ODIN: Investigating the Star Formation Histories and Radiative Transfer of LAEs at Cosmic Noon

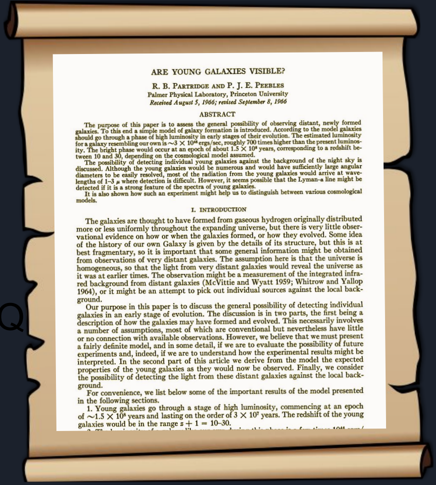
Nicole Firestone, PhD Candidate
Advised by Eric Gawiser

RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY

NSF

LAEs: A Conventional Model

Partridge & Peebles (1967)



ARE YOUNG GALAXIES VISIBLE?

R. B. PARTRIDGE AND P. J. E. PEEBLES
Palmer Physical Laboratory, Princeton University
Received August 5, 1966; revised September 8, 1966

ABSTRACT

The purpose of this paper is to assess the general possibility of observing distant, newly formed galaxies. To this end a simple model of galaxy formation is introduced. According to the model galaxies should go through a phase of high luminosity in early stages of their evolution. The estimated luminosity for a galaxy resembling our own is $\sim 3 \times 10^{46}$ ergs/sec, roughly 700 times higher than the present luminosity. The bright phase would occur at an epoch of about 1.5×10^8 years, corresponding to a redshift between 10 and 30, depending on the cosmological model assumed.

The possibility of detecting individual young galaxies against the background of the night sky is discussed. Although the young galaxies would be numerous and would have sufficiently large angular diameters to be easily resolved, most of the radiation from the young galaxies would arrive at wavelengths of 1–3 μ where detection is difficult. However, it seems possible that the Lyman-α line might be detected if it is a strong feature of the spectra of young galaxies.

It is also shown how such an experiment might help us to distinguish between various cosmological models.

I. INTRODUCTION

The galaxies are thought to have formed from gaseous hydrogen originally distributed more or less uniformly throughout the expanding universe, but there is very little observational evidence on how or when the galaxies formed, or how they evolved. Some idea of the history of our own Galaxy is given by the details of its structure, but this is at best fragmentary, so it is important that some general information might be obtained from observations of very distant galaxies. The assumption here is that the universe is homogeneous, so that the light from very distant galaxies would reveal the universe as it was at earlier times. The observation might be a measurement of the integrated infrared background from distant galaxies (McVittie and Wyatt 1959; Whitrow and Yallop 1964), or it might be an attempt to pick out individual sources against the local background.

Our purpose in this paper is to discuss the general possibility of detecting individual galaxies in an early stage of evolution. The discussion is in two parts, the first being a description of how the galaxies may have formed and evolved. This necessarily involves a number of assumptions, most of which are conventional but nevertheless have little or no connection with available observations. However, we believe that we must present a fairly definite model, and in some detail, if we are to evaluate the possibility of future experiments and, indeed, if we are to understand how the experimental results might be interpreted. In the second part of this article we derive from the model the expected properties of the young galaxies as they would now be observed. Finally, we consider the possibility of detecting the light from these distant galaxies against the local background.

For convenience, we list below some of the important results of the model presented in the following sections.

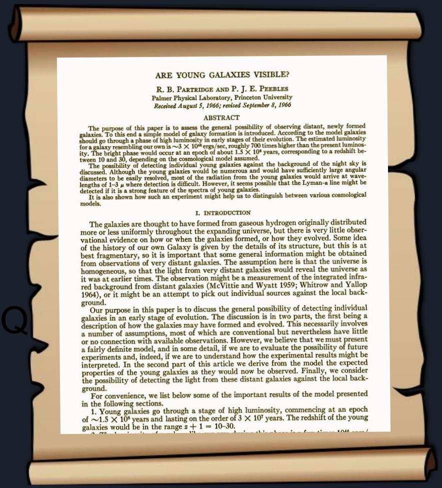
1. Young galaxies go through a stage of high luminosity, commencing at an epoch of $\sim 1.5 \times 10^8$ years and lasting on the order of 3×10^7 years. The redshift of the young galaxies would be in the range $z + 1 = 10$–30.

- Young, low-mass galaxies experiencing their ***first*** burst of star formation
- Due to resonant scattering, Lyα photons experience much higher dust extinction than UV continuum radiation

… However, up until this point limitations in data quality and analysis techniques have made it difficult to truly test these hypotheses

LAEs: A Conventional Model

Partridge & Peebles (1967)



ARE YOUNG GALAXIES VISIBLE?

R. B. Partridge and P. J. E. Peebles
Palmer Physical Laboratory, Princeton University
Received August 5, 1966; revised September 8, 1966

ABSTRACT

The purpose of this paper is to assess the general possibility of observing distant, newly formed galaxies. To this end a simple model of galaxy formation is introduced. According to the model galaxies should go through a phase of high luminosity in early stages of their evolution. The estimated luminosity for a galaxy resembling our own is $\sim 3 \times 10^{46}$ ergs/sec, roughly 700 times higher than the present luminosity. The bright phase would occur at an epoch of about 1.5×10^8 years, corresponding to a redshift between 10 and 30, depending on the cosmological model assumed.

The possibility of detecting individual young galaxies against the background of the night sky is discussed. Although the young galaxies would be numerous and would have sufficiently large angular diameters to be easily resolved, most of the radiation from the young galaxies would arrive at wavelengths of 1–3 μ where detection is difficult. However, it seems possible that the Lyman-α line might be detected if it is a strong feature of the spectra of young galaxies.

It is also shown how such an experiment might help us to distinguish between various cosmological models.

I. INTRODUCTION

The galaxies are thought to have formed from gaseous hydrogen originally distributed more or less uniformly throughout the expanding universe, but there is very little observational evidence on how or when the galaxies formed, or how they evolved. Some idea of the history of our own Galaxy is given by the details of its structure, but this is at best fragmentary, so it is important that some general information might be obtained from observations of very distant galaxies. The assumption here is that the universe is homogeneous, so that the light from very distant galaxies would reveal the universe as it was at earlier times. The observation might be a measurement of the integrated infrared background from distant galaxies (McVittie and Wyatt 1959; Whitrow and Yallop 1964), or it might be an attempt to pick out individual sources against the local background.

