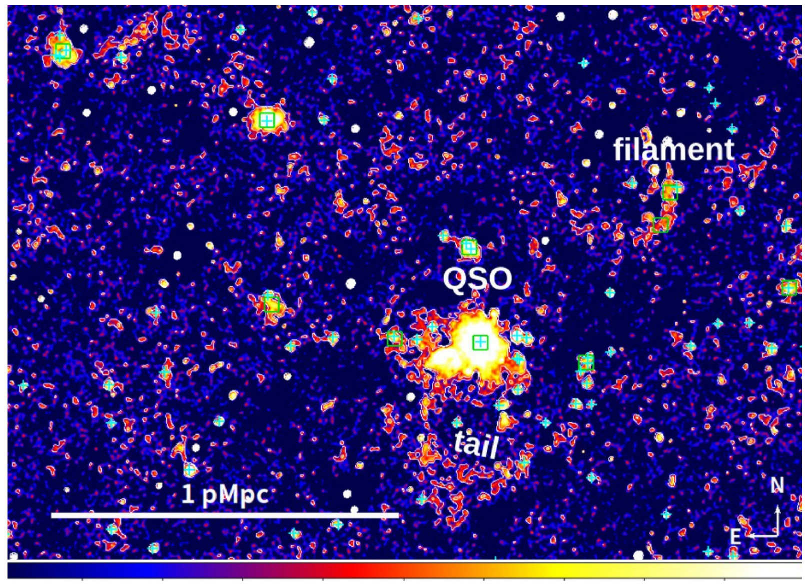
HSC 狭帯域フィルターを用いた z~3 の淡い Lyα 放射の研究



Kikuta et al. 2019

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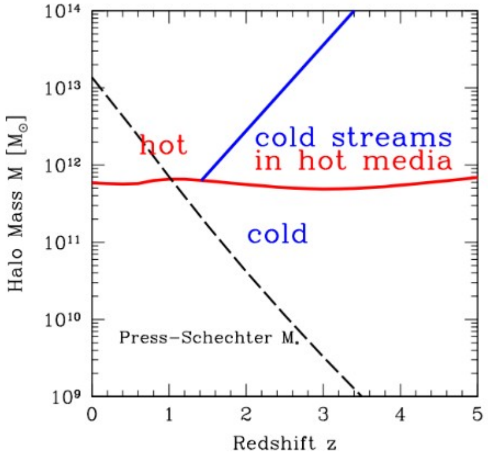
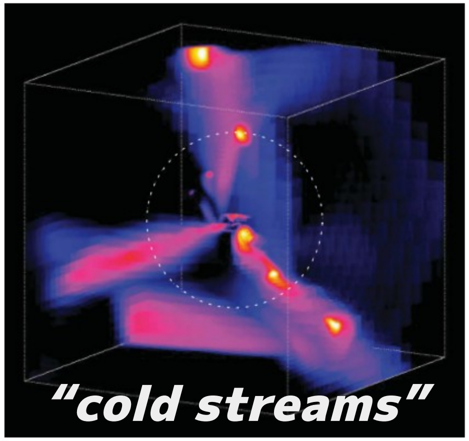
すばる望遠鏡データ解析講習会
2022/11/29

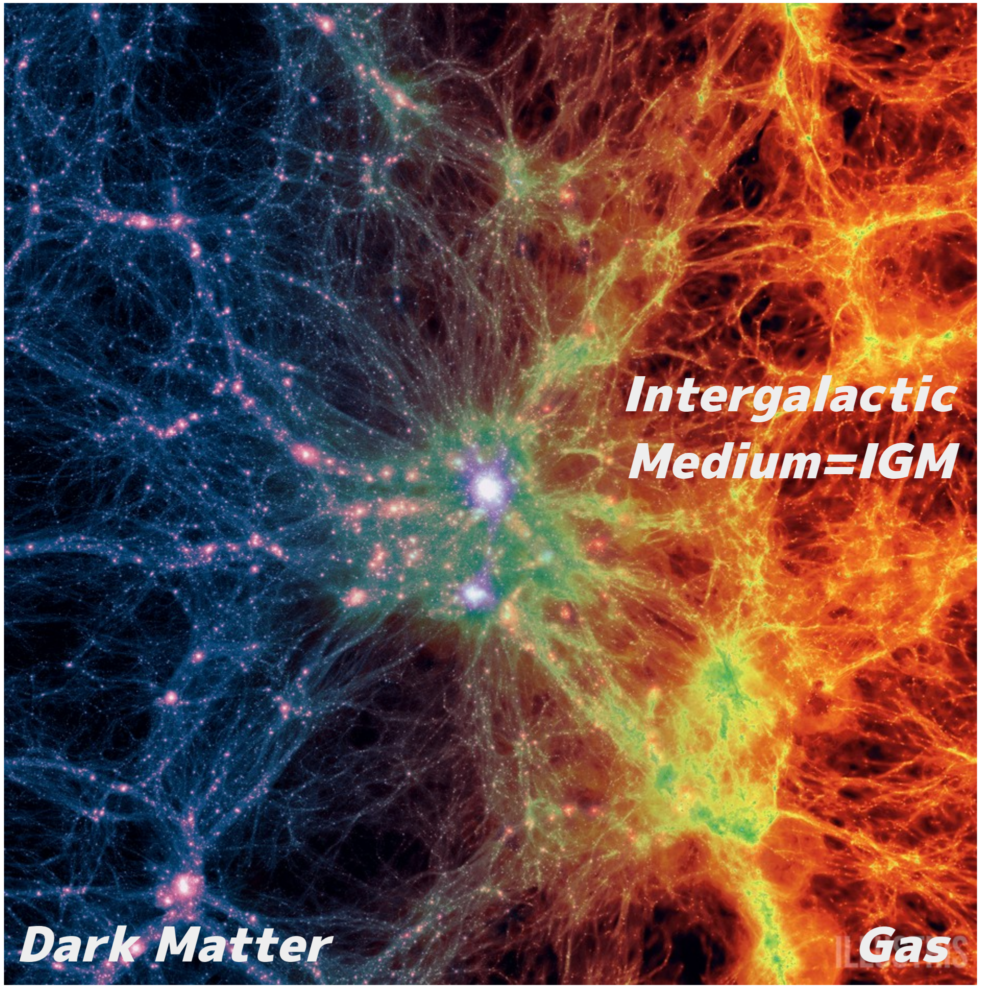
Introduction: Galaxy Formation

- 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"
  - observationally poorly constrained!
- Massive stars, SNe, AGNs inject energy into ISM/CGM
  - "feedback"



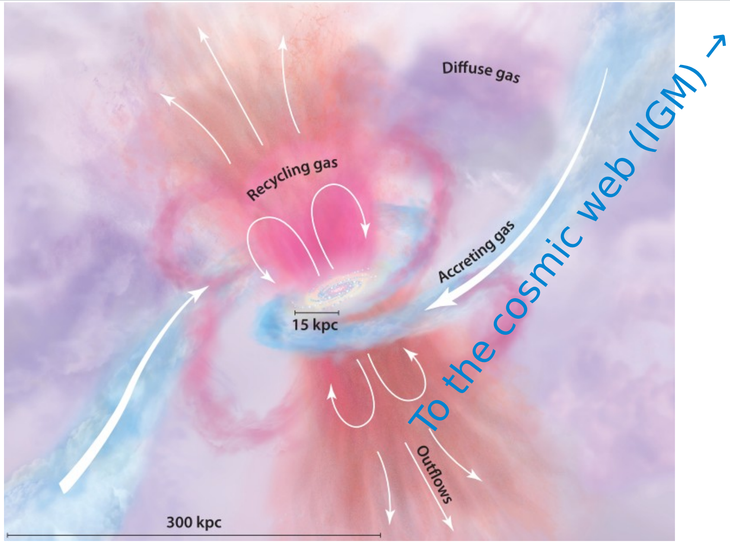
Dekel+09



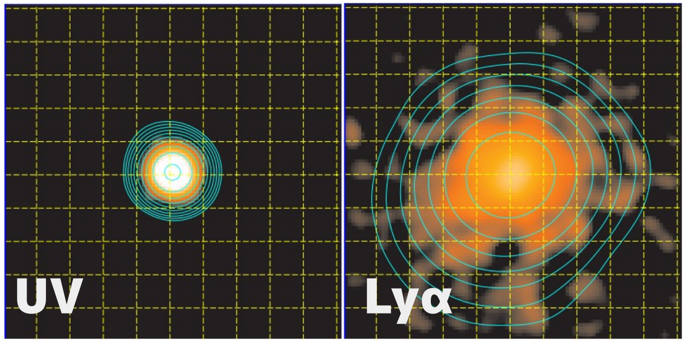


Inter/Circum-galactic medium (IGM/CGM) & Lyα emission

- Gas circulation between IGM/CGM is very important for galaxy evolution
- can be traced with Lyα emission at high redshift (z>2)
  - Turned out to be ubiquitous, **but very faint** (SB<10^{-18} erg/s/cm^2/arcsec^2)
  - IFU or deep NB imaging are powerful tools



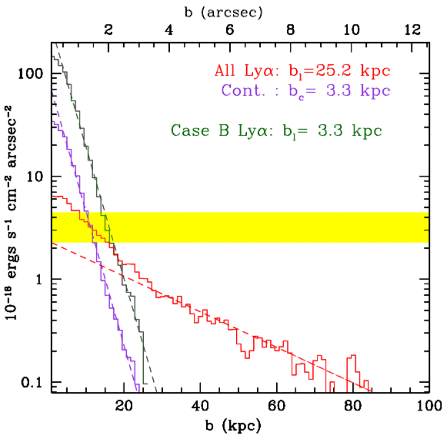
Tumlinson et al., 2017



so-called **Lyα halo!**

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

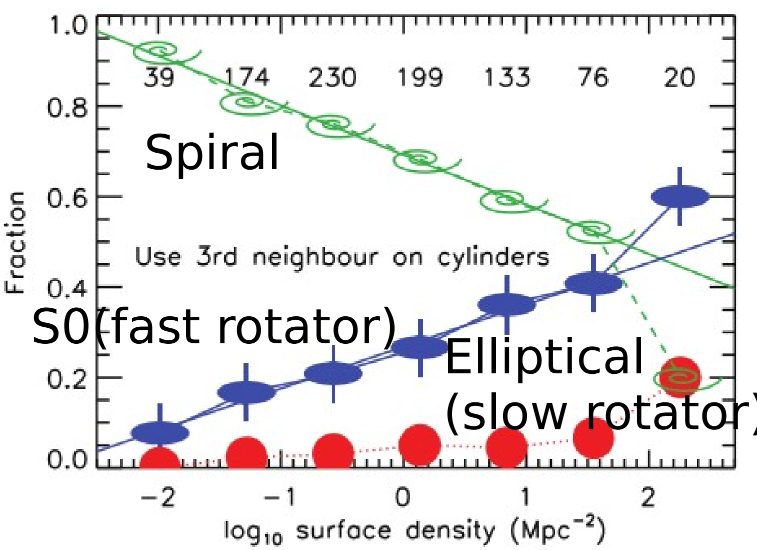
←Their SB profiles (Steidel+11)



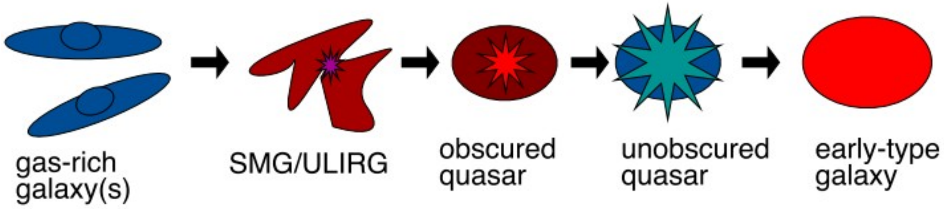
Galaxy in Different Environments

- 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
  - High gas accretion rate, high merger rate, etc. may be related to abundant active populations (starburst, AGN, LAB, ...)

