Title: Review Talk: Reconciling the Past and Present IGM/CGM/Galaxy Ecosystems

Speakers: Charles Steidel

Collection/Series: Cosmic Ecosystems

Subject: Cosmology

Date: August 01, 2025 - 9:00 AM

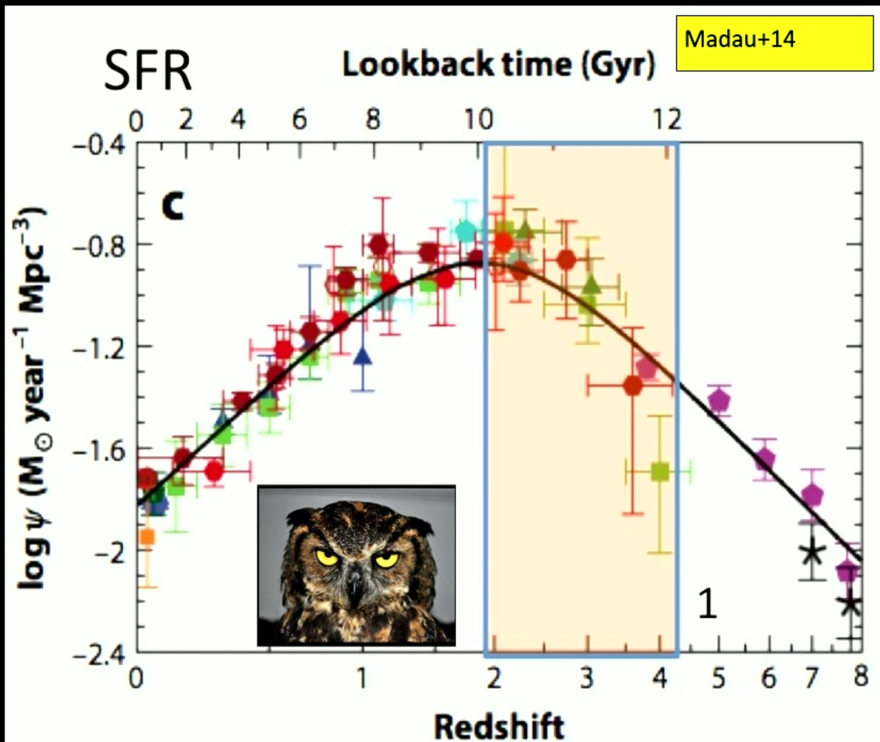
URL: https://pirsa.org/25080001

Abstract:

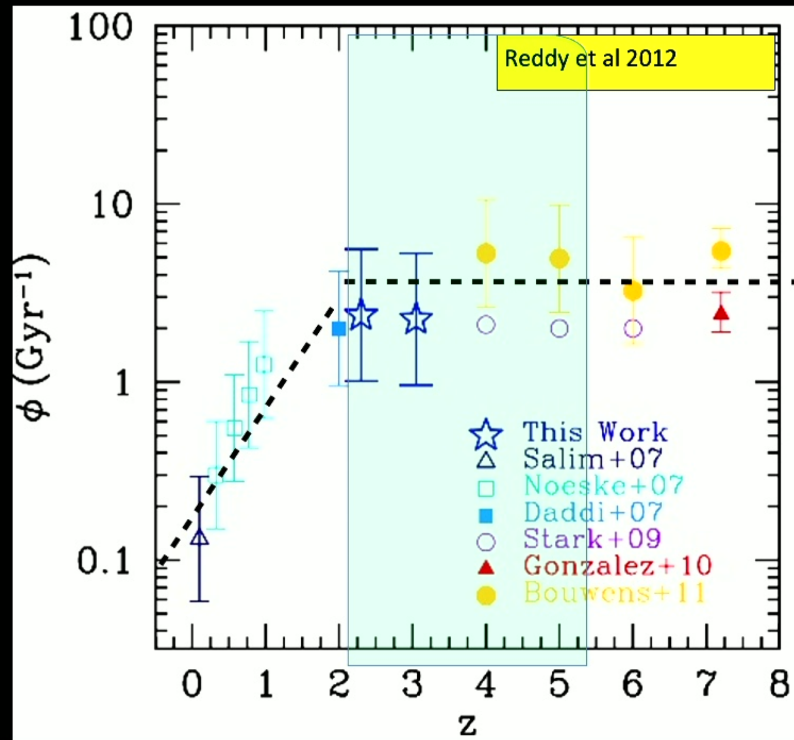
Remarkable parallels exist between observations of diffuse baryons and their connections to galaxies in the high redshift universe compared to z~0 ... in spite of apparently vast differences between the properties of the galaxies themselves and the nature and intensity of the feedback processes operating within them. I will attempt to draw connections between "contemporaneous" observations of galaxy-scale feedback in the adolescent universe with observable signatures "today", and attempt to distinguish between evolutionary sequences and possible coincidences that need further investigation.


The CGM/IGM/Galaxy Ecosystem:
Connecting “live-action footage” and the “fossil record”
C. Steidel
(Caltech)
Cosmic Ecosystems - Perimeter Institute - 2025 Aug 1

SFR density vs. Redshift



sSFR = (SFR/M*) vs Redshift



$$\frac{1}{M^*}\frac{dM^*}{dt} = \mathrm{sSFR} \approx 4-5\mathrm{Gyr}^{-1} \sim \frac{1}{\tau};$$

$$\tau \sim 200\mathrm{Myr}$$

e-folding time for <u>increase</u>
in SFR for individual galaxies

Obvious Questions

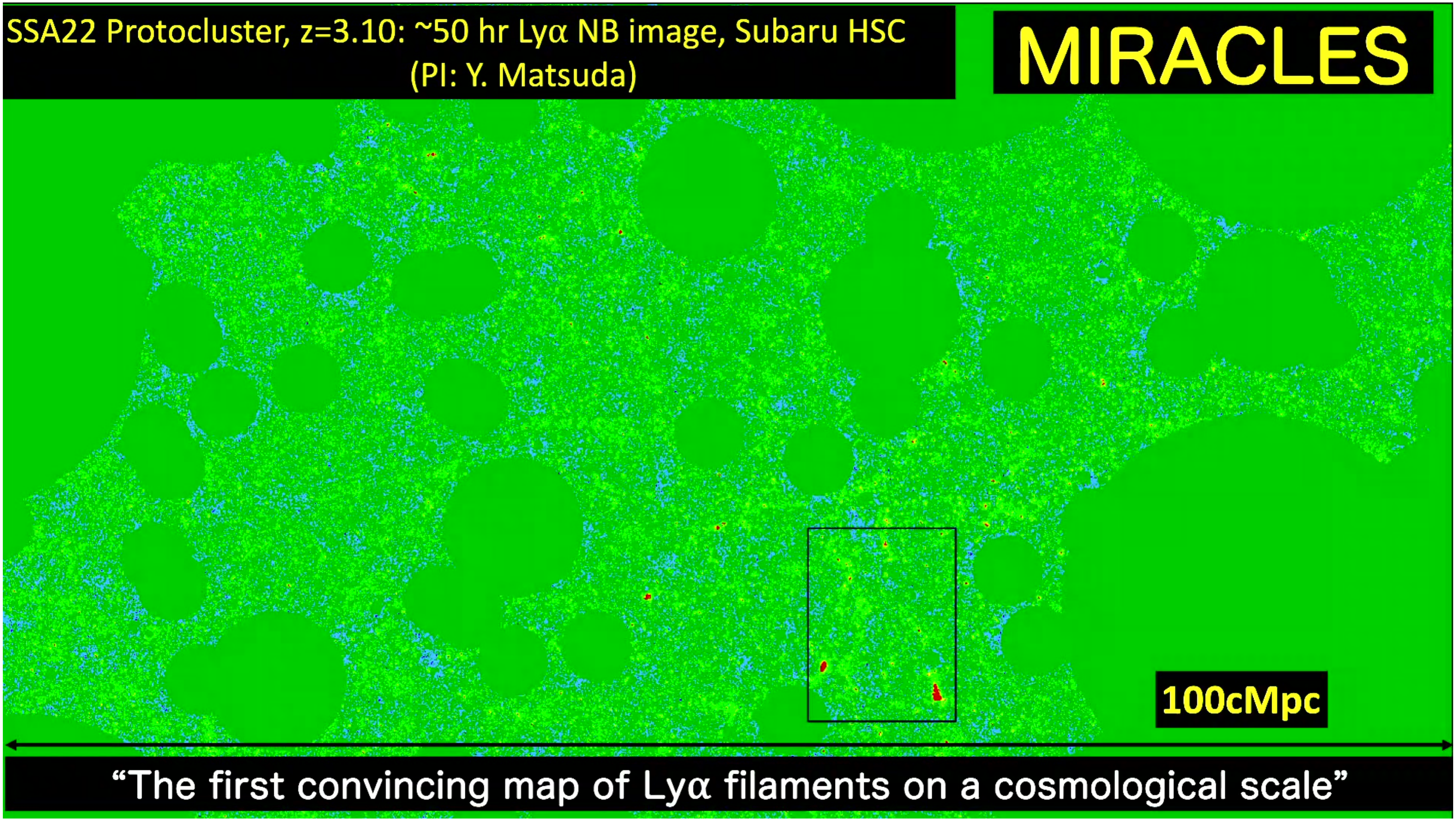
- What feedback processes are operating, as a function of time, galaxy mass, evolutionary state?
- How far do ejected gas, metals go ?
  - For which galaxies do they eventually return?
- What is the physical state of circumgalactic gas: metallicity, temperature, density, total mass?
- Do outflows compete directly with infall/accretion?
  - What are the observational signatures?
- Can we find all of the gas that is meant to be accreting?
- When did "hot atmospheres" around SF galaxies actually develop?
  - This could be important to the effectiveness of AGN feedback

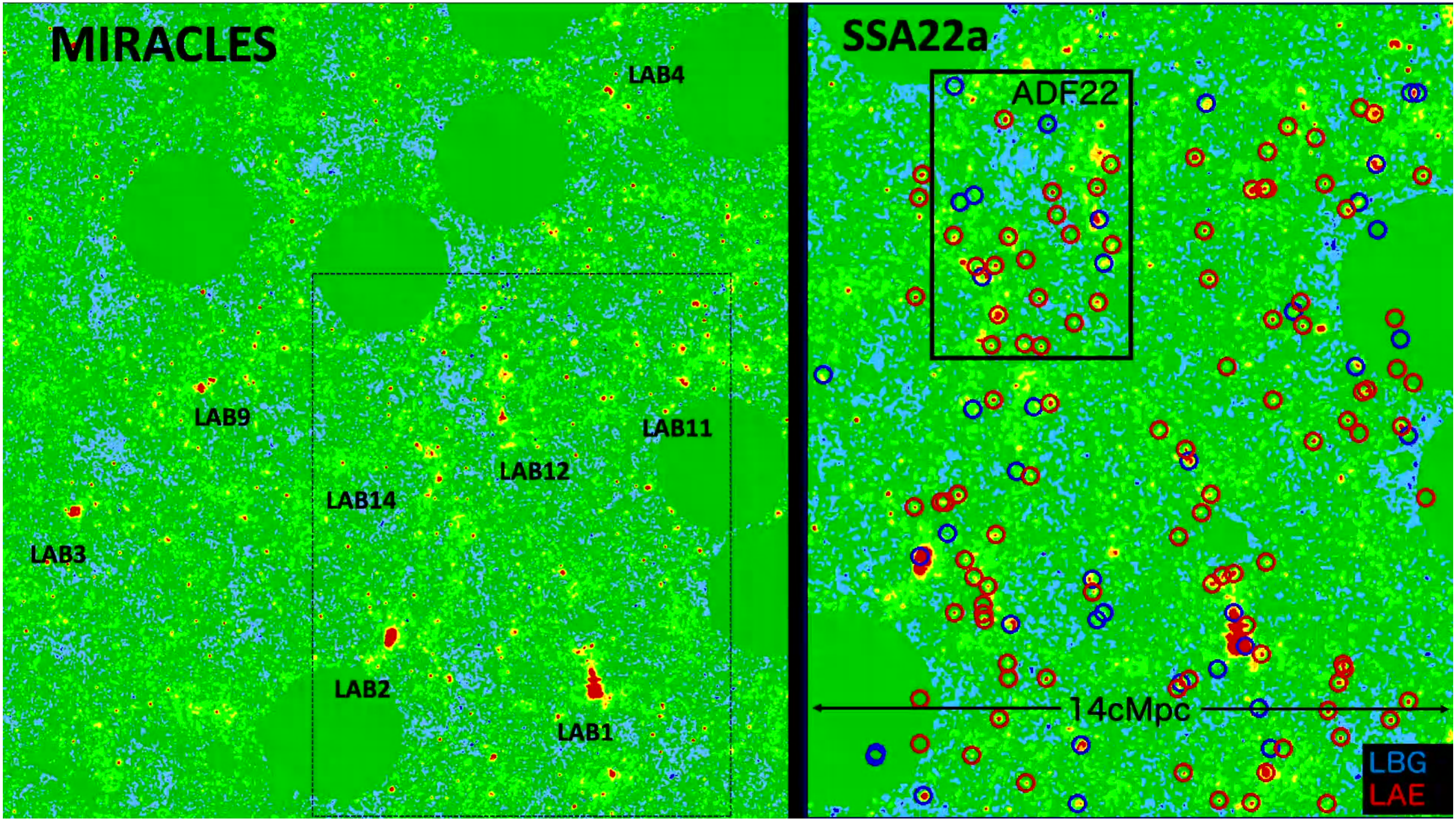
Why z=2-3 is Optimal for Establishing Statistical Baselines between Galaxies, AGN, and Diffuse Gas:

