PFS Deep Survey
for
Galaxy Formation and Cosmic Reionization

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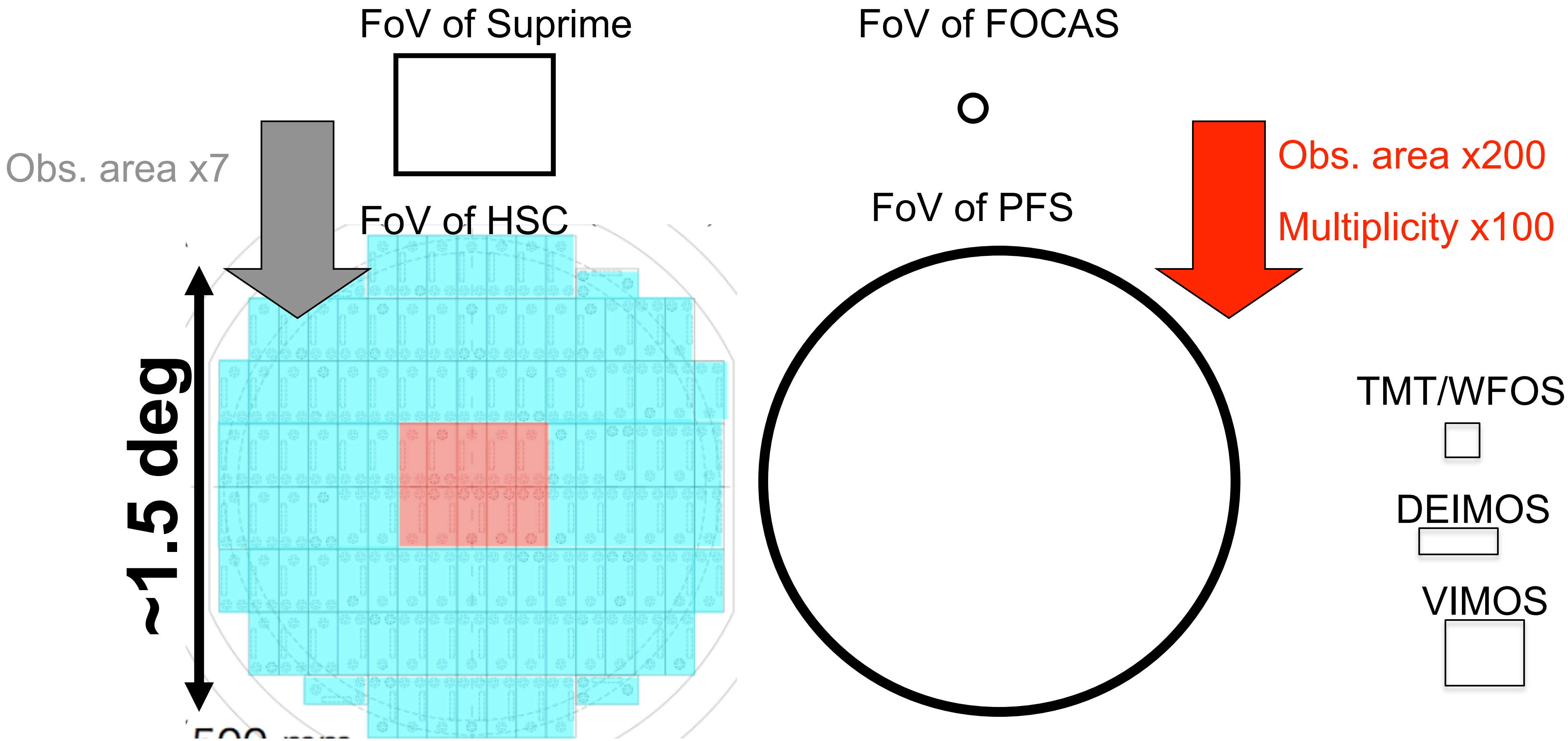
Prime Focus Spectrograph (PFS)



- Suprime-Cam→HSC (obs. area x7) from 2011-
- FOCAS→PFS (obs. area x200, multiplicity x100) from 2016?-

Complementary to the other 8m-telescope and ELT spectrographs

→PFS could revolutionalize spec. studies of highz galaxies reachable with >8m telescopes. No competing studies.

Magnitude limit surveys do not reach galaxies up to z~7

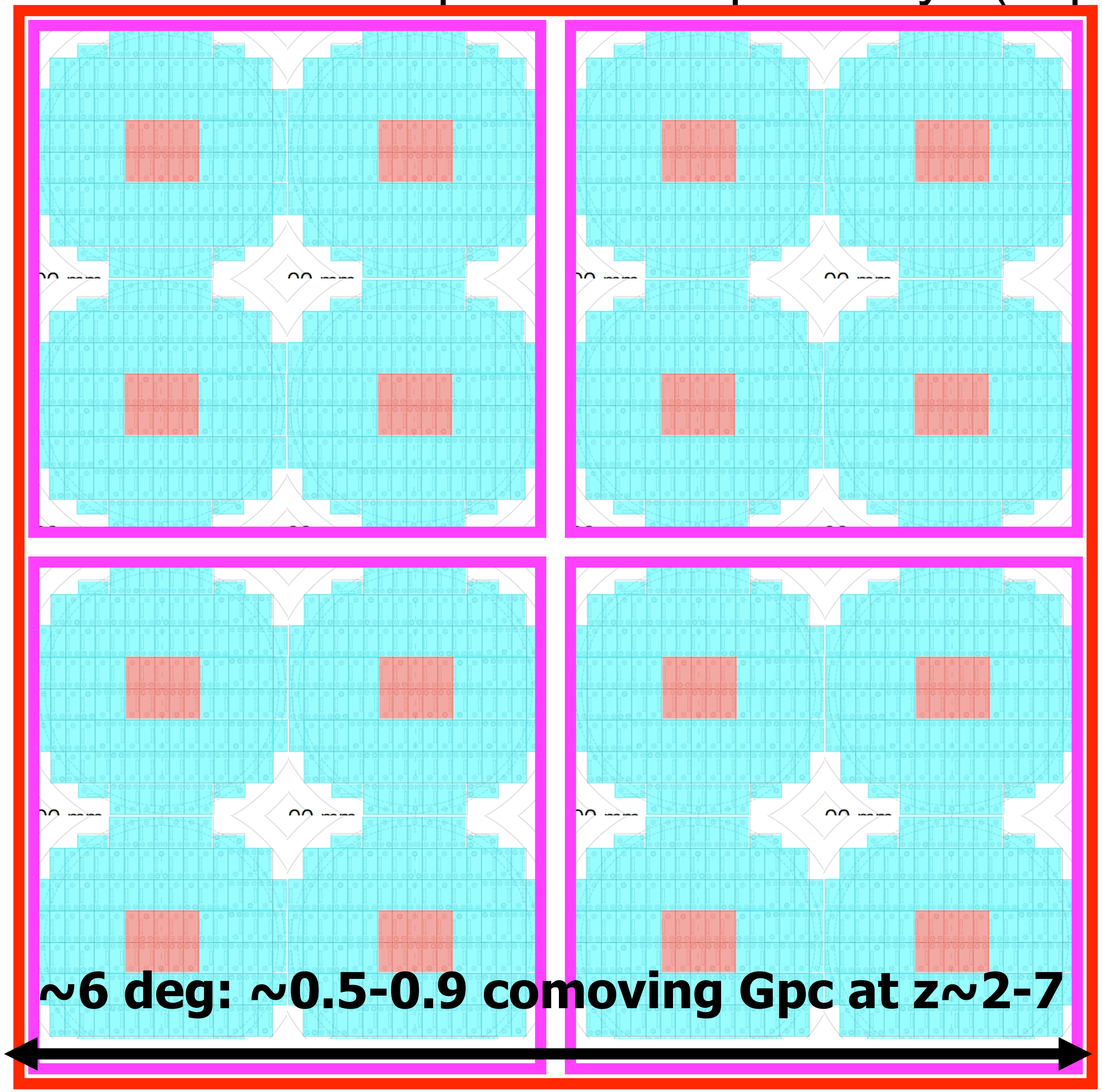
mag	N(1FoV)	Exp(total;hr)
$m_z<$ 23.0	76000	10
m_z=23.0-23.5	32000	11
m_z=23.5-24.0	45000	42
m_z=24.0-24.5	64000	128
total		191(hr)

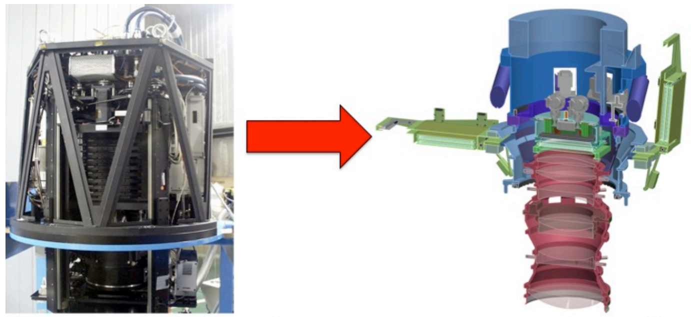
For 1 FoV(WFMOS) ~ 30nights (for 2008 WFMOS Kona meeting)

The brightest z~7 galaxy in 0.5 deg^2 have m~25.5 (Ouchi et al. 2009)

Targeting color selected galaxies for high redshifts

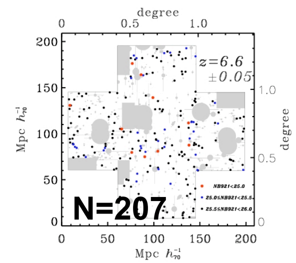
Perfect Targets Supplied from HSC Deep/Ultra-Deep surveys (Japan-Princeton-Taiwan)



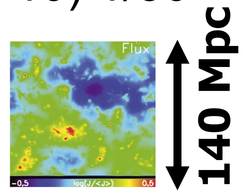


Suprime-Cam

Hyper Suprime-Cam(HSC; 2011-)