Cappellari+11



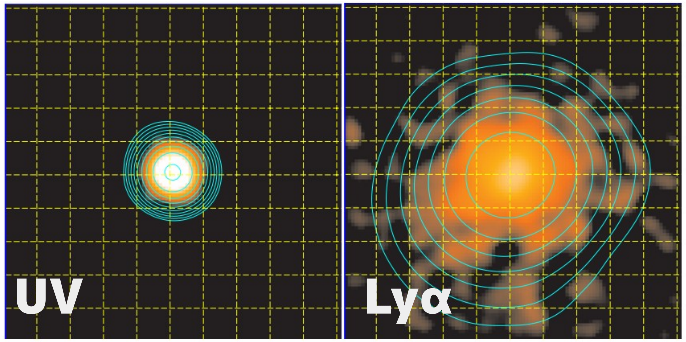
galaxy density →



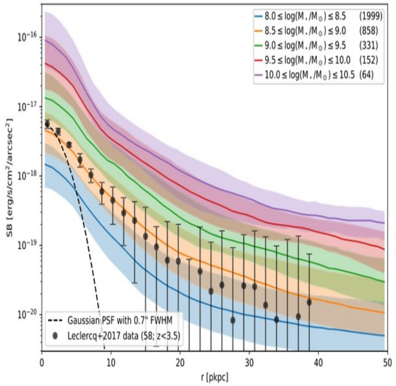
Alexander & Hickox 12

Observations of Lyα halos around SF galaxies at z>2

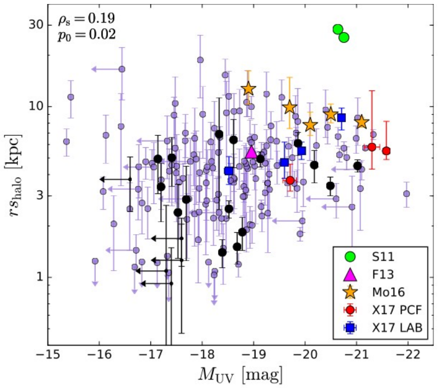
- **Diffuse Lyα halo is ubiquitous if we go as deep as <1e-18 erg/s/cm²/arcsec² – but its origin is still under debated!**
- LAH shape and its dependence on various host properties should have useful information
  - Host UV magnitude, Lyα luminosity, the large-scale **environments**, etc.
  - Observations in the literature have not reached consensus. More obs. are needed to pin down the origins and probe the CGM



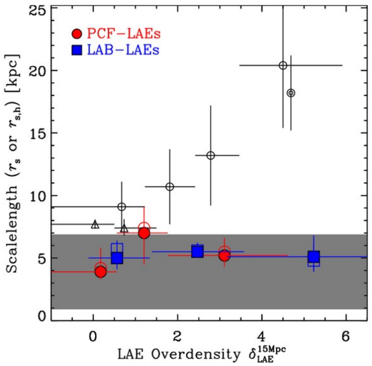
Stacked UV(left) and Lyα(right) image of **LBG** @ z=2.65 (Steidel+11)



Byrohl+21 Simulation



Leclercq+17 Halo scale-length vs M_{UV}

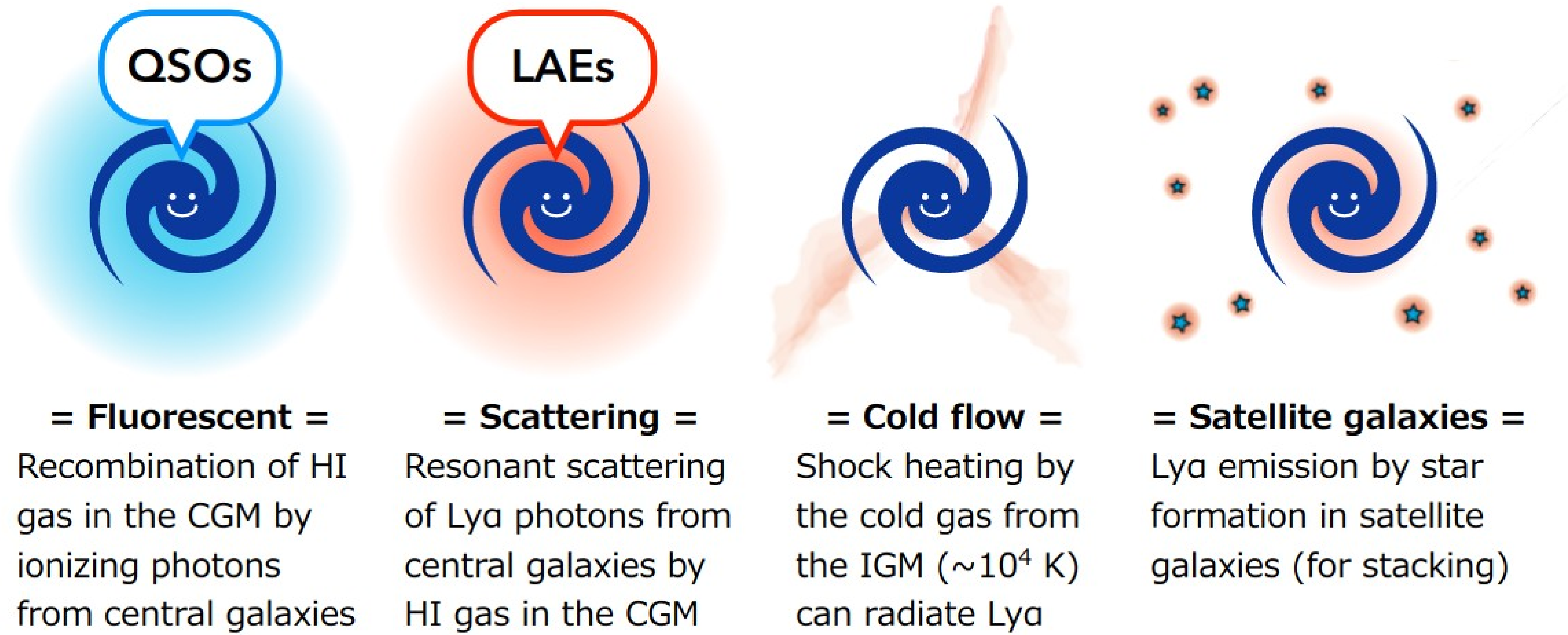


Matsuda+12: LAEs in denser environments have more extended LAHs

vs.

Xue+16: No such dependence →

Origin of Lyα emission in the CGM



- Ionizing photon production rate
- Lyα luminosity
- HI distribution
- DM halo mass
- DM halo mass

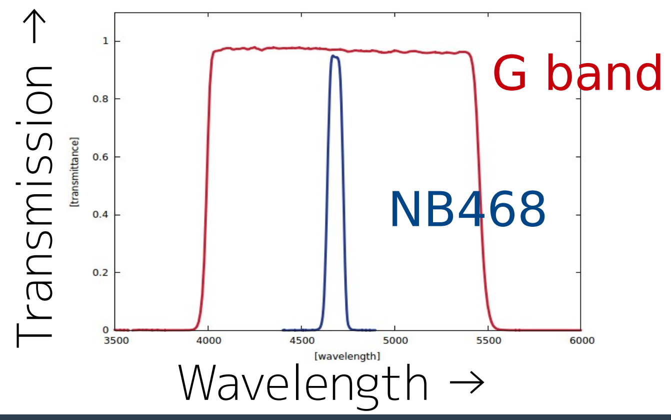
Taken from Momose-san's slide
See also Momose+16

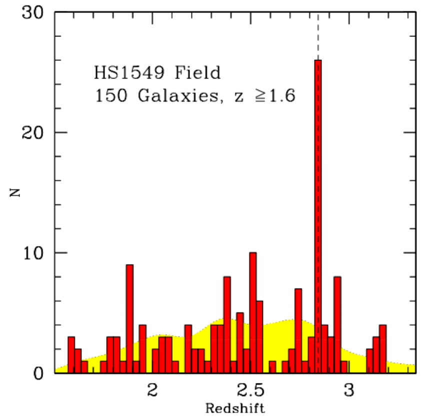
Deep HSC imaging for diffuse emission

- Target: Field around a hyperlumious QSO at z=2.84 (HS1549+1919)
  - reside in massive overdensity (proto-cluster)
- Observed with Subaru/HSC (PI: Yuichi Matsuda)

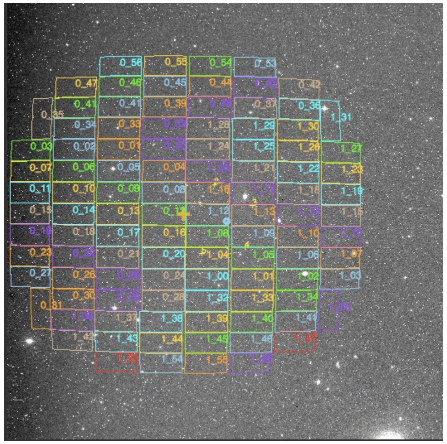
G	2.2 hr (20s	×389 shots) → 27.4 mag (5σ, 1.5” aperture~2×seeing 0.77”)
NB468	6.3 hr (300s	×113 shots) → 26.6 mag (5σ, 1.5” aperture)

  - To avoid saturation of the QSO, exposures need to be short
  - Large dithering (N_{dith}=5, R_{dith}=10’) + PA rotation (30°×N)
    - To reduce the impact of diffuse ghosts



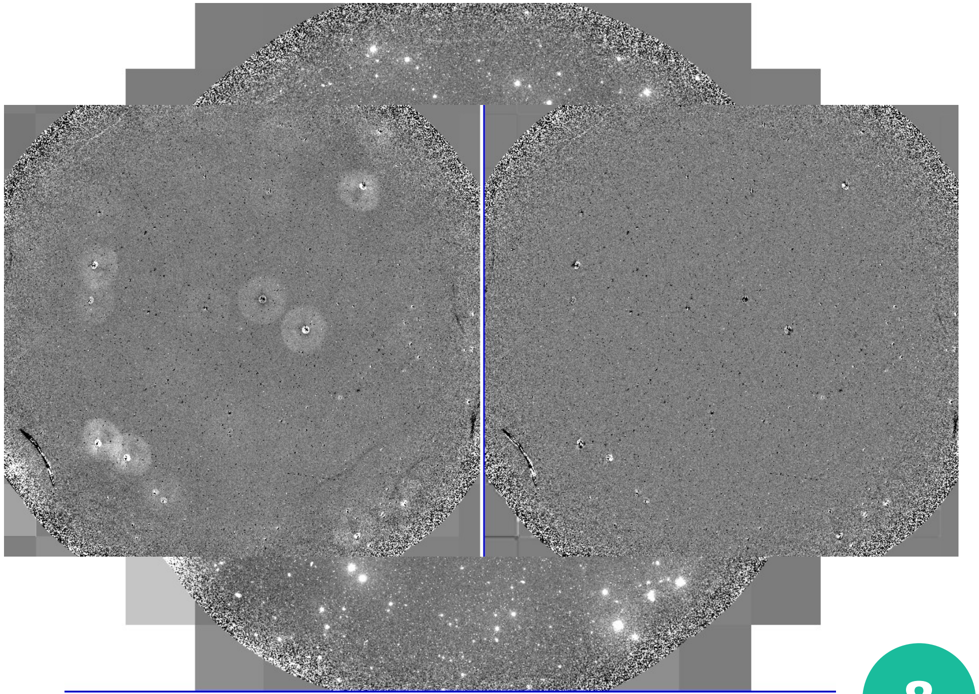


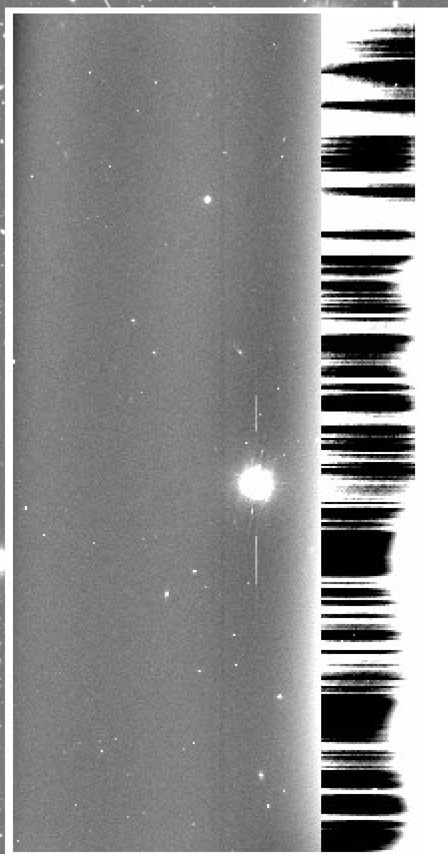
Mostardi+13



Data Reduction

- Data reduced using HSC pipeline (hscPipe 4.0.5)   raw data: ~1.3TB
  - With **global sky subtraction** + ghost mask package +addtional mask by myself
    - https://hsc.mtk.nao.ac.jp/pipedoc/pipedoc_4/j_tips/skysub.html#global-sky
    - https://hsc.mtk.nao.ac.jp/pipedoc/pipedoc_4/j_tips/ghost.html
- For further analysis, we subtract the sky with SExtractor with arbitrary sky mesh size
  - For point source detection, we used 64 pixel
  - For extended source analyses, we used 176 pixel (=30”)





Solutions:

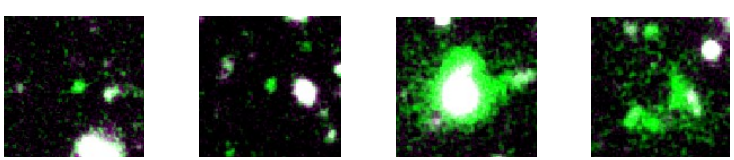
- Ignore problematic CCDs
- Define and register “defect”
- Mask problematic regions
  - Edit fits mask layer

LAE/LAB Detection

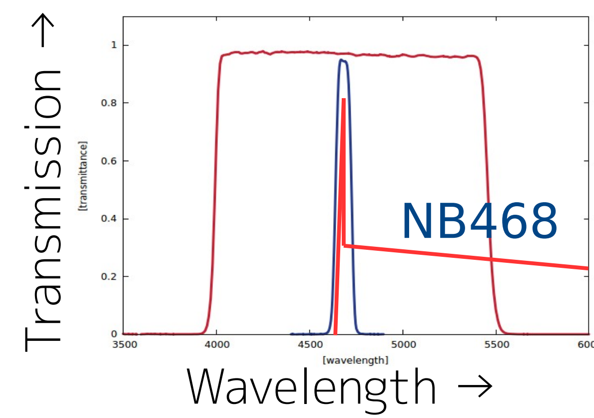
Source detection & photometry with Source Extractor (Bertin & Arnouts 96)

