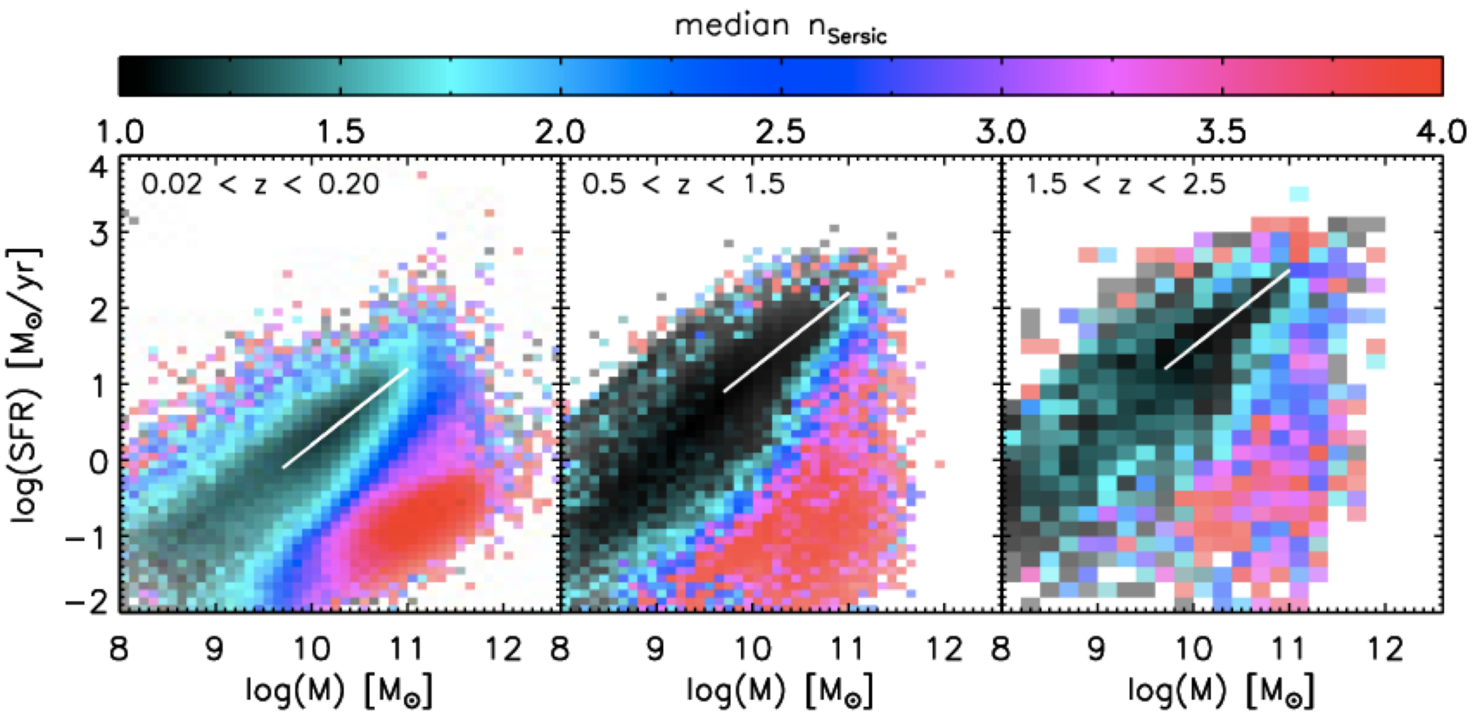
COURAGE: Cold outflows ruffling the AGN environment*

