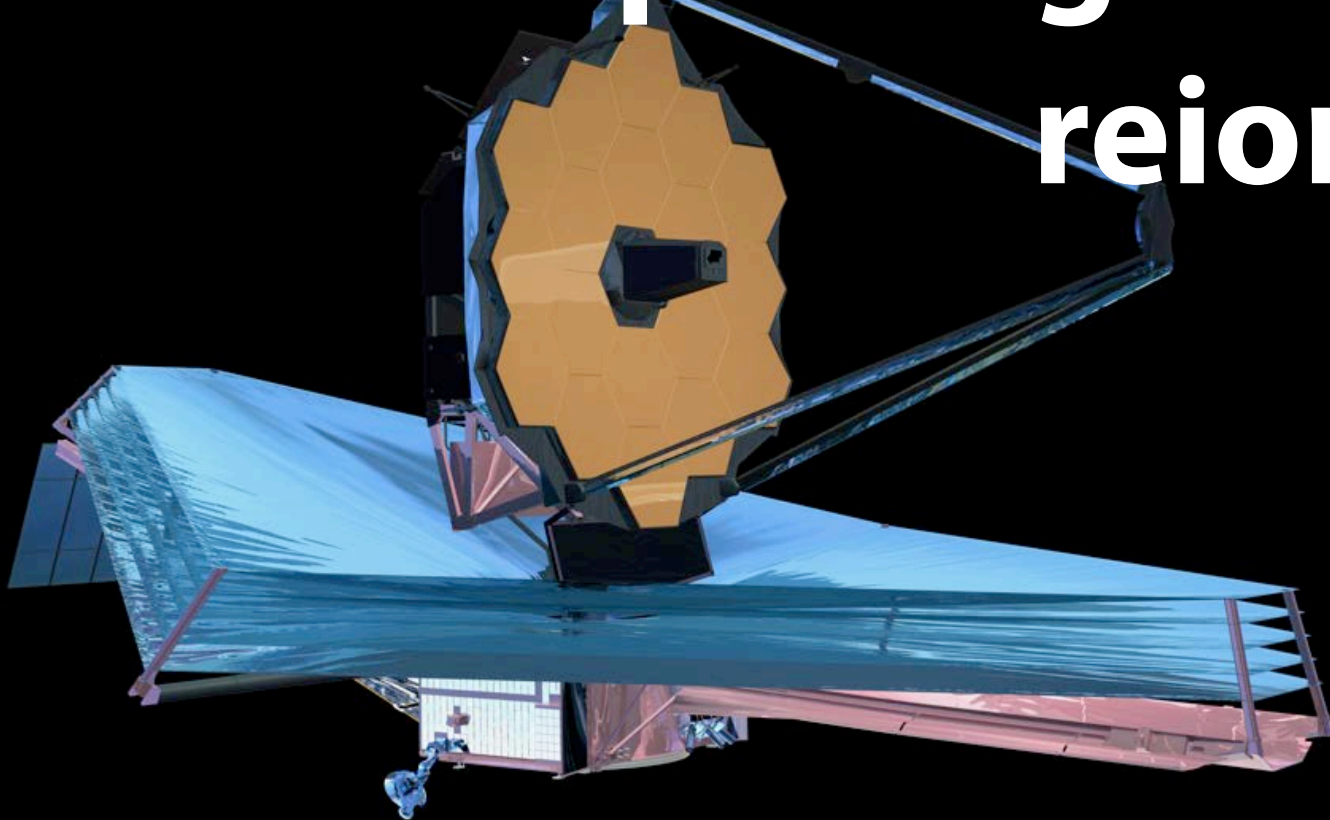
銀河・銀河間ガス研究会, 筑波, 8-10 Aug 2018

Exploring the end tail of cosmic reionization with JWST



Daichi Kashino (ETH Zurich)

Collaboration with
S. Lilly, R. Simcoe, B. Rongmon

Today's talk

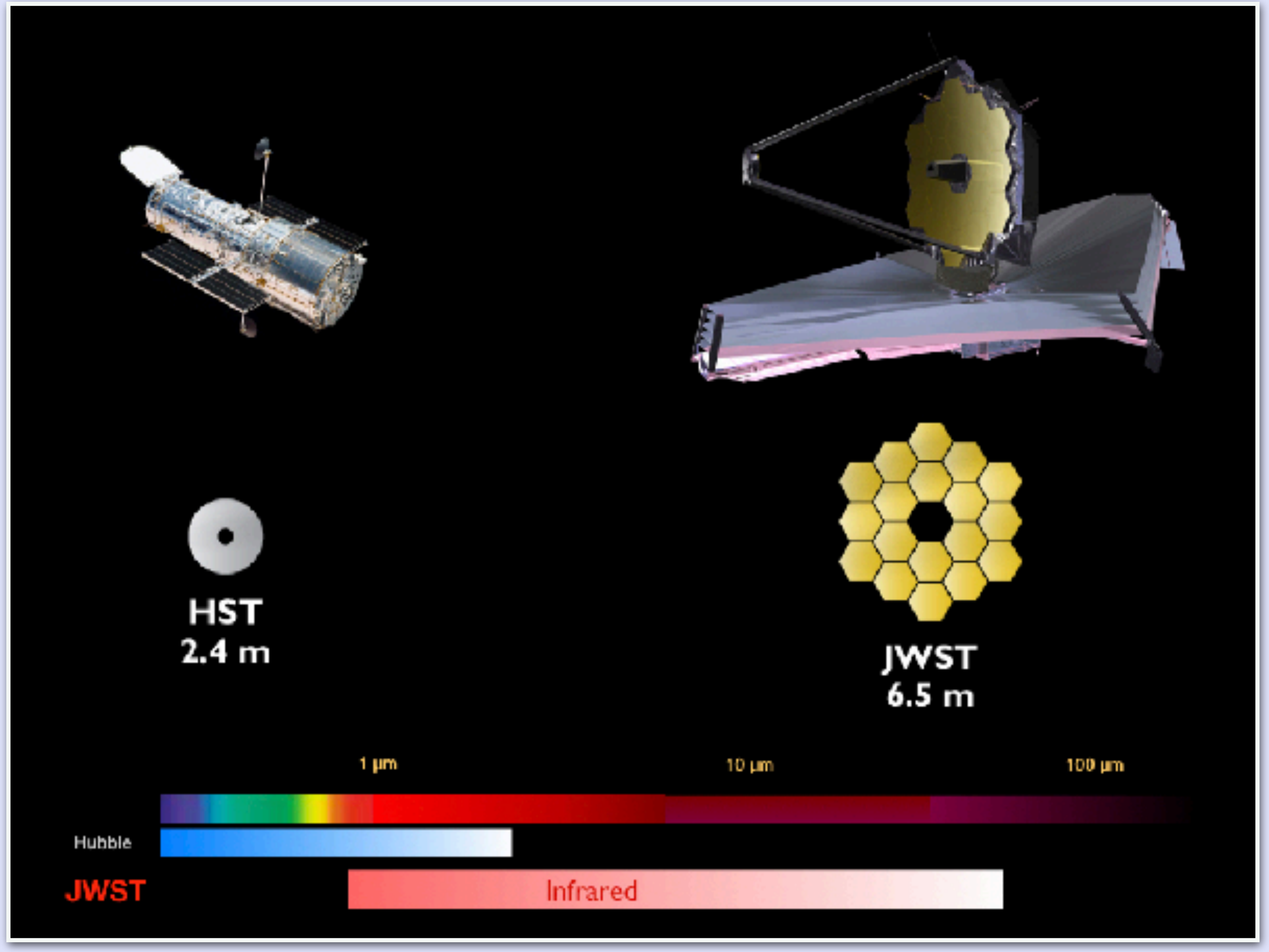
- Overview of JWST, the instruments, and the ERS programs
- Our project: exploring the end of reionization
  - Variation in τHI with galaxy density
  - Identification of the host systems of metal absorbers
- Summary

Overview of JWST, the instruments, and the ERS programs

Technical information is based mostly on
JWST User Documentation
https://jwst-docs.stsci.edu

What is JWST?

- **Open our window to INFRARED (up to 25μm)!**
  - High-resolution and very deep “rest-frame optical” images and **<u>spectra</u>** in the reionization era!



What is JWST?

- **Open our window to INFRARED (up to 25μm)!**
  - High-resolution and very deep "rest-frame optical" images and **spectra** in the reionization era!

- Lifetime
  - at least 5.5 years after launch, with the goal having >10 years.
  - Limited by the amount of fuel to control the attitude and to maintain the orbit.

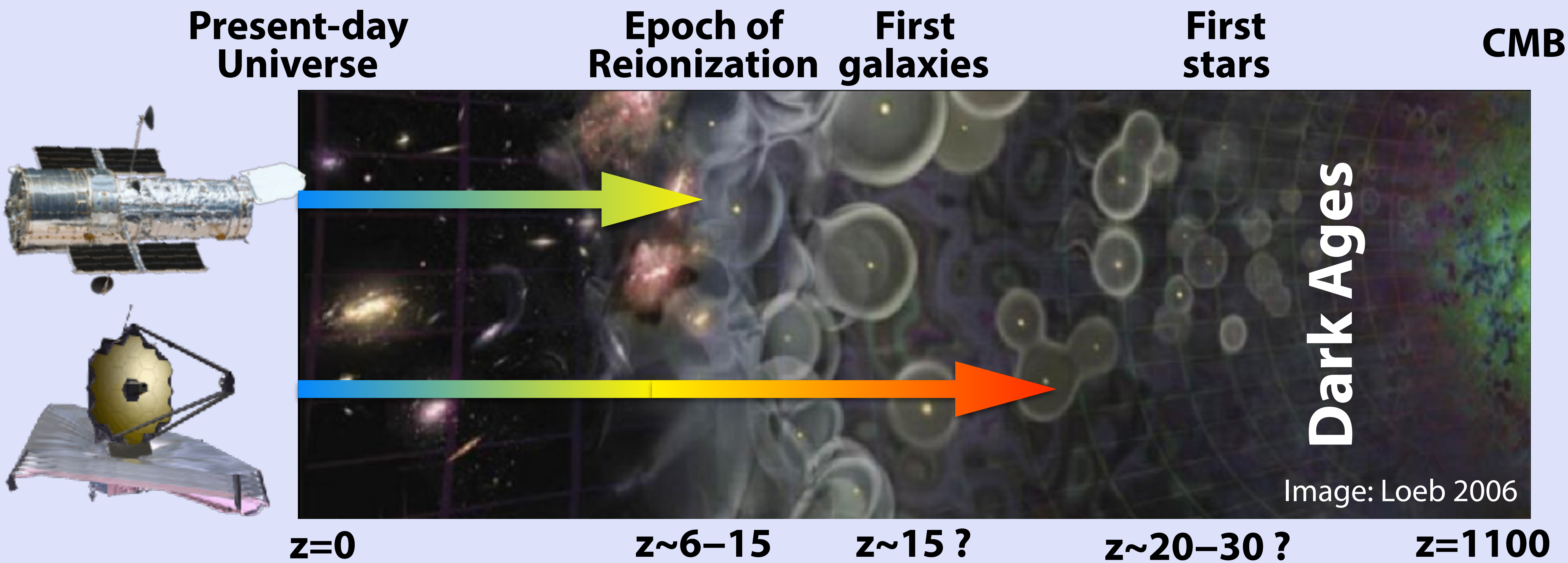
- Very expensive
  - 10 billion USD ~ 1兆円 (25 x Subaru)

A major goal of JWST

Exploring out to the end of dark ages

Formation of first luminous objects

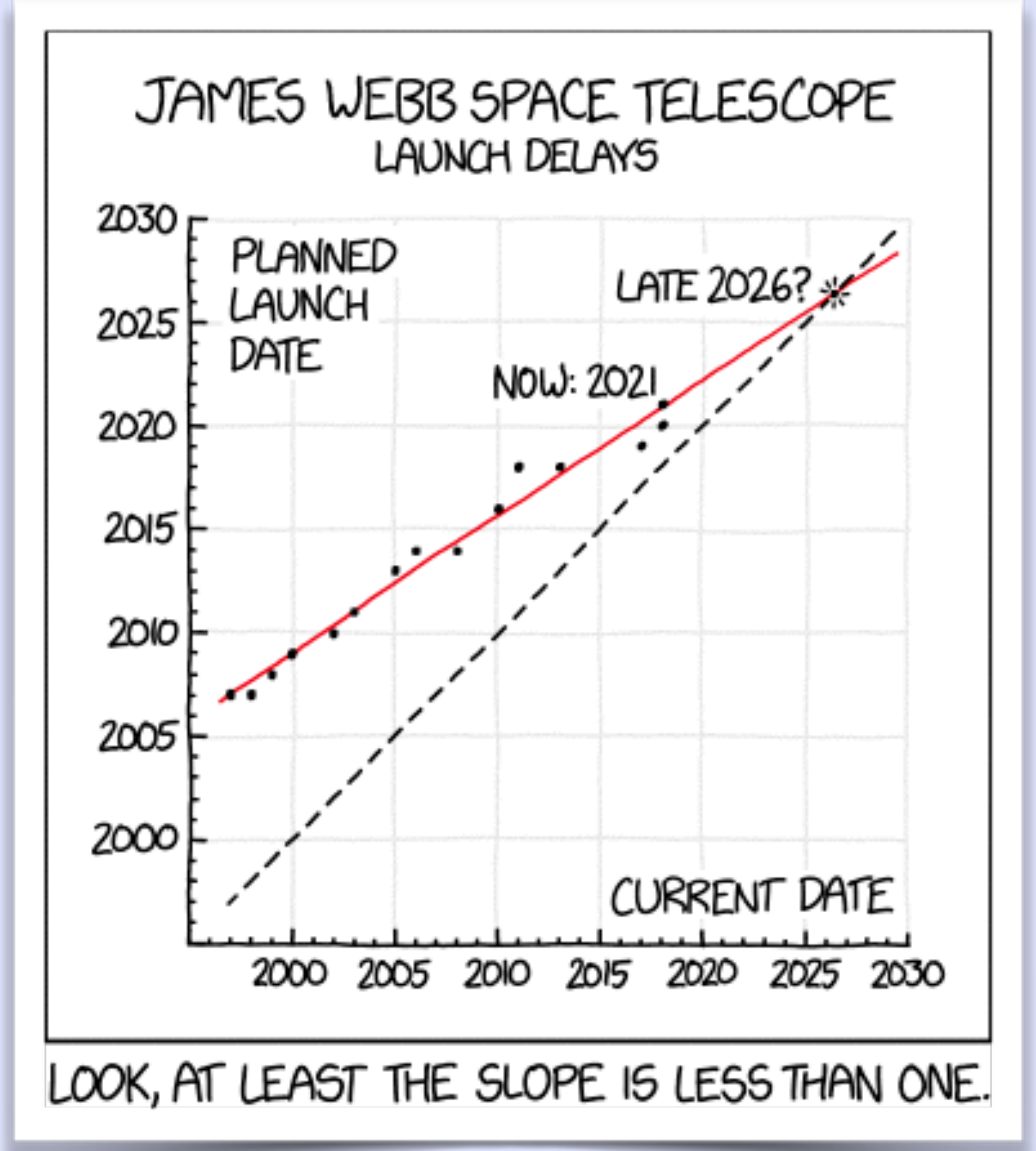
Cosmic reionization



When will he fly?

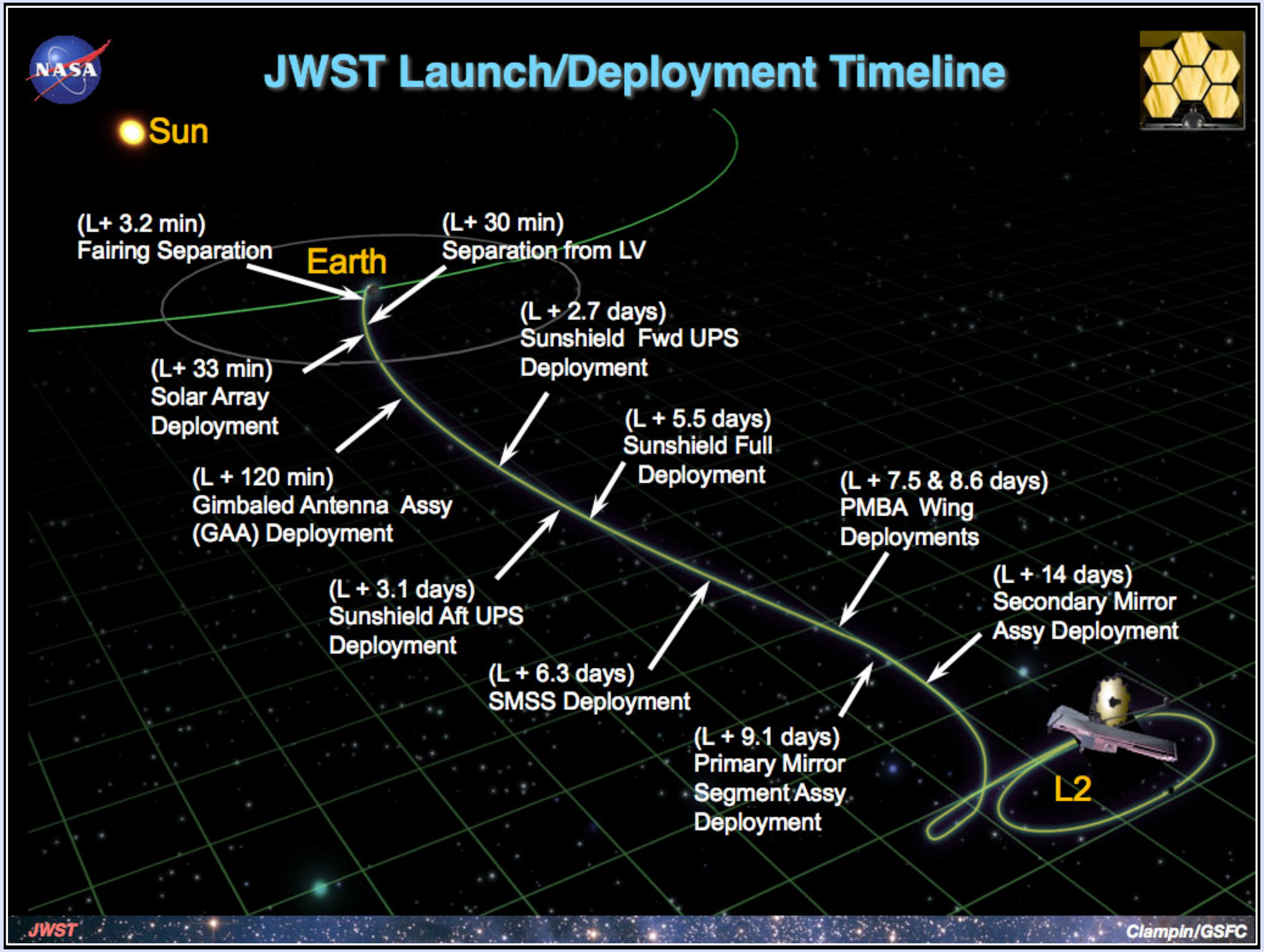
- Currently, being re-scheduled in 2022.

- Recent delays
  - 2017 Sept:
    delayed to Spring 2019
    from Oct 2018
  - 2018 March:
    delayed until 2020 Spring
  - 2018 June:
    delayed until 2021 March 30 (20?)
  - **Proposal deadline:
    no earlier than Feb 1 2020,
    ~9 months before launch**



Where will he go?

