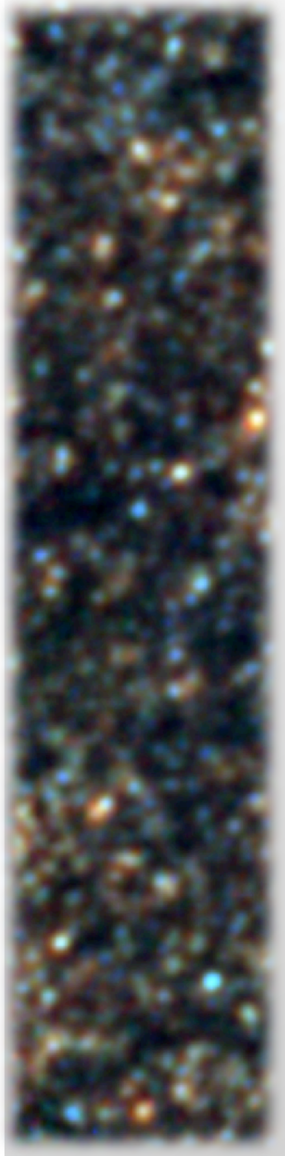


The Dust Emission of Lyman Break Galaxies at $1 \leq z \leq 4$ with Herschel

Denis Burgarella, LAM, France

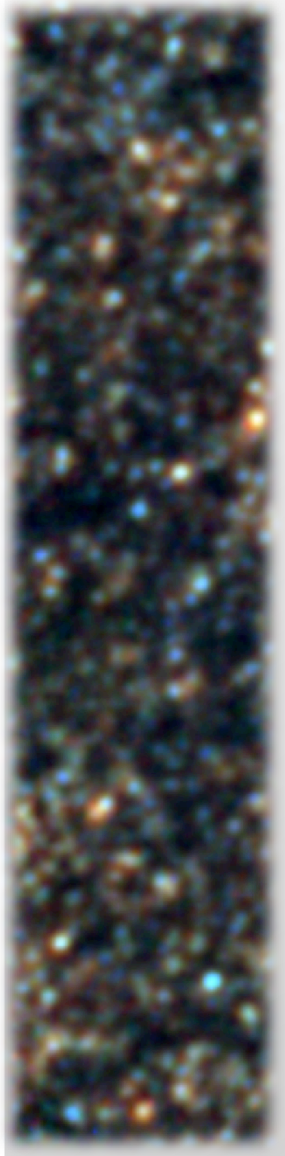
& the Herschel HerMES Team
& the Herschel PEP Team
& the COSMOS Team

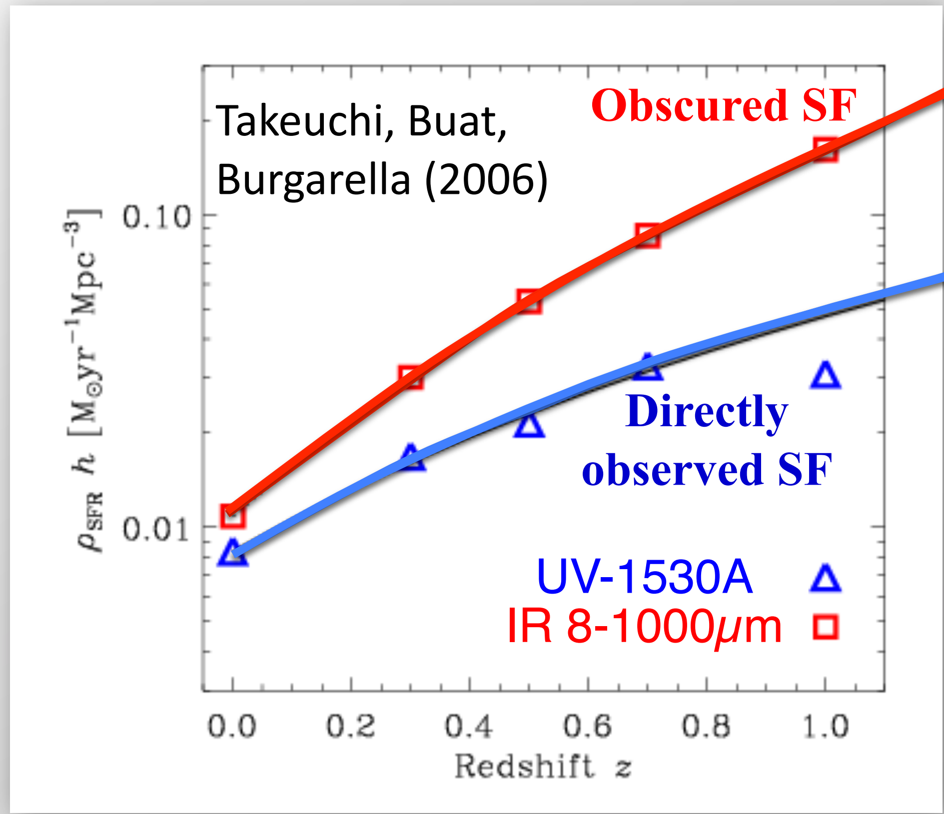
HERMES

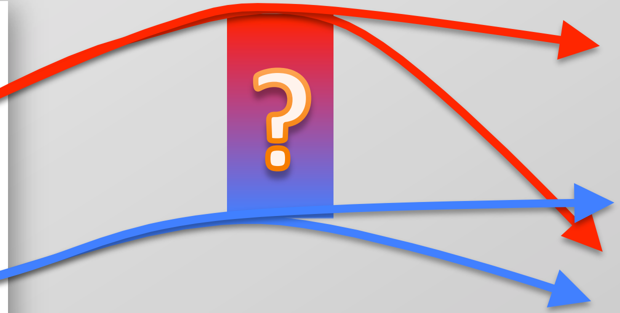
Acknowledgements

- FIR data are from the Herschel key-programme HerMES (S. Oliver, J. Bock) and from the Herschel key-programme PEP (D. Lutz)
- UV-NIR data are from COSMOS (N. Scoville)
- Spectroscopic redshifts are from z-COSMOS (S. Lilly)
- SED analysis carried out with CIGALE (D. Burgarella)

Why do we need FIR/submm data for UV-selected galaxies ?





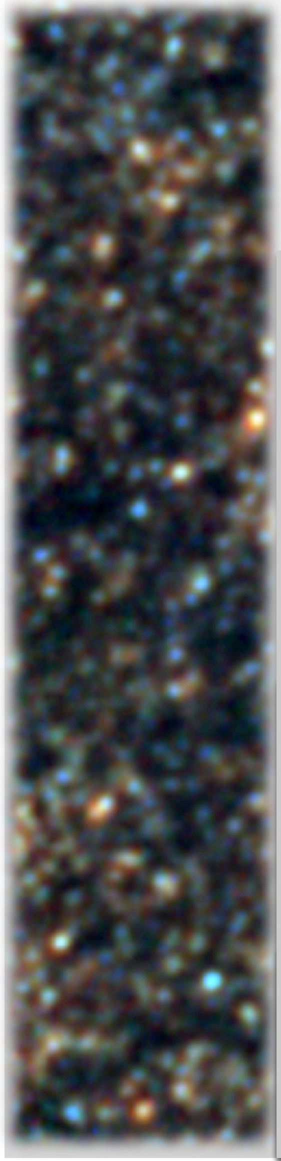


The local fraction of the obscured/FIR SF is 50-60%, while the fraction at $z \approx 1$ reaches around 80%.

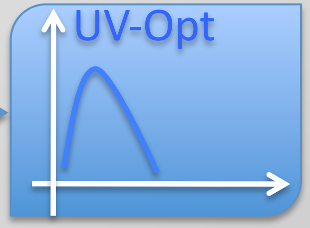
Thank you Naveen
for the nice introduction
earlier in the afternoon

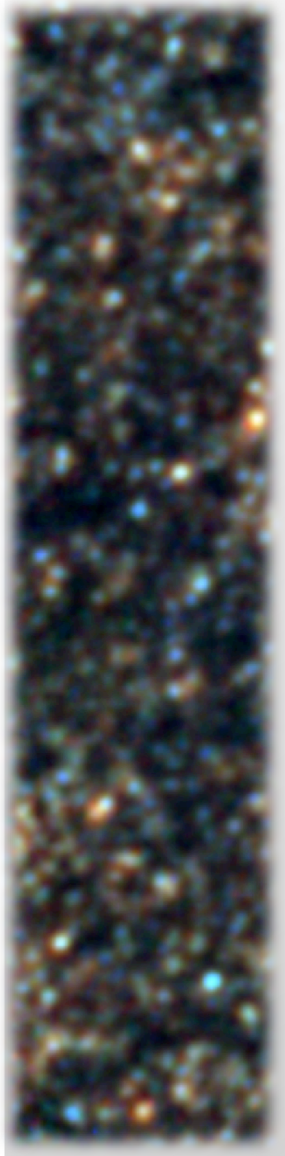
SED Fitting with CIGALE

http://cigale.oamp.fr



One or Two SFHs (expo or box) → Dust-free Stellar Spectra from Maraston → Creation of dust-free emission spectra from models →



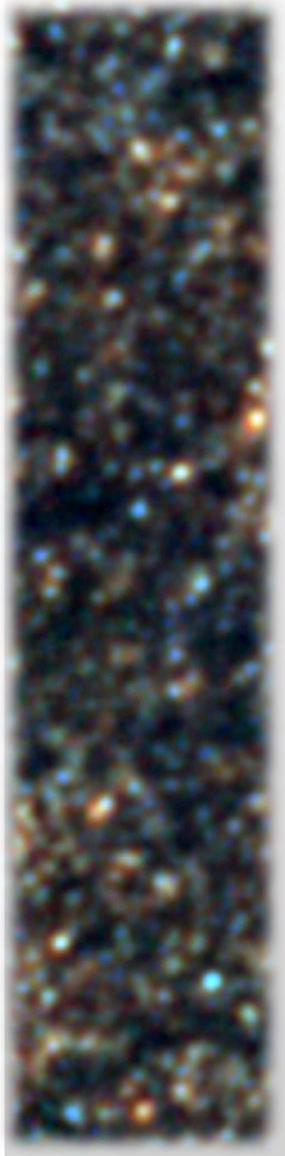


0.5 < z < 2 LBGs:

From: Spitzer-24um (Burgarella et al. 2006)

To: Herschel-FIR (Burgarella et al. 2011)

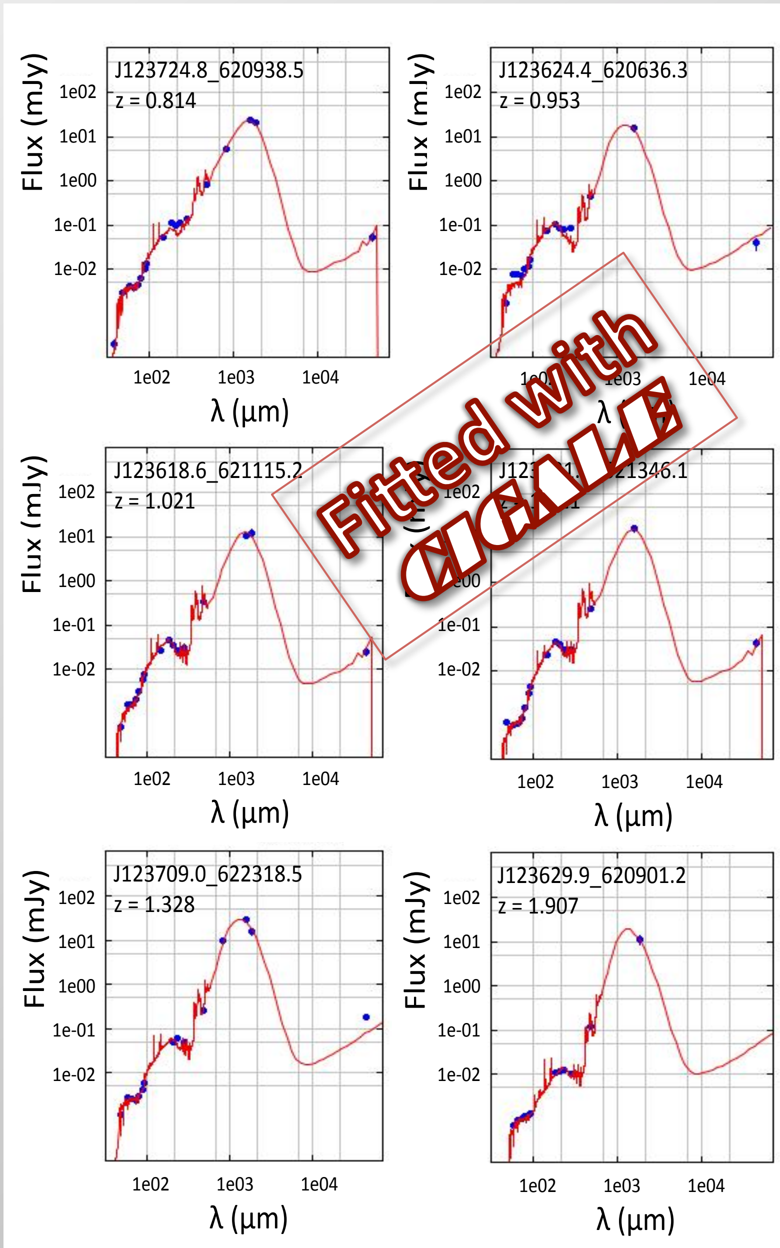
CIGALE SED Fitting from FUV to radio of a sample of 0.7 < z < 2.0 LBGs in GOODS-N



(Burgarella et al. 2011, ApJ 734, L12)

In average, these LBGs are:

- UV-bright:
  $\log \langle L_{FUV} \rangle = 10.7 \pm 0.7\ L_{\odot}$
- borderline of ULIRGs:
  $\log \langle L_{dust} \rangle = 11.9 \pm 0.3\ L_{\odot}$
- massive:
  $\log \langle M_{*} \rangle = 11.0 \pm 0.5\ M$
- High UV dust attenuation:
  $A_{FUV}=3.252$
- consistent with
  no AGN



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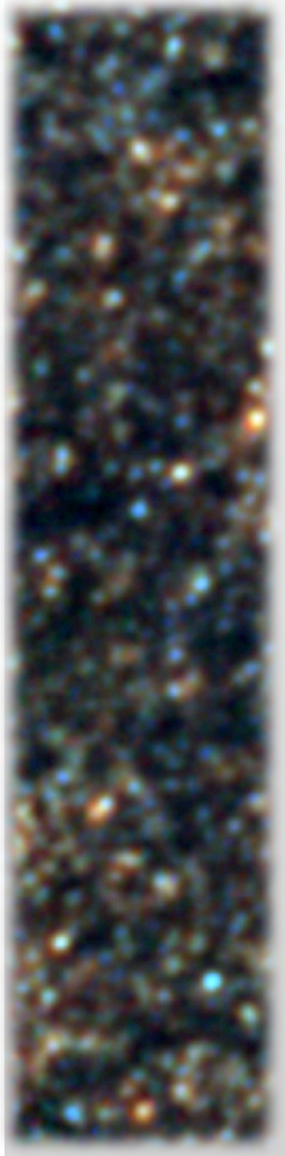
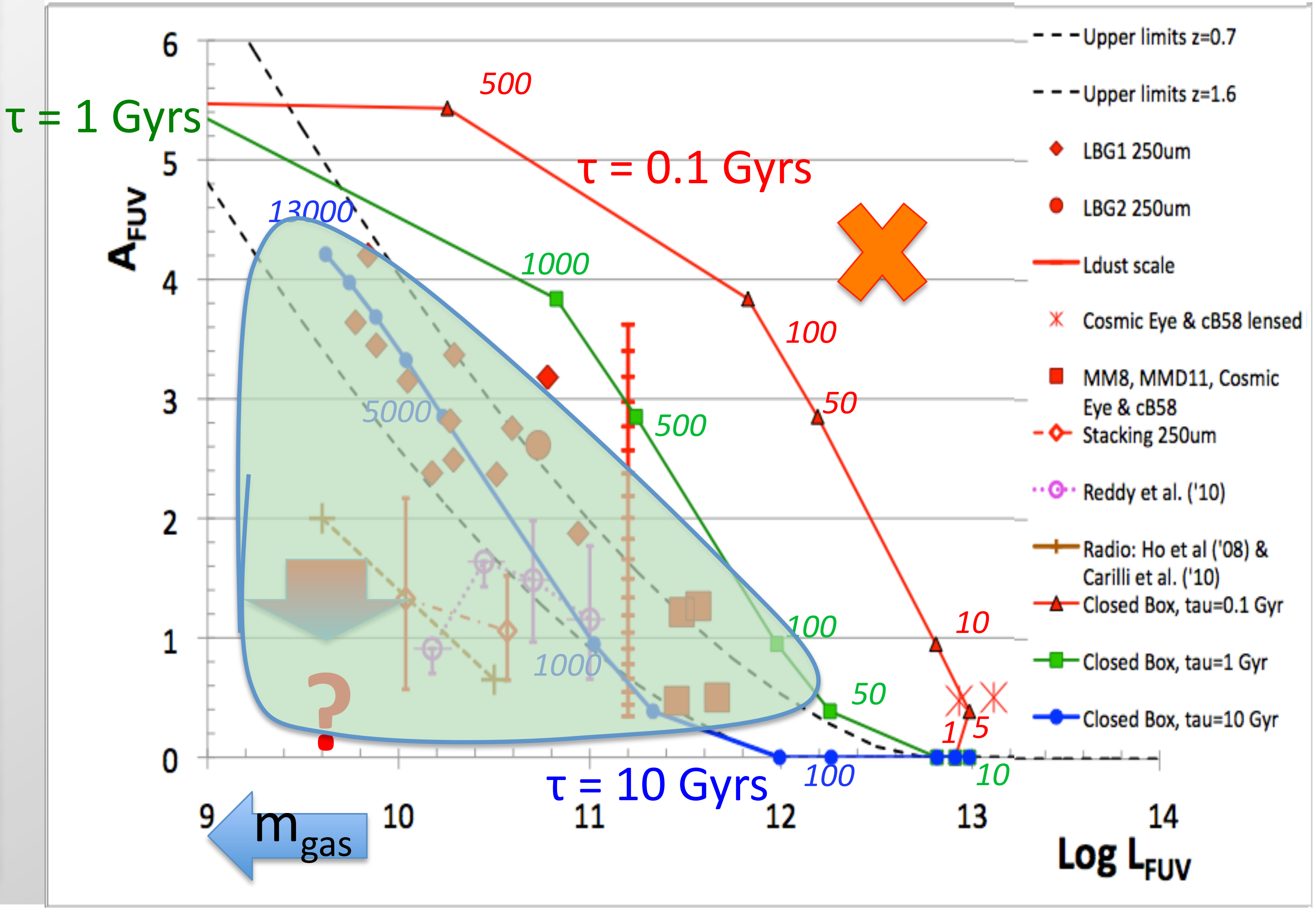
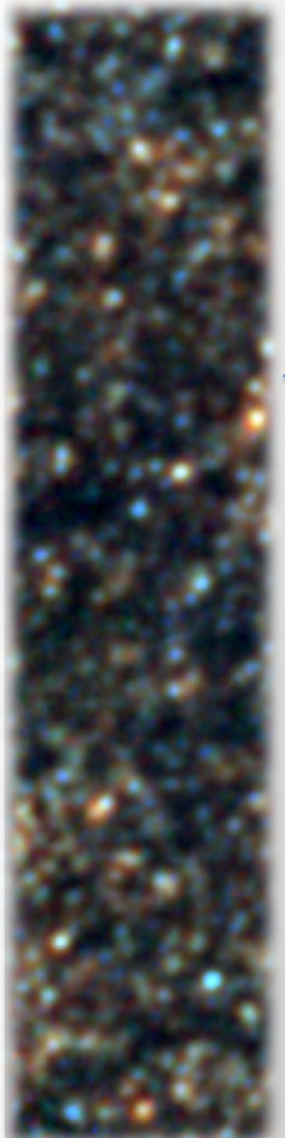
From Spitzer (Burgarella et al. 2006, A&A 450, 69)
to Herschel (Burgarella et al. 2011, ApJ 734, L12)