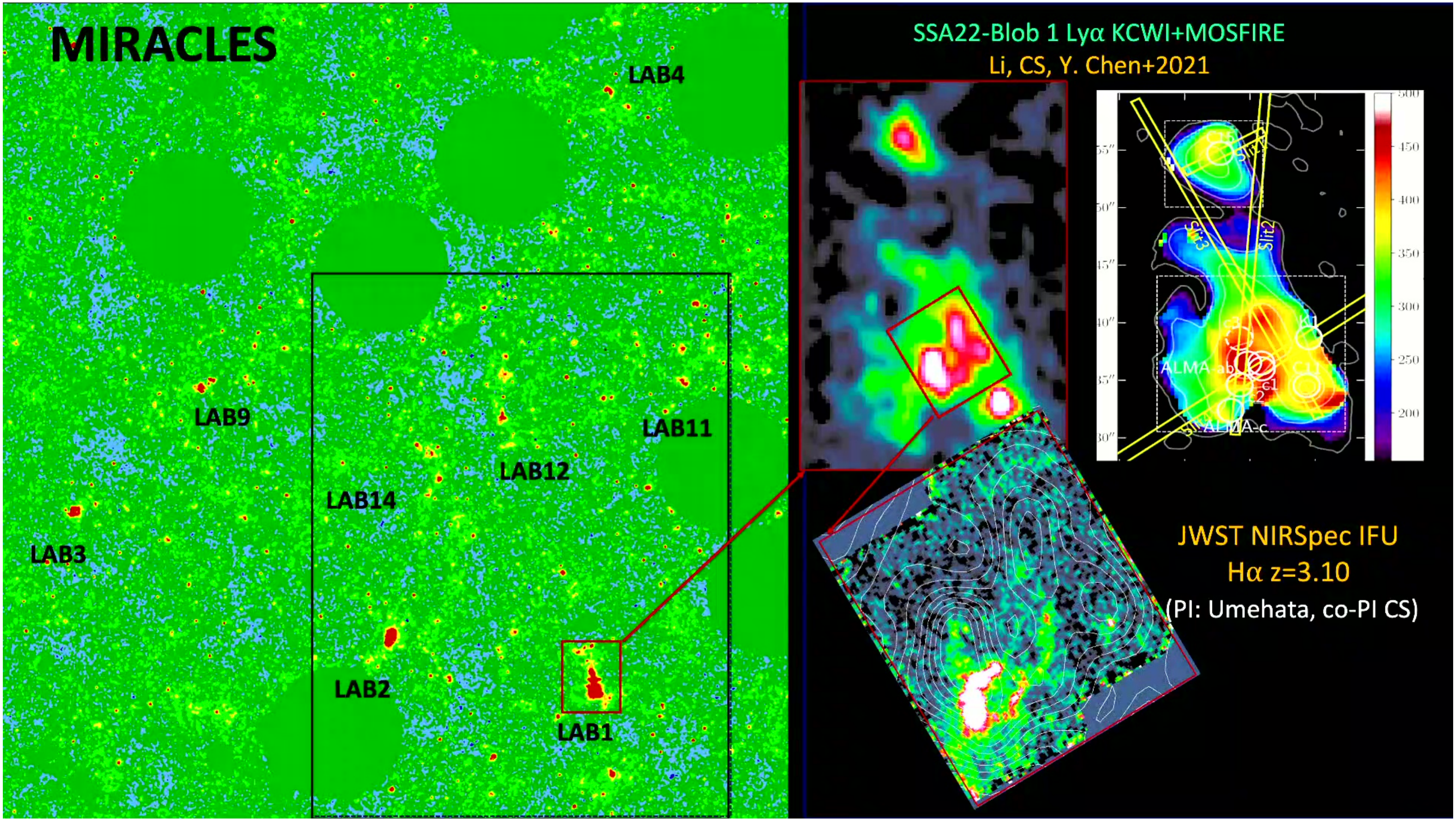
- Peak of the "epoch of galaxy formation", black hole accretion, blah, blah
- The "magic" redshift range for diagnostic rest-optical nebular spectroscopy from terrestrial sites : z=2.1-2.6

→n_e, ionization, excitation, extinction, SFR, kinematics, chemistry; long heritage from nearby galaxy studies

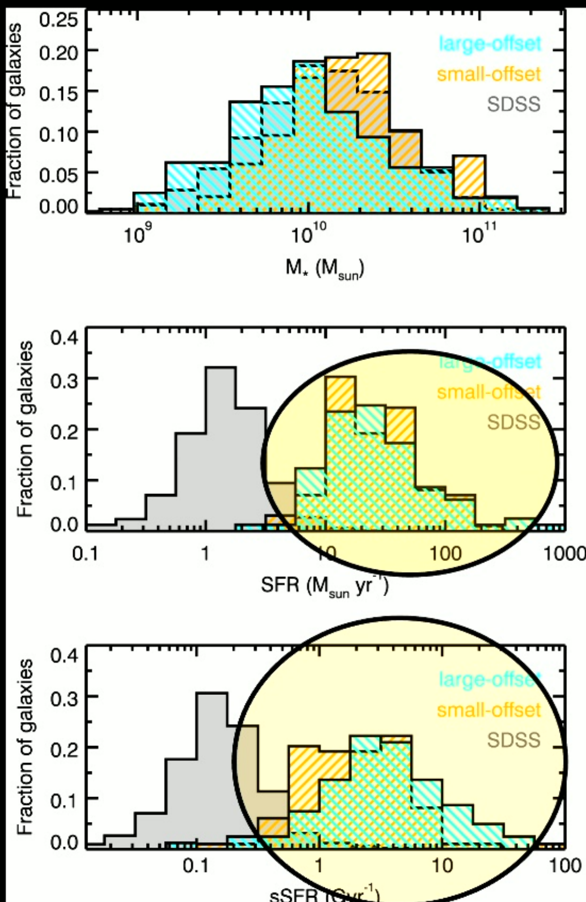
- Rest-frame far-UV can be observed without going to space, Lyα forest opacity is manageable
  - 3200-3730 Å : OVI @z=2.1-2.6 , higher Ly series
  - 3200-6000 Å Lya, Lyb, CII,CIII,CIV,SiII,SiIII,SiIV,NII,NV,etc.
  - L_{uv}* → g'=24.0 at z=2.3: lots of galaxies to make the "grid"


SSA22 Protocluster, z=3.10: ~50 hr Lyα NB image, Subaru HSC
(PI: Y. Matsuda)
MIRACLES
100cMpc
“The first convincing map of Lyα filaments on a cosmological scale”


MIRACLES
LAB4
LAB9
LAB11
LAB12
LAB14
LAB3
LAB2
LAB1
SSA22a
ADF22
14cMpc
LBG
LAE


MIRACLES
LAB4
LAB9
LAB11
LAB12
LAB14
LAB3
LAB2
LAB1
SSA22-Blob 1 Lyα KCWI+MOSFIRE
Li, CS, Y. Chen+2021
JWST NIRSpec IFU
Hα z=3.10
(PI: Umehata, co-PI CS)

Except for M_{star} , z~2.5 galaxies (and their AGN) are disjoint populations relative to z~0.

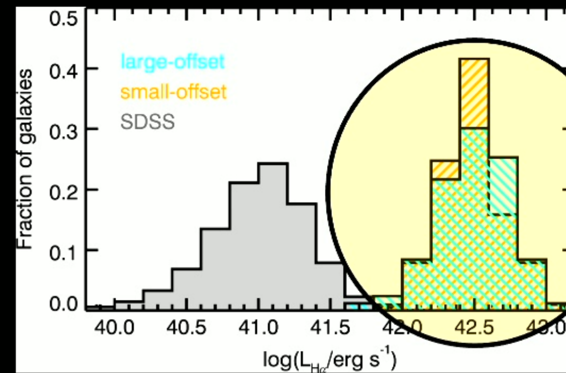


M_*

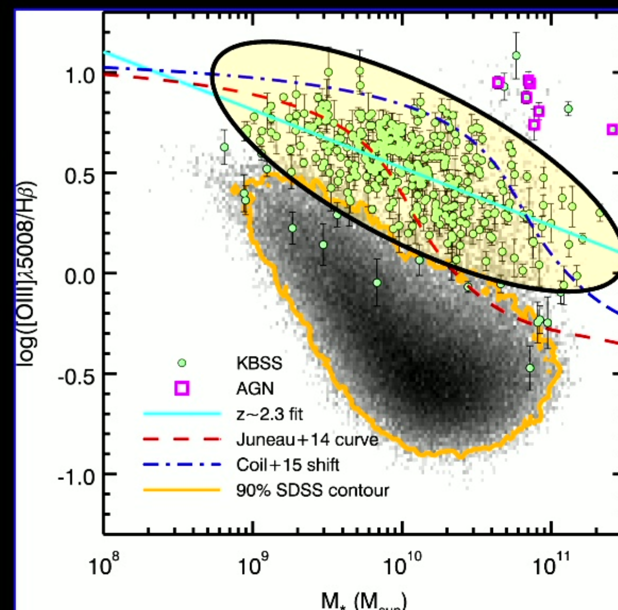
SFR

sSFR

L(Hα)



Excitation

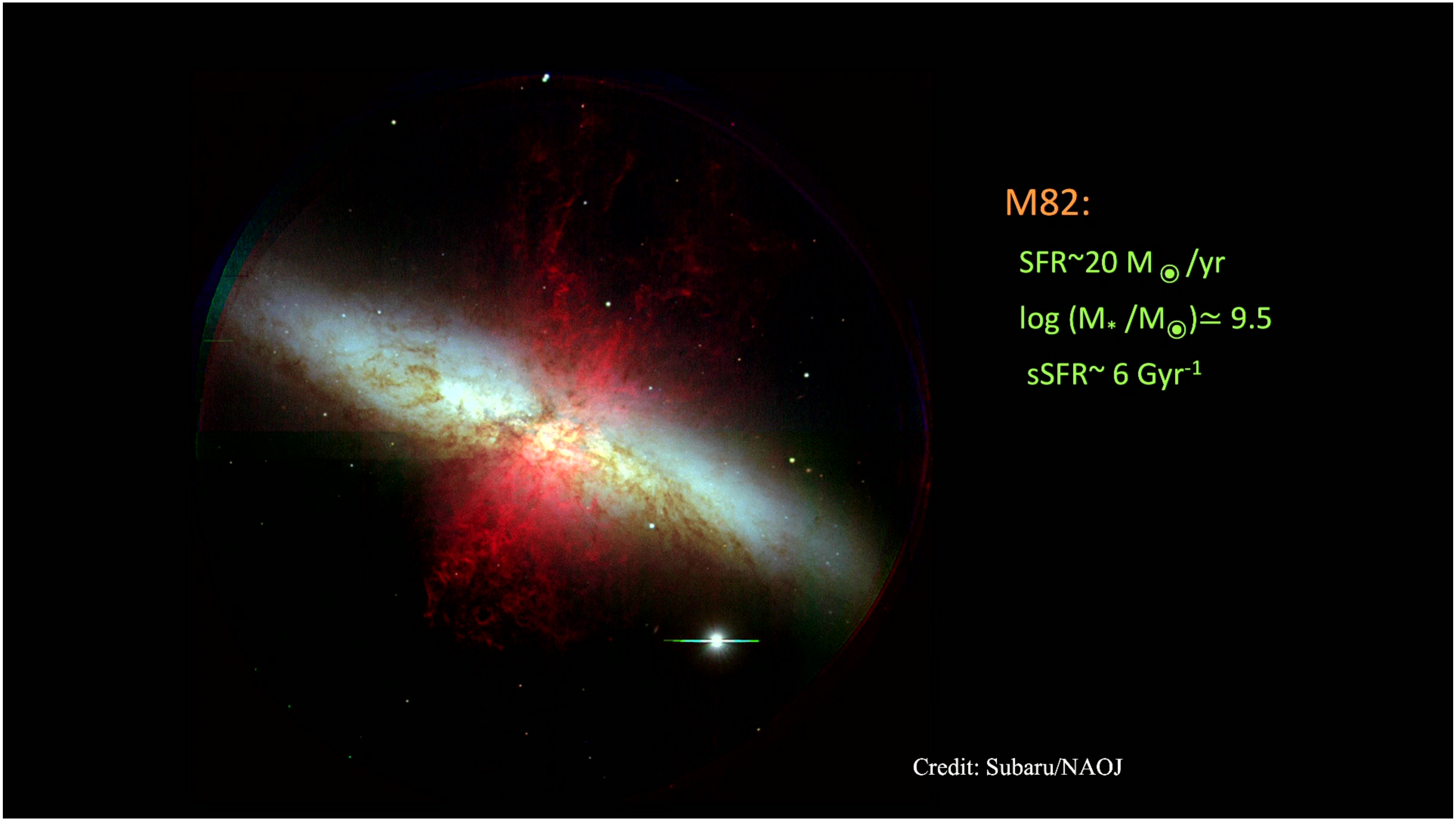


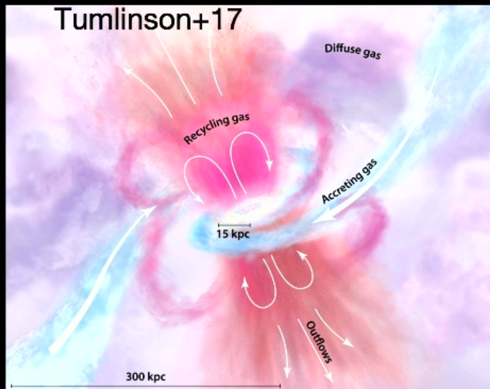
Strom, CS, Rudie+2017

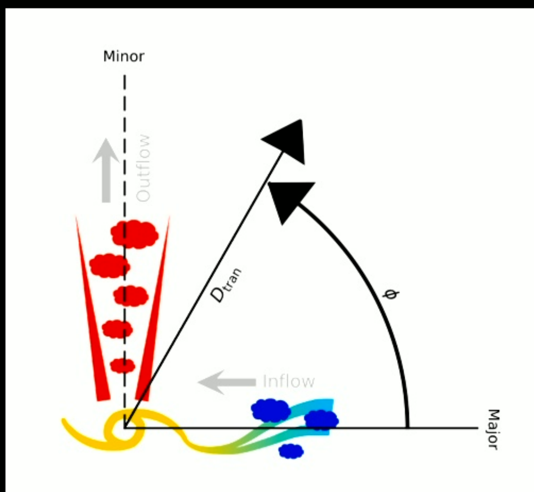
Comparing apples to apples….