- The L2 point in the Sun-Earth system
- Deployment + commissioning ~ half a year

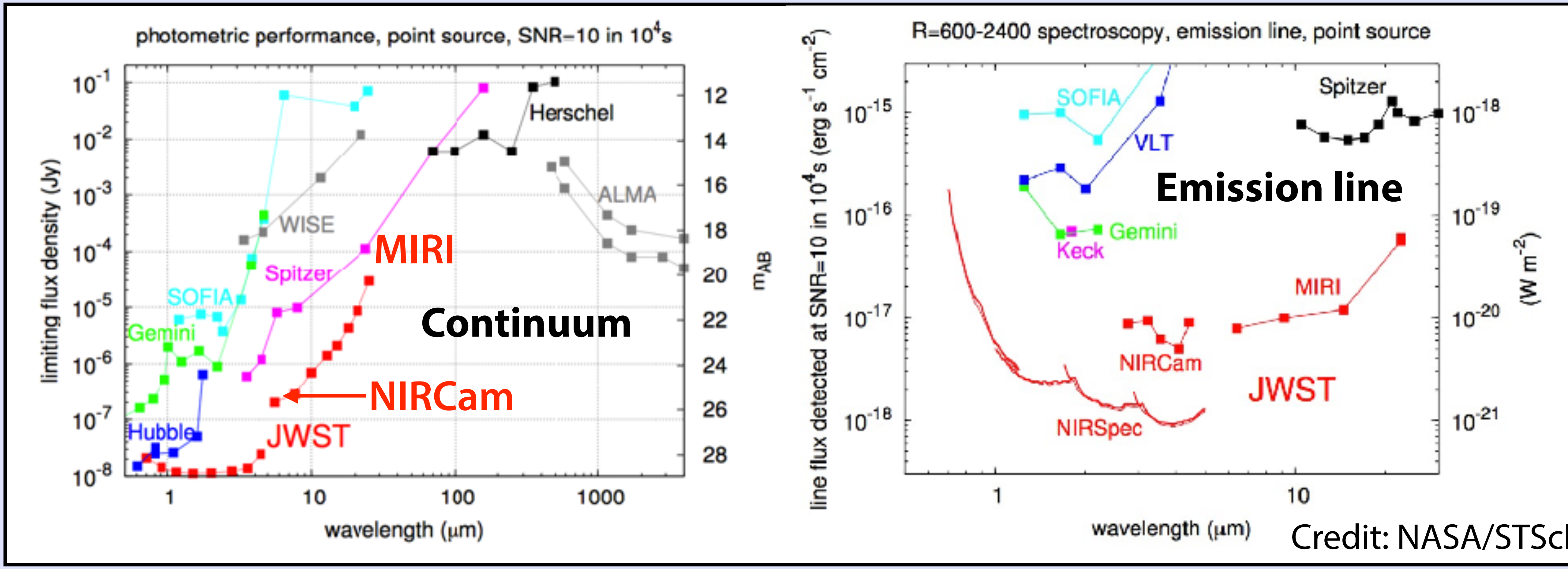


Science instruments

Instrument	What we can do?
Near-InfraRed Camera **NIRCam**	• Imaging at 0.6–5.0 μm in two 2.2′ x 2.2′ FoVs • Wide-field Slitless spectroscopy (WFSS; R~1000) • Coronagraphic imaging
Mid-InfraRed Instrument **MIRI**	• Imaging at 5.6–25.5 μm in 74" × 113" FOV • Low-resolution slitted and slit less spectroscopy • IFU spectroscopy in 4.9–28.8 μm • Coronagraphic imaging
Near-InfraRed Spectrograph **NIRSpec**	• MOS with multi-shutter assembly at 0.6–5.3 μm • 3″ x 3″ IFU spectroscopy • High contrast single object spectroscopy
Near InfraRed Imager and Slitless Spectrograph **NIRISS**	• Low-res. (R~150) WFSS in 0.8–5.0 μm (2.2′ x 2.2′ FoV) • Single object slit less spectroscopy • Aperture-masking interferometry (beyond λ/D) • Imaging at 0.9 and 5.0 μm

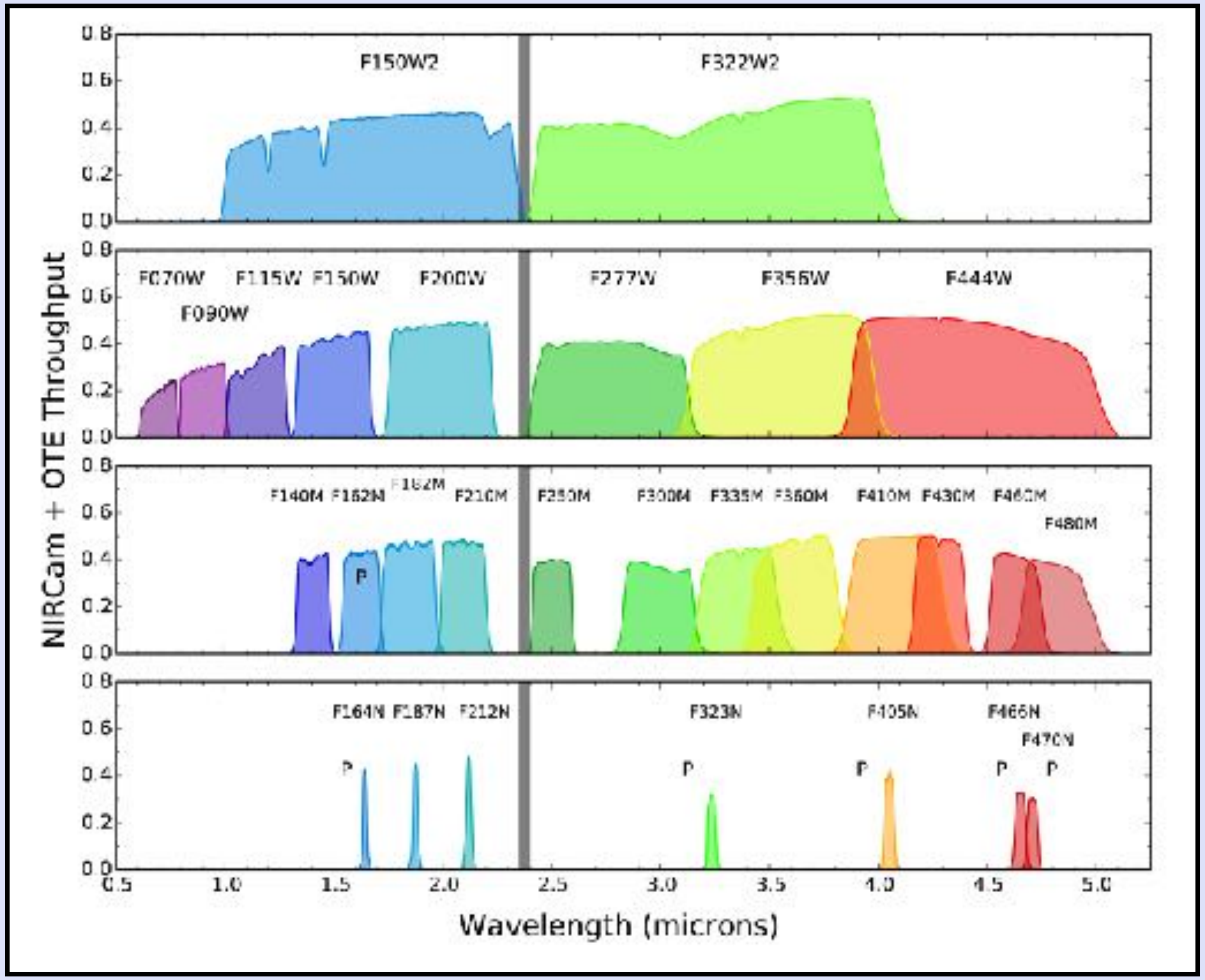
Sensitivities at a glance

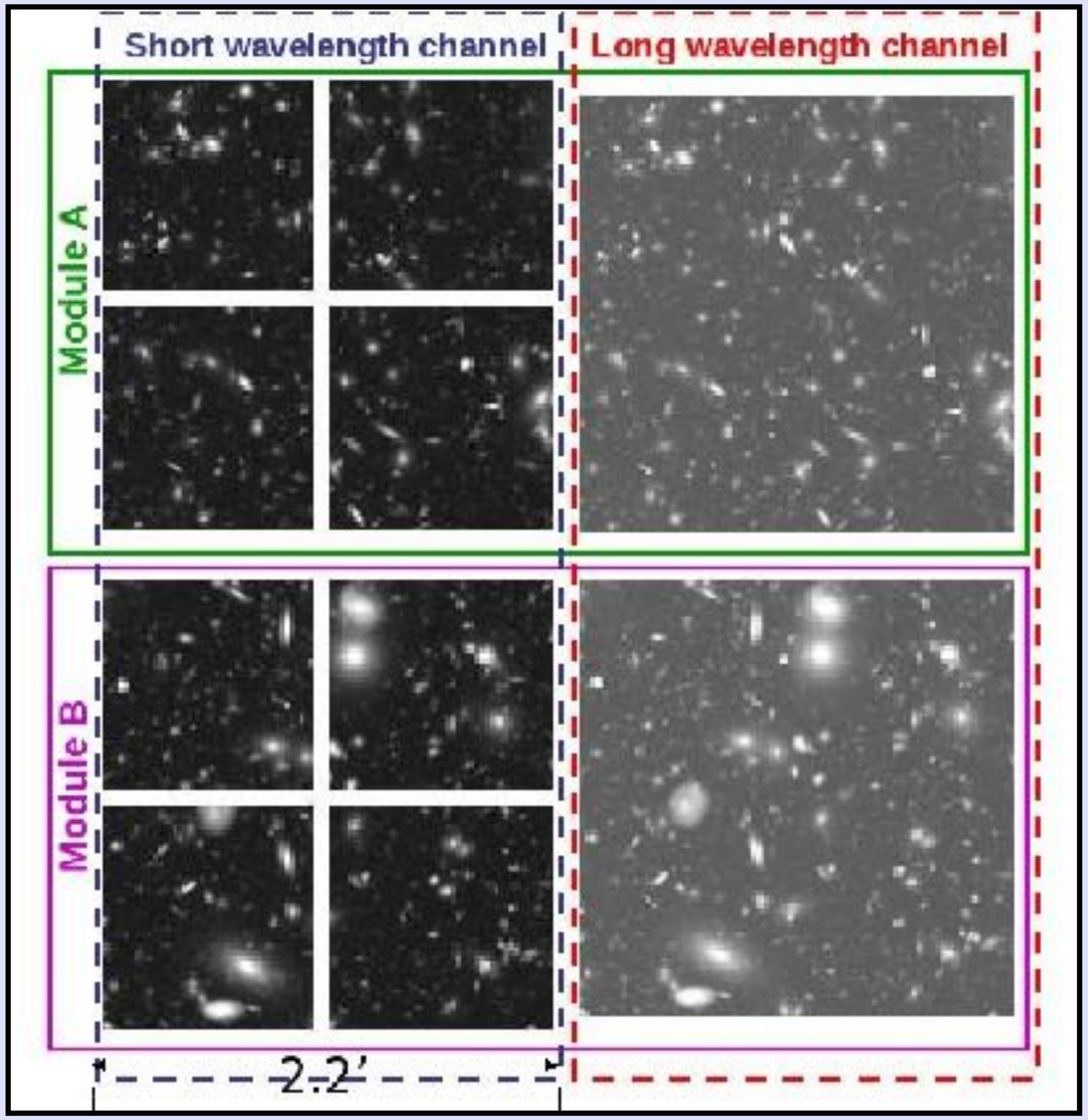
- **SNR=10 in 10⁴ seconds**



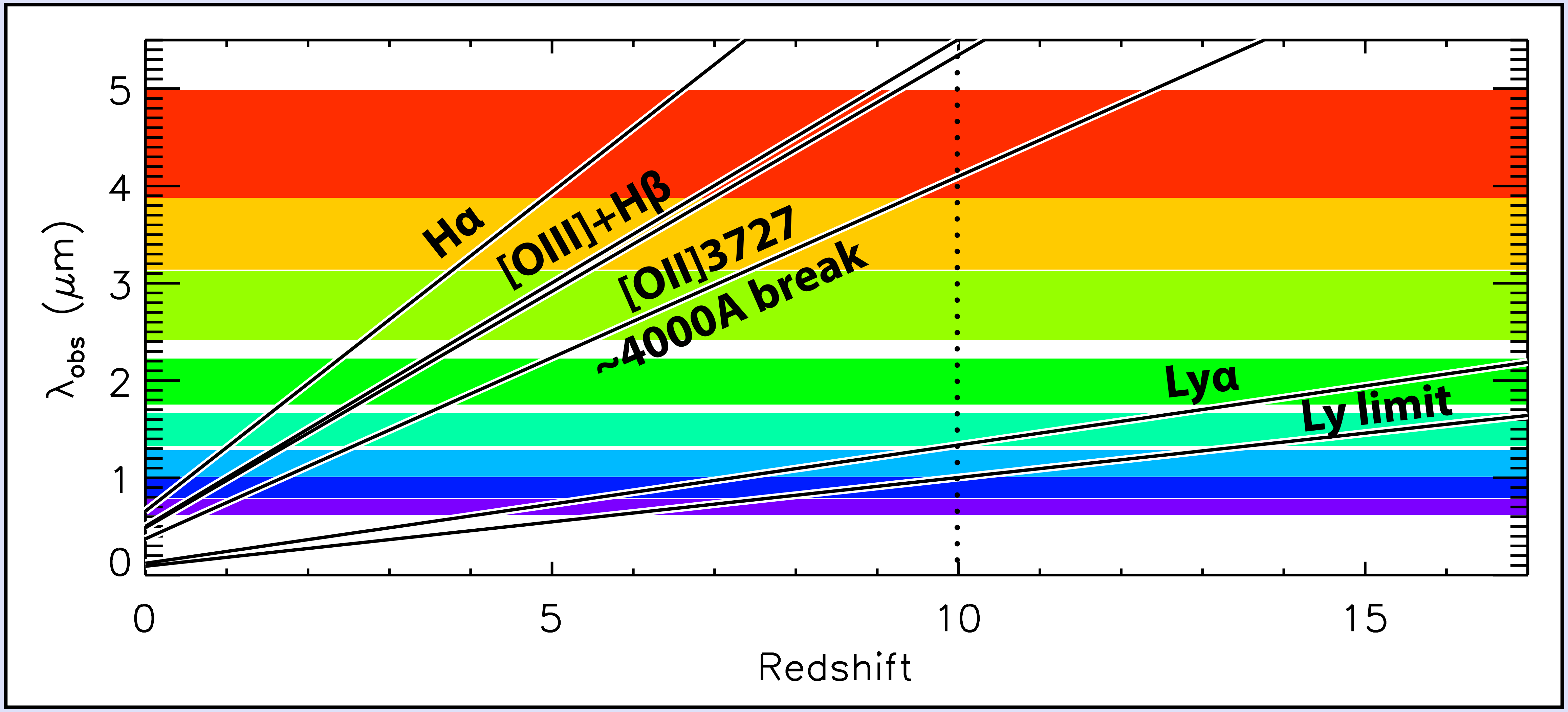
Primary survey camera: NIRCam (PI Marcia Rieke)

- Simultaneous dichroic imaging of 0.6 - 2.3 µm and 2.4 - 5.0 µm, over two 2.2′ x 2.2′ FoVs
- Wide-field Slitless spectroscopy (WFSS; R~1000) in long-wavelength
- Coronagraphic imaging





- Rest-optical strong lines from mid-reionization era
- Three-color diagnosis (like UGR, BzK) up to z~10
- High enough sensitivity to detect Lyα and/or Lyman-break at z>11
- Possible rest-UV detection even beyond z~15
- High-S/N spectroscopy with NIRSpec with the same spectral coverage



Early Release Science (ERS)

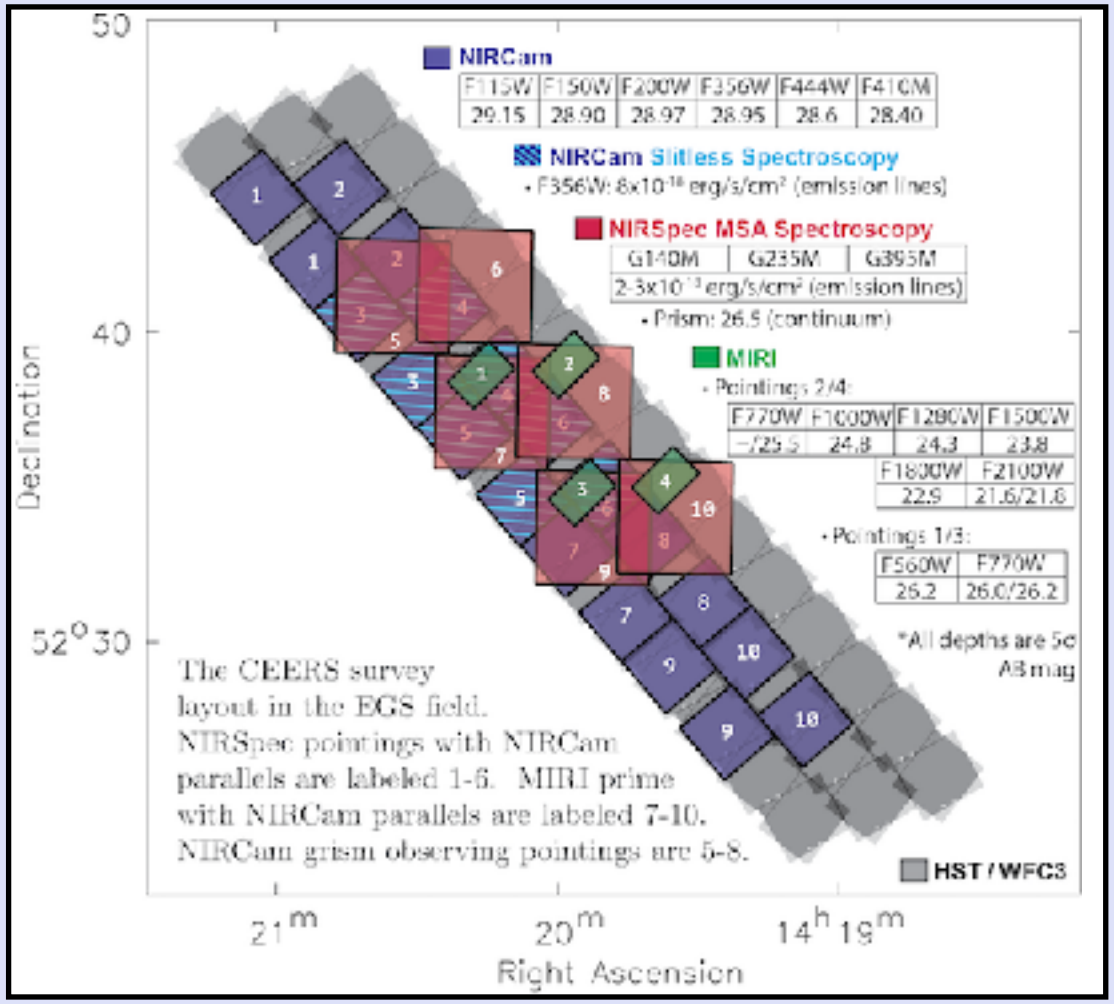
- Will take place during the first 5 months of the science operations
- **No exclusive access period**
- A couple of programs in each science area:
  - Solar system
  - Planets and planet formation
  - Stellar population
  - Stellar physics
  - Massive black holes and their host galaxies
  - **Galaxies and IGM**

Cosmic Evolution Early Release Science Survey (CEERS)

PI Steven Finkelstein (University of Texas at Austin)

- Imaging and spectroscopy covering ~100 sq. arcmin of the HST/CANDELS field
- **Imaging**: NIRCam and MIRI
- **Spectroscopy**: NIRSpec MSA (R~100 and 1000) and NIRCam grism (R~1500)

- ***"First Light and Reionization" and "The Assembly of Galaxies":***
  - The discovery of 20-80 galaxies at z~9-13
  - Deep spectra of >400 galaxies at z>3
  - dust-obscured star-formation and supermassive black hole growth at z~1-3.



