The multiphase baryon cycle in galaxies and future prospects with the ELT

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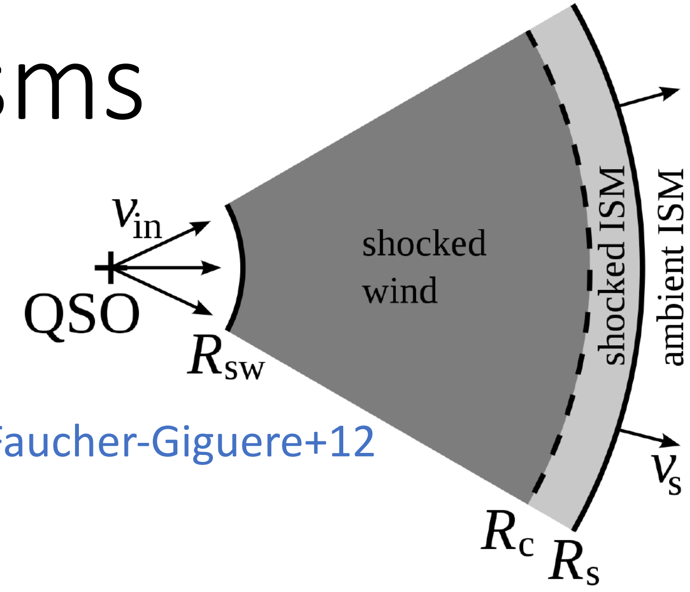
Outflow driving mechanisms

1. **Starbursts:** 'Super winds' driven by (i) E_{kin} released by clustered SNe + stellar winds and/or (ii) momentum transferred by UV radiation to dusty clouds. Expect $dM_{out}/dt \sim SFR$
   Chevalier+Clegg85, Heckman+90, Veilleux+05, Murray+05, Dave+11

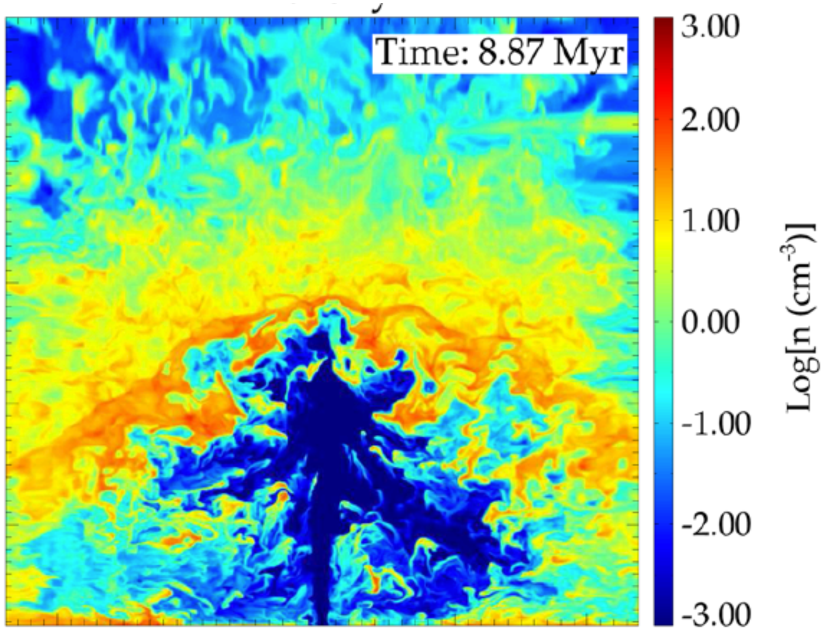
2. **AGN - Blast-wave**: nuclear winds with v~0.1c shock surrounding ISM and generate large-scale energy-conserving outflow. Expect: (i) presence of a X-ray wind; (ii) Kinetic power ~a few % L_{AGN}; momentum flux > L_{AGN}/c
   Silk+Rees98, King2010, Zubovas+King12,14, Faucher-Giguere+12, Costa+14,+15, Nims+15

3. **AGN - Radiation pressure on dusty clouds**, enhanced for τ_{IR}>>1 and high L_{AGN}. Kinetic power depends on τ_{IR} and ISM geometry. $dE_{kin,OF}/dt<1\%\ L_{AGN}$ and momentum fluxes ~ 1-5 L_{AGN}/c
   Fabian12,Thompson+14, Ishibashi+Fabian15, Bieri+17, Ishibashi+18, Costa+18ab

4. **AGN – jets:** Interaction between expanding jet and ISM generates outflows. Key parameters: (i) power/compactness of radio jet and (ii) clumpy ISM. *Not necessarily the classical 'radio loud' AGNs* Wagner+Bicknell12, Wagner+13, Mukherjee+16



Faucher-Giguere+12

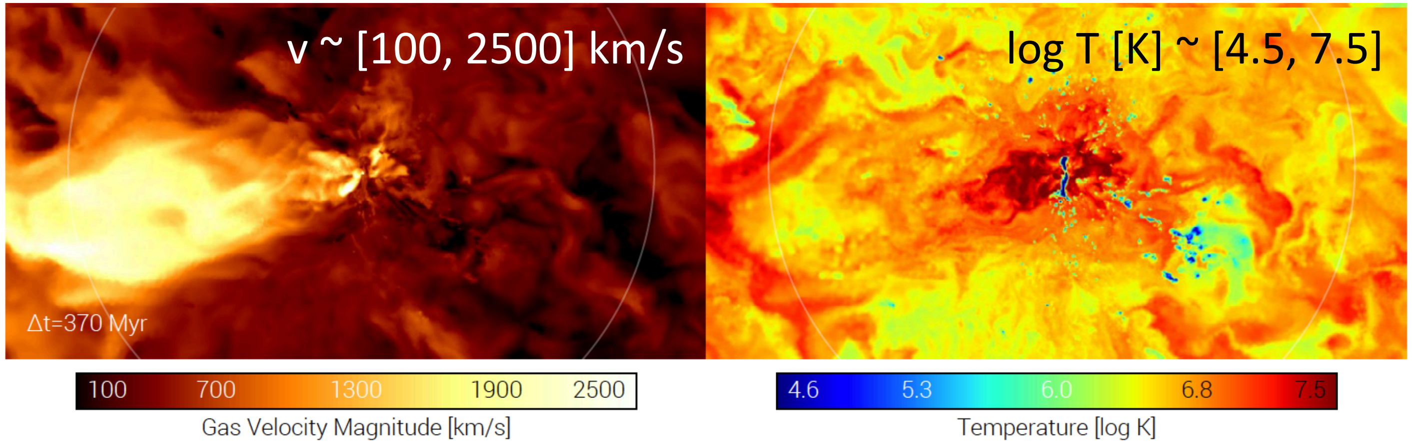


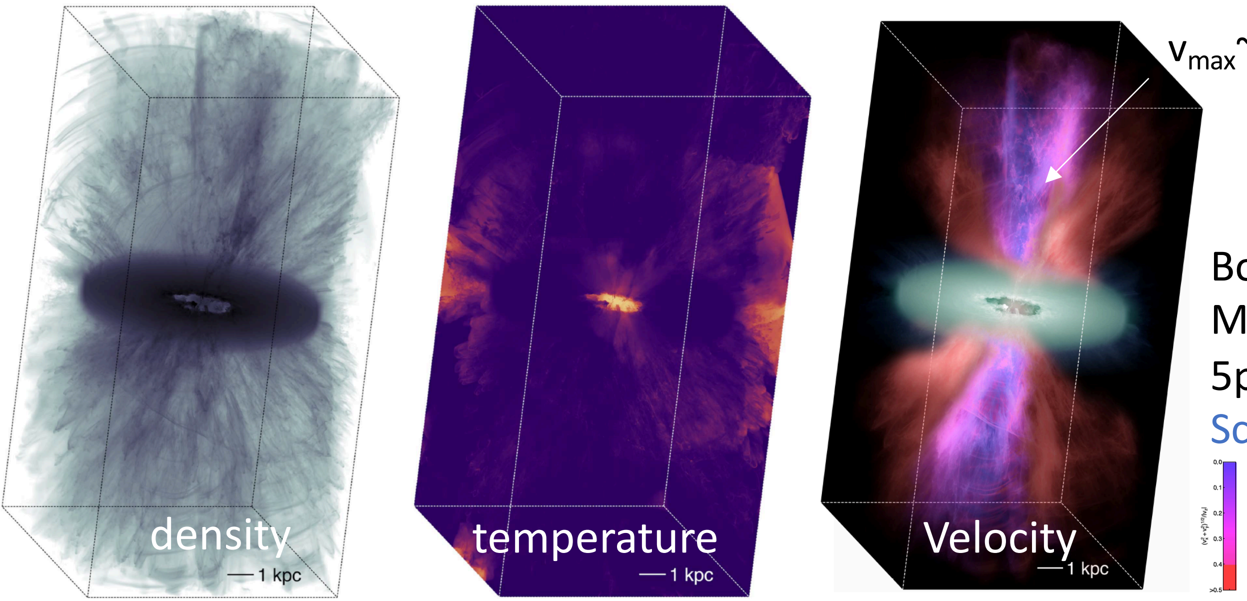
Mukherjee+16

All outflows are multi-phase and multi-scale

(Some 'observational' considerations here: Cicone+18a)

