Clumpy vs. Extended Lyman Alpha Emitters at High Redshift

PhD Thesis Defense

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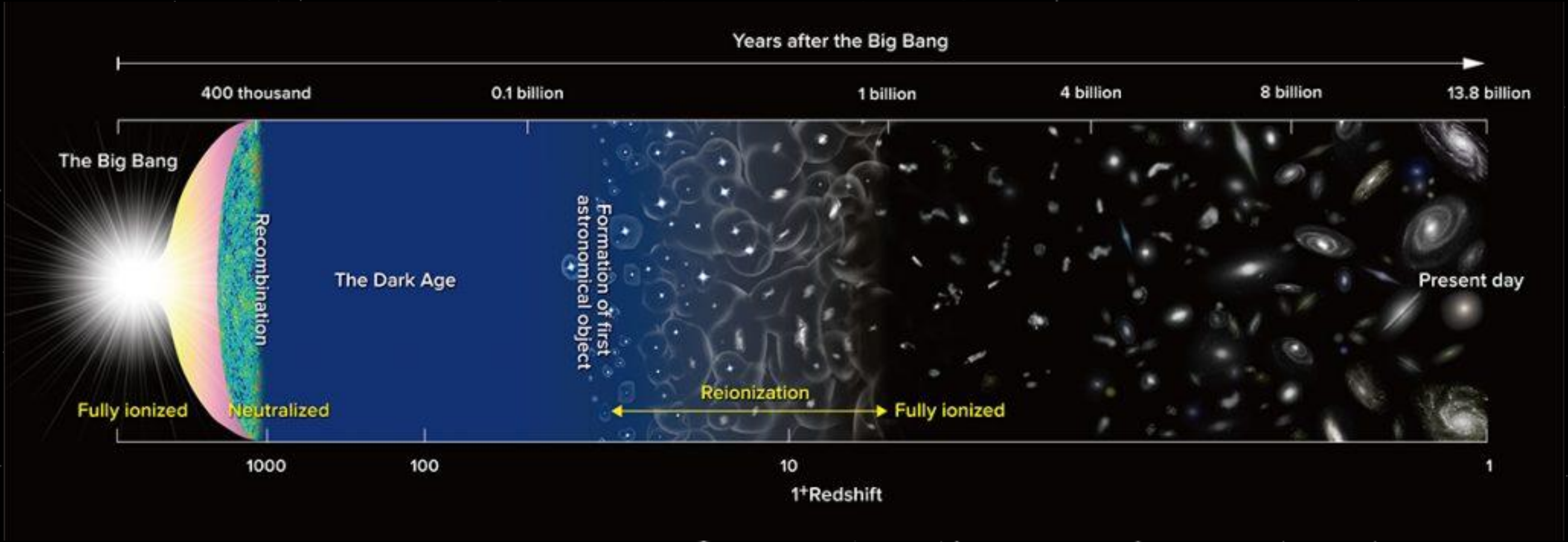
History of The Universe



Redshift z : A proxy for “lookback” time based on the expansion of the universe.

Image Credit: NAOJ

Why is Reionization Interesting?

- First Stars & Star Clusters?
- First Galaxies?
- First AGN?
- What sources caused Reionization?

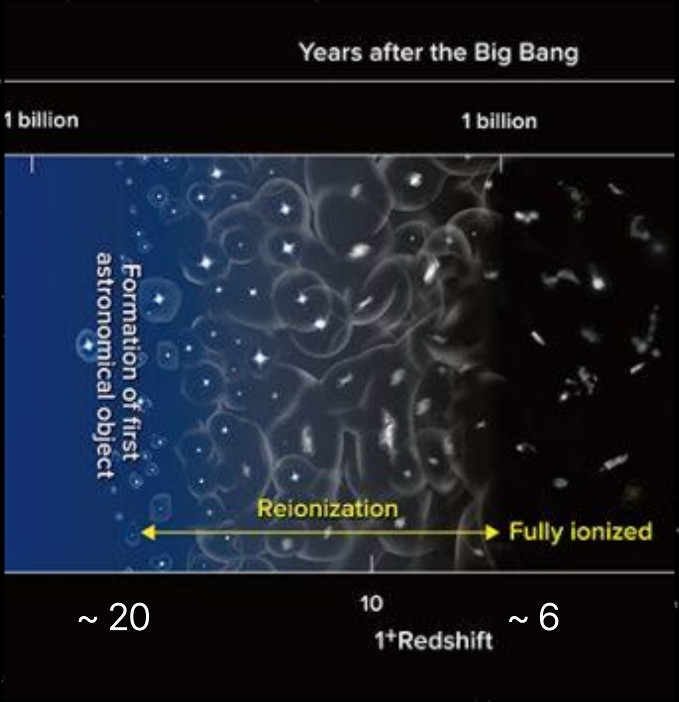


Image Credit: NAOJ

Calculating Ionizing Contribution

$$\dot{n}_{\mathrm{ion}} = \rho_{\mathrm{UV}} \times \xi_{\mathrm{ion}} \times f_{esc}$$

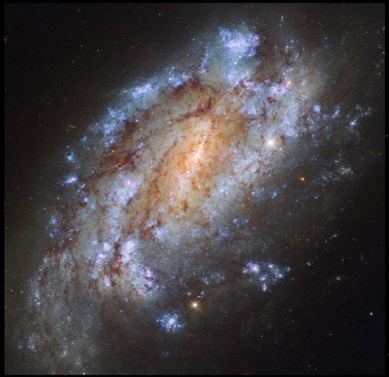
Ionizing Photon Rate

UV Luminosity Density
-
Can Measure with Telescopes

Efficiency of Ionizing Photon Production
-
Predicted by Stellar Synthesis Models

Ionizing Photon Escape Fraction
-
Difficult to Obtain

What Caused Reionization?



