Probing the gas fuelling and outflows in nearby AGN with ALMA

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AGN Feedback

How the energy generated by the AGN can regulate its gas accretion?

Quasar mode

- Through radiative processes or winds
- AGN luminosity is high, close to the Eddington luminosity L_{Edd}
- High z, young QSOs

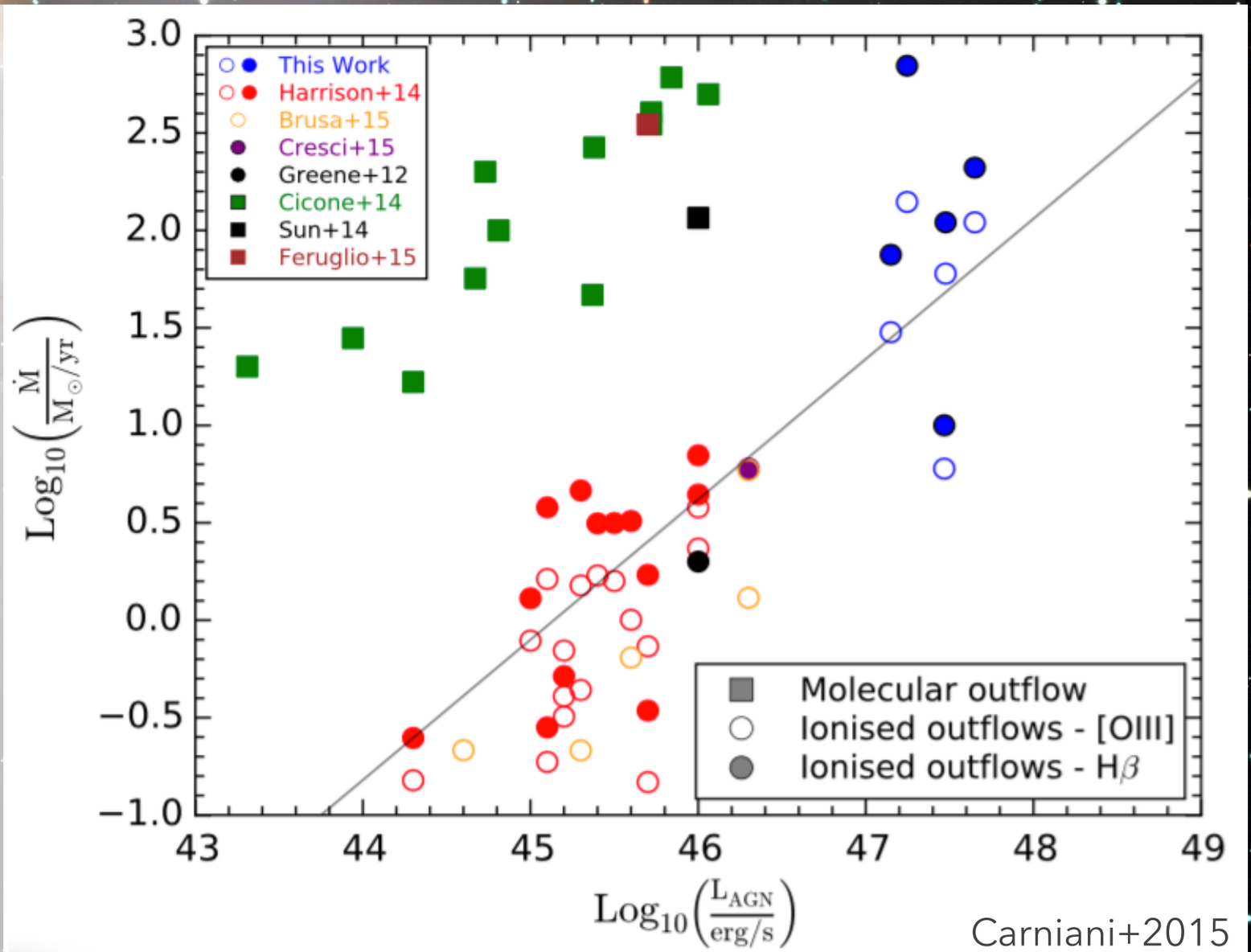
Radio mode

- (kinetic mode) with radio jets, occurring mainly in low-luminosity AGN (LLAGN)
- Appears to maintain the balance between cooling and heating
- Low z massive galaxies

Observations of Outflows

far-IR - Herschel (eg., Sturm et al., 2011; Veilleux et al., 2013) & mm-wave with IRAM and ALMA (Combes et al., 2013, García-Burillo et al., 2014, Dasyra & Combes 2012, Morganti et al. 2013, Cicone et al. 2014)

Detected as broad wings or as residuals along or near the minor axis



Carniani+2015

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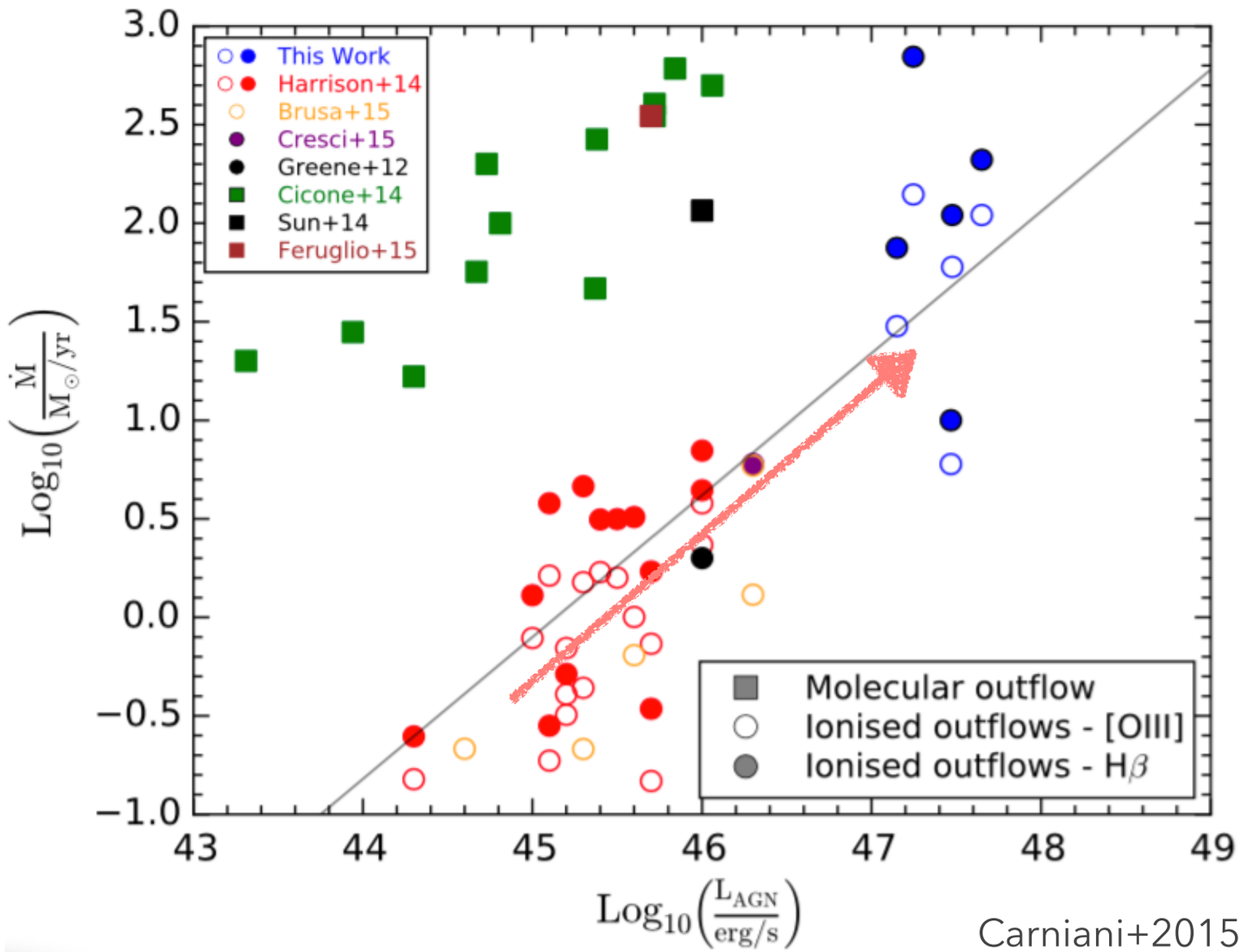

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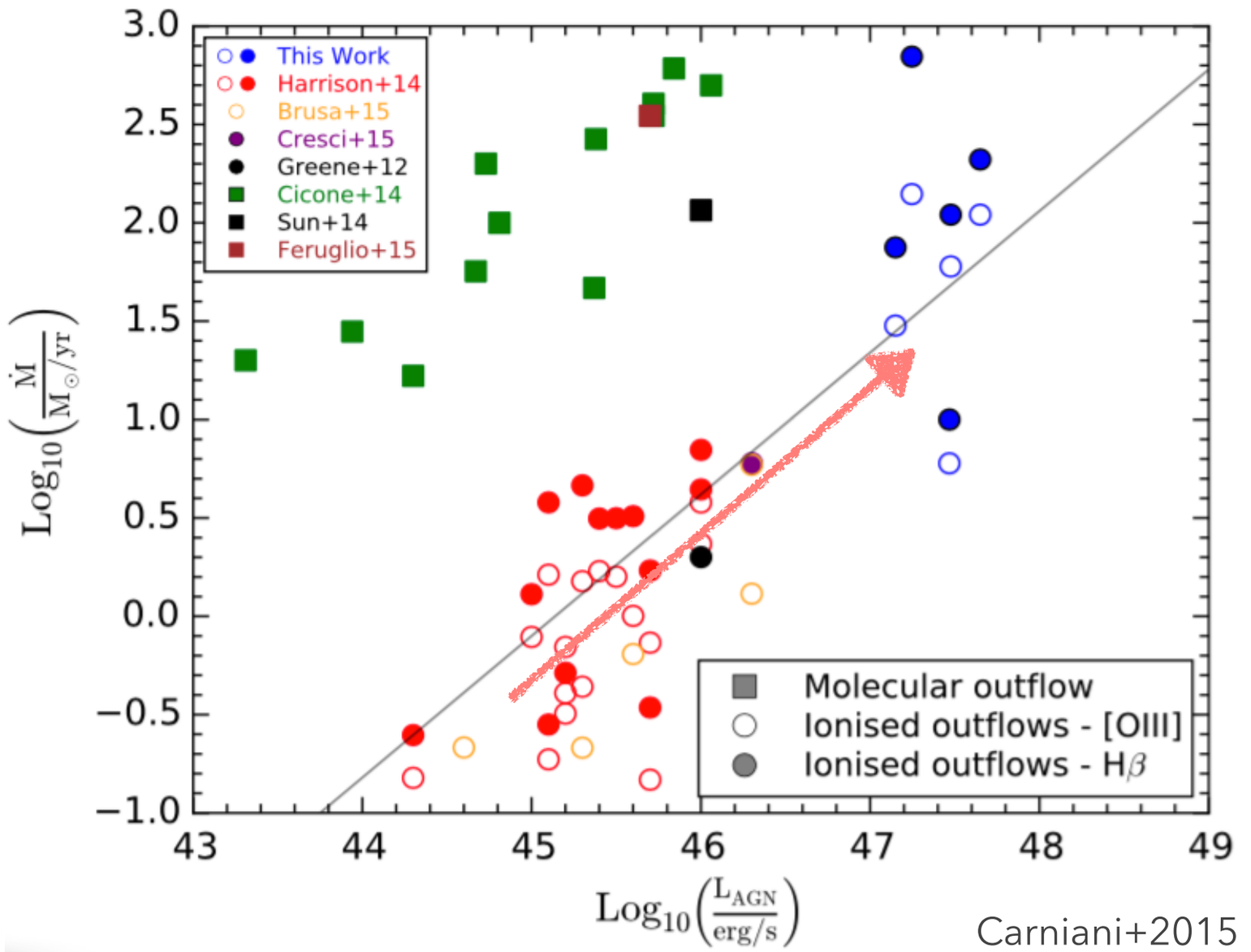
AGN pushes away the gas through a radiatively driven fast wind

