Multiwavelength signatures of AGN feedback in local AGN

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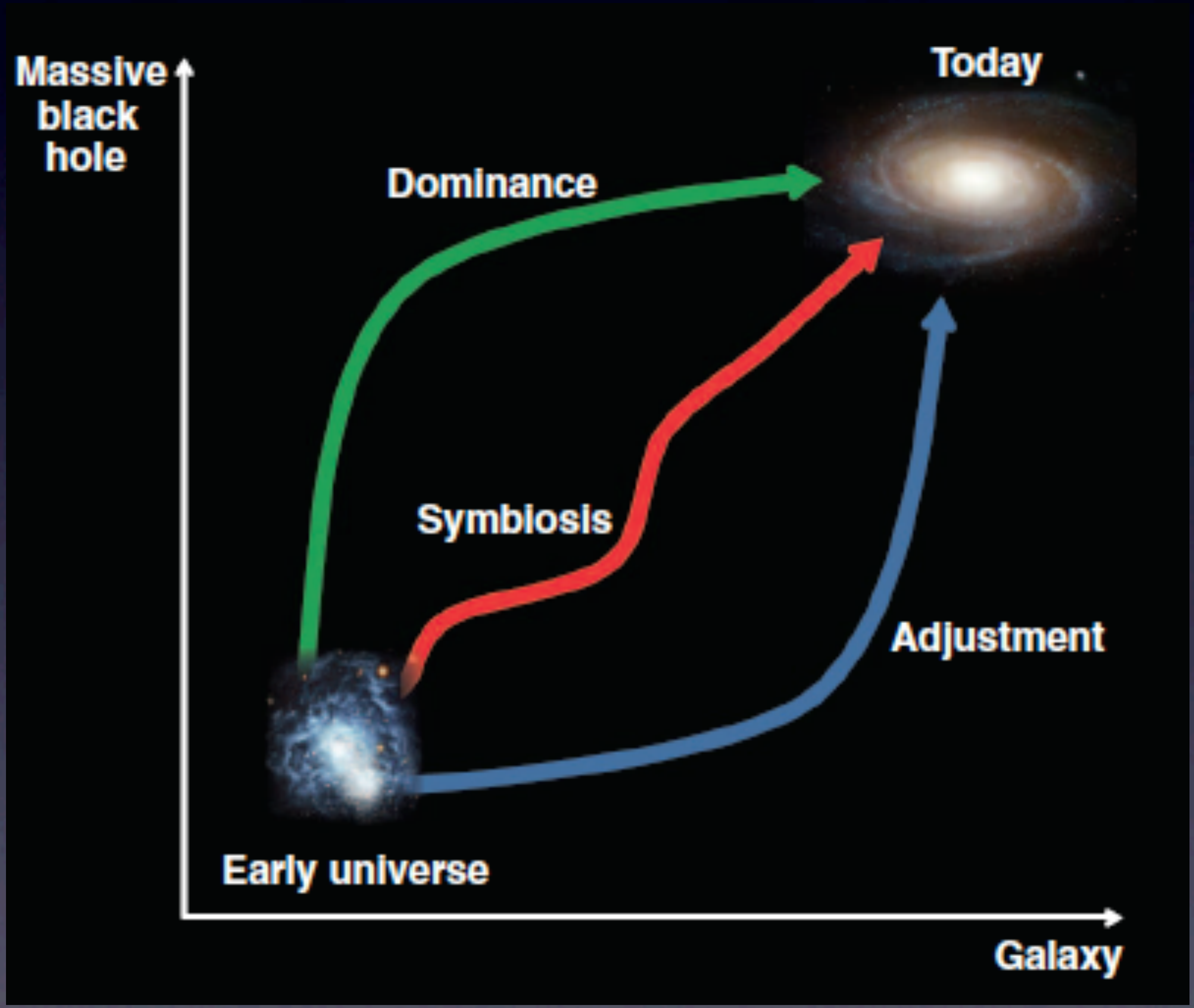
Thanks to: G. FABBIANO (CfA), F. FIORE (INAF)

INAF - Bologne, 6 Mai 2013

Galaxy - Massive Black Hole evolution

Through which path does the common growth occur?

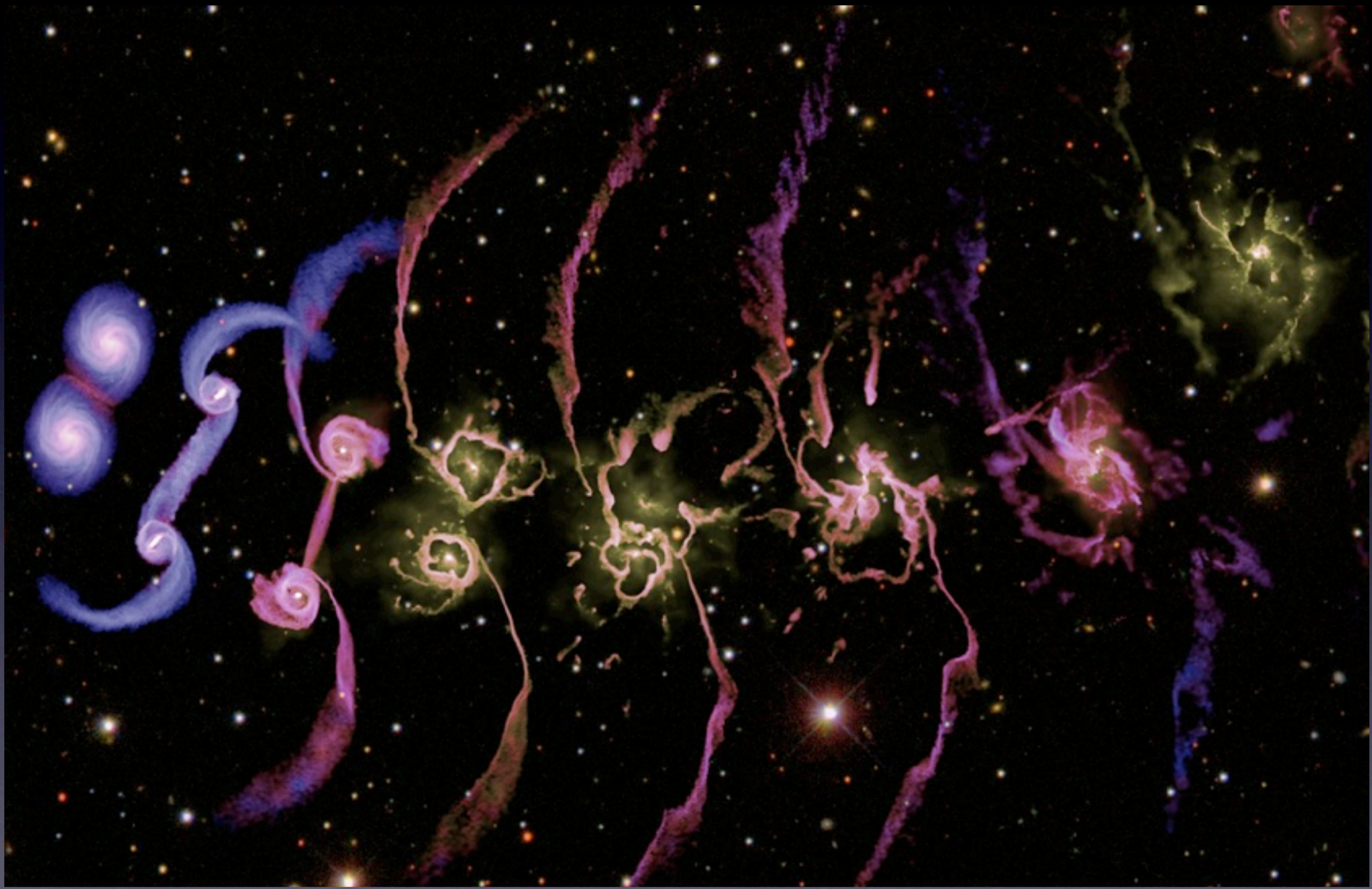


Volonteri 2012, Science

Processes:

- **Merging**
  - Galaxy
  - MBH
    - accretion
- **Feedback**
  - Stellar / SN
  - AGN

Merging evolution



Di Matteo, Springel, Hernquist 2005 - Nature

The merging sequence

Two Spirals

Early stage : the Antennae

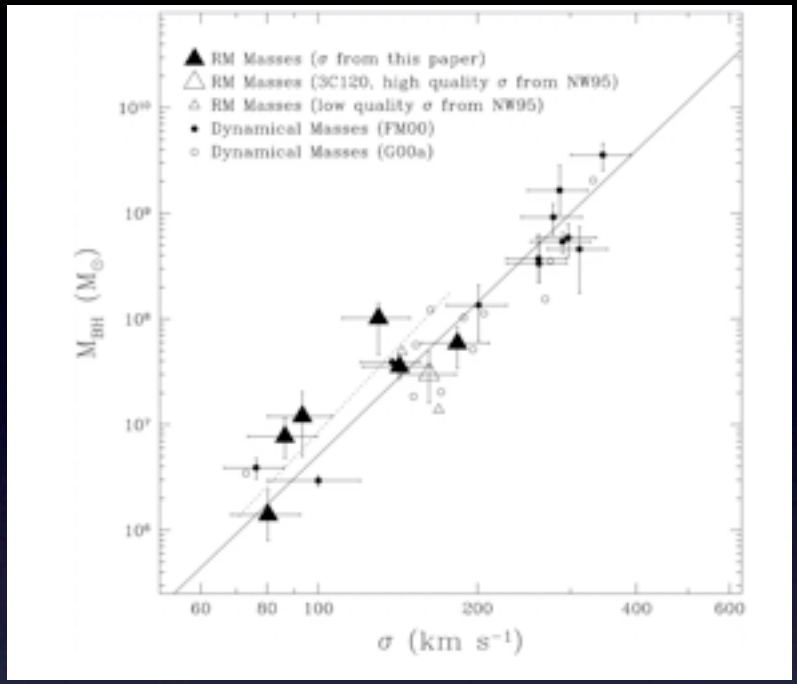
Intermediate stage: NGC 6240

Late stage: Mrk 231

Elliptical Galaxy

Merging nuclear massive BHs

When galaxies merge their nuclear MBHs also merge



Menci et al. 2003:

- merging histories of the DM clumps imply that Mgas $\sim\sigma^{2.5}$
- destabilization of Mgas by interactions steepens by another σ
- SN feedback depletes the residual gas shallow potential wells, further steepening the correlation.

Peng 2007:

- galaxy merging average out extreme values of MBH /M$_*$, converging toward a narrow correlation

Jahnke & Maccio 2010:

- number of mergers consistent with that of standard merger trees models for the formation of galaxies (and SMBH)

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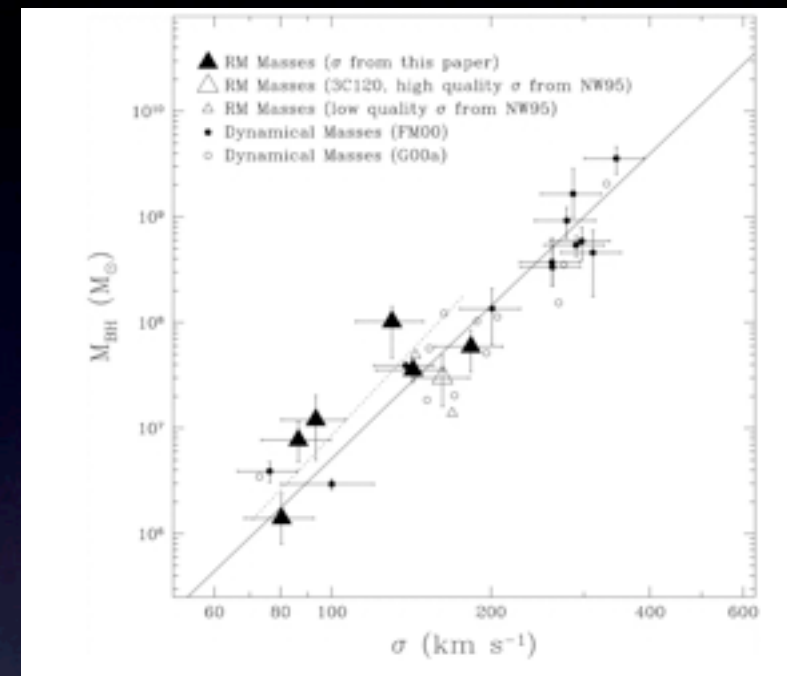
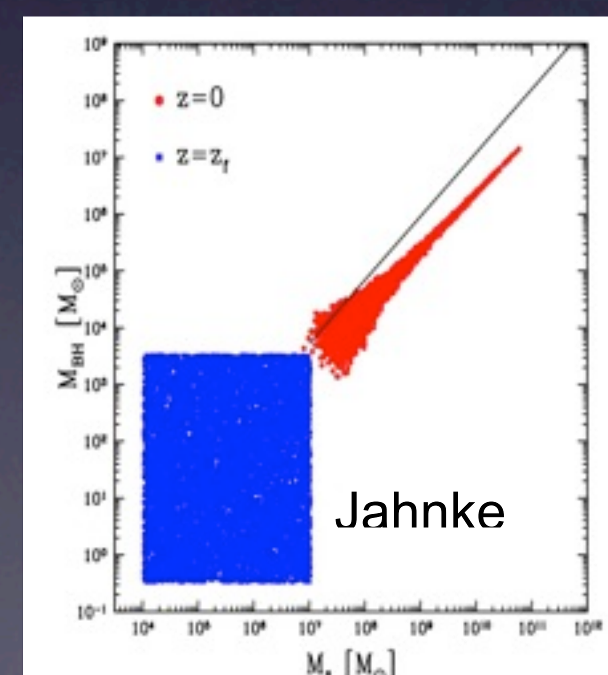
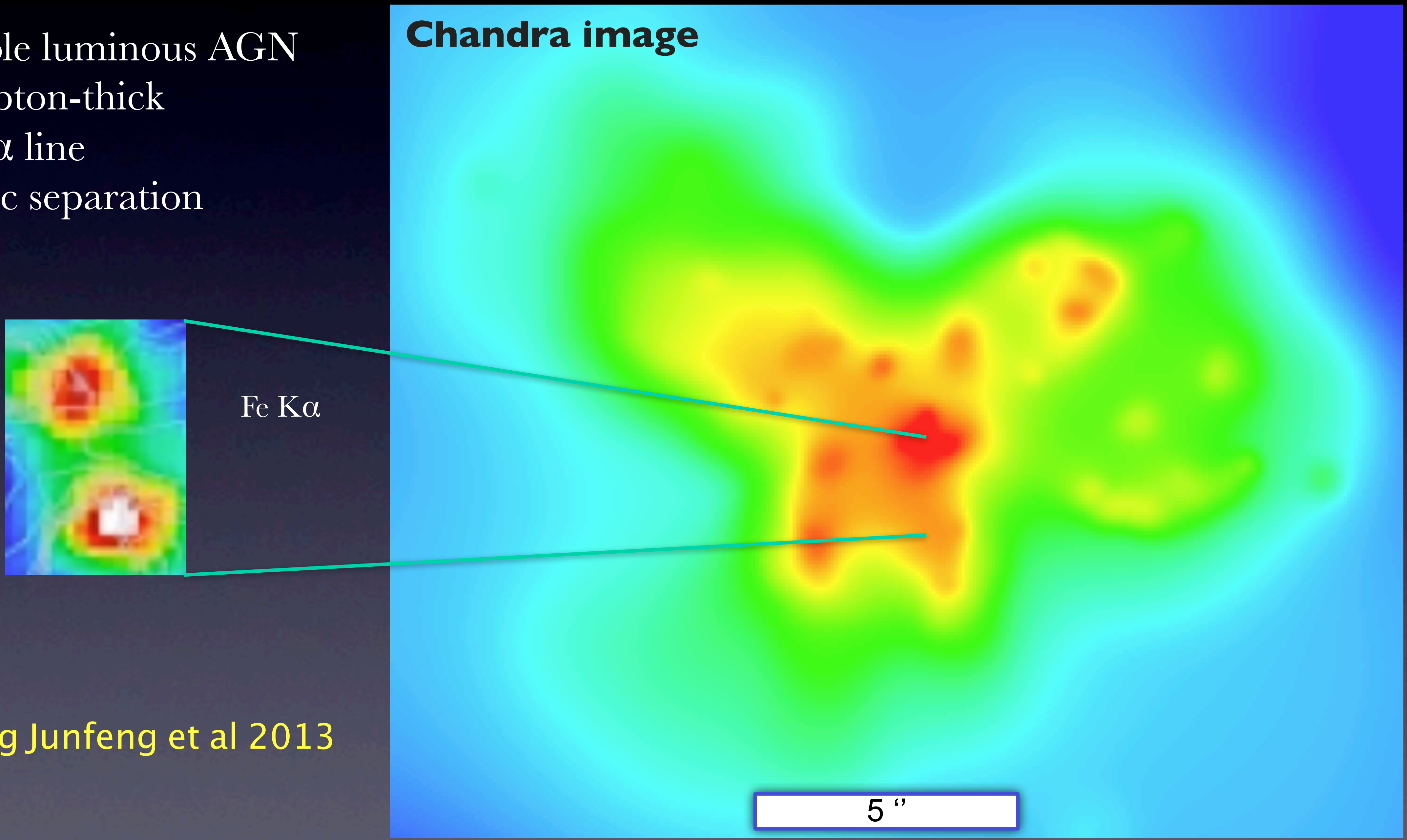




