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A Radio Jet Drives a Molecular & Atomic Gas Outflow in Multiple Regions within 1 kpc^2 of the Nucleus of IC5063

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Background: AGN feedback & galaxy evolution

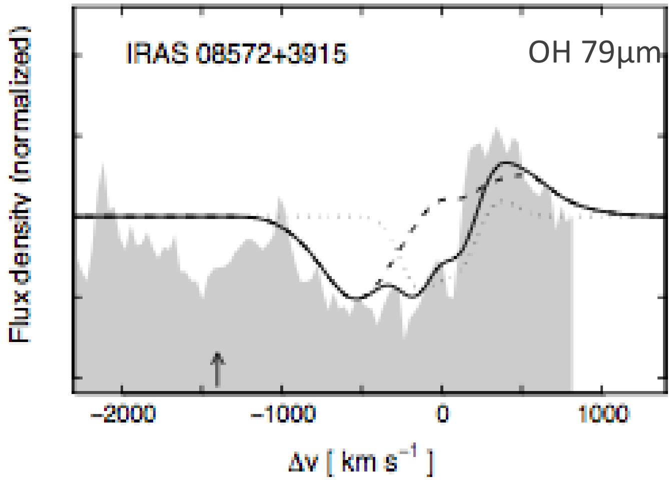
The importance of molecular outflows – why a focal point of the last years?

- *They concern star forming phase, and they can have high mass flow rates wrt ionized gas.*
  ($\dot{M}_{outflow} \sim M_{gas} U_{gas} / d$ – 10-1000$M_{\odot}$/yr – matter if accelerated to $V > V_{esc}$)

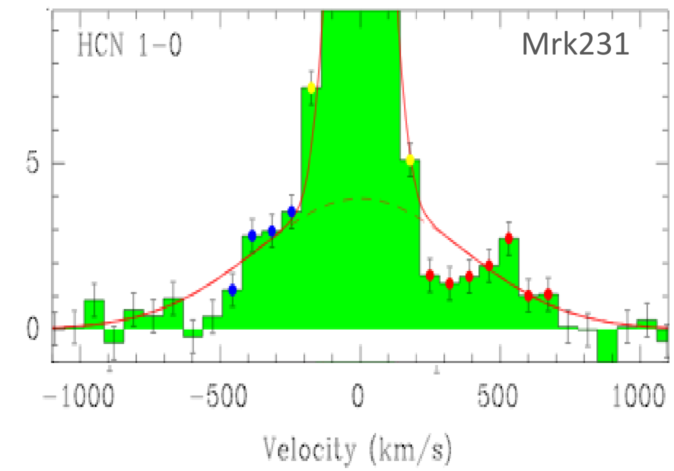
- *Direct detection of dense (typically >10^6 /cm^3) gas tracers suceeded in outflows.*

- *By now ~50 massive molecular outflows have been observed (Herschel, ALMA, PdB, ….)*
  Fischer et al. (2010); Feruglio et al. (2010); Sturm et al. (2011); Alatalo et al. (2011); Dasyra & Combes (2011) Aalto et al. (2012); Morganti et al. (2013), Veilleux et al. (2013); Spoon et al. (2013); Combes et al. 2013; Cicone et al. (2014); Garcia-Burillo et al. (2014); Sakamoto et al. (2014), Morganti et al. (2015)…

Sturm et al. (2011)



Aalto et al.(2012)



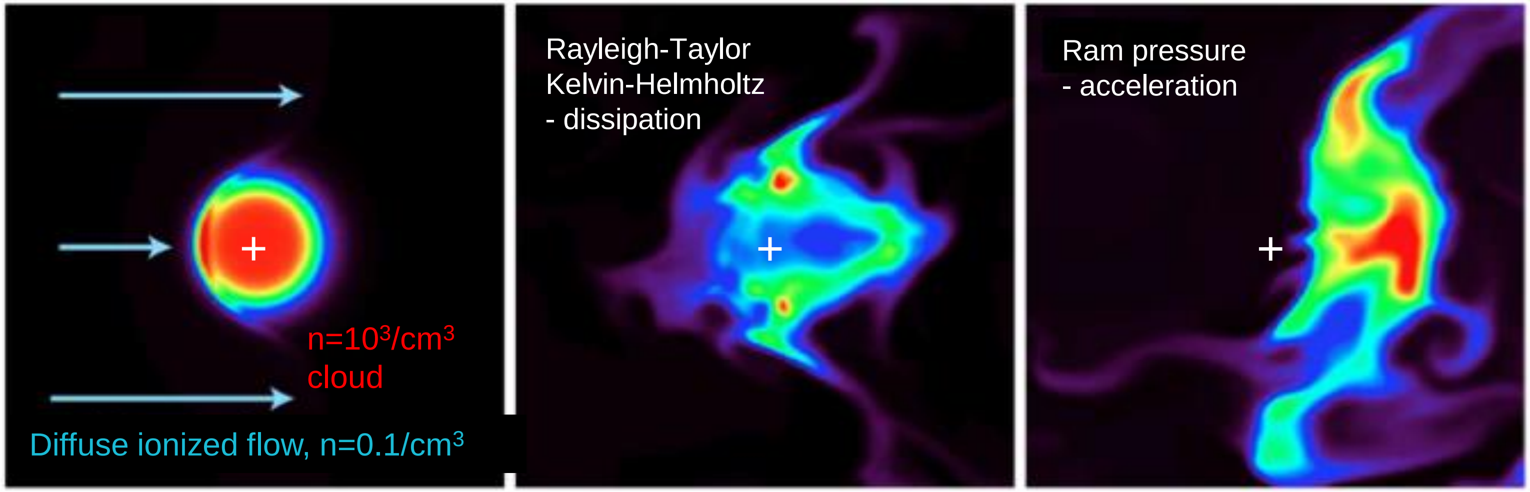
Background: AGN feedback & galaxy evolution

Observationally, massive outflows are common. How are they initiated?

Radiation pressure *drives a tenuous (ionized) gas wind around dense clumps in the galaxy.*
Ram pressure *assisted by hydro instabilities destroys &accelerates clouds (Hopkins & Elvis 2010).*
Cloud reformation *takes place fast in dense regions*

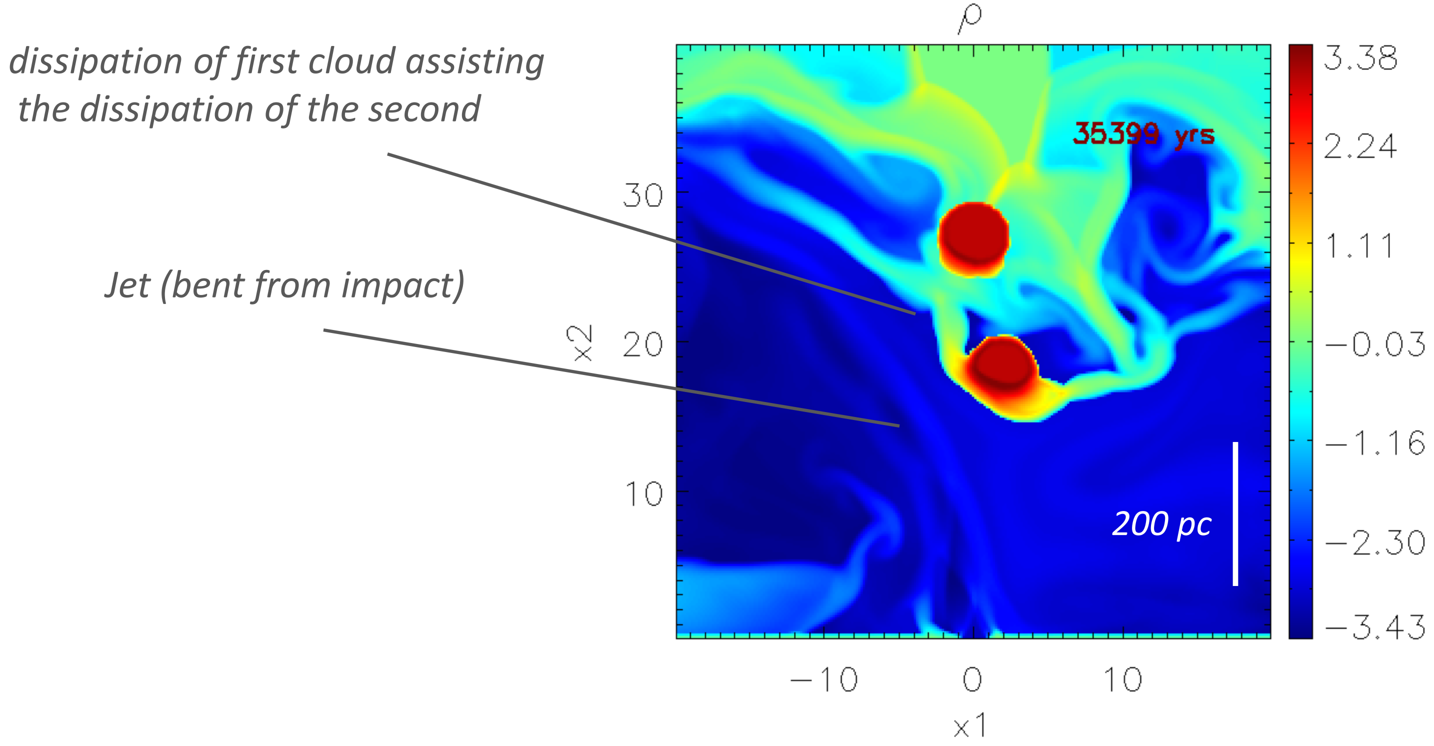
$$t_{\rm cool,mol} \sim 24 \left(\frac{T}{1.1\times10^4\,{\rm K}}\right)^2 R_{\rm kpc}^2\,\sigma_{200}^{-10/3}\ {\rm yr}$$ (Spitzer 1978)

Cascade effect *lead to mass loading.*



Observationally, massive outflows are common. How are they initiated?

