Nuclei of Galaxies (NUGA) resolved by ALMA

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TORUS 2018
Puerto Varas, Chile, 13 December 2018

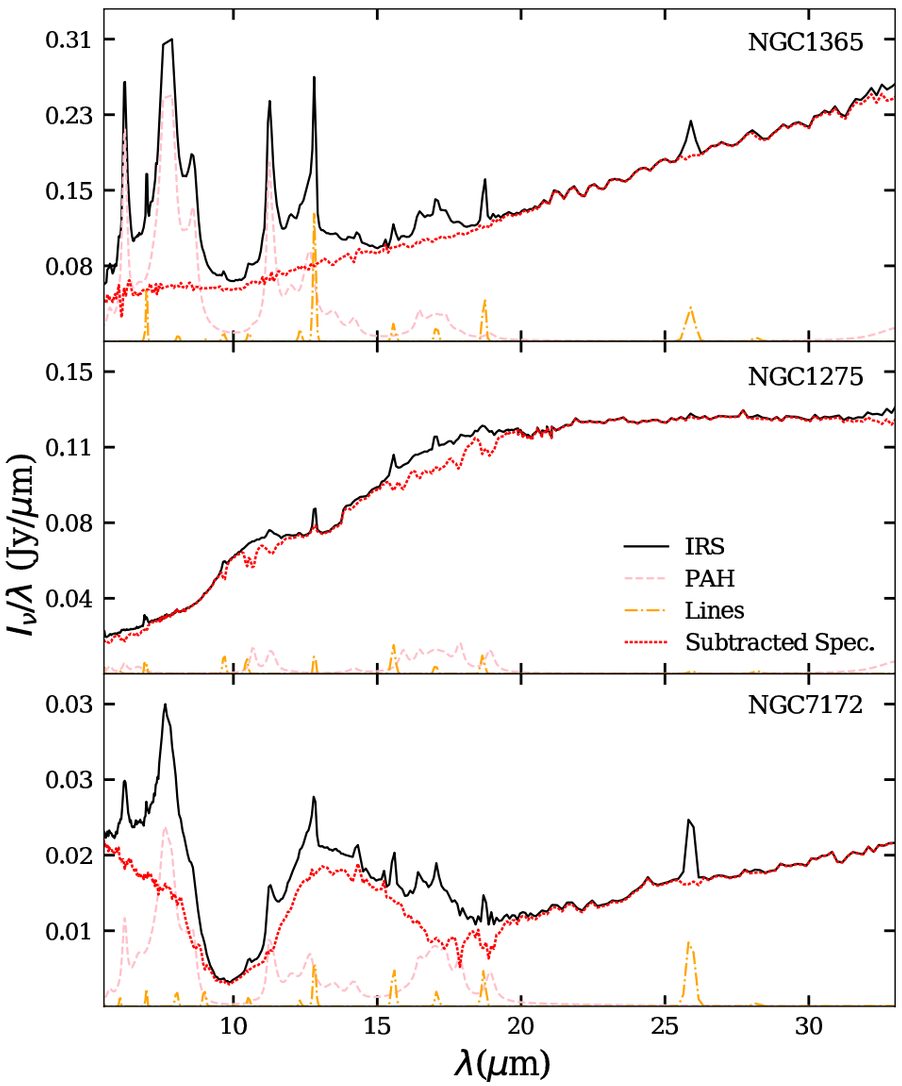
- Torus Models and ir sed
- Resolving the Molecular Tori

  +Feeding and Feedback

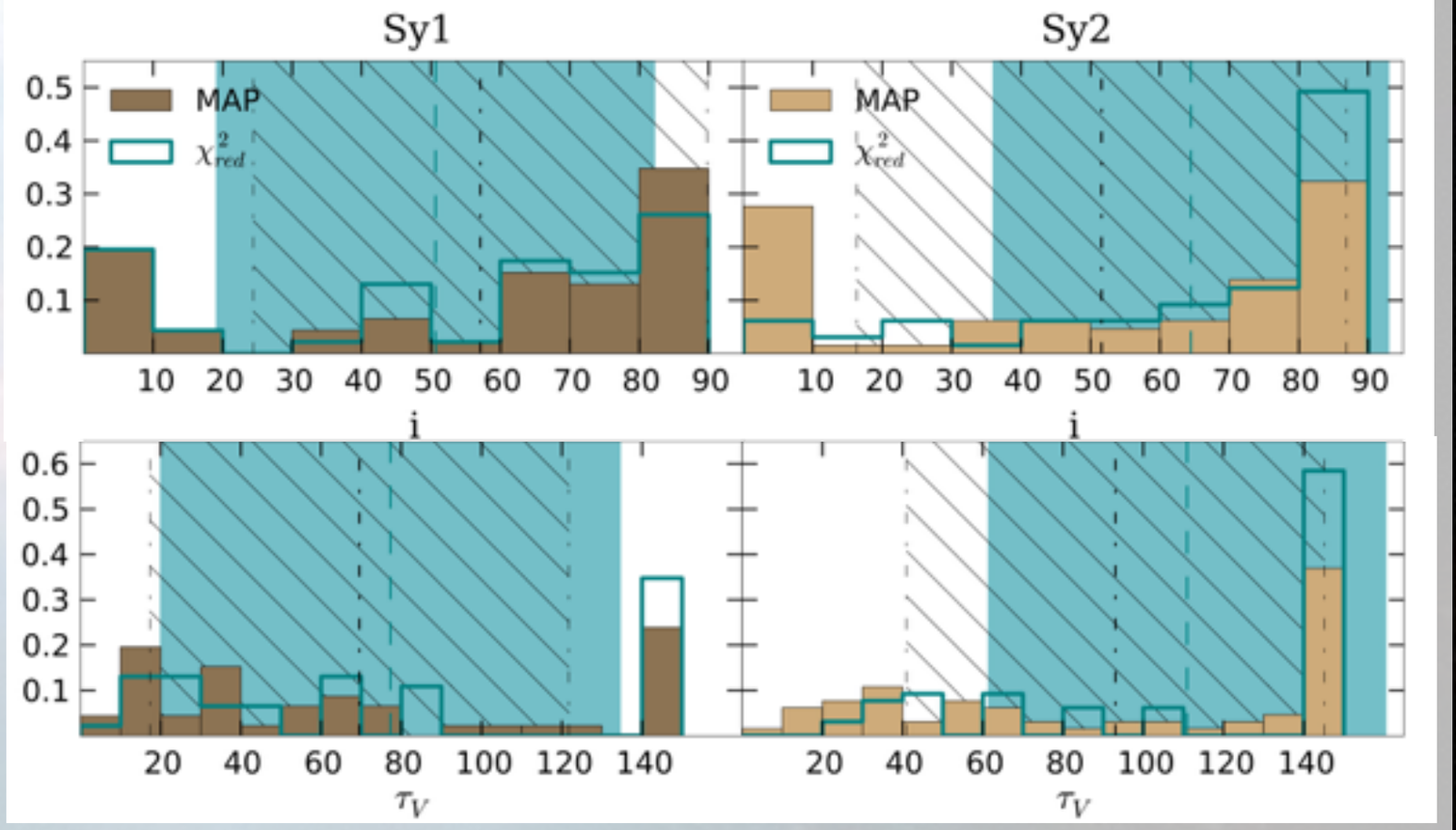
Torus Models and ir sed

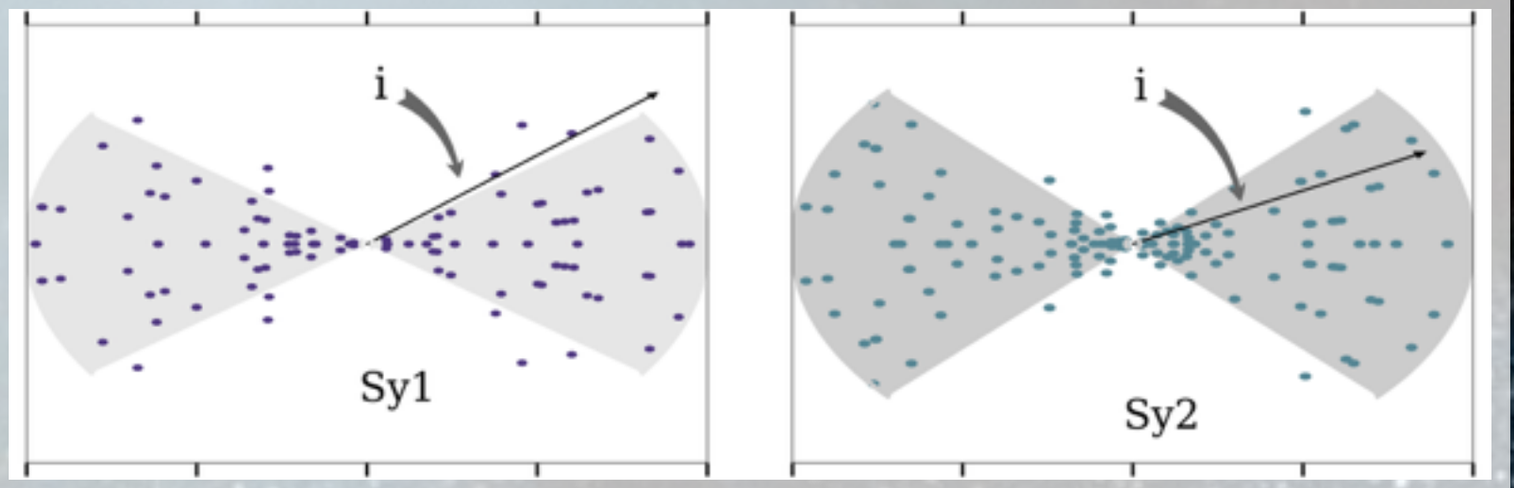
Probing the AGN Unified Model: Torus Properties in Seyfert Galaxies

- IRS Spitzer observations
- 111 galaxies
- CLUMPY models (Nenkova+08)



Audibert+2016





Seyfert 1 = Seyfert 2?

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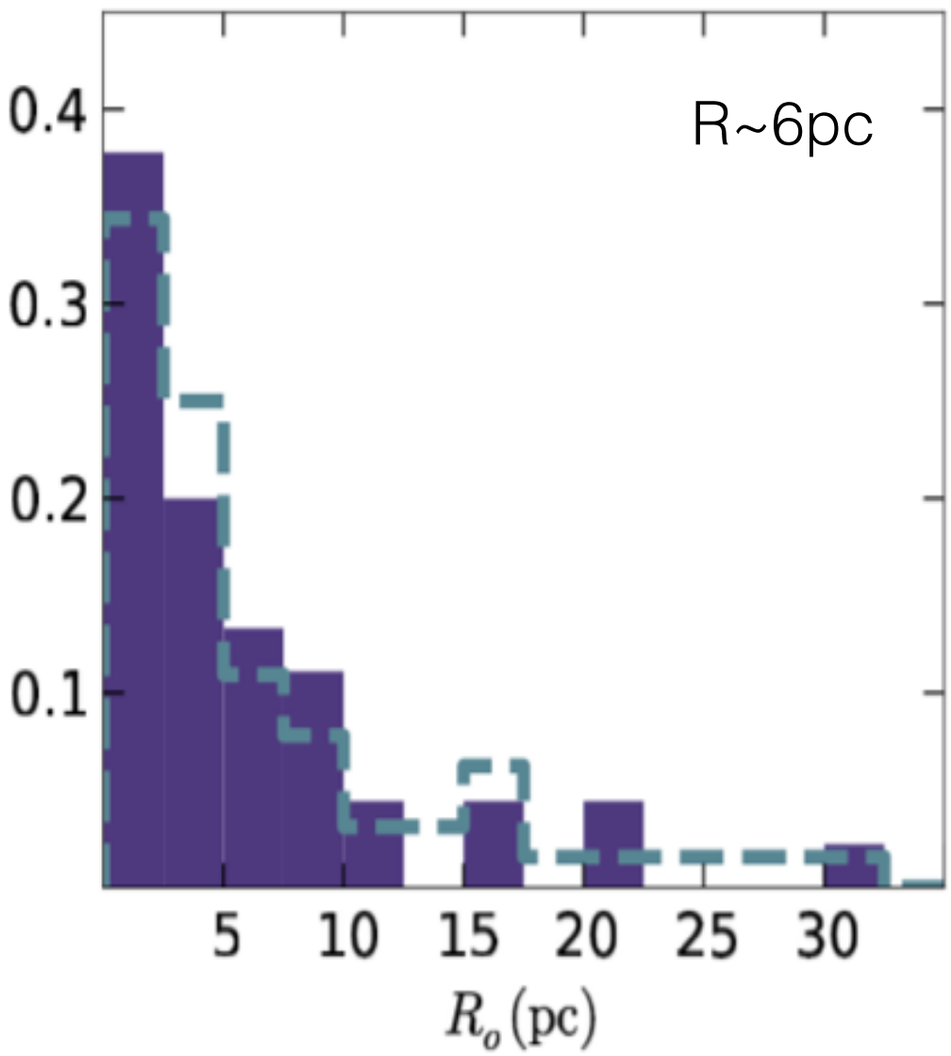

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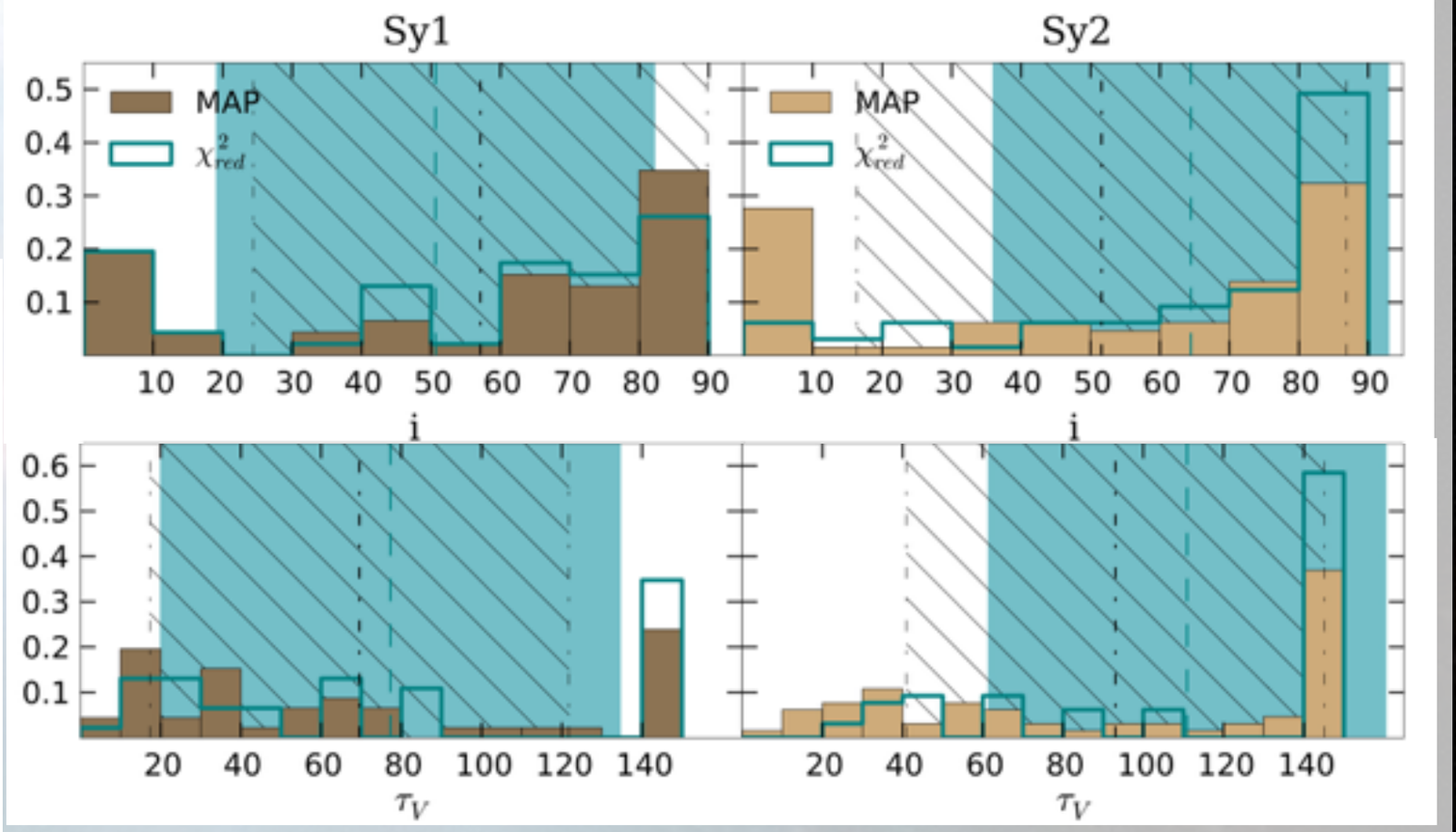
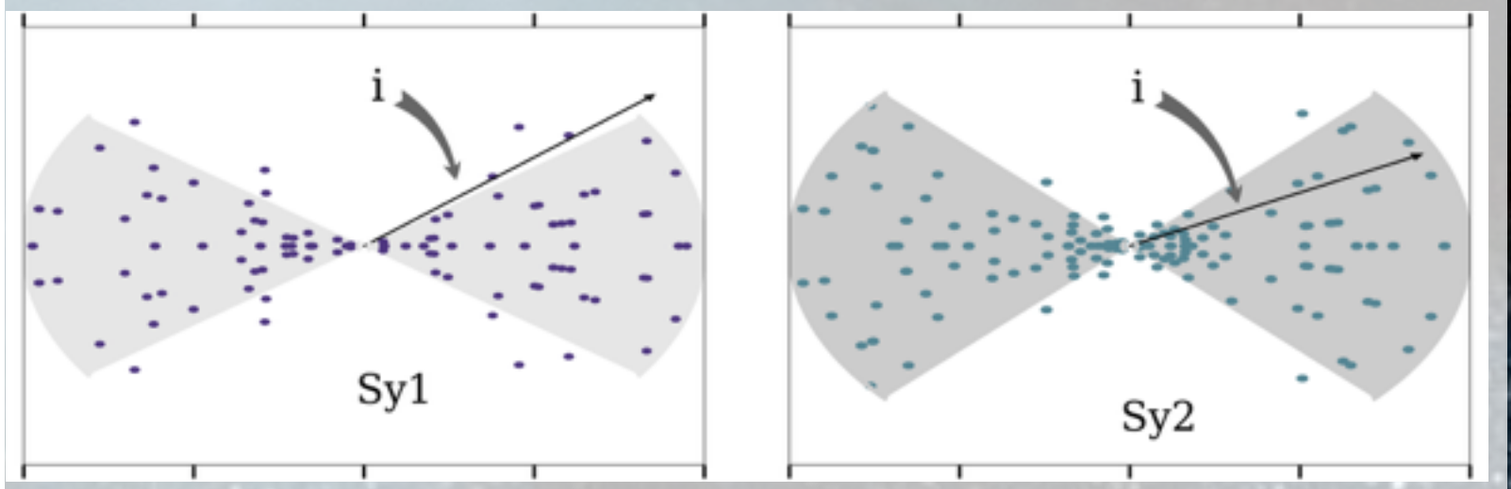




Seyfert 1 = Seyfert 2?

