Blobs, Galaxies, and Protoclusters Found with Lyman Alpha: Early Science from ODIN

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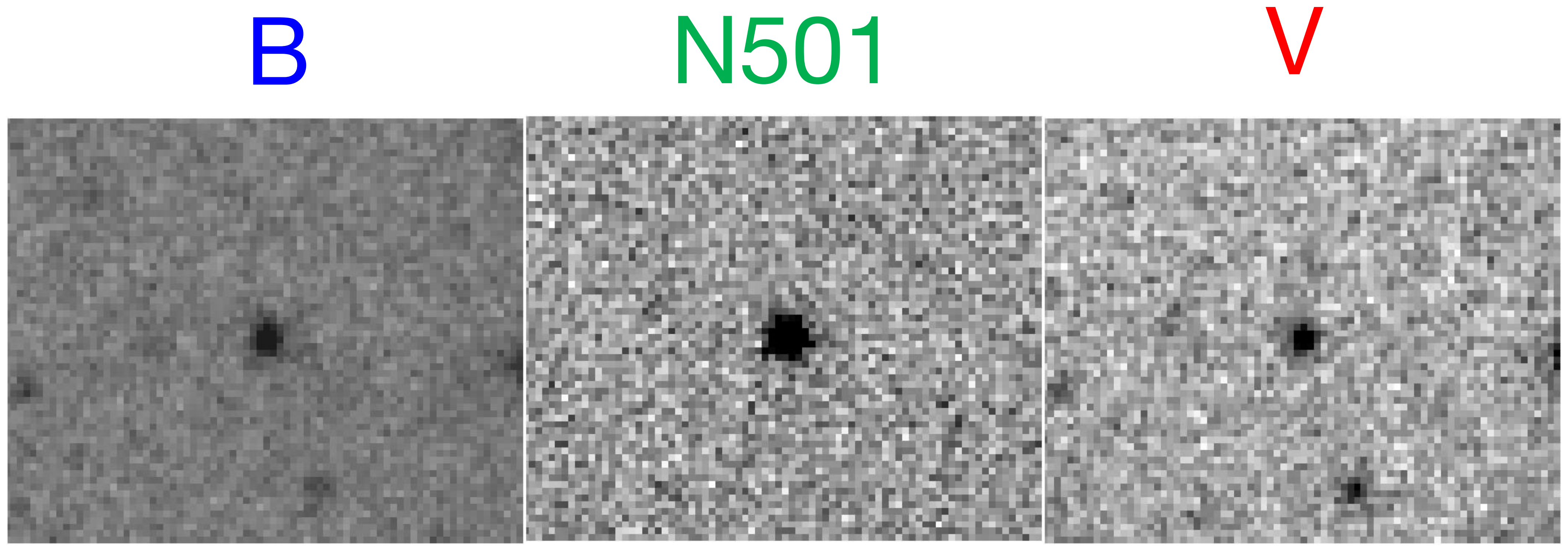
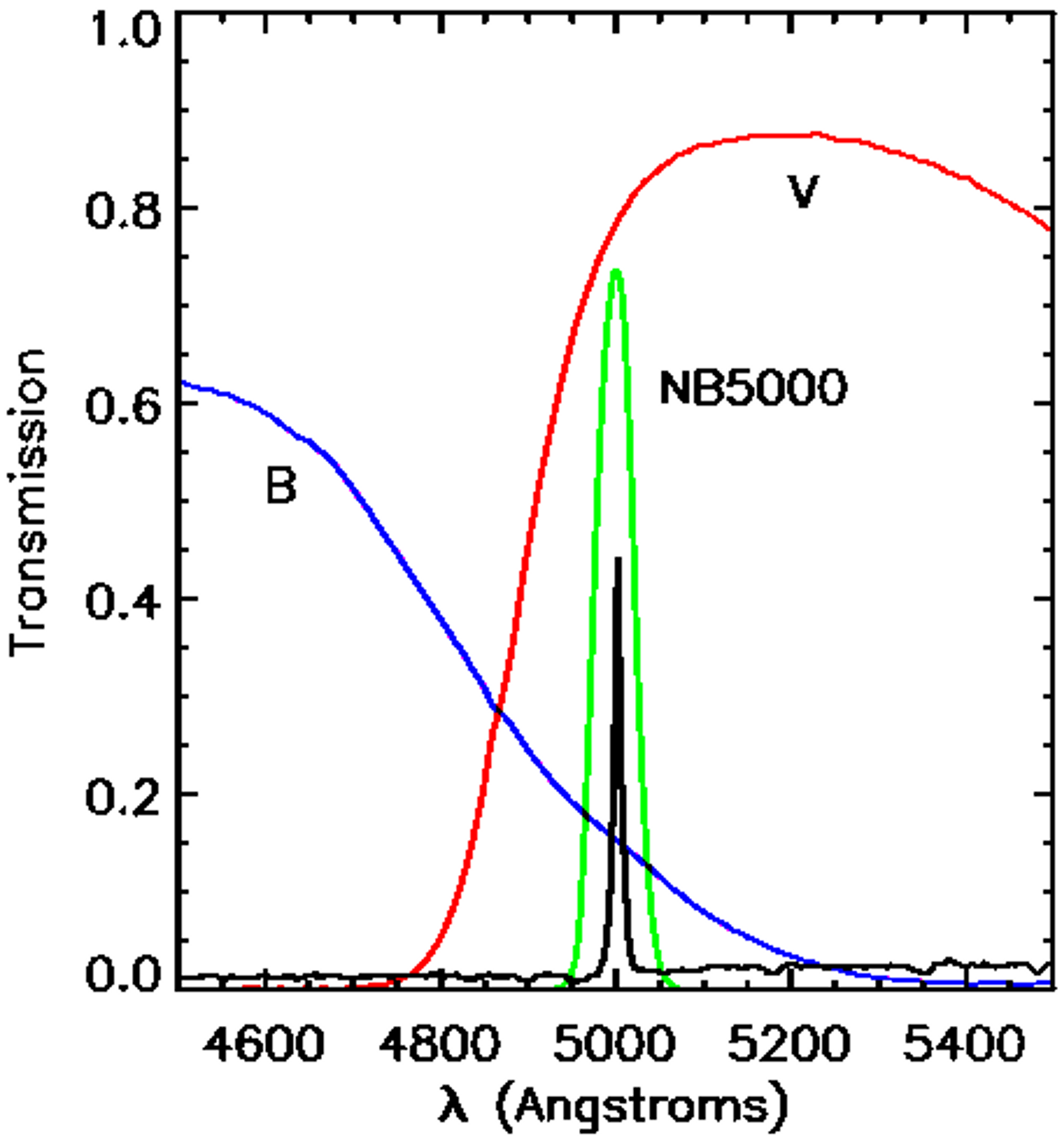
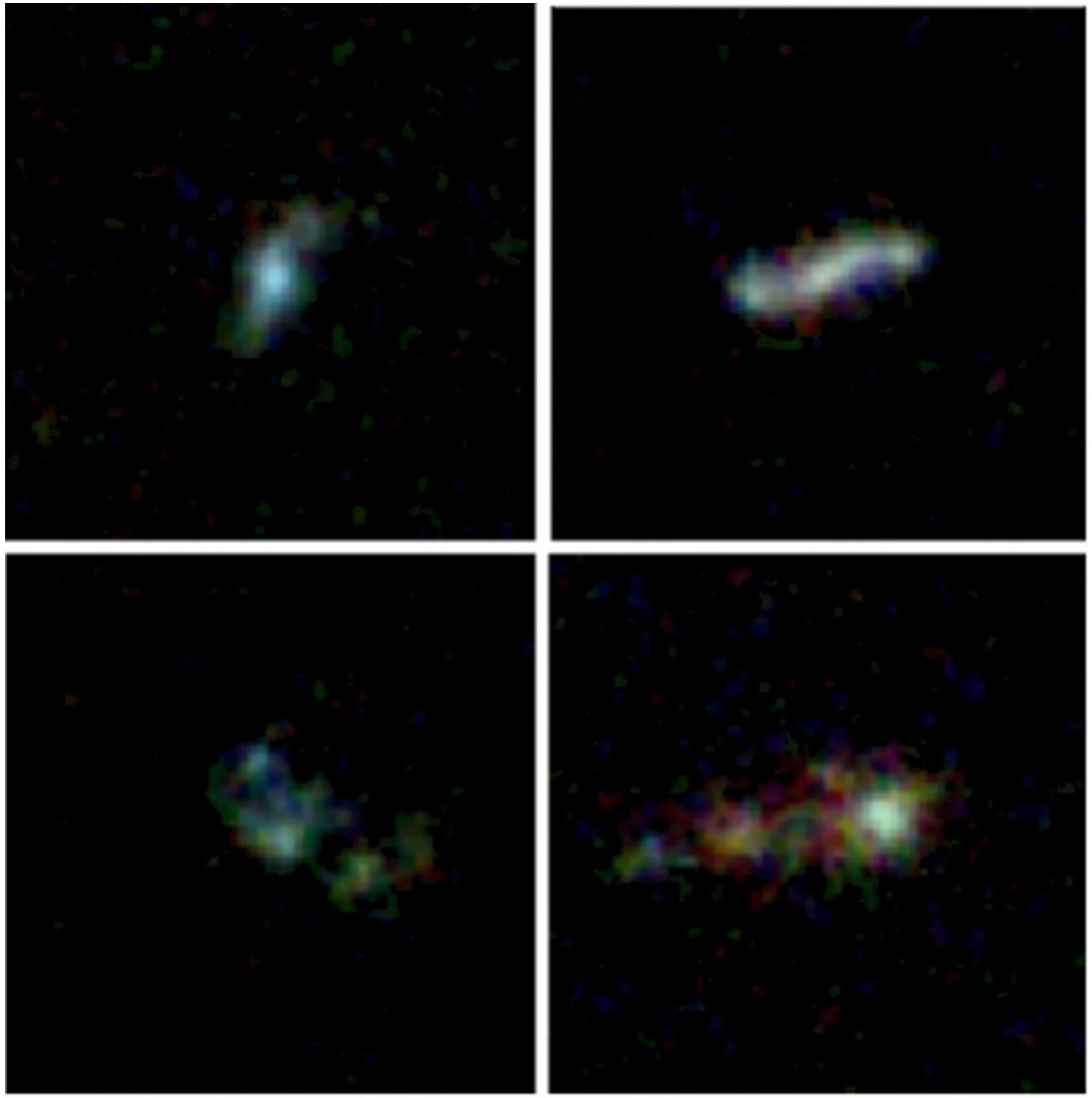
Presented on behalf of the ODIN Team, including PI Kyoung-Soo Lee, Barbara Benda, Arjun Dey, Rameen Farooq, Nicole Firestone, Yun Huang, Shreya Karthikeyan, Byeongha Moon, Changbom Park, Vandana Ramakrishnan, David Schlegel, Frank Valdez, Yujin Yang, et al.

