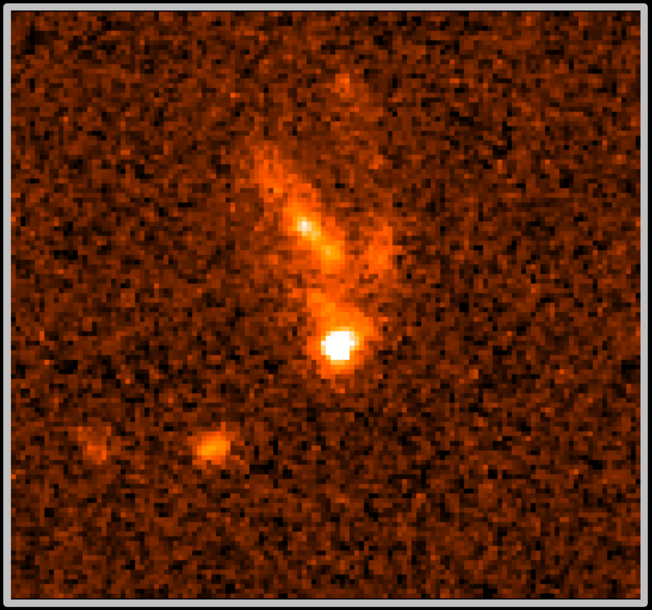
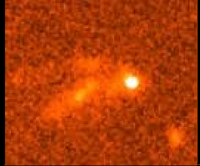
Gamma-Ray Bursts as Tracers of High-Redshift Star Formation: *Promises and Perils*

Daniel Perley
(Caltech)

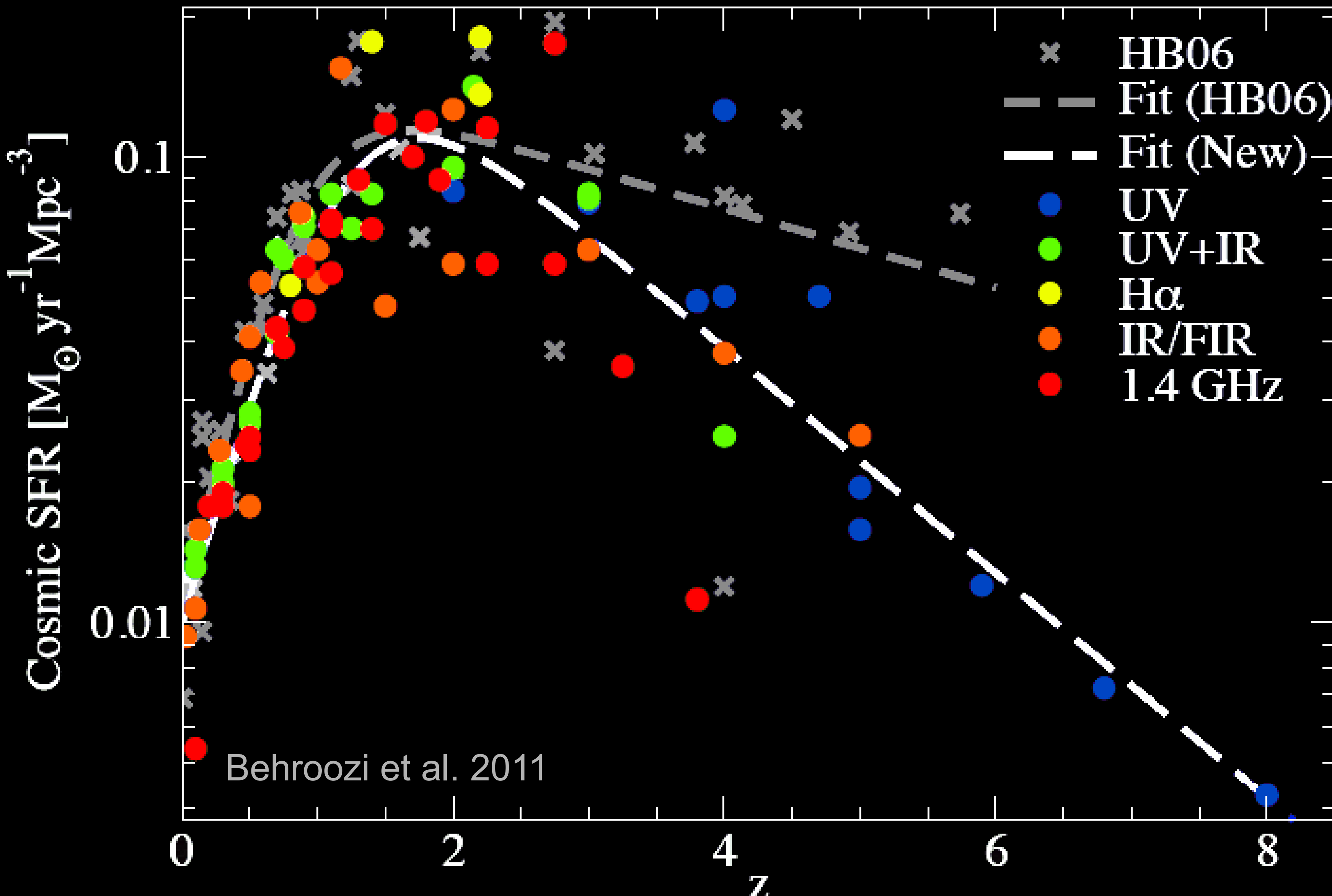
Collaborators: Nial Tanvir, Andrew Levan, Brad Cenko, Jens Hjorth, Daniele Malesani, Steve Schulze, Thomas Kruehler, Andy Fruchter



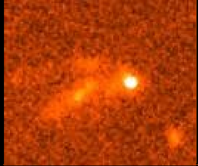
Animation of GRB990123 superimposed on its (very luminous) host galaxy
Courtesy A. Fruchter, STSCI

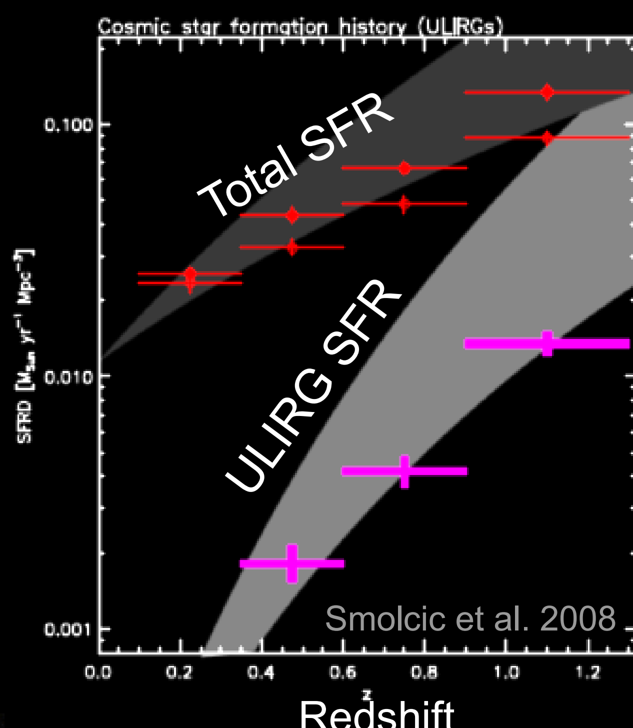


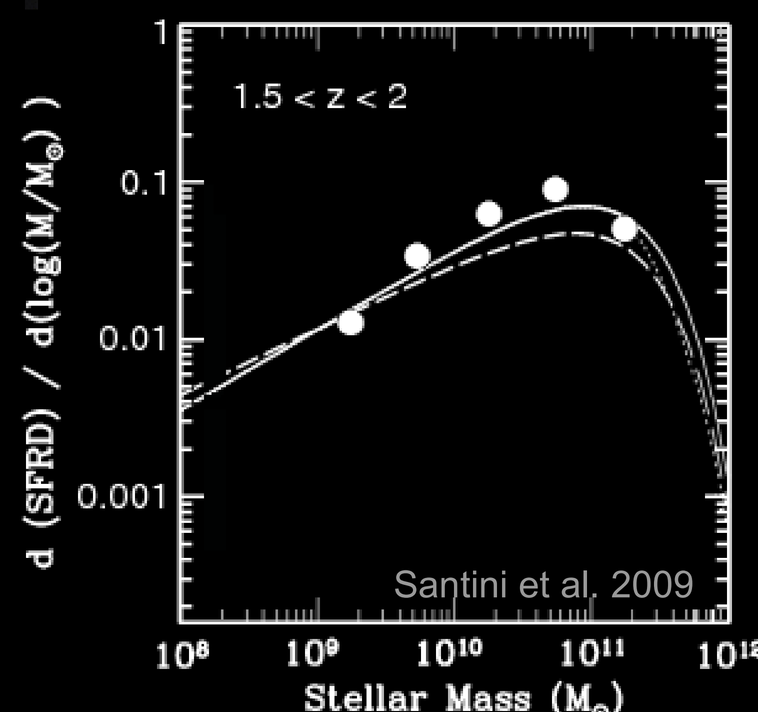
Cosmic Star-Formation History

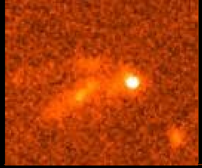


Cosmic Star-Formation Sites



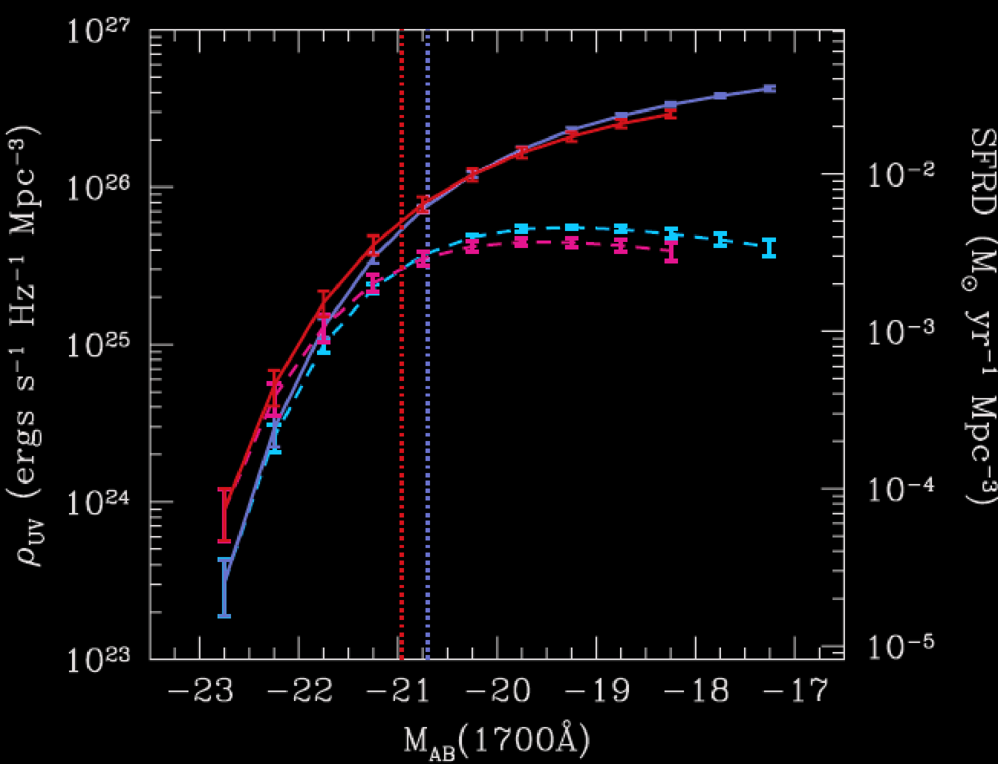


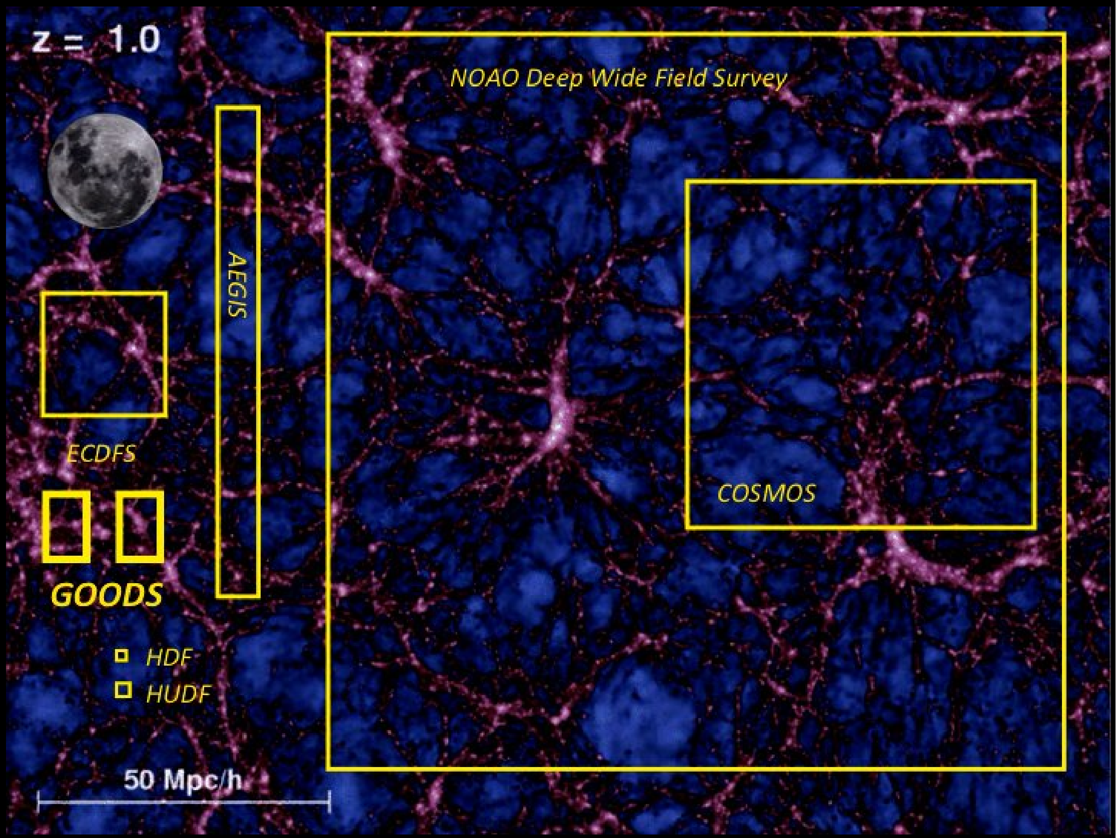




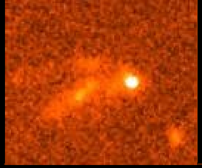
Field Surveys and SFR

Usual strategy: add up the **UV emission** from all galaxies combined and convert to a star-formation rate.





from CANDELS blog



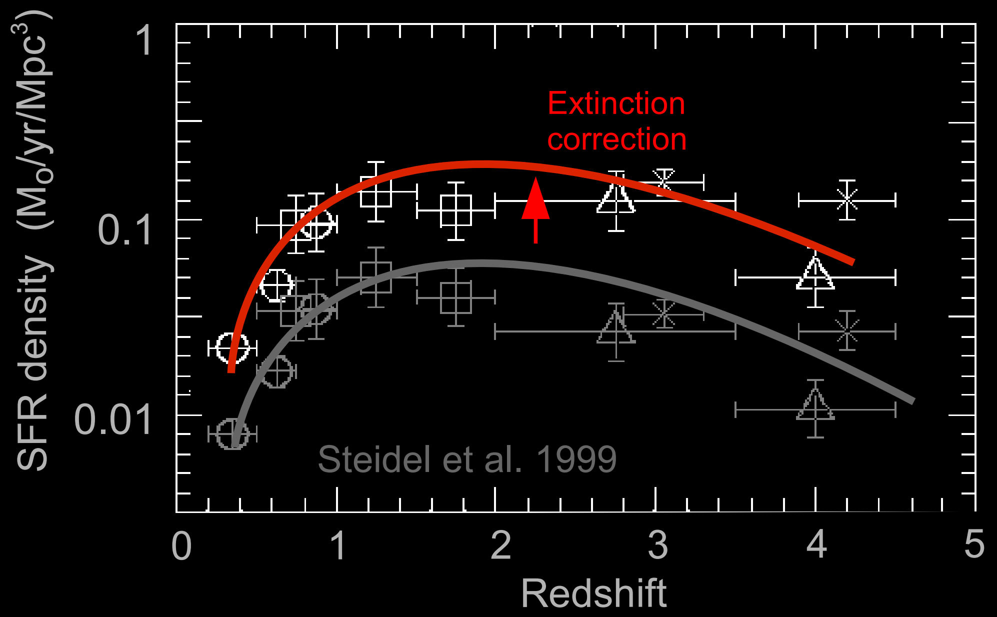
Limitations of Field Surveys

Dust Correction

~80% of UV light is absorbed by dust at z~2

UV dust corrections are empirical (is Calzetti prescription universal? It fails for ULIRGs.)

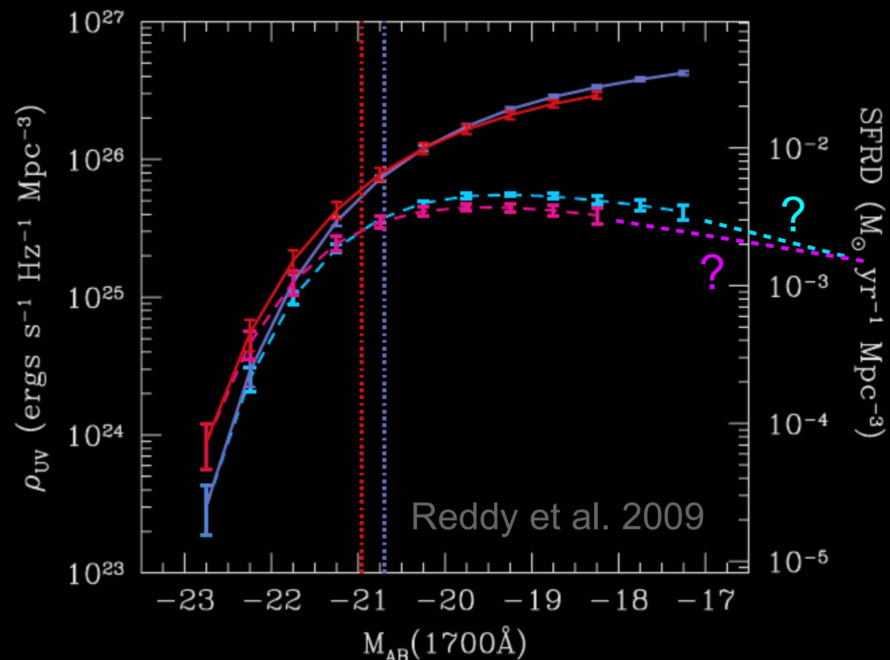
UV energy can be "recovered" at 8μm / FIR / submm, but these wavelengths have poor sensitivity to faint galaxies



Missing galaxies

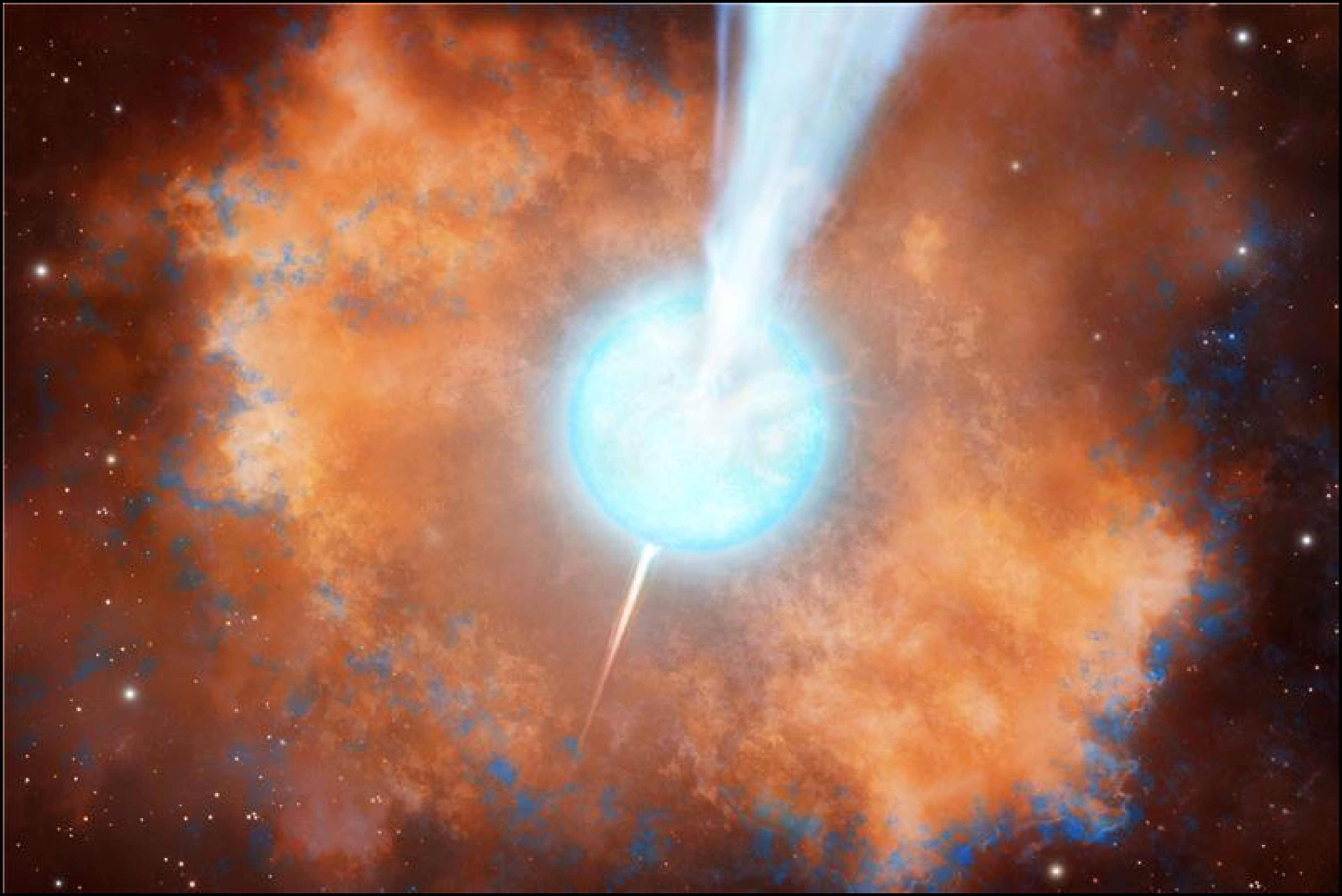
Faint galaxies (<0.1 L*) require extrapolation from bright end

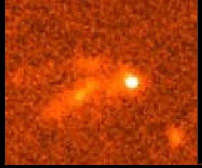
Redshift measurement imposes further biases



These problems are particularly limiting at z>3

(Long) GRBs: Massive Stellar Core-Collapse





Advantages of GRB Selection

Inexpensive

Optical afterglow redshifts are cheap
(Host follow-up not as cheap, but still doable.)

