ALMA observations of local galaxies and AGN

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Photo credit:Y. Beletsky/ESO

Outline

Introduction

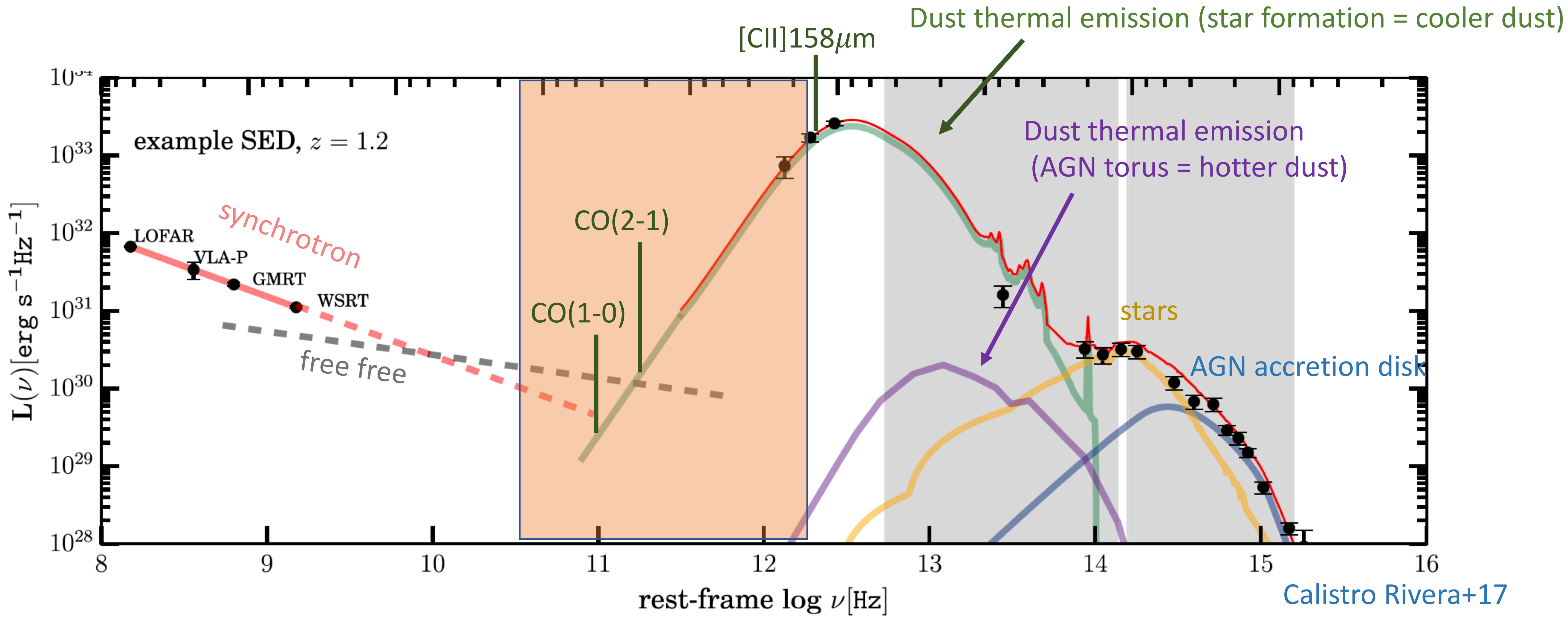
6 science cases for ALMA (local galaxies and AGNs)

1. Star formation laws, CO and high density tracers
2. AGN vs SF diagnostic diagrams in the mm/submm
3. Resolving the obscuring torus and AGN fueling
4. SMBH mass estimates and M-σ relation
5. Extremely obscured nuclei
6. Massive molecular outflows and feedback mechanisms

1-5 expected ~10 yrs ago (Maiolino2008)

Conclusions

The cold ISM: dust

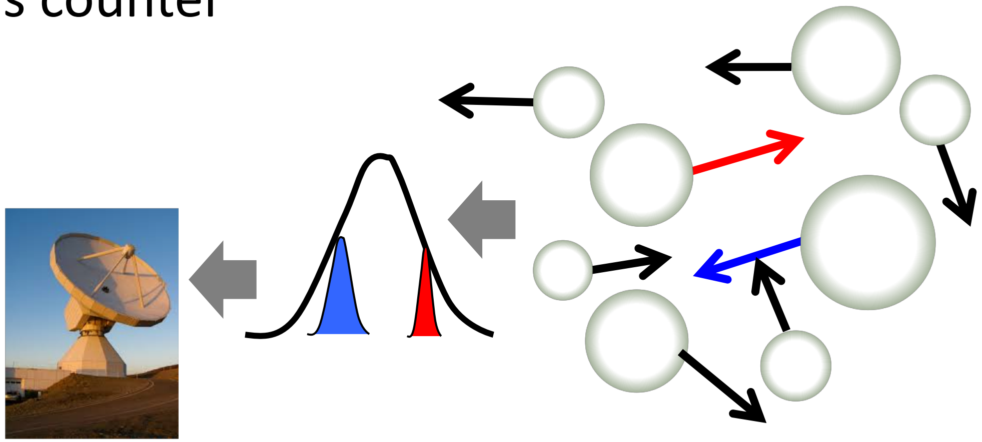


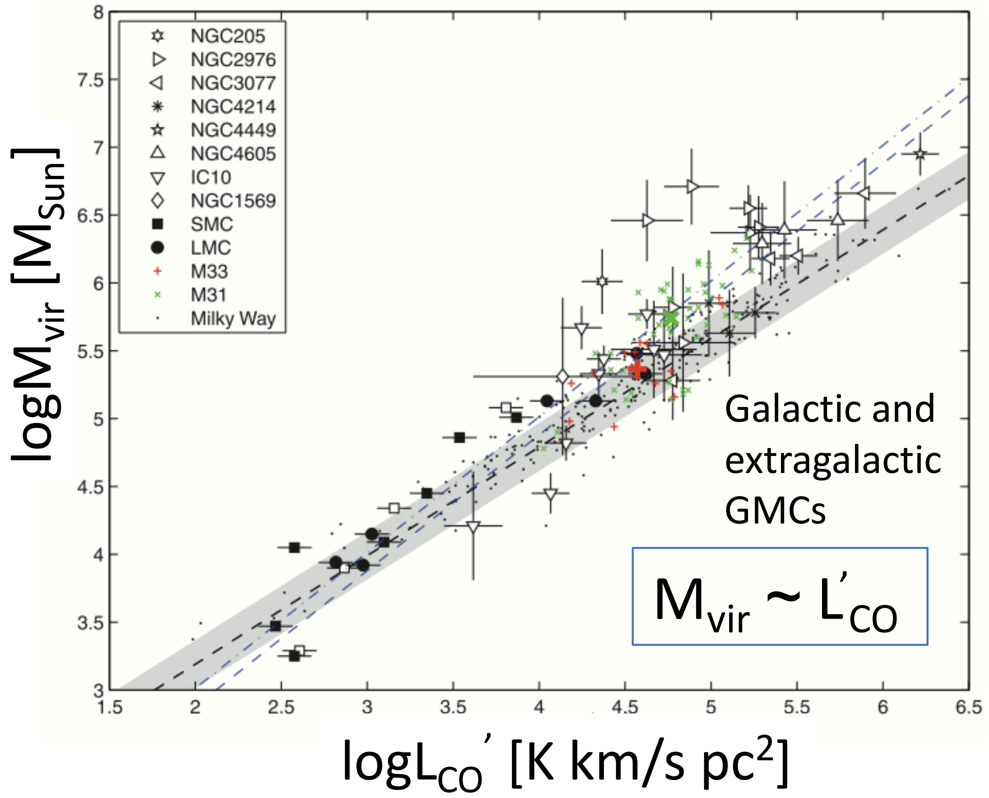
ALMA windows
(Bands 1 -11)

Spectral energy distribution (SED) of a dusty star forming galaxy with an AGN

The cold ISM: using CO to trace H_2

- H_2 IR rovibrational transitions *do no trace* cold H_2 (= bulk of H_2 gas), so we use ^{12}CO(1-0), ^{12}CO(2-1)
- But these low-J ^{12}CO transitions are optically thick in individual clouds: we only see 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}:

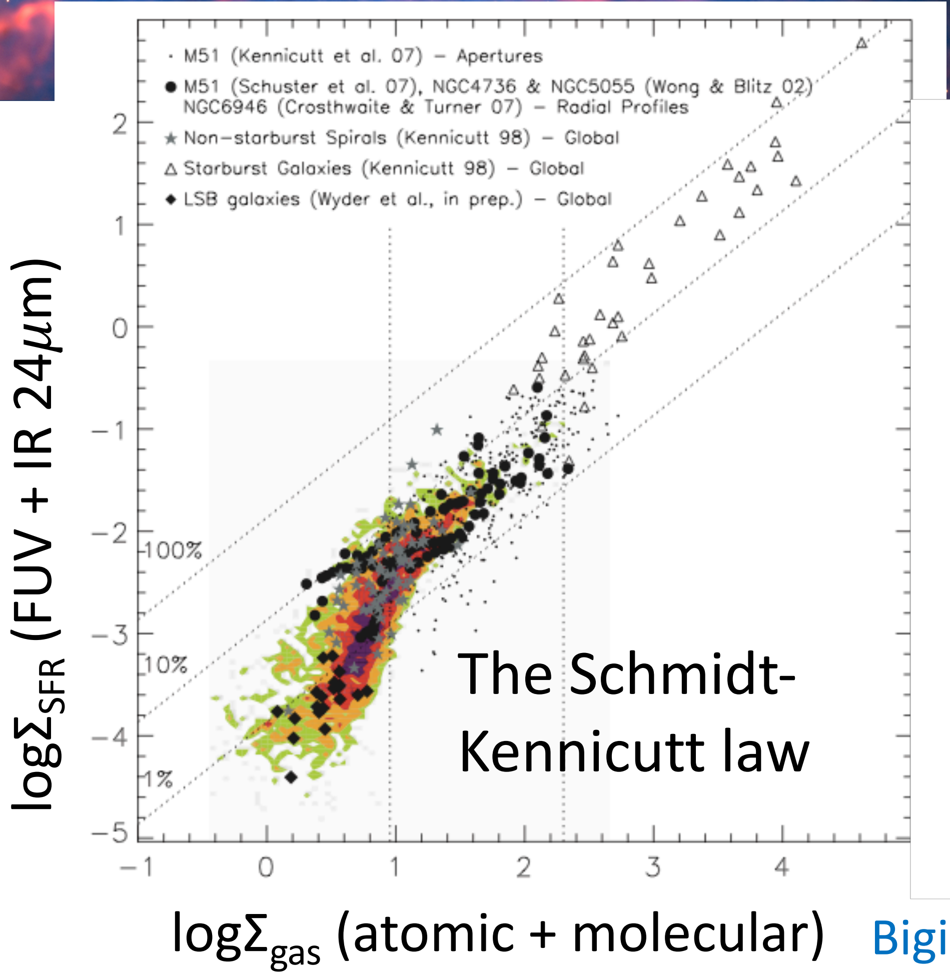
$$M_{mol} = \alpha_{CO} L_{CO}'$$

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

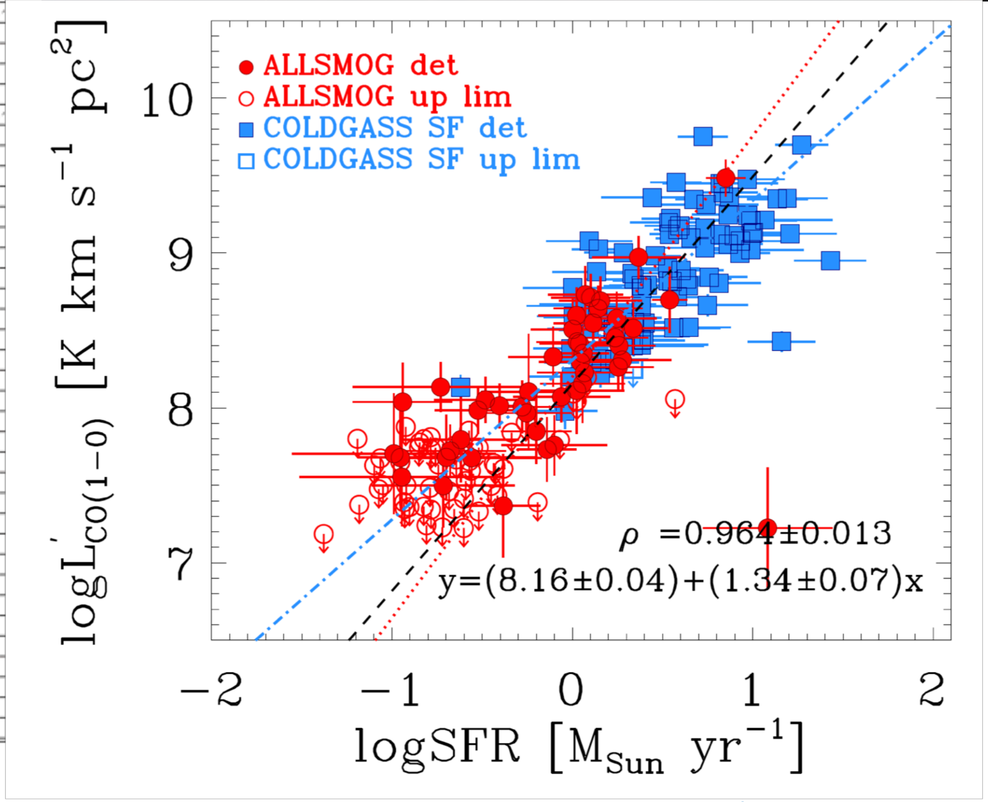
CO observations and S-K law

Map showing the Orion nebula, a star forming region in our Galaxy. Molecular gas in red and stellar IR emission in blue

