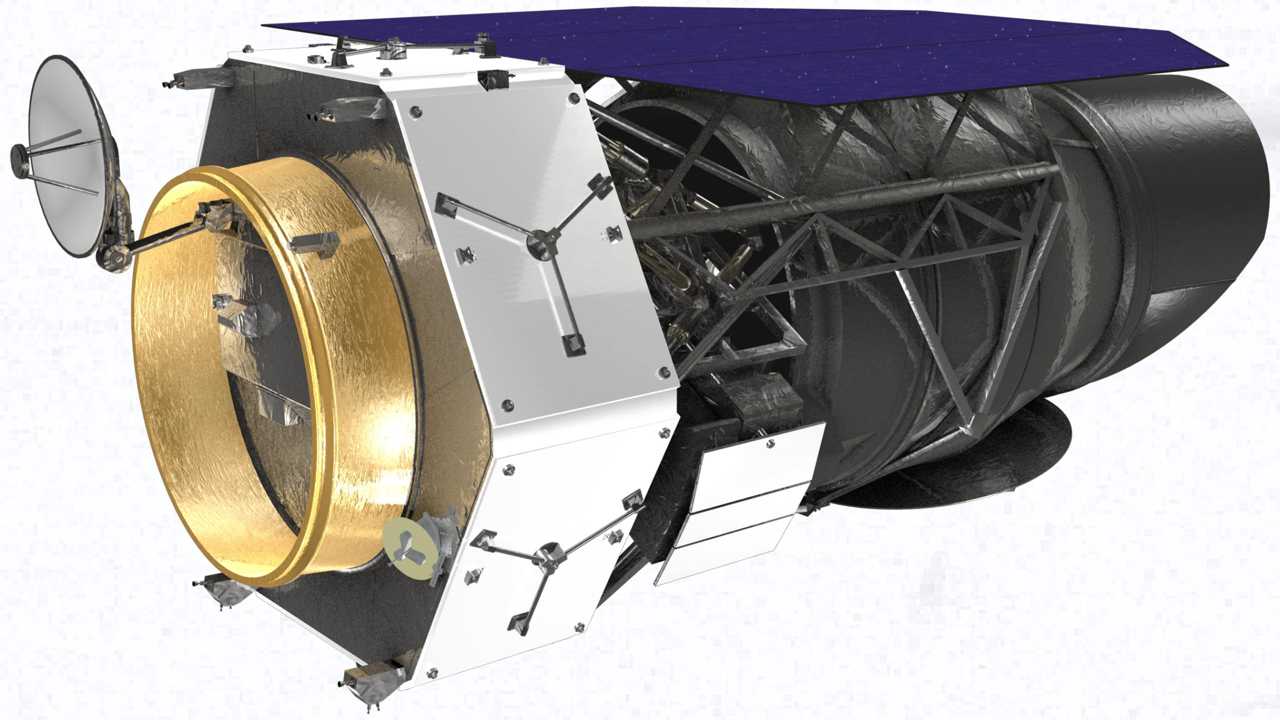
Galaxy Formation & Evolution in the WFIRST Era:

From Census to Synthesis of the Lifecycles of Galaxies



Kate Whitaker

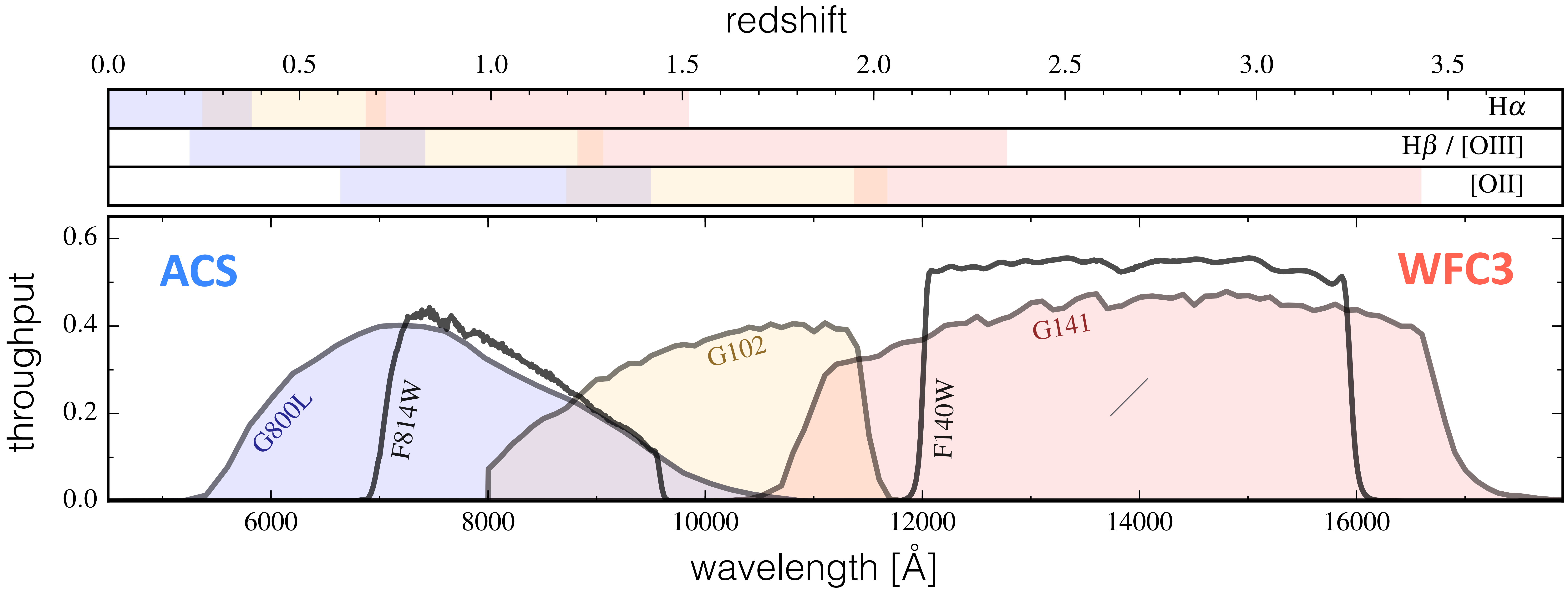
Assistant Professor
University of Connecticut
www.whitaker.physics.uconn.edu

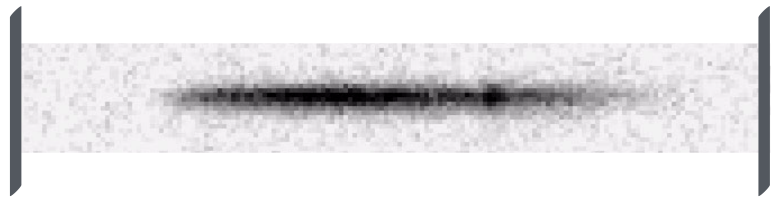
z~1.3
z~1.4
z=0
z=11.1!
z~0.3
z~2
z~1.4

Wide-field slitless surveys at z=1-2:

- Large, uniform, roughly **unbiased samples**
- **Spatially-resolved line diagnostics** @ HST resolution
- **Accurate redshifts** ($\Delta z/(1+z)$ ~ 0.003): large scale structure & stacking analyses

Near-Infrared Spectroscopic Surveys with the Hubble Space Telescope





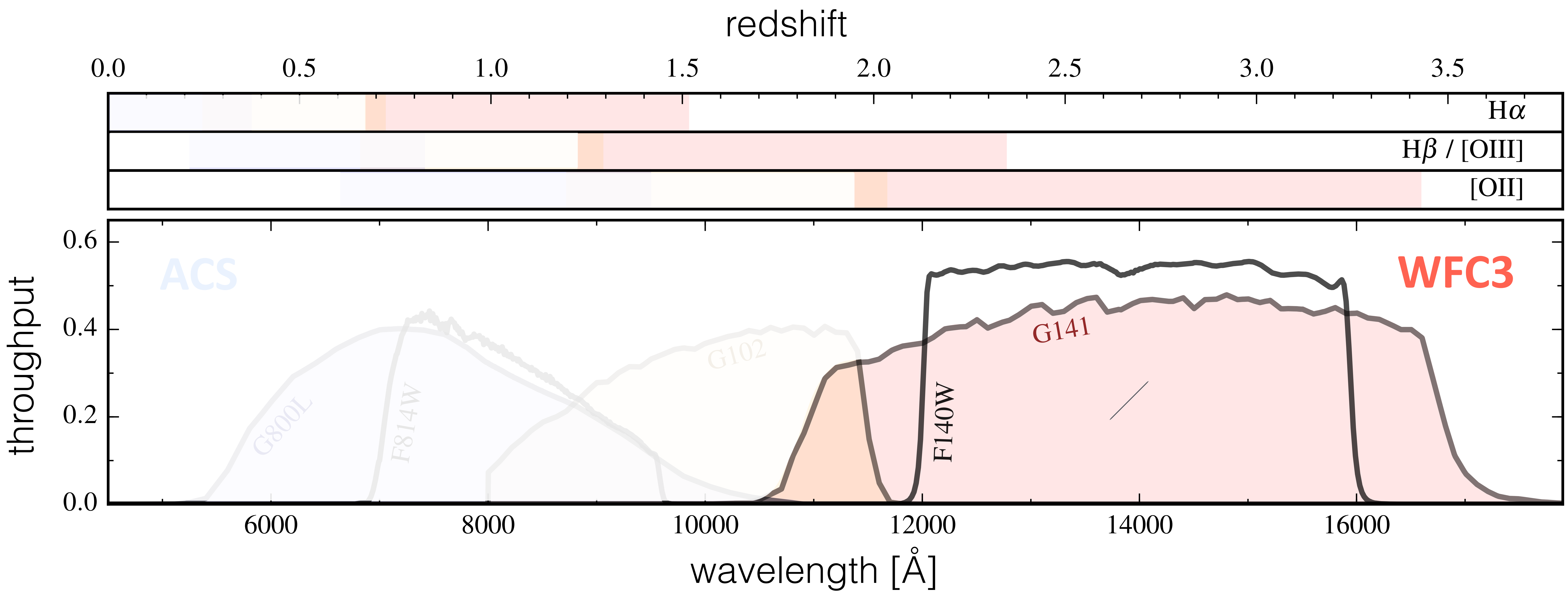
ACS specs:

- 2-4 orbit coverage
- 0.55 to 1.0 μm
- 40 Å/pix

WFC3 specs:

- 2 orbit coverage
- 1.1 to 1.65 μm
- 46.5 Å/pix

Near-Infrared Spectroscopic Surveys with the Hubble Space Telescope



ACS specs:

- 2-4 orbit coverage
- 0.55 to 1.0 μm
- 40 Å/pix

WFC3 specs:

- 2 orbit coverage
- 1.1 to 1.65 μm
- 46.5 Å/pix

The Team

PI: Prof. Pieter van Dokkum (Yale)
Project Manager: Dr. Ivelina Momcheva (STScI)


3D-HST group meeting in San Juan, Puerto Rico, October 2013

Co-I's:

Dr. Gabriel Brammer (STScI)
Prof. Dawn K. Erb (UW-Milwaukee)
Prof. Marijn Franx (Leiden)
Dr. Natascha Förster Schreiber (MPE)
Dr. Xiaohui Fan (University of Arizona)
Prof. Joseph Hennawi (MPIA)
Prof. Garth Illingworth (UC Santa Cruz)
Prof. Guinevere Kauffmann (MPIA)
Prof. Mariska Kriek (UC Berkeley)
Dr. Ivo Labbé (Leiden)
Dr. Patrick McCarthy (Carnegie)
Prof. Danilo Marchesini (Tufts)
Dr. Anna Pasquali (MPIA)
Dr. Shannon Patel (Carnegie)
Dr. Ryan Quadri (Texas A&M)
Prof. Hans-Walter Rix (MPIA)
Prof. Charles C. Steidel (Caltech)
Prof. David Wake (Open University)
Prof. Katherine E. Whitaker (UConn)

Collaborators:

Prof. Rachel Bezanson (Pitt)
Dr. Fuyan Bian (ANU)
Prof. Elisabeta da Cunha (ANU)
Ms. Claire Dickey (Yale)
Dr. Mattia Fumagalli (Leiden)
Dr. Joel Leja (Harvard/CfA)
Prof. Britt Lundgren (UNC Asheville)
Dr. Dan Magee (UC Santa Cruz)
Dr. Michael Maseda (Leiden)
Dr. Ian McGreer (University of Arizona)
Mr. Stanimir Metchev (Western University)
Prof. Adam Muzzin (York)
Dr. Erica Nelson (MPE/Harvard CfA)
Dr. Pascal Oesch (Yale)
Dr. Camilla Pacifici (STScI)
Dr. Moire Prescott (University of New Mexico)
Dr. Sedona Price (MPE)
Dr. Kasper Schmidth (UC Santa Barbara)
Dr. Rosalind Skelton (SAAO)
Prof. Daniel Stark (University of Arizona)
Dr. Tomer Tal (UC Santa Cruz)
Prof. Jonathan Trump (UConn)
Ms. Saskia van den Broek (Leiden)
Dr. Arjen van der Wel (MPIA)
Dr. Simone Weinmann (MPIA)
Ms. Anna Williams (UW - Madison)

The Team

PI: Prof. Pieter van Dokkum (Yale)

Project Manager: Dr. Ivelina Momcheva (STScI)

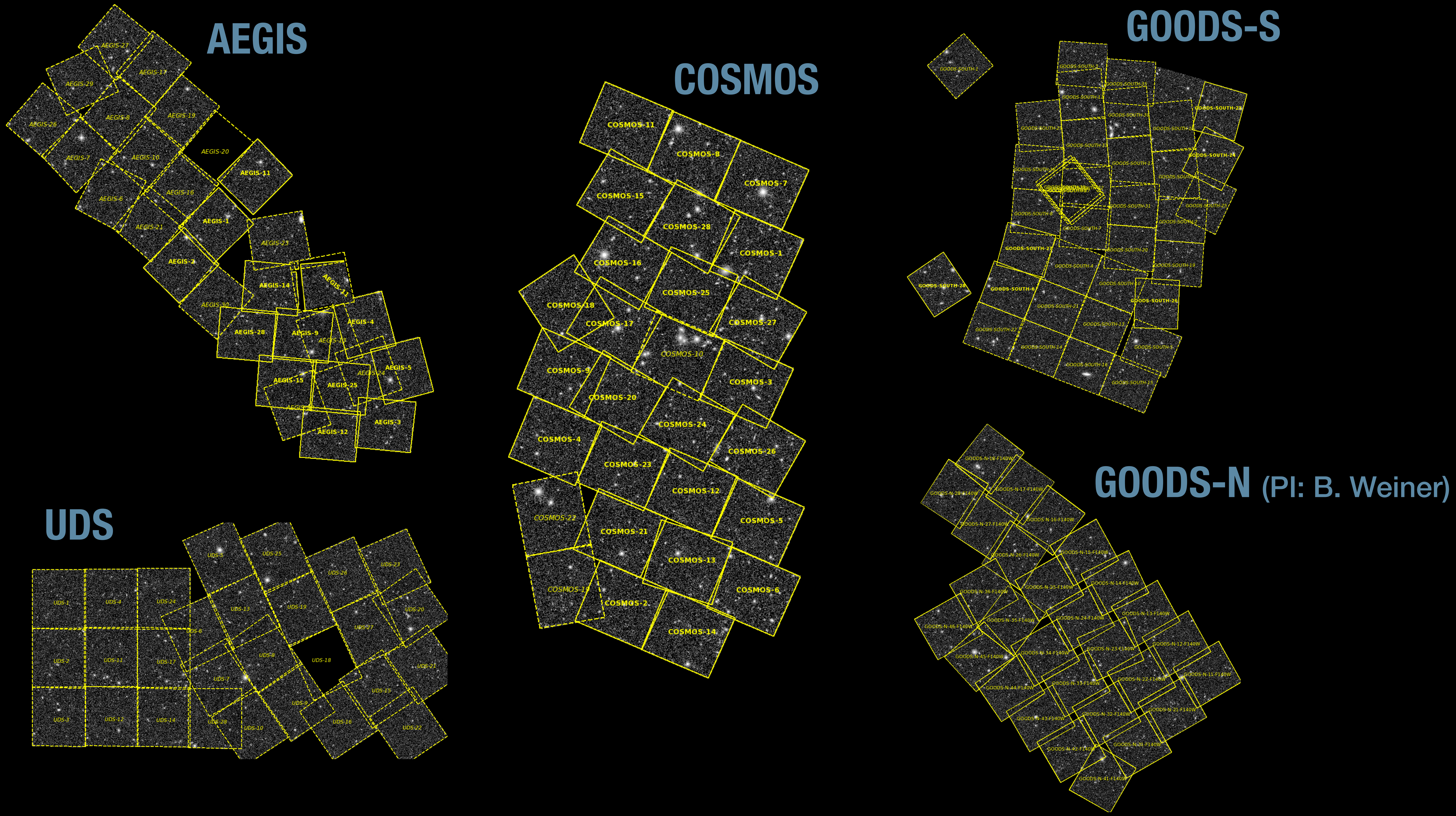
Co-I's:

Dr. Gabriel Brammer (STScI)
Prof. Dawn K. Erb (UW-Milwaukee)
Prof. Marijn Franx (Leiden)
Dr. Natascha Förster Schreiber (MPE)
Dr. Xiaohui Fan (University of Arizona)
Prof. Joseph Hennawi (MPIA)
Prof. Garth Illingworth (UC Santa Cruz)
Prof. Guinevere Kauffmann (MPIA)
Prof. Mariska Kriek (UC Berkeley)
Dr. Ivo Labbé (Leiden)
Dr. Patrick McCarthy (Carnegie)
Prof. Danilo Marchesini (Tufts)
Dr. Anna Pasquali (MPIA)
Dr. Shannon Patel (Carnegie)
Dr. Ryan Quadri (Texas A&M)
Prof. Hans-Walter Rix (MPIA)
Prof. Charles C. Steidel (Caltech)
Prof. David Wake (Open University)
Prof. Katherine E. Whitaker (UConn)

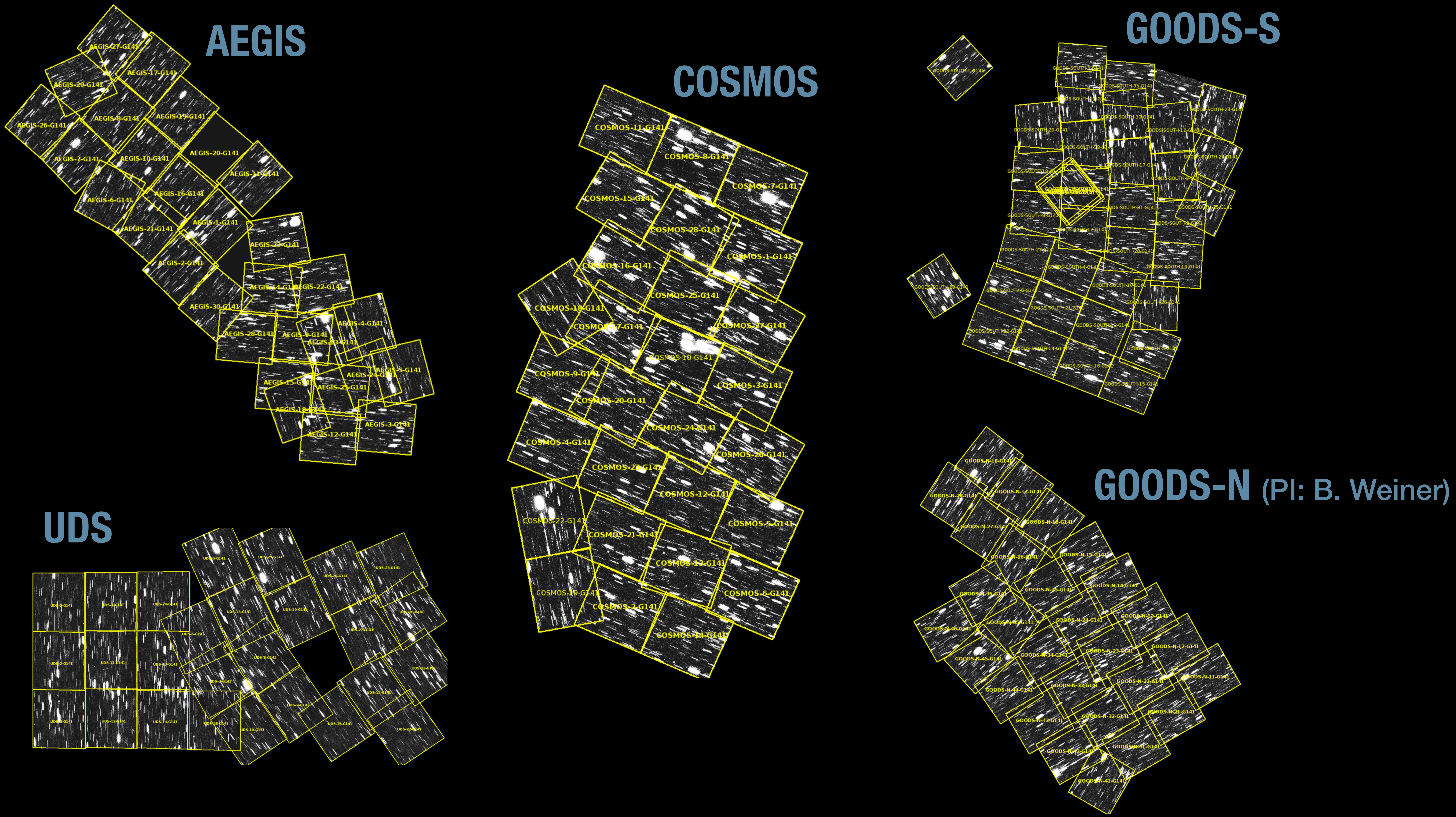
Collaborators:

Prof. Rachel Bezanson (Pitt)
Dr. Fuyan Bian (ANU)
Prof. Elisabeta da Cunha (ANU)
Ms. Claire Dickey (Yale)
Dr. Mattia Fumagalli (Leiden)
Dr. Joel Leja (Harvard/CfA)
Prof. Britt Lundgren (UNC Asheville)
Dr. Dan Magee (UC Santa Cruz)
Dr. Michael Maseda (Leiden)
Dr. Ian McGreer (University of Arizona)
Mr. Stanimir Metchev (Western University)
Prof. Adam Muzzin (York)
Dr. Erica Nelson (MPE/Harvard CfA)
Dr. Pascal Oesch (Yale)
Dr. Camilla Pacifici (STScI)
Dr. Moire Prescott (University of New Mexico)
Dr. Sedona Price (MPE)
Dr. Kasper Schmidth (UC Santa Barbara)
Dr. Rosalind Skelton (SAAO)
Prof. Daniel Stark (University of Arizona)
Dr. Tomer Tal (UC Santa Cruz)
Prof. Jonathan Trump (UConn)
Ms. Saskia van den Broek (Leiden)
Dr. Arjen van der Wel (MPIA)
Dr. Simone Weinmann (MPIA)
Ms. Anna Williams (UW - Madison)

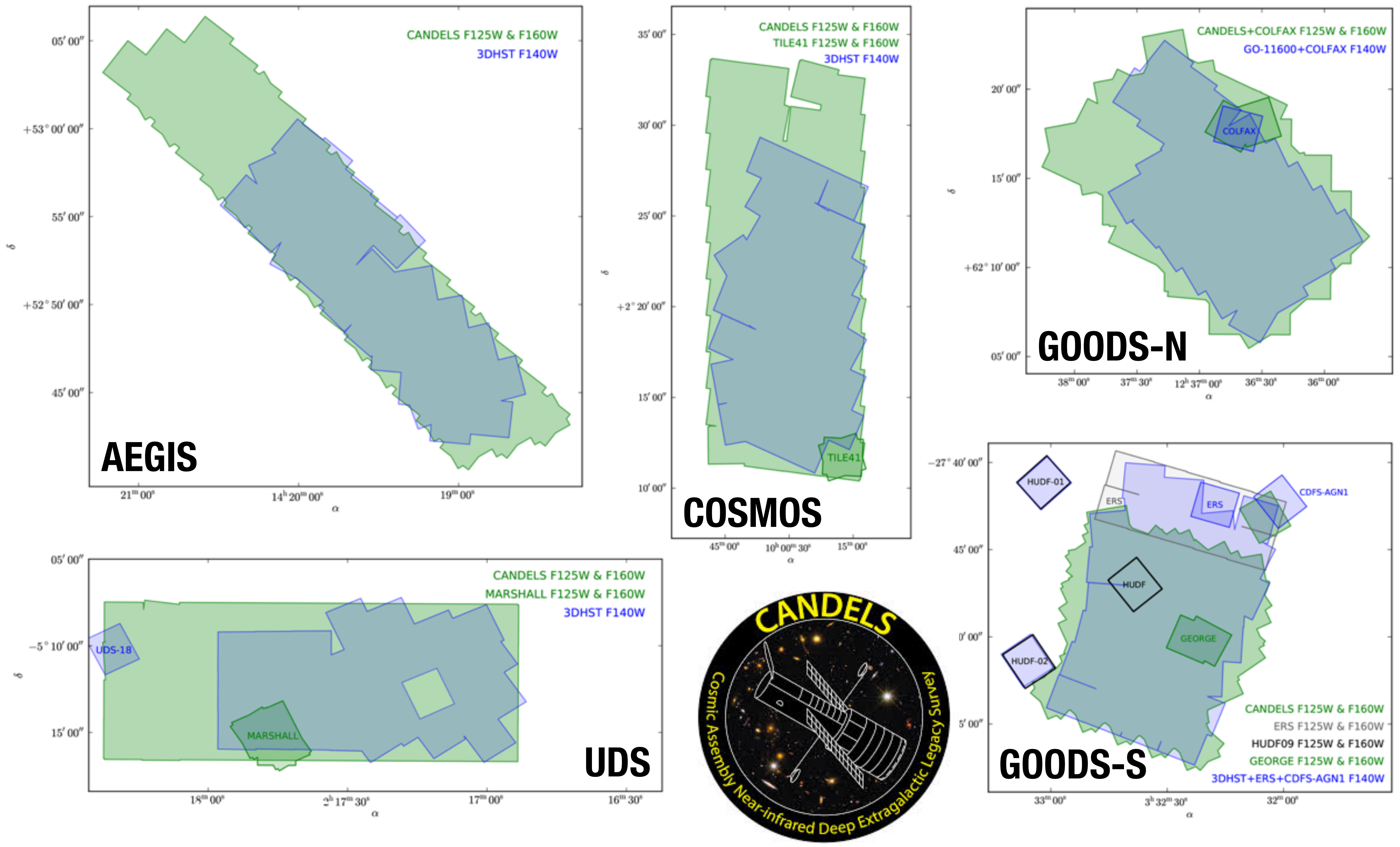
3D-HST group meeting in San Juan, Puerto Rico, October 2013



3D-HST F140W Mosaics
3dhst.research.yale.edu

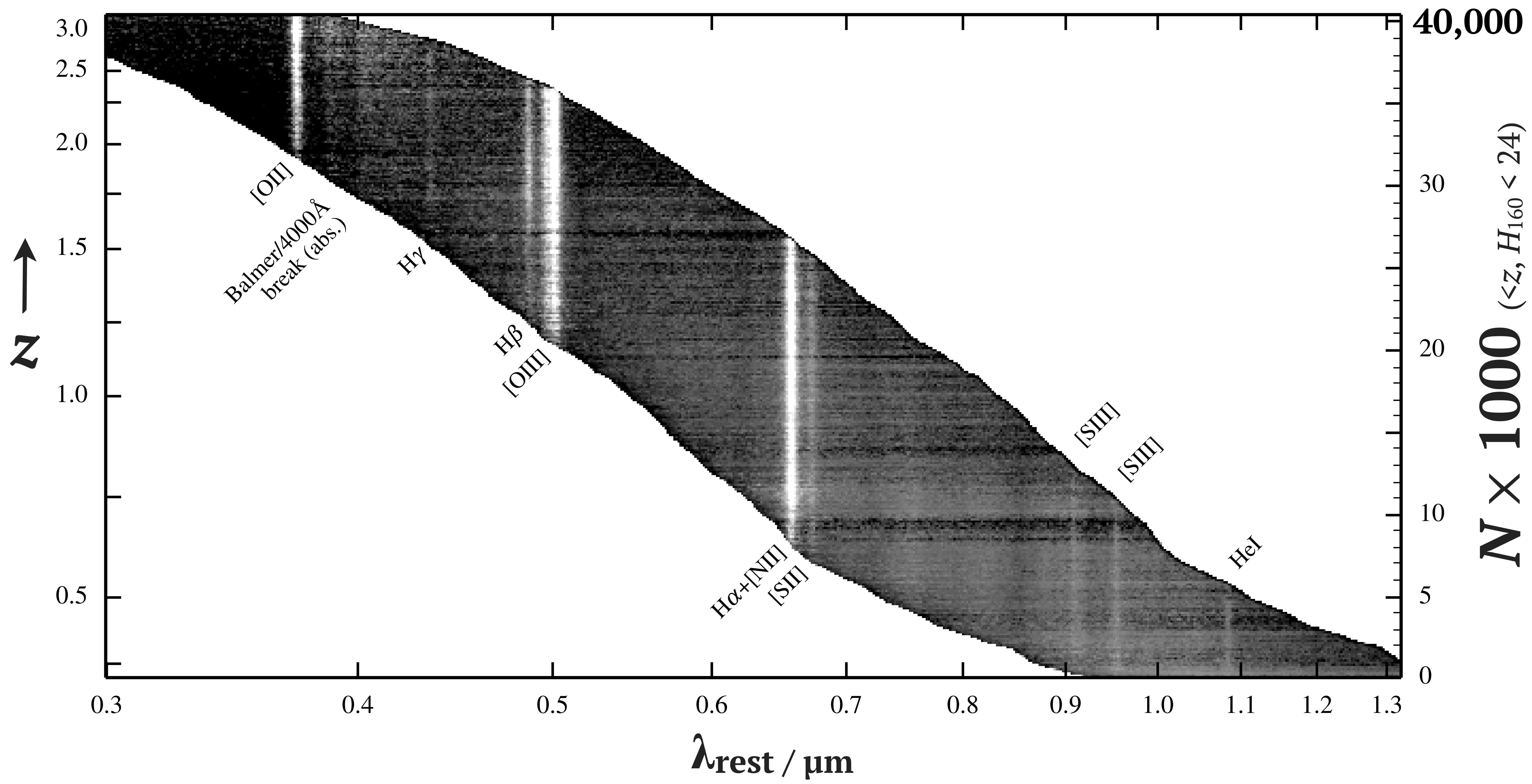


3D-HST F140W Mosaics
3dhst.research.yale.edu



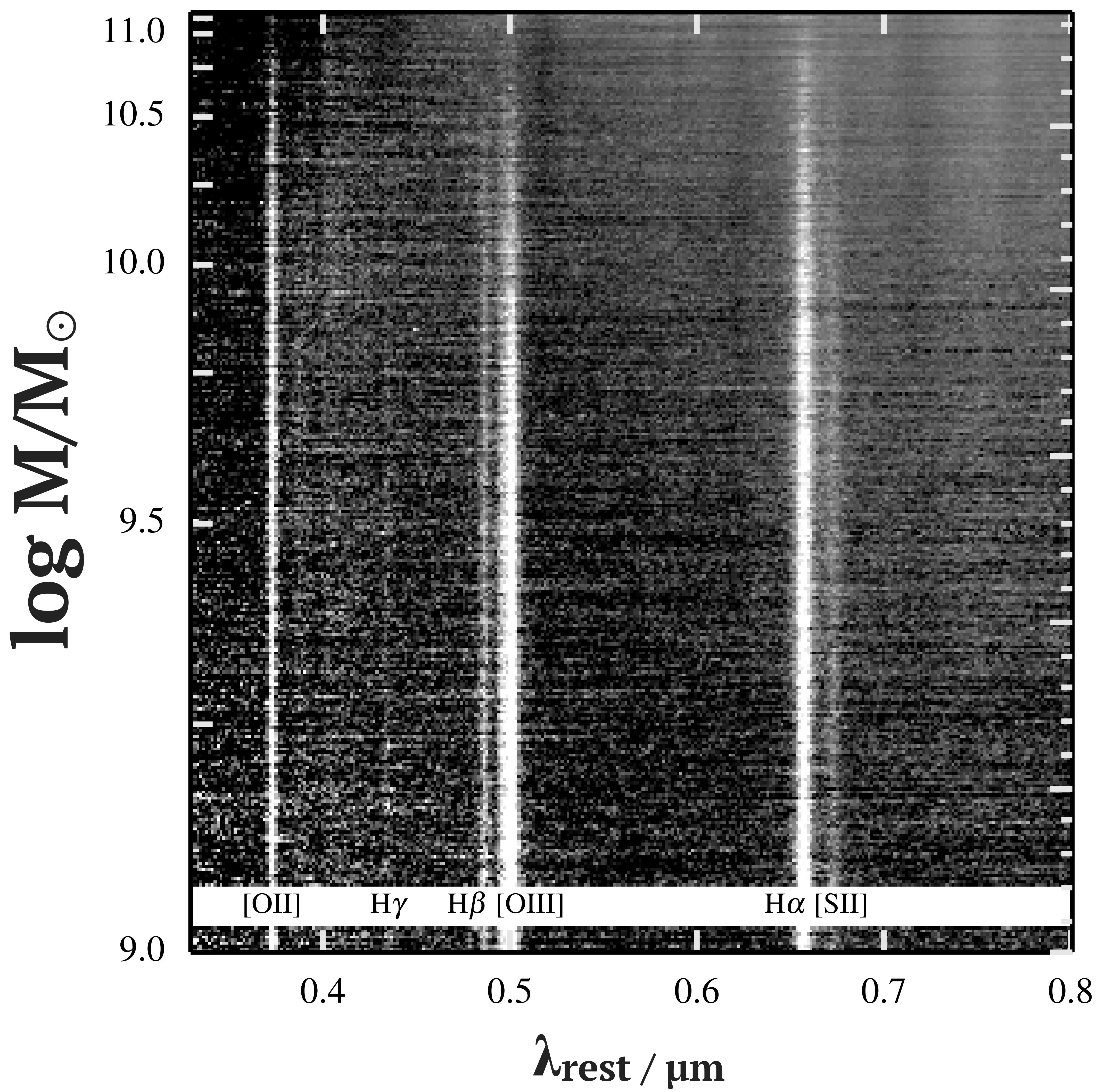
3D-HST

Footprint of **CANDELS** and **3D-HST** Surveys
3dhst.research.yale.edu



Automated extraction enables robust quantitative measurements for **10s of thousands of galaxies**

Momcheva et al., (2015)

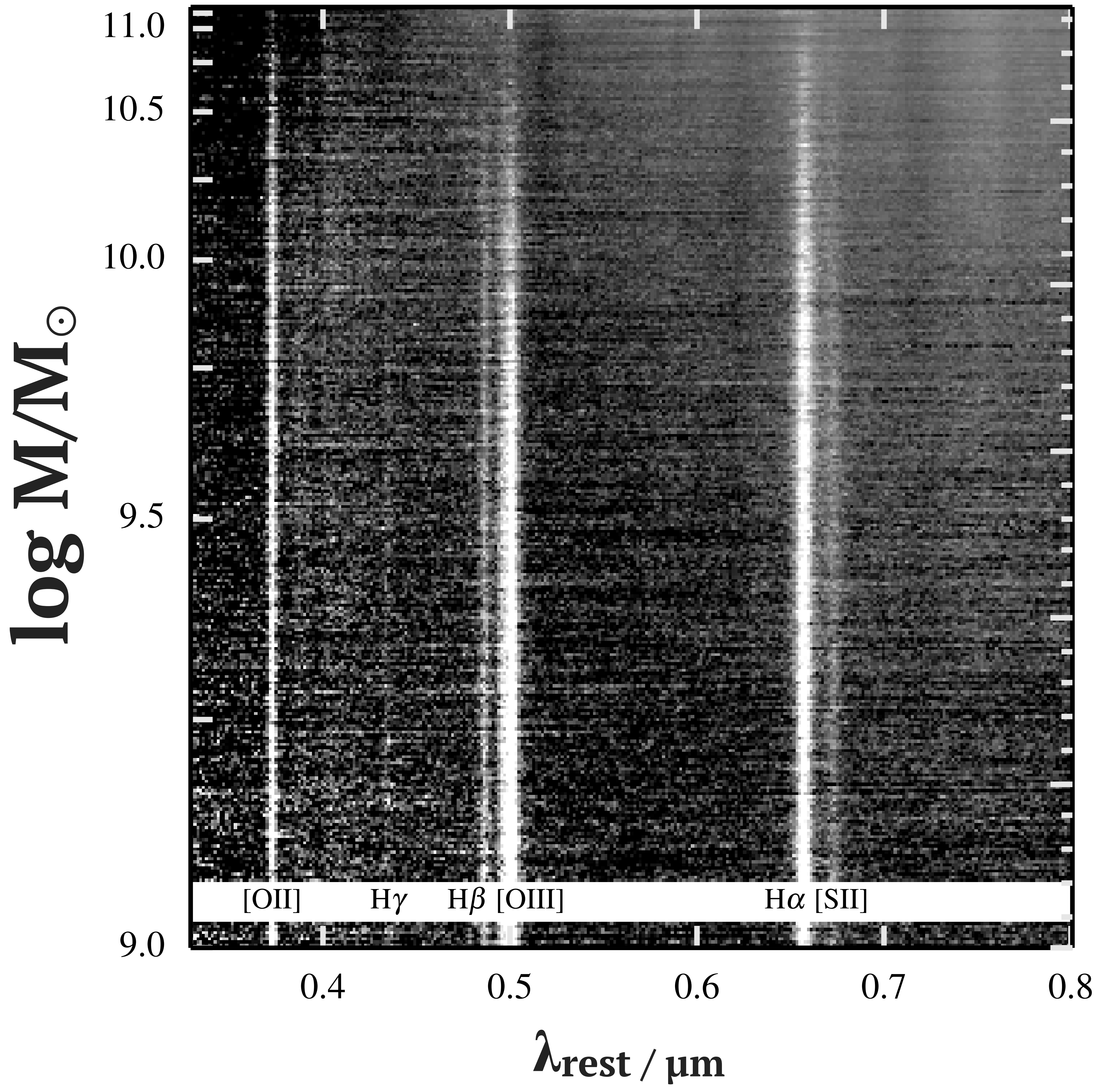


CANDELS+3D-HST:

- **Photometric Catalogs** Skelton, Whitaker et al. 2014
  - >200,000 catalog entries
  - 147 different bands, including available medium and narrow bands
  - few % photometric redshifts
  - morphology, rest-frame color, and stellar population parameters
- **Grism Spectroscopy** Momcheva, Brammer et al. 2015
  - ~20,000 objects to F140W<24 (~10^5 to F140W<26)
  - Grism+photometry redshifts, $dz/(1+z)$~0.003
  - Emission line fluxes, equivalent widths

Highly complete spectroscopic coverage allows detailed studies of evolving galaxy properties

http://3dhst.astro.yale.edu
https://archive.stsci.edu/prepds/3d-hst/



CANDELS+3D-HST:

- **Photometric Catalogs** Skelton, Whitaker et al. 2014
  - >200,000 catalog entries
  - 147 different bands, including available medium and narrow bands
  - few % photometric redshifts
  - morphology, rest-frame color, and stellar population parameters
- **Grism Spectroscopy** Momcheva, Brammer et al. 2015
  - ~20,000 objects to F140W<24 (~10^5 to F140W<26)

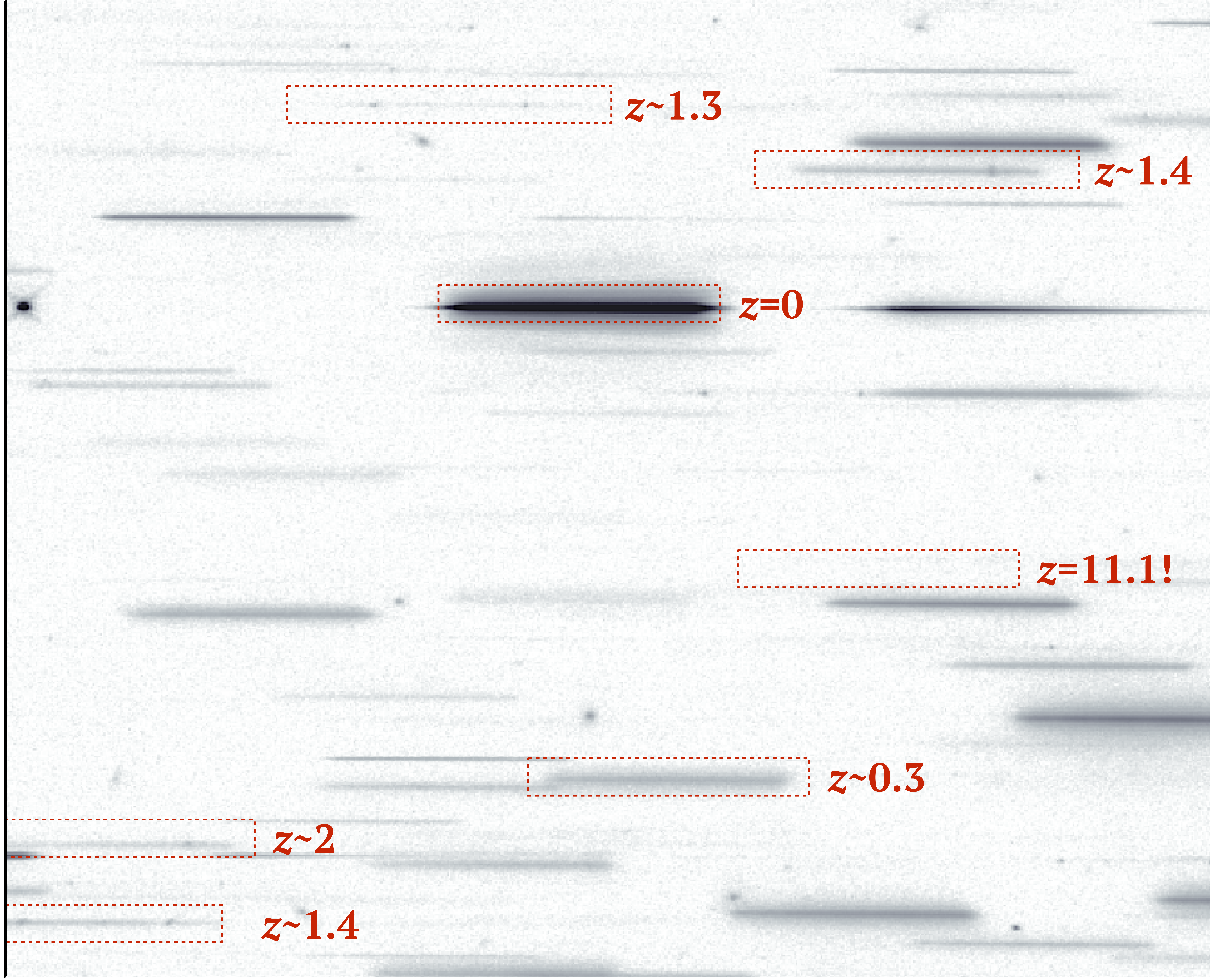
All high level science data products publicly available!