Our GTO program:
Exploring the end of cosmic reionization

PI Simon Lilly, ETH Zurich
In collaboration with Rob Simoe, Rongmon Bordoloi (MIT)

We have various major goals:

- The structures of the IGM opacity and galaxies at $z\sim6$
- The identification of the host systems of metal absorbers at $z>5$
- The nature of $z>6$ quasars and their host galaxies
- Ancillary science investigations of star-forming galaxies at $z=4$–5

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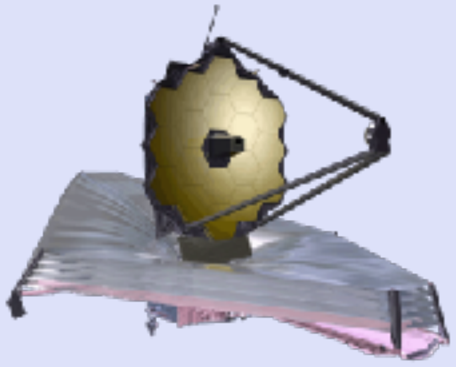
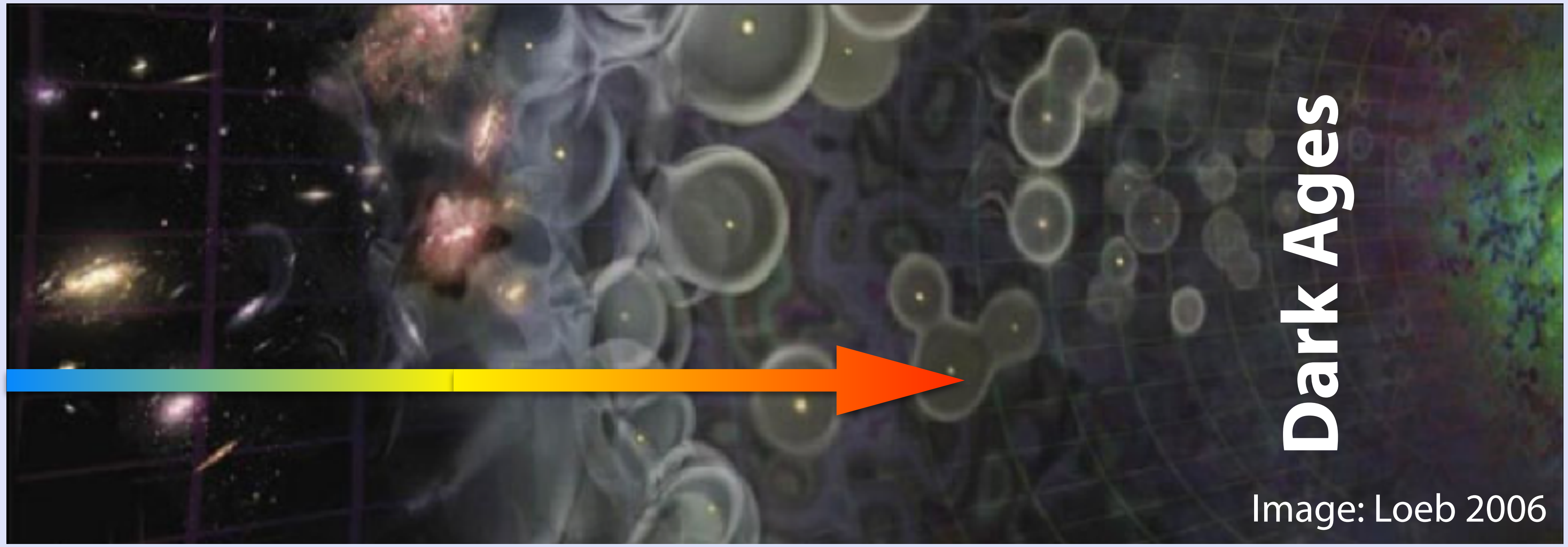
- **<u>The structures of the IGM opacity and galaxies at z~6</u>**
- The identification of the host systems of metal absorbers at z>5
- The nature of z>6 quasars and their host galaxies
- Ancillary science investigations of star-forming galaxies at z=4–5

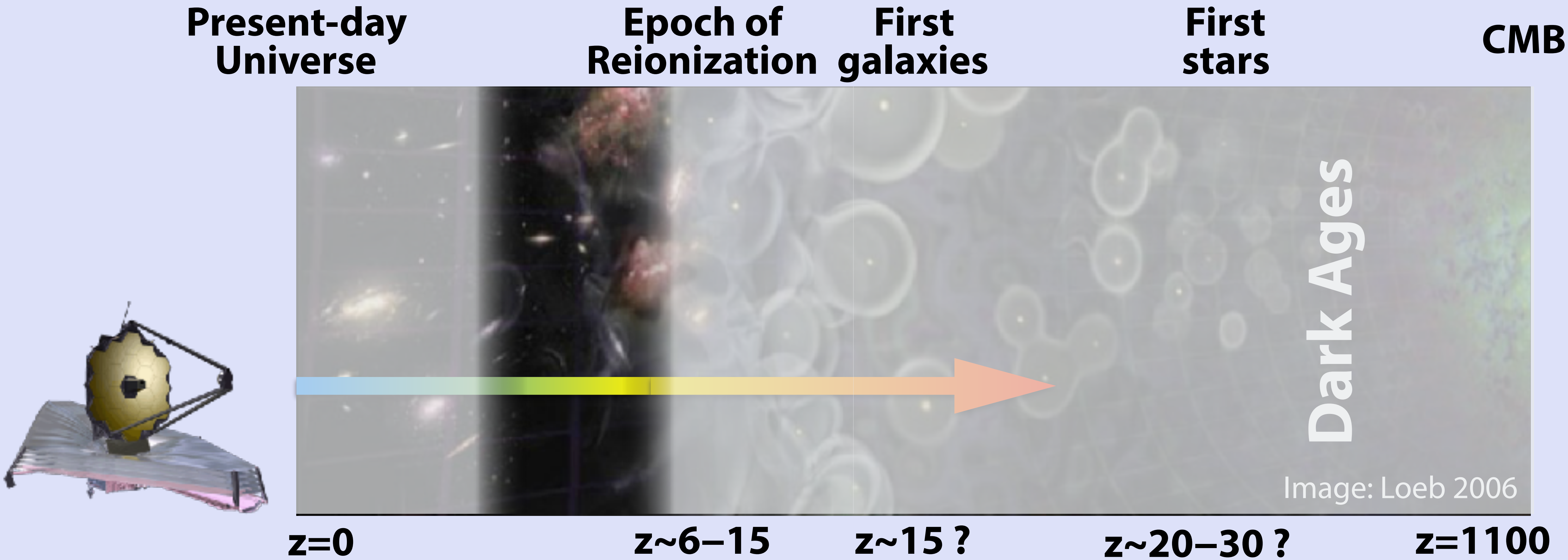
Ages of our special interest:



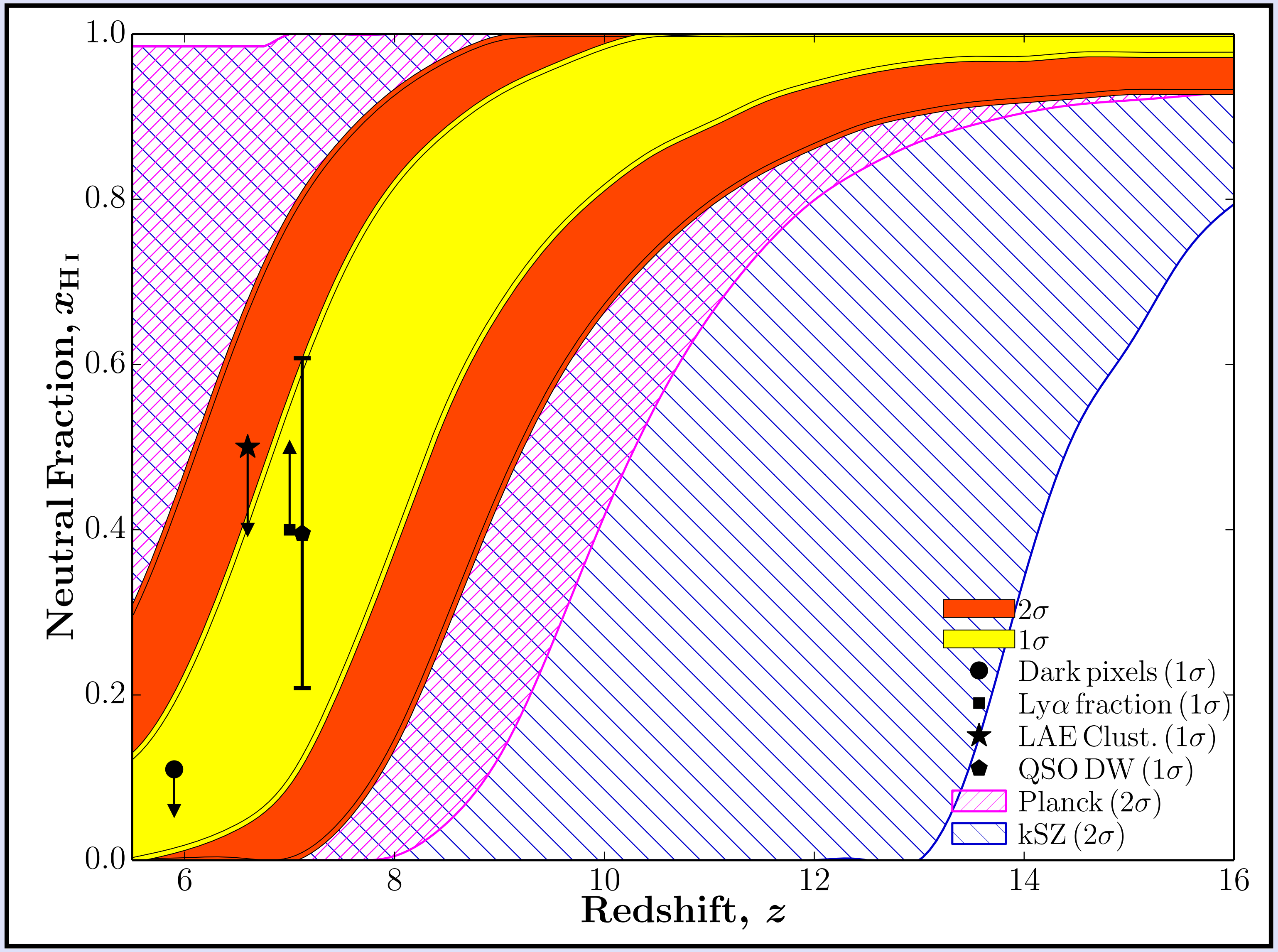


Ages of our special interest:

The end of cosmic reionization, redshift z=5–6



Reionization almost ended until z~6

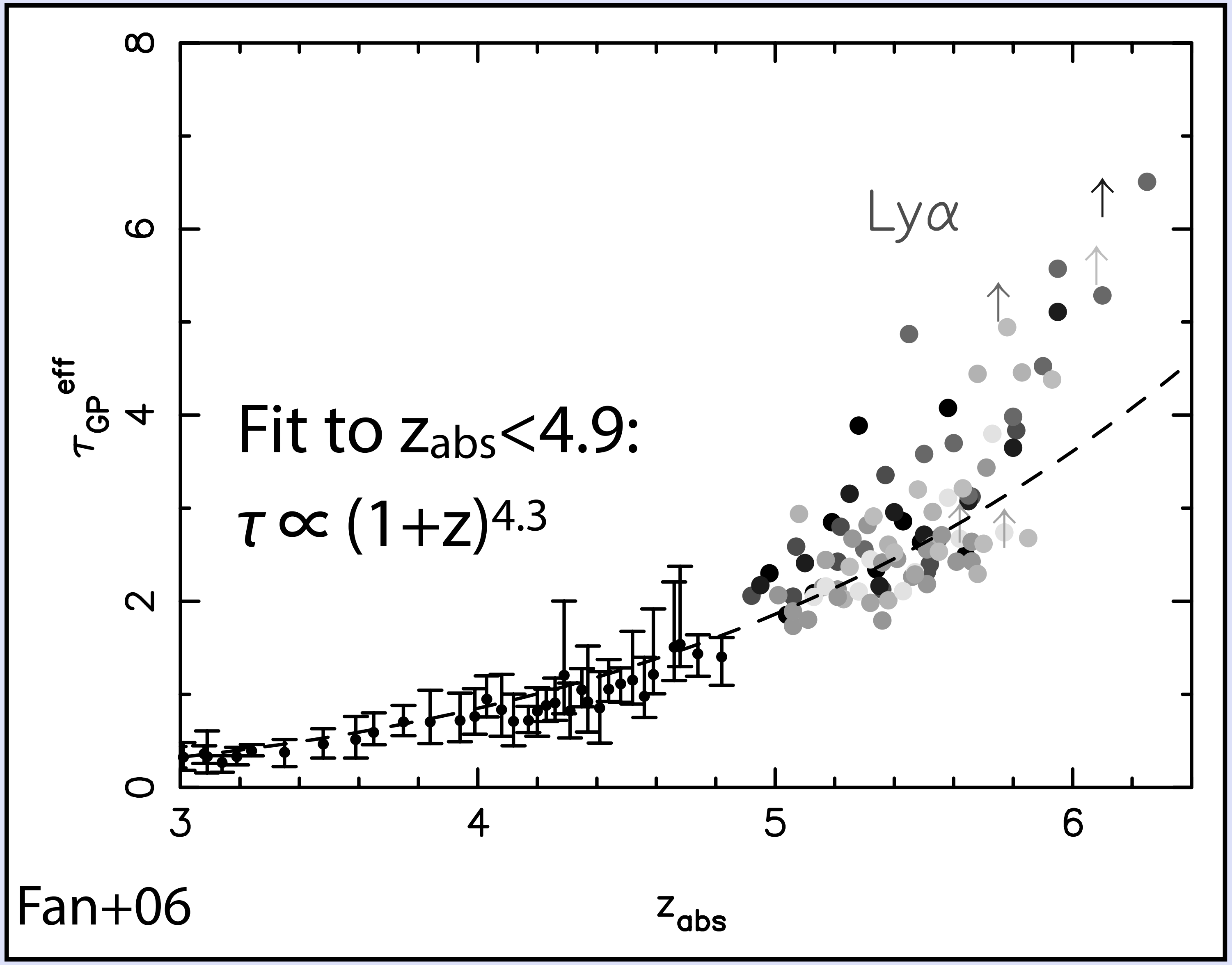


Constraint by Greig & Mesinger 2017, using MC simulations with 21CMFAST

- Lyα forest and Gunn-Peterson troughs in quasar spectra (e.g., Fan+2006, McGreer+2015)
- Electron scattering optical depth to the CMB Planck, τ_e=0.058±0.012
- Lyα emission from galaxies: rapid drop-off in Lyα luminosity function at z>7
- Quasars' ionized near-zone: constraint on the amount of HI around galaxies

Evolution of the Lyα optical depth

Averaged over Δz=0.15 (~50 h^{-1} cMpc)



- Lyα optical depth increases with redshift
- **The scatter appears to rapidly grow upwards higher τ_{eff} at z~5–5.5**

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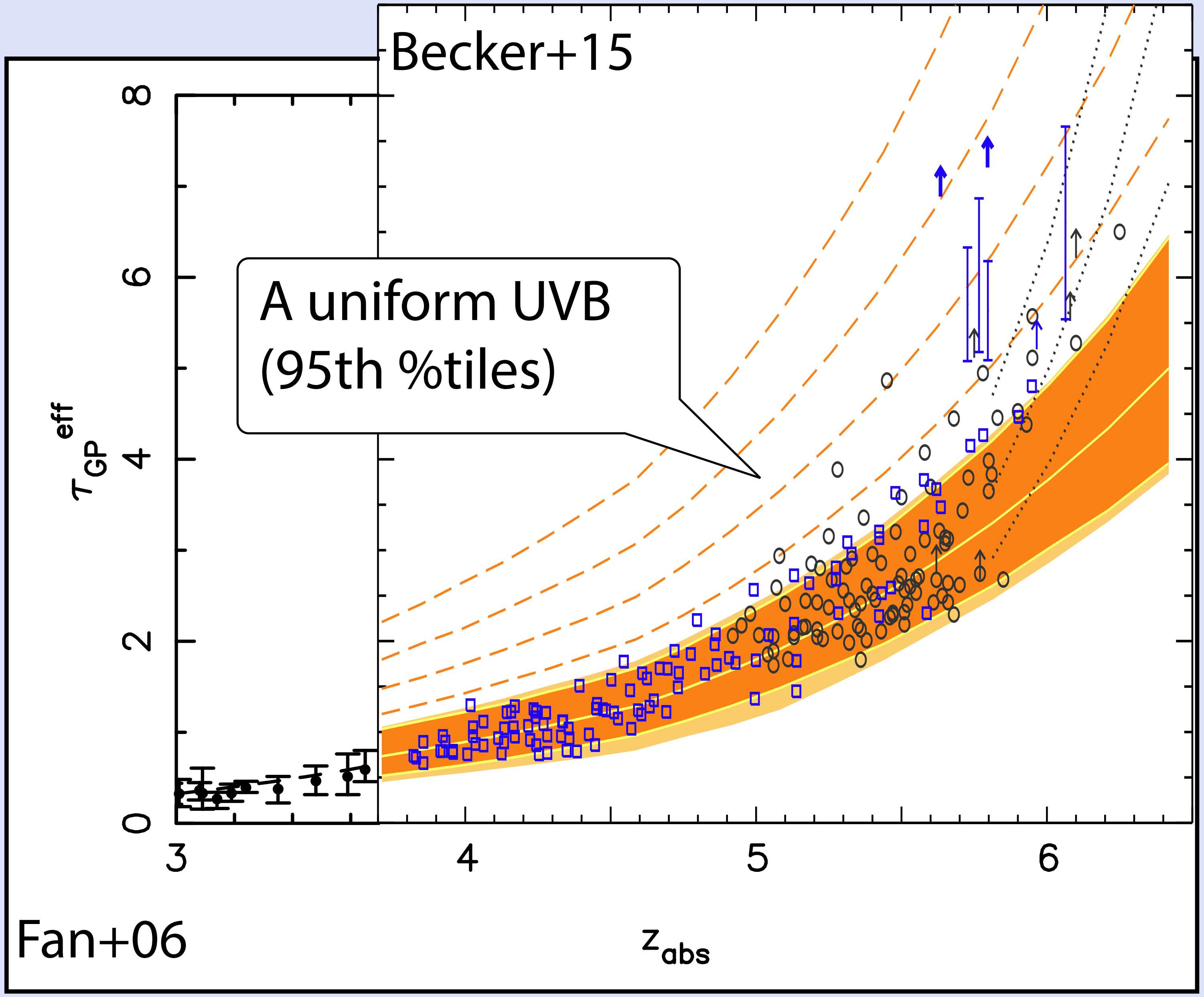
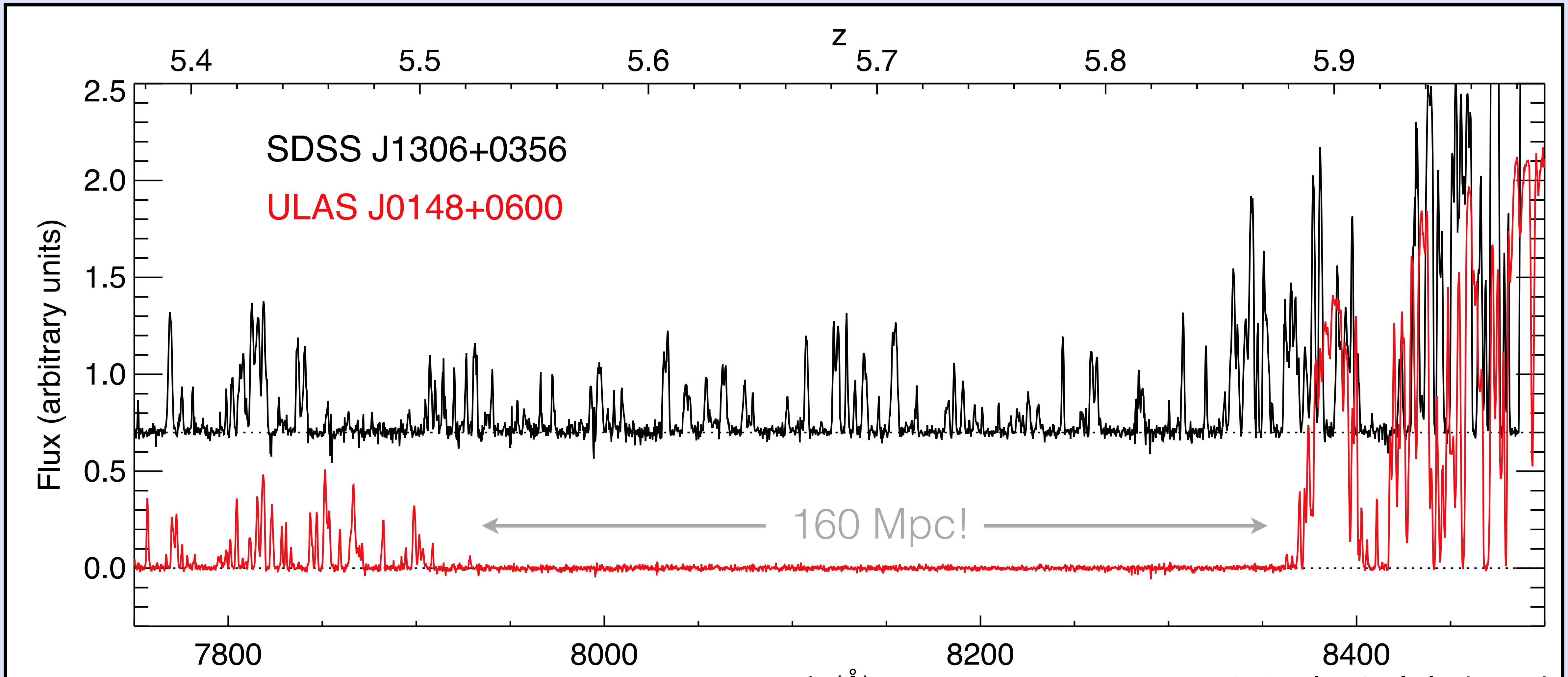


