# Galaxy Formation in a z=2.84 protocluster probed with HSC (and ALMA)


**Satoshi KIKUTA**
(NAOJ/Sokendai → University of Tsukuba, CCS)

& Yuichi Matsuda, Renyue Cen, Charles Steidel, Tomoki Saito


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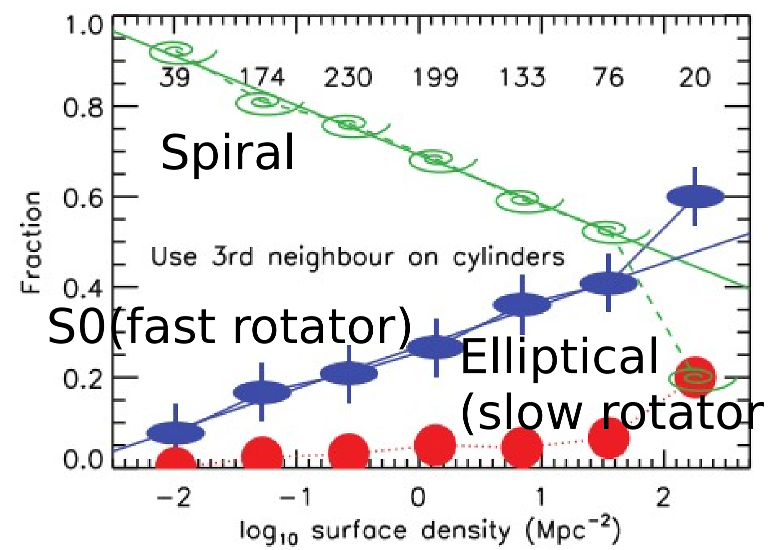
# Galaxy in Different Environments

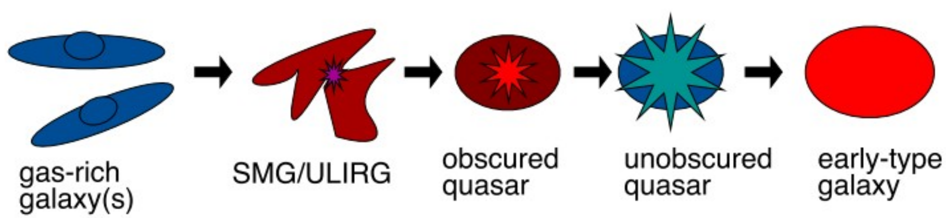
- Environmental segregation at z=0 suggests some processes preferentially work on galaxies in dense environments

- Observations of **protoclusters** hold the key
  - At z>2, the local relation reverses
  - Rich gas reservoir and high merger rate may be related to trigger various active populations (starburst, AGN, LAB, ...)

Cappellari+11




galaxy density →



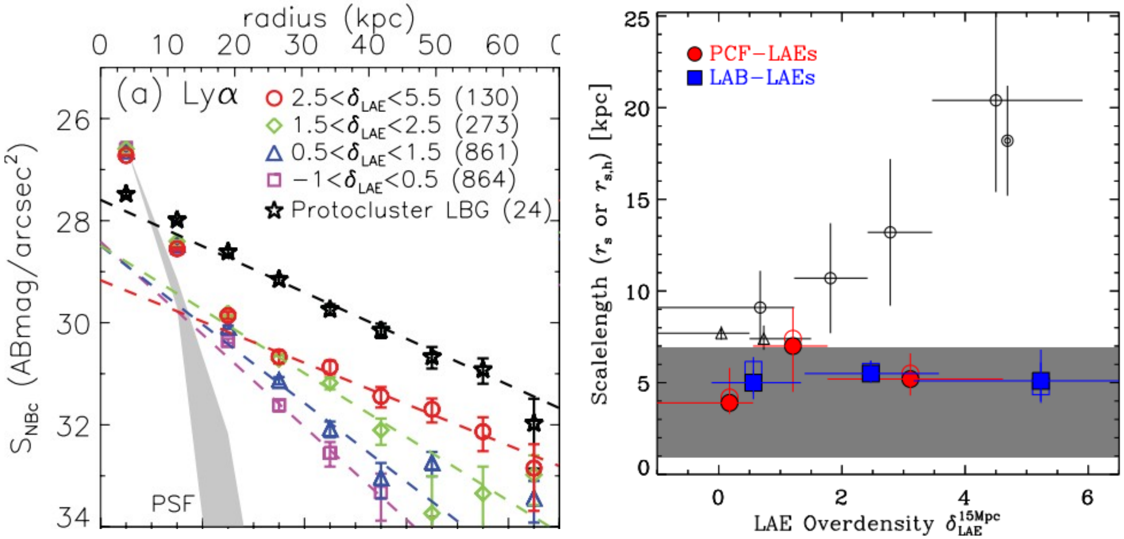

Alexander & Hickox 12

# Lyα halos of LAEs across environment

- **Are LAHs larger in denser environments?**

  If so, and if LAHs are good proxy for the CGM gas, this has implications for the environmental effects