Radio jets: *A similar acceleration path - propagation of a shock front, accumulation of gas in a cocoon, ram pressure, dense clump dissipation, molecular reformation, cascade effects.*

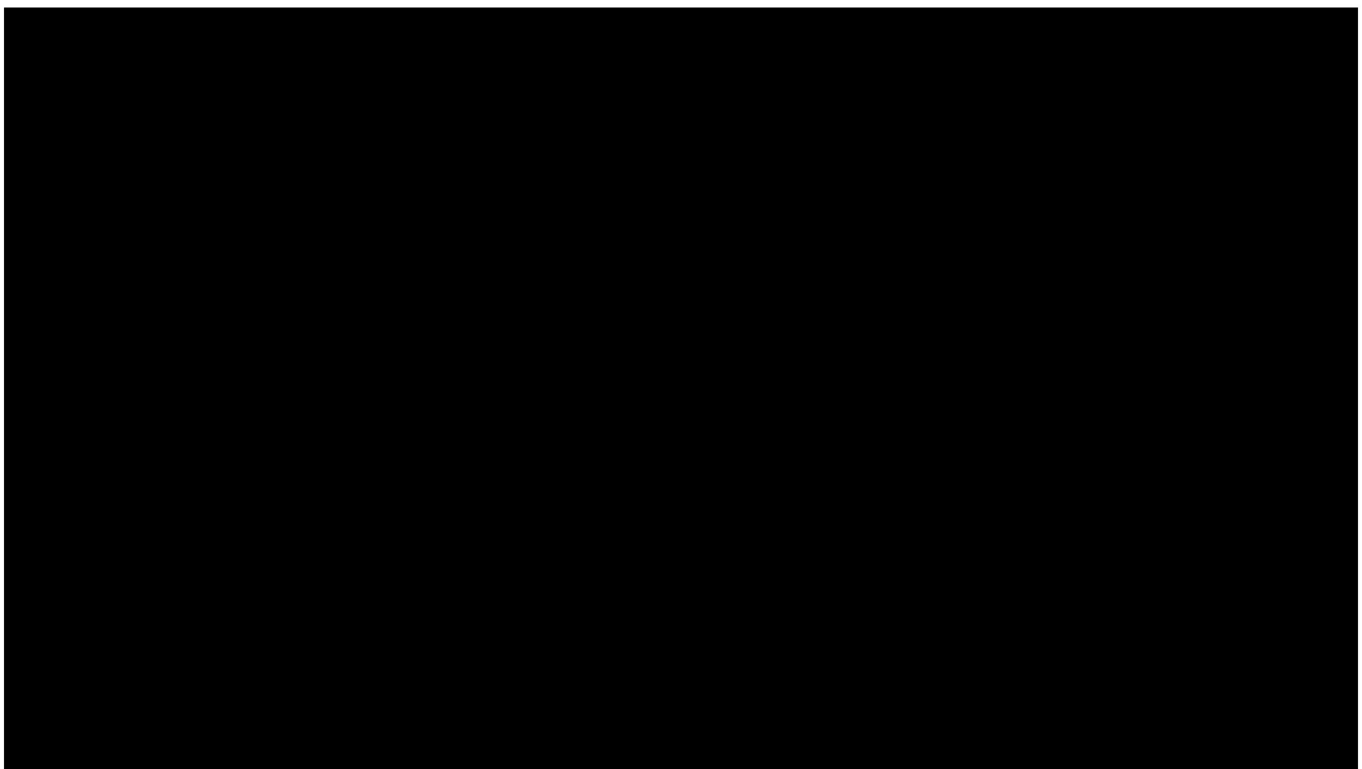


According to the 3D galaxy-wide HD simulations of Wagner et al. 2011, 2013:

jets can change the gas distribution in disks even at >500 pc in the direction perpendicular to the propagation despite their collimation.

-> of interest for high-z: at z~2-3, ~30% of ULIRGs are radio galaxies (Sajina+2011)

Goals: Is this true observationally? : Do we observe heating of the gas?



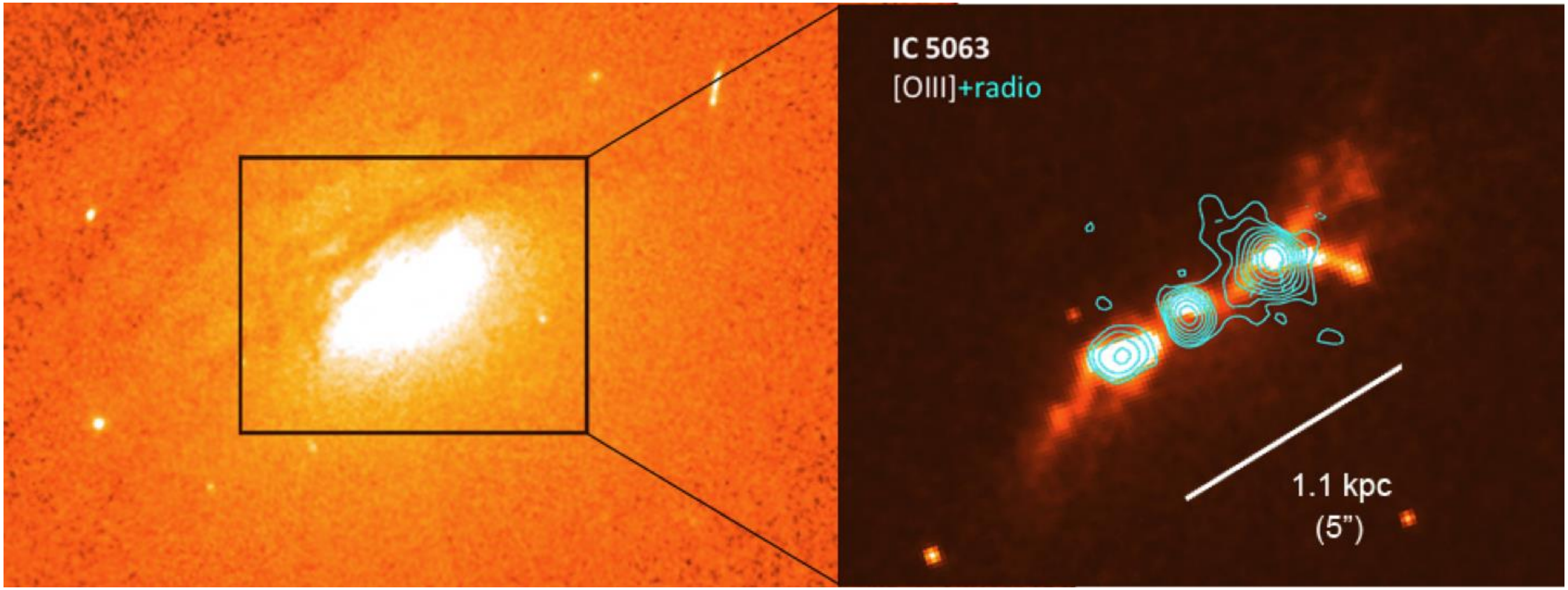
IC5063: gas acceleration & excitation by a radio jet

Observational evidence for a jet affecting the ISM at large scales in the elliptical IC5063:

(Morganti+2005,2007,2013,…)

(1) A radio jet almost aligned with a disk

(2) [OIII] emission along the jet trail, with highest emission at north & south radio lobes