Claudia Cicone

Astrofit2 fellow @ INAF-OABrera

*This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 664931

Galaxy quenching

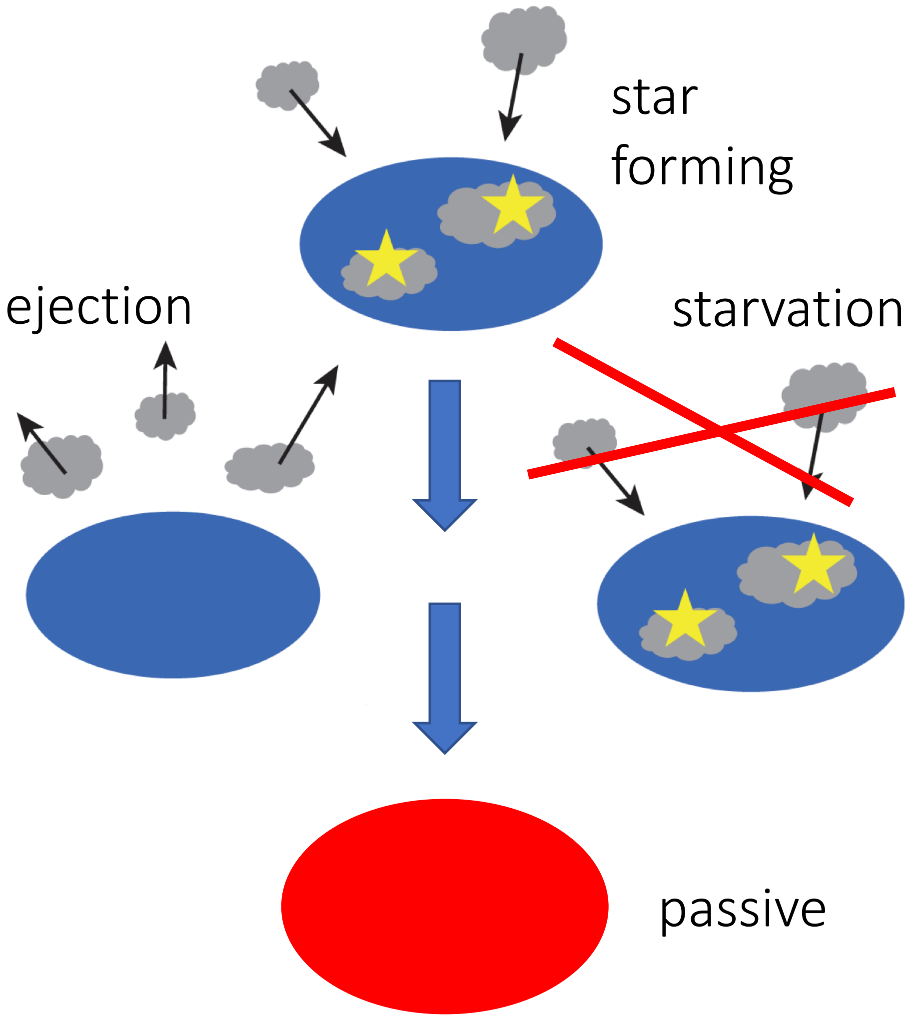


Wuyts+11, Baldry+04, Noeske+07, Peng+10, Heckman+Best 14, Schawinski+14, Whitaker+14, Renzini+Peng15

SSFR = SFR/M_* bimodality up to z>2.5: galaxies are either star forming or passive (quenched)

Galaxy quenching is a big unresolved problem in galaxy evolution: how is star formation suppressed and what keeps galaxies red and dead?

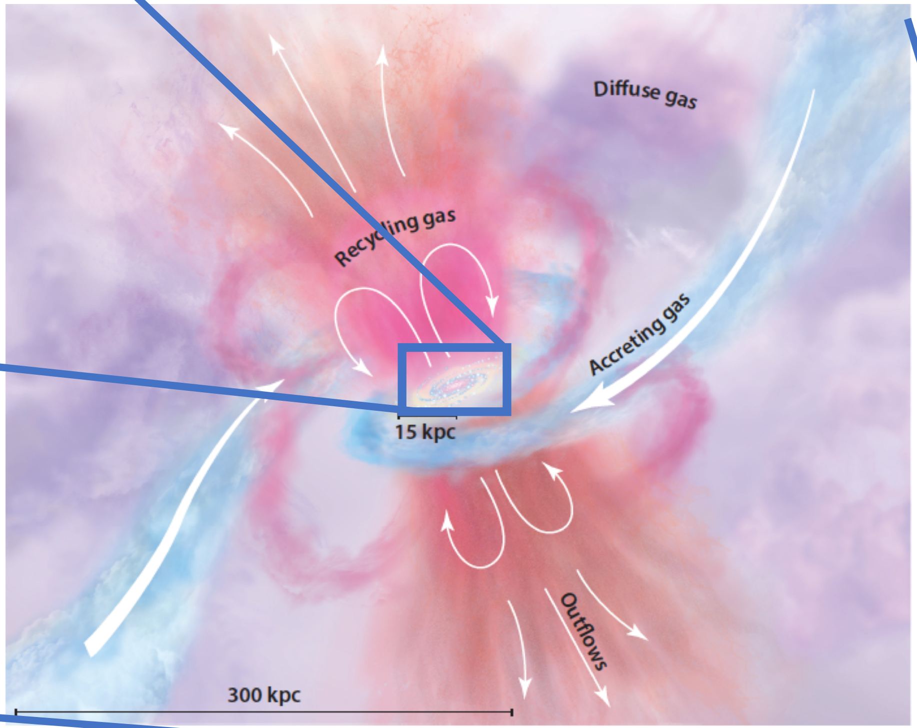
How to quench a galaxy



- Star formation can be suppressed through "ejection" of fuel or "starvation" (= cut feeding). Observational evidence exists for both (Peng+Maiolino15)
- Massive ellipticals quenched rapidly (<1 Gyr, e.g. Thomas+10), which points to an early ejection mechanism but still need to prevent further cooling to keep them passive
- AGNs are the preferred and most promising explanation (both `ejective' and `preventive' feedback) (e.g. Su, Hopkins +18, Biernacki+Teyssier18)

