# Massive outflows of cold gas and their role in the baryon cycle of galaxies

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INAF OABrera → University of Oslo (Sep 2019)

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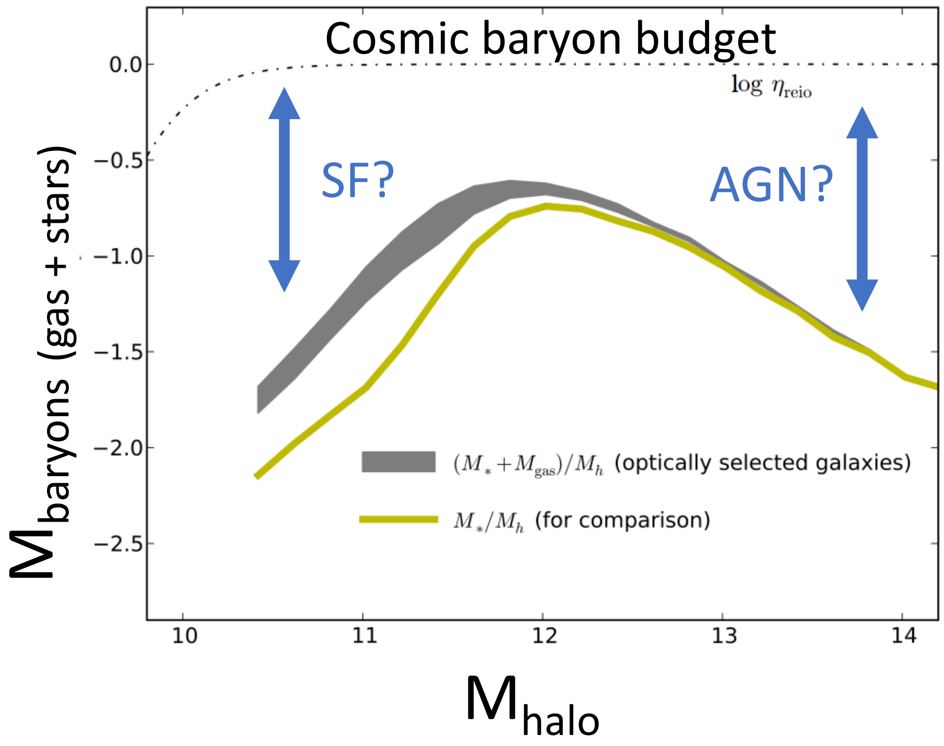
# Outflows proposed as a solution for (too many?) galaxy evolution puzzles

1. $M_{baryon}$ – $M_{halo}$ relation: little baryons in (low and high-M) haloes due to (SF- and AGN-driven) outflows? Dekel+Silk86, Papastergis+12, Hopkins+14



# Outflows proposed as a solution for (too many?) galaxy evolution puzzles

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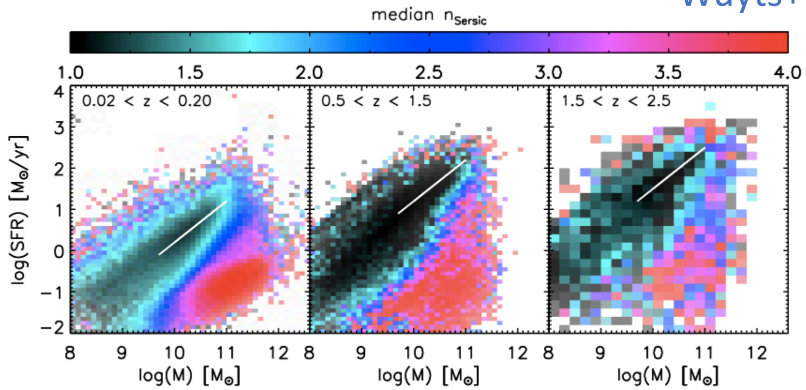
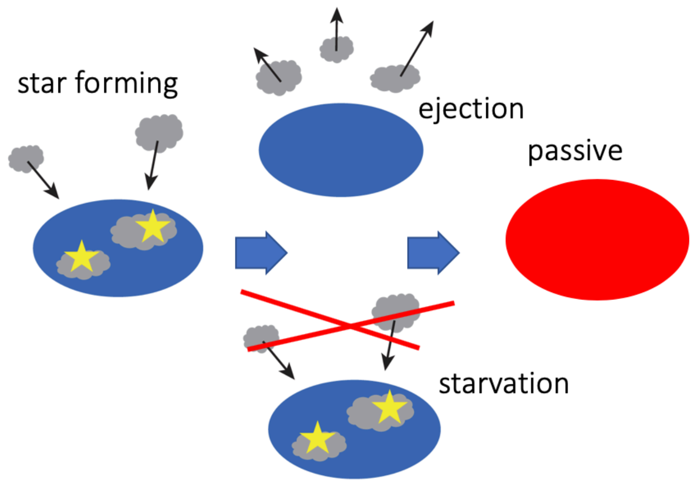
2. SSFR (=SFR/$M_*$) bimodality and [$\alpha$/Fe]-enhancement of massive spheroids:
   - Quenching through direct ejection? Di Matteo+05, Menci+08, Hopkins+08, Zubovas+King12
   - Delayed impact, quenching through starvation? Gabor+Bournaud14, Roos+15, Peng+15, Costa+18ab, Biernacki+Teyssier18

Wuyts+11



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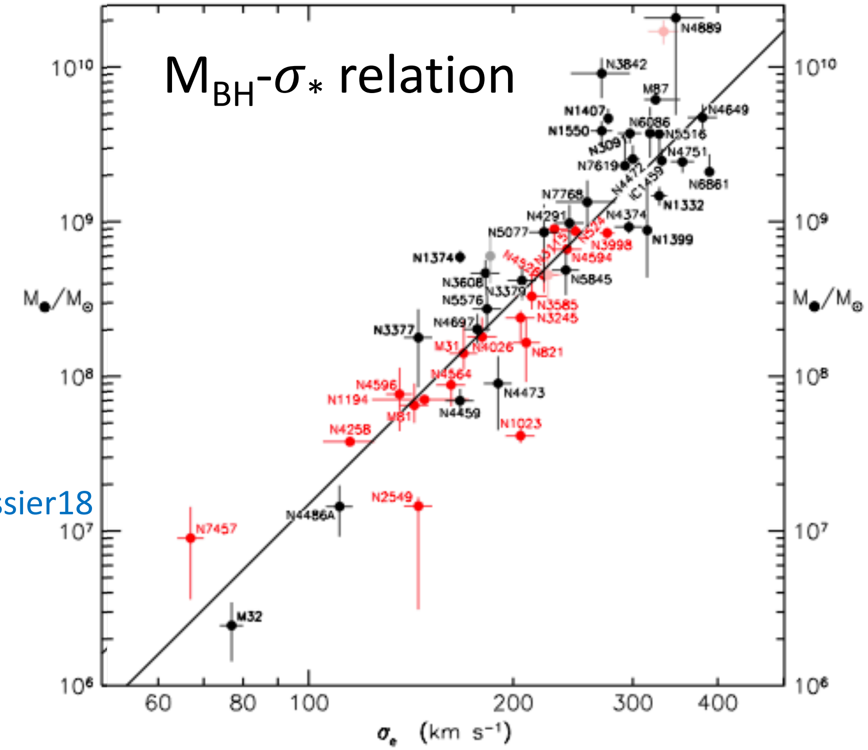
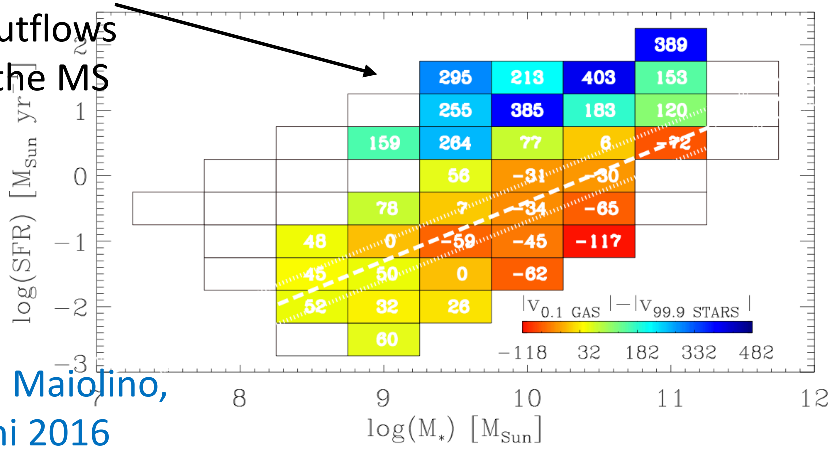
3. $M_{BH} - \sigma_*$ relation, AGN-galaxy coevolution set by AGN-driven outflows? Silk+Rees98, King+03, Sijacki+07
4. [Mass-metallicity relation, CGM metal enrichment, missing metals, etc…] Shen+12,+13,Tumlinson+17



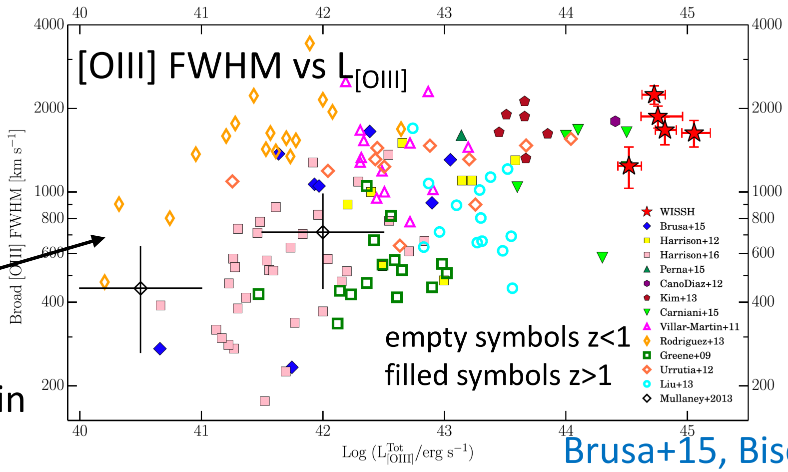

Kormendy & Ho 2013

# Outflows as ‘just’ another component of galaxies

Prevalence of [OIII] outflows above the MS




Cicone, Maiolino, Marconi 2016




Broad [OIII] ubiquitous in AGNs

Brusa+15, Bischetti+17

- Increase in sensitivity boosted outflow detections in individual sources down to relatively low SFRs (0.1 $M_{Sun}$/yr), $\Sigma_{SFR}$ ($10^{-3}$ $M_{Sun}$/yr/kpc$^2$) and $L_{AGN}$ ($\lesssim 10^{43}$ erg/s) Ho+16, Venturi+18, Mingozzi+19
- Ubiquitous in galaxies with ‘some’ SF and/or AGN activity

  Chen+10, Westmoquette+12, Rodriguez-Zaurin+13, Mullaney+13, Cicone+16, Woo+16, Concas+17,18
- Dedicated surveys needed to probe outflow scaling relations, esp. at high-z

  Harrison+16, Circosta+18, Forster-Schreiber+18

# Focus on a few questions

1) What drives galactic outflows and how?

2) What are the physical conditions of the outflowing ISM?

3) Where does the outflowing ISM end up?

# Warning: outflows are multiphase

| **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–$10^2$ | $\geq 10^3$ |

Cicone, Brusa+18a

- Multi-phase nature of galactic winds acknowledged since the 1980s, including coldest $H_2$ component Turner85, Nakai+87
- High level of complexity especially in AGNs and (U)LIRGs, often little overlap between different gas phases in outflow

Rupke+Veilleux13, Rupke+17

# Focus on a few questions

1) What drives cold* galactic outflows and how?

2) What are the physical conditions of the cold* outflowing ISM?

3) Where does the cold* outflowing ISM end up?

