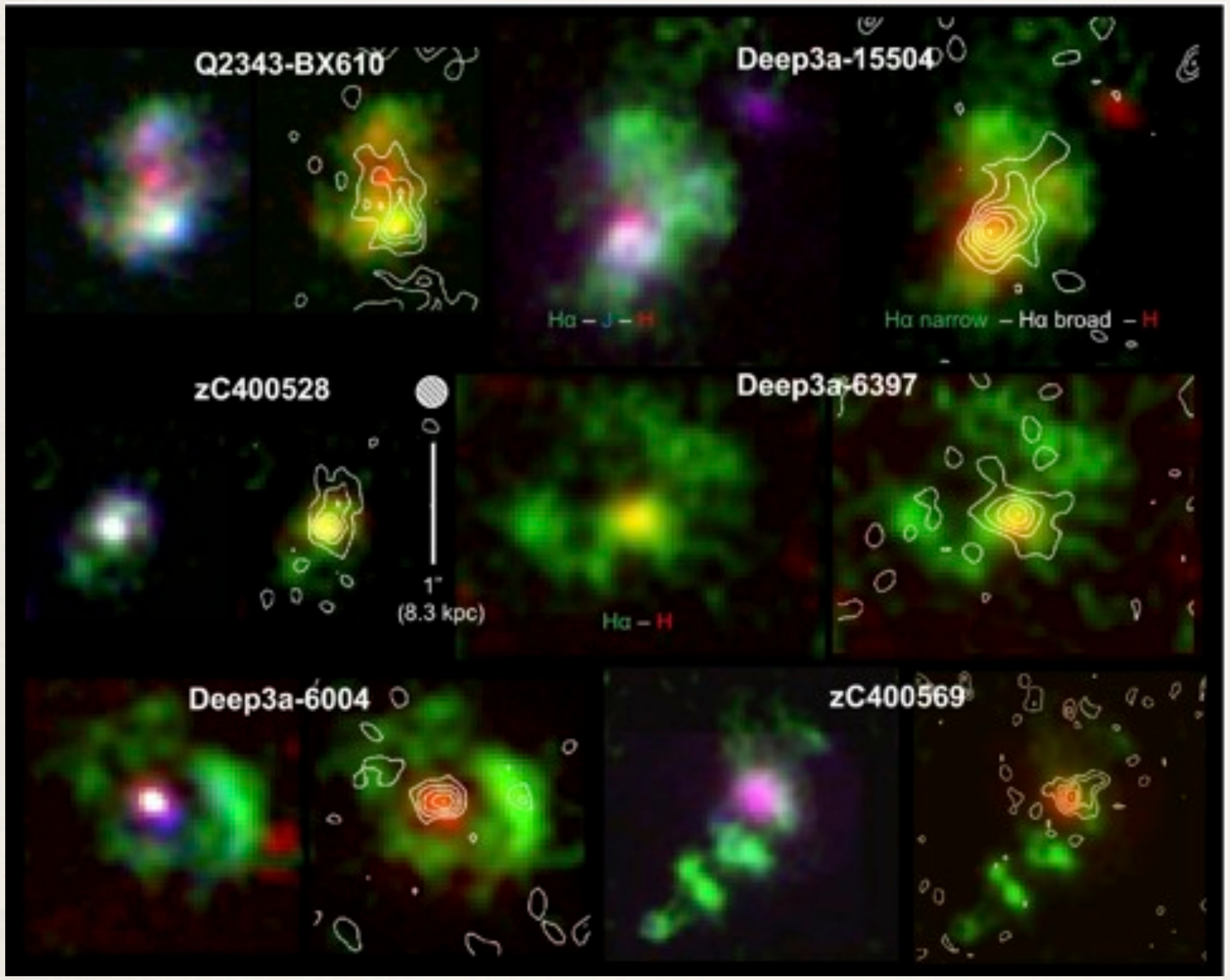
Power in cavities proportional to AGN radio luminosity

Only BCG in clusters with *low inner entropy* (short cooling time) have an active nucleus: **cold accretion!**

..and only BCG with low inner entropy are **actively forming stars!**



Quasar-mode: ionized phase outflows

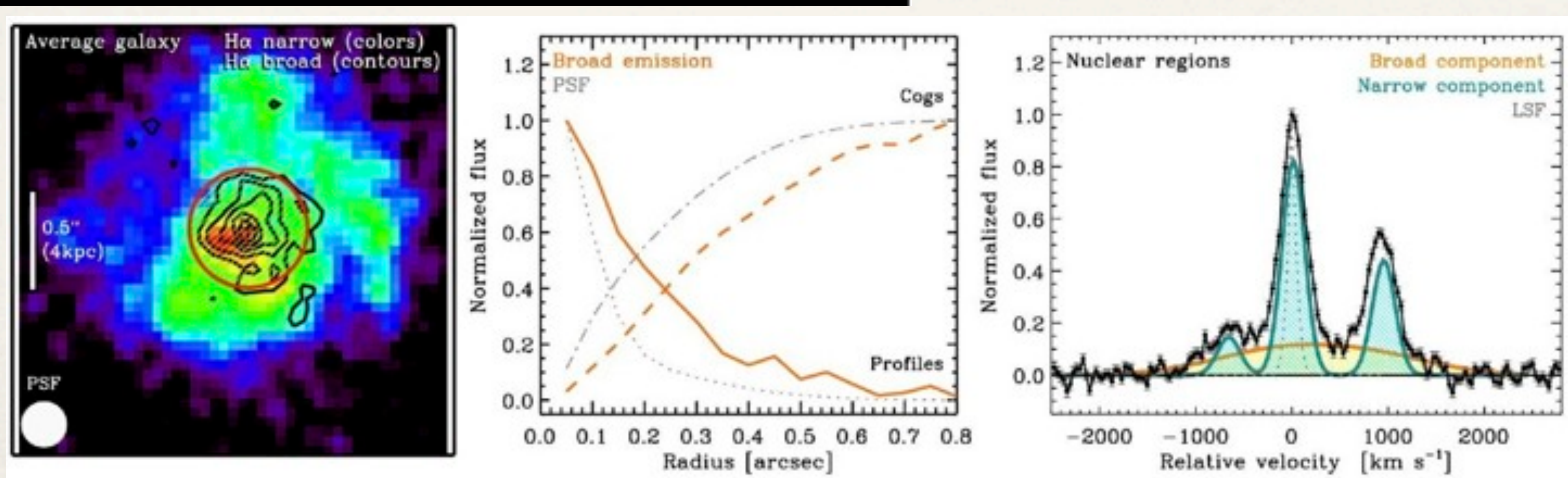


AGN feedback via nuclear extended (2-3 kpc) outflows widespread among massive z~2 SFG of the main sequence.

Mass outflow rates ~ 100 Msun/yr

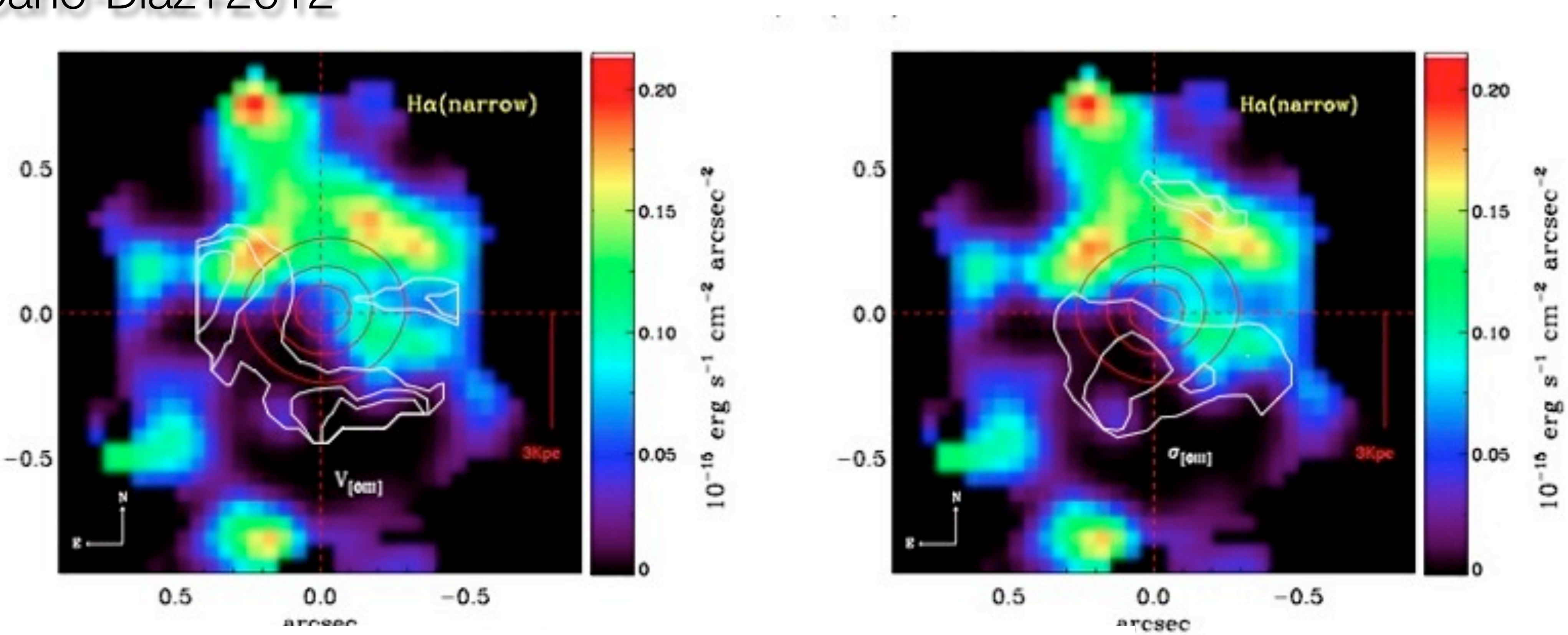
Spatial offset between broad/ narrow Halpha => feedback

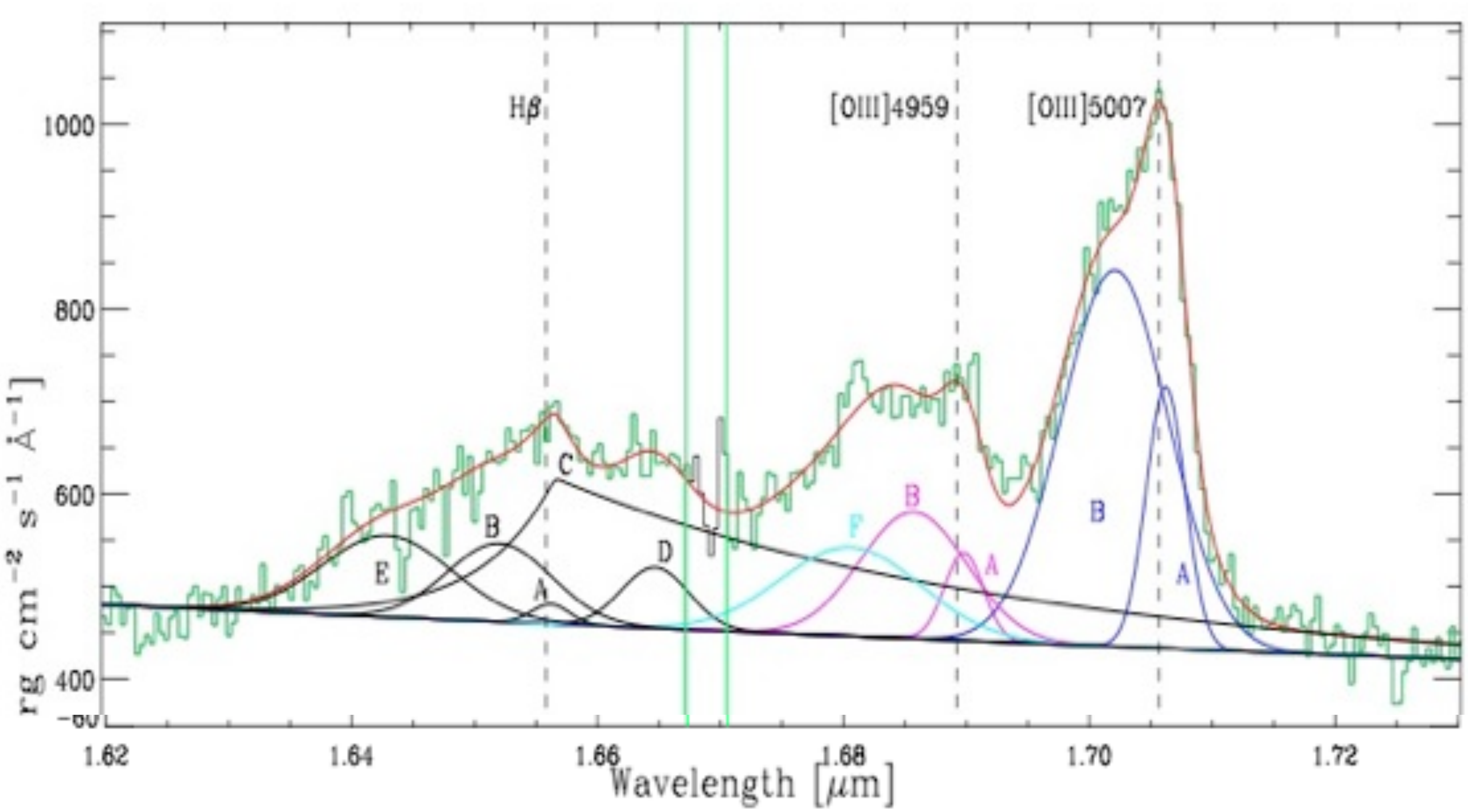
Genzel+2008 Forster Schreiber +2014
Genzel+2014