Dust-Unbiased, in principle

Gamma-ray burst and X-ray/radio afterglows unimpeded by dust

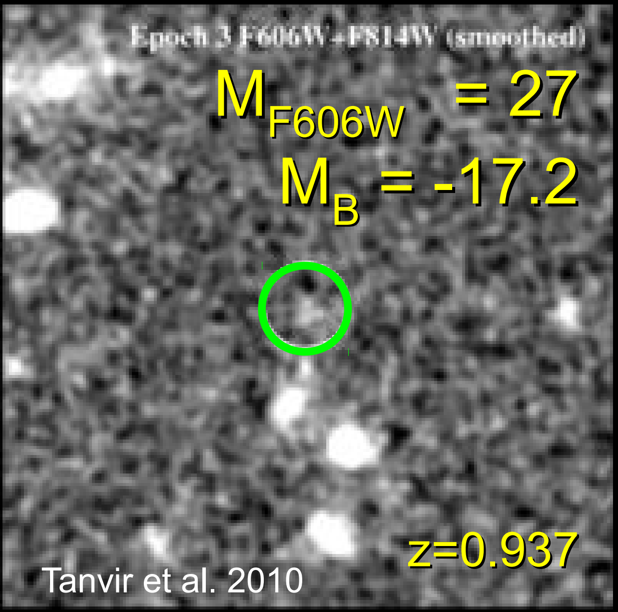
Sensitive to sub-threshold SFR

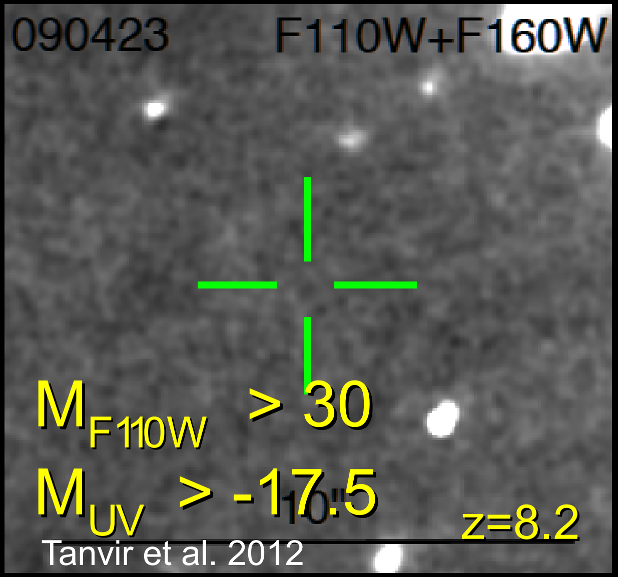
Host nondetections give a direct constraint on importance of undetectable galaxies

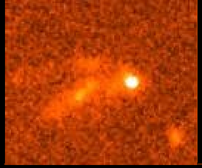
Extendable to **z>8** and potentially higher

No Cosmic Variance

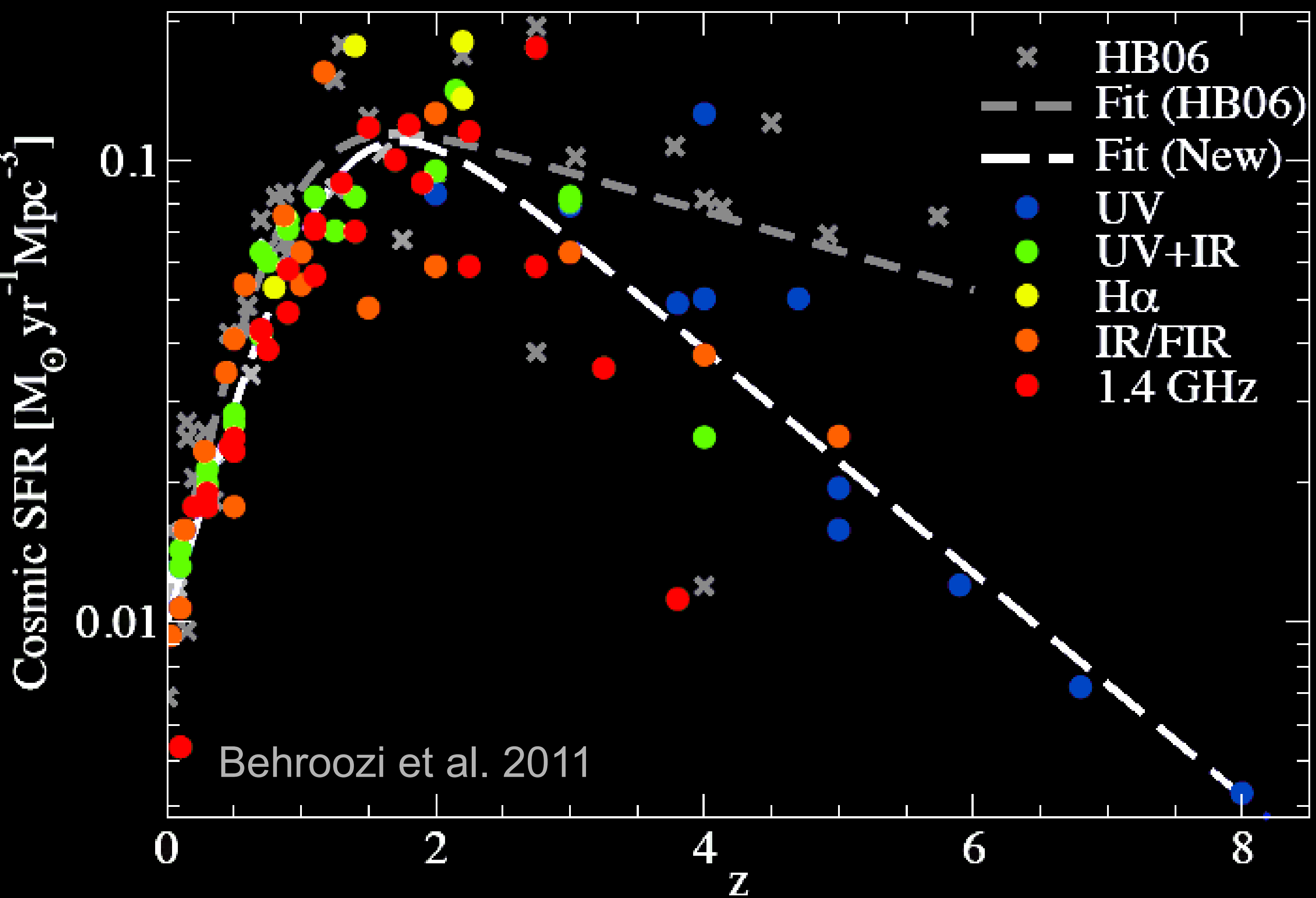
GRB satellites see (close to) the whole sky



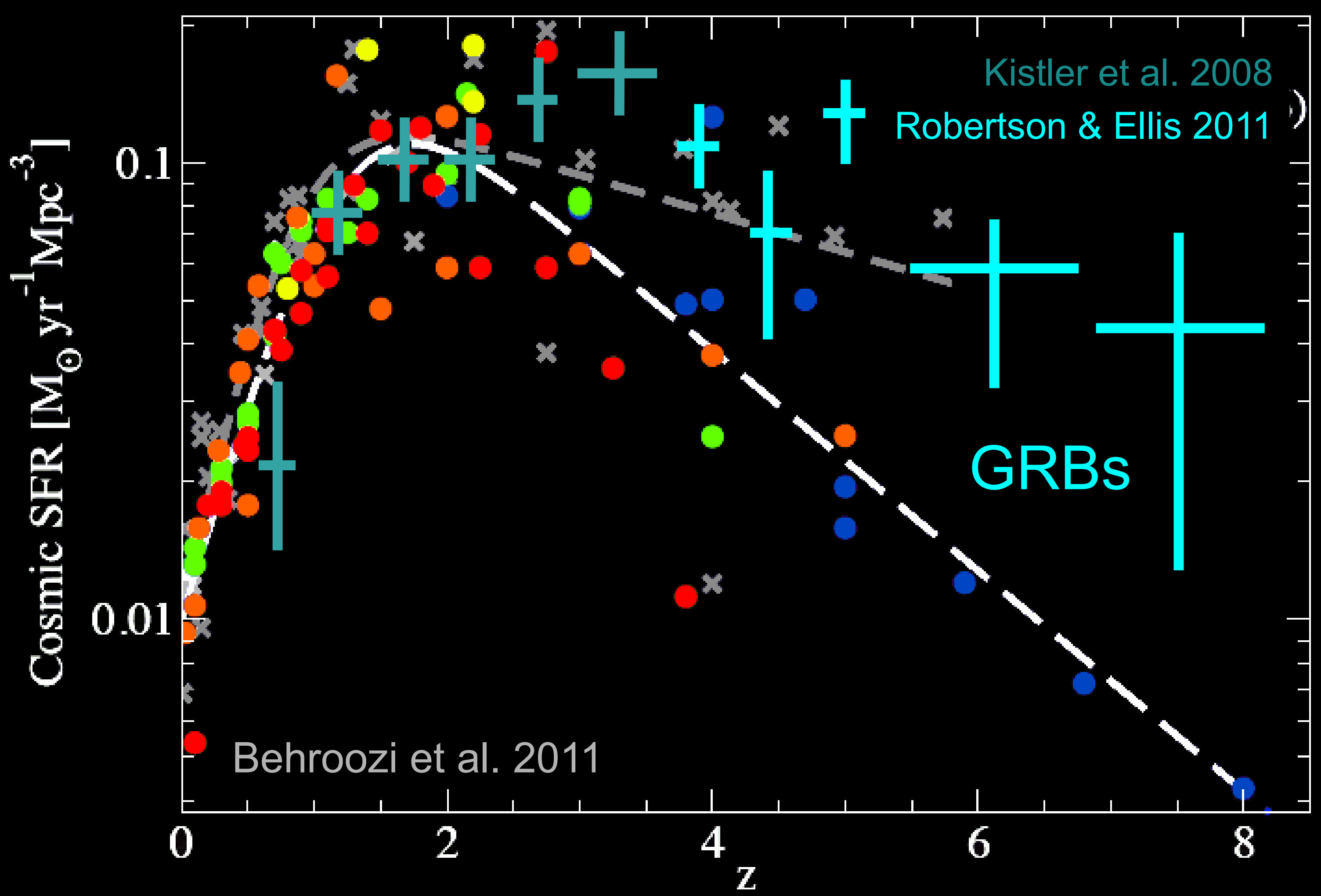




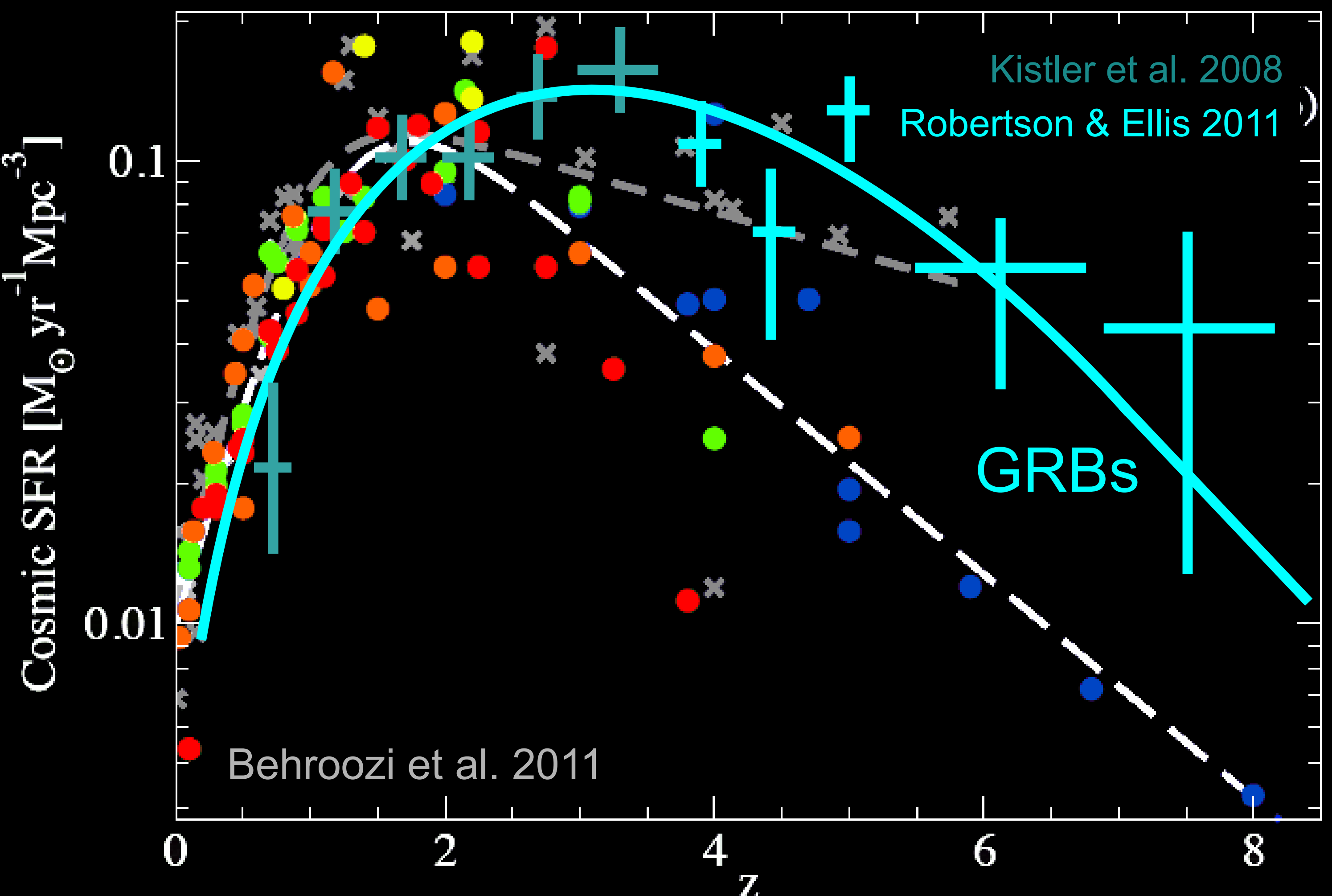
High-z SF History from GRBs



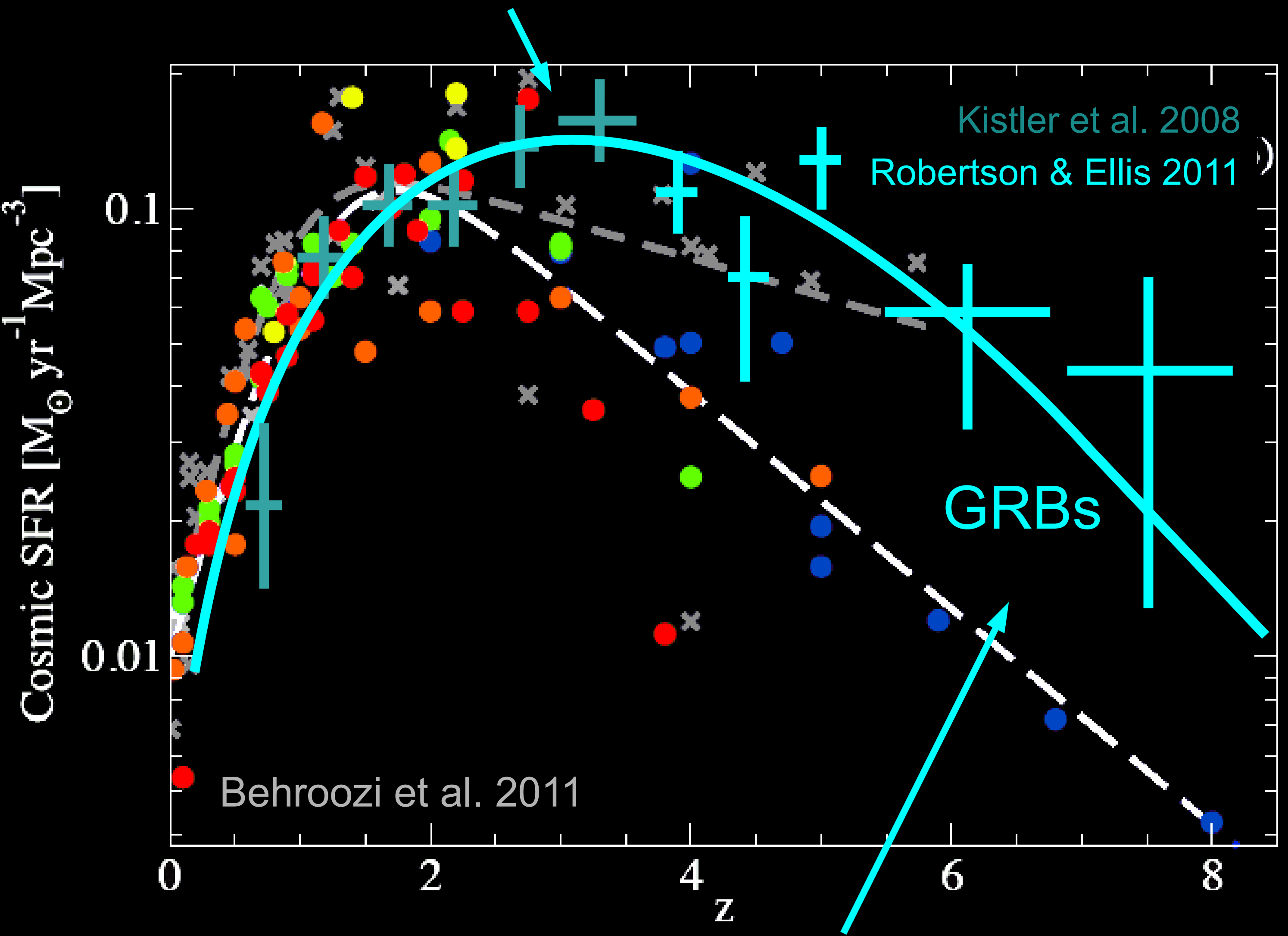
High-z SF History from GRBs

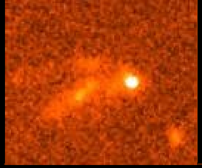


High-z SF History from GRBs



High-z SF History from GRBs

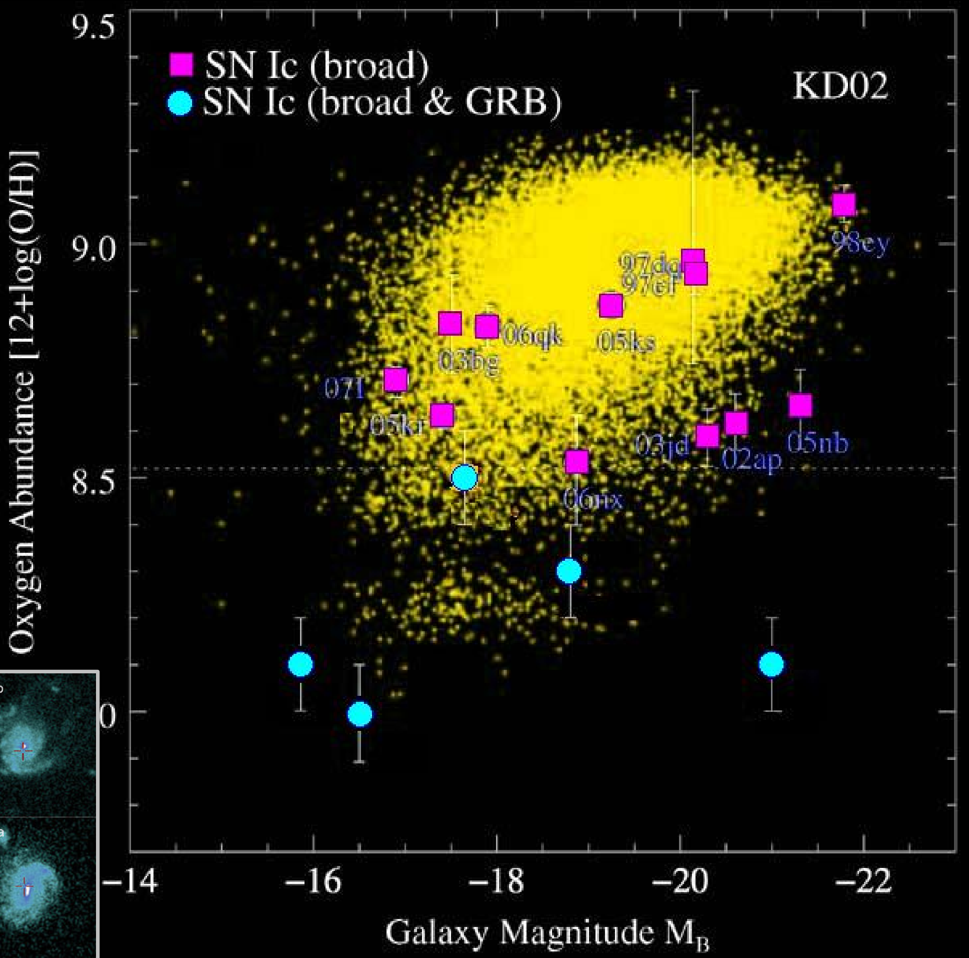




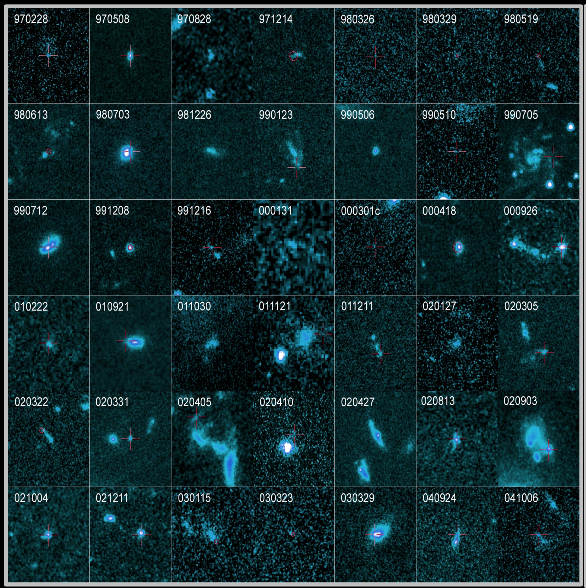
Successful high-z GRB detections imply large z>5 SFRD

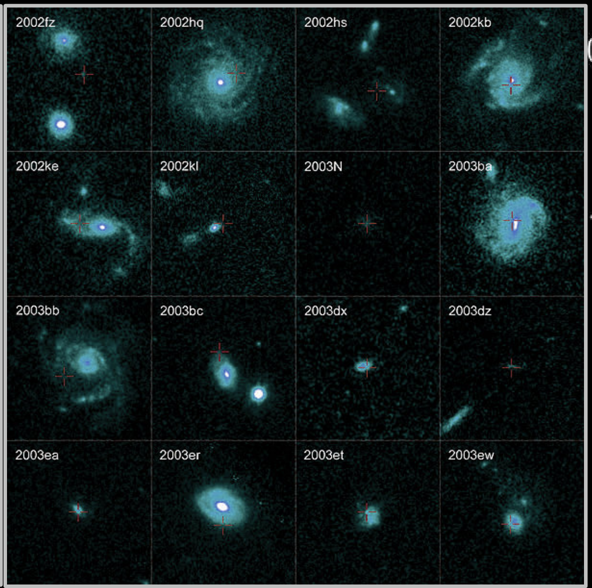
A Biased Tracer?

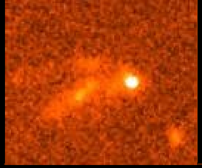
Low-z GRB hosts have lower metalliciticies than Ic supernovae
Modjaz et al. 2008
Graham & Fruchter 2012



Low-z GRB hosts are more irregular than Ib supernova hosts
Fruchter et al. 2006

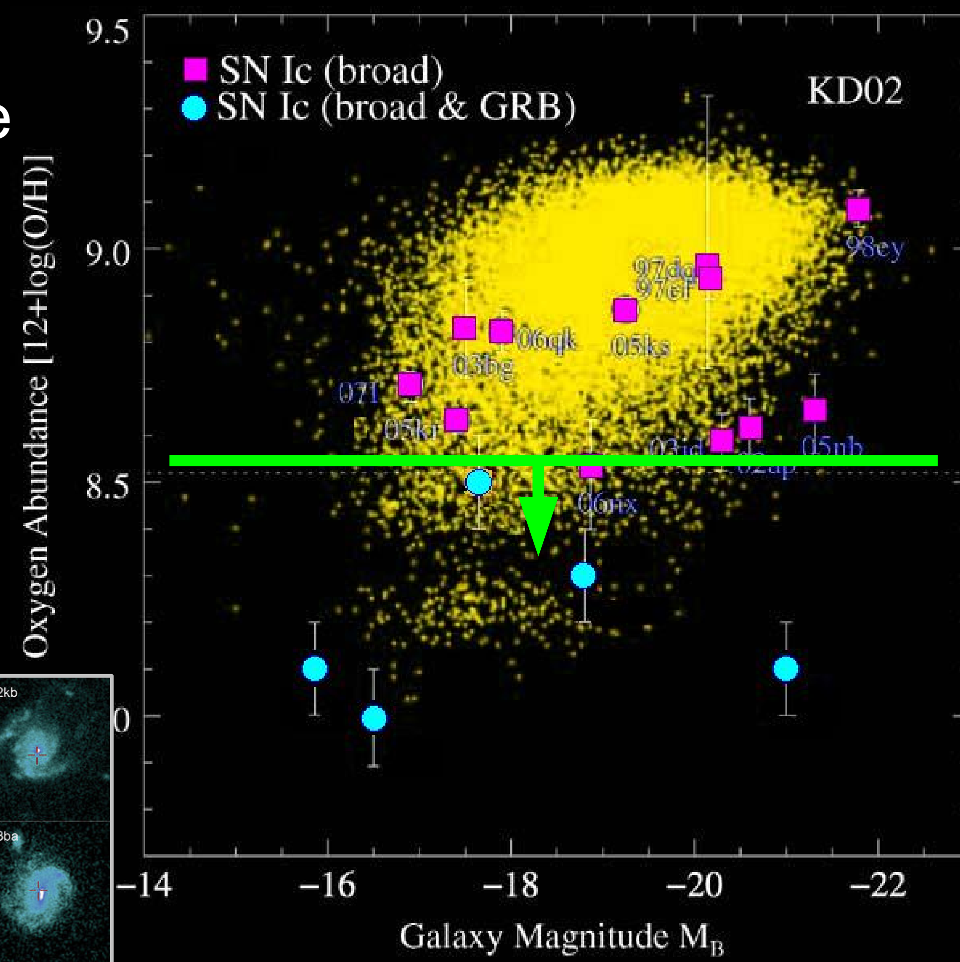




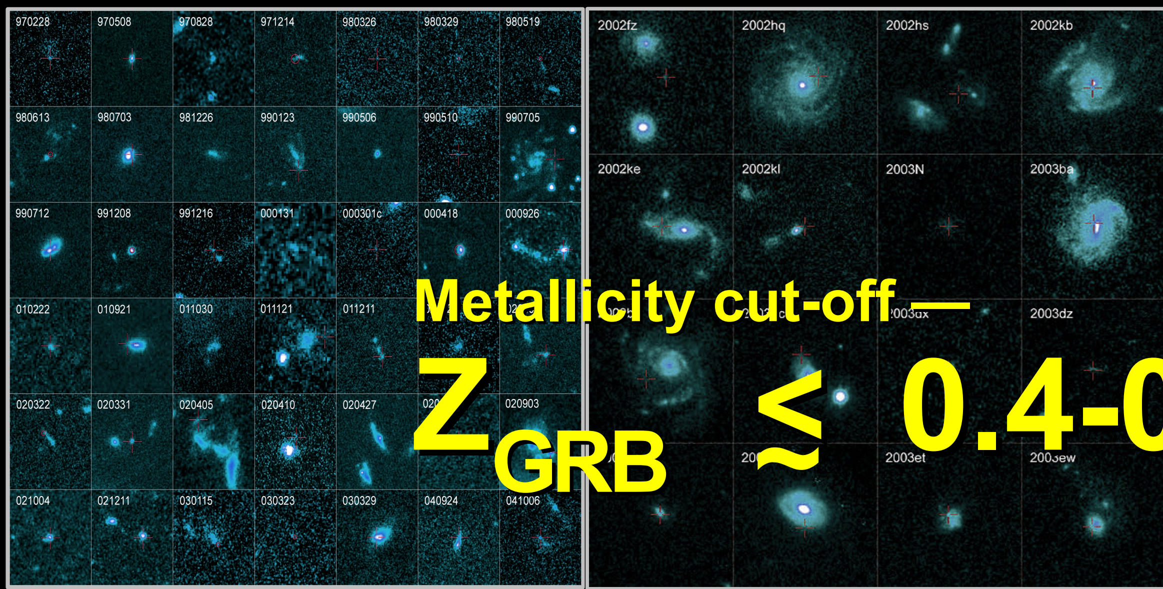


A Biased Tracer?