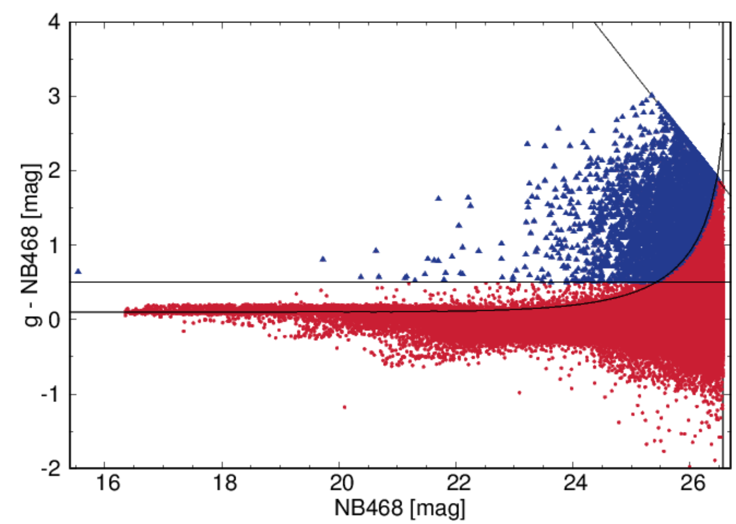
- **LAE selection criteria (2.815<z<2.887):**
  - NB < 26.57(5σ)
  - G – NB > max{0.5, 0.1+4σ(G-NB)} (rest $EW_{Ly\alpha}$ >12Å)
- **LAB (Lyα blob)selection criteria:**
  - criteria above(in isophotal mag) + Lyα 2σ isophotal area>16 $arcsec^2$ in the smoothed Lyα image (gaussian with σ=3 pixel)

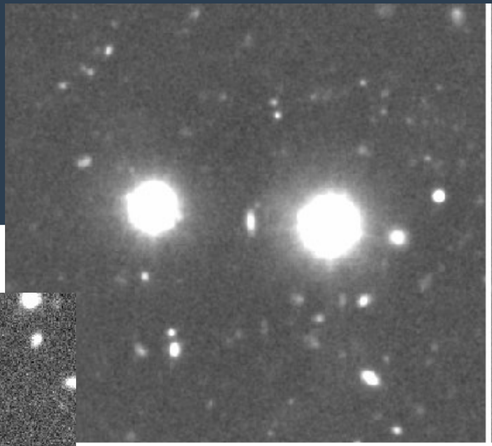
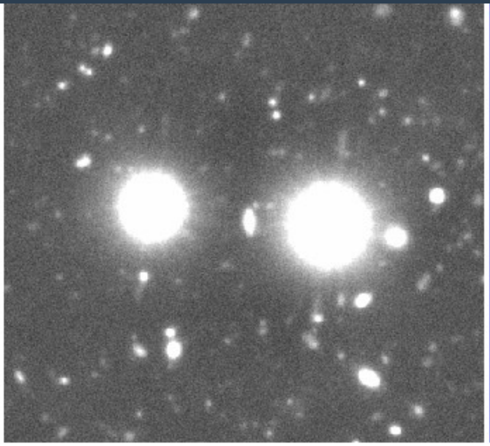
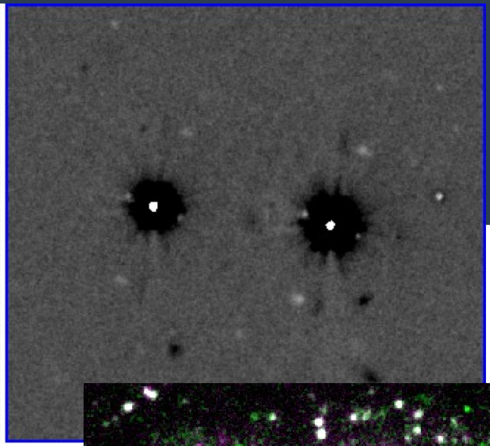
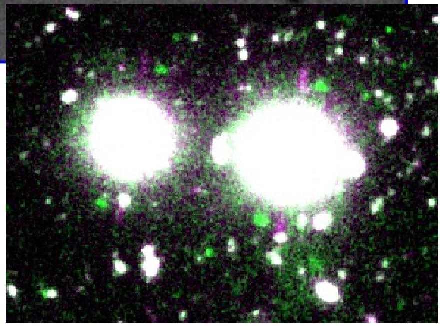
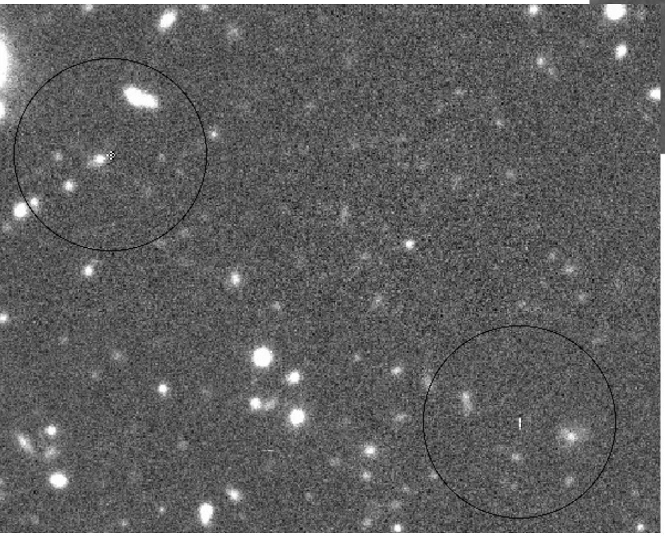
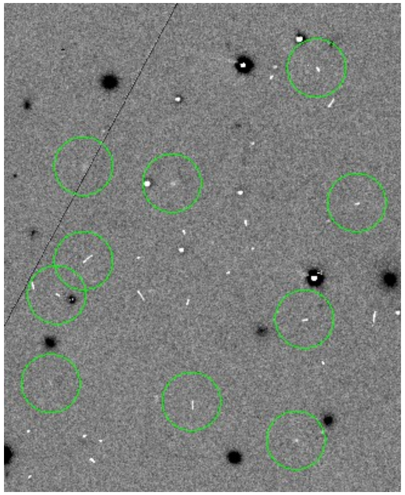
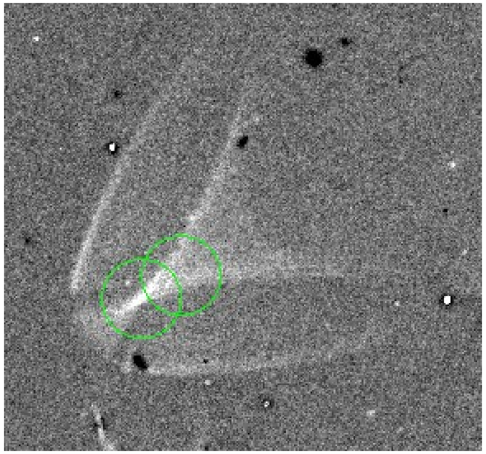
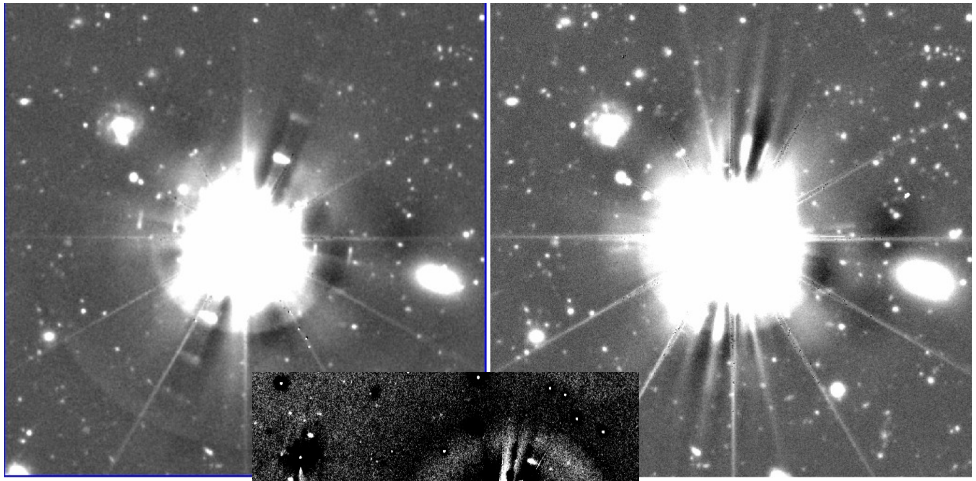
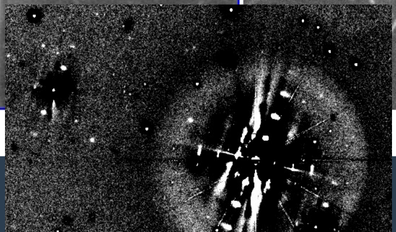
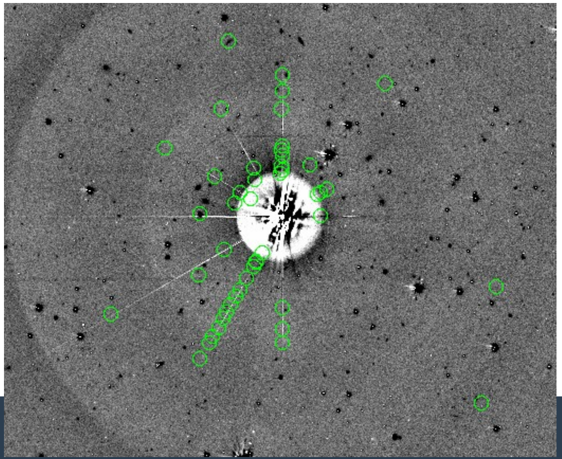
→ 3490 LAEs and 76 LABs found



★Narrow-band technique

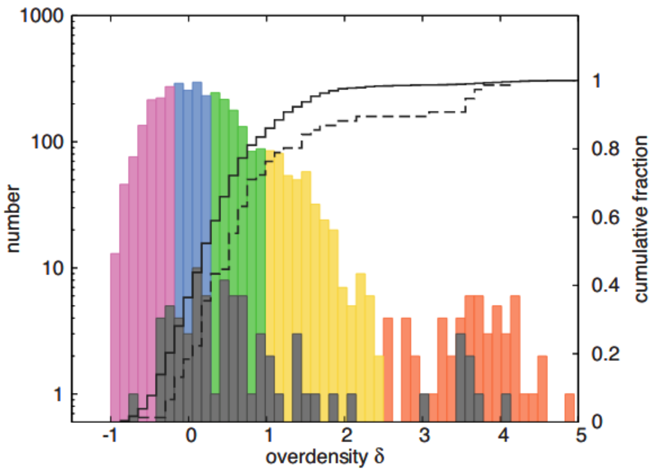




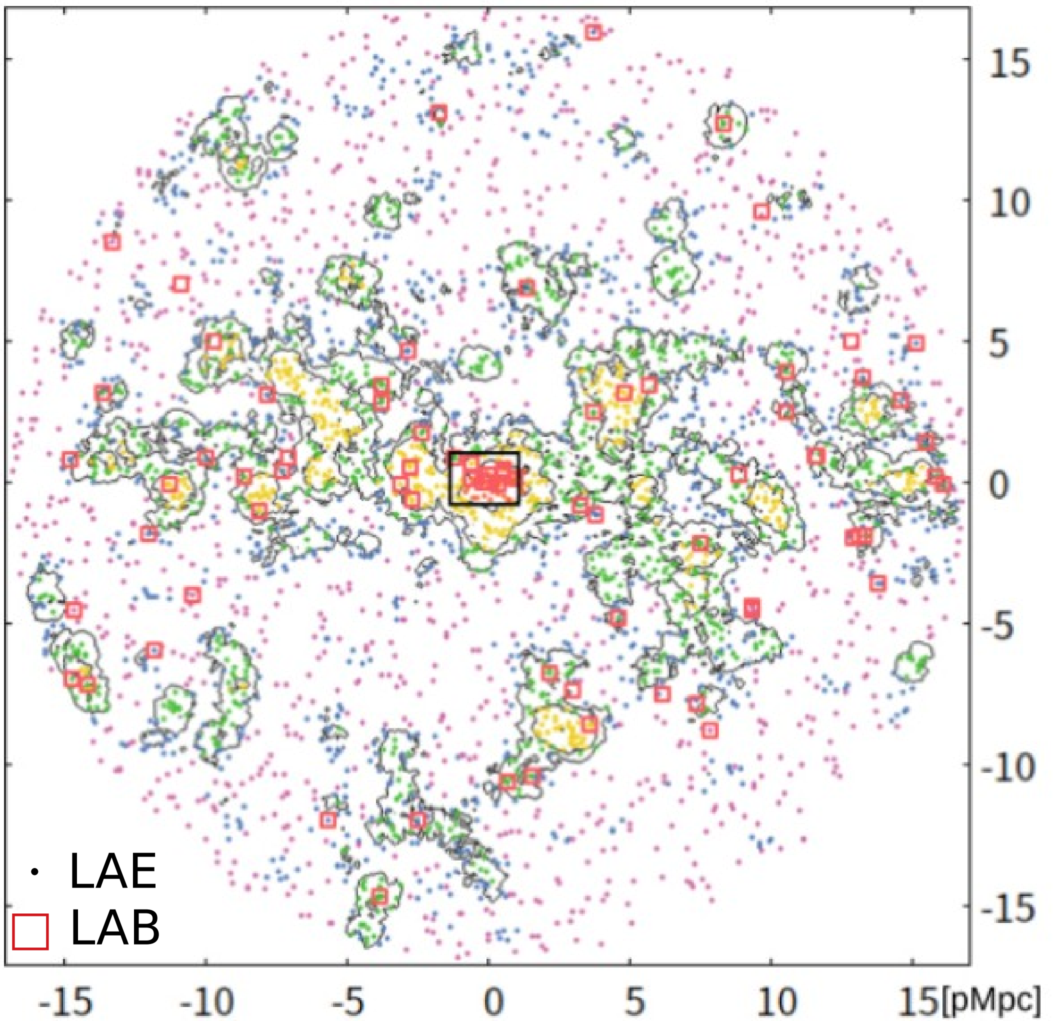
Distribution of LAEs & LABs

- Filamentary structure detected
- 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