Probing the AGN Unified Model: Torus Properties in Seyfert Galaxies

- IRS Spitzer observations

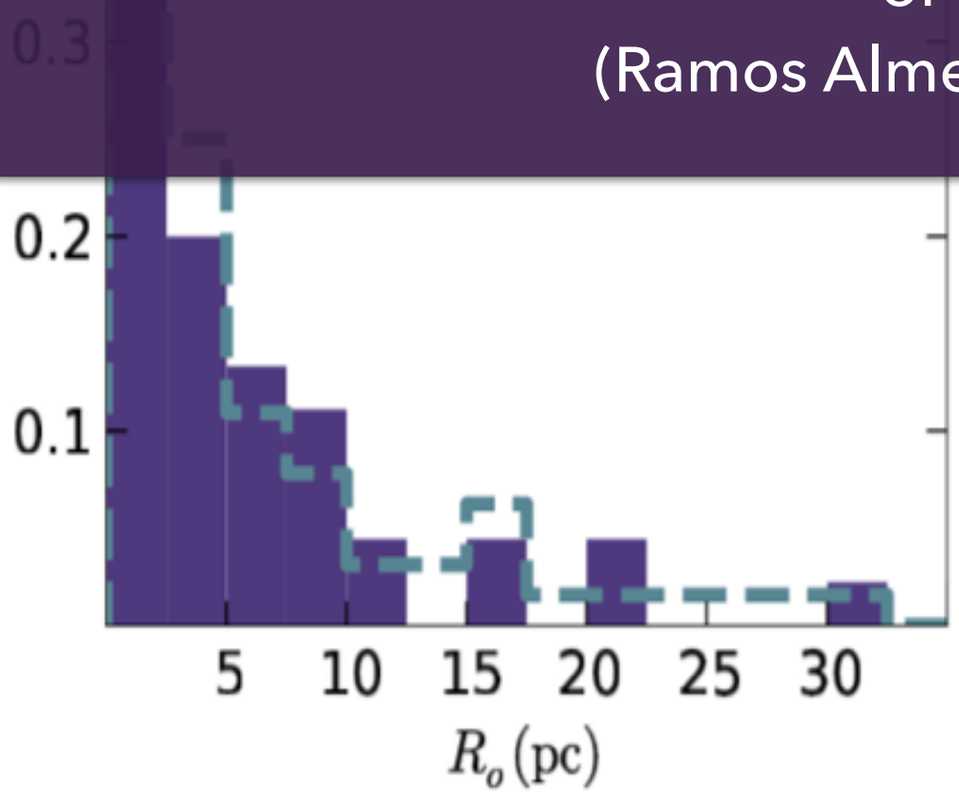
Audibert+2016

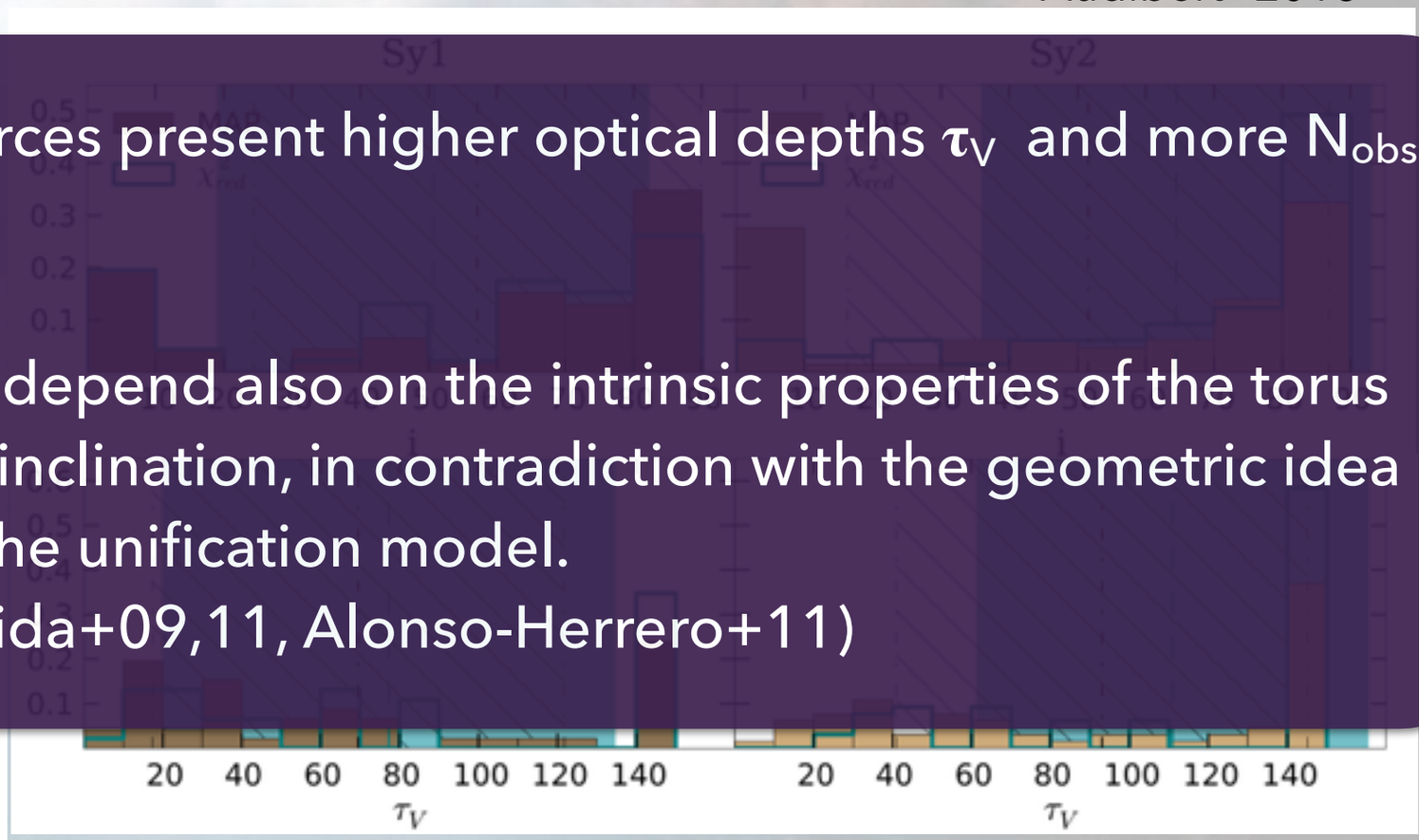
- CLUMPY models (Nenkova+08)

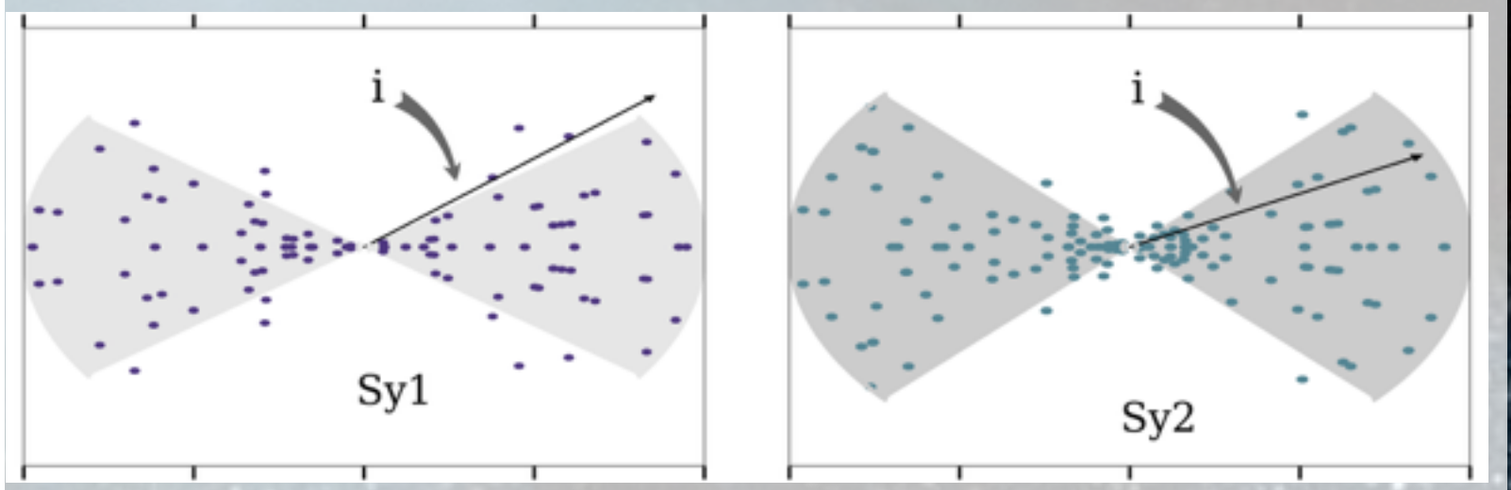
Obscuration properties: type 2 sources present higher optical depths τ_V and more N_{obs}.

The classification of a galaxy may depend also on the intrinsic properties of the torus clouds rather than simply on their inclination, in contradiction with the geometric idea of the unification model.

(Ramos Almeida+09,11, Alonso-Herrero+11)





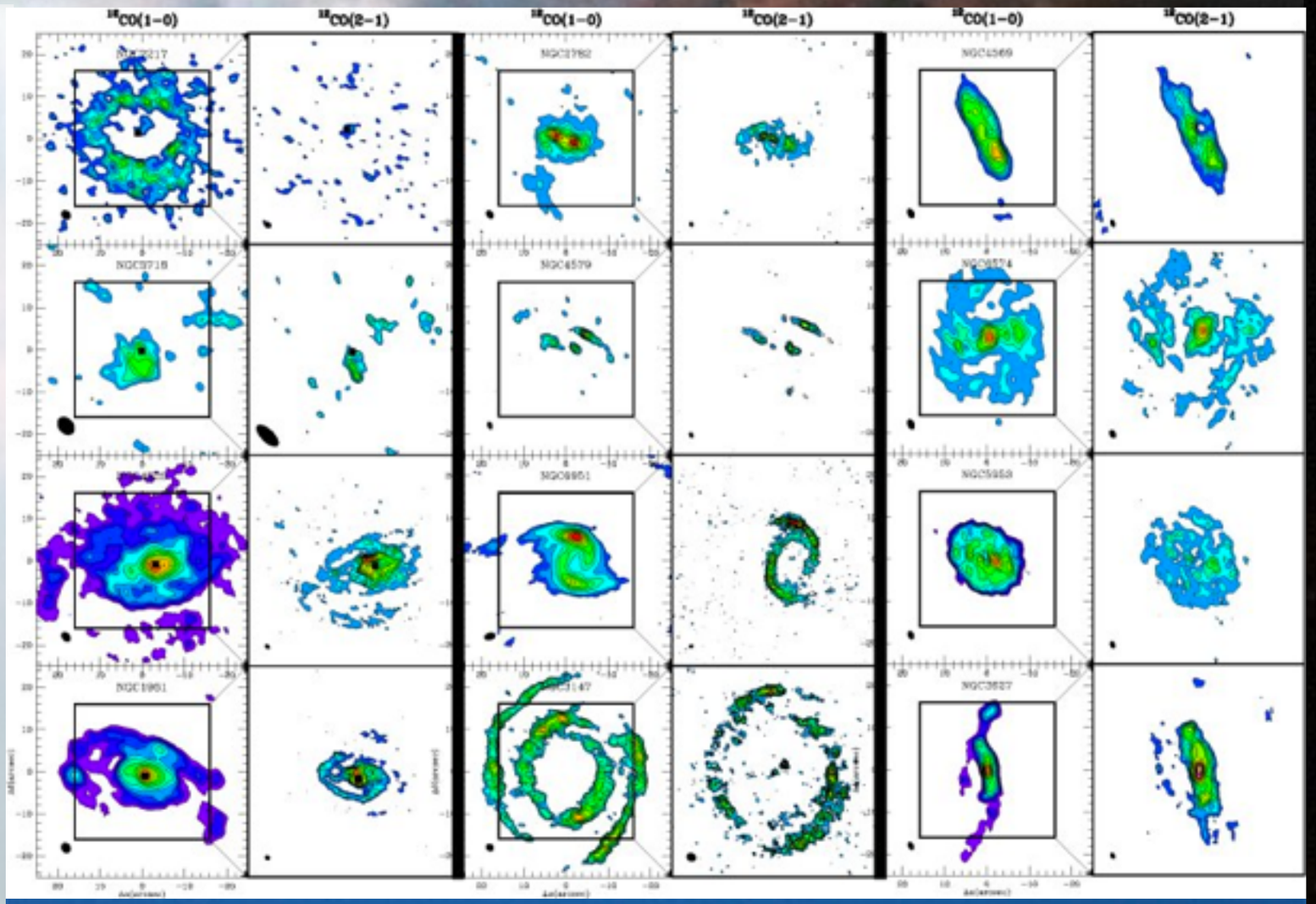


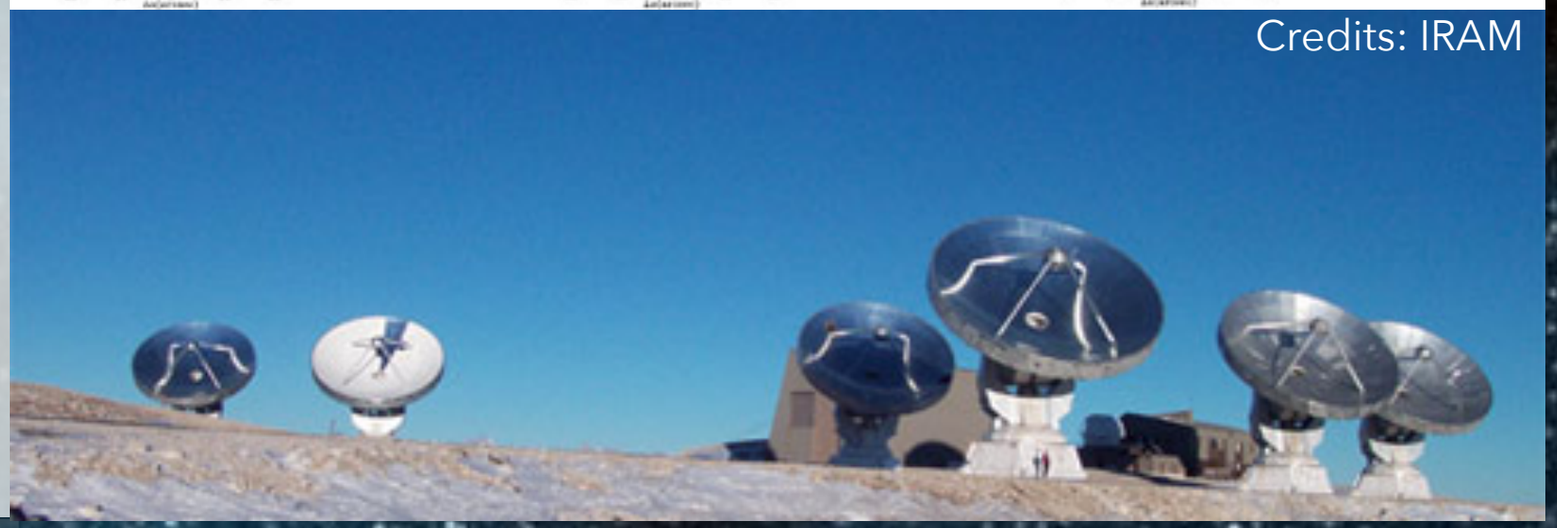
Seyfert 1 = Seyfert 2?