Low-z GRB hosts have lower metallicitities than Ic supernovae
Modjaz et al. 2008
Graham & Fruchter 2012



Low-z GRB hosts are more irregular than Ib supernova hosts
Fruchter et al. 2006



Metallicity cut-off —

$$Z_{GRB} \lesssim 0.4\text{-}0.9\ Z_{Solar}$$

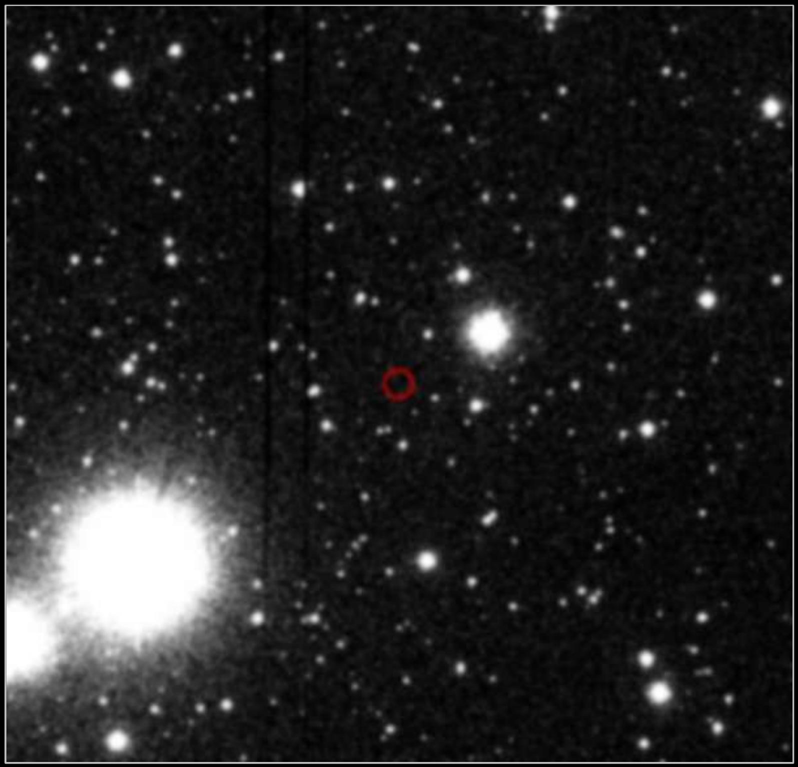
Dark GRBs

~25% of GRBs are **dark**:

e.g,Groot et al. 1998, Djorgovski et al. 2001, Cenko et al. 2009

No optical afterglow,
even with early follow-up.

- Can't identify host without X-ray or radio follow-up.
- Can't measure redshift without large ground-based telescopes.



Palomar 60-inch follow-up of GRB 061222A
~10 minutes after burst

Most are **dust-obscured**

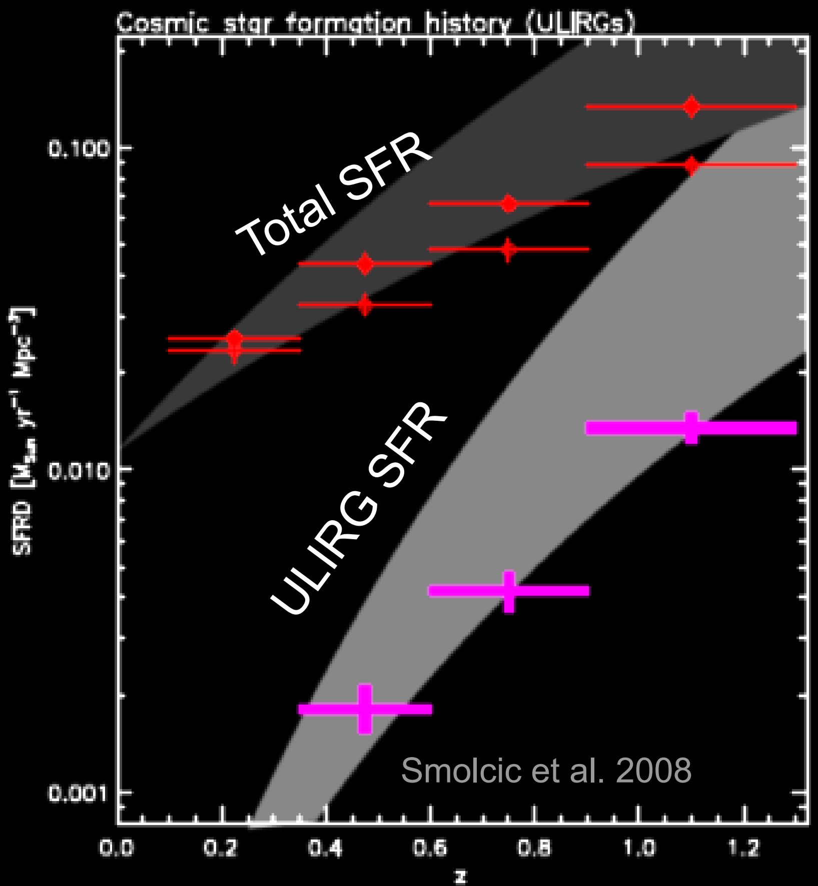
Perley et al. 2009, Greiner et al. 2011

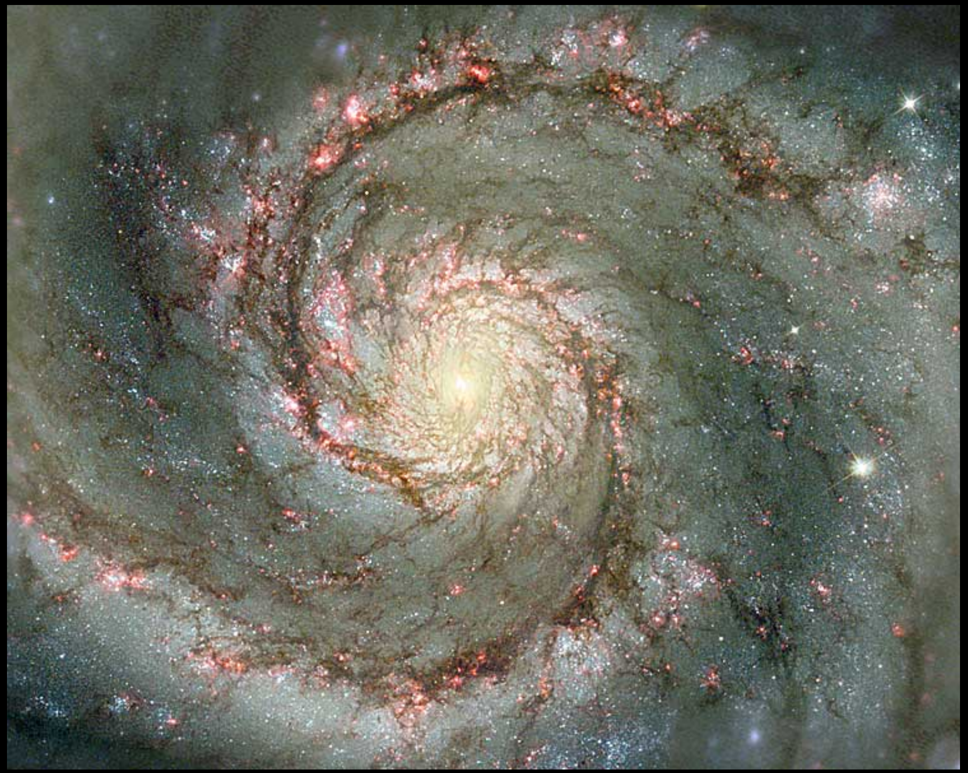
These hosts were *not routinely followed* in previous work: bias?

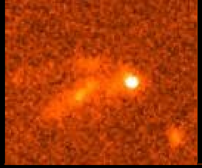
Dust and Star Formation

Dusty galaxies become vastly more prevalent at z>1:
are dark GRBs concealing an entire class of host galaxies?

Or, is this just a product of patchy dust / geometry?

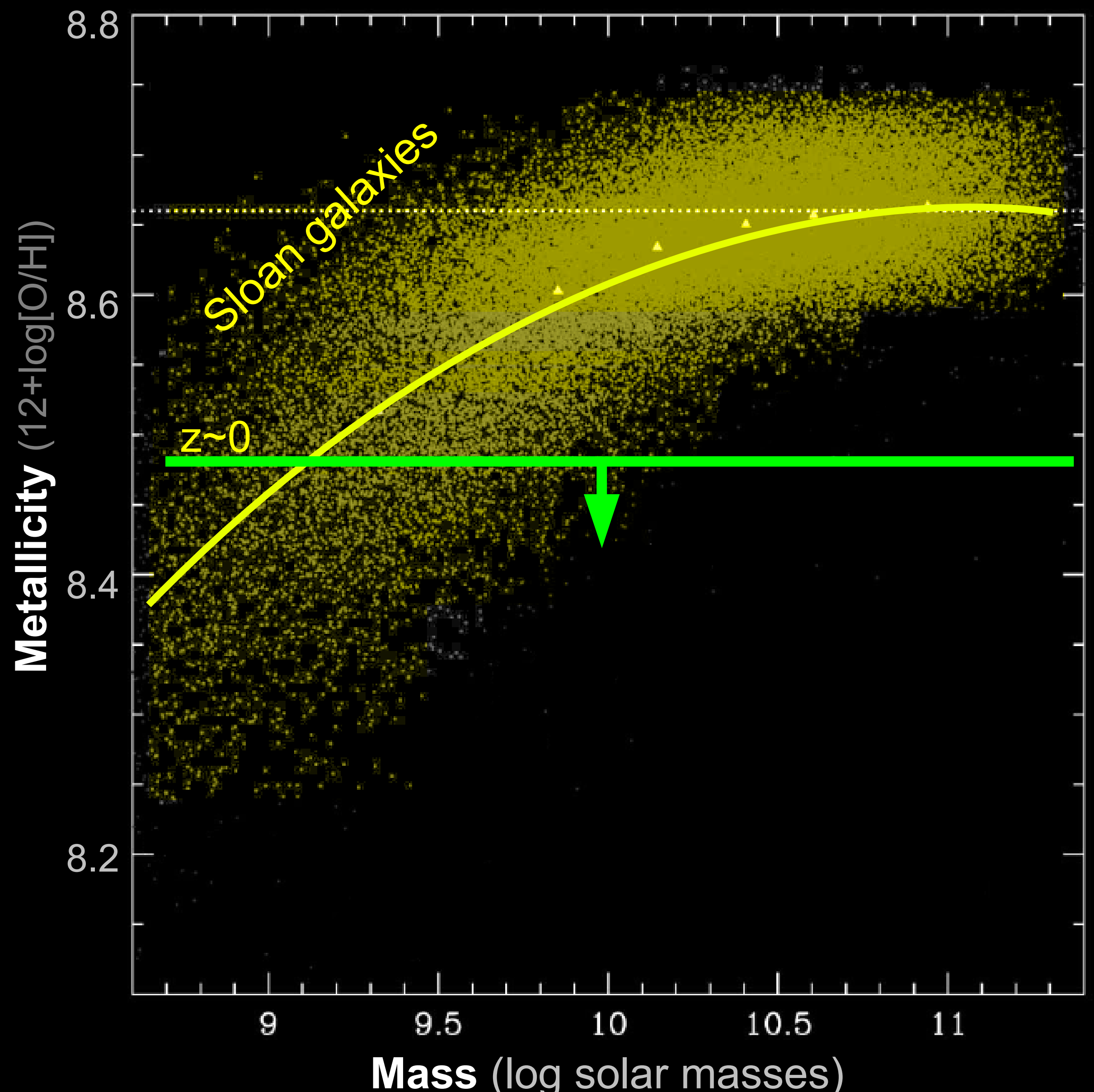






A Biased Tracer?

Only the most metal-poor galaxies today seem to routinely produce GRBs...

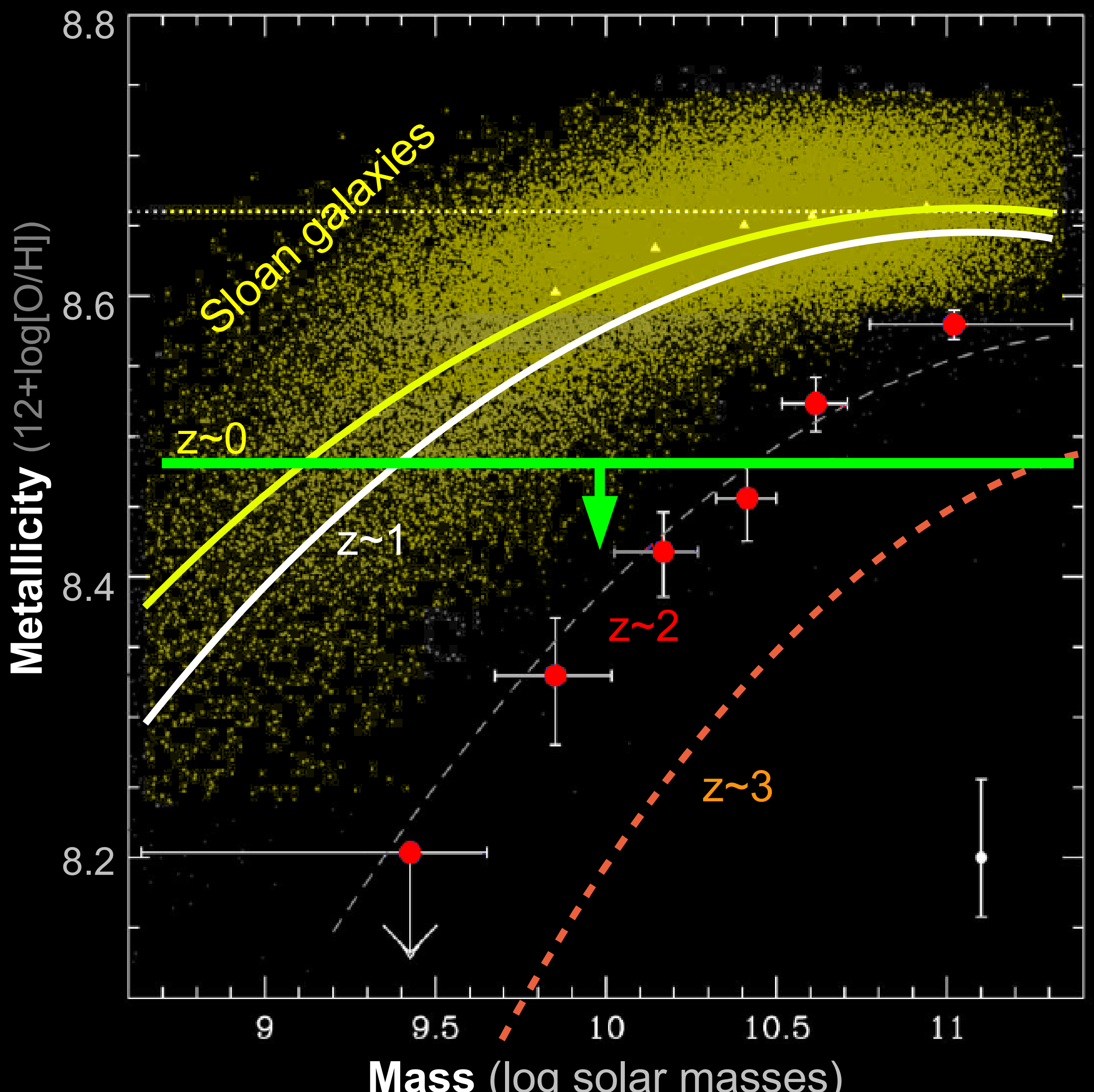


Kewley et al. 2008

A Biased Tracer?

Only the most metal-poor galaxies today seem to routinely produce GRBs...

But *most* galaxies at z>2-3 are similarly metal-poor.



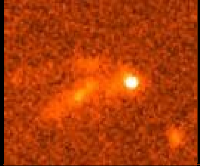
Kewley et al. 2008, Savaglio et al. 2005,, Erb et al. 2006, Maiolino et al. 2008,2009

Questions

- Do dust-obscured hosts differ from ordinary hosts?
- How does this affect the overall population, and the link between GRBs and SFR?
- What does this imply about dust distributions in high-redshift star-forming galaxies?

- Is metallicity actually the sole cause of the low-redshift discrepancies?
- Can we understand its nature and correct for it?

- Do GRB hosts become more like “typical” star-forming galaxies at higher redshift?
- Is there a redshift range where GRBs are unbiased SFR-tracers (*e.g.* high-z, where we need them most?)

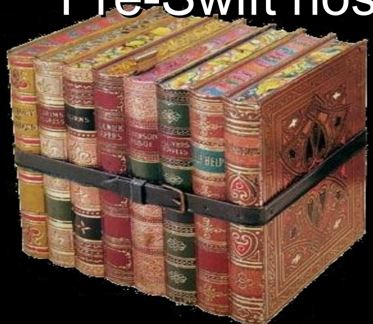


Completing the Host Sample

HST IR Snapshot program
Tibbets-Harlow in prep.

VLT Optically Unbiased Host Project (“TOUGH”), known-z
Hjorth et al. 2012

Pre-Swift hosts from literature
grbhosts.org



+

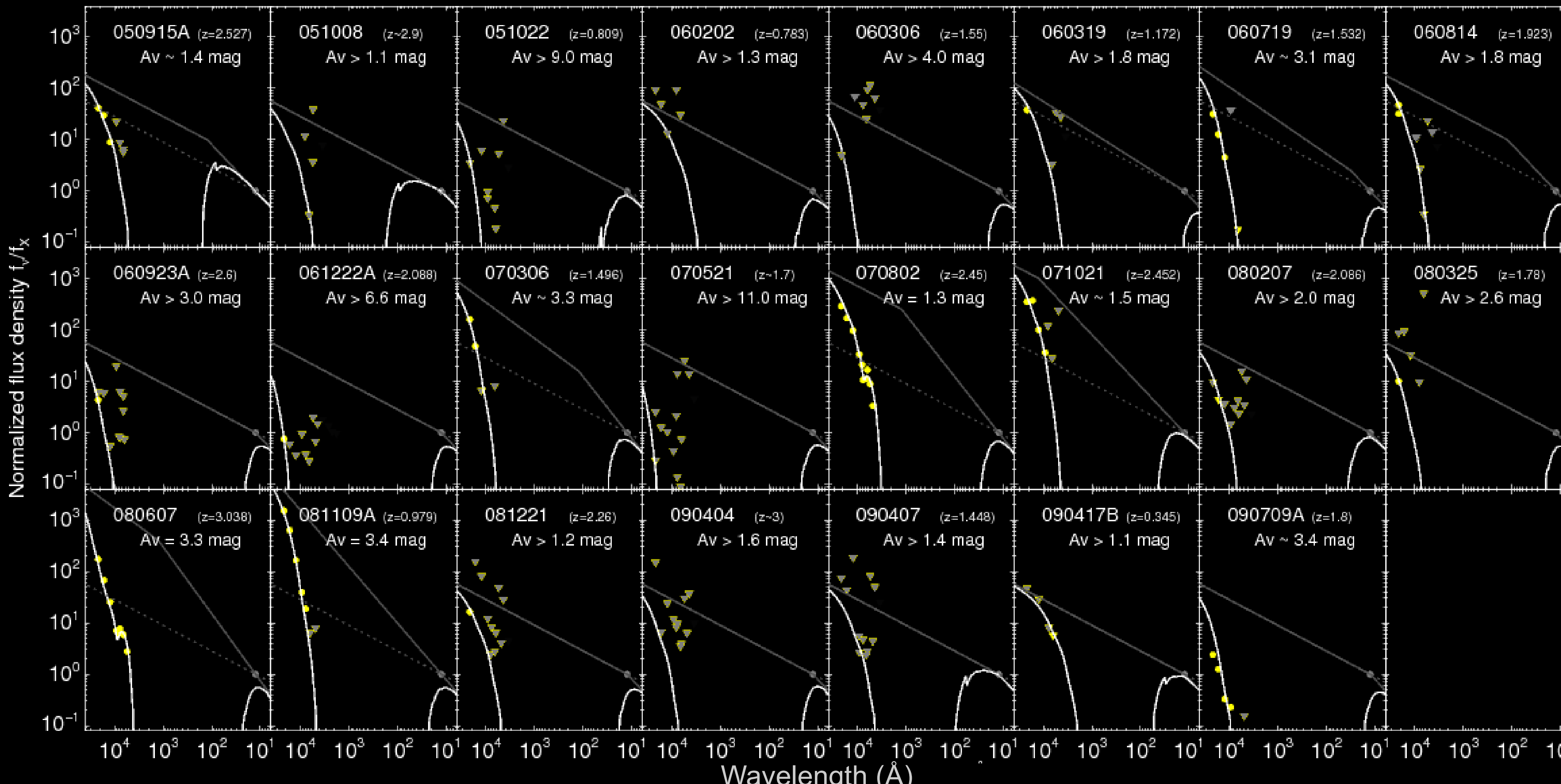
Dust-obscured sample

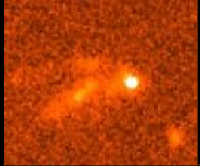
Perley et al. 2013
arXiv/1301.5903

Selecting a Dusty-GRB Host Sample

Selection: *Every* Swift-era burst with clear indication of Av > 1 mag

23 events from 2005-2009 - only 2 with optical afterglow redshift



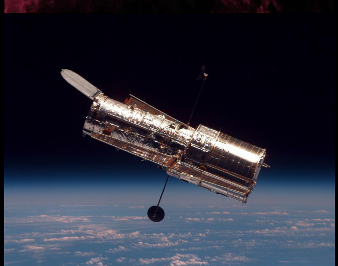


Observing a Dusty-GRB Host Sample

Keck: Optical photometry & UV star-formation rates.
Photometric & spectroscopic redshifts.

Gemini: NIR photometry for photo-z's, stellar masses.

