Galaxy Formation Probed with Lyα Imaging with a Narrowband Filter

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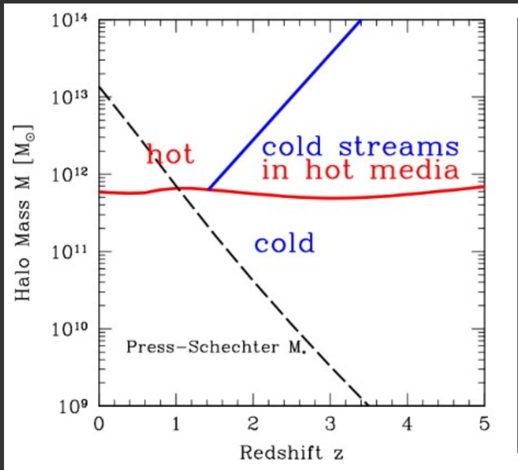
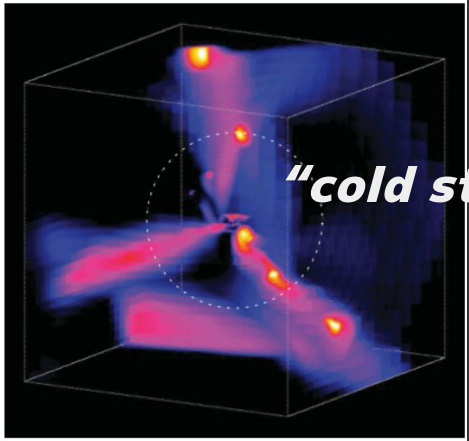
TCHoU members meeting

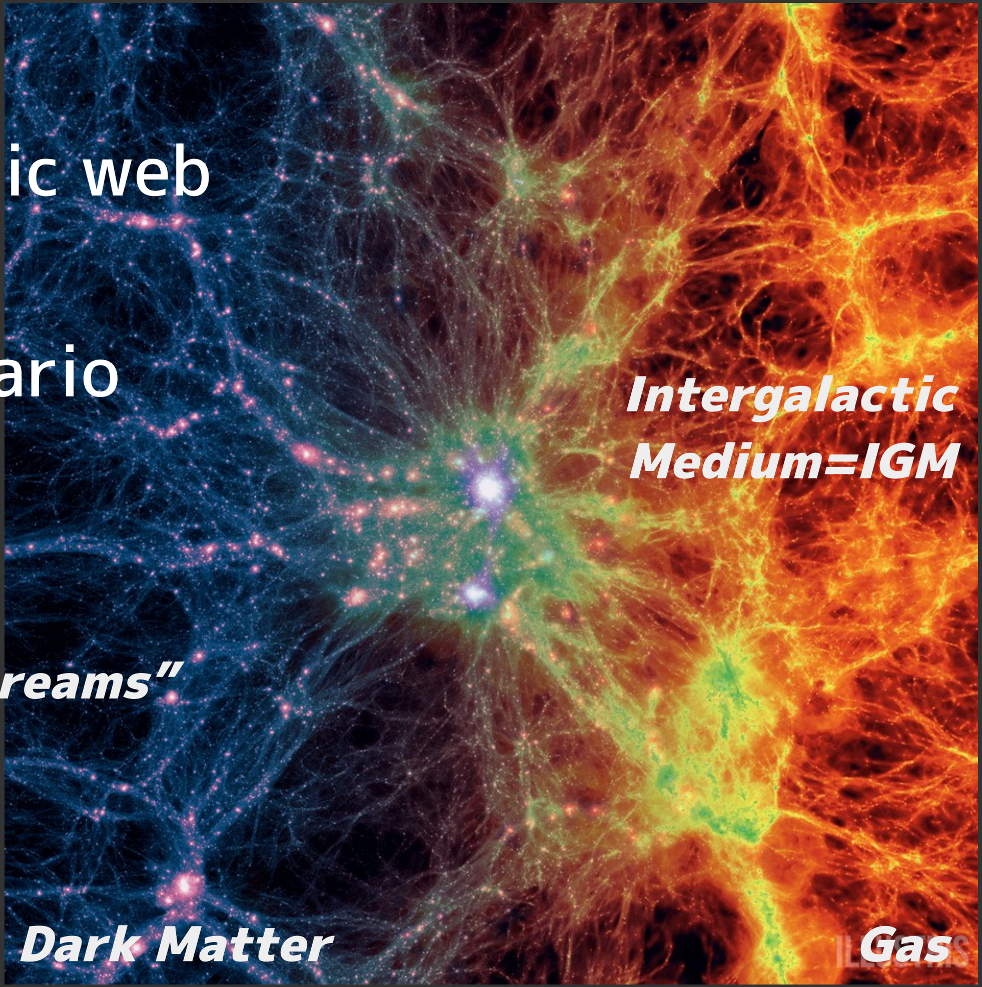
Galaxy Formation

Galaxies are formed within **the cosmic web**, a network of dark matter & baryons

Gas accretion along the cosmic web governs galaxy evolution
- "cold mode accretion" scenario





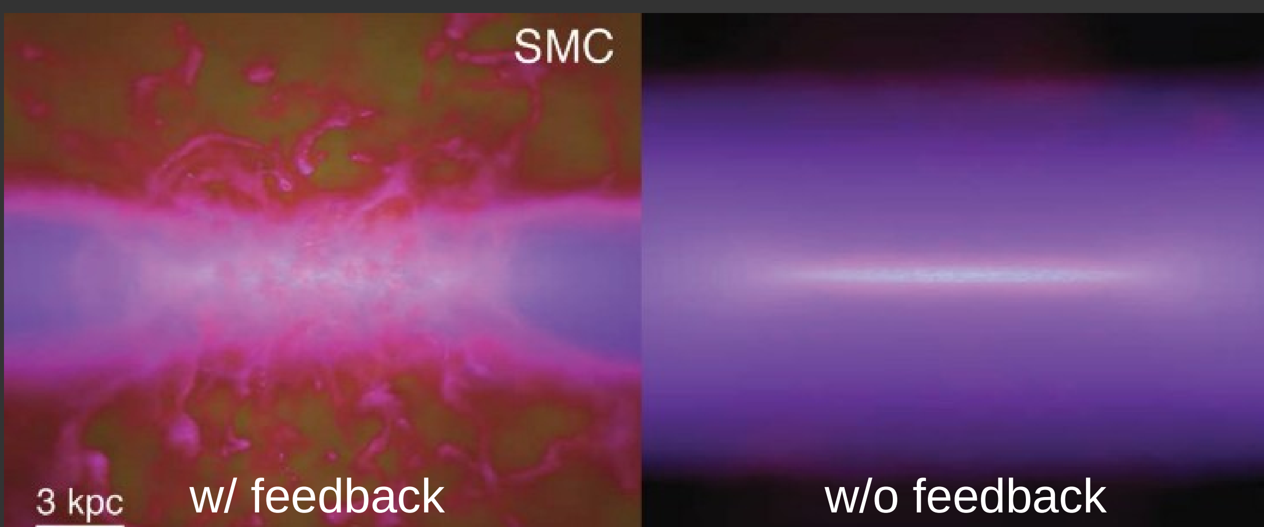


Dekel+09

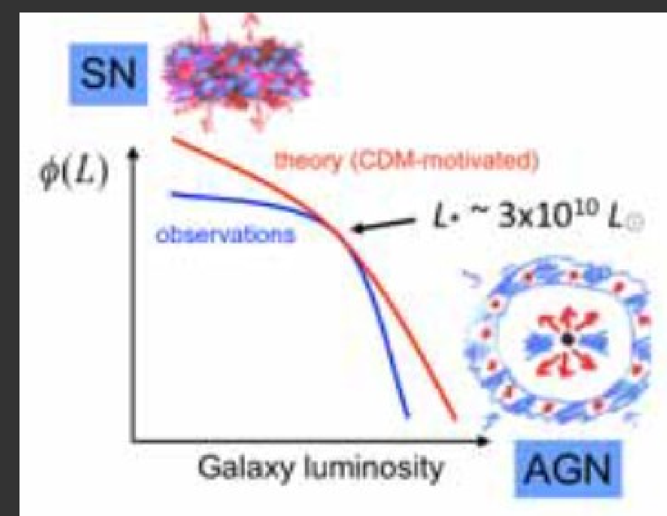
Feedback Mechanisms

Massive stars, supernovae, and AGNs (active super-massive black holes) inject energy back into ISM/CGM

These **feedback** mechanisms are the cause of lower SFE in lower/higher mass halos



Hopkins+12



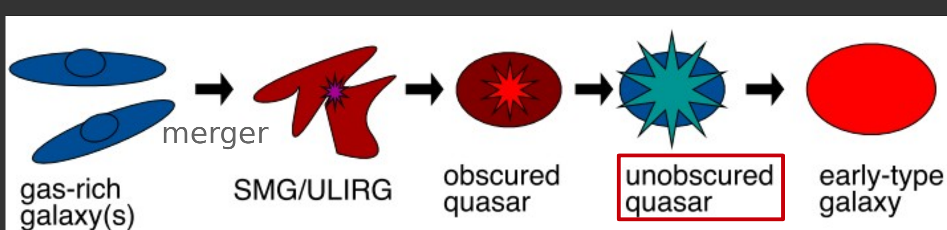
Silk+12

Role of Environment

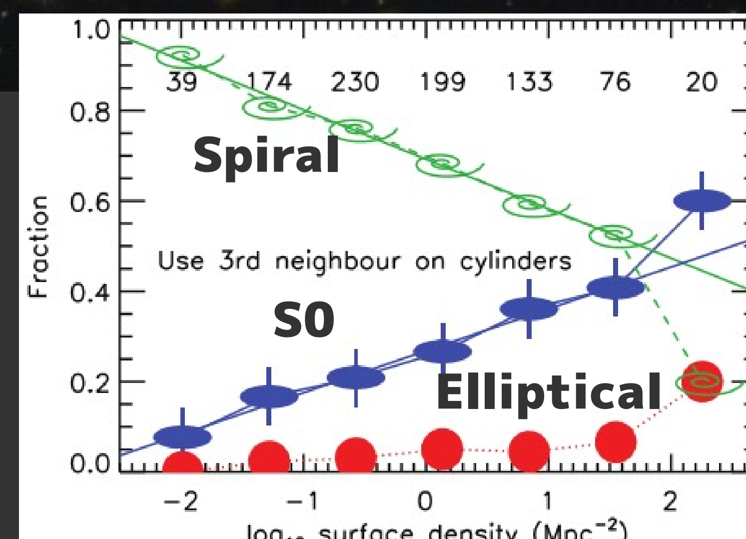
Galaxy properties depend on their **environments**

Observations of **protoclusters** hold the key

- At z>2, the local relation reverses
- **Enhanced inflow and merger rate** should be related