Present largest obs. (Ouchi+10) 1/30

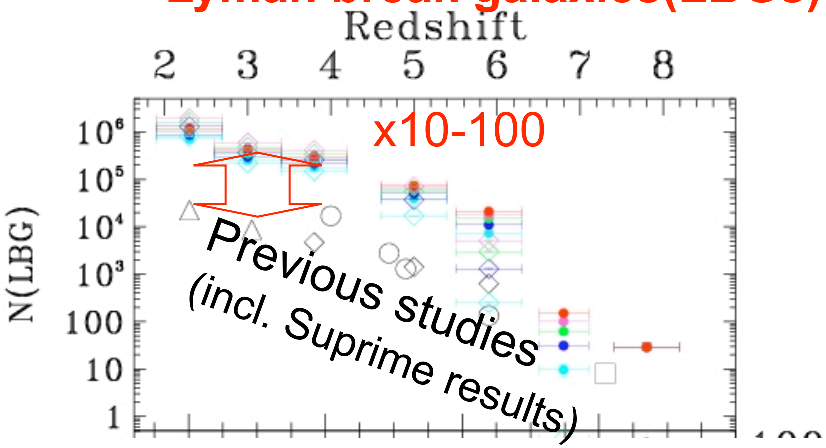


Current model (Mesinger+09)

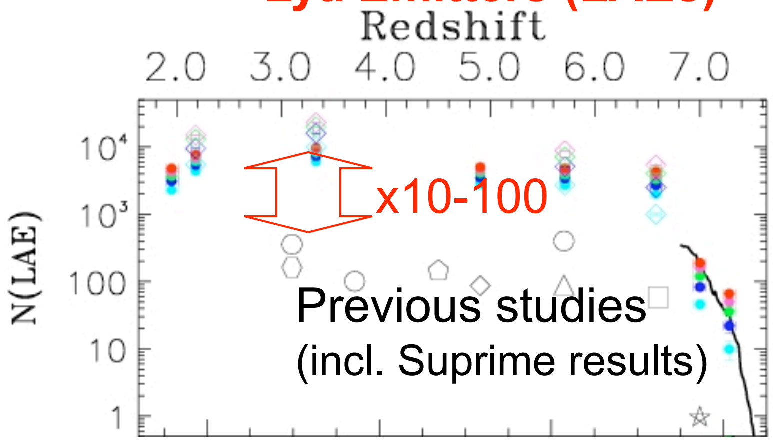
- High-z galaxies: Lyman break galaxies (LBGs) and Lya emitters (LAEs). Bright in optical bands→ Ideal for PFS optical spectroscopy. Nearly 'complete' spectroscopy down to a given UV-continuum magnitude or Lya flux.

Candidates from HSC (being designed)

Lyman break galaxies(LBGs)



Lya Emitters (LAEs)



Expected numbers of high-z galaxies (Ouchi+)

- Tentative plans
  - Deep survey (i~27mag, NB~25mag) for ~30deg^2
  - Ultra deep survey (i~28mag, NB~26mag) for ~3.5deg^2

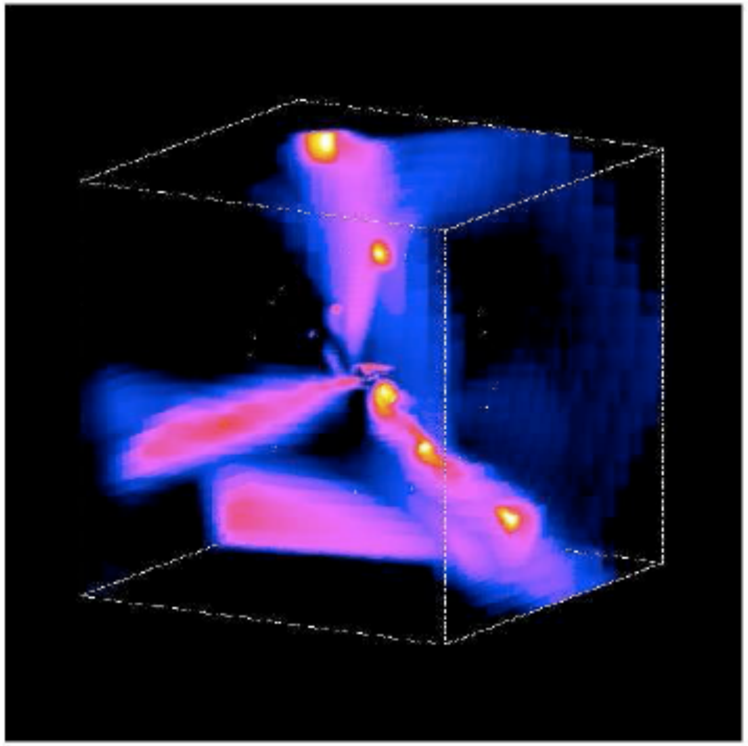
  →10k-1M LBGs and 1k-10k LAEs at z=2-7. # of galaxy candidates is boosted by 10-100x.
- 10-100 times more spec. targets will be waiting for spectroscopy. Large enough for PFS spectroscopy.

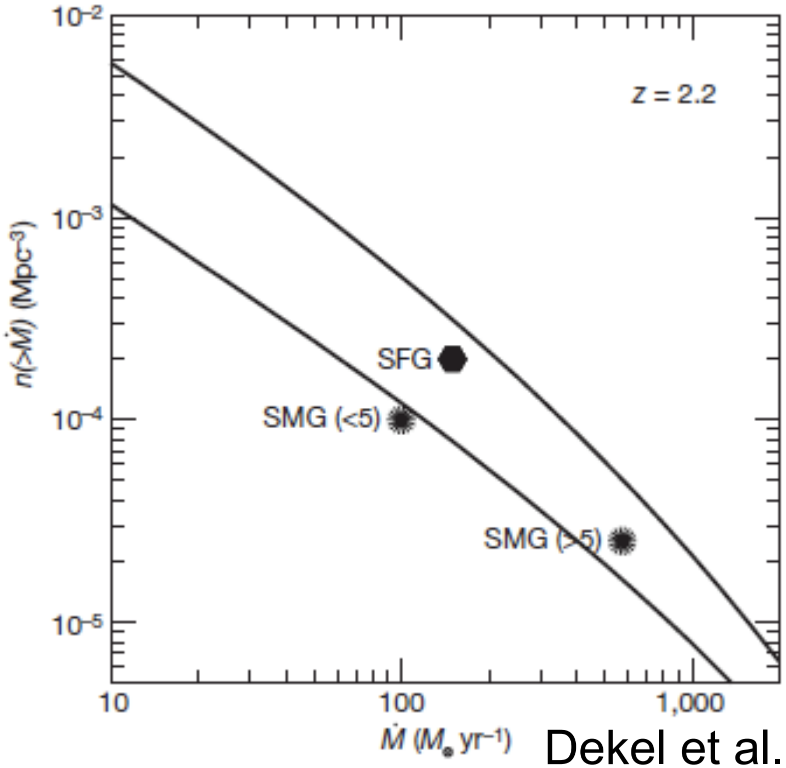
Deep PFS Surveys
Four Science Drivers (TBD)

1. Mass assembly of massive galaxies. What is the major process, accretion or mergers? Is stellar (or dark mass) assembly first?
2. Chemical and dynamical evolution of intense star-forming galaxies
3. Galaxy, AGN, and proto-cluster formation in large scale structure at early stage
4. Cosmic reionization probed with galaxies

1) Mass Assembly of Massive Galaxies

Mergers or cold accretion?