Lyman Alpha Emitter (LAE) at z=3.1

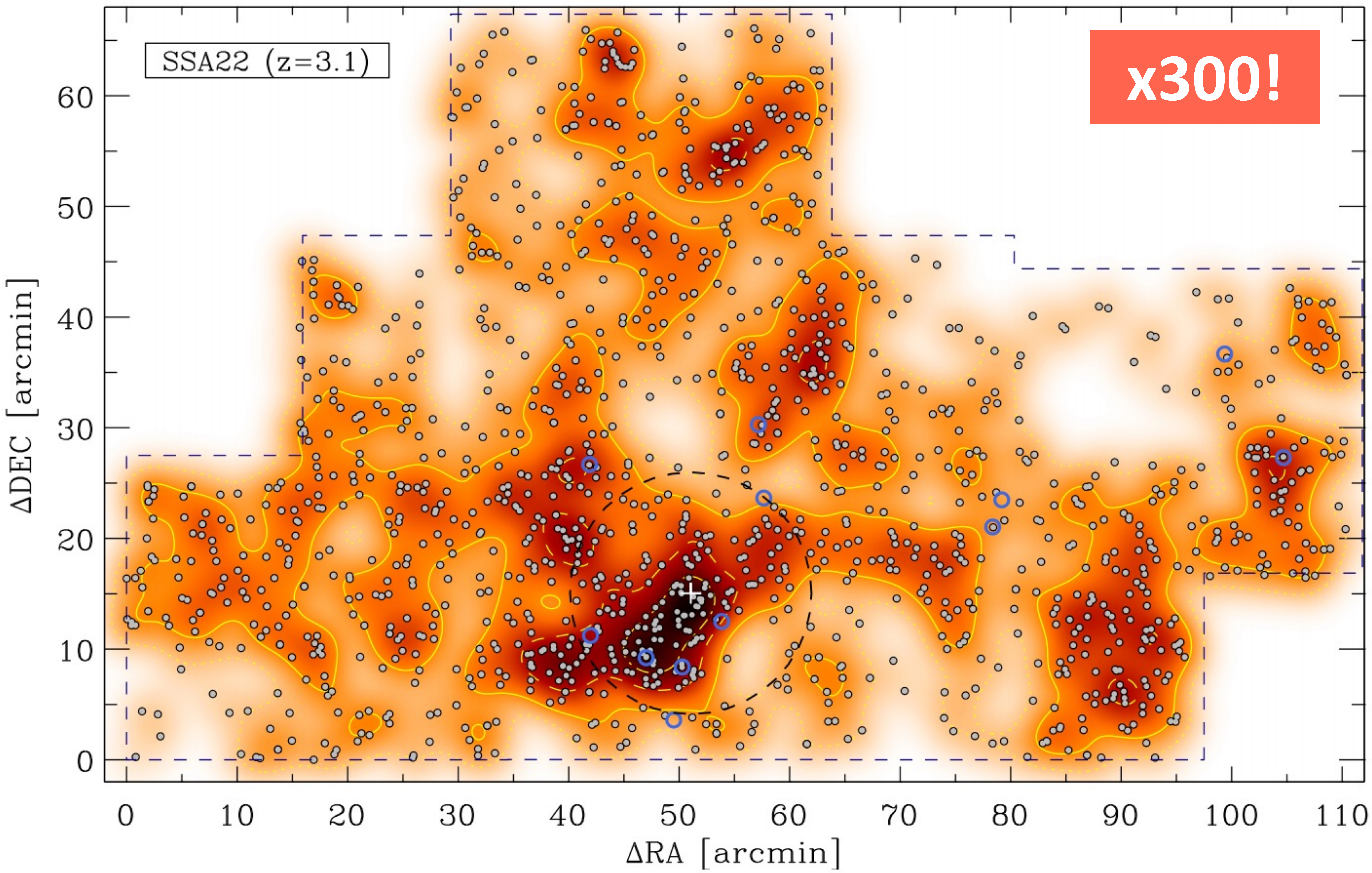




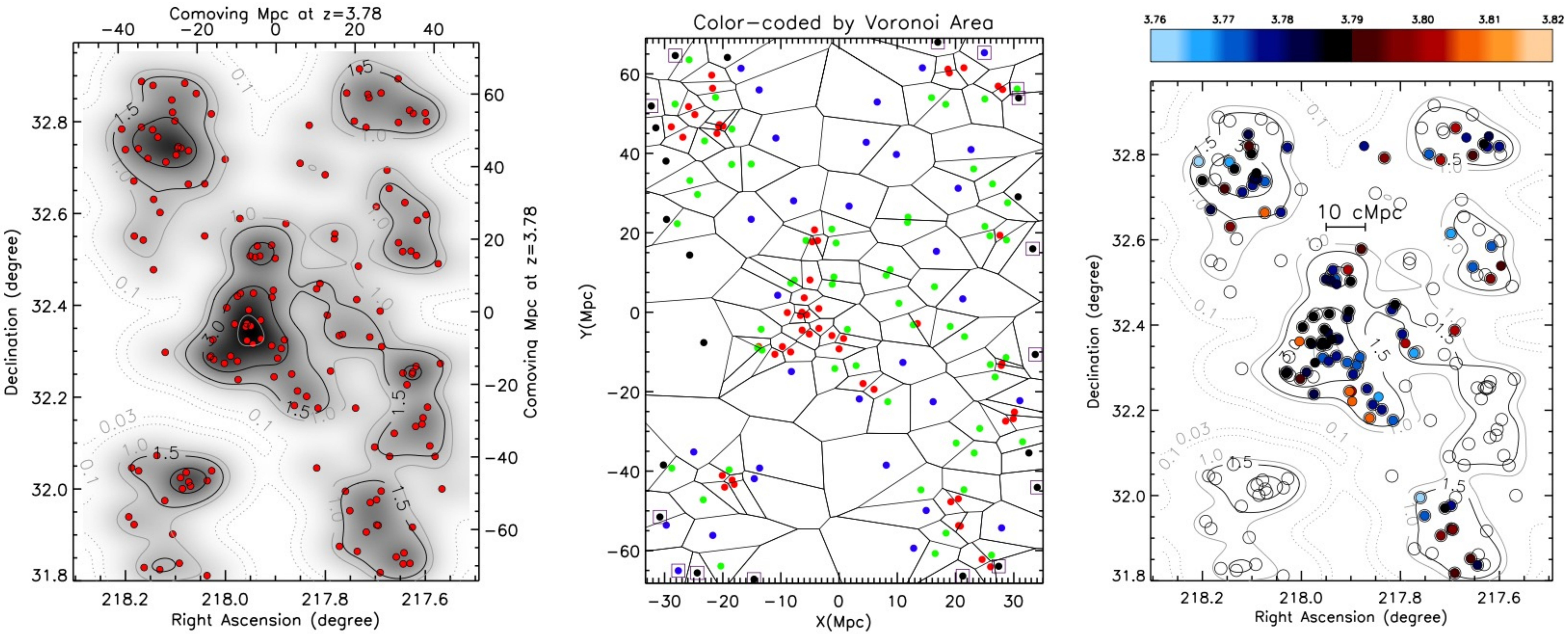


HST resolves ~half of LAEs;
Half-light radii <~2 kpc

SSA22 protocluster at Lyman alpha wavelength



Lyman Alpha imaging finds protoclusters!



Protocluster and surrounding large-scale structure at z=3.78 revealed as LAE overdensities

Left: LAEs (red) with gaussian smoothing (Lee et al. 2014)

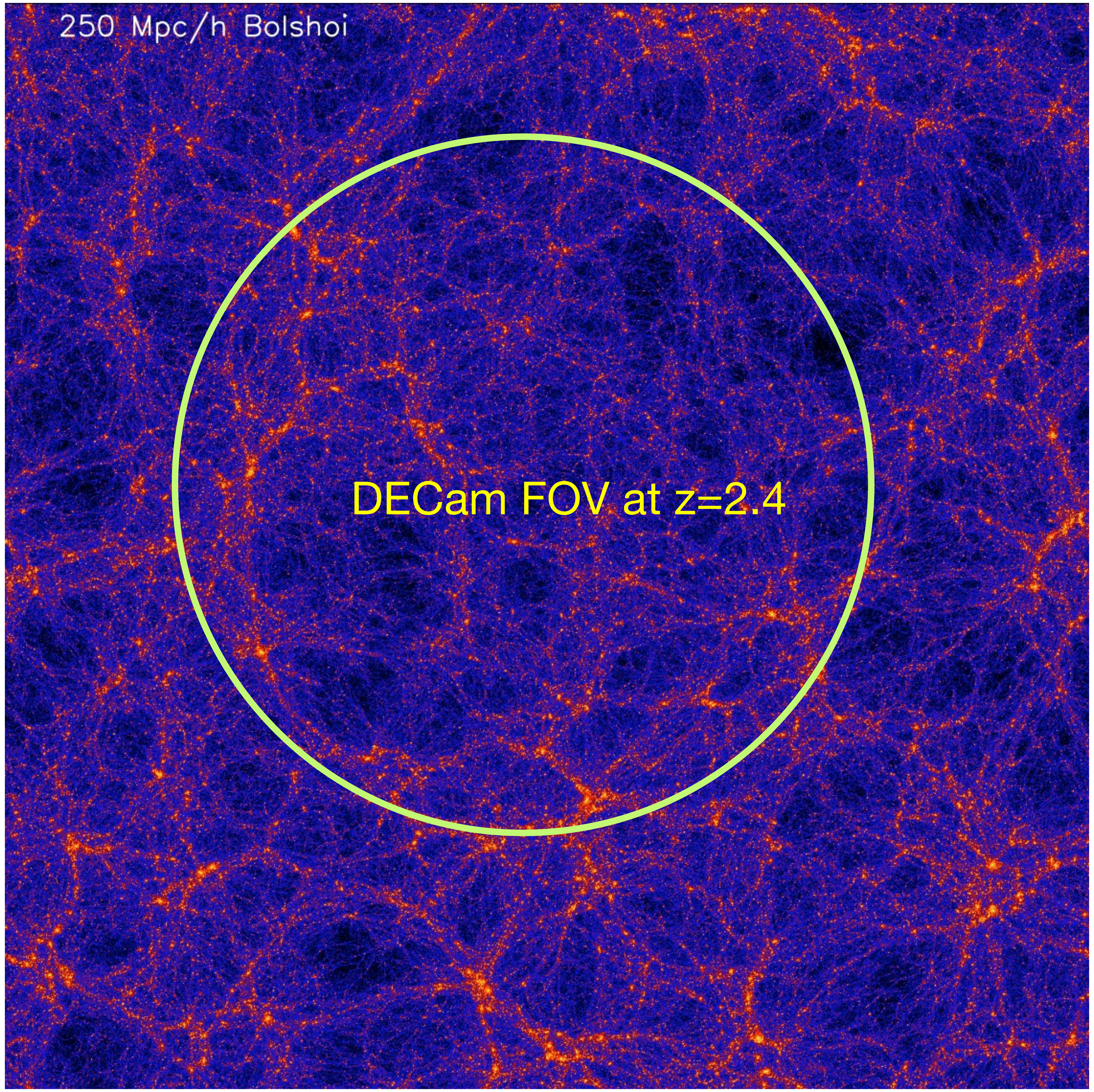
Middle: Voronoi tessellation to define environmental density

Right: Spectroscopic redshifts (Dey et al. 2016)

Lyman Alpha imaging finds nebulae (blobs)!

LAB in ODIN-COSMOS at z ~ 3.1 with 30×30 arcsec^2 images
Blob is detected in continuum-subtracted narrow-band image
(from Ramakrishnan et al. 2022, in prep)

The Dark Energy Camera (DECam) covers 3 square degrees, so even a single DECam pointing offers a good sample of LSS – no longer plagued by "cosmic variance"



ODIN (One-hundred deg^2 DECam Imaging in Narrowbands): Goals

1. Find largest samples yet of Lyman Alpha Emitting (LAE) galaxies at z=4.5,3.1,2.4 to study their clustering and star formation histories
2. Identify the largest ever sample of galaxy protoclusters as strong overdensities in the angular distribution of LAEs
3. Find largest samples of Lyman Alpha Nebulae (a.k.a. Lya Blobs) via diffuse emission

Built 3 custom narrow-band filters for the Dark Energy Camera centered at [419, 501, 673] nm with FWHM of [8,8,10] nm

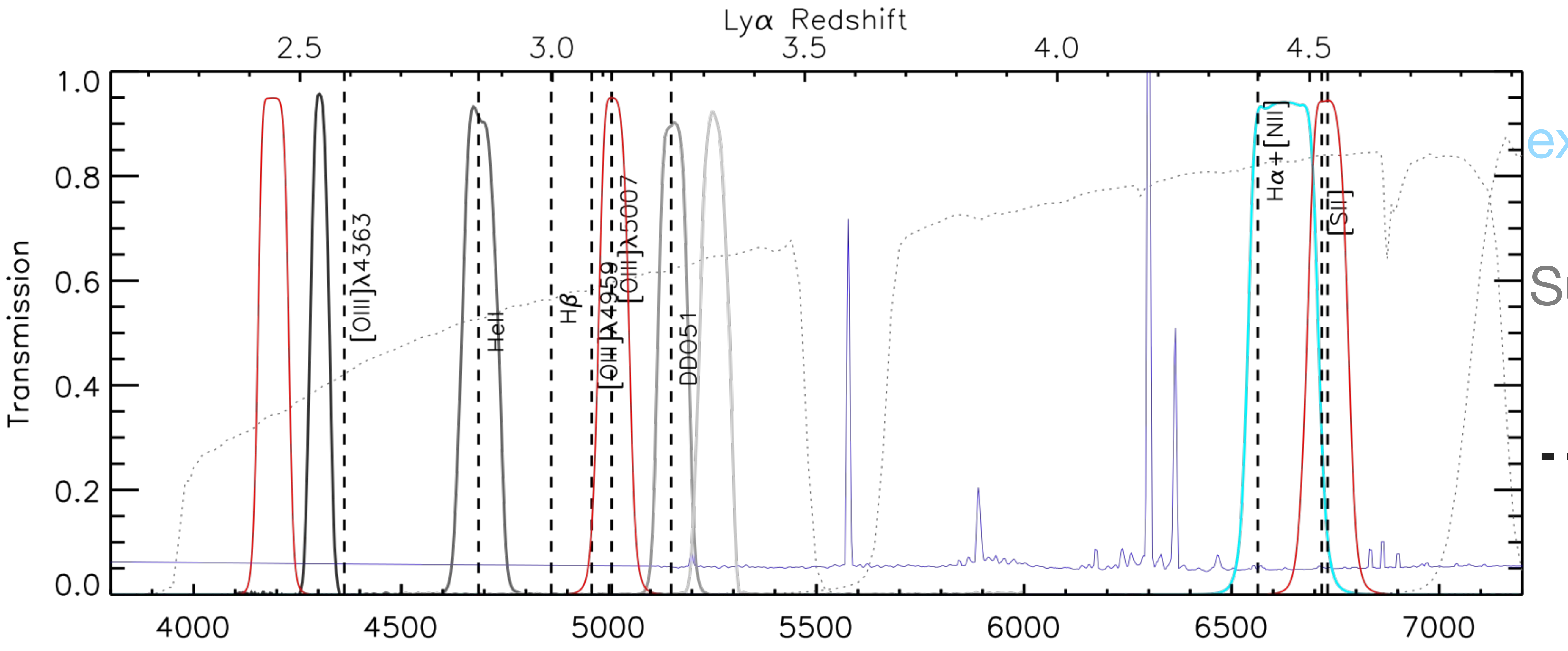
Just need 3 months of observing time on DECam…

ODIN

Awarded a NOIRLab Survey

PI Kyoung-Soo Lee (Purdue)

Council includes Eric Gawiser (Co-PI), Changbom Park (KIAS) & Yujin Yang (KASI)



existing DECam NB filter

new DECam NB filters

Subaru HSC NB filters

atmospheric emission

emission lines

ODIN: By The Numbers

Three cosmic time slices – z~4.5, 3.1, 2.4 (t_{age}=1.3, 2.0, 2.7 Gyr since BB) – with 3 narrow-band filters sampling peak epoch of cluster formation.