  **But no consensus yet!**




Matsuda+12 vs Xue+17

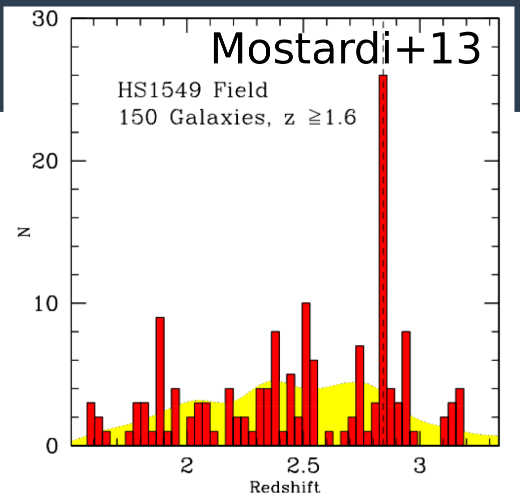
- Target obs. for more PCs are required
- Huge FoV of HSC enables us to simultaneously probe various environments

# Previous Studies on LAHs

| Field / Sample | Redshift | Environment | $N_{\rm gal}$ | Notes | Reference |
|---|---|---|---|---|---|
| O2 | 2.07 | blank field | 187 | 4m, 36hr, 50Å | Feldmeier et al. (2013) |
| C-O3 | 3.10 | | 241 | 4m, 24hr, 50Å | |
| K-O3 | 3.12 | | 179 | 4m, 16hr, 57Å | |
| LAB | 2.66 | $3.5 < \delta_{\rm LAE}$ | 29 | 4m, 8.3hr, 42Å | Xue et al. (2017) |
| | | $1.4 < \delta_{\rm LAE} < 3.5$ | 139 | | |
| | | $\delta_{\rm LAE} < 1.4$ | 86 | | |
| PCF | 3.78 | $2.0 < \delta_{\rm LAE}$ | 44 | 8m, 3hr, 201Å | |
| | | $0.5 < \delta_{\rm LAE} < 2.0$ | 76 | | |
| | | $\delta_{\rm LAE} < 0.5$ | 43 | | |
| SSA22, HS1549, HS1700 | 3.09, 2.85, 2.30 | protocluster | 92 | 10m, 17/5/22hr, 80/88/90Å | Steidel et al. (2011) |
| SSA22, GOODS-N, SXDS-C/N/S | 3.1 | $2.5 < \delta_{\rm LAE}$ | 130 | 8m, 5-10hr, 77Å | Matsuda et al. (2012) |
| | | $1.5 < \delta_{\rm LAE} < 2.5$ | 273 | | |
| | | $0.5 < \delta_{\rm LAE} < 1.5$ | 861 | | |
| | | $-1\delta_{\rm LAE} < 0.5$ | 864 | | |
| COSMOS, GOODS-N/S, SSA22, SXDS | 2.2 | $0.5 < \delta_{\rm LAE} < 1.5$ | 1047 | 8m, 2-3hr, 94Å | Momose et al. (2016) |
| | | $-1 < \delta_{\rm LAE} < 0.5$ | 348 | | |
| HS1549 | 2.85 | $2.5 < \delta_{\rm LAE}$ | 55 | 8m, 6hr, 88Å | Kikuta et al. |
| | | $1.0 < \delta_{\rm LAE} < 2.5$ | 433 | | |
| | | $0.3 < \delta_{\rm LAE} < 1.0$ | 944 | | |
| | | $-0.15 < \delta_{\rm LAE} < 0.3$ | 1076 | | |
| | | $-1 < \delta_{\rm LAE} < -0.15$ | 982 | | |

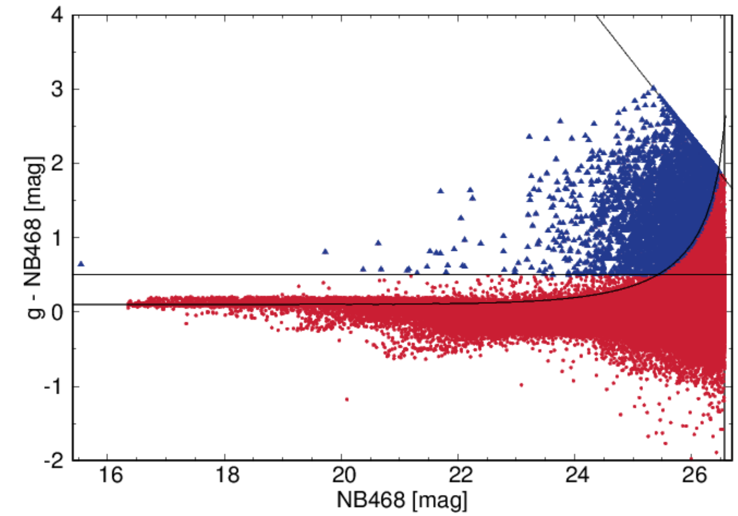
Deep observations including dense environments are scarce

# Target Field & LAE/LAB Detection




**Target: the HS1549 protocluster @ z=2.84)**
hyperluminous QSO HS1549+1919 is at its center
(e.g., Steidel+11, Mostardi+13)

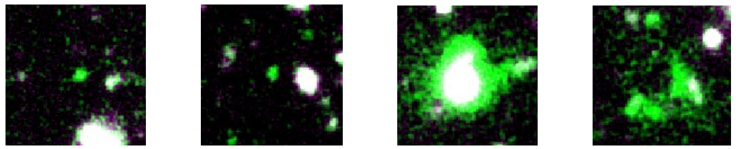
Observed with **Subaru/HSC**, g(2.2hr) and NB468(6.3hr)
→ Data reduced with HSC pipeline (hscPipe 4.0.5)




