WISH Exploration of Galaxies in the Epoch of Cosmic Reionization

2012/07/19

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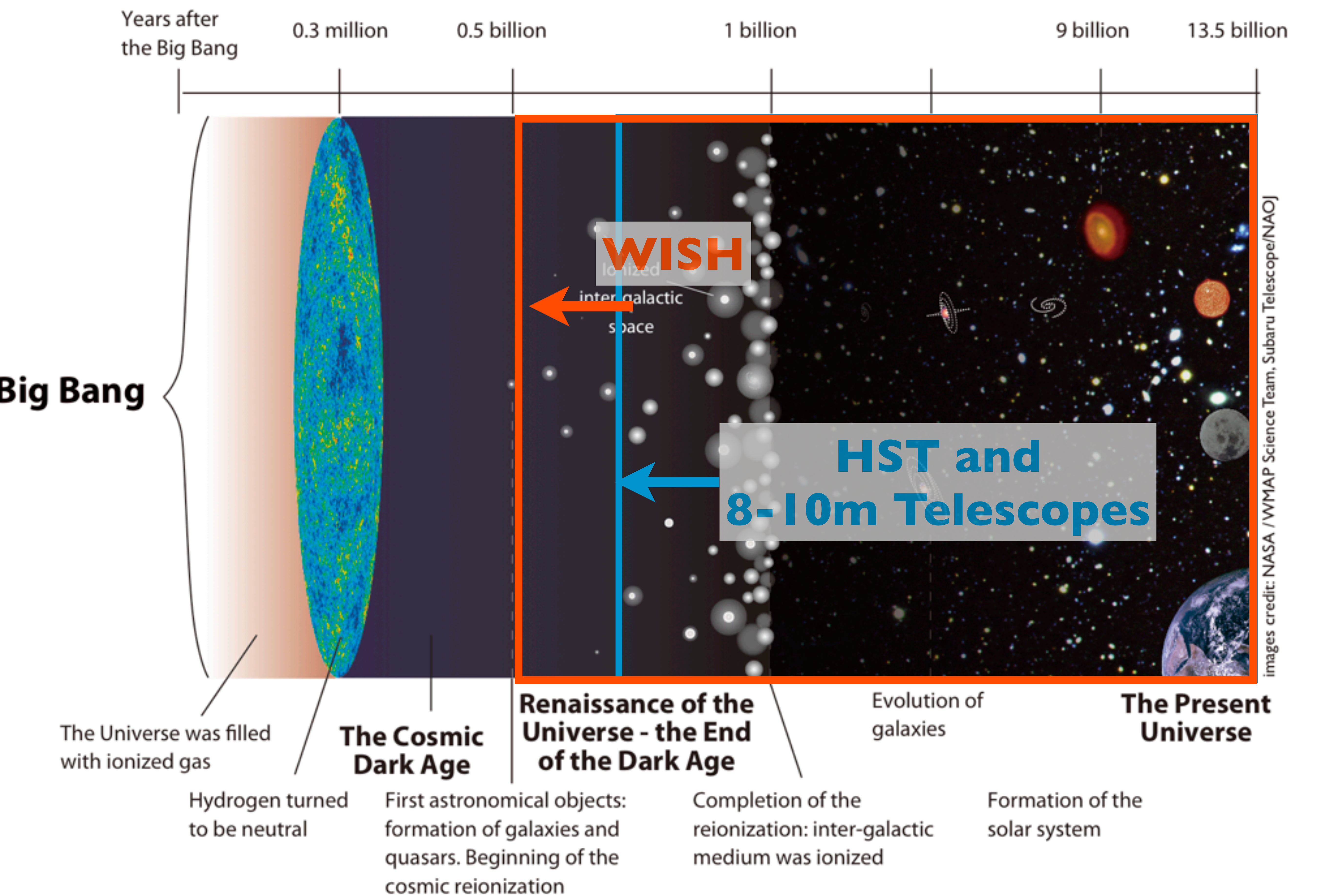
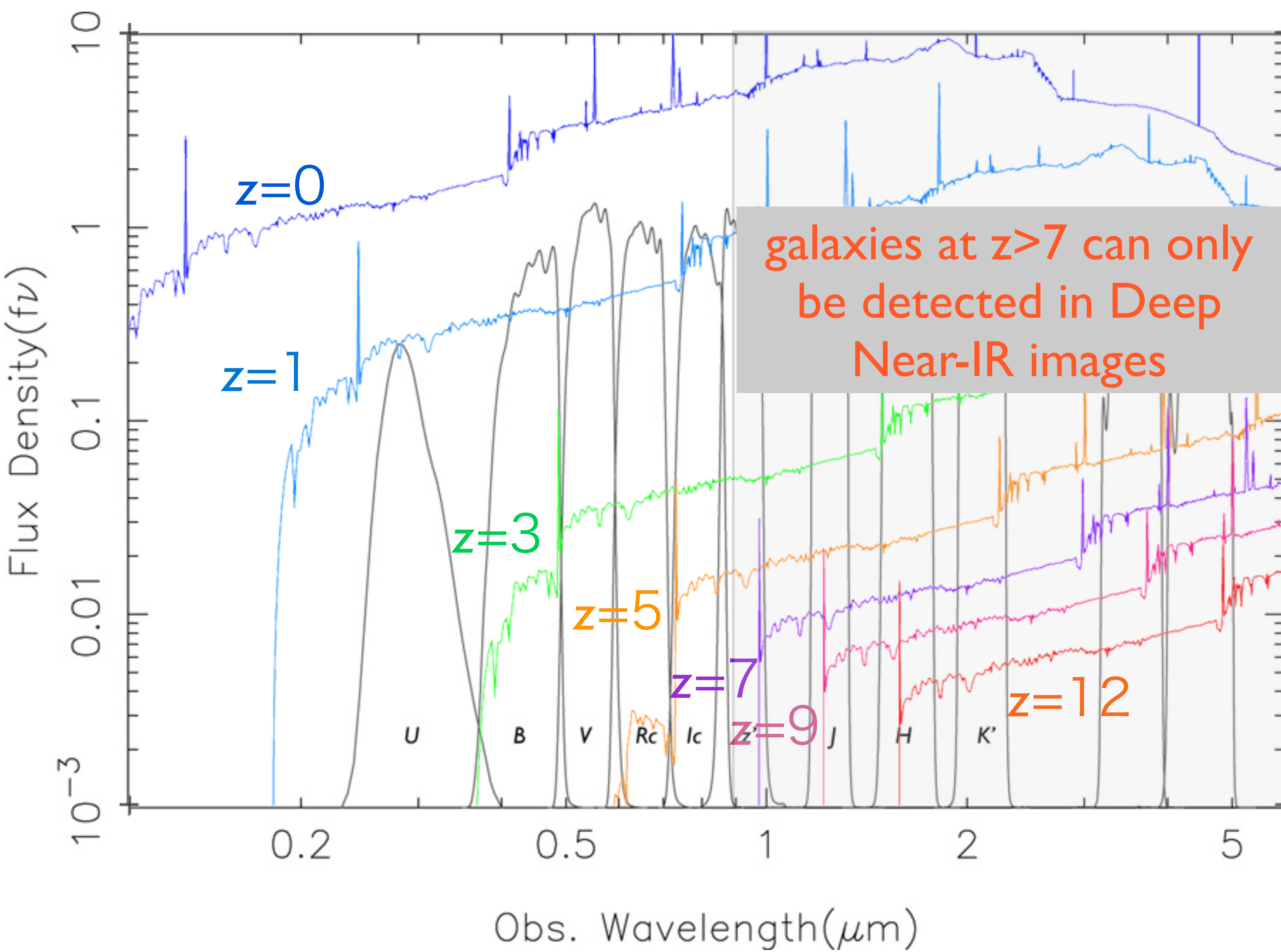
Scientific Objectives

- Detections of 'First Galaxies' ($z>10$)
- Understanding of the Cosmic Reionization

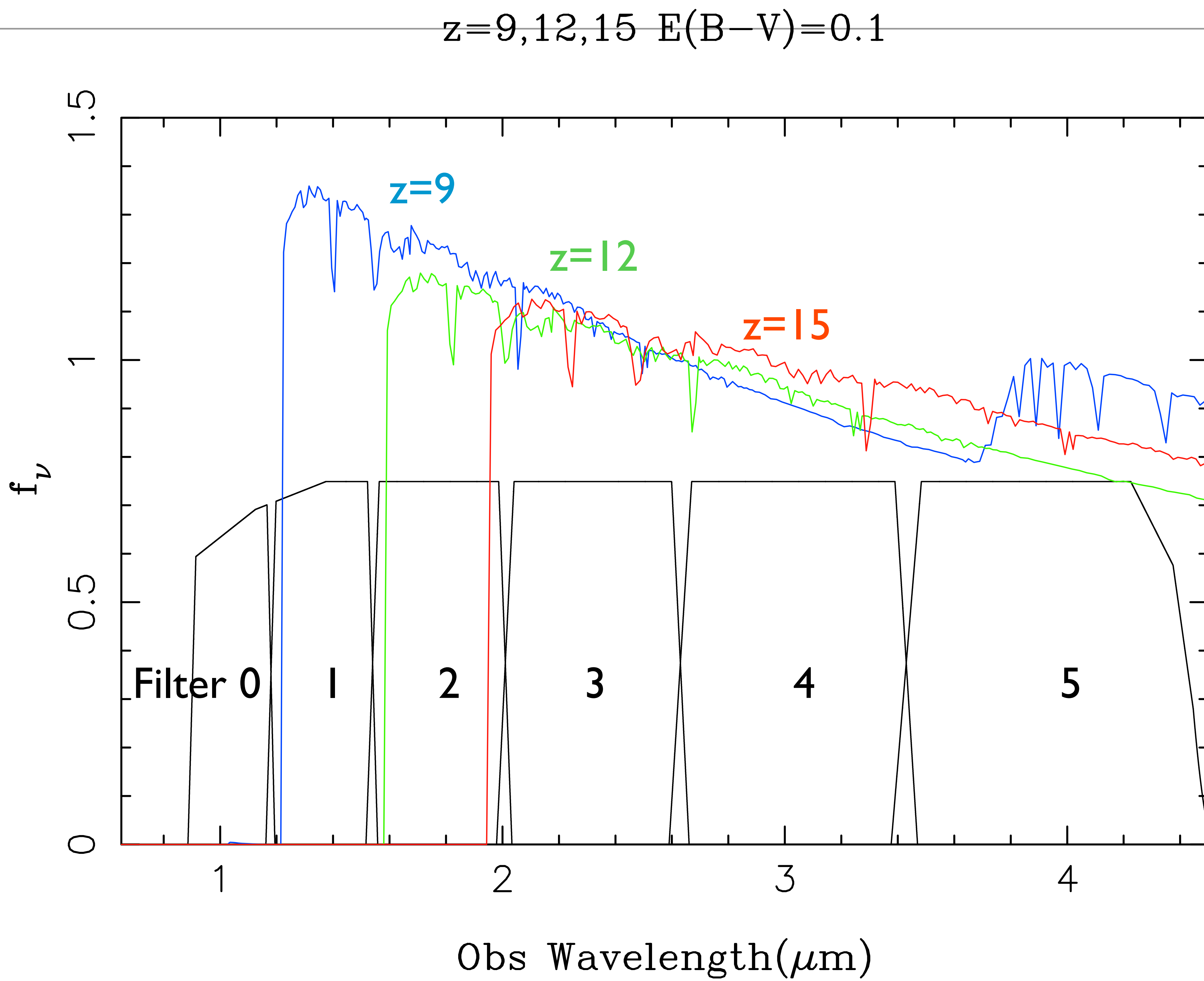


Years after the Big Bang
0.3 million
0.5 billion
1 billion
9 billion
13.5 billion
Big Bang
WISH
Ionized inter galactic space
HST and 8-10m Telescopes
images credit: NASA / WMAP Science Team, Subaru Telescope/NAOJ
The Universe was filled with ionized gas
Hydrogen turned to be neutral
The Cosmic Dark Age
First astronomical objects: formation of galaxies and quasars. Beginning of the cosmic reionization
Renaissance of the Universe - the End of the Dark Age
Completion of the reionization: inter-galactic medium was ionized
Evolution of galaxies
Formation of the solar system
The Present Universe

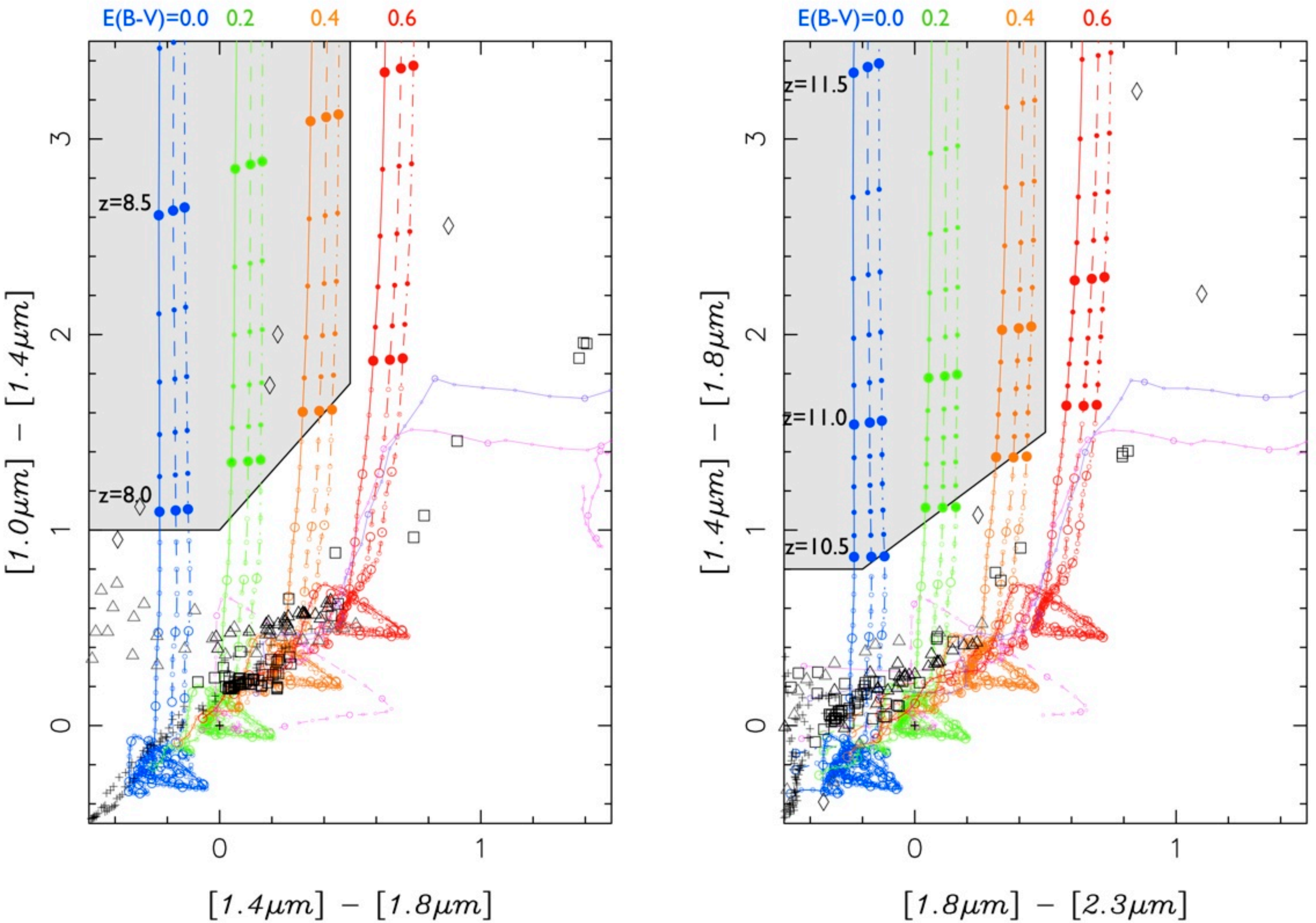


Flux Density(fν)
10
1
0.1
0.01
10^{-3}
0.2
0.5
1
2
5
Obs. Wavelength(μm)
z=0
z=1
z=3
z=5
z=7
z=9
z=12
U
B
V
Rc
Ic
z'
J
H
K'
galaxies at z>7 can only be detected in Deep Near-IR images

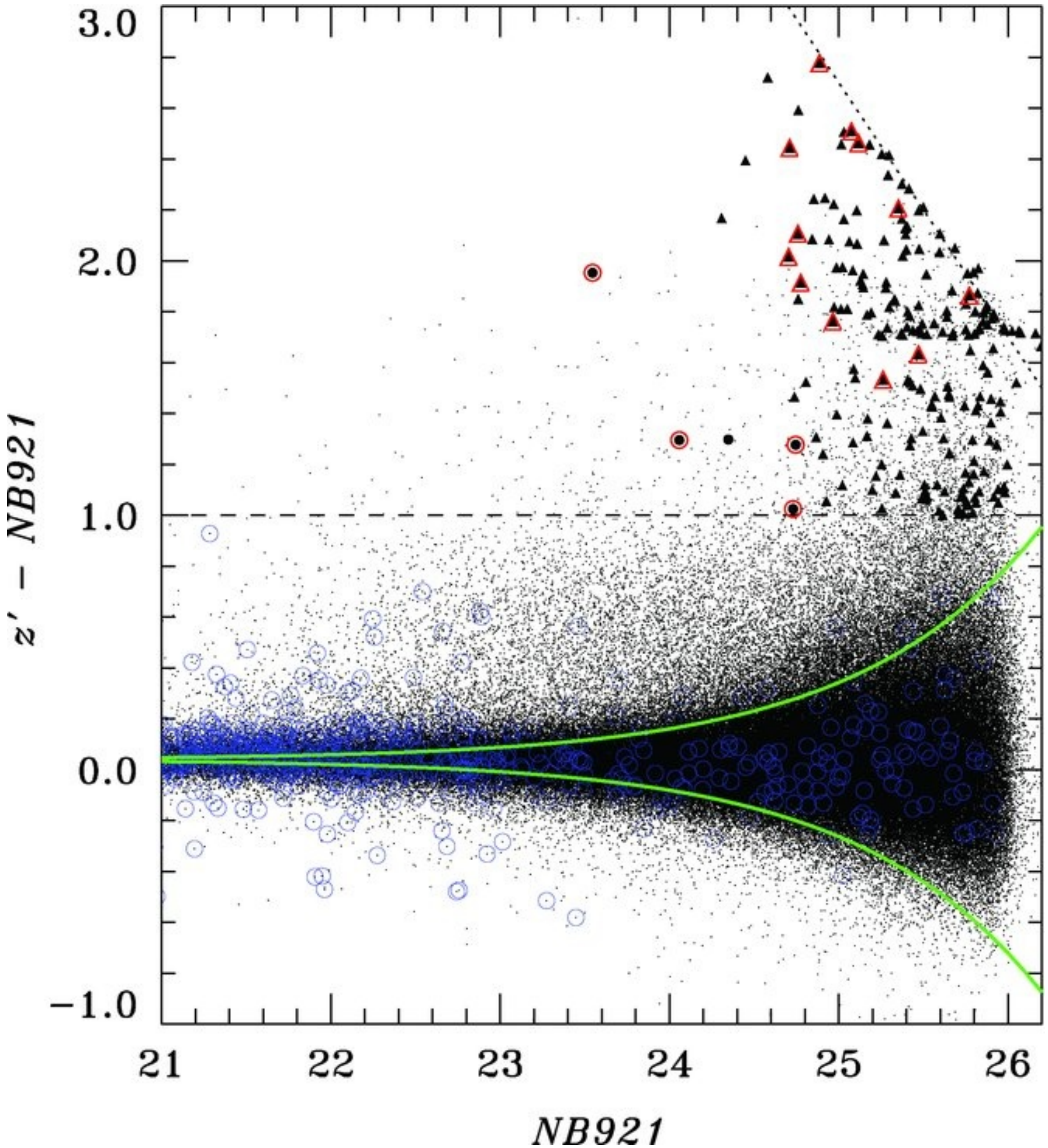
'Drop-out' Method - Lyman Break Galaxies



Selection of High-z Galaxies with Two-Colors



Narrow-band Search for Lymanα Emitters (LAEs)