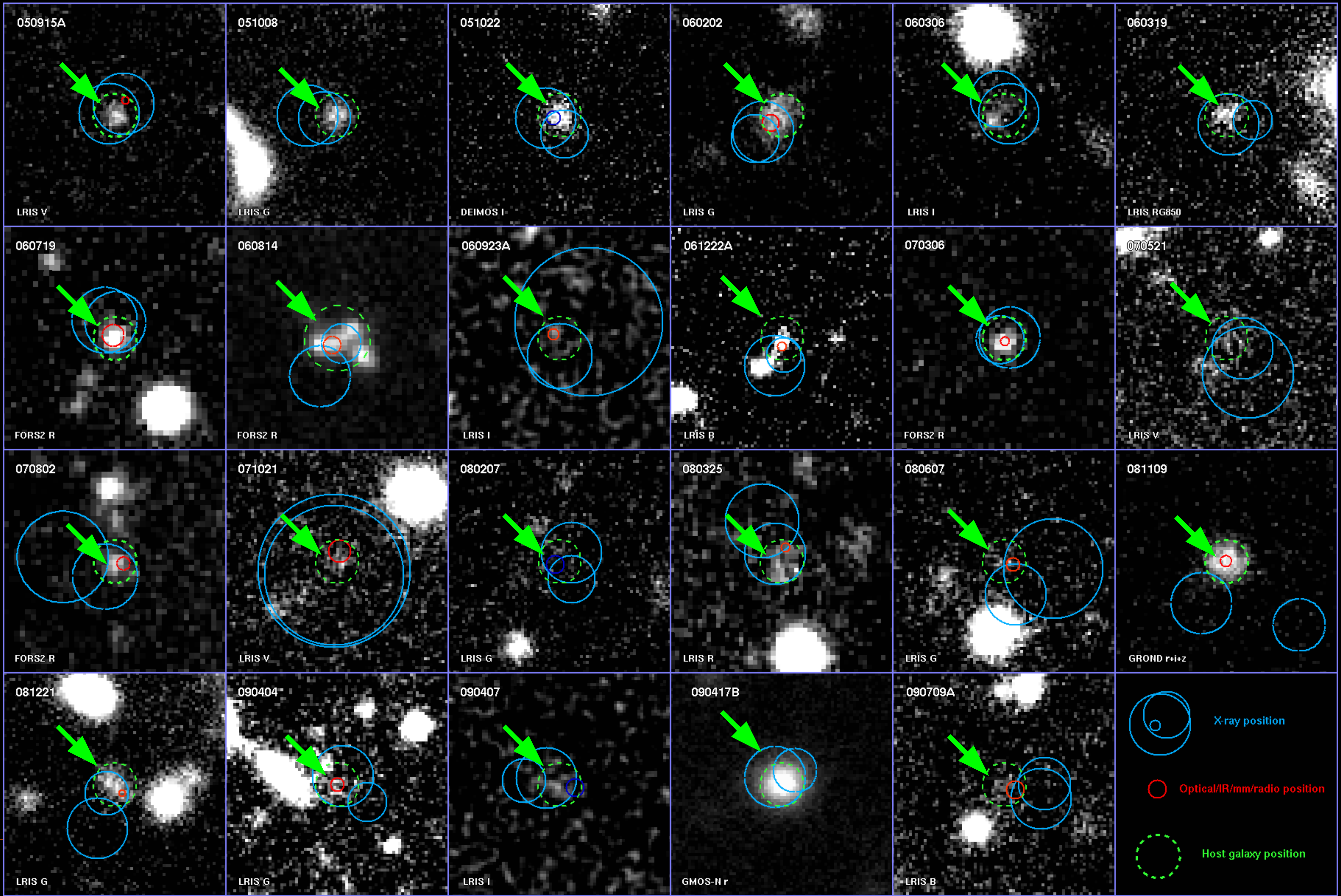
Spitzer: Rest-frame NIR photometry for stellar masses.

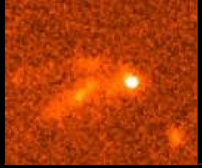


HST: NIR photometry, especially of faint targets.

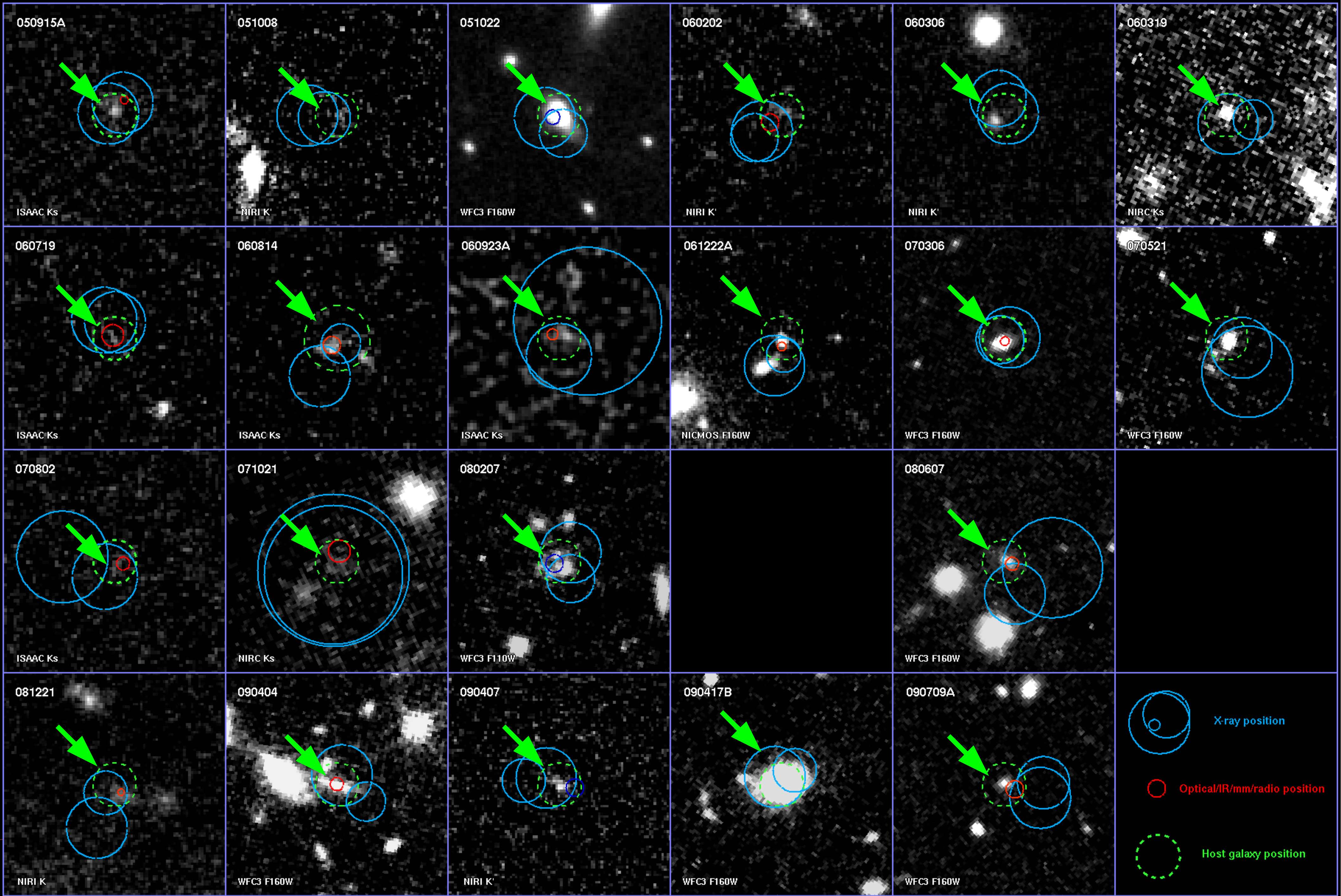
VLT: R- and K-band photometry, spectroscopy for southern sources
(part of TOUGH project, Hjorth et al. 2012)

Optical Host Mosaic

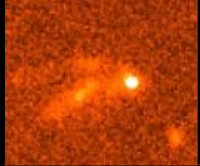


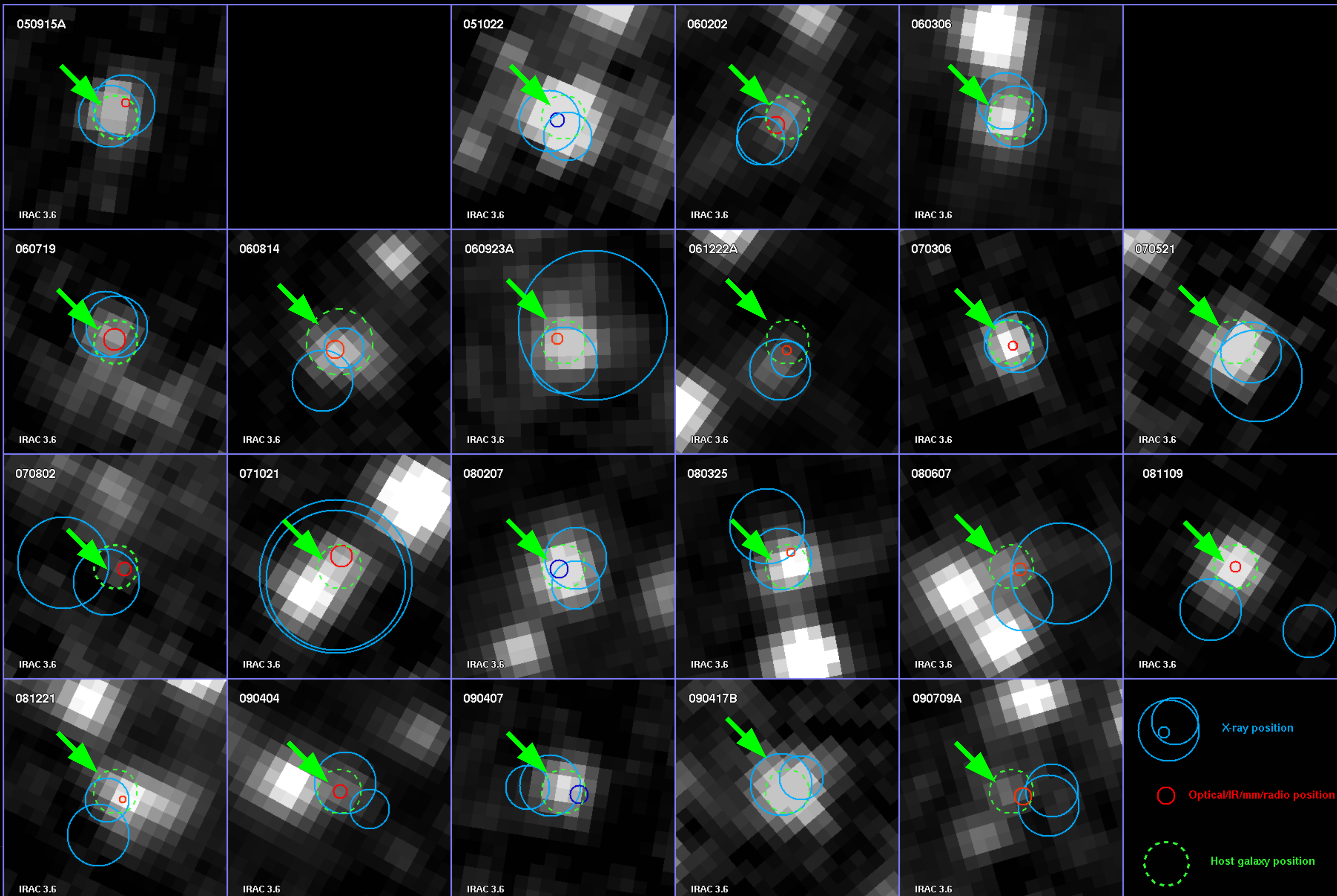


Near-IR Host Mosaic



Spitzer Host Mosaic



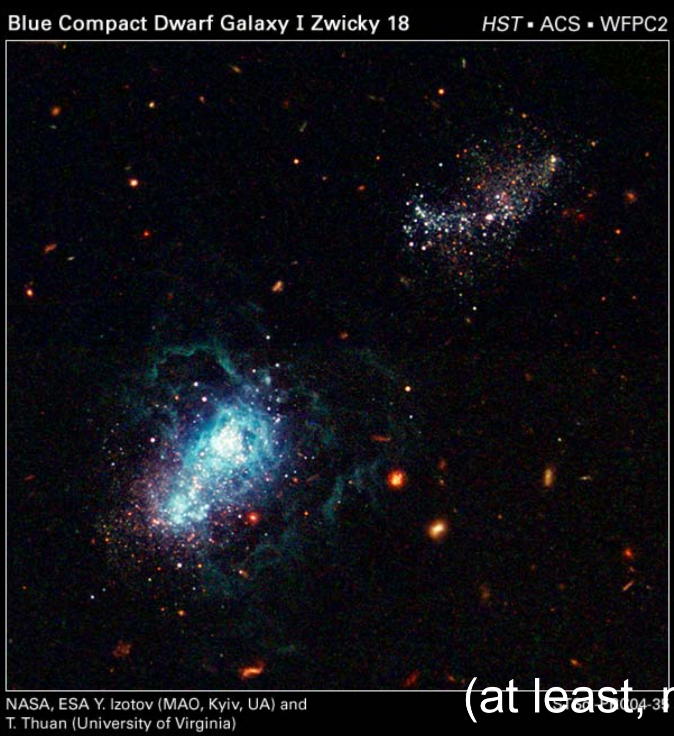


Detection Statistics

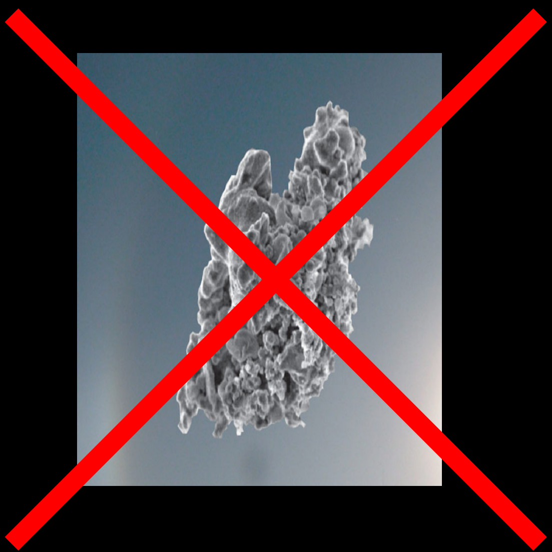
All 23 hosts detected in **all three bands**

(2 not observed with IRAC yet.)

No "ultra-faint" hosts – every host galaxy would have been detected in a deep survey.
(This is *not* true of unobscured GRBs.)

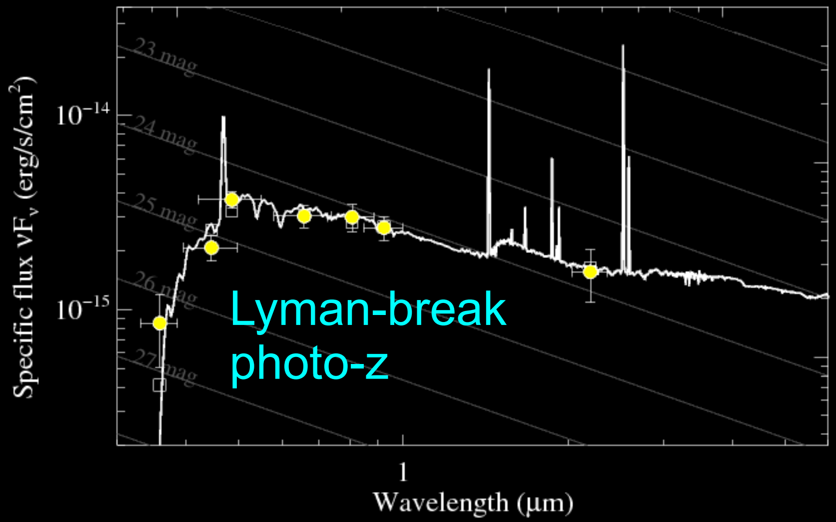


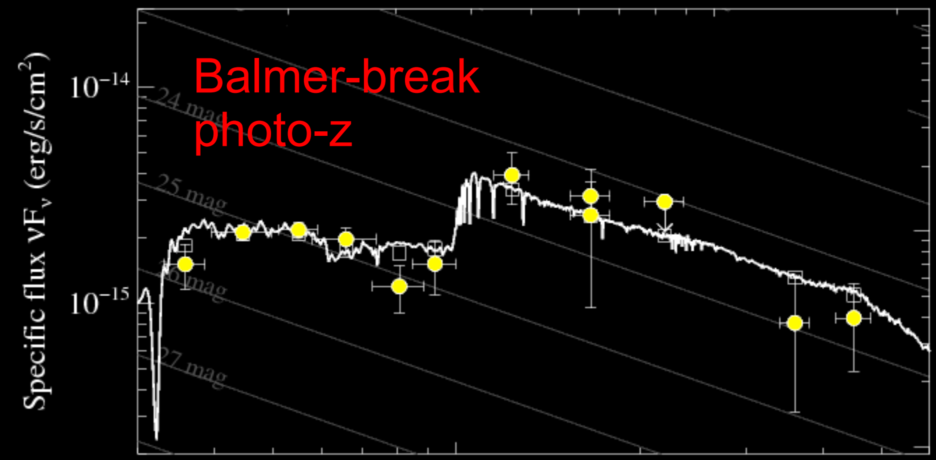
=



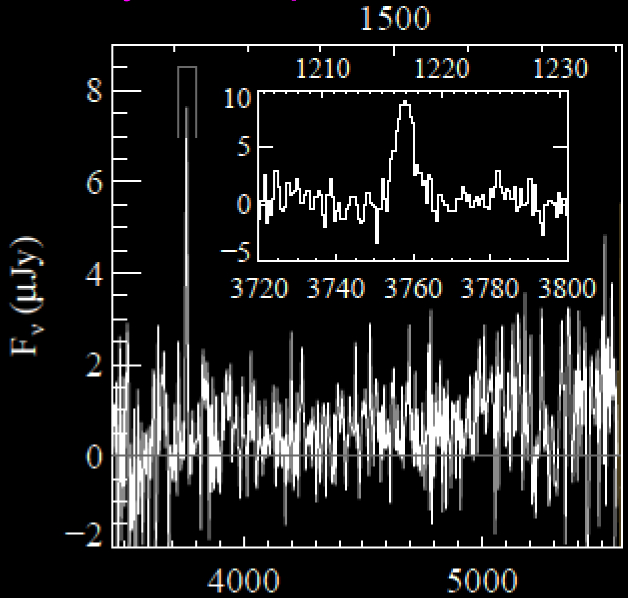
(at least, not commonly: a few post-2009 examples...)

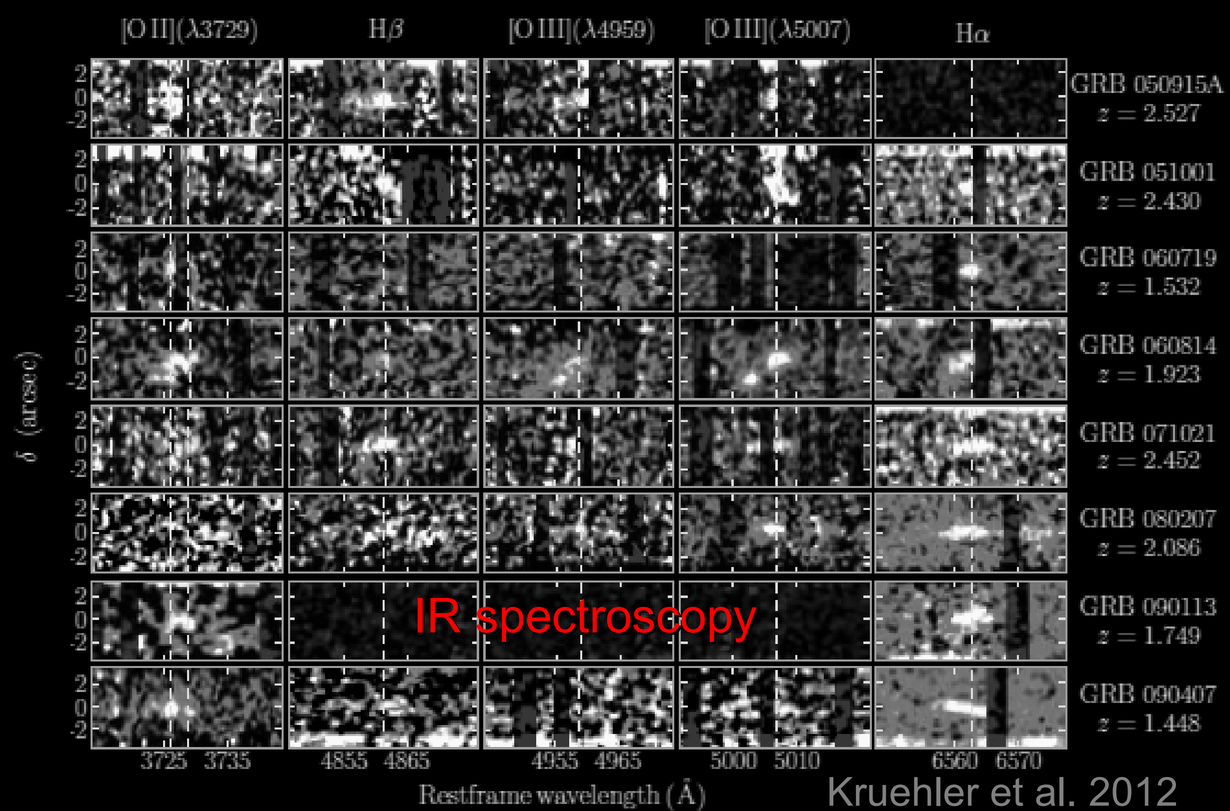
Redshift Measurement





Lyman alpha emission



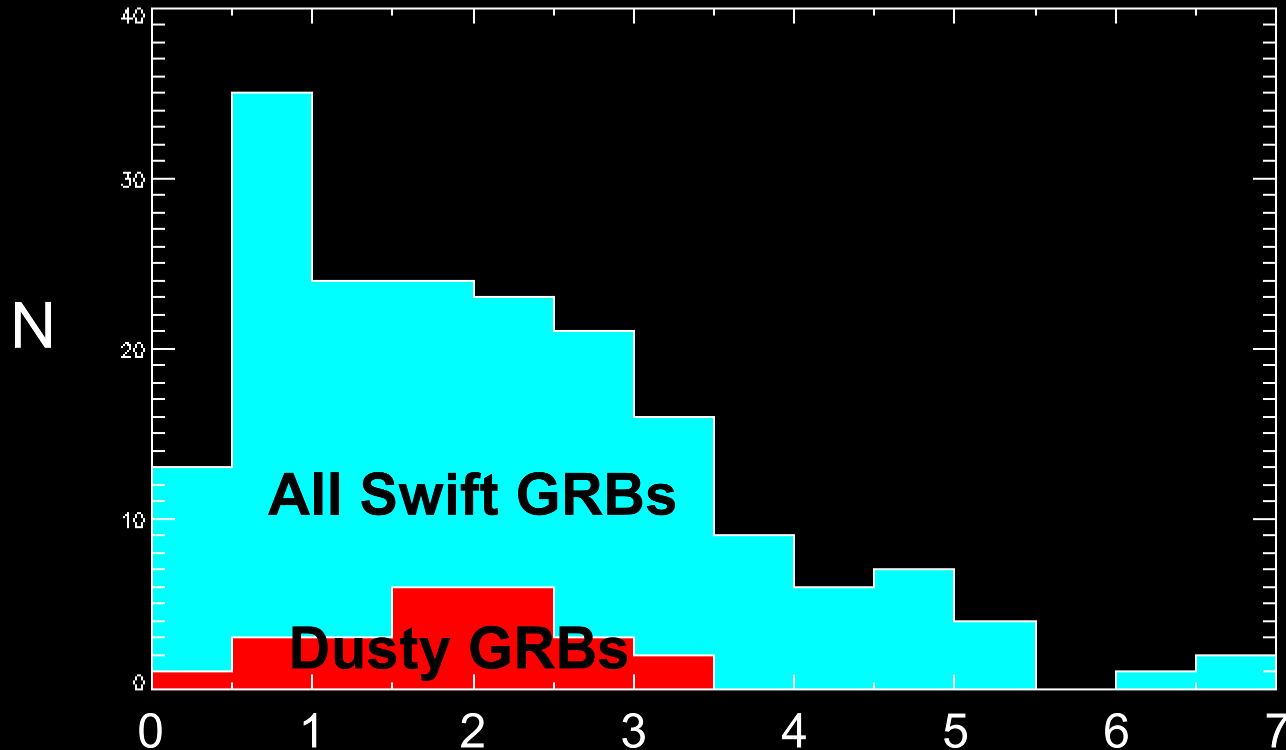


Kruehler et al. 2012

Redshift Distribution

23 / 23 successful redshifts!