Quasar-mode: ionized phase outflows

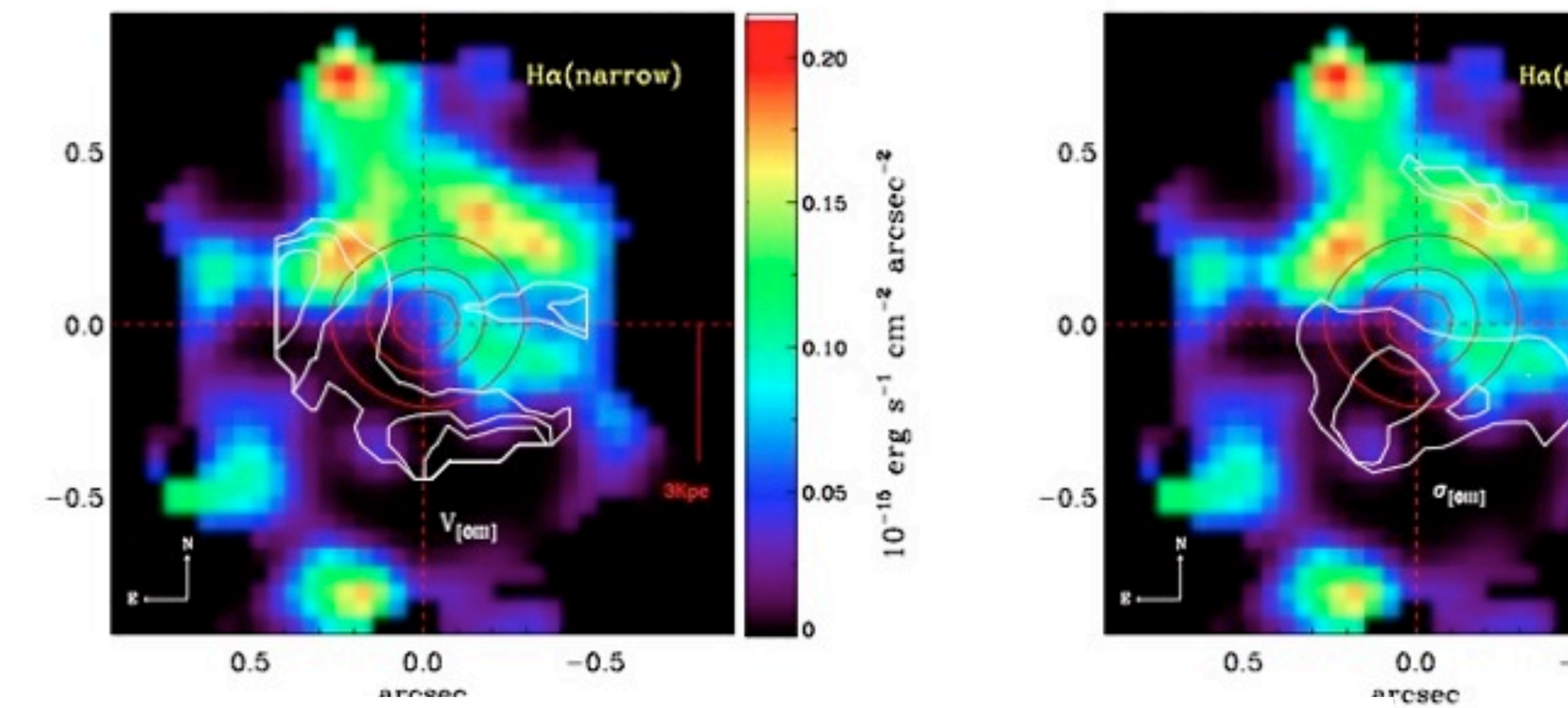
Cano-Diaz+2012





Quasar-mode: ionized phase outflows

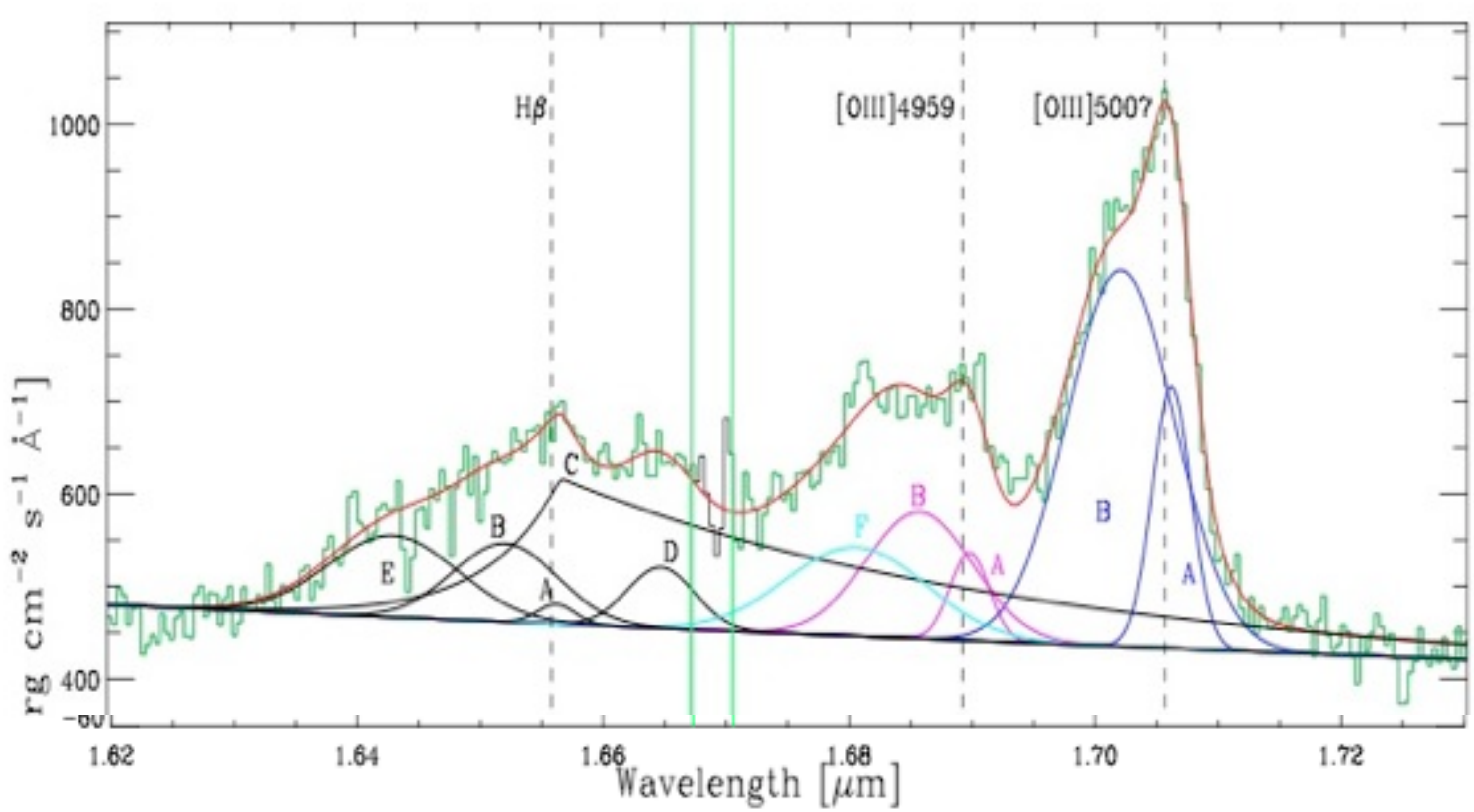
Cano-Diaz+2012



$$M_{\rm out}^{\rm ion} = 5.33 \times 10^{7} \, \frac{C \, L_{44}([\rm OIII])}{\langle n_{e3} \rangle \, 10^{[\rm O/H]}} \, M_{\odot}$$

$$\dot{M}_{\rm out}^{\rm ion} = \langle \rho \rangle_{V} \, v \, \Omega R^{2}$$

$$\dot{M}_{\rm out}^{\rm ion} = 164 \, \frac{C \, L_{44}([\rm OIII]) \, v_{3}}{\langle n_{e3} \rangle \, 10^{[\rm O/H]} \, R_{\rm kpc}} \, M_{\odot} \, {\rm yr}^{-1}$$

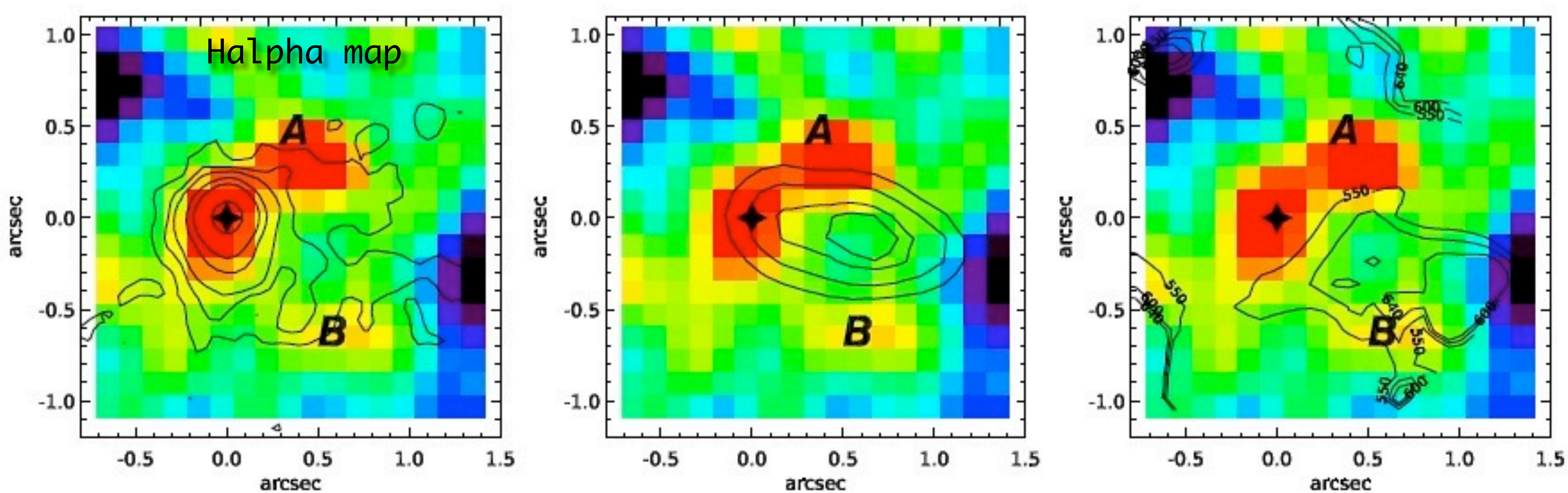


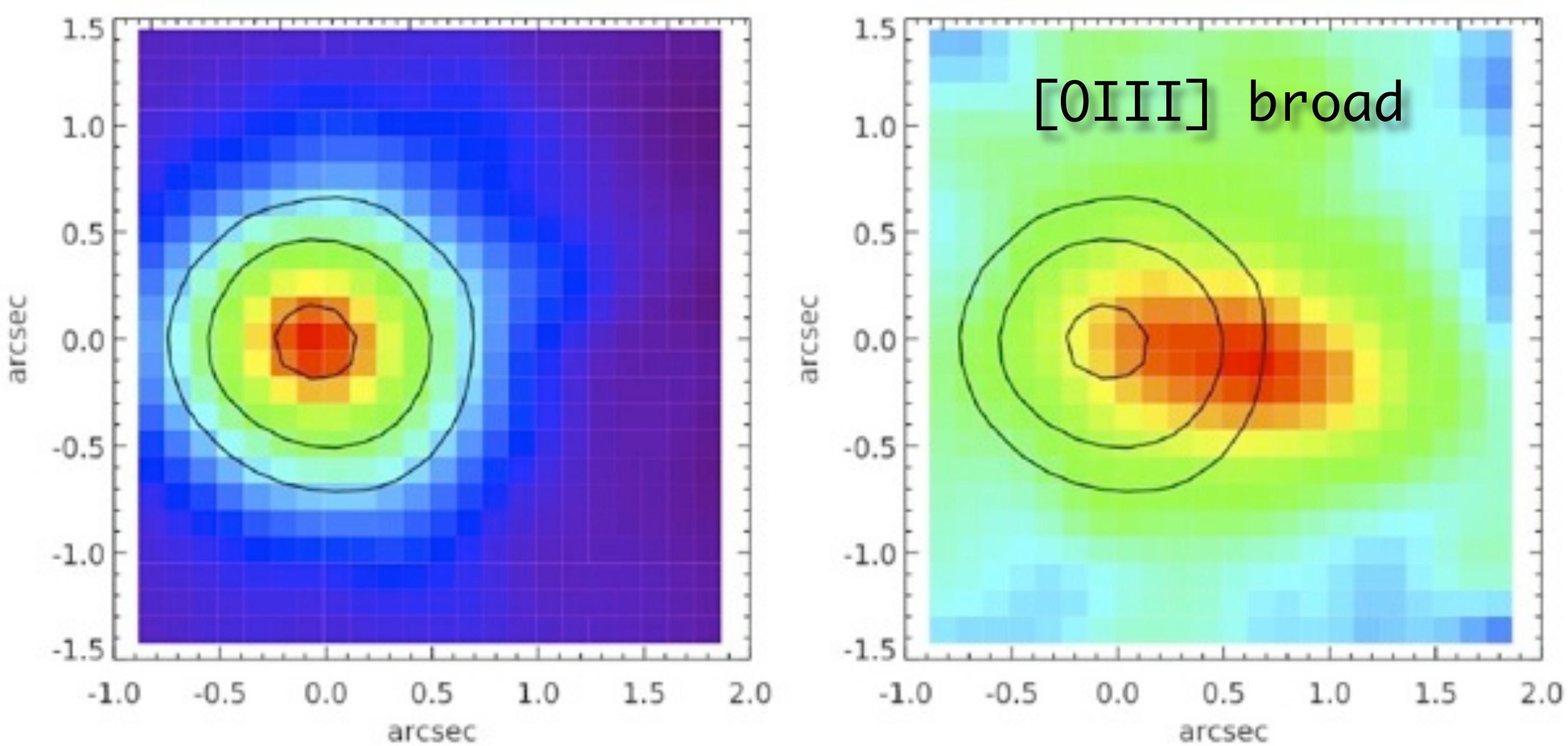
v_{out}~1000-10000 km/s
logL[OIII]=42-44 ergs/s
$\log n_{H}$=3-4 NELR
r~1-10kpc

M_{out}~10-1000$M_{\otimes}$/yr

Quasar-mode: ionized phase outflows

Brusa+2014, **Cresci+2014** **NEXT TALK**





XID 2028

logLx~45

logLbol~46

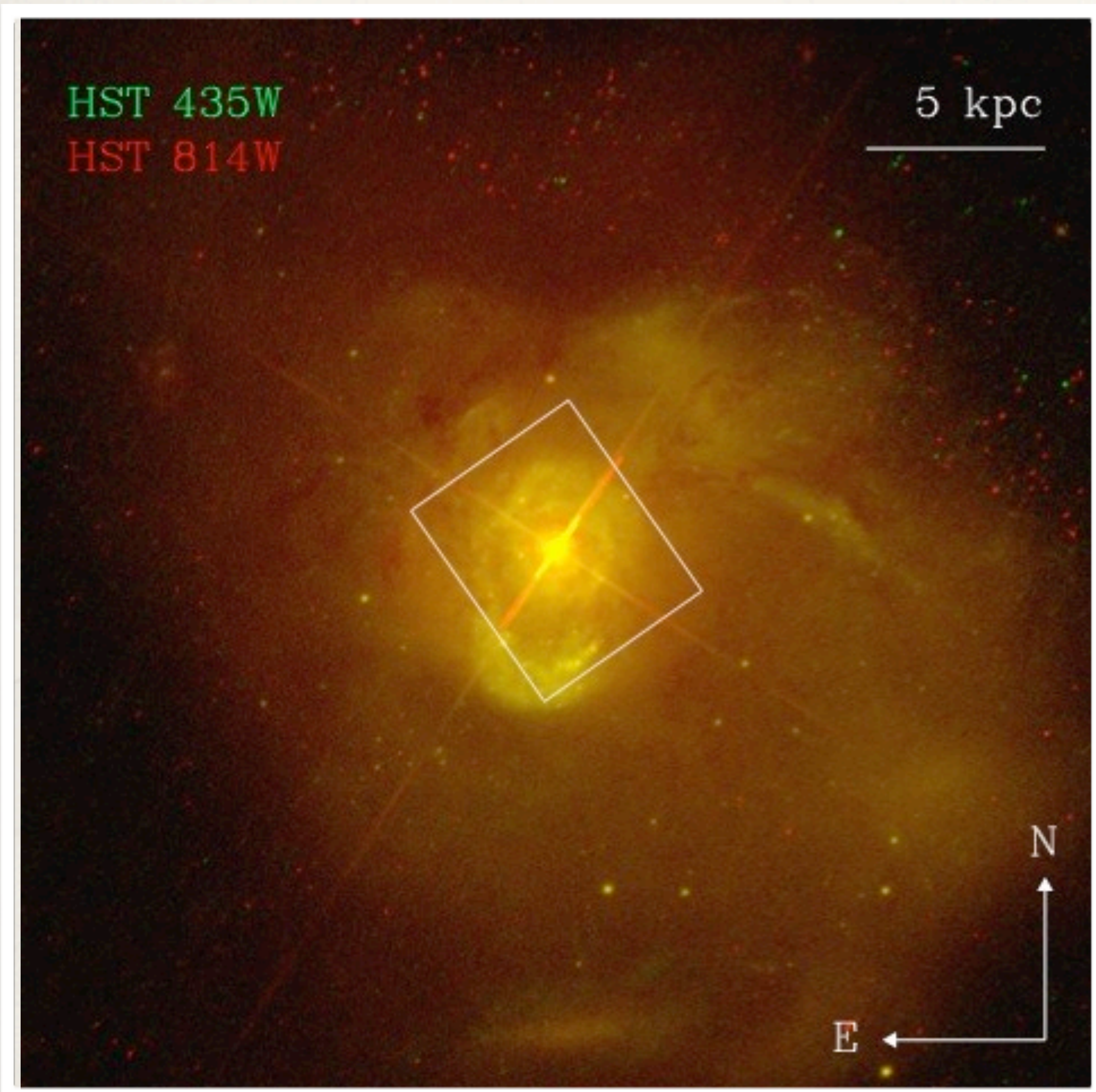
SFR~450 M_{Sun}/yr

logM_{star}=11.7

M_{out}~1000 M_{Sun}/yr

Spatial anticorrelation fast/quiescent gas

Mrk231

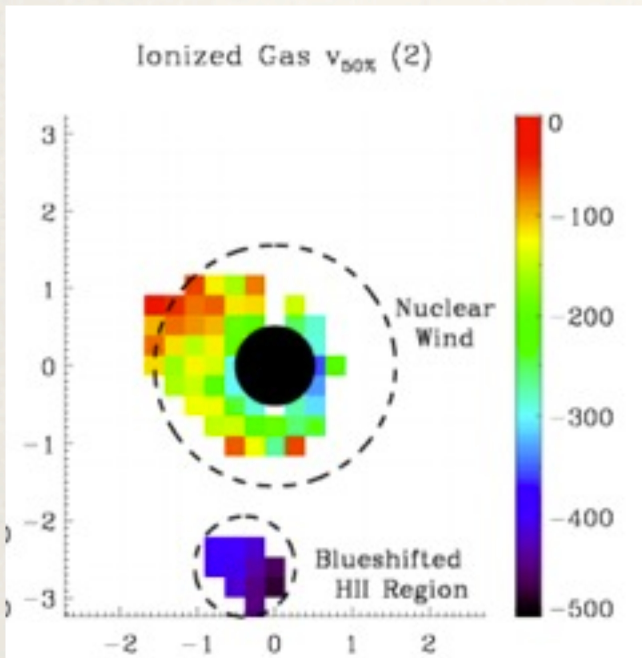


- nearest QSO (z=0.042)
- most luminous ULIRG in the local Universe L_{IR}=3.6 10^{12} $L_\odot$
- >40% L_{bol} in SB activity
- late-state merger
- X-ray under-luminous AGN: Lx=10^{43} erg/s
- BAL QSOs
- Expanding shells on Kpc scales