Highly complete spectroscopic coverage allows detailed studies of evolving galaxy properties

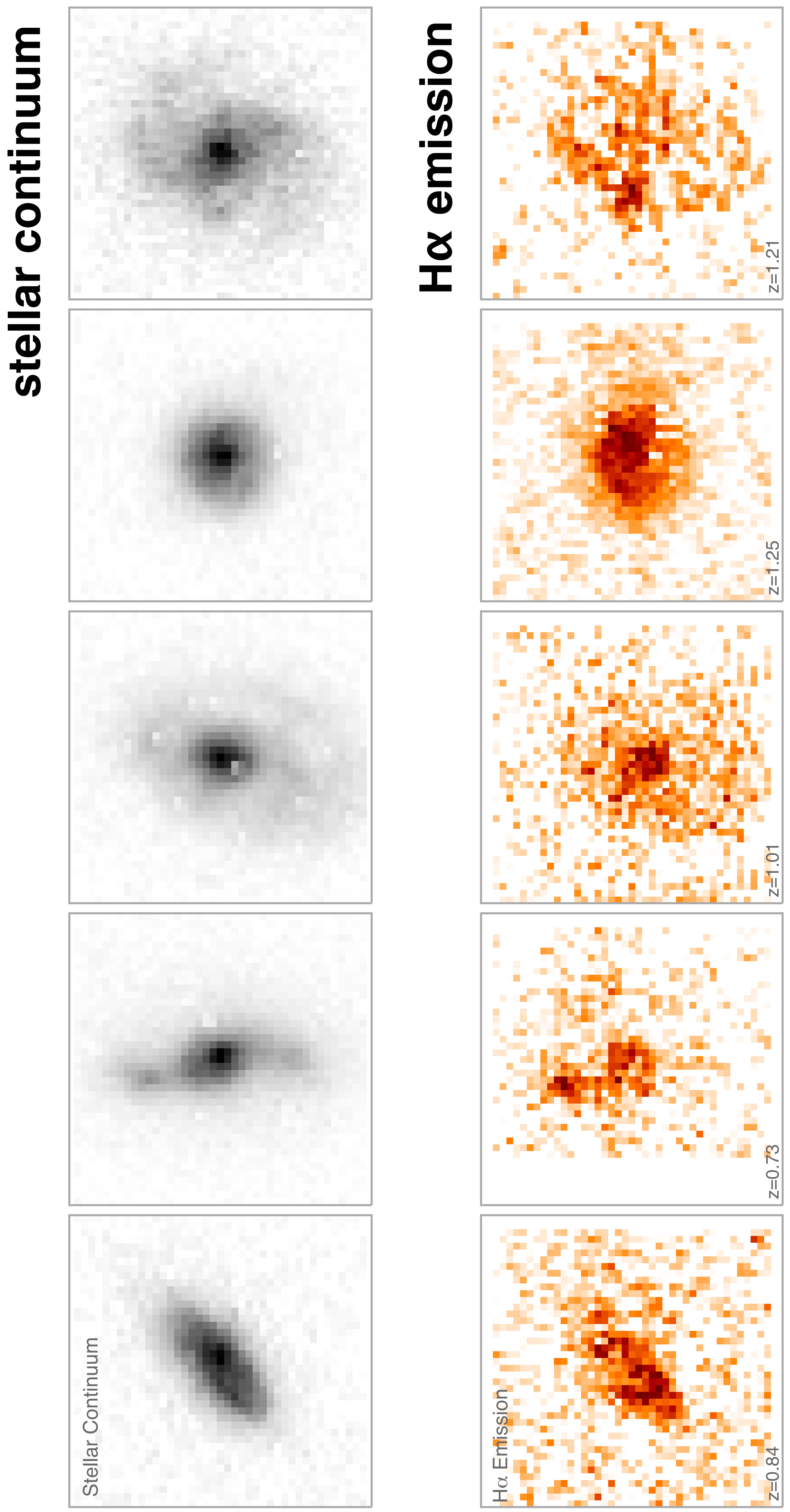
http://3dhst.astro.yale.edu
https://archive.stsci.edu/prepds/3d-hst/

Science Highlights

3D-HST



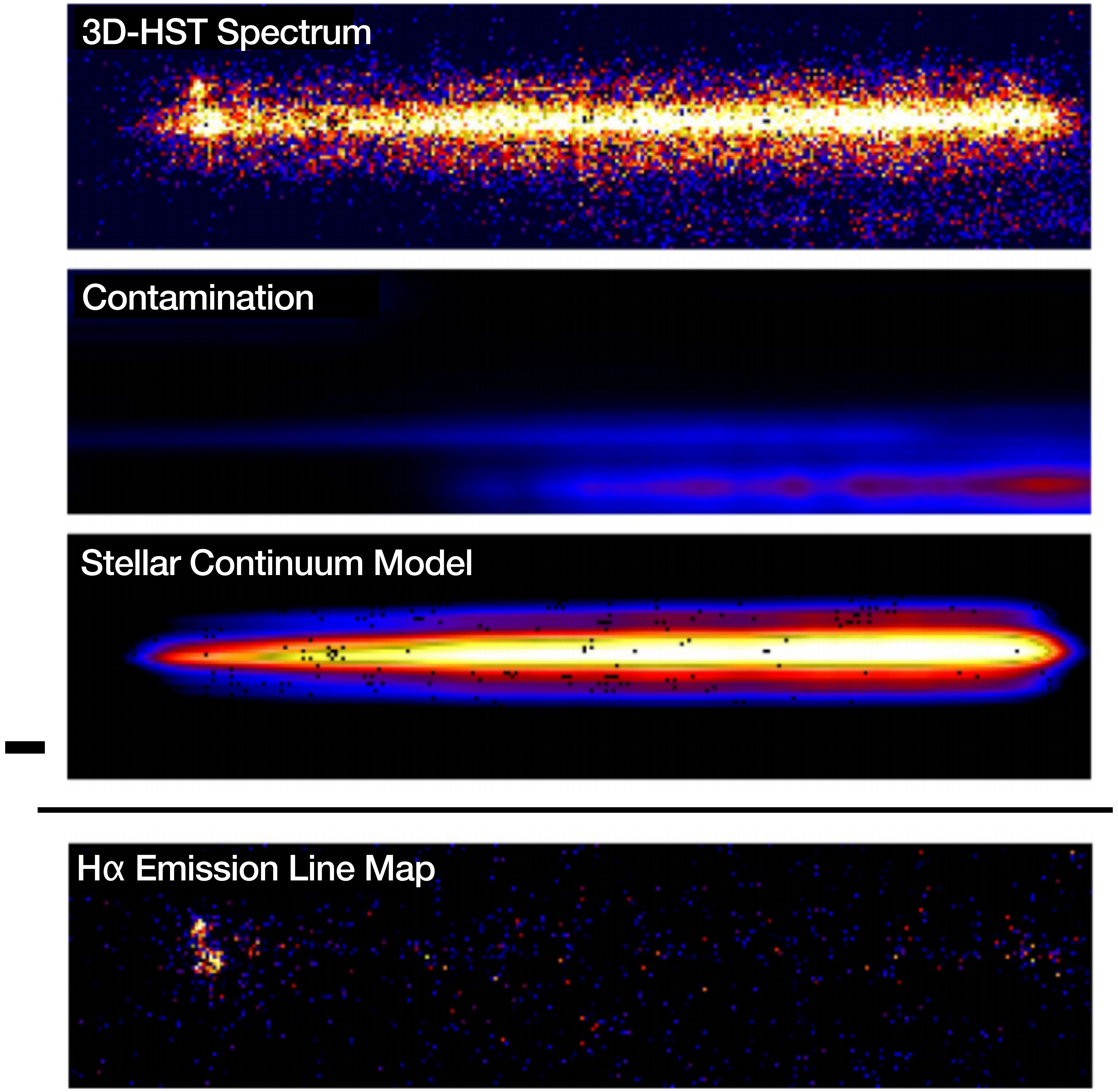
Line Morphologies provide spatially resolved information on ~1kpc scales



- **Star-formation activity** ($\Sigma_{SFR}(r)$) Wuyts et al. 2013, Nelson et al. 2016
- **Star-formation history** (Hα vs. continuum) Nelson et al. 2013, 2015
- **Dust extinction** Price et al. 2014, Nelson et al. 2016
- **Ages** Whitaker et al. 2013, Fumagalli et al. 2016
- **Active Galactic Nuclei** Trump et al. 2011, 2014, Bridge et al. 2016
- **Metallicity gradients** Jones et al. 2014, Wang et al. 2016
- **Age gradients** Whitaker et al., in prep

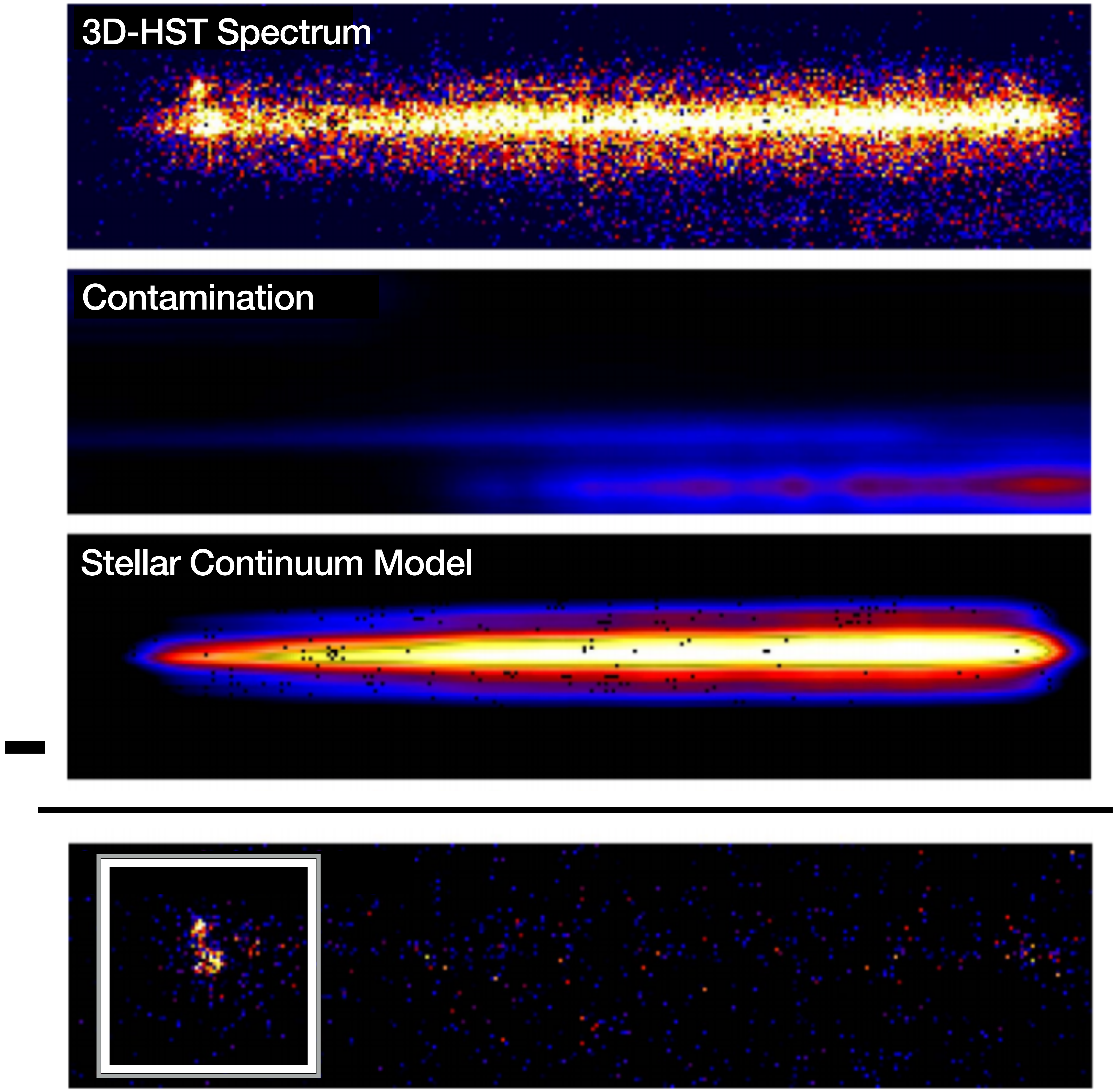
} **gravitational lensing helps!**

Hα Maps: Leveraging large sample sizes with stacking



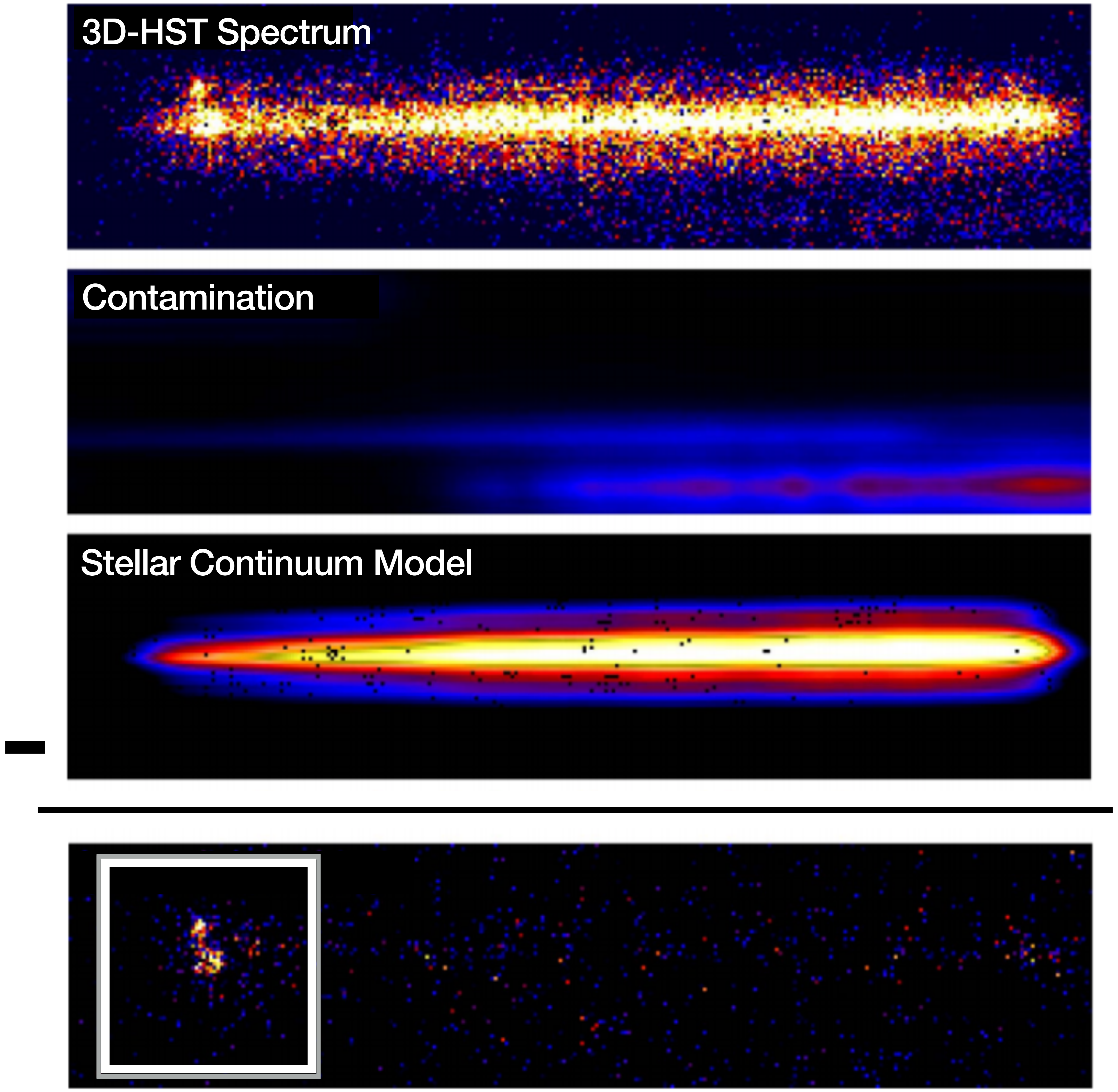
Nelson et al. 2016

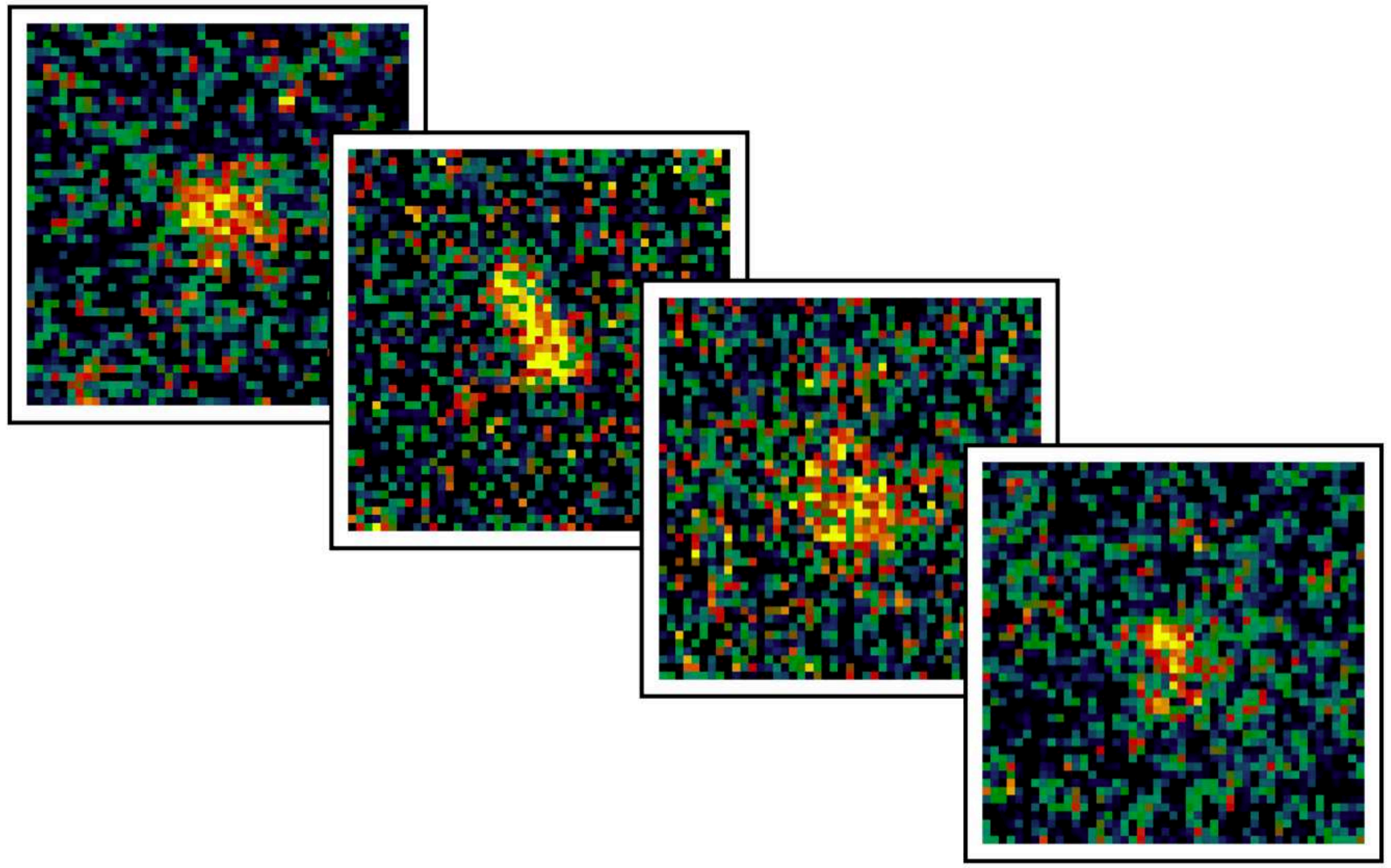
Hα Maps: Leveraging large sample sizes with stacking