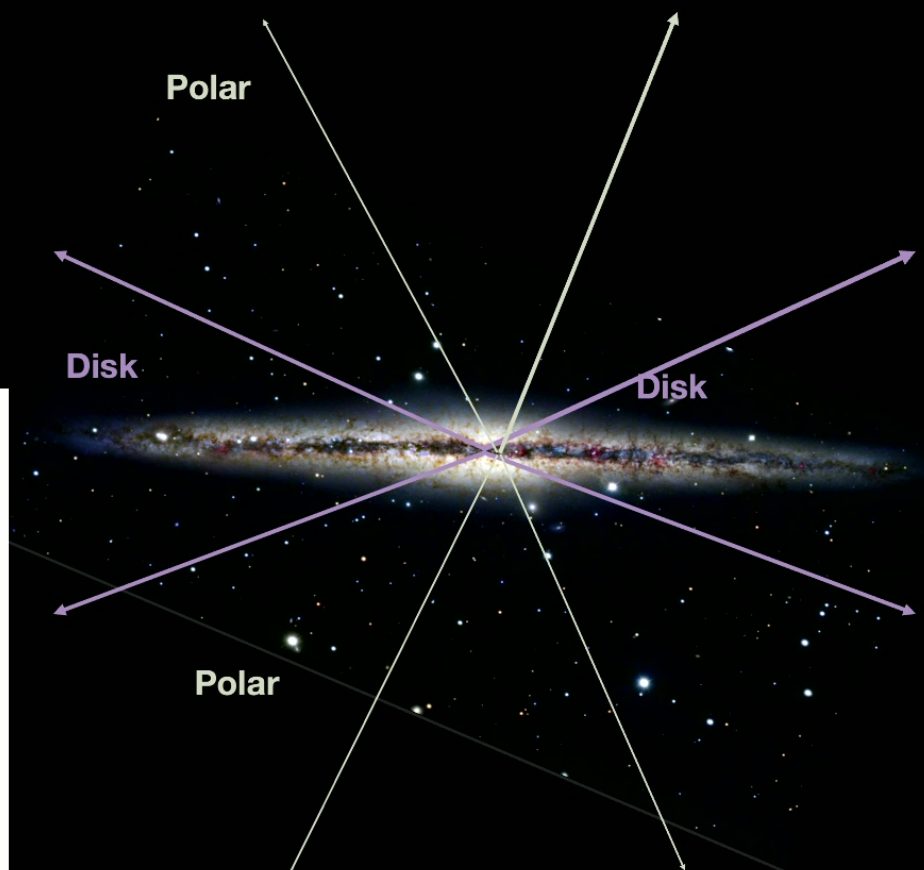
	Z~0	Z~2.5	Comment
$\log (M_h/M_\odot)$	13.1	12.5	QSO hosts @z~2.5
$\log (M_*/M_\odot)$	11.1	10.2	
R_{200}	450 pkpc	135 pkpc	LRGs/groups @z~0
$\mathrm{sSFR/Gyr^{-1}}$	<0.05	2.5	
$\log (M_h/M_\odot)$	12.0	11.5	MW progenitor @z~2.5
$\log (M_*/M_\odot)$	10.5	9.2	
R_{200}	~225 pkpc	~60 pkpc	MW @z~0
$\mathrm{sSFR/Gyr^{-1}}$	0.08	5.0	

Most of the galaxies that had reached log (M*/Ms) >10 at z=2.5 are passive now; the only local galaxies that come close to the typical z~2.5 galaxy are M82-like

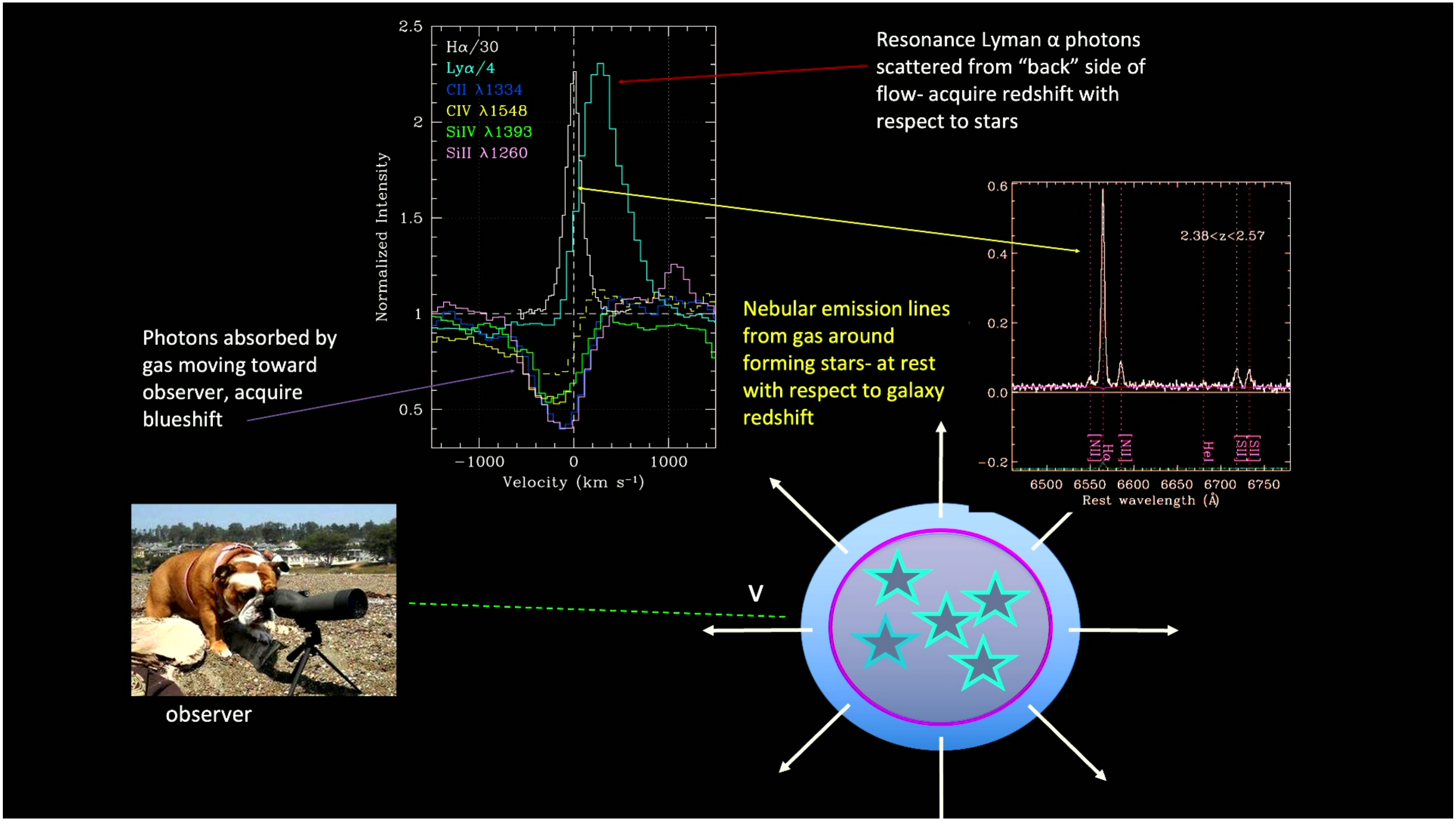

M82:
SFR~20 $M_\odot$/yr
log $(M_* / M_\odot) \simeq 9.5$
sSFR~ 6 Gyr^{-1}
Credit: Subaru/NAOJ



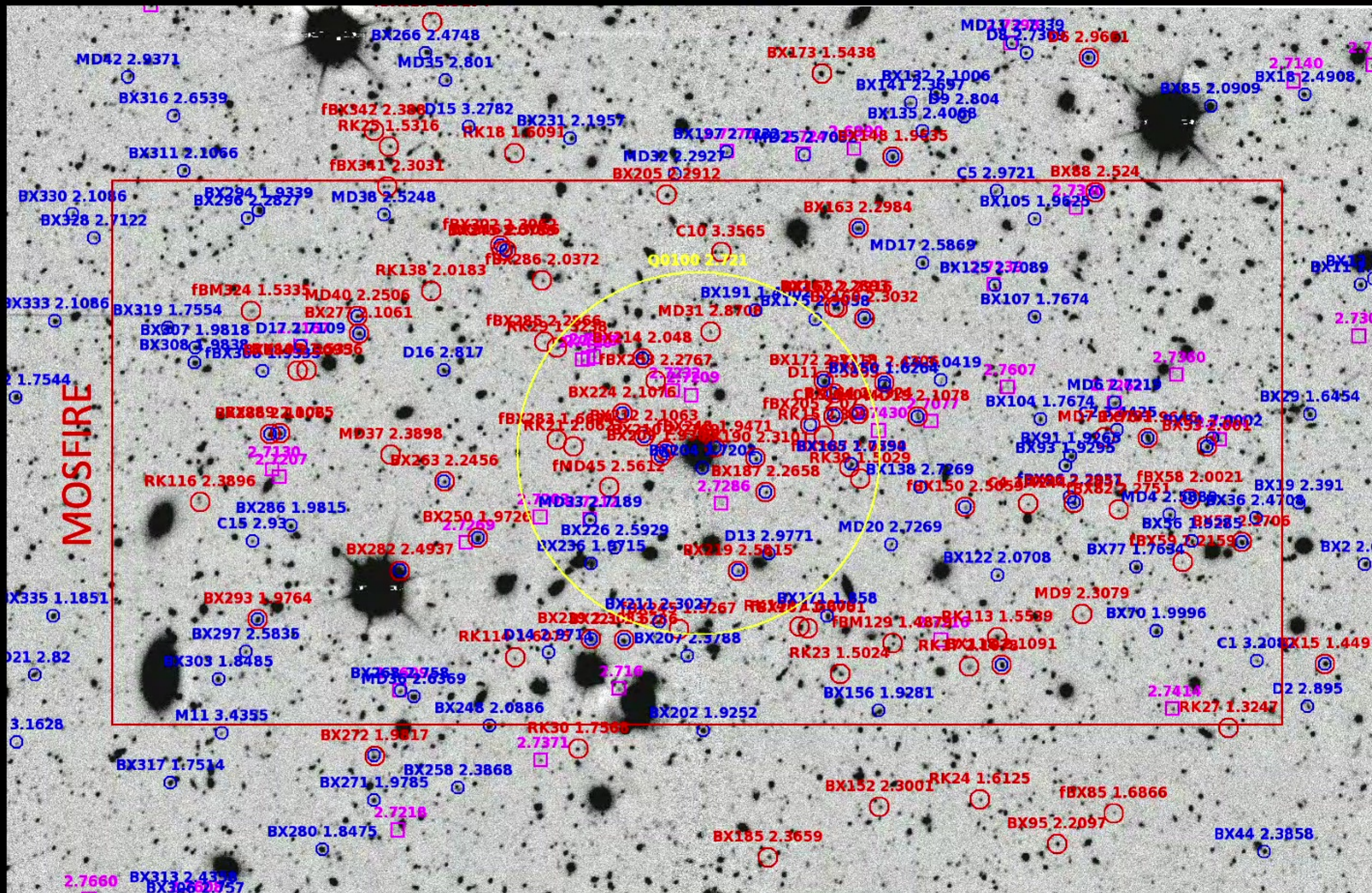




Does the “bi-conical outflow”, quasi-collimated picture work at high redshift (z>2)?

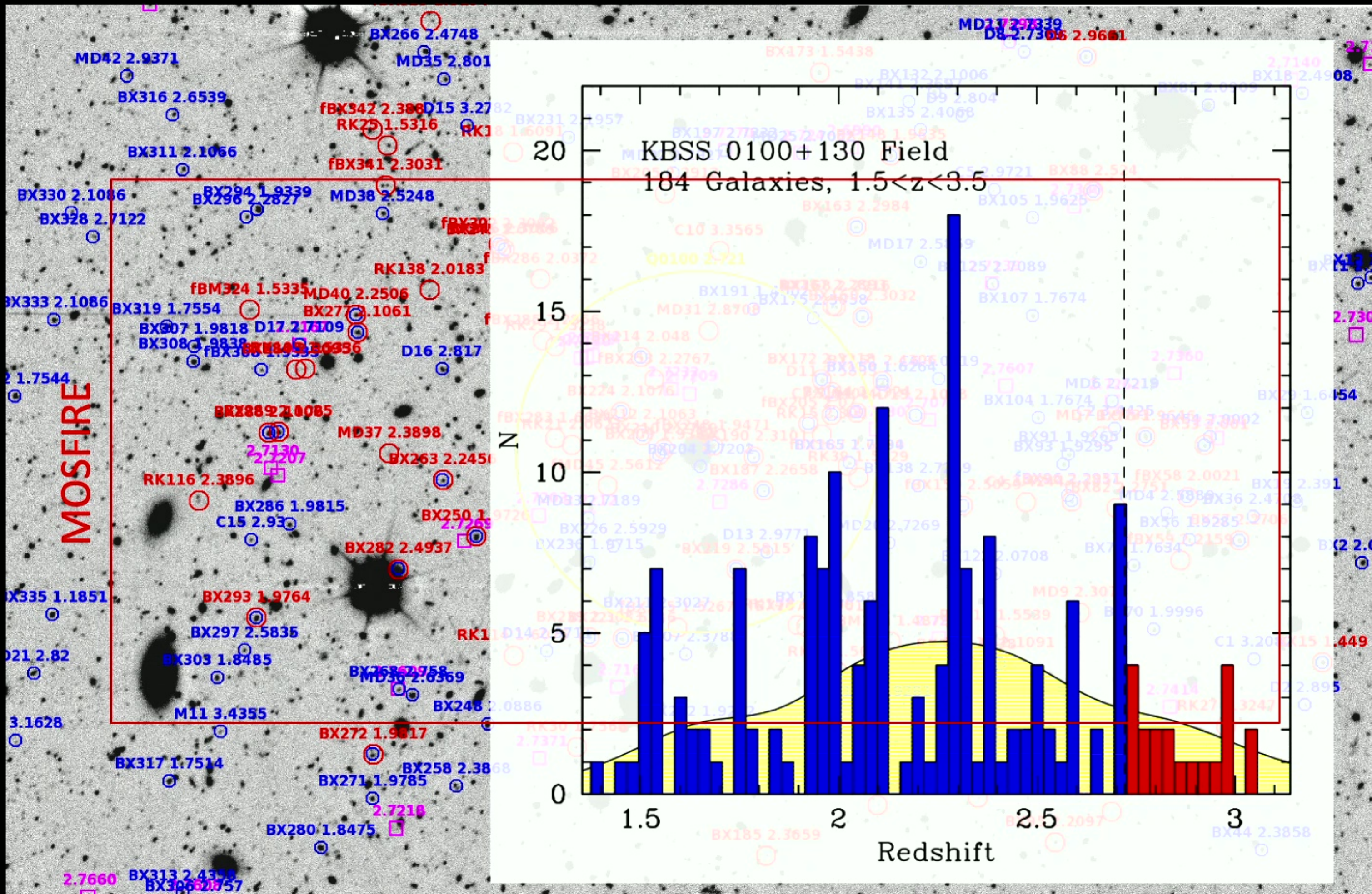

Resonance Lyman α photons scattered from “back” side of flow- acquire redshift with respect to stars
Hα/30
Lyα/4
CII λ1334
CIV λ1548
SiIV λ1393
SiII λ1260
Normalized Intensity
Velocity (km s⁻¹)
Photons absorbed by gas moving toward observer, acquire blueshift
Nebular emission lines from gas around forming stars- at rest with respect to galaxy redshift
2.38<z<2.57
Rest wavelength (Å)
[NII]
Hα
[NII]
HeI
[SII]
[SII]
observer
V