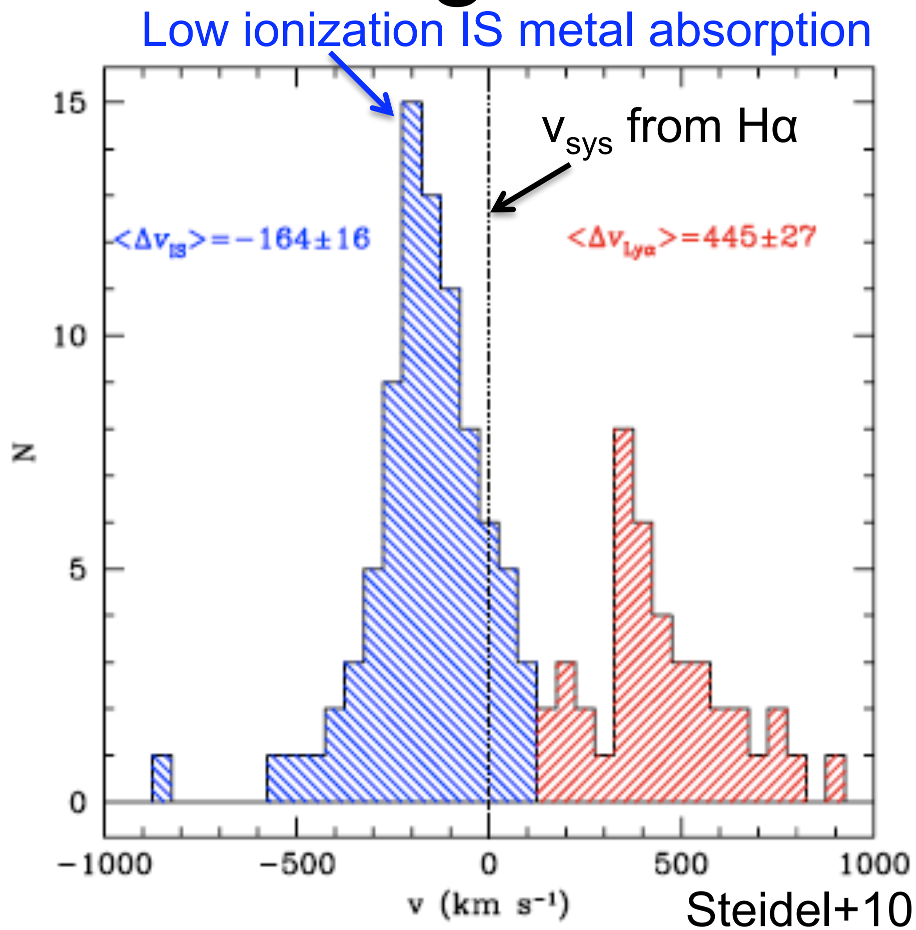




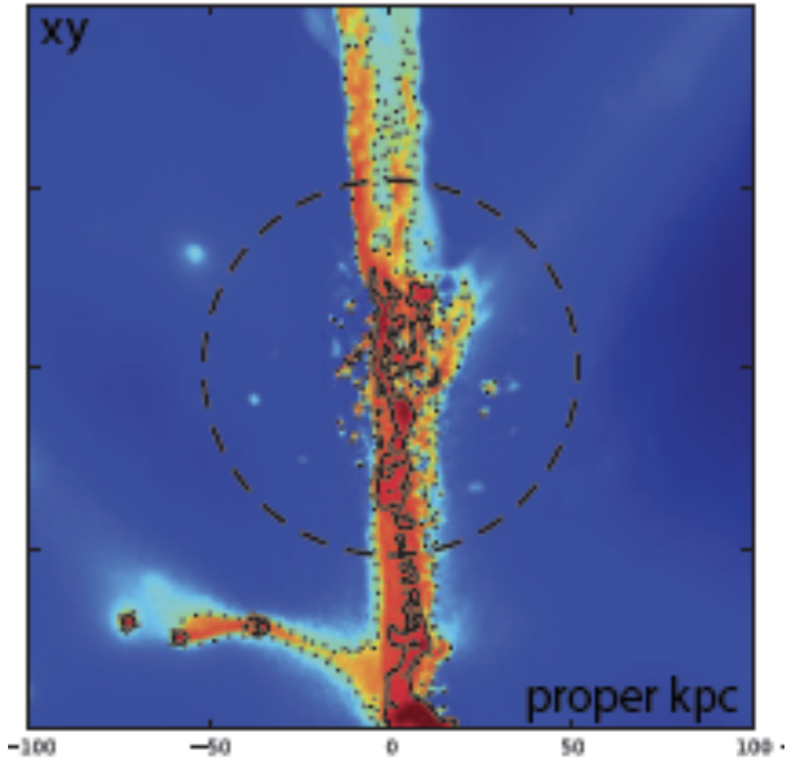
Dekel et al. (2009)

- 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. Katz+03, Keres+09, Dekel+09) ?
- Is this true? Any observational signatures?

Testing Cold Accretion Hypothesis



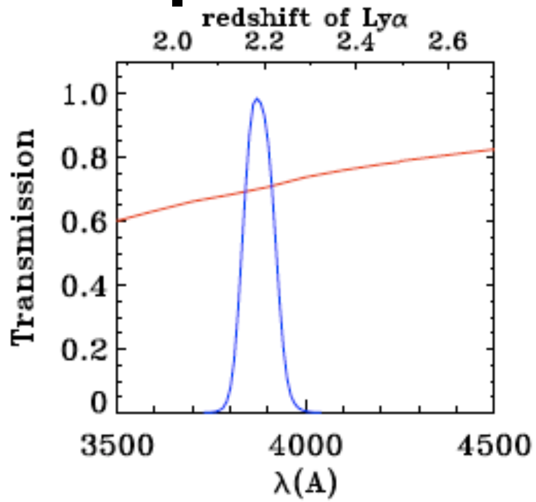
Steidel+10

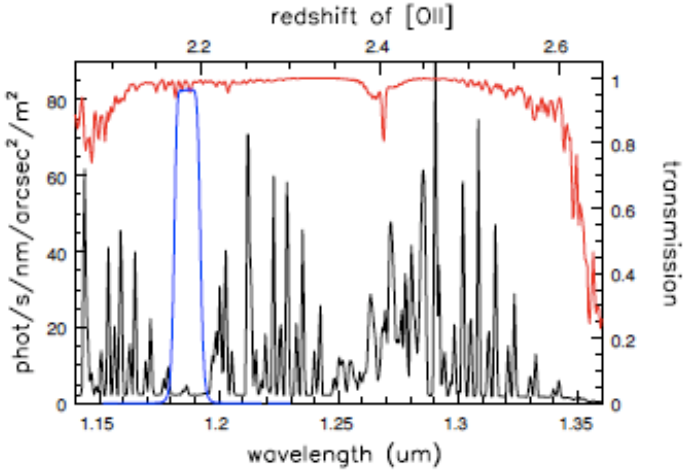


Faucher-Giguere+10

- No signature of cold gas accretion, but outflow based on 89 LBGs at z~2, (Steidel et al. 2010).
- But, consistent with cold accretion models, because a covering factor of cold accretion gas is very small ~1-2%(Faucher-Giguere+10), and a signal can be obtained when a cold filament is exactly aligned with the line of sight, Kimm +10).→need very large optical+NIR spectroscopic sample of LBGs

1) Targeting LBGs at z=2.1-2.4 Sweet Spot of PFS Galaxy Survey





- Three channels; Blue(3800-6700A), Red(6500-10000A), and IR(10000-13000A)
- Blue+IR channels→ UV spectra (Lya, IS absorption lines) and [OII] lines for LBGs at z=2.1-2.4.

1. Absorption lines in UV cont and Lya → inflow/outflow indicators
2. [OII] lines→ systemic velocities

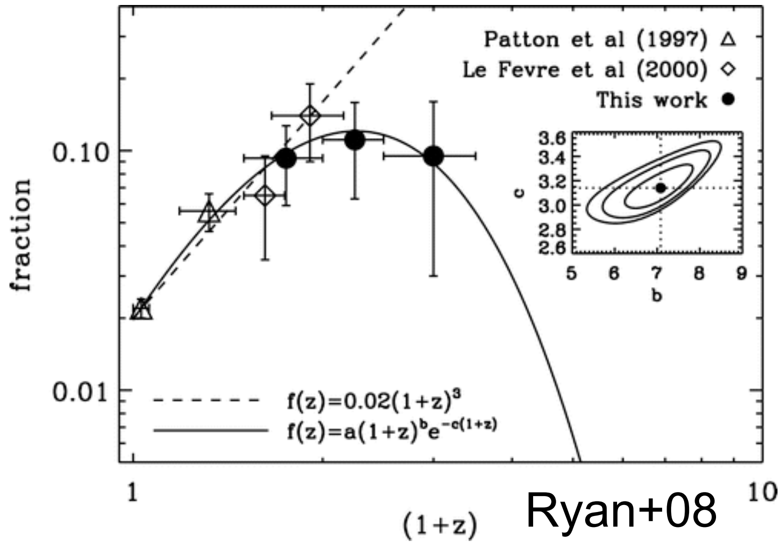
Signature of cold accretion and/or constraints on a covering factor of accretion gas with a 10-100x larger sample than prev. study

Major Mergers

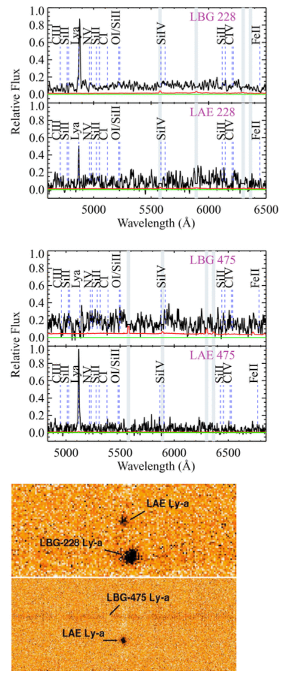
Driving mechanism of galaxy evolution in hierarchical structure formation
Relates to starburst, AGN activity, formation of early-type galaxies

Few measurements at z>1 using close pairs
(eg, Ryan+08, Bluck+09, Cooke+10)
very small statistics
mostly based on phot-z

cf. method using morphology
is complementary but has
a limitation



Ryan+08



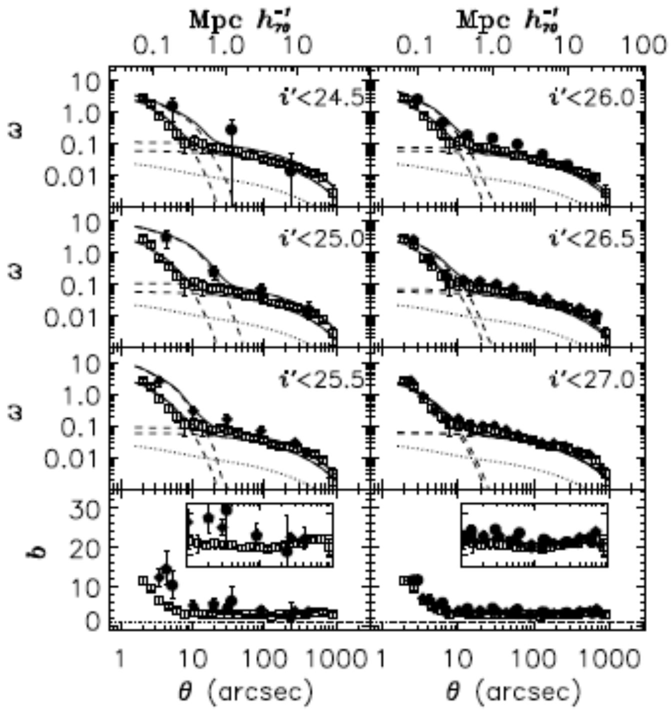
Cooke+10

Study with PFS

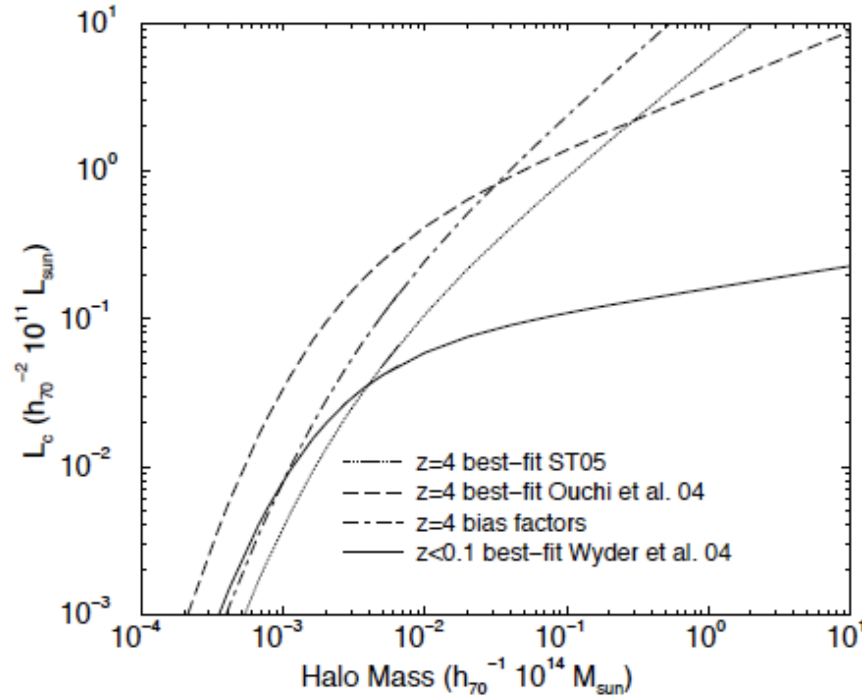
Identify physically associated close pairs from large LBG+LAE samples. (Exploiting the positive correlation of stellar-mass and UV luminosity, e.g. Papovich+01,Yabe+09)