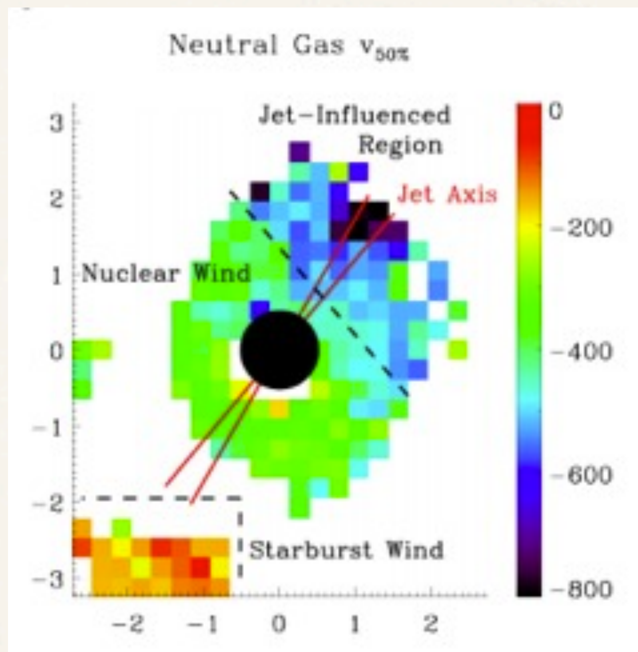
Dust enshrouded AGN/ star-forming galaxy

AGN feedback in Mrk 231

★ ionized



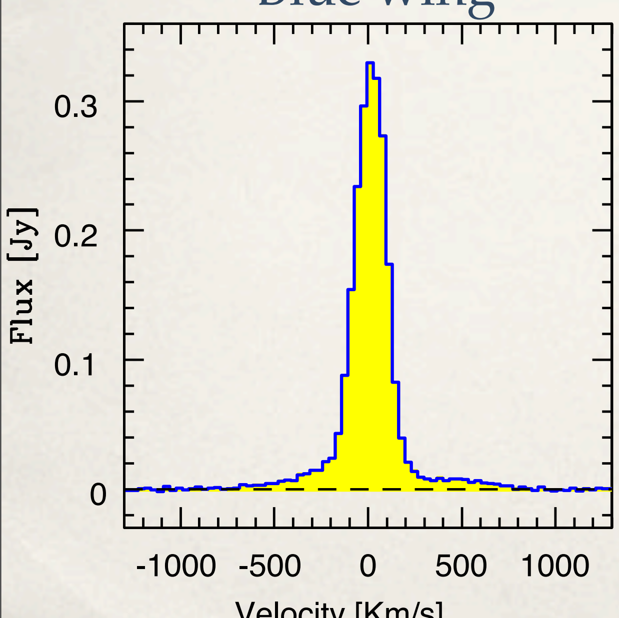
★ neutral



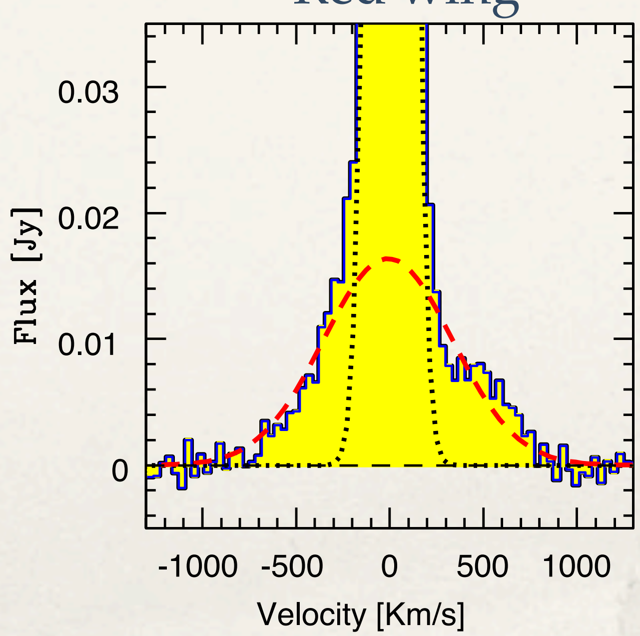
(Rupke & Veilleux 2010)

★ molecular CO(1-0)

Blue wing



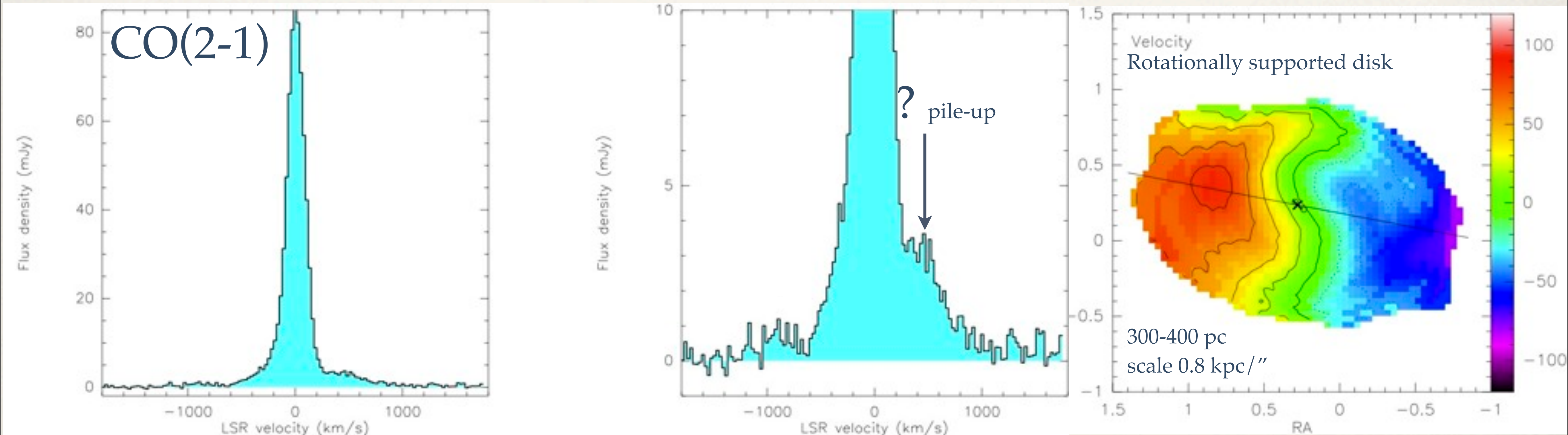
Red wing



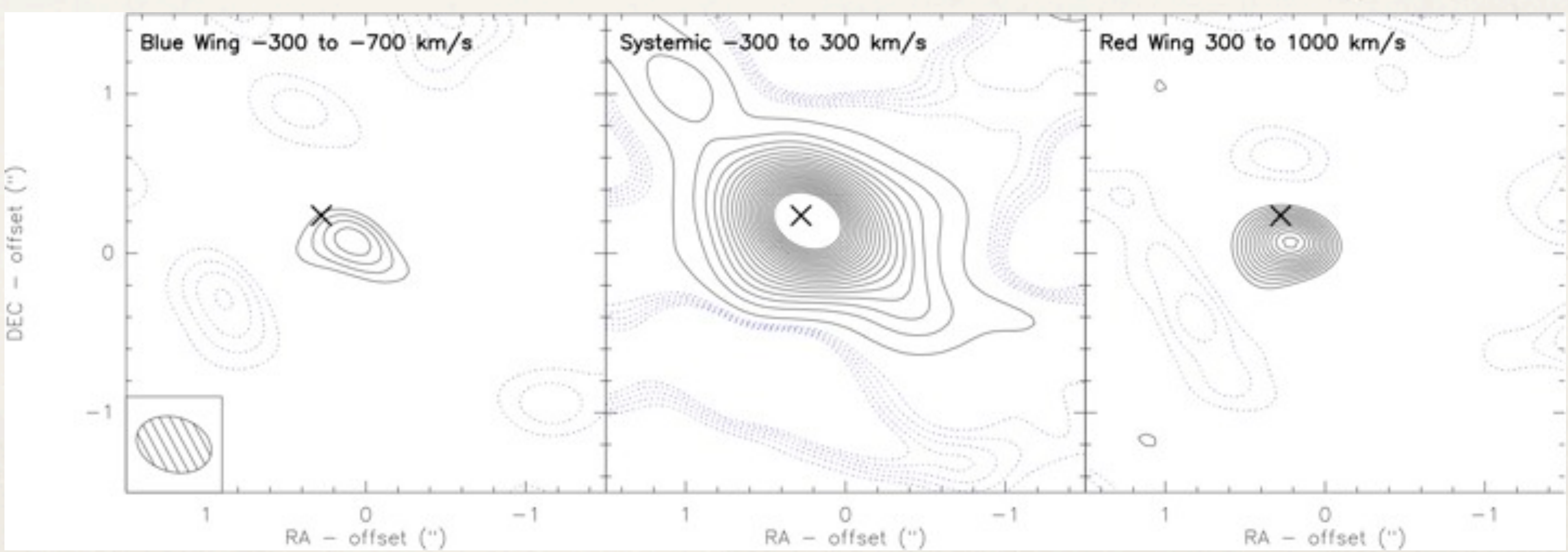
- Outflows observed in the **ionized, neutral** and **molecular** gas
- $\dot{M}_{out}$ [700 $M_\odot$/yr] > SFR [200 $M_\odot$/yr]
- Outflow Kinetic power ~ 6% AGN L_{bol} (as expected for a shock wave produced by radiation pressure onto the ISM)
- Outflow on > 0.6 kpc scale

AGN feedback in Mrk 231: mapping the CO OF

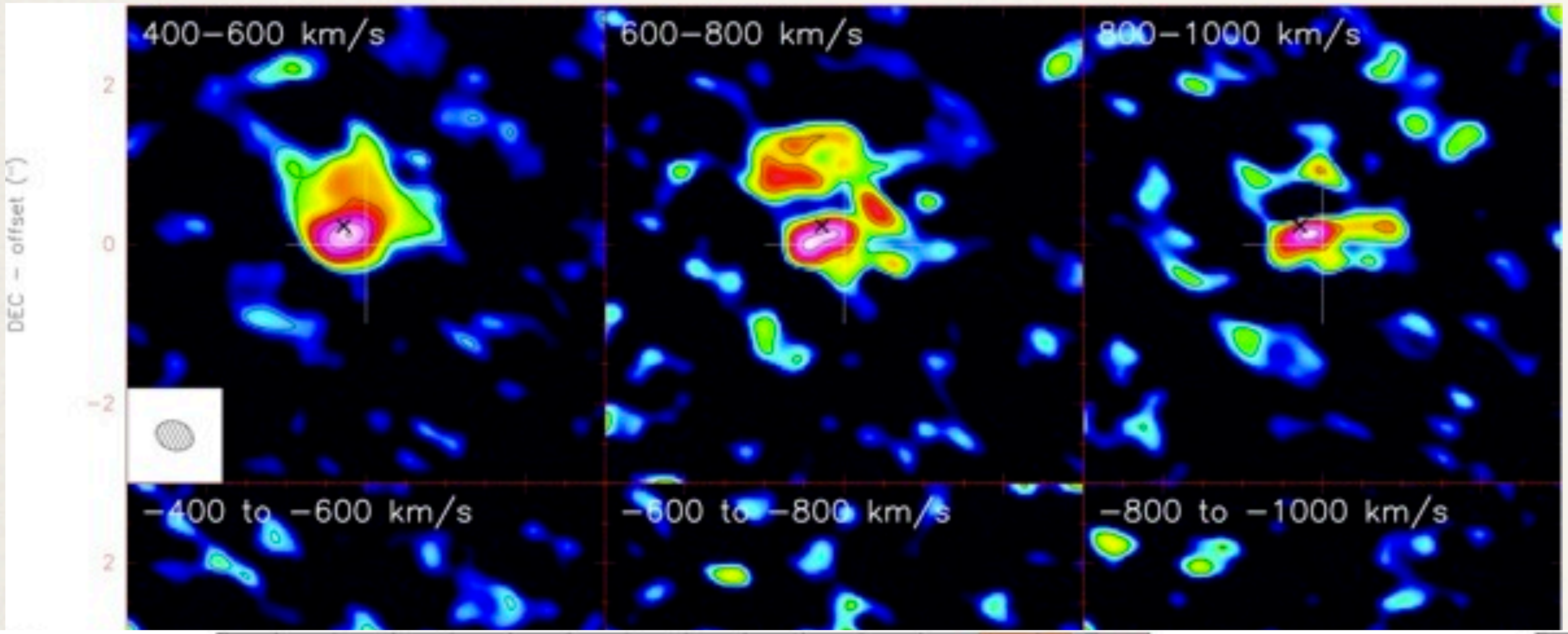
Feruglio + 2014



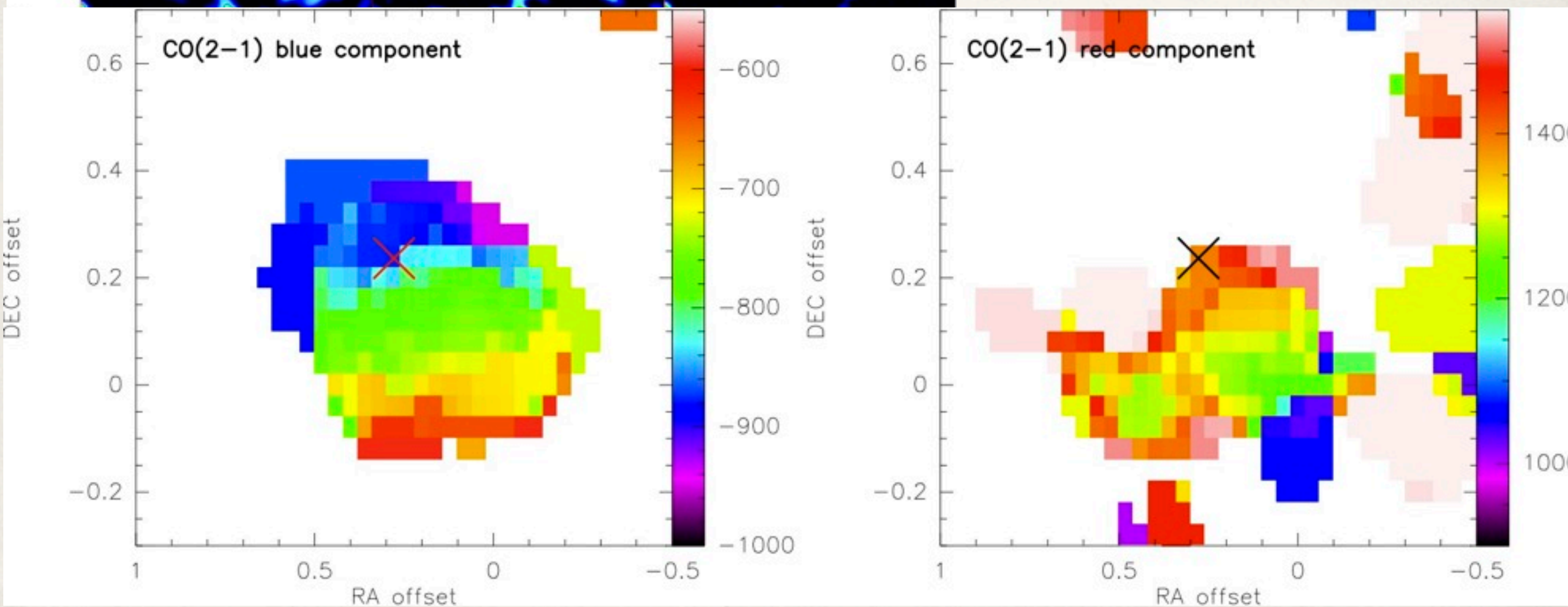
High velocity components are not centered on AGN.
Both blue and red are offset by ~ 200 pc in the same direction.