Star-Forming

ANOTHER JWST RESULT:
Atek et al. 2023 measures 4x larger ξ_{ion} than canonical value

JWST RESULT:
UNCOVER / CEERS
find many faint AGN during EoR (~50 - 100% of budget)

(EoR)

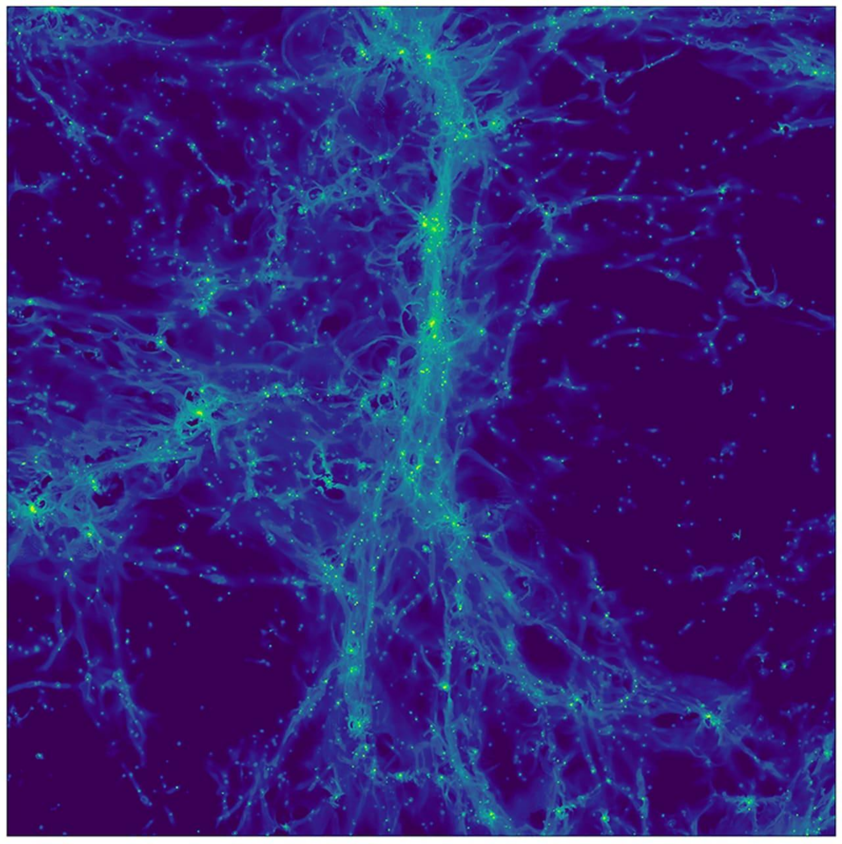
The Answer?

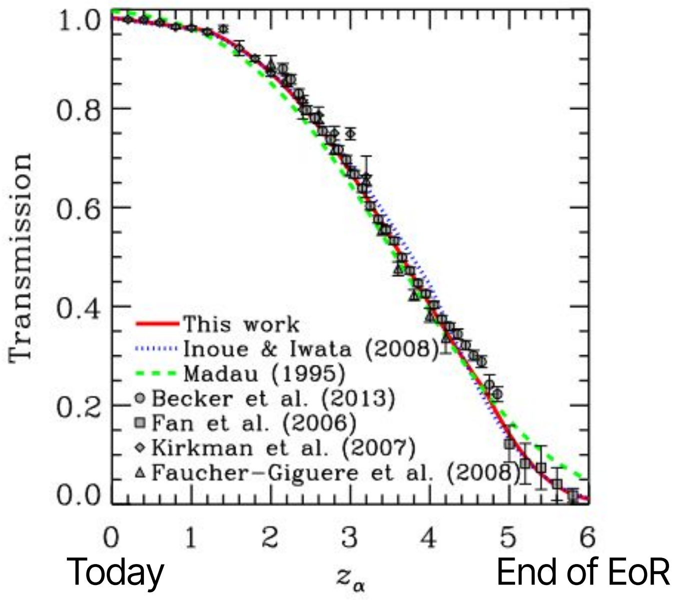
Both
(Dominant Source Still an Open Question)

Image Credit: NASA, ESA, Hubble

ARTWORK: NASA, ESA, Joseph Olmsted (STScI)

Observing
Re
Di





*Technically Lyα Transmission

Image Credit: Inoue et al. 2014

Lyman Alpha (Lyα) Radiative Transfer

- Lyman Alpha (Lyα): The transition between n = 1 and n = 2 state in neutral hydrogen. (1215 Å, ~10.2 eV)
  - **Not** destroyed by neutral hydrogen
  - Very Bright → Easier to detect

- Lyα has non-trivial interactions with neutral hydrogen
  - Scatterings
  - Doppler Shifts

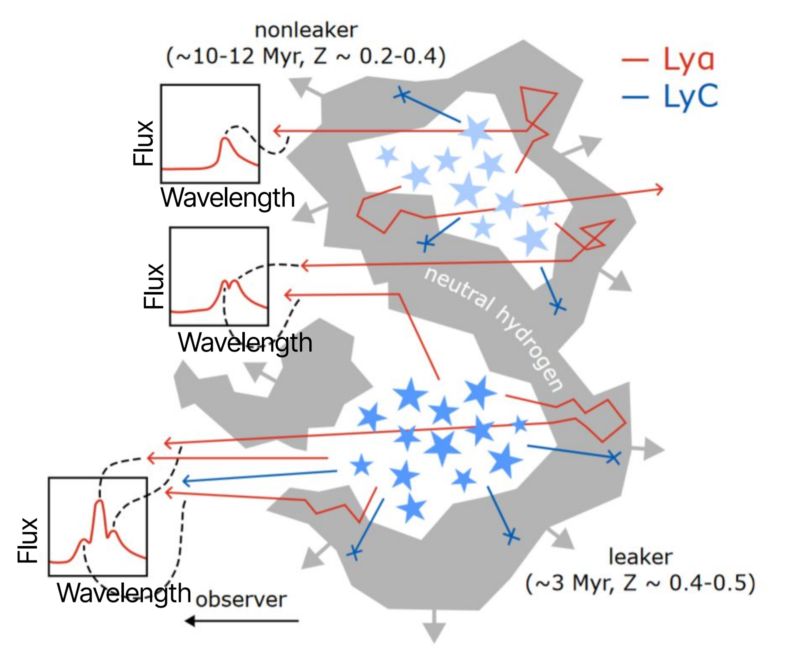


Image Credit: Owens et al. (in prep)

Lyα as a tracer of LyC

- Lyα preferentially escapes along the same routes as LyC

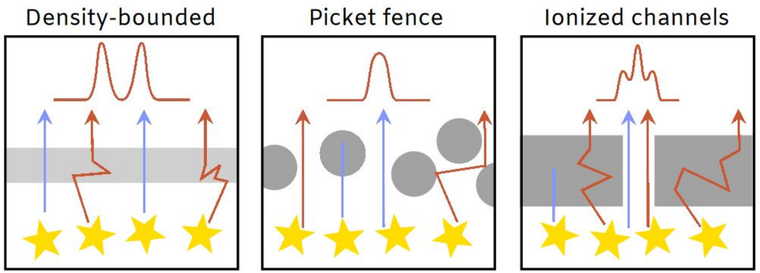
- LyC escapes in two ways
  - Density-Bounded
  - Gaps

- Lyα EW and Lyα peak separation have been correlated with LyC escape.
  - E.g. Izotov+21, Kramarenko+23

Figure Credit: M. Gronke; (Rivera-Thorsen et. al 2017)

Blue - LyC

Red - Lyα



$$\sigma_{H,LyC} = 6.3\times10^{-18}\times\left(\frac{h\nu}{13.6\,\mathrm{eV}}\right)^{-3}\ \mathrm{cm}^2$$

$$\sigma_{H,Ly\alpha} \approx 7\times10^{-11}\ \mathrm{cm}^2$$

Lyα Emitters (LAEs)

- Lyα Emitters (LAEs)
  - Undergoing star formation → young stellar populations
  - Low amounts of interstellar dust (molecules that absorb and scatter UV light)

- LAEs seem to be a stage in galactic evolution

- Problem: Resolving sub-galactic structure at high-z requires high resolution and lots of observing time.

