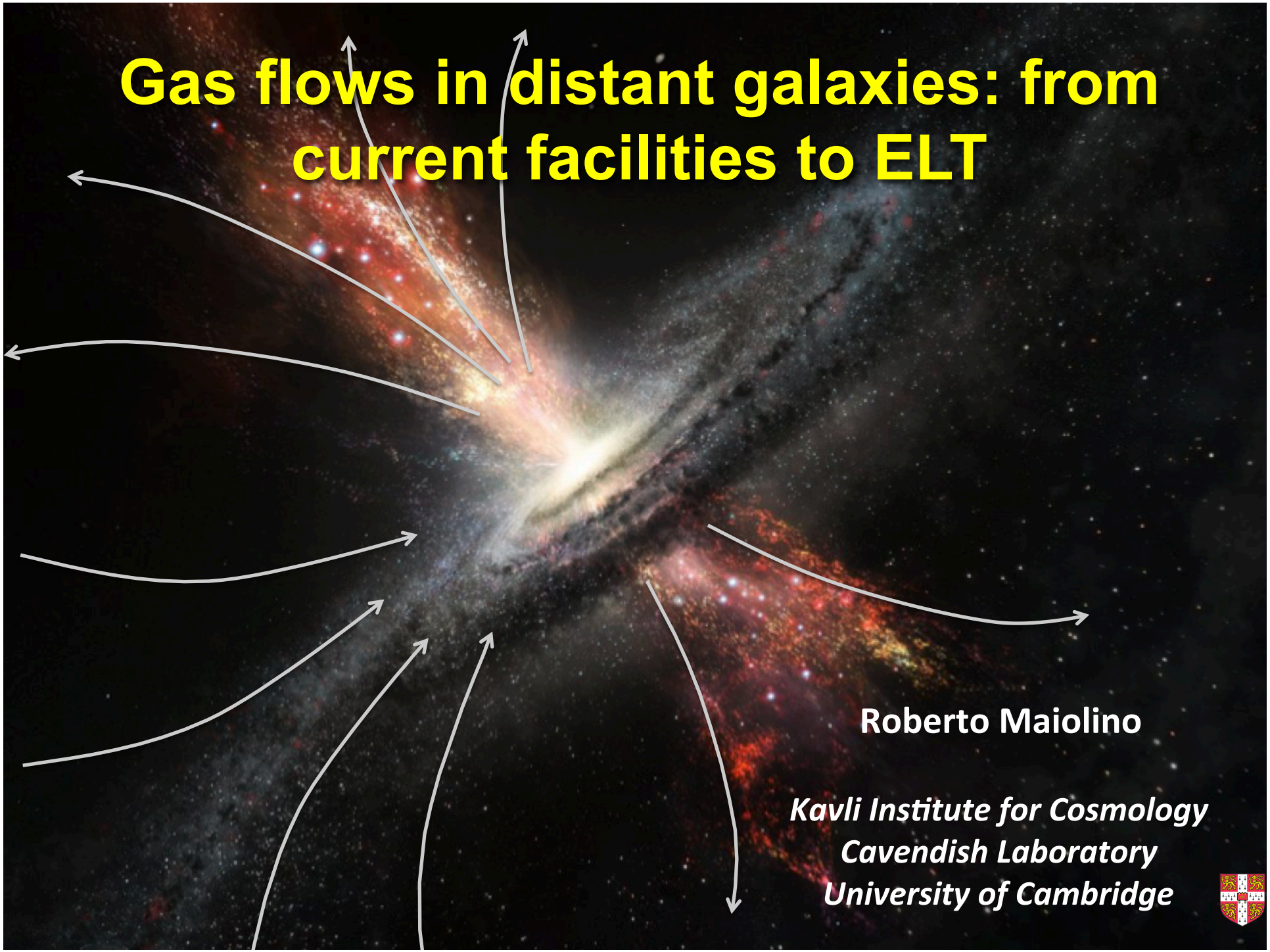
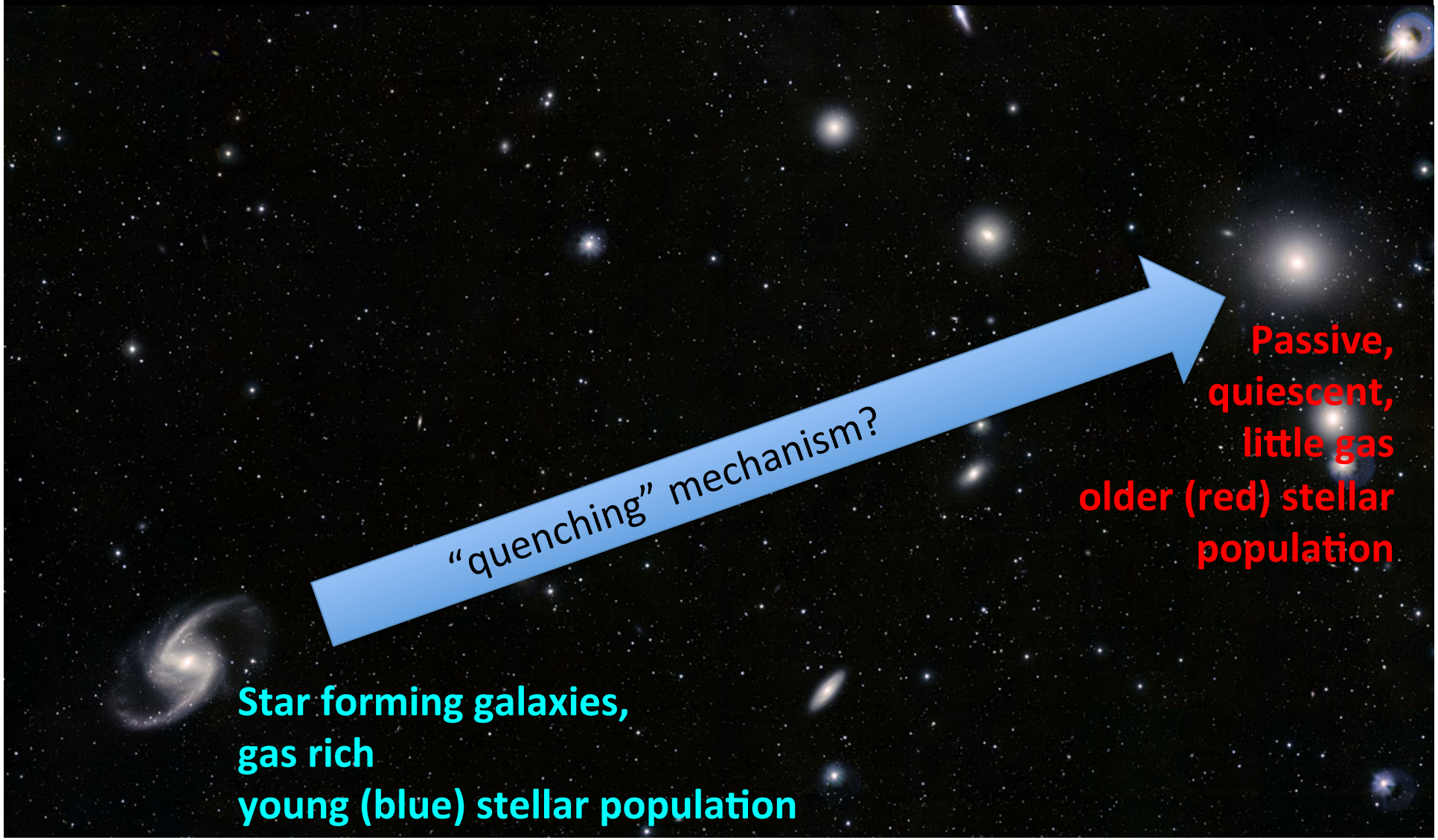
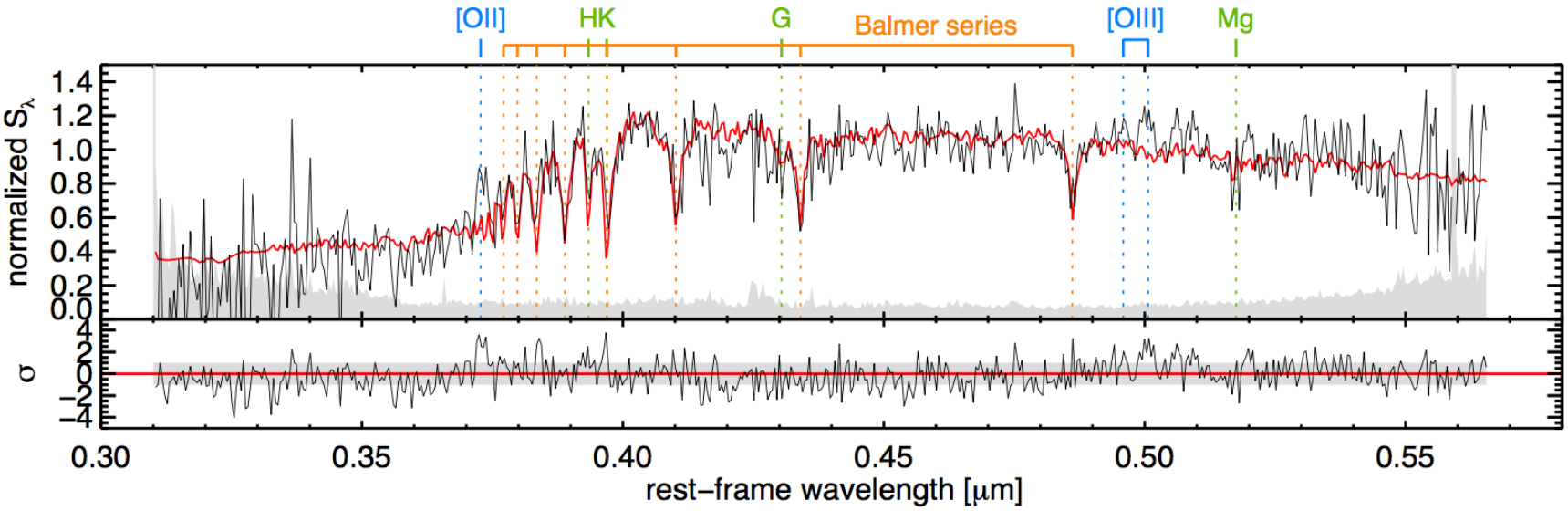

Gas flows in distant galaxies: from current facilities to ELT
Roberto Maiolino
Kavli Institute for Cosmology
Cavendish Laboratory
University of Cambridge

What is the role of galaxy flows in quenching star formation in galaxies?



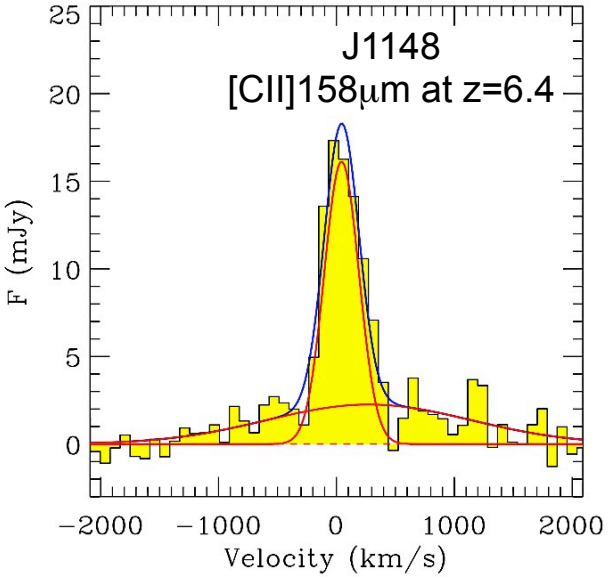
Passive old galaxies already in place by z~2-3, possibly even by z~4-5

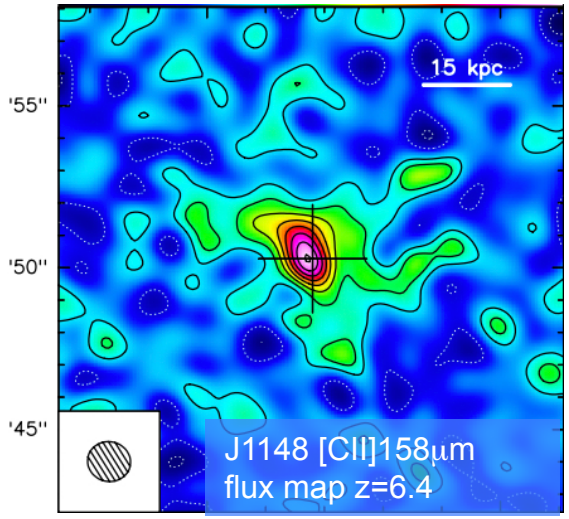


Schraber+18, Straatmen+14, Morishita+19, Cimatti+04, Saracco+04, Whitaker+13, Glazebrok+17, Santini+19, Merlin+18

Requires quenching at z>6

Quasar-driven outflows *invoked* to clean galaxies at high-z
Massive quasar-driven cold outflows *observed* at high -z