$\dot{E}_{out} \sim 5\% L_{AGN}$



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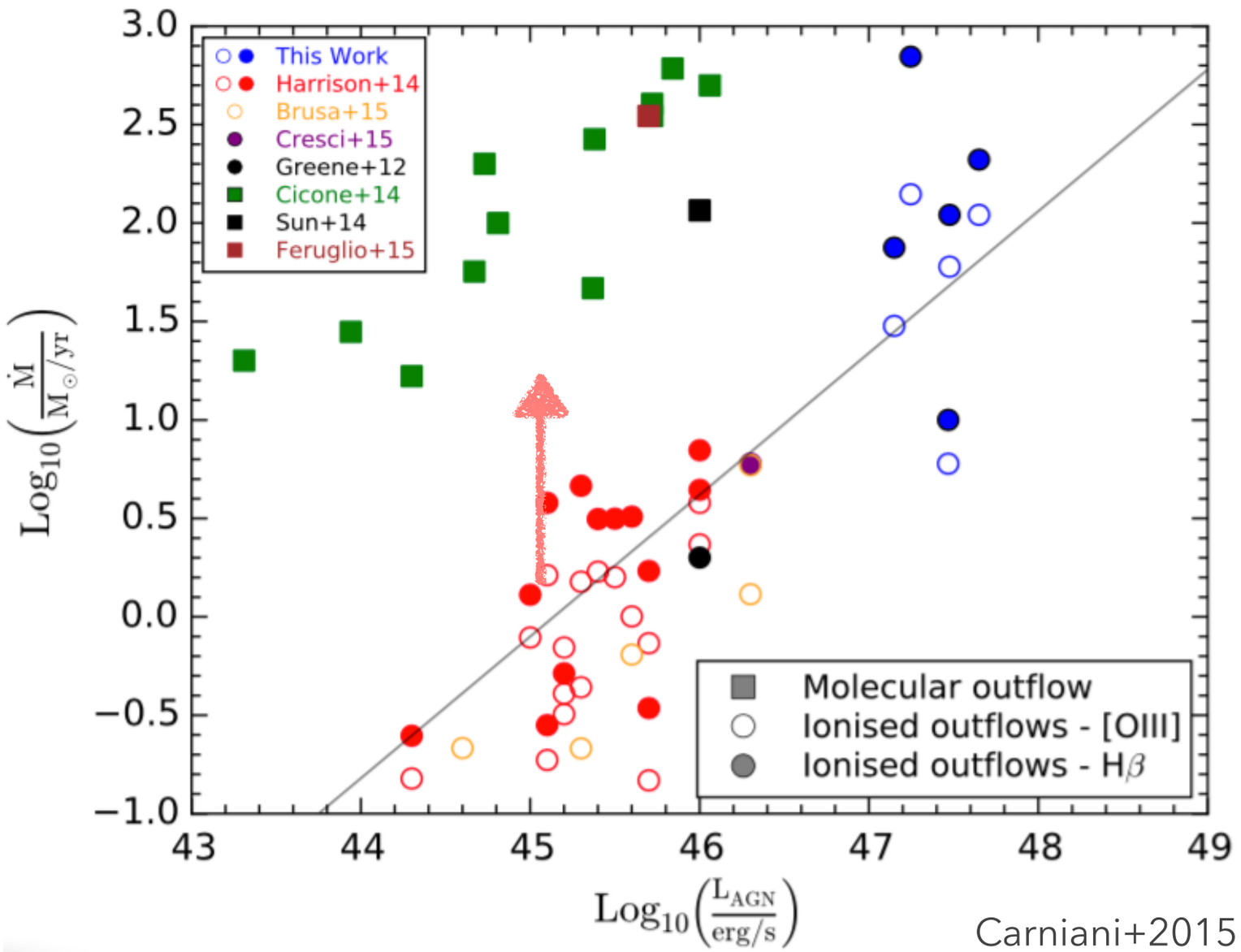

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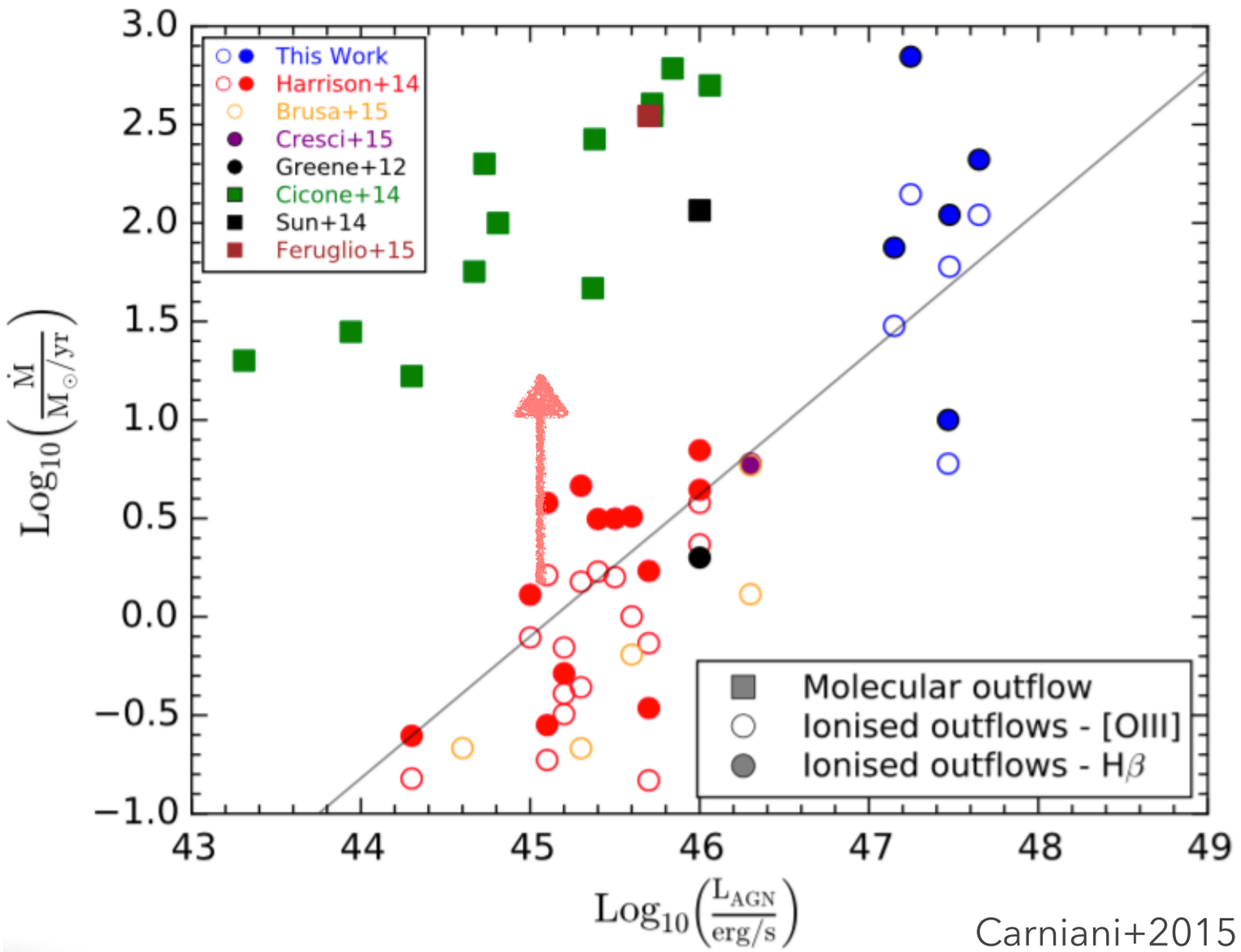

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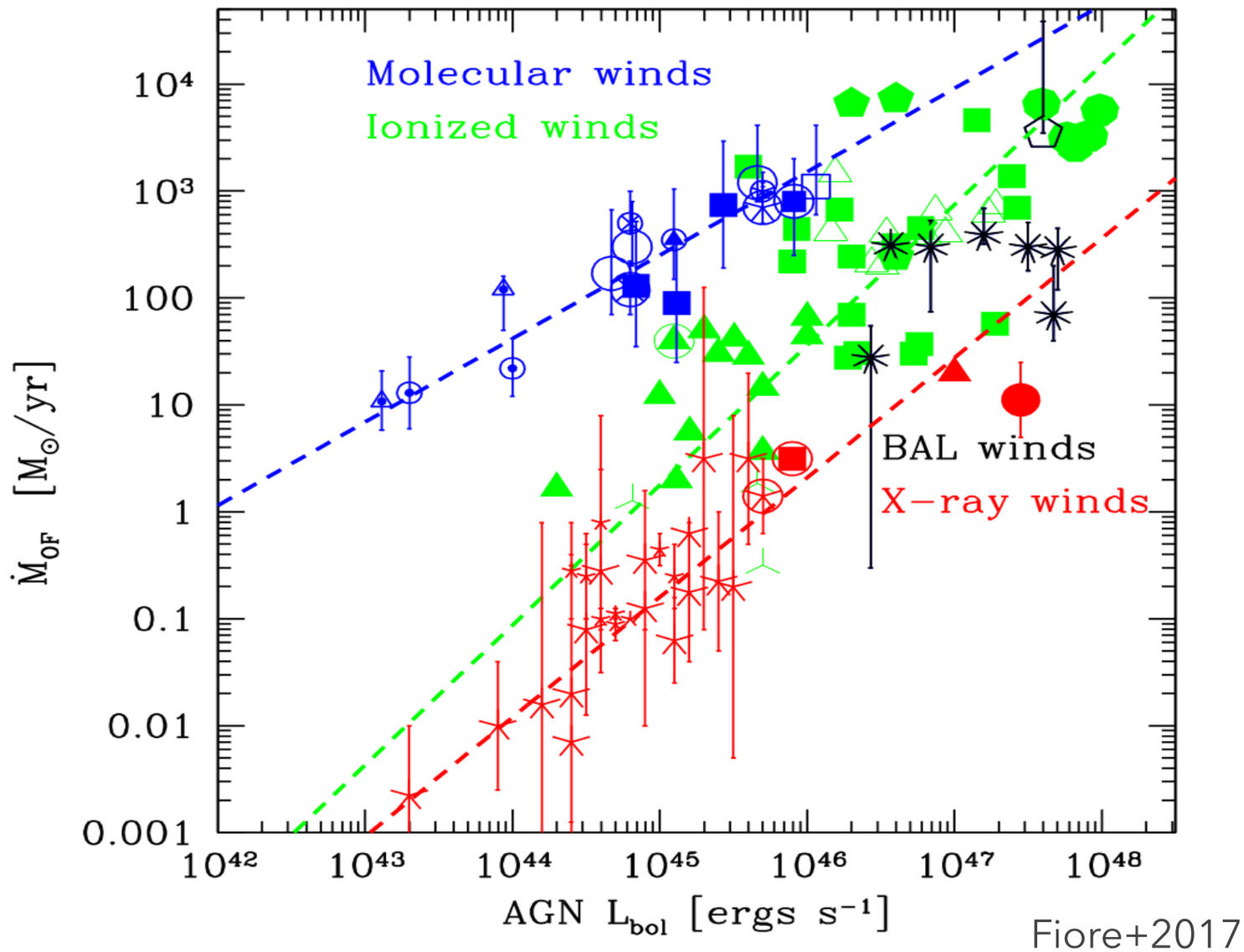

Fiore+2017

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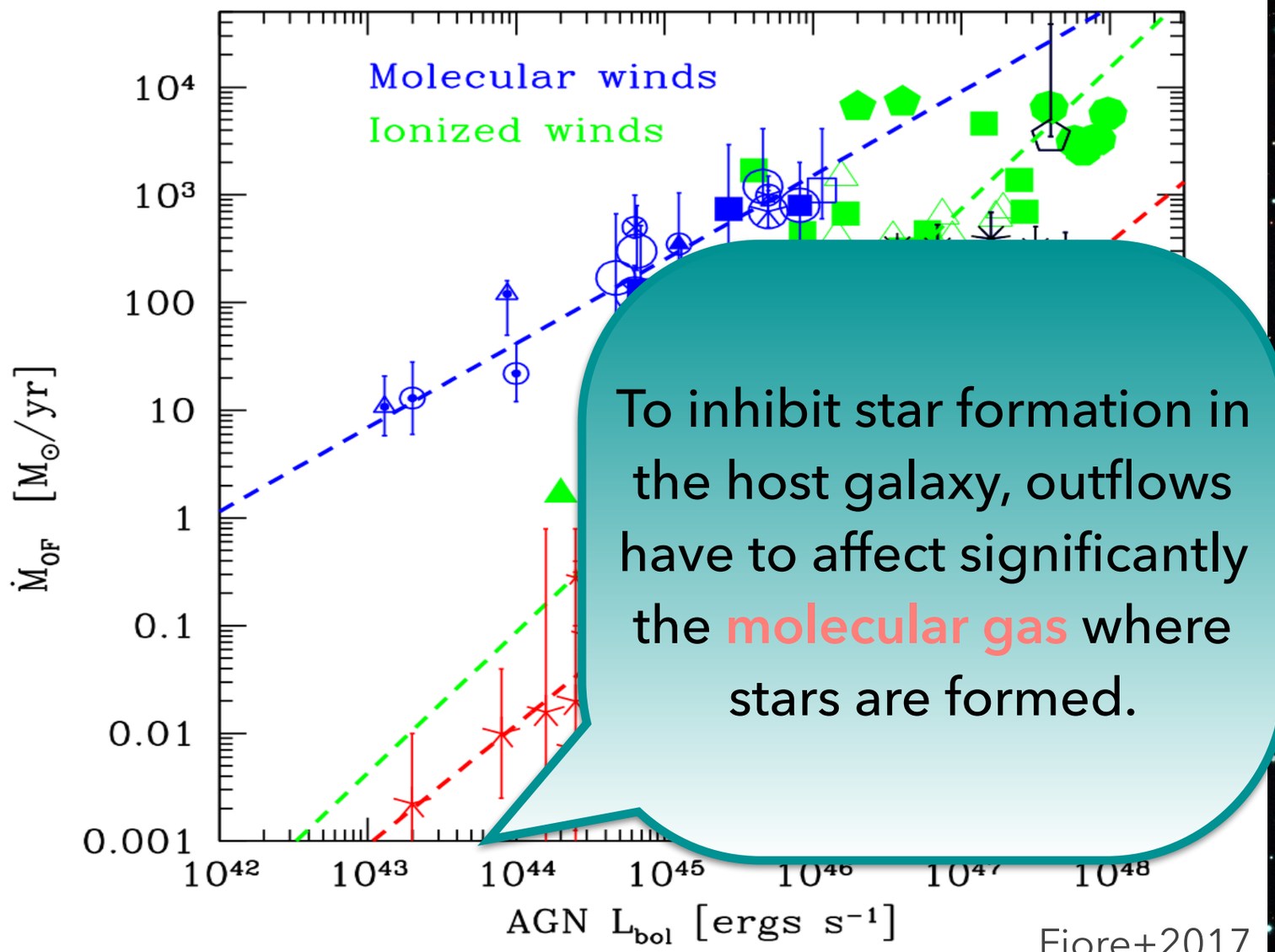
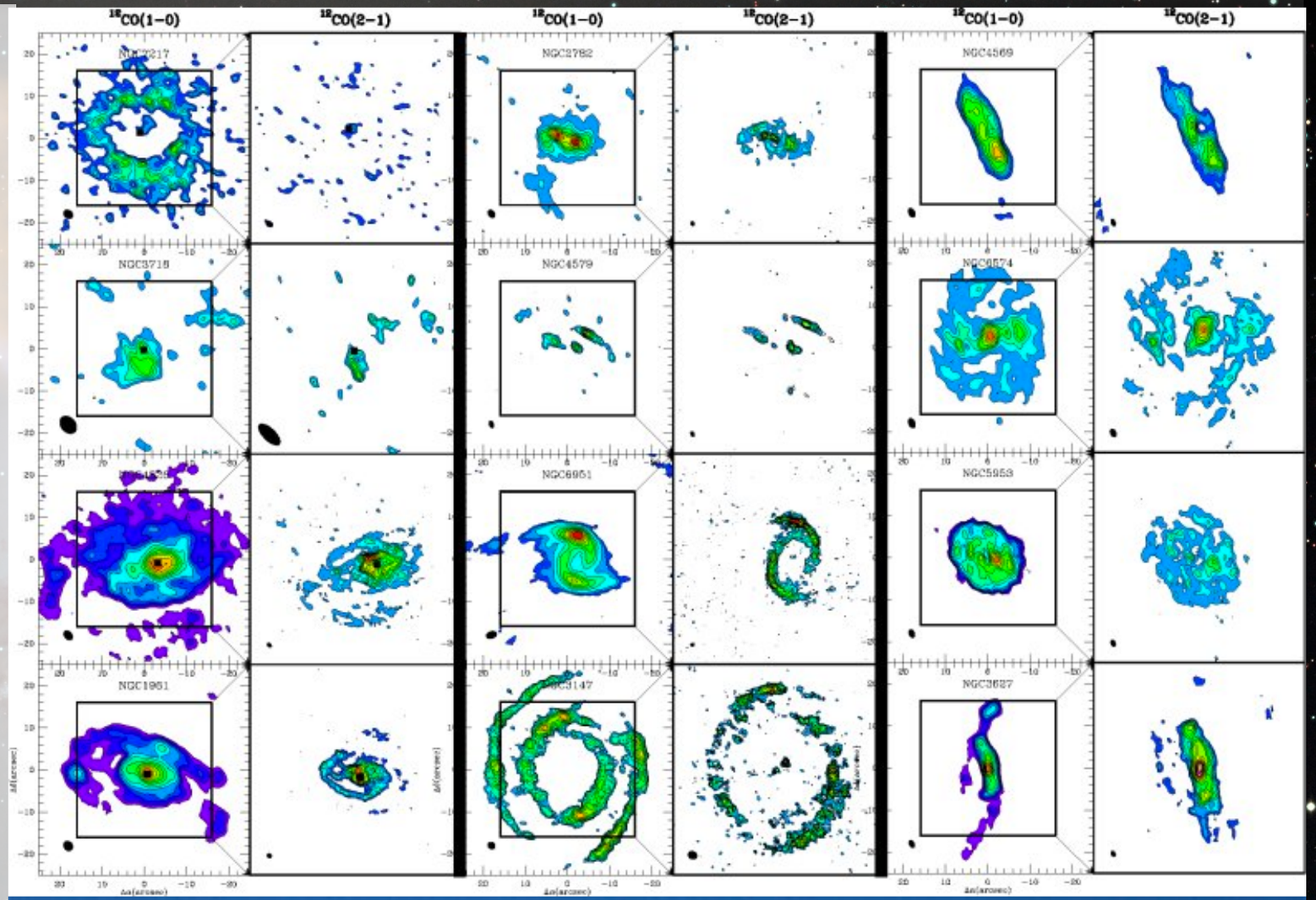