Image **91 deg^2** each with all 3 filters down to 25.5 AB (5σ, 2”) over **83** nights over 3 years (2021-2023)

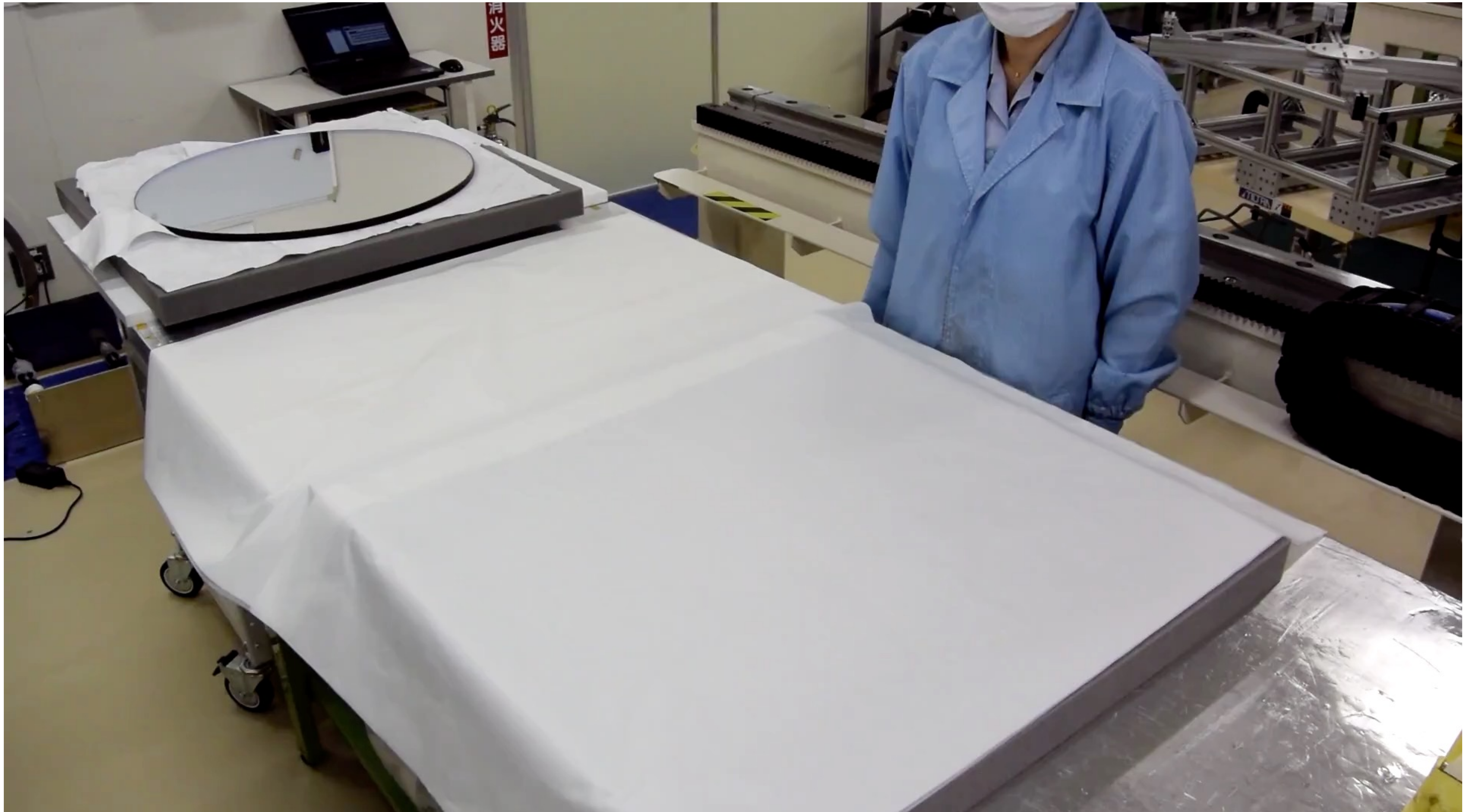
Seven deepest wide-imaging fields (in existence and upcoming):
four LSST Deep Drilling Fields, **two** Euclid Deep Fields, **three** SSP fields, and **one** HETDEX field.

The combined cosmic volume: **0.24 Gpc^3** (~70% of the Millennium sim)

>100,000 Lya-emitting galaxies (LAEs), **~45 Coma** progenitors, **~600** Virgo progenitors, and **~1,000** extreme Lya nebulae

ODIN: The Filters

Purchased from Asahi Ltd. (Japan) for $70K @



ODIN: The Fields

Table 3: Summary of Target Fields and Broad-Band Availability Timeline

Field	Coordinates (J2000)	Area [deg^2]	Pointing #	Visibility	Notable Facts
ELAIS-S1	00:37-44:00	10	4	Aug-Nov	DDF
SHELA	01:30-00:00	24	9	Sep-Nov	HETDEX, DESI access
XMM-LSS	02:22-04:45	10	4	Sep-Dec	DDF, SSP, DESI access
E-CDFS	03:32-28:06	10	4	Sep-Jan	DDF, EDF
EDF-S	04:10-48:10	20	7	Sep-Jan	EDF/SPHEREx DF
E-COSMOS	10:00+02:10	10	4	Jan-Mar	DDF, SSP, DESI access
Deep2-3	23:02+00:16	7	3	Jul-Oct	SSP, DESI access
Total	-	**91**	**35**	-	

LSST Deep Drilling Fields (DDFs)

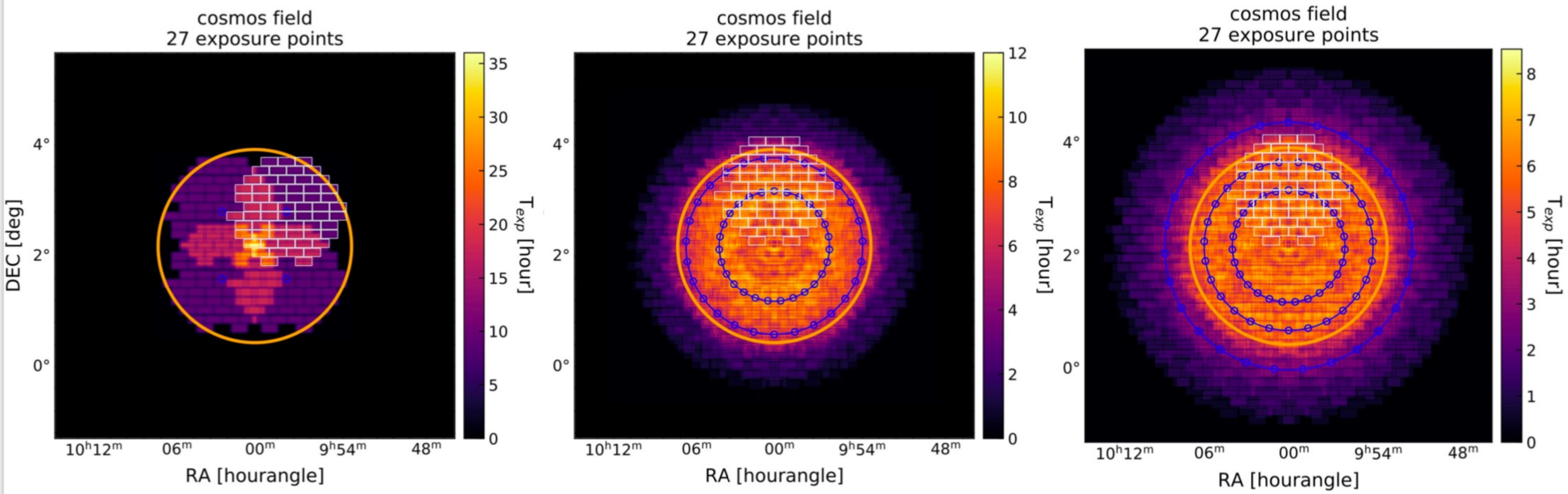
- XMM-LSS, E-COSMOS, ELAIS-S1, E-CDFS – and probably EDF-S
- LSST field-of-view (3.5 deg in diameter = 9.6 deg^2 in area) requires 4 heavily overlapping DECam pointings to cover
- SSP depth already sufficient for key science cases; DDF Y1 will already offer unprecedentedly deep broad-band imaging
- 3 DDFs covered (fully) to AB~23.1 in IRAC [3.5,4.8] by SERVS

	u	g	r	i	z	y
DDF Y1	26.7	27.9	28.1	27.4	26.6	25.3
DDF Y3	27.3	28.5	28.7	28.0	27.2	25.9
DDF Y5	27.6	28.8	29.0	28.3	27.5	26.2
DDF Y10	28.0	29.2	29.4	28.7	27.9	26.6
main Y10	26.3	27.5	27.7	27.0	26.2	24.9
SSP	27.1	27.5	27.1	26.8	26.3	25.3

ODIN: Pointings

Pointing strategy needed to achieve a ~uniform survey of LSST Deep Drilling Field circles using smaller DECam focal plane
After extensive simulations by Byeongha Moon & Yujin Yang, chose a 2-ring strategy:

Options

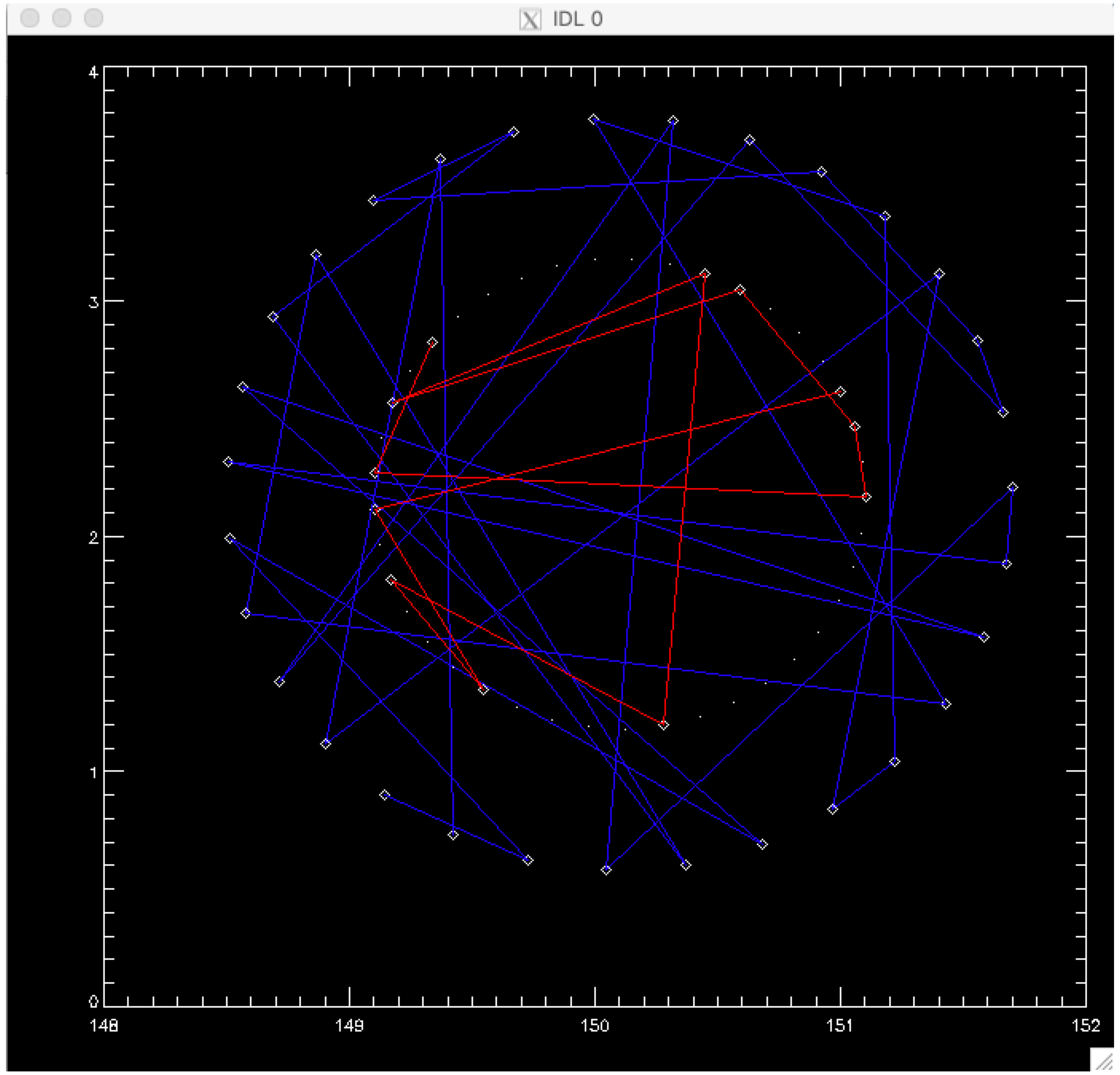


- **Option #1: 4 pointings with small dithers**
- **Option #2: two rings (27 dithers per ring)**
- **Option #3: three rings (27 dithers per ring)**

