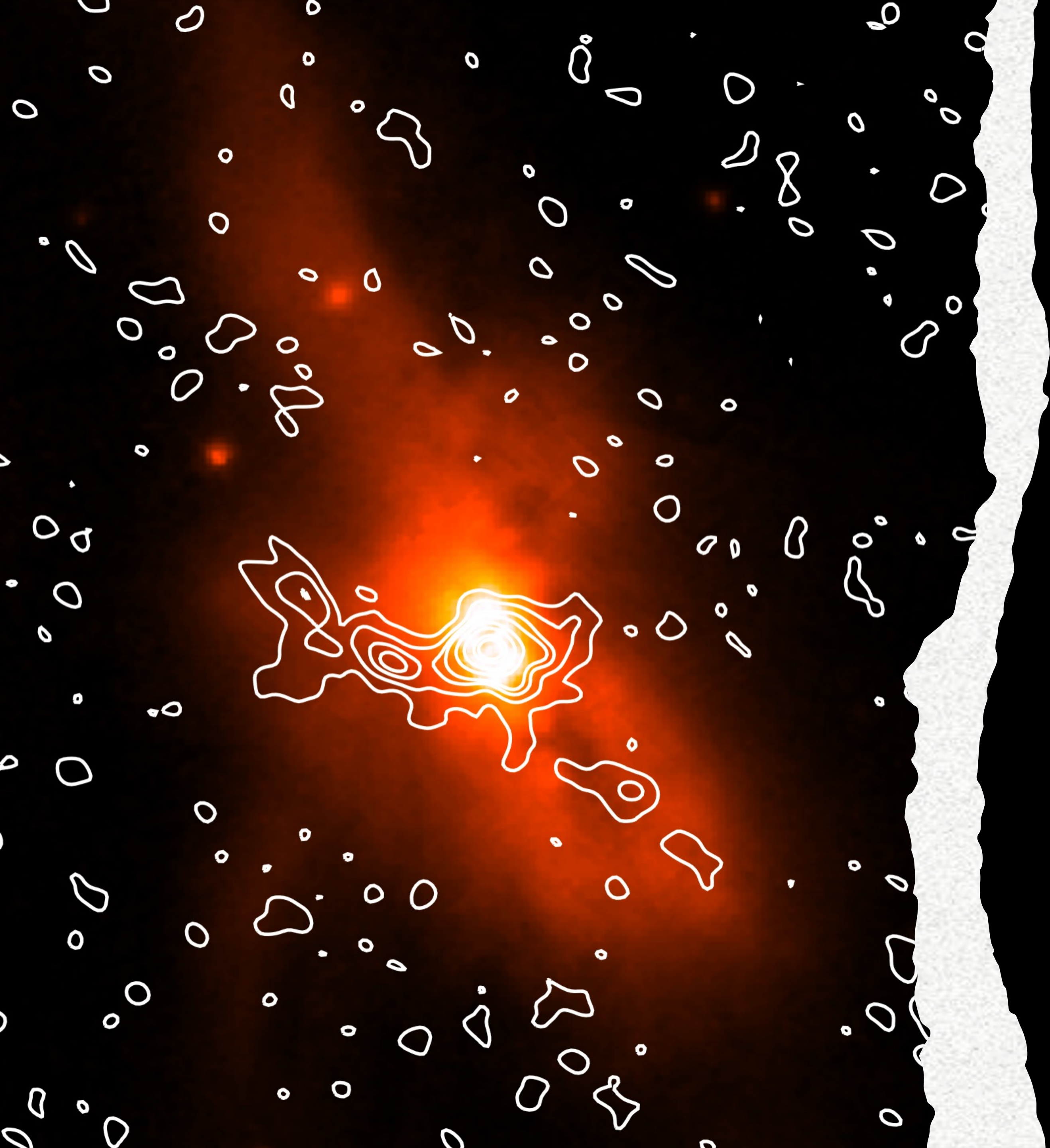


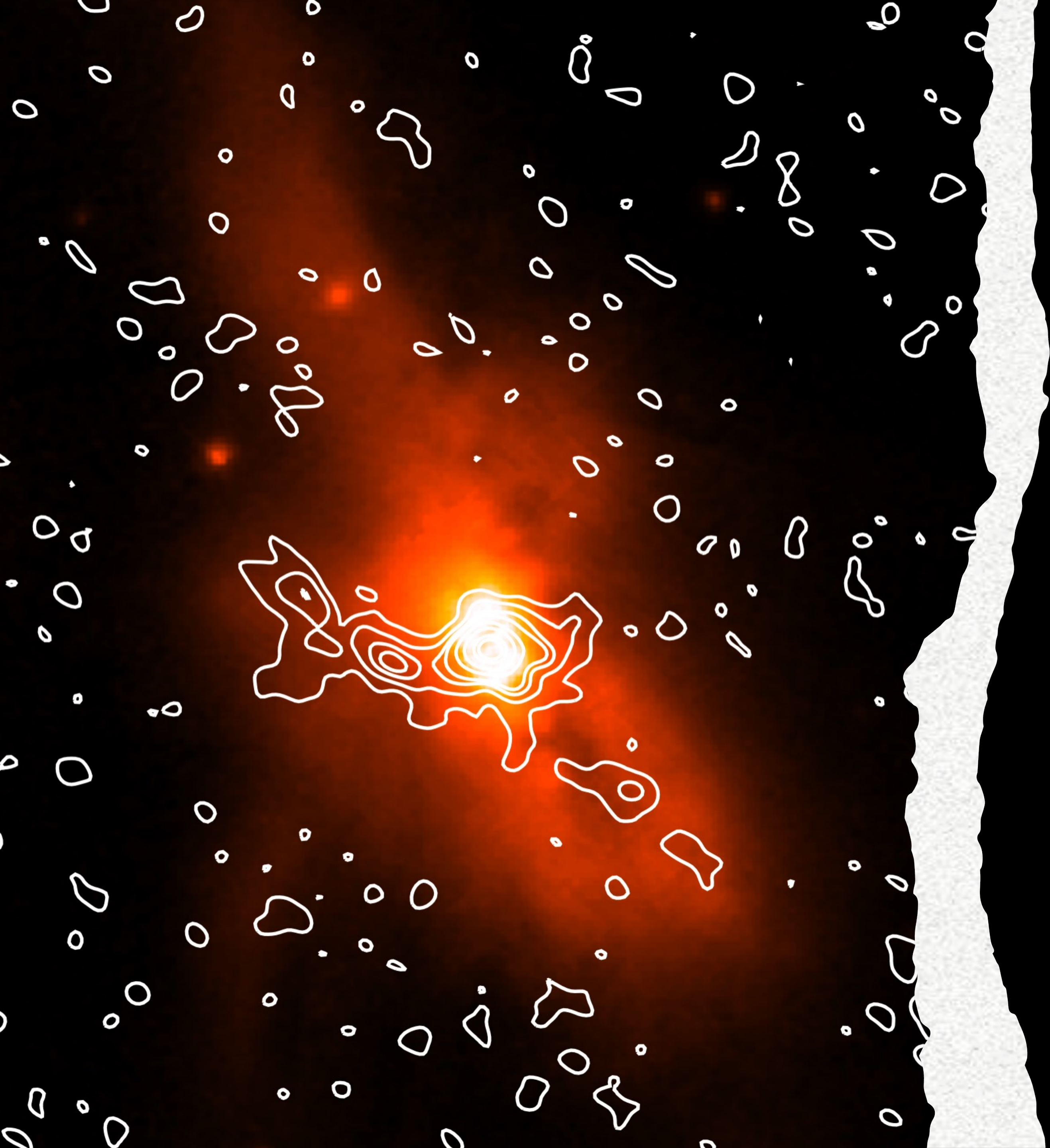
Studying feedback in galaxies with ALMA Band 2

Claudia Cicone

University of Oslo

claudia.cicone@astro.uio.no

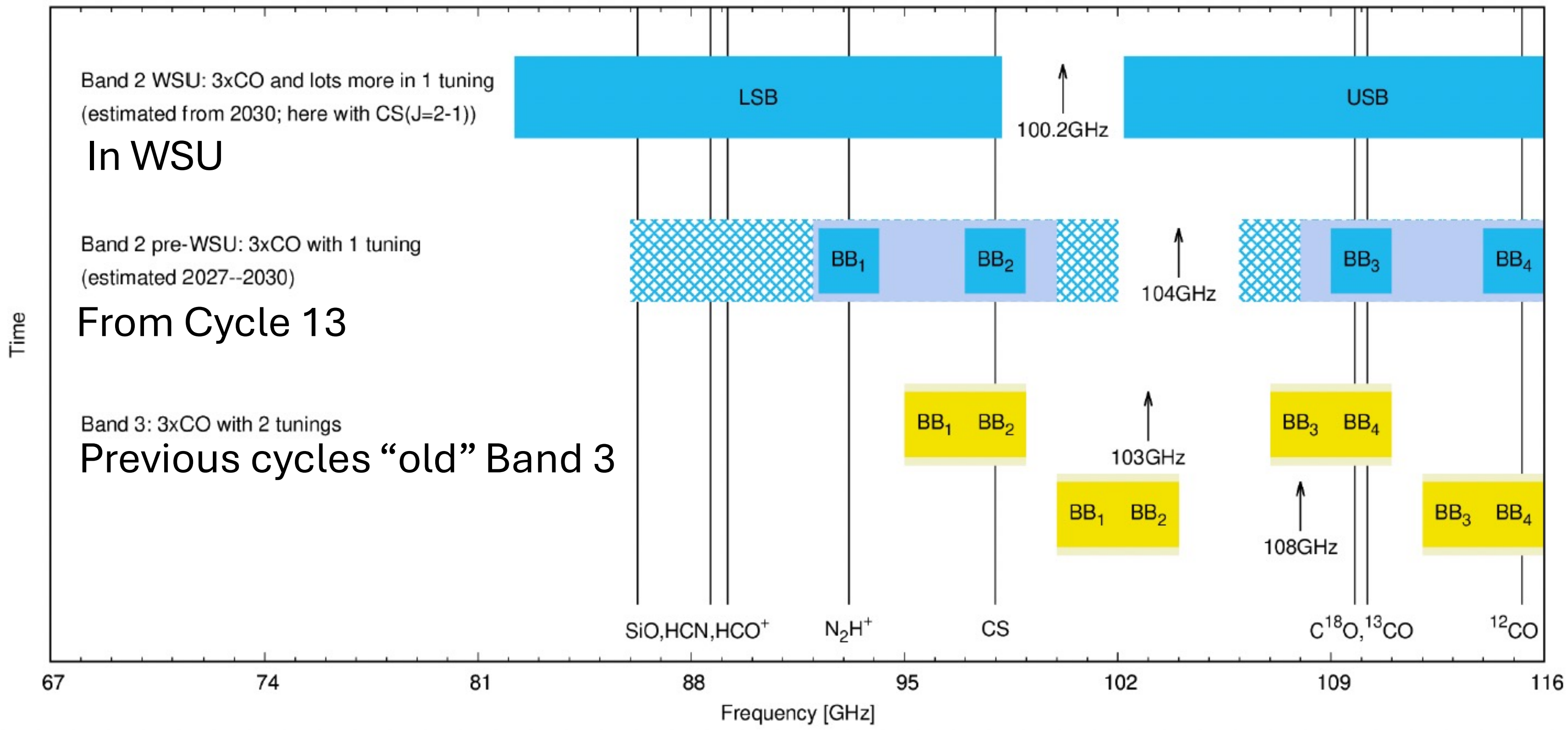
Funded by the European Union



Talk outline

- What we like about ALMA Band 2
- Background for science cases
- Science Case I: cold molecular outflows out to z~2.5
- Science Case II: dense molecular outflow tracers at z<0.3
- Science Case III: *cold* halos at Cosmic Noon and beyond
- Present and future synergies

What we like about ALMA Band 2

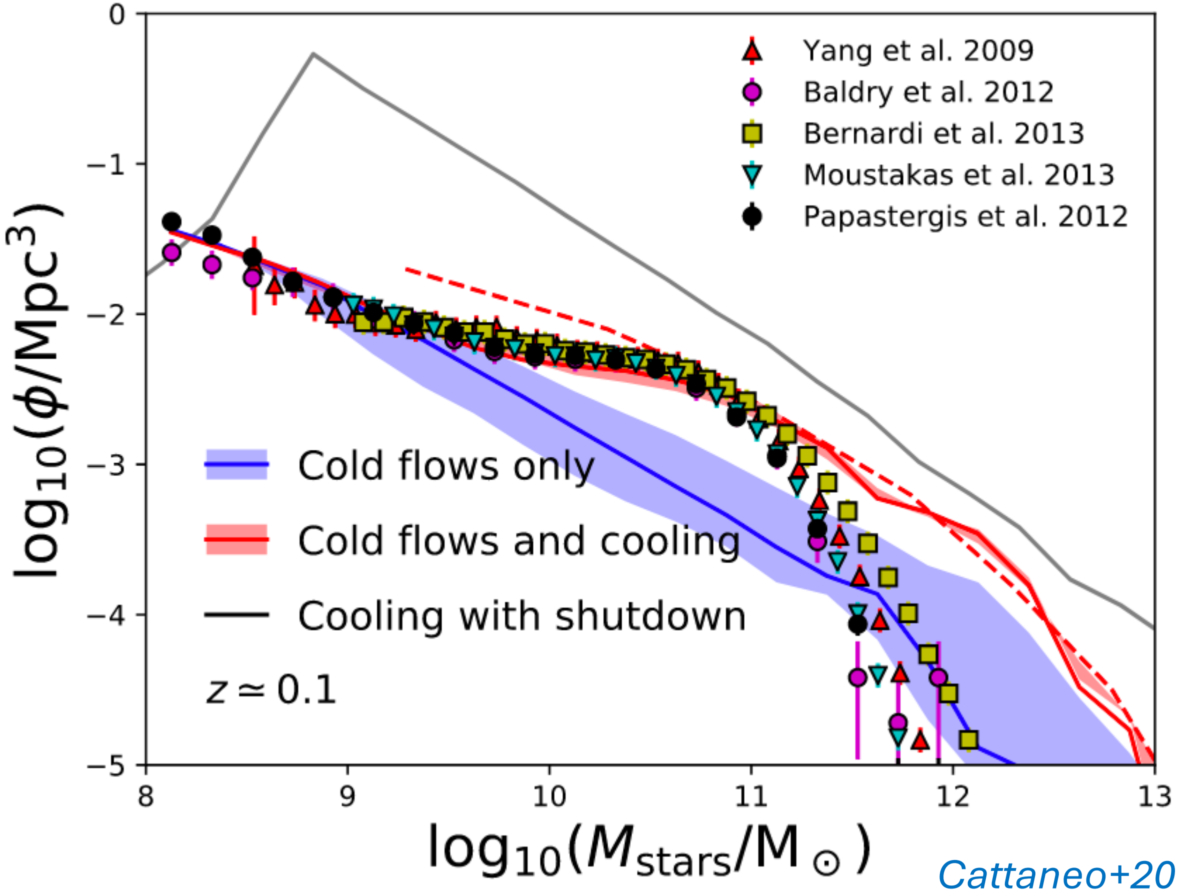


Phillips, N, 2024 (10.5281/zenodo.13681547)

(See also Tuesday's talks..)