Individual quasars and stacks at z~6

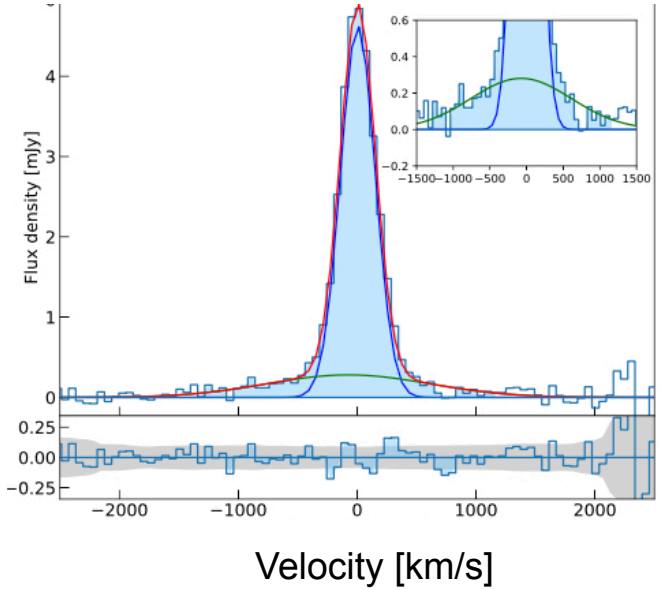
several kpc-scale outflows

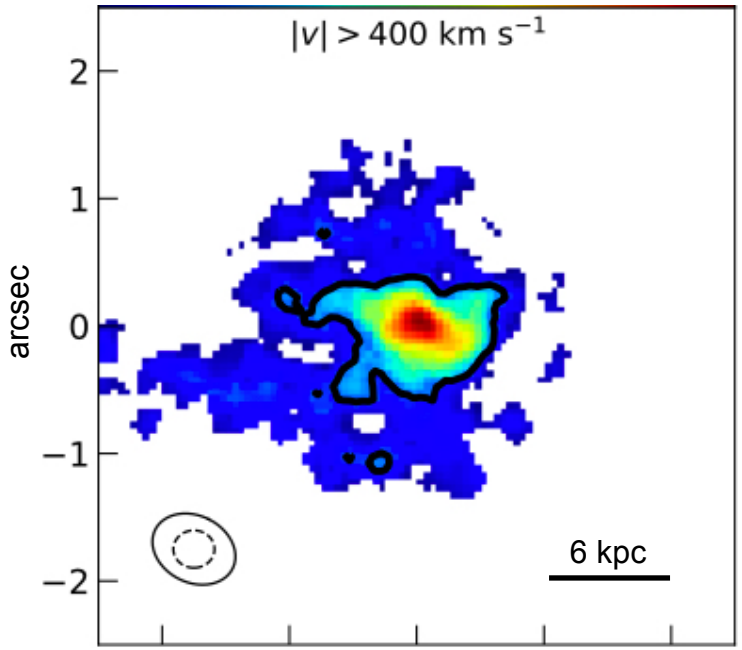
Outflow rates:

100's – 1000 $M_\odot$ yr^{-1}

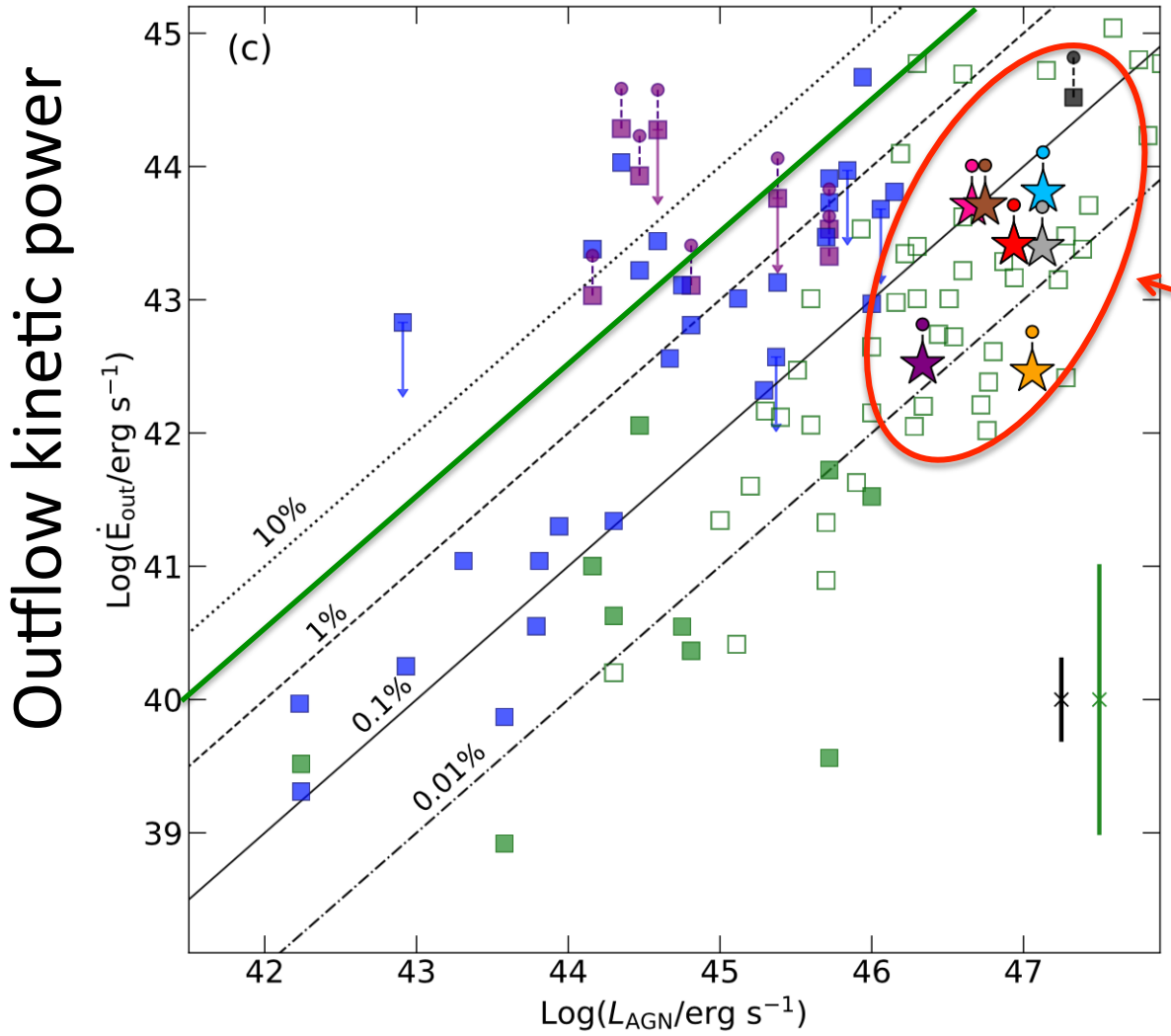
Maiolino+12, CIcone+15, Carniani in prep.

Bischetti+19
Stanley+19





Properties of high-z quasar-driven cold outflows: not as effective as initially thought



Expectation for efficient, energy-conserving outflows (required by ejective feedback models)

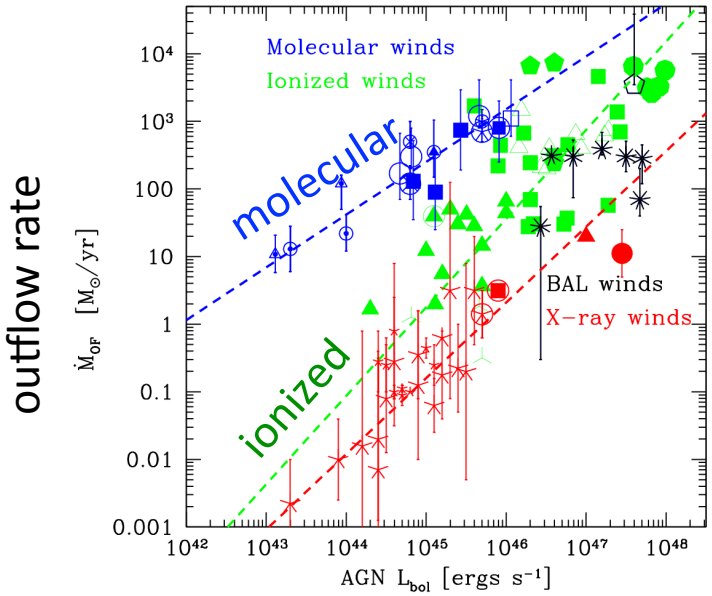
high-z quasars

see also
Balmaverde+17
Schulze+19

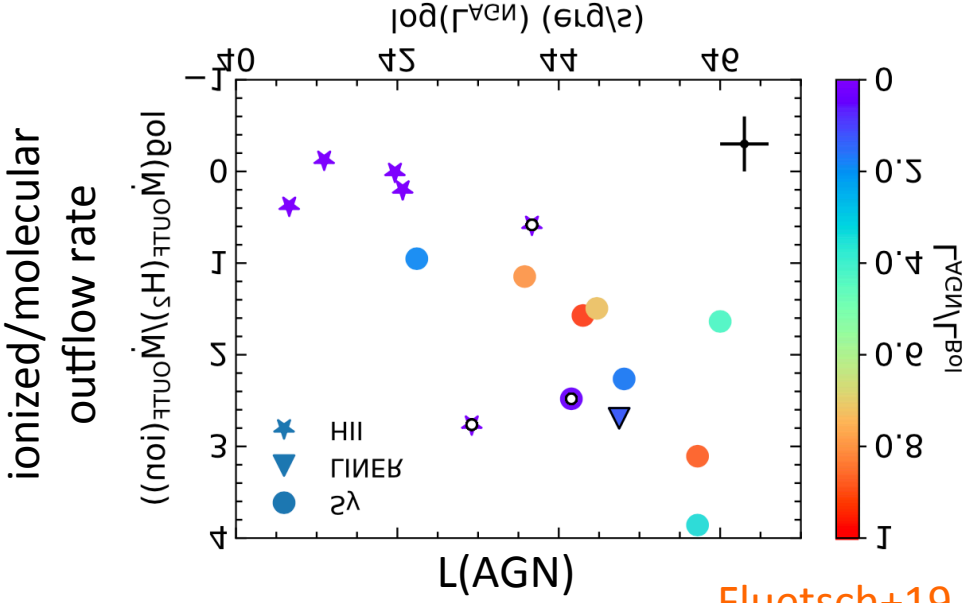
Bischetti+19

Maybe most of the outflowing mass and energy in the ionized phase?

Conflicting results so far...

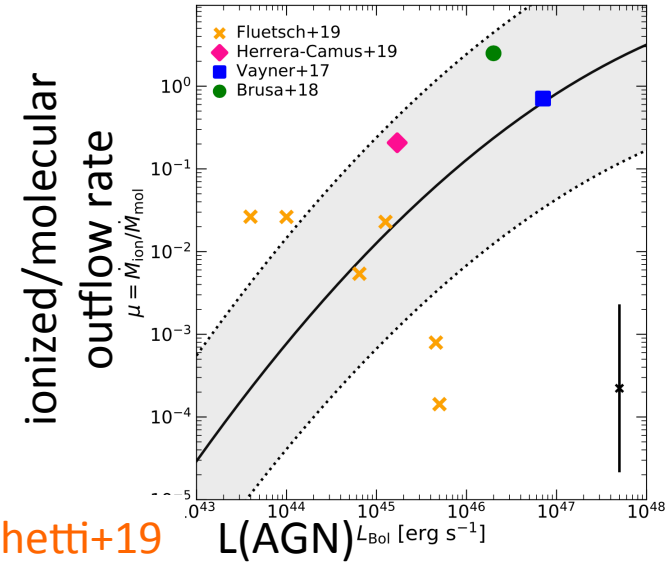


Fiore+17



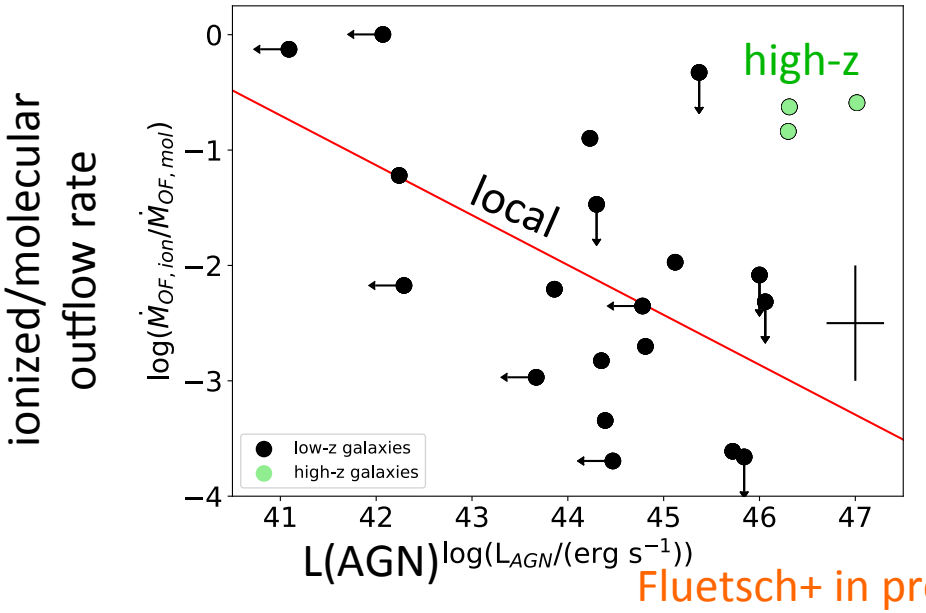
Fluetsch+19

L(AGN)



Bischetti+19

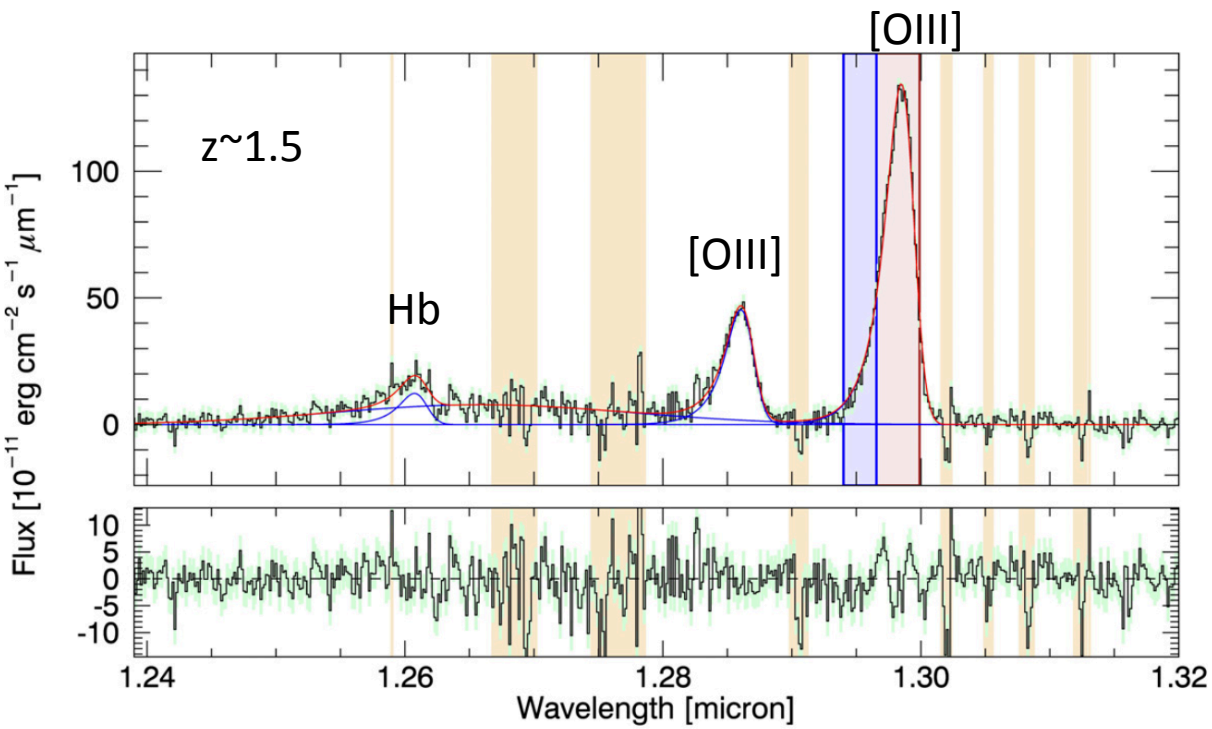
L(AGN)