Hacar+18



Bigiel+08, Leroy+13



Cicone+17

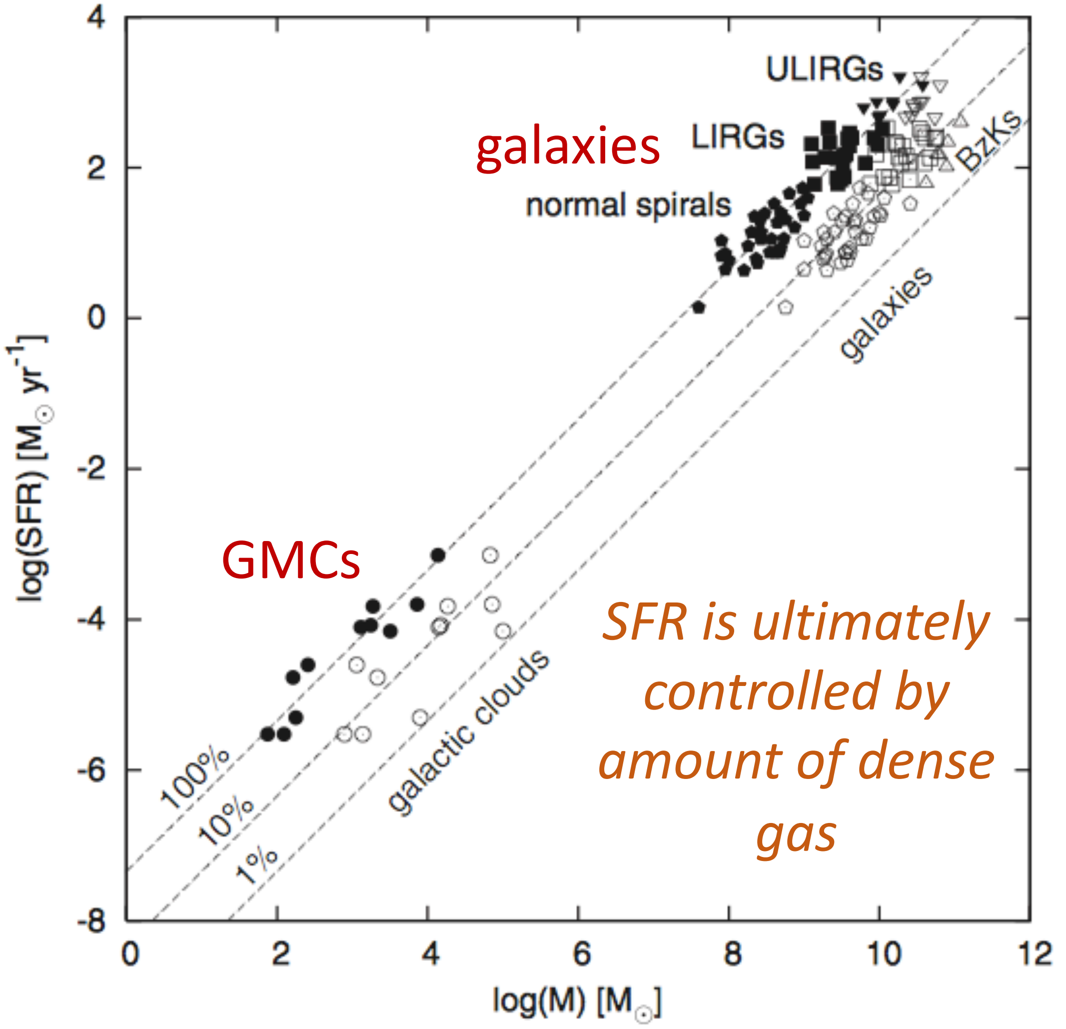
Fundamental relation between H_2 mass and SFR, holding over different redshifts, SFR and gas tracers with different slopes (slope >1 if using CO, implies τ_{H2} shorter for large M_{H2} and SFR)

But CO census of galaxy population is incomplete

High density tracers and star formation law

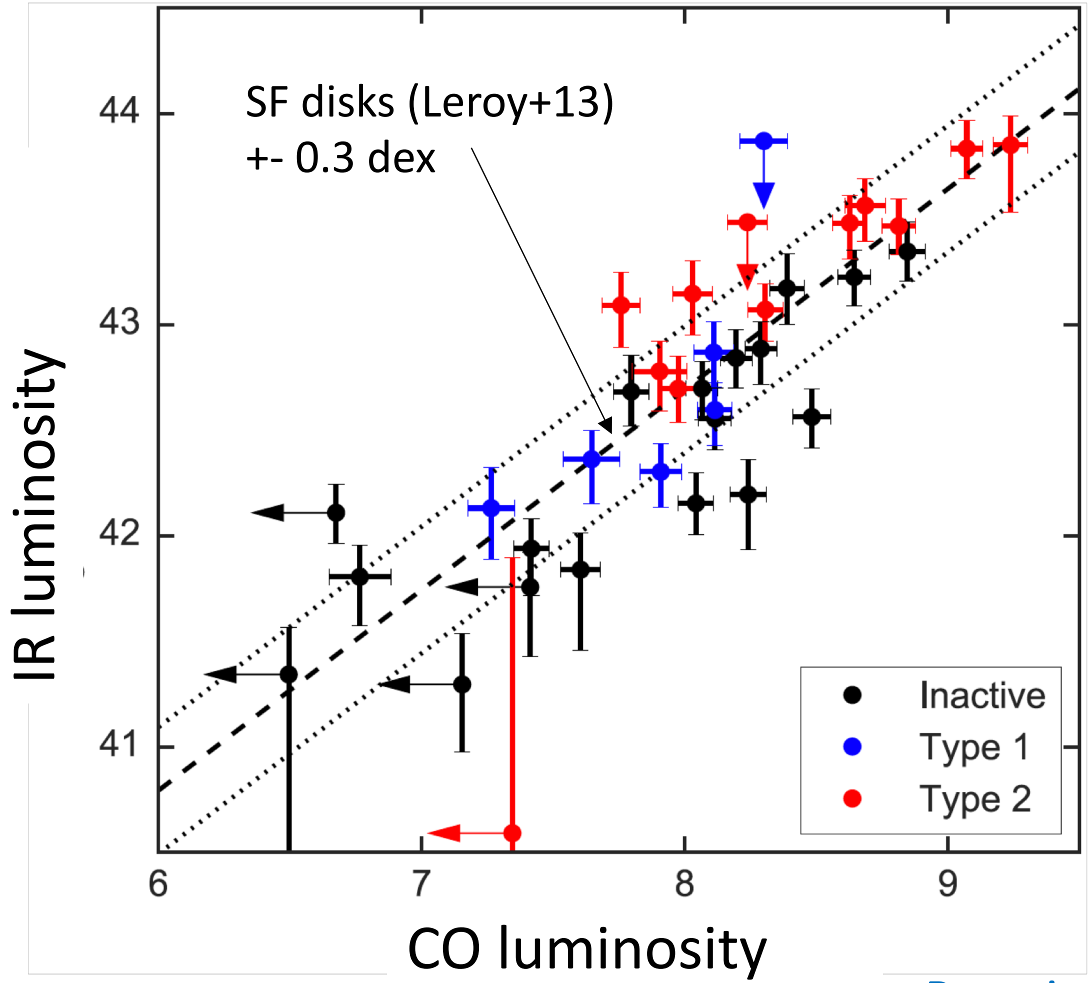
Line	$n_c\,[\mathrm{cm}^{-3}]^\dagger$
CO(1-0) →	2.1×10^2
CO(2-1)	1.9×10^3
CO(3-2)	6.8×10^3
CN(1-0) $J = 3/2$-$1/2$	6.4×10^4
CN(1-0) $J = 1/2$-$1/2$	
HCO^+(1-0)	1.4×10^4
HNC(1-0)	7.0×10^4
HCN(1-0) →	7.1×10^4
HCN(3-2)	2.4×10^6

Critical densities (calculated at T_{kin}~100 K under optically thin conditions) of some among the brightest molecular transitions



Gao+Solomon04, Wu+05, Lada+12

H_2 gas content of inactive vs active galaxies



Rosario+18

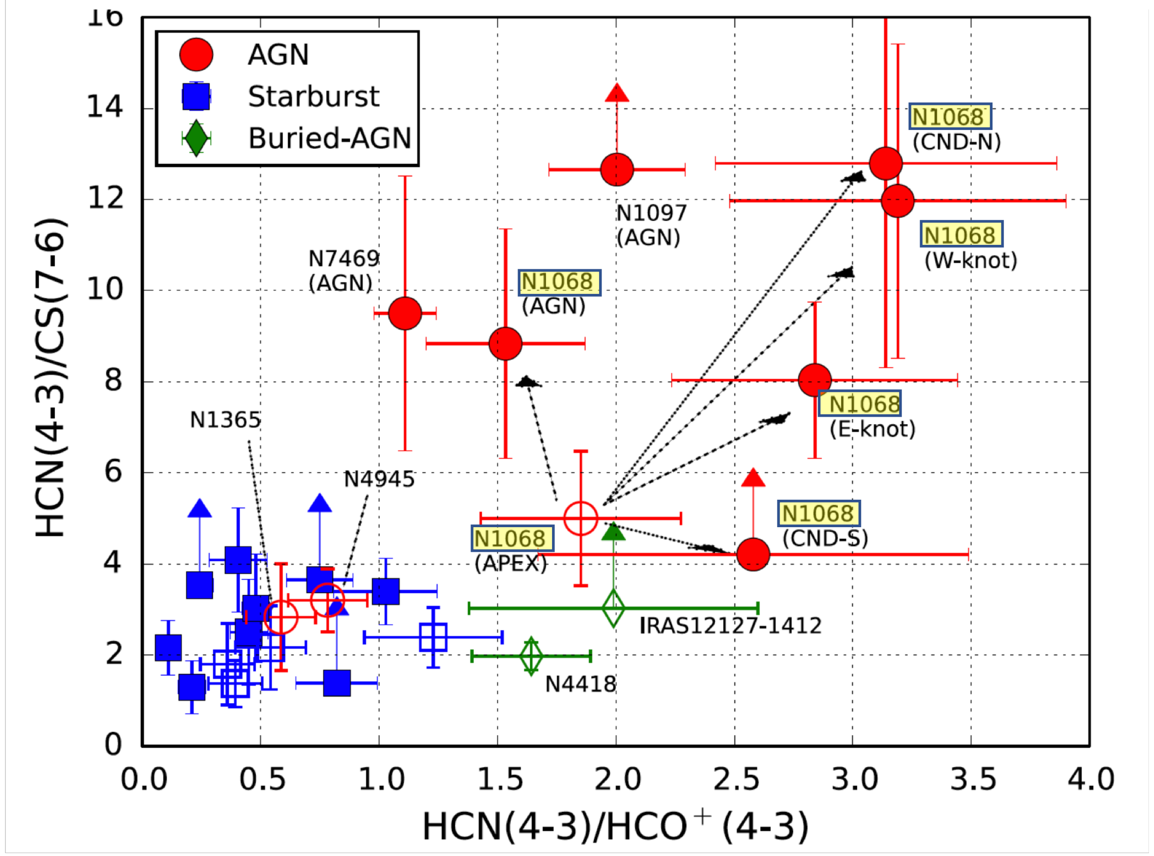
Conflicting results:

- No difference? Maiolino+97, Rosario+18
- AGNs (H_2) gas richer? Vito+14
- AGNs (H_2) gas poorer? Mostly based on high-z studies of AGNs (additional complications) Brusa+15, Fiore+17, Kakkad+17, Perna+18

There is room for a large, unbiased survey of H_2 gas in AGNs but need multi-wavelength characterization of host galaxy: different SFR tracers, metallicity, and account for selection effects to isolate role of AGNs

