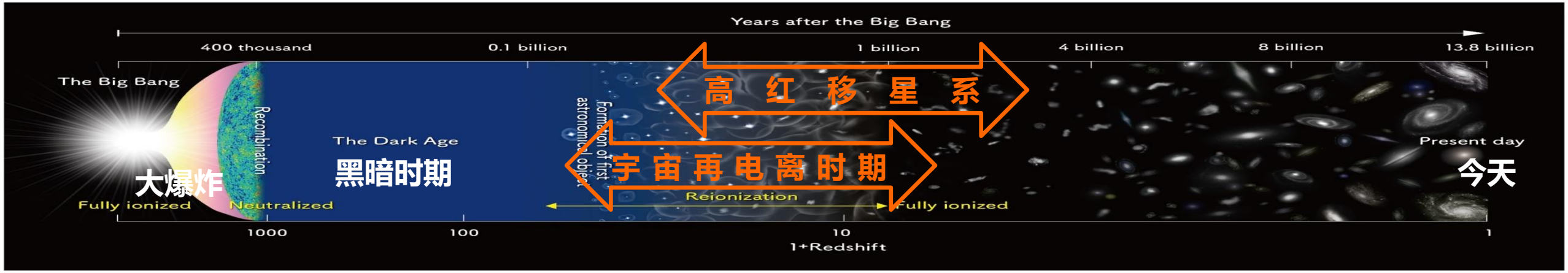


Cosmic Reionization & High-redshift Galaxies

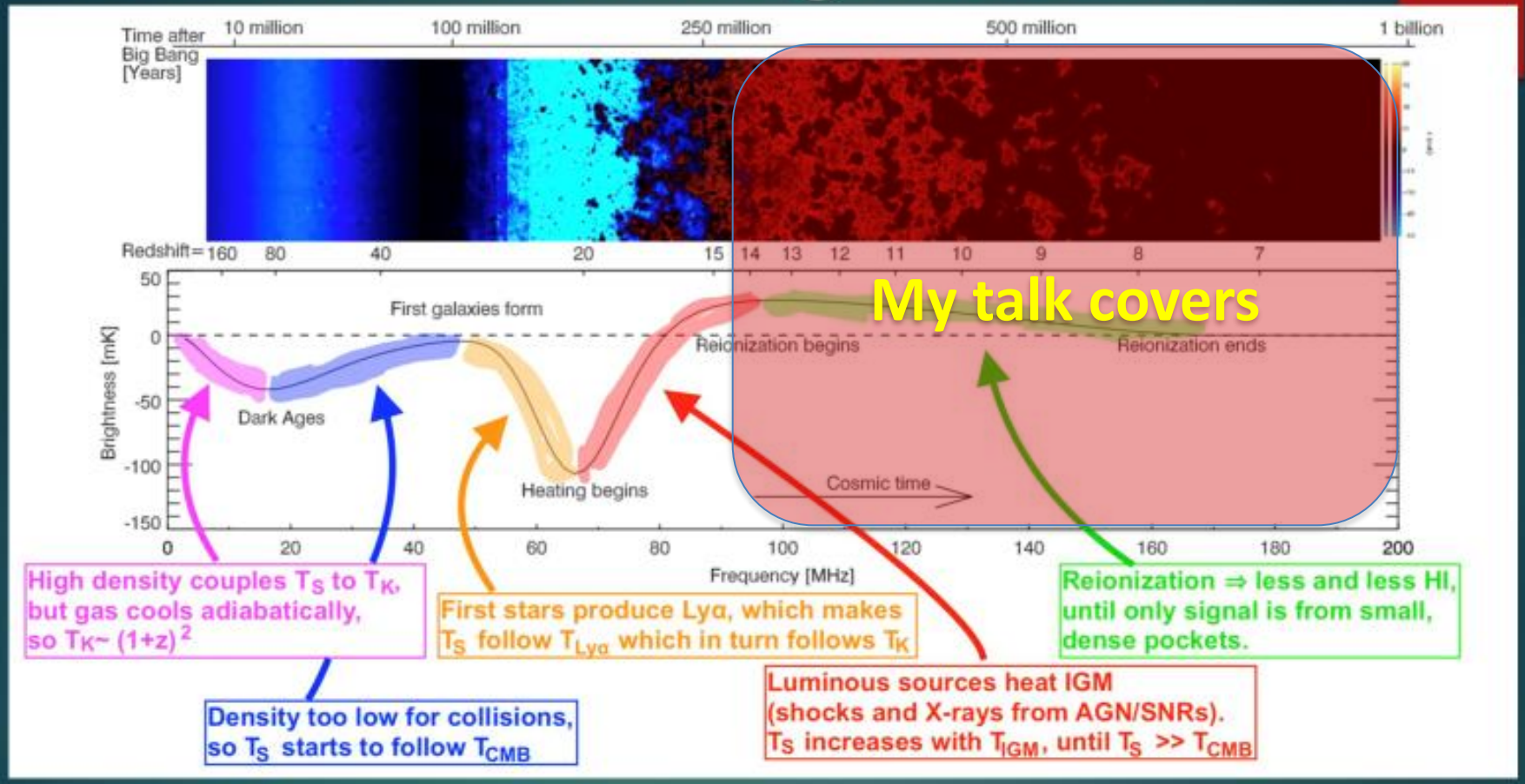
宇宙再电离和高红移星系

Zhen-Ya Zheng （郑振亚）

Shanghai Astronomical Observatory, CAS

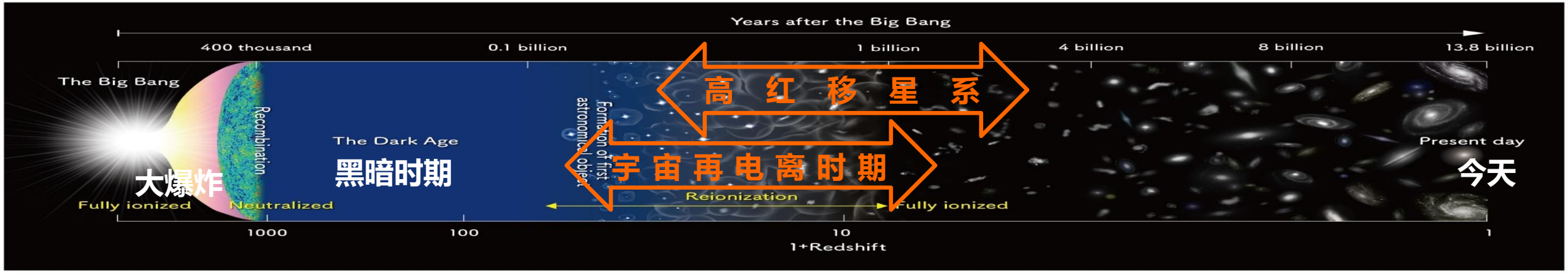
The Summer School for 21cm Cosmology

Global 21 cm signature



- 200<Z<1100: T_s = T_CMB, no 21cm signals
- 40<z<200: Ts~Tk, Tk~(1+z)^2, T_b < 0
- Z_*<z<40: collisional coupling ineffective and radiative coupling to the CMB sets T_s = T_cmb, no 21cm signals

Slide Credit: Quan Guo



Why study cosmic reionization?

- Cosmic reionization is the last major phase transition of most baryonic matter in the Universe. It involves the conversion of cold, neutral hydrogen into highly ionized hydrogen in the intergalactic medium, implying the end of the Dark Age and the beginning of the Age of Galaxies.

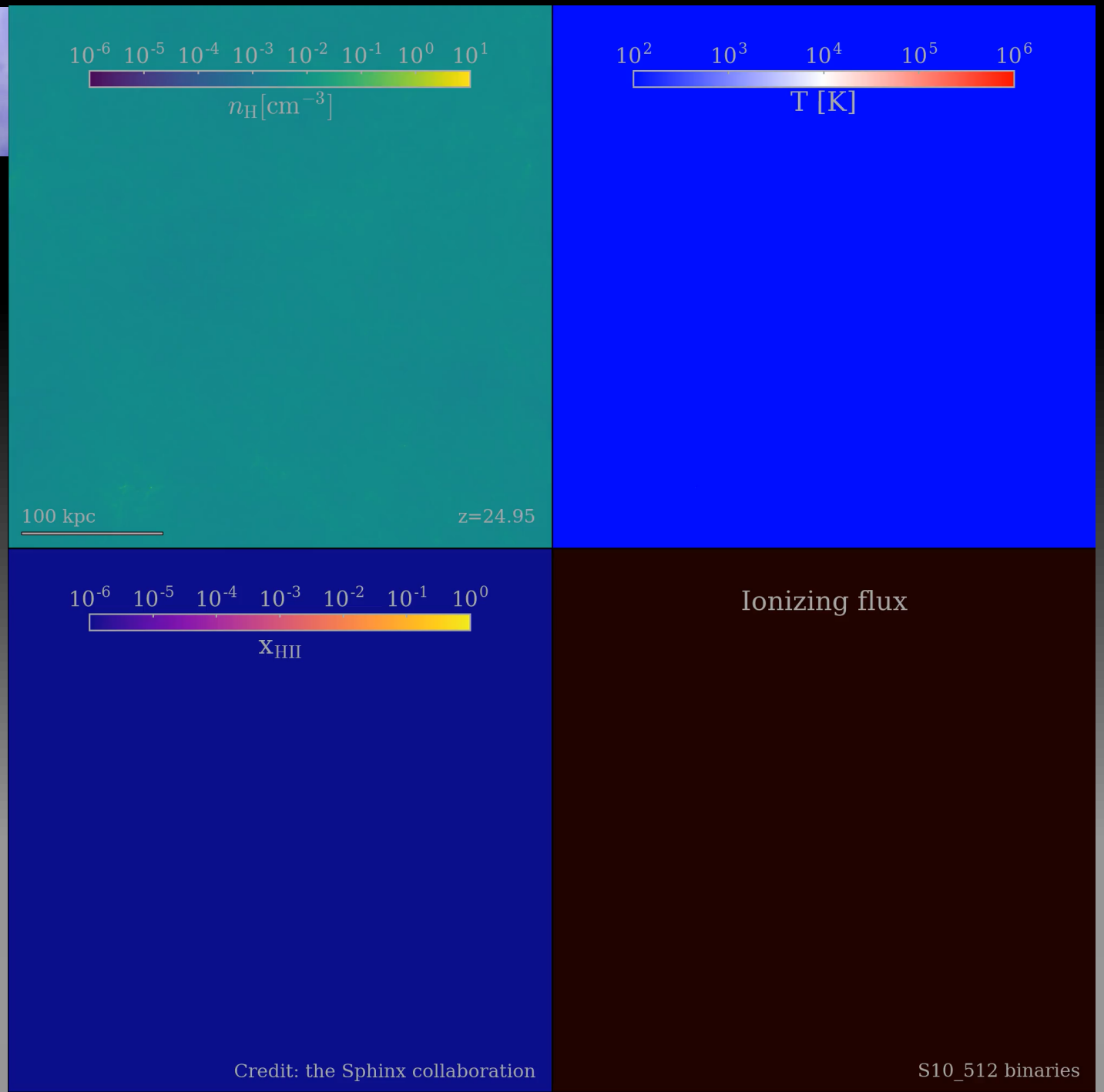
- This process reflects the formation, radiation, and dynamical characteristics of first-generation objects, small-scale density fluctuations, cosmic chemical evolution, early stellar formation and black hole accretion histories, and a complex series of feedback mechanisms.

THE SPHINX PROJECT

Cosmological radiation-hydrodynamical simulations of reionization

- n_H: density of H
- T(K): Temperature
- X_{HII}: fraction of HII
- Ionizing flux: LyC photons

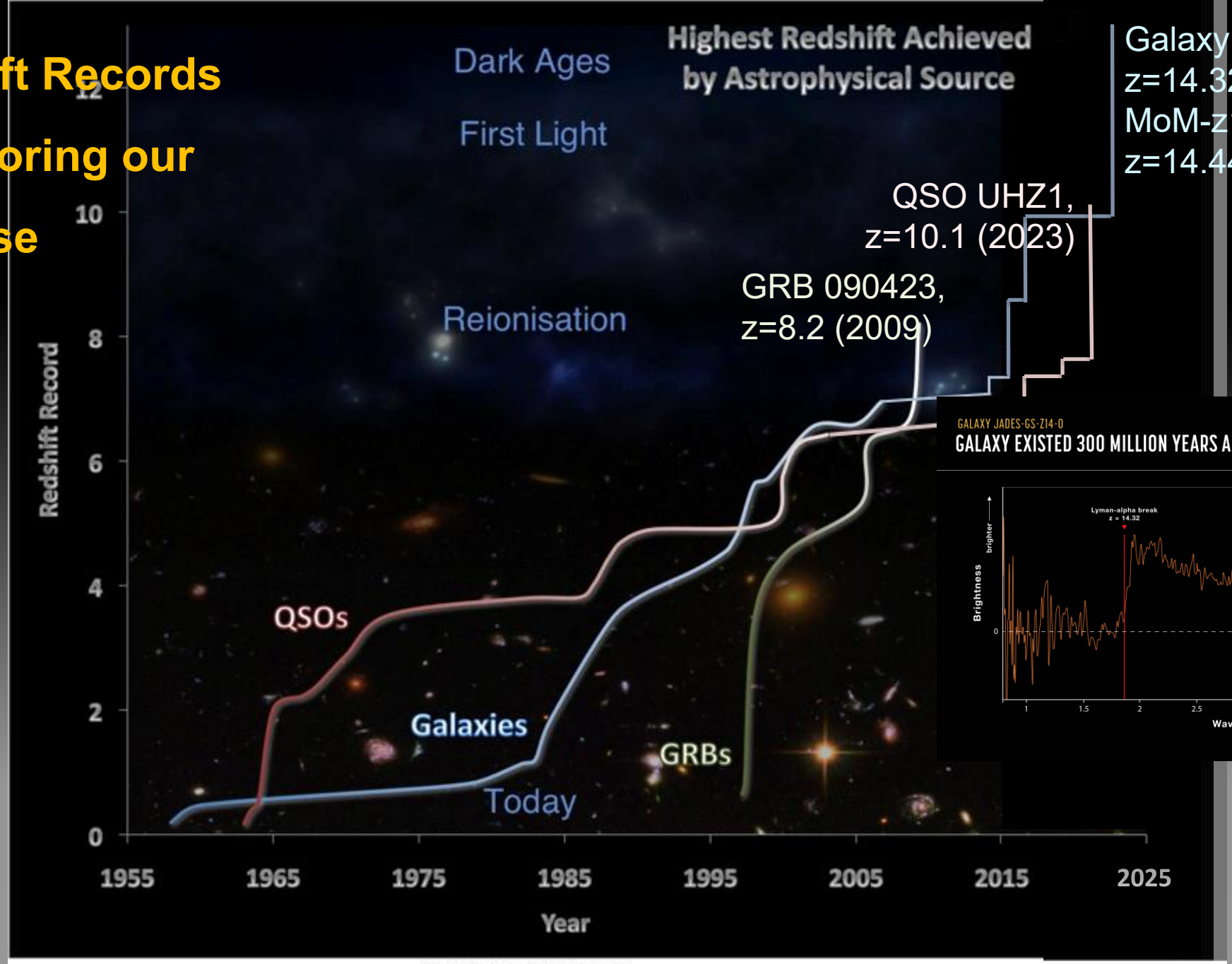
https://sphinx.univ-lyon1.fr/



Outlines

- Galaxies in the Early Universe
- Reionization Probes：QSOs，CMB，21cm，Lya
- Reionization Topology
  - Clustering of Lya Galaxies
  - Lya-21cm CCF
- Reionization Contributors
  - Galaxies vs. AGN/Quasars
  - Properties of LyC Leaking Galaxies
- Current & Future Galaxies Surveys for Reionization

Redshift Records in Exploring our Universe



The evolution of the redshift record

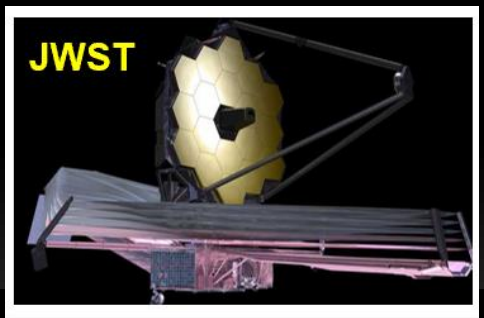
Image courtesy of Darach Watson (Dark Cosmology Centre, University of Copenhagen) with data from Nial Tanvir (University of Leicester) and Gerry Gilmore (University of Cambridge)

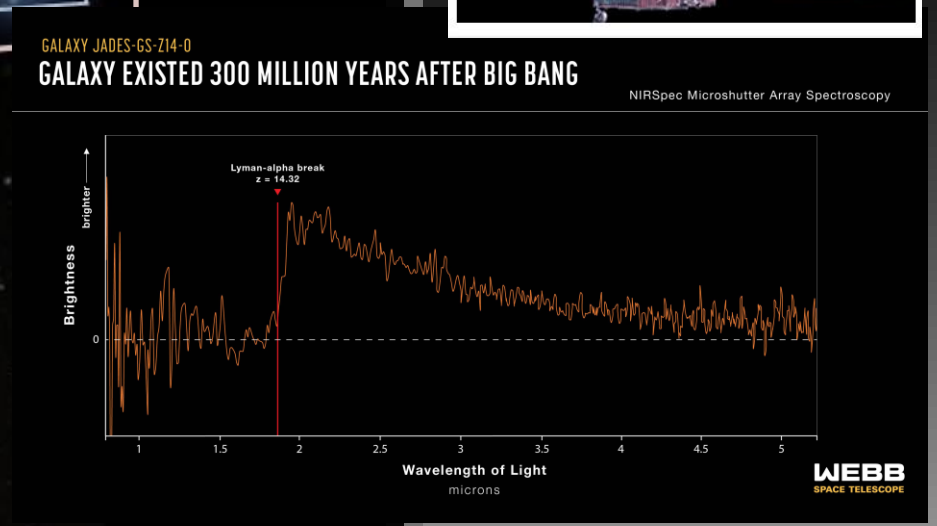
European Space Agency

Galaxy JADES-GS-z14-0, z=14.32(2024); MoM-z14, z=14.44(2025)

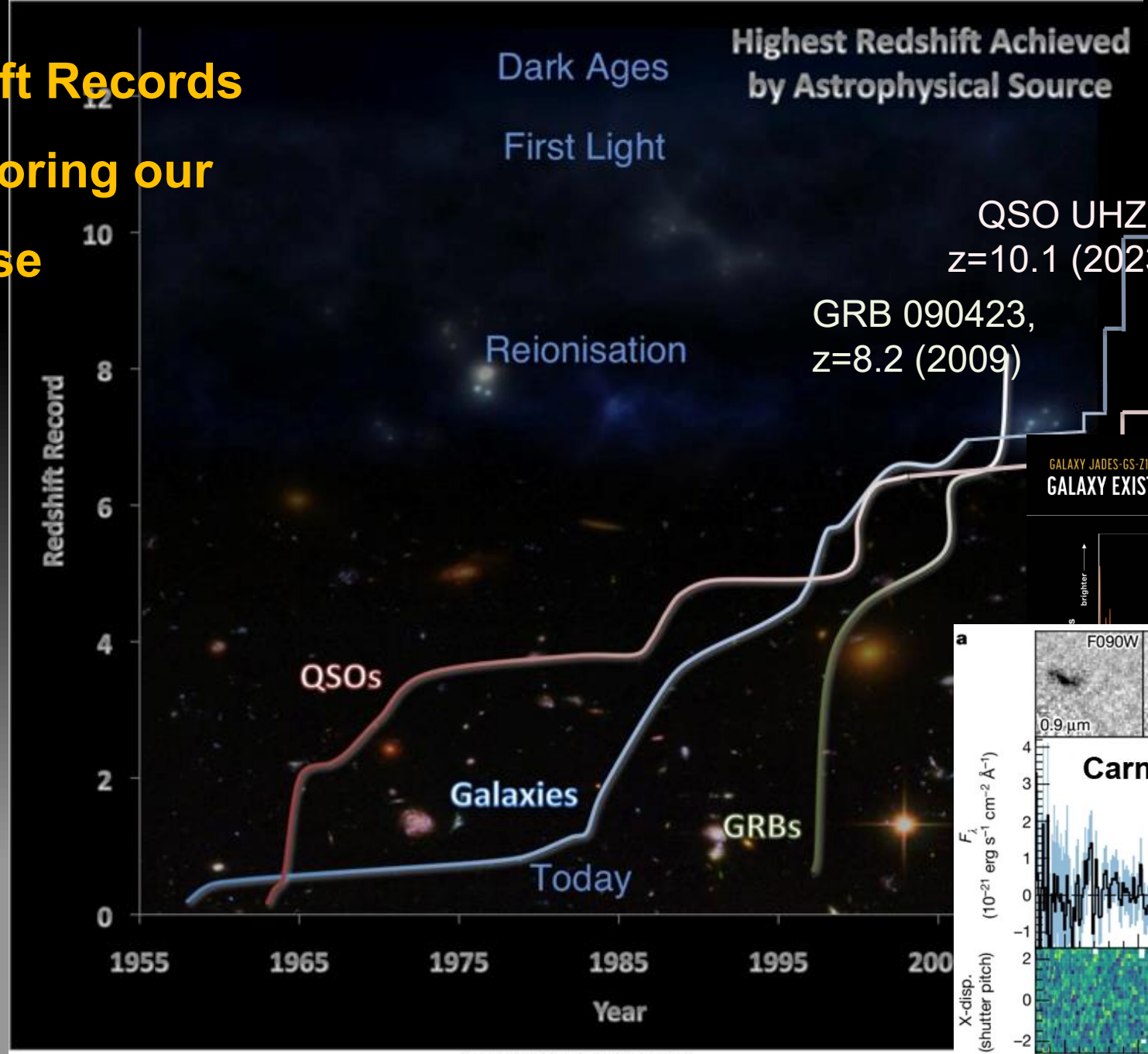
QSO UHZ1, z=10.1 (2023)

GRB 090423, z=8.2 (2009)





Redshift Records in Exploring our Universe



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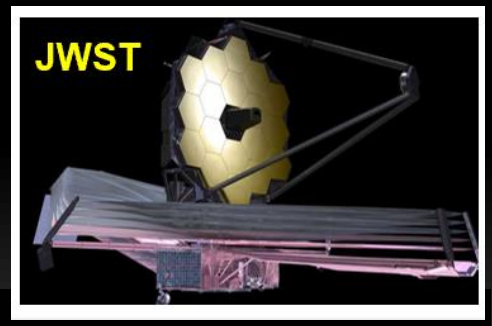
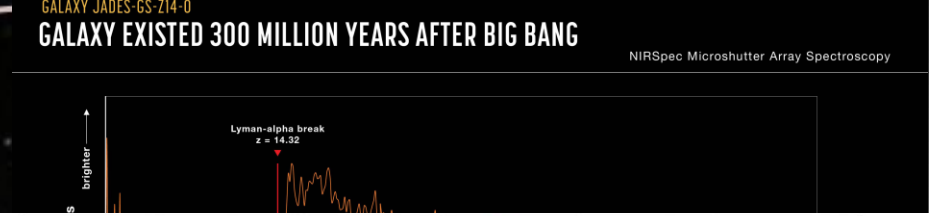
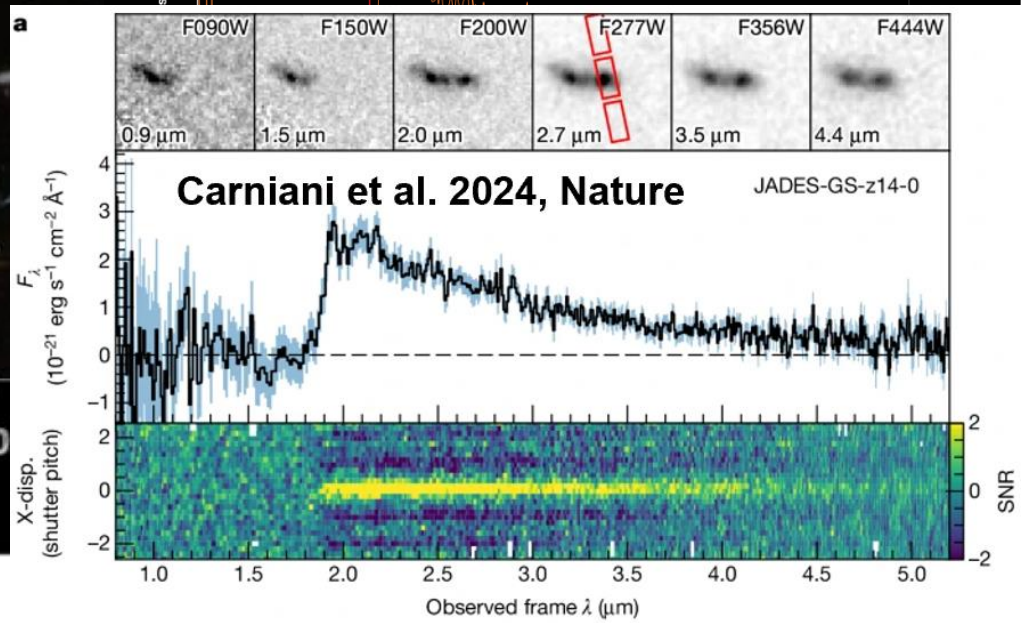
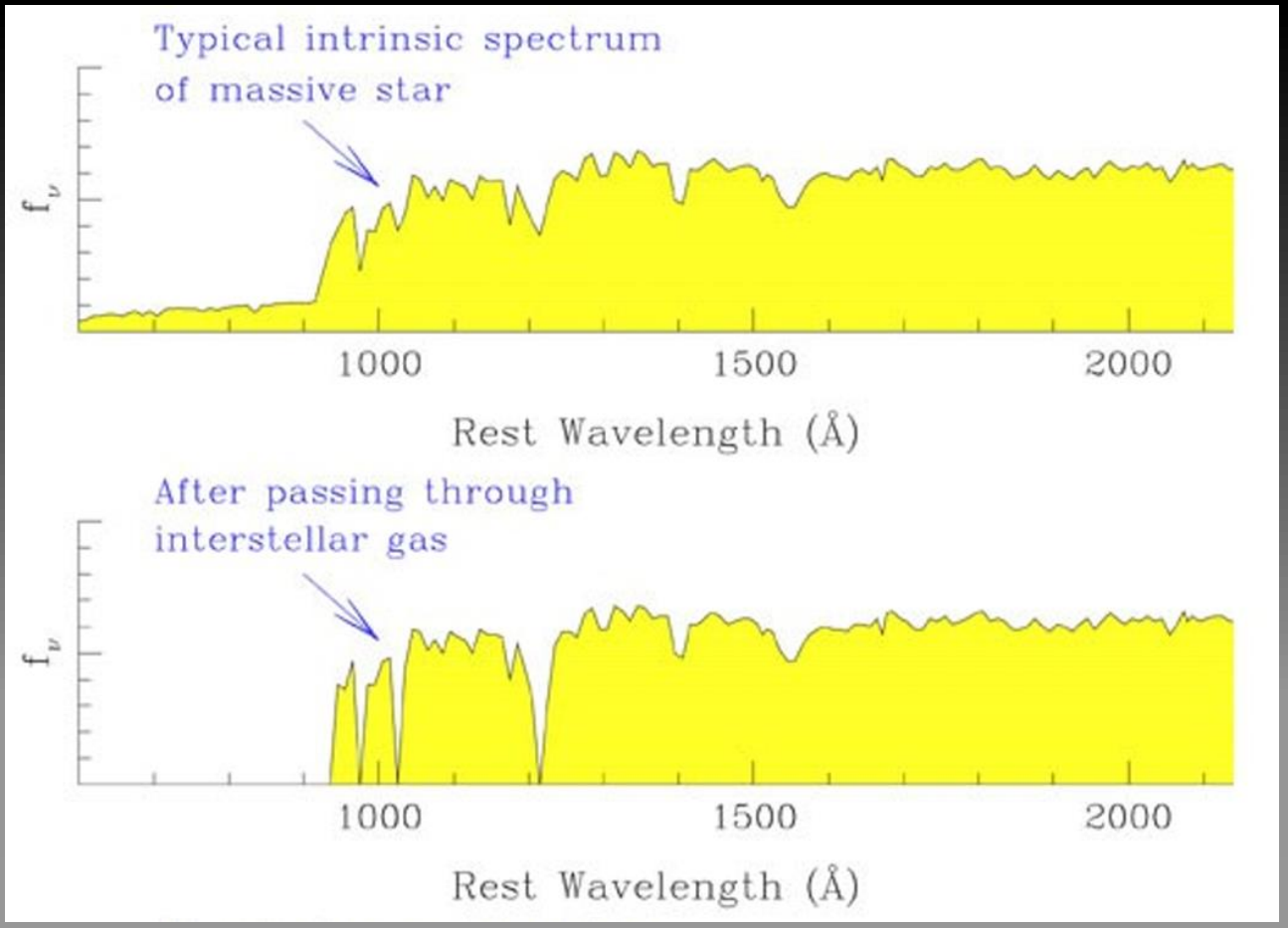


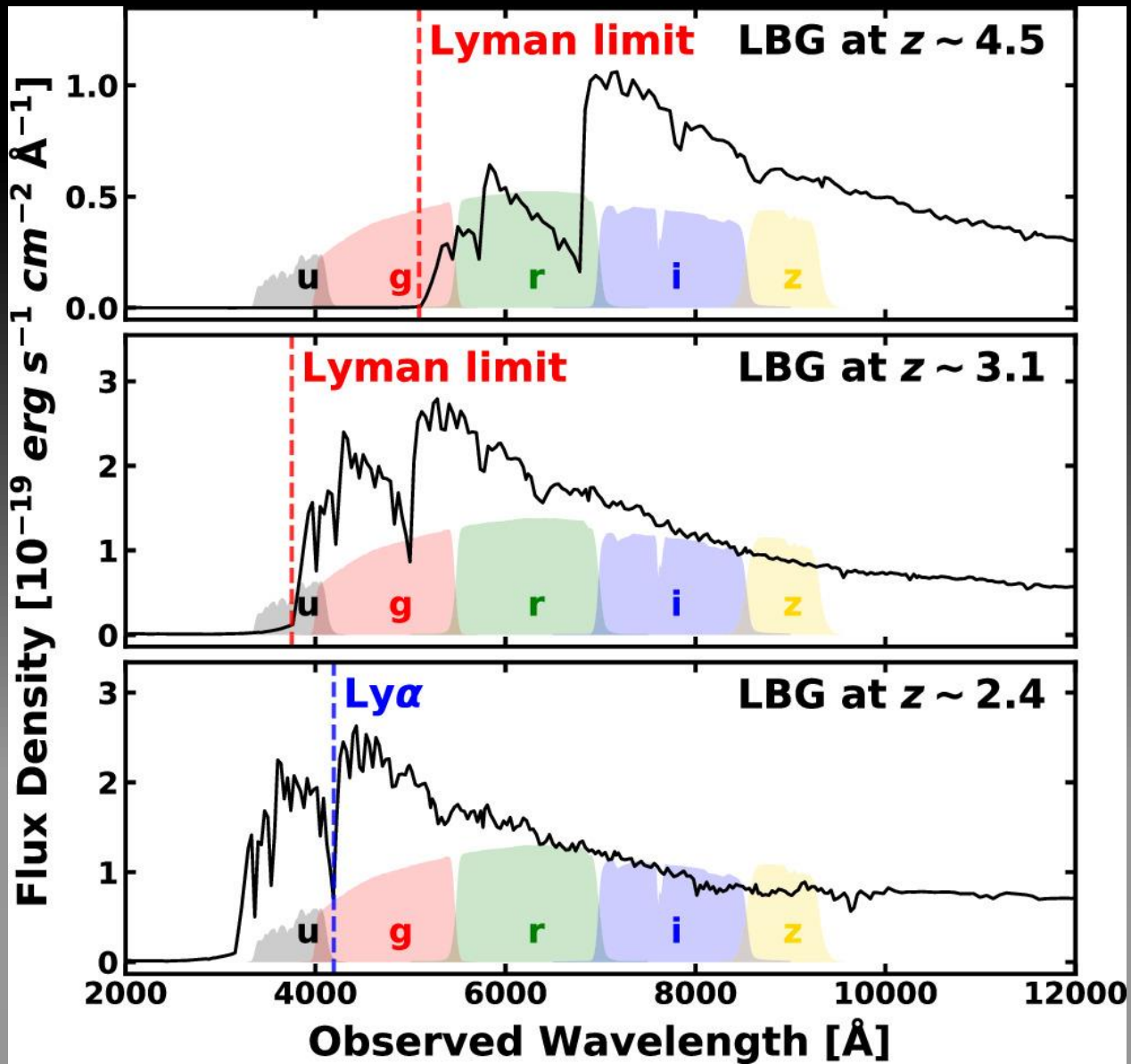




How do we search for high-z objects?