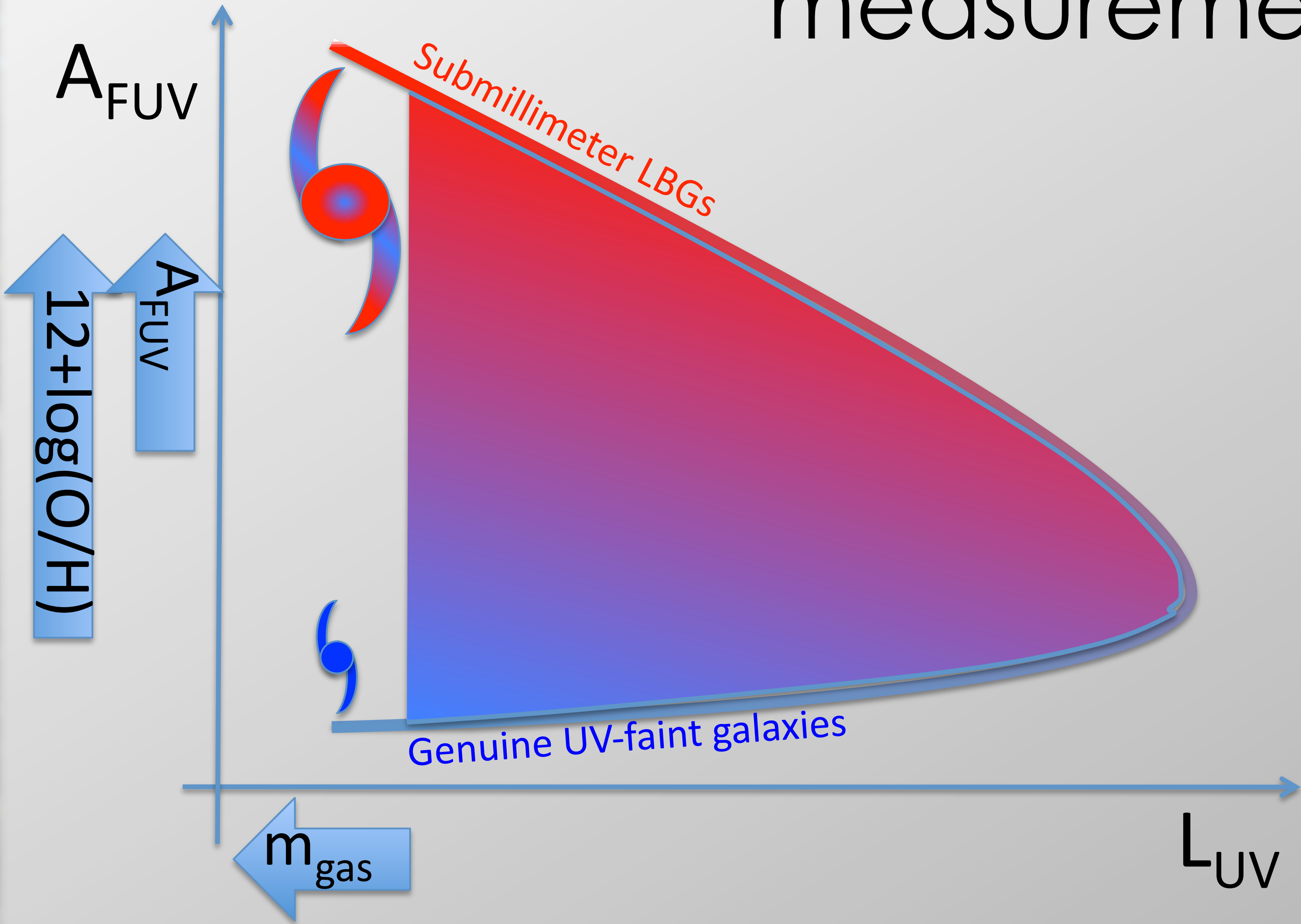
LBGs @ z > 2.8: Siana et al. (2008, 2009), Chapman et al. (2000), Chapman & Casey (2010), Tanvir et al. (2009), Boone et al. (2007), Webb et al. (2007)



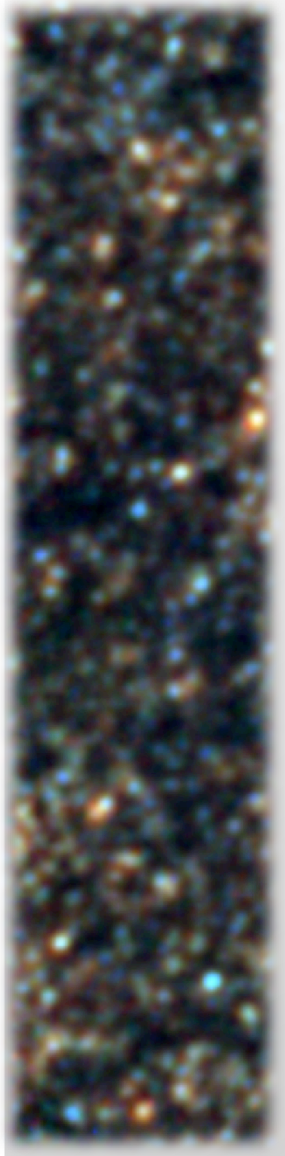


Two limiting regimes for UV-faint LBGs from FIR measurements

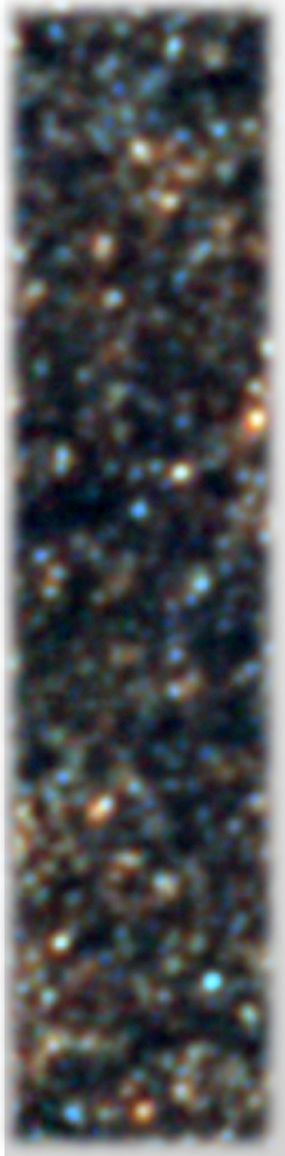




Moving to higher redshifts …
when the size of the fields helps a lot



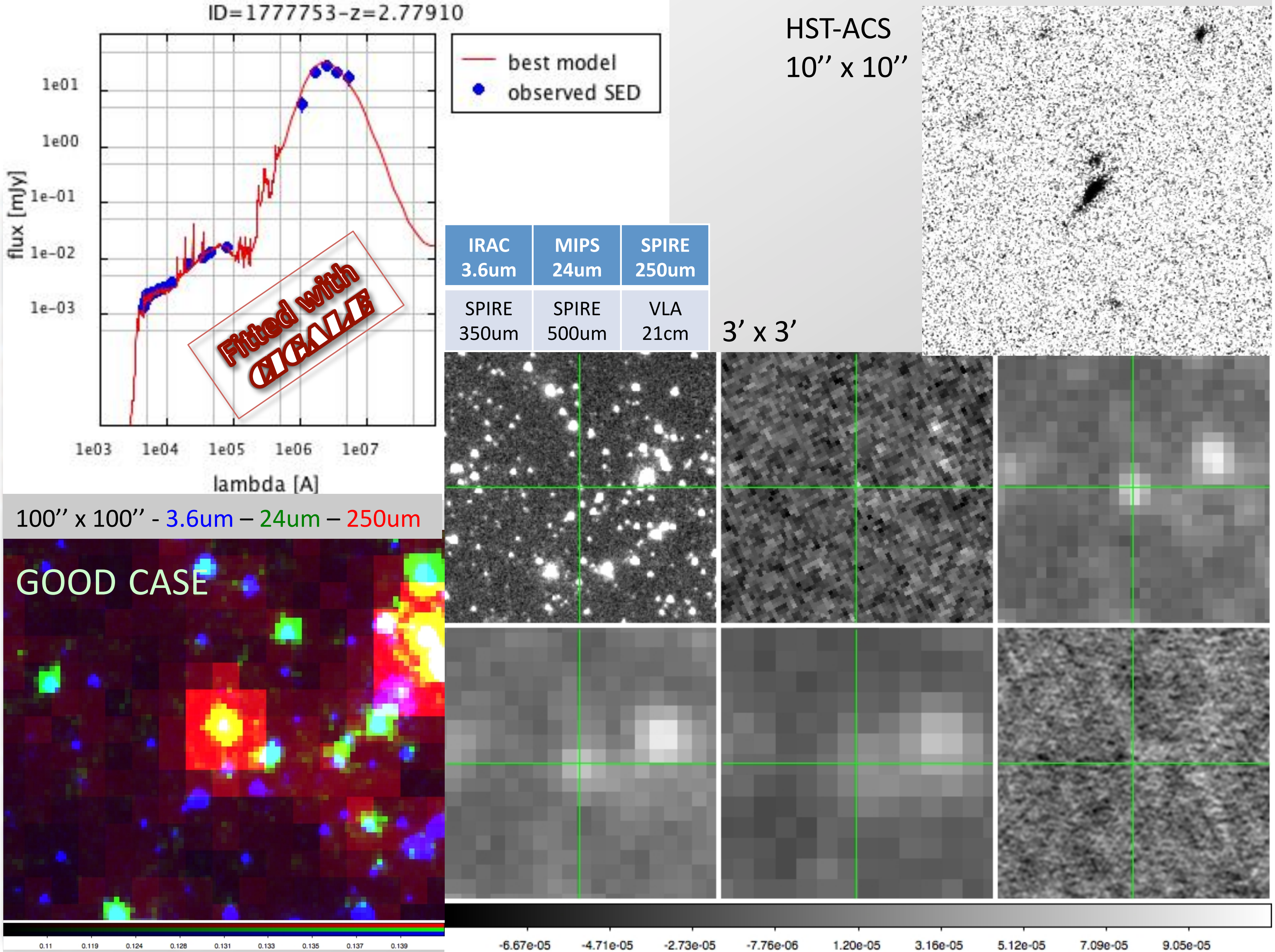
The LBG preliminary samples



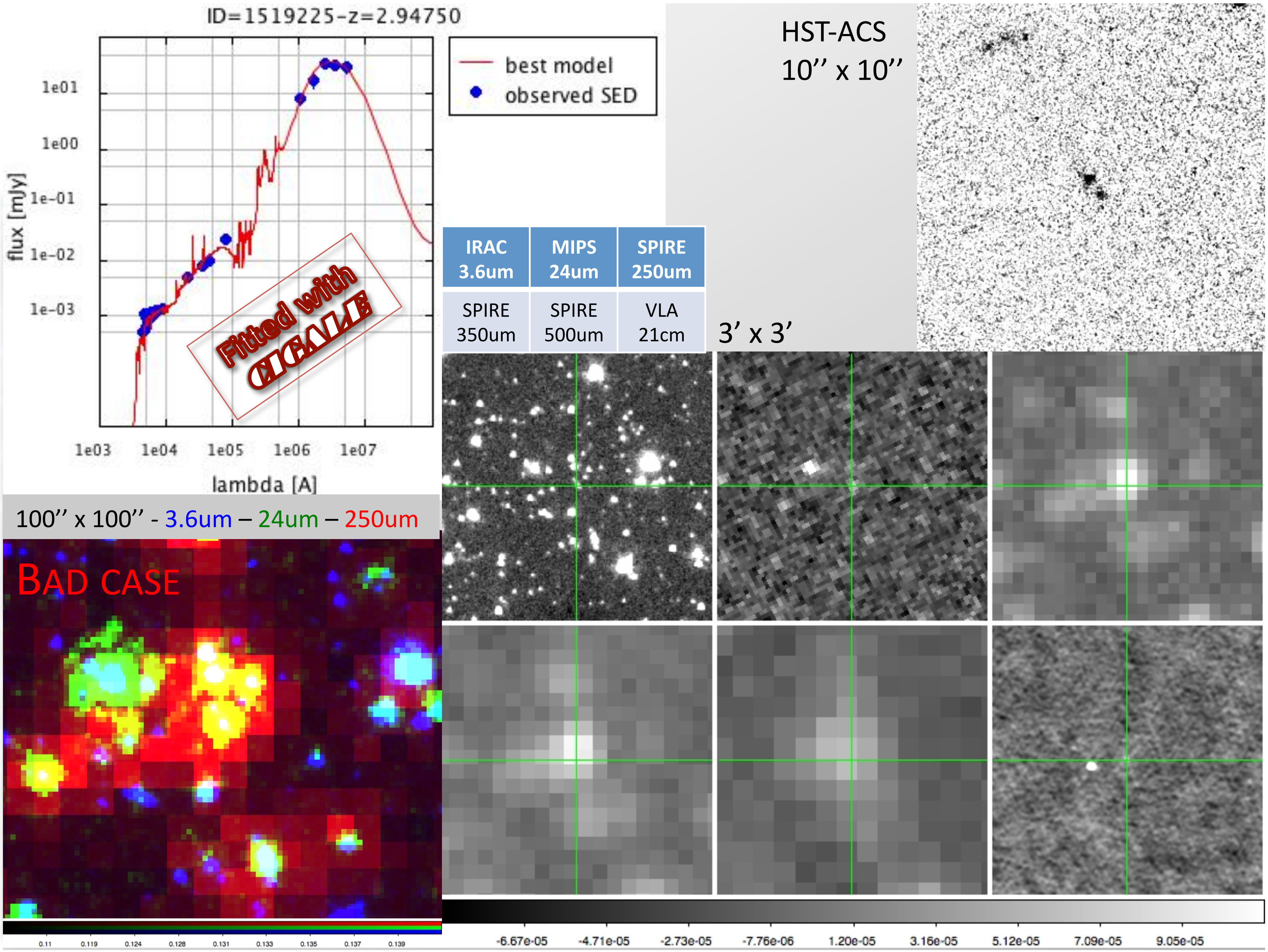
- We have selected two LBGs samples in the 2deg^2 COSMOS field at $1 \leq z \leq 2.5$ and $2.5 \leq z \leq 5.0$ using color-color diagrams and we obtain (for SNR>5):

	Redshift range	Good z	Good z_{spec}	Good z_{phot} & z_{spec} w/ FIR
LBG 1	1.0 < z < 2.5	27190	2205	836
LBG 3	2.5 < z < 5.0	15592	669	34 (z_{max} ~ 4)