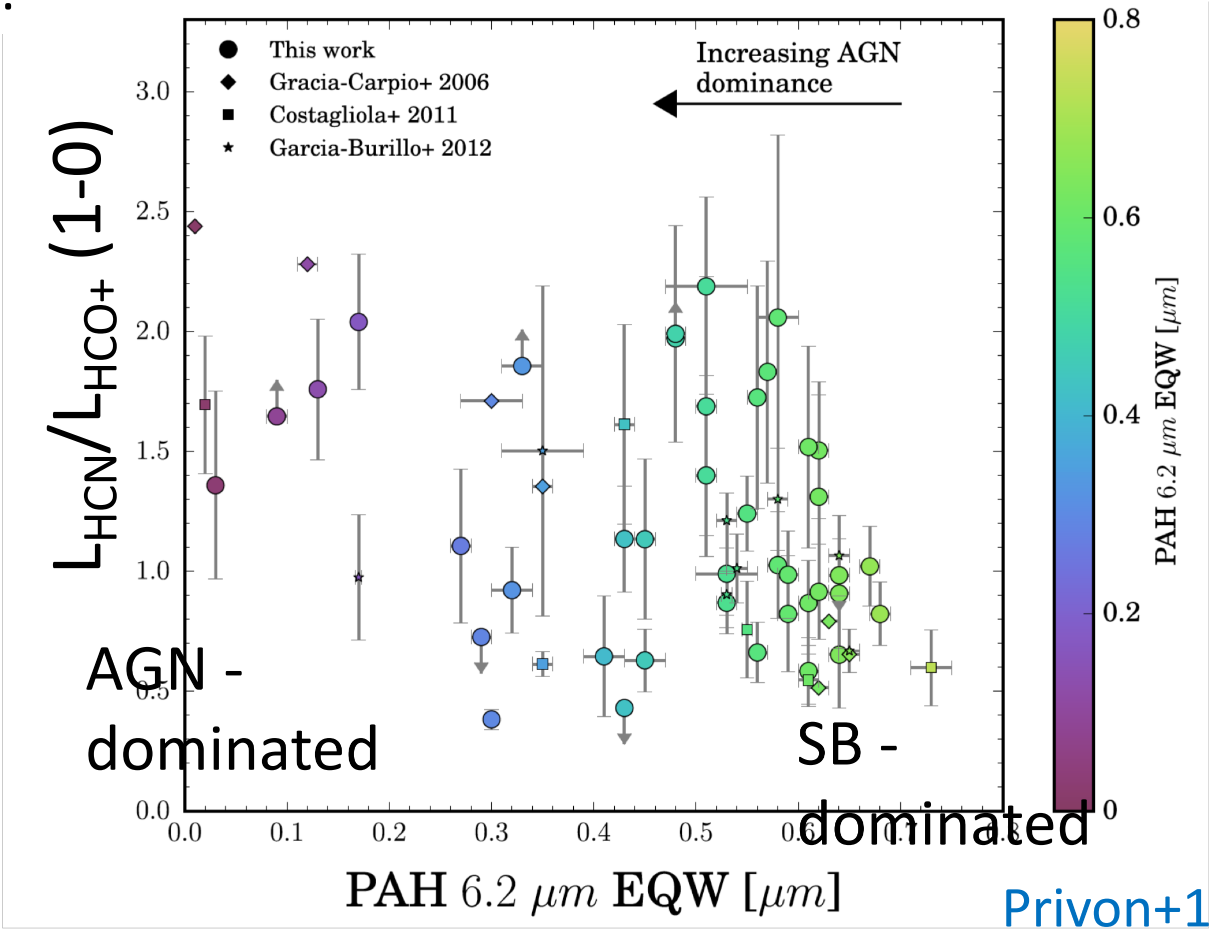
Identifying AGNs in the (sub-)mm band: diagnostic line ratios

Sub-mm (i.e. J>3) HCN enhancement in AGNs?

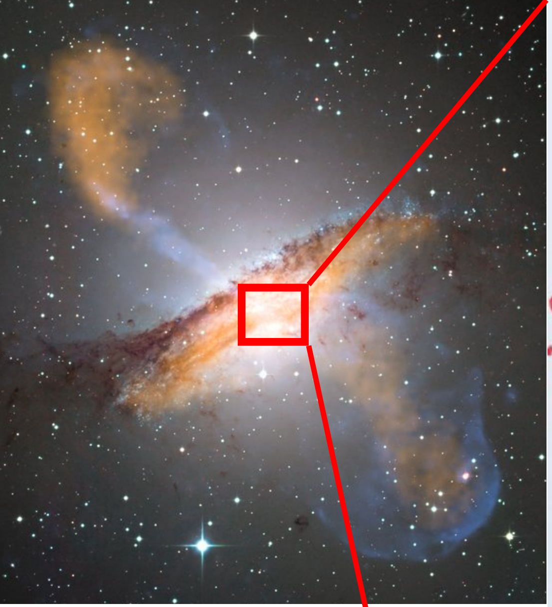


Izumi+16, Kohno+01

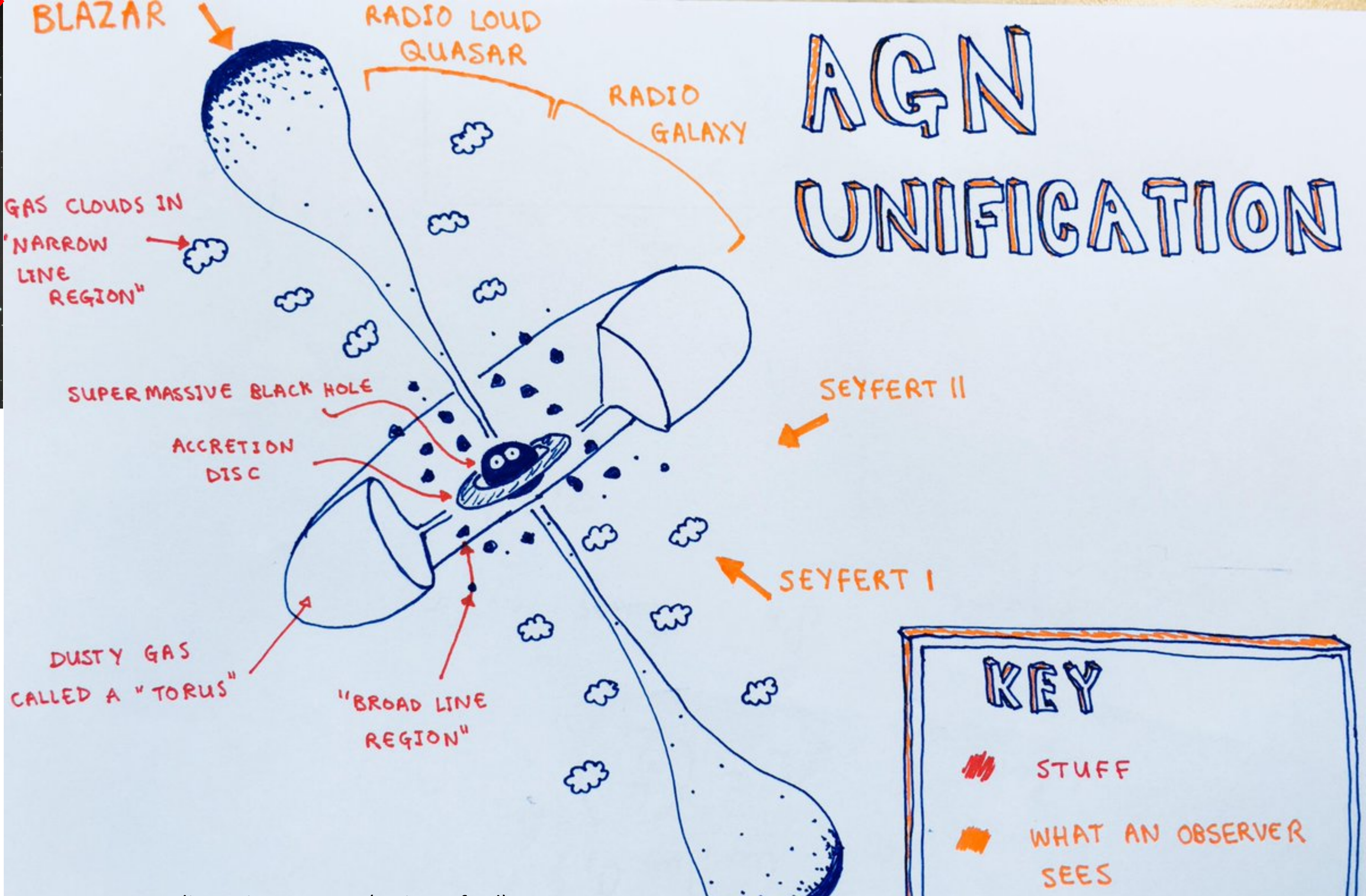
HCN/HCO$^+$>1.5 not only in AGNs. Shocks/CRs?



Privon+15



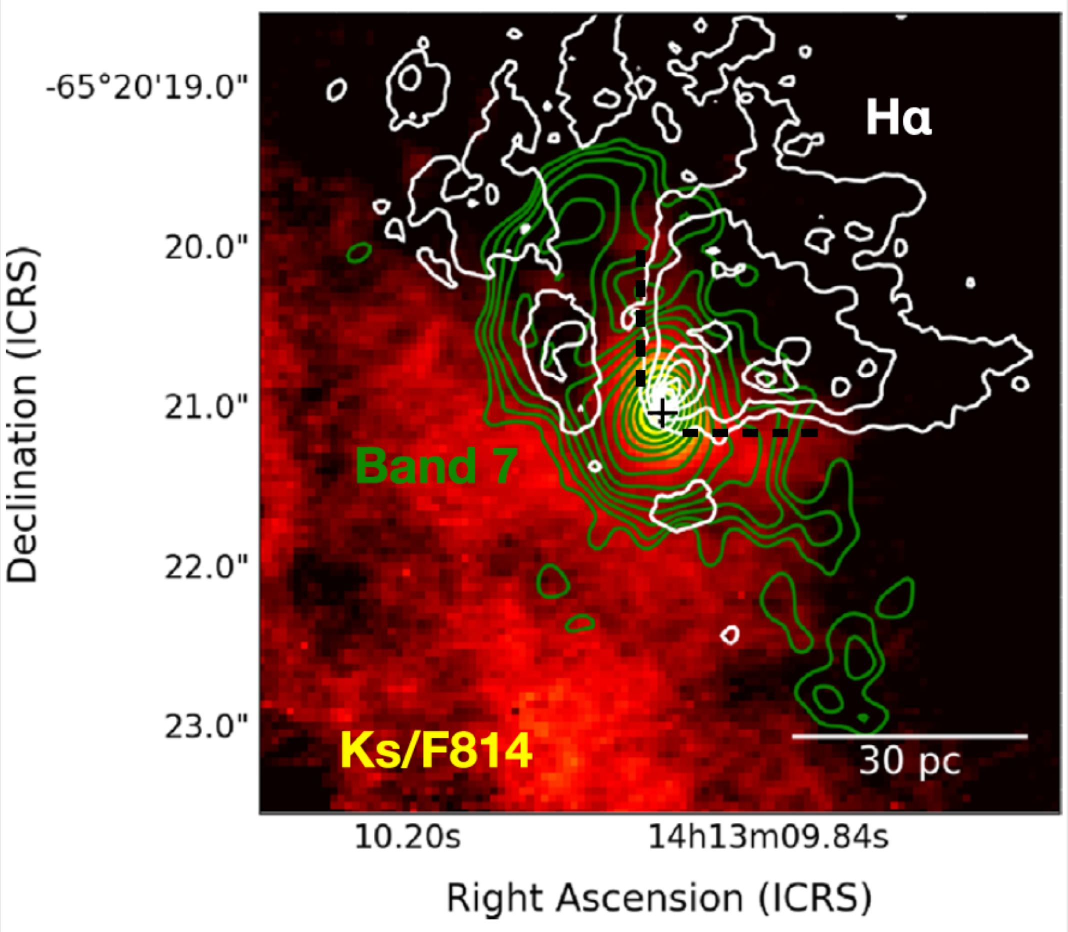
‘Big’ science case for ALMA: AGN ‘torus’ (obscuring source) and AGN feeding



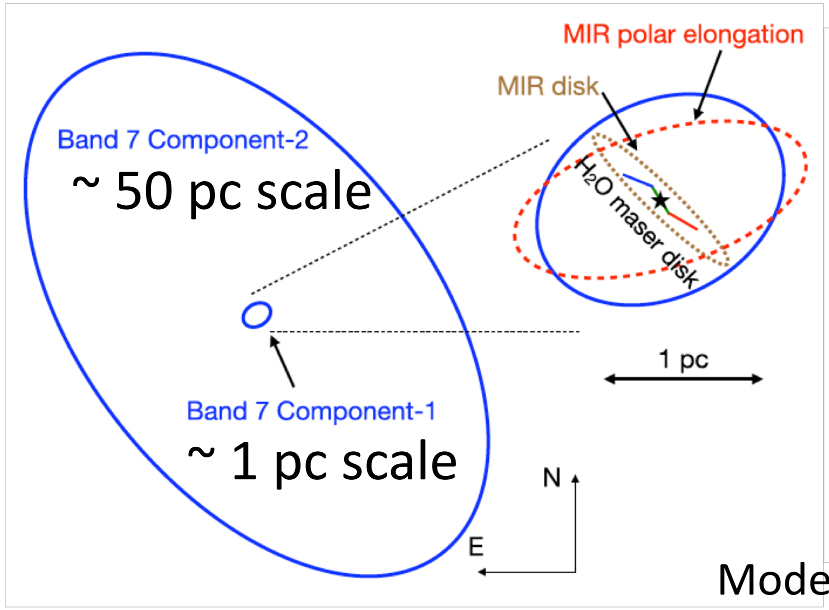
Images credit: Josie A. Peters (Univ. Oxford)
Twitter: @josieapeters @artartyeahart