Nelson et al. 2016

Hα Maps: Leveraging large sample sizes with stacking





Nelson et al. 2016

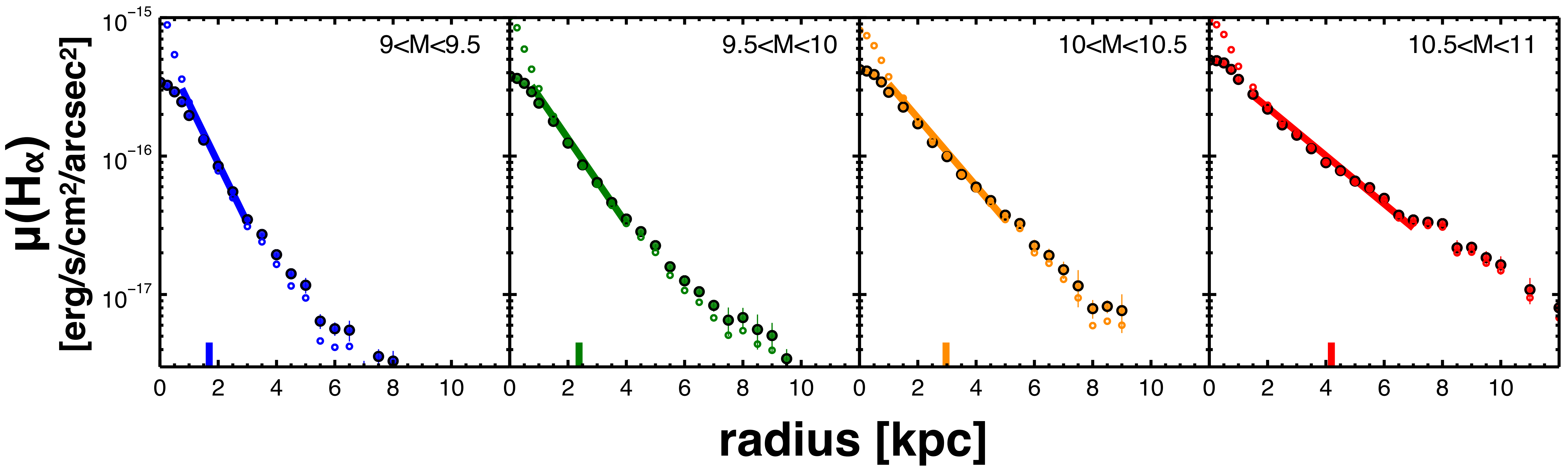
Hα Maps: Leveraging large sample sizes with stacking

Nelson et al. 2016

Hα Maps: Leveraging large sample sizes with stacking

Nelson et al. 2016

Where do stars form? The inside-out growth of exponential disks



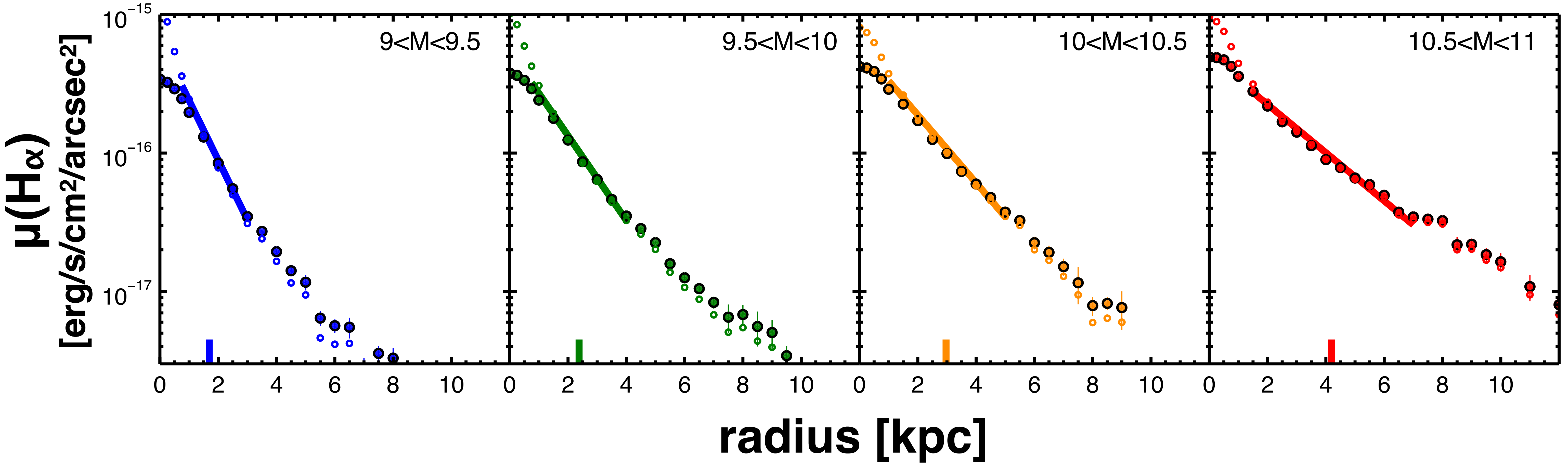
~2700 galaxies 0.7 < $z_{H\alpha}$ < 1.5

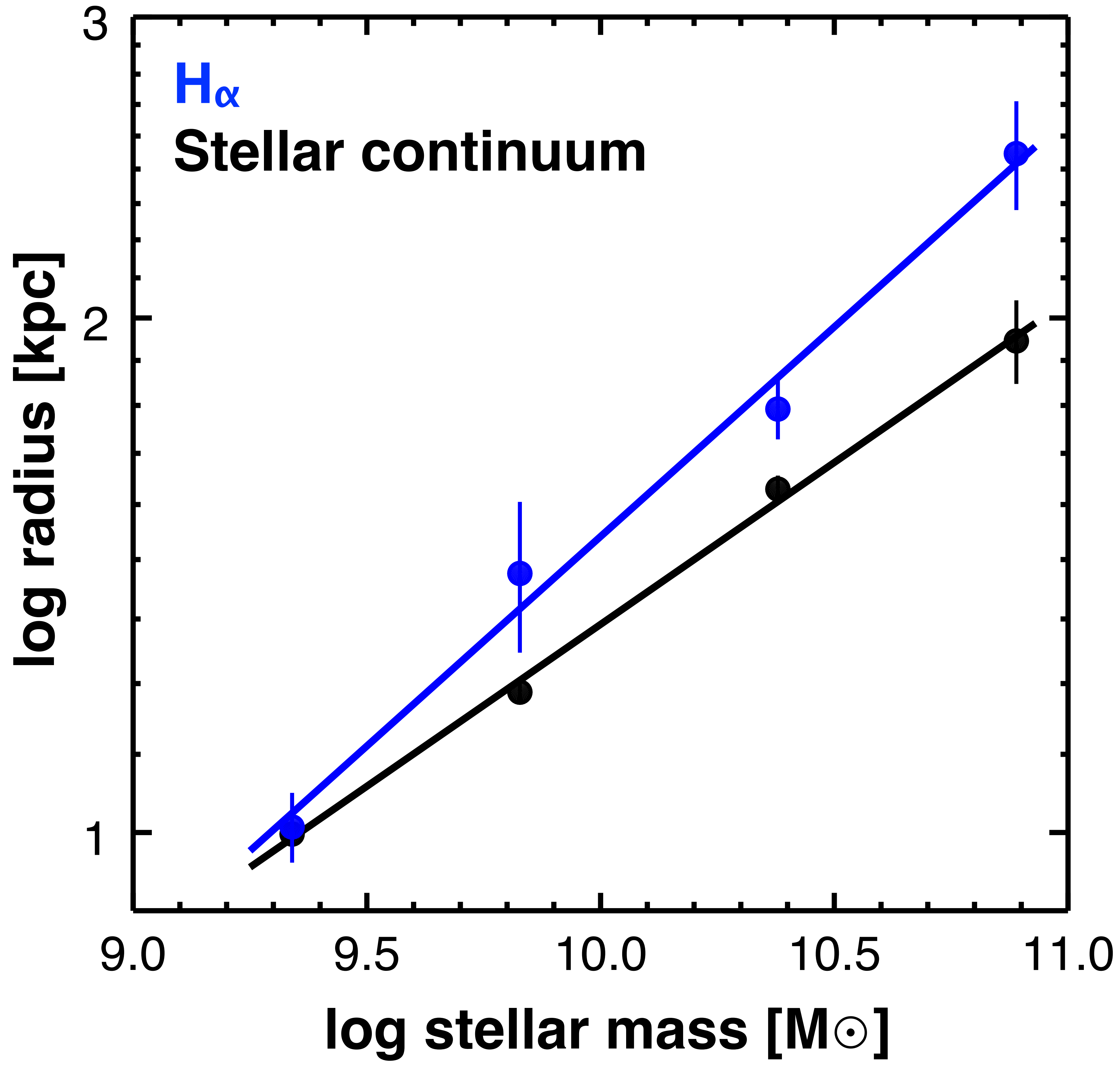
- H_α profiles exponential in all mass bins >10^9 $M_\odot$ ....

  star formation occurs in disks

Nelson et al. 2013, 2015

Where do stars form? The inside-out growth of exponential disks



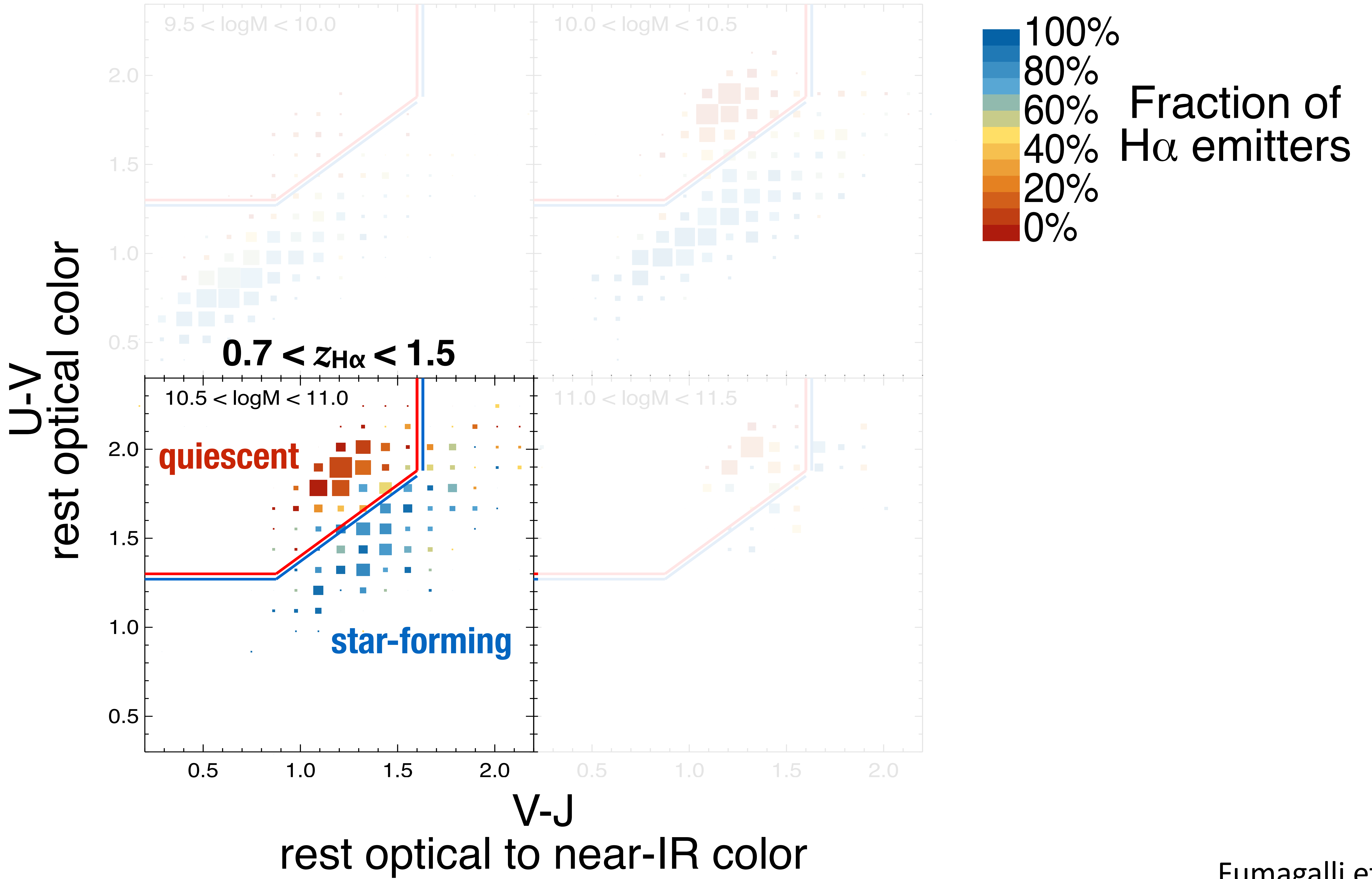


~2700 galaxies $0.7 < z_{H\alpha} < 1.5$

- Hα profiles exponential in all mass bins $>10^9$ M⊙ ….
  star formation occurs in disks
- Hα (SFR) sizes larger than stellar continuum (mass)
  …. *disks are building inside out*