- New Band 2 (67-116 GHz) opens up a **new frequency range for ALMA: 67-84 GHz**
- **Increased IF bandwidth:** from current 4-8 GHz IF in Band 3 to 2-14 GHz IF pre-WSU to 2-18 GHz IF after WSU → **spectral coverage and flexibility**
- Enable **simultaneously targeting lines at new Band 2 and (current) Band 3** sky frequencies

Negative feedback: gas ejection is a key but unconstrained ingredient of models

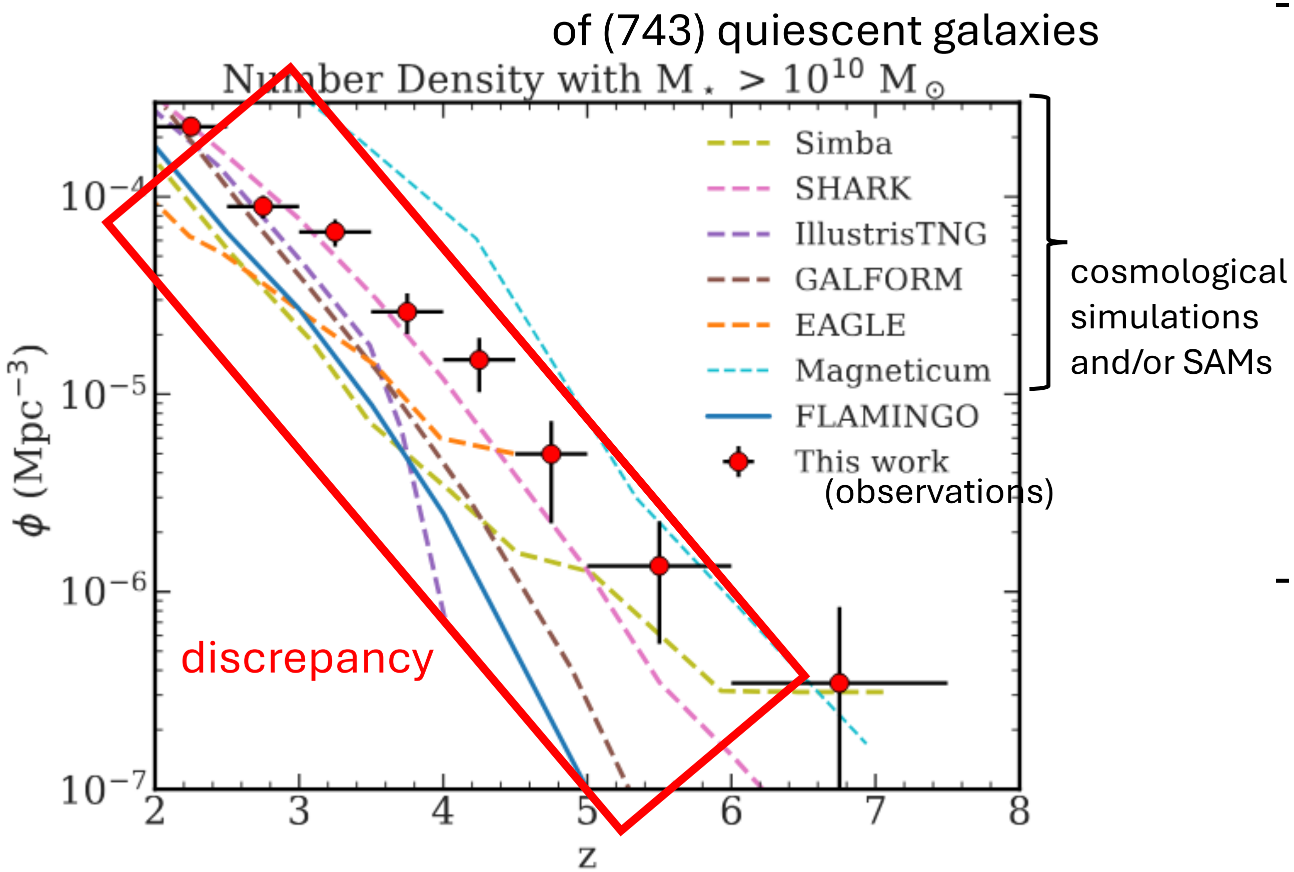


Cattaneo+20

- Low-M_* end of galaxy stellar mass function (SMF):
  - energy-driven SN feedback e.g. Silk2003 + (?) AGN e.g. *Koudmani+22*
  - re-accretion from CGM key to match data at z~2 *Tollet+19*
- High-M_*: need both pre-emptive and ejective AGN feedback
- Outflow rates are uncertain → possible to overestimate gas accretion and still reproduce the SMF by compensating with over-ejection *Cattaneo+20*

→ *balance* between outflows and inflows fine-tuned in models to match stellar mass functions
→ Need direct observational constraints on feedback to break such degeneracy

Strong negative feedback at work at z>6



Baker+25

- Quiescent galaxies observed at z>2 out to z~5 and higher, with JWST in increasingly higher numbers *Cimatti+04, Carnall+23, Valentino+23, + many more JWST works*
  → Negative feedback at work at z>6 (<1Gyr)
  → Some galaxies display fast quenching (<~100 Myr) → need to search for **rapid ejection**

- More quiescent galaxies exist at high-z than predicted by models *Lagos+25, Baker+25*
  → **We need direct observational constraints of gas ejection at z>2** instead of extrapolating from z~0 observations

M82, Veilleux+05

Massive **galactic outflows** can quickly suppress star formation in ("active") galaxies by ejecting gas out of disks

→ *Promising negative feedback mechanism*

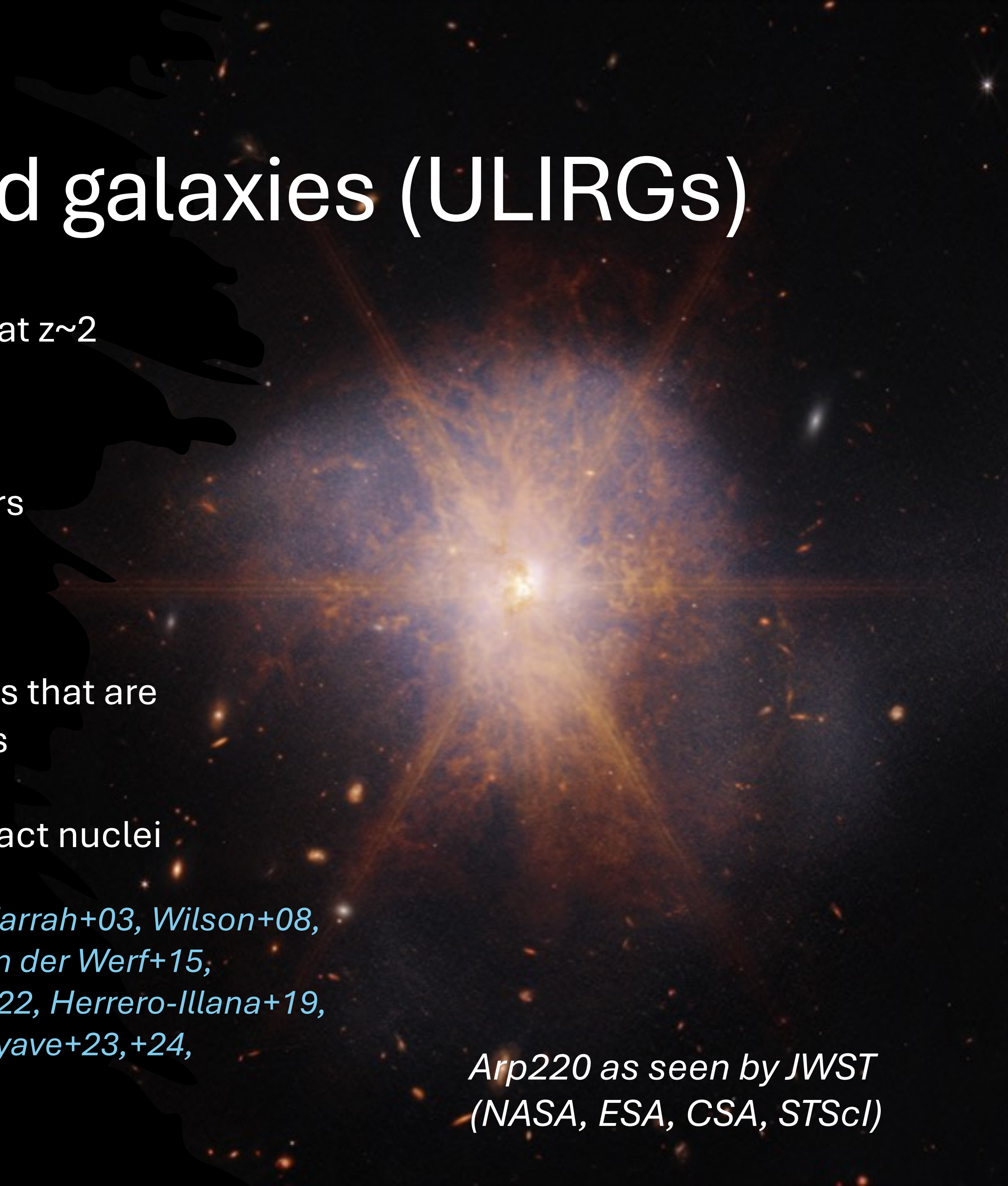
However: not all galactic outflows are efficient at removing gas from star forming regions

→ The most extreme galactic outflows are those that ***contain a lot of molecular gas (~ 10^9 M_{Sun}),*** which, at z~0, have been detected **mainly in IR-bright galaxies**, especially Ultra Luminous Infrared Galaxies (ULIRGs)

Ultra luminous infrared galaxies (ULIRGs)

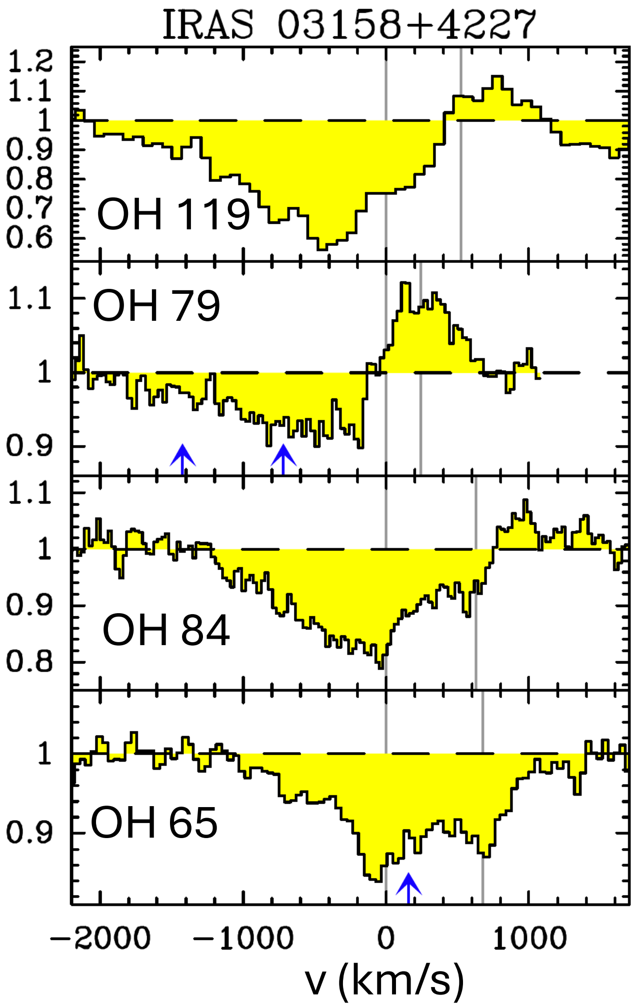
- L_{IR}(8-1000μm) ≳ 10^{12} $L_{\odot}$, rare at z~0, x100 more common at z~2
- IR powered by dust heated by starbursts and AGN
- At z~0 ULIRGs correspond to dusty gas-rich major mergers
- ISM strongly affected by gravity and feedback
- Very bright in the (sub-)mm: allows multi-tracer H_2 studies that are prohibitive in normal galaxies. Often used as benchmarks
- Host one or multiple SMBHs, some host extremely compact nuclei

Aalto+95,+12,+15,+19, Sanders+Mirabel96, Downes+Solomon98, Farrah+03, Wilson+08, Magnelli+11, Papadopoulos+12,+18, Ueda+14, Kamenetzky+14, van der Werf+15, Rosenberg+15, Israel+15, Veilleux+20, Perez-Torres+21, Vivian U 2022, Herrero-Illana+19, Imanishi+19, Cicone+12,+14,+18,+20, Molyneux+24, Montoya-Arroyave+23,+24, Carlsen+26, Hagedorn+26



Arp220 as seen by JWST (NASA, ESA, CSA, STScI)

Massive molecular outflows in galaxies



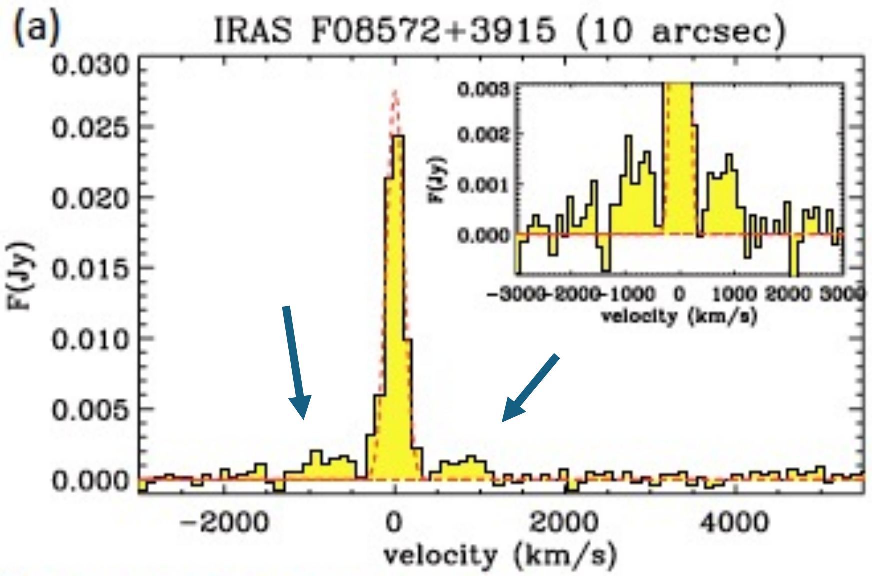
Gonzalez-Alfonso et al. 2017

See also: *Fischer+10, Sturm+11, Veilleux+13, Spoon+13*

P-Cygni or blue-shifted absorption lines (e.g. OH, H_2O) against FIR continuum observed with Herschel
→ **launching point of molecular outflows**