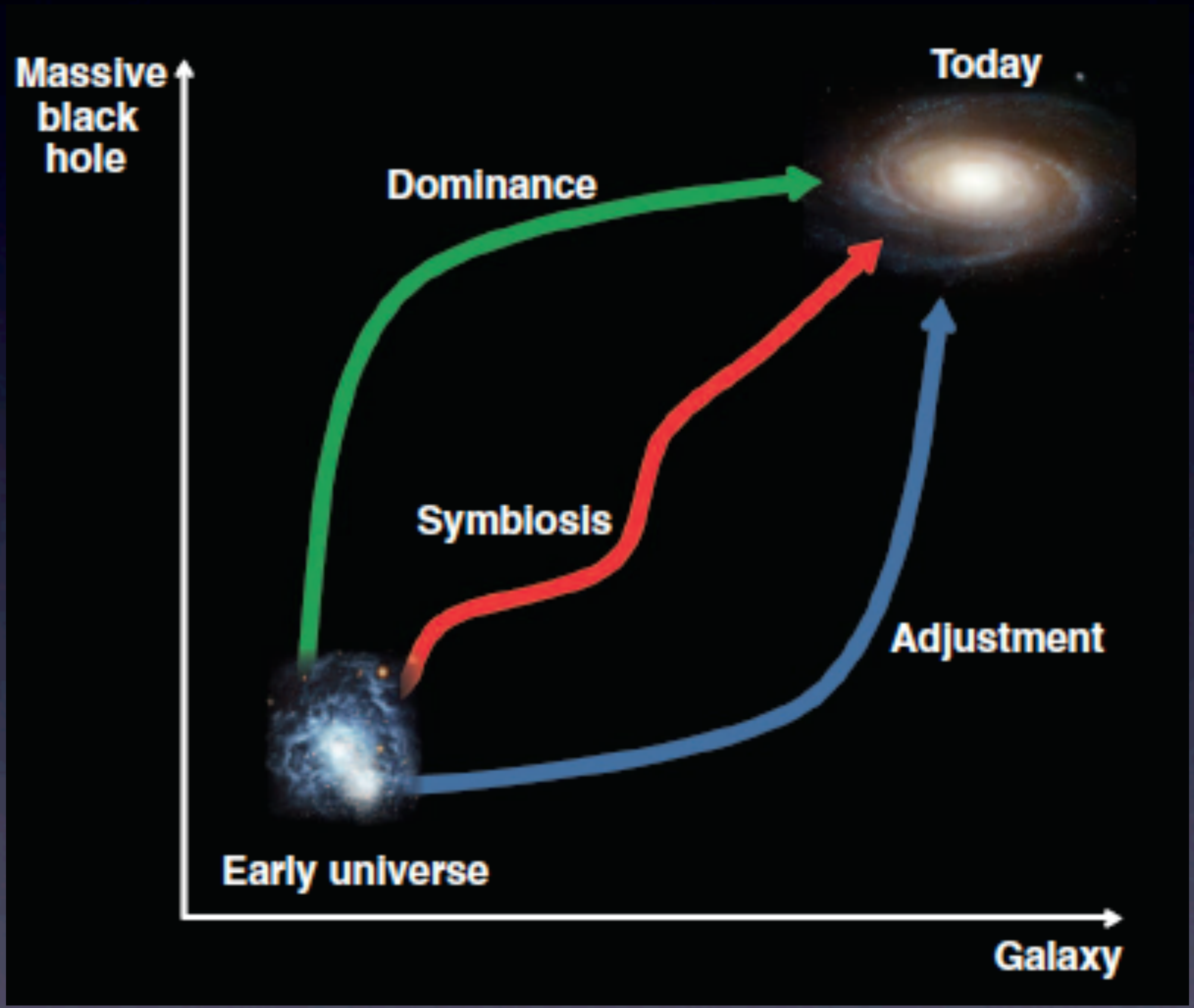
Merging massive BHs : NGC6240

Double luminous AGN
Compton-thick
Fe Kα line
~2 kpc separation



Wang Junfeng et al 2013

Galaxy - Massive Black Hole growth

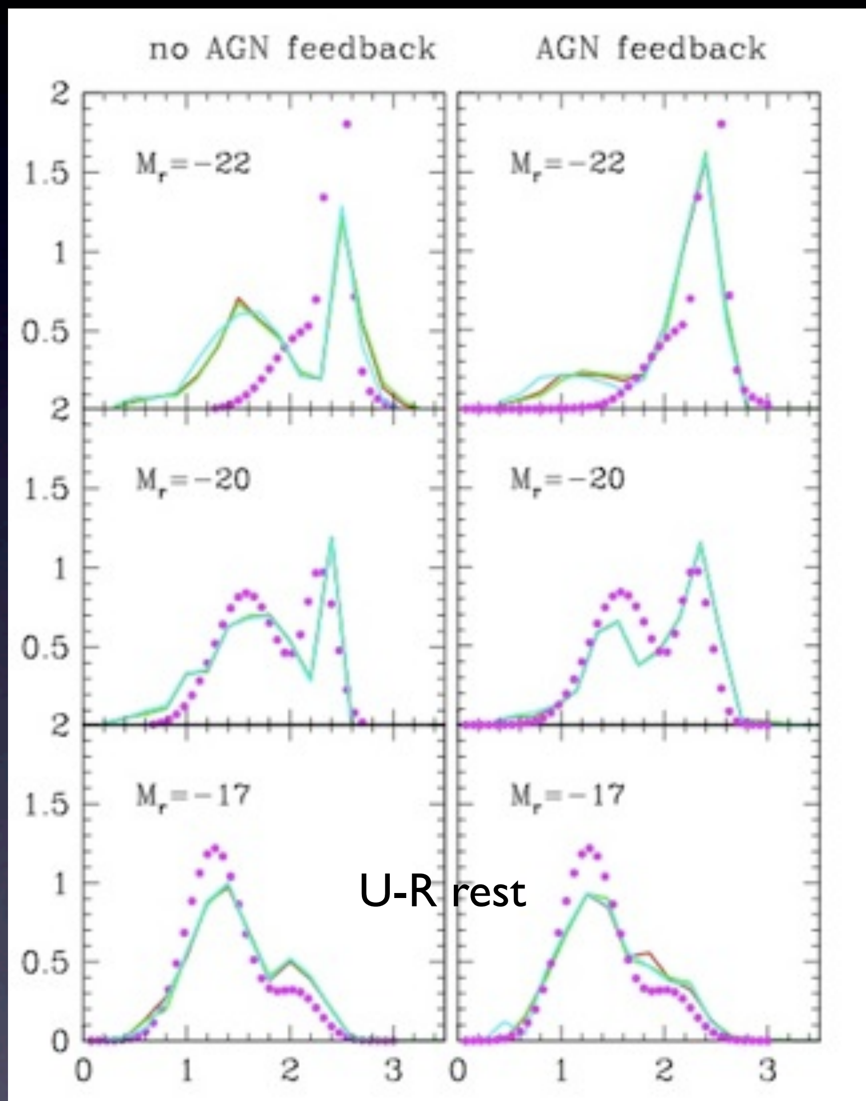


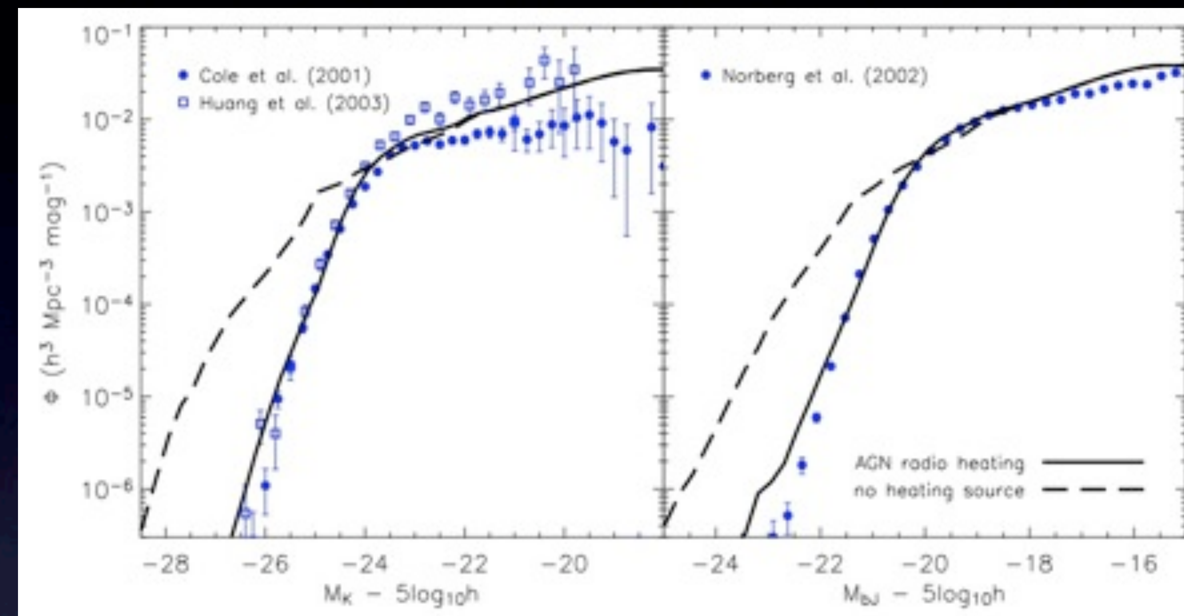
Volonteri 2012, Science

- **Merging**
  - Galaxy
  - MBH
    - accretion
- **Feedback**
  - Stellar / SN
  - AGN

AGN feedback

- AGN heat ISM stopping both star formation and accretion





Without AGN heating SAMs:

1. **overpredict luminosities of massive galaxies by ~2 mags**

and/or

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

Menci et al. 2006, Croton+2006, Millenium

AGN feedback could be the solution. Observations of feedback in action can support.

AGN feedback

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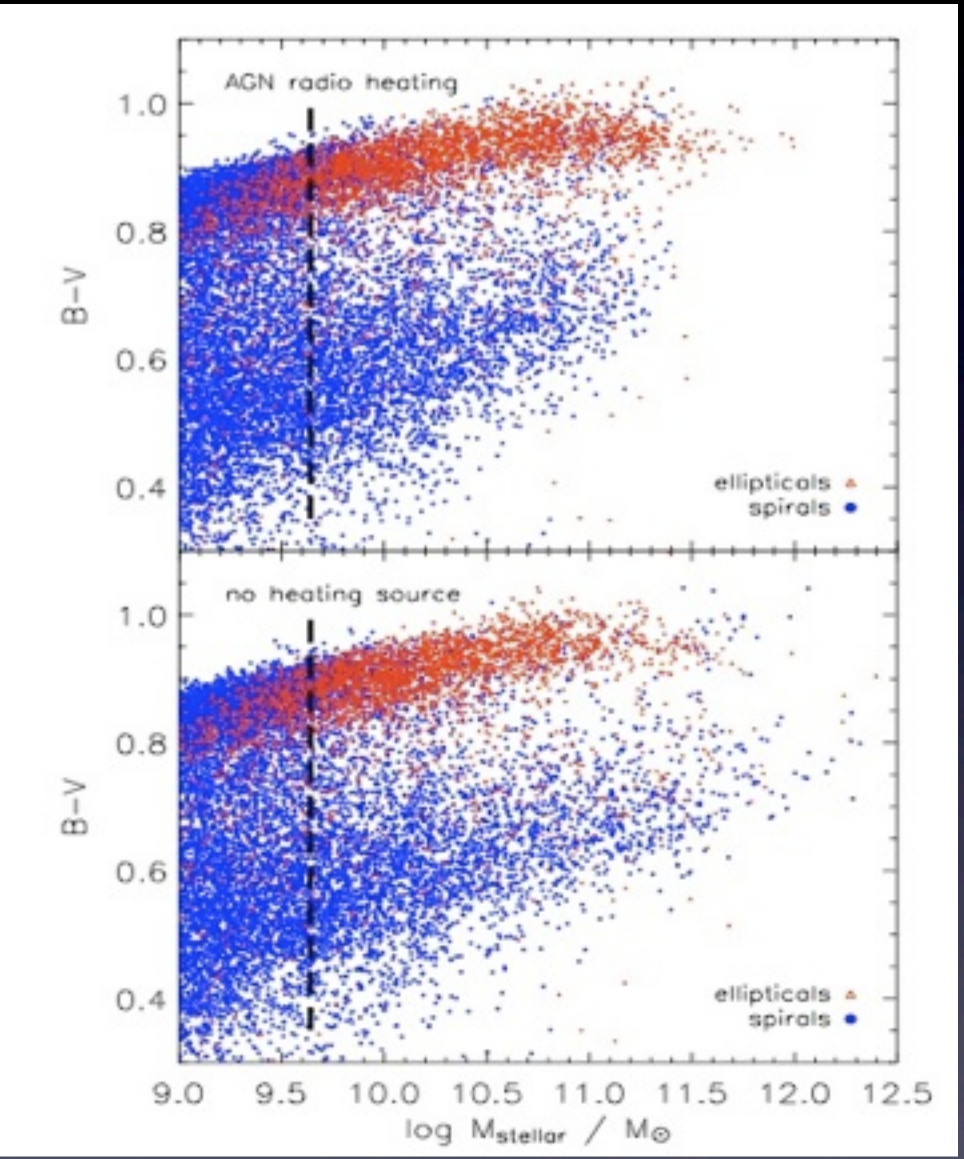

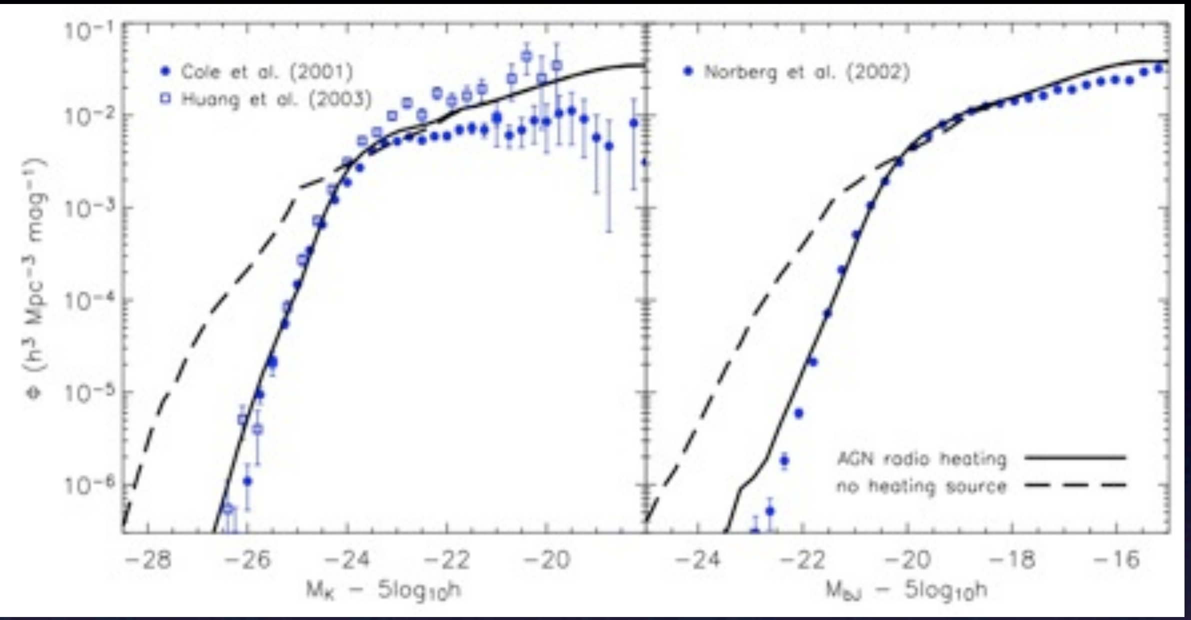

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AGN Feedback
& AGN accretion mode

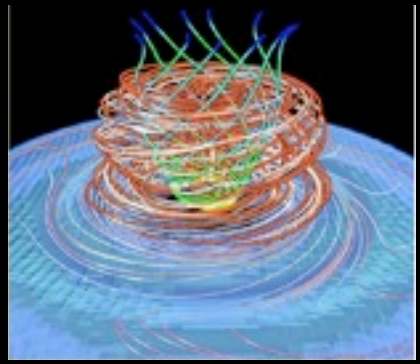
Quasar mode

- 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

Menci+ 2003,2004,2006,2008

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

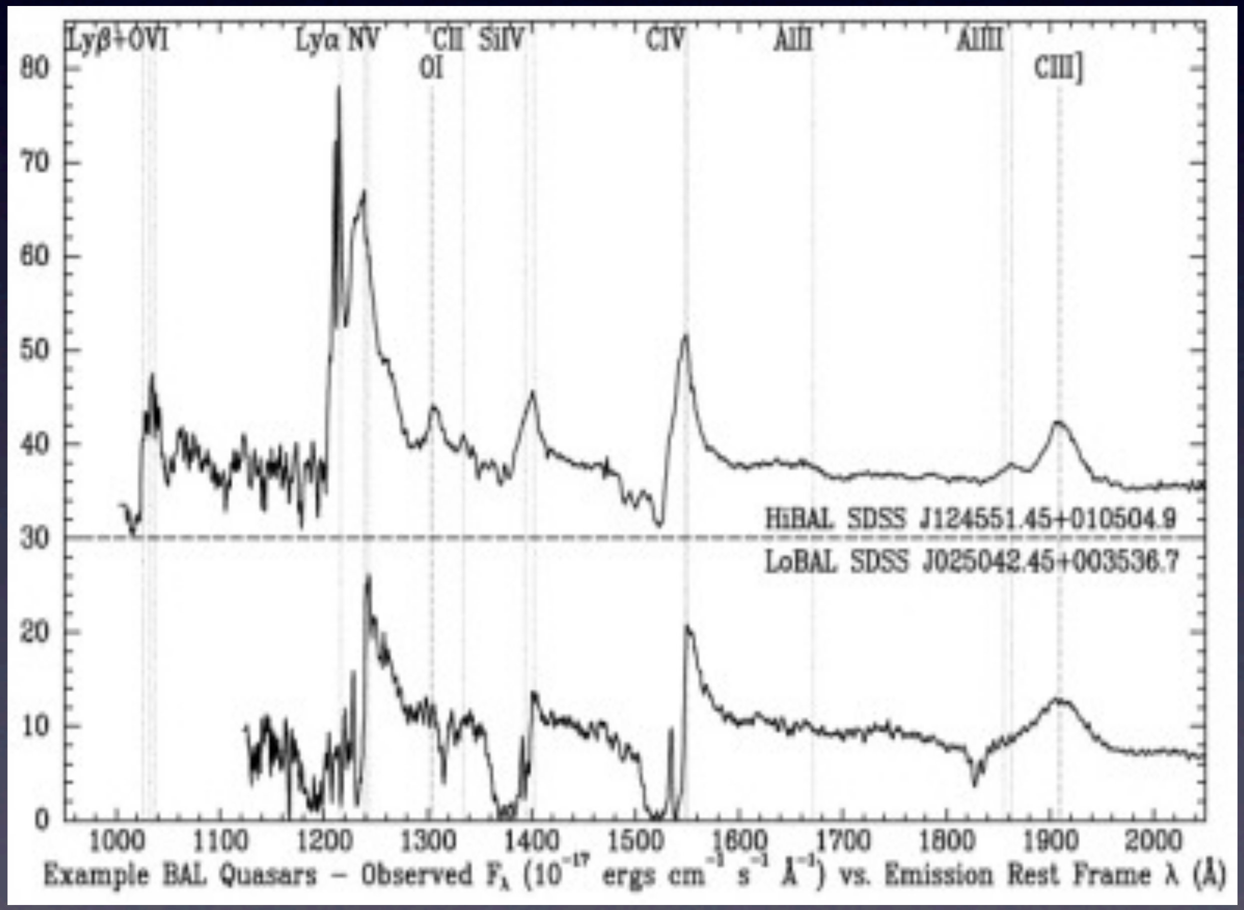
Croton+ 2006



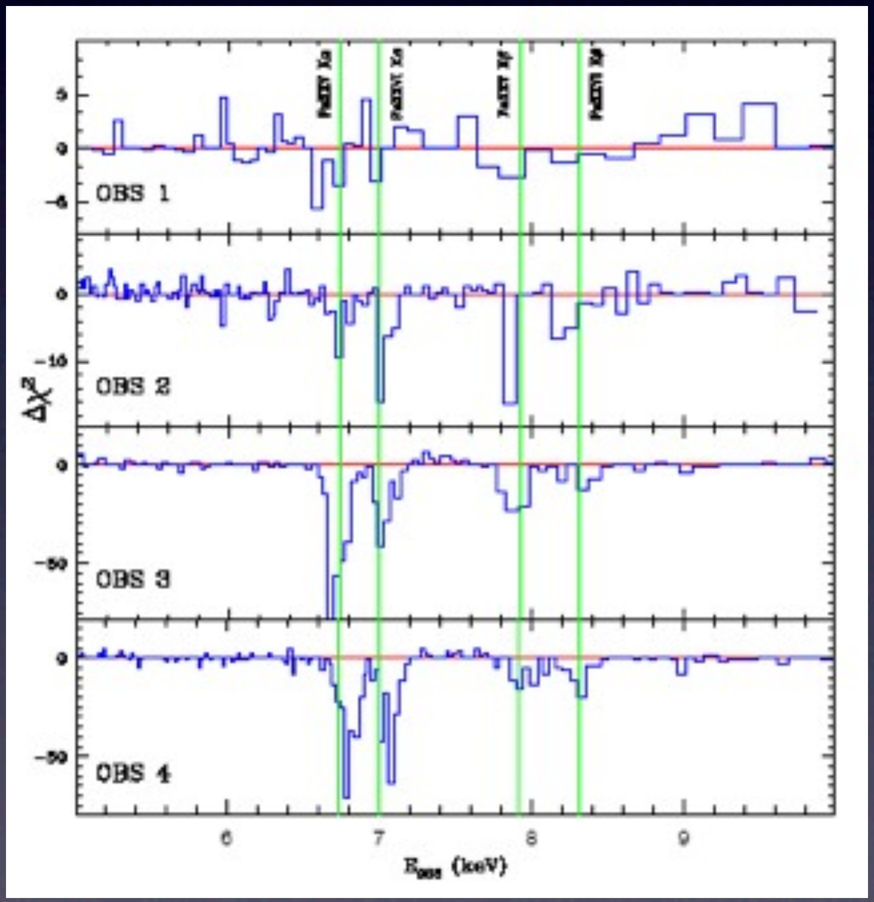
AGN winds and outflows

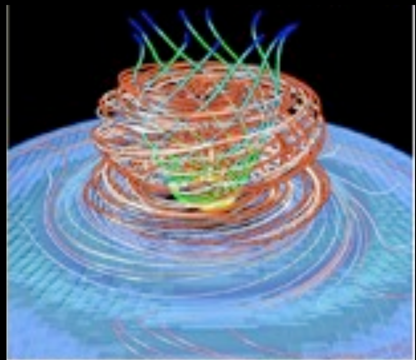
Fast winds with velocity up to a fraction of c observed in the central regions of AGN.
Likely originate from the acceleration of disk outflows by the AGN radiation field
Crenshaw+03, Pounds+03, Reeves+09, Moe+09

BAL QSOs (10-40% of all QSOs)



NGC1365 Risaliti+ 2005





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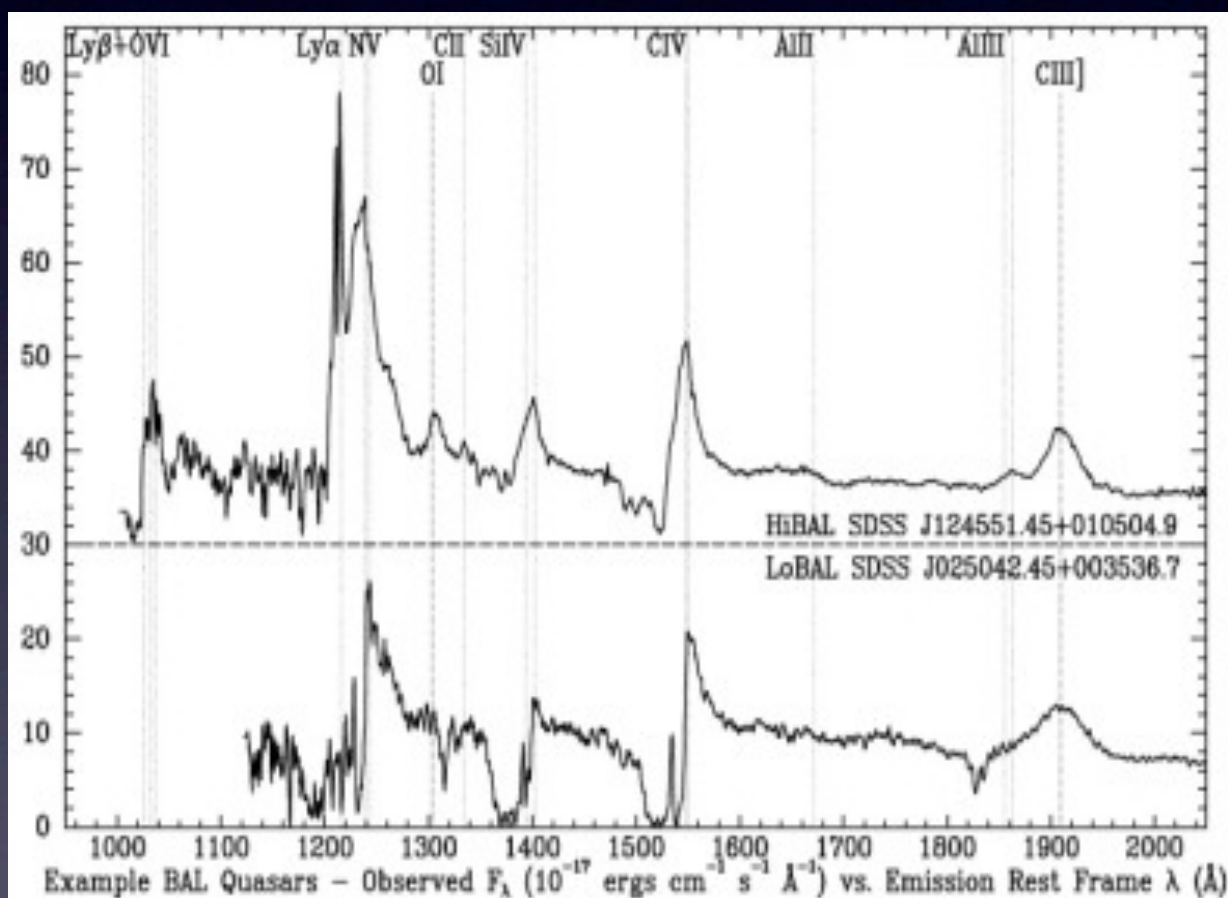