Our purpose in this paper is to discuss the general possibility of detecting individual galaxies in an early stage of evolution. The discussion is in two parts, the first being a description of how the galaxies may have formed and evolved. This necessarily involves a number of assumptions, most of which are conventional but nevertheless have little or no connection with available observations. However, we believe that we must present a fairly definite model, and in some detail, if we are to evaluate the possibility of future experiments and, indeed, if we are to understand how the experimental results might be interpreted. In the second part of this article we derive from the model the expected properties of the young galaxies as they would now be observed. Finally, we consider the possibility of detecting the light from these distant galaxies against the local background.

For convenience, we list below some of the important results of the model presented in the following sections.

1. Young galaxies go through a stage of high luminosity, commencing at an epoch of $\sim 1.5 \times 10^8$ years and lasting on the order of 3×10^7 years. The redshift of the young galaxies would be in the range $z + 1 = 10$–30.

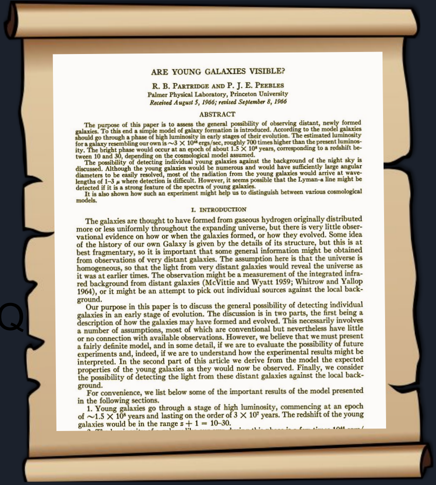
- Young, low-mass galaxies experiencing their ***first*** burst of star formation
- Due to resonant scattering, Lyα photons experience much higher dust extinction than UV continuum radiation

… However, up until this point limitations in data quality and analysis techniques have made it difficult to truly test these hypotheses

LAEs are often used for statistical analyses of galaxy formation/evolution & cosmology, BUT we do not fully understand the precise stage of galaxy evolution that LAEs correspond to.

LAEs: A Conventional Model

Partridge & Peebles (1967)



ARE YOUNG GALAXIES VISIBLE?

R. B. Partridge and P. J. E. Peebles
Palmer Physical Laboratory, Princeton University

Received August 5, 1966; revised September 8, 1966

ABSTRACT

The purpose of this paper is to assess the general possibility of observing distant, newly formed galaxies. To this end a simple model of galaxy formation is introduced. According to the model galaxies should go through a phase of high luminosity in early stages of their evolution. The estimated luminosity for a galaxy resembling our own is $\sim 3 \times 10^{46}$ ergs/sec, roughly 700 times higher than the present luminosity. The bright phase would occur at an epoch of about 1.5×10^{8} years, corresponding to a redshift between 10 and 30, depending on the cosmological model assumed.

The possibility of detecting individual young galaxies against the background of the night sky is discussed. Although the young galaxies would be numerous and would have sufficiently large angular diameters to be easily resolved, most of the radiation from the young galaxies would arrive at wavelengths of 1–3 μ where detection is difficult. However, it seems possible that the Lyman-α line might be detected if it is a strong feature of the spectra of young galaxies.

It is also shown how such an experiment might help us to distinguish between various cosmological models.

I. INTRODUCTION

The galaxies are thought to have formed from gaseous hydrogen originally distributed more or less uniformly throughout the expanding universe, but there is very little observational evidence on how or when the galaxies formed, or how they evolved. Some idea of the history of our own Galaxy is given by the details of its structure, but this is at best fragmentary, so it is important that some general information might be obtained from observations of very distant galaxies. The assumption here is that the universe is homogeneous, so that the light from very distant galaxies would reveal the universe as it was at earlier times. The observation might be a measurement of the integrated infrared background from distant galaxies (McVittie and Wyatt 1959; Whitrow and Yallop 1964), or it might be an attempt to pick out individual sources against the local background.

Our purpose in this paper is to discuss the general possibility of detecting individual galaxies in an early stage of evolution. The discussion is in two parts, the first being a description of how the galaxies may have formed and evolved. This necessarily involves a number of assumptions, most of which are conventional but nevertheless have little or no connection with available observations. However, we believe that we must present a fairly definite model, and in some detail, if we are to evaluate the possibility of future experiments and, indeed, if we are to understand how the experimental results might be interpreted. In the second part of this article we derive from the model the expected properties of the young galaxies as they would now be observed. Finally, we consider the possibility of detecting the light from these distant galaxies against the local background.

For convenience, we list below some of the important results of the model presented in the following sections.

1. Young galaxies go through a stage of high luminosity, commencing at an epoch of $\sim 1.5 \times 10^{8}$ years and lasting on the order of 3×10^{7} years. The redshift of the young galaxies would be in the range $z + 1 = 10$–30.

- Young, low-mass galaxies experiencing their ***first*** burst of star formation
- Due to resonant scattering, Lyα photons experience much higher dust extinction than UV continuum radiation

… However, up until this point limitations in data quality and analysis techniques have made it difficult to truly test these hypotheses

LAEs are often used for statistical analyses of galaxy formation/evolution & cosmology, BUT we do not fully understand the precise stage of galaxy evolution that LAEs correspond to.

What makes an LAE an LAE?

What Makes an LAE an LAE?

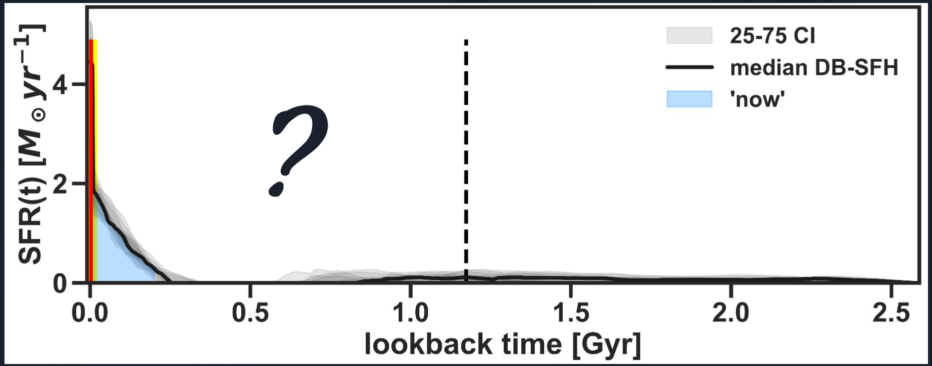
Stellar Mass Assembly (intrinsic) + **Radiative Transfer** (observed)

What Makes an LAE an LAE?