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

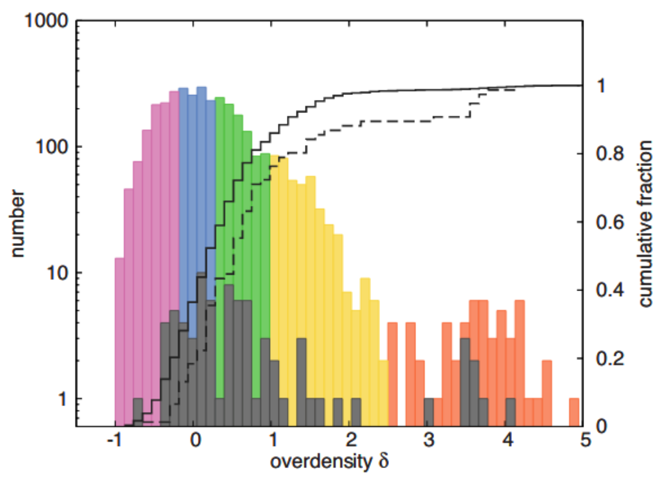
- **LAE selection criteria ($2.815<z<2.887$):**
  - NB < 26.57(5$\sigma$)
  - G – NB > max{0.5, 0.1+4$\sigma$(G-NB)}
    (rest $EW_{Ly\alpha}$ >12Å)
- **LAB (Lyα blob)selection criteria:**
  - criteria above(in isophotal mag) + Lyα isophotal area>16 arcsec$^2$

**→ 3490 LAEs and 76 LABs found**



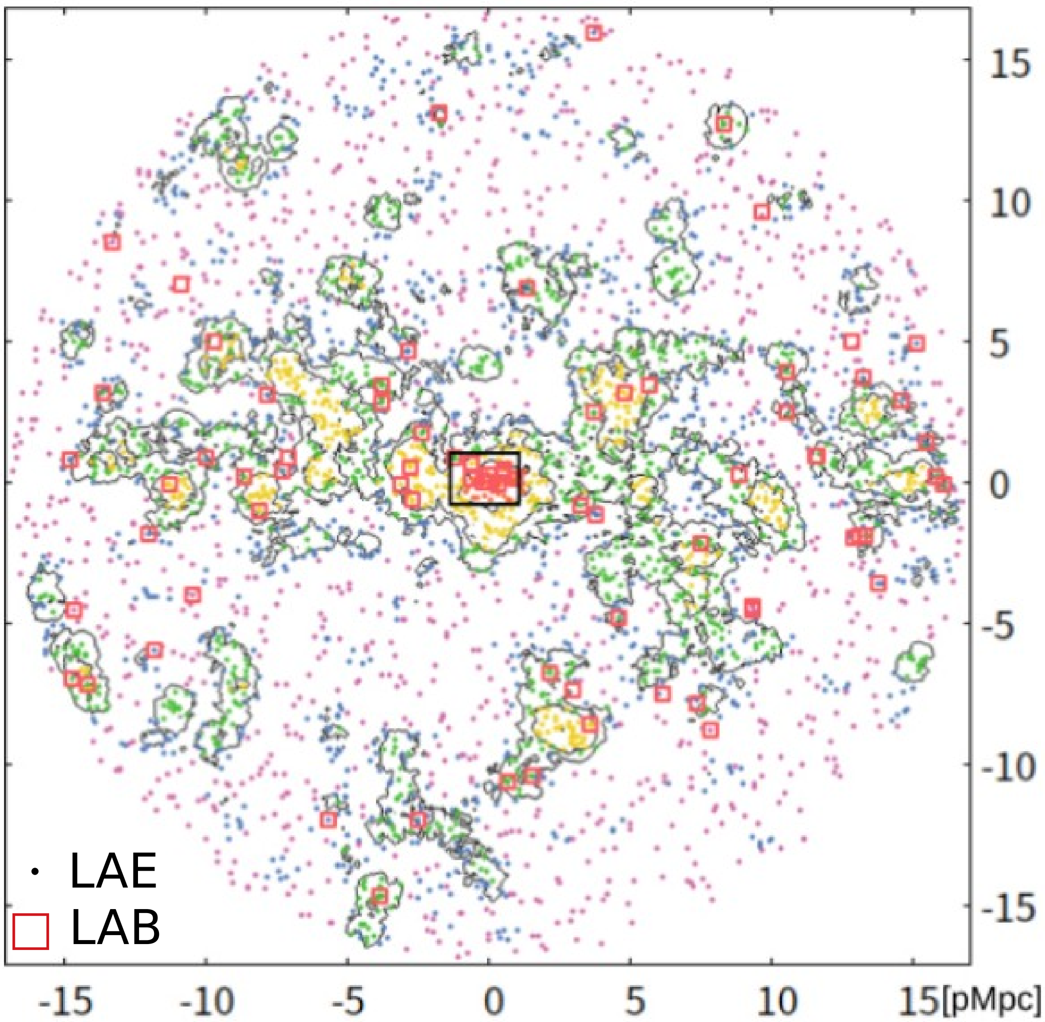
# Distribution of LAEs & LABs

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




KS-test p-value:0.00173

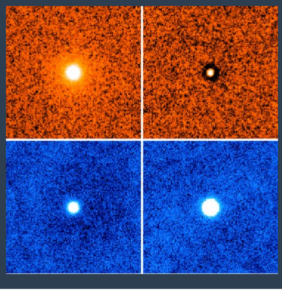
※$\delta_{gal}=n/n_{ave}-1$, n is the number of LAEs within a 1.8’ aperture at a given point