ODIN: Dithering

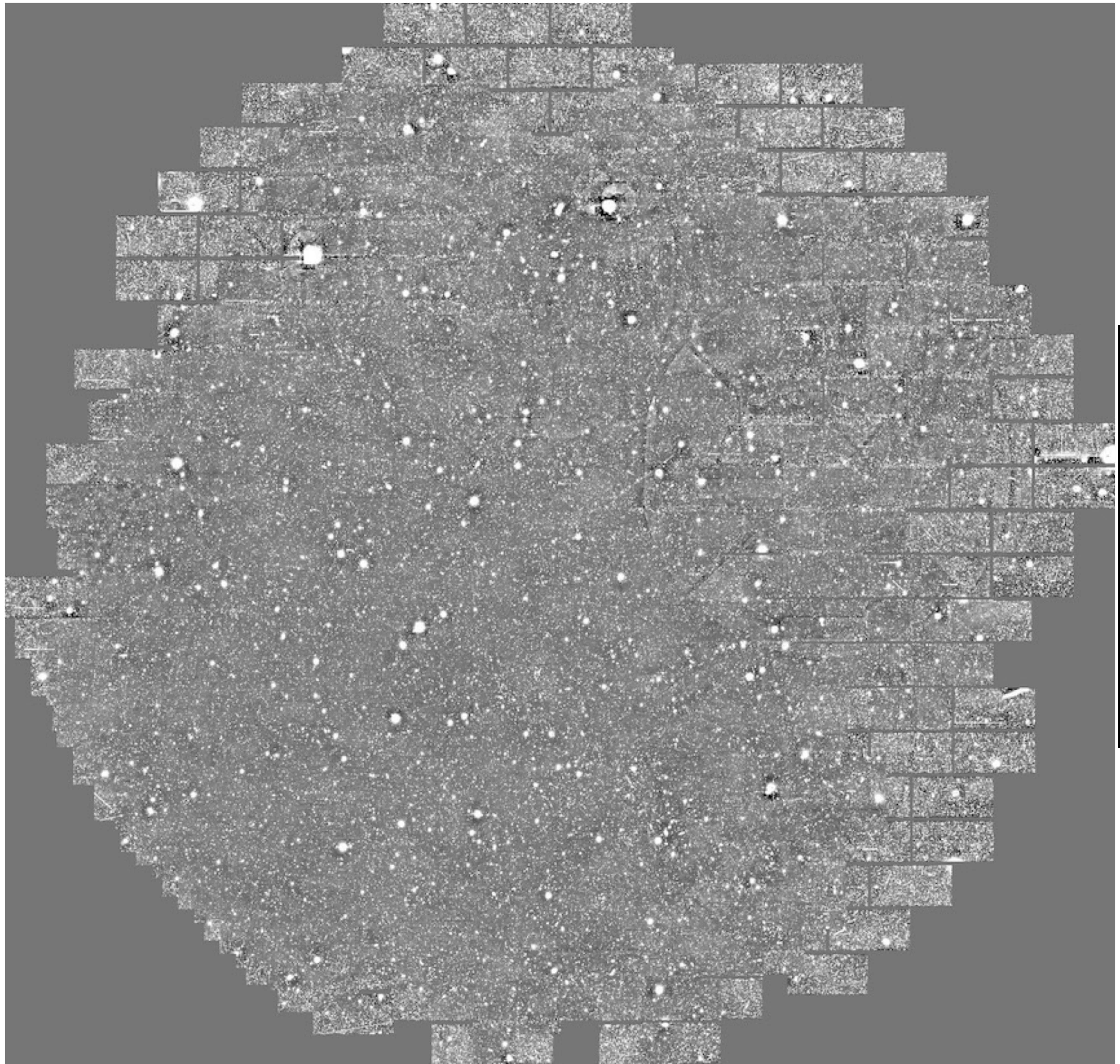
Track observations made each night and output updated scripts for following night

Move randomly on each ring to distribute observing conditions ~uniformly

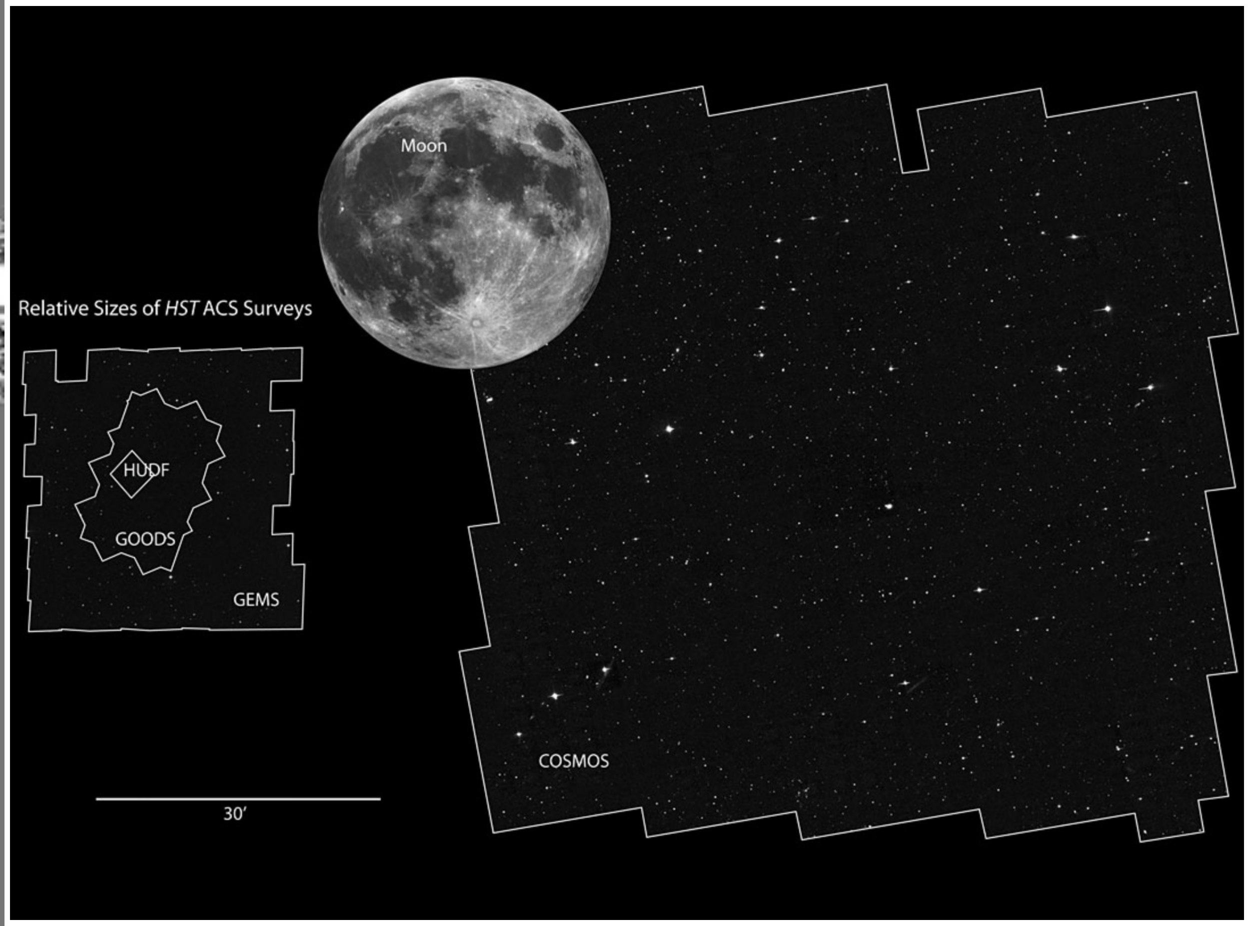


ODIN: Data Reduction

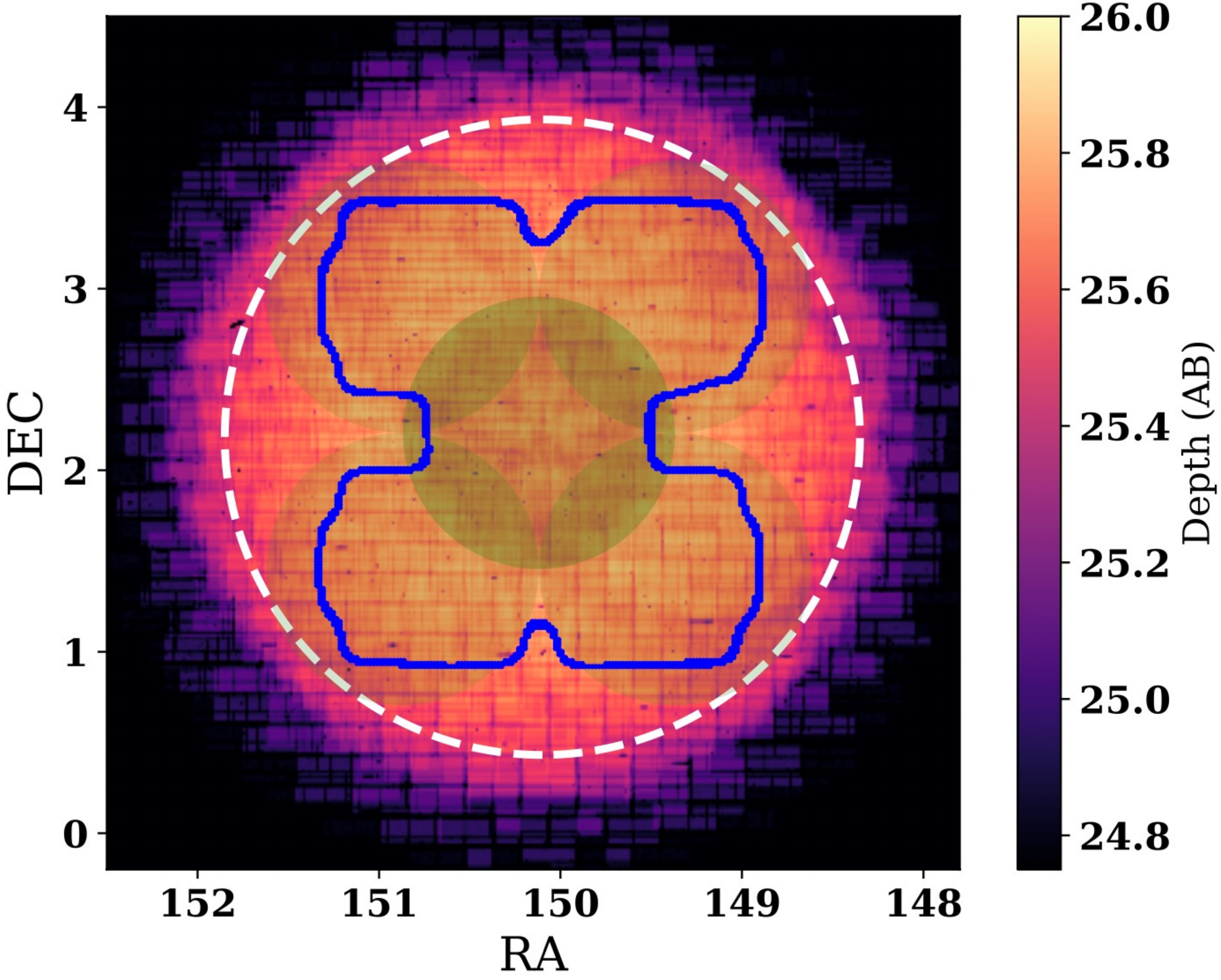
Initial nights of N501 data reduced with the DECam Community Pipeline –
thanks to Frank Valdez for heroic data reduction including CP pipeline improvements!



vs. public COSMOS HST image, to scale

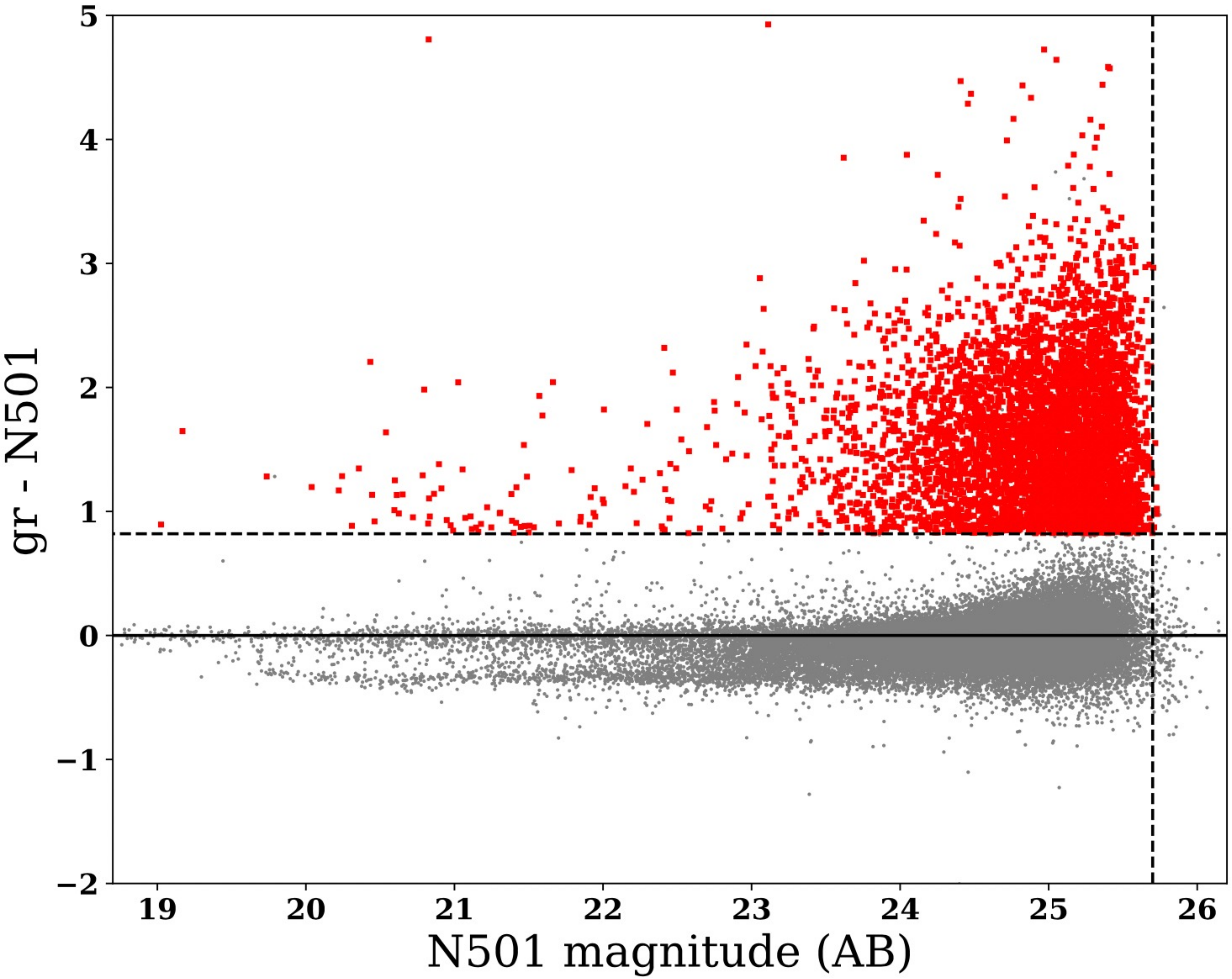


The First ODIN Field/Filter: COSMOS/N501



Green = 5 HSC-SSP pointings
Blue = CLAUDS u-band imaging
White = LSST DDF outline

