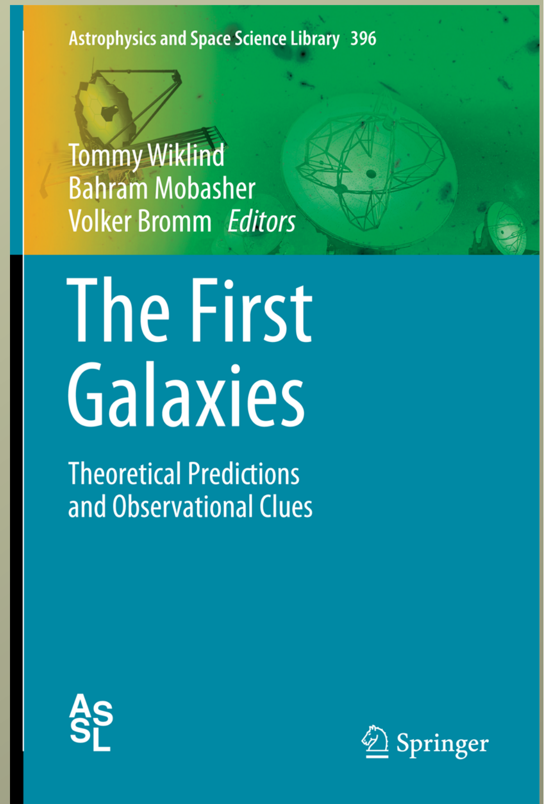
First / distant galaxies

Daniel Schaerer (Geneva Observatory, CNRS)

- Introduction
- Populations of known high redshift galaxies: main properties and implications
- Unification of LAE and LBG populations
  →First glimpse into cosmic reionisation epoch
- Physical properties of the high-z galaxies
- PopIII: a brief status report
- Conclusions



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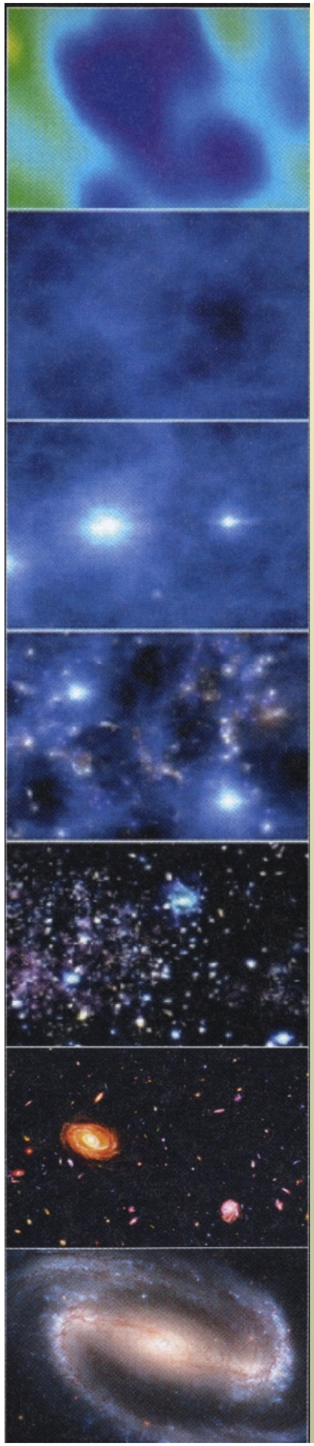
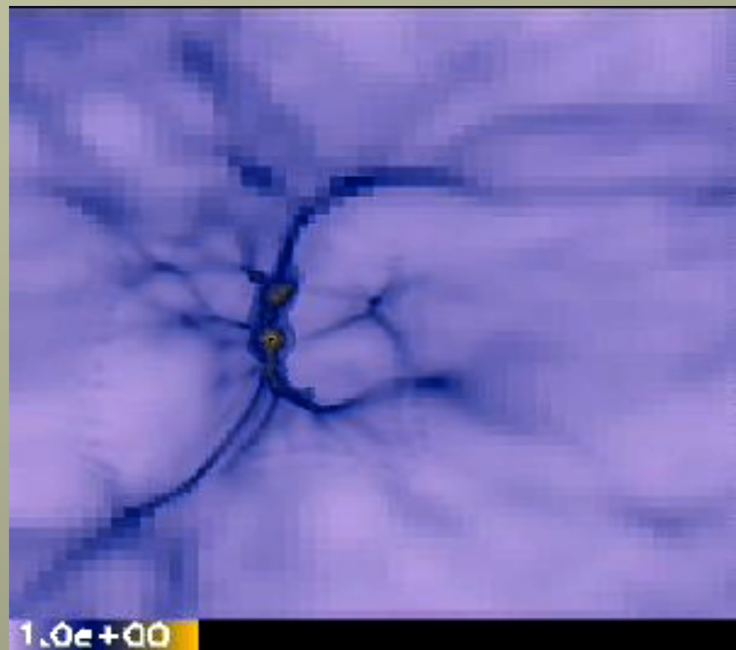
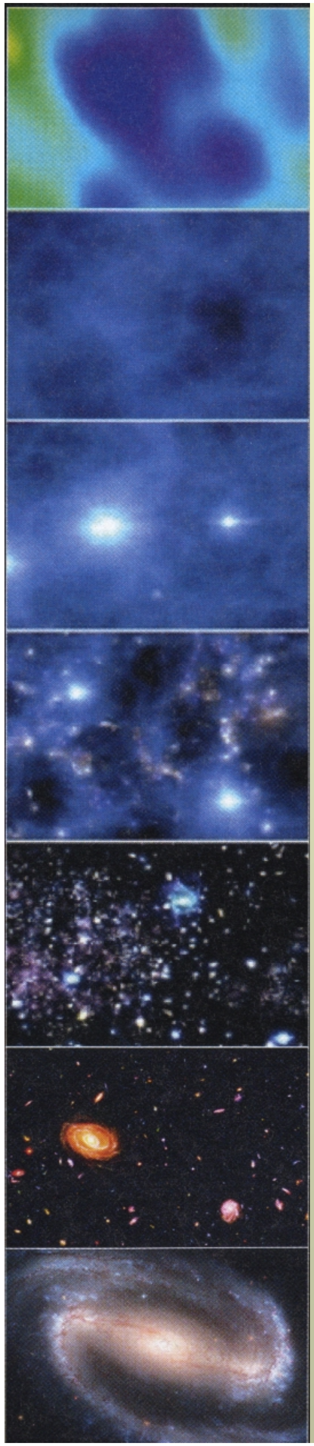


Formation and evolution of galaxies and star formation: the theoretical framework

Hierarchical structure formation model (Teyssier et al. 2007)

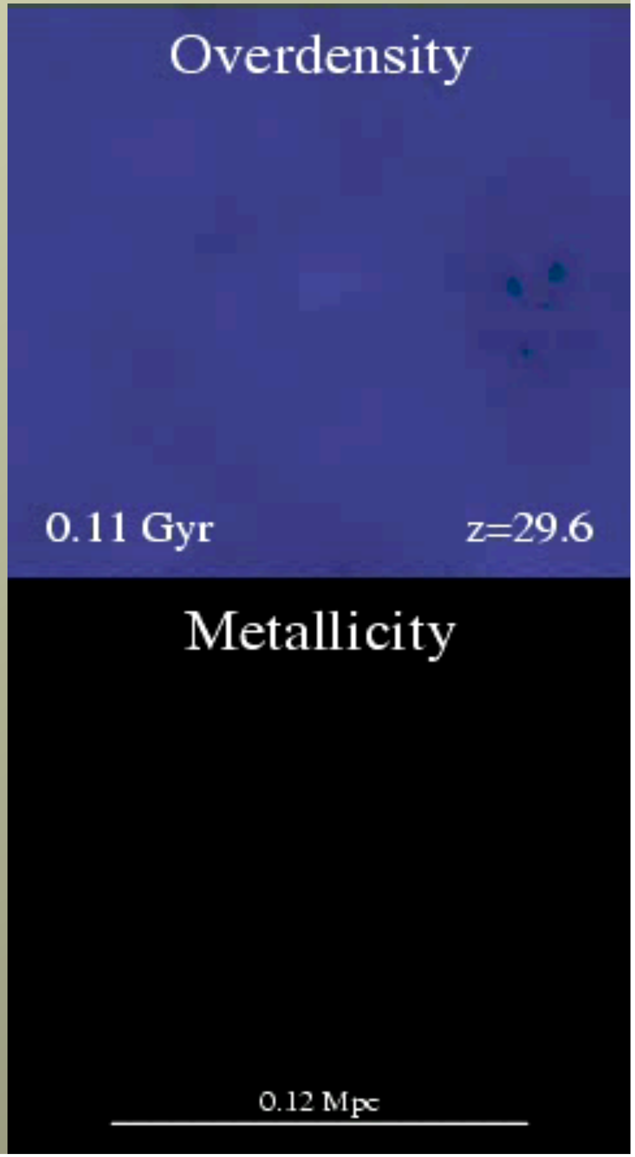
Formation of the first stars (Abel et al. 2005)



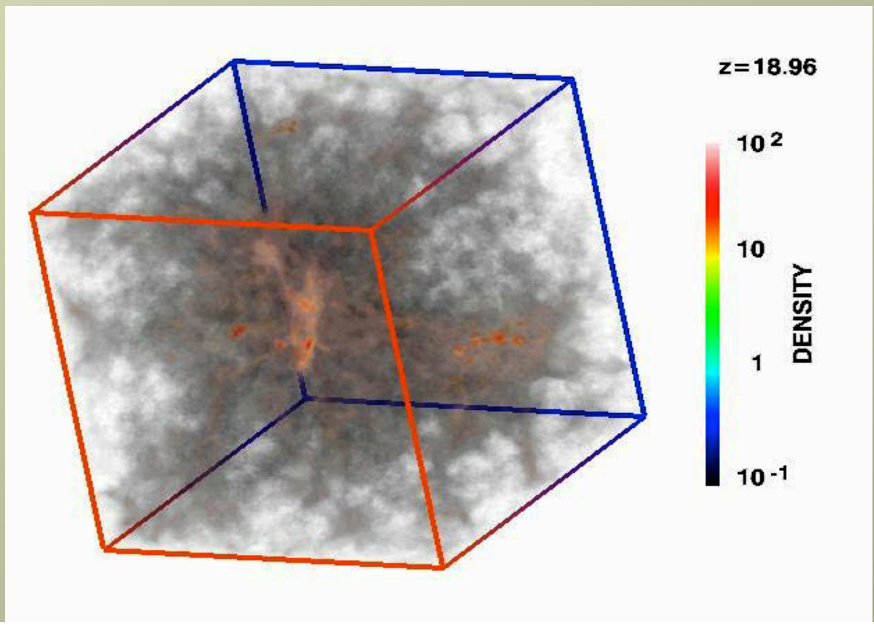


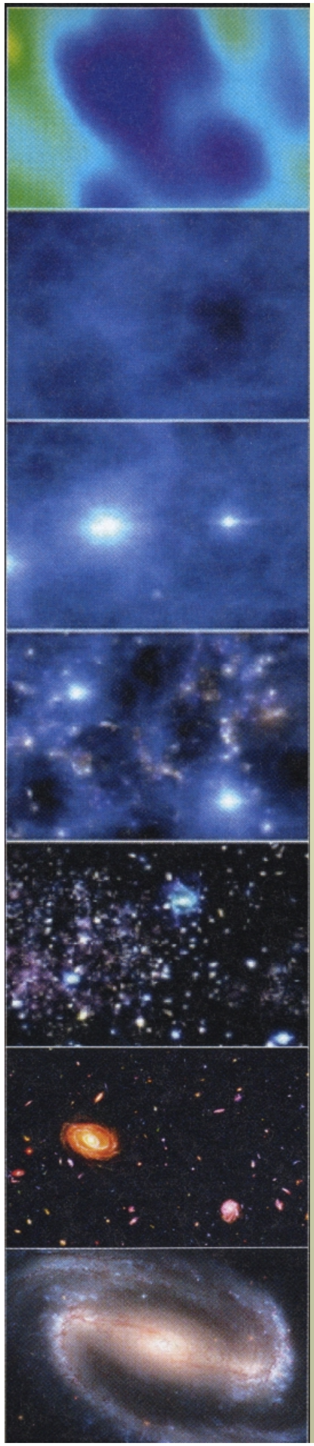
Formation and evolution of galaxies and star formation: the theoretical framework

Simulations including star formation and chemical enrichment (Oppenheimer et al. 2007)



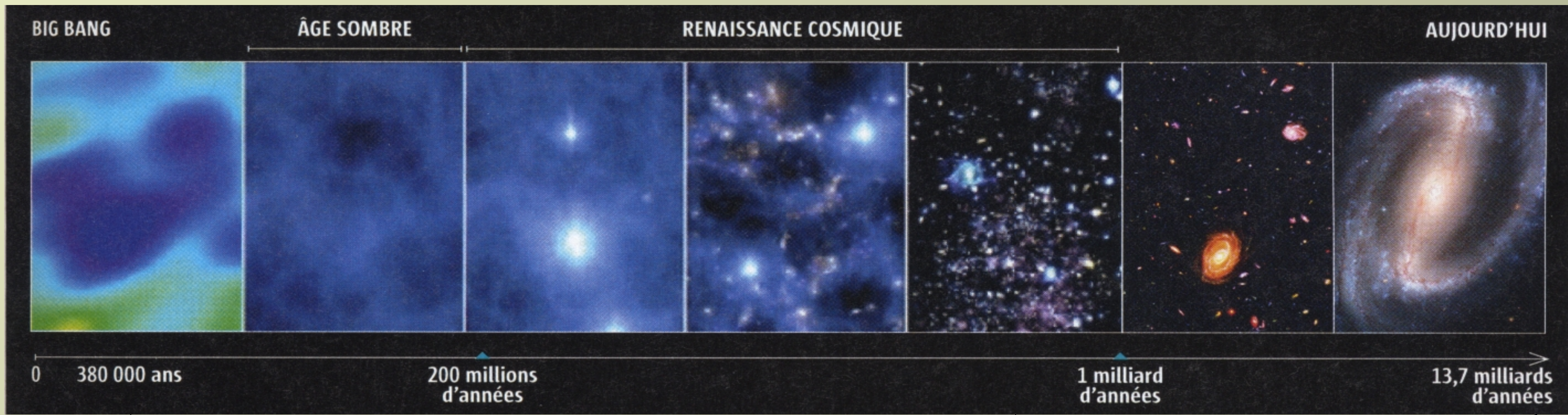
Hierarchical model with propogation of ionisation in IGM (Gnedin 2005)





Important phases in the history of the universe

age → ← **redshift z**



CMB:
z=1100
~380' 000 yr

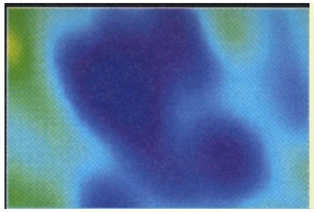
End of reionisation:
z ~ 6
~1 Gyr

Today:
z=0
13.7 Gyr

First stars and galaxies

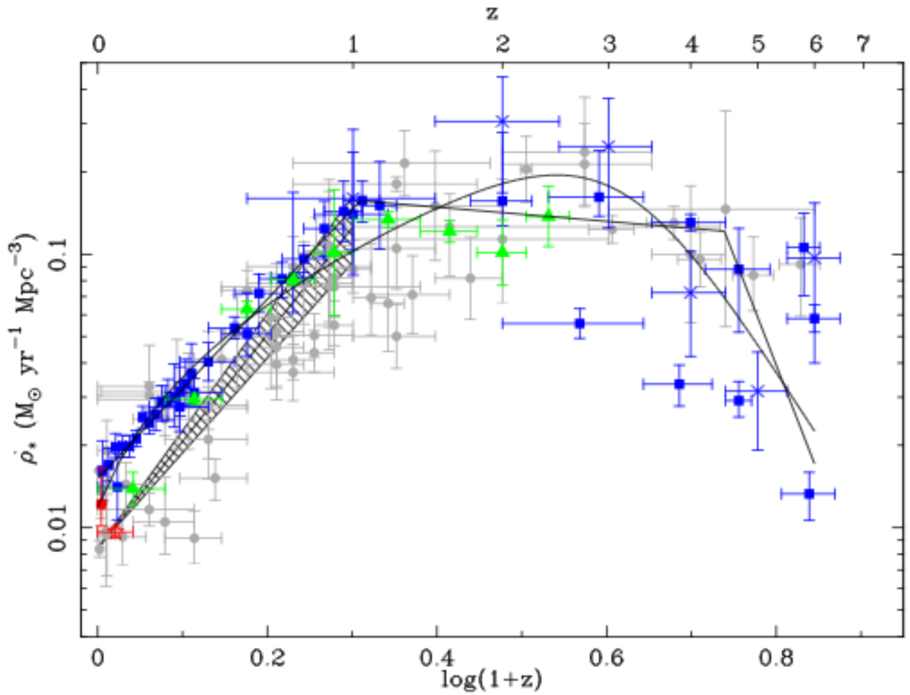
Vigourous star formation in galaxies

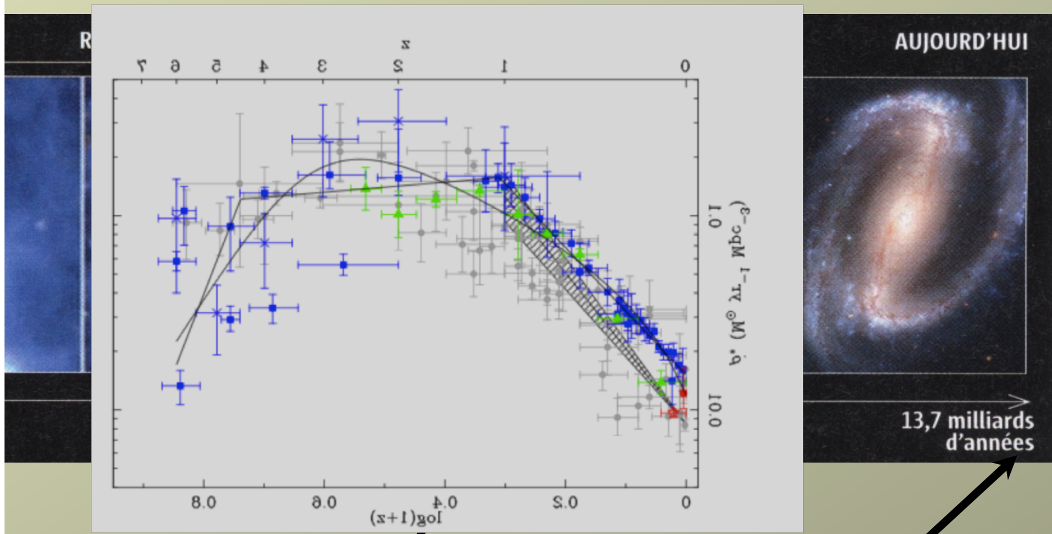
Decreasing star formation



Important phases in the history of the universe

redshift z





End of reionisation:
z ~ 6
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z=0
13.7 Gyr

“Madau-Lilly” diagram

Compilation from Hopkins & Beacom (2006)

First stars and galaxies

Vigourous star formation in galaxies

Decreasing star formation

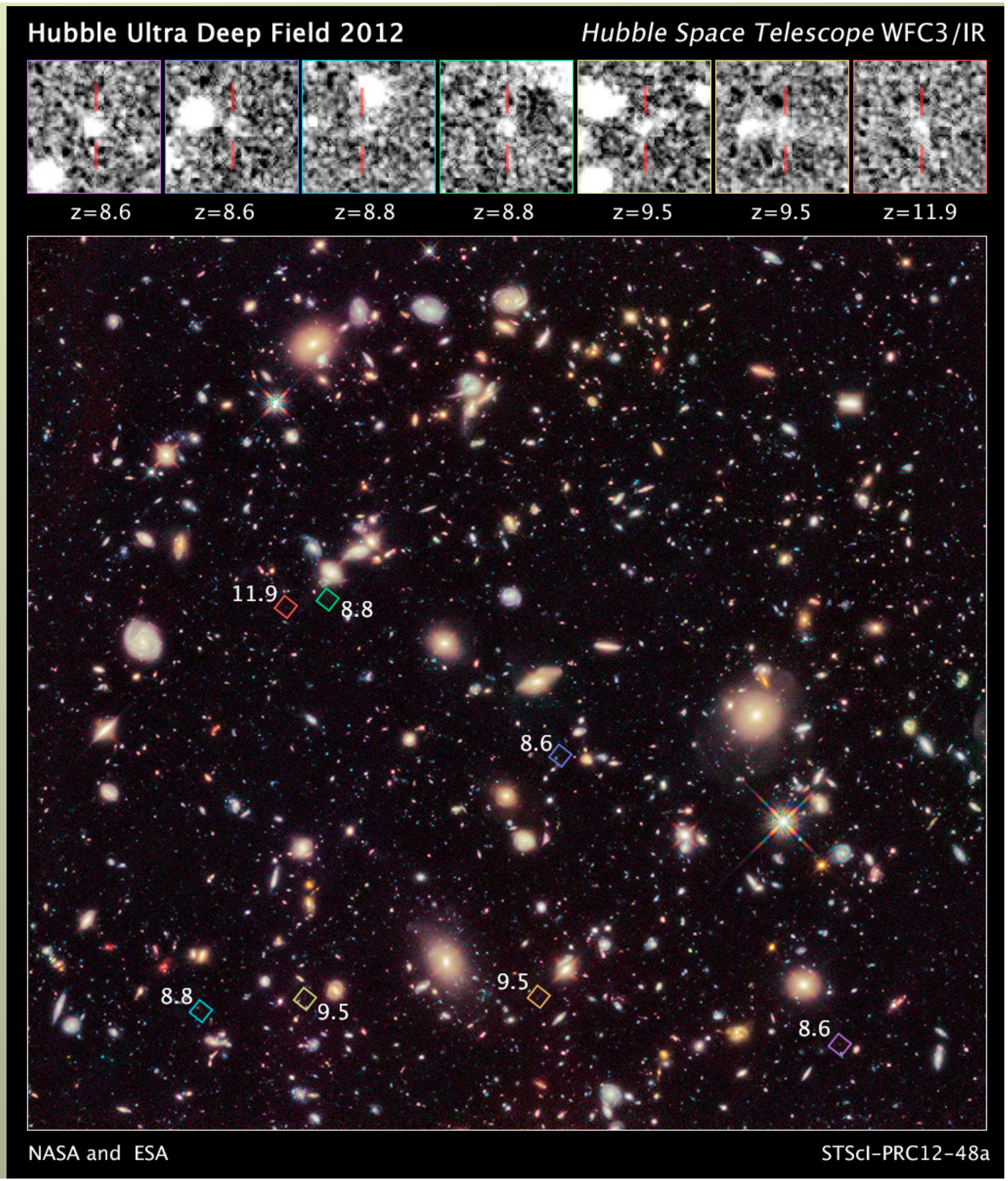
How do we find the first/distant galaxies?

