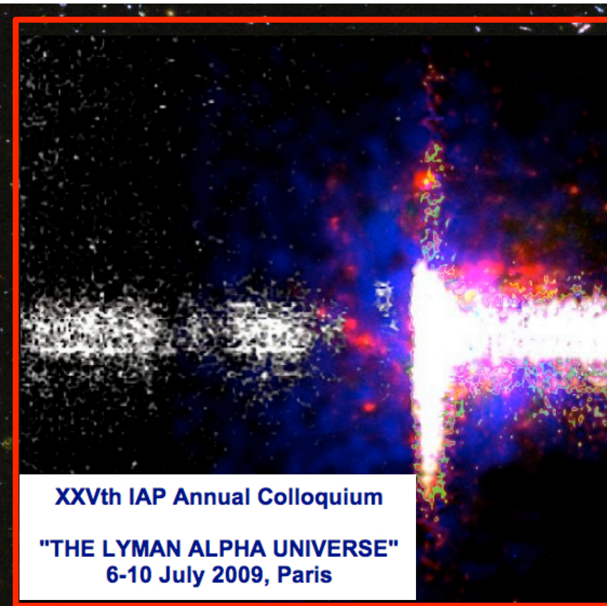
INSTITUT D'ASTROPHYSIQUE DE PARIS

Unité mixte de recherche 7095 · IAP · CNRS - Université Pierre et Marie Curie

XXVth IAP 2009 The Lyα Universe



Cosmic Star Formation since z~7-8: The SFR Density from the Reionization Epoch to z~2.5

Garth Illingworth

Rychard Bouwens

Marijn Franx, + many others

LBG galaxy populations at z~2.5-8: LBG results ⇔ Lyα results

Inputs

LBG selected samples of z~7-8 to z~2 galaxies from HST ACS & NICMOS + Spitzer IRAC

Spitzer MIPS data for IR populations + SCUBA

SUMMARY

Faint z~4, 5 and 6 UV Luminosity Function LF to ~3-4 mags below L* have steep slope: $\alpha \sim -1.7$

Low luminosity galaxies (L<0.07L*) contribute ~50% of luminosity density (and SFR)

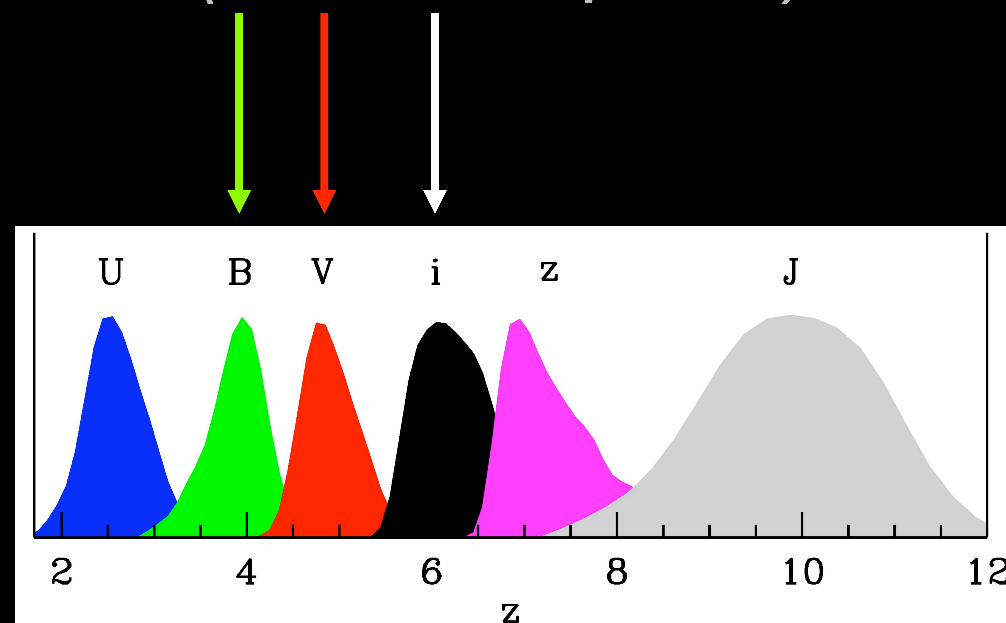
Less extinction for low luminosity galaxies and at higher z

Evolved/dusty 0.1L* – 2L* galaxies rare by z~4-5

ULIRGs/SMGs contribute ~20% of total SFR density at z~2.5, and <10% at z~4-5

Luminosity Functions at *z*~4, 5 & 6: Luminosity Density & SFR

(B, V, i-dropouts)

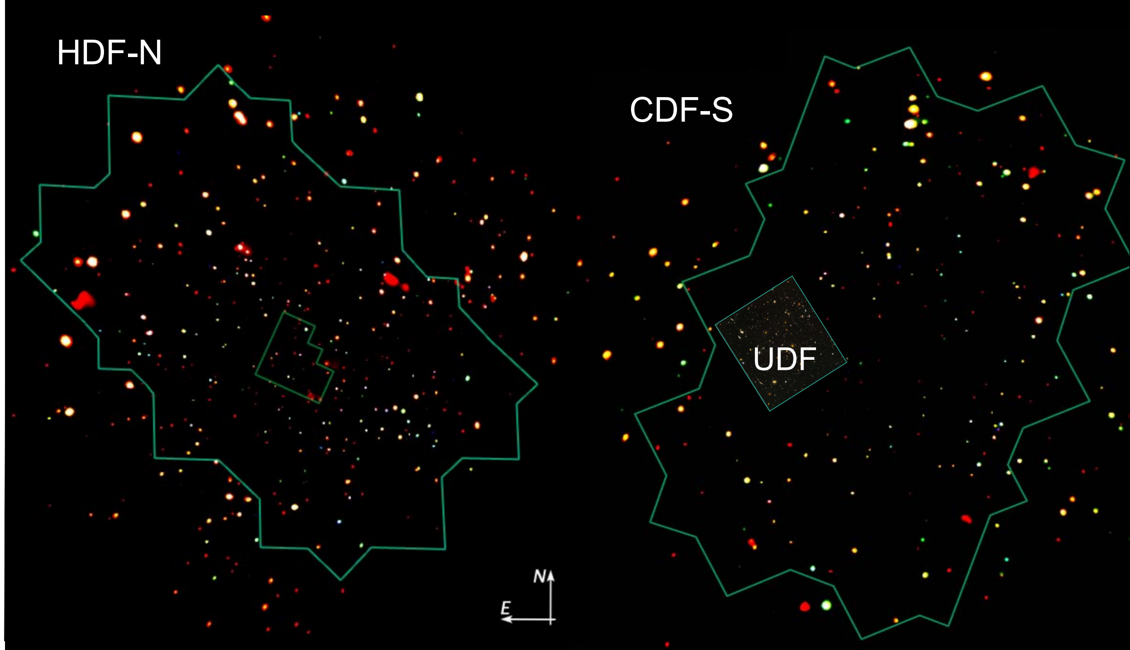


Dropout Redshift Selection Functions

GOODS+ HUDF for *z~10* => *z~2.5*

Wide ⟷ Deep

GOODS



$z_{850,AB}$~ 28.0 (5σ)

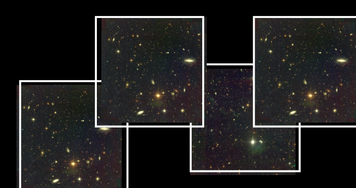
320 arcmin²

HUDF

$z_{850,AB}$~ 29.3 (5σ)

11 arcmin²

HUDF-Parallels



$z_{850,AB}$~ 28.8 (5σ)

40 arcmin²

4671 z~4 B-dropouts
1416 z~5 V-dropouts
627 *z~6 i-dropouts*!

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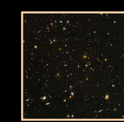
GOODS+ HUDF for *z~10* => *z~2.5*

Wide ⟷ Deep

GOODS

HUDF



$z_{850,AB}$~ 29.3 (5σ)

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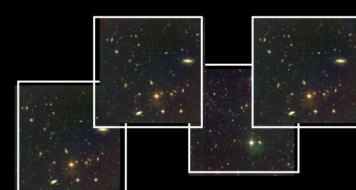
HUDF-Parallels



$z_{850,AB}$~ 28.8 (5σ)

40 arcmin²

$z_{850,AB}$~ 28.0 (5σ)

320 arcmin²

But wait for 2010 post-SM4 WFC3 & ACS results!

→

4671 z~4 B-dropouts
1416 z~5 V-dropouts
627 *z~6 i-dropouts*!

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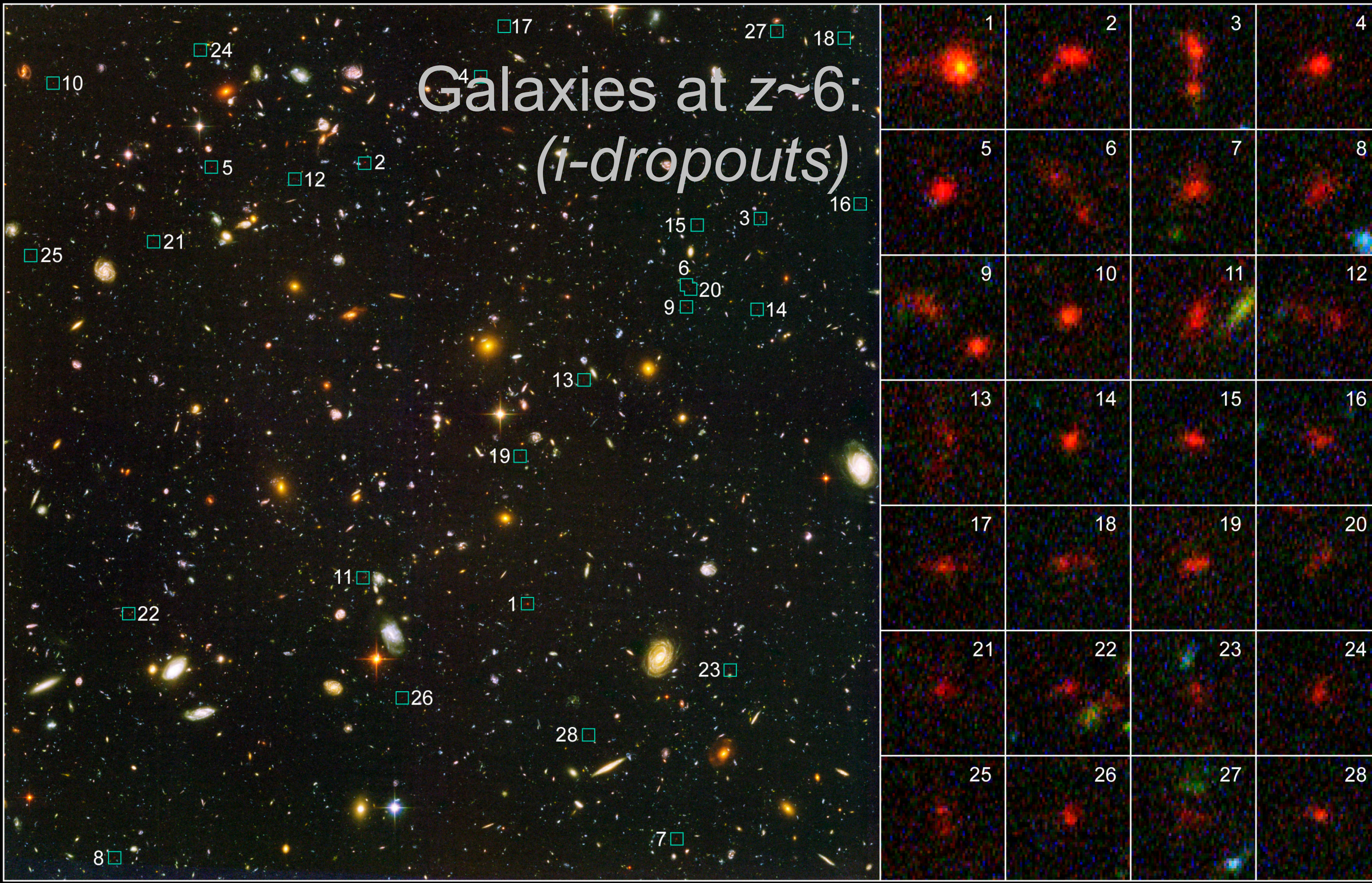


