2020年代の銀河形成研究

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Outline

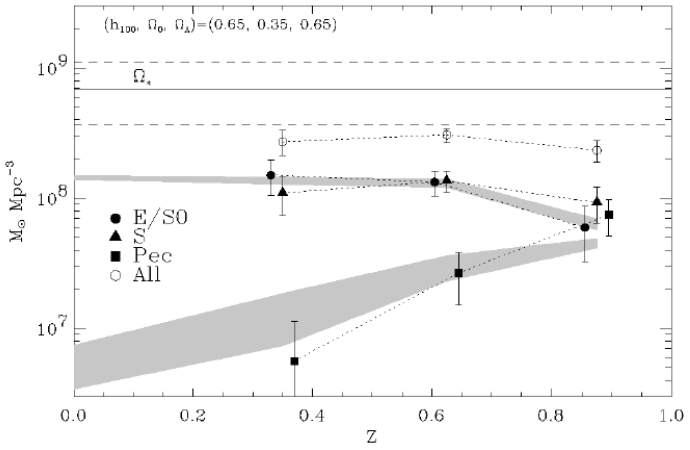
- Galaxy formation studies in the past and future
- Review of 2000s studies→ Open questions
- Problems addressed with the next generation OIR instruments in 2010s and 2020s

Outstanding Goal in 2000s
Uncovering Stellar Mass Assembly History

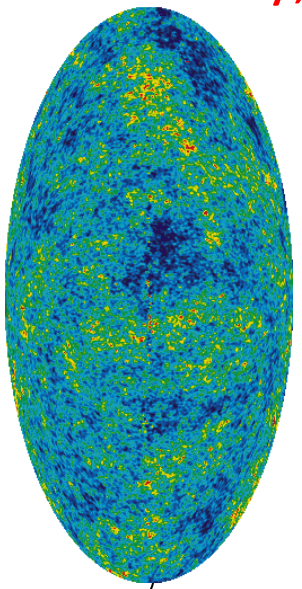
- Cold Dark Matter (CDM) model

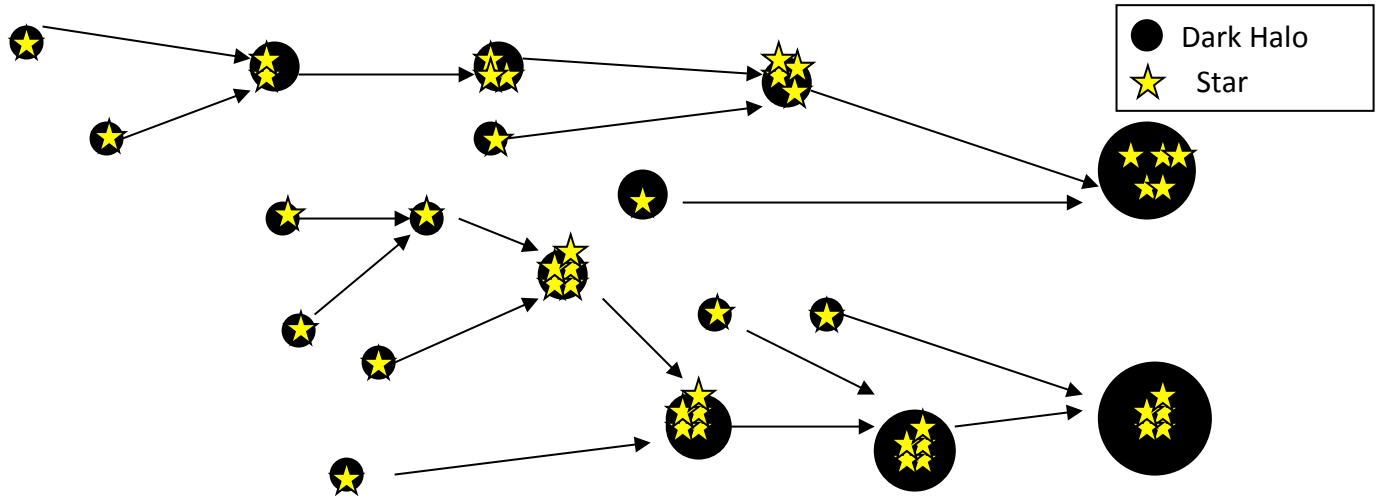
→Hierarchical structure formation

- Galaxy formation should follow this bottom up scenario.
- Revealing stellar mass function -> stellar mass density, ρ_{SM}, evolution beyond z>1.



Brinchmann & Ellis 2000





Early Universe

Mergers for mass assembly

Present

Complementary Quantity
Cosmic SFR Density

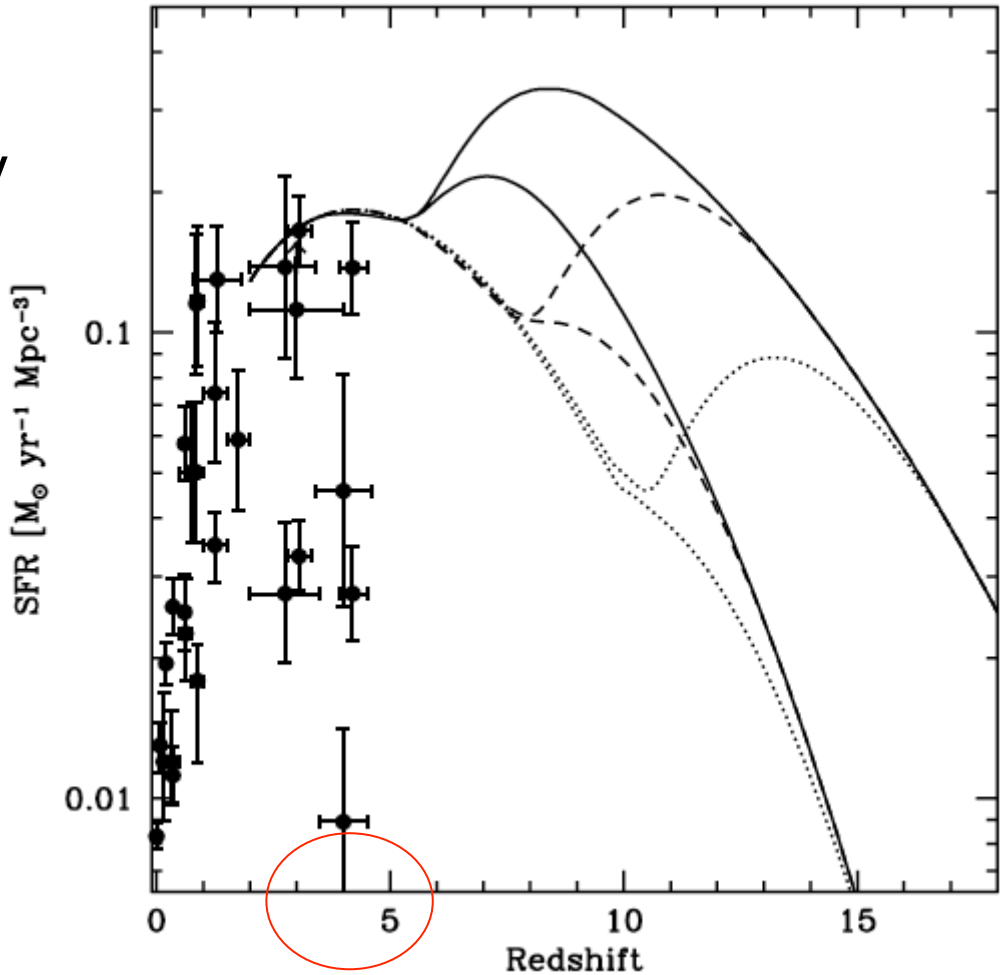
- Stellar Mass Density (SMD) : ρ_{SM} [Mo/Mpc^3]
- Star Formation Rate Density (SFRD) : ρ_{SFR} [Mo/yr/Mpc^3]

$\rho_{SM} = \int \rho_{SFR}\, dt$

(or $d\rho_{SM}/dt = \rho_{SFR}$)

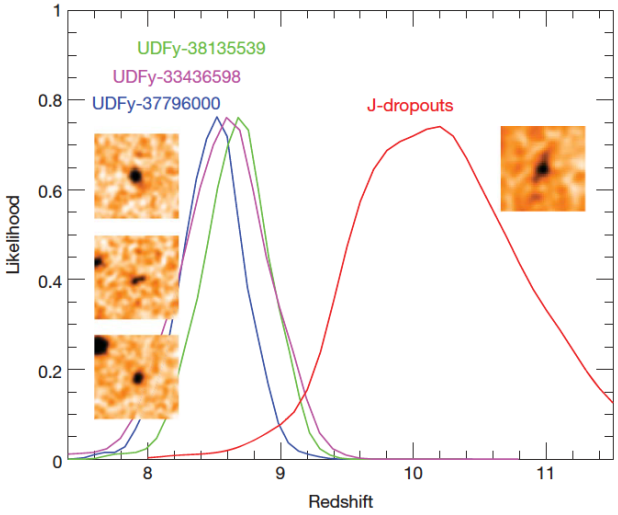
- Thus, SFRD is used for
  - a complementary probe
  - a consistency check.