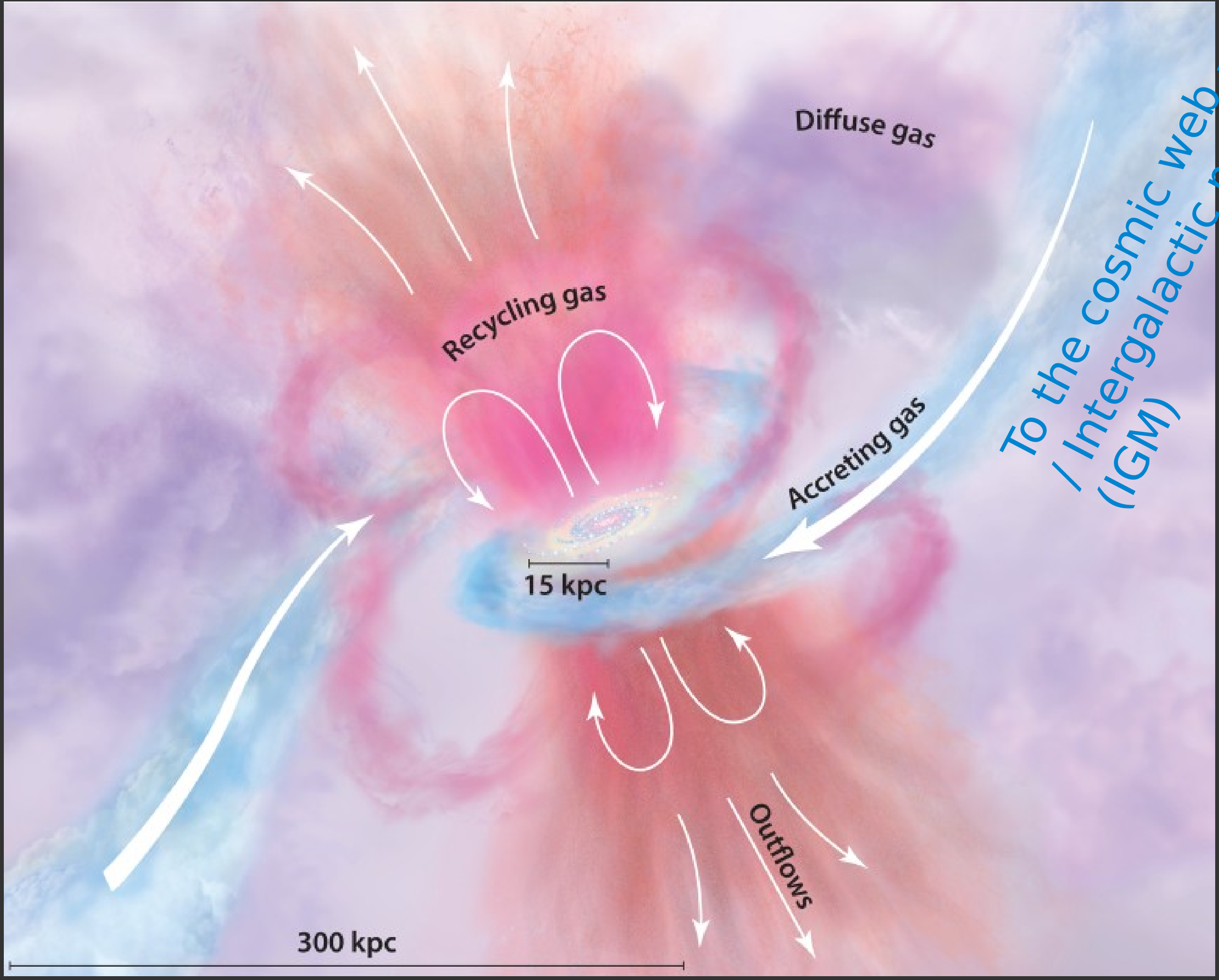


Alexander & Hickox 2012



Cappellari et al. 2011

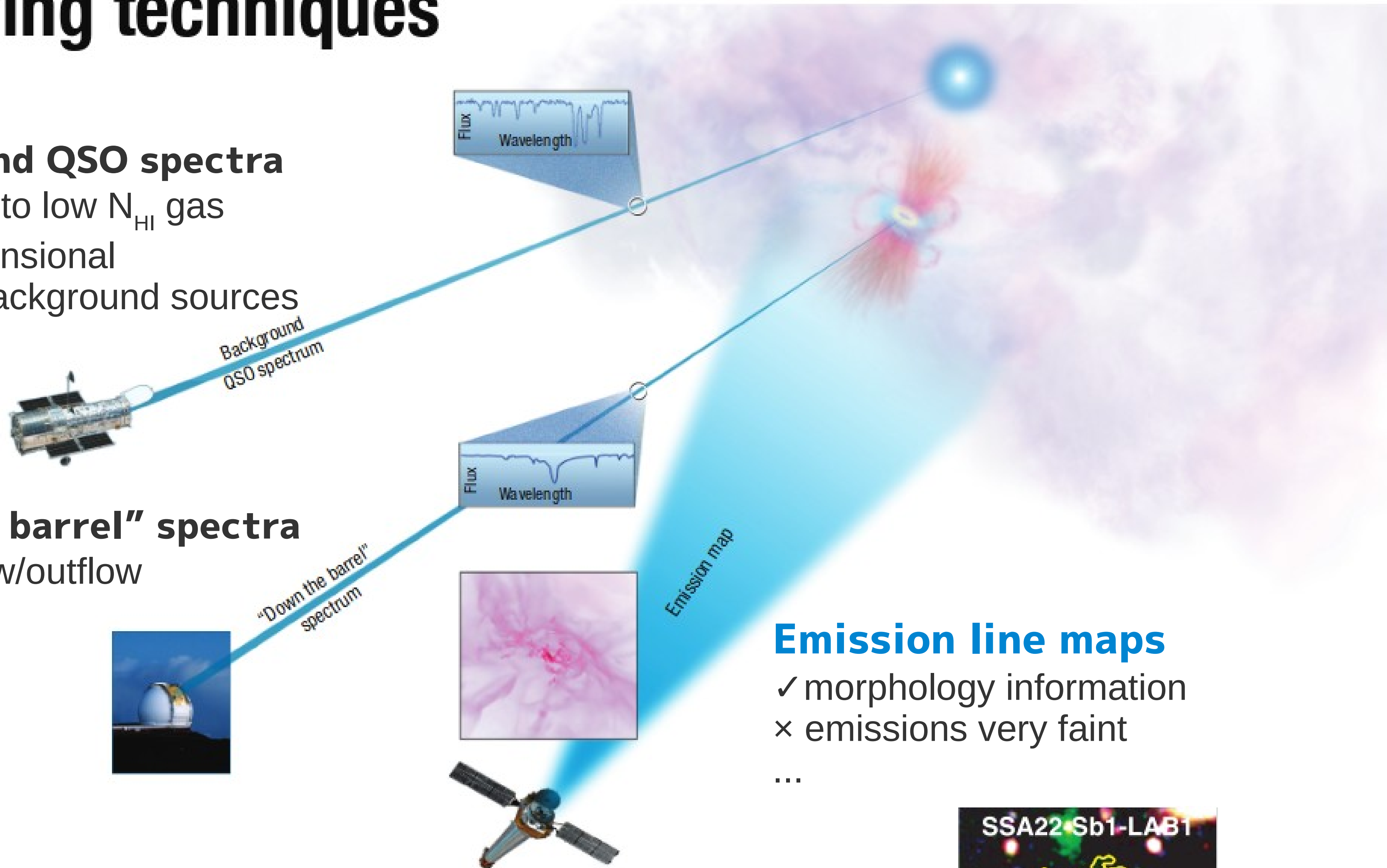
Circumgalactic/Intergalactic Medium (CGM/IGM)



To the cosmic web → / Intergalactic medium (IGM)

※No clear demarcation between CGM and IGM

Observing techniques



Background QSO spectra

✓sensitive to low N_{HI} gas

× one dimensional
sparse background sources

...

"Down the barrel" spectra

✓trace inflow/outflow

...

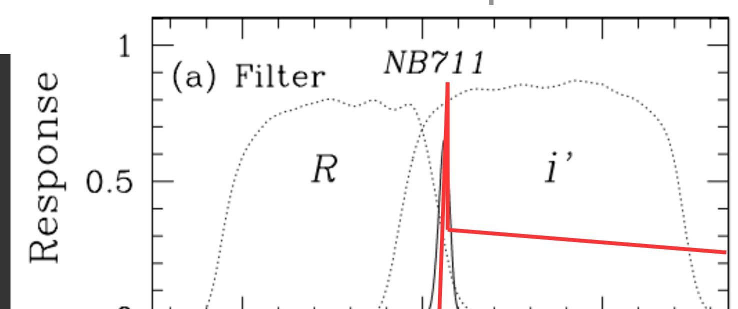
Emission line maps

✓morphology information

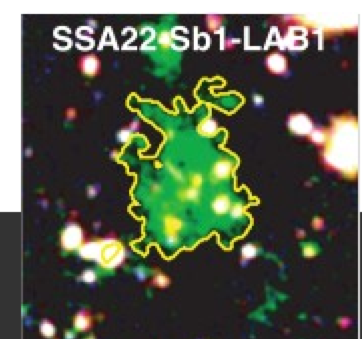
× emissions very faint

...

★Narrow-band technique



Ouchi+03



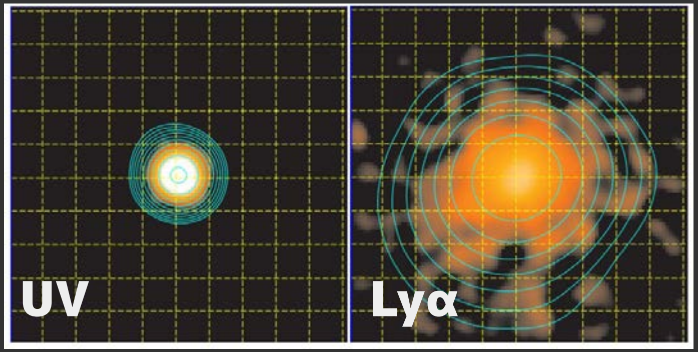
Lyman alpha blobs or **LAB**s Matsuda+11

©Tumlinson, Peeples, and Werk, ARAA, 2017

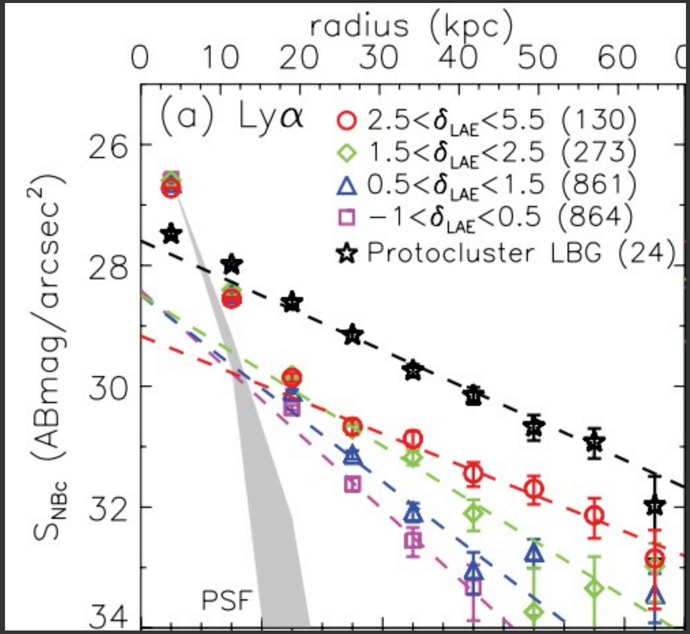
Lyα Halos around SF Galaxies

Diffuse Lyα halo is ubiquitous
if we go as deep as
<<10^{-18}erg/s/cm^2/arcsec^2

LAH dependence on environments may cause environmental segregation



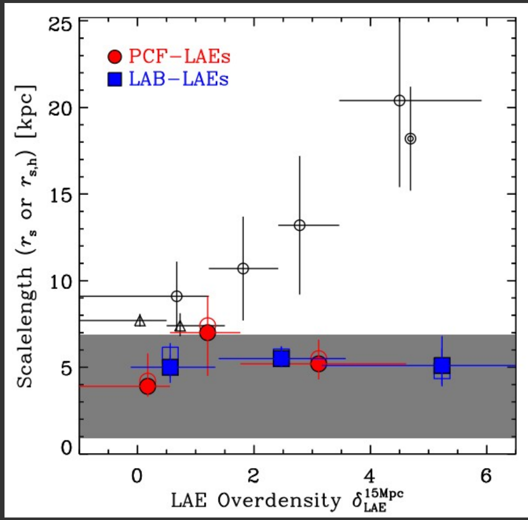
Stacked UV(left) and Lyα(right) image of **LBG** @ z=2.65 (Steidel+11)



Matsuda+12:
LAEs in denser environments have more extended LAHs

vs.

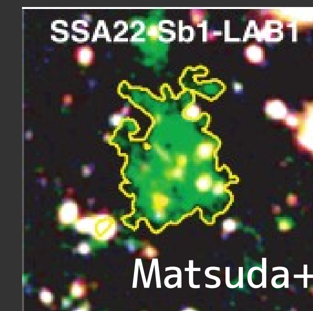
Xue+16:
No such dependence →



Extreme Cases

- Lyα blobs (LABs)
  - Mostly found in dense environments

Typical extent:
> 100 kpc !!