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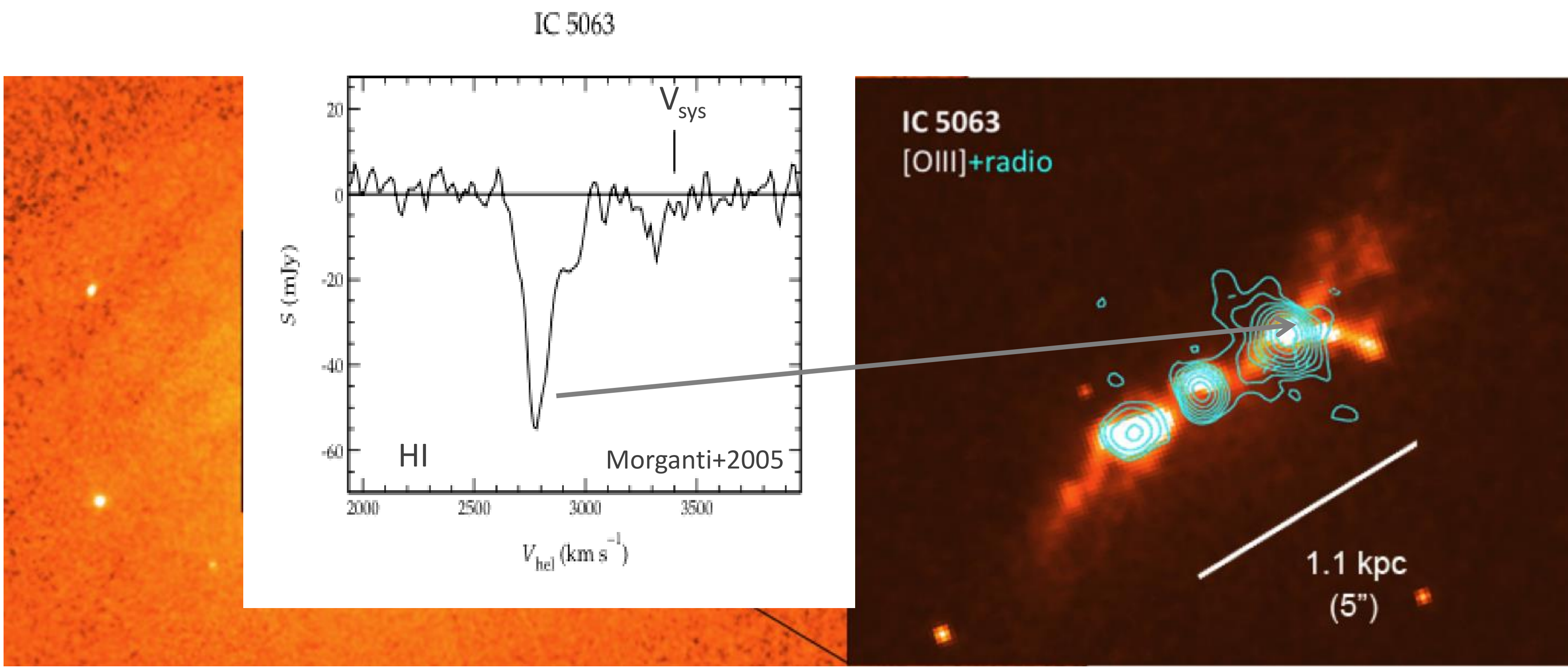

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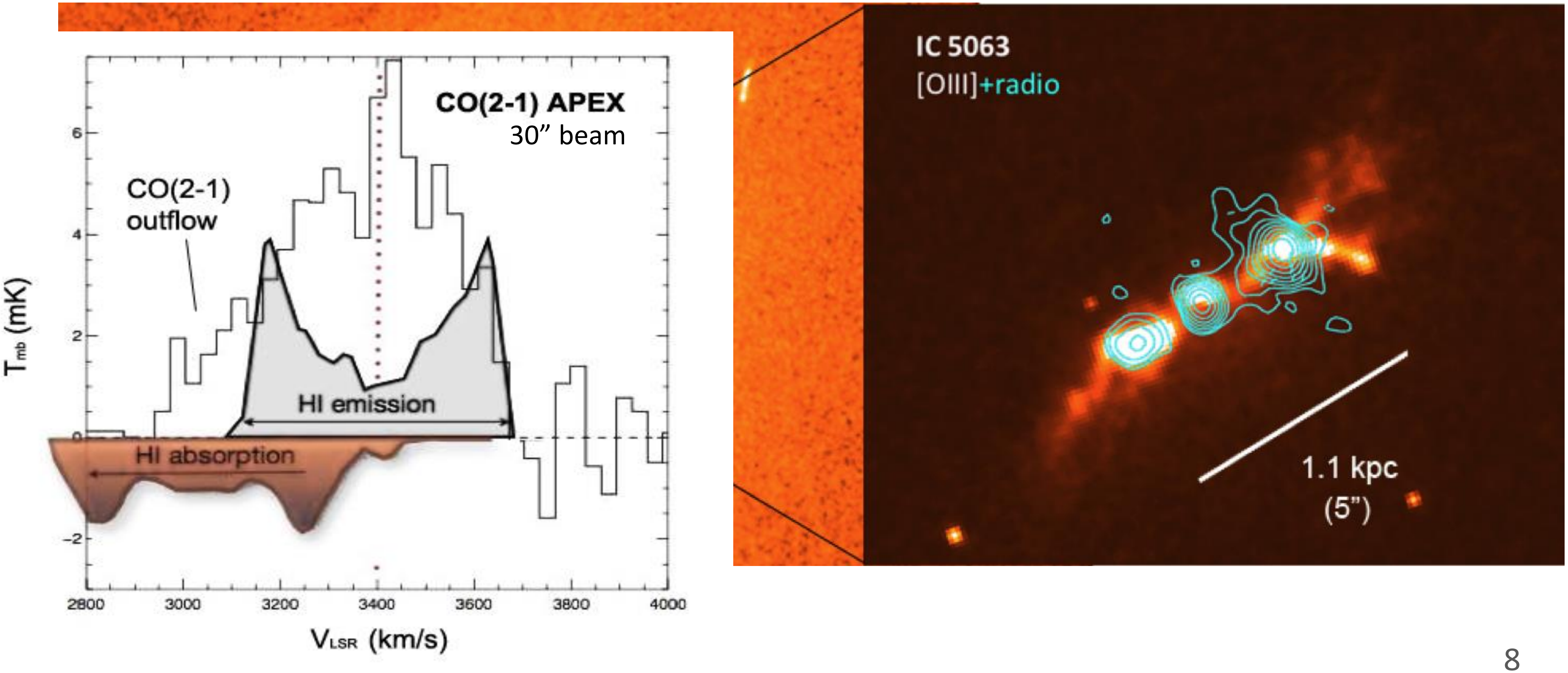
(3) HI absorption in front of the north lobe, -500 km/s wrt ordered motions
(4) A massive wind (of 10^7-10^8 $M_\odot$ in CO) with an H_2 counterpart in the NIR within central 2 kpc.

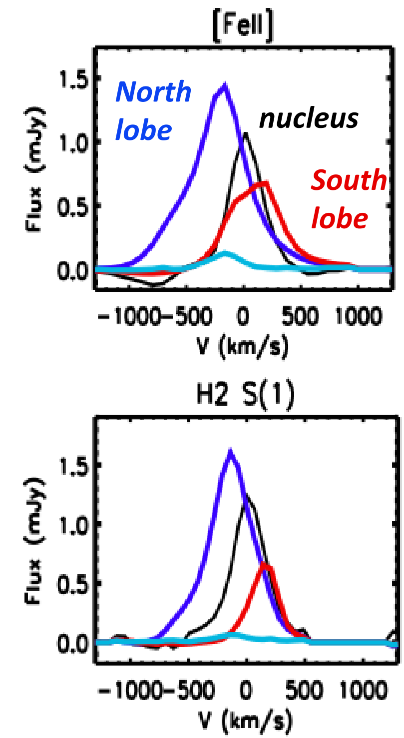


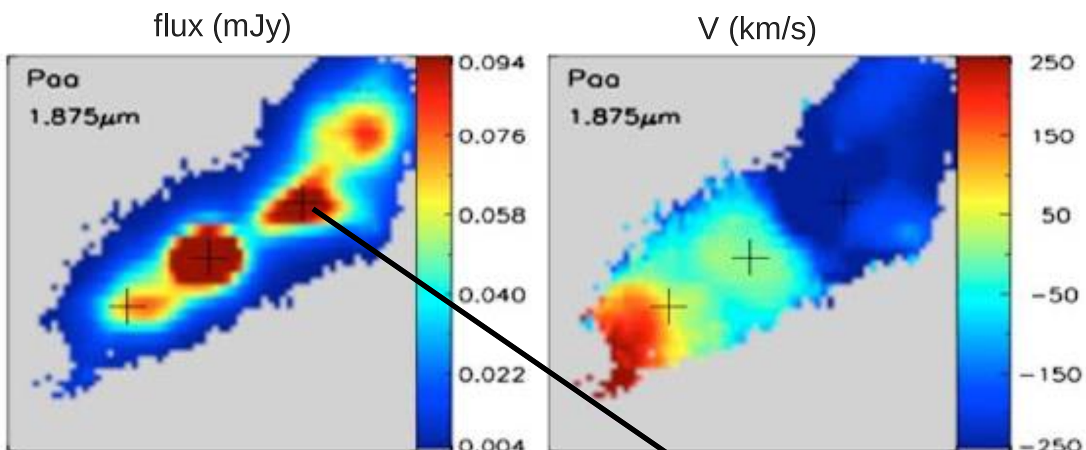
IC5063: gas acceleration & excitation by a radio jet