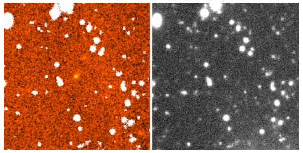
# Stacking Analyses

LAE non-LAE

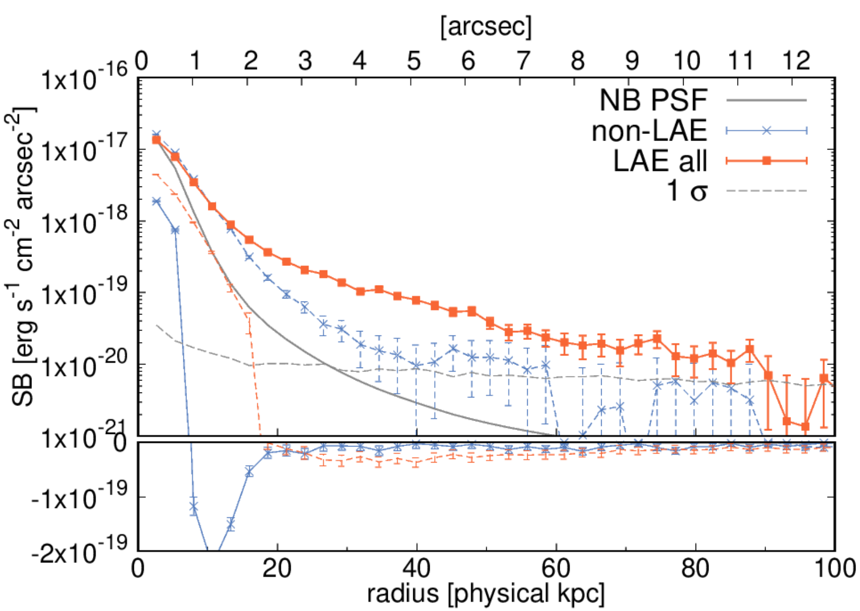
Lyα Cont.



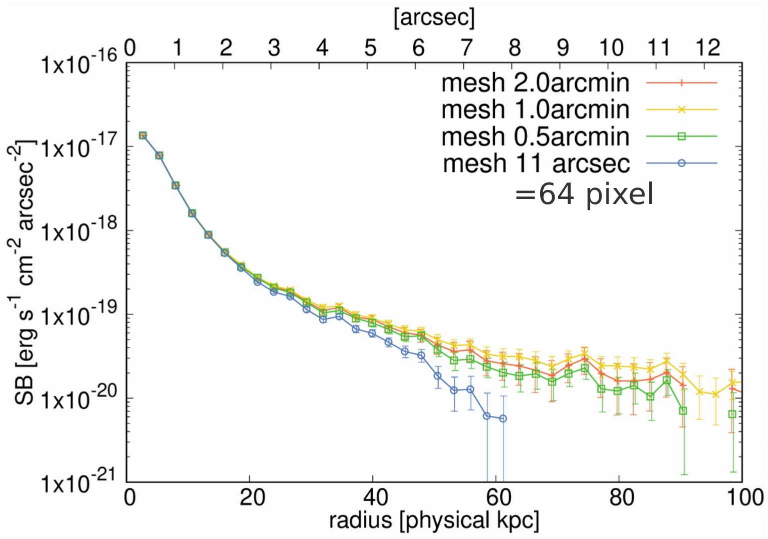
- Use cutout Lyα images of LAEs (sky mesh size=30”) with continuum sources masked
- Stack Lyα & continuum images with IRAF imcombine (median, no clipping)
- Sky noise behaves well (noise ∝ ~$N^{-1/2}$)
- “Non-LAE” sample is constructed to check total systematics (see Momose+14)
- **Detect diffuse Lyα emission down to ~$10^{-20}$ erg/s/cm²/arcsec²**



Lyα Cont.



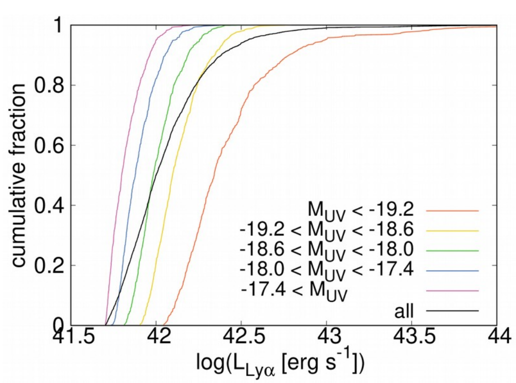

solid: Lyα, dashed: Cont.

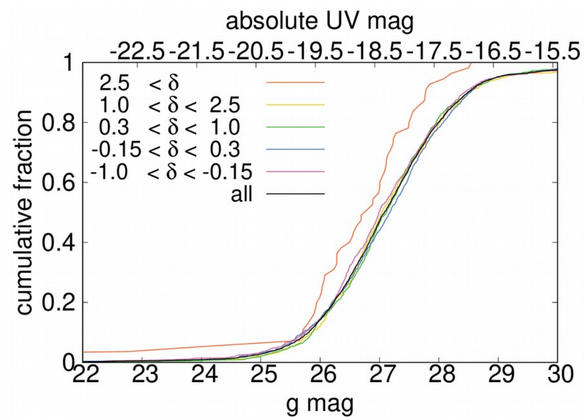



**Sufficiently large sky mesh size is crucial!!**

# LAH Dependence on Various Properties

- Divide LAEs into 5 groups according to their photometric properties
- "Distance from the HLQSO" is for checking the impact of strong radiation field made by the QSO
- Note the correlations between quantities