Gravitational Lensing

1. Distortion
2. Magnification

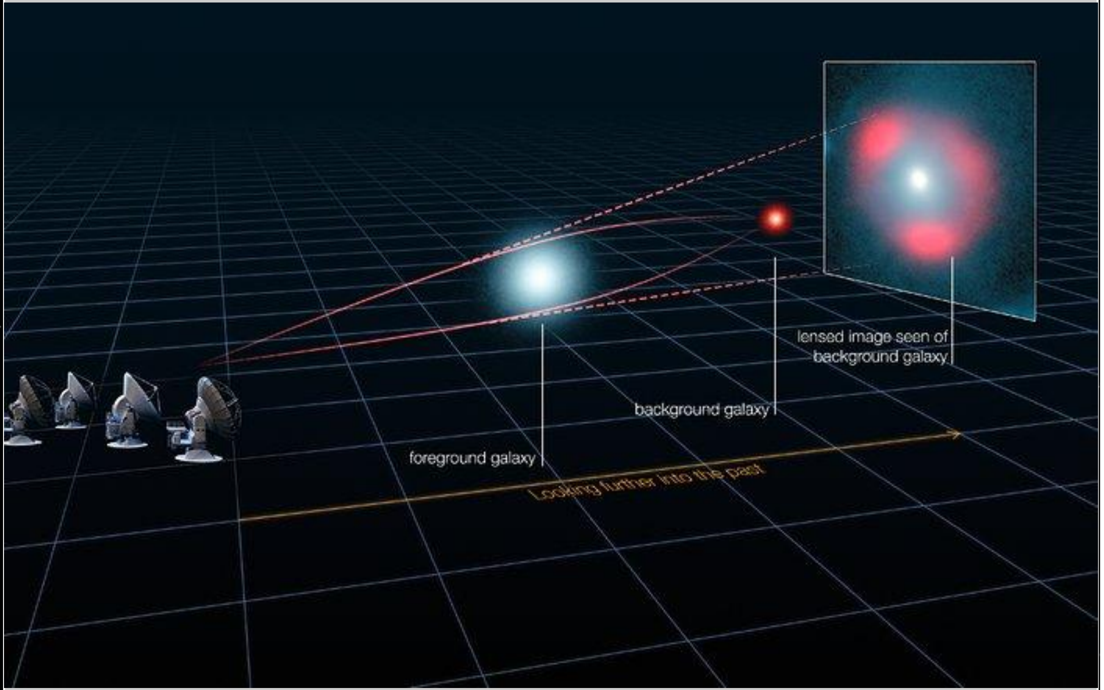
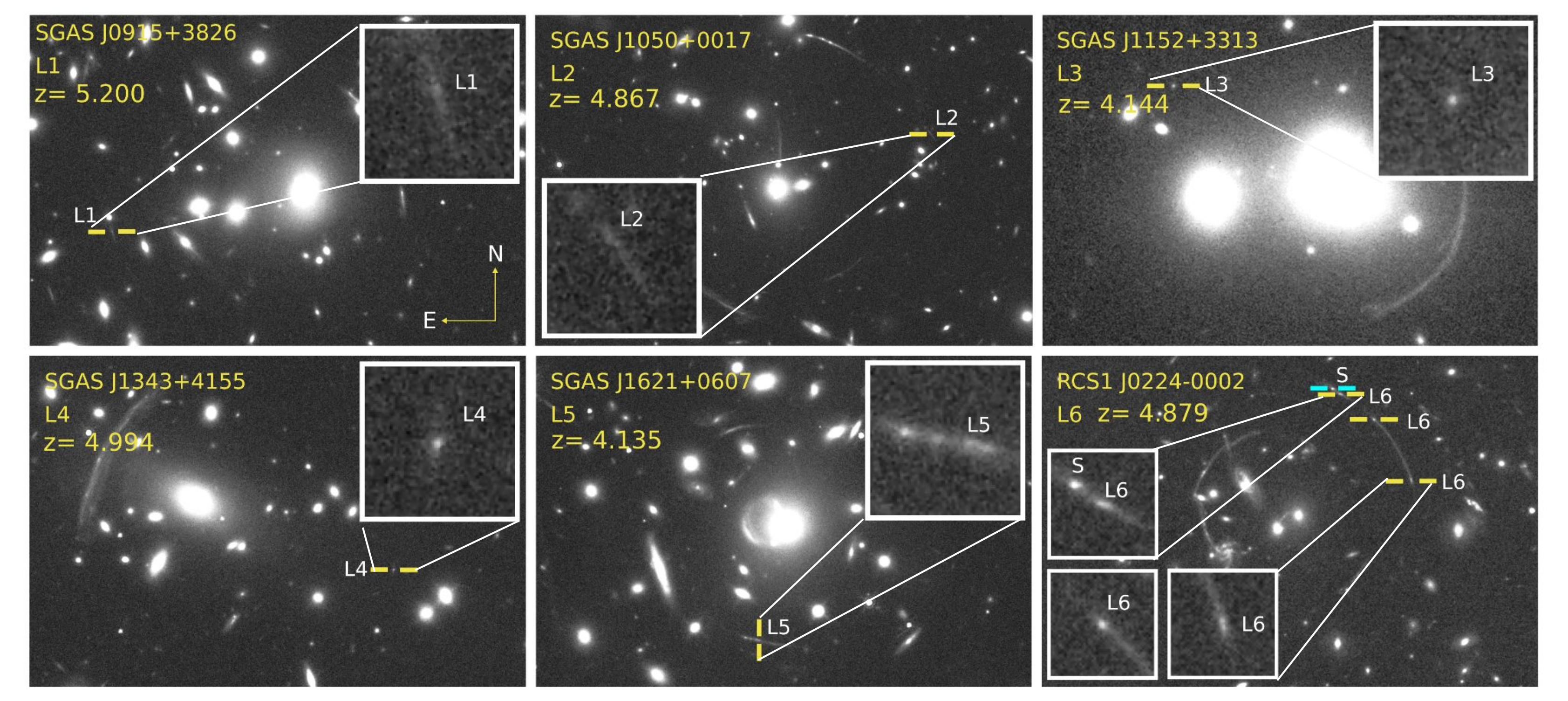