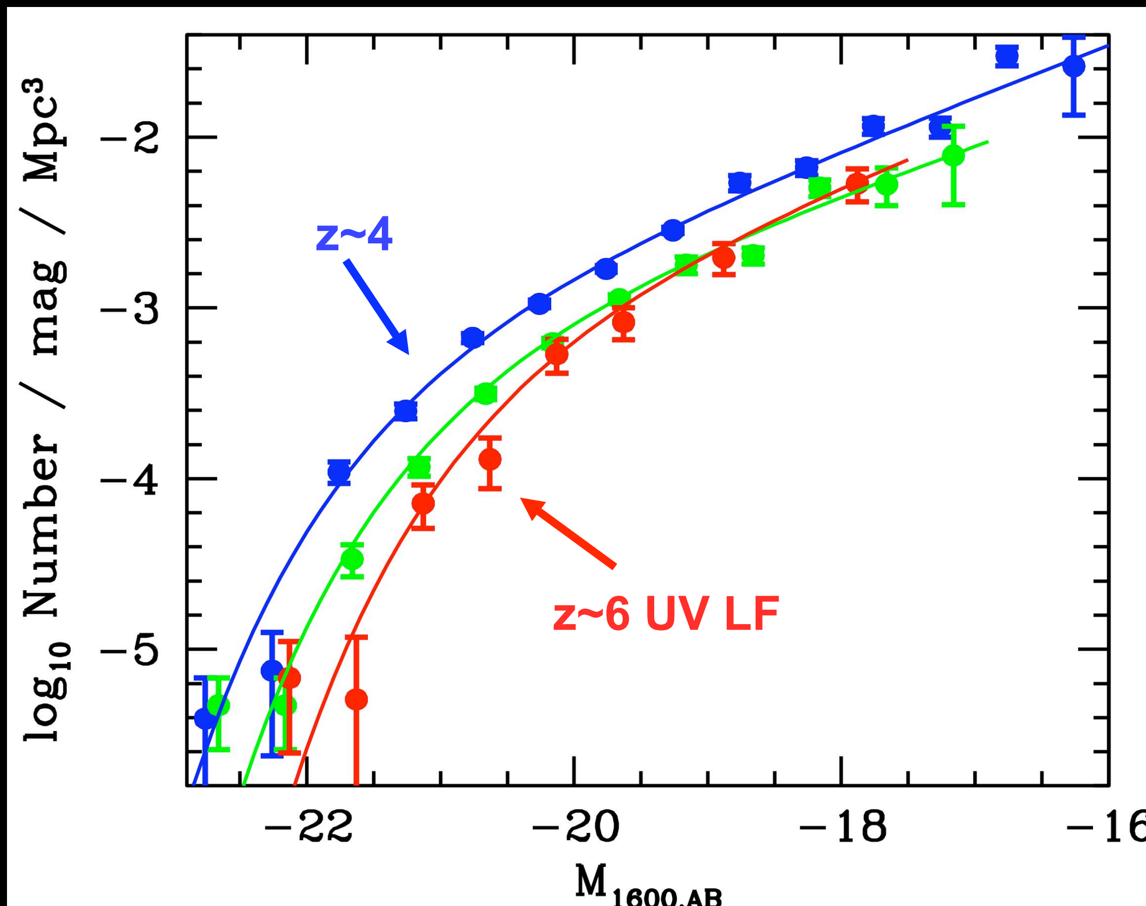
Distant Galaxies in the Hubble Ultra Deep Field

Hubble Space Telescope • Advanced Camera for Surveys

z~4, 5, 6 UV Luminosity Functions

Rest frame UV 1600 Å

Log # mag^{-1} Mpc^{-3}



Measurements done over a very large range in M_{1600} From -16/18 to -22.5!

Faint-end slope steep & ~constant $\alpha \sim -1.75$

L* is fainter at higher z

Bouwens, Illingworth, Franx and Ford ApJ 2007

Consistent LF analysis using all data across GOODS fields, UDF and the parallel fields.

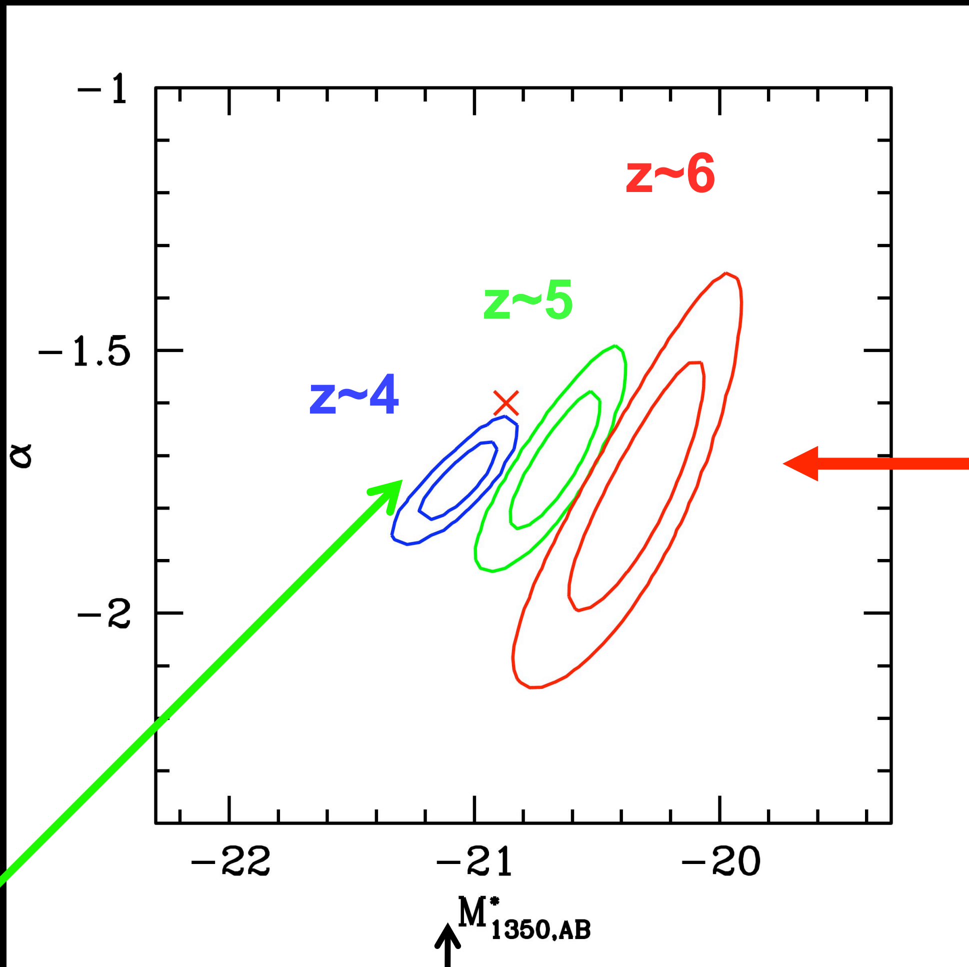
Schechter Luminosity Function Parameters: α vs L*

Shallow

Faint-end slope α

Steep

α same at z~2-3: Reddy et al 2008



Bright L* Faint

Density φ* is ~constant

~constant faint end slope: α ~ -1.7

L* brightens by ~0.8 mag

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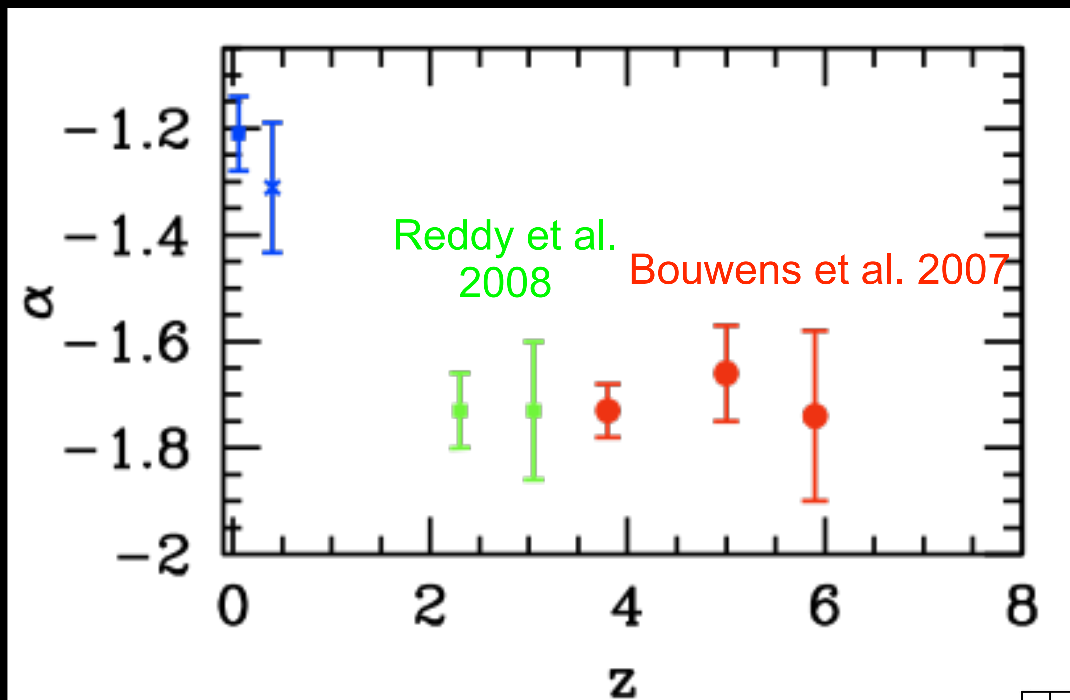
Faint-end Slope of the UV Luminosity Function

Shallow

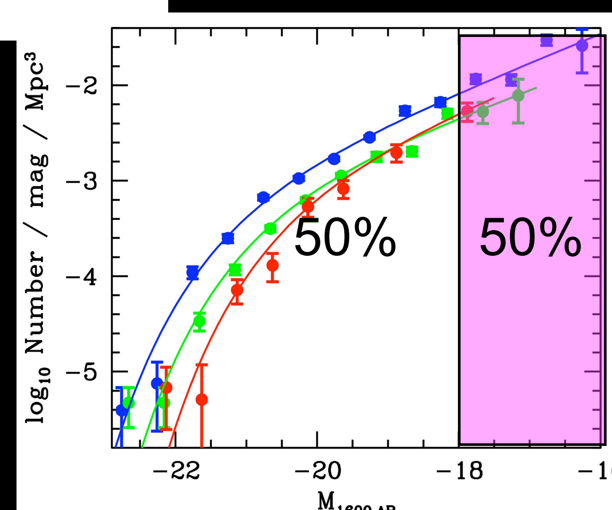
Faint-end slope α

Steep



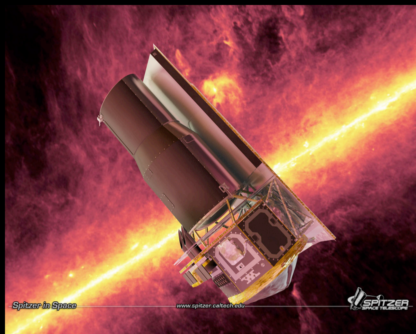
Steep faint end slopes => substantial volume density of lower luminosity galaxies:

50% of the UV luminosity density is <0.07 L*



Bouwens et al. 2007

also Beckwith et al. 2006 and Oesch et al. 2007)

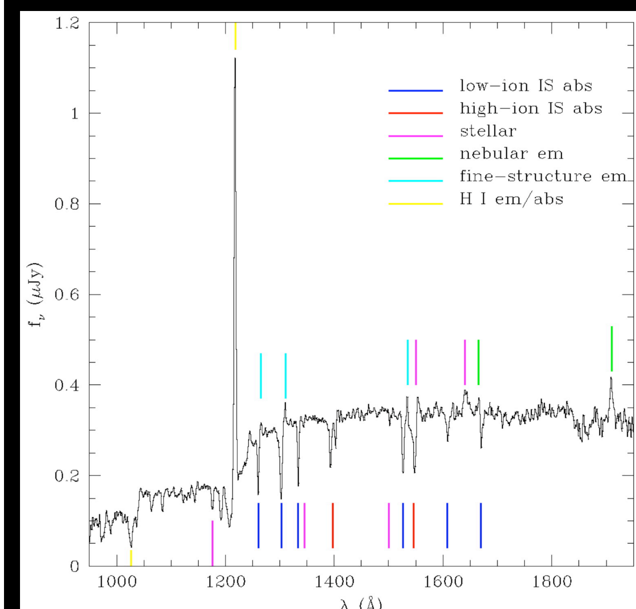


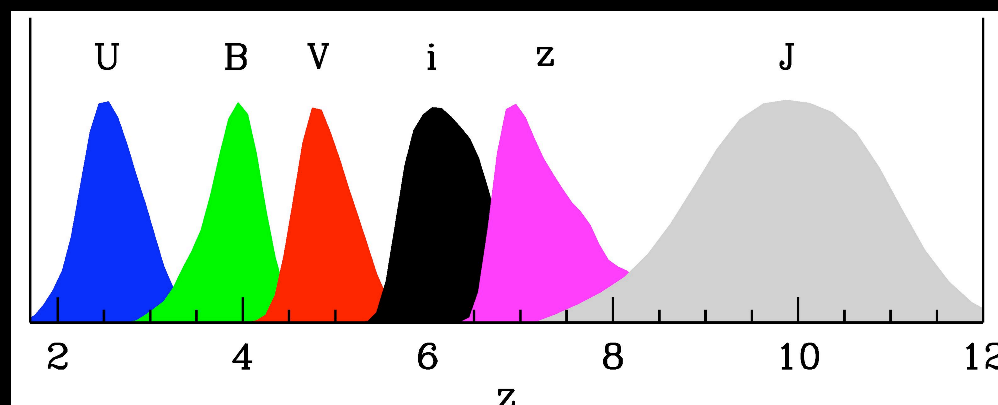
Galaxies at z~7-8+ & z~10

Reionization Epoch

(z & J-dropouts)