- **Lyman Break Galaxies (LBGs)**

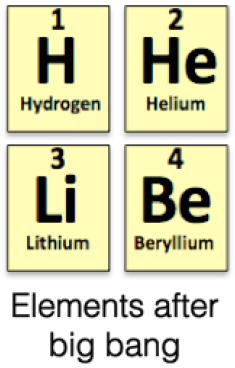




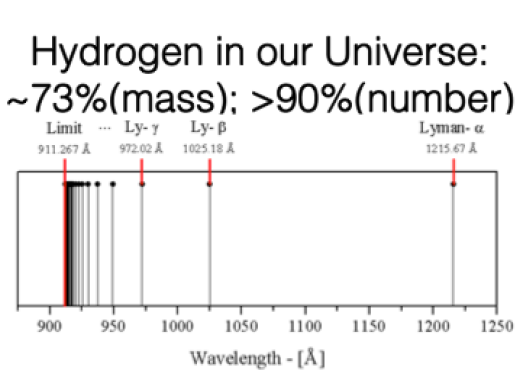
Im et al. 2024

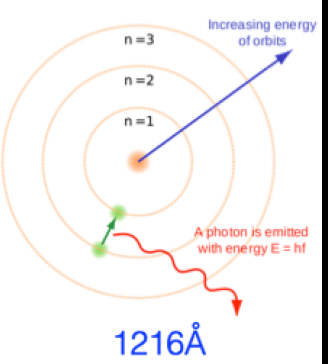
How do we search for high-z obje

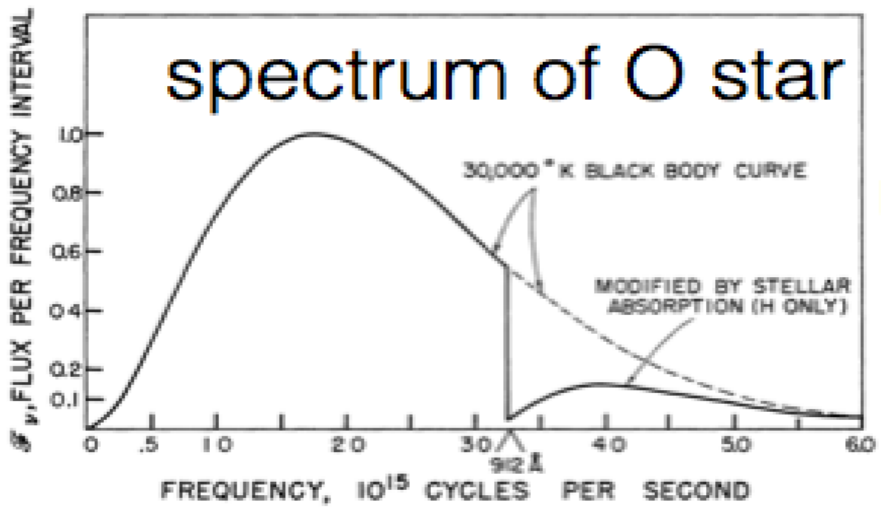
- **Lyman-alpha Emitters (LAEs)**



Elements after big bang







UV photons radiative-transfered by neutral hydrogen

N(Ly-a)/N(UV) ~ 68%

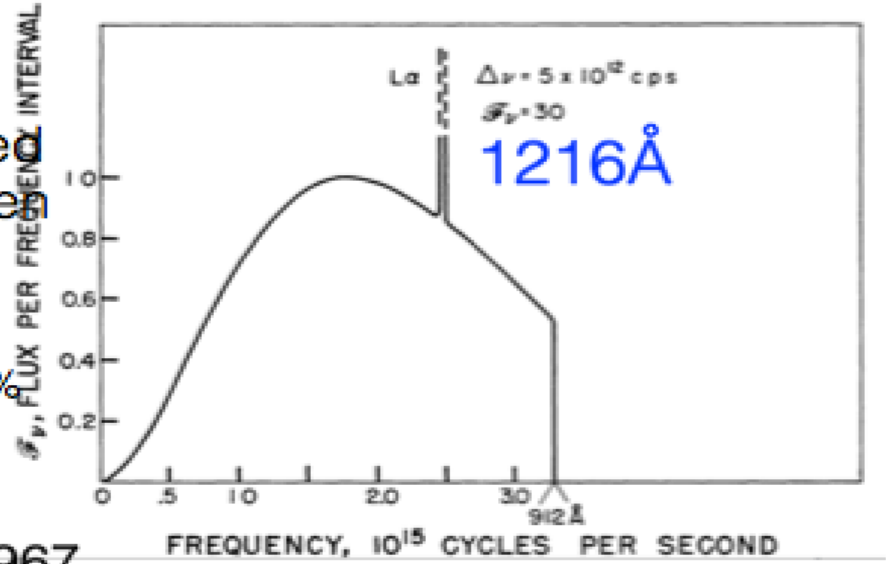
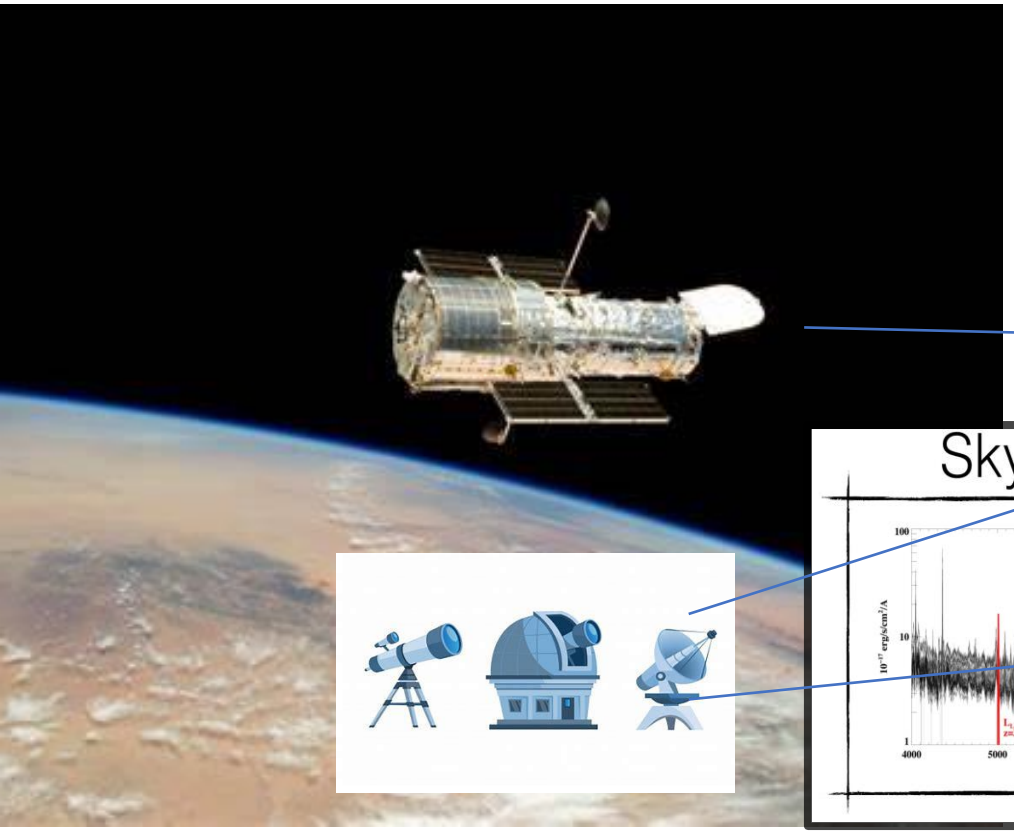


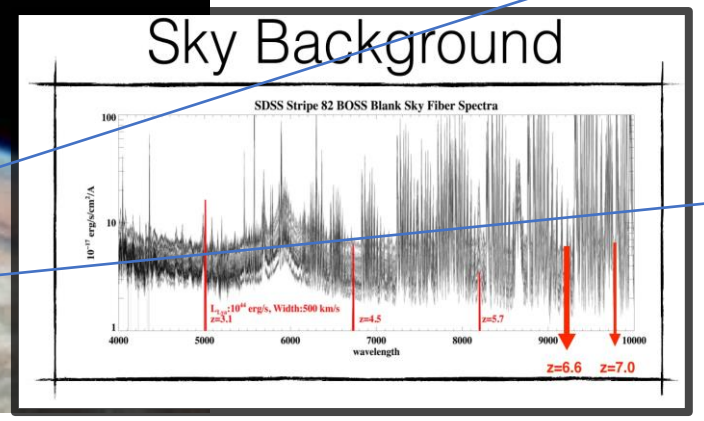
FIG. 2.—The spectrum is a black-body spectrum calculated for $T_* = 30000°$ K (the assumed effec-

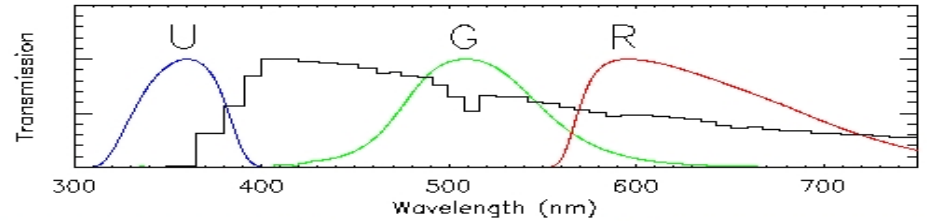
Partrige & Peebles 1967

- Primeval galaxies (at very high-z) are composed of newly formed massive stars.
- The ionizing UV photons generated by massive stars are transferred into strong Lyman-α emission lines with hydrogen atoms in the interstellar medium.
- These galaxies are known as Lyman-α emitter galaxies (LAEs).

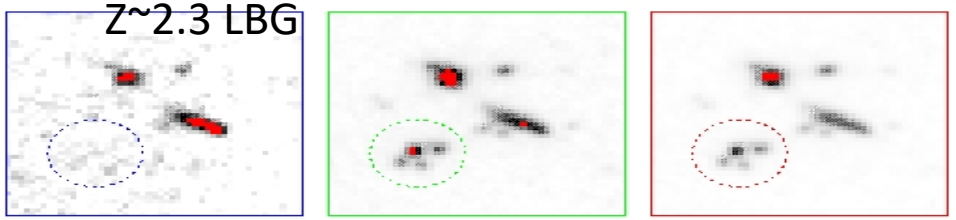
• Searching Methods for High-z Galaxies







Z~2.3 LBG

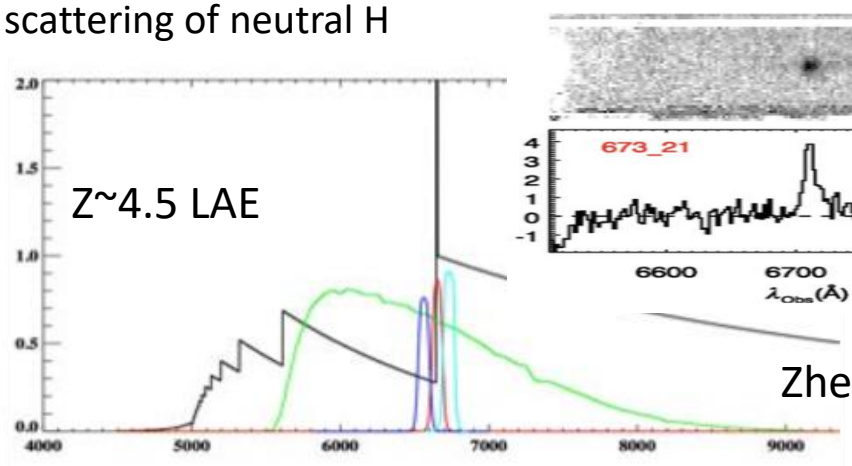


• Lyman-Break Galaxies (LBGs)

Spectral break around (rest-frame) 912Å by absorption of neutral H

• Lyman-α Emitter Galaxies (LAEs)

Spectral line around (rest-frame) 1216Å by resonant scattering of neutral H

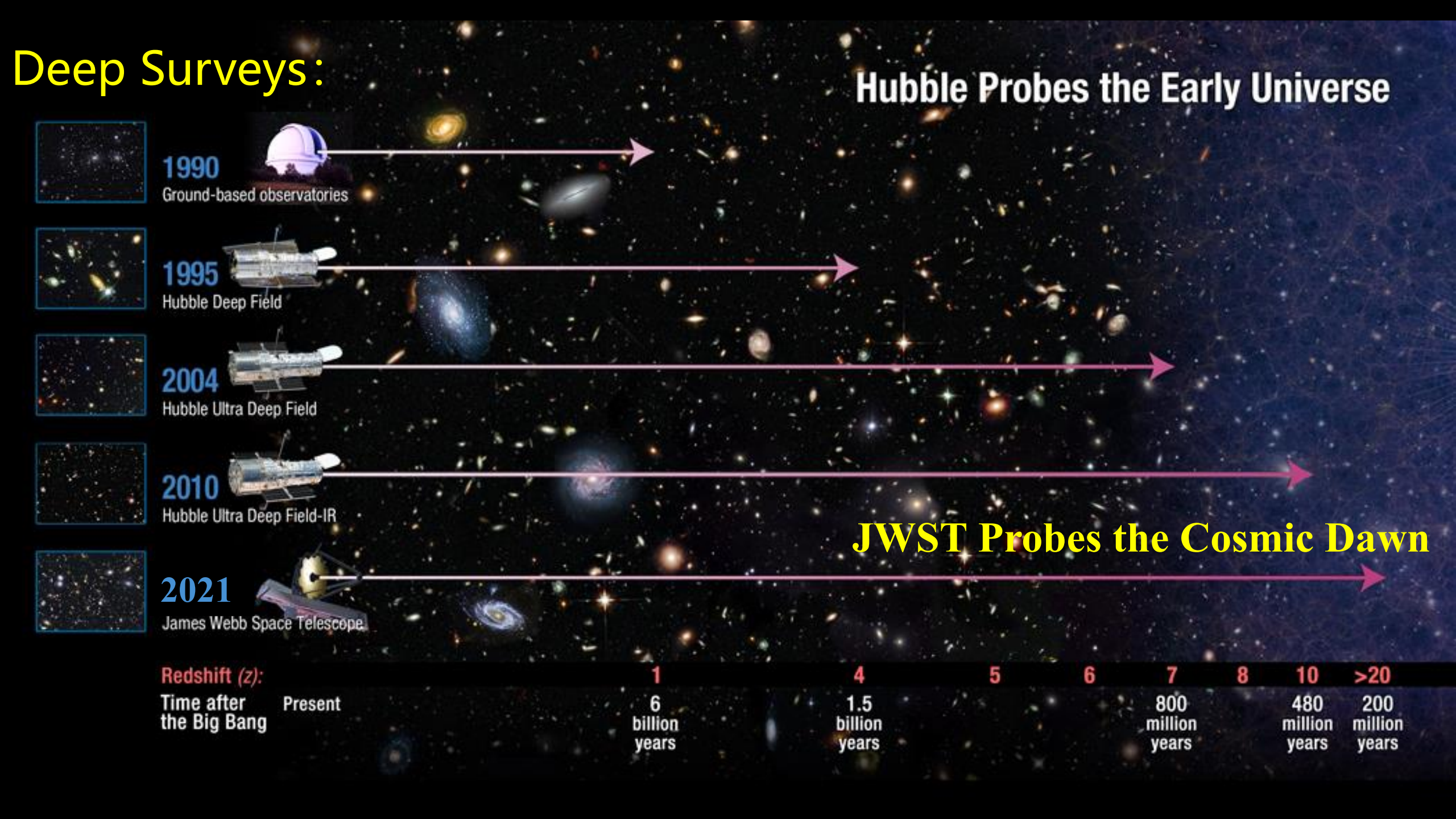


- **Deep surveys for LAEs at z>2:**

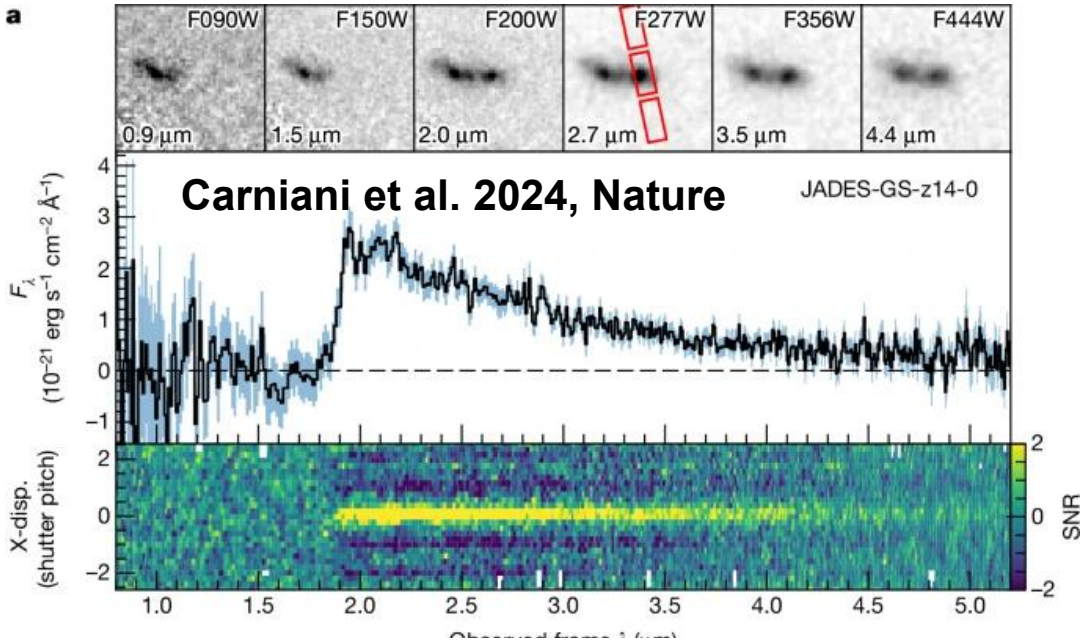
Hawaii Survey: Cowie&Hu98; LALA Survey: Rhoads+00; Subaru surveys: Ouchi+03; MUSYC: Gawiser+07; HETDEX Pilot Survey: Adams+11; VLT/MUSE survey: Bacon+17; LAGER: Zheng+17; SILVERRUSH , CHORUS； ODIN, Lee+24…

- **LBG surveys started from Steidel+95**

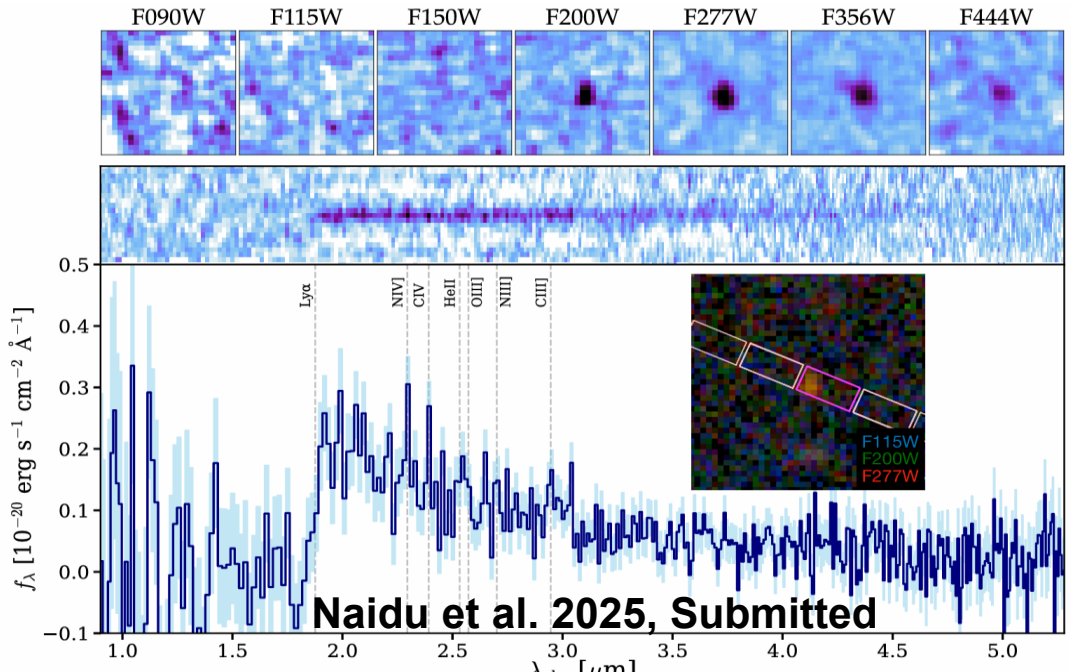
Deep Surveys:



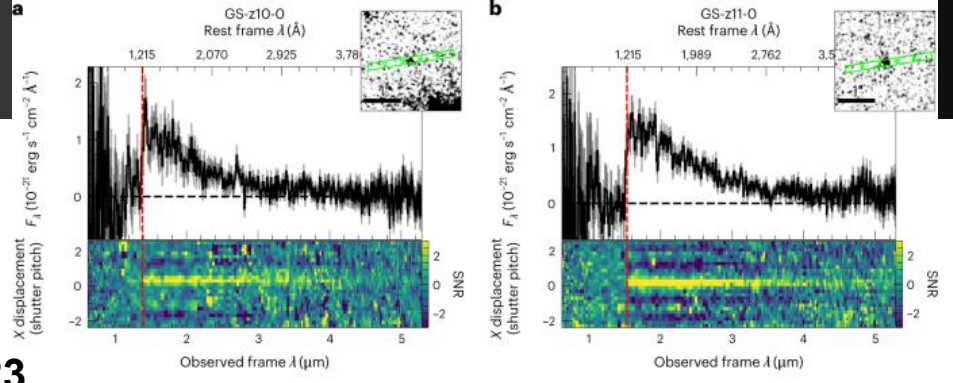
The Early Universe probed by JWST



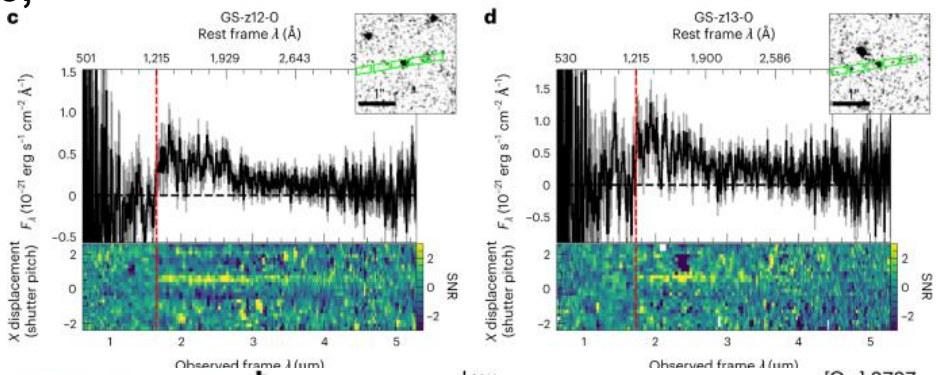
Carniani et al. 2024, Nature



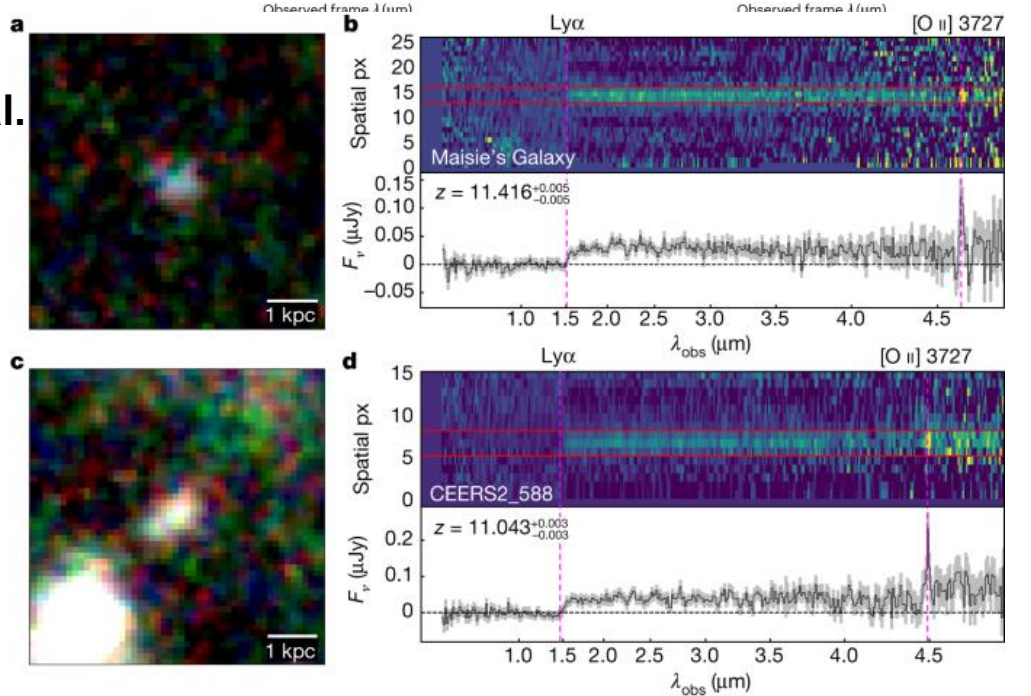
Naidu et al. 2025, Submitted



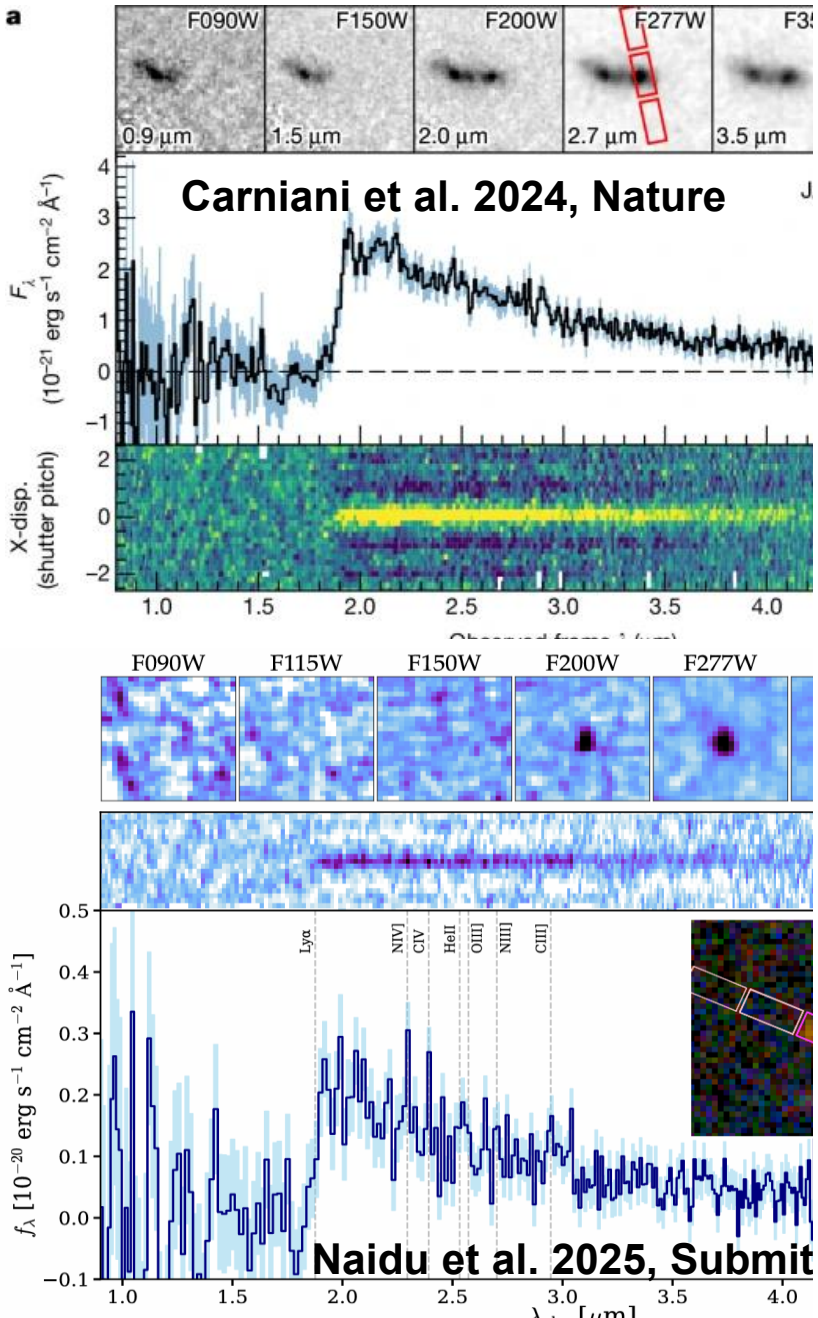
Curtis-Lake et al. 2023, Nature Astronomy