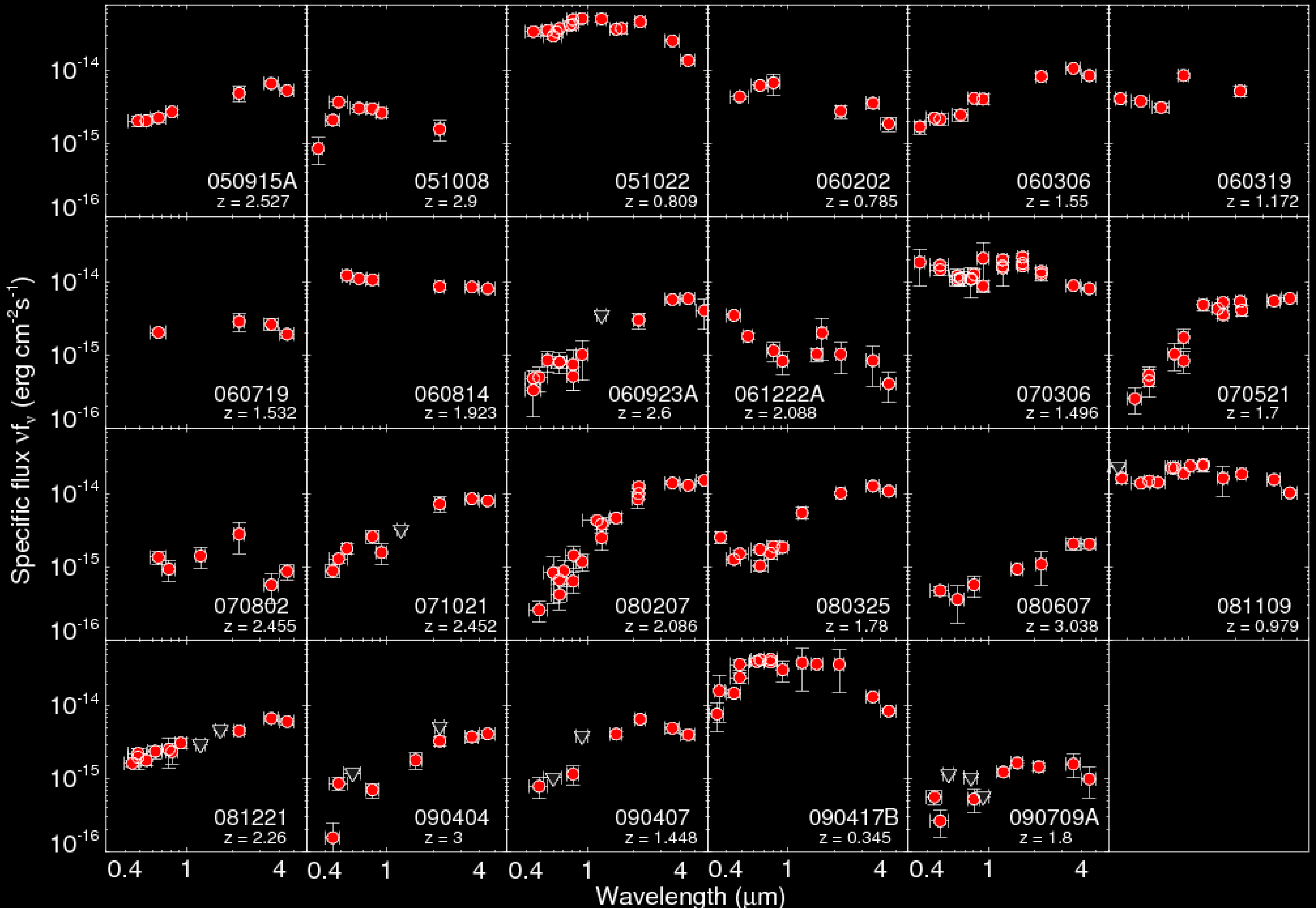
18 spectroscopic, 5 photometric



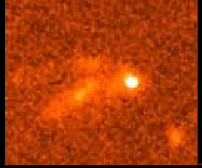
Broadly similar to overall GRB redshift distribution

(possibly more strongly concentrated at z~2 –
not yet significant, and sample-selection biases could matter)

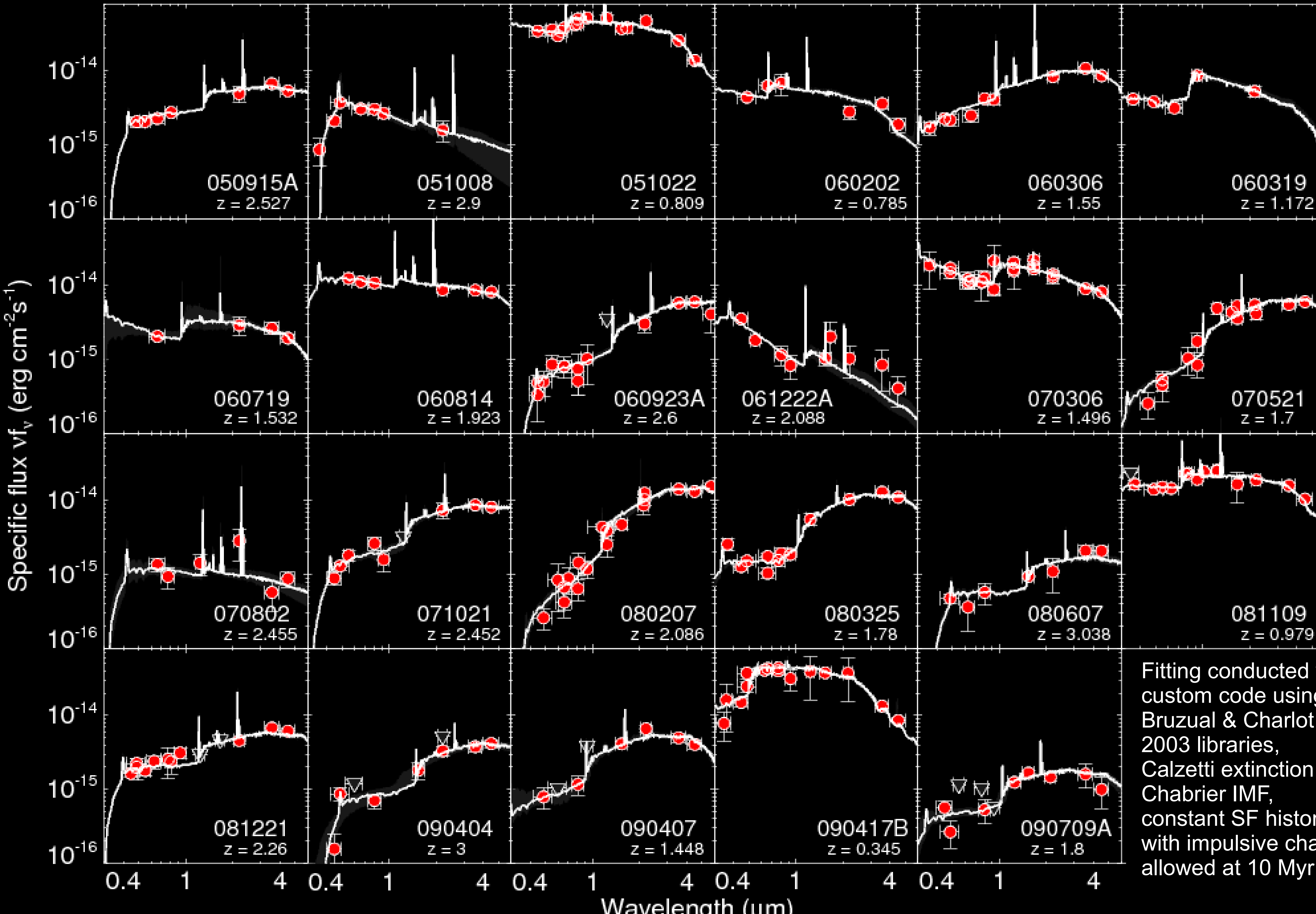
SED Fitting



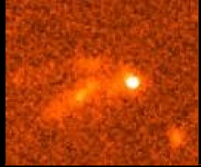
050915A
z = 2.527
051008
z = 2.9
051022
z = 0.809
060202
z = 0.785
060306
z = 1.55
060319
z = 1.172
060719
z = 1.532
060814
z = 1.923
060923A
z = 2.6
061222A
z = 2.088
070306
z = 1.496
070521
z = 1.7
070802
z = 2.455
071021
z = 2.452
080207
z = 2.086
080325
z = 1.78
080607
z = 3.038
081109
z = 0.979
081221
z = 2.26
090404
z = 3
090407
z = 1.448
090417B
z = 0.345
090709A
z = 1.8
Specific flux νf_ν (erg cm^{-2}s^{-1})
10^{-14}
10^{-15}
10^{-16}
0.4
1
4
Wavelength (μm)



SED Fitting



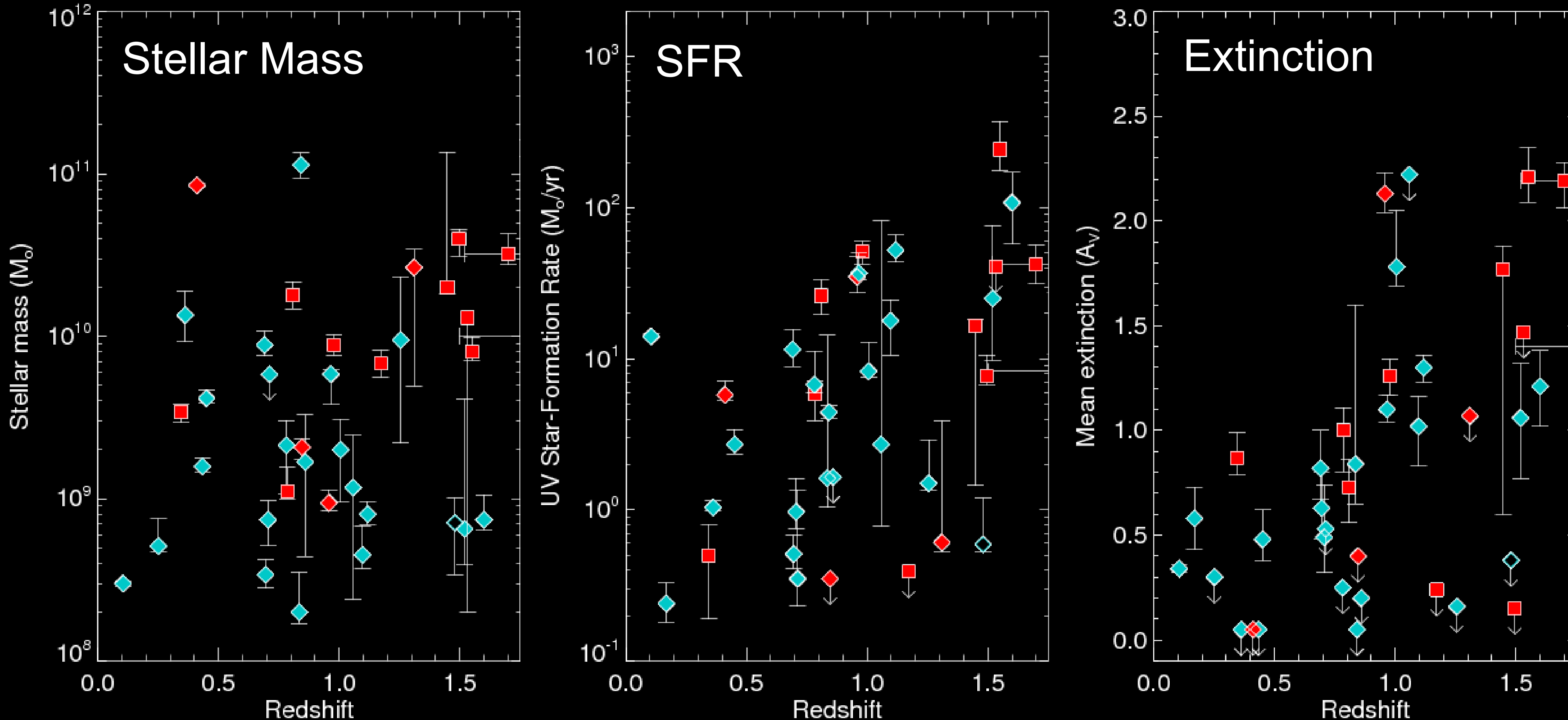
Fitting conducted with custom code using Bruzual & Charlot 2003 libraries, Calzetti extinction, Chabrier IMF, constant SF history with impulsive change allowed at 10 Myr



Obscured vs. Unobscured GRB hosts

Combined pre-Swift + dark sample:

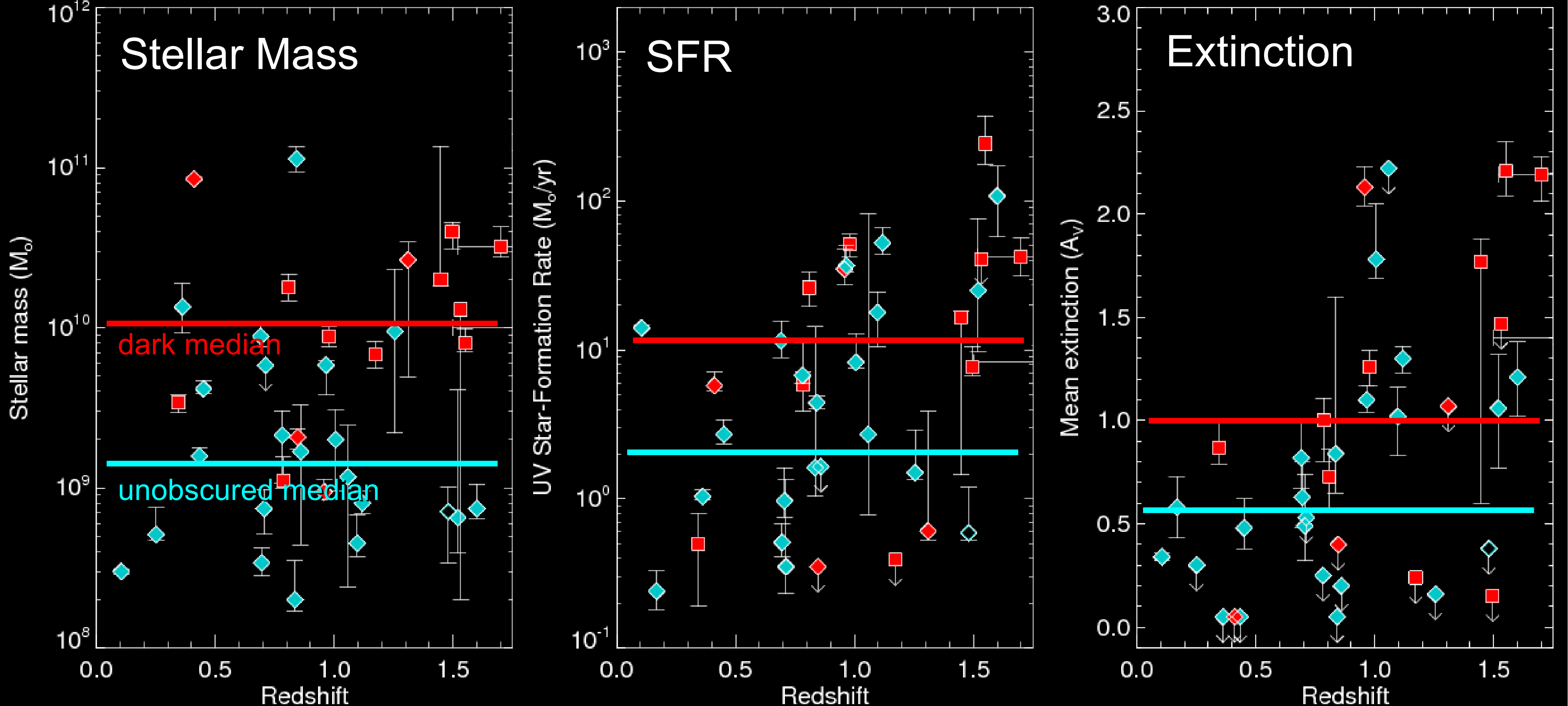
Blue=unobscured GRB, Red = obscured GRB.



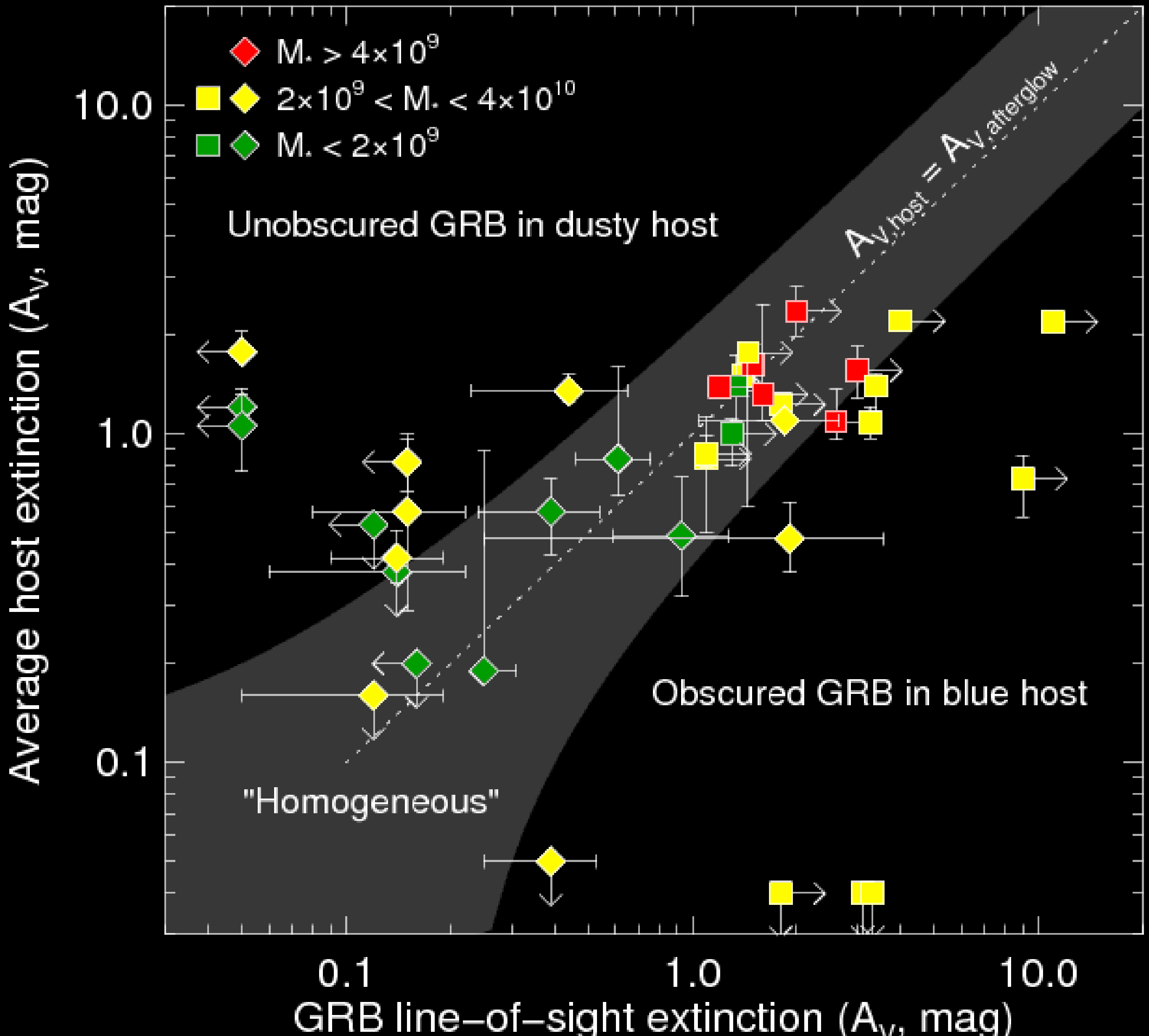
Obscured vs. Unobscured GRB hosts

Dust-obscured GRB hosts are a diverse population – but *on average*, obscured-GRB hosts are more massive, star-forming, and dusty.

Combined pre-Swift + dark sample: Blue=unobscured GRB, Red = obscured GRB.

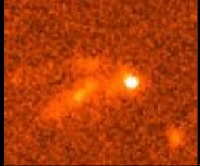


Obscured vs. Unobscured GRB hosts



GRB and host extinction correlate:

Dust in high-z galaxies is fairly homogeneous, with a few dramatic exceptions.

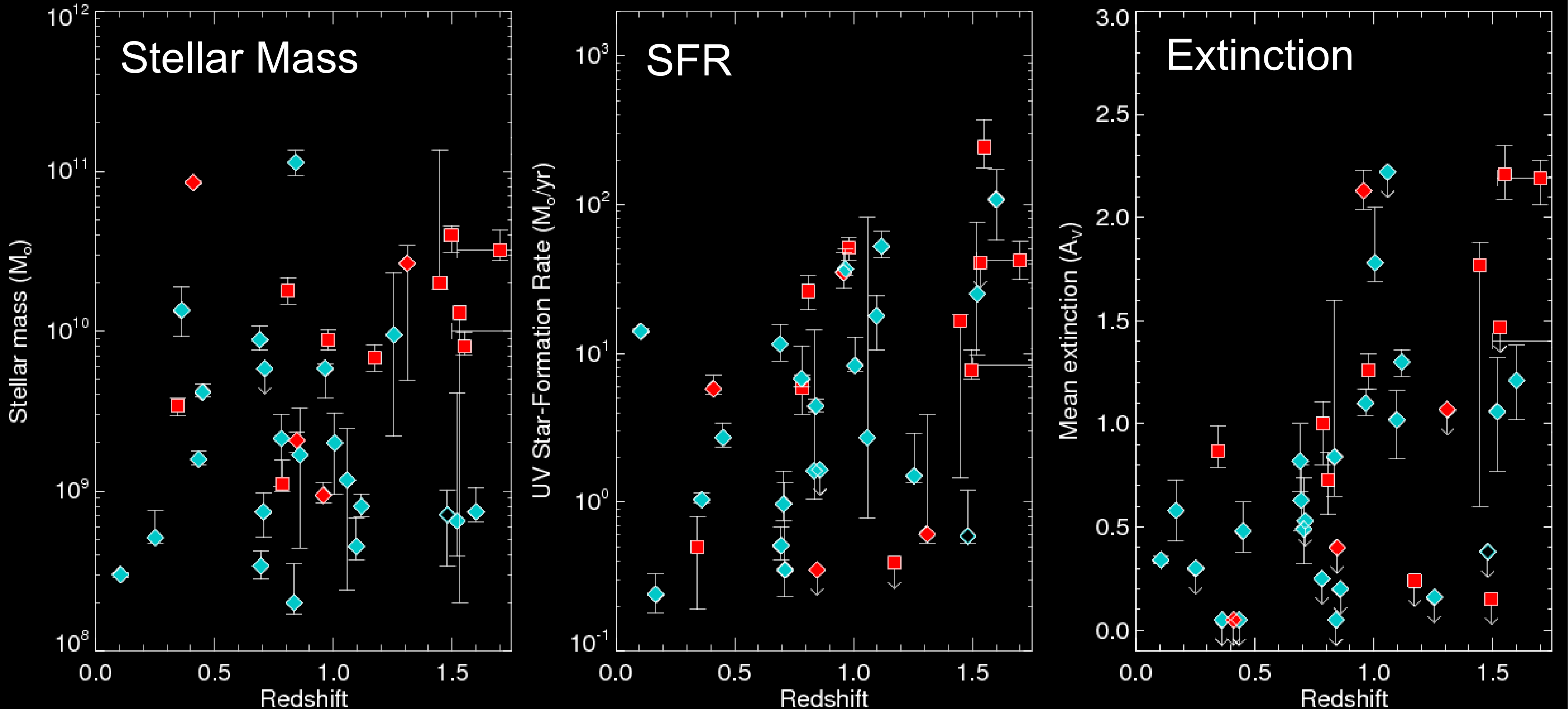


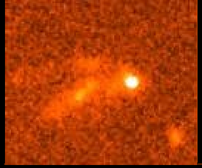
Obscured vs. Unobscured GRB hosts

Dust-obscured GRB hosts are a diverse population – but *on average*, obscured-GRB hosts are more massive, star-forming, and dusty.

Combined pre-Swift + dark sample:

Blue=unobscured GRB, Red = obscured GRB.