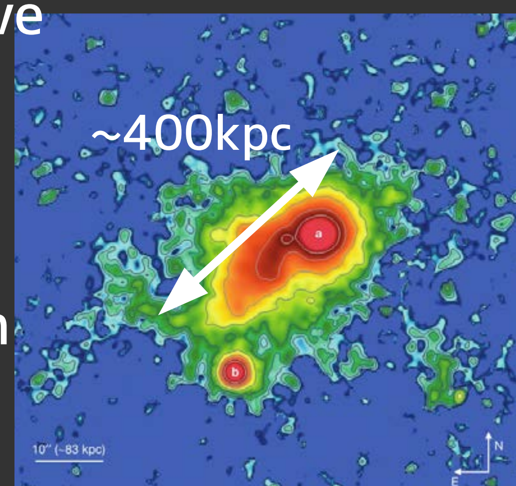
Matsuda+11

- QSO nebulae
  - Bright QSOs at z~3 almost always have associated Lyα nebulae (Borisova+16)

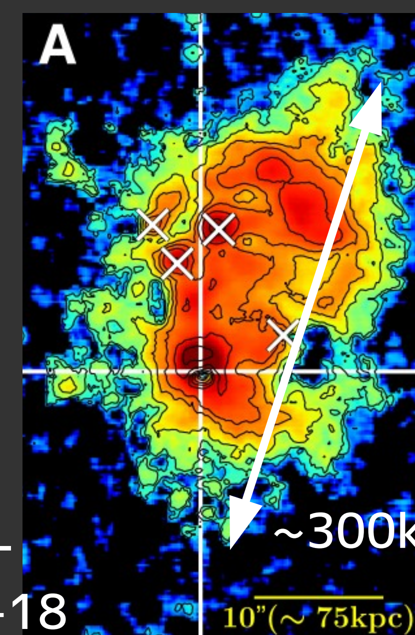
    Ionizing radiation likely help detection

    But, most nebulae do not have cold stream-like morphology

Key targets to understand the cosmic web and cold accretion



Cantalupo+14



Arrigoni-Battaia+18

Our Work

Central questions:

1. Does filamentary IGM gas and the cold-mode accretion really exist around massive halos at cosmic noon?
2. Is there a difference in the CGM as a function of environment?

- To tackle these problems, we
  - **Search for traces of the cosmic web and cold-mode accretion** around the core of a protocluster at z=2.84
  - **Probe environmental dependence of LAHs** with numerous LAEs residing in various environments from voids to protoclusters

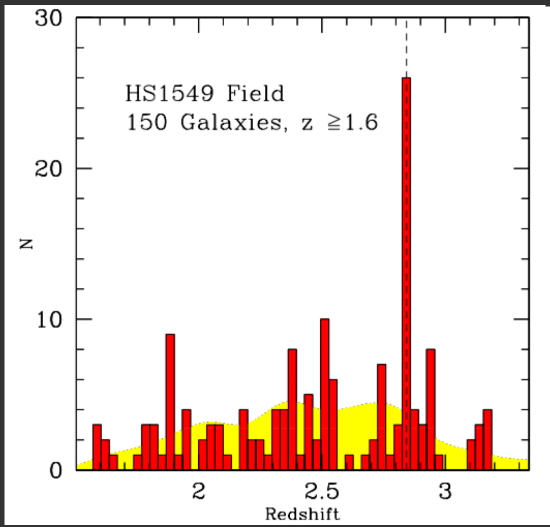
1. Lyα View around a Hyperluminous Quasar at a Node of the Cosmic Web

(Kikuta et al. 2019, PASJ, 71, L2)

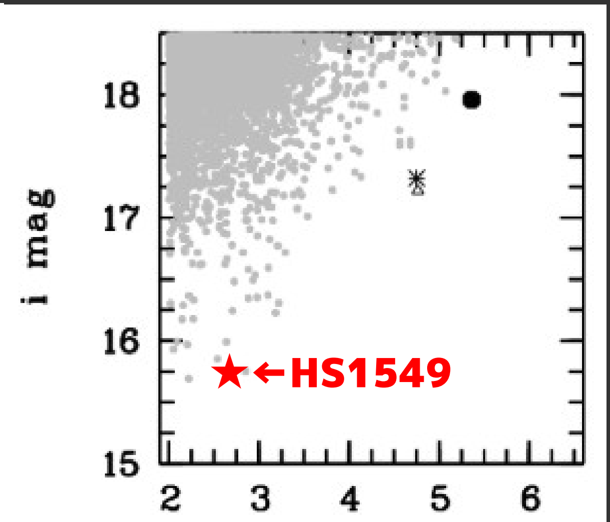
Subaru Observation

Hyperlumious QSO at z=2.84: **HS1549+1919**

- $L_{1450(\nu L\nu\ @\ \lambda=1450A)}=1.5\times10^{14}\ L_\odot$, $M_{BH}=4.6\times10^{9}\ M_\odot$
  ※$L_\odot=3.8\times10^{33}$ erg/s (Trainor & Steidel 2012)
- reside in **massive overdensity (proto-cluster)**
- Deep imaging & spectroscopic data available at the center
- Observed with Subaru **Hyper Suprime-Cam (HSC)**



Mostardi+13



Redshift

May+18

Observation: HS1549+1919

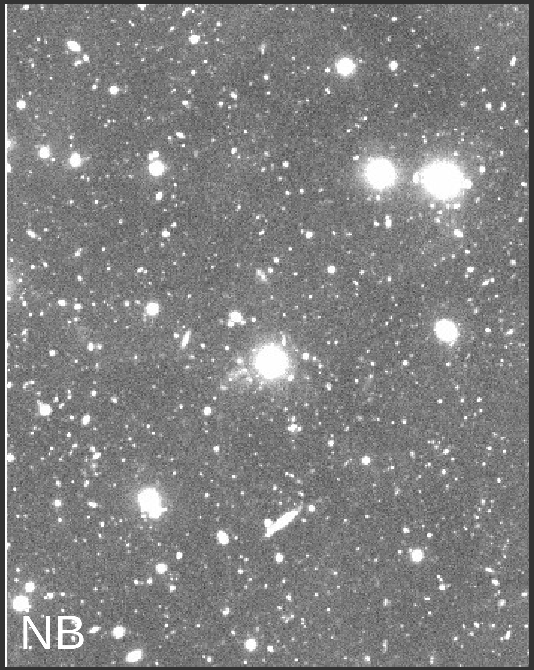
Hyper Suprime-Cam(HSC) Observation (S16A-110, PI: Yuichi Matsuda)

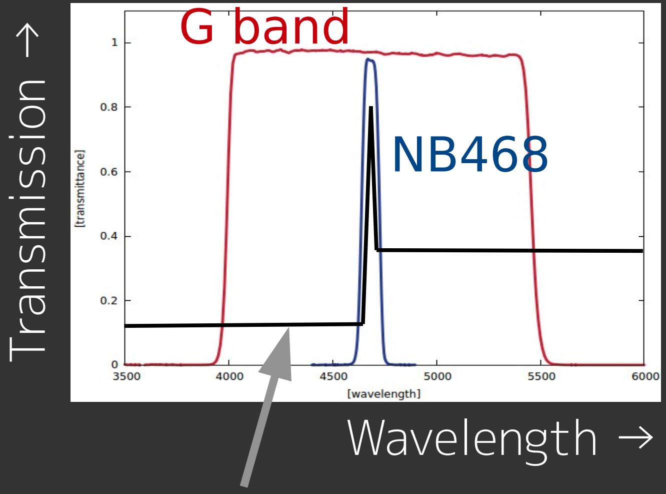
FoV= *1.5 deg diameter* = **42 pMpc/165 cMpc @ z=2.84**

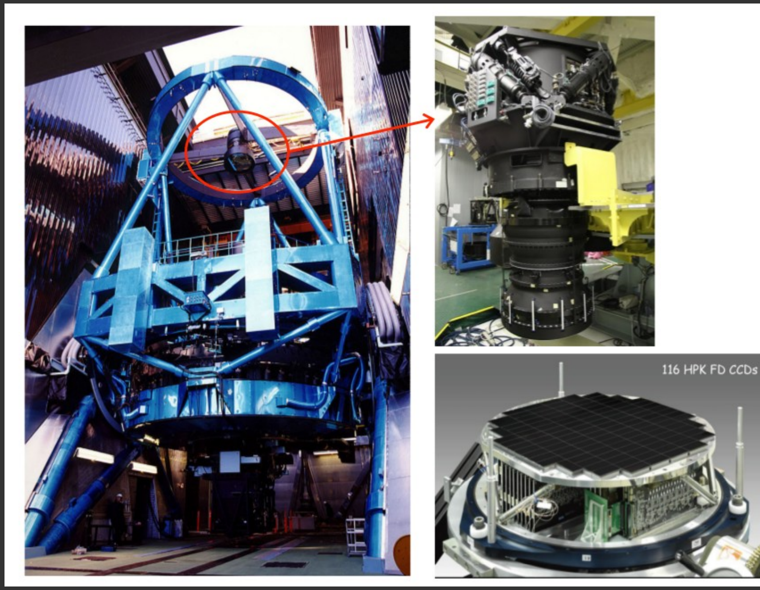
G 2.2 hr (389 shots) → 27.4 mag (5σ, 1.5″ aperture=2×seeing FWHM 0.77″)

NB468 6.3 hr (113 shots) → 26.6 mag (5σ, 1.5″ aperture)

Data reduced using HSC pipeline (hscpipe 4.0.5)







LAE Detection

Source detection & photometry
with Source Extractor (Bertin & Arnouts 96)

LAE selection criteria:

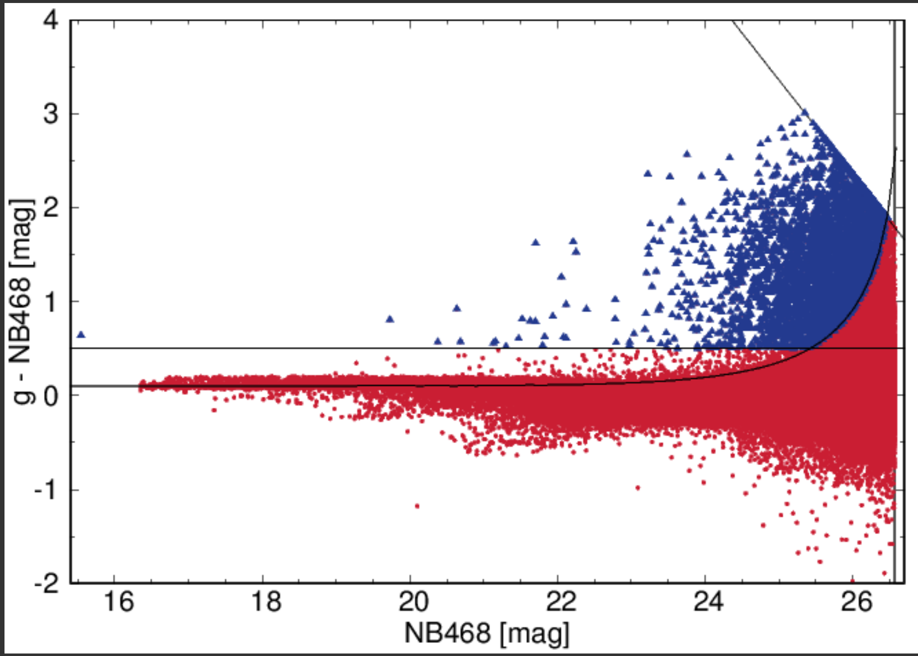
- NB < 26.57(5σ)
- G – NB > max{0.5, 0.1+4σ(G-NB)}
- (rest $EW_{Ly\alpha}$ >12Å)

LAB selection criteria:

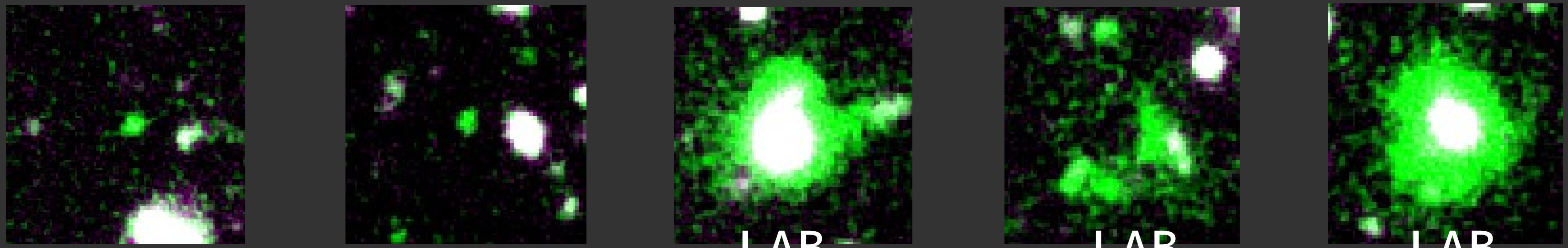
- criteria above(isomag)+ $A_{Ly\alpha,iso}$>16arcsec^2