To inhibit star formation in the host galaxy, outflows have to affect significantly the molecular gas where stars are formed.

Fiore+2017

NUGA - NUclei of GAlaxies

- IRAM PdBI + ALMA CO survey
- 25 nearby LLAGNs covering all stages of nuclear activity (Seyferts - LINERs - starbursts)
- angular (0.5’’) and spectral resolution (3 - 6 km/s)
- 1/3 galaxies revealed smoking-gun evidence of AGN fuelling (Garcia-Burillo & Combes 2012)



Credits: IRAM

NUGA - NUclei of GAlaxies

- ALMA Band 7 observations of CO(3-2)

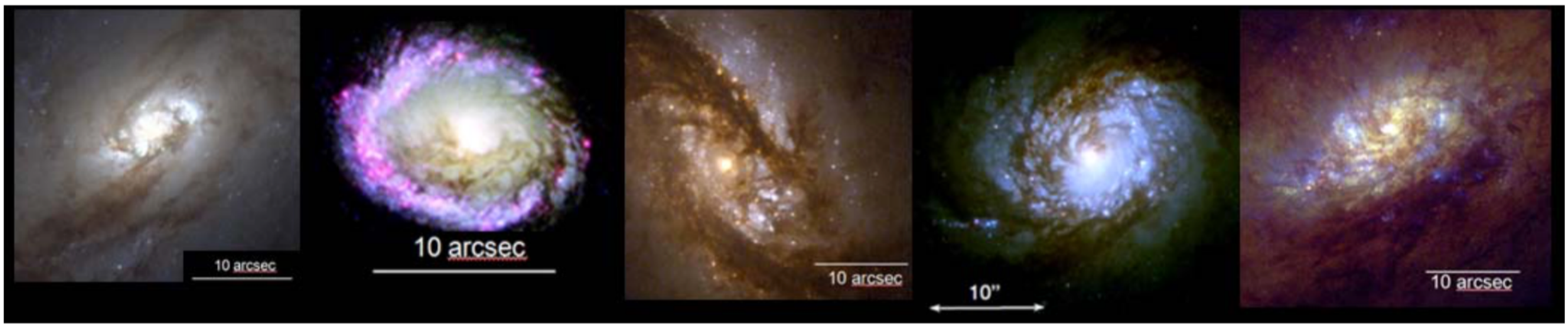
ALMA Cycle 3

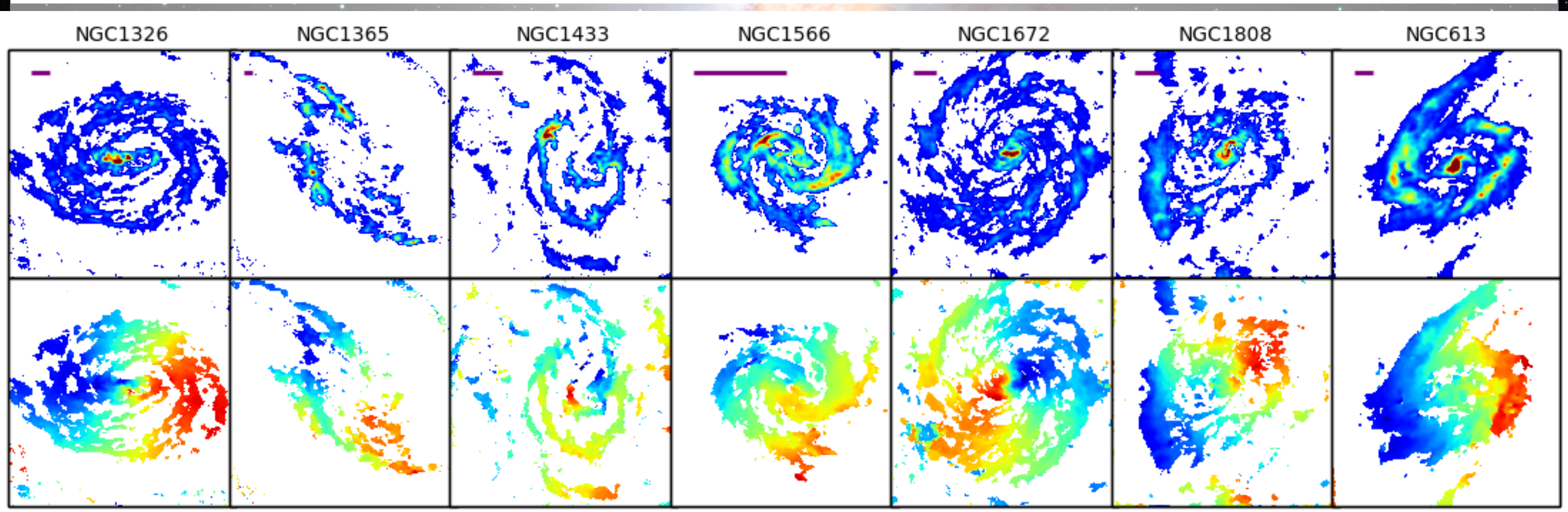
- + dense gas tracers HCN(4-3)/HCO+(4-3)/CS(7-6)
- 5 galaxies
- 0.14-0:3" resolution
- covering the whole **nuclear disks and rings**.

ALMA Cycle 4

- 7 galaxies
- 0.06-0.09” resolution
- resolve the **molecular torus**

NUGA - NUclei of GAlaxies





NGC 1433

- D= 9.9 Mpc
- i= ~33°
- Seyfert 2
- SB(r)ab
- "Lord of the Rings" (Buta &Combes 1996)
- ALMA Cycle 0
- CO(3-2) @ 344.6GHz (Band 7)

30''

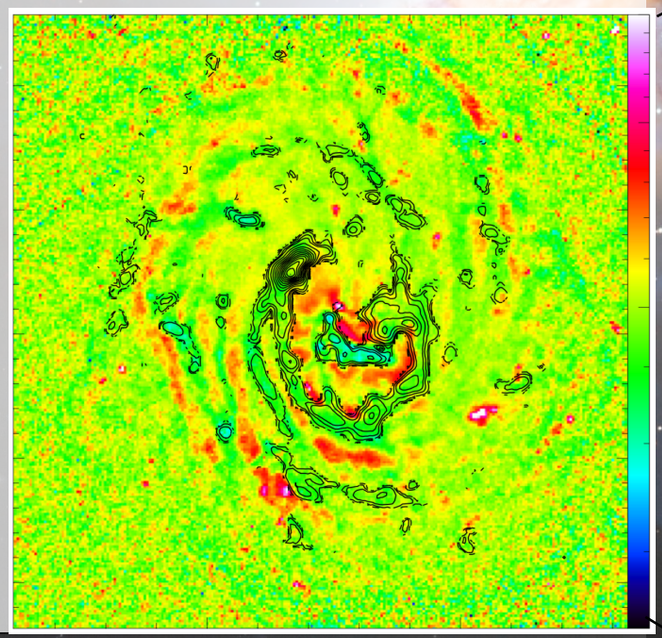
Credits: Carnegie-Irvine Galaxy Survey

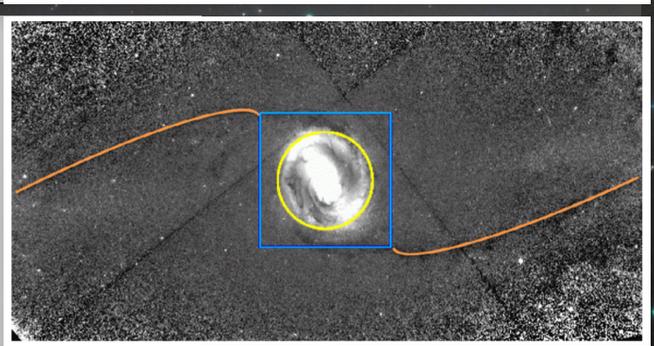
- Offset peak: no concentration of molecular gas in the center: widely distributed multiple-arm spiral of CO emission

- gas do not follow the nuclear ring (10”): **pseudo-ring at ~ 200pc**

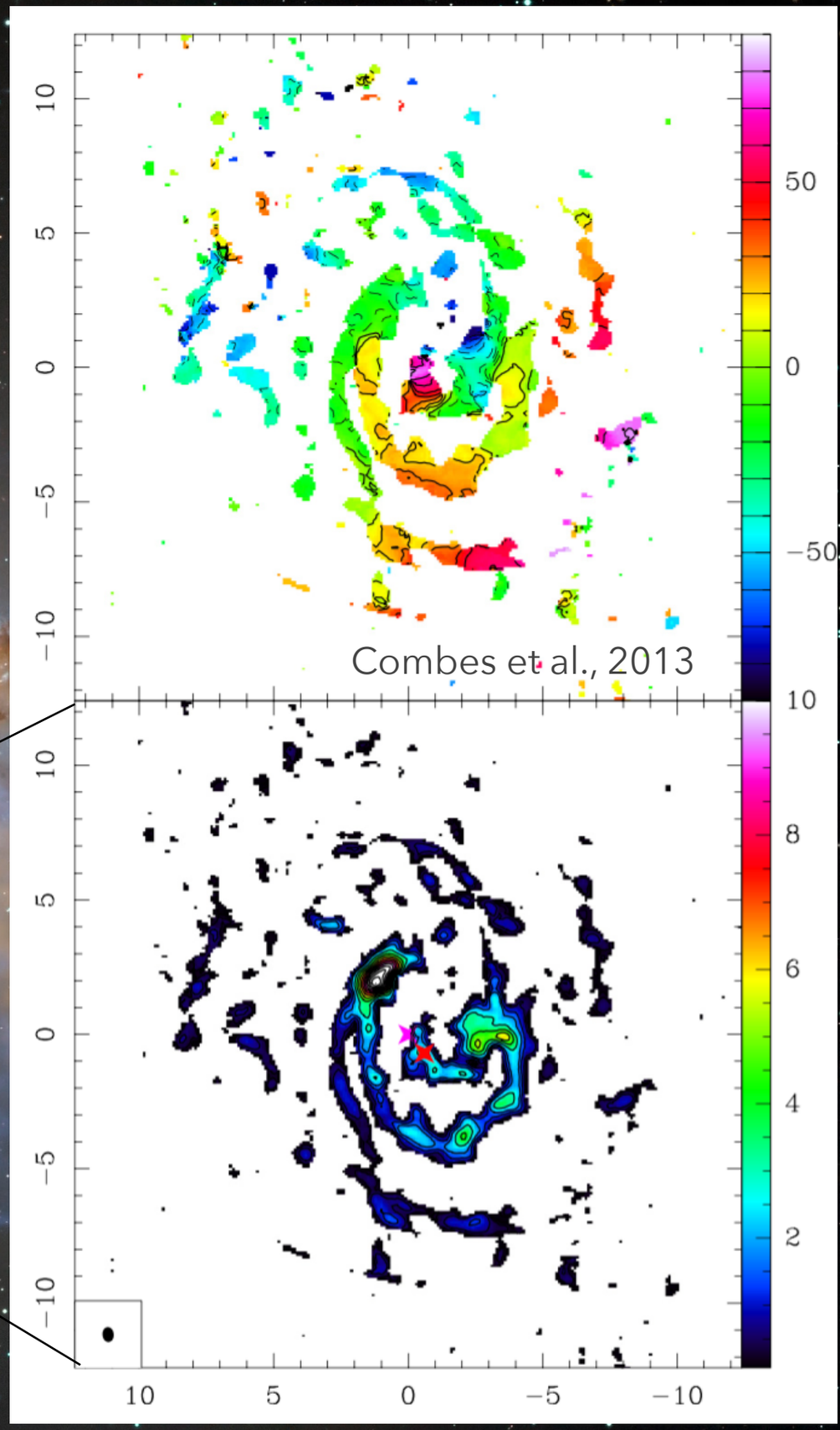
- velocity field well described by rotation