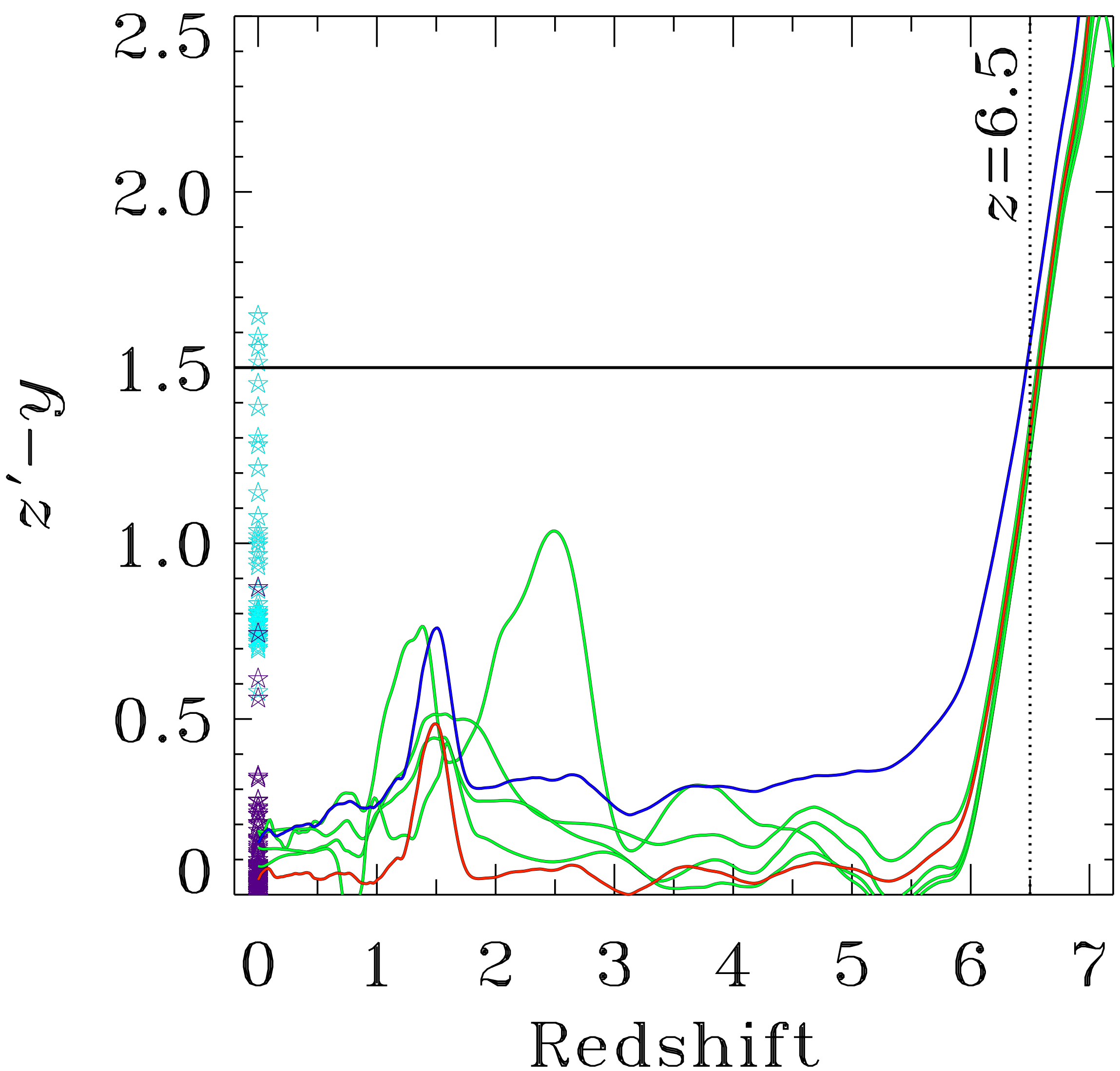


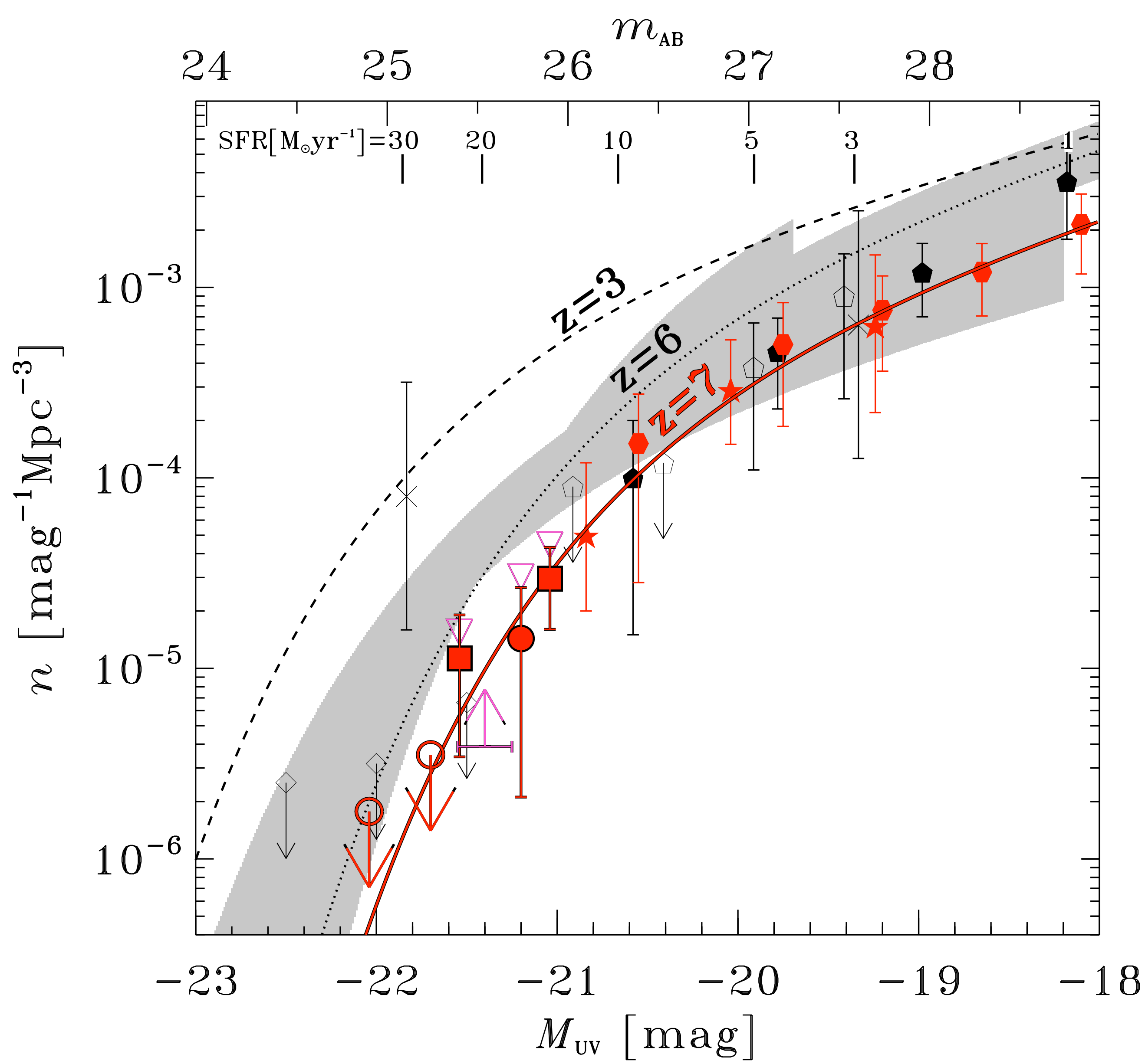
Ouchi et al. 2010, ApJ 723, 869

Reionization Epoch explored with Subaru

Ouchi et al. 2009 - z~7 LBGs

- Suprime-Cam imaging of SDF and GOODS-N. 1568 arcmin2 (0.5 deg2)
- z-y > 1.5
- y-band limit (3σ): 26.4 - 26.2 AB mag.
- 22 candidates

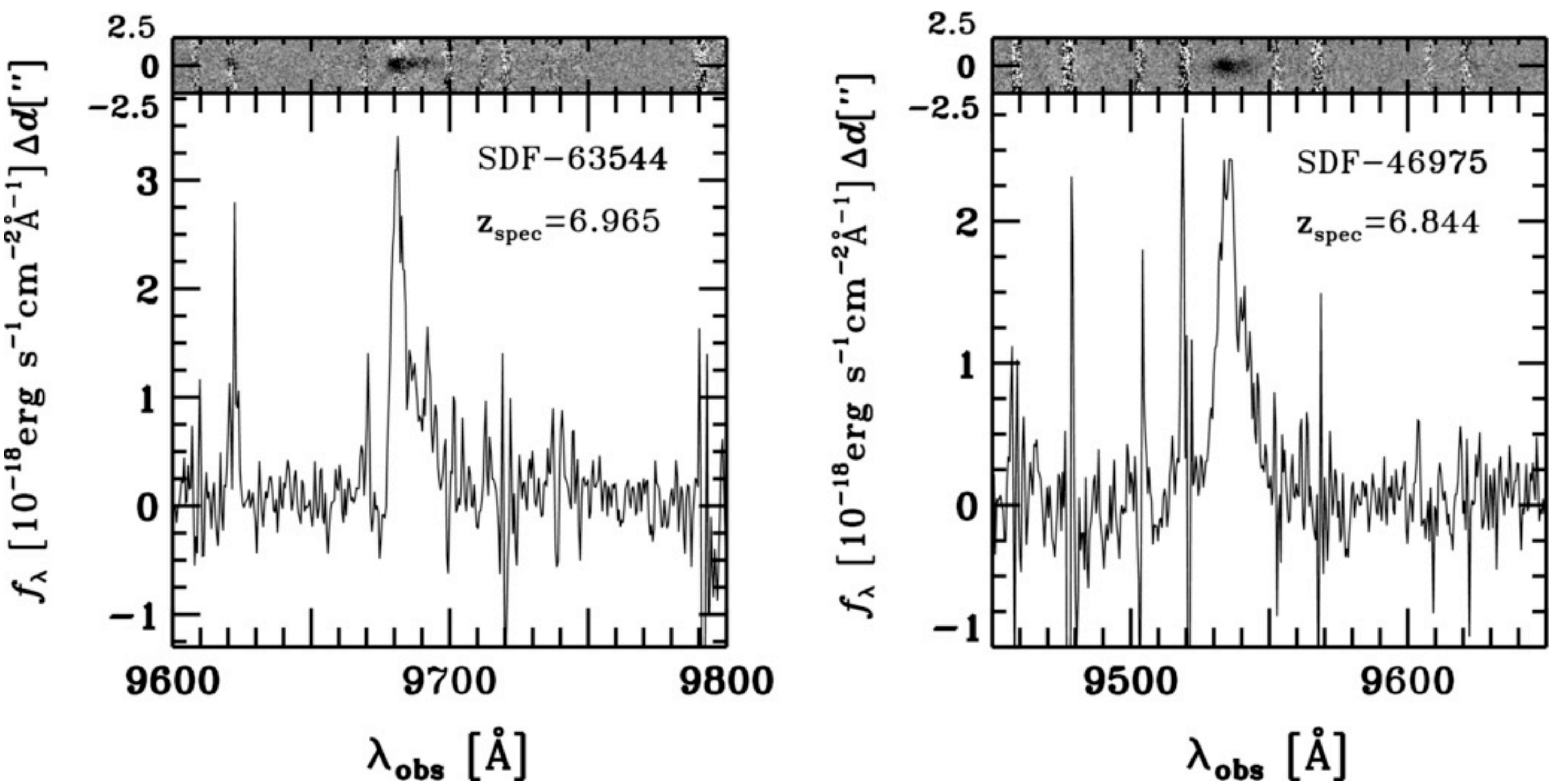




Ouchi et al. 2009, ApJ 706, 1136

Ono et al. 2012 - Spectroscopic confirmations

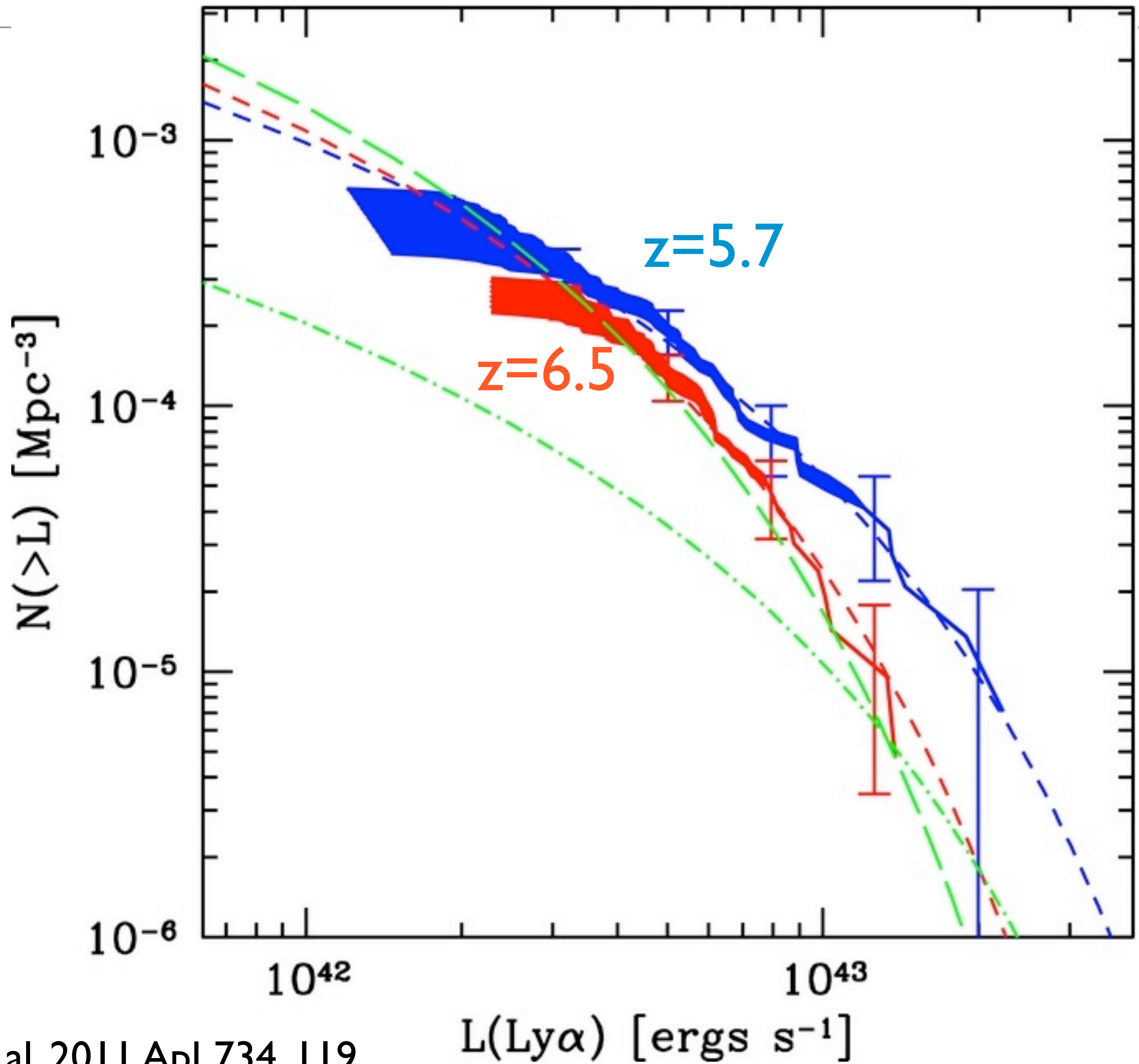
- Keck / DEIMOS spectroscopy of 11 z~7 candidates
- Three z~7 galaxies were identified
- Lower fraction of Lyα galaxies - evolution of IGM neutral hydrogen fraction?



Suprime-Cam Narrow-band Searches for Lymanα Emitters (LAEs)

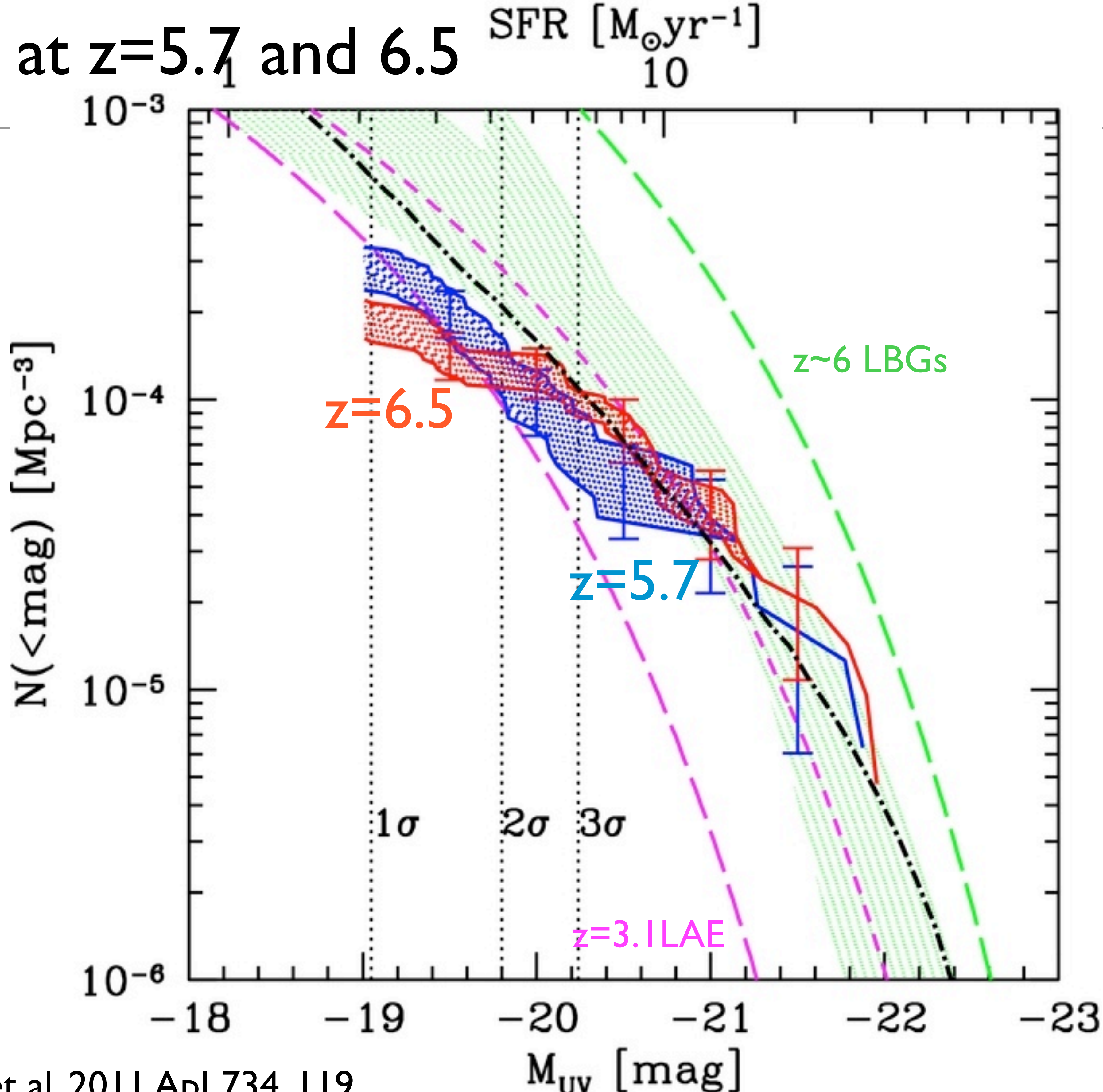
- NB921 (z=6.6): Kodaira et al. 2003; Taniguchi et al. 2005; Kashikawa 2006; Ouchi et al. 2010
- NB973 (z=7.0): Iye et al. 2006; Ota et al. 2008; Hibon et al. 2012
- NB1006 (z=7.3): Shibuya et al. 2012