The baryon cycle: galaxies are not closed boxes

Figure upon request (too big for upload)



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ISM
- Star formation
- Accretion onto SMBH (AGN)

Baryon cycle:
outflows & inflows

IGM
- Structure growth
- Cosmic evolution

The multiphase nature of outflows in AGN host galaxies

Table 1 | Properties of the different outflow phases discussed in this Comment

Outflow gas phase	Primary tracers	Average gas temperature, $<T_{gas}>$ (K)	Average gas density, $<n_{gas}>$ (particles per cm^3)
Highly ionized	X-ray absorption lines	10^6–10^7	10^6–10^8
Ionized	[O III]; Hα	10^3–10^4	10^2–10^4
Neutral atomic	H I 21cm; NaID; [C II]	10^2–10^3	1–10^2
Molecular	CO; OH; [C II]; H_2 infrared lines	10–10^2	$\geq 10^3$

- Constraining the multiphase nature of outflows is the first step to understand their true impact on galaxy evolution
- Need for unbiased surveys conducted on statistically significant samples
- Multiphase properties needed to compute outflow masses and energetics -> and compare with models

Figure upon request (too big for upload)

Cicone+18a, Nature Astronomy
[INAF press release: http://www.media.inaf.it/2018/03/01/parola-al-vento/]

Molecular outflows detected in CO emission

Figure upon request (too big for upload)

- CO wings tracing outflow >10-20 times fainter than line peak

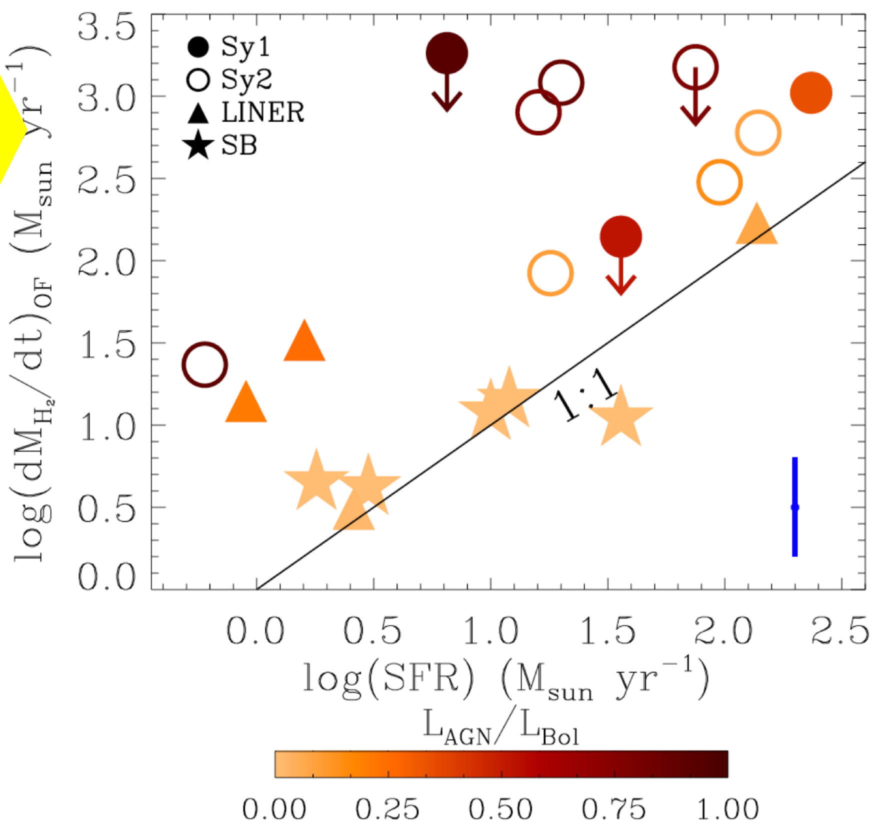
- CO wings identified in the spectra and in the PV diagram: high-v (up to 1200 km/s) emission clearly deviates from disk rotation pattern