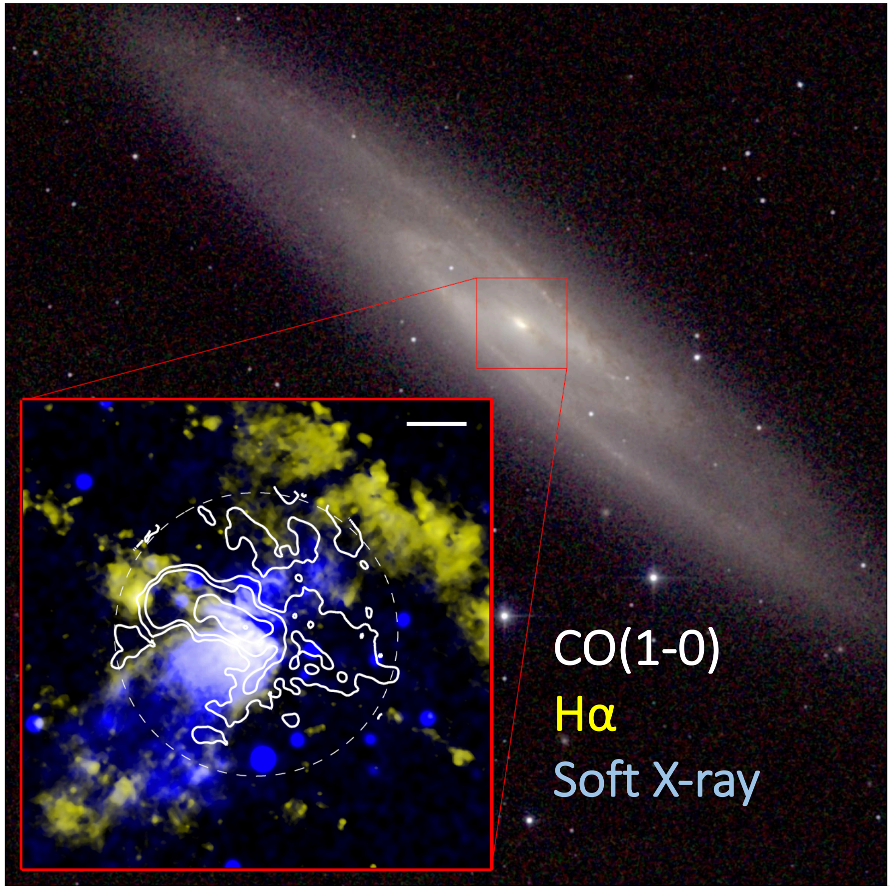
*$T_{gas} \leq 10^3$ K
HI and $H_2$ phases

Cold phase in outflow is probably the most challenging to understand and model

# 1) What drives galactic outflows and how?

# 'Pure' starburst galaxies

NGC253, Bolatto+13



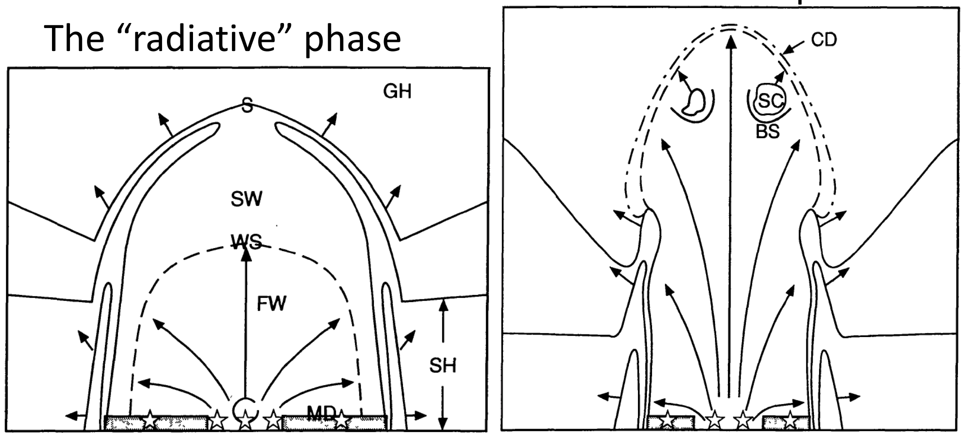




Fig. 1a Fig. 1b Heckman+90

'Super winds' driven by (i) kinetic energy released by clustered SNe + stellar winds and/or (ii) by momentum transferred by UV radiation to dusty clouds

Chevalier+Clegg85, Heckman+90, Veilleux+05, Murray+05, Dave+11

In both scenarios we expect (~as observed):

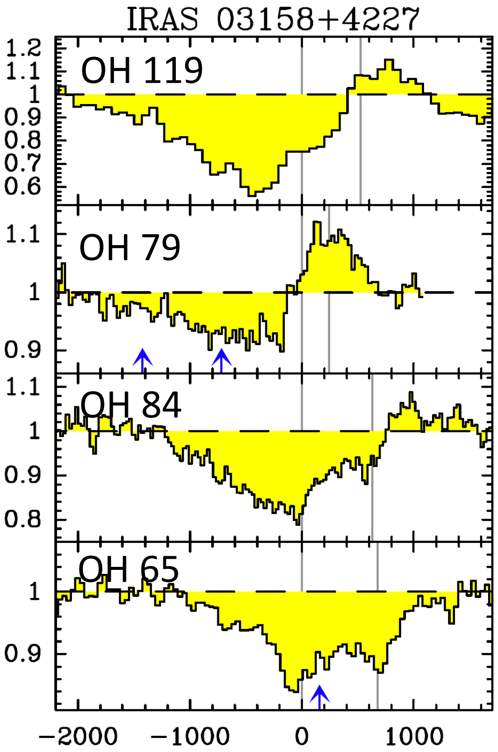
$dM_{out}/dt \sim$ SFR -> mass loading $\eta \sim 1$ Hopkins+12

(although see NGC 253: $\eta$~10-20?) Zschaechner+18

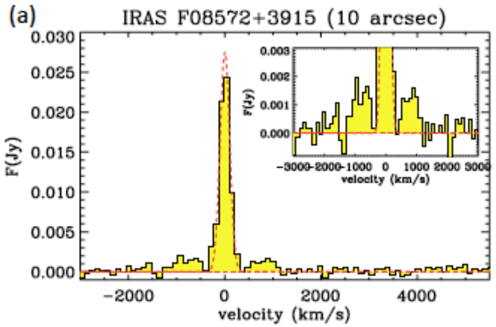
# Ultra luminous infrared galaxies (ULIRGs)

(--> galaxies with $L_{IR}$>$10^{12}$ $L_{sun}$, mostly major mergers with intense SB + AGN)

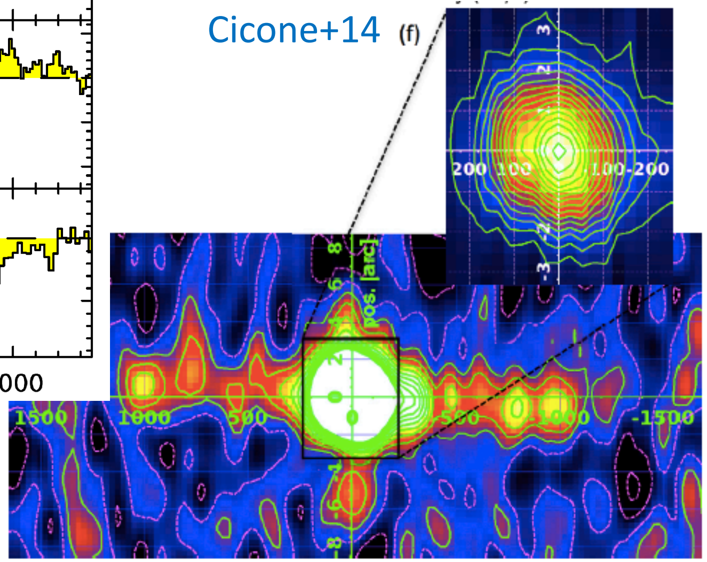
Outflow velocities ~ 1000 km/s




Gonzalez-Alfonso+17




Cicone+14

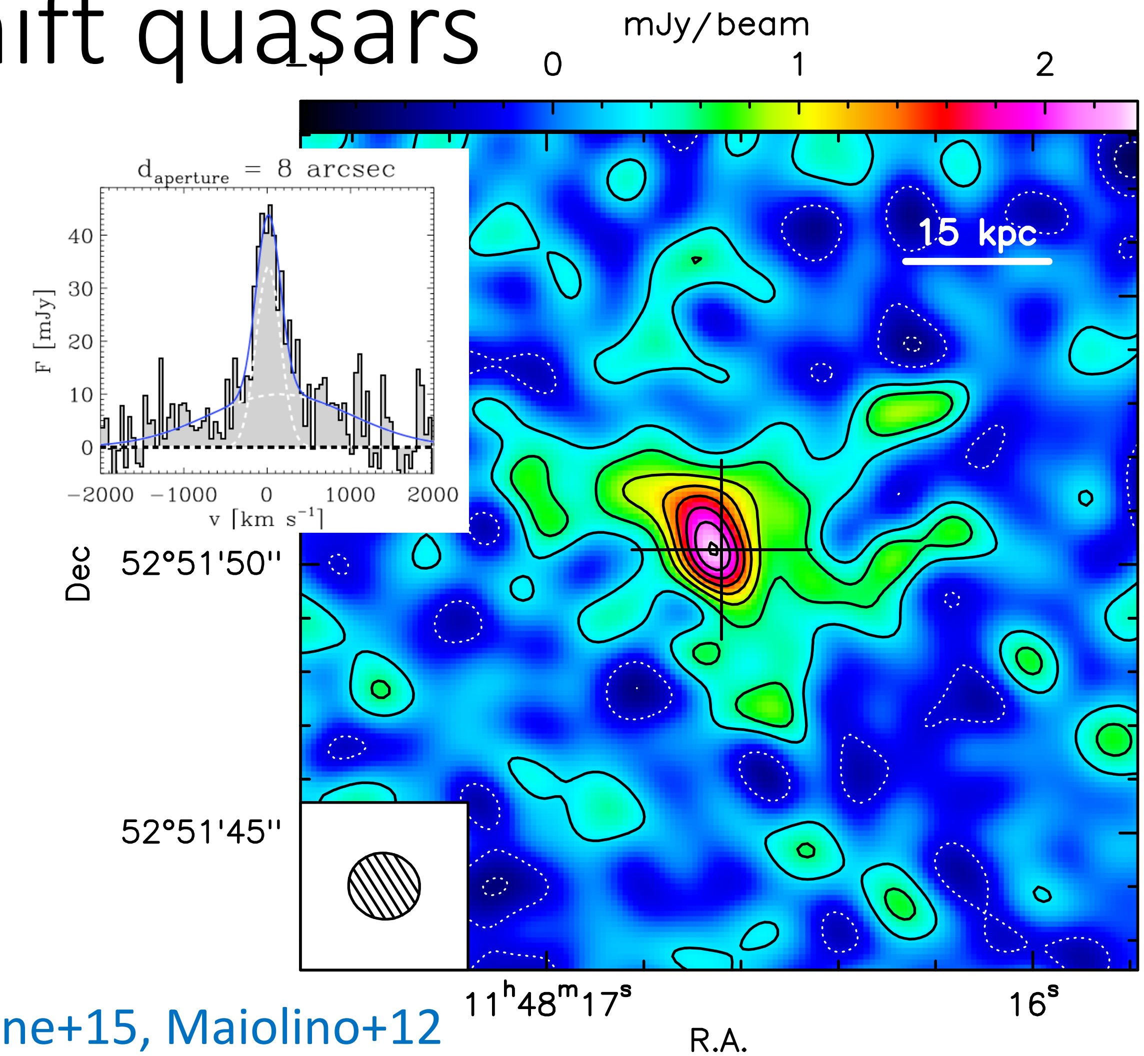



- Ubiquitous OH P-Cygni profiles show unambiguous outflows but large uncertainties on energetics (high $\tau$ of OH119, geometry, etc.)
  Fischer+10, Sturm+11, Veilleux+13, Spoon+13, Gonzalez-Alfonso+17,18
- CO wings >10-20 times fainter than line peak but allow to get energetics
  Feruglio+10, 13, 15, Alatalo+11,15, Aalto+12,15 Cicone+14, Garcia-Burillo+14 Veilleux+17, Gowardhan+18, Fluetsch+18, Longinotti+18 etc..
- *Energetics suggest link with AGN:*
  - OH $v_{out}$ scales with $L_{AGN}$
  - CO-based $dM_{out}/dt$ >> SFR in AGN-dominated sources ($dM_{out}/dt$ ~ 1000 $M_{Sun}$/yr)