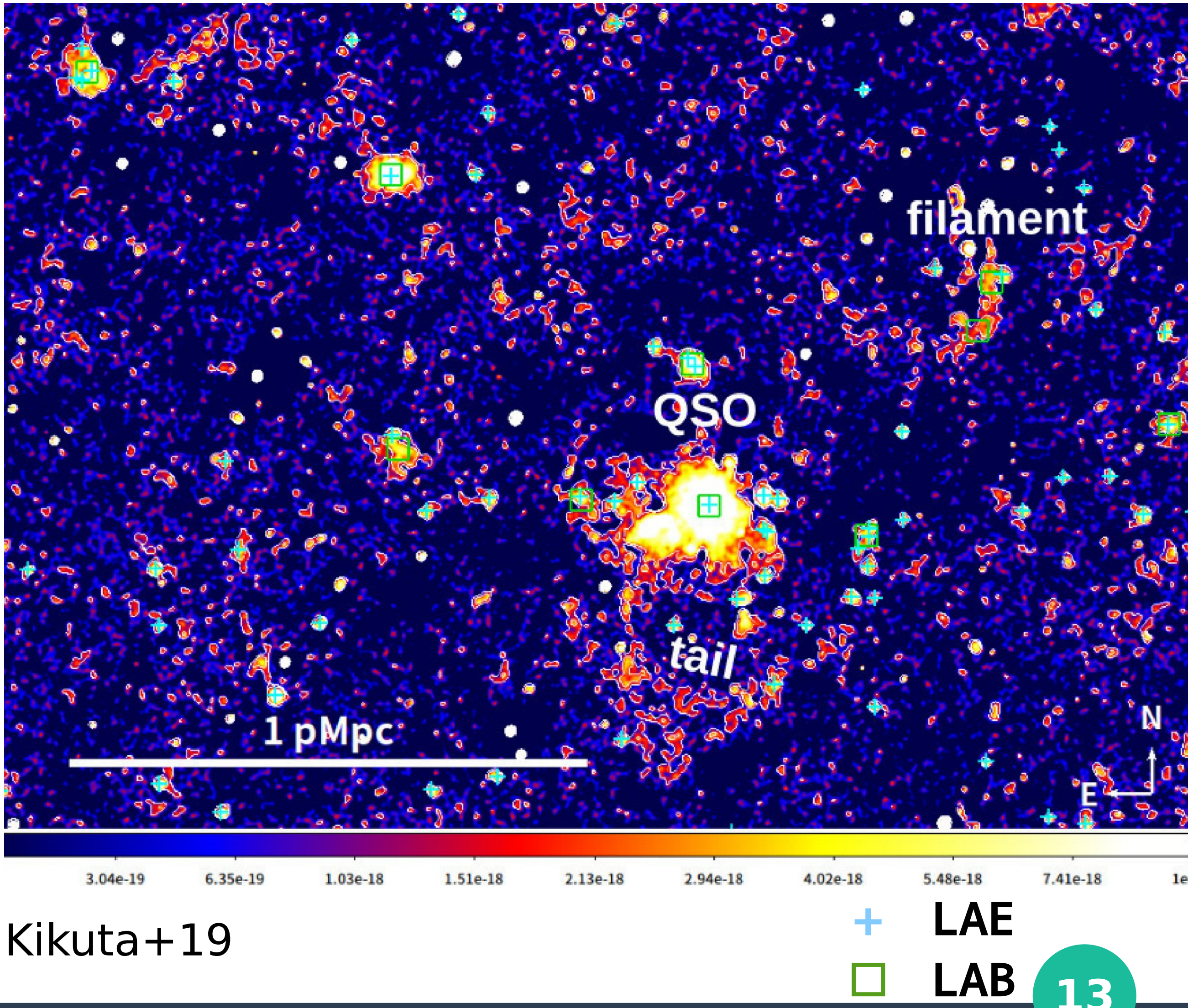
※$\delta_{gal}=n/n_{ave}-1$, n is the number of LAEs within a 1.8' aperture at a given point



Kikuta+19

Diffuse Lyα emission from protocluster core

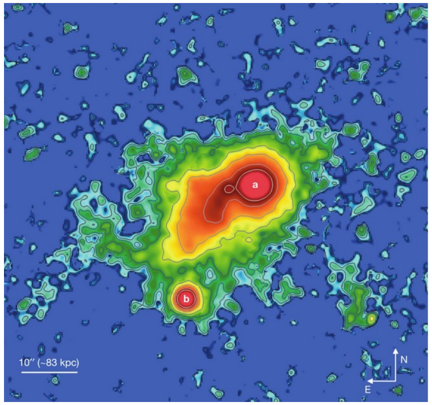
Diffuse emission down to 1e-18 erg/s/cm2/arcsec2 (white contour)



Kikuta+19

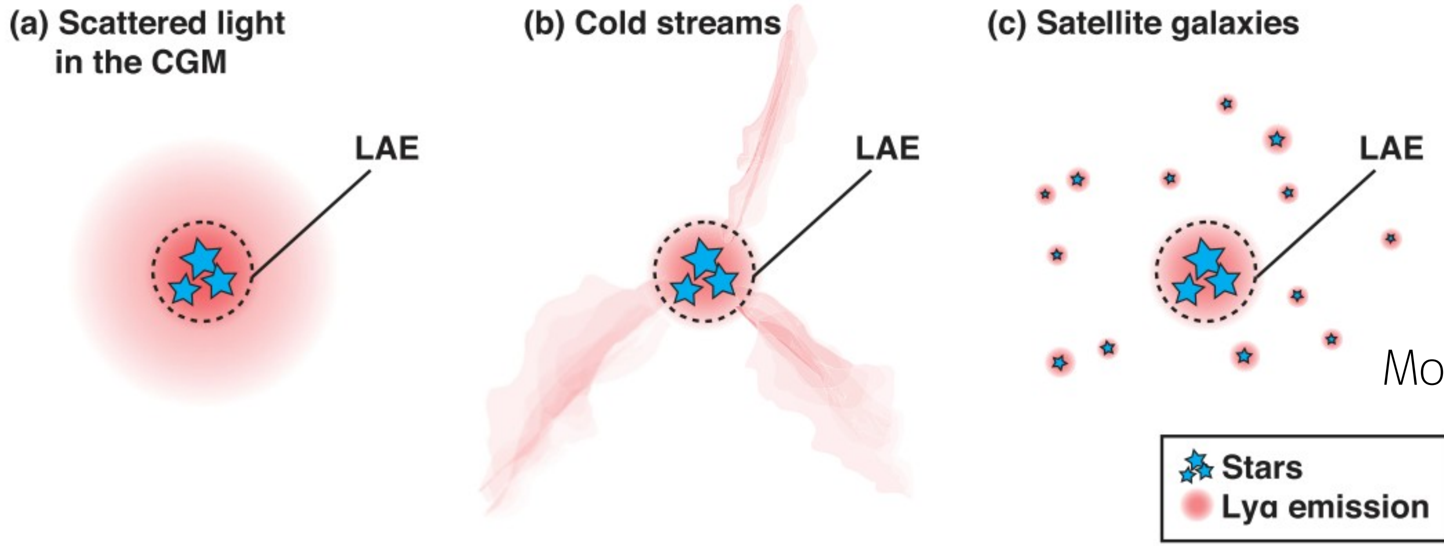
Physical Origin of Extended Lyα Emission

- **Lyα photons are emitted from excited/ionized hydrogen atoms**
  - Photoionization (>13.6eV, 921nm) → Recombination
  - N=2→1, 10.2eV, 1216nm
  - Collision



Cantalupo+14

Yoshida+16

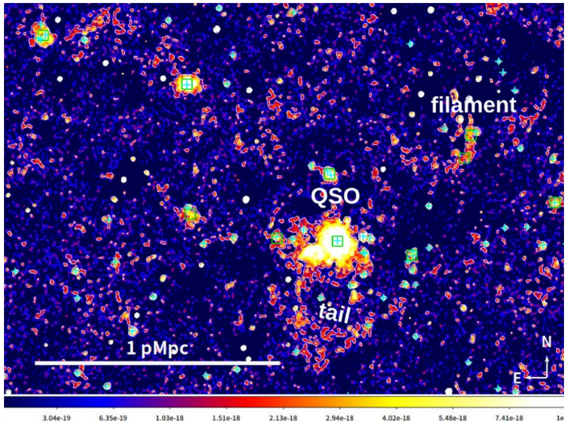


Momose+16

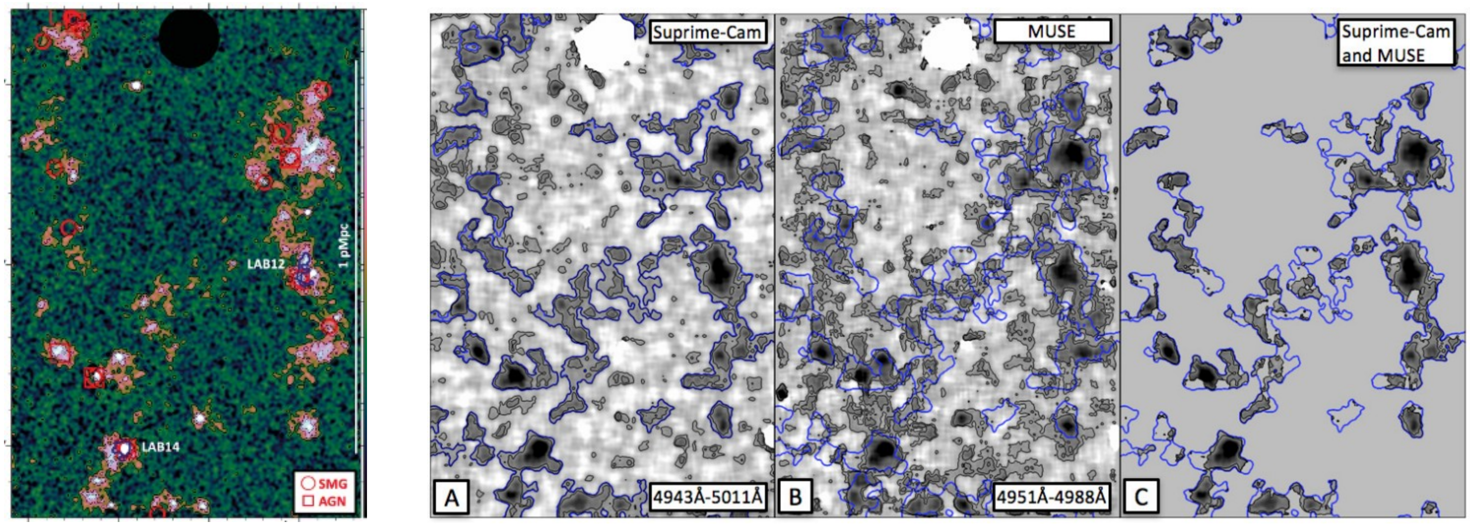
Diffuse Emission from Protocluster Core at Cosmic Noon

- There are so many AGNs around the central part of the protocluster core
- Abundant cool gas & active source (provide ionizing radiation) can boost the Lyα emission from the filamentary structure
- New direct way to test galaxy formation theory!

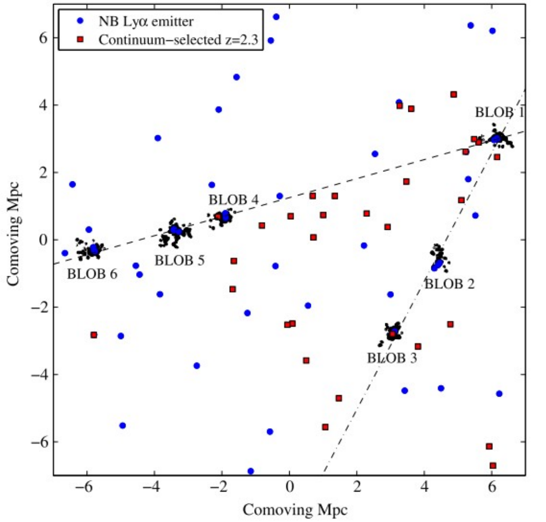
Kikuta+19, HS1549@z=2.8



Umehata+19: SSA22@z=3.1

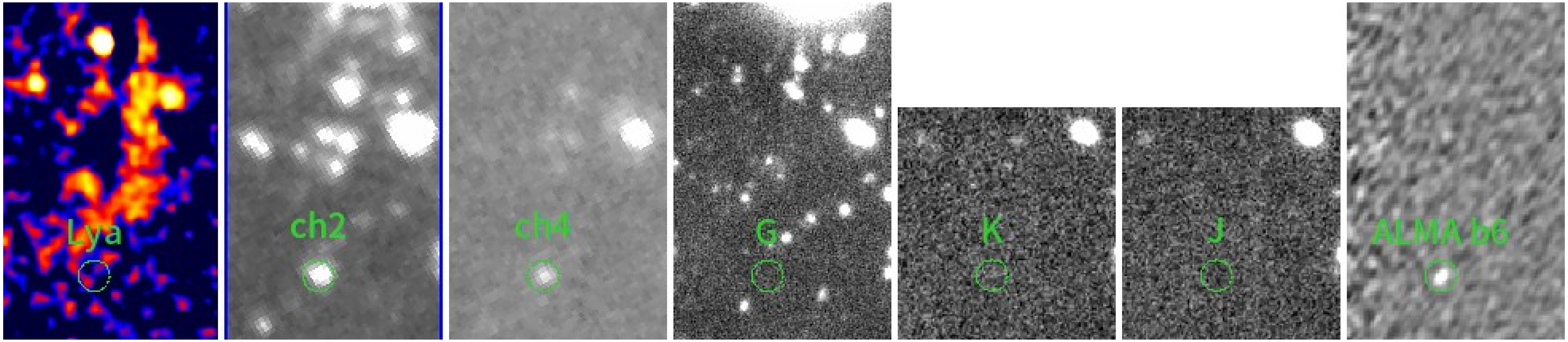


Erb+11, HS1700@z=2.3

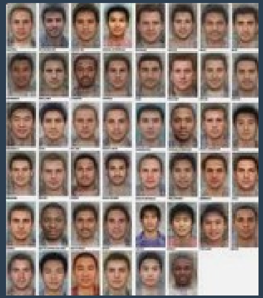


Detection of an SMG at the tip of the "filament" (preliminary)

- interesting diffuse LAB with filamentary shape, pinpointing the HLQSO – may trace the cold streams?
- To know the origin, we conducted **Keck/KCWI observations**
  - Achieved S/N is not high due to weather, but we tentatively detect a double-peaked Lyα line
- **A sub-mm source detected at the tip by our ALMA observations**
  - Spec-z not obtained yet...