→ **3490** LAEs and **76** LABs found

G-NB468



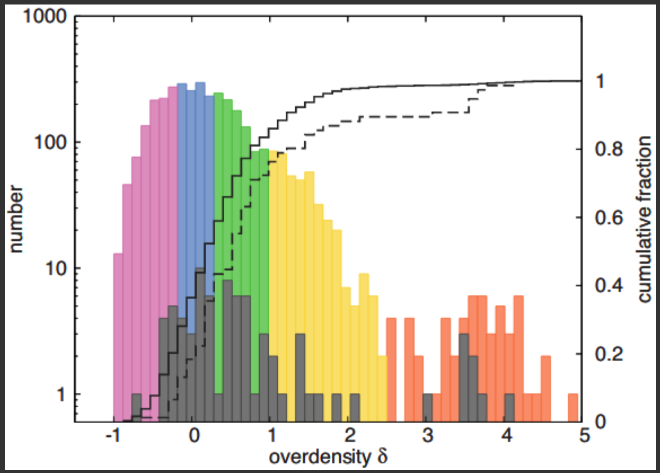
NB468



False-color image
R: G
G: NB
B: G

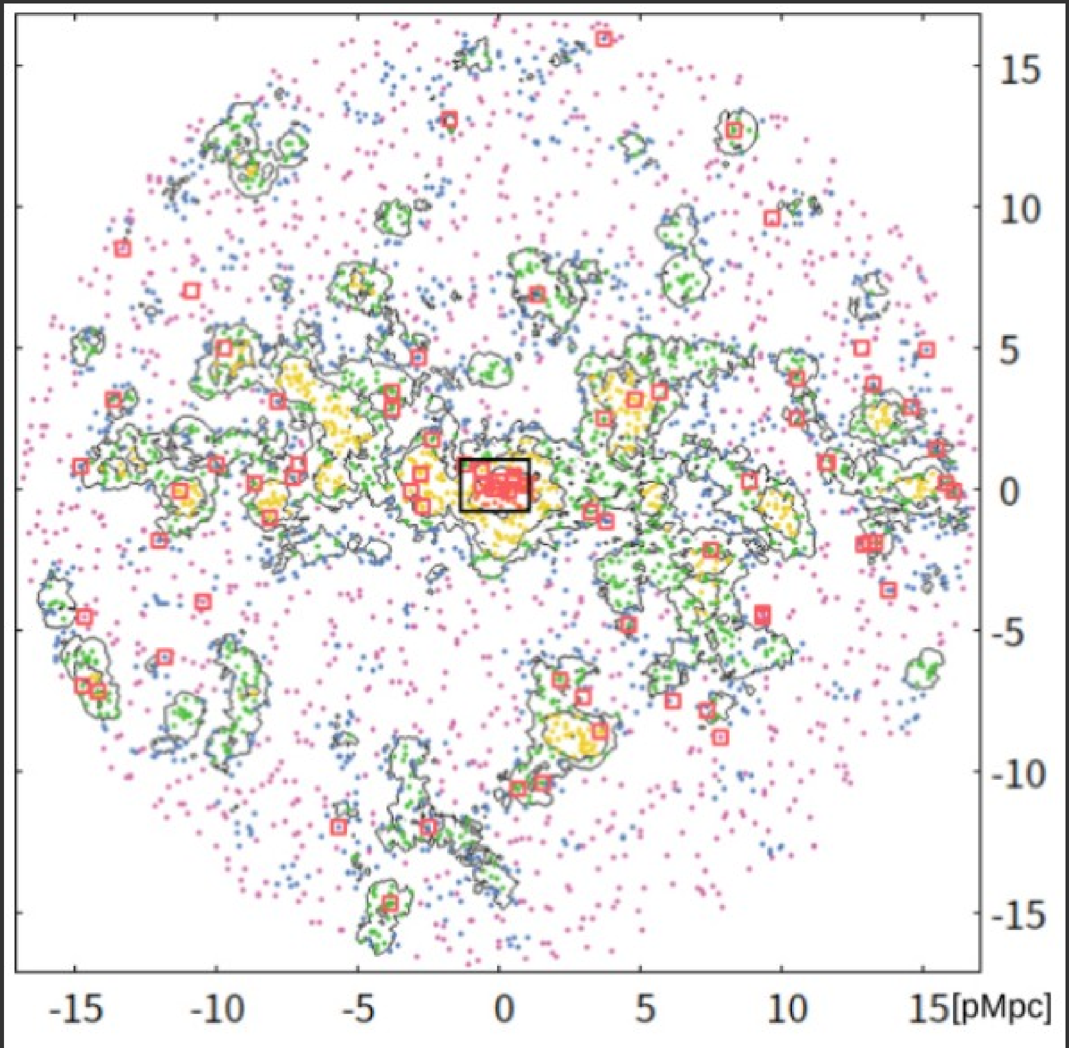
LAE Distribution

- Filamentary structure
- Overdensity at the center suggests M_{halo} of the protocluster will become $10^{15}M_{\odot}$ at z=0
- LABs are distributed along the structure & clearly prefer denser environments



KS-test p-value: 0.00173

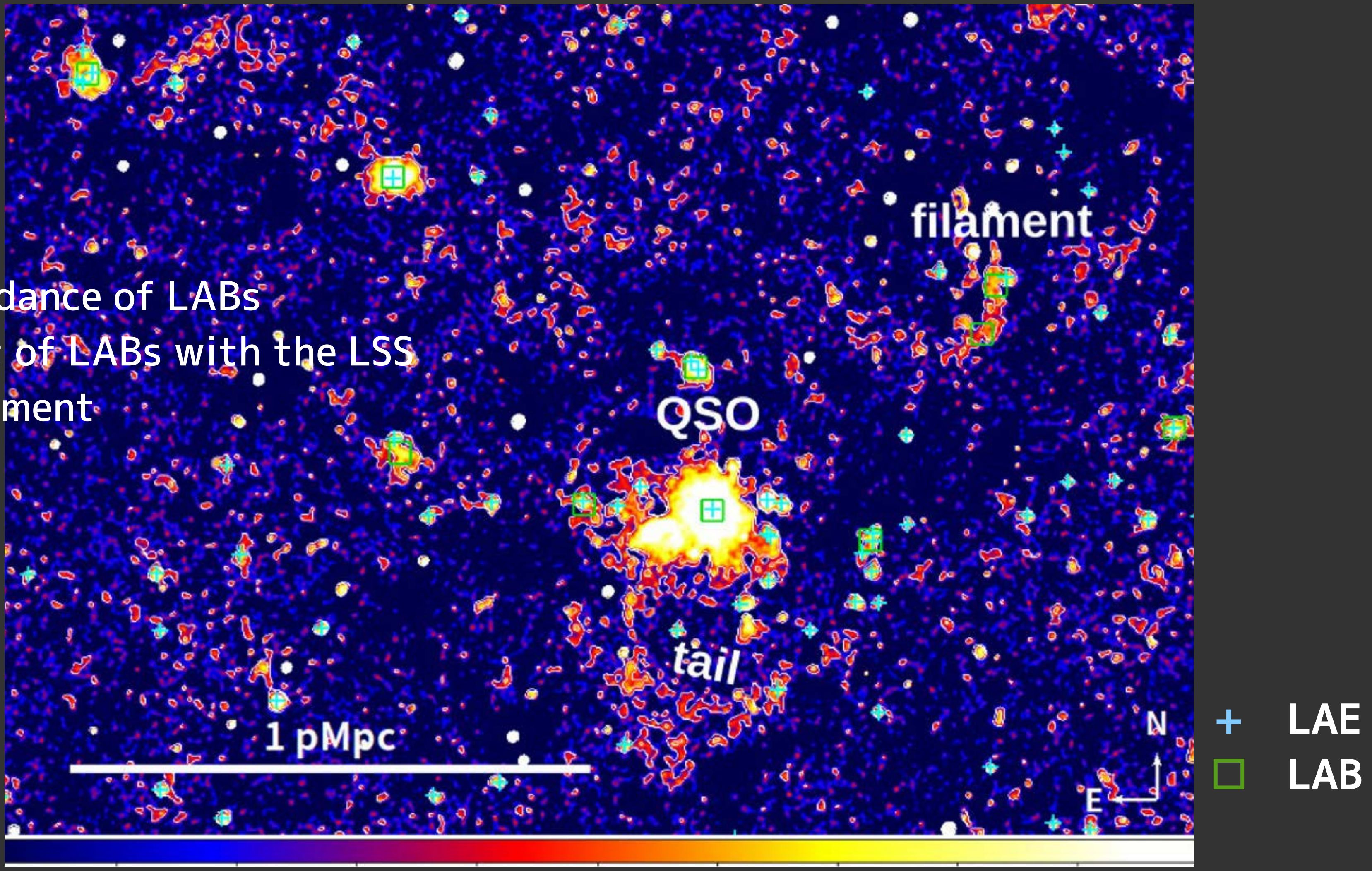
※$\delta_{gal}=n/n_{ave}-1$



Kikuta+19

Lyα View around the QSO

-Overabundance of LABs
-Alignment of LABs with the LSS
-Tail & Filament



Summary (1)

- We found that the HS1549 protocluster corresponds to the intersection of ~100 cMpc-scale structure.
- Significant overdensity of LABs and their apparent alignment with that of the large-scale structure are found near the protocluster core.
- Discovery of a candidate of gaseous filament along the cosmic web
  - Might be facilitated by the HLQSO irradiation
  - Significant step toward direct test of cold accretion scenario!
  - Follow-up observation scheduled (tomorrow!!)

2. Lyα Halos around LAEs across Environments

Grouping & Stacking LAEs

- Group LAEs according to various properties
  → Stack them (median) & examine their Lyα SB profiles
- Large sample size → very high sensitivity achieved (~1e-19 erg/s/cm²/arcsec²)
- Note the correlations between quantities

quantity	criteria	N
UV magnitude	$M_{\rm UV} < -19.2$	690
	$-19.2 < M_{\rm UV} < -18.6$	696
	$-18.6 < M_{\rm UV} < -18.0$	773
	$-18.0 < M_{\rm UV} < -17.4$	648
	$-17.4 < M_{\rm UV}$	683
Lyα luminosity	$42.25 < \log L_{{\rm Ly}\alpha}$	647
	$42.05 < \log L_{{\rm Ly}\alpha} < 42.25$	833
	$41.95 < \log L_{{\rm Ly}\alpha} < 42.05$	610
	$41.85 < \log L_{{\rm Ly}\alpha} < 41.95$	645
	$\log L_{{\rm Ly}\alpha} < 41.85$	755
Lyα equivalent width	${\rm EW}_{0,{\rm Ly}\alpha} < 30$Å	686
	30Å$< {\rm EW}_{0,{\rm Ly}\alpha} < 55$Å	727
	55Å$< {\rm EW}_{0,{\rm Ly}\alpha} < 90$Å	698
	90Å$< {\rm EW}_{0,{\rm Ly}\alpha} < 160$Å	735
	160Å$< {\rm EW}_{0,{\rm Ly}\alpha}$	644
Environment	$2.5 < \delta$	55
	$1.0 < \delta < 2.5$	433
	$0.3 < \delta < 1.0$	944
	$-0.15 < \delta < 0.3$	1076
	$-1.0 < \delta < -0.15$	982
Distance from the HLQSO	$d_{\rm Q} < 6.2$ pMpc	679
	6.2 pMpc $< d_{\rm Q} < 9.5$ pMpc	739
	9.5 pMpc $< d_{\rm Q} < 12.0$ pMpc	633
	12 pMpc $< d_{\rm Q} < 14.8$ pMpc	778
	14.8 pMpc $< d_{\rm Q} < 18.0$ pMpc	661