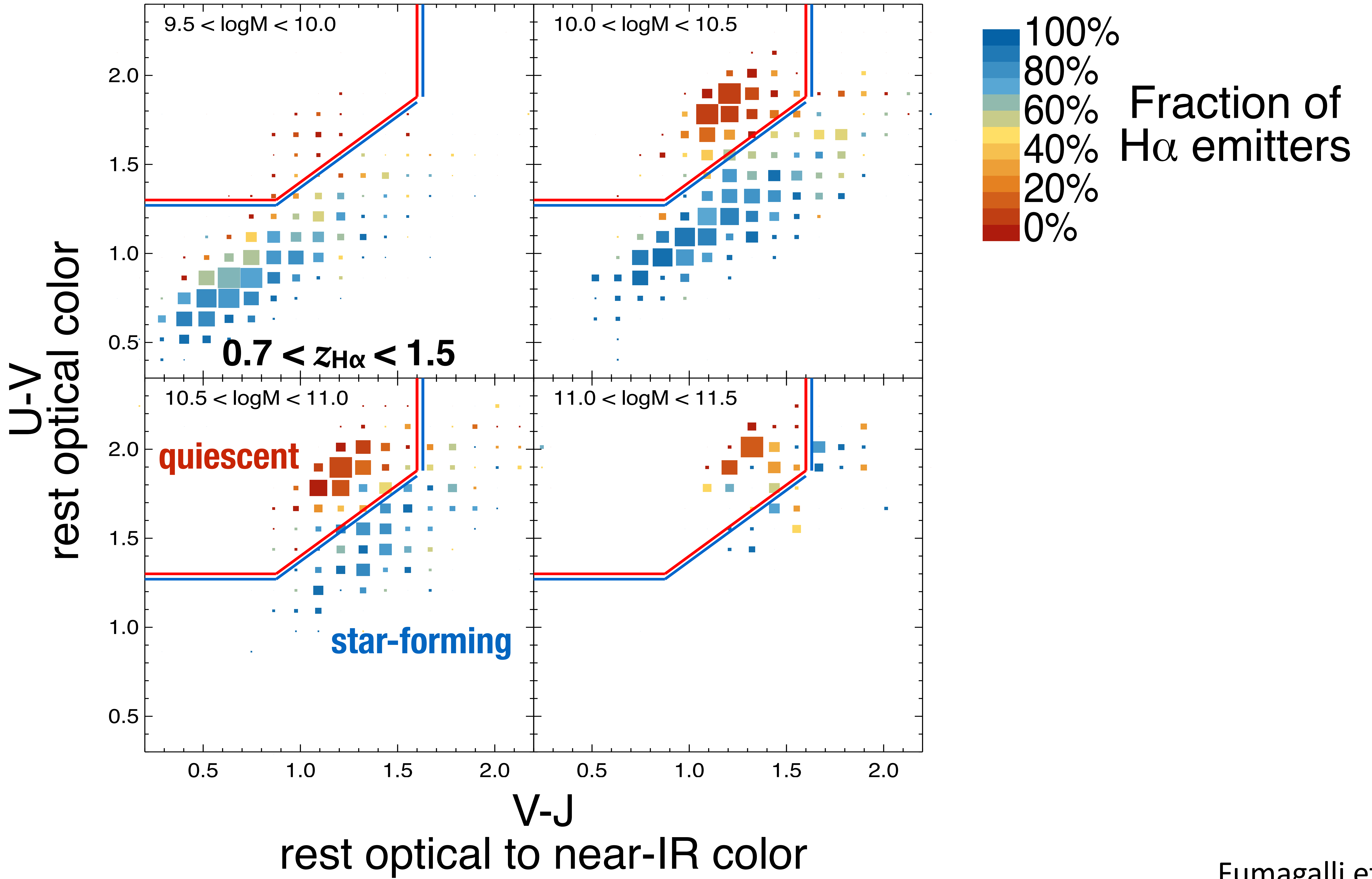
Nelson et al. 2013, 2015

When did the stars form? Bimodality of Galaxy Populations



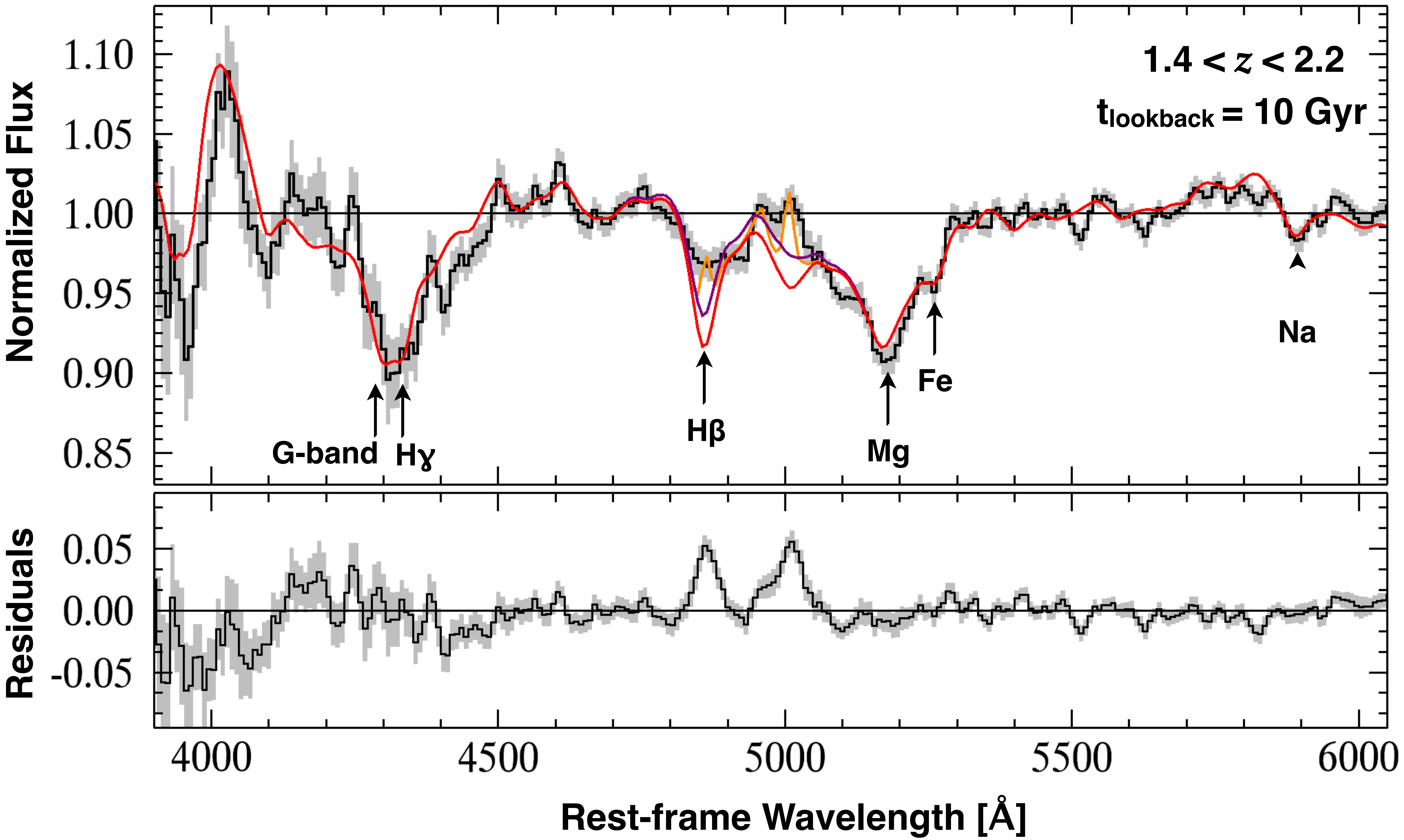
Fumagalli et al. in prep

When did the stars form? Bimodality of Galaxy Populations



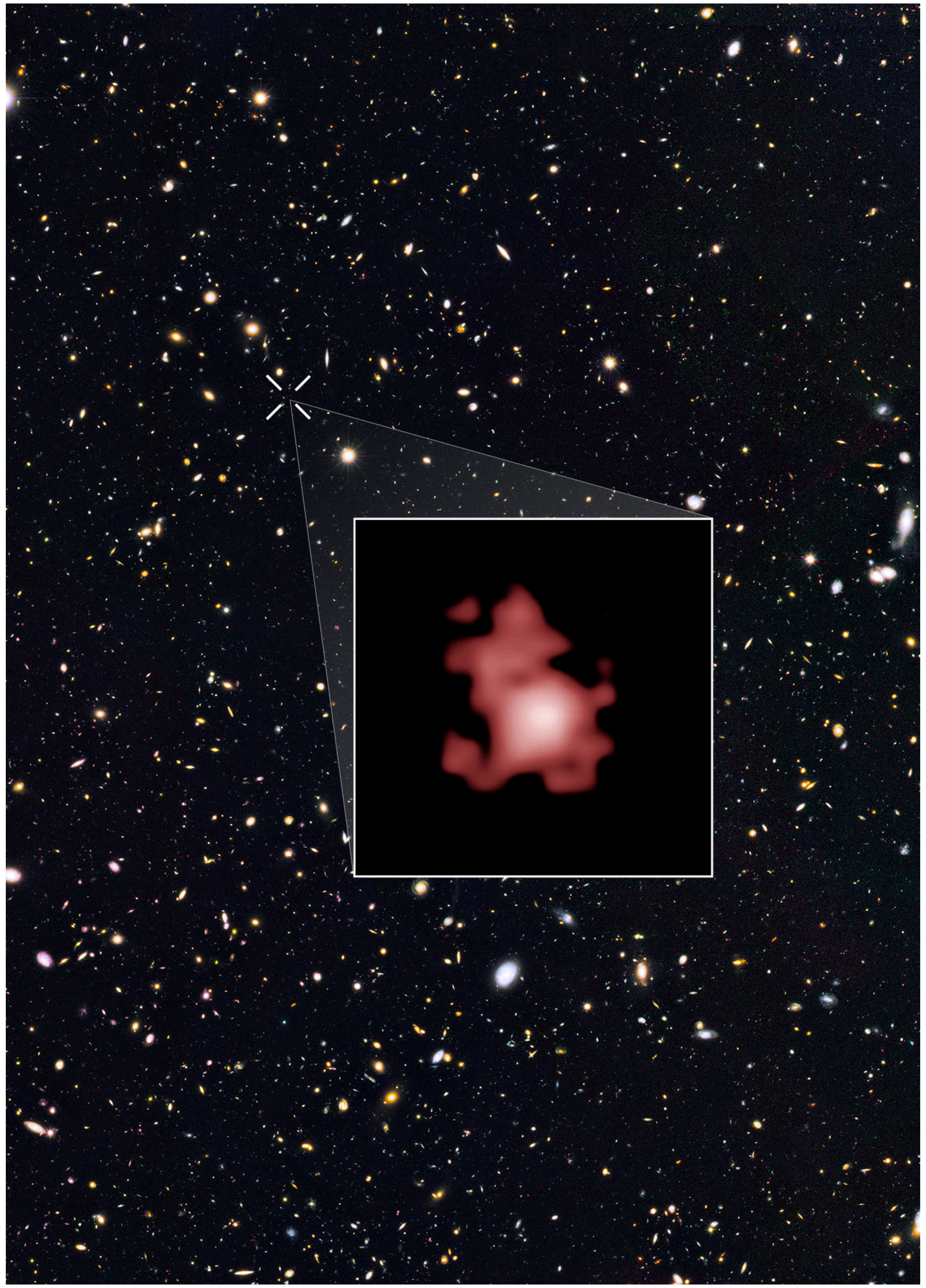
Fumagalli et al. in prep

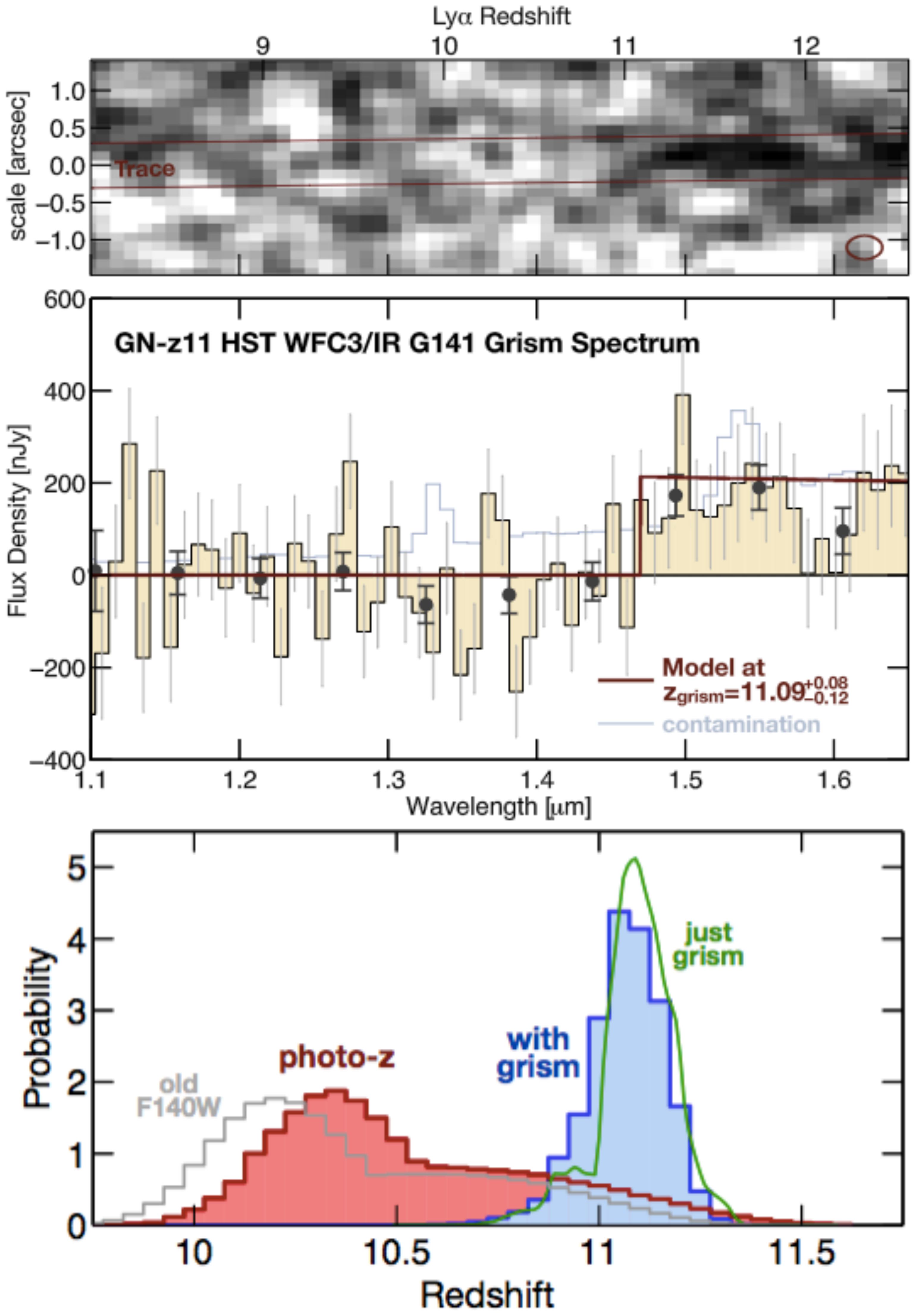
When did the stars form? Ages of quenched galaxies



Whitaker et al. 2013

Cosmic Dawn and serendipitous discoveries of the first galaxies

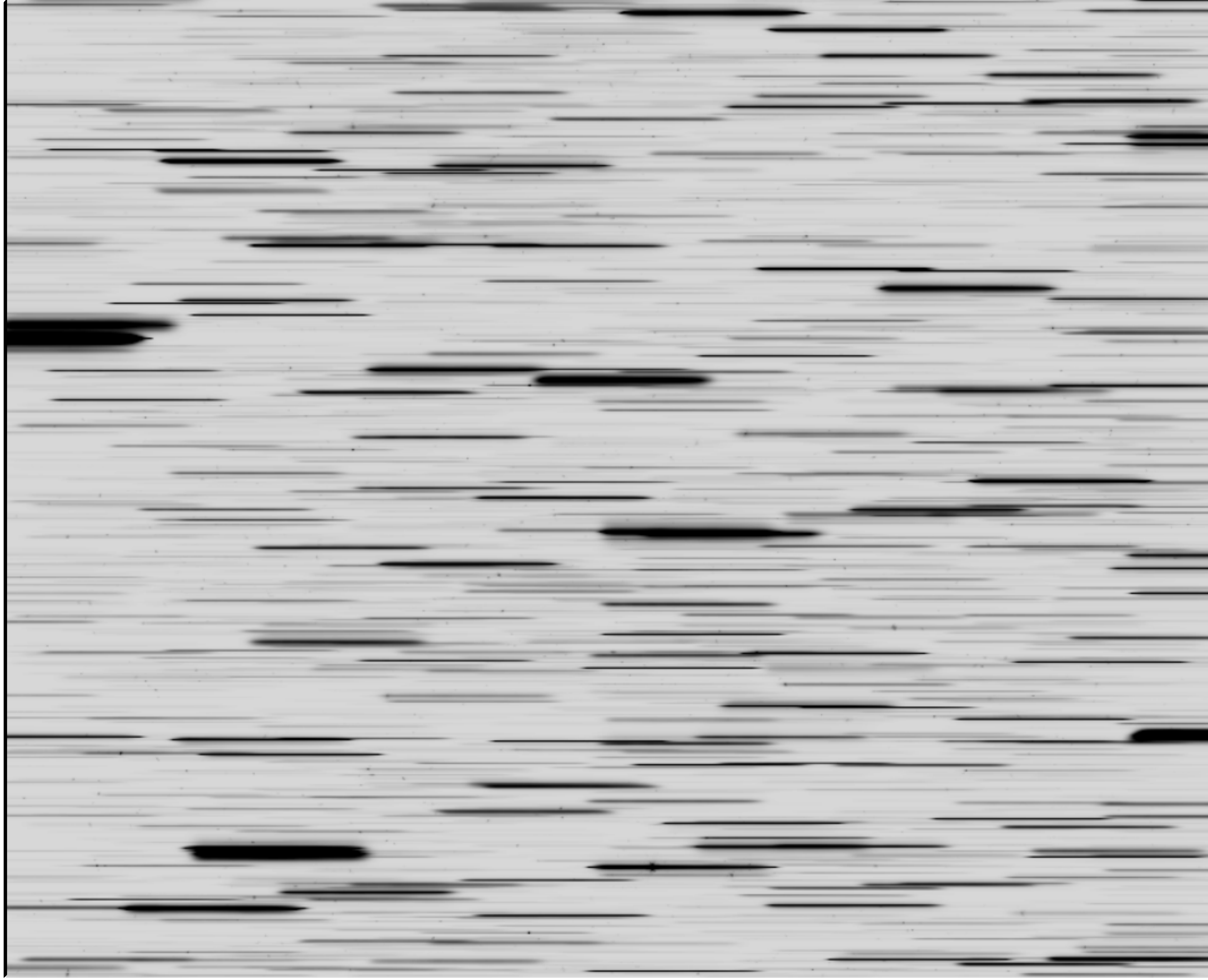




- **Hubble beats the cosmic distance record** with a best-fit redshift of combined grism spectrum and photometry of ***z* = 11.1 ± 0.1**
  - Overall 5.5σ detection at λ>1.47 μm
  - Lyman break factor of >3.1 (2σ, 500Å)
  - Grism + photometric data rule out all plausible lower redshift solutions.

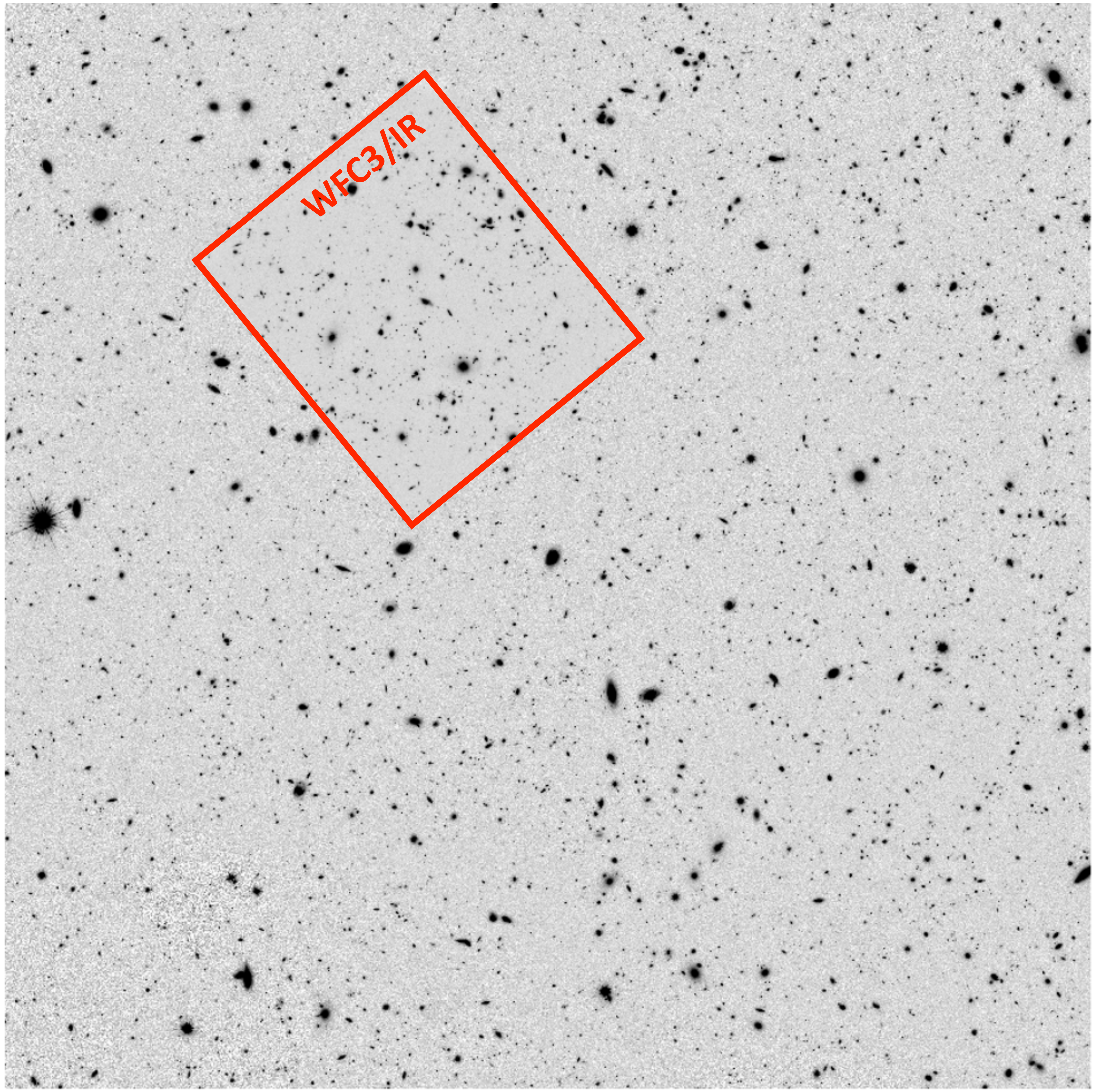
Oesch et al. 2016

Future Prospects



WFIRST Simulations: what can we expect?

Single 4k WFIRST detector

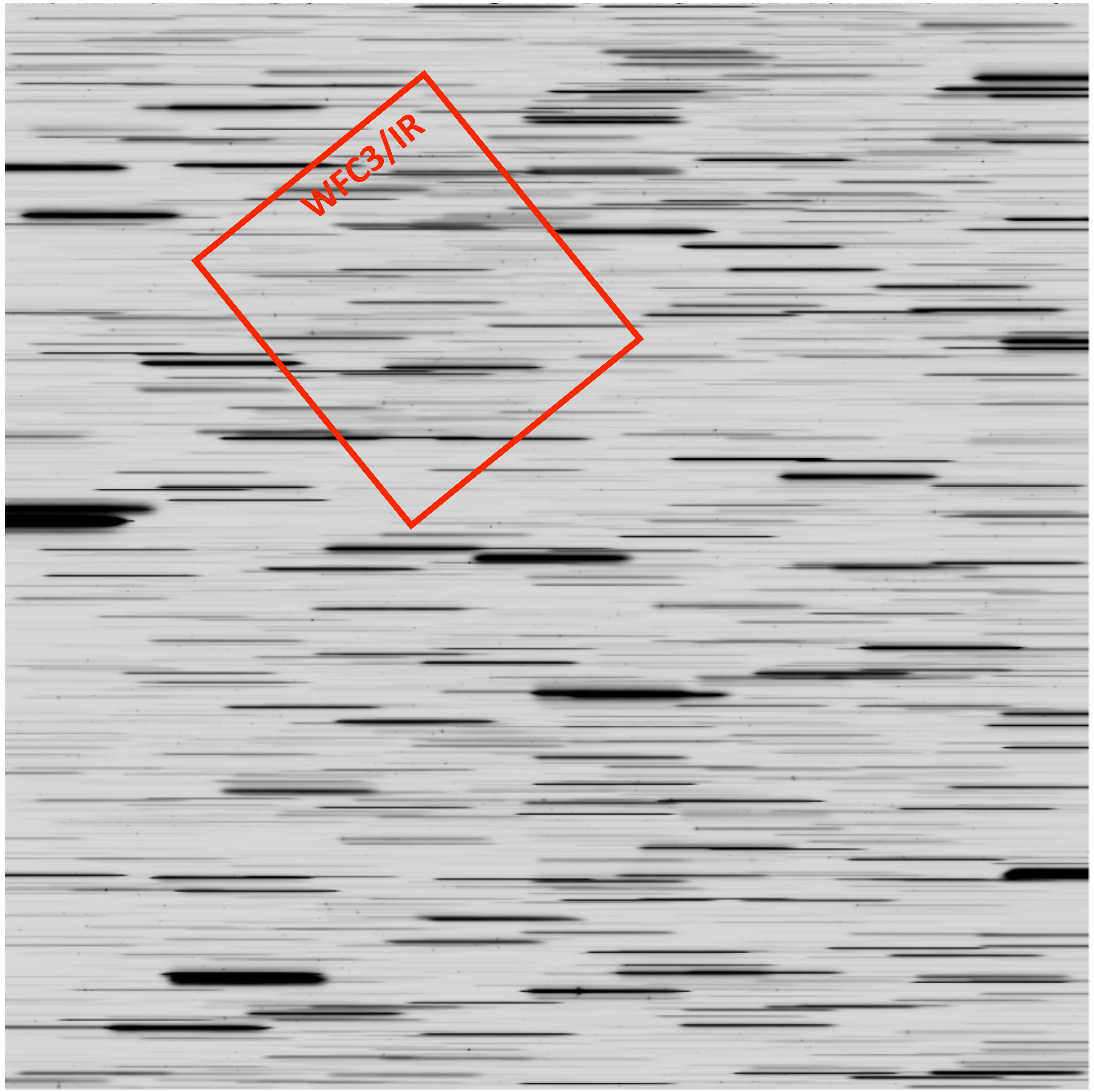


Simulation by G. Brammer
https://github.com/gbrammer/grizli/

WFIRST Simulations: what can we expect?