TNG50, res ~200 pc, cooling floor T = 10^4 K Nelson+19, Pillepich+19





v_{max}~1000 km/s

Box sim. of M82 outflow, 5pc res Schneider+18

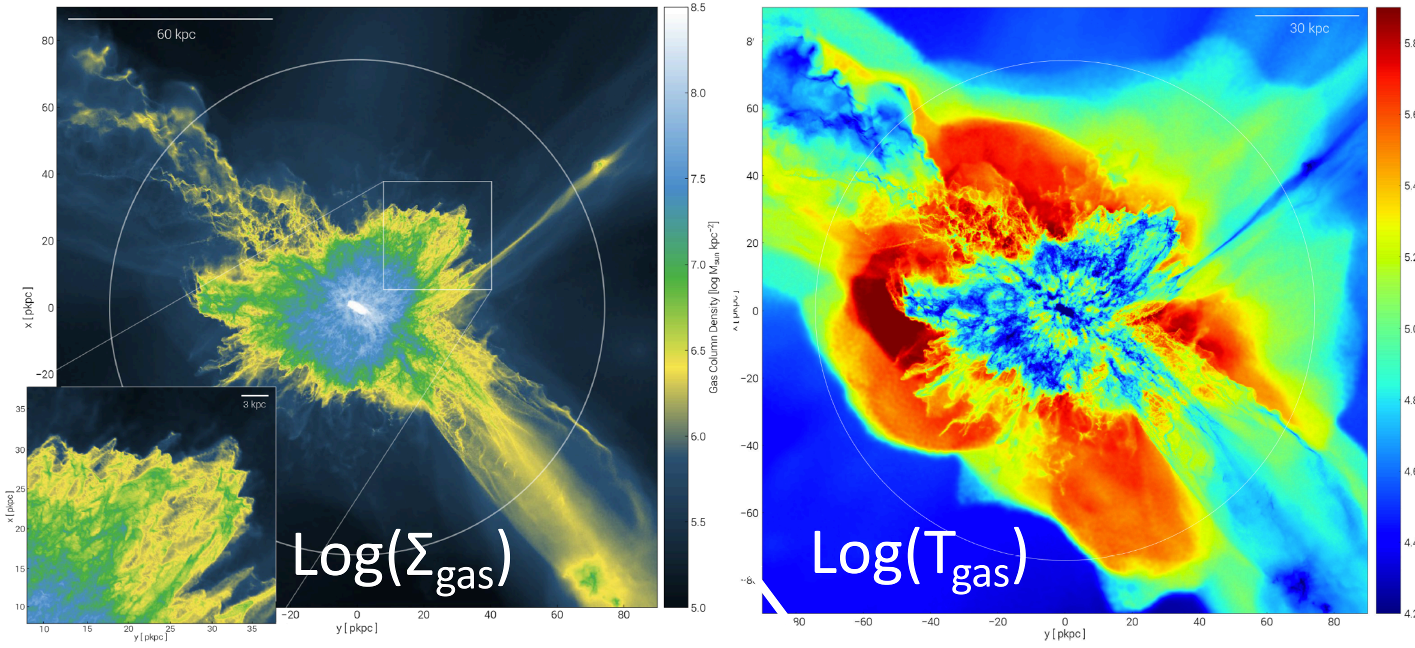
- ***Multiphase***: Some (e.g. ULIRGs) entrain puzzlingly large amounts ($\gtrsim 10^{10}$ M_{Sun}) of cold (T~10^{1-2} K) + dense (n_{H2}~10^{3-4} cm^{-3}) H_2 gas. Simulations need to resolve pc scales to capture gas cooling and hydro instabilities Zubovas+King14, Costa+15, Brüggen+Scannapieco16, Richings+18, Gronke+Oh18, Armillotta+17, Decataldo+17,19

- ***Geometry***: not all outflows look like M82's. At high-z even more complex, less collimated morphologies Nelson+19

- *We struggle to understand the "simplest" outflows in local starbursts, let alone the much less observationally constrained high-z outflows (higher SFR and L_{AGN}, higher f_{gas}, more mergers, lower spatial resolution, lower sensitivity, lower statistics)*

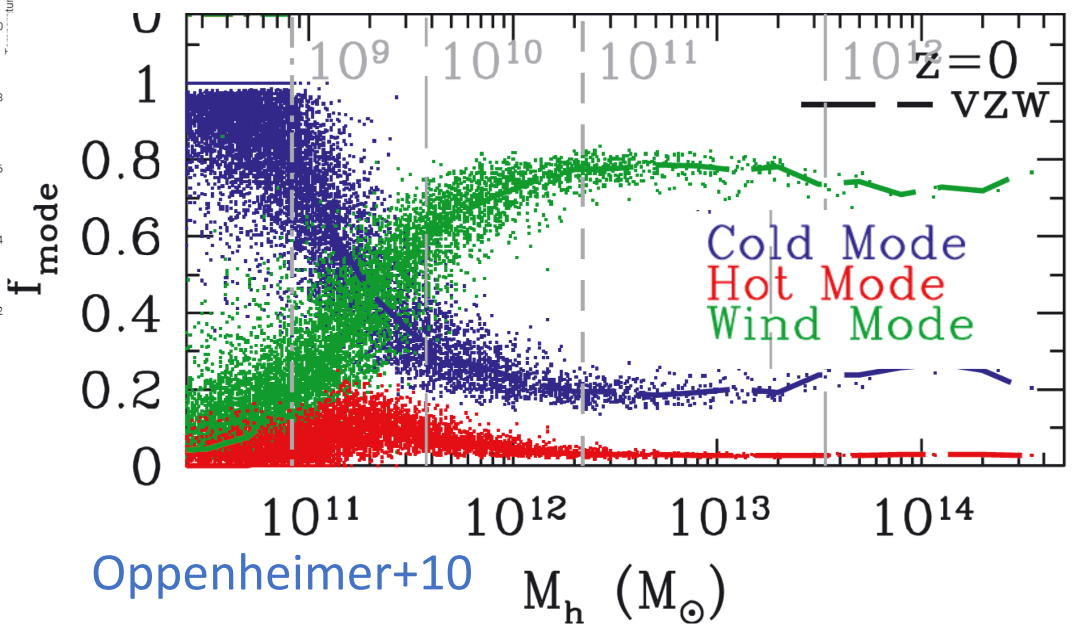
Outflows feed the CGM and the CGM feeds galaxy growth: leading role in quenching *and* accretion

‘CGM-zoom’ simulation with AREPO, 95 pc res



- “CGM-zoom” simulations show 3/4 of cold CGM at z=2 is due to rapid cooling out of outflow material (dominates up to > 0.5 R_{vir}), only 25% due to cosmic inflows and satellite stripping Suresh+19

- A substantial fraction of star formation fed by CGM-recycled gas once entrained in outflows (from central and satellite galaxies). Outflows store multiphase gas and metals in CGM for ~1 Gyr Ford+14, Hafen+19, Christensen+18