- Decrease vs. flat SFRD beyond z~3? (e.g. Madau+96)

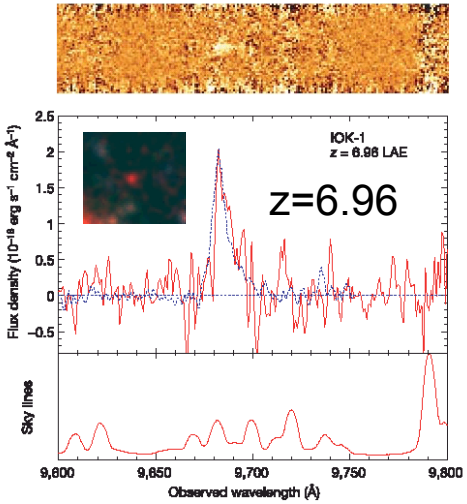


SF History understood/predicted a decade ago (Barkana & Loeb 2000)

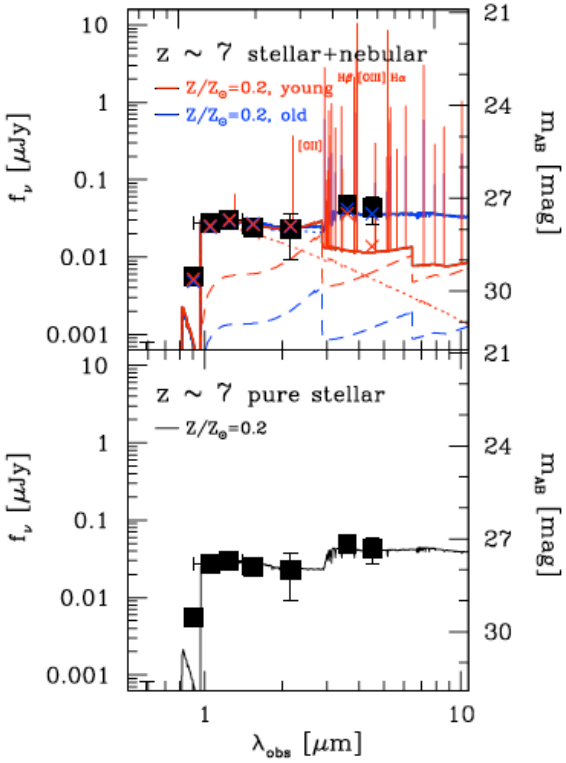
Extending Redshift Frontier from z~4 to 10



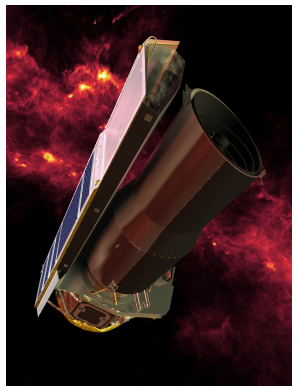
Bouwens et al. 2011



Iye et al. 2006

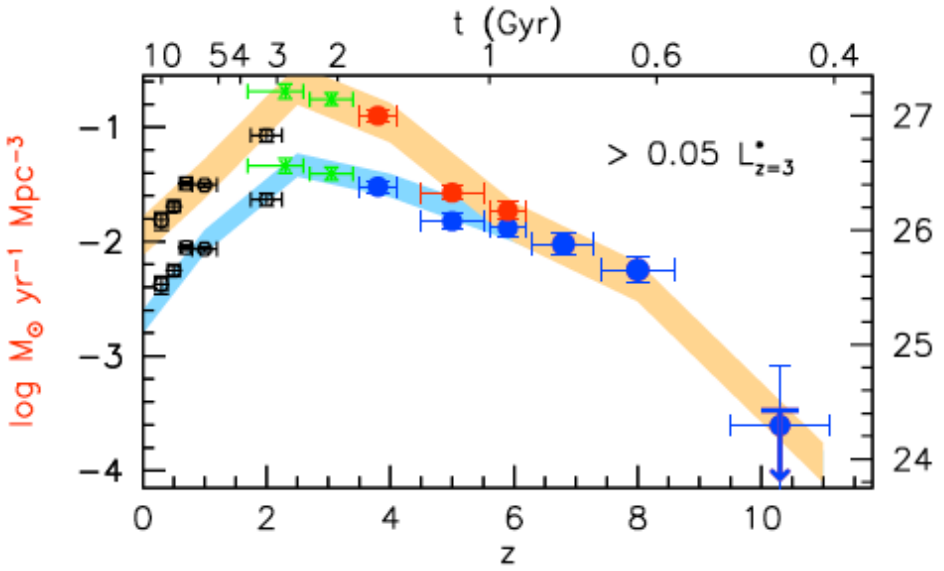


Ono et al. 2010

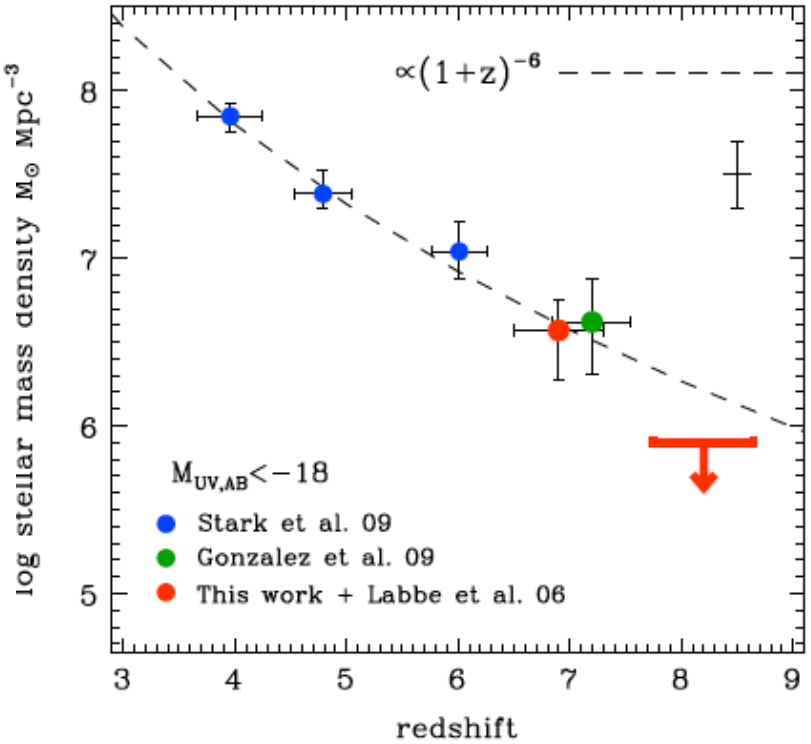


- Galaxy candidates, thus cosmic SFRD, up to z~10
- Spectroscopic confirmation up to z~7
- Complementary Spitzer IR data→SMD up to z~7

SFRD and SMD Known to Date



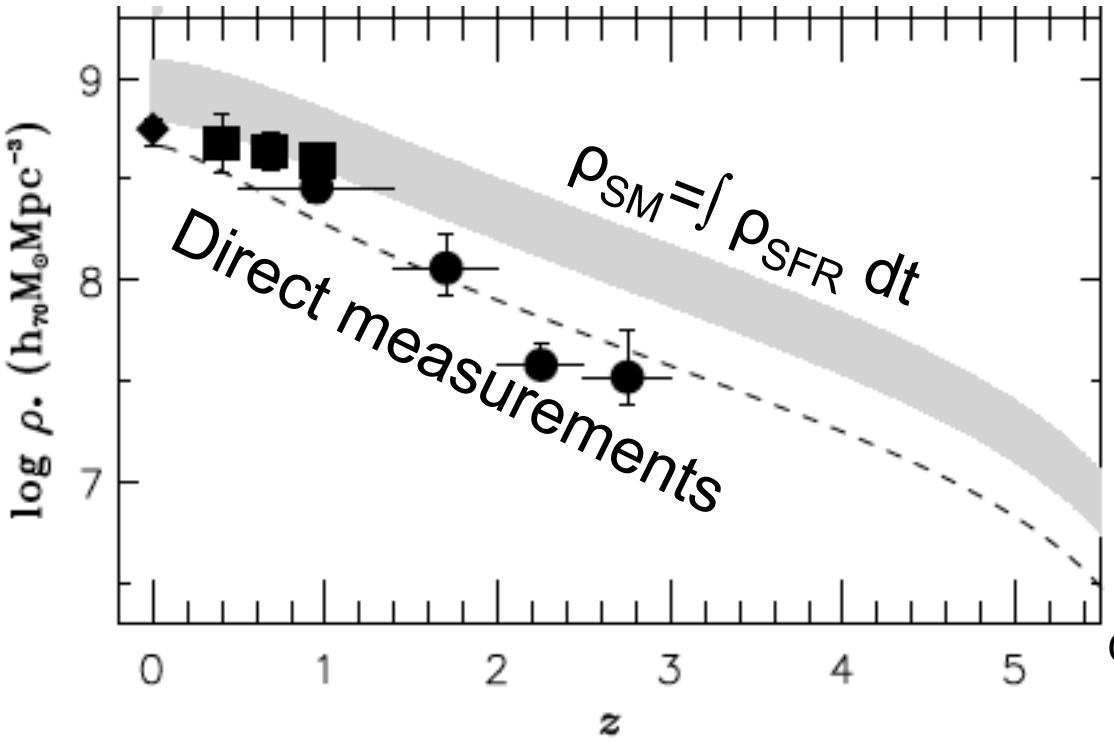
Bouwens et al. 2011



Labbe et al. 2010

- SFRD peaks at z~2-3 and monotonically decreases towards high-z (1/100 at z~7-8)
- SMD is about 1/10 at z~4, and 1/100 at z~7.

Star-Formation History (SFRD) Consistent with Stellar Mass Density (SMD) Evolution?