Lyα searches key complementary approach





Dropout Redshift Selection Functions

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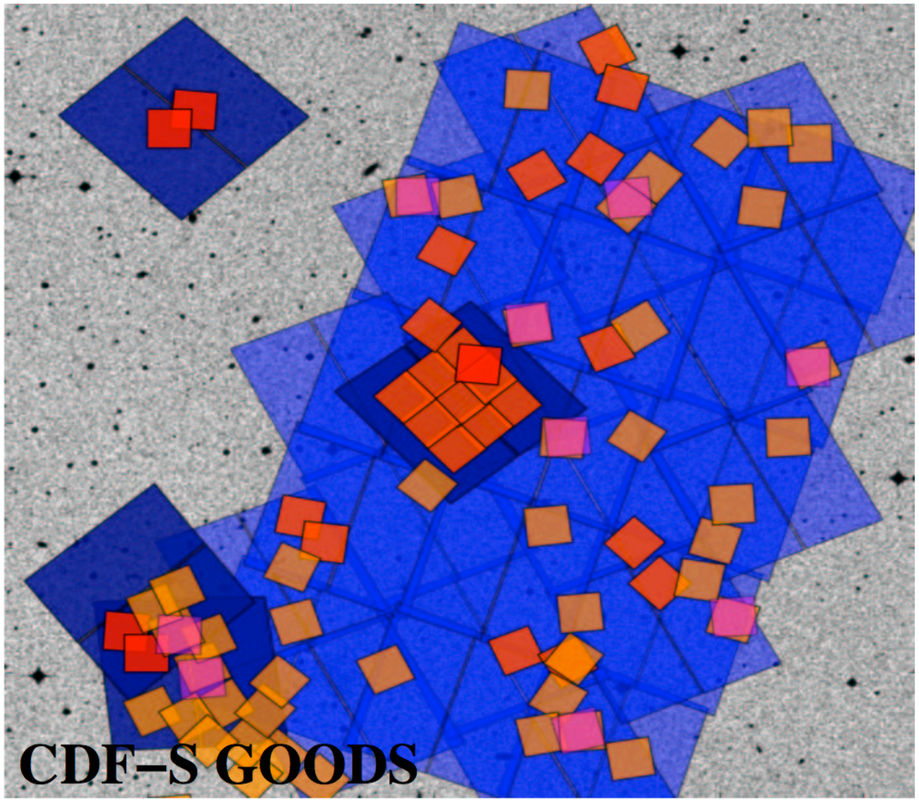
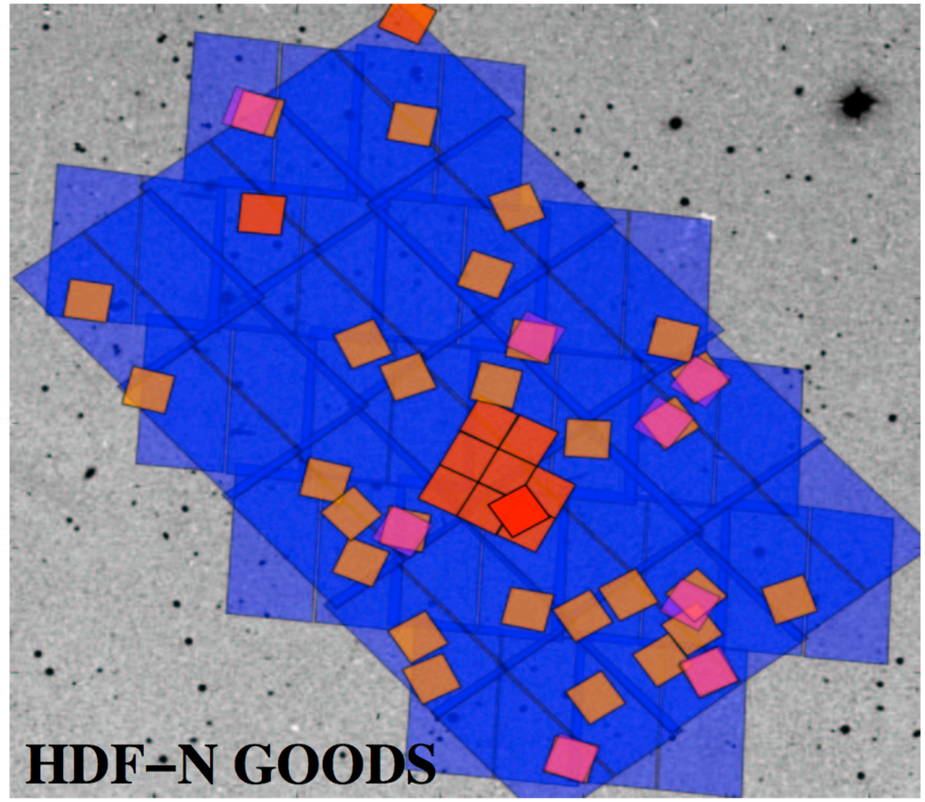
Latest Searches for *z~7-8-10* Galaxies

Many more fields with NICMOS data for dropout searches – BUT need WFC3 IR area!!

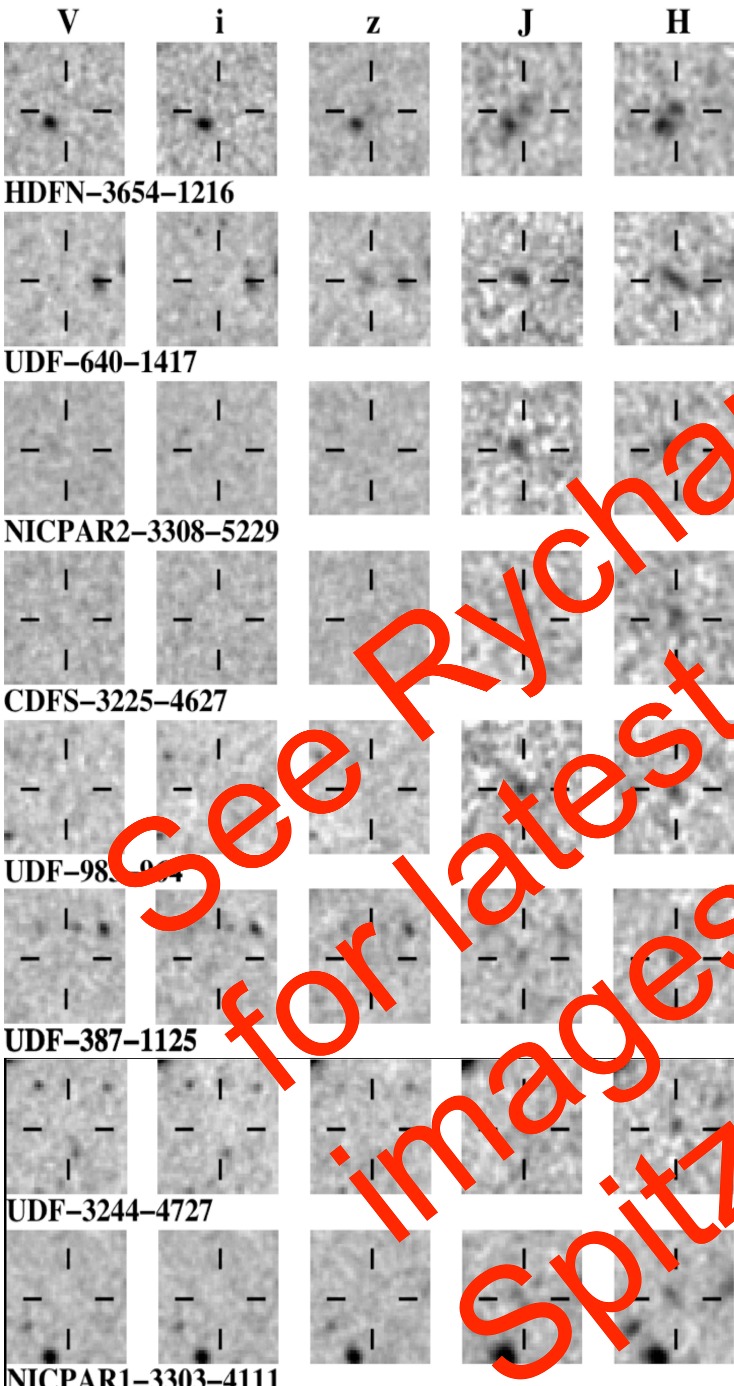


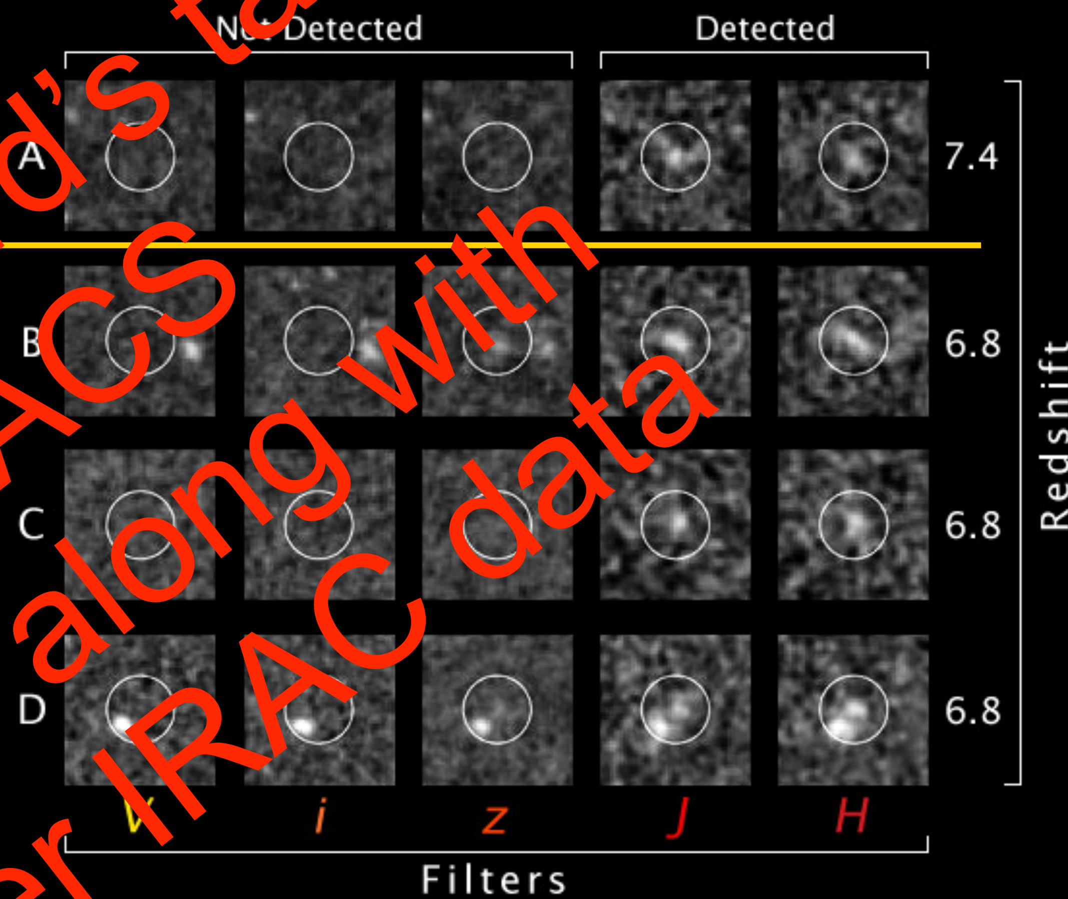


New 2008/9 Searches => ~15 z~7 sources

No z~9-10 sources

z~7-8 z-dropouts



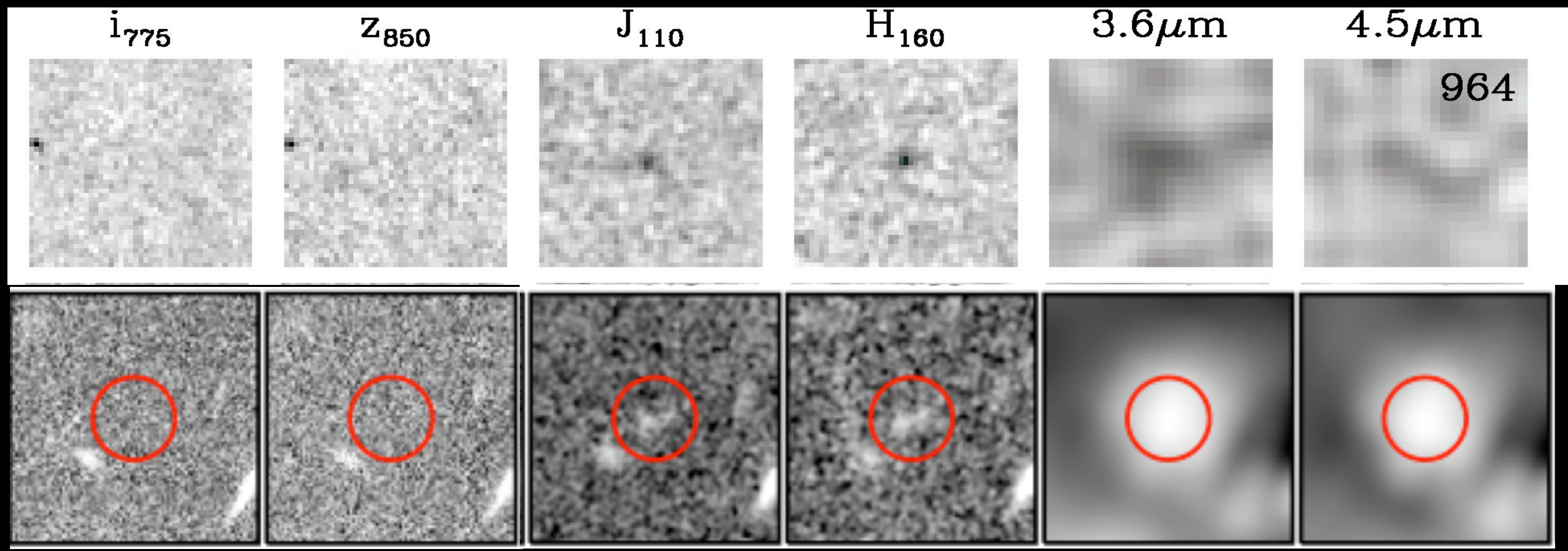


See Rychard's talk for latest ACS images along with Spitzer IRAC data

Bouwens & Illingworth, *Nature*, 2006

Bouwens, Illingworth et al. 2008

Are we really finding z>7 galaxies?