Single 4k WFIRST detector

Dispersed by the HLS grism



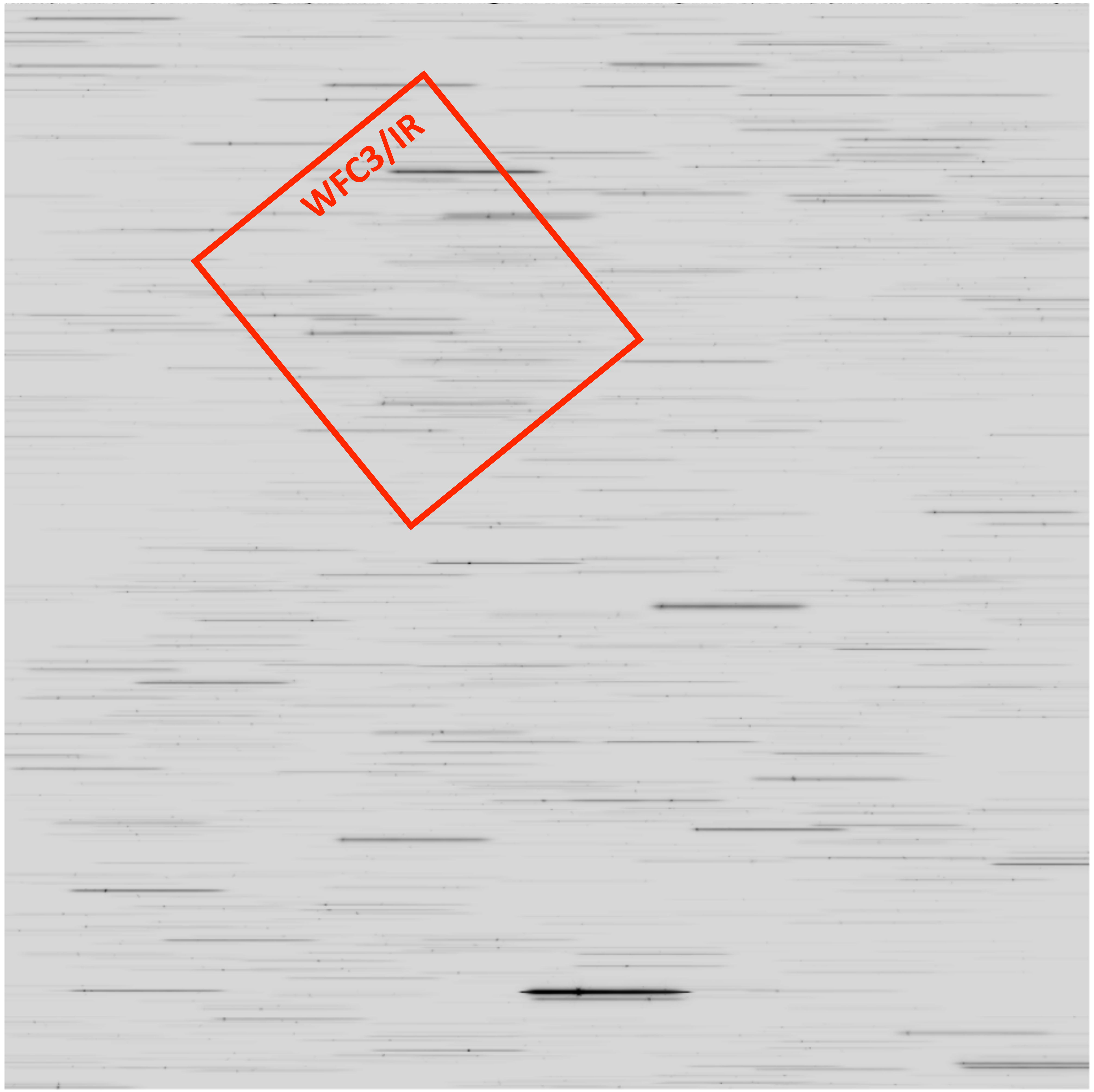
Simulation by G. Brammer
https://github.com/gbrammer/grizli/

WFIRST Simulations: what can we expect?

Single 4k WFIRST detector

Dispersed by the HLS grism

Hα: 1.1 < z < 1.9
(full range 0.5 < z < 1.9)



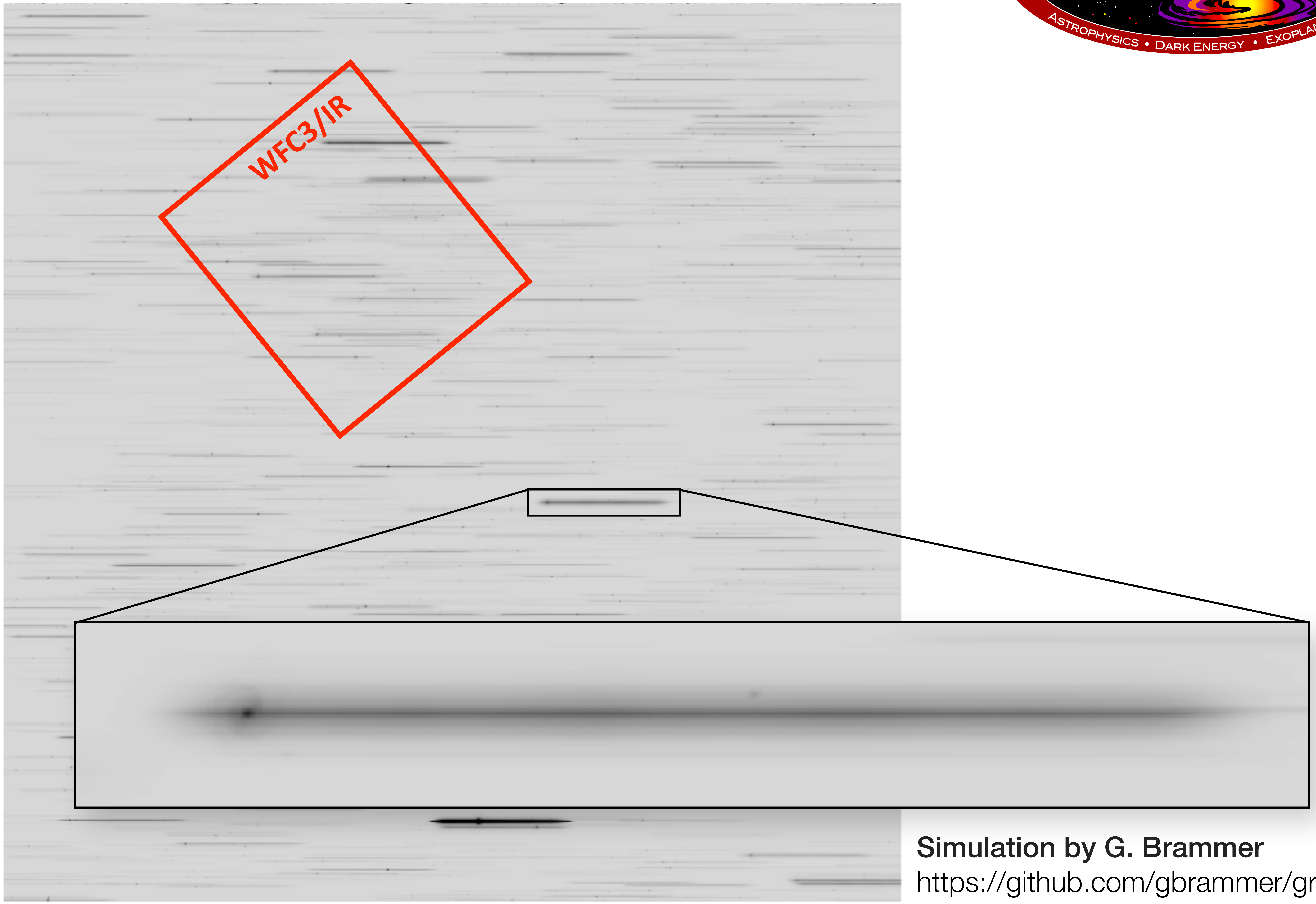
Simulation by G. Brammer
https://github.com/gbrammer/grizli/

WFIRST Simulations: what can we expect?

Single 4k WFIRST detector

Dispersed by the HLS grism

Hα: 1.1 < z < 1.9
(full range 0.5 < z < 1.9)



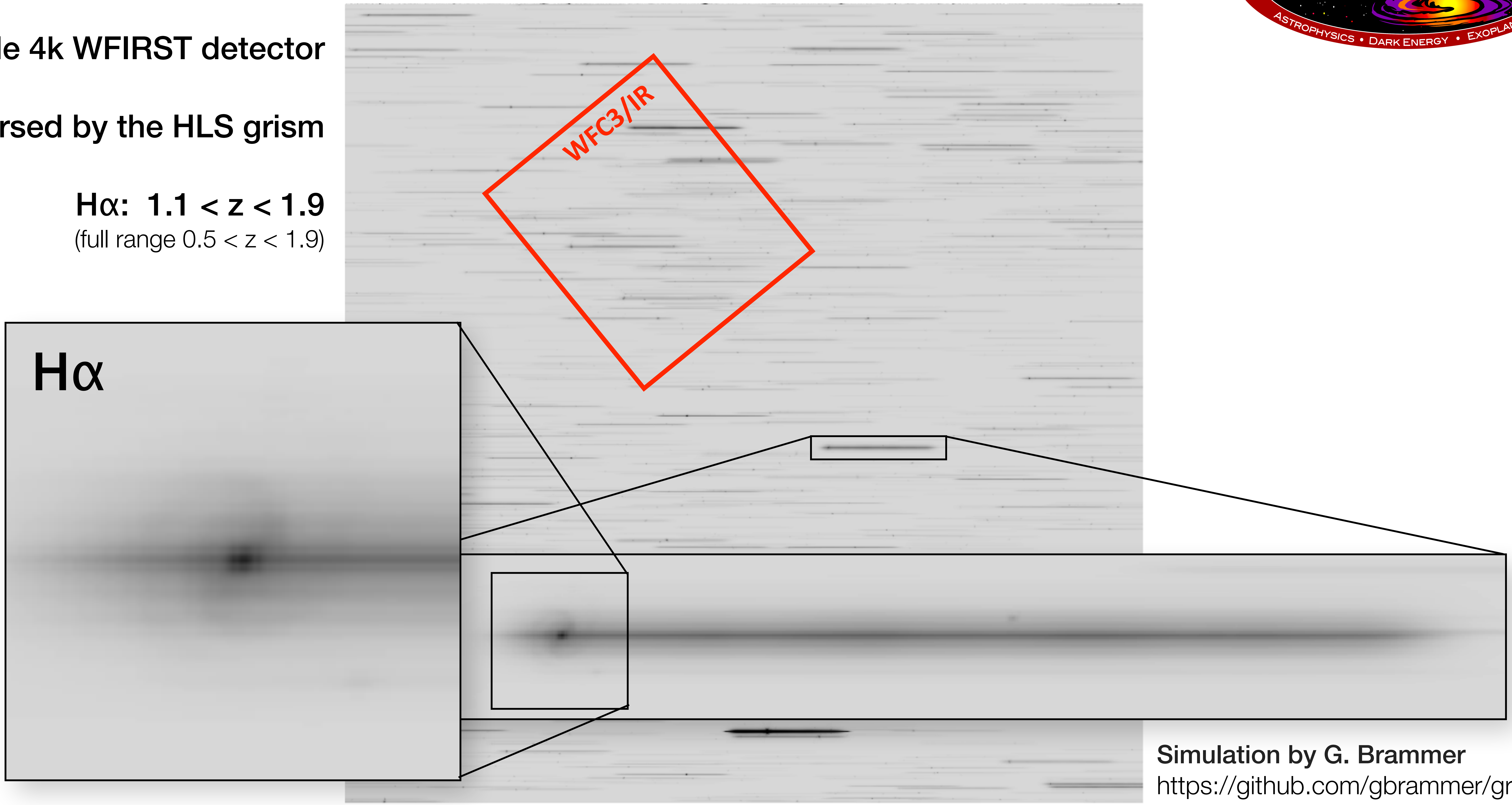
Simulation by G. Brammer
https://github.com/gbrammer/grizli/

WFIRST Simulations: what can we expect?

Single 4k WFIRST detector

Dispersed by the HLS grism

Hα: 1.1 < z < 1.9
(full range 0.5 < z < 1.9)



Simulation by G. Brammer
https://github.com/gbrammer/grizli/

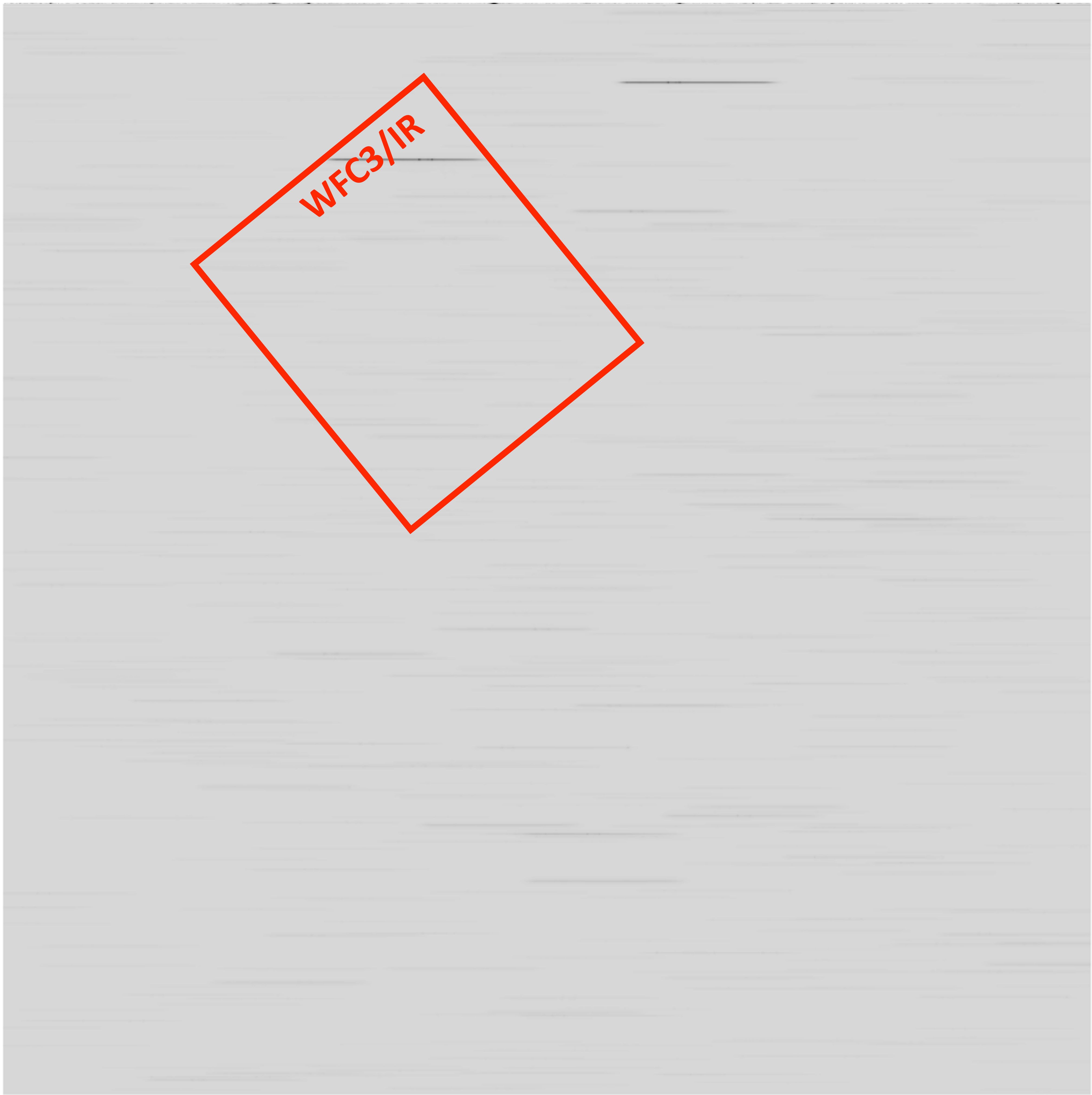
WFIRST Simulations: what can we expect?

Single 4k WFIRST detector

Dispersed by the HLS grism

Hα: 1.1 < z < 1.9
(full range 0.5 < z < 1.9)

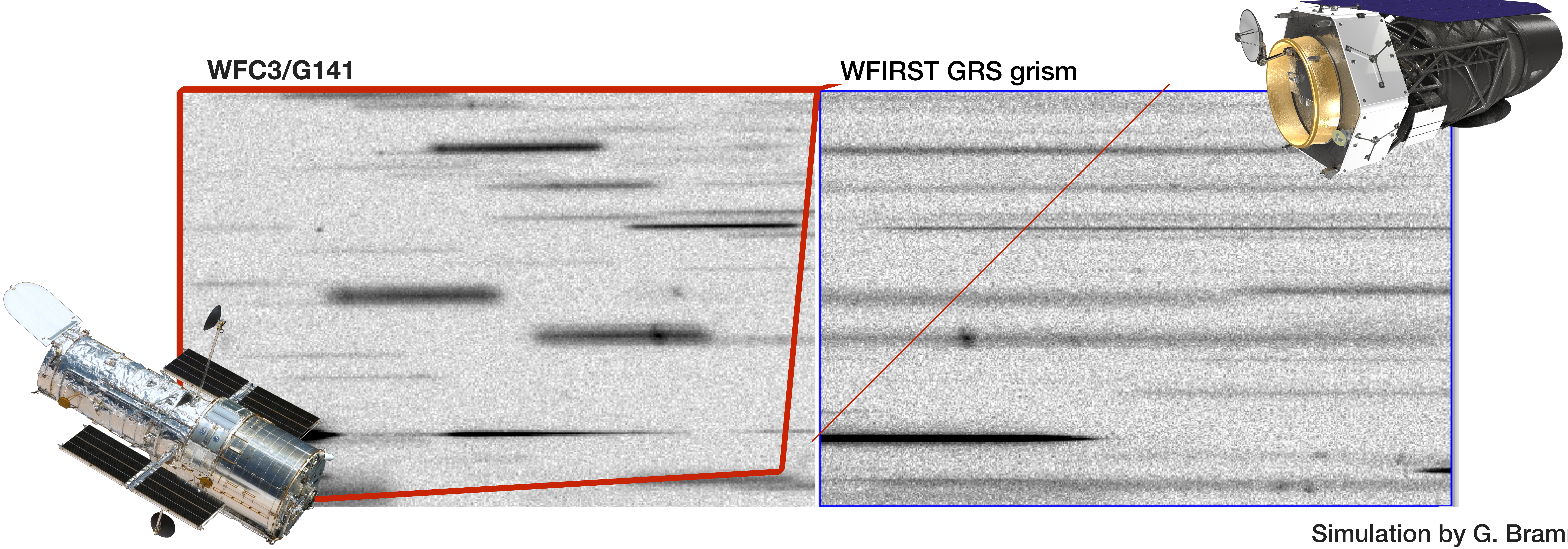
[OIII]+Hβ: 1.9 < z < 2.8
(full range 1.0 < z < 2.8)



Simulation by G. Brammer
https://github.com/gbrammer/grizli/

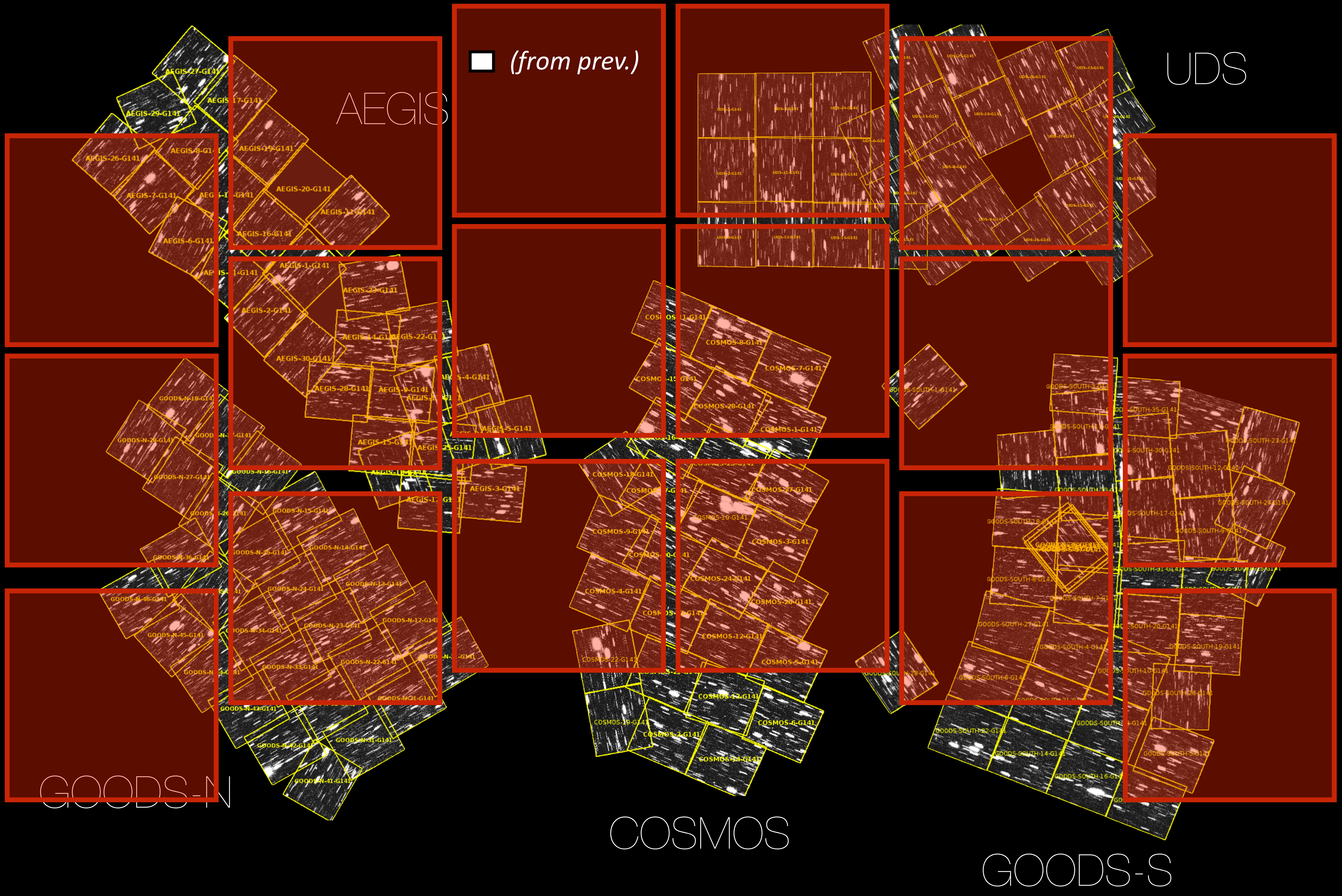
WFIRST: new capabilities with slitless spectroscopy