LAE LF at z=5.7 and 6.5



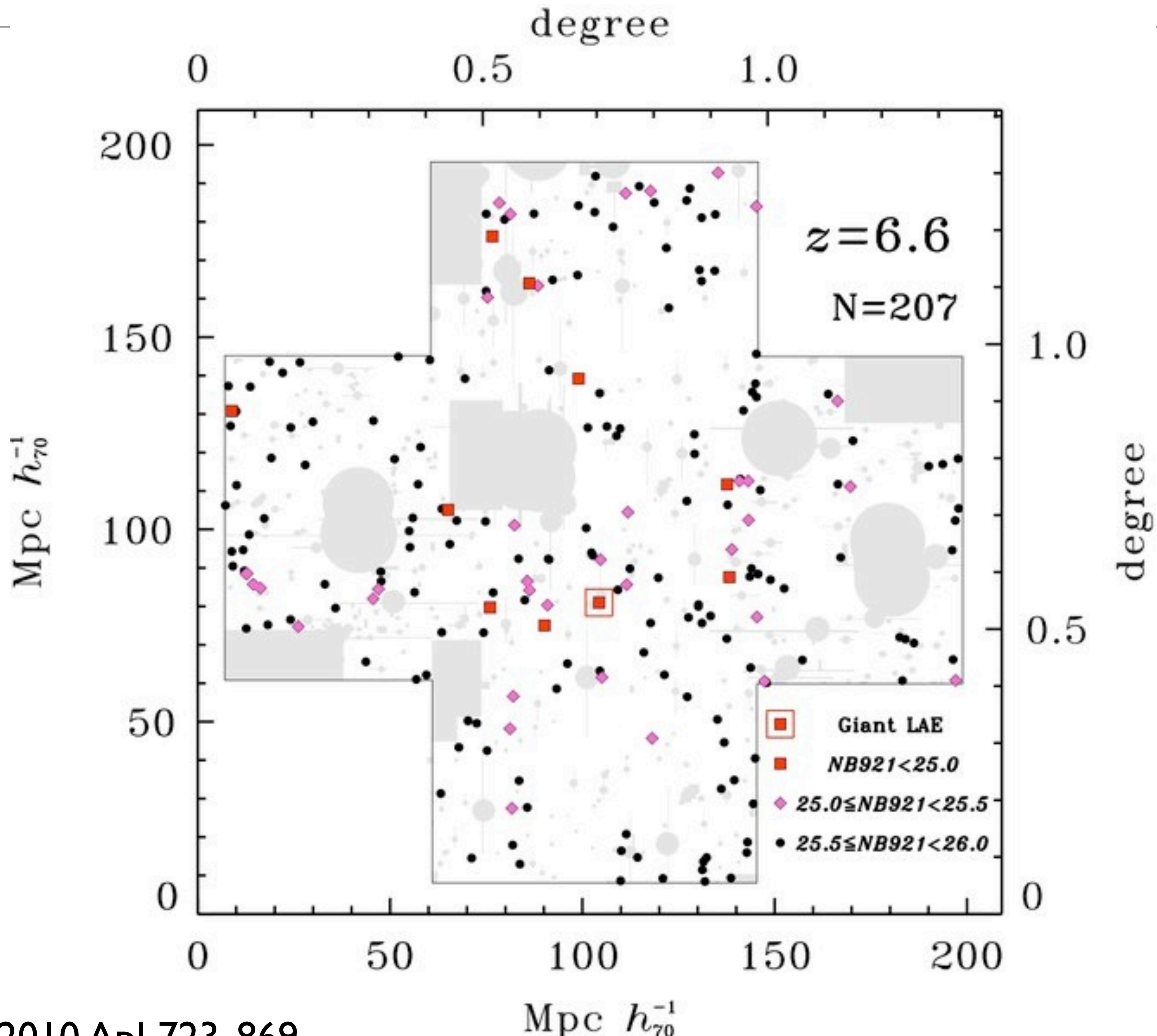
Kashikawa et al. 2011 ApJ 734, 119

LAE LF at z=5.7 and 6.5



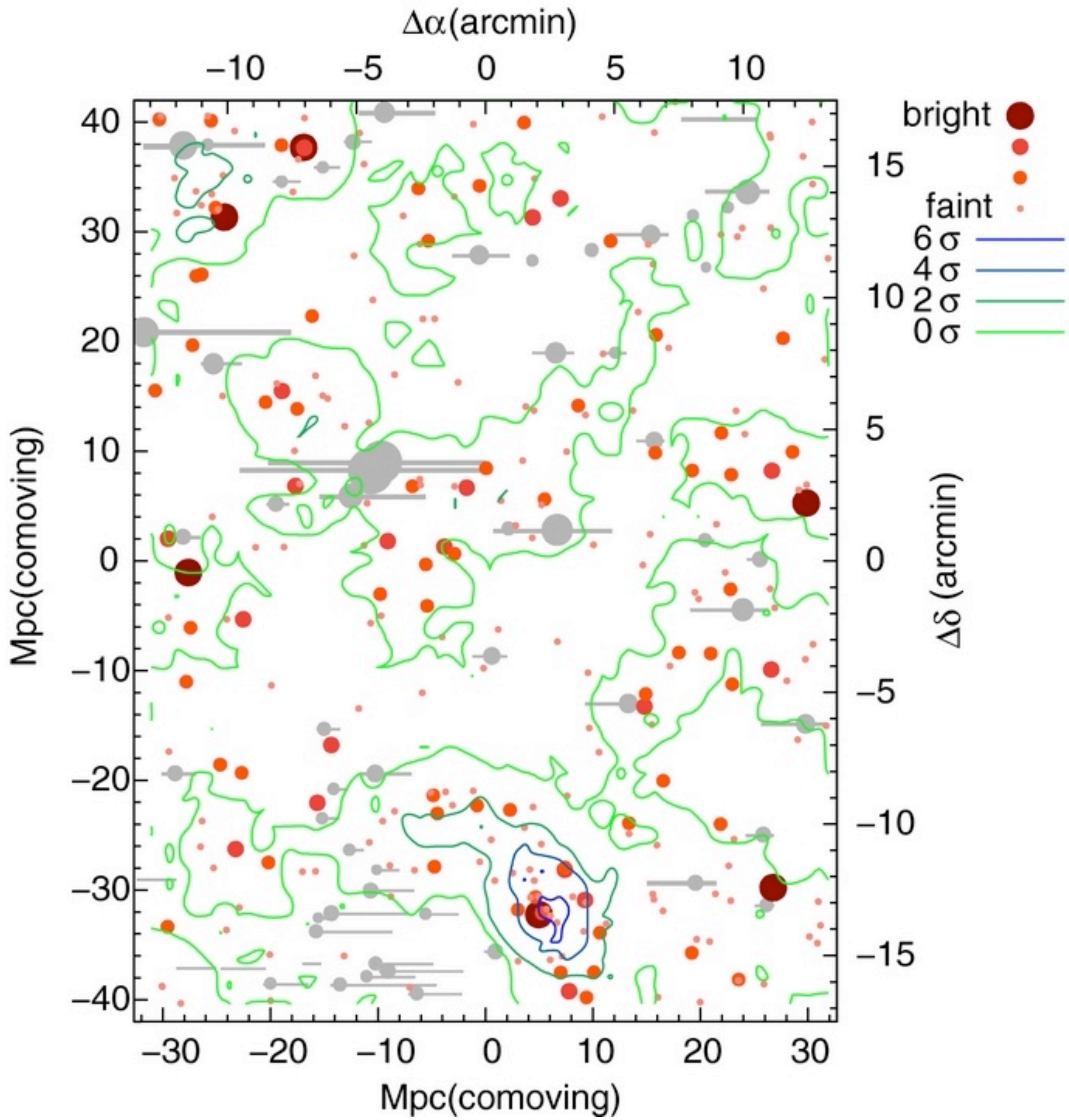
Kashikawa et al. 2011 ApJ 734, 119

Clustering of z=6.6 LAEs



Ouchi et al. 2010 ApJ 723, 869

Toshikawa et al. 2012 - Protocluster at z~6

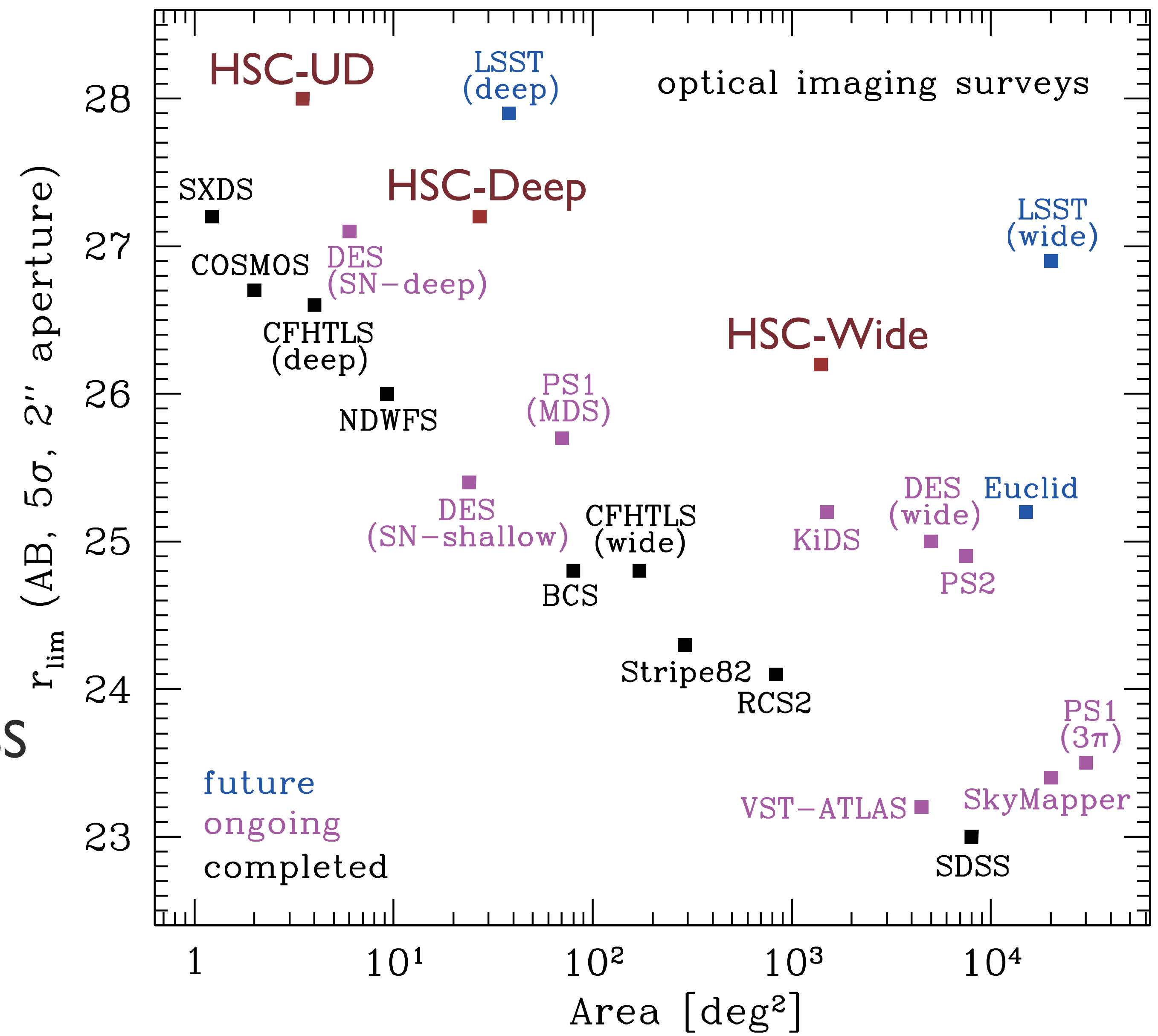


Toshikawa et al. 2012, ApJ 750, 137

Hyper Suprime-Cam Strategic Survey

- Deep Layer: 28 deg^2
  - grizy + NB387, NB816, NB921
  - z=26.0 y=25.3 (5σ)
- Ultra-Deep Layer: 3.5 deg^2
  - grizy + NBs 387, 527, 718, 816, 921, 101
  - z=26.8 y=26.3 (5σ)

- Hundreds of z-drop (z~7)
  - Tens of y-drop (z~8) with VISTA/UKIDSS
- Thousands of z=5.7 and 6.6 LAEs
- Several tens of z=7.3 LAEs



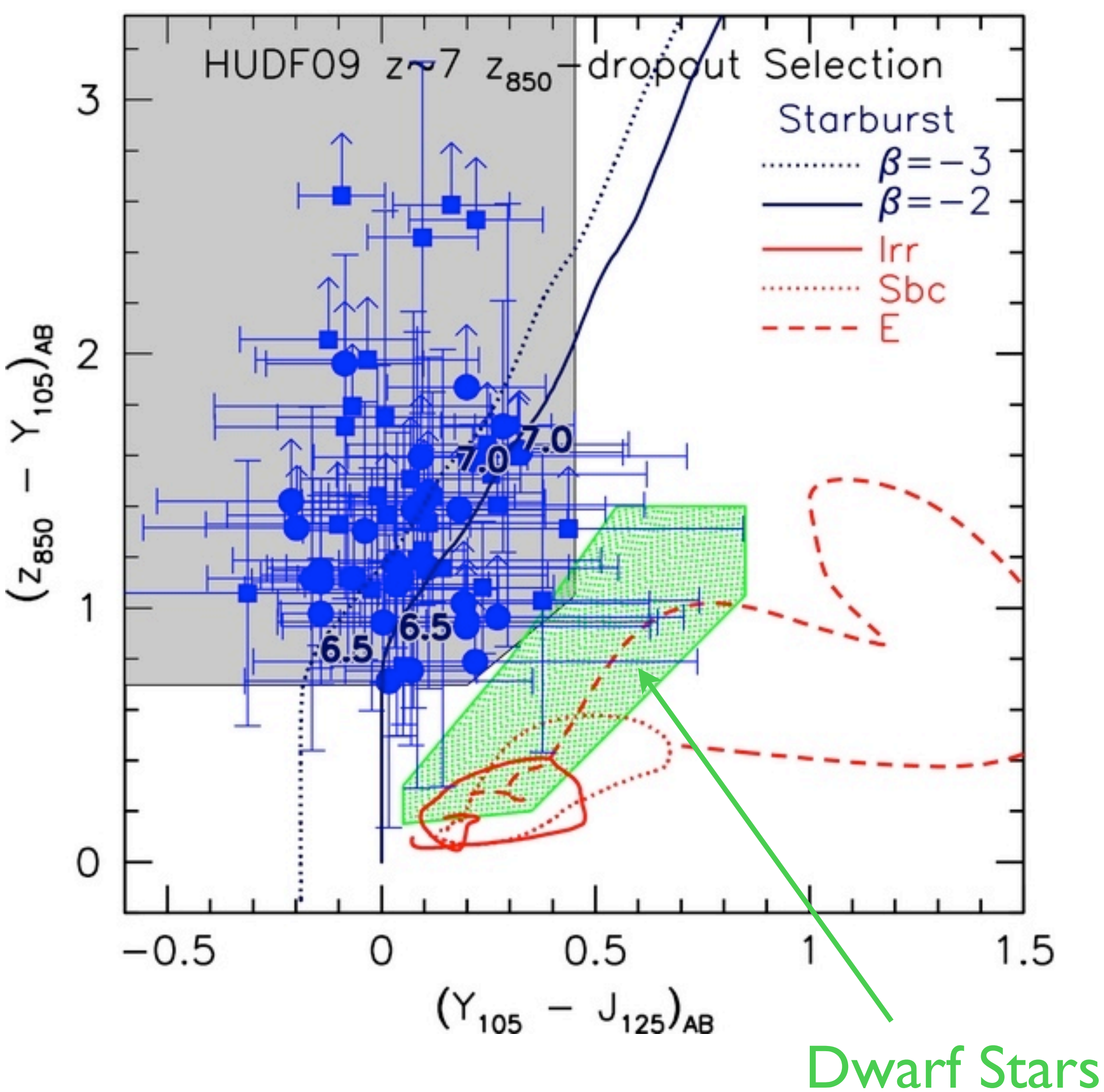
from HSC SSP proposal draft

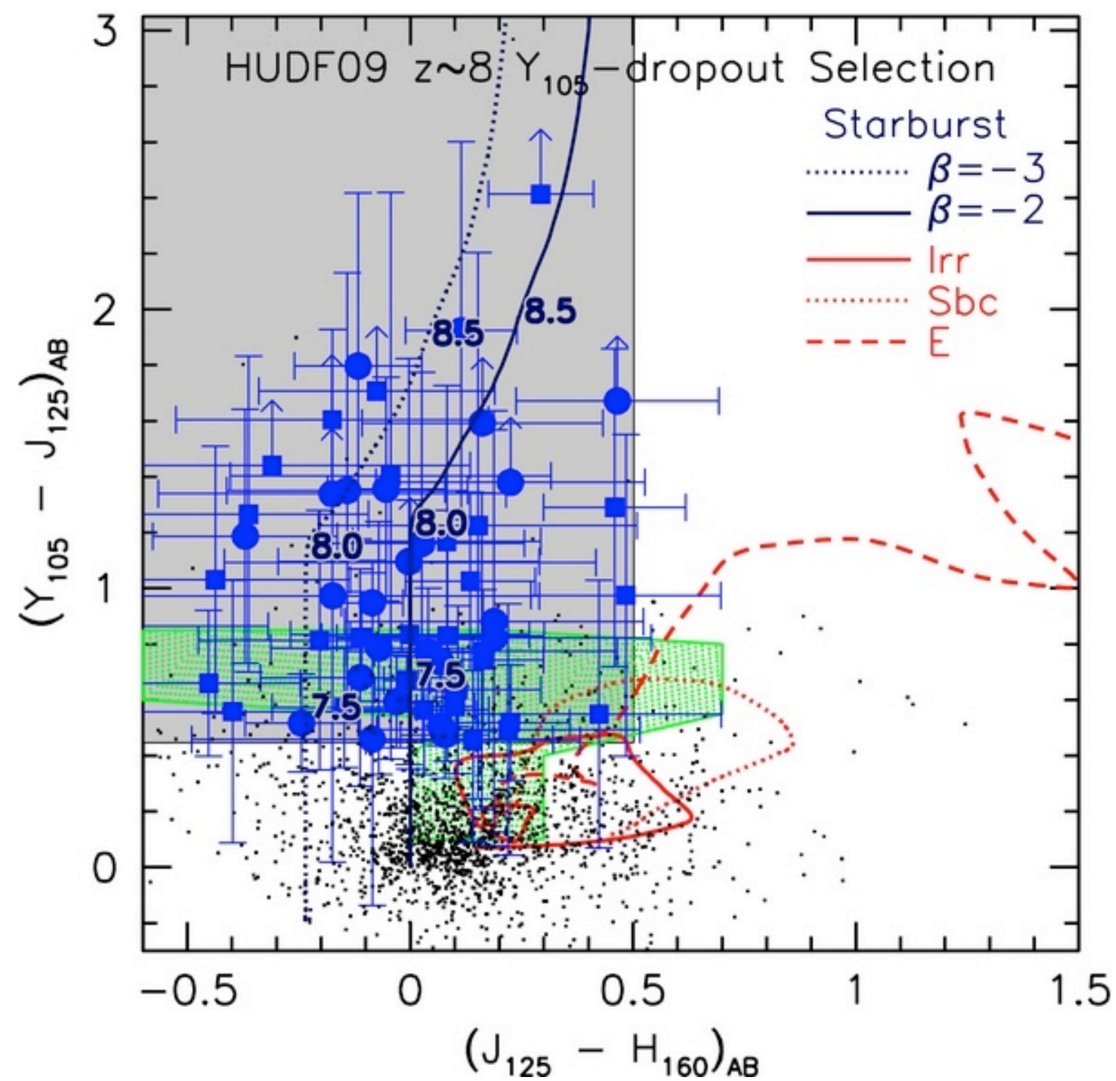
Galaxies at z>7 explored with HST

Bouwens et al. 2011, ApJ 737:90

- HUDF09 + two nearby fields: 14 $arcmin^2$
  - ACS: 29.4 - 30.1 mag. (HUDF09), 28.8 - 29.2 mag. (nearby fields)
  - WFC3/IR: 29.6 - 29.9 mag. (HUDF09), 29.0 - 29.5 (nearby fields)
- WFC3/IR Early Release Science observations: 40 $arcmin^2$
  - ACS: 28.0 - 28.5 mag.
  - WFC3/IR: 27.9 - 28.4 mag.

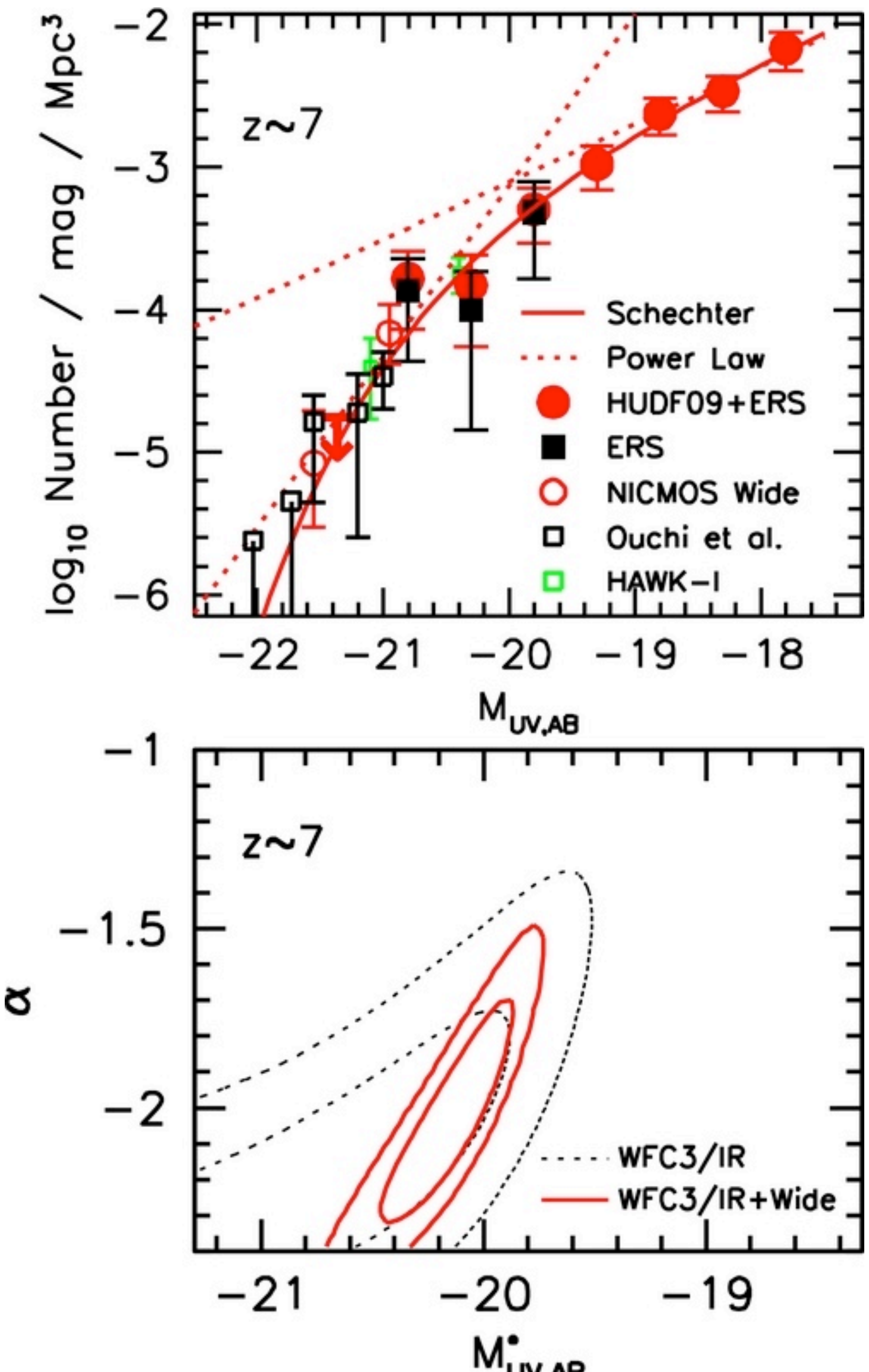
Color Selection Criteria (for HUDF09)

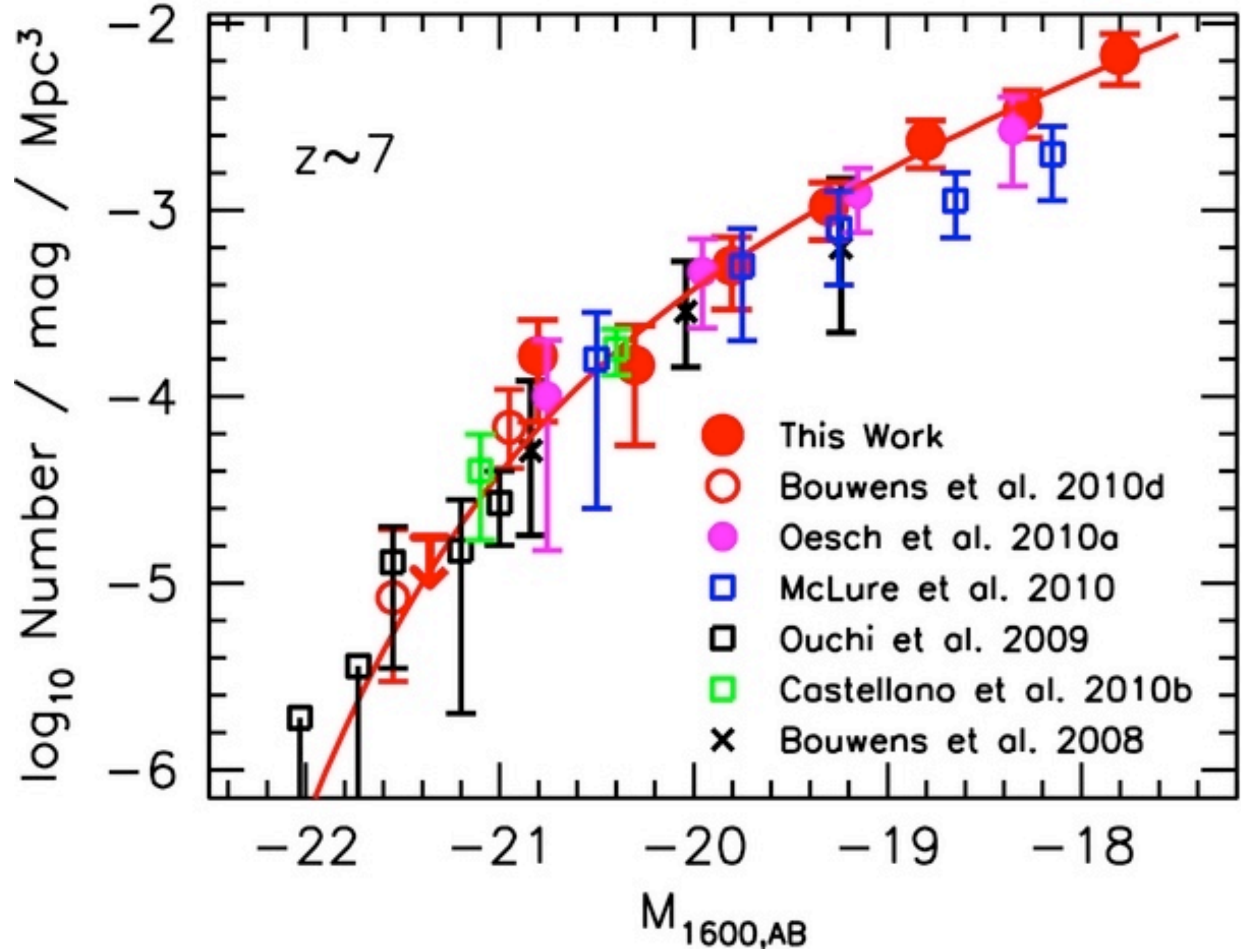




Bouwens+2011, ApJ 737:90

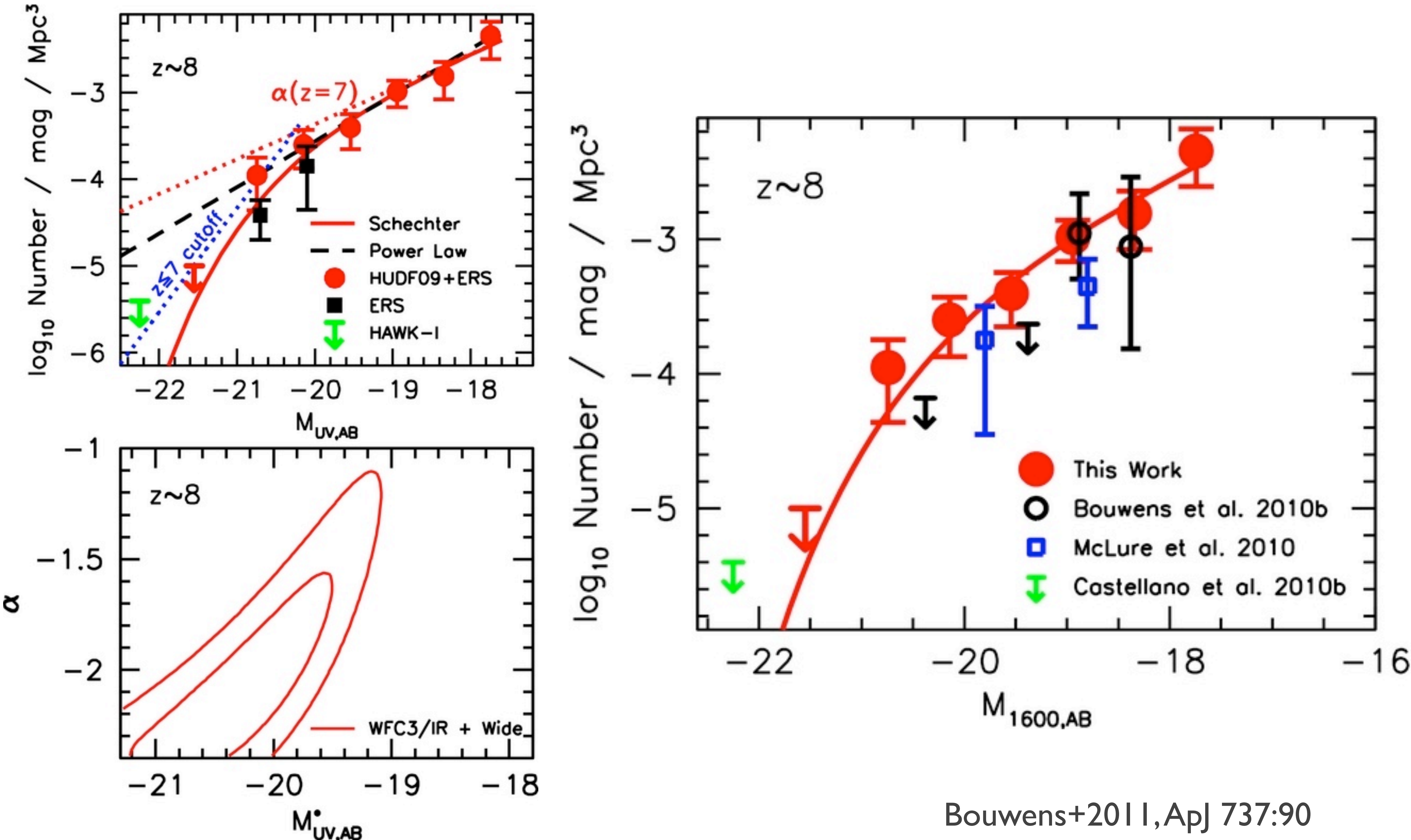
UV Luminosity Function at z~7





Bouwens+2011, ApJ 737:90

UV Luminosity Function at z~8



Bouwens+2011, ApJ 737:90

HST WFC3/IR Studies for z>7 Galaxies

- Bradley et al. arXiv:1204.3641
  - WFC3 Pure Parallel Survey ($7.4 < z < 8.8$)
  - 274 arcmin^2 with Y, J, H - 33 Y-drop with $25.5 < J < 27.4$
  - No evidence of an excess at bright-end
- Oesch et al. arXiv:1201.0755
  - CANDELS GOODS-S
  - 95 arcmin^2 - 16 Y-drop
  - Confirms pure luminosity evolution in UVLF from z~8 to z~4
- Lorenzoni et al. 2011, MNRAS 414, 1455
  - HUDF 4.2 arcmin^2 + ERS 37 arcmin^2
  - Ionization photon budget
- Search for Gravitationally Lensed LBGs
  - CLASH: Zitrin et al. 2012, ApJ 747, L9
  - Bouwens et al. 2009, ApJ 690, 1764