# High redshift quasars

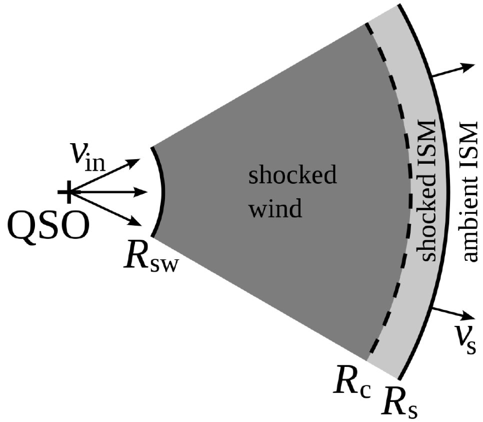
- [CII] 158$\mu$m observations of a z=6.4 quasar reveal most extended (r = 30 kpc) and highest-v ($\sigma_v$ ~500 km/s, v ~2000 km/s) neutral outflow ever detected
- Stacking of ALMA data suggests (less extreme) [CII] outflows present in other high-z quasars Bischetti+18
- Other studies cast doubt on high incidence of such outflows Decarli+18

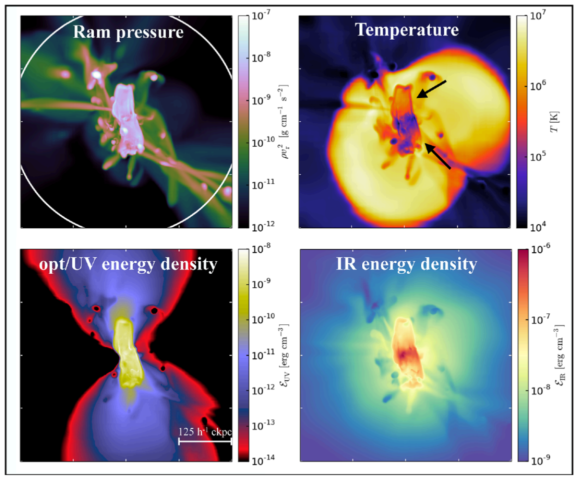
*Diffuse emission easily filtered out by interferometers, in this case stacking would not help enhance the signal*




Cicone+15, Maiolino+12

# Theoretical models of AGN-driven outflows




Costa+18b

Outflows, UFOs) with v=0.1c shock surrounding ISM and generate large-scale energy-conserving outflow

(i) Concurrence of X-ray UFO and galactic outflow

(ii) If energy-conserving, kinetic power ~a few % $L_{AGN}$ momentum flux ~ 20 $L_{AGN}$/c

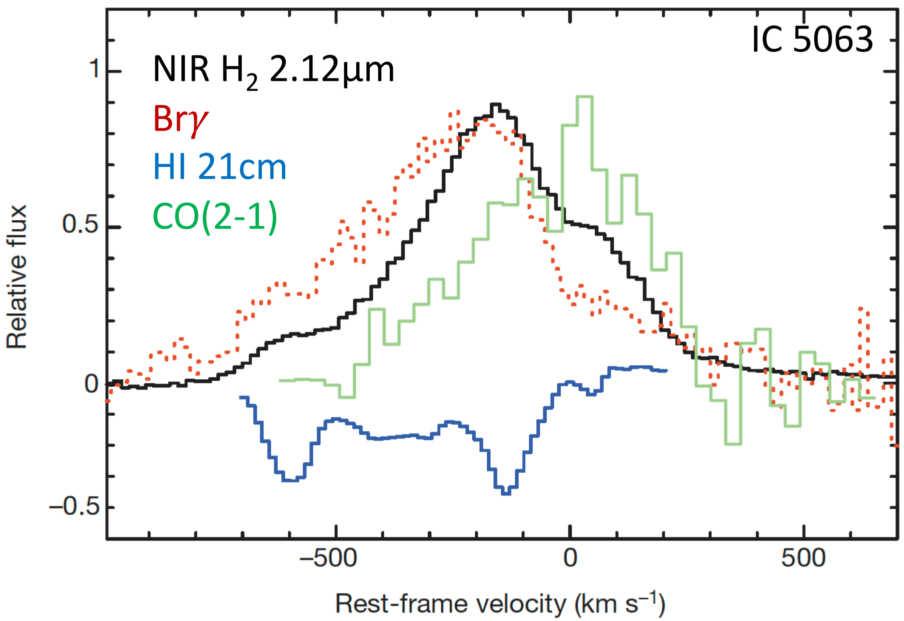
Silk+Rees98 King10 Zubovas+King12 Faucher-Giguere+12 Costa+14,+15, Nims+15

2. **Direct radiation pressure on dusty clouds**, enhanced for $\tau_{IR}$>>1 and high $L_{AGN}$. Kinetic power depends on $\tau_{IR}$ and source geometry, but mostly $dE_{kin,OF}/dt$<1% $L_{AGN}$ and momentum fluxes ~ 1-5 $L_{AGN}$/c

Fabian12, Thompson+14, Ishibashi+Fabian15, Bieri+17, Ishibashi, Fabian+Maiolino18, Costa+18ab

# Radio jets can drive multiphase outflows too..

Best studied case: **IC5063** Morganti+98,+07,+13,+15, Oosterloo+00,+17, Dasyra+15,+16, Tadhunter+14

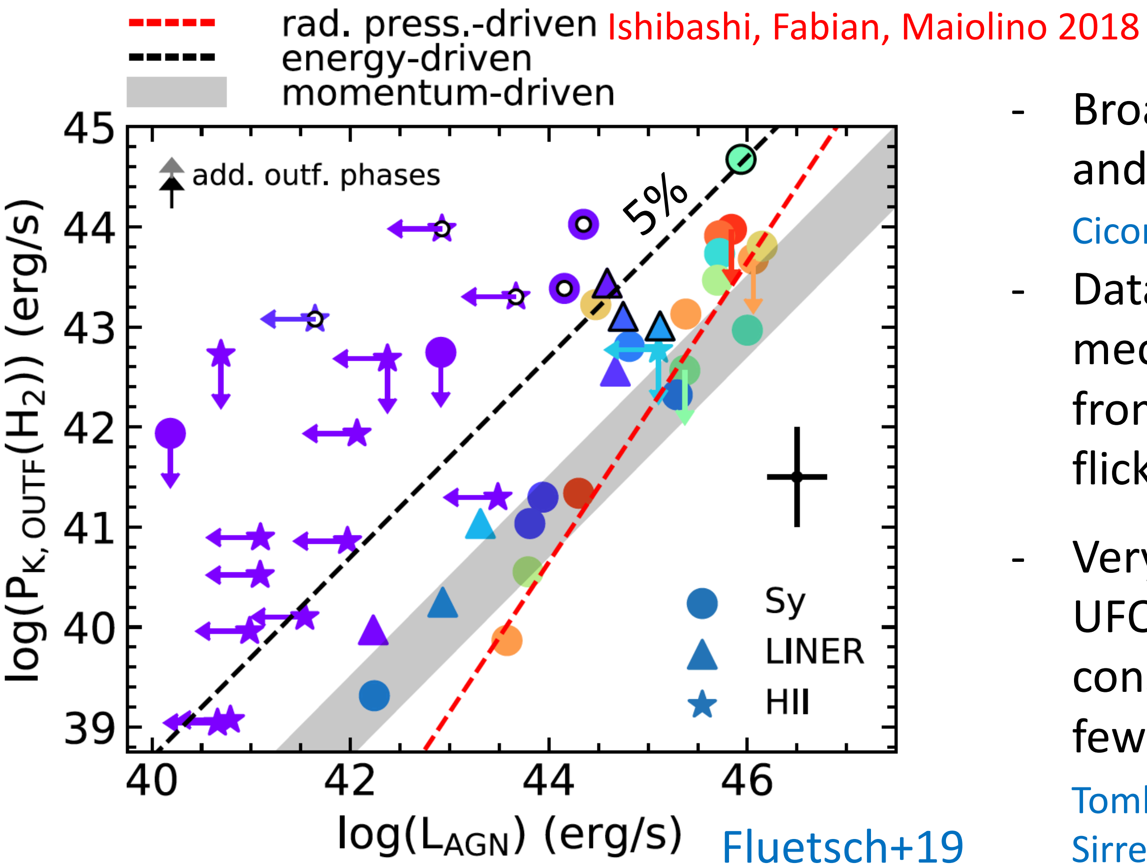



- Interaction between expanding jet and ISM generates outflows. Key parameters: (i) power/compactness of radio jet and (ii) ISM clumpiness
  Wagner+Bicknell12, Wagner+13, Mukherjee+16
- Stronger in younger/restarted radio sources (compact jets -> more lateral spreading). *Not necessarily the classical 'radio loud' AGNs*
- *Several cases now identified observationally*

  Morganti+05 Teng+13, Maccagni+17 Nesvadba+17, Husemann+16

Candidates for jet-driven $H_2$ outflows: **NGC1266** (Alatalo+11,+15), **NGC1433** (Combes+13), **NGC1377** (Aalto+12,+16), **M51** (Matsushita+07), **NGC3256** (Sakamoto+14) and a few 'surprising' ones: **Mrk231, NGC1068, Arp220**