Resolving the Molecular Tori

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 (García-Burillo & Combes 2012)





Credits: IRAM

NUGA with ALMA

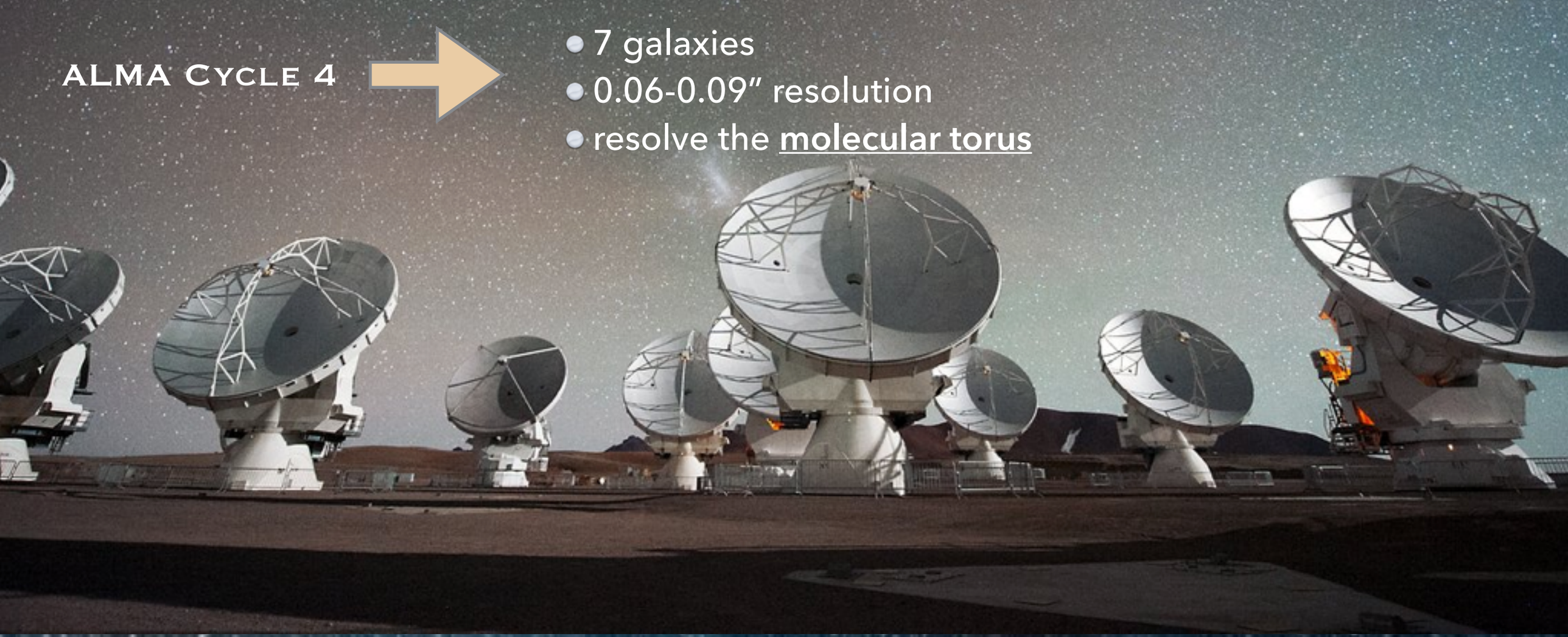
- ALMA Band 7 observations of CO(3-2)

ALMA Cycle 3

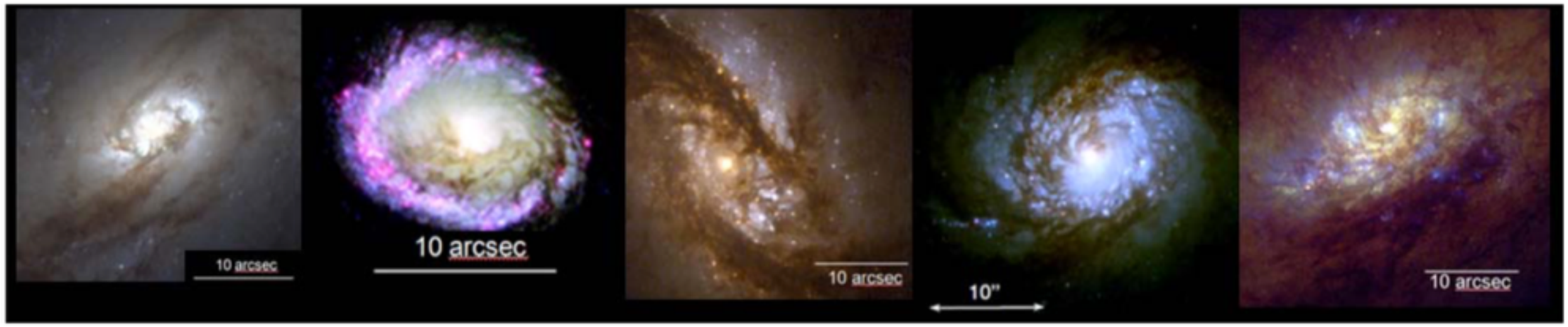
- + dense gas tracers HCN(4-3)/HCO^+(4-3)/CS(7-6)
- 5 galaxies
- 0.14-0.3" resolution
- covering the whole **nuclear disks and rings**.

ALMA Cycle 4

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

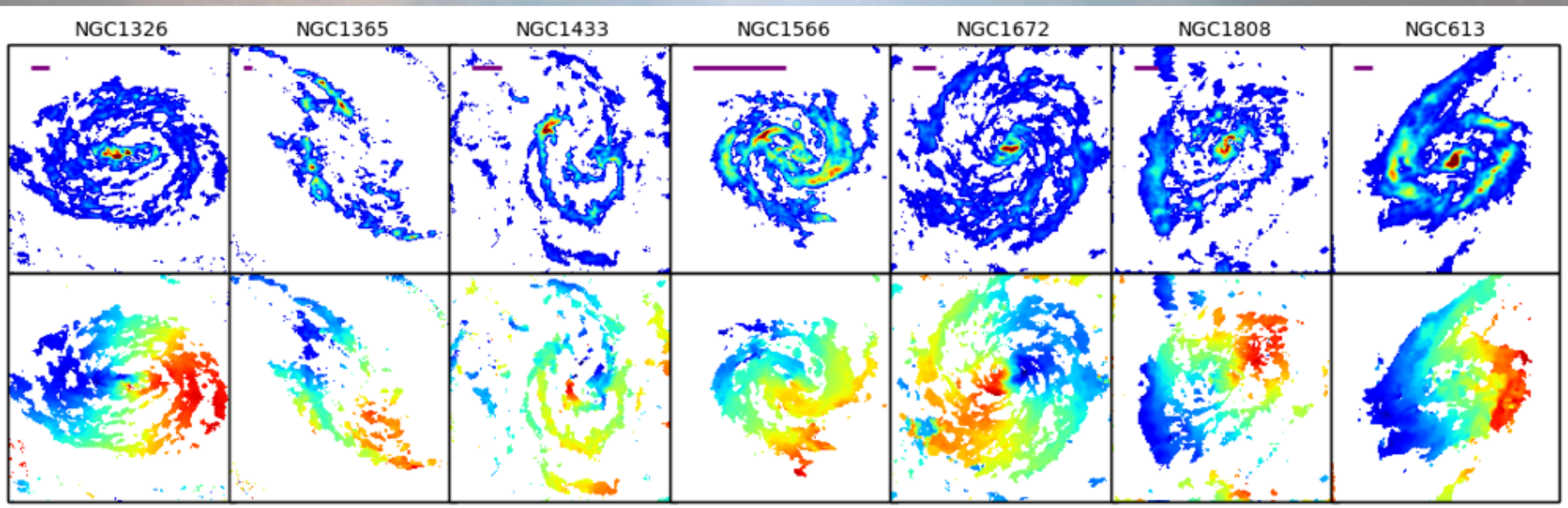


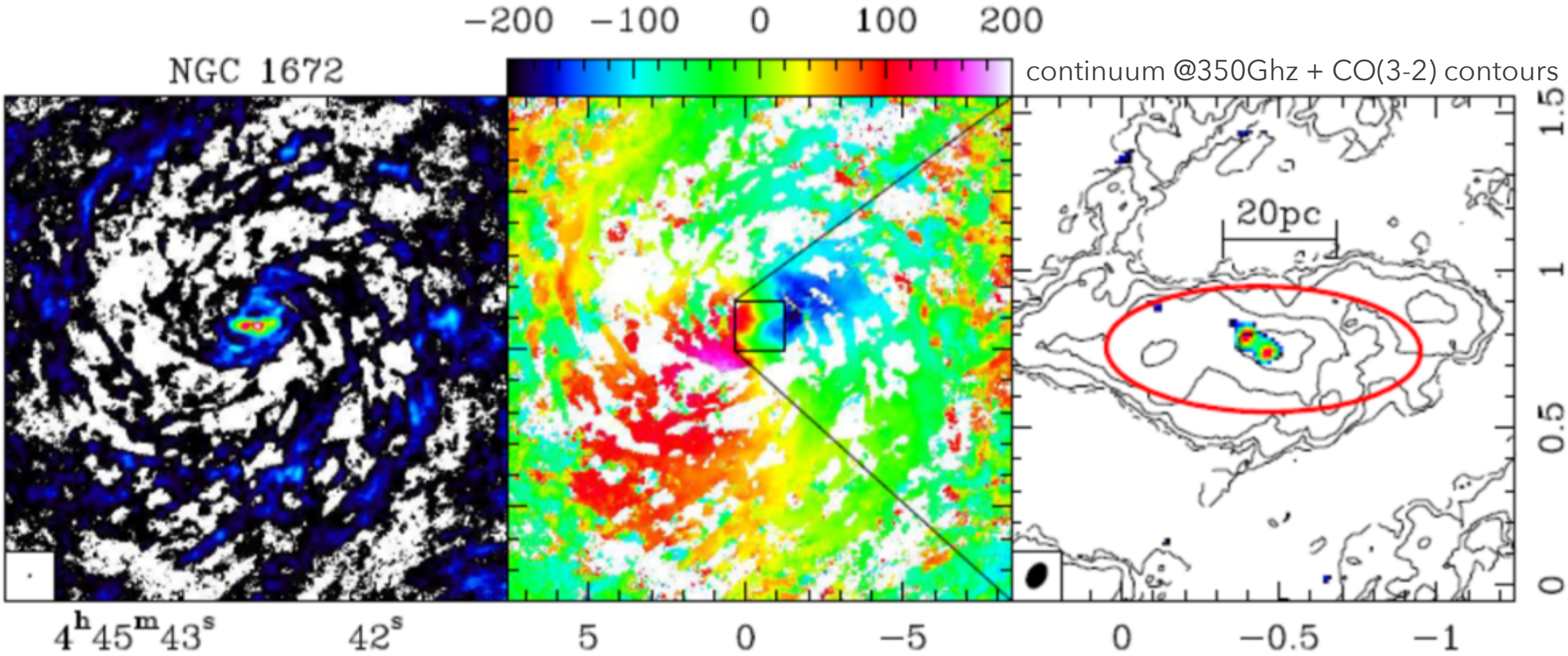
NUGA Sample



span factor of 100 in AGN power, a factor of 10 in SFR

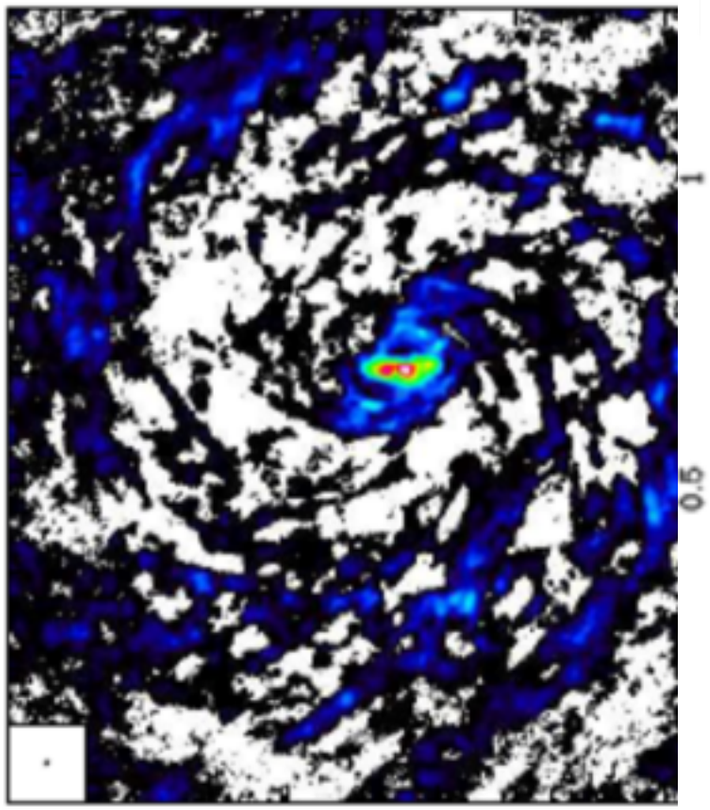
wide range of galaxy inner morphology (with or without double bars, circumnuclear rings)