Additional Requirements to Eliminate Contaminations

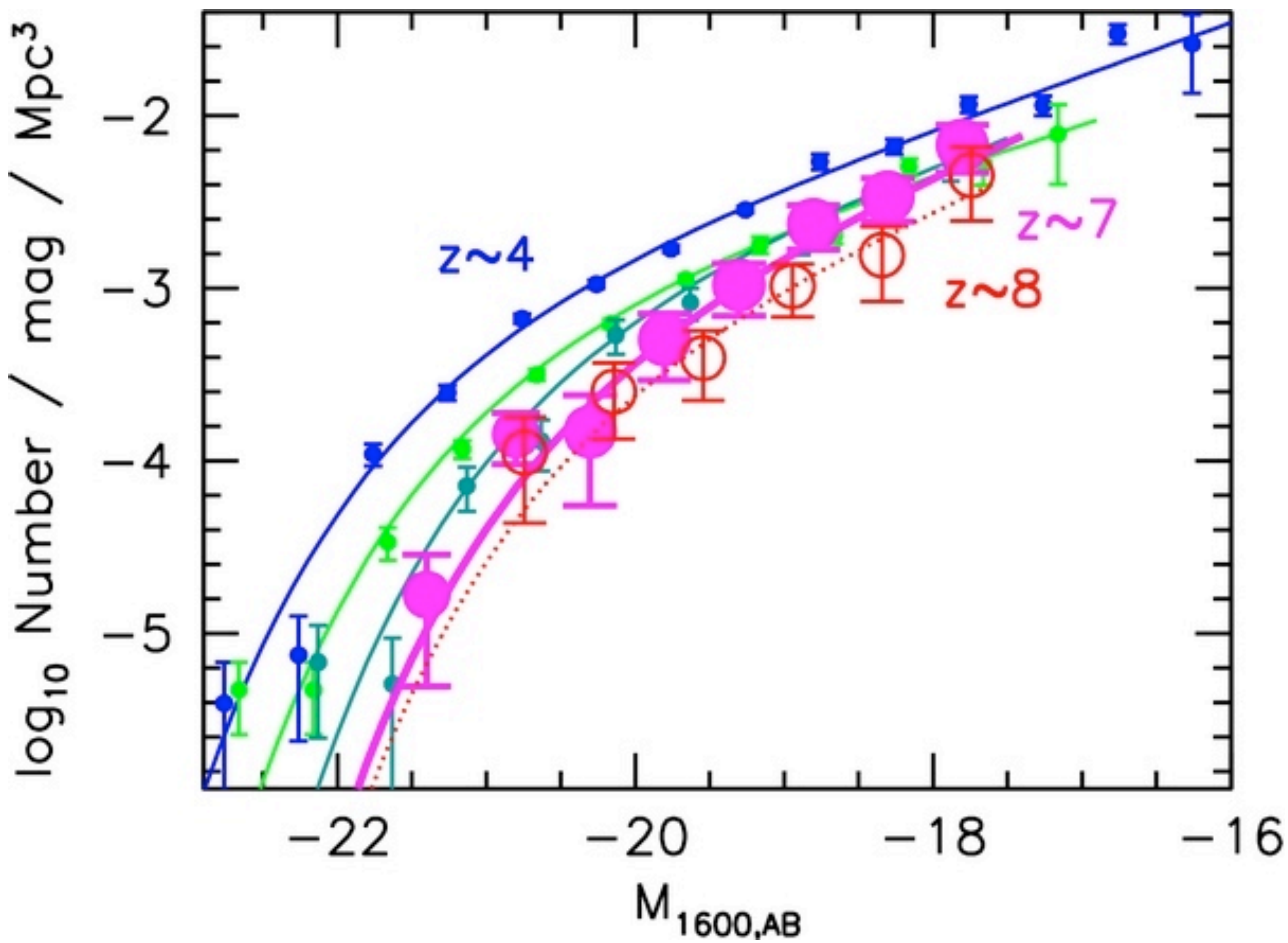
- No detection in optical bands
  - Reject >2sig single detection and >1.5sig detection in more than one band
  - $$\chi^2_{\mathrm{opt}} = \Sigma_i \mathrm{SGN}(f_i)(f_i/\sigma_i)^2. \qquad (1)$$
    - SGN(f_i): 1 if fi>0, -1 if fi<0
    - Reject objects with χ^2>5 or 3
- Simulations to estimate contaminations:
  - Contamination rate: 6-8% for HUDF09, 22-38% for ERS
- Dwarf stars, SNe: eliminate point sources
  - Minor populations: only one unresolved sources within the criteria

Bouwens+2011, ApJ 737:90

	z~7 (z850-dropouts)	z~8 (Y105-dropouts, *Y098-dropouts)
HUDF09	29	24
HUDF09-1	17	14
HUDF09-2	14	15
ERS	13	6 *
total	73	59

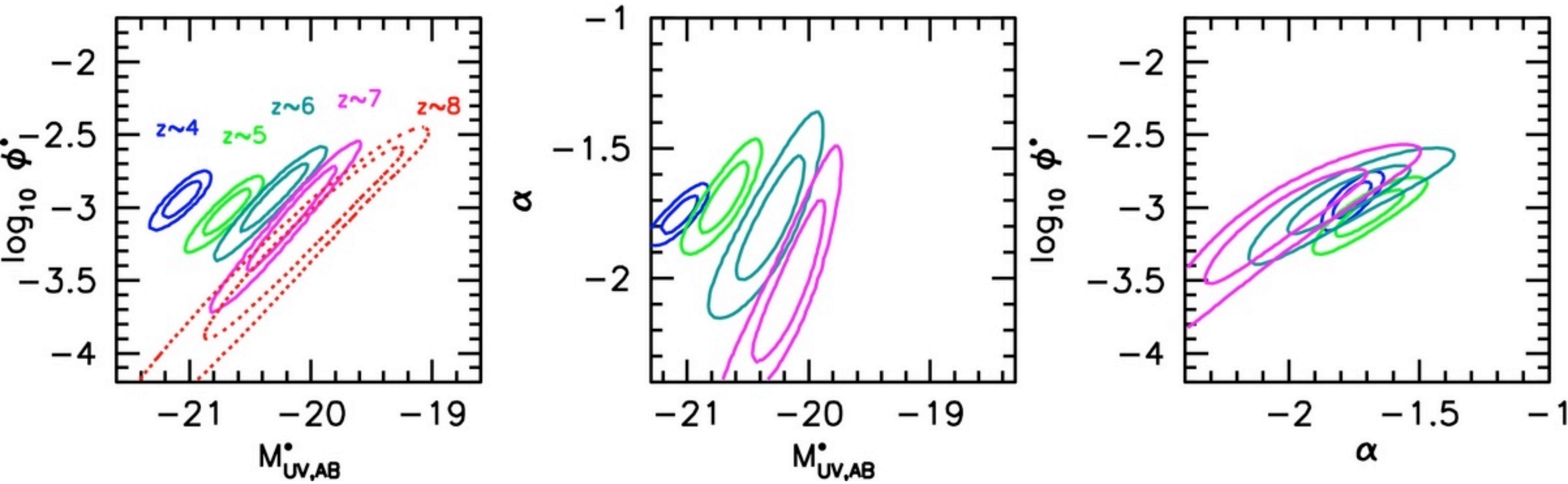
Bouwens+2011, ApJ 737:90

UVLF Evolution



Bouwens+2011, ApJ 737:90

UVLF Evolution (Schechter function parameters)

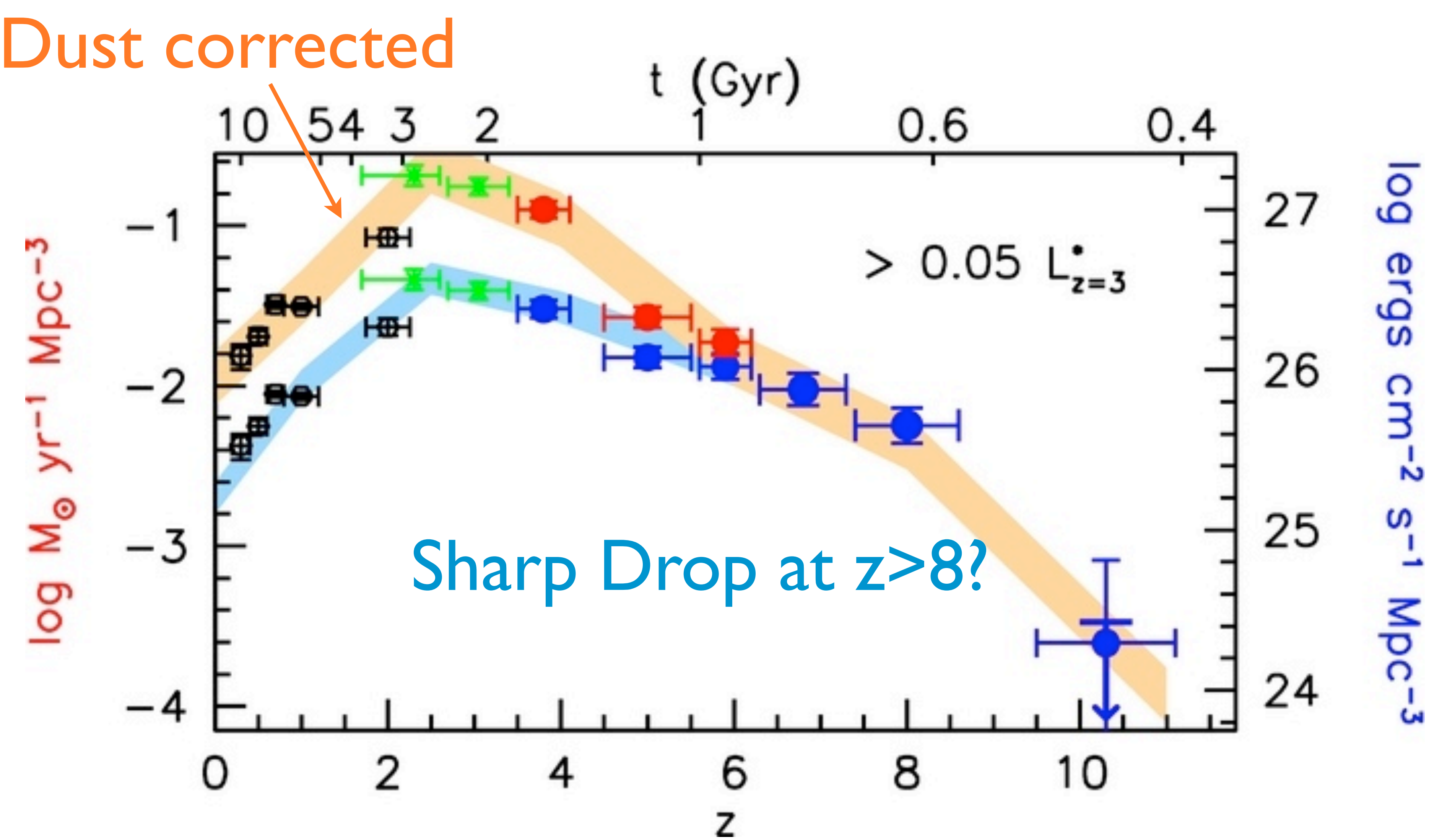


Bouwens+2011, ApJ 737:90

Issues on LBGs in the Reionization Epoch

- Evolution of UVLF and Star-formation Rate Density
- Ionization Photon Budget
  - Steepness of Faint-end slope?
- Steep UV slope - Metal-poor stellar populations?
- Number density of luminous LBGs

UV Luminosity Density (SFR Density)



Conversion to SFR density:
Salpeter IMF, 0.1<M/Msun<125
Assuming Constant SF over >100Myr

Bouwens+2011, ApJ 737:90

UV Luminosity Density (SFR Density)

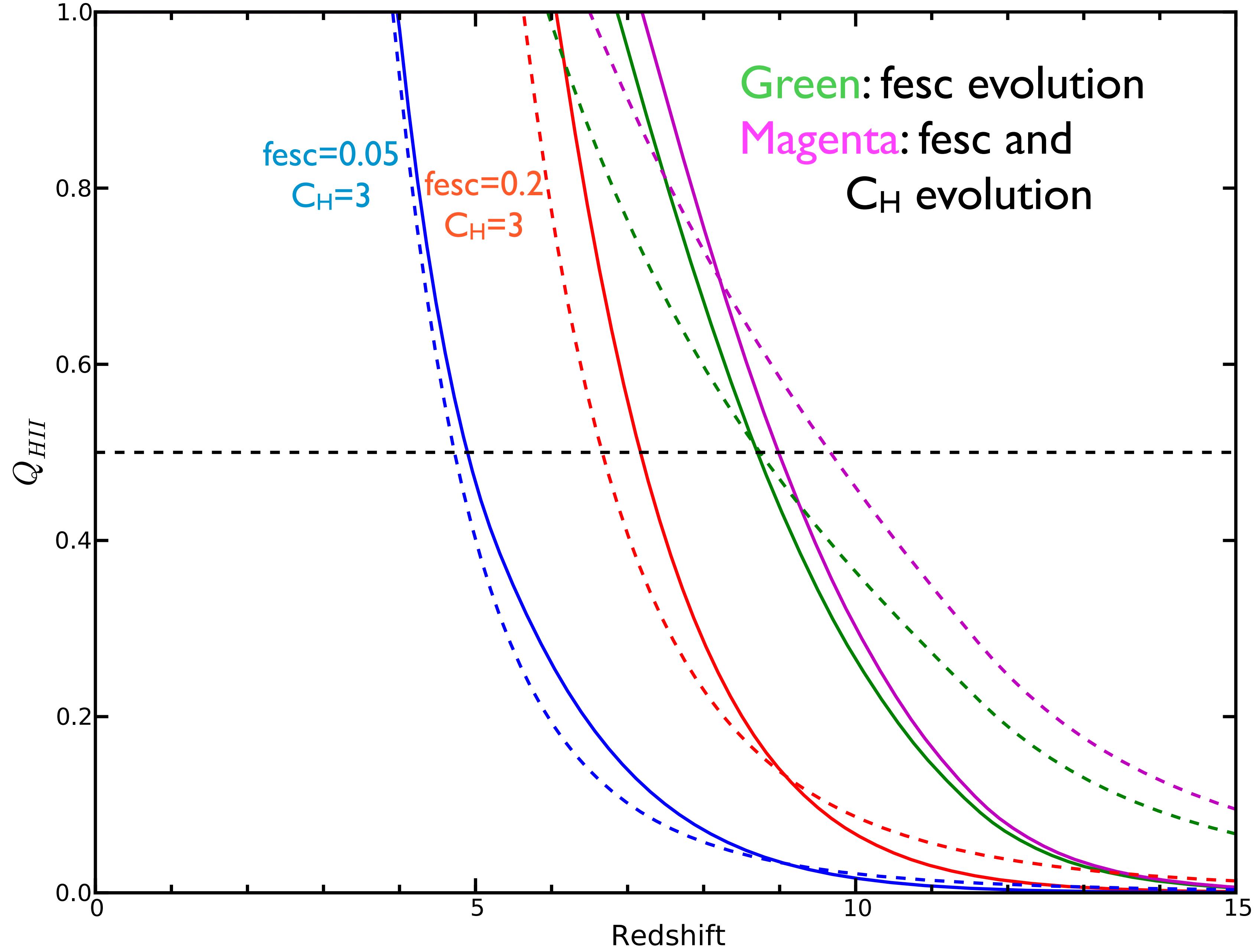
Table 8
UV Luminosity Densities and Star Formation Rate Densities to −17.7 AB mag[a]

Dropout Sample	$\langle z \rangle$	$\log_{10}\mathcal{L}$ (erg s^{-1} Hz^{-1} Mpc^{-3})	$\log_{10}$ SFR density ($M_\odot$ Mpc^{-3} yr^{-1})	
			Uncorrected	Corrected[b]
z	6.8	25.88 ± 0.10	-2.02 ± 0.10	-2.02 ± 0.10
Y	8.0	25.65 ± 0.11	-2.25 ± 0.11	-2.25 ± 0.11
J[d]	10.3	$24.29^{+0.51}_{-0.76}$	$-3.61^{+0.51}_{-0.76}$	$-3.61^{+0.51}_{-0.76}$
J[d]	10.3	<24.42[c]	< -3.48[c]	< -3.48[c]
B	3.8	26.38 ± 0.05	-1.52 ± 0.05	-0.90 ± 0.05
V	5.0	26.08 ± 0.06	-1.82 ± 0.06	-1.57 ± 0.06
i	5.9	26.02 ± 0.08	-1.88 ± 0.08	-1.73 ± 0.08

Critical SFR Density in Shull et al. 2011:
log10(0.018)= -1.74

Bouwens+2011, ApJ 737:90

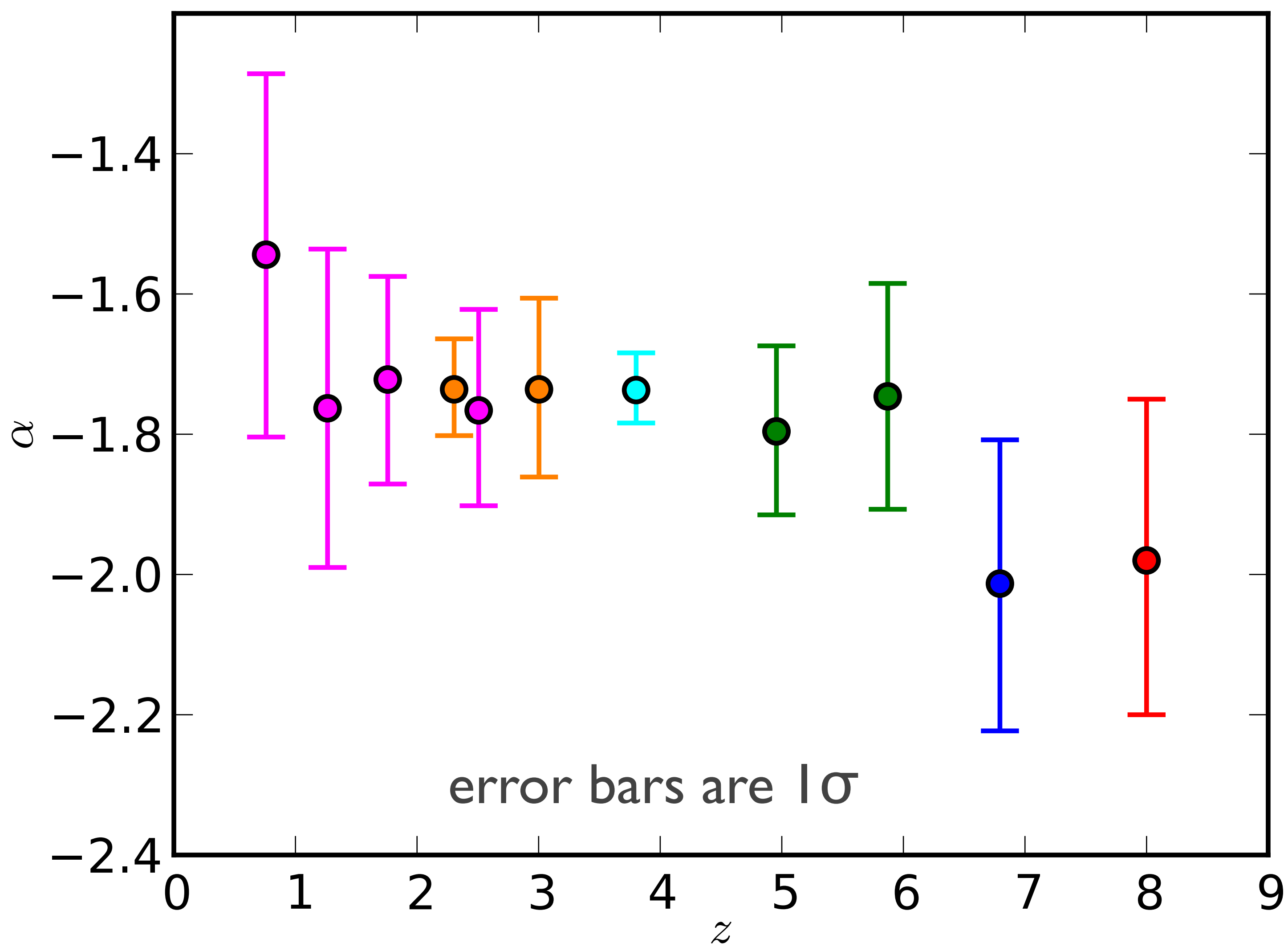
Ionization Fraction Dependence on SFR History