Grouping & Stacking LAEs

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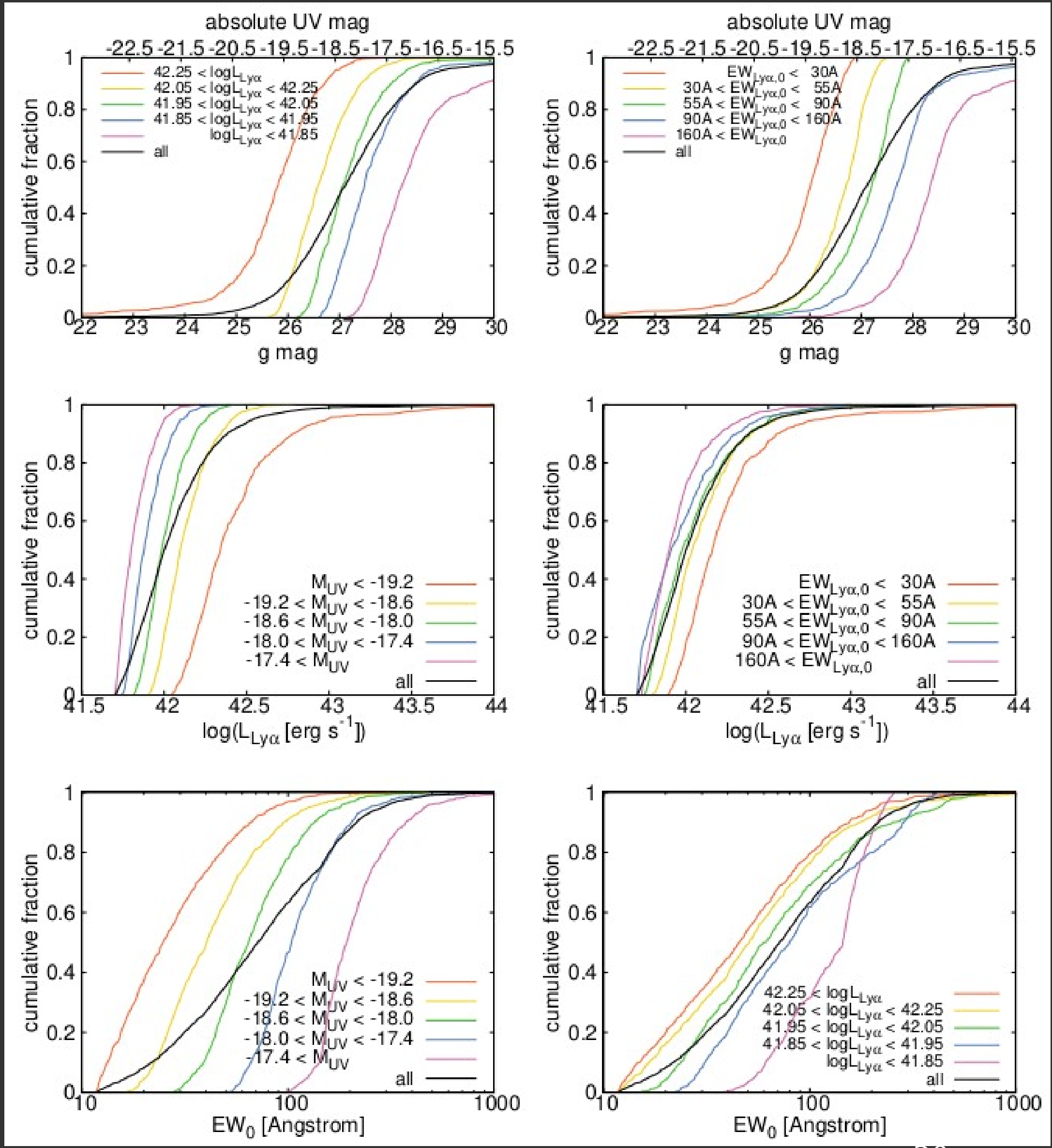

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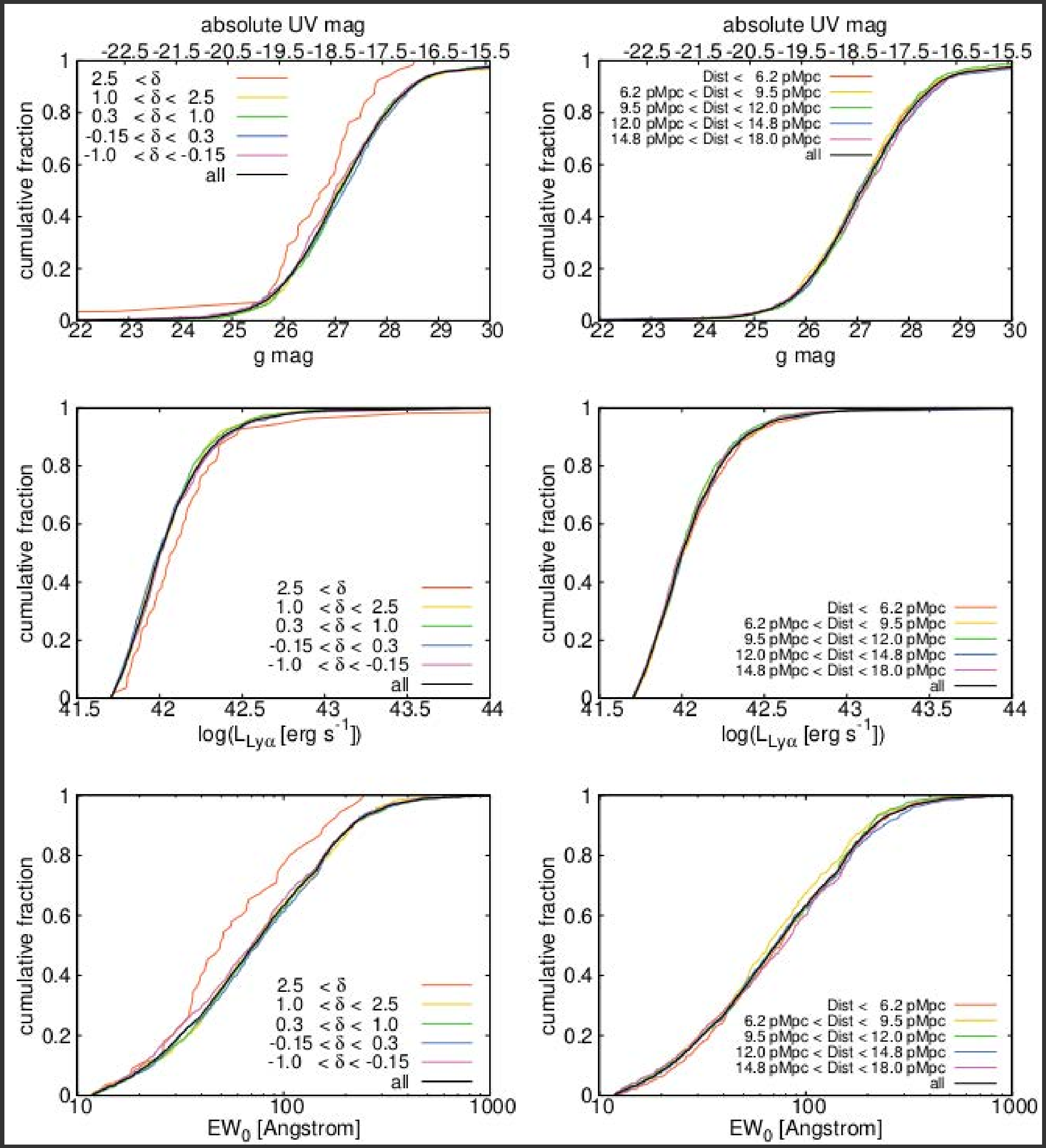
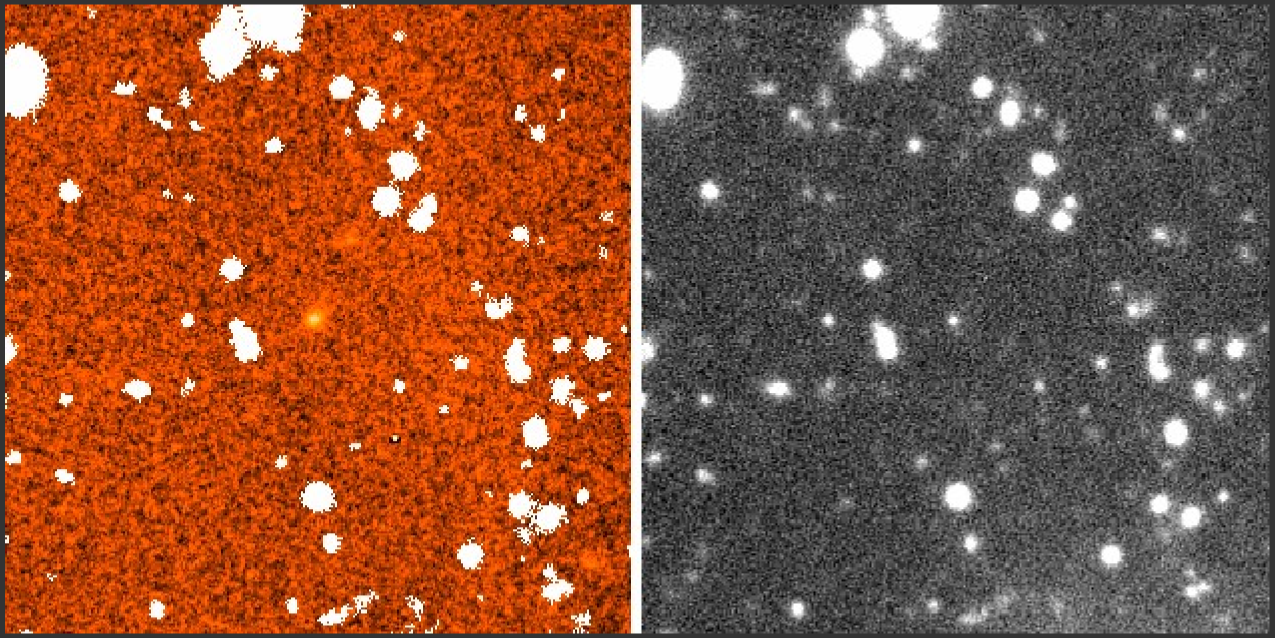


Stacking Analyses

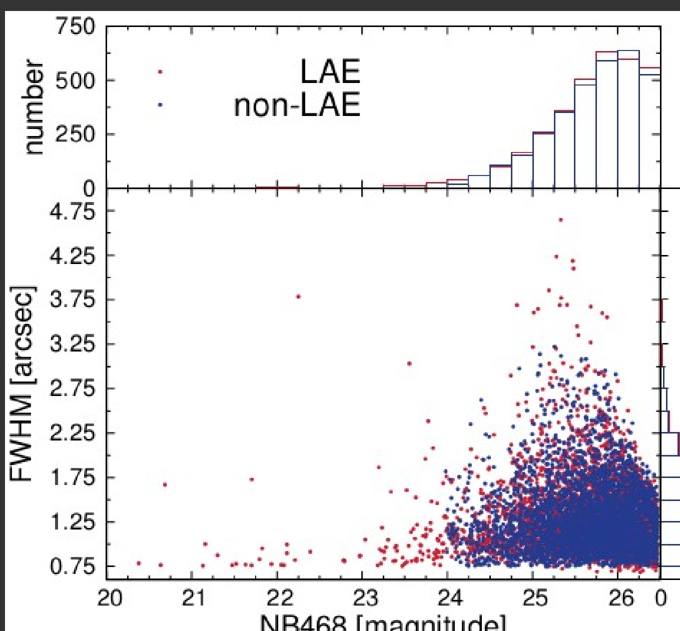
- Use cutout Lyα images of LAEs (sky mesh size=30”)
- Mask continuum source & unmask a target of interest
- stack Lyα & continuum images with IRAF imcombine



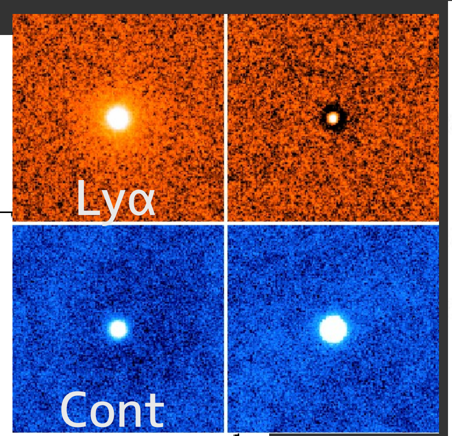
Masked Lyα Continuum

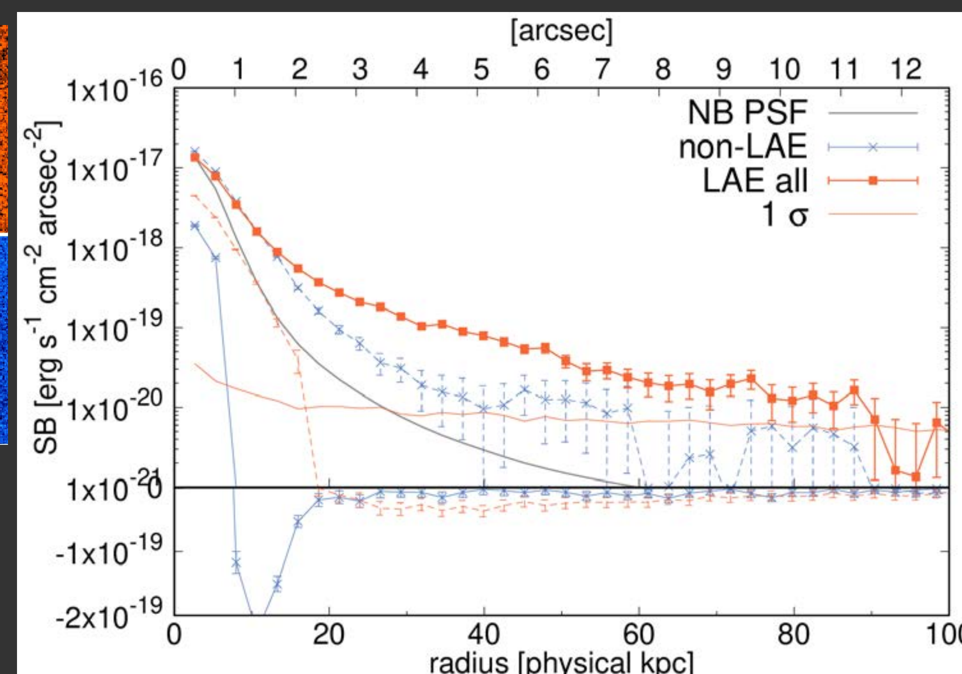
Uncertainties

- Sky noise behaves well (noise ∝ $N^{-1/2}$; Fig 3.4)
- Slight difference in shapes of PSFs are noted
- "Non-LAE" sample is constructed to check total systematics