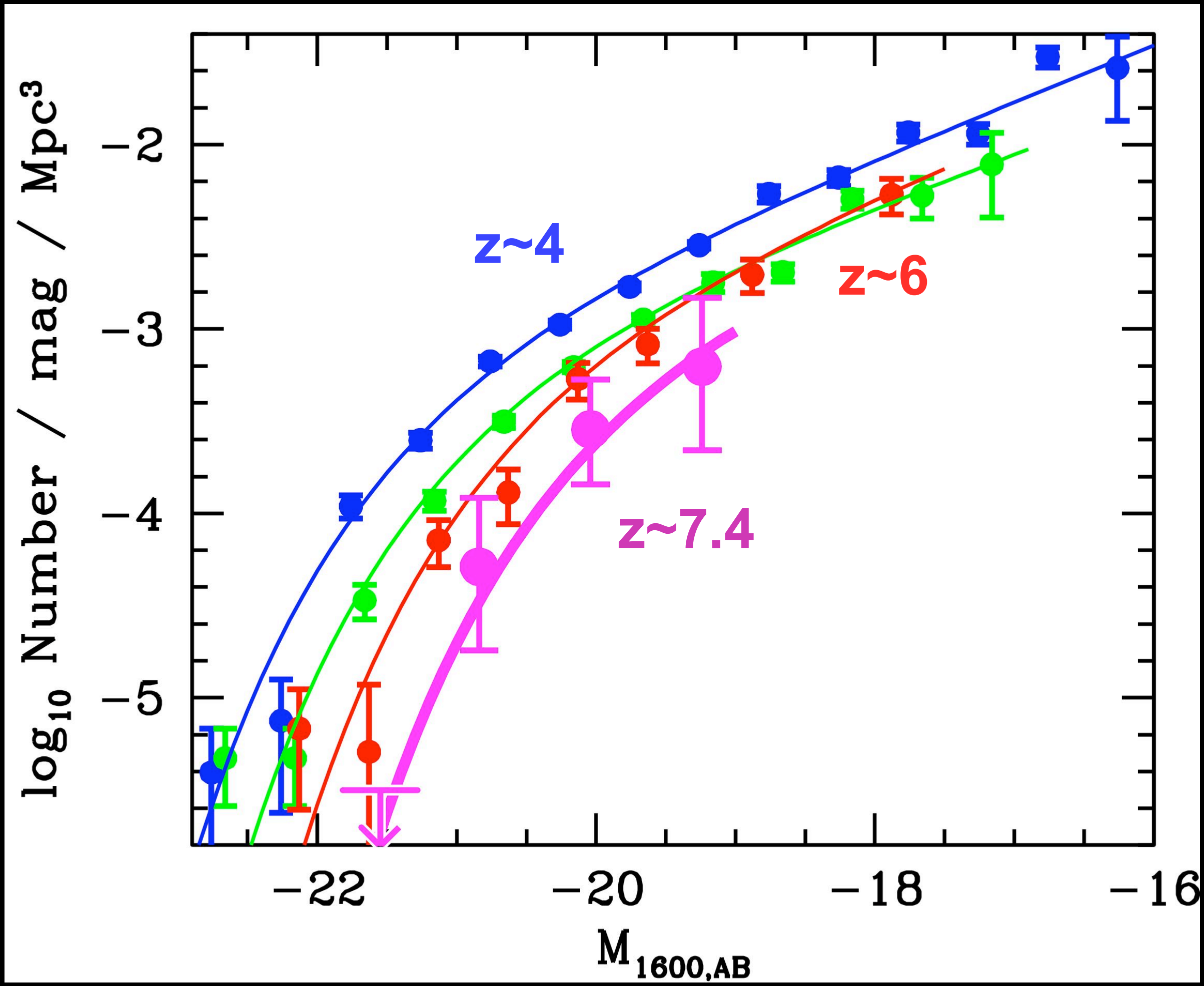
- 5σ detections in J, H, IRAC 3.6μ , and 2.5σ in IRAC 4.5μ
- Very blue J - H colors
- Undetected in the HUDF B, V, i, and z-band imaging
- (z-J) > 3 – too red to be a brown dwarf
- (H - 3.6m) colors similar to z~6 objects

Labbe, Bouwens, Illingworth, Franx, *Ap.J.*, 2006

z~4-7 UV Luminosity Functions

As before but with z~7 LF added

Log # mag^{-1} Mpc^{-3}



Bright

Faint

"Cosmic Variance" due to large scale structure:
at z~4-6 ~14% RMS
at z~7-8 ~30% RMS
at z~10 ~19% RMS

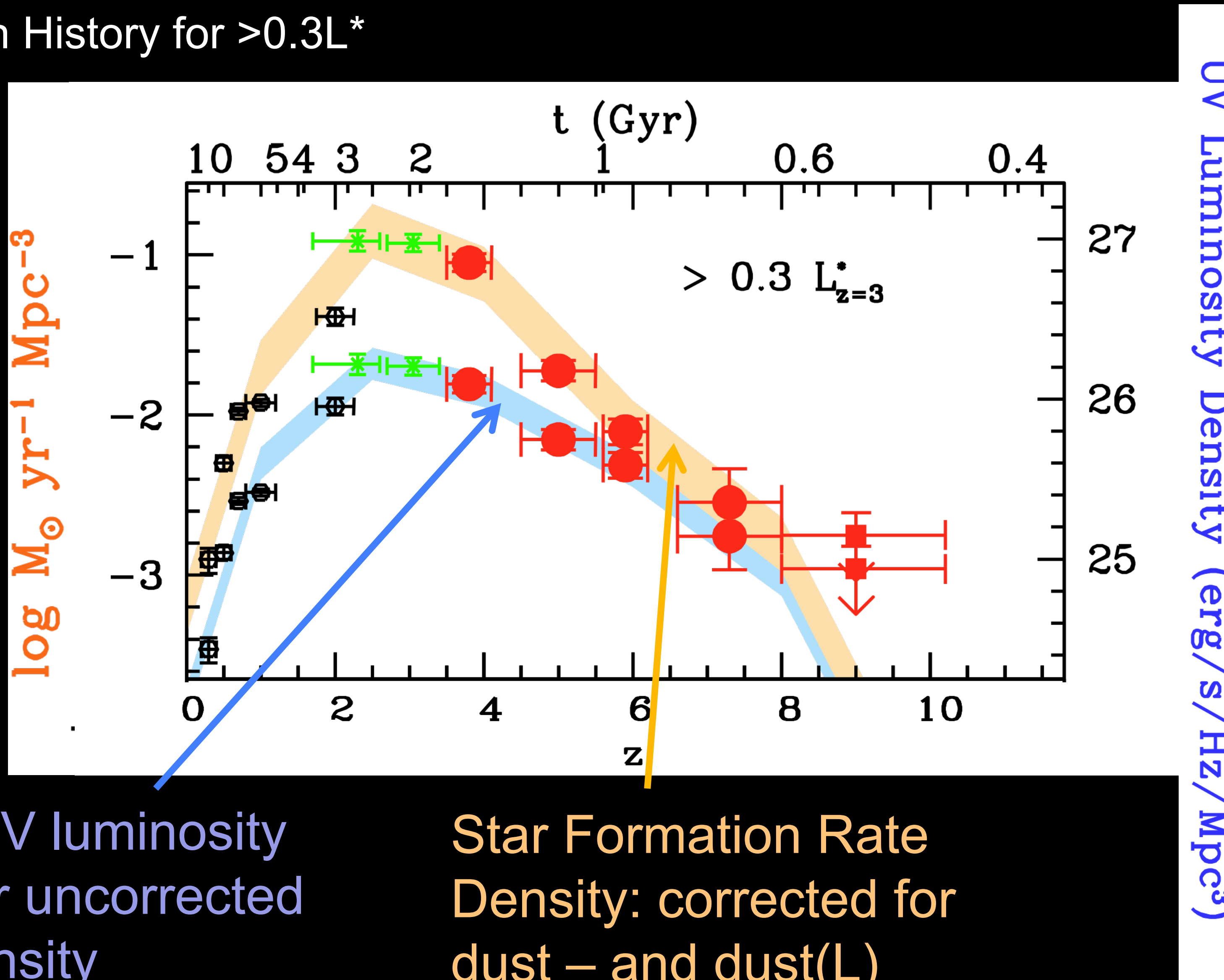
Bouwens, Illingworth et al. 2008/9

Luminosity function => SFR density for z~10 => 2

Star Formation History for >0.3L*

Correct for dust to get SFR density

Log SFR: $M_{\odot}$ yr^{-1}Mpc^{-3}



UV LF => UV luminosity density – or uncorrected UV SFR density

Star Formation Rate Density: corrected for dust – and dust(L)

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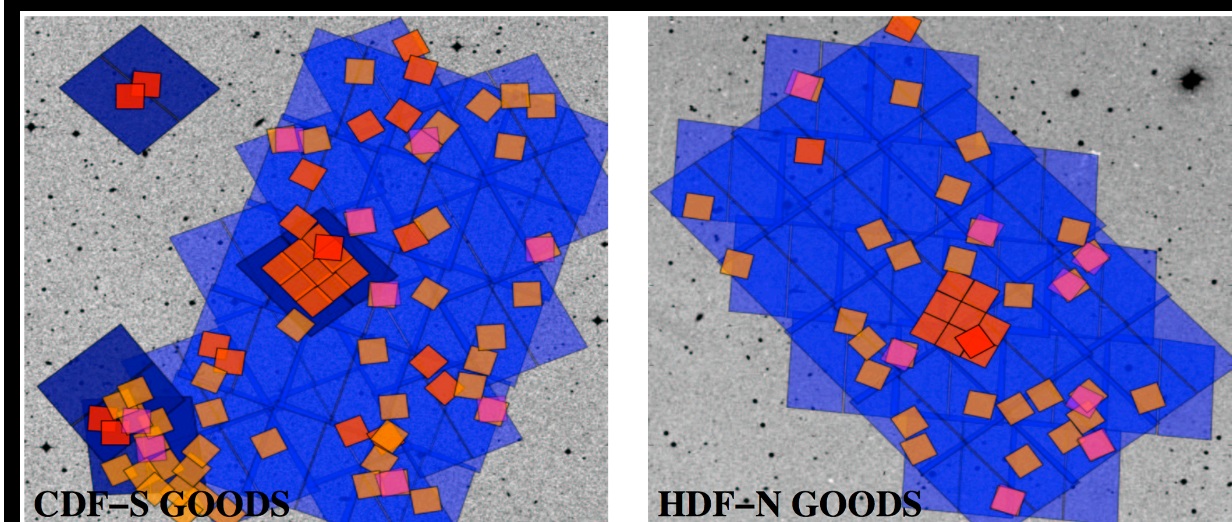
The UV Slopes at z~2.5-6: Dust and SFR Density

Contributions from UV and IR Sources

UV CONTINUUM SLOPE AND DUST OBSCURATION FROM $z \sim 6$ TO $z \sim 2$: THE STAR FORMATION RATE DENSITY AT HIGH REDSHIFT[1]

R.J. Bouwens[2,3], G.D. Illingworth[2], M. Franx[3], R-R. Chary[4], G.R. Meurer[5], C. Conselice[6], H. Ford[5], M. Giavalisco[7]



Submitted to ApJ

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UV Slopes & SFR

UV flux widely used to characterize SFR

UV slope β correlates with dust extinction
(Meurer et al (1995, 7, 9) and many other recent studies)

UV slope β measured over ~1600Å to 2300Å – ideal for high z studies
(optical and near-IR HST imaging).

Large samples for β at z~2.5 and z~4
GOODS fields and HUDF from ACS

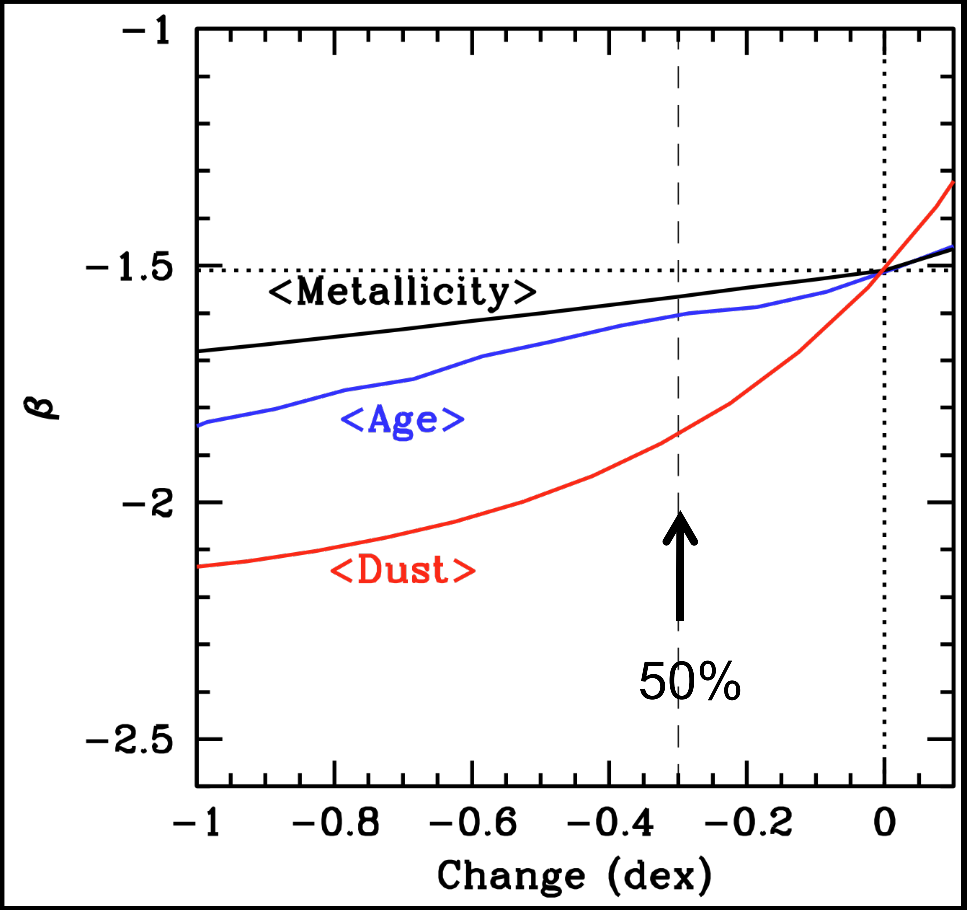
HST IR data needed for z~5 and z~6.