Stellar Mass Assembly (intrinsic) + **Radiative Transfer** (observed)

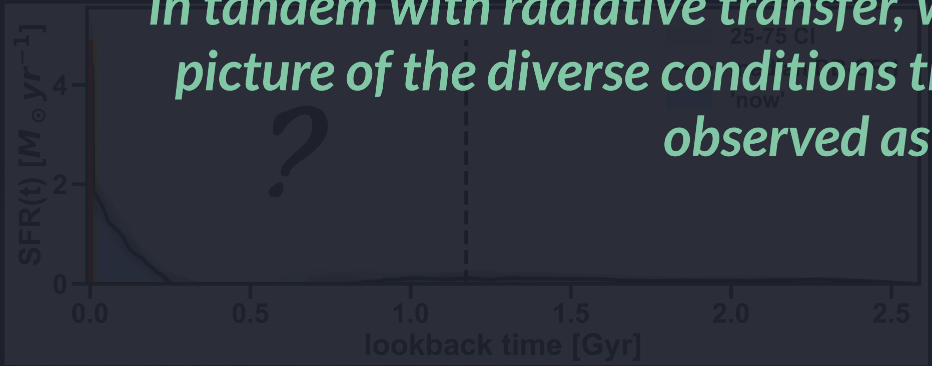
What Makes an LAE an LAE?

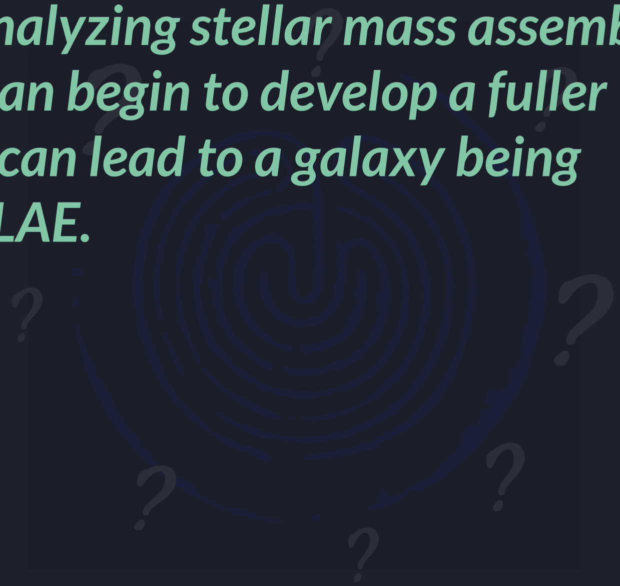
Stellar Mass Assembly (intrinsic) + **Radiative Transfer** (observed)



What Makes an LAE an LAE?

Star Formation (intrinsic) + Radiative Transfer (observed)





By breaking down our assumptions and analyzing stellar mass assembly in tandem with radiative transfer, we can begin to develop a fuller picture of the diverse conditions that can lead to a galaxy being observed as an LAE.

The ODIN Survey

(One-hundred deg^2 DECam Imaging in Narrowbands; Lee et al. 2023)

- 2021-2024 NOIRLab survey program used to discover LAEs via narrowband imaging
- Using Dark Energy Camera (DECam) on Blanco 4m telescope at CTIO in Chile
- Built 3 custom-made narrowband filters (FWHM ~10nm) for DECam centered at…
  - 419 nm → z = 2.4 → 2.8 billion years after the Big Bang
  - 501 nm → z = 3.1 → 2.1 billion years after the Big Bang
  - 673 nm → z = 4.5 → 1.4 billion years after the Big Bang

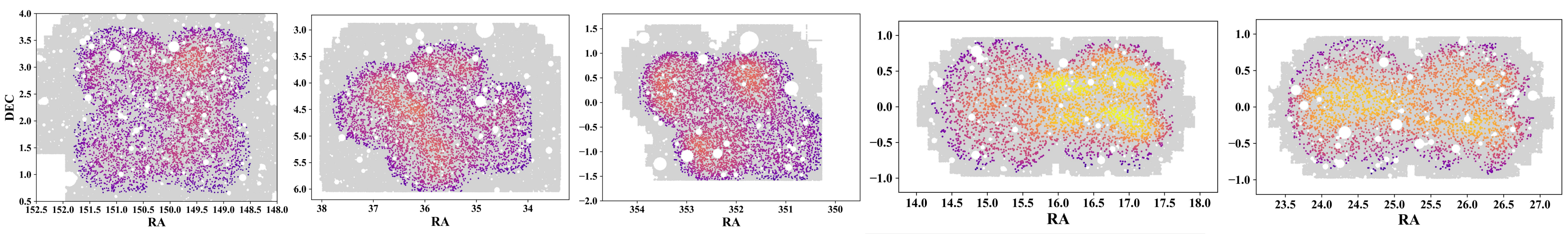
  } Cosmic Noon
- Pair with archival broadband data (HSC, CLAUDS, LSST)
- Expect to discover >100,000 LAEs across 7 fields of the sky, up to ~25.7 AB covering 100 deg^2

images:NOIRLab, www.sgphotos.com, Rubin Observatory

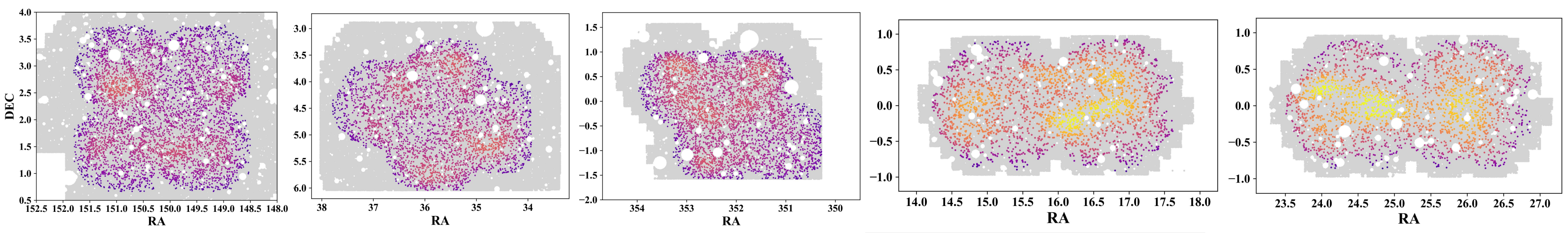
ODIN LAE Samples

(Firestone et al. 2024, plus more fields)