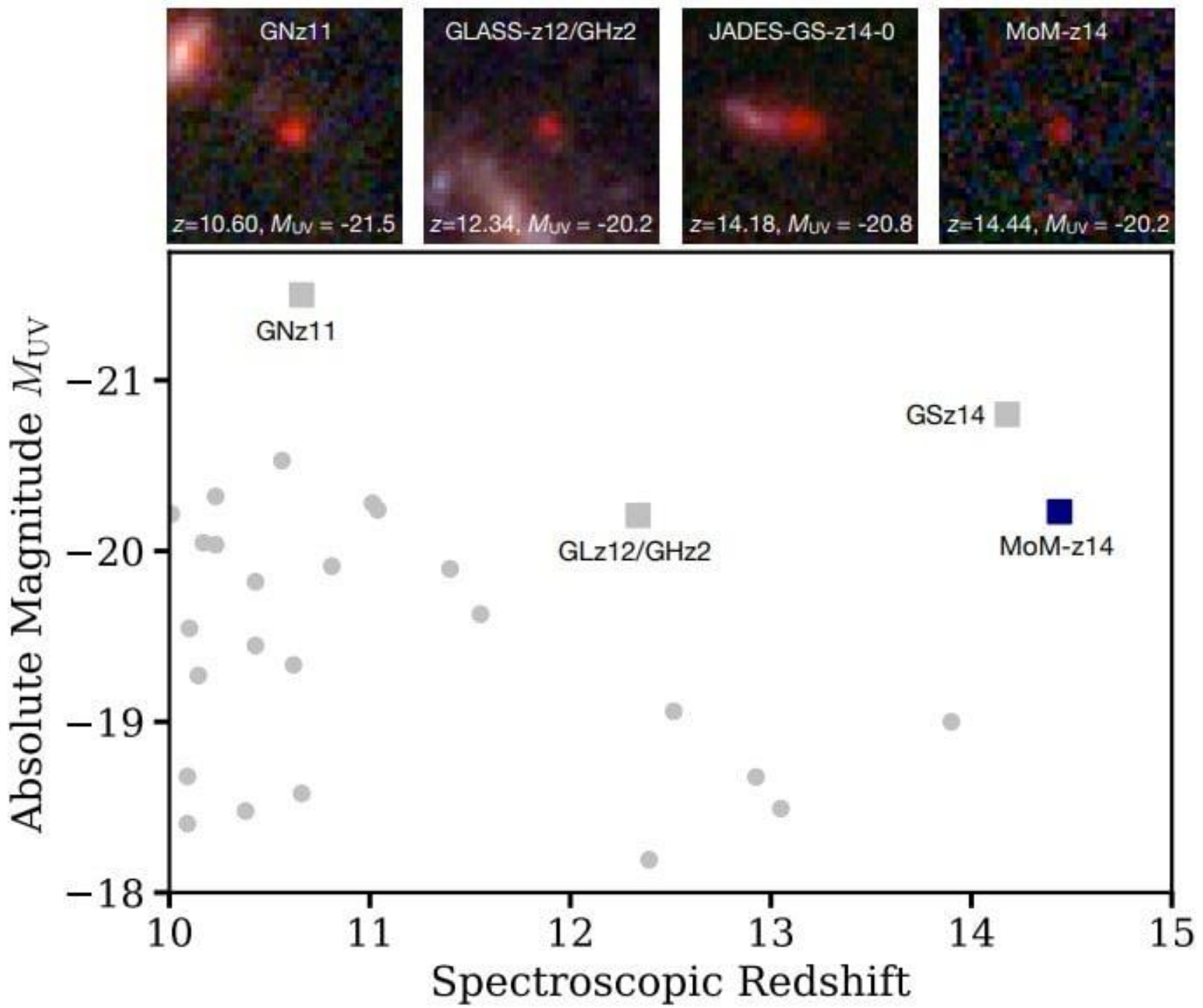


Arrabal Haro et al. 2023, Nature

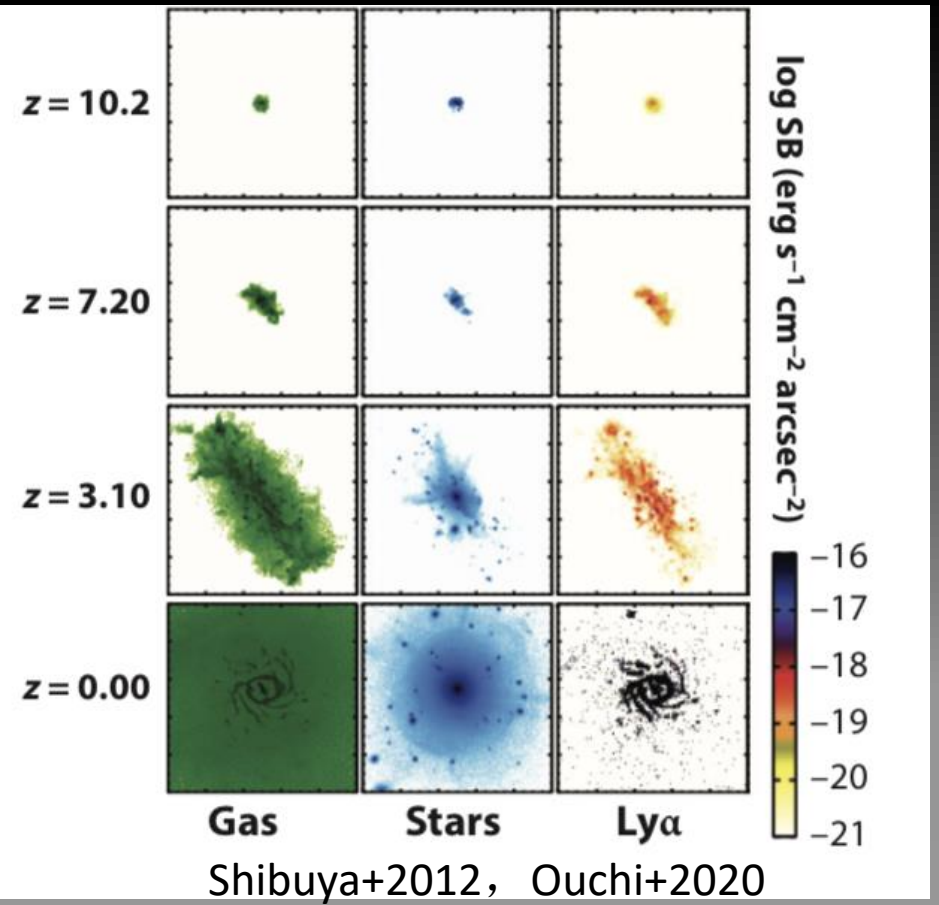


The Early Universe pr

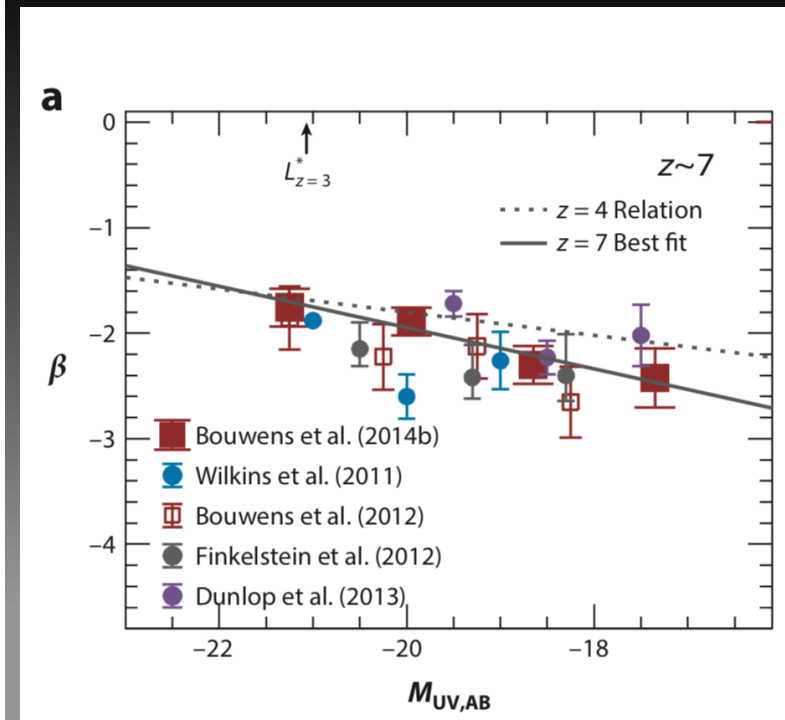


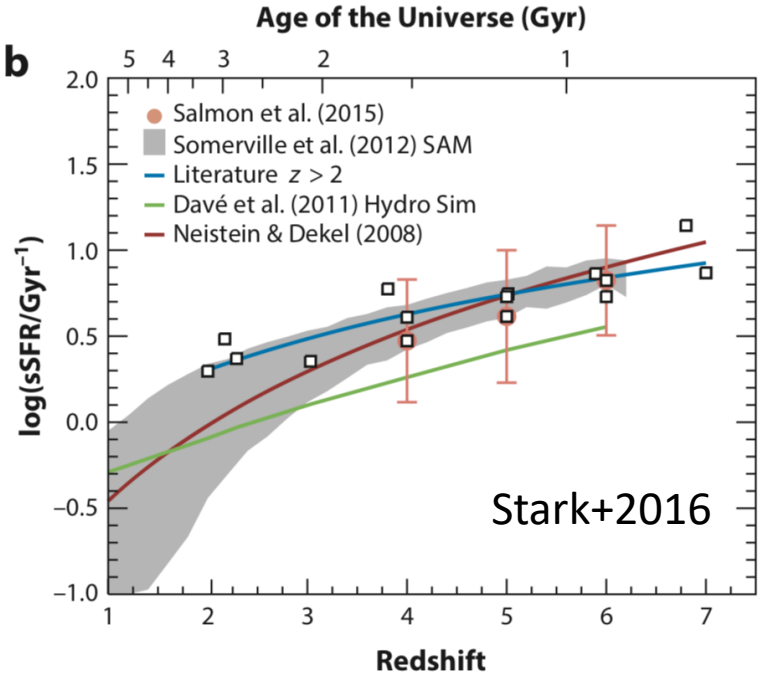


High-z Galaxies: basic properties



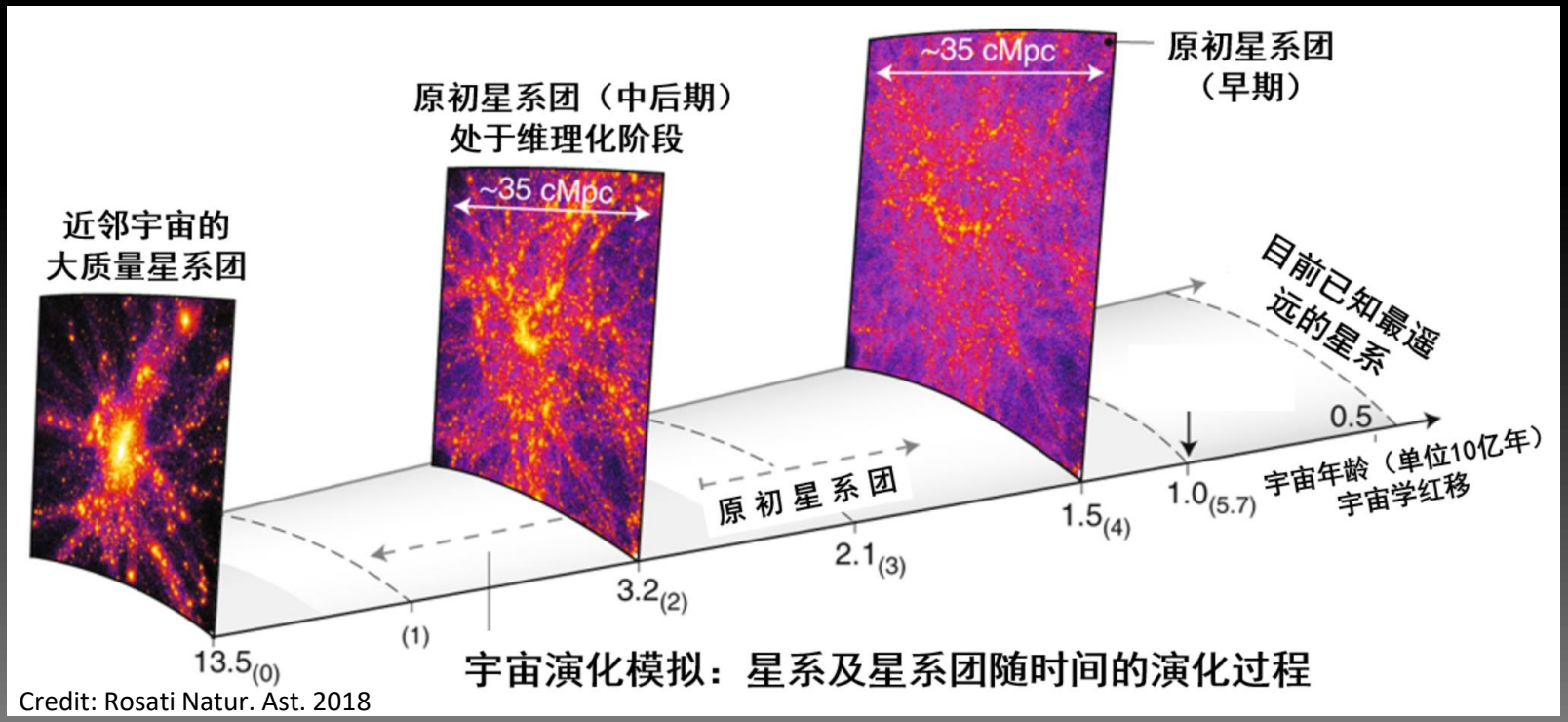
Shibuya+2012， Ouchi+2020





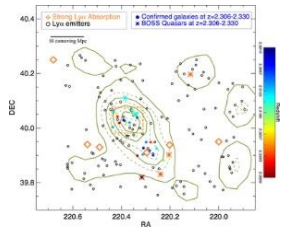
High-z Galaxies: Tracing the Environment

Using Lyman-alpha emitters to search for protoclusters and large-scale structures



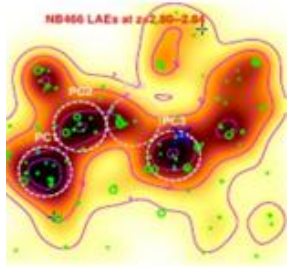
Credit: Rosati Natur. Ast. 2018

Cai+2017, ApJ



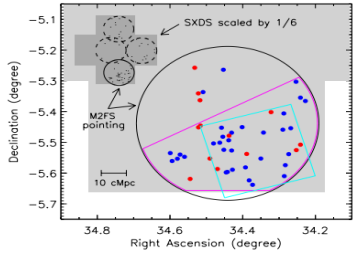
BOSS1441, z=2.3

Zheng+2016,ApJS



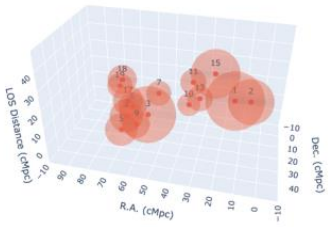
CDFS, z=2.8

Jiang+2018, Natur. Ast



SXDF, z=5.7

Hu+2021, Natur. Ast



COSMOS, z=6.9

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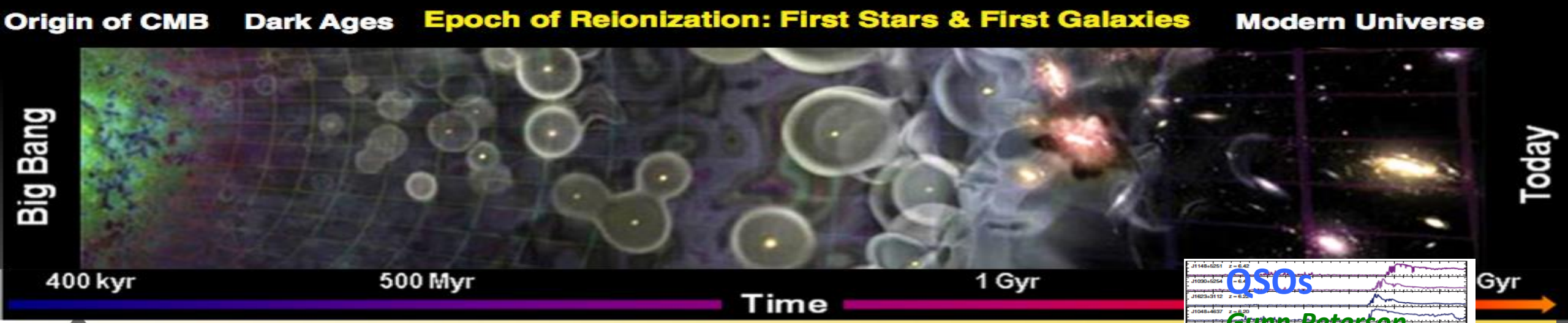
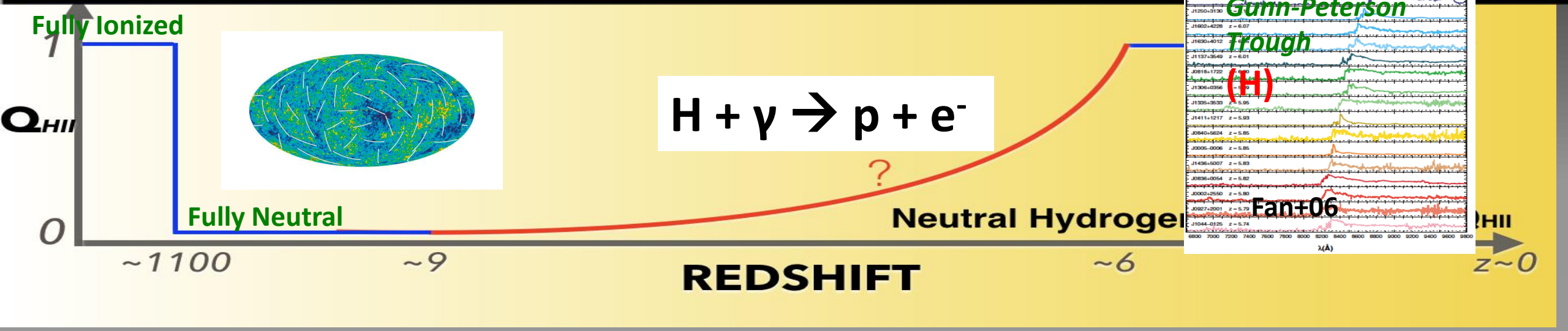
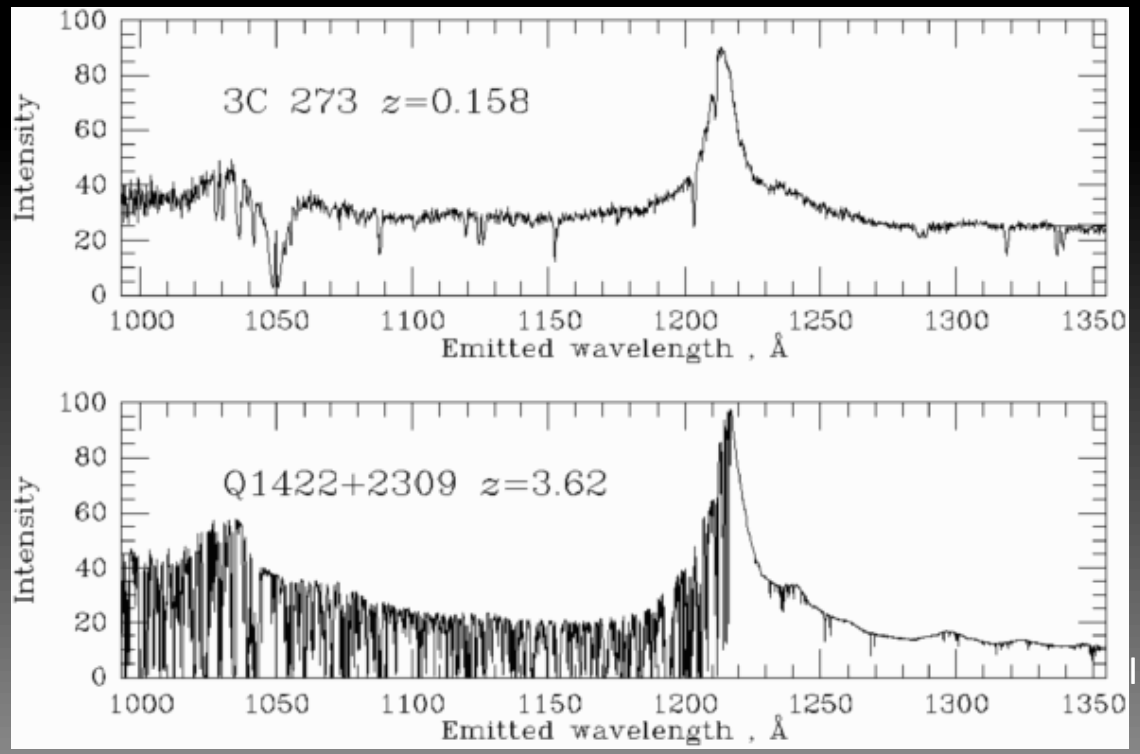
Reionization Probes





The first Probe of Reionization： Quasars



$$\tau_{GP}(z) = 4.9 \times 10^5 \left(\frac{\Omega_m h^2}{0.13}\right)^{-1/2} \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{1+z}{7}\right)^{3/2} \left(\frac{n_{HI}}{n_H}\right)$$

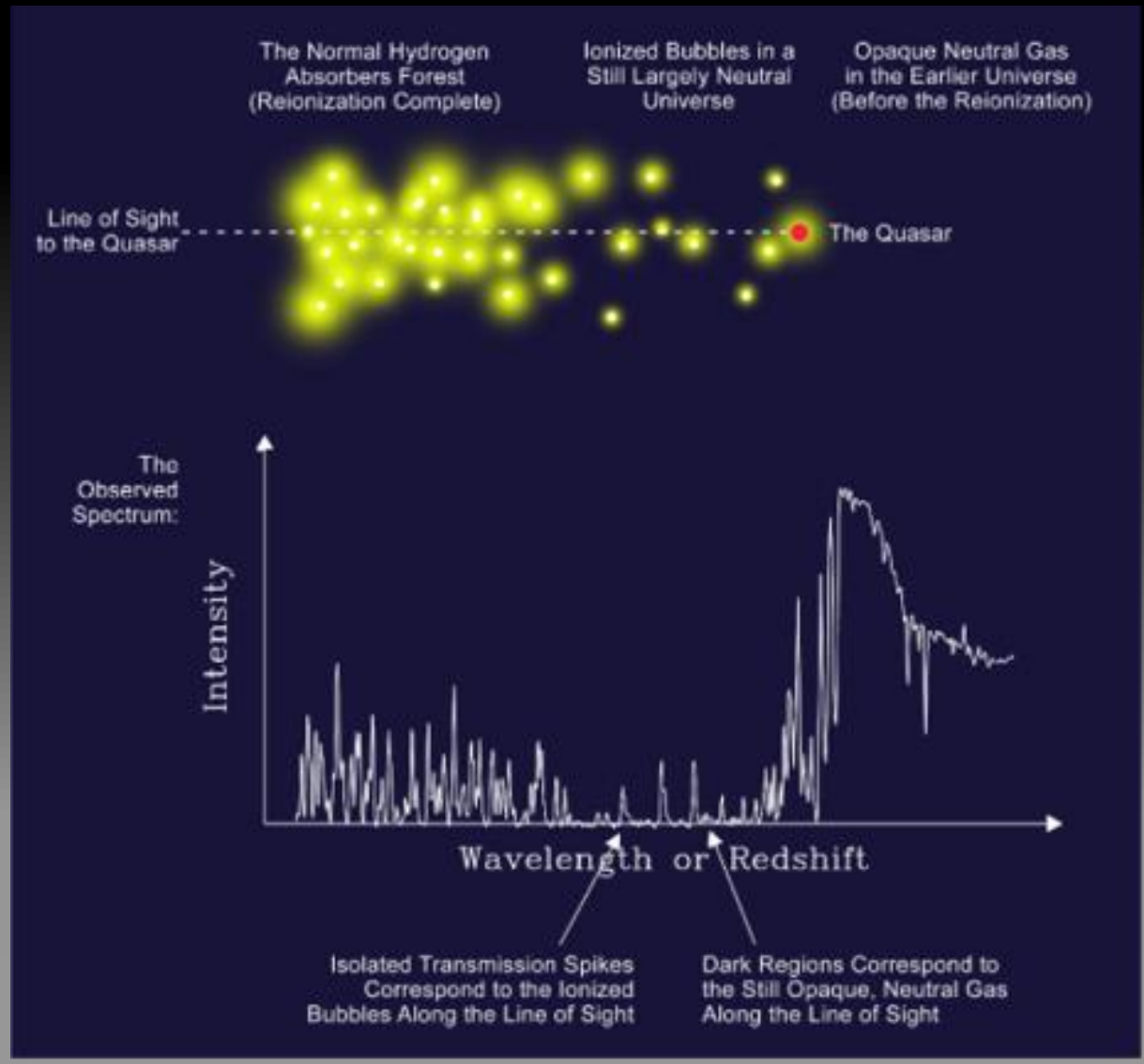


Image credit: A. Loeb (Harvard) & S. G. Djorgovski et al. (Caltech)

The first Probe of Rei

Gunn & Peterson 1965

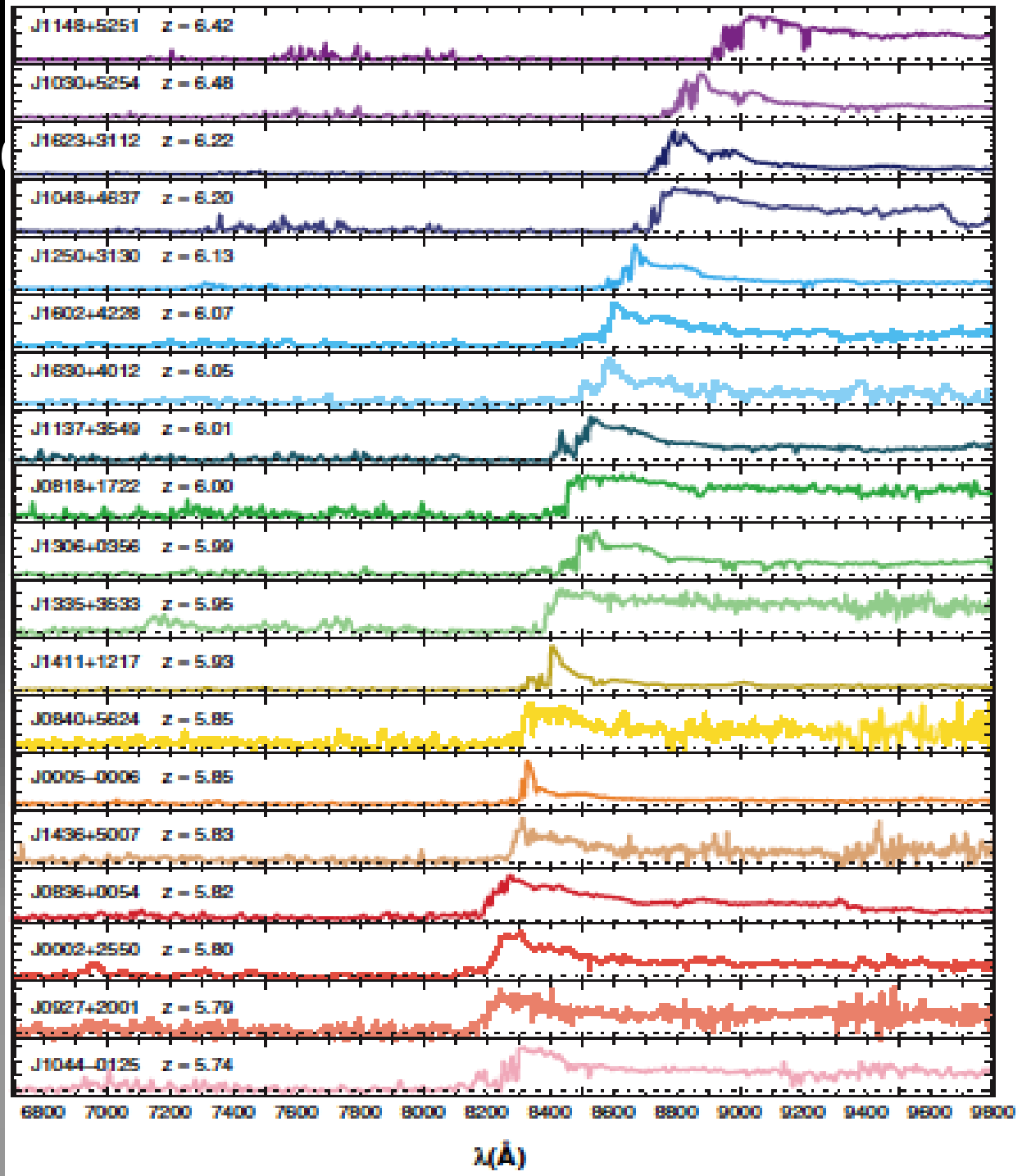
Gunn-Peterson Test (GP optical depth $e^{-\tau_{GP}}$)

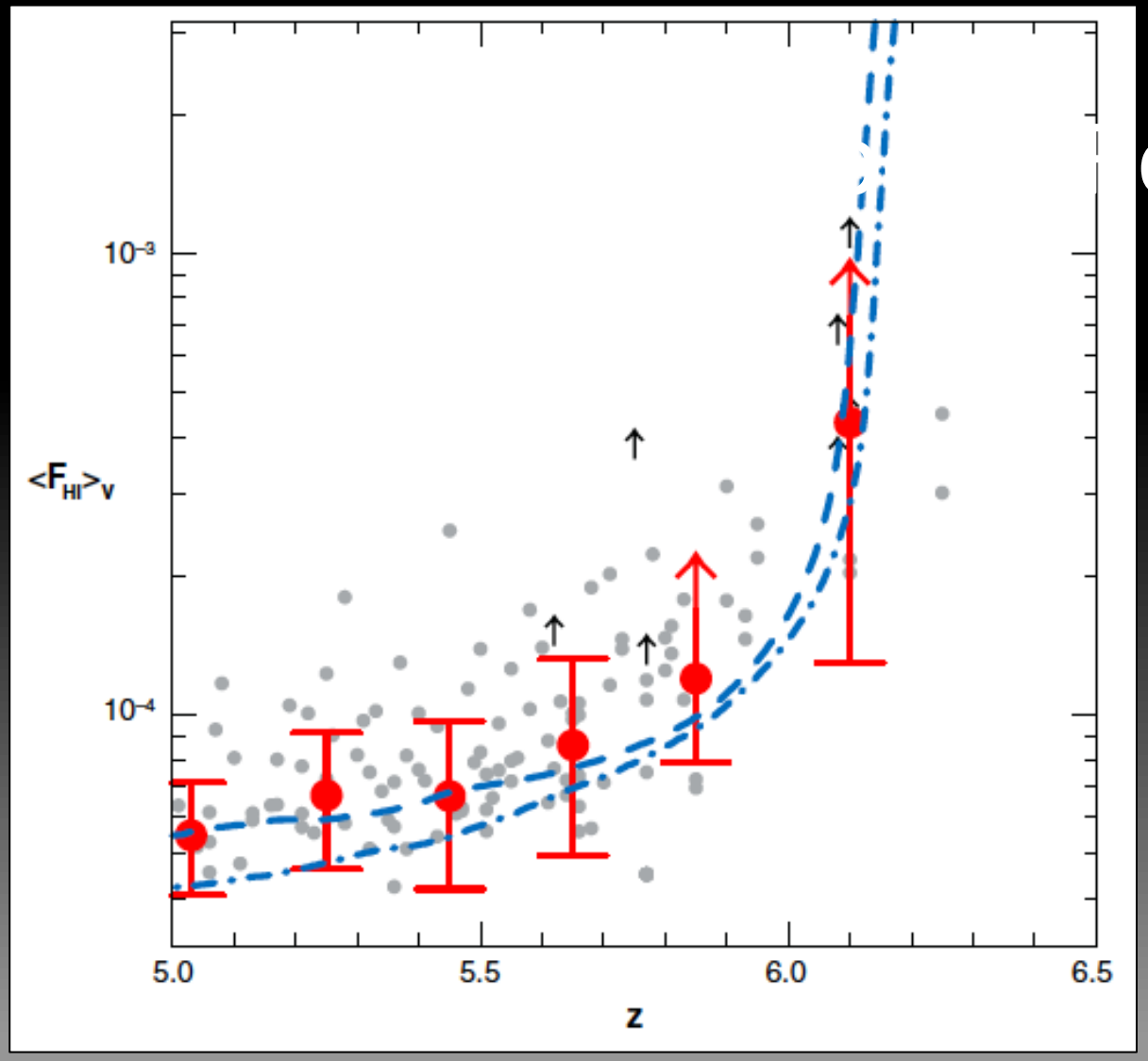
Ly**α** absorption saturated: $\tau_{GP} \geq 10^5\, x_{HI}$

$$\tau_{GP}(z) = 4.9 \times 10^5 \left(\frac{\Omega_m h^2}{0.13}\right)^{-1/2} \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{1+z}{7}\right)^{3/2} \left(\frac{n_{HI}}{n_H}\right)$$