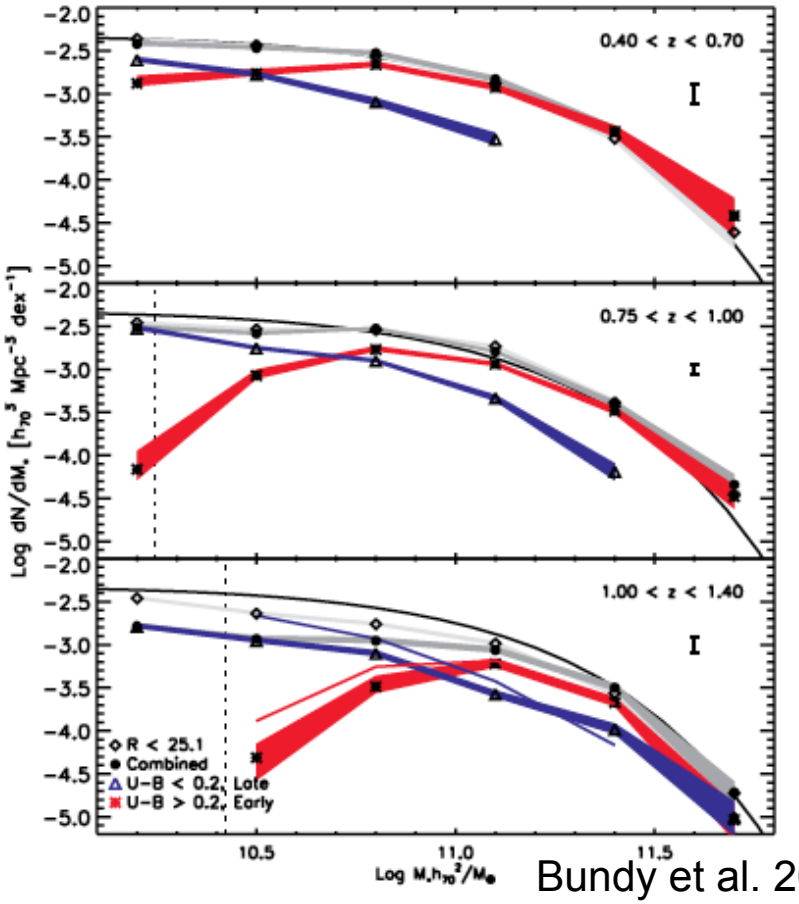
Ouchi et al. 2004

- Discrepancy between the SFRD estimates and SMD measurements.

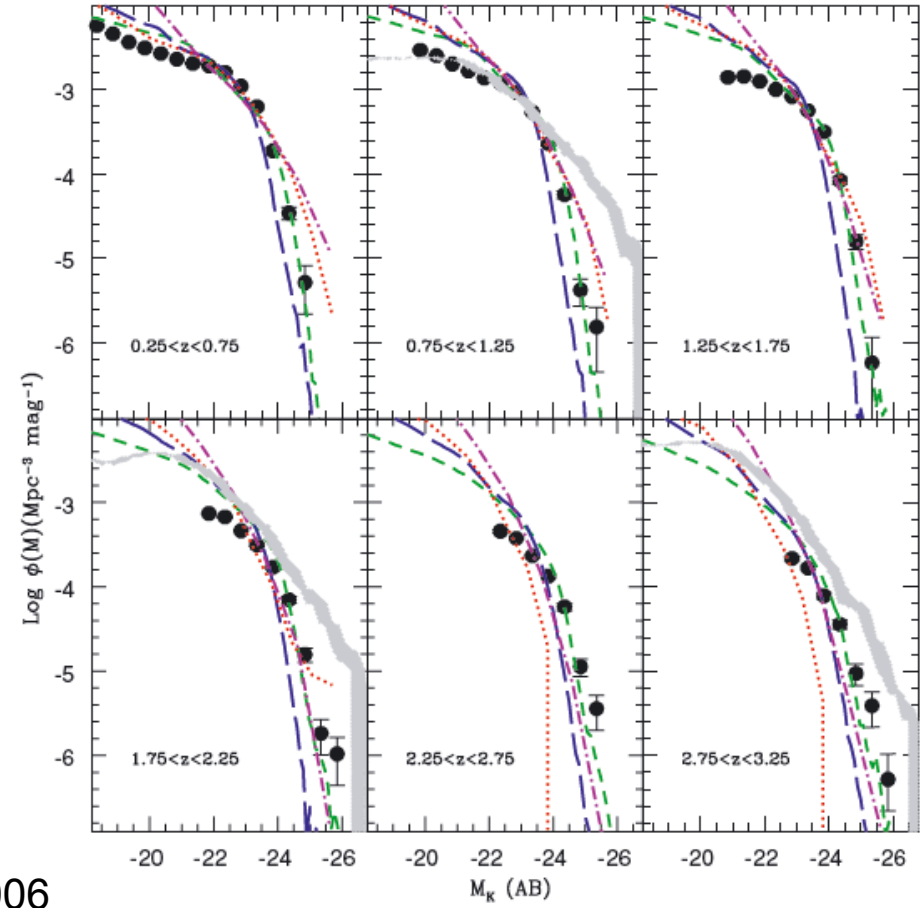
→ More stars have to be made with the given SFRD. Why?

- Change of IMF (flatter IMF for massive short-lived stars), dust extinction correction of SFRD, etc?

Downsizing (anti-hierarchical?)



Bundy et al. 2006

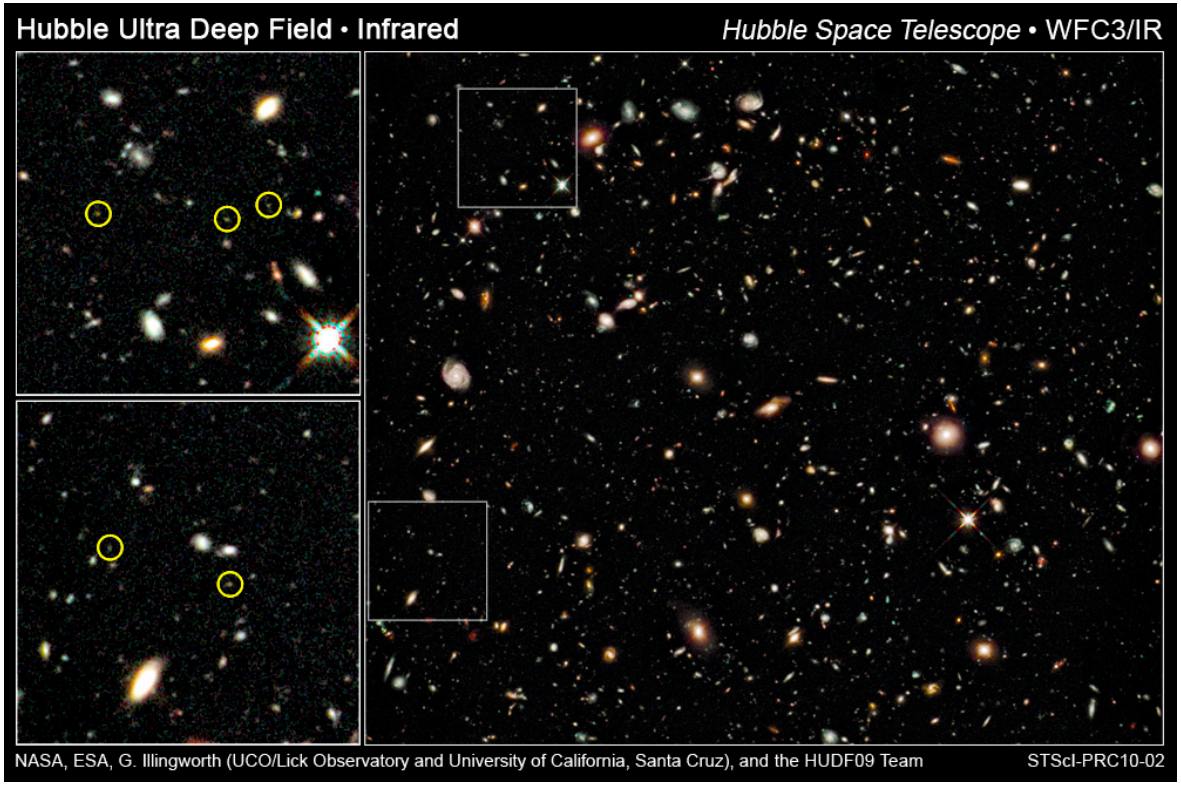


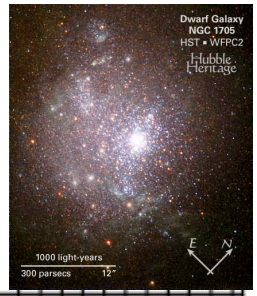
Cirasuolo et al. 2006

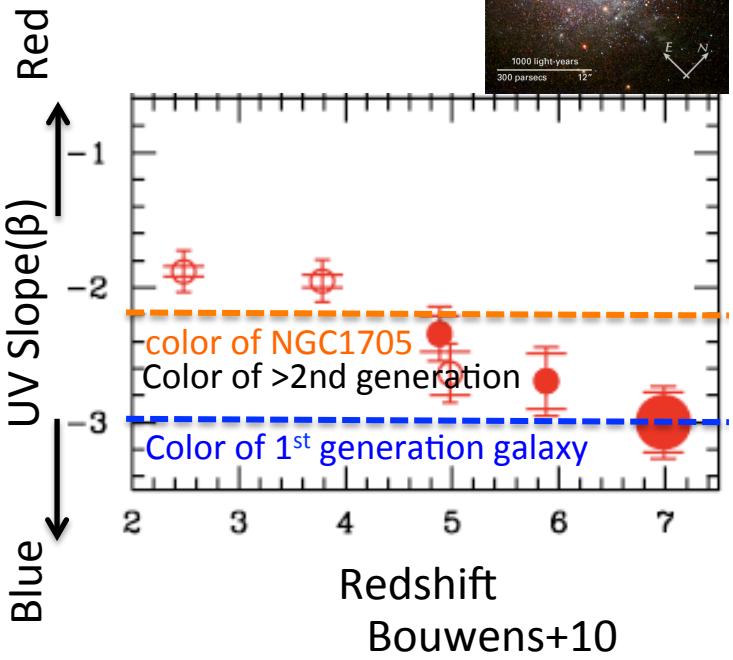
- Originally found in the late 1990s (Cowie et al. 1996).
- Massive galaxies formed first?→ anti-hierarchical?
- Early galaxy models (semi-analytic) could not explain it.