- Lyα optical depth increases with redshift
- **The scatter appears to rapidly grow upwards higher τ_{eff} at z~5–5.5**

A surprising observation

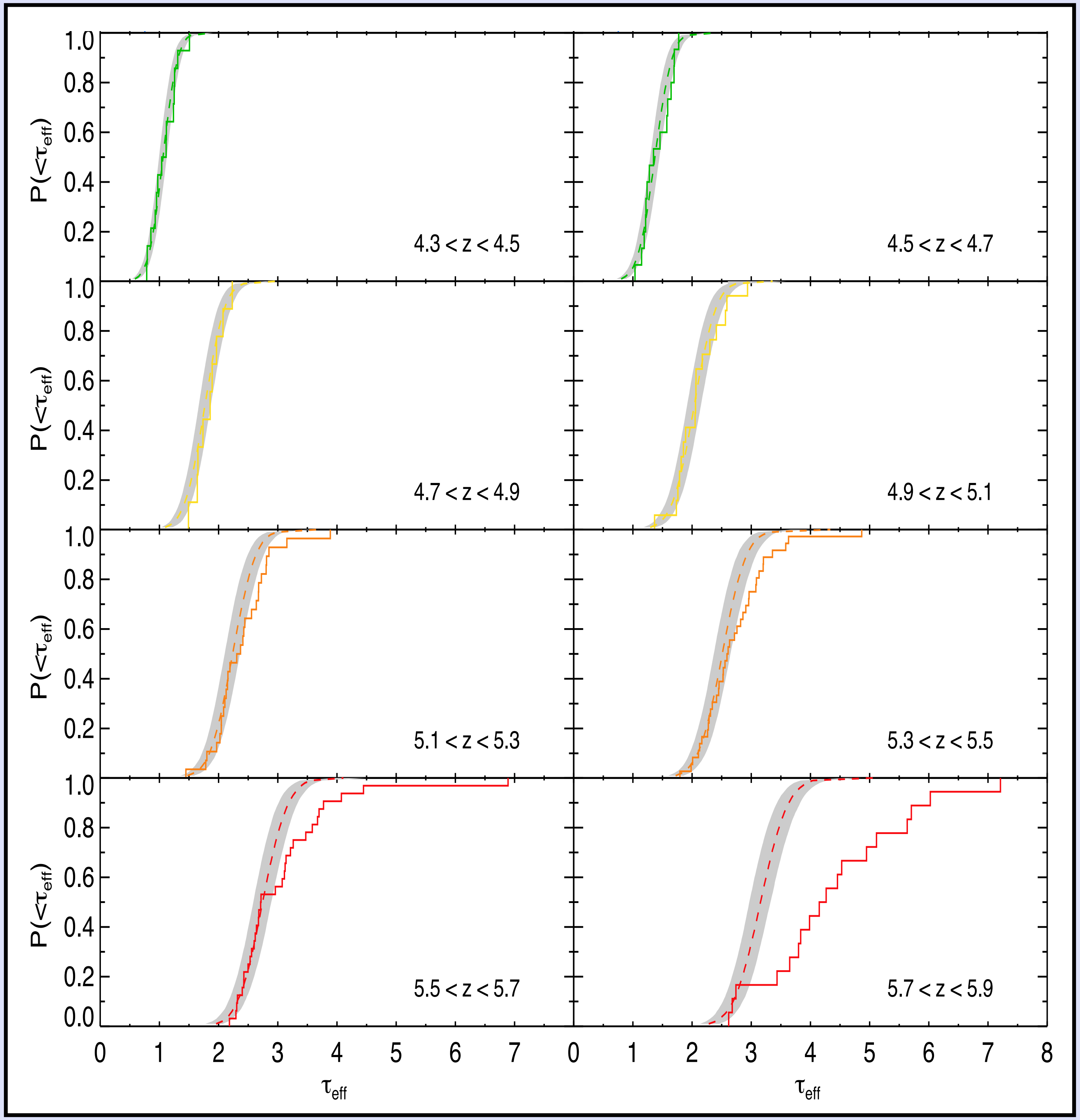
A remarkably **dark** ($\tau_{\rm eff} \gtrsim 7$) and **huge** (~160 cMpc) Lyα trough has been found at z=5.5–5.8 towards QSO J0148+0600 (z=5.98), even though the Universe was largely ionized by then!



G. Becker's slide (2016)

Probability distribution of τ_{eff}

Observation vs. a uniform UVB model: Becker+15



At z<5, the probability distribution of τ_{eff} can be reproduced by cosmological hydrogen distribution illuminated by a uniform UVB.

At z$\gtrsim$5, the probability distribution broadens much beyond the level expected from a uniform UVB model

Three possible scenarios

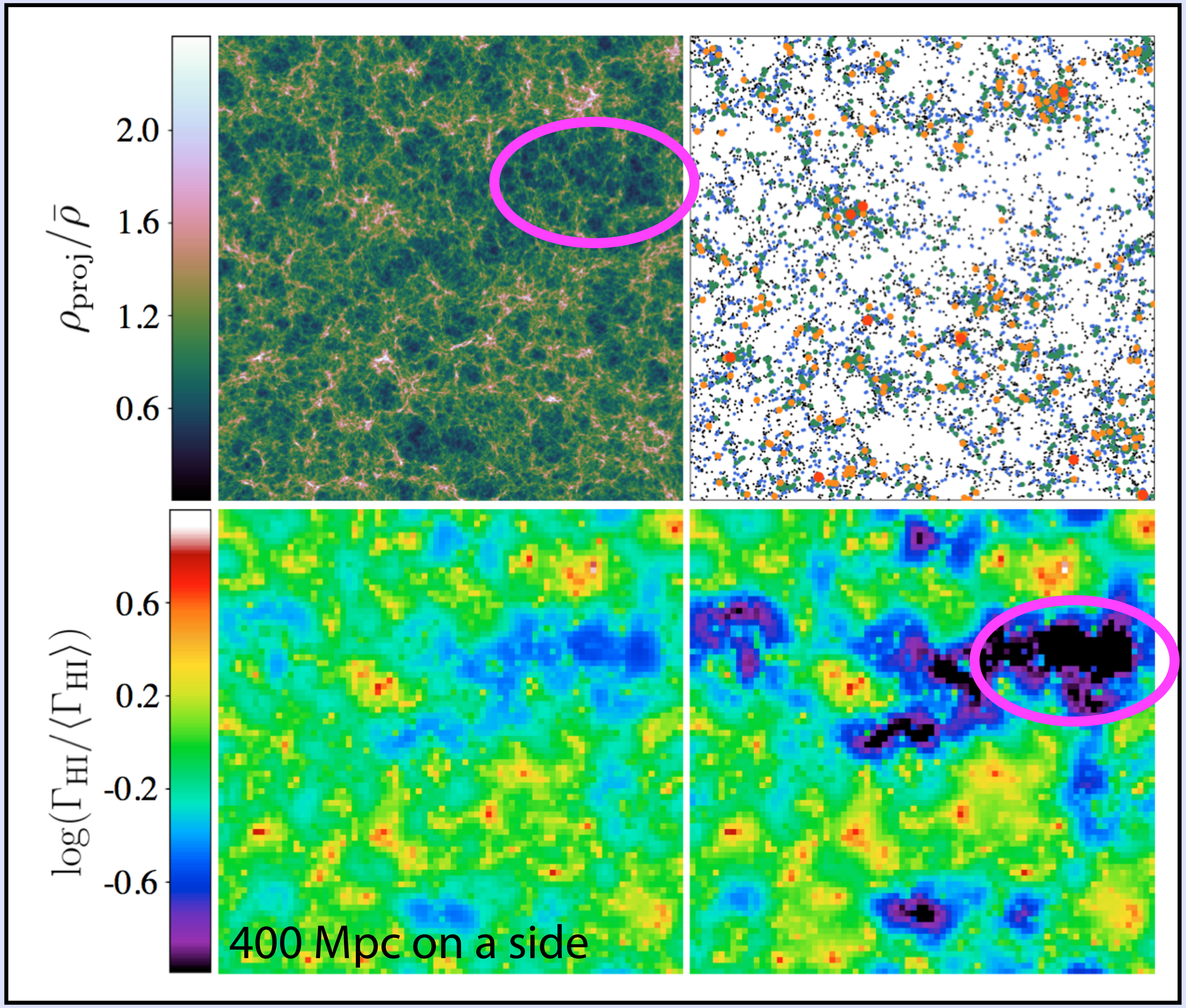
Neutral fraction $x_{\mathrm{HI}} \propto \Delta\, \Gamma^{-1}\, T^{-0.72}$

UBV Temperature

1. **Fluctuating UVB model**
2. **Fluctuating relic temperature model**
3. **Bright-quasar model**

1. Fluctuating UVB model Davies & Furlanetto (2016)

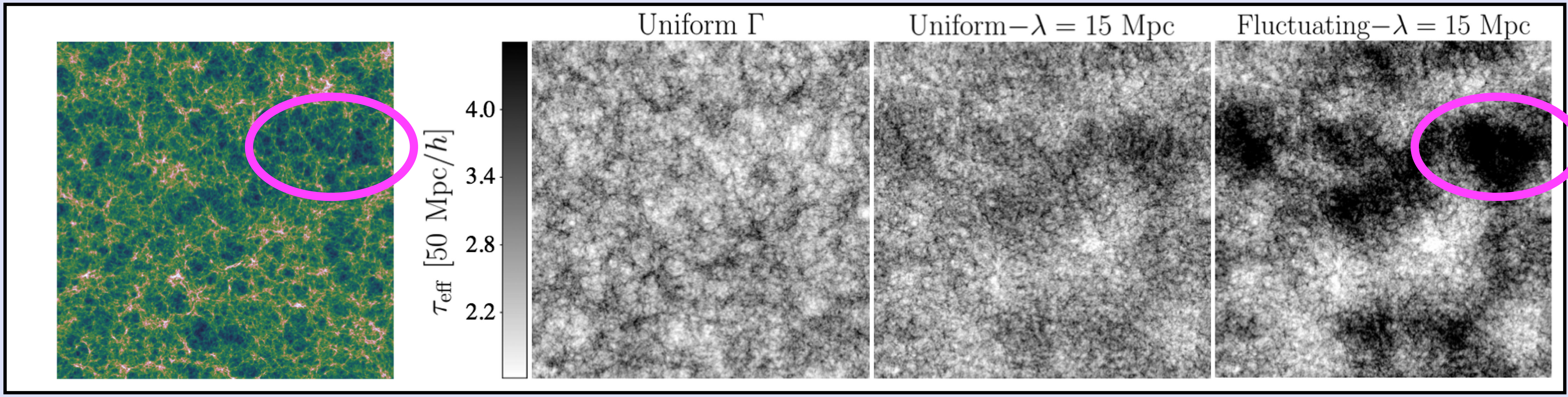
Galaxy UVB with fluctuating λ_{mfp} $\lambda(\Gamma, \Delta, \nu) = \lambda_0(\Gamma_{\rm H\,I}/\Gamma_0)^{2/3}\Delta^{-1}(\nu/\nu_{\rm H\,I})^{0.9}$,

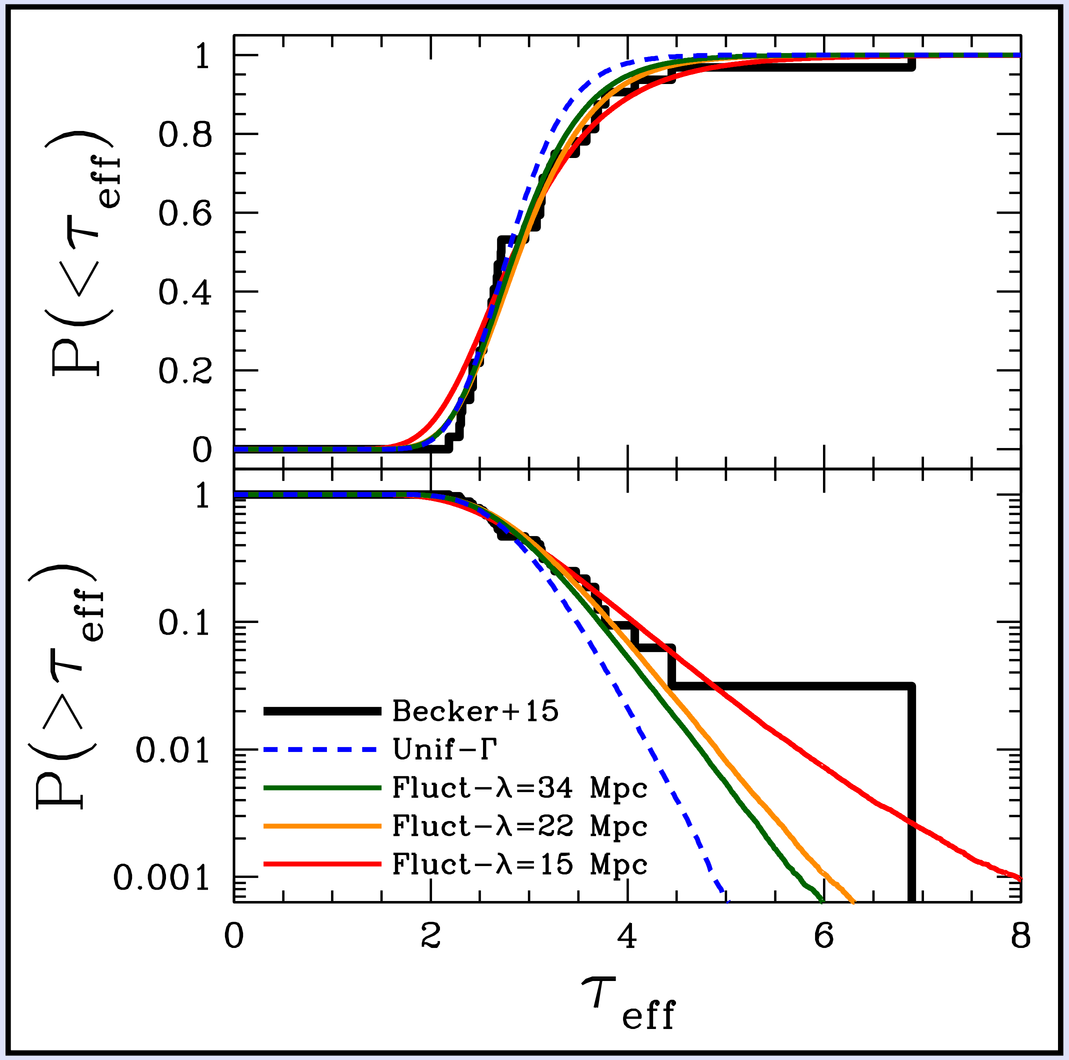


Davies & Furlanetto (2016)

Overdensities:
self-shielded agains ionization by resident galaxies due to their short λ_{mfp}

Voids:
protected from ionization and kept neutral





Davies & Furlanetto (2016)

Anticorrelation between ρ and τ_{eff}

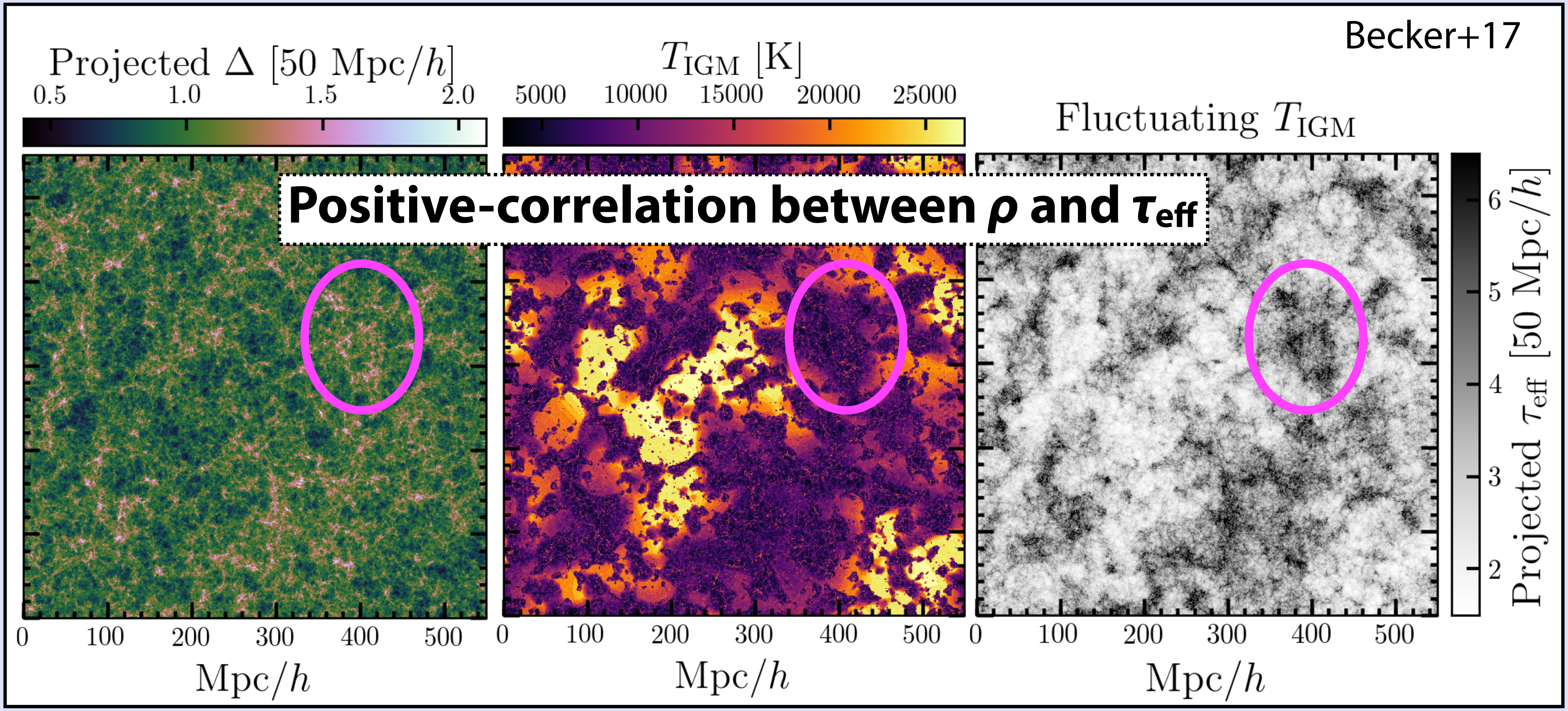
Dark Lyα troughs trace **low-density** regions (voids), which are protected from ionization.