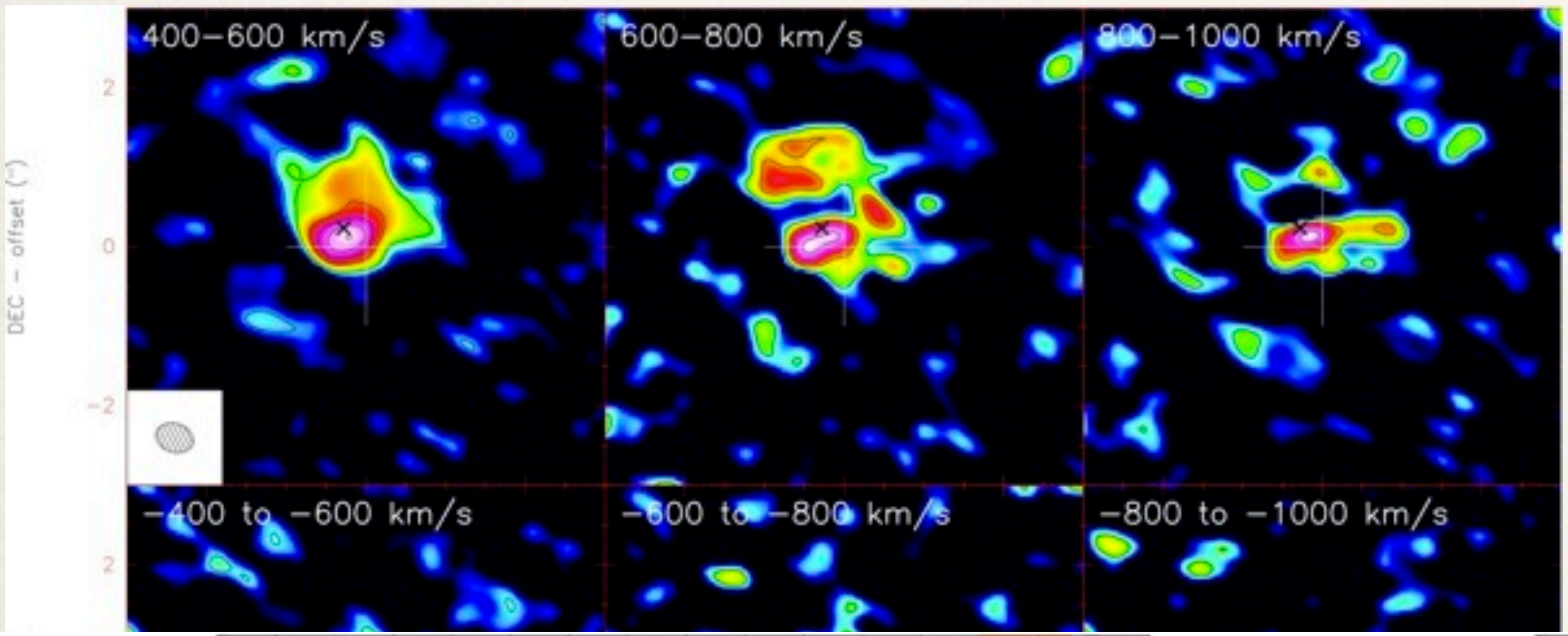
AGN feedback in Mrk 231: mapping the CO OF



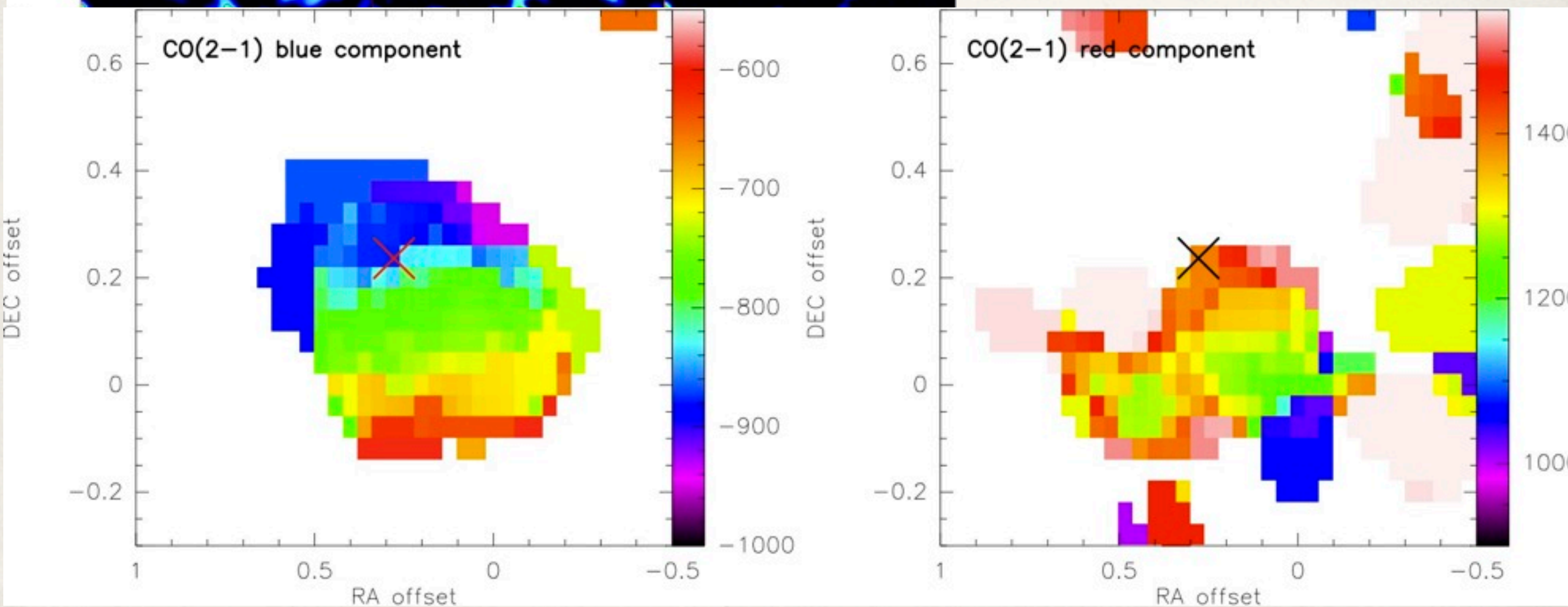
- A diffuse faint component north with + 500 km/s (HCN also)
- Highest velocities are more compact
- Outflow is stratified
- projected size ~ molecular disk size



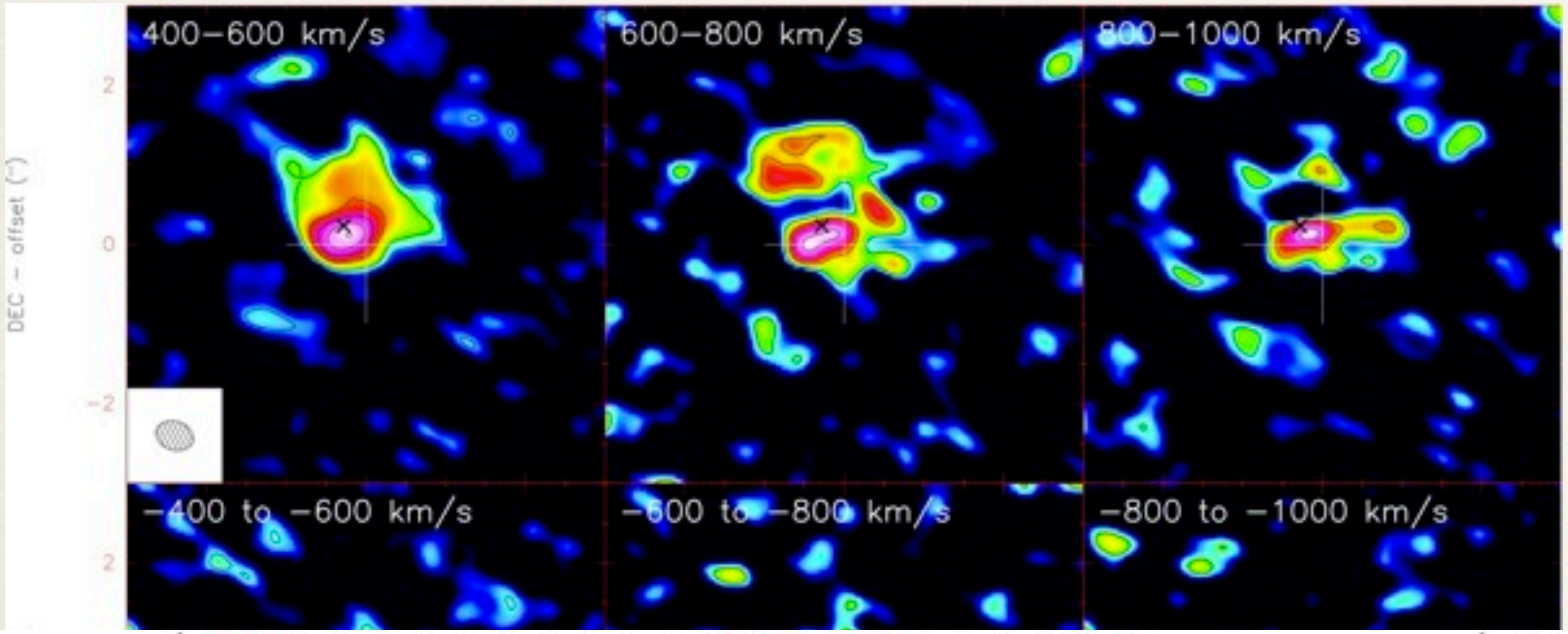
AGN feedback in Mrk 231: mapping the CO OF



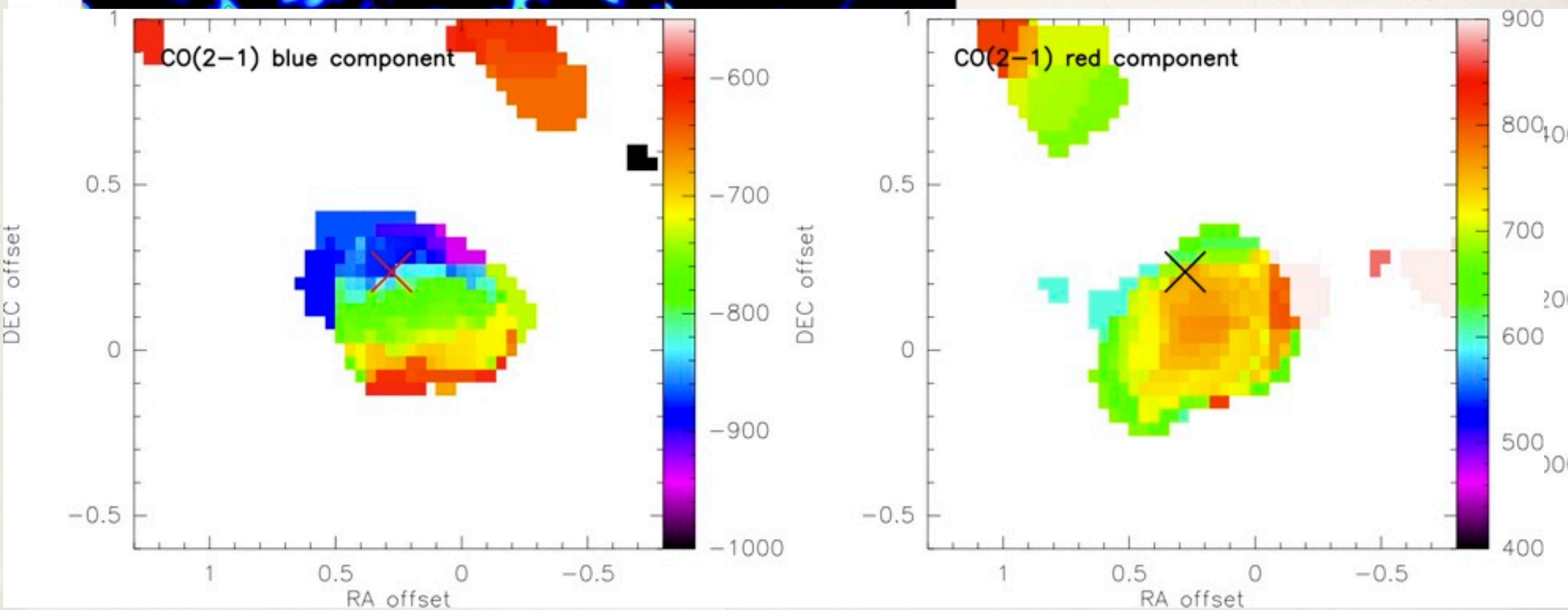
- A diffuse faint component north with + 500 km/s (HCN also)
- Highest velocities are more compact
- Outflow is stratified
- projected size ~ molecular disk size