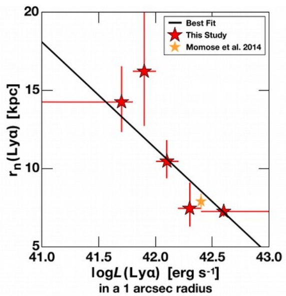


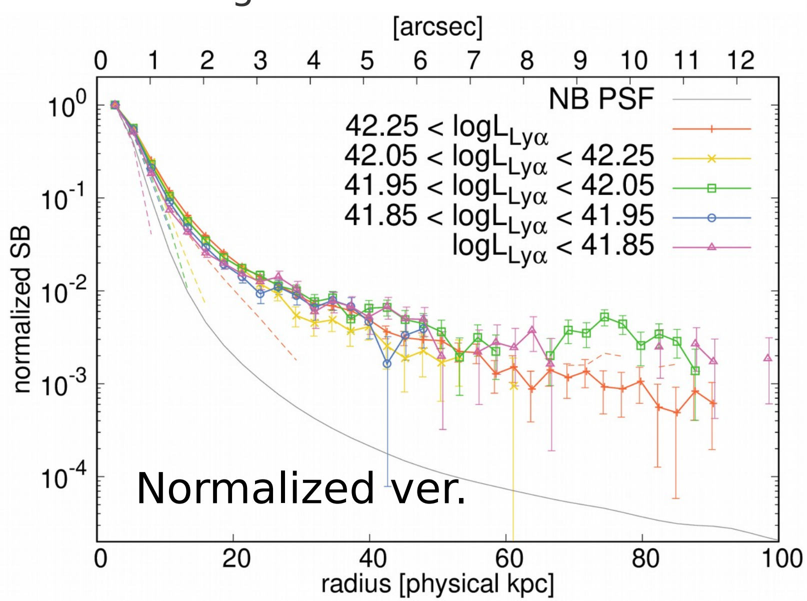

| quantity | criteria | $N$ |
|---|---|---|
| UV magnitude | $M_{\rm UV} < -19.2$ | 690 |
| | $-19.2 < M_{\rm UV} < -18.6$ | 696 |
| | $-18.6 < M_{\rm UV} < -18.0$ | 773 |
| | $-18.0 < M_{\rm UV} < -17.4$ | 648 |
| | $-17.4 < M_{\rm UV}$ | 683 |
| Ly$\alpha$ luminosity | $42.25 < \log L_{\rm Ly\alpha}$ | 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 |
| Ly$\alpha$ 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 |

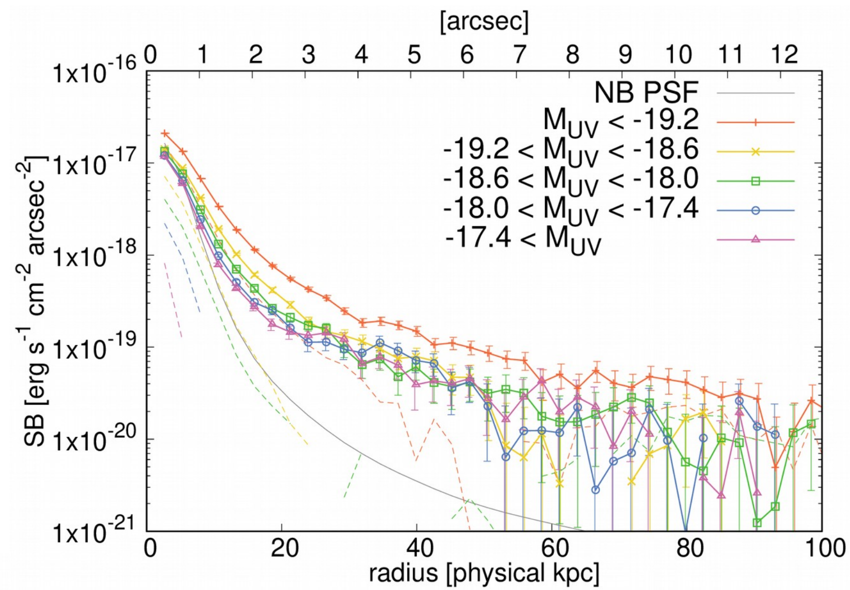
# Results of Stacking: UV, $L_{Ly\alpha}$, EW

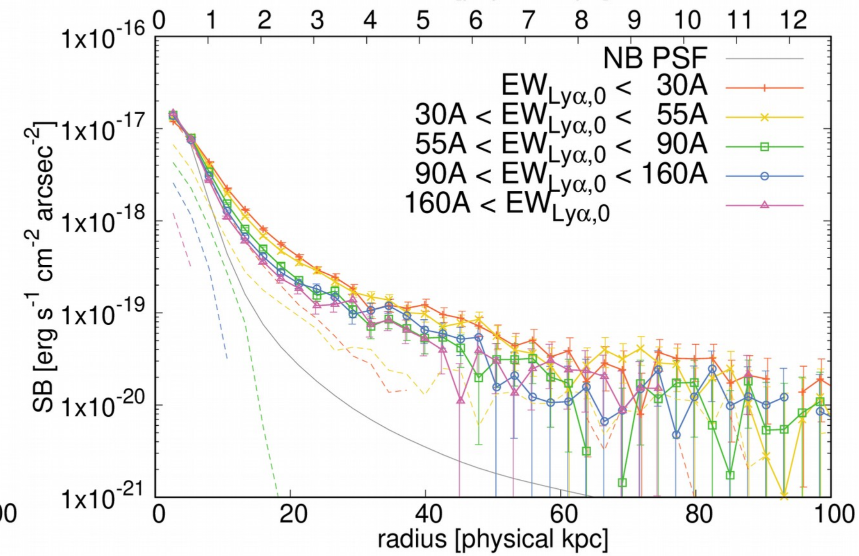
- LAHs are detected for all subsamples
- Bright/low-EW LAEs tend to have larger LAHs
  - Consistent with [CII] halo at higher-z (though mass range is different)
- Trends in Momose+16 are not clearly seen