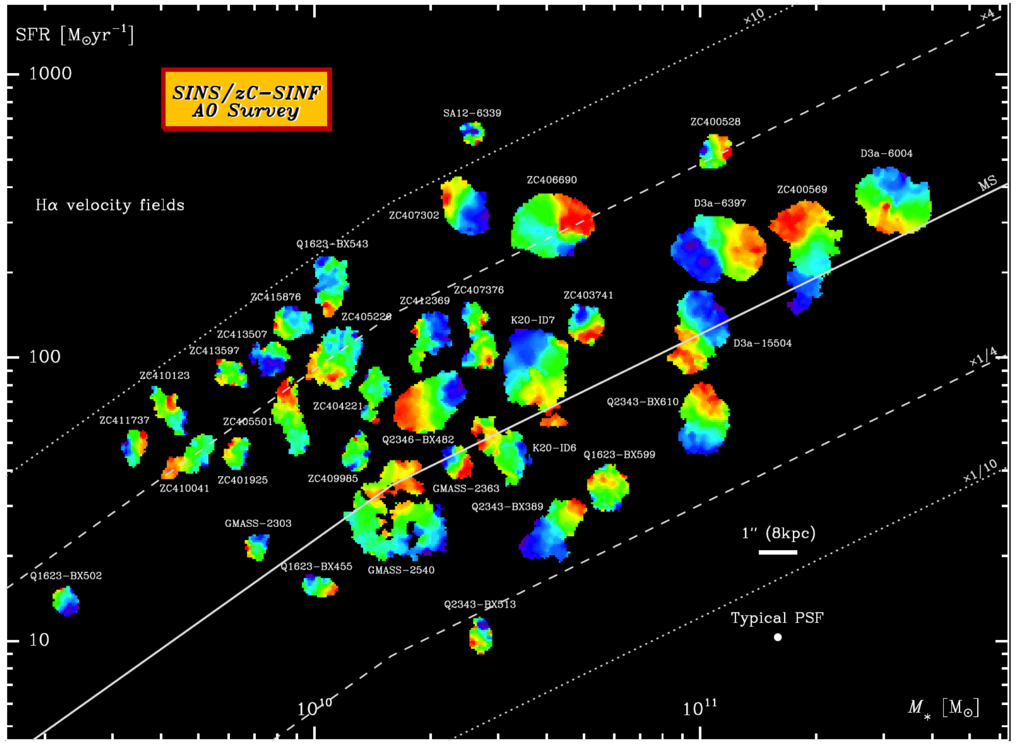


Oppenheimer+10

1. Identify outflows, spatially resolve geometry and launching base

Identifying high-z outflows that are less extended than the (more luminous) 'quiescent' ISM

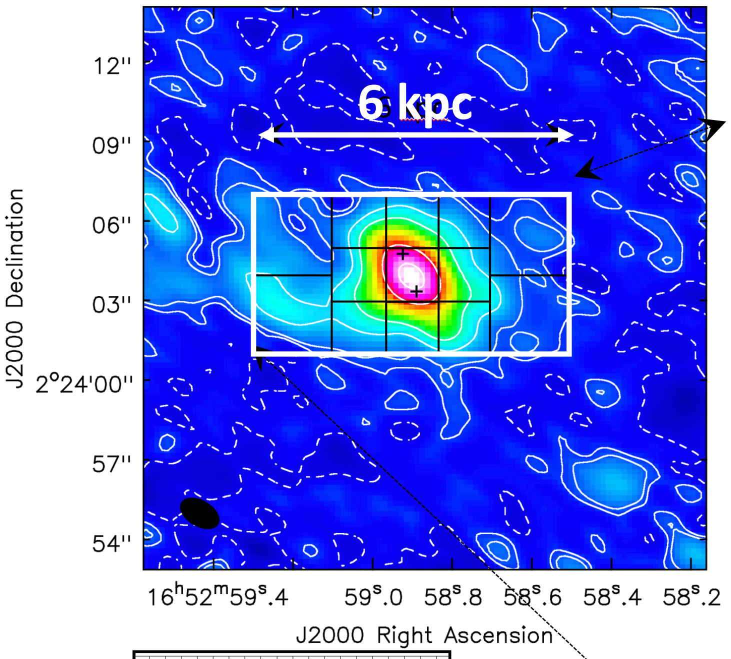
Forster-Schreiber+18



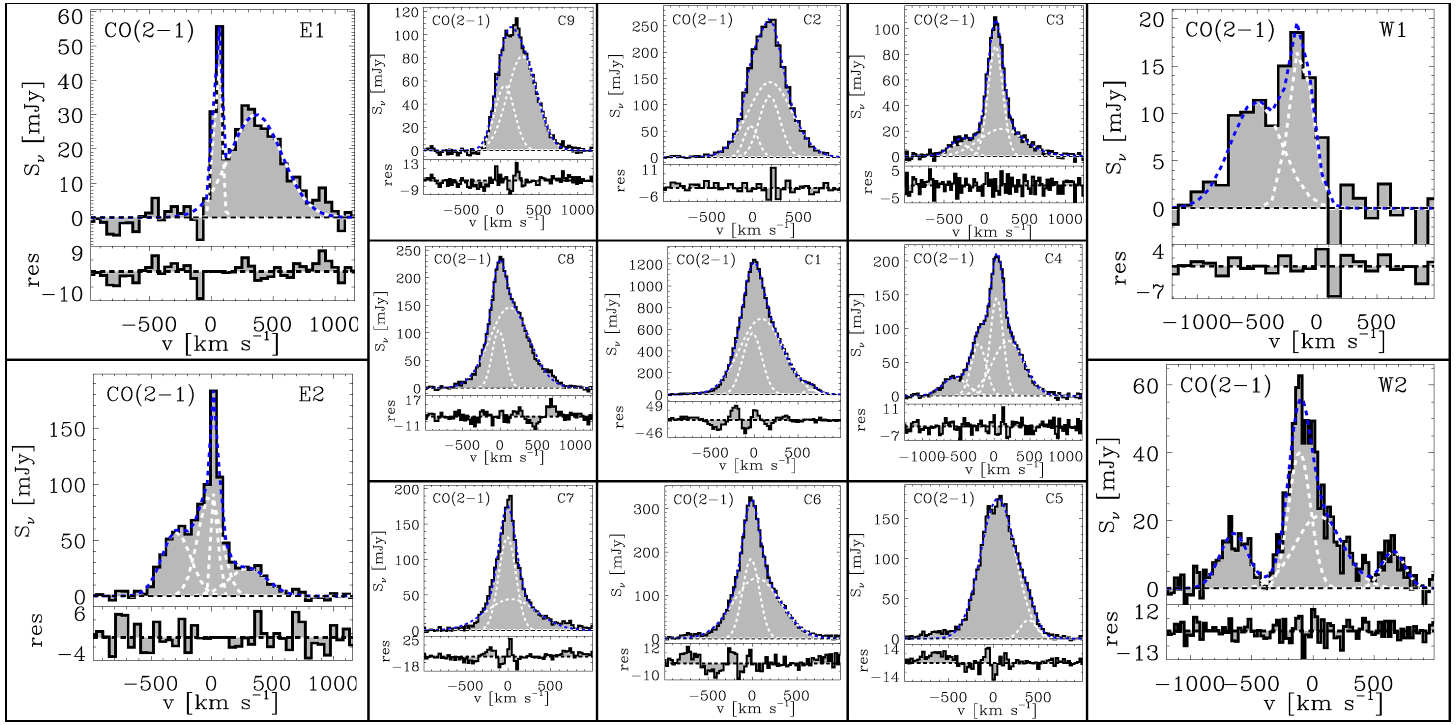
Hα velocity gradients of high-z SF galaxies tracing disks (or mergers disguised as disks, e.g. Simon+19). In AGNs need to account for nuclear BLR and beam smearing (e.g. Carniani+15, Harrison+16)