DEEP SURVEYS …

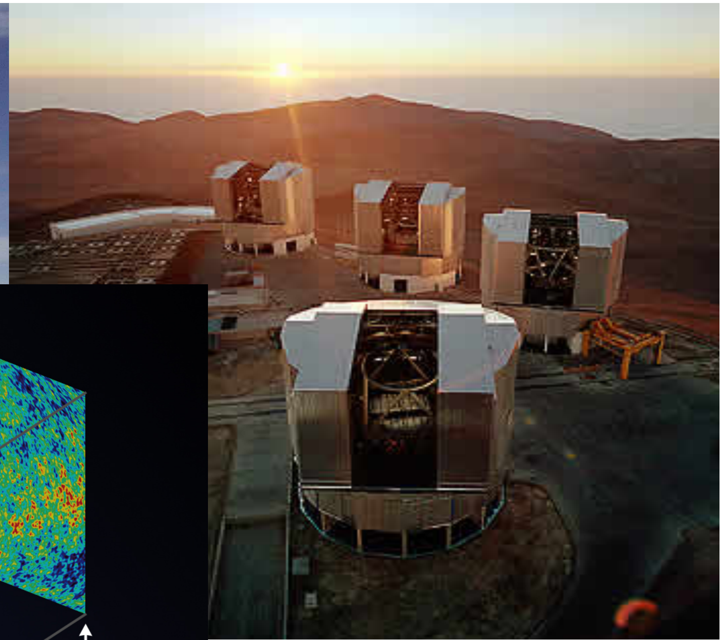
in the optical + near-IR

- 5 sigma depth: 29.5-30 mag (AB) in Y, J, H filters
- Similar depth in optical

UDF09, HUDF12, CANDELS, CLASH, …

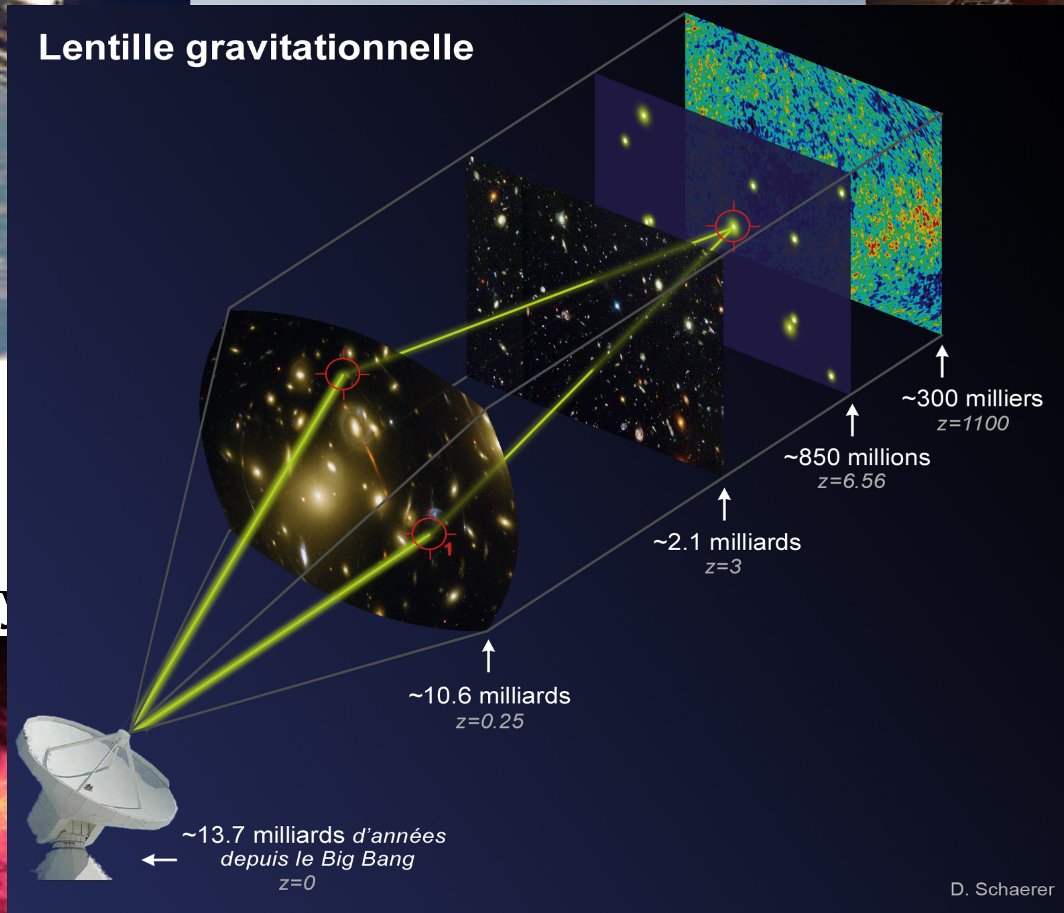






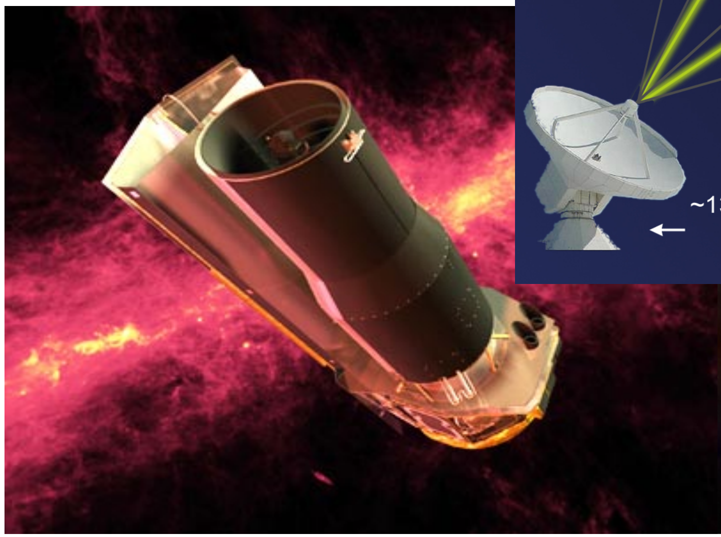
HST (UV-IR)

ible-near-IR)



Spitzer (IR near-moy

M (mm)



How do we find the first/distant galaxies?

Main categories of star-forming galaxies:

UV selected galaxies (→ cf. talk Garth Illingworth)

1) Lyman break galaxies (LBG)
2) Lyman-alpha emitters (LAE)

IR/mm selected galaxies (→ talk Francoise Combes)

Other methods:

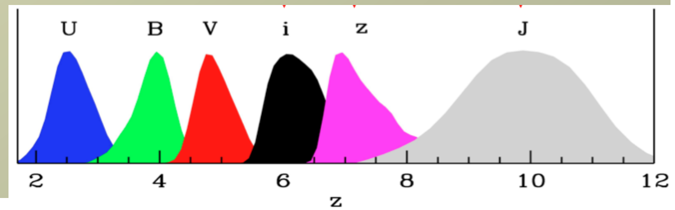
- Balmer break
- GRB hosts
- Blind emission line surveys (vis, near-IR, mm-radio)

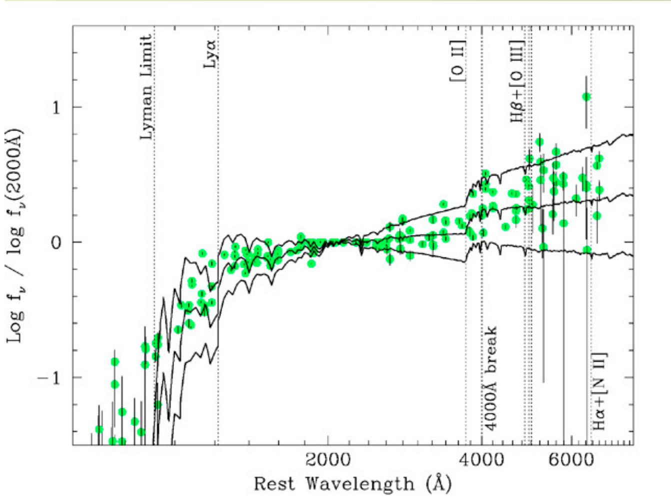
LBG, LAEs: reviews see e.g.
Shapley (2011, ARAA, 49, 525), Dunlop (2012, arXiv:1205.1543)

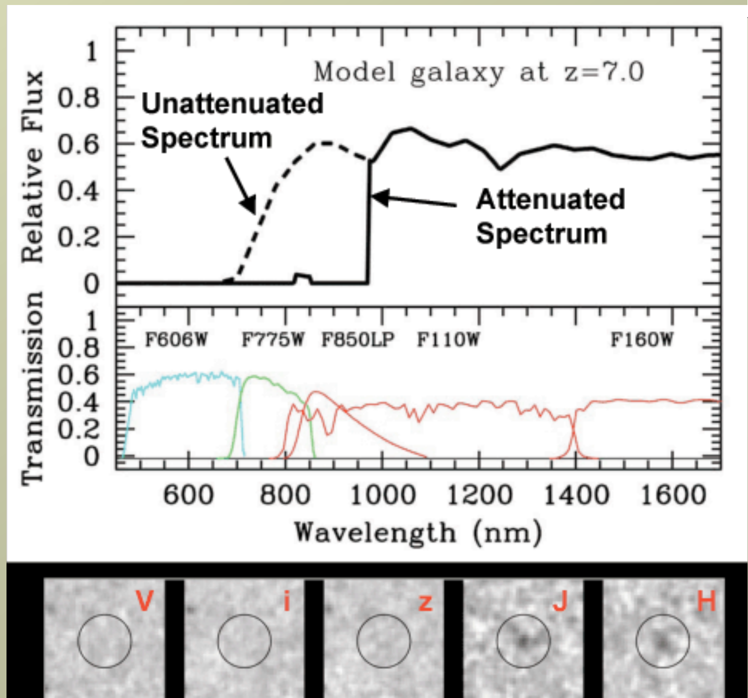
How do we find the first/distant galaxies?

UV-selected: Lyman break galaxies (LBG)

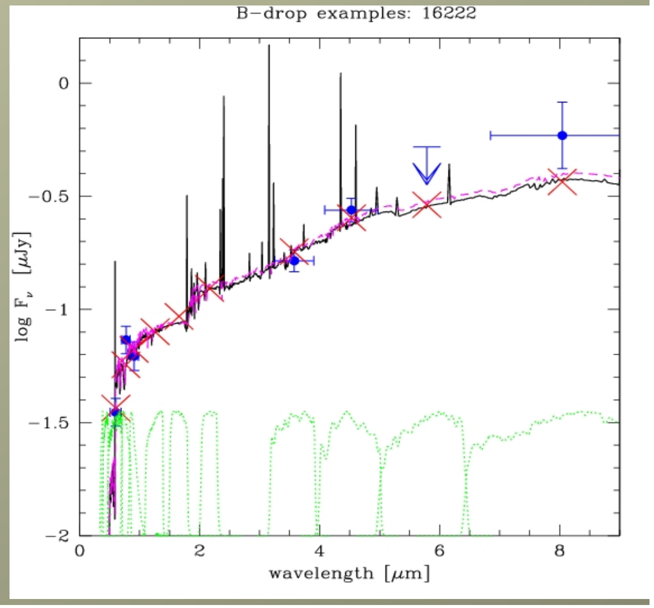
- Intrinsic UV emission (massive star formation)
- Lyman break (due to ISM or IGM)
- Localisation provides photometric redshift estimate







Example:
B-drop, z~4

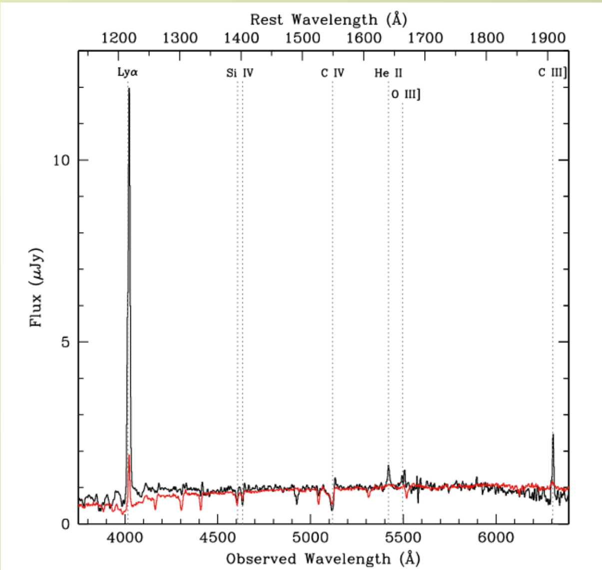


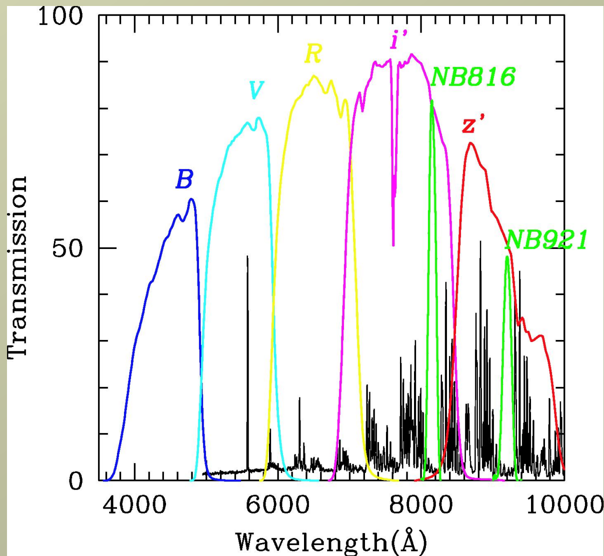
Lyman break or
« dropout technique»

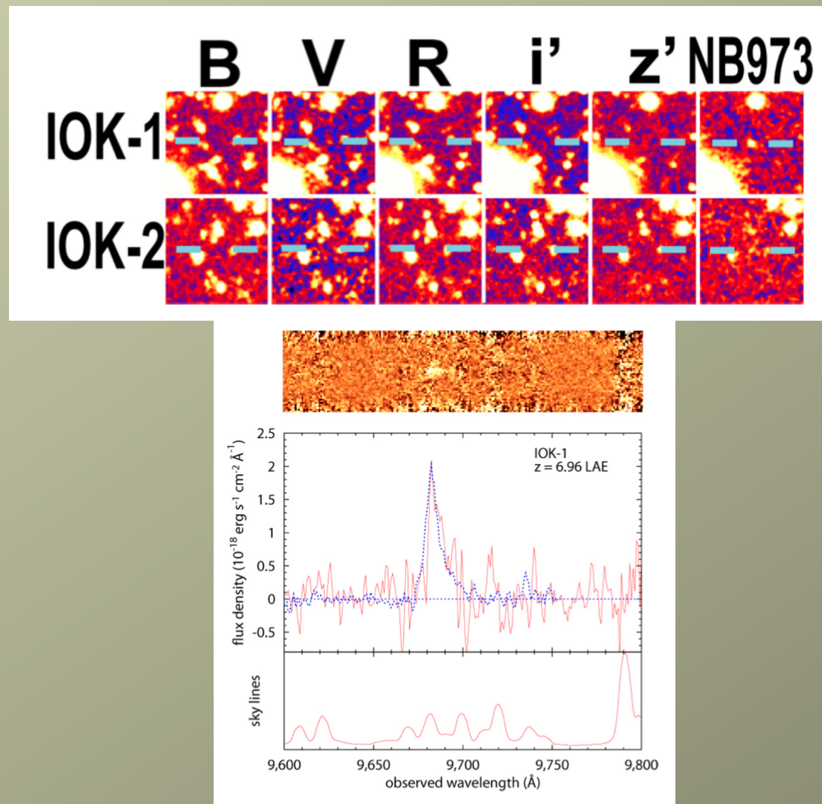
How do we find the first/distant galaxies?

UV-selected: Lyman alpha emittters (LAE)

- Intrinsic UV emission (massive star formation)
- Strong emission lines (HII regions) → Lyman-alpha emission
- Lya emission detected as EXCESS in narrow-band filter
- (combined with Lyman break)
- Spectroscopic follow-up







LAE, narrow-band technique

z=6.96, Iye et al. (2006)

How do we find the first/distant galaxies?

IR/mm-selected:

- Strong star formation + large dust content
- Intrinsic UV-vis emission absorbed and re-emitted by dust in thermal IR
- Redshift determination from IR SED uncertain (z ±1) →spectroscopic follow-up (vis,near-IR or mm-radio)

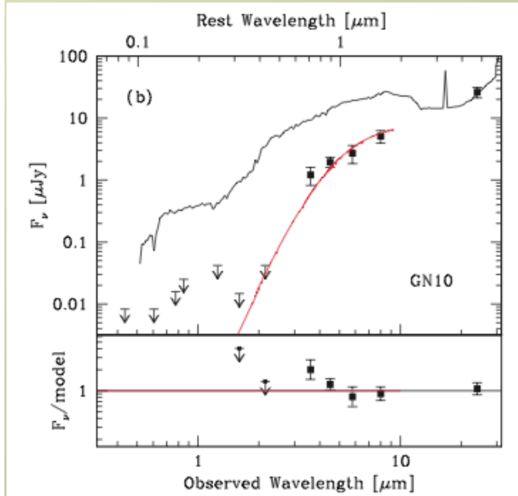
- New facilities&instruments: « CO redshift machines » (GBT, Z-spec@CSO, EMIR@IRAM, ALMA, …)

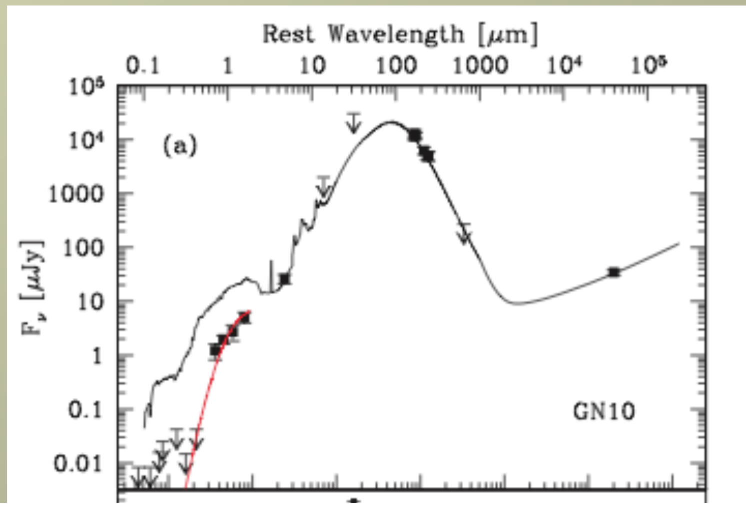
Sub-mm galaxies (SMGs):

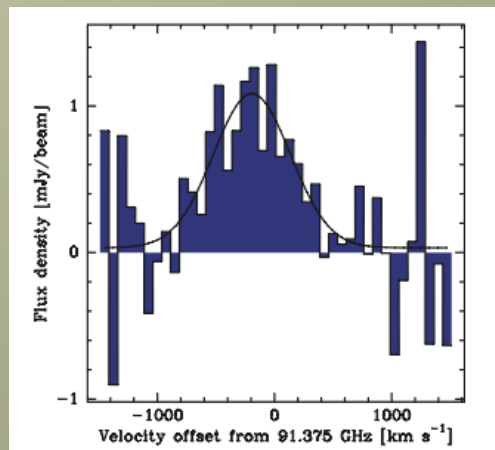
- Many examples now

(Chapman et al. 2003, Weiss et al. 2009, Combes et al. 2012, Walter et al. 2012)

* Current frontier: z~5-6







z=4.02, Daddi et al. (2010)

LBGs and LAEs at high redshift

How many galaxies found?

LBGs

Table 2
Lyman-break Samples Used to Measure the Distribution of UV-continuum Slopes β as a Function of Redshift and UV Luminosity

Sample[a]	Field	Luminosity Range[b]	No. of Sources
$z\sim4$	HUDF09	$-23 < M_{\mathrm{UV,AB}} < -16$	308
	ERS/CANDELS	$-23 < M_{\mathrm{UV,AB}} < -18$	1524
$z\sim5$	HUDF09	$-23 < M_{\mathrm{UV,AB}} < -17$	137
	ERS/CANDELS	$-23 < M_{\mathrm{UV,AB}} < -18.5$	277
$z\sim6$	HUDF09	$-23 < M_{\mathrm{UV,AB}} < -17$	70
	ERS/CANDELS	$-23 < M_{\mathrm{UV,AB}} < -19$	101
$z\sim7$	HUDF09	$-22 < M_{\mathrm{UV,AB}} < -17$	57[c,d]
	ERS/CANDELS	$-22 < M_{\mathrm{UV,AB}} < -19$	44

z~8	~50-60
z~8.5-10	~7
z~10-12	~3

Bouwens et al. (2012), McLure et al. (2012), Ellis et al. (2013), Oesch et al. (2013), Zheng et al. (2012), Coe et al. (2013)

LAEs

z=3.1, 3.7, 5.7	~800
z=6.6	207
z=6.96	~3
z=7.7	0

Hu et al. (2010), Ouchi et al. (2008, 2010), Iye et al. (2011), Kashikawa et al. (2011), Hibon et al. (2011), Clement et al. (2012).
Also Tilvi et al. (2010), Krug et al. (2011)

LBGs and LAEs at high redshift – overview of main information

Statistical properties:

- Number counts as fct of redshift
- Luminosity function (z)
- Star formation rate density (z)
- Sizes
- Clustering

as function of redshift and UV magnitude

Physical properties:

- Stellar mass
- Star formation rate (SFR)
- Age of stellar population
- Dust attenuation

- Metallicity
- (ISM) kinematics

needs near-IR …up to 5-6 μm

- Dust mass
- Gas content
- Dark matter content?

needs IR-mm data!