OTHER OUTSTANDING QUESTIONS RAISED IN 2000s

Discovery of Extremely Blue Galaxies
1st Generation Galaxies??



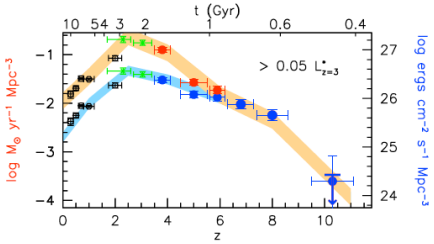


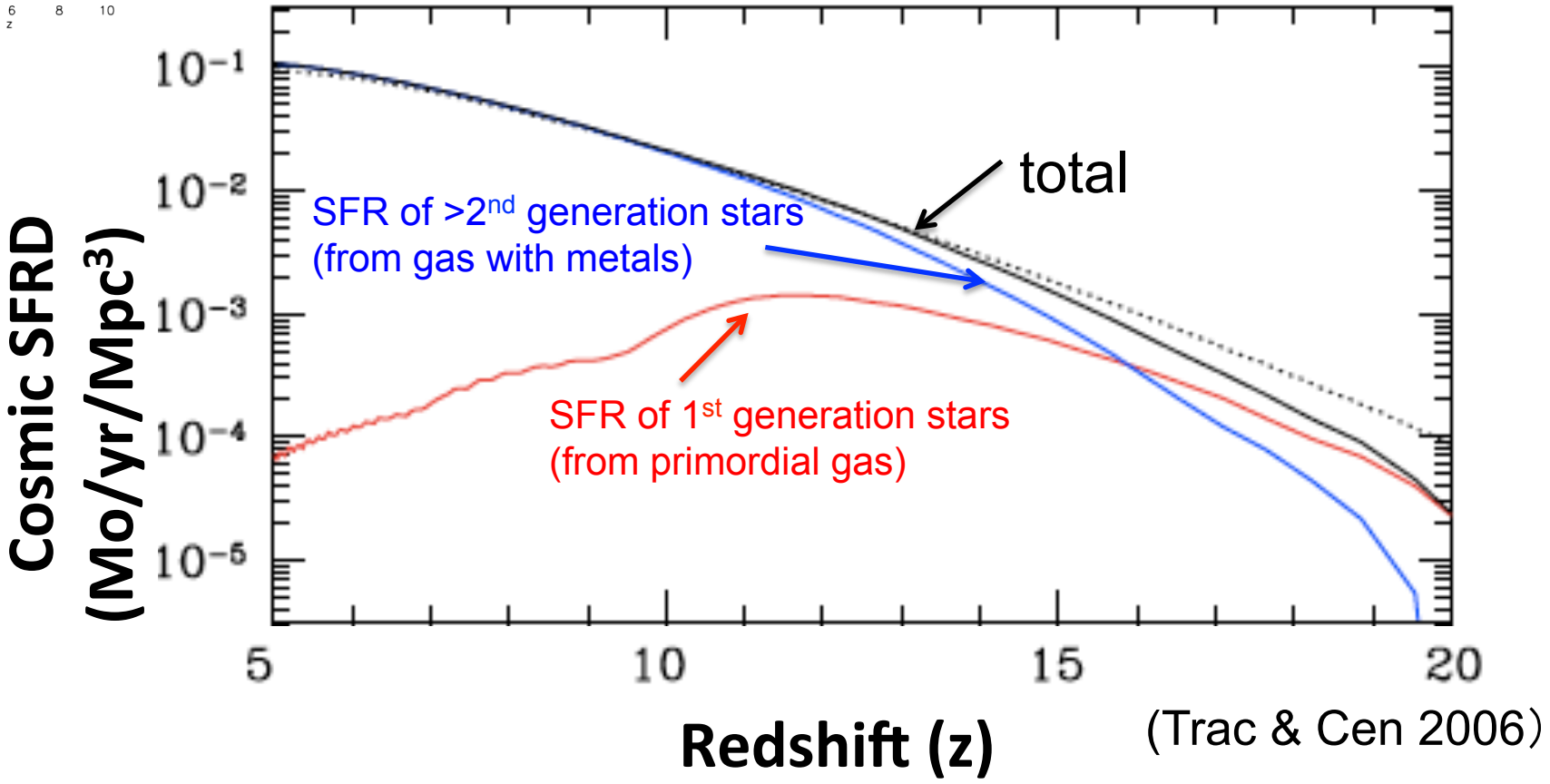


Redshift 7-8 galaxies

- Define colors with β where $f_\lambda \propto \lambda^\beta$
- Report of extremely blue (β=-3) galaxies at z~7 (Bouwens et al. 2009)
- Discovery of first galaxies!?
- Is it significant over the measurement uncertainties?→β~-2.5（Finkelstein+10,Dunlop+11)
  → Bouwens et al. report β~-2.5 with the latest data in the next paper (Bouwens et al. 2011)
  They are not first galaxies. However, these galaxies are very blue（β~-2.5)→More primordial (w less metal) than the other galaxies found to date.

Epoch of First Generation Stars/galaxies Predicted by Theoretical Models

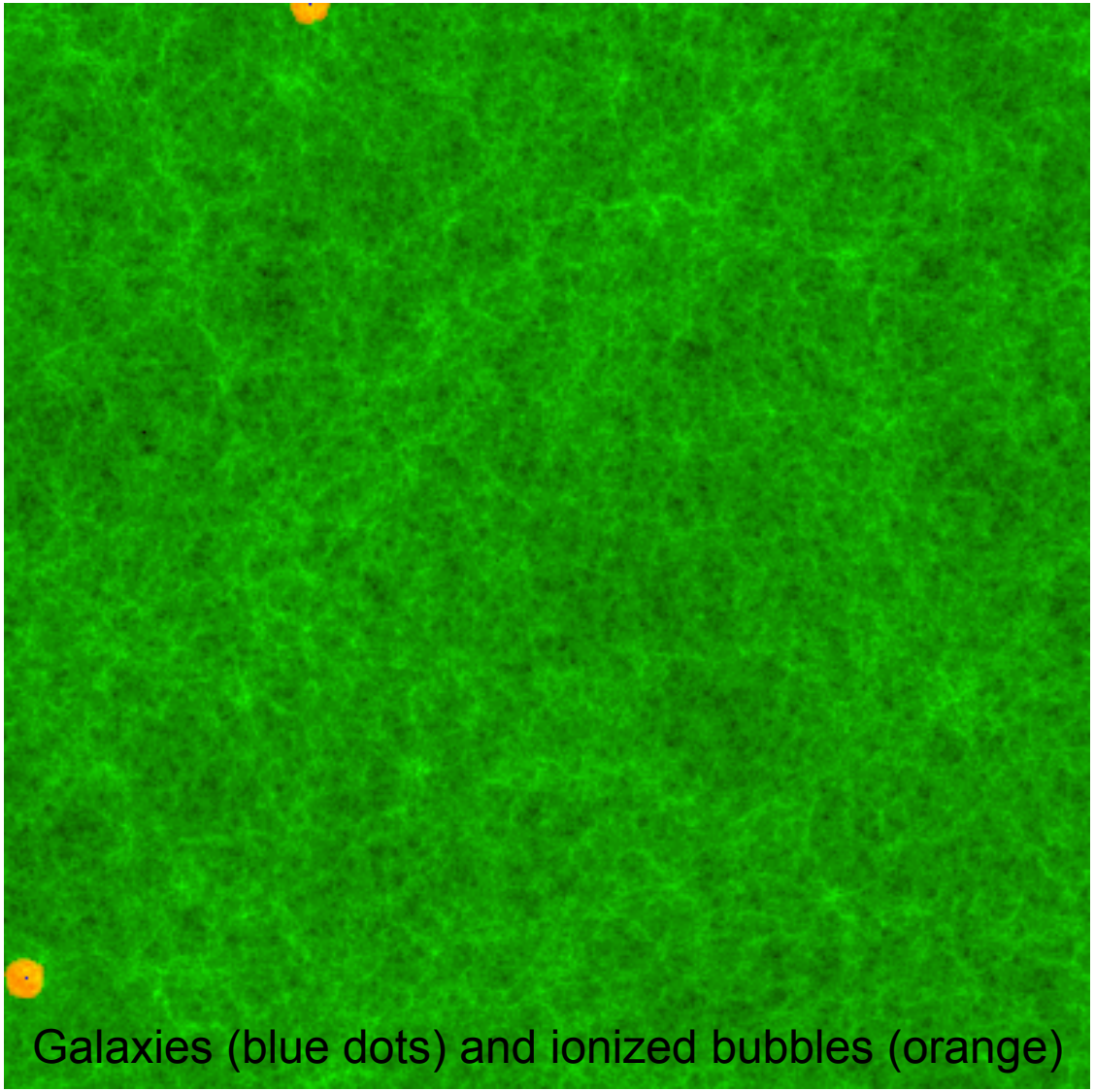




(Trac & Cen 2006)

- Theoretical models predict that 1st generation stars dominate to total SFRD at z~>10-15.