- N~1000 close pairs with spec-z
- merger fraction at different z, SFR, stellar mass

Dark mass assembly: connecting stars (baryon) and dark halos



z=4 LBG correlation function fit by HOD model (Ouchi+06,Hamana+06)

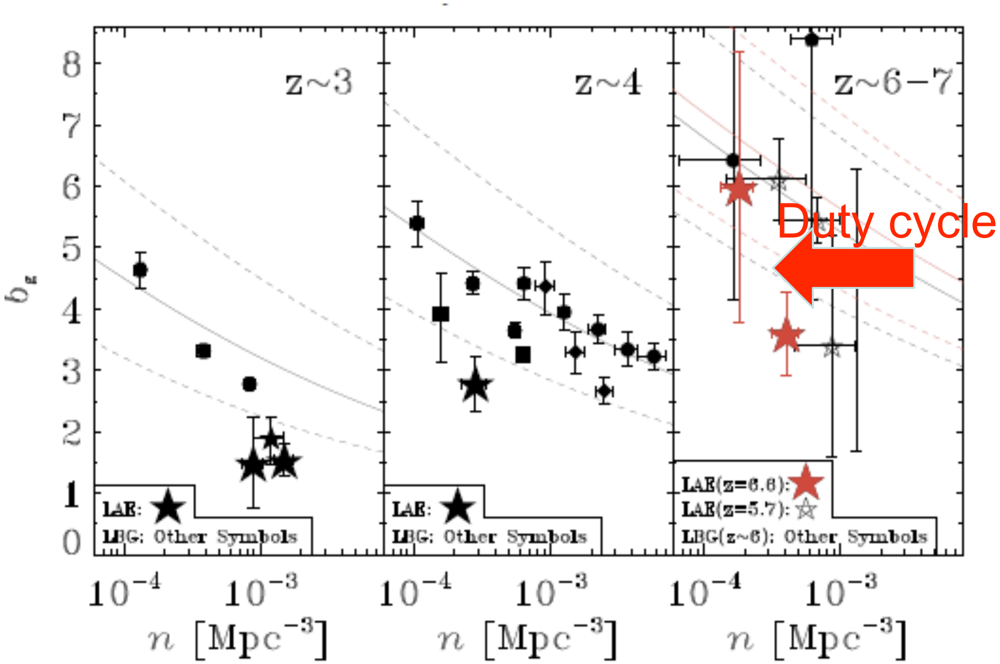


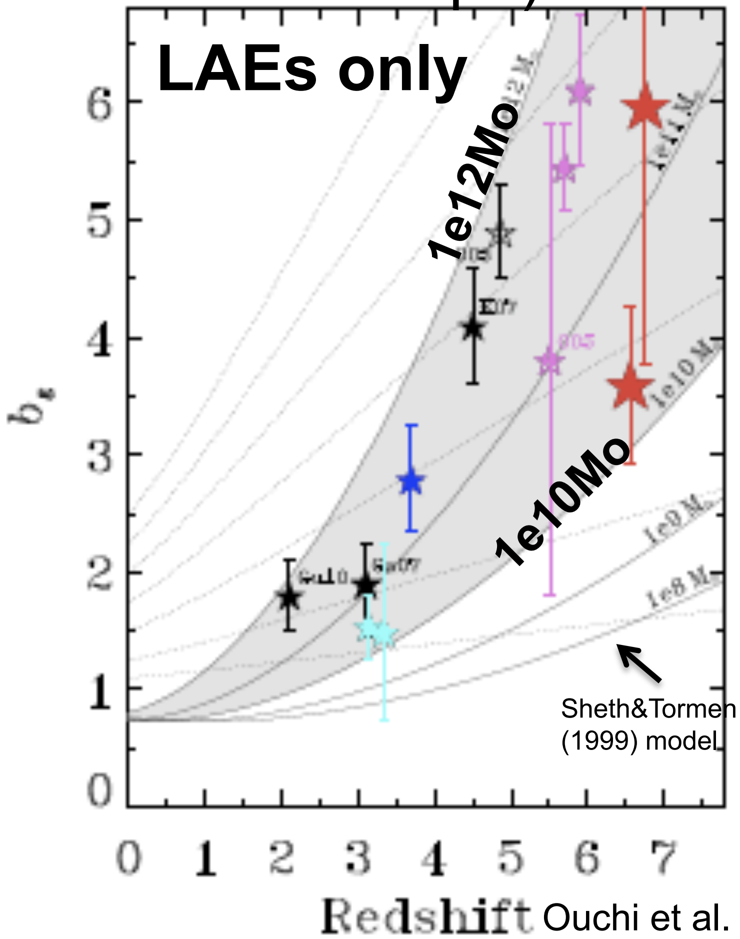
z=4 Mass-luminosity relation by conditional luminosity func. model (Cooray&Ouchi 06)

- Precision measurements of LF and CF
  - Largest uncertainties→ sample contamination and N(z)
  - Constraining star-forming galaxies with numerical simulation, halo occupation distribution (HODs) and conditional luminosity func. models

Star-Formation Duty Cycle

(intermittent SF history for stellar-mass buildup?)

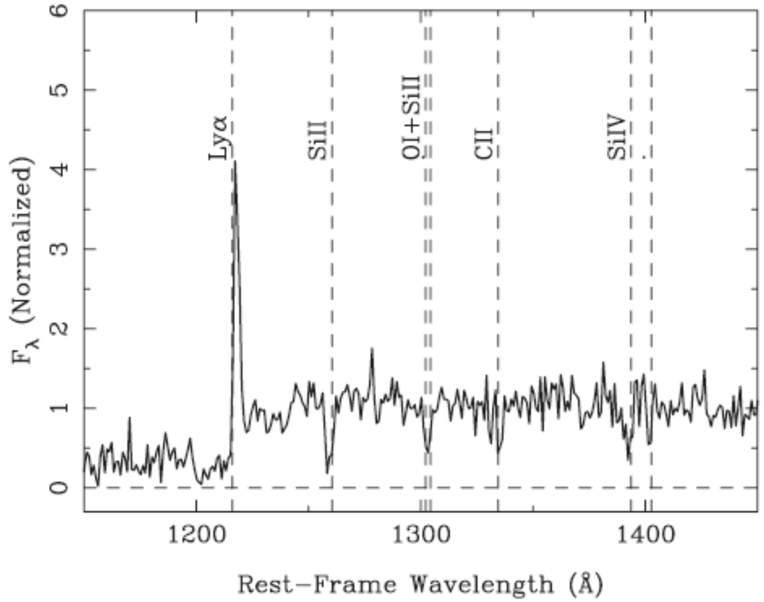


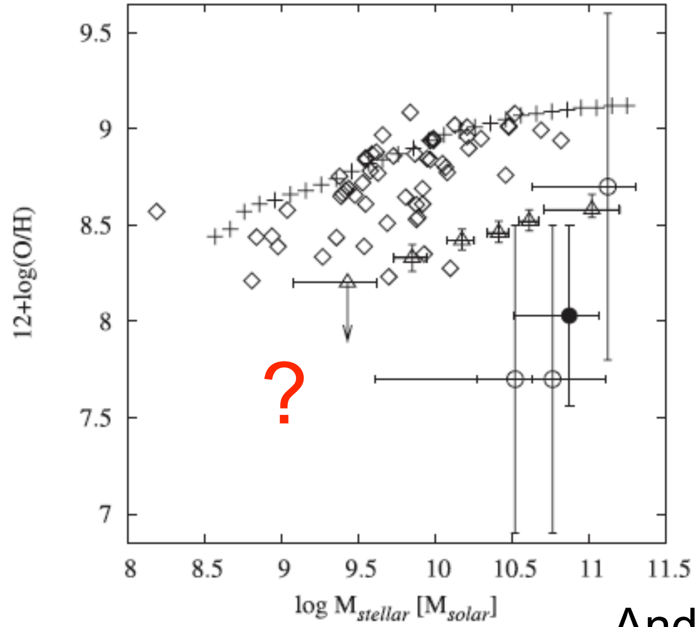


Ouchi et al. (2010)

- Precision measurements of high-z galaxy luminosity function and correlation function.→ hosting halo mass+HOD+duty cycle (Ouchi et al. 2004, Lee et al. 2009, Ouchi et al. 2010)
- Halo mass determination (just an accuracy of an order-a factor of ~5)
- Duty cycle of dropout and Lya emitting population is ~10% and ~1%, respectively (just an accuracy of an order). Constraints on SF history and Lya production mechanism.