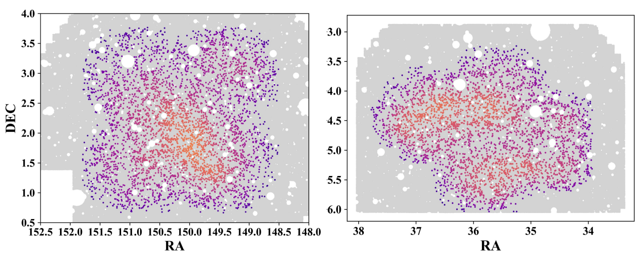
z = 2.4



z = 3.1



z = 4.5

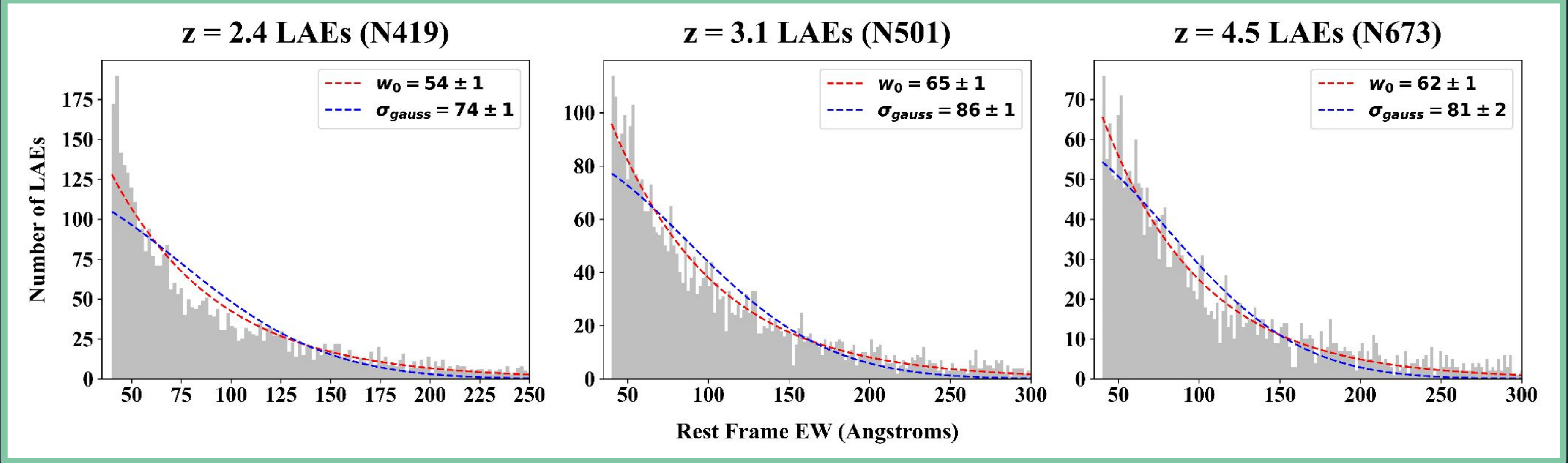


With ODIN's data so far, we have been able to introduce several improvements to LAE selection techniques and curated a sample of ~50,000 LAEs.

This is the *largest* narrowband-selected LAE sample to date.

The First Hint: Equivalent Width Distributions

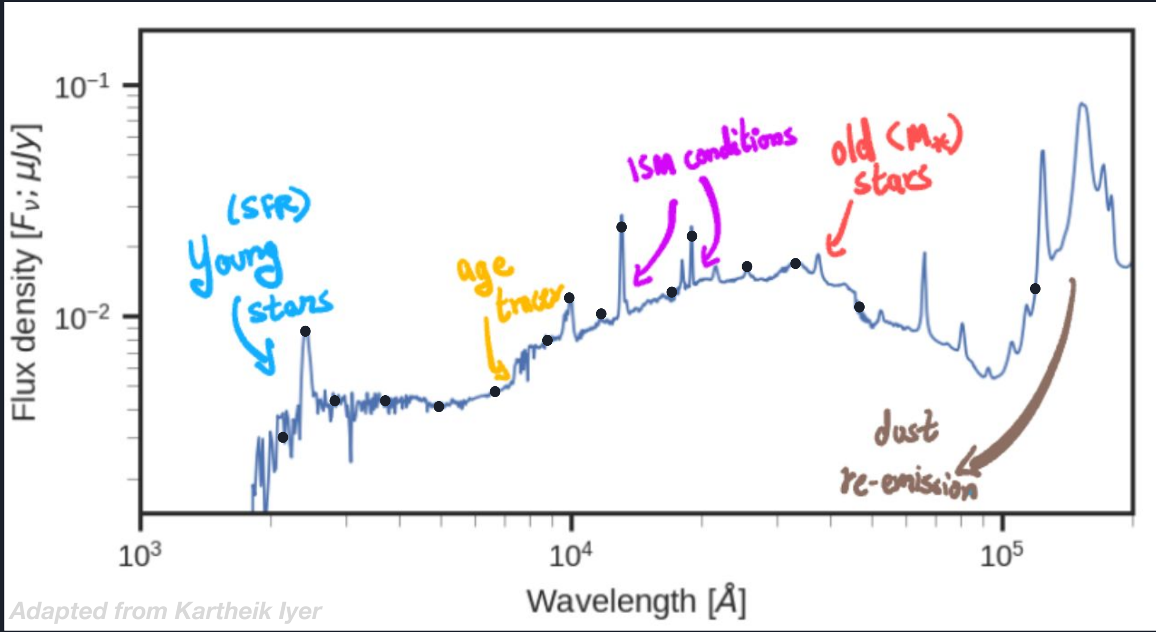
(Firestone et al. 2024)



LAEs with true EWs ≥ 240 Angstroms suggest that LAEs may have nontrivial radiative transfer scenarios, including complex ISM conditions.

SEDs to Star Formation Histories

A spectral energy distribution is a powerful tool for uncovering the history of star formation and quenching throughout the lifetime of a galaxy.

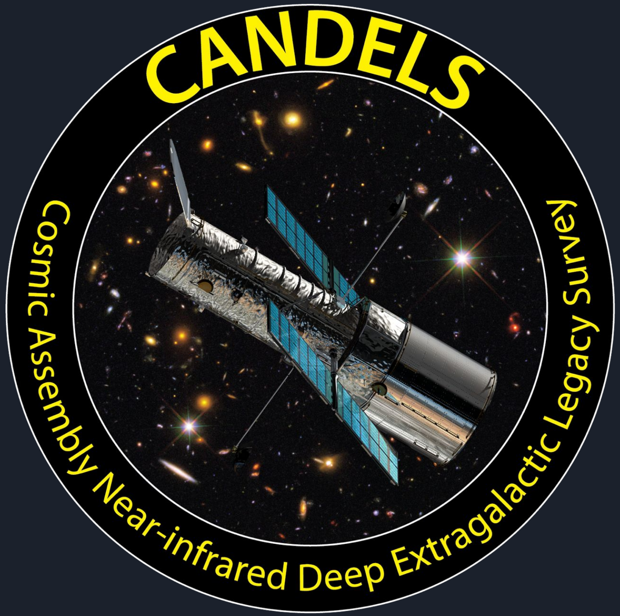


Adapted from Kartheik Iyer

Fitting Parameters for This Work

(Firestone et al. 2025)