← That is: $L_{Ly\alpha}$/UV faint LAEs have larger LAHs



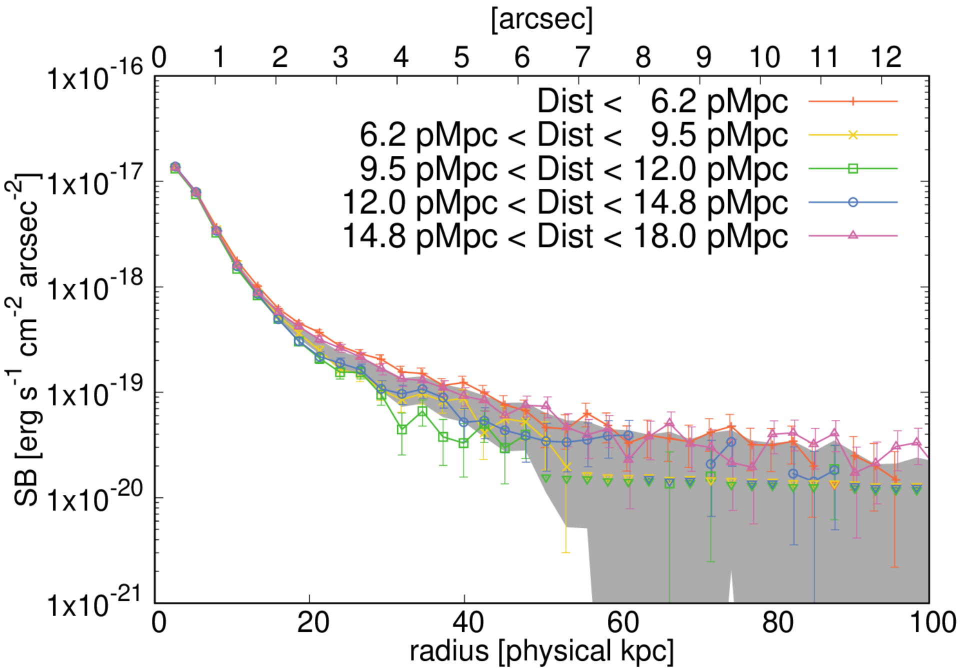



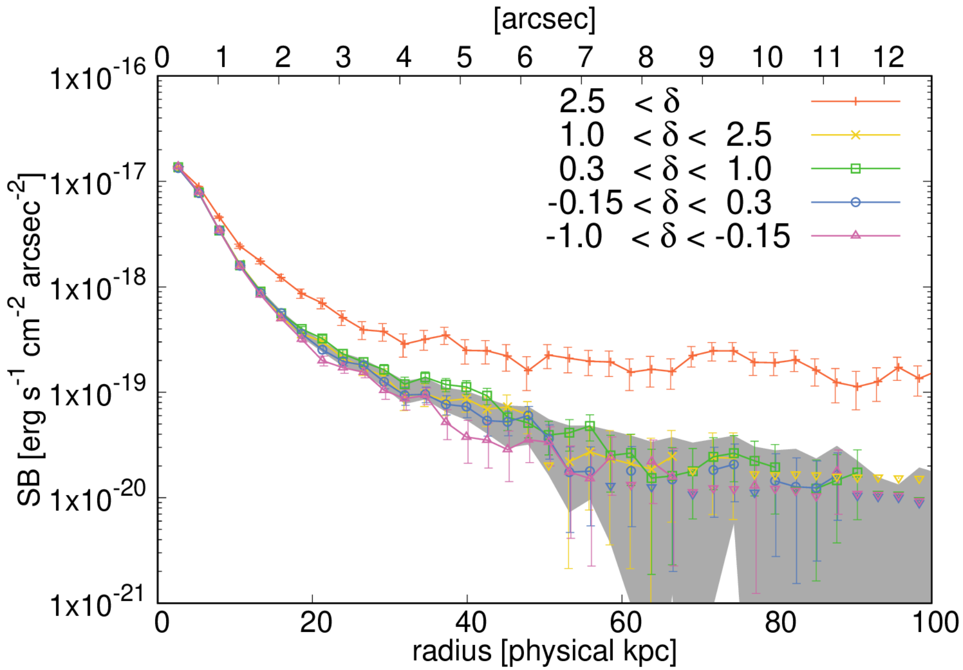



# Results of Stacking: Distance, Environment

- LAHs are detected for all subsamples, **even at underdense regions**
- **No clear trend** is noted (except for the large LAH in the δ>2.5 subsample)

Gray shade ··· 5th and 95th percentile of the stacked Lyα SB distribution of 700(Left)/1000(Right) randomly selected LAEs