2) Constraints on Metallicity at z~2-6 with Metal Absorption Lines

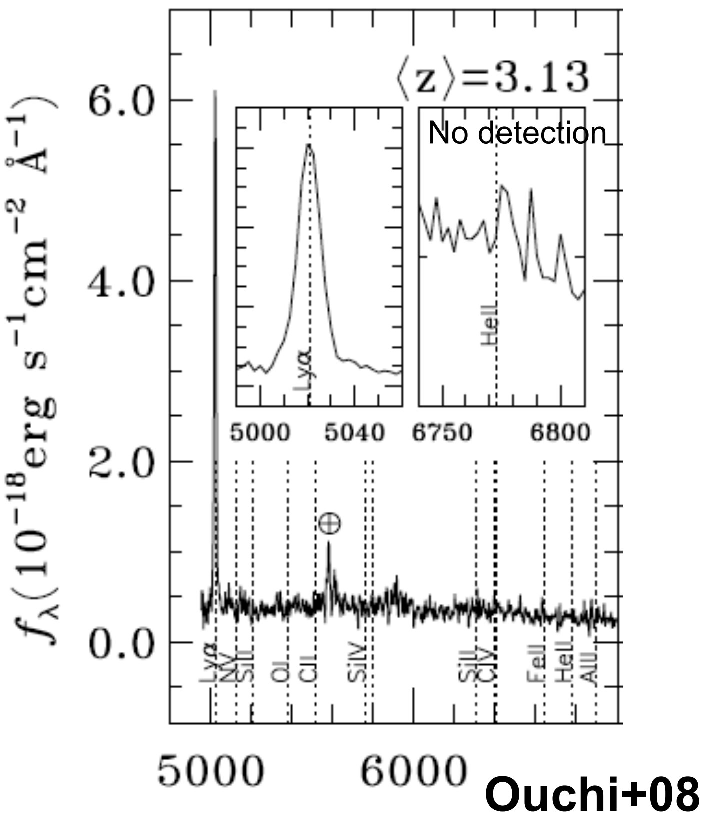




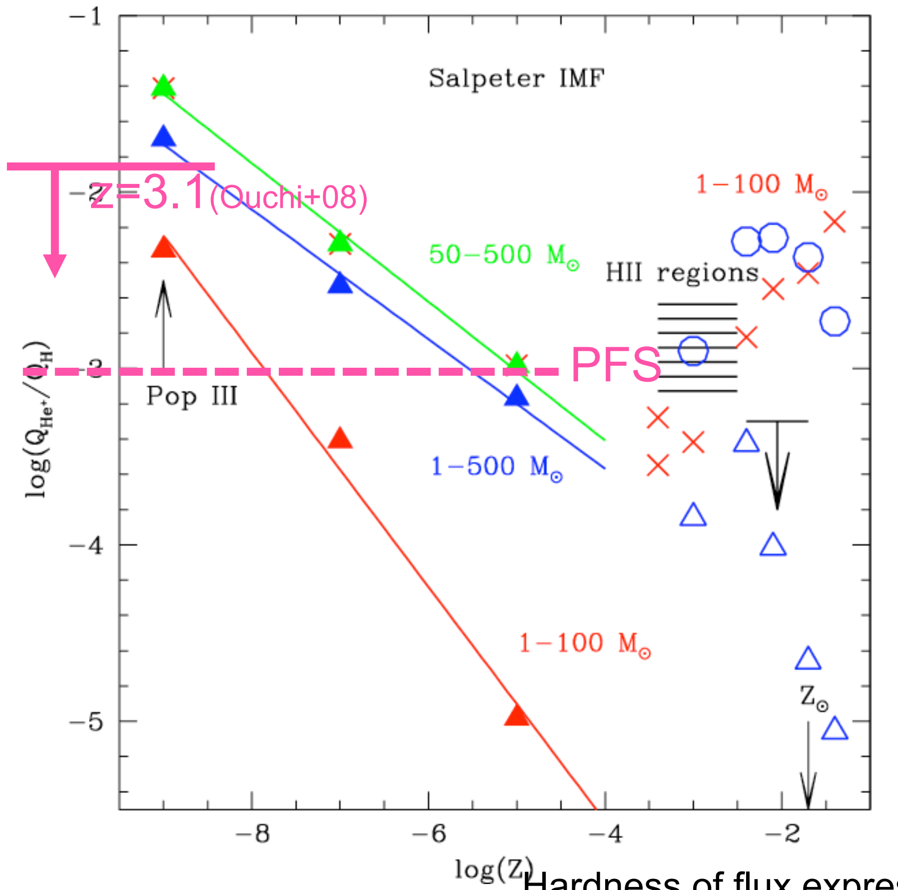
Ando et al. (2007)

- Metallicity estimated from low-ionization IS lines (Heckman et al. 1998), CIV-index (Mehlert et al. 2003) etc.
- Composite spectra of very faint LBGs→ metallicity of very faint/less-massive galaxies (~300 m telescope science)
- Complementary to ELT(z<2-4) and JWST(bright) studies

2) Do z~2-7 Galaxies include PopIII starbursts?



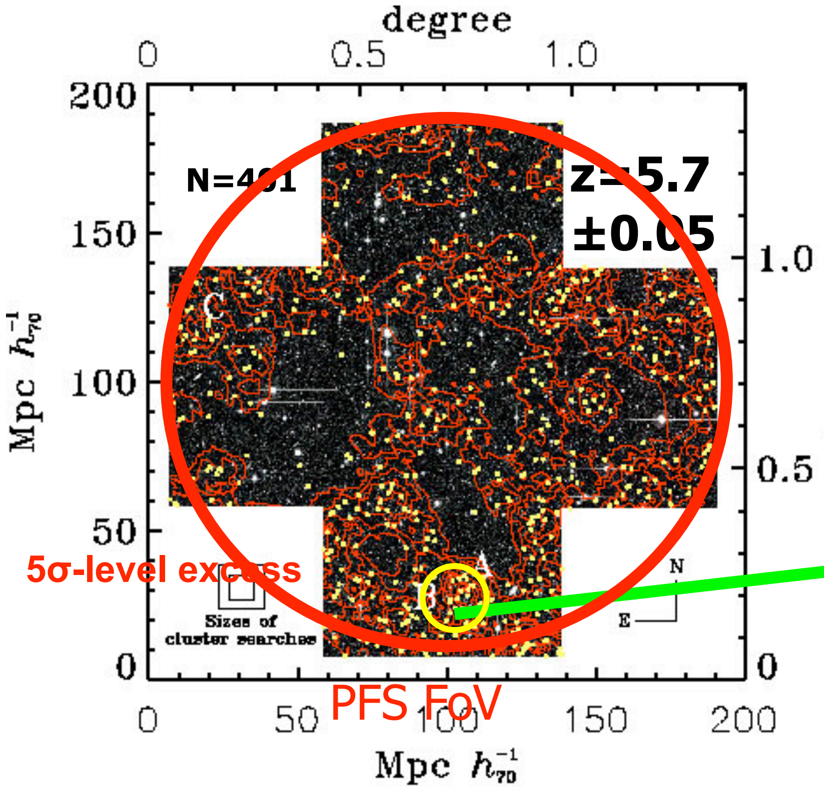
Ouchi+08

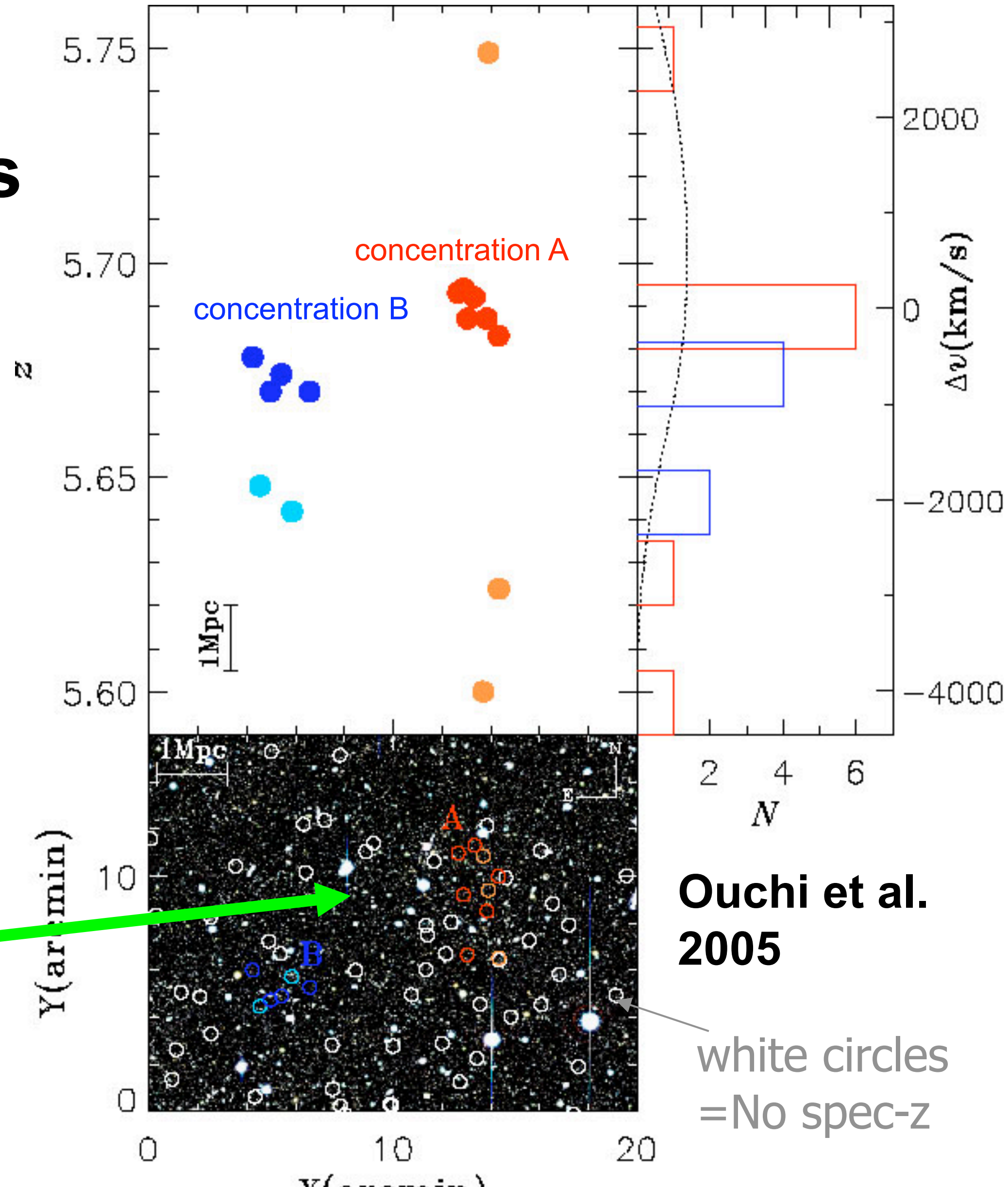


Hardness of flux expressed by the ratio of He+ to H ionising flux (Schaerer 2003)

- HeII is an indicator of forming galaxies (ionized by massive stars).
- Composite spectra→no HeII emission (no signature of popIII/cooling radiation)
  - 3σ upper limits: f(HeII)/f(Lya)< 2% at z=3.13 (Ouchi et al. 2008)
- No signatures of popIII SF.
- PFS observations for 10k high-z galaxies→ identifying popIII SB comp. with a top heavy IMF.