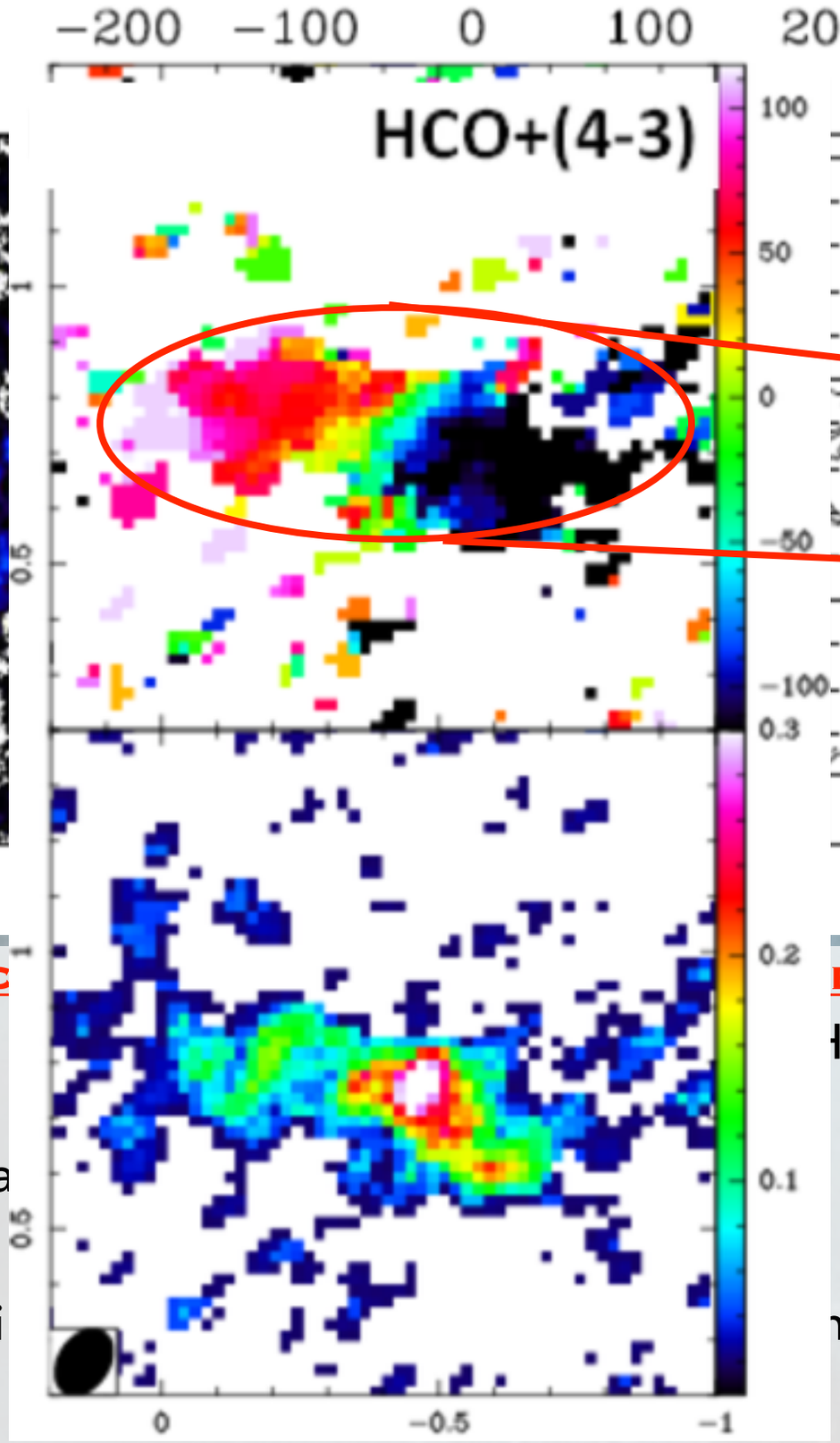


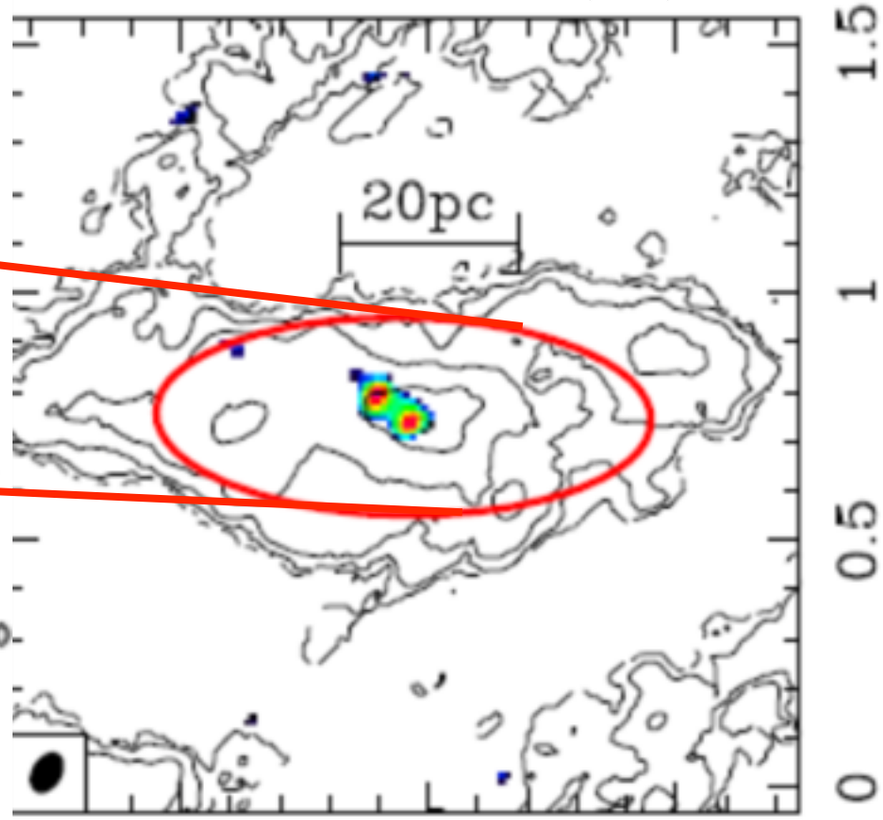


- **COMPACT NUCLEAR DECOUPLED DISK AT 27PC RADIUS: MOLECULAR TORUS**
  (defined by the 0th and 1st moments, and dense gas tracer HCO^+(4-3)
- continuum emission peaks just at the centre
- Inside the ring, some thin filaments join towards a central concentration
- torus has a more edge-on orientation than the large-scale disk: i=66 and PA=0 (Sy2)

Combes, García-Burillo, Audibert+2018







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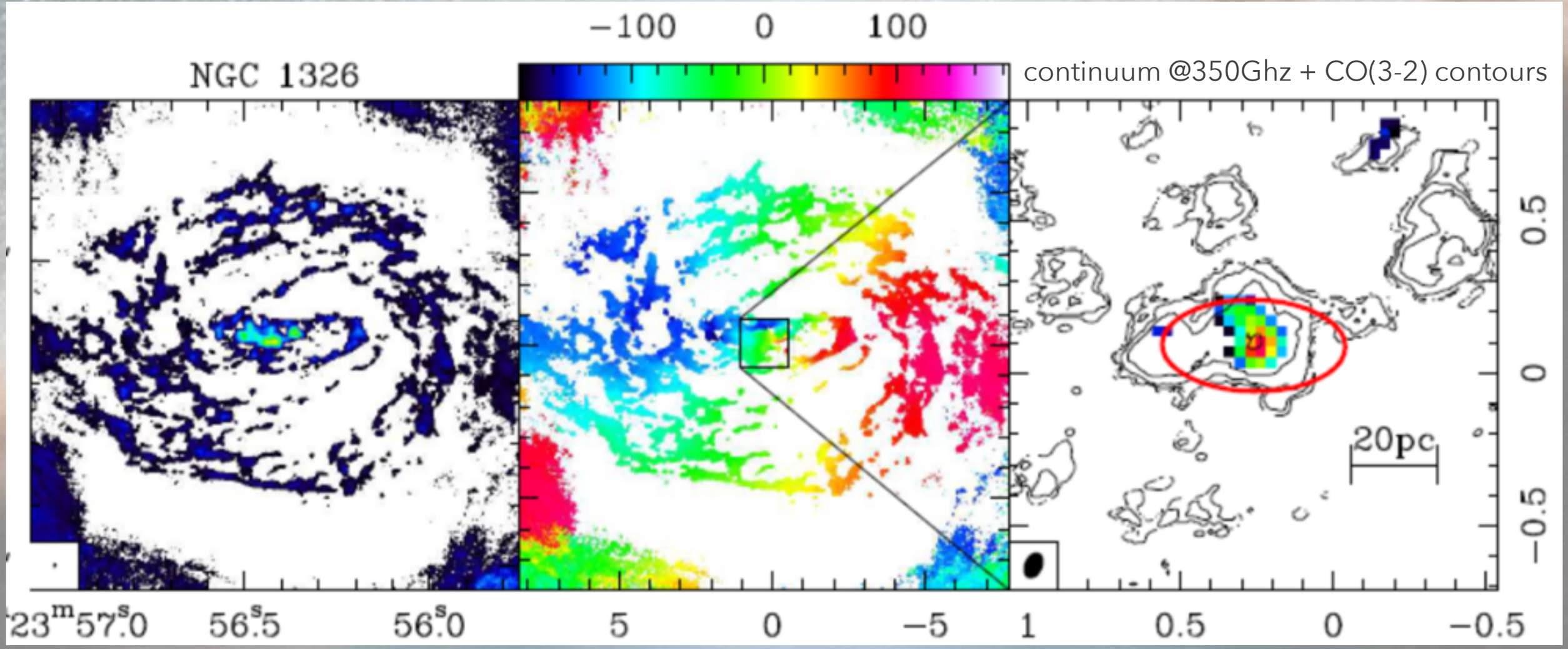
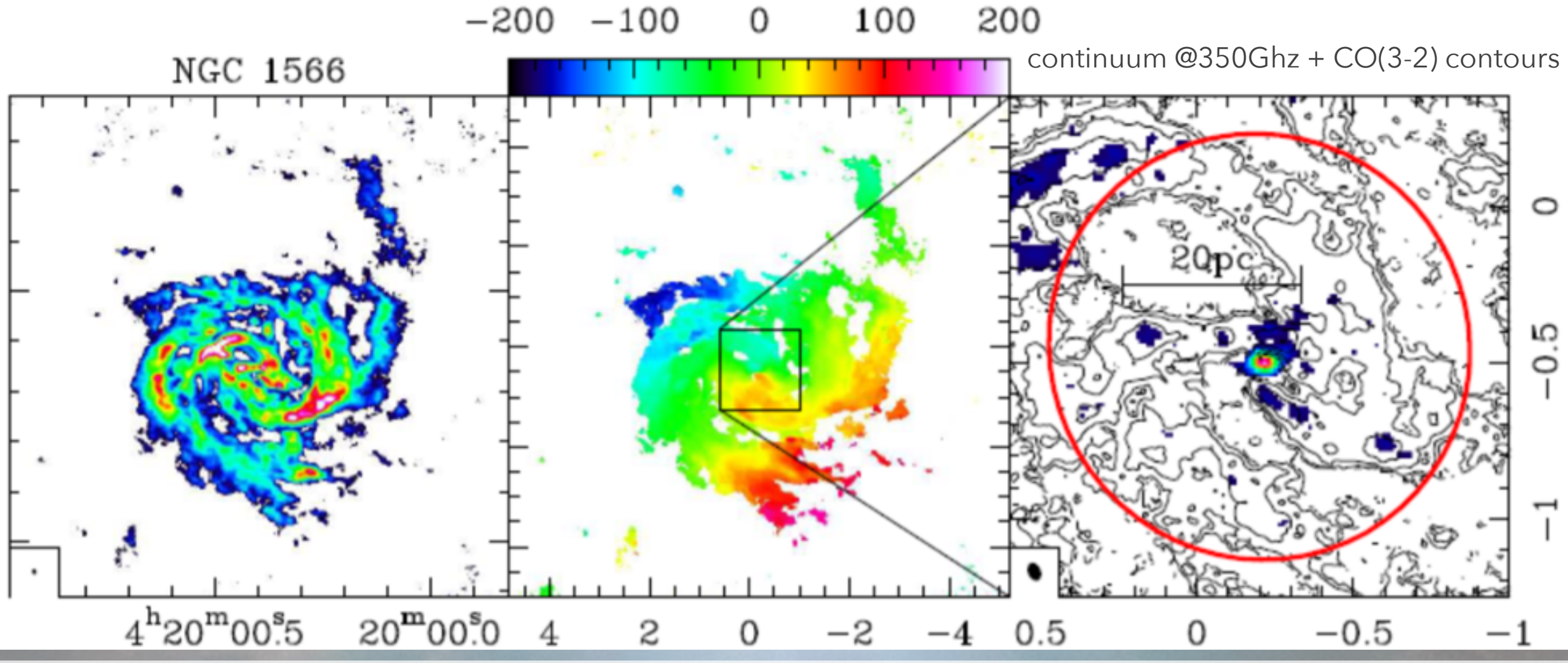
Combes, García-Burillo, Audibert+2018



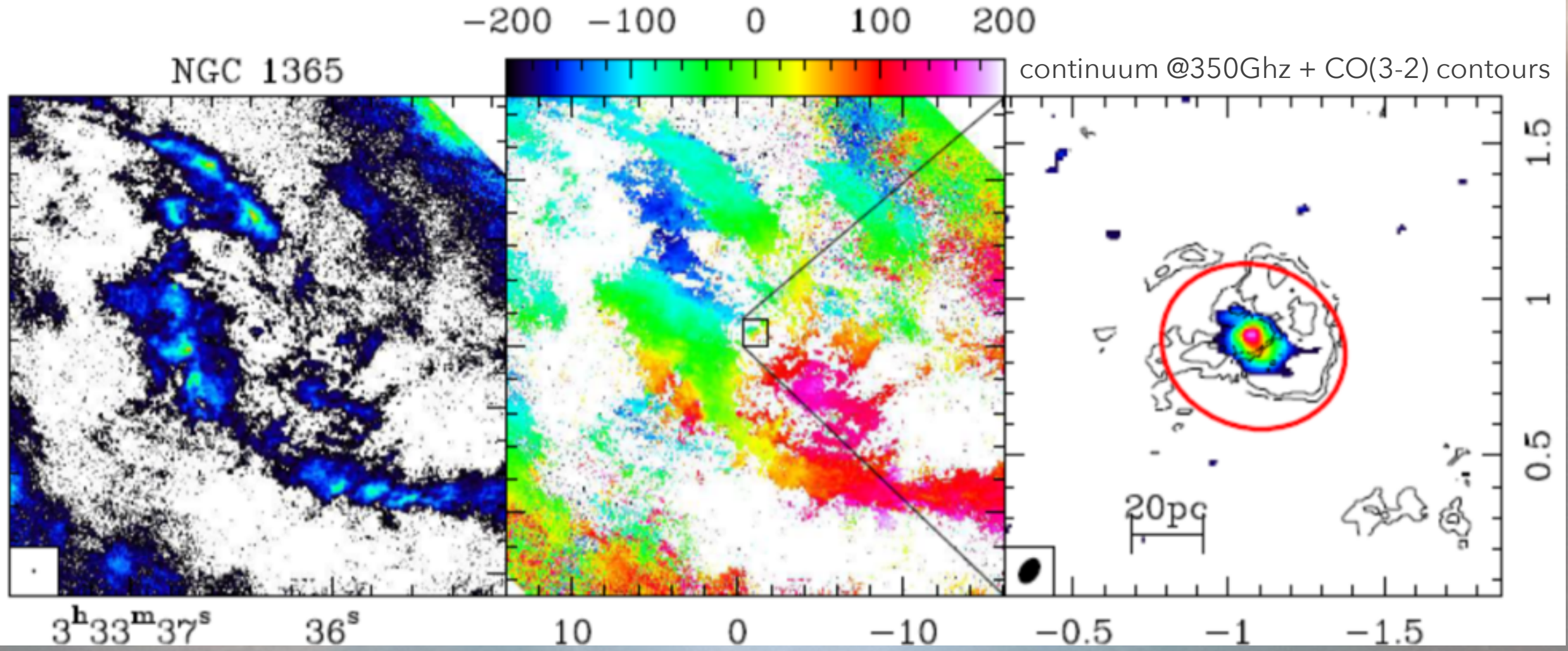
- **21pc radius molecular torus**
- weak continuum source, coinciding with the maximum of the CO(3-2) emission
- very inclined torus: i=60 and PA=90

Combes, García-Burillo, Audibert+2018



- **24pc radius molecular torus**
- extended continuum
- clumpiness emission
- inside the inner spiral fueling the nucleus (50 to 300 pc in size, Combes+2014)