# Testing models through outflow energetics

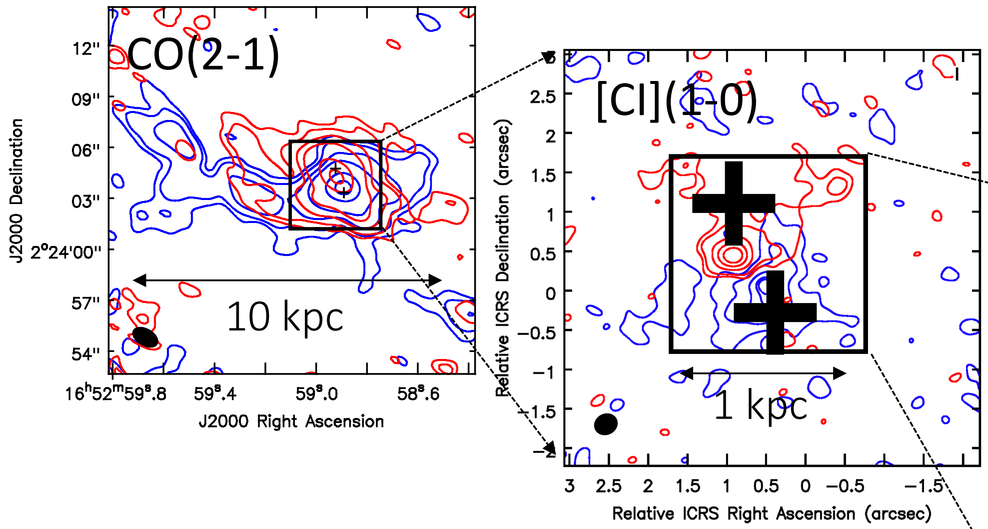


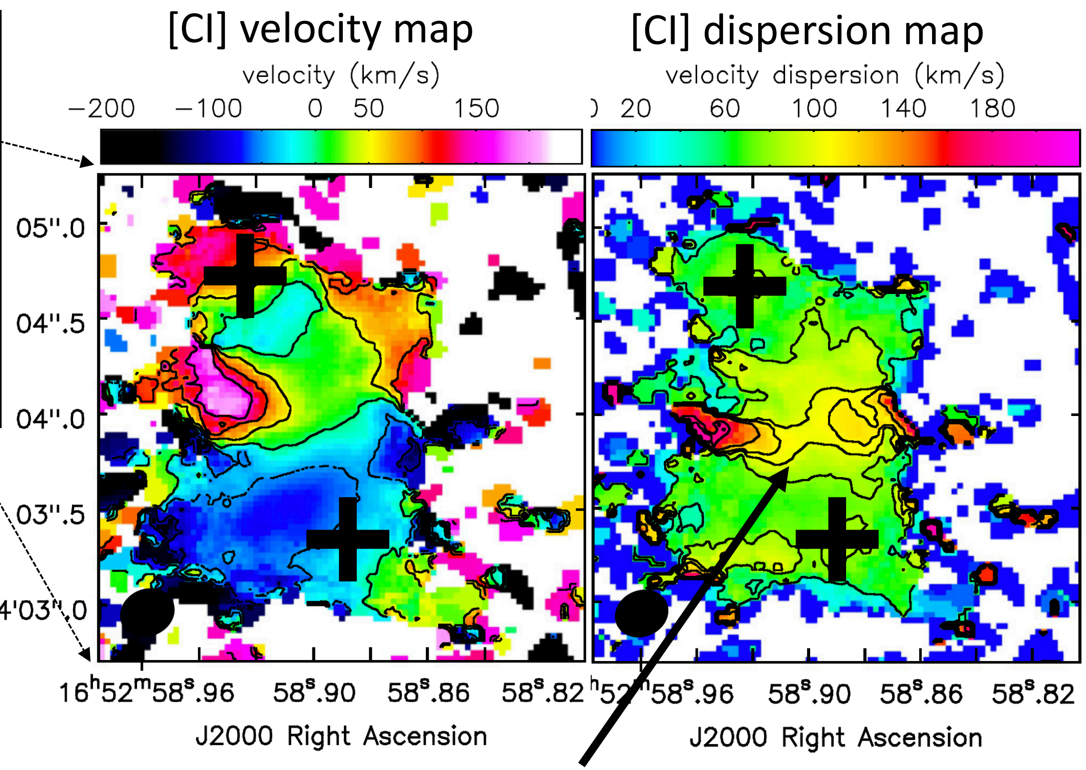

Fluetsch+19

- Broad range of kinetic powers (0.1-5% $L_{AGN}$) and momentum fluxes (1-20 $L_{AGN}/c$)
  Cicone+14 Fiore+17 Bischetti+18 Fluetsch+19
- Data points consistent with both AGN driving mechanisms. Outliers due to contribution from SF, hidden jets, or AGN variability/ flickering
- Very few simultaneous detections of X-ray UFOs and galactic $H_2$ outflows, not clear constraints, large uncertainties and biases, a few counter-examples found
  Tombesi+15 Veilleux+17 Feruglio+17 Bischetti+19
  Sirressi, Cicone+ in prep

# Resolving the outflow launching point in NGC6240

--> LIRG and dual AGN (~1 kpc separation)




- Launching point *between the* two AGNs
- ***Extreme energetics* suggests AGN-driving:**
- $dM_{out}/dt = 2500\ M_{Sun}/yr = 50\ (\pm\ 30)$ SFR
- $dE_{out}/dt = 3.3\ (\pm\ 1.9)\ \%\ L_{AGN}$
- $dp_{out}/dt = 80\ (\pm\ 50)\ L_{AGN}/c$
- ***Geometry* suggests link with merger (**see Hani+18**)**

*Errors include uncertainty on $\alpha_{CO}$*

'hourglass' feature = launching base of outflow (res ~ 0.24" = 120 pc)

Cicone+18b

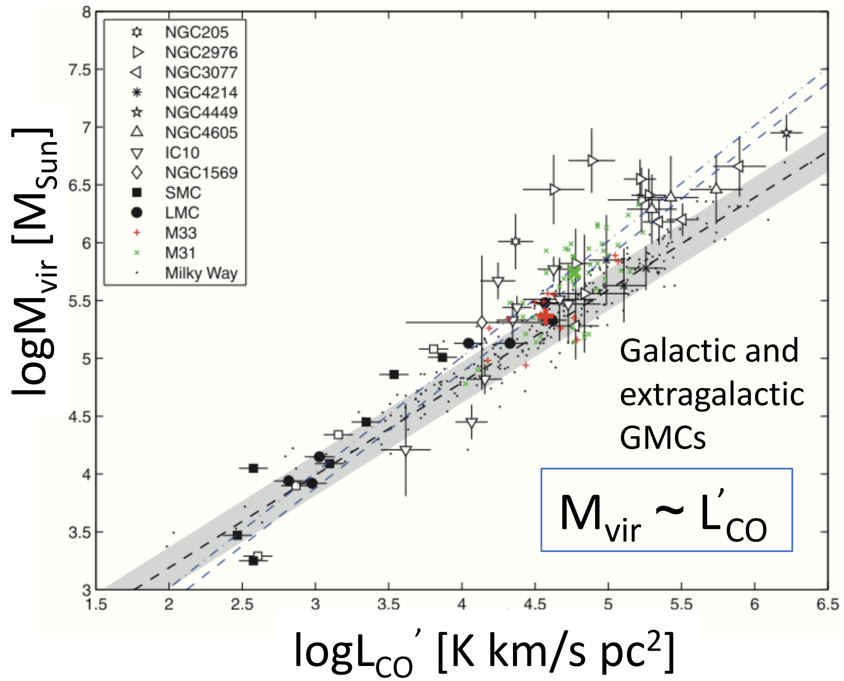
# 1) What drives galactic outflows and how?

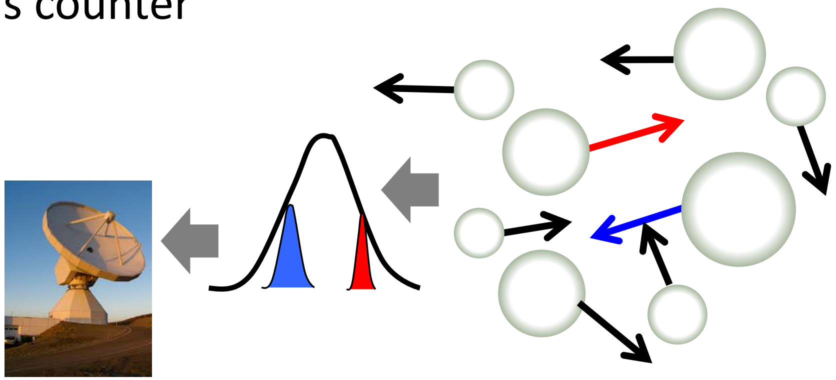
- Star formation
- AGNs
- Radio jets
- All of the above, in synergy
- Outflow morphology and energetics depend strongly on the properties of the surrounding ISM (shaped by prior feedback events and galaxy mergers)

# 2) What are the physical conditions of the outflowing ISM?

# The molecular ISM: using CO to trace $H_2$

- $H_2$ IR rovibrational transitions *do no trace cold $H_2$* (= the bulk of $H_2$ gas), so we use $^{12}CO(1\text{-}0)$, $^{12}CO(2\text{-}1)$
- But these low-J $^{12}CO$ transitions are *optically thick* in individual clouds: we only see the emission from the outer layers. Where is the trick?
  1) For individual GMCs, $L_{CO}$ is proportional to $M_{vir}$
  2) For collections of GMCs (i.e. a galaxy), $L_{CO}$ is a "clouds counter"

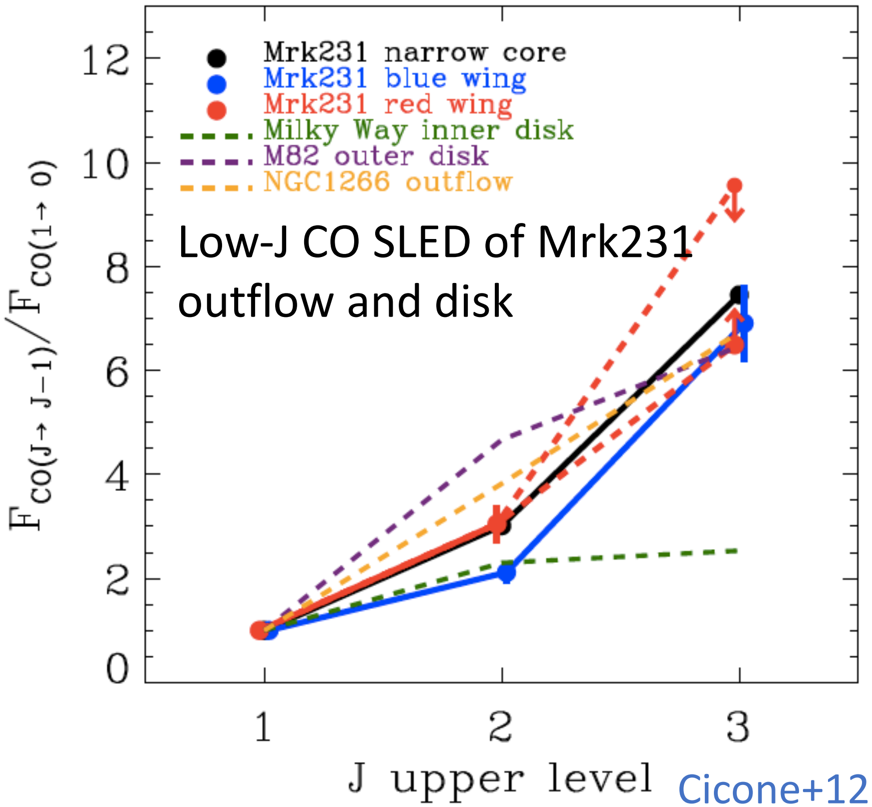


Allows use of $^{12}CO$ to measure $M_{mol}$:
$M_{mol} = \alpha_{CO}\, L_{CO}'$

Solomon+87, Scoville03, Bolatto+08, Kennicutt+Evans12

# The CO(2-1)/CO(1-0) $T_b$ ratio ($r_{21}$)




Cicone+12

- $r_{21}$ ~ 1 or below suggests optically thick CO emission (BUT *remember high degeneracy in $T_{kin}$ and density for $r_{21} \lesssim 1$ values* )
- In Mrk231's outflow $r_{21}$ ~ 0.6-0.9, similar between disk and outflow

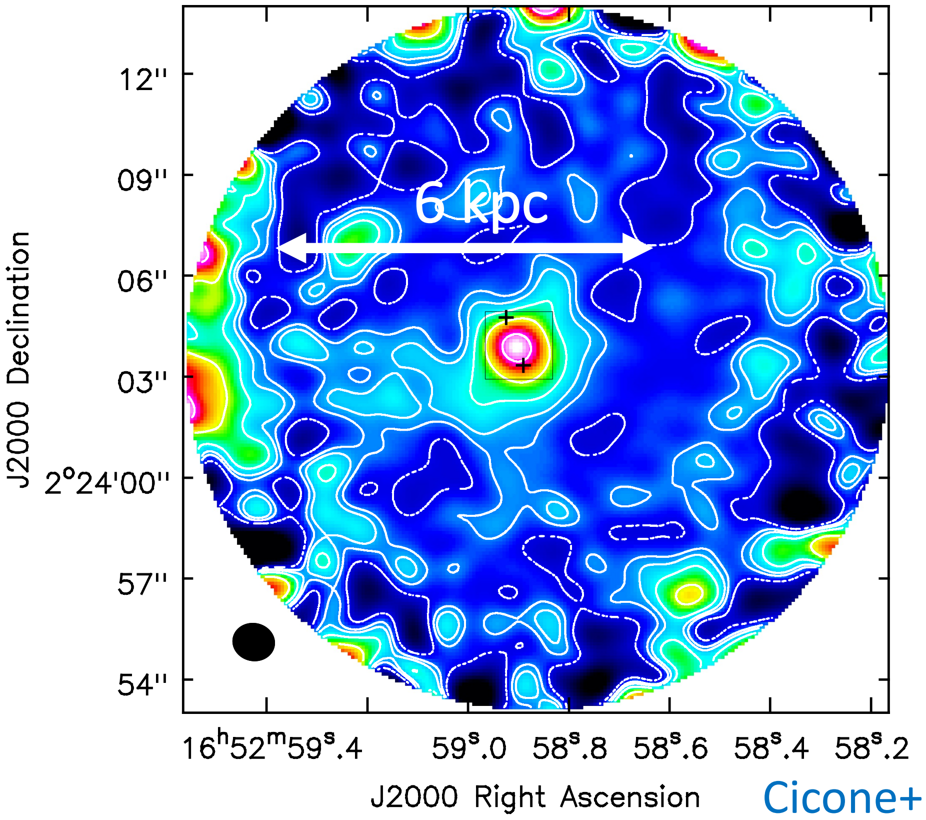
  Cicone+12, Cicone+in prep
- $r_{21} \lesssim 1$ measured also in NGC253's outflow, supporting *optically thick CO* similar to central starburst