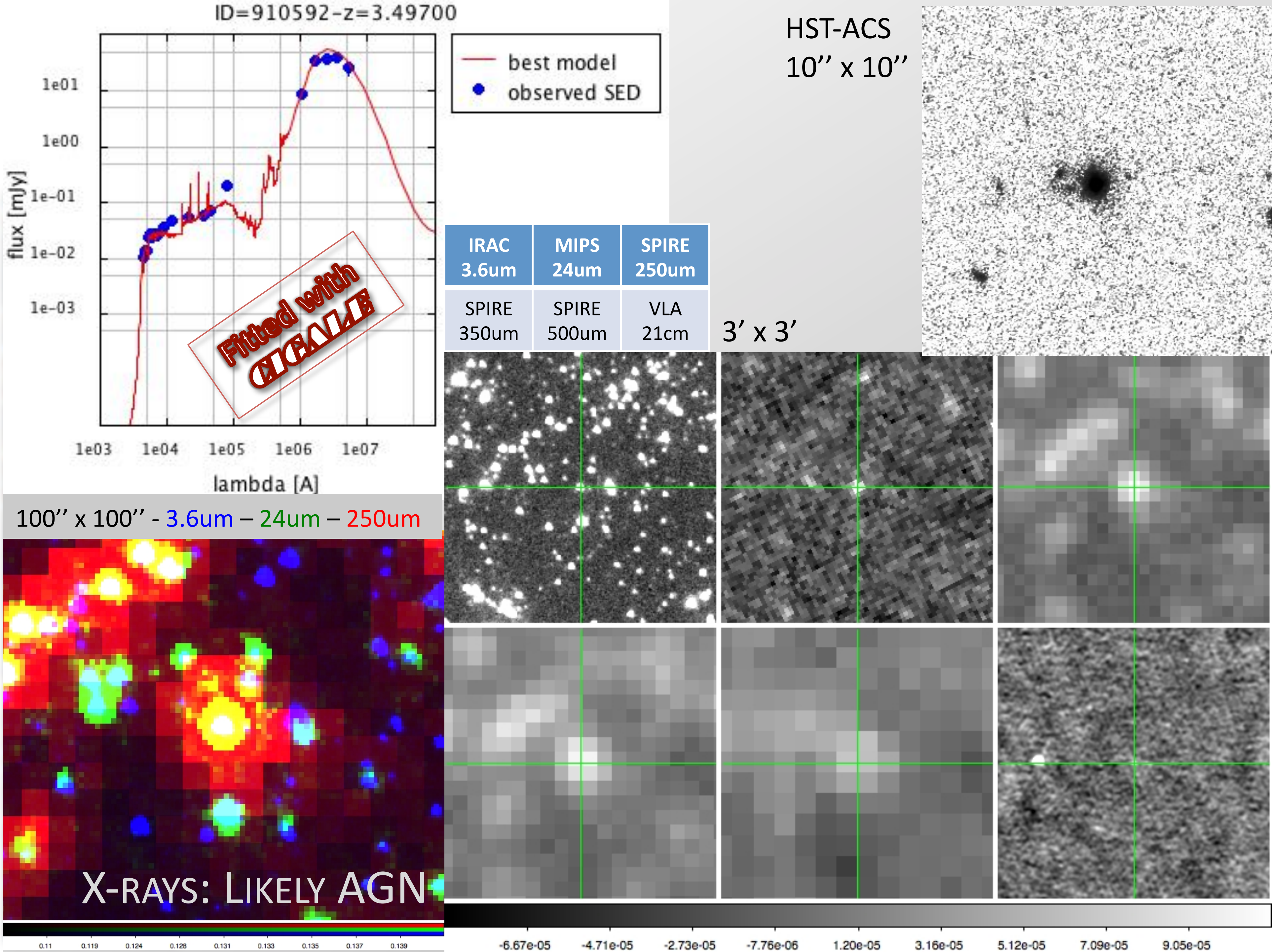
- SNR=5 ⬄ [f_{lim}(250um)=13mJy, f_{lim}(350um)=17mJy, f_{lim}(500um)=27mJy)
- At z>2.5 and SNR>5, the <u>pure chance association</u> (optimized to r = 0.8'') is estimated to <u>~1/3 of the sample</u>
  - arbitrarily shifting the Herschel (RA, Dec) sources and re-associating LBGs to FIR sources ➔ 10 chance associations for 33 candidates (i.e. Pb ~ 1/3)
  - $Pb = 1 - \exp(\rho_{LBG} \times S_{r=0.8''}) = 1.21 \times 10^{-3}$ or 9.98 chance associations out of 33 candidates (1/3) in excellent agreement with the simulations



ID=1777753-z=2.77910
best model
observed SED
flux [mJy]
1e01
1e00
1e-01
1e-02
1e-03
1e03
1e04
1e05
1e06
1e07
lambda [A]
Fitted with CIGALE
HST-ACS
10'' x 10''
IRAC 3.6um
MIPS 24um
SPIRE 250um
SPIRE 350um
SPIRE 500um
VLA 21cm
3' x 3'
100'' x 100'' - 3.6um – 24um – 250um
GOOD CASE
-6.67e-05
-4.71e-05
-2.73e-05
-7.76e-06
1.20e-05
3.16e-05
5.12e-05
7.09e-05
9.05e-05

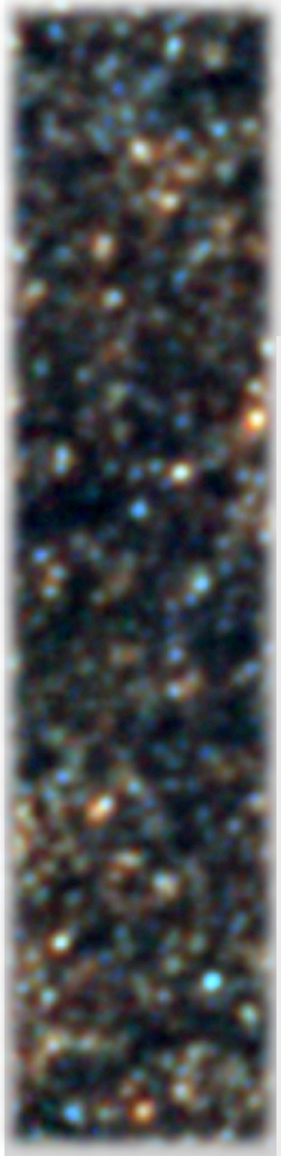


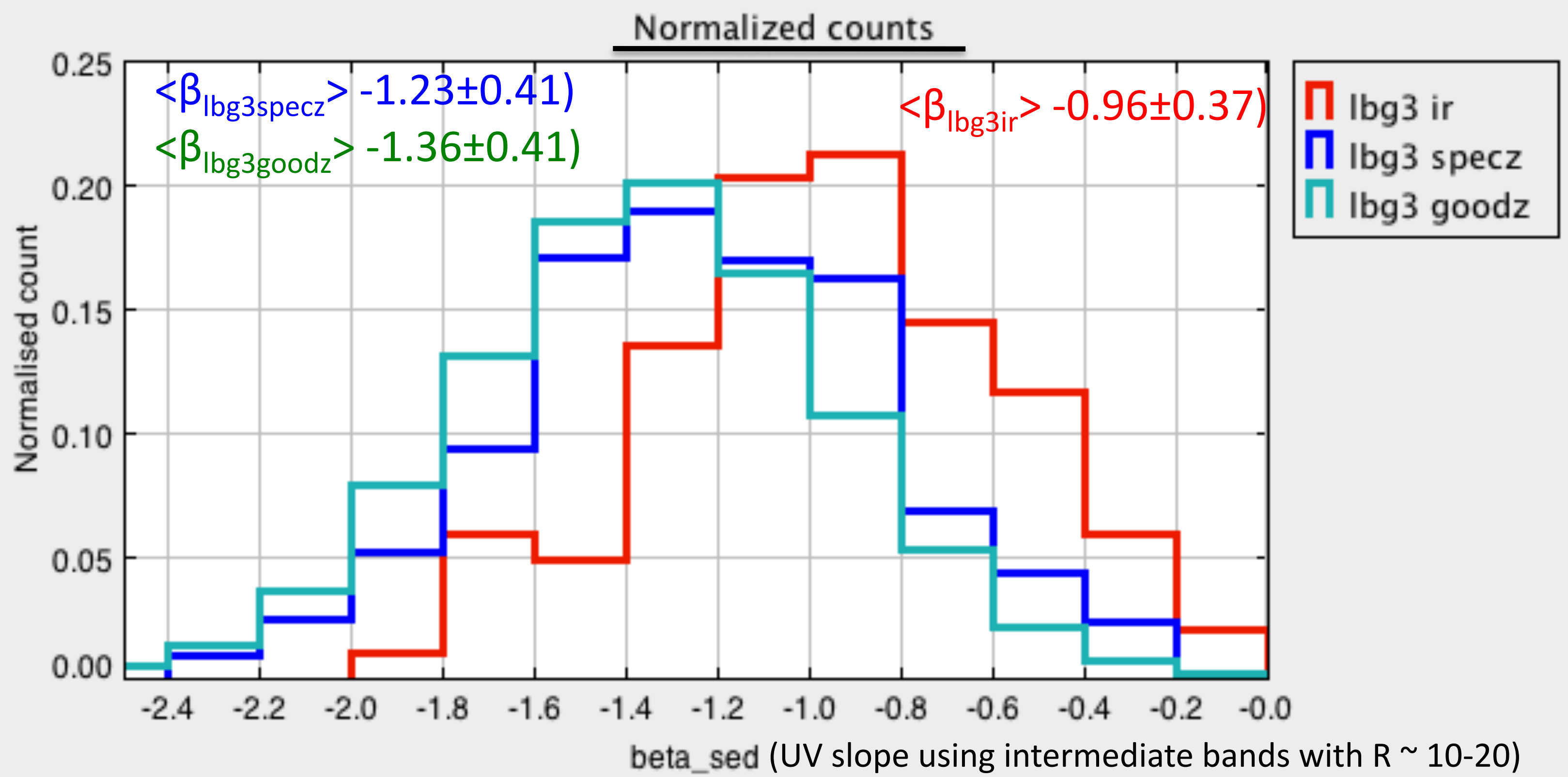
ID=1519225-z=2.94750
best model
observed SED
flux [mJy]
1e01
1e00
1e-01
1e-02
1e-03
1e03
1e04
1e05
1e06
1e07
lambda [A]
Fitted with CIGALE
HST-ACS
10'' x 10''
IRAC 3.6um
MIPS 24um
SPIRE 250um
SPIRE 350um
SPIRE 500um
VLA 21cm
3' x 3'
100'' x 100'' - 3.6um – 24um – 250um
BAD CASE
-6.67e-05
-4.71e-05
-2.73e-05
-7.76e-06
1.20e-05
3.16e-05
5.12e-05
7.09e-05
9.05e-05


ID=910592-z=3.49700
best model
observed SED
flux [mJy]
1e01
1e00
1e-01
1e-02
1e-03
1e03
1e04
1e05
1e06
1e07
lambda [A]
Fitted with CIGALE
HST-ACS
10'' x 10''
IRAC 3.6um
MIPS 24um
SPIRE 250um
SPIRE 350um
SPIRE 500um
VLA 21cm
3' x 3'
100'' x 100'' - 3.6um – 24um – 250um
X-RAYS: LIKELY AGN
0.11
0.119
0.124
0.128
0.131
0.133
0.135
0.137
0.139
-6.67e-05
-4.71e-05
-2.73e-05
-7.76e-06
1.20e-05
3.16e-05
5.12e-05
7.09e-05
9.05e-05

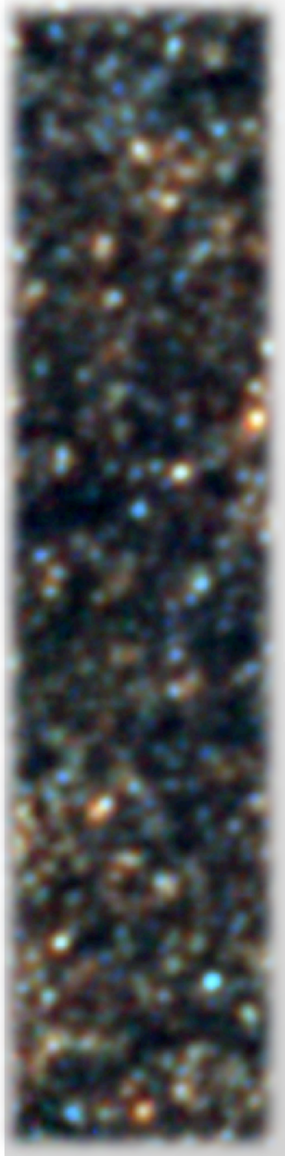
The LBG preliminary samples: suggests associations are statistically OK

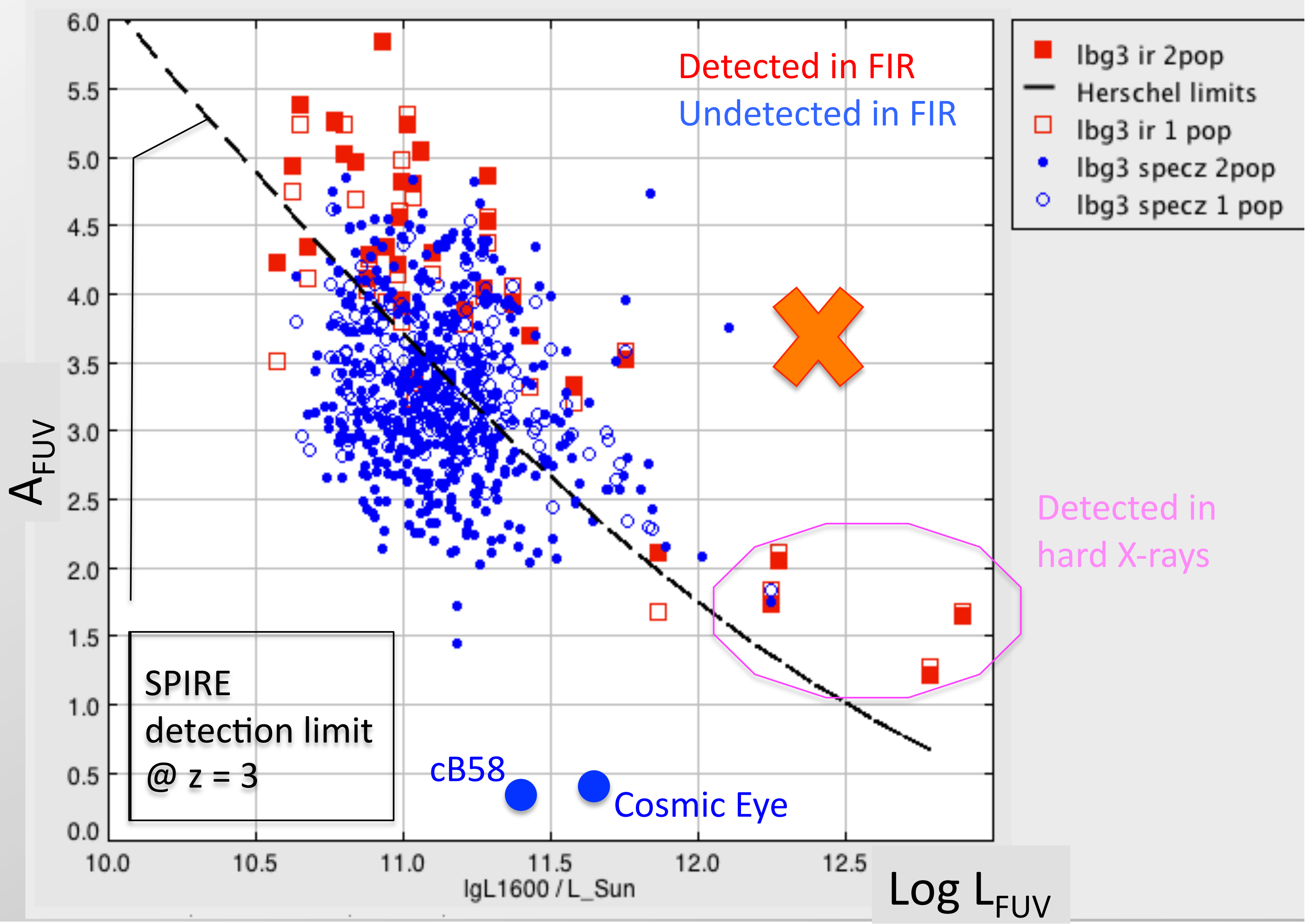
- 34 LBGs @ 2.5 ≤ z ≤ 4.0 detected @ 5 sigmas with SPIRE (104 LBGs @ 3 sigmas)
- 669 LBGs 33 LBGs @ 2.5 ≤ z ≤ 4.0 undetected @ 3 sigmas with SPIRE
- 15 000 LBGs with photometric redshifts