Cosmic reionization

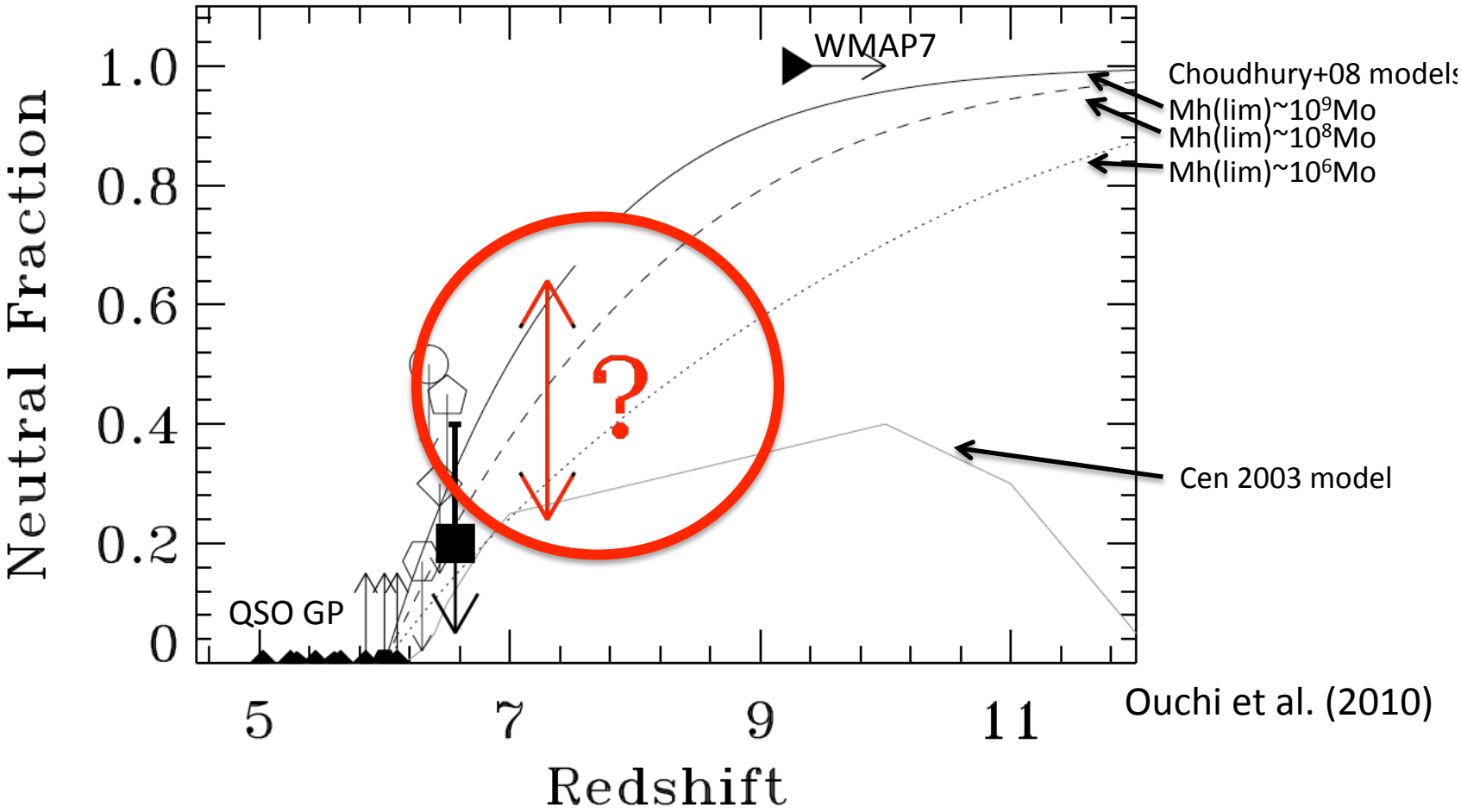


Galaxies (blue dots) and ionized bubbles (orange)

RT simulations (Iliev et al. 2006)

- Basic picture: Ionizing photons from star-forming galaxies make ionized bubbles that fill the universe-> reionization.

Open Question
Evolution of Neutral Hydrogen Fraction



Ouchi et al. (2010)

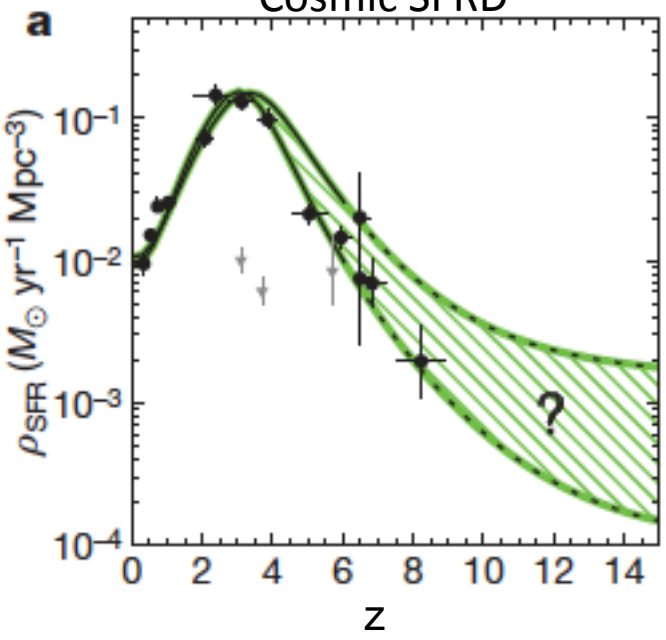
– z>∼6: reionization epoch (QSO Gunn-Peterson test)
– z∼10: CMB Thomson scattering optical depth

sharp reionization (e.g. Fukugita+94) or extended reionization (Dunkley+09)?

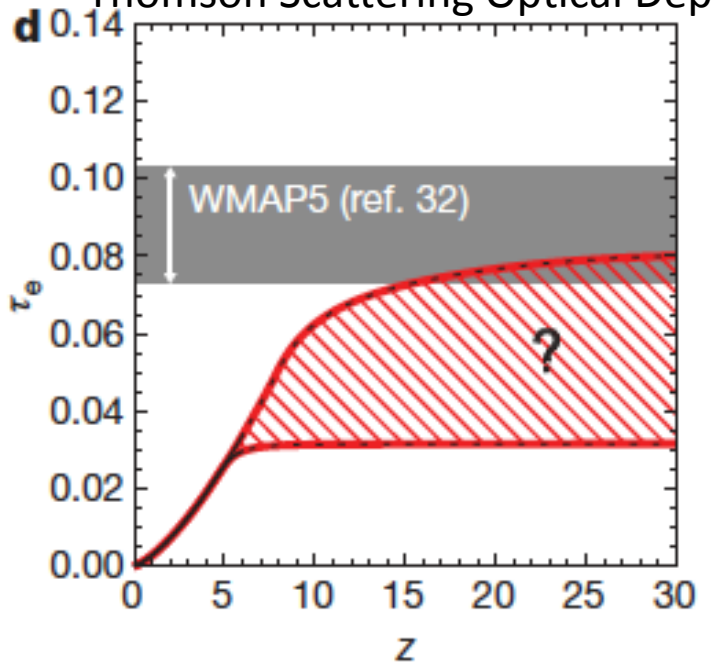
Probing z>~7 w/ spec. (near heart of EoR) to constrain reionization models.→very high-z. Not easy!

Missing Ionizing Photon Problem?

Cosmic SFRD



Thomson Scattering Optical Depth



Robertson+10

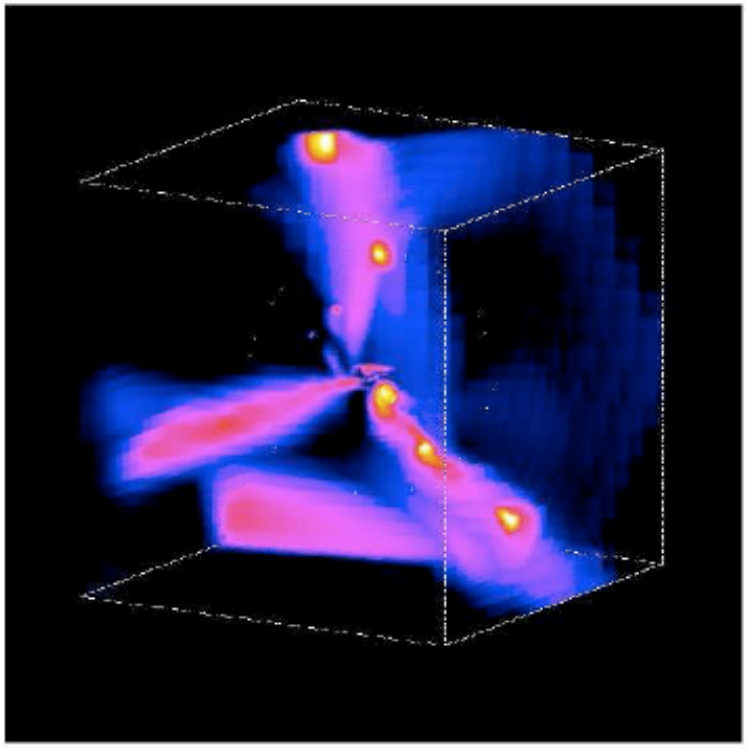
Estimating ionizing photon budget.