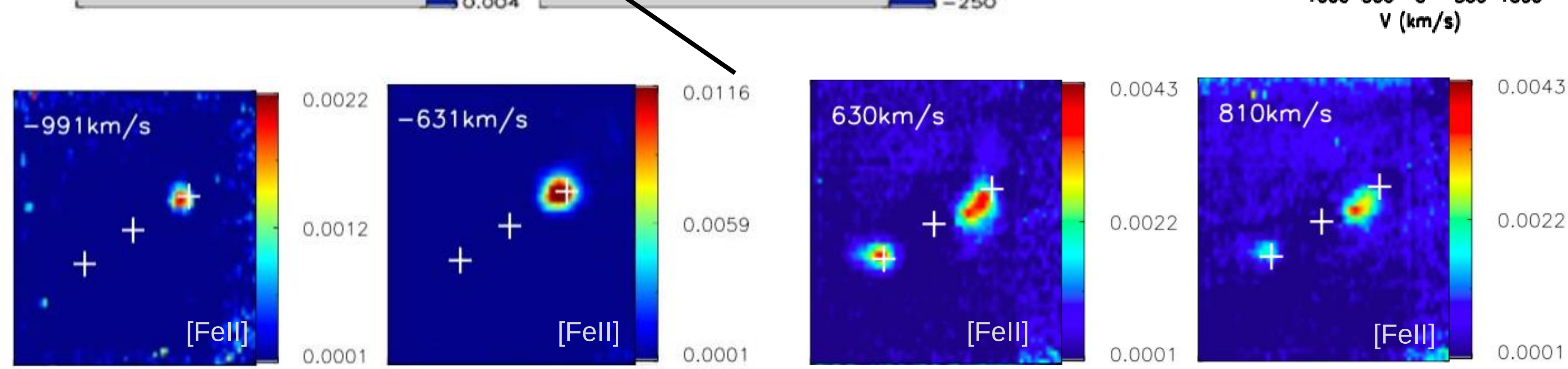
Our work: spatially-resolved gas acceleration & excitation study based on 4hr-long SINFONI data

(Dasyra et al. 2015, arXiv:1503.05484)

- ***At the lobes, velocities (>600 km/s or >V_{rot}+3σ), indicative of fast outflow.***
- *Gas moving at 1000 km/s against the disk is detected at the north lobe.*







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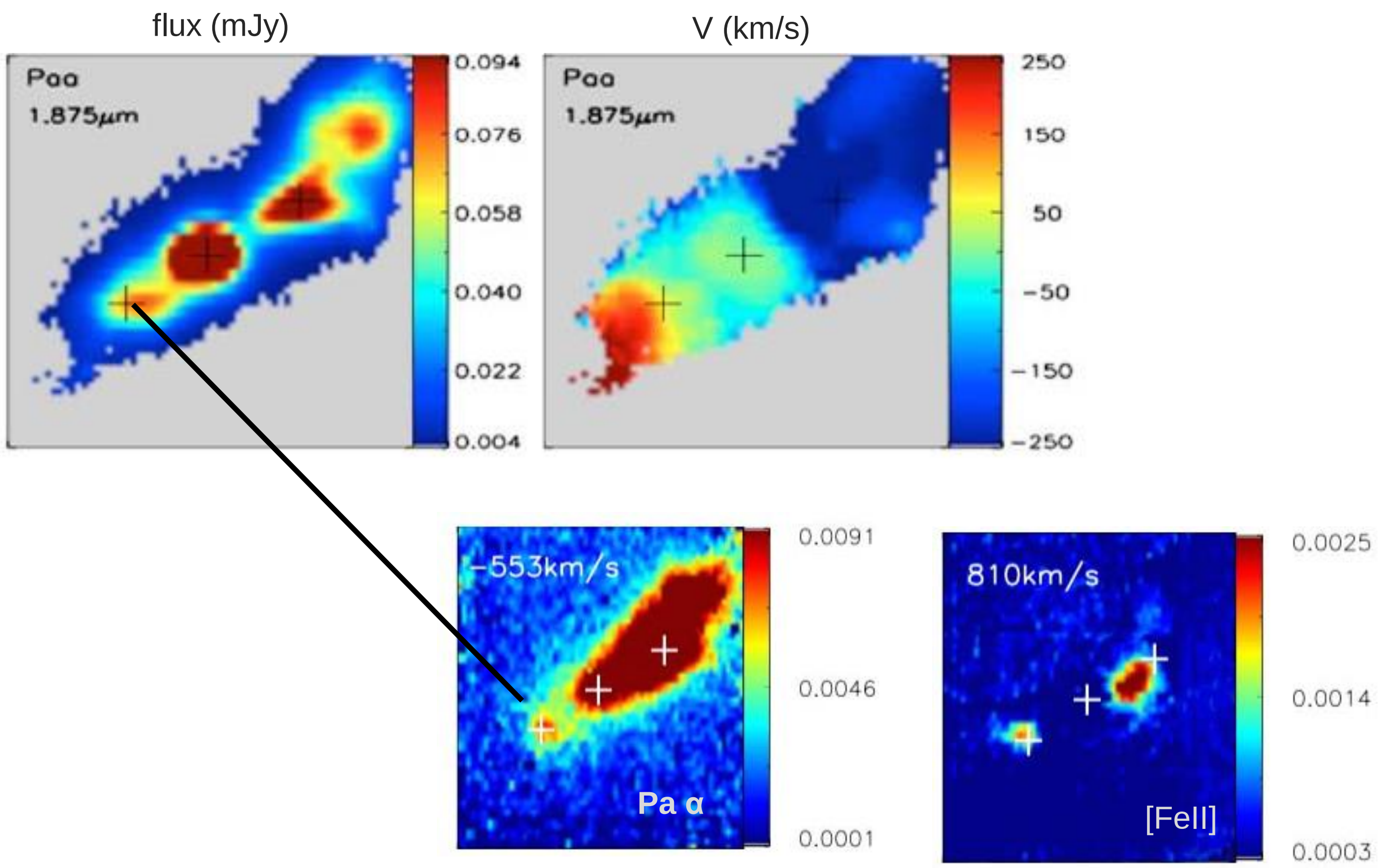
- *Gas moving at 1000 km/s against the disk is detected at the north lobe.*
- *High velocities also at the southern nucleus: result rules out merger remnant scenario*



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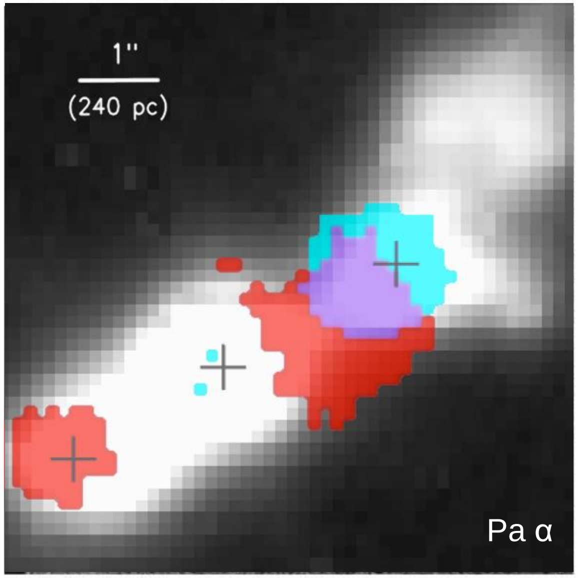
In the north, gas moving toward us is nearer to the hotspot than the gas moving away from us:

- Fast outflow has different directions near the jet-ISM impact point



fast outflow extent for all gas tracers
Cyan=blueshifted, Red=redshifted

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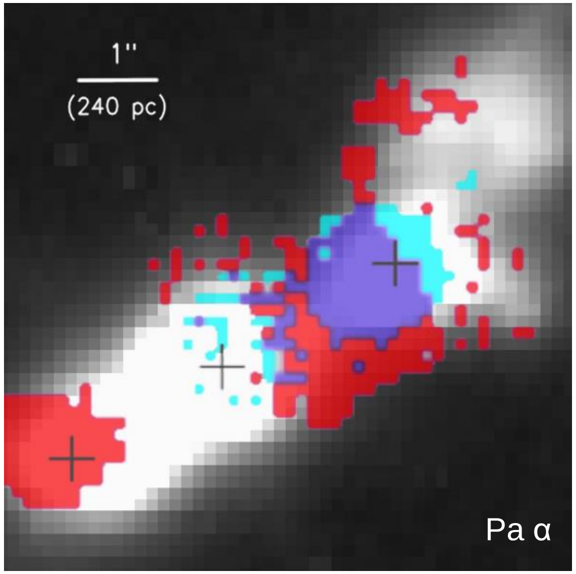
In the north, gas moving toward us is nearer to the hotspot than the gas moving away from us:

- Fast outflow has different directions near the jet-ISM impact point
- faint emission even along the northern-most branch:
(confirmed by significant detection at 200<V<400km/s)



fast outflow extent for all gas tracers
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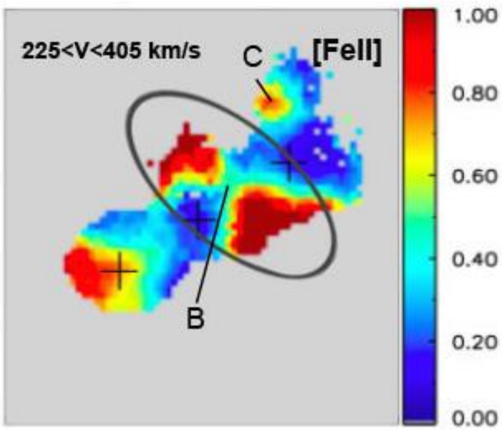
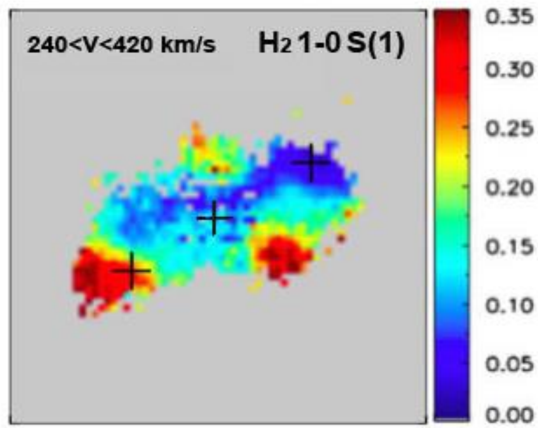
IC5063: gas acceleration & excitation by a radio jet

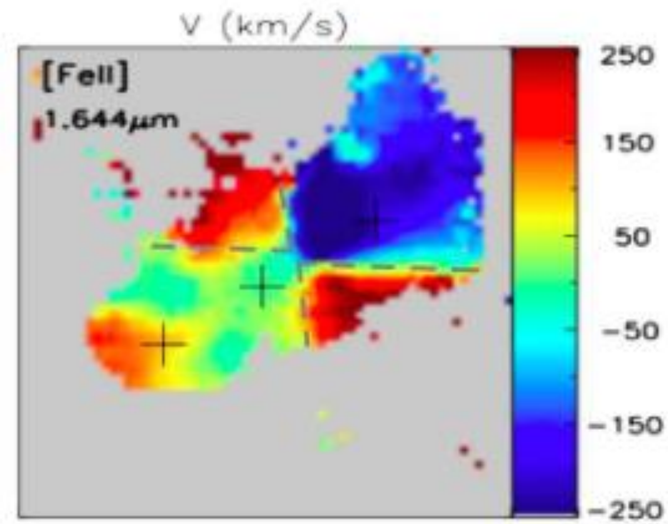
Most striking feature of gas moving at lower V against the disk is a diffuse biconical outflow that starts ~250pc from the nucleus.

$I_{outflow}/I_{ambient}$:





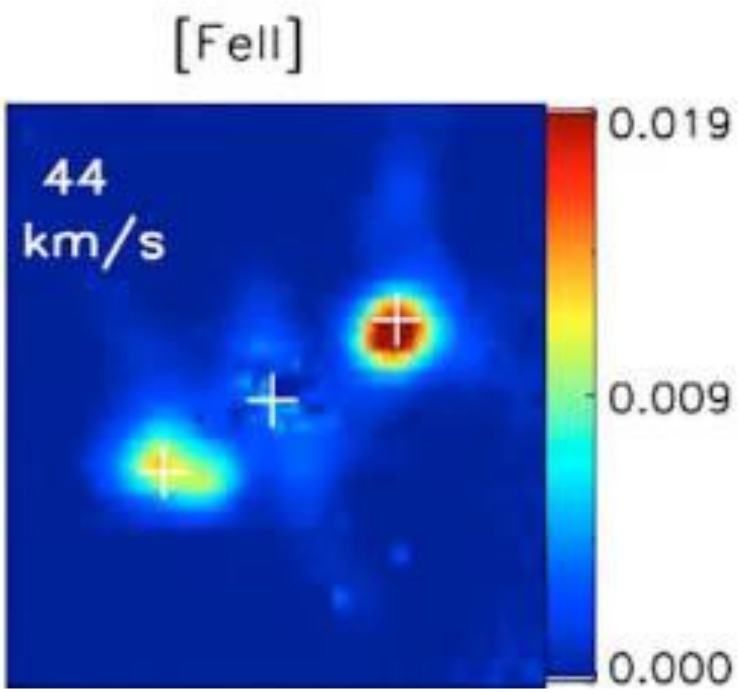
Its geometry is not consistent with an AGN/SB driving it:
Jet can lead to redshifted emission both N/S of the disk.

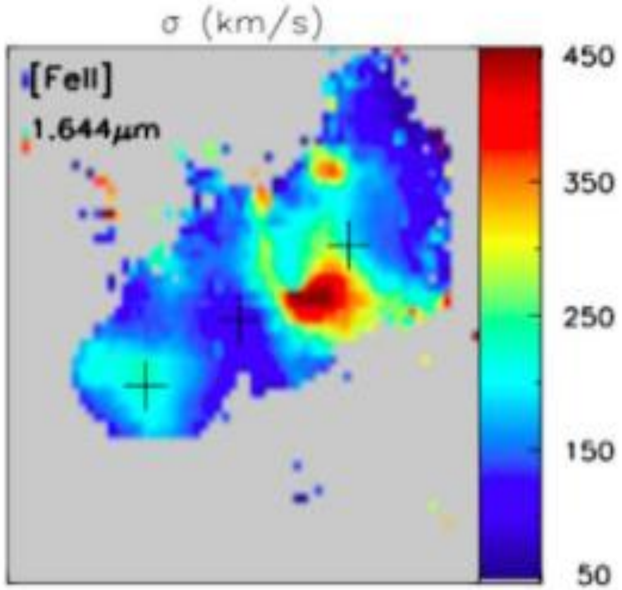


IC5063: gas acceleration & excitation by a radio jet

[FeII] and H_2 emission unfolds away from the nucleus & around the jet trail with increasing V.

stops in the north – in a region where we see a high-σ ridge.





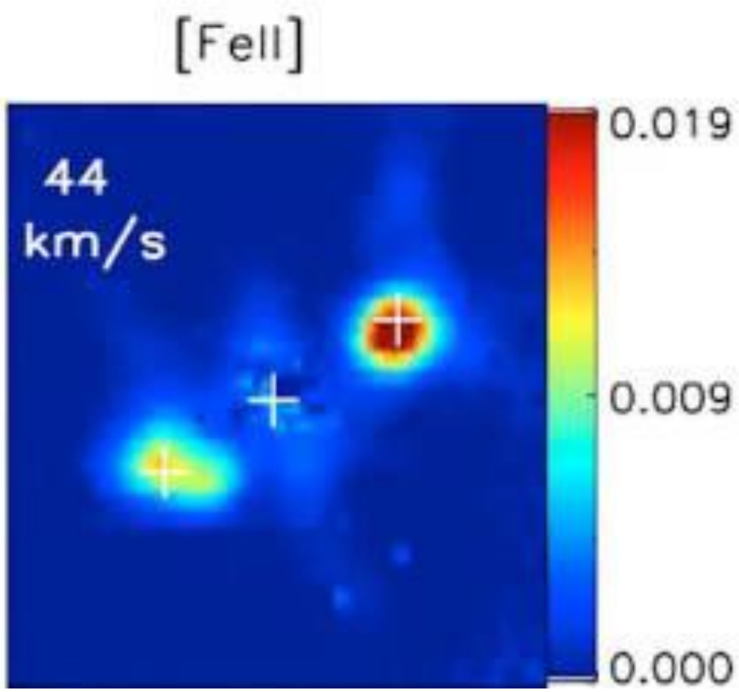
H2 (1-0) S(3)

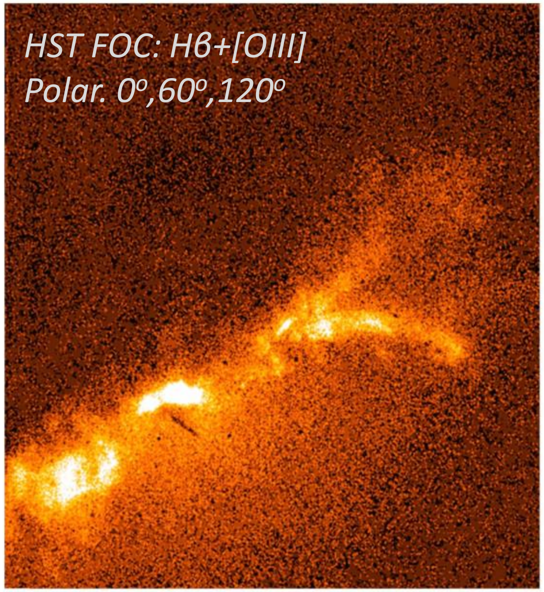
IC5063: gas acceleration & excitation by a radio jet