Fan+2006

SDSS Quasars Spectra

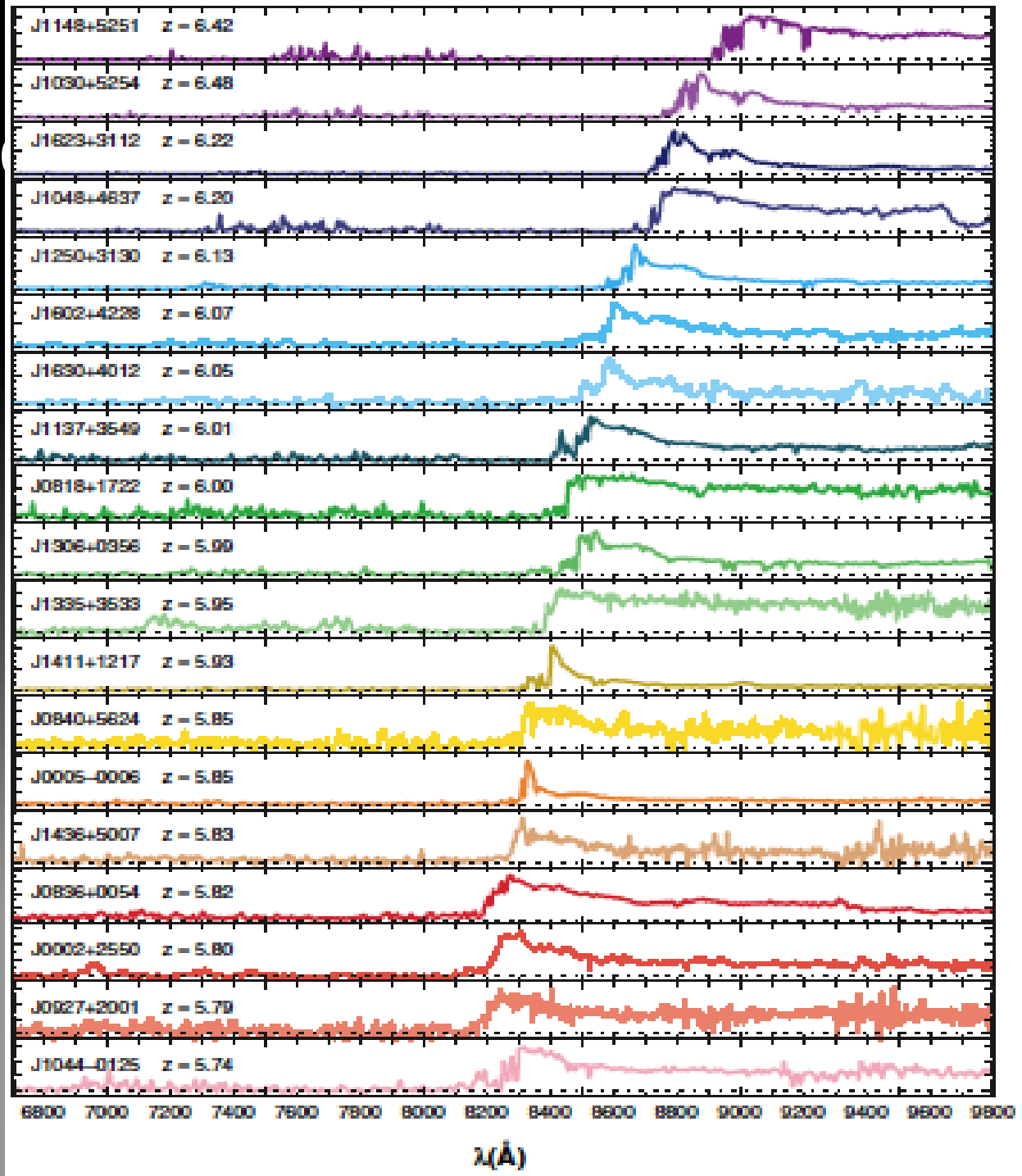




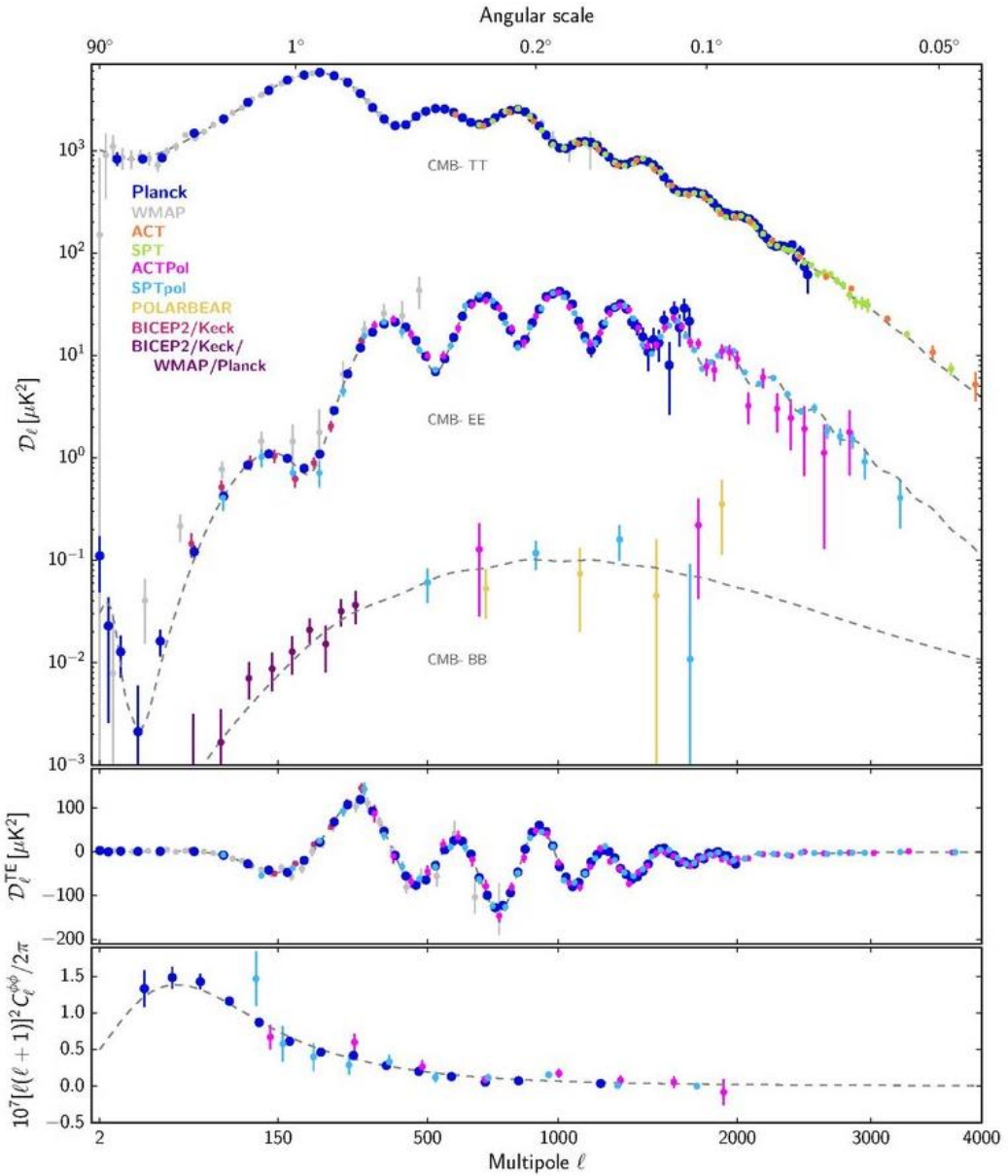
$$\tau_{GP}(z) = 4.9 \times 10^5 \left(\frac{\Omega_m h^2}{0.13}\right)^{-1/2} \left(\frac{\Omega_b h^2}{0.02}\right) \left(\frac{1+z}{7}\right)^{3/2} \left(\frac{n_{HI}}{n_H}\right)$$

Fan+2006

SDSS Quasars Spectra



CMB and Precise Cosmology

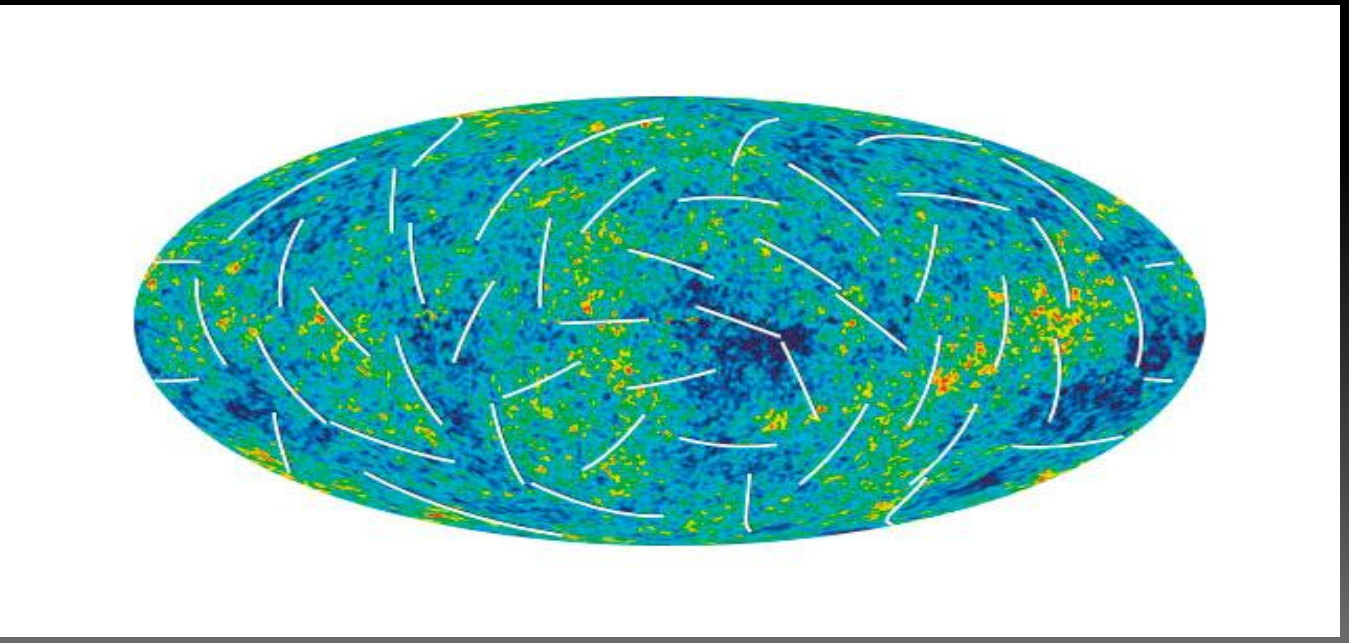


Planck Collaboration Cosmological parameters

	Description[18]	Symbol	Value-2018[19]
Independent parameters	Baryon density today[a]	$\Omega_b h^2$	0.0224 ± 0.0001
	Cold dark matter density today[a]	$\Omega_c h^2$	0.120 ± 0.001
	100 × approximation to r∗/DA (CosmoMC)	$100\theta_{MC}$	1.040 89 ± 0.000 31
	Reionization optical depth	τ	0.054 ± 0.007
	Log power of the primordial curvature perturbations	$\ln(10^{10} A_s)$	3.043 ± 0.014
	Scalar spectrum power-law index	n_s	0.965 ± 0.004
Fixed parameters	Total matter density today (inc. massive neutrinos	$\Omega_m h^2$	0.1428 ± 0.0011
	Equation of state of dark energy	w	$w_0 = -1$
	Tensor/scalar ratio	r	$r_{0.002} < 0.06$
	Running of spectral index	$dn_s/d\ln k$	0
	Sum of three neutrino masses	$\sum m_\nu$	0.06 eV/c^2
	Effective number of relativistic degrees of freedom	N_{eff}	2.99 ± 0.17
Calculated Values	Hubble constant	H_0	67.4 ± 0.5 km·s^{-1}·Mpc^{-1}
	Age of the universe	t_0	(13.787 ± 0.020) × 10^9 years[22]
	Dark energy density parameter[b]	Ω_Λ	0.6847 ± 0.0073
	The present root-mean-square matter fluctuation, averaged over a sphere of radius $8h^{-1}$ Mpc	σ_8	0.811 ± 0.006
	Redshift of reionization (with uniform prior)	z_{re}	7.68 ± 0.79

Slide Credit: Zhao Wen

The Global Probe of Reionization： CMB



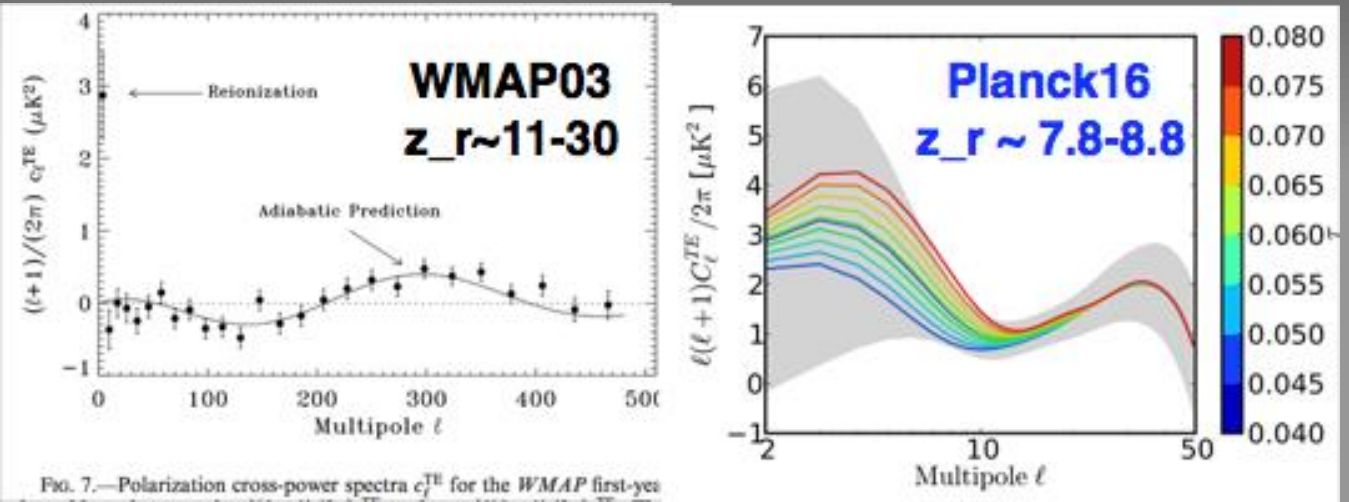


FIG. 7.—Polarization cross-power spectra c_ℓ^{TE} for the *WMAP* first-yea

CMB Polarization
Free electrons (integrated)

- CMB photons interact with free electrons in the ionized (+partly ionized) universe via Thomson scattering → Suppression on Temperature Fluctuation & Bump on Polarization Power Spectra
- Optical depth of Thomson scattering : an integration of free electron density

$$\tau(z) = \sigma_T \int_0^z n_e(z') \frac{dl(z')}{dz'} dz',$$

- Instantaneous reionization at z_r (Lewis2008)

$$\tau(z_{ri}) \approx 0.07 \left(\frac{h}{0.7}\right) \left(\frac{\Omega_{b,0}}{0.04}\right) \left(\frac{\Omega_{m,0}}{0.3}\right)^{-1/2} \left(\frac{1+z_{ri}}{10}\right)^{3/2}.$$

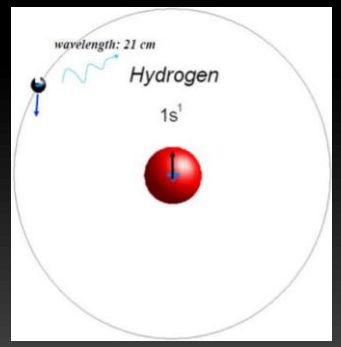
- τ_e = 0.066 ± 0.016 (Planck2015; cf. WMAP9 + Planck2013 = 0.084±0.013, WMAP1 = 0.17±0.06!)

→z_r~8.8+1.7/-1.4 (instantaneous reionization)

- **Problem: No time resolution**

The Global Probe of Reionization： 21cm

- Hydrogen atom



Hyper-fine transition in the ground state of neutral hydrogen produces 21cm lines

excitation rate= (Lya & atomic collisions)+(radiative coupling to CMB)

Couple T_s *to* T_k *Couples* T_s *to* T_γ

spin

p *e-* *p* *e-*

Spin Temperature $\frac{n_1}{n_0} = 3\exp(-\frac{0.07\mathrm{K}}{T_s})$

Absorption or emission?

Differential brightness temperature:

$$\delta T_b \approx \frac{T_s - T_{CMB}}{1+z}\tau \propto (1 - T_{CMB}/T_s)$$

$T_{CMB} >> T_s \Rightarrow$ absorption

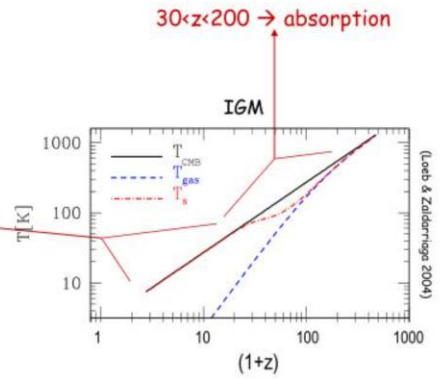
$T_s >> T_{CMB} \Rightarrow$ emission

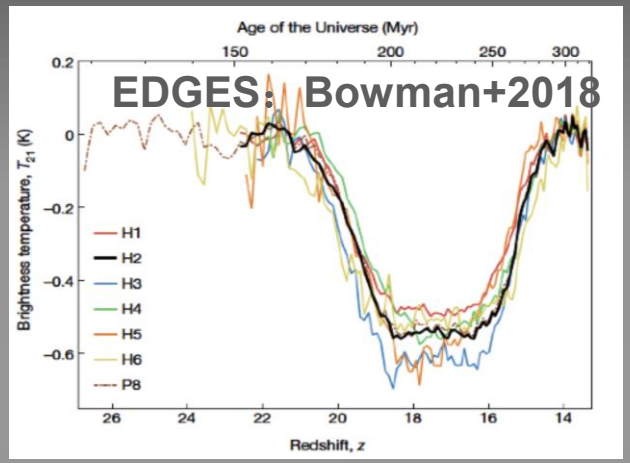
30<z<200 → absorption

z_ion<z<30 → emission

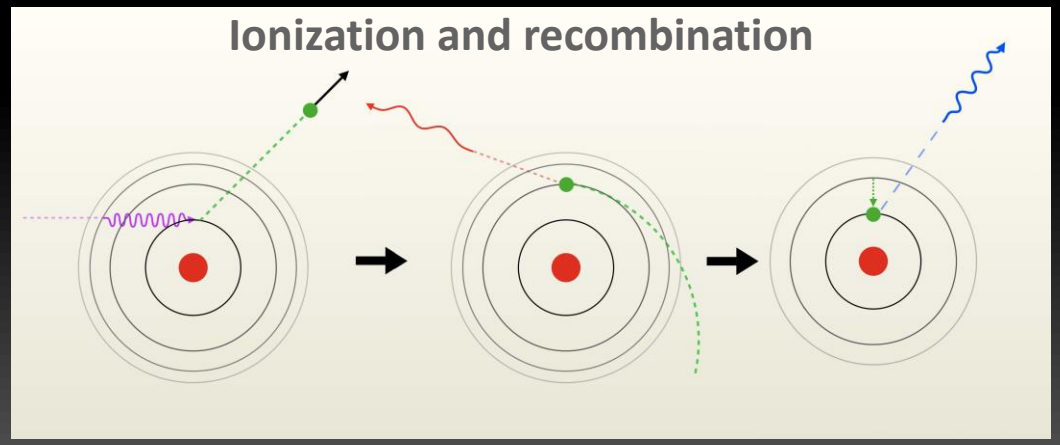
Heating by Lyalpha or X-ray photons, shock heating

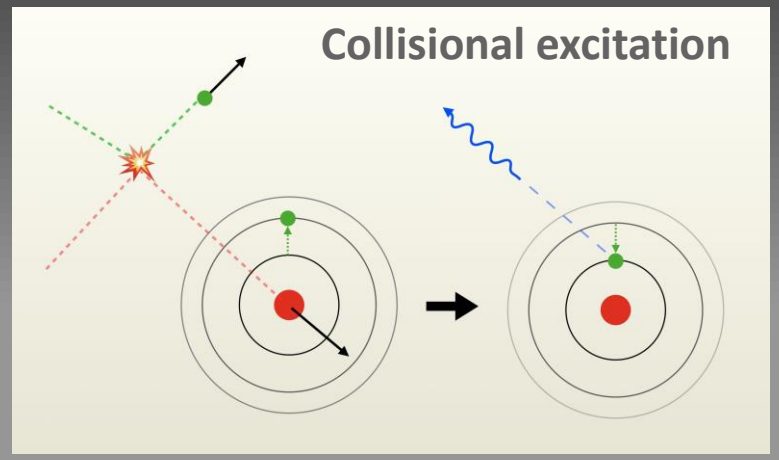
(Madau, Meiksin & Rees 1997; Giroux & Shull 2001; Glover & Brand 2002; Chen & Miralda-Escude' 2003; Gnedin & Shaver 2004)