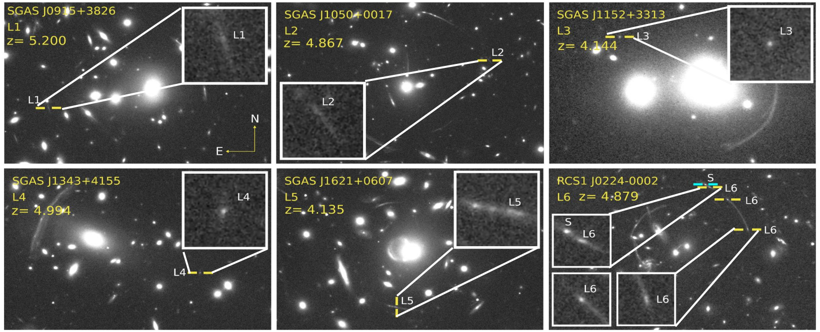
Image Credit: ESO

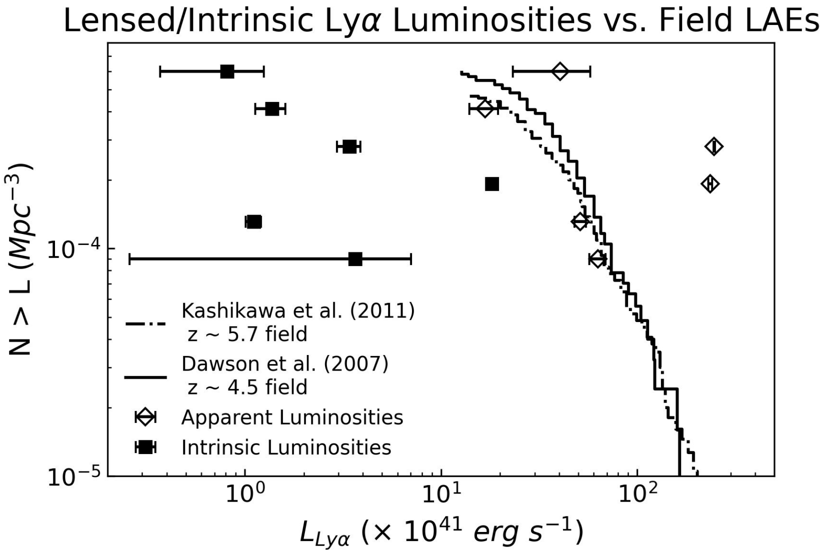
My Sample of LAEs



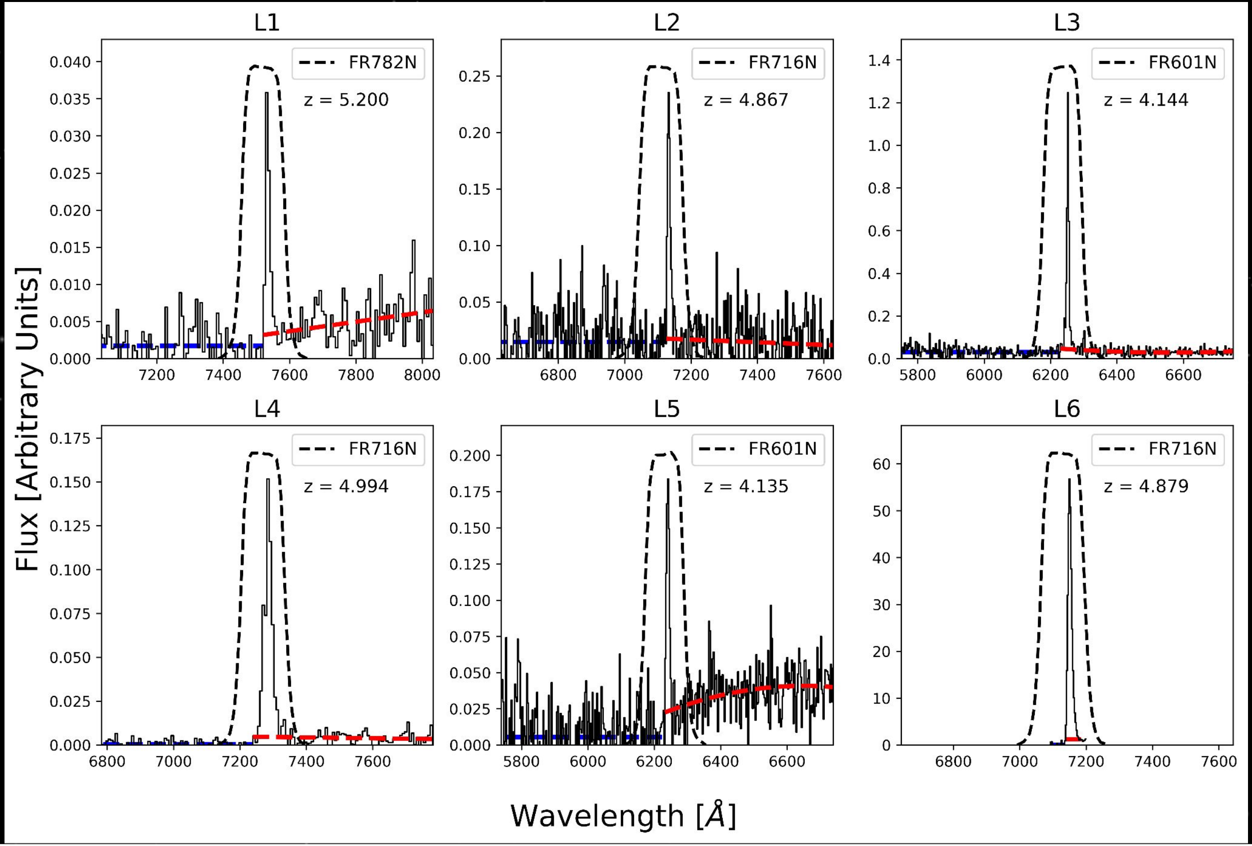
Why this sample?

- As bright or brighter than unlensed LAEs
- Represent intrinsically faint LAEs
- We can see sub-galactic scales!