- **WFIRST GRS grism**
  - **0.28 deg^2** at a shot, **2000 deg^2 (!) High Latitude Survey** (z for BAO, RSD, public survey)
  - **2.4m** telescope (≈HST)
  - 1.0–1.9 μm, **R = 4 × G141** (e.g., just resolves Hα, [NII])

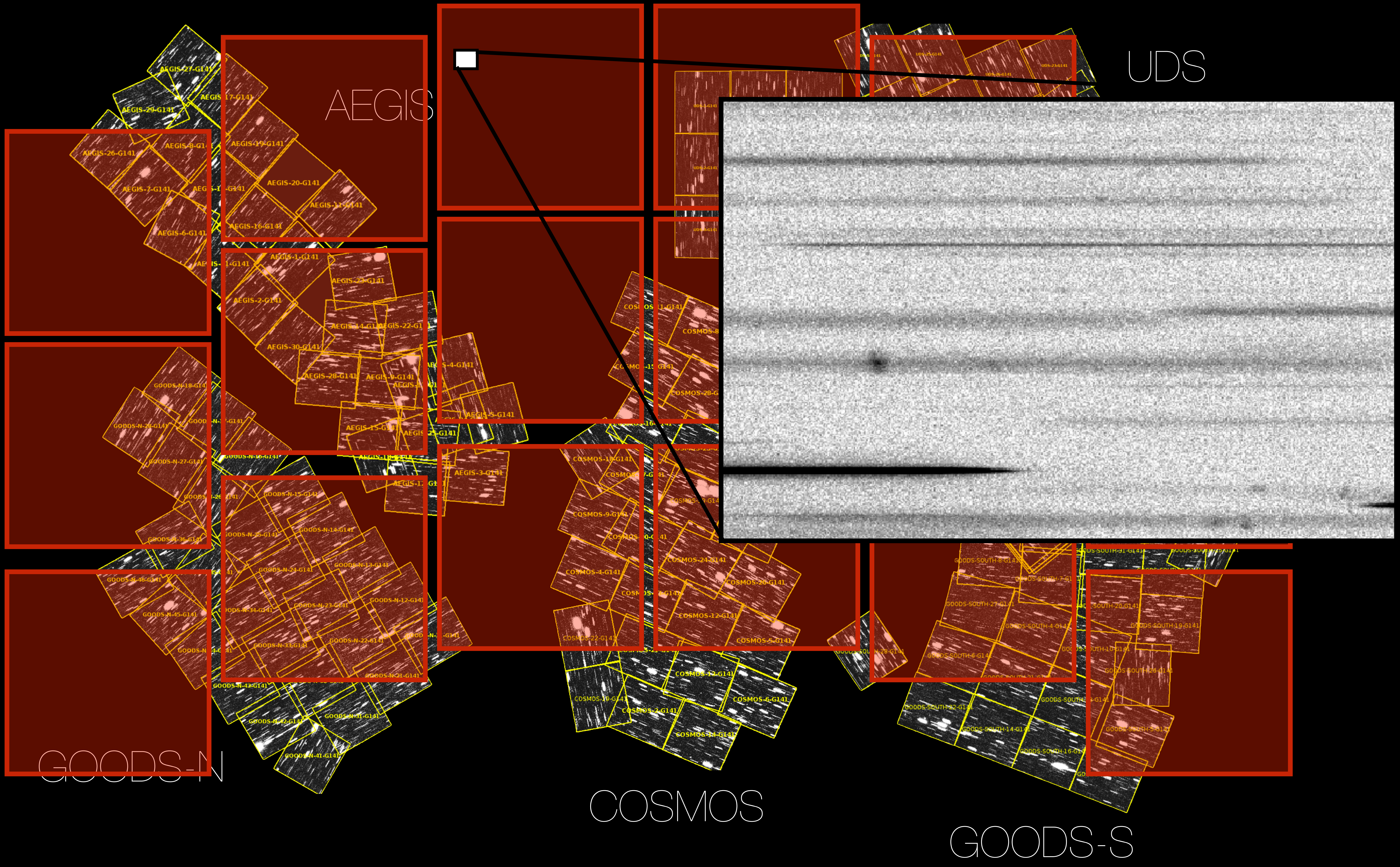


Simulation by G. Brammer
https://github.com/gbrammer/grizli/

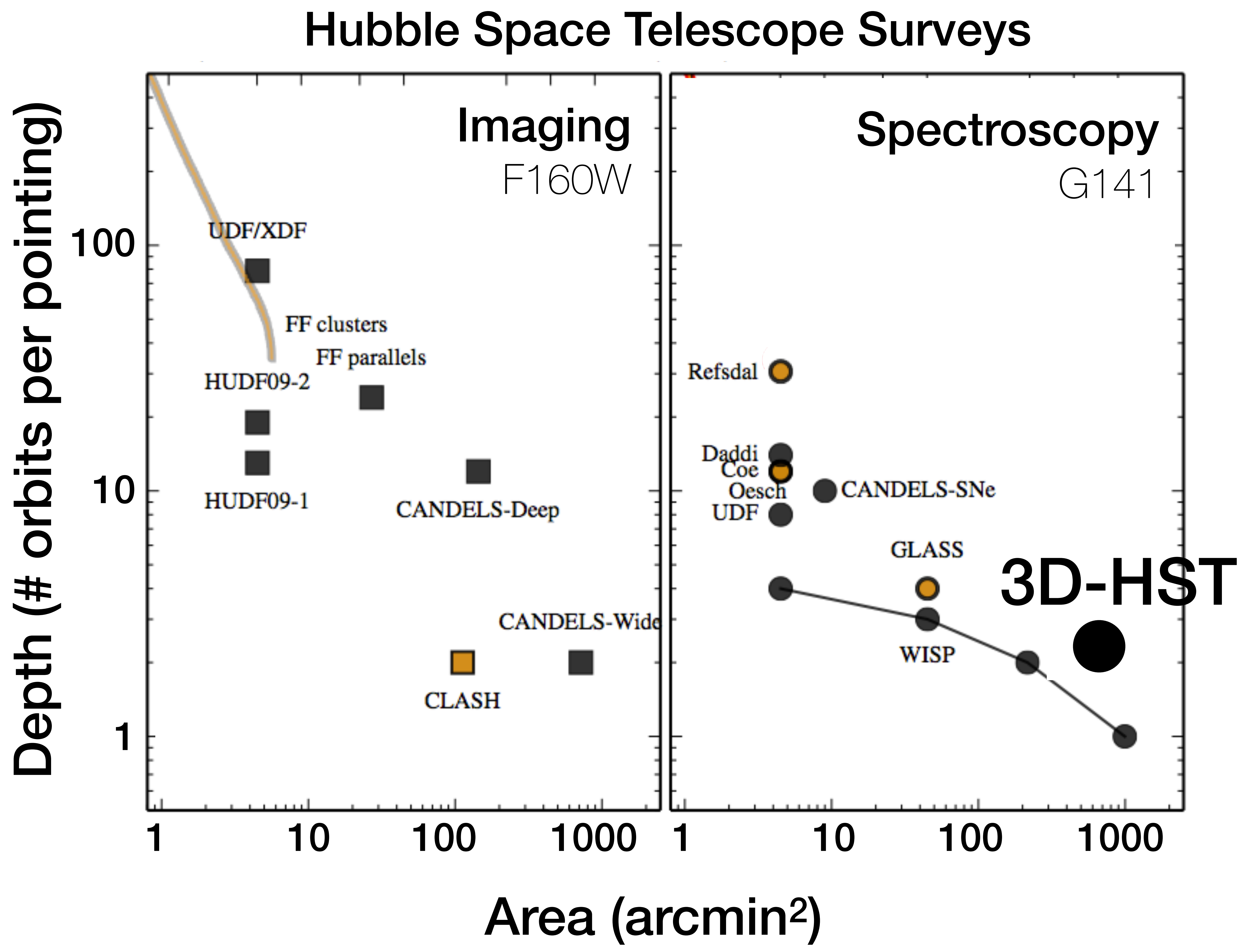
WFIRST: 0.28 deg² / pointing, 2000 deg² total



WFIRST: 0.28 deg² / pointing, 2000 deg² total

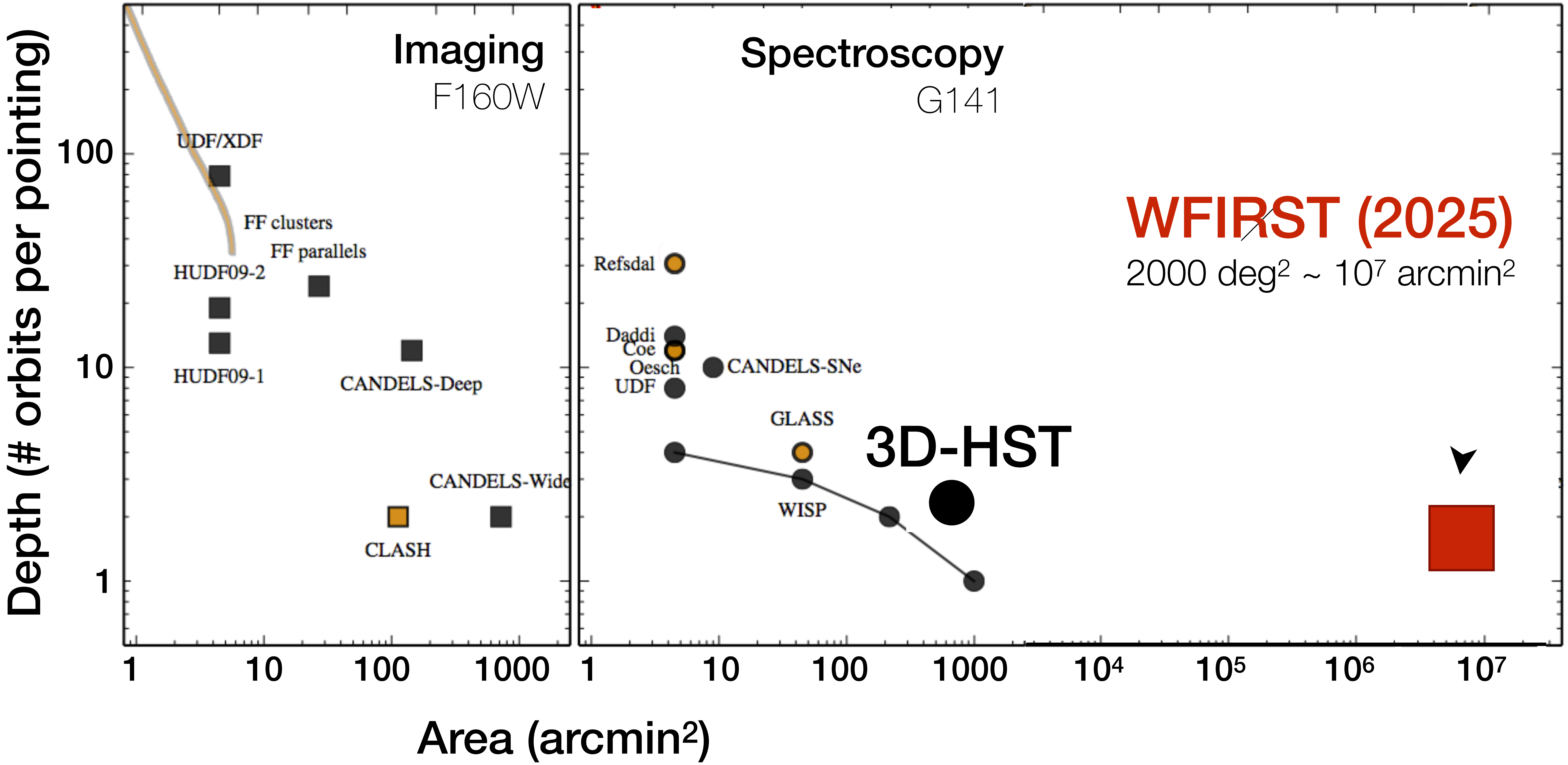


WFIRST High Latitude Survey pushes into uncharted parameter space



WFIRST High Latitude Survey pushes into uncharted parameter space

Hubble Space Telescope Surveys



Line Morphologies provide spatially resolved information on ~1kpc scales

- **2000 deg² (!)**
- **2.4m** telescope (≈HST)
- 1.0–1.9 μm
- **R = 4 × G141** (resolves Hα, [NII])

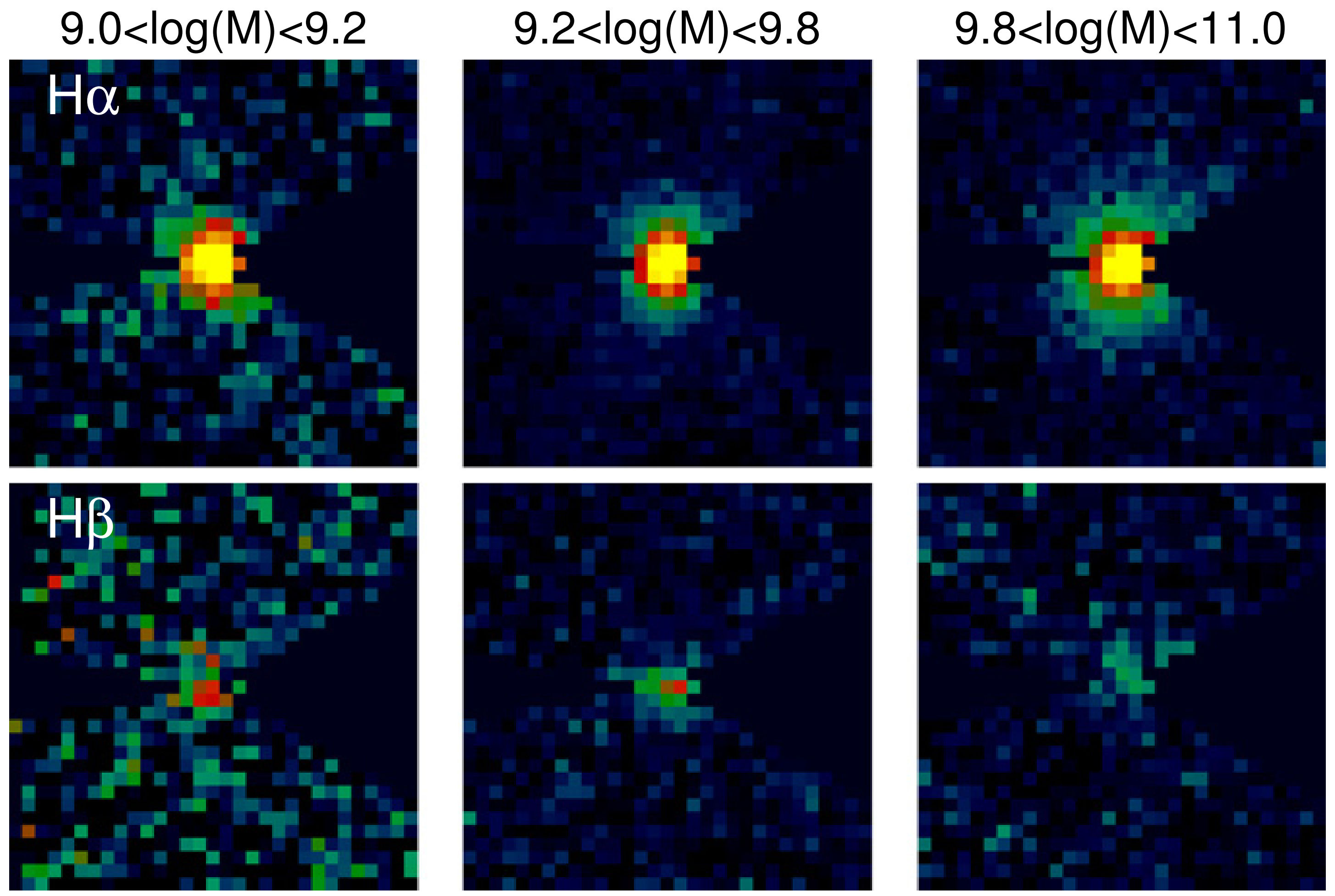
- **Star-formation activity** (SFR, $\Sigma_{SFR}(r)$) Wuyts et al. 2013, Nelson et al. 2016
- **Star-formation history** (Hα vs. continuum) Nelson et al. 2013, 2015
- **Dust extinction** Price et al. 2014, Nelson et al. 2016
- **Ages** Whitaker et al. 2013, Fumagalli et al. 2016
- **Active Galactic Nuclei** Trump et al. 2011, 2014, Bridge et al. 2016
- **Metallicity gradients** Jones et al. 2014, Wang et al. 2016
- **Age gradients** Whitaker et al., in prep
- **Cosmic Dawn** Oesch et al. 2016

Line Morphologies provide spatially resolved information on ~1kpc scales

- **2000 deg² (!)**
- **2.4m** telescope (≈HST)
- 1.0–1.9 μm
- **R = 4 × G141** (resolves Hα, [NII])

Offers amazing number statistics!

Nelson et al. 2016



N_{3DHST}~600 galaxies total

$N_{WFIRST-HLS}$~**10 million** galaxies total

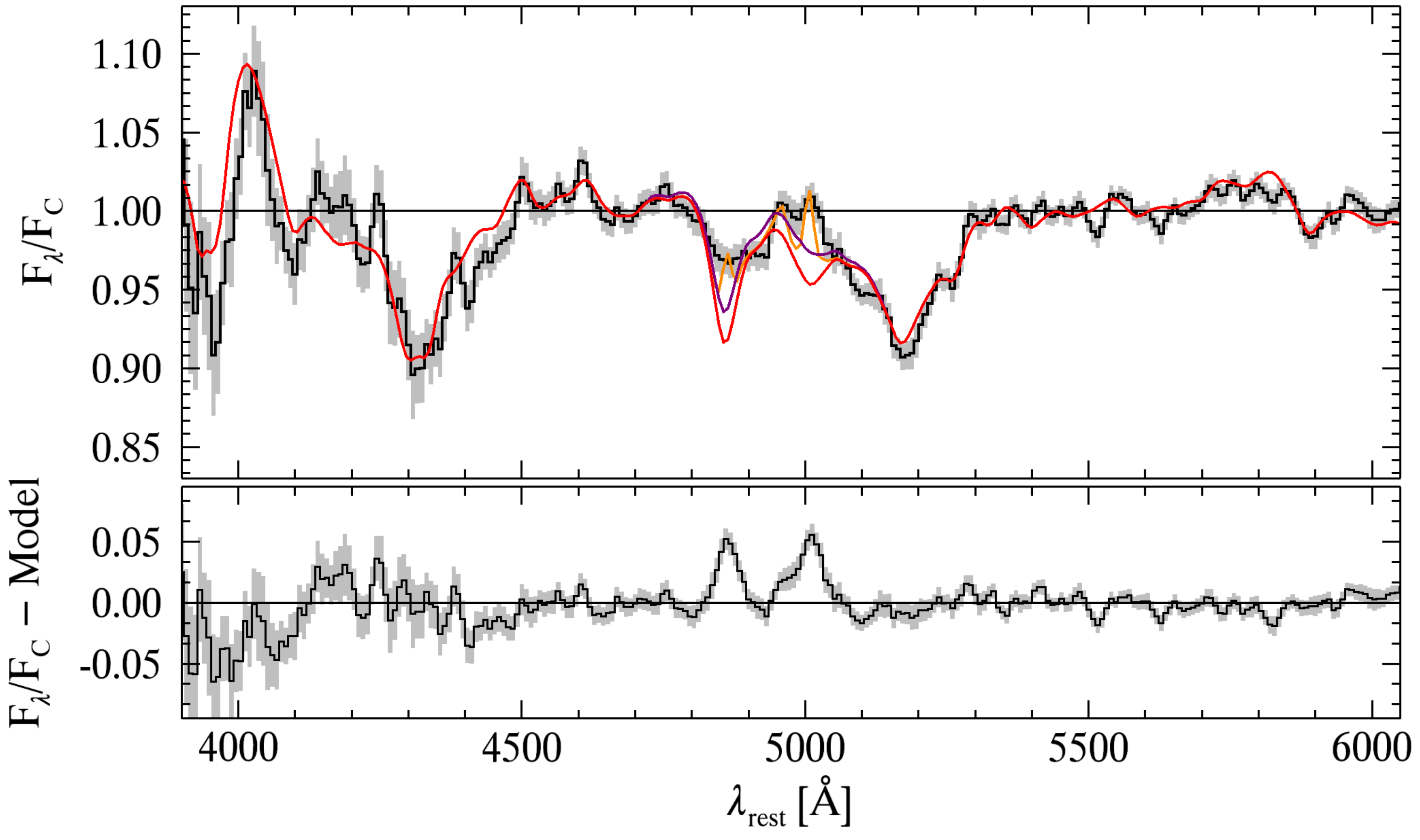
- **Star-formation activity** (SFR, $\Sigma_{SFR}(r)$) Wuyts et al. 2013, Nelson et al. 2016
- **Star-formation history** (Hα vs. continuum) Nelson et al. 2013, 2015
- **Dust extinction** Price et al. 2014, Nelson et al. 2016
- **Ages** Whitaker et al. 2013, Fumagalli et al. 2016
- **Active Galactic Nuclei** Trump et al. 2011, 2014, Bridge et al. 2016
- **Metallicity gradients** Jones et al. 2014, Wang et al. 2016
- **Age gradients** Whitaker et al., in prep
- **Cosmic Dawn** Oesch et al. 2016

Line Morphologies provide spatially resolved information on ~1kpc scales

- **2000 deg² (!)**
- **2.4m** telescope (≈HST)
- 1.0–1.9 μm
- **R = 4 × G141** (resolves Hα, [NII])

Offers amazing number statistics!