Recent NICMOS data has improved sample size
– but WFC3 IR data eagerly awaited….

UV Slopes & SFR

Changes in the UV slope β over 1600-2300Å
vs changes in mean age, metalliity and dust
(for "typical" Papovich et al high-z star-forming model)

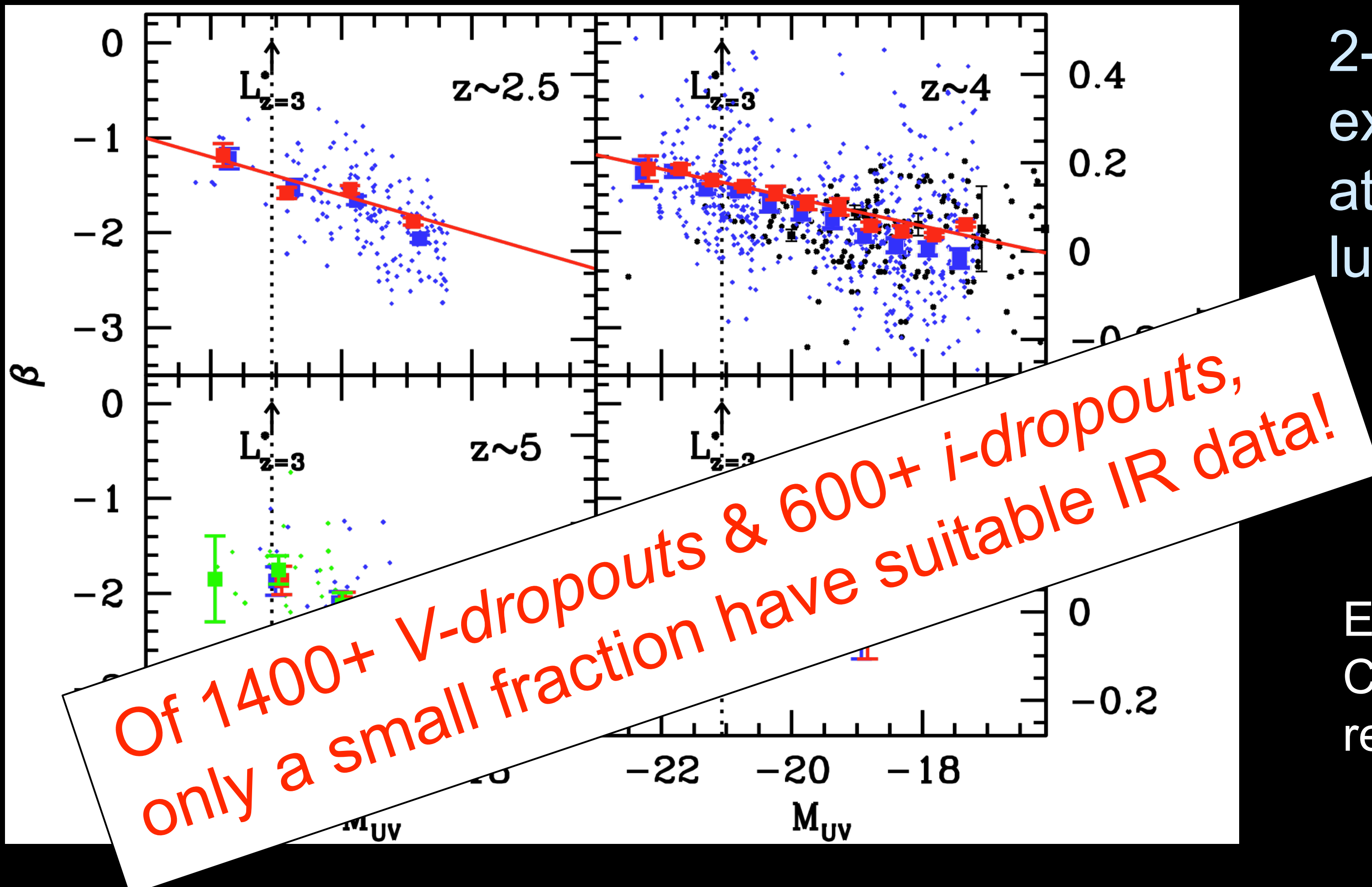
β



Note that changes in <dust> have largest effect on β

IMF changes have minimal effect

UV slopes β at z~2.5, 4, 5, 6

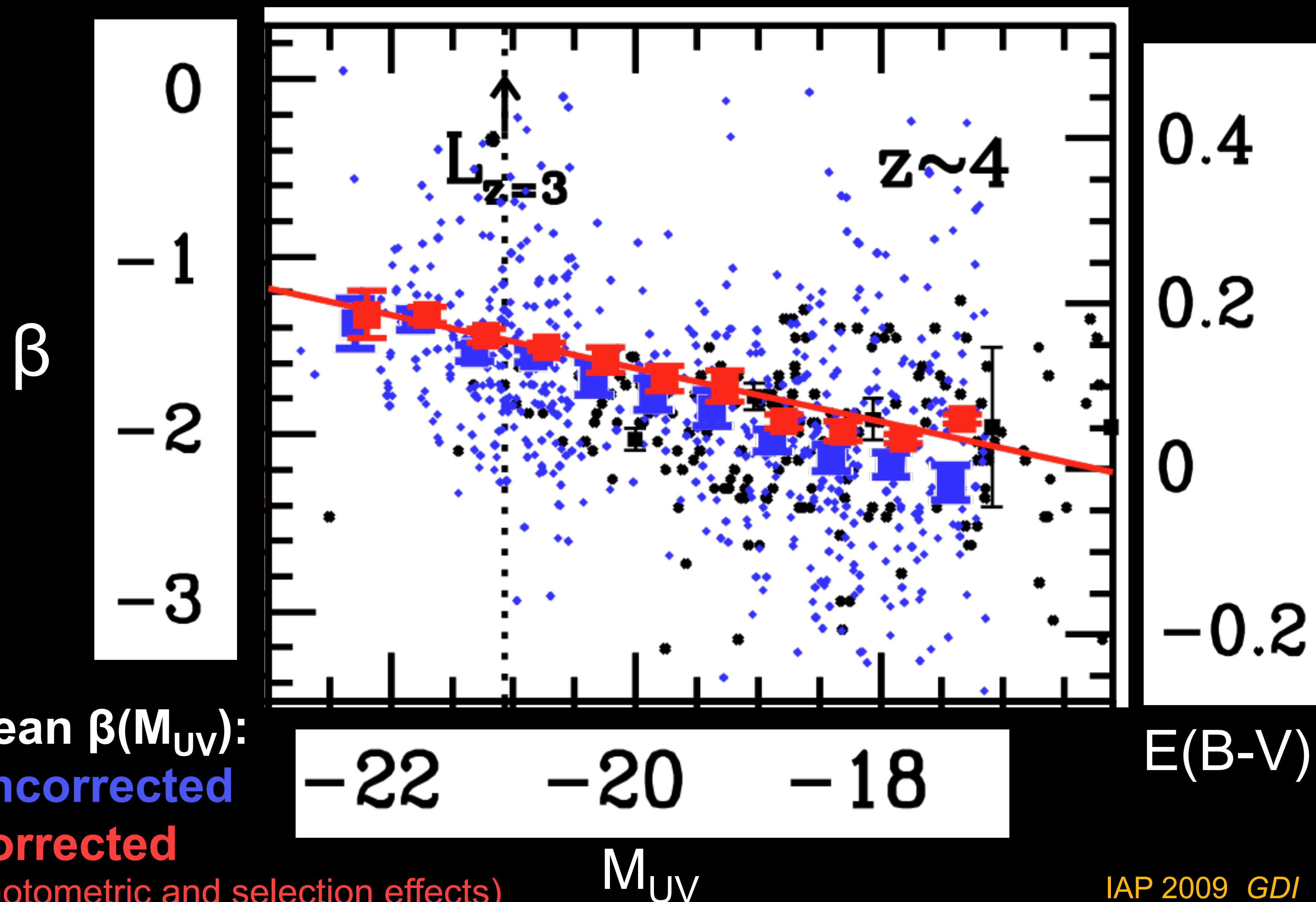


2-3x less extinction at low luminosity

E(B-V) from Calzetti et al reddening

Samples:	z~2.5	z~4	z~5	z~6
	168	1111	79	14

UV slope β at z~4



Mean β(M_{UV}):
Uncorrected
Corrected
(photometric and selection effects)

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β from z~6 to z~2.5

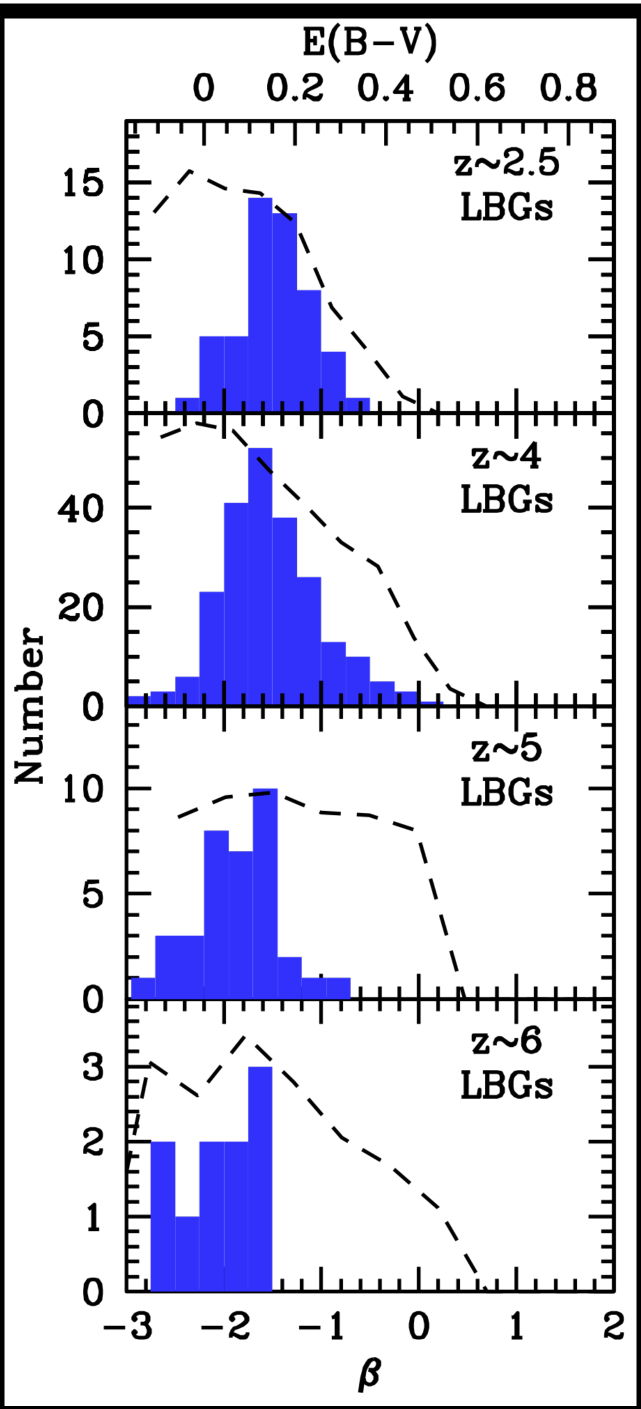
Note that β is "bluer" at earlier times => less dust extinction