LAE non-LAE





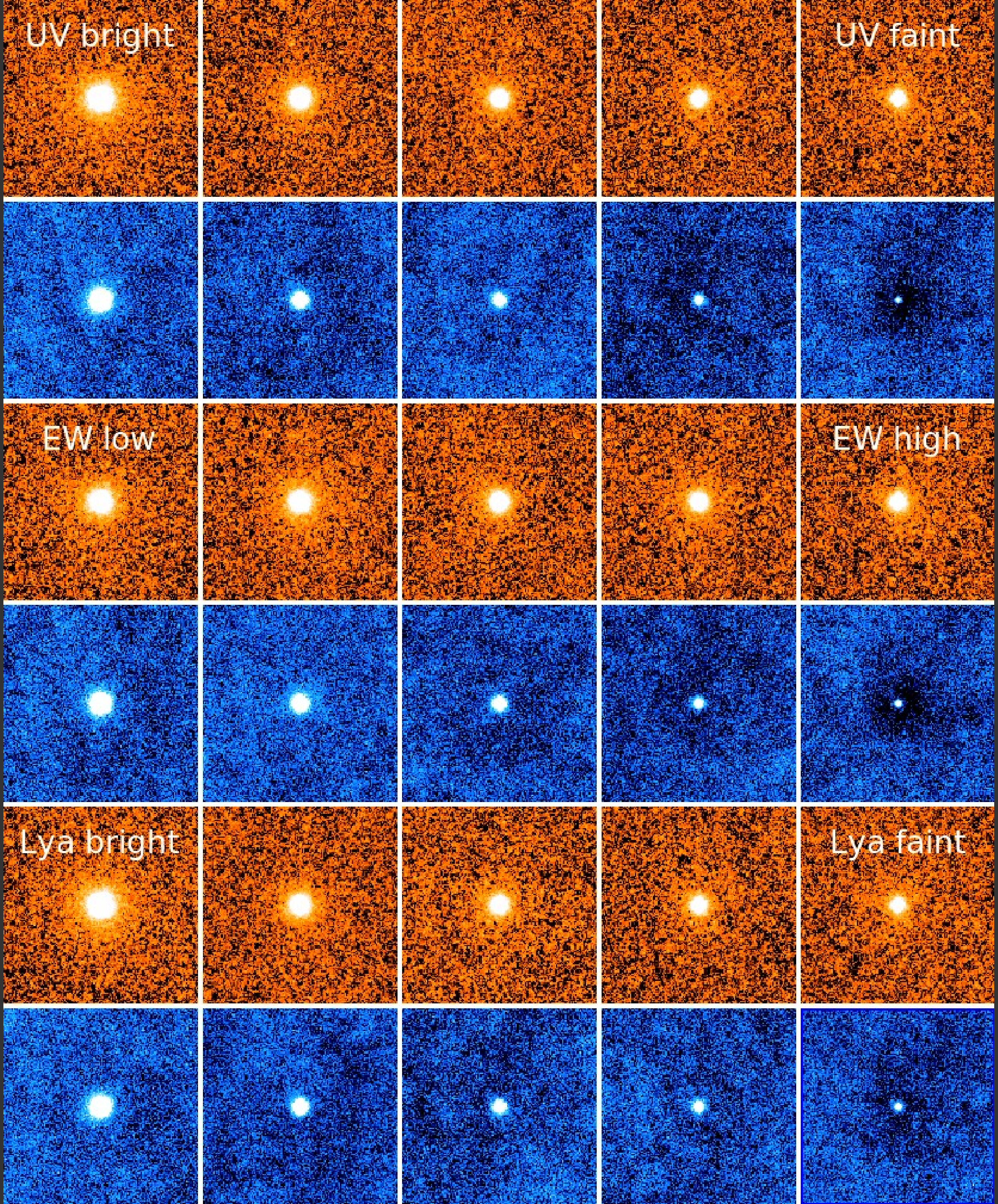


Fig 3.9

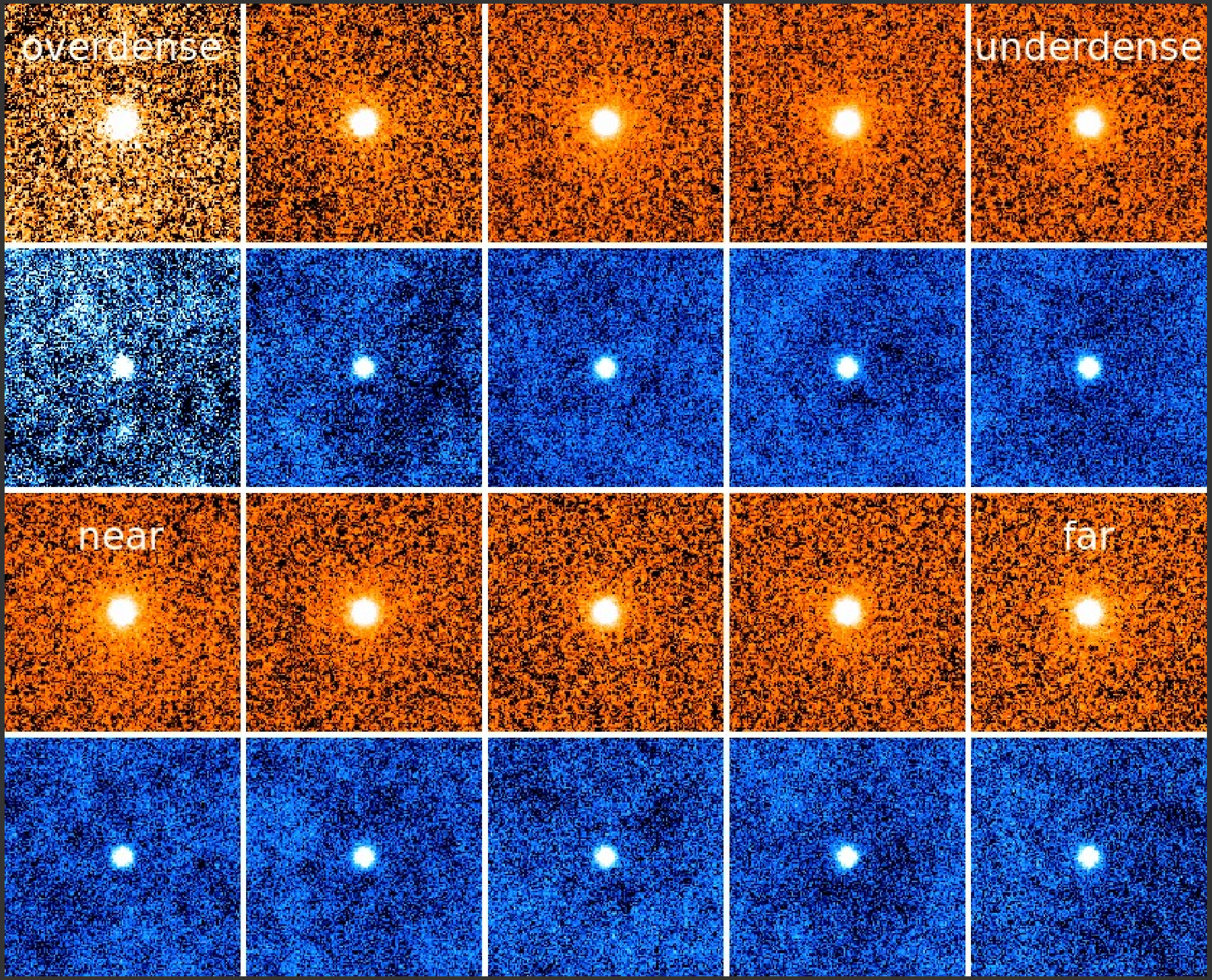


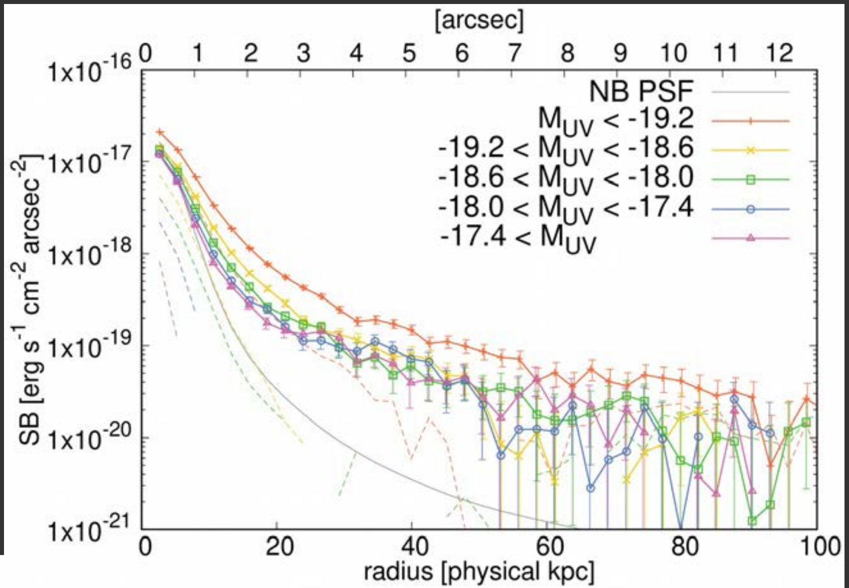
Fig 3.10

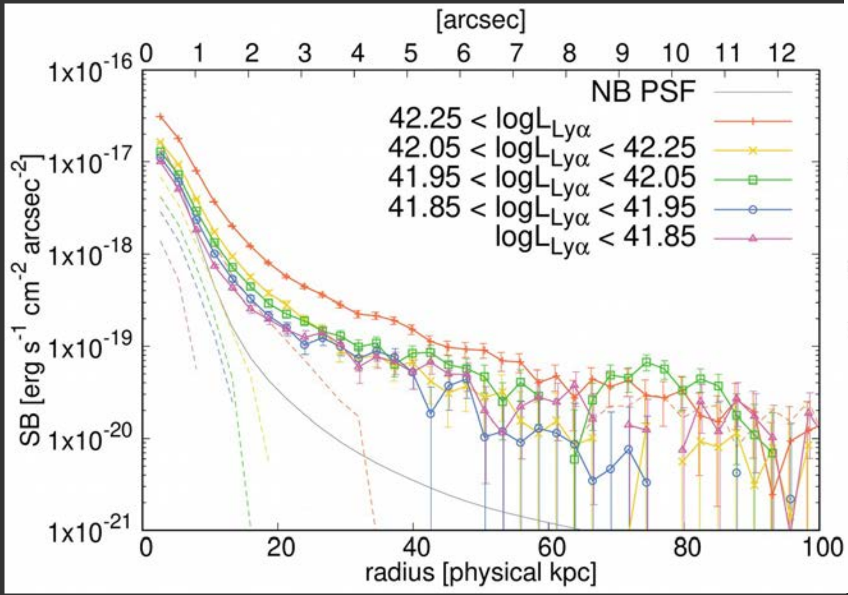
Results of Stacking

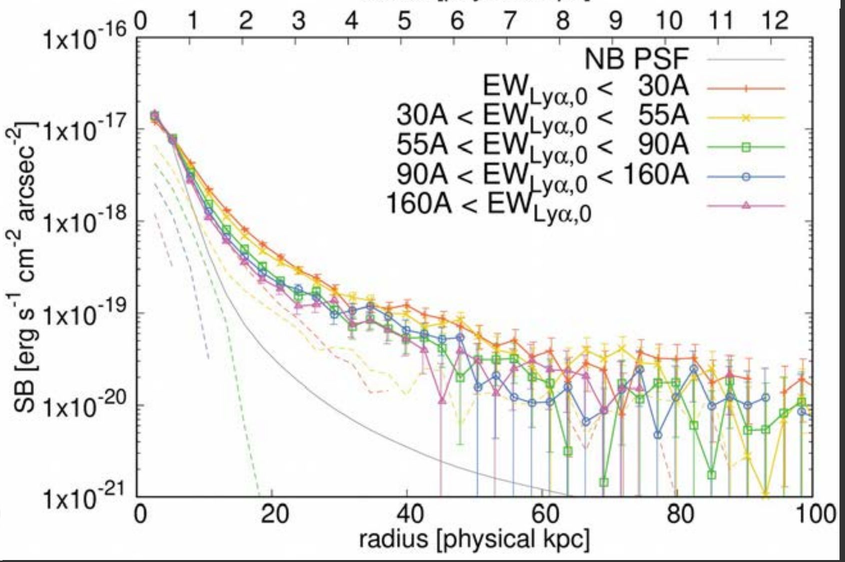
LAHs are detected for all subsamples

Obviously, brighter (in both UV/Lyα) LAEs have larger LAHs

High $EW_{Ly\alpha,0}$ LAEs have compact LAHs



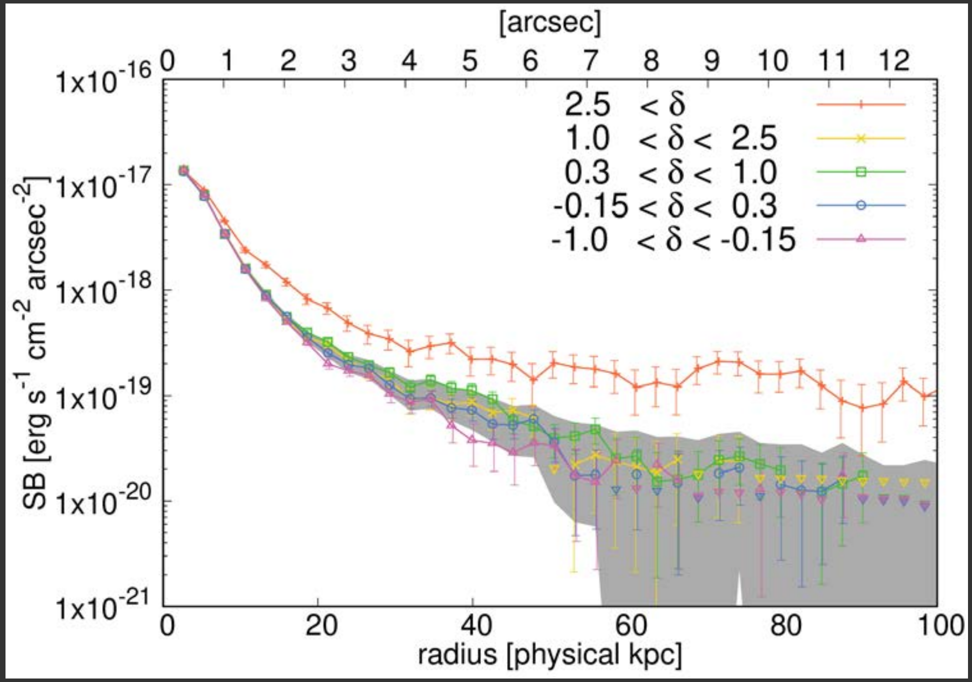


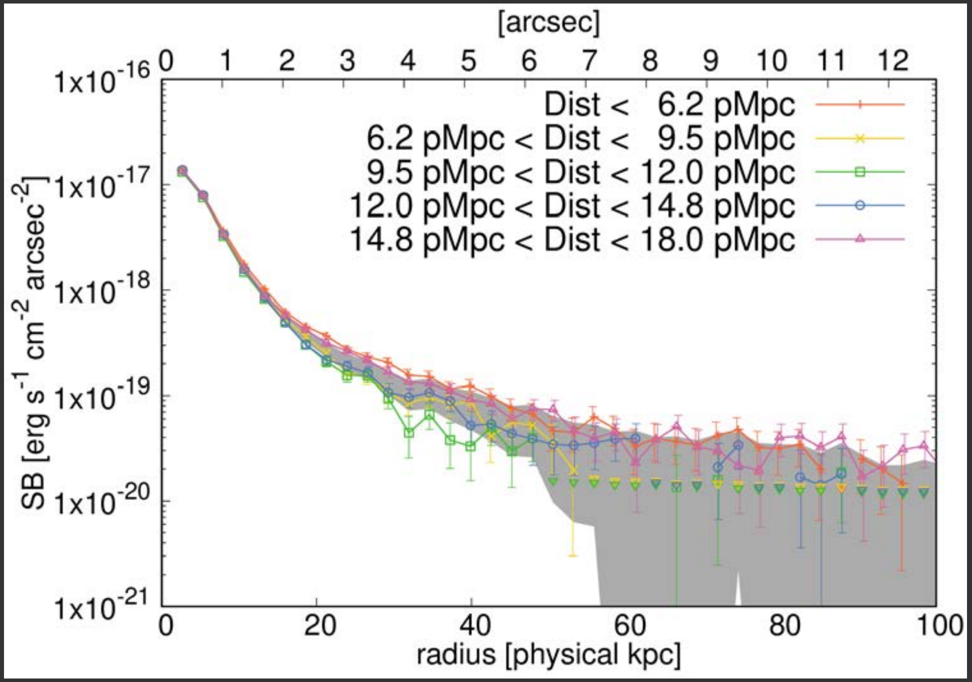


Results of Stacking