- *Most* high-z ionized outflows extend by <1-2 kpc Newman+12, Carniani+15, Forster-Schreiber+18, Kakkad+19
- Even with ~20h on source + AO assisted data, limited S/N and res of current facilities (*best res* *Davies+19 SINFONI-AO= FWHM$_{PSF}$ = 0.15" = 1.4 kpc at z=2*) imply outflow analyses have to rely on many assumptions and stacking -> energetics very uncertain
  - *ELT diffraction-limited PSF core in NIR (2 μm) $\gtrsim$0.010" → $\gtrsim$90 pc at z=2*
  - *ELT diffraction-limited PSF core in MIR (10 μm) $\gtrsim$0.060" → $\gtrsim$550 pc at z=2*

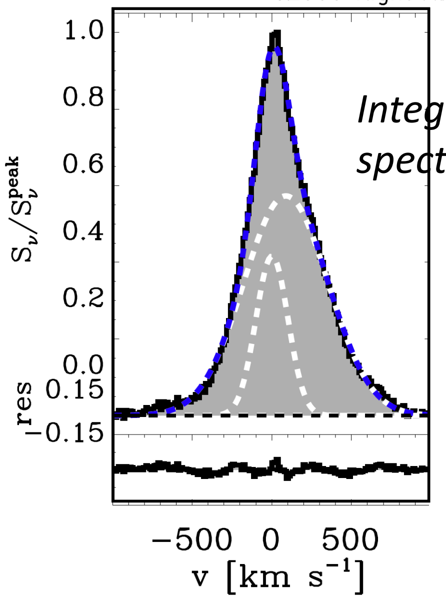
Impact of S/N and res on outflow identification



ALMA CO(2-1) observations of NGC6240, 1.2" angular res (600 pc)



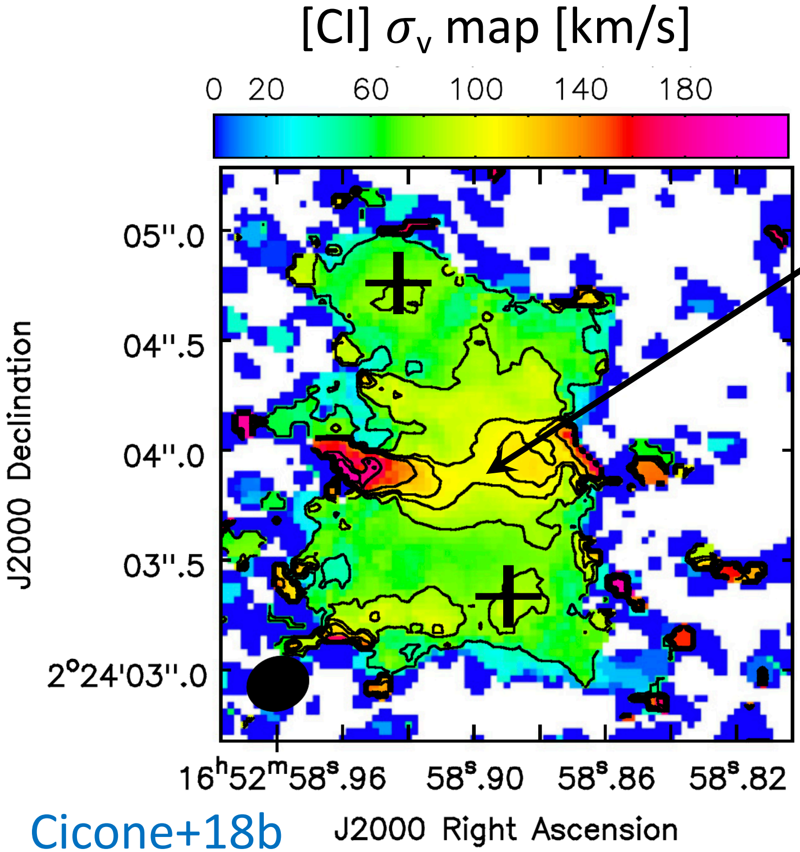
ELT can achieve similar spatial res at z=2 in MIR lines (warm H_2)



Cicone+18b, Feruglio+13

- **60+-20% of CO emission is due to the outflow** ($\gtrsim 10^{10}$ M_{Sun} of H_2 gas in outflow): heavily underestimated (and even missed) in integrated spectrum
- Outflow features *dominate* emission *only at some positions* within the source and may be completely missed in integrated data (see also optical and NIR IFS studies of local AGN/ULIRGs: Rupke+Veilleux13, Cazzoli+14,16, Colina+15, Ramos Almeida+17, U+19)

Resolving base of the outflow to identify driving mechanism(s)



Cicone+18b

'hourglass' feature = launching base of outflow between the two quasars

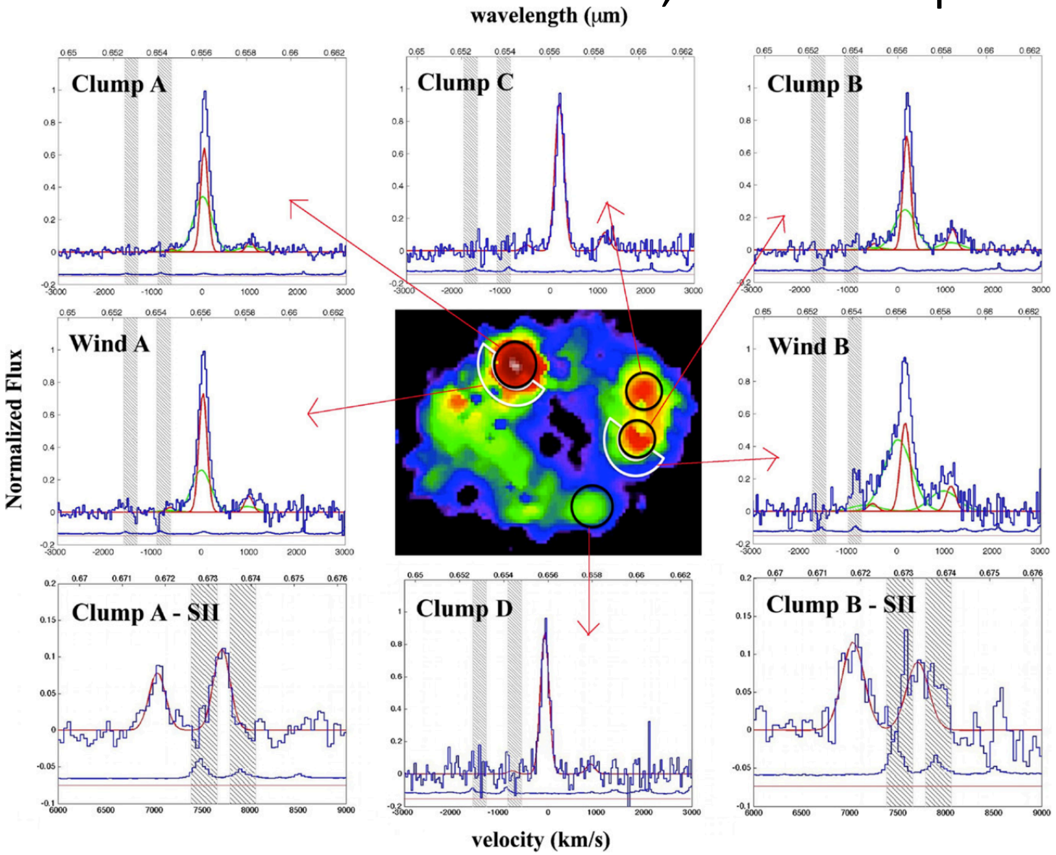
Geometry suggests link with merger stage

Global energetics suggests AGN-driving

ALMA [CI] 609.14 μm data of NGC6240 (z=0.024)
Res ~ 0.24" = 120 pc
ELT can achieve similar spatial res at z=2 in NIR