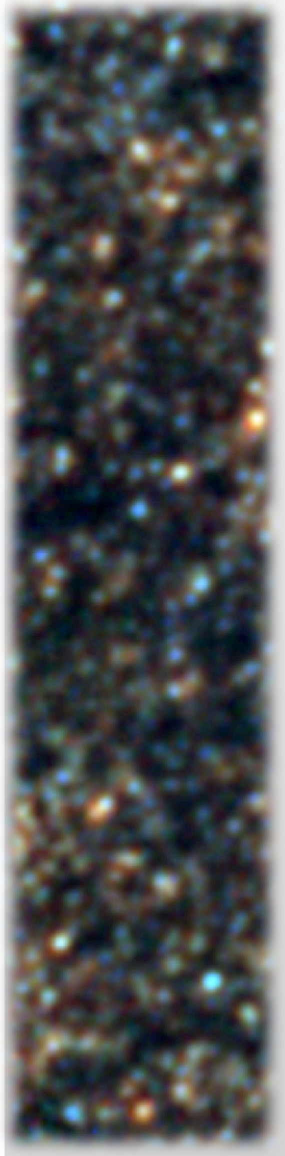


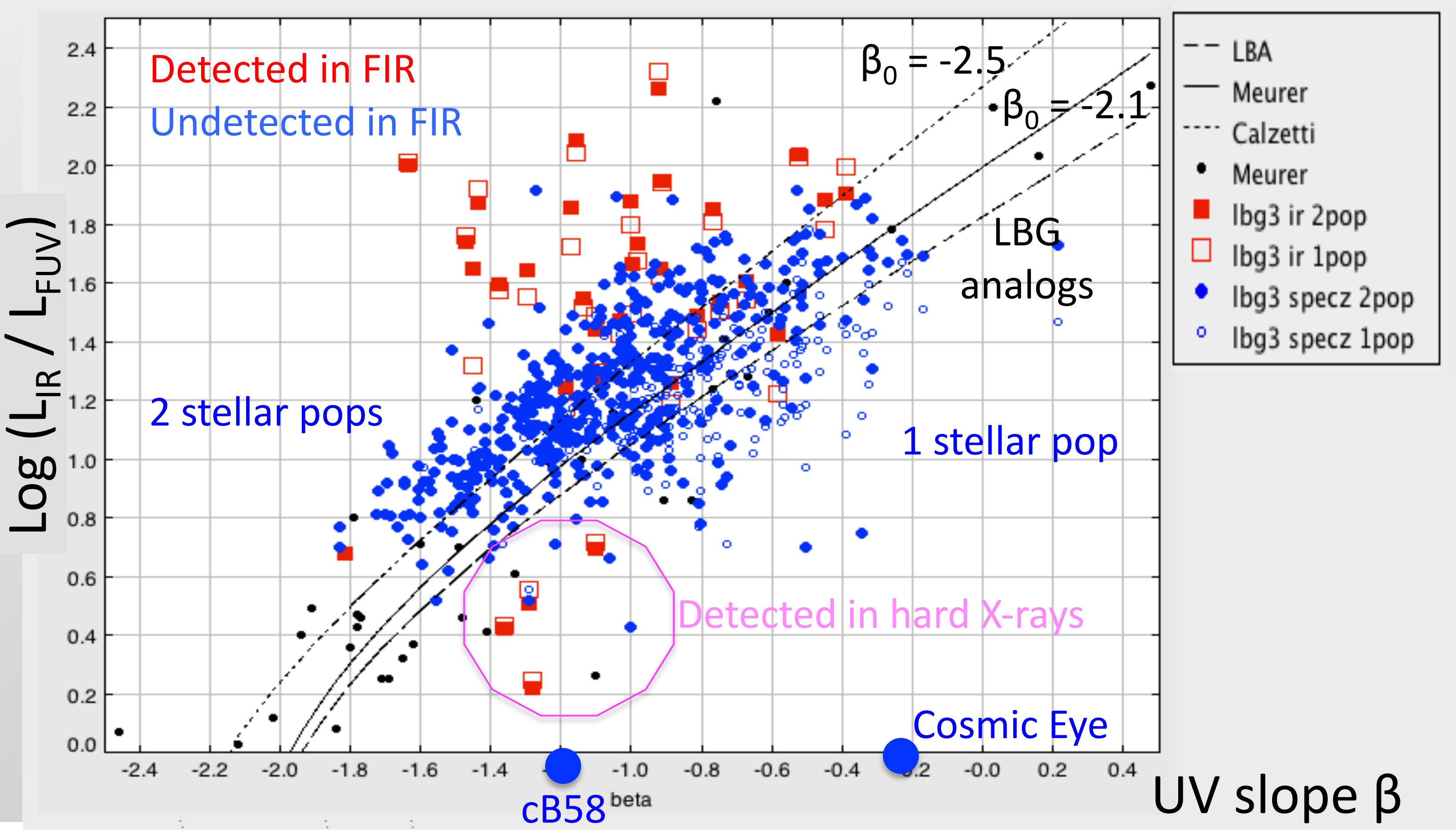
The dust attenuation does not decrease for UV-faint galaxies. We confirm Burgarella et al. (2006, 2011) at 2.5 < z < 4.0



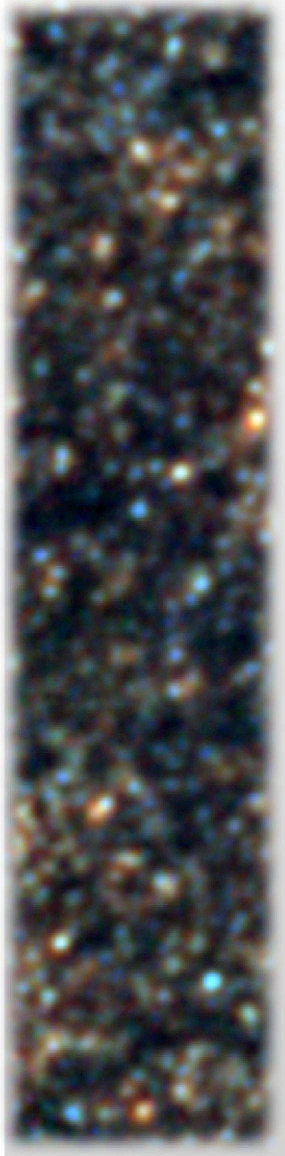


* IRX-beta relation for LBGs detected if FIR with SNR > 5 @ 2.5 < z < 4 not in agreement with Meurer et al. (1999).
* For undetected ones, relative agreement with Calzetti et al. (2000) but dispersed by up to 1mag when 2 stellar pops used (assuming an unreddened UV slope β_0 = -2.5)
* … but similar agreement with Meurer et al. (1999) when 1 stellar pop used (assuming β_0 = -2.1)
* RED LBGs are detected in FIR but BLUE (w/ z_{spec}) LBGs are not (L_{IR} estimated by SED fitting with the above restrictions on the quality).





Conclusions, Questions and Prospects

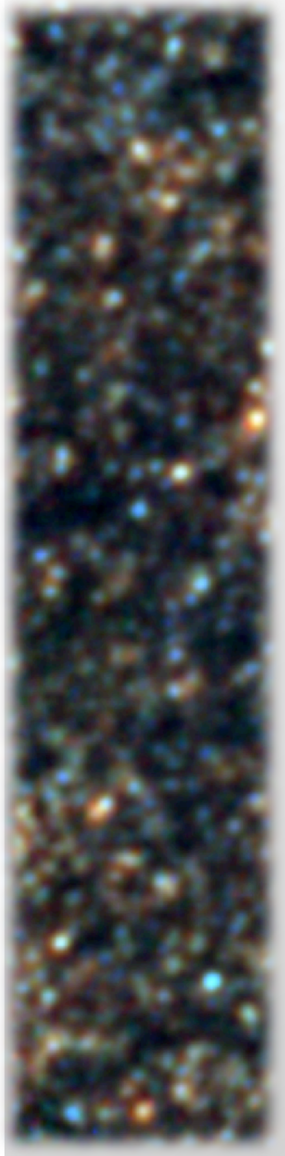


- The selection introduces biases which have to be fully accounted in the following of the study
- Most LBGs are not detectable with Herschel => stacking is necessary and will be performed
- A few percent are: a bridge between LBGs and SMGs
- FIR-detected LBGs are redder than undetected ones.
- Some of them probably host an AGN (hard X-rays)
- We see (*directly from FIR data*) two limiting regimes for faint UV galaxies.
- Statistically, the dust attenuation of UV galaxies does not decrease with the UV luminosity (in the range sampled here).
- Meurer's law does not provide good A_{FUV} for IR-LBGs.
- For undetected ones, we see a large dispersion by up to 1 mag but, above all, A_{FUV} is model-dependent.

  - ***This work is in progress at z>2.5 and also at 1.0< z <2.5 where many more LBGs are detected in FIR***

Burgarella et al. (2011, ApJ 734, L12)
http://www.oamp.fr/cigale

Thank you
Merci



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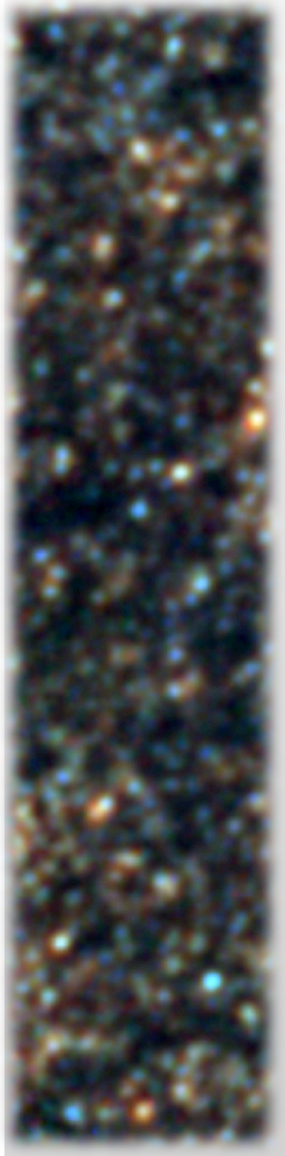
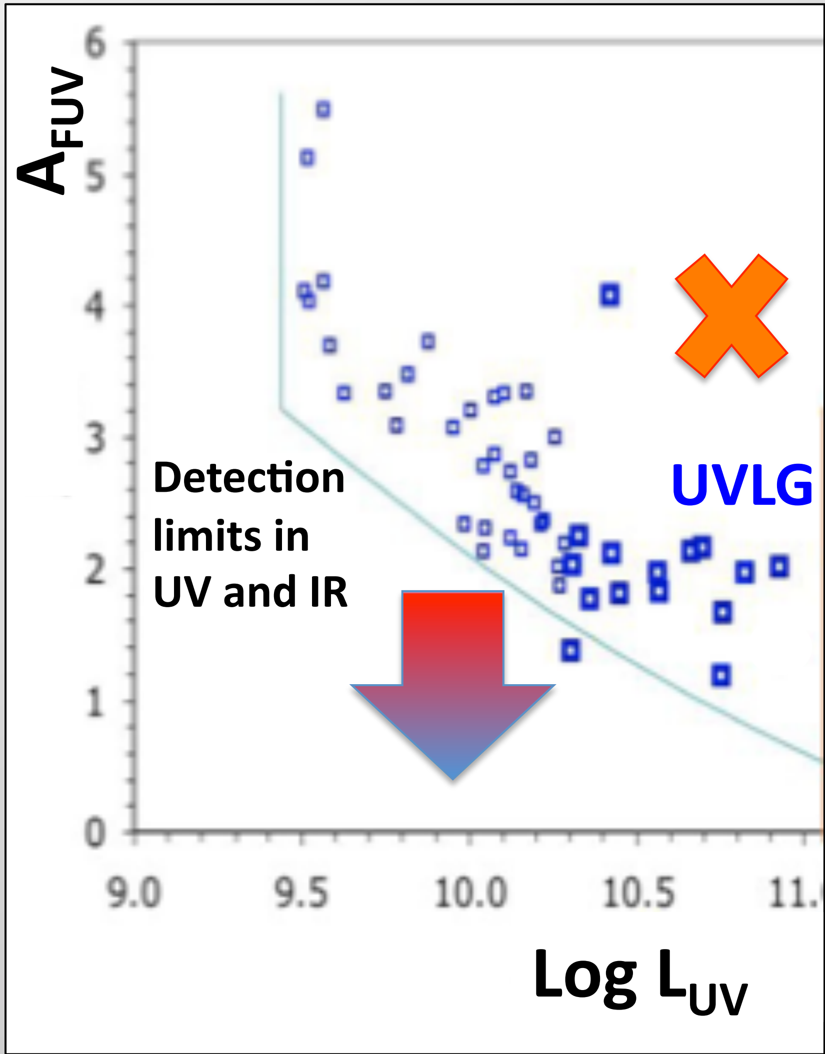
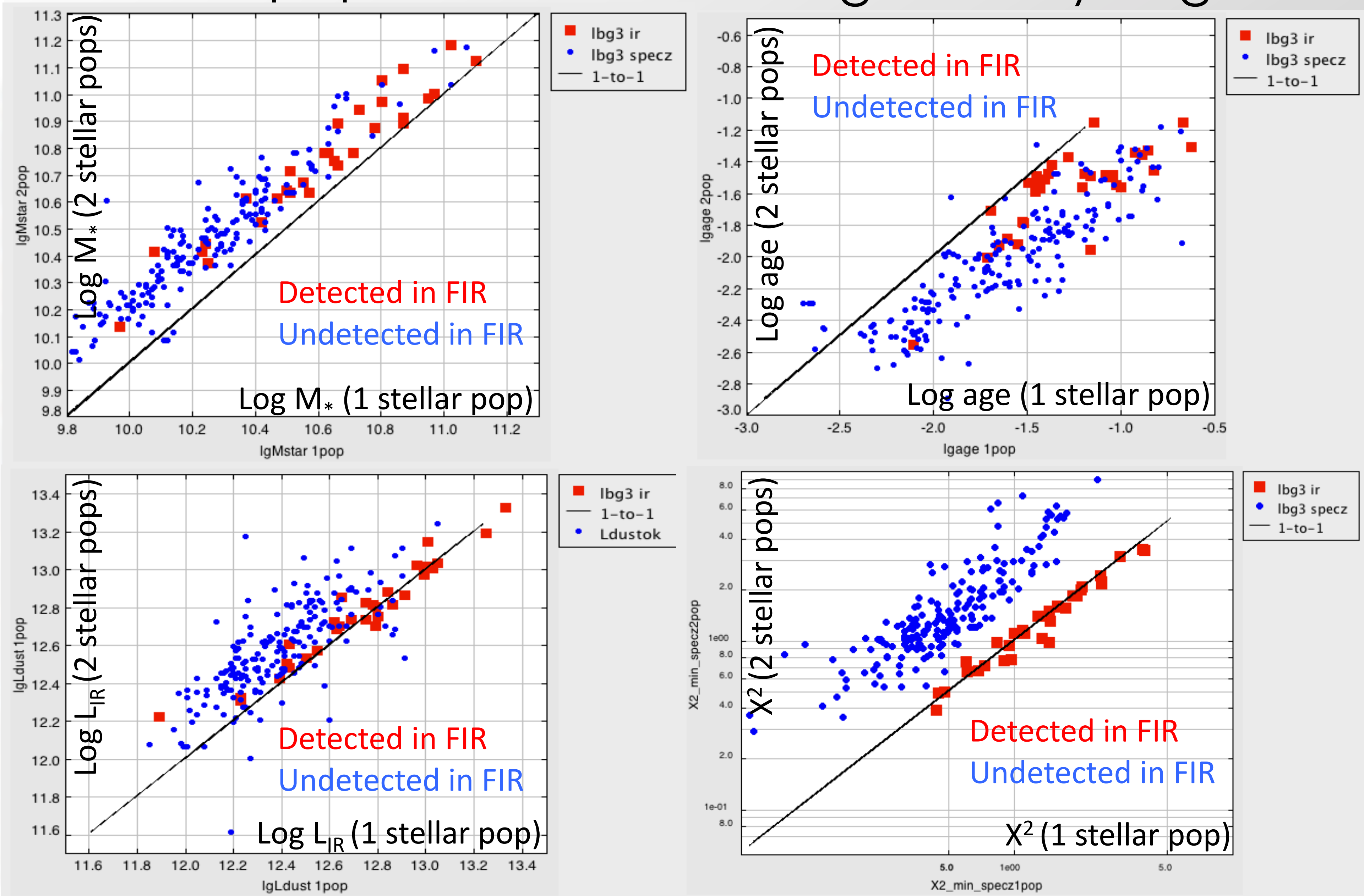
LBGs @ z ~ 1 from Spitzer 24um

(Burgarella et al. 2006)

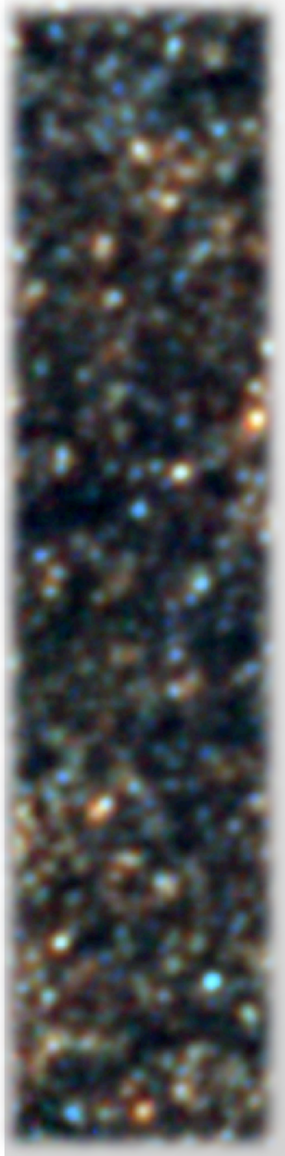


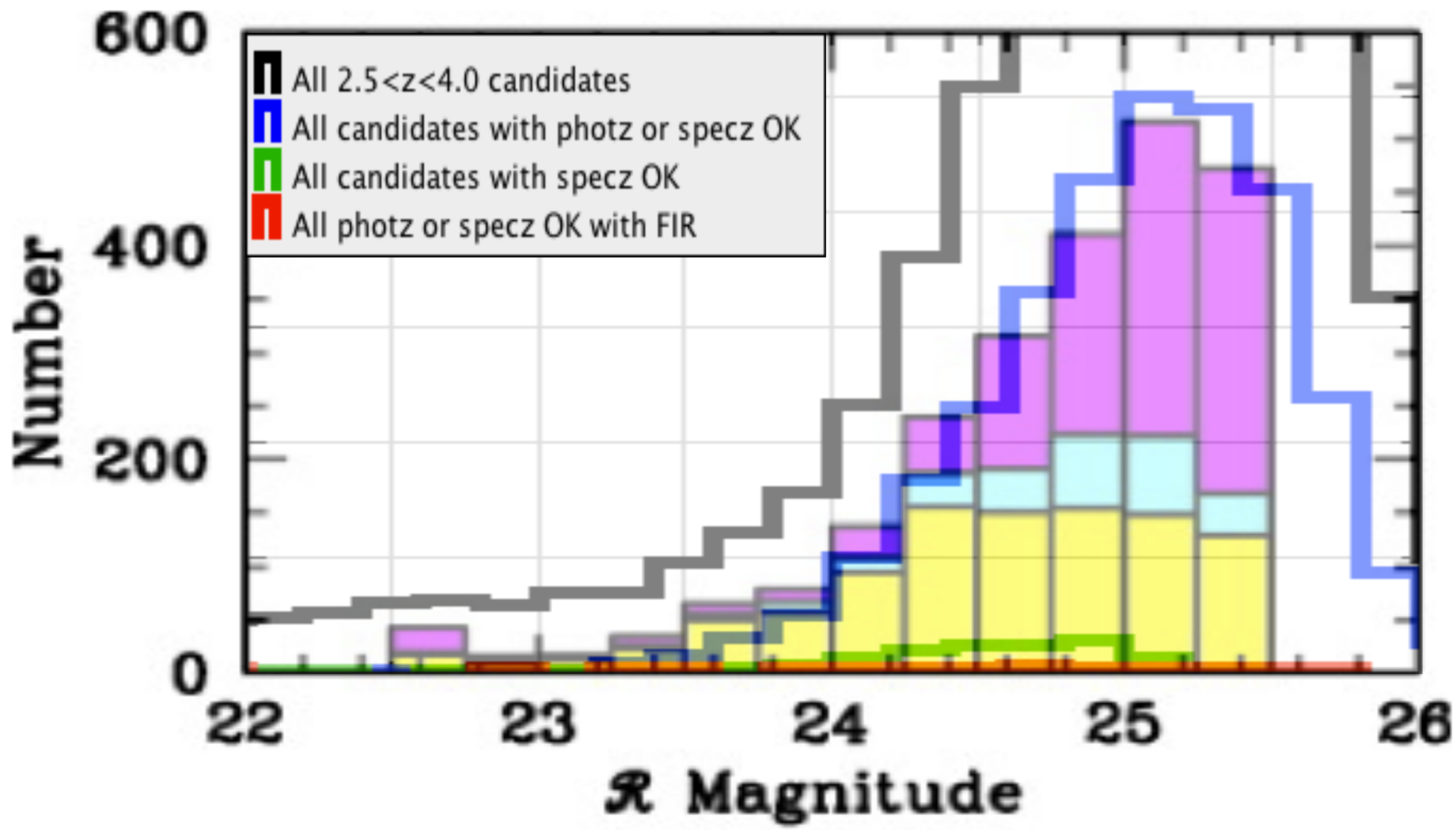


A few words of warning: fitting SEDs assuming 1 or 2 stellar populations can change what you get