3) Large-scale structures and proto-clusters at z>4

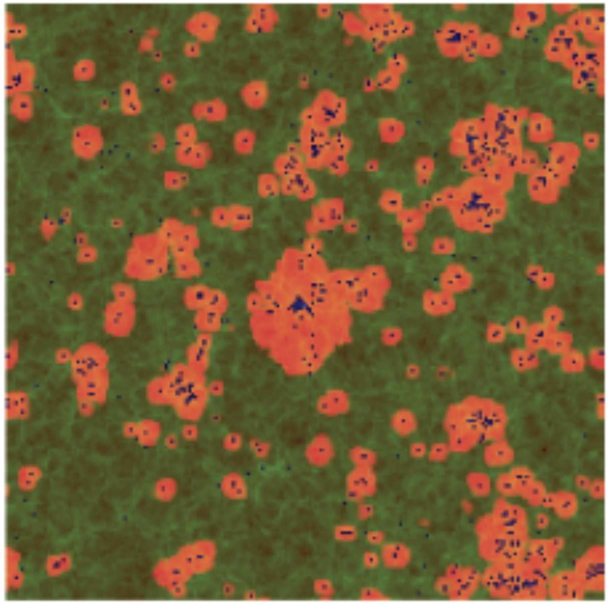




- Searching for large-scale structures and proto-clusters in a volume 100 x larger than the previous Subaru surveys. (cf. the filamentary LSSs+proto-cluster at z~3-6 Shimasaku+03, Hayashino+04, Ouchi et al. 2005). (100 proto-clusters at z~5-6)
- 3D maps of high-z universe for charting large scale structures

4) Cosmic Reionization
Tight Relation with Galaxy Formation

Reionization

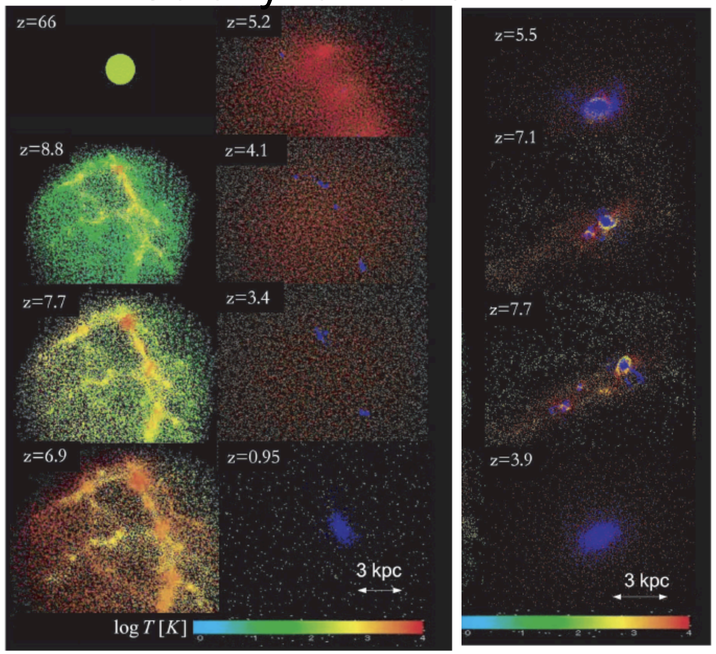


Ionized IGM(orange), neutral IGM(green), and Galaxies (blue)

Ly-continuum photons to ionize the universe

Intense UV background to suppress dwarf-galaxy formation

Galaxy formation

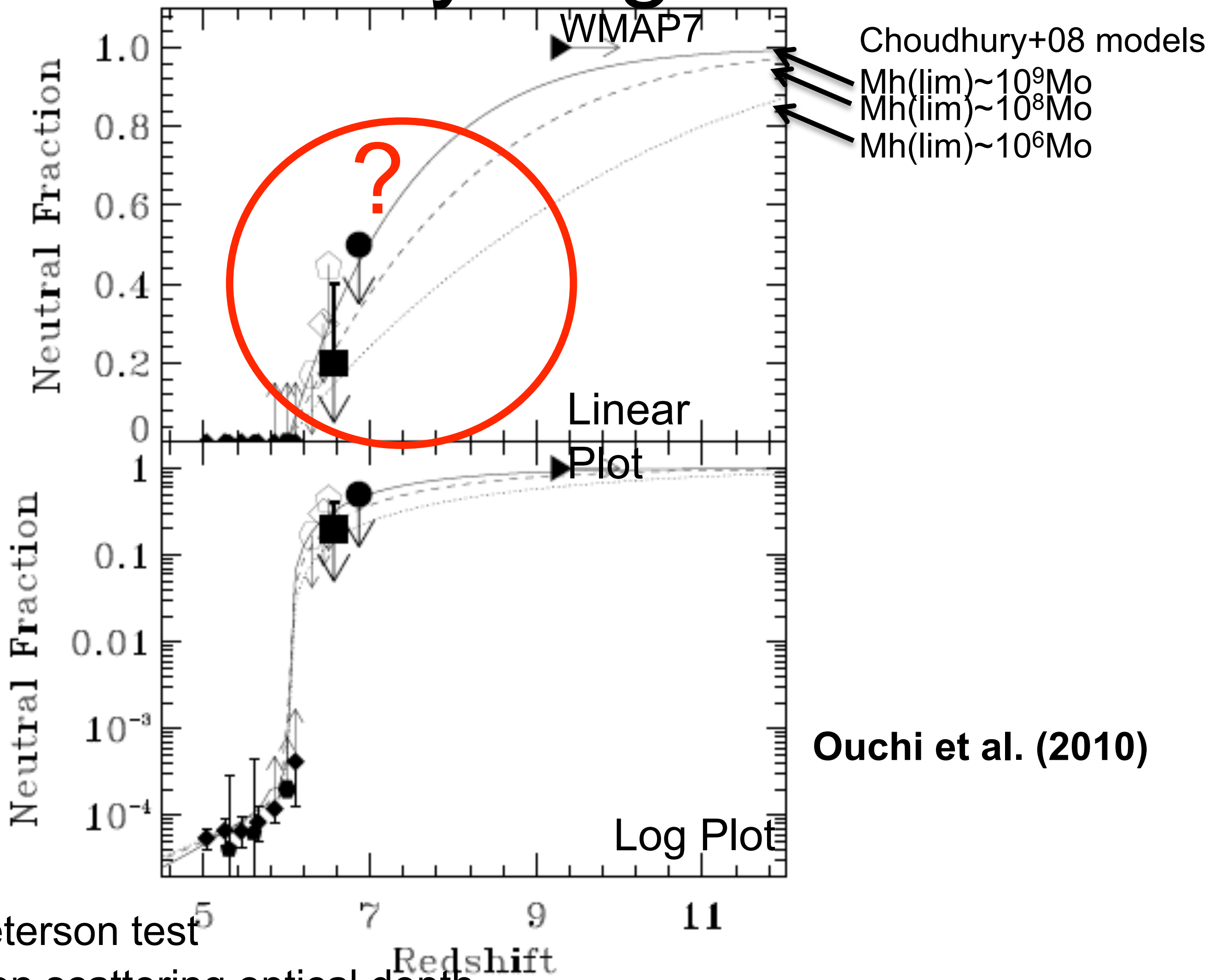


M(halo)=6e7 Mo
z_c=1.7

M(halo)=6e8 Mo
z_c=7.6

Susa & Umemura+04

Open Questions (1)
Evolution of Neutral Hydrogen Fraction



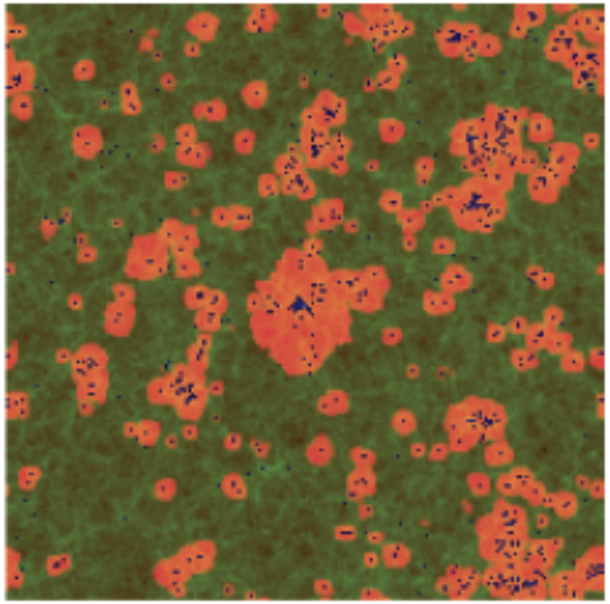
Ouchi et al. (2010)

- z∼6: QSO Gunn-Peterson test
- z∼11: CMB Thomson scattering optical depth

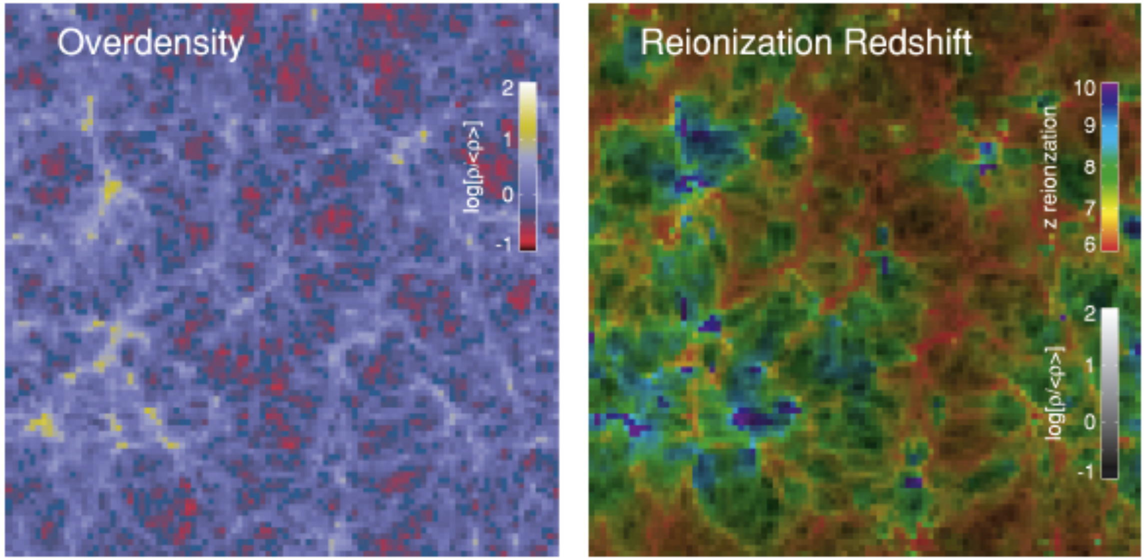
sharp reionization or extended reionization (Dunkley+09)? ? Is significant minihalo (Mh~10^6Mo) contribution (Choudhury+08) required??