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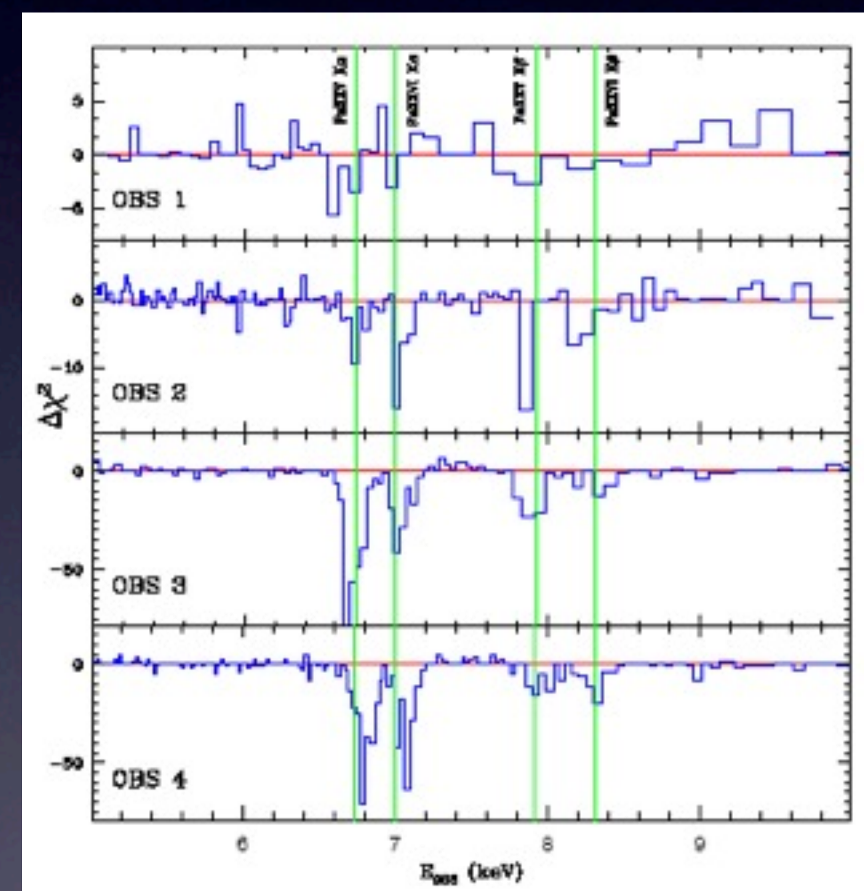
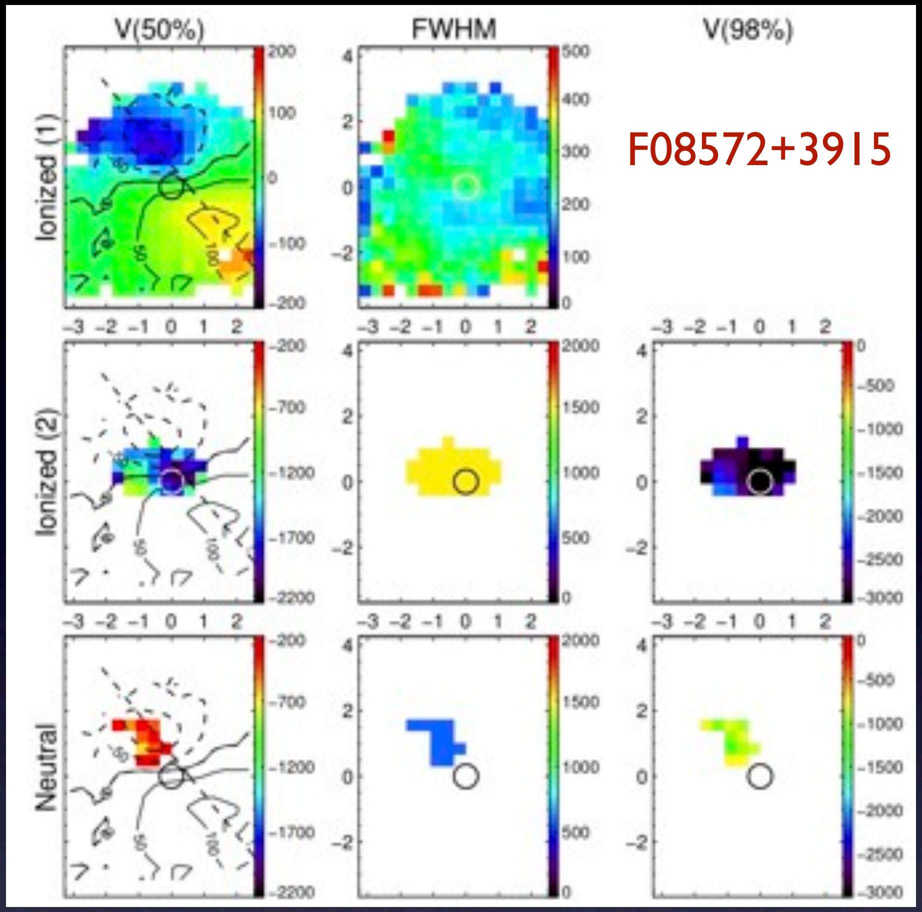


- Atomic phase makes small fraction of the gas present in a galaxy disk
- Physical scale unknown or small (nuclear)

Extended outflows of neutral/ionized gas

kpc scale outflows observed in the neutral & ionized gas phases in:

- **In Local major mergers with and without QSO (Westmoquette et al. 20120, Rupke & Veilleux 2013) , with bipolar structure over 1-5 kpc. Outflows more powerful in QSO hosts.**
- **radio galaxies, up to z=2.5 (Nesvabda+ 2006, Swinbank+ 2005,2006), IFU observations of [OIII] emission**
- **SMMJ1237, a QSO in a z~2 ULIRG (Alexander+ 2010)**
  - **Extent of broad [OIII] ~4-8kpc**
  - **E_{kin}~10^{59} ergs over 30 Myr ~ binding energy of galaxy spheroid**



- **Giant SF clumps at z~2 (Genzel +2011)**
  - **Broad Hα, mass outflow rate > SFR**

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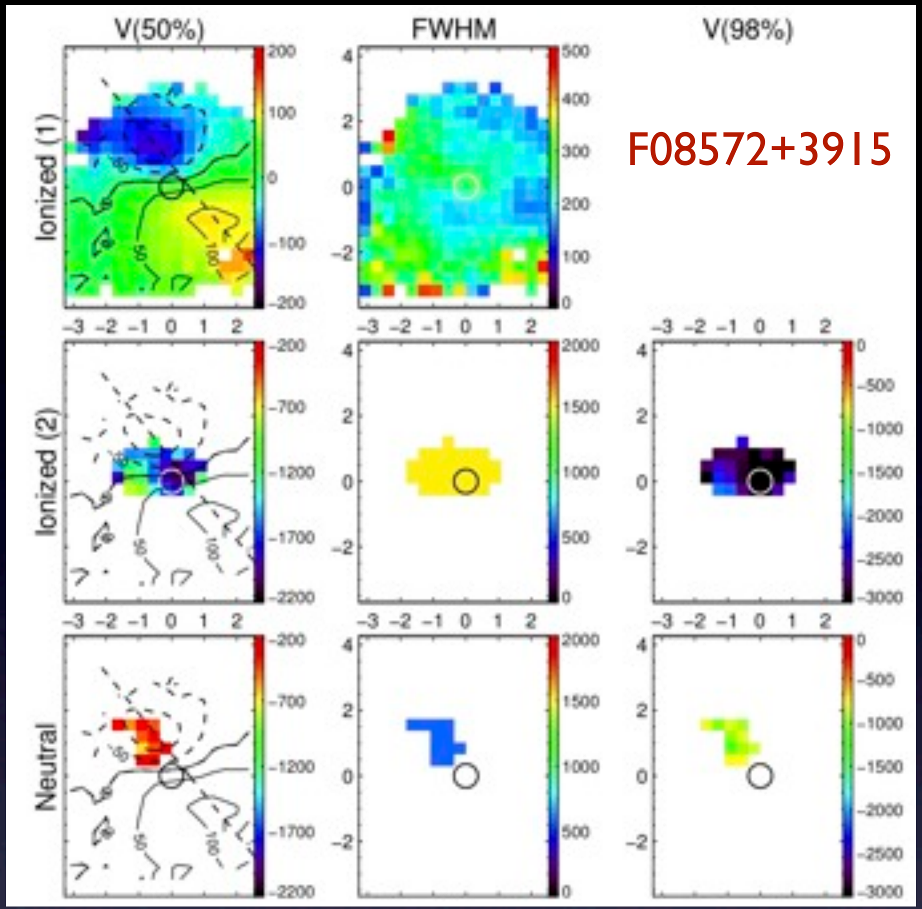

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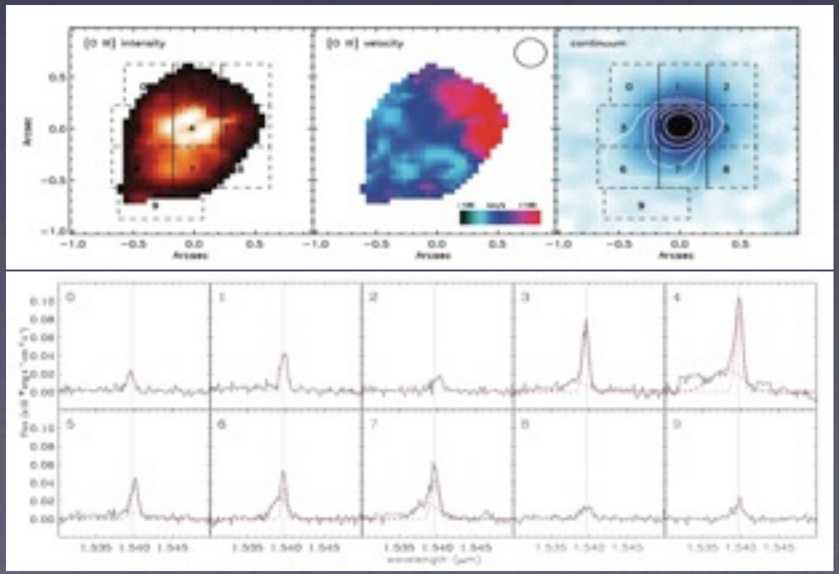

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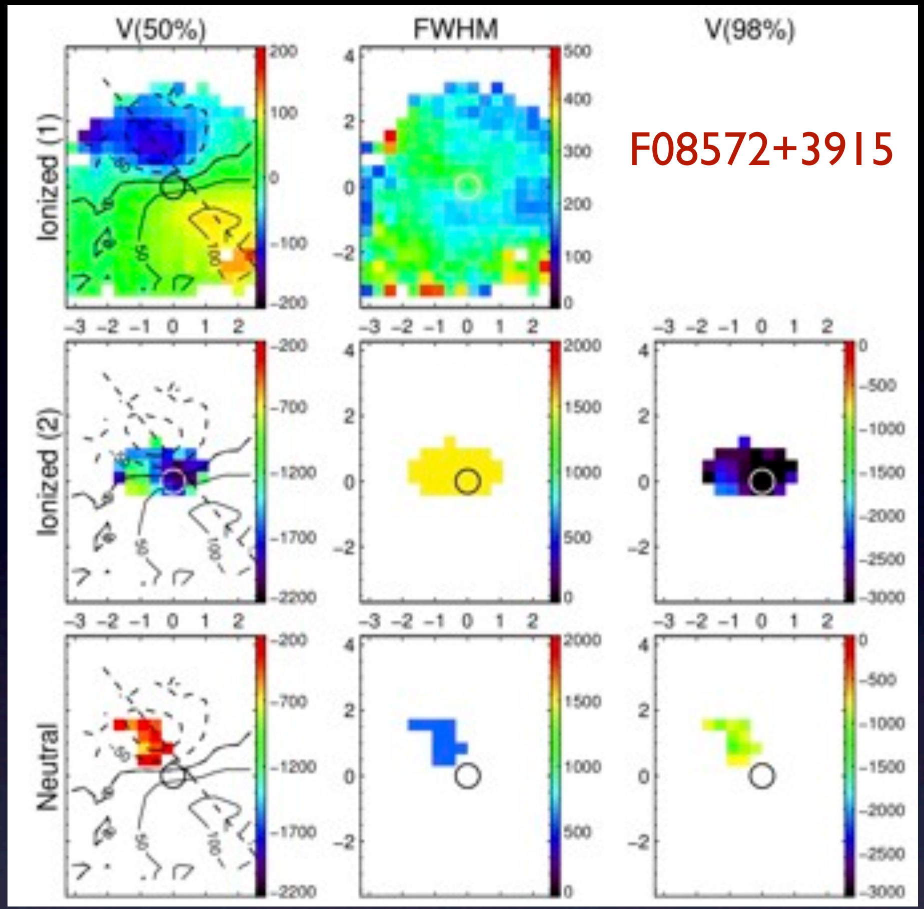

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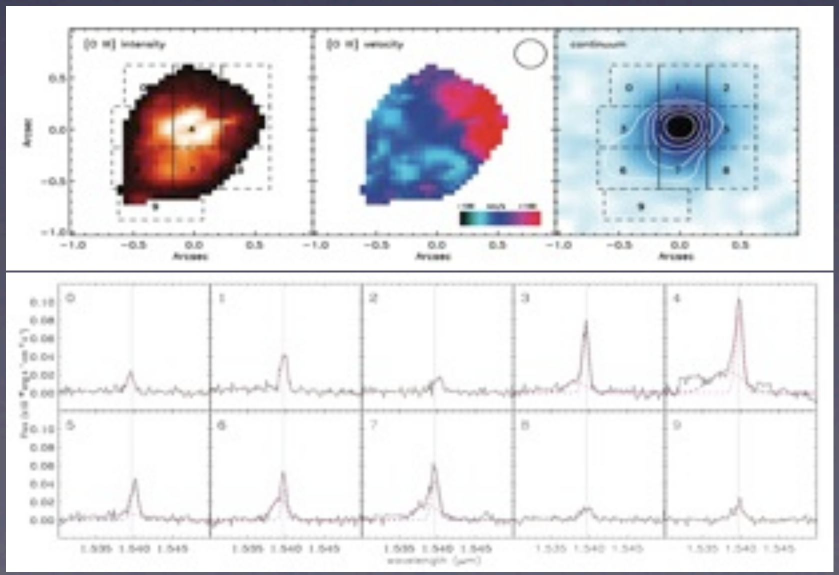

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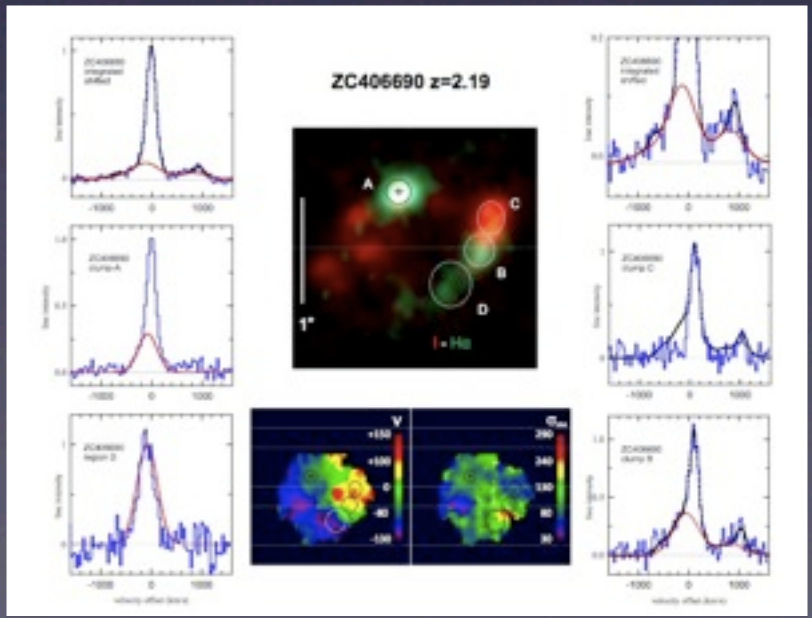


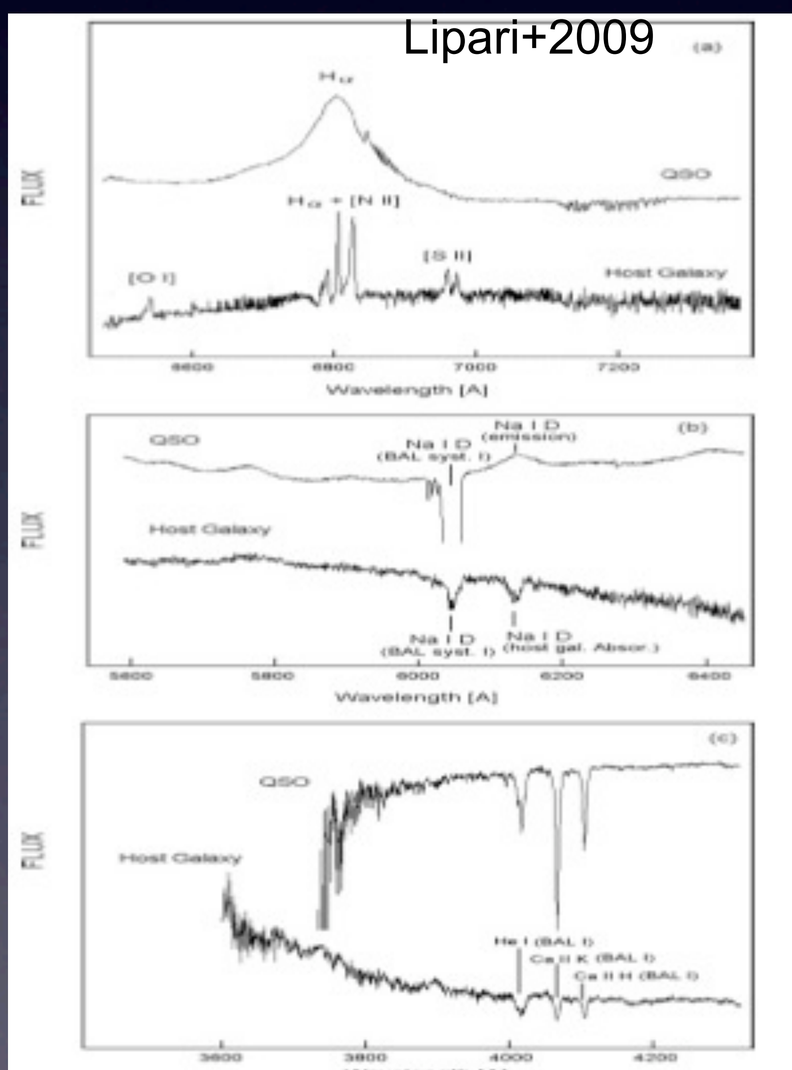
Galaxy scale molecular outflows : the case of Mrk 231

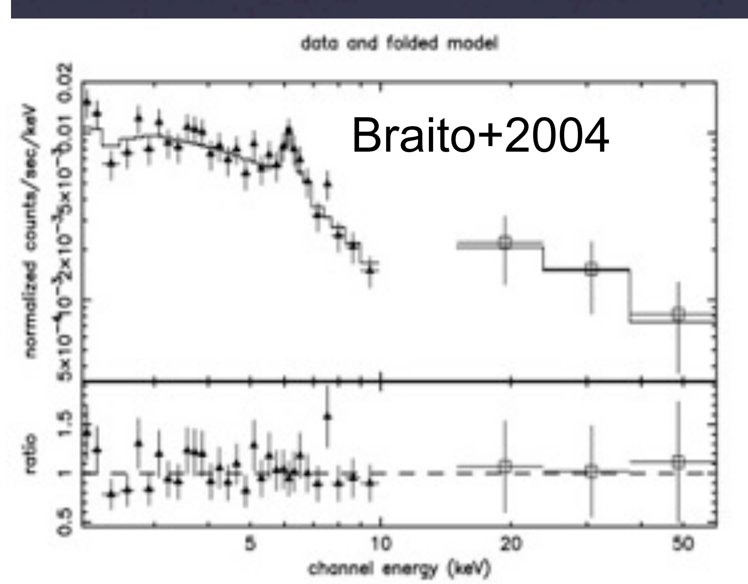
THE nearest ULIRG with SFR= 200 $M_\odot$/yr and hosting a obscured, luminous (BAL) QSO

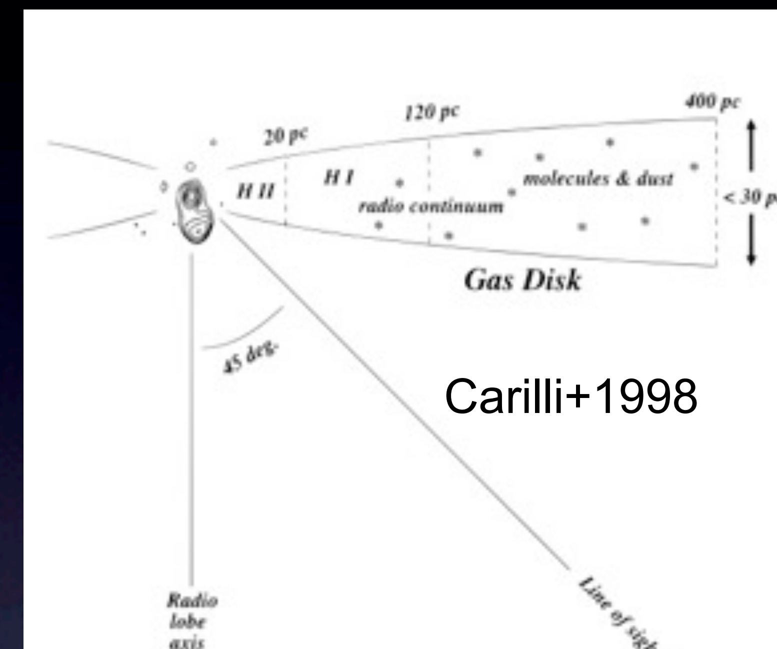
high luminosity (L_{bol}~10^{46} erg/s),

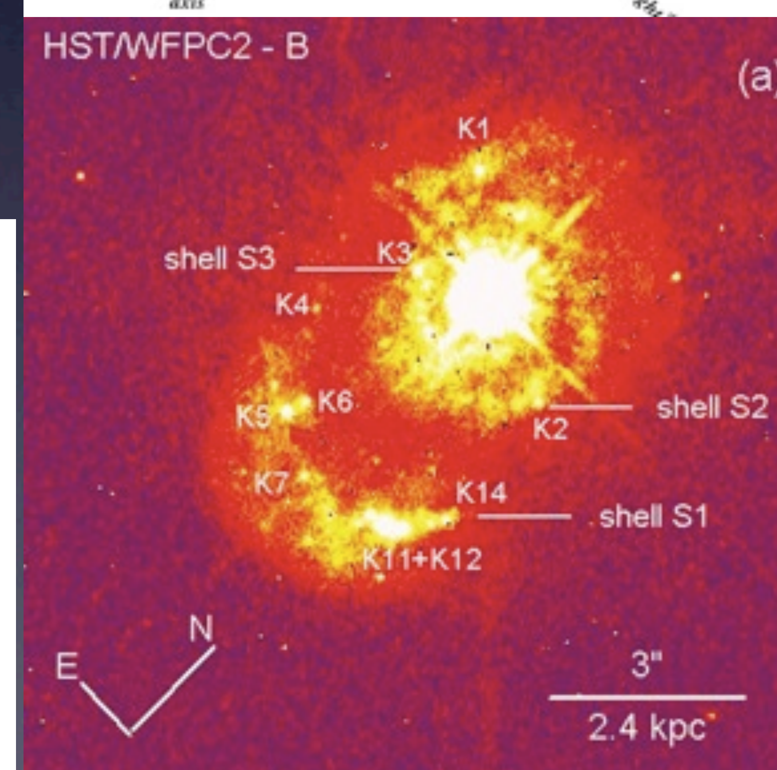
highly obscured (N_H~10^{24} cm^{-2})

late stage merger.