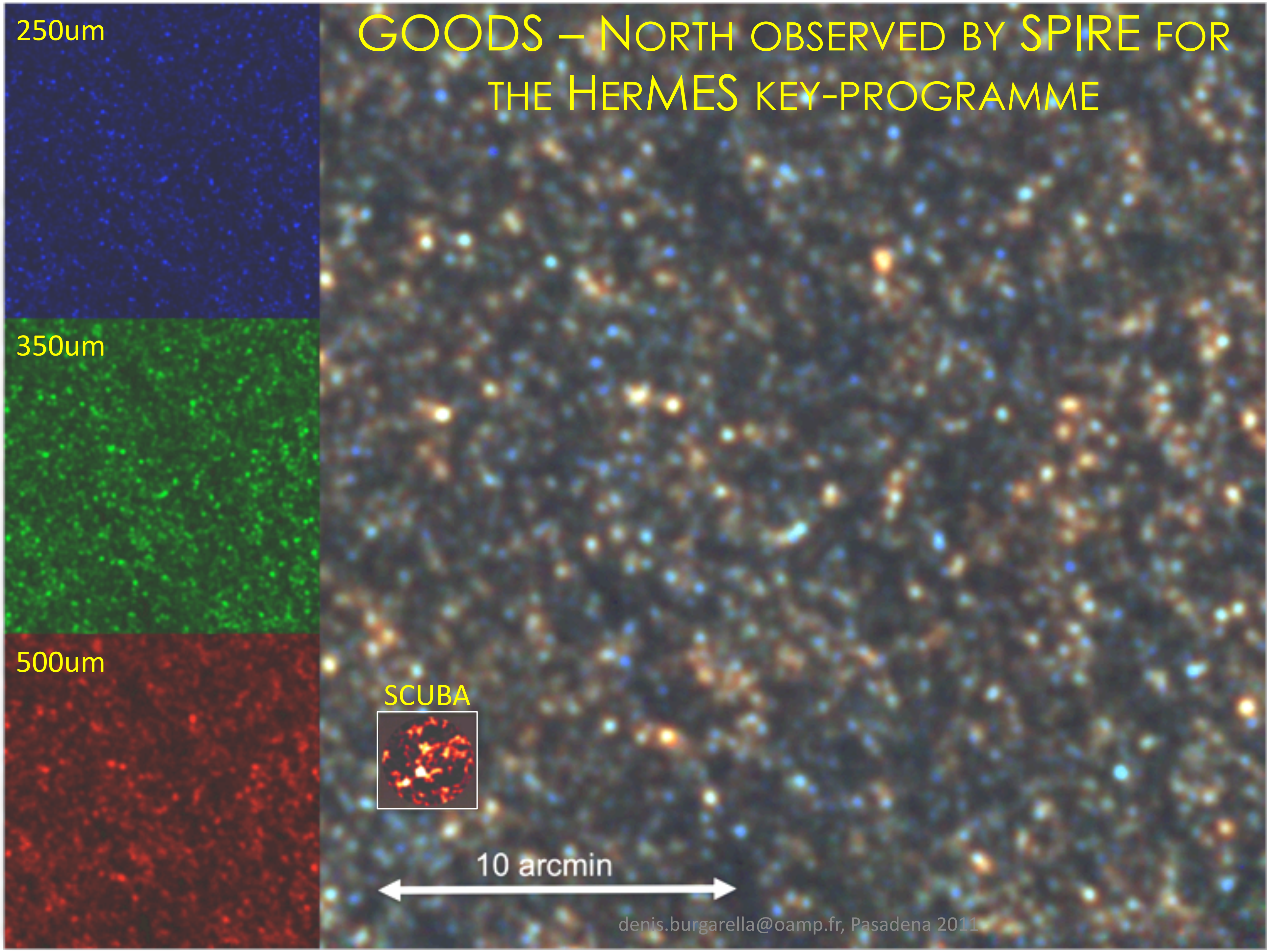


Normalized counts in agreement with Steidel et al. 2003 dropouts

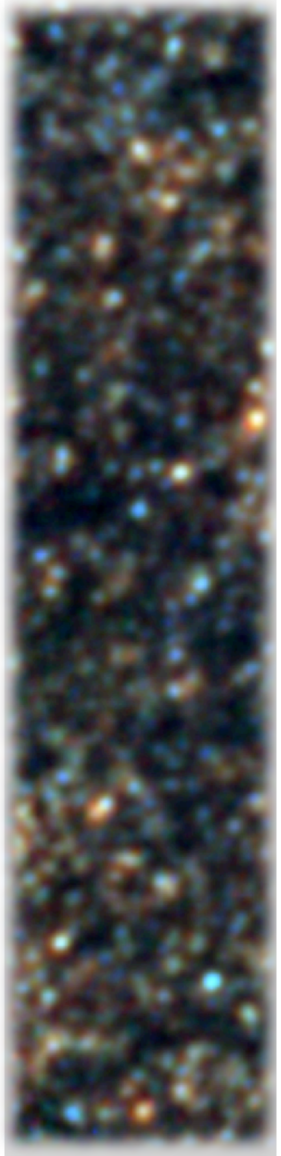




Top: Magnitude distribution of the full photometric LBG sample (*magenta*), the subsample targeted for spectroscopy (*cyan*), and the subsample with successful spectroscopic redshifts (*yellow*). *Bottom:* Fraction of the full photometric sample represented by the spectroscopically observed subsample (*cyan*) and the spectroscopically successful samples versus apparent magnitude. The black curve represents the fraction of spectroscopically observed objects that yielded successful redshifts, as a function of apparent $\mathcal{R}$ magnitude.


GOODS – North observed by SPIRE for the HerMES key-programme
250um
350um
500um
SCUBA
10 arcmin
denis.burgarella@oamp.fr, Pasadena 2011

Reddy et al. 2010
(BM/BX galaxies @ z ~2 from 24um)



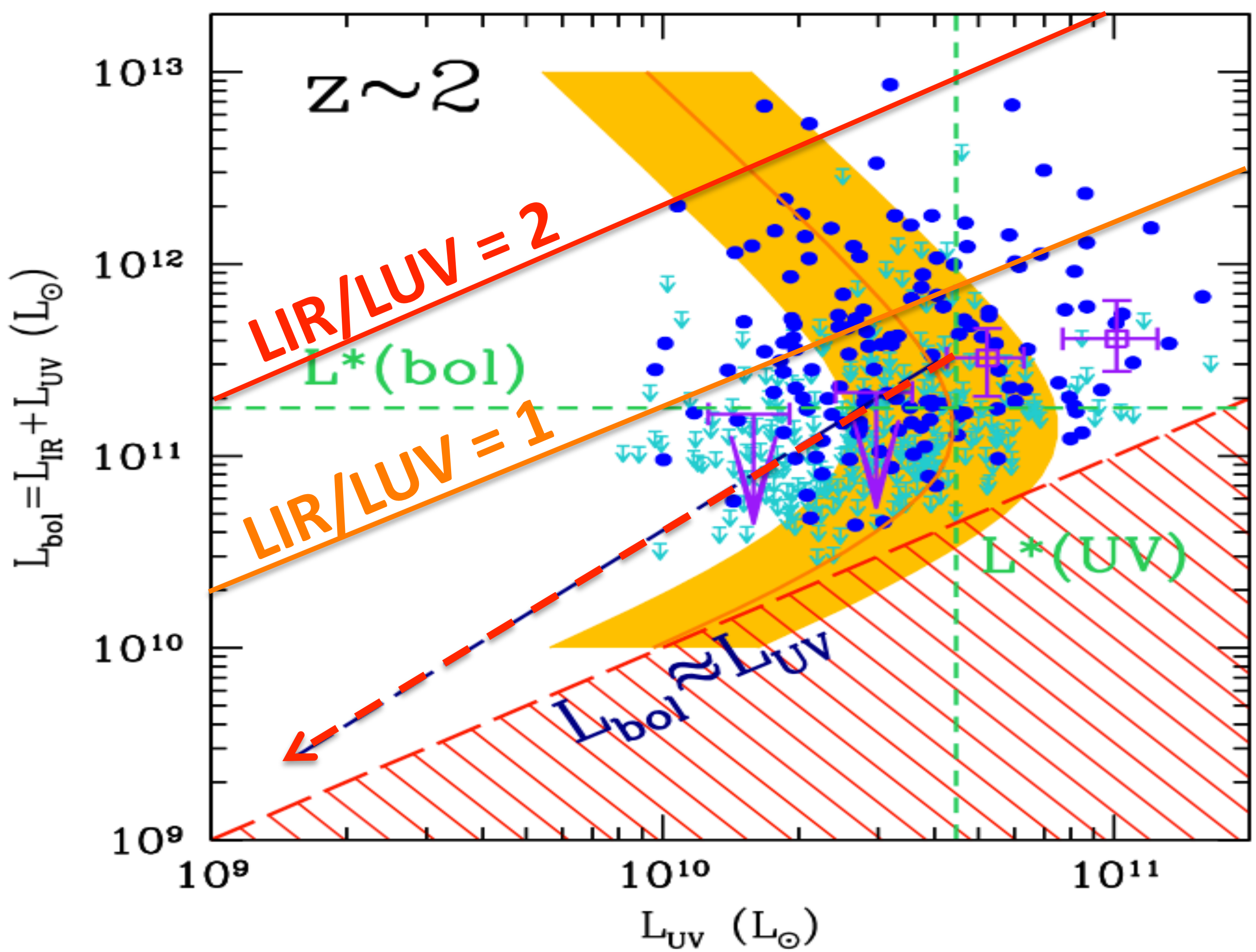
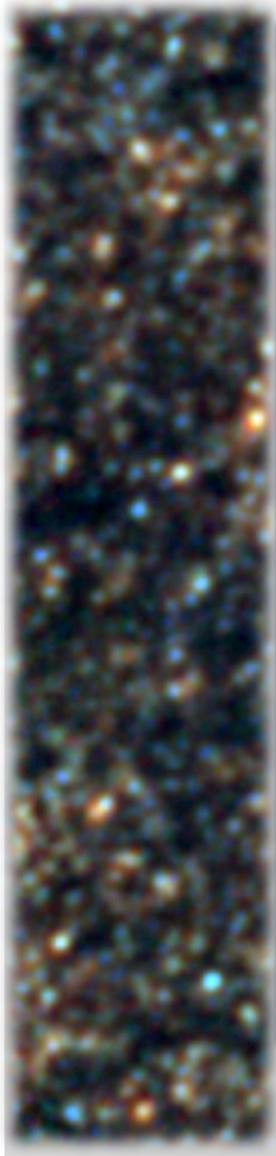
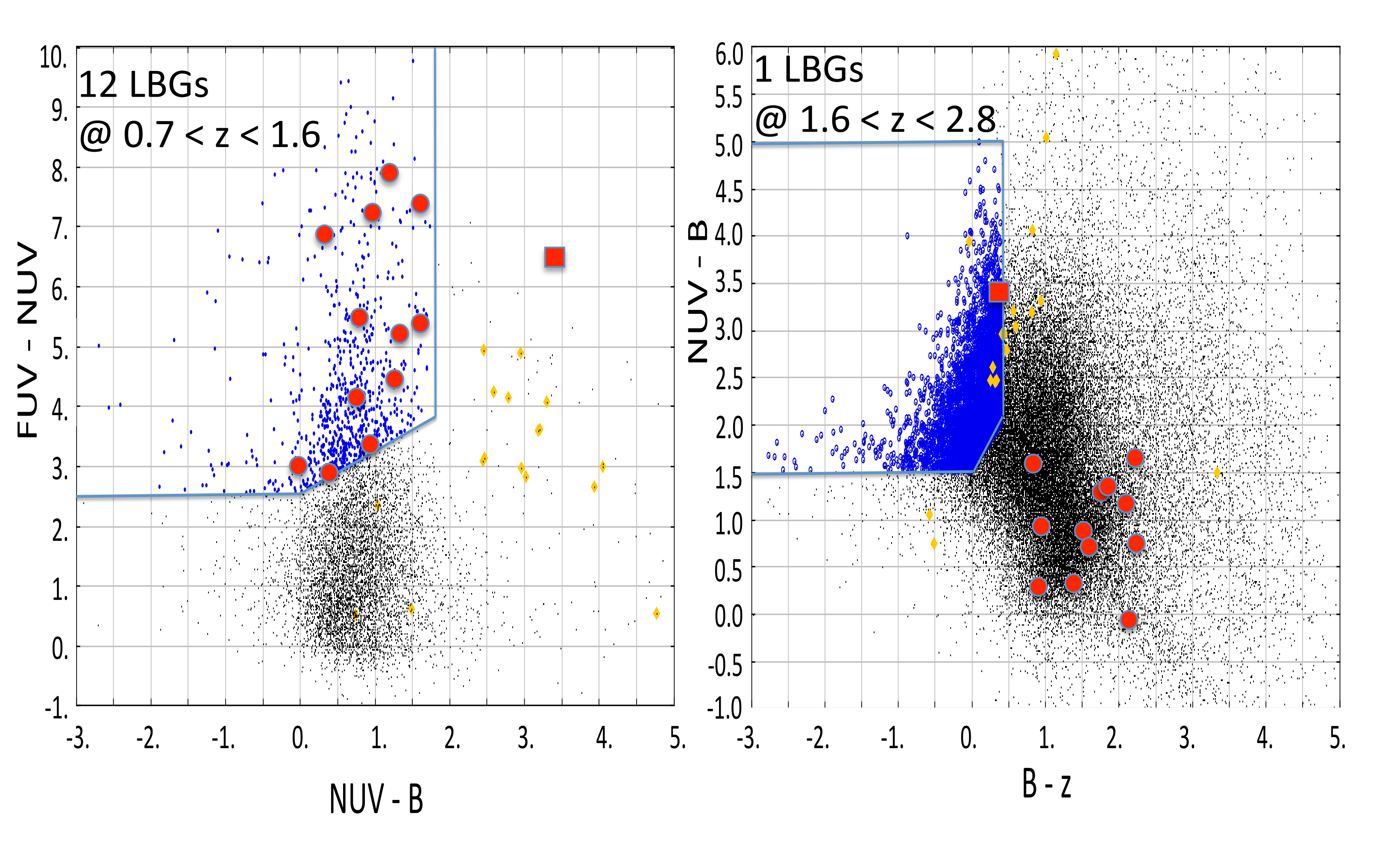


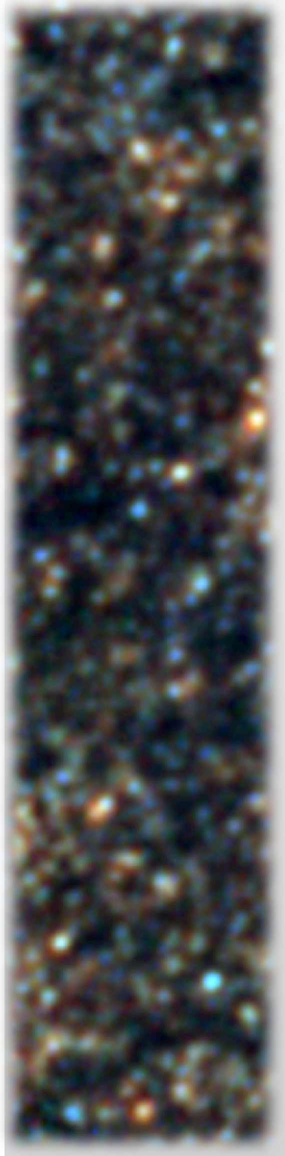
FIG. 13.— Bolometric luminosity ($L_{\rm bol}$) versus observed UV luminosity ($L_{\rm UV}$). Small points and arrows indicate galaxies detected and undetected, respectively, at 24 μm. The 24 μm stacked results are shown by the open squares and large arrows (*purple*). The shaded region denotes $\pm 1\ \sigma$ about the mean relation implied by the correlation between $L_{\rm bol}$ and dust attenuation (Eq. 4). The hashed region indicates the area excluded by the fact that $L_{\rm bol}$ must be greater than $L_{\rm UV}$. The dashed horizontal and vertical lines delineate the values of $L^*_{\rm UV}$ and $L^*_{\rm bol}$ at $z \sim 2$ (Reddy & Steidel 2009; Reddy et al. 2008), and the thicked dashed line shows the extrapolation of the relation to UV-faint galaxies (see text).