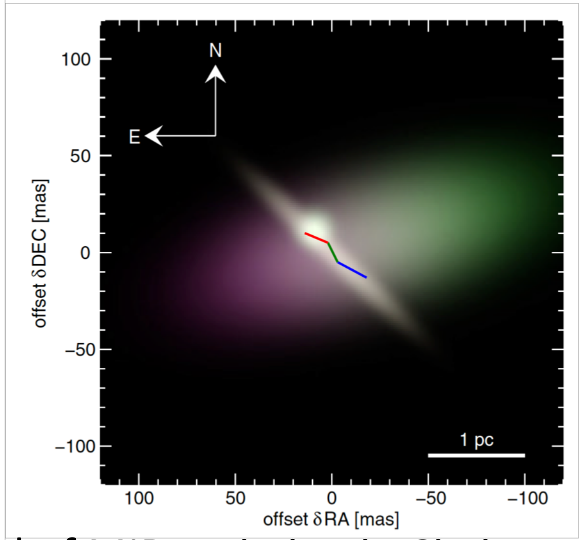
Circumnuclear structures around AGNs

Circinus (central ~200 pc)



Band 7, [CI] and CO3-2 data Izumi+18





Model of MIR emission in Circinus based on VLTI, Tristram+14

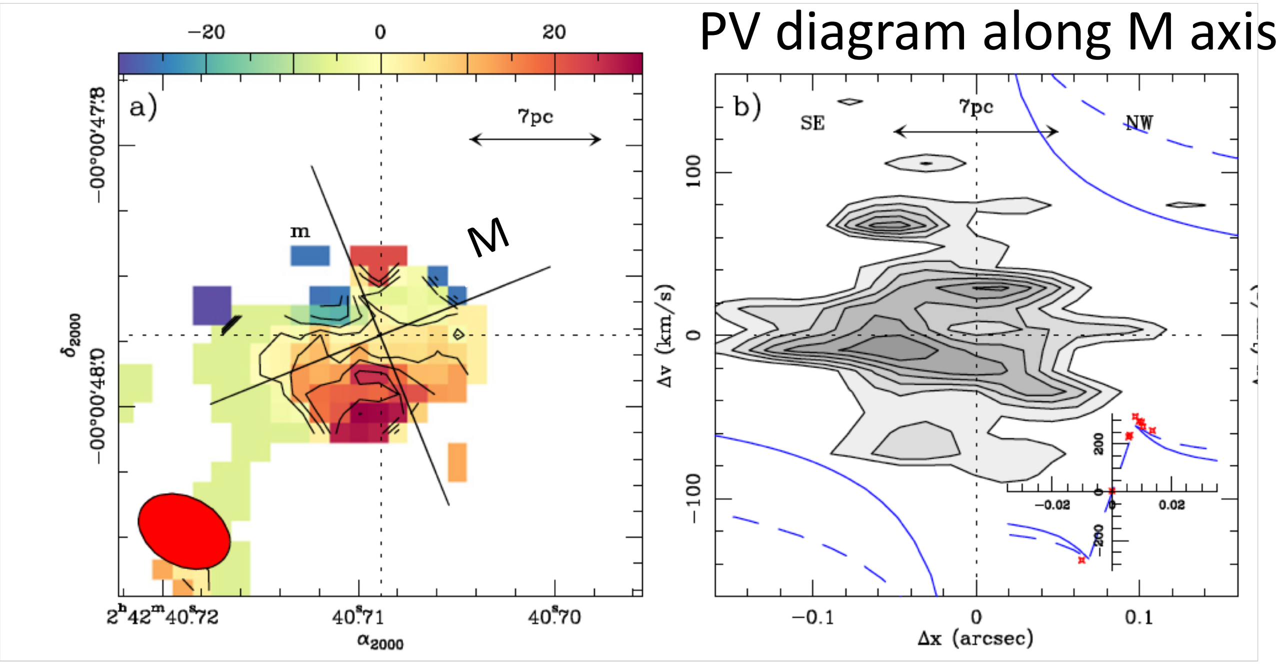
Molecular Circumnuclear disks (CND) commonly found in AGNs. Sizes ~ 50 -100 pc. M_{H2} ~ a few 10^6 M_{sun}, beam-averaged N_{H2}~a few 10^{23} cm^{-2}: CND contributes to beam-averaged nuclear obscuration

Garcia-Burillo+14, Izumi+15, Martin+15

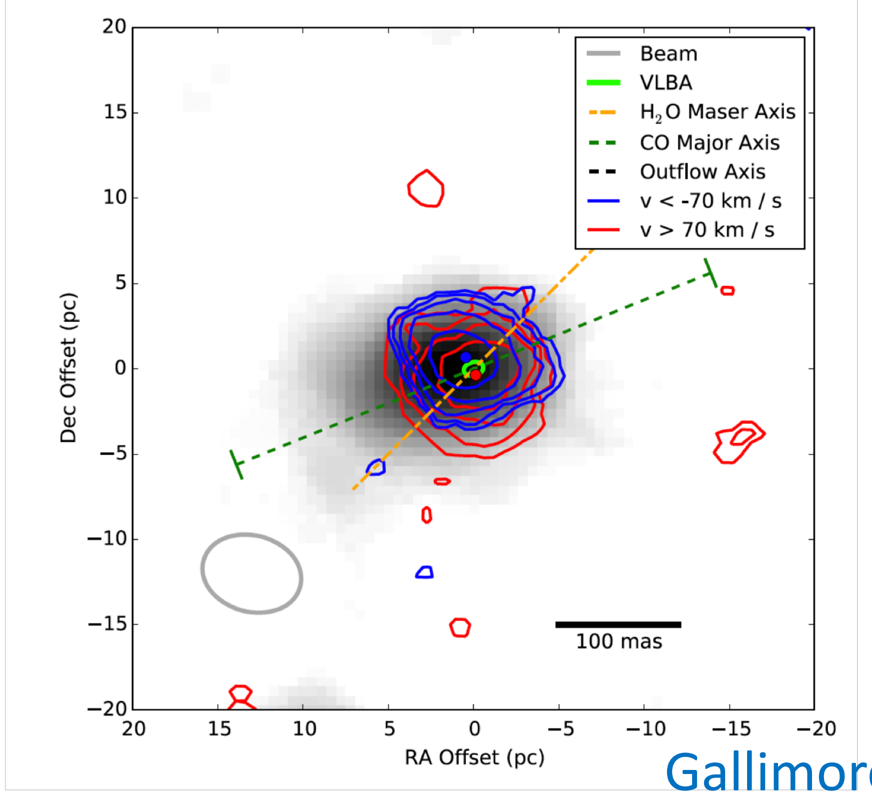
Polar 'torus' structure suggests fountain/outflow origin

The torus of NGC1068 as seen by ALMA

PV diagram along M axis



Dusty torus in NGC1068 detected in CO(7-6)



Gallimore+16

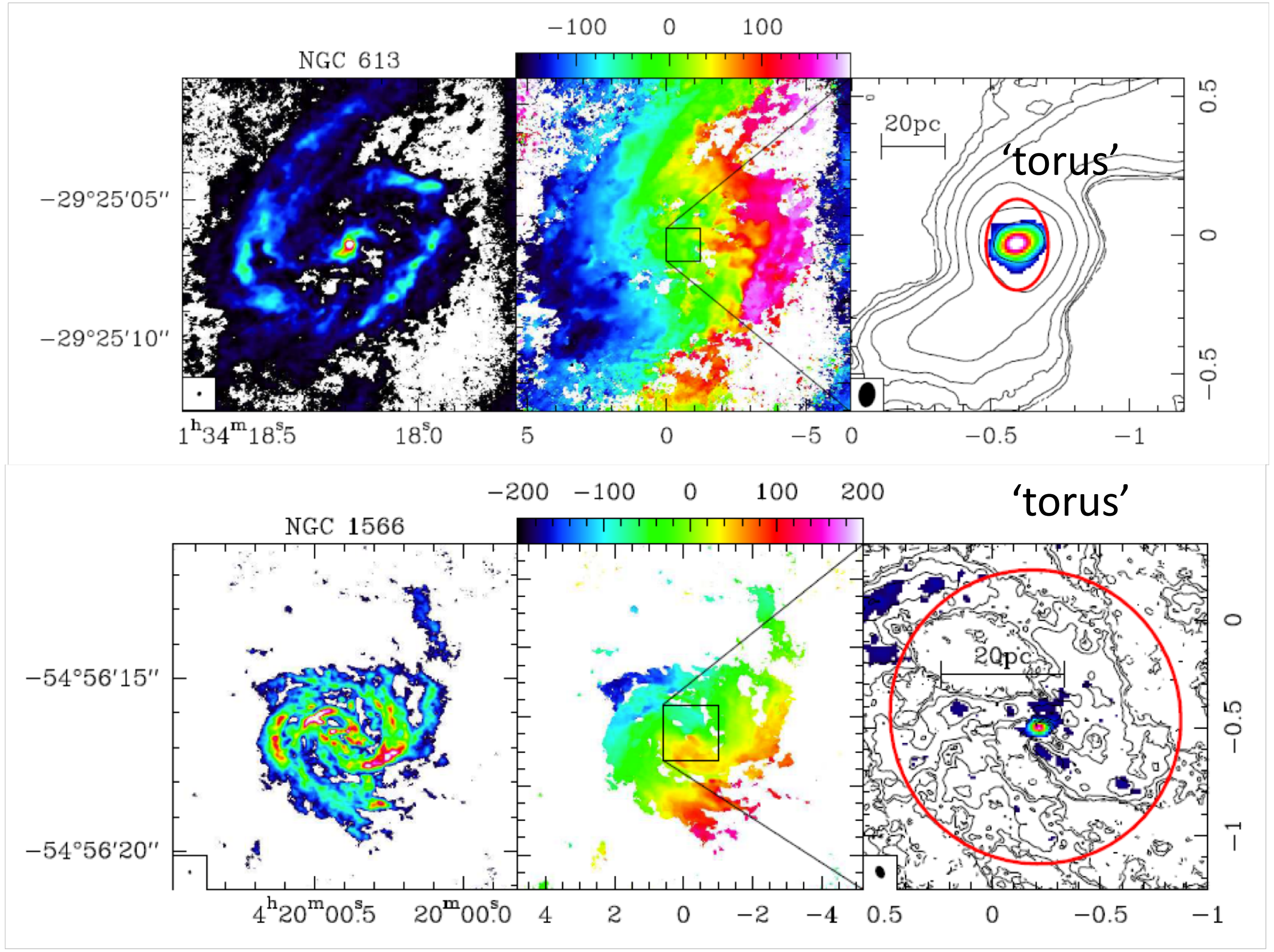
Garcia-Burillo+16
Imanishi+16,18

CO7-6 and CO6-5 data, res ~ 4 pc

Rotation pattern perturbed by strong non circular motions and turbulence -> related to AGN feeding and feedback?