Typical Field, 5.5’ x 7’, 240 spectroscopic redshifts , z~1.5-3.5



KBSS 0100+13 z_Q=2.721

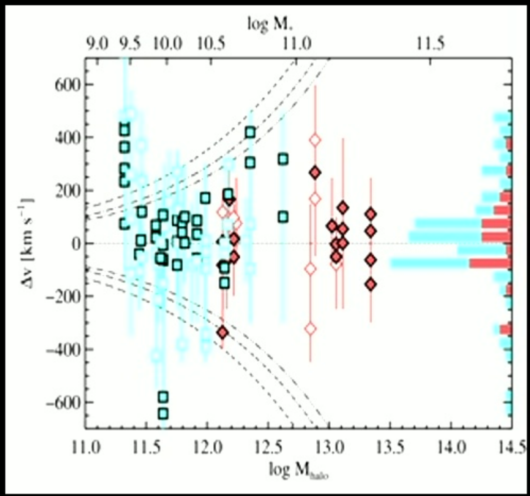
Typical Field, 5.5' x 7', 240 spectroscopic redshifts , z~1.5-3.5



KBSS 0100+13 z_Q=2.721

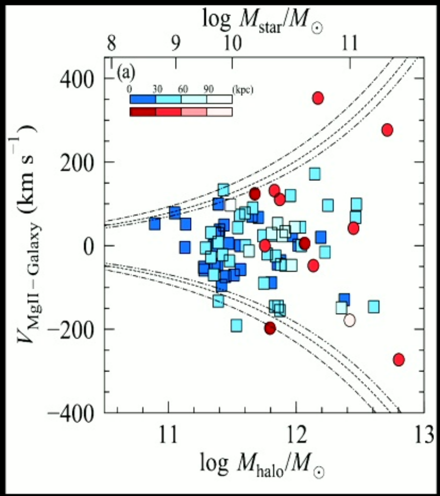
Kinematics of the Low-z CGM

Neutral Hydrogen



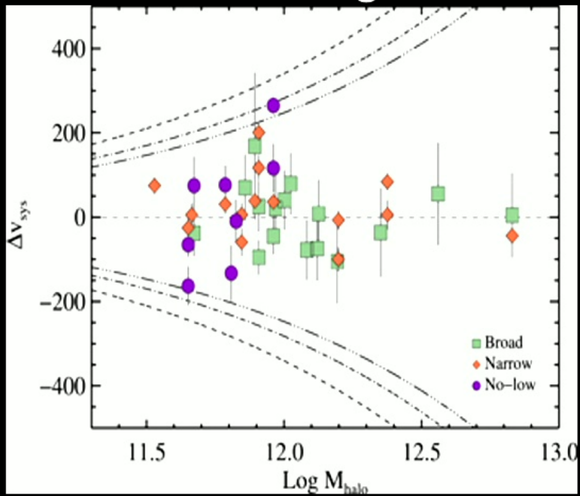
Tumlinson+ 2013

MgII ~10^4 K gas



Huang+ 2021

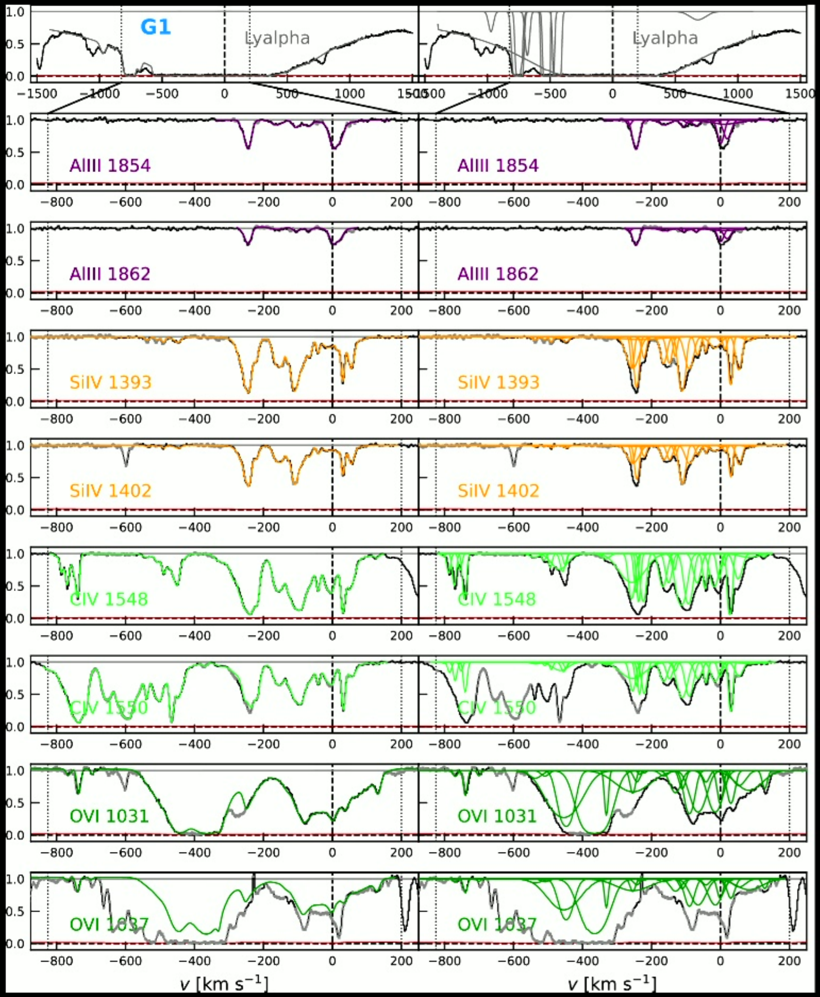
OVI ~10^5 K gas

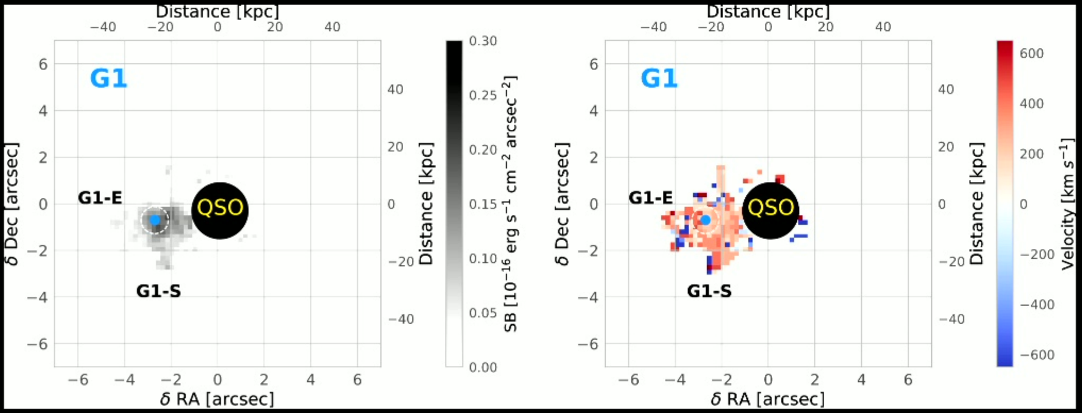


Werk+ 2016

All probed phases of the CGM are bound in L* and massive galaxies.

KBSS “In-CLOSE” : KCWI+MOSFIRE





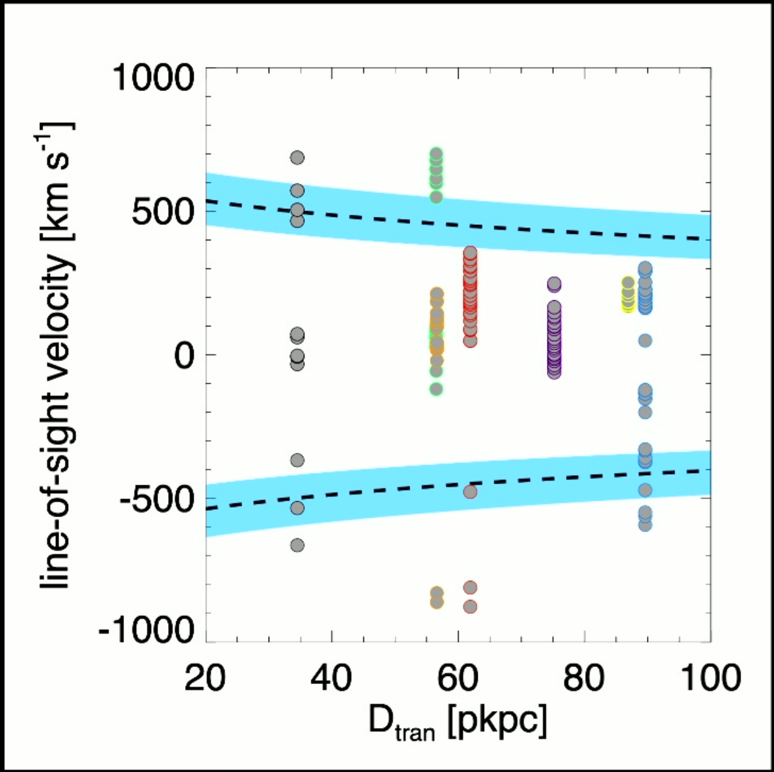
Sub-DLA, z=2.432, D=26 kpc
Δv(CIV,OVI)~ 1000 km/s

G1, z=2.4343
log($M_*/M_\odot$)=9.9
SFR =15 $M_\odot$/yr
log (sSFR) = -8.69

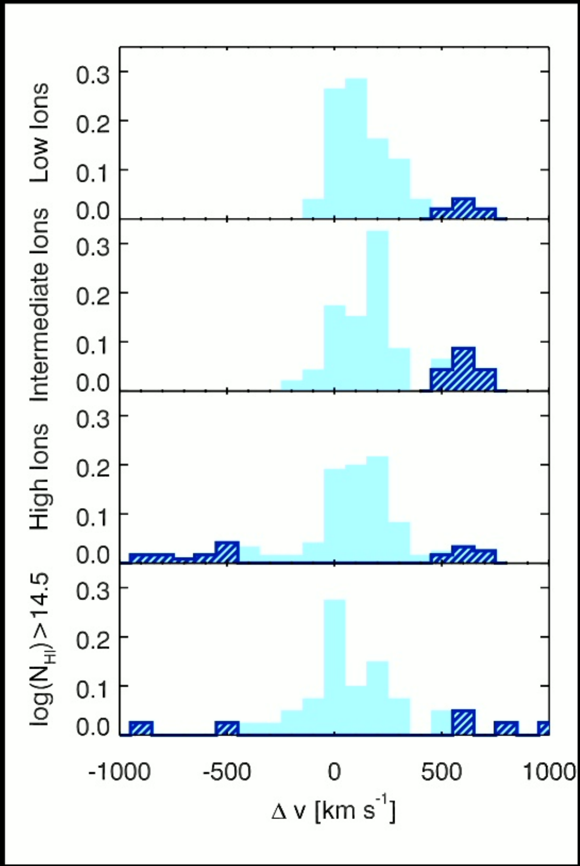
Nunez, CS, Kirby, Rudie,+2024

E. Nunez-Cravin,
Caltech PhD 2025

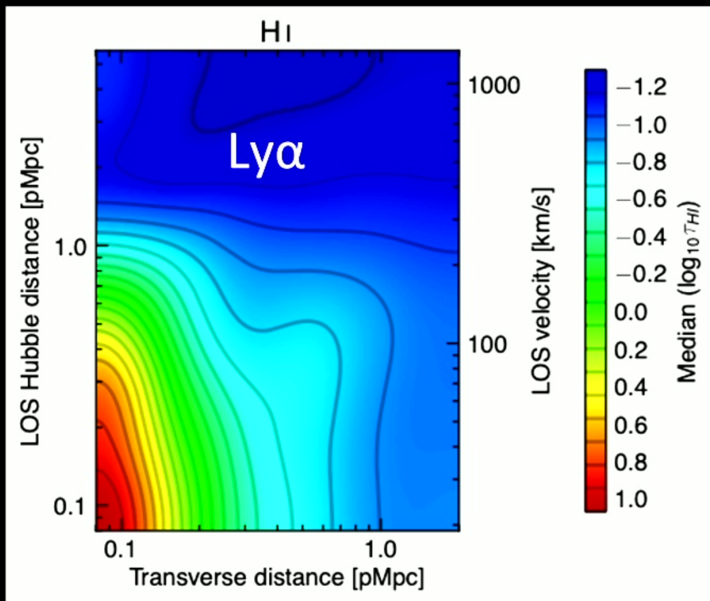
Most high-z galaxies have unbound metal-enriched gas within 100 kpc and 1000 km/s

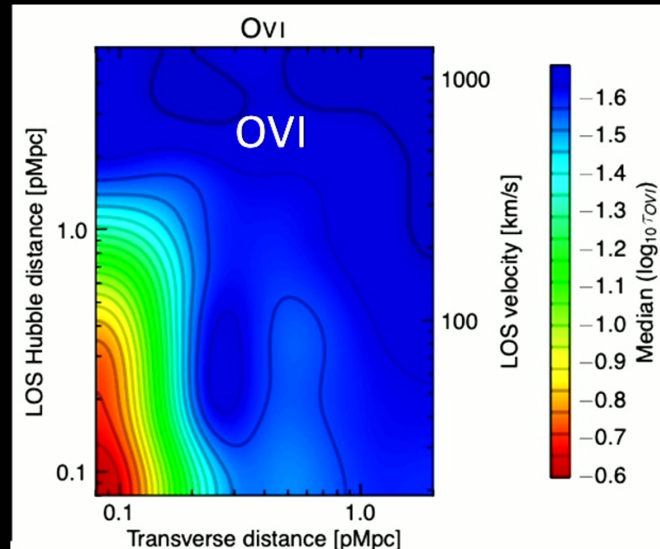


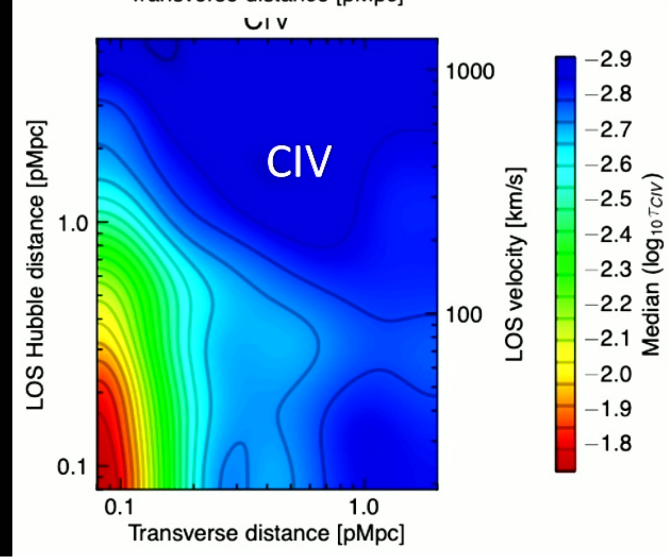
Rudie, CS,+ 2019



KBSS Galaxy-centric 2-D maps of HI, metals







Turner+2014, KBSS-MOSFIRE sample

Galaxy redshifts to σ≈15 km/s

The Smoking Gun of Galaxy Feedback?:

- hot (>300,000 K) Gas within 200 kpc of forming galaxies…
- near-solar metal content, and still moving at high velocity
- <z>=2.4, <d>=140 kpc (physical).