z=3.1 LAE Selection in COSMOS/N501



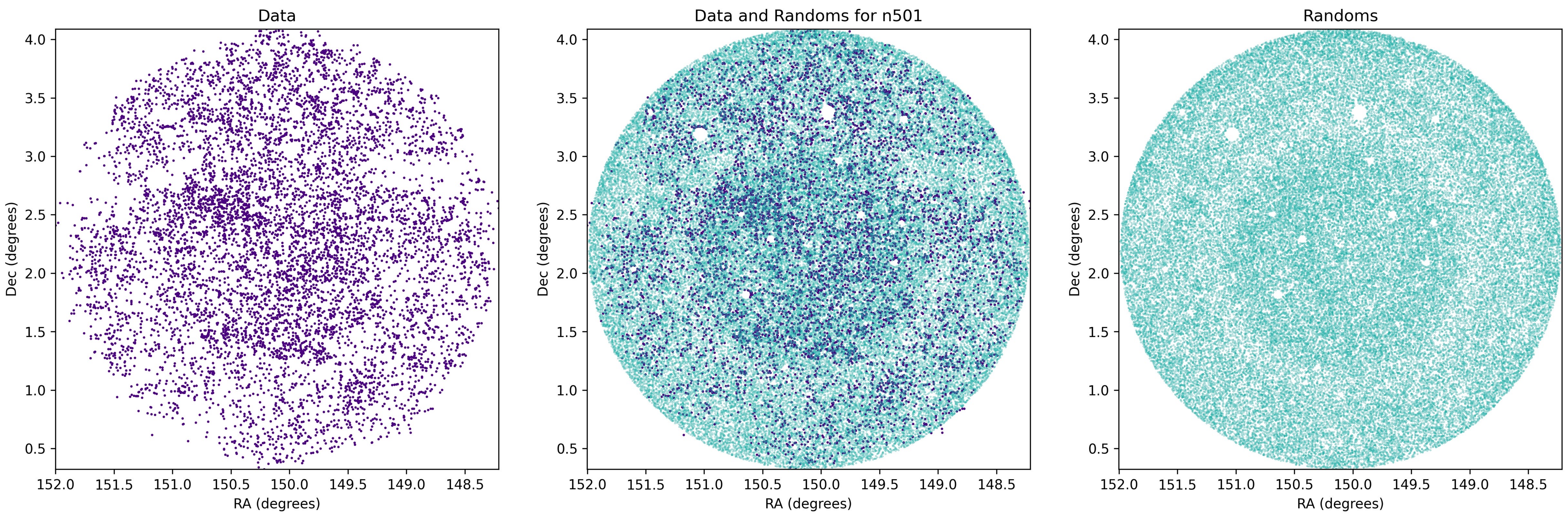
gr = continuum mag estimate formed from combined g,r photometry weighted to estimate 501 nm continuum

Red = 5352 LAE candidates selected via excess flux density in narrow-band

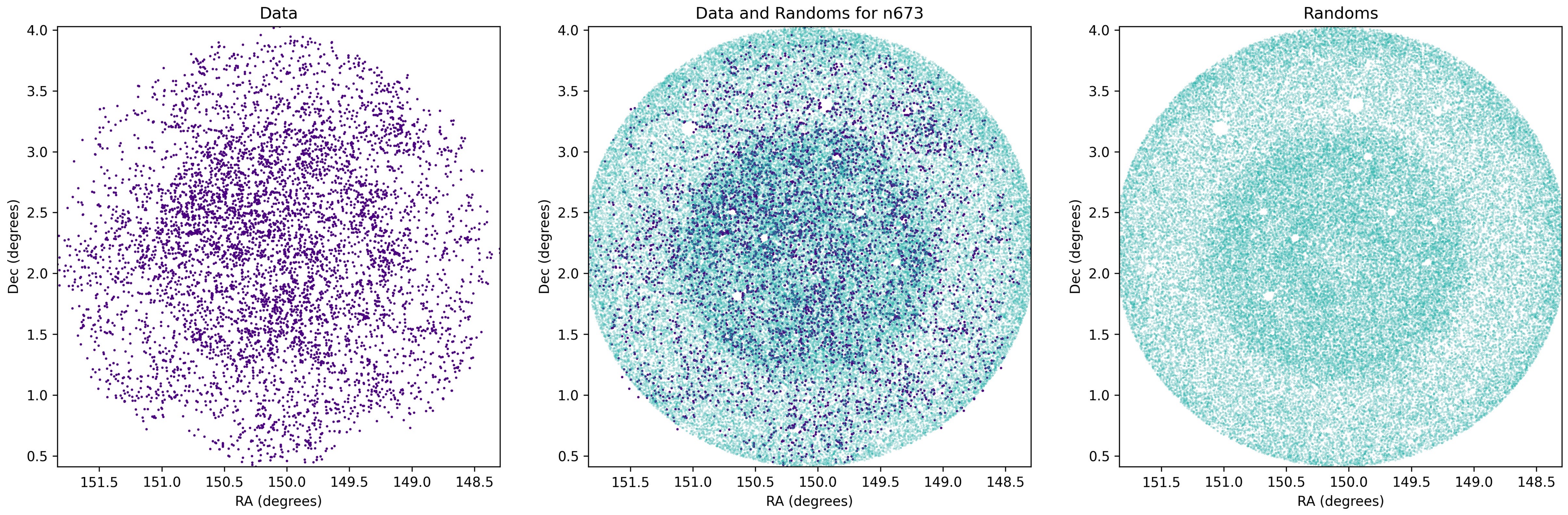
Grey = N501-detected catalog (sub-sampled for display)

Sky distribution of data and randoms at z=3.1 & z=4.5

z=3.1 LAE candidates selected by UG student Rameen Farooq



z=4.5 LAE candidates selected by REU student Shreya Karthikeyan



Angular Cross-correlation Function

$$dP_{12} = (1 + w_{12}(\theta))\ \eta_1\eta_2\ d\Omega_1 d\Omega_2$$

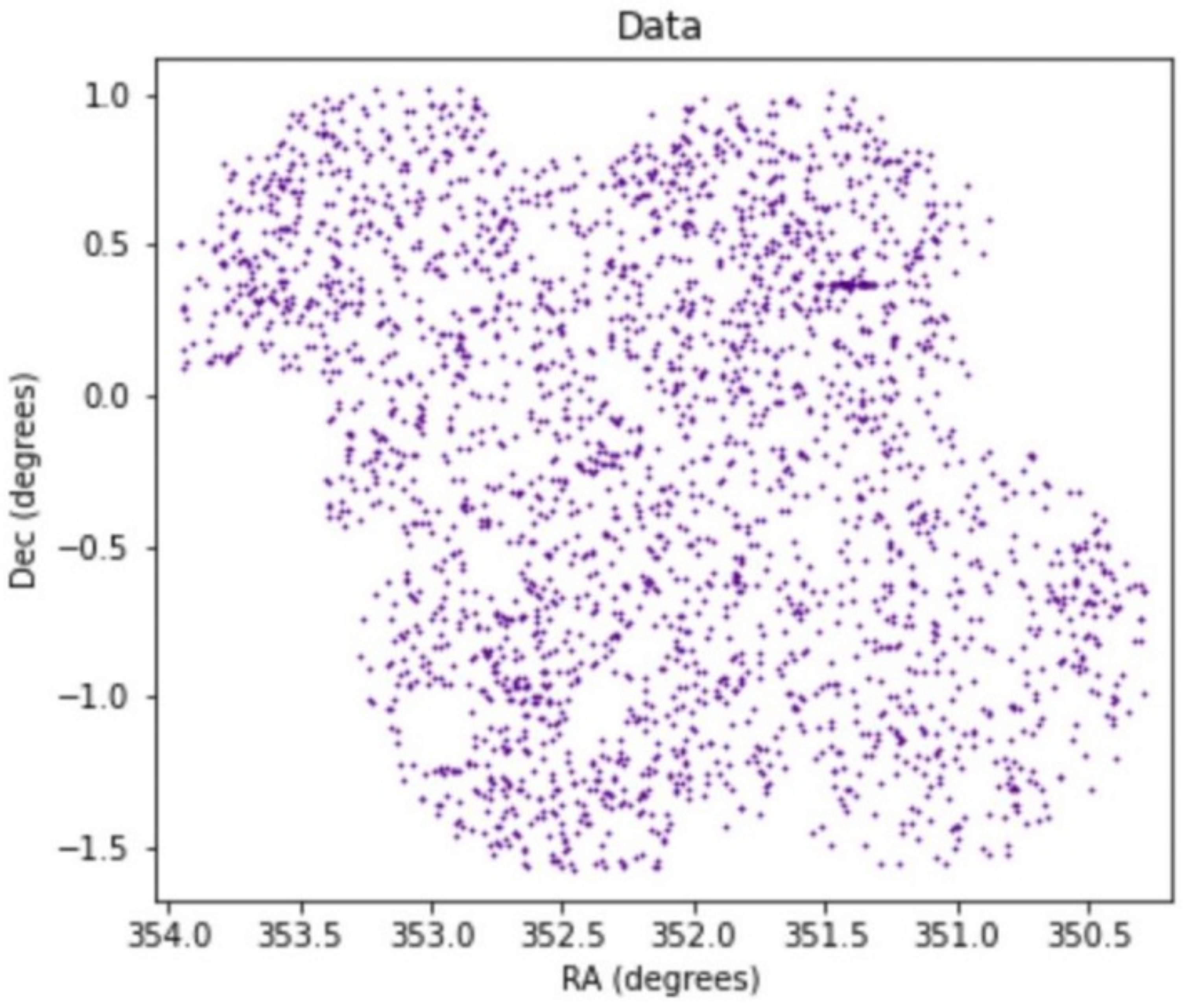
Probability of finding a galaxy of type 1 and a galaxy of type 2 separated by θ
given the sky density of each type and small bits of solid angle