- Match ODIN LAEs with CANDELS photometric catalog in COSMOS field (74 LAEs)
    - Exclude NB and IB filters containing Lyα (~44 filters used)



Fitting Parameters for This Work

(Firestone et al. 2025)

- Match ODIN LAEs with CANDELS photometric catalog in COSMOS field (74 LAEs)
  - Exclude NB and IB filters containing Lyα (~44 filters used)
- Use *Dense Basis* non-parametric gaussian process based SFH reconstruction (Iyer & Gawiser 2017; Iyer et al. 2019)

dense basis

Fast, flexible fitter for galaxy stellar populations

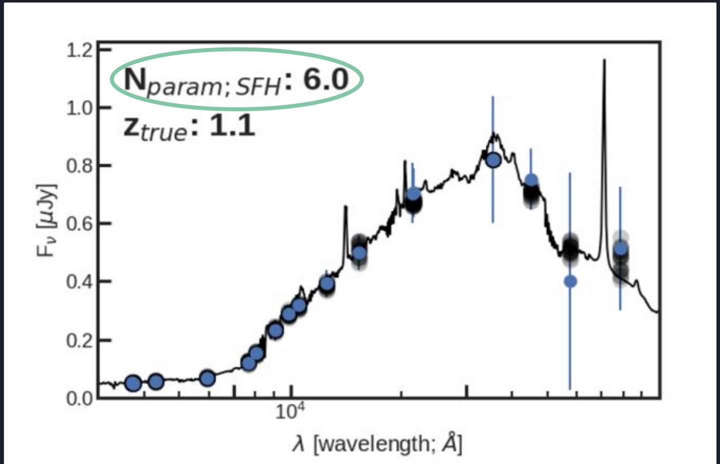
Fitting Parameters for This Work

(Firestone et al. 2025)

- Match ODIN LAEs with CANDELS photometric catalog in COSMOS field (74 LAEs)
  - Exclude NB and IB filters containing Lyα (~44 filters used)

- Use *Dense Basis* non-parametric gaussian process based SFH reconstruction (Iyer & Gawiser 2017; Iyer et al. 2019)

Fast, flexible fitter for galaxy stellar populations



Iyer & Gawiser 17, ApJ 838 127

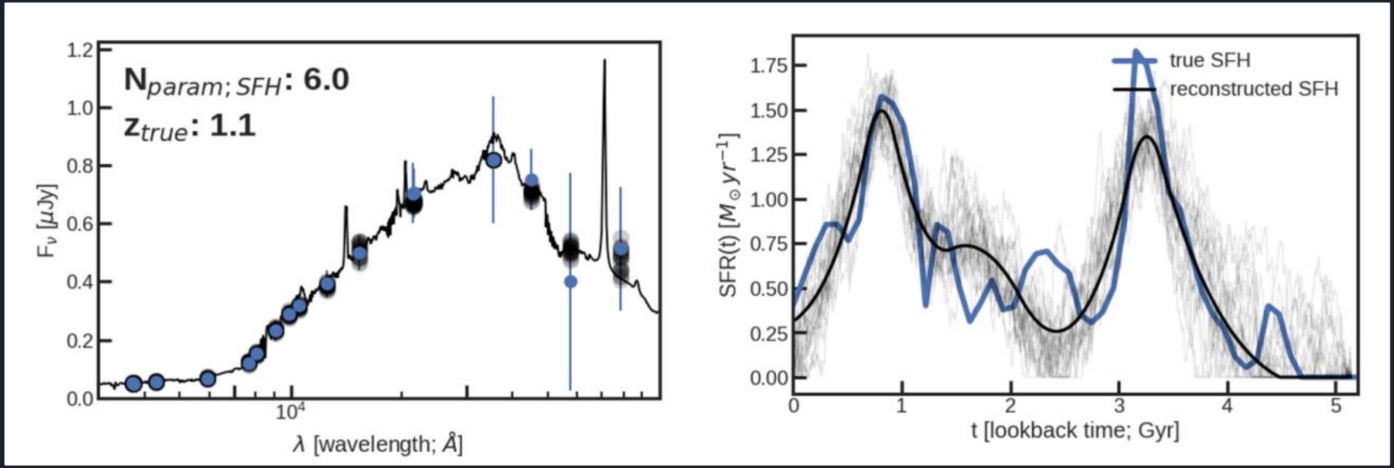
non-parametric
→ flexible number of parameters

Fitting Parameters for This Work
(Firestone et al. 2025)

- Match ODIN LAEs with CANDELS photometric catalog in COSMOS field (74 LAEs)
  - Exclude NB and IB filters containing Lyα (~44 filters used)

- Use *Dense Basis* non-parametric gaussian process based SFH reconstruction (Iyer & Gawiser 2017; Iyer et al. 2019)

dense basis
Fast, flexible fitter for galaxy stellar populations

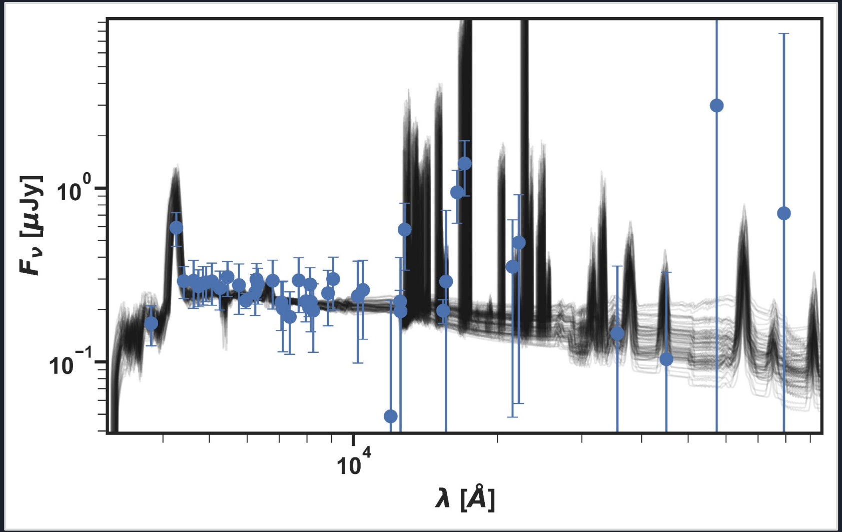


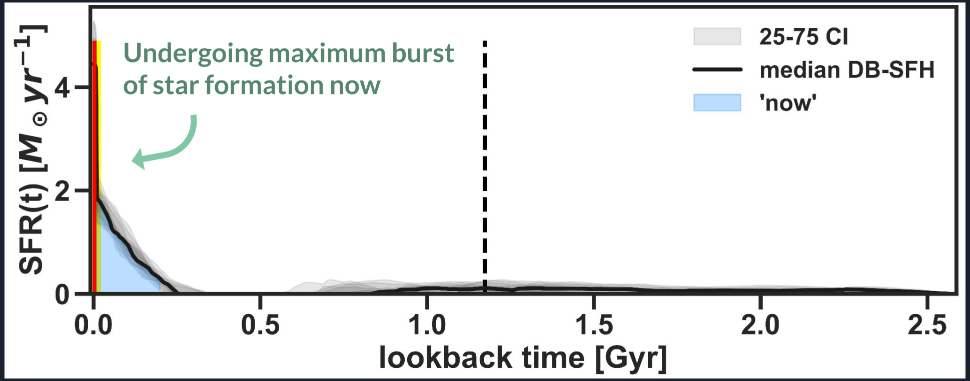
Iyer & Gawiser 17, ApJ 838 127

gaussian process → smooth SFH

Expected LAE Star Formation History

(Firestone et al. 2025)