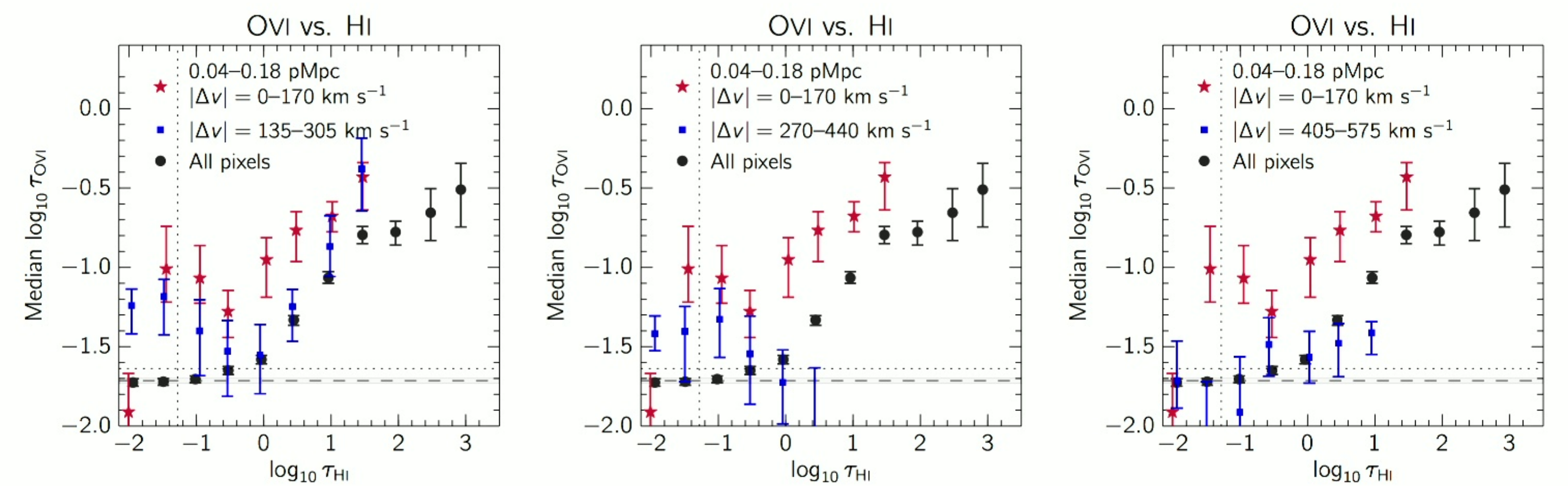
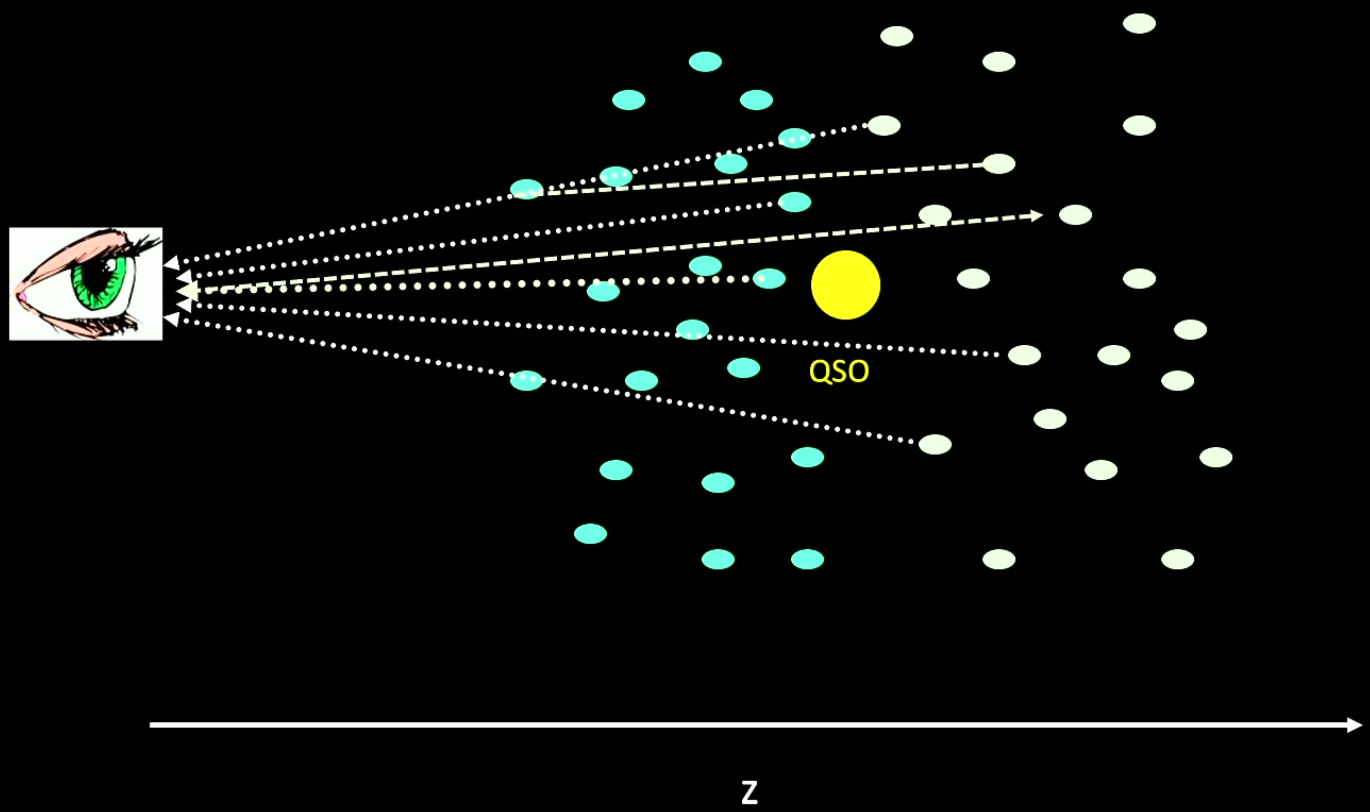


Figure 2. The same as Fig. 1 but we have overplotted the result of taking different velocity cuts when considering the small galactocentric distance points (blue squares). We have chosen velocity bins such that each cut spans the same velocity range of 340 km s^{-1}, and find that the enhancement of OVI at fixed $\tau_{\rm HI}$ is present for $\tau_{\rm HI} \lesssim 0.1$ out to the $|\Delta v| = 270$–440 km s^{-1} velocity cut. Using the central value of this velocity range as our upper limit, we conclude that the enhancement persists out to ~ 350 km s^{-1}, which is $\gtrsim 1.5$ times the typical circular velocities of the galaxies in our sample.

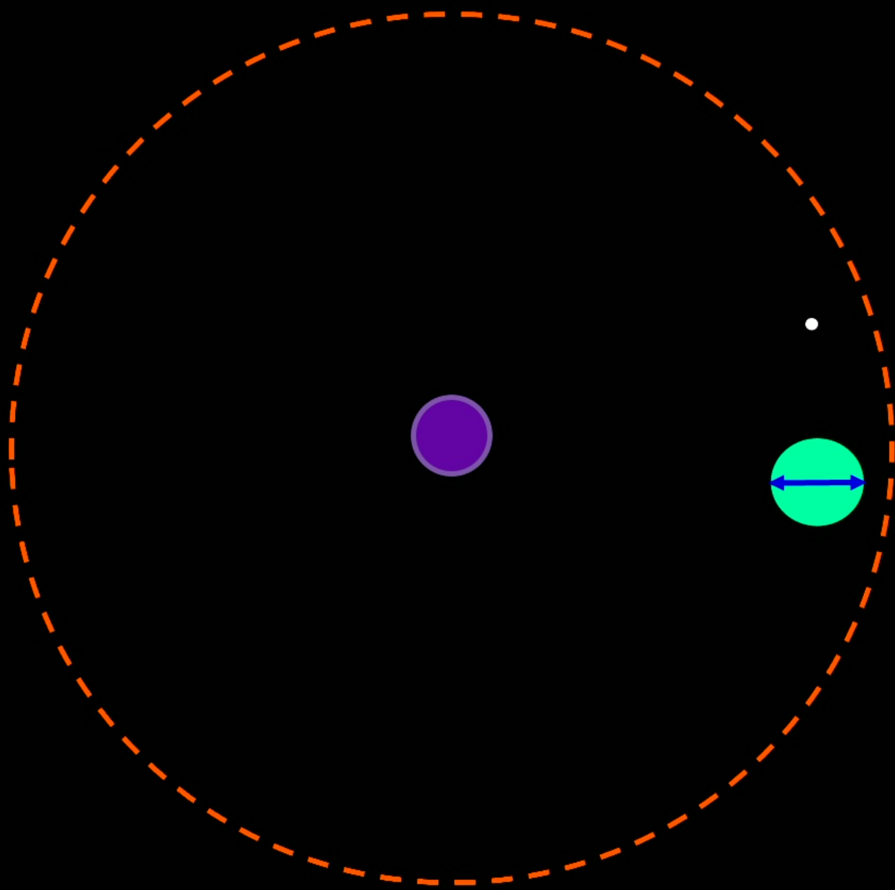
Turner, Schaye, CS, Rudie, Strom 2015

Densely Sampling the Universe @z~1.8-3.2

Learning to love the “Lo-fi grid”



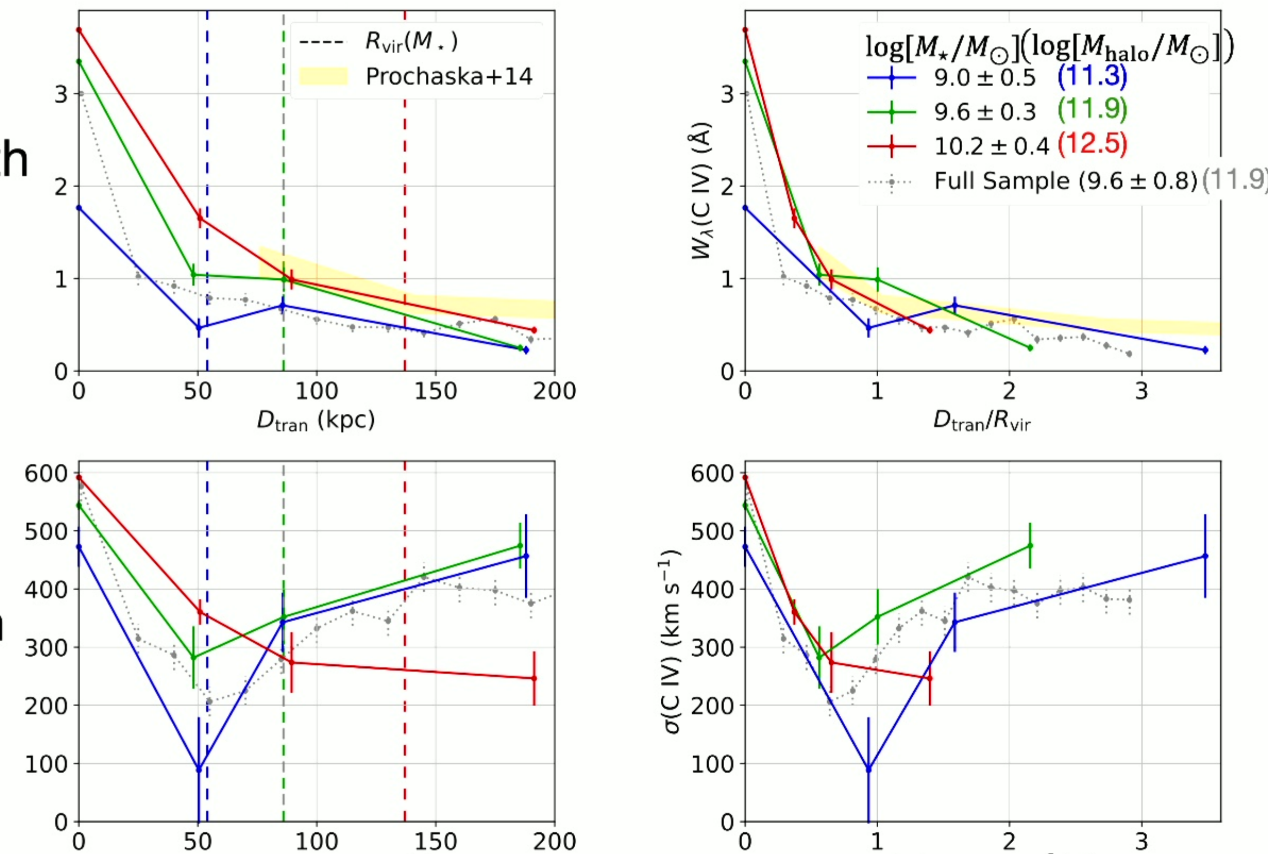
Galaxies vs. Point Sources as Probes of CGM



C IV vs. $M_\star$

Equivalent Width W_λ (Å)

Velocity Dispersion σ (km s^{-1})