Combes, García-Burillo, Audibert+2018

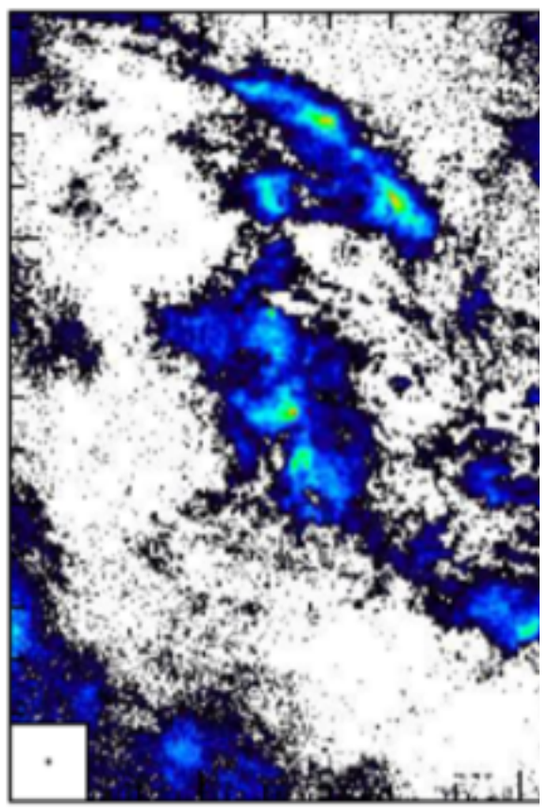


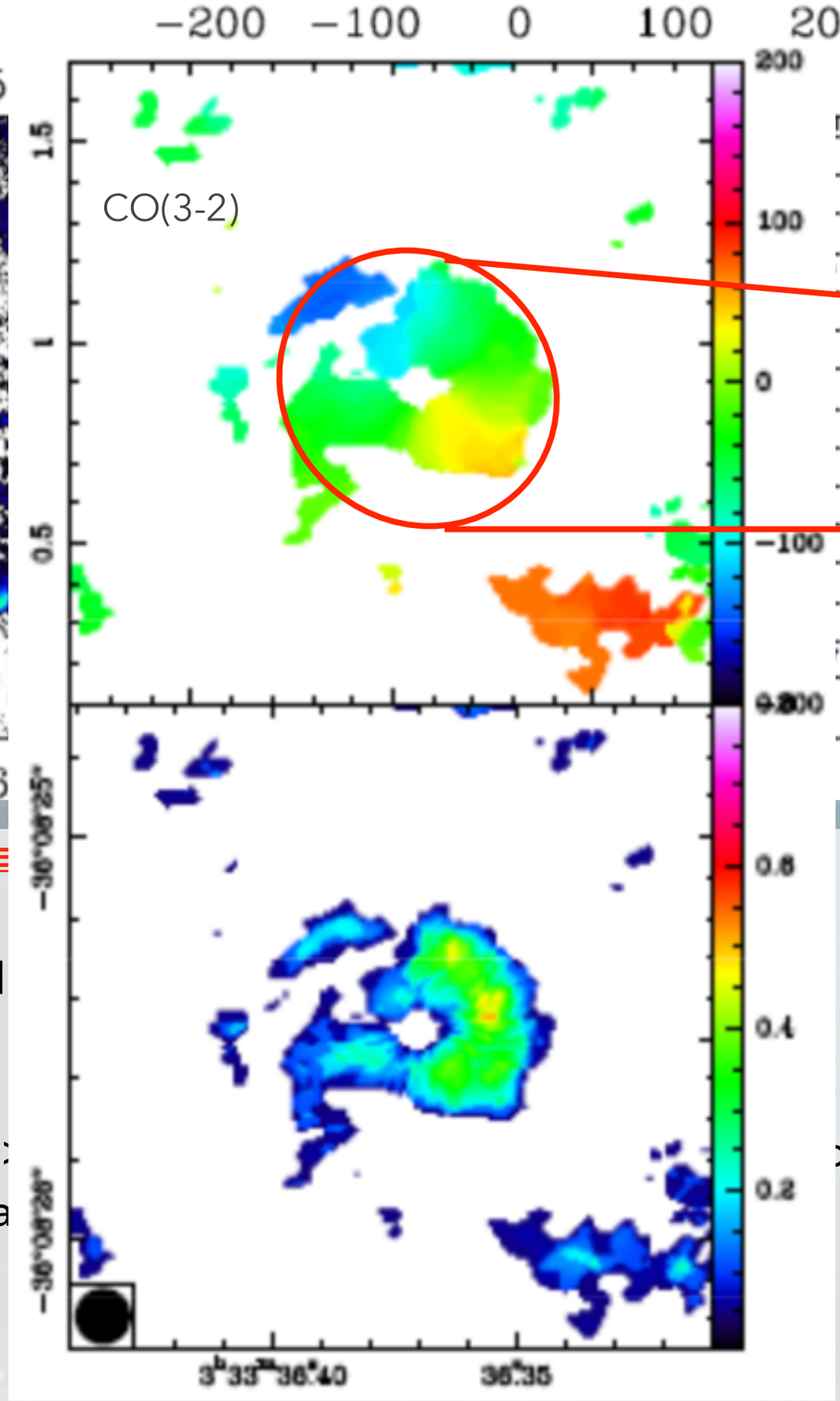
- **26pc radius molecular torus**

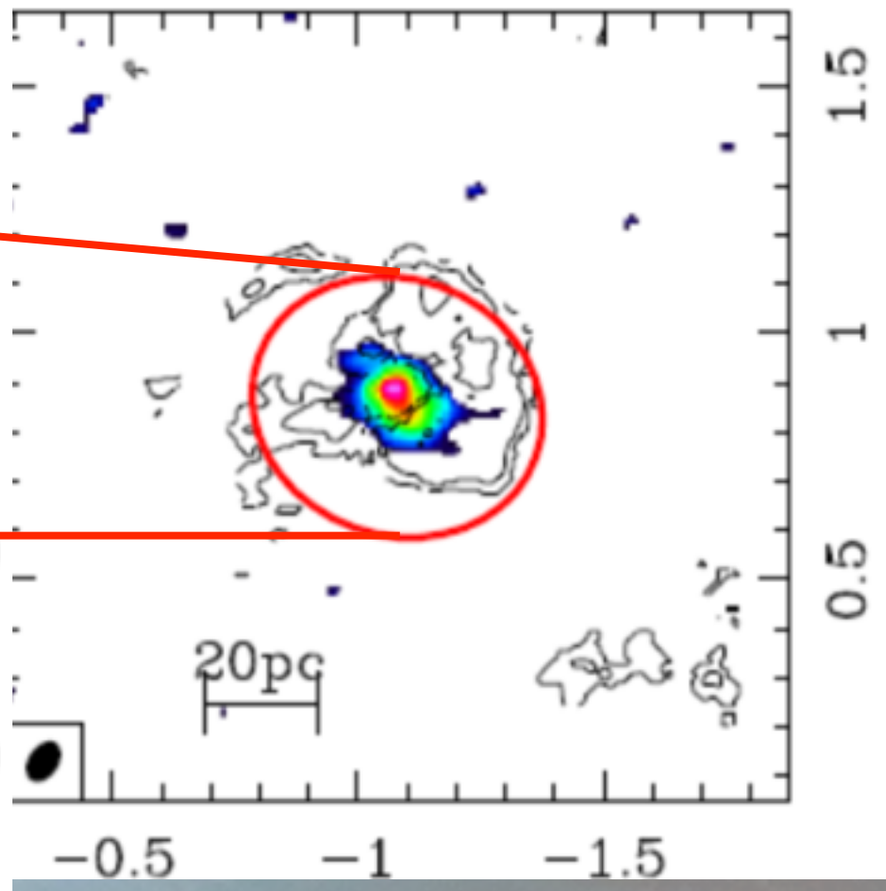
- we detect a central continuum point source

- the only one case -> AGN is centred on the central gas hole of the torus and a rotating ring encircles the central continuum source

Combes, García-Burillo, Audibert+2018

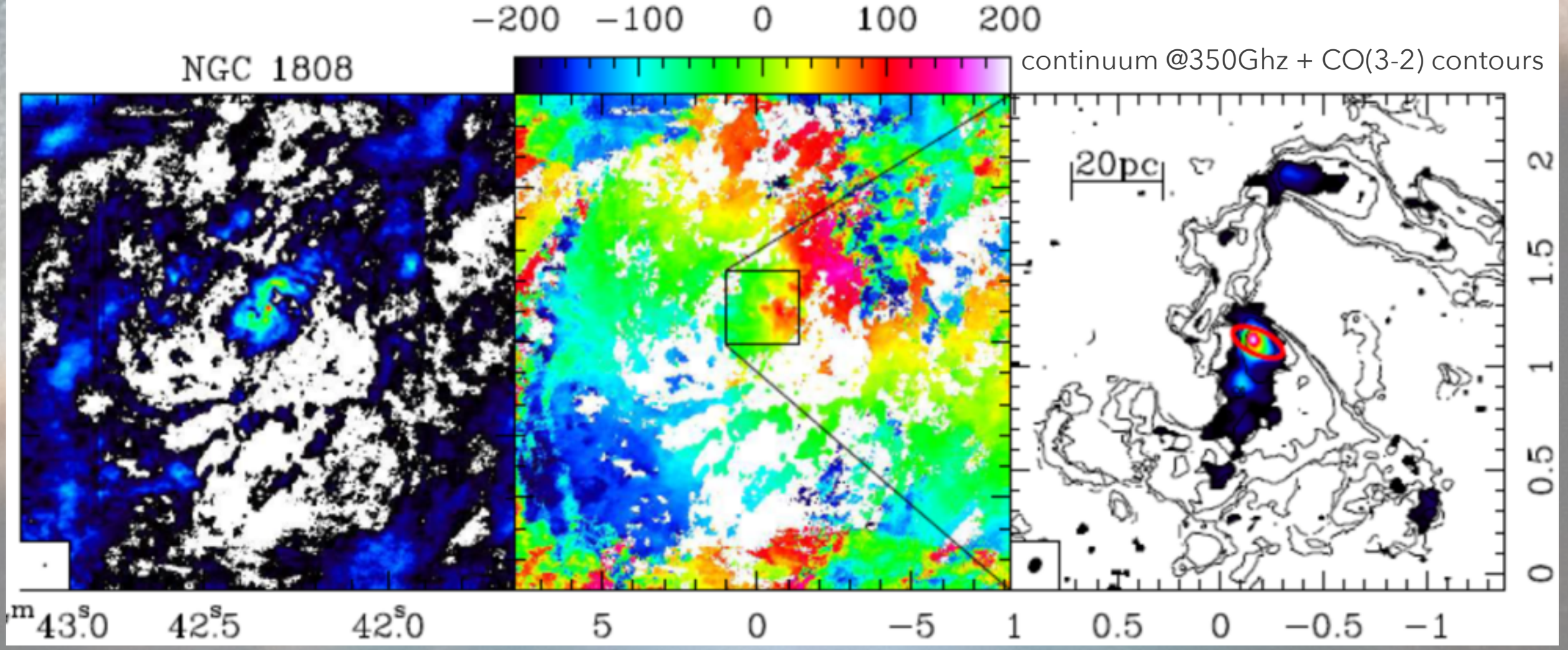






- **26pc radius mole**
- we detect a central
- the only one case -> of the torus and a rotating ring encircles the centra

Combes, García-Burillo, Audibert+2018



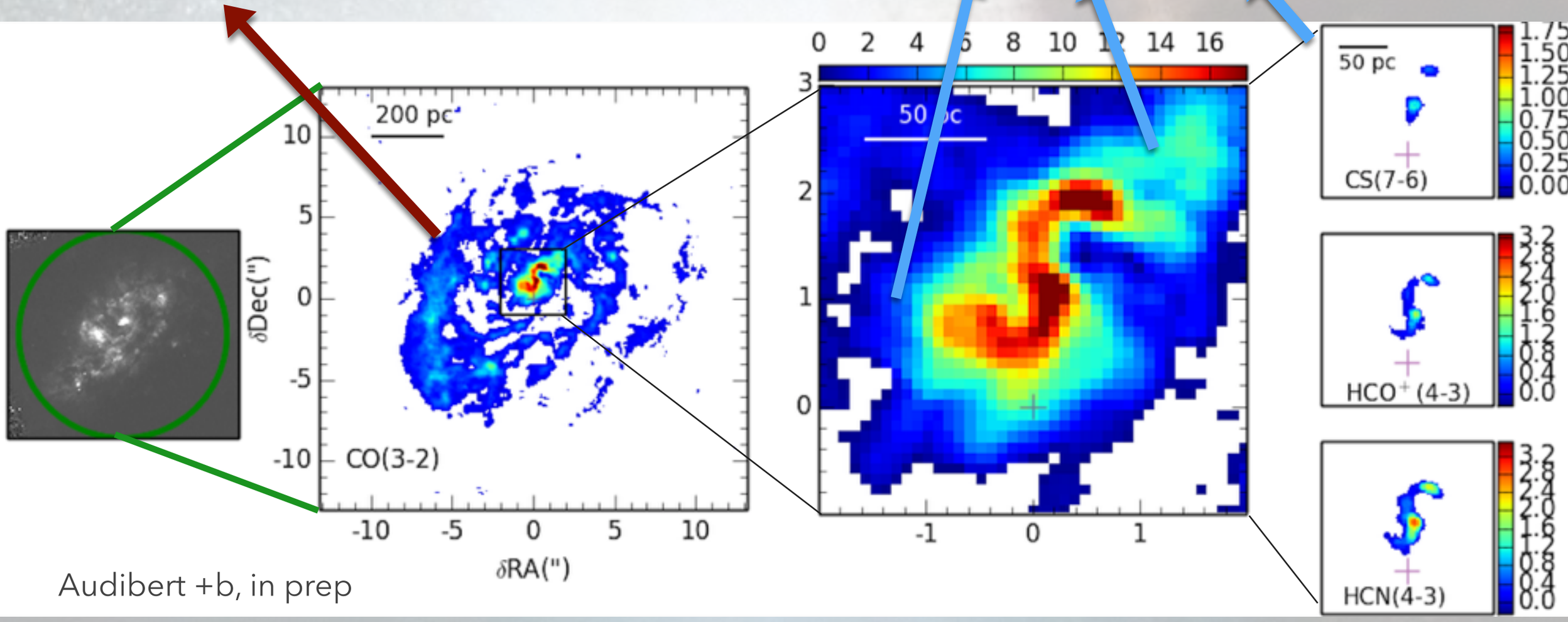
- **6pc radius molecular torus**
- point source continuum
- trailing spiral structure at 100pc scales: fuelling