- noticeable **redshifted perturbation at the very center** (~100pc extent)

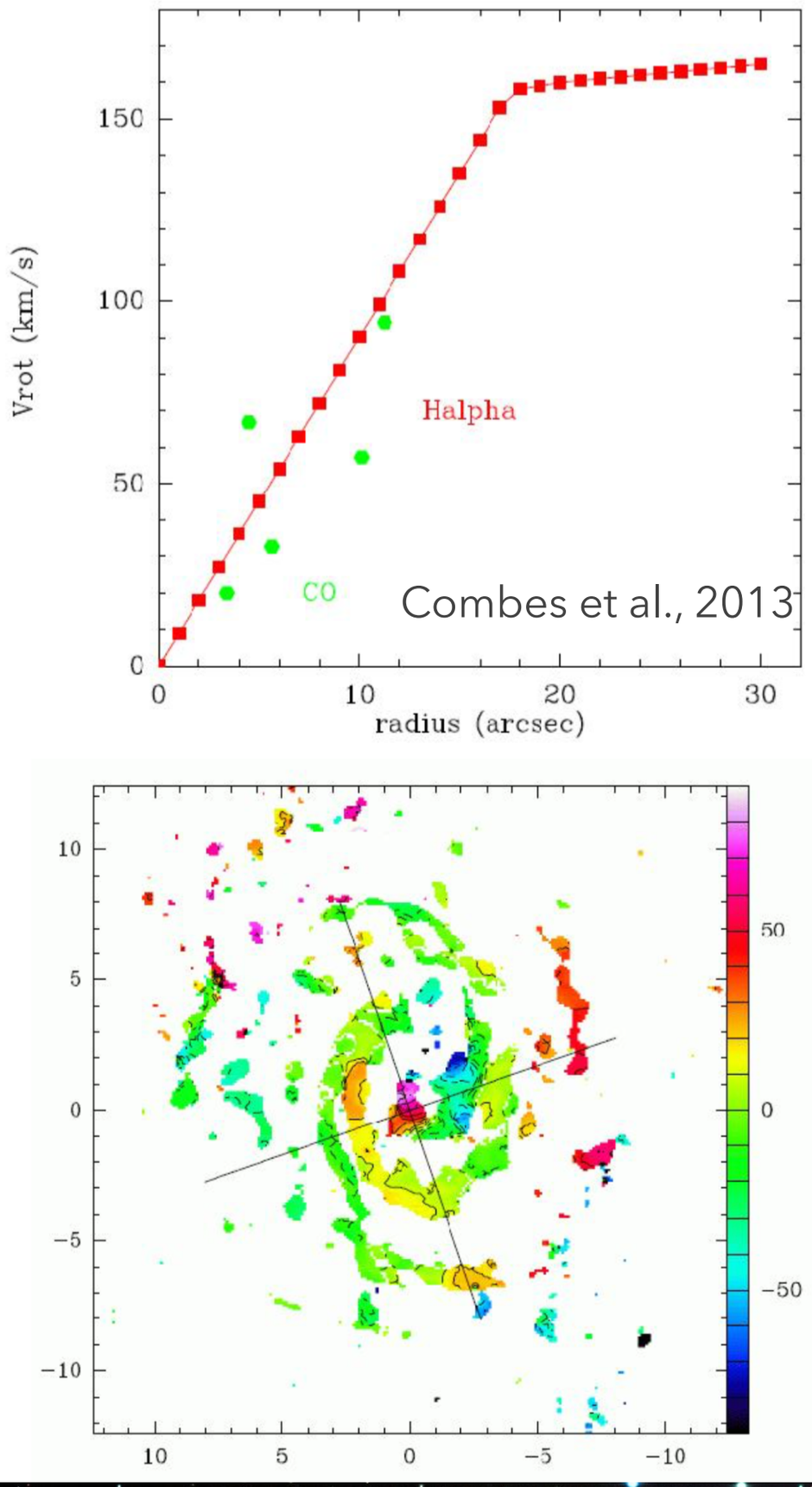




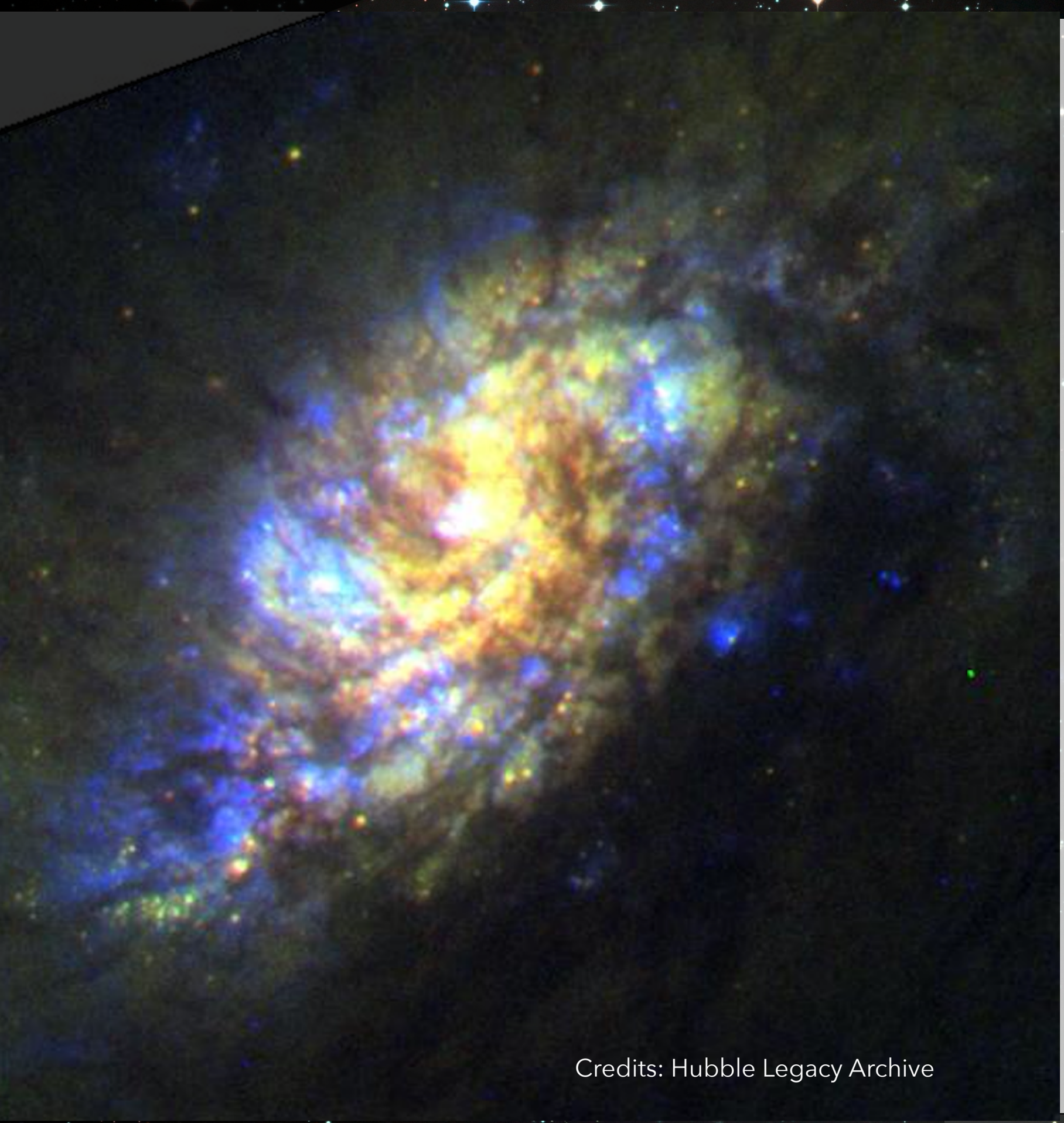
CO(3-2) contours overlaid to F450W HST image and I-image: the nuclear ring, dust lanes leading edge of the main bar (orange)



Velocity field and integrated intensity of the CO(3-2) emission clipped at >2σ



- Subtraction Hα rotation curve (Buta+2001)
- high-velocity CO emission feature redshifted to 200 km/s with a blue-shifted counterpart, at 2" (100 pc)
- The outflow revealed in NGC 1433 is the **smallest molecular outflow** ever seen in a galaxy nucleus (3.6x10^{6}M$\odot$ and ~ 7 M$\odot$/yr)
- SFR~0.2M$\odot$/yr (IRAS fluxes, 1.3x10^{9}L$\odot$)
- Flow **mainly boosted by the AGN through its radio jets** (1.4GHz continuum detected in the very center, Ryder+1996)



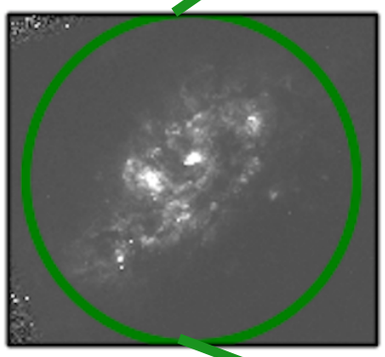
Credits: Hubble Legacy Archive

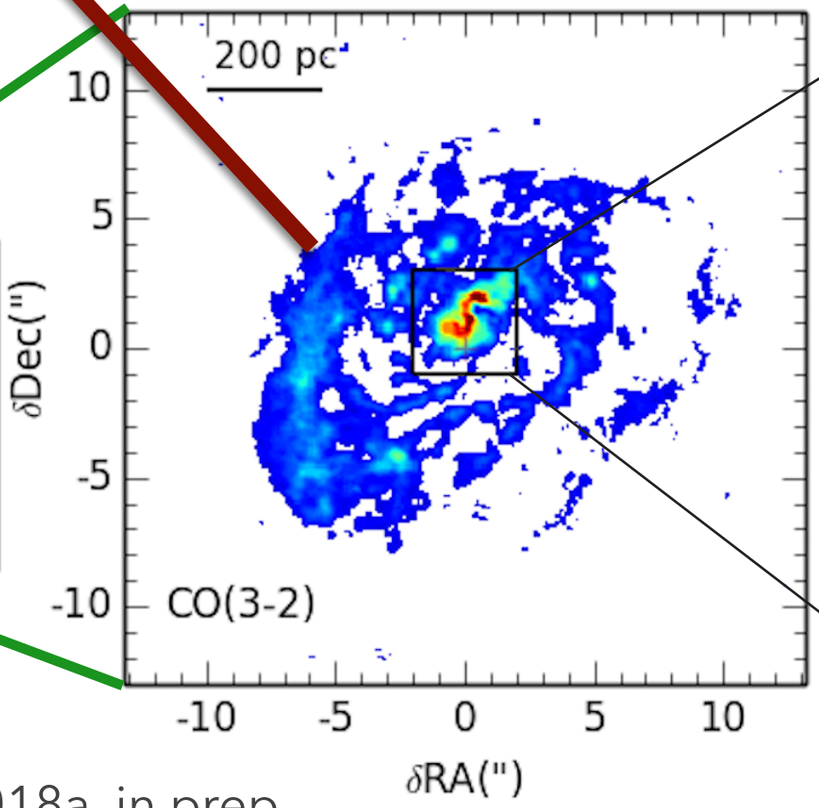
NGC1808

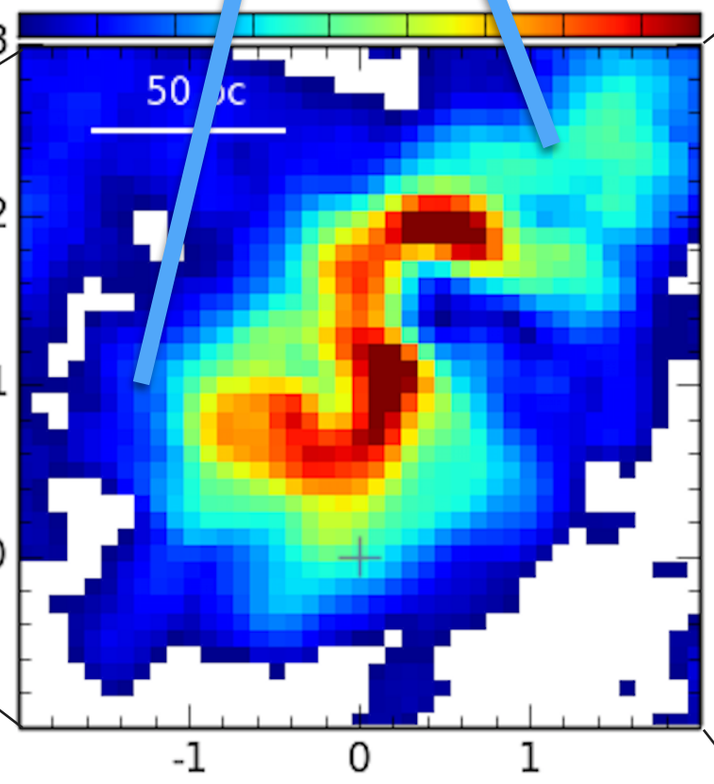
- D= 12.3Mpc
- i= ~57°
- Starburst/Seyfert 2
- SAB(s)a
- “Hot spots”
- ALMA Cycle 3
- CO(3-2) @ 344.6GHz (Band 7)