Difficulty:
Average λ_{mpf} is required to be much shorter (~15 Mpc) than expected (~40 Mpc, Worseck+14)

2. Fluctuating relic temperature model D'Aloiso+15

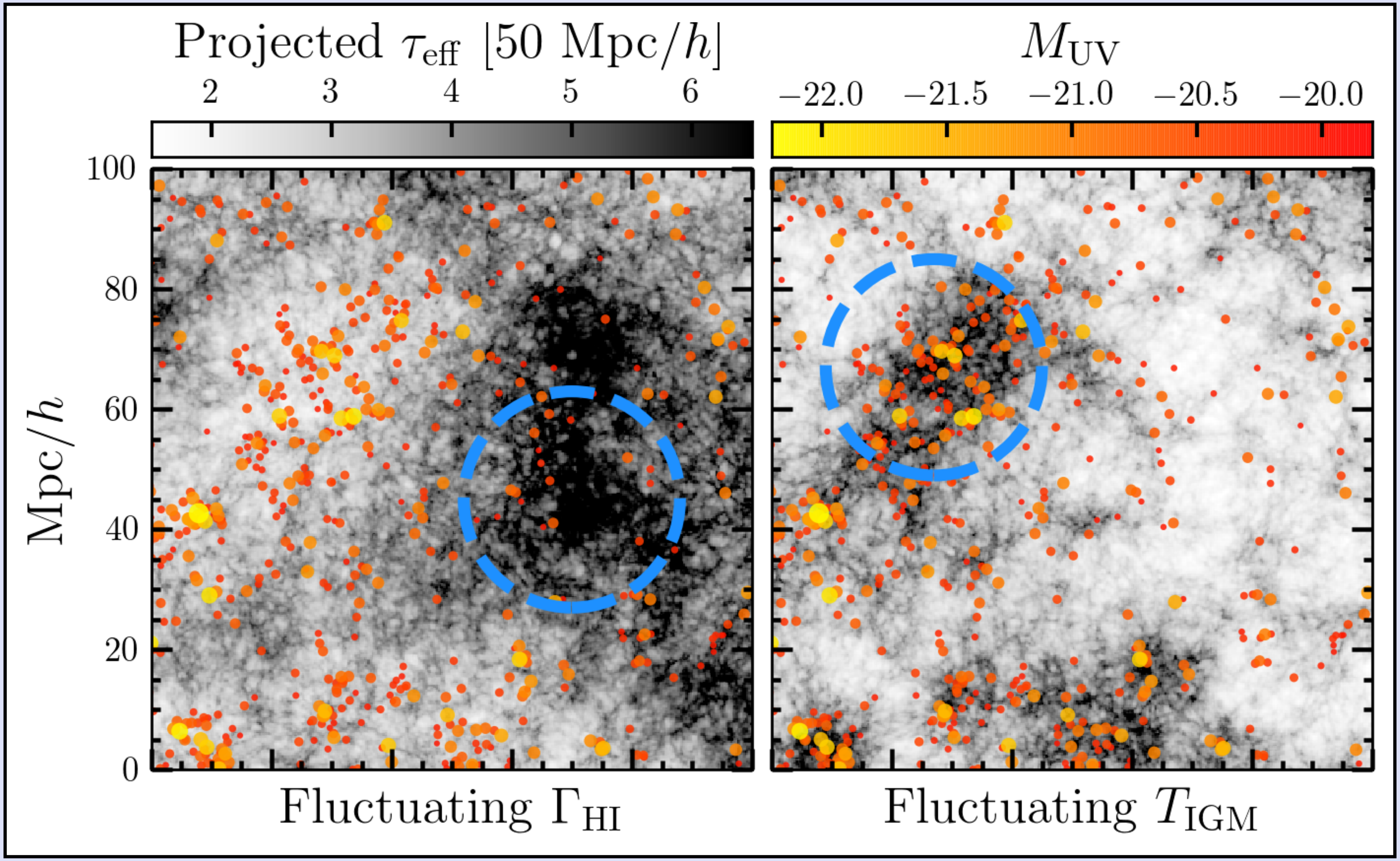
Dark troughs trace **over-dense** regions,
where the gas is ionized earlier but then have enough time to cool,
resulting in the survival of some neutral gas (larger recombination rate)

Difficulty: an extreme temperature boost (ΔT=3e4 K) is required.



Fluctuating UVB vs. Fluctuating temperature

Becker+17

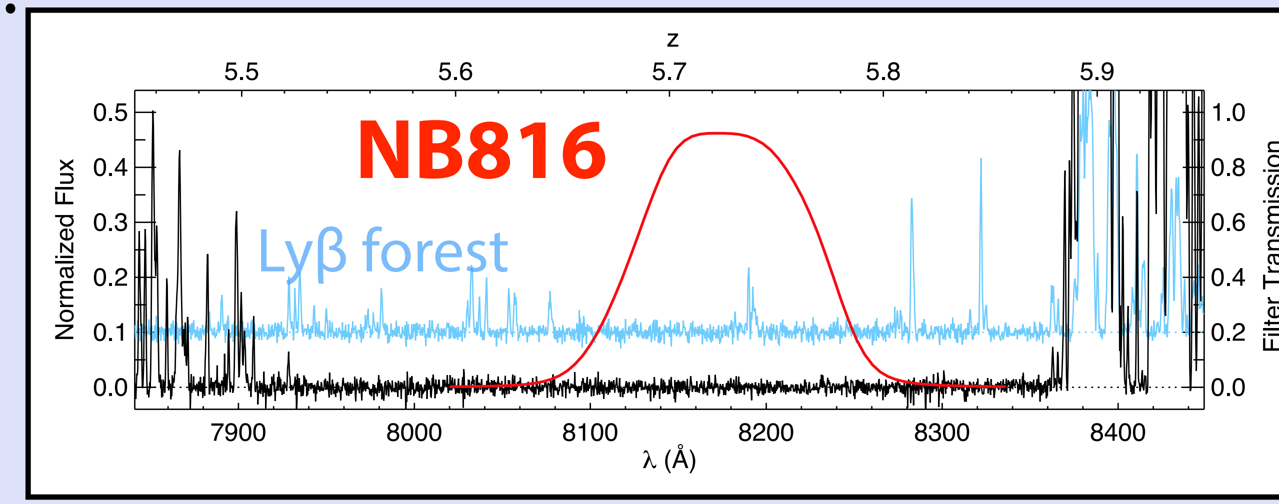


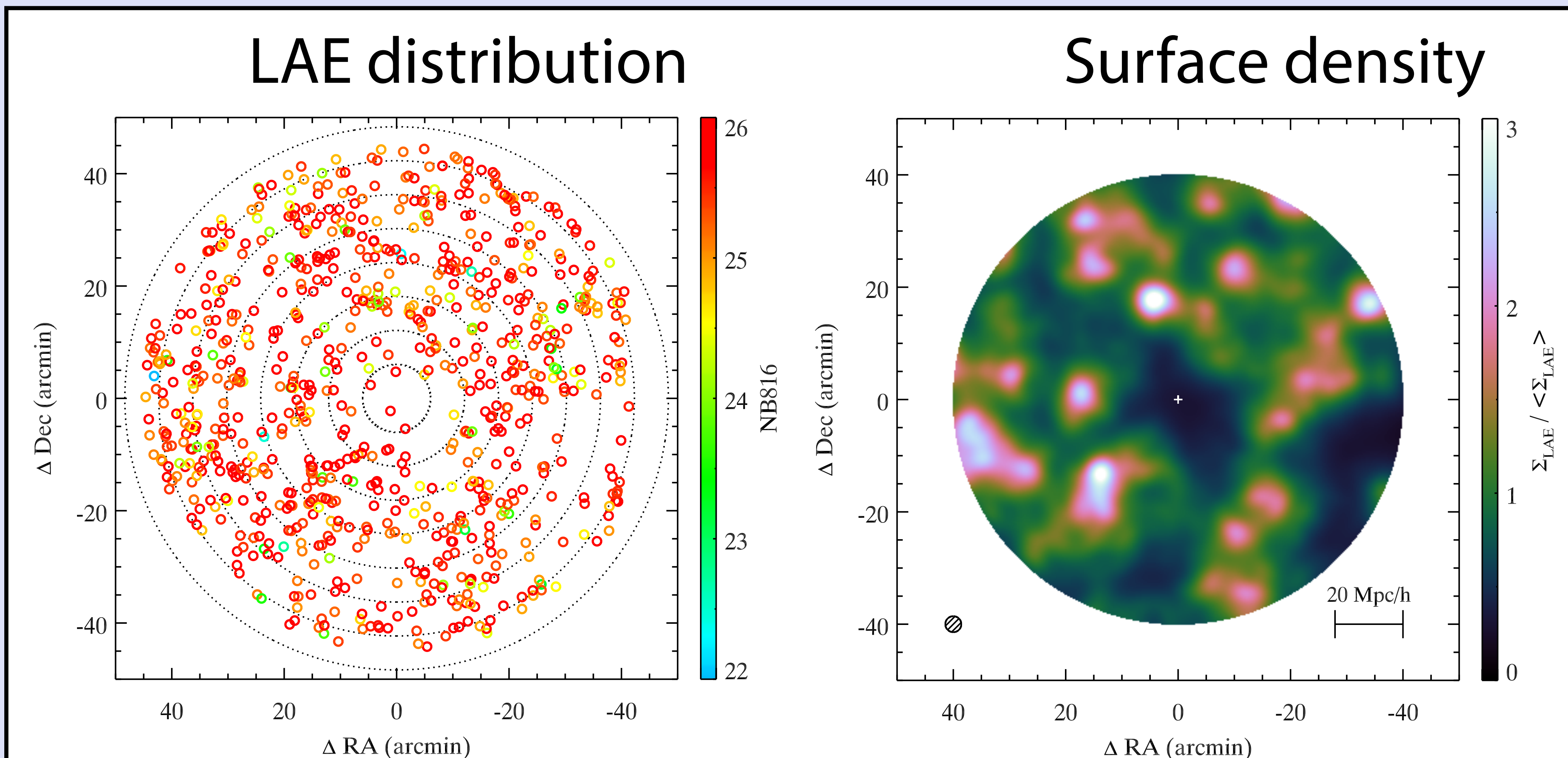
Recent report by Becker et al.

LAE survey with NB816 (z=5.7) in the field of QSO0148+0600, corresponding to the long dark trough.

High-τ_{HI} is likely to be associated with high LAE surface density.

The fluctuating-Γion is more preferred.



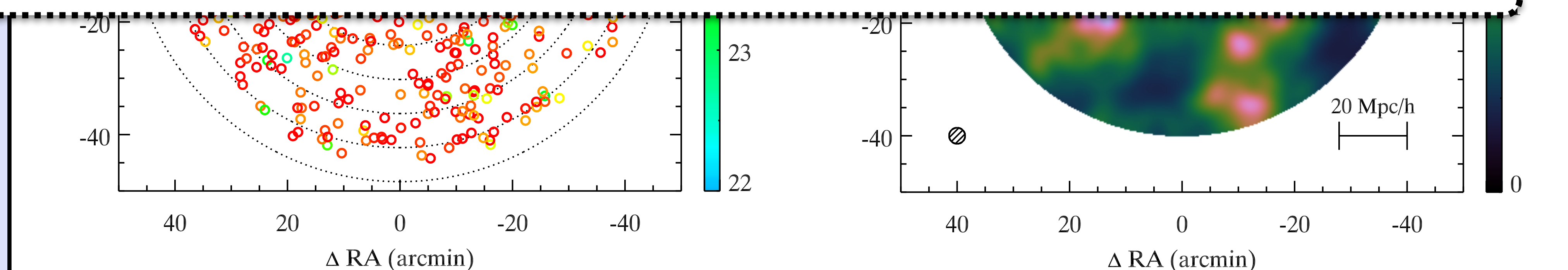


Recent report by Becker et al.

LAE survey with NB816 (z=5.7) in the field of QSO0148+0600, corresponding to the long dark trough.

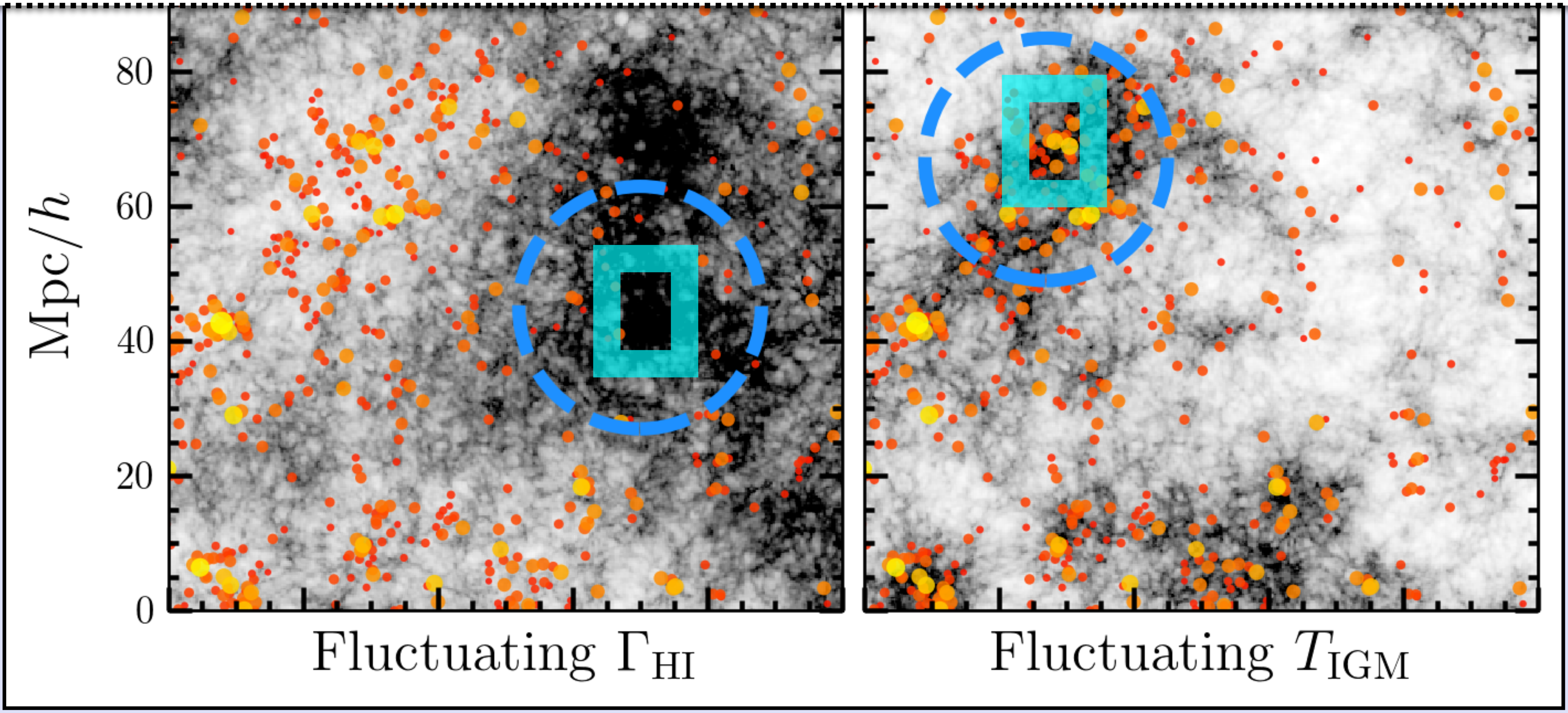
Only a single point in the Σgal vs τ_{HI} plane.
More data points across a wide range of τ_{HI} are required to see the correlation.

Are LAEs really tracing the underlying density field?
Complimentary surveys of other types of galaxies are required.



Fluctuating UVB vs. Fluctuating temperature

Correlating the galaxy distribution with the IGM opacity enables us to distinguish these scenarios, and will tell us about the process of reionization at earlier times.

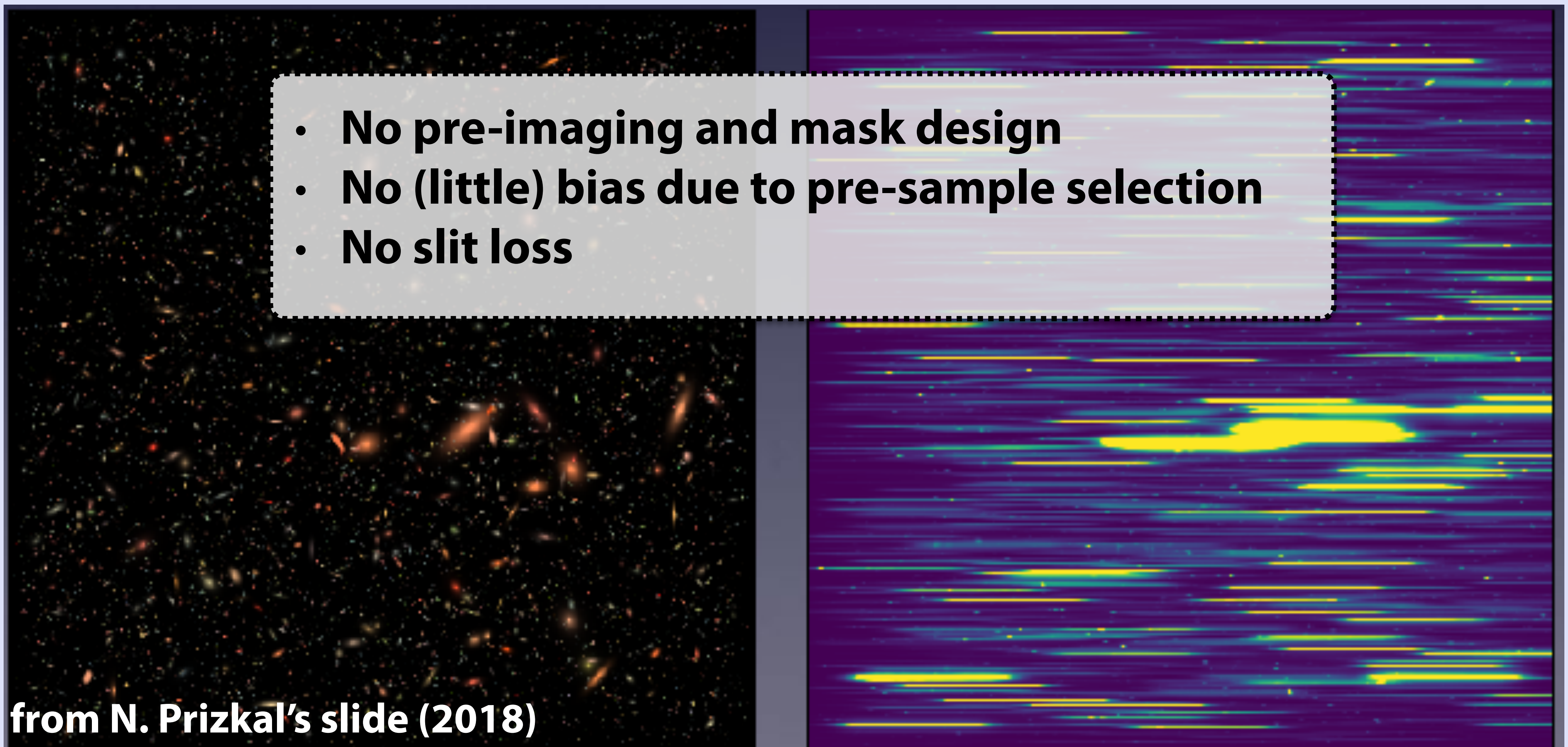


Survey strategy

Wide-field slitless spectroscopy with NIRCam

What is “slitless” spectroscopy?