Cicone+14

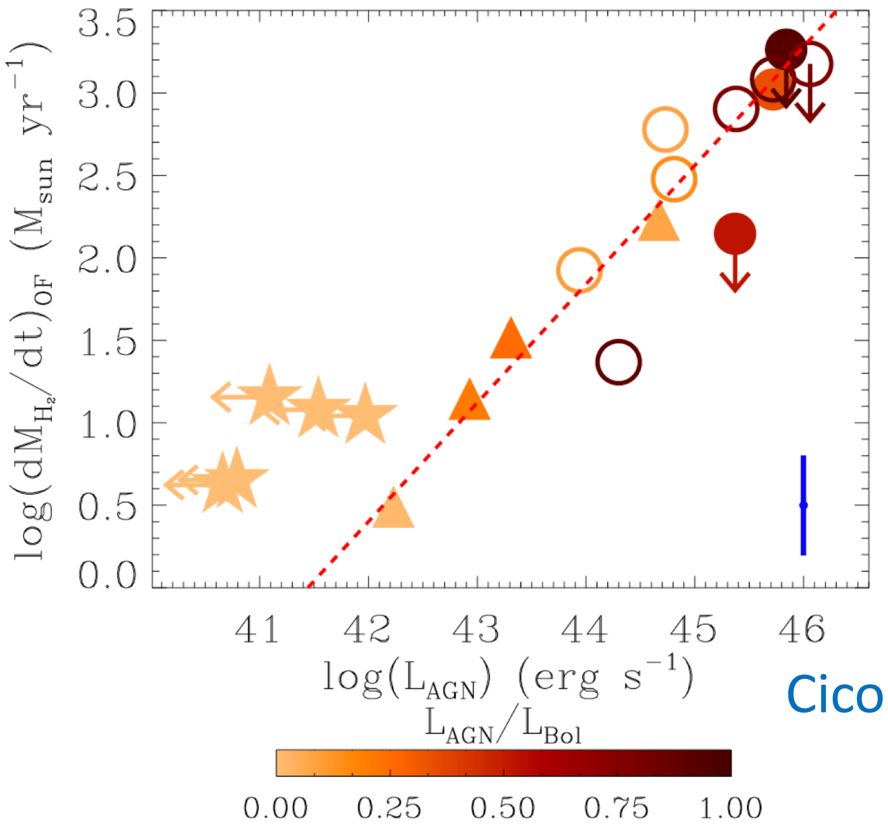
CO-based energetics reveal link with AGN

Depends on α_{CO}

Energetics consistent with AGN feedback models but uncertainties are large!



dM_{out}/dt ~ SFR in starbursts
dM_{out}/dt >> SFR in AGN-dominated sources



Cicone+14

Tentative correlation between dM_{out}/dt and L_{AGN} in AGN hosts (in reality dM_{out}/dt depends on SFR, L_{AGN} and M_*)

Open questions and ways to address them

What are the physical conditions of the gas in outflow? → Use multiple H_2 tracers (high-J CO, [CI], [CII], HCN, CN, CS)

What drives the outflows (AGN vs SF) and how is the energy communicated from pc to kpcs? → Resolve launching point of the outflow at high-res

How much gas is ejected from the halo (vs how much stalls in CGM/falls back)? → Study outflowing gas on >>1 kpc scales

ALMA [CI]$^3P_1$-$^3P_0$ observations of NGC6240

First resolved [CI](1-0) map of molecular outflow in a quasar (ALMA + ACA Band 8)

Figure upon request (too big for upload)

Cicone+18b ApJ

Strategy: combine [CI] and CO to estimate α_{CO}

CO and CI well mixed in molecular ISM and outflows (thanks to turbulence and cosmic ray) Papadopoulos+04,+18, Bisbas+15,+17, Glover+15