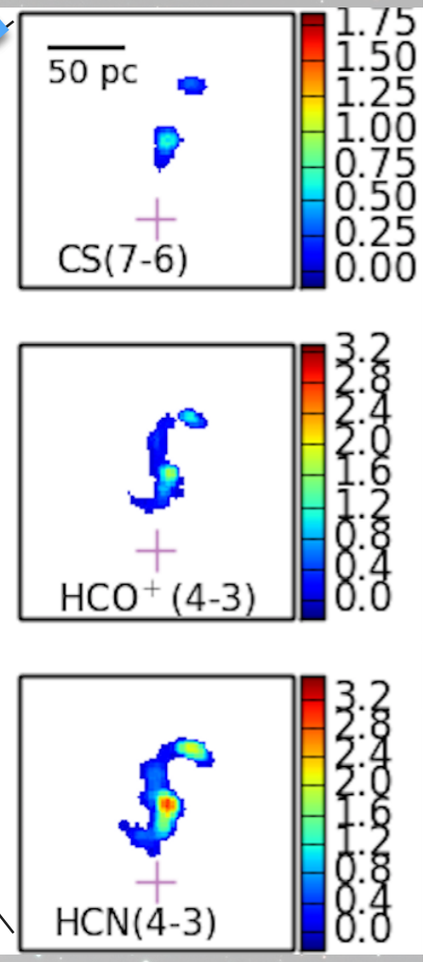
Star-forming ring at 450pc

Trailing 2-arm spiral



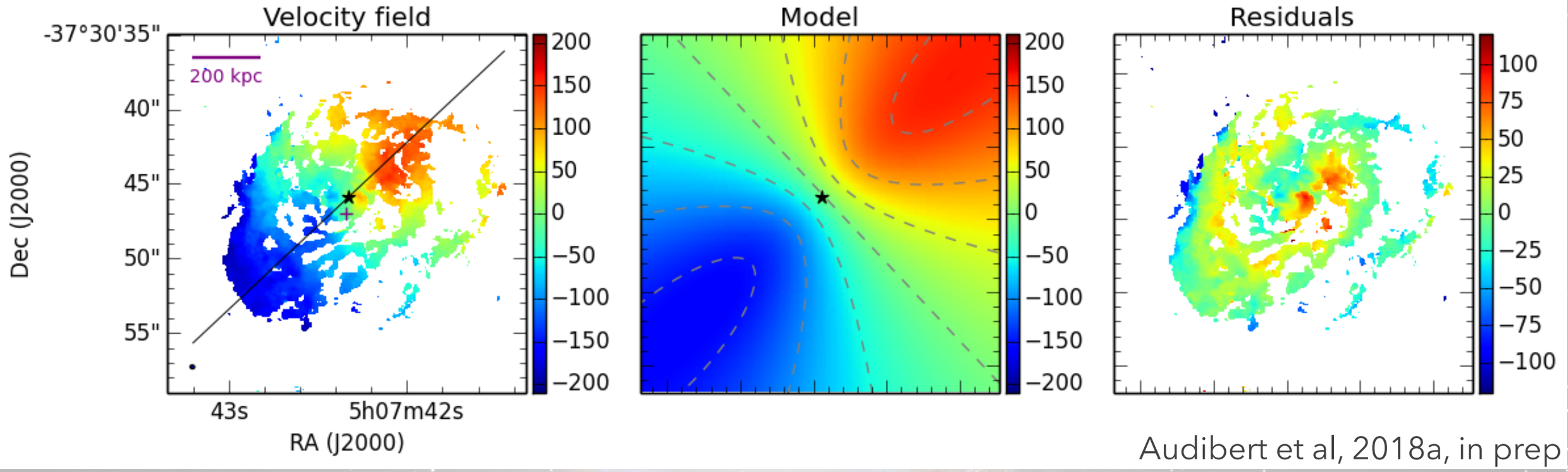






Audibert et al, 2018a, in prep

- CO(3-2) emission follows the star-forming central 450 pc ring
- also detected in the NIR with SINFONI (Busch et al., 2017).
- center, a 2-arm structure indicates a **spiral trailing fuelling the AGN**, feature also seen in the dense gas



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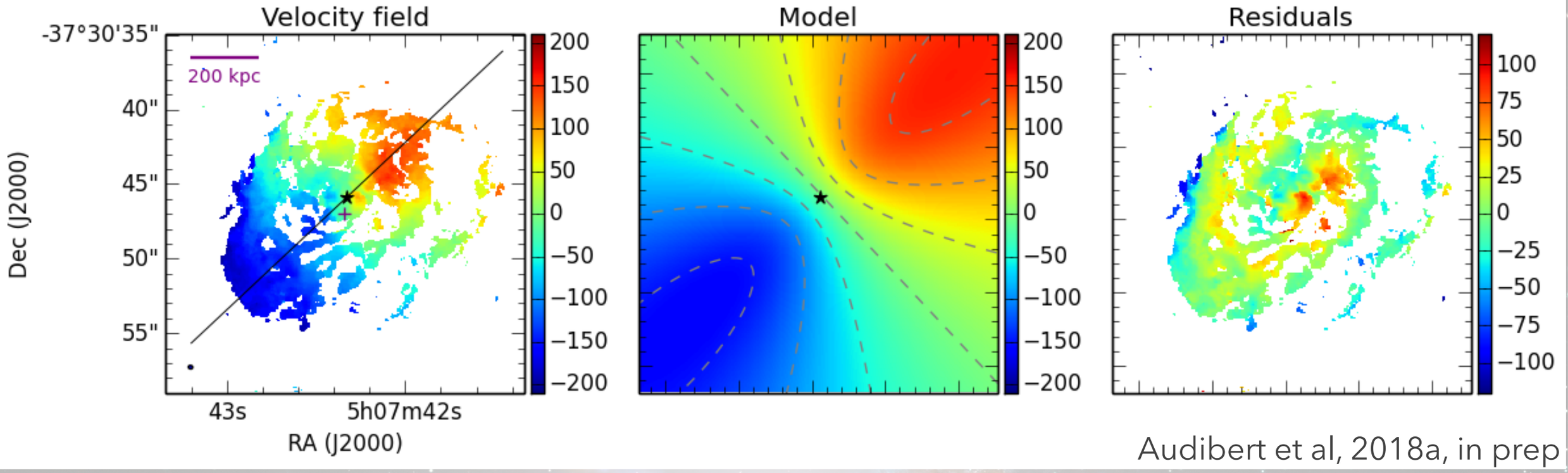
- 1st moment dominated by circular motions
- Subtracting a velocity field model (Bertola et al. 1991): no significant patterns
- No detection of outflow in CO(3-2) in our FoV (~17")
- Salak+2016: evidence of an outflow in CO(1-0) only seen in the PVD –> a 100km/s blueshifted component in the NE corresponding to v~48–128 km/s



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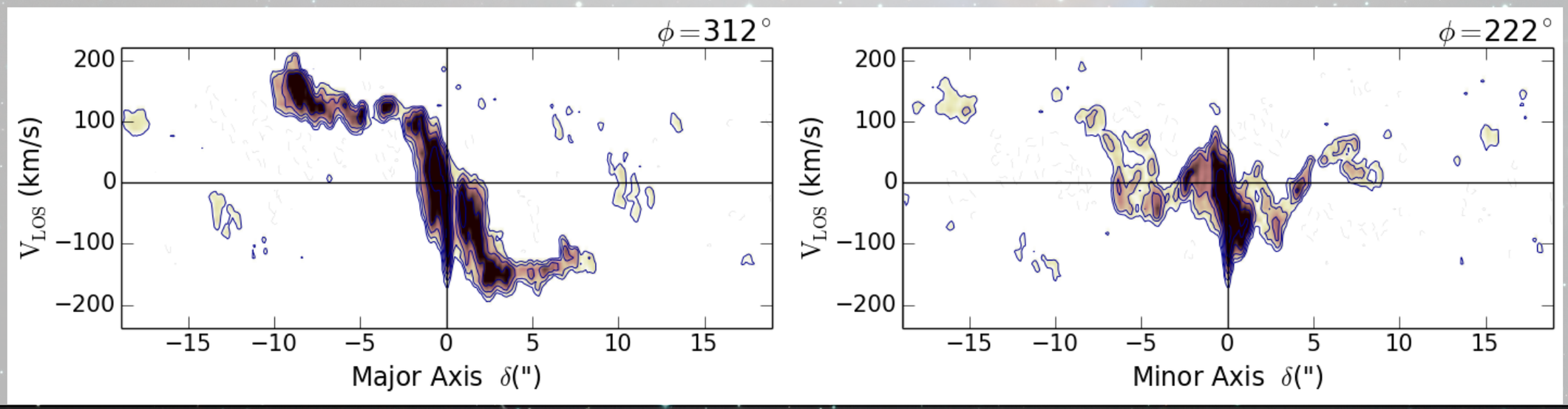