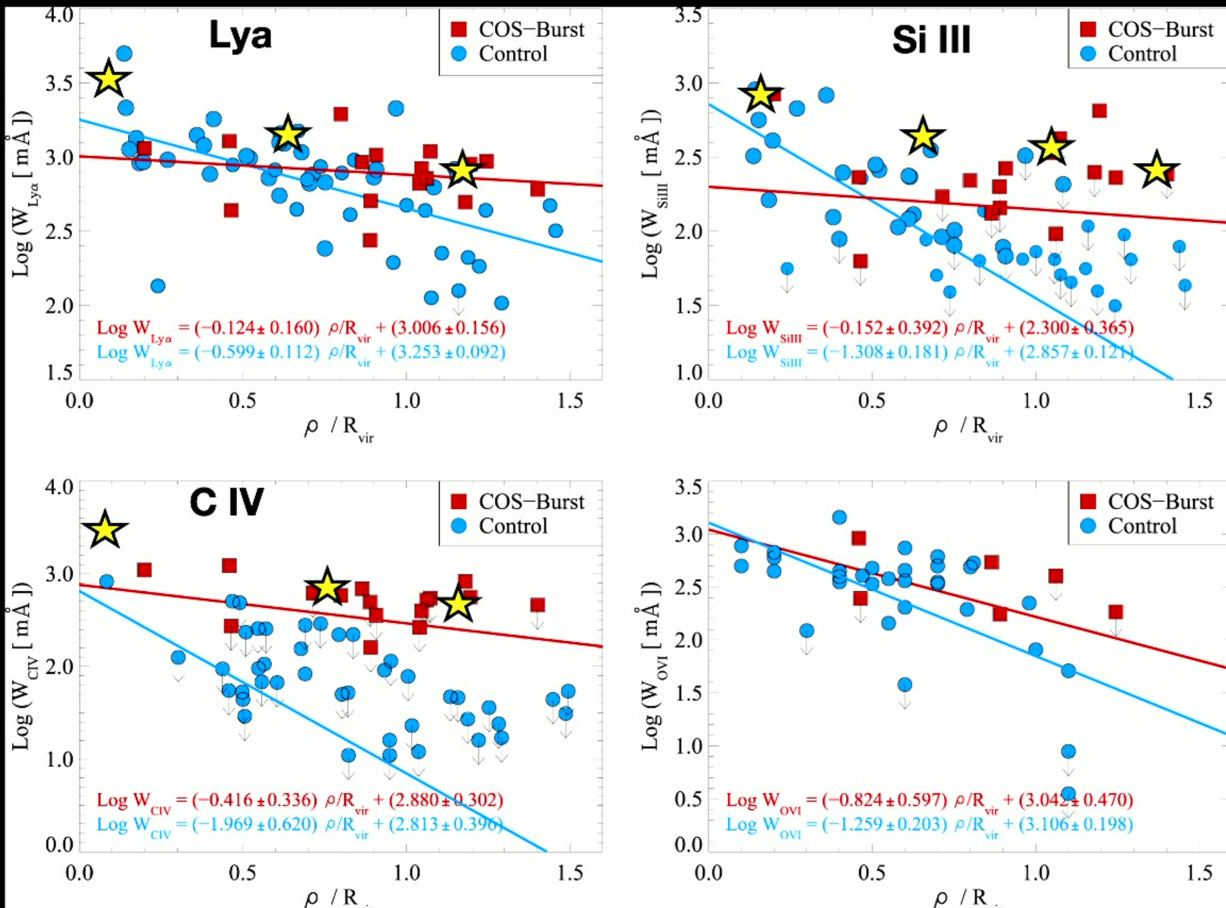


N. Prusinski's talk

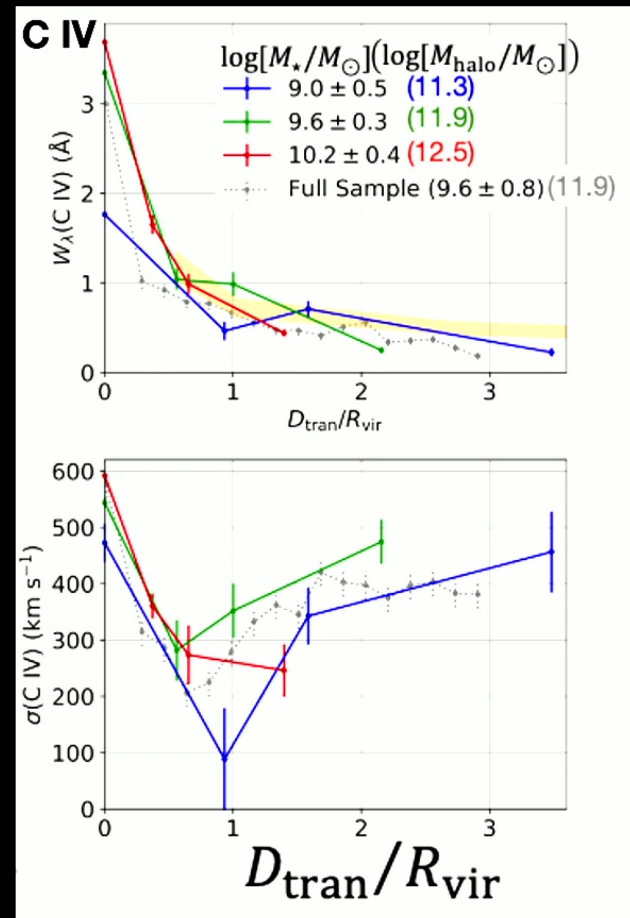
Impact Parameter D_{tran} (kpc)

D_{tran}/R_{vir}

Absorption Line Strength vs. Impact Parameter

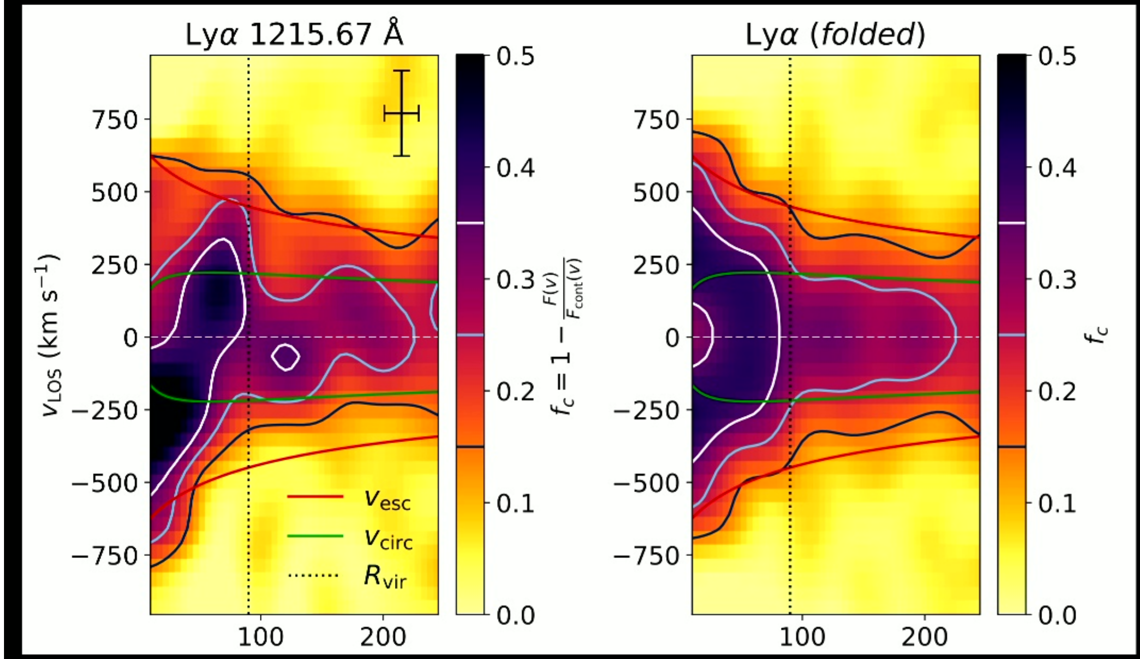


Heckman+2017 “COS-Burst”



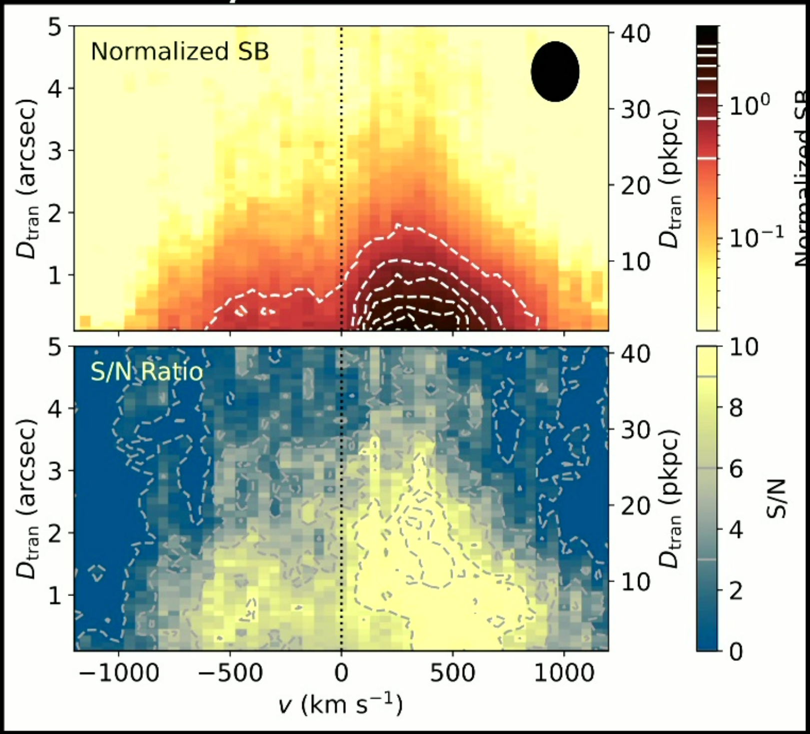
Prusinski, CS, Chen 2025 - KBSS Pairs

Lyα Absorption



Prusinski, CS, Y. Chen 2025

Lyα Emission

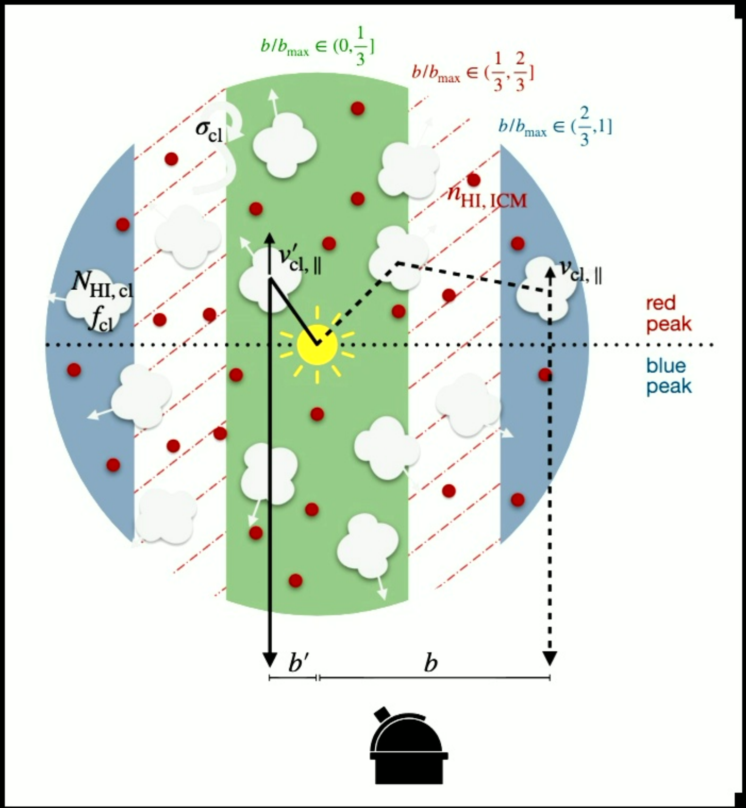


Y. Chen,CS,+2025

Clumpy Outflow Model

(e.g., CS+2010, 2011; Dijkstra+2012; Gronke+2016; Li, CS, Gronke+2020,2021, Li+Gronke 2022, Erb, Li, CS, Chen, Gronke+2023)

Zhihui Li , PhD 2024



- Model CGM as 2-phase medium:
  - clumps, inter-clump medium
  - parameters $v_{\rm cl}, f_{\rm c}, n_{\rm ICM}, \sigma_{\rm cl}$

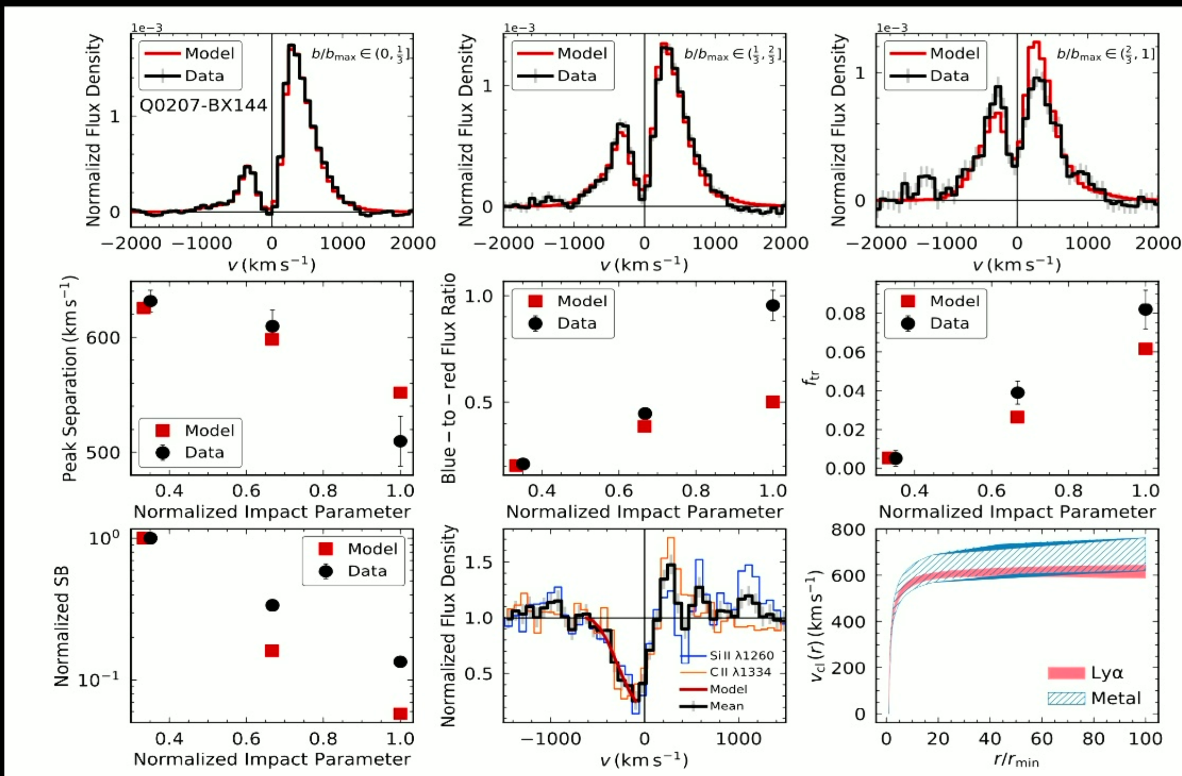
Use observations to constrain the parameters

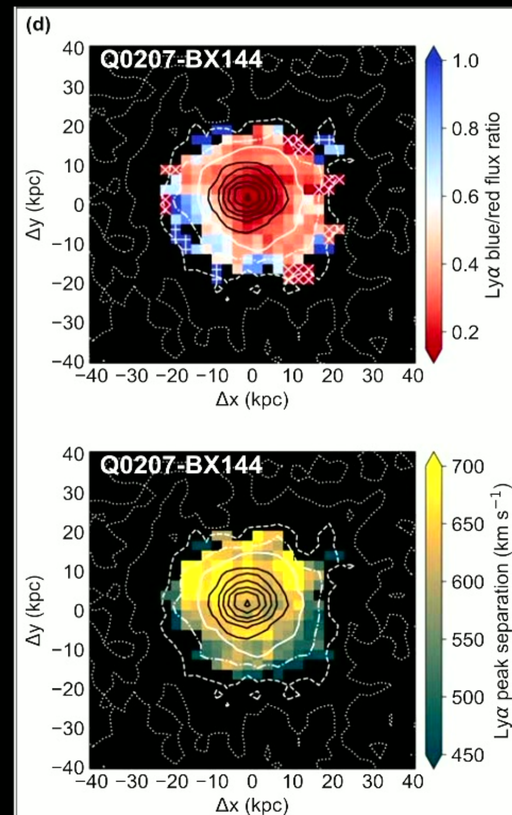
Basic idea: moving clumps act as the scattering medium: depth of lines "down the barrel" modulated by ion "covering fraction" $f_{\rm c}$