Solid: SFR history
from Trenti et al. 2010
Dashed: from Haardt and Madau 2011

Shull et al. arXiv:1108.3334

Faint-End Slope of UVLF

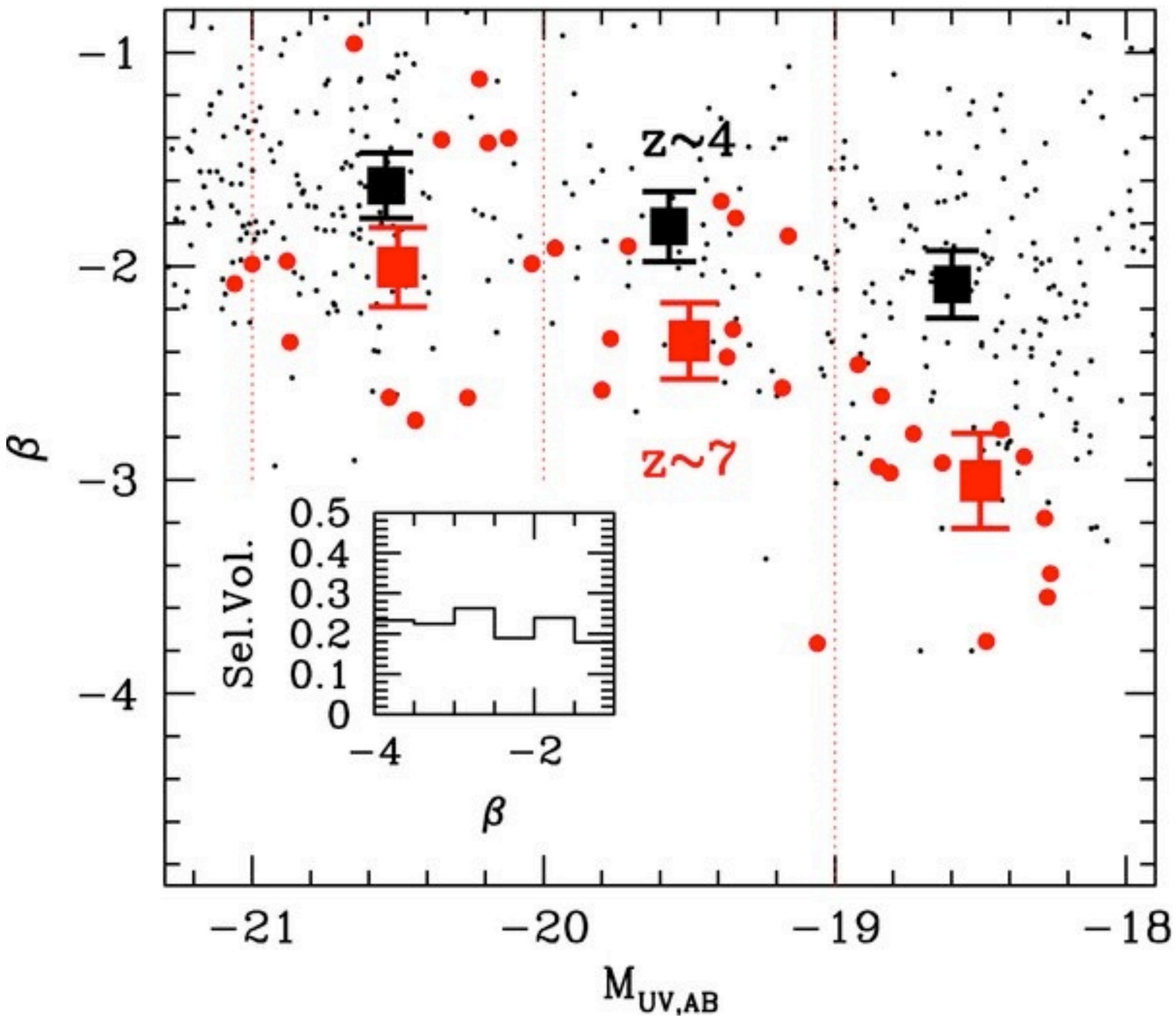


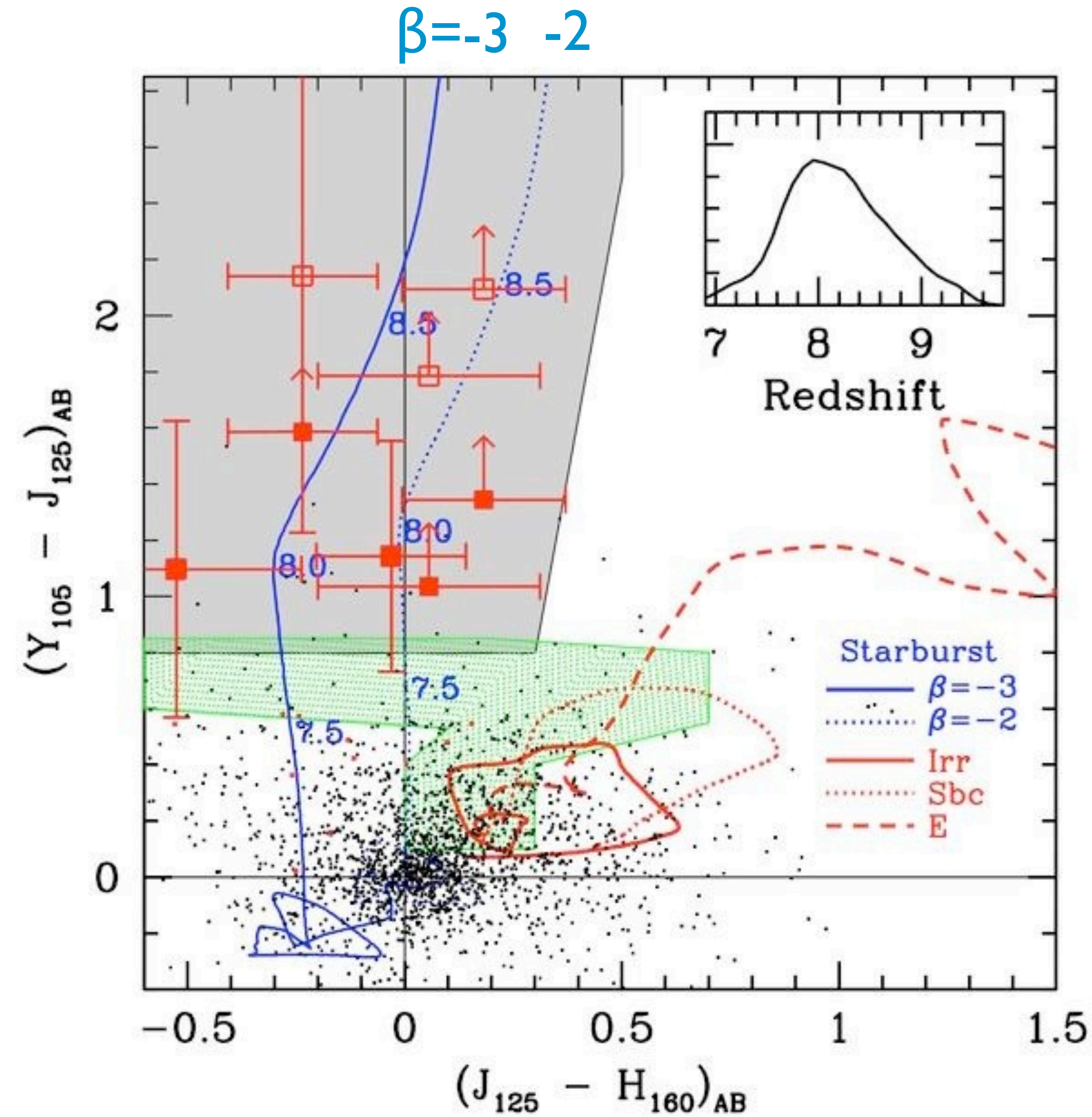
Bradley et al. 2012 arXiv:1204.3641

- Number density of faint galaxies has critical importance in Ionization Photon Budget.
- Some numerical simulations return steep UV slope at z>6 (Jaacks et al. MNRAS 420, 1606)
- Very deep observations are required.

Steep UV Slope - Extreme Stellar Populations?

- Bouwens et al. 2010, ApJ 708, L69; ApJ 709, L133; Finkelstein arXiv:1110.3785



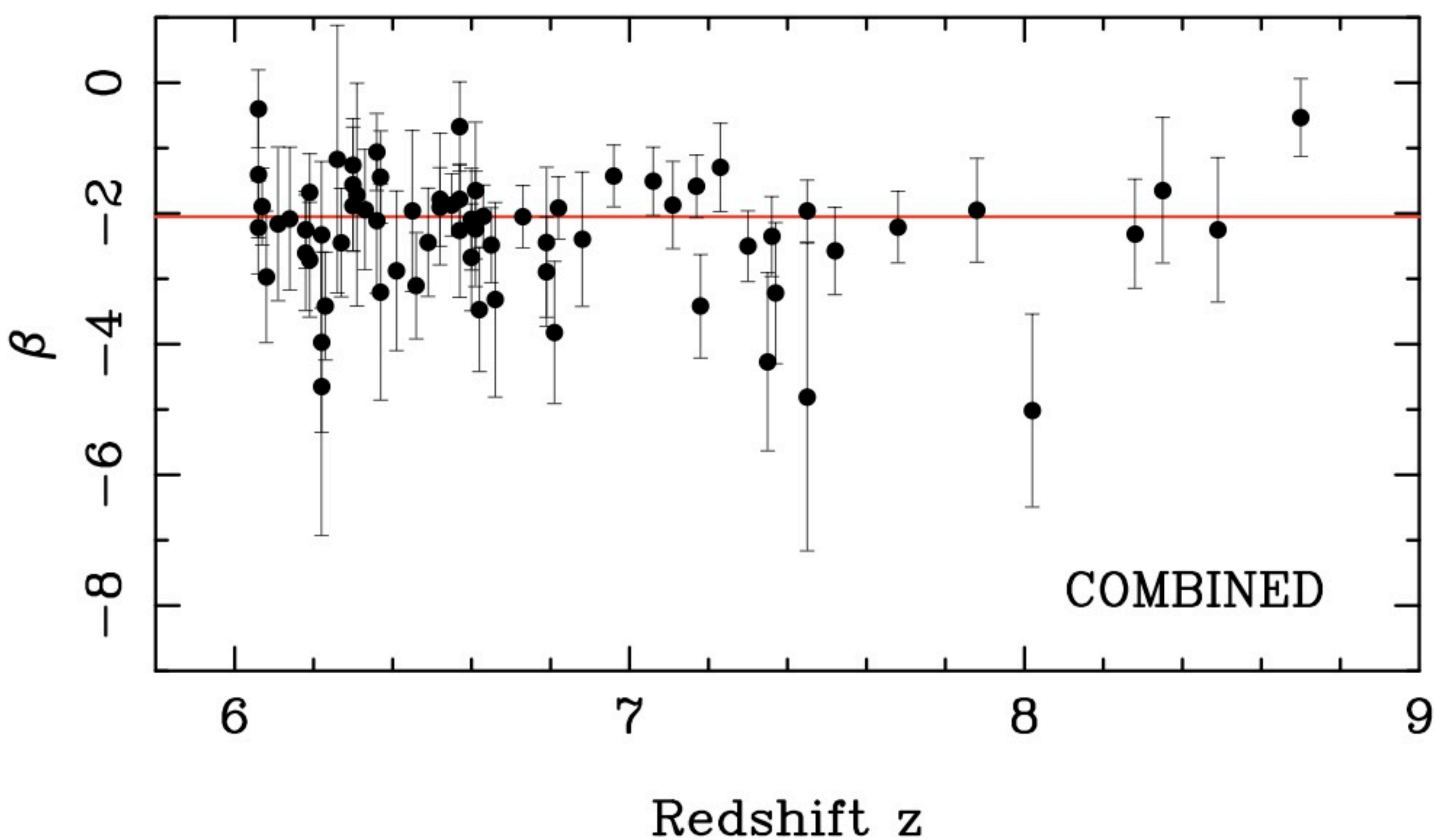


But β can be <-2 without extremely metal poor stellar populations

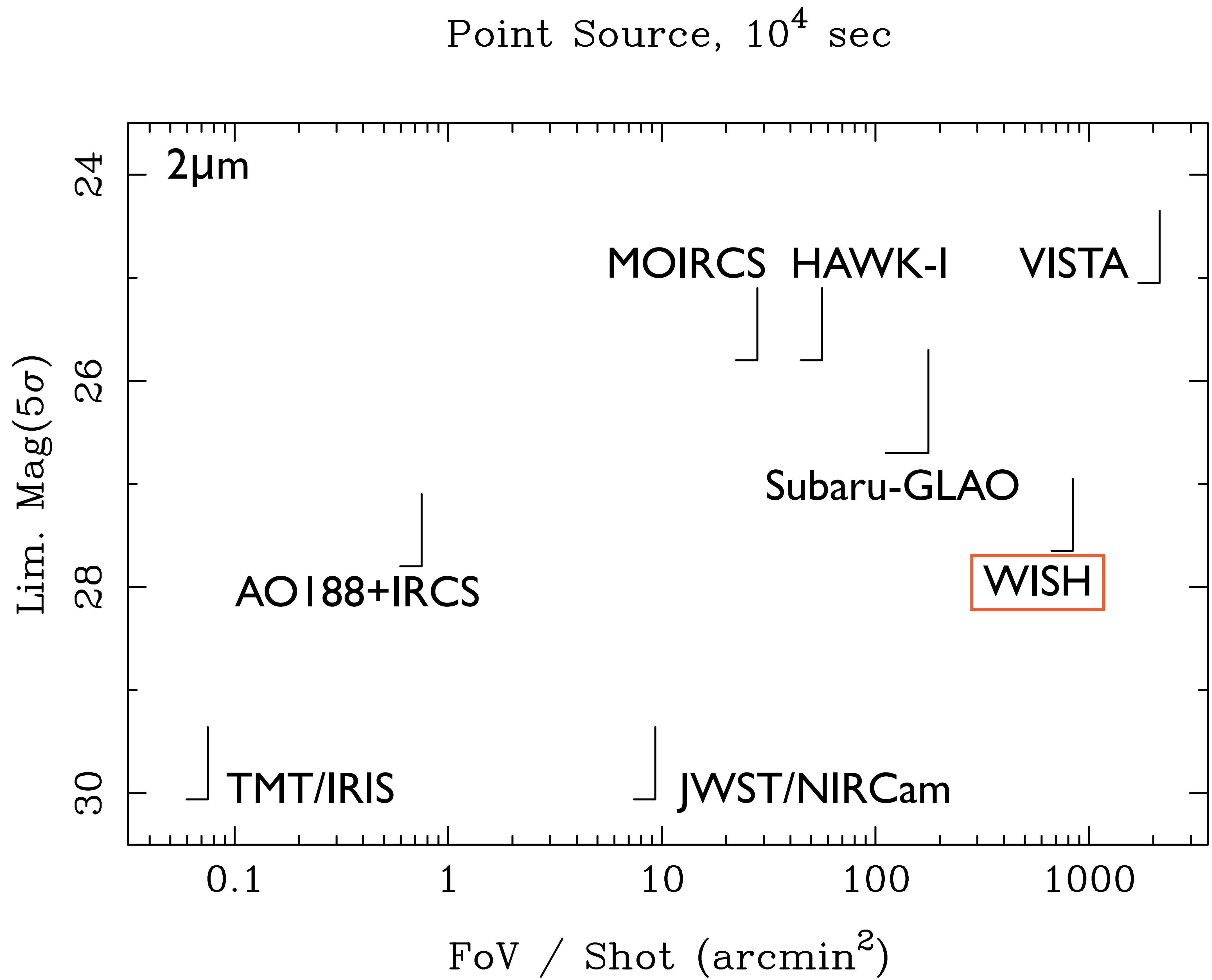
(Schaerer and de Barros 2010, A&A 515, A73)

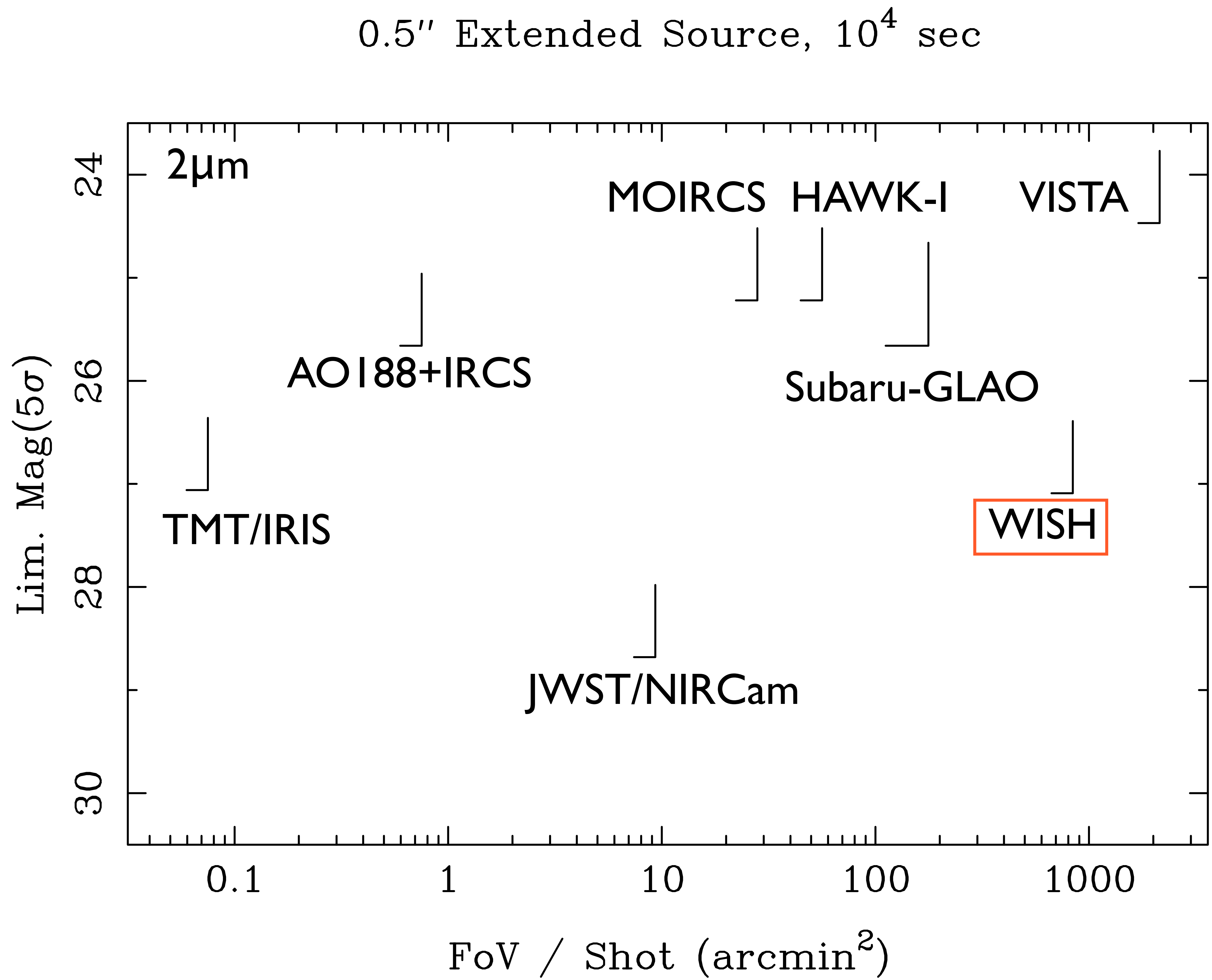
McLure et al. 2011 MNRAS 418, 2074

- McLure et al. 2011, MNRAS 418, 2074:
  - HUDF + ERS 6.0 < phot-z < 8.7
  - 70 objects
  - UV Slope β Mean: -2.05 ↔ β < -2.5 (Bouwens et al. 2010, Labbe et al. 2010)



WISH Ultra-Deep Survey

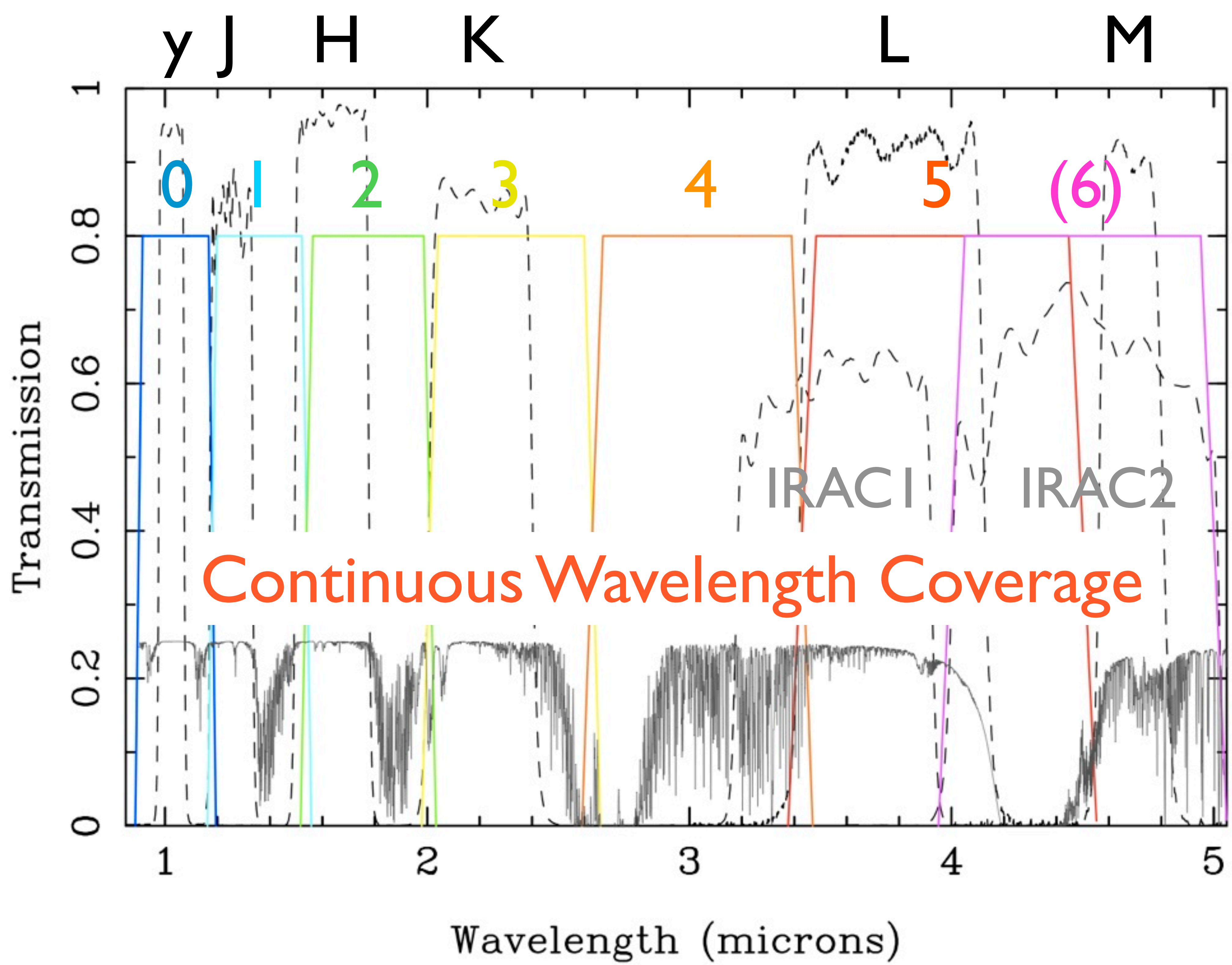

Point Source, 10^4 sec
2μm
MOIRCS
HAWK-I
VISTA
Subaru-GLAO
WISH
AO188+IRCS
TMT/IRIS
JWST/NIRCam
24
26
28
30
Lim. Mag(5σ)
0.1
1
10
100
1000
FoV / Shot (arcmin^2)