Newman+12

SINFONI 10h, res ~ 1.85 kpc



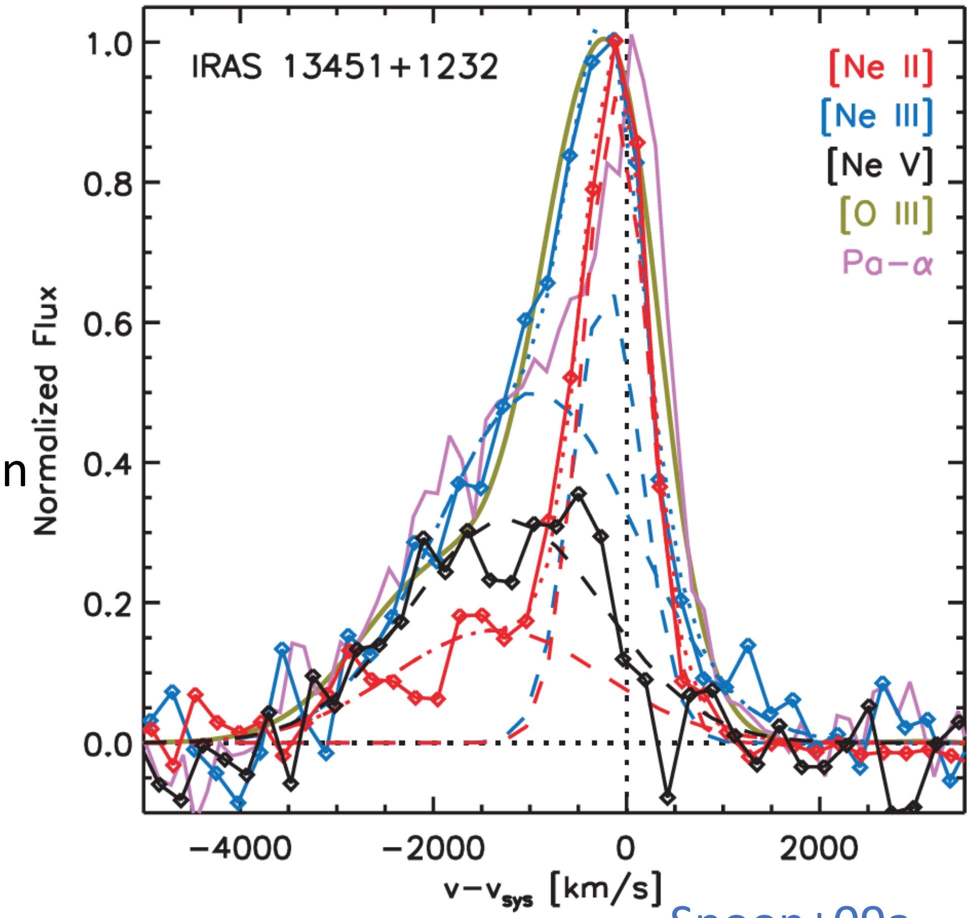
In this massive z~2 SF galaxy, Hα outflows launched from regions offset from the nucleus

Identification of buried outflows through mid-IR fine structure lines ([NeII], [NeIII])

- Local ULIRGs: [NeII] and[NeIII] show strongest wings. When detected, [NeV] totally dominated by broad component and identifies AGN-driven outflows Spoon+Holt09, Spoon+09
- Dust-penetrating power of mid-IR spectroscopy (e.g. Inami+13) makes these lines best tracers of ***buried outflows*** and ***dust-enshrouded launching regions***
- Global mid-IR line ratios can be used as ***shock tracers*** and can easily identify outflow-dominated sources (e.g. NGC6240)

ELT: Mid-IR Neon fine structure lines at z~0 - 0.5

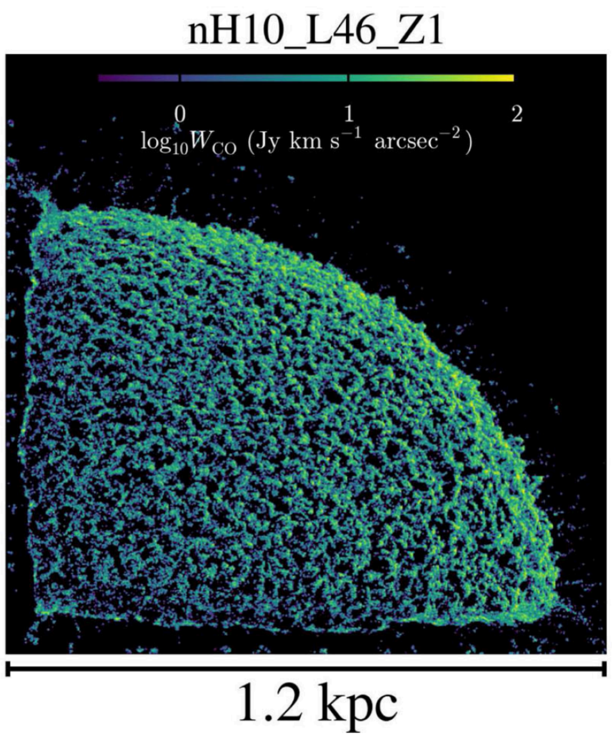
[NeII] 12.81μm (in METIS λ=3-19 μm range up to z~0.5)
[NeIII] 15.56μm
[NeV] 14.32μm



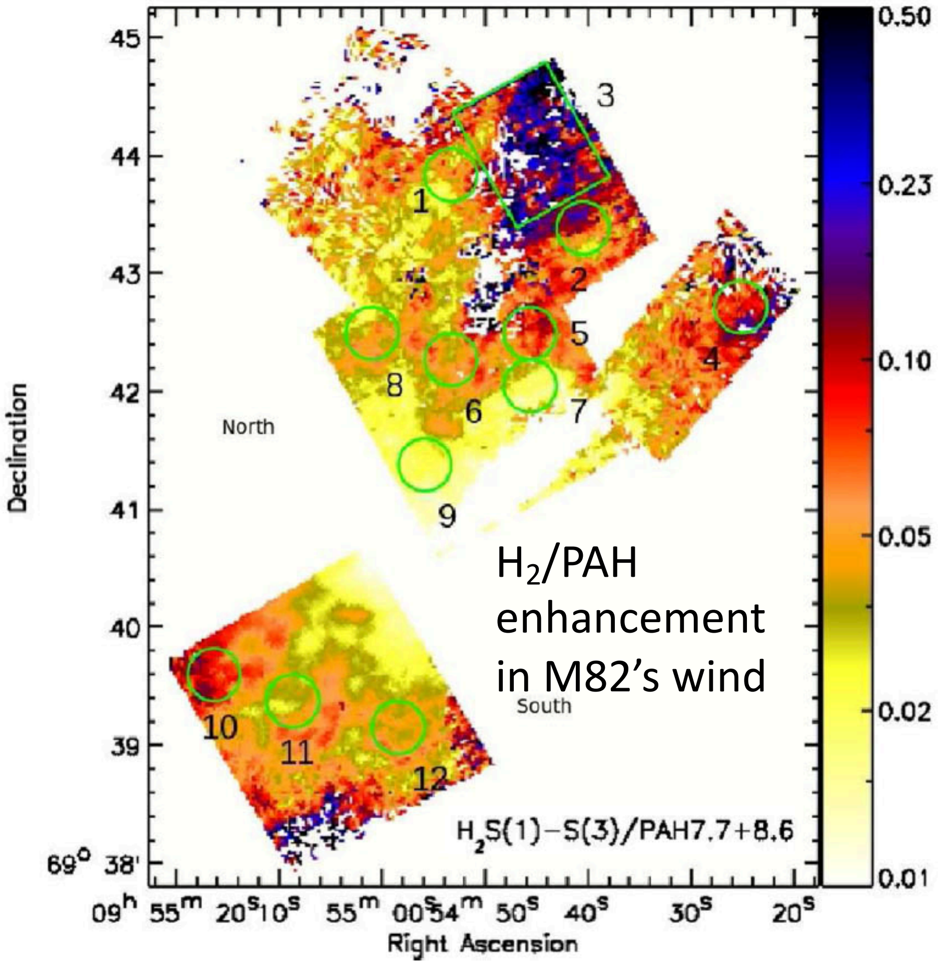
Spoon+09a

2. Study gas cooling within multiphase outflows through IR H_2 lines

Excess mid-IR H_2/PAH in ULIRGs and outflows



- Strong mid-IR H_2 lines expected from cooling of post-shock ISM swept by AGN winds. Most of H_2 outflow in this phase (T~ few 100 K) Richings+18a
- ULIRGs show enhanced mid-IR H_2/PAH emission (by x 3), correlating with shock tracers (Hill+Zakamska14, Inami+13) and with broader lines (Petric+18)
- At z~0, ELT (METIS) mid-IR H_2 emission down to <100 pc res
- At higher z: H_2 S(3) 9.66μm up to z~1 (~800 pc res at z=1)