➡ We can obtain spectra for **all** objects in the FoV **simultaneously**



- **No pre-imaging and mask design**
- **No (little) bias due to pre-sample selection**
- **No slit loss**

from N. Prizkal’s slide (2018)

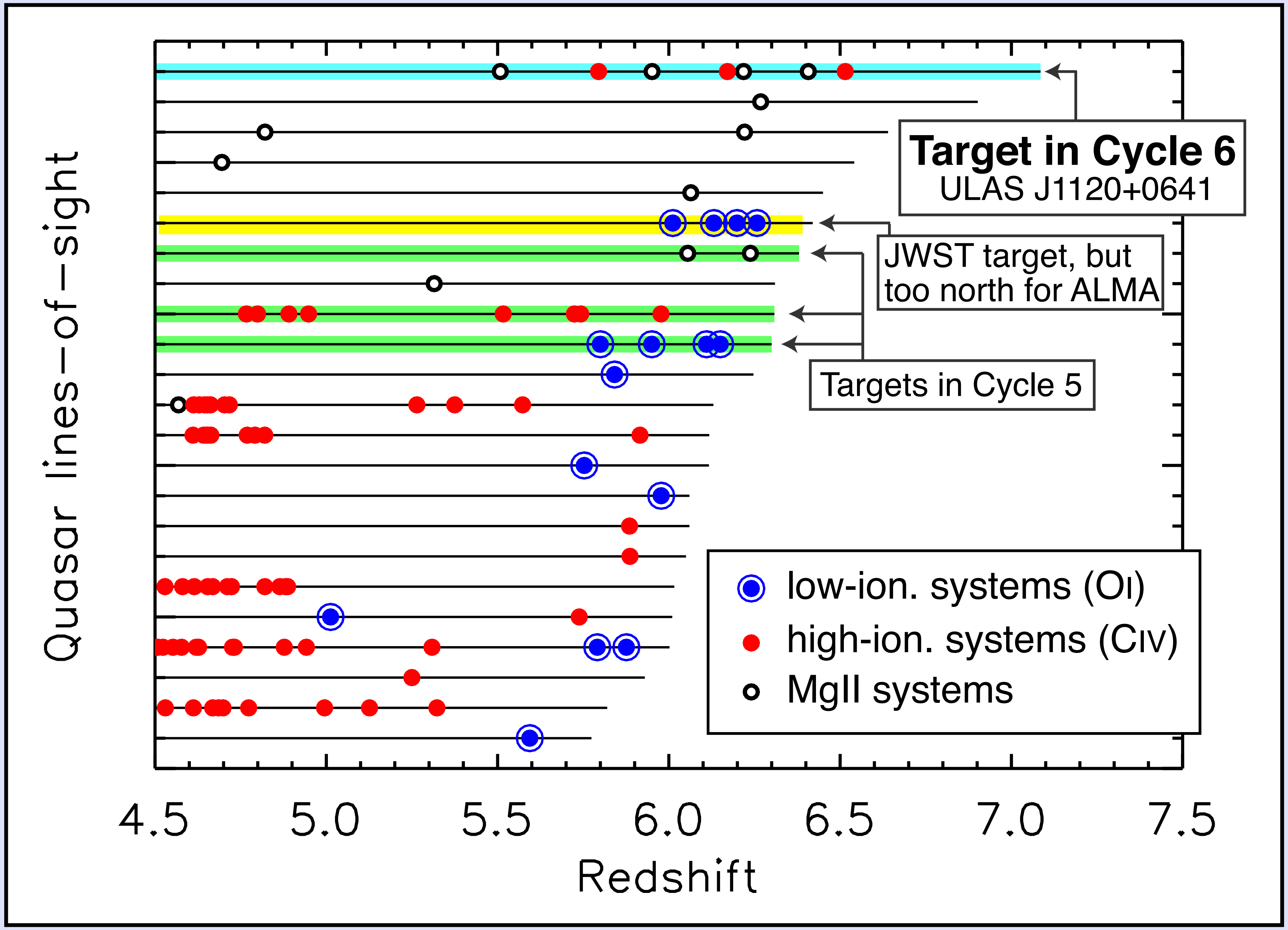
Wide-field slitless spectroscopy with NIRCam

Where should we observe?

➡ Where we have the direct measurements of $\tau_{\rm eff}$ = **high-z quasar fields**

ID	$z_{\rm QSO}$	Opacity $\tau_{\rm eff}$	Absorption sys.
J0148+0600	5.98	very long, opaque (τ>7) GP trough	-
J0100+2802	6.33	high τ~3—6	4 OI (5.8<z<6.2)
J1030+0524	6.31	large variation τ~2–7	4 CIV (5.5<z<6.0), 4 CIV (z~4.8)
J1148+5251	6.44	large variation τ~3–6	4 OI (6.0<z<6.3)
J1120+0641	7.08	almost saturated τ	CIV (z=6.5), MgII (z=6.4)
PSO J159-02	6.35	No data yet	MgII absorption

Absorption systems towards z>6 quasars

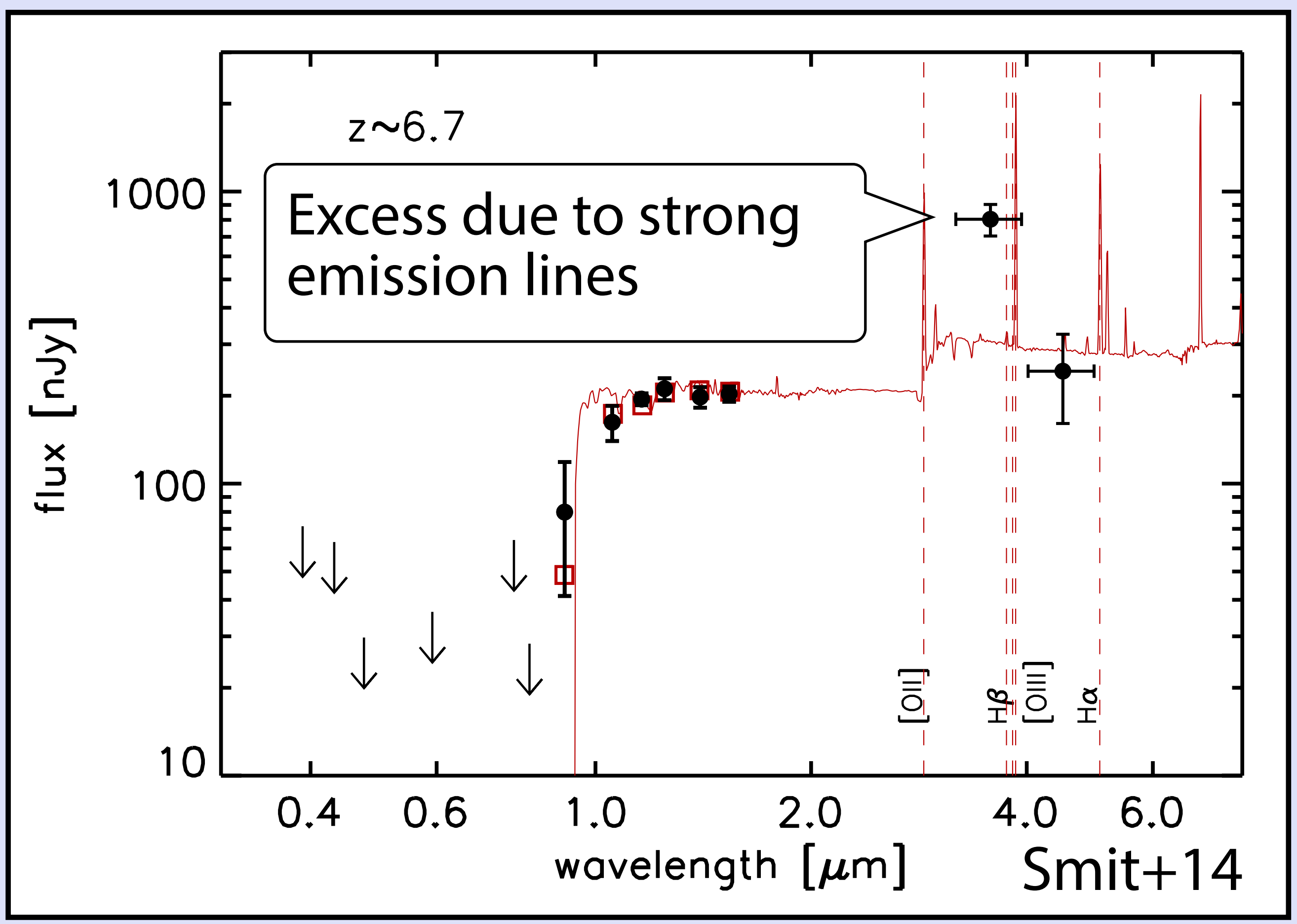


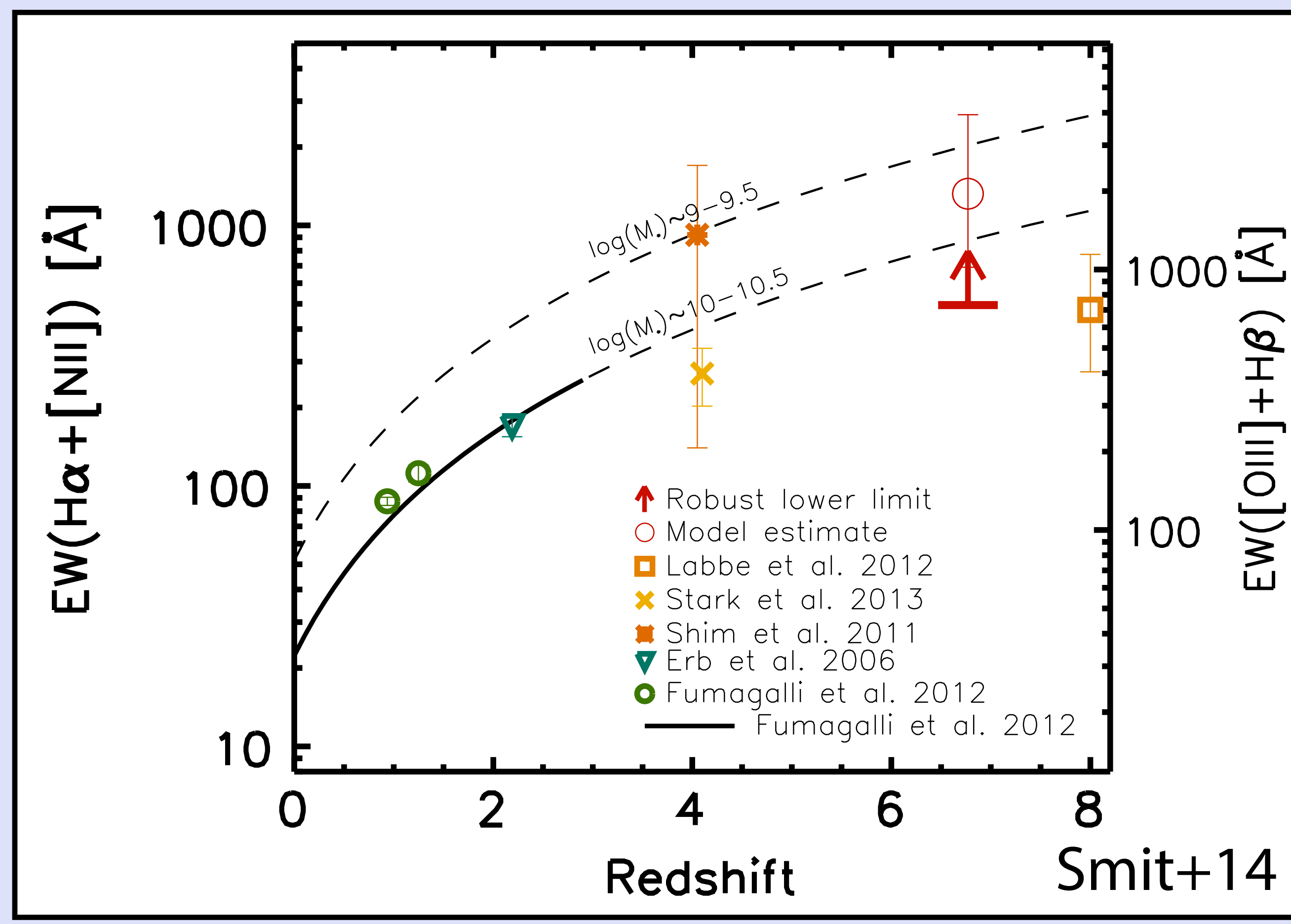
What we want to detect:

Star-forming galaxies at z=5–7 with a strong [OIII]5007 line

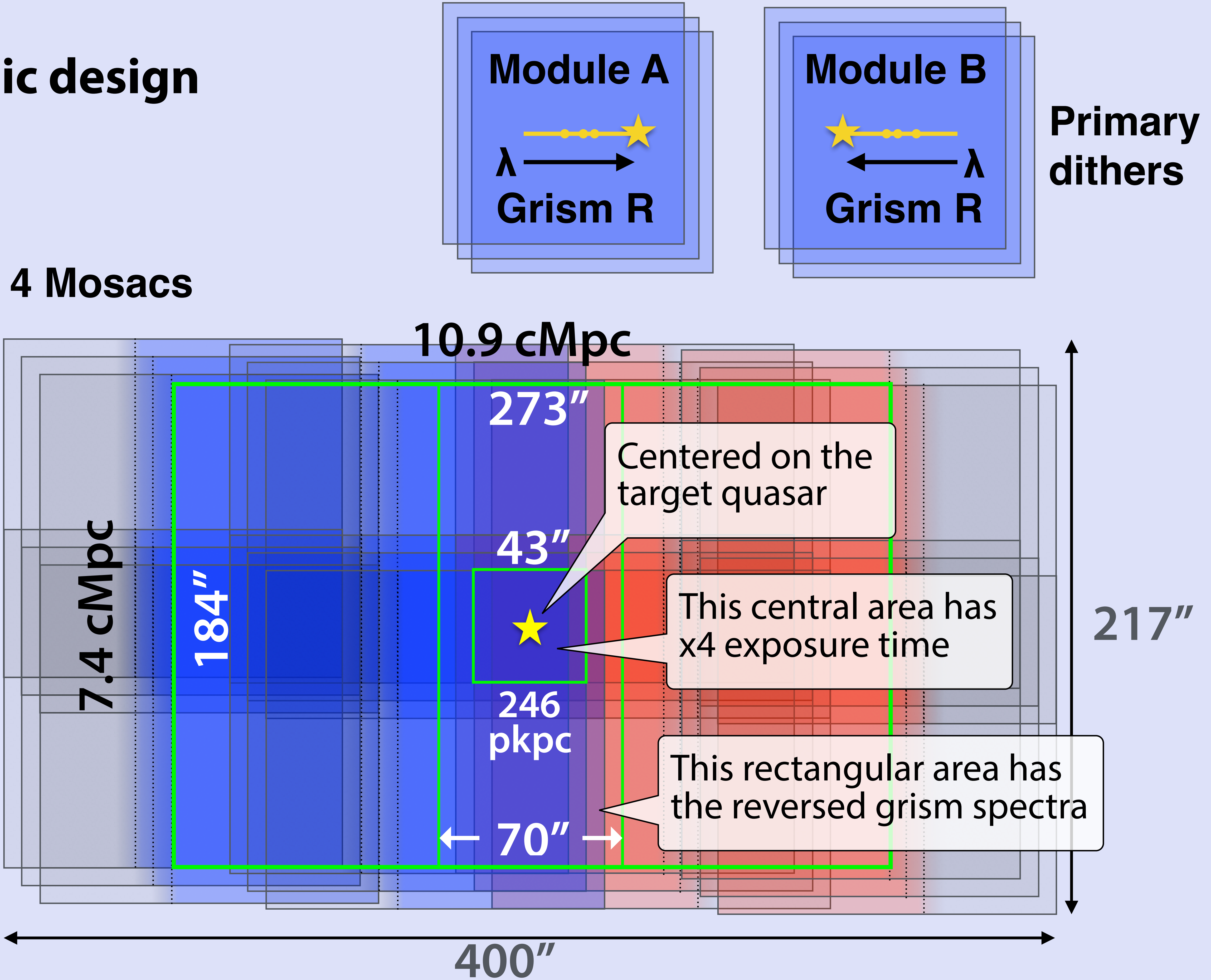
The [OIII]5007 is the strongest rest-frame optical emission lines.

Large EWs (> several x 100Å) are commonly expected at high redshifts (z>4; e.g., Labbe+13, Smit+14).



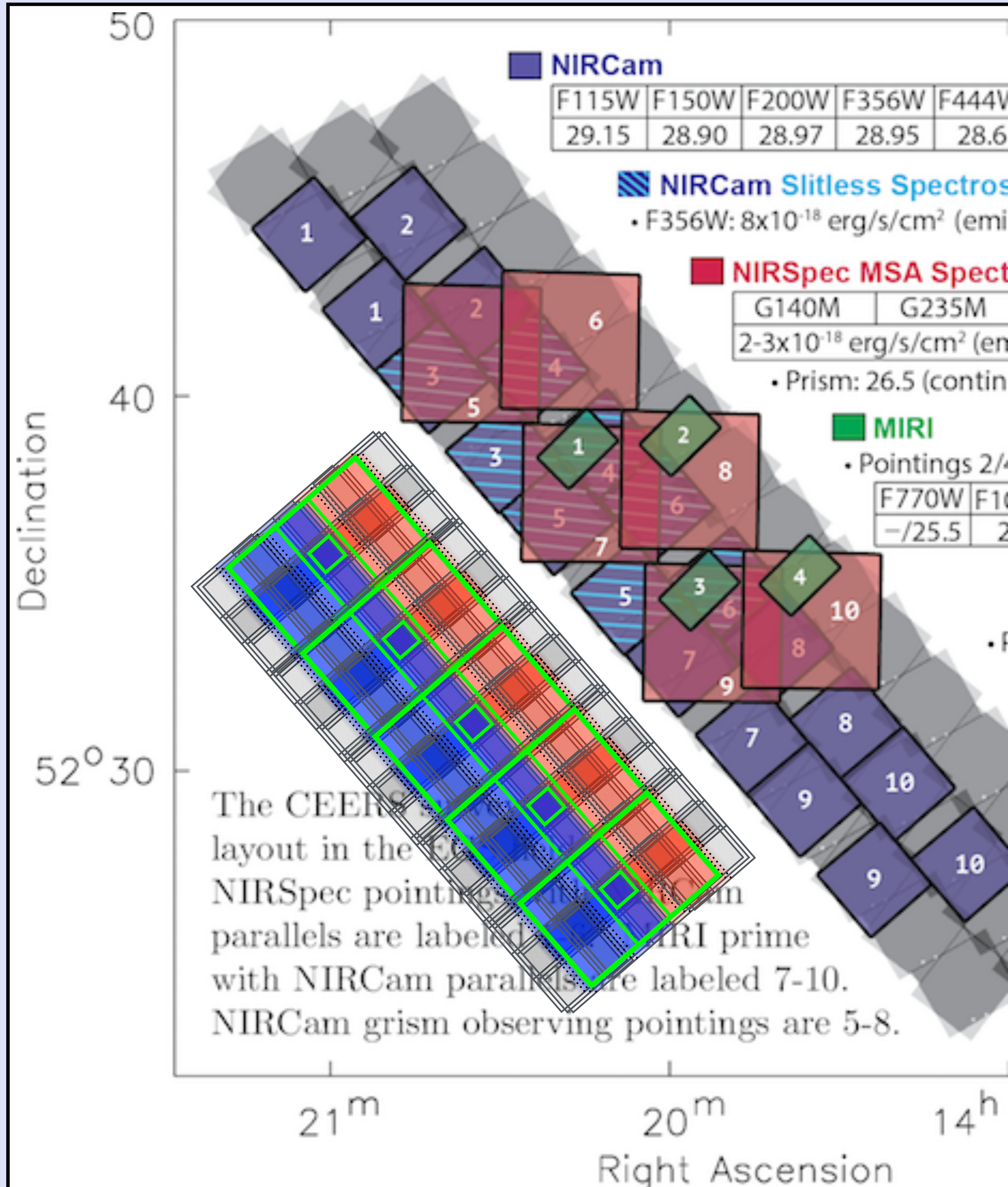


Mosaic design

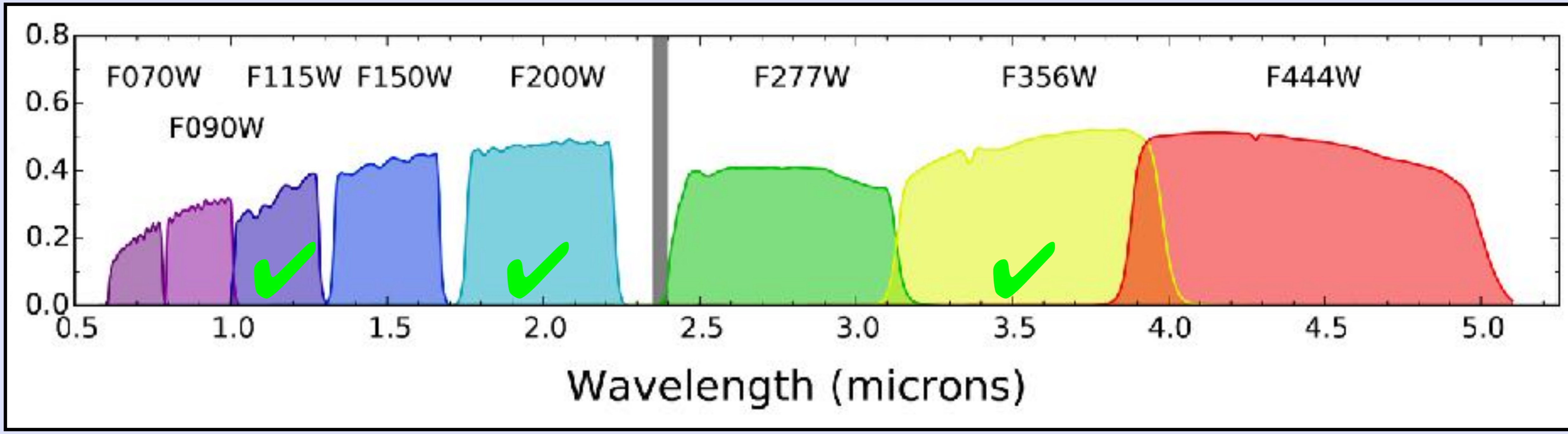


With six target quasars, the total survey area is ~140 sq. arcmin, having both SW deep imaging + spectra.