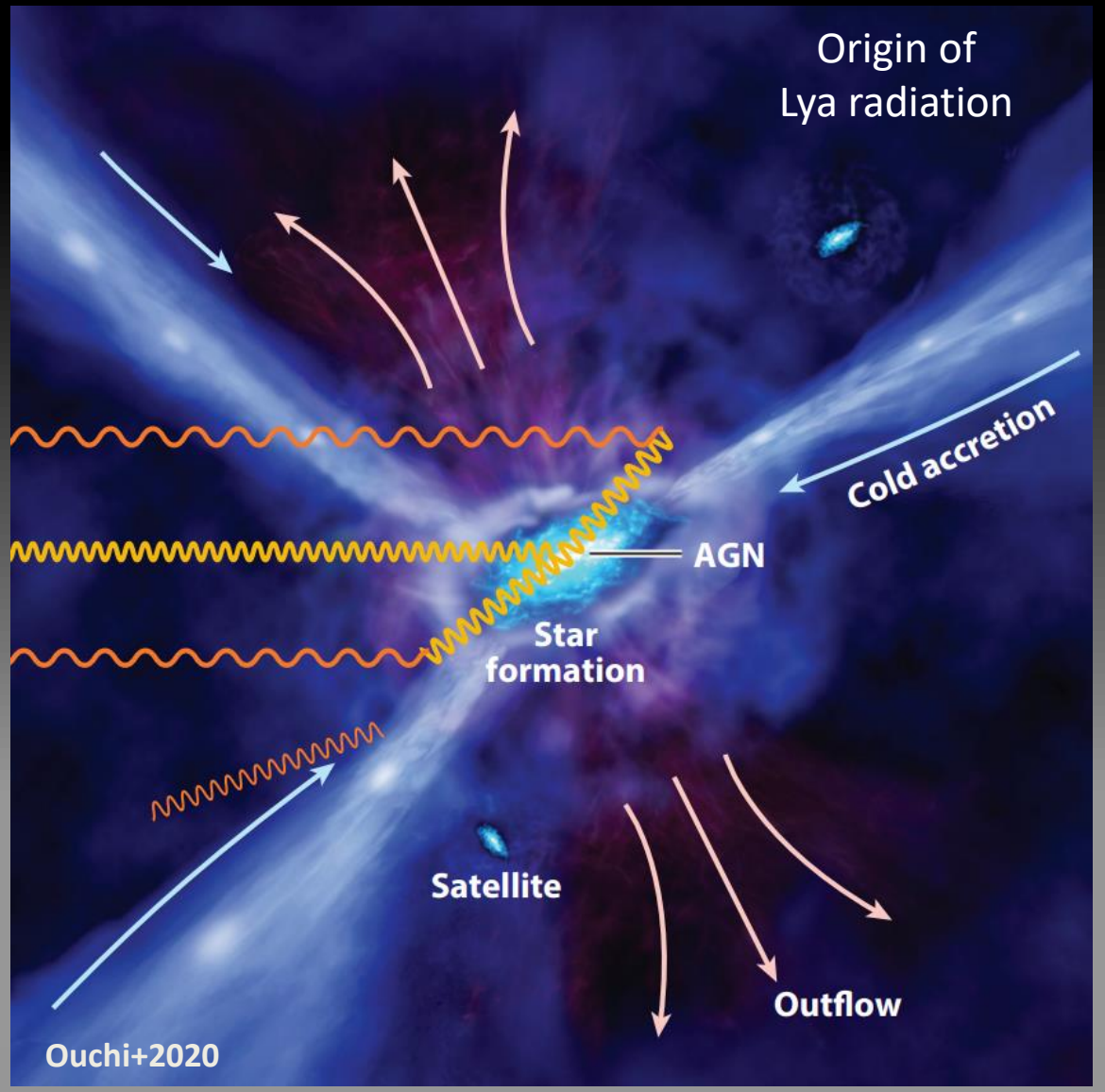


The Widely Used Probe of Reionization： Lya

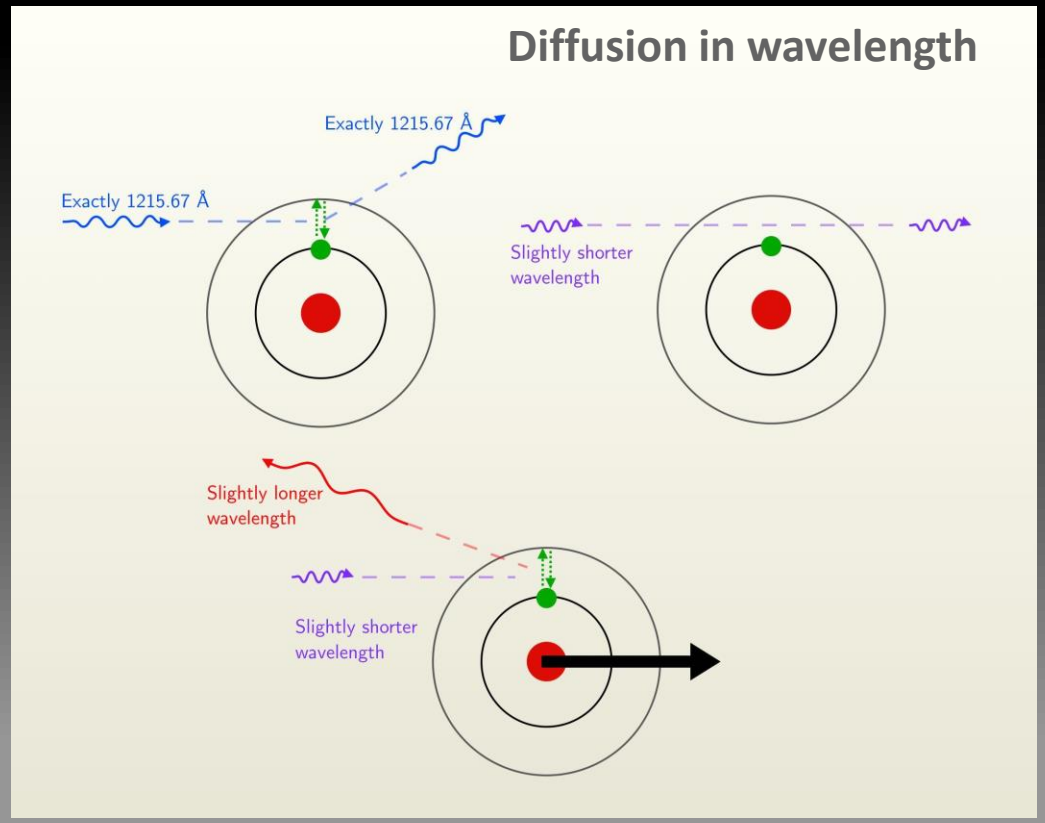


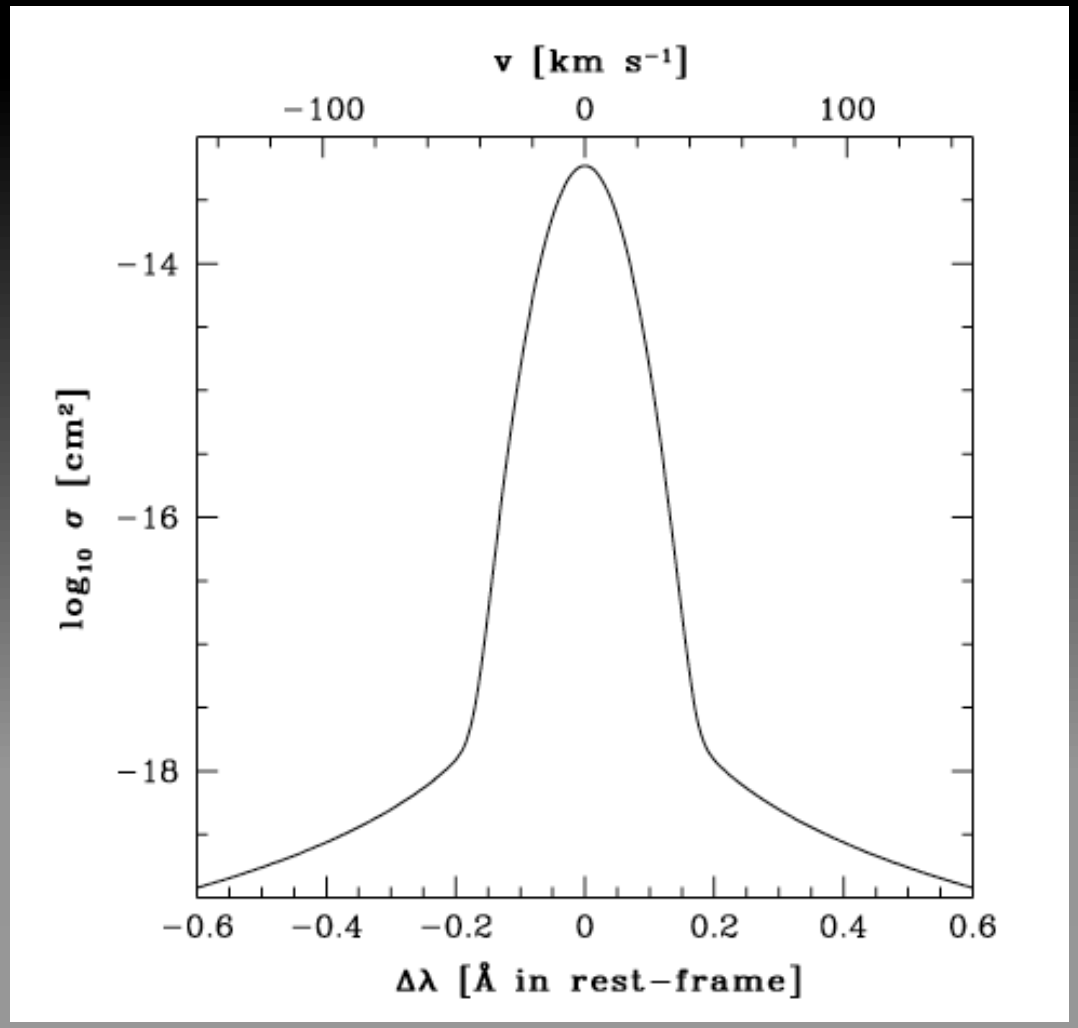


https://www.anisotropela.dk/encyclo/lyman_alpha.html



Resonant Scattering and Doppler Effect

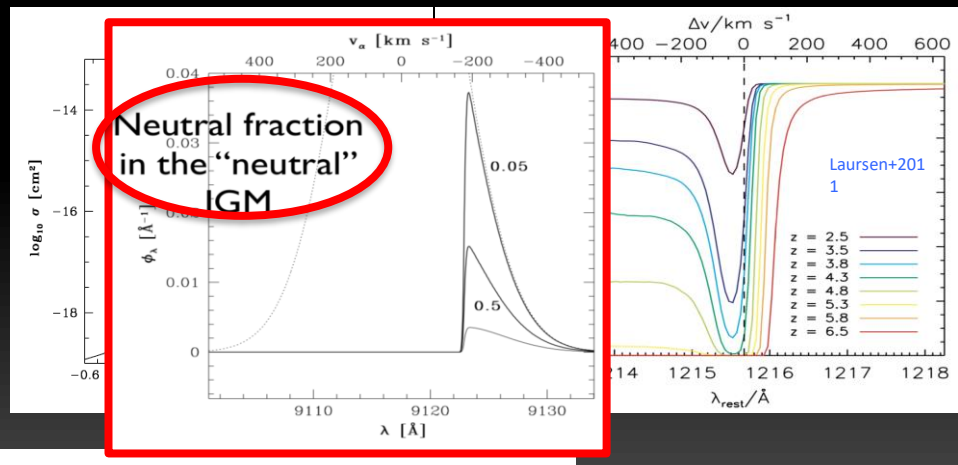


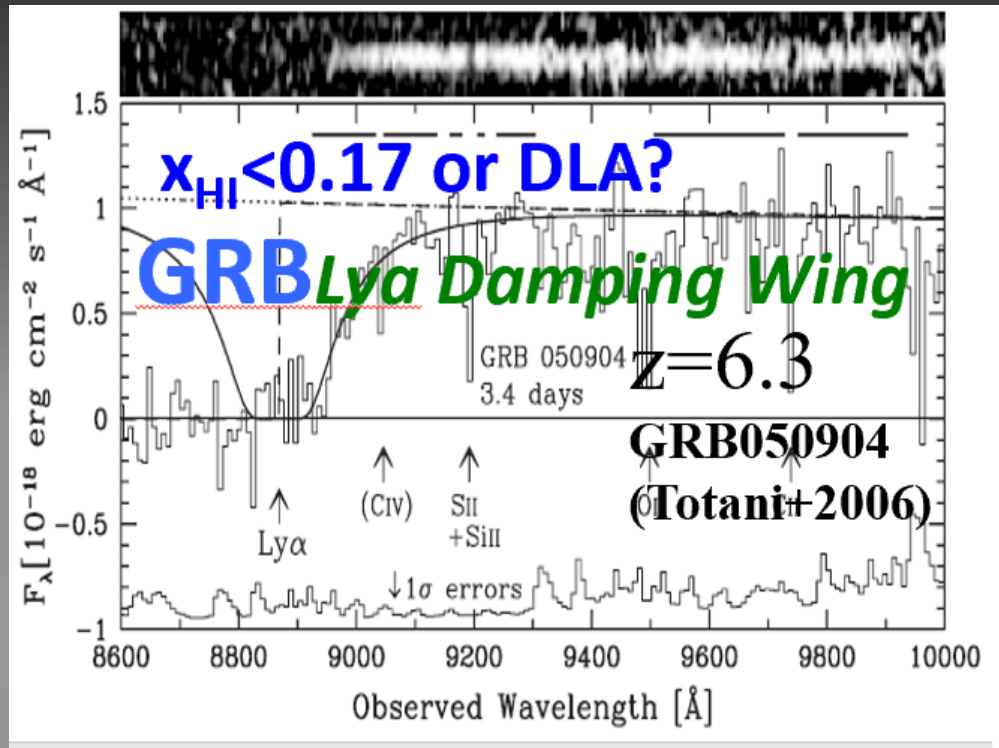


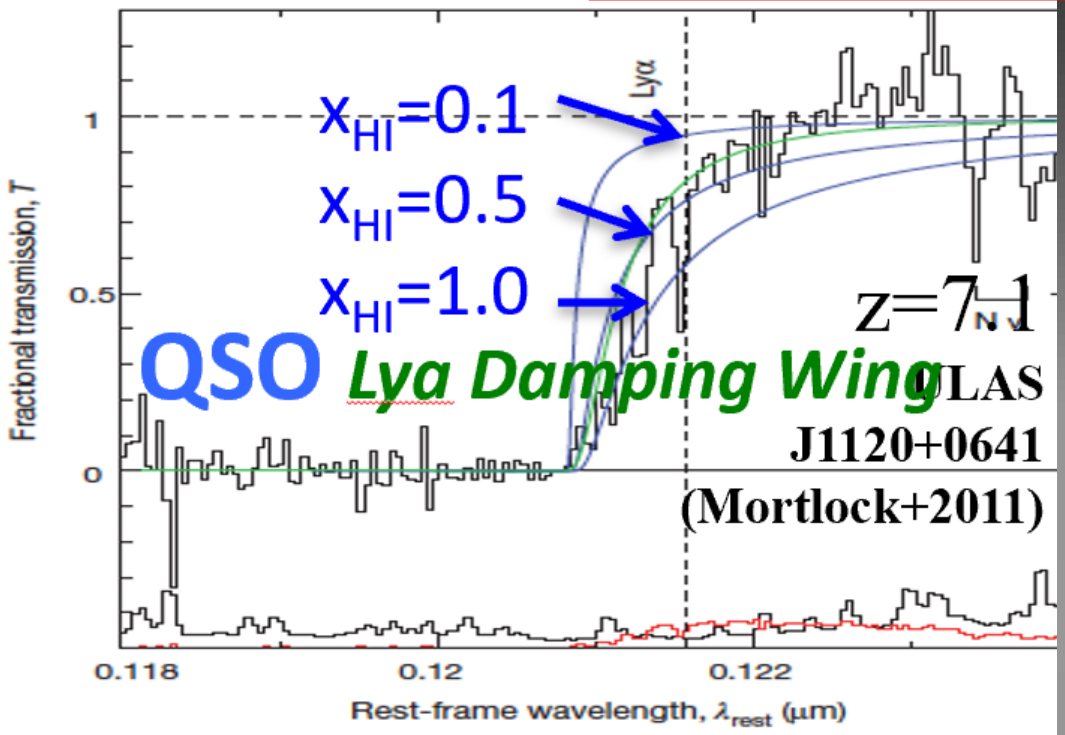
https://www.anisotropela.dk/encyclo/lyman_alpha.html

Probing Reionization with Lyα Profiles

- **Theory**: Damping Wing Absorption of Ly**α** Photons by (partially) Neutral IGM
- **Probing line-of-sight EoR History**: GRBs, QSOs, bright Lya Galaxies

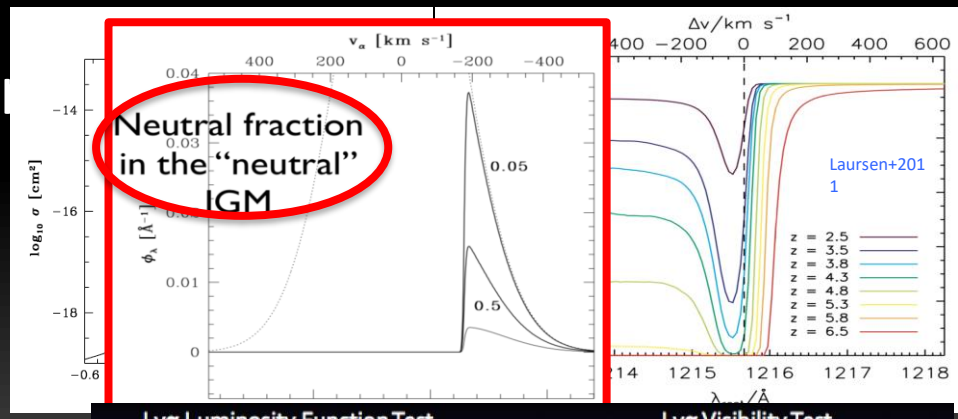


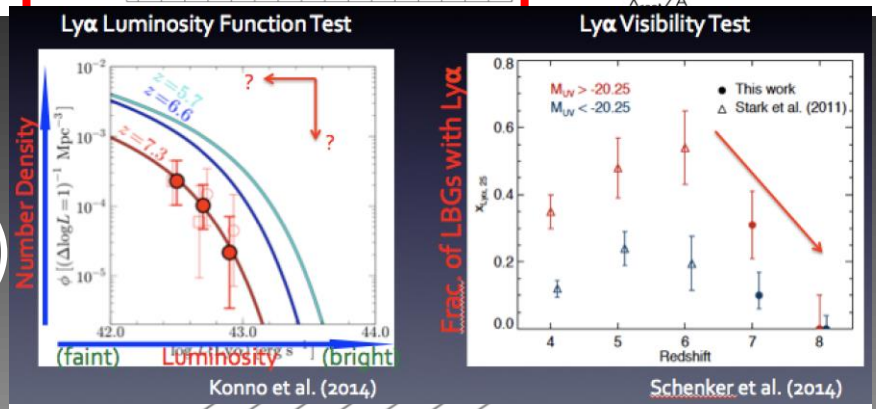


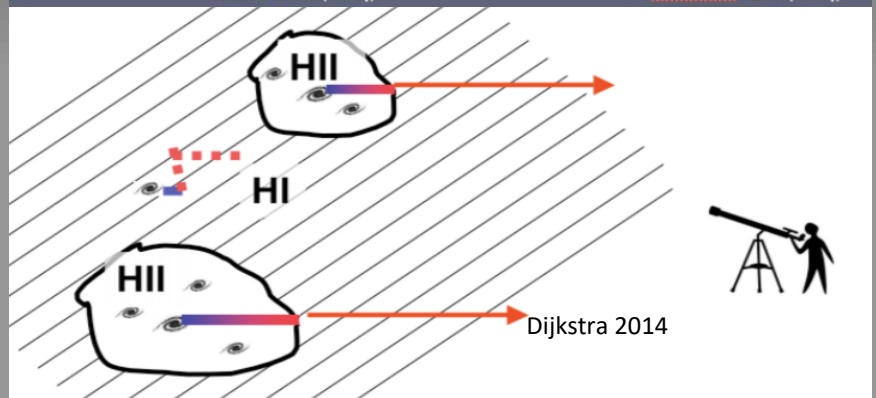


Probing Reionization with Lyα Galaxies

- **Theory**: Damping Wing Absorption of Lyα Photon by (partially) Neutral IGM
- **Probing EoR History**: Comparing the Statistical Properties of Lyα Galaxies in EoR and Post-Rionization Epoch (Lyα LF Test, Lyα Visibility Test,…)
- **Mapping EoR Topology**: IGM Environment on the Appeared Distribution of Lyα Galaxies (Clustering Analysis, Ionizing Volume, Lya & 21cm CCF)



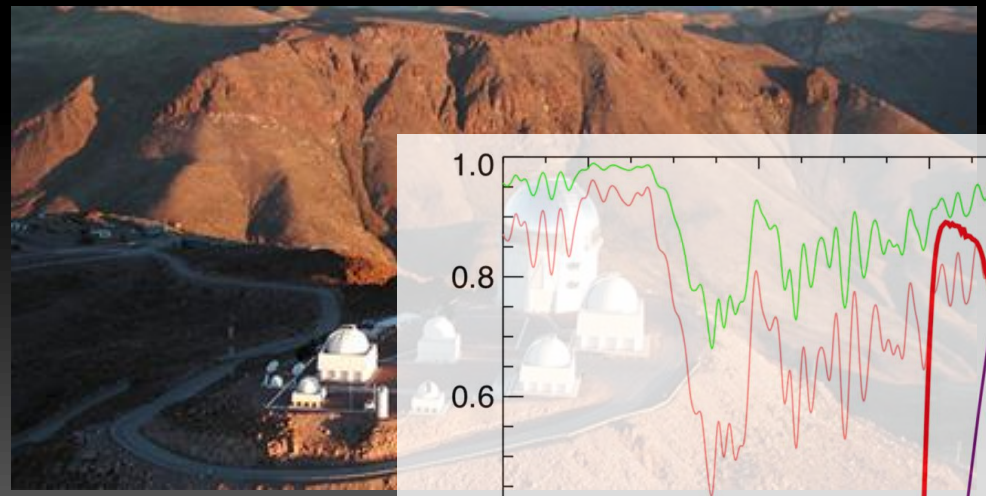


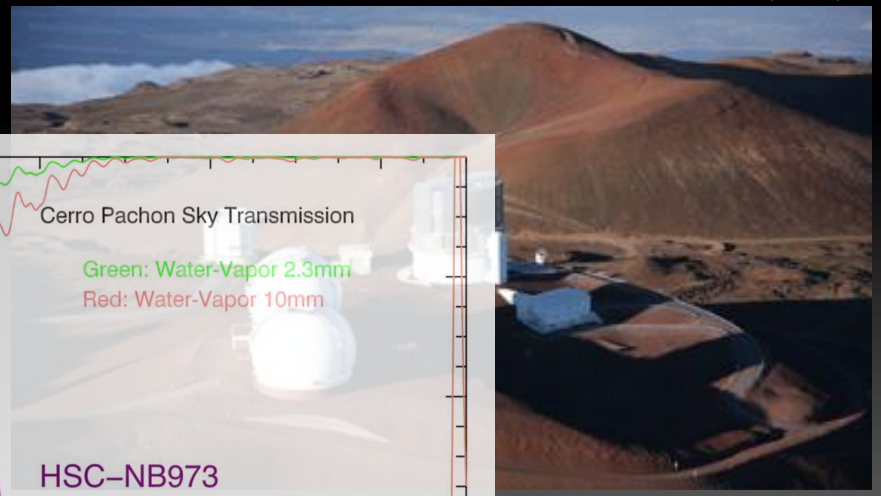


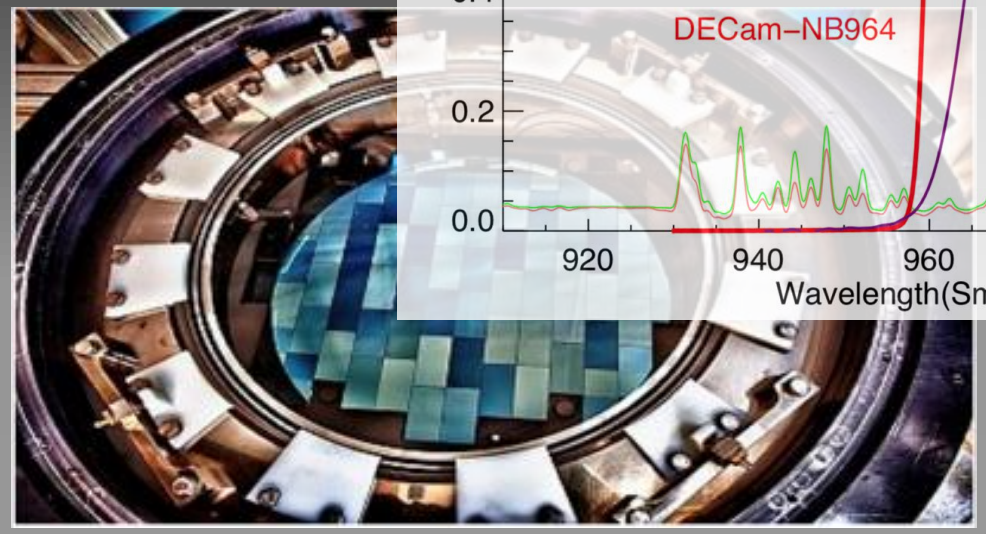
Ground based Narrowband Surveys for z~7 LAEs: LAGER vs. CHORUS

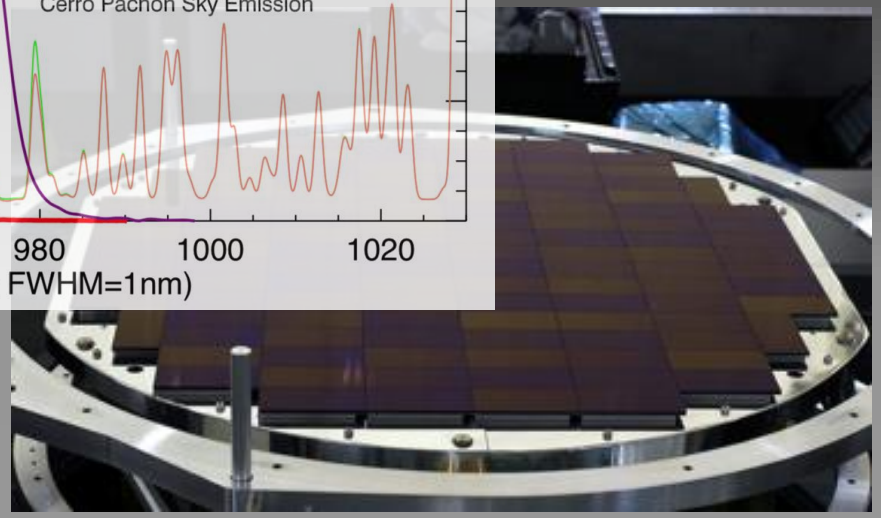
Chile Blanco (4m)

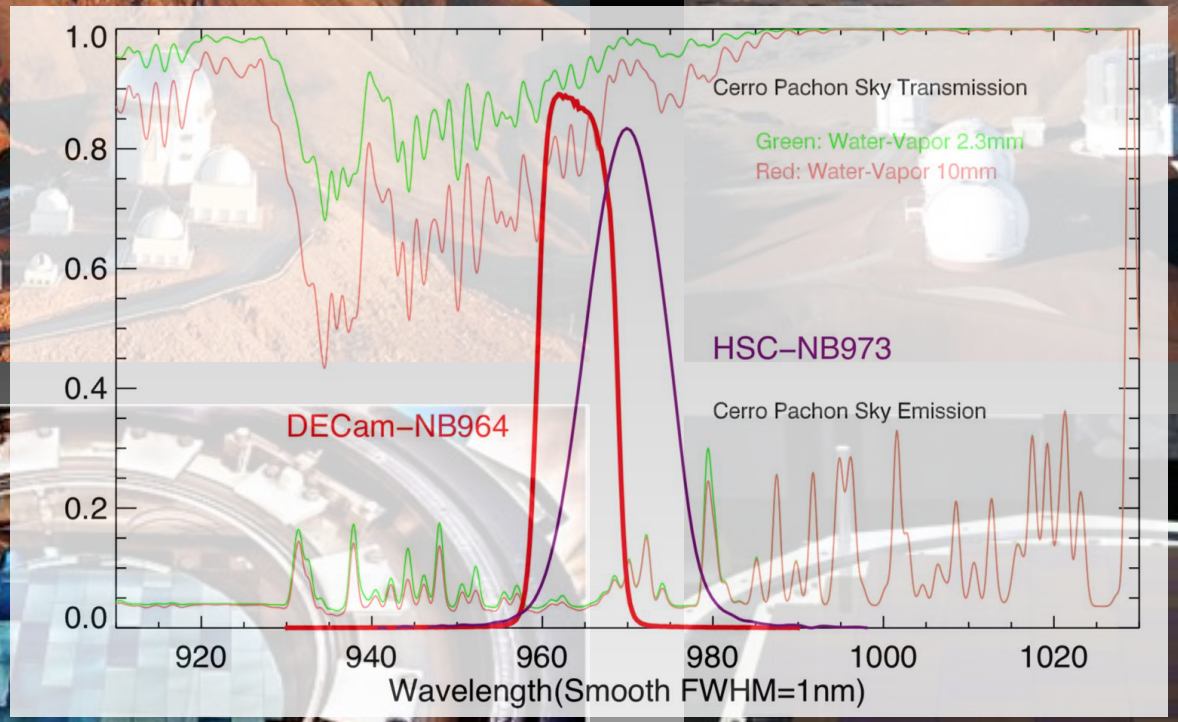
Hawaii Subaru (8m)





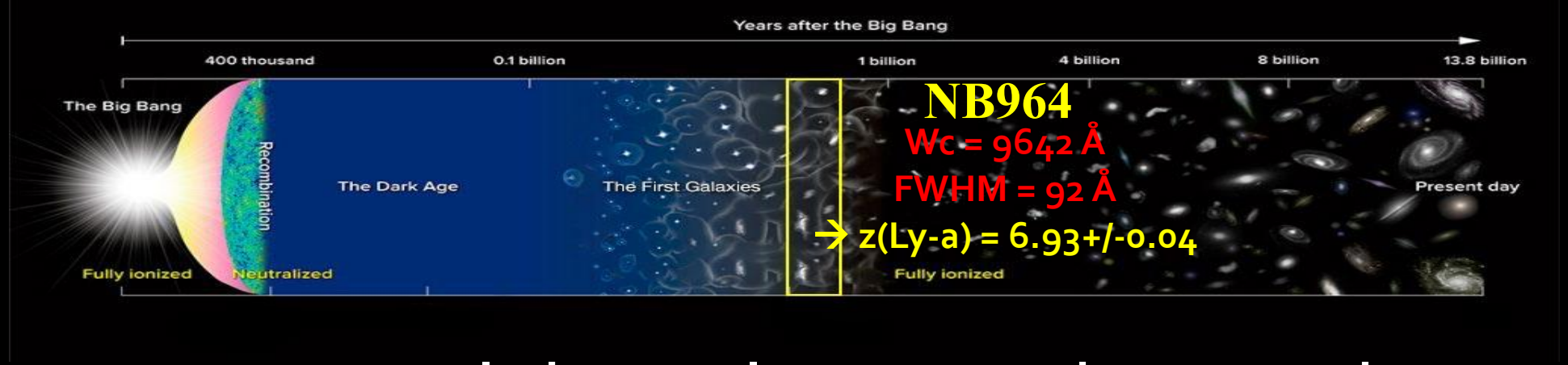






DECam (3 sq-deg, f-ratio: 2.9)

HSC (1.7 sq-deg, f-ratio: 2.2)



Lyman Alpha Galaxies in the Epoch of Reionization (LAGER)

CHINA

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Zhenya Zheng (SHAO)*,
Weida Hu (USTC),
Linhua Jiang (PKU/KIAA),
Chunyan Jiang (SHAO),
Xu Kong, Wenyong Kang (USTC),
Xianzhong Zheng (PMO) …

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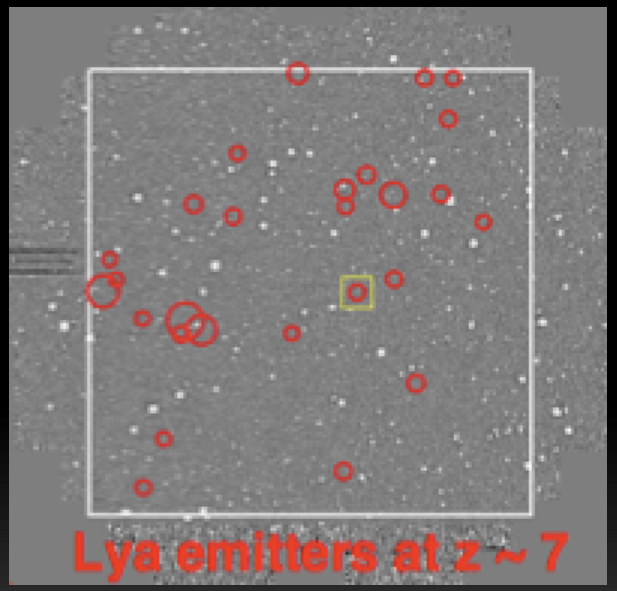
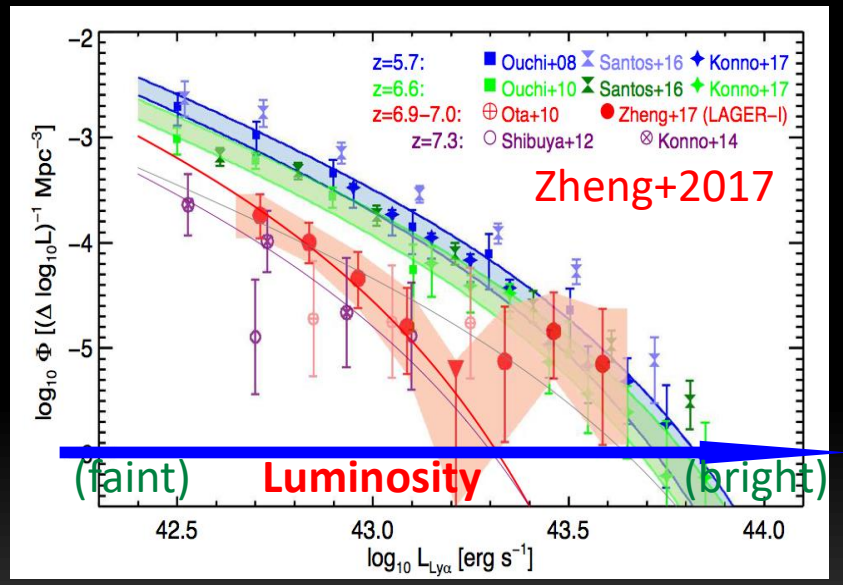
Sangeeta Malhotra (ASU, GSFC)*,
James Rhoads (ASU, GSFC)*,
Alistair Walker (CTIO),
Francisco Valdes (NOAO)
Alicia Gonzalez (ASU),
Vithal Tilvi (ASU) , …

CHILE

Leopoldo Infante (LCO,PUC)*,
Felipe Barrientos (PUC)*,
Huan Yang (LCO),
Pascale Hibon (ESO),
Gaspar Galaz (PUC),
Franz Bauer (PUC), …





- LAGER Lya LF evolution （Zheng+2017）

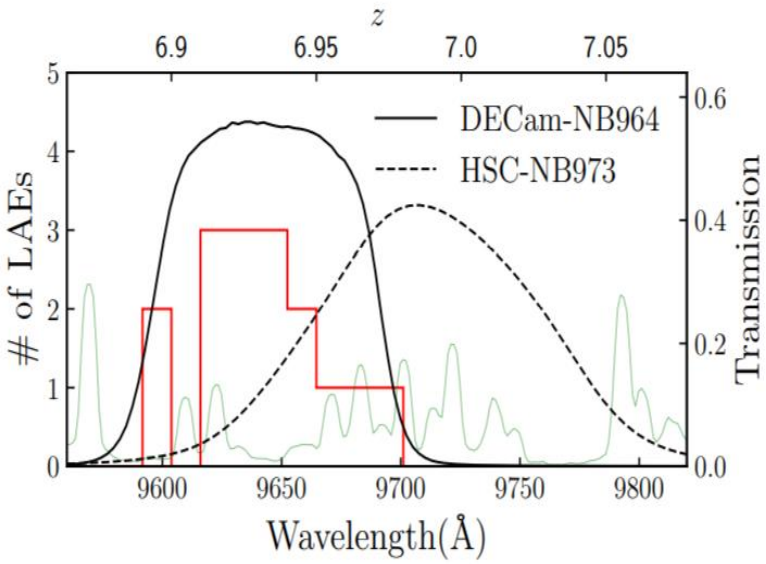
x_HI~50% at z~6.9

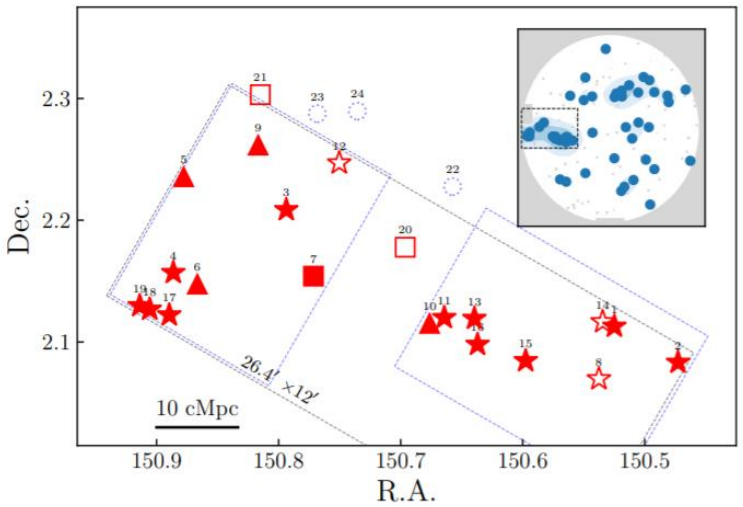
→

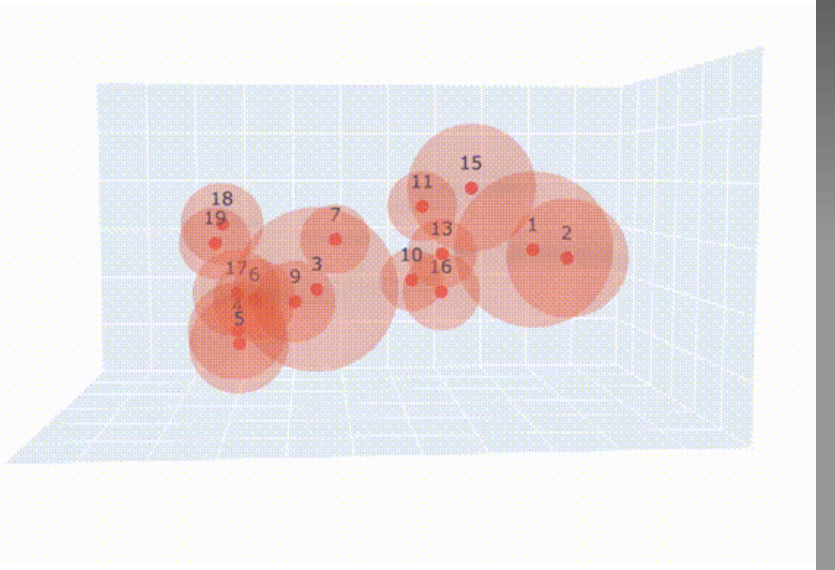
LAGER 4 fields Lya LFs (Wold+2022)

x_HI<30% at z~6.9

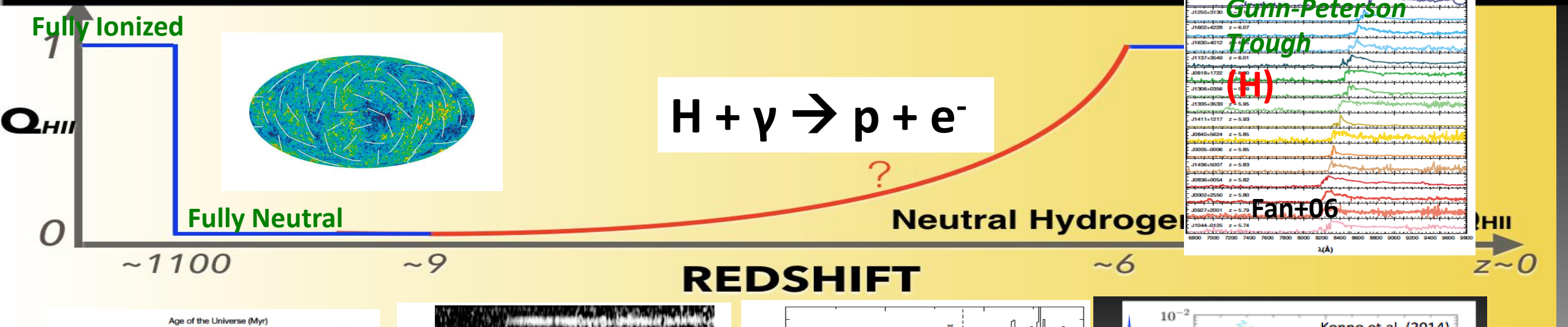
- LAGER Lya LF bright-end excess（Zheng+2017）→ Protocluster at z~6.9 (Hu+2021)

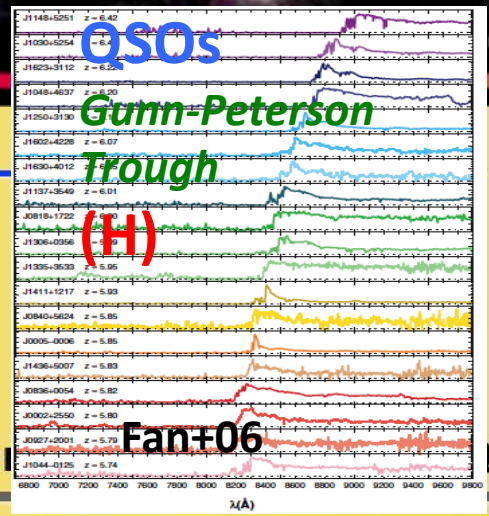


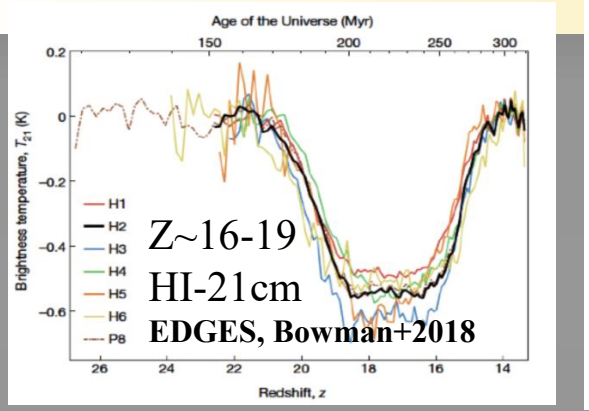


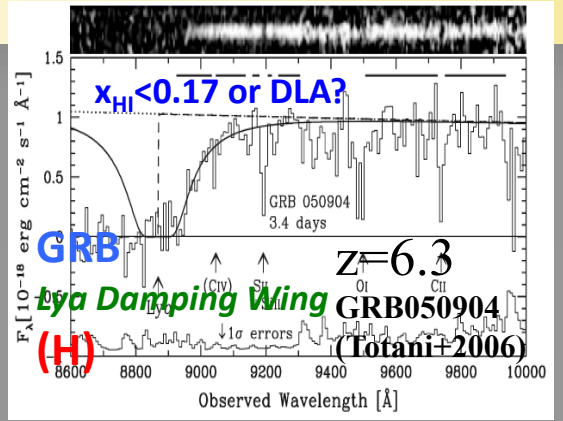


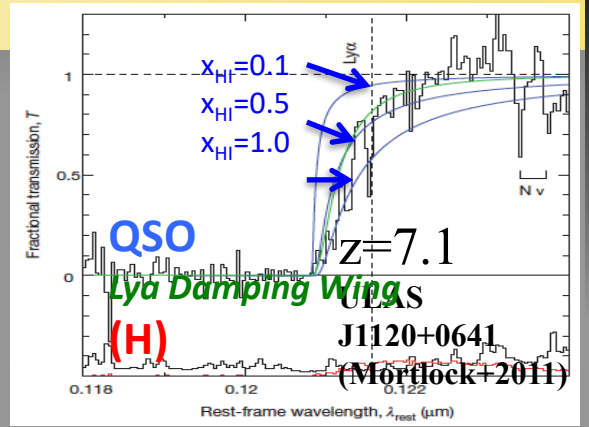
Origin of CMB
Dark Ages
Epoch of Reionization: First Stars & First Galaxies
Modern Universe
Big Bang
Today
400 kyr
500 Myr
1 Gyr
Gyr
Time

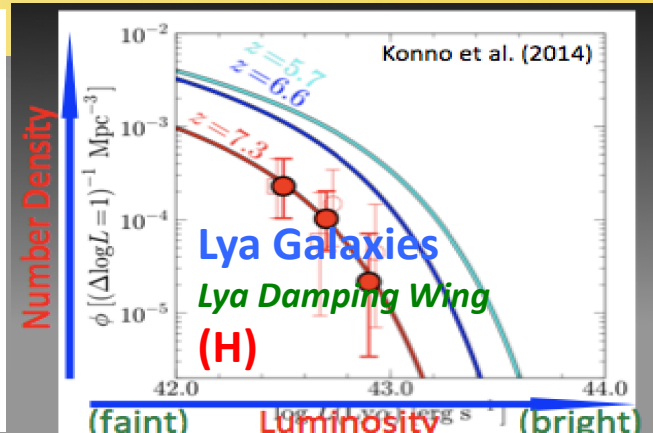

Fully Ionized
1
Q_{HII}
0
Fully Neutral
~1100
~9
~6
z~0
REDSHIFT
Neutral Hydroge
HII
H + γ → p + e⁻
?