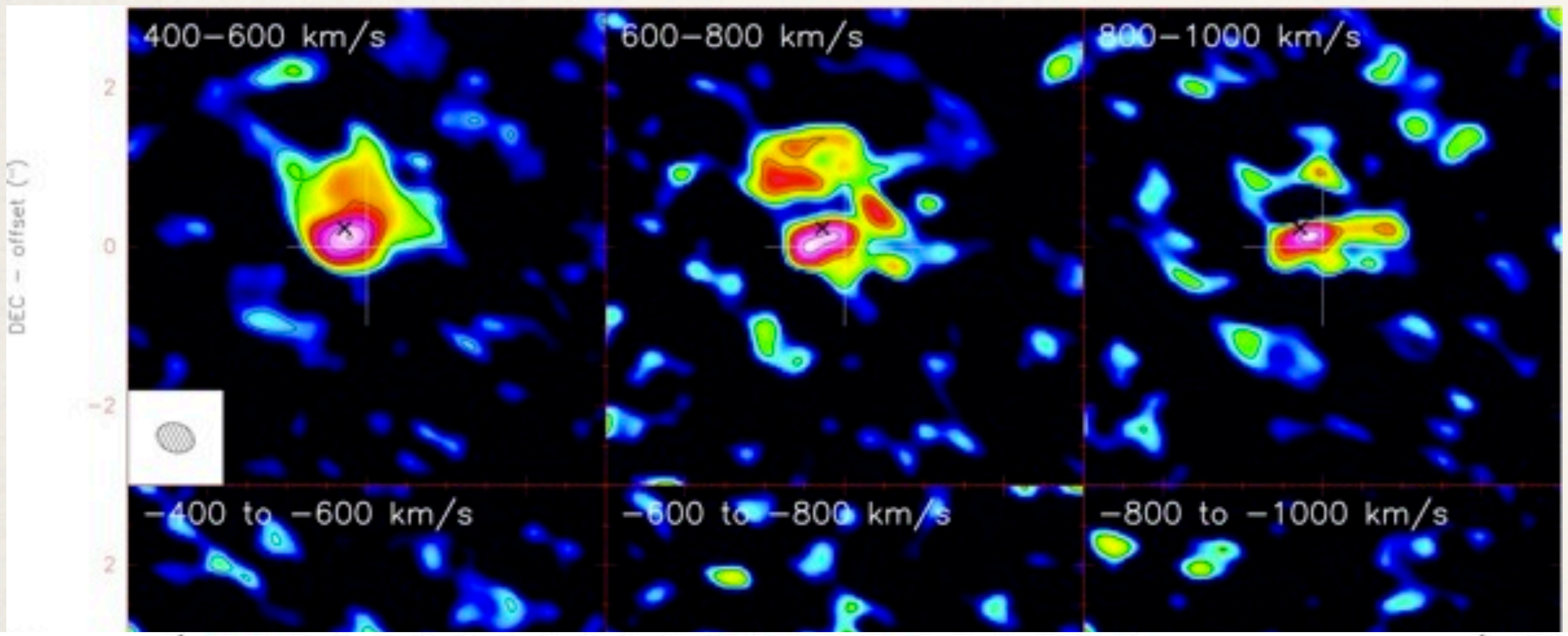
AGN feedback in Mrk 231: mapping the CO OF



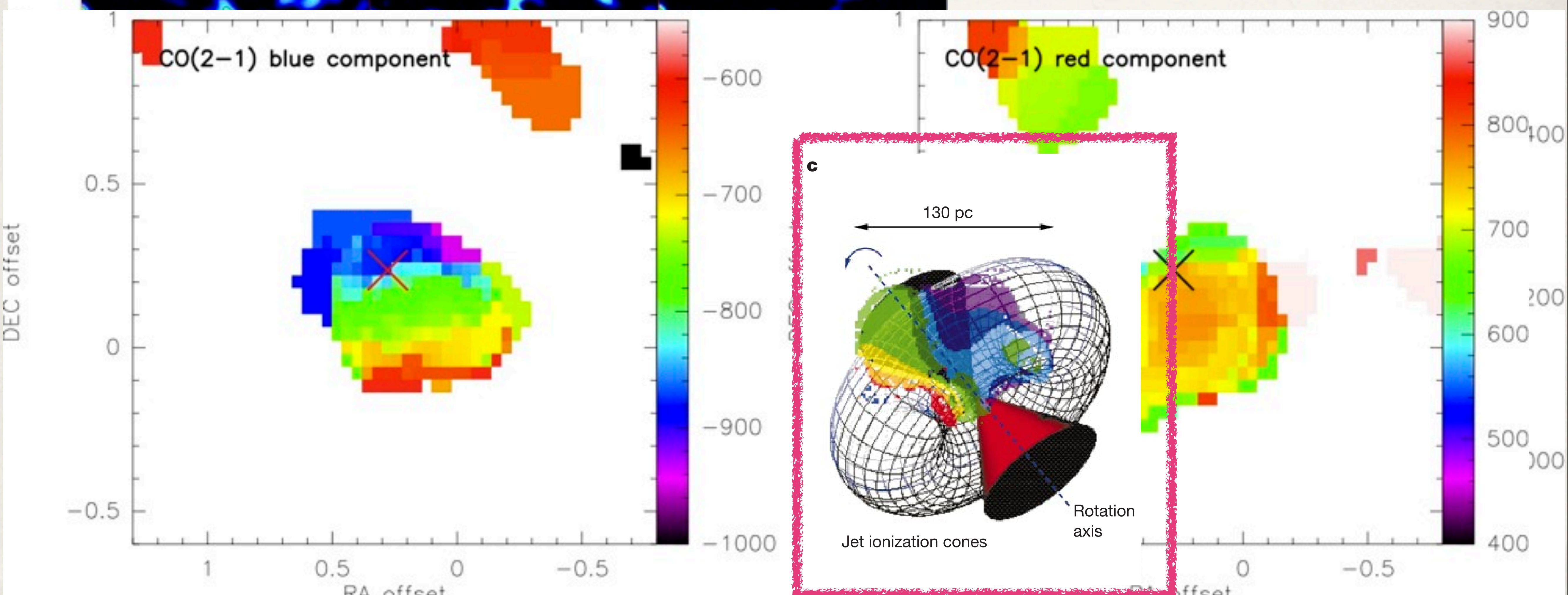
- A diffuse faint component north with + 500 km/s (HCN also)
- Highest velocities are more compact
- Outflow is stratified
- projected size ~ molecular disk size



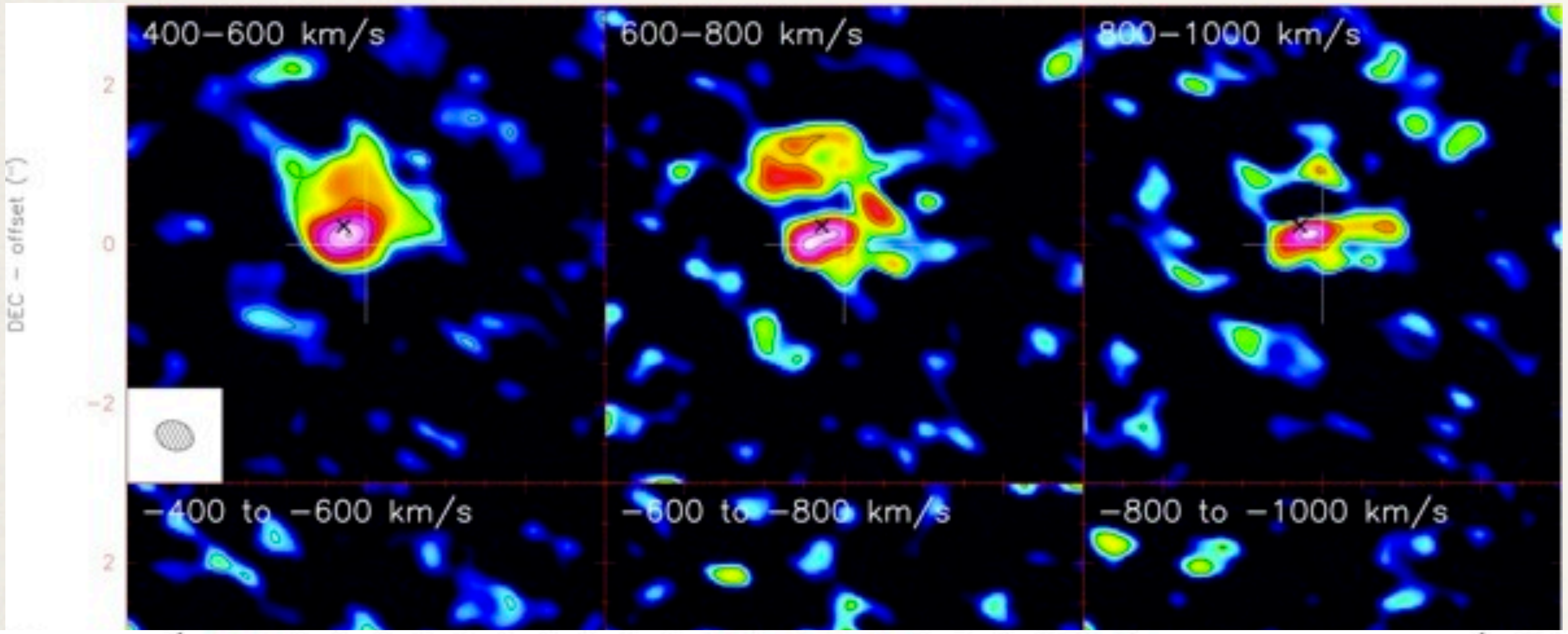
AGN feedback in Mrk 231: mapping the CO OF



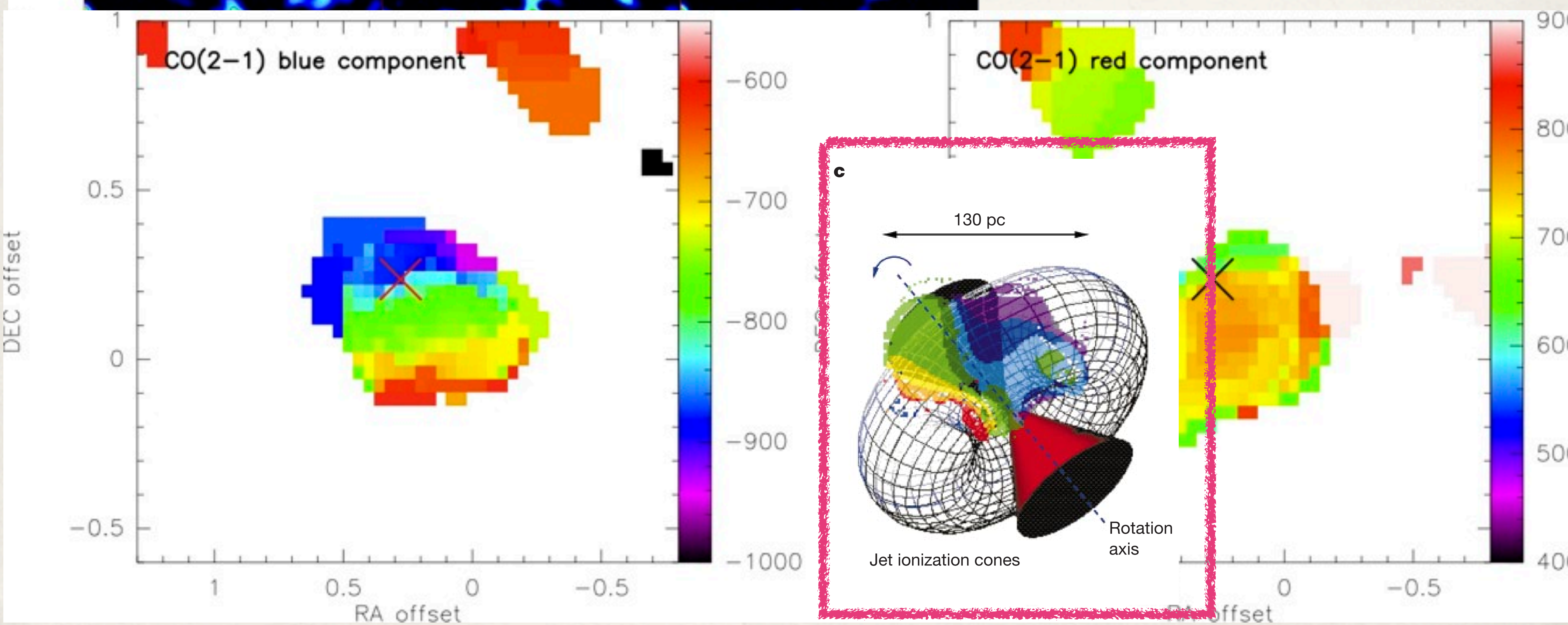
- A diffuse faint component north with +500 km/s (HCN also)
- Highest velocities are more compact
- Outflow is stratified
- projected size ~ molecular disk size



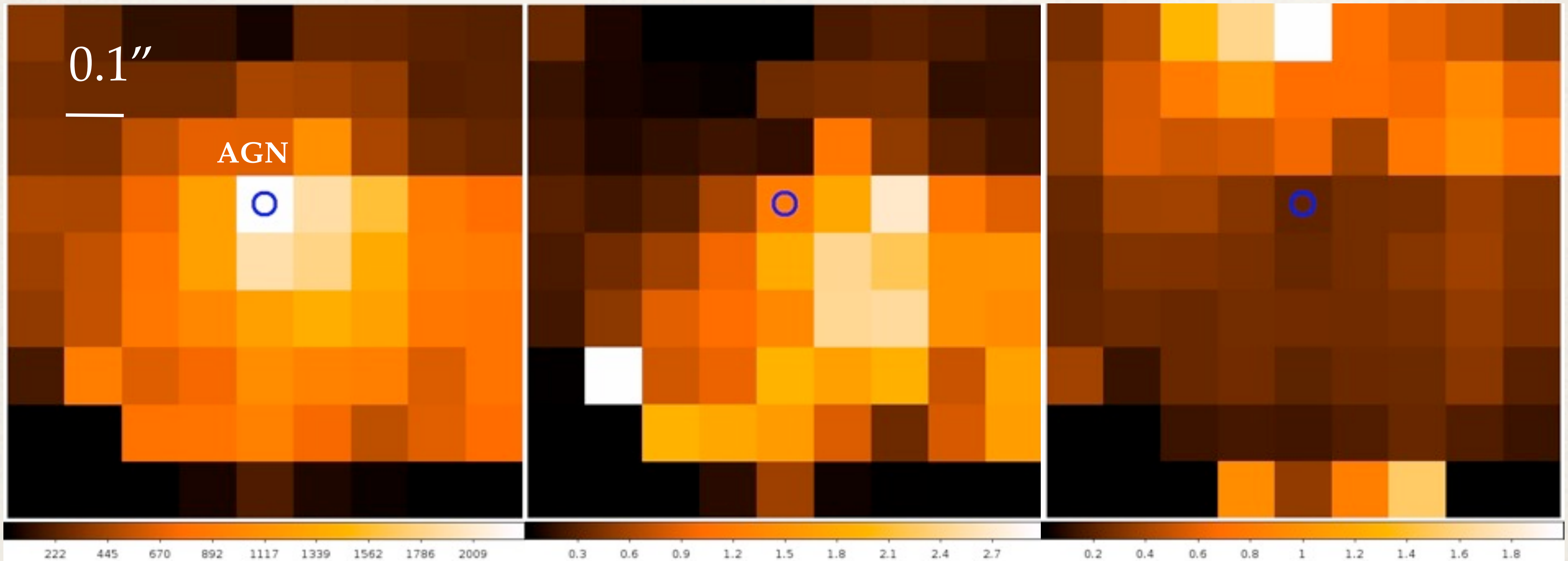
AGN feedback in Mrk 231: mapping the CO OF



- A diffuse faint component north with +500 km/s (HCN also)
- Highest velocities are more compact
- Outflow is stratified
- projected size ~ molecular disk size



AGN feedback in Mrk 231: mapping the CO OF



Mass outflow rate [M_{Sun}/yr]

Ekin rate [10^{44} ergs/s]

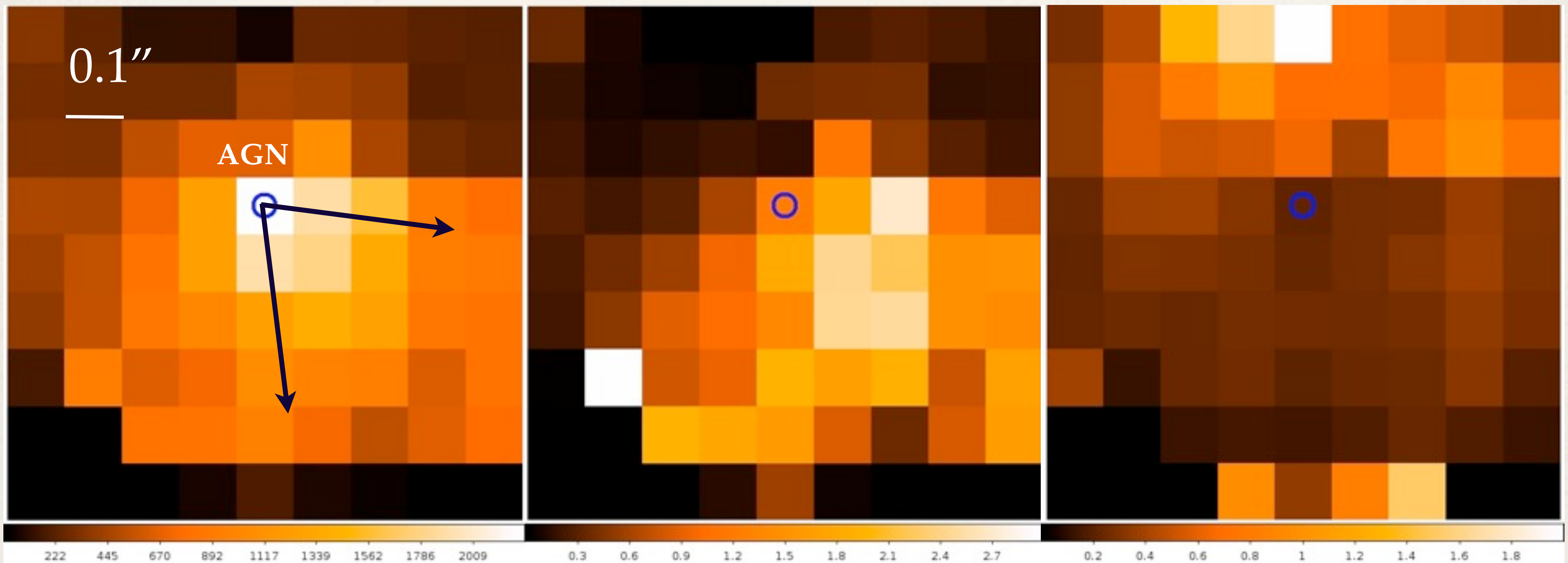
Depletion time [Myr]

Stars older than ~1Myr in the central kpc? (Lipari+2009)

To be verified by on going LBTI imaging on PAH to trace SF regions on 100 pc scale.