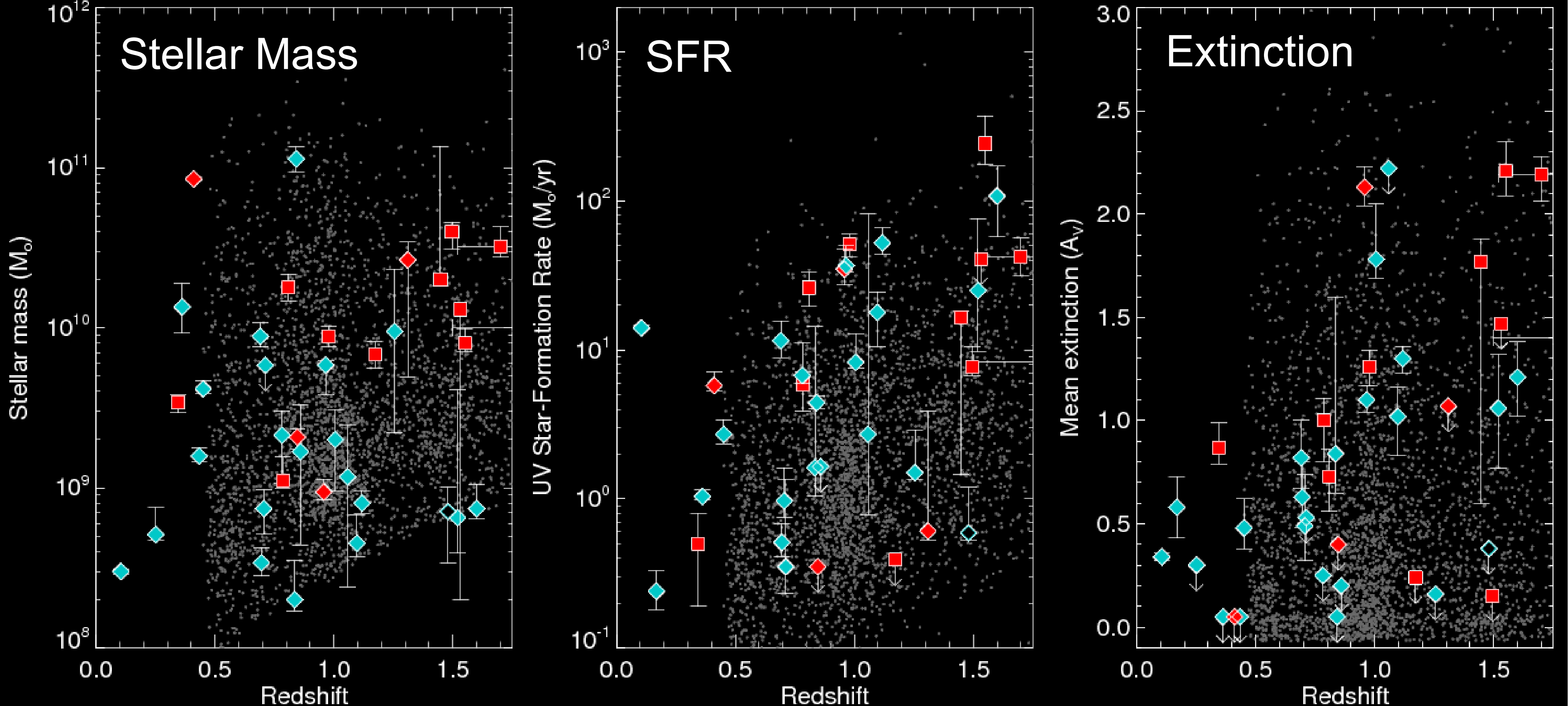


GRBs vs. Field Galaxies at z~1

Properties look “consistent” with field galaxy *number* distributions...

Grey points: field galaxies from MOIRCS deep survey (Kajisawa et al. 2011), omitting AGN (hard X-ray detection).

Combined sample versus field galaxies:

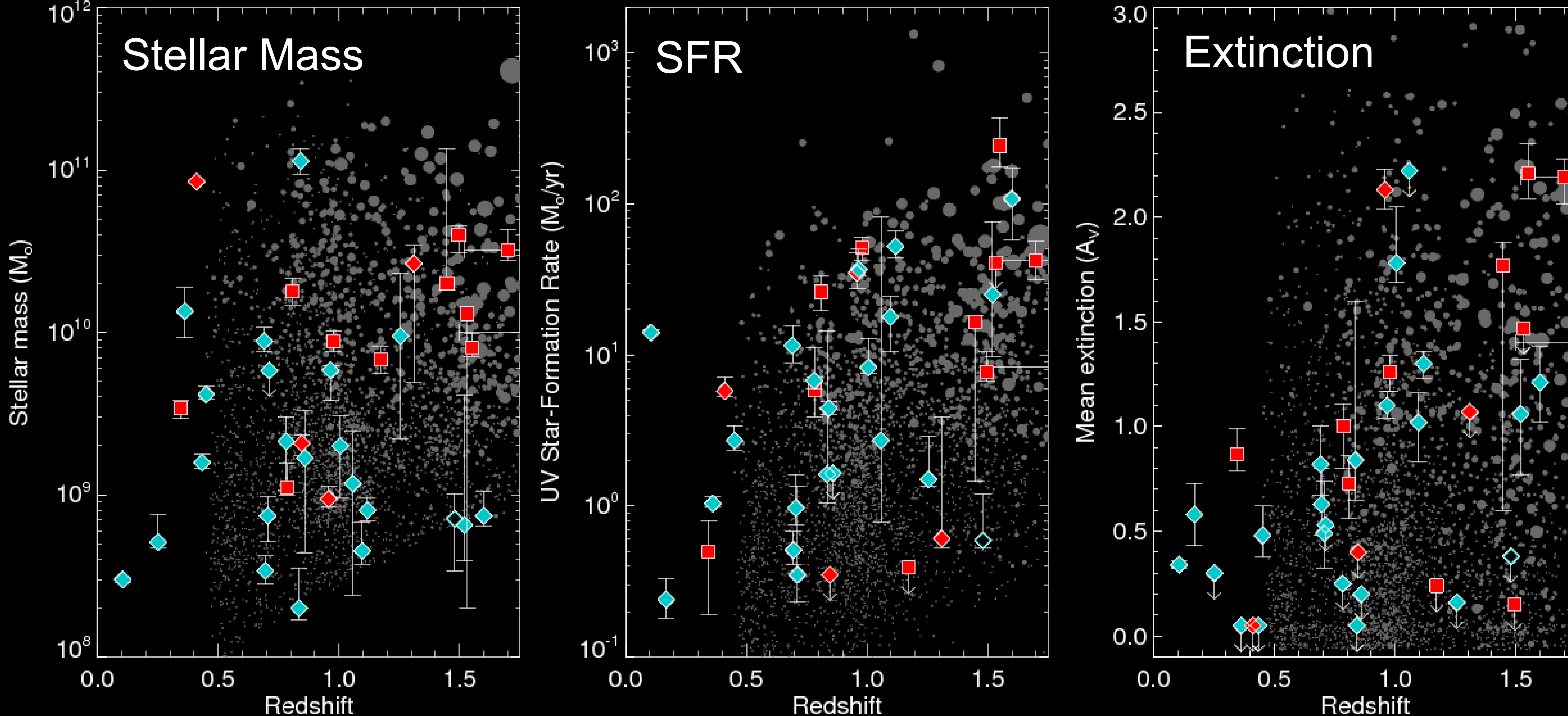


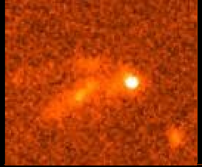
GRBs vs. Field Galaxies at z~1

But need to weight by SFR!

Combined sample versus field galaxies:

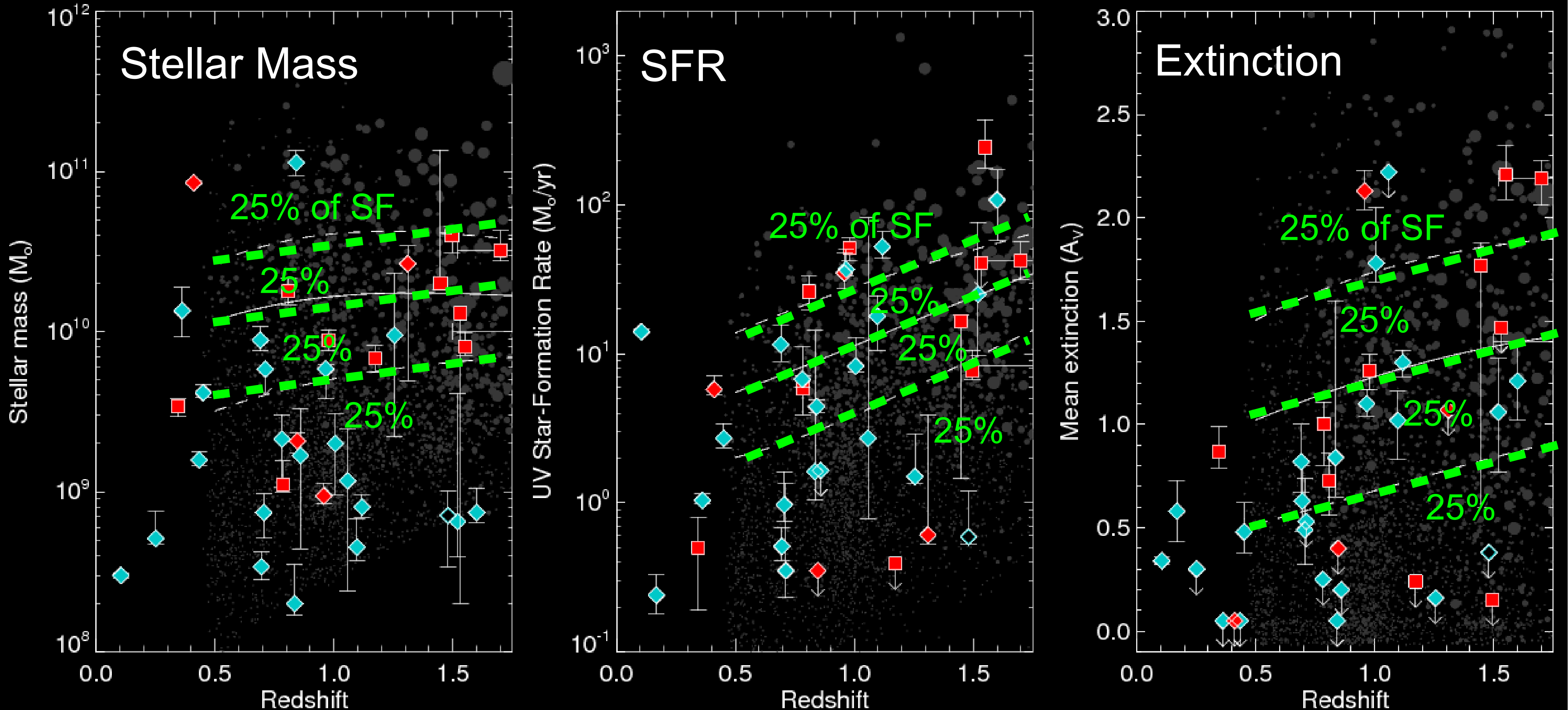
Grey points: field galaxies from MOIRCS deep survey (Kajisawa et al. 2011), omitting AGN (hard X-ray detection). Point size scaled by UV+IR SFR.

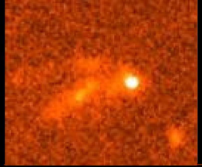




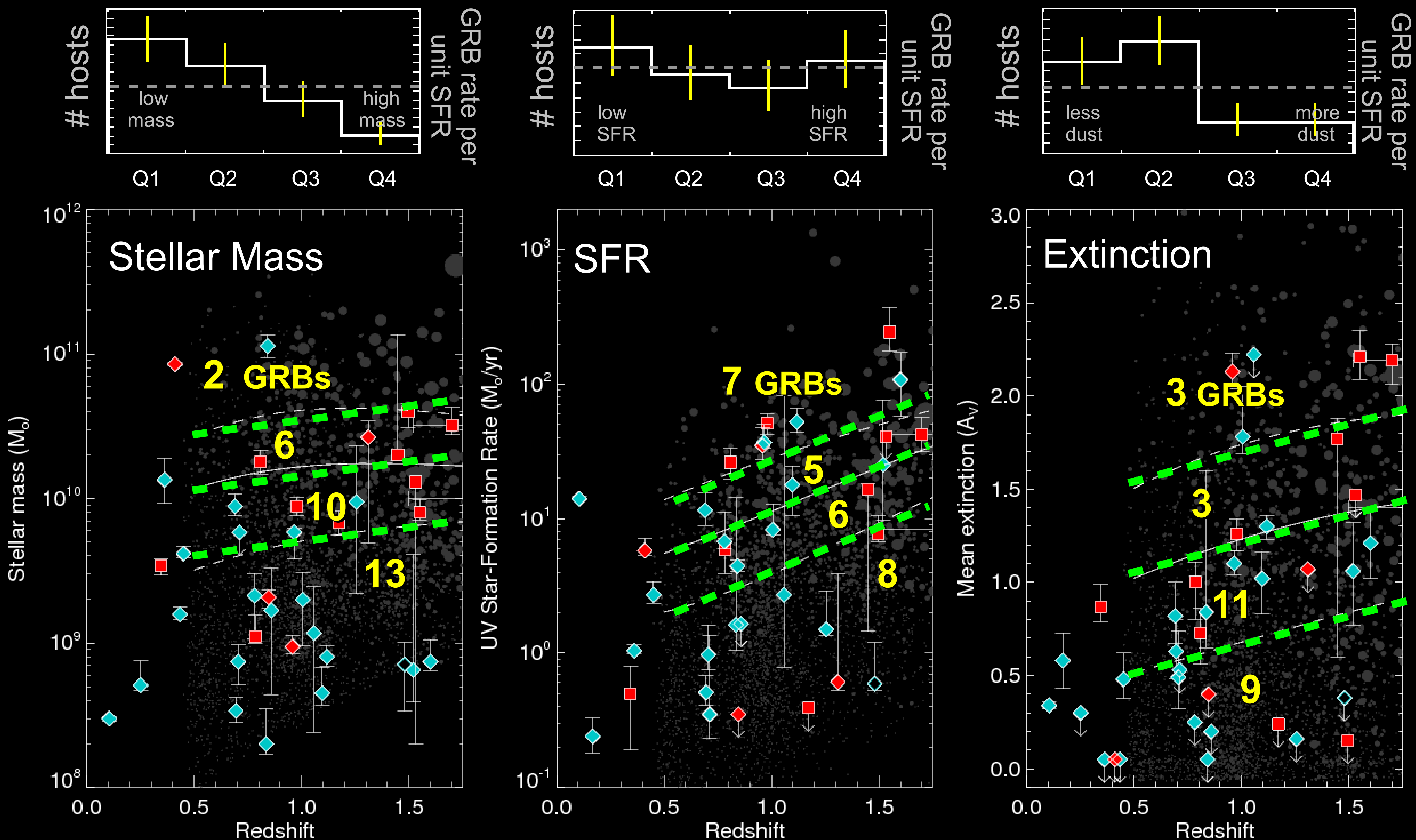
GRBs vs. Field Galaxies at z~1

Calculated *predicted quartile boundaries* of a SFR-weighted galaxy distribution as a function of redshift. If RGRB ∝ SFR then GRBs should distribute evenly among the 4 quartiles (modulo statistics.)

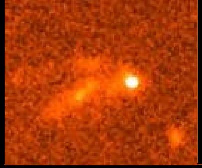


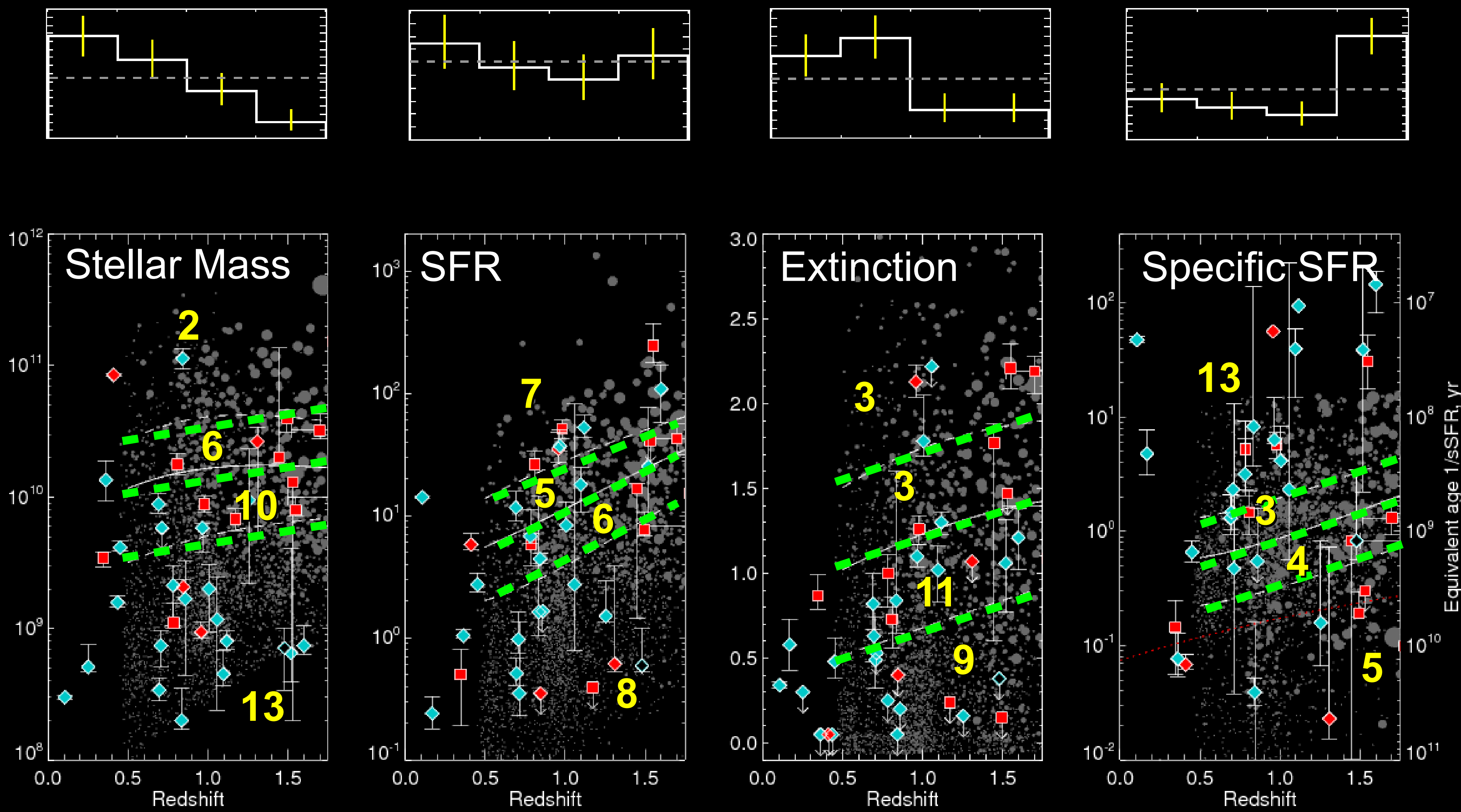


GRBs vs. Field Galaxies at z~1



Origins of GRB Rate Variations



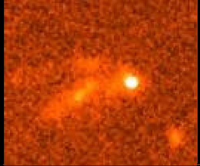


GRBs vs. Field Galaxies at z~1

GRBs are poor tracers of (at least) 50-75% of star-formation at z~1.

GRB rate *per unit SFR* is strongly depends (factor of ~5) on stellar mass (metallicity, chemical effects), but is not clearly dependent on SFR (UV intensity, gas temperature)*.

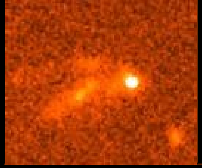
* But it is dependent on specific SFR – may be related to metallicity dependence also (under investigation).



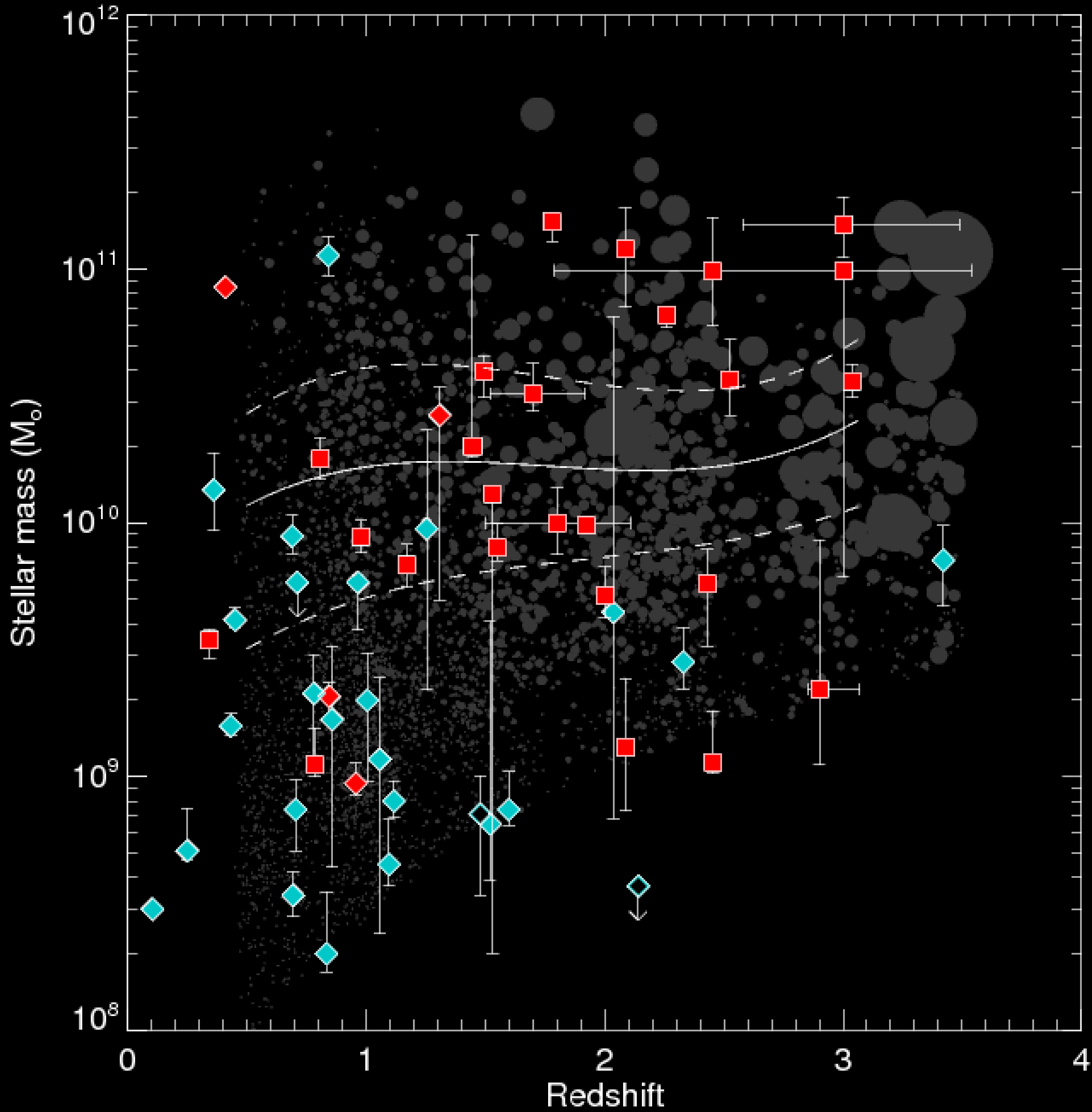
Moving beyond z>1.5

Are GRBs unbiased tracers of star-formation at...

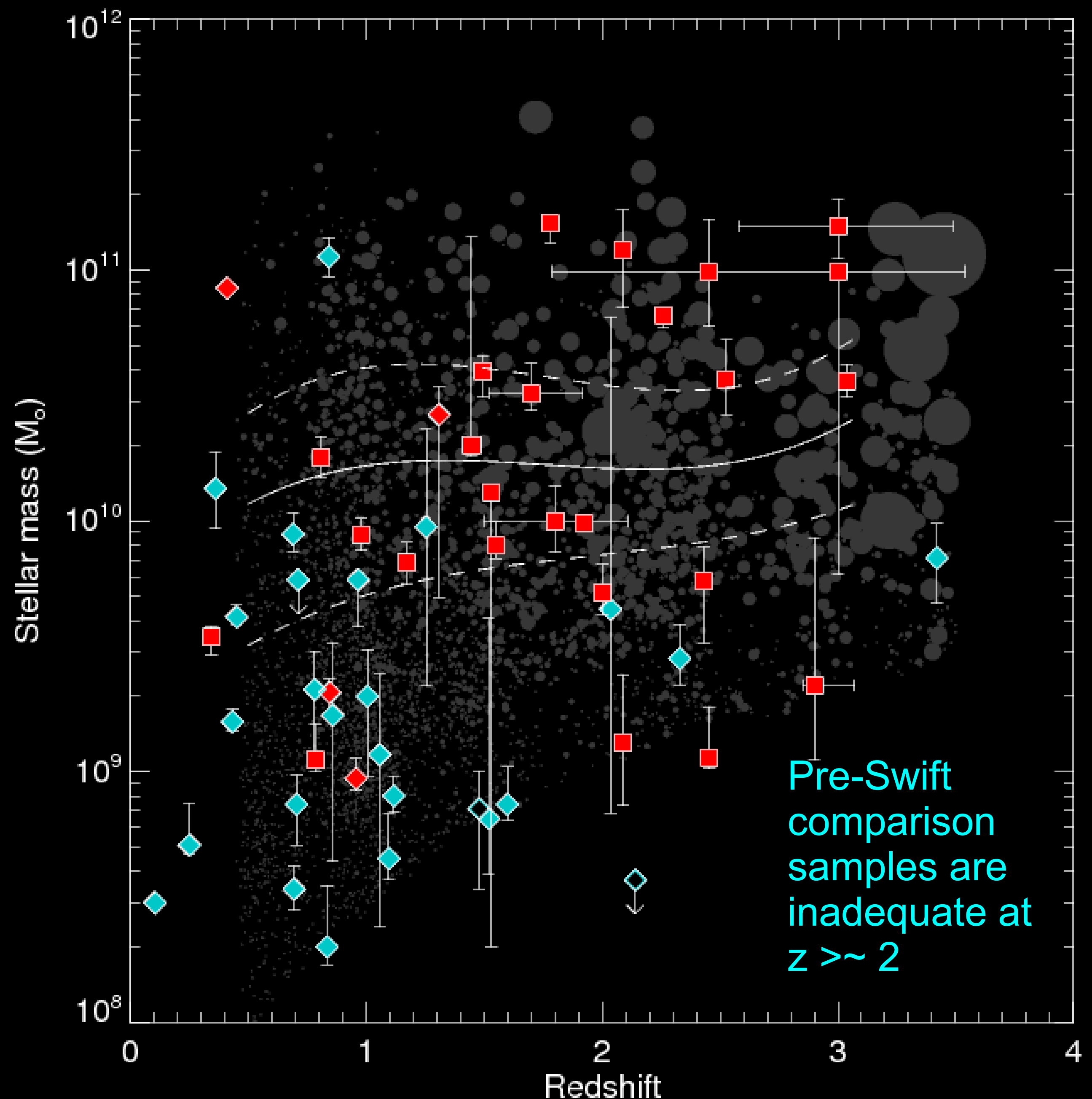
- ☒ z ~ 1?
- ☐ z ~ 2?
- ☐ z ~ 3?
- ☐ z > 4?