Open Questions (2)
Ionization process

Inside-out? Outside-in?



Or filament-last?

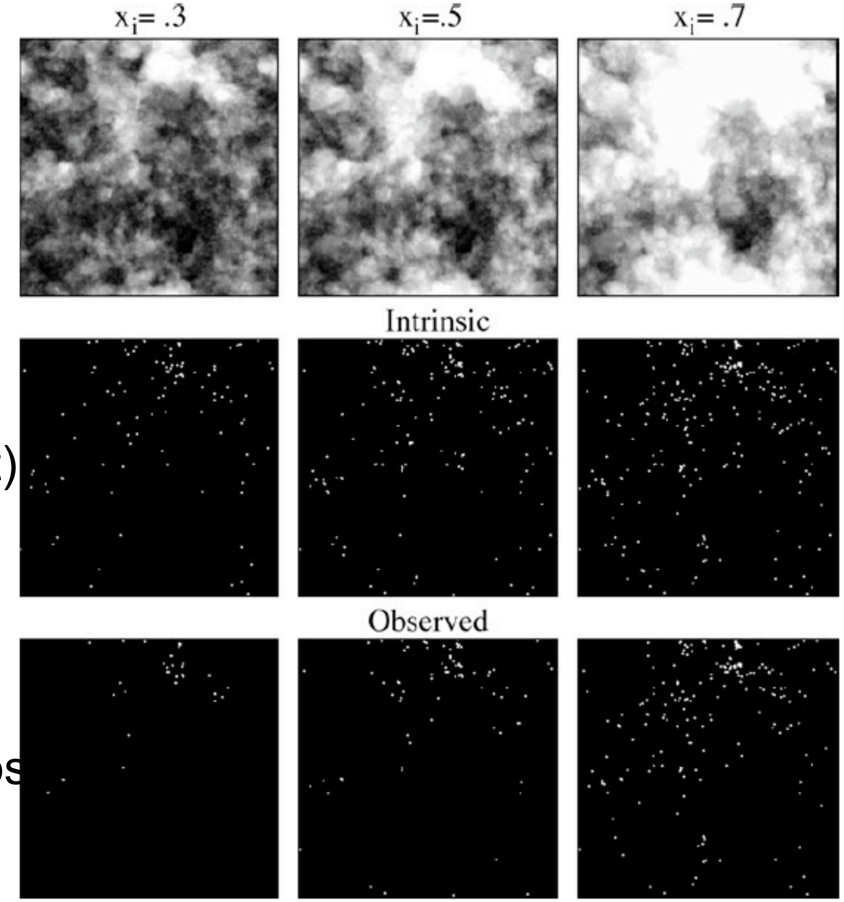


Finlator+09

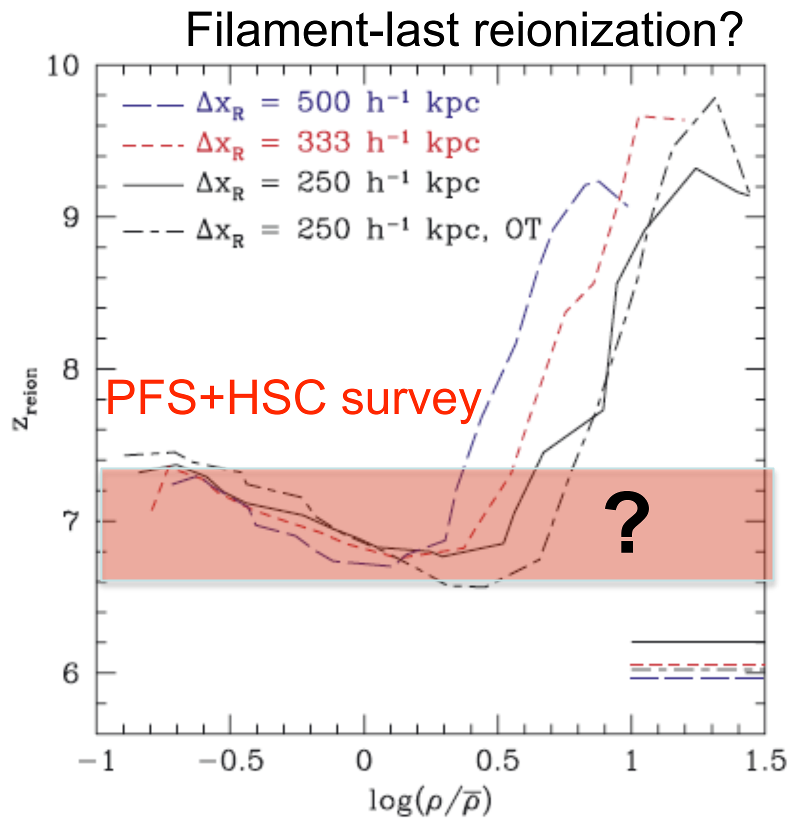
- The ionization process: How did the ionized regions extend?
  - Depending on distribution of ionizing sources and IGM density
  - Inside-out (e.g. Furlanetto et al. 2004), outside-in (e.g. Miralda-Escude et al. 2000), or filament-last (Finlator et al. 2009).

Not enough S/N with the present 21cm-obs facilities such as LOFAR

Reionization and Physical Processes



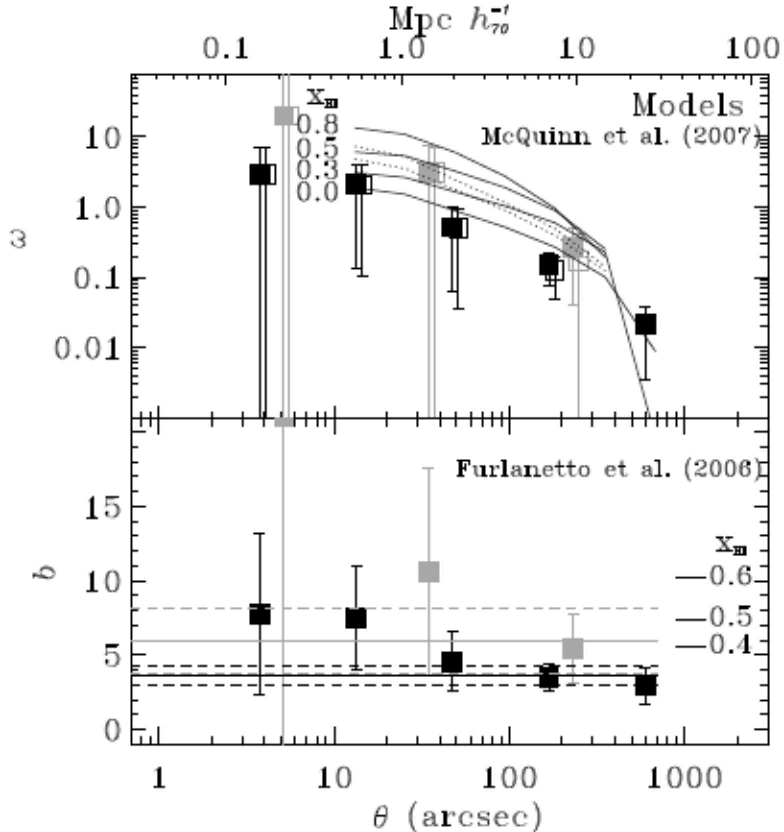
McQuinn+07

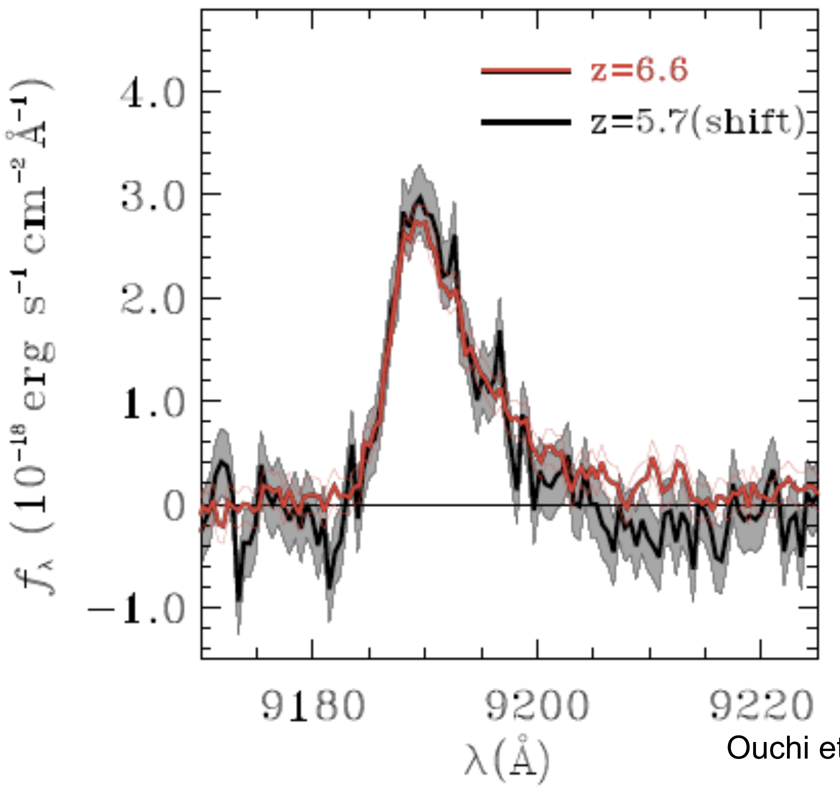


Finlator+09

- Physical processes from topology (inside-out, outside-in, filament-last?)
- Clustering of Lya emitters: imprints of neutral fraction and ionized bubble topology (McQuinn et al. 2007)