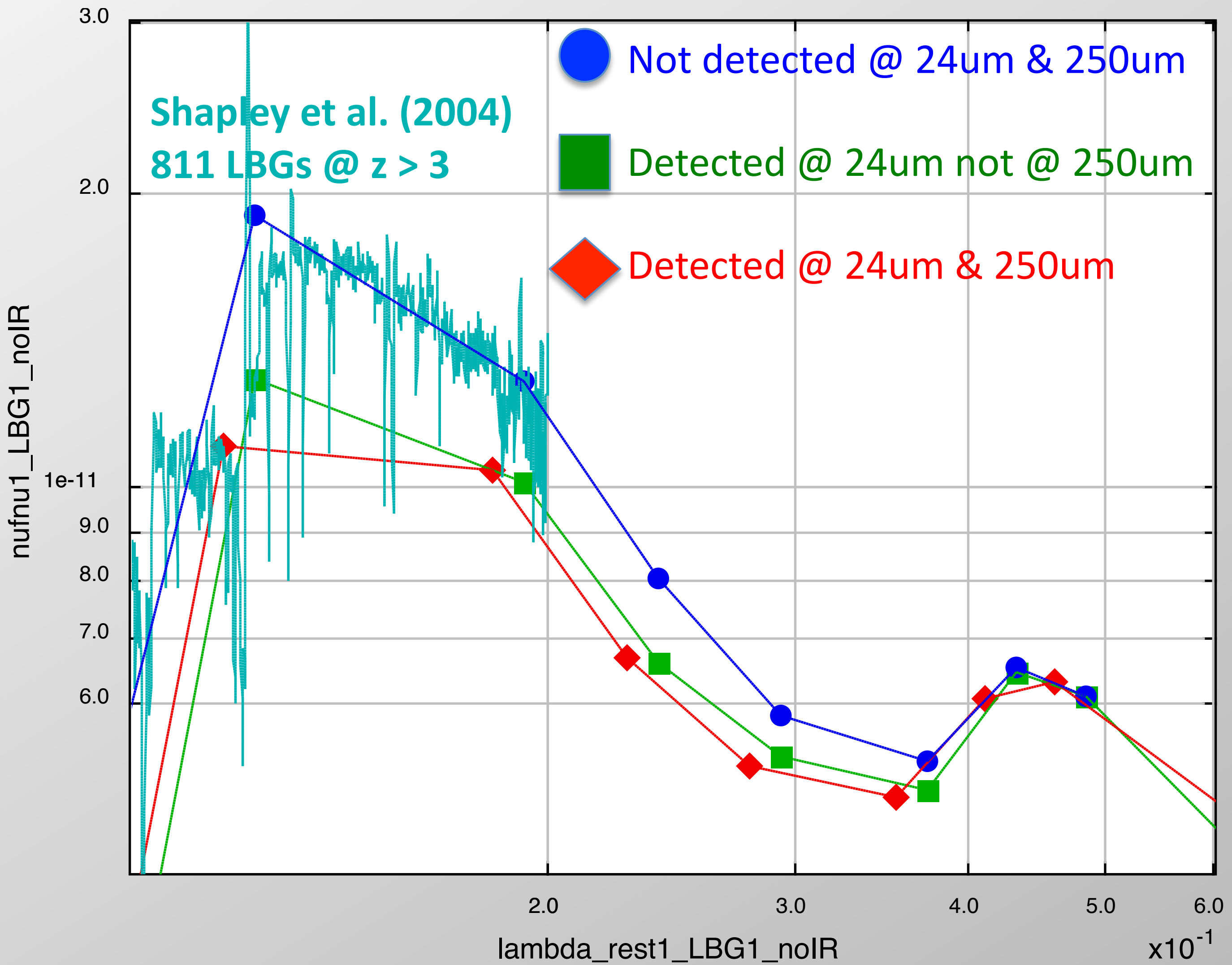
GALEX LBG Selections
0.7≤ z ≤1.6 & 1.6≤ z ≤2.8



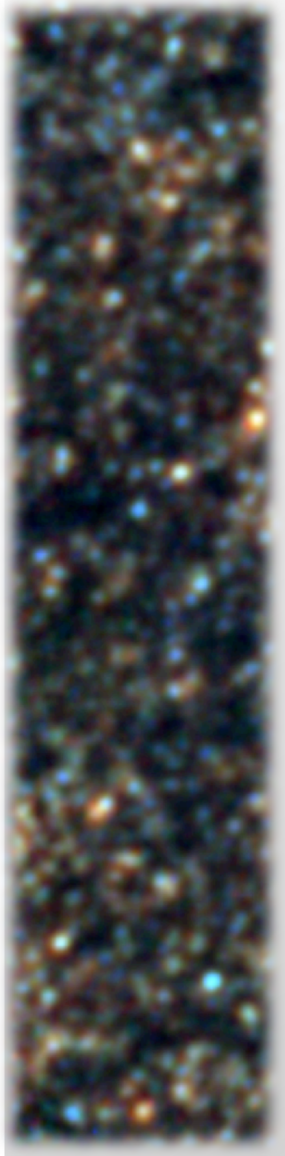


Z ~ 1 SED similar in UV to hi-z LBGs





Toy Model (easier to control but more sophisticated under development with infall and outflow)



- Outflows at least in some LBGs (e.g. Shapley et al. 2003)
- Inflows from the IGM or during interactions
- Closed-box model:
  - Unreddened spectra from Maraston ('05)
  - $\dot{\Omega}_{gas} + \dot{\Omega}_{star} = 0 \Rightarrow \Omega_{gas}(t) + \Omega_{star}(t) = M_{total}$
  - $\Psi(t) = \Psi_0 e^{-\frac{t}{\tau}}$
  - $Z_{oxygen} = -y_{oxygen} . \ln\left(\frac{\Omega_{gas}}{M_{total}}\right) = 0$
  - $Empirical \quad 12 + \log\frac{O}{H} - \frac{L_{IR}}{L_{UV}} \; relation$

$$\left.\begin{array}{l} Z_{oxygen} = -y_{oxygen} . \ln\left(\frac{\Omega_{gas}}{M_{total}}\right) = 0 \\ Empirical \quad 12 + \log\frac{O}{H} - \frac{L_{IR}}{L_{UV}} \; relation \end{array}\right\} \Rightarrow \frac{L_{IR}}{L_{UV}}(t)$$

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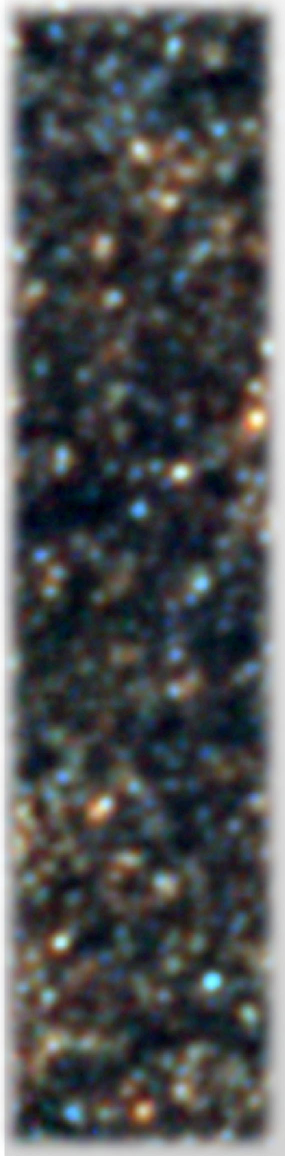
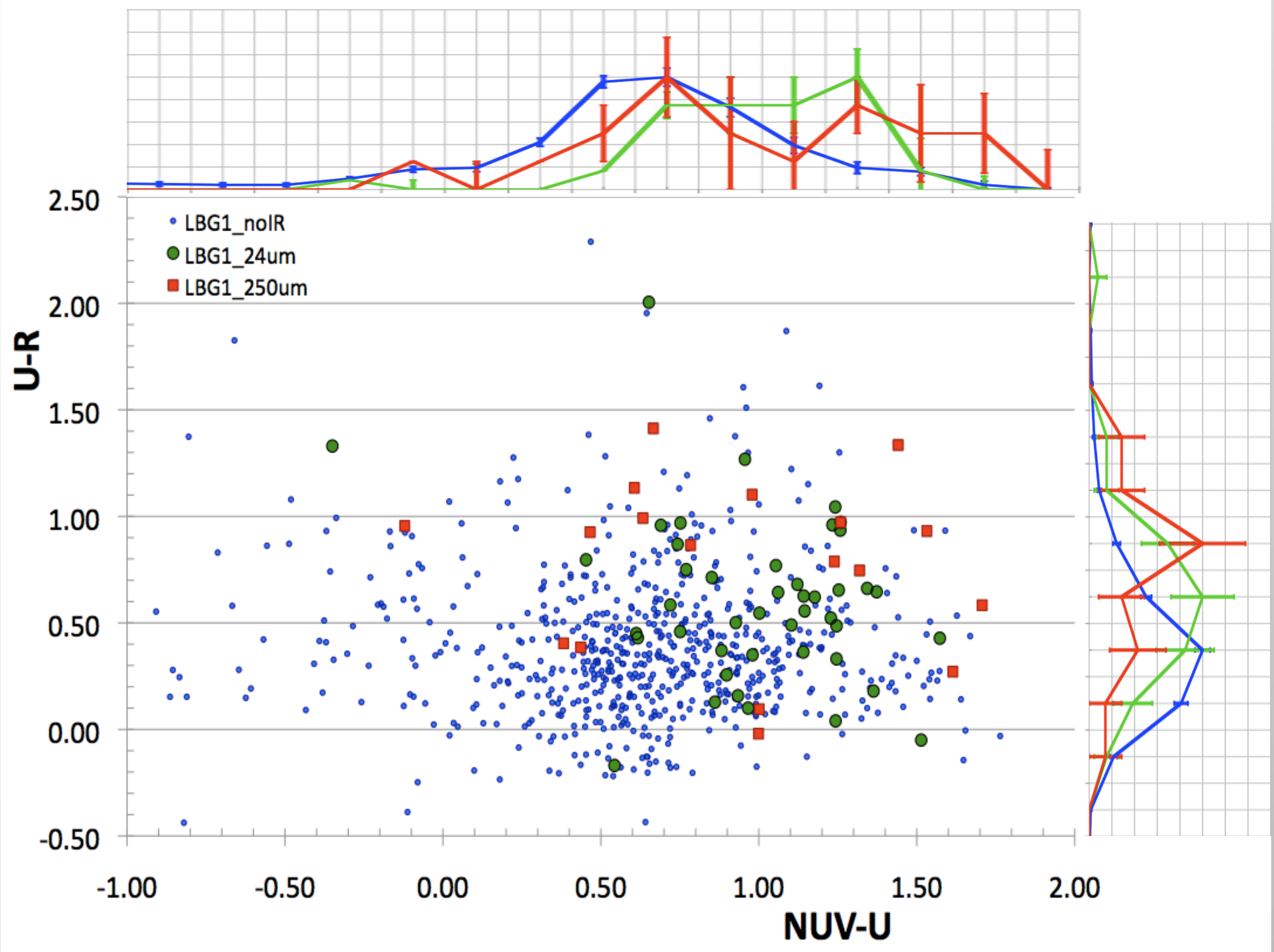
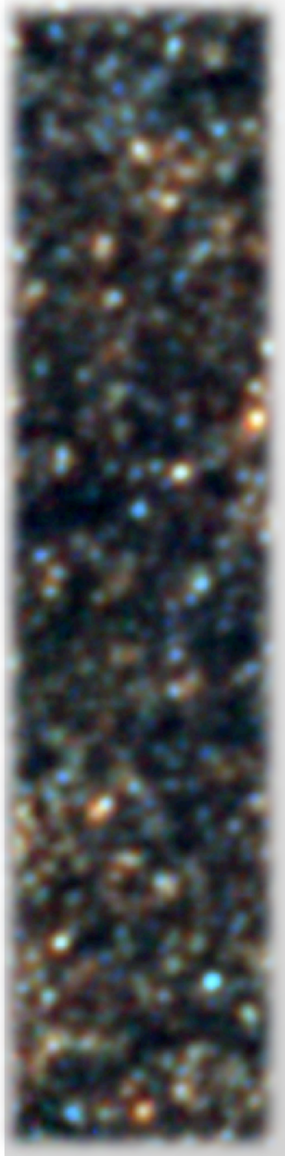
Rest-frame UV colors



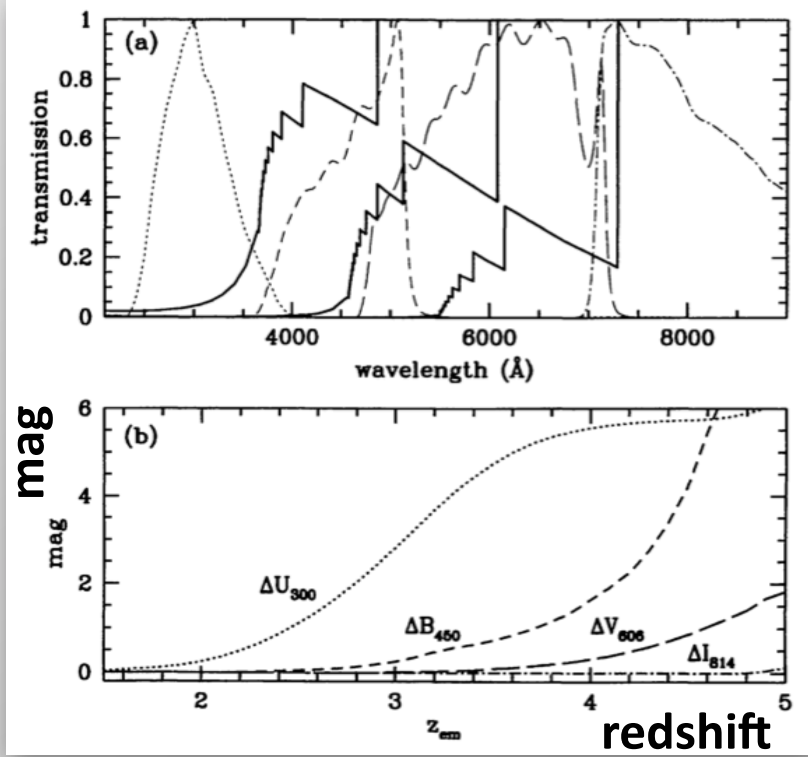


What are Lyman Break Galaxies ?



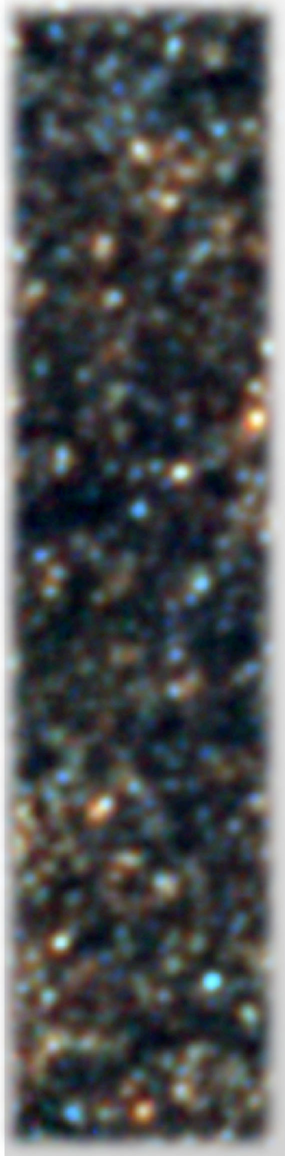
- Lyman Break Galaxies (LBGs) are galaxies presenting a discontinuity at restframe wavelengths below 0.912nm

- This discontinuity is due to a combination of the Lyman Break :
  - o stellar emission,
  - o galaxy self absorption from the ISM,
  - o integrated opacity of the IGM (Madau et al. 1996) for z > 2 LBGs.



- <u>Objective</u> : ***IDENTIFY*** high-z galaxies

What are SMGs ?

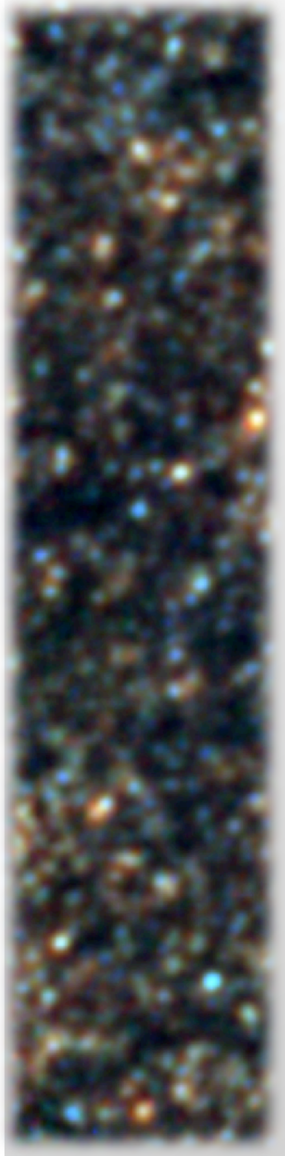


- Submillimeter galaxies (SMGs; e.g. Blain et al. 2002) are massive galaxies with intense heavily obscured starbursts that rapidly consume their gas through star formation.

- SMGs may trace a common phase in the evolution of massive galaxies in the early universe, making them the likely progenitors of today's massive spheroidal galaxies (Swinbank et al. 2010).

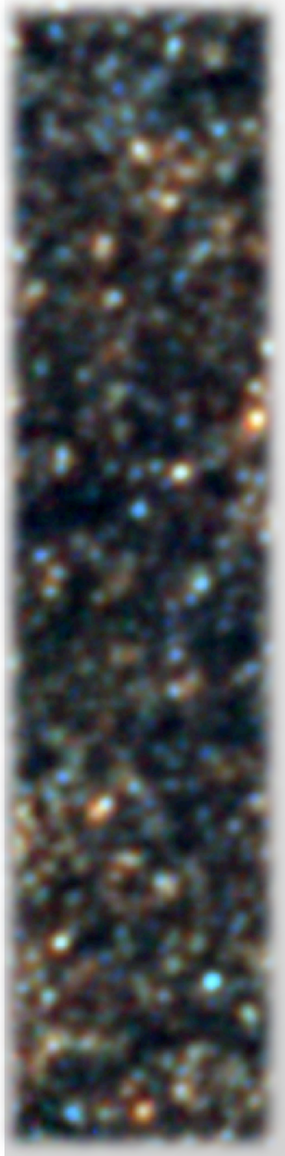
- Based partly on the large increase in SFR that should accompany gas-rich major mergers, it is believed (although some debate exists) that SMGs are large, gas-rich, merger-induced starbursts, observed in a phase where their luminosity is boosted (e.g. Narayanan et al. 2009).