Moving beyond z>1.5



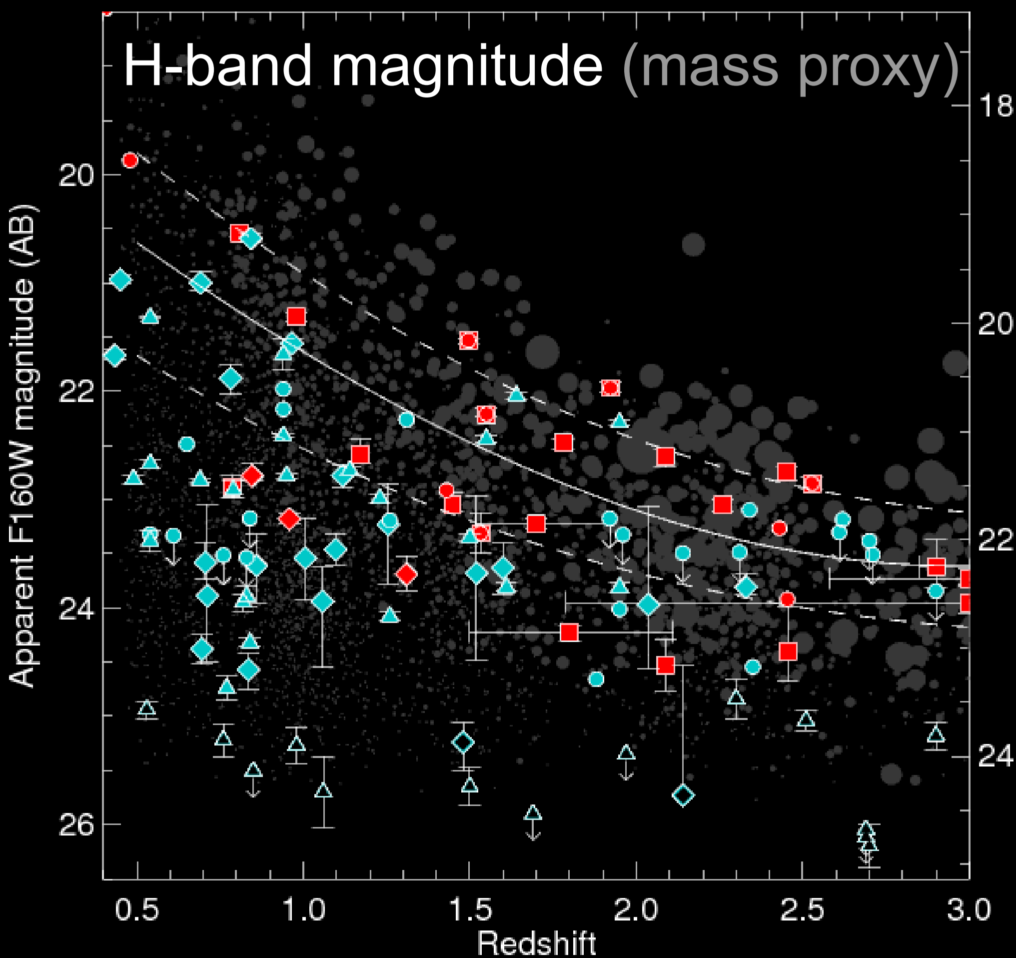
Moving beyond z>1.5

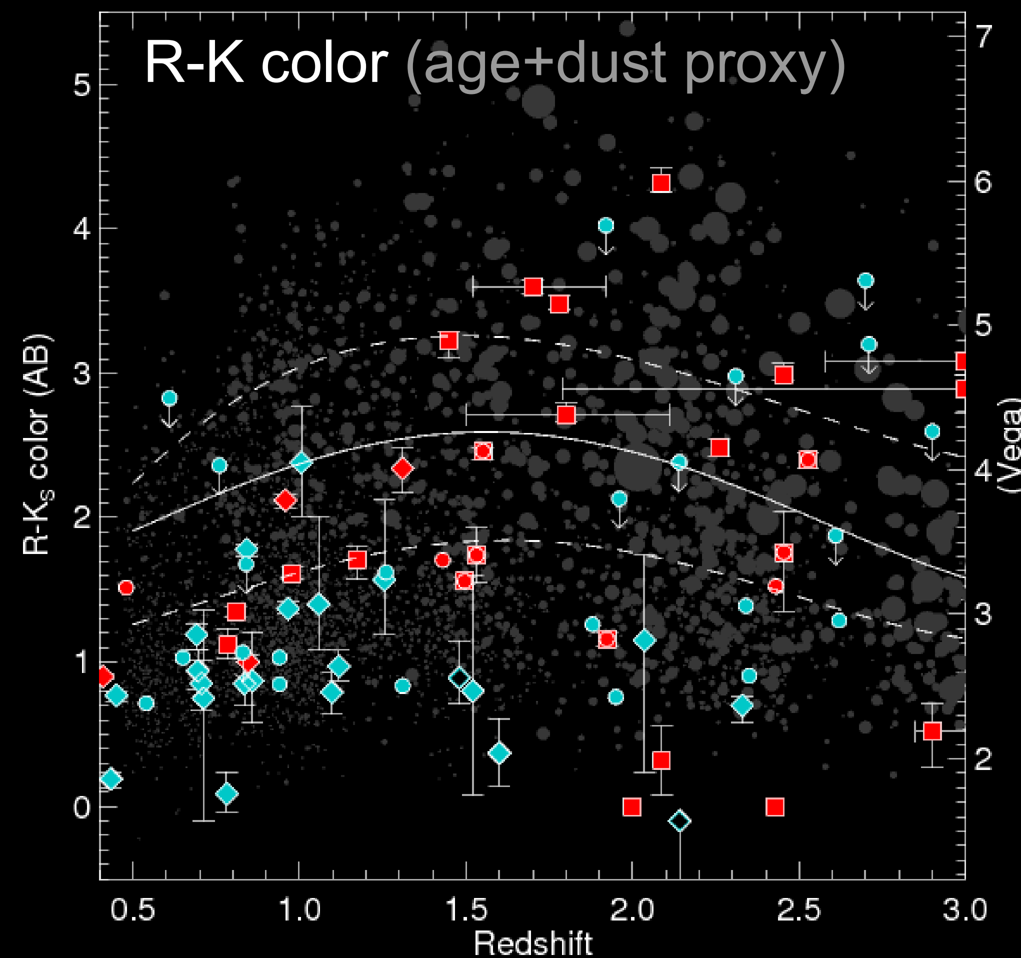


GRBs vs SFR at z~2

Use magnitudes and colors as substitutes for formal SED modeling.

Dark + pre-Swift + Snapshot + VLT

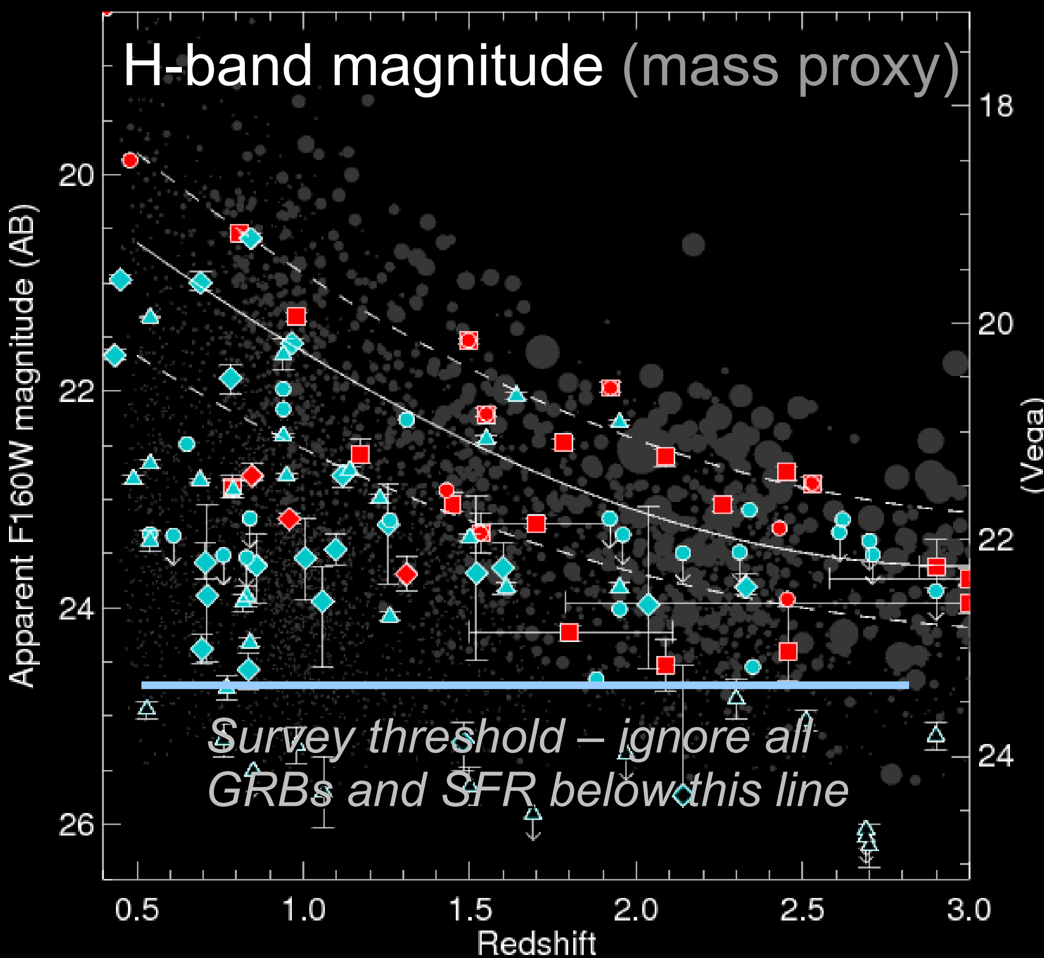


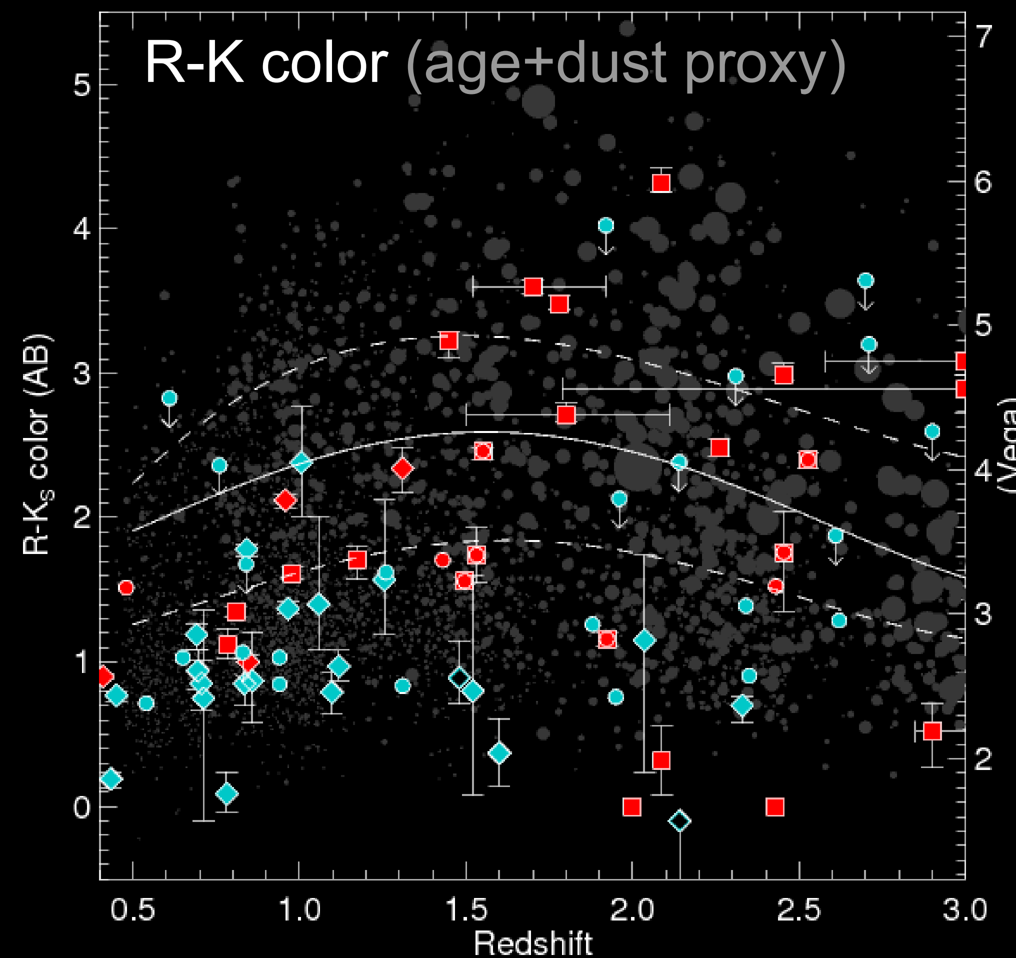


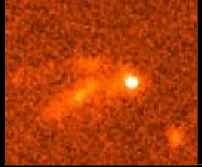
GRBs vs SFR at z~2

Use magnitudes and colors as substitutes for formal SED modeling.

Dark + pre-Swift + Snapshot + VLT



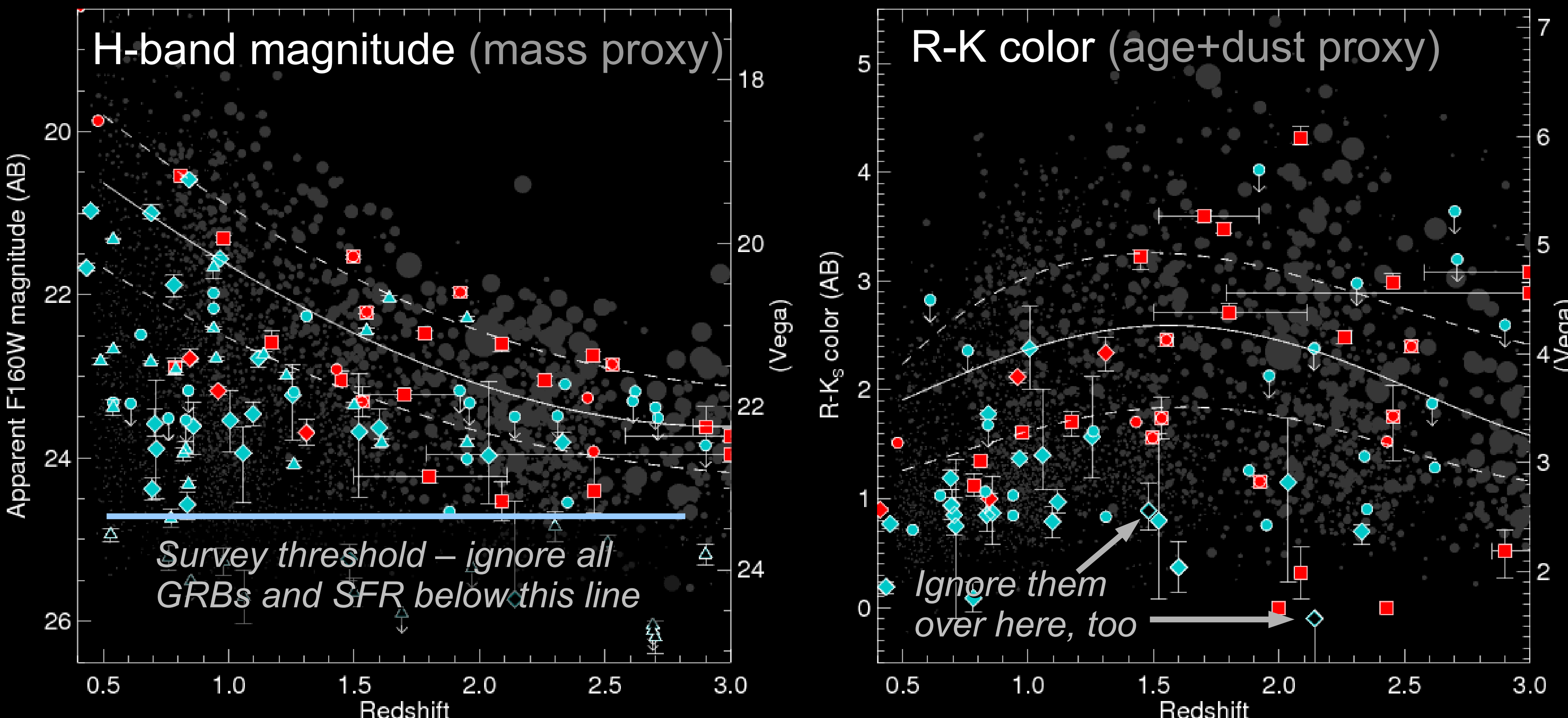




GRBs vs SFR at z~2

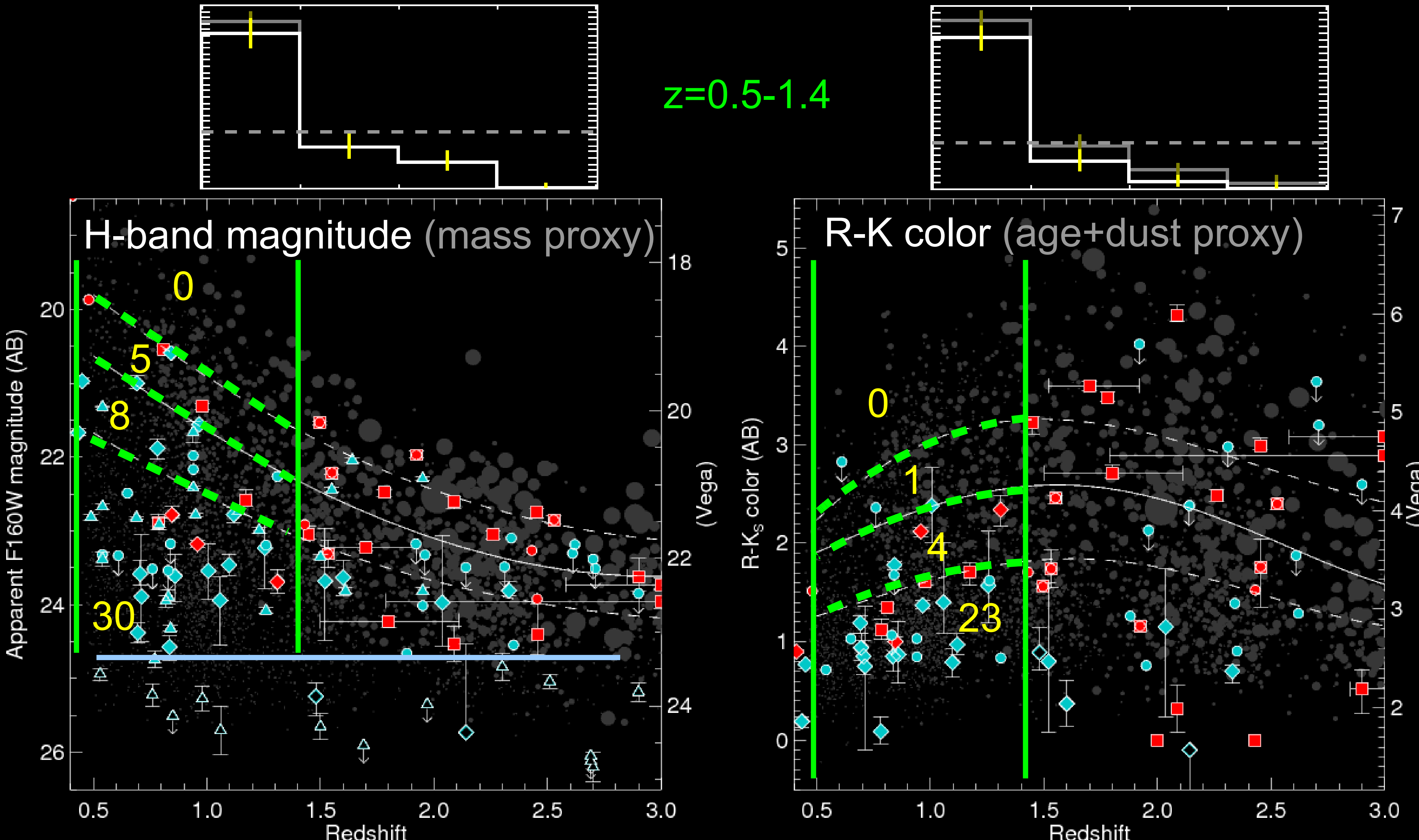
GRB hosts can probe down to faint galaxies not accounted for in field surveys – simply throw these out to keep comparison fair.