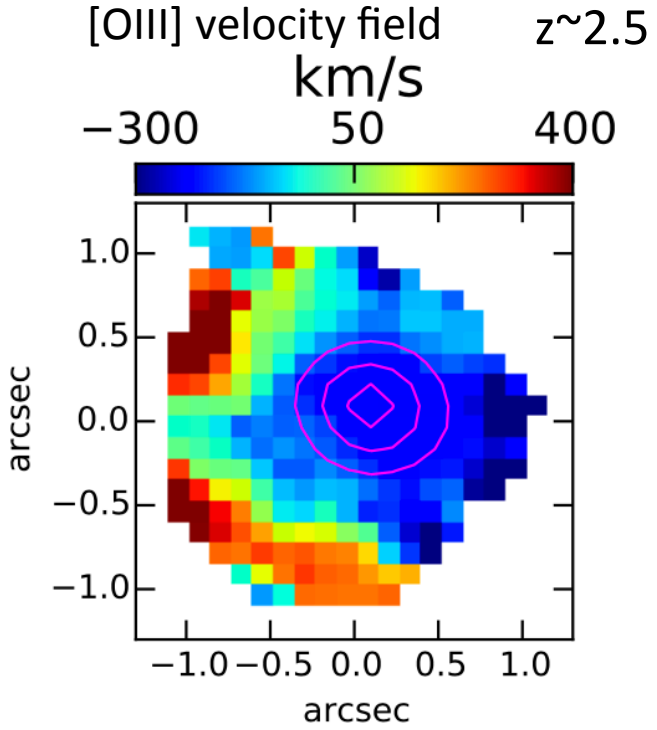


Fluetsch+ in prep.

Ionized phase of SB and quasar-driven outflows probed at high-z through near-IR integral field spectroscopy: primarily [OIII]5007 and Hα high velocity wings

Struggling in terms of angular resolution and sensitivity to extended emission



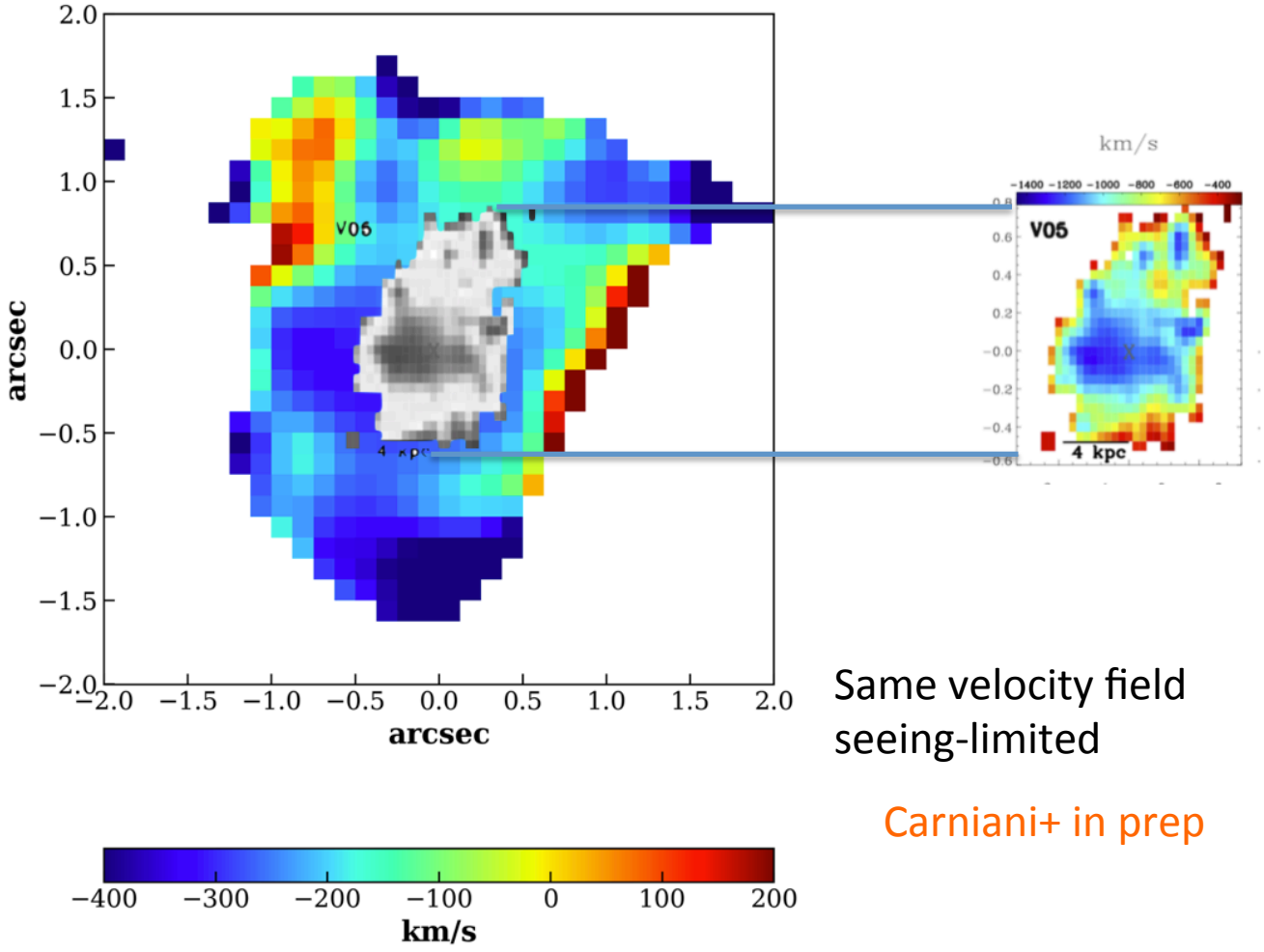


Carniani+15,16

Cresci+15

Cano-Diaz+12, Harrison+16, Genzel+15, Forster-Schreiber+19, Davies+19,....

Adaptive Optics helps... but at expenses of sensitivity to extended emission



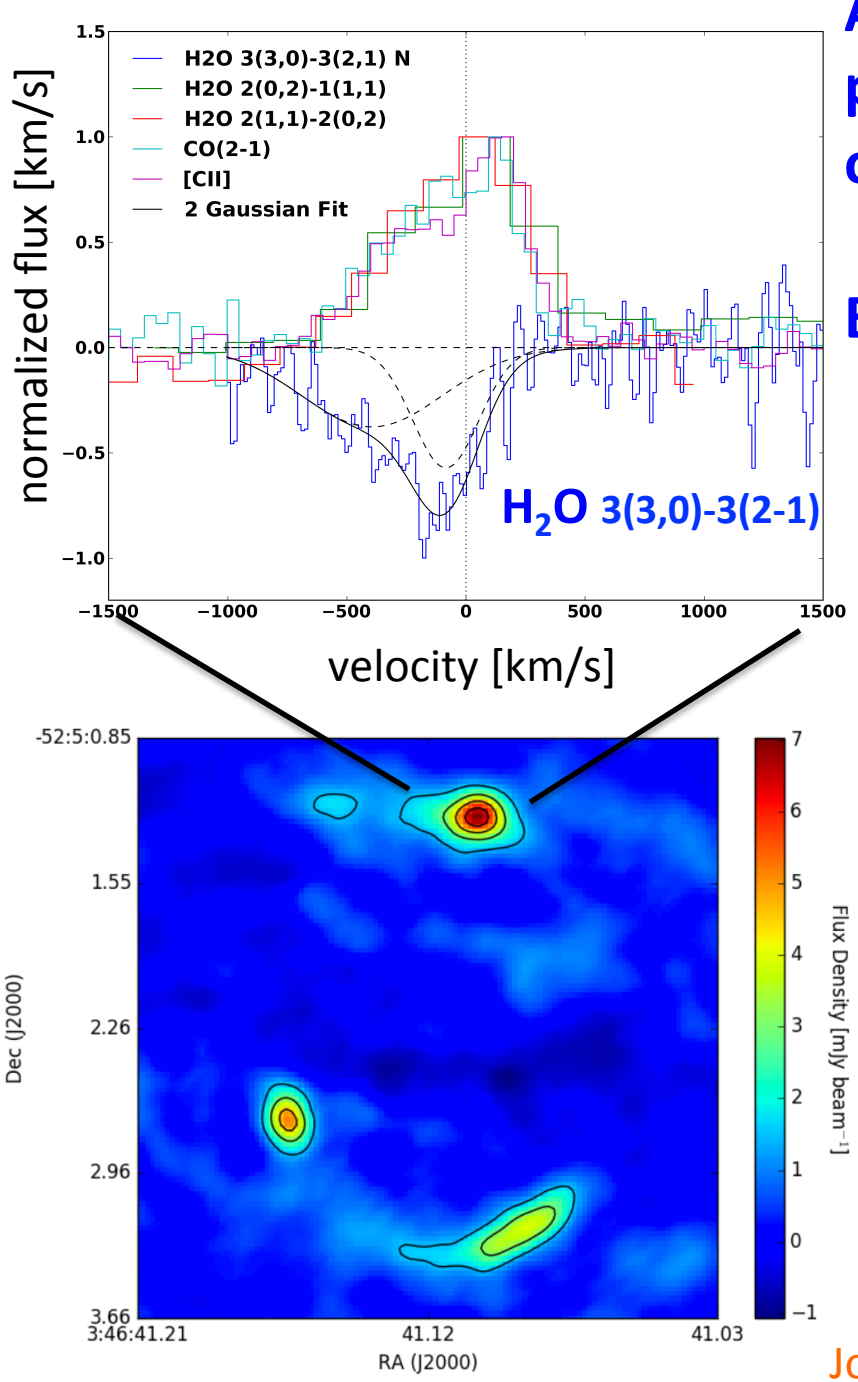
Velocity field [OIII] of quasar-driven outflow at z~1.5 with Adaptive Optics

Brusa+17

Same velocity field seeing-limited

Carniani+ in prep

ELT's (e.g. HARMONI) will provide the perfect combination of high angular resolution (0.01"-0.05") and sensitivity to extended emission



Alternatively, outflows do not have to play an active quenching role or even a "regulating" role..

Extreme hyper-Eddington starbursts

Lensed SPT galaxy z=5.6

Σ_{SFR} = 10,000 $M_\odot$ yr^{-1} kpc^{-2}

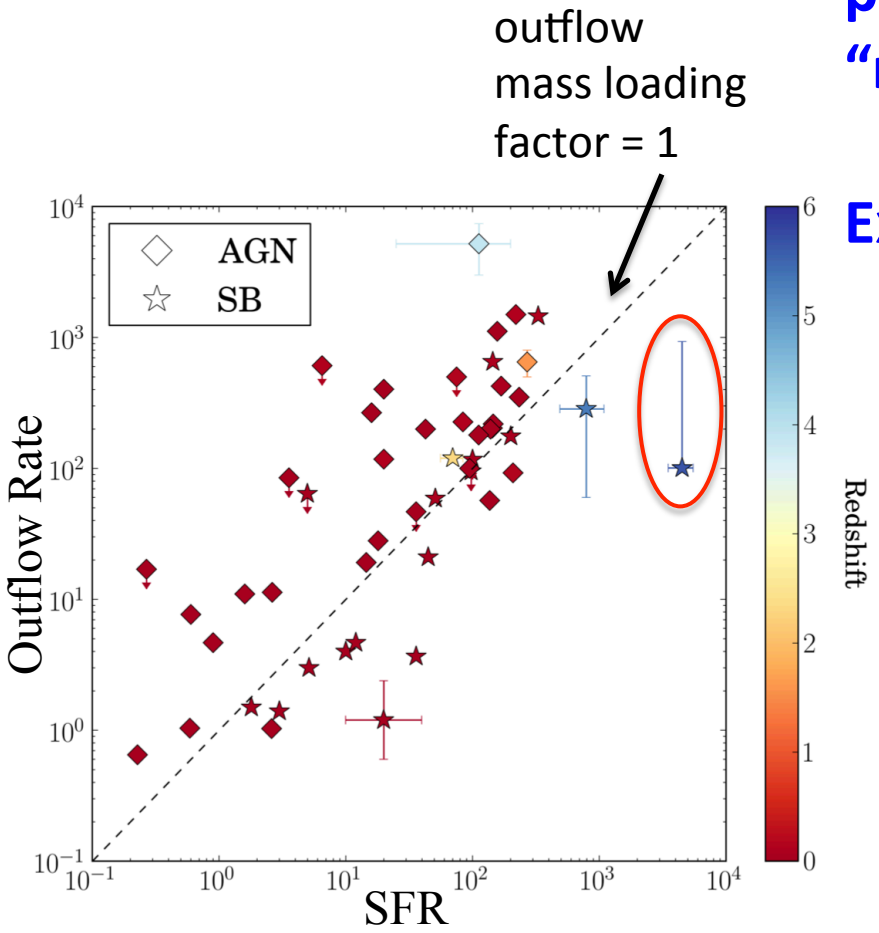
~ 10 x "Maximal" starburst!!!

Blueshifted water absorption

-> massive, dense molecular wind

Jones+ submitt.