Evidence for a bipolar CO outflow (v~400 km/s): disk-wind scenario for the obscuring torus

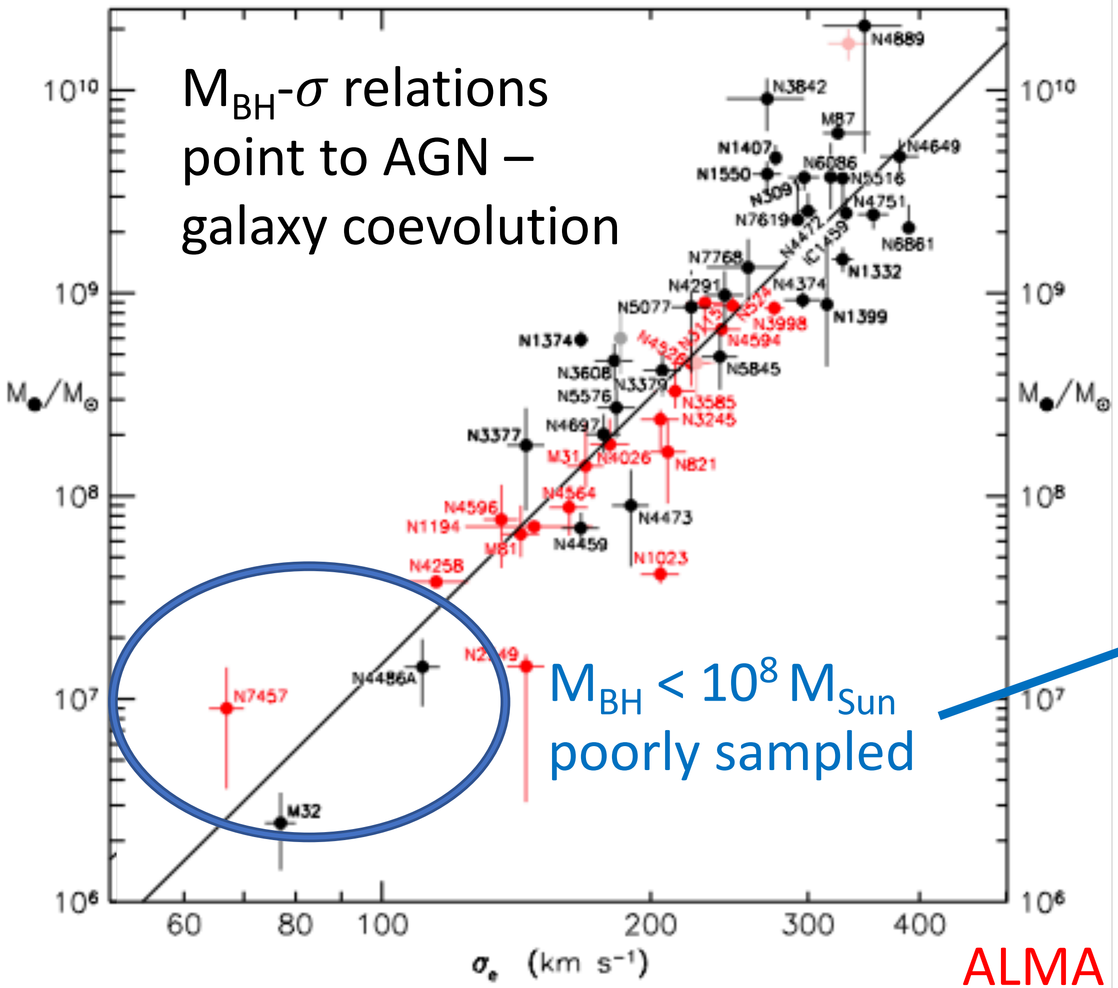
Resolving the torus and AGN fueling



Combes+19

- Systematic study of molecular tori with ALMA on nearby low luminosity AGNs. CO(3-2), resolution ~ a few pc
- Structures consistent with tori in 6/7 sources. Sizes ~ 6-30 pc, M~ few x 10^7 M_{sun}
- *Torus kinematics decoupled from larger-scale disk: different inclination and angle*
- AGN tori are asymmetric and off-centered. Two sources show a nuclear spiral supporting AGN fueling

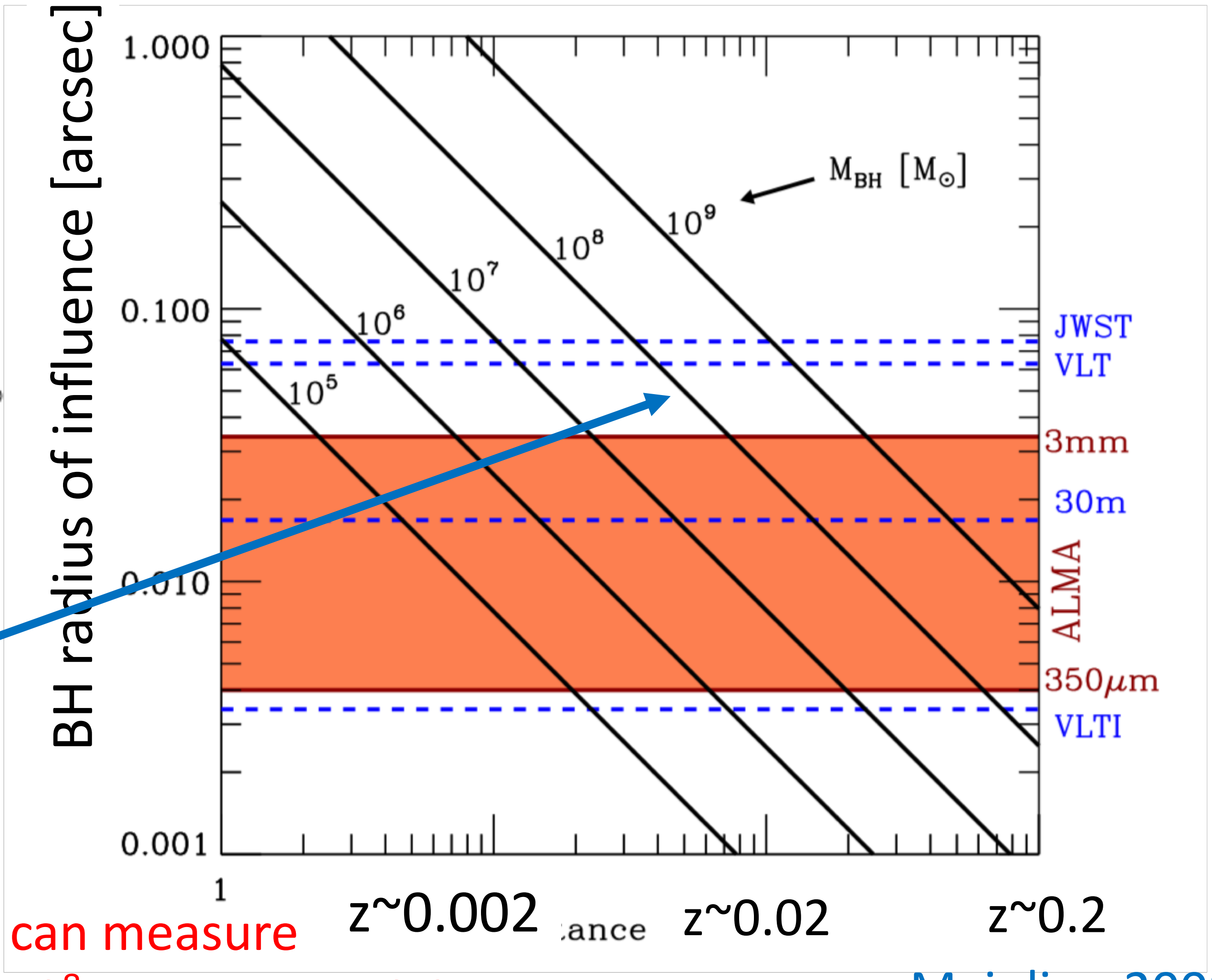
SMBH masses and $M_{SMBH} - \sigma_{star}$ relations



M_{BH}-σ relations point to AGN – galaxy coevolution

$M_{BH} < 10^8\ M_{Sun}$ poorly sampled

Kormendy+Ho2013

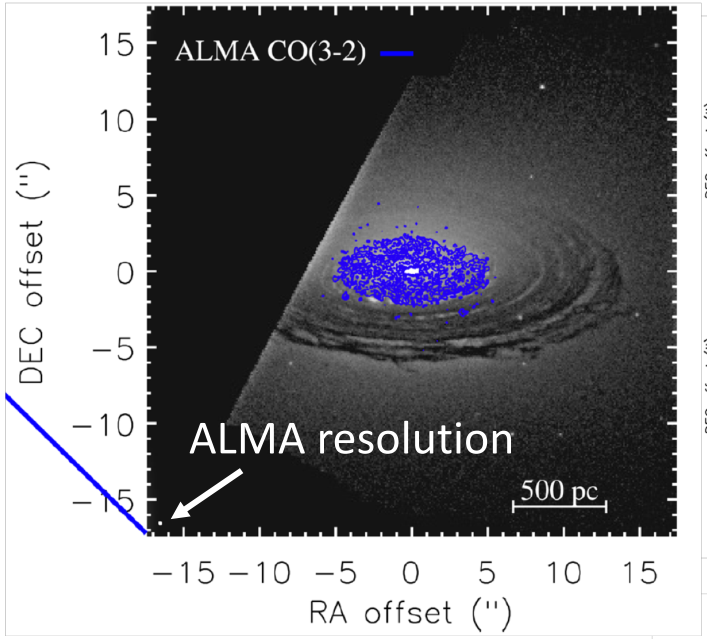


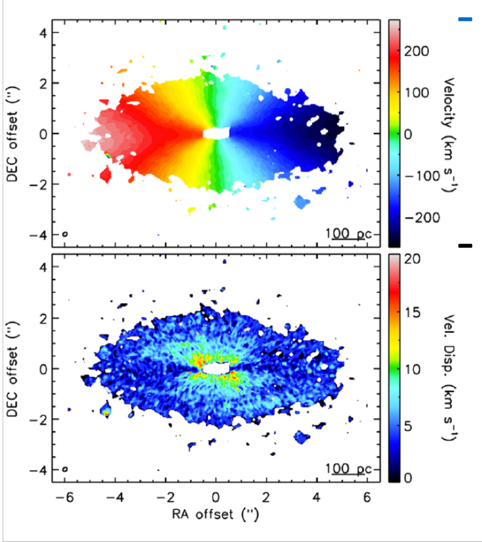
ALMA can measure $M_{BH} < 10^8\ M_{sun}$ up to z~0.2

Maiolino 2008

ALMA-based SMBH masses

CO(3-2) obs of lenticular galaxy

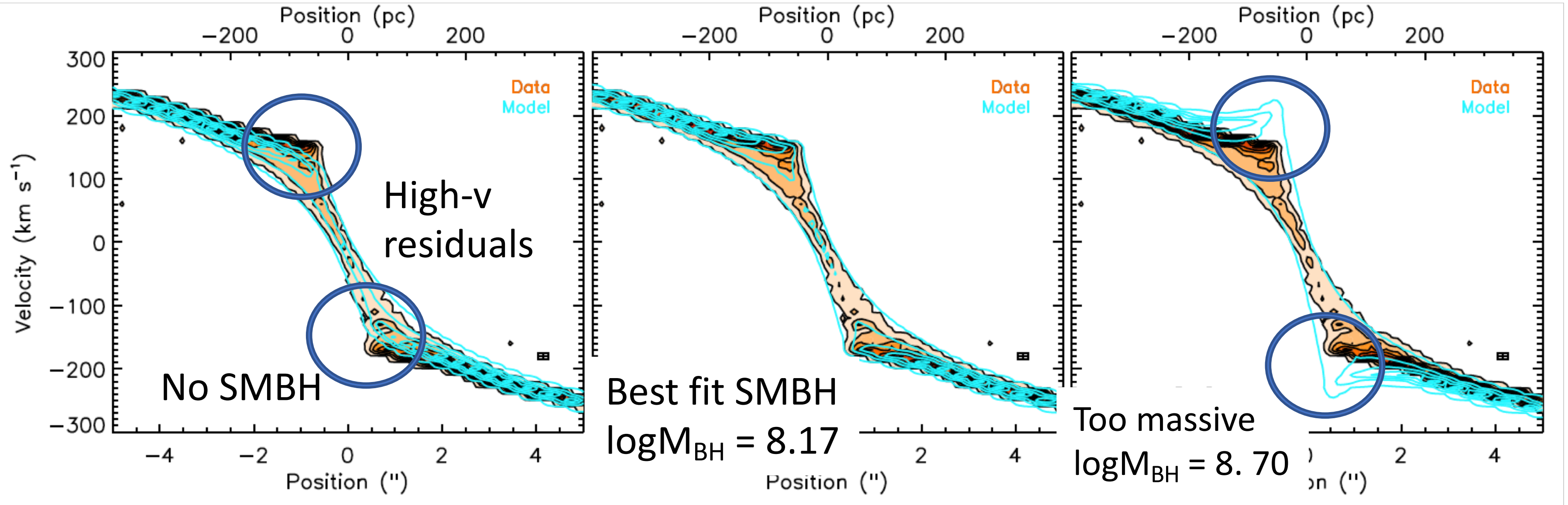




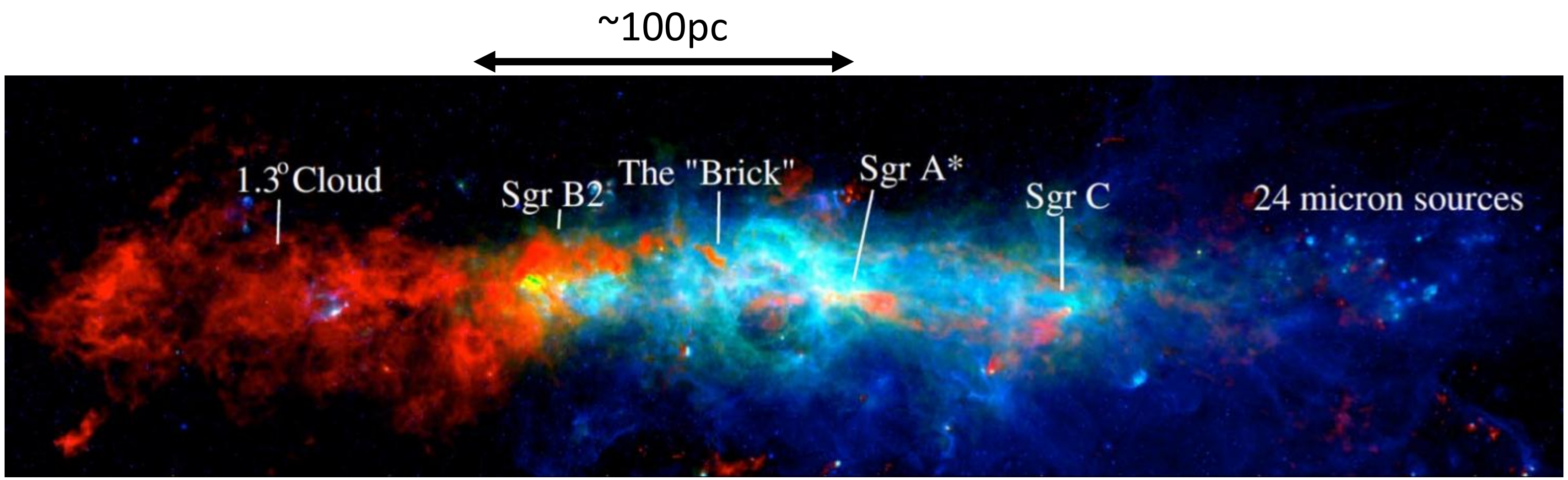
- Davis2014: CO-based M_{BH} estimates only need to resolve x2 the formal SMBH sphere of influence ($r_{SOI} \sim GM_{BH}/\sigma_*^2$)
- Kinematic signature of SMBH = rotational velocities higher than expected from luminous matter (stars), can be detected up to $2r_{SOI}$ but need good model of stars and dynamically cold + unperturbed CO disks