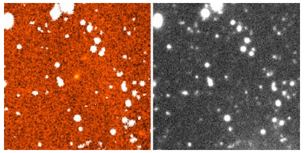
Stacking Analyses



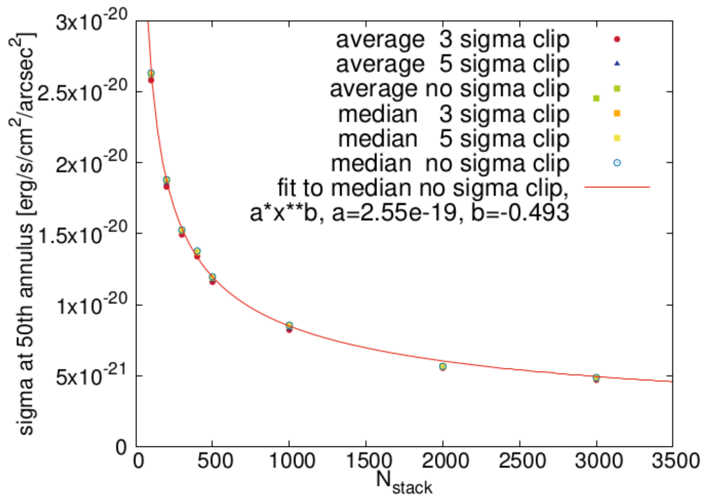
→

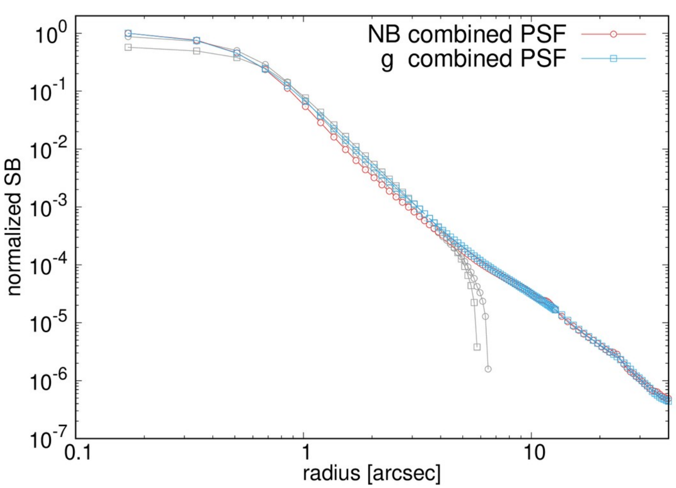
"average face" of Japanese men

- Use cutout Lyα images of LAEs (sky mesh size=30") with continuum sources masked
- Stack Lyα & continuum images with IRAF imcombine
- Sky noise is estimated with "sky cutouts"; behaves well ($\propto \sim N^{-1/2}$)
- PSFs of NB/g-band images are measured with bright point sources
  - Central part: objects with CLASS_STAR> 0.95 and 18 < g < 22
  - Outer part: stars with $13 < g_{SDSS} < 15$ from SDSS DR14 catalog
  - These are connected at r = 20 pixels following a method described in Infante-Sainz et al. (2019)



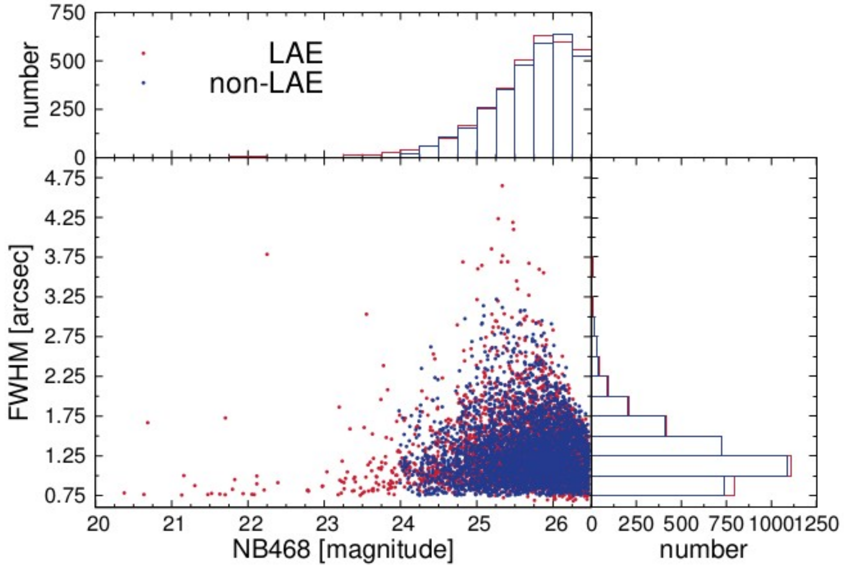
Lyα Cont.

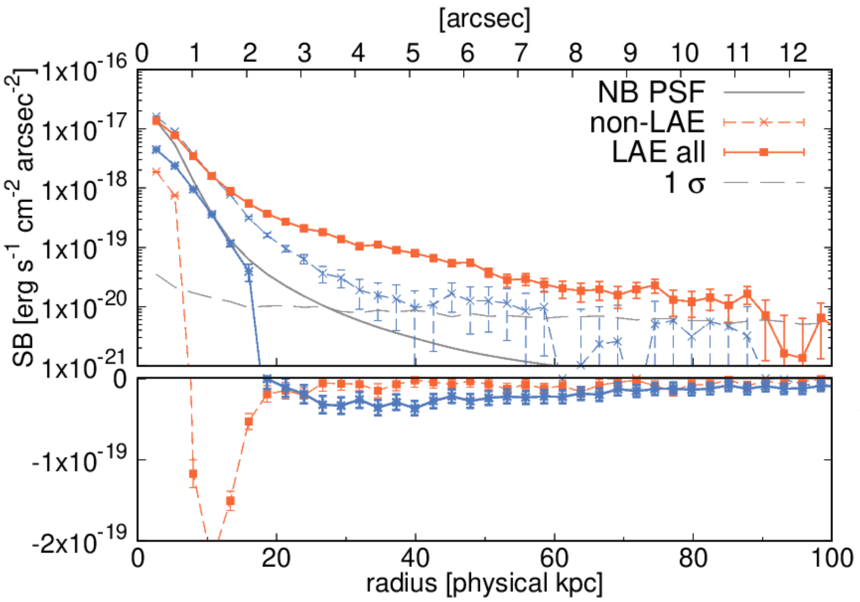


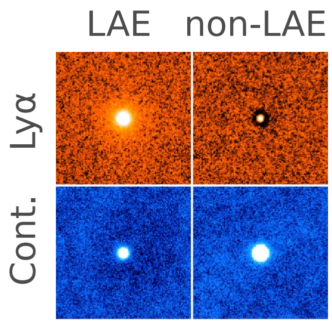


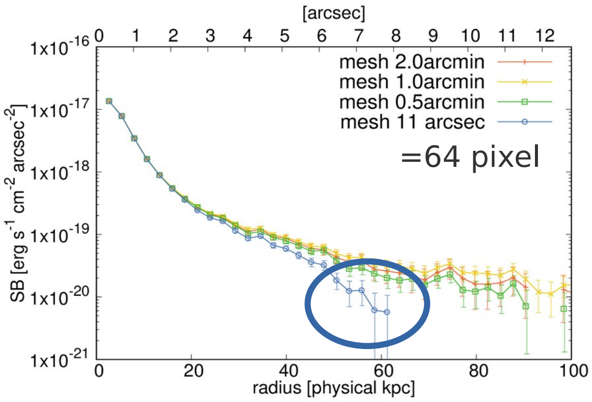
Stacking Analyses

- “Non-LAE” sample is constructed to check total systematics (see Momose+14)
  - Stack randomly selected objects with similar NB mag & FWHM and check if they are extended
- **Detect diffuse Lyα emission down to ~10^{-20} erg/s/cm²/arcsec²**









Sufficiently large sky mesh size is crucial!!

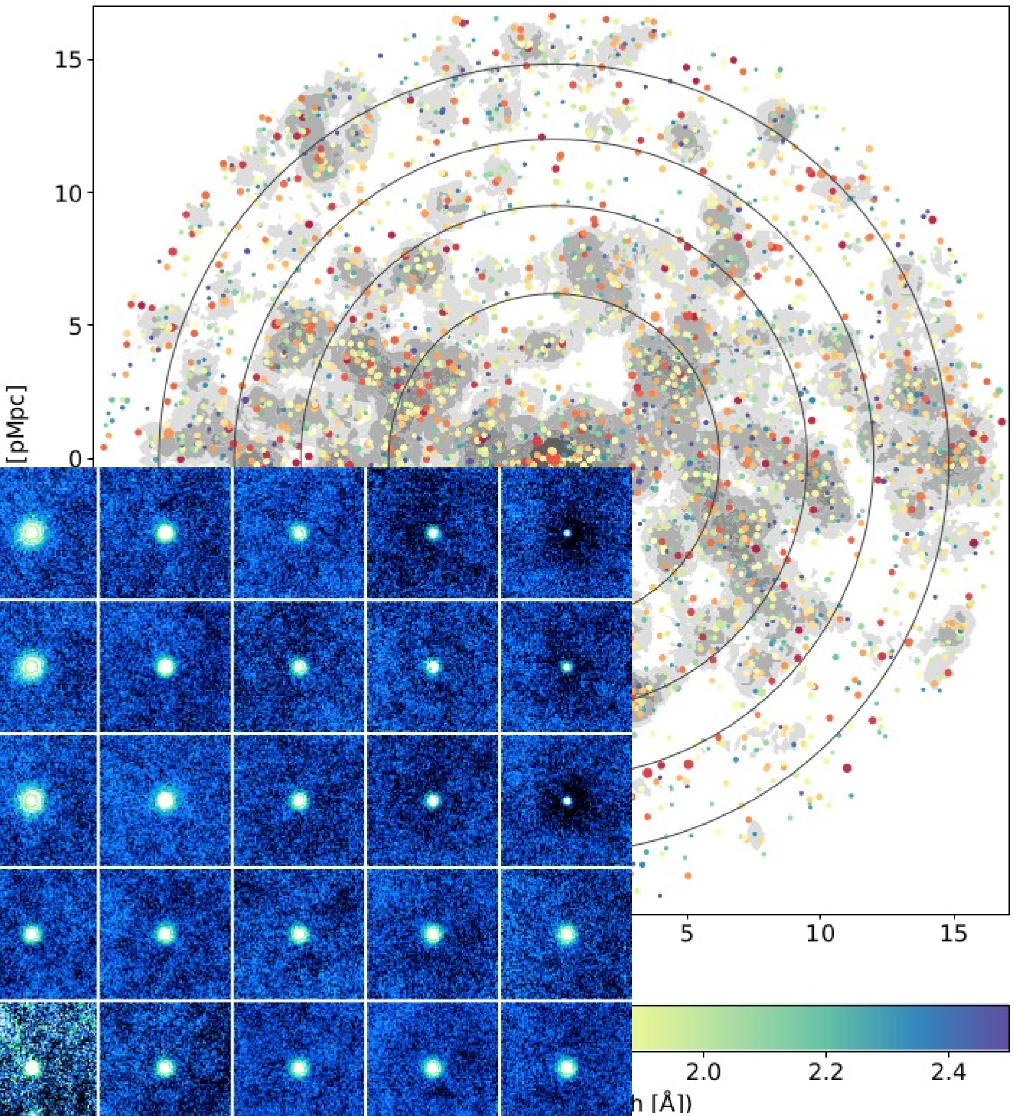
orange: Lyα, blue: Cont.
Solid: LAE, dashed: non-LAE