Alternatively, outflows do not have to play an active quenching or even "regulating" role..



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~ 10 x "Maximal" starburst!!!

Blueshifted water absorption

-> massive, dense molecular wind

Outflow capacity saturates -> no regulation

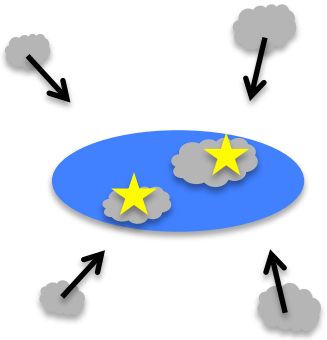
-> runaway process

-> extreme starburst use up all gas in less than 10 Myr

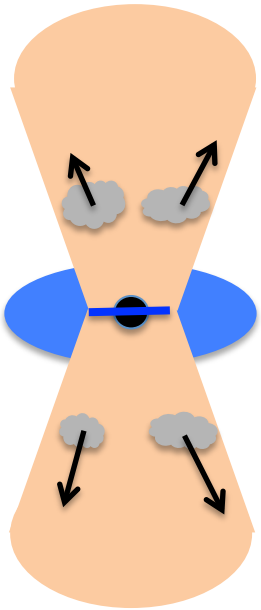
-> quickly becomes passive, unless replenished

Yet, outflows likely contribute to the halo heating -> quenching by starvation

gas accretion and star formation

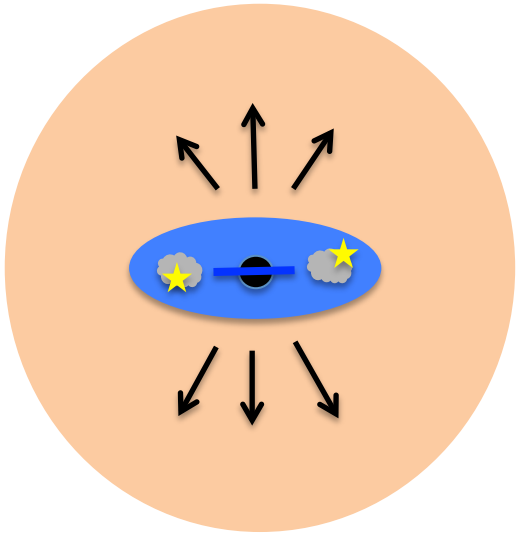


AGN outflow: gas ejection mostly from central regions

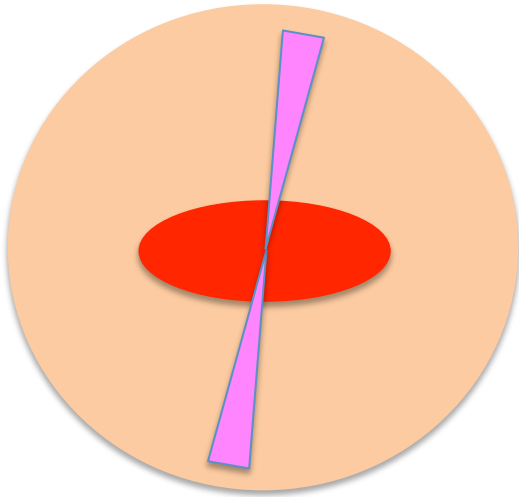


heating of the circumgalactic medium

Halo heating prevents cooling -> starvation



Delayed quenching

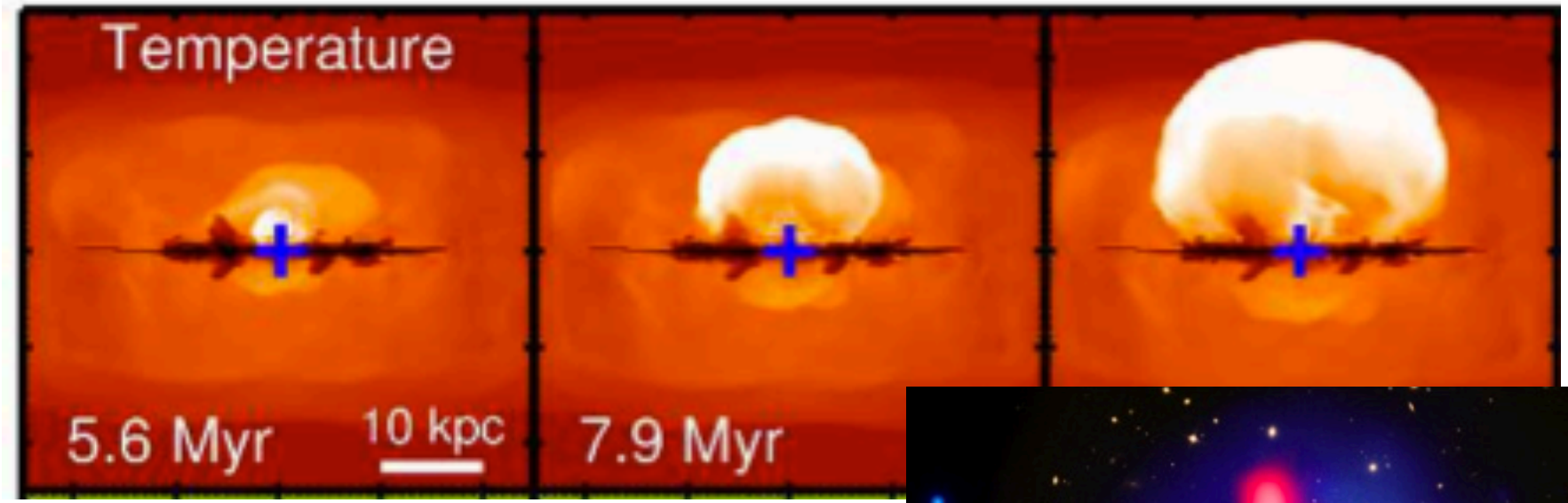


additional radio/ maintenance mode kicks in

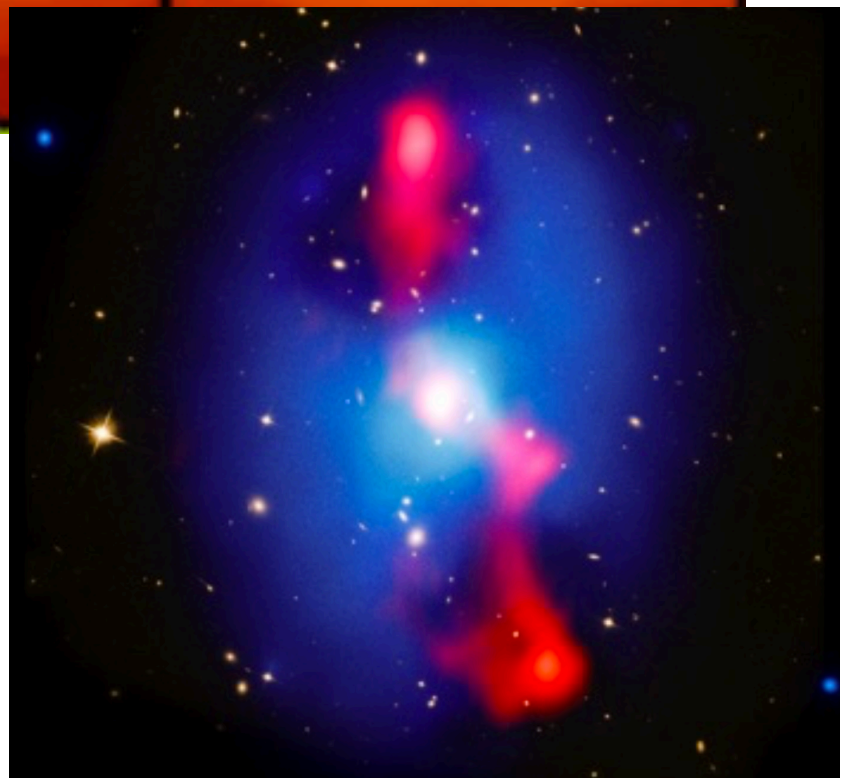
Bower+16, Gilli+17, Pillepich+17

(early) preventive feedback

Heating of the halo by quasar-driven outflows in models and simulations



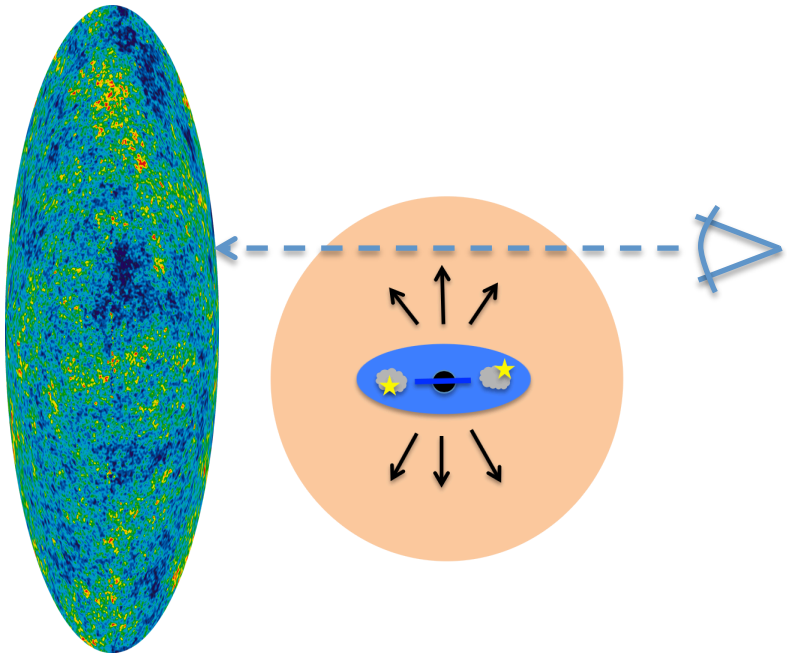
Gabor+14
Costa+14,15,17
Hartwig+17
Roos+15
Bower+16, Gilli+17, Pillepich+17
Henden+19, (and many more...)

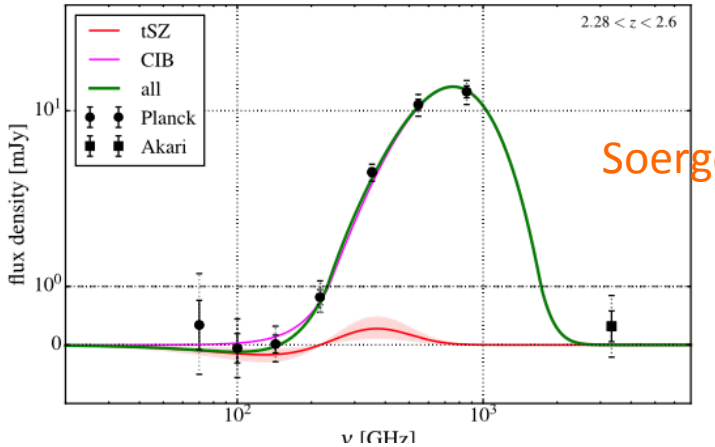


Similar to the “radio-mode” in which halo heating happens through radio-jets

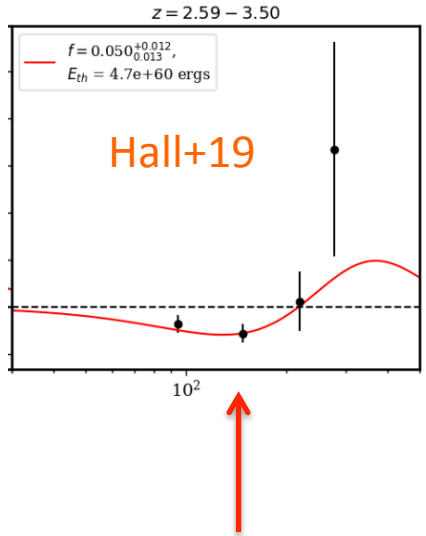
Attempts to directly detect AGN halo heating

Attempts to detect associated S-Z by using CMB data
and stacking at quasar positions (Planck, ACT, Herschel)





Soergel+17



Hall+19

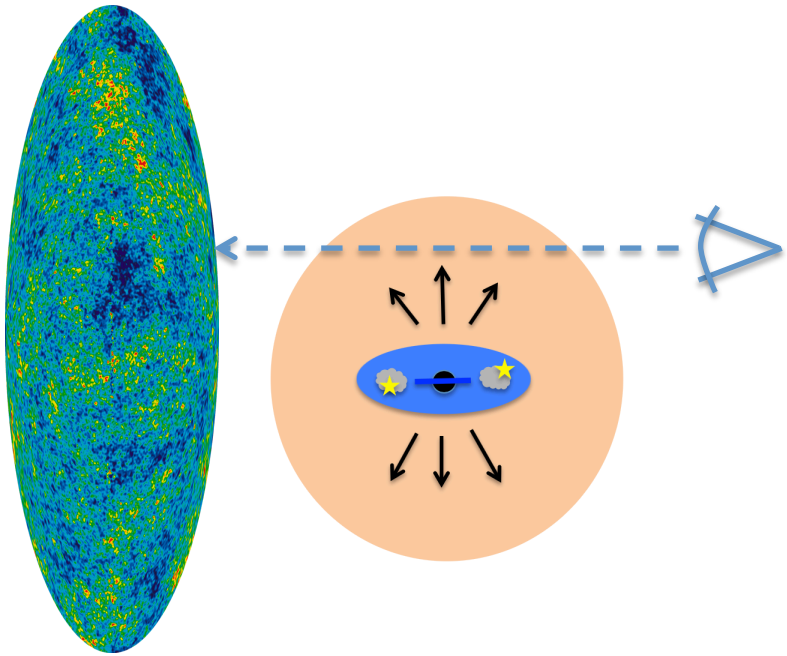
Ruan+15
Verdier+16
Crichton+16
Henden+19