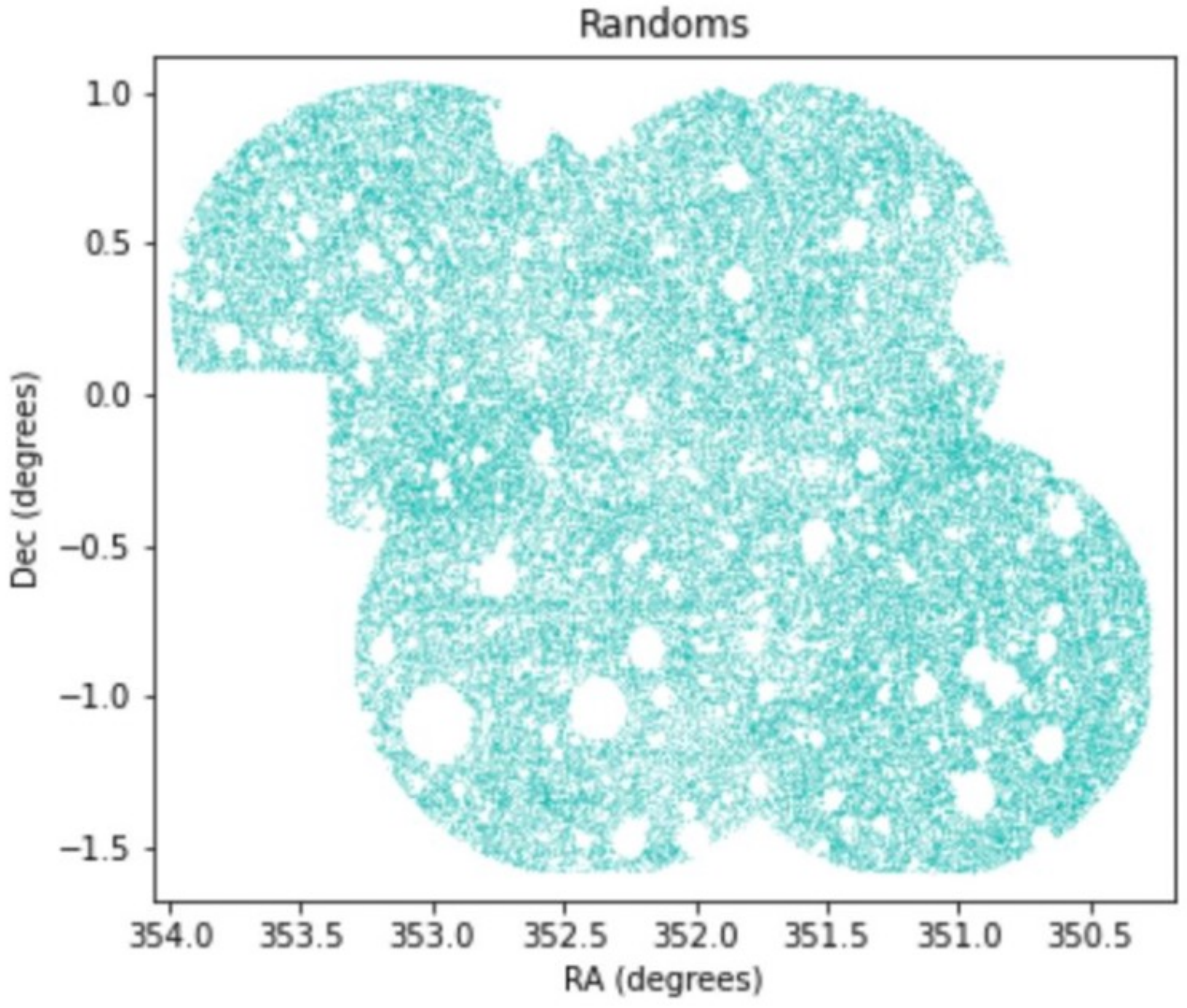
The Landy-Szalay Estimator

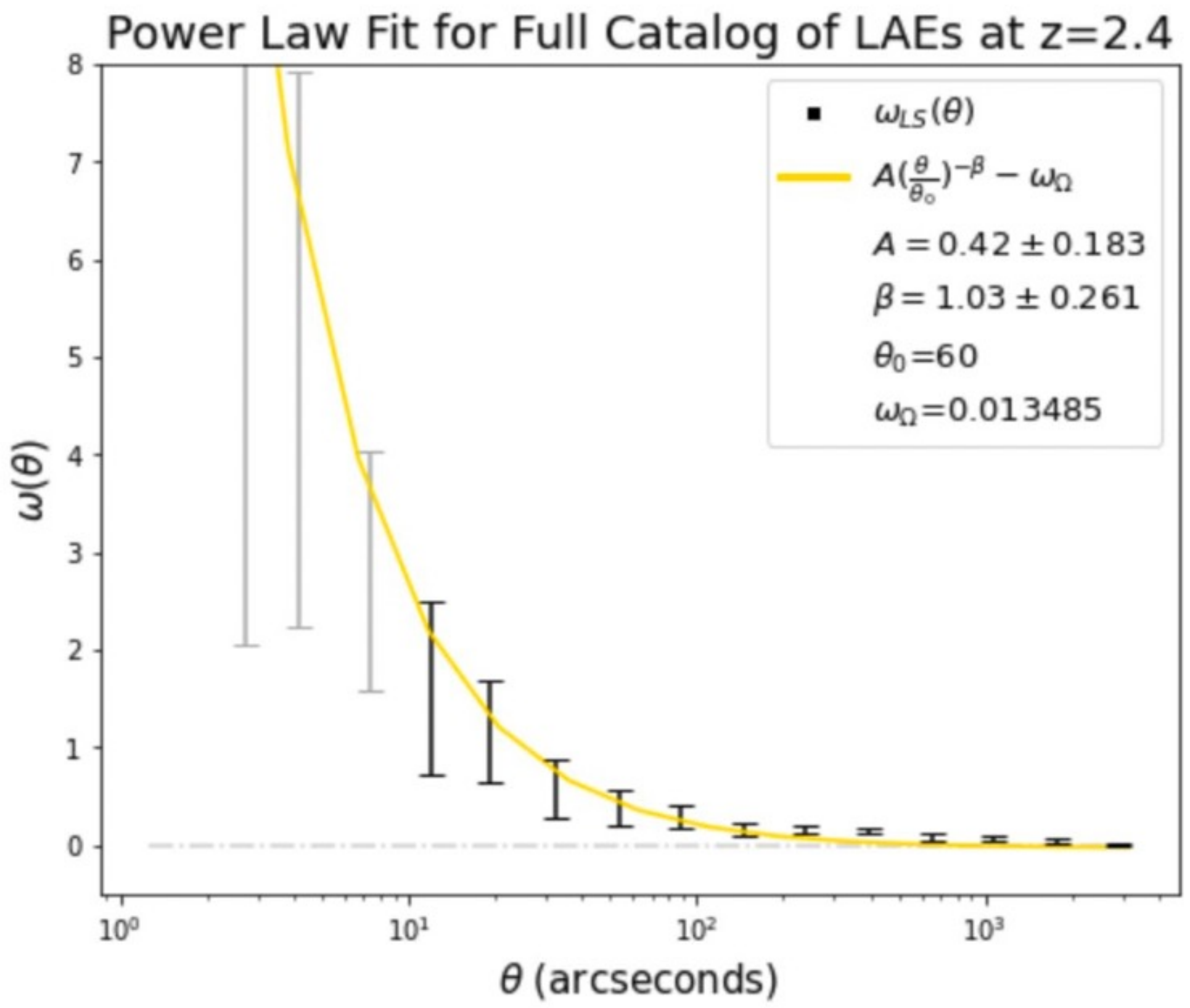
$$w(\theta) = \left(\frac{D-R}{R}\right)\left(\frac{D-R}{R}\right) = \frac{DD - 2DR + RR}{RR}$$

DD = Data pairs histogram, DR = Data-Random pairs histogram,
R=Random pairs histogram, those all depend on θ

Sky distribution of data and randoms at z=2.4







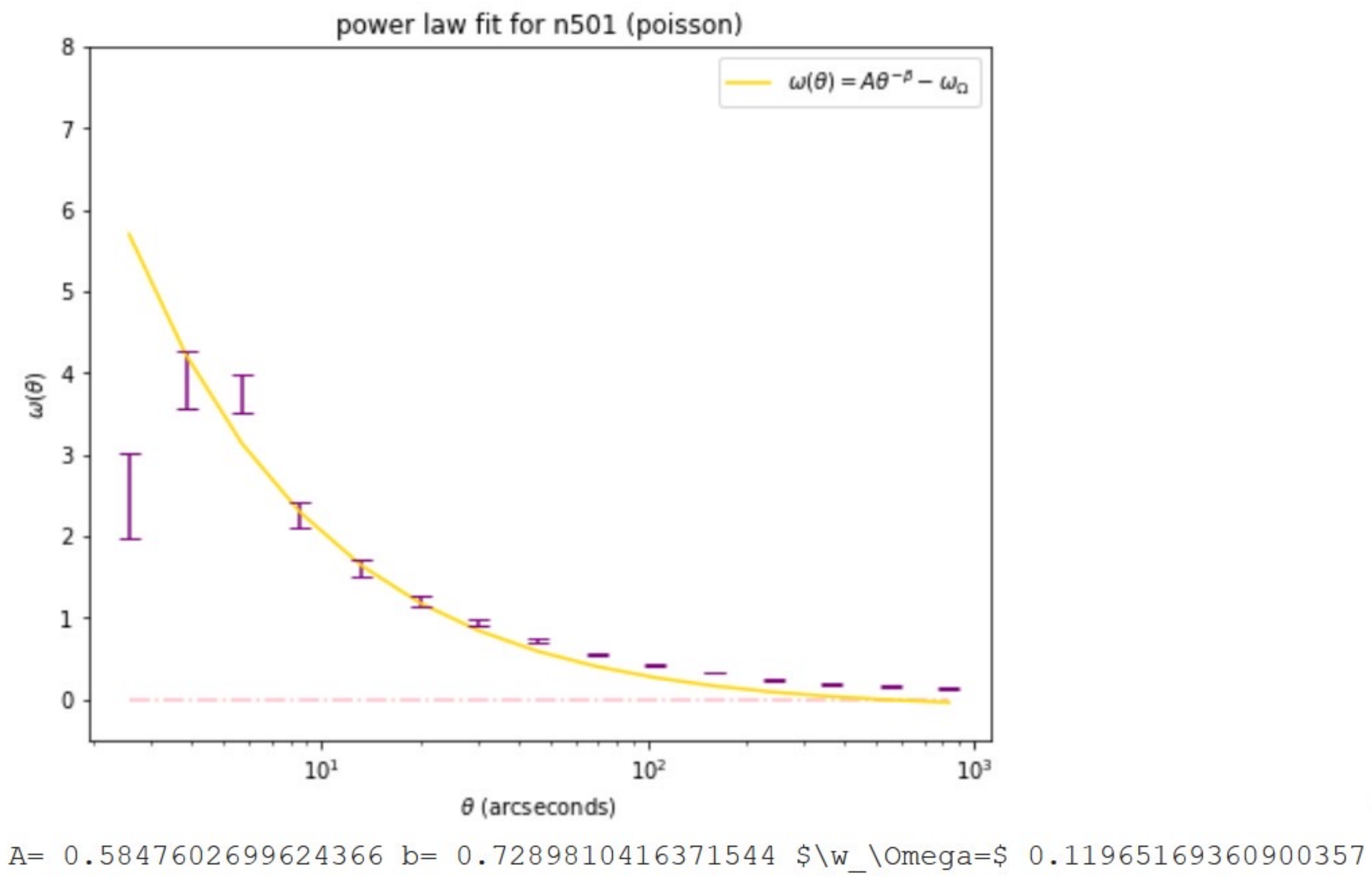
z=2.4 LAE candidates in Deep2-3/N419 image selected by grad student Nicole Firestone

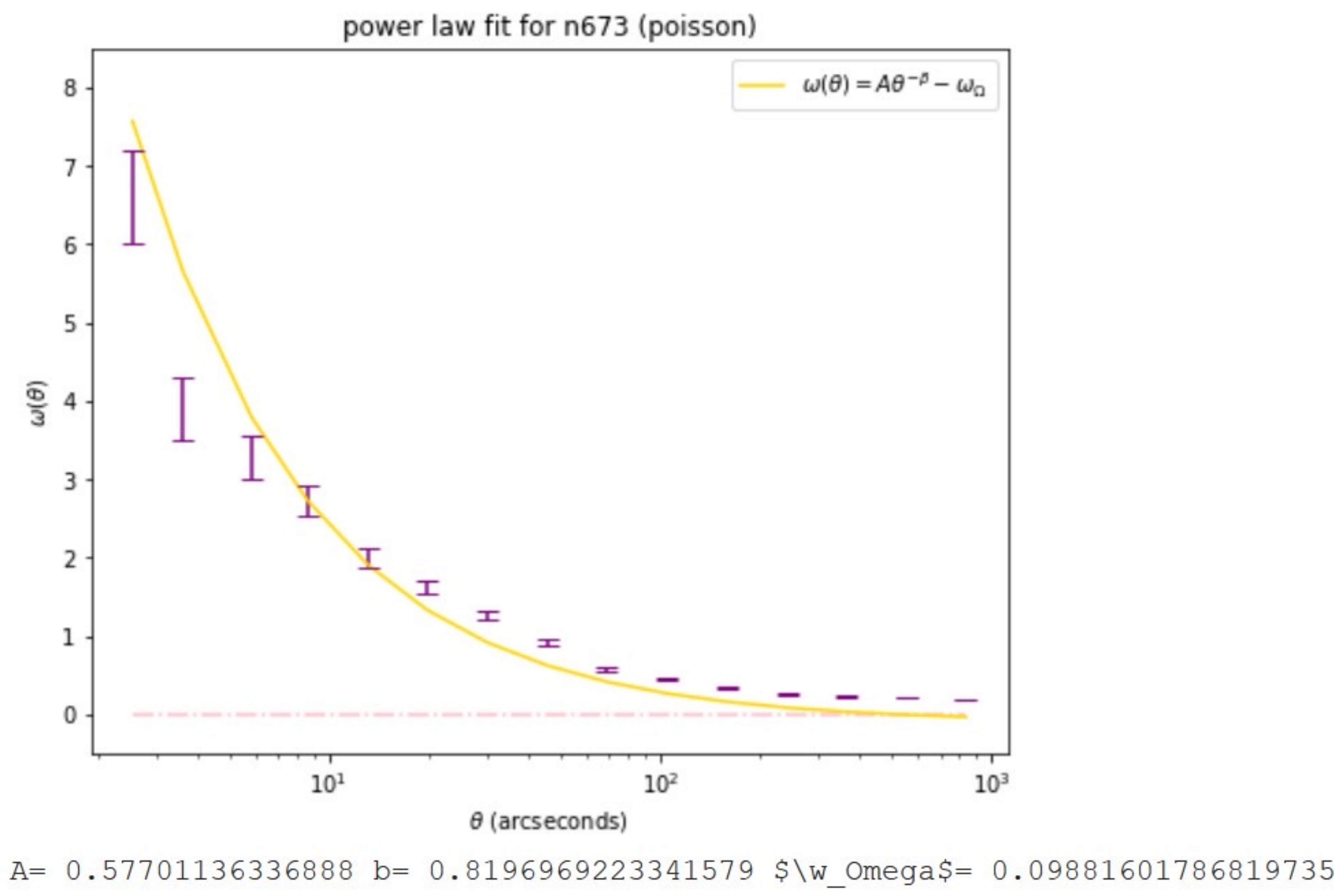
Random catalog, including star-mask, made by UG student Barbara Benda

z=2.4 LAE angular correlation function calculated by Barbara Benda

Angular correlation functions at z=3.1 & z=4.5

z=3.1



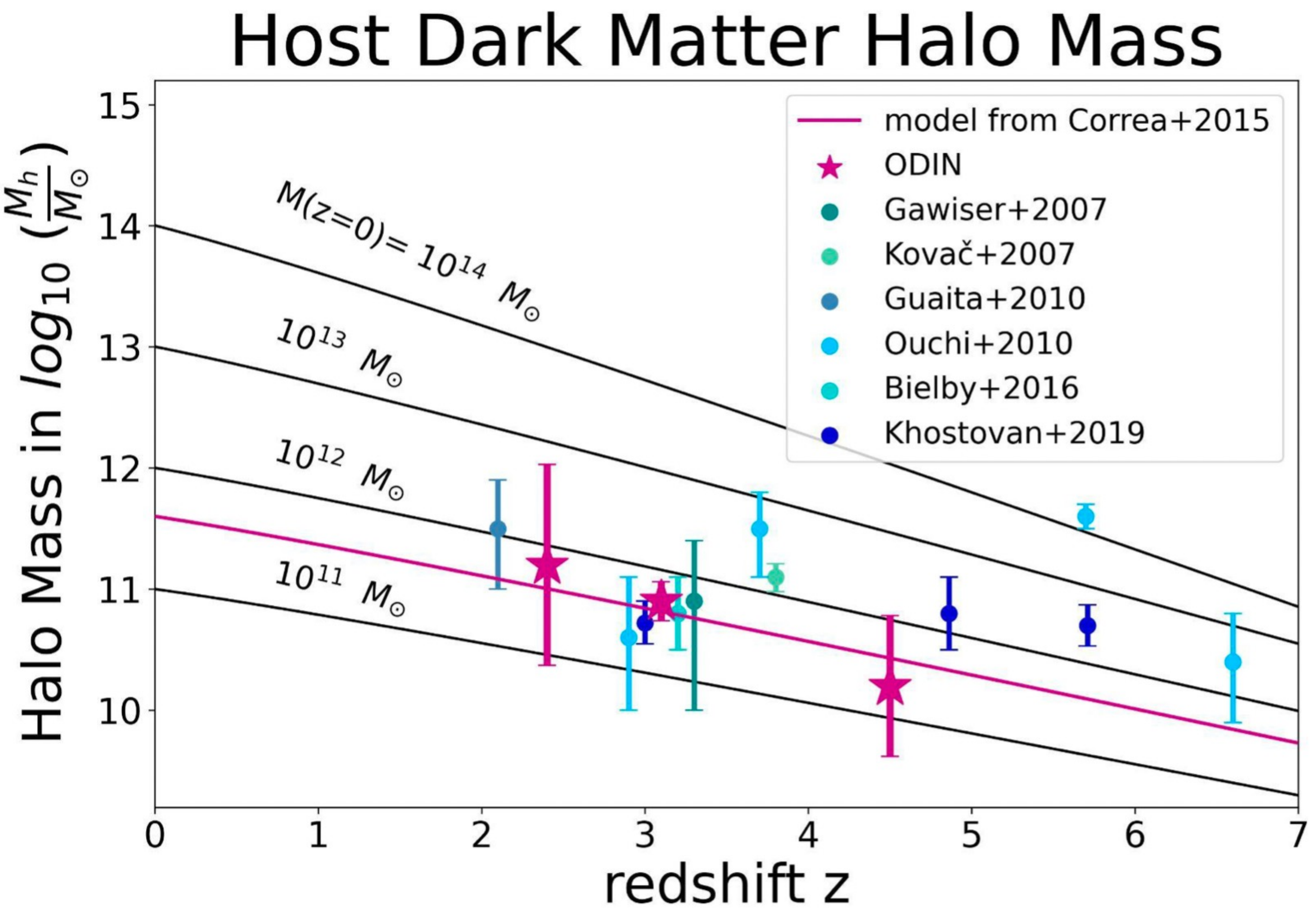


z=4.5

Intriguing features at small separation in the “one-halo” regime
Unexplained power at larger separation is a systematic