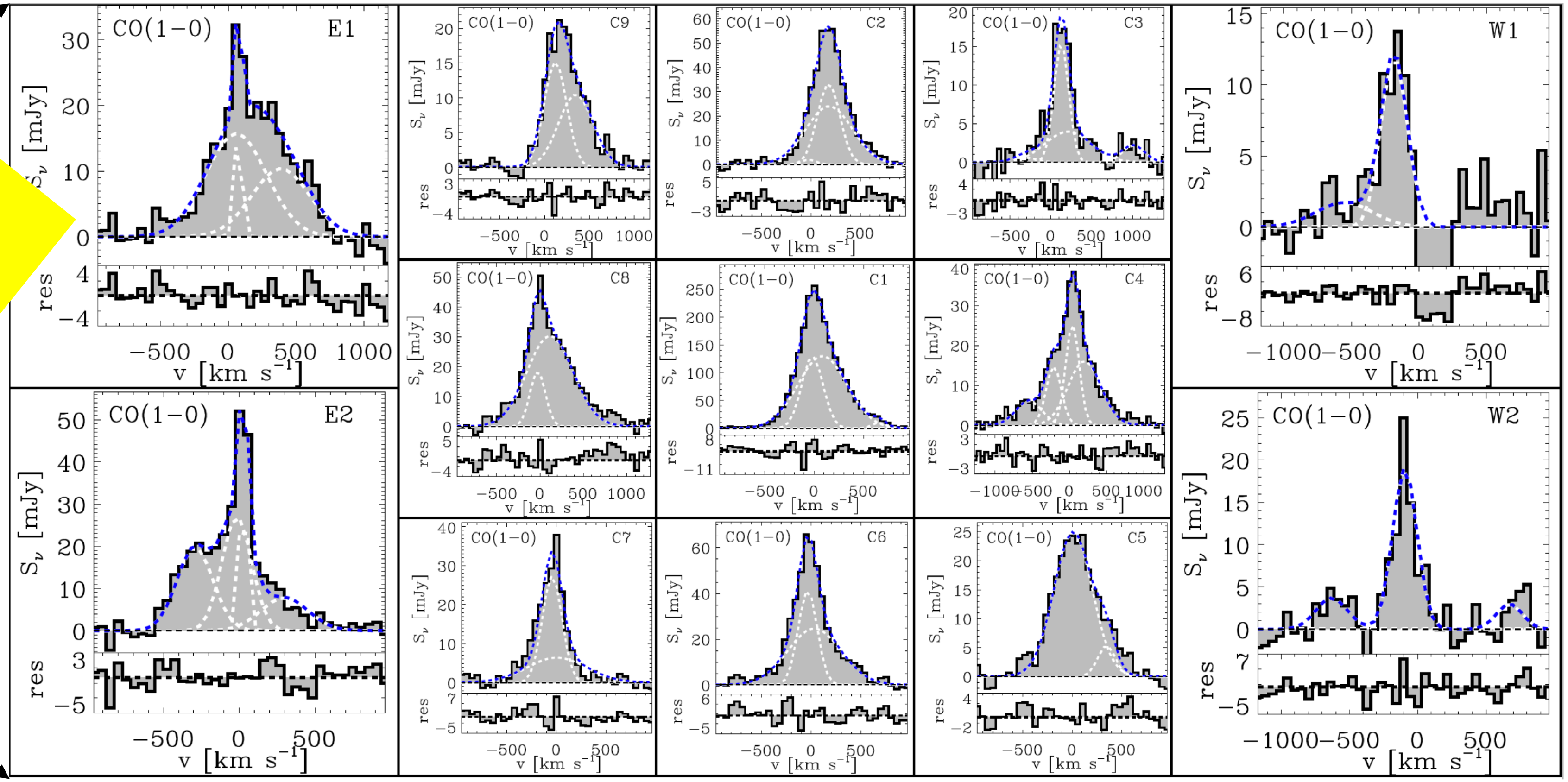
[CI]1-0 allows to estimate M_{out} independent of α_{CO}. Use T_{ex}=30 K and X_{CI}=(3+-1.5)x10^{-5} (appropriate for ULIRGs, e.g. Weiss+03,05)

Great legacy value for high-z studies with ALMA as [CI] lines trace bulk of ISM (contrary to high-J CO) and are not affected by CMB (contrary to low-J CO, e.g. Zhang+16)

Identification of outflow components

CO(1-0

Figure upon request (too big for upload)