Extremely powerful and massive in ULIRGs:

v_{out}~ 100s to 1000 km/s
M_{out} (H_2) up to ~ 10^9 M_{sun} or higher
dM_{out}/dt ~ up to few 100s M_{Sun}/yr



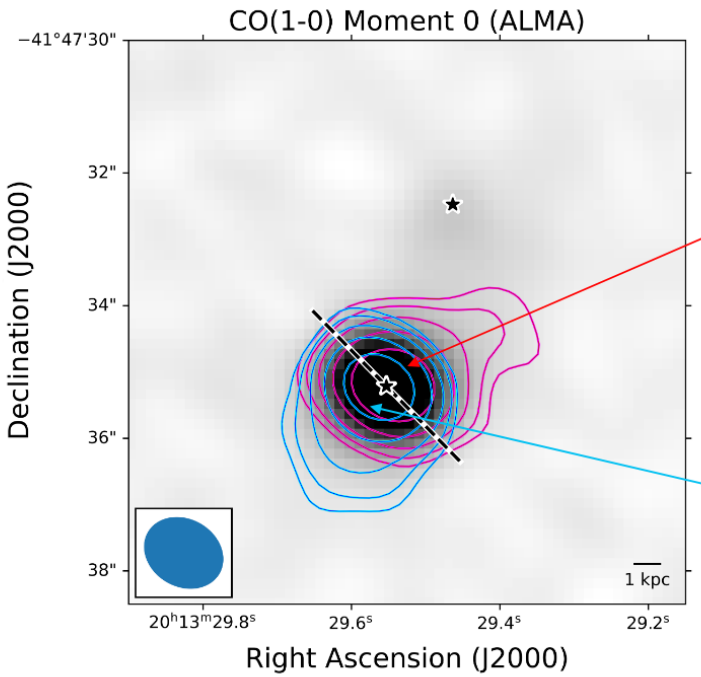
Cicone et al. 2014

Broad/high-v components of molecular (e.g. CO, HCN, etc) emission lines not consistent with disk rotation → >20 times fainter than line peak
→ **Enable to track large-scale components and provide constraints on mass and energetics**

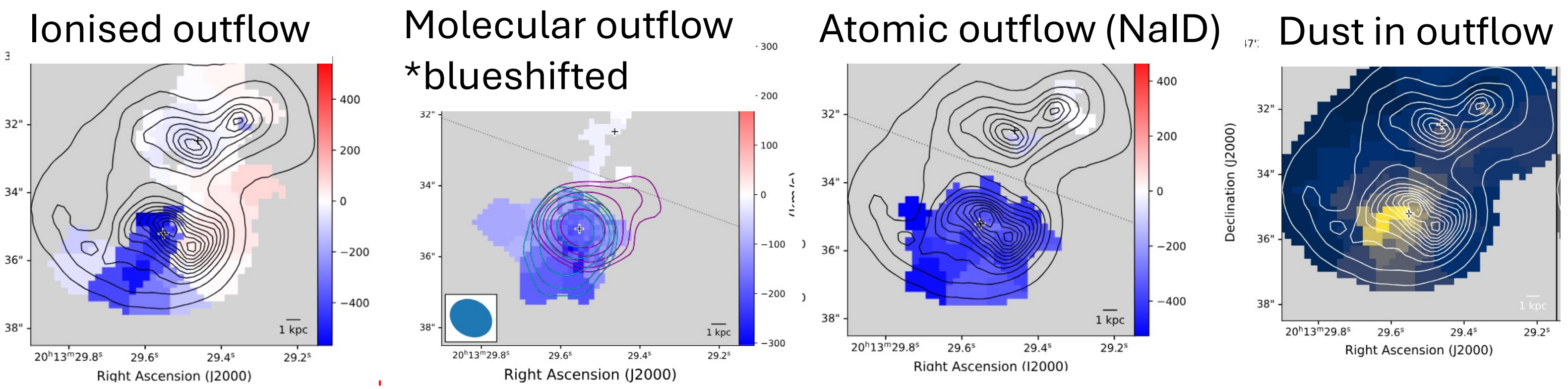
Feruglio+10,+15, Aalto+12, Alatalo+15, Cicone+12,+14,+18,+20, Dasyra+16, Pereira Santaella+18, Fluetsch+19, Lutz+20, Lamperti+22, Veilleux+20, Hagedorn+26

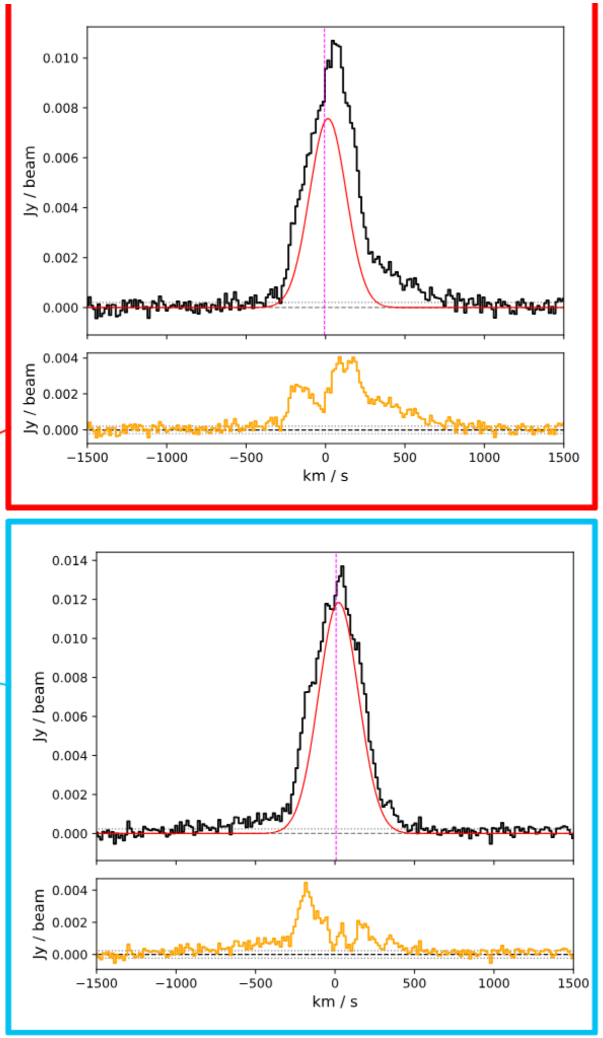
H_2 dominates outflow mass in ULIRGs

IRAS20100-4156 at z=0.1297



Hagedorn, Cicone+26





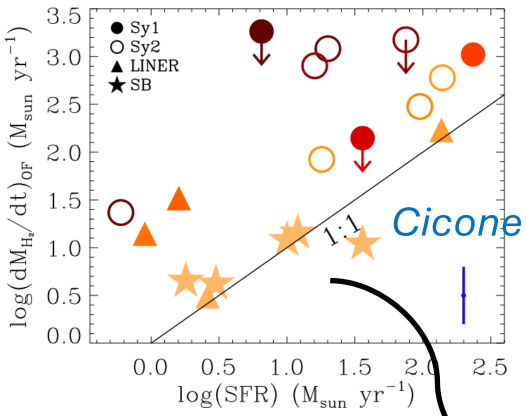
- **Outflow H_2 mass: $9x10^9$ M_{Sun}, i.e. 40% of total molecular gas in the system**
- HI in outflow ~15% of H_2 outflow mass
- HII in outflow ~3% of H_2 outflow mass
- 3.5 x 10^7 M_{Sun} of dust in the outflow

Outflow shows a biconical morphology centered on the brightest galaxy of the system, detected out to R=5 kpc and does not slow down at larger radii

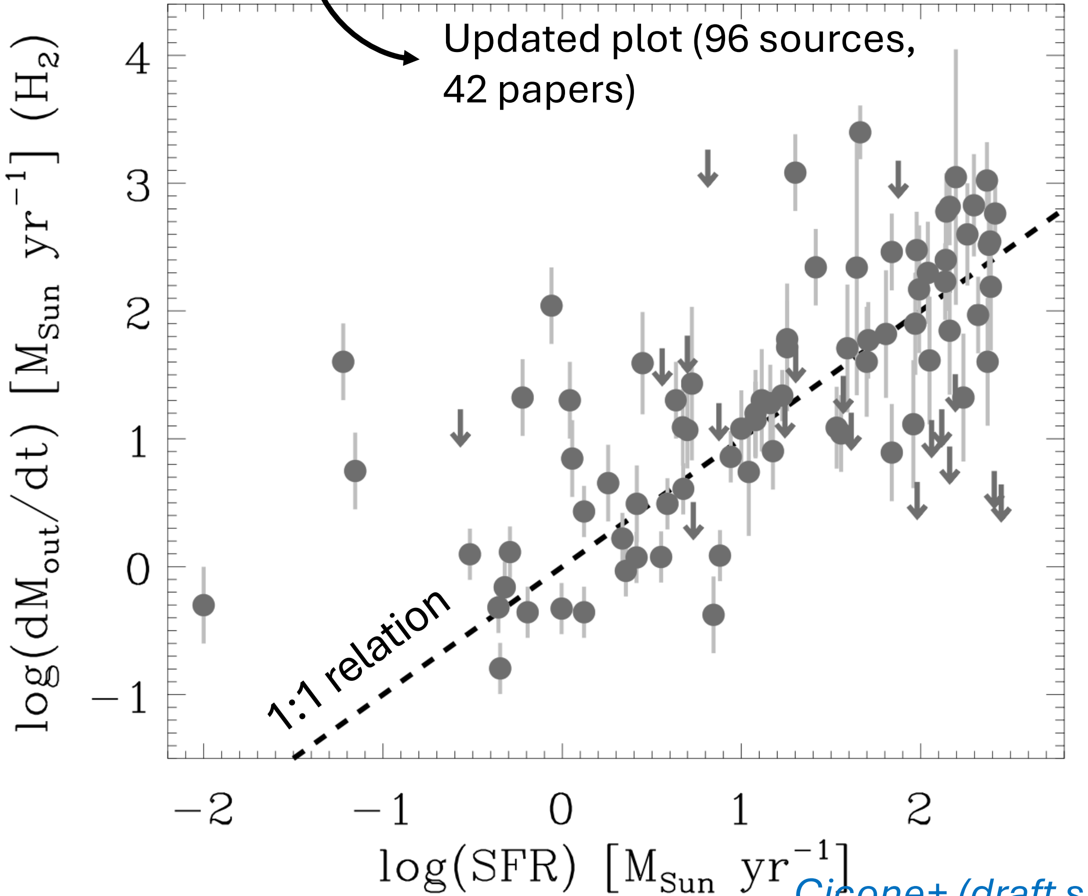
→ **quenching potential of molecular outflows in ULIRGs**

(See also **NGC6240: outflow mass ~1.2 x 10^{10} M_{sun}** *Cicone+18, Carlsen+26*)

>70% of z~0 ULIRGs hosts massive molecular outflows



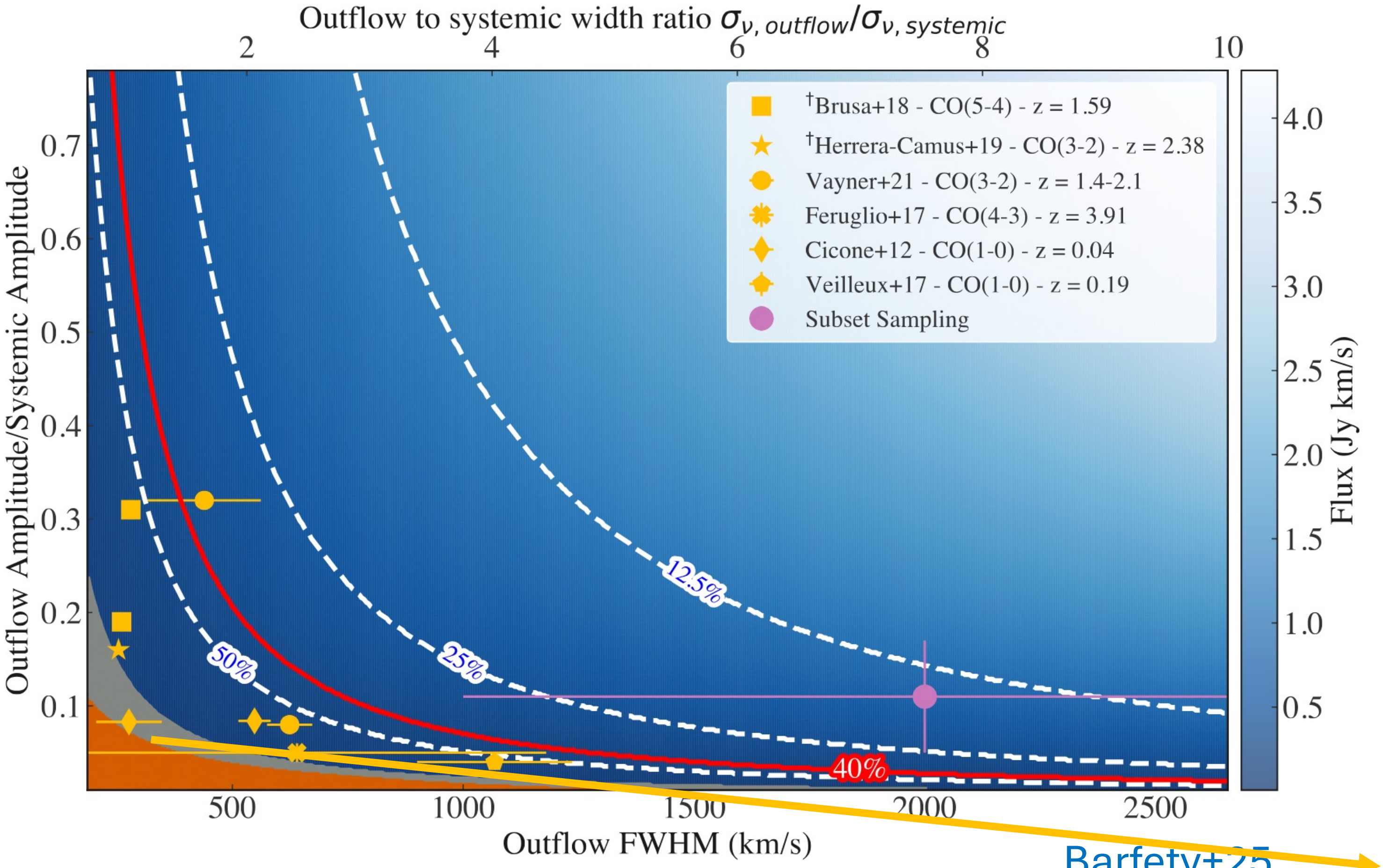
Cicone+14



Cicone+ (draft sitting in my laptop)

- Detection rate ~25% in main sequence galaxies *Stuber+21*, **>70% in ULIRGs** *Veilleux+13, Lamperti+22*
- Molecular gas dominates outflow mass *Cicone+14, +18, Fiore+17, Carniani+15, Hagedorn+26*
- With improved statistics, a scaling between outflow rates and SFR has clearly emerged, with few outliers above this relation: at low SFRs, low lum AGN with exceptions, e.g. NGC253; at high SFRs: AGN-dominated ULIRGs
- → **suspected link between most powerful massive molecular outflows and AGN feedback**

Molecular outflows at high z ?