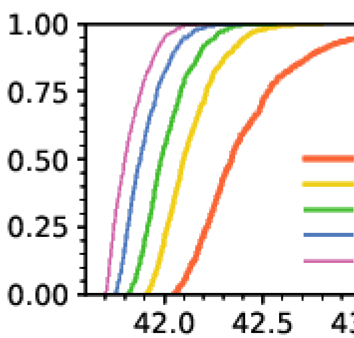
LAH Dependence on Various Properties

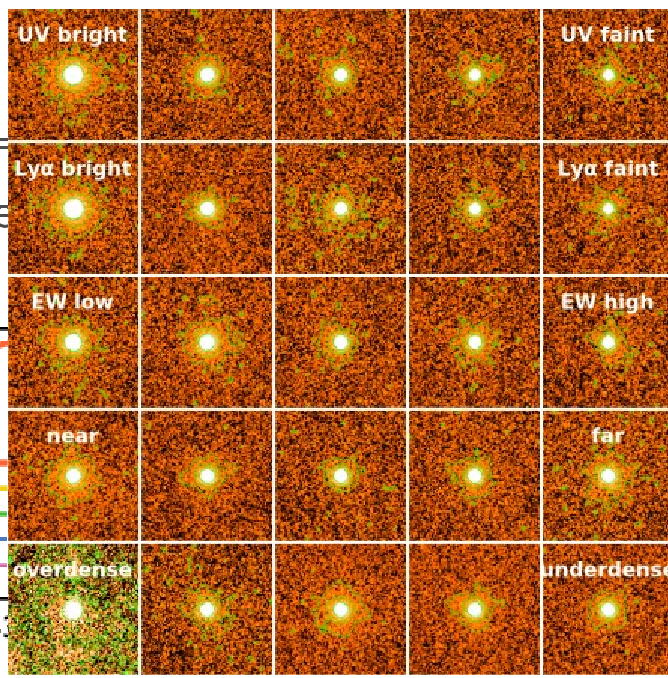
- Divide LAEs into 5 groups according to their photometric properties
- “Projected distance from the HLQSO” is used to test whether QSO radiation affects the LAHs
- Note the correlations between quantities

※overdensity δ=

within a 1.8’ ape

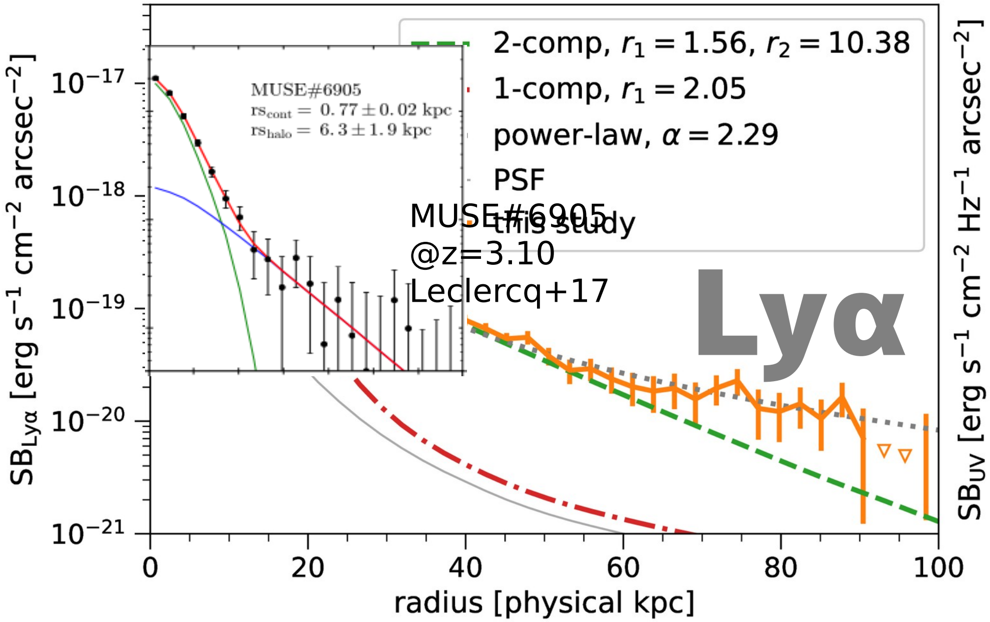


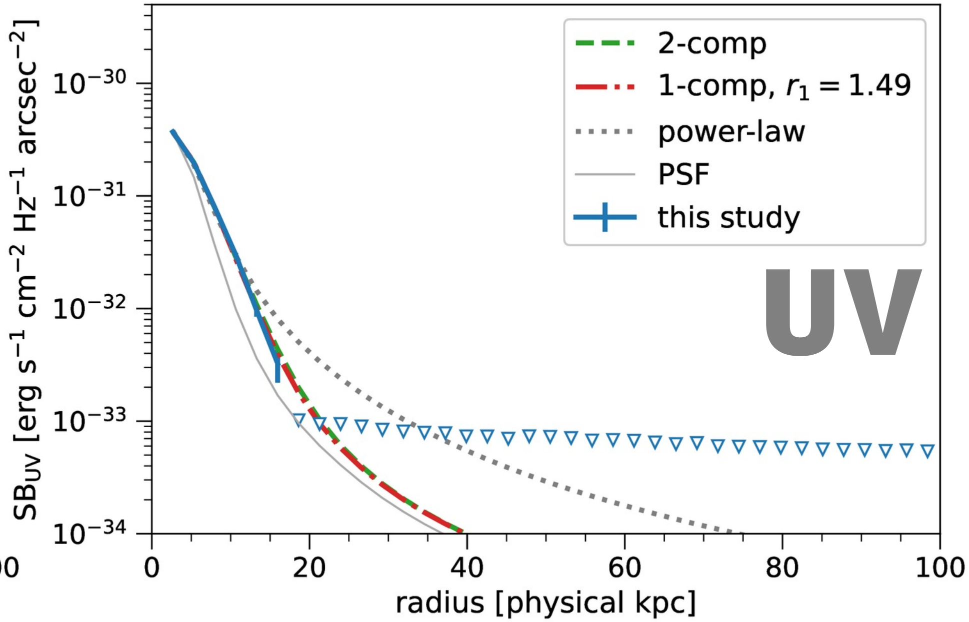


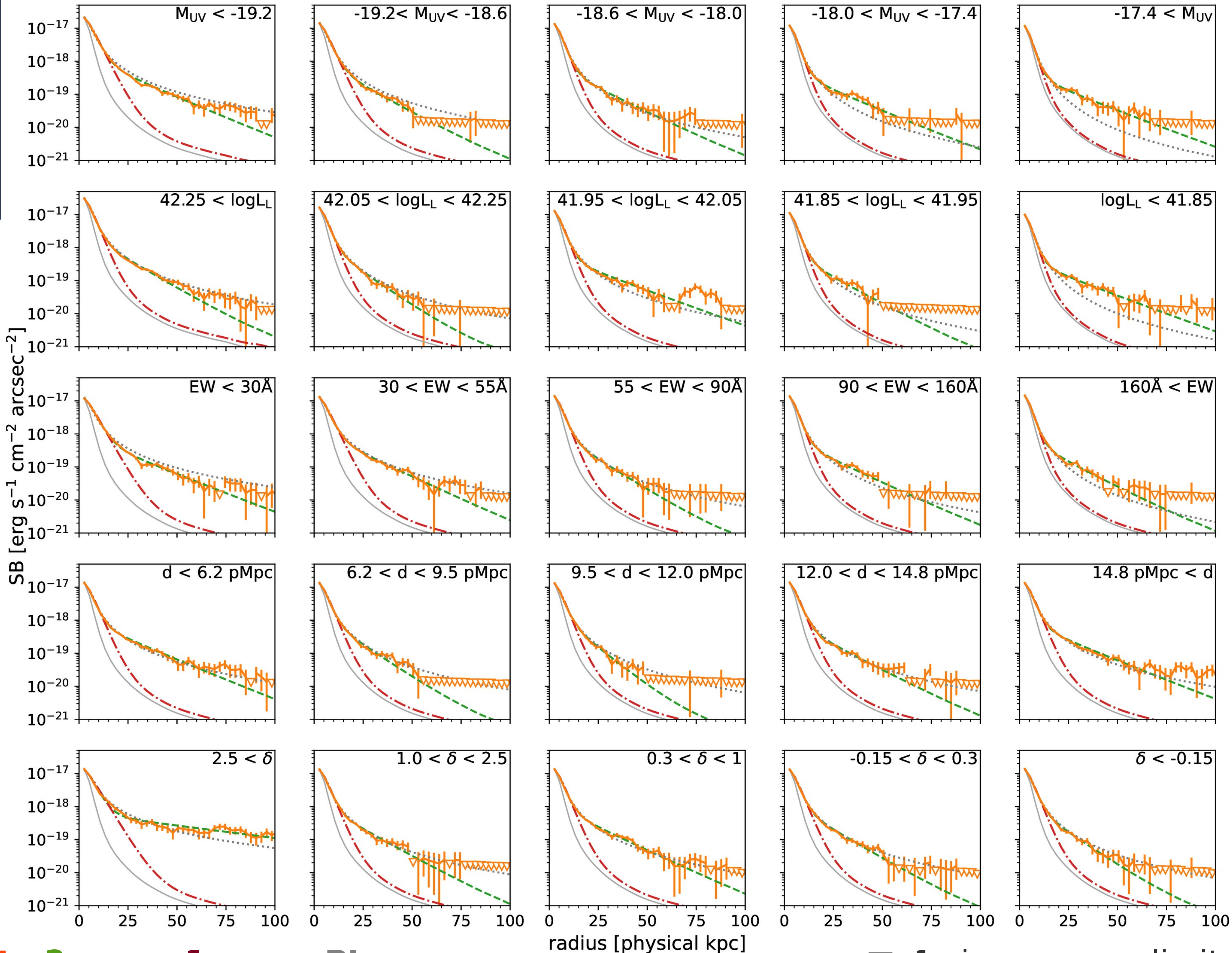


Fitting exponential functions

- SB radial profiles are fit with the following functions:
  - **2-component exponential**: PSF*(C_1×exp(-r/r_1))
  - **1-component exponential**: PSF*(C_1×exp(-r/r_1)+C_2×exp(-r/r_2))
  - **Power-law**: PSF*(C_1×$r^{-\alpha}$) as suggested by a model in Kakiichi & Dijkstra 2018