Combes, García-Burillo, Audibert+2018

NGC 1808

Trailing 2-arm spiral

Star-forming ring at 450pc



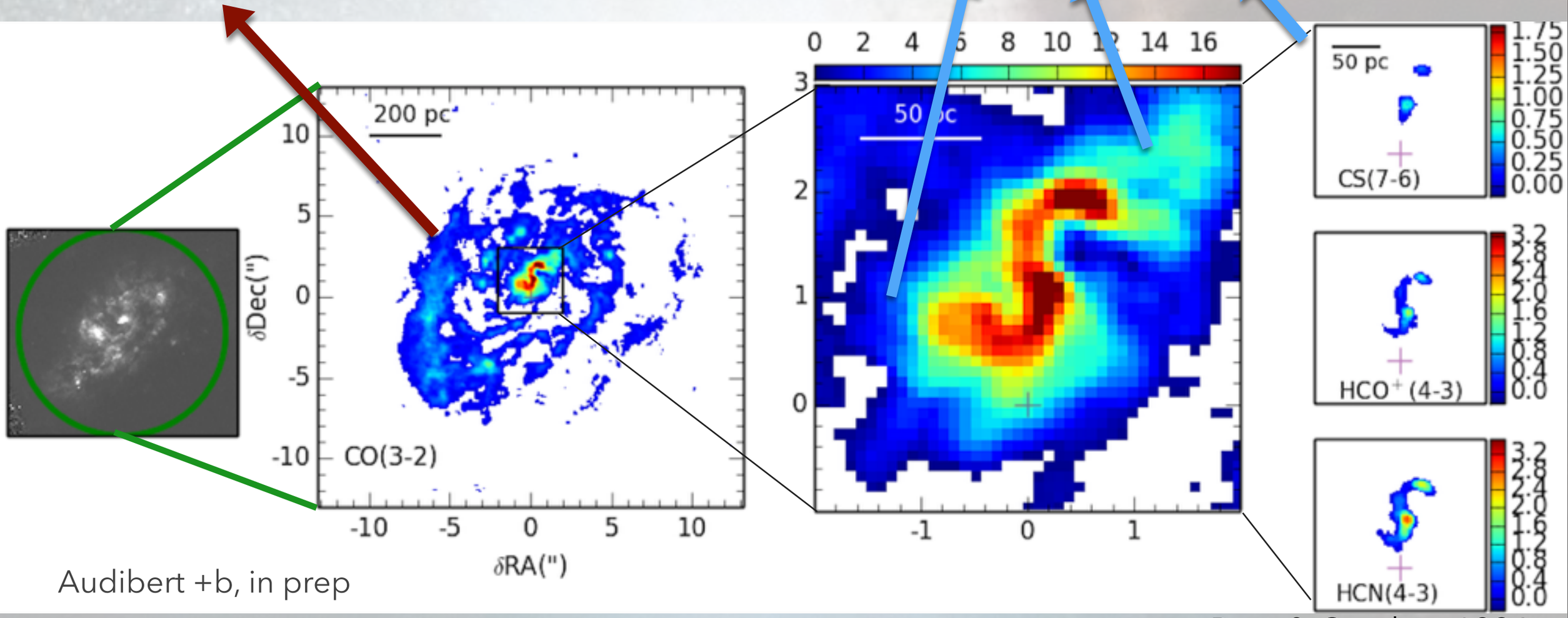
Audibert +b, in prep

- 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

NGC 1808

Star-forming ring at 450pc

Trailing 2-arm spiral



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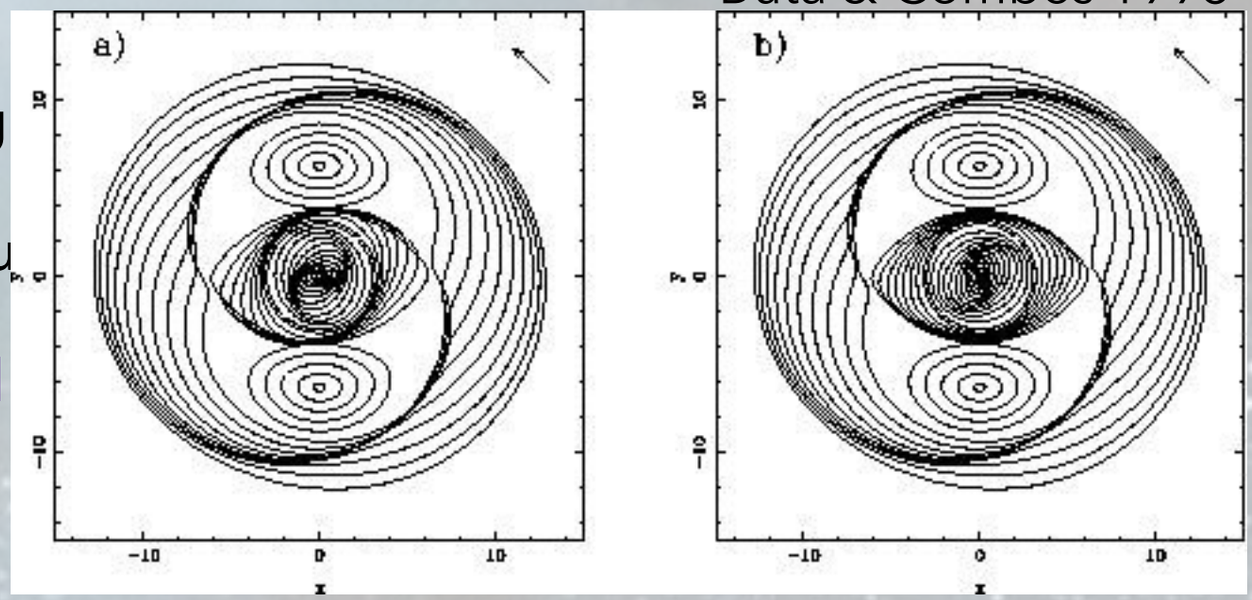
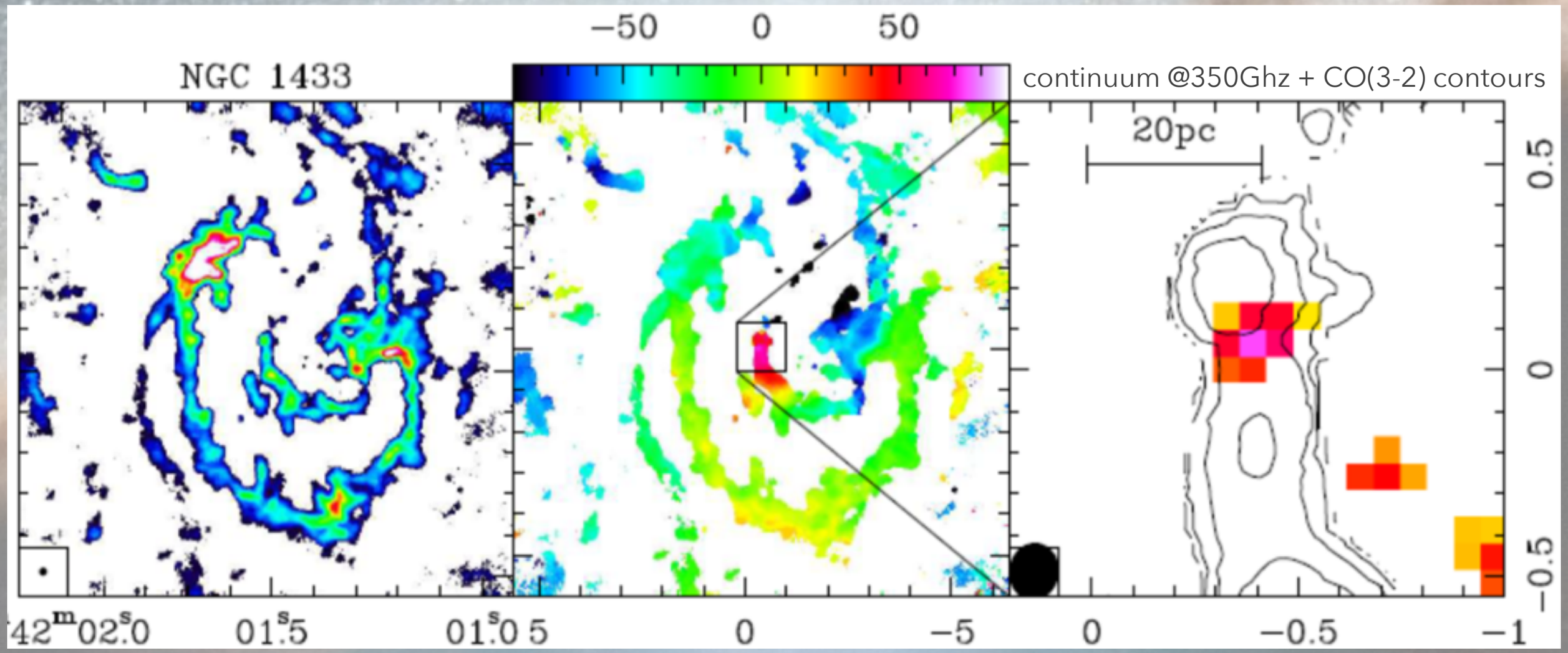
Buta & Combes 1996

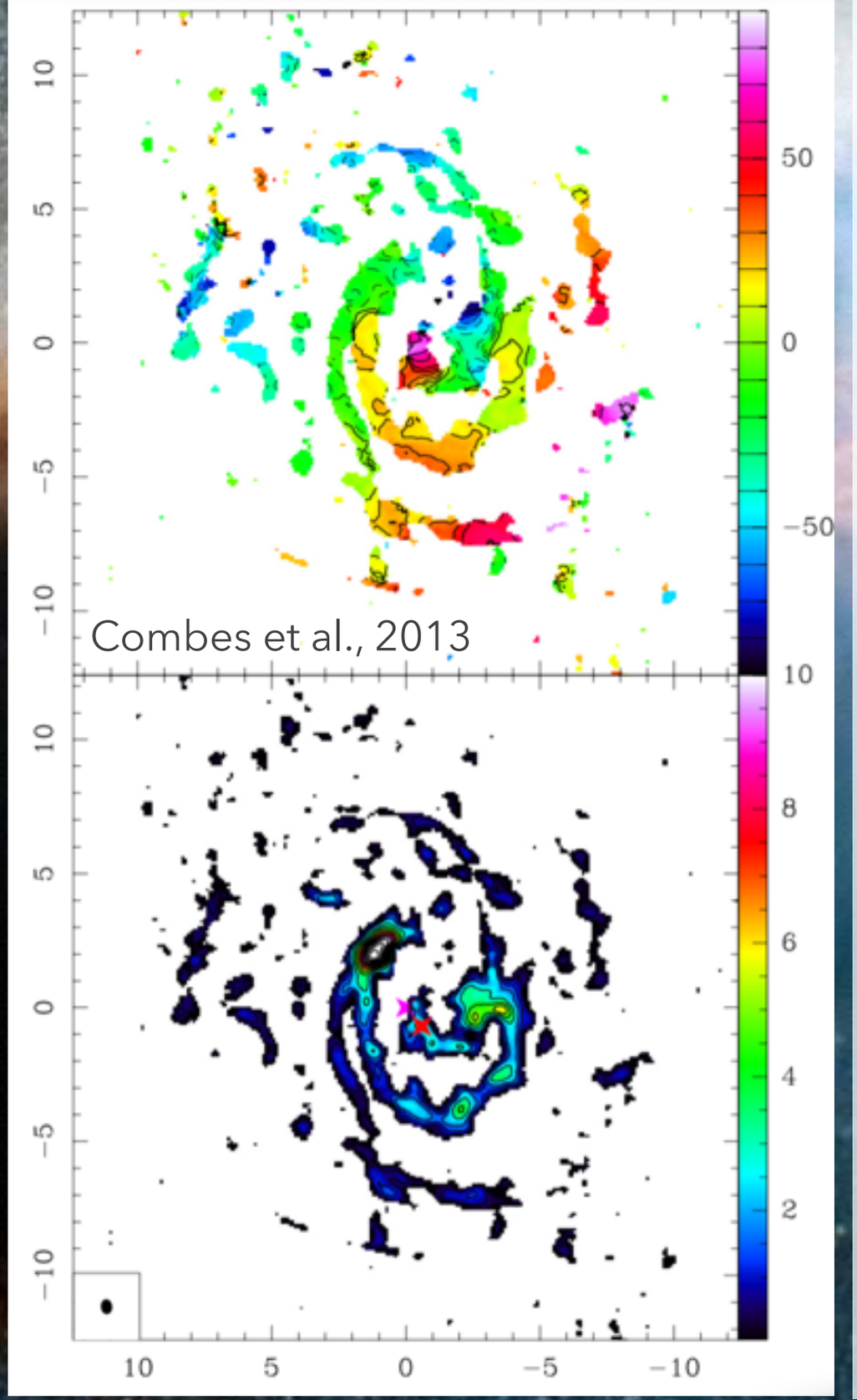




- **No evidence for a molecular torus**
- The tentative continuum point source near the center is not confirmed
- “Lord of Rings”: nuclear, inner and outer rings
- mild molecular outflow (ALMA Cycle 0, Combes+2014)

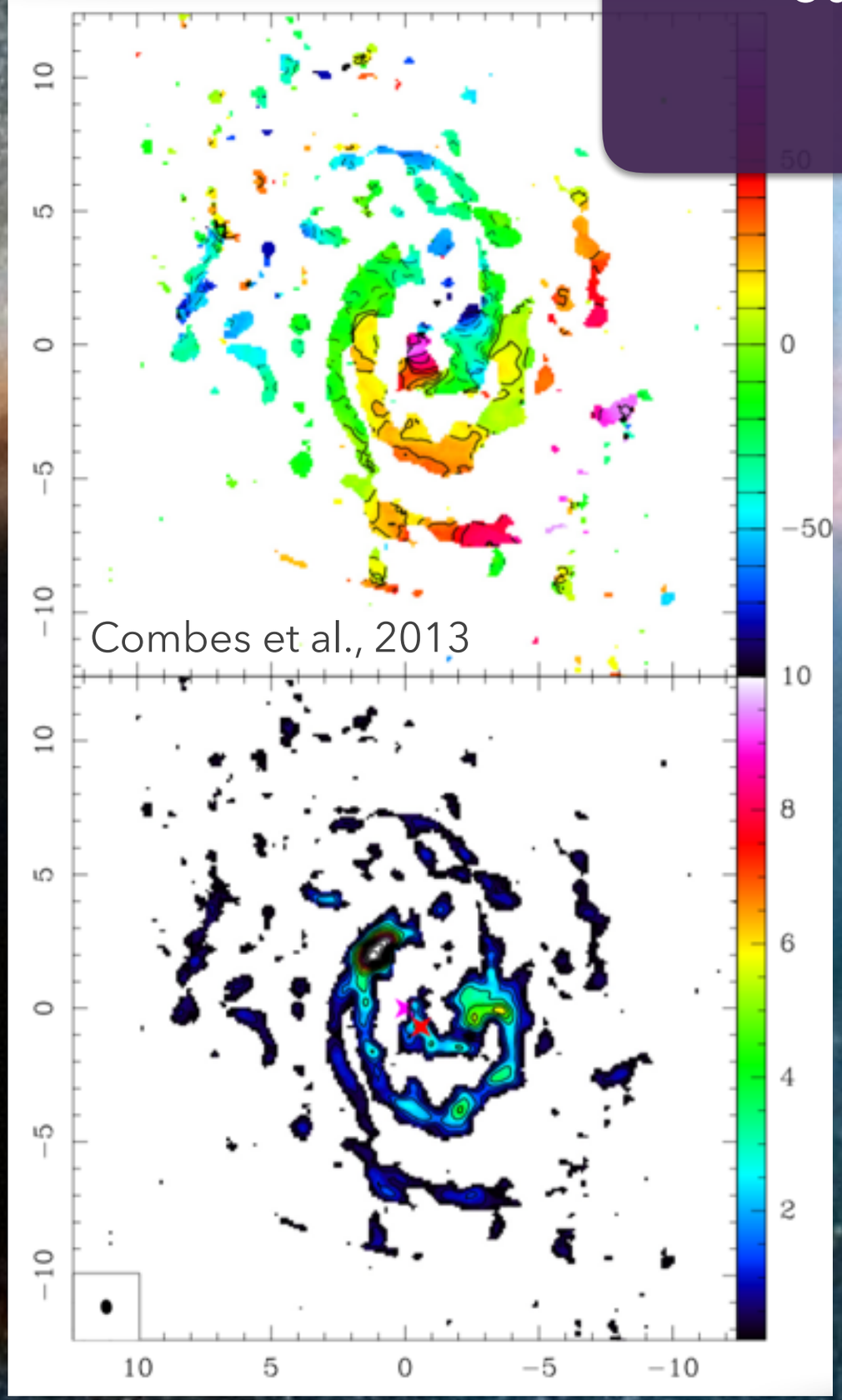
Combes, García-Burillo, Audibert+2018

NGC1433



- velocity field well described by rotation
- noticeable **redshifted** perturbation at the very **center** (~100pc extent)
- After subtraction of rotation field: 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~0.2$M_\odot$/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)

NGC 1433



outflow in a previous more powerful phase has destroyed a potential torus?

- velocity field well described by rotation
- noticeable redshifted perturbation at the very **center** (~100pc extent)