QSOs
Gunn-Peterson Trough
(H)
Fan+06

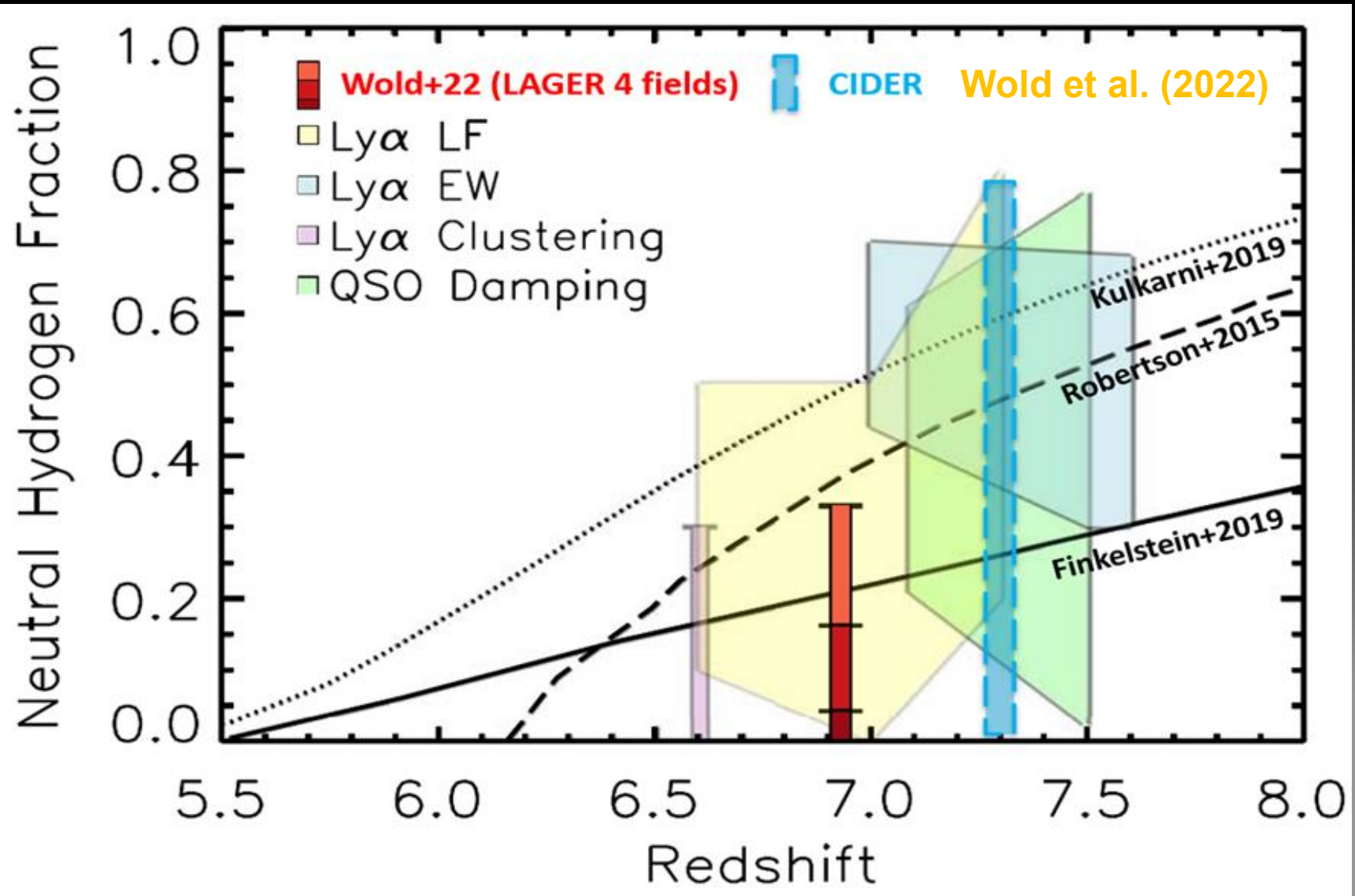

Age of the Universe (Myr)
Brightness temperature, T_{21} (K)
Redshift, z
Z~16-19
HI-21cm
EDGES, Bowman+2018


x_{HI}<0.17 or DLA?
GRB
Lya Damping Wing
(H)
z=6.3
GRB050904
(Totani+2006)
Observed Wavelength [Å]


x_{HI}=0.1
x_{HI}=0.5
x_{HI}=1.0
QSO
Lya Damping Wing
(H)
z=7.1
ULAS
J1120+0641
(Mortlock+2011)
Rest-frame wavelength, λ_{rest} (μm)


Number Density
Konno et al. (2014)
z=5.7
z=6.6
z=7.3
Lya Galaxies
Lya Damping Wing
(H)
(faint)
Luminosity
(bright)

Combing all constraints together



- Quasar Gunn-Peterson
- Quasar Damping Wing
- GRB Damping Wing

EoR Probes with Galaxies:

1. Lya LF of Lya Galaxies in EoR
2. Lya Visibility
3. Clustering of Lya Galaxies

- X_{HI} increases from z~6
- Large dispersion at z>~7 → Limited galaxy sample at z >~ 7

See also: Sharma+16, Robertson+15, Mitra+15, Bouwens+15, Kakiichi+16, Greig & Mesinger17, Finkelstein+19 …

Outlines

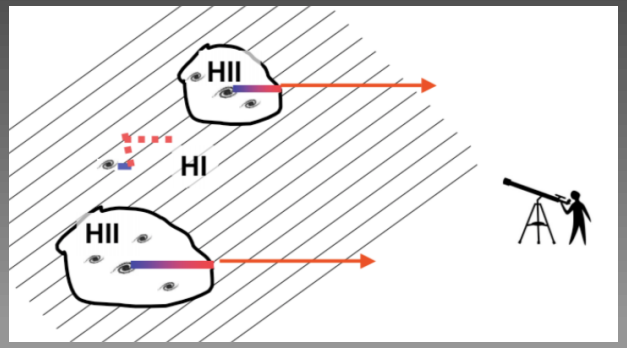
- Galaxies in the Early Universe
- Reionization Probes：QSOs，CMB，21cm，Lya
- **Reionization Topology**
  - Clustering of Lya Galaxies
  - Lya-21cm CCF
- Reionization Contributors
  - Galaxies vs. AGN/Quasars
  - Properties of LyC Leaking Galaxies
- Current & Future Galaxies Surveys for Reionization

Exploring Reionization Topology via LAEs

EoR Simulations

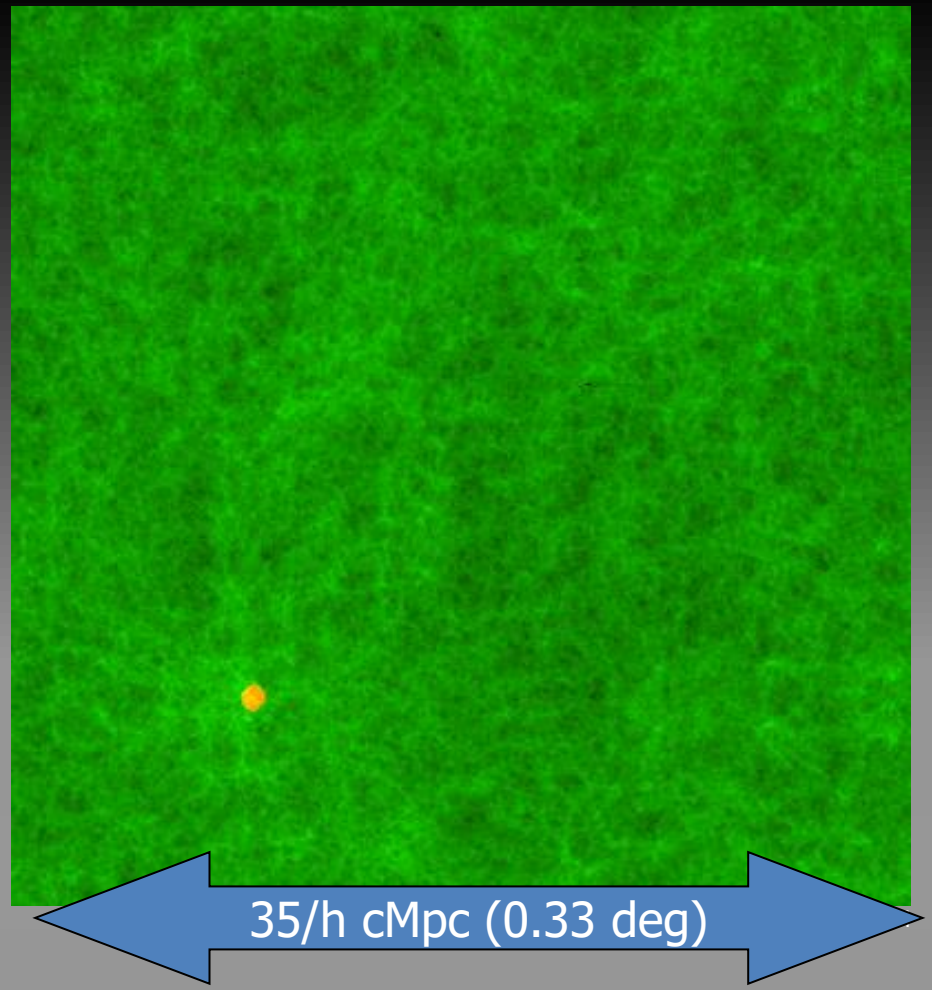
from work of Iliev, Mellema, Shapiro, Mao, and collaborators

- Movie of density field and HII regions
- Green: neutral
- Red: Ionized

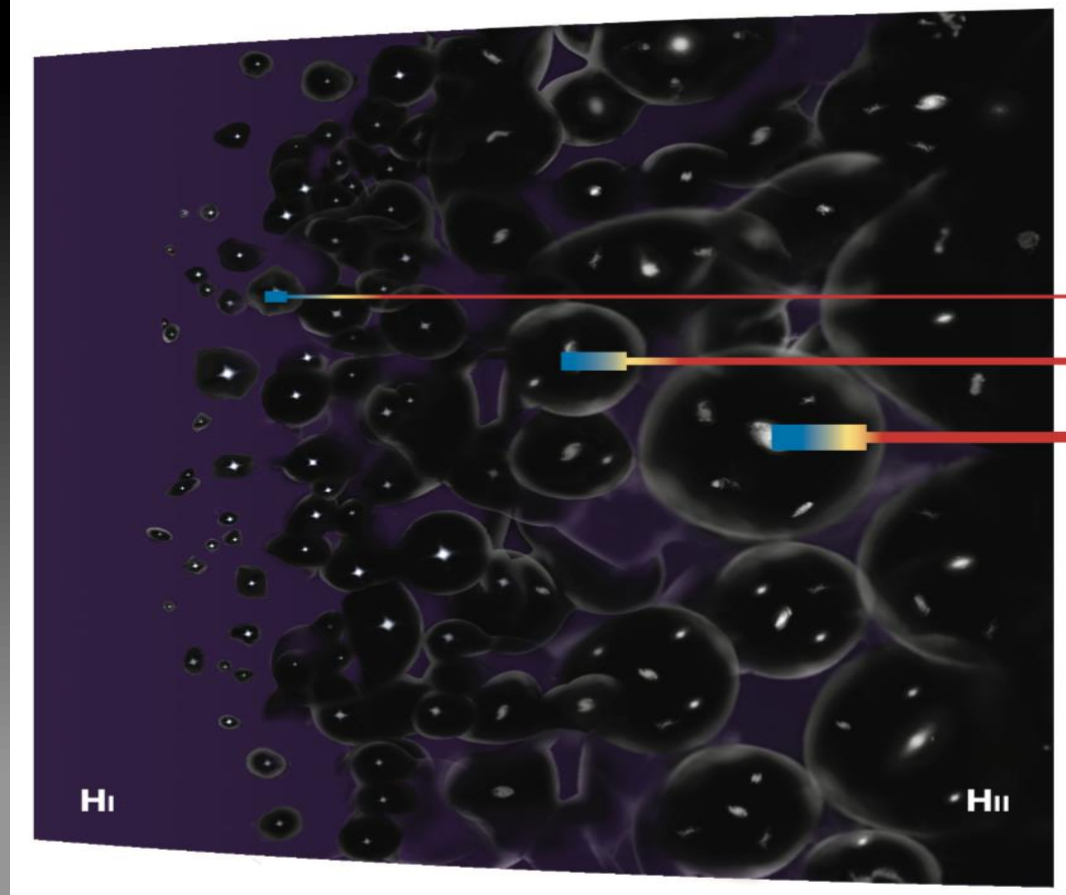


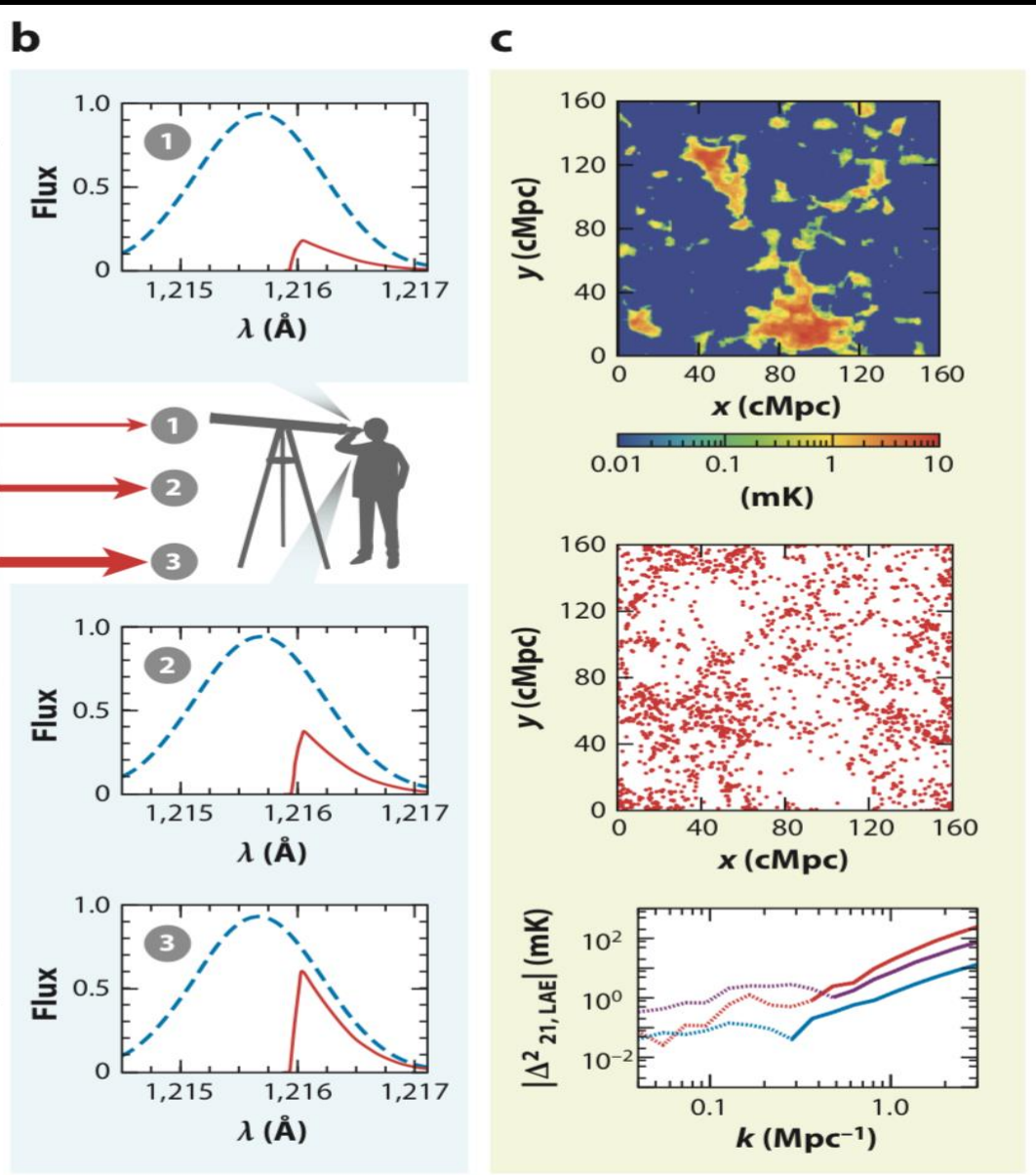
- Note:
  - Clustering
  - Bubble
  - Overlap

- From z=20 to 10.

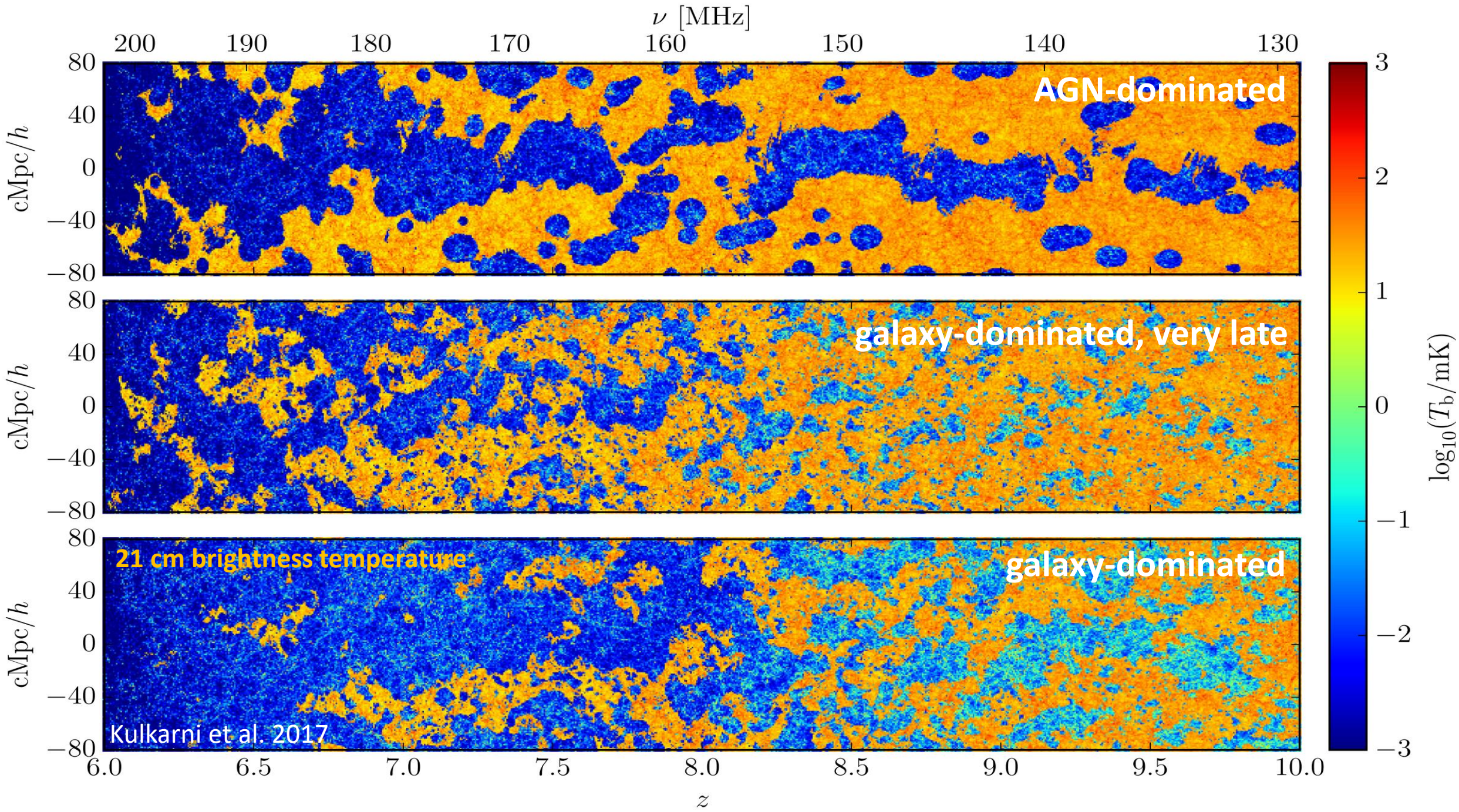


Joint analysis with LAEs and 21cm to probe EoR





Ouchi, Ono & Shibuya 2020, ARAA


ν [MHz]
200
190
180
170
160
150
140
130
AGN-dominated
galaxy-dominated, very late
galaxy-dominated
21 cm brightness temperature
Kulkarni et al. 2017
cMpc/h
80
40
0
−40
−80
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
z
log10(Tb/mK)
3
2
1
0
−1
−2
−3

Detectability with 21-cm LAE cross-correlation

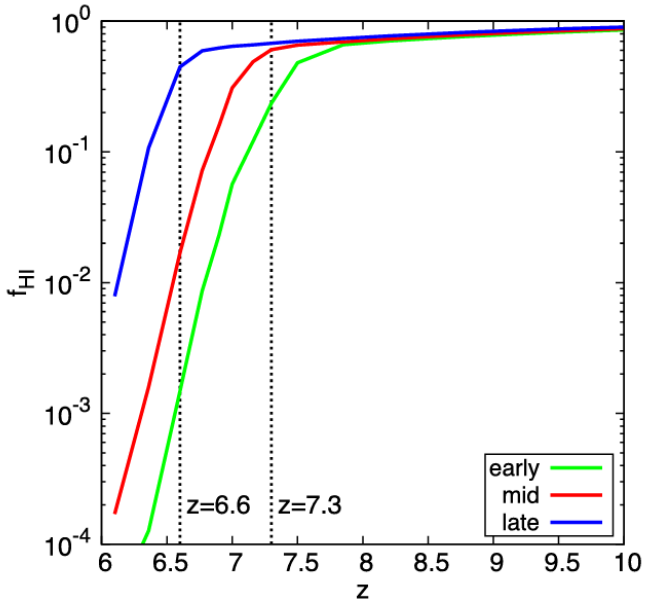


Figure 1. Evolution of the mean neutral hydrogen fraction f in our reionization simulation box as a function of redshift. The green, red and blue lines show the evolution in the early, mid and late models, respectively.

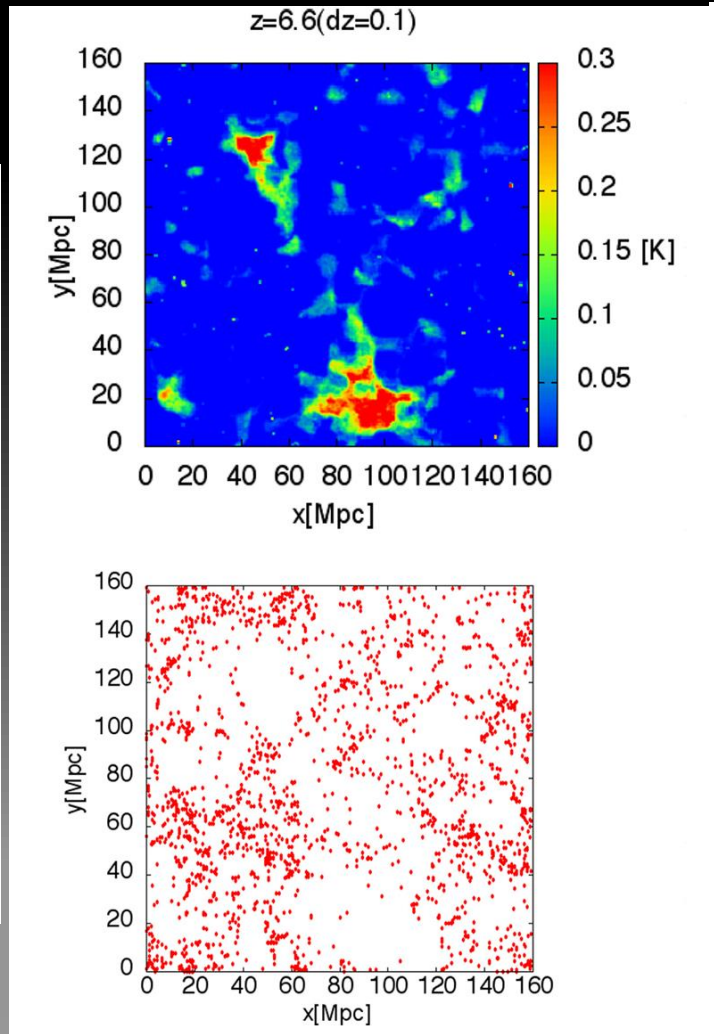
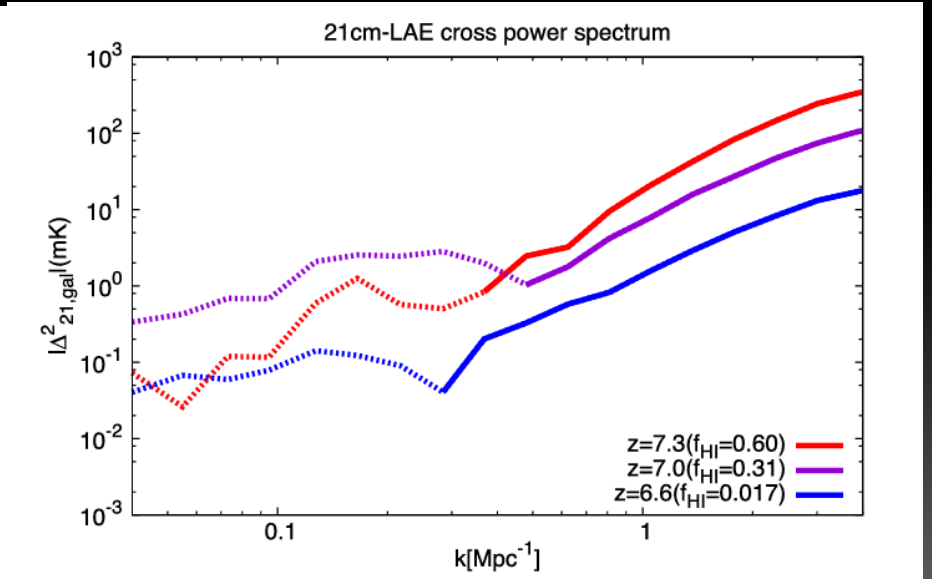
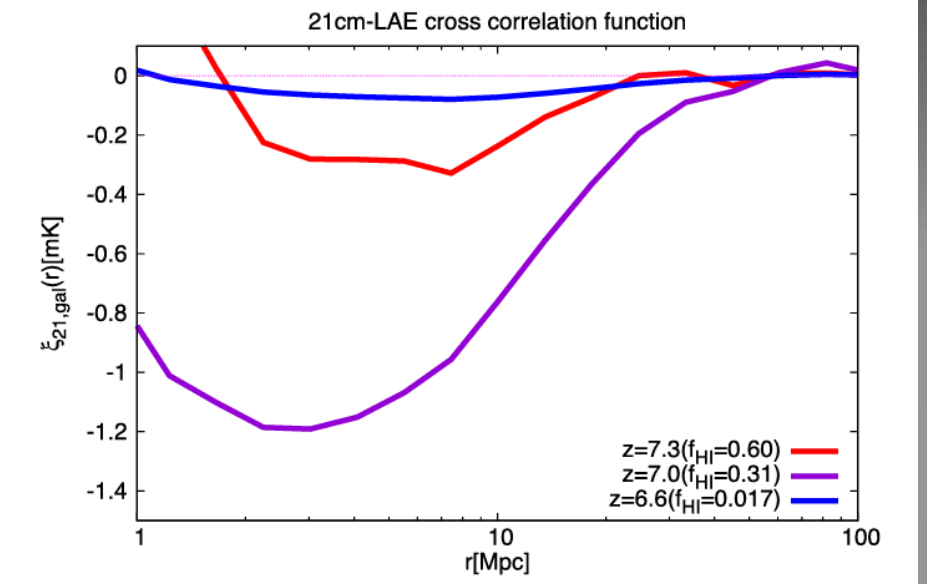


Figure 2. The 21-cm brightness temperature in the mid model at redshift $z = 6.6$ (top model). In the fully ionized region, $\delta T_b \sim 0$ mK. The associated LAE distribution (bottom panel). The panels are maps integrated within $\Delta z = 0.1$–40 Mpc.