H_2/PAH enhancement in M82's wind

Beirao+15

- NIR H_2 lines (T_{gas}~1000 K) entrain little H_2 mass but probe innermost regions Rupke+Veilleux13b, Emonts+17, Dasyra+Combes11

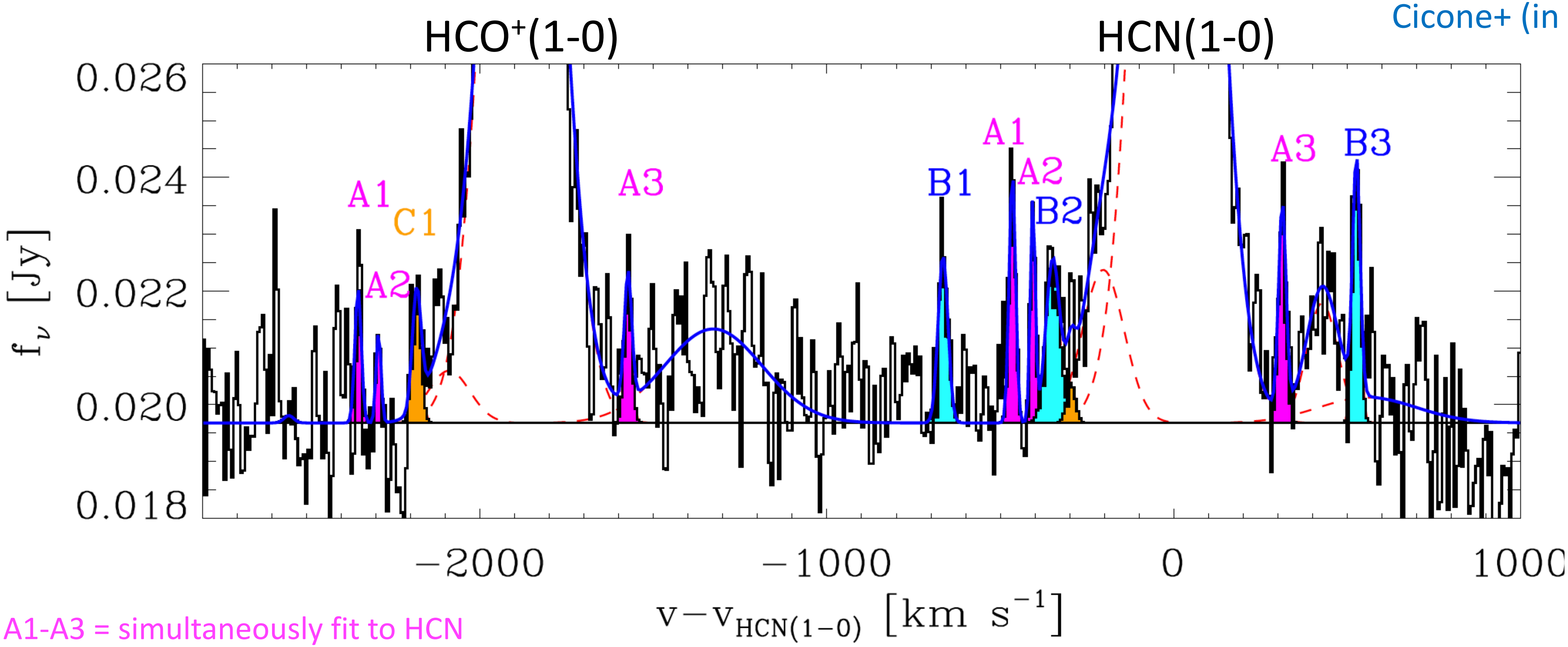
ELT HARMONI → NIR H_2 emission down to <10 pc at z=0 (AGN 'torus')

ELT METIS → NIR H_2 (S(0)2.22μm, S(1)2.12μm) up to z>7 (res~500 pc)

3. Star forming complexes (GMCs) and HII regions within outflows

Massive dense clumps in Mrk231's outflow

Cicone+ (in prep)



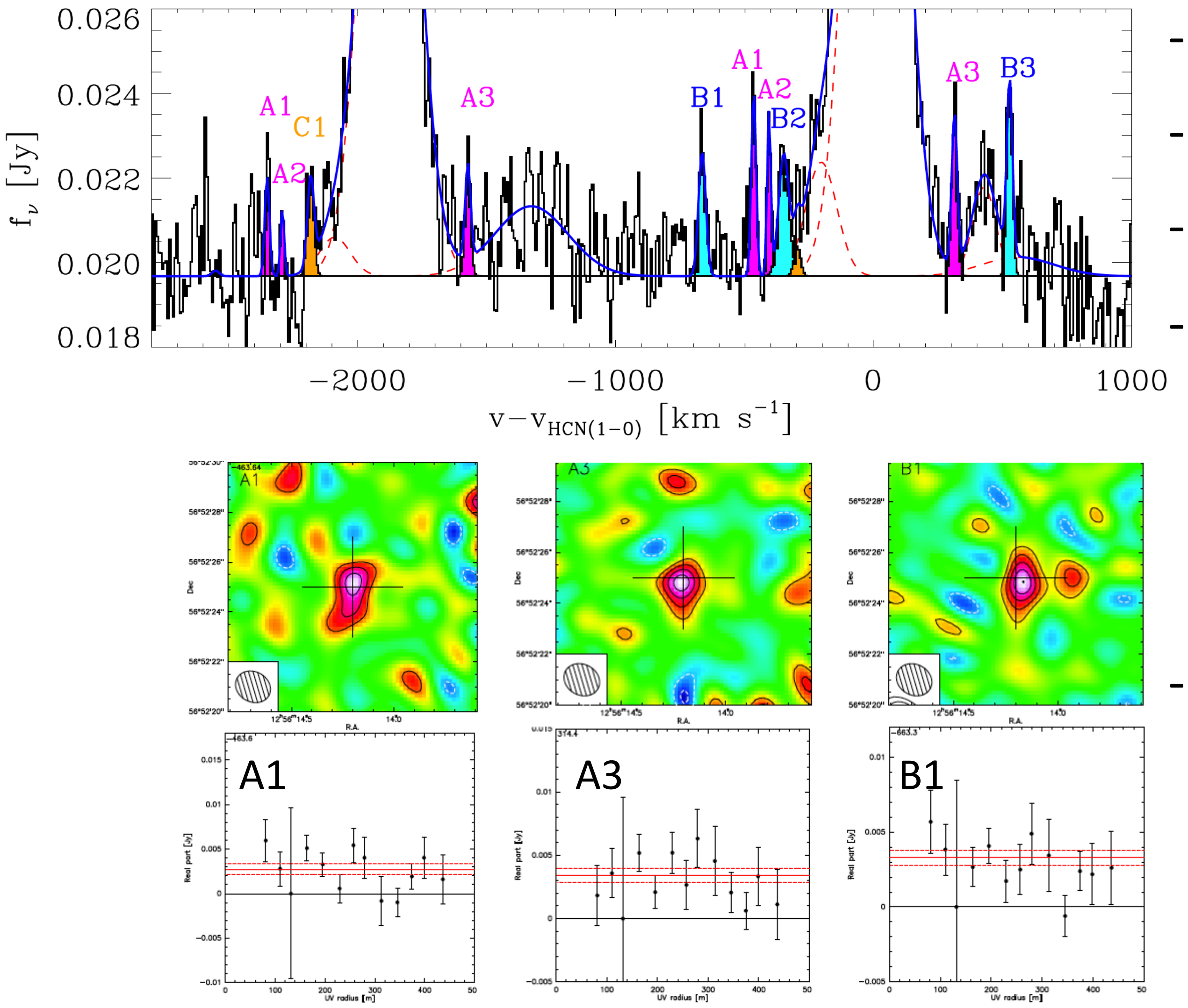
A1-A3 = simultaneously fit to HCN and HCO^+ (same σ_v and v)