No systematic trend is observed for environments and distance from the QSO, though protocluster LAHs are large

Gray shade … 5th and 95th percentile of the stacked Lyα SB distribution of 700 randomly selected LAEs



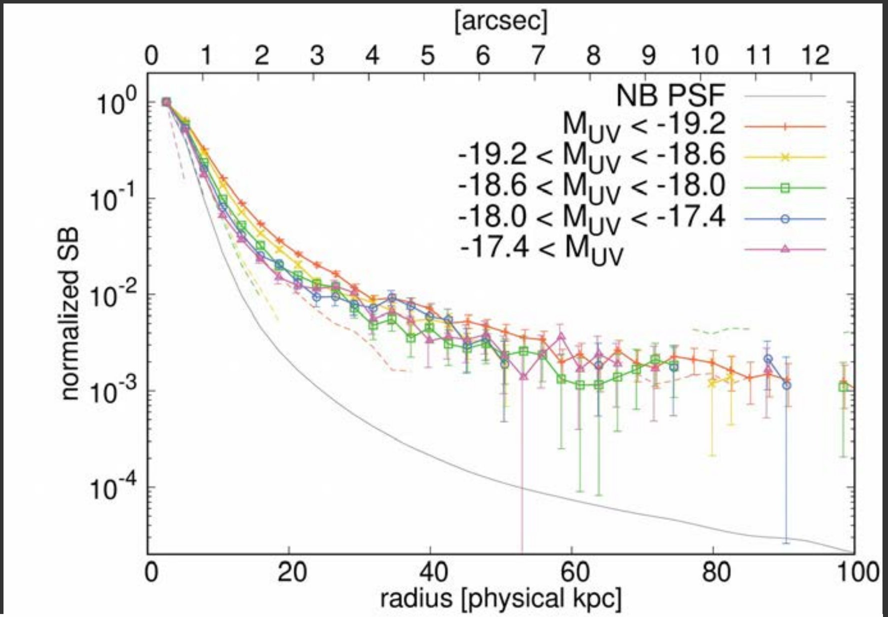


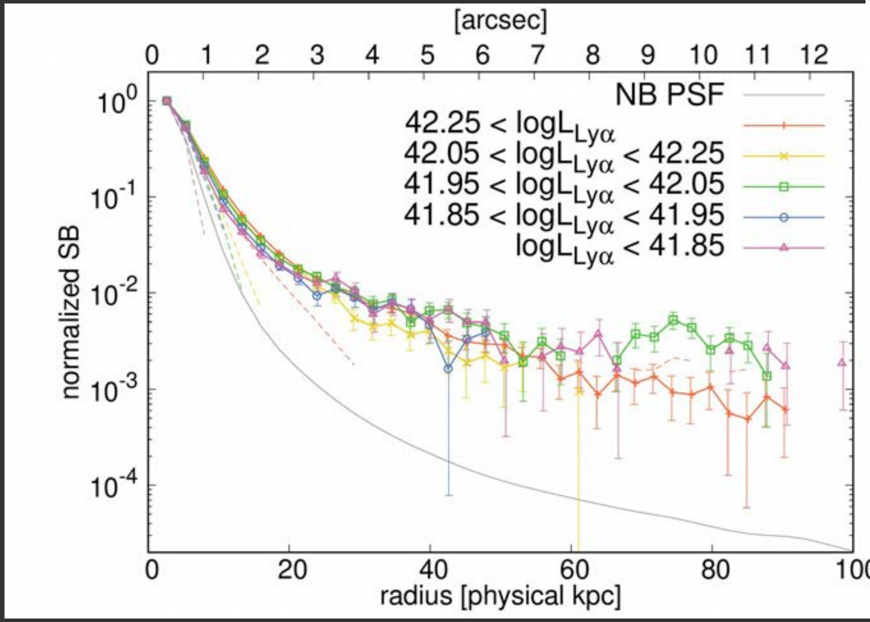
LAH Dependence on Galaxy Properties

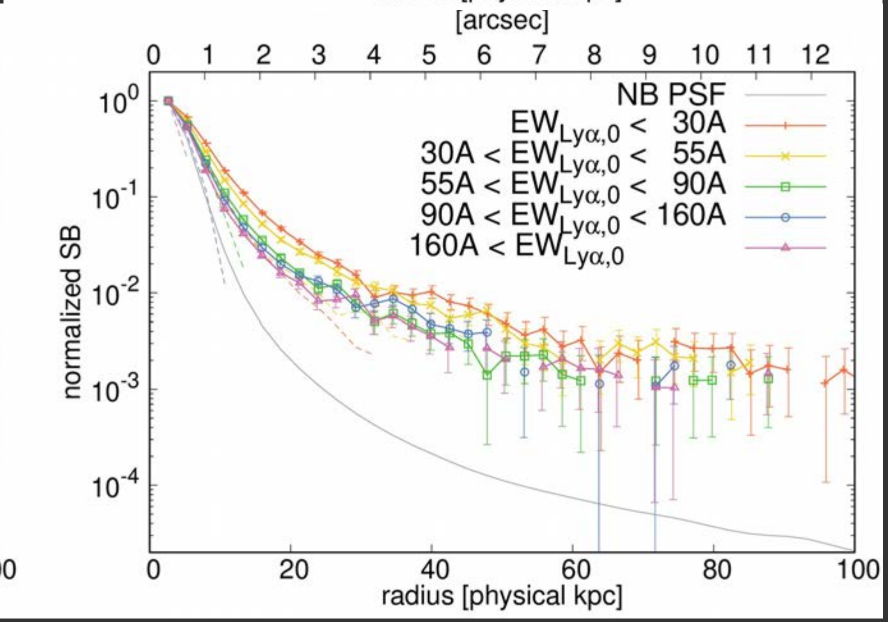
Hard to discuss trend beyond >30 pkpc due to low S/N

Trend of UV bright LAEs having larger LAHs is consistent with previous studies (Momose+14), while the trend for $L_{Ly\alpha}$ is not