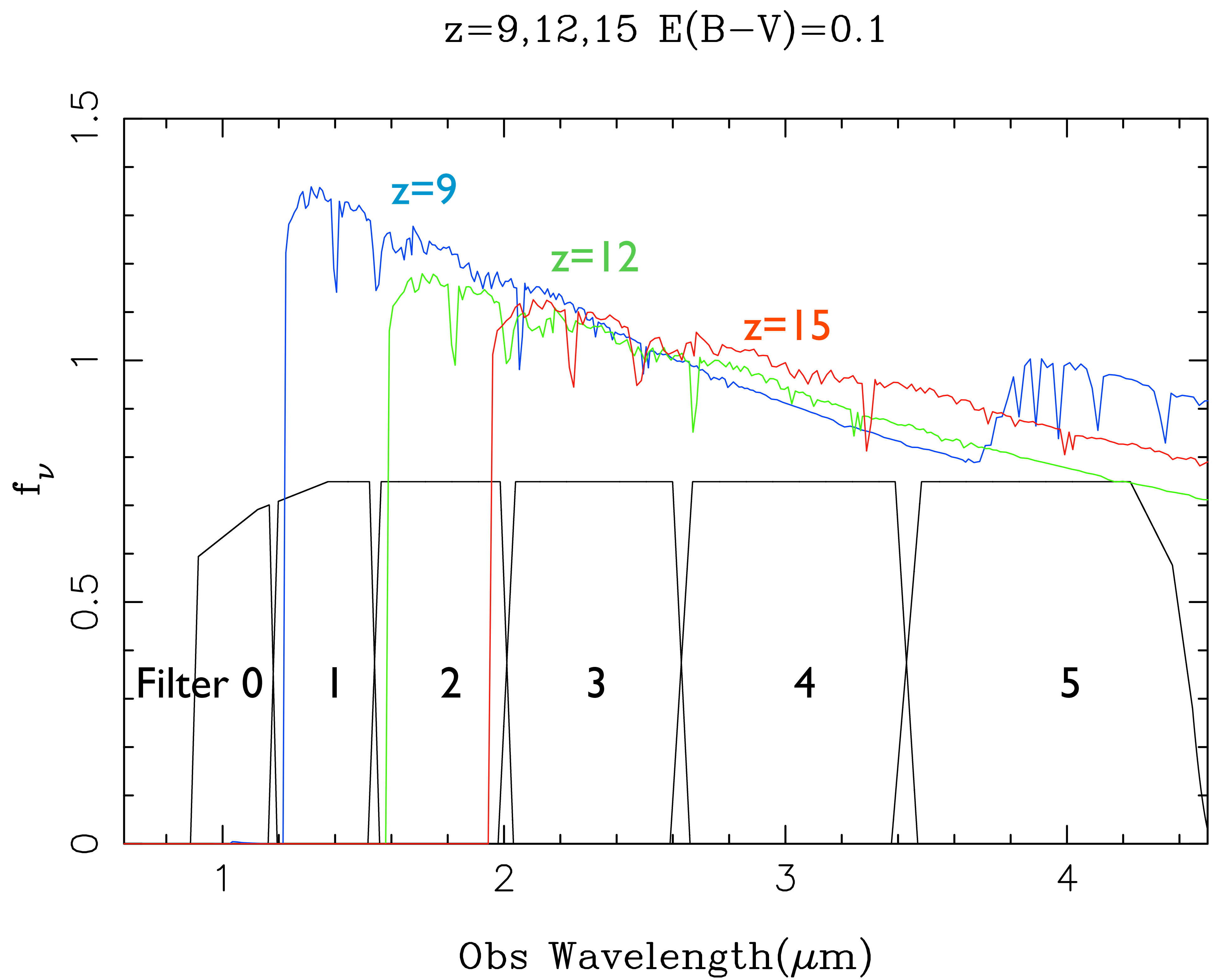

0.5″ Extended Source, 10^4 sec
2μm
MOIRCS
HAWK-I
VISTA
AO188+IRCS
Subaru-GLAO
TMT/IRIS
WISH
JWST/NIRCam
24
26
28
30
Lim. Mag(5σ)
0.1
1
10
100
1000
FoV / Shot (arcmin^2)

WISH Survey Plan

	Depth [AB mag.]	Area [sq. deg]	Days
Ultra Deep Survey	28.0	100	1,500
Ultra Wide Survey	25.0	1,000	50-100
Extreme Survey	~29.5	~1	<100

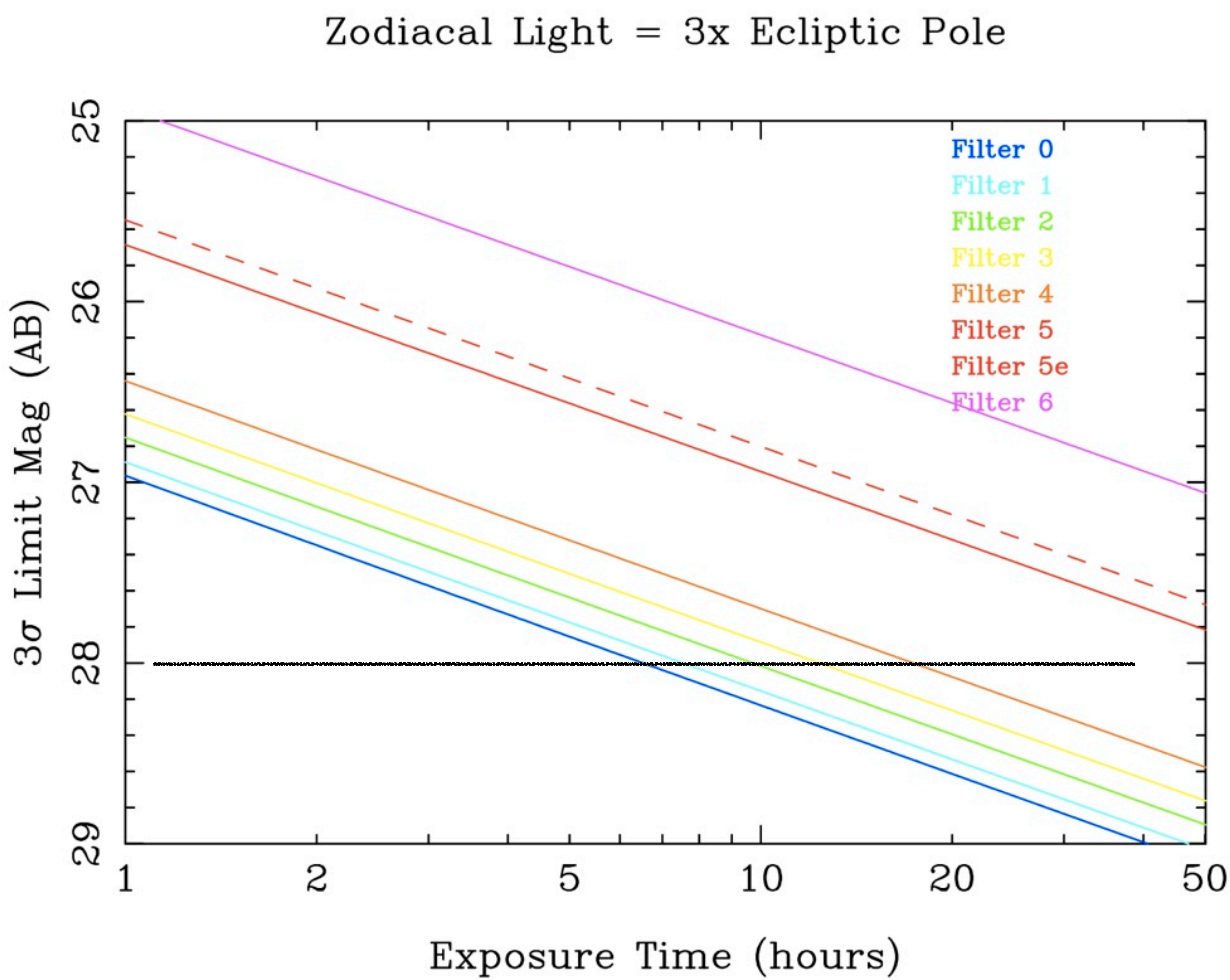
WISH Broad-band Filter Set



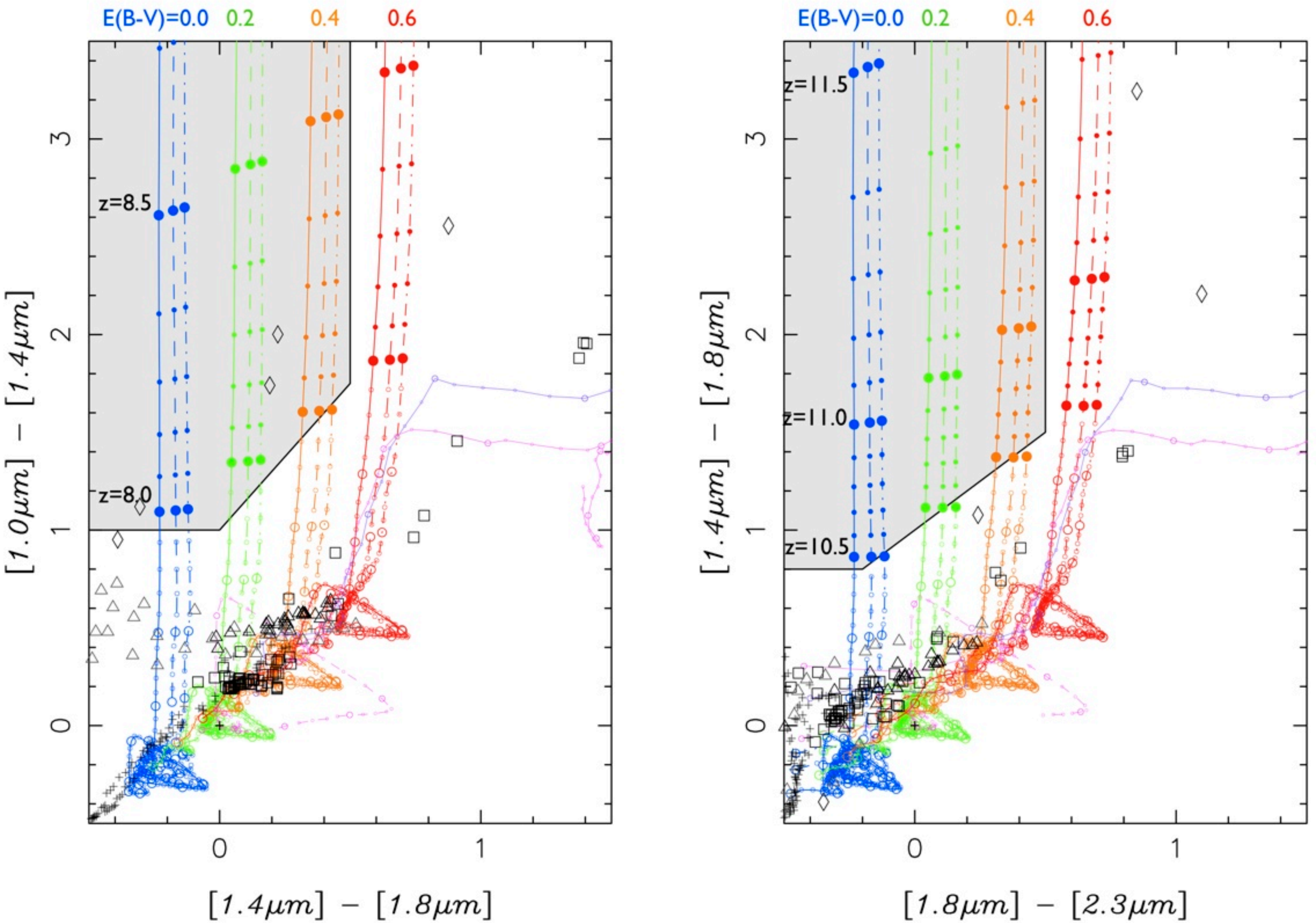


- Continuous Sampling for z>8
- Determine UV Slope

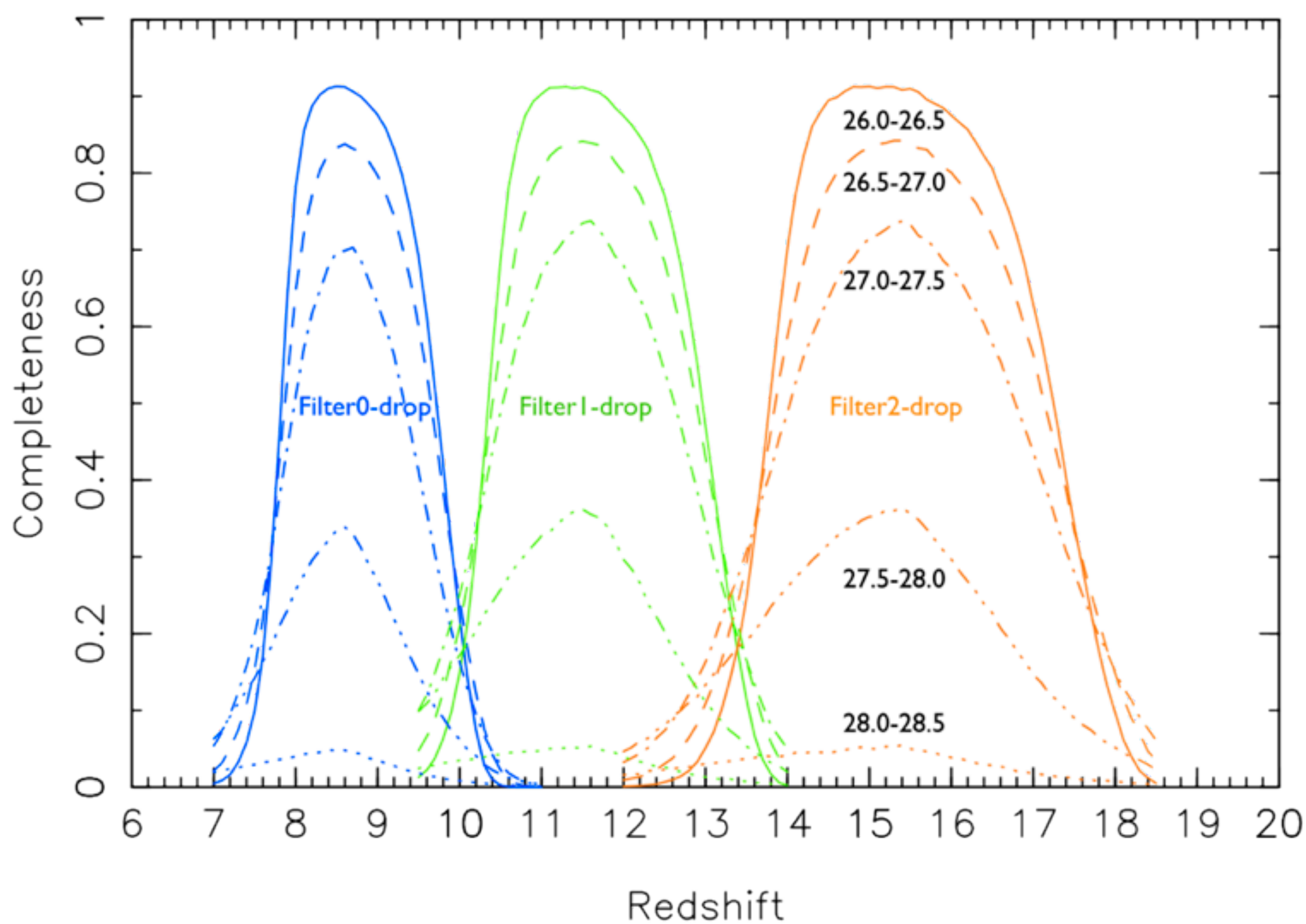
WISH: Expected Sensitivity



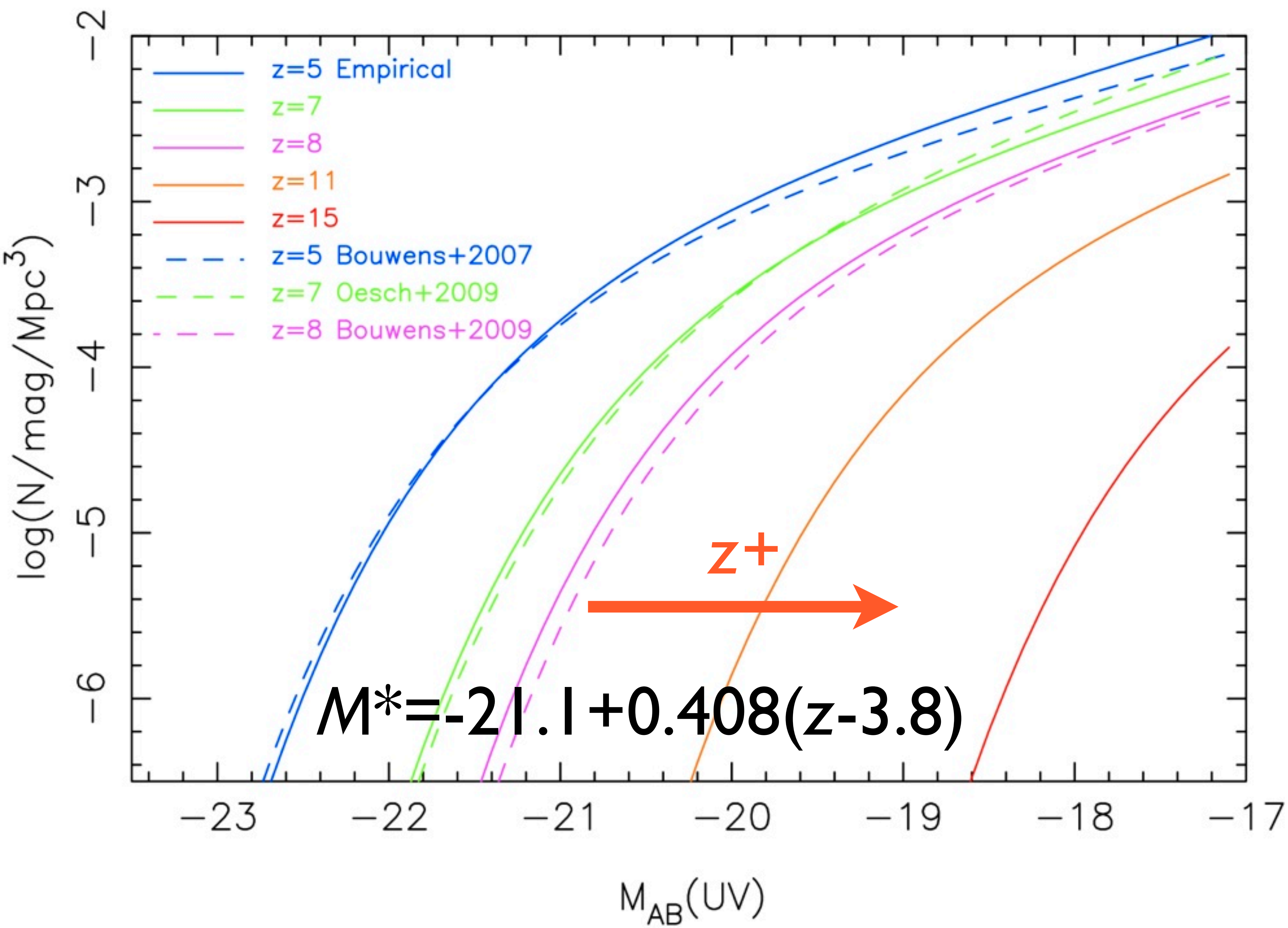
Selection of High-z Galaxies with Two-Colors



Completeness Estimates

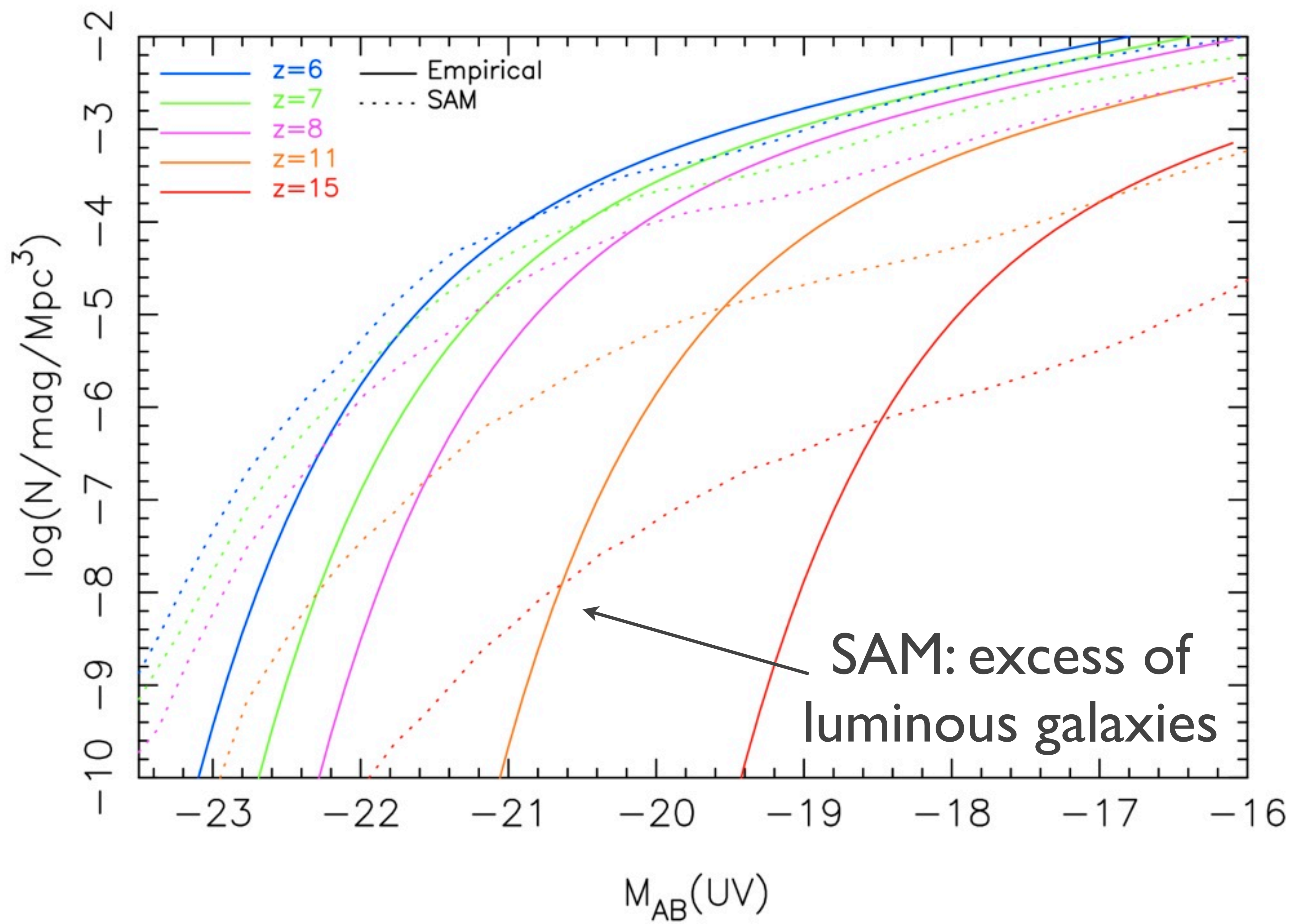


Assumption on Evolution of Luminosity Function(1)
Empirical Evolution



$M^*=-21.1+0.408(z-3.8)$

Assumption on Evolution of Luminosity Function(2) Semi-Analytic Model by Kobayashi et al.