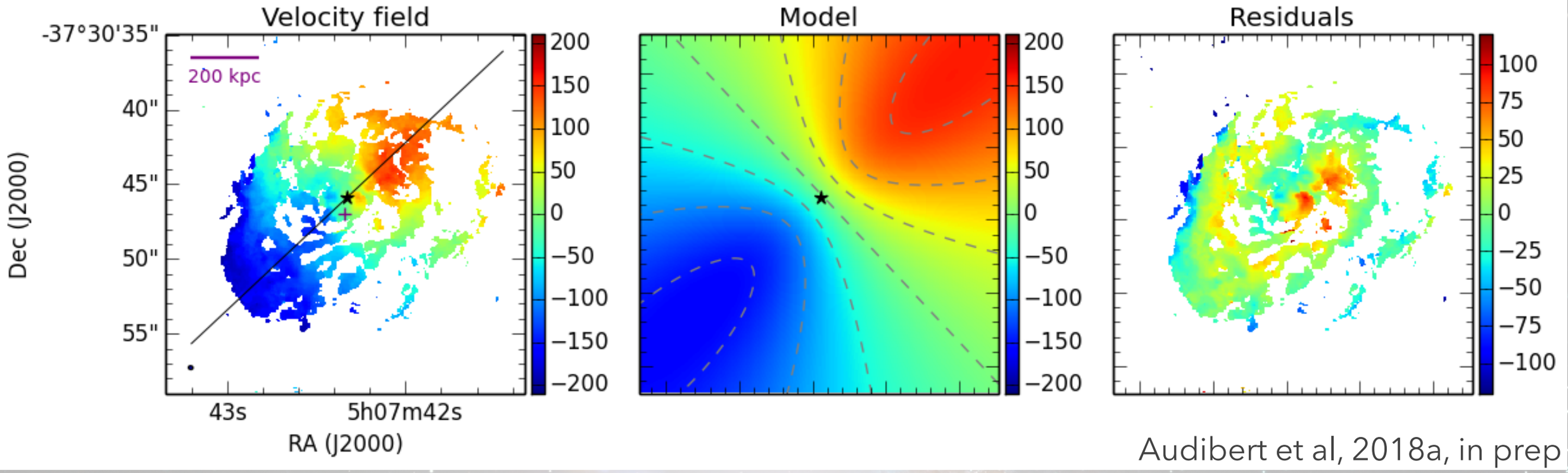

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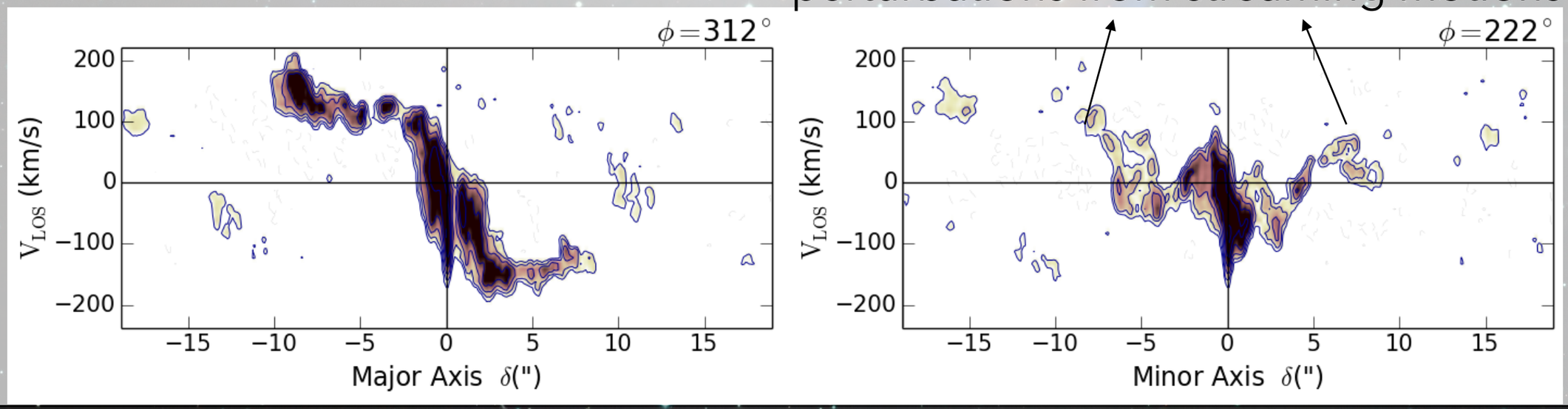
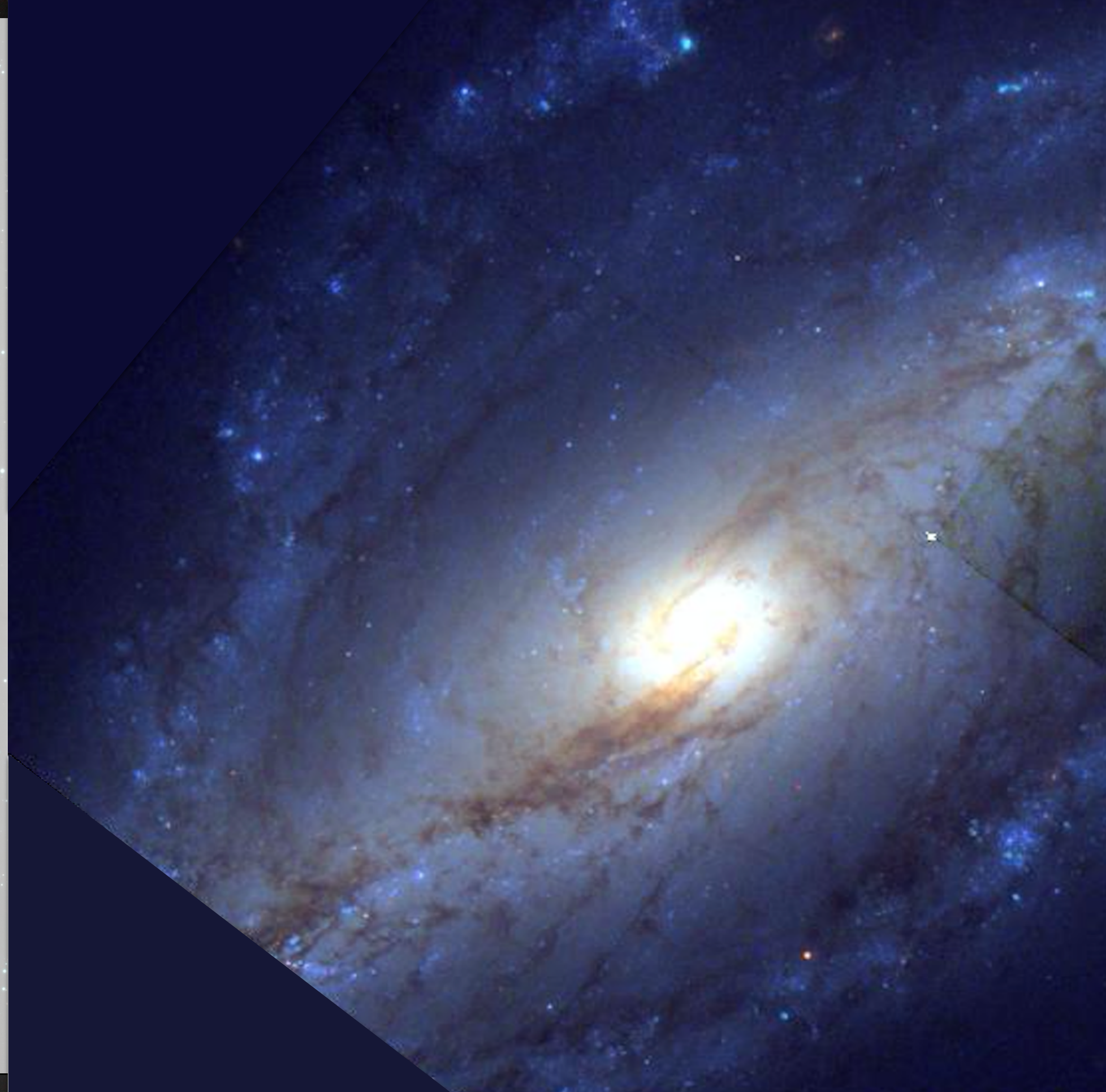
perturbations from streaming motions



NGC613

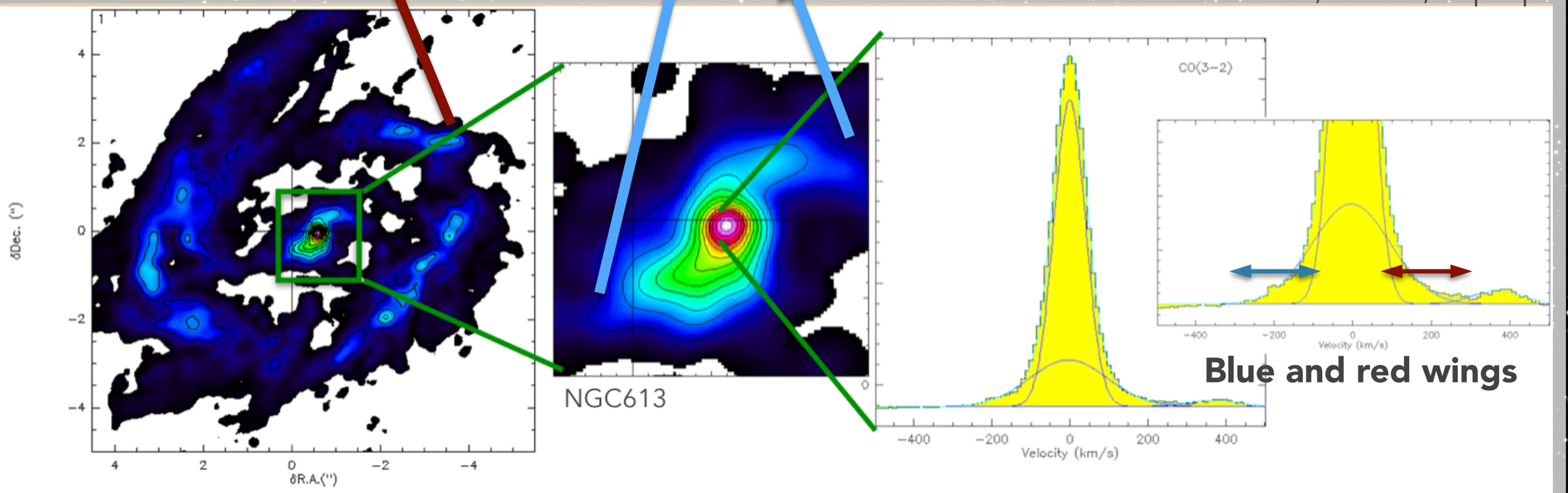
- D= 17.2 Mpc
- i= ~41°
- Seyfert/HII
- SBbc
- ALMA Cycle 3+4



ILR nuclear ring at 300pc

Trailing 2-arm spiral

Audibert et al, 2018b, in prep



- The CO emission follows the inner Lindblad resonance (ILR) nuclear ring (300pc)
- Star forming clumps -> NIR (Falcón- Barroso et al. 2014).
- Clear nuclear 2-arm spiral: **inflowing of gas** towards the center.
- Nuclear emission: broad wings -> **molecular outfow in the very central region** (~30pc). Also seen in HCN(4-3)/HCO^+ (4-3)/CS(7-6).

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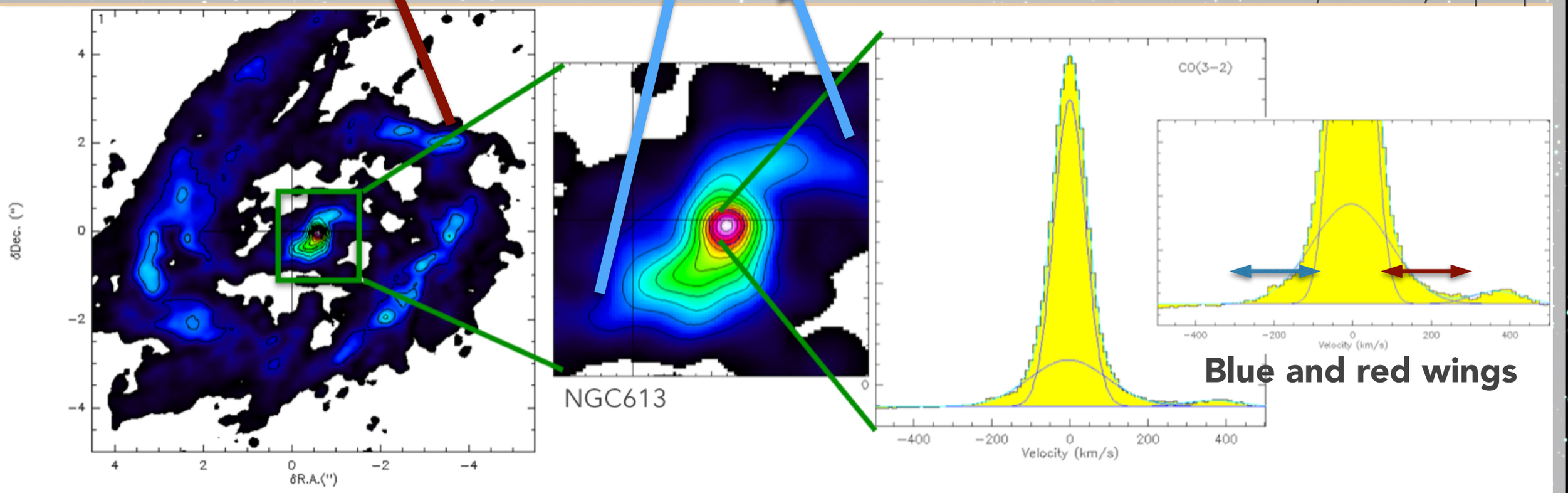

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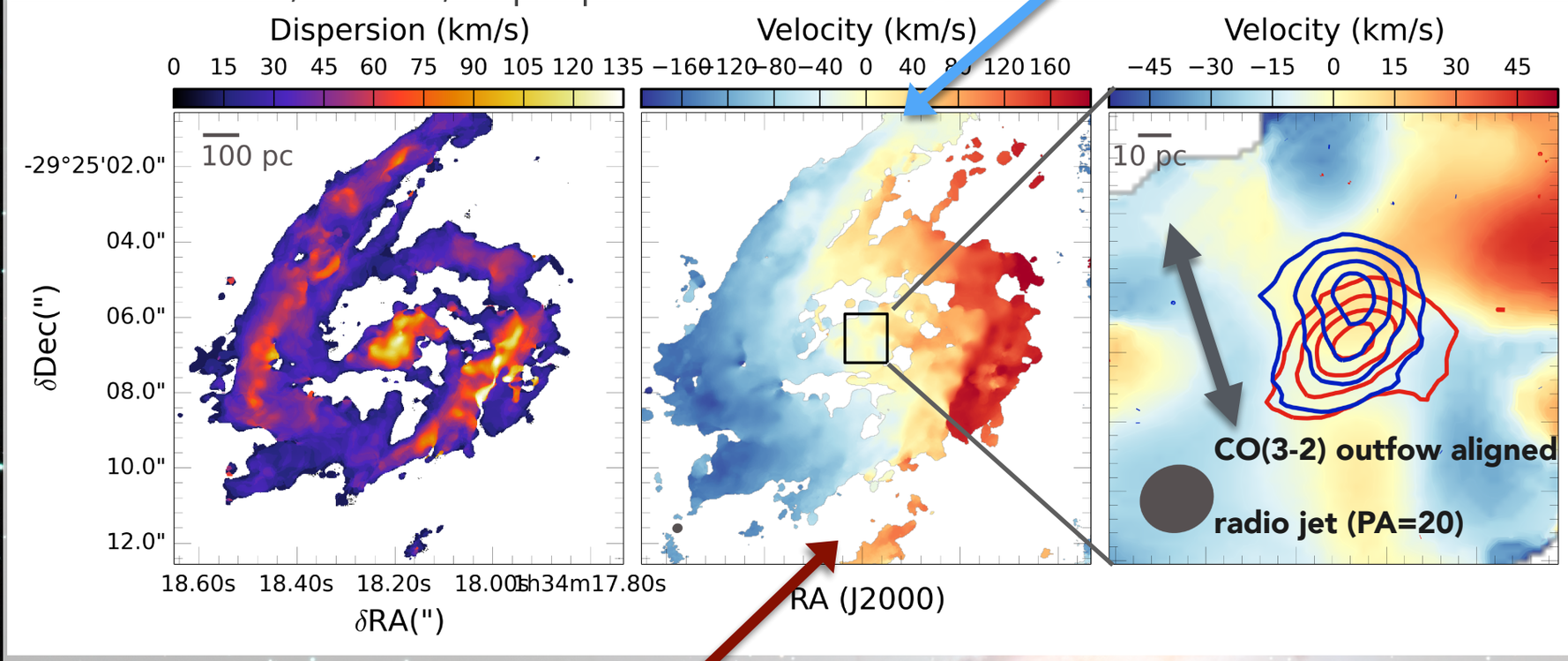
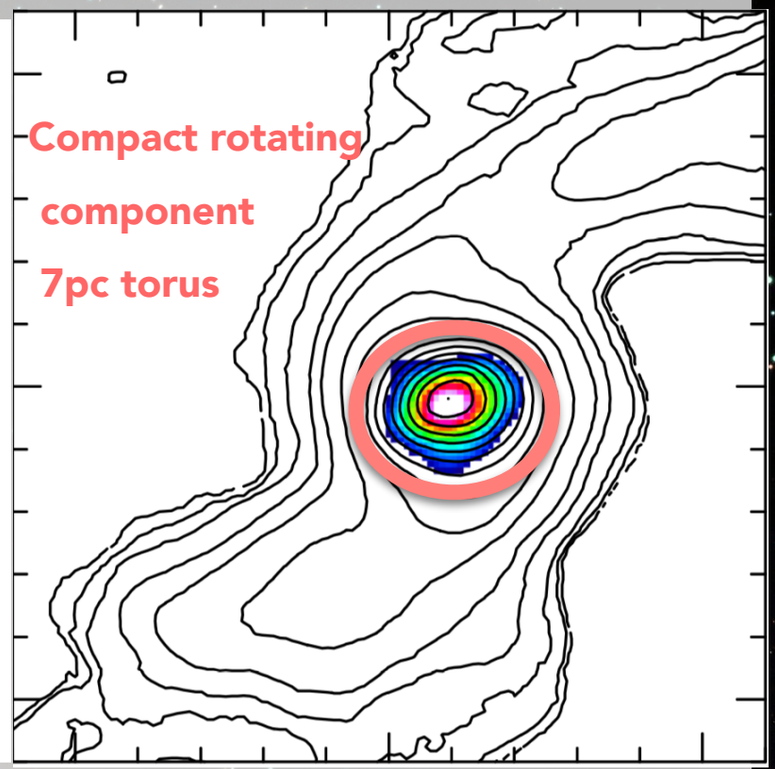
Outflow: FWHM Δv~270 km/s of mass ~$1 \times 10^7 M_\odot$ and $\dot{M}_{out}=340 M_\odot$/yr