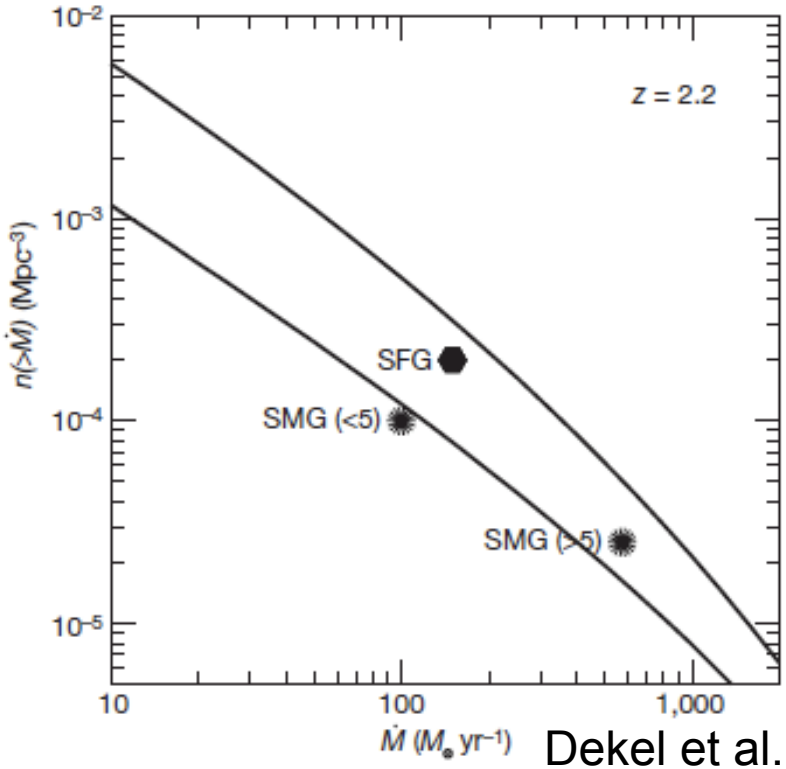
- SF history ($\propto \rho_{uv}$)→ ionizing photon rate (dN_{ion}/dt)
- Electron density, $n_e(z)$→ Thomson scattering τ_e
- τ_e from galaxies is smaller than τ_e from CMB measurement

Shortage of ionizing photons. Are ionizing photons missing?

Mass Assembly of Massive Galaxies

Cold accretion?



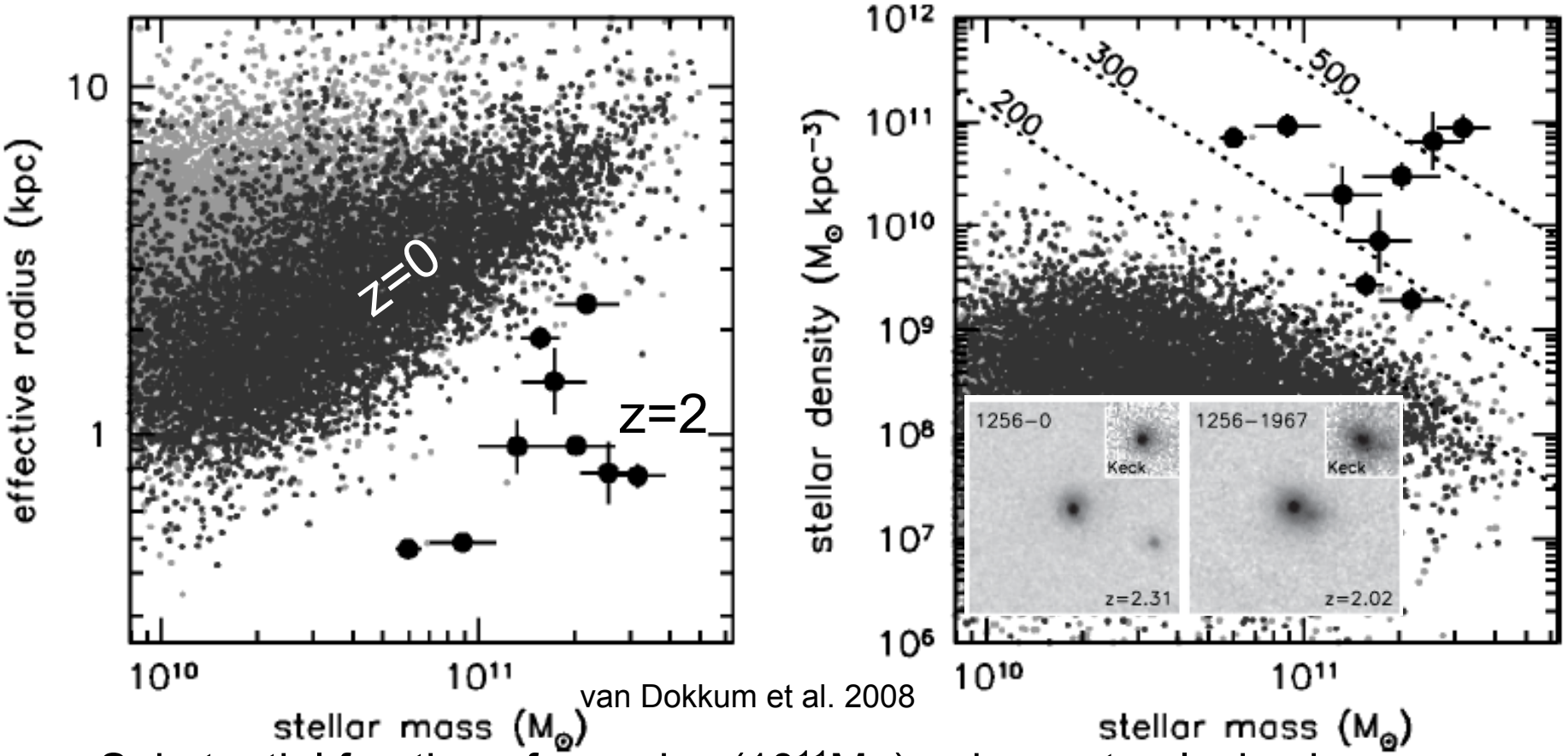


Dekel et al. (2009)

- Violent SF at z>2, but mostly no merger signatures
- Galaxies acquired most of baryon (~70%!) at z~2-3 via cold accretion (e.g. Dekel+09) ?
- Is this true? Any observational signatures?

- So far, no signature of cold gas accretion has found to date…
- Does cold accretion really exist?

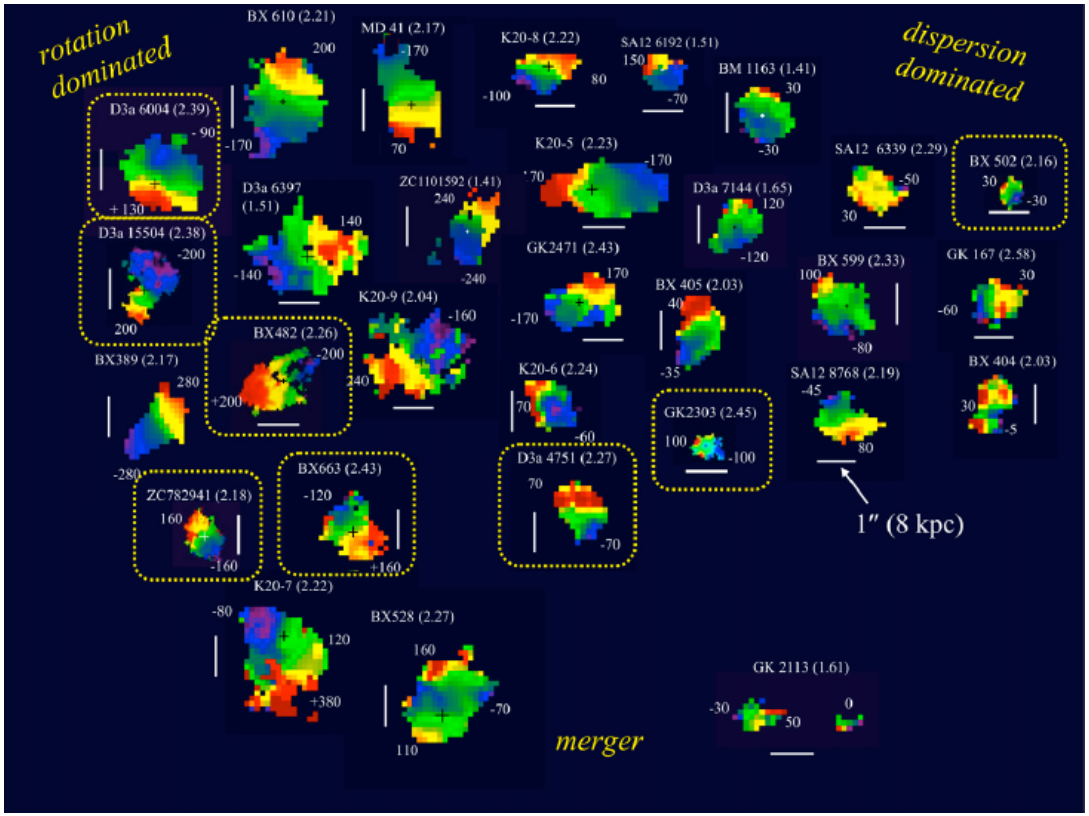
Compact Massive Quiescent Galaxies at z~2



van Dokkum et al. 2008

- Substantial fraction of massive (10^{11}Mo) quiescent galaxies have a compact size (r_e~1kpc; cf. 5kpc for the present-day ellipticals/S0s, 2.5kpc for Milky way/M31 bulges). [cf. Subaru/MOIRCS studies]
- Inside-out galaxy formation? What is the role of these compact massive quiescent galaxies at z~2?

Evolution of Galaxy Dynamics up to z~2 Revealed by IFS(+AO) Obs.



Foster Schreiber e al. 2009

- VLT SINFONI(+AO) ~60 galaxies at z~2 down to 1.5kpc.
- Rotation dominated (1/3), Dispersion dominated (1/3), and Mergers (1/3).

Open Questions

- Formation of first stars/galaxies (probably z>~10)
- Reionization history, sources of reionization?
- Reasons of inconsistent cosmic SFRD and SMD histories?
- Physical origins of downsizing?
- Cold accretion vs. mergers?
- Chemical evolution vs. fundamental mass-metallicity relation?
- Role of compact quiescent galaxies? Inside-out formation?
- When and how did disks and ellipticals form?
- Dynamical evolution?