Constraints So Far Obtained





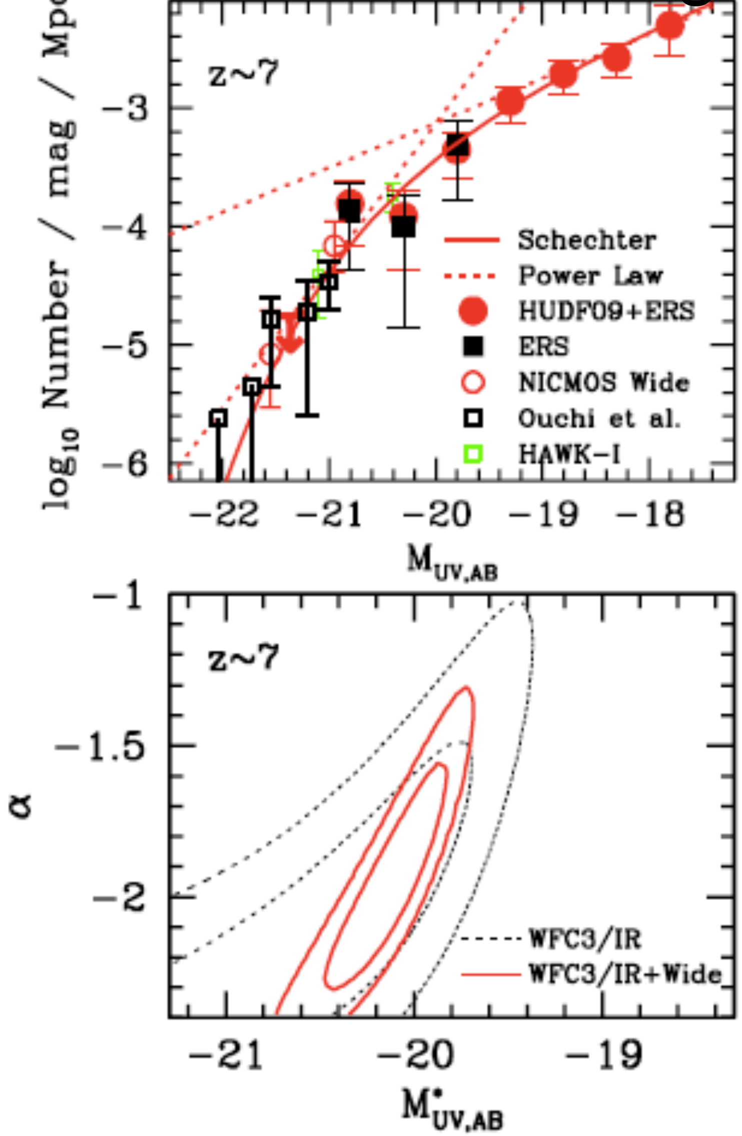
Ouchi et al. (2010)

– The clustering of Lya emitters at z~7 is not well constrained with the present Subaru studies, due to small statistics.（phot.sample~200, spec.sample~30 at z=6.6) →x_{HI}<~0.5 at z=6.6. None for the ionized bubble topology

- PFS+HSC→~100 x larger sample（~10k LAEs）→x_{HI} and topology

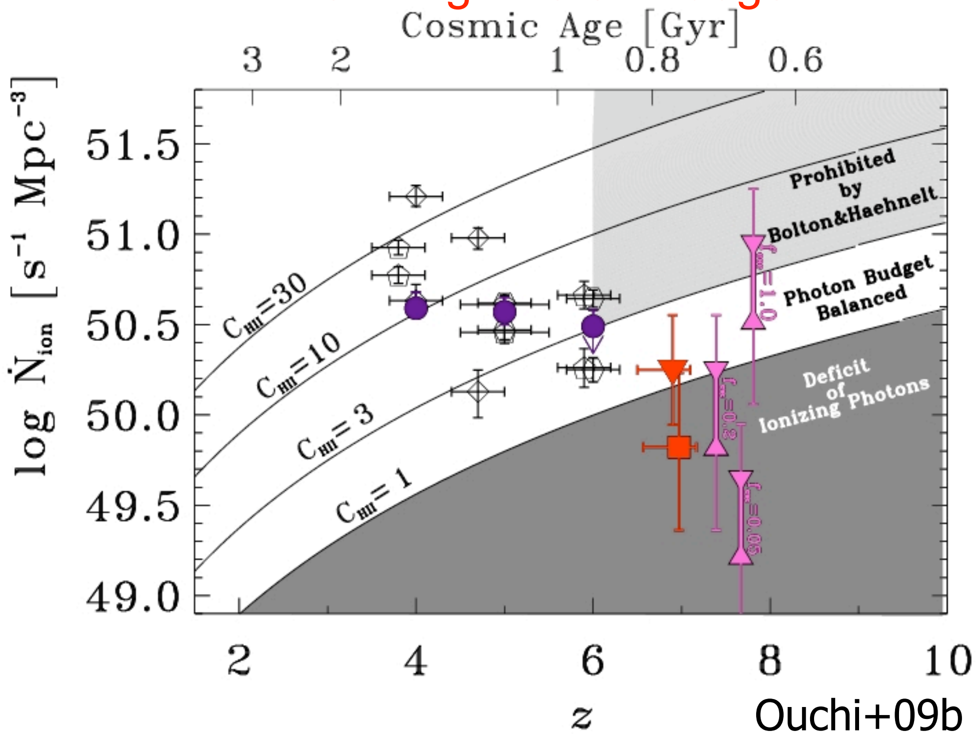
PFS: Composites of Lya line profiles in a few 10Mpc area. Spatial variance of line broadening/Lya-FWHM relation for reionization test.

Bright-end LF determination
For Budget of Ionizing Photons



Bouwens+10

Ionizing Photon Budget



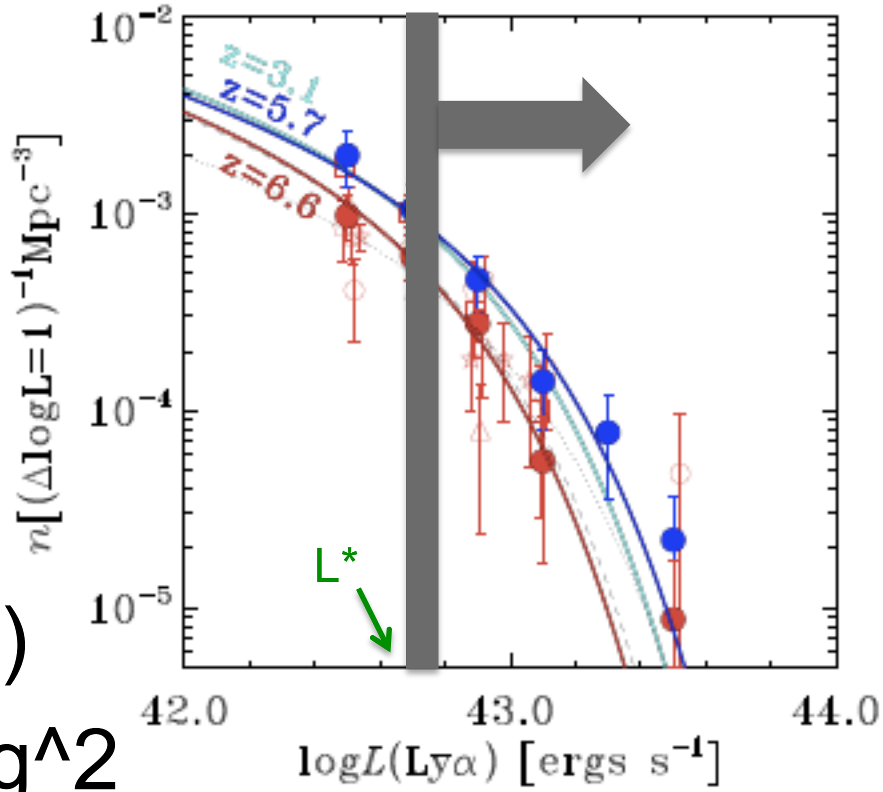
Ouchi+09b

- At z~7, did galaxies produce ionizing photons enough for ionizing the hydrogen IGM?
  - Galaxies alone may not reionize the universe

    or
  - Universe is already ionized by galaxies, but these galaxies have higher escape fraction[>0.2], (lower metallicity top-heavy IMF) or undetected faint galaxy population (α<~-1.9?).
- The determination of α with PFS+HSC data, HUDF, and the forthcoming CANDLES data.

OBSERVATIONS AND REQUIREMENTS

PFS Observations (TBD)



- PFS 12 hour (6hour each) integration/pos. for 30 deg^2
  - Covering HSC DS area (30deg^2): ~60 nights incl. overhead+weather with PFS
  - Goals: logL>42.7-42.8 erg/s; 6000 LAEs at z=5.7-6.6 and >10000 LBGs+LAEs at z=2-7

Required PFS Performance

- Faint limits of PFS performance, this survey requires good→ high sensitivities with good sky subtraction. The high throughput (10-20%) is indispensable. Moreover, for good sky subtraction and less smearing of signals, we request a stability of spectrograph ideally as high as Keck/LRIS and DEIMOS.
- A half of sensitivity → twice of Subaru nights (or probably more, due to the systematics)
- Fiber diameter should be optimized. High S/N for a point source is desirable.

Summary

PFS Deep Survey for Galaxies at z=2-7

Spectroscopic follow-up of ~30 deg^2 HSC D/UD fields

1. Mass assembly of massive galaxies. (Cold accretion or mergers?)
2. Chemical and dynamical evolution of intense star-forming galaxies
3. Galaxy, AGN, and proto-cluster formation in large scale structure at early stage
4. Cosmic reionization probed with galaxies

Required nights (~60-120 nights; TBD)

Required performance→high sensitivity (incl. stability)