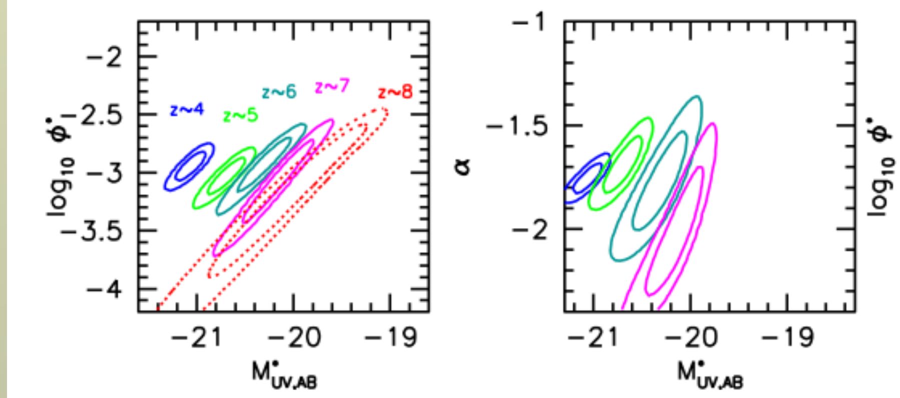
as function of redshift and UV magnitude

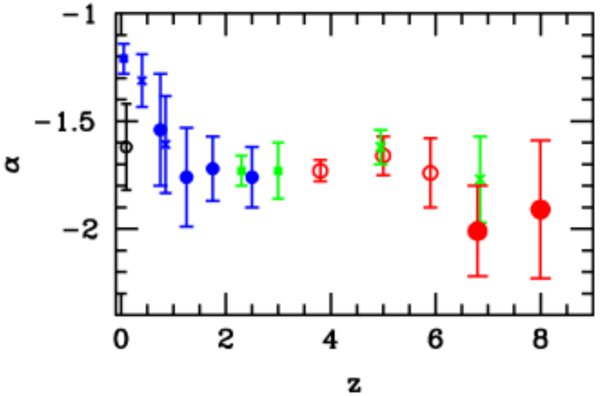
LBG populations at high redshift – main results

Rapid evolution of the UV LF with redshift:

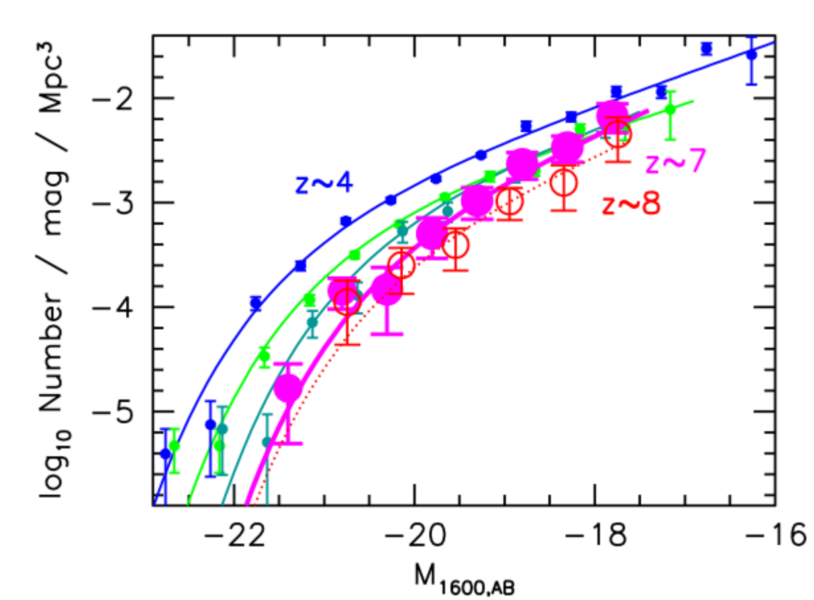
- Characteristic M^*_{UV} fainter at high z
- Very steep faint end of the LF

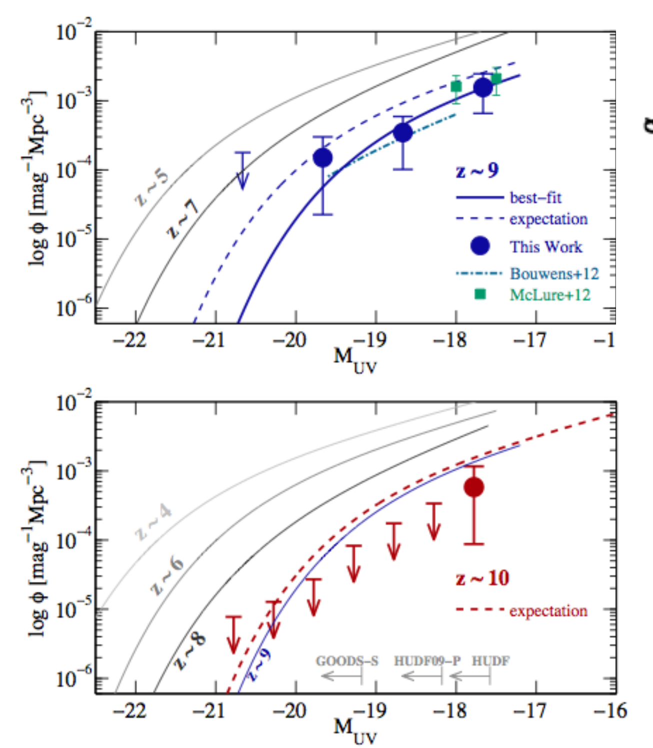
→ UV luminosity dominated by faint galaxies





Bouwens et al. (2012)





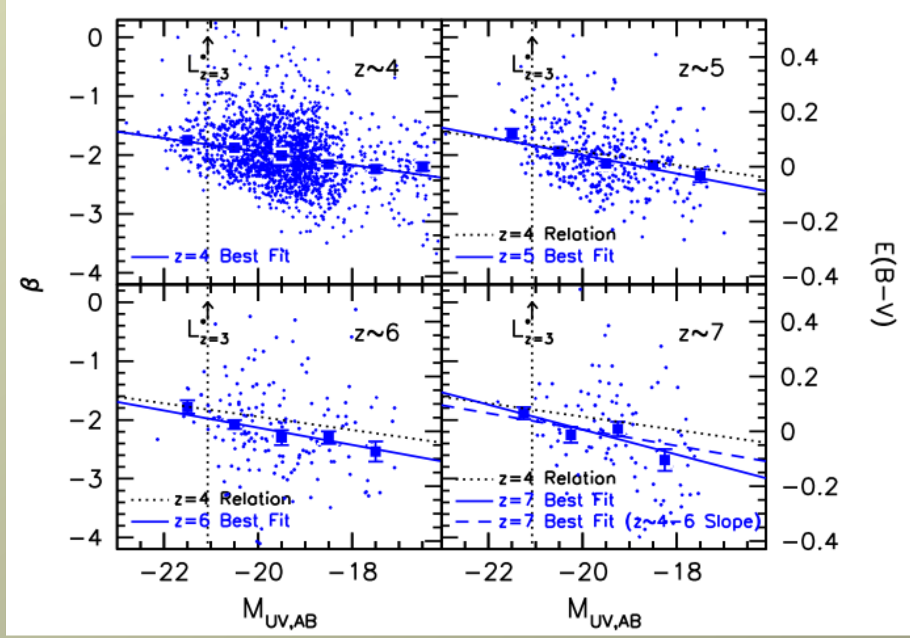
Laporte et al. (2012)
Oesch et al. (2013)

LBG populations at high redshift – main results

UV slope as function of magnitude and redshift:

- UV slope bluer (on average) for fainter galaxies
- Galaxies become bluer at high redshift

→ Interpreted as due to decreasing amount of dust attenuation for fainter galaxies + higher z



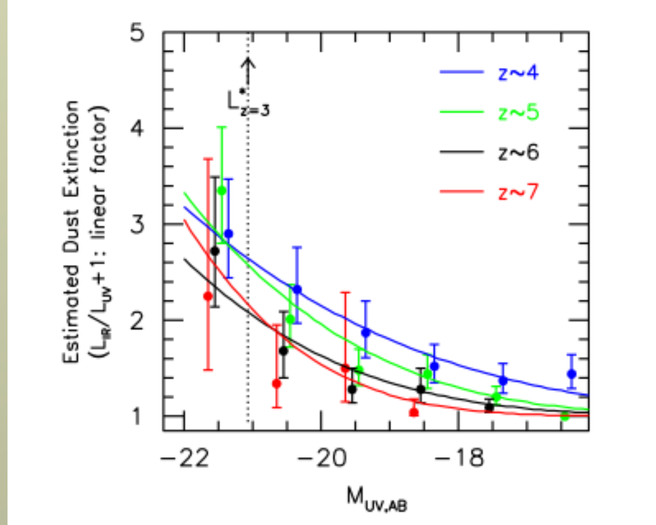
Bouwens et al. (2012)

BUT: assumes age 50-100 Myr and constant SFR

Some debate on reality/significance of these trends and very blue slopes (e.g. Castellano et al. 2012, Dunlop et al. 2012, Finkelstein et al. 2012, Schaerer & de Barros 2010)

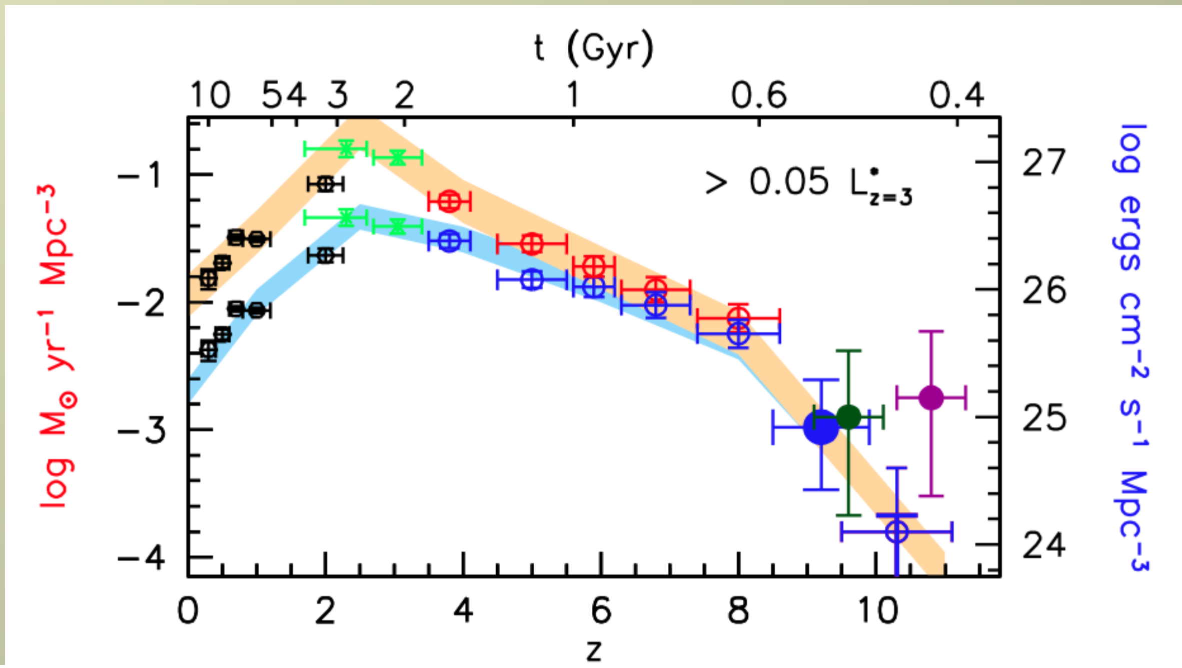
LBG populations at high redshift – main results

→ Correction of dust extinction



Bouwens et al. (2012)

From integral over UV LF compute
→ **total (extinction corrected) UV star formation rate density as a fct redshift**



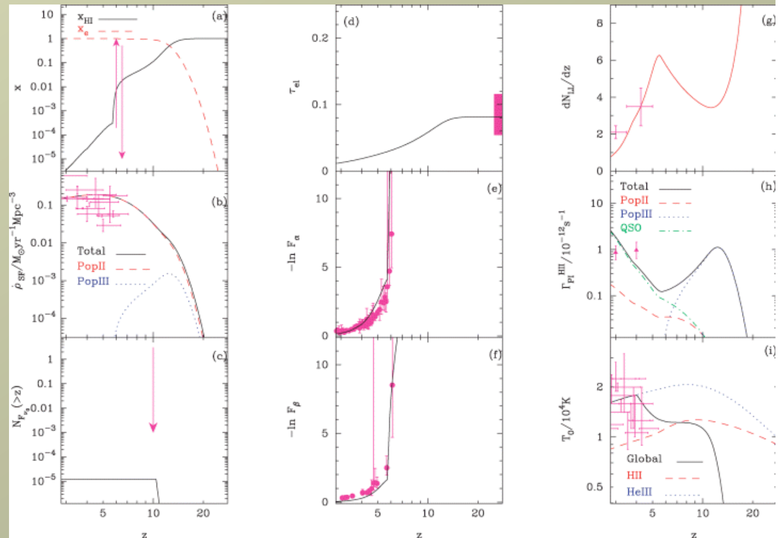
LBG populations at high redshift – contribution to cosmic reionisation

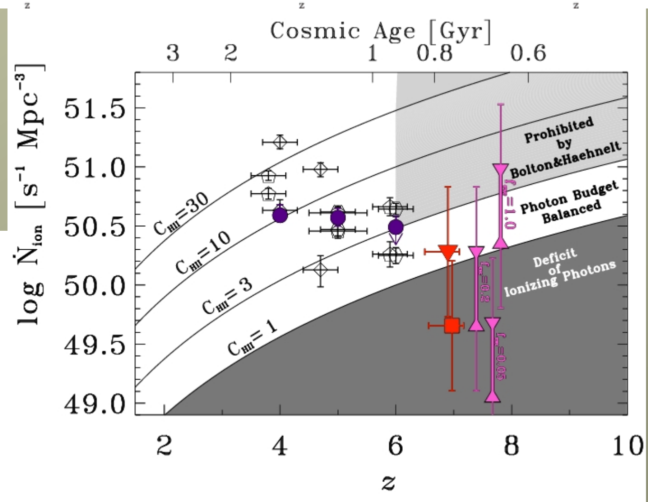
Data constrained reionisation models including constraints from WMAP, Lya forest, IGM, galaxy LFs:

- Currently detected galaxies **insufficient** to produce and maintain reionisation
- Significant/main contribution from FAINT galaxies required
- Escape fraction of ionising photons ~10-20%

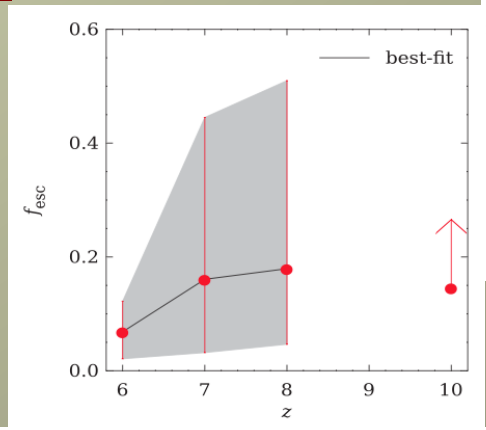
Major ongoing quest for reionisation sources!

PopIII contribution unknown/small

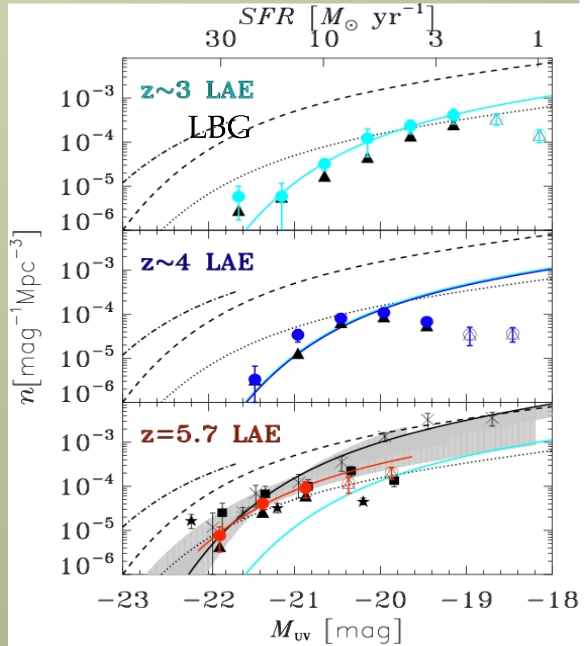




Choudhury & Ferrara (2005, 2006), Mitra et al. (2013), Bolton & Haehnelt (2007), Ouchi et al. (2010), Robertson et al. (2010),



LAE populations at high redshift – main results



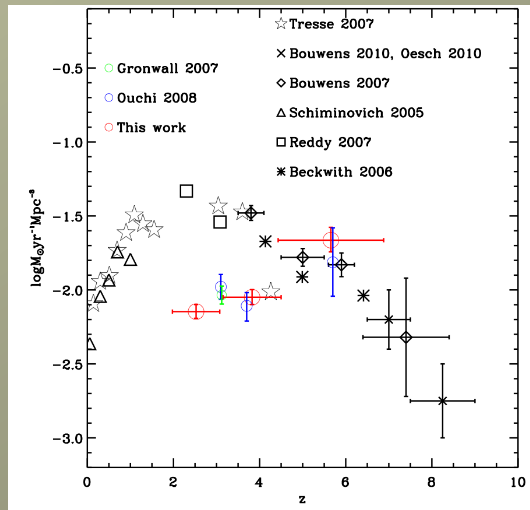
Ouchi et al. (2007)

- LBG dominate number of galaxies and star formation at z~3-4
- Increasing role of LAE with z:
  - Number density LAE/LBG ↗ from ~25% to ~50% between z~ 3 and 5.7
  - SFRD multiplied by ~2
- UV continuum LFs of LBGs and LAE converge towards z~6

--> Natural « unification » of LAEs and LBGs

What explains the relative evolution of the LAE and LBG galaxy populations?

What beyond z>6?



Cassata et al. (2010)

Unification of LAEs and LBGs

- Both galaxy populations *UV selected*
- Show same absence of high EW(Lya) in UV bright galaxies
  (« Ando » plot)
- Radiation transfer models explain « *transformation* » *of Lya emission* <--> *absorption* (Schaerer & Verhamme 2008, Verhamme et al. 2008)
- Radiation transfer explains trends of Lya (mainly) due to dust:
  - → *Fainter objects have stronger Lya emission*
  - → *Higher redshift galaxies have stronger Lya emission*

  Verhamme et al. (2008), Schaerer & Verhamme (2008), Atek et al. (2009), Hayes et al. (2010)
- *Fraction of LBGs with Lya in emission increases with redshift*
  Stark et al. (2011), Schaerer et al. (2011), Curtis-Lake et al. (2012)
- *Correlation lengths* of populations at z~3 are compatible
  (cf. Adelberger et al. 2005, Gawiser et al. 2007)

➔ Same underlying population of distant star-forming galaxies

➔ At z~3: overlap between LAE and LBG population is ~25%.
Much larger overlap @ z~6. Beyond z>6.5 affected by reionisation…

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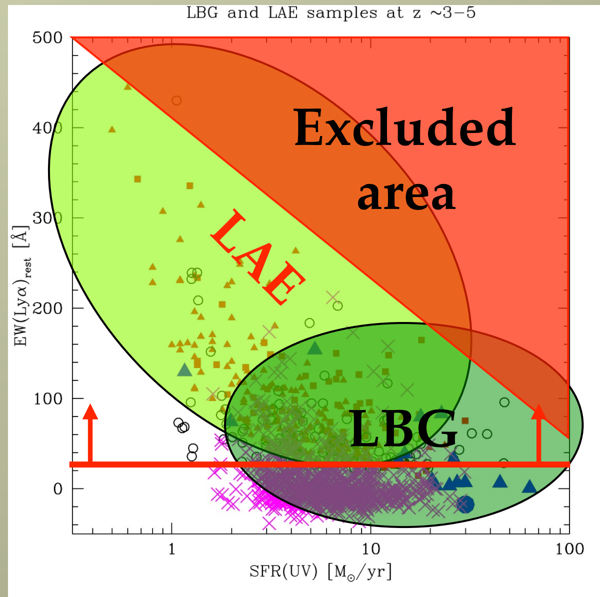
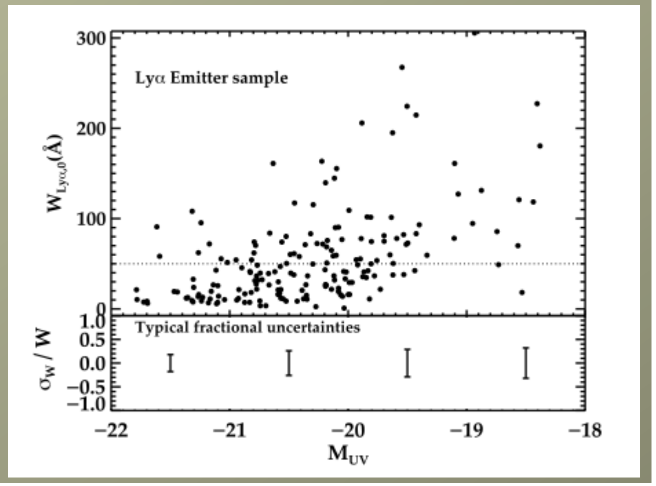


Verhamme et al. (2008)



Stark et al. (2010)

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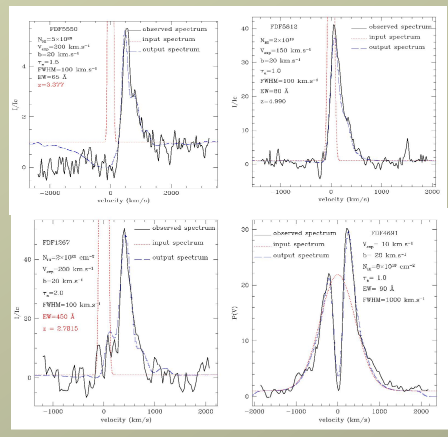
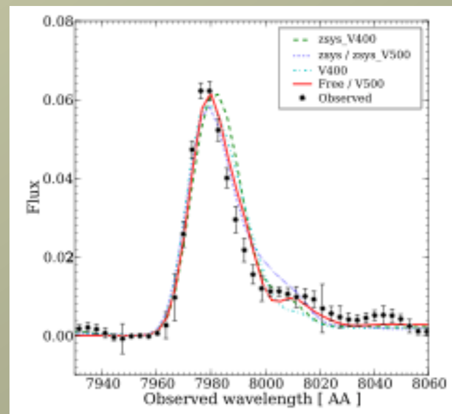
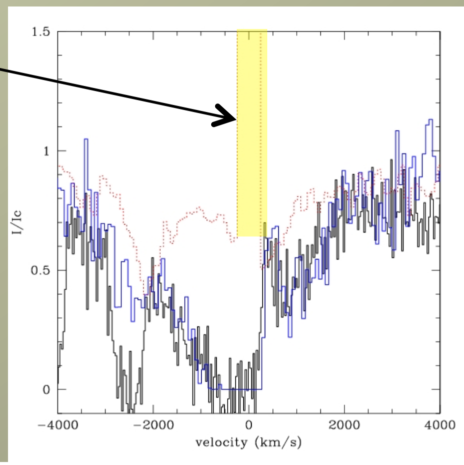
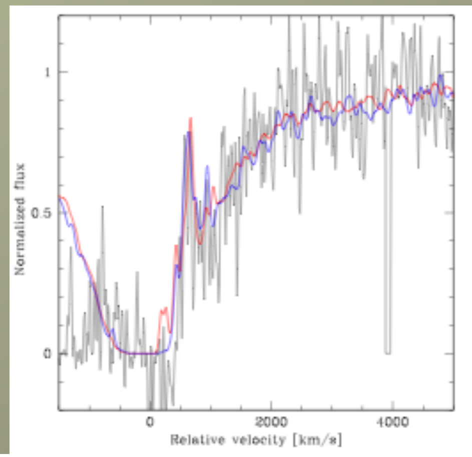