[FeII] and H_2 emission unfolds away from the nucleus & around the jet trail with increasing V.

stops in the north – north of the Hb+[OIIII] ridge perpendicularly to the jet trail

-> we are associating an outflow with that perpendicular branch deviating from jet trail <-



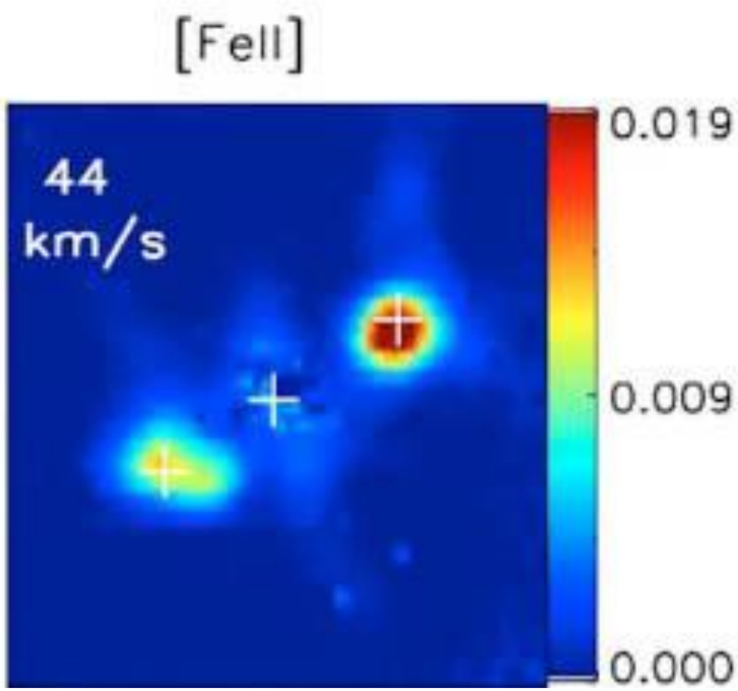


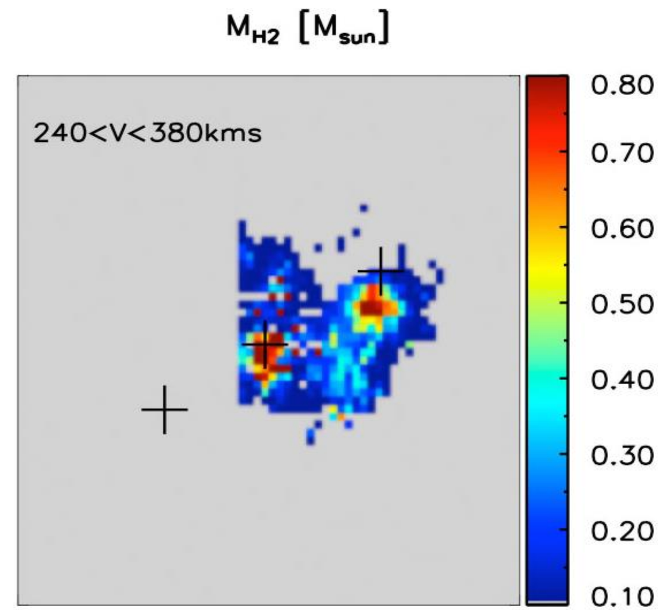
High-resolution (~10pc) ionized gas data

H2 (1-0) S(3)

[FeII] and H_2 emission unfolds away from the nucleus & around the jet trail with increasing V.

Diffuse outflowing H_2 gas mass is highest there - computed from H2 (1-0) S(1) and S(3).





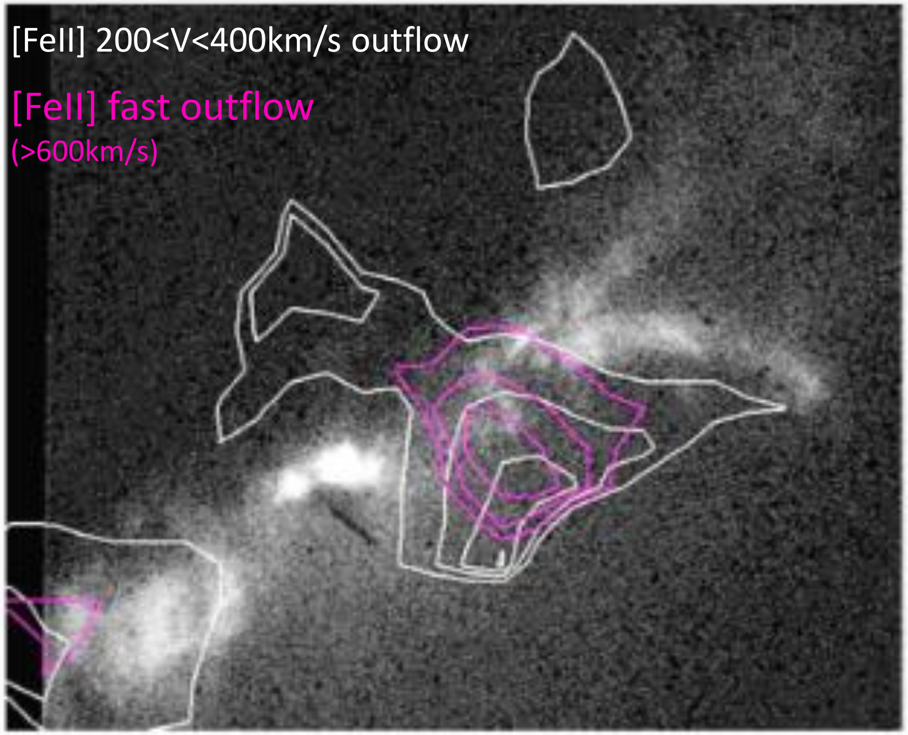
Gas scattering:

-> The diffuse/biconical outflow probes a wind created by the cocoon expansion & mass loading OR scattered gas from the dense clouds upon impact of the jet (Dasyra et al. 2015, submitted)

IC5063: gas acceleration & excitation by a radio jet

Overall model: Jet passing through disk, at a small angle.
It consecutively encounters several ISM clouds, driving an outflow in (at least) 4 points.

Overall, an outflow is found in >700pc in each direction (perpendicular & parallel to the jet).
The effects of the jet passage on the gas kinematics are galaxy-wide, as in the simulations.



IC5063: gas acceleration & excitation by a radio jet

Properties of the accelerated gas at different phases:

- Spatial distribution, V are highest for ionized gas, yet comparable for the warm H_2 & [FeII]

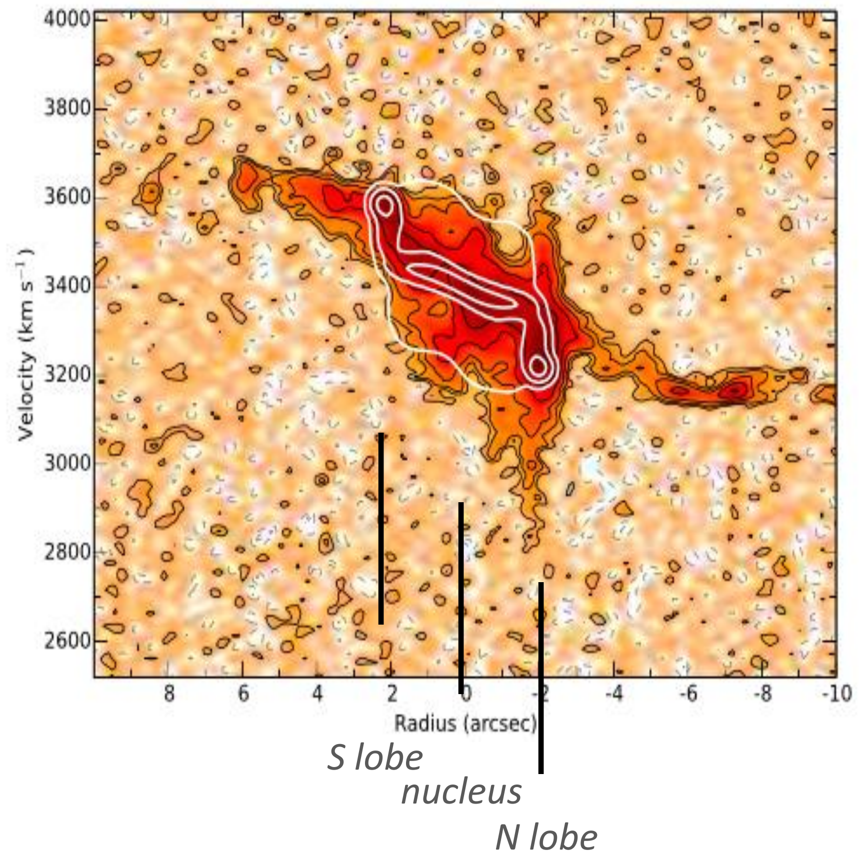
ALMA CO(2-1) data:

the cold H_2 outflow velocity is 2-4 times lower

(No info on the spatial distribution of diffuse gas)