Davis 2014, Onishi+17, Davis+17,18

Molecular gas disk with radius = 400 pc and inner hole with r= 40 pc (sphere of influence of SMBH is ~15 pc)



Extremely opaque nuclei (or CONs)

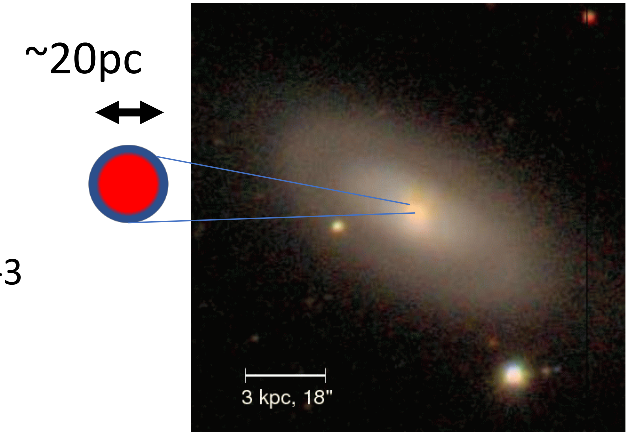


Milky Way's central molecular zone (CMZ):
Size ~ 450 x 150 pc
M_{H2} ~ 2-6 x 10^7 M_{Sun}

Martin+04, Molinari+14, Kauffmann+17

NGC4418:
Compact obscured nucleus
Size < 20 pc
M_{H2} ~ 10^8 M_{sun}
$N_H > 10^{25}$ $cm^{-2,}$ <n>~10^7 cm^{-3}

Sakamoto+10,13, Costagliola+13, Varenius+14



Some (U)LIRGs harbor CONs. Hot optically thick SBs vs hidden AGNs? Hard X-rays are absorbed and mid-IR is optically thick

To identify CONs: Aalto+15ab, Martin+16

1) High resolution (sub)mm continuum imaging
2) Luminous vibrationally excited HCN lines
3) Self absorbed HCN, HCO+ lines, P-Cygni or reversed P-Cygni in nuclear regions

Galactic outflows as a solution for 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

2. SSFR 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, Trussler+18, Costa+18ab, Biernacki+Teyssier18

3. $M_{BH} - \sigma_*$ relation, AGN-galaxy coevolution set by AGN-driven outflows? Silk+Rees98, King+03, Sijacki+07

4. [Mass-metallicity relation, missing metals, etc…]

Galactic outflows are multiphase

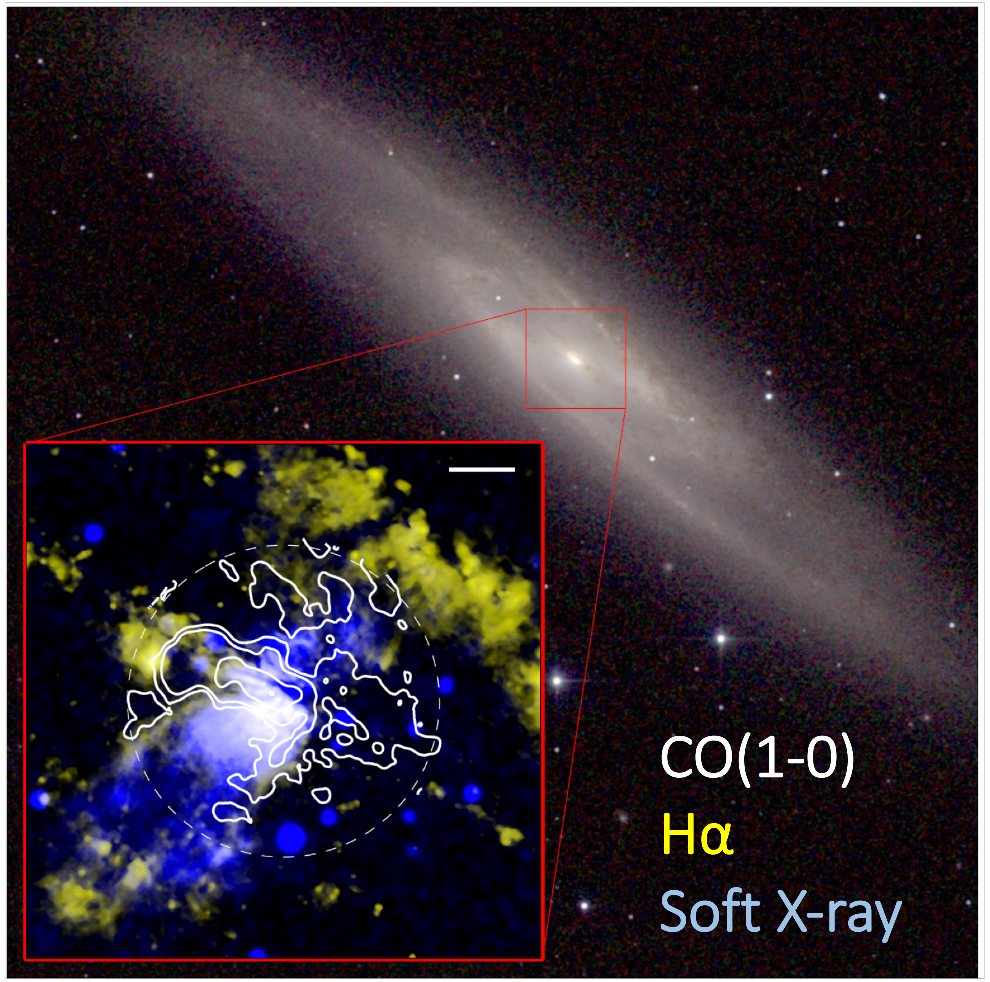
Outflow gas phase	Primary tracers	Average gas temperature, $\langle T_{gas} \rangle$ (K)	Average gas density, $\langle n_{gas} \rangle$ (particles per cm^3)
Highly ionized	X-ray absorption lines	10^6–10^7	10^6–10^8
Ionized	[O III]; Hα	10^3–10^4	10^2–10^4
Neutral atomic	H I 21cm; NaID; [C II]	10^2–10^3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

Cicone+18a

- Multi-phase nature of galactic winds acknowledged since the 1980s, including 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

Cold H_2 phase in outflow probably the most challenging to understand and model:
Clearly a science case for ALMA

Outflows in starburst galaxies



NGC253, Bolatto+13 (ALMA), Sakamoto+06 (SMA)

The "radiative" phase

The "blowout" phase

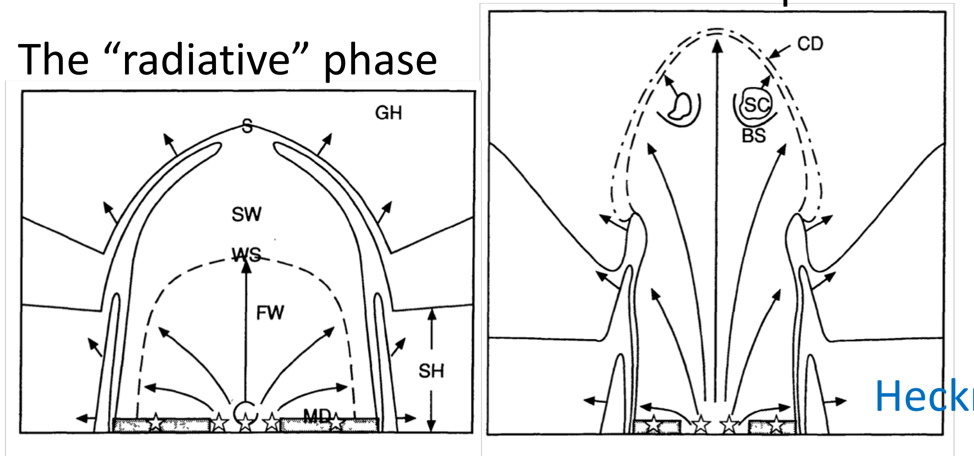


FIG. 1a FIG. 1b

Heckman+90

'Super winds' driven by kinetic energy released by clustered SNe + stellar winds and/or by momentum transferred by UV radiation to dusty cloud

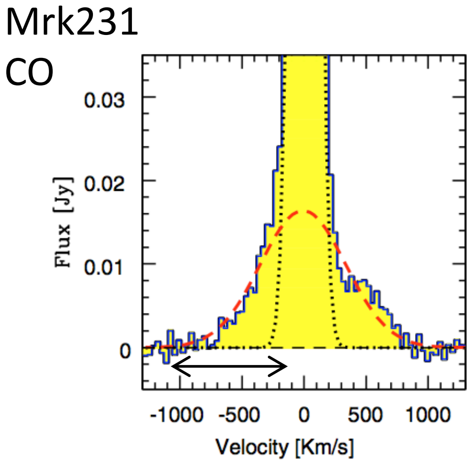
Chevalier+Clegg85, Heckman+90, Veilleux+05, Murray+05, Dave+11

Multiphase outflows commonly observed in local SBs

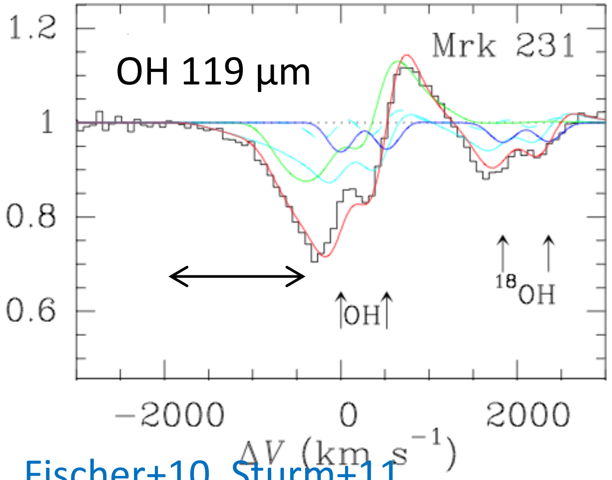
$dM_{out}/dt \sim SFR \rightarrow$ mass loading $\eta \sim 1$

(although see NGC 253: $\eta \sim 10\text{-}20$?) Zschaechner+18

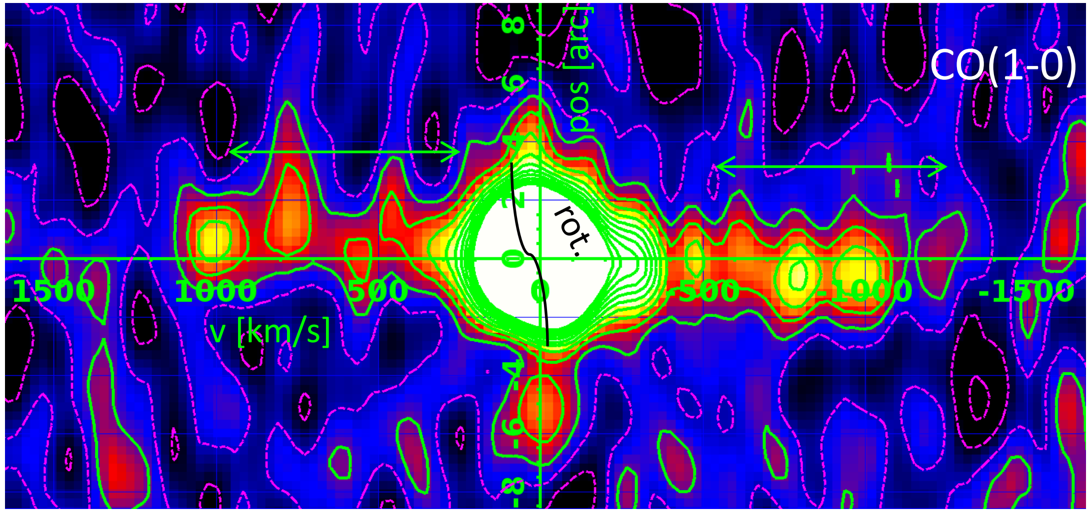
Massive molecular outflows in (U)LIRGs



Feruglio+10,+15,
Cicone+12, Aalto+12, 15



Fischer+10, Sturm+11,
Gonzalez-Alfonso+14,17,18



Cicone+14

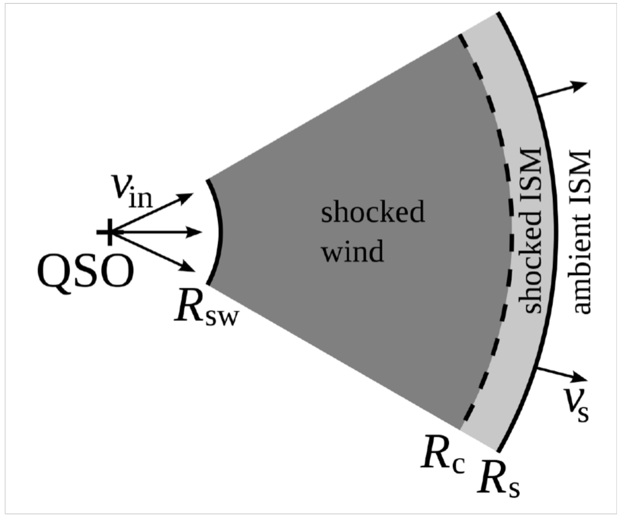
- *A revolution in the field (2010):* discovery of extremely massive molecular outflows in local (U)LIRGs: M~10^8-10^9 M_{Sun} of cold H_2 gas at v ~ 10^2-10^3 km/s and extending by several kpc