Intrinsic emission





Schaerer & Verhamme (2008)
Dessauges-Zavadsky et al. (2010)
Lidman et al. (2011)

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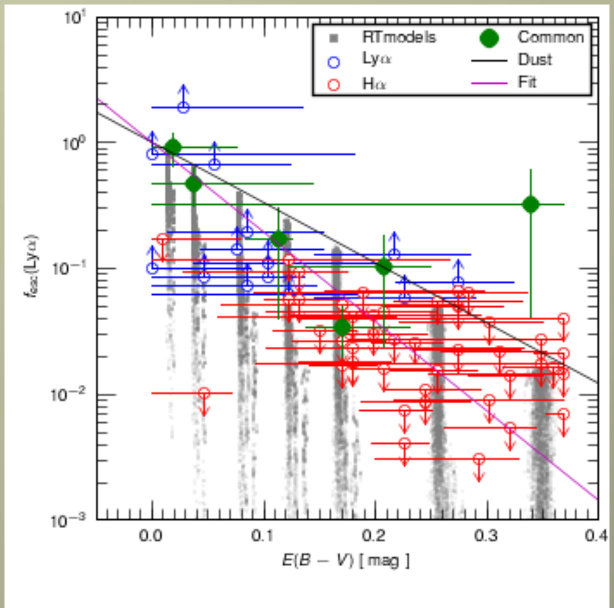

Hayes et al. (2010)

Unification of LAEs and LBGs

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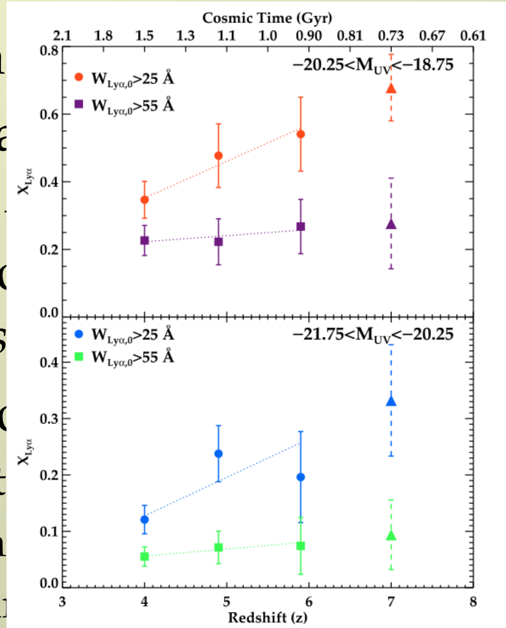
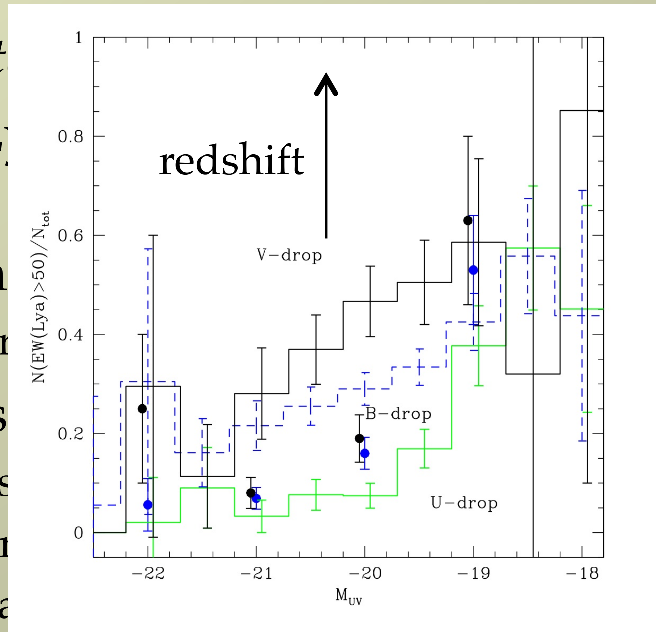




- Fraction of LBGs with Lya in emission increases with redshift
  Stark et al. (2011), Schaerer et al. (2011), Curtis-Lake et al. (2012)

Unification of LAEs and LBGs

LAE and LBGs unified:

➔ Same underlying population of distant star-forming galaxies.
Main difference: dust content (related to stellar mass)

➔ At z~3: overlap between LAE and LBG population is ~25%.
Large(r) overlap @ z~6. Beyond z>6.5 affected by reionisation…

Cosmological evolution of the mean Lyα escape fraction (from SF galaxies)

Determined from ratio of observed / intrinsic Lyα luminosity density

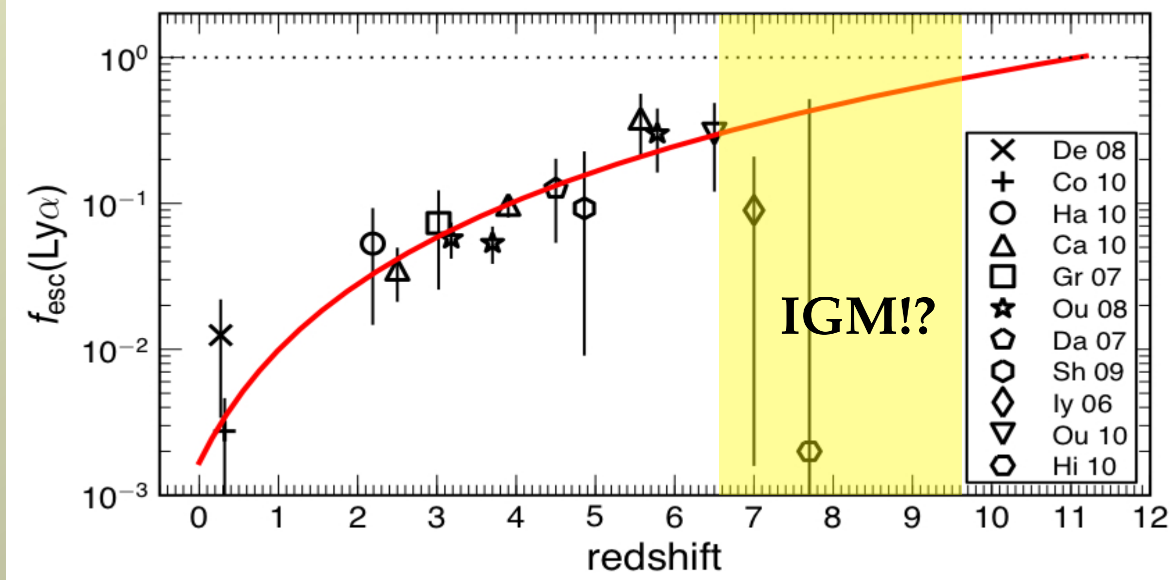
$$f_{\rm esc}^{\rm Ly\alpha} = \frac{\rho^{\rm Obs}_{\rm L,Ly\alpha}}{\rho^{\rm Int}_{\rm L,Ly\alpha}} = \frac{\int_{L_{\rm lo}}^{\infty} \Phi(L)^{\rm Obs}_{\rm Ly\alpha} \times L \times dL}{\int_{L_{\rm lo}}^{\infty} \Phi(L)^{\rm Int}_{\rm Ly\alpha} \times L \times dL},$$

Intrinsic Lyα luminosity density from extinction-corrected Hα or UV luminosity density

==> Monotonic increase of fesc(z) from galaxies from z~0 to 6.5

==> Trend understood from radiation transfer models: due to decreasing dust attenuation

==> Above z>~6.5: decrease of relative Lyα luminosity density most likley due to IGM



Hayes et al. (2011)

Consistent with increased fraction of Lyα emission in LBGs (Stark et al. 2010, 2011)

Consistent with lack/difficulty to find Lyα in z>7 galaxies: cf. Stark et al. 2010, Fontana et al. 2010, Vanzella et al. 2012, Pentericci et al. 2012, Hibon et al. 2011, Clément et al. 2012 +others

Probing cosmic reonisation with the first galaxies

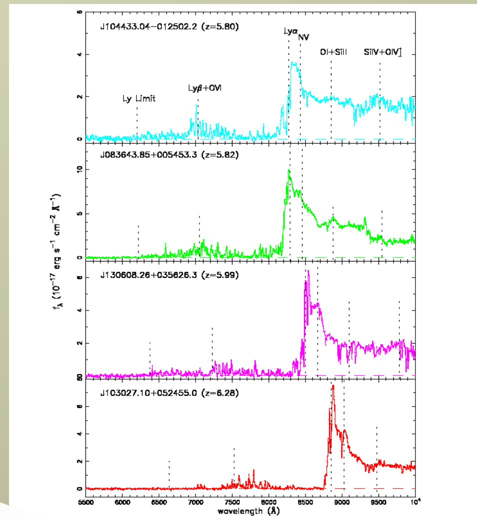
Methods:

- Redshifted 21 cm (LO
- Lyman-alpha (LAE I ong LBGs, Lya line profile, clusteri

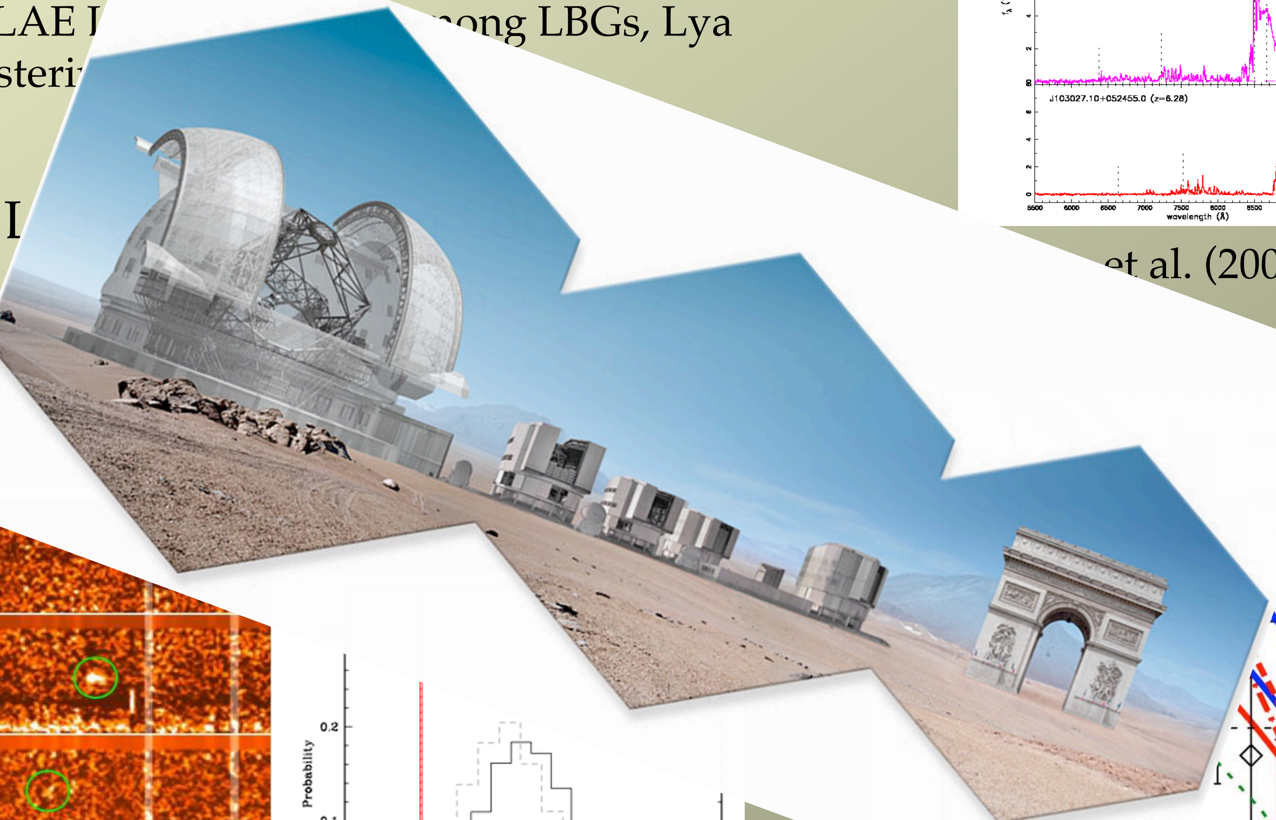
Recent results:

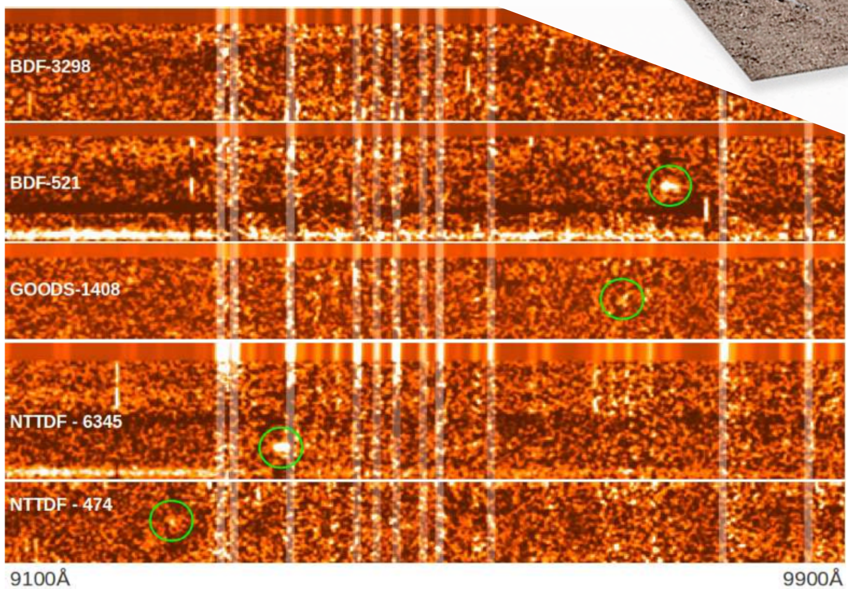
- Low fraction of I
- Strong decrease

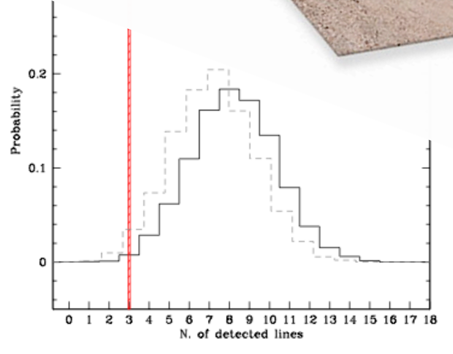
→ Spectroscopy c telescopes



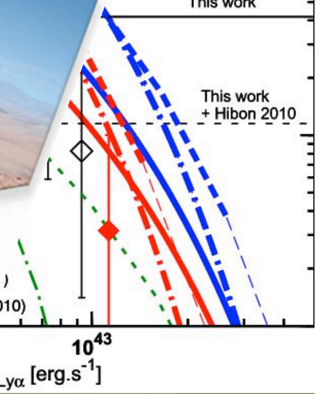
et al. (2003)







Pentericci et al. (2011)



Clément et al. (2012)

Physical properties of high-redshift star-forming galaxies

Motivation / main questions:

- Properties of high-z galaxies ? SFR, mass, age, extinction, metallicity etc.
- « Old » galaxies in the high-z universe ? Formation redshift?
- Are high-z galaxies dusty? Dust evolution with redshift?

- Typical timescales of star formation and SF histories?
- What drives SF in distant galaxies ? Cold accretion, mergers…? Importance of feedback?

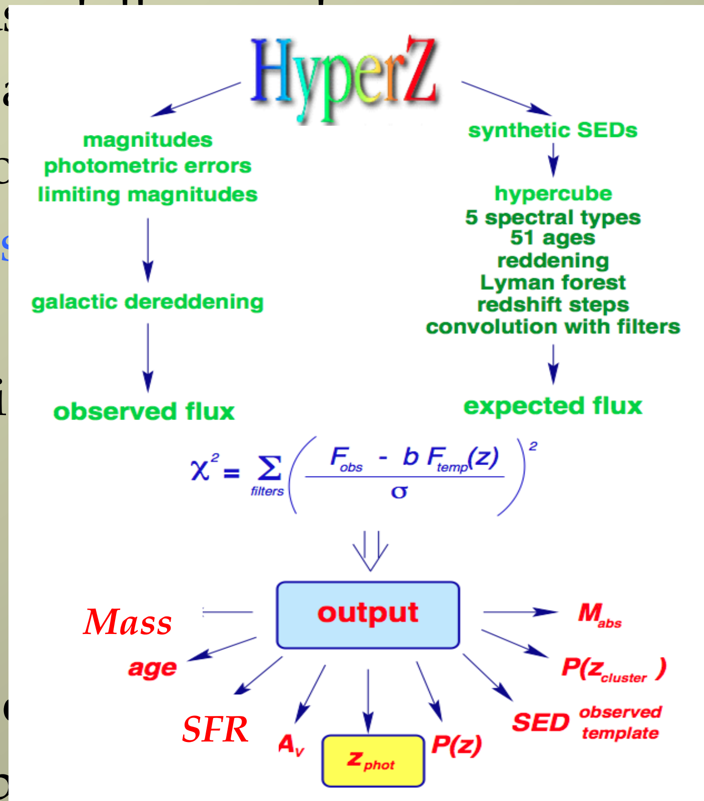
Many deep multi-band surveys available (ground-based, HST, Spitzer…) up to z ~6-7

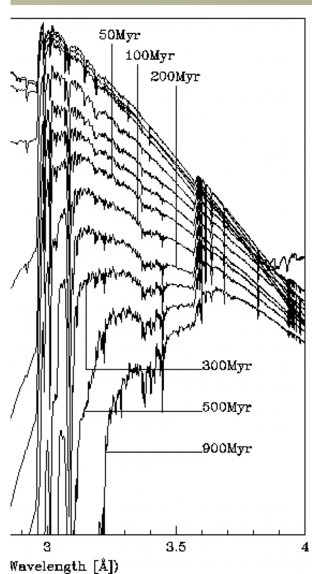
SED modeling/fitting of galaxies

Input physics:

- Stellar evolutionary tracks
- HII region physics: nebul
- Stellar initial mass functio
- → Simple stellar populations
- Star formation history
- Dust attenuation/extincti
- IGM attenuation

g galaxies





erer et al. (1999)

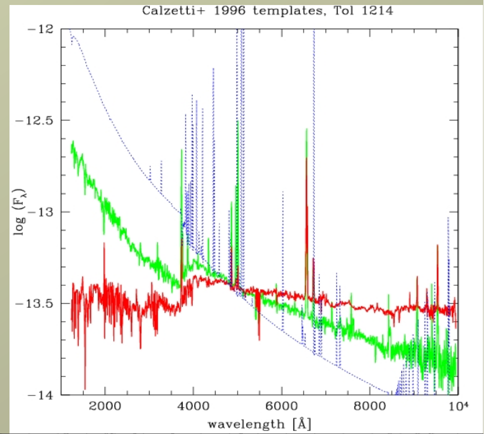
Options:

- Dust model to predict IR
- Geometry of galaxy comp
- Radiation transfer …

see e.g. "The Spectral Energy Distribution of Galaxies" 2012, IAU Symp. 284
reviews by Walcher et al. (2011), Conroy (2013, ARAA)

SED modeling of star-forming galaxies – need for nebular emission

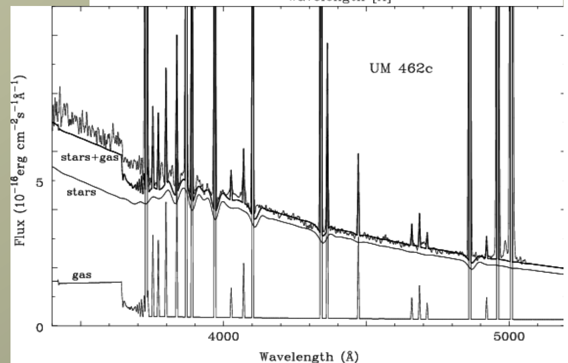
- **Emission lines** (H, He recombination lines, metal lines)
- **Nebular continuous emission** (2-photon, H +He free-bound) Emissivity increases with λ^2



Ubiquitous in star-forming galaxies (from low to high-z)

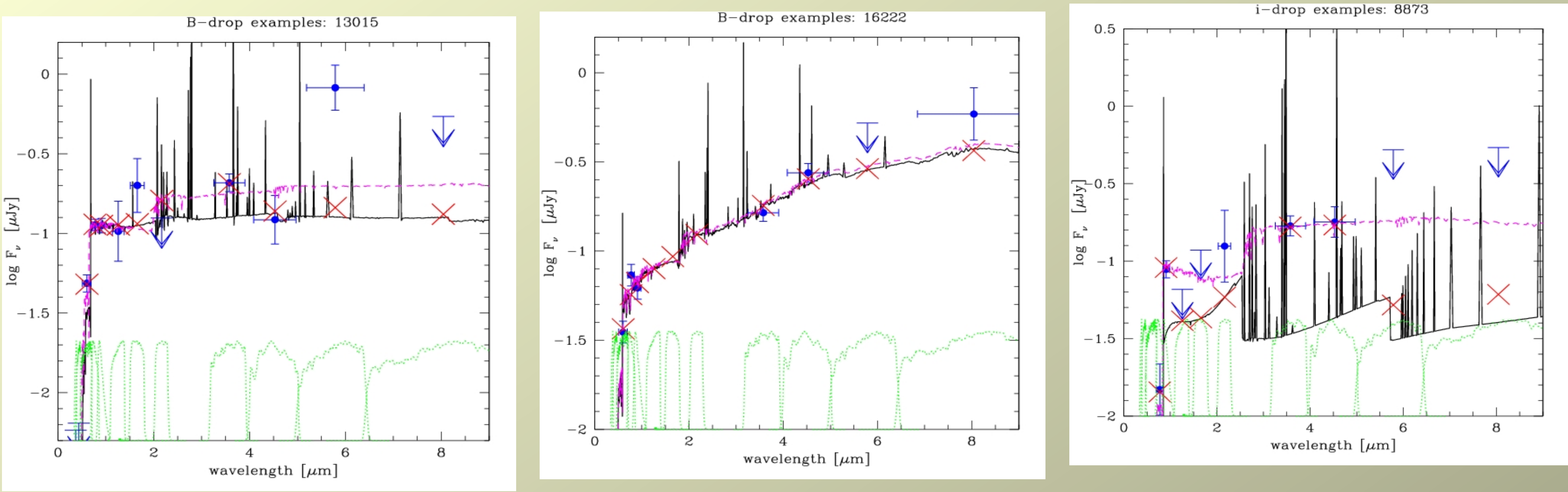
Importance of nebular emission increases with:

- decreasing metallicity
- decreasing age of stellar population
- increasing ionisation parameter



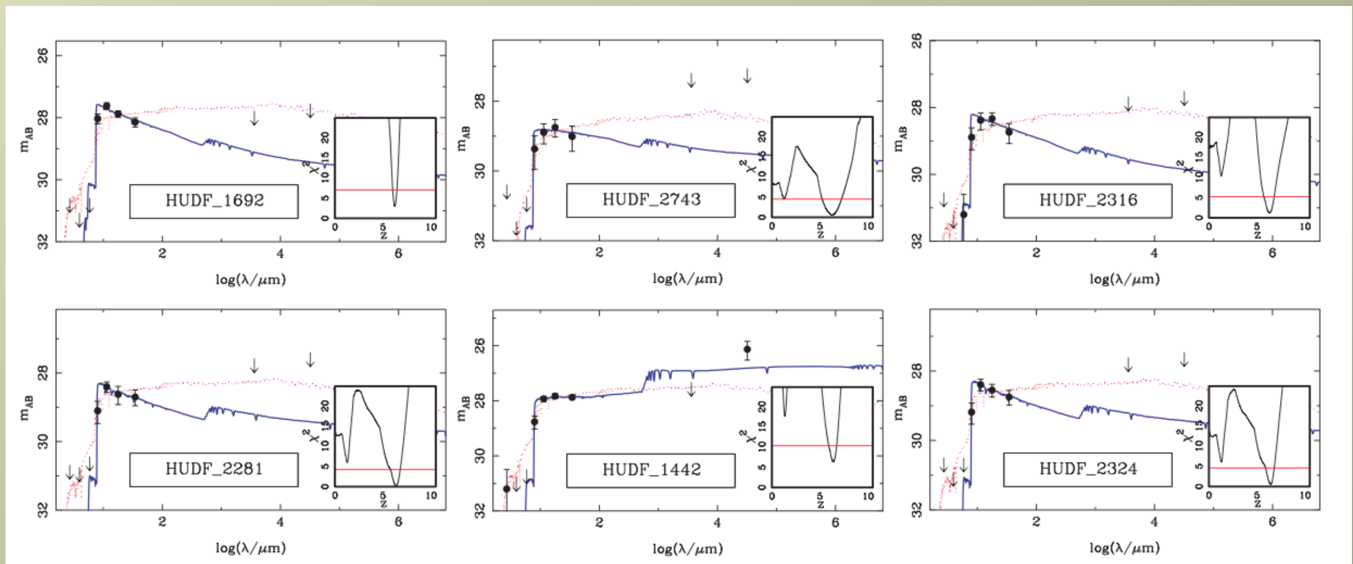
Contribution of emission lines to photometry increases with redshift **(EW_{obs} ~(1+z))**

Also: **dynamical time ~ $(1+z)^{-3/2}$ ==> shorter starburst lifetimes**



Example: GOODS-S, UBVizJHK,3.6,4.5,5.5,8.0 photometry. z~4 and 6 galaxies

de Barros et al. (2012)



Example: Hubble UDF (ACS, WFC3, Spitzer)

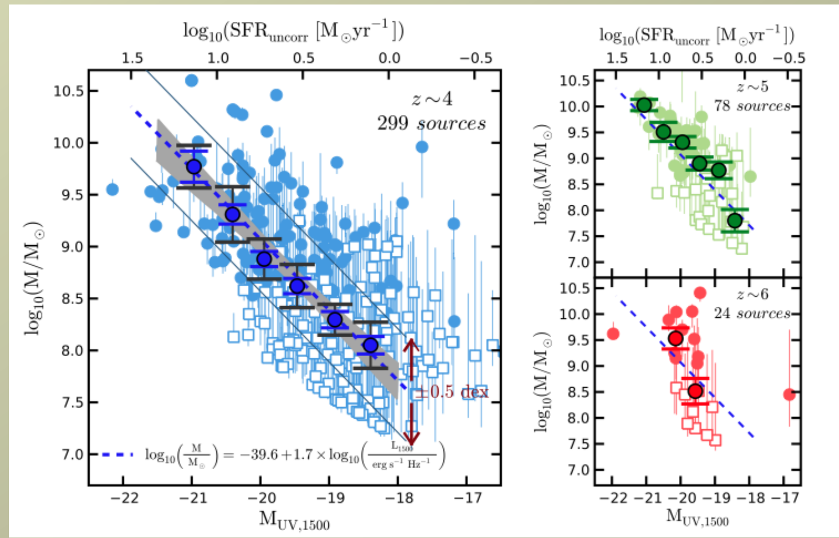
McLure et al. (2012)

z~6-8 sample

Physical parameters of high-z LBGs: first/early results (with « standard » SED models)

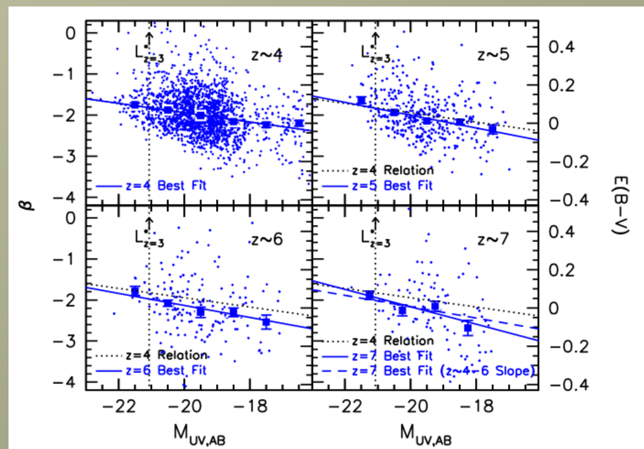
- Mass - UV magnitude relation:

  Gonzalez et al. (2011)



- Extinction versus UV magnitude and as fct of redshift:

  Bouwens et al. (2009 – 2012)



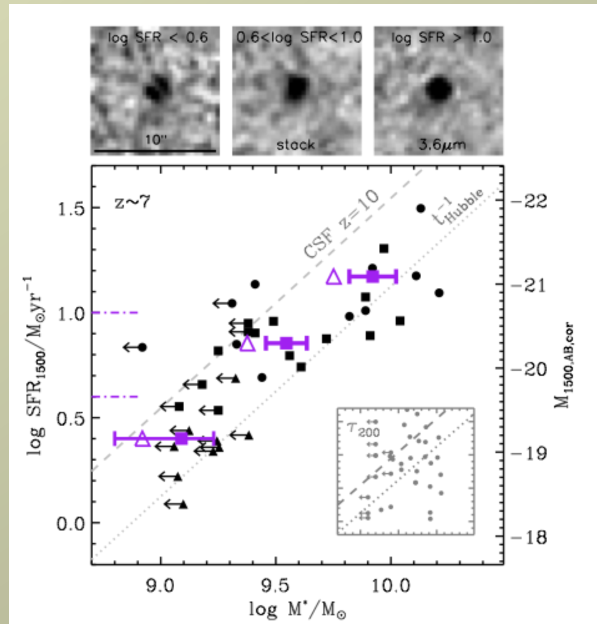
Physical parameters of high-z LBGs: first/early results

- Mass - SFR: tight relation up to z~7

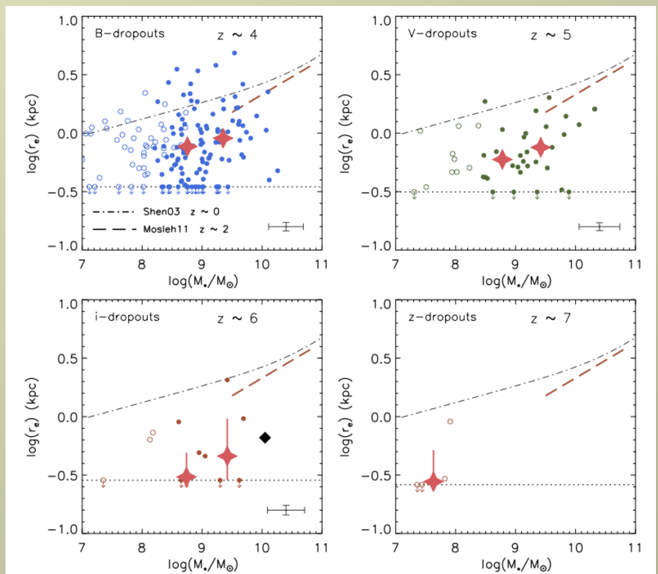
  e.g. Labbé et al. (2010)

  « Star-formation main sequence »

  well established at z~0 to 2 (cf. Noeske et al. (2007), Daddi et al. (2007), Elbaz et al. (2011) …)

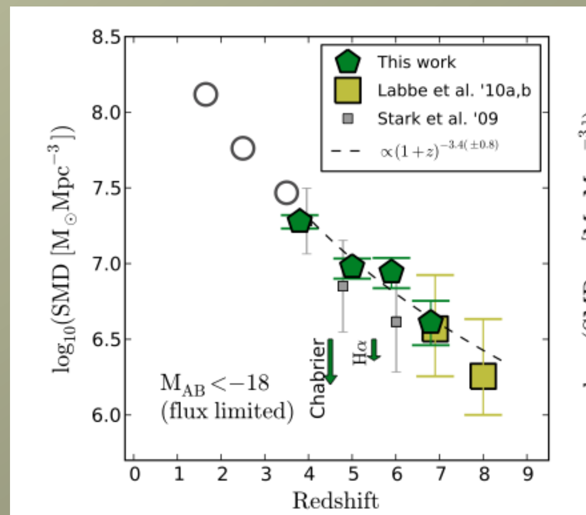


- Mass size-relation: high-z LBGs more compact Mosleh et al. (2012), …



- Evolution of stellar mass density with z

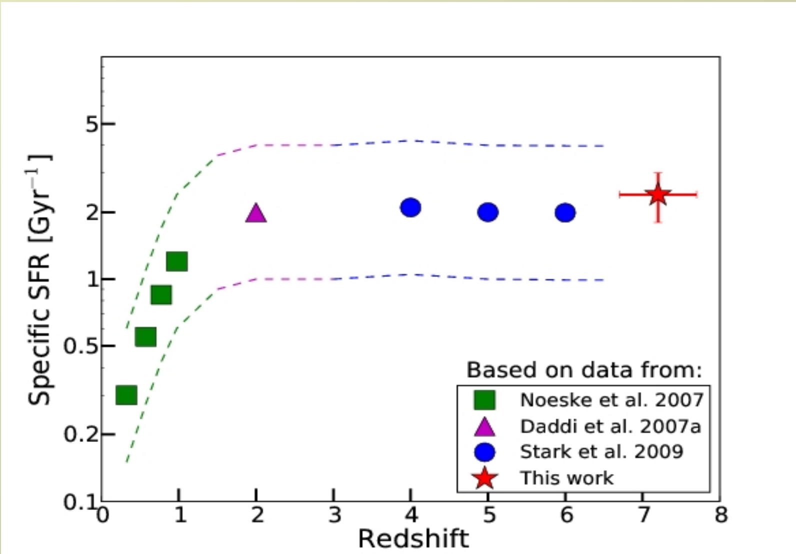
  e.g. Labbé et al. (2010), Gonzalez et al. (2011)



Physical parameters of high-z LBGs: first/early results

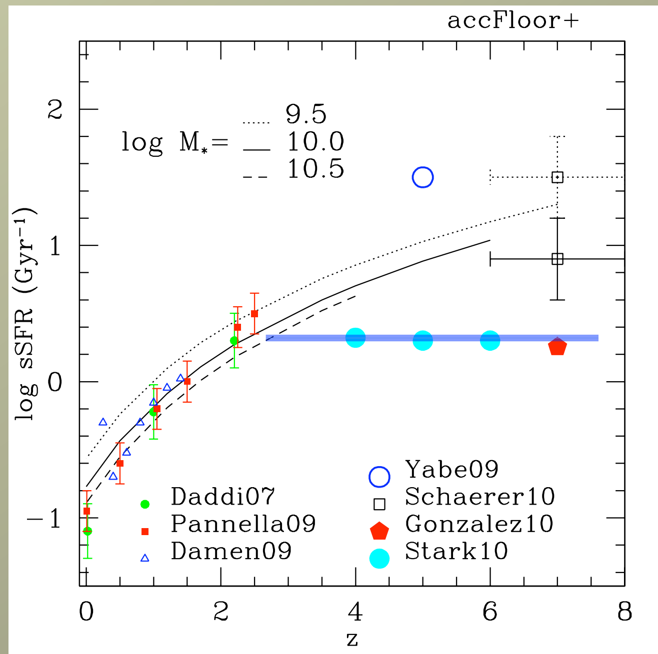
- Plateau of the specific star formation rate (sSFR=SFR/M*) from z~2 to 7 !

Gonzalez et al. (2010)



Serious problem for galaxy formation models?

Bouché et al. (2010), Dutton et al. (2010), Weinmann et al. (2011), Davé et al. (2011)…



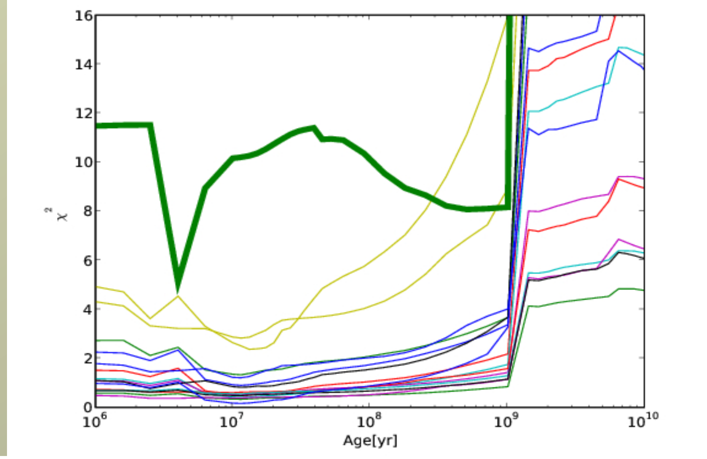
Physical parameters of high-z LBGs: first/early results

« Old » galaxies in the high-z universe ? **high formation redshift?**

(cf. Eyles et al. 2005, 2007, Yan et al. 2006, Labbé et al. 2010)

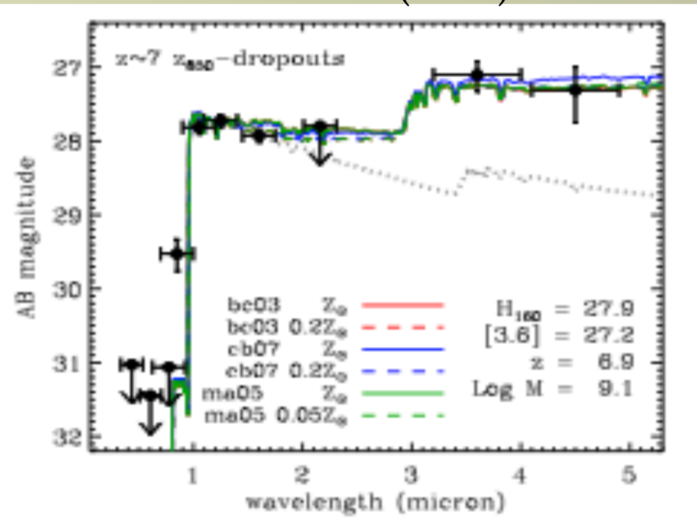
- Age estimated from Balmer break
- **Emission lines can mimick large break**

(Schaerer & de Barros 2009)



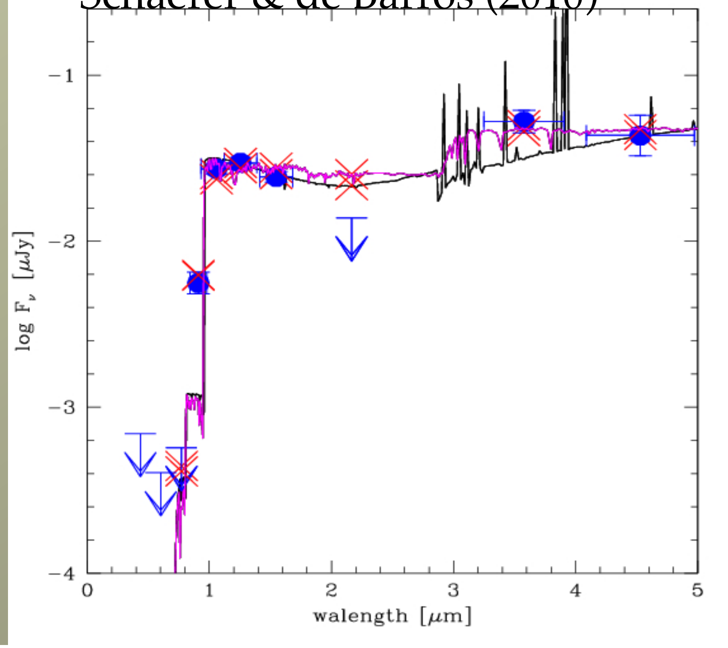
Stacked SED (14 objects @ z~7) :
classical SED fits
•Weighted age ~350 (+30-170) Myr
--> onset of SF at z~30 (+30-19) !?

Labbé et al. (2010)

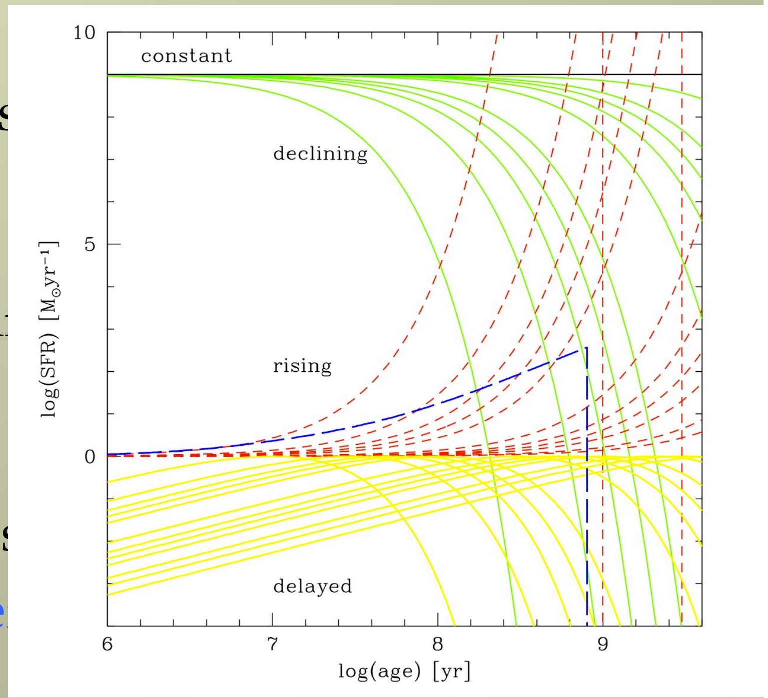


Models including nebular lines:
- Age~4 Myr
- A_V~0.2
- M^*~5. 10^7 $M_\odot$

Schaerer & de Barros (2010)



Modeling z~3-8 star-forming galaxies



- Extensive exploration of parameter s
  - Redshift
  - Attenuation
  - SF histories (SFR=const, exp. declini
  - Age
  - Metallicity
- Uncertainties determined from MC s
- First time: systematic study taking e
  into account
- Uniform and consistent analysis of z~3 to 8 galaxies with same code (modified Hyperz code)
- Large sample of UV selected drop-out galaxies with multi-band photometric data

==> de Barros, Schaerer, Stark (2011, 2012); Schaerer et al. (2013)

Sample 1 (z~3-6)

Dropout selected galaxies from GOODS-S field

- Selection criteria: « standard » (see Stark et al. 2009)
- Optical to near-IR photometry from VLT, HST and Spitzer (IRAC):
  UBViz, JHK, and 3.6, 4.5, 5.8 and 8.0 μm
- GOODS-MUSICv2 (Santini et al. 2009)

U-dropouts (z~3): 440 --> 389 after photometric redshift « cleaning »
B-dropouts (z~4): 859 --> 705
V-dropouts (z~5): 277 --> 199
i-dropouts (z~6): 66 --> 60

Sample 2 (z~6-8)

- 70 objects with z~6.0-8.7 selected by McLure et al. (2011)
- HUDF, HUDF09-2, ERS fields
- HST and Spitzer photometry (F775W, F850LP, F098M/F105W, F125W, F160W + *IRAC1, IRAC2 limits/fluxes)*

Two categories of LBGs revealed

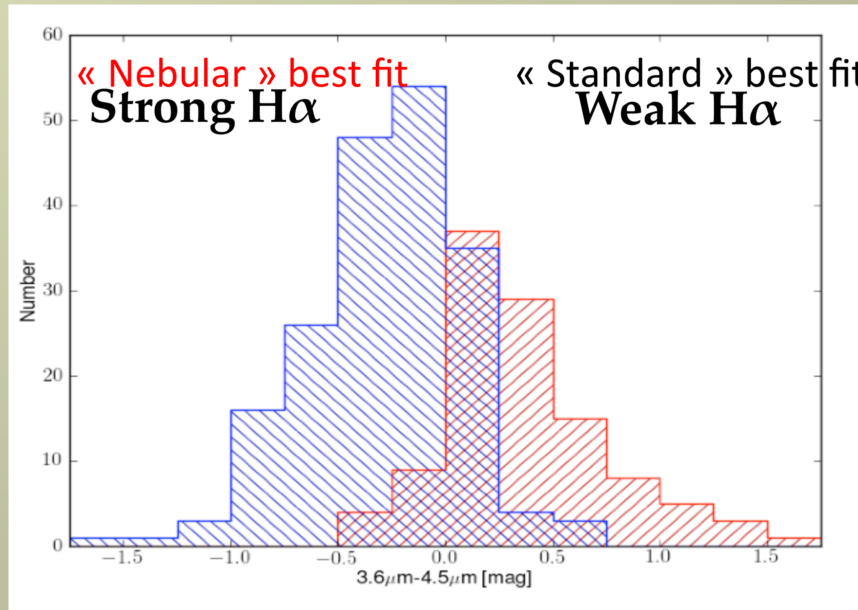
==> ~65% of galaxies show « strong » emission lines