Clumps also responsible for scattering Lyα photons until they can escape

Clumpy Outflows RT Models Applied to Individual Galaxies

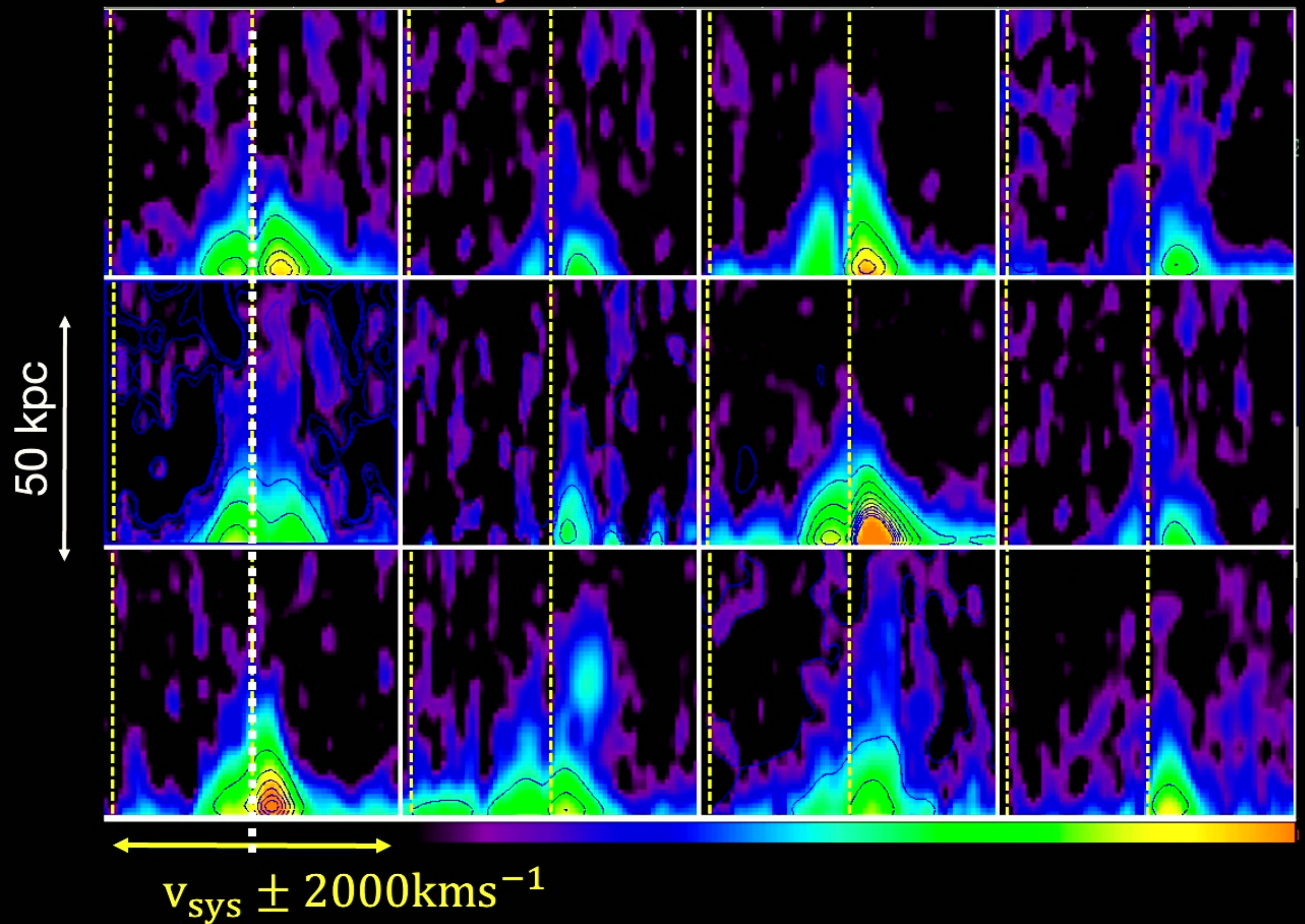
Q0207-BX144 Lya Halo: spatial-spectral fit





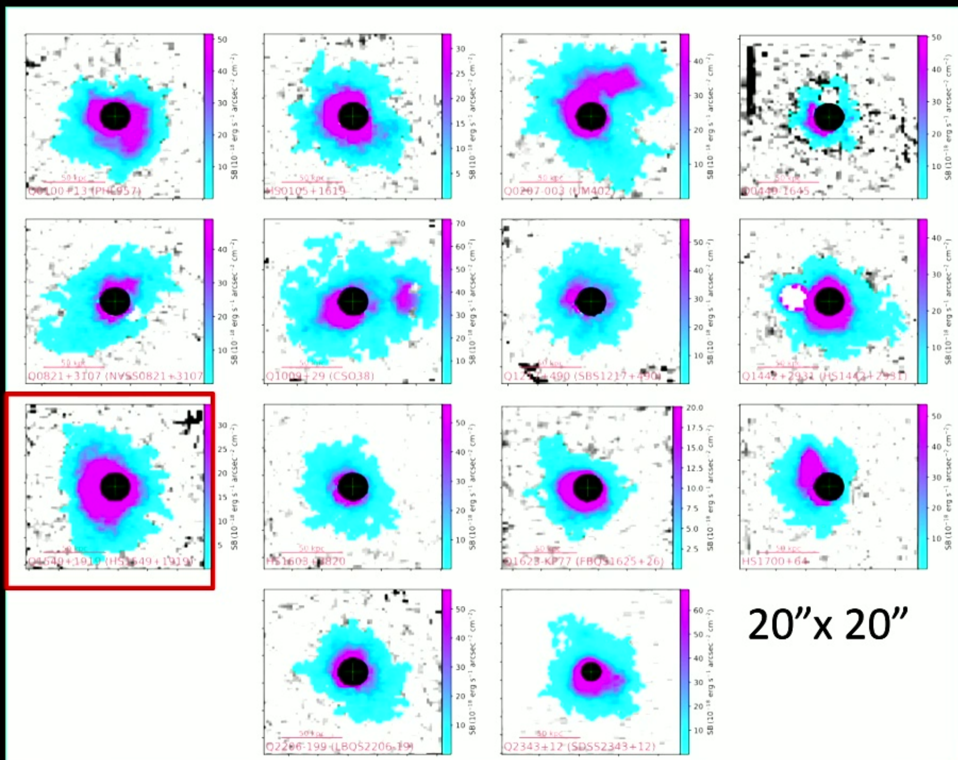
Erb, Zhihui Li, CS, Y. Chen, Gronke+2023