Barfety+25

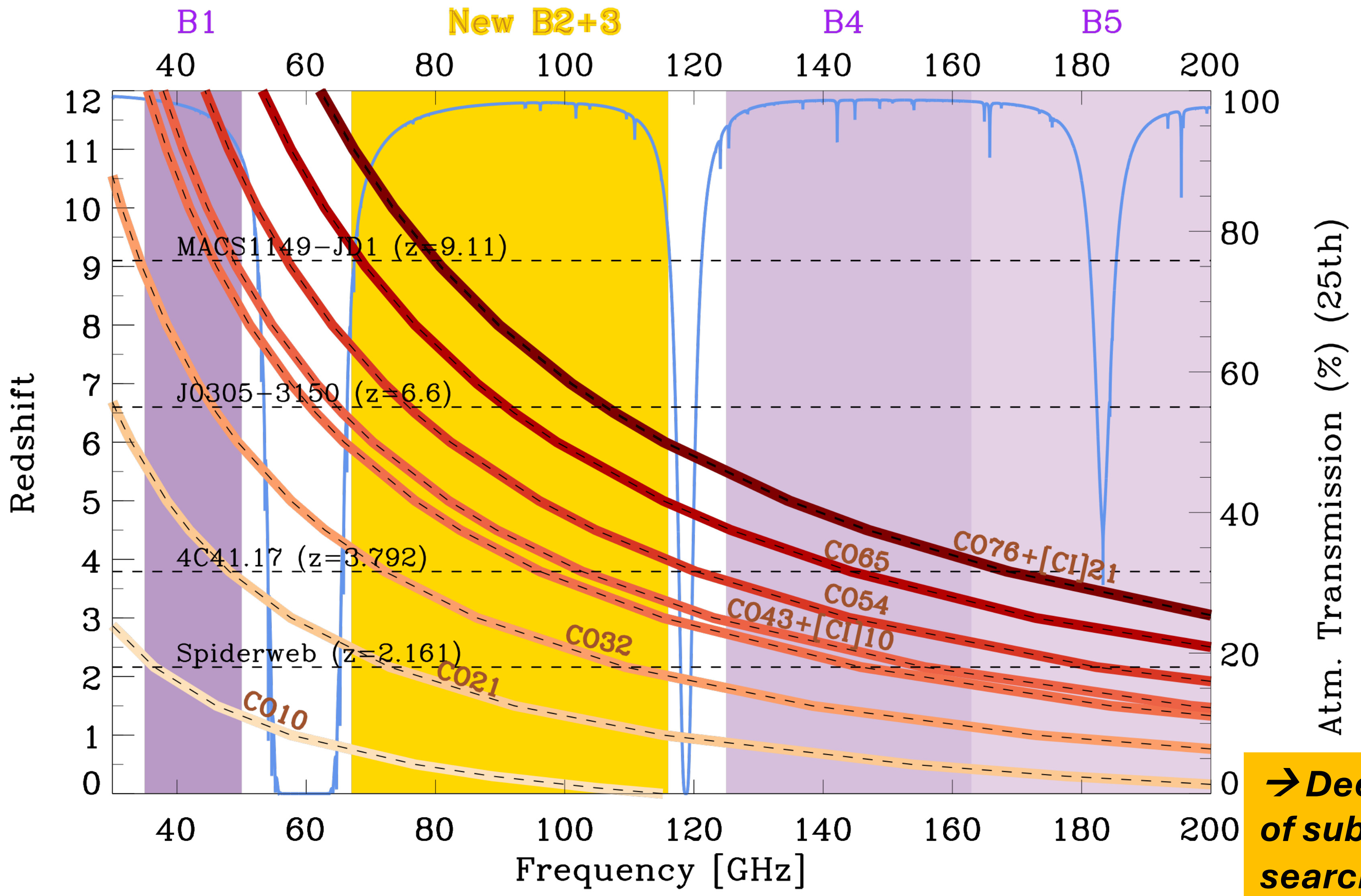
Stacking analysis, 154 galaxies with CO data at z (0.5, 2.6)
Subset (purple circle): stack of 40 galaxies with tentative outflow signature

- Only handful of detections based on CO *Feruglio+17, Brusa+18, Herrera Camus+19, Vayner+21*
- Stacking analyses struggle to find clear signal *Barfety+25, Langan+26*

Why?
- In integrated spectra, CO wings >10-20 times fainter than peak → **we need S/N>30-60!! No high-z CO observation reaches this high S/N**
- **Aperture effects and surface brightness sensitivity** play a role
- Sample selection: main sequence galaxies not best targets

This stacking exercise would miss even the (extreme!) outflow of Mrk231 (grey region is below noise)

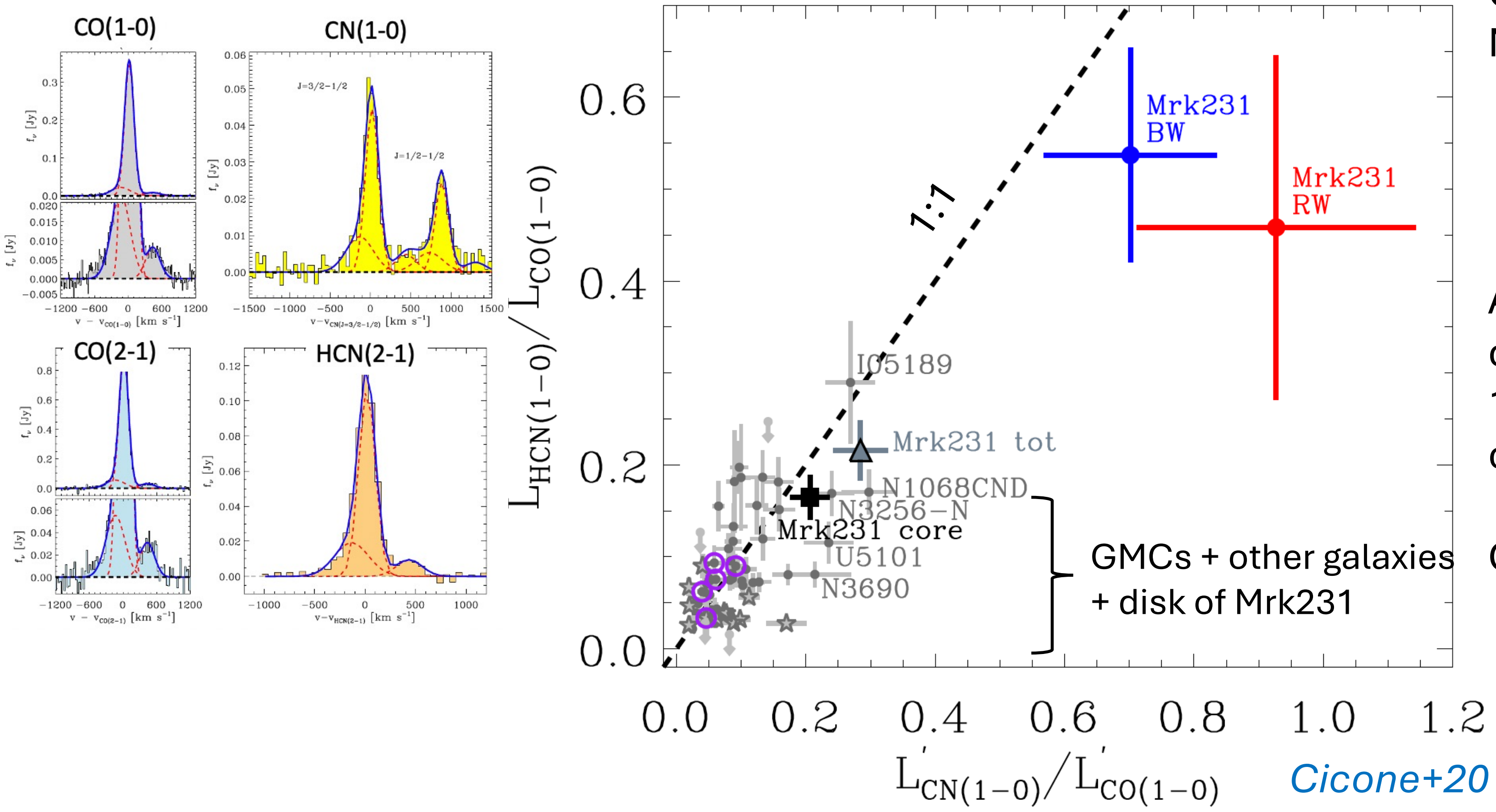
Science case I: *cold* molecular outflows out to z~2.5



- Low-J CO lines to trace ***cold phase of outflows***
- Band 2 (plus Band 1) **extends CO(1-0) and/or CO(2-1) coverage out to z=2.44**
- [CI]1-0 also available z~3.2 to 6.3 using Band 2: independent total H_2 mass tracer (e.g. *Papadopoulos+04,18*)

→Deep (S/N>50) CO2-1 observations of submm-selected galaxies at z~2 searching for molecular outflows

Puzzling enhancement of dense molecular gas tracers in (some) molecular outflows



CN/CO and HCN/CO ratios in Mrk231's outflow:

- x5 times higher than disk
- higher than any source known so far

Assuming CN and HCN from same cloud population (T_{kin} ~ 20 K and n_{H2} ~ $10^5 – 10^6$ cm^{-3}) → X_{CN} > X_{HCN} by a factor of 3 in the outflow

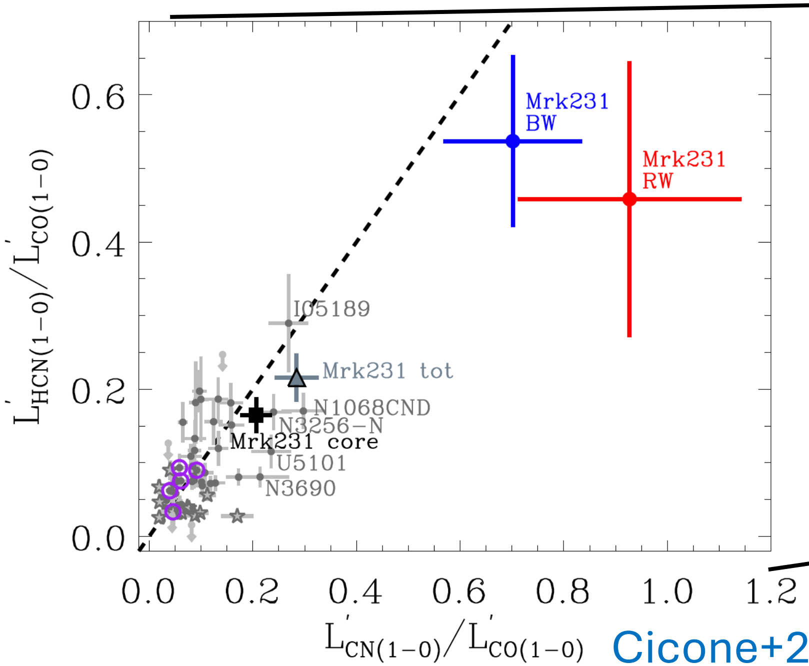
CN, HCN enhancement points to:

- (i) entrainment of dense gas clouds $n_{H2} \gtrsim 10^5$ cm^{-3}
- (ii) strong UV radiation affecting the chemistry e.g. young massive stars?

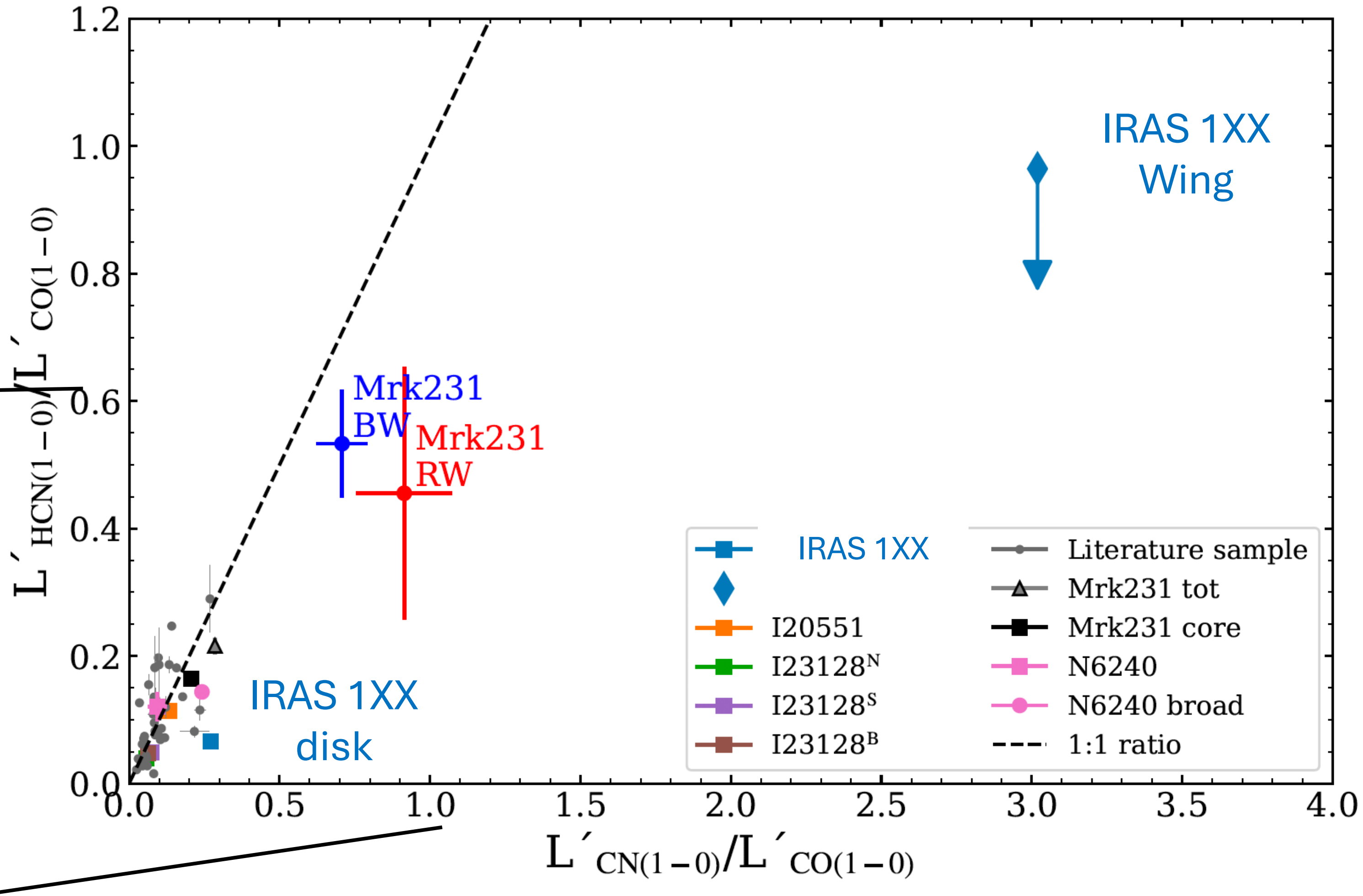
But not all massive molecular outflows are enhanced in dense tracers