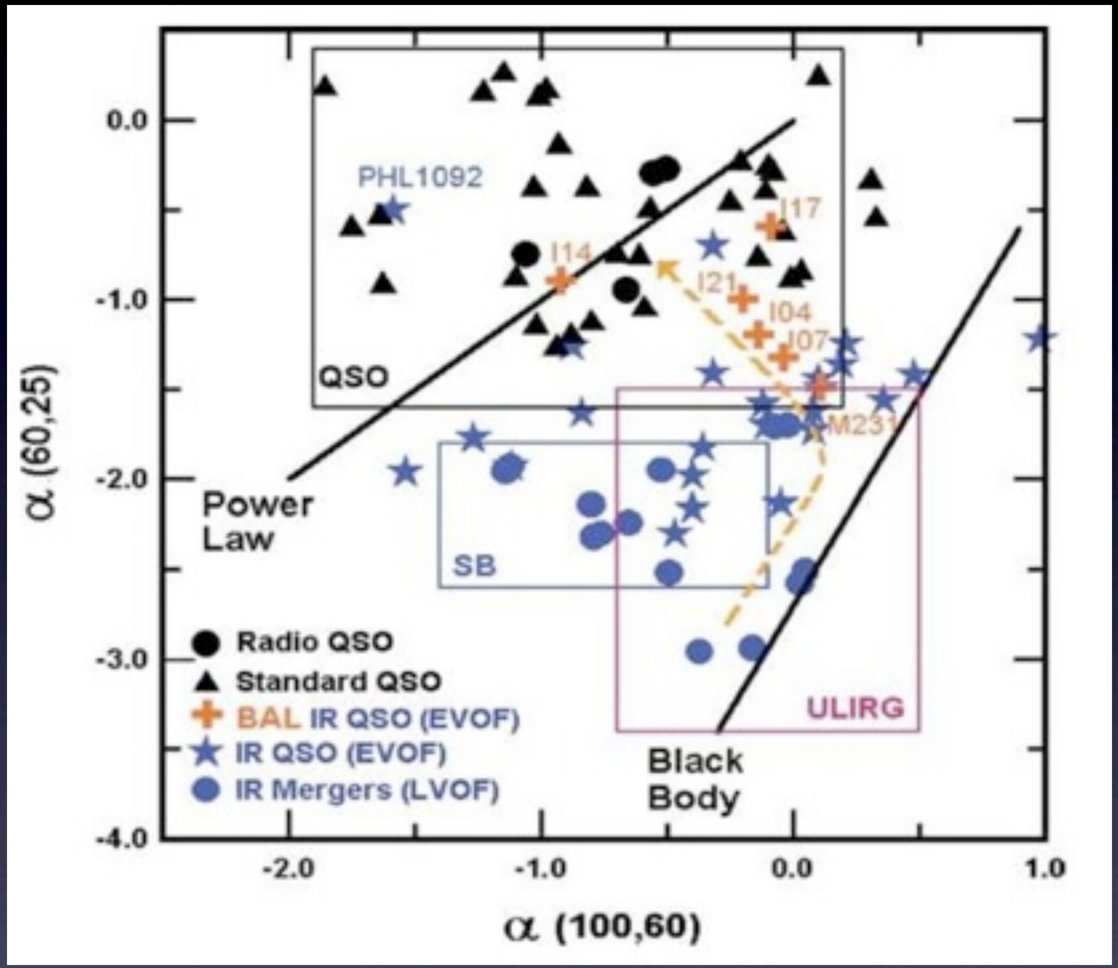








BAL QSOs transition objects



BAL sequence Lipari+ 2006

BAL: fast outflows & transition objects

between phase obscured/dust enshrouded and

un-obscured QSO

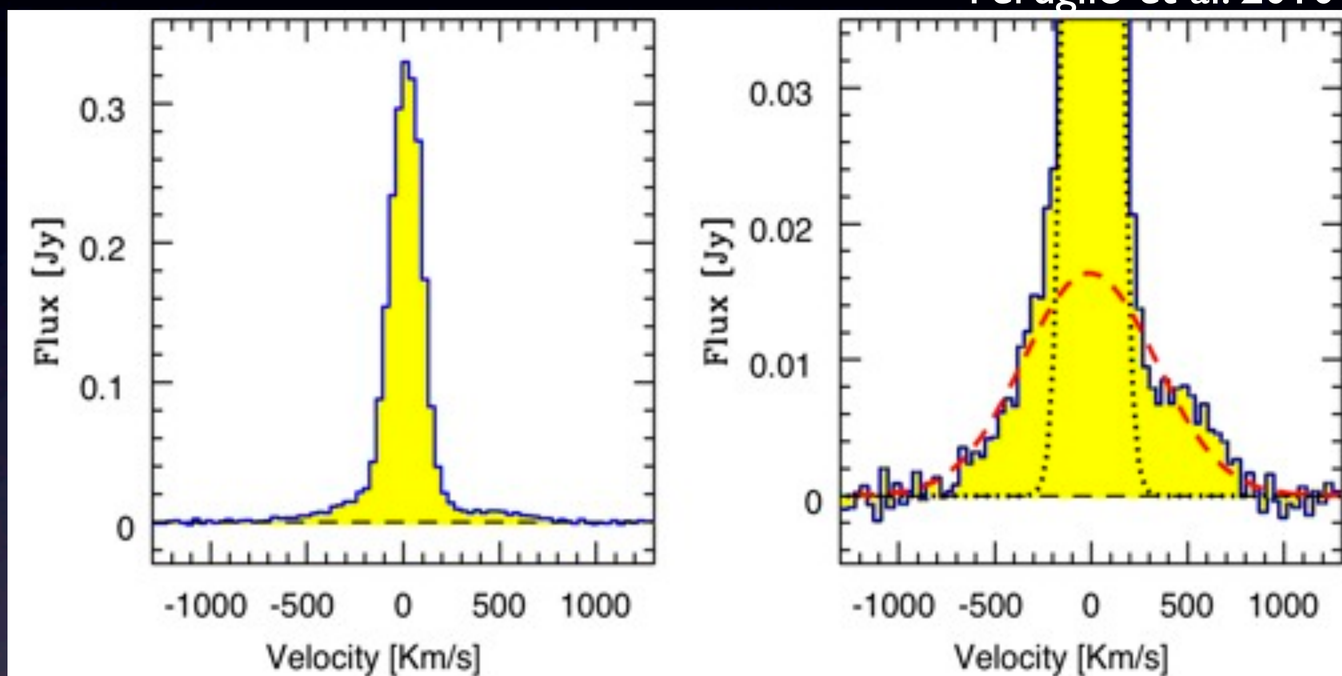
Look promising to observe effect of outflows on large scales

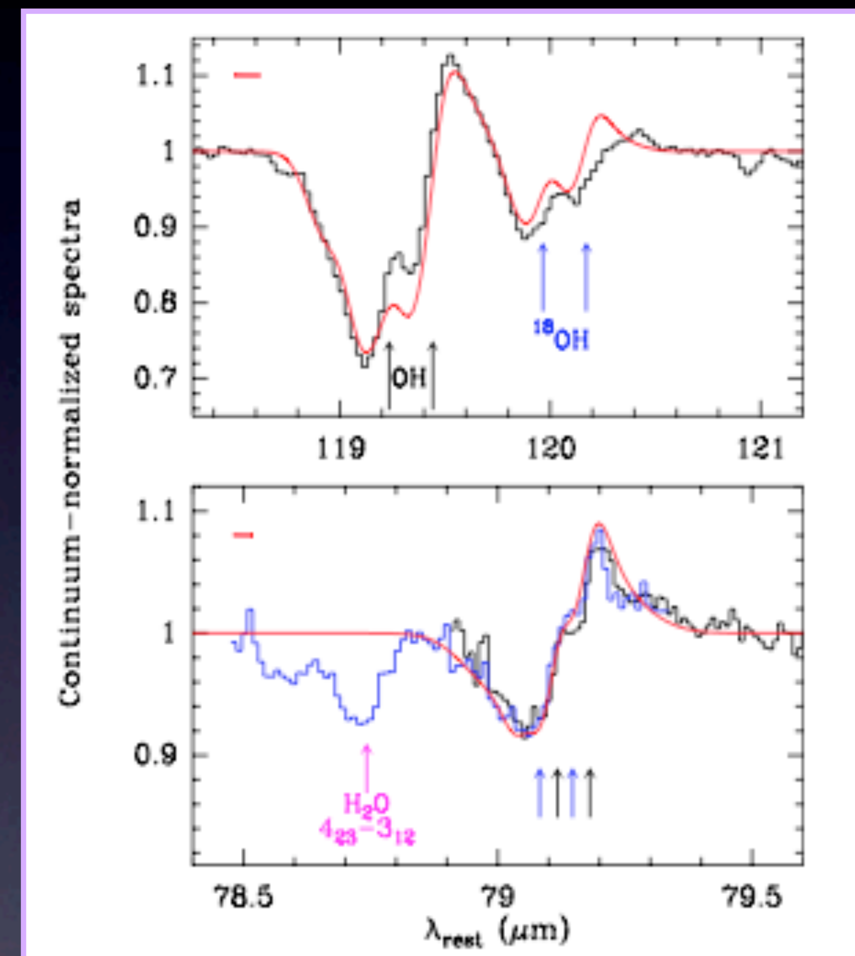
Galaxy scale molecular outflows : the case of Mrk 231

Narrow component of CO(1-0) + low surface brightness broad component extending out to +-800 km/s
FWZI = 1500 km/s

P-cygni profile in OH line from Herschel (Fischer et al. 2010)

Feruglio et al. 2010





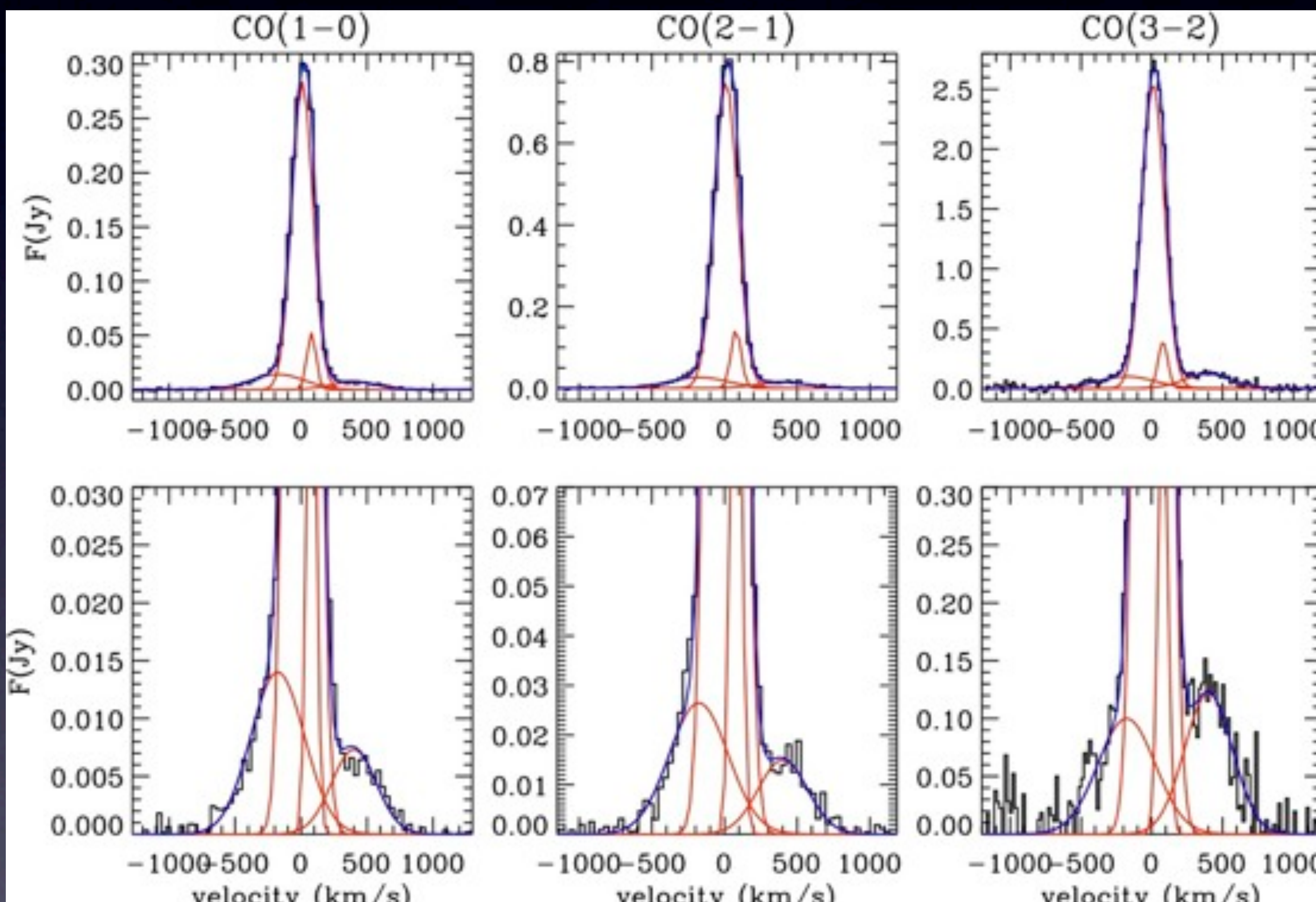
Mass in the OF: $M(H_2) > 7\ 10^7\ M_\odot$

Uncertainties due to unknown conversion factor CO-to-H2 for the outflow component

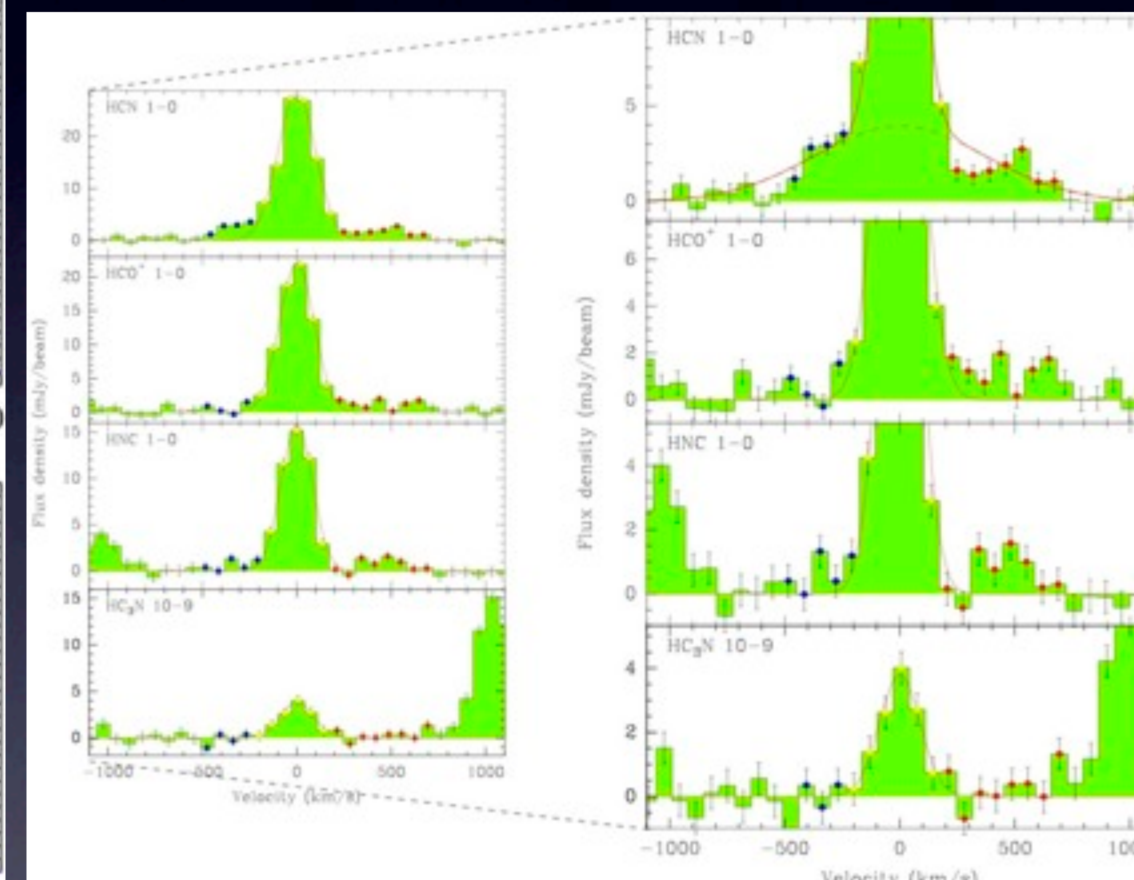
alpha = 0.5 conservatively assumed

Galaxy scale molecular outflows : the case of Mrk 231

Outflow detected in several other molecular transitions (Aalto et al. 2012, Cicone et al. 2012)

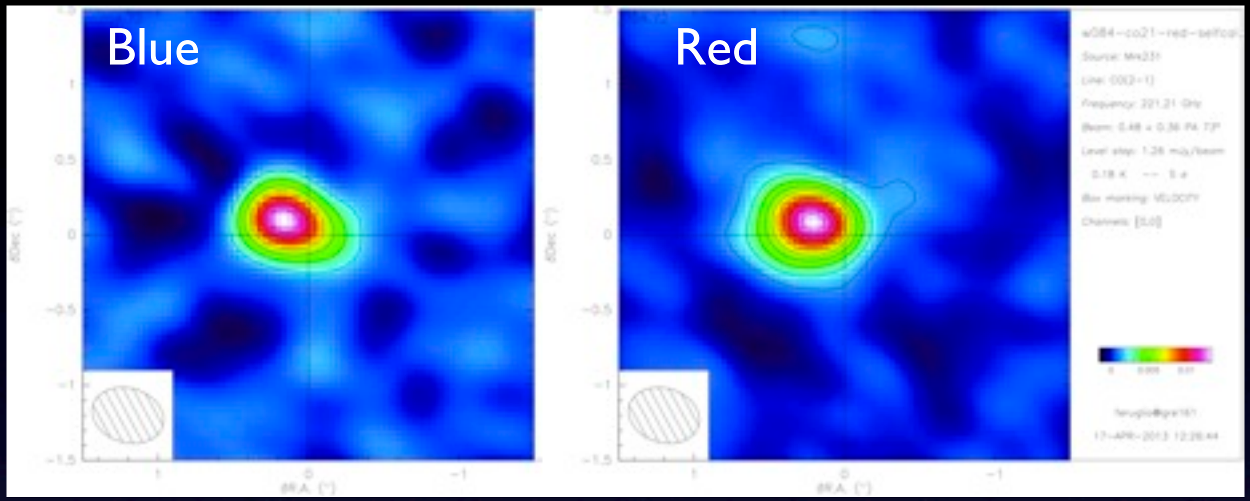


CO transitions



HCN HCO+ tracing dense clumps

Galaxy scale molecular outflows : the case of Mrk 231



Size measured ~ 1 kpc

Mass loss rate; $dM(H_2)/dt \sim 1000\ M_\odot/yr$

MASS LOSS RATE LARGER THAN THE SFR : GAS DEPLETION TIME OF THE ORDER 10^7-10^8 YR

NO STELLAR POPULATIONS YOUNGER THAN 10^6 YEARS IN THE CENTRAL KPC (LIPARI ET AL.)

Kinetic energy of outflowing gas: **E =1.2 10^{44} erg/s = a few % L_{Bol} (5 10^{45} erg/s) of the AGN**

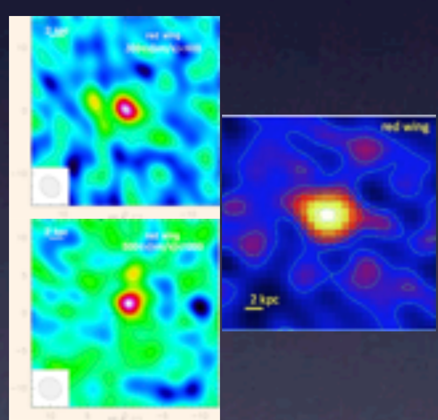
compatible with models of AGN-driven outflow through a shock wave.

Emission of CO at +- 800 km/s. Mach number is large.
If CO is shocked, excitation conditions in the outflow should be different: outflowing gas more excited than low velocity gas.

Key Questions to answer

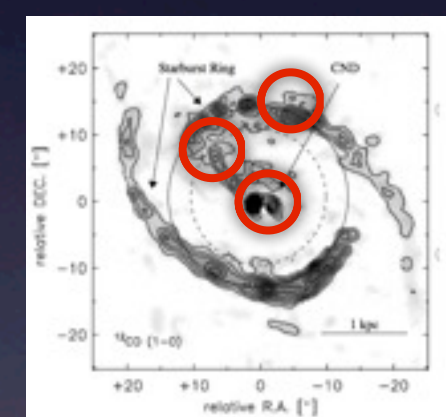
1. **origin of outflows (AGN, SF, both?) and expansion mechanism: morphology needed**
2. **What os the role of molecular outflows in the heating of the ISM compared to other mechanisms (CR, UV and X-ray fields)**
3. **What correlation between mass loss rate and AGN luminosity, obscuration, SFR?**
4. **Are molecular outflows common in galaxies/AGN in the peak phase of galaxy assembly and Accretion onto SMBH, z~ 2?**

Nearby galaxies: detailed morphological studies of molecular outflows
Statistics, correlations.

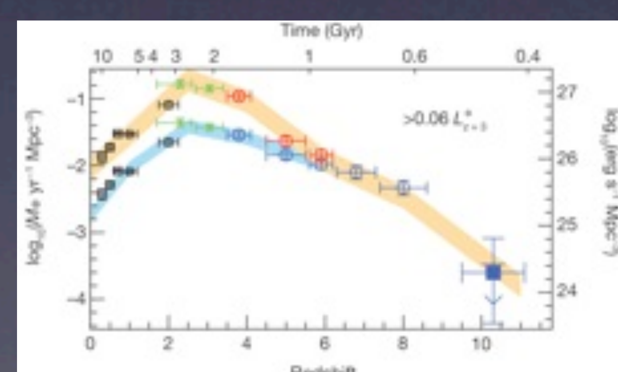


Studies complementary to one another

ISM Heating mechanisms:
outflow vs XR, CR, UV
in narby galaxies (NGC1068)



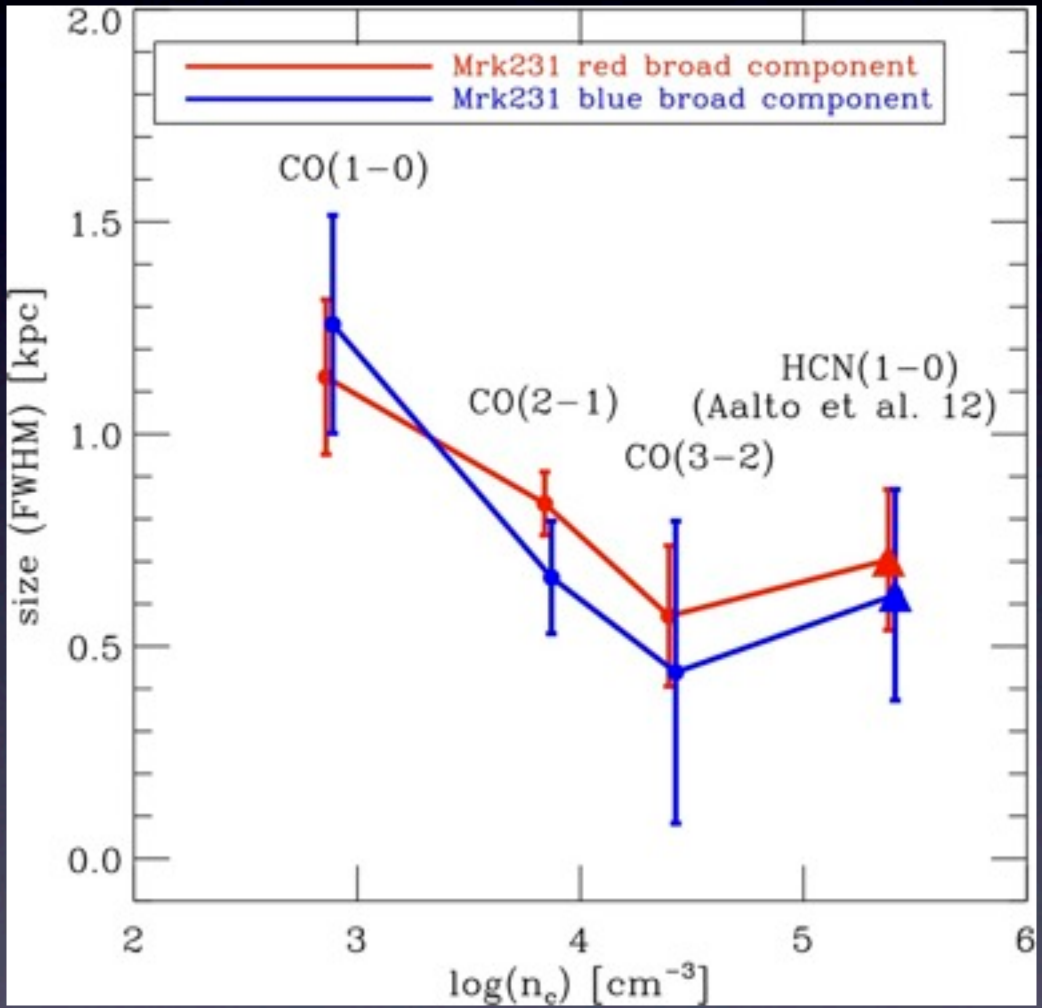
Study molecular outflow at
the peak of star formation and accretion activity: z ~2



Role of AGN in the transformation of their host galaxies

Galaxy scale molecular outflows : the case of Mrk 231

Size is anti-correlated with the critical density, denser gas has more compact morphology.
Size confirmed by observations with high spatial resolution with PdBI in 2013.