Morganti et al. (2015)

Major axis position-V diagram

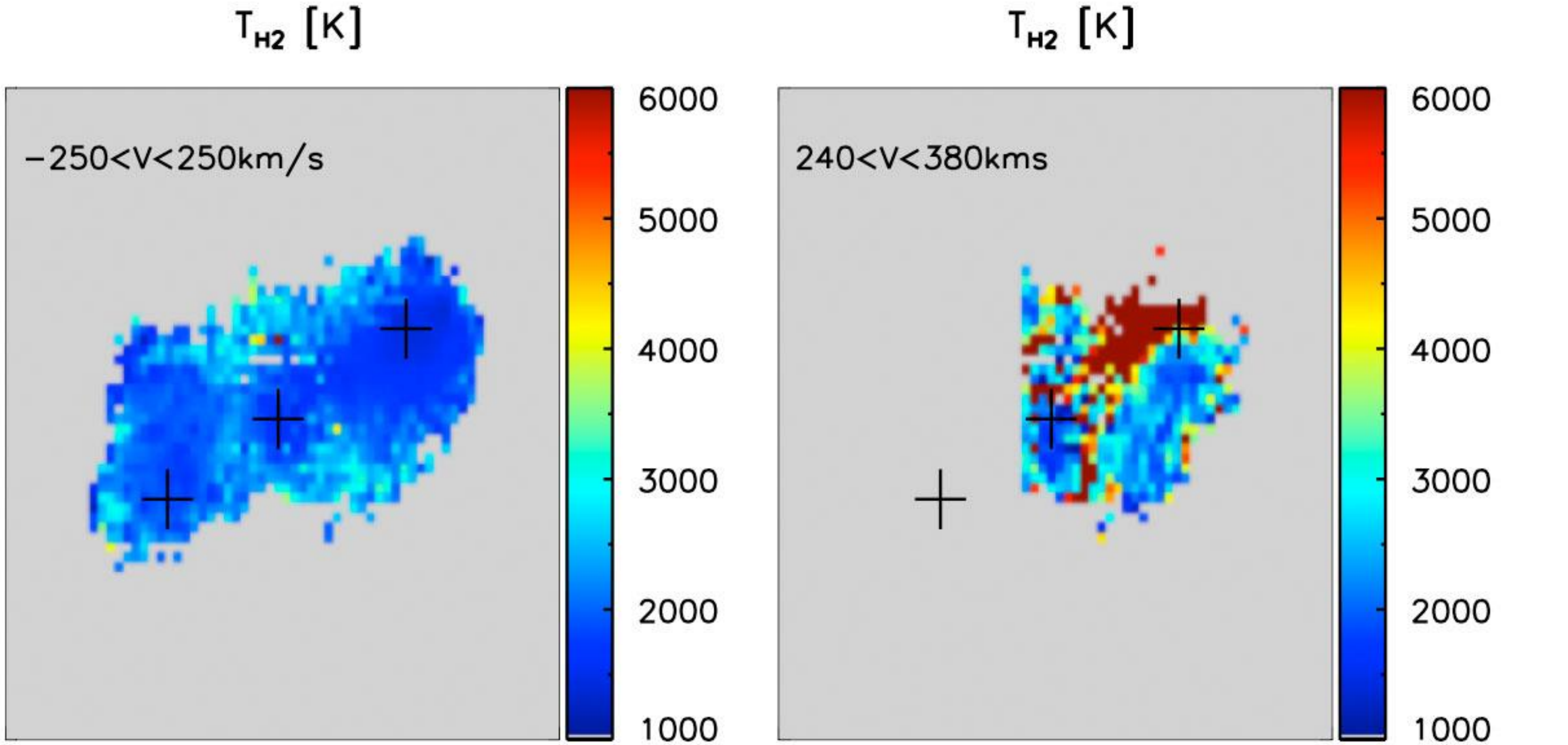


IC5063: gas acceleration & excitation by a radio jet

***Excitation of the molecular gas**: temperature maps assuming LTE*

Along the north side of the jet, H_2 (1-0) S(3)/S(1) flux ratio exceeds maximum value for LTE
-> fluorescence (+heating) *(Dasyra et al. 2015, arXiv:1503.05484)*

Dust at north radio lobe hotter than at nucleus (Young+07)



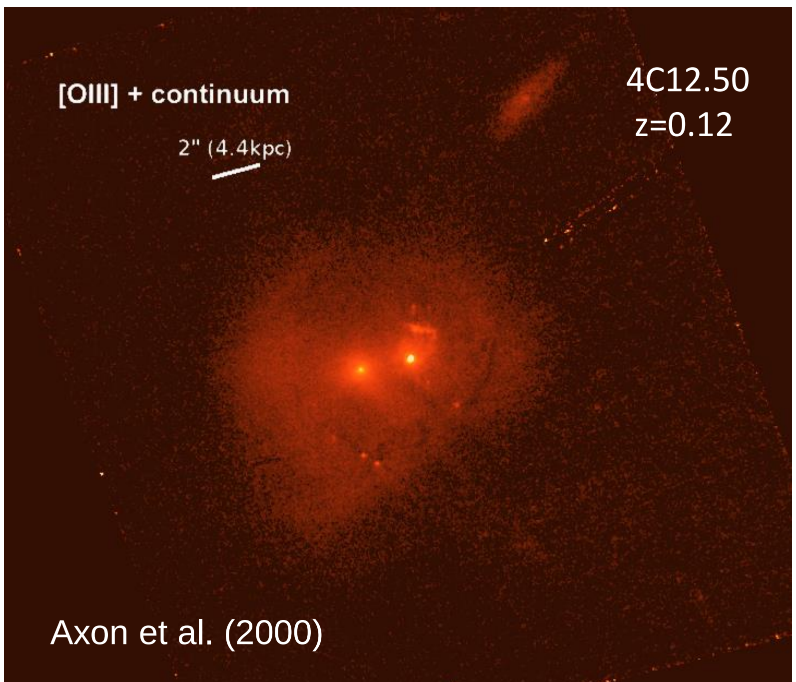
4C12.50: acceleration & heating of the molecular gas

Another example of gas excitation attributed to a radio jet.

Radio-loud galaxy 4C12.50 / IRAS 13451+1232:

Outflow & regular emission seen in MIR lines H_2 (0-0) S(1) and S(2) in Spitzer Space Telescope data.
***Outflow carrying 1/3rd of the warm ambient gas, with** $M_{outflow}(400K)=5*10^7\ M_\odot$*

(Dasyra & Combes 2011)



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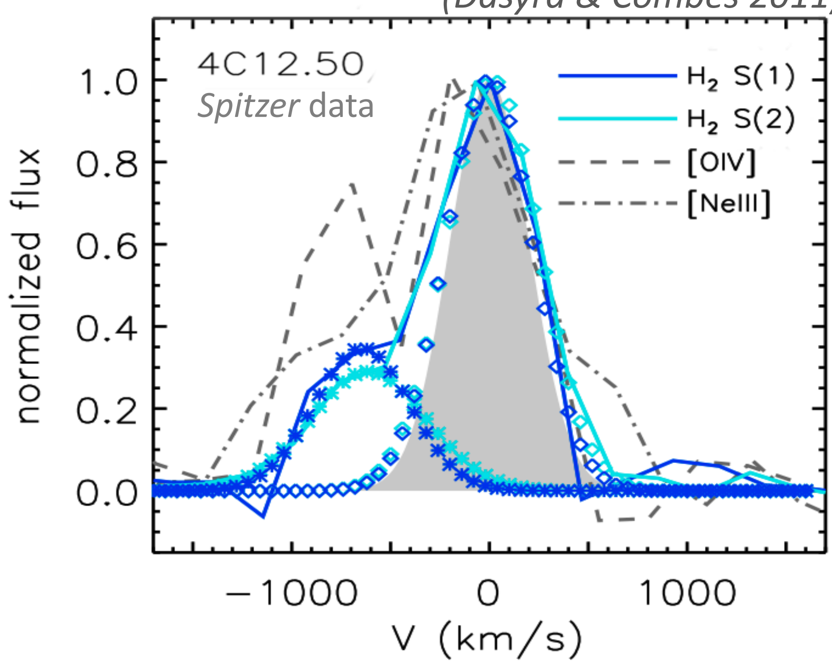