Winding spiral arm

Audibert et al, 2018b, in prep





Winding spiral arm

- Velocity field disturbed by the winding arms
- A very dense and compact (<7pc) rotating structure, interpreted as a **molecular torus**
- molecular material (dense gas) is entrained in a AGN-driven outflow

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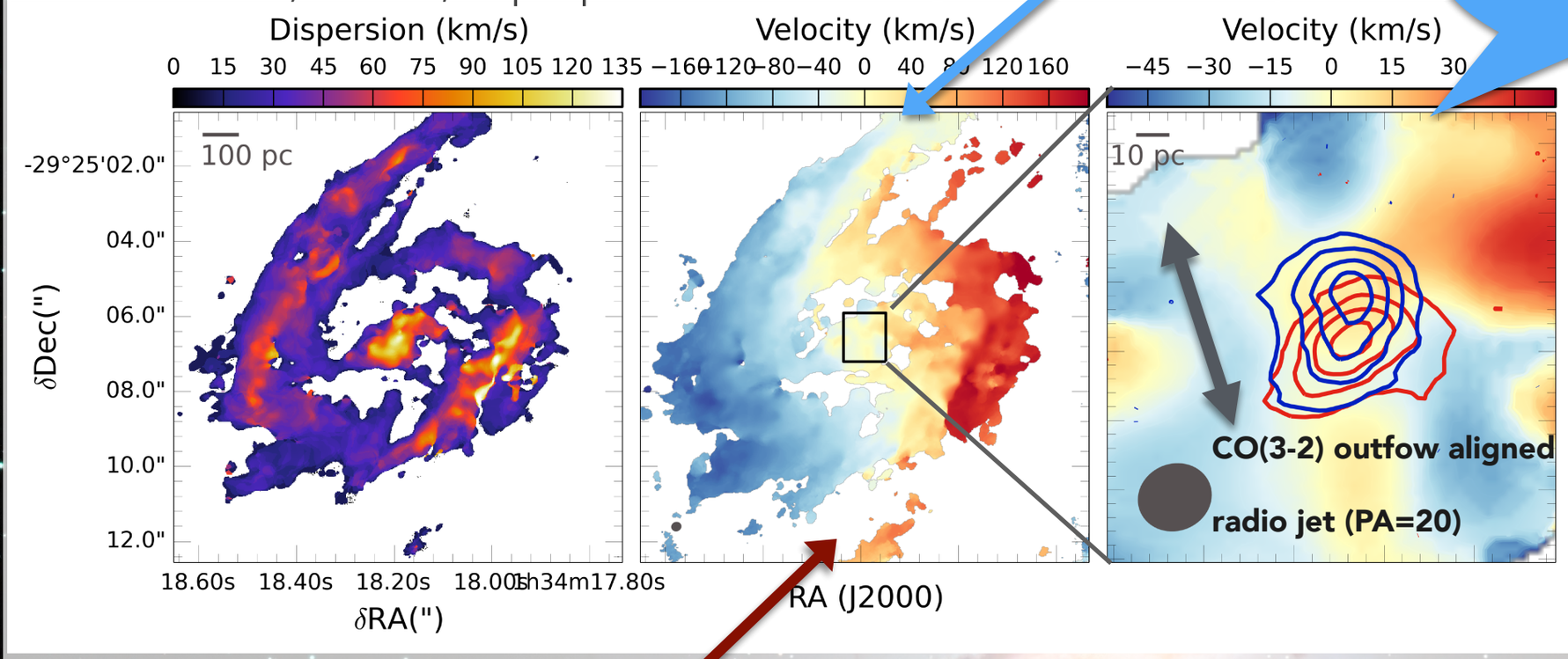
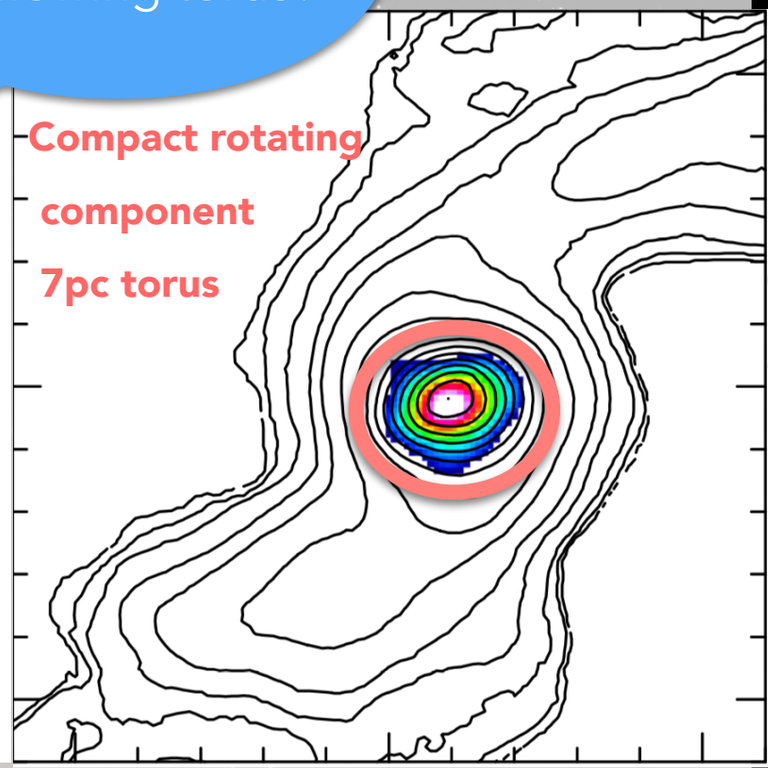
Audibert et al, 2018b, in prep



Molecular outflowing torus?



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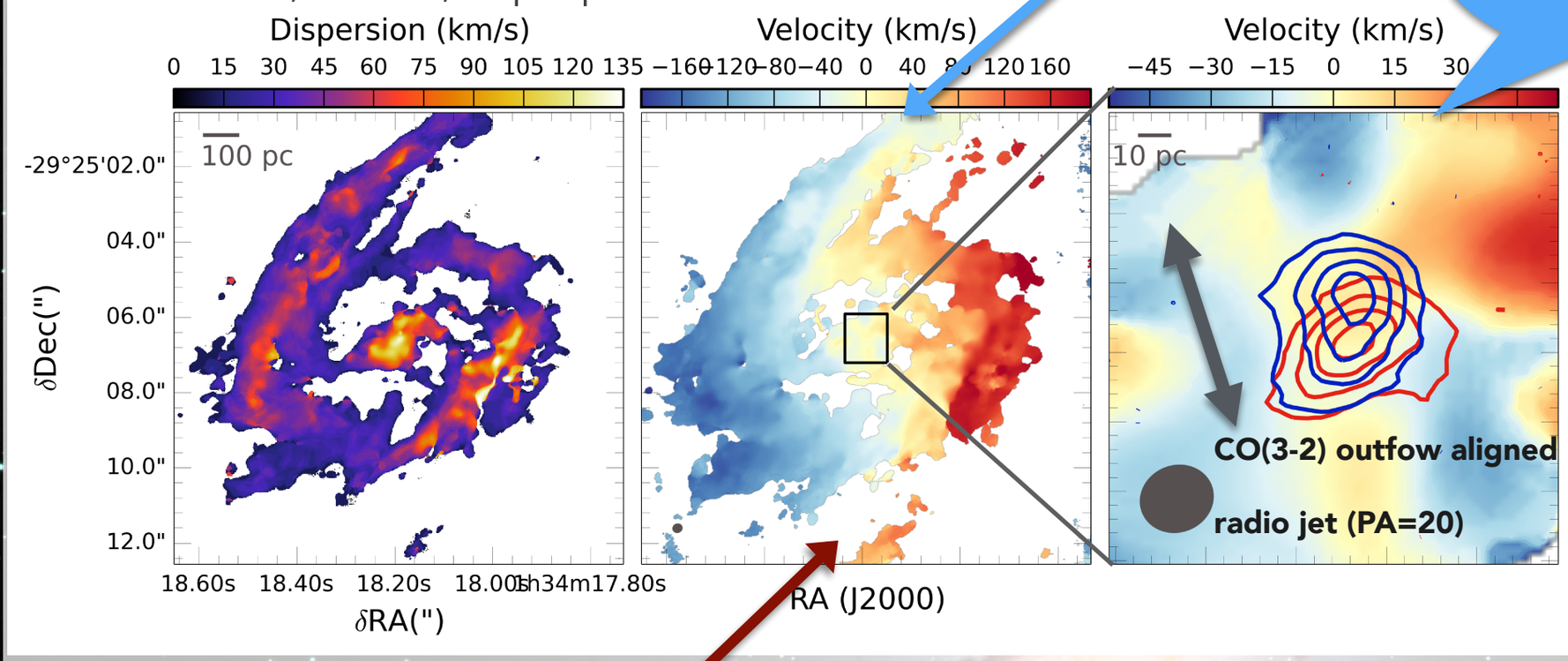

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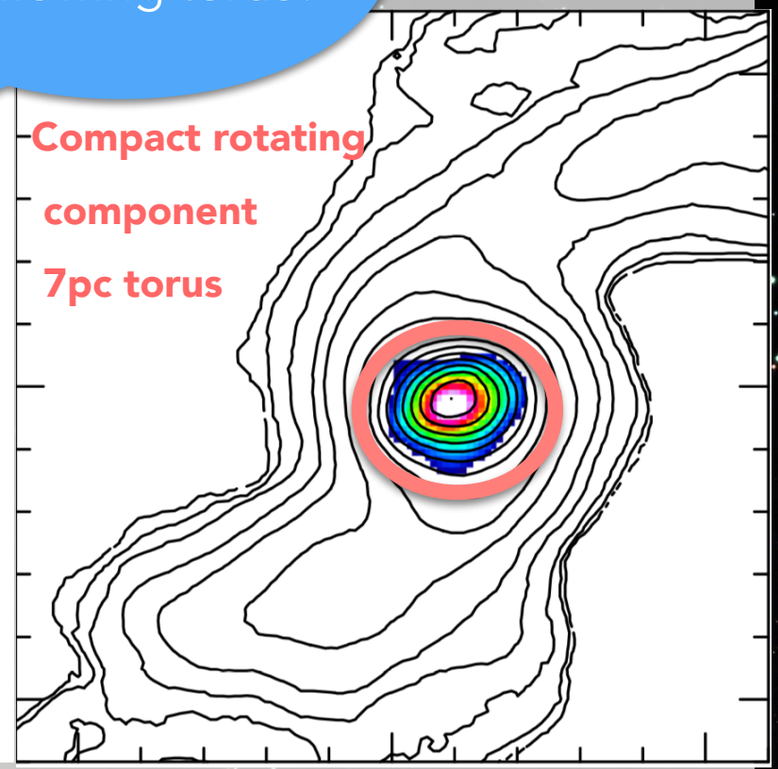
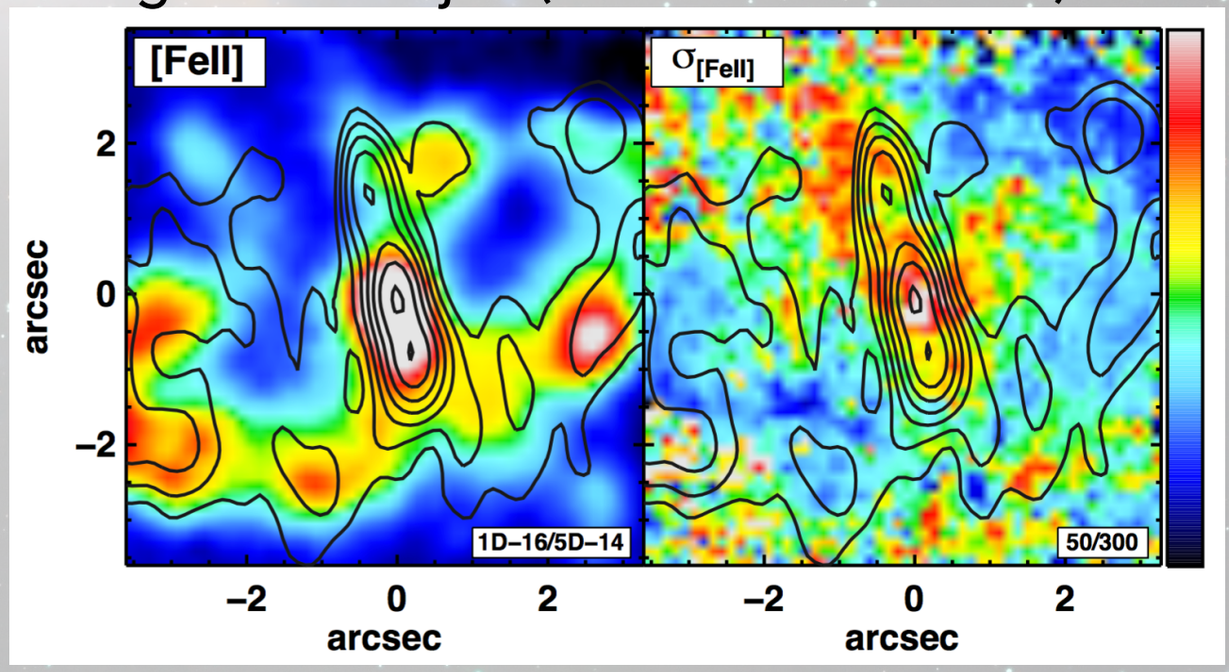