A link between IR-LBGs and SMGs ?

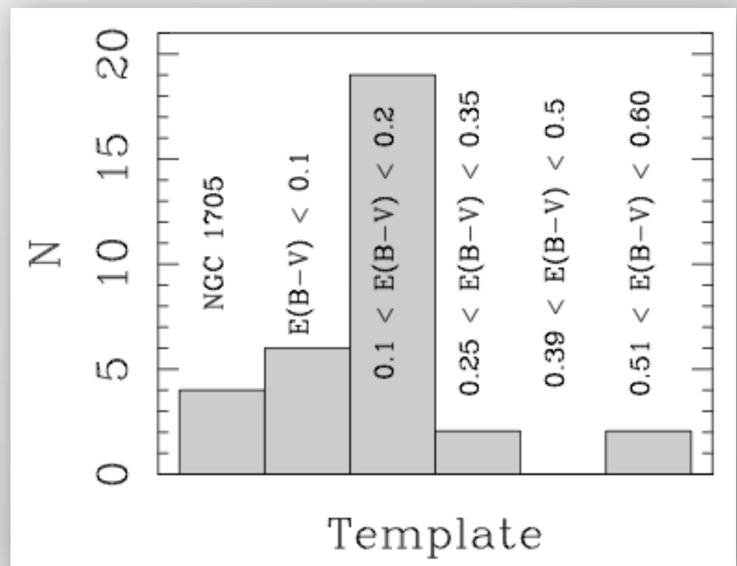


- Although the morphology of LBGs is found to be diverse (Lowenthal et al. 2009, Ravindranath et al. 2006), part of the LBG population might also be young ellipticals/spheroids.
- Ravindranath et al. (2006) find ~ 30% of the LBGs have profiles expected for spheroids.
- The proportion of IR-bright LBGs is even lower (a few percents, Burgarella et al. 2006, Huang et al. 2005, Burgarella et al. 2011)

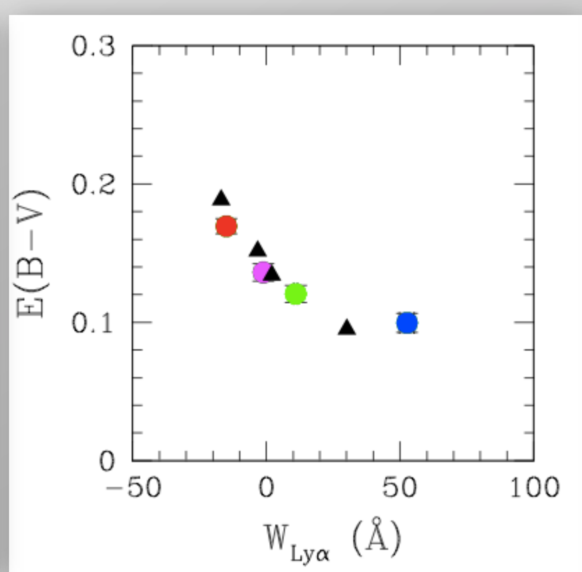
LBGs and Dust

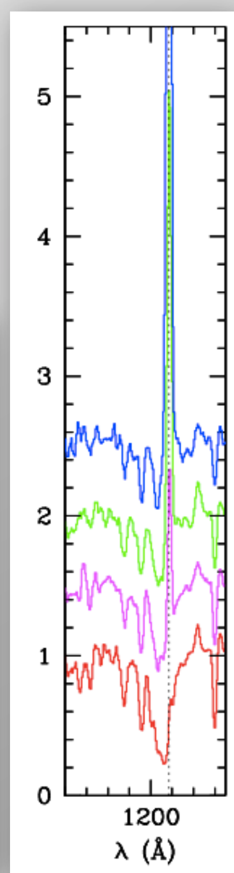


- Papovich et al. (2004): most LBGs have low E(B-V)
- Shapley et al. (2003): significant correlation between UV continuum extinction and *W(Ly α)*



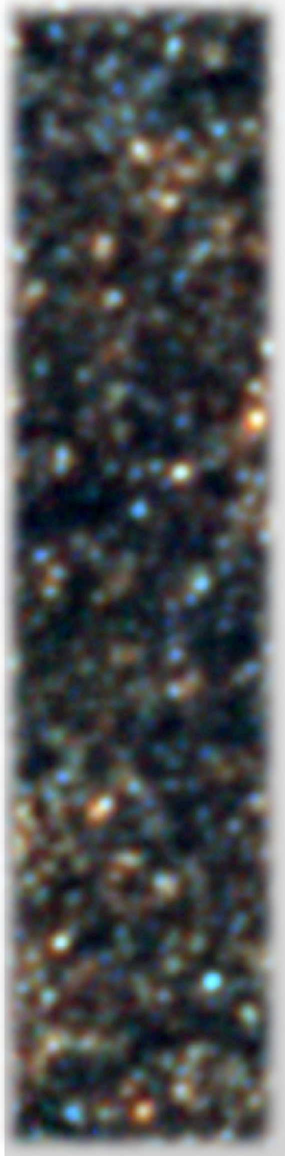
Papovich et al. (2004)



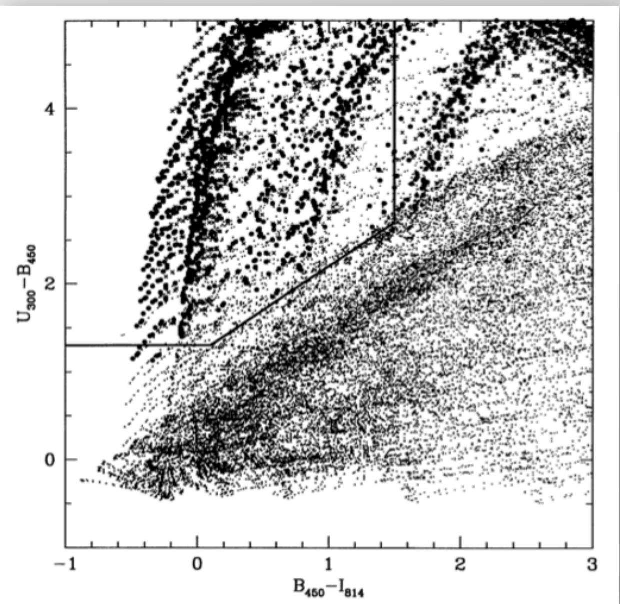


Shapley et al. (2004)

How do we identify LBGs ?

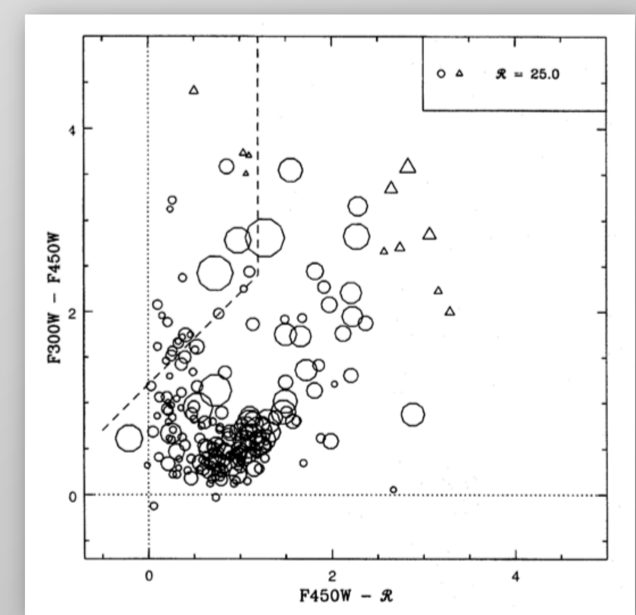


- The Lyman Break is an efficient color-color selection to identify high-z galaxies
- Steidel et al. (1996) state that about > 70% of robust candidates are confirmed high-z galaxies at z ~ 3



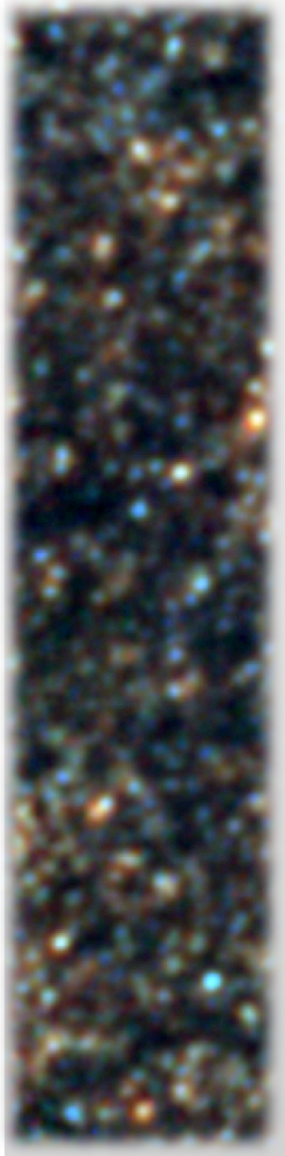
Madau et al. 1996

2 < z < 3.5, A_B < 1 & age < 100Myr



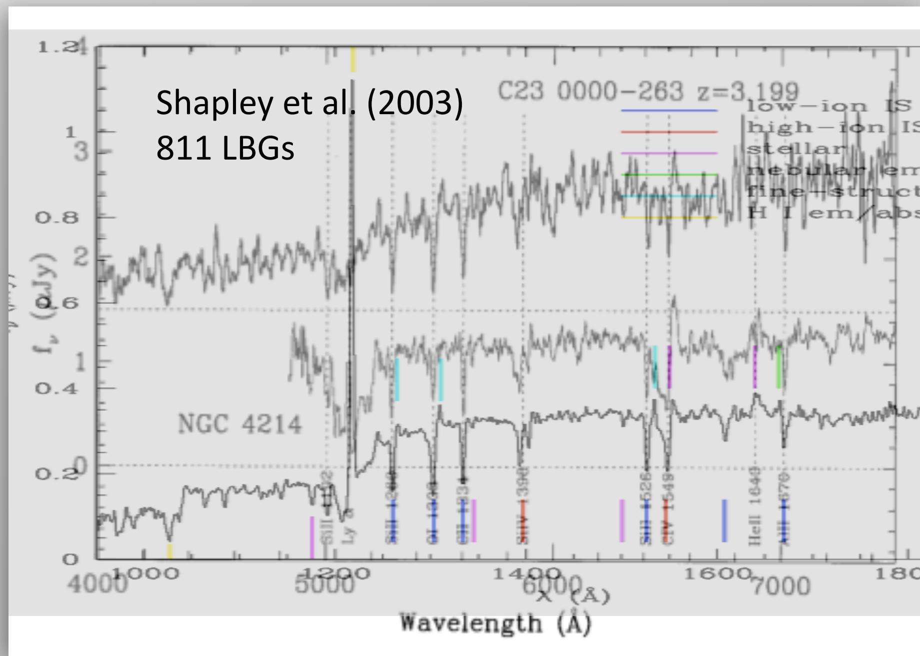
Steidel et al. 1996

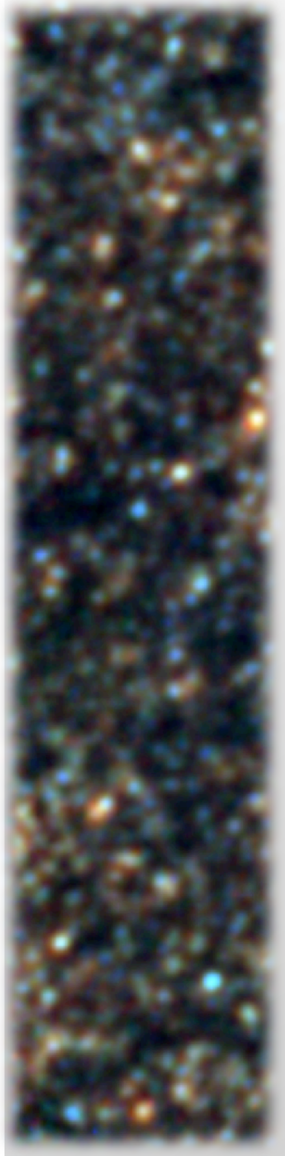
Nature of Lyman Break Galaxies ?



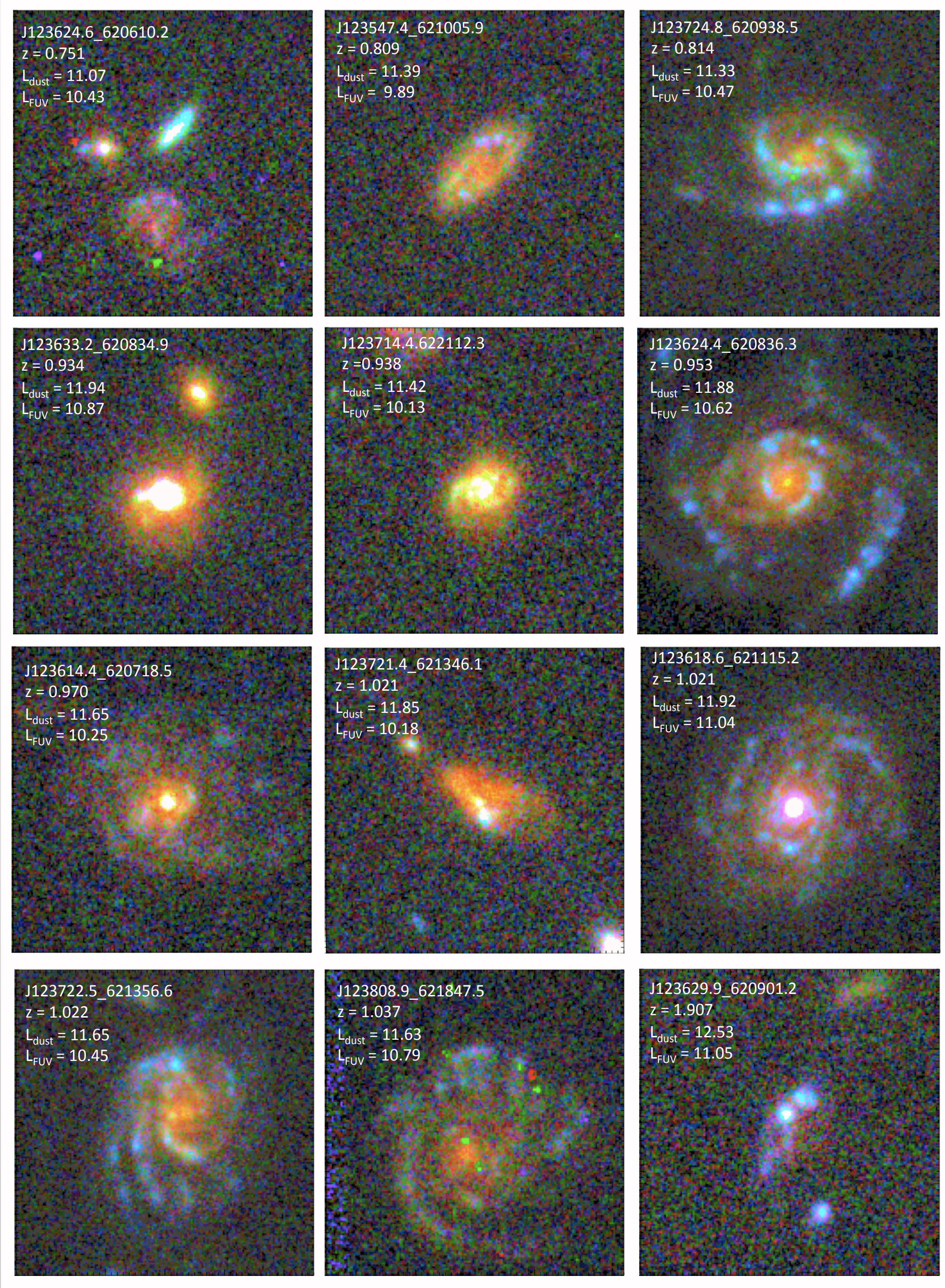
e.g. Shapley et al. (2003) :

- Lyman Break Galaxies are star-forming galaxies with spectra very similar to local starbursts
- FUV Spectra consistent with unreddened models of young star-forming galaxies with E(B-V)<0.3
- SFR_{UV} ~ 10 – 100 Mo/yr
- Flat continuum

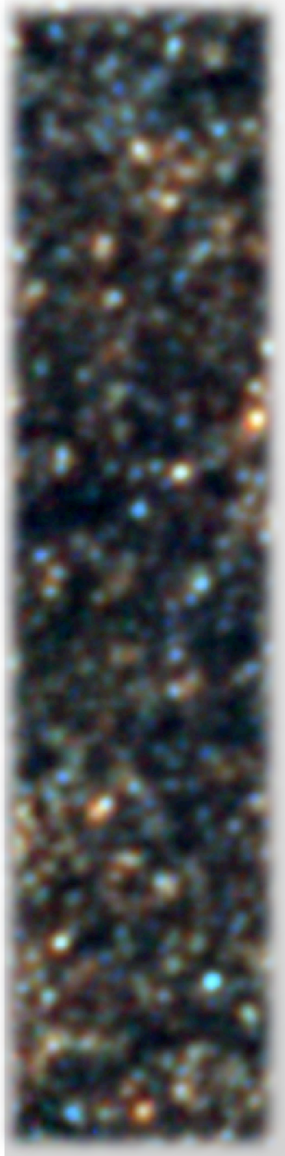


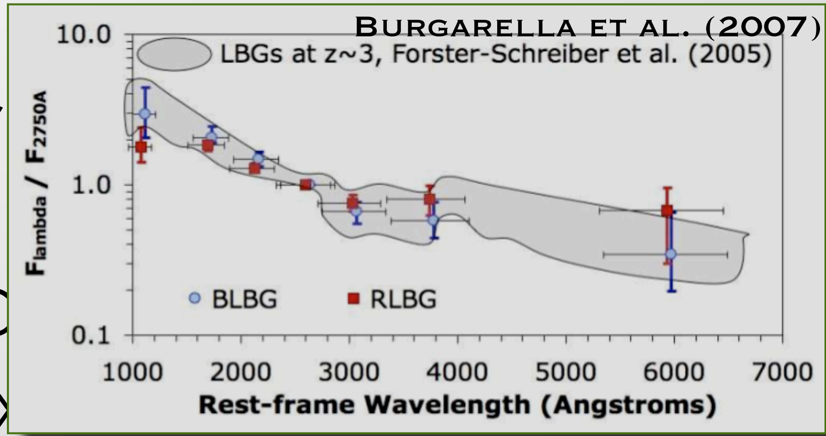


What do they look like at z ~ 1?