Whitaker et al. 2013



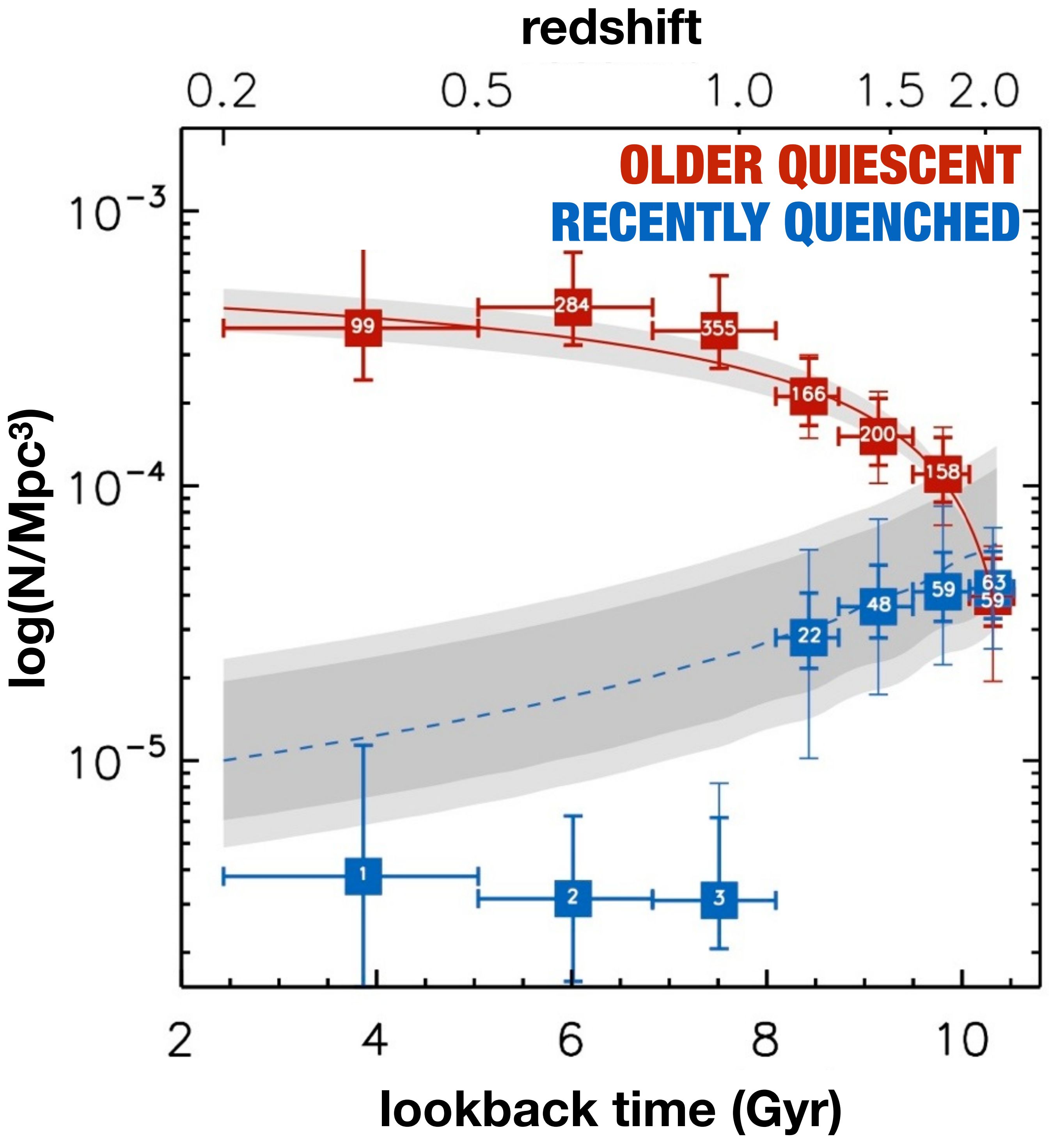
N_{3DHST}~200 quiescent galaxies

$N_{WFIRST\text{-}HLS}$~**2 million** quiescent galaxies

- **Star-formation activity** (SFR, $\Sigma_{SFR}(r)$) Wuyts et al. 2013, Nelson et al. 2016
- **Star-formation history** (Hα vs. continuum) Nelson et al. 2013, 2015
- **Dust extinction** Price et al. 2014, Nelson et al. 2016
- **Ages** Whitaker et al. 2013, Fumagalli et al. 2016
- **Active Galactic Nuclei** Trump et al. 2011, 2014, Bridge et al. 2016
- **Metallicity gradients** Jones et al. 2014, Wang et al. 2016
- **Age gradients** Whitaker et al., in prep
- **Cosmic Dawn** Oesch et al. 2016

Line Morphologies provide spatially resolved information on ~1kpc scales

- **2000 deg² (!)**
- **2.4m** telescope (≈HST)
- 1.0–1.9 μm
- **R = 4 × G141** (resolves Hα, [NII])



Whitaker et al. 2012

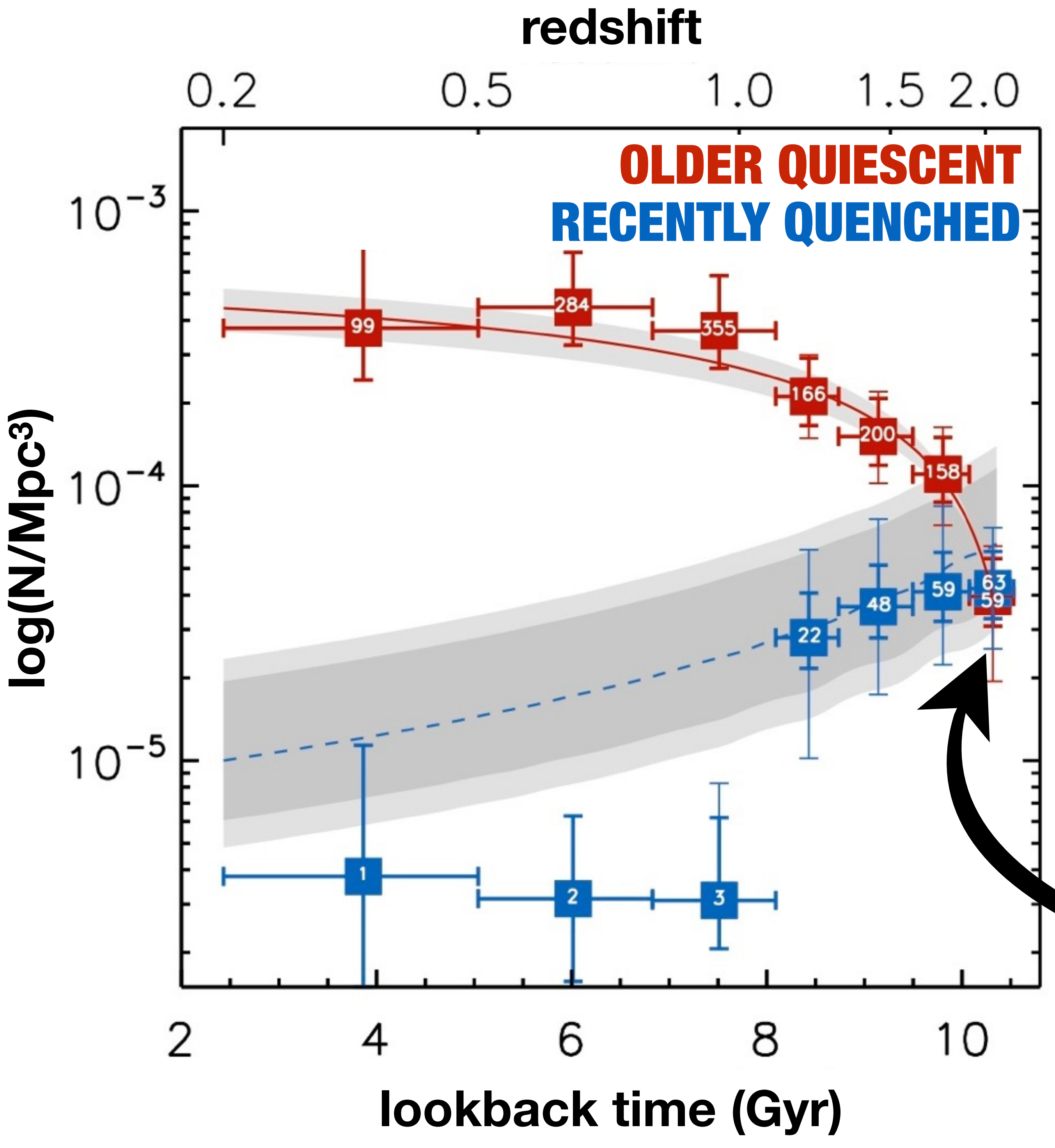
Wide area + unbiased sample + spectral information = perfect probe of ENVIRONMENT!

- **Star-formation activity** (SFR, $\Sigma_{SFR}(r)$) Wuyts et al. 2013, Nelson et al. 2016
- **Star-formation history** (Hα vs. continuum) Nelson et al. 2013, 2015
- **Dust extinction** Price et al. 2014, Nelson et al. 2016
- **Ages** Whitaker et al. 2013, Fumagalli et al. 2016
- **Active Galactic Nuclei** Trump et al. 2011, 2014, Bridge et al. 2016
- **Metallicity gradients** Jones et al. 2014, Wang et al. 2016
- **Age gradients** Whitaker et al., in prep
- **Cosmic Dawn** Oesch et al. 2016

Line Morphologies provide spatially resolved information on ~1kpc scales

- **2000 deg² (!)**
- **2.4m** telescope (≈HST)
- 1.0–1.9 μm
- **R = 4 × G141** (resolves Hα, [NII])

Wide area + unbiased sample + spectral information
= perfect probe of ENVIRONMENT!



Whitaker et al. 2012

- **Star-formation activity** (SFR, Σ_{SFR}(r)) Wuyts et al. 2013, Nelson et al. 2016
- **Star-formation history** (Hα vs. continuum) Nelson et al. 2013, 2015
- **Dust extinction** Price et al. 2014, Nelson et al. 2016
- **Ages** Whitaker et al. 2013, Fumagalli et al. 2016
- **Active Galactic Nuclei** Trump et al. 2011, 2014, Bridge et al. 2016
- **Metallicity gradients** Jones et al. 2014, Wang et al. 2016

al., in prep

. 2016

WFIRST takes us from ~50 to ~50,000 recently quenched galaxies at z~2!

Line Morphologies provide spatially resolved information on ~1kpc scales

- **2000 deg² (!)**
- **2.4m** telescope (≈HST)
- 1.0–1.9 μm
- **R = 4 × G141** (resolves Hα, [NII])

Wide area + unbiased sample + spectral information = perfect probe of ENVIRONMENT!

- What role does environment play in star formation efficiency?
- Does dust attenuation depend on environment?
- Do galaxies quench earlier in denser environments?
- What role do AGN play in quenching?
- …

- **Star-formation activity** (SFR, $\Sigma_{SFR}(r)$) Wuyts et al. 2013, Nelson et al. 2016
- **Star-formation history** (Hα vs. continuum) Nelson et al. 2013, 2015
- **Dust extinction** Price et al. 2014, Nelson et al. 2016
- **Ages** Whitaker et al. 2013, Fumagalli et al. 2016
- **Active Galactic Nuclei** Trump et al. 2011, 2014, Bridge et al. 2016
- **Metallicity gradients** Jones et al. 2014, Wang et al. 2016
- **Age gradients** Whitaker et al., in prep
- **Cosmic Dawn** Oesch et al. 2016

Line Morphologies provide spatially resolved information on ~1kpc scales

- **2000 deg² (!)**
- **2.4m** telescope (≈HST)
- 1.0–1.9 μm
- **R = 4 × G141** (resolves Hα, [NII])

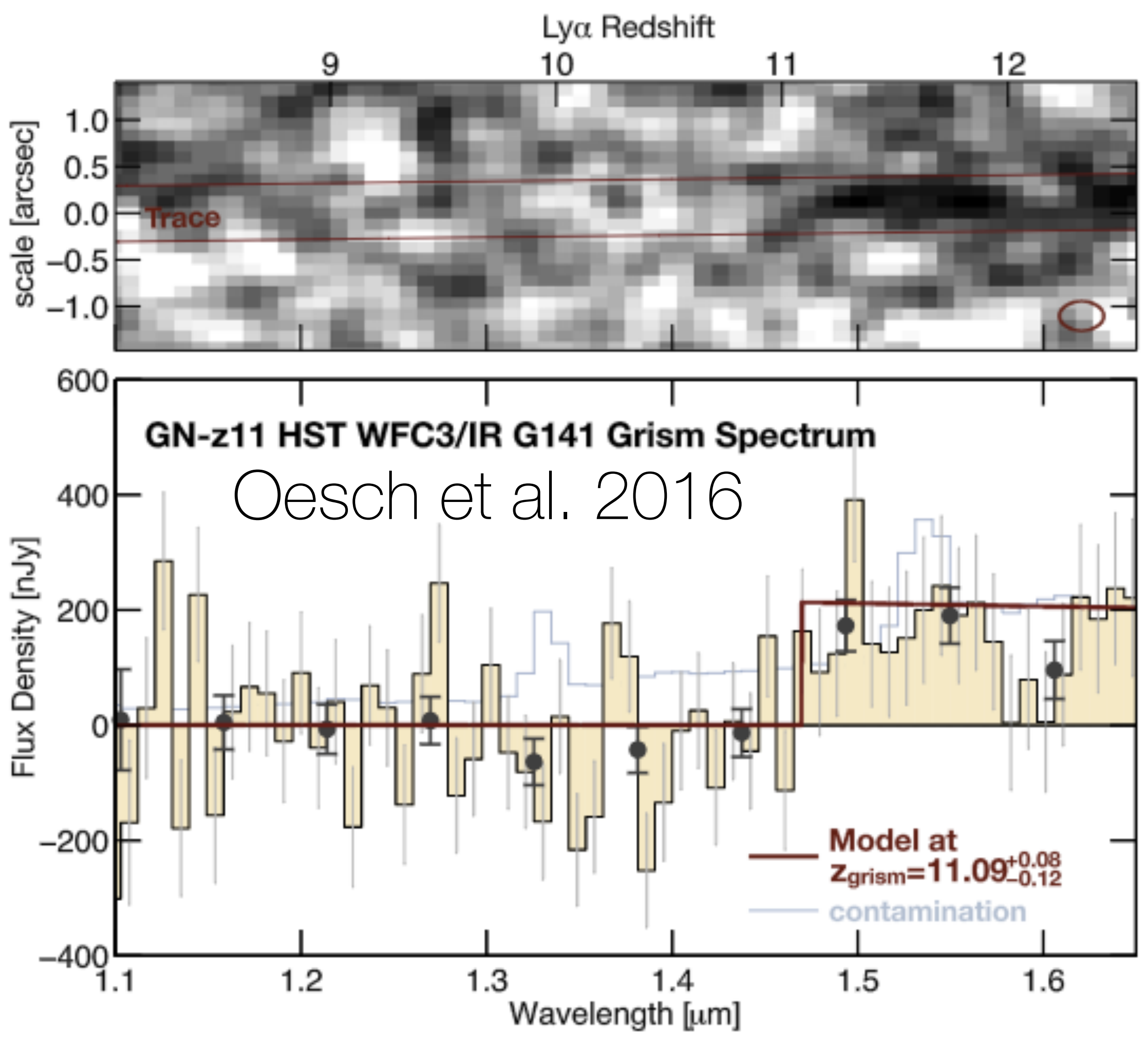
Wide area + unbiased sample + spectral information = perfect probe of ENVIRONMENT!

- **Star-formation activity** (SFR, $\Sigma_{SFR}(r)$) Wuyts et al. 2013, Nelson et al. 2016
- **Star-formation history** (Hα vs. continuum) Nelson et al. 2013, 2015
- **Dust extinction** Price et al. 2014, Nelson et al. 2016
- **Ages** Whitaker et al. 2013, Fumagalli et al. 2016
- **Active Galactic Nuclei** Trump et al. 2011, 2014, Bridge et al. 2016
- **Metallicity gradients** Jones et al. 2014, Wang et al. 2016
- **Age gradients** Whitaker et al., in prep
- **Cosmic Dawn** Oesch et al. 2016

New samples of gravitationally lensed targets! {Metallicity gradients, Age gradients}

Line Morphologies provide spatially resolved information on ~1kpc scales

- **2000 deg² (!)**
- **2.4m** telescope (≈HST)
- 1.0–1.9 μm
- **R = 4 × G141** (resolves Hα, [NII])



WFIRST will reveal 100s-1000s of luminous galaxies in the epoch of reionization!

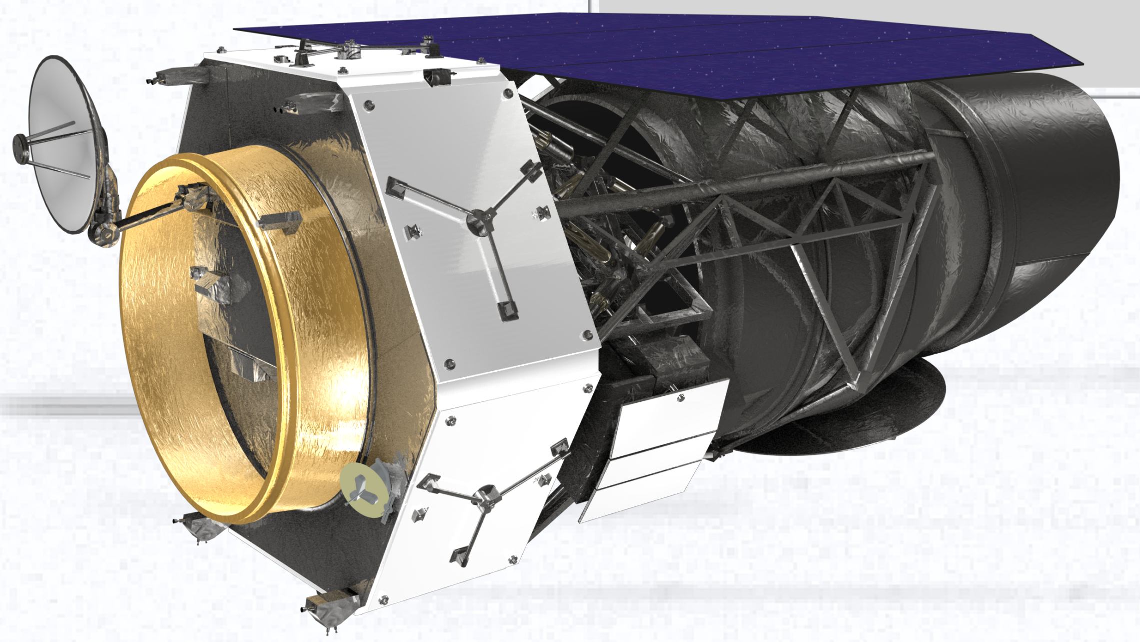
Wide area + unbiased sample + spectral information = perfect probe of ENVIRONMENT!

- **Star-formation activity** (SFR, $\Sigma_{SFR}(r)$) Wuyts et al. 2013, Nelson et al. 2016
- **Star-formation history** (Hα vs. continuum) Nelson et al. 2013, 2015
- **Dust extinction** Price et al. 2014, Nelson et al. 2016
- **Ages** Whitaker et al. 2013, Fumagalli et al. 2016
- **Active Galactic Nuclei** Trump et al. 2011, 2014, Bridge et al. 2016
- **Metallicity gradients** Jones et al. 2014, Wang et al. 2016
- **Age gradients** Whitaker et al., in prep
- **Cosmic Dawn** Oesch et al. 2016

Galaxy Formation & Evolution in the WFIRST Era:

From Census to Synthesis of the Lifecycles of Galaxies

- Slitless grism surveys like 3D-HST offer a **highly complete spectroscopic resource** for galaxy evolution studies
- The slitless nature of the spectra presents **formidable data analysis challenges**, but with **significant benefits** (e.g., continuum depth, completeness, spatial resolution)
- Lessons, science, and targets from current HST grism programs will help pave the way for upcoming space missions like WFIRST!



Kate Whitaker

Assistant Professor
University of Connecticut
www.whitaker.physics.uconn.edu