Best fit with nebular emission

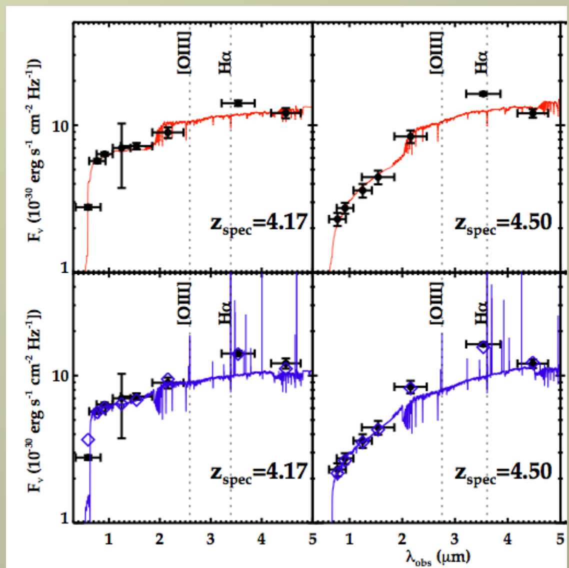
==> 35% weak/no lines

Fits similar with / without lines

Similar trends and distinctions at all magnitudes and all redshifts (z~3 to 6)



303 galaxies with 3.5 and 4.6 μm data available and z = [3.8,5]



For z = [3.8,5]: Hα in 3.6 μm filter and fewer lines in 4.5 μm filter

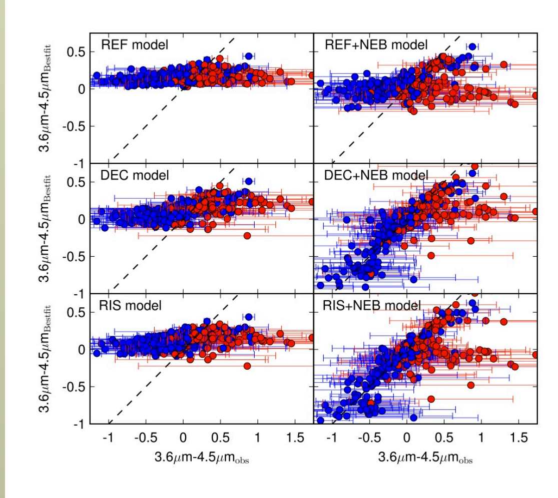
➔ *« empirical » distinction of Hα-emitters and non-emitters*

(cf. Shim et al. 2011)

Distinctions among two LBG categories

- **constant SFR + age>50 Myr: unable to reproduce observed range of (3.6-4.5) colors**

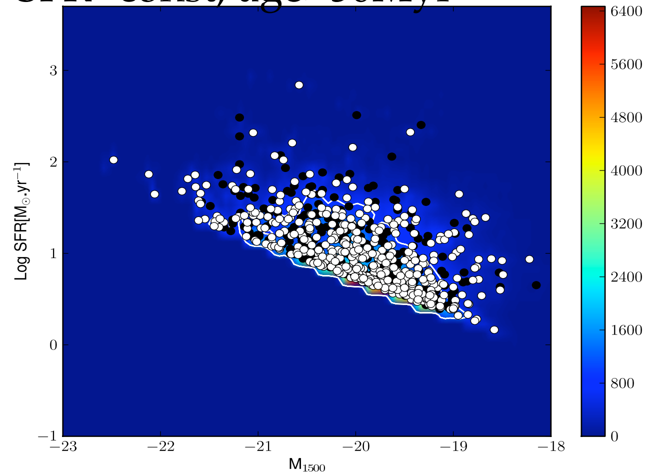
- **(3.6-4.5) color only recovered by models including nebular emission**



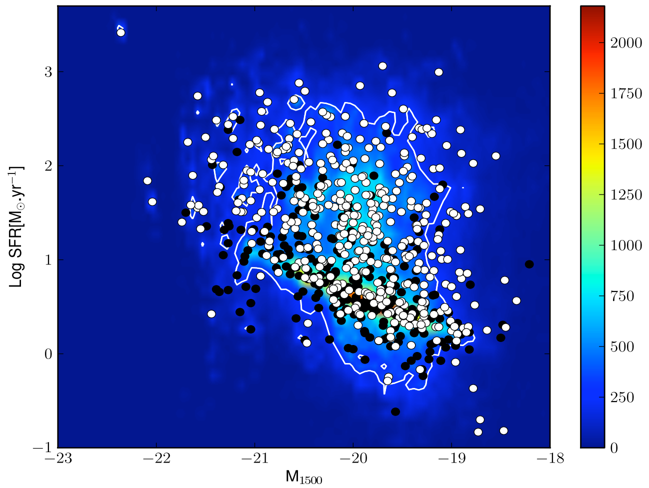
- 35% of galaxies have « low » nebular emission ==> **lower SFR**
- ~65% of galaxies have « strong » nebular emission ==> **higher SFR**

Similar trends and distinctions at all magnitudes and all redshifts (z~3 to 6)

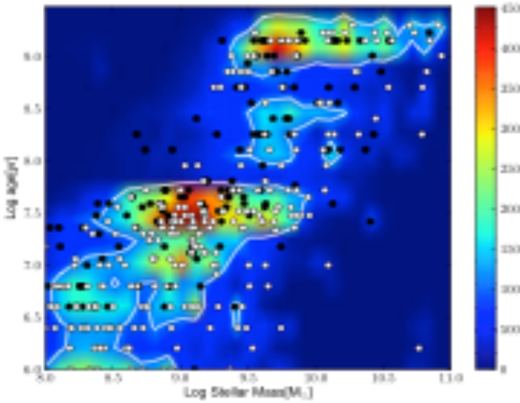
SFR=const, age>50Myr



variable SF histories + nebular



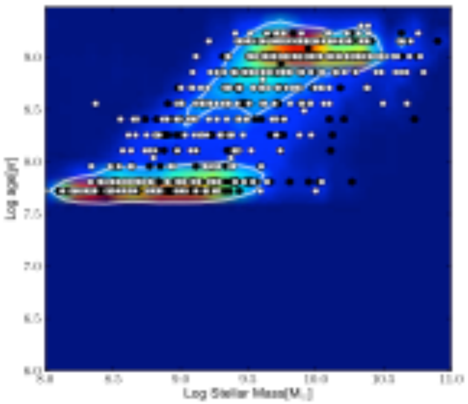
Properties of high-z galaxies: age

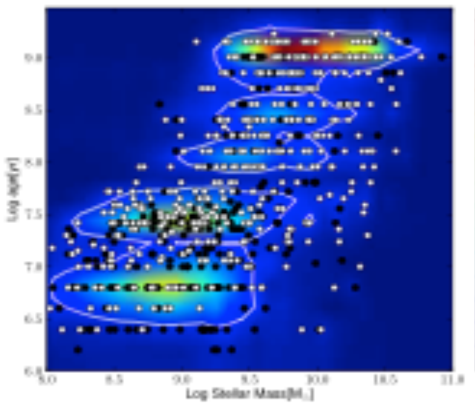


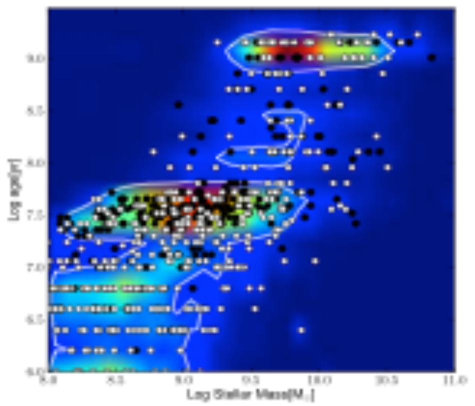
z~3

z~4

SFR=const, age>50Myr | variable SF histories | **variable SF histories + nebular**

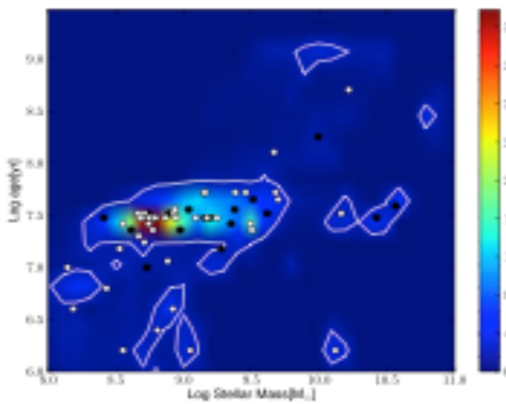




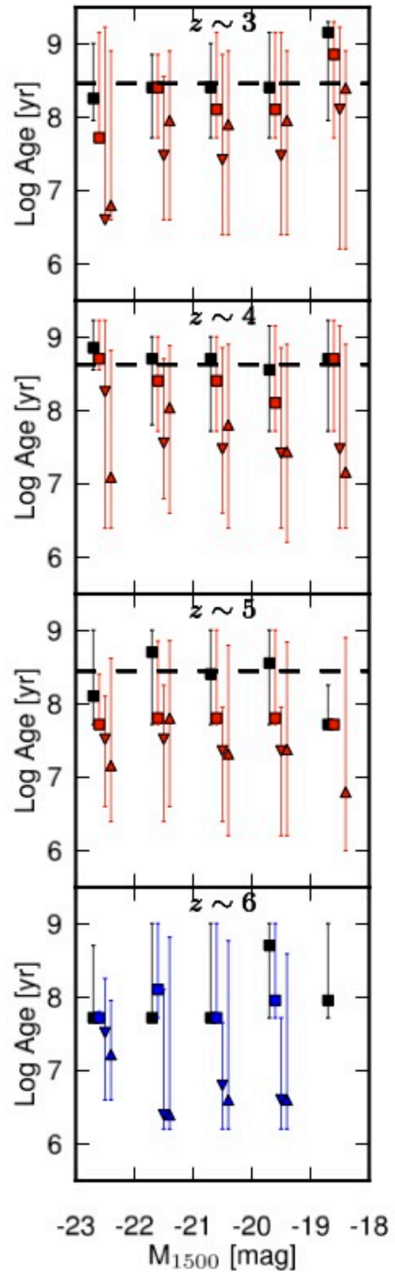


log(age)

log(M*) | log(M*) | log(M*)

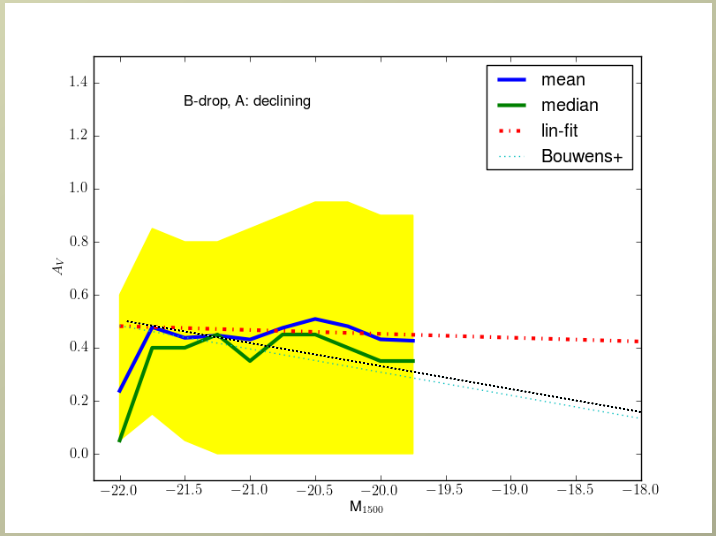


z~6

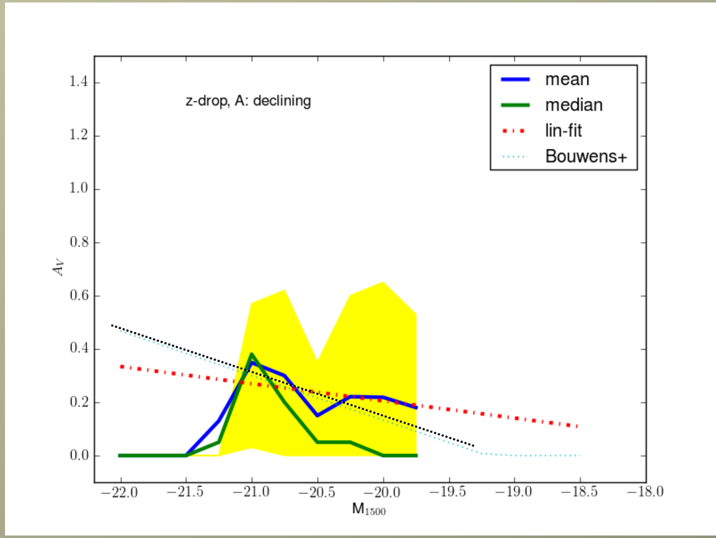


Properties of high-z galaxies: dust attenuation

- Small dependence of extinction on UV magnitude
- Decrease of average extinction with redshift ↗
- Non-zero extinction at z>6
- Use of UV slope to determine reddening/extinction is uncertain: Assumptions SFR=const and age>100 Myr may break down



z~4



z~7

de Barros, Schaerer, Stark (2012); Schaerer et al. (2013)

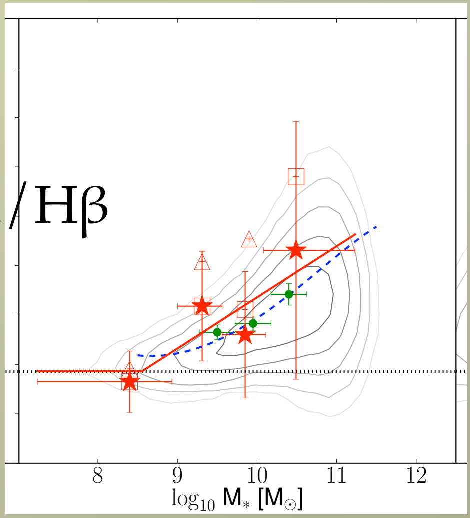
Properties of high-z galaxies: dust attenuation

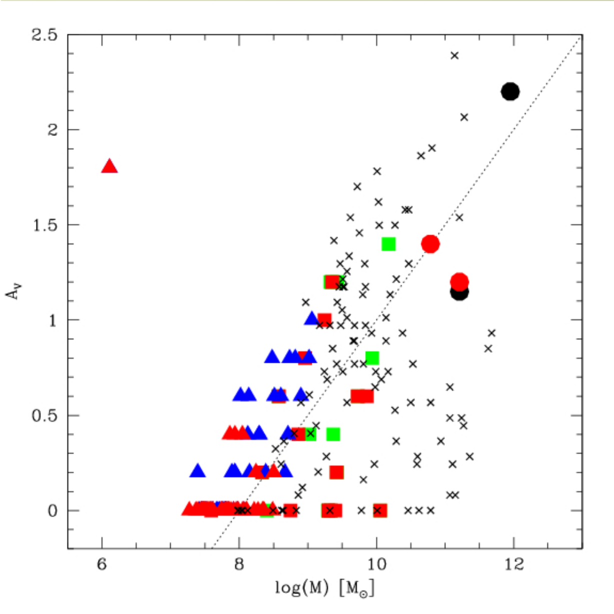
Dominguez et al. (2012): Balmer decrement at $0.75 \leq z \leq 1.5$

- Mass – dust attenuation correlated at high z

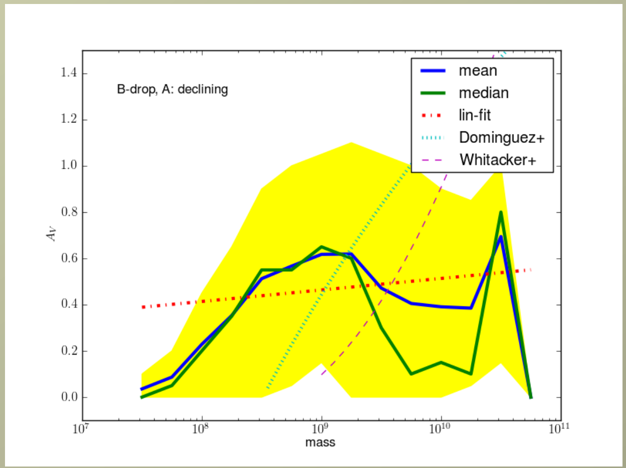
- Correlation well established at low redshift (z~0 to 1.5)
  cf. SDSS, Whitacker et al. 2012, Dominguez et al. (2012), Zahid et al. 2013,…

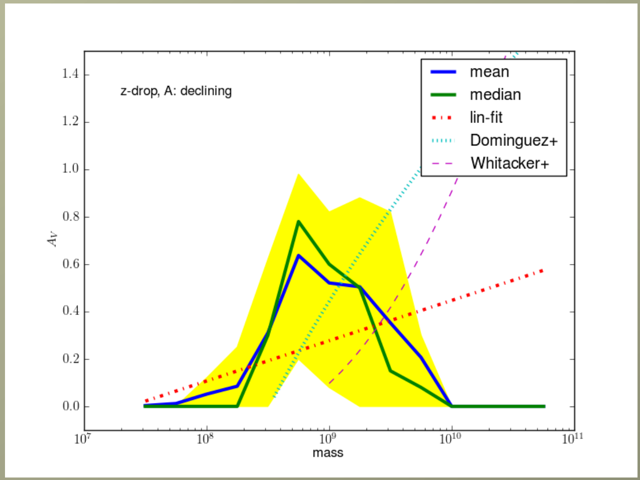
$H\alpha / H\beta$





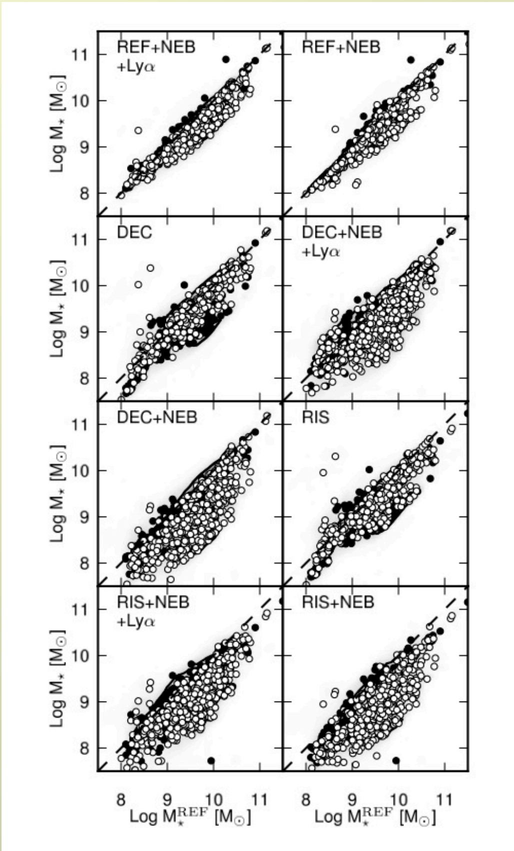
z~6-8 LBGs: Schaerer & de Barros (2010)





z~3-8 sample:
de Barros, Schaerer, Stark (2012); Schaerer et al. (2013)

Properties of high-z galaxies: stellar mass and implications

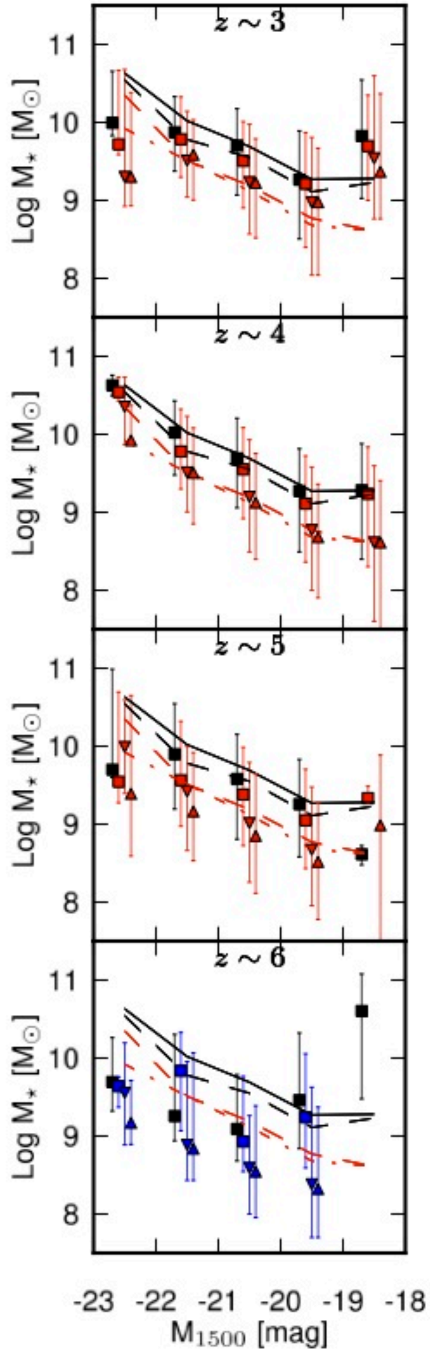


- stellar masses systematically lower (than SFR=const) with nebular emission and for variable SF histories: *typically ~2-3 times lower mass*

- Redshift (non-)evolution of M*-M_UV from z~5 to 3
  ➔ **SFR=const excluded**
  ➔ **episodic SF favoured**
  (cf. Stark et al. 2009)

- **(Fastly) rising SF histories over *long* timescale**
  ➔ too many bright galaxies expected
  (cf. Reddy et al. 2012)

- **Slowly rising SF** (e.g. Papovich et al. 2012) **not applicable to individual galaxies** → need to turn-off SF

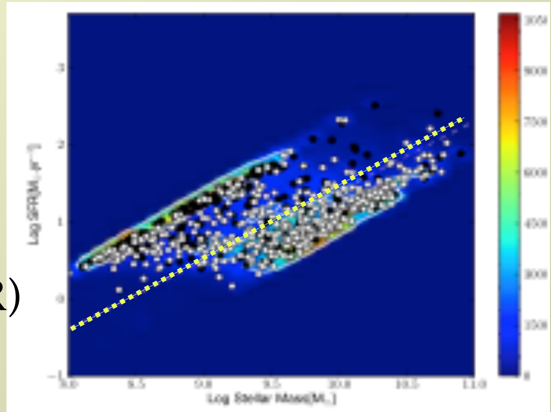


Properties of high-z galaxies (example @z~4): SFR - mass relation

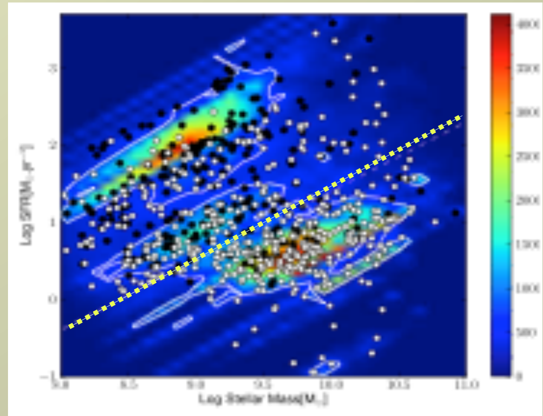
SFR=const, age>50Myr | variable SF histories | **variable SF histories + nebular**