<u>Even wider than CEERS!</u>



Filter strategy



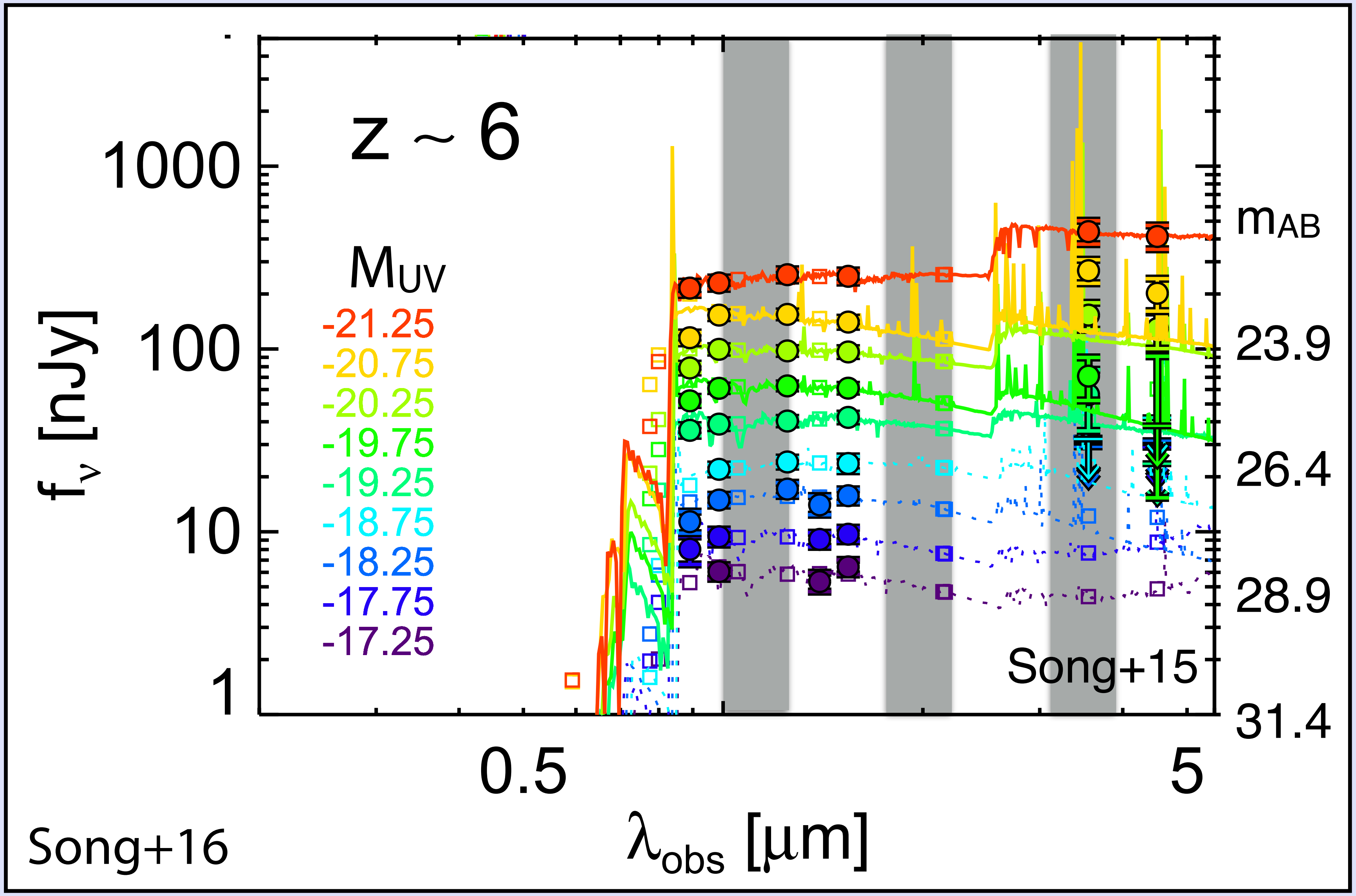
Short-wavelength unit
Imaging in F115W and F200W
Texp=3700 sec / pt.

Lont-wavelength unit
Grism(+imaging) in F356W
Texp=7500 sep

SW imaging and LW grism can be conducted simultaneously

Filter strategy

This combination of the three filters is very suited to characterize the global properties of the galaxies, like commonly-used BzK technique at z~2



Summary

JWST will explore the ages of first luminous objects and reionization.

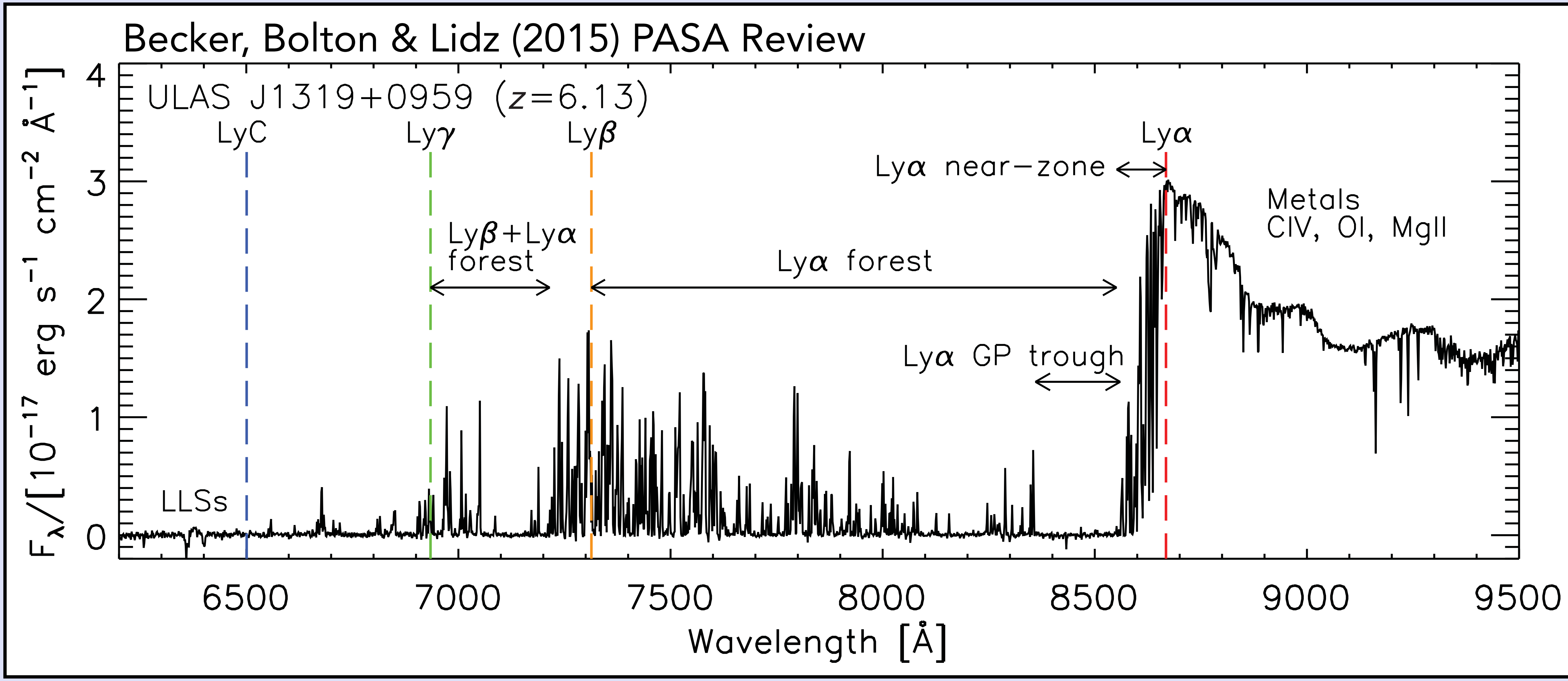
JWST will provide us with “**rest-frame optical**” spectra at $z>5$.

We will carry out “wide-field slitless” spectroscopy in the fields of six luminous quasars at $z>6$.

Our project will construct a large sample (an order of 10^3) of [OIII]-emitters at $z=5–7$.

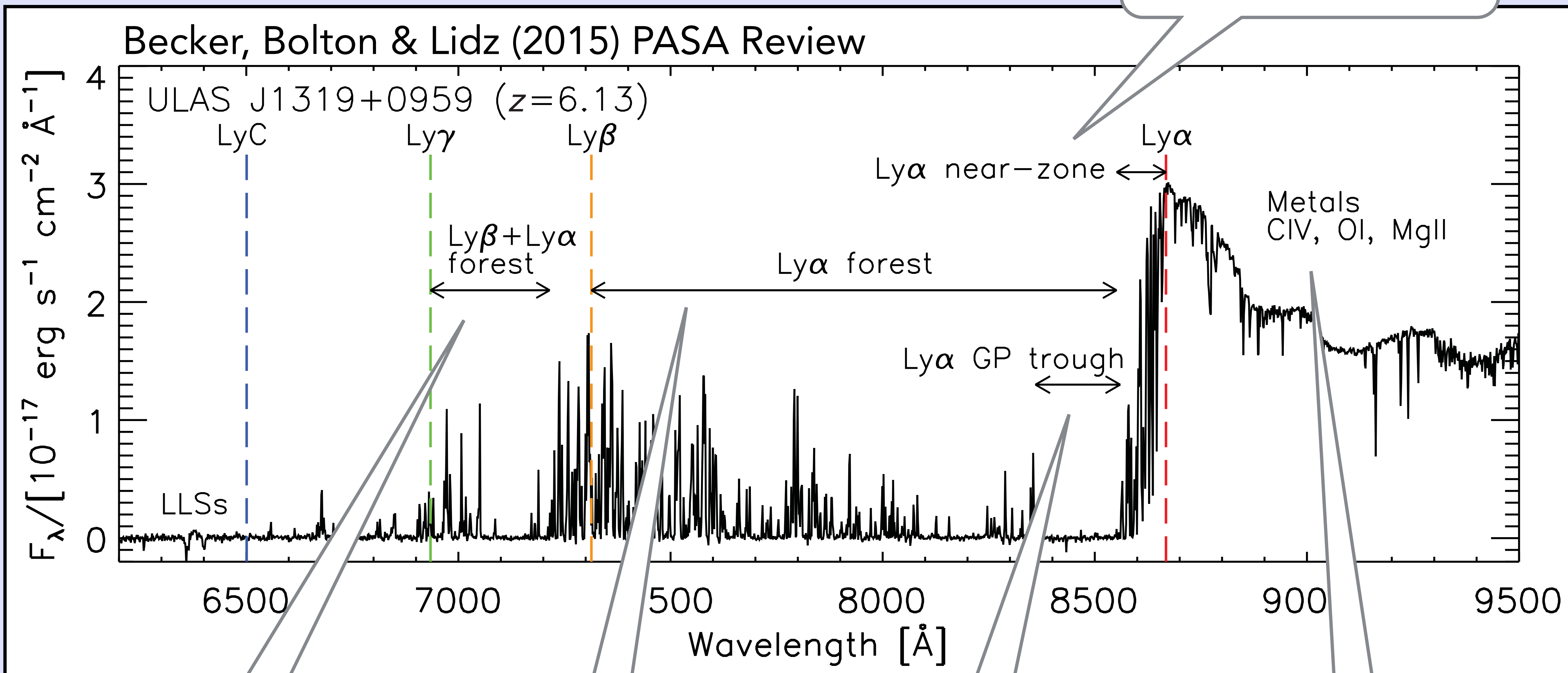
Backup slides

High-z quasar spectra tell us a lot about the gas



High-z quasar spectra tell us a lot about the gas

Structure of the gas in the quasar near-zone (R~10Mpc)



Denser neutral gas with smaller cross-section of Lyβ

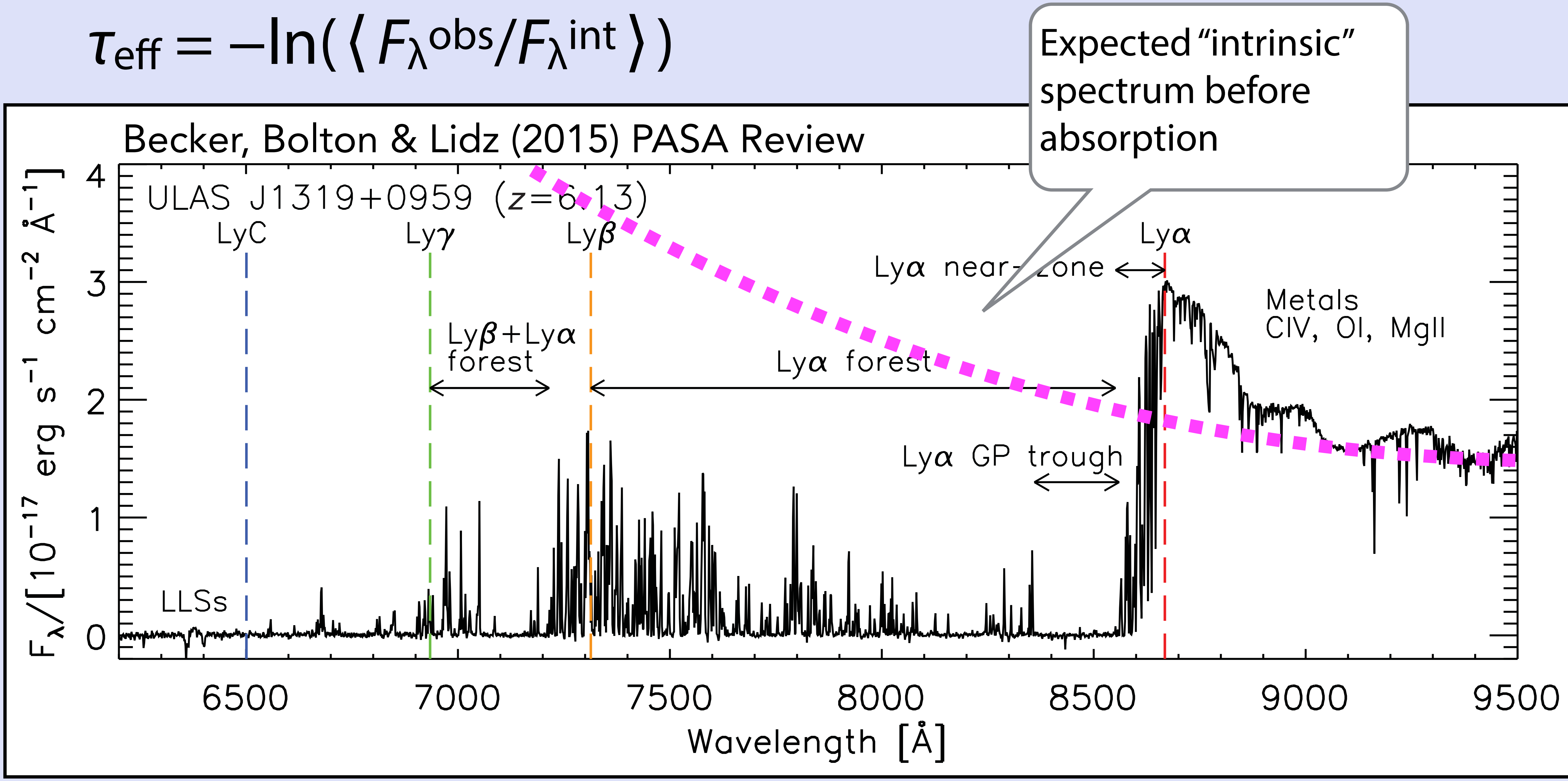
Large-scale structures of the IGM

The amount of neutral gas in the IGM

Chemical state of the CGM

Gunn-Peterson Lyα optical depth

$\tau_{\mathrm{eff}} = -\ln(\langle F_\lambda^{\mathrm{obs}}/F_\lambda^{\mathrm{int}} \rangle)$



Intrinsic quasar spectra at $\lambda_{\mathrm{rest}} < \lambda_{\mathrm{Ly}\alpha}$ is usually modeled by a power law: typically $F_\lambda^{\mathrm{int}} \propto \lambda^{-0.5}$

Formulation of the Lyα optical depth

Total optical depth at ν along the line-of-sight (z=0 to z_{QSO}):

$$\tau^{\alpha}_{\rm GP} = \int_0^{z_{\rm q}} \sigma_{\rm s}[\nu(1+z)] n_{\rm HI}(z) \frac{{\rm d}l}{{\rm d}z} {\rm d}z,$$

Ignoring line-broadening effects, the cross-section is

$$\sigma_{\rm s}[\nu(1+z)] = \sigma_\alpha \nu_\alpha \delta[\nu(1+z) - \nu_\alpha],$$ $\nu_{Ly\alpha} = c / \lambda_{Ly\alpha} = c$ / 1216Å

Lyα cross-section: $\sigma_\alpha = 4.48 \times 10^{-18}\ {\rm cm}^2$

Expression with cosmological parameters:

$$\tau^{\alpha}_{\rm GP} \simeq 2.3 \times 10^5 \langle x_{\rm HI} \rangle \left(\frac{\Omega_{\rm b} h^2}{0.022}\right) \left(\frac{\Omega_{\rm m} h^2}{0.142}\right)^{-1/2} \times \left(\frac{1-Y}{0.76}\right) \left(\frac{1+z}{5}\right)^{3/2},$$

$\langle x_{HI} \rangle$:neutral fraction at z when $\nu(1+z)=\nu_{Ly\alpha}$

Y: primordial helium fraction

Hydrogen photoionization

Ionization rate (the number of hydrogen atoms ionized per unit time)

$$\Gamma_{\rm HI}(z) = \int_{\nu_{\rm LL}}^{\infty} \frac{4\pi J(\nu, z)}{h_{\rm P}\nu} \sigma_{\rm HI}(\nu) {\rm d}\nu$$