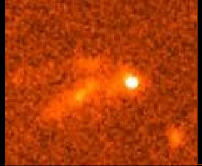
Dark + pre-Swift + Snapshot + VLT



GRBs vs SFR at z~1

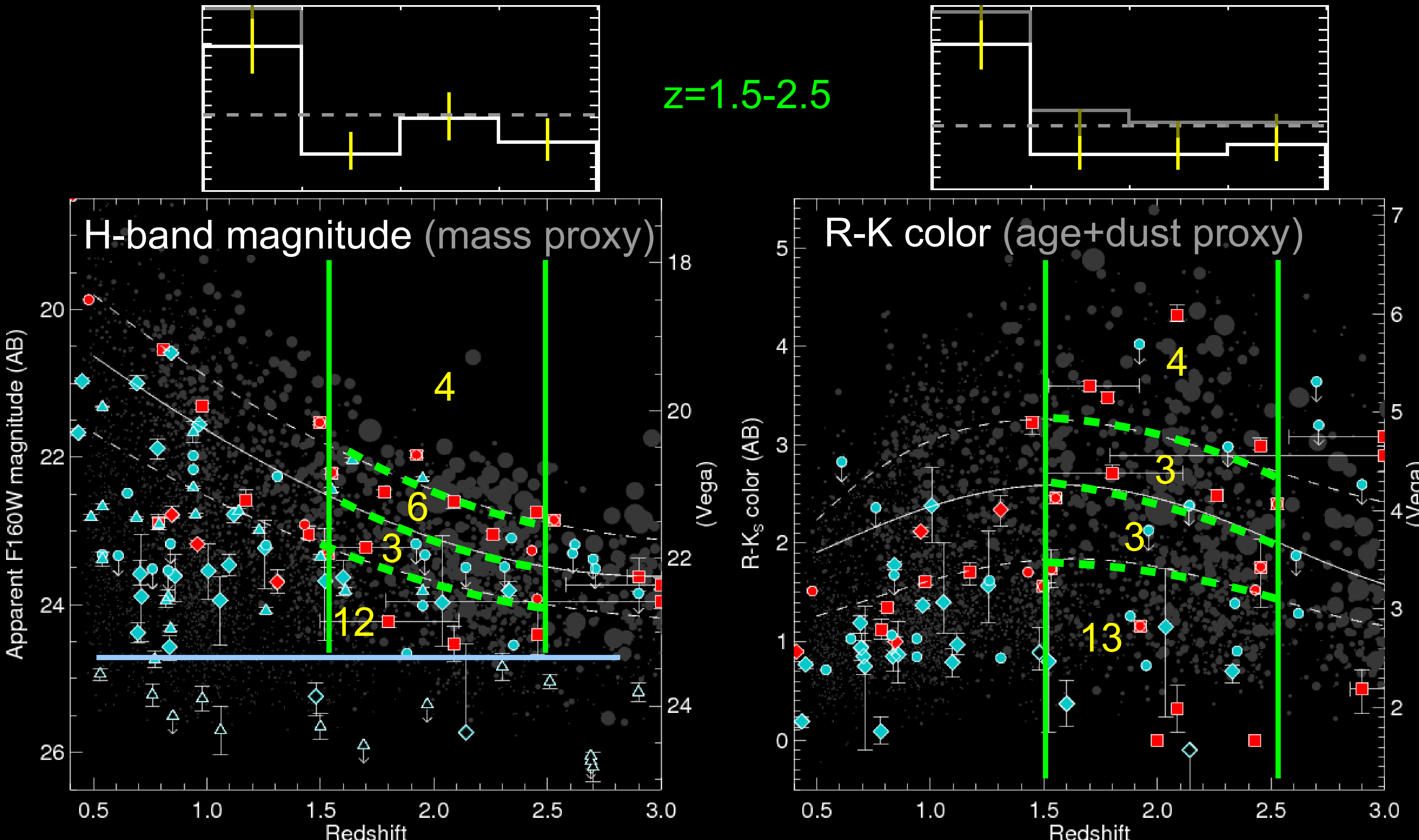
Divide by star-formation quartiles, repeating analysis at z~1 first:





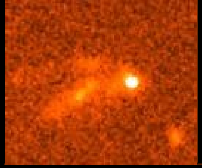
GRBs vs SFR at z~2

Divide by star-formation quartiles at z~2. Trend still present (but less pronounced)



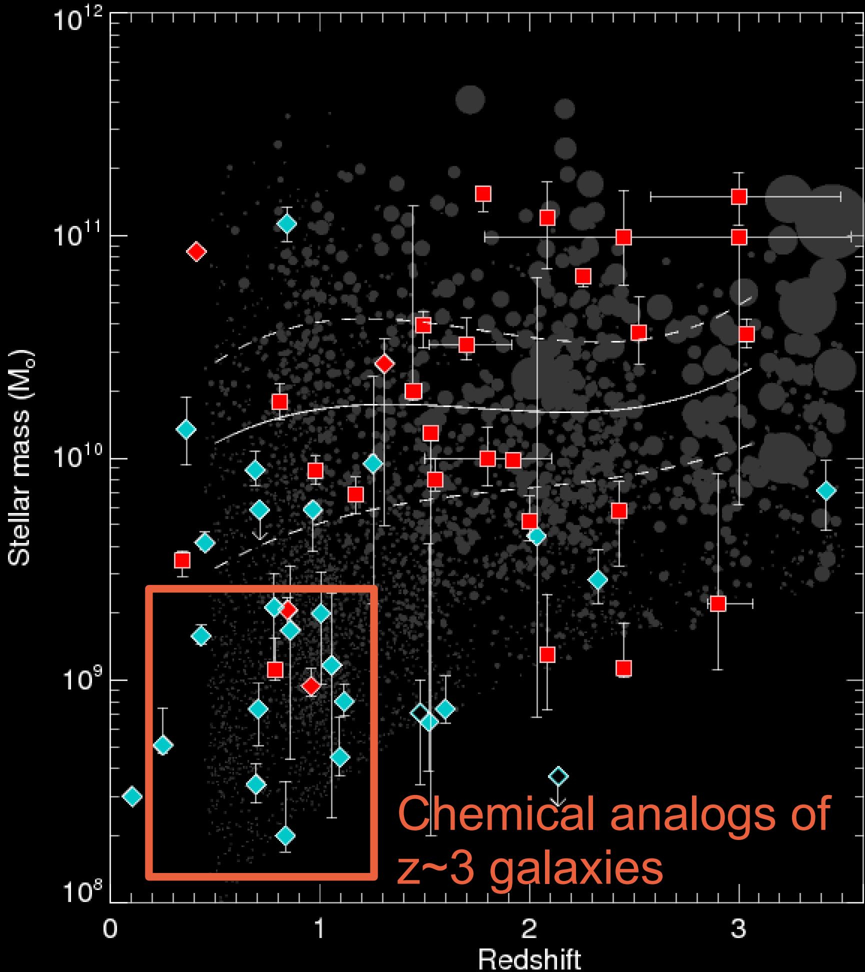
Are GRBs unbiased tracers of star-formation at...

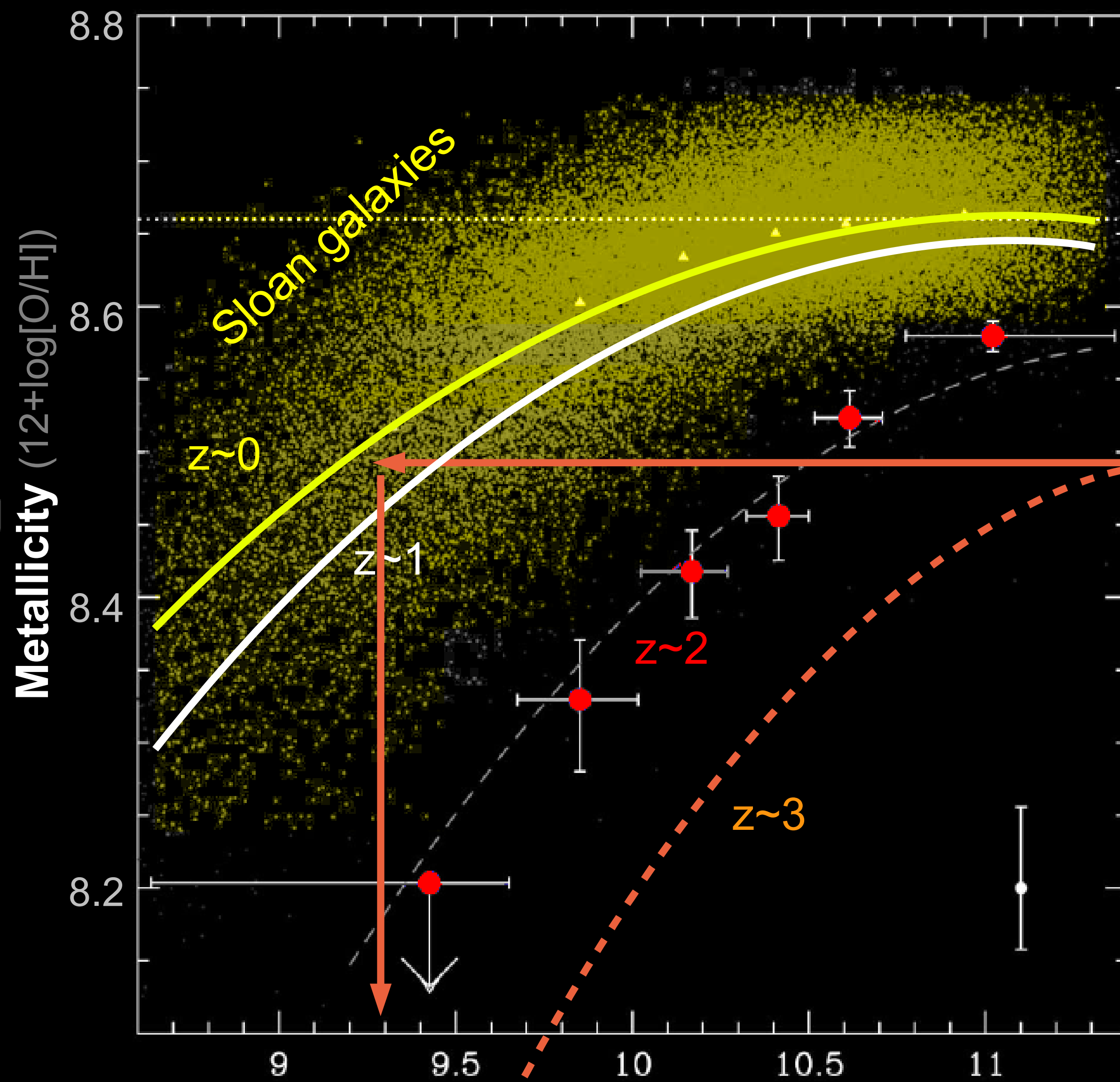
- [x] $z \sim 1$?
- [x] $z \sim 2$?
- [ ] $z \sim 3$?
- [ ] $z > 4$?



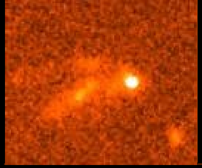
Is There Hope for High Redshift?

Massive z~3 galaxies
should have similar metallicity to
~2×10⁹ Mₒ, z~1 galaxies

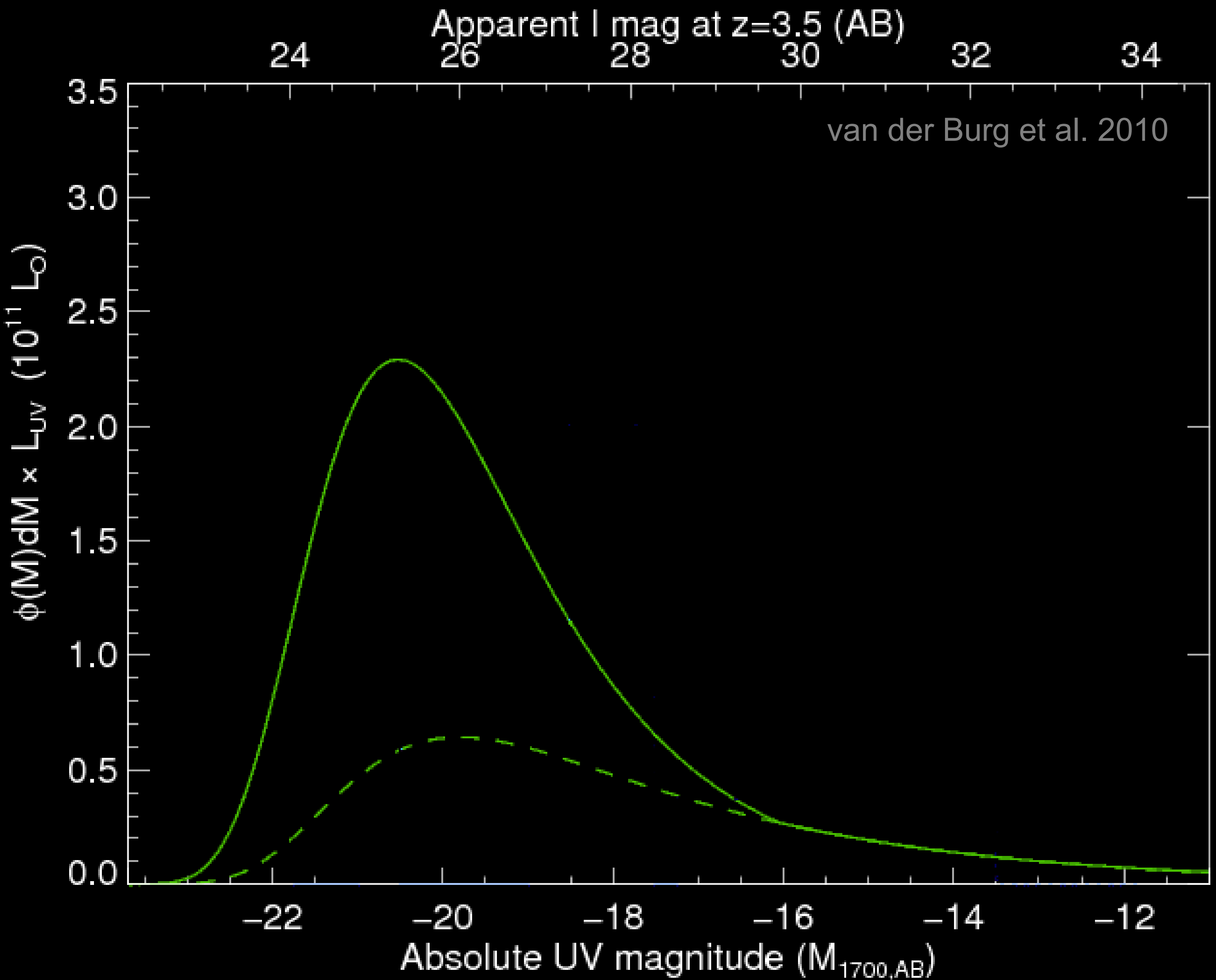




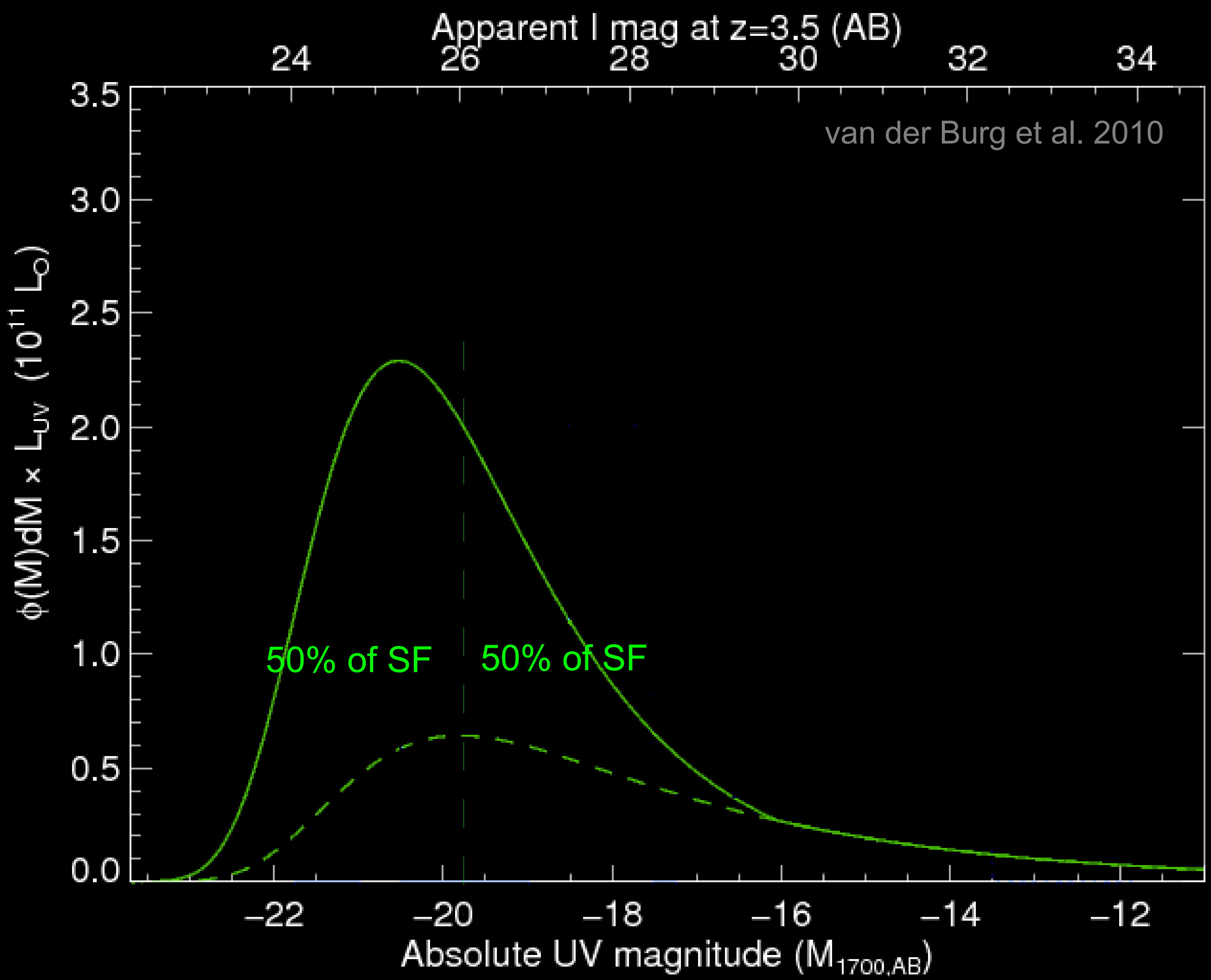
A massive z~3.5 galaxy should have similar metallicity to a typical (low-mass) z~0.5 GRB host.



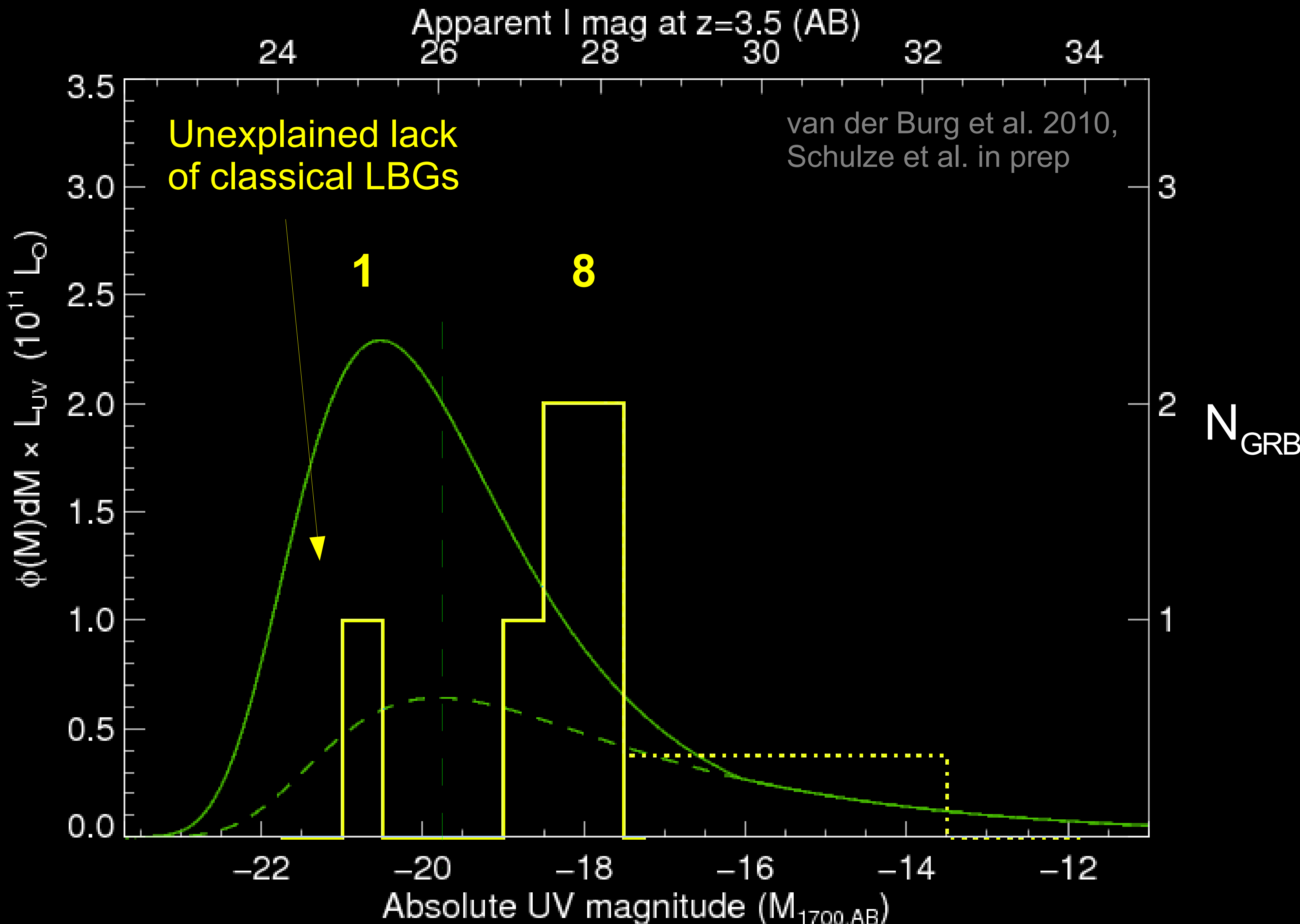
UV luminosity distribution at z~3.5

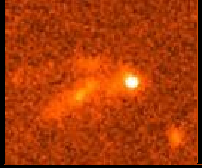


UV luminosity distribution at z~3.5

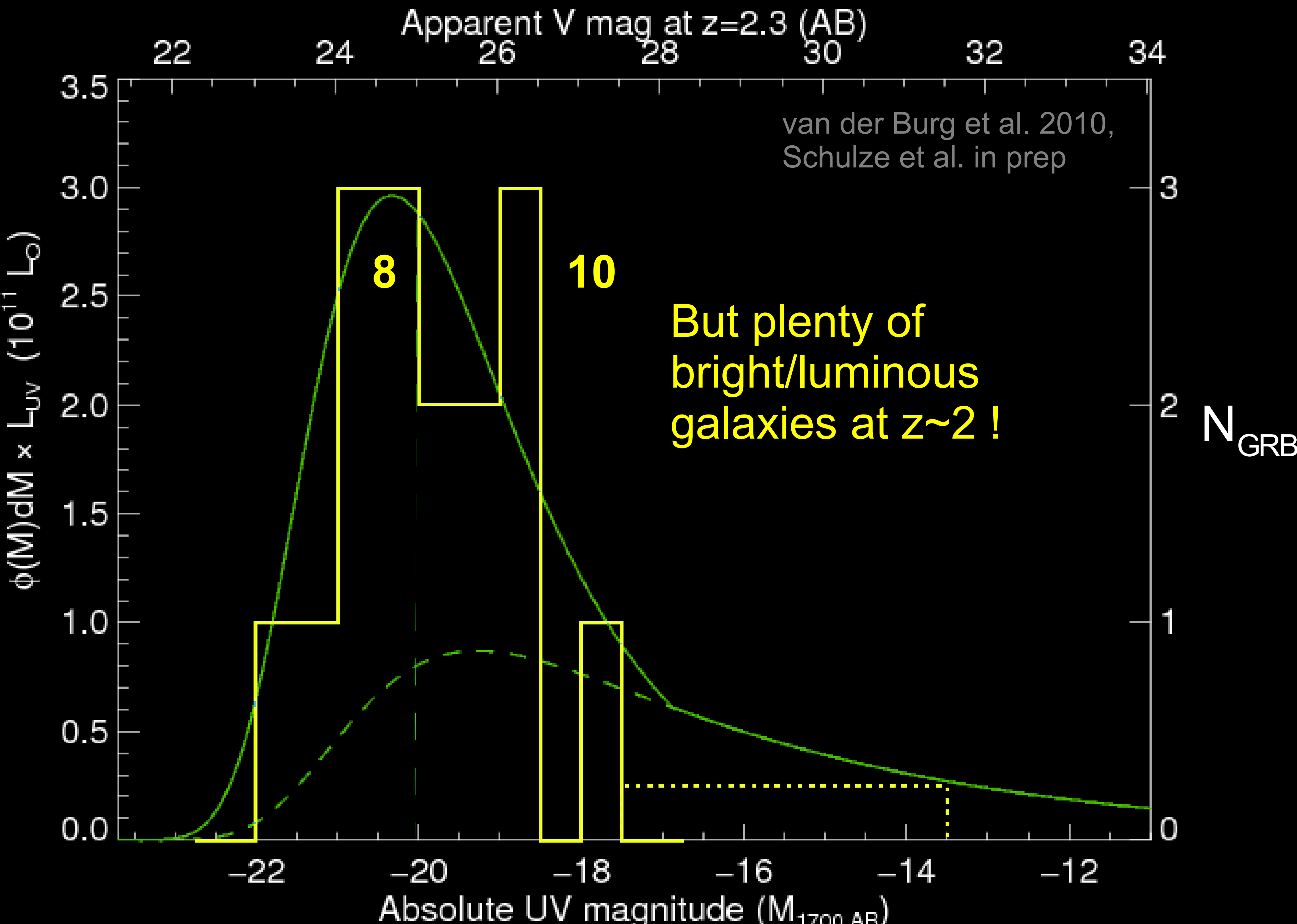


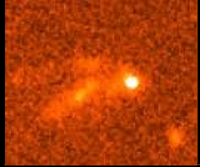
UV luminosity distribution at z~3.5





UV luminosity distribution at z~2





Are GRBs unbiased tracers of star-formation at...

- ☒ z ~ 1?
- ☒ z ~ 2?
- [?] z ~ 3?
- [?] z > 4?

Conclusions

Dust-obscured GRB hosts: diverse, massive, luminous.

No dusty GRBs in lowest-mass galaxies.
Dust distribution more homogeneous than heterogeneous.

GRBs at z<2 are not unbiased tracers of star-formation.

GRB rate vs. SFR in low-mass galaxies =
- ~10x rate in high-mass galaxies at z~1
- ~4x rate in high-mass galaxies at z~2

Consistent with metallicity dependence.
- Possible secondary effect in high-sSFR galaxies?
- Consolation prize – tracing metal-poor SFR?

GRB hosts at z~3.5 also differ from SFR predictions.

Based on 10 galaxies; not expected from lower-z results
- Apparently *worse* tracers than at z~2?
- Small sample? Dust bias? Luminosity functions in error?

Clearly more work to do to understand the cause and implications!

Cycle 9 *Spitzer* program: observations of 130 *uniformly-selected* hosts