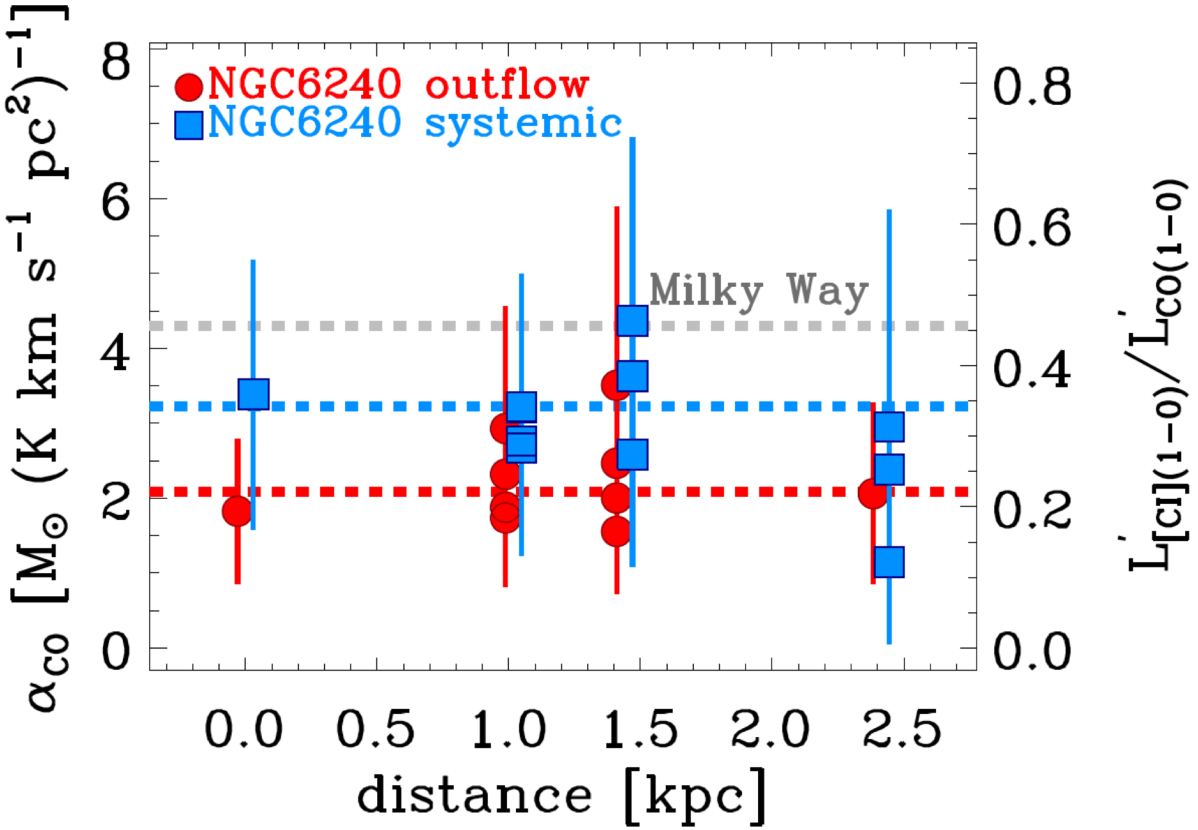


Cicone+18b, ApJ

(i) Fit simultaneously the CO(1-0), CO(2-1), and [CI](1-0) spectra at various positions

(ii) Look for high-σ/high-v components that are spatially offset from nucleus and inconsistent with rotation or dynamical effects due to merger (e.g. inflows, tidal tails)

The α_{CO} of quiescent vs outflowing gas: origin of the 'envelope' ISM of ULIRGs



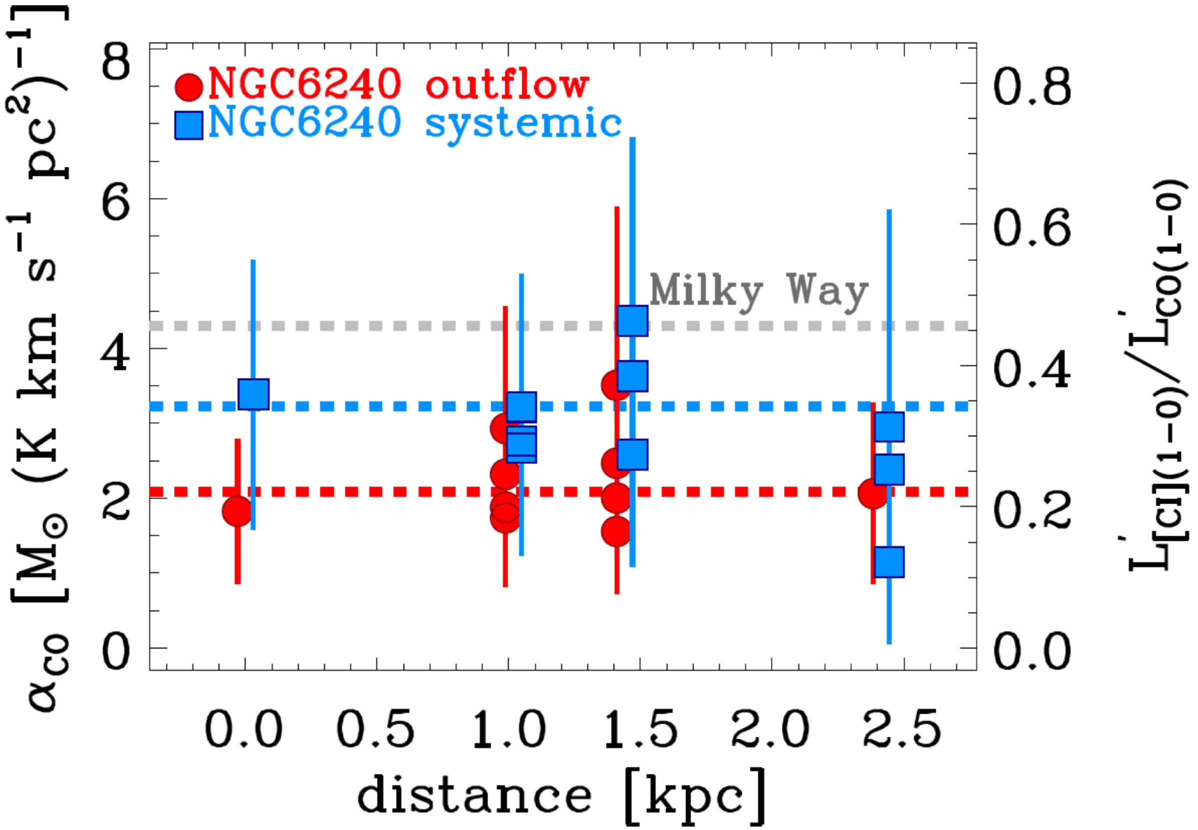
$\alpha_{CO}^{quiescent} = 3.2\ (\pm\ 1.8)\ M_{Sun}\ [\mathrm{K\ km\ s^{-1}\ pc^2}]^{-1}$