Expected Numbers with WISH Ultra-deep Survey

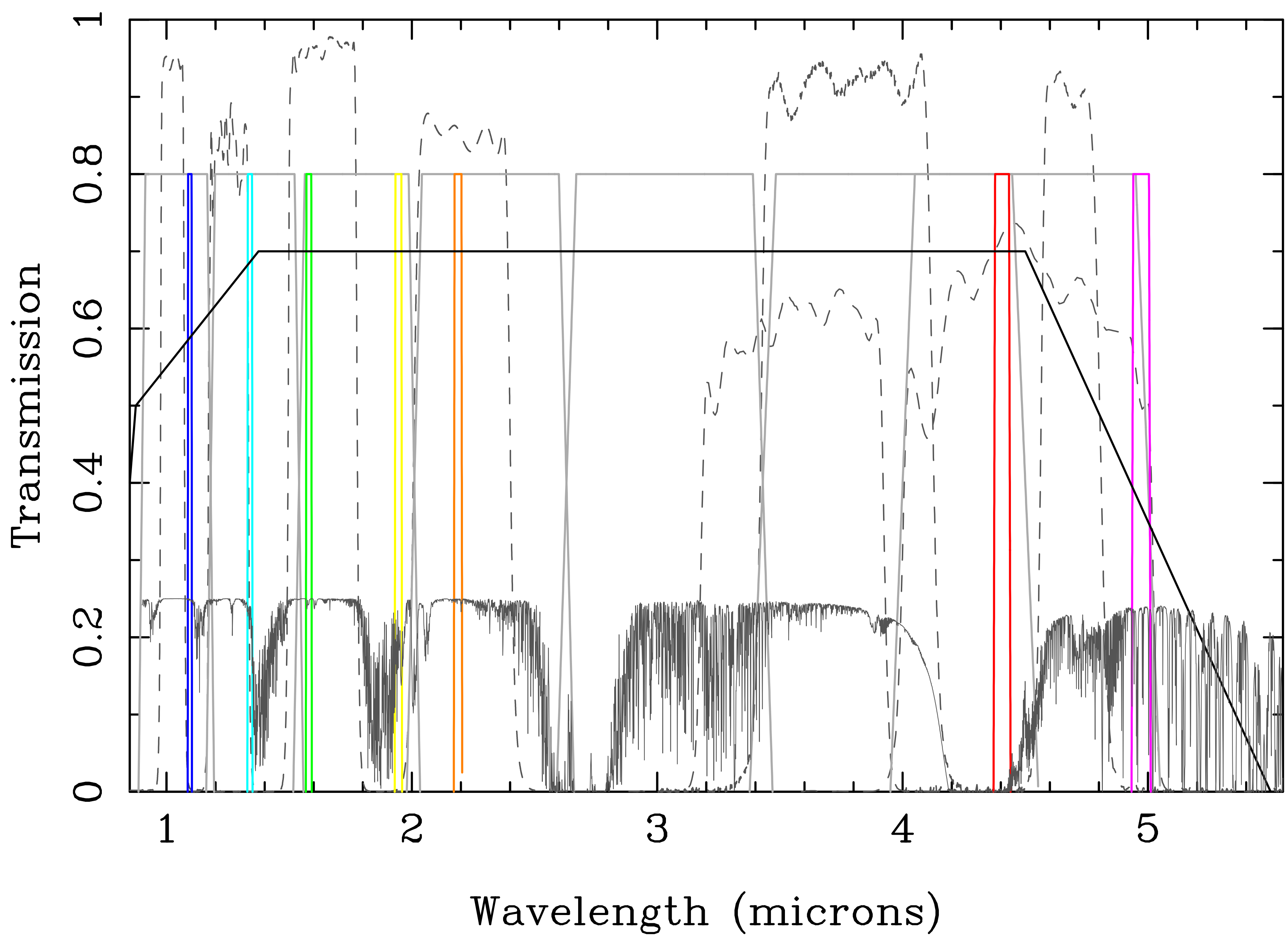
- 100 sq. deg survey with 5 filters from 1.0μm to 3.0μm
  - Limiting magnitudes 28AB (point source, 3σ)
  - Total 1,500 days

N/deg^2	z=8-9	z=10-12	z=13-17
Empirical Ev.	1690	104	0.72
SAM	631	49.7	1.07
DMH	852	4.12	0.003

WISH Can Determine
How Bright-End of UVLF Evolves at z>8

Narrow-band Filter Search for LAEs

NBF Set 01

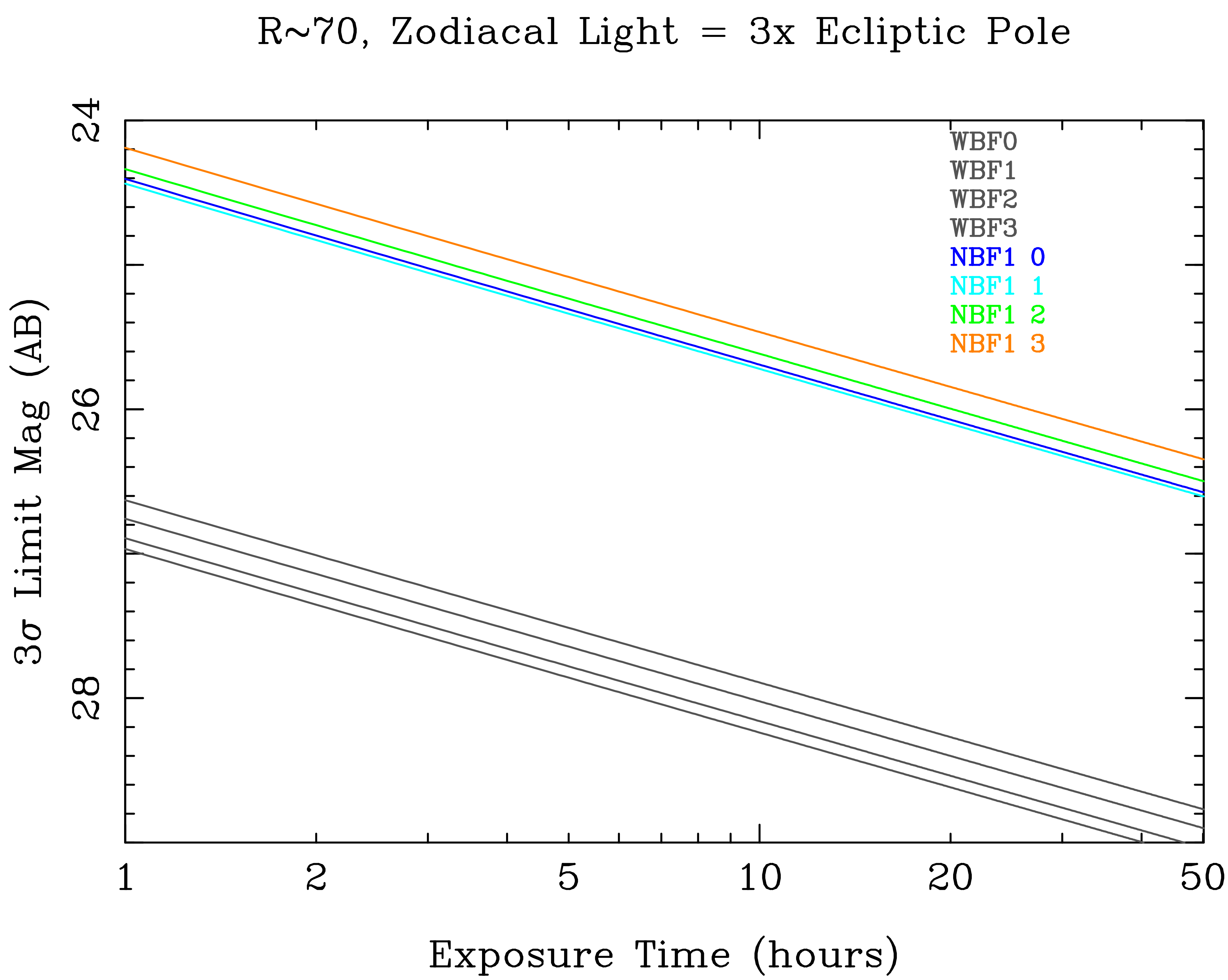


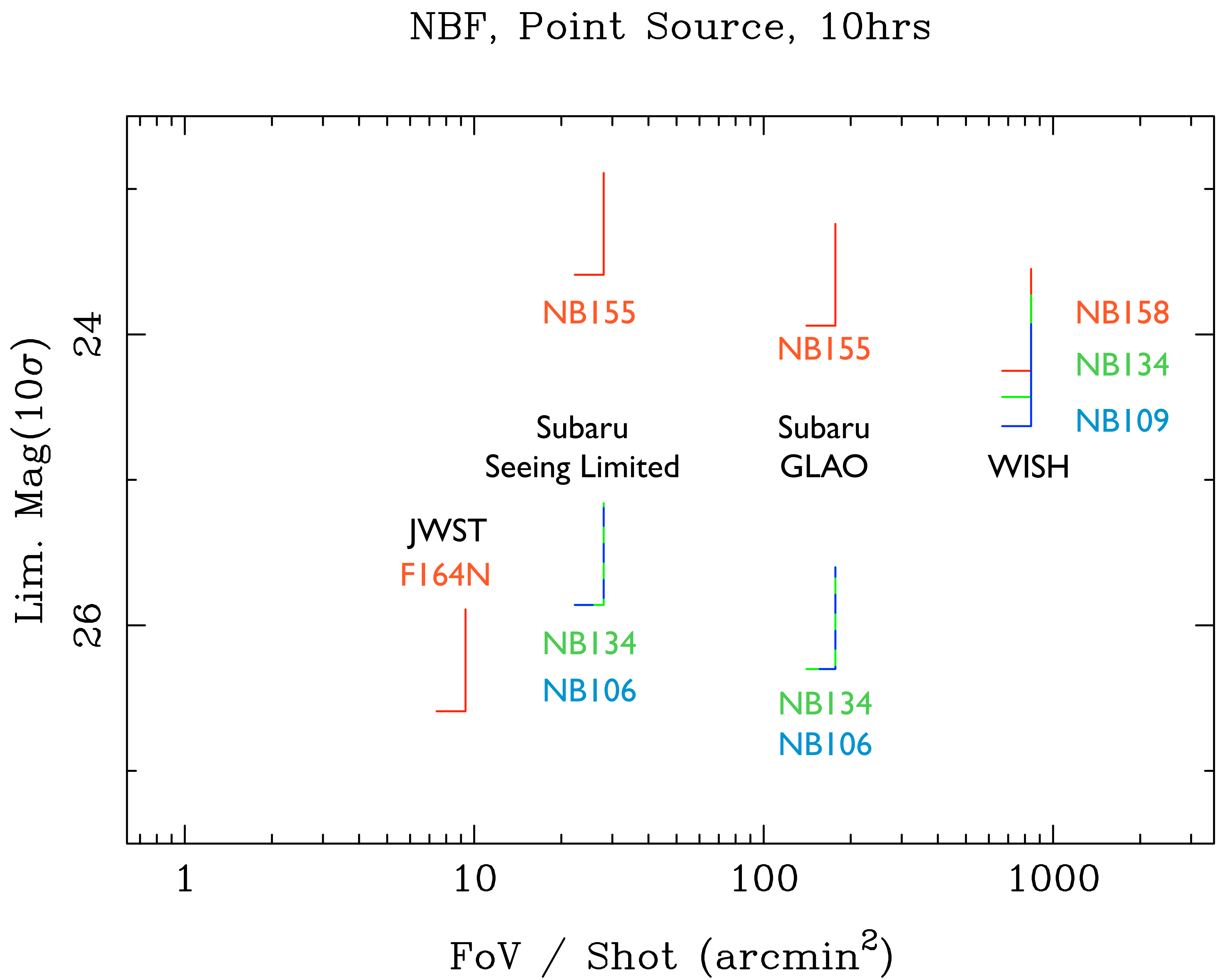
NBF Set 01 (R~70)

Name	λc	z	FWHM	R
0100_00	1.095	8.0	0.015	73.0
0100_01	1.340	10.0	0.019	70.5
0100_02	1.580	12.0	0.022	71.8
0100_03	1.945	15.0	0.027	72.0
0100_04	2.188	17.0	0.031	70.6
0100_05	4.4052	5.71*	0.063	69.9
0100_06	4.9720	6.58*	0.071	70.0

* redshift for $H\alpha$

NBF Set 01, Limiting Mag.





NBF, Point Source, 10hrs
Lim. Mag(10σ)
24
26
1
10
100
1000
FoV / Shot (arcmin²)
NB155
Subaru
Seeing Limited
JWST
F164N
NB134
NB106
NB155
Subaru
GLAO
NB134
NB106
NB158
NB134
NB109
WISH

Summary of Limiting Magnitudes and Expected Number of Detections for WISH

Limits are for 3σ

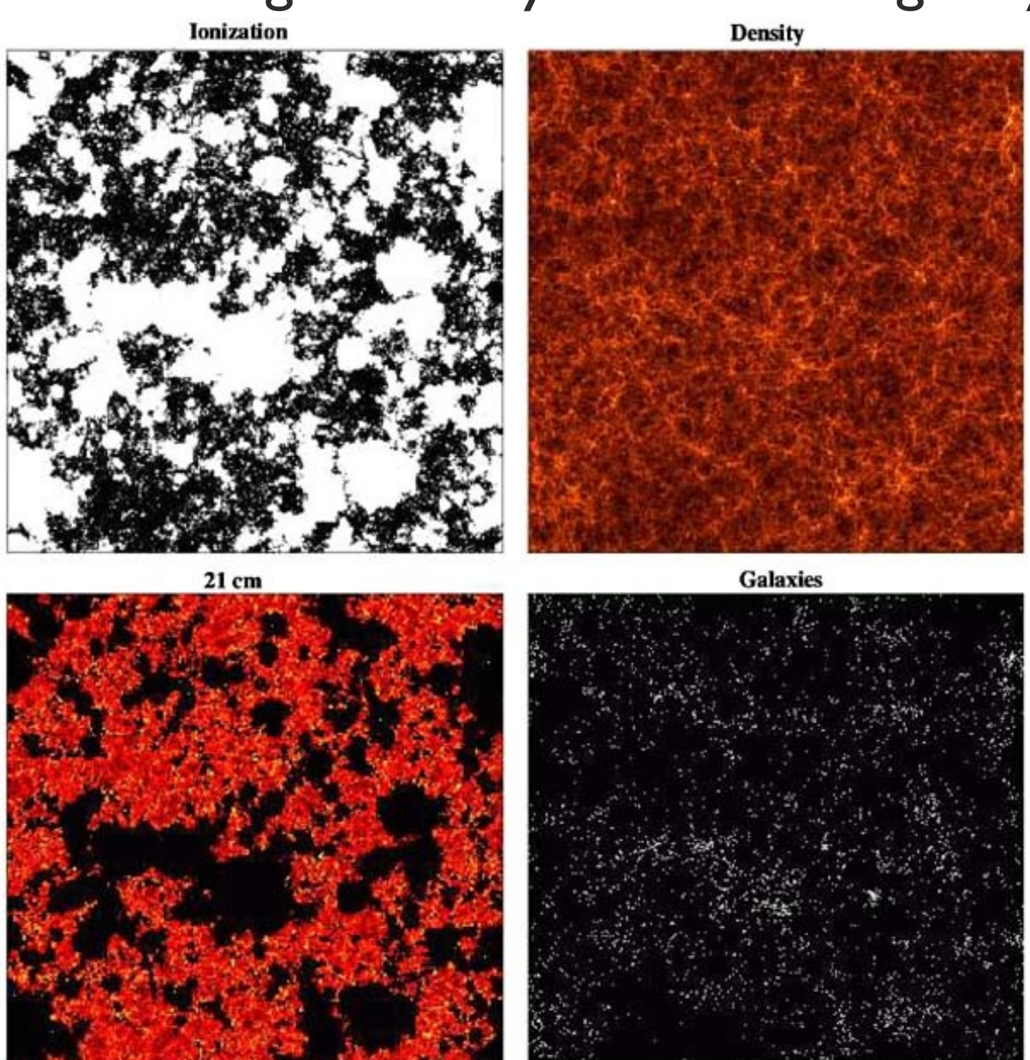
		R=50		R=100	
redshift	Exp Time	Lim Mag.	N/deg^2	Lim Mag.	N/deg^2
z=8	10h	26.0	52.9	25.3	9.1
	50h	26.9	91.3	26.2	71.1
z=10	10h	26.1	9.3	25.4	0.96
	50h	27.0	18.8	26.3	9.7
z=12	10h	26.0	2.40E-02	25.3	2.20E-02
	50h	26.9	0.40	26.2	0.42

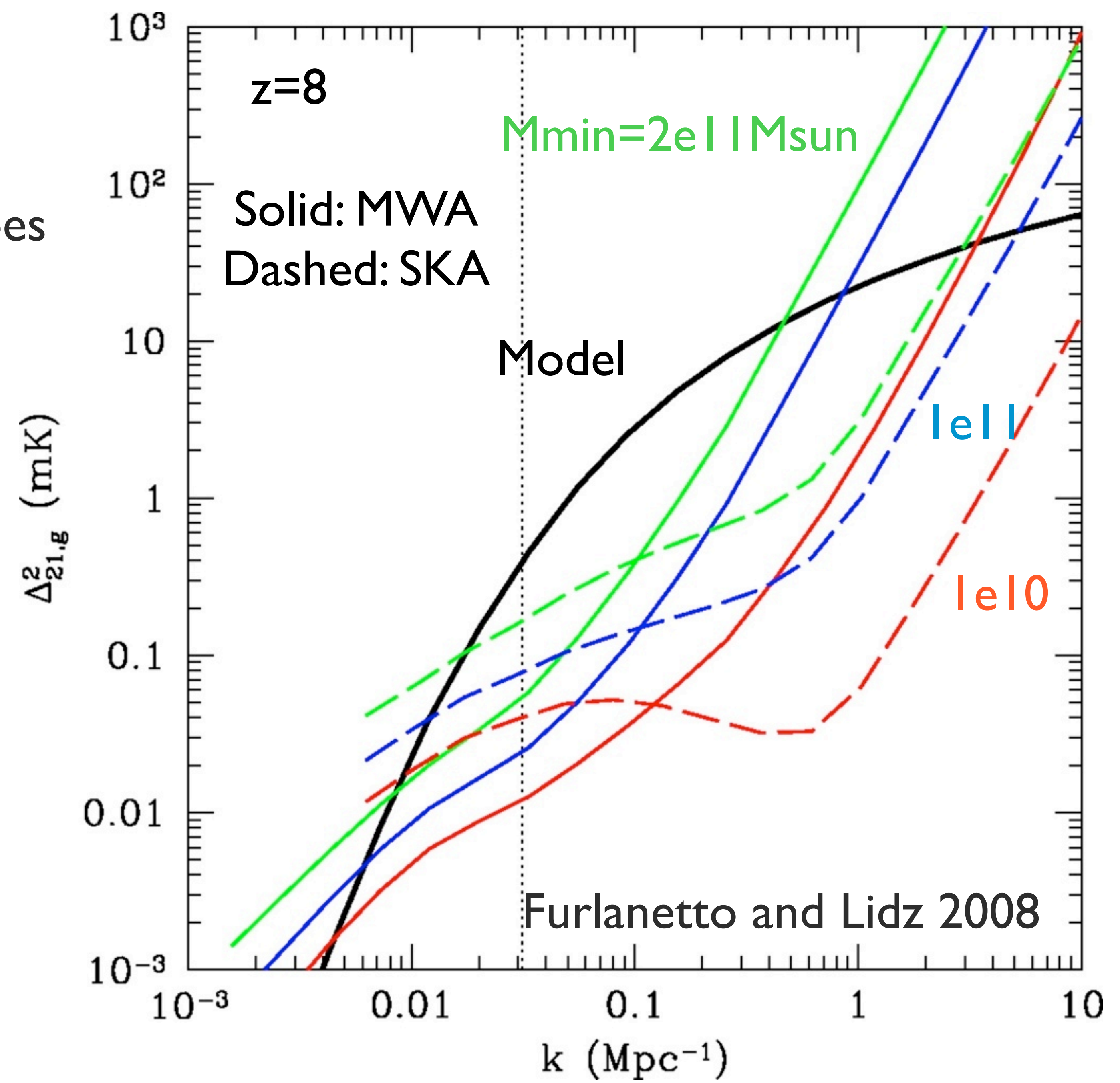
WISH Can Detect
Large Sample of LAEs at z=8-10

Cross-Correlation of Galaxies and IGM 21cm Emission

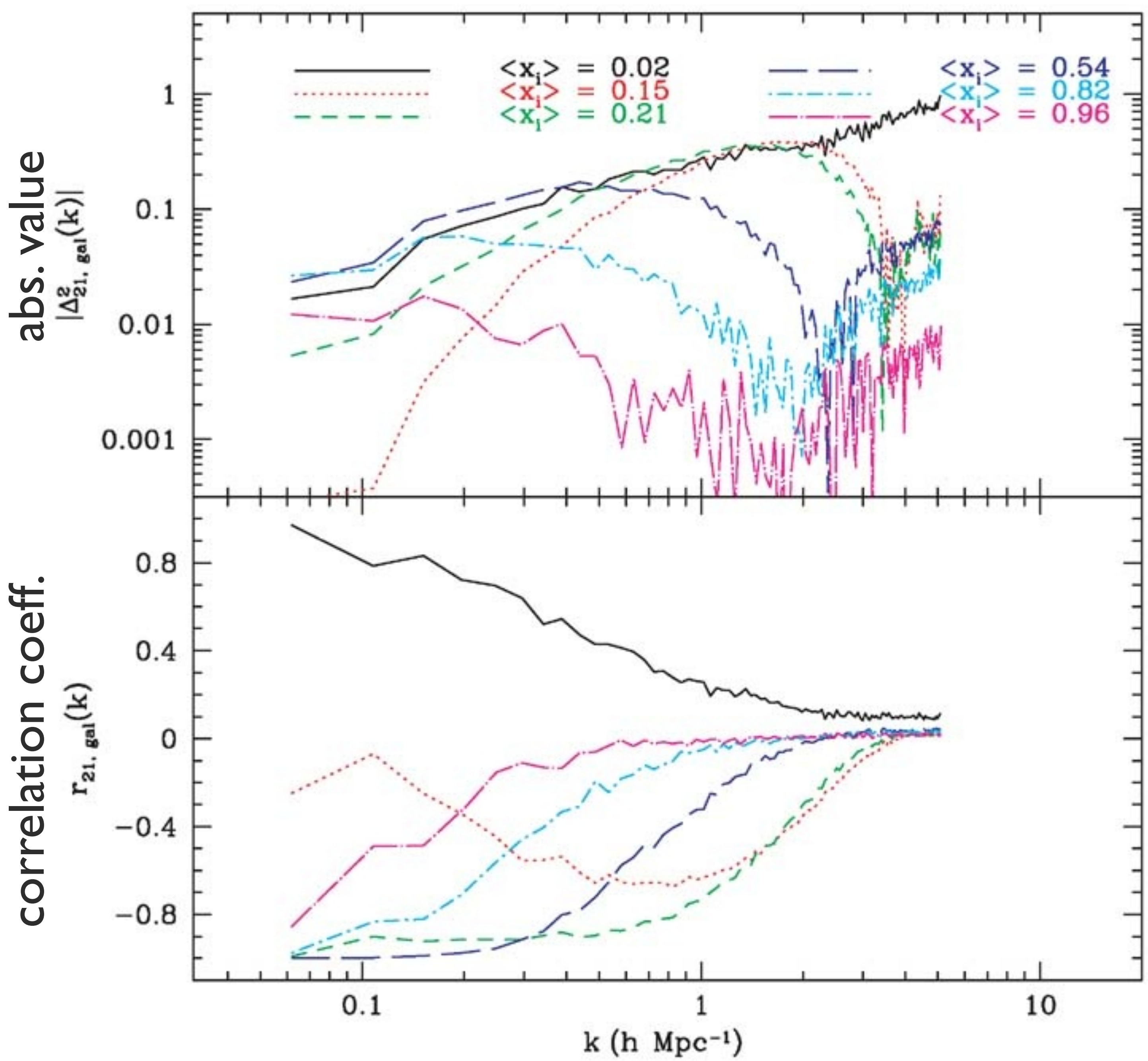
Cross-Correlation of HI 21cm Emission and Galaxies

- Wyithe and Loeb 2007, MNRAS 375, 1034; Furlanetto and Lidz 2008, ApJ 660, 1030
- Advantage of Galaxy - 21cm line cross correlation over 21cm signal alone:
  - Eliminates foreground contaminations
  - Possible S/N improvement
  - Ionizing efficiency for different galaxy types