Molecular outflows in Mrk231 and IRAS 1XX very CN-enhanced. Mrk231's outflow is also enhanced in HCN and – the red wing – in HCO^{+}1-0

NGC6240's outflow not enhanced in either HCN nor CN nor HCO+

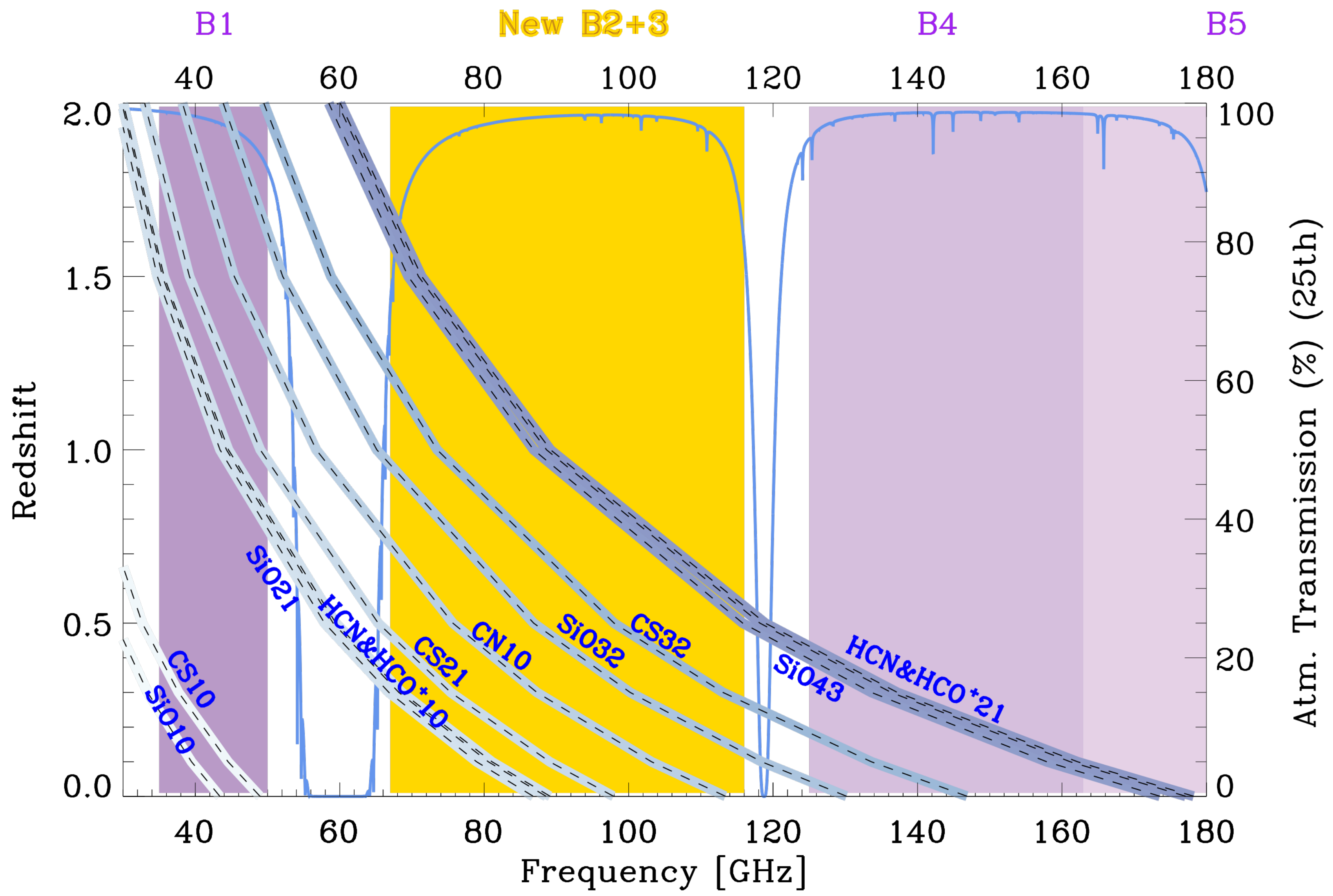


Cicone+20



Håvardslien, Cicone + in prep

Science case II: dense H_2 tracers in outflows

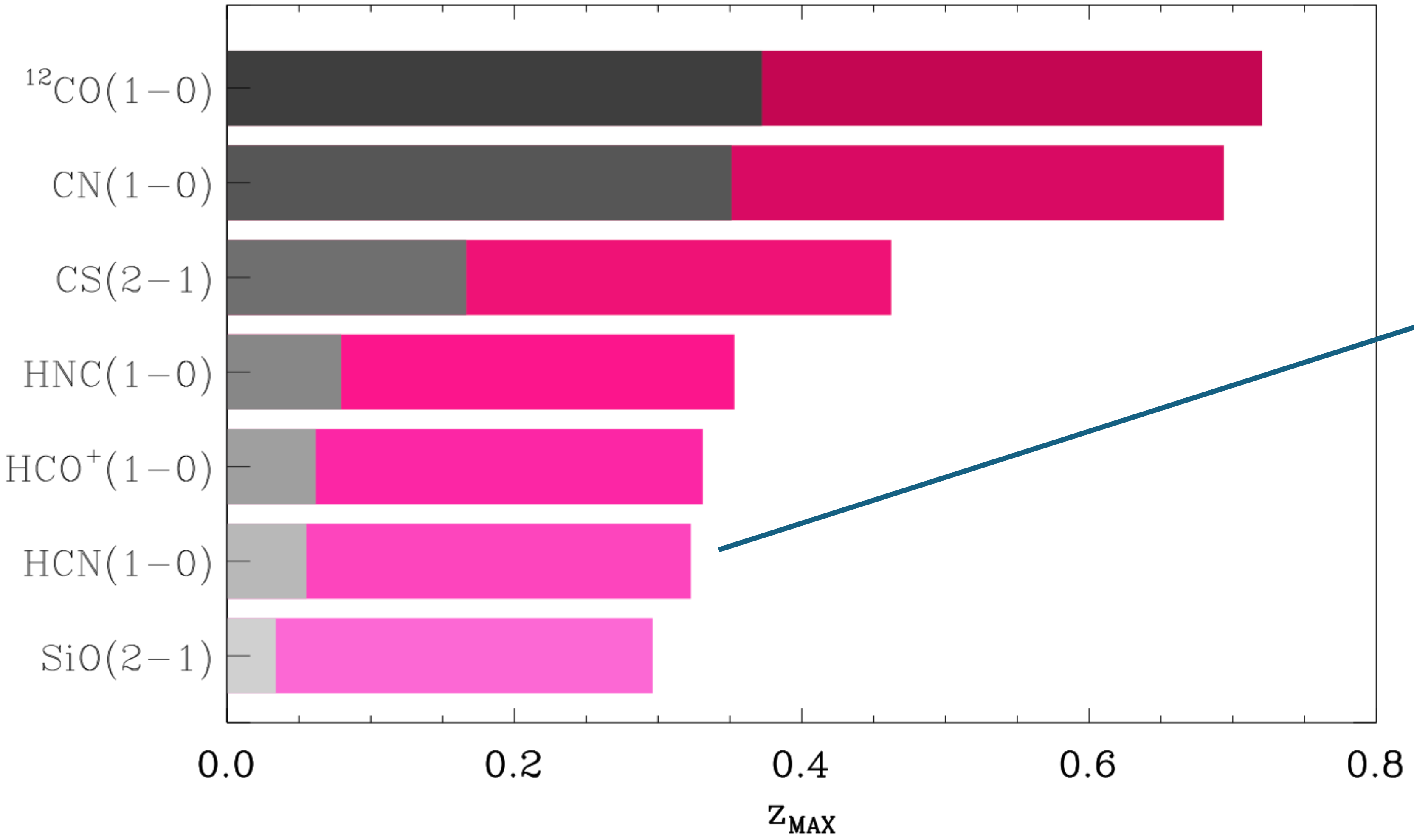


Band 2 can make a real difference for this science case

Main points:

1) Key high density tracers become observable to higher redshifts
2) Band 2 spectral coverage in WSU

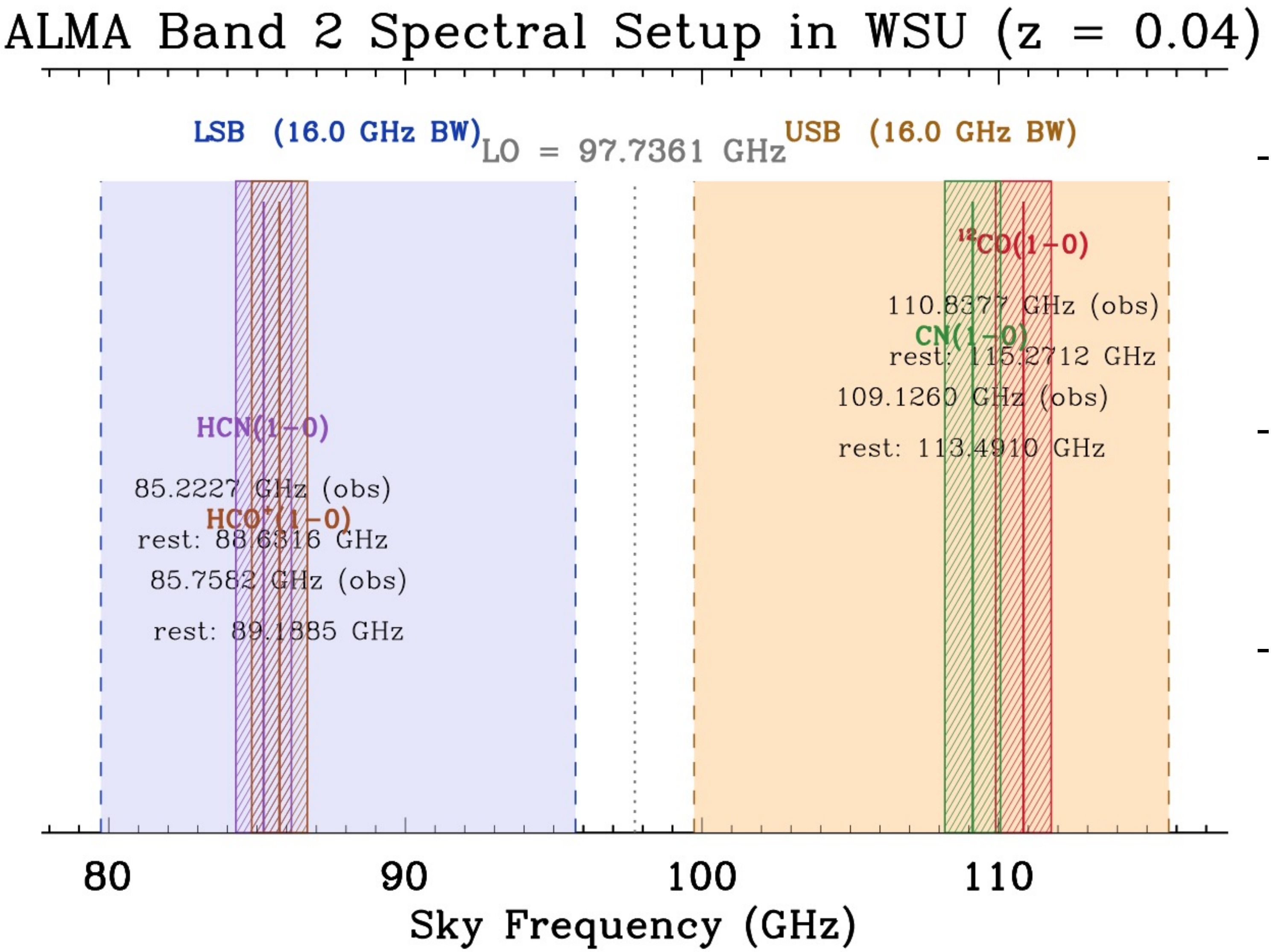
1) Key high density tracers become observable to higher redshifts



Enormous gain in statistics: allows to study how common CN- and HCN-boosted outflows are

HCN(1-0) z_{max} increases from 0.055 to 0.32 → **opens up a volume x160 larger** → increase in observable galaxies is ~ x 160 for normal massive galaxies and much higher **~ x300-x600 for IR bright galaxies**

2) Band 2 spectral coverage in WSU



- Detecting faint line wings in external galaxies is time consuming → >10x fainter than line peak → **needs total S/N>50**

- Ability to **target simultaneously 4 lines across Band 2 and Band 3 ranges** will cut the total observing time by >50%