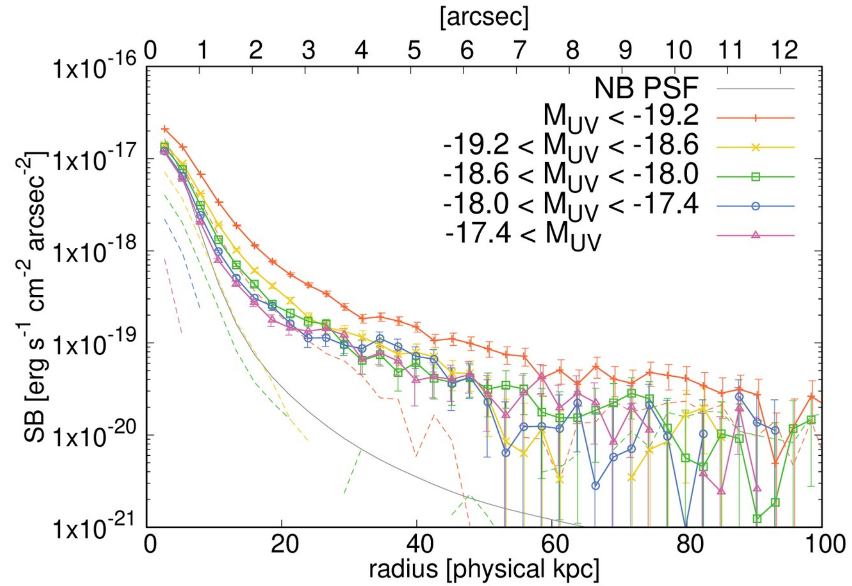


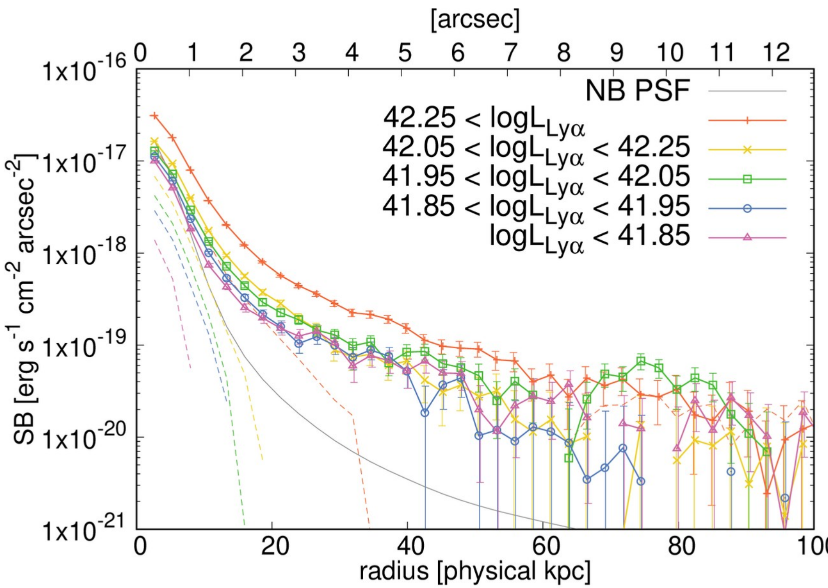
Data 2-comp 1-comp PL

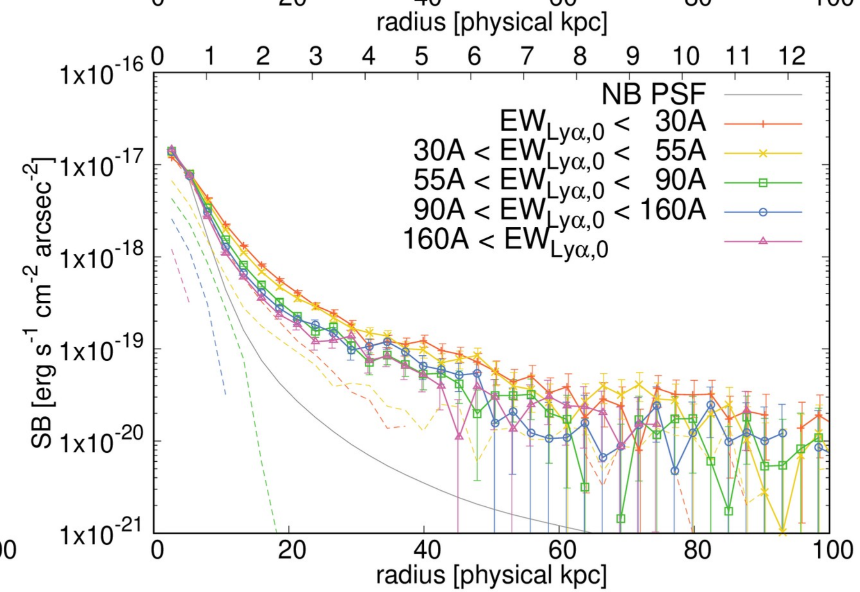
▽: 1-sigma upper limit

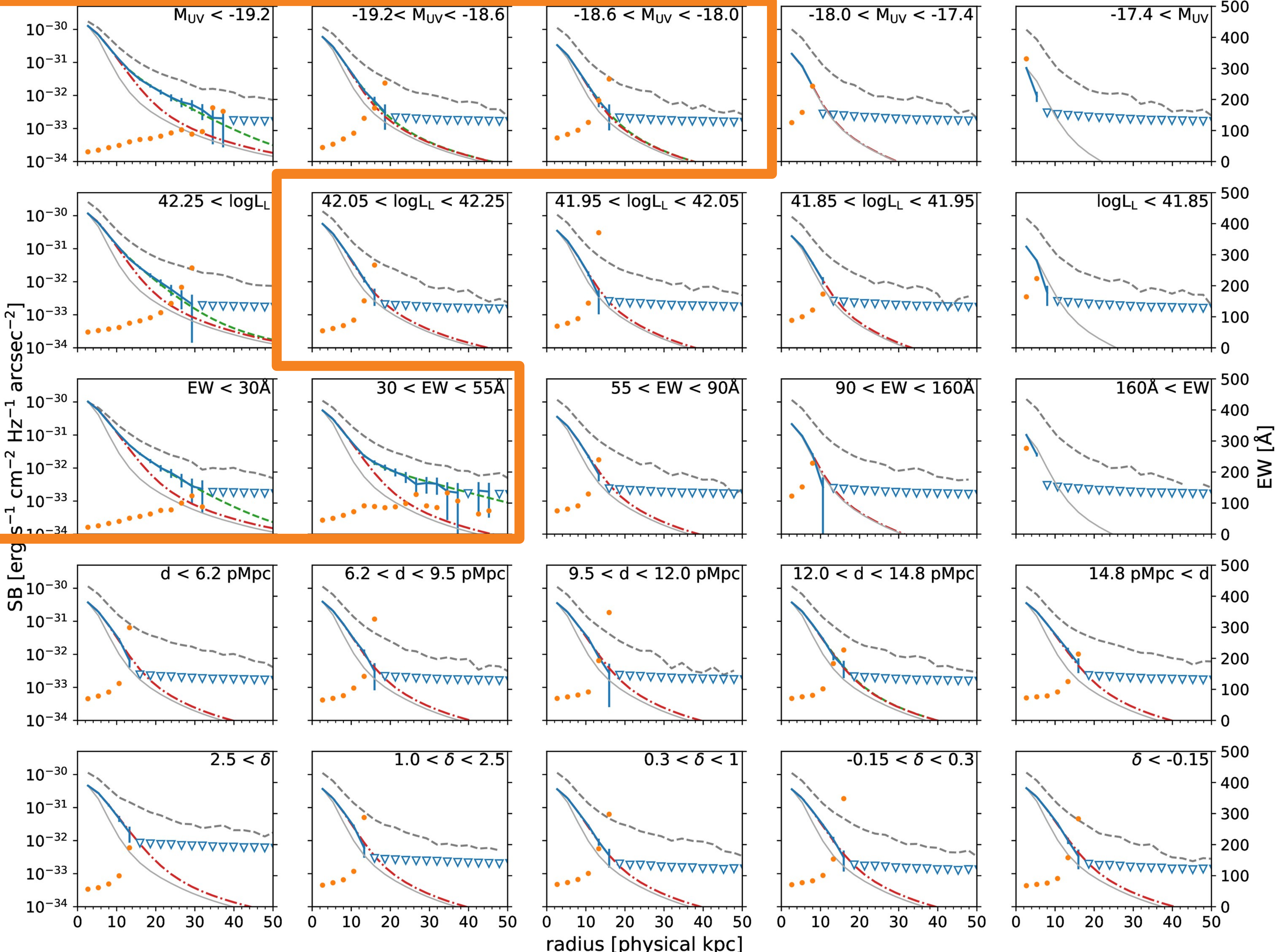
Results of Stacking: UV, $L_{Ly\alpha}$, EW

- LAHs are detected for all subsamples
- Bright/low-EW LAEs tend to have larger LAHs







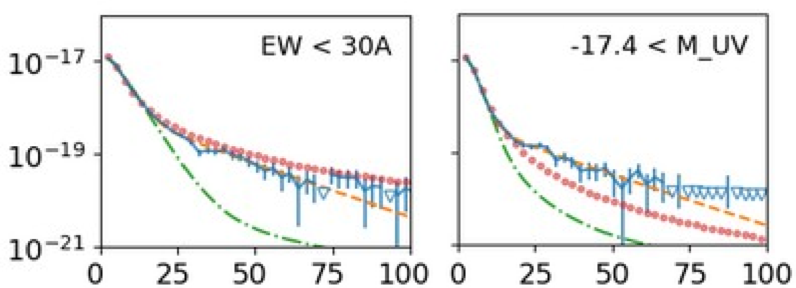


Data 2-comp 1-comp EW profile

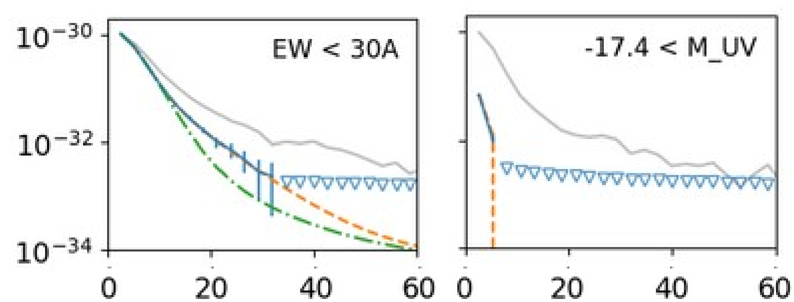
Gray: scaled Lyα

Fitting exponential functions

- **2-comp exp. functions are needed for Lyα SB profiles**, while 1-comp exp. functions are enough for UV in most cases
- Bright (in Lyα/UV) / low-EW LAEs require the **UV 2nd component**
  - **This is the first robust detection at high-redshift**
- Power-law sometimes fails to capture the transition from 1st to 2nd component



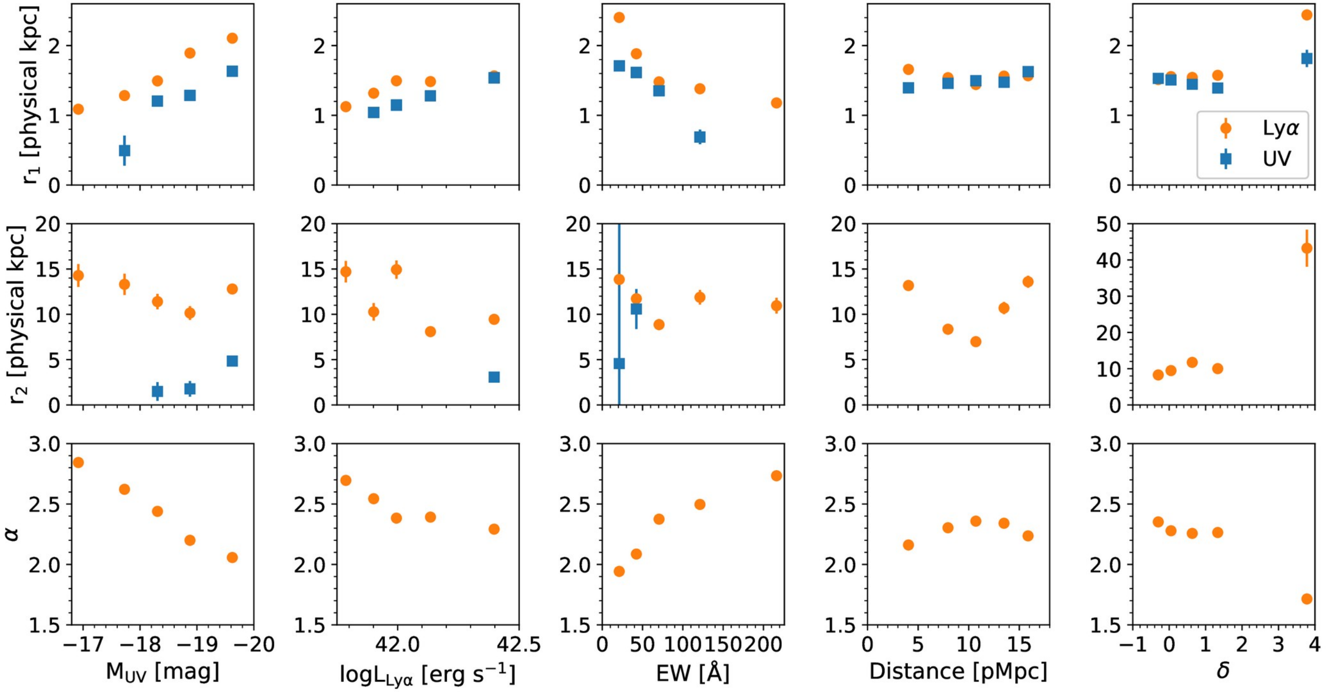
Lyα



UV

Results of Fitting

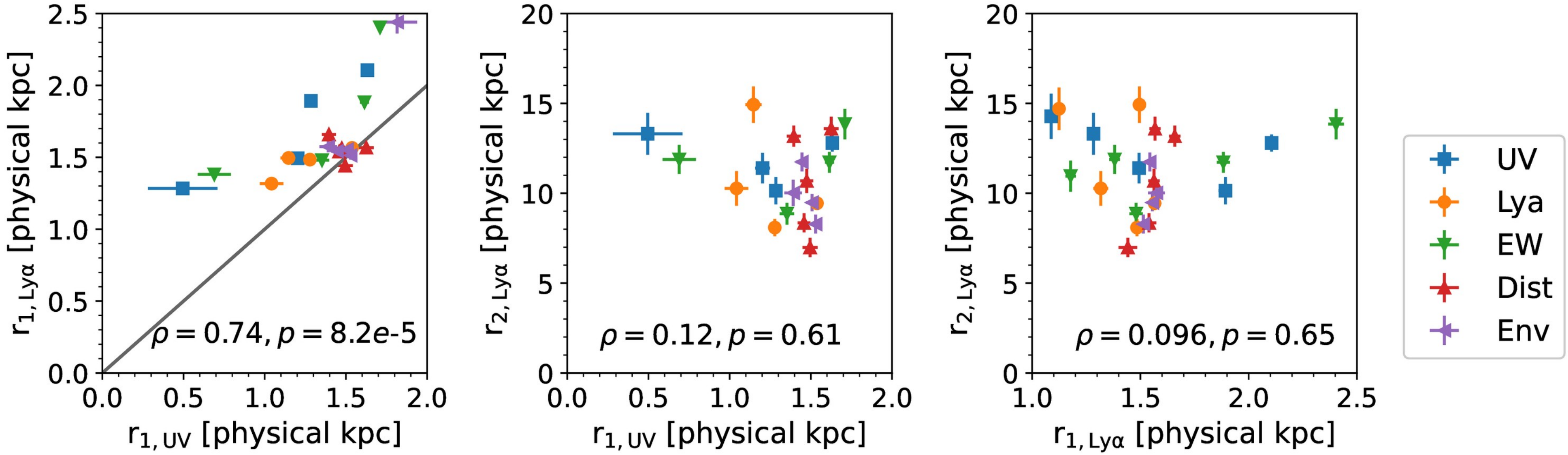
- Lyα/UV 1st components correlate with M_{UV}, $L_{Ly\alpha}$, EW
  - Brighter LAEs have larger cores
- Lyα 2nd component behaves stochastically
- Protocluster sample (δ>2.5) stands out



Lyα
UV

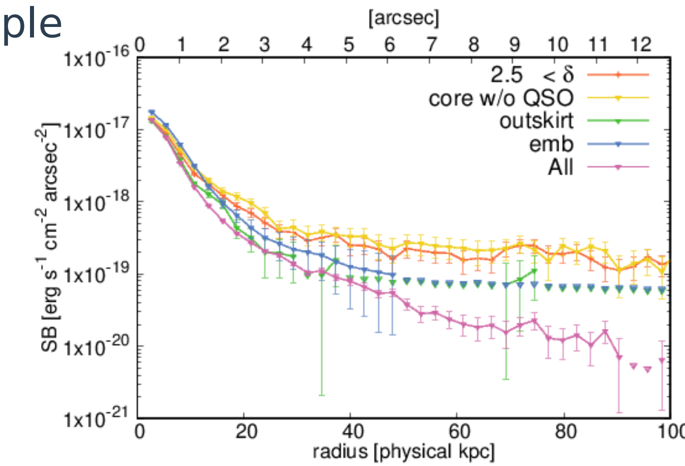
Relation between scalelengths $r_{1,UV}$, $r_{1, Ly\alpha}$, $r_{2, Ly\alpha}$