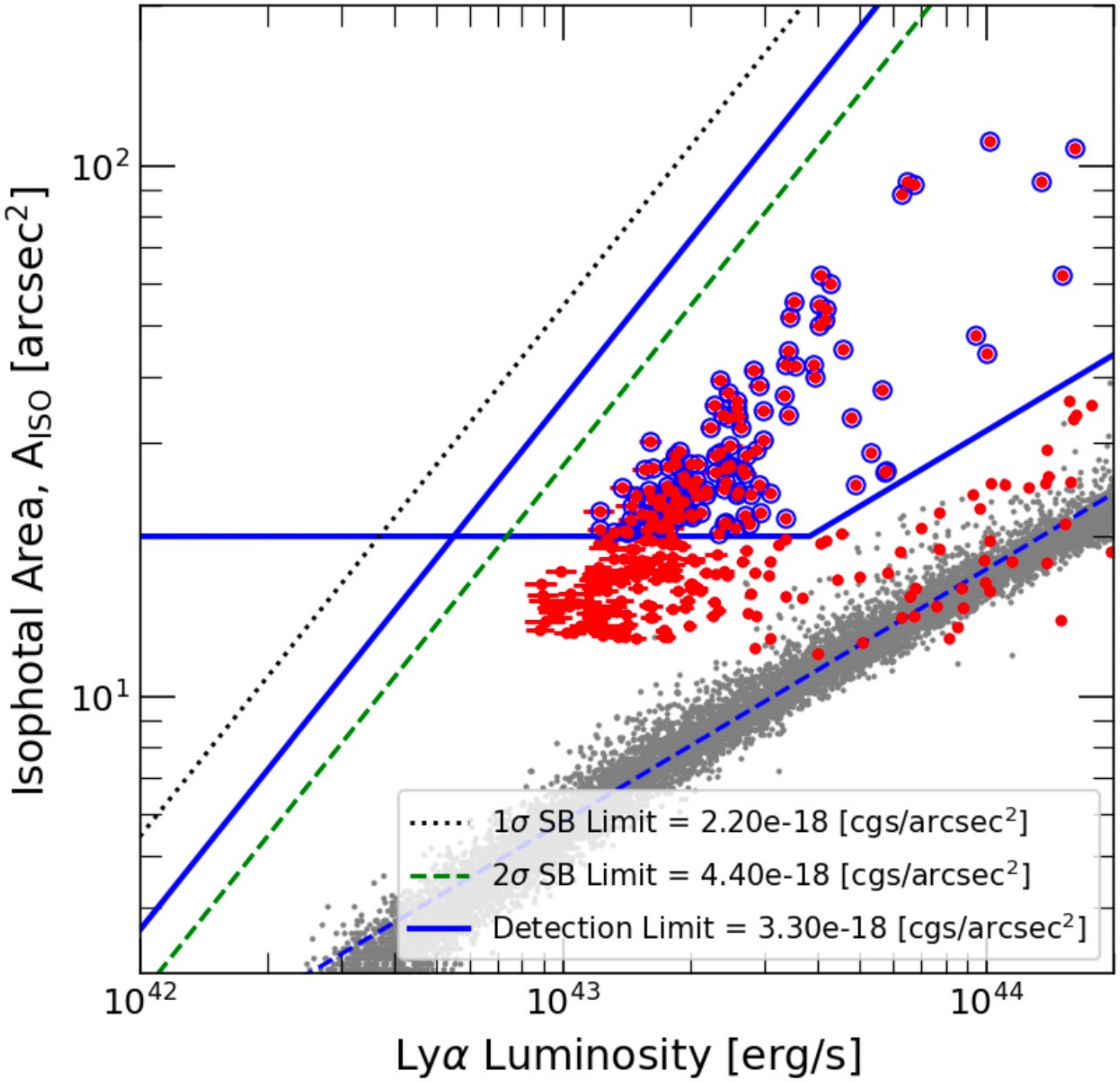
From Barbara Benda’s senior honors thesis

Evolution of LAE halo mass



Preliminary ODIN results for LAE halo mass evolution are comparable with literature results. Uncertainties should shrink by 3-10X when the survey is complete!

z=3.1 Lyman Alpha Blob (LAB) Selection in COSMOS/N501

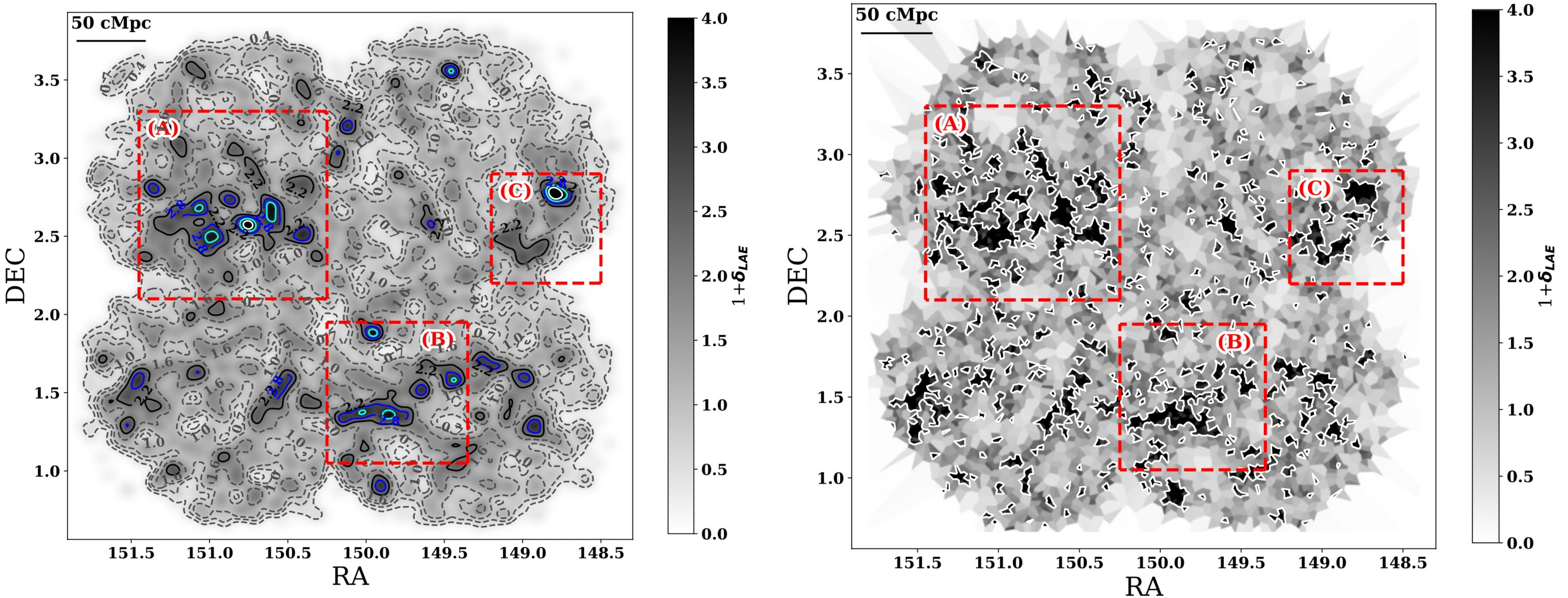


Blue-around-red = 129 LAB candidates selected above the solid blue curve based on isophotal area and distance from the blue-dashed relation for simulated point sources (gray)

A statistical sample of Lyman Alpha Blobs!

from Ramakrishnan et al. 2022, in prep

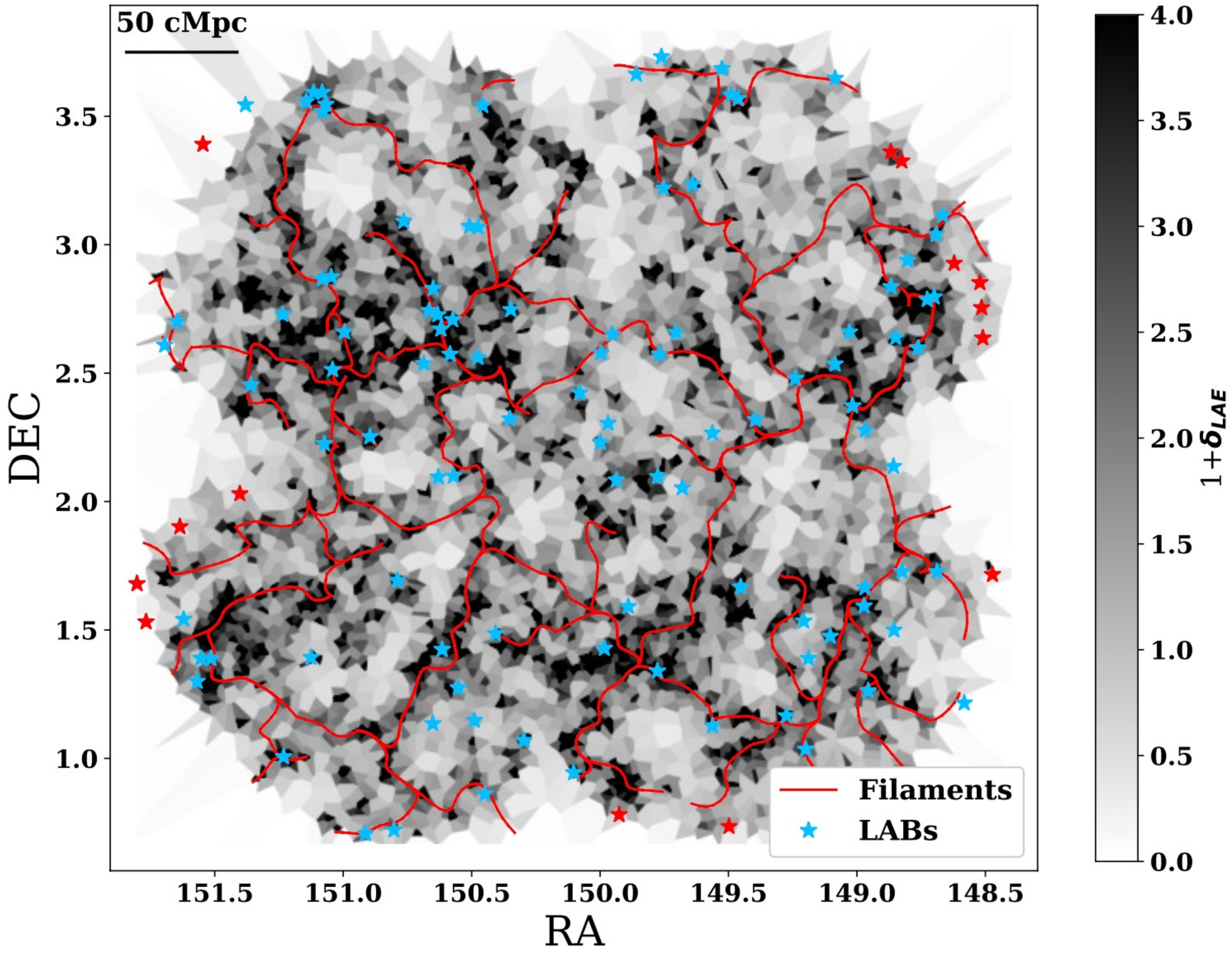
z=3.1 Protoclusters in COSMOS/N501



Gaussian smoothing (left) and Voronoi tessellation (right) yield several overdensities concentrated in three regions worthy of follow-up spectroscopy

from Ramakrishnan et al. 2022, in prep

z=3.1 LABs and Filaments in COSMOS/N501



DISPERSE (Sousbie+11) finds filaments (red)
LABs (blue stars) typically fall on or near a filament!