Ionization equilibrium (balance between ionization and recombination)

$$n_{\rm HI}\Gamma_{\rm HI} = n_{\rm e} n_{\rm HII} \alpha_{\rm HII}(T)$$

$\alpha_{\rm HII}$: Case-A recombination coefficient

Neutral fraction $x_{\rm HI}=n_{\rm HI}/n_{\rm H}$ is given as:

$$x_{\rm HI} \simeq 9.6 \times 10^{-6} \, \Delta \frac{(1+\chi_{\rm He})}{\Gamma_{-12}} \left(\frac{T}{10^4\,{\rm K}}\right)^{-0.72} \left(\frac{\Omega_{\rm b} h^2}{0.022}\right) \times \left(\frac{1-Y}{0.76}\right) \left(\frac{1+z}{5}\right)^3 ,$$

$\chi_{\rm He}$: effect of Helium

Δ: fractional gas density to cosmic mean

$$\boxed{x_{\rm HI} \propto \Delta\, \Gamma^{-1}\, T^{-0.72}}$$

Who is James Webb?

credit: NASA

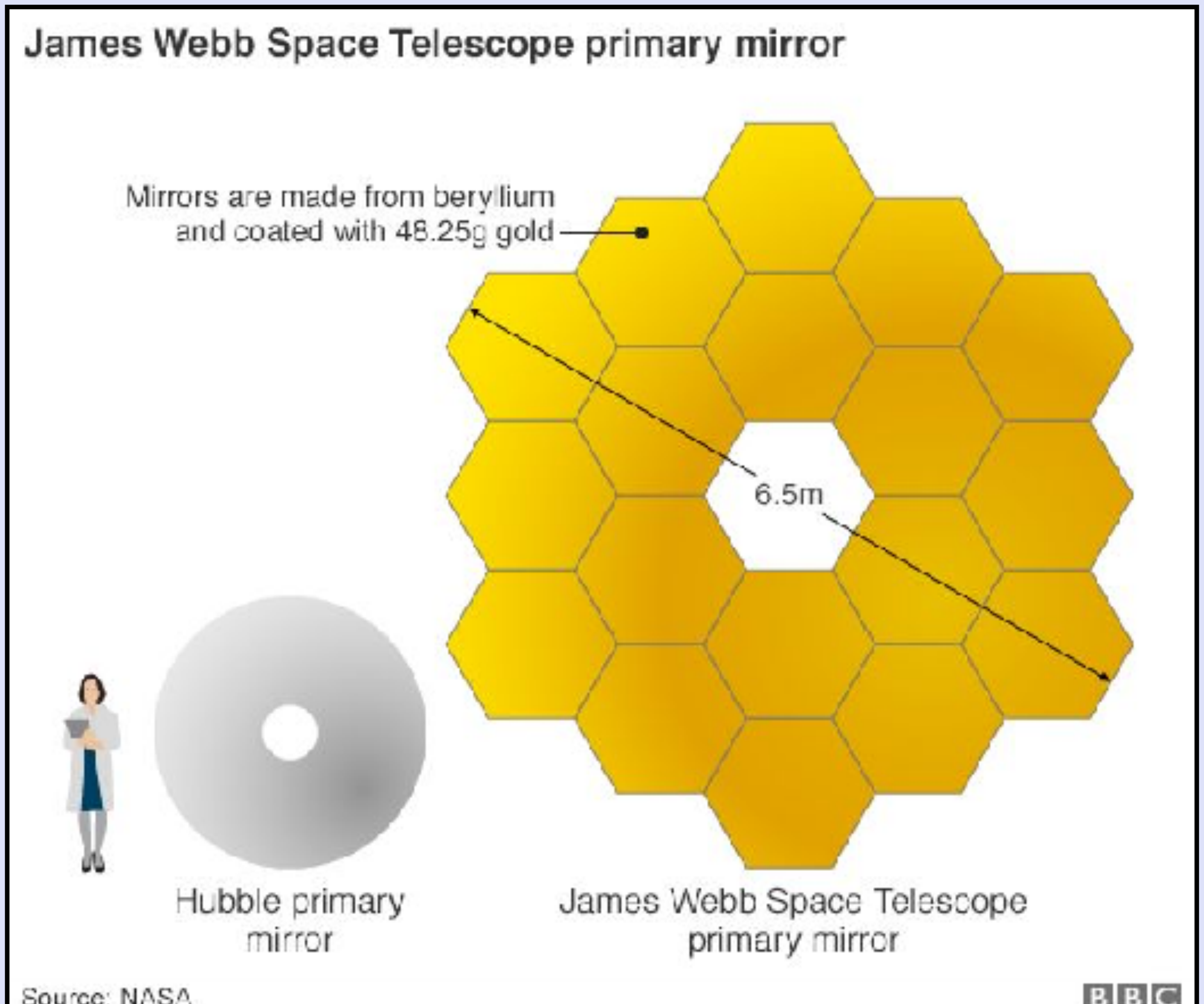
James E. Webb (1906–1992)

The second NASA's administrator (1961–1968)

played a key role in the Apollo program and established scientific research as a core NASA activity

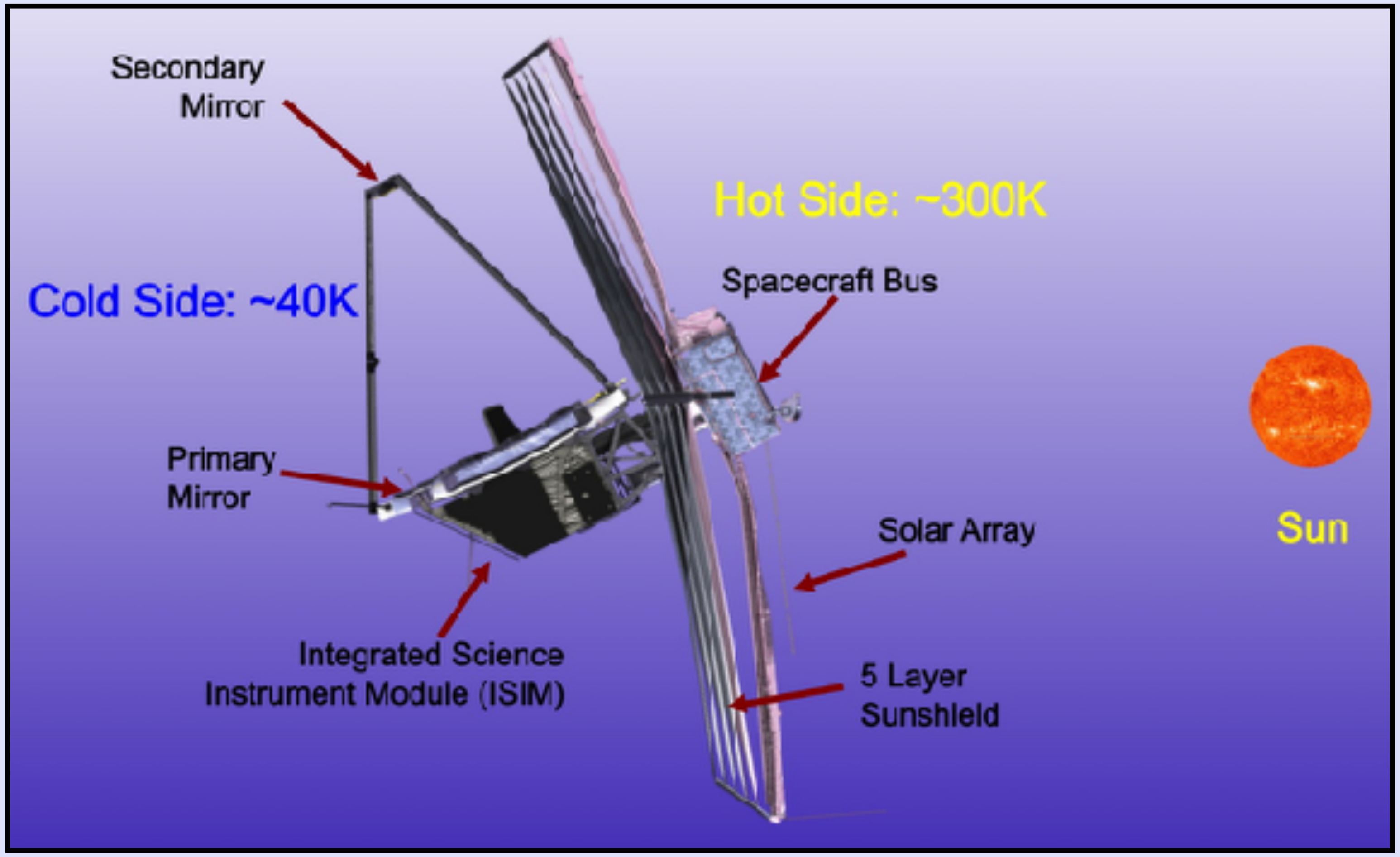
Primary mirror

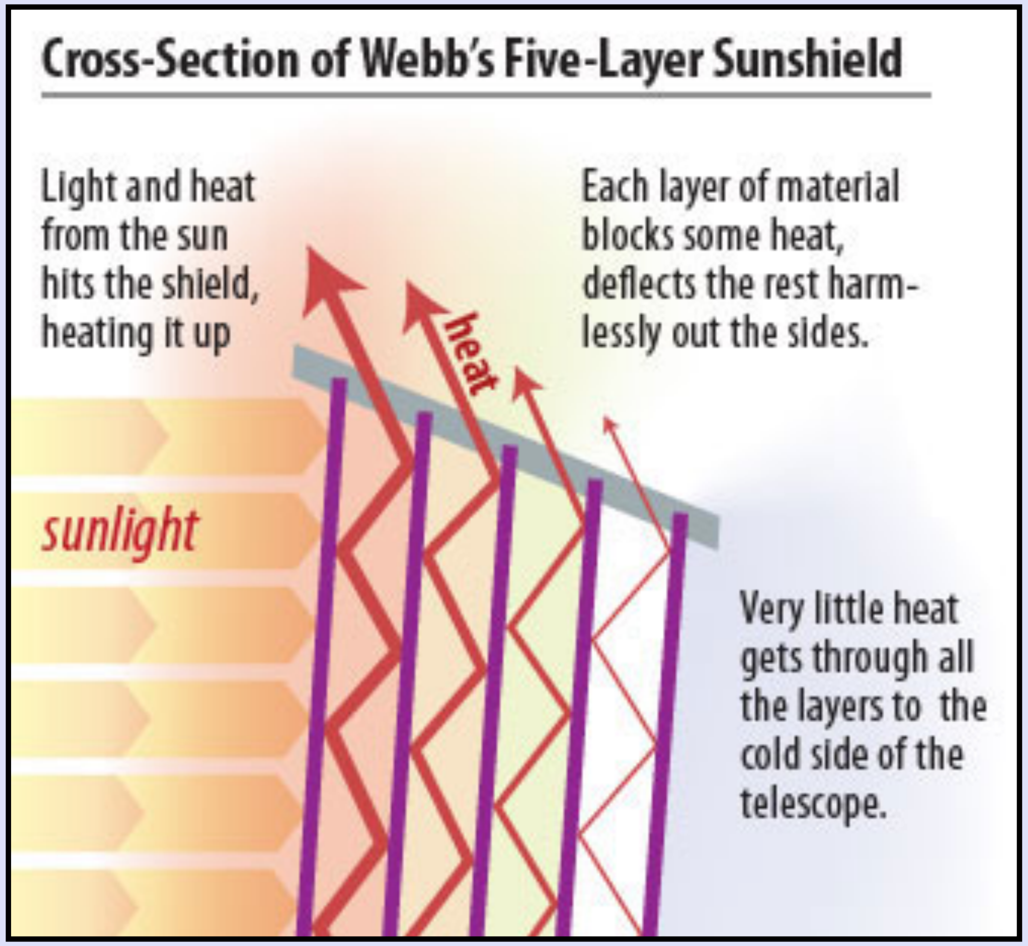
- Segmented primary mirror 6.5-m in diameter
- Coated by gold: high and uniform reflectivity at $1 \lesssim \lambda/\mu m \lesssim 25$
- Diffraction limit ~ λ/D ~ 0.11″ at 3.6 μm ([OIII]5007 at z~6)
- Same as HST in Red (0.8 μm)



Observatory

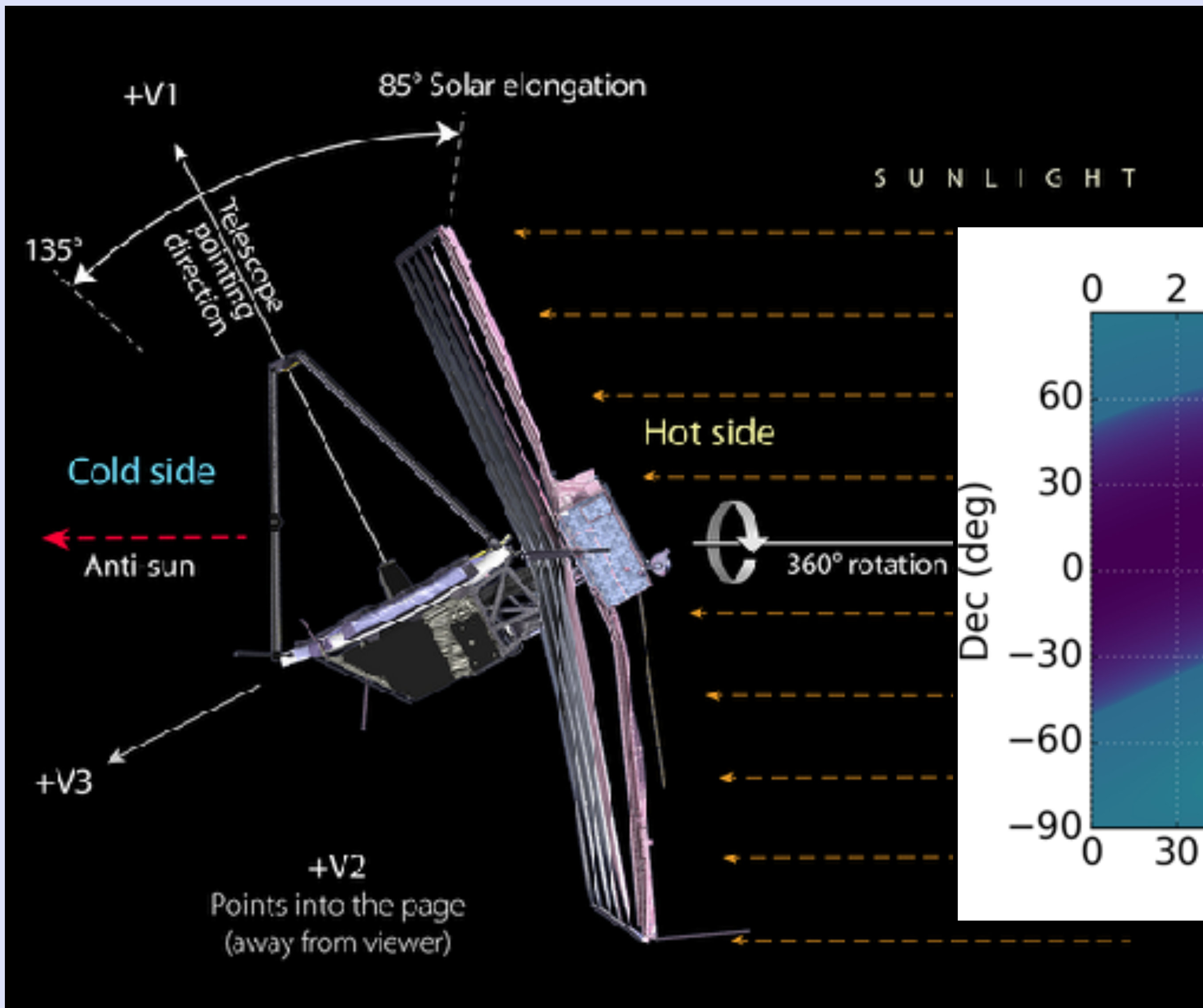
- Efficient and perfect cooling is essential for IR observations.
- Sun shield is not only for blocking the sunlight,
but also for heats.

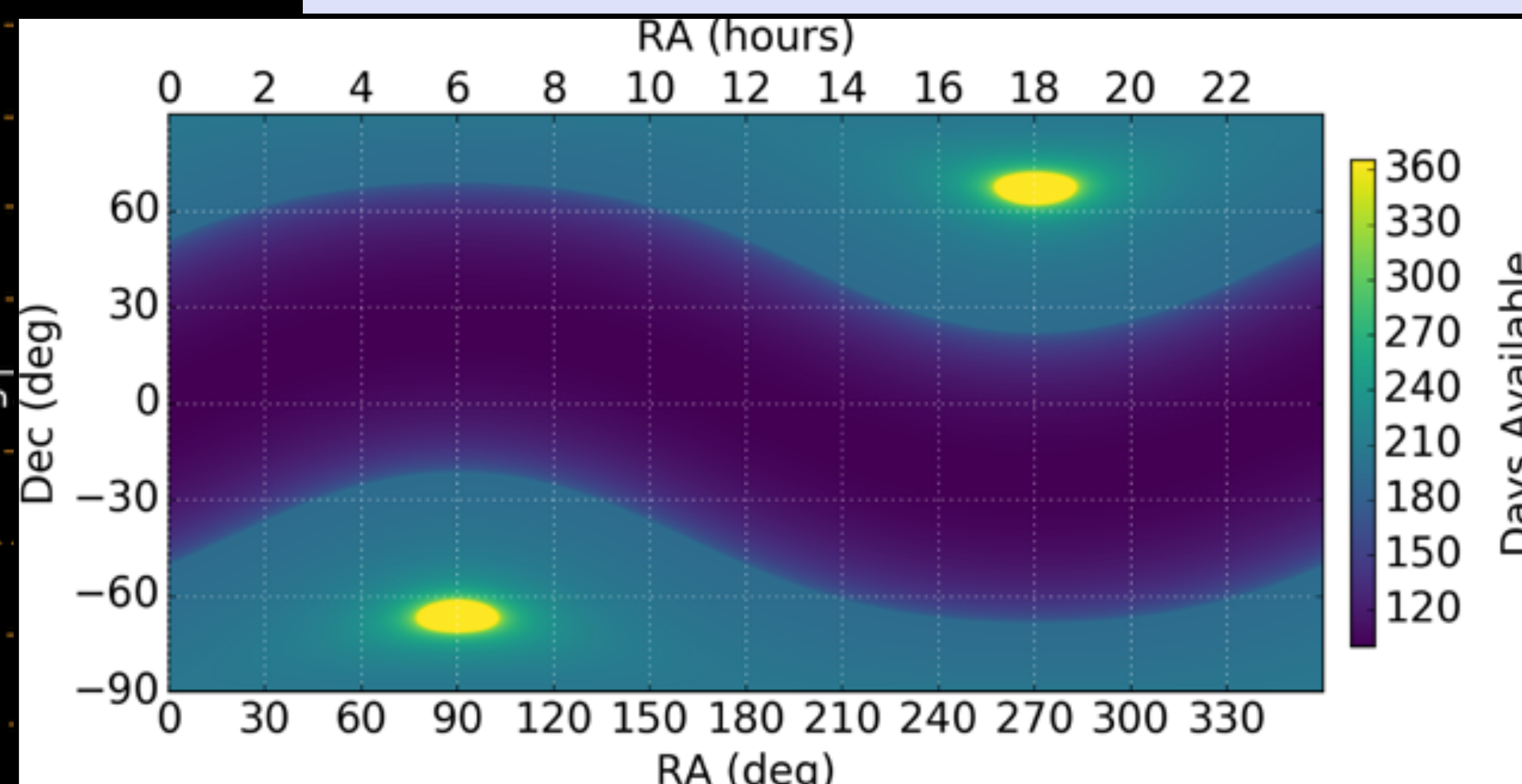




Field of Regard

- Visibility of the telescope is very limited, in order to keep always the sunshield against the sun.
- More chance at higher ecliptic latitude.
- JWST can moves only very slowly: rotating 90 degs takes 1 hour.





Where will he go?

- The L2 point in the Sun-Earth system
- Traveling + commissioning ~ half a year