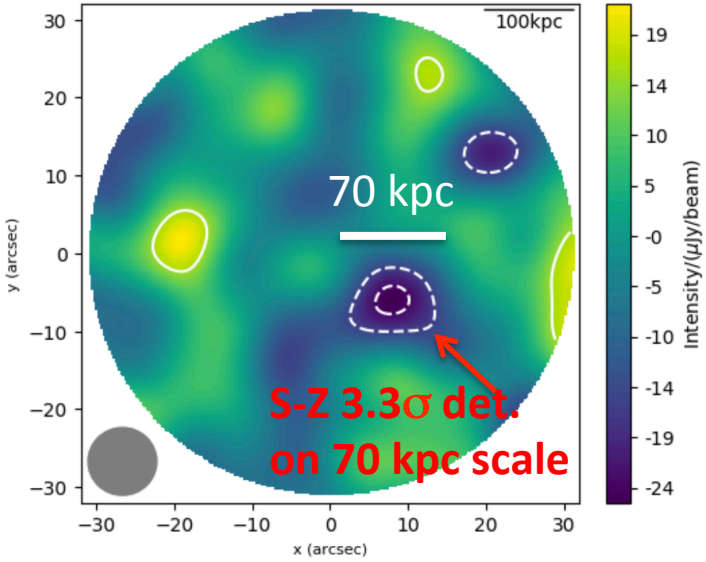
tentative (~2-4σ) detections
~ in agreement
with models

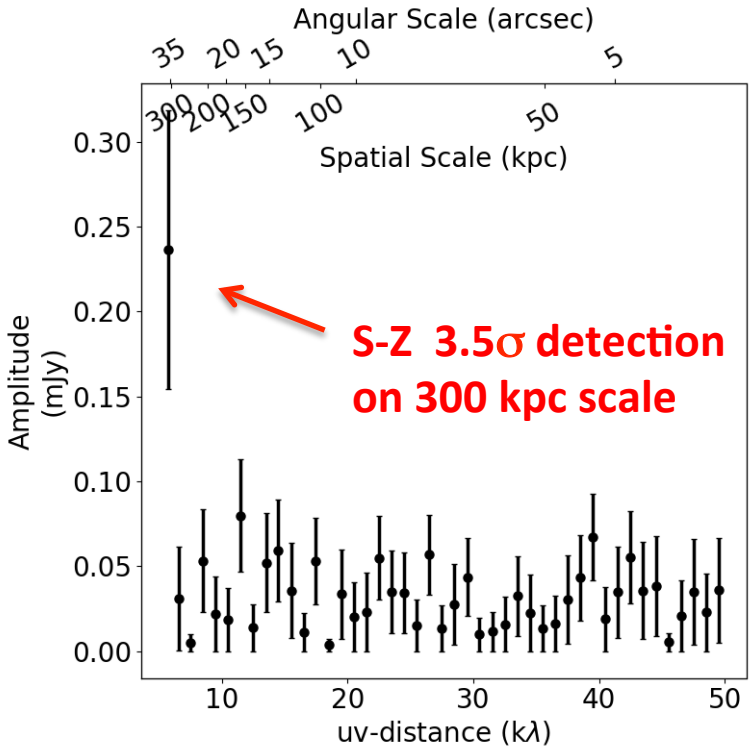
Attempts to directly detect AGN halo heating

ALMA deep exposures on individual quasars

z=1.5 band-4 (140 GHz) (dip of S-Z)

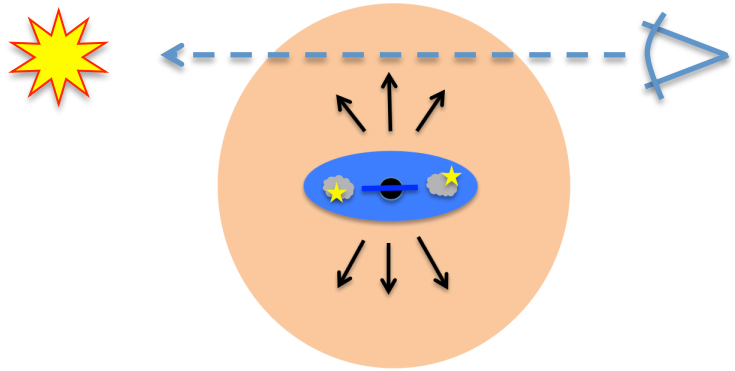


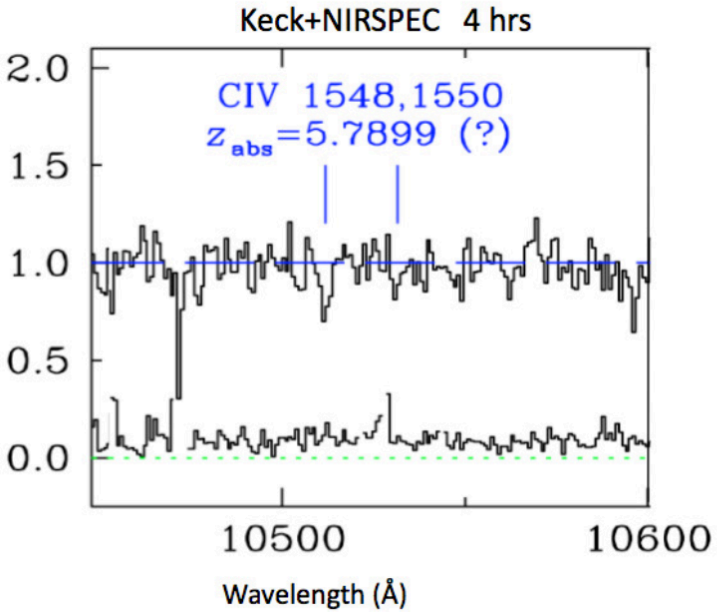


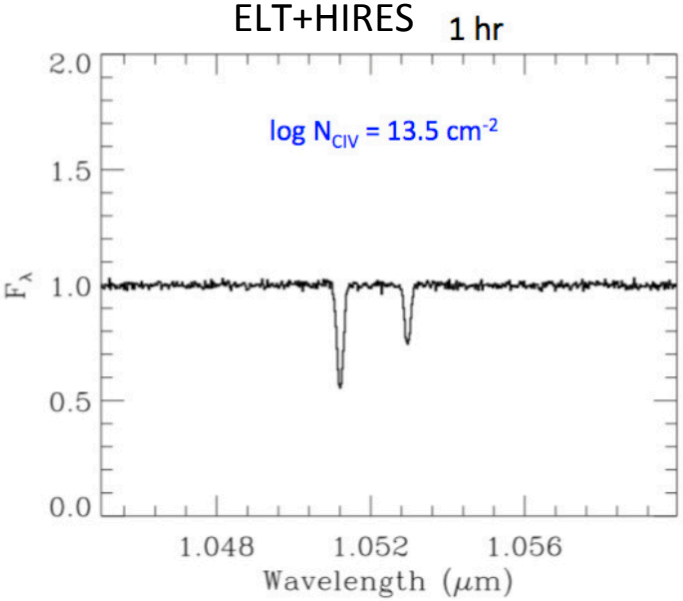


Brownson+, subm., Lacy+19

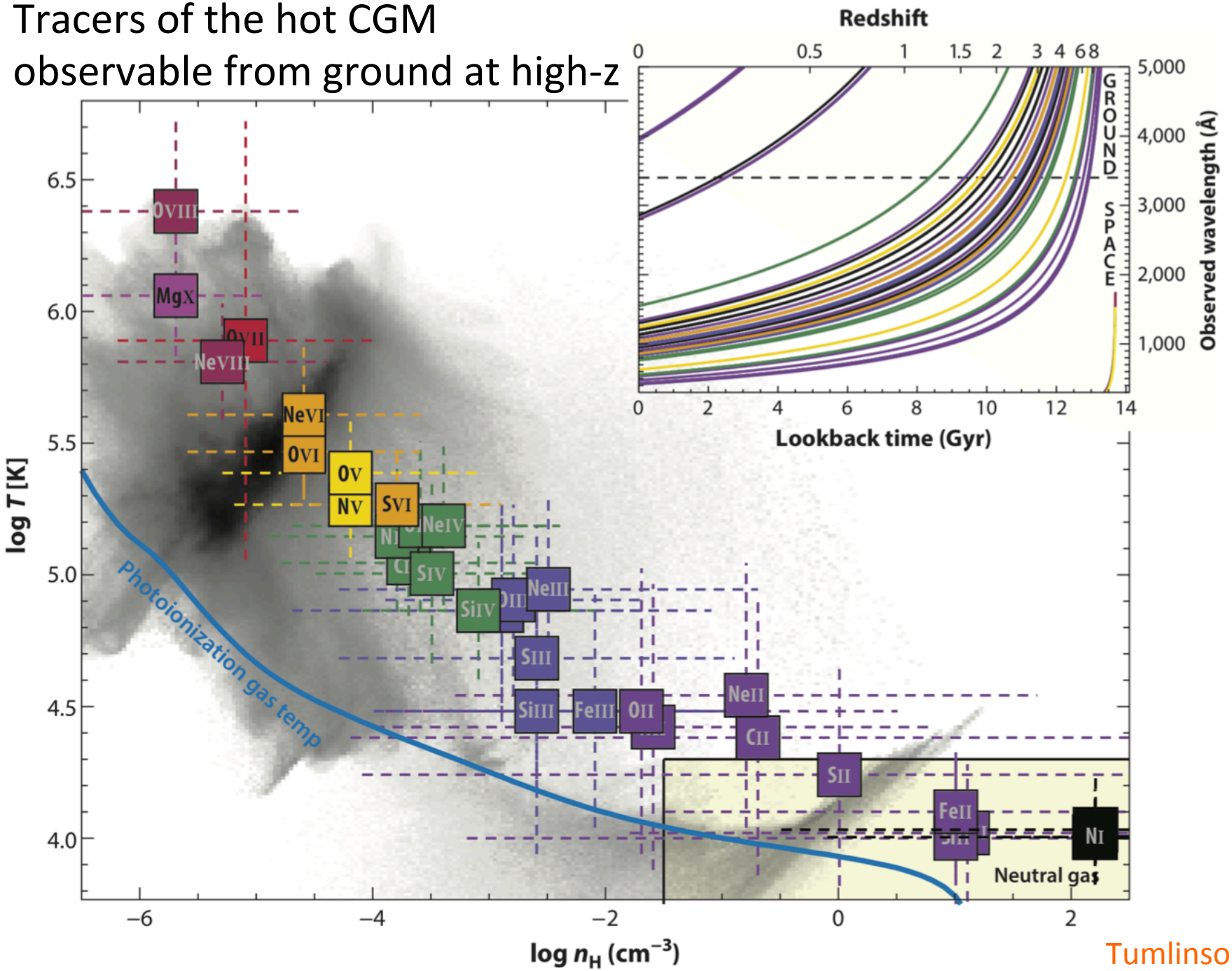
The ELT will allow us to probe the warm/hot phase of the CGM through high resolution absorption spectroscopy of background quasars