  Zschaechner+18

*-> support similar (optically-thick) $\alpha_{CO}$ for outflow and disk*

# $[CI]^3P_1$-$^3P_0$ as an alternative $H_2$ tracer: the first resolved [CI] map of a molecular outflow

*The molecular outflow of NGC6240 as seen in [CI](1-0)*



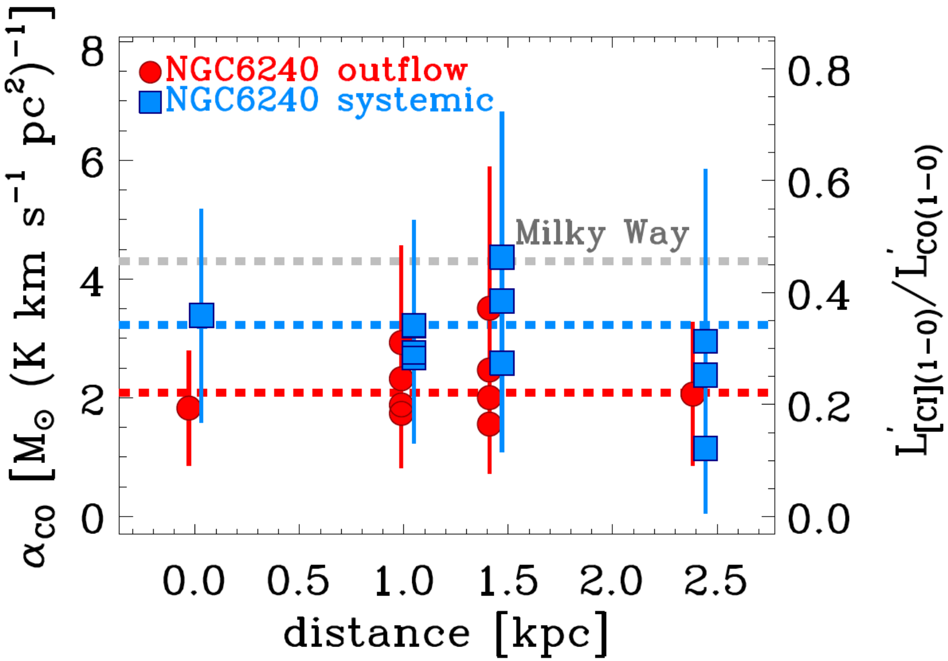

Cicone+18b

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

[CI]1-0 allows to estimate $M_{H2}$ independent of $\alpha_{CO}$. Use $T_{ex}$=30 K and $X_{CI}$=(3+-1.5)x$10^{-5}$ (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 )

# The $\alpha_{CO}$ of molecular outflowing 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$^2$]$^{-1}$**

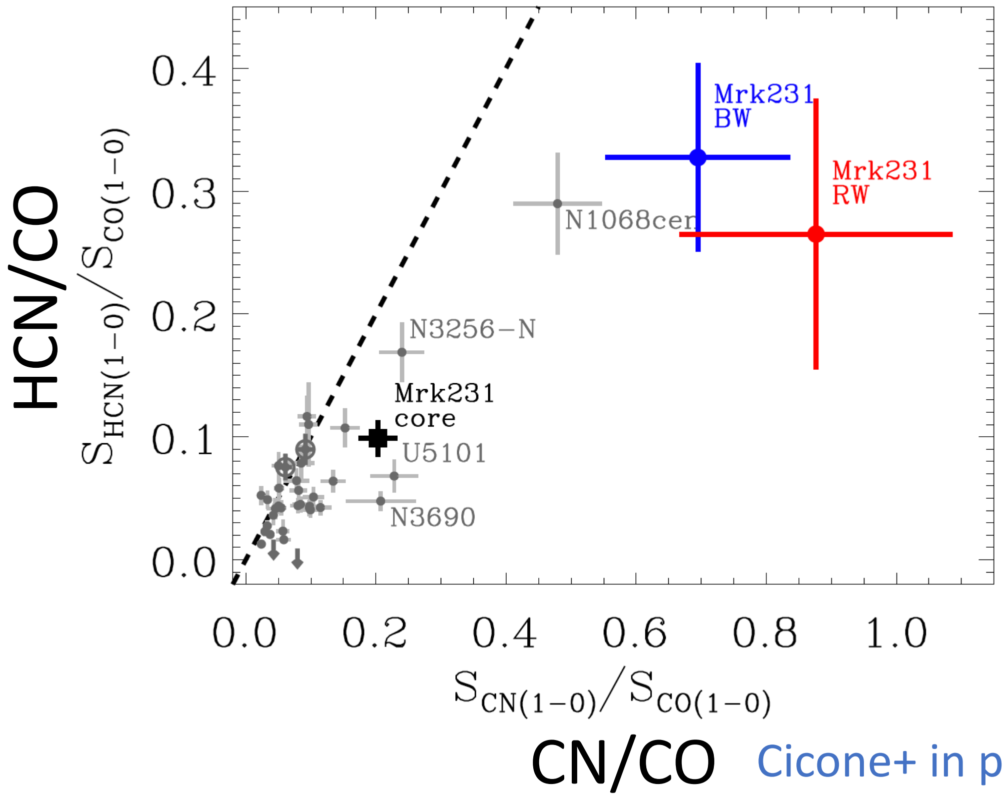
- In quiescent gas $\alpha_{CO}$ is *formally* consistent with MW value (~4.3) even for a messy galaxy merger and dual AGN such as NGC6240

- $\alpha_{CO}$ lower in outflow, independent of R: outflows host *warm + diffuse $H_2$ 'envelope'* phase advocated by earlier ULIRGs studies Aalto+95, Downes+Solomon98

- However $\alpha_{CO}$ > 0.3 and > 'ULIRG' value (0.8) everywhere. Not all outflow material is diffuse and warm, but *dense gas is entrained*

Cicone+18b

# Puzzling enhancement of dense gas tracers in Mrk231's outflow




Cicone+ in prep

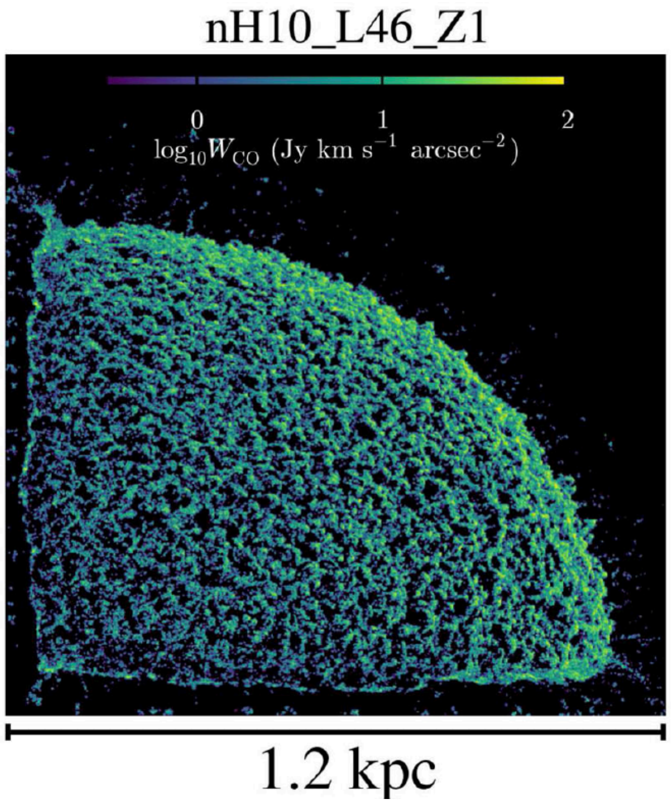
- Spectacular enhancement of CN and HCN emission in Mrk231's outflow

  Aalto+12,+15, Lindberg+16, Cicone+ in prep
- CN generally enhanced by UV radiation (PDR tracer)
- *CN/CO ratio in Mrk231's outflow is unprecedented in extragalactic sources*
- Implies high CN abundance and substantial dense gas (n ~ $10^4$ $cm^{-3}$)
- Conditions favourable for star formation?

  Maiolino+17, Gallagher+18, Cresci+Maiolino18

# Explaining cold $H_2$ in outflow is an issue

(-> problem similar to multiphase CGM)




Molecules forming in outflows

(i) Entrainment?

- $H_2$ clouds overtaken by fast hot winds destroyed well before reaching $v_{out}$~1000 km/s because hydro instabilities (KH, RT) mix the phases ('cloud crushing' timescale < dragging timescale)

  Scannapieco&Brüggen15, Brüggen&Scannapieco16

- But if radiative cooling is efficient ($t_{cool} < t_{cc}$), then bigger (>2pc for HI) clouds survive entrainment, and may even grow in mass through cooling-induced 'focusing' on cloud's tails Gronke+Oh18, Armillotta+17

(ii) Rebirth?

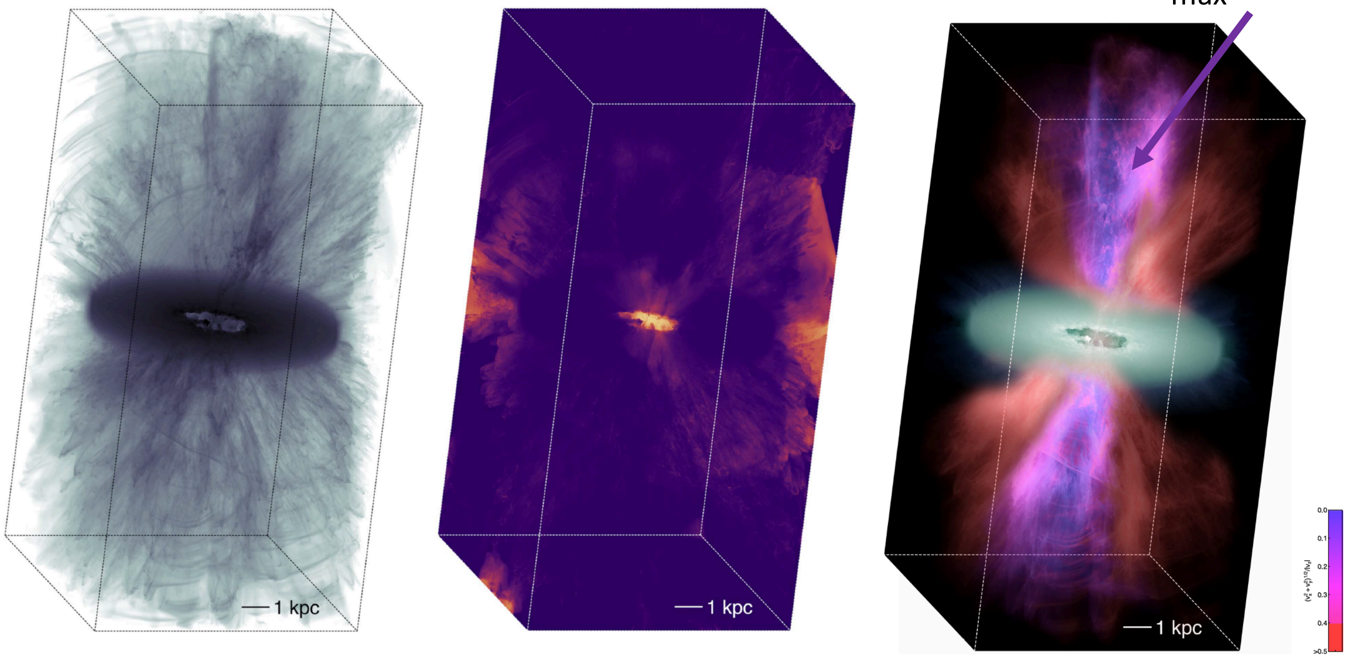
- Explore cooling out of a hot/warm outflow. $H_2$ can reform in <1 Myr, but needs high density, metallicity, *and* dust