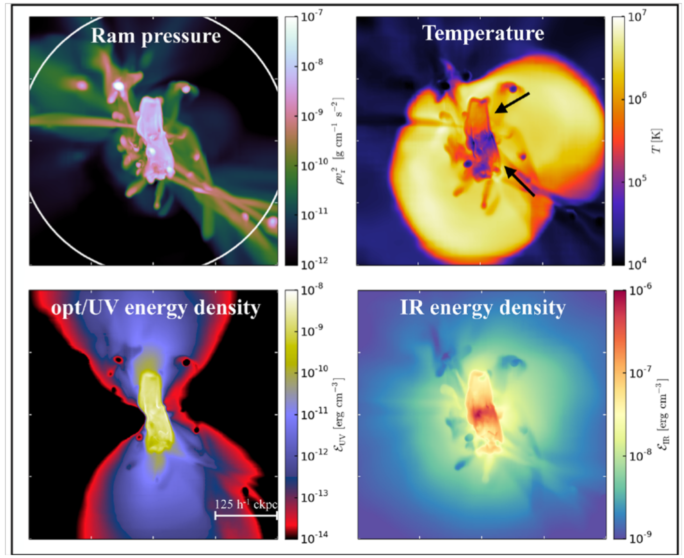
- Much more extreme than previously known H_2 outflows (e.g. M82, NGC253): dM_{out}/dt >> SFR, point to AGN driving mechanism

- CO wings tracing the outflow are >10-20 times fainter than line peak -> *ALMA is a game changer*

ALMA –based z~0 molecular outflow studies: Combes+13, Garcia-Burillo+14, Sakamoto+14, Sun+14, Alatalo+15, Dasyra+16, Zschaechner+16,+18, Veilleux+17, Vayner+17,Privon+17, Gowardhan+18, Harada+18, Barcos-Munoz+18, Aladro+18, Fluetsch+19 (etc..)

Theoretical models of AGN-driven outflows





Costa+18b

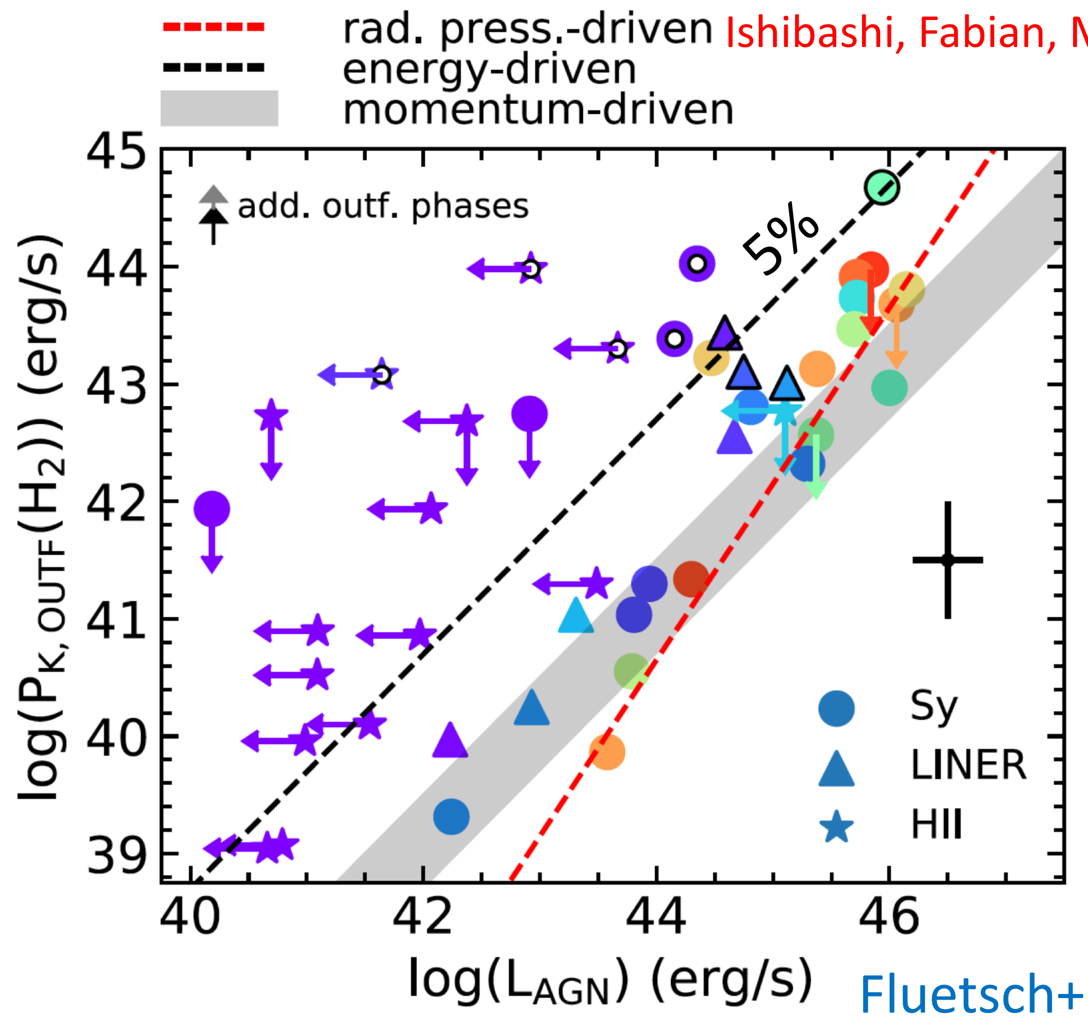
1. **Blast-wave**: nuclear winds with v=0.1c shock surrounding ISM and generate large-scale energy-conserving outflow
   (i) Concurrence of X-ray UFO and galactic outflow
   (ii) Kinetic power ~a few % L_{AGN}; momentum flux ~ 20 L_{AGN}/c

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

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

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

Testing AGN feedback models through outflow energetics



Ishibashi, Fabian, Maiolino 2018

Fluetsch+19

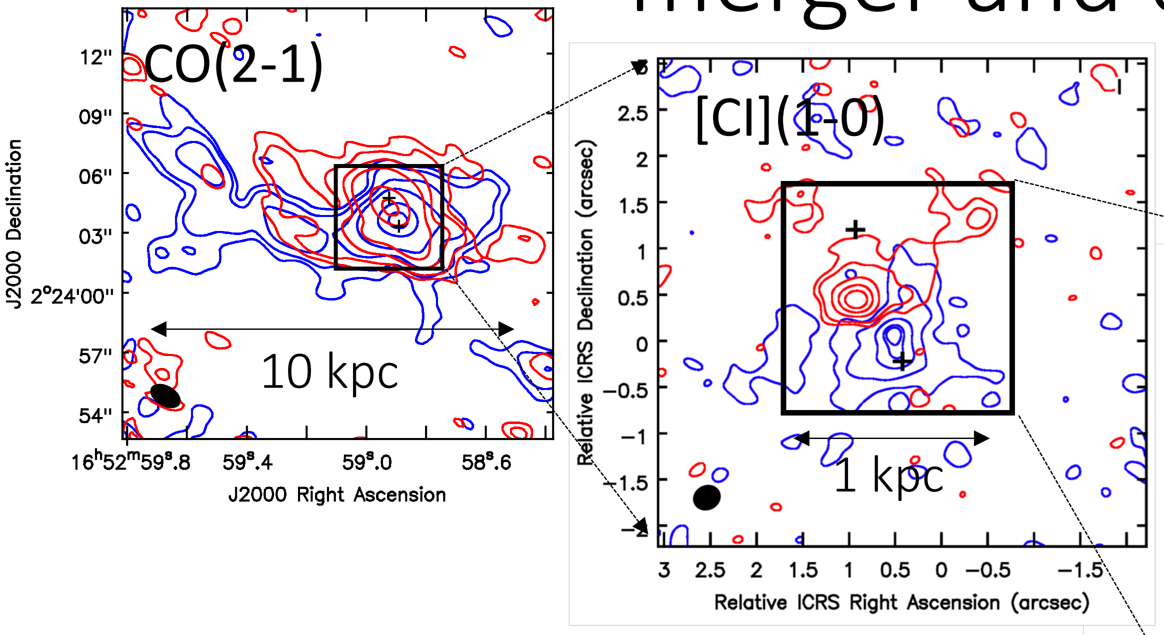
- Broad range of kinetic powers (0.1-5% L_{AGN}) and momentum fluxes (1-20 L_{AGN}/c)

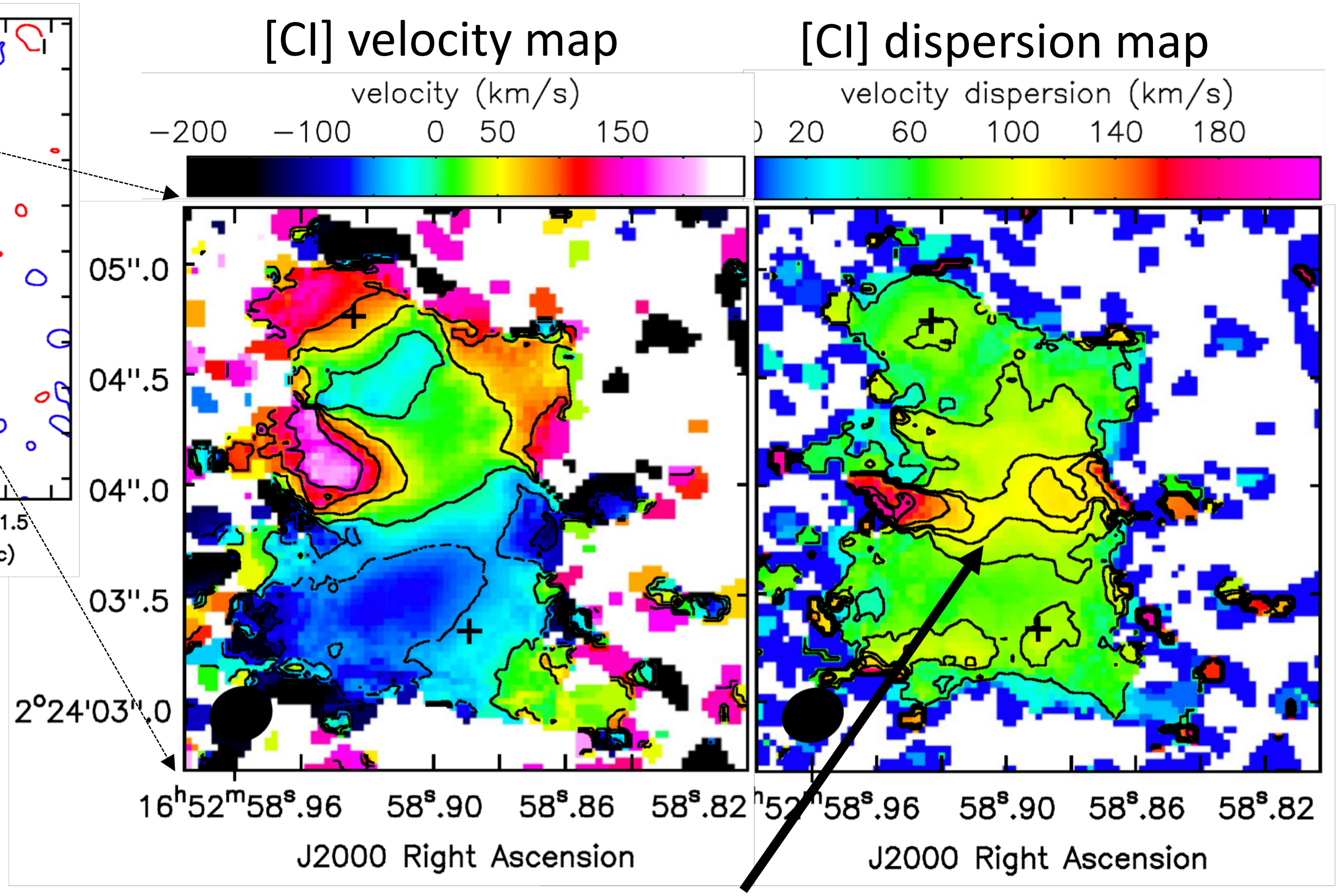
  Cicone+14 Fiore+17 Bischetti+18 Fluetsch+19