But what is the morphology?
High resolution maps needed to establish the morphology of the outflowing gas.
Morphology can tell about the driving mechanism.
Work in progress...

Galaxy scale molecular outflows : Mrk 231

(Rupke et al. 2011)

Comparison with the morphology seen for neutral gas.
Is the outflow influenced by the radio jet?

Extended outflow detected in IFU IR observations of neutral gas

Showing the complex nature of Mrk 231 : AGN + Starburst winds

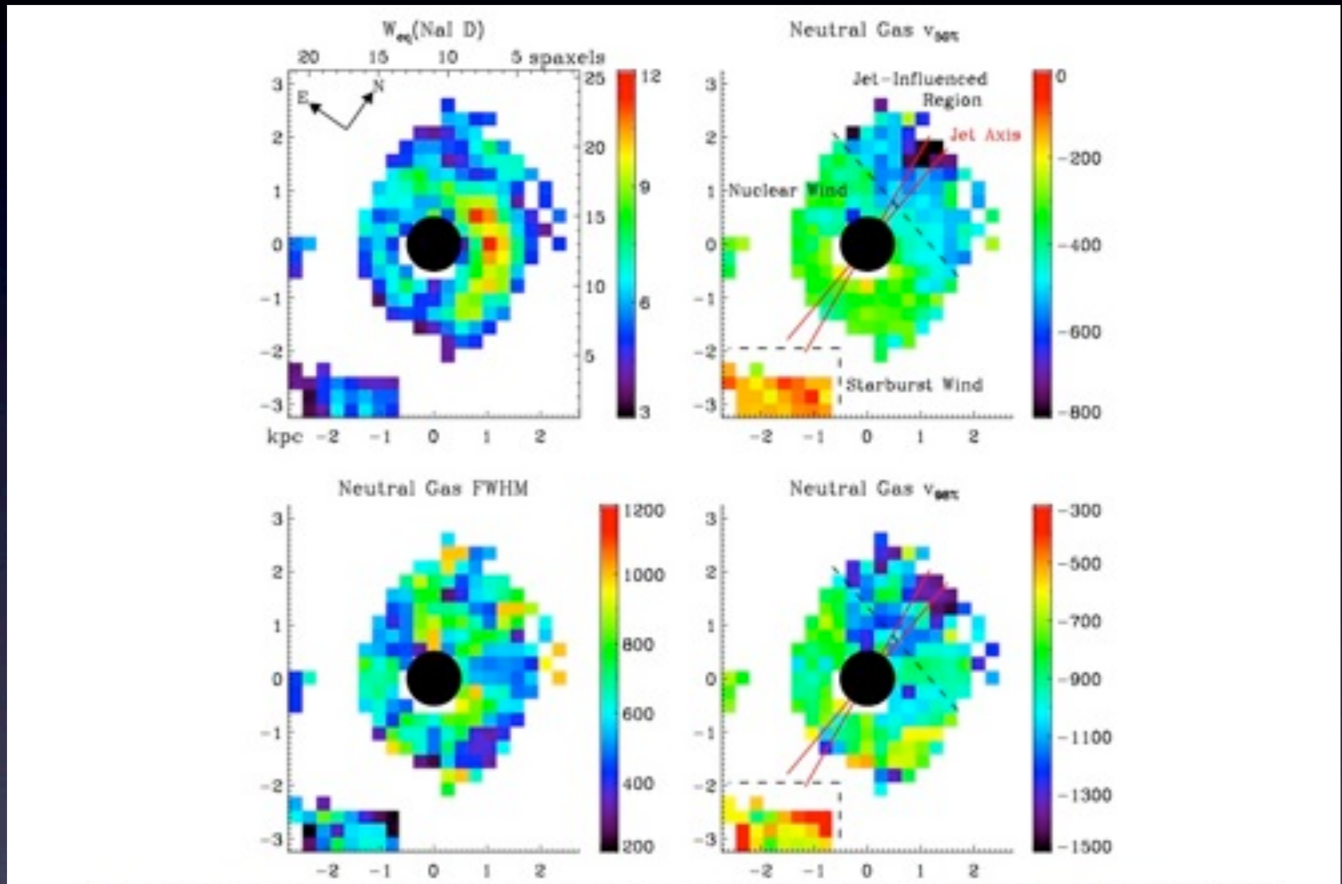


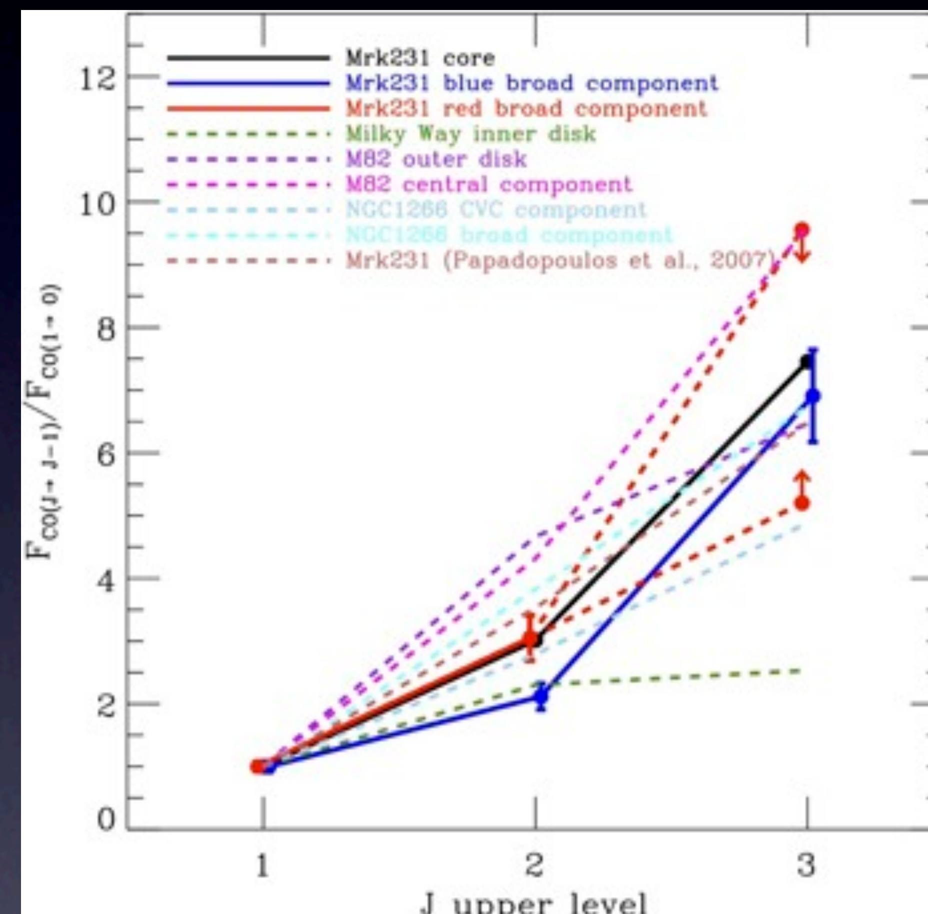
Figure 4. Equivalent width, central velocity, FWHM, and $v_{98\%}$ maps of Na I D. A nuclear outflow extends from the nucleus up to 2–3 kpc in all directions (as projected in the plane of the sky). The high velocities suggest that the AGN powers the nuclear wind. The northern quadrant of the nuclear wind is further accelerated by the radio jet. A lower-velocity starburst-driven outflow is present in the south.

Galaxy scale molecular outflows : the case of Mrk 231

No difference easily detected in excitation of CO transitions in the high velocity vs low velocity gas. Large uncertainties, contamination from H13CN(4-3) blended in the red wing of CO(4-3)

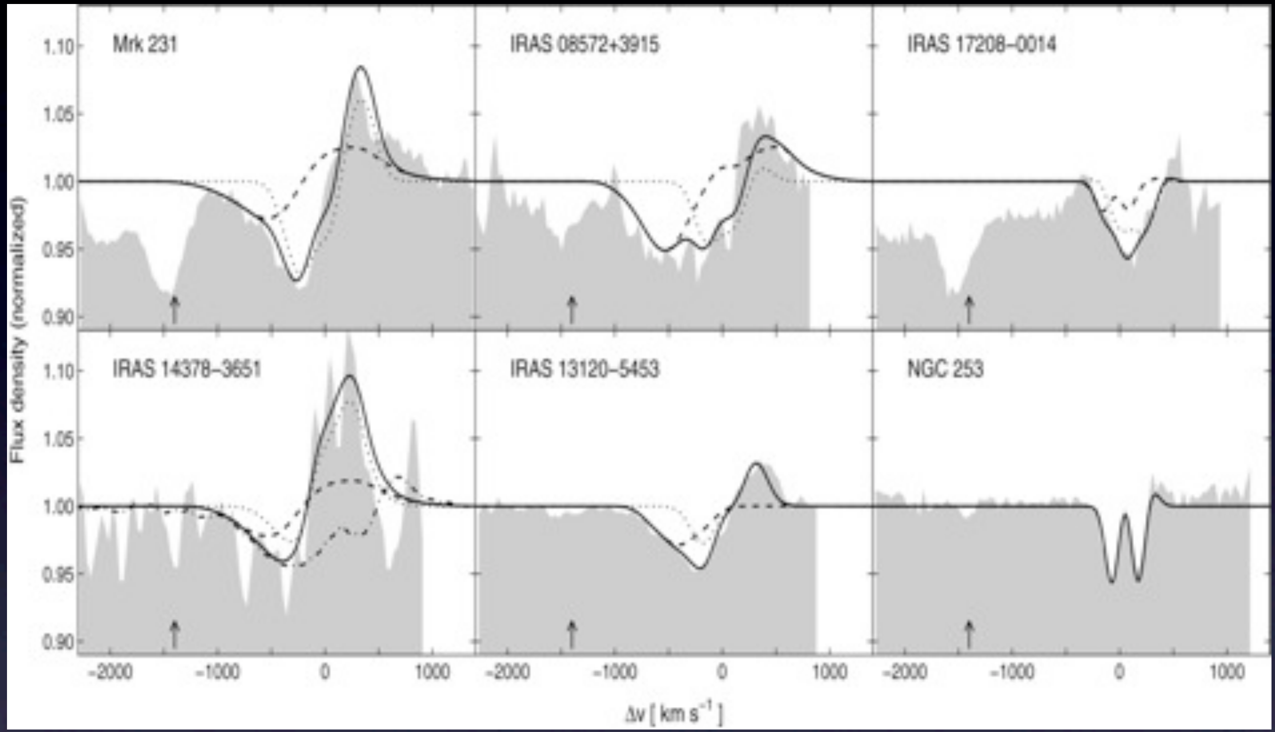
Agrees with King & Zubovas 2012: dense outflowing clouds embedded in a atomic outflow are not excited by shocks.

Cicone et al. 2012

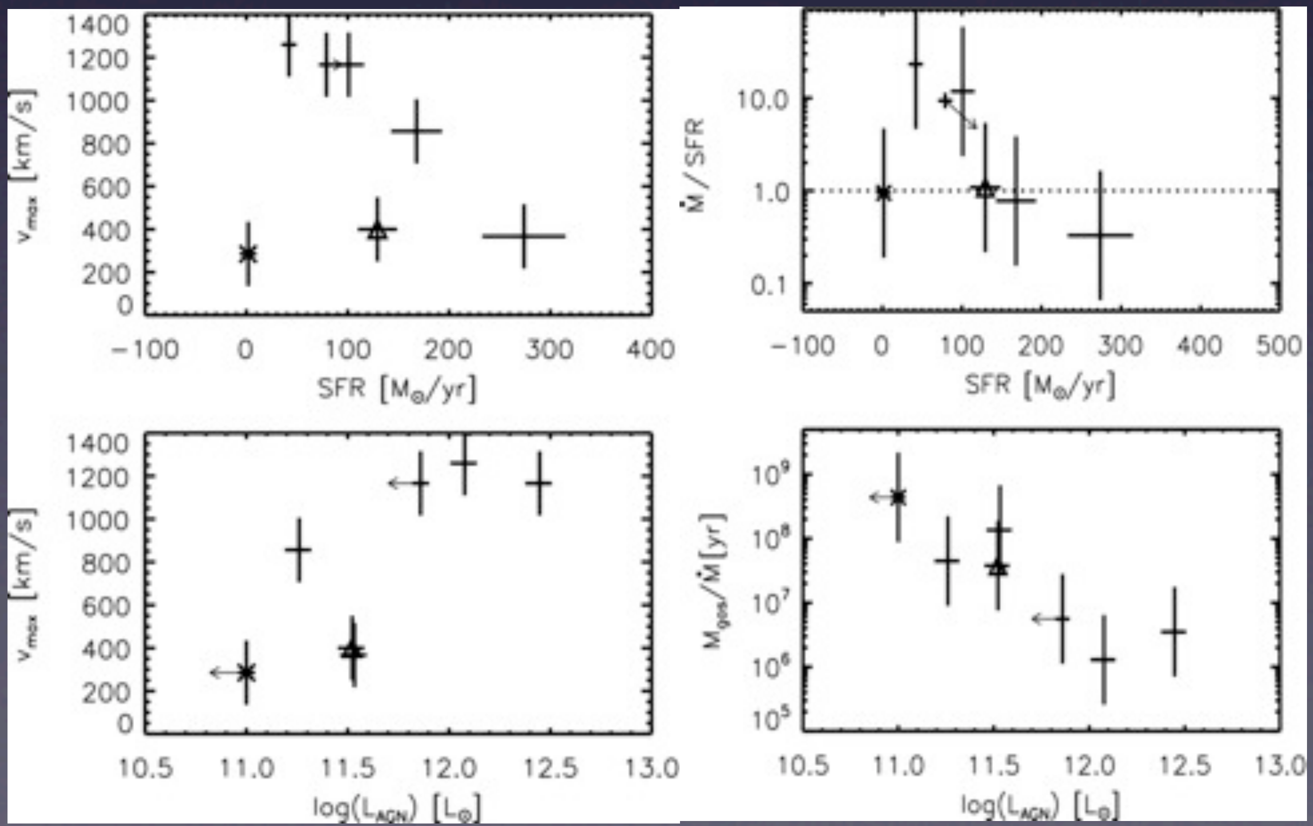


How common are molecular outflows in ULIRG/QSO?

Local ULIRGs surveyed by Herschel (Sturm etl a. 2011), composite sample of both AGN and SF-dominated .
Outflows detected through P-cygni profiles of OH.



Mass loss rate > several hundreds M /yr



Terminal velocity v_{max} correlated with L_{AGN} --> powered mainly by the AGN

Terminal velocities > 1000 km/s in AGN-dominated objects

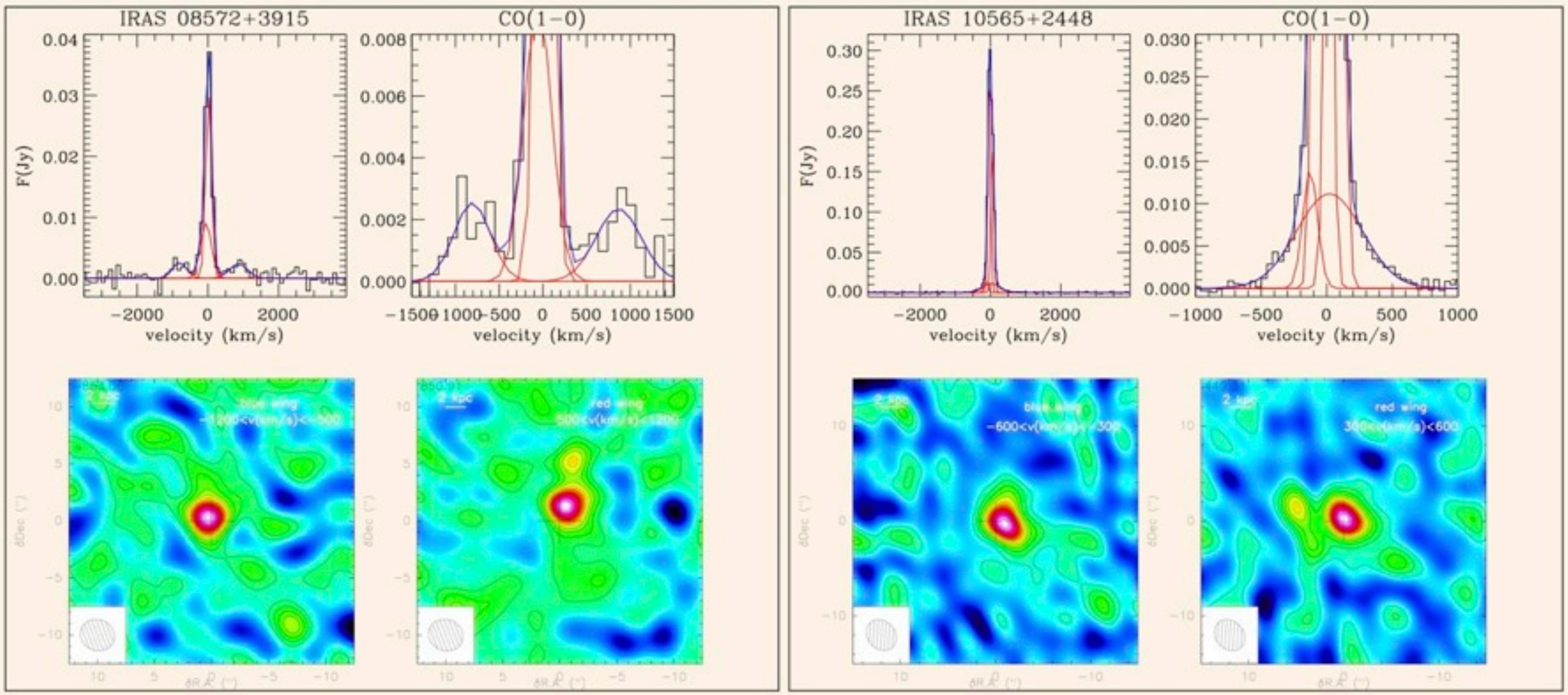
(also seen with GMOS in Rupke & Veilleux 2013, sample of 6 local mergers)

How common molecular outflows in ULIRG/QSO?

(Sturm et al. in prep, Cicone et al. in prep.)