$\alpha_{CO}^{outflow} = 2.1\ (\pm\ 1.2)\ M_{Sun}\ [\mathrm{K\ km\ s^{-1}\ pc^2}]^{-1}$

- Select components from simultaneous fit where CO(1-0) and [CI](1-0) are both detected, derive M_{mol} from L'_{CI}, and then $\alpha_{CO} = M_{mol} / L'_{CO}$
- We find α_{CO} lower in outflow than in quiescent gas independent of distance: molecular outflows host warm + diffuse H_2 lower-α_{CO} 'envelope' phase advocated by earlier ULIRGs studies, e.g. Aalto+95, Downes+Solomon98

Cicone+18b, ApJ

The α_{CO} of quiescent vs outflowing gas: dense gas



$\alpha_{CO}^{quiescent}$ = 3.2 (± 1.8) M_{Sun} [K km s^{-1} pc^2]$^{-1}$

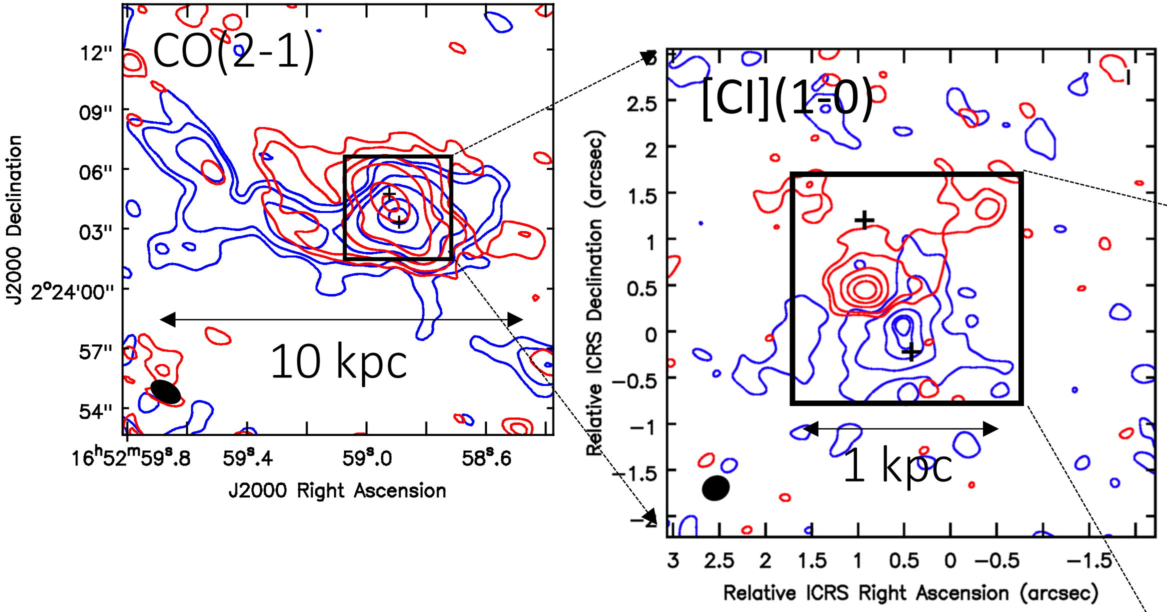
$\alpha_{CO}^{outflow}$ = 2.1 (± 1.2) M_{Sun} [K km s^{-1} pc^2]$^{-1}$