from Ramakrishnan et al. 2022, in prep

More LAE Science: Spectral Energy Distribution (SED) fitting

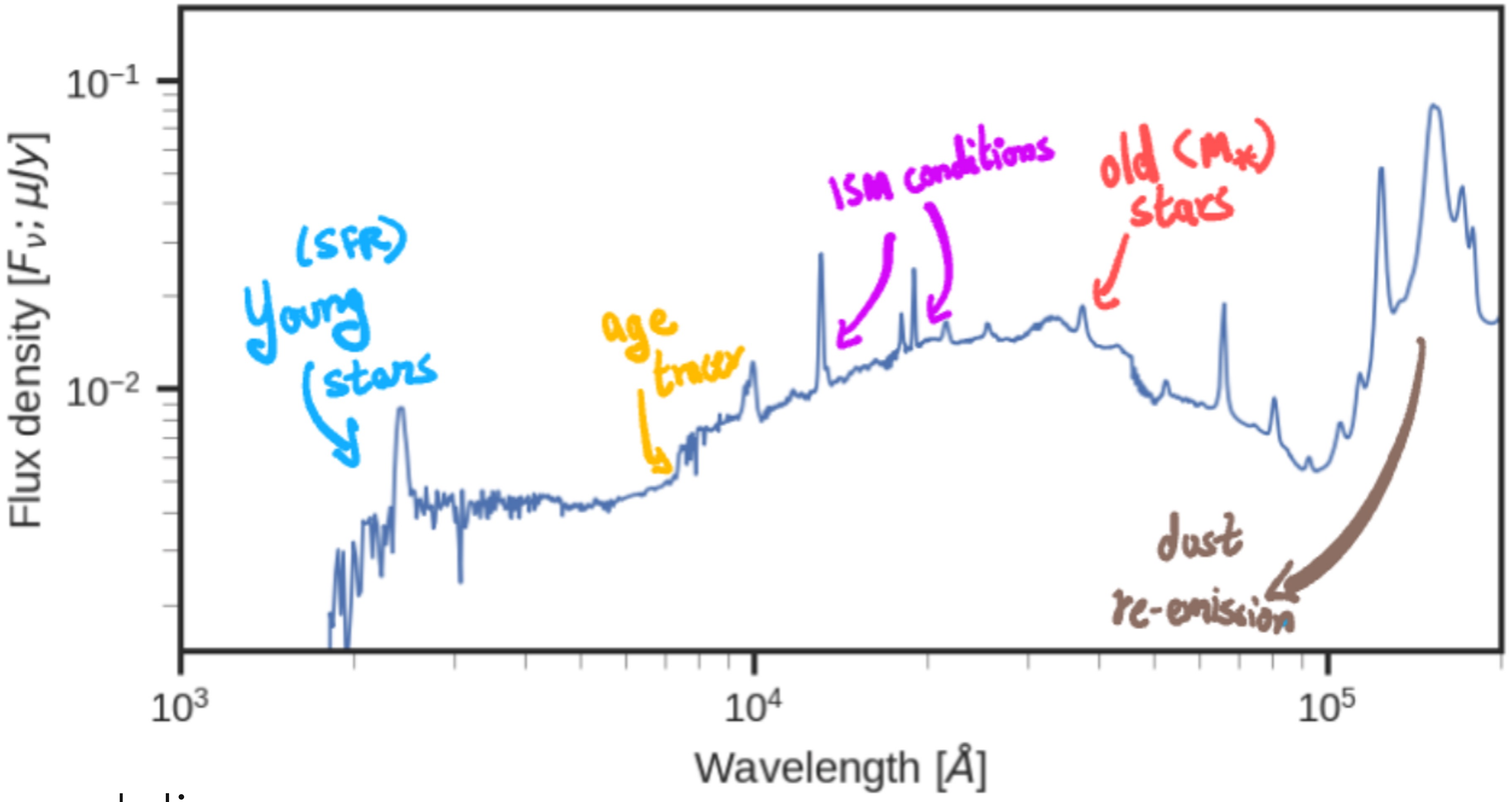
Use UV-through-near-IR broadband photometry of >100 LAEs in CANDELS fields for Star Formation History (SFH) reconstruction (Pacifici+12, Iyer+19, Leja+19), which yields more accurate regular SED parameters (Iyer & Gawiser 17).

Identify fraction of LAEs that are experiencing their first starburst!

Spectral Energy Distribution fitting

The integrated light from galaxies contains a lot of information about their present and past.

- Redshift (z)
- Stellar mass (M_*)
- Star Formation Rate (SFR)
- Chemical abundances (stars and ISM gas)
- Dust properties
- AGN properties

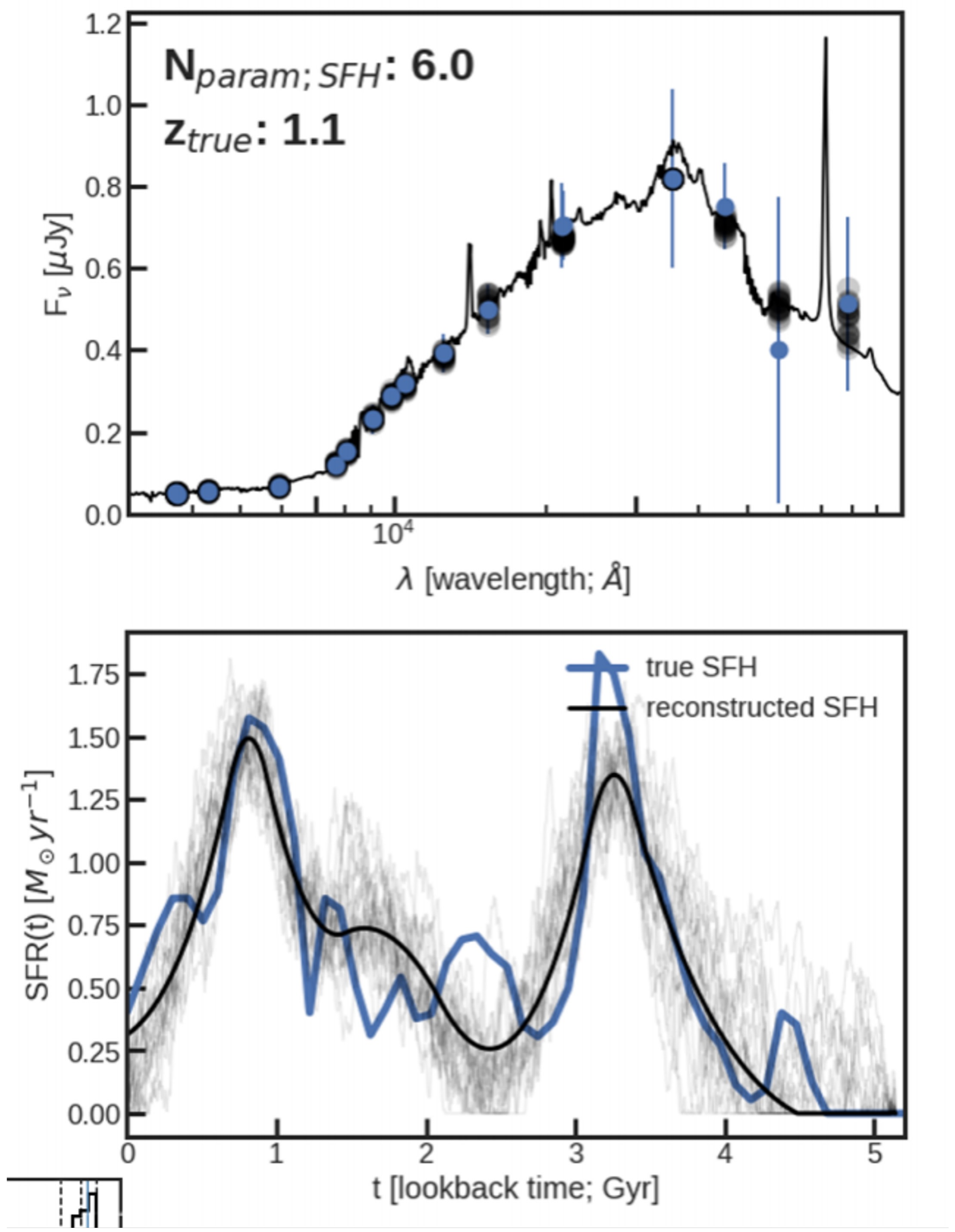


We infer these properties by forward-modeling SEDs using stellar population synthesis models (stellar tracks and isochrones)

Slide from Kartheik Iyer

Dense Basis:
Describe SFH with a tuple:
(M_*, SFR, [tx])

In Spectral Energy Distribution space, fit for SFH parameters simultaneously with models for dust, metallicity, redshift, nebular emission, IGM absorption, etc.



Full posteriors

Iyer et al. 19, ApJ 879, 116

Recent discovery enabled by Dense Basis star formation history reconstruction:

Star Formation Histories from Spectral Energy Distributions and Color Magnitude Diagrams Agree: Evidence for Synchronized Star Formation in Local Volume Dwarf Galaxies over the Past 3 Gyrs

THE ASTROPHYSICAL JOURNAL

Star Formation Histories from Spectral Energy Distributions and Color–magnitude Diagrams Agree: Evidence for Synchronized Star Formation in Local Volume Dwarf Galaxies over the Past 3 Gyr

Charlotte Olsen[1], Eric Gawiser[1], Kartheik Iyer[2], Kristen B. W. McQuinn[1], Benjamin D. Johnson[3], Grace Telford[1], Anna C. Wright[4], Adam Broussard[1], and Peter Kurczynski[5]

Published 2021 May 24 •

The Astrophysical Journal, Volume 913, Number 1

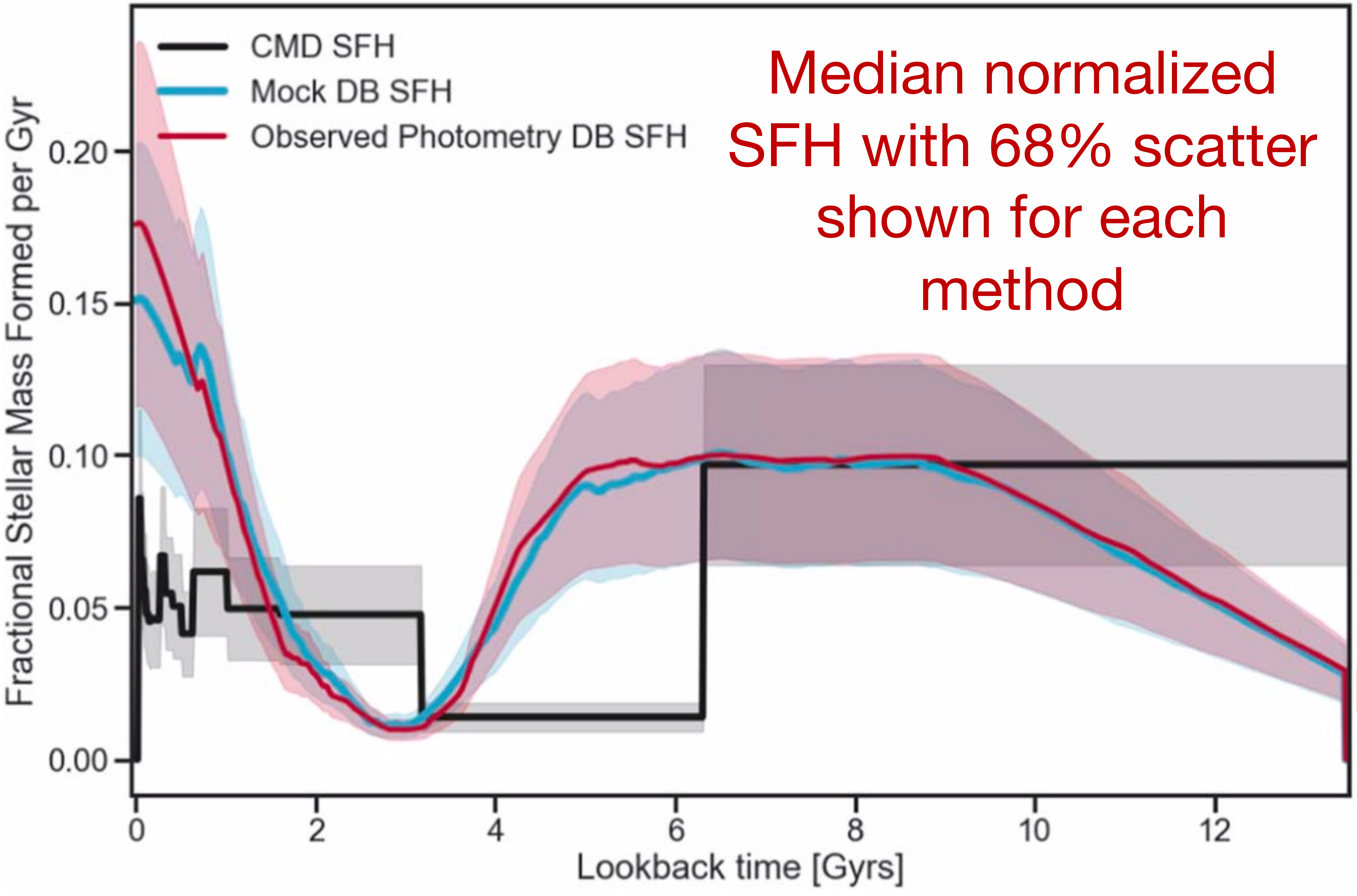
Citation Charlotte Olsen *et al* 2021 *ApJ* **913** 45

Charlotte Olsen

Advisor: Prof. Eric Gawiser

Rutgers University, New Brunswick, NJ

Dense Basis & CMD SFHs for ANGST Dwarf Galaxies at <4 Mpc



From Olsen+21, ApJ 913, 45

Found a ~1 Gyr systematic offset, but **methods agree that SFR declined 4-6 Gyr ago and was rejuvenated 2-3 Gyr ago**.

Such **large-scale coordination NOT predicted by galaxy formation models!**

An unexpected connection with popular culture

From Dr. Who, Season 13, Episode 6

Conclusions

- ODIN is using DECam to obtain unprecedented samples of LAEs, LABs, and protoclusters in 7 well-studied fields
- ODIN Early Science involves state-of-the-art analyses of the spatial clustering of these objects, including cross-correlations, as well as LAE star formation histories
- Stay tuned!
- Official conference motto?

"The Dark Energy Camera facility developed here by the humans is way beyond adequate for our purposes."