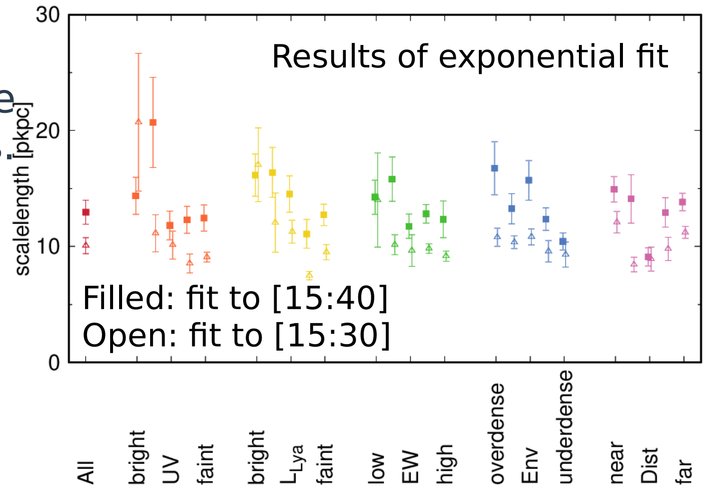



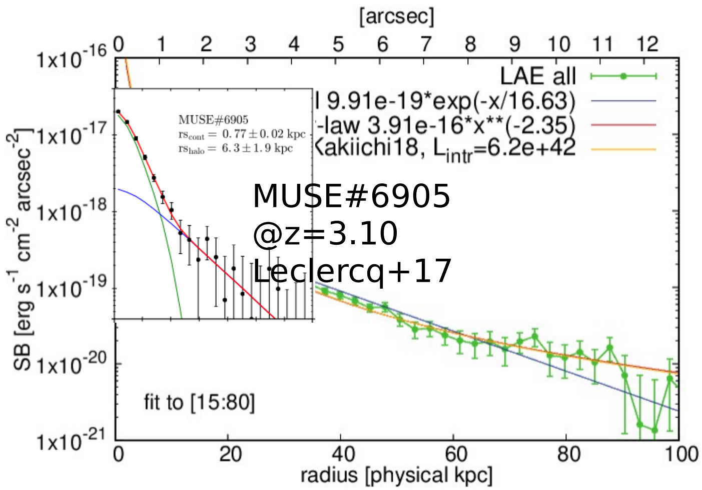
# Discussion 1: exponential or power-law

- Exponential fit may not good; considering the curvature, results strongly depend on fitting range – the shallower the data (and the smaller the fitting range) used, the smaller scalelengths one gets. **Our data prefer power-law**.
- **Sufficient sensitivity out to large radius is the key!**
- Very good match to prediction of Kakiichi & Dijkstra 18

$$\langle \mathrm{SB}_\alpha(r_\perp)\rangle/[\,\mathrm{erg\ s^{-1}\ cm^{-2}\ arcsec^{-2}}] \approx 2.1\times10^{-18}\left(\frac{\langle L_\alpha^{\rm intr}\rangle}{3.7\times10^{43}\ \mathrm{erg\ s^{-1}}}\right)\left(\frac{r_\perp}{20\ \mathrm{pkpc}}\right)^{-2.4}$$

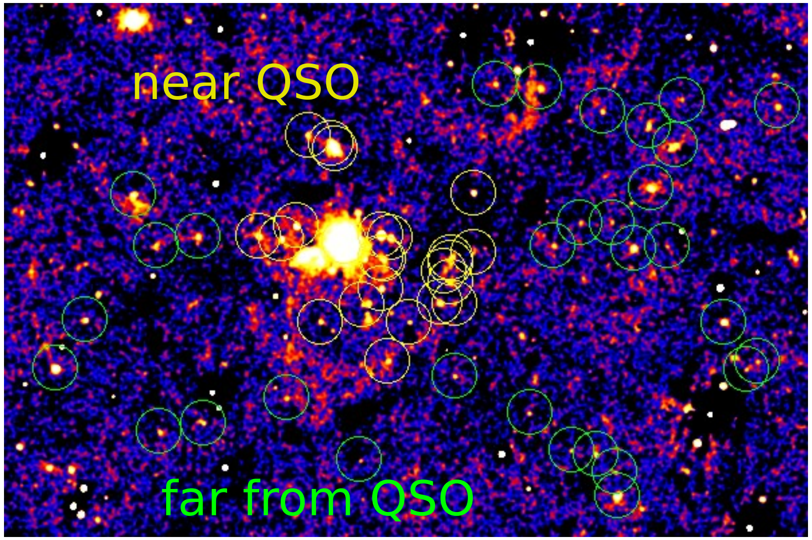
  - Our fit indicate $L^{intr}$=6.2e+42, while our median $L_{Lya}$~1e+42 – suggests Lyα escape fraction ~16%
- UV brightest sample have a shallower slope (~-2.2)
- The model also predicts UVB dependence, but the distance from the QSO seems not to affect LAHs
  - Is the HLQSO very young? Anisotropic? Or fluorescence is dominant over Lyα scattering?
  - The PC LAEs are very close to the QSO, but the effect of high density around the PC core would more effective