  Zubovas+King14, Nims+15, Thompson+16, Richings+18ab

# Rebirth and entrainment of cold clouds in outflow 'observed' in high-res simulations

Spatial res ~ 5 pc

$v_{max}$~1000 km/s




Density

Density-weighted temperature

Velocity

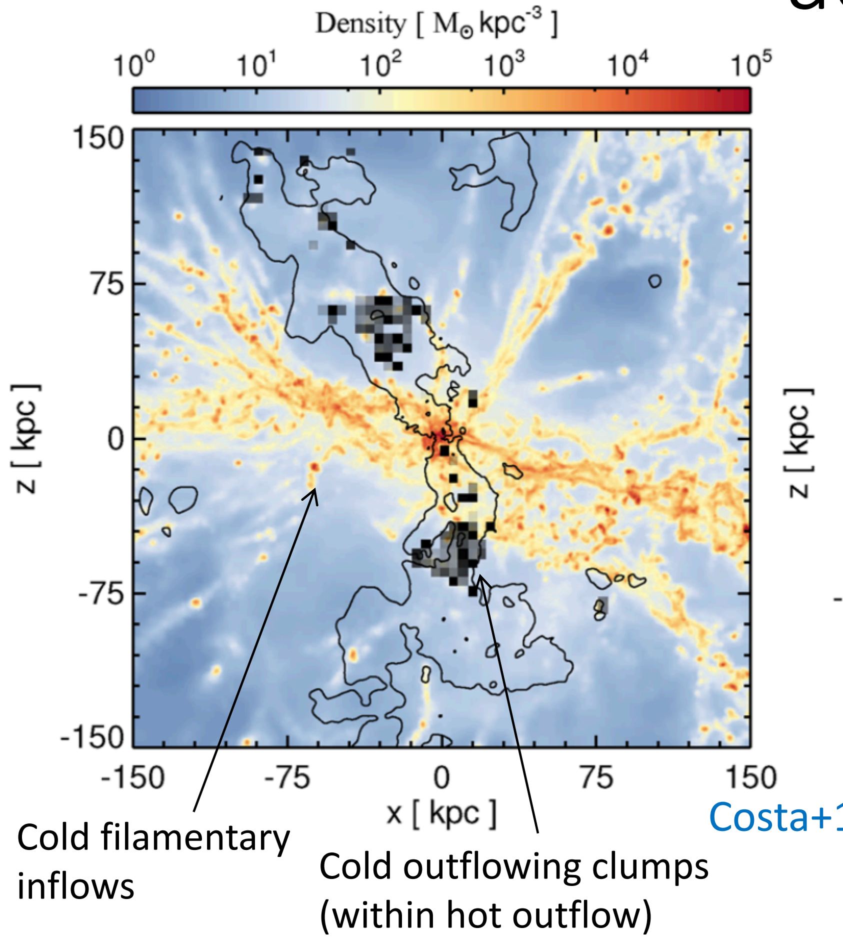
Thompson+16, Schneider+18

SB-driven wind, kinetic energy injected in clusters spread across the disk

Not one single cooling radius, but several density fluctuations and rapidly varying and interacting outflow solutions. Cooling efficient at high $dM_{out}/dt$ and $\Sigma_{SFR}$

Cold ($T$~$10^4$ K) high-v (1000 km/s) gas due to a combination of "reborn" cold clouds and clouds lifted out from disk

# More efficient when AGN + SB feedback act together

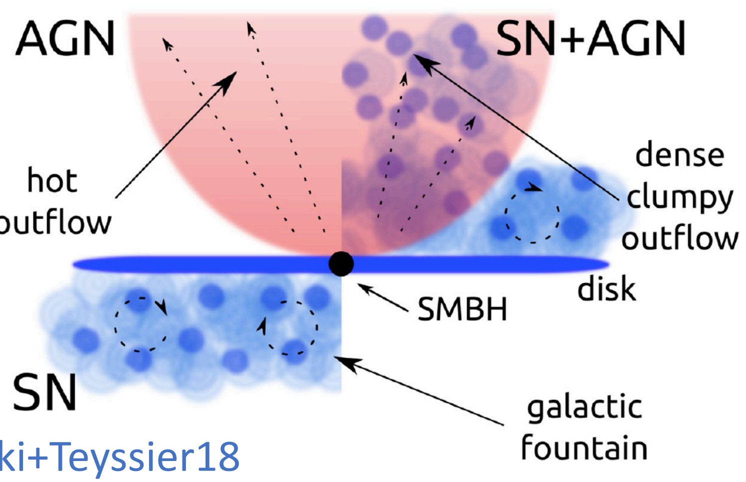



Costa+15

Interplay between AGN and SB feedback is key to form a more massive outflow and enhance cooling

*SN feedback and galactic fountains change the environment* across which the AGN-driven outflows propagate: more gas, more metal rich, denser gas

See also: Prieto+17, Bieri+18, Koudmani+19



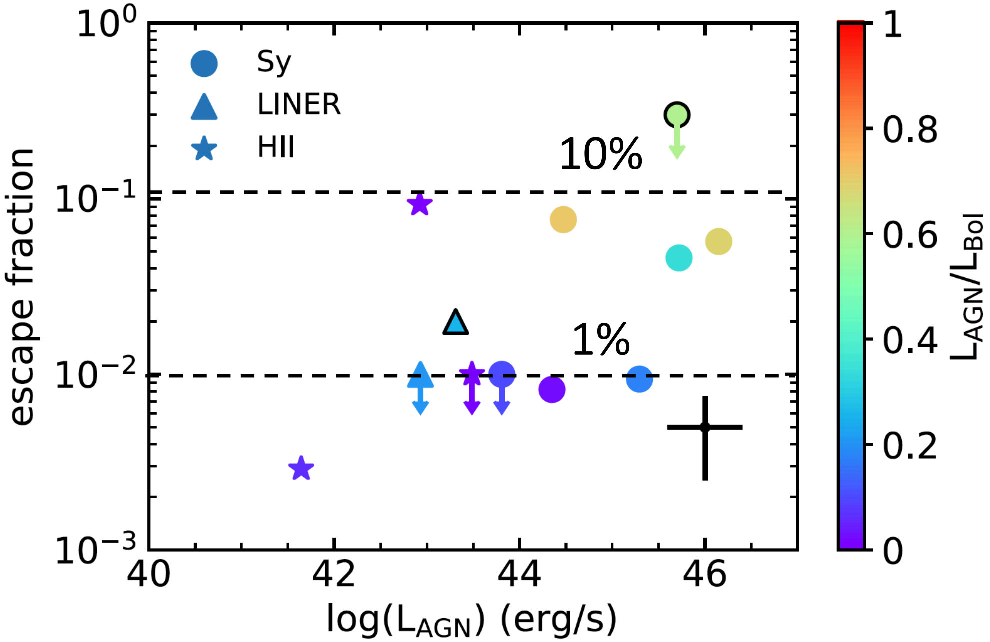

Biernacki+Teyssier18

# 2) What are the physical conditions of the outflowing ISM?

- Global $r_{21}$ in outflow not too dissimilar from ‘parent’ ISM
- $\alpha_{CO}^{outflow} \sim 2$ in NGC6240 suggests outflow consists of unbound envelope + dense clumps entrained
- CN, HCN enhancement points to ‘unusual’ chemistry and high densities ($n \gtrsim 10^4$ cm$^{-3}$)
- Very high-res simulations are needed to capture entrainment and rebirth of cold clumps in outflows
- Cooling enhanced when SF + AGN feedback act in synergy

# 3) Where does the outflowing ISM end up?

# Low escape fraction of $H_2$ outflows

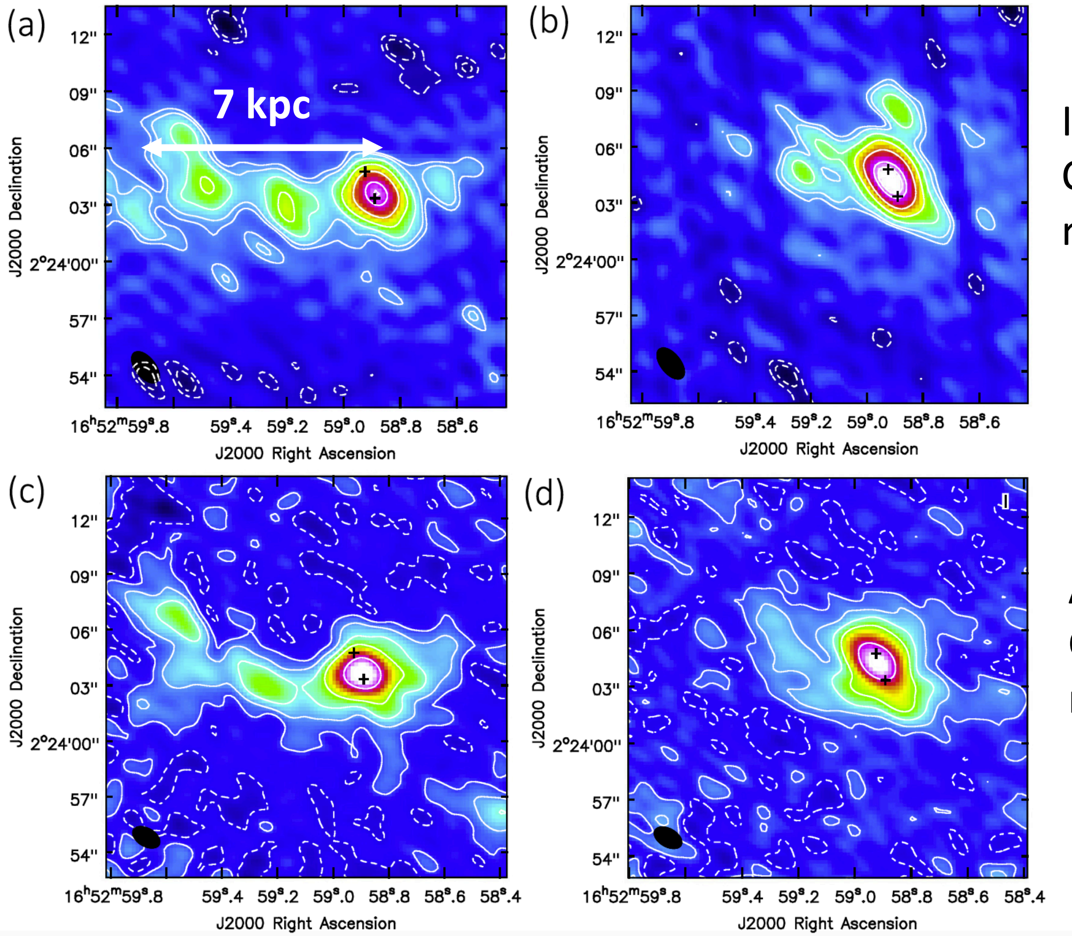



Fluetsch+19

- Based on their low velocities, molecular and atomic outflows appear to have a low escape fraction from the galaxy ( <1%)
  Alatalo+15, Cazzoli+16, Concas+18
- In M82, the cold $H_2$ abandons the outflow at >1 kpc: $H_2$ gas either stalls above the disk or falls back in a different position/state (galactic fountain) Leroy+15
- Studies based on stellar metallicities suggest that 'statistically' ejection was not very efficient in currently passive galaxies: 'starvation' dominant quenching mechanism
  Peng, Maiolino+15, Trussler+18