On-going projects with the PdBI and ALMA to constrain sizes and mass loss rate (P.I. Sturm)

Broad lines detected, maps also show substructures (clumps) .
Mass loss rate > 600 M⊙ /yr and above 1000 M⊙ /yr in AGN-dominated objects



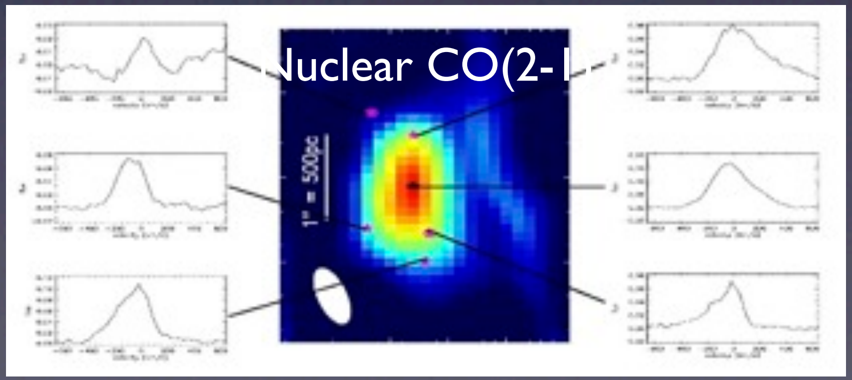
Source	log(L_{AGN}) [$L_\odot$]	SFR [$M_\odot$ yr^{-1}]	$v_{OF,max}$ [km/s]	FWHM (CO(1-0)) [kpc]	OF rate [$M_\odot$ yr^{-1}]
Mrk 231	12.45	200	~1000	1.2	~700-1000
IRAS 08572+3915	12.08	42	~1500	2.5	~1400
IRAS 10565+2448	11.38	84	~600	2.4	~600

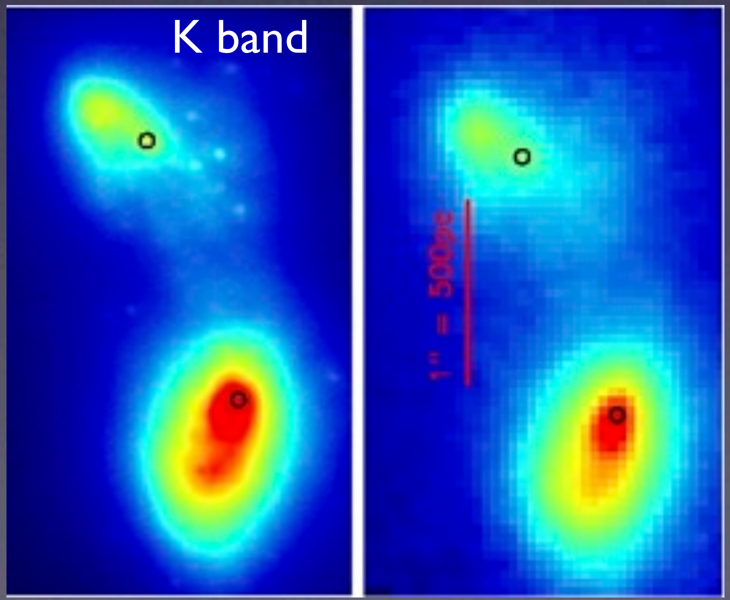
NGC6240: a complex system with broad CO

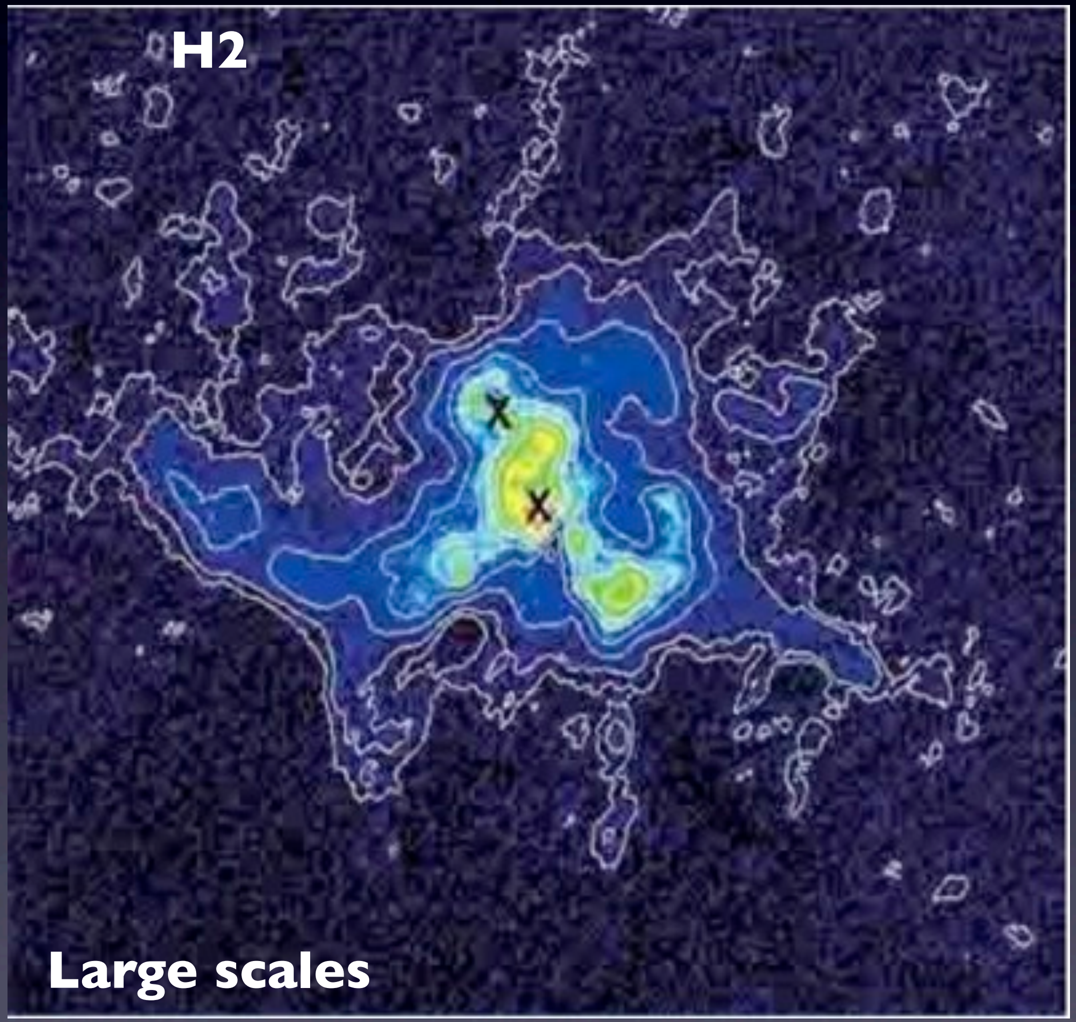
Major merger in early stage of 2 gas rich spirals, with complex morphology, streamers, tidal tails
2 AGN nuclei both heavily obscured, with L(2-10) keV > 10^{44} erg/s and M(BH) > 10^{8} M ⊙

Hα **nebula with bipolar pattern (east-west) : wind sock heating the ISM**

H2 emission, tracer of shocked





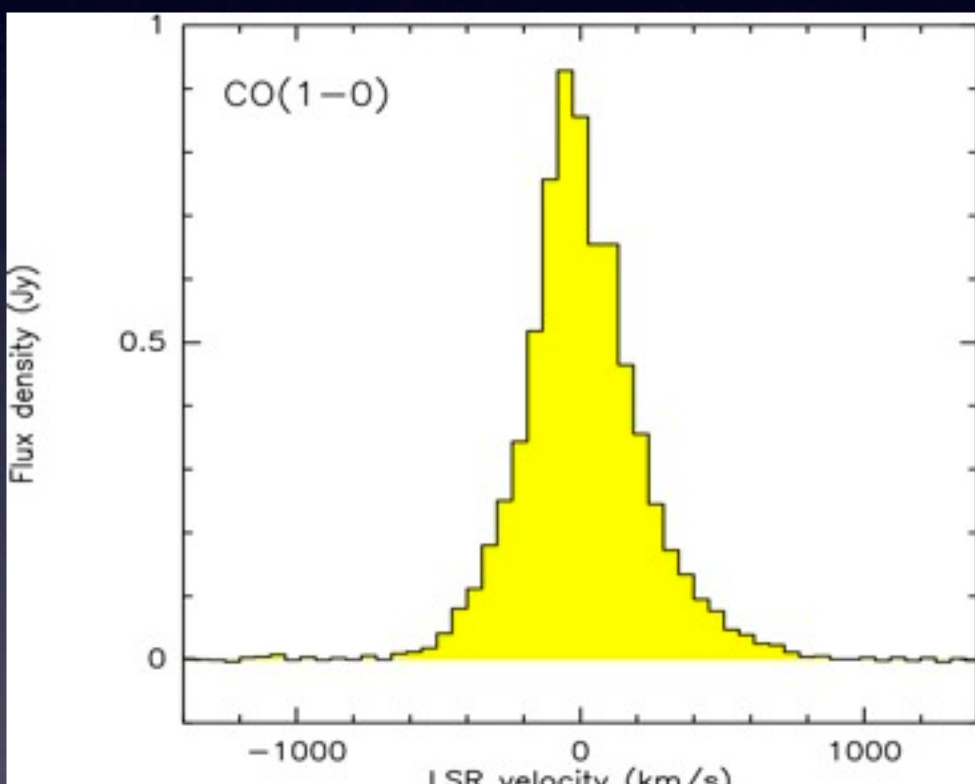


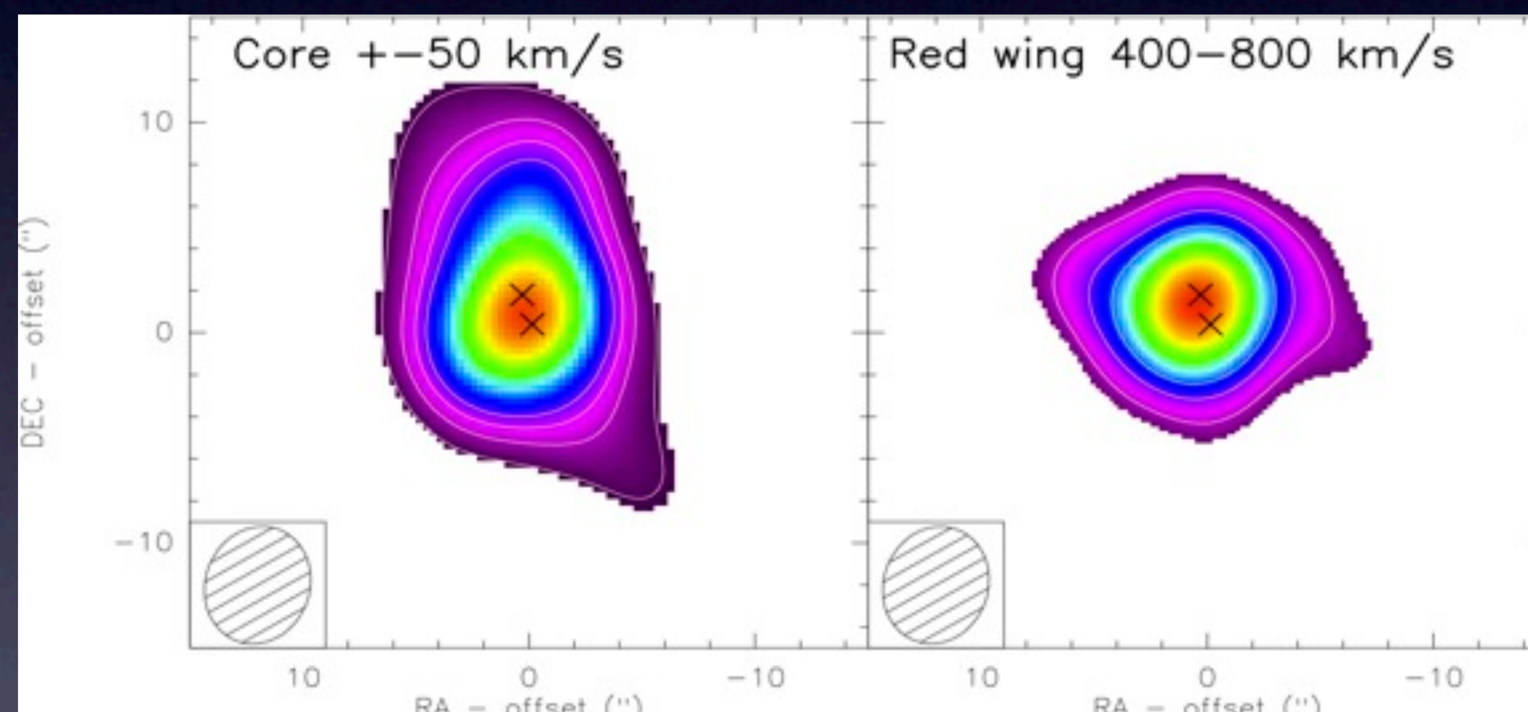
Max et al. 2005

NGC 6240: a complex system with a CO outflow

New sensitive PdBI observations of CO(1-0) : broad CO(1-0) detected out to +- 800 km/s

Central concentration of CO in between the 2 AGN :   M(H2) ~ 5 109 Msun



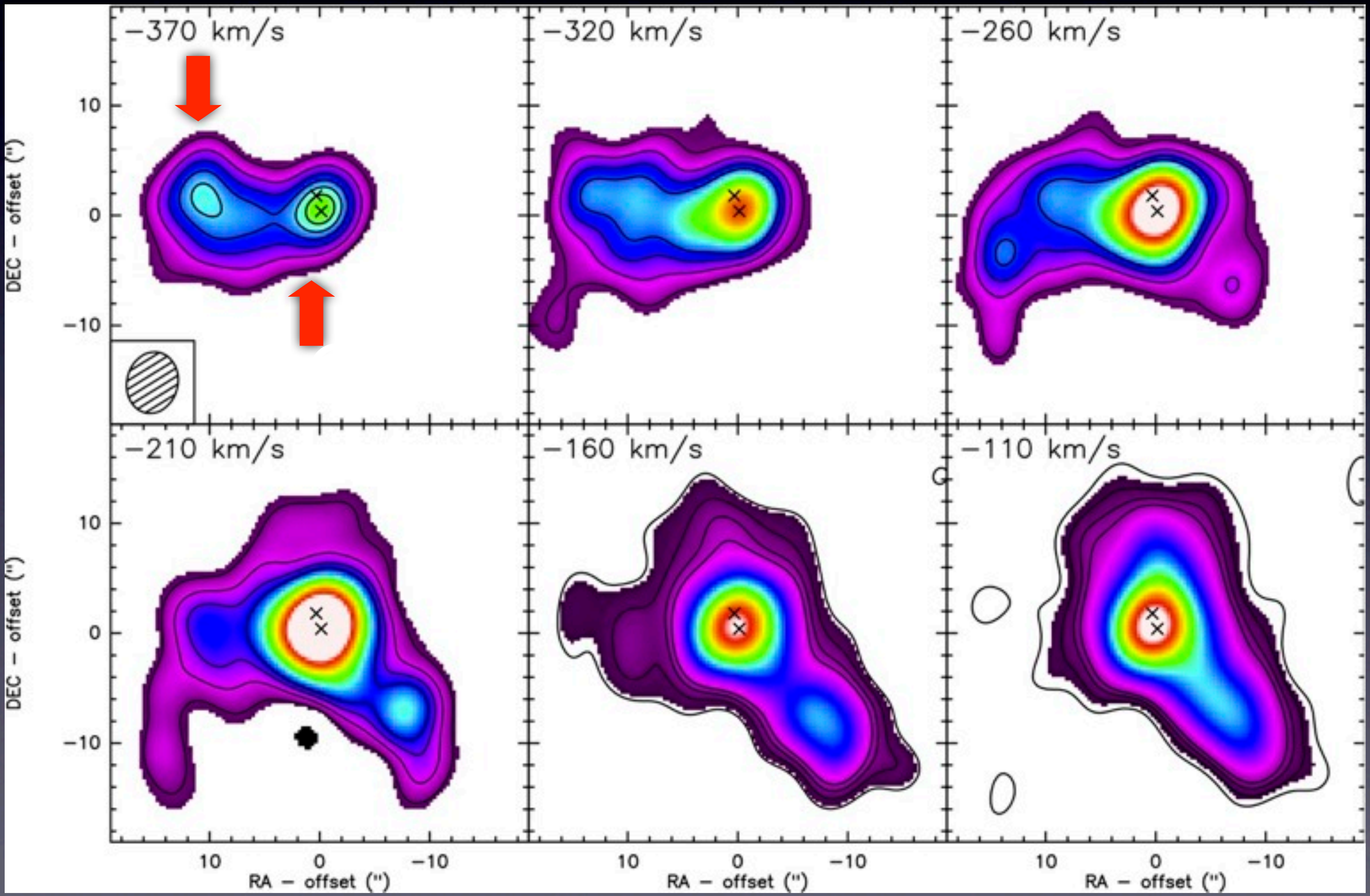


Feruglio et al. 2013

NGC 6240: a complex system with a CO outflow

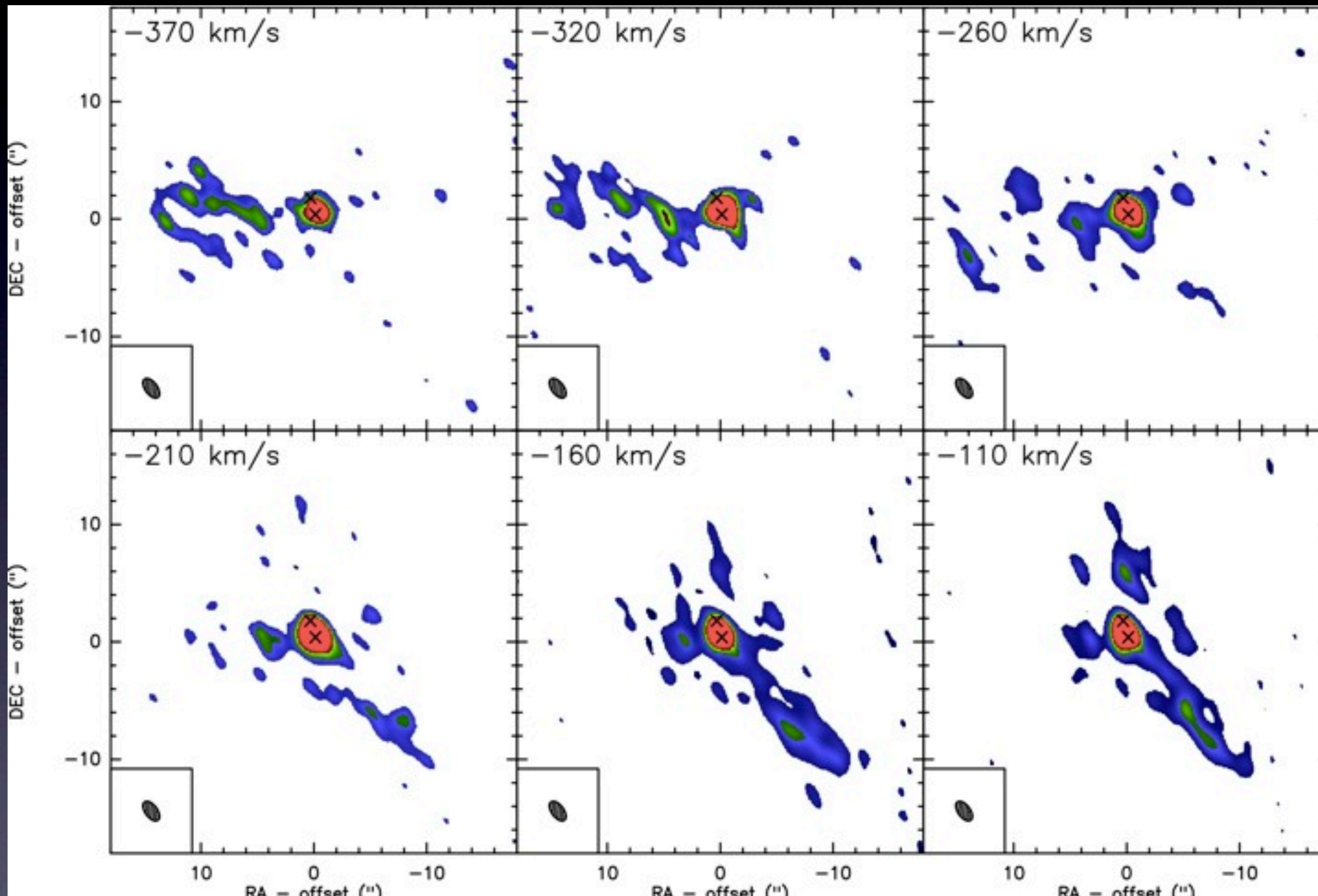
Blue-shifted extended structures detected on scales of 7 kpc
Mass of the central concentration M(H2) ~ 5 x 109 Msun
Outflow M(H2) ~ 7 x 108 Msun

CO(1-0) channel maps **Feruglio et al. 2013**



NGC 6240: a complex system with a CO outflow

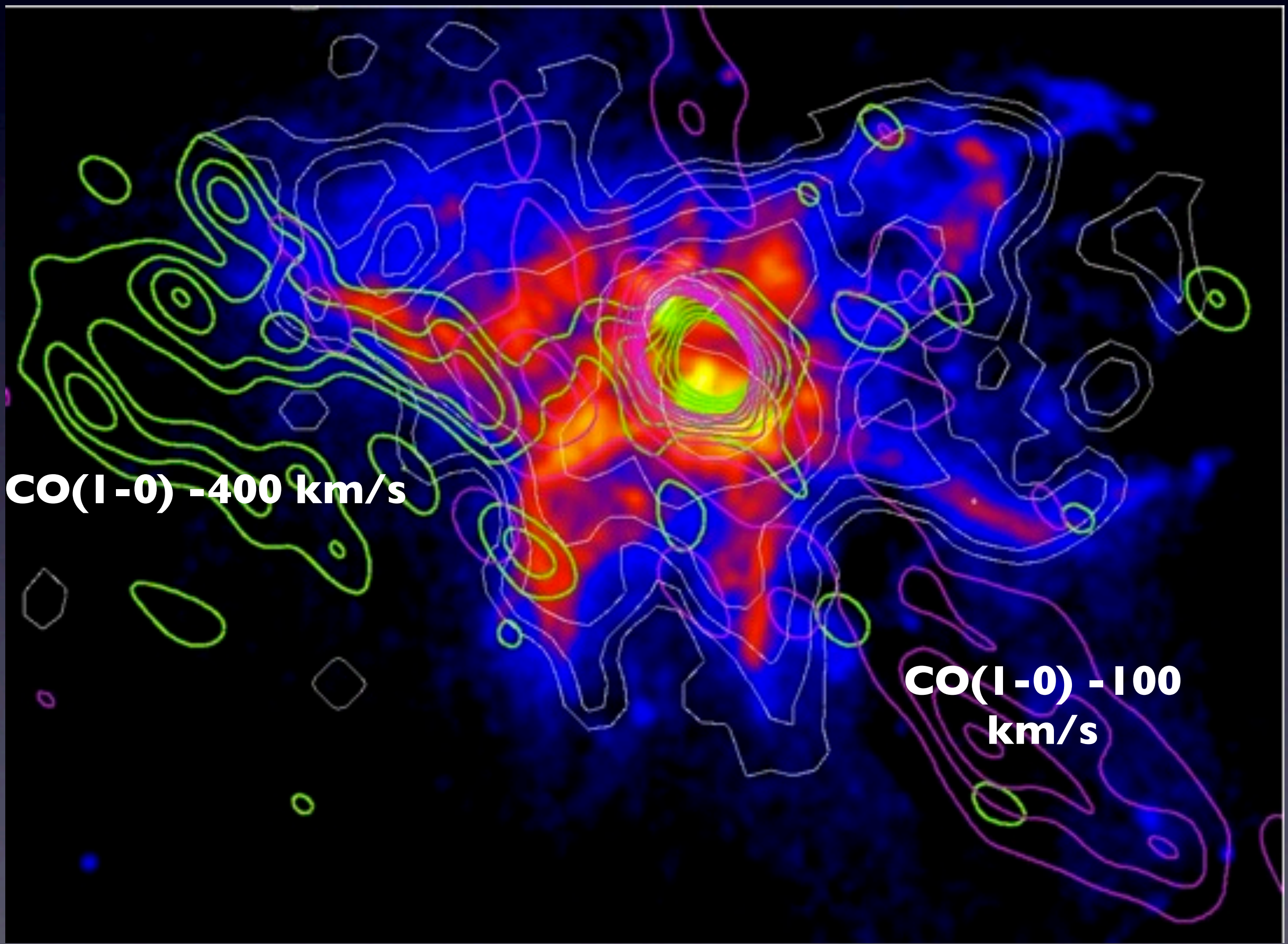
CO(1-0) map in velocity channels, high spatial resolution **Feruglio et al. 2013**