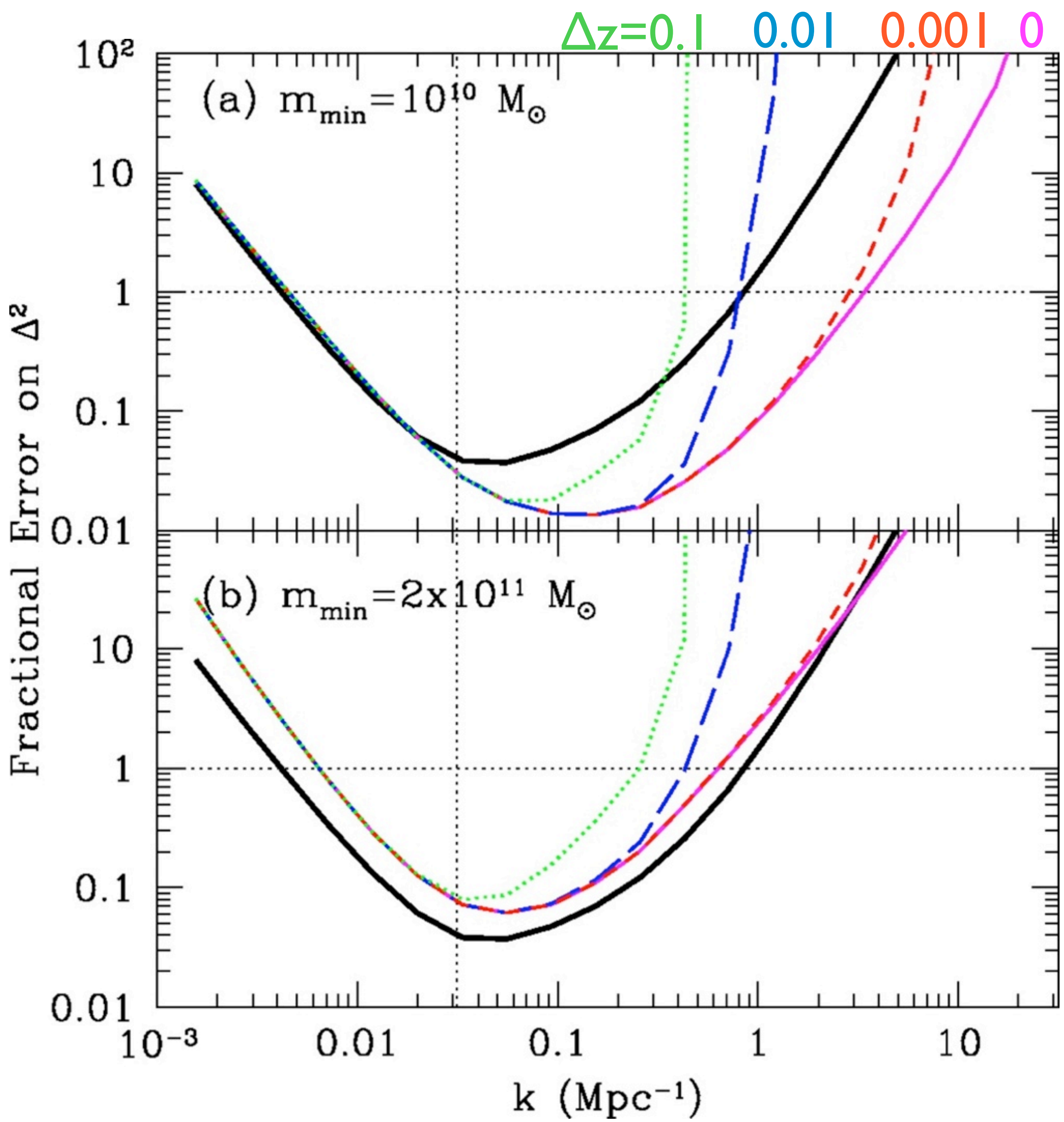
Resolving History of Reionization



Lidz et al. 2009, ApJ 690, 252

- Beginning: galaxy and 21cm are positively correlated
- Galaxies ionize overdense regions. Underdense regions remain neutral - Brief period of low amplitude cross-correlation (Xi=0.15 in the left model)
- Galaxy and 21cm quickly become anticorrelated

Requirements on the Galaxy Survey

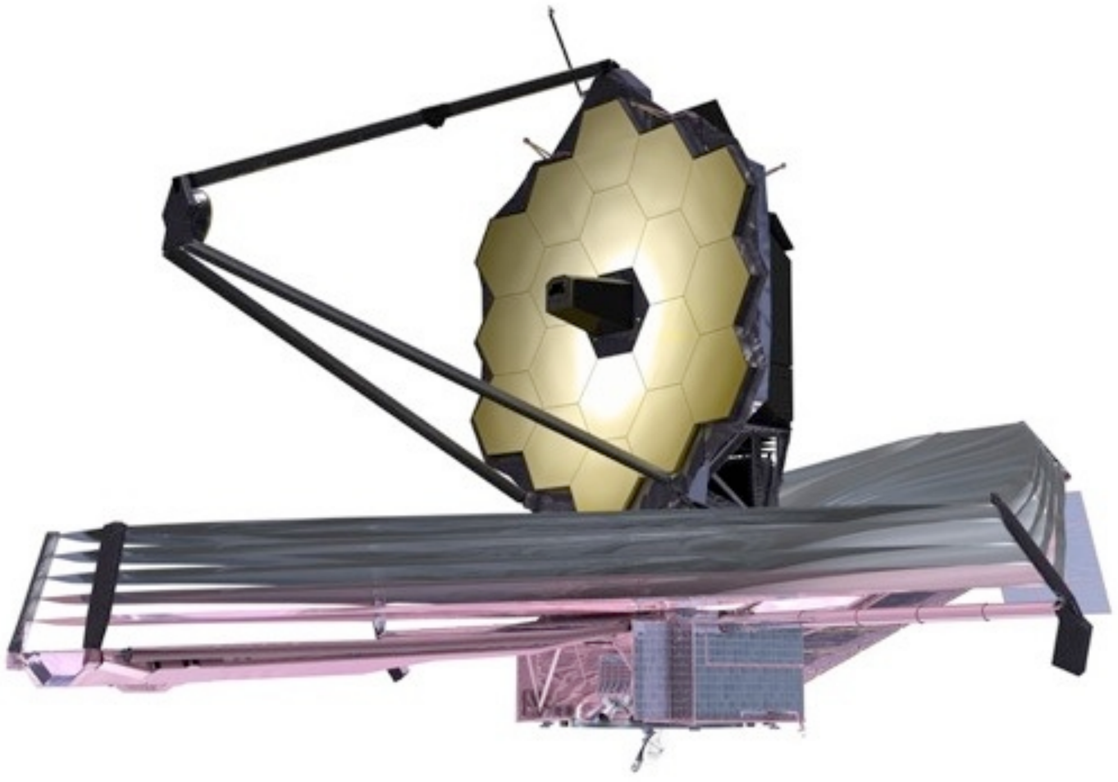


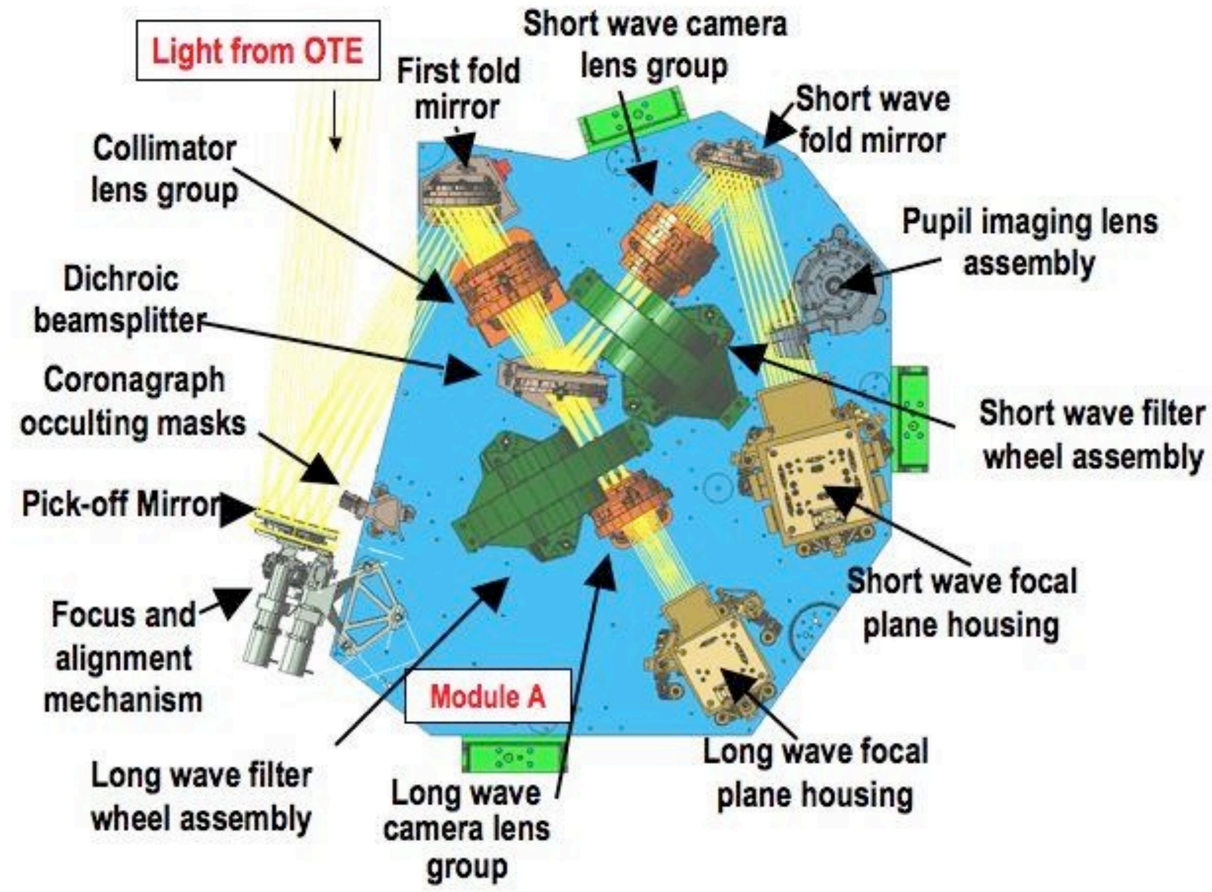
Furlanetto and Lidz 2008

- Accurate redshifts
  - LAE survey would be good
- Large area coverage
  - to improve S/N
  - >100 deg^2 survey area, coordinated with 21cm line obs.

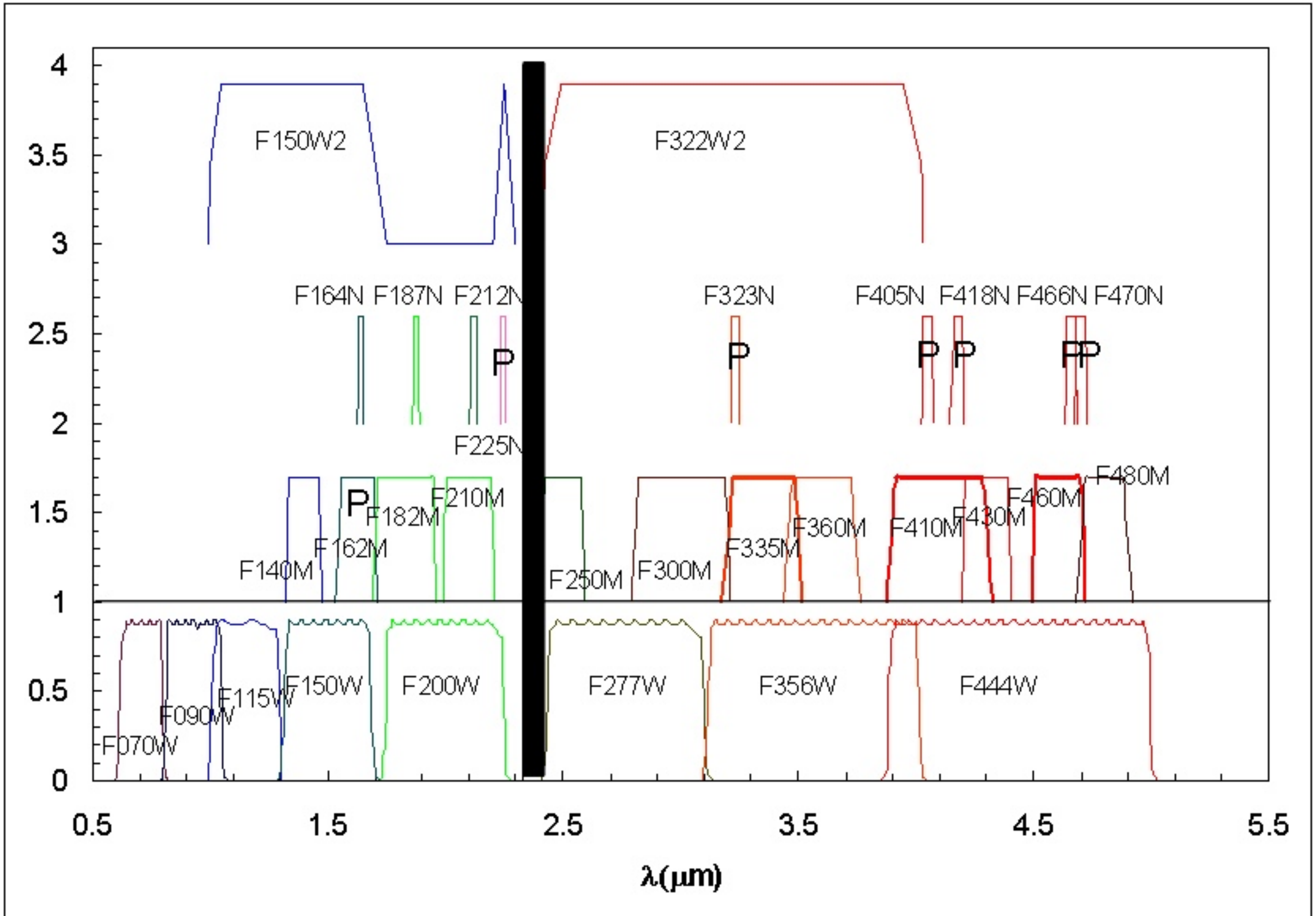
JWST NIRCam

- Two Channels, both 2.2’ x 4.4’
  - Short: 0.5 - 2.3 µm, 32 mas (8 H2RGs)
  - Long: 2.5 - 5.0 µm, 64 mas (2 H2RGs)
- Coronagraphic High Contrast Imaging
- Slitless Grism Spectroscopy R~1800





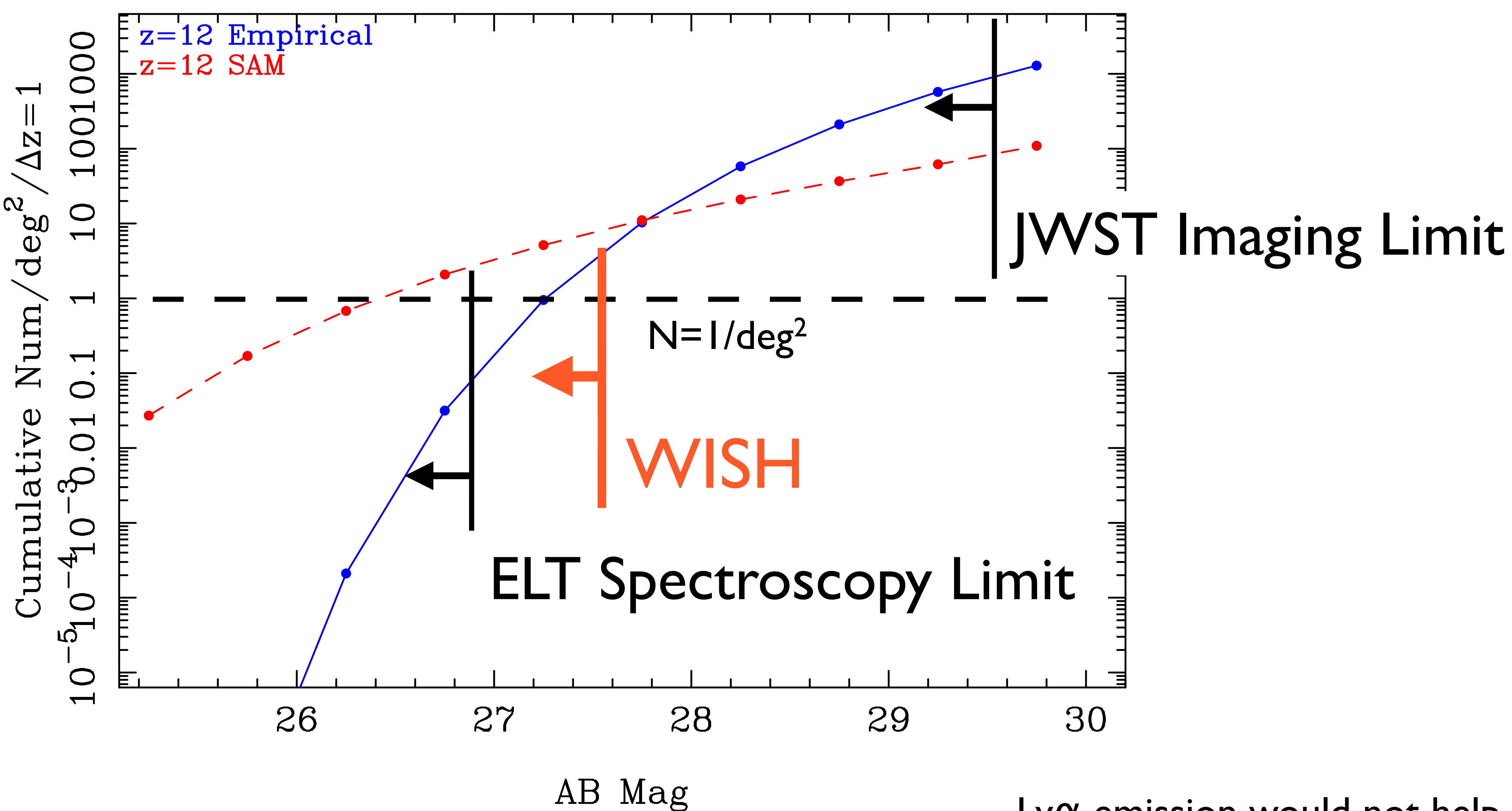
NIRCam Filters



JWST / NIRCam Expected Surveys

- Assume operation similar to HST
- Mirror size: x 2.6, Field of View: x 2.0
- HST WFC3/IR Deep Surveys: ~300 $arcmin^2$ in a few years
- NIRCam Surveys with Depth Similar to Current WFC3/IR Surveys (~29 AB mag.)
- → ~1 deg^2 in a few years. Several deg^2 in 5-10 years.

Number Density of z=12 Galaxies



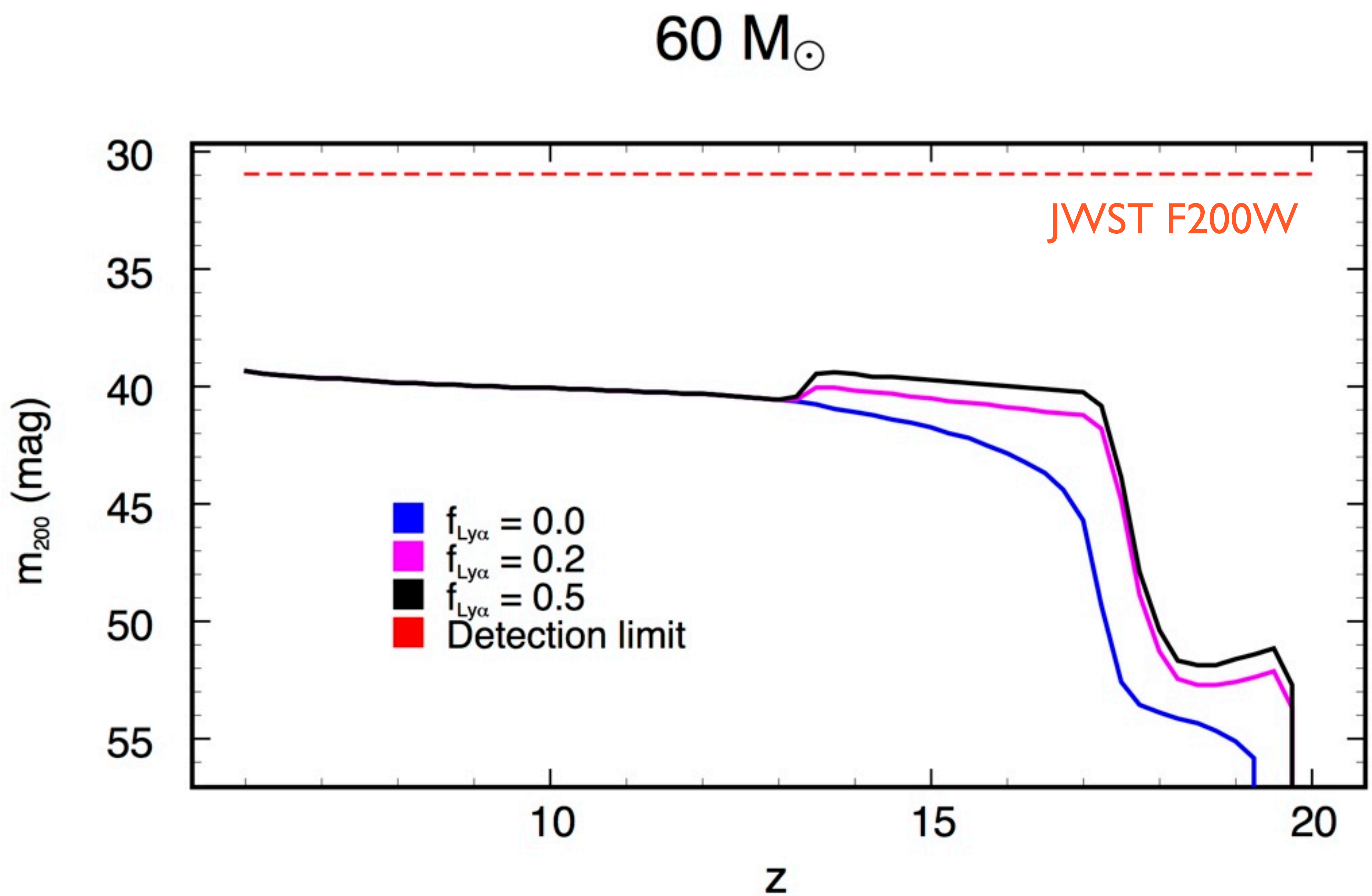
Lyα emission would not help improving the detection limit with ELTs for extended sources

WISH and JWST for Exploration of EoR

- WISH:
  - Discovery of Bright LBGs at 8 < z <15
    - Feed Spectroscopy Targets to ELTs
  - Bright-End of UV Luminosity Function
  - UV Slope of Bright LBGs
  - LAEs at z=8 and 10
    - Feed to ELTs
    - Cross-correlation with HI 21cm Line Surveys?
- JWST:
  - Determination of Faint-End of UV Luminosity Function
    - Contribution of Faint Galaxies to the Cosmic Reionization
  - Discovery of Galaxies at z>8 (up to z~20?)
    - Spectroscopy with NIRSpec
  - Limited Survey Area

‘First Stars’?

Expected Mag. of Isolated Pop-III Stars



Rydberg et al. arXiv:1206.0007

Comparison: Imaging

	Subaru MOIRCS	Subaru GLAO	TMT IRIS	HST WFC3/IR	JWST NIRCam
望遠鏡口径	8.2m	8.2m	30m	2.4m	6.5m
波長域	0.9-2.5μm	0.9-2.5μm	0.84-2.4μm	0.9-1.7μm	0.9-2.3μm / 2.4-5.0μm
空間サンプリング	0.117”/pix 0.4”@2μm	~0.1”/pix 0.2”@2μm	4 mas 10mas@1μm	0.13”/pix FWHM~ 0.25”	32 mas / 64 mas
視野	28 □’	~120 □’	0.075 □’	4.65 □’	9.7 □’

Comparison: Spectroscopy

	Subaru MOIRCS	Subaru GLAO	TMT IRIS	HST WFC3/IR	JWST NIRSpec
波長域	0.9-2.5μm	0.9-2.5μm	0.84-2.4μm	0.9-1.7μm	0.6-5μm
空間サンプリング	0.117”/pix 0.4”@2μm	~0.1”/pix 0.2”@2μm	4 - 50 mas	0.13”/pix FWHM~ 0.25”	0.2”x0.45”
視野	~25 □’	~120 □’	0.2-10 □”	4.65 □’	12.24 □’(MSA) 3”x3”(IFS)
分光機能	Single-Slit MOS IFS	Multi-IFS	IFS	Slitless	Slits Microshutters IFS
波長分解能	600-3000	-3000?	4000-10000	TBW	100, 1000, 2700

Euclid, WFIRST, and WISH

	Euclid	WFIRST	WISH
Mirror	1.2m	1.3m	1.5m
FoV	0.5 deg^2	0.3deg^2	0.23deg^2
Visual Imager	RIz	↓	--
NIR Imager	YJH	0.6-2.0μm	0.9-5.0μm
Lim. Mag.	24AB	25.9AB	28AB
Survey Area	20,000 deg^2	>11,000 deg^2	100 deg^2
Primary Science	Dark Energy	DE, Exoplanet, QSO	First Galaxies