Feruglio+2014

AGN feedback in Mrk 231: mapping the CO OF



Mass outflow rate [M_{Sun}/yr]

Ekin rate [10^{44} ergs/s]

Depletion time [Myr]

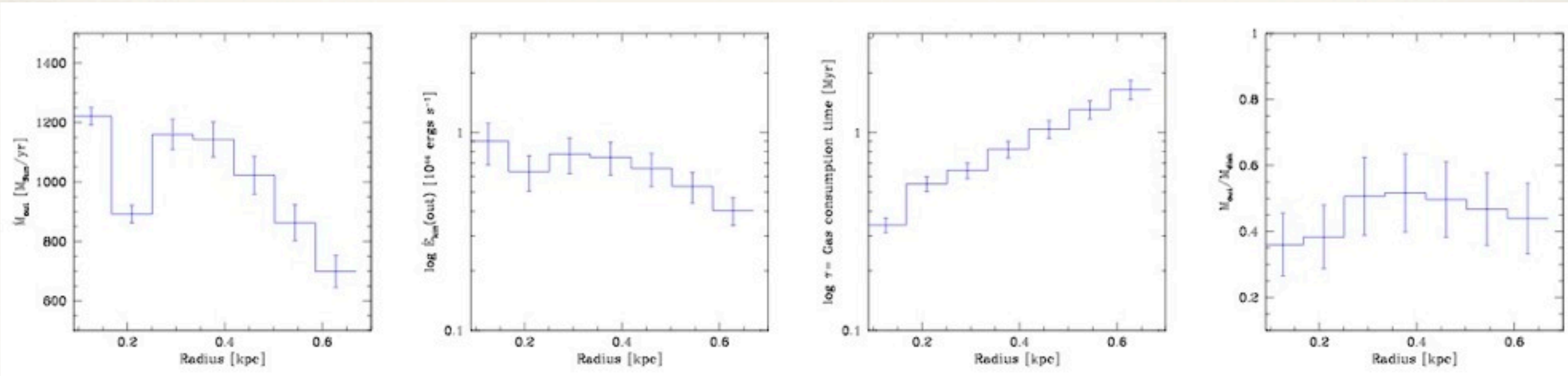
<u>Stars older than ~1Myr in the central kpc? (Lipari+2009)</u>

To be verified by on going LBTI imaging on PAH to trace SF regions on 100 pc scale.

Feruglio+2014

AGN feedback in Mrk 231: mapping the CO OF

Radial profiles



Mass outflow rate [MSun/yr]

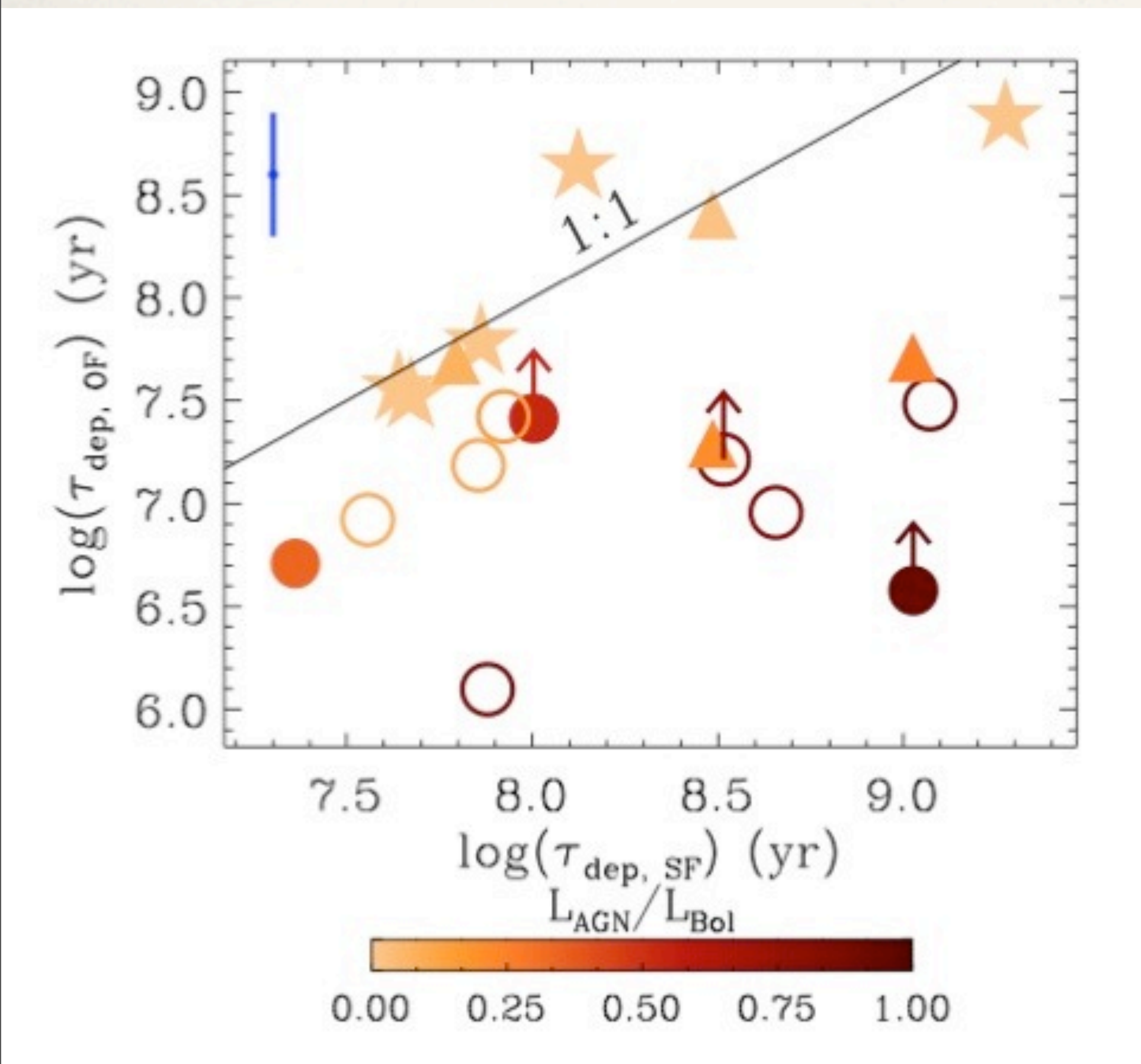
Ekin rate [10^{44} ergs/s]

Depletion time [Myr]

Mout/Mdisk

Feruglio+2014

Statistics of extended outflows



Cicone+2014

AGN outflow depletion timescale
<< star-formation depletion timescale

Problem:

t_{dep} << AGN timescale!!! →

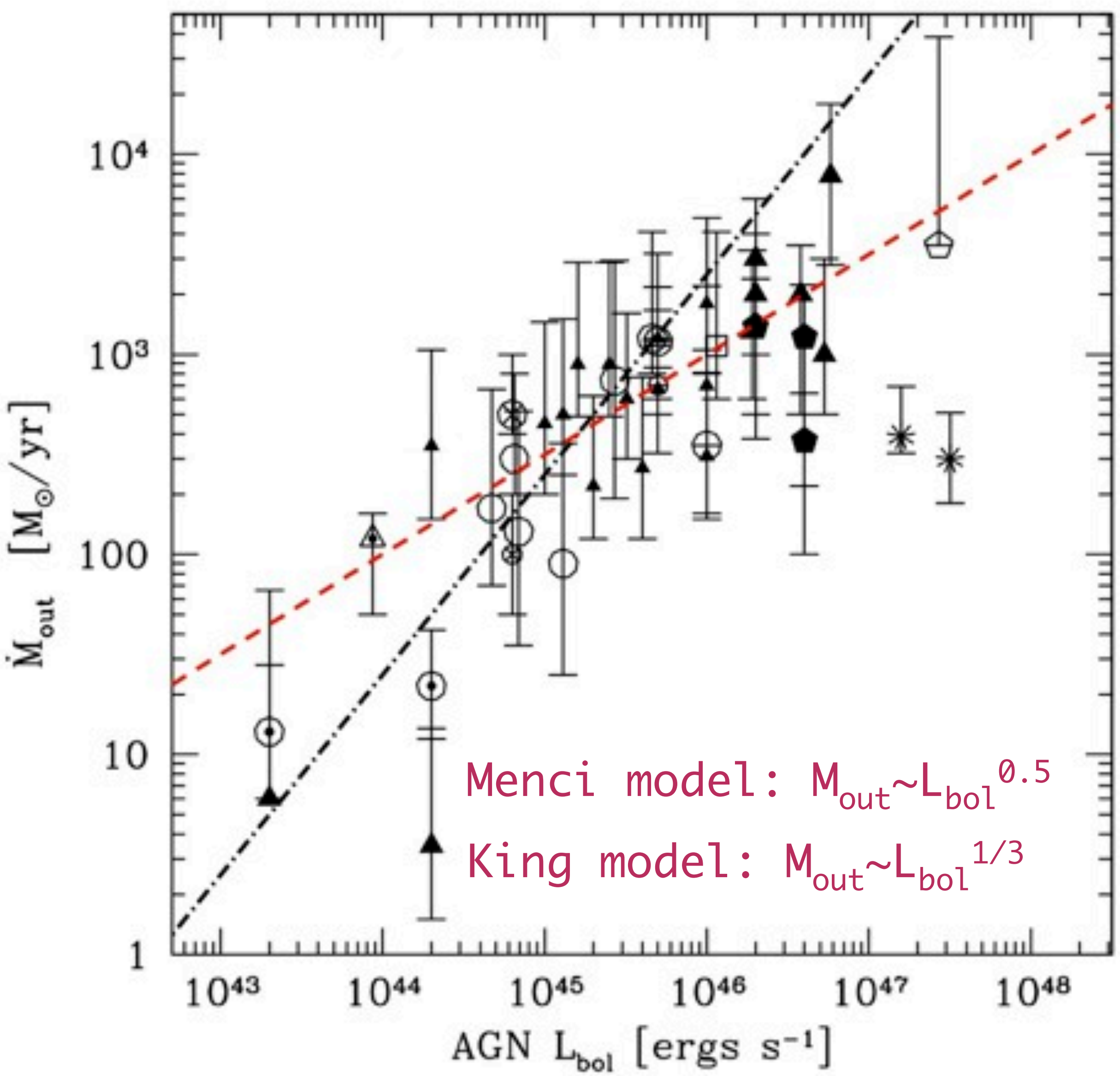
observations of outflows should be rare! They are ubiquitous instead...

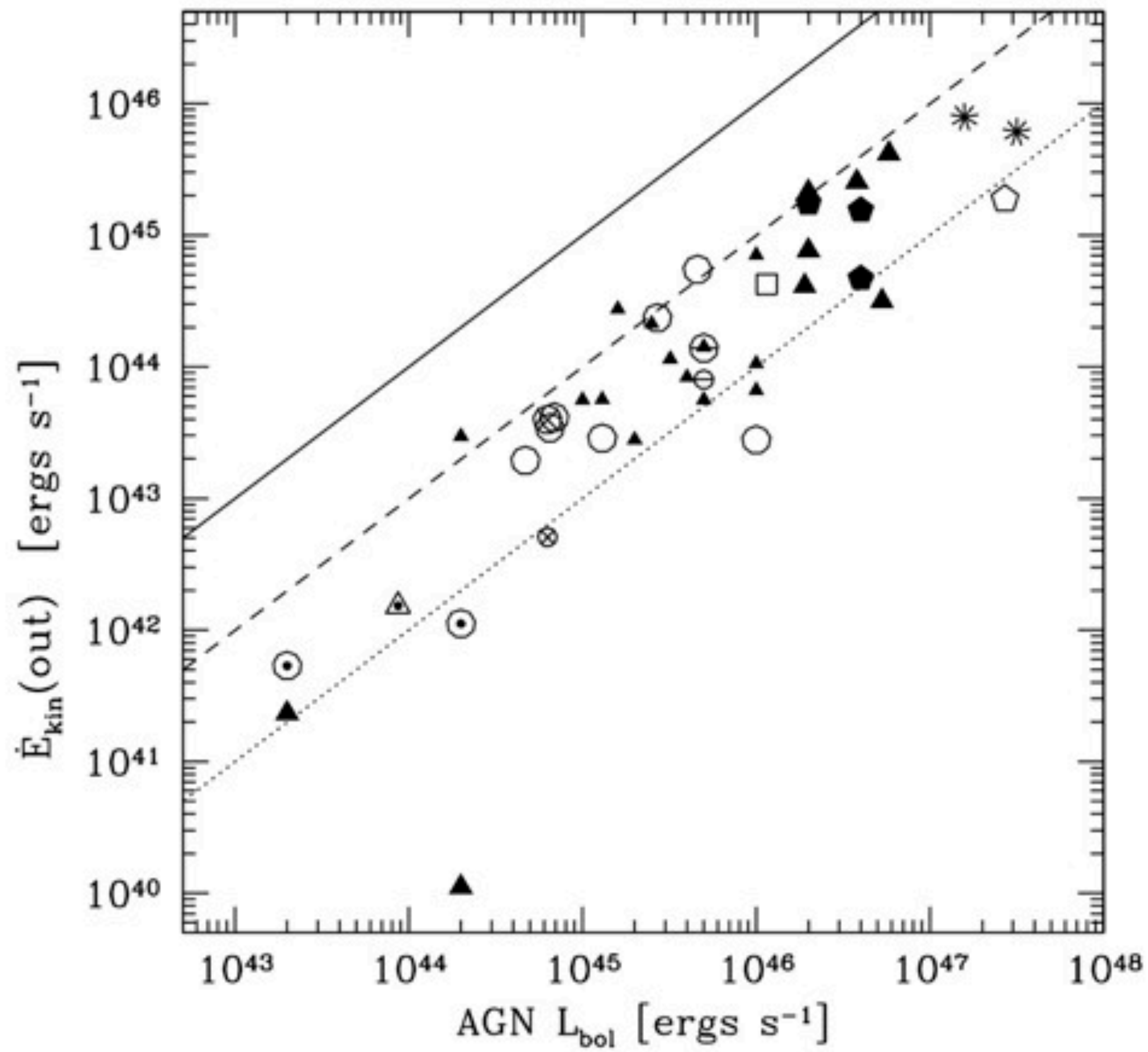
Two possibilities:

1) Outflows are characteristic of a ***short*** phase during AGN evolution and samples are ***biased*** toward this phase (obscured AGN)

2) Outflows are *cyclic* phenomena. The ISM is first accelerated outward and heated. It then decelerates after cooling, raining back into the galactic disk: SF and accretion restarted