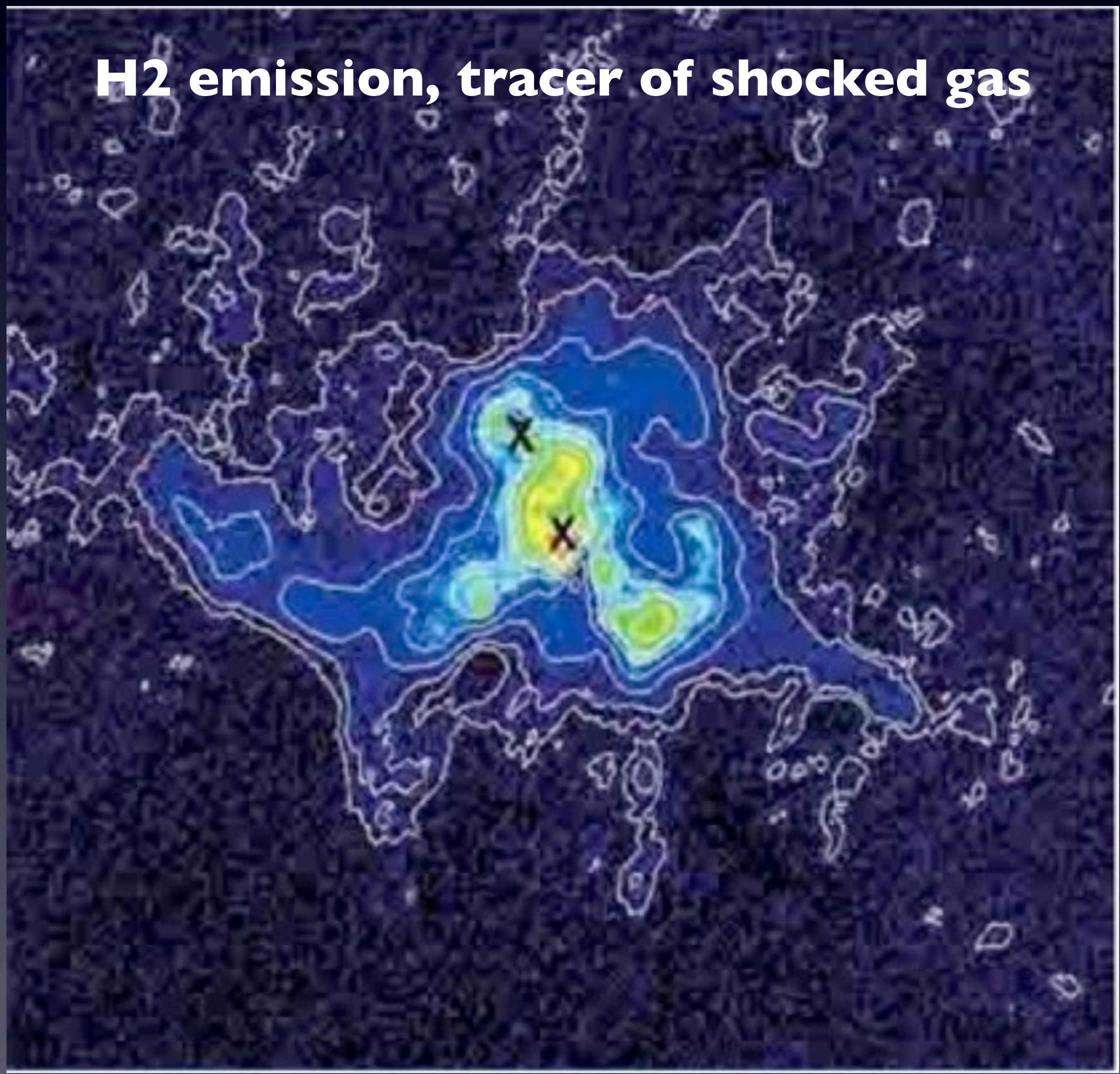


NGC 6240: a complex system with a CO outflow

Hα nebula traces biconical pattern aligned E-W: super-wind from the southern AGN shock-heats the ISM

CO at -100 kms/ coincides with the dust lane seen in HST image in the S-W region
CO with -400 km/s coincident with Hα filaments in the Eastern region

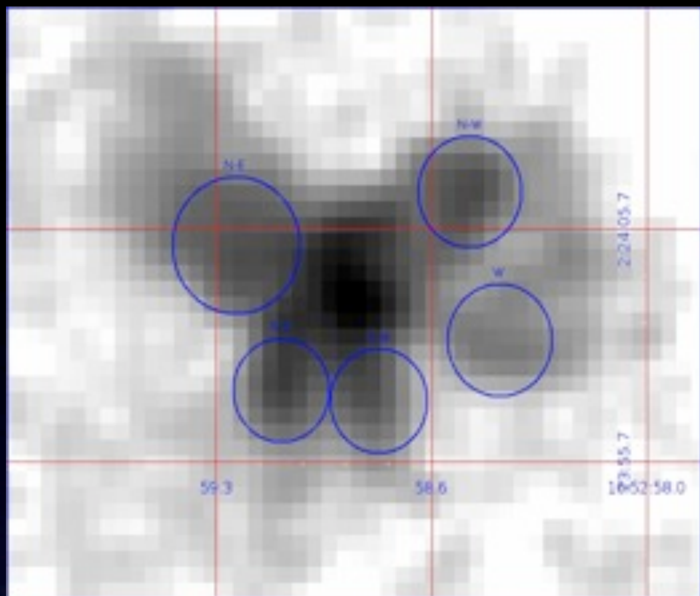




If CO outflow from the southern AGN, mass loss rate of several 100 $M_\odot$/yr

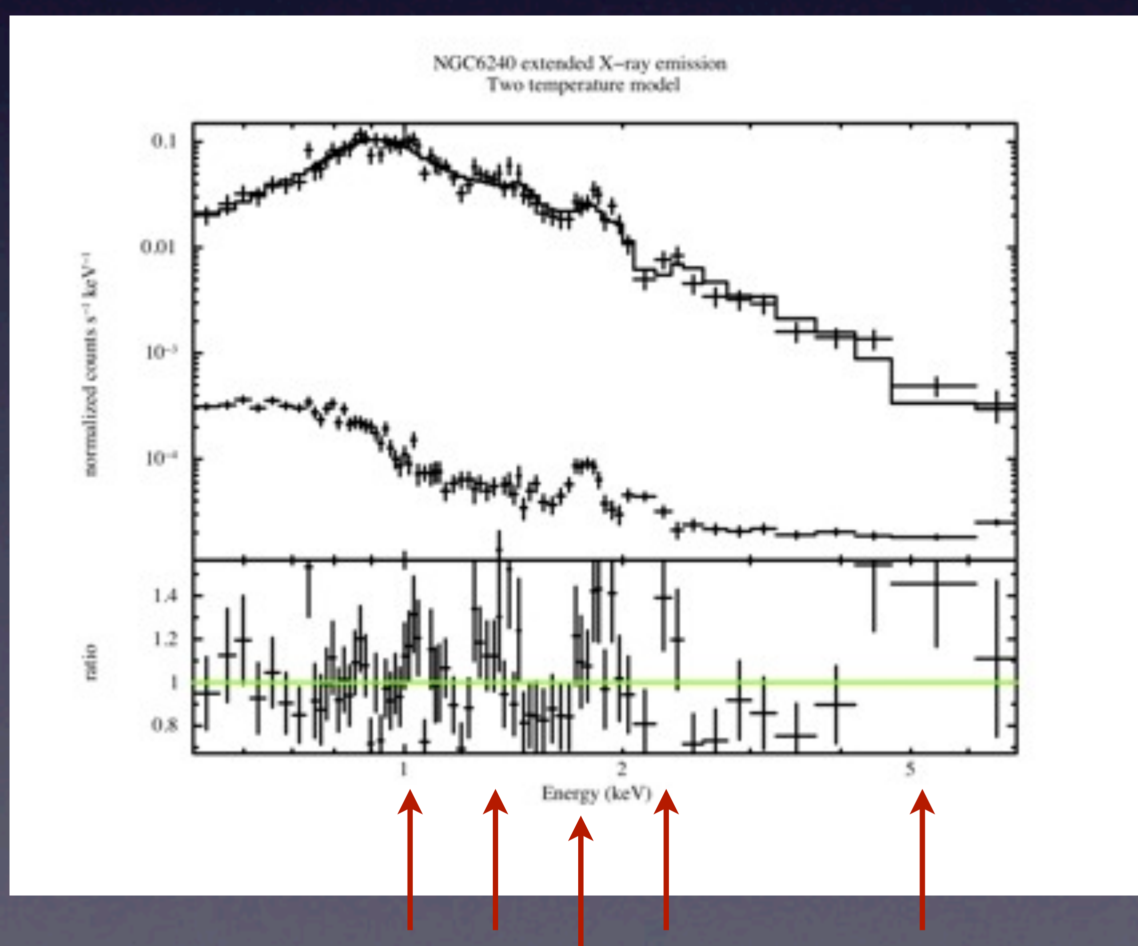
]

Spatially resolved spectroscopy with *Chandra*



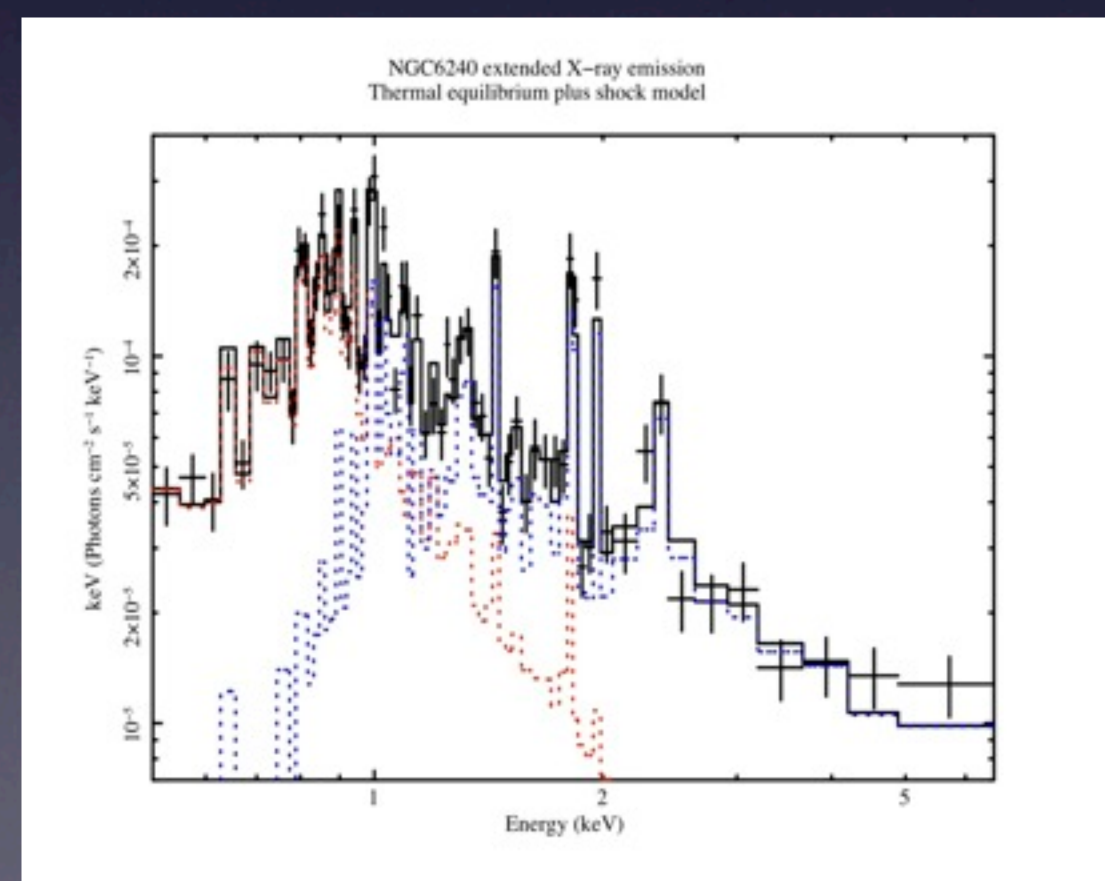
Analysis of the Chandra X-ray:
evidence for shocked gas at the position of the Hα emission, suggests
that a shock is propagating eastwards and compressing the molecular gas, while crossing it.

Thermal equilibrium, 2 Temperatures

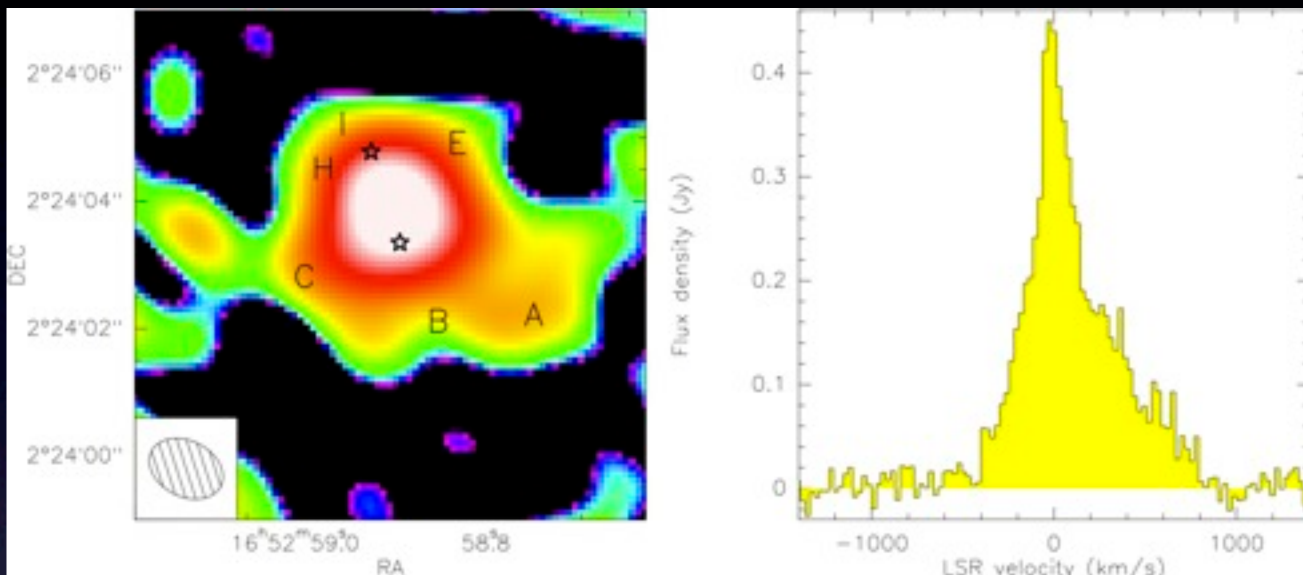


Residuals at pos of Mg, Si, S emission

Thermal + shock , prominent high-ionization emission lines indicating higher T

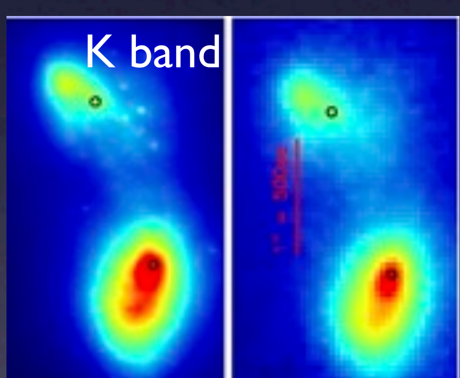


NGC 6240 zoom in the nuclear region

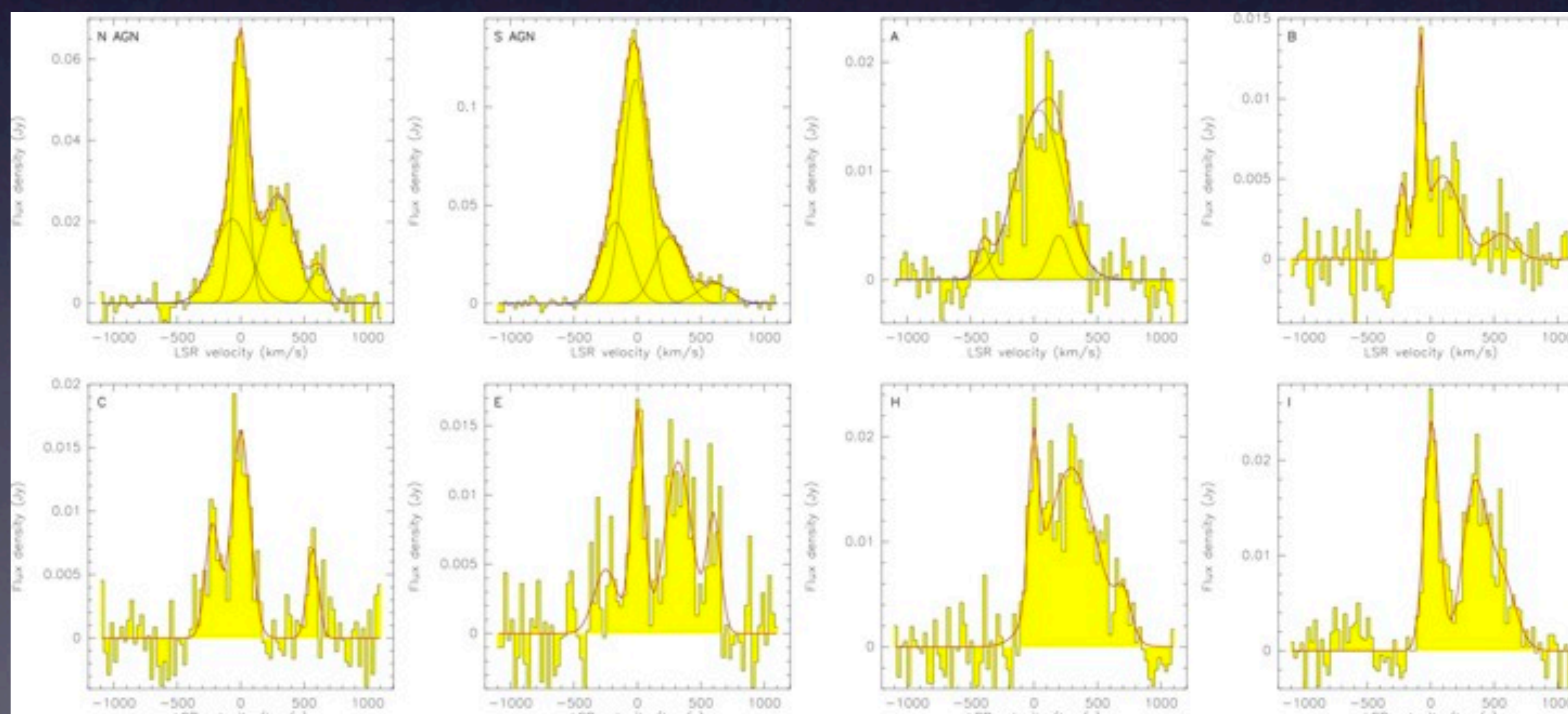


Central concentration of CO in between the 2 AGN
+
Extended diffuse emission (see Tacconi+1999)

Complex velocity field showing several dynamical components



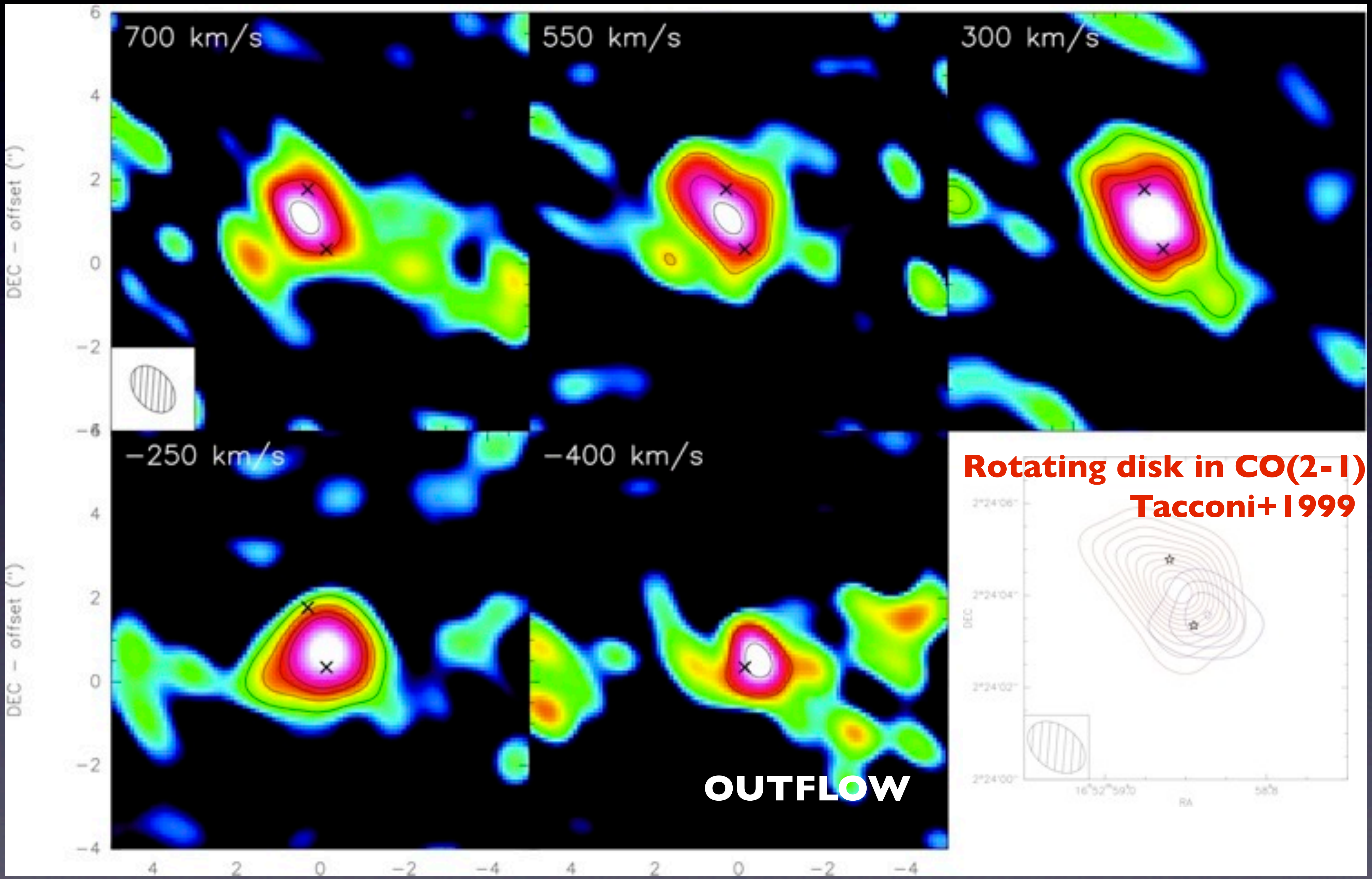
Stars still bound to the progenytors (Engel 2010)



NGC 6240 zoom in the nuclear region

Red-shifted gas: concentrated between the 2 AGN

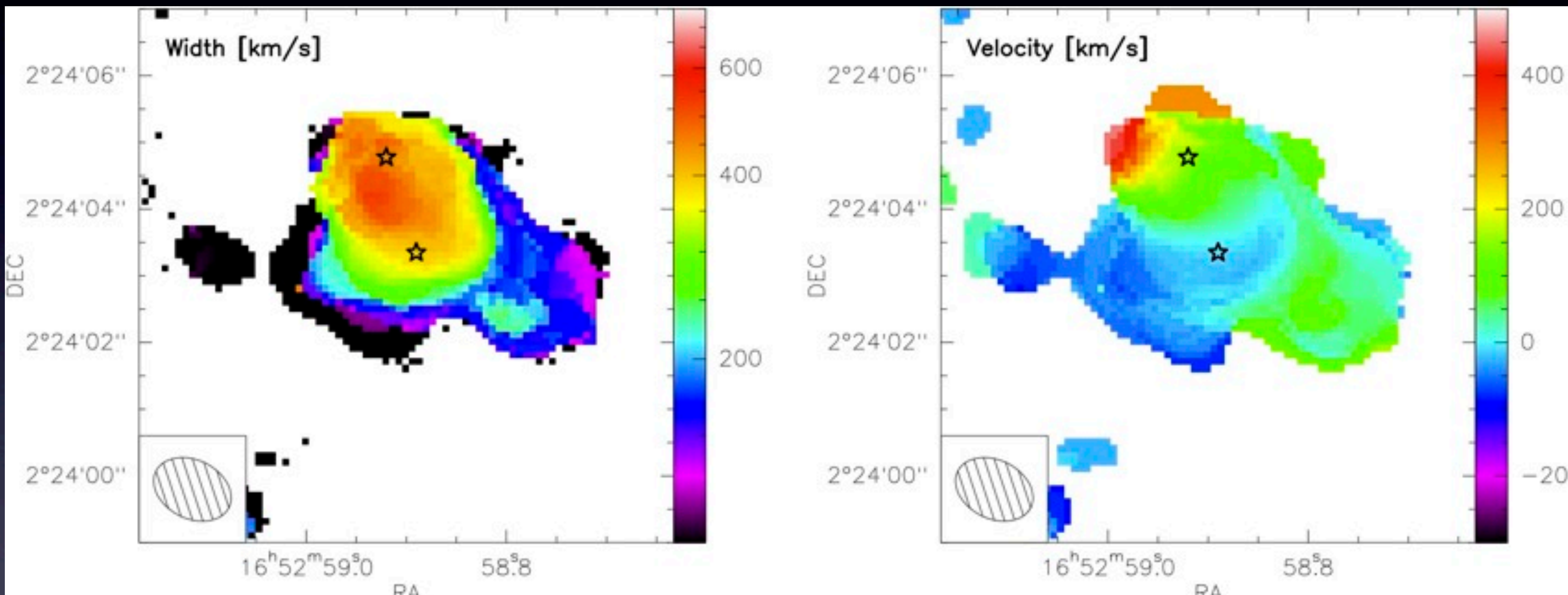
Blue-shifted gas centered on the southern AGN : OUTFLOW seen also in absorption by PACS

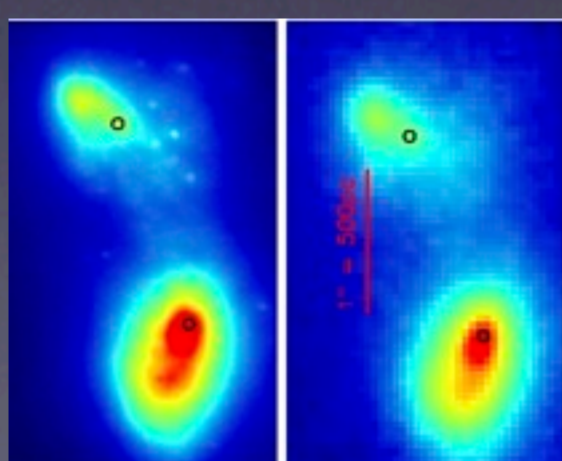


Previously interpreted as turbulent rotating disk BUT NOW velocity too large for a rotating disk!