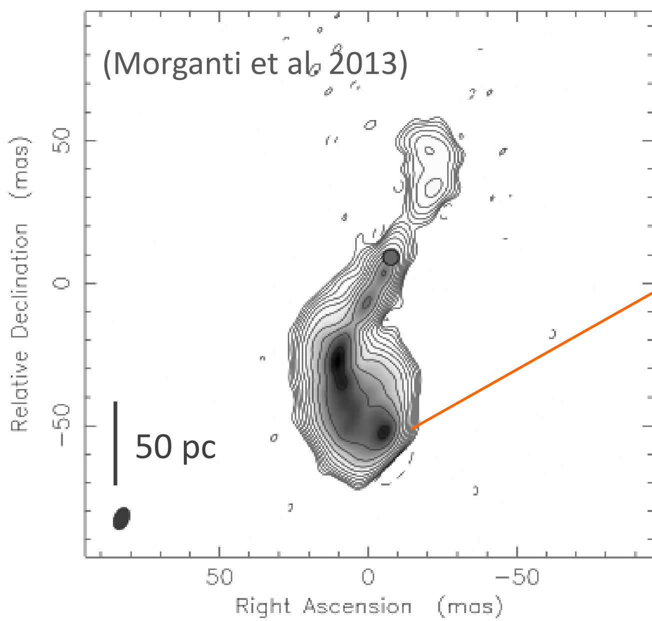
4C12.50: acceleration & heating of the molecular gas

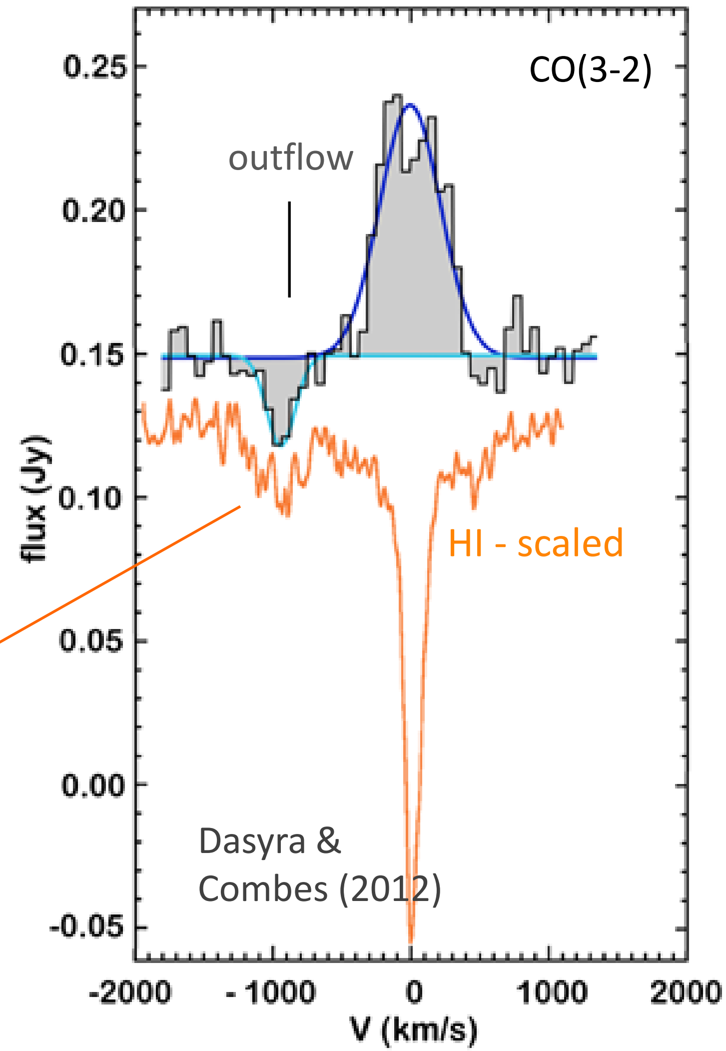
The cold molecular gas in the outflow was seen in absorption, **in CO(2-3), at -1000 km/s**

absorption probes few LOS – total mass from emission limit from PdB data: $\mathbf{M_{out} < 1.3 \times 10^{8}\, M_{\odot}}$

Dasyra et al. (2012; 2014)

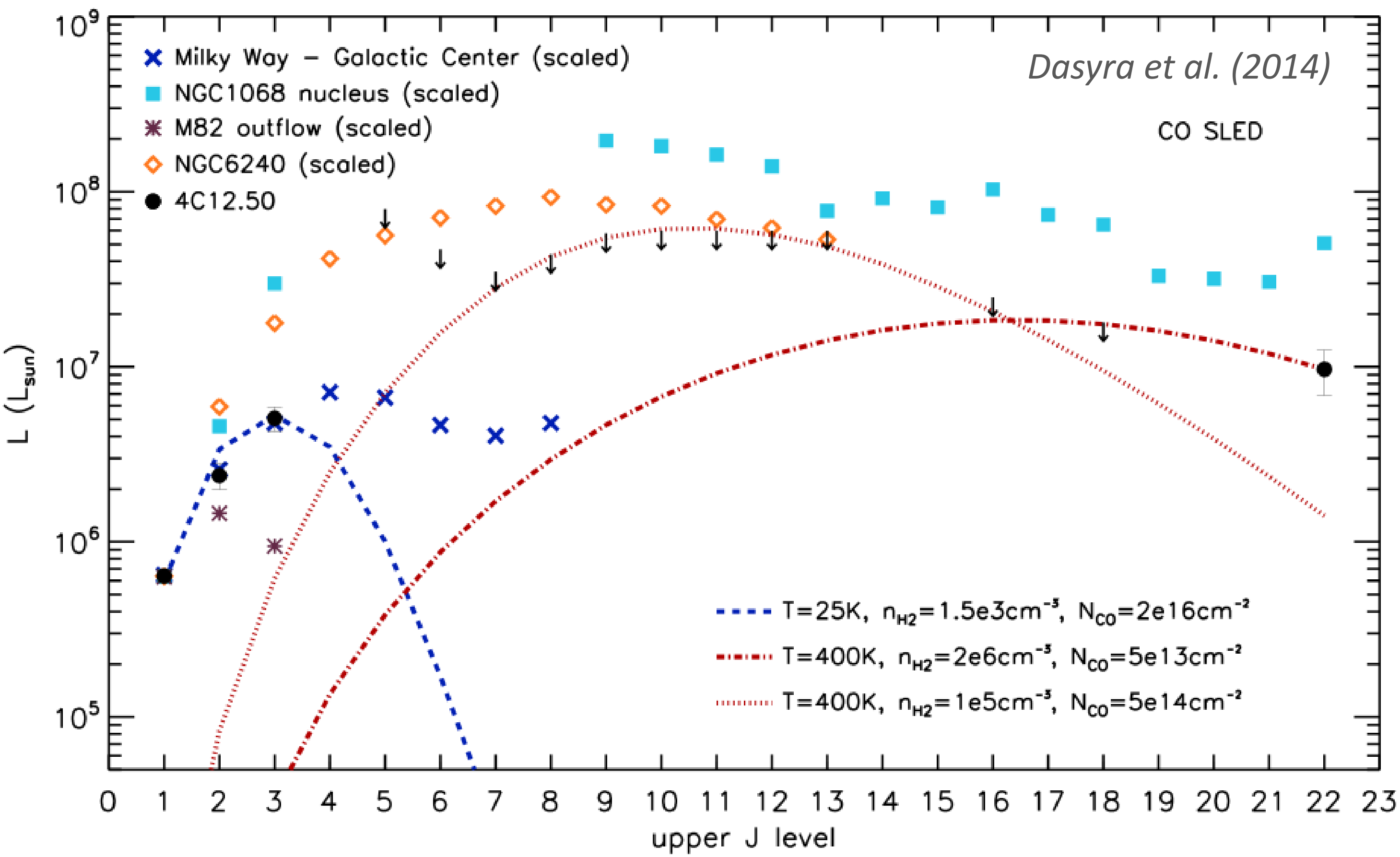
$$\frac{M_{400K}}{M_{25K}}\ \text{(outflow)} > 30\ \frac{M_{400K}}{M_{25K}}\ \text{(ambient)}$$





4C12.50: acceleration & heating of the molecular gas

- *Heating & fluorescence are again likely to be taking place*
- *They could lead to a highly excited CO SLED that could facilitate the discovery at high z.*



The future of the field: ALMA

Massive outflows and galaxy evolution - exciting times ahead of us:

- *ALMA will lower the detection limit to $5x10^5 M_\odot$ in the local Universe & to the PdB limit at z~1*
- *Archive now built.*

Detection limits:

	line	T (K)	M ($M_\odot$)	
PdB	CO(1-0)	10	5×10^7	
ALMA	**CO(1-0)**	**10**	5×10^5	*z=0.025*
JWST	**H_2 S(1)**	**100**	5×10^5	*(d=100 Mpc)*
ALMA	**CO(2-1)**	**10**	$\sim10^8$	*Z~1*