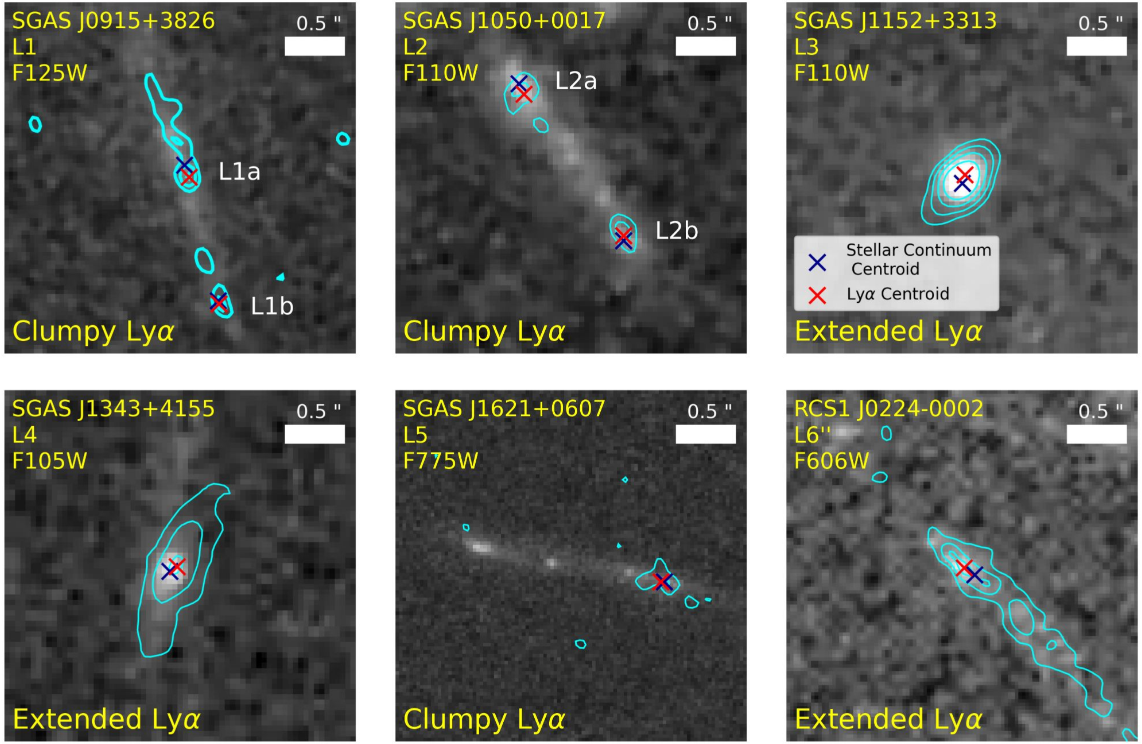
Lyα Spectroscopic Confirmation



Lyα on Sub-Galactic Scales

- Background of stellar continuum
- Cyan contours from narrowband Lyα imaging.

- Two "types" of LAE
  - Clumpy
  - Extended



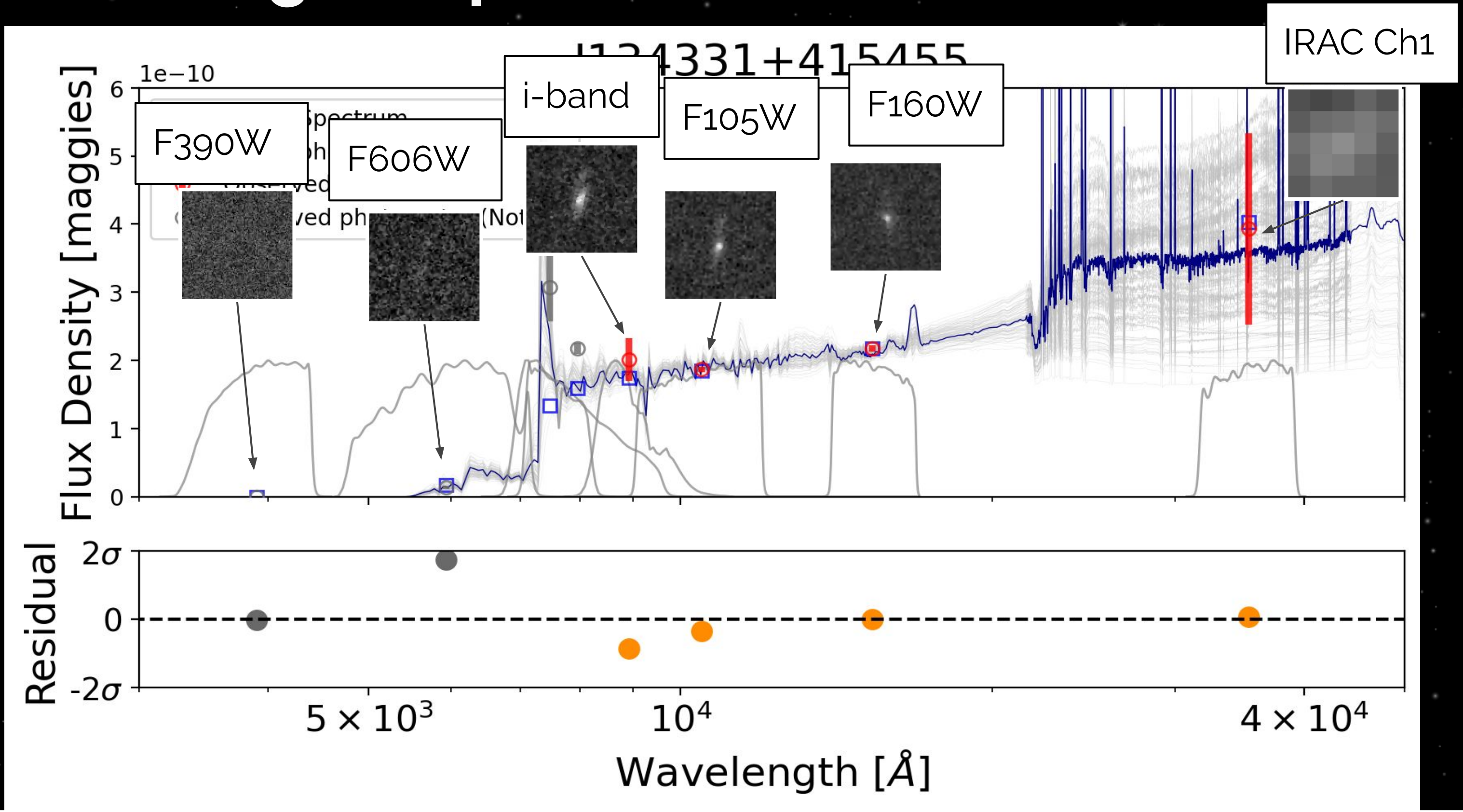
SED Fitting with prospector

- SED = Spectral Energy Distribution
  - Infer Stellar Population Properties from Spectral Shape

- Stellar Spectrum Libraries + Dust Model + Emission Line Libraries + etc
    - Many free parameters! → High-dimensional parameter space