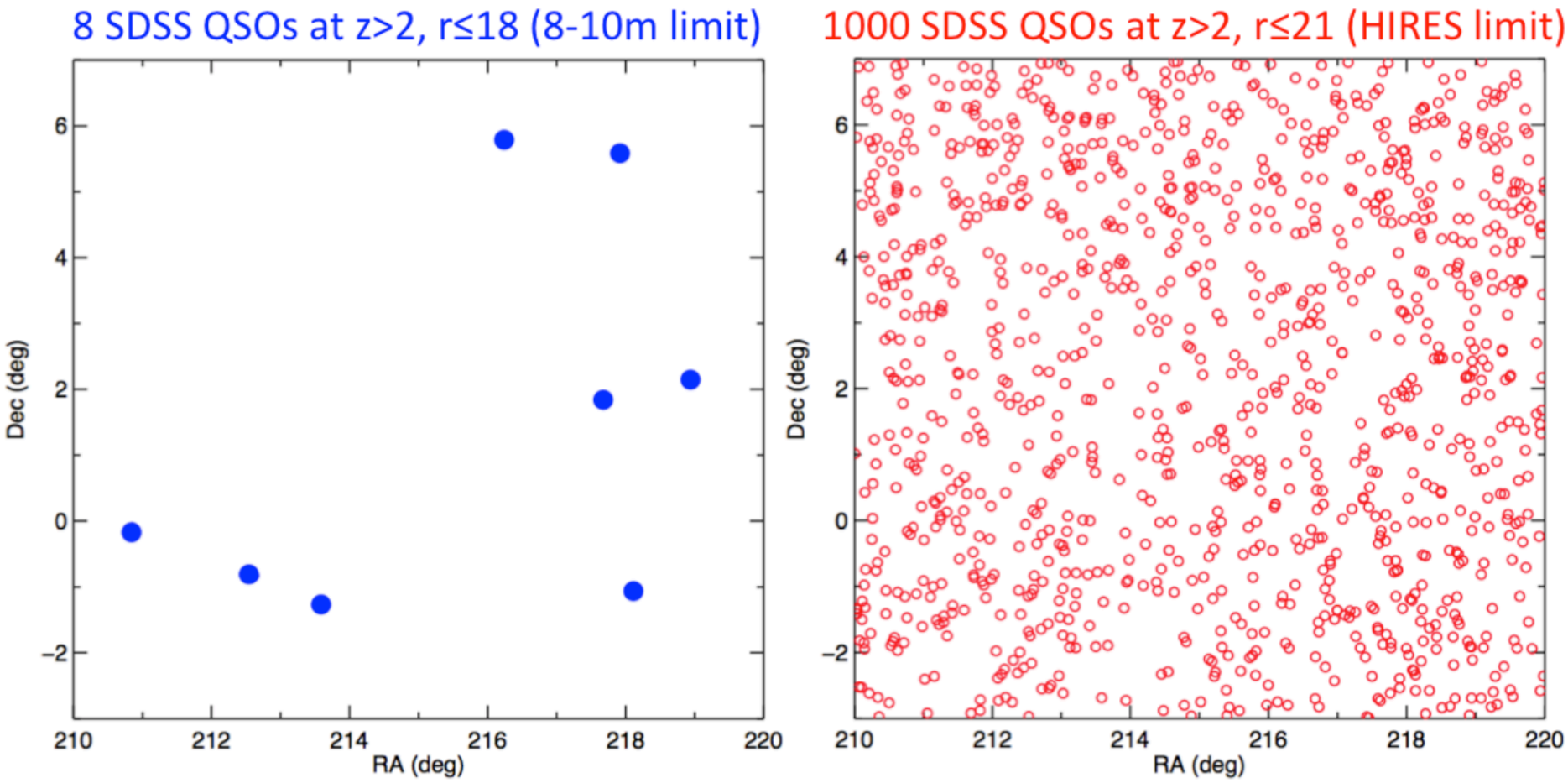


Tracers of the hot CGM
observable from ground at high-z



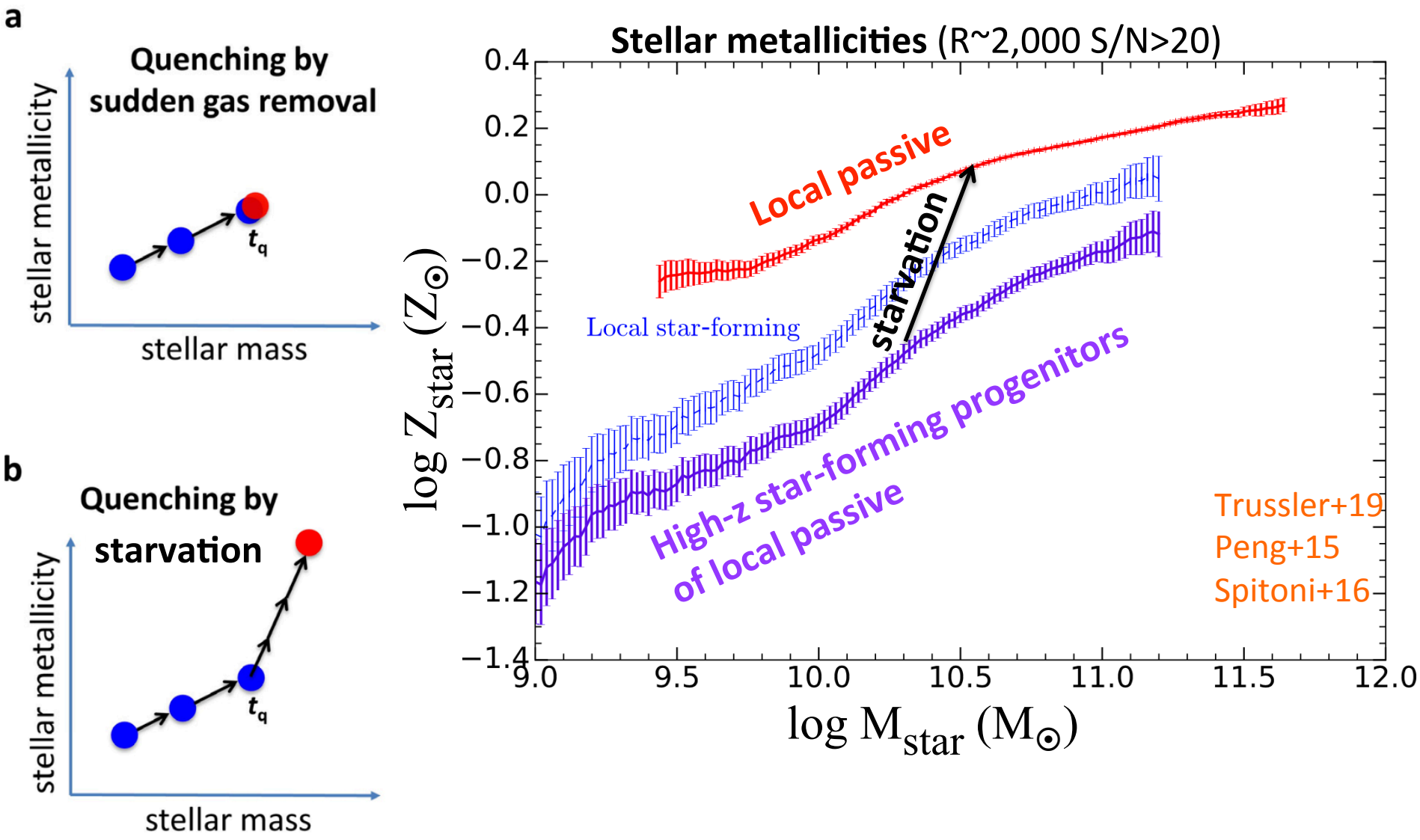
Tumlinson+17

Background quasars available in 10x10 deg^2 for R=100,000 spectroscopy



At R~10,000 can probe r~22-23 => population of star forming galaxies
x 20 higher density of background
sources -> MOSAIC

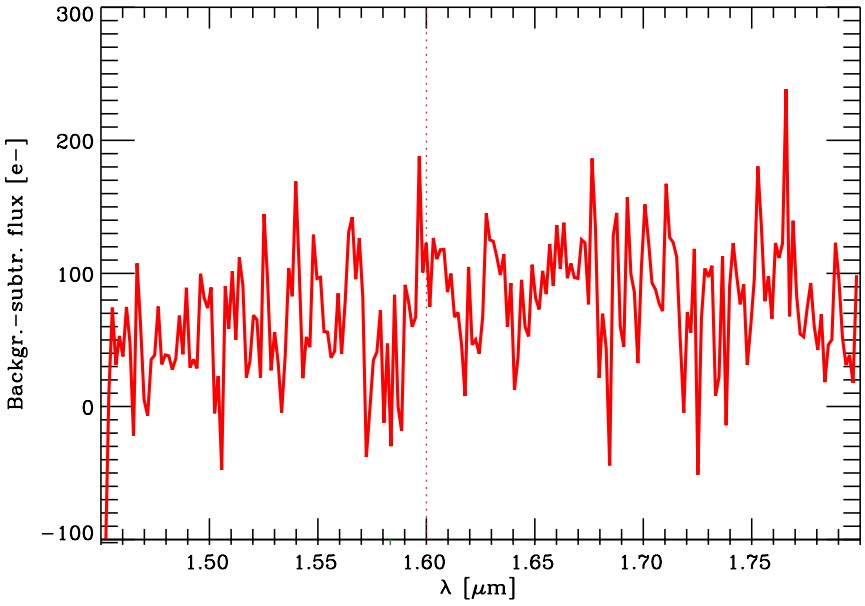
Tracing inflows or *lack thereof* through chemical enrichment



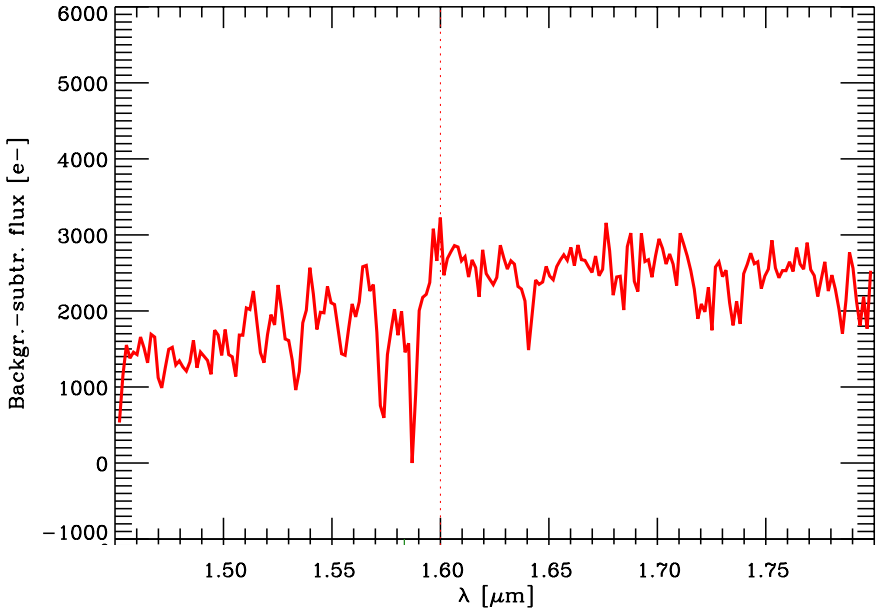
Exploring the starvation scenario at high redshift
requires measuring the stellar metallicity of passive galaxies at high-z
=> AB>24 => ELT (note JWST does not help much here)

passive galaxy at z=3 H_{AB}=24.5 T_{int}=8hr

VLT

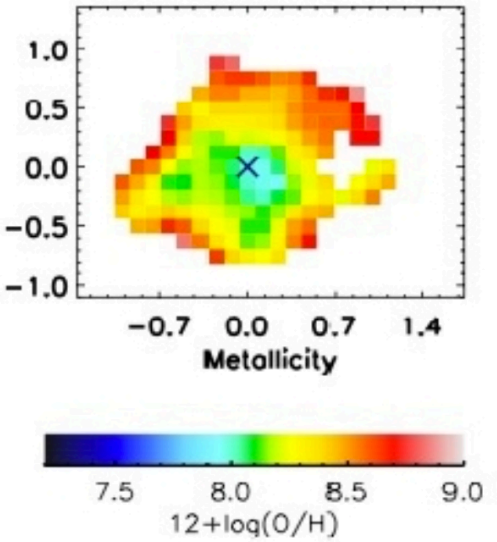


ELT (HARMONI or MOSAIC)

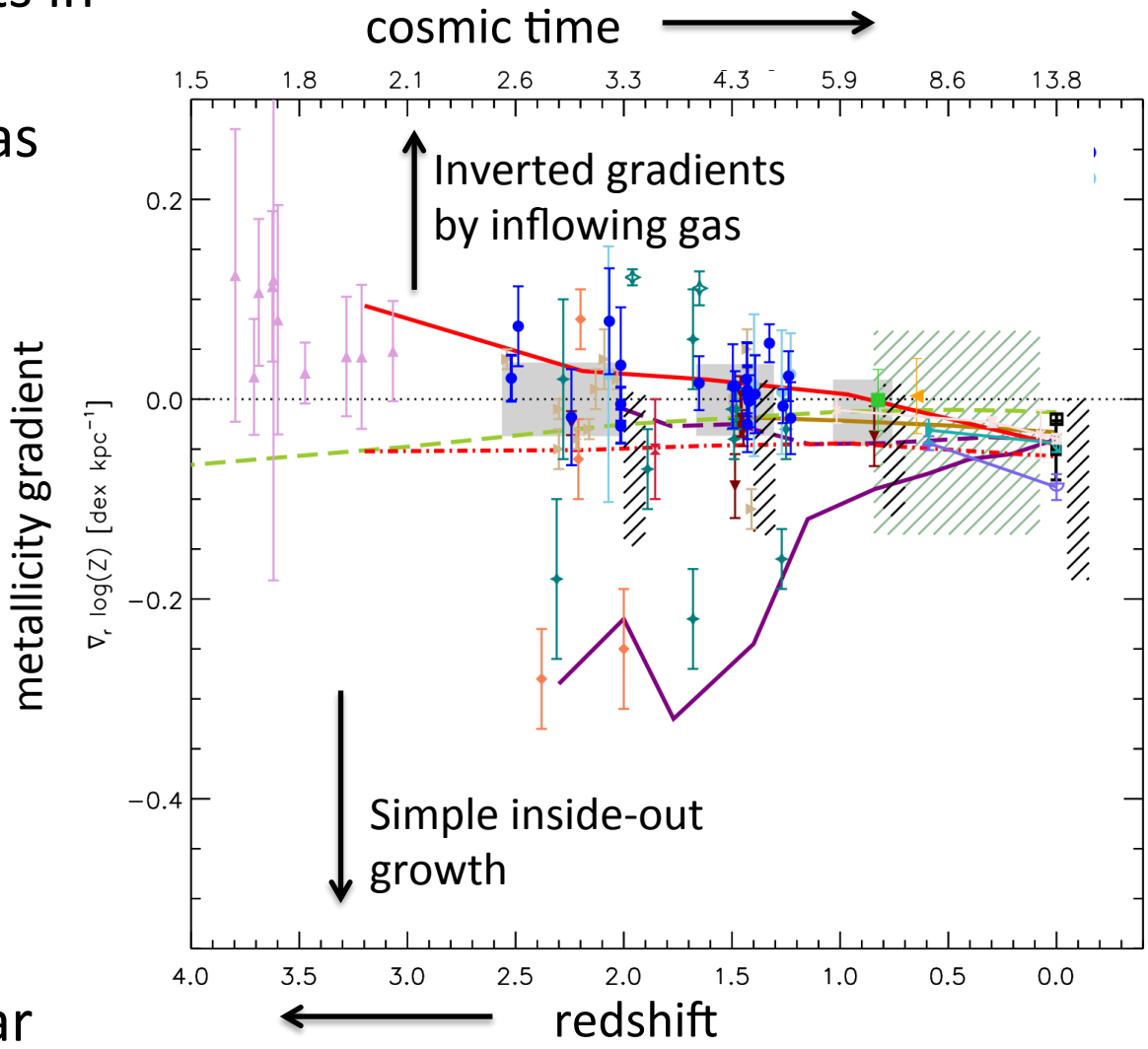


Tracing *inflows* or lack thereof through chemical enrichment

Inverted metallicity gradients in high-z star forming galaxies: proxy of inflow of pristine gas