# NGC6240: tracking the $H_2$ outflow to r > 5 kpc

IRAM PdBI
CO(1-0)
blue-shifted




IRAM PdBI
CO(1-0)
red-shifted

ALMA
CO(2-1)
blue-shifted

ALMA
CO(2-1)
red-shifted

Substantial outflowing gas exists at r > 5 kpc

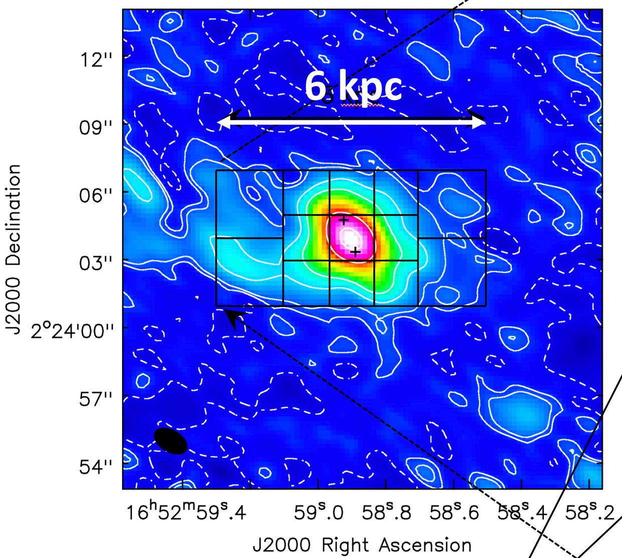
Escaping is easier at larger distances

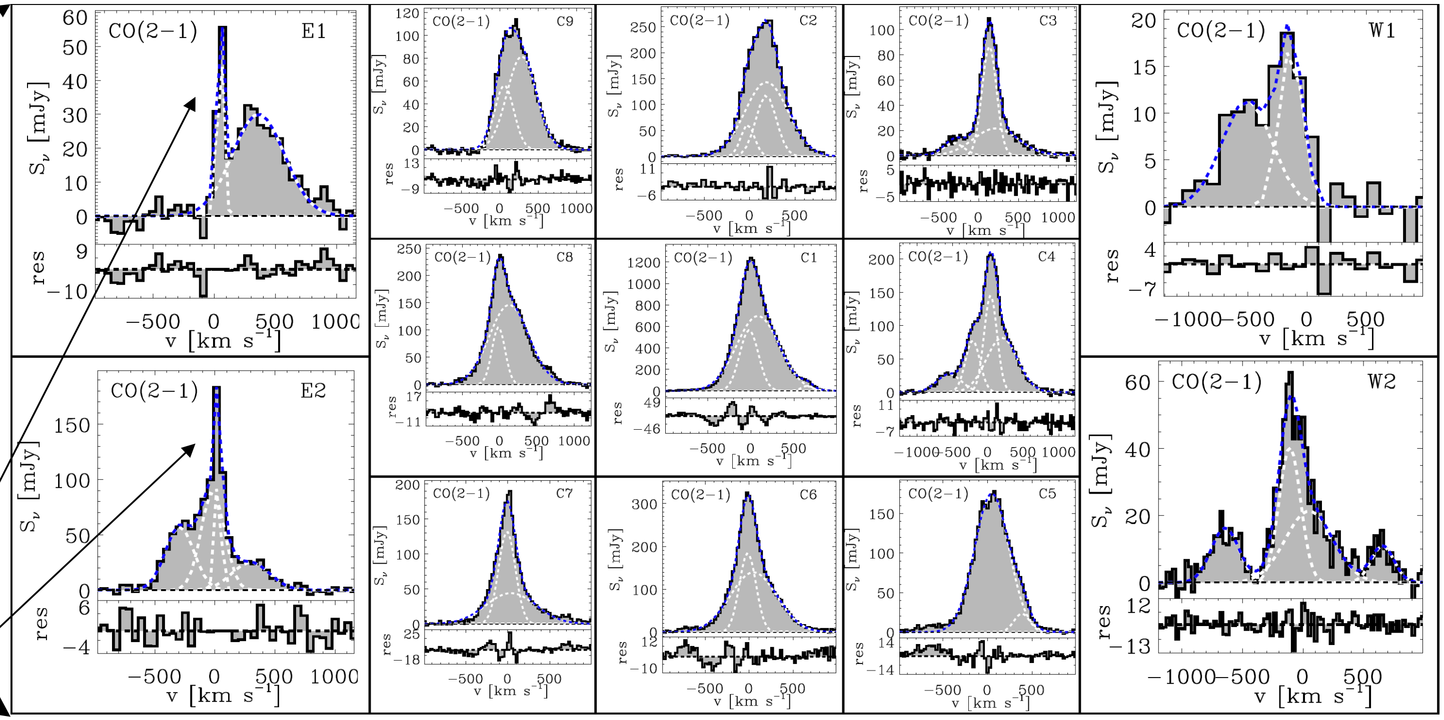
Probing larger scales requires high sensitivity *and* short baselines

Cicone+18b

# NGC6240: tracking the $H_2$ outflow to r > 5 kpc

NGC6240
ALMA CO(2-1) data



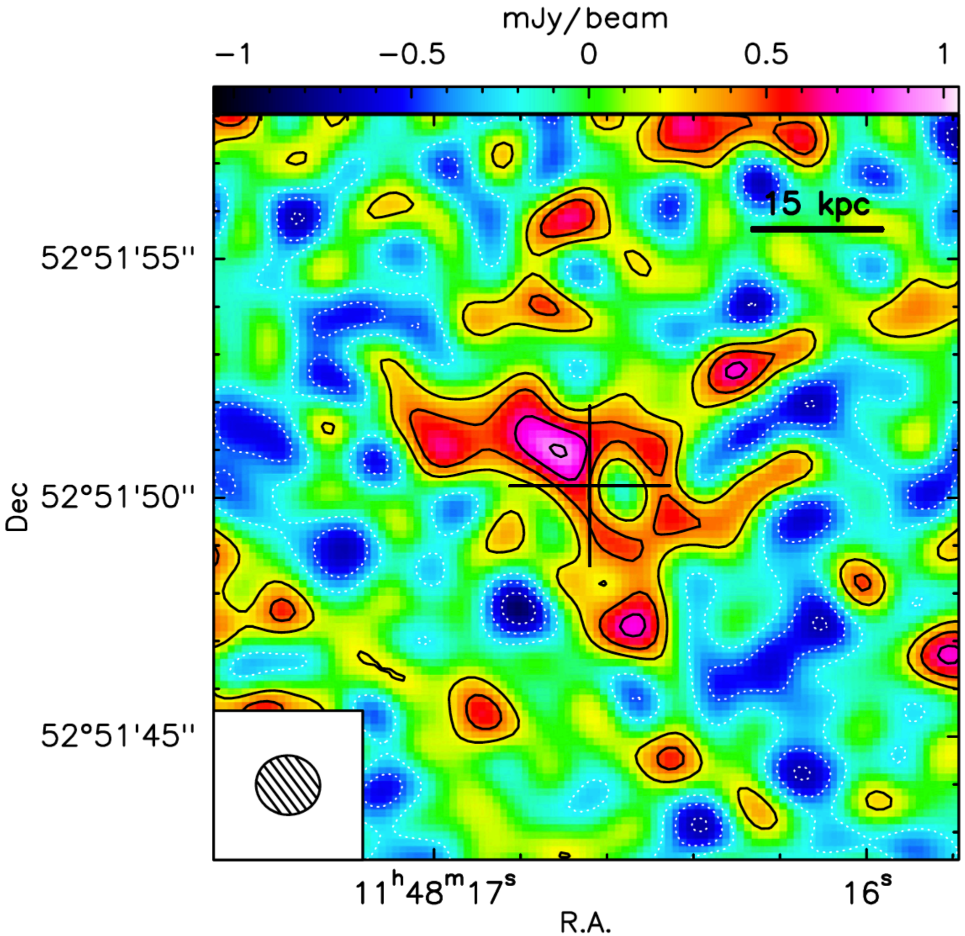

*Not much quiescent $H_2$ at r>2-3 kpc: outflow dominates CO emission*

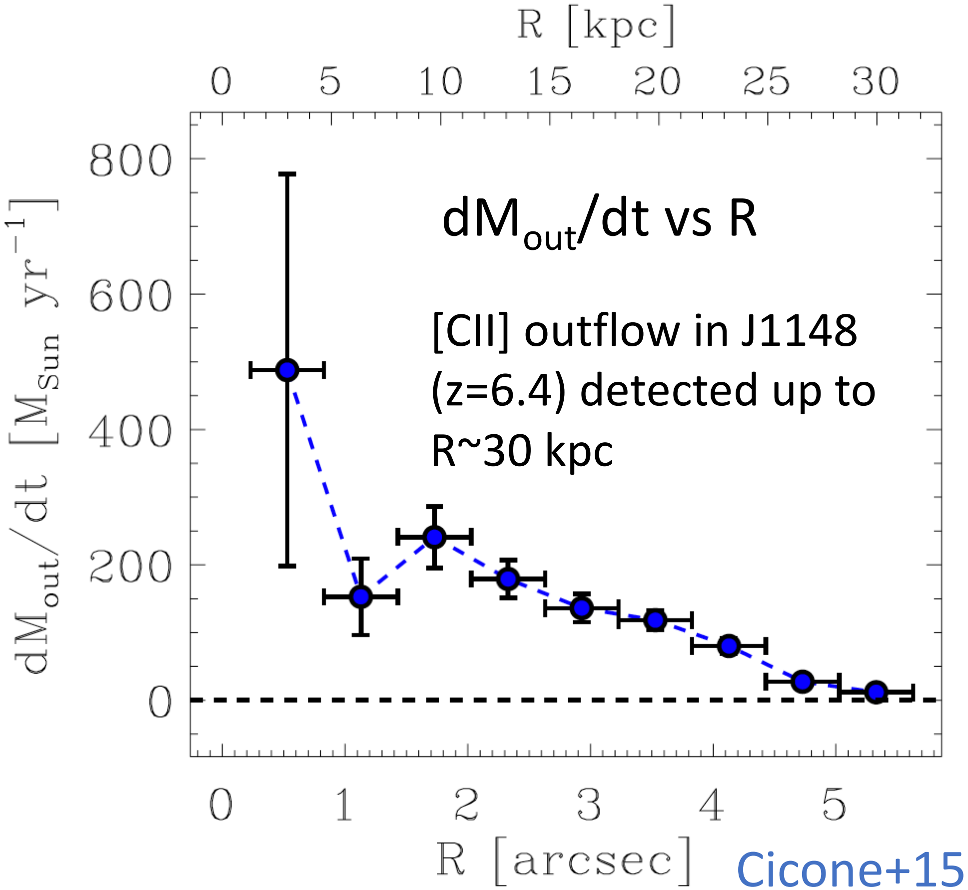
Molecular gas entrained closer to nucleus and dragged up to r>5 kpc?