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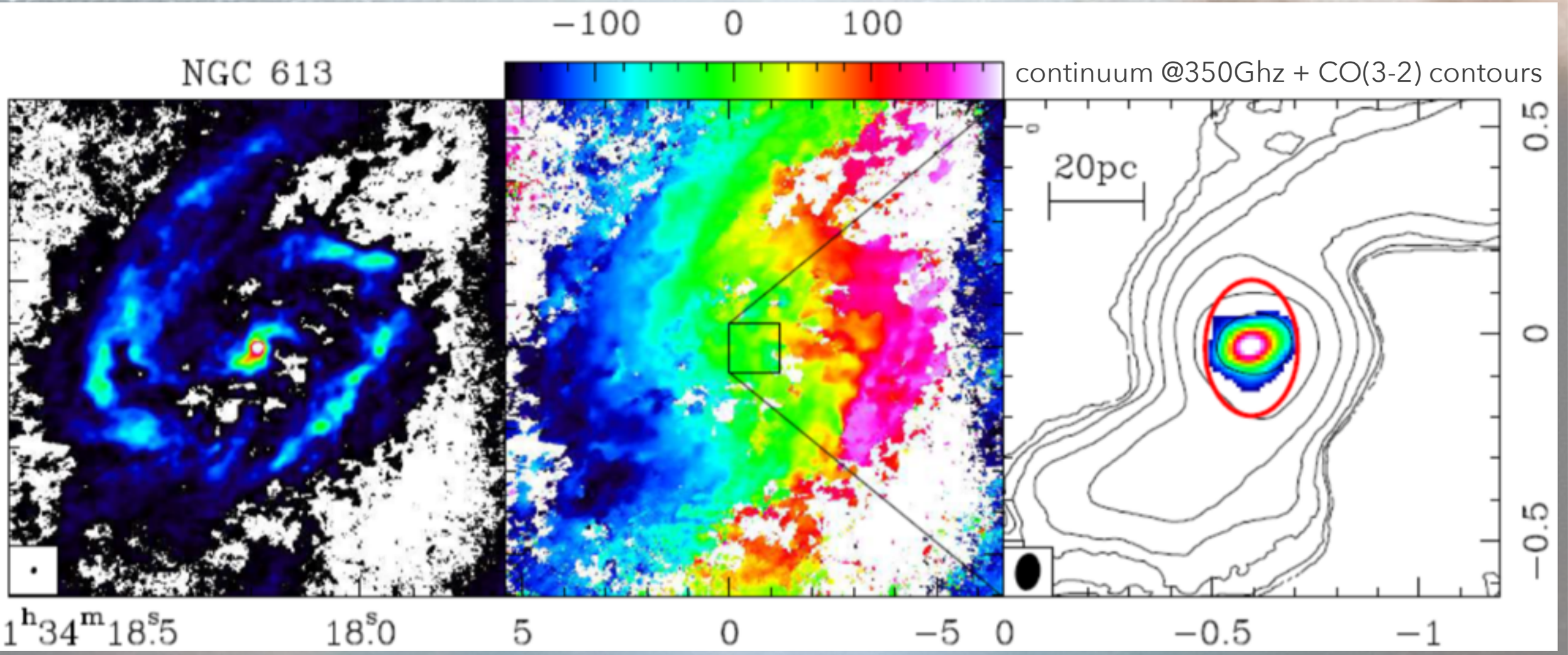
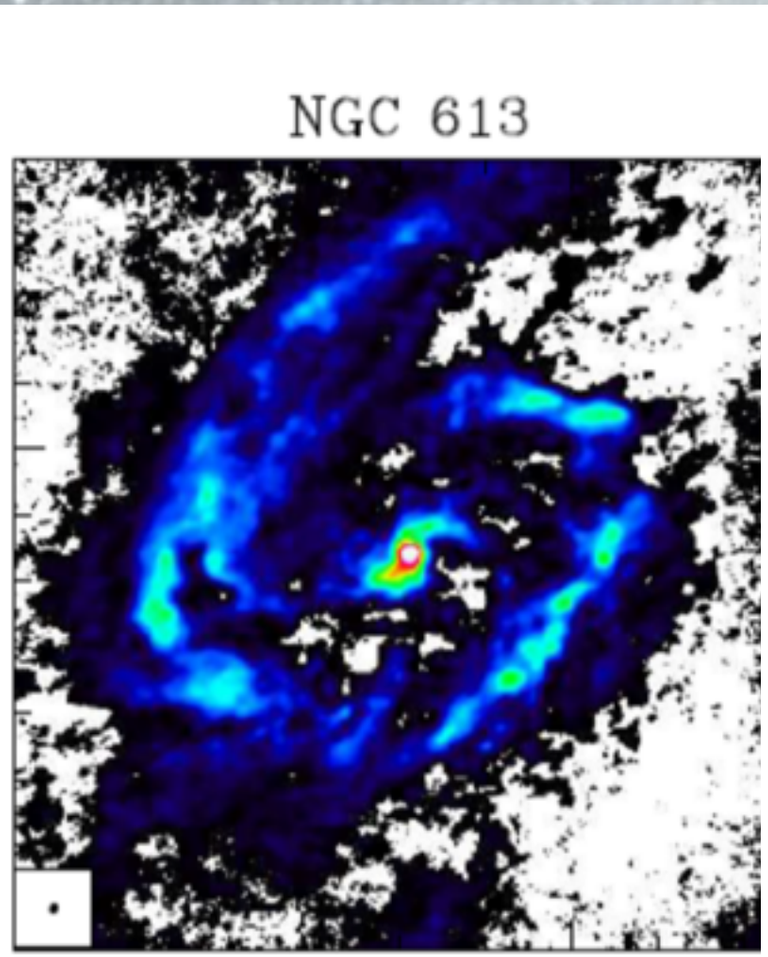
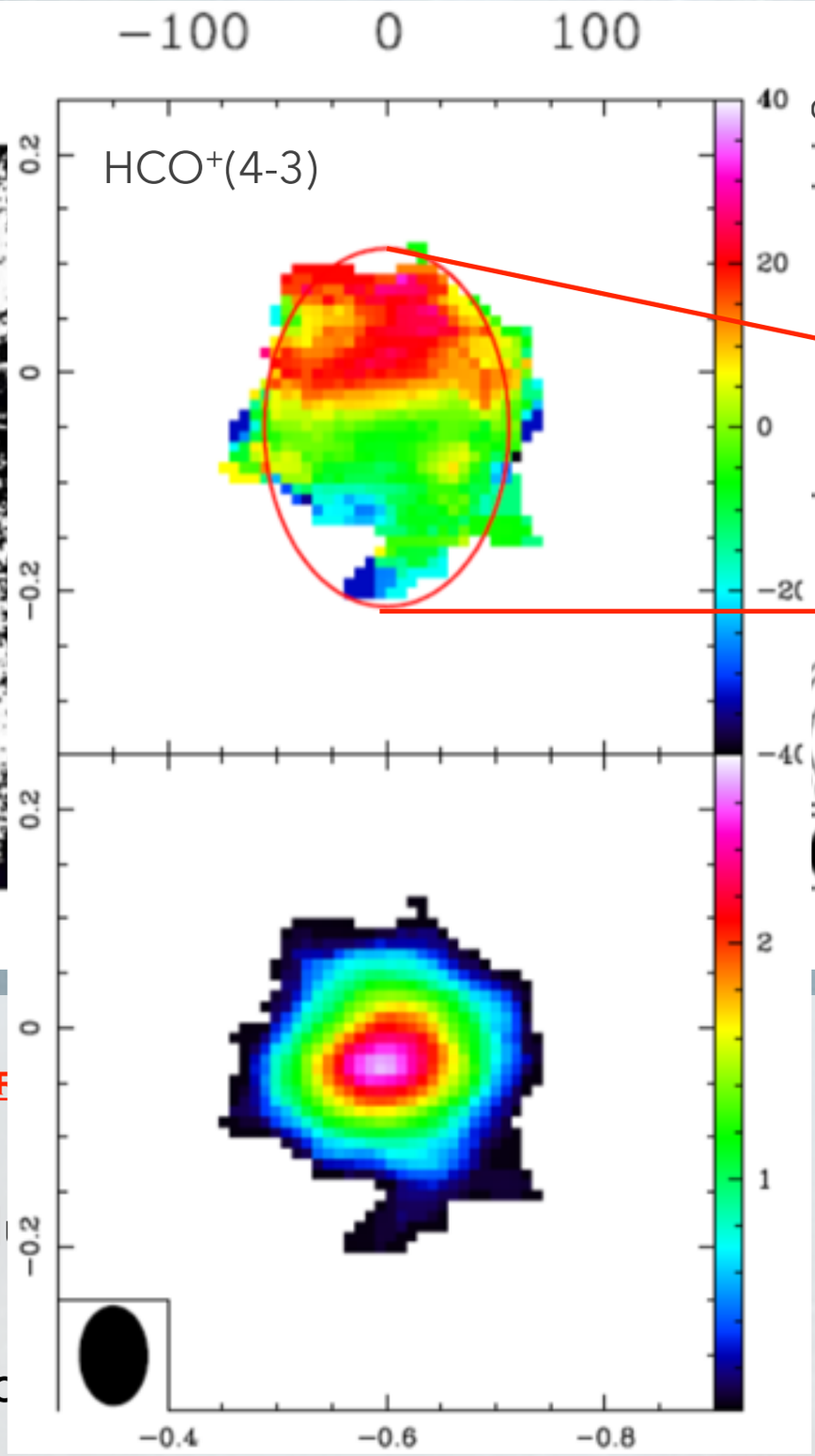
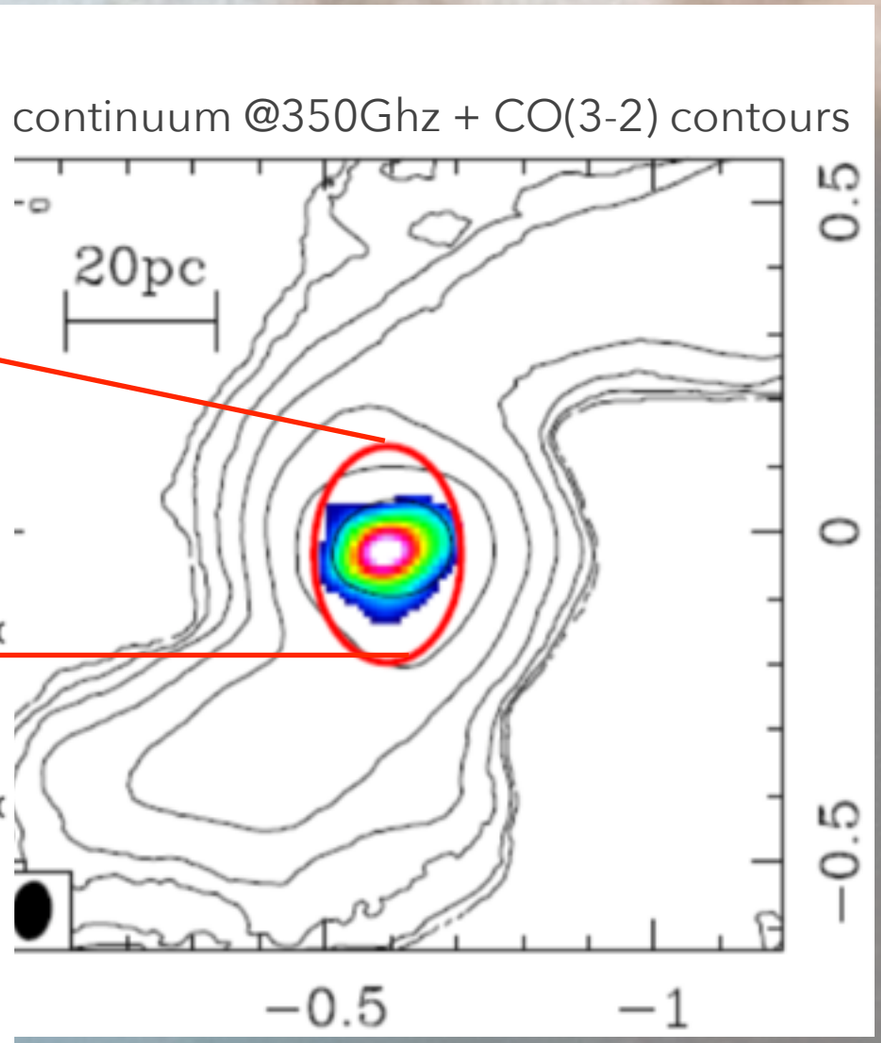


- **14pc radius: molecular torus**
- point source continuum, due mostly to synchrotron emission
- skewed kinematics in the centre : outflow
- trailing spiral structure at 100pc scales: fueling

Combes, García-Burillo, Audibert+2018







- **14pc radius: molecular**
- point source continuum, d
- skewed kinematics in the c
- trailing spiral structure at 100pc scales: fueling

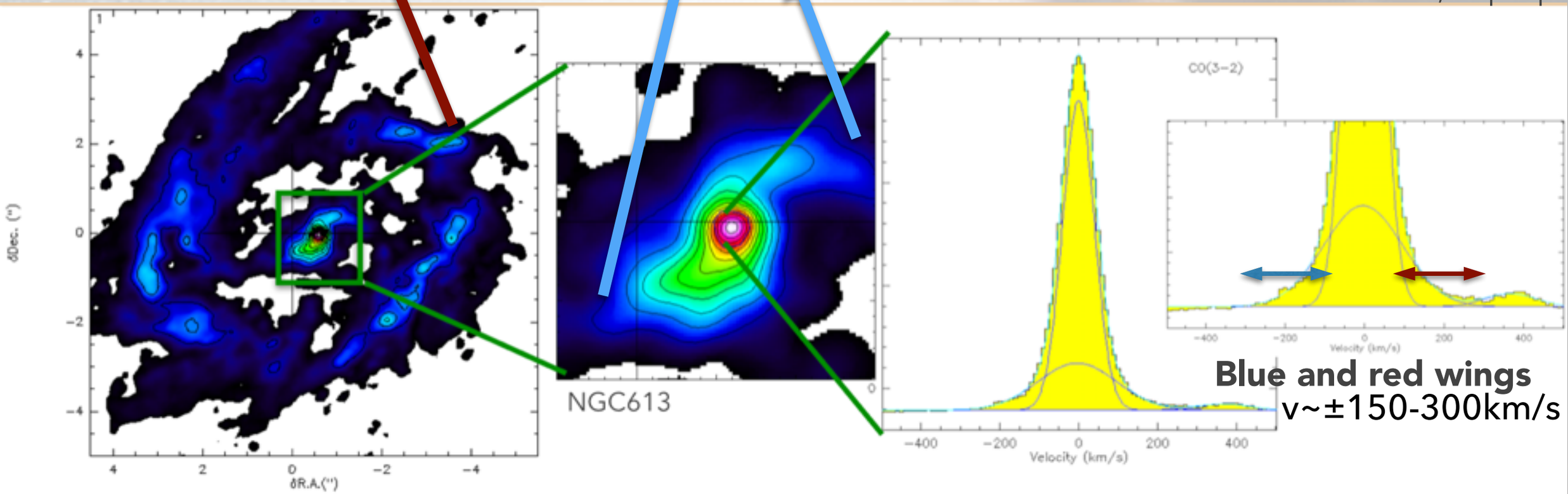
Combes, García-Burillo, Audibert+2018

NGC613

ILR nuclear ring at 300pc

Trailing 2-arm spiral

Audibert+a, in prep



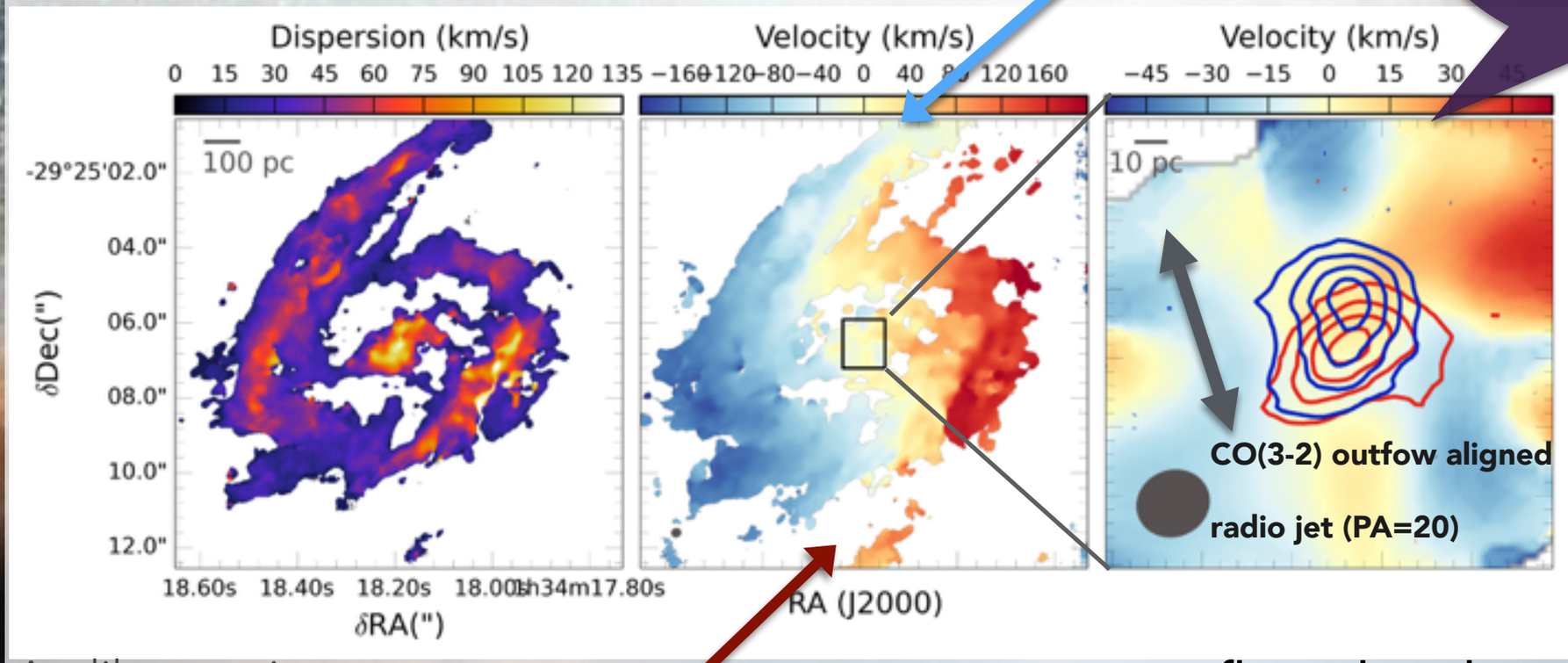
- The CO emission follows the inner Lindblad resonance (ILR) nuclear ring (300pc)
- Star forming clumps -> NIR (Falcón- Barroso et al. 2014).
- Clear nuclear 2-arm spiral: **inflowing of gas** towards the center.
- Nuclear emission: broad wings -> **molecular outfow in the very central region** (~25pc). Also seen in HCN(4-3)/HCO^+(4-3)/CS(7-6).

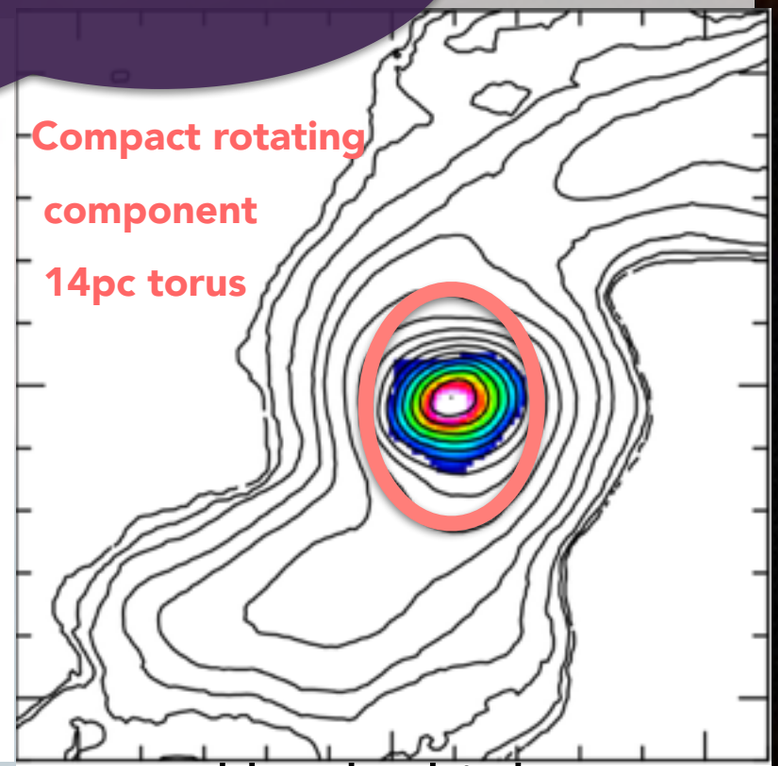
Outflow: FWHM Δv~270 km/s of mass ~$2 \times 10^6 M_\odot$ and $\dot{M}_{out}=62 M_\odot/yr$

NGC613

Winding spiral arm

Molecular outflowing torus?