- Consistent with both AGN driving mechanisms, with a contribution from SF and possibly hidden jets. Consider also AGN variability/flickering

- *ALMA is providing us with better statistics and the picture is getting even more complicated (see Mattia Sirressi's talk yesterday)*

ALMA resolves the outflow launching point in merger and dual AGN NGC6240





- Launching point *between the* two AGNs
- Extreme energetics suggests AGN-driving:
- $dM_{out}/dt = 50\ (\pm 30)$ 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)

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

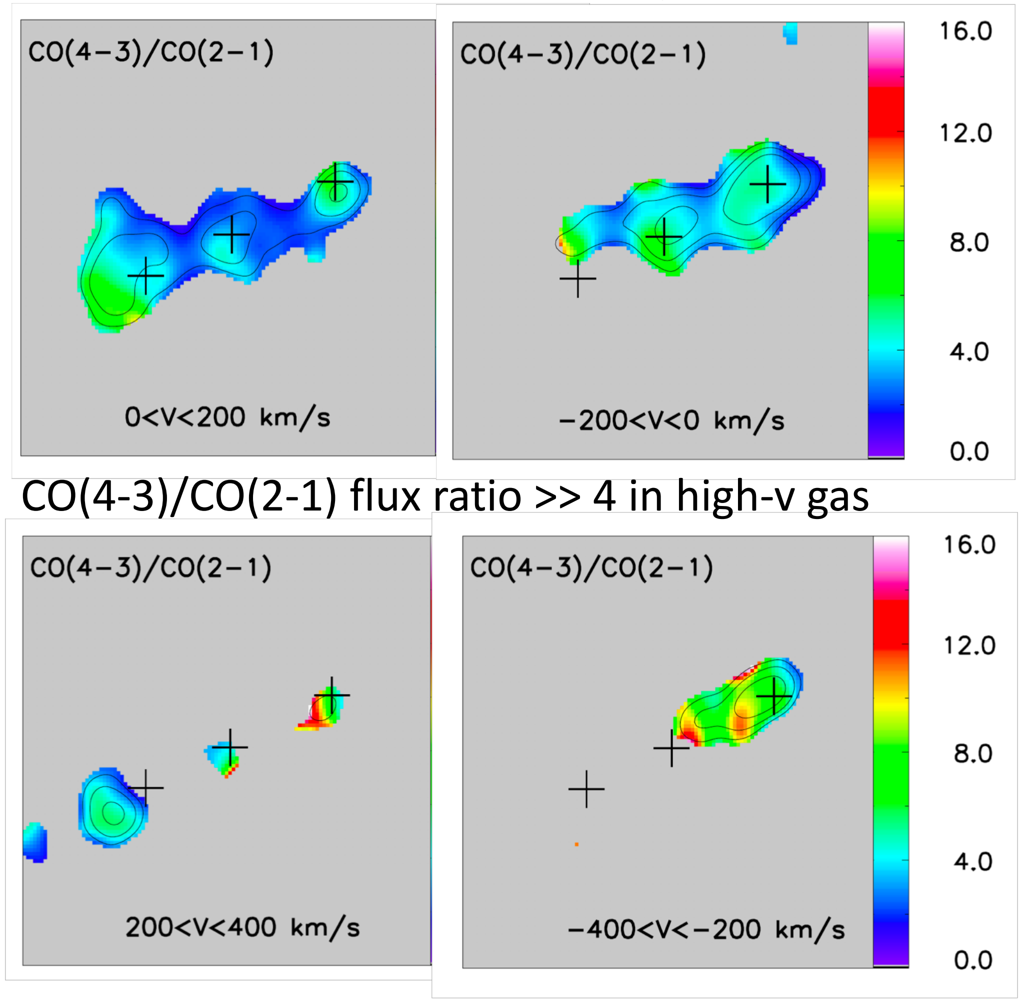
Cicone+18b

Large uncertainties on H_2 outflow energetics

- To understand feedback we need tighter constraints on outflow masses/energetics -> *need multiple tracers (possible with ALMA)*
- Estimates based on CO, OH or [CII] in the absence of additional tracers are affected by large uncertainties (especially when only high-J CO transitions are available)
- Reasonably, $\boldsymbol{\alpha_{CO}}$ ($\equiv M_{mol}/L'_{CO(1\text{-}0)}$) in metal-rich outflows ranges **between 0.3 and 4** (α_{CO} ~ 0.8 often recommended for ULIRGs)
- Low α_{CO} ~ 0.3 measured in jet-driven outflows in line with Richings & Faucher-Giguere 2018

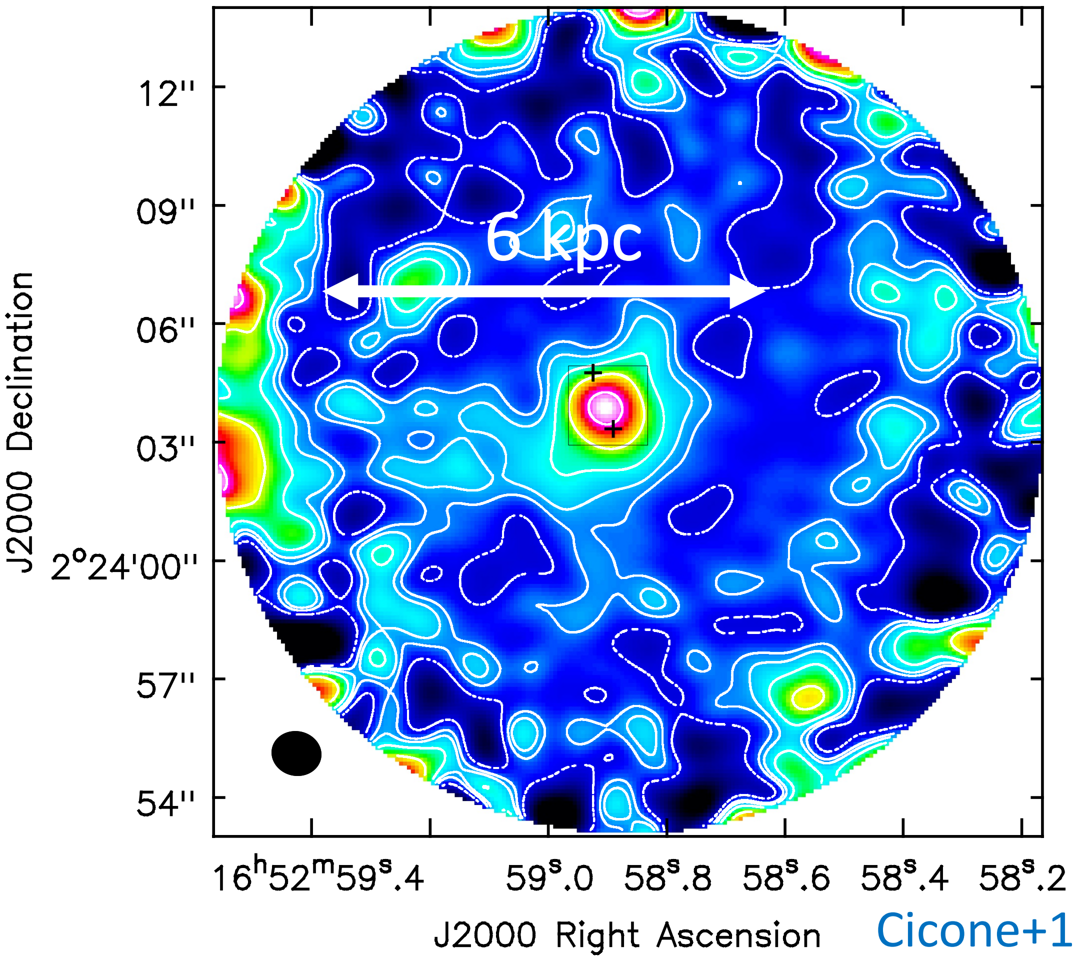
CO(4-3)/CO(2-1) flux ratio < 4 in quiescent disk

CO(4-3)/CO(2-1) flux ratio >> 4 in high-v gas



Dasyra+16, Oosterloo+17

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



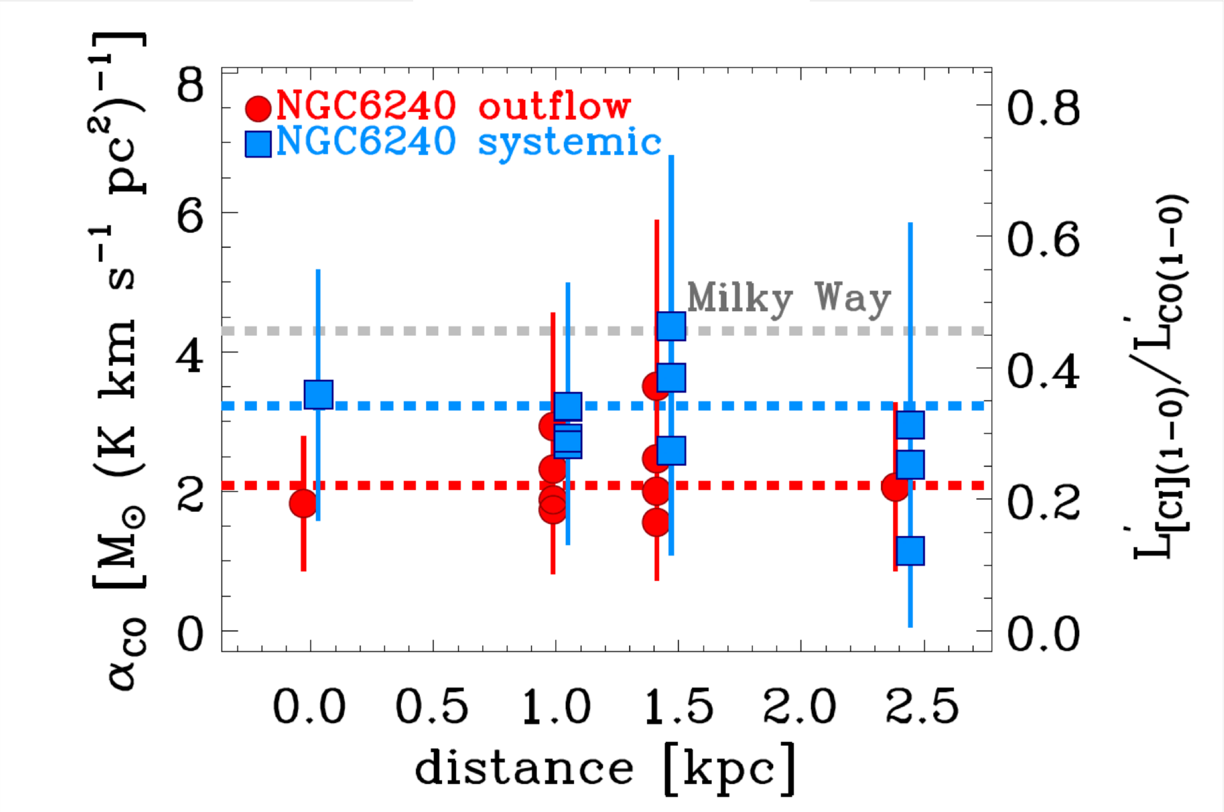
Cicone+18b

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 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 [CI] studies with ALMA

The α_{CO} of 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 α_{CO} is *formally* consistent with MW value (~4.3)

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

Cicone+18b

Summary and future prospects with ALMA (personal view)

1. Star formation laws: S-K relation, CO and high density tracers

Populate S-K law (low-M_*, AGNs, green valley), overcome statistical biases, explore different H_2 tracers

2. AGN vs SF diagnostic diagrams in the mm/submm

Not clear whether this is a promising line of research for ALMA: time consuming, need more solid theoretical grounds, poor predicting power. Future facilities will provide IR/optical diagnostics on large samples

3. Resolving the obscuring torus and AGN fueling

Comes for free with ALMA long baseline campaigns targeting galaxy nuclei and AGNs

4. SMBH mass estimates and M_{BH}- σ_* relation

Calibrating method in local galaxies useful to address biases at high-z. Rotation perturbed down to torus scales

5. Extremely obscured nuclei (CONs)

Important clues on AGN-galaxy coevolution and spheroid formation, HCN-VIB surveys

6. Massive molecular outflows and feedback mechanisms

Detailed multi-tracer (multi-J CO, [CI], CN, HCN, etc) studies, constrain physical properties of gas in outflow