B1-B3 = detected only in HCN

C1 = detected only in HCO^+

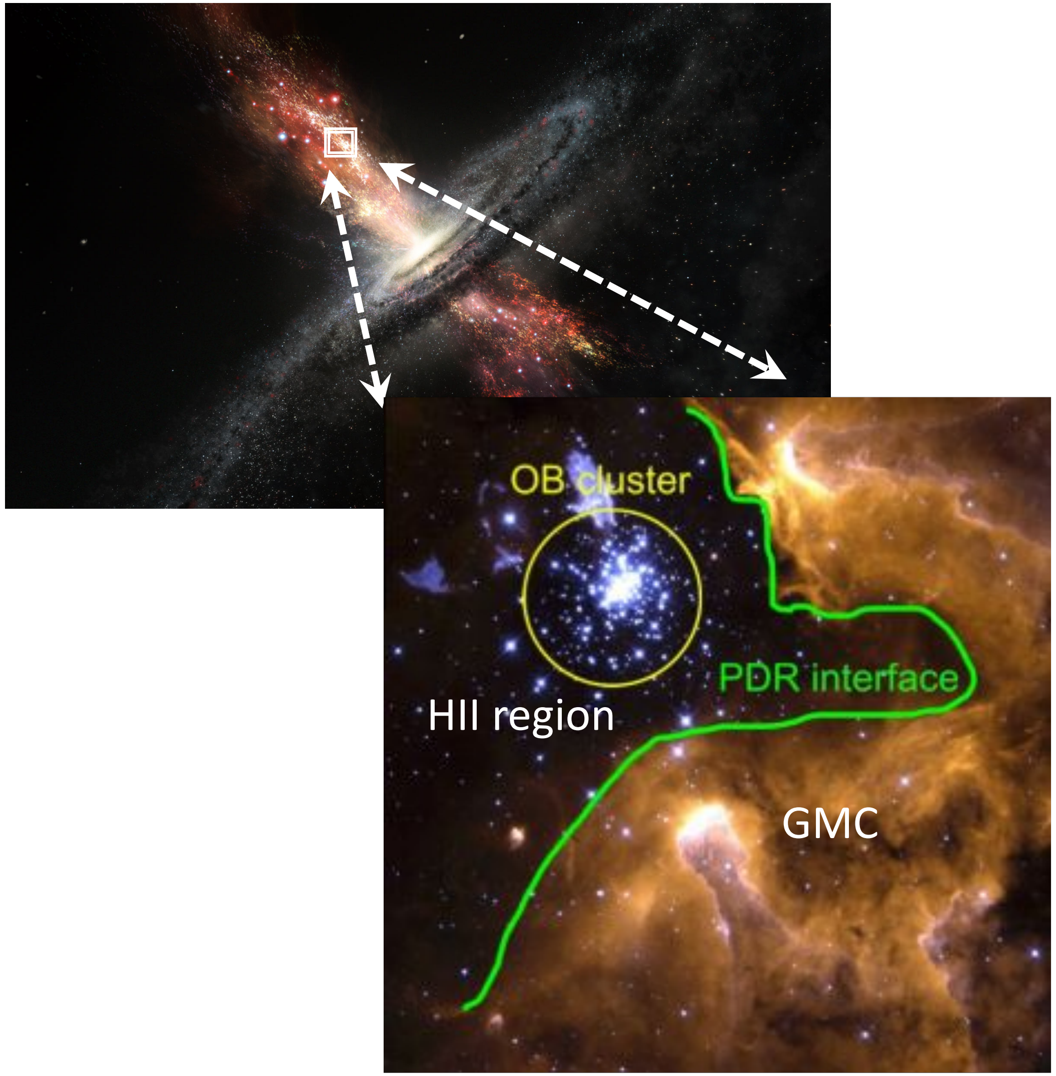
- Mrk231's molecular outflow detected also in 'dense' gas tracers (HCN, HCO+, CN, e.g. Aalto+12,15,Lindberg+16)
- At high spectral res, HCN and HCO+ wings break down into individual resolved 'clumps' (while CO wings remain smooth down to dv ~ 5 km/s res)

Clumps in Mrk231's outflow: some numbers



- S/N of HCN clumps ~ 4-5 (spectral fit)
- Unresolved at the ~ 1 kpc res of the data
- σ_v = 7-11 km/s
- M_{clumps} ~ 5 x 10^7 M_{Sun} for α_{HCN} ~ 3 M_{Sun} [K km s^{-1} $pc^2]^{-1}$ (Garcia-Burillo+12). Comparable to highest GMC masses at M83 centre (Freeman+17) -> more massive and turbulent GMCs expected in denser environments
- M_{clumps} ~ 4 x 10^8 M_{Sun} for α_{HCN} ~ 24 (estimated by Leroy+15 for GMCs in NGC253): these masses would correspond to more complex structures than individual GMCs

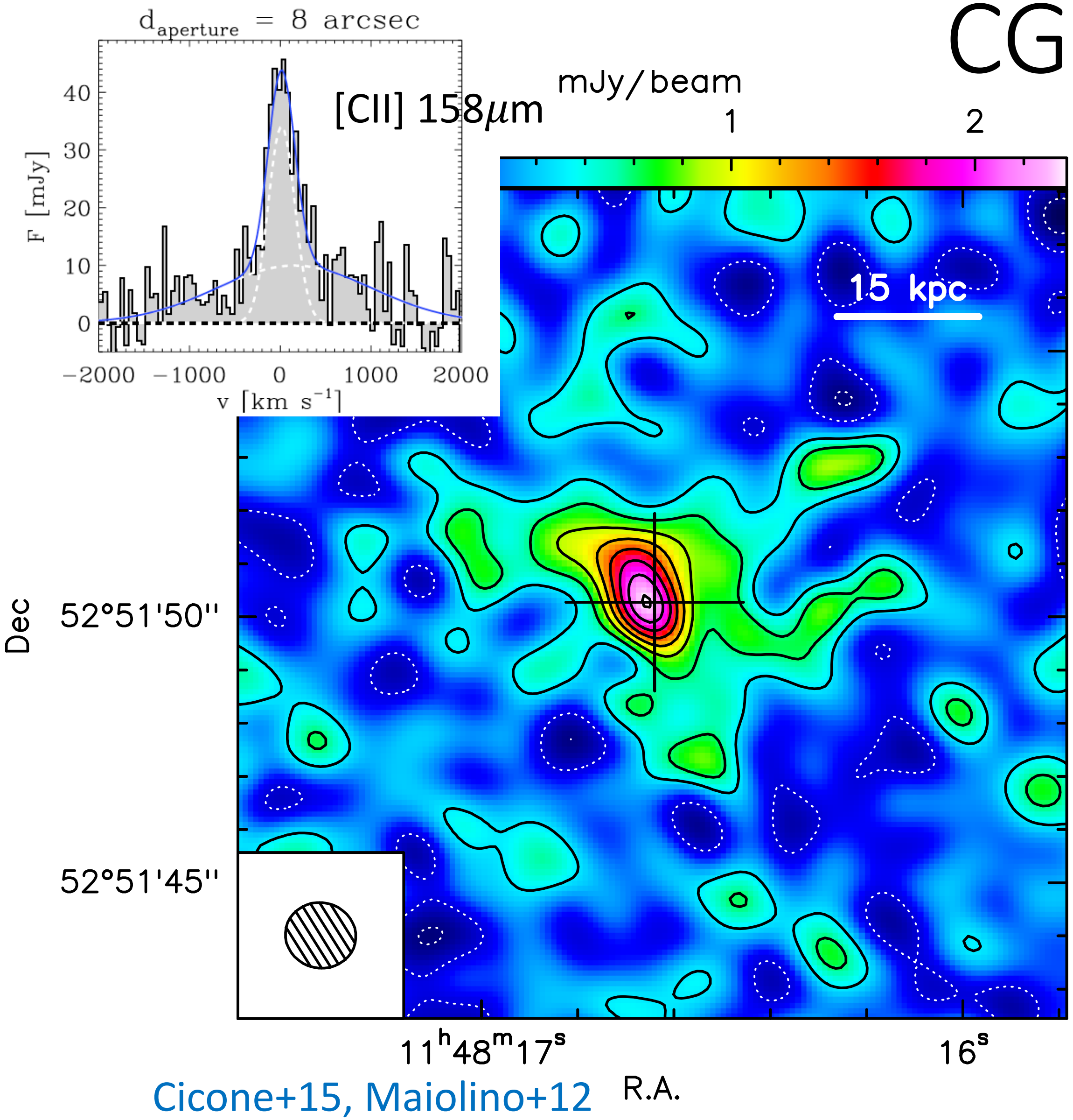
ELT can resolve PDR envelopes of GMCs and HII regions inside outflows