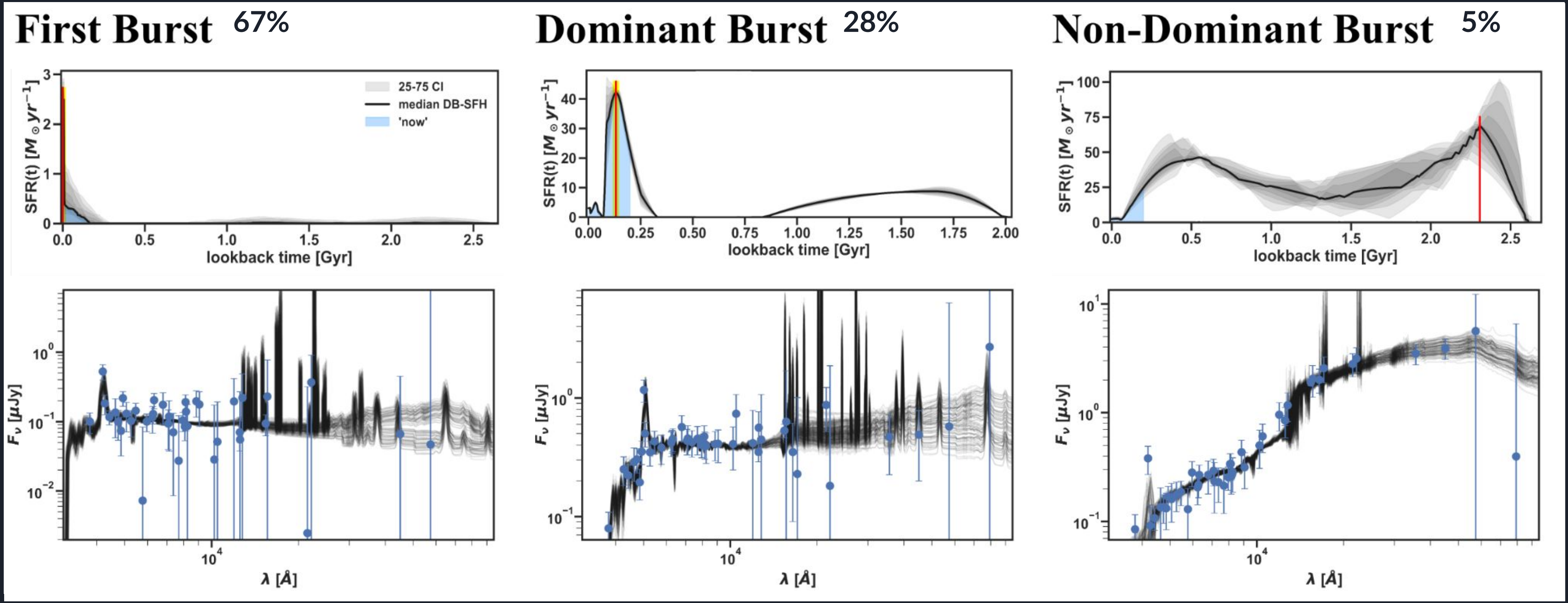




Observed LAE Star Formation Histories

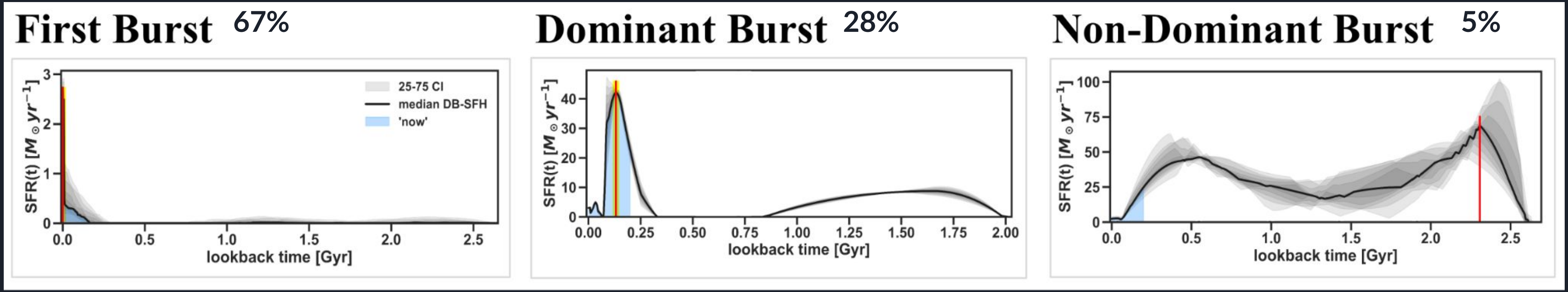
(Firestone et al. 2025)

ODIN's LAE SFHs fall into 3 archetypes…



Observed LAE Star Formation Histories

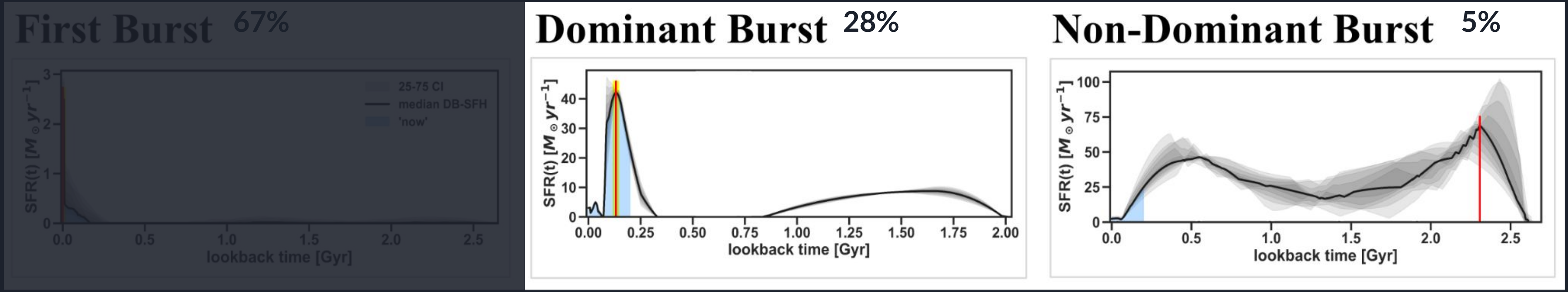
(Firestone et al. 2025)



LAEs actually have several different stellar mass assembly scenarios!