- Origin of super massive blackhole (SMBH)
- Coevolution of galaxies and SMBHs

NEXT DECADES, 2010s, 2020s, AND BEYOND?

Astro2010 Survey

Executive Summary

The priority science objectives chosen by the survey committee for the decade 2012-2021 are 1 searching for the first stars, galaxies, and black holes; 2 seeking nearby habitable planets; and 3 advancing understanding of the fundamental physics of the universe. These three objectives represent a much larger program of unprecedented

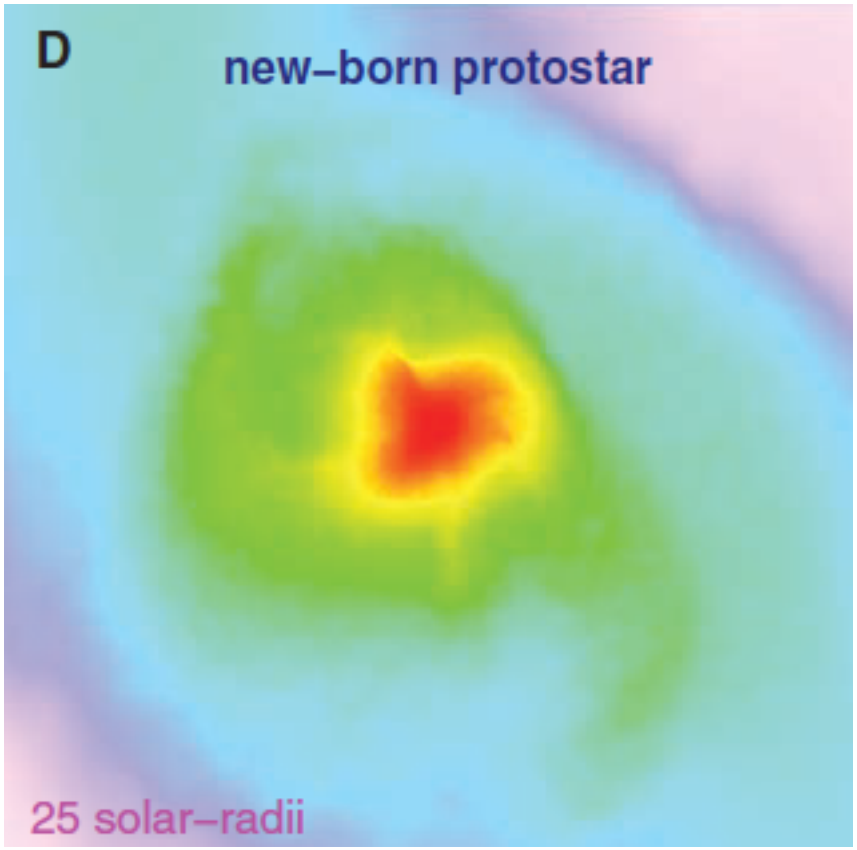
- Astro2010 Survey (National Academies in the U.S.)

Project List

- TMT
- 京都3.8m望遠鏡
- TAO
- 南極望遠鏡(2.5m赤外線望遠鏡）
- 東アジア天文台(2.5m光赤外チベット)
- PFS
- Subaru/GLAO
- SPICA
- JASMINE
- WISH
- JTPF
- Euclid/WFIRST

順序は光赤天連資料に従った

Identifying First-Generation Galaxies

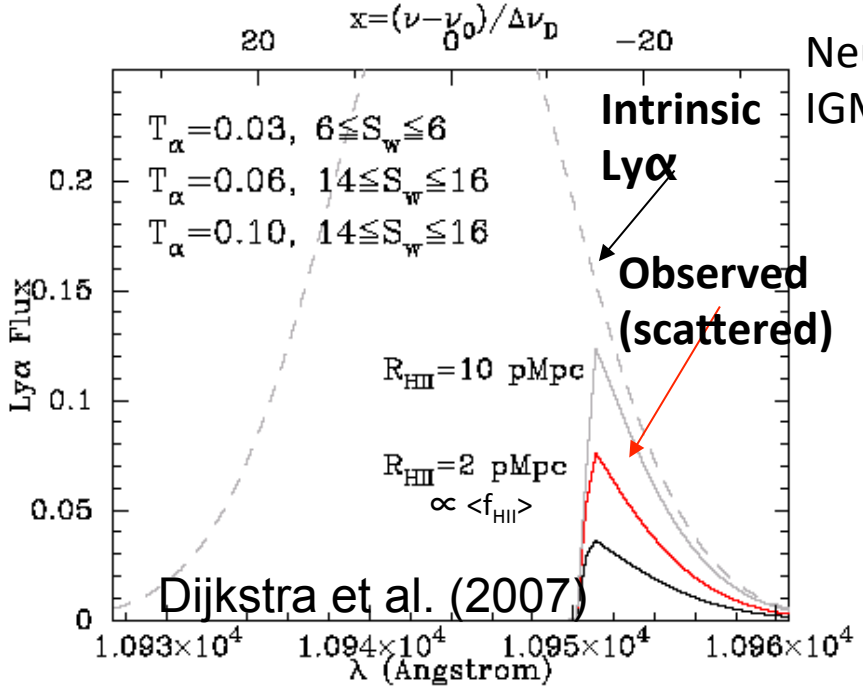


Theoretical prediction of the first-generation stars
(Yoshida et al. 2008; Temperature distribution)

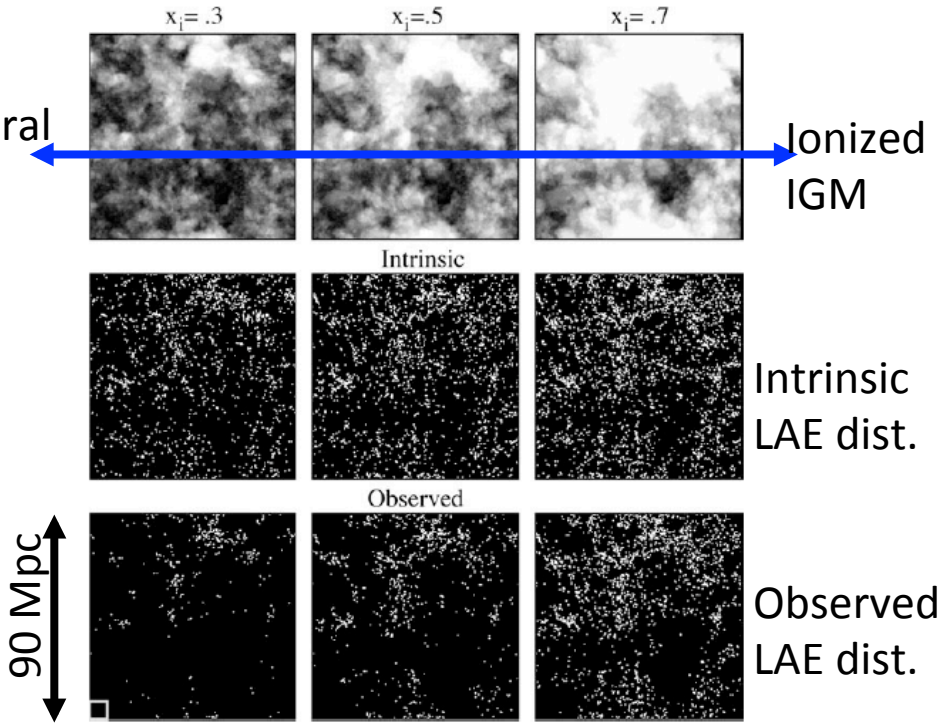
- Identification of first-generation stars/galaxies→ Exploring z>~10-15
- TMT (+other ELTs and JWST), WISH (up to z~10?)
  - Remaining issue: How can we distinguish between 1st and >2nd generation galaxies (too faint HeIIλ1640 indicator; Schaerer+03)
- Another possibility: SPICA H_2 observations up to z~3

Reionization History

- PFS: Clustering of Lya emitters at z=6-7. Reionization history and topology. Physical processes (inside-out, outside-in, filament-last?)



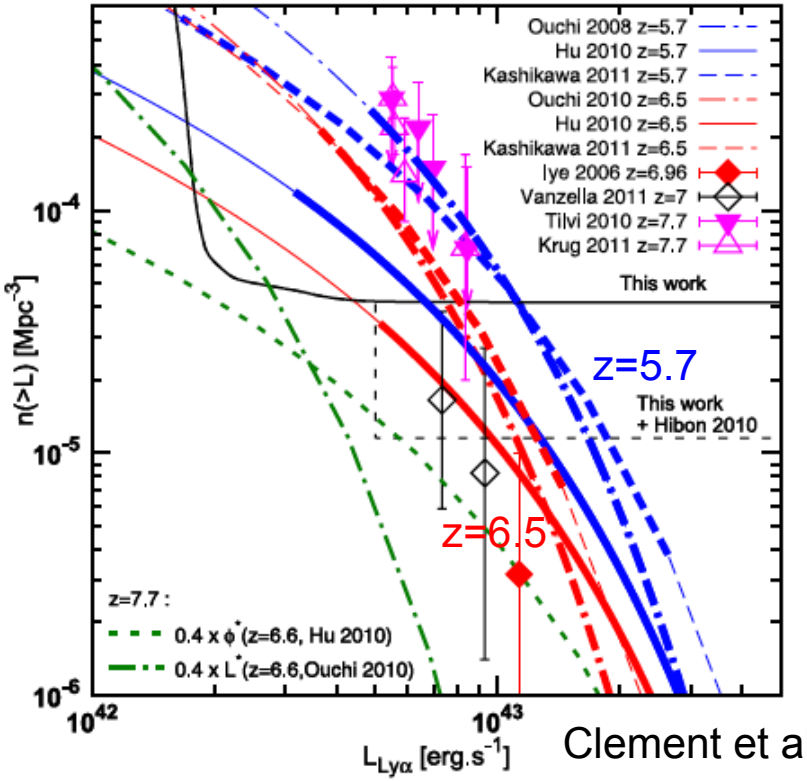
Lya damping wing scattering→ neutral hydrogen