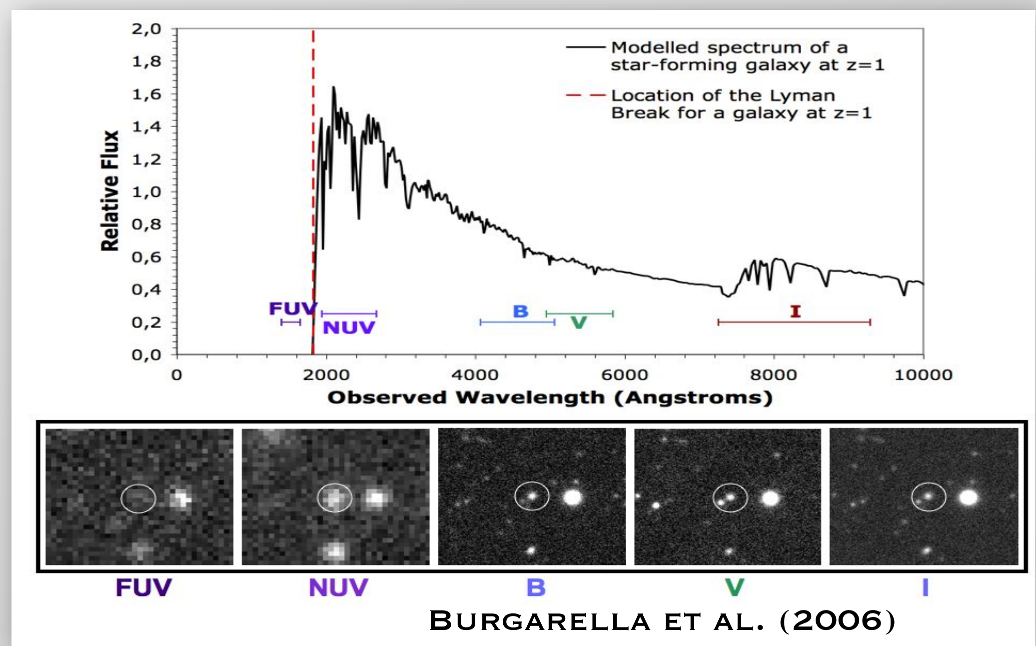


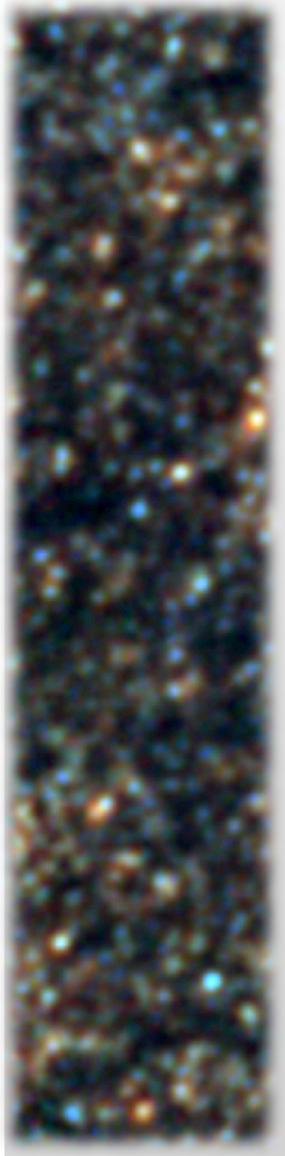
GALEX/Spitzer





- Redshifts from COMBO
- 420 Lyman Break Galax
- ~ 15% are detected at 24 um (Spitzer)
- ~ 85% are undetected at 24 um (Spitzer)

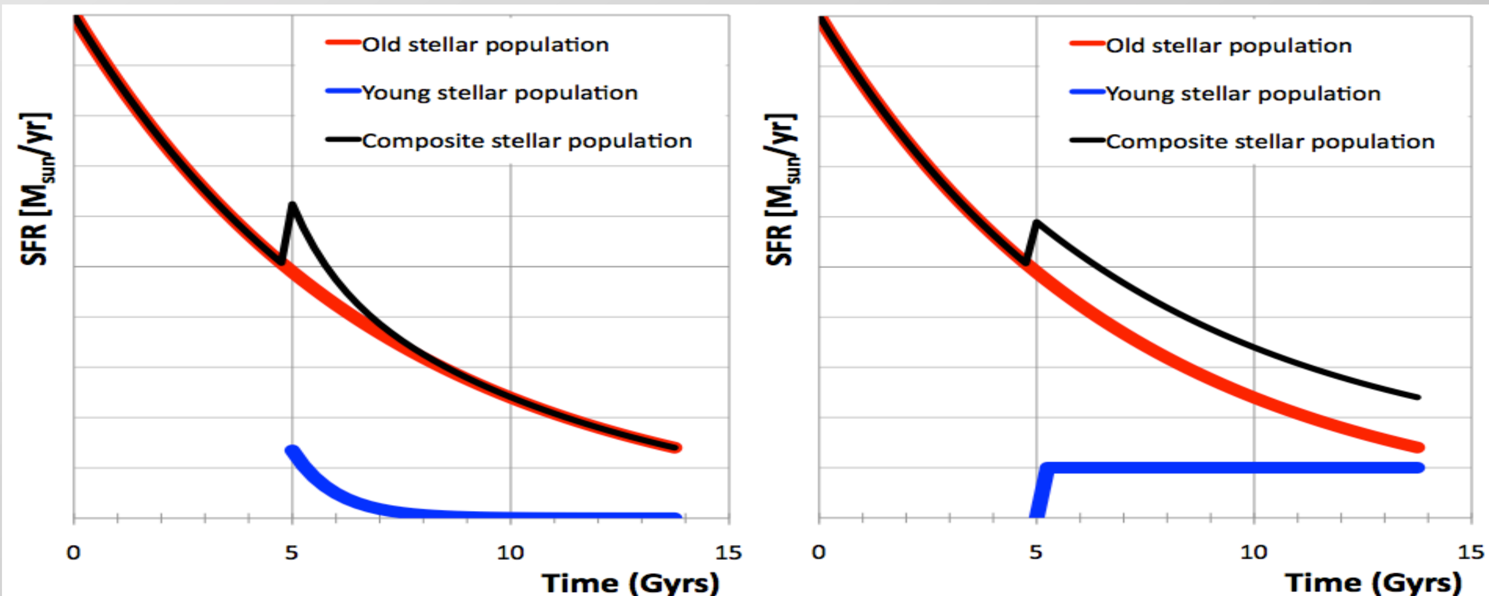




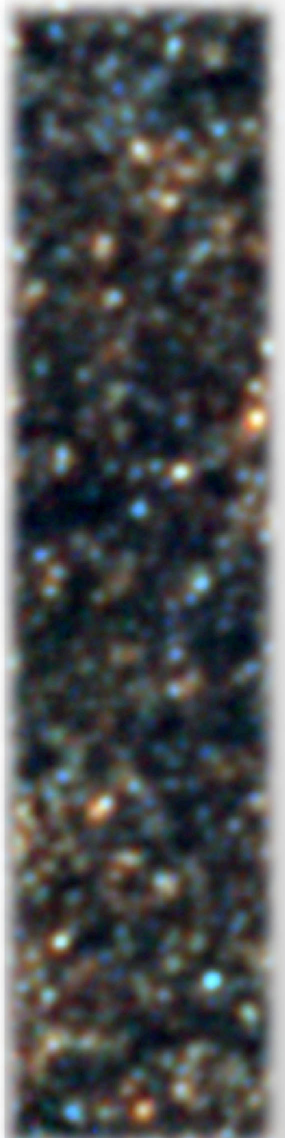
SED Fitting with CIGALE

http://www.oamp.fr/cigale

- Code Investigating GALaxy Emission (Burgarella et al. 2005, CIGALE, Noll et al. 2009)
- Several SSPs (PEGASE II and Maraston ('05)
- Several dust emission models & templates (Dale & Helou, Siebenmorgen & Krügel, Chary & Elbaz)
- Construction of the SFH with two different complex stellar population models and different amounts of attenuation
- Varius dust attenuation law (different from Calzetti's)

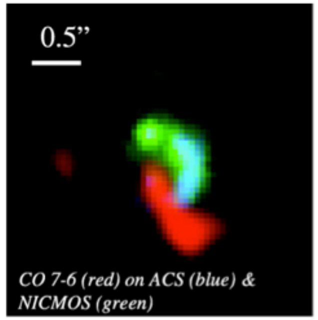


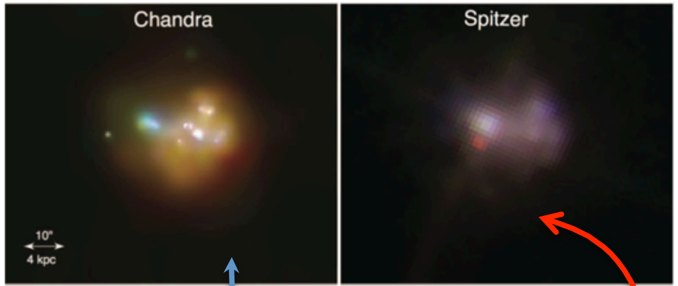
Another less local analog at z ~2.4



N2850.4 at z = 2.39 from Tacconi et al. (2008)

- *CO(7-6) emission in red,*
- *ACS image in blue,*
- *NICMOS image in green (Swinbank et al. 2005).*

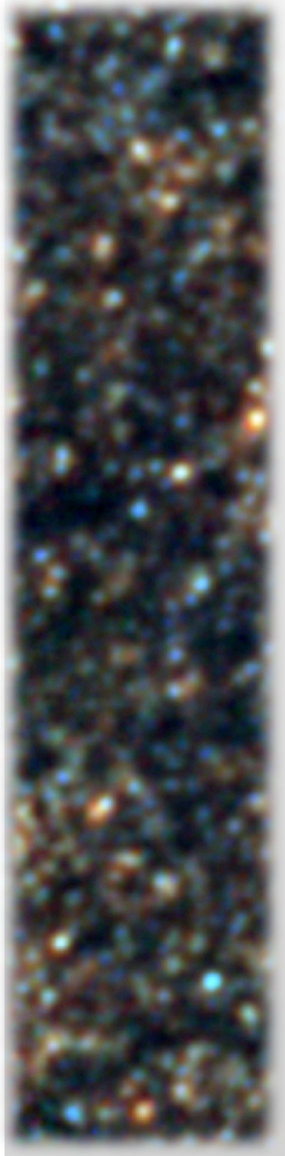




The FUV and FIR components are only distinguishable at a scale of ~0.5 arcsec

- ➢ *one of the two components of the LBG analog is bright in the X-ray and FUV (left)*
- ➢ *one is bright in the mid- and Far IR (right)*

A local LBG analog: VV114



- One of these analogs to LBGs is the starburst galaxy VV114 (Grimes et al. 2006).
- In the FUV, VV114 appears as a local galaxy merger with strong similarities to typical LBGs.
- Observations support a model where a violent central inflow of gas triggers an intense starburst activity which possibly boosts the IR luminosity (Iono et al. 2004; Le Floc'h et al. 2002).

VV114: STIS-FUV and ISO-15um

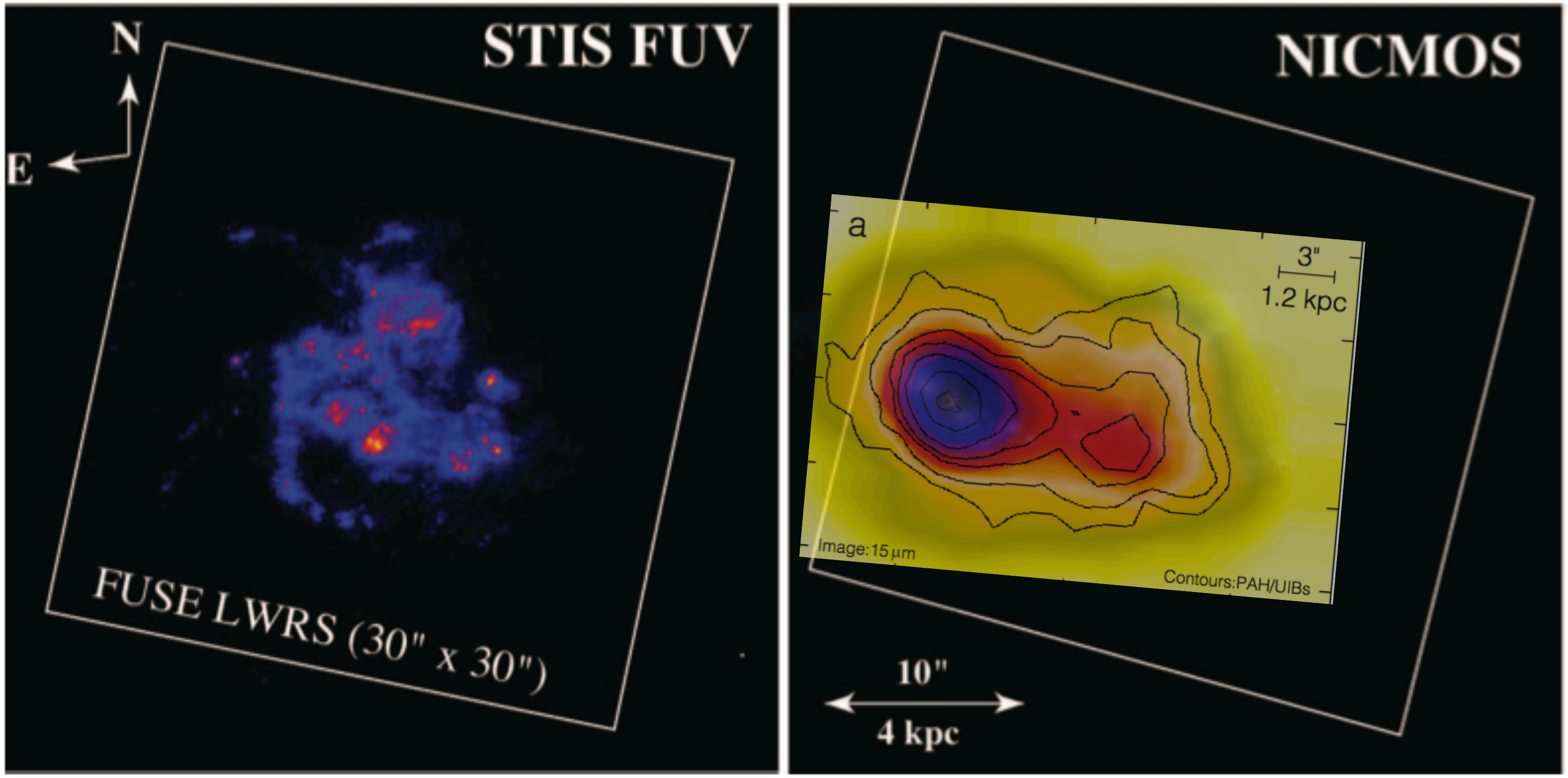
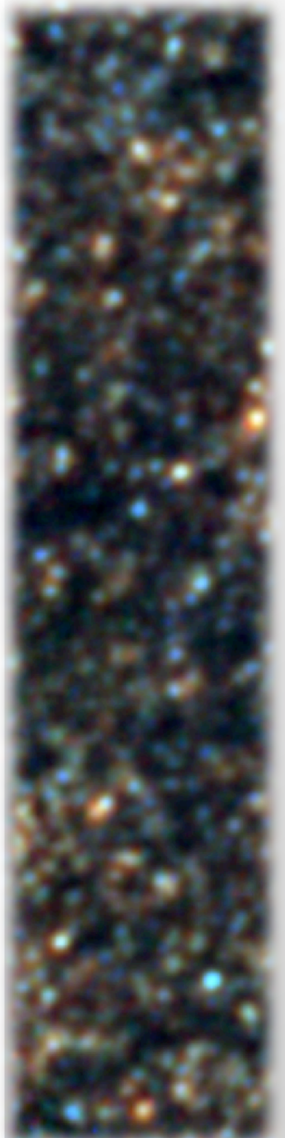


FIG. 1.—*FUSE* LWRS aperture overlaid on a *HST* STIS FUV and NICMOS false-color image. Only the western component is visible in the FUV image. Both images are from Goldader et al. (2002) and use a logarithmic scale map. The NICMOS false-color image is an overlay of the F110W (1.025 μm), F160W (1.55 μm), and F222M (2.3 μm) images as blue, green, and red, respectively.

Visible and NIR starlight …
only $^1/_2$ the radiation from a typical galaxy



- ✦ Dust and gas absorbs and re-emits $^1/_2$ the starlight in the IR as thermal continuum radiation and fine structure lines.
- ✦ The other $^1/_2$ is found in the optical and NIR (@ z=0).