- Uses Emcee (Monte-Carlo Markov Chain) to search for good solutions

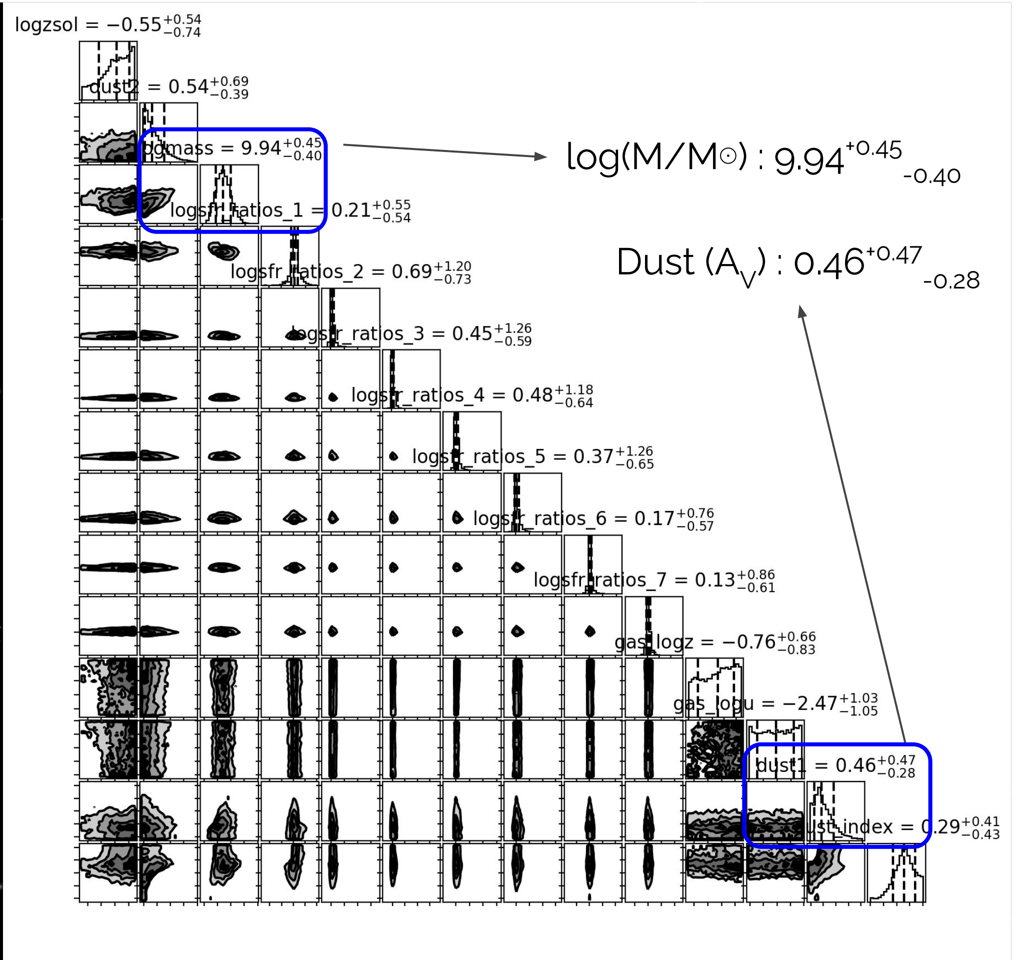
SED Fitting Output



Prospector cont.

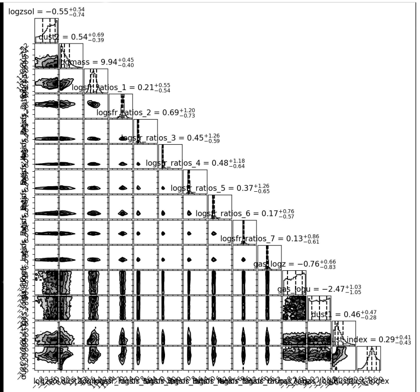
- Our models contain many parameters

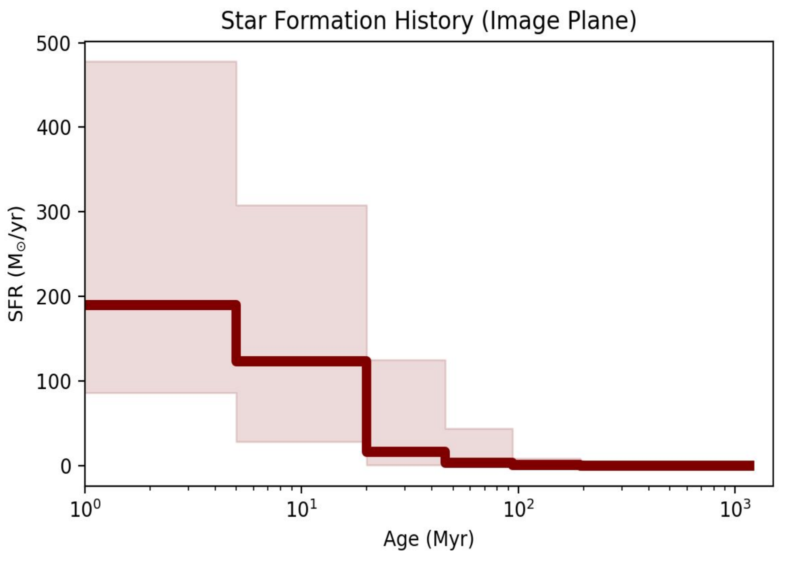
- Our data best constrains stellar mass, age, and amount of dust.

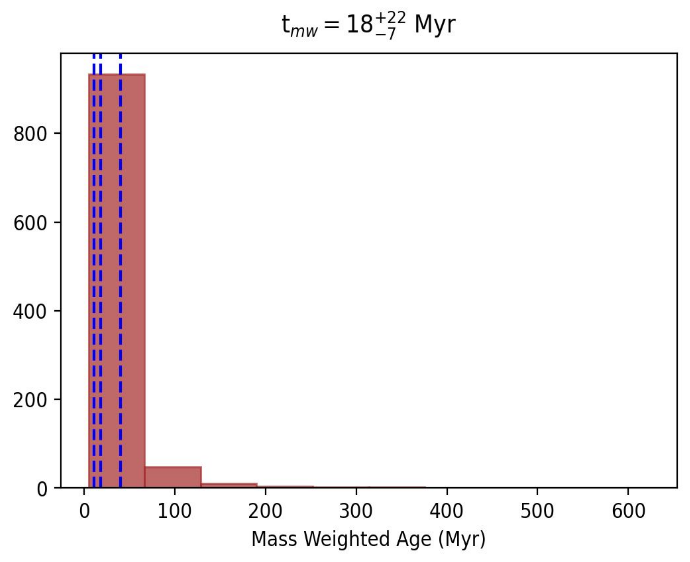


Prospector cont.

- Non-parametric star-formation histories
- Average age of stellar population







Prospector cont.