- However α_{CO} > 0.3: not all outflow material is diffuse and warm but also dense gas entrained (as already seen in other outflows with bright HCN and CS emission: Aalto+12,Alatalo+15, Aladro+18)

- In quiescent gas α_{CO} > 'ULIRG' value (0.8) and formally consistent with MW α_{CO} value. Suggests dense gas and self-gravitating GMCs in ISM of ULIRGs

The launching point of the outflow

High-v (|v|>200 km/s) blue/red wings



[CI](1-0) moment maps (|v|<200 km/s)

Figure upon request (too big for upload)

'hourglass' outflow feature

- The high-v emission peaks between the AGNs: outflow launching point offset from AGNs not easily explained in AGN feedback scenario
- The outflow dominates even the emission at |v|<200 km/s in this nuclear region, see moment maps. No signs of rotating disk(s)

Cicone+18b, ApJ

Open questions and tentative answers

What are the physical conditions of the gas in outflow? → $\alpha_{CO}^{outflow} \sim 2$ and $r_{21}^{outflow} \sim 1.4$ suggest strongly unbound envelope + dense clumps entrained (seen in CN, HCN, CS)

What drives the outflows (AGN vs SF) and how is the energy communicated from pc to kpc scales? → Combined action of SB + quasar, with (little?) help from merging process that redistributes gas and enhances impact of AGN+SB radiation

How much gas is ejected from the halo (vs how much stalls in CGM/falls back)? → Substantial outflowing gas exists at $r > 5$ kpc. Probing larger scales requires HIGH sensitivity

Main additional activities (Oct 2017-Oct 2018)

- **10 accepted publications** (**2 as first author**, 1 as second author) + **3 submitted** manuscripts
- **2 APEX ESO PI projects accepted** in P101 (**60h** of data obtained in Summer 2018)
- **Observing**: (i) 5 nights at **ESO-La Silla (NTT)** in Feb 2018, data part of PhD thesis of S. Belladitta; (ii) **ESO-APEX observing run**, 10 days in Apr-May 2018, service-mode observer for ESO projects + collected data for my own PI projects; (iii) >50h of remote observations at **ARO 12m** telescope (Kitt Peak) for the ESO large programme `MASCOT' of which I am co-I.
- **2 Invited colloquia** (Cardiff University, Bonn MPIfR)
- **6 international workshops/conferences** (1 invited review, 2 invited talks, 2 contributed talks)
- **Organization (LOC) of a national conference** in Oct 2018
- **2 internal seminars** (INAF-OABrera, INAF-Merate)
- **Job applications**: 4 submitted (1 fellowship, 1 for ESO-ALMA staff, 1 tenure track, 1 tenure), shortlisted + interviewed for 1 tenure position
- **Supervision** of students: external supervisor of a Master thesis student at Uni Milano-Bicocca

Foreseen publications in 2019

Advanced stage (to be submitted within 2-3 months):

- **Cicone et al.**: extragalactic science case **white paper for a new millimeter facility** (AtLAST), to be submitted to US 2020 decadal survey in Jan 2019
- **Cicone et al**. Dense gas tracers in the molecular outflow of Mrk231 (Based on PI and archival observations).
- **Belladitta (inc. Cicone et al.)**, Based on NTT-EFOSC2 data collected by Cicone and Belladitta and DDT X-Shooter data (PI:Moretti). PhD thesis of S. Belladitta.

Preliminary stage (data analysis stage):

- Cicone et al. in prep: “The cold CGM of a local galaxy merger”, based on APEX ESO (PI:Cicone) data obtained in summer 2018
- Cicone et al. in prep.: “The hidden cold CGM of z>2 AGN host galaxies”, based on APEX ESO (PI:Cicone) data obtained in 2017/2018)
- At least two papers by SUPER Collaboration (Circosta et al.; Kakkad et al.)
- At least one paper from MASCOT collaboration (work done by a PhD student at ESO-Garching)
- Sirressi, Cicone, Severgnini et al. Based on ALMA (PI: Severgnini, Cicone) data obtained in 2017. Master thesis of Mattia Sirressi (Uni Milano Bicocca)
- At least one paper from an X-ray study of dual/binary AGN candidates (Serafinelli, Severgnini, Cicone, Della Ceca)