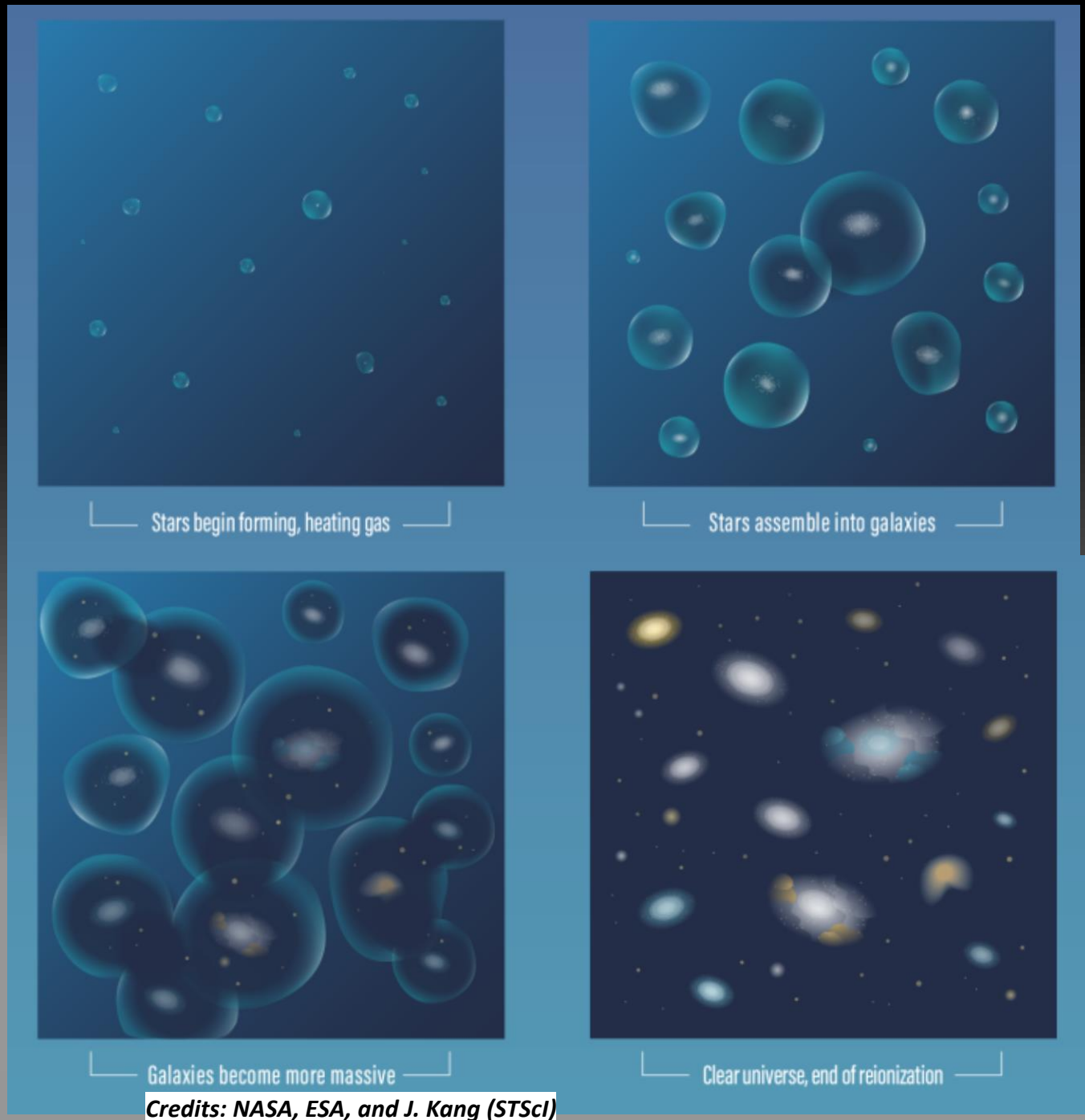
K. Kubota et al, 2018, MNRAS

Outlines

- Galaxies in the Early Universe
- Reionization Probes：QSOs，CMB，21cm，Lya
- Reionization Topology
  - Clustering of Lya Galaxies
  - Lya-21cm CCF
- **Reionization Contributors**
  - Galaxies vs. AGN/Quasars
  - Properties of LyC Leaking Galaxies
- Current & Future Galaxies Surveys for Reionization

Reionization Contributors

- Galaxies (First/Pop-III Stars)
- Quasars/AGN (First Massive Black-Holes)
- Galaxy Protoclusters (First Structure)



Credits: NASA, ESA, and J. Kang (STScI)

$H + \gamma \rightarrow p + e^-$

Ionizing Budget

Exploring Reionization Contributors

Reionization Equation (Madau+99)

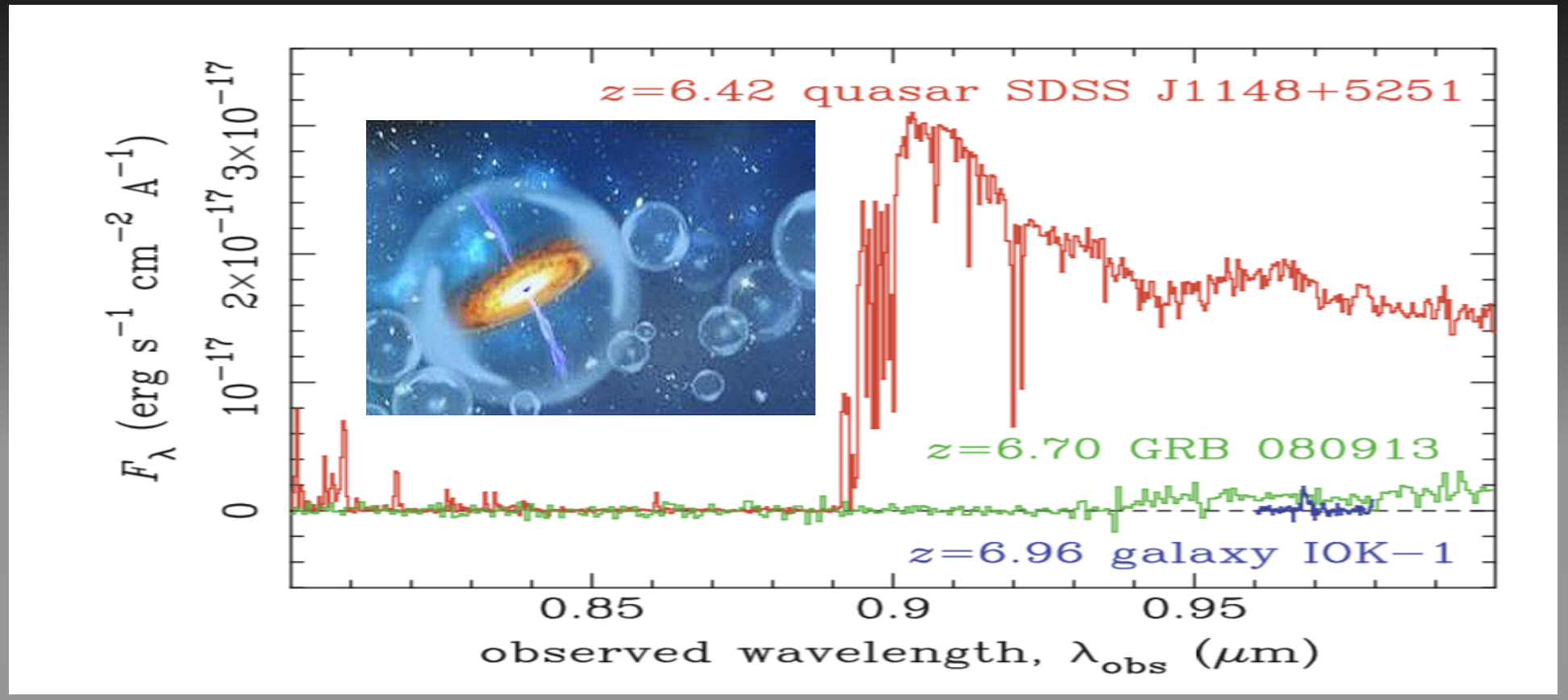
$$\frac{dQ_{HII}}{dt} = \dot{n}_{ion} - \frac{Q_{HII}}{\bar{t}_{rec}},$$

Production rate of ionization photons:

$$\dot{n}_{ion}^{com} = \int_{M_{lim}}^{\infty} dM_{UV}\, \phi(M_{UV}) \gamma_{ion}(M_{UV})\, f_{esc}\,.$$

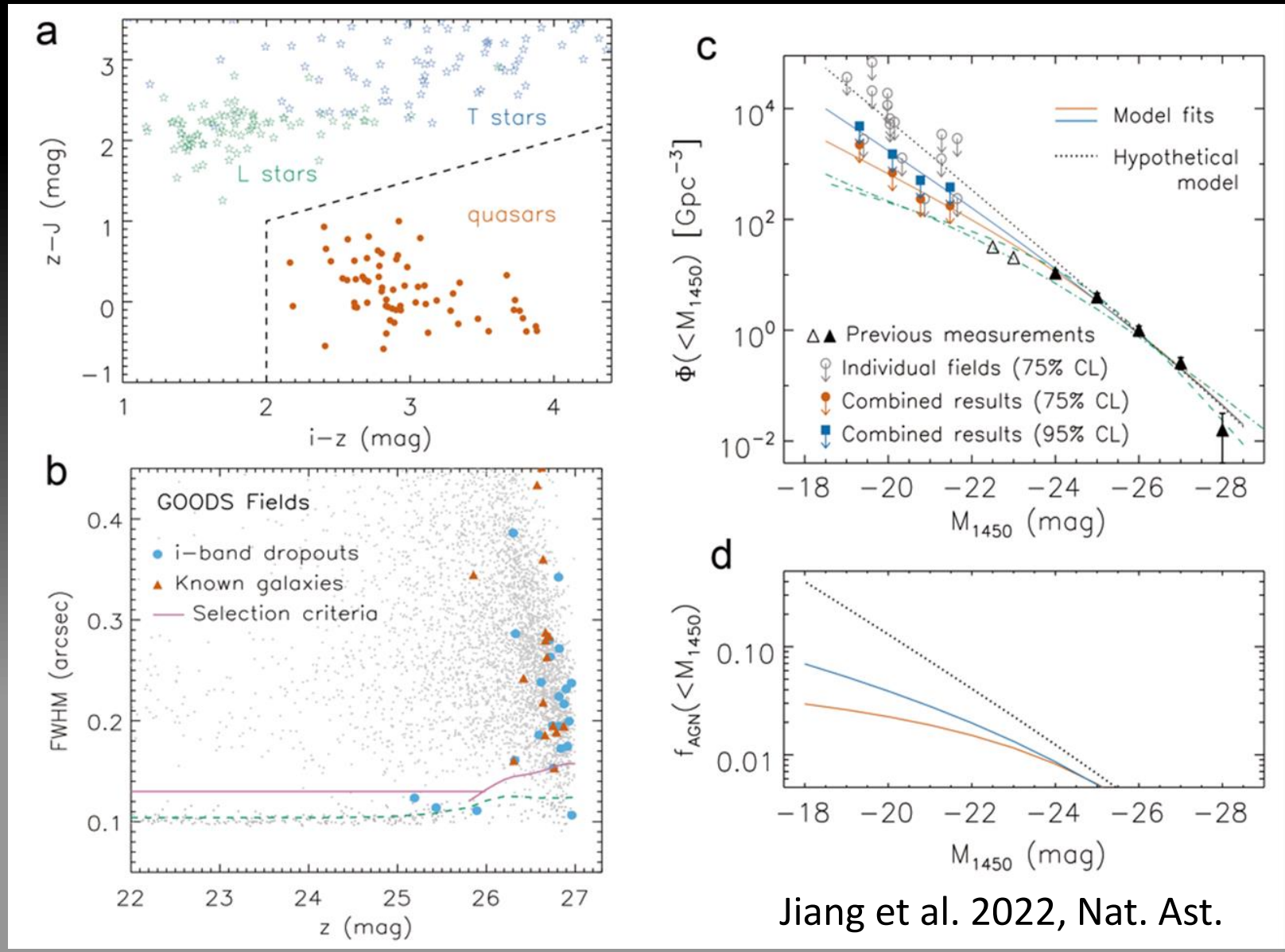
Optical depth of free electron:

$$\tau_e = \int_0^{\infty} dz \frac{c(1+z)^2}{H(z)} Q_{HII}(z)\, \sigma_T\, \bar{n}_H\, (1 + \eta Y/4X),$$



AGNs are not likely the dominant sources for EoR

- **Bofere the launch of JWST:** Quasar could not dominate the budget (<7% at z>6, Jiang et al. 2022; 1% at z>7, Matsuoka et al. 2023)
- **After the launch of JWST:** Although an unexpectedly large number of AGNs were identified (i.e., “Little Red Dots”), they still play a minimal role in dominating the ionizing budget (e.g., Dayal et al. 2024, Jiang et al. 2025).



Jiang et al. 2022, Nat. Ast.

Sources responsible for reionization

The current view: SFGs dominate the budget of ionizing photons required by the EoR
(e.g., Robertson et al. 2013, 2015)

The amount of ionizing photons from SFGs: $n_{ion} = f_{esc} \times \xi_{ion} \times \rho_{UV}$

ρ_{UV} UV luminosity density, obtained by intergrating UV LF (Oesch et al. 2018, Bowler et al. 2020, Bouwens et al. 2021a, Harikane et al. 2022)

ξ_{ion} Ionizing Photons Production Efficiency, obatined by observations of nebular lines (Bouwens et al. 2016, Lam et al. 2019, De Barros et al. 2019)

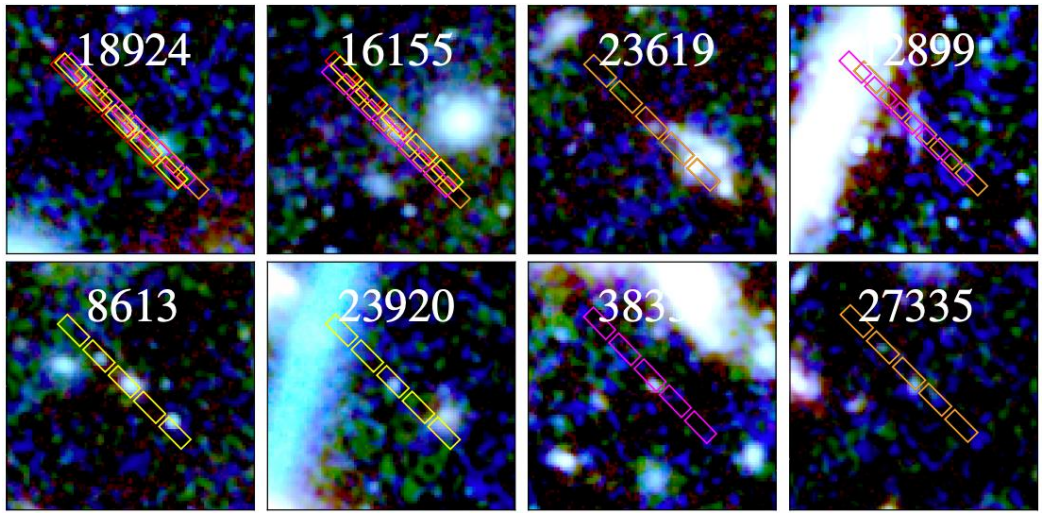
f_{esc} Escape Fraction of LyC Photons -> How many ionizing photons could escape from galaxies?

Currently, the uncertainty of the budget is dominated by f_{esc}

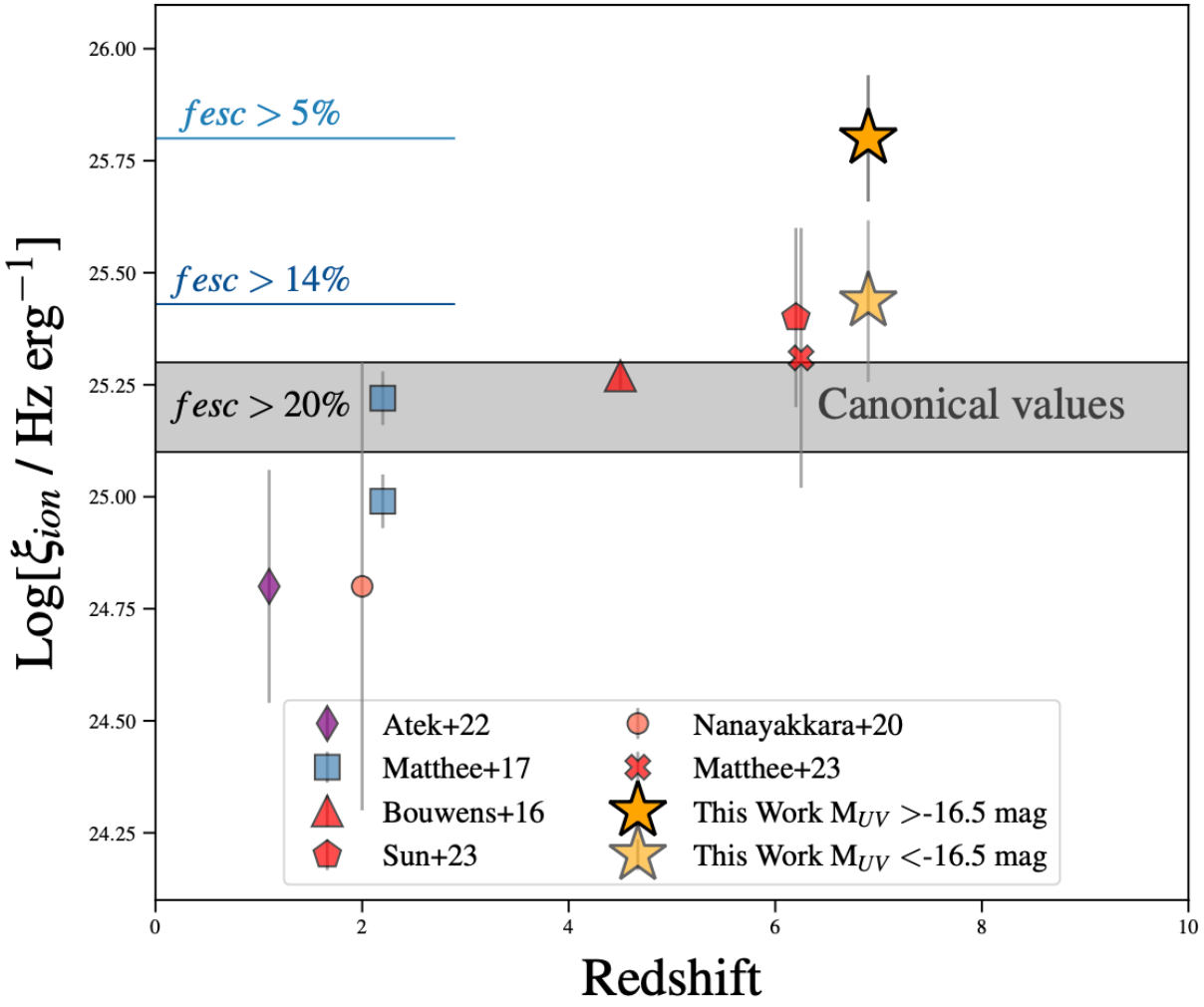
Requirements on f_{esc}

Previous studies claim that an average fraction of 20% or a comparable value is required to satisfy the boundary condition measured by probes of the EoR (e.g., Robertson et al. 2013, 2015)

Recent JWST observations found that the ξ_{ion} for faint galaxies is higher than the canonical values, thus loosening the requirements on *fesc*.



$$n_{ion} = f_{esc} \times \xi_{ion} \times \rho_{UV}$$



e.g, Atek et al. 2024

The Generation and Escape of LyC Photons

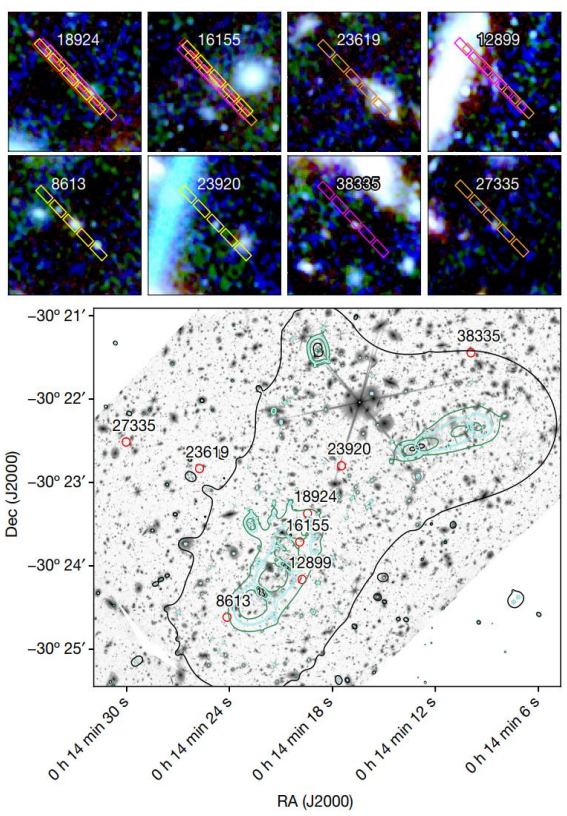


Fig. 1 | Layout of the ultra-faint galaxies identified in A2744 cluster field.

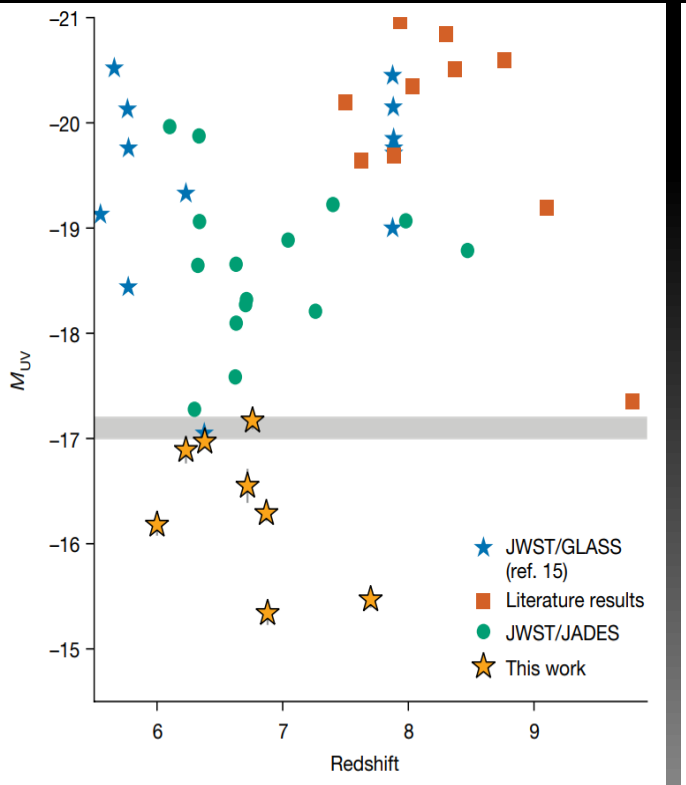
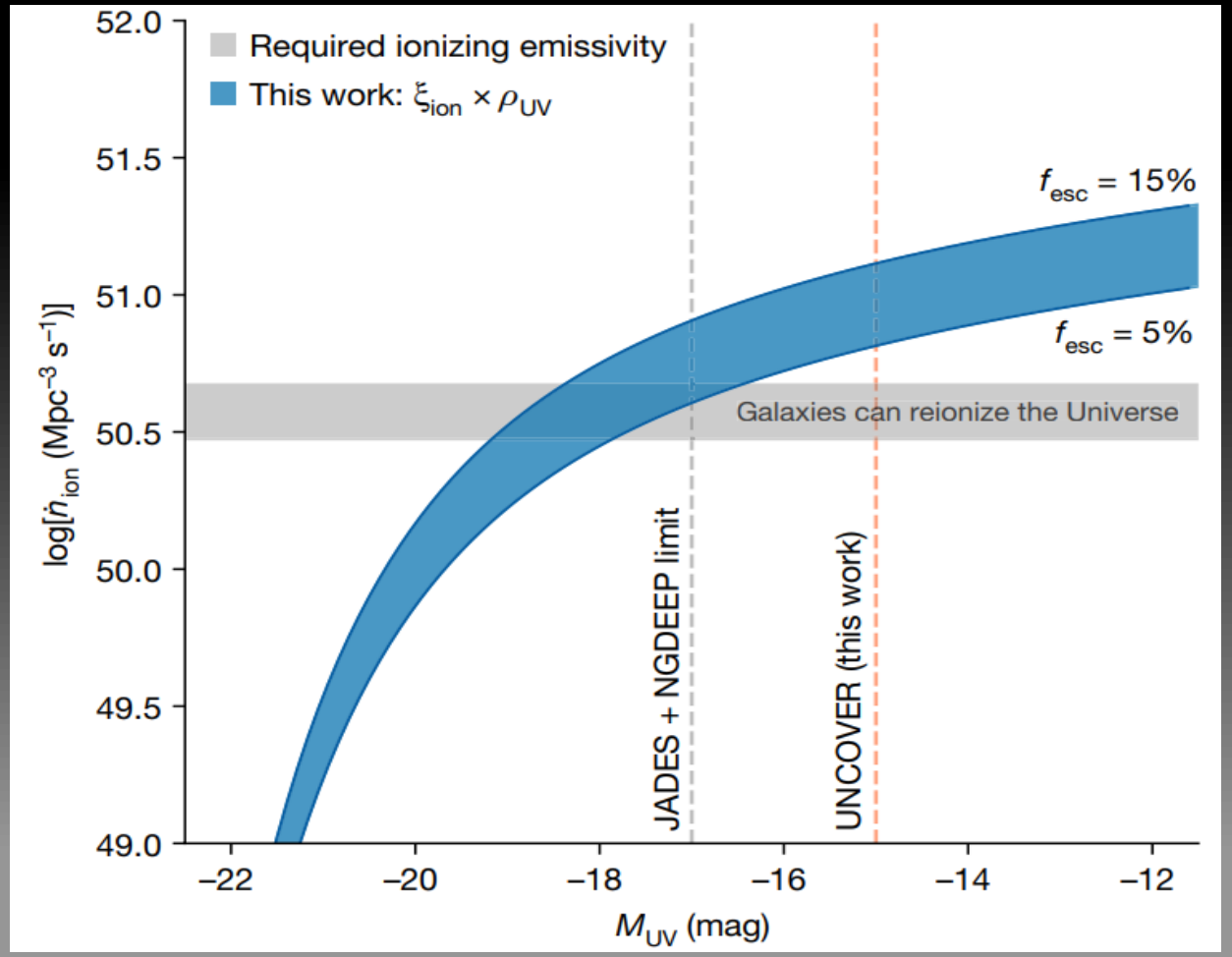


Fig. 2 | Spectroscopic observations of the faintest galaxies during the epoch of reionization. Various literature results from ground-based, HST and



Atek et al. 2024, Nature

- Reionization is **Dominated by** SFGs rather than AGNs in the EoR **(**Jiang et al. 2022, Atek et al. 2024, Jiang et al. 2025)。 But **JWST's Little Red Dots** may bring in sth. new(e.g., Matthee et al. 2023; Madau+2024)

The Generation and Escape of LyC Photons

Measuring f_{esc} from analogs of galaxies in the EOR

- **Low- z starburst system: The low mass compact galaxies with active star formation are good candidates (Izotov,. Guseva & Thuan 2011, Jaskot & Oey 2013) and many positive detection are reported (e.g., Borthakur et al. 2014, Izotov et al. 2018a, 2018b, Flury et al. 2018).**

- **Galaxies at 3<z<4: LAEs/LBGs at 3<z<4 and some LyC leakers and candidates are reported (Vanzella et al. 2012, 2015, 2018, Yuan et al. 2021, Wang et al. 2023, Liu et al. 2023).**
- **However, the difficulty is the identification (faintness, contamination by lower redshift interlopers, and attenuation by partially neutral intergalactic medium).**

- **Galaxies at z>5: Impossible to detect their LyC signals due to the IGM absorption.**

A Systematic Study of LyC Leaking Galaxies at 3<z<4.5

Average fesc is low

- Most galaxies are non-detections in the LyC regime, and the average fesc is low (< 10%)
  - Wang et al. 2024: fesc < 6% for ~80 non-detections at 2.4<z<3.7, Rutkowski et al. 2016 fesc~2.1%–9.5% at z ~ 1.