- Stellar masses are consistent with low or mid-range mass LAEs.
- Young stellar populations
- Low amounts of dust

ID	Lyα Morphology	log(Stellar Mass) $[M_\odot]$ (Lensed)	log(Stellar Mass) $[M_\odot]$ (Intrinsic)	Mass-Weighted Age [Myr]	t_{50} [Myr]	t_{90} [Myr]	Dust1 $[A_V]$
L1	Clumpy	$9.85^{+0.62}_{-0.48}$	$8.15^{+0.64}_{-0.51}$	17^{+19}_{-8}	13^{+14}_{-7}	44^{+510}_{-25}	$0.10^{+0.23}_{-0.08}$
L2	Clumpy	$9.72^{+0.43}_{-0.61}$	$8.60^{+0.44}_{-0.61}$	8^{+9}_{-3}	4^{+11}_{-1}	18^{+220}_{-13}	$0.09^{+0.14}_{-0.07}$
L3	Extended	$9.69^{+0.58}_{-0.68}$	$7.79^{+0.58}_{-0.68}$	33^{+83}_{-20}	38^{+230}_{-26}	187^{+850}_{-150}	$0.57^{+0.84}_{-0.43}$
L4	Extended	$9.94^{+0.45}_{-0.40}$	$8.82^{+0.45}_{-0.40}$	20^{+27}_{-9}	17^{+41}_{-7}	87^{+580}_{-68}	$0.46^{+0.47}_{-0.28}$
L5	Clumpy	$10.41^{+0.09}_{-0.08}$	$8.71^{+0.10}_{-0.10}$	7^{+2}_{-1}	4^{+1}_{-1}	33^{+12}_{-18}	$0.23^{+0.06}_{-0.06}$
L6	Extended	$10.55^{+0.26}_{-0.26}$	$9.24^{+0.47}_{-0.37}$	16^{+11}_{-06}	14^{+26}_{-6}	130^{+490}_{-110}	$0.42^{+0.56}_{-0.31}$

Do these parameters affect clumpiness?

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CrossMark

Resolving Clumpy versus Extended Lyα in Strongly Lensed, High-redshift Lyα Emitters

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L3	Extended	$9.69^{[illegible]}_{-0.68}$	$7.79^{[illegible]}_{-0.68}$	$33^{[illegible]}_{-20}$	$38^{[illegible]}_{-26}$	$187^{[illegible]}_{-150}$	$0.57^{[illegible]}_{-0.43}$
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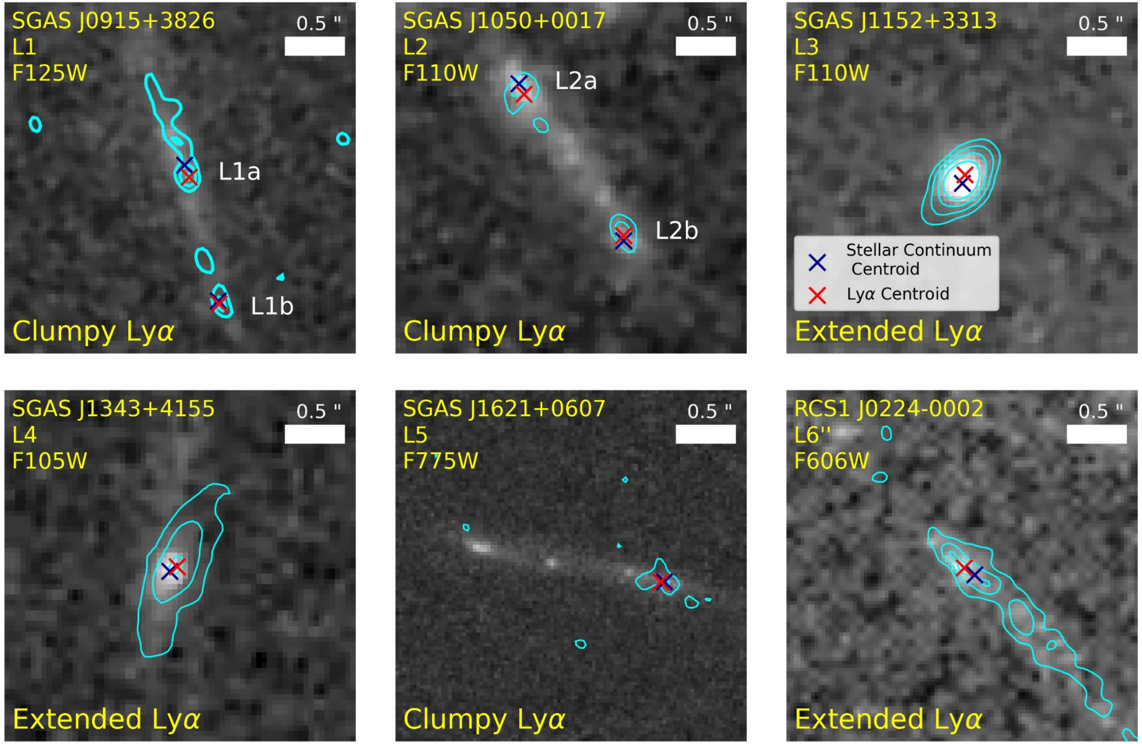
Modeling the Lyα distributions

- Image Plane = On sky
  - Distortion takes away meaning

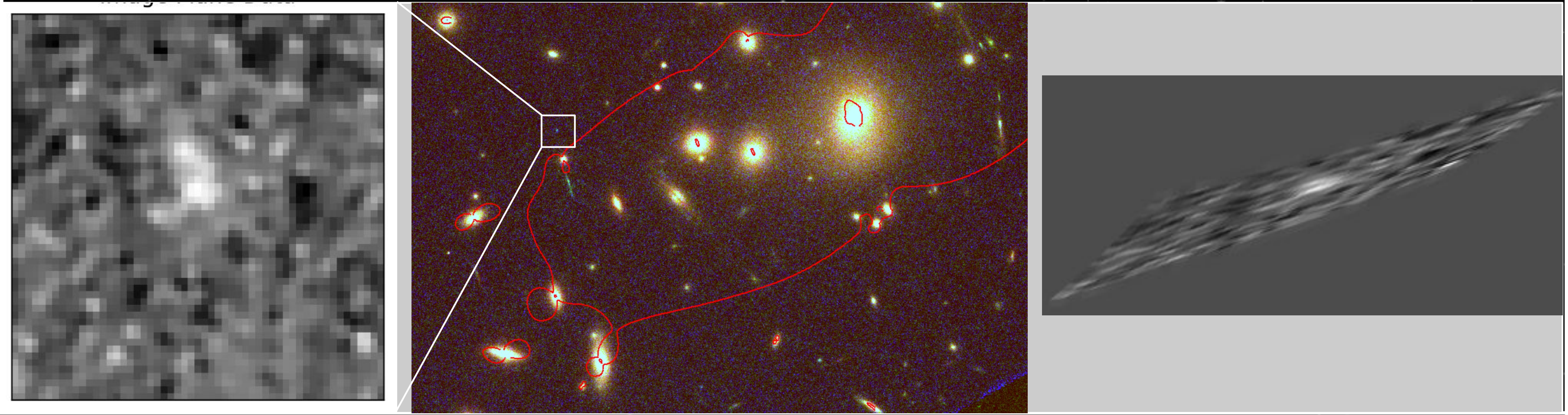
- Source Plane = On delensed sky
  - Difficult
  - Need Tools