Winding spiral arm

- Velocity field disturbed by the winding arms
- A very dense and compact (<7pc) rotating structure, interpreted as a **molecular torus**
- molecular material (dense gas) is entrained in a AGN-driven outflow

outflow already suggested by the high $\sigma_{[FeII]}$ along the radio jet (+Davies et al 2017)



Falcón- Barroso et al. 2014

- **NGC613:** $L_{bol,AGN}$=3.2x10^{42} erg/s, $\dot{M}_{out}$~340M⊙/yr, SFR =5.30M⊙/yr
- **NGC1433:** $L_{bol,AGN}$=1.3x10^{43} erg/s,$\dot{M}_{out}$~7M⊙/yr, SFR =0.2M⊙/yr

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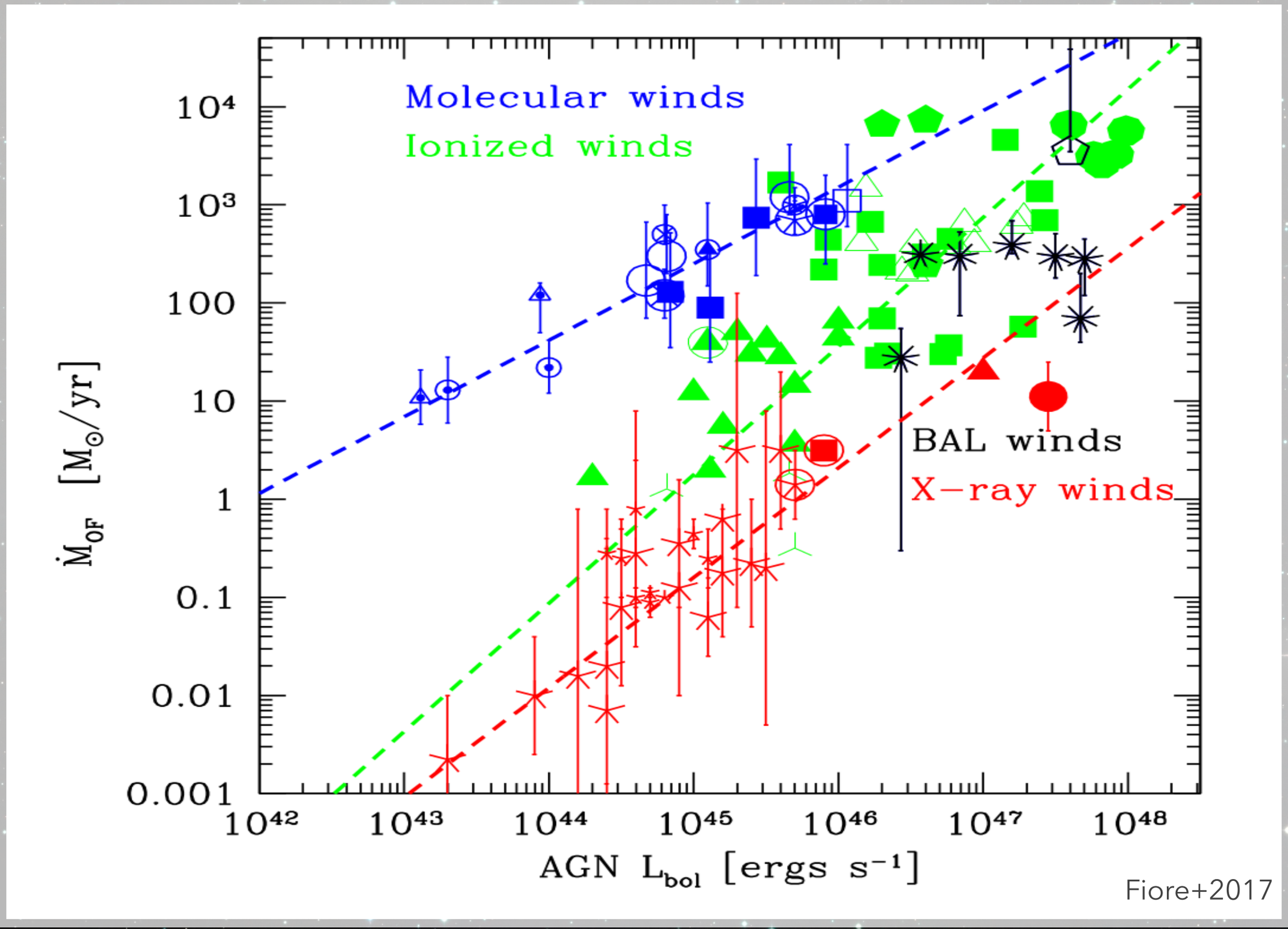

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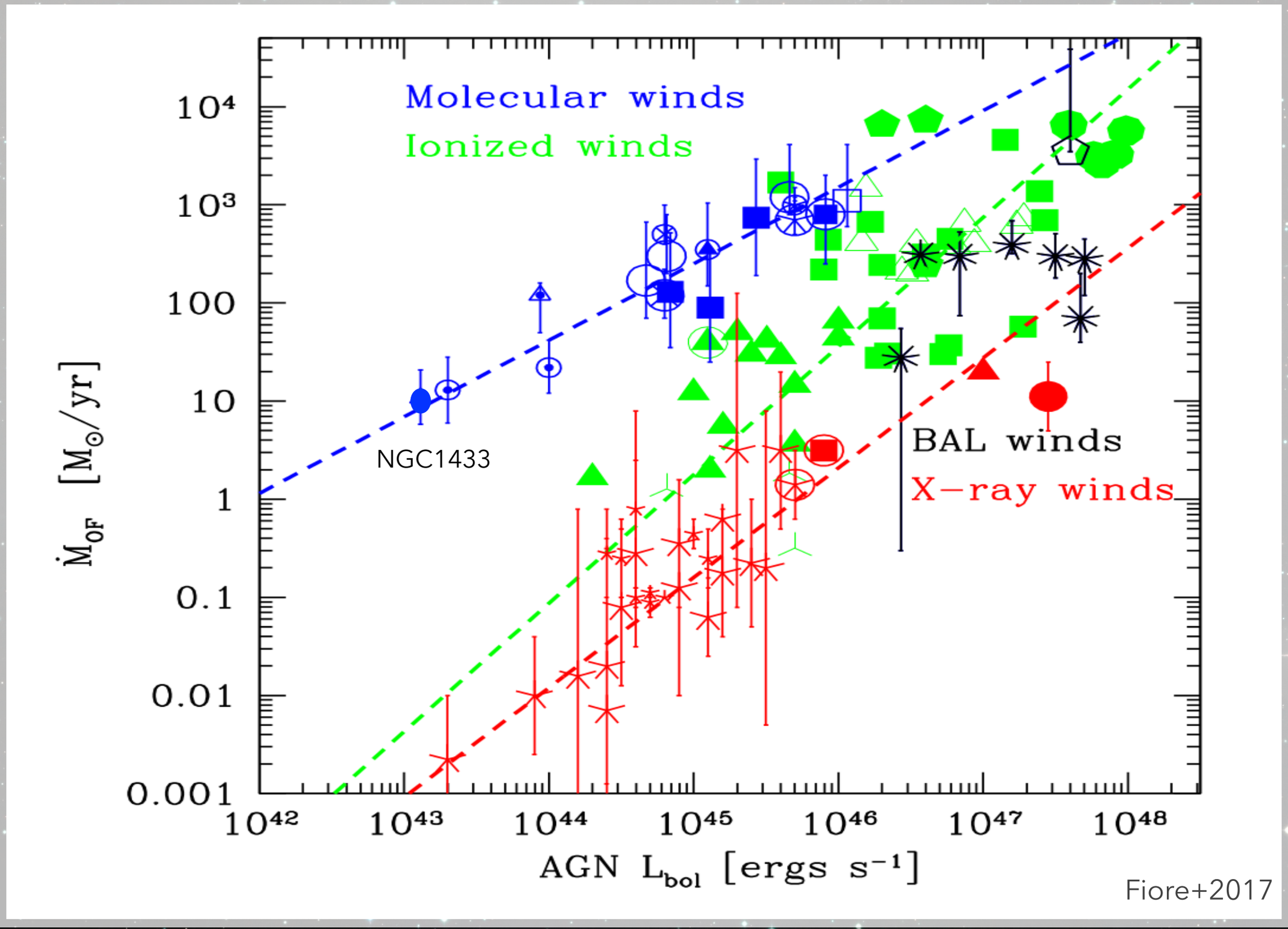
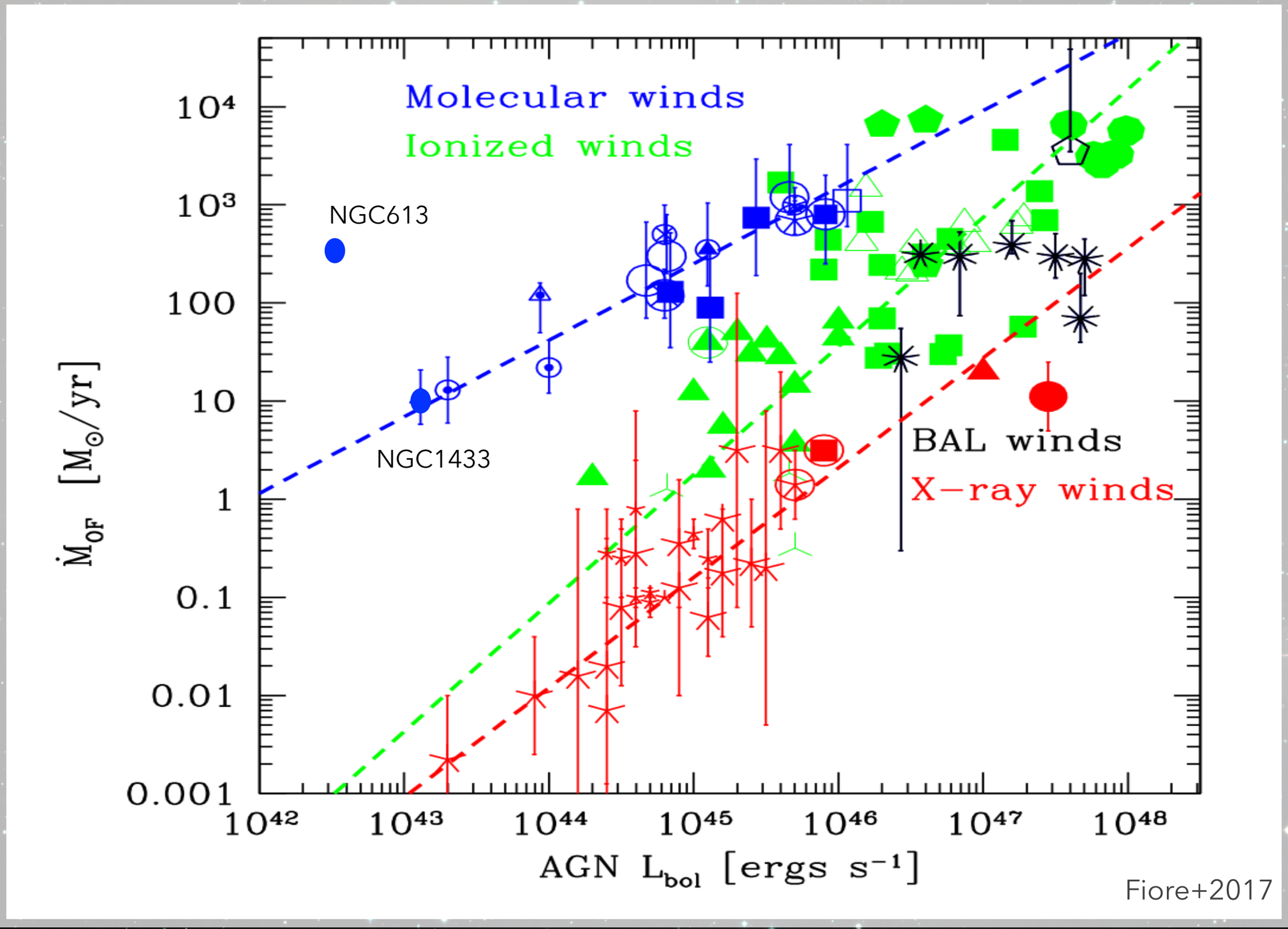


Fiore+2017

- **NGC613:** $L_{bol,AGN}$=3.2x10^{42} erg/s, $\dot{M}_{out}$~340M⊙/yr, SFR =5.30M⊙/yr
- **NGC1433:** $L_{bol,AGN}$=1.3x10^{43} erg/s,$\dot{M}_{out}$~7M⊙/yr, SFR =0.2M⊙/yr



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SUMMARY

- NGC 1433: outflow is one of the smallest molecular outflow ever seen in a galaxy nucleus (3.6x10^6 M⊙ and ~ 7 M⊙/yr), **FIRST TIME SEEN IN A LLAGN**

- NGC613 and NGC1808 show clear feeding episodes caught in action as trailing spirals (~100pc scales)

- NGC1808: no evidence of outflow in our FoV

- NGC613: feeding and feedback observed: massive molecular outflow ~25pc and $\dot{M}_{out}$~340M⊙/yr

Feeding the SMBH

How active nuclei (AGN) are fueled in galaxies?

Fueling gas towards the center to sustain nuclear activity requires the removal of angular momentum from the gas (creation of large non-axisymmetries)

Feeding the SMBH

10kpc scales, torques are produced by galaxy interactions and mergers (Hopkins et al. 2006; di Matteo et al. 2008);

kpc scales, bar instabilities, either internally driven by secular evolution, or triggered by a companion can first feed a central starburst and fuel the SMBH (Garcia-Burillo et al 2005).

300pc scales nested, kinematically decoupled bars are able to effectively funnel gas into the nucleus (Garcia-Burillo & Combes 2012)

10pc scales fueling involves a cascade of dynamical instabilities (m=2, m=1), and the formation of a thick gas disk similar to a torus (Hopkins et al. 2010,2012)