A_V free

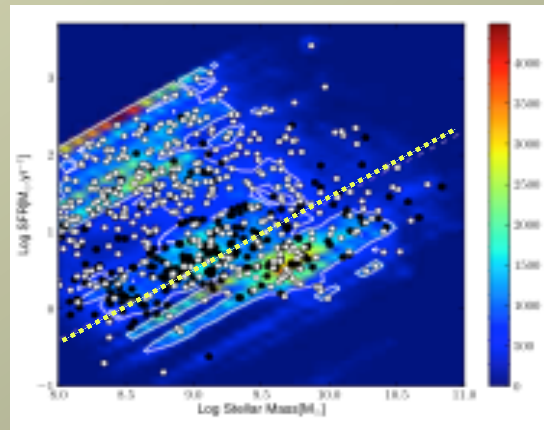
log(SFR)



log(M*)



log(M*)



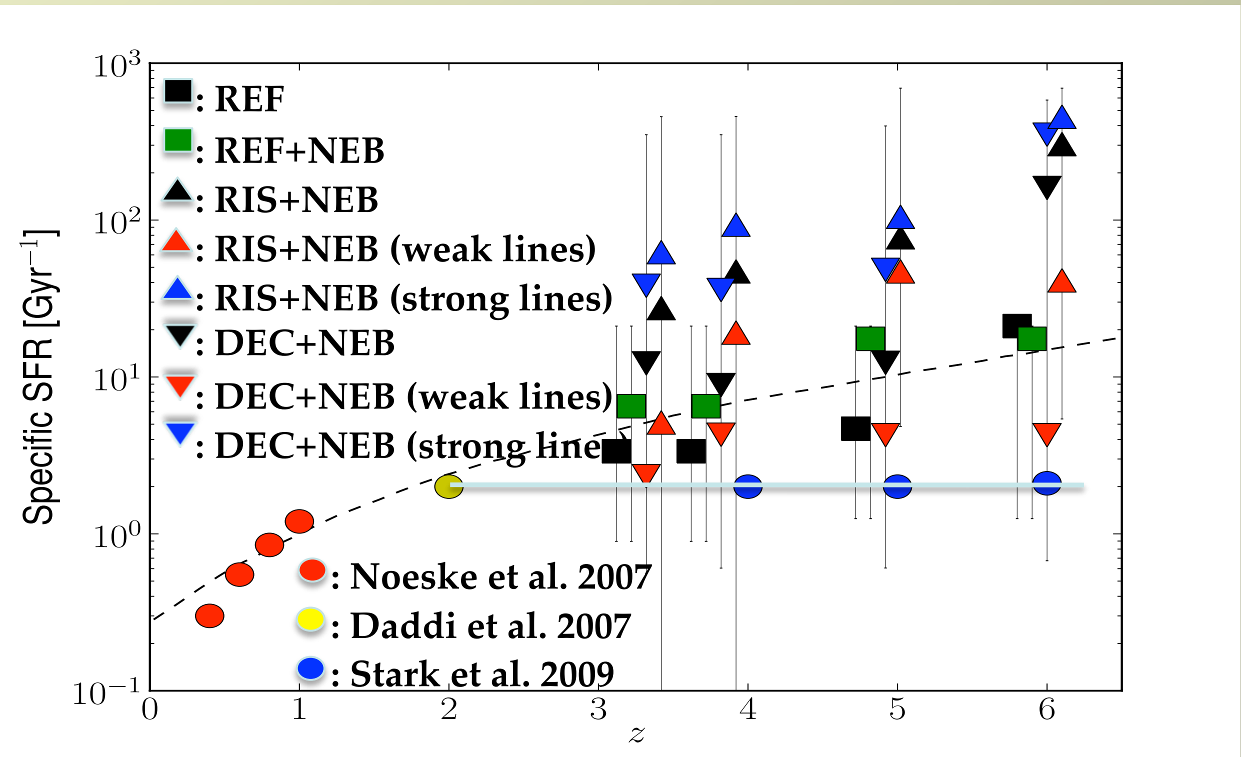
log(M*)

- large scatter in (instantaneous) SFR-mass relation
- specific SFR (=SFR/M*) lower for high mass galaxies (as at low redshift)

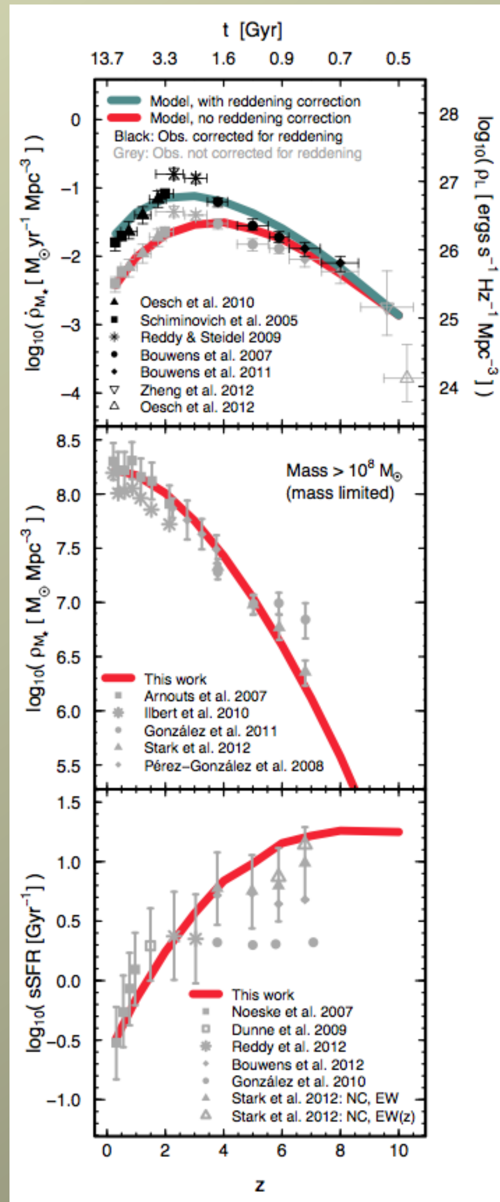
Caution: biases, selection criteria+ can severely affect the possible correlations
(e.g. Dunne et al. 2009, Stringer et al. 2011)

Evolution of the specific SFR with redshift

- High sSFR=SFR/M* at high redshift
- Large scatter expected – short SF timescales
- sSFR(z) increase in agreement with simple galaxy formation models

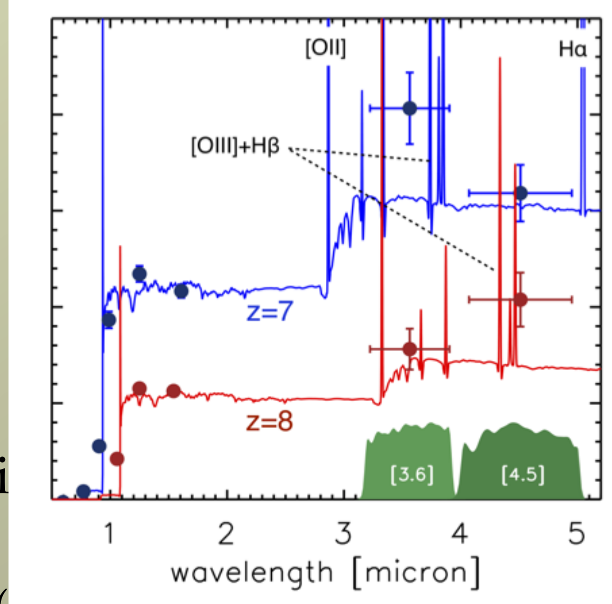


de Barros, Schaerer & Stark (2011, 2012)



Tacchella et al. (2012)

Evidence for (strong) emission lines at high-z

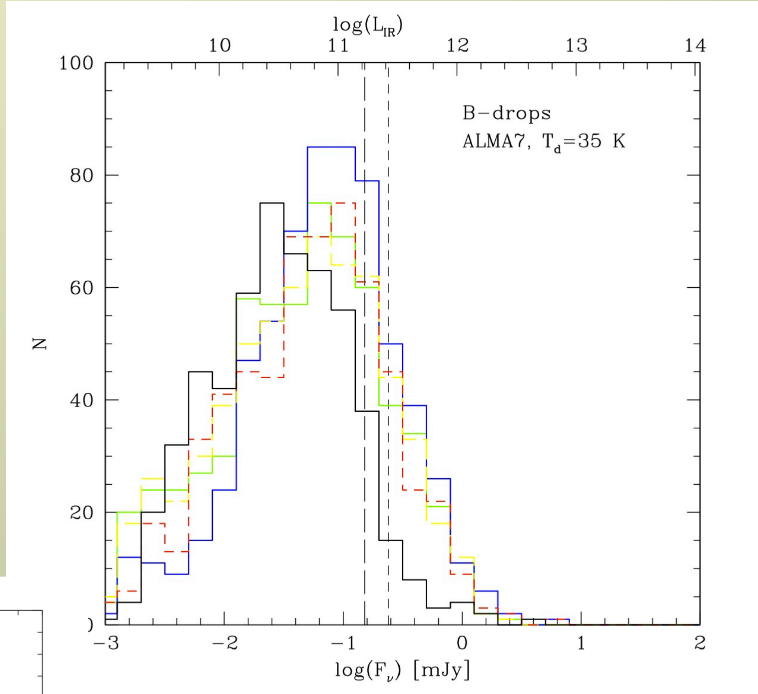


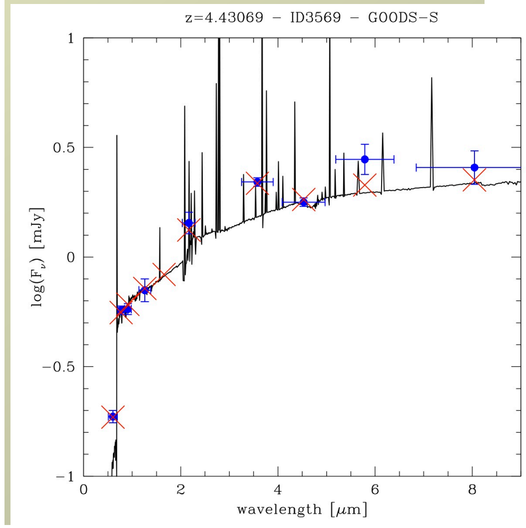
- LBGs: broad-band excess in **z~2 LBGs** with strong Hα
  (Erb et al. 2006, Reddy et al.)
- **LBGs at z~4**: excess at 3.6 micron due to Hα
  (Shim et al. 2011, de Barros et al. 2011, Stark et al. 2012)
- **LBGs at z~7**: excess at 3.6 micron due to [OIII]+Hβ
  (Labbé et al. 2012)
- **Lyman-alpha emitters (LAE) at z=3.1**: [OIII] lines domi
  (McLinden et al. 2011)
- Strong Halpha emission in **massive galaxies at z~1-1.5** (van Dokkum et al. 2011)
- **WFC3 grism surveys**: detect many strong emission line galaxies at z~1-2, whose photometry is/would be dominated by lines
  (e.g. Atek et al. 2011, Trump et al. 2011)
- …
- Increasing fraction of LBGs with Lyman-α emission at high-z
  (Ouchi et al. 2008, Stark et al. 2010, Schaerer et al. 2011, …)

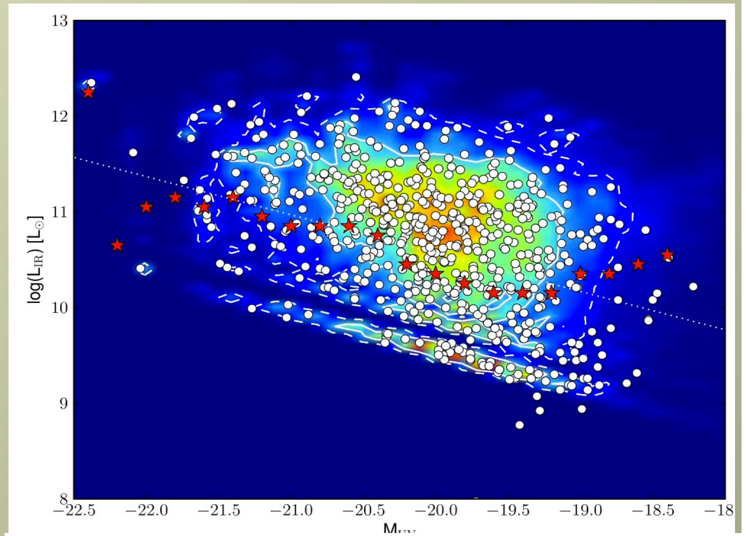
- Also: by *selection* **LAE** (Lyman-alpha emitters) must have strong H recombination lines (+others)

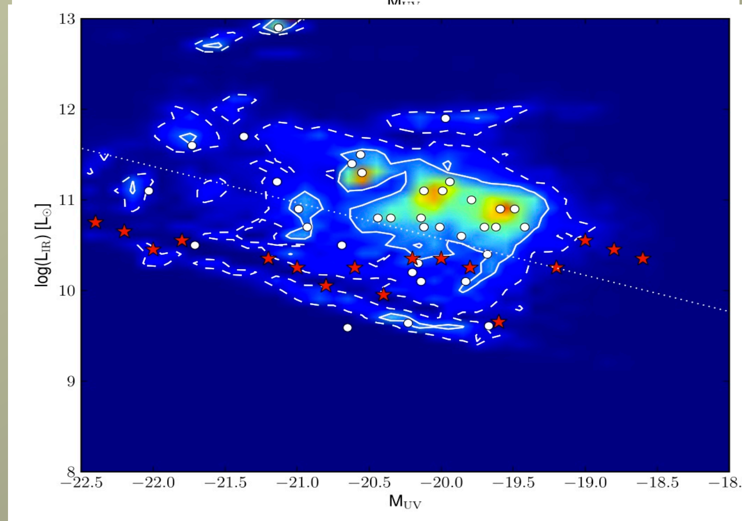
IR emission: comparison/prediction

IR predictions for z~3-6 LBG (consistently from SED fits)









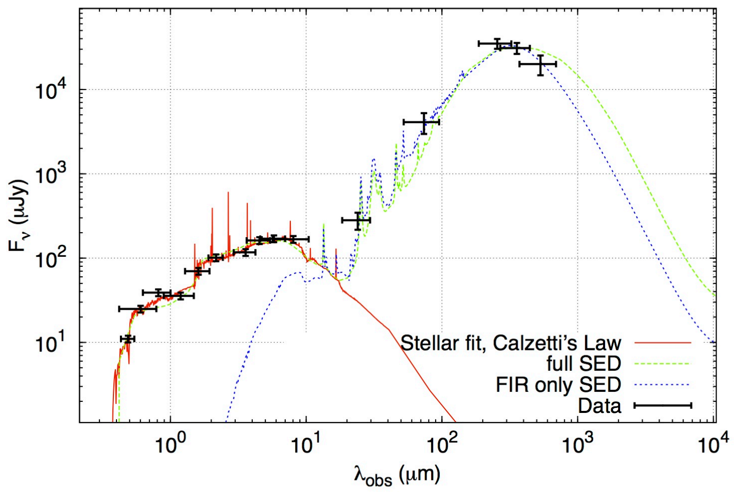
➔ Different SF histories and high sSFR testable with ALMA

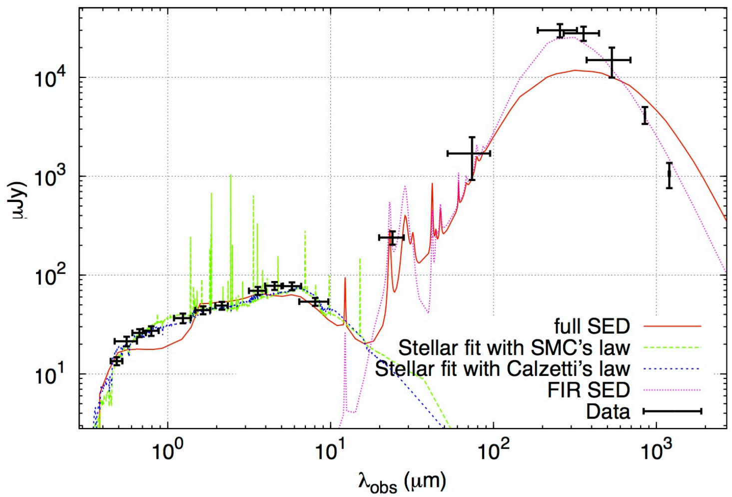
Schaerer, de Barros, Sklias (2012)

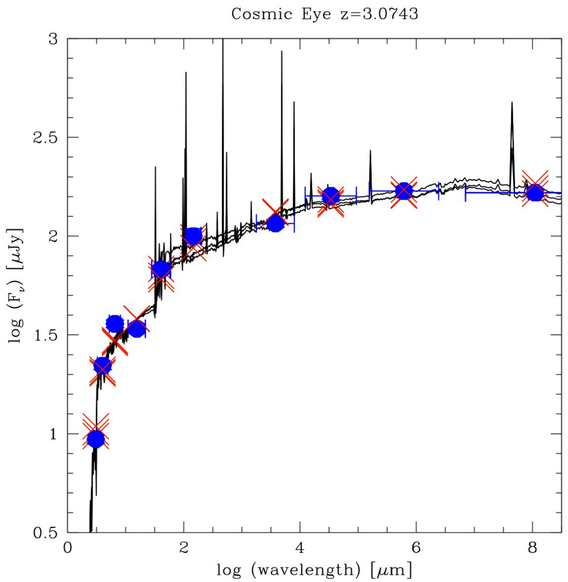
Test cases

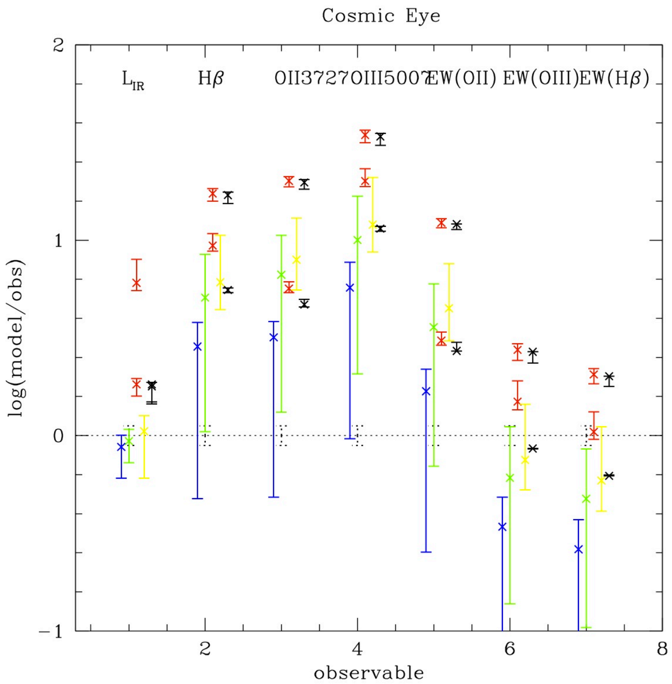
2 lensed galaxies with near-IR spectroscopy + IR measurements: Cosmic Eye (z=3.07), cB58 (z=2.7)

- Good agreement for cB58 with different SFHs
- Constant and rising SFHs incompatible with observations of Cosmic Eye







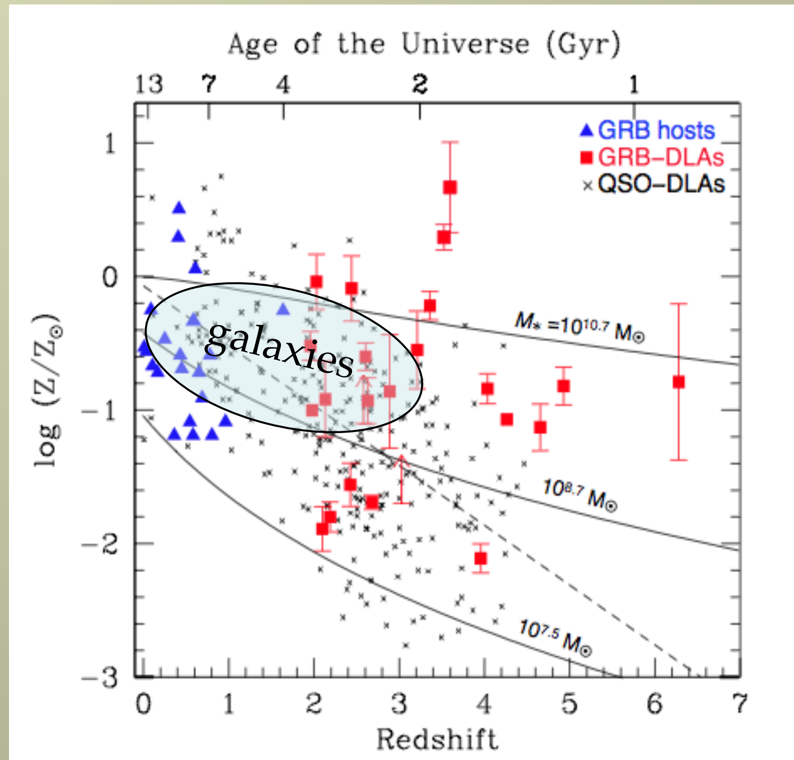


Sklias et al. (2013)

From the currently observed (tip of iceberg) to the first generation (Population III) …

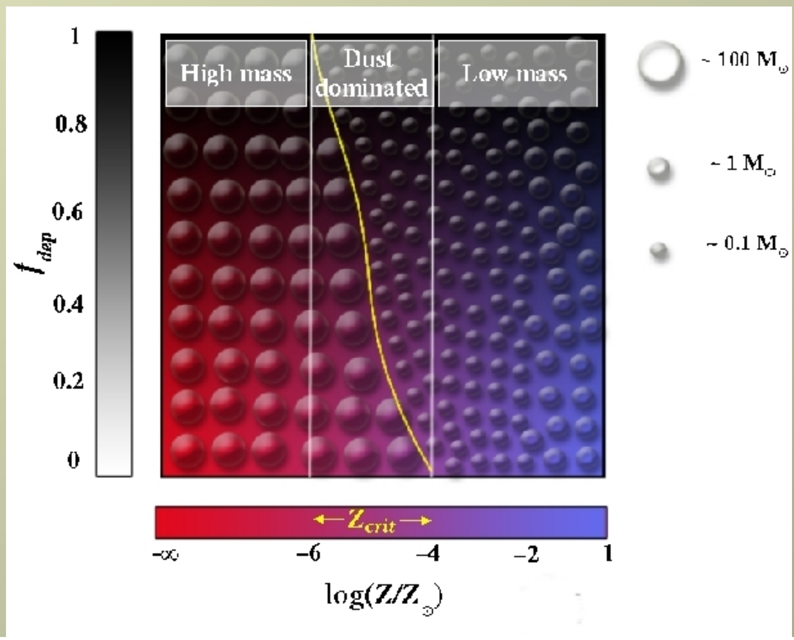
- Currently observed metallicities (galaxies, DLA, GRBs) are substantially higher than critical metallicity ($Z_{crit}/Z_{\odot}$ ~$10^{-5\pm1}$) for PopIII star formation

- Below Z_{crit} formation of massive stars (typical mass ~10-100 $M_{\odot}$) expected



Savaglio et al. (2012)

New UL: Simcoe et al. (2012)



Schneider et al. (2003)

Possible observations of high-z PopIII objects

Signatures

- Abundances:
  - no metals …
  - peculiar ratios, e.g. Si/C, C/O from pair instability SN
  - low ([OIII]+[OII])/H ratio

- Strong Lyα emission
- (strong) nebular HeII emission

- SED: blue UV slope? Difficult; maybe?
- Lyman bump
- Peculiar colors?