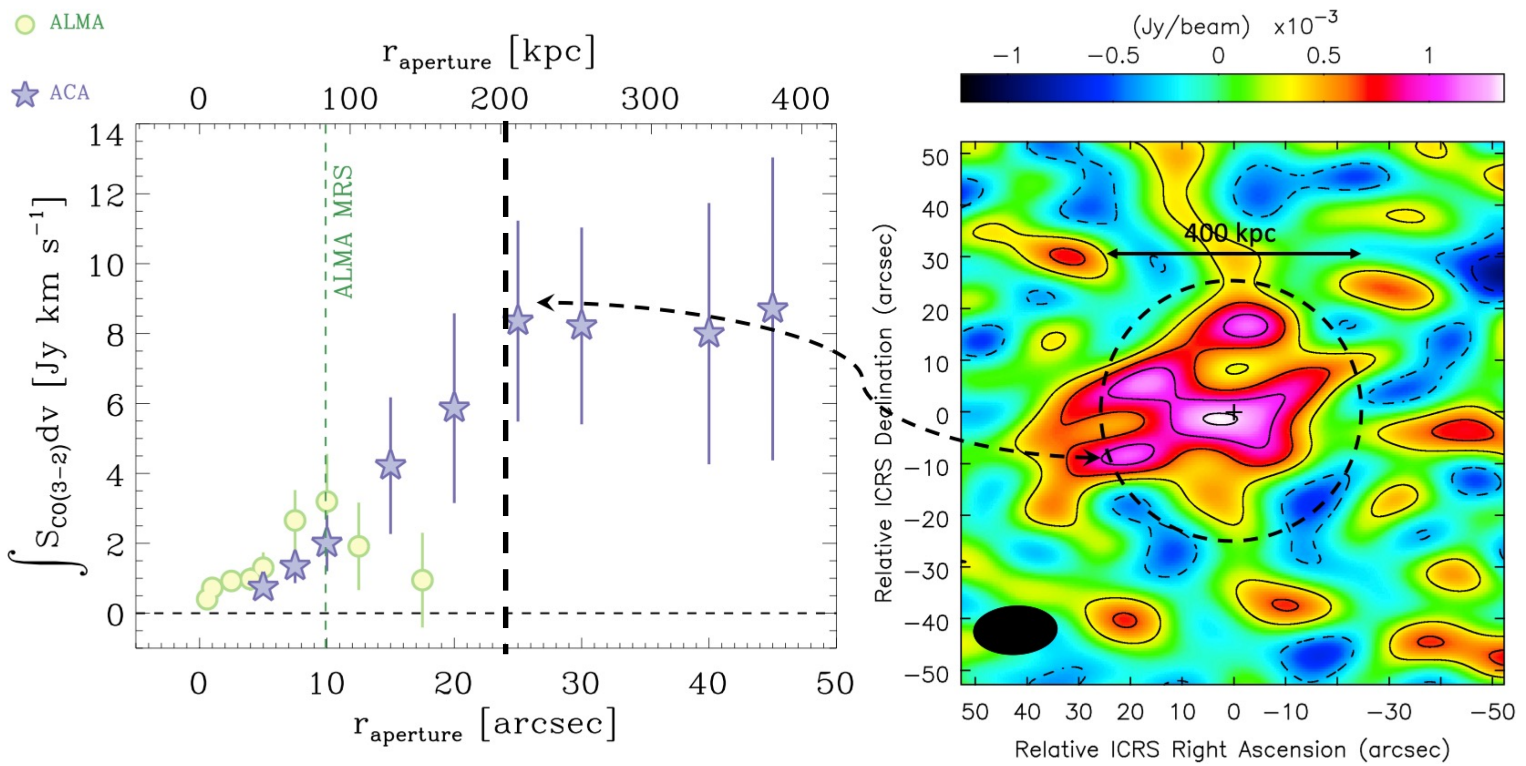
- Spectral setup example shows simultaneous observation of **^{12}CO(1-0), CN(1-0), HCN(1-0) and HCO+(1-0)** in a galaxy at z=0.04, assumes WSU capabilities (>2030)

Growing # of observations of cold CGM at z>2

CGM sensitive to feeding and feedback in galaxies: enriched by tidal debris, outflows, and cosmic inflows but ***elusive to observations*** due to large area, low surface brightness, and multiphase (HII, HI and H_2)

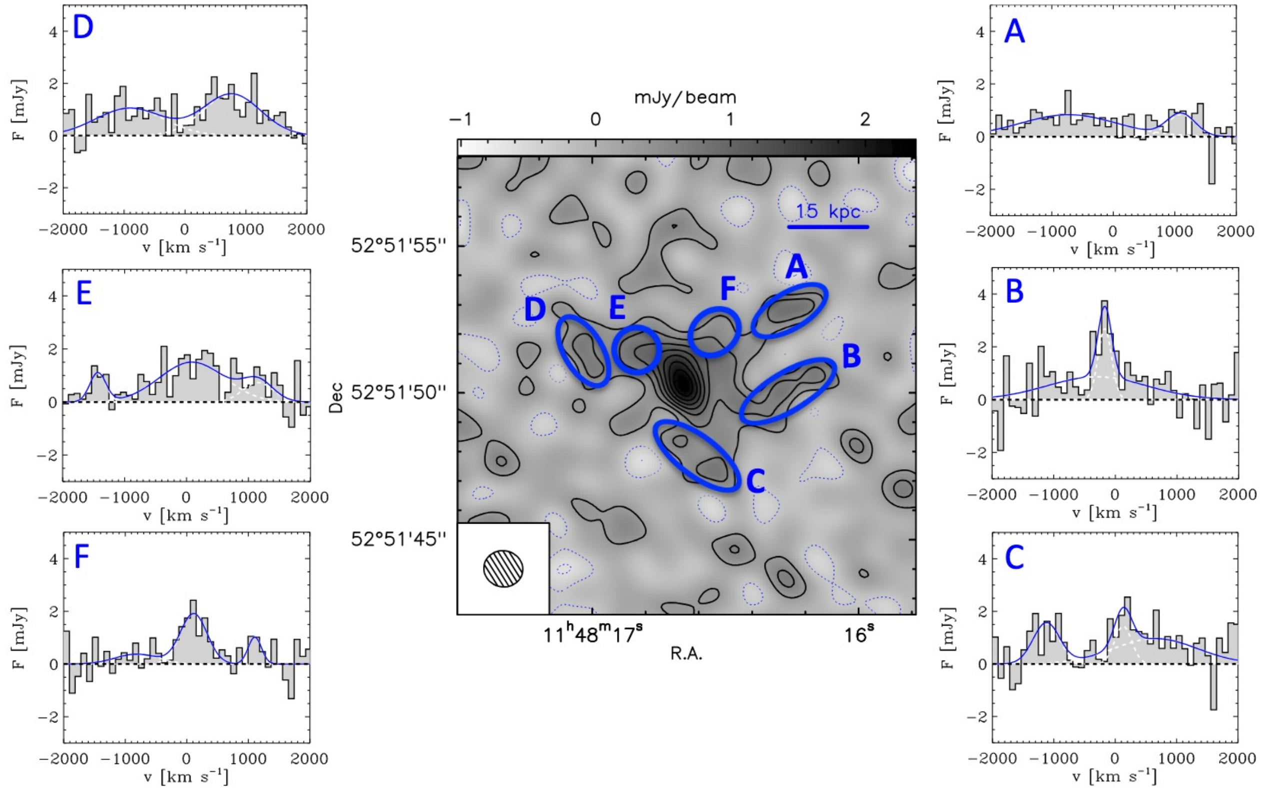
- Molecular + atomic CGM detections: mix of true halo gas and unresolved satellites
  - ~10-15 kpc haloes (individual targets) *Cicone+15, Meyer+22, Fujimoto+19,20,22, Ginolfi+20, Fudamoto+22, Akins+22, Jones+23*
  - >~50 kpc haloes and streams (mostly known over-densities) *Emonts+16,18, 23, Li+21,23,25, Ginolfi+17, Cicone+21, Sulzenauer+26*
- Small beam of ALMA is a problem for CGM studies: S/N ∝ $(d_{CGM}/d_{beam})^{-2}$ → ***mitigated at low frequencies (Band 2) and at z~1-2***

see *Lee, Schimek, Cicone+25* for a review

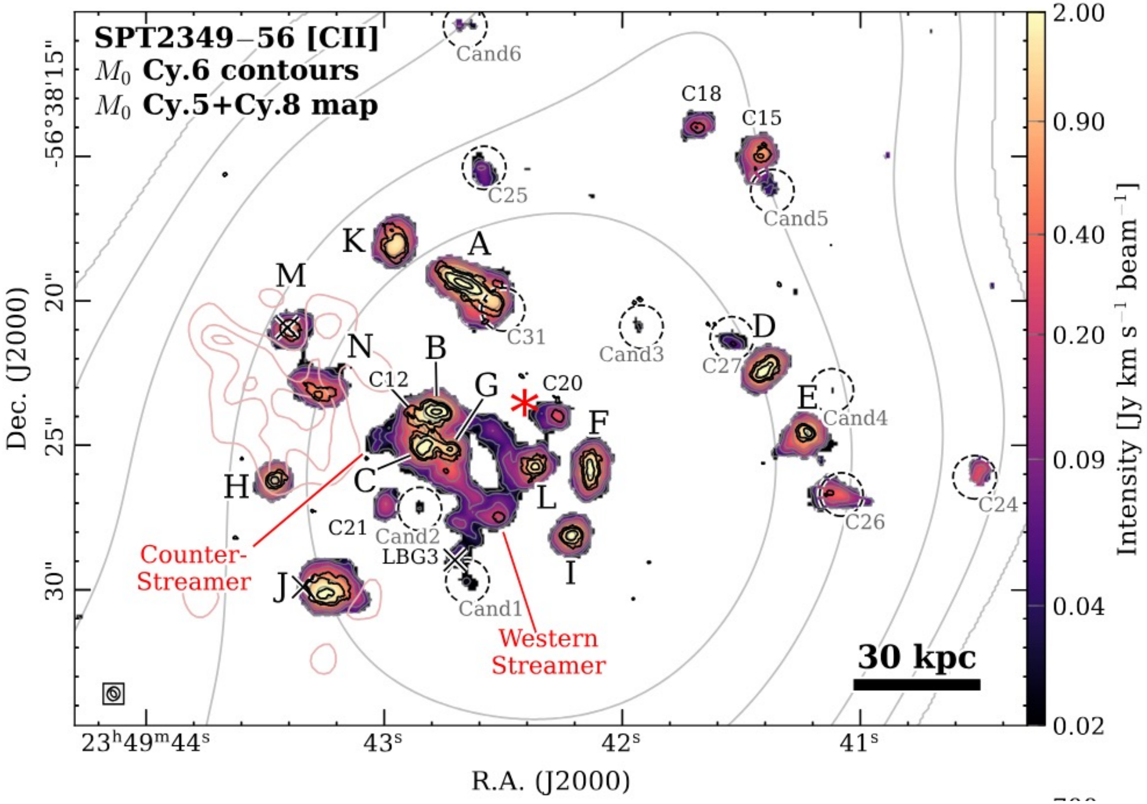


Cicone+21

Most cold CGM observations use "ambiguous" [CII]



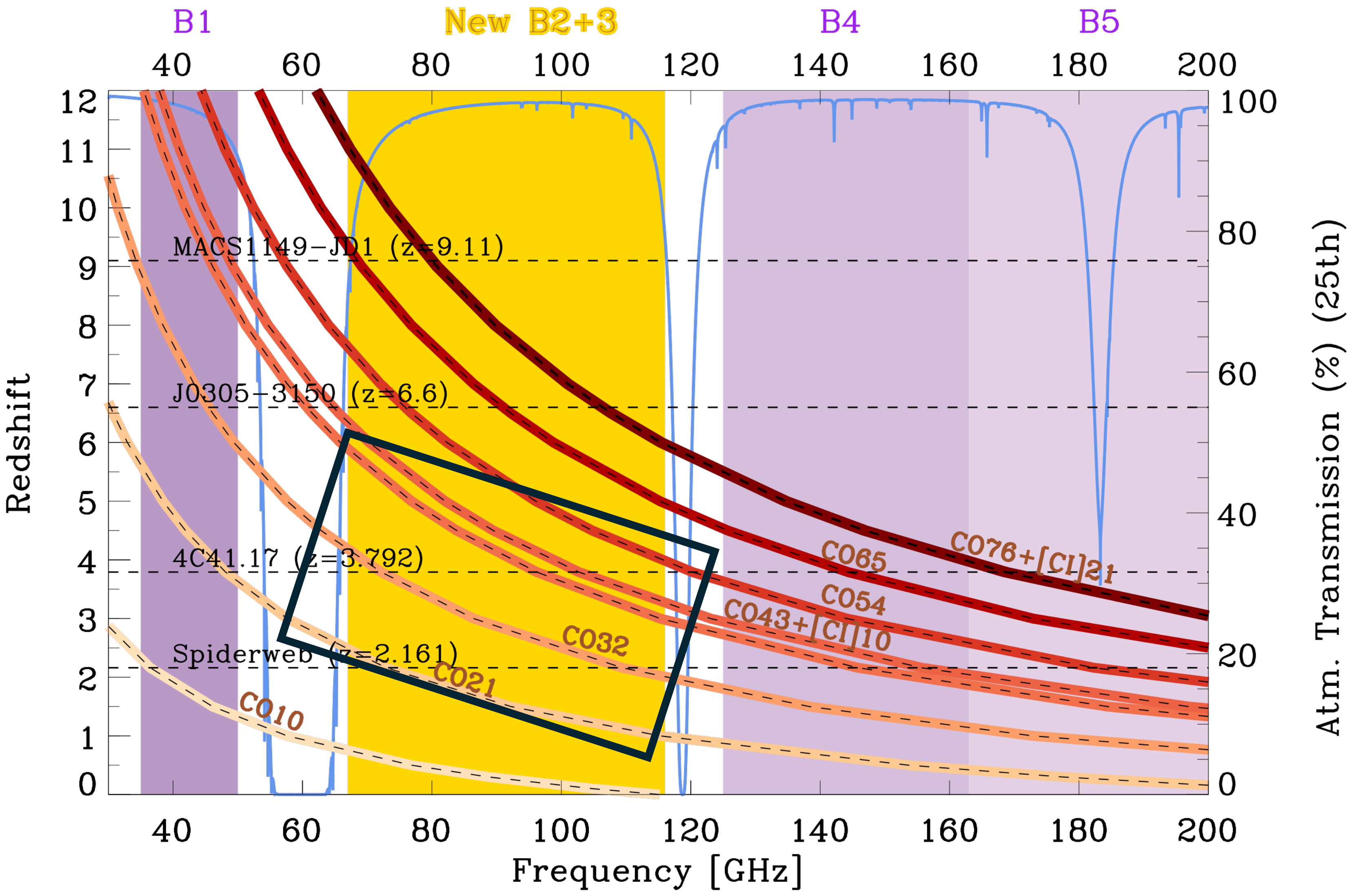
Cicone+15 [CII] halo (outflow + quiescent gas) at z = 6.4