Two results =>

1) Less dust at early times

2) Less dust at lower luminosity

Number



z

β

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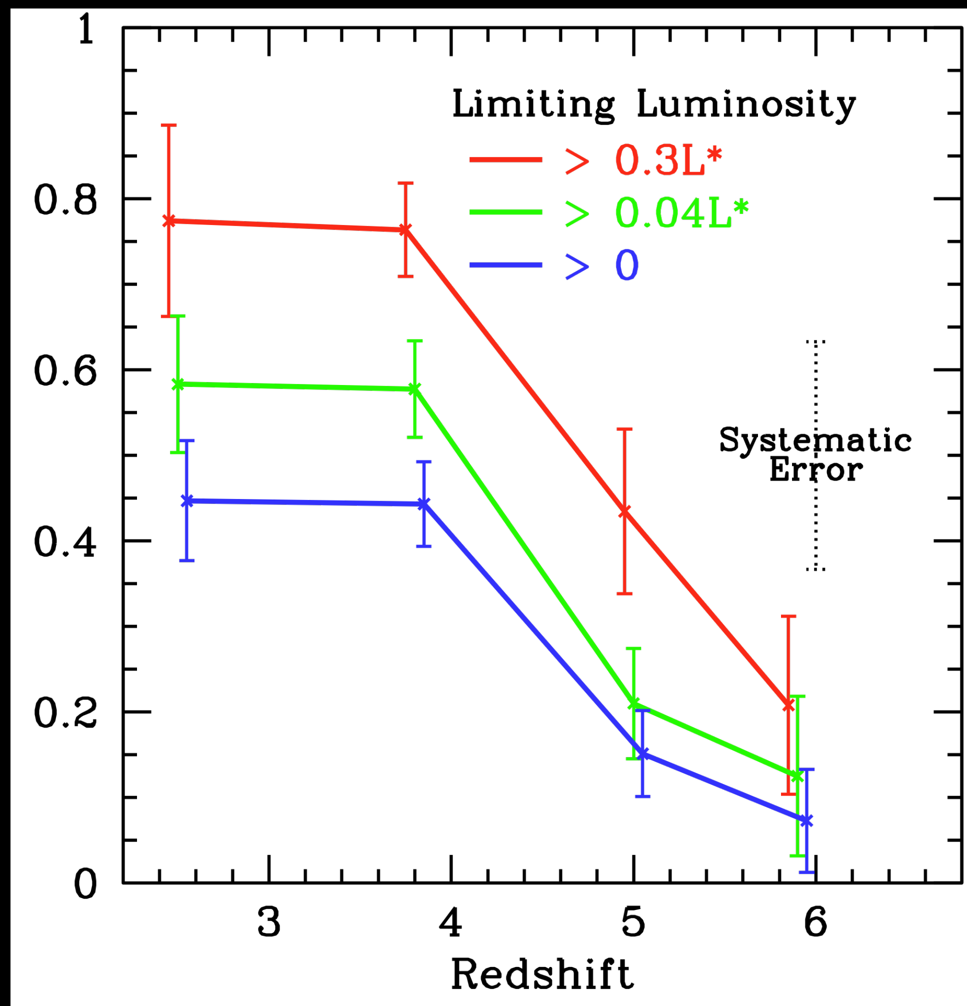
Dust extinction from z~6 to z~2.5 vs luminosity

Mean dust extinction at 1600Å for different luminosities

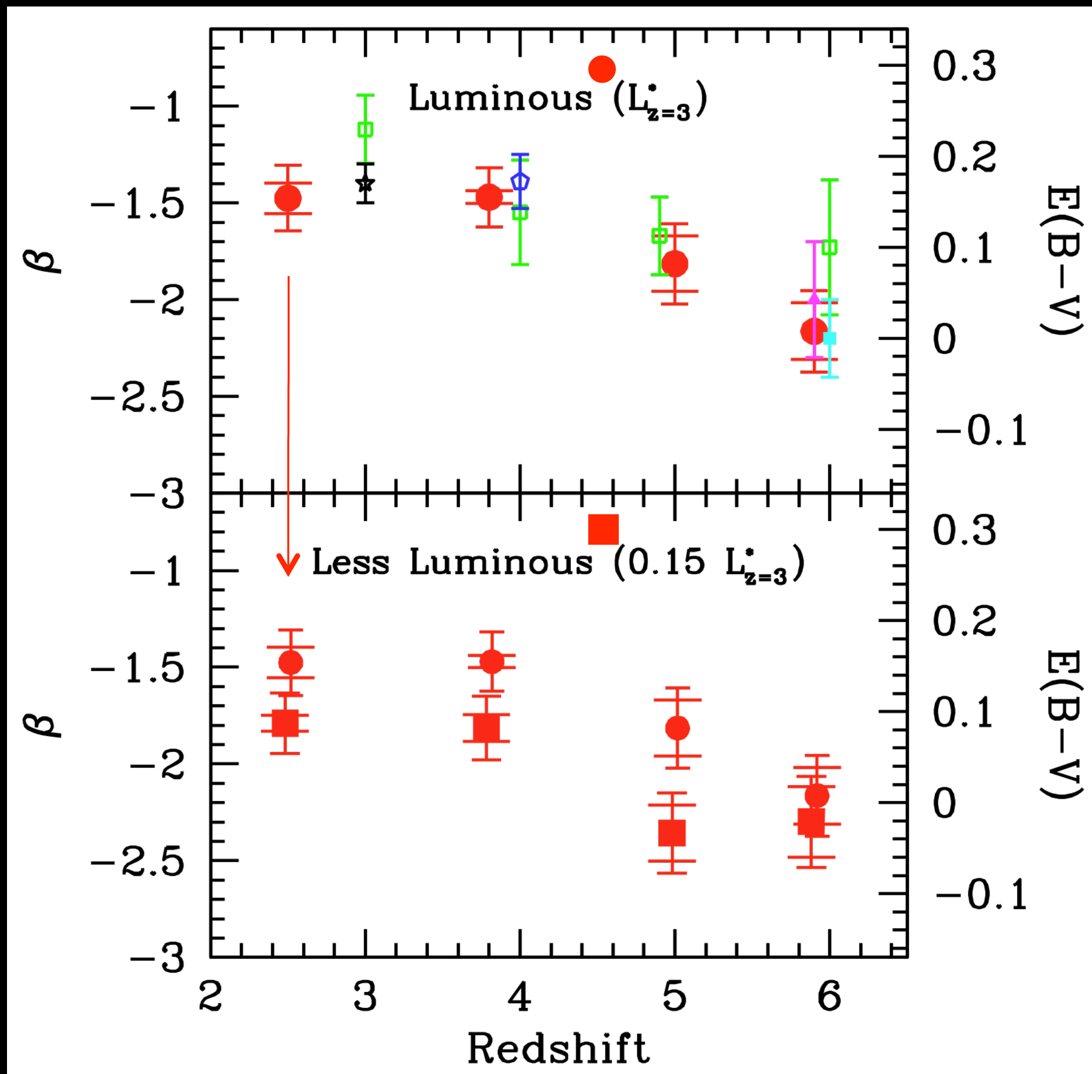
(Note – this is a log scale)



Dust extinction increases at later times

UV slope β from z~6 to z~2.5

β



1) Note that β is "bluer" at earlier times => less dust extinction

2) Note that β is "bluer" for less luminous galaxies => less dust extinction

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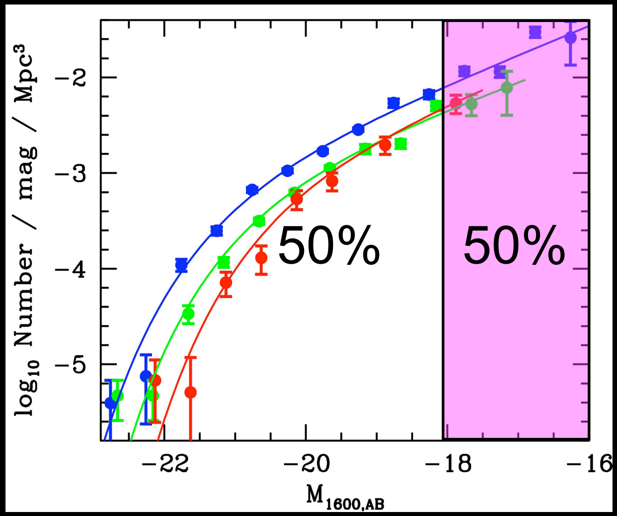
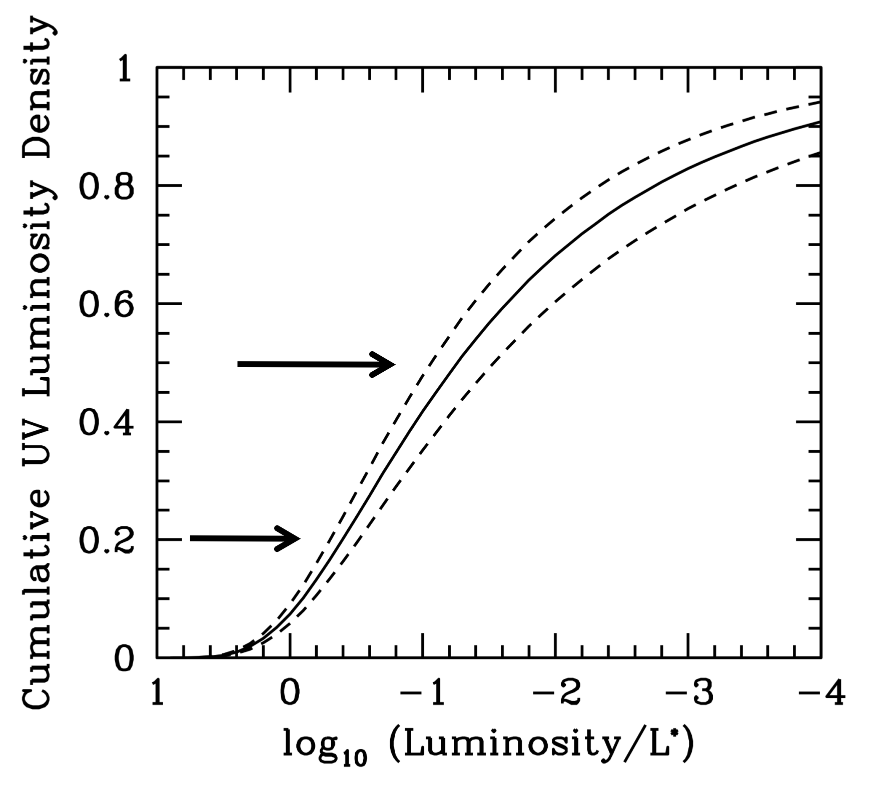
Low Luminosity Galaxies
Dominate UV flux for z~2-6….

Steep faint end slope β =>
β ~ 1.7 from z~2.5 to z~6

50% in galaxies fainter than 0.05L*

80% in galaxies fainter than 0.4L*!



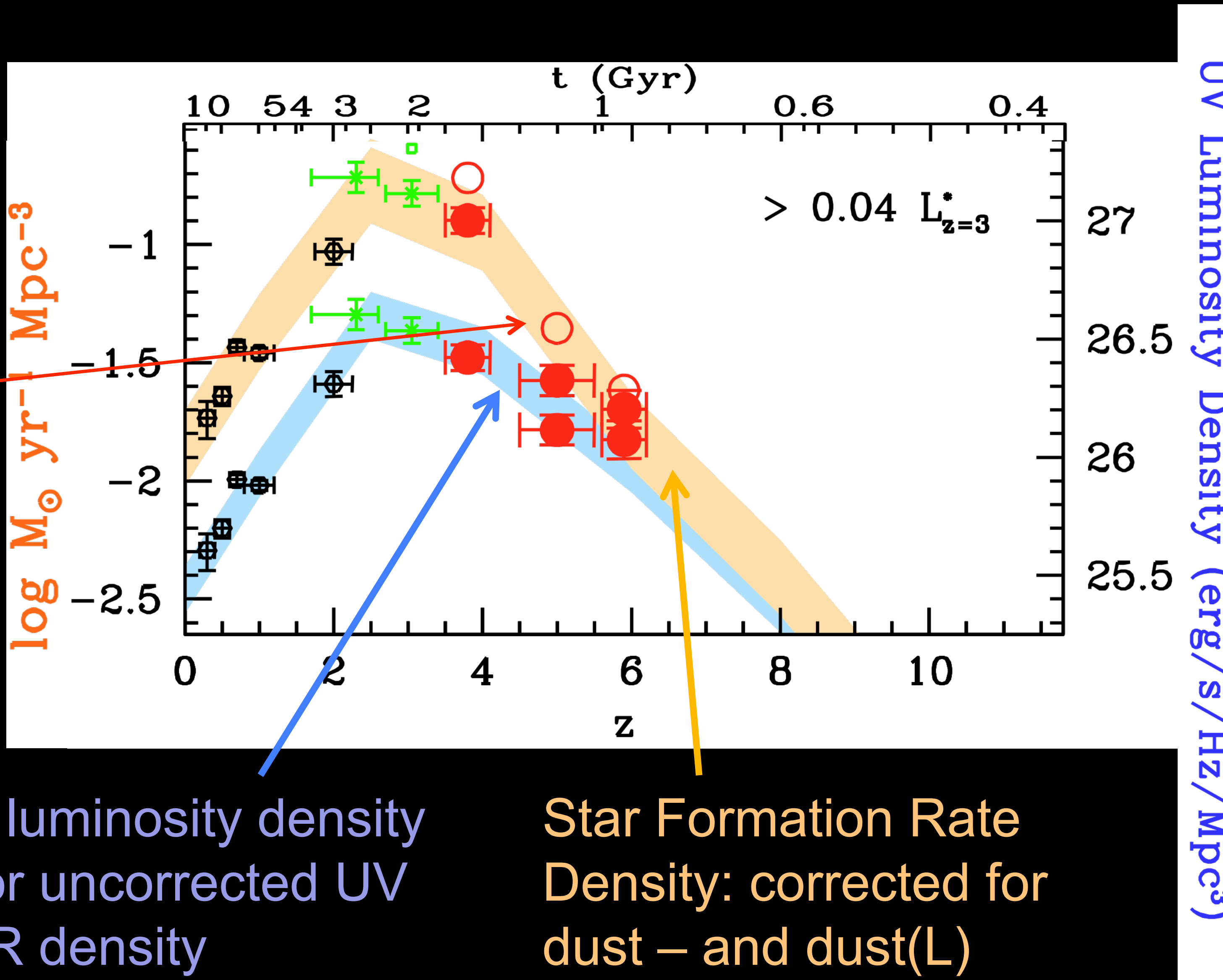


Bouwens, Illingworth et al. 2007, 2009

See also: Sawicki & Thompson 2006; Yan & Windhorst 2004; Beckwith et al. 2006

SFR– with latest dust corrections

FAINT LIMIT: >0.04L*



Note: O Overestimate of SFR if constant dust extinction for all luminosity

UV luminosity density – or uncorrected UV SFR density

Star Formation Rate Density: corrected for dust – and dust(L)