Observed LAE Star Formation Histories

(Firestone et al. 2025)

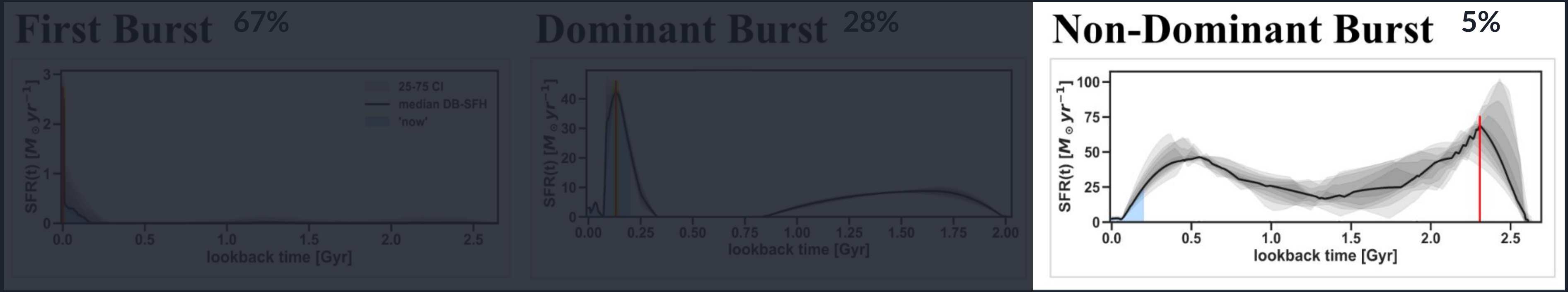


LAEs actually have several different stellar mass assembly scenarios!

The amplitude of past star formation in *Dominant Burst* and *Non-Dominant Burst* LAEs suggests that a galaxy may be an LAE at several periods during its lifetime, ie. ***the LAE phenomenon is both temporary and of varying duration***.

Observed LAE Star Formation Histories

(Firestone et al. 2025)

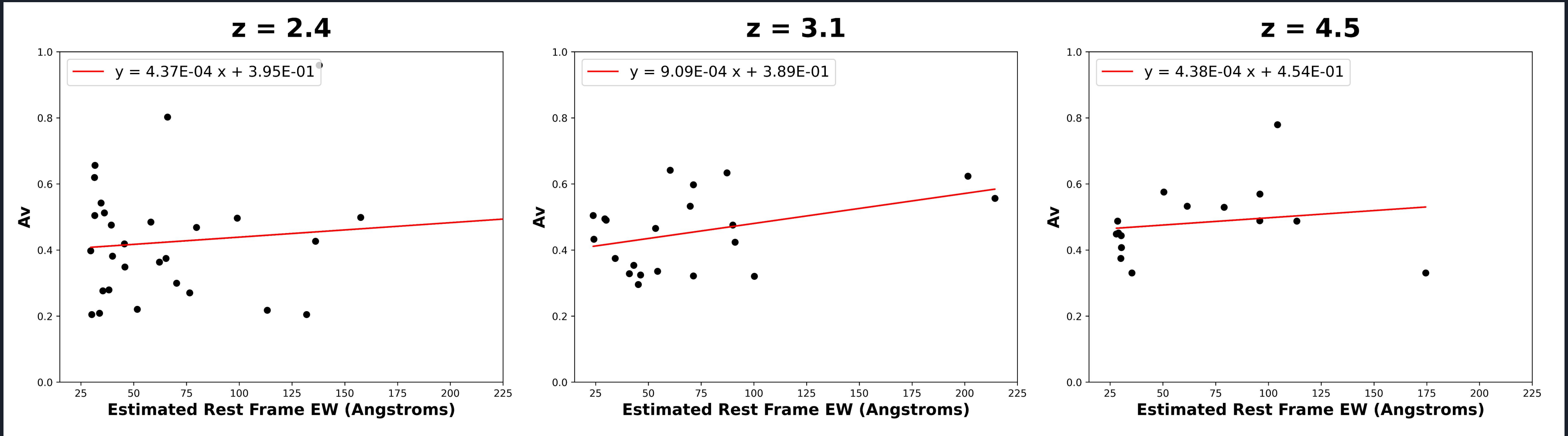


LAEs actually have several different stellar mass assembly scenarios!

Non-Dominant Burst LAEs suggest that some LAEs are the product of ***galaxy mergers***. We would therefore expect that they experience extreme dust destruction or anisotropic radiative transfer with fortuitous Lyα escape.

Av–EW Relationship

If LAE stellar mass assembly is more complex than we thought and some LAEs have older stellar populations, what radiative transfer mechanisms make Lyα in LAEs easily detectable?



This relationship suggests that the Lyα photons we observe may not be impacted by resonant scattering.

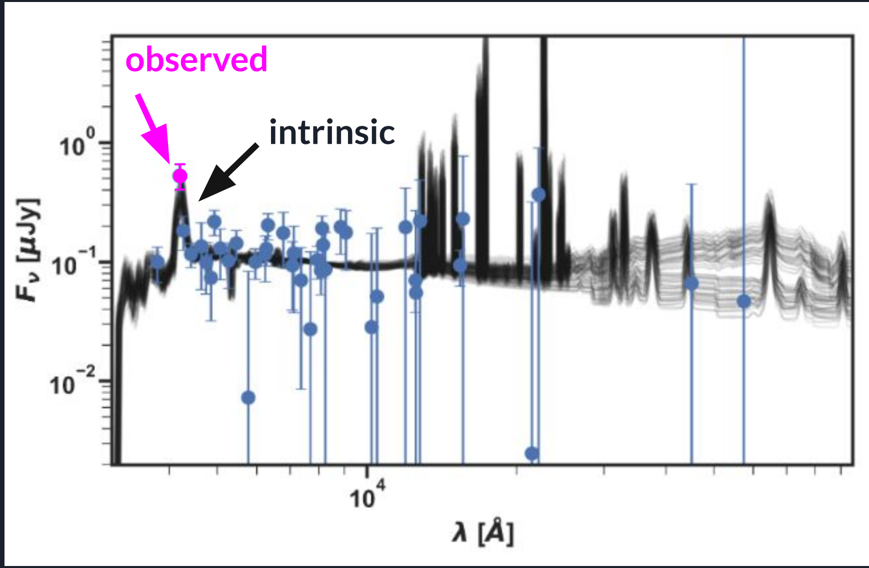
…Radiative transfer may instead be driven by gas velocities and/or a clumpy ISM.