Forward Modeling

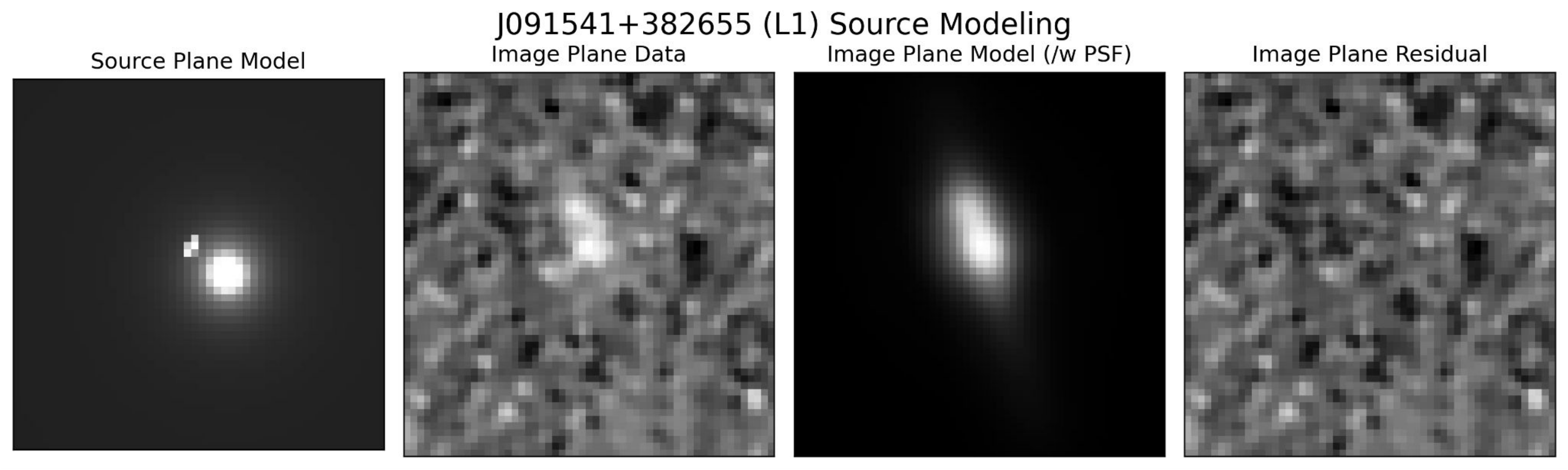
- Modeling a galaxy profile through the lensing potential
- Unfortunately, we cannot disentangle PSF effects

Image Plane → Lensing Potential → Source Plane



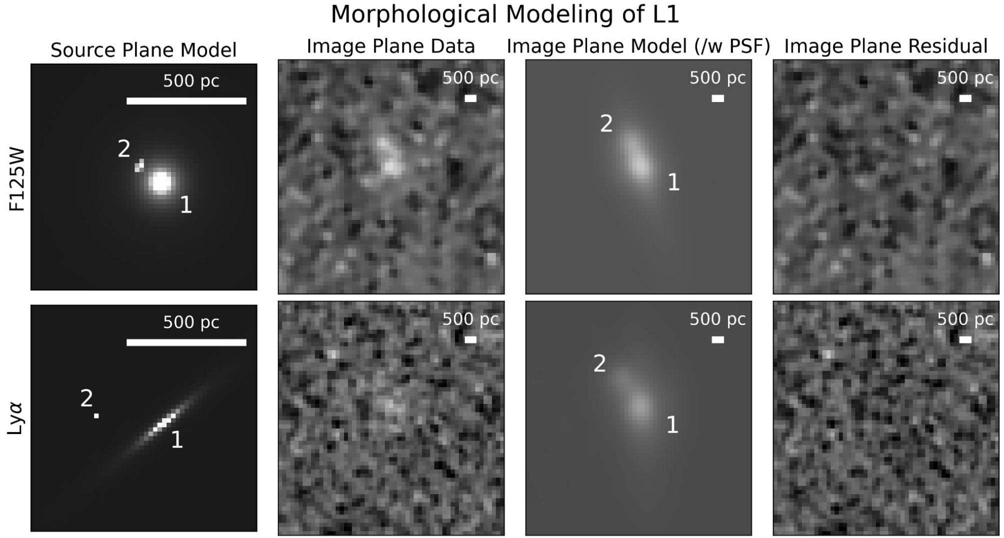
Forward Modeling cont.

- Create models in source plane → apply lensing → evaluate in image plane
- Created with the use of the Emcee algorithm and collaborator Michael Florian



Results

- L1 : Two Clumps
- Preliminary results find Lyα distributions statistically equivalent in size
  - → Ionized Channel?



Band	Clump #	Half-Light Radius $r_{1/2}$	$r_{1/2}$	Amplitude I_e	Ellipticity e	Sérsic Index n
-	-	[$''$]	[pc]	[erg/s/cm^2 $\times$ 10^{-3}]	-	-
F125W	1	$0.00045^{+0.00050}_{-0.00014}$	$2.8^{+3.1}_{-0.9}$	$2.3^{+2.6}_{-1.8}$	$0.31^{+0.13}_{-0.18}$	$5.95^{+1.53}_{-1.92}$
Lyα	1	$0.00080^{+0.00039}_{-0.00027}$	$5.0^{+2.5}_{-1.7}$	$0.5^{+0.2}_{-0.2}$	$0.70^{+0.15}_{-0.32}$	$7.42^{+0.49}_{-2.04}$
F125W	2	$0.00003^{+0.00001}_{-0.00001}$	$0.2^{+<0.1}_{-<0.1}$	$791.9^{+576.0}_{-419.6}$	$0.46^{+0.20}_{-0.24}$	$3.73^{+2.25}_{-1.58}$
Lyα	2	$0.00004^{+0.00002}_{-0.00001}$	$0.3^{+0.1}_{-<0.1}$	$159.9^{+91.9}_{-110.4}$	$0.45^{+0.34}_{-0.31}$	$5.22^{+1.77}_{-2.15}$

Thank you

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Summary

- Lyα is a good tracer for LyC
- Gravitational Lensing allows us to see sub-galactic scales otherwise inaccessible
- Our sample of LAEs is perfect for studying high-z Lyα
- We find a suggestive trend of clumpiness with stellar population age.
- New forward modeling technique shows that clumpy Lyα distributions may be coming from ionized channels.