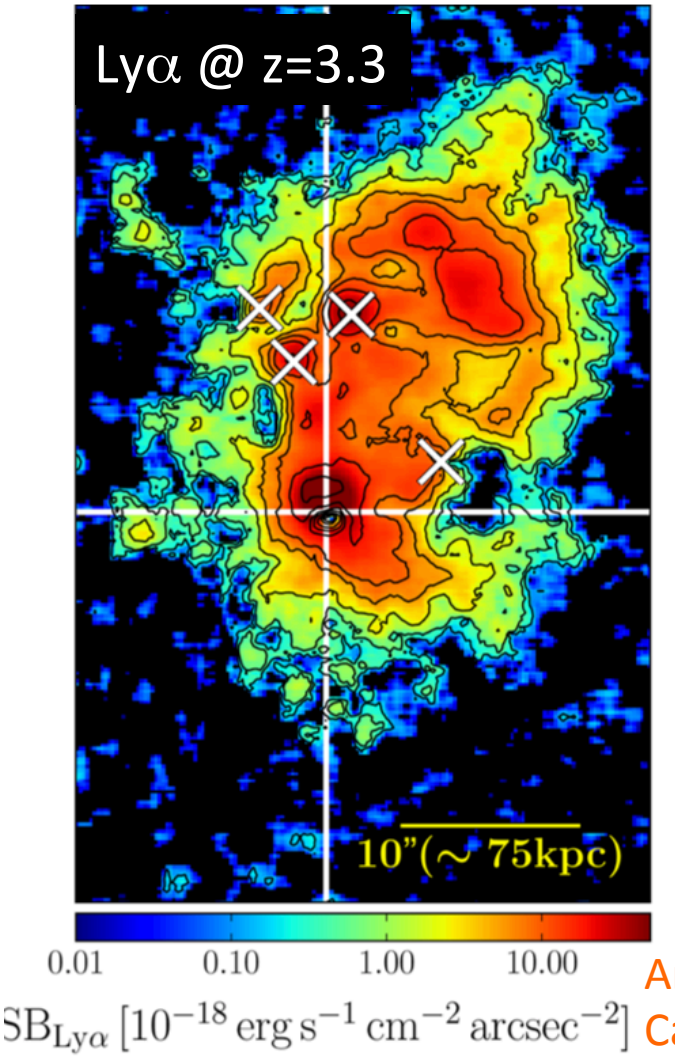
Cresci+10
Troncoso+14



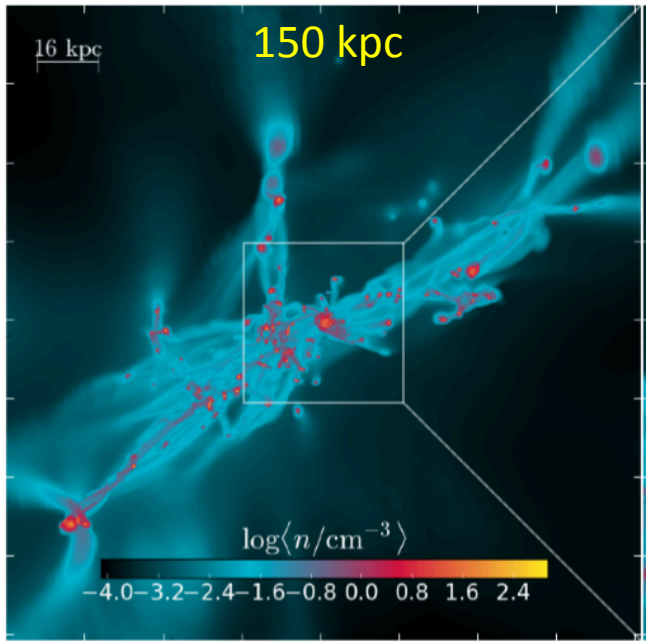
ESO-KMOS Klever large programme (first results)
Curti+ submitted

Primary limitation is angular resoluation and sensitivity
-> ELT's (e.g. HARMONI)

Gas inflow at high redshift probed by Lyα haloes/filaments around high-z quasars (and galaxies)?

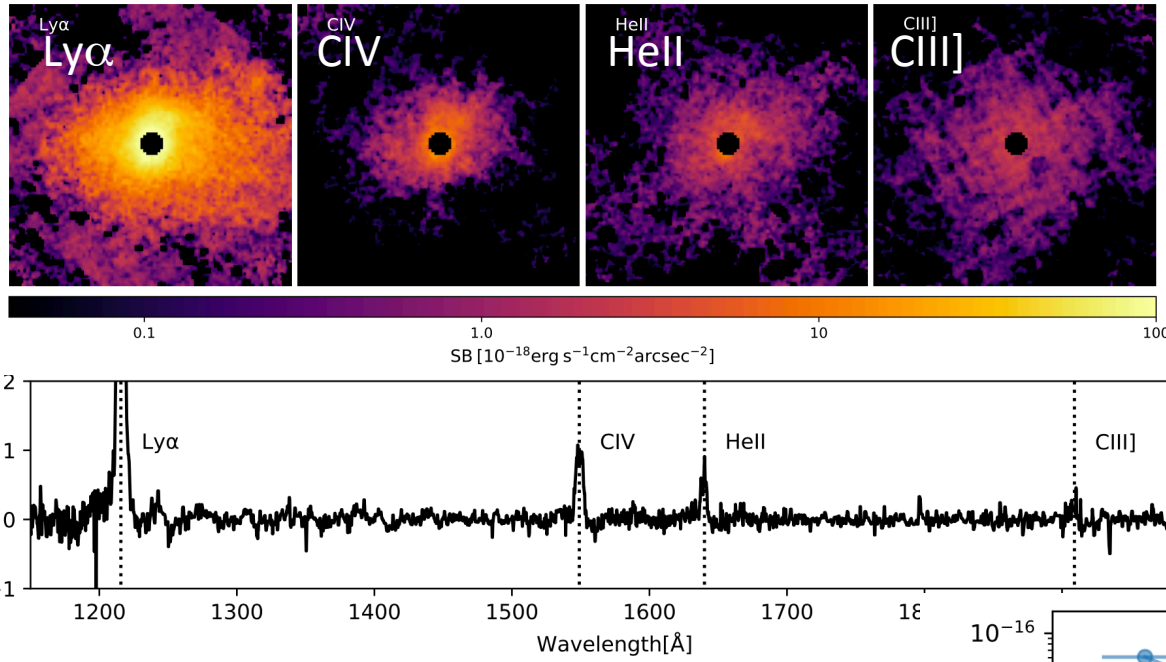


Arrigoni-Battaia+18, Borisova17, Cai+18, Cantalupo+16, Fumagalli+17, etc...



Pallottini+16
Dubois+16
Dekel+12

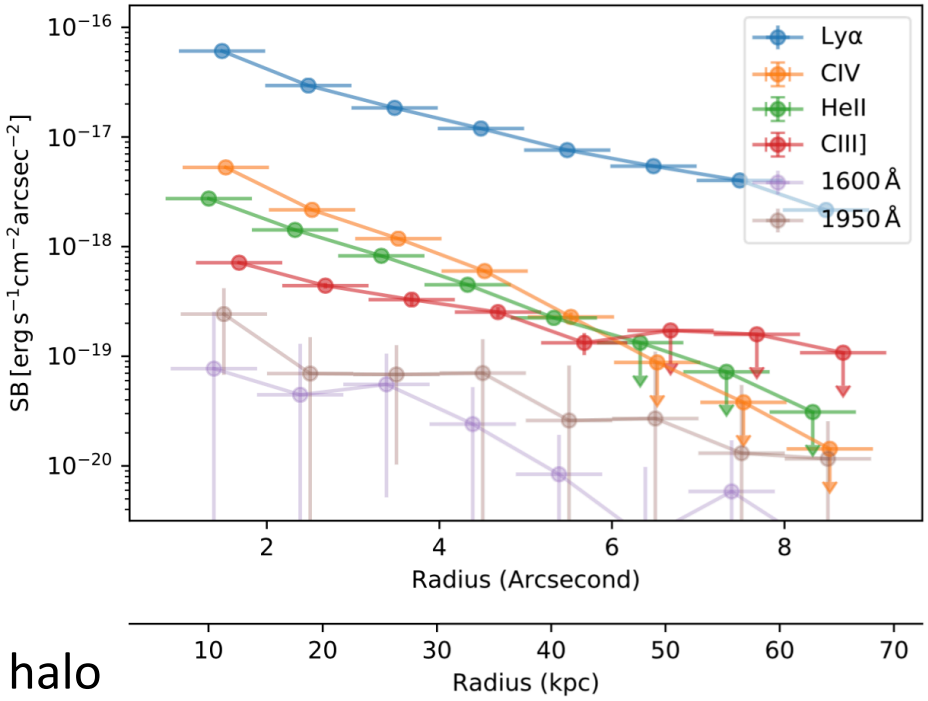
Detection of metal lines in stacked MUSE cubes of z~3 quasars



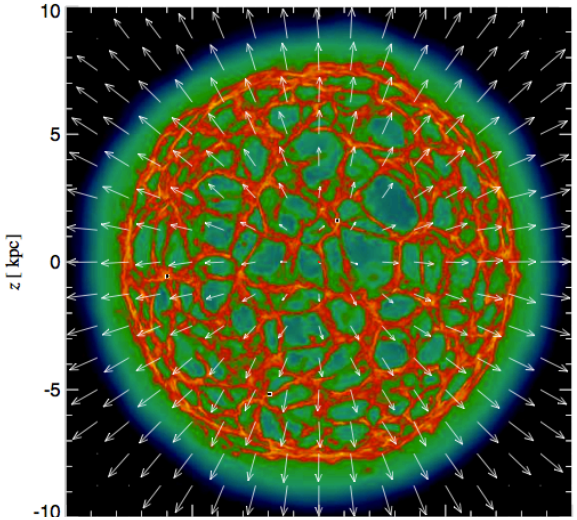
Guo+ subm.

High metallicity ($Z>0.5Z_{\odot}$)
within the central 50kpc
-> likely CMG pre-enriched
by quasar-driven outflow

Yet, outer halo might be
more metal poor and
consistent with IGM ~near-pristine inflow
-> needs ELT to probe metal lines in outer halo

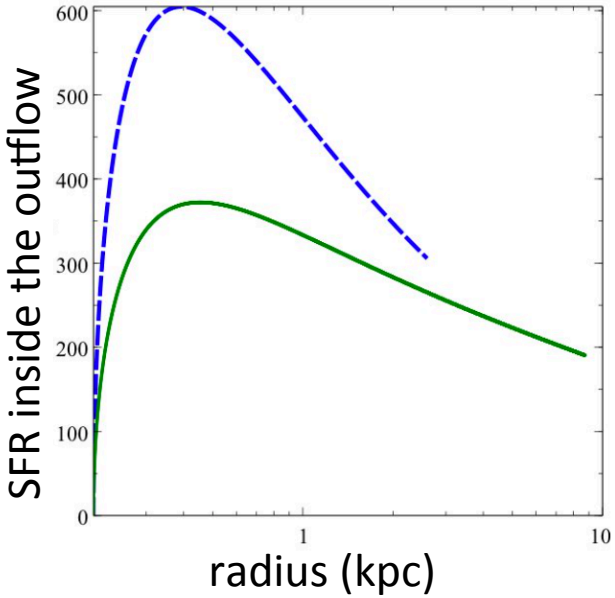


Several recent models expect outflowing molecular clouds undergo compression, fragmentation, gravitational collapse
-> star formation *inside* outflows
-> Stars should form at high velocities on ~radial orbits
➔ major potential implications for the formation of galactic spheroidal component



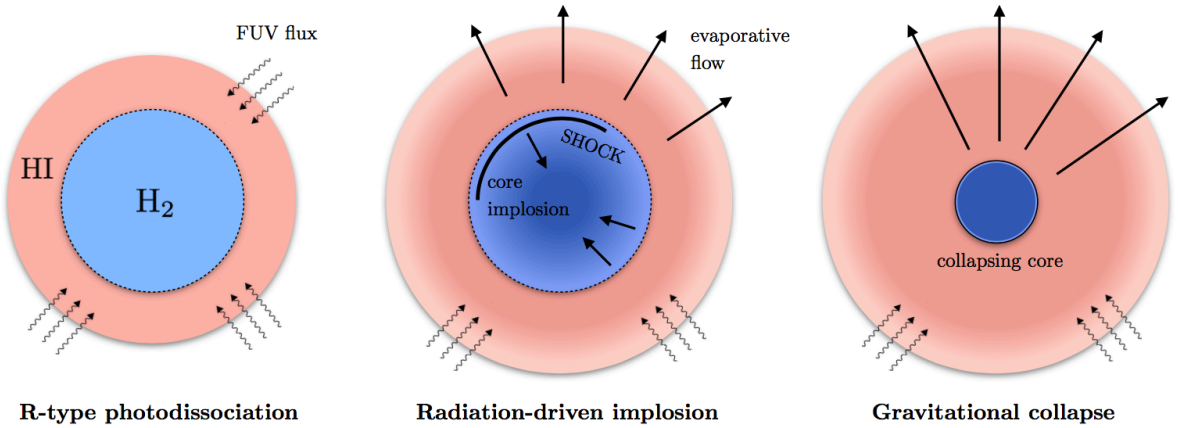
Ishibashi & Fabian +14, +15,+17

Zubovas+13,17,
Zubovas & King '13



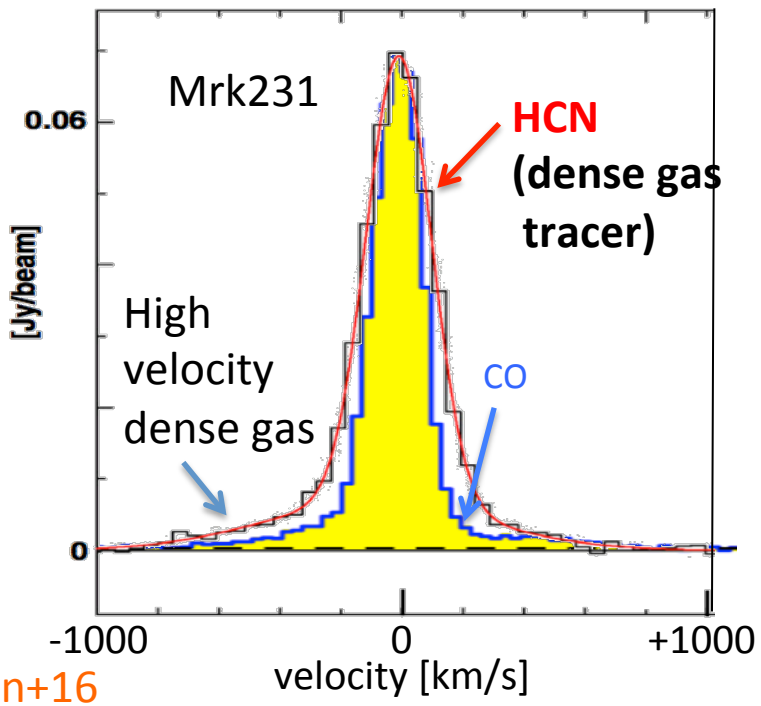
Silk+15, +17
El-Badry+2016
Nayakshin+12, Zachary+14
Gaibler+12, Wang & Loeb '18
Dugan+2014, Mukherjee et al. 2018