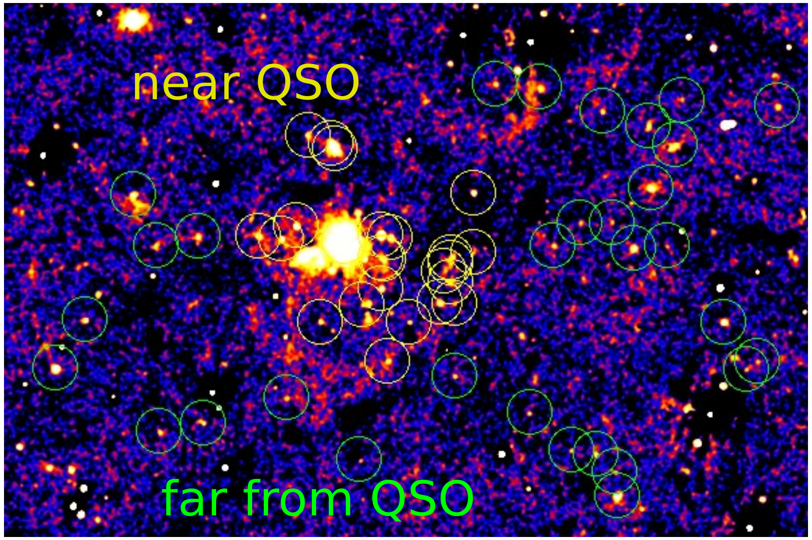
- Correlation found only for $r_{1,UV}$ - $r_{1,Ly\alpha}$
  - $r_{2,Ly\alpha}$ is difficult to predict
- Commonly used assumption of $r_{1,UV} = r_{1,Lya}$ is not valid (gray line: 1:1 rel.)
  - Caution: small value for $r_{1,UV}$ may be just due to nondetection in continuum images



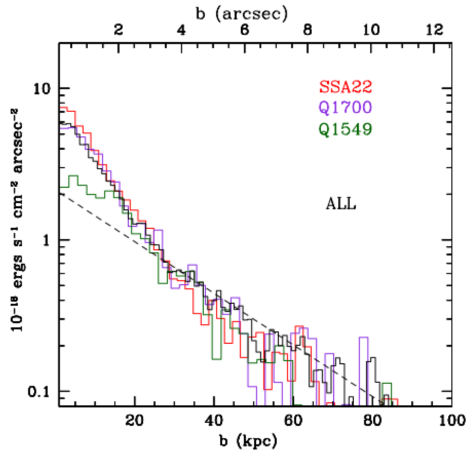
Discussion:
Origin of the Large LAH in PCs

- Overlapping of galaxies or UV brightness of the PC LAEs cannot fully explain the large LAH
- We further divide the PC sample into near/far from the QSO sample
  - Far sample no longer has a very large LAH
  - Near sample shows an even larger LAH
- **Diffuse emission around the PC core may be the cause**
  - Related to abundant cool gas irradiated by active members in the PC core

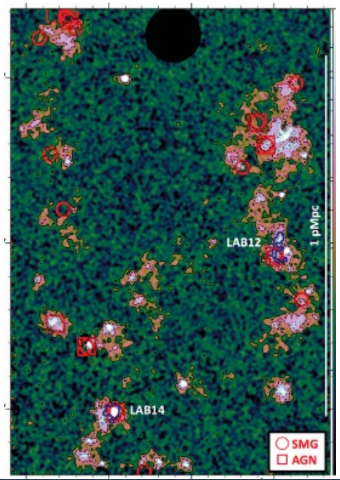




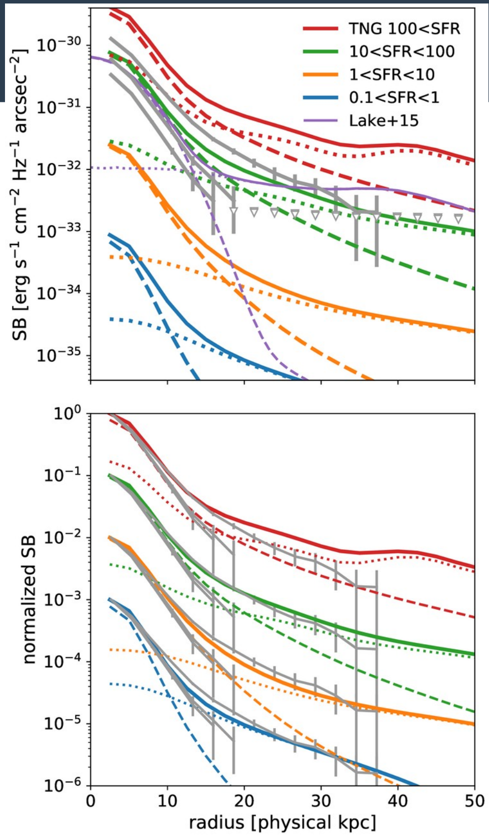
Steidel+11: SSA22, HS1700, HS1549



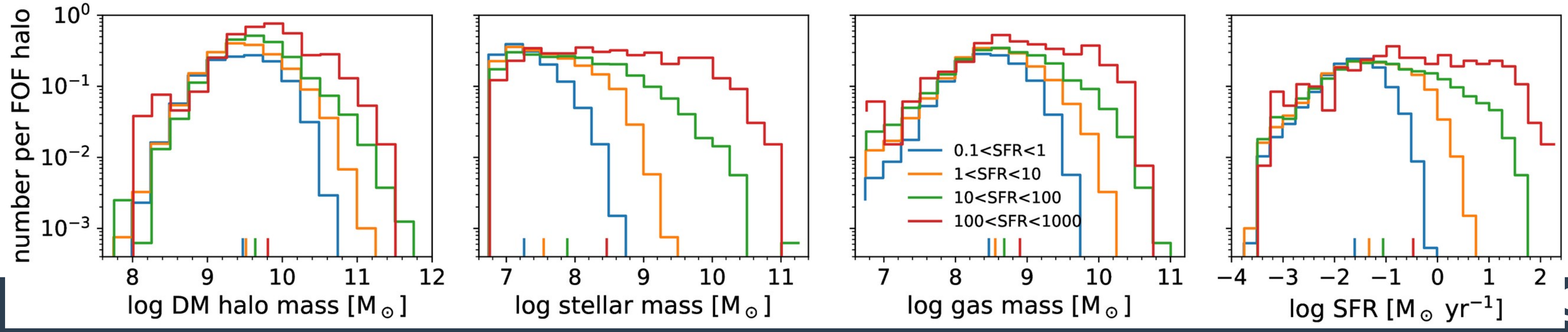
Umehata+19: SSA22



Discovery of “UV Halos” and Its Implication to Low-Mass Galaxy Evolution



- **Comparison with the TNG100 run of the IllustrisTNG simulation**
  - make median stacked SFR surface density profiles of FOF (friends-of-friends) halos at z = 3
- **The UV-brightest subsample has a similar shape as the SFR surface density profiles of TNG galaxies with 1 < SFR < 10 and 10 < SFR < 100 subsamples**
  - Given the similarity of the profiles, the UV halo of the UV-brightest LAEs would be also due to satellite galaxies
  - On average, they have 1.9 and 2.3 satellites, with median DM halo masses of 3.3×10^9 $M_\odot$ and 4.4×10^9 $M_\odot$
  - the UV halo may be comprised of **a few satellite galaxies**, not by an intrinsically diffuse stellar halo, unlike local mature galaxies
  - Such satellites have 0.01 < SFR < 0.1 – detectable with JWST?



Insights into the Origin of LAHs

- **First detection of the UV 2nd component** (r < 40 pkpc) offers direct evidence for a contribution from **satellite SF**
  - Agree with recent simulation results (Byrohl+20, Mitchell+20, Lake+15)
  - Can be tested with JWST by seeing if "**Hα halos**" exist or not
- To determine the origin of LAH at larger radii, deeper obs. & comparison with state-of-the-art simulations are needed
  - Current simulations still cannot treat all relevant physics
  - Fluorescent Lyα emission may contribute significantly at outer regions within protocluster cores at cosmic noon and/or near bright QSOs

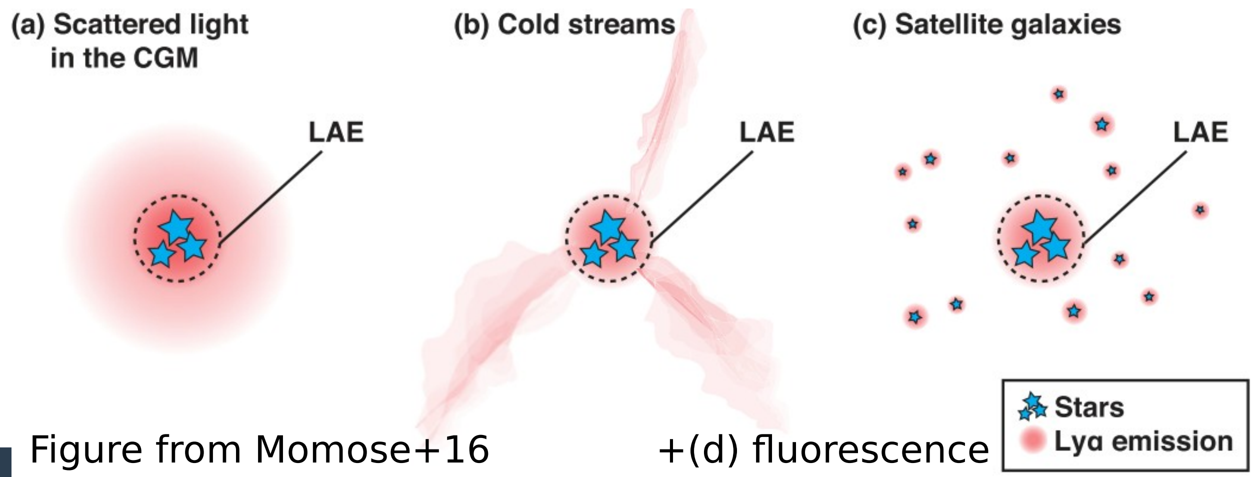
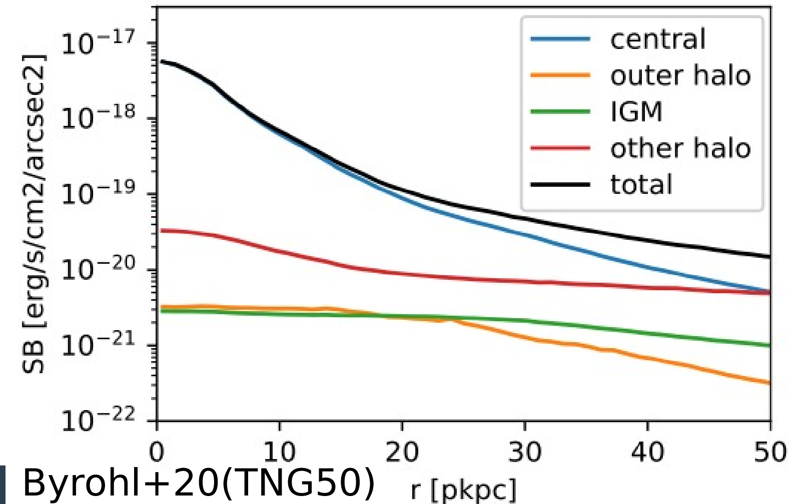


Figure from Momose+16

+(d) fluorescence



Byrohl+20(TNG50)

Summary

- The HS1549 protocluster corresponds to the intersection of ~100cMpc-scale structure. **"Cold stream"-like structure is discovered near its core**.
- Sensitivity close to 1e-20 erg/s/cm^2/arcsec^2 is necessary for safe argument (at z~3) of LAHs – **NB stacking with Subaru/HSC is still a powerful tool in the era of sensitive IFUs!**
- Lyα SB profiles are well fit with 2-component exponential functions with $r_{2,Ly\alpha}$~10 pkpc
- $r_{1,Ly\alpha}$ and $r_{1,UV}$ correlate, but $r_{2,Ly\alpha}$ does not correlate with any photometric property – insufficient S/N?
- Very large $r_{2,Ly\alpha}$ in the PC suggest the importance of "fluorescence" as a LAH origin under some situations
- **We found "UV halos"** around bright/low-EW LAEs
  - demonstrates **satellite SF** as important contributor
  - Comprised of a few low-mass satellites?
- To determine the origin of LAH at larger radii, deeper obs. & comparison with state-of-the-art simulations are needed

Take home messages for HSC research

- **やりたいことを念頭に観測戦略を立てる**
  - ディザリング、一枚あたり露出時間、観測効率、 etc
- **データ整約、解析も目的に応じて適切なものを選ぶ**
  - アーカイブ画像を使う場合、観測条件や解析過程がやりたいサイエンスと照らして適切かをチェックする
  - 例：スカイ引きのメッシュサイズが目標天体に対して十分大きいか
- **画像の質は必ず自分の目で確かめる**
  - カタログには人工信号が混入している可能性あり
  - データが巨大な近年では機械学習で人工信号を除くなどの例も
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