Cicone+18b

# Tracking outflows at R>20 kpc

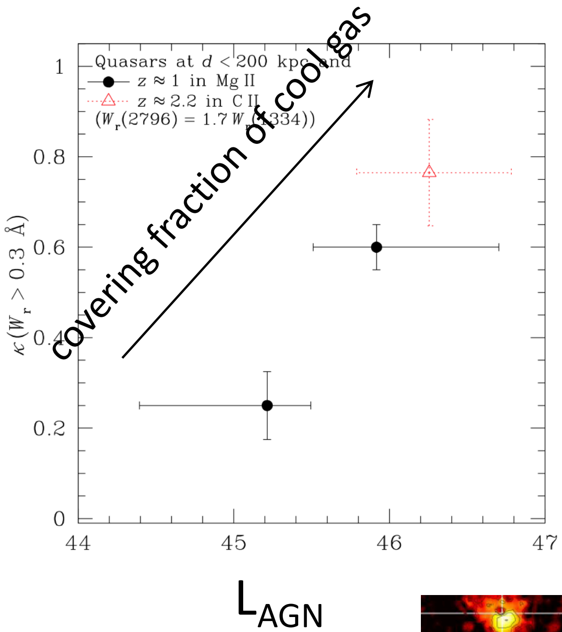
(>>ISM scales, ~ CGM scales)



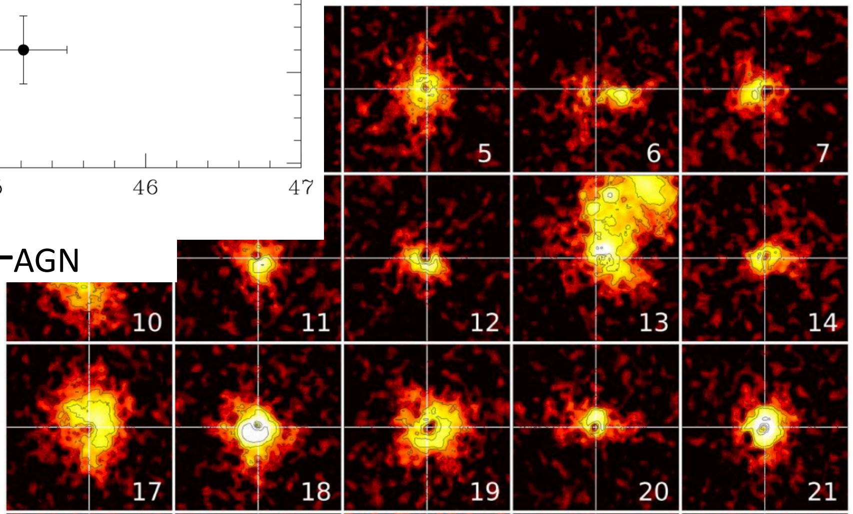

Cicone+15

# Quasar feedback responsible for puzzling massive (cool) CGM reservoirs?




Johnson+15
Prochaska+13,+14

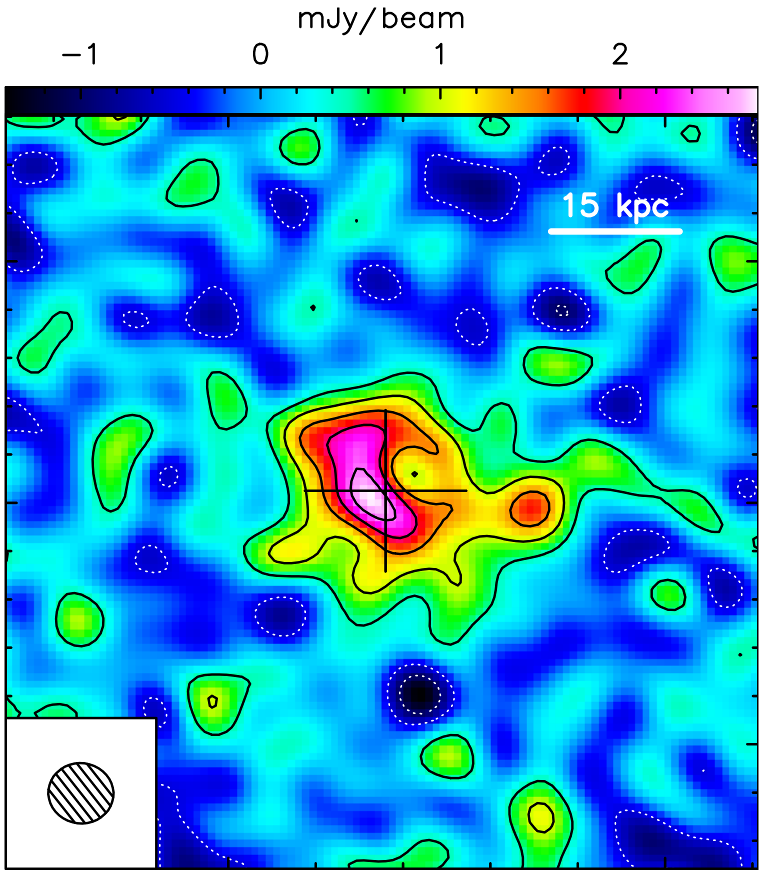
Ubiquitous Lyα nebulae around z=3 quasars Borisova+16, Arrigoni Battaia+19




- Observational evidence of enhanced cool (T<$10^4$ K) gas reservoirs surrounding high-z quasars on scales of 10s to 100s kpc
- Cannot be explained by stellar feedback alone (Fumagalli+15)
- *Early quasar feedback may have created massive cold CGM*

*We now have observational evidence that this is happening*

# Cold CGM reservoirs at high redshift



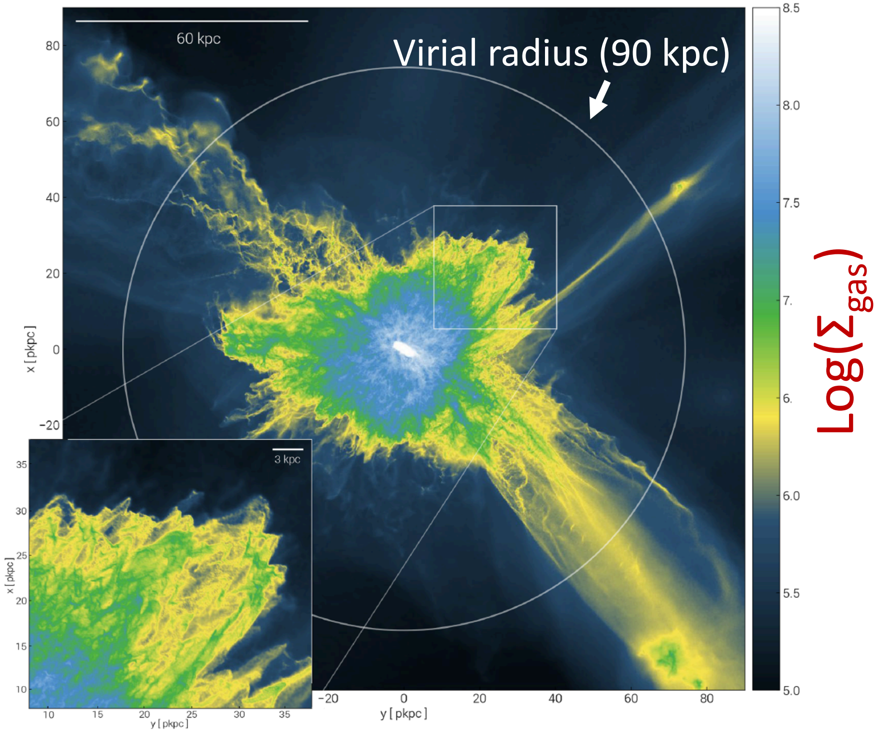

Cicone+15

70% of low-velocity [CII] in J1148 at z=6.4 not in kpc-scale disk but extends up to ~30 kpc: traces a cold (mostly HI + $H_2$) CGM reservoir

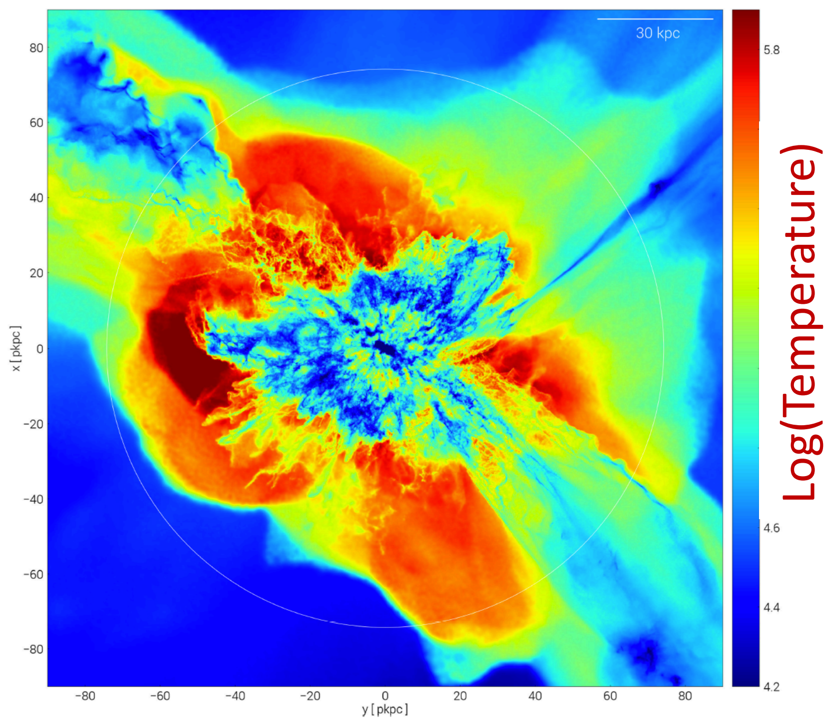
*First evidence of a `quiescent' massive cold CGM reservoir in a quasar that also shows powerful cold outflows*

Cold (including $H_2$) CGM reservoirs detected in other massive high-z structures (Ginolfi+17,Emonts+16,18)

# Lack of cold gas in simulated CGM is a bias of *some* (low-res) simulations rather than a prediction




~95 pc spatial res in the CGM



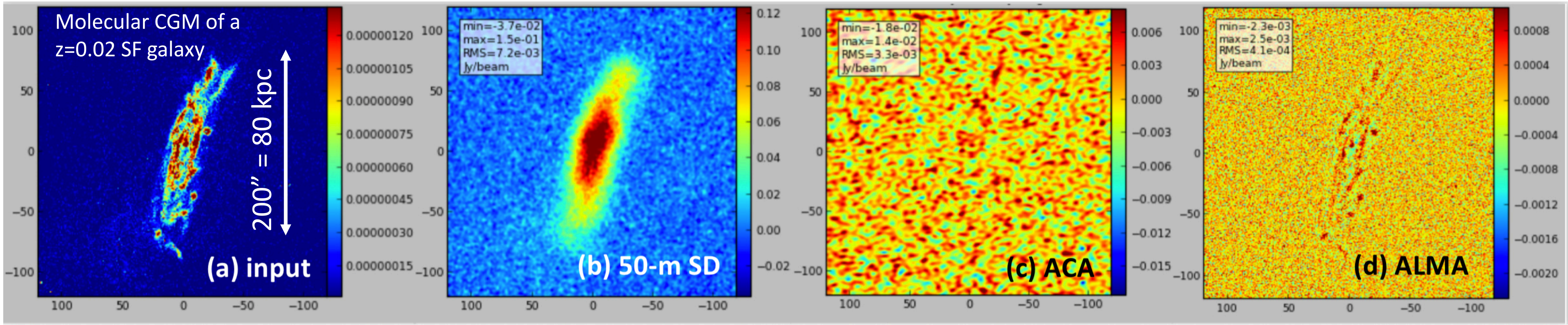

At z~2 mix of cold ($T \sim 10^4$ K) and hot ($T \sim 10^6$ K) gas in CGM

*SF feedback only*

*By z~2, 3/4 of cold CGM has formed through SF-driven outflows, 1/4 due to inflows and stripping*

Suresh+19 (see also Hummels+18, van de Voort+19 , and pioneering studies by Shen+12,+13)

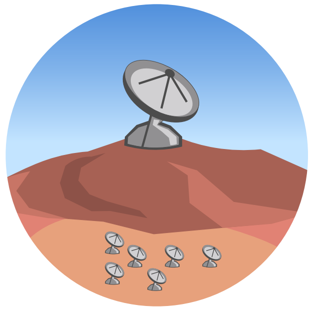
# Probing cold ($H_2$) gas on CGM scales is an issue even for observers




Cicone+19, Astro2020 White Paper

Large-scale emission is filtered out by interferometers: almost impossible to detect in local galaxies (sizes ~ several arcmins on sky) even with 100s of hours of integration with ALMA/ACA!!

*Detecting the cold CGM requires a 50-m class submm single dish*
*→ AtLAST (>2030s)*



# 3) Where does the outflowing ISM end up?

- Most of the outflowing gas stalls in the CGM and will later fall back onto the galaxy
- Some (little fraction) escapes the halo reaching the IGM
- Cold CGM reservoirs naturally expected from observations of cold outflows. Not predicted by most current simulations, due to low spatial resolution on CGM scales, neither observed due to spatial scale filtering of interferometers and low sensitivity of single dishes
- **Consider role of outflows in baryon cycle as a whole: *feeding and feedback, both short- and long-term effects***