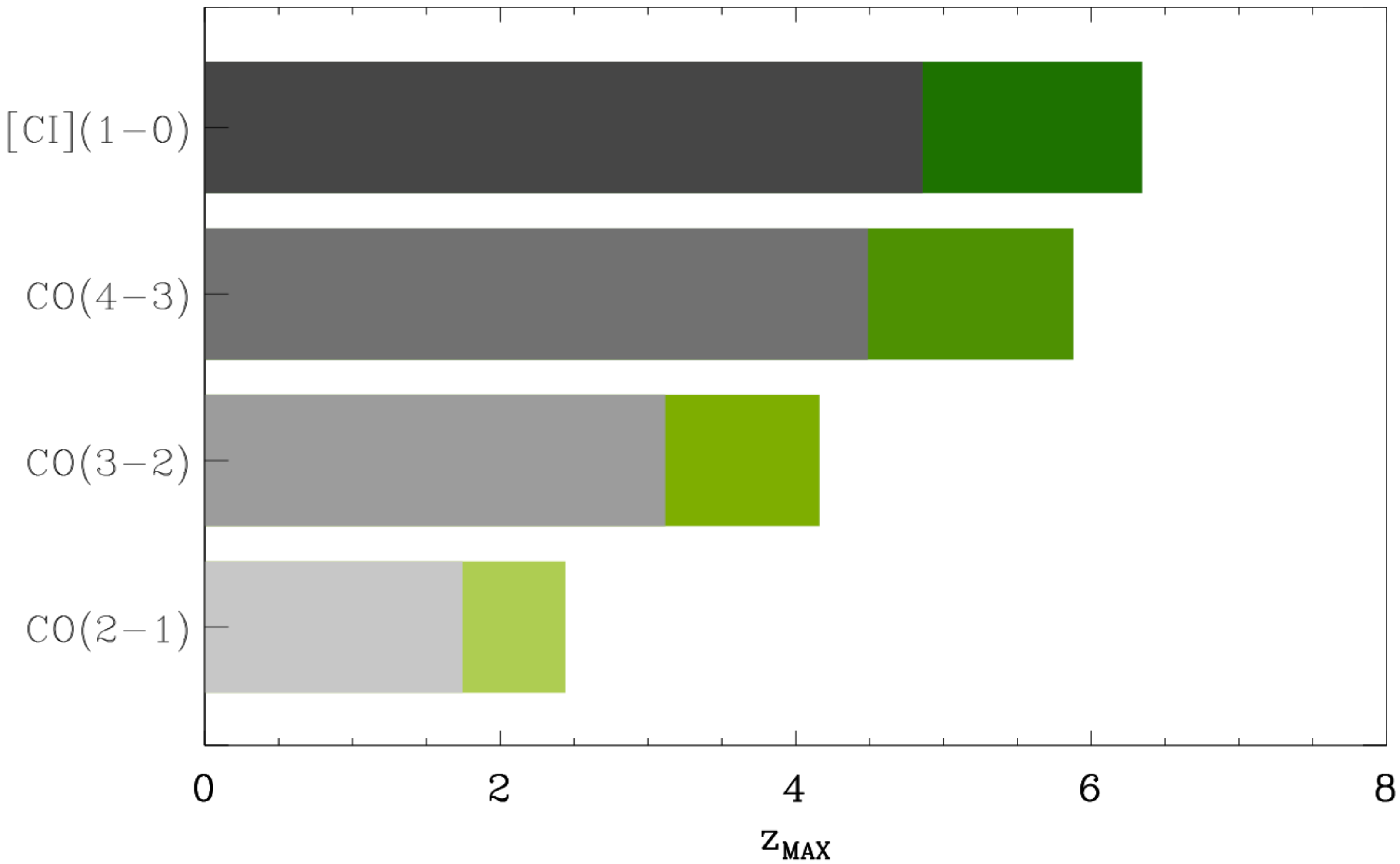
Sulzenauer+26 [CII] streamers and CGM at z = 4.3

- [CII] haloes/streamers in CGM of high-z galaxies likely trace shocked molecular gas (not PDRs)
- **Need more accurate H_2 measurements → low-J CO lines and [CI] lines**

Science Case III: cold haloes at Cosmic Noon



More tracers available for measuring cold CGM mass at high-z

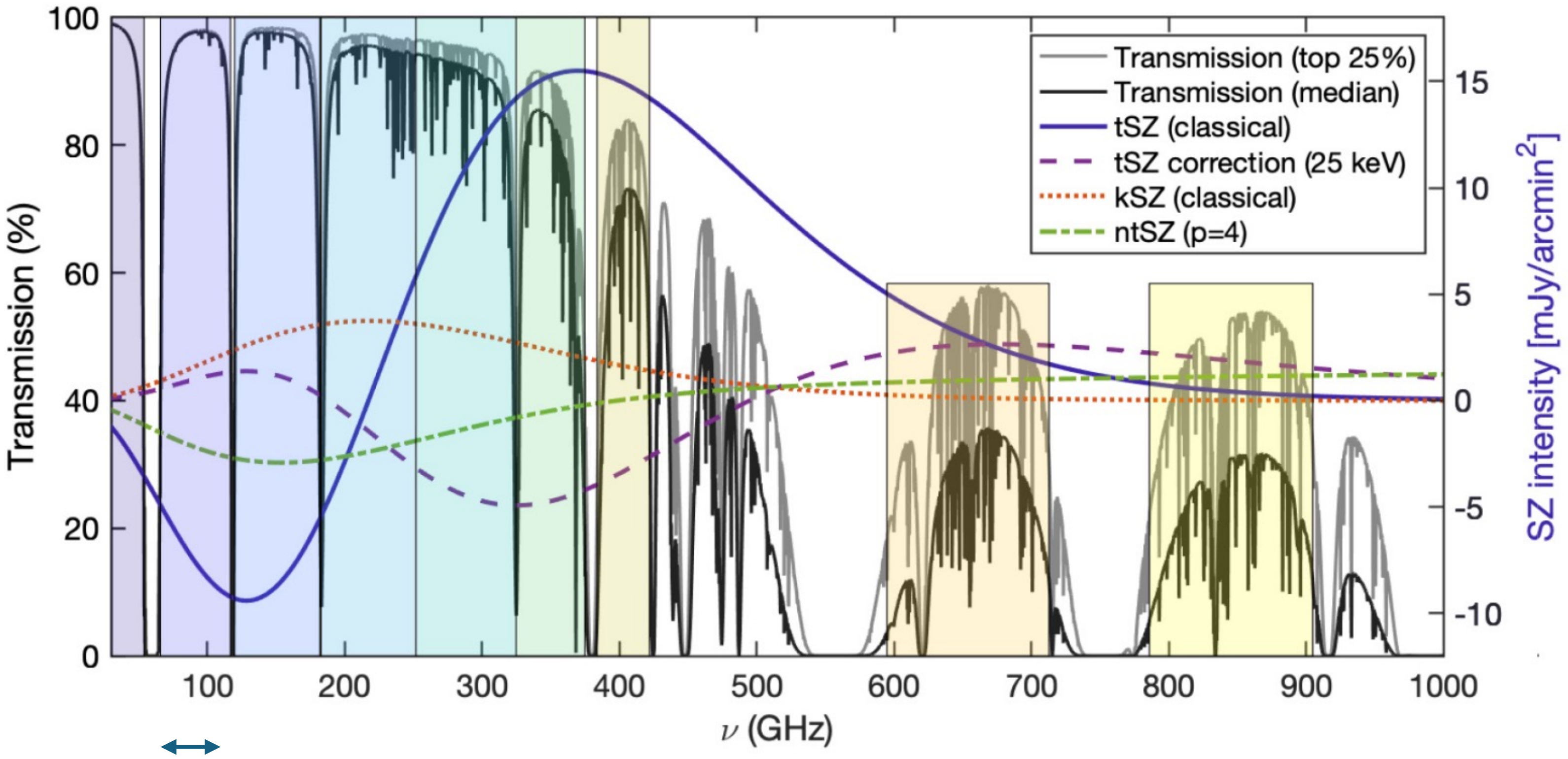


New Band 2 opens up (with respect to old Band 3):

- CO(2-1) at z~2
- CO(3-2) at z~3-4
- CO(4-3) and [CI](1-0) at z~4-6

→ The latter is a key redshift range so far accessible mainly through *ambiguous* [CII] line

Probe hot CGM phase through the SZ effect



Band 2

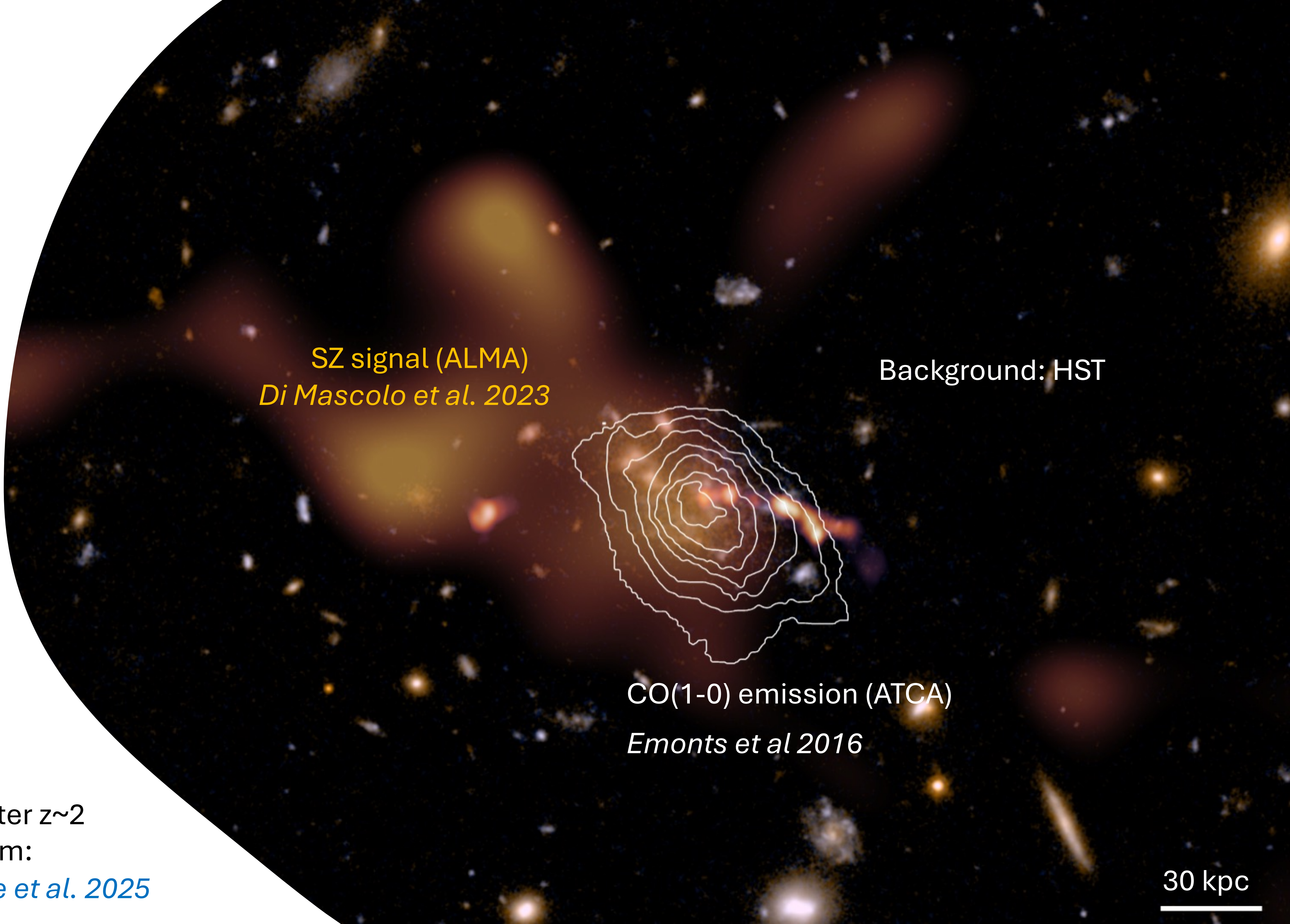
Di Mascolo+25 and refs therein

- Warm/hot ionized phase ($T>10^5$ K) of CGM can be detected through the Sunyaev-Zeldovich (SZ) effect
- → **important for AGN feedback**

- Band 2 SZ sensitivity is better (than e.g. Band 1 or 3) thanks to increased IF bandwidth

- **Synergies:** Band 2 allows **data combination** with existing (SRT, GBT) and future (AtLAST) facilities

Obtaining the cold and hot CGM at once



Spiderweb protocluster z~2
Composite image from:
Lee, Schimek, Cicone et al. 2025

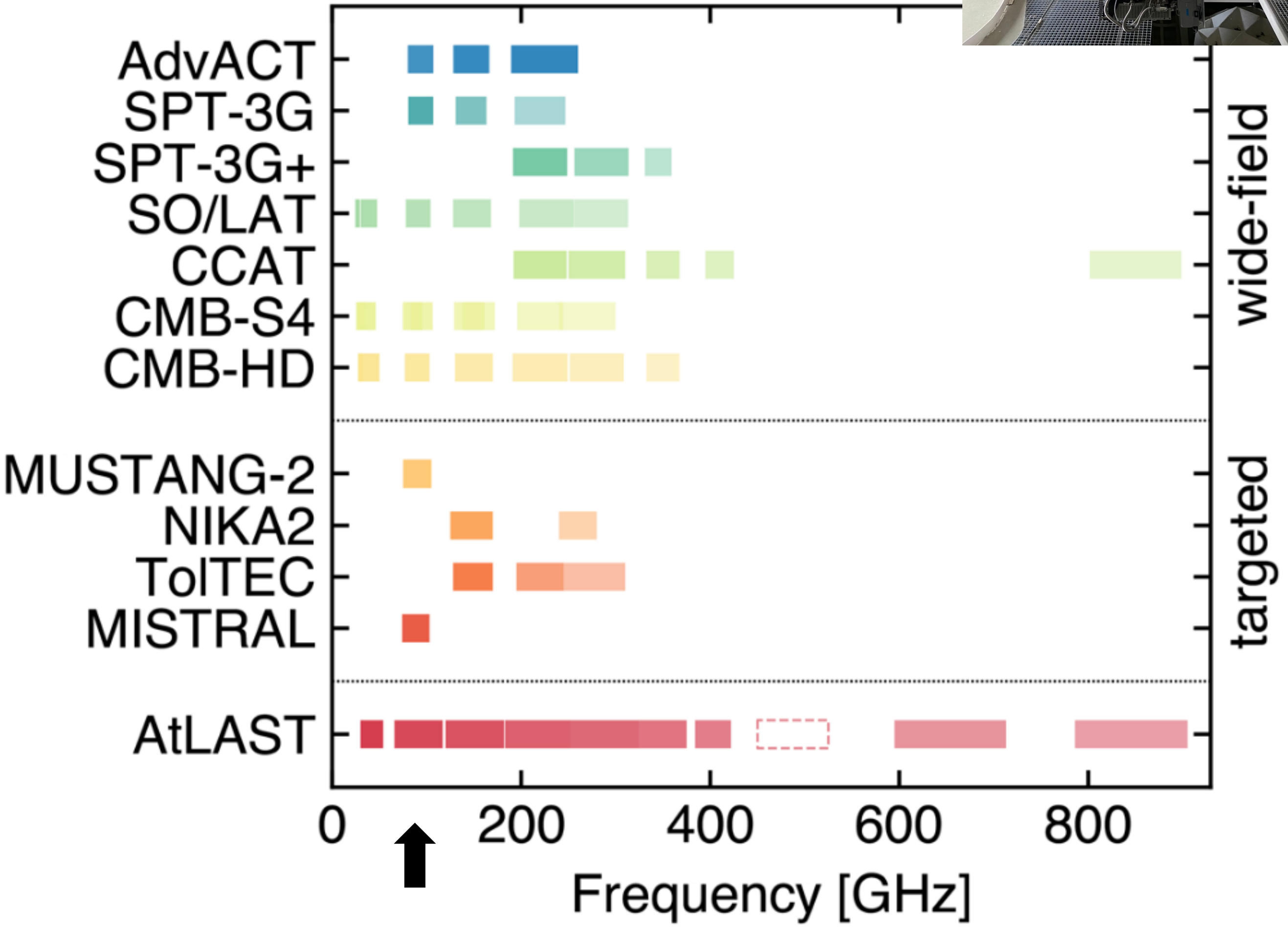
Synergies

- **ALMA Band 1 (current):** Band 2 + Band 1 provide CO(1-0) + CO(2-1) coverage out to z~2.3
- **Single dishes (current): MISTRAL at SRT**, MUSTANG-2 at GBT, **N3AR at APEX** (new 3mm receiver at APEX: 67-116 GHz)