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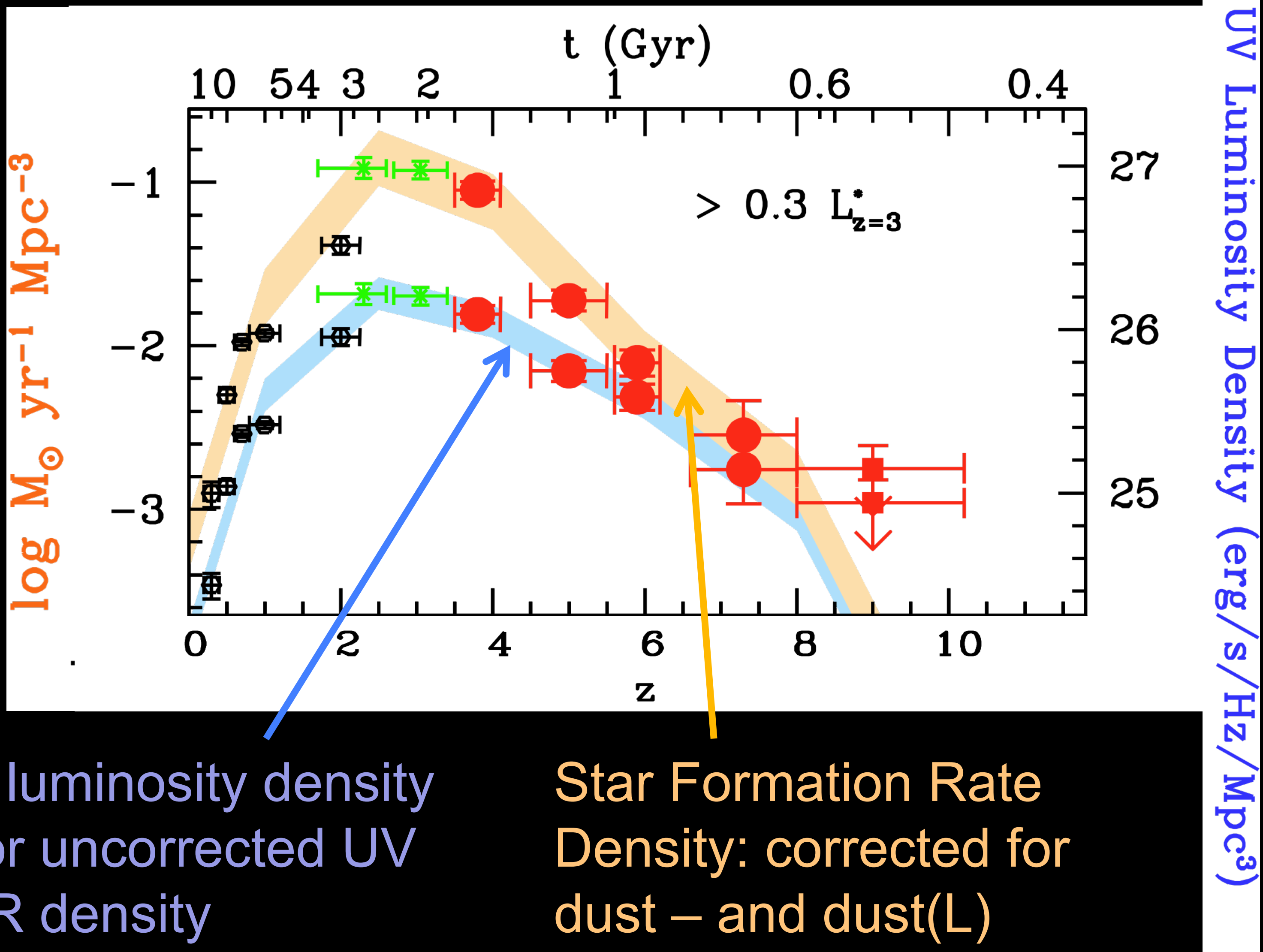
SFR– with latest dust corrections

FAINT LIMIT: >0.3L*



For >0.3L*, can add sources at z~7 and limits at z~10

UV luminosity density – or uncorrected UV SFR density

Star Formation Rate Density: corrected for dust – and dust(L)

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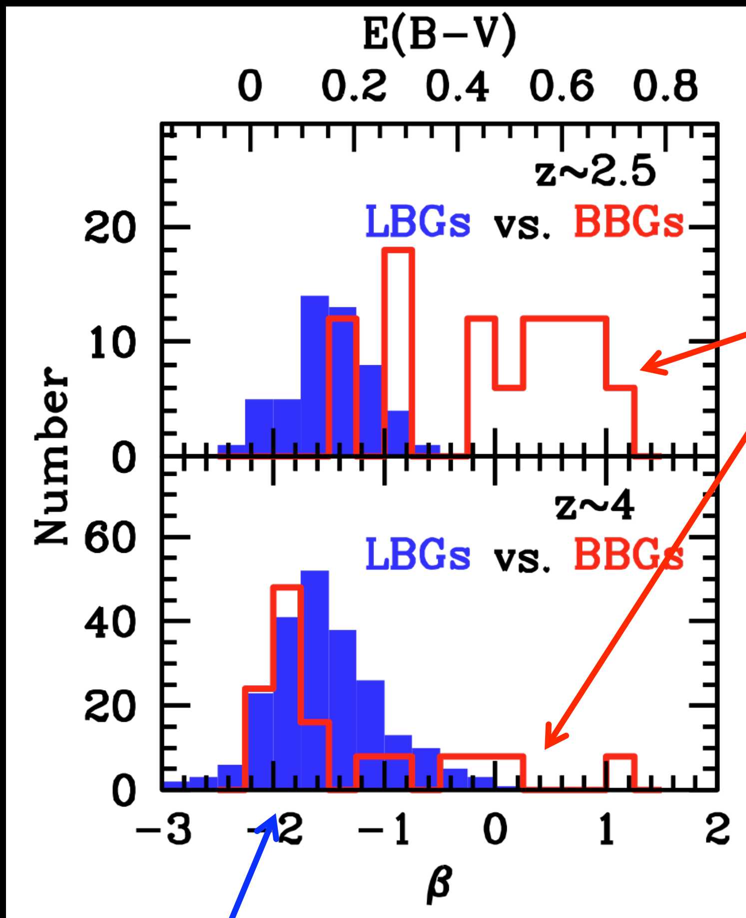
Evolved Galaxies at z ~ 4+?

Evolved galaxies at z~2-3) are a significant part of the galaxy population. (van Dokkum, Franx et al DRGs, and many others since).

Distant Red Galaxies (DRG)

But what happens at z~4 and earlier?

Evolved galaxies at z~4+?



Galaxies selected by DRG criteria for z~2.5 and for z~4

Brammer and van Dokkum 2007

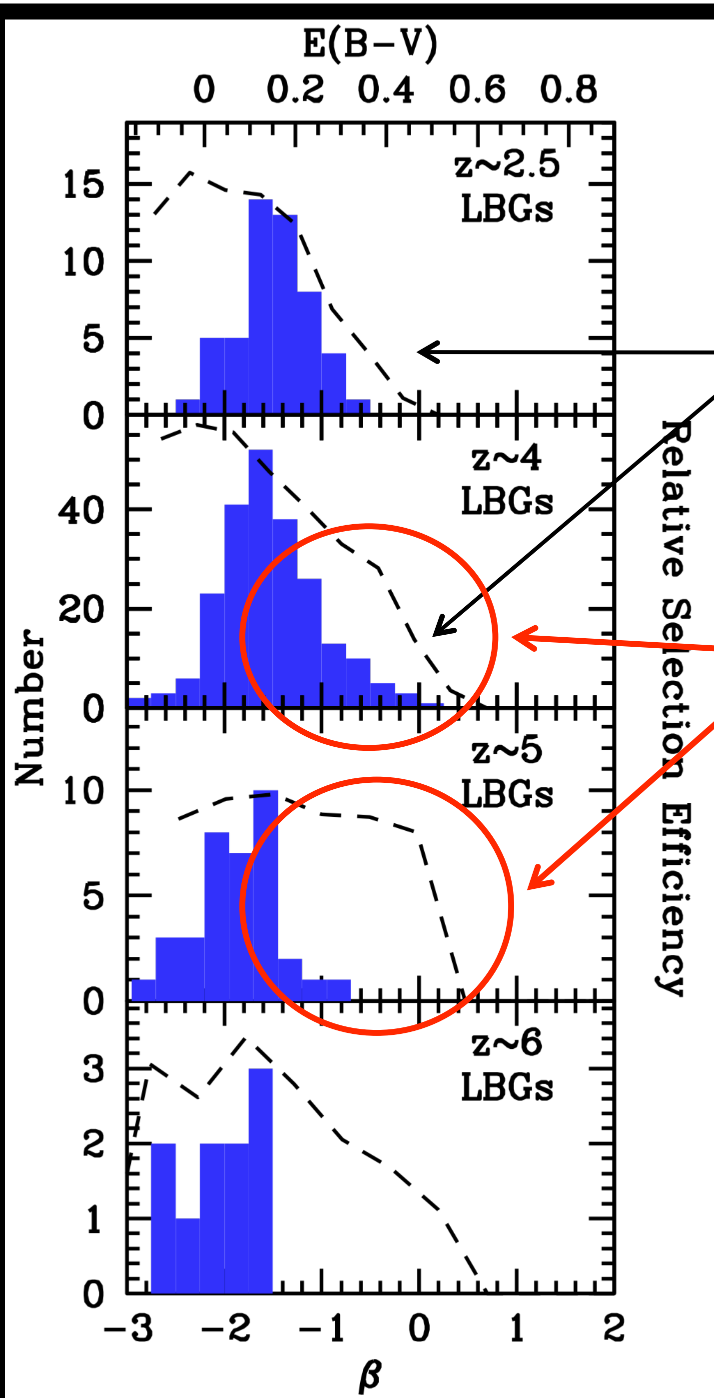
Most of the z~4 galaxies would be found in LBG surveys

⇒ smaller fraction of evolved galaxies & so LBG surveys at z~4 are more complete

LBGs

Bouwens et al 2009

Evolved Galaxies not significant at z>4?



Selection Efficiency

"Redder", evolved sources could be detected in these ~0.1L* to ~2L* samples at z~4 and z~5+

There is *NOT* a continuum of UV slopes: => if there are evolved galaxies or dusty ~L* galaxies at z>4 they must have *distinctly* different UV properties or be quite rare

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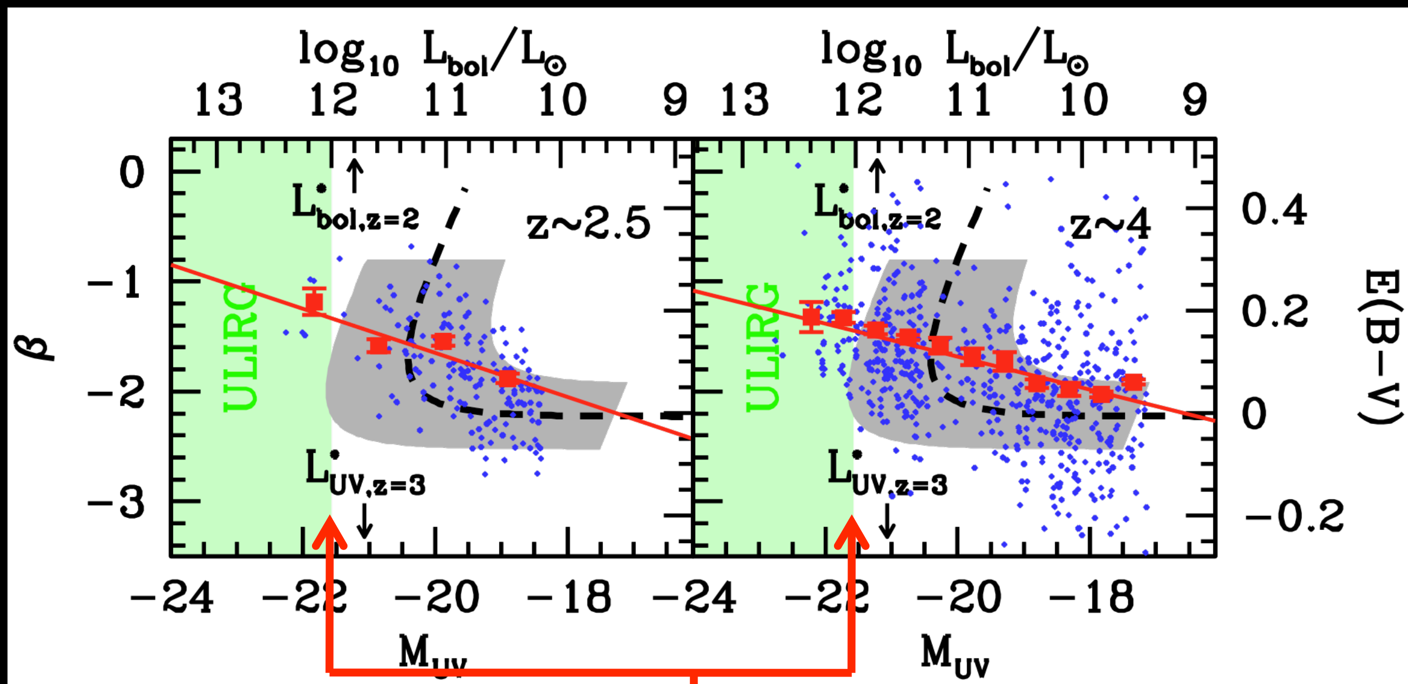
Massive Star Forming Galaxies at z>~3

What is the likely contribution to the SFR density of massive evolved galaxies with infrared fluxes – e.g., ULIRGS/SMGs/etc?