Decataldo+19

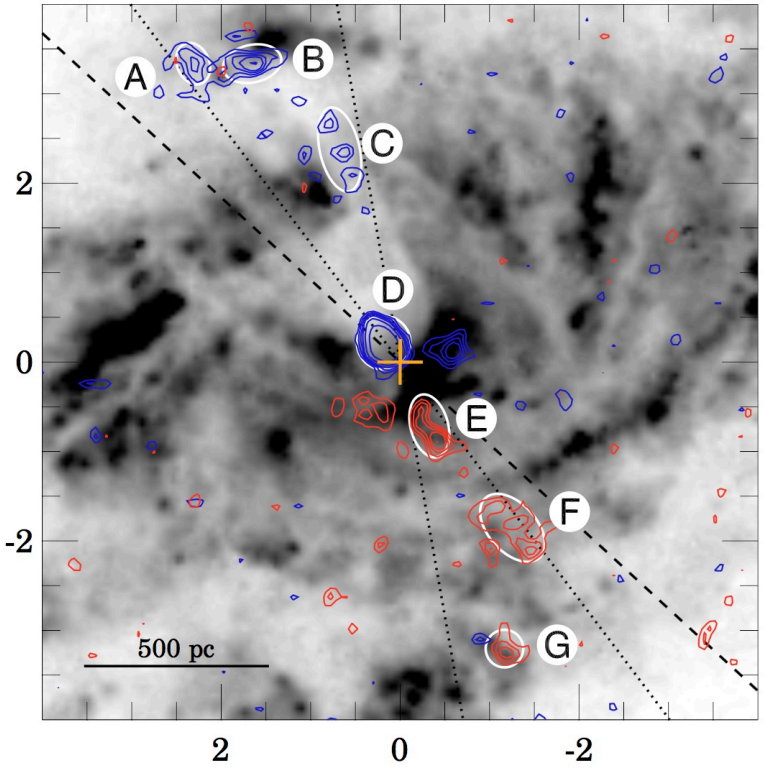


A large fraction of the outflowing molecular gas is indeed

- very dense ~10^5-10^6 cm^{-3}
- very clumpy (clump sizes 1-100 pc)



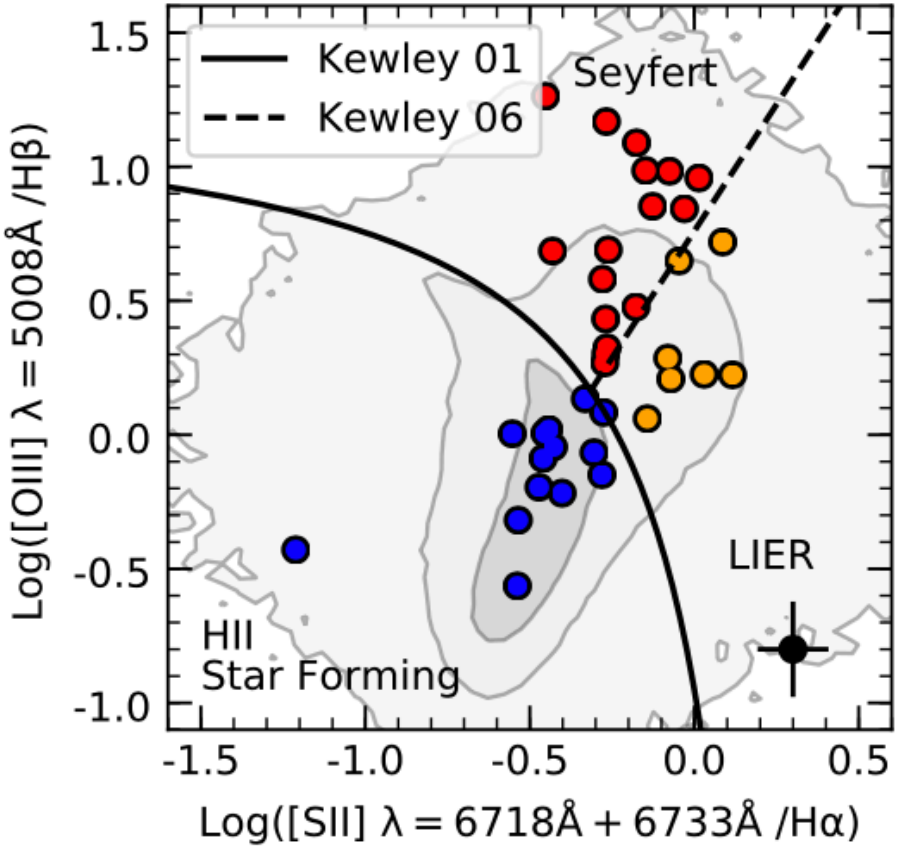
Lin+16
Aalto+15, 16
Walter+17
Alatalo+15
Gonzalez-Alfonso+17
Zschaechner+15
Tunnard+15
Sakamoto+08



➔ **Gas properties similar to star forming regions**

Pereira-Santaella+16
Aalto+15
Finn+15
Borguet+12
Feruglio+15

Manga + MUSE Survey: BPT classification of galactic outflows



~30% of galactic outflows classified as "star forming"

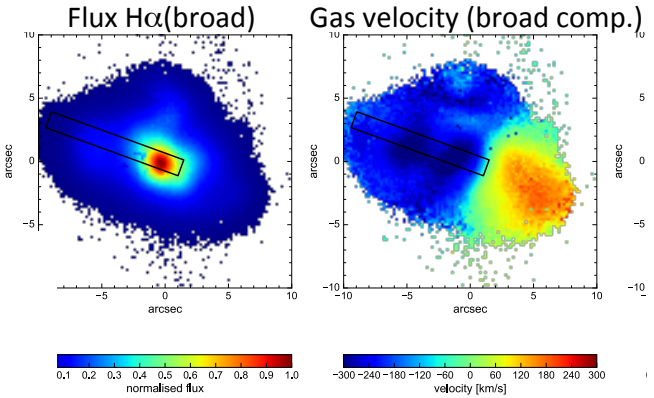
Gallagher+19
Rodriguez del Pino+19
Fluetsch+ in prep.

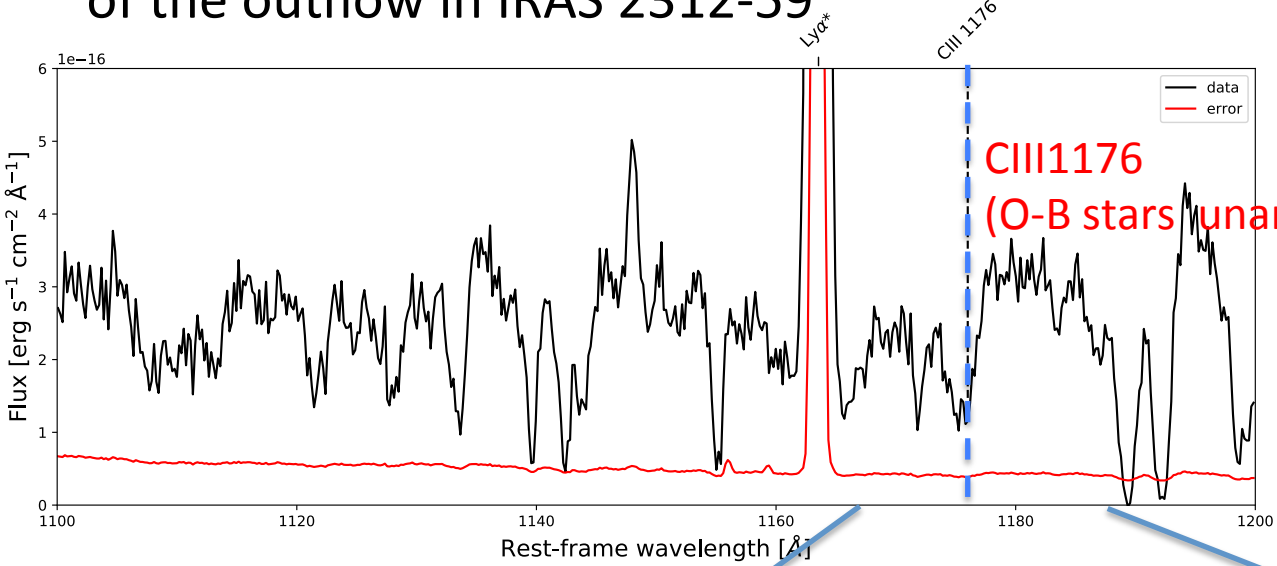
Confirmed in a few cases with independent near-IR diagnostics

Maiolino+17
Fluetsch+ in prep.

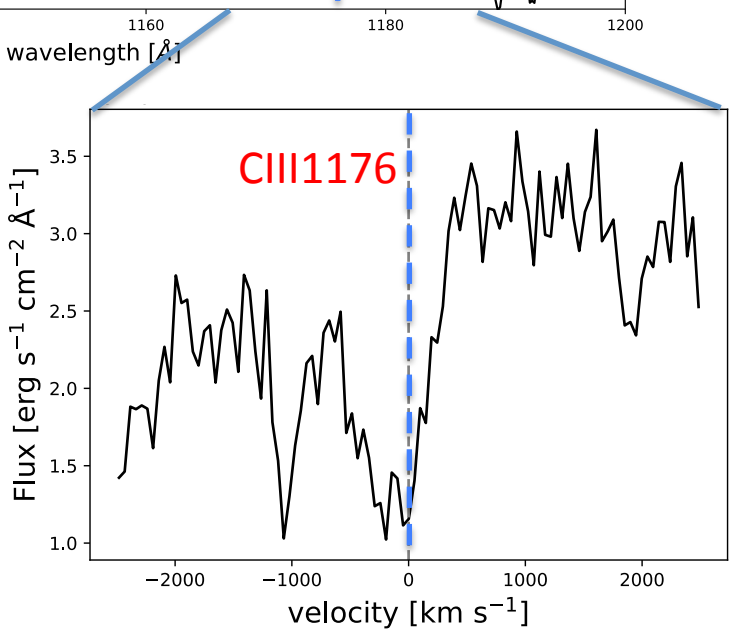
Direct detection of young (O-B) stars formed in the outflow

UV HST-COS long observation of the outflow in IRAS 2312-59





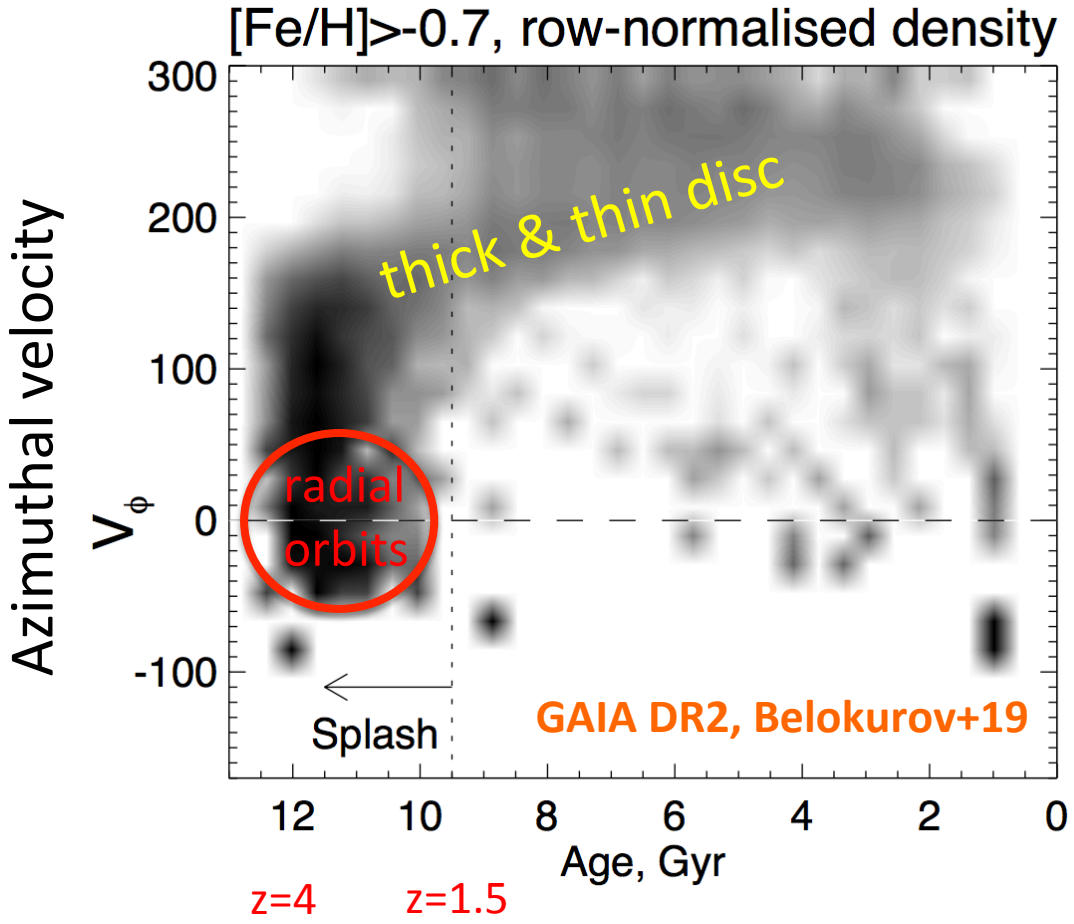
CIII1176
(O-B stars unambiguous tracer)



blueshifted by
~300 km/s out to
~1000 km/s
as outflowing gas

Belfiore+, in prep.

Signature of stars formed in outflow in the Milky Way



The early formation of stellar population inside galactic outflows can be probed at high-z with the ELT's

As expectated from models
Zubovas+13

the bulge, but due to their large radial-velocity kicks now belong to the galactic halo. Such halo stars could thus stand out due to their highly radial orbits and (likely) higher metallicity compared to a typical low-metallicity halo star. The most extreme of these stars, in the outskirts of the dark matter haloes of their host galaxies, may

Summary

Quasar-driven galactic outflows seem little effective in directly (ejective mode) quenching star formation in massive galaxies

To be verified with ELT near-IR IFU spectroscopy

Galactic outflows likely effective in heating the halo

-> prevent cold accretion

-> starve galaxies

Can be tested with ELT high resolution spectroscopy

Signature of galactic inflows can be obtained through high resolution metallicity maps of distant galaxies

ELT near-IR IFU spectroscopy badly needed

Star formation inside galactic outflows:

new channel contributing to the formation of galactic spheroids

Can be explored at high-z with ELT spectroscopy