Statistics of extended outflows



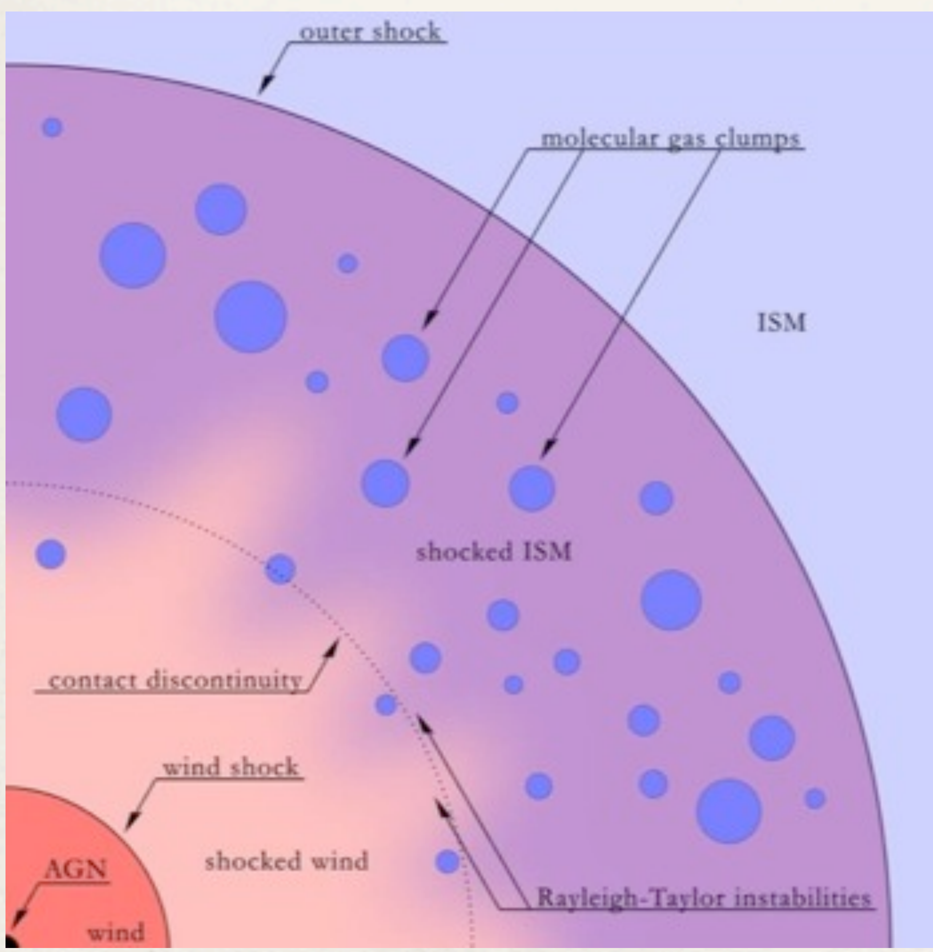


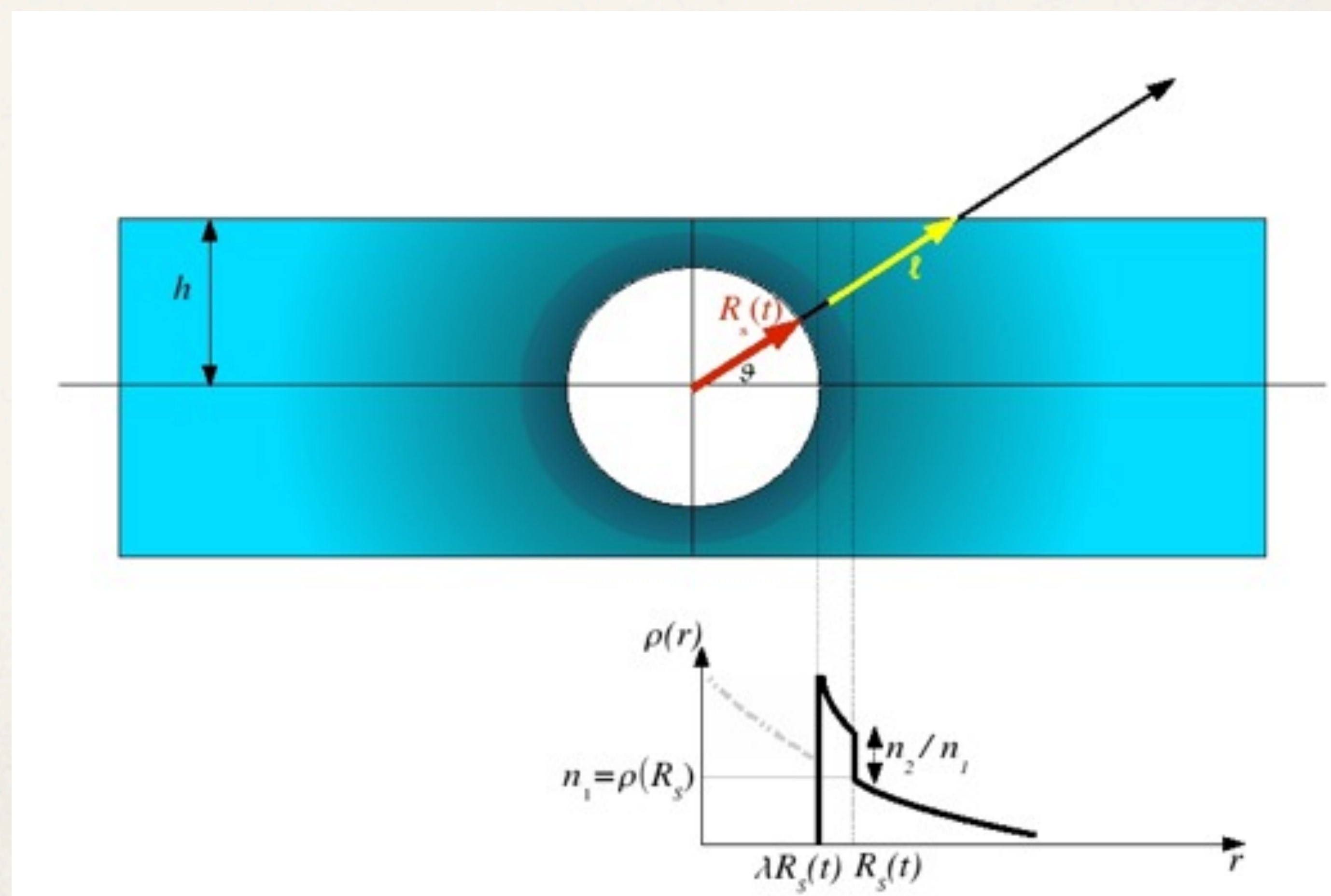
Remarkable correlation between AGN outflow rate and AGN bolometric luminosity: $L_{bol}/M_{out} \sim 7.5\times10^{42}$ erg/s / $M_\odot$/yr

AGN feedback models - I

AGN radiation launches a relativistic wind from very close in.
The wind shocks against the surrounding gas and drives an outflow.
If the mass of the black hole powering the AGN > 10^8 M⊙, the wind shock can propagate to large distances.
The previously weak and cold, momentum-driven outflows become violent, energy-driven outflows, that can clear galaxies of their gas. *Energy conserving.*

Lapi, Menci & Cavaliere 2005, Blast wave model.
King 2003, Zubovas&King 2014





AGN feedback models - II

Radiation pressure driven winds **(momentum conserving)**:

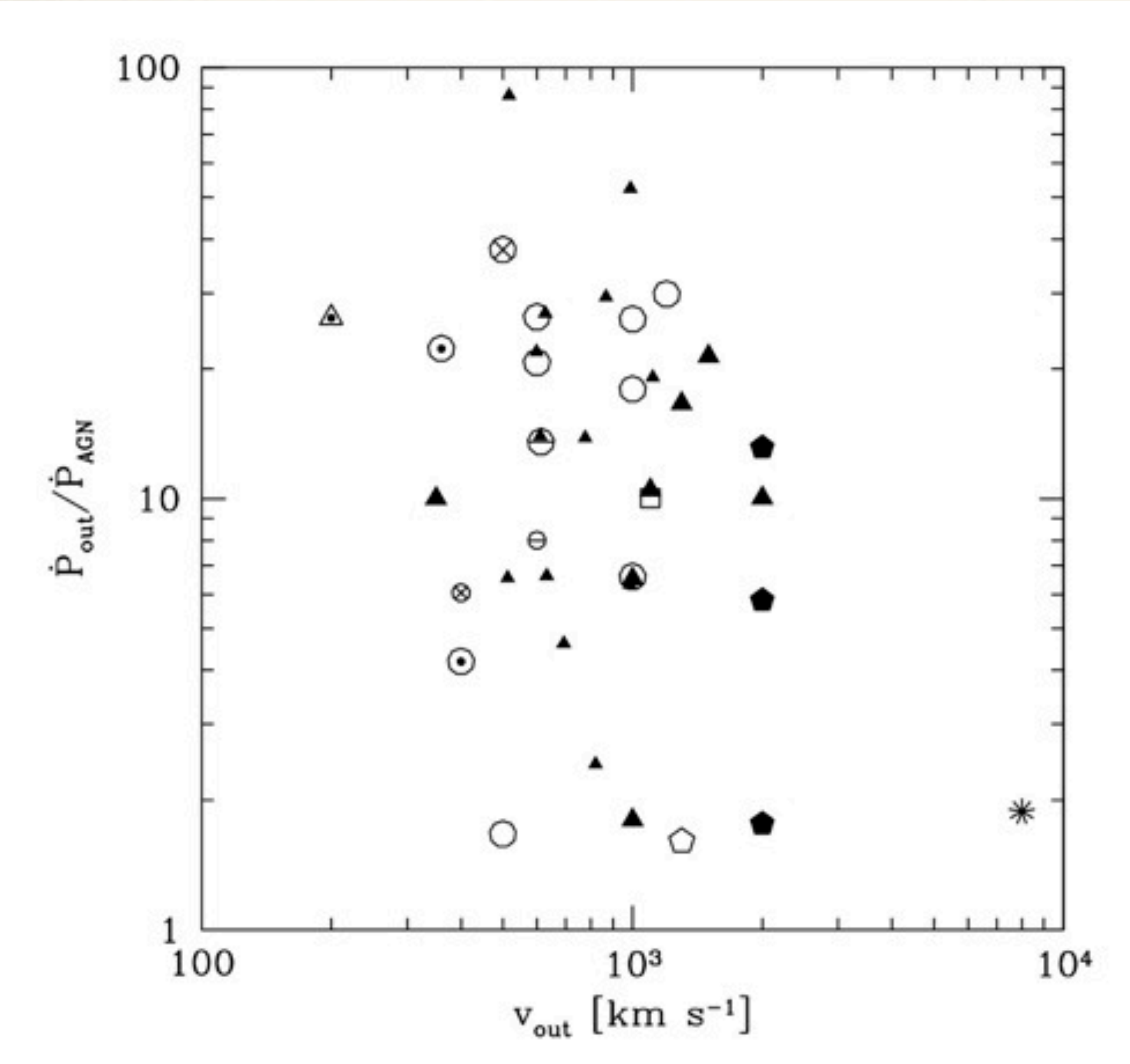
If the outflow is momentum driven molecular gas may not reach escape velocity and falls back. $P_{out}/P_{AGN}<1\text{-}3$.

SF would not be strongly inhibited (Gabor & Bournoud 2014)

Dusty shells may reach escape velocity (thousand km/s, Thompson+2014).

$P_{out}/P_{AGN}<10$

Statistics of extended outflows



AGN outflow momentum rate

>>

AGN radiatiation momentum rate

Most outflows energy-conserving

(but uncertainties are LARGE)

What is feedback?

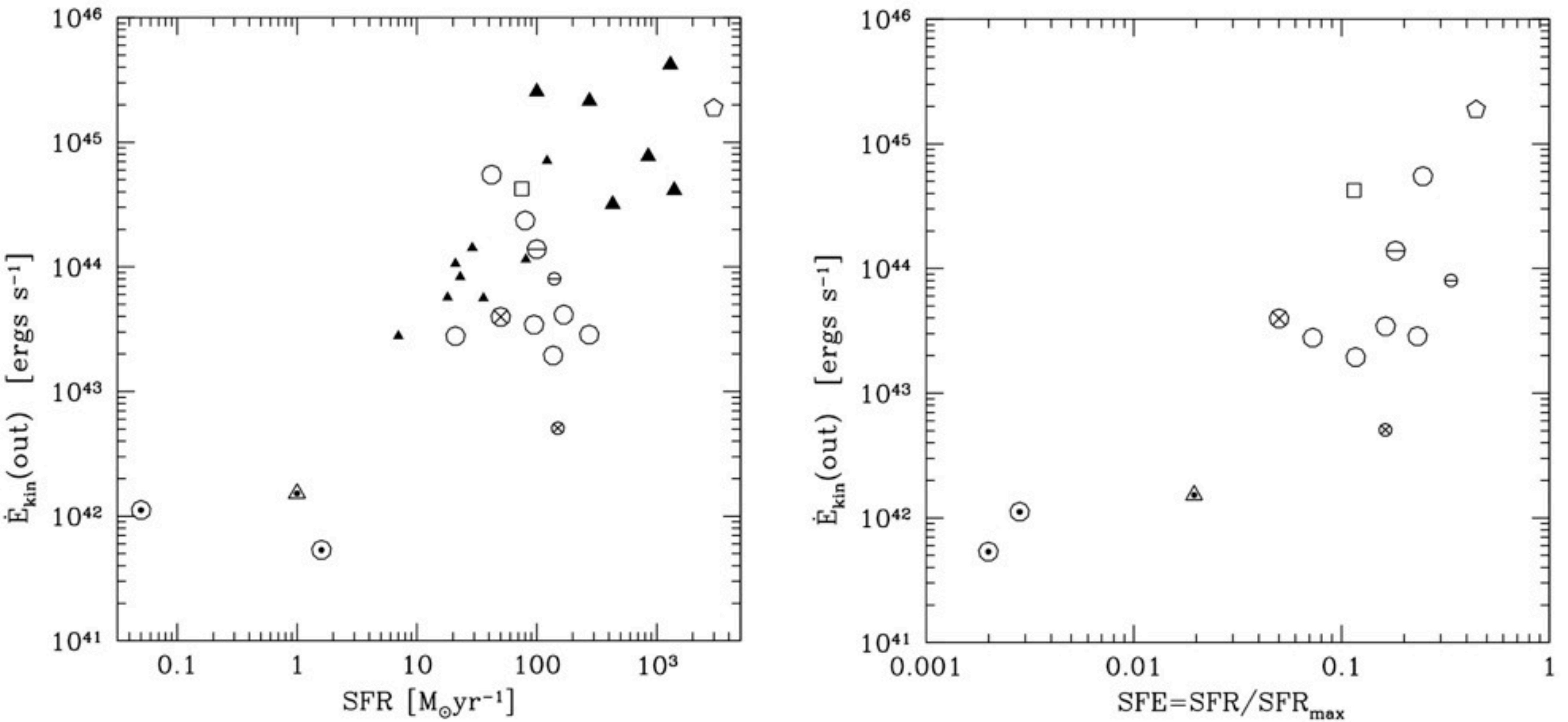
- Do AGN outflows ***clear*** a galaxy from its gas

or

- Do AGN outflows ***regulate*** the conversion of gas in stars, i.e. the SFR, by increasing the gas entropy?