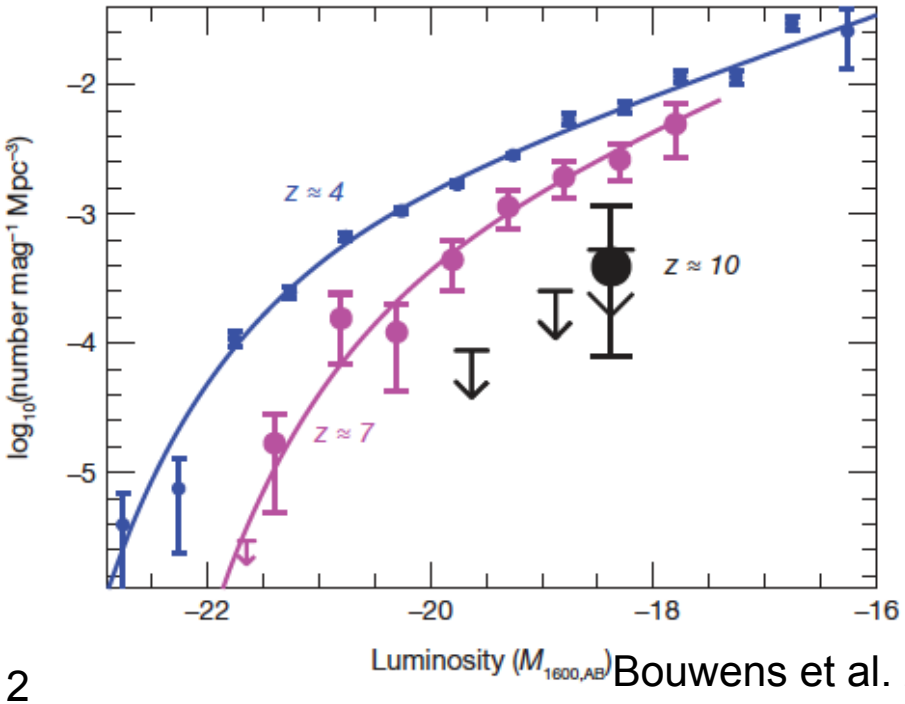
McQuinn et al. (2007)

LAEs in ionized bubbles can be observed→ Bubble topology by Clustering of LAEs

LF Evolution and Sources of Reionization



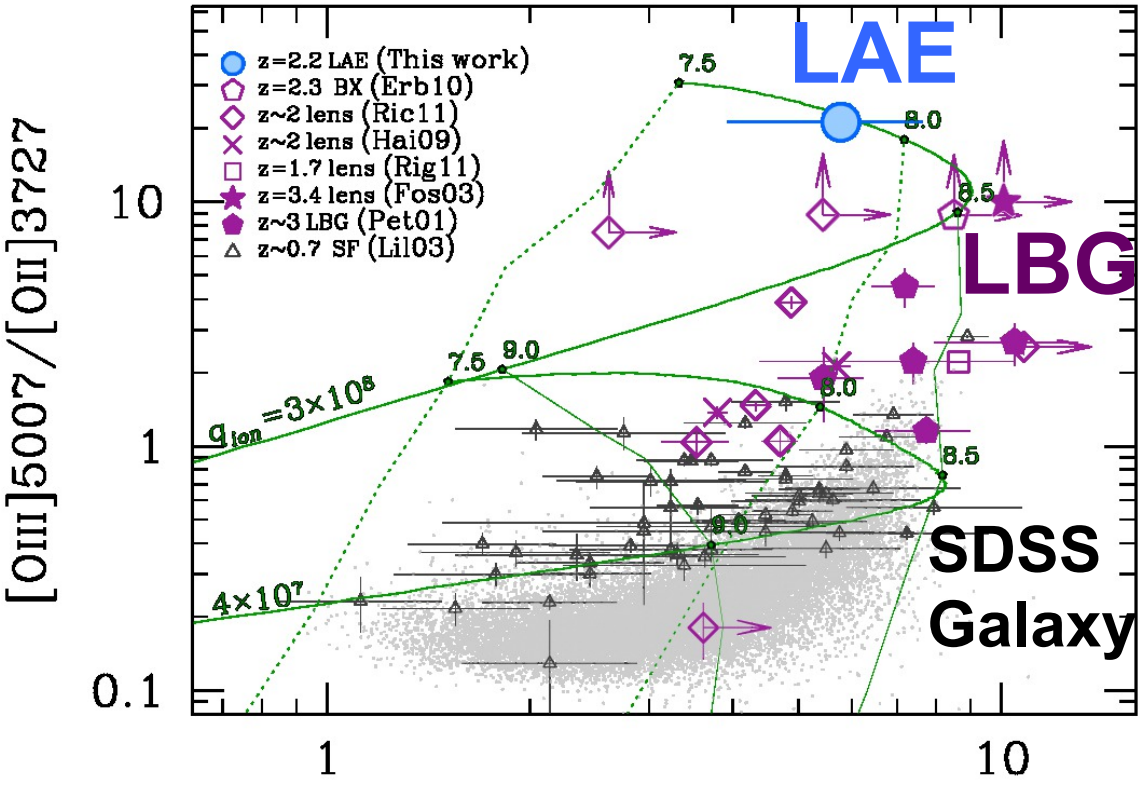
Clement et al. 2012



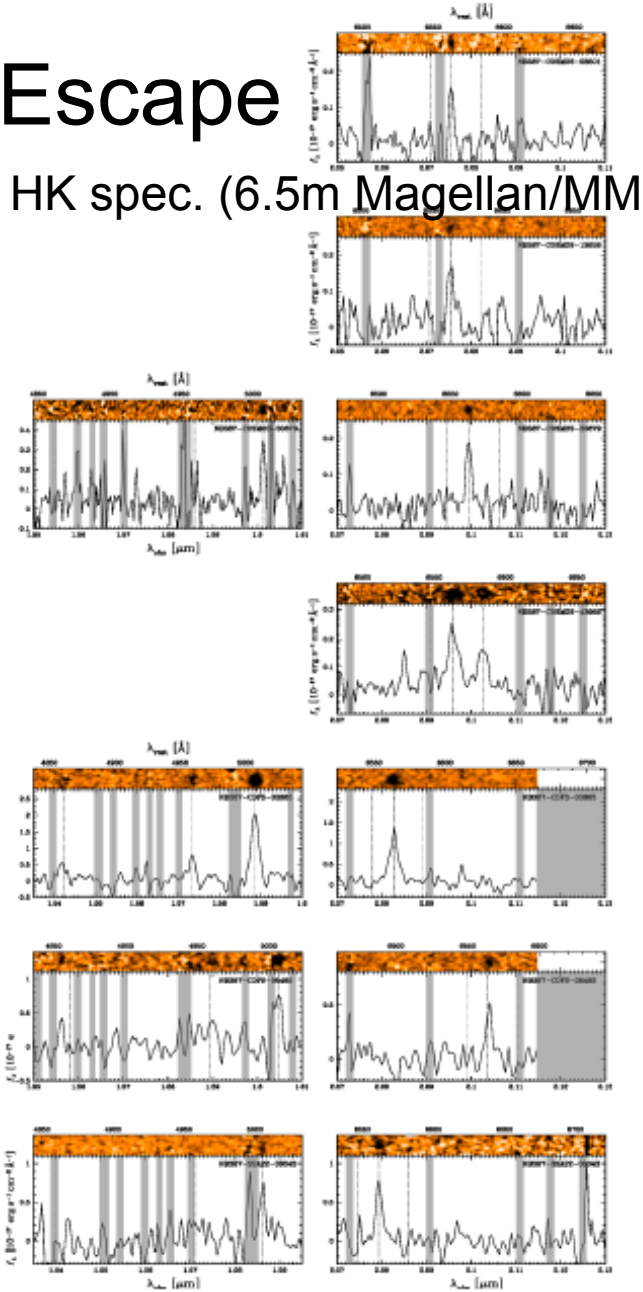
Bouwens et al. 2011

- TMT, WISH: Determining UV/Lya LFs down to ~-15mag and below (w GL) at EoR.
- Subaru/GLAO,EUCLID: Bright-end LFs up to z~7-8 Contribution of bright-faint galaxy for ionizing photon budget.

Ionizing Photon Production & Escape



Nakajima et al. (2012)



HK spec. (6.5m Magellan/MMIRS)

Hashimoto/Nakajima et al. 2012

- TAO, Subaru/GLAO,: Determining Ionization parameter(+metallicity)
- Also, cold accretion from the determination of Ha emission (NIR) (+UV metal absorption velocities; optical from PFS?).

Summary

- Review of 2000s studies
  → Open questions

Japanese OIR instruments in 2010s and 2020s

- Formation of first stars/galaxies (probably z>~10) (TMT [WISH/SPICA])
- Reionization history, sources of reionization? (TMT, WISH, Euclid-WFIRST, PFS, SPICA, TAO, Subaru/GLAO)
- Cold accretion vs. mergers? (TAO, Subaru/GLAO, PFS)
- Reasons of inconsistent cosmic SFRD and SMD histories?
- Physical origins of downsizing?
- Chemical evolution vs. fundamental mass-metallicity relation? (Subaru/GLAO, TAO)
- Role of compact quiescent galaxies? Inside-out formation?
- When and how did disks and ellipticals form? (TMT)
- Dynamical evolution? (TMT, Subaru/GLAO)

- Similar scientific goals, but different parameter space. Corporation and interaction between different projects are indispensable !