Individual KCWI Lyman-α Radial/Kinematic Profiles

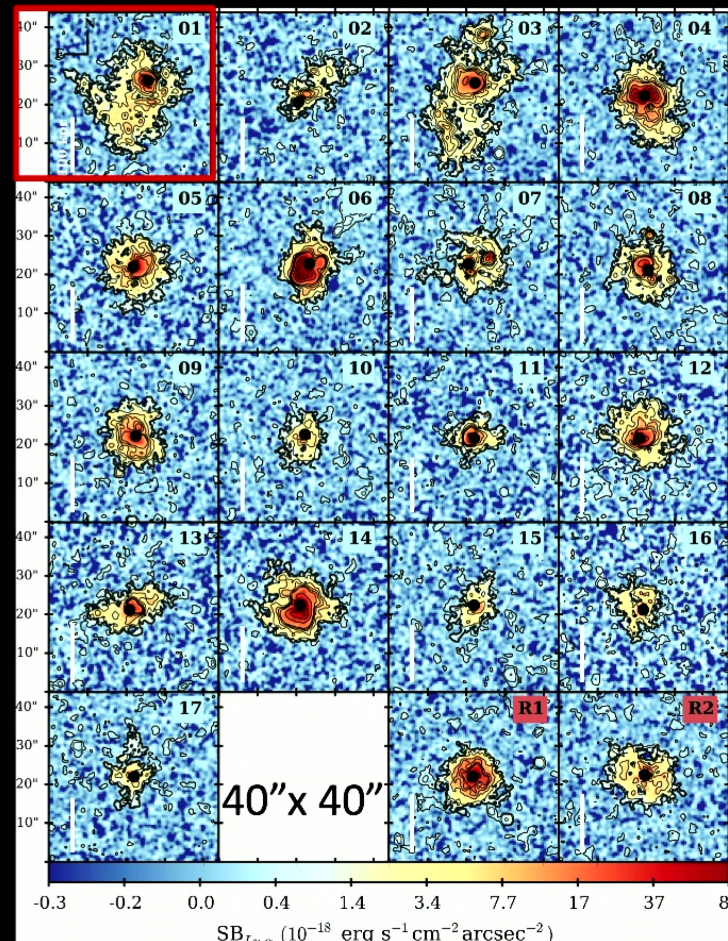


QSO Lyman-α Nebulae @z=2-3.5

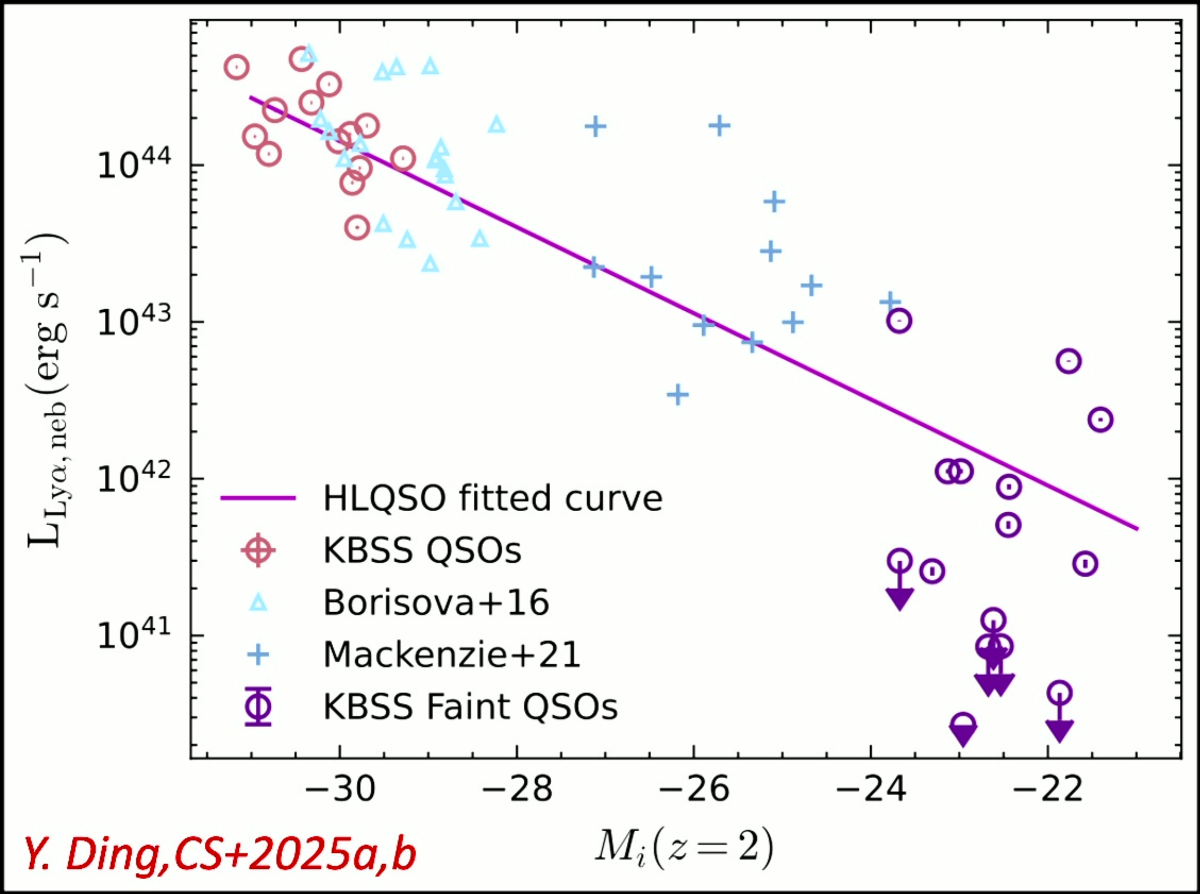
Borisova, Cantalupo,+2016 VLT/MUSE



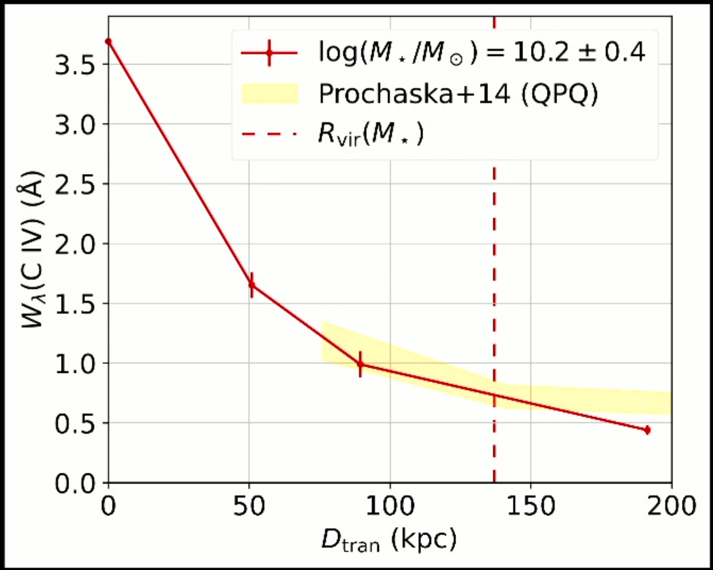
Ding, CS,+2025
KBSS-KCWI HLQSOs



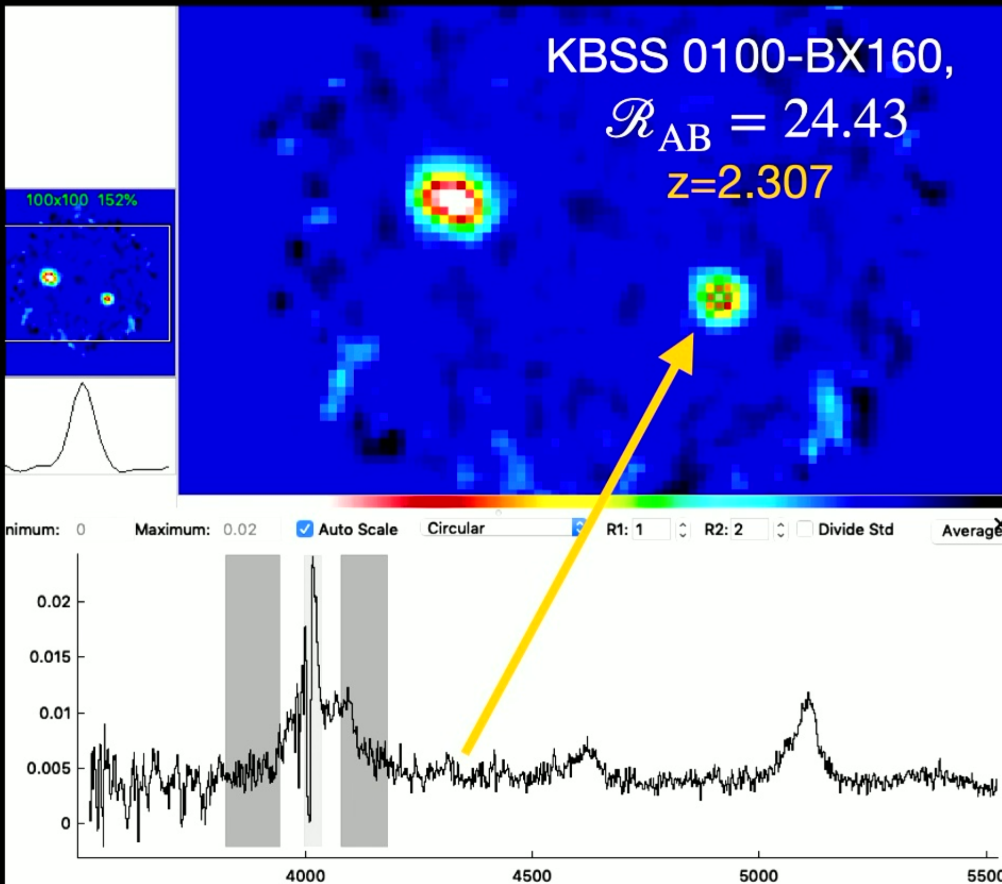
Cold Gas Around (Type 1) QSOs at all luminosities:



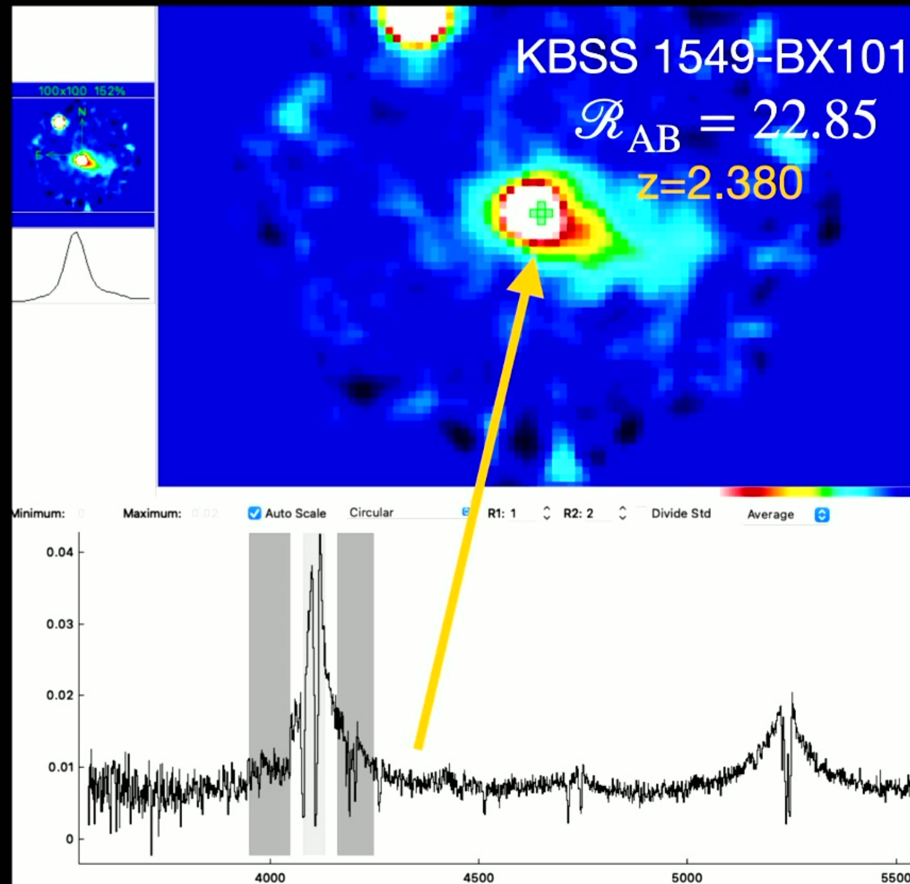
- $\log(L_{bol}/L_{\odot})$ =10.7-15.3
- $L(Ly\alpha) \sim L_{bol}^{0.1}$
- all in halos with $\log(M_h/M_s) \simeq 12.5$ (as for the highest M_* bin @z=2.5)



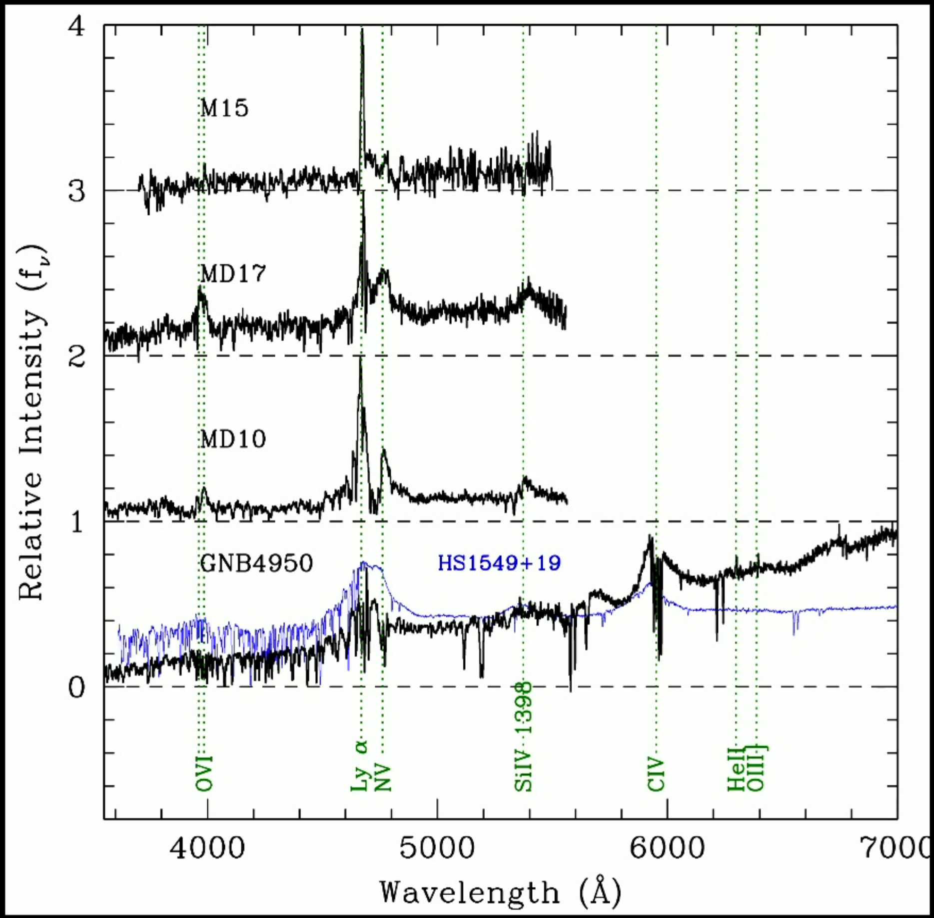
Faint Type 1 QSOs in KBSS-KCWI sample , with and without Lyα nebulae

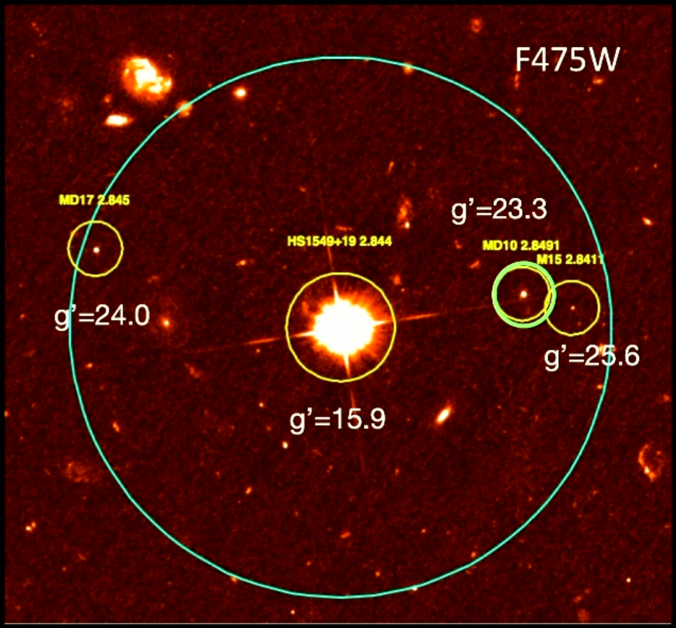


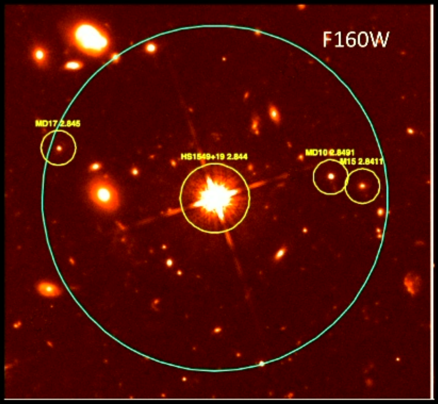
No Ly-alpha halo (also no NLR)



Bright Ly-α halo (strong NLR)



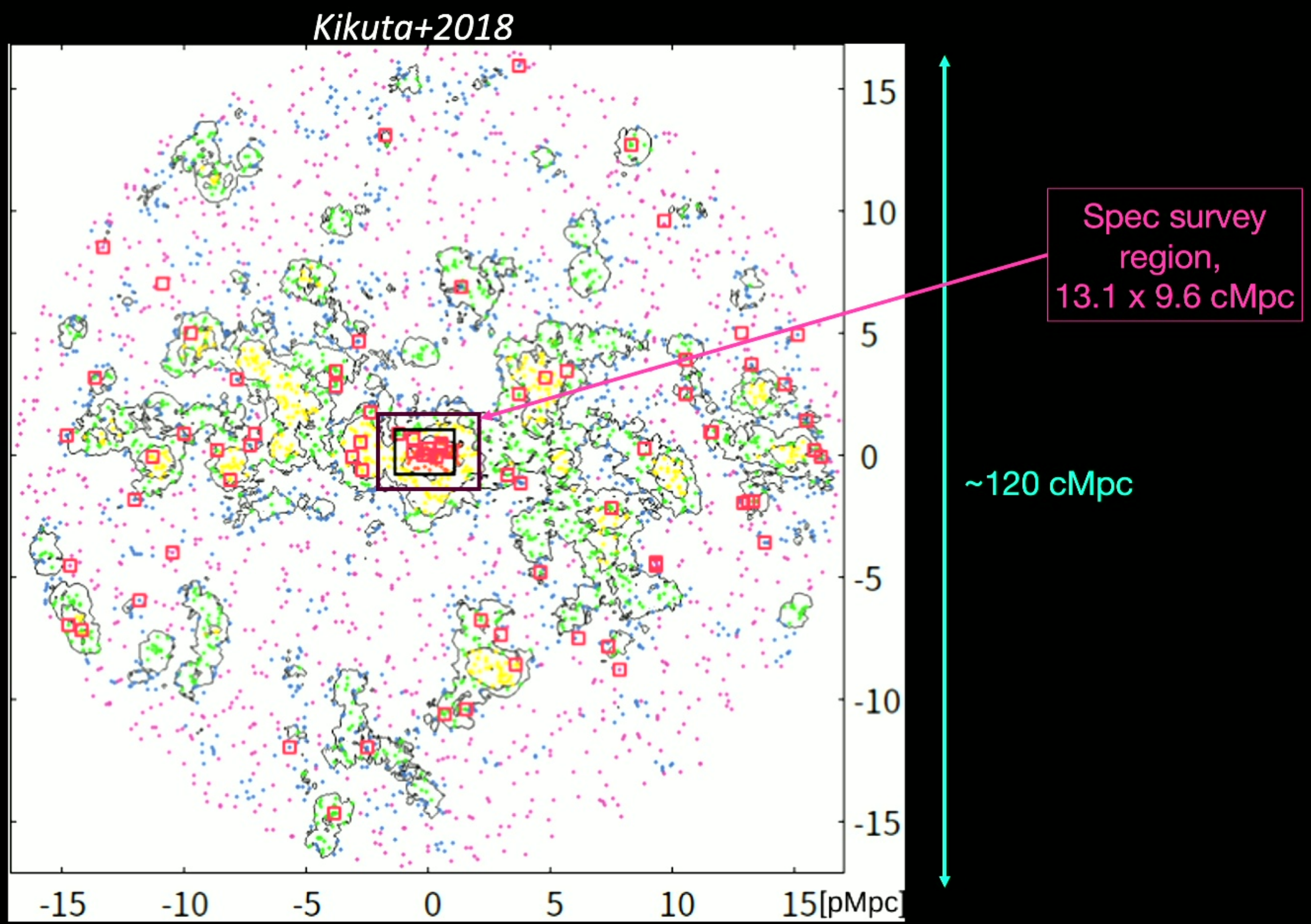




-4 QSO/AGN @z=2.84 within 20" (160 pkpc) of HS1549 QSO

- at least 6 within 3' ; 4 are ALMA 1.1mm sources

HS1549+19 z=2.84 protocluster follow-up, Subaru HSC NB468 Lyα



AGN feedback @Cosmic Noon?

- There is a lot of cool gas around in the QSO era - indications are that QSOs are having little effect on their environment except in the “ionization cone”.

- Suggests that the period of most rapid BH growth is not responsible for the redistribution of baryons in host DM halos that we have heard about at this conference.

  - What are the optically-faint Type 1 QSOs with (apparently) no cool gas?

- So, when do the AGN do their thing, and what does it look like when they are doing it?