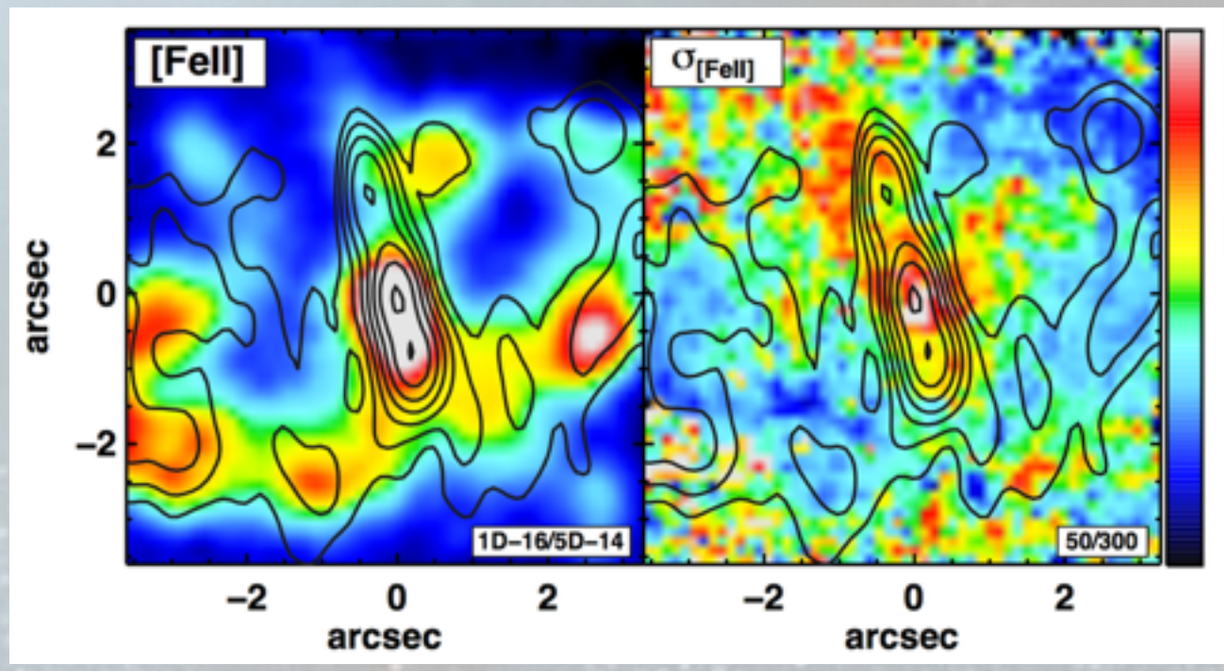


Audibert+a, in prep

Winding spiral arm

- Velocity field disturbed by the winding arms
- A very dense and compact (~14pc) rotating structure, interpreted as a **molecular torus**
- molecular material (dense gas) is entrained in a AGN-driven outflow

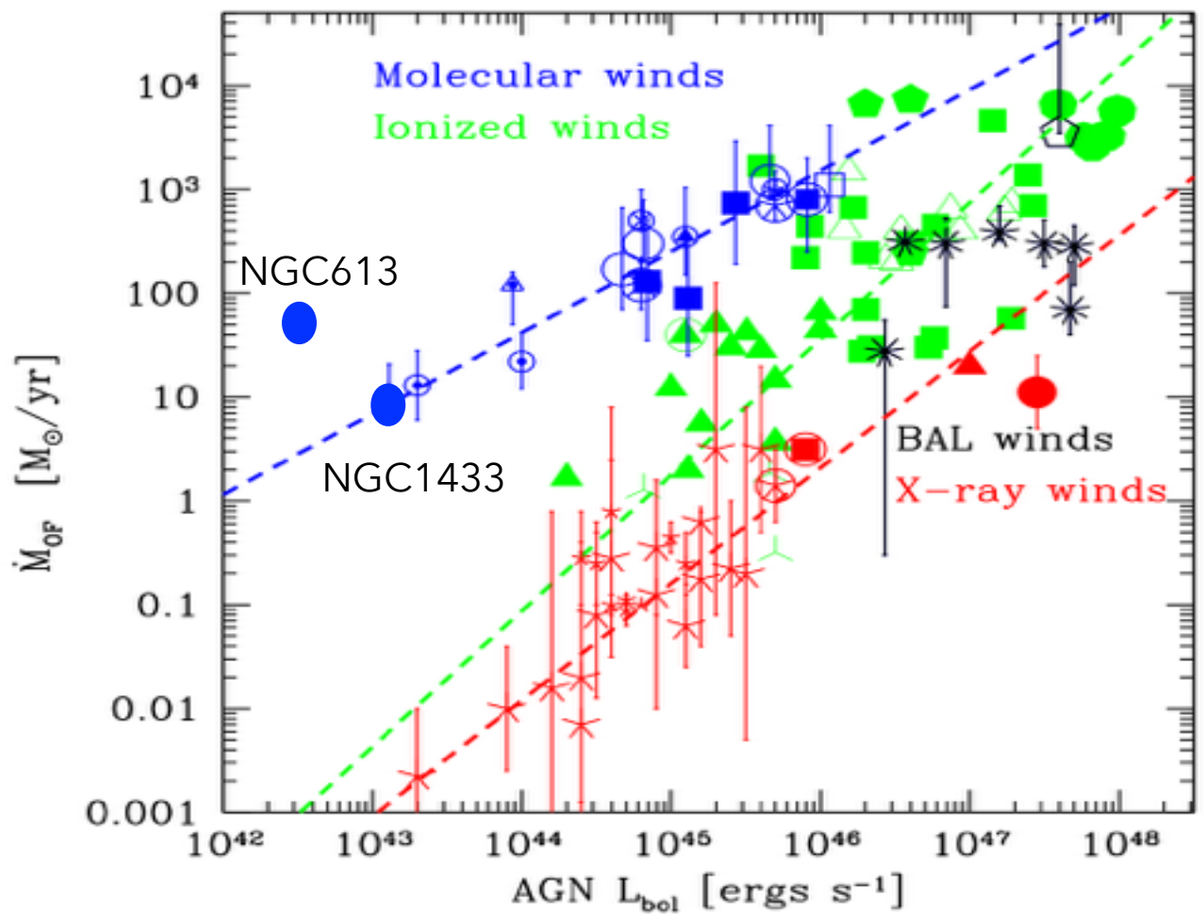
outflow already suggested by the high $\sigma_{[FeII]}$ along the radio jet (Falcón- Barroso et al. 2014, Davies et al 2017)

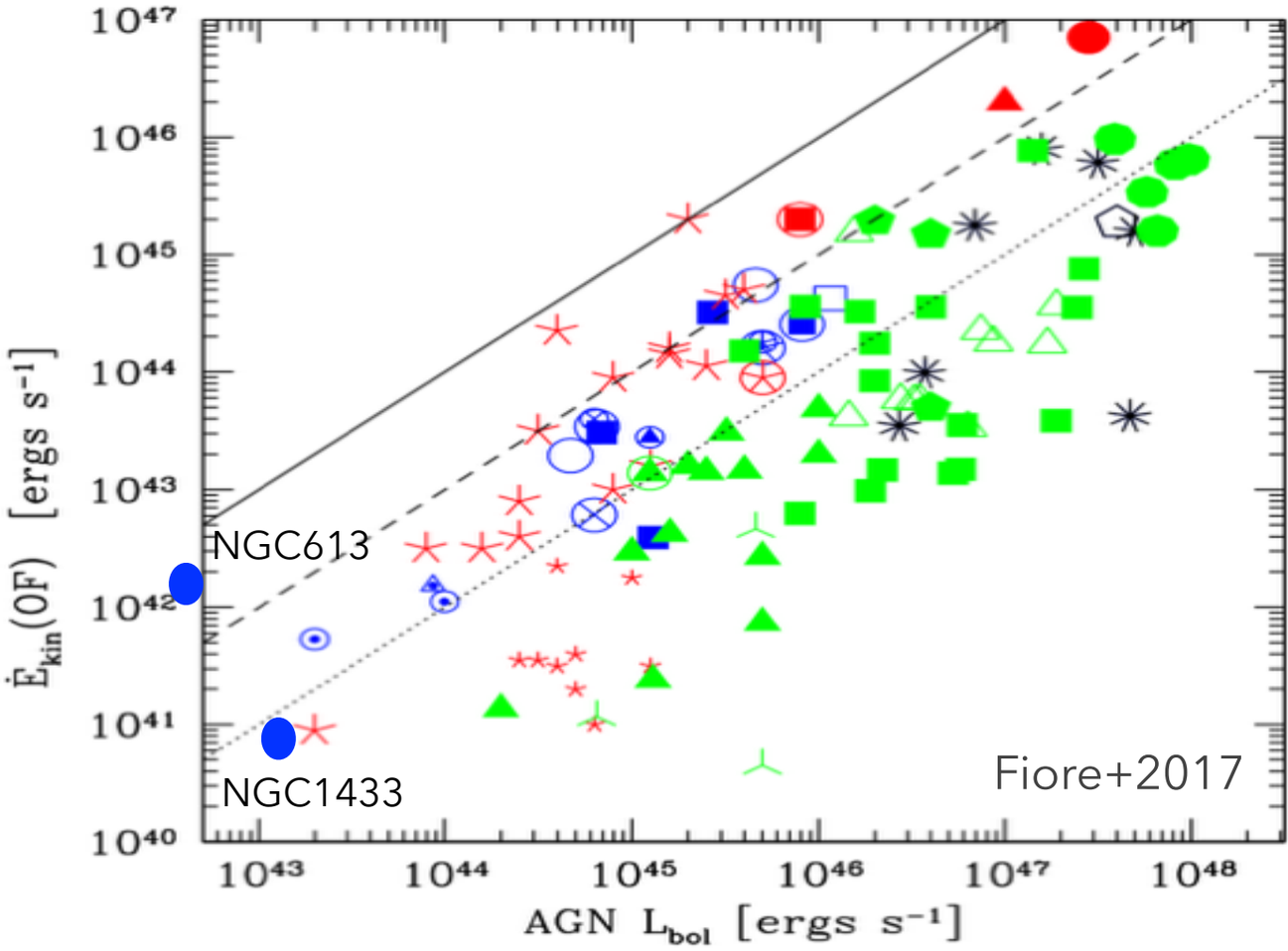


ENERGETICS OF THE OUTFLOWS

- **NGC613**
  - $L_{bol,AGN}=3.2x10^{42}$ erg/s
  - $\dot{E}_{kin}= 1.4x10^{42}$
  - $\dot{M}_{out}$~60M⊙/yr
  - SFR =5.30M⊙/yr

- **NGC1433:**
  - $L_{bol,AGN}=1.3x10^{43}$ erg/s
  - $\dot{E}_{kin}=7.8x10^{40}$
  - $\dot{M}_{out}$~7M⊙/yr
  - SFR =0.2M⊙/yr





Molecular Torus properties

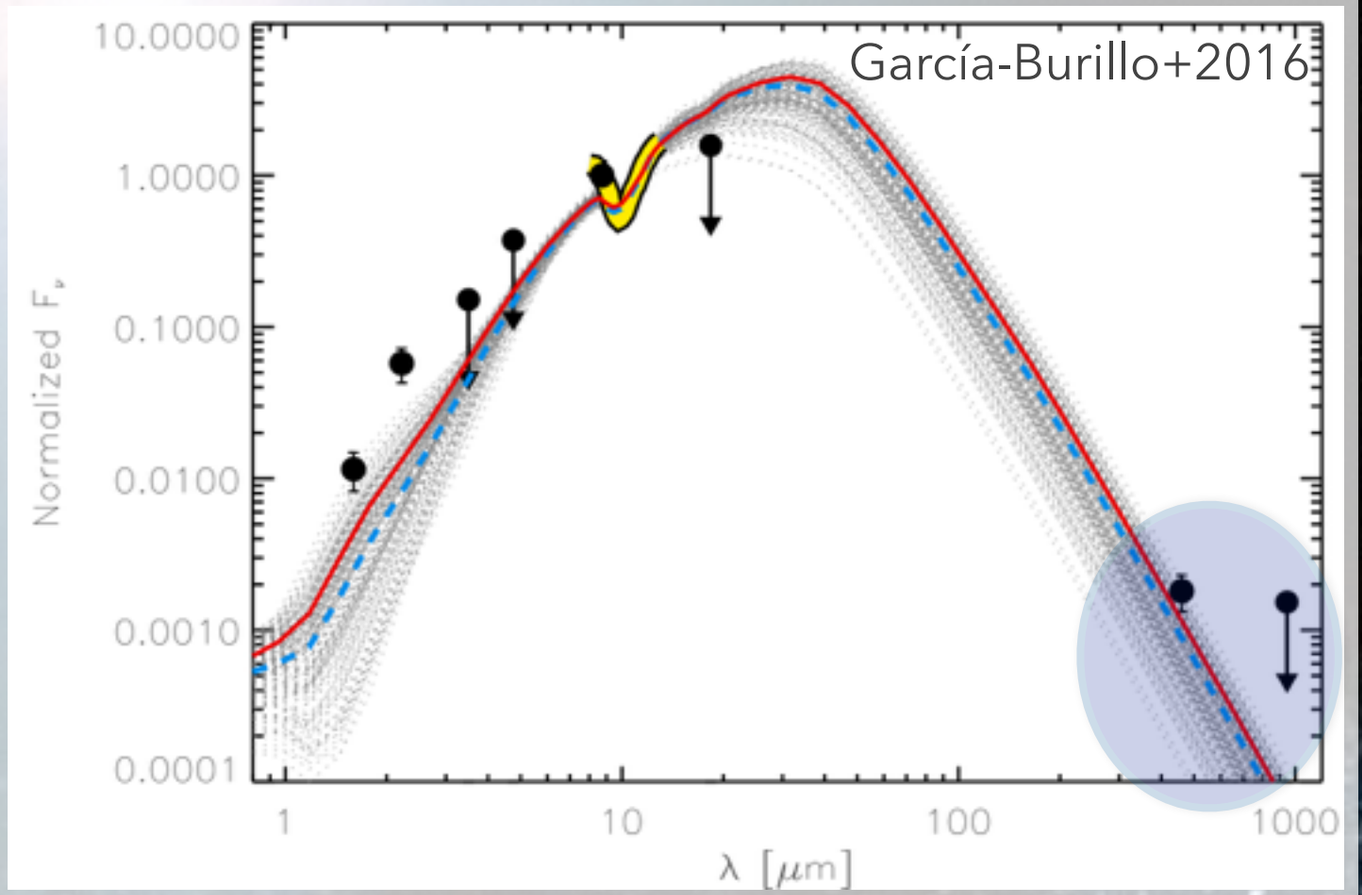
Galaxy	Radius (pc)	S(CO)dV Jy km/s	Mass[a] 10^7 $M_\odot$	inc(°) torus	PA(°) torus	inc(°)[b] gal	Beam (pc)	logNH_2 (cm^{-2})	M_{cent} 10^6 $M_\odot$	off-centring (pc)
NGC 613	14±3	56±20	3.9±1.4	46±7	0±8	36	6.2	25.3±.001	10.	42.
NGC 1326	21±5	18±2	0.95±0.1	60±5	90±10	53	5.3	23.9±.02	0.3	21.
NGC 1365	26±3	10±3	0.74±0.2	27±10	70±10	63	6.3	23.5±.01	0.	86.
NGC 1433	–	–	–	–	–	67	2.9	23.5±0.1	0.04	–
NGC 1566	24±5	72±10	0.88±0.1	12±12	30±10	48	1.7	24.5±.01	0.1	7.
NGC 1672	27±7	80±9	2.5±0.3	66±5	0±10	28	4.0	24.3±.01	0.4	27.
NGC 1808	6±2	46±6	0.94±0.1	64±7	65±8	84	3.1	24.6±.004	0.5	58.

- the torus has been identified as the nuclear component inside the nuclear spiral structure (NGC 613, 1566 and 1808) -> torus is replenished in gas through the spiral structure
- the most edge-on orientations of the torus correspond to obscured Seyferts
- frequently, the torus and the AGN are slightly off-centred, implying that the BH is wandering by a few 10 pc amplitude around the center of mass of the galaxy
- only one case (NGC 1365), the AGN is centred on the central gas hole of the torus: "donut"

NEXT STEPS: SED FITTING INCLUDING ALMA

- ALMA Cycle 6: 2 dense torus, NGC613 and NGC1672, @band 9
- CO(6-5) at ~2pc resolution: to explore their clumpy and turbulent structure
- detect the dust emission of their torus
- Better constrain the SED
- Test different torus models

(choose your favourite!)



SUMMARY

- the most edge-on orientations of the torus correspond to obscured Seyferts
- **OFF-CENTER** torus and the AGN: the BH is wandering by a few 10 pc amplitude around the center of mass of the galaxy
- NGC 1433: outflow is one of the smallest molecular outflow ever seen in a galaxy nucleus (3.6×10^6 M$\odot$ and ~ 7 M$\odot$/yr), **HAS DESTROYED THE TORUS?**
- NGC613, NGC1566 and NGC1808 show clear **FEEDING EPISODES** caught in action as trailing spirals (~100pc scales): torus is replenished in gas through the spiral structure
- NGC613: feeding and feedback observed: massive molecular outflow ~25pc and $\dot{M}_{out}$~60M$\odot$/yr boosted by **RADIO JET + MOLECULAR TORUS?**
- Inclusion of ALMA data at band 9 to fit the SED using different torus models