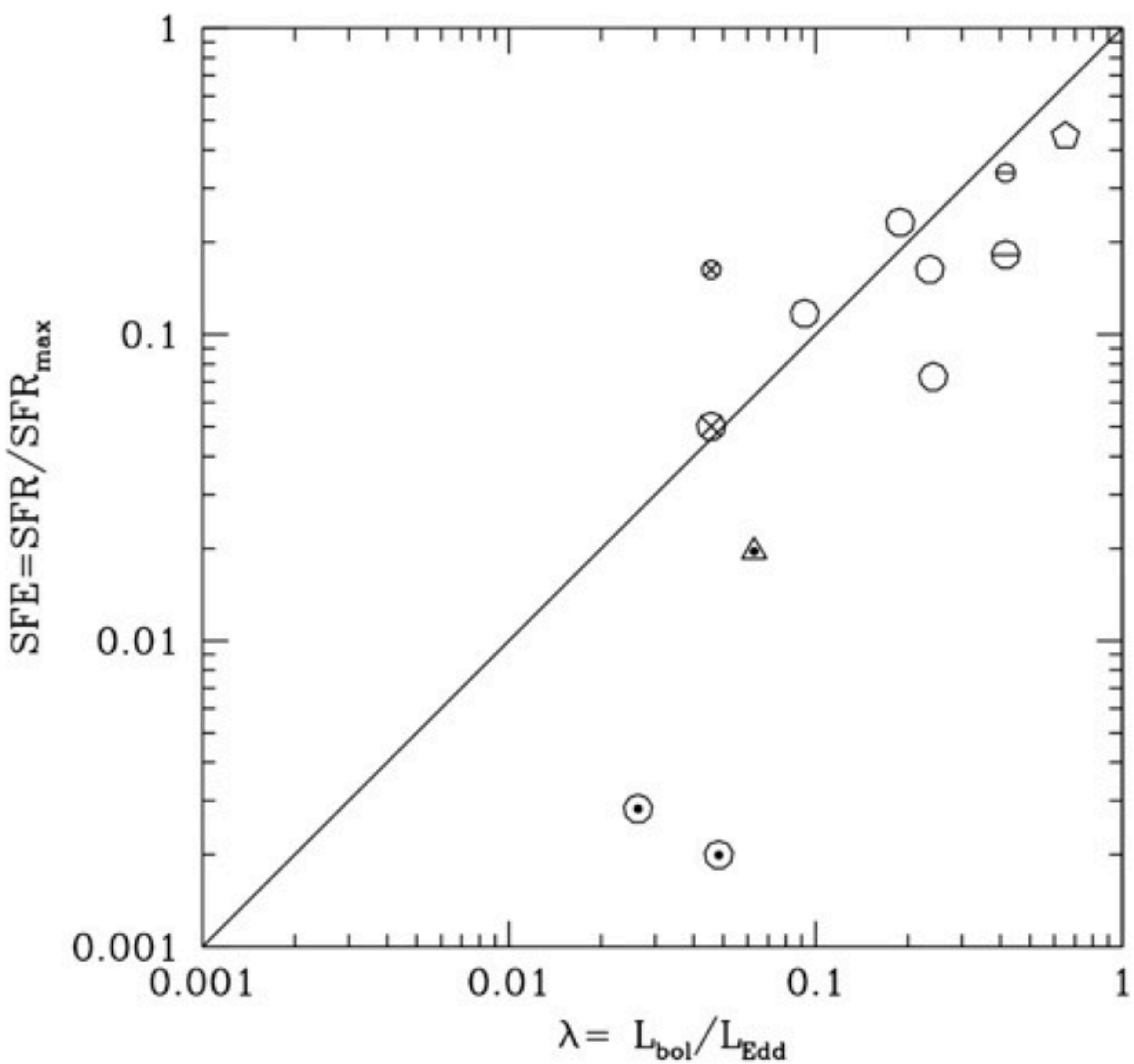
Statistics of extended outflows

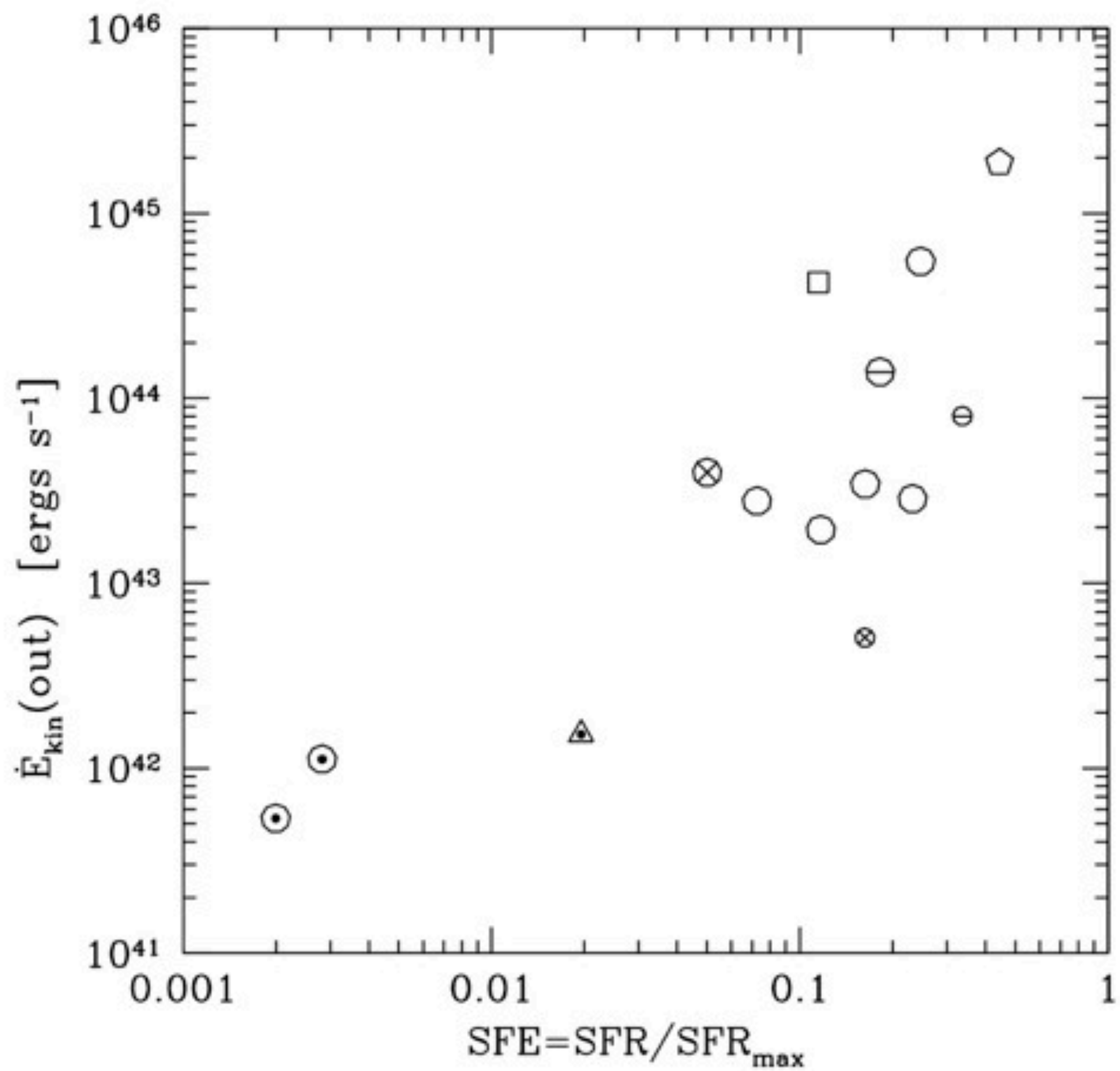
FF,CF+2014



Statistics of extended outflows

FF,CF+2014

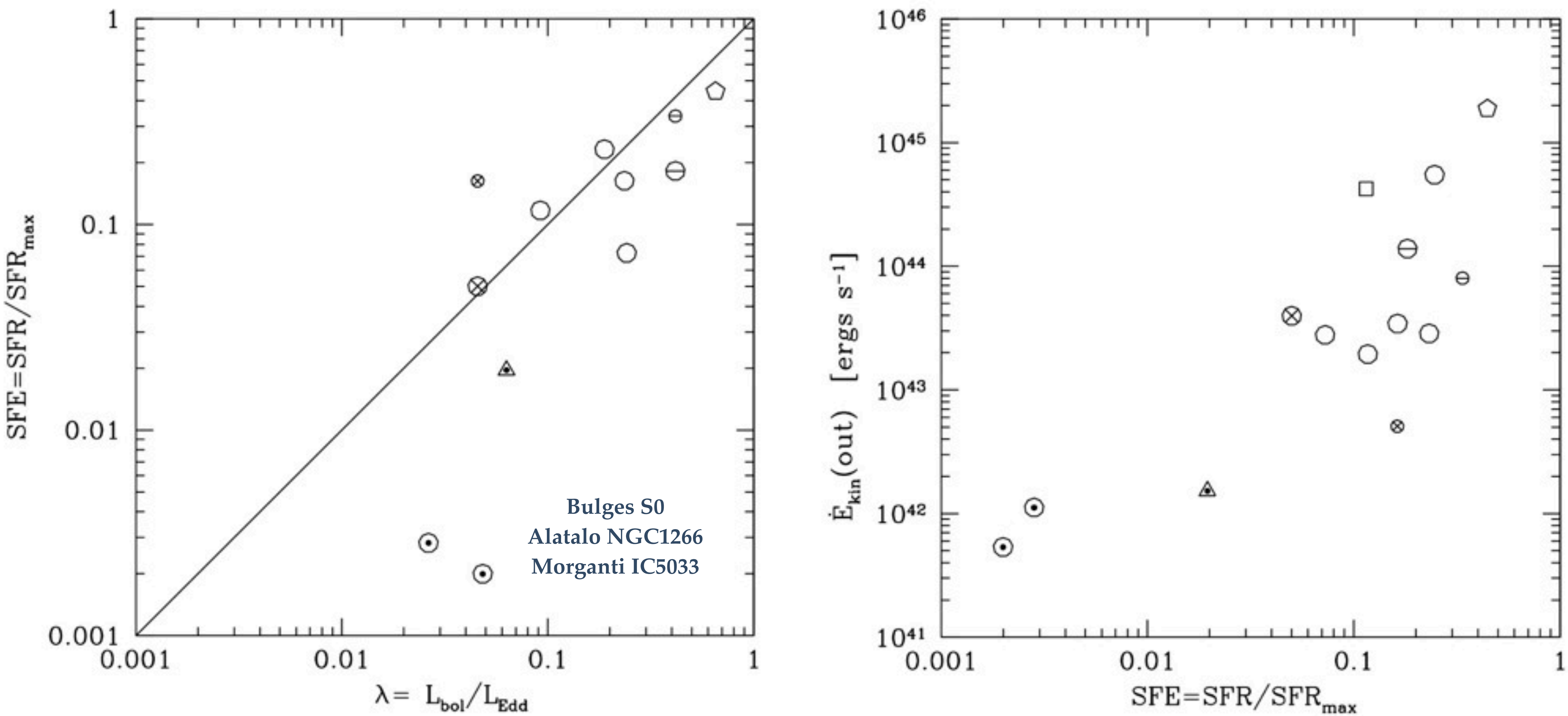




higher the energy injected in the ISM higher the SFR and SFE!!
and higher the SFE higher the Eddington ratio!!

Statistics of extended outflows

FF,CF+2014



higher the energy injected in the ISM higher the SFR and SFE!!
and higher the SFE higher the Eddington ratio!!

Open questions & developments

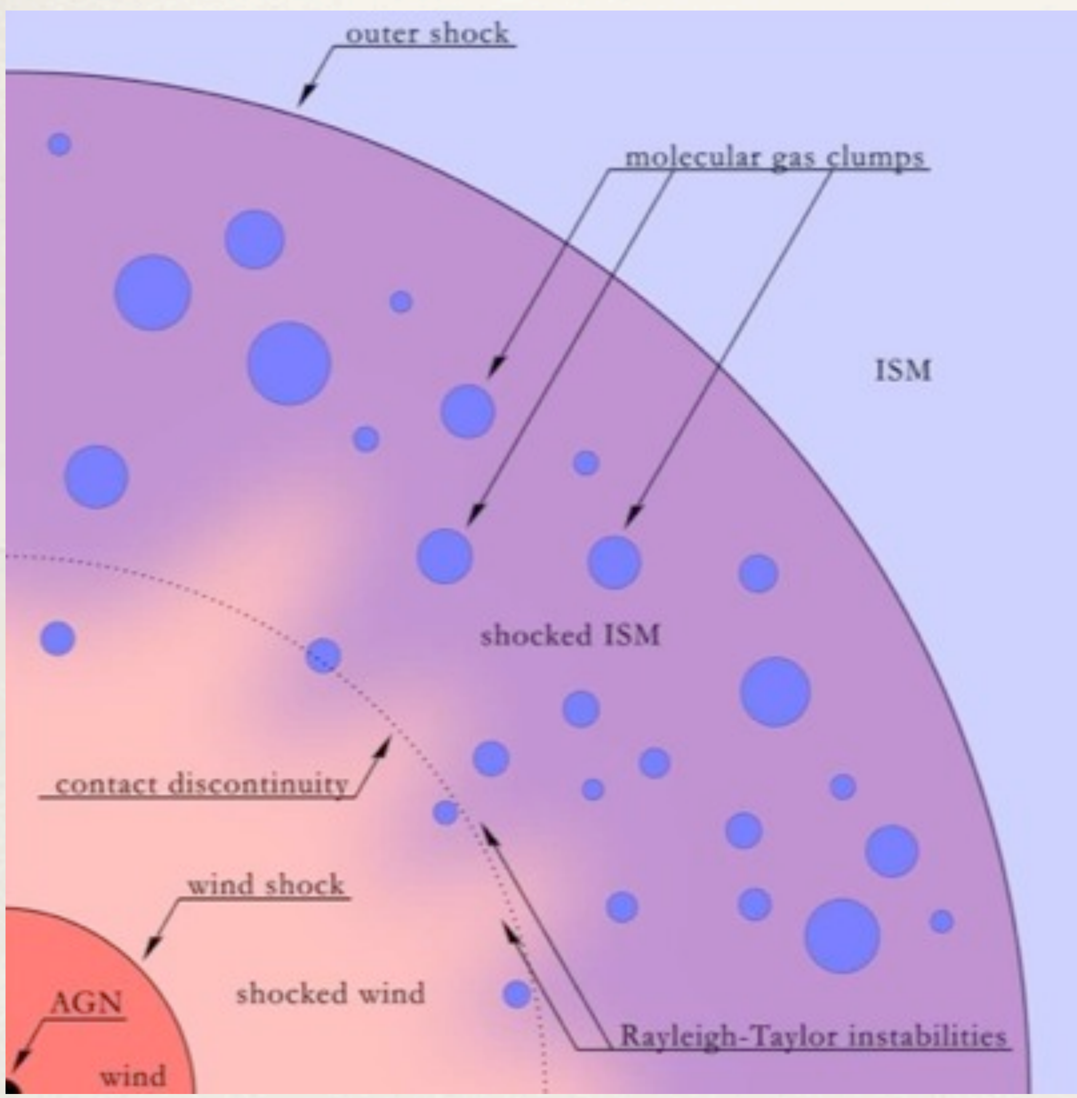
- Need to image more AGN-driven outflows : High resolution and high sensitivity maps to assess the **morphology of the outflows and how they compare to quiescent gas**
- Dense gas phase (HCN, CS, ...) outflows (stars born from dense clouds)

NOEMA / ALMA will tell

- Are outflows a **short** or a **cyclic** phase in AGN evolution?
- Desperately seeking more examples of quasar-mode feedback!
- How does feedback work? *Clearing or regulation*?

Open questions & developments

Assess whether the outflow is driven or not by a shock, to understand the energy transport mechanism from nucleus to disk



Is the outflow energy-conserving?
Is it powerful enough to heat/expel most molecular gas?

How:
X-ray and mm observations of outflows in the same source.
ALMA/NOEMA observations of UFO sources.
Athena systematic observations of sources with molecular outflows.

Open questions & developments

Unified scheme for AGN outflows

Are UFOs the relativistic wind launched by AGN radiation ?

How are UFOs related to the molecular flows?

Systematic X-ray / mm studies are needed, Athena/ALMA ?

Are ionised outflows and BALs co-spatial with molecular outflows? Or rather an evolutionary phase? (Zubovas & King 2013)

Optical/NIR IFU observations of sources with UFOs and BALs can tell