Quantifying ISM Clumpiness

The q-factor allows us to measure ISM clumpiness.

$$f_{Ly\alpha,obs} = f_{Ly\alpha,int} \times \exp[-q\tau_c]$$

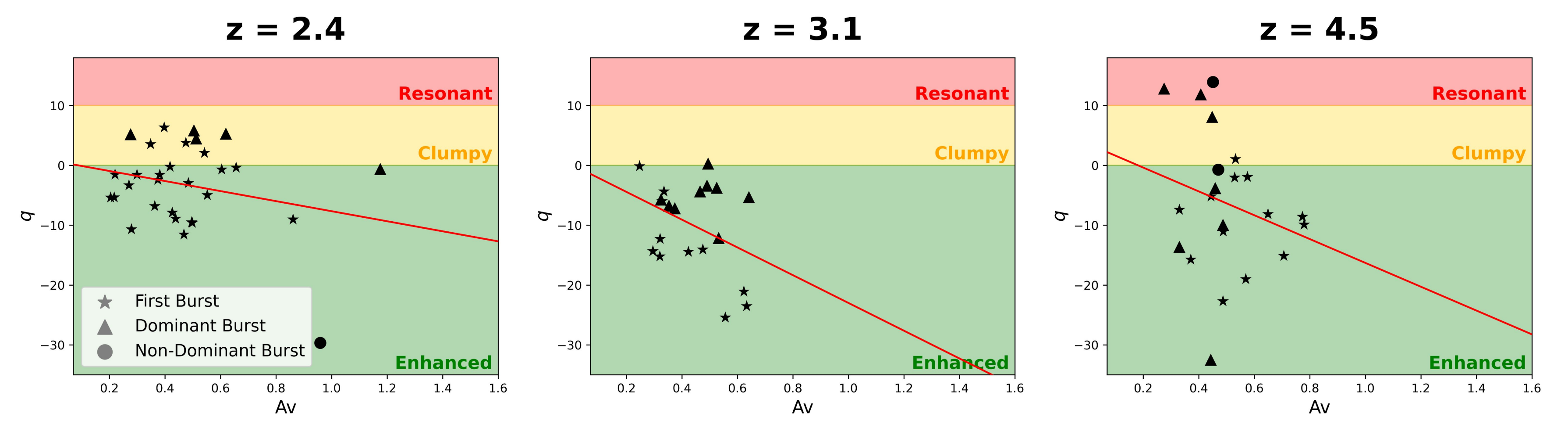
$$q = \tau_c^{-1} \times \log_{10}\left(\frac{f_{Ly\alpha,int}}{f_{Ly\alpha,obs}}\right)$$



Goal: Connect SFH archetype with radiative transfer scenario to gain a full picture understanding of the diversity of conditions that lead to a galaxy being observed as an LAE.

Quantifying ISM Clumpiness

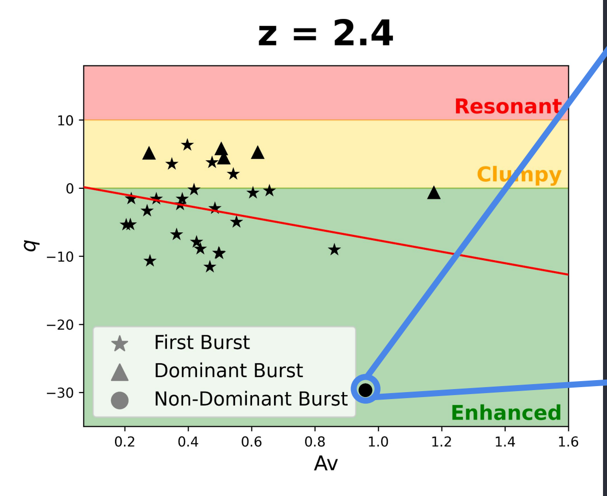
The q-factor allows us to measure ISM clumpiness.

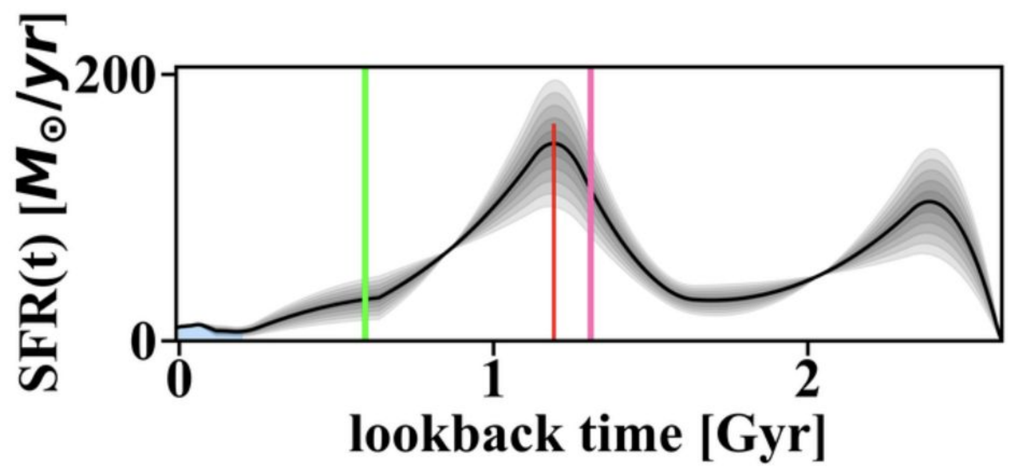


Early results suggest that LAEs with more dust typically experience stronger Lyα enhancement.

Quantifying ISM Clumpiness

The q-factor allows us to measure ISM clumpiness.





Likely a product of a galaxy merger, which experienced rejuvenated SF and has little dust due to strong outflows.

LAEs: A **Revised** Model

“LAE” is an observation-driven classification defined by a complex interplay of star formation, merger status, and radiative transfer scenario.

- LAE stellar mass assembly is more complicated than we thought
- Some LAEs have significant older stellar populations
- “LAE” may be a time dependant classification, with several galaxies possibly acting as LAEs at several periods in their lifetime
- A small sub-sample of LAEs has undergone several massive bursts of SF in the past– possibly due to merger events
- Lyα radiative transfer plays a huge factor in deciding whether or not a galaxy is observed as an LAE
- Lyα radiative transfer is likely often driven by gas velocities rather than resonant scattering, and may be impacted by a clumpy ISM