- ALMA can detect dense H_2 gas complexes inside outflows (GMCs) but not unambiguous signature of ongoing star formation (e.g. Maiolino+17, Gallagher+19)
- Enhancement of CN in Mrk231's outflow indicates strong UV fields -> look for photon- dominated regions (PDRs) inside outflows
- Larger σ_v and M_{H2} of HCN clumps in Mrk231: much more massive (and likely bigger) than Milky Way's GMCs: structures of ~100s pc could be resolved by ELT at z>1
- In local ULIRGs the ELT may image compact continuum sources like super stellar clusters embedded in outflows
- At z~0 ELT NIR <10 pc res
- At z>1 ELT NIR <100 pc res

4. The $z>6$ CGM

Emission line observations of multiphase CGM at z>6



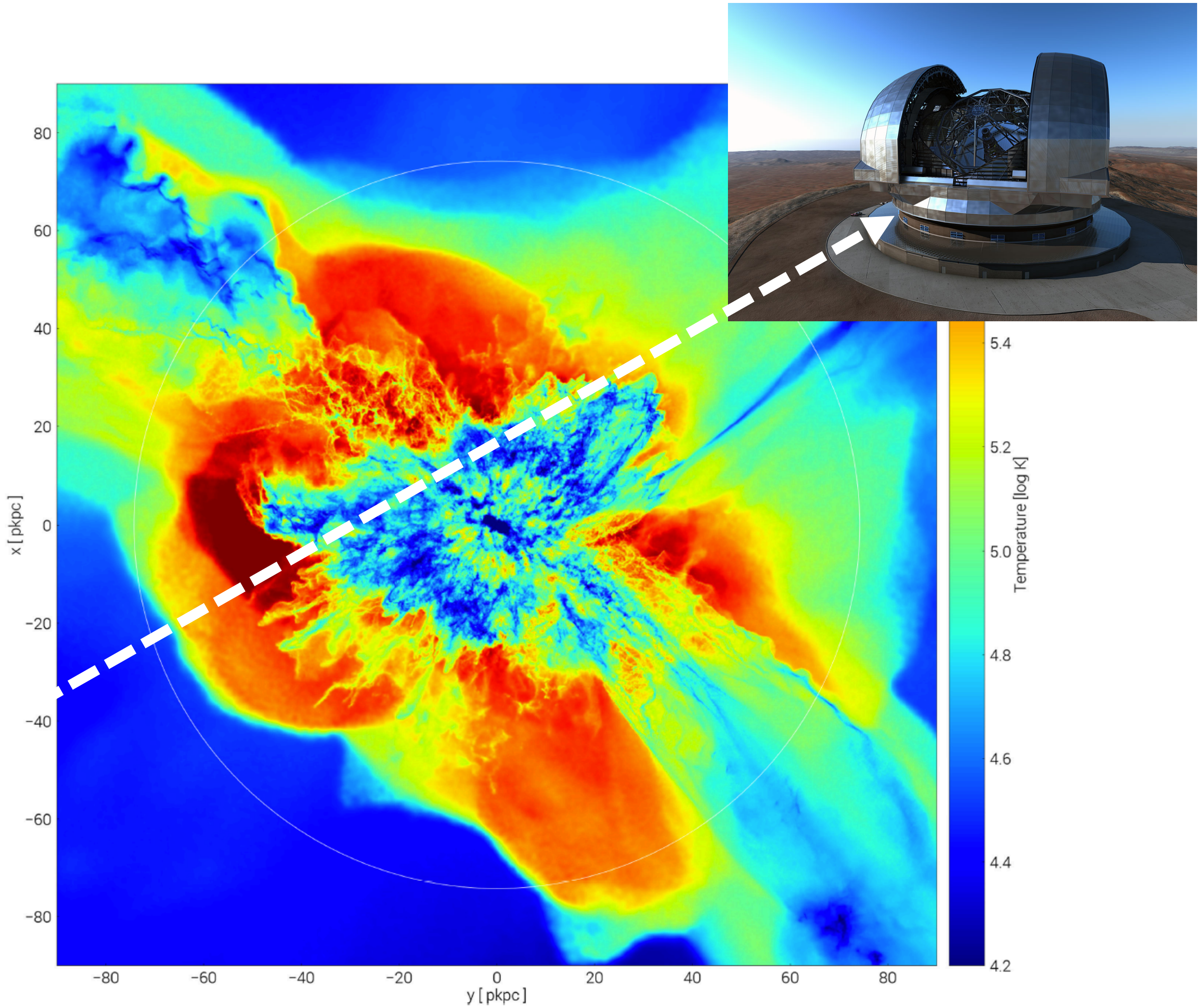
Cicone+15, Maiolino+12

- Deep mm observations of z=6.4 quasar reveal [CII]158μm 'halo' with r=30 kpc (>>ISM scales)
- Part of [CII] traces the most extended highest-v cold outflow ever detected (R ~ 30 kpc, σ_v ~ 500 km/s, v_{max} ~ 2000 km/s)
- Not just the 'outflowing' [CII] is extended: only 30% of narrow [CII] is in kpc-scale ISM, 70% is in CGM
- Hence (i) z>6 CGM is multiphase and includes neutral HI + H_2 gas, (ii) we can study these high density regions with the ELT in Lyα emission (see ubiquitous Lyα nebulae at z=2-3: Cantalupo+14, Hennawi+15, Borisova+16, Wisotzki+18 , Arrigoni Battaia+19, Marino+19)

The ELT can resolve <100 pc CGM structures traced by Lyα at z>6

HARMONI IFS (max FoV ~10" ~ 50 kpc at z>6)
MICADO Lyα narrow band imaging at z>6
MOSAIC (8-10 IFUs) for a wider FoV and more objects

Absorption line observations of multiphase CGM/IGM at z>6



- ELT HIRES will detect CGM and IGM in absorption around more 'normal' sources thanks to much higher sensitivity and spectral resolution

- Different ions trace different CGM phases (and with different origin, e.g. Ford+14)

- OI 1302Å is a promising tracer of z>6 CGM: EW (OI) decreases from z=3 to z=5 (due to metallicity), then increases at z>5. Cannot be due to more metals but must be due to more gas in this phase traced by OI (Becker+12).
- OI 1302Å redshifted to NIR 1.04μm at z>7, "OI forest" ~1.5 μm at z=10

Summarising, the ELT will be key to:

1. **Identify outflows, study geometry and launching base:**
    - Outflows can remain hidden in unresolved data (most high-z outflow have sizes $\lesssim$ 1-2 kpc)
    - Most buried regions undetectable in optical/NIR tracers, require mid-IR lines
    - Without geometry we have to rely on too many assumptions to get energetics right
    - Launching regions inform us about driving mechanisms

2. **Study gas cooling within the multiphase outflows:**
    - Models suggest mid-IR H_2 lines trace large masses of post-shock gas cooling out of outflows
    - IR H_2/PAH enhancement observed in local (U)LIRGs hosting powerful outflows
    - NIR H_2 lines trace little H_2 mass but can probe innermost regions

3. **Resolve star forming complexes within outflows**: the ELT may resolve PDR envelopes and HII regions within outflows

4. **Investigate the z>6 CGM**:
    - Outflows in the early universe shaped multiphase CGM (= main reservoir for later accretion)
    - CGM at z>6 entrains metal-enriched neutral (HI and H_2) gas
    - The ELT can study the `normal' z>6 CGM in emission (Lyα) and absorption (OI, CIV, MgII etc)