Some galaxies exhibit high fesc values (LyC leakers, at 3<z<4)

- GOODS-S**:** Saxena et al. 2022, Rivera-Thorsen et al. 2022, Vanzella et al. 2012; Ji et al. 2020 (*Ion1*), Vanzella et al. 2015, 2016 (*Ion2*), Yuan et al. 2021 (CDFS-6664)
- SSA22: Fletcher et al. 2019, Micheva et al. 2017, Nestor et al. 2013
- Others: Mostardi et al. 2016, Steidel et al. 2018, Wang et al. 2023, Prichard et al. 2021, Mestric et al. 2020, Iwata et al. 2019

LyC leakers at Low-z (z<1)

- LzLCS+samples: Flury et al. 2022 and reference therein, Saha et al. 2020, Dhiwar et al. 2024. See also Roy et al. 2024

A Systematic Study of LyC Leaking Galaxies at 3<z<4.5

Motivations: using same methods to achieve unbiased conclusions

Table 2. The photometric data and SED models

Refs.	Data	N_{phot}	Wavelength range	IMF	SPS Model	SFH	Z ($Z_\odot$)	Extinction curve	Nebular Model	f_{esc}
S22	HST, Ks, *Spitzer*	14	0.4-8 μm	KB02	BC03	ExpDec	0-1	C00	F13	No
RT22	HST	11	0.2-1.5 μm	KB02	BC03	Delayed	0.2	C00	F17	No
Y21	HST, Ks, *Spitzer*	10	0.3-24 μm	Salpeter	BC03	Delayed	0.02-1	C00/CCM89	I10	Yes
DB16	HST, *Spitzer*	9	0.4-8 μm	Salpeter	BC03	Constant	0.2	S79	-	No
J20	HST, Ks, *Spitzer*	16	0.4-8 μm	K01	FSPS	Delayed	1	C00	F98,13	No
This work	HST, Ks, *Spitzer*, JWST	26	0.4-8 μm	Salpeter	BC03	Delayed	0.2	C00/CCM89	I10	Yes

Systematic offsets in properties of different studies

↓

Using the same method and data

Inaccurate SED models (missing nebular emission models)

↓

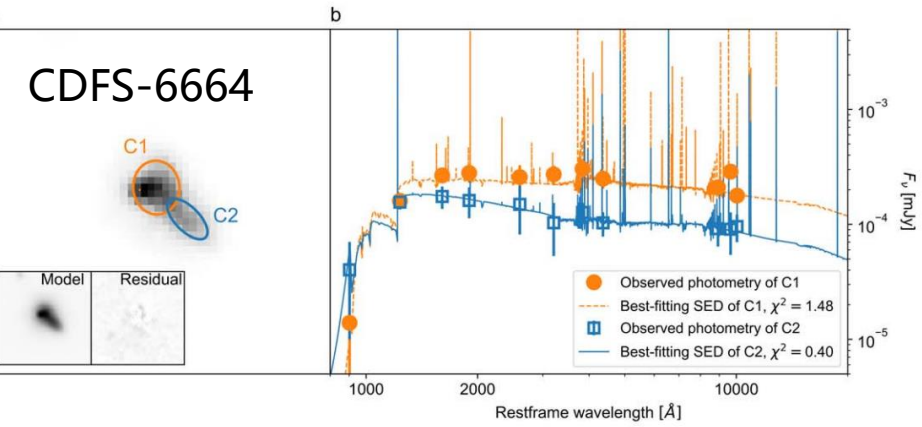
Improving by sophisticated SED models

Inaccurate photometric data at $\lambda > 2.5 - 3\ \mu m$

↓

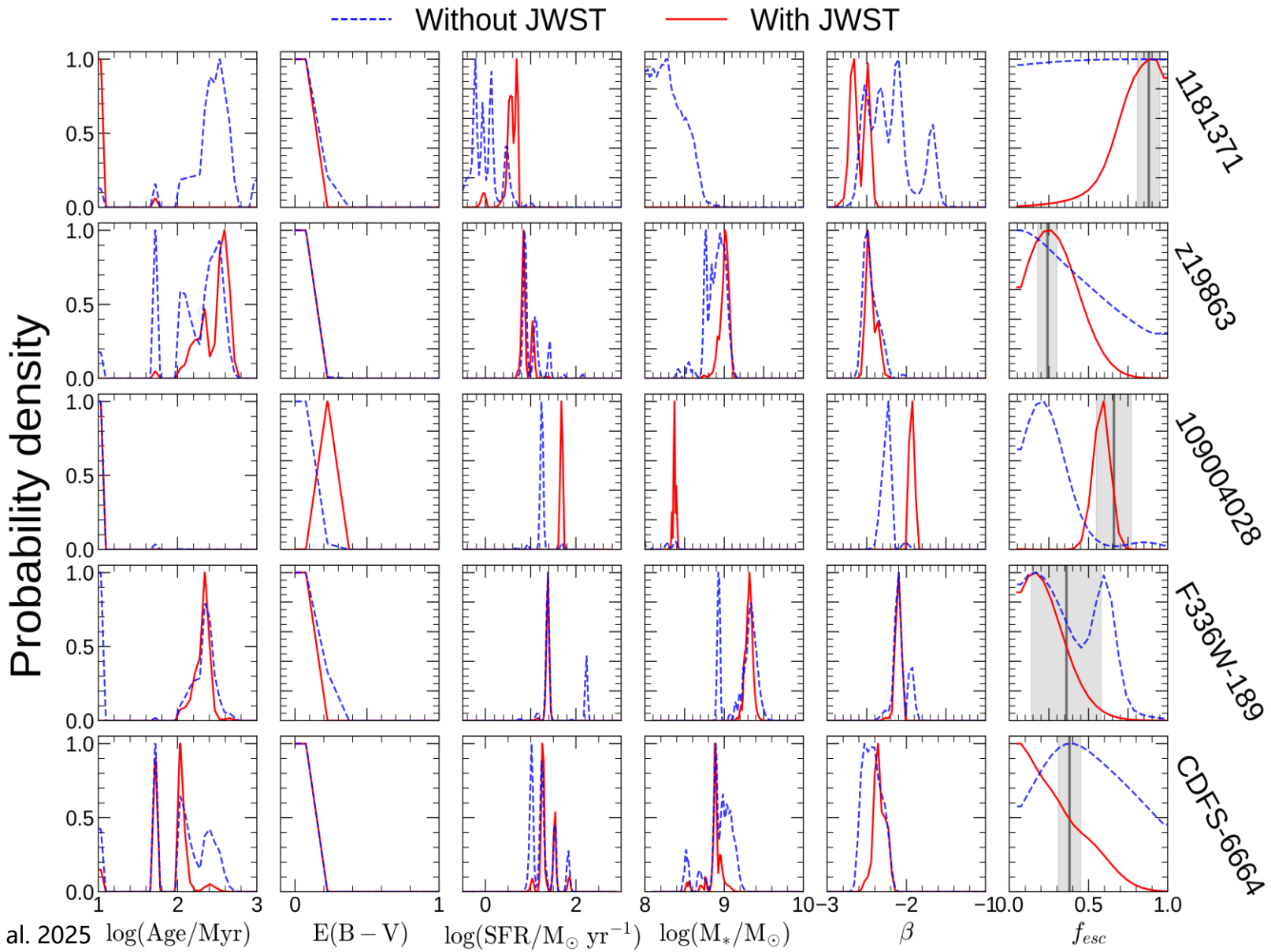
Improving by using JWST data

Result 1: The SED of LyC Leakers-I



JWST helps constrain properties better

- Narrow the distributions of probability densities
- Break the degeneracy in properties



Yuan, Zheng et al. 2021,2024; Zhu, Yuan et al. 2025; Zhu, Zheng et al. 2025

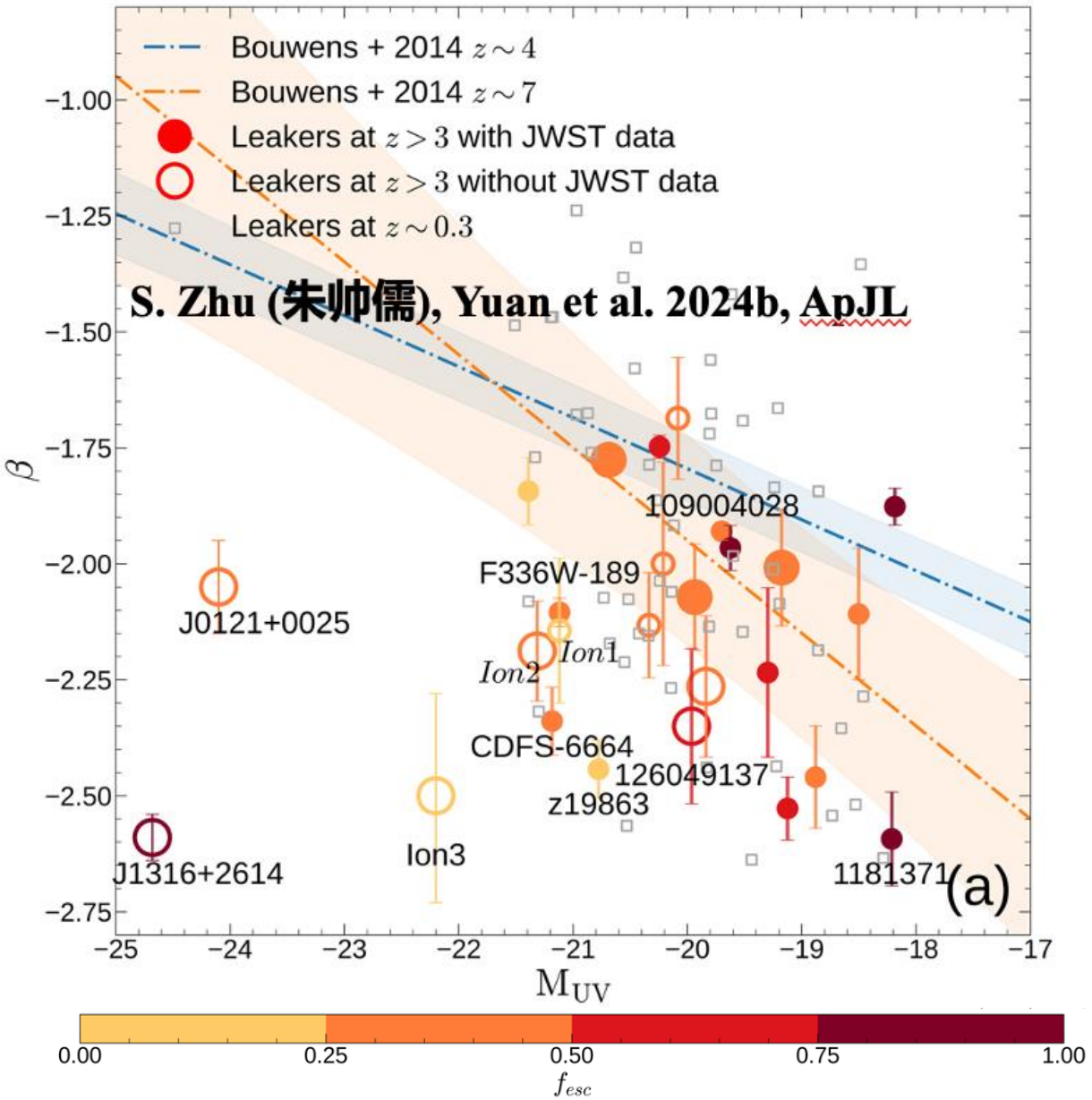
Result 1: The SED of LyC Leakers-I

The UV property I

Low-z leakers: They are consistent with the beta-M_{UV} relation at z~7, also a fesc-beta correlation is reported (Chisholm et al. 2022)

High-z leakers: Most LyC leakers align with z~7 the β-M_{UV} relation and some overlap with z~8 galaxies in the β -M_{UV} diagram.

Comparison: High-z leakers are bluer than those at low-z



Yuan, Zheng et al. 2021,2024; Zhu, Yuan et al. 2025; Zhu, Zheng et al. 2025

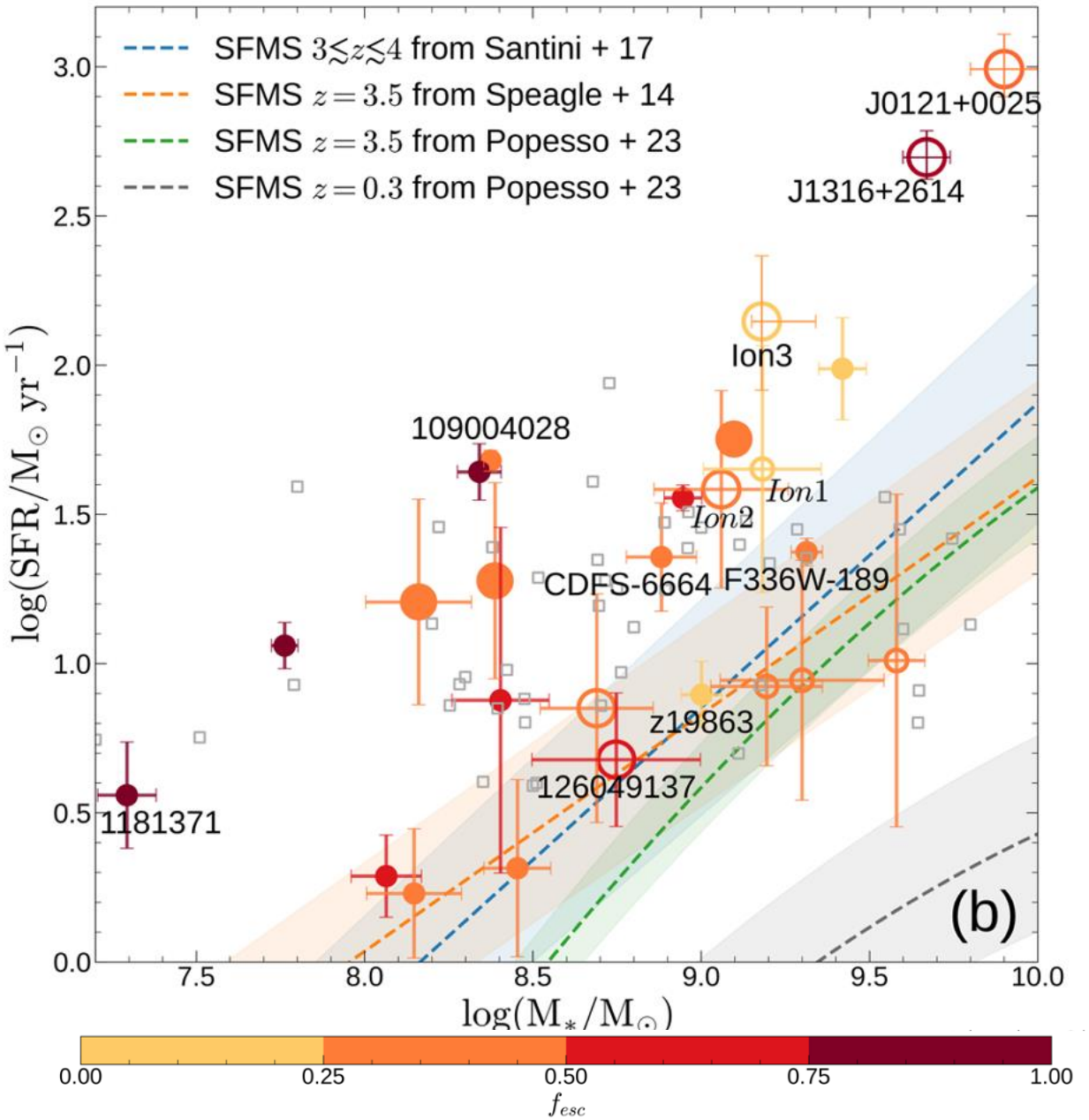
Result 1: The SED of LyC Leakers-II

The star formation property I

Low-z leakers: All leakers are in the starburst region.

High-z leakers: Some high-z LyC leakers are not starburst systems, although some leakers are undergoing intense star formation.

Comparison: High-z and low-z leakers fall in a similar region in this diagram.



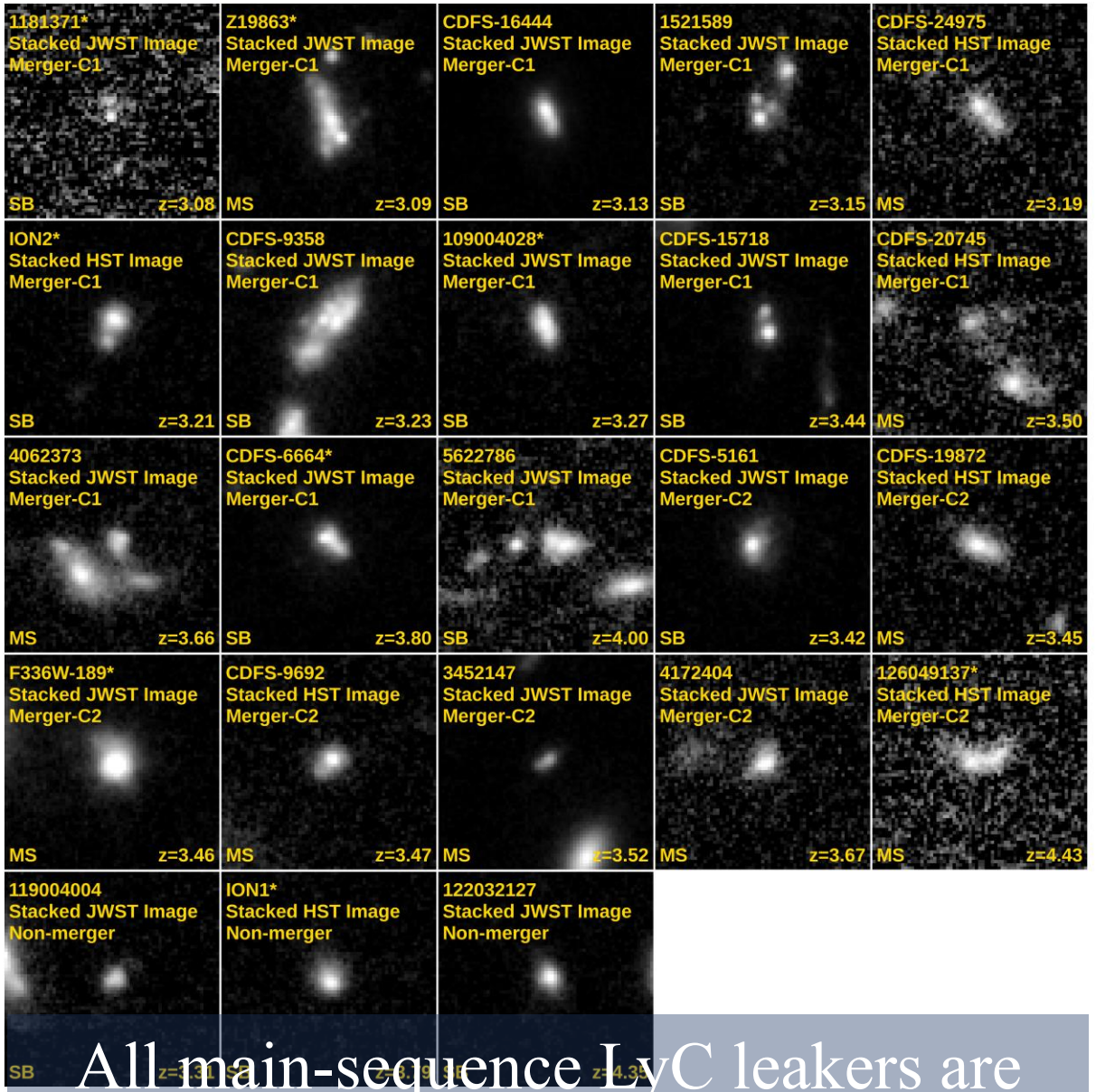
Yuan, Zheng et al. 2021,2024; Zhu, Yuan et al. 2025; Zhu, Zheng et al. 2025

Result 2: The Morphology of LyC Leaker-I

Visual inspection (High-z)

- **Methods:** Two types of galaxy mergers are identified in this work: (1) galaxies with two or more cores and/or close companions and (2) galaxies that exhibit extended, elongated structures or long tails.
- **Results:** 20/23 for high-z
- **Comparison:**
  - ~ 40% - 50% for brightest galaxies at z~2-3; ~56% for high-z LAE & LBG sample (See Jiang et al. 2012 and reference therein)
  - Witten et al. 2024 **: 100%** of LAEs in their sample at z>7 have close companions

Yuan, Zheng et al. 2021,2024; Zhu, Yuan et al. 2025; Zhu, Zheng et al. 2025

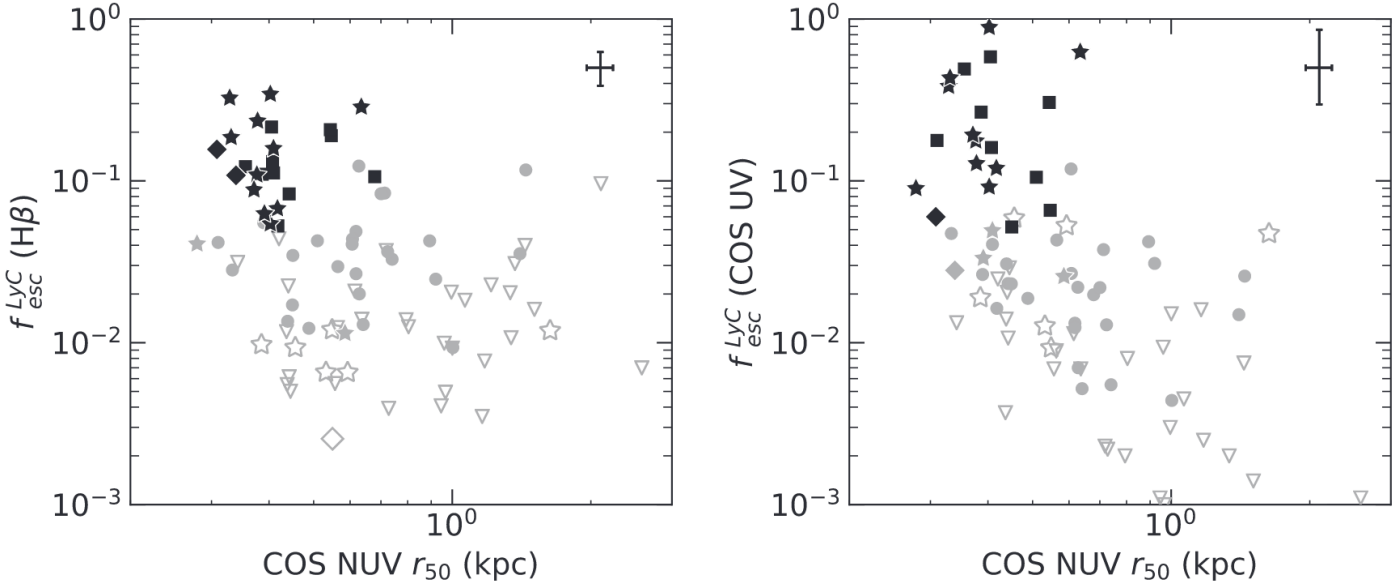


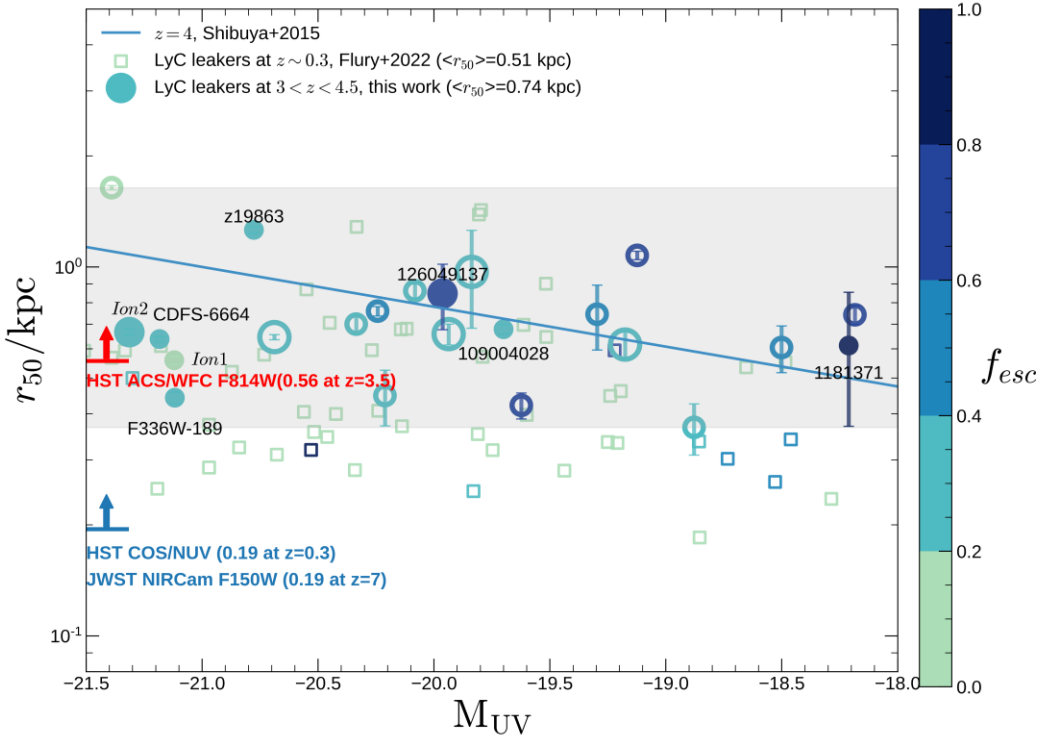
All main-sequence LyC leakers are mergers

Result 2: The Morphology of LyC Leaker-II

Sizes versus fesc

- **At low-z:** A clear trend between fesc and UV sizes is found based on the LzLCS+ sample, however massive leakers exhibit extended structures
- **At high-z:** No such trend is found based on our sample





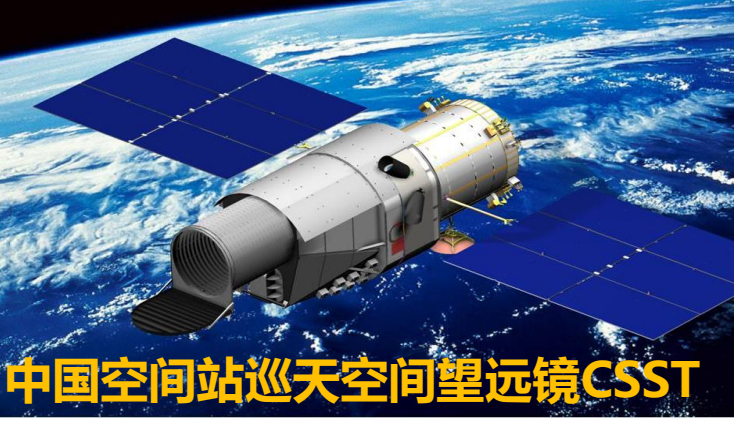
Yuan, Zheng et al. 2021,2024; Zhu, Yuan et al. 2025; Zhu, Zheng et al. 2025

Summary on Our Systematic Study of LyC Galaxies at 3<z<4.5

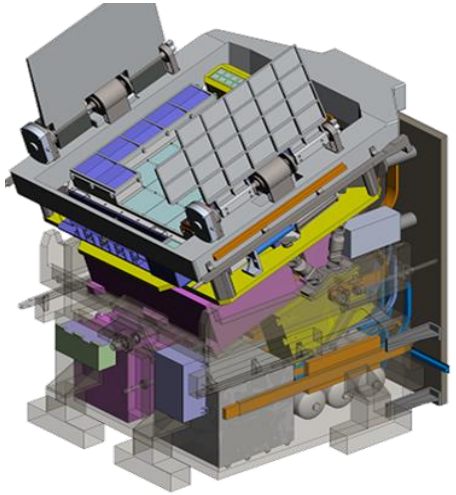
- We conduct a systematic analysis of the physical properties and morphologies of LyC leakers at 3<z<4.5 and compared them to those at z~0.3:
  - **UV properties:** The high-z leakers exhibit more blue UV color compared to low-z leakers;
  - **Star formation:** Unlike low-z leakers, our results show intense bursts of star formation are not necessarily required for the leakage of LyC photons for galaxies at z>3. They also exhibit lower Σ_{SFR} but Σ_{SFR} are similar in the comparable size range;
  - **Morphology:** All main-sequence leakers are mergers and almost all leakers are mergers, suggesting merging activity could also facilitate the LyC photon escaping;
  - **Sizes:** High-z leakers in the GOODS-S tend to be more extended, compared to the galaxies at z>5 and low-z leakers.

What's next? More deep UV surveys are needed!

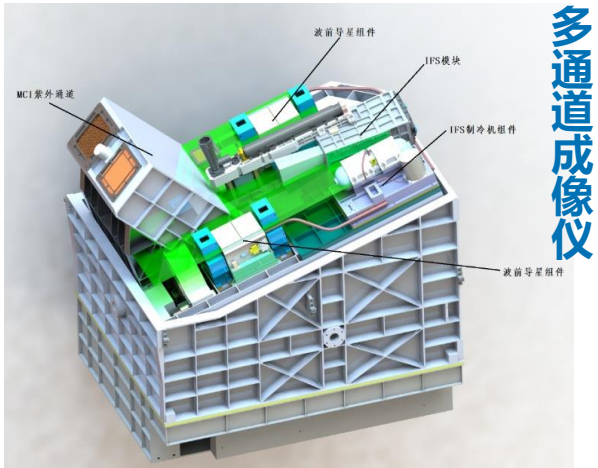
Yuan, Zheng et al. 2021,2024; Zhu, Yuan et al. 2025; Zhu, Zheng et al. 2025



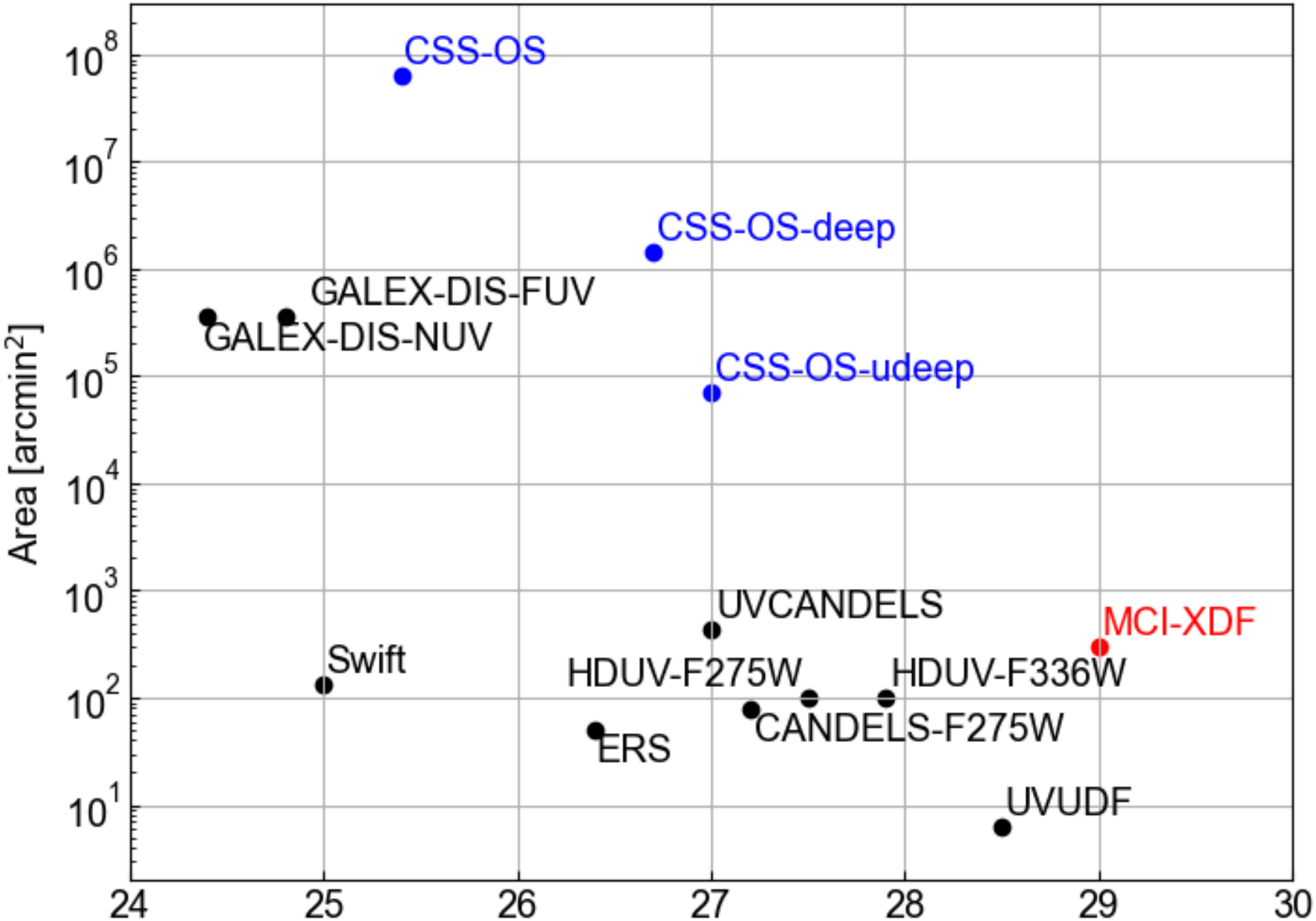
巡天模块



积分视场光谱仪
多通道成像仪



CSST Deep UV Surveys vs. Current UV Surveys



袁方婷，郑振亚等，中国科学，2022

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  - Galaxies vs. AGN/Quasars
  - Properties of LyC Leaking Galaxies
- **Current & Future Galaxies Surveys for Reionization**

- Individual Obs.: **HST/JWST**, **CSST**, **14.5m**, TMT/GMT/E-ELT, ALMA

- Ground multi-color/band Surveys: LSST; J-PAS, SILVERRUSH, **LAGER/CIDER**
- Ground multi-object spectroscopy: Subaru-PFS, VLT-MOONS, MSE, JUST, MUST

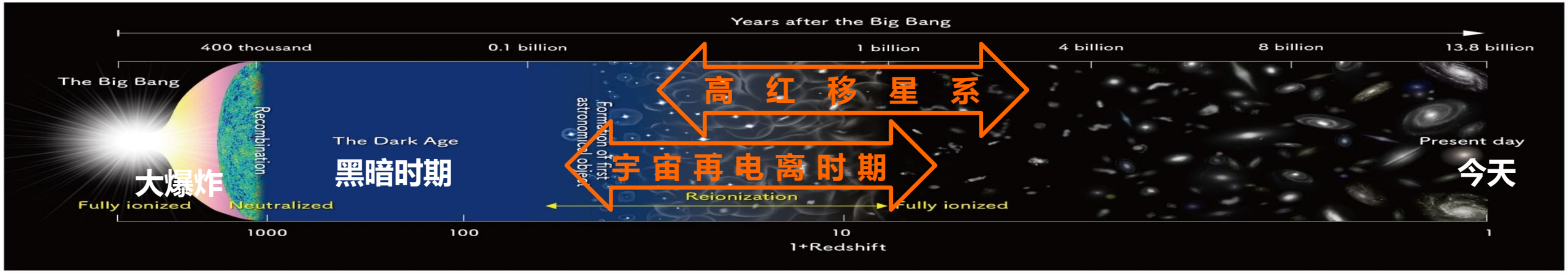
- Space multi-color/band survey: **CSST (OS/MCI)**
- Space multi-spectrograph: **CSST**, WFIRST, Euclid, SPHEREx

- CMB: Planck
- Low-frequency Obs.: SKA pathfinder (21CMA, MWA, LOFAR, HERA, …), **SKA I/II**

- Cosmic reionization is the last major phase transition of most baryonic matter in the Universe. It involves the conversion of cold, neutral hydrogen into highly ionized hydrogen in the intergalactic medium, implying the end of the Dark Age and the beginning of the Age of Galaxies.
- Current and future large opt./NIR telescopes, such as JWST/HST/CSST， 14.5m/GMT/E-ELT, and ALMA/SKA， will unveil the Cosmic Reionization and the formation and evolution of the first objects.

- We are using LAGER/CIDER to probe the reionization history at z~6.9 and 7.3, and using deep UV surveys to study the generation and escape of LyC photons.

◆Hope you get breakthroughs in this area in the near future!



Thanks for your attention!

https://people.ucas.edu.cn/~zhengzy

zhengzy@shao.ac.cn