Trend for EW are likely made by correlation with UV mag and/or fluorescence





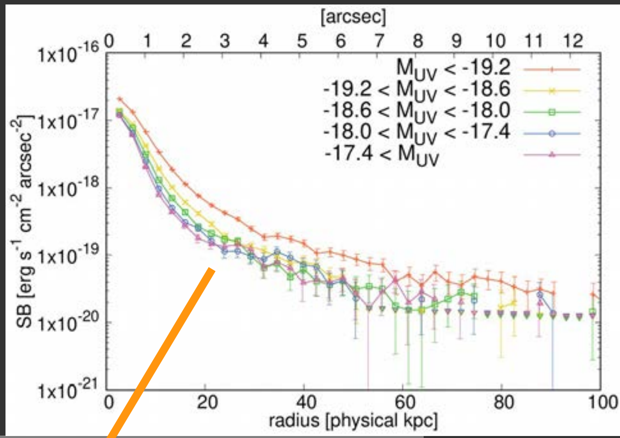


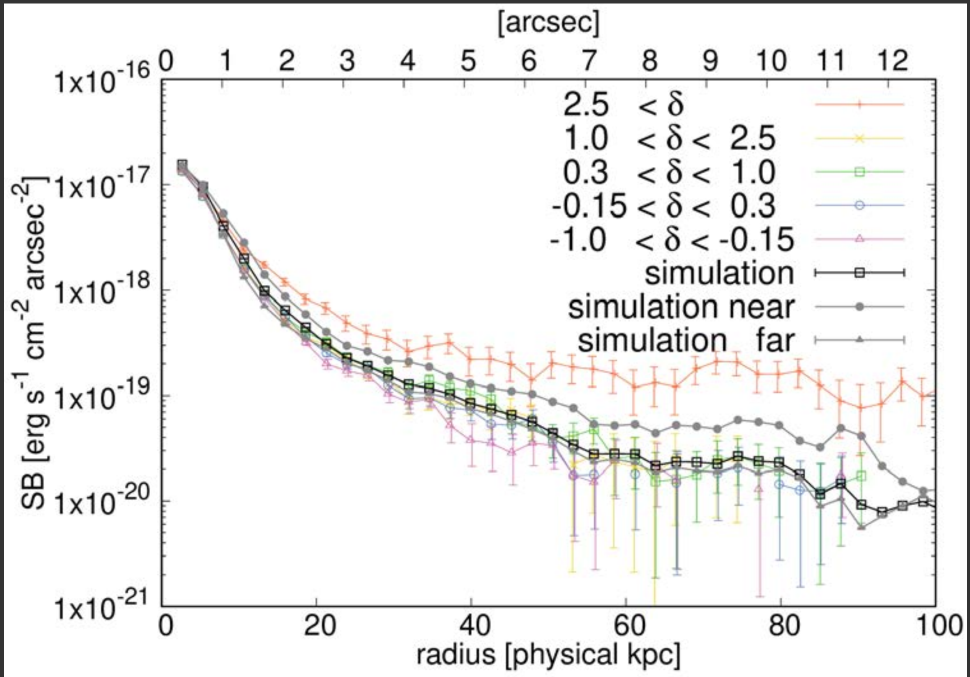
Origin of the Large LAH of Protocluster LAE

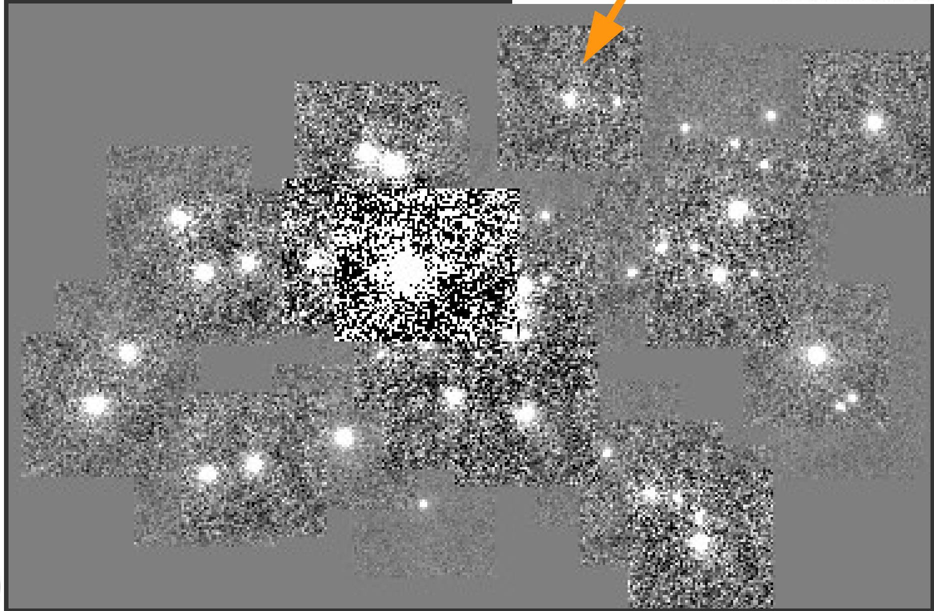
Protocluster LAEs are brighter in UV and this may be the cause of larger LAHs

→ Our simulation suggests NO

Overlap of LAEs also cannot explain the trend







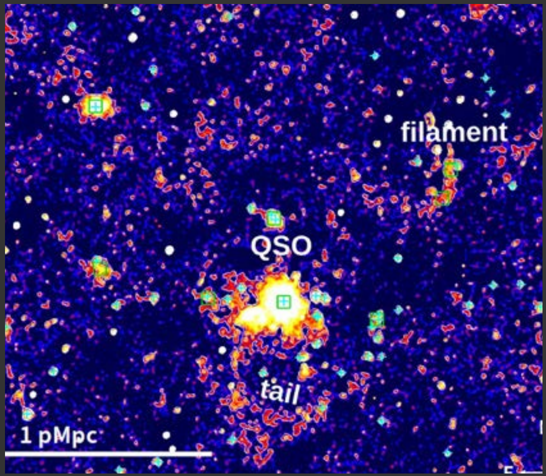
Origin of the Large LAH of Protocluster LAE

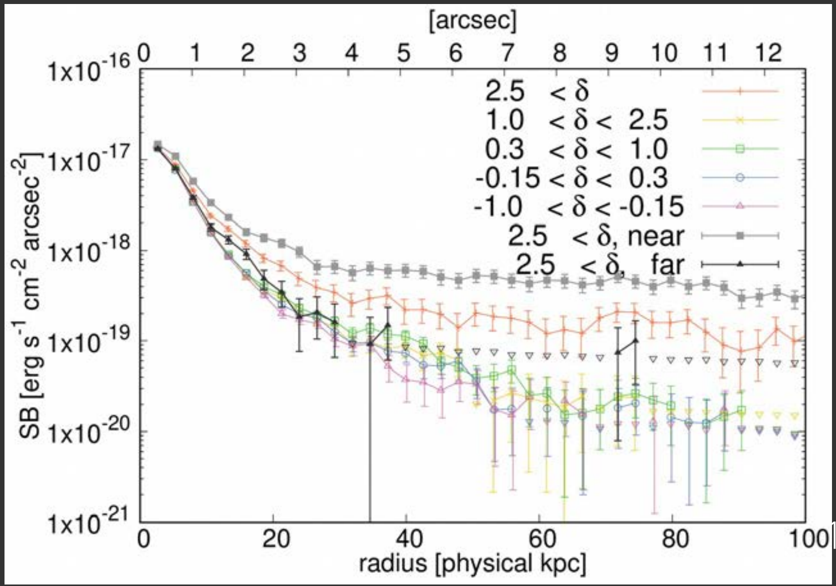
Diffuse Lyα emission around the core may boost the signal

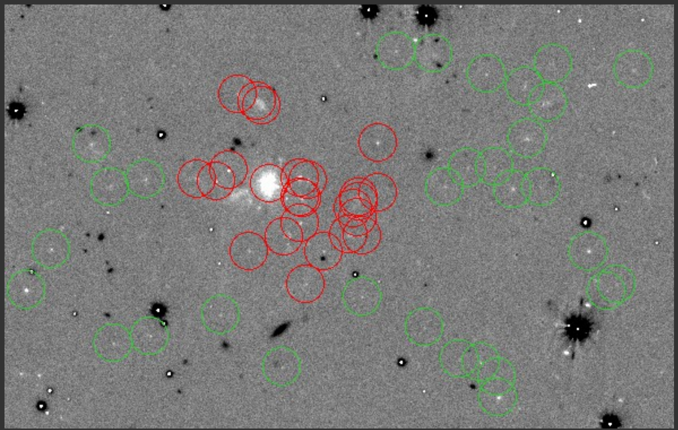
→ further divide LAEs with $\delta > 2.5$ into two and stack again

→ The result suggests the extent is made by the diffuse Lyα emission

Almost no dependence on environments outside of the protocluster







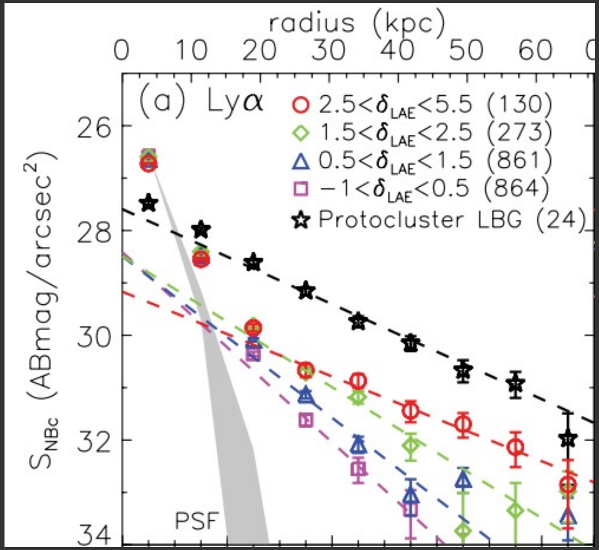
LAH dependence on environments

In the HS1549 field, a likely cause of large LAHs is diffuse emission around the protocluster core

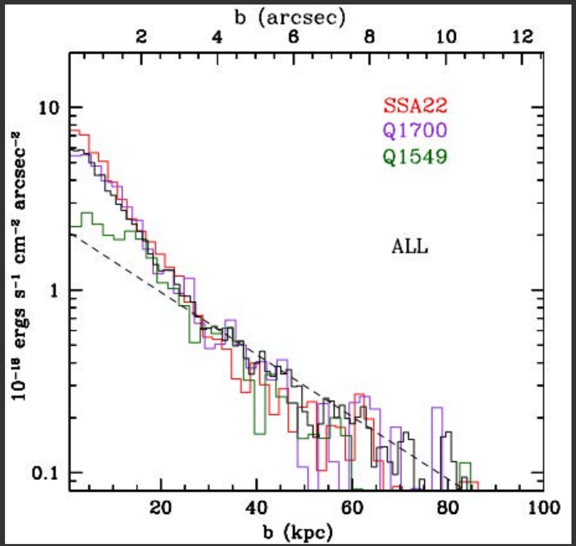
All studies which reported such large LAHs are targeted at protoclusters at z=2-3, which could have diffuse Lyα emission

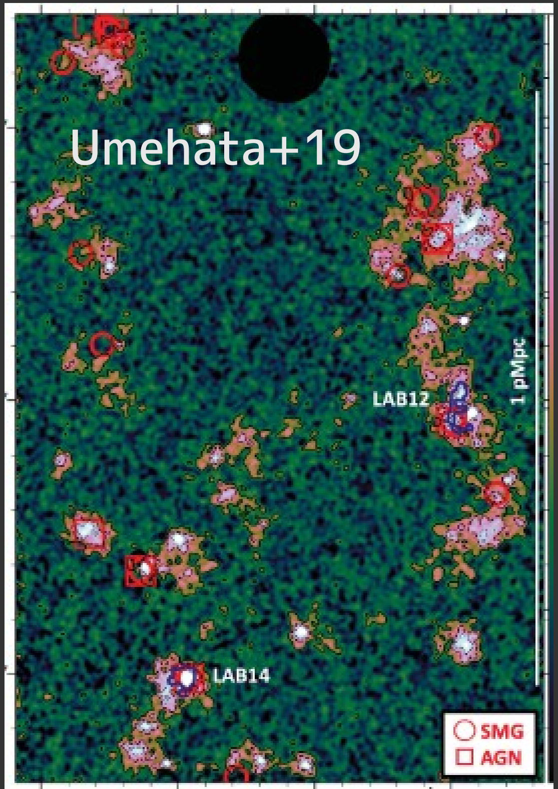
→ **No dependence on environments *out of protoclusters***

Matsuda+12: SSA22



Steidel+11: SSA22, HS1549, HS1700





Highlights

- Our target protoclusters are found to be at the intersection of a filamentary structure.
- Significant overdensity of LABs and their apparent alignment with that of the large-scale structure are found near the protocluster core.
- We detect huge Lyα emitting structure around the core of the HS1549 protocluster. Especially, **we discovered a candidate of cold streams at the node of the cosmic web**.
- LAHs of LAEs across environments are investigated with the same datasets, **finding almost no dependence on environments**.
- Large LAHs observed are likely due to diffuse Lyα emission that permeates the core of protoclusters at cosmic noon. Such protoclusters are good places to search for cold streams.

Conclusion

- Does the cosmic web gas and cold-mode accretion really exist in massive halos at cosmic noon?
  - **Maybe yes**, this should be confirmed with future IFS observations.
  - Our method worked well for increasing candidates of such filament.
- Is there a difference in the CGM as a function of environment?
  - **No**, except for protocluster LAEs – their CGM traced by LAHs are likely to be affected by diffuse Lyα emission.
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