- **AtLAST (future):**
  - Unbiased surveys with AtLAST will unlock positions of million of galaxies for ALMA follow-ups → Band 2 optimal for large FoV
  - **AtLAST+ALMA data combination**, recovery of large-scale flux → important for CGM (both line and SZ)

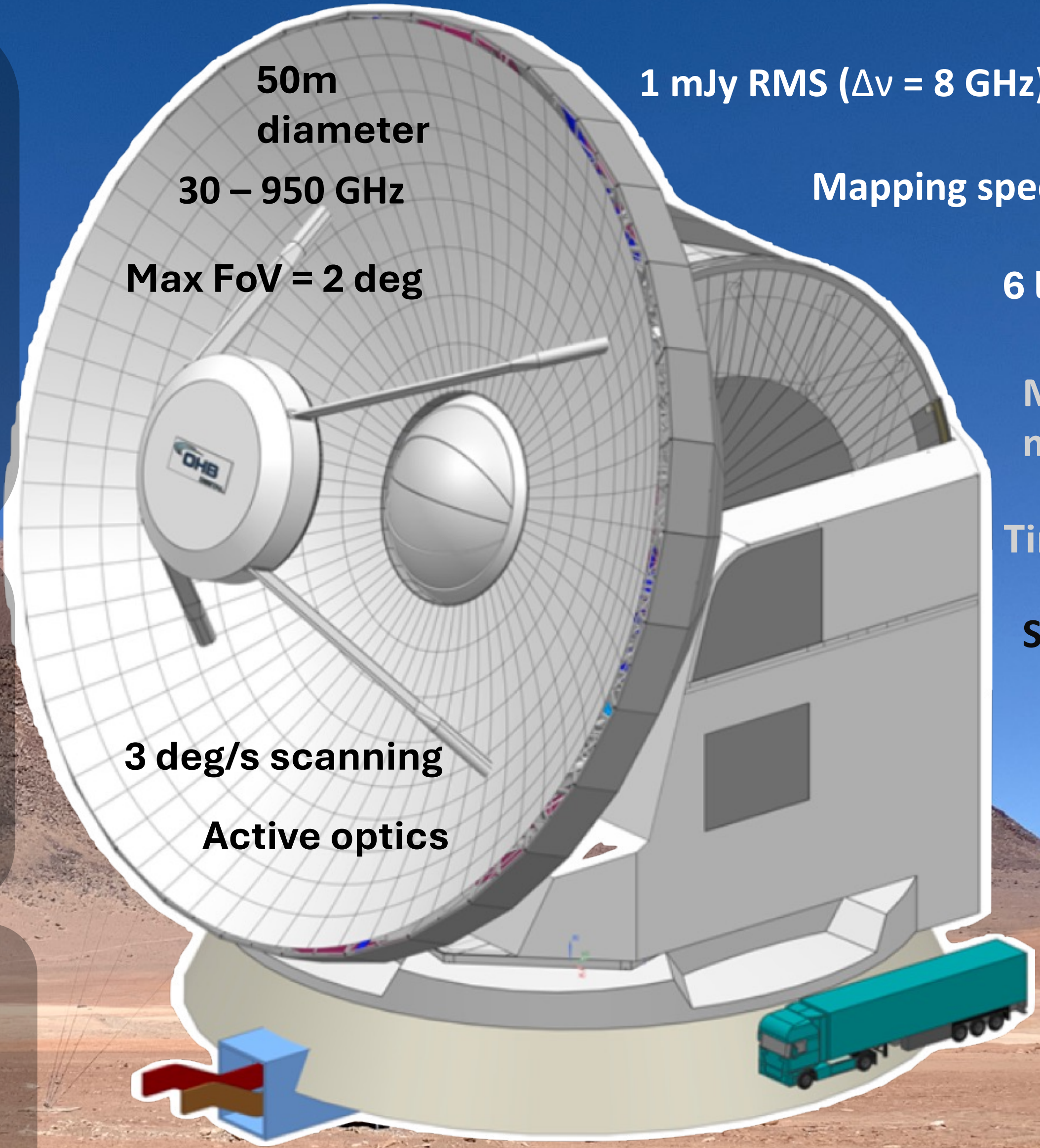
MISTRAL at 64-m SRT
90 GHz, FoV 4', 12" res
Barbavara+24

Plot tailored to SZ studies, from *Di Mascolo+25*



The Atacama Large Aperture Submm Telescope (AtLAST)

- ✓ First high-res (< 2" at ν > 650 GHz) and wide-field (> 1 deg) single-dish submm observatory
- ✓ Pioneering sustainable astronomy: tailored off-grid renewable energy system
- ✓ Global effort building upon European and Japanese submm expertise
- ✓ A facility for >30 yr, committed to open science



1 mJy RMS (Δν = 8 GHz) @ 350 GHz in < 8 s

Mapping speed 10^3 - 10^5 x ALMA

6 large instrument cabins

Multi (>10^5)- beam & multi-band receivers

Time domain science

Solar observations

Continuum & line polarization

MILKY WAY, GALAXIES, AND COSMOLOGY

- Link sub-pc protostellar cores & disks with their large-scale environment in our Galaxy
- Resolve the cosmic infrared background
- SDSS-like submm surveys of the local Universe
- Map elusive gas flows and cosmic web filaments

CROSS-FIELDS

- Discover transient & time-varying submm sky
- Solve missing flux issue of interferometers

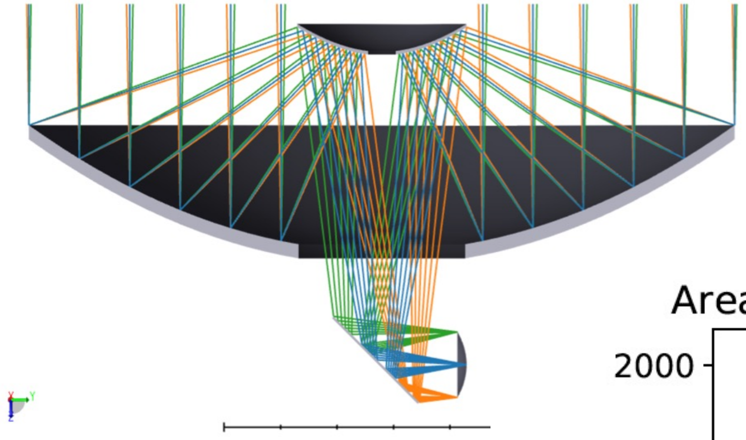
SOLAR SYSTEM

- Track solar activity driving space weather
- Survey HDO & D_2O in comets

Find out more: atlast-telescope.org

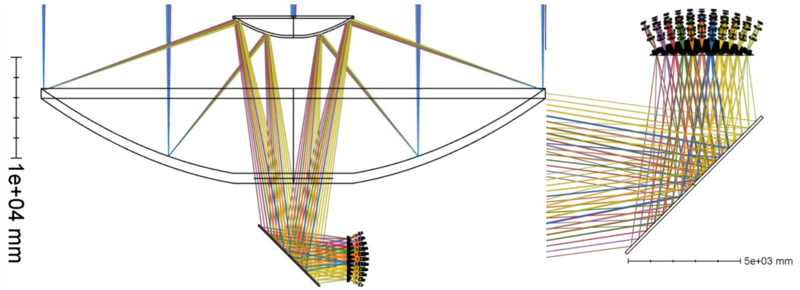
Funded by the European Union

At λ=4mm AtLAST achieves diffraction-limited performance over full 2 deg FoV

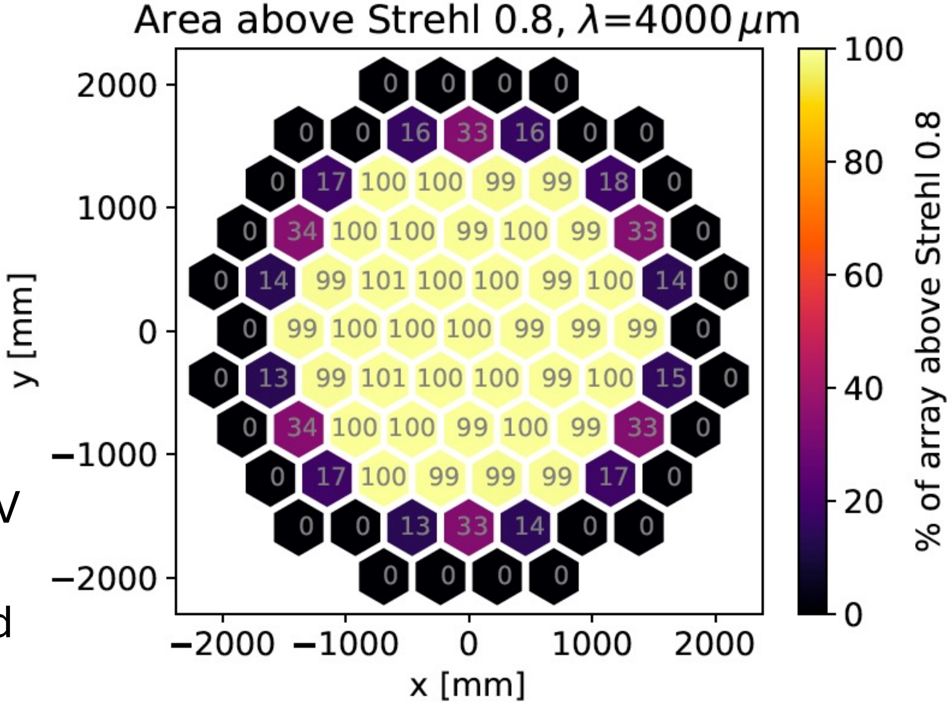


Gallardo+24, SPIE

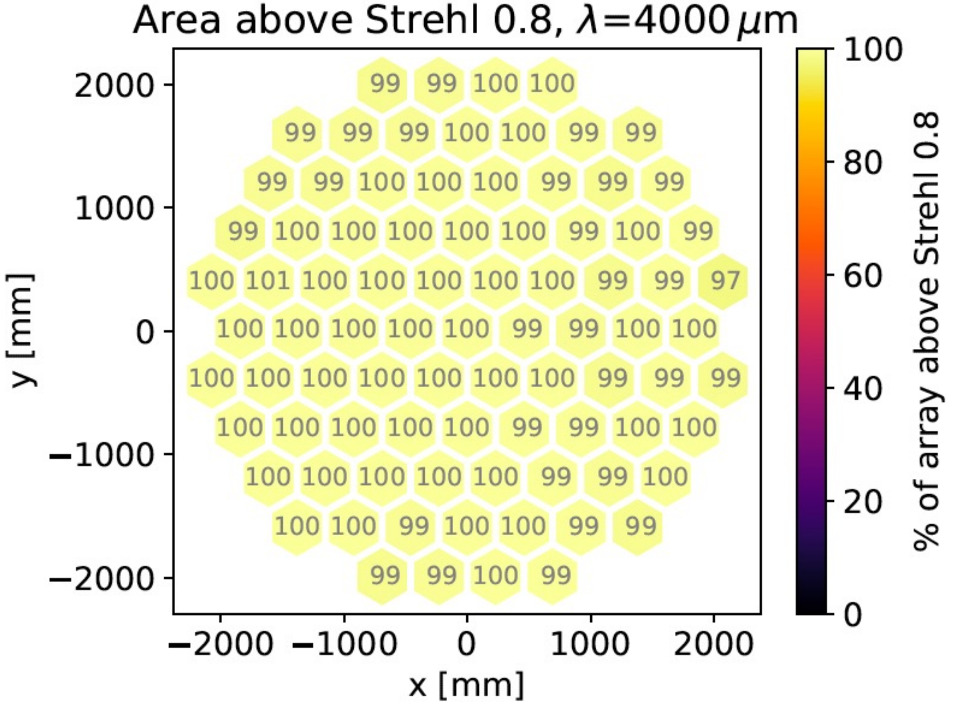
85 cameras concept for AtLAST that makes use of a biconic lense to correct for dominant optical aberration in the two-mirror telescope



At wavelength of 4mm or higher (freq < 75 GHz), the full 2 deg FoV of AtLAST can be used with diffraction-limited performance



Radially simmetric second lens



3-lens system with a biconic second lens

Conclusions

- Models of galaxy formation and evolution make heavy use of negative feedback prescriptions that are not backed up by real observations
- JWST results point to strong negative feedback at work at early times → crucial to observe massive outflows at z>2
- Massive molecular outflows in local ULIRGs are a promising negative feedback mechanism
- Too few molecular outflows at high-z can be explained by inadequate S/N and coverage

- *Science case I*: Band 2 (+1) enable studies of molecular outflows at z~2 with CO1-0 and CO2-1 → trace cold phase of outflows, better mass estimates. Also {CI]1-0 at z~3-6
- *Science case II*: Band 2 can make a difference for understanding enhancement of high density tracers (CN, HCN) in some molecular outflows, by opening x160 larger volume and enabling more efficient observations in WSU (4 key transitions observable at once)
- *Science case III*: cold CGM at high-z: CO2-1 at z~2, CO3-2 at z~3-4, CO4-3 and [CI] at z~4-6, also hot CGM observations through SZ become more efficient

Main Synergies: ALMA Band 1, MISTRAL/SRT, and AtLAST