NGC 6240 zoom in the nuclear region

Velocity dispersion maximum in between the 2 AGN
Shocks?





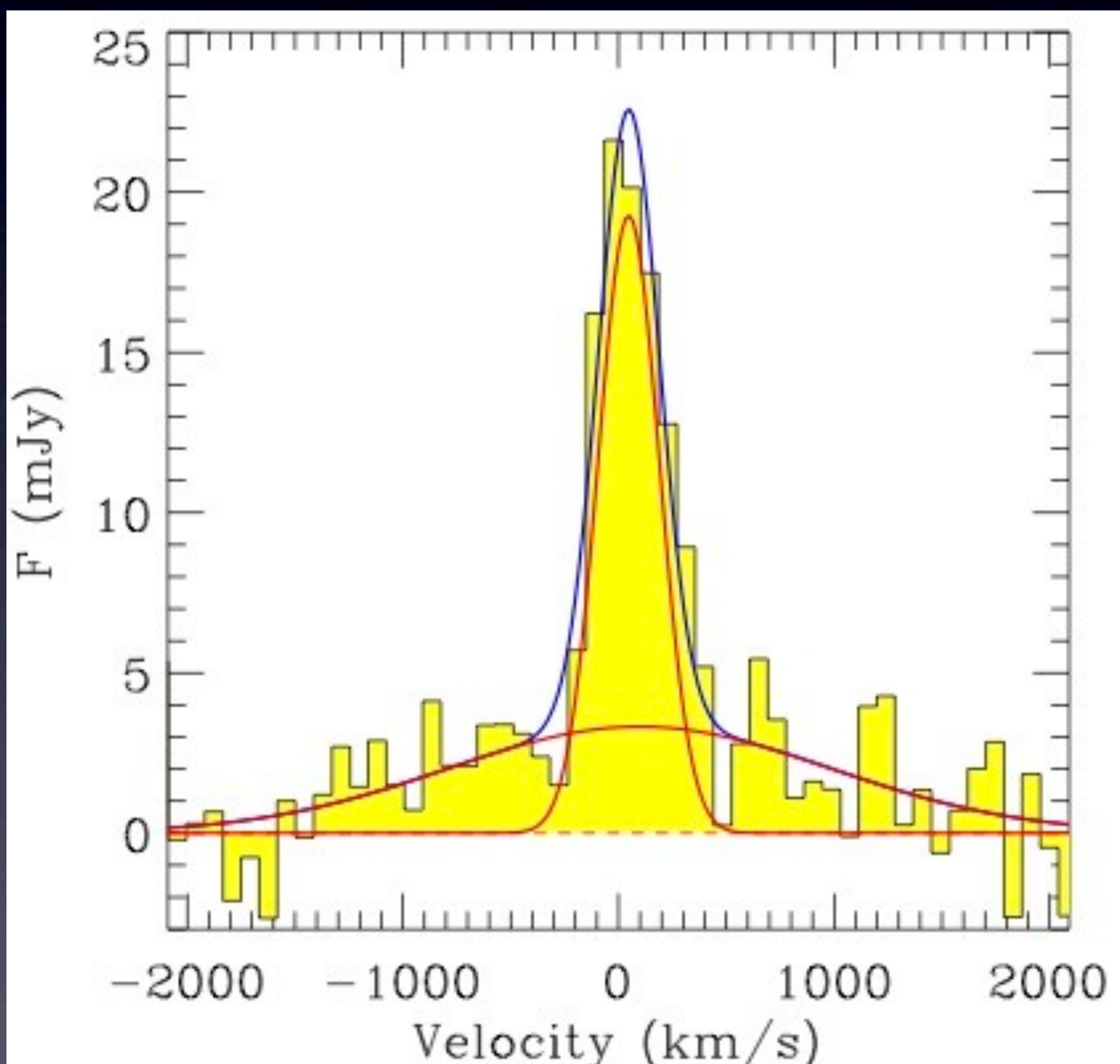
U et al. 2011 conf proc: gas disks of the progenitors infalling and orbiting based on CO(3-2).

Outflows in the distant universe

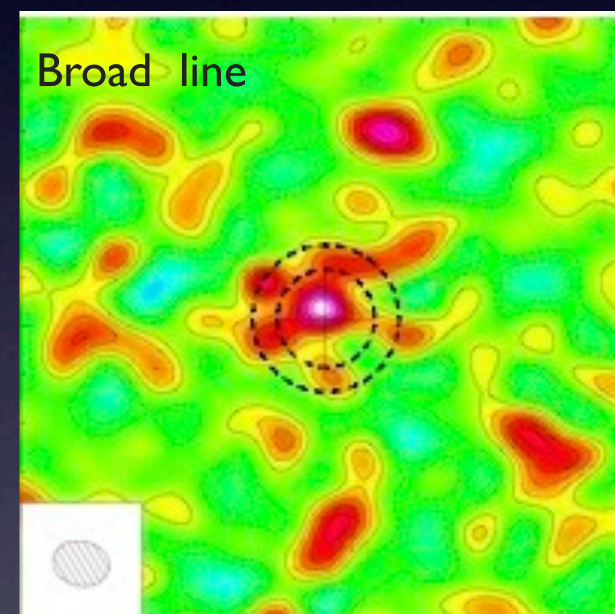
Extremely luminous quasar SDSS J1148 at z=6.4
Host galaxy has SFR ~ 3000 Msun/yr and M(H2) ~ 2 e10 $M_{\odot}$

Broad wings detected in [CII]158um with FWHM = 2000 km/s (Maiolino et al. 2012)

Vmax = 1300 km/s already points towards AGN-driven outflow and shocks



Mof > 7 e9 Msun <u>under conservative assumptions</u>
(X(C+), n_crit , Temperature)



Broad component concentrated in the center but extended on scales of 16 kpc

gives mass loss rate of dM/dt > 3500 Msun/yr !!!

and kinetic power Pkin > 2 e45 erg/s

< 1% of the AGN LBol

Well above the power injected by SNa = η * SFR * 7e41 (η ~ 0.1)

<u>To be confirmed by high resolution maps!</u>

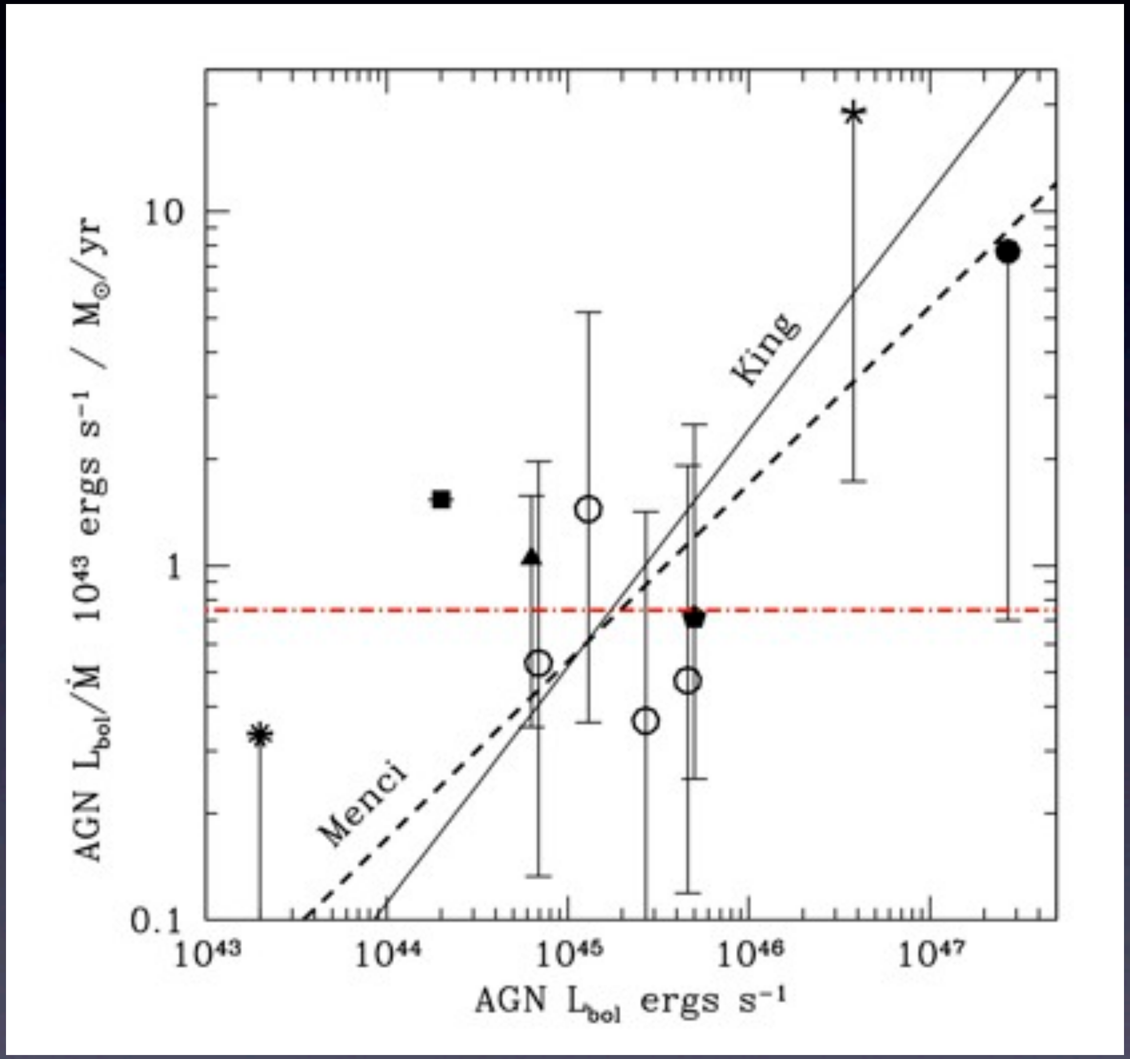
A summary of AGN extended outflows

Correlation between AGN outflow rate and AGN bolometric luminosity:

$L_{bol}/M_{out} \sim 7.5\times10^{42}$ erg/s / $M_\odot$/yr

Menci model: $M_{out} \sim L_{bol}^{0.5}$

King model: $M_{out} \sim L_{bol}^{1/3}$

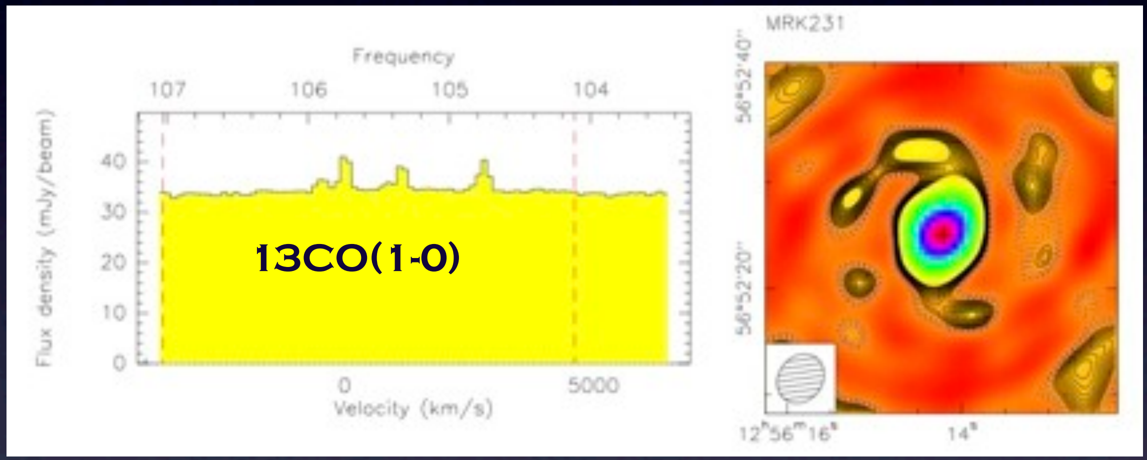


Conclusions

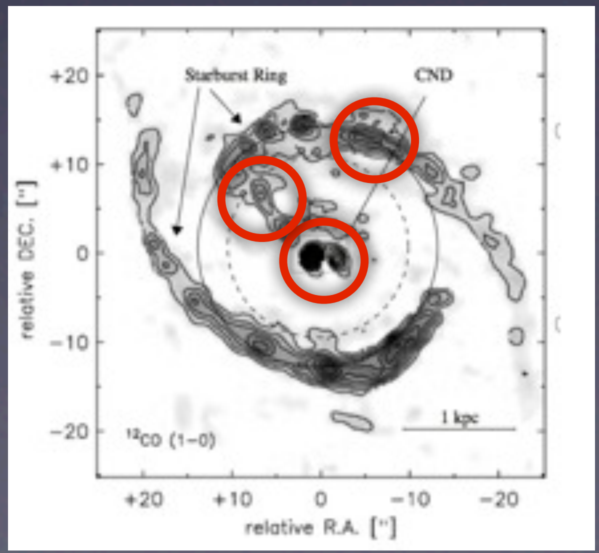
What we have learnt:

- ✳ Molecular outflows common in ULIRG/QSOs , massive & powerful
- ✳ High velocity suggests that the outflow is driven by AGN through shocks
- ✳ SLED of Mrk 231 do not support a shock scenario

What's next :



- Reliable **conversion factor from L(CO) to M(H2)** needed to measure the mass loss rate (for now we live with the one measured in M82 outflows)
- Detailed **morphological studies of the outflows**
- Assess whether the **outflow is driven by a shock or not**, to understand the **energy transport mechanism** from the nucleus to the disk, bref: the DRIVER.
- how is feedback correlated with L_{AGN}, obscuration? which link between the large NH seen in X-rays and the molecular gas in outflows?



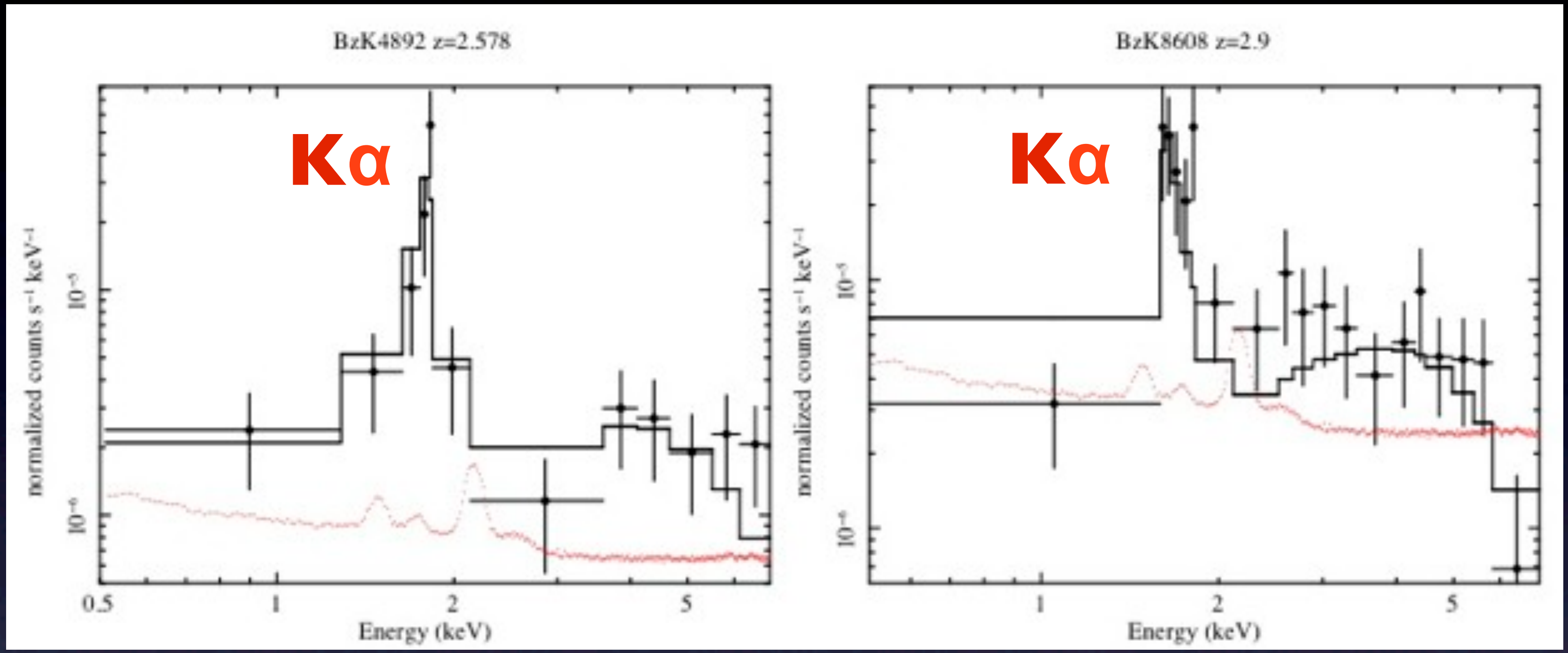
- Spatially resolved study of the heating mechanisms in the ISM of NGC1068.

-> Observations of N2H+ (HCO+, H13CO+, CO) can discriminate between X-ray- Cosmic Rays and shock excitation in circum-nuclear disk, bar, starburst ring (ASTROMOL team - IPAG)

What's next:

- **How common is AGN feedback at the peak of galaxy/AGN evolution, z=2-3? and beyond.**

In Compton-thick QSOs hosted in luminous IR galaxies



CO easily detectable with ALMA in these sources.

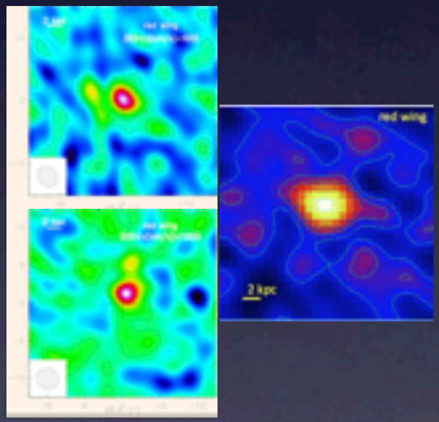
Observations done on CDFS with PdBI and EVLA yielded upper limits ...

- **In which phase of host/AGN evolution does AGN feedback start to be active and how long does the active phase last?**

Key Questions to answer

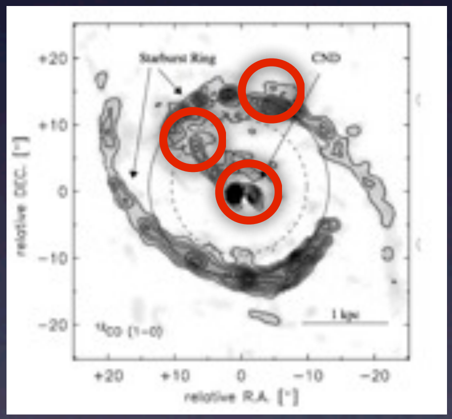
1. **origin of outflows (AGN, SF, both?) and expansion mechanism: morphology**
2. **What os the role of molecular outflows in the heating of the ISM compared to other mechanisms (CR, UV and X-ray fields)**
3. **What correlation between mass loss rate and AGN luminosity, obscuration, SFR?**
4. **Are molecular outflows common in galaxies/AGN in the peak phase of galaxy assembly and Accretion onto SMBH, z~ 2?**

Nearby galaxies: detailed morphological studies of molecular outflows
Statistics, correlations.

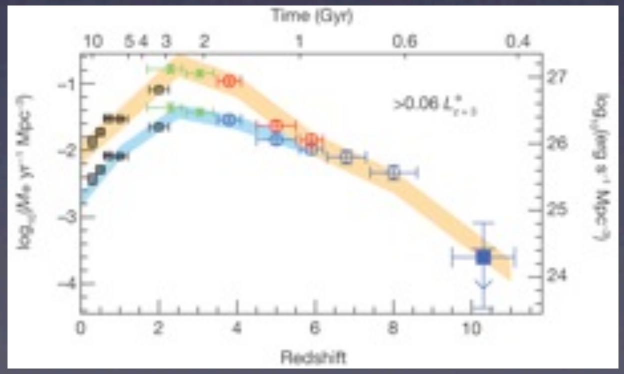


Studies complementary to one another

Etude du role des mecanismes de rechauffement du gas : outflow vs XR, CR, UV en galaxies proches (NGC1068)



Study molecular outflow at the peak of star formation and accretion activity: z ~2



Role of AGN in the transformation of their host galaxies