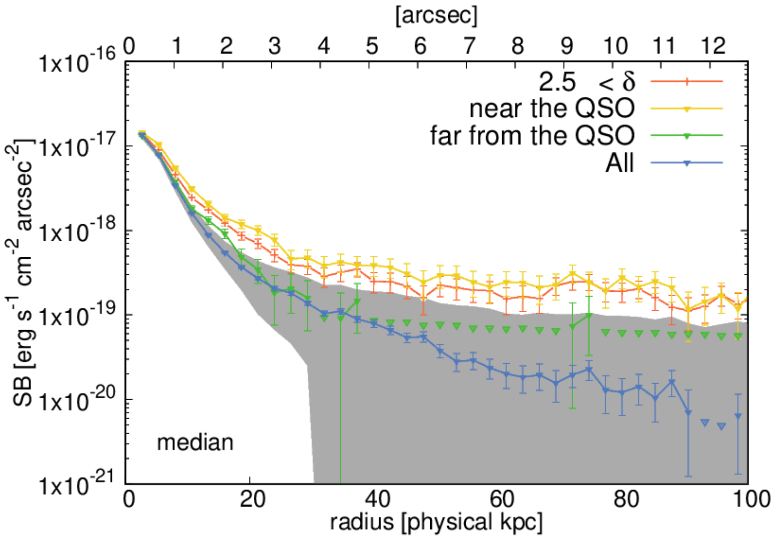


# Origin of the Large LAH in PCs

- Overlapping of many galaxies or UV brightness of the PC LAEs cannot fully explain the large LAH
- When we further divide the PC sample into near/far from the QSO sample, far sample no longer has a large LAH.
- **Diffuse emission around the PC core may be the cause**



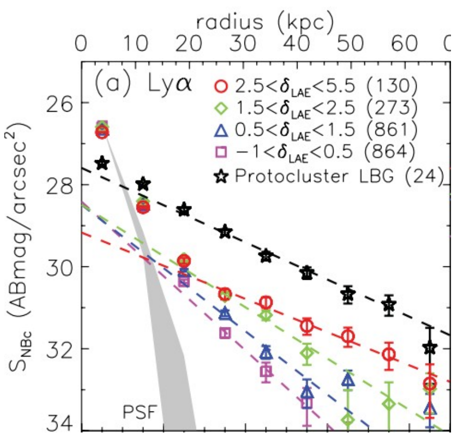




Gray shade ··· 5th and 95th percentile of the stacked Lyα SB distribution of 55 randomly selected LAEs

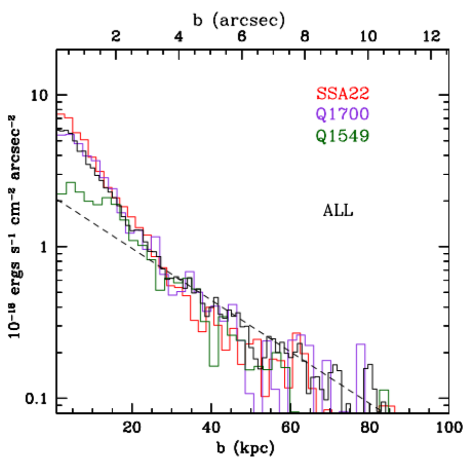
# Origin of the Large LAH in PCs

- Previous nondetection of env. dependence could just be due to low sensitivity
- Previous studies that reported very large LAHs probes massive LBGs and/or protocluster SFGs at z~2-3, in which diffuse Lyα emission may permeate
- Steidel+11 results are based on ~10 times more massive LBGs
  - LAHs of such massive galaxies are currently not well studied because continuum selection cannot select galaxies from a narrow redshift range
- Follow up of HS1700 with NB400 would be interesting

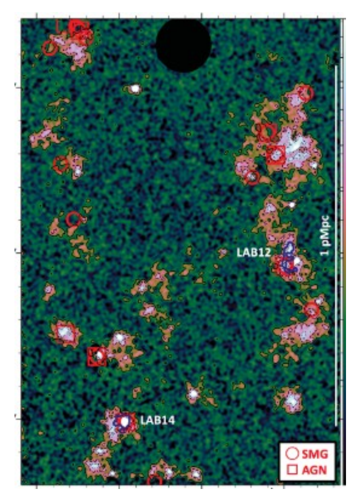
Matsuda+12: SSA22

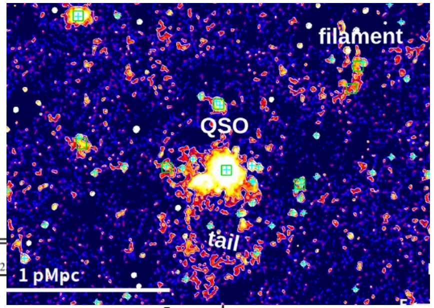



Steidel+11: SSA22, HS1700, HS1549

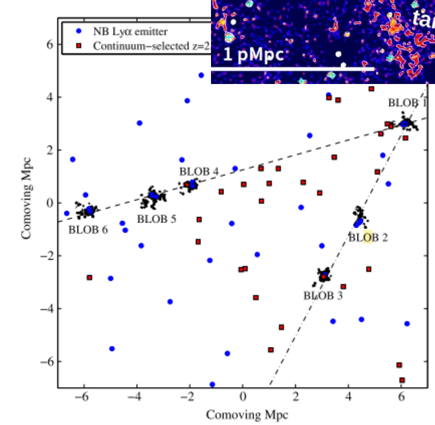



Umehata+19: SSA22




Kikuta+19: HS1549




Erb+11: HS1700

# Take home message about LAH

- Sensitivity close to 1e-20 erg/s/cm$^2$/arcsec$^2$ is necessary for safe argument (at z~3) – **NB stacking with Subaru/HSC is still a powerful tool in the era of sensitive IFUs!**
- **Power-law is better for fitting** <u>if you have sufficient sensitivity.</u>
- Comparison with a model suggest $f_{Ly\alpha}$ ~0.16 .
- Weak dependence on large-scale environments, but very large LAHs may emerge in PCs at cosmic noon due to diffuse Lyα emission (or because just they are massive).