Luminous Galaxies

L_{BOL}

β



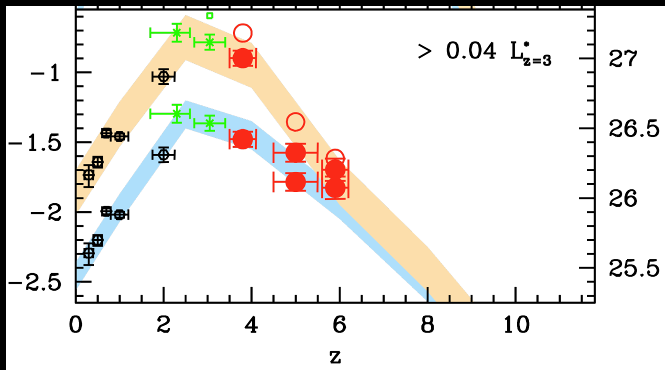
M_{UV}

ULIRGs/SMGs/etc. ← | → UV LBGs

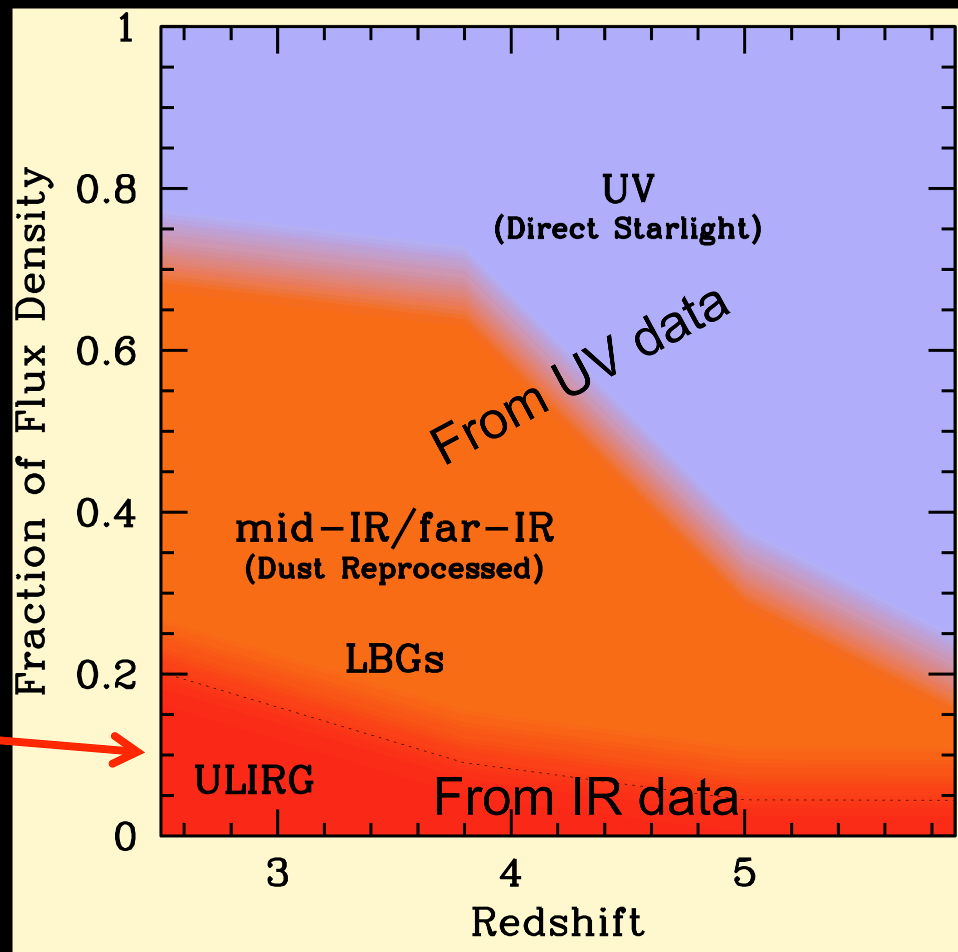
cf. Naveen's talk

Increasing dust limits UV flux at L>L* –
IR data used to derive constraints at L>2L*

Flux Density in UV & IR



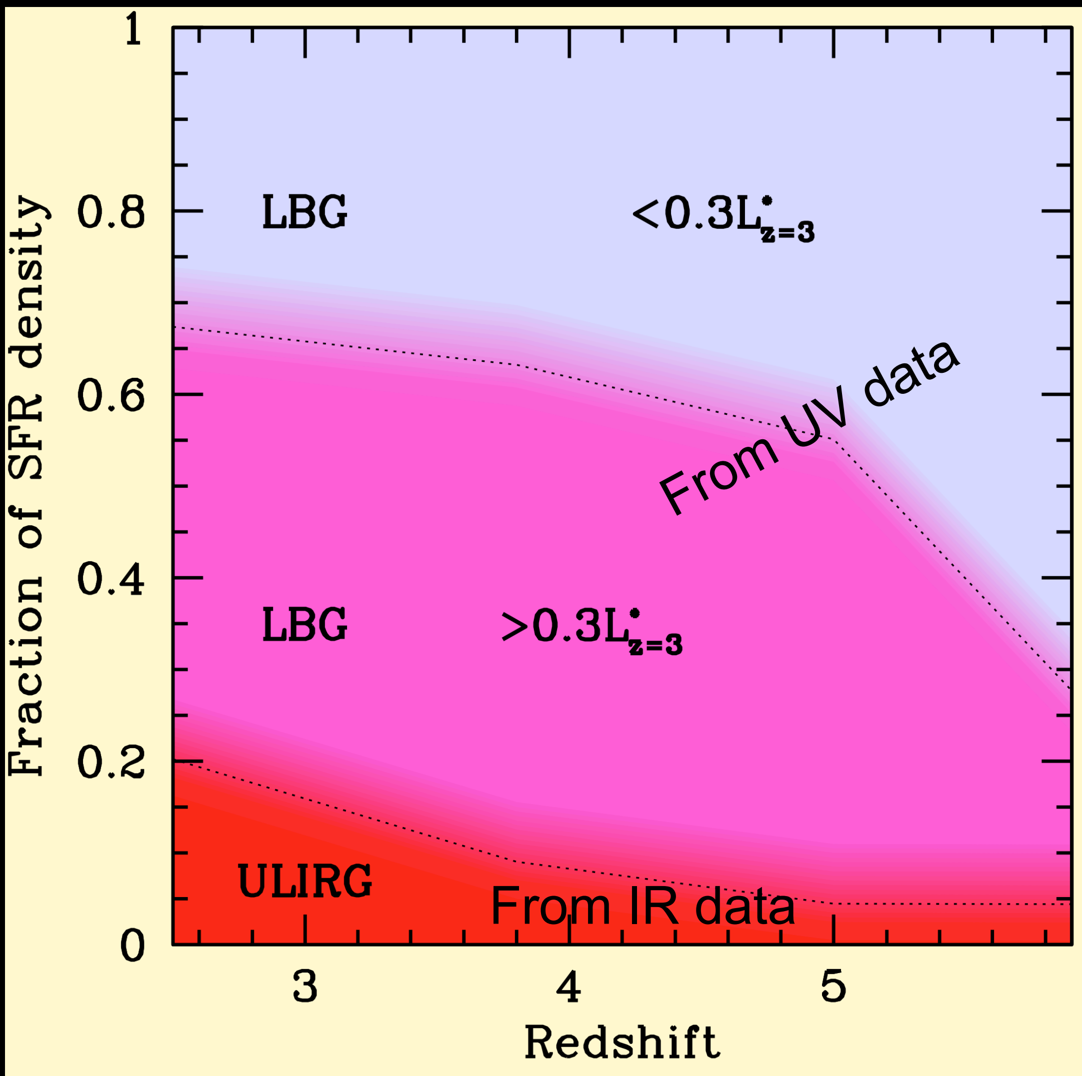
From star forming galaxies…



>80% of energy output in UV & IR can be derived from UV detected sources

ULIRG estimate based on IR 24μ z~2 LF by Caputi et al. (2007: see Reddy and Steidel 2009) and from Daddi et al. (2009) SCUBA data at z~4

The Star Formation Rate Density from z~7 to z~2.5: LBGs and ULIRGs/SMGs



ULIRG estimate based on IR 24μ z~2 LF by Caputi et al. (2007: see Reddy and Steidel 2009) and from Daddi et al. (2009) SCUBA data at z~4

Faint LBGs

Luminous LBGs

IR ULIRGs/SMGs

z~2 baseline ULIRG estimate from Reddy et al (2008)

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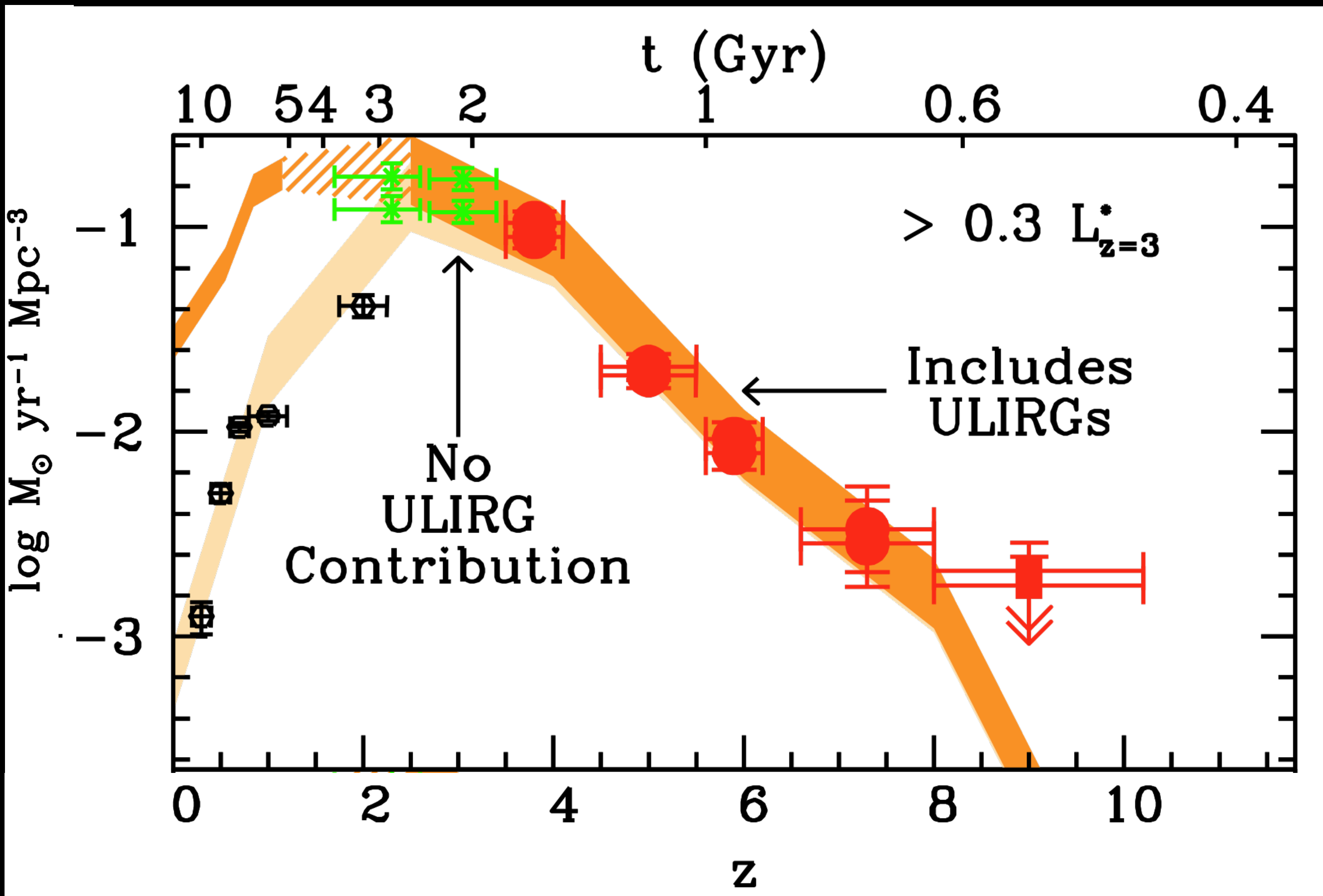
The Star Formation Rate Density from z~7 to z~0, including ULIRGs/SMGs etc



UV data for LBGs & IR data for dusty luminous sources (ULIRGS)

Galaxy Build-up in the First 1-2 Billion Years

Faint z~4, 5 and 6 UV Luminosity Function LF to ~3-4 mags below L*: steep slope α~1.7 unchanged from z~6 to z~2

Low luminosity galaxies (L<0.07L*) contribute ~50% of luminosity density (and much of SFR)

Less extinction: (1) low luminosity galaxies; (2) at higher z

Evolved/dusty ~0.1L* – ~2L* galaxies rare by z~4-5

ULIRGs/SMGs contribute ~20% of total SFR density at z~2.5, and <10% at z~4-5