Tumlinson et al. (2001), Schaerer (2002), …
Inoue (2009), Zackrisson et al. (2012), …

Direct signatures

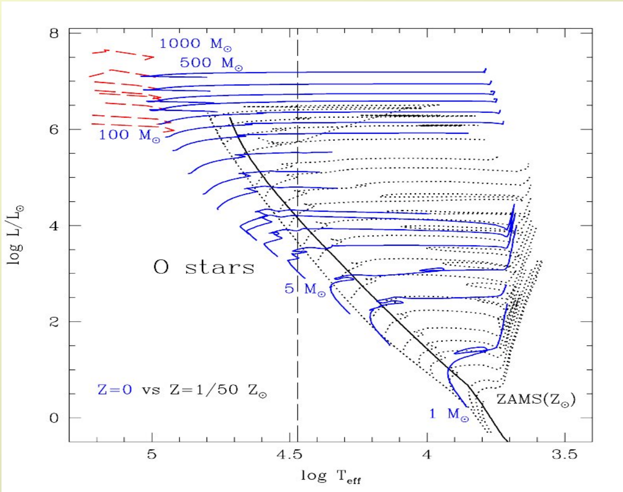
- starburst: rest-frame UV emission, optical lines?!
- individual SN (rest optical-near-IR)
- mid-IR molecular hydrogen in supernova cooling shells
- high energy neutrinos from GRB (fast X-ray transients)
- …

Haiman & Loeb 1997, Miralda-Escude & Rees 1997, Oh 1999, Tumlinson et al. 2001, Ciardi & Ferrara 2001, Bromm et al. 2001, Schneider et al. 2002, …

- near-IR background: spectral features, fluctuations

Santos et al. (2002), Cooray et al. (2004), Kashlinsky et al. (2002-2012), …

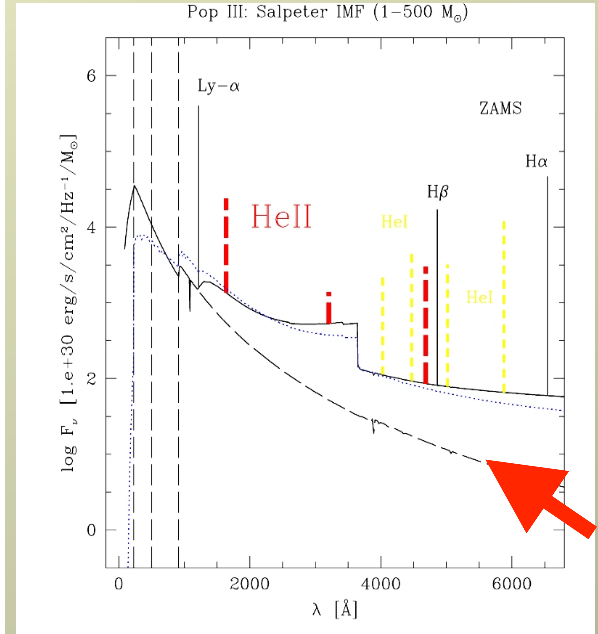
Properties of PopIII stars and integrated populations



Zero metallicity: expect
- Strong Lya
- HeII emission
- Very blue UV slopes

...

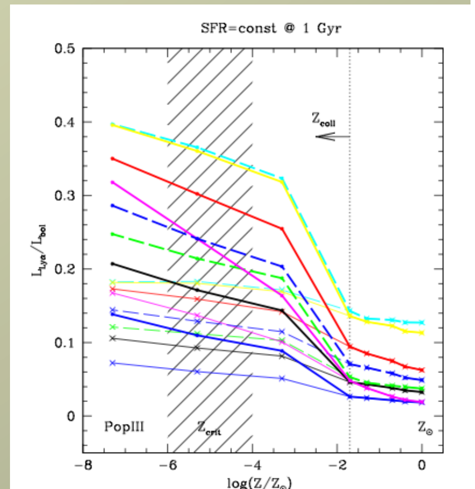
Schaerer (2002, 2003)
Raiter et al. (2010)
Also Tumlinson et al. (2000, 2001)
Bromm et al. (2001)

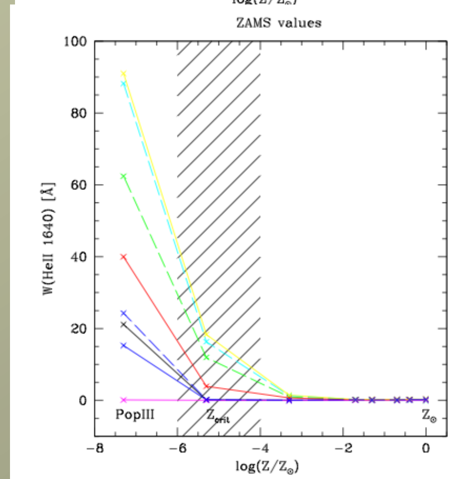


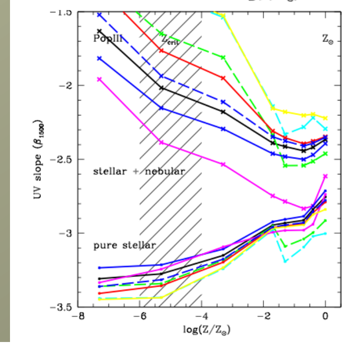
stellar + nebular

stellar

Schaerer (2002)







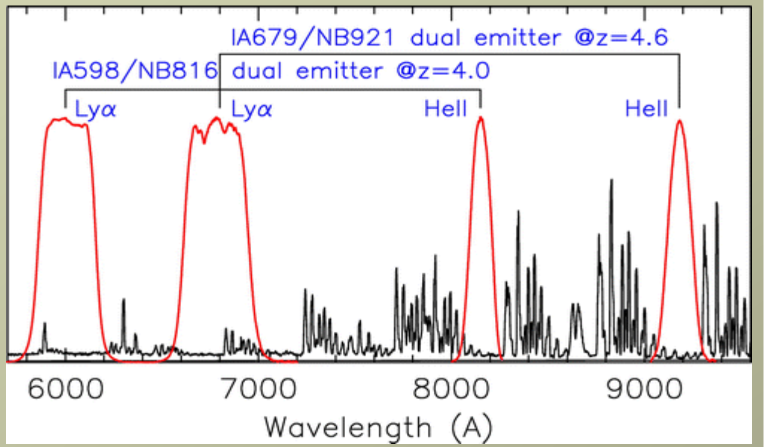
Many (unsuccesfull) searches for PopIII at high redshift

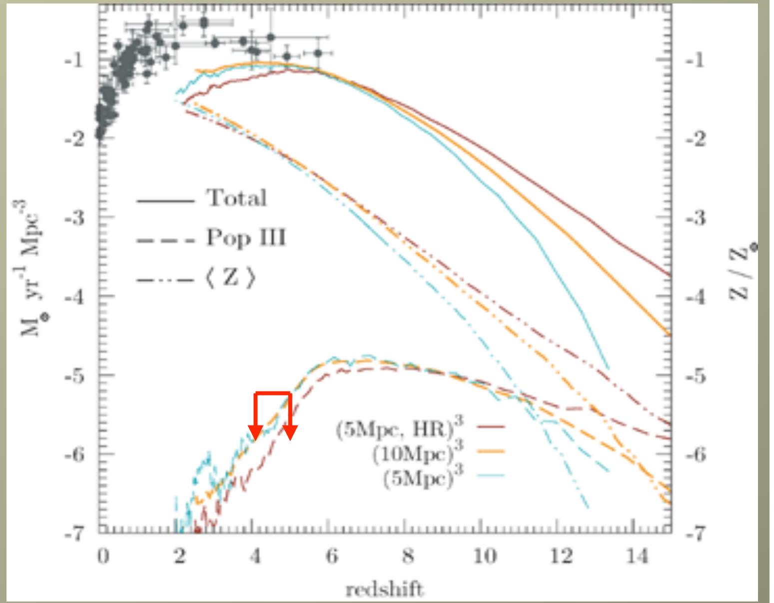
In LAEs: Malhotra&Rhoads, Dawson et al. (2004), Djikstra et al., Nagao et al. (2005), Ouchi et al. (2007), … Cai et al. (2011)

Unconvincing claims:
e.g. Jimenez & Haiman (2006), Shimasaku et al. (2006), Dijkstra & Wyithe (2007)

→ Photometric survey for Lyα-HeII dual emitters at z~4 and ~4.6 in the Subaru Deep Field (Nagao et al. 2008)
→ first upper limit on cosmic SFRD(PopIII) from HeII1640

See reviews Schaerer (2008, IAU symp 255), Schaerer (2009)



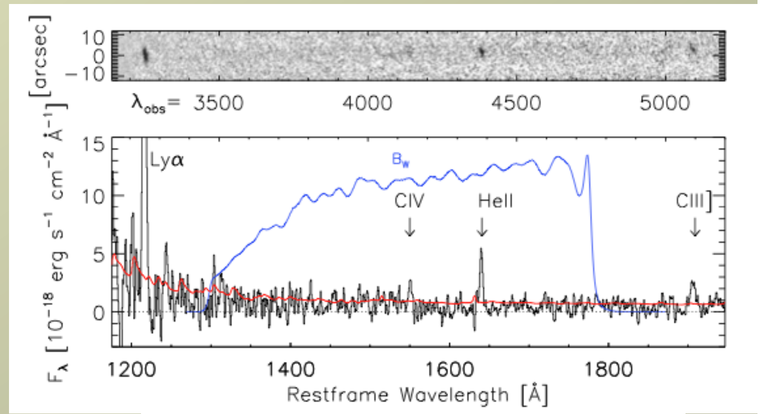


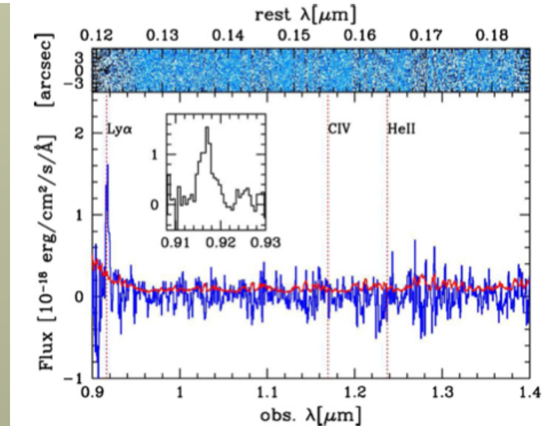
Tornatore et al. (2007)

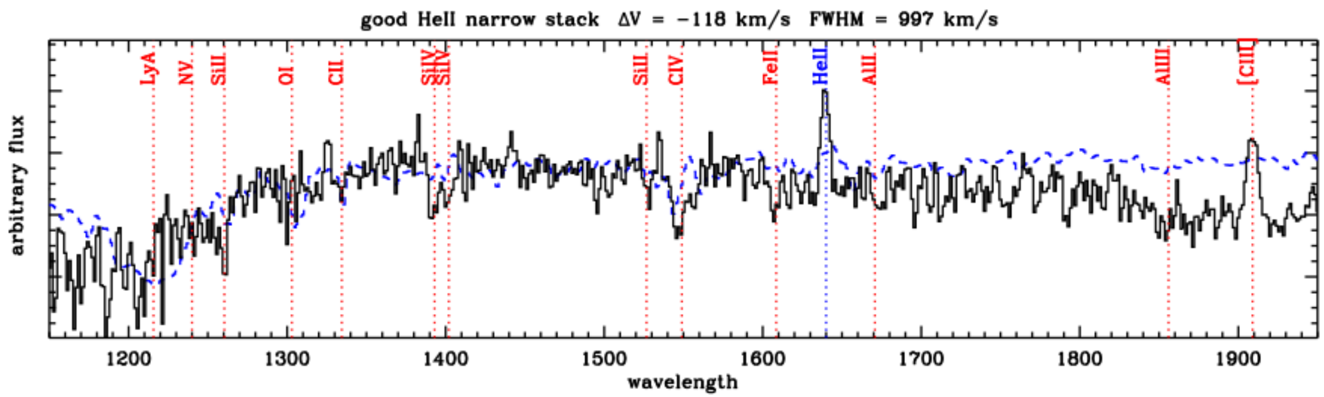
Many searches for PopIII at high redshift:

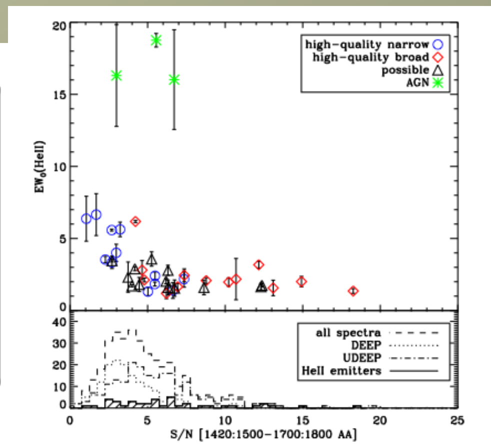
Some peculiar (+recent) cases:

- Lya + nebular HeII detections in « Lya blobs »:
  Prescott et al. (2009), Scarlata et al. (2009)
  → CIV detected in 1 of them
  → 1 associated AGN
- Kashikawa et al. (2012) – strong Lya (EW=436^{+422}_{-149} Å) but no HeII, no CIV
  → Origin of Lya unclear
- Raiter et al. (2010), Fosbury et al. (2003): strong Lya, spectrum dominated by nebular emission, …
- Cassata et al. (2012): large number of z~2-4.8 LBGs with HeII emission (stellar + nebular)
  → PopIII pockets?



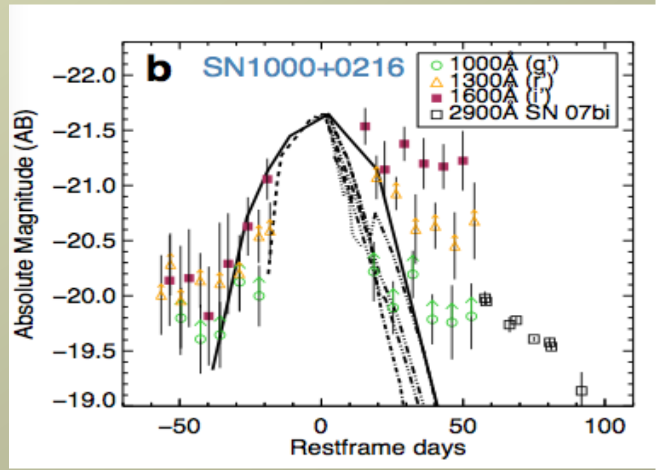




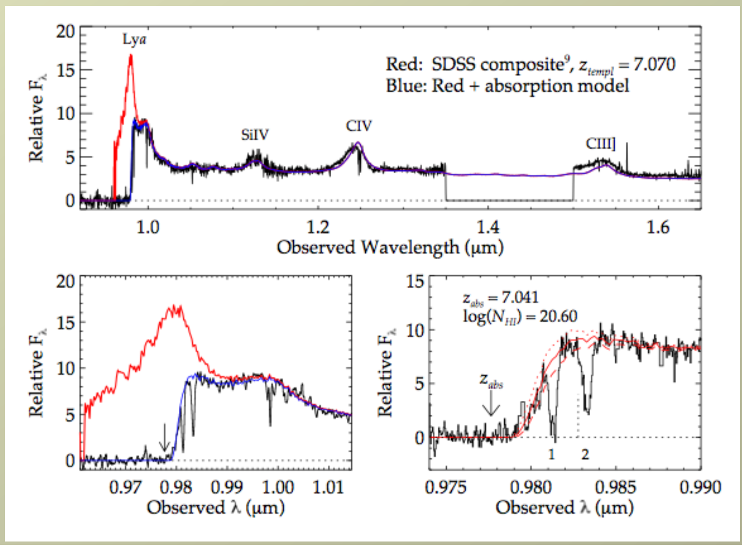


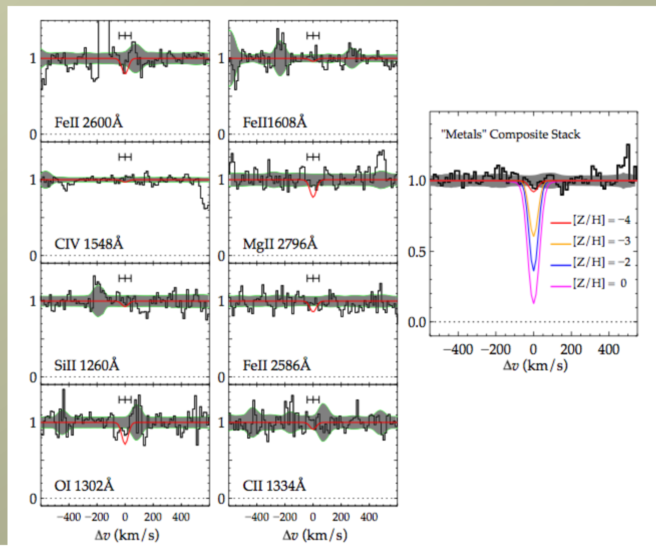
The elusive PopIII: recent observational progress

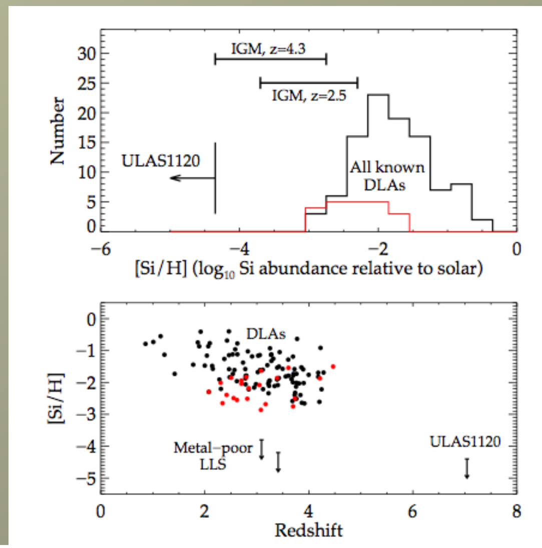
- **Pair instability (creation) Supernovae (PISN or PCSN):** end-products of very massive stars (130-260 Msun).
  → Good candidates observed recently at z=2.05 and 3.09: ***Super-luminous SN,*** Cooke et al. (2012, Nature)
  Not restricted to PopIII



- **Metal-free IGM gas found!** → $[O,Si/H] <\sim 10^{-4}$
  Simcoe et al. (2012, Nature)



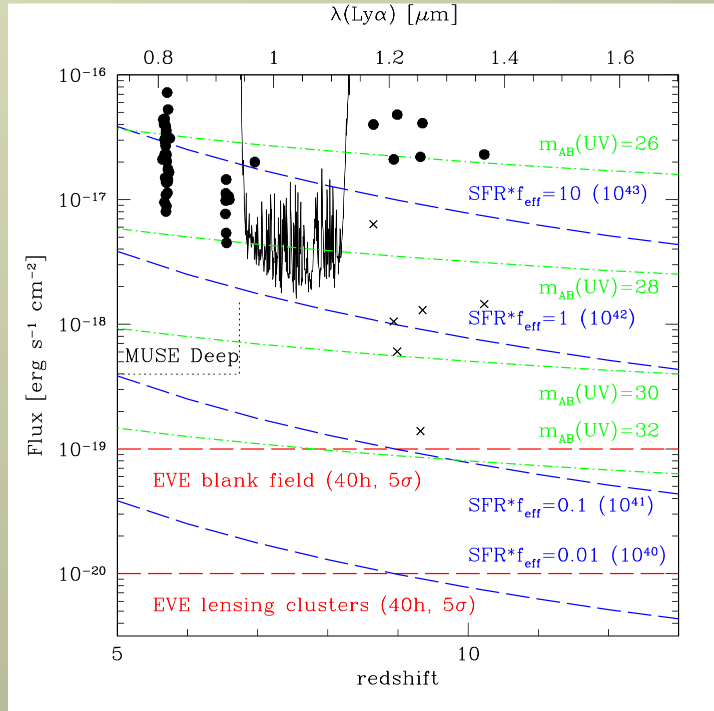




Upcoming - future facilities

- Atacama Large Millimeter Array
  (ESO, USA, Japan +)
  → gas, dust, dynamics, composition…
- European Extremely Large Telescope
  (ESO) --> 2018
- James Webb Space Telescope
  (NASA, ESA) - >2018

→ Large discovery space for first galaxies!



Conclusions

- Main populations of star-forming galaxies (LBG, LAE) identified from z~3 to z~9-10 (500 Myr after Big Bang).
- Relation between populations understood
- Observed galaxy populations at z>6 insufficient for cosmic reionisation

- Galaxy properties *change with increasing redshift:*
  M* ↘, age younger, dust extinction ↘
  SFR ↗, specific SFR ↗
  SF timescales ↘, variable SF histories (duty cycle <1)

- No indications for extreme metallicities
  No robust sign of Population III yet

- Current observations probe « tip of the iceberg »
- Many open questions on early galaxies and cosmic reionisation (formation, metallicity, IMF, Lyman continuum leakage, reionisation history …)

→ Significant progress expected with new facilities (ALMA, JWST, ELT …)

Conclusions

- First systematic study of z~3 to 6 (8) LBGs (~1700 objects) taking effects of nebular emission into account

- Majority of z ≥3 galaxies better fit with SEDs with nebular emission
- 2 groups of SF galaxies (65% with emission lines, 35% few/no lines) found at each redshift -- starburst/post-starburst!

- Stellar mass typically ↘ factor 2-3. Ages younger. Extinction, SFR ~higher
- Large(r) scatter in relations: SFR-mass, sSFR-mass +
- Median sSFR higher than derived by earlier studies

- Successive/repetitive periods of SF observed between 1 - 2 Gyr after Big Bang. Constant and strongly rising SFHs over 200 Myr excluded
- Timescale/variations of SFH driven by feedback?
- Rising/declining histories testable with ALMA

==> de Barros, Schaerer, Stark (2